

# FUTURE CIRCULAR COLLIDER AND DETECTORS

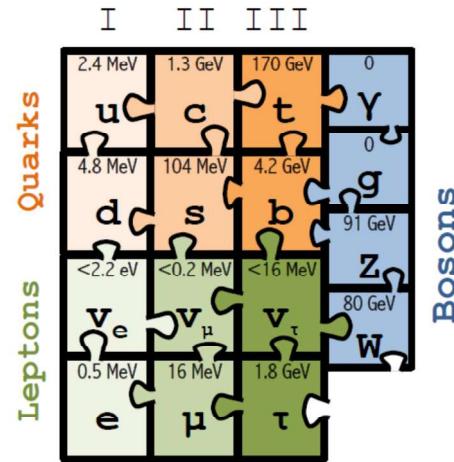


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Scuola rivelatori Cogne  
15 Giugno 2022

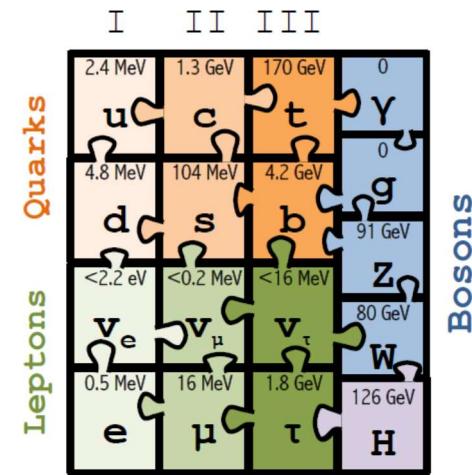
# THE PHYSICS LANDSCAPE

- Particle Physics has arrived at an important moment of its History:

**1989-1999:**  
**Top mass predicted**  
 (LEP  $m_Z$  and  $\Gamma_Z$ )  
**Top quark observed**  
 at the right mass  
 (Tevatron, 1995)  
**Nobel Prize 1999**  
 (t'Hooft & Veltman)



**1997-2013:**  
**Higgs mass cornered**  
 (LEP EW + Tevatron  $m_{top}$ ,  $m_W$ )  
**Higgs boson observed**  
 at the right mass  
 (LHC 2012)  
**Nobel Prize 2013**  
 (Englert & Higgs)



- It looks like the Standard Model is complete and consistent theory
- It describes all observed collider phenomena – and actually all particle physics (except neutrino masses)
  - Was beautifully verified in a complementary manner at LEP, SLC, Tevatron, and LHC
  - EWPO radiative corrections predicted top and Higgs masses assuming SM and nothing else
  - With  $m_H = 125$  GeV, it can even be extrapolated to the Plank scale without the need of New Physics.
- Is it the *END* ?

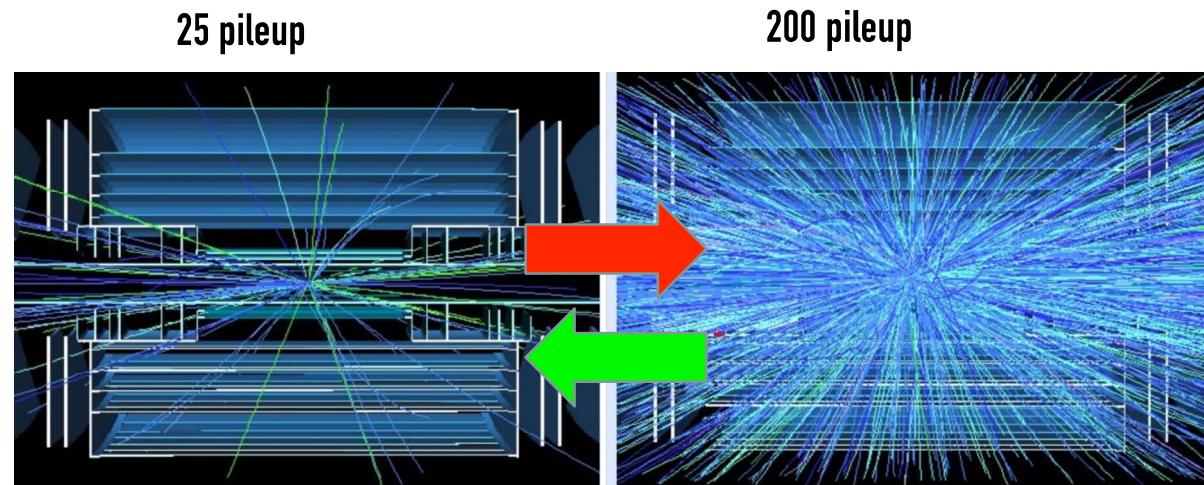
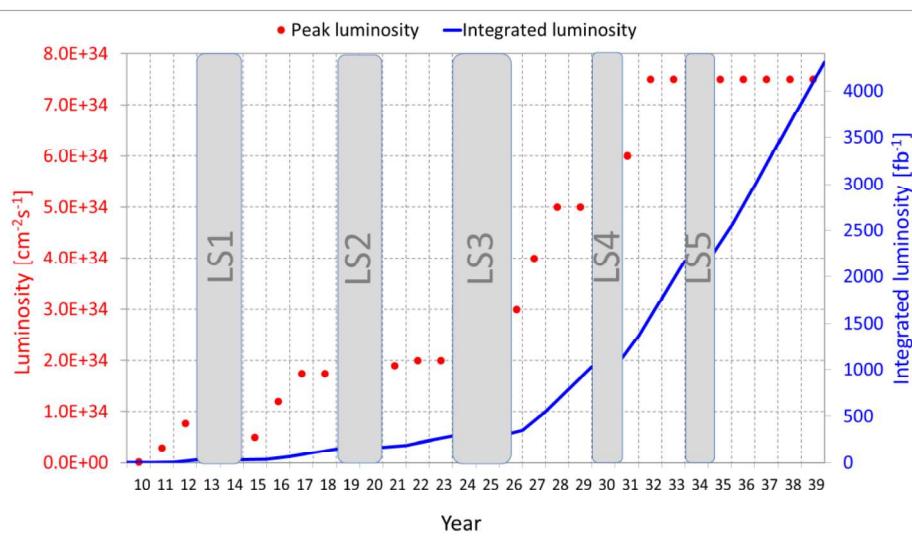
## WHY NEW COLLIDER(S) / EXPERIMENTS?

- We need to extend mass & interaction reach for those phenomena that SM cannot explain:
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
  - Baryon Asymmetry of the Universe
    - Where is anti-matter gone?
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?

These facts require Particle Physics explanations  
We must continue our quest, but HOW ?

## WHERE WE ARE HEADING

- The LHC is still pretty much in its childhood: factor 10 more luminosity to be collected with HL-LHC

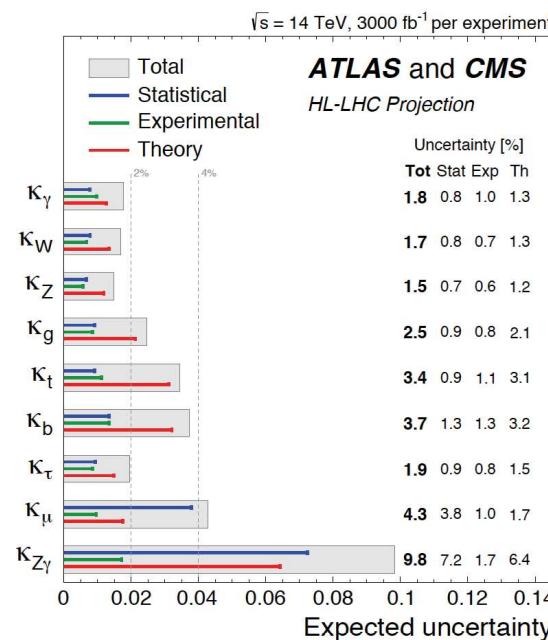


- High luminosity → 200 soft pp interactions per crossing
- Detector elements and electronics are exposed to high radiation dose : requires new tracker, endcap calorimeters, forward muons, replacing readout systems
- We have demonstrated that the new detectors will be able to explore the full physics potential of HL-LHC even in these conditions.

Expected HL-LHC results used as starting point for future machines performance! 4



## Uncertainties on Higgs couplings of the order of 2-4%



## AFTER HL-LHC : HIGGS

HH production  $\sigma \sim 39.5 \text{ fb}@14\text{TeV}$   
Combined sensitivity on  $\lambda_3$  above  $4\sigma$

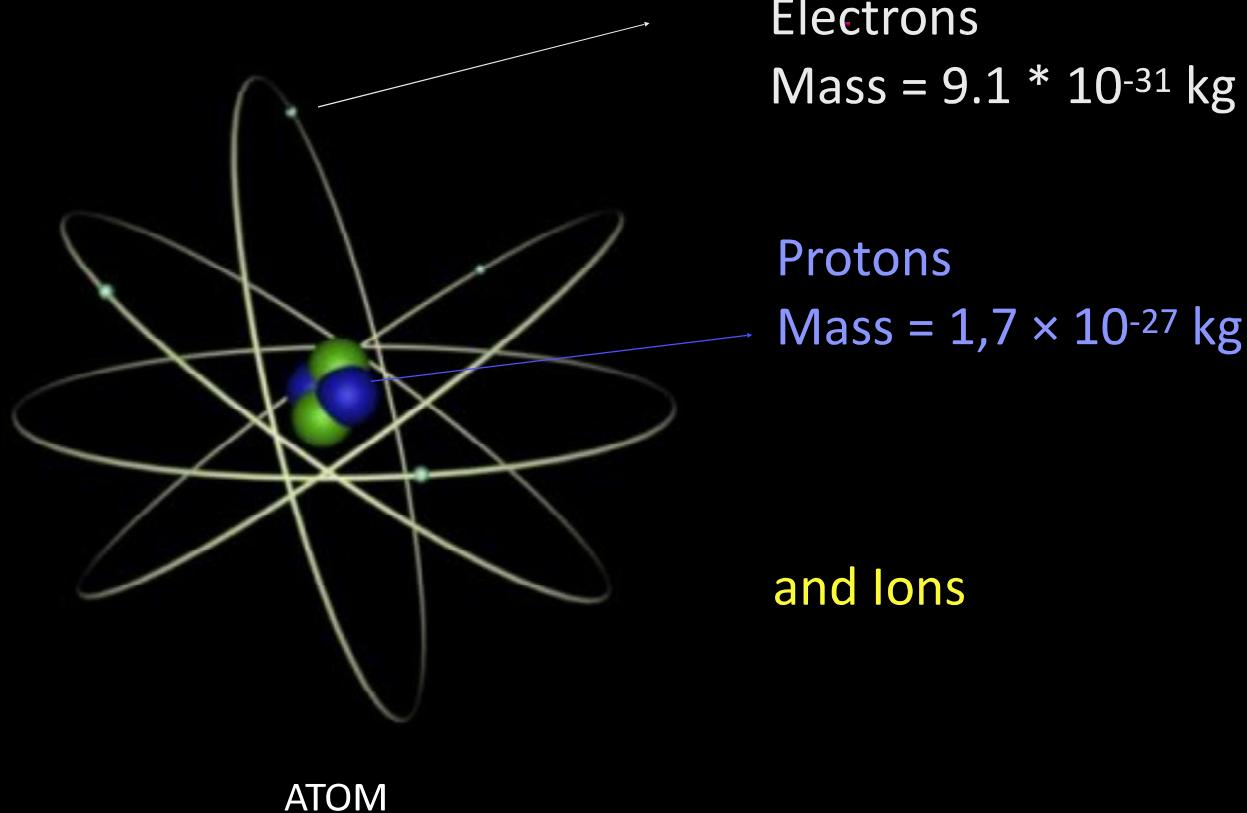
	Statistical-only ATLAS	Statistical + Systematic ATLAS	Statistical-only CMS	Statistical + Systematic CMS
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(l\bar{l}\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
Combined	4.5	Combined	4.0	Combined

- Careful studies and projections for the physics at the HL-LHC have shown the upgraded detectors will be able to deal with the 200PU conditions
  - This precision might still not be sufficient to show the effect of new physics...
  - Let's not forget that Run3 might still bring more improvements and surprises...!

## HOW DO WE PROPOSE AND CHOOSE FUTURE FACILITIES?

- The physics potential of any “after HL-LHC” HEP facility should be evaluated weighting the following criteria:
  - **guaranteed deliverables:** increase in knowledge that will be acquired independently of potential discoveries
    - Discussion theme: how in your opinion?
  - **the exploration potential:** ability to target the BSM scenario that are more « known » and the sensitivity to ensure coverage of unusual/unexpected signatures
    - Discussion theme: how in your opinion?
  - **potential to provide conclusive yes/no answers to broad questions** such as:
    - is the SM dynamics all there is at the TeV scale
    - is there a TeV-scale solution to the hierarchy problem?
    - is DM a thermal WIMP?
    - did baryogenesis take place during the electroweak phase transition?

## PARTICLE IN THE ACCELERATORS == CHARGED PARTICLES



## Hadrons

- large mass reach  $\Rightarrow$  exploration?
- S/B  $\sim 10^{-10}$  (w/o trigger)
- S/B  $\sim 0.1$  (w/ trigger)
- requires multiple detectors  
(w/ optimized design)
- only pdf access to  $\sqrt{s}$
- $\Rightarrow$  couplings to quarks and gluons

## Circular

- $\sqrt{s}$  limited by synchrotron radiation
- higher luminosity
- several interaction points
- precise E-beam measurement  
( $O(0.1\text{MeV})$  via resonant depolarization)

## WHICH MACHINES?

### Leptons

- S/B  $\sim 1 \Rightarrow$  measurement?
- polarized beams  
(handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- $\Rightarrow$  EW couplings

### Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamstrahlung
- “greener”: less power consumption

: (New) **Which lepton?** Electrons or muons :

# e+e- COLLIDERS: CIRCULAR OR LINEAR?

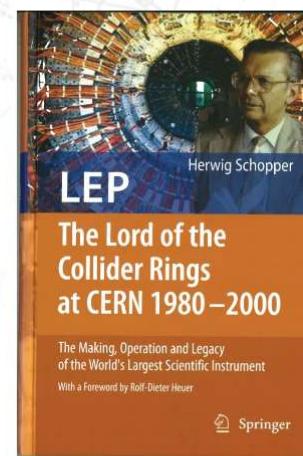
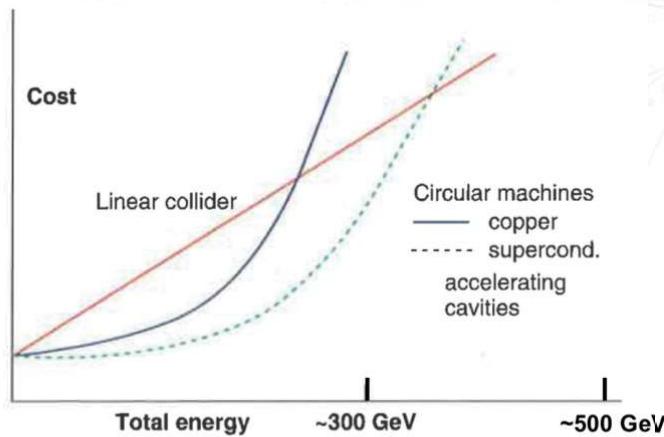
- ◆ Why not a 500 GeV circular collider ?

- Synchrotron radiation in circular machines

❖ Energy lost per turn grows like

$$\Delta E \propto \frac{1}{R} \left( \frac{E}{m} \right)^4 , \text{ e.g., 3.5 GeV per turn at LEP2}$$

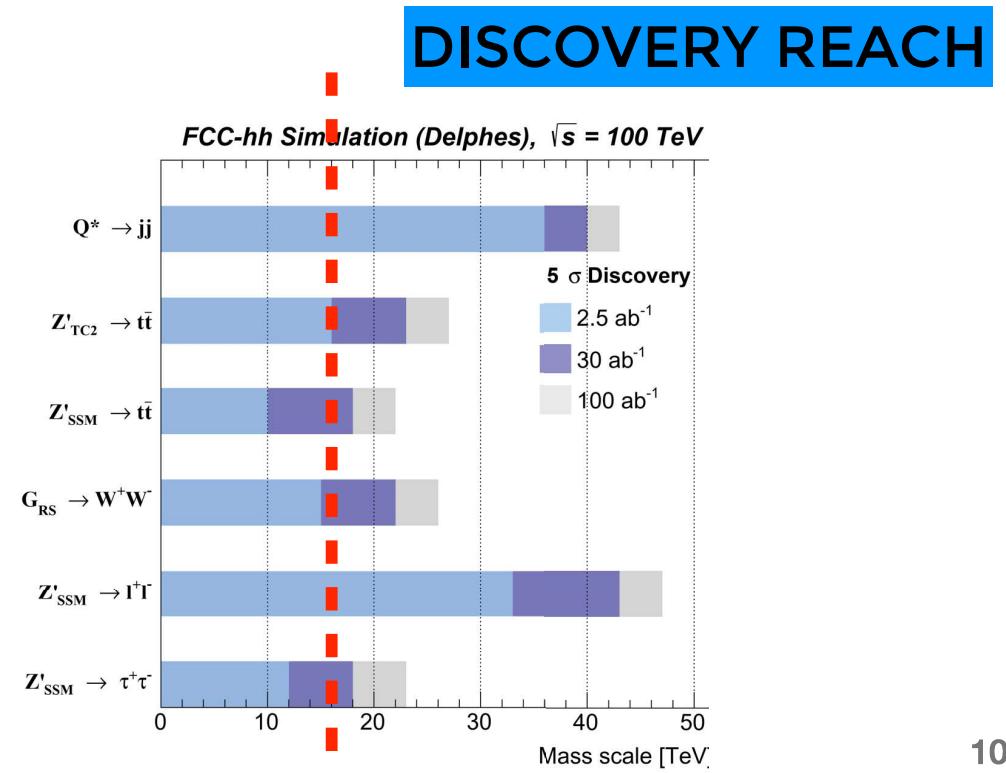
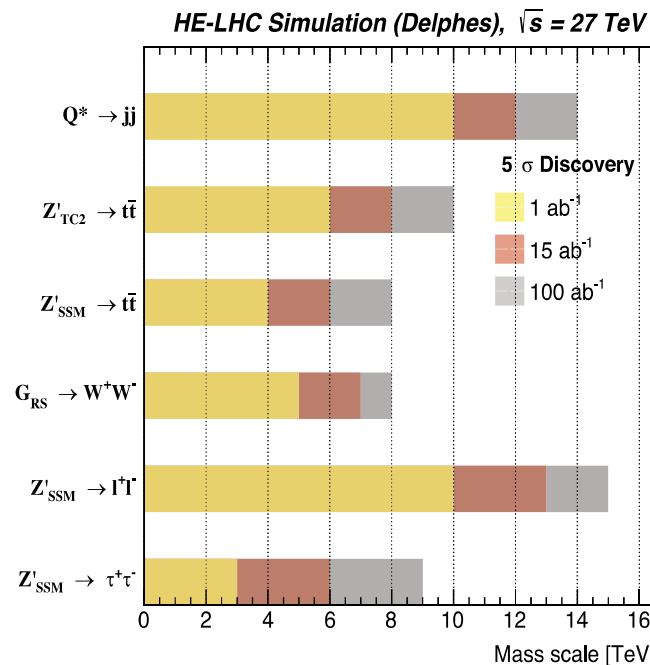
▪ Must compensate with  $R$  and accelerating cavities → Cost grows like  $E^4$  too



- "Up to a centre-of-mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option", Herwig Schopper
  - At and above 500 GeV, a e+e- collider can only be linear

# HADRON COLLIDERS: WHICH $\sqrt{s}$ ?

- HE-LHC 27 TeV pp collisions  $15 \text{ ab}^{-1}$  in the LHC tunnel with new 16T field accelerator magnets in the LHC tunnel
- HE-LHeC ep Collider with  $\sqrt{s}=1.7 \text{ TeV}$  collecting  $1 \text{ ab}^{-1}$
- FCC-hh 100 TeV pp collisions  $30 \text{ ab}^{-1}$  with new 16T field accelerator magnets in a new tunnel of a 100km
- FCC-eh collecting  $2 \text{ ab}^{-1}$  of ep collisions



CLIC is highest energy proposal with CDR

- at the limit of what one can do (decades of R&D)
- No obvious way to improve

Cost 18 MCHF, power 590 MW

#### Muon Collider:

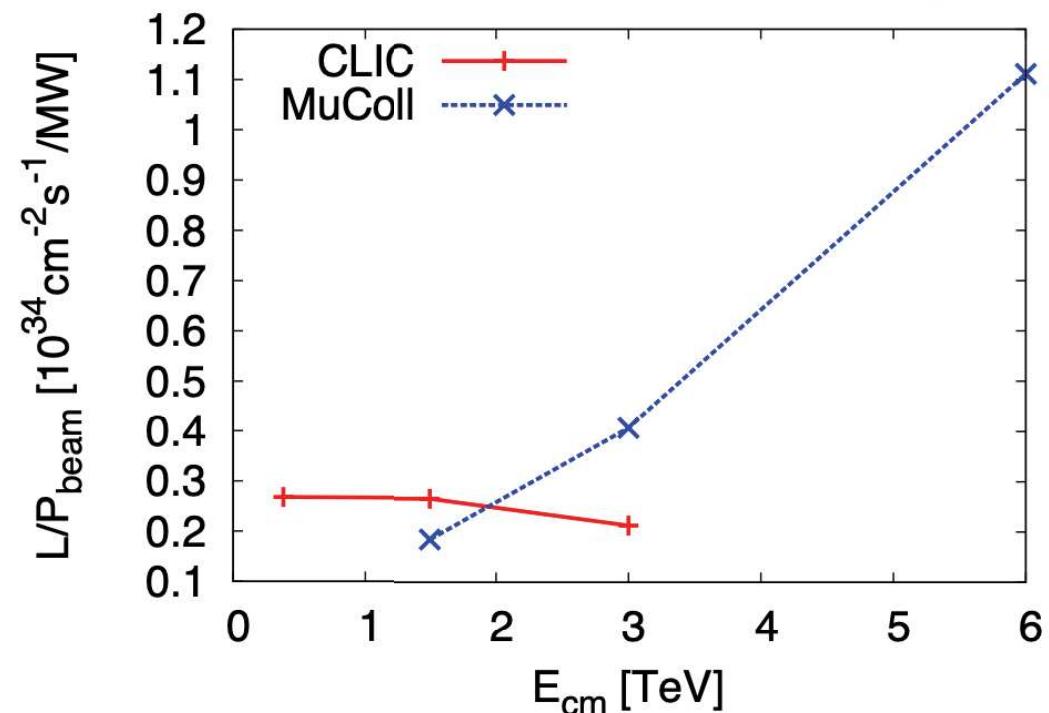
Acceleration and collision in multiple turns in rings promises

- **Power efficiency**
- **Compact tunnels**
  - 10 TeV similar to 3 TeV CLIC
- **Cost effectiveness**
- **Natural staging** is natural

Synergies exist (neutrino/higgs

Detailed studies needed for quantitative statements

## MUON COLLIDERS: HIGH ENERGY



Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**



## WHICH TYPE OF COLLIDER?

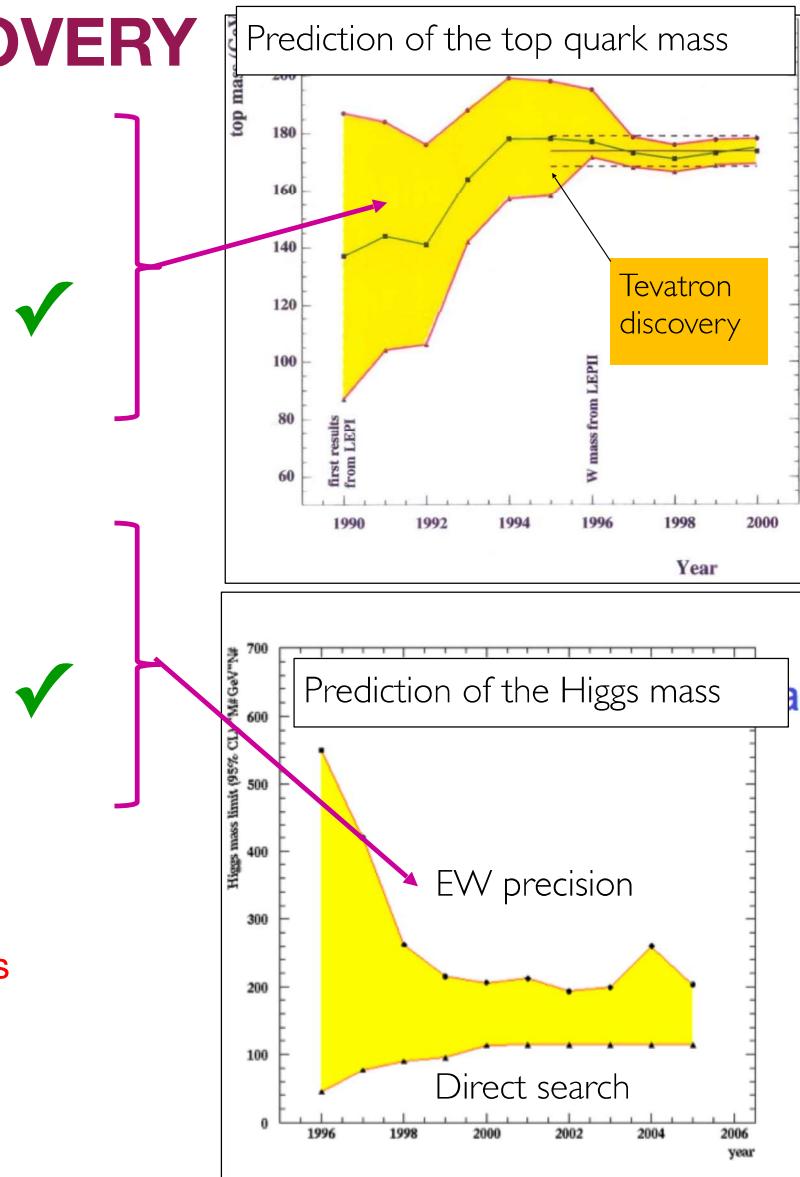
- Energy: direct access to new resonances
  - Precision: indirect evidence of deviations at low and high energy.
- The next facility must be versatile with a reach as broad and as powerful as possible – as there is no specific target

### More SENSITIVITY, more PRECISION, more ENERGY

- The Future Circular Collider (FCC-ee,hh,eh) **integrated project** offers the most adapted response to this situation:
- Largest luminosity
  - highest parton energy
  - synergies and complementarities between the machines (past, and future)

# PRECISION FOR DISCOVERY

- Top quark
  - 1990-1994: Mass predicted from quantum loops
    - ❖  $m_{\text{top}}(\text{pred.}) = 178.0 \pm 10 \text{ GeV}$
  - 1995: Discovered at the Tevatron (DØ, CDF)
    - ❖ Today:  $m_{\text{top}}(\text{obs.}) = 173.23 \pm 0.7 \text{ GeV}$
  
- Higgs boson
  - 1996-2011: Mass predicted from quantum loops
    - ❖  $m_{\text{Higgs}}(\text{pred.}) = 98^{+25}_{-21} \text{ GeV}$
  - 2012: Discovery at the LHC (ATLAS, CMS)
    - ❖ Today:  $m_{\text{Higgs}}(\text{obs.}) = 125.09 \pm 0.24 \text{ GeV}$
  
- Lesson:
  - Precision measurements interpreted via quantum loop corrections can give very strong constraints on particles at higher masses than what can be directly probed!

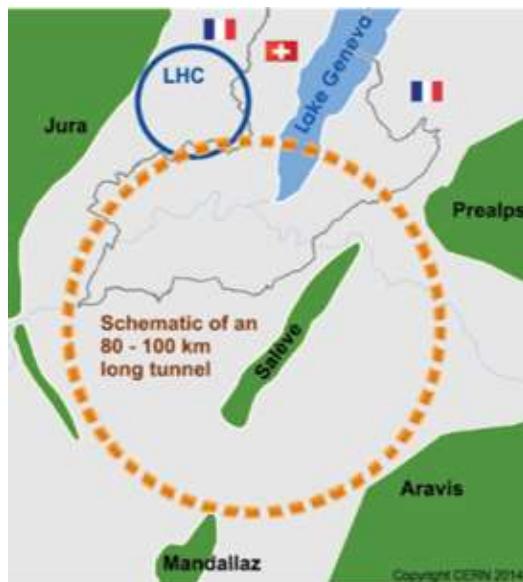


# THE FCC INTEGRATED PROGRAM: INSPIRED BY SUCCESSFUL LEP – LHC PROGRAMS AT CERN

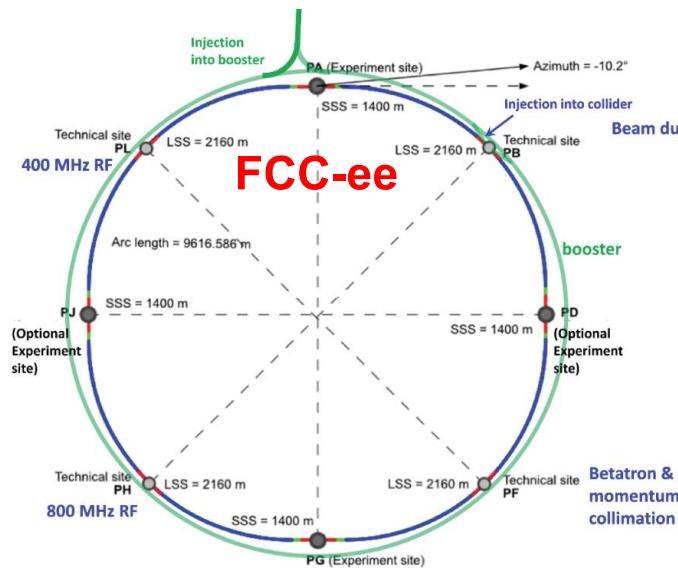
**comprehensive long-term program maximizing physics opportunities**

M. Benedikt

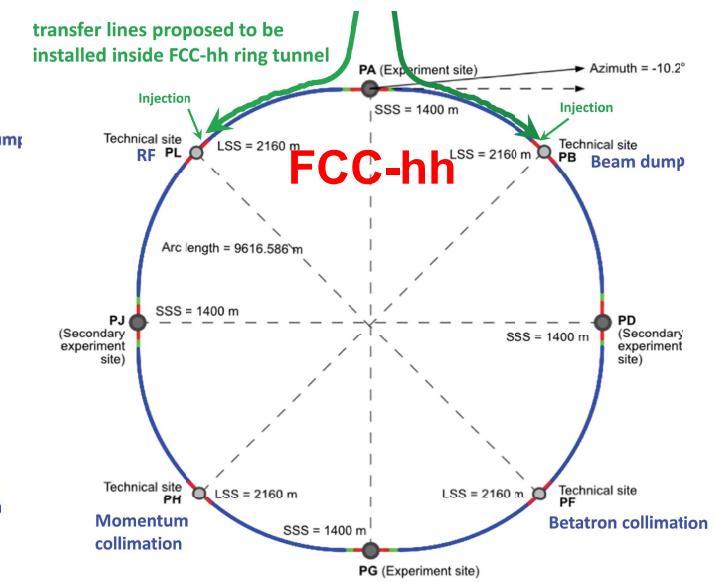
- stage 1: FCC-ee ( $Z$ ,  $W$ ,  $H$ ,  $t\bar{t}$ ) as Higgs factory, electroweak & top factory at highest luminosities
- stage 2: FCC-hh ( $\sim 100$  TeV) as natural continuation at energy frontier, with ion and eh options
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program



2020 - 2040



2045 - 2060



2070 - 2090++

## 8-SITE BASELINE "PA31"

<b>Number of surface sites</b>	8
<b>LSS@IP (PA, PD, PG, PJ)</b>	1400 m
<b>LSS@TECH (PB, PF, PH, PL)</b>	2143 m
<b>Arc length</b>	9.6 km
<b>Sum of arc lengths</b>	76.9 m
<b>Total length</b>	91.1 km



- 8 sites – less use of land, <40 ha instead 62 ha
- **Possibility for 4 experiment sites in FCC-ee**
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP

# Stage 1: FCC-ee updated parameters

Parameter [4 IPs, 91.2 km, $T_{rev}=0.3$ ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [ $10^{11}$ ]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [ $\mu\text{m}$ ]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter $\xi_x / \xi_y$	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	182	19.4	7.3	1.33
total integrated luminosity / year [ $\text{ab}^{-1}/\text{yr}$ ]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

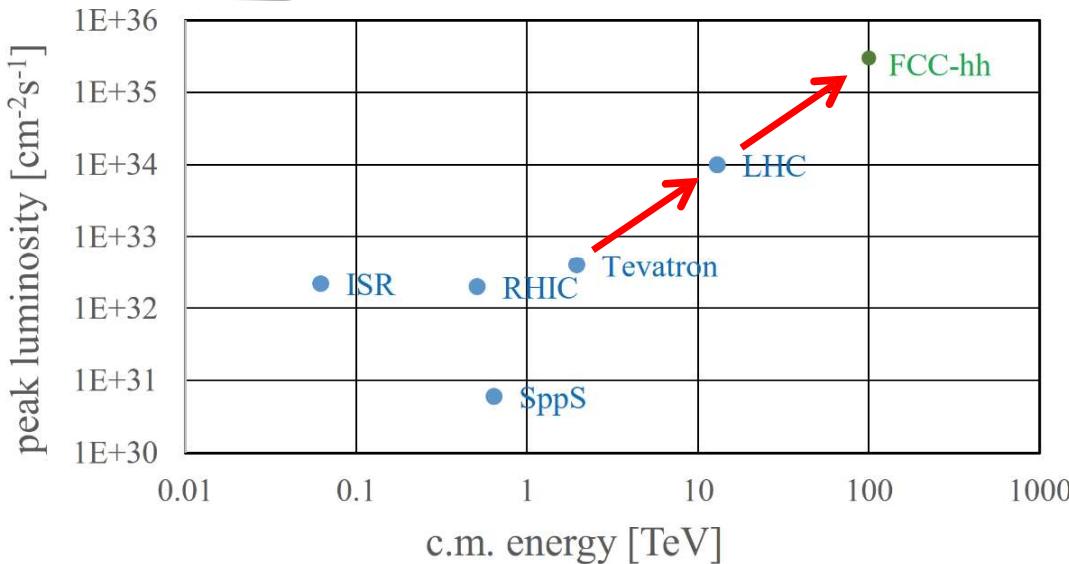
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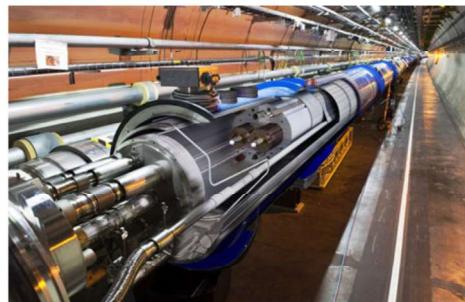
## Stage 2: FCC-hh (pp) collider parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	<b>100</b>		14	14
dipole field [T]	<b>~17 (~16 comb.function)</b>		8.33	8.33
circumference [km]	<b>91.2</b>		26.7	26.7
beam current [A]	<b>0.5</b>		1.1	0.58
bunch intensity [ $10^{11}$ ]	<b>1</b>	<b>1</b>	2.2	1.15
bunch spacing [ns]	<b>25</b>	<b>25</b>	25	25
synchr. rad. power / ring [kW]	<b>2700</b>		7.3	3.6
SR power / length [W/m/ap.]	<b>32.1</b>		0.33	0.17
long. emit. damping time [h]	<b>0.45</b>		12.9	12.9
beta* [m]	<b>1.1</b>	<b>0.3</b>	<b>0.15 (min.)</b>	<b>0.55</b>
normalized emittance [ $\mu\text{m}$ ]	<b>2.2</b>		<b>2.5</b>	<b>3.75</b>
peak luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	<b>5</b>	<b>30</b>	<b>5 (lev.)</b>	<b>1</b>
events/bunch crossing	<b>170</b>	<b>1000</b>	<b>132</b>	<b>27</b>
stored energy/beam [GJ]	<b>7.8</b>		<b>0.7</b>	<b>0.36</b>

# FCC-hh: HIGHEST COLLISION ENERGIES



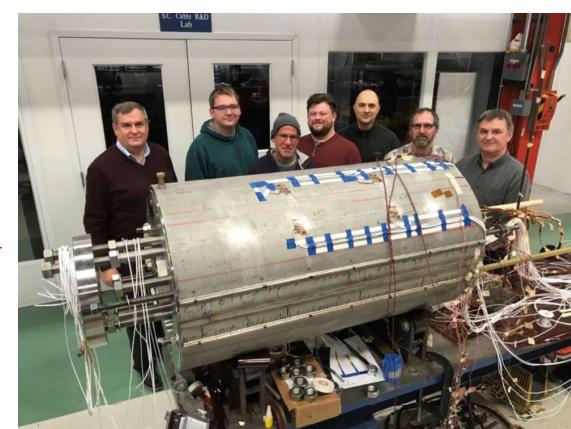
from  
LHC technology  
8.3 T NbTi dipole



via  
HL-LHC technology  
12 T Nb<sub>3</sub>Sn quadrupole

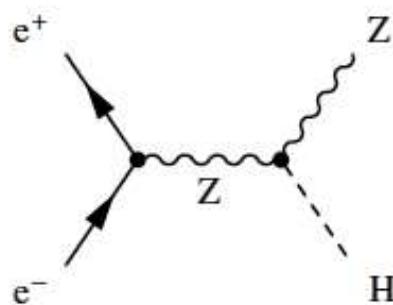


- **order of magnitude performance increase in both energy & luminosity**
- **100 TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab<sup>-1</sup> per experiment collected over 25 years** of operation (vs 3 ab<sup>-1</sup> for LHC)
- **similar performance increase as from Tevatron to LHC**
- **key technology: high-field magnets**



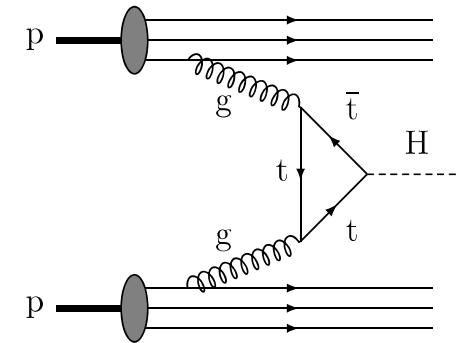
FNAL dipole  
demonstrator  
4-layer cos $\vartheta$   
14.5 T Nb<sub>3</sub>Sn  
in 2019

# e<sup>+</sup>e<sup>-</sup> VS pp COLLISIONS - THE BASICS



## e<sup>+</sup>e<sup>-</sup> collisions

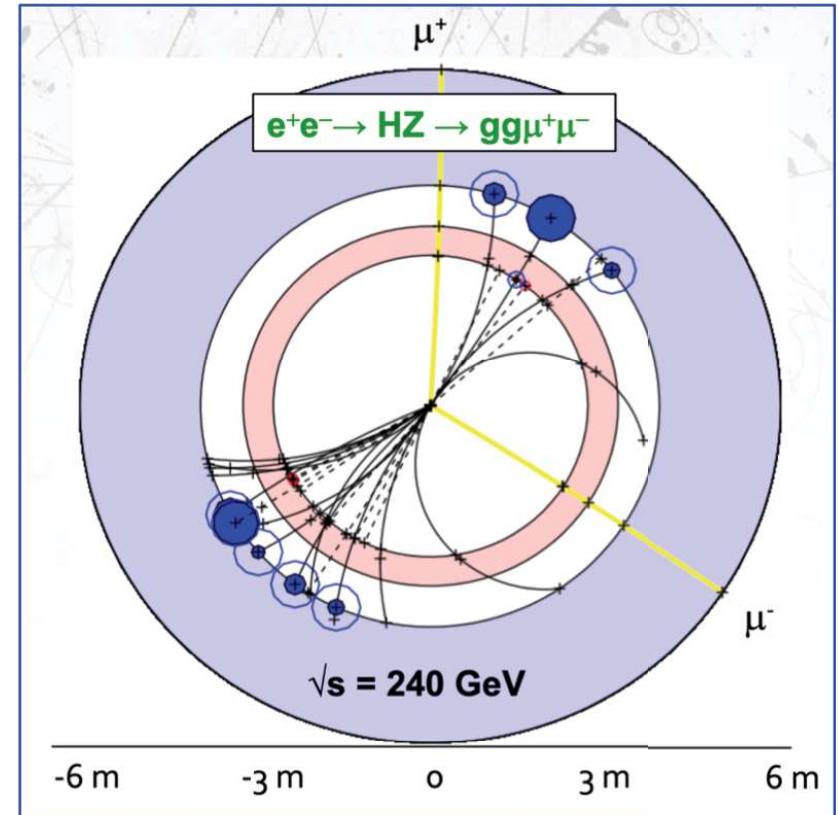
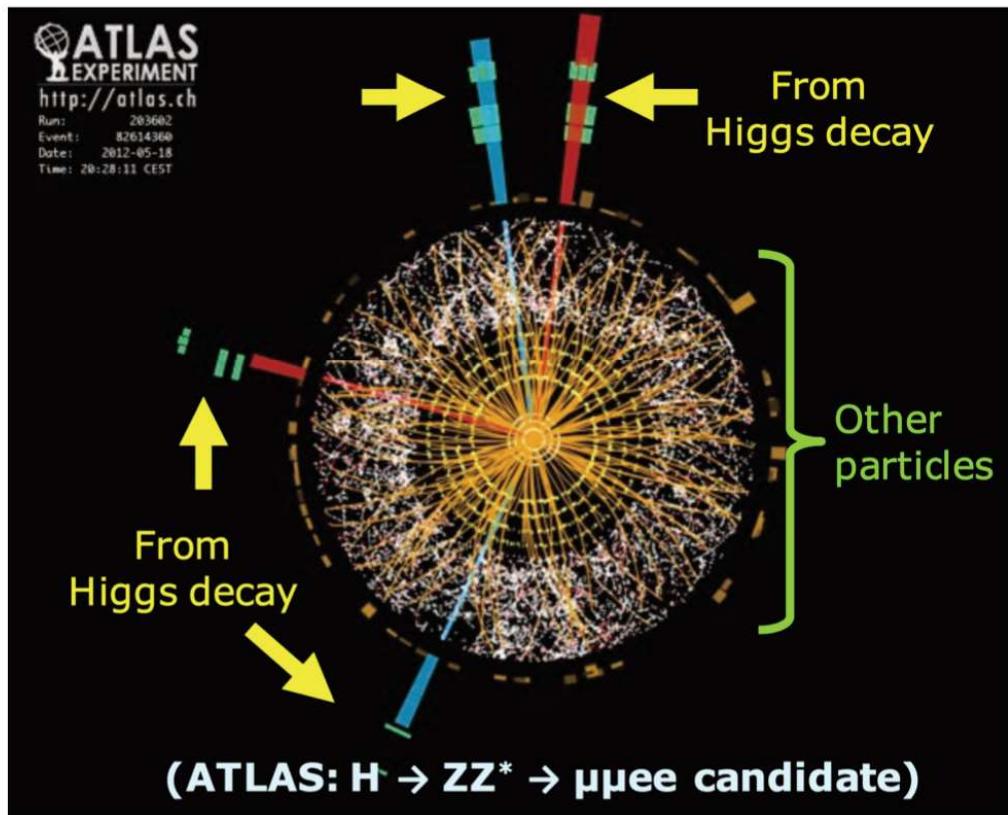
- e<sup>+</sup>e<sup>-</sup> are point-like
  - Initial state well defined ( $E, p$ ), polarisation
  - High-precision measurements
- Clean experimental environment
  - Trigger-less readout
  - Low radiation levels
- Superior sensitivity for **electro-weak states**
- At lower energies ( $\leq 350$  GeV), **circular** e<sup>+</sup>e<sup>-</sup> colliders can deliver **very large luminosities**.
- Higher energy ( $> 1$  TeV) e<sup>+</sup>e<sup>-</sup> requires **linear** collider.



## p-p collisions

- Proton is compound object**
  - Initial state not known event-by-event
  - Limits achievable precision
- High rates of QCD backgrounds**
  - Complex triggering schemes
  - High levels of radiation
- High cross-sections for **colored-states**
- High-energy **circular** pp colliders feasible

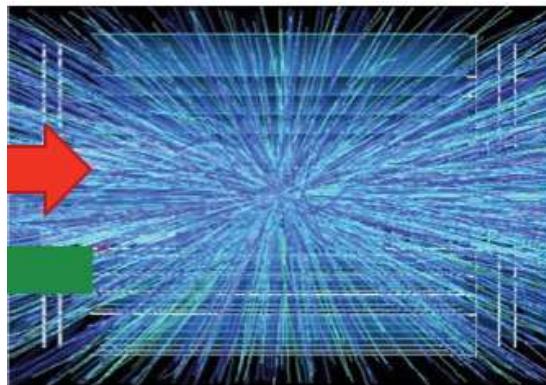
## HIGGS EVENT IN ee AND pp



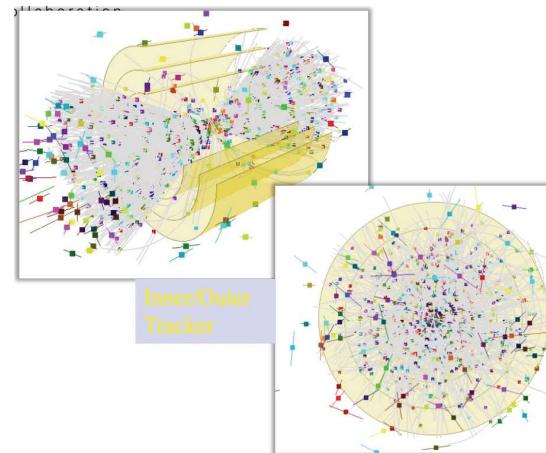
## SIDE NOTE: BACKGROUNDS VS PRECISION

- Various machines at high energy have processes that create noise and occupancy in the detector: [analyses in general assume this will be OK](#)
- “Clean events” also means that production cross section for background processes are orders of magnitudes bigger at a hadron collider, while they are not at a lepton collider. This is also a limit on the precision.
- Contrary to protons, electron/muons are ELEMENTARY particles: the  $\sqrt{s}$  of the process is known. No spectators. No PDF. This limits the ultimate precision.

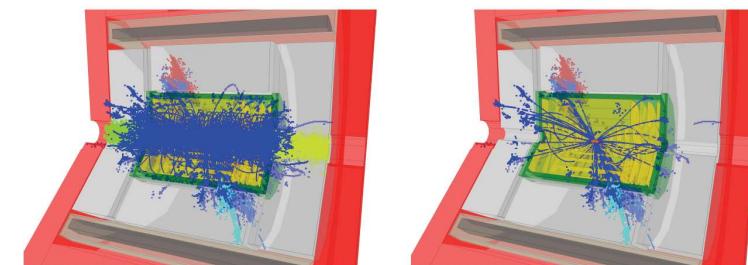
FCC-hh 100 TeV  
~1000 pileup



Muon Collider 10TeV  
Beam Induced Background



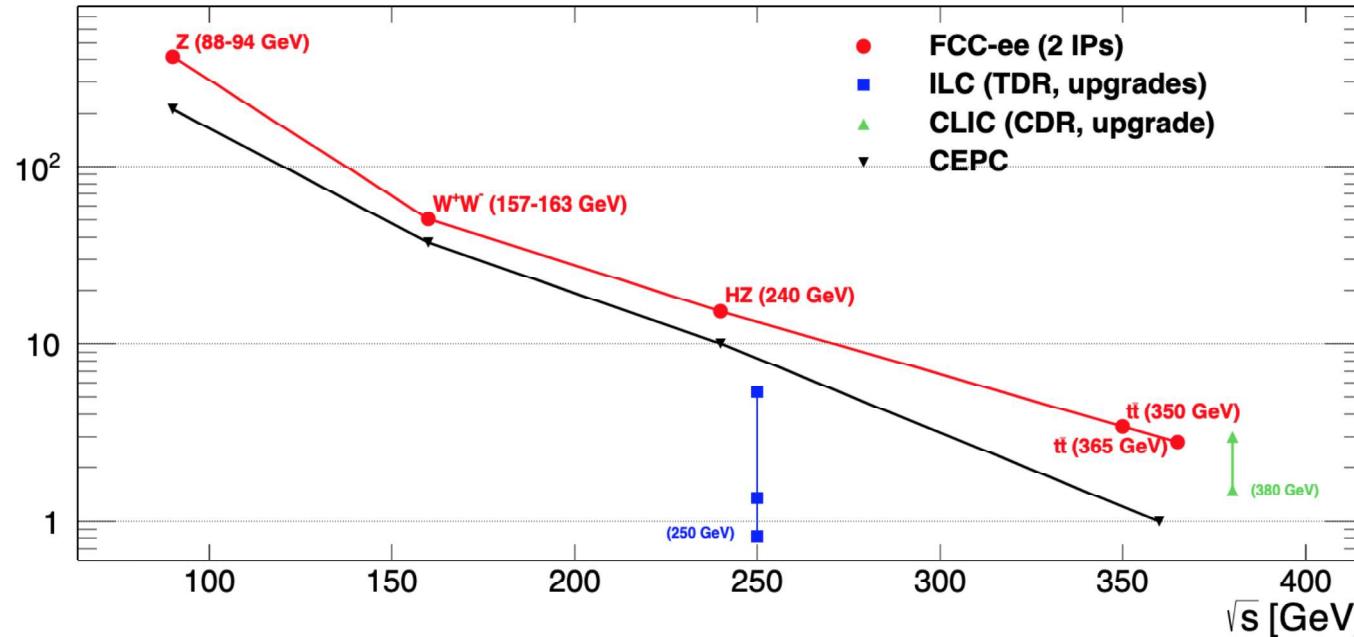
CLIC 3TeV  
Beamstrahlung Background





THE FCC-ee

# ENERGY RANGE & LUMINOSITY

Luminosity [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]

Can produce all the  
heaviest particles of  
the Standard Model:  
Z, W, H and top

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity ( $\text{ab}^{-1}$ )	Event Statistics
FCC-ee-Z	4	88-95	150	$3 \times 10^{12}$ visible Z decays
FCC-ee-W	2	158-162	12	$10^8$ WW events
FCC-ee-H	3	240	5	$10^6$ ZH events
FCC-ee-tt	5	345-365	1.5	$10^6$ $t\bar{t}$ events
s-channel H	???	125 GeV		$\sim 5000 e^+e^- \rightarrow H$ events

$\sqrt{s}$ uncertainty
<100keV
<300keV
$\sim 2\text{MeV}$
$\sim 5\text{MeV}$

# PHYSICS PROGRAM AT-A-GLANCE

## "Higgs Factory" Programme

- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k  $WW \rightarrow H$  events
- Higgs couplings to fermions and bosons
- Higgs self-coupling ( $2-4\sigma$ ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production  $e^+e^- \rightarrow H$  @  $\sqrt{s} = 125$  GeV

## Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor  $\sim 300$  improvement in *statistical* precision wrt current WA

- $5 \times 10^{12} Z$  and  $10^8 WW$ 
  - $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W^{eff}, R_Z^\ell, R_b, \alpha_s, m_W, \Gamma_W, \dots$
- $10^6 tt$ 
  - $m_{top}, \Gamma_{top}, EW$  couplings

Indirect sensitivity to new phys. up to  $\Lambda=70$  TeV scale

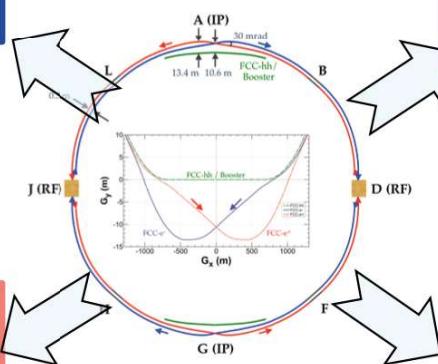
## Heavy Flavour Programme

- Enormous statistics:  $10^{12} bb, cc; 1.7 \times 10^{11} \tau\tau$
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, "flavour anomaly" studies, e.g.  $b \rightarrow s\tau\tau$ , rare decays, CLFV searches, lepton universality, PNMS matrix unitarity

## Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below  $m_Z$ :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes – LLPs



# DETECTOR REQUIREMENTS TO GUIDE NEW IDEAS

## "Higgs Factory" Programme

- Momentum resolution of  $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5} \text{ GeV}^{-1}$  commensurate with  $\mathcal{O}(10^{-3})$  beam energy spread
- Jet energy resolution of 30%/VE in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

LC-inspired.  
Update from  
physics studies  
ongoing

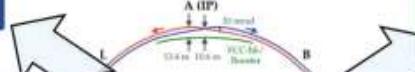
## Ultra Precise EW Programme & QCD

- Absolute normalisation (luminosity) to  $10^{-4}$
- Relative normalisation (e.g.  $\Gamma_{\text{had}}/\Gamma_\ell$ ) to  $10^{-5}$
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution  $< 0.1 \text{ mrad}$  (BES from  $\mu\mu$ )
- Stability of B-field to  $10^{-6}$ : stability of  $v_s$  meas.

**It is not unlikely that the most stringent requirements will come from the intensity frontier  
Just pick up a case study in the TeraZ programme, and you'll make a unique contribution**

## Heavy Flavour Programme

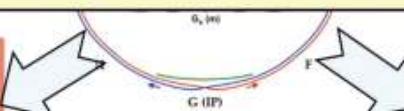
- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time meas.
- ECAL resolution at the few %/ VE level for inv. mass of final states with  $\pi^0$ s or  $\gamma$ s
- Excellent  $\pi^0/\gamma$  separation and measurement for tau physics
- PID: K/ $\pi$  separation over wide momentum range for b and  $\tau$  physics



## Feebly Coupled Particles - LLPs

Benchmark signature:  $Z \rightarrow vN$ , with N decaying late

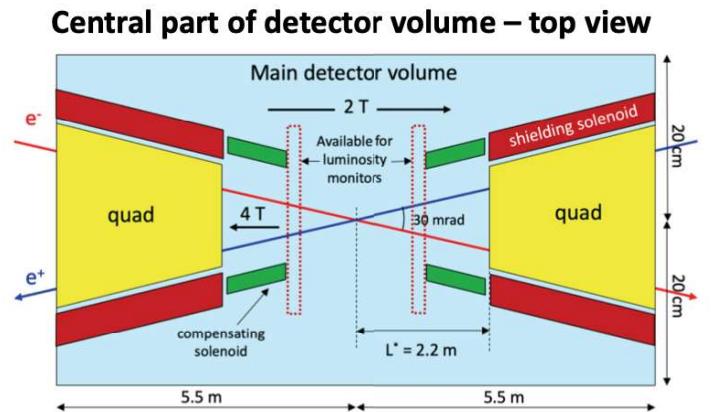
- Sensitivity to far detached vertices ( $m m \rightarrow m$ )
  - Tracking: more layers, continuous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths  $\Rightarrow$  extended detector volume
- Precise timing for velocity (mass) estimate
- Hermeticity



# EXPERIMENTAL CHALLENGES

M. Dam

- ◆ 30 mrad beam crossing angle
  - Detector B-field limited to 2 Tesla at Z-peak operation
  - Very complex and tightly packed MDI (Machine Detector Interface)
- ◆ "Continuous" beams (no bunch trains); bunch spacing down to 20 ns
  - Power management and cooling (no power pulsing)
- ◆ Extremely high luminosities
  - High statistical precision – control of systematics down to  $10^{-5}$  level
  - Online and offline handling of  $\mathcal{O}(10^{13})$  events for precision physics: "Big Data"
- ◆ Physics events at up to 100 kHz
  - Fast detector response ( $\lesssim 1 \mu\text{s}$ ) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems
    - ❖ At the same time, keep low material budget: minimise mass of electronics, cables, cooling, ...
- ◆ More physics challenges
  - Luminosity measurement to  $10^{-4}$  – luminometer acceptance (radius) to  $\mathcal{O}(1 \mu\text{m})$
  - Detector acceptance to  $\sim 10^{-5}$  – acceptance definition to few  $\times 10 \mu\text{m}$ , hermeticity (no cracks!)
  - Stability of momentum measurement – stability of magnetic field wrt  $E_{\text{cm}}$  ( $10^{-6}$ )
  - Impact parameters, detached vertices – Higgs physics (b/c/g jets); heavy flavour physics, life-time measurements
  - Particle identification ( $\pi/\text{K}/\text{p}$ ) without ruining detector hermeticity – heavy flavour physics (and rare processes)



## BASELINE DETECTOR CONCEPTS FOR THE CDR

- FCC-ee: It was demonstrated that detectors satisfying the requirements are feasible. Two options considered for now with complementary designs: CLD and IDEA
  - physics performance, beam background, invasive MDI event rates...
- New detector design ideas are coming and being tested: new group in FCC PED based on “Detector concepts”
  - With 4 IP there is space for more ideas and possibly “specific detectors” (flavour, BSM)
    - Very nice material from FCC Week 2022 in Paris: <https://indico.cern.ch/event/1064327/timetable/>
    - Presentations from: Mogens Dam, Paolo Giacomelli (IDEA), André Sailer (CLD), Martin Alexa(Liquid Argon) -> thanks for the material :-)
- FCC-hh: one detector concept, ATLAS inspired, has been used for the physics studies in the CDR.
  - Some activity still ongoing, but priorities have switched to the FCC-ee needs at the moment.

# CURRENT DETECTOR CONCEPTS

**CLD CDR**

- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continuous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - $\sigma_p/p$ ,  $\sigma_E/E$
  - PID ( $\mathcal{O}(10 \text{ ps})$  timing and/or RICH)?
  - ...
- Robust software stack
  - Now ported (wrapped) to FCCSW

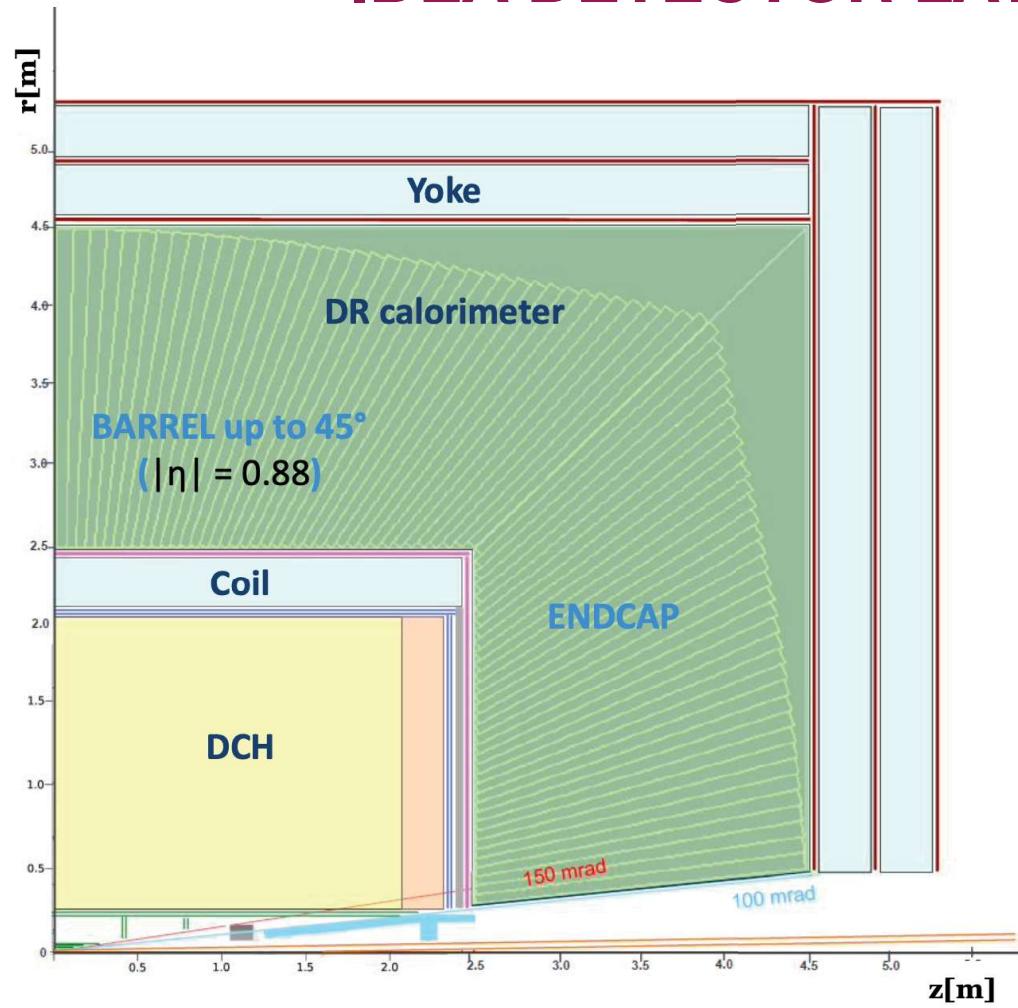
**IDEA CDR**

- Less established design
  - But still ~15y history: 4<sup>th</sup> Concept
- Developed by very active community
  - Prototype construction / test beam campaigns
  - Italy, Korea,...
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals
- Software under active development
  - Being ported to FCCSW

**Noble Liquid ECAL based**

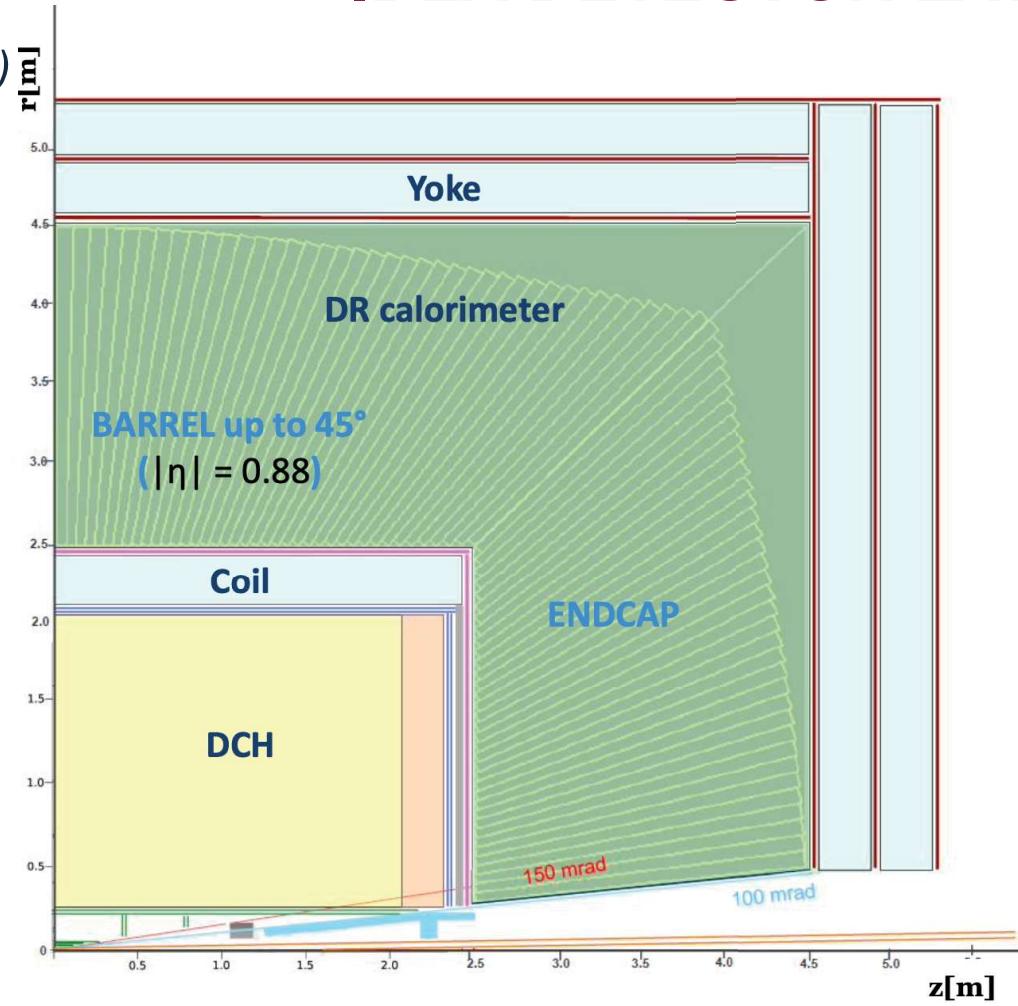
- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, ...
  - Software & performance studies
- Full simulation of ECAL available in FCCSW

## IDEA DETECTOR LAYOUT



Beam pipe: R~1.5 cm (*now 1cm*)

## IDEA DETECTOR LAYOUT



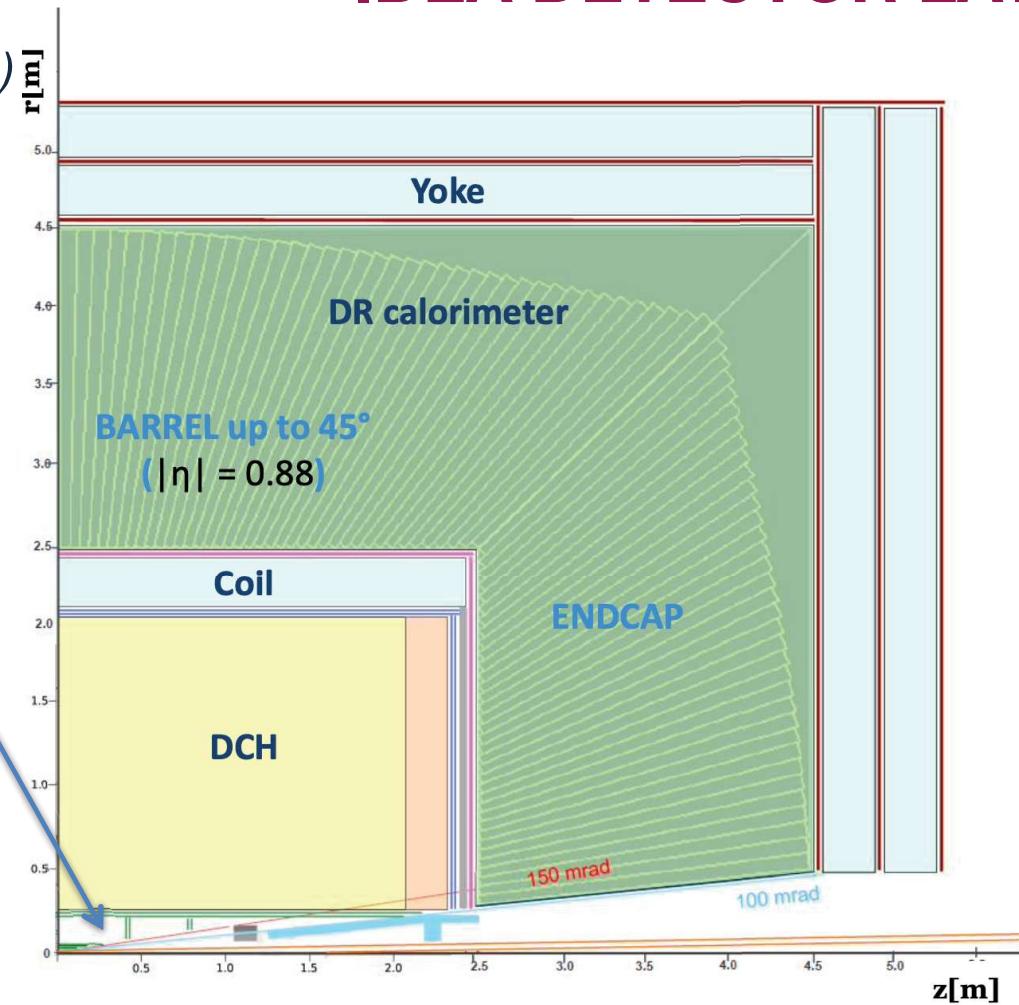
Beam pipe: R~1.5 cm (*now 1cm*)

Vertex:

5 MAPS layers

R = 1.7-34 cm

## IDEA DETECTOR LAYOUT



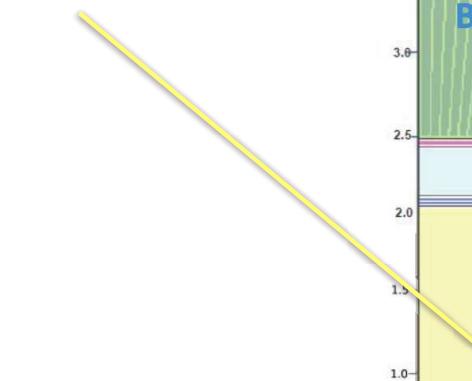
Beam pipe:  $R \sim 1.5$  cm (*now 1cm*)

Vertex:

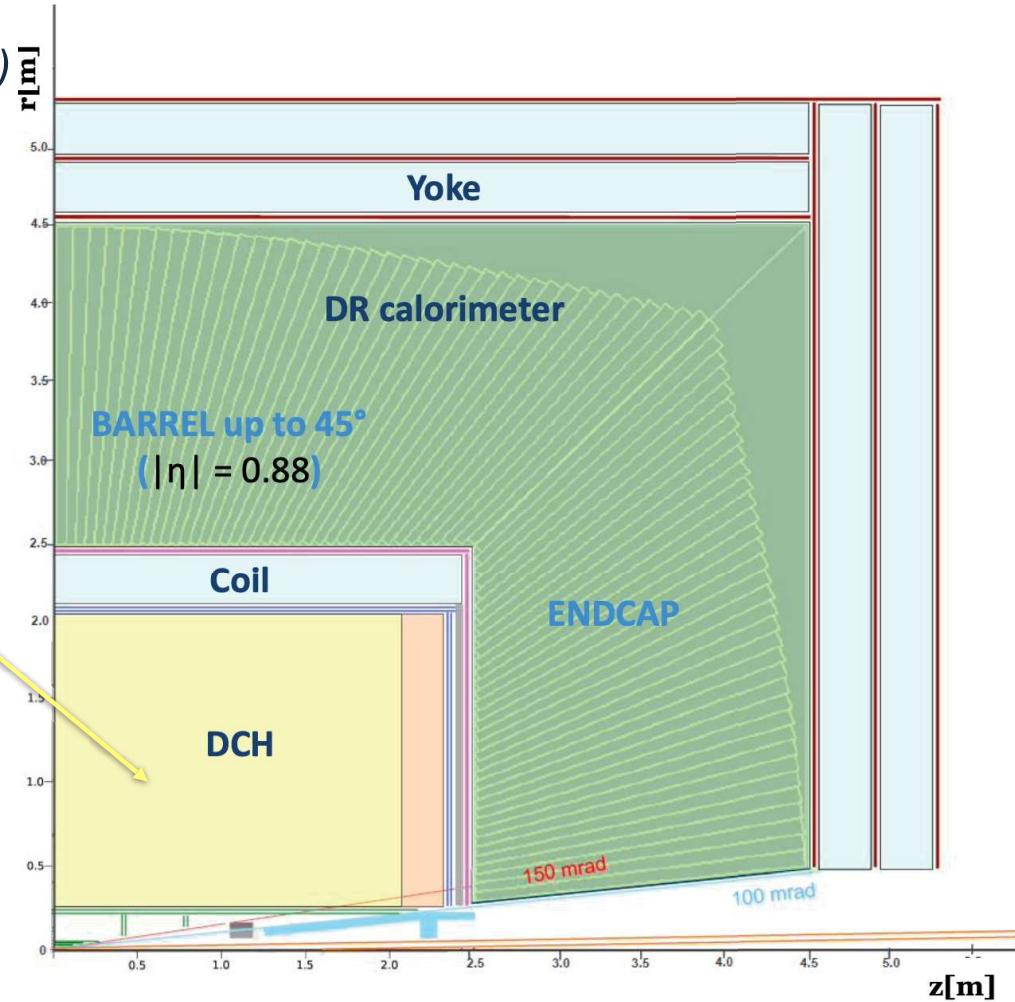
5 MAPS layers

$R = 1.7\text{-}34$  cm

Drift Chamber: 112 layers  
4 m long,  $R = 35\text{-}200$  cm



## IDEA DETECTOR LAYOUT



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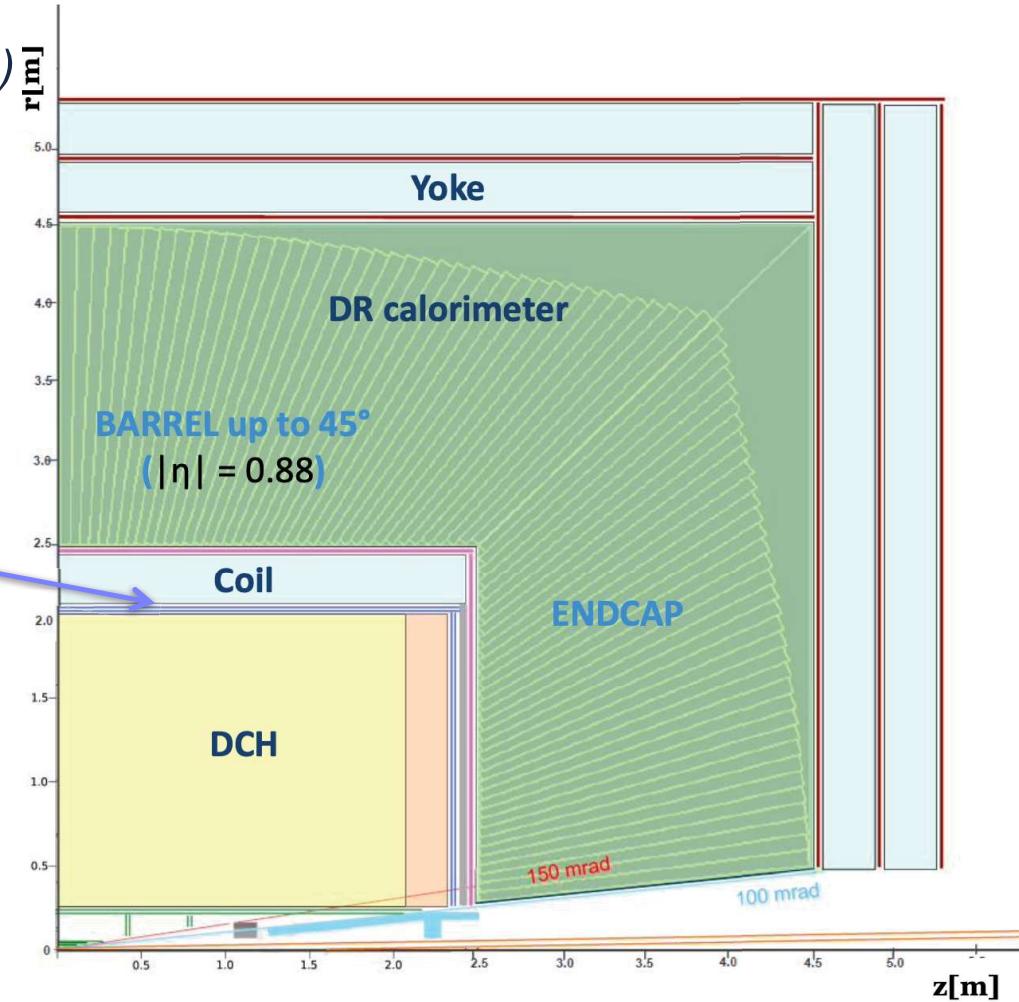
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$R = 1.7\text{-}34$  cm

Drift Chamber: 112 layers  
4 m long,  $R = 35\text{-}200$  cm

Outer Silicon wrapper:  
Si strips

## IDEA DETECTOR LAYOUT



**Beam pipe:** R~1.5 cm (*now 1cm*)

**Vertex:**

5 MAPS layers

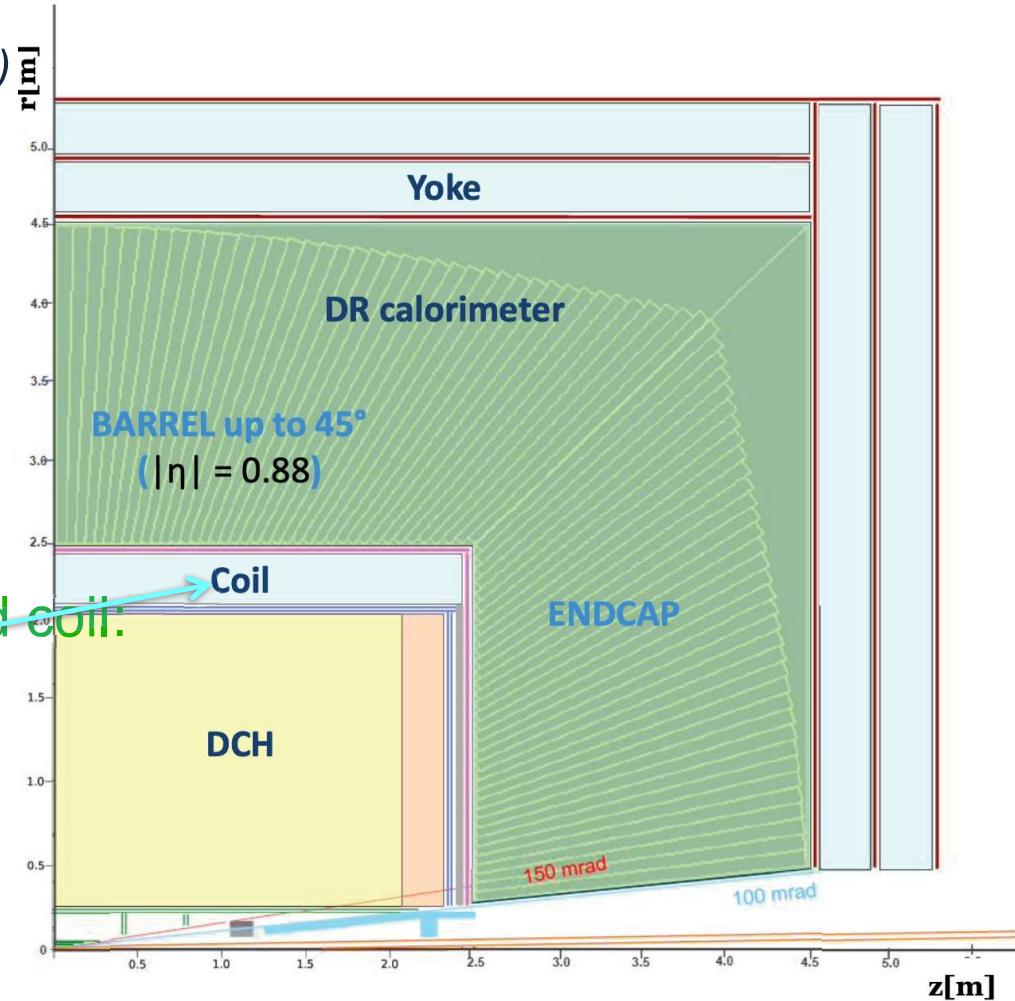
R = 1.7-34 cm

**Drift Chamber:** 112 layers  
4 m long, R = 35-200 cm

**Outer Silicon wrapper:**  
Si strips

**Superconducting solenoid coil:**  
2 T, R ~ 2.1-2.4 m  
0.74  $X_0$ , 0.16  $\lambda$  @ 90°

## IDEA DETECTOR LAYOUT



**Beam pipe:** R~1.5 cm (*now 1cm*)

**Vertex:**

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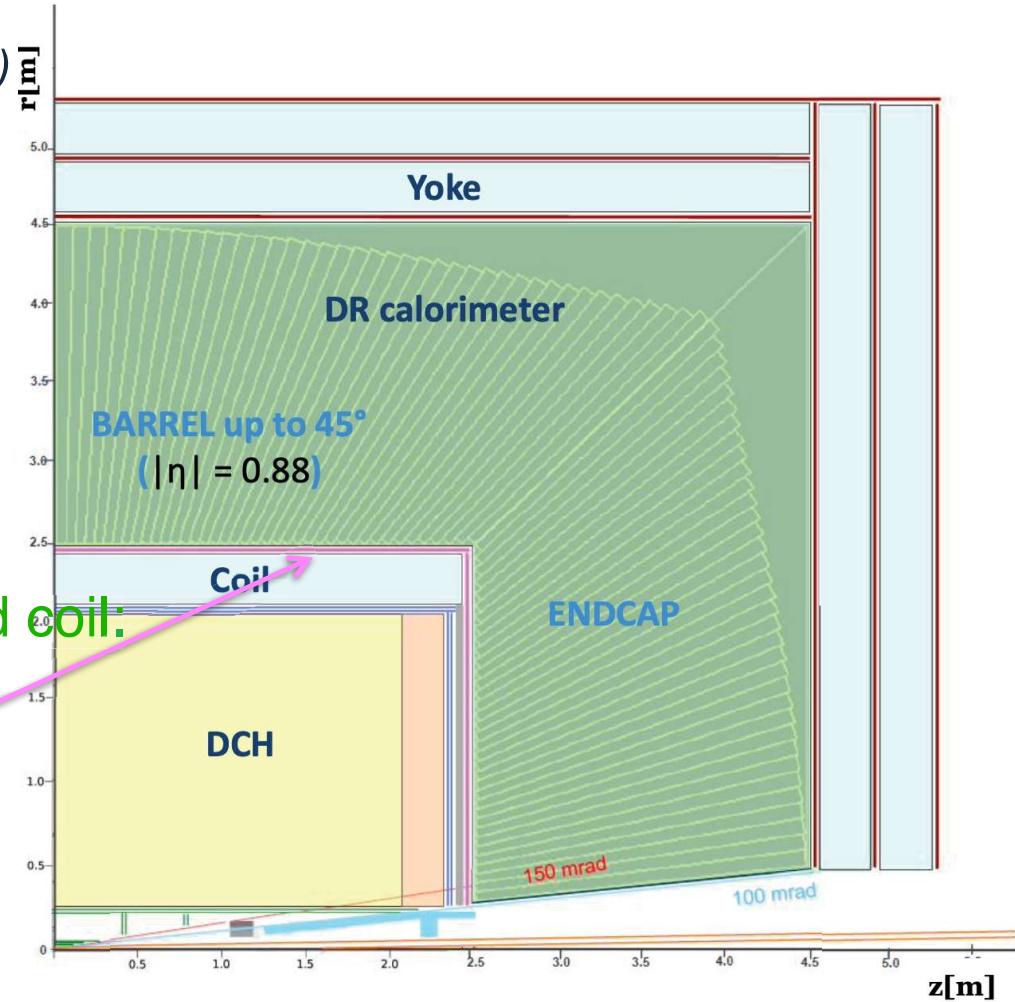
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**Preshower:**  $\sim 1 X_0$

## IDEA DETECTOR LAYOUT





**Beam pipe:** R~1.5 cm (*now 1cm*)

**Vertex:**

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R = 1.7-34 cm

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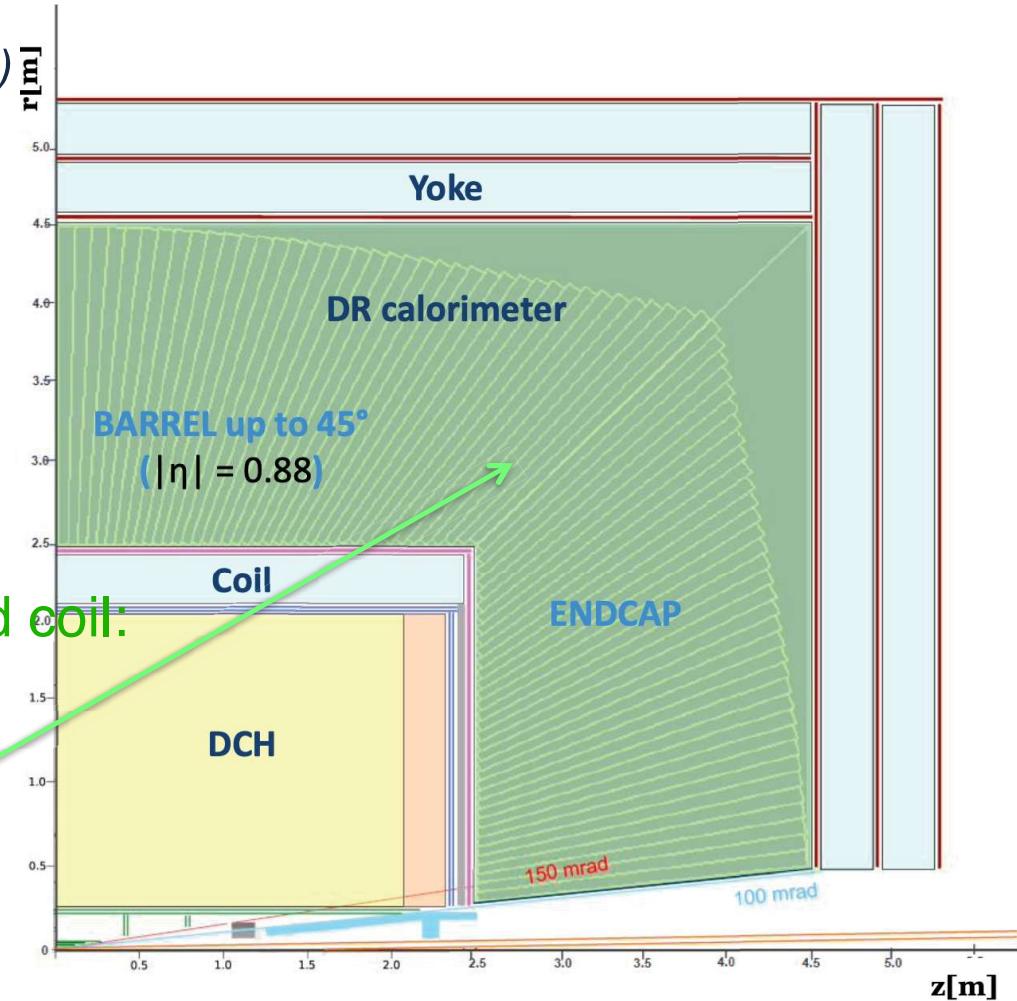
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**Dual-Readout Calorimeter:**  
2m / 7  $\lambda_{int}$

## IDEA DETECTOR LAYOUT



**Beam pipe:** R~1.5 cm (*now 1cm*)

**Vertex:**

5 MAPS layers

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**Drift Chamber:** 112 layers  
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**Outer Silicon wrapper:**  
Si strips

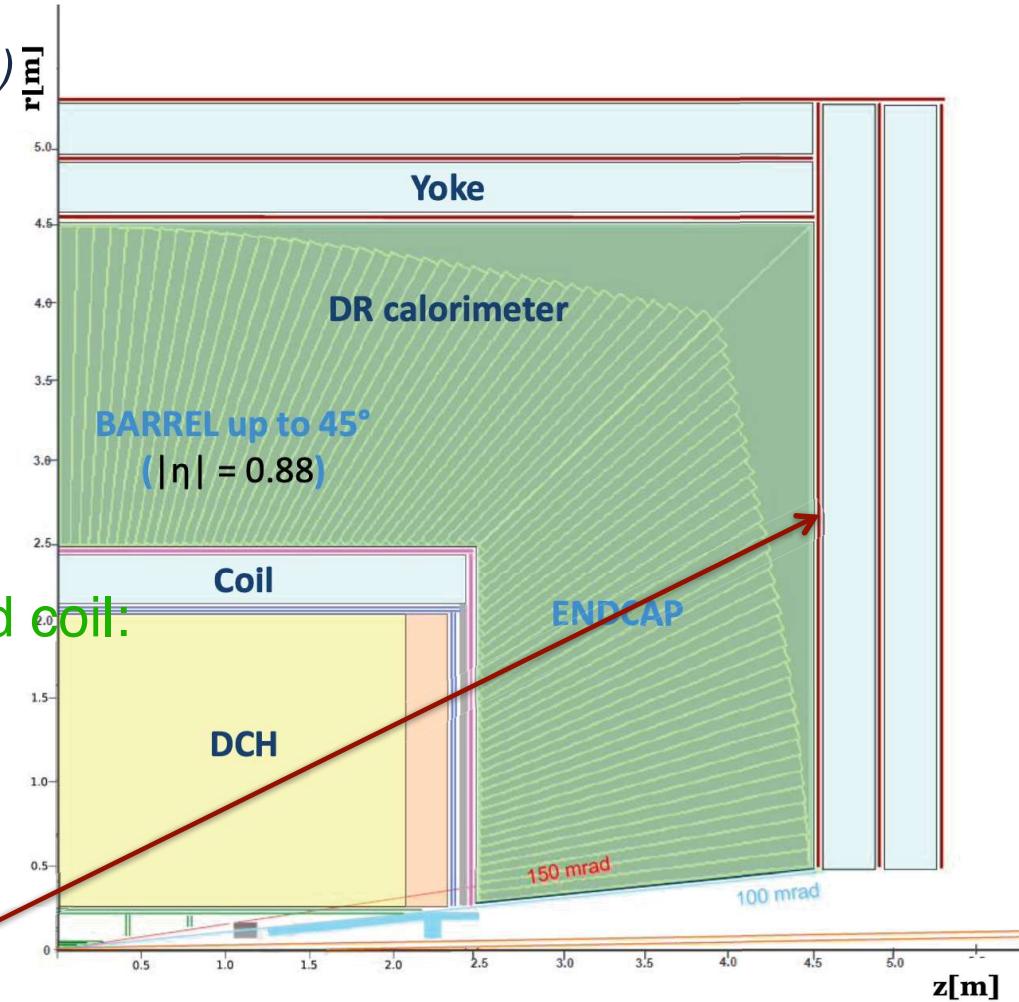
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0.74  $X_0$ , 0.16  $\lambda$  @ 90°

**Preshower:**  $\sim 1 X_0$

**Dual-Readout Calorimeter:**  
2m / 7  $\lambda_{int}$

**Yoke + Muon chambers**

## IDEA DETECTOR LAYOUT

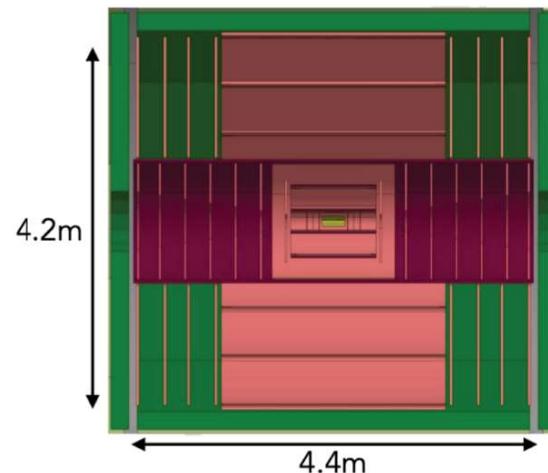


### Two solutions under study

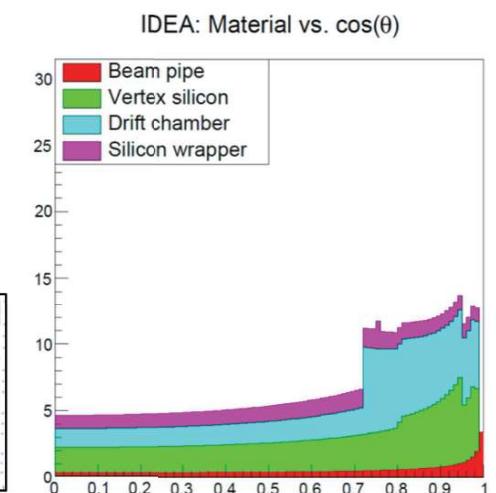
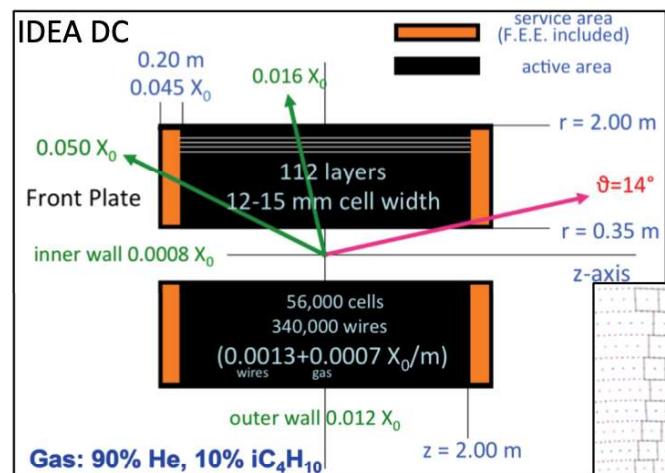
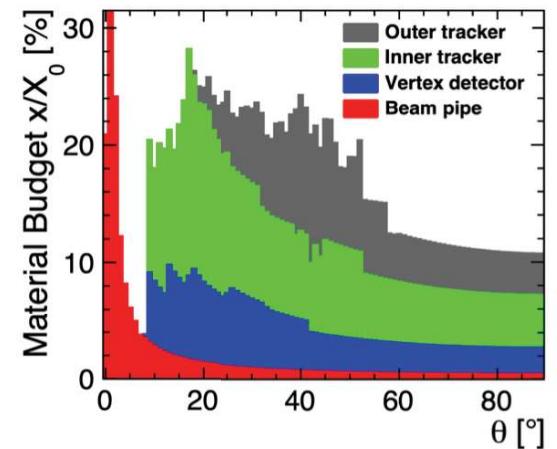
- ◆ CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers ( $1\% X_0$  each)
  - Outer: 3 (4) barrel (fwd) layers ( $1\% X_0$  each)
  - Separated by support tube ( $2.5\% X_0$ )
  
- ◆ IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10%  $iC_4H_{10}$
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of  $X_0$  at  $90^\circ$ 
    - ❖ Tungsten wires dominant contribution
  - Full system includes Si VXT and Si “wrapper”

### What about a TPC?

- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties...

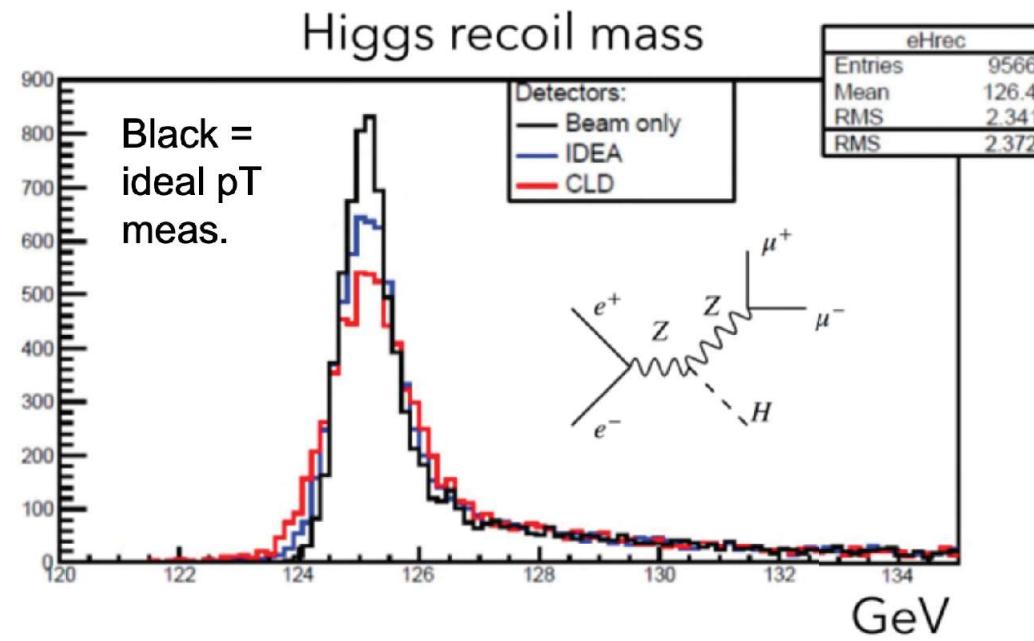
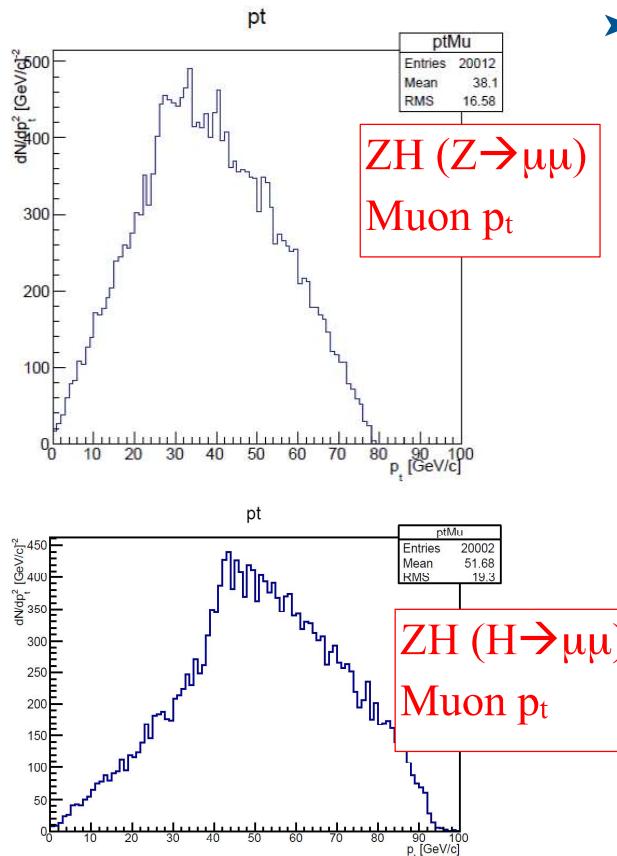


## TRACKING OPTIONS

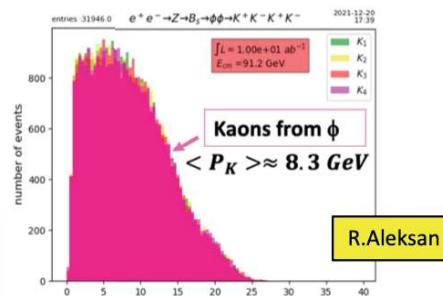


# DRIFT CHAMBER

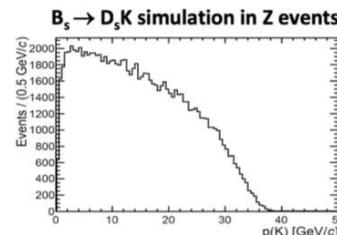
- In general, tracks have rather low momenta ( $p_T \lesssim 50$  GeV)
  - Transparency more relevant than asymptotic resolution
- Drift chamber (gaseous tracker) advantages:
  - Continuous tracking: reconstruction of far-detached vertices (K0S,  $\Lambda$ , BSM, LLPs)
  - Outstanding particle separation via cluster counting ( $dN/dx$ ) or  $dE/dx$ 
    - $>3\sigma$  K/ $\pi$  separation up to  $\sim 35$  GeV



### K/ $\pi$ separation asked for over large momentum range



### Flavour physics



$Z \rightarrow \tau\tau$ ;  $\tau \rightarrow \pi\nu$  vs  $\tau \rightarrow \bar{\nu}\nu$   
 $\pi/K$  separation from 0 to 45.6 GeV

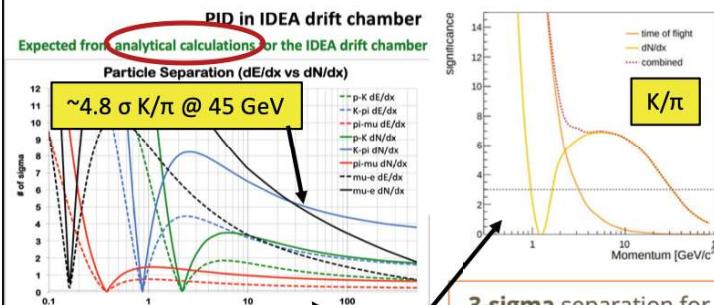
### Higgs physics

- Derive sensitivity to Higgs strange Yukawa coupling
- Develop a **strange tagger** and apply the tagger to a direct **SM  $h \rightarrow s\bar{s}$**  or **BSM  $H \rightarrow cs$**  analysis

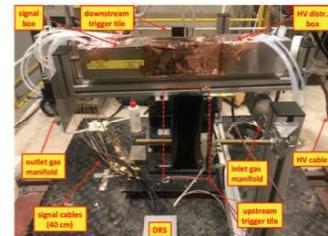
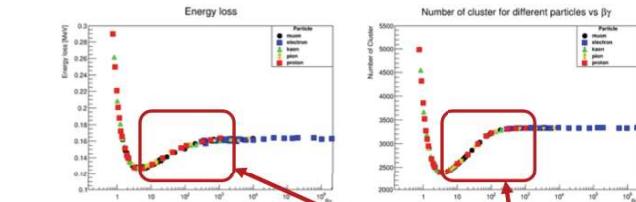
## Particle Identification

Liverpool slide

### IDEA Drift Chamber exploiting cluster counting



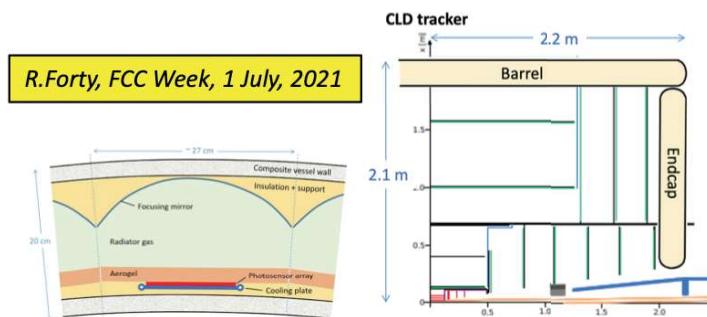
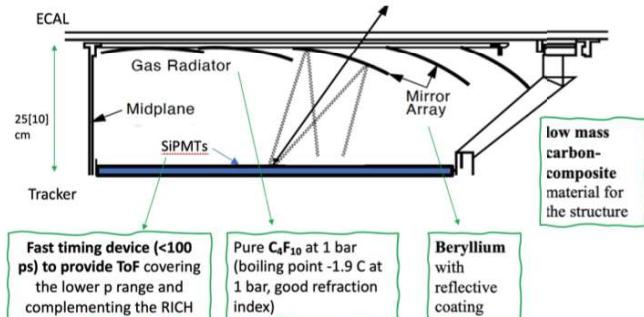
Geant4: Relativistic plateau earlier for  $dN/dx$

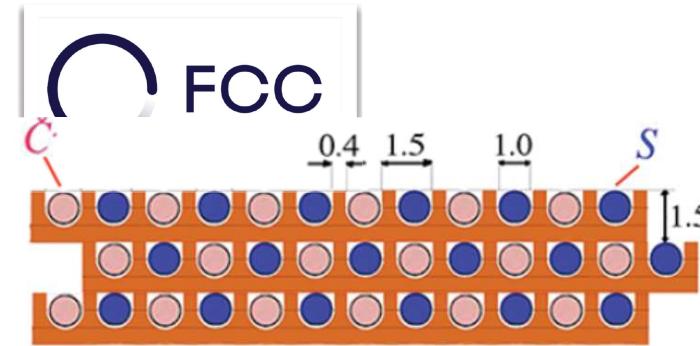


Test beam campain summer 2022: investigate relativistic rise region

### Two initiatives on compact RICH

## Valentina Maria Martina Cairo (CERN) Compact Gaseous RICH with SiPMTs

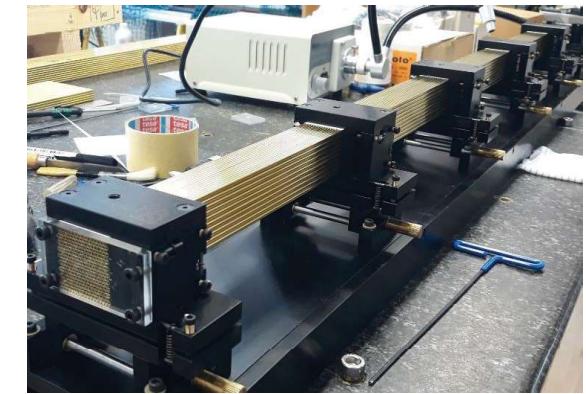




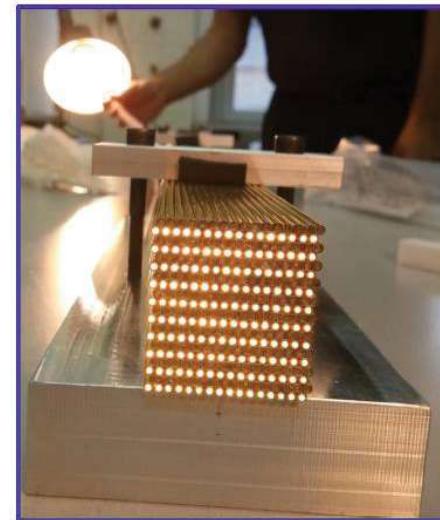
Alternate  
Cherenkov fibers  
Scintillating fibers

## DUAL READOUT CALORIMETRY

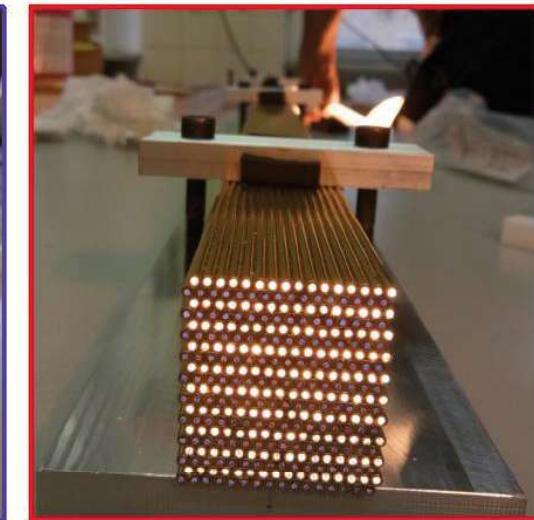
~2m long capillaries



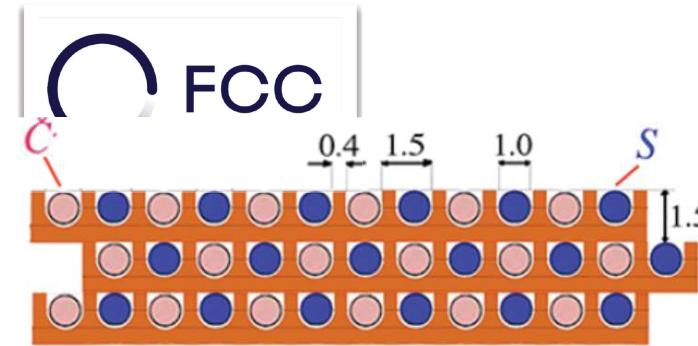
Newer DR calorimeter  
(bucatini calorimeter)



Scintillation fibers



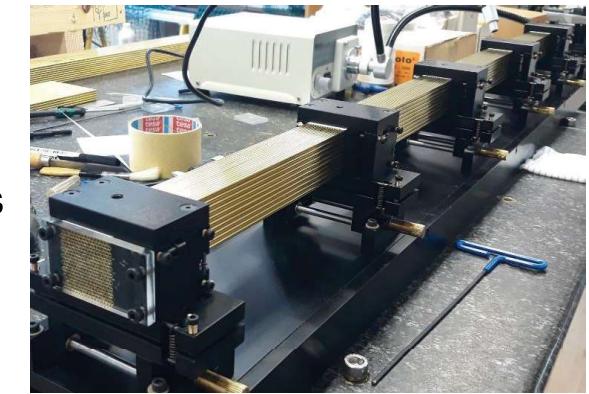
Cherenkov fibers



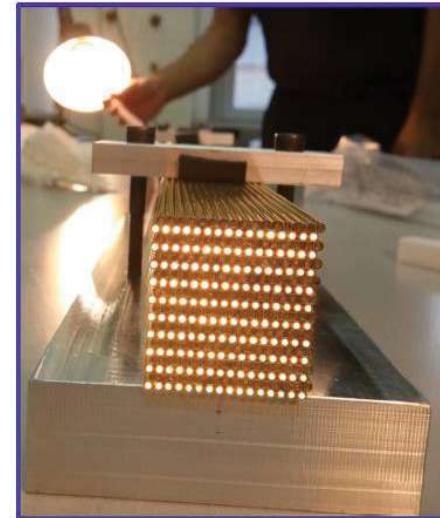
Alternate  
Cherenkov fibers  
Scintillating fibers

## DUAL READOUT CALORIMETRY

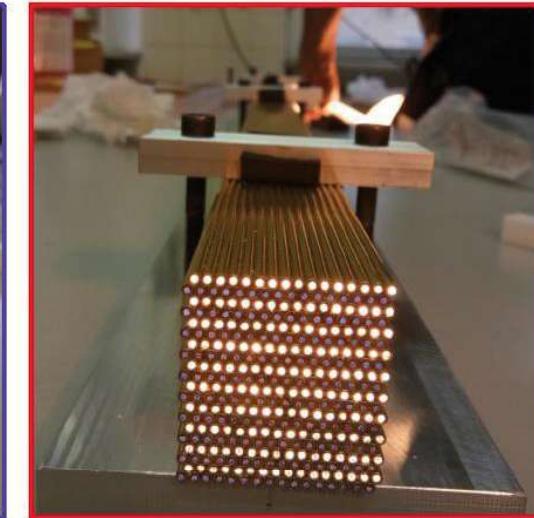
~2m long capillaries



Newer DR calorimeter  
( bucatini calorimeter)

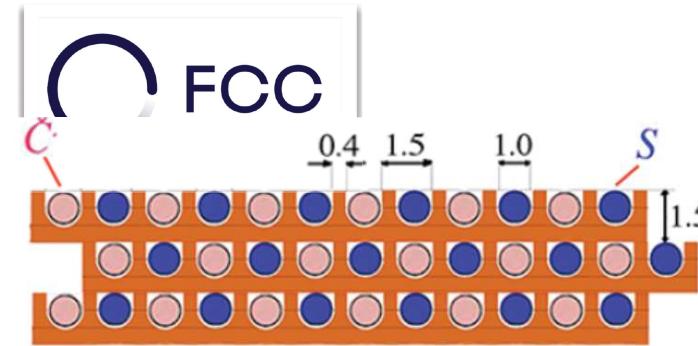


Scintillation fibers



Cherenkov fibers

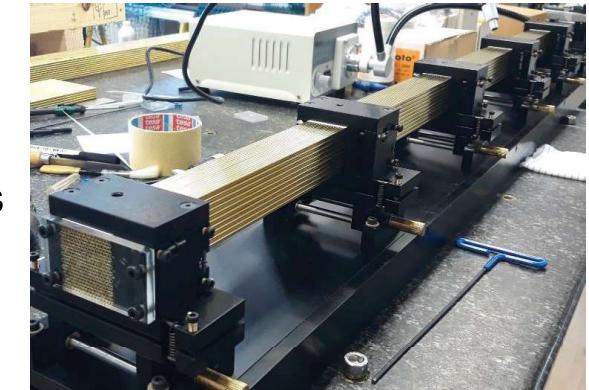
- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with e-



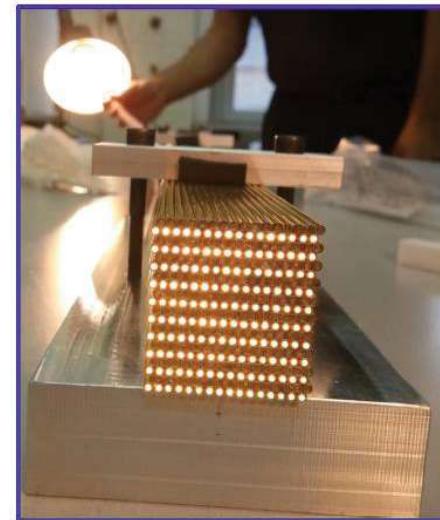
Alternate  
Cherenkov fibers  
Scintillating fibers

## DUAL READOUT CALORIMETRY

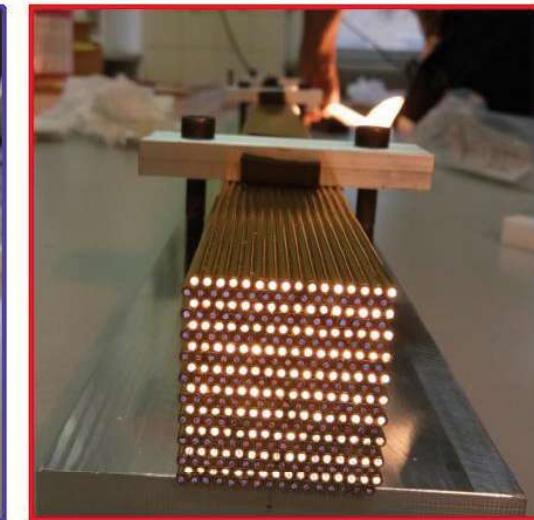
~2m long capillaries



Newer DR calorimeter  
( bucatini calorimeter)

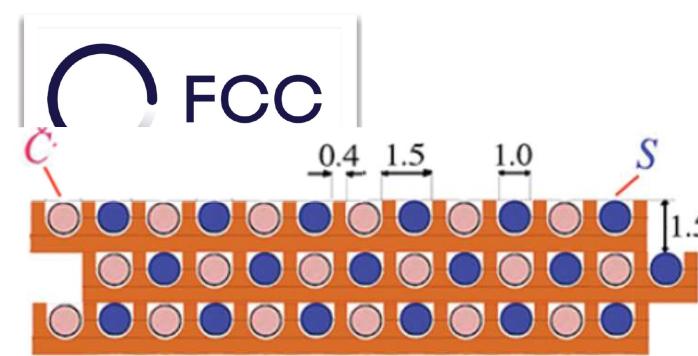


Scintillation fibers



Cherenkov fibers

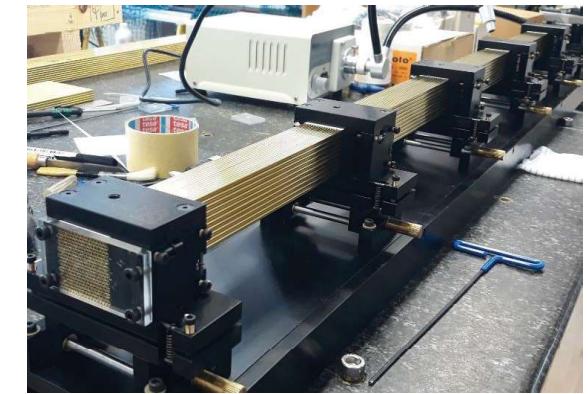
- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with  $e^-$
- Unfold event by event fem to obtain corrected energy



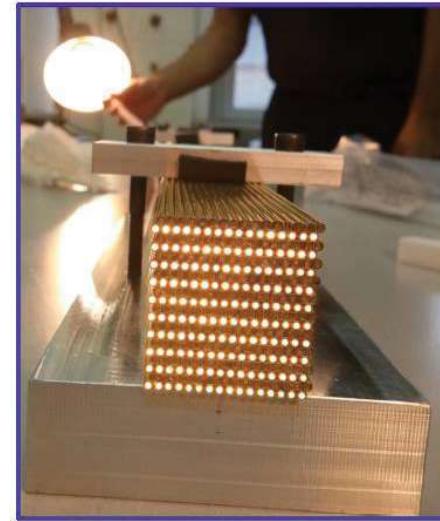
Alternate  
Cherenkov fibers  
Scintillating fibers

## DUAL READOUT CALORIMETRY

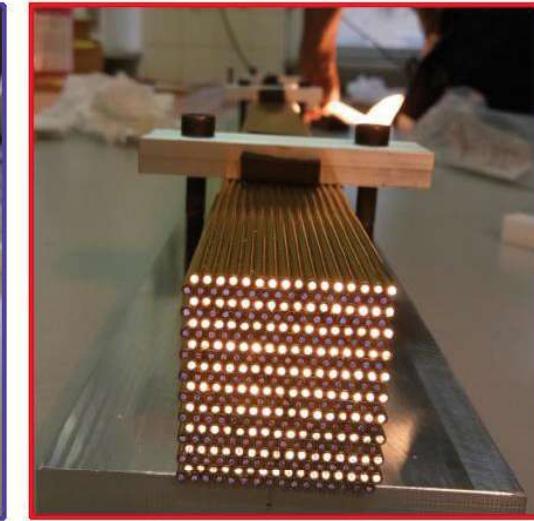
~2m long capillaries



Newer DR calorimeter  
(bucatini calorimeter)



Scintillation fibers



Cherenkov fibers

- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with  $e^-$
- Unfold event by event fem to obtain corrected energy

$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

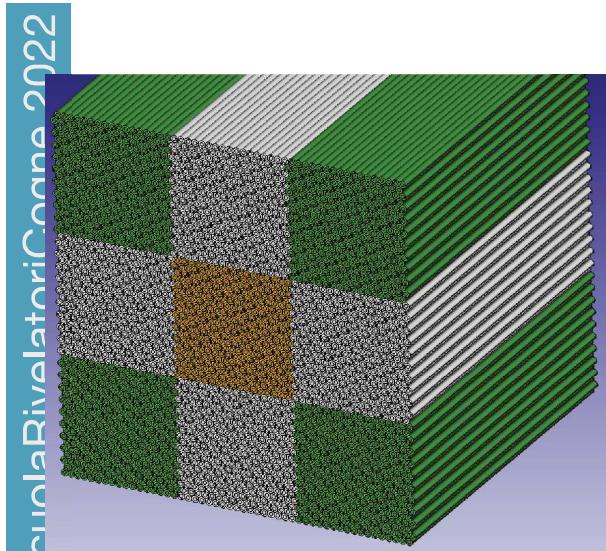
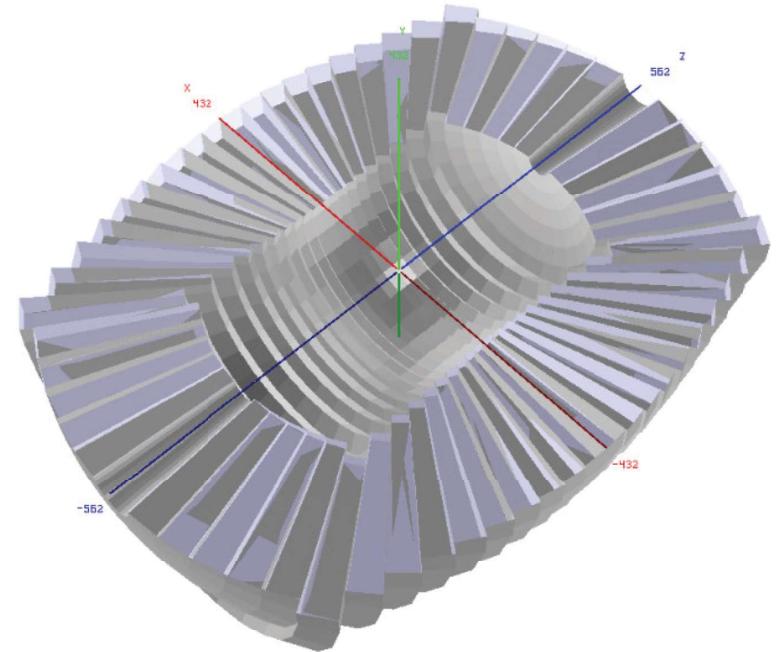
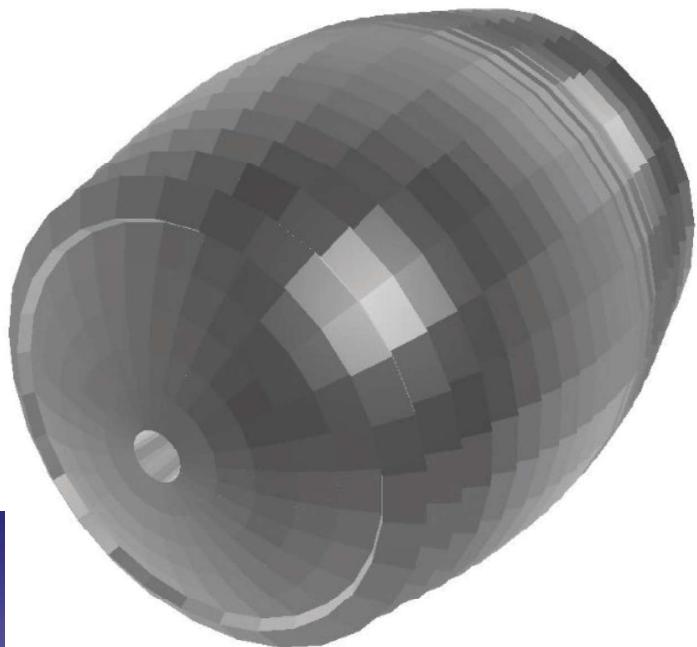
$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with: } \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

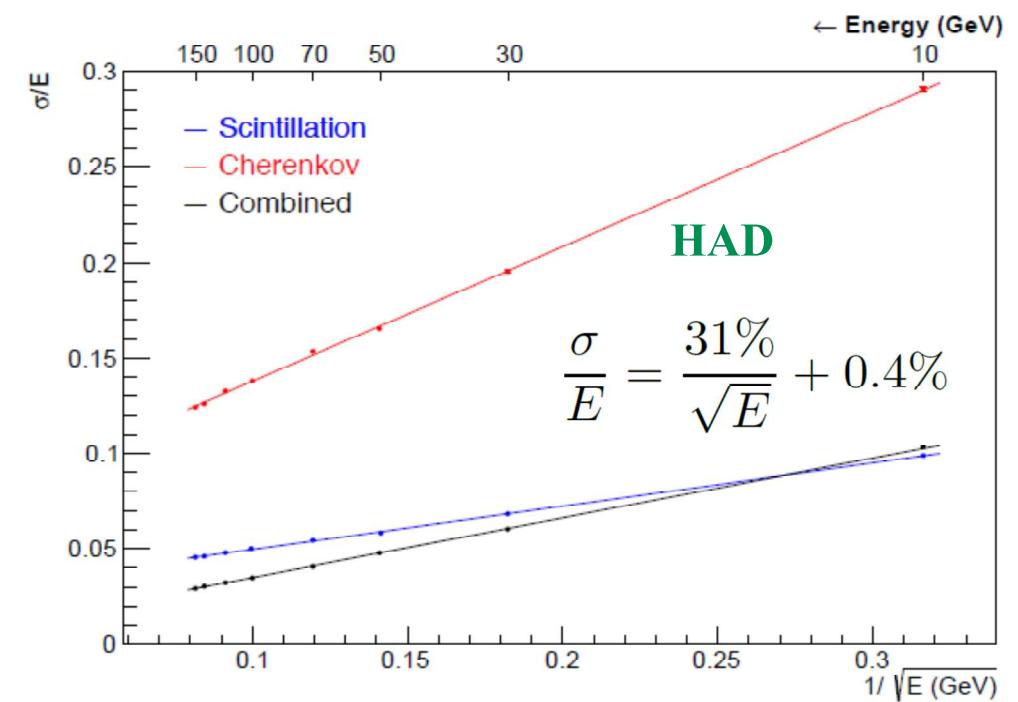
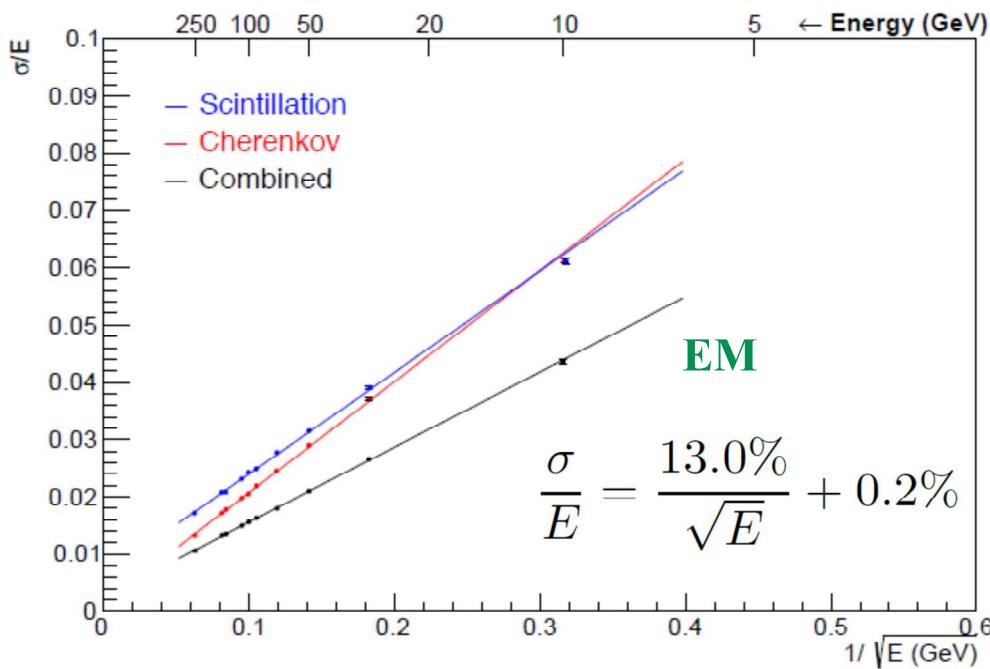


## DUAL READOUT CALORIMETER

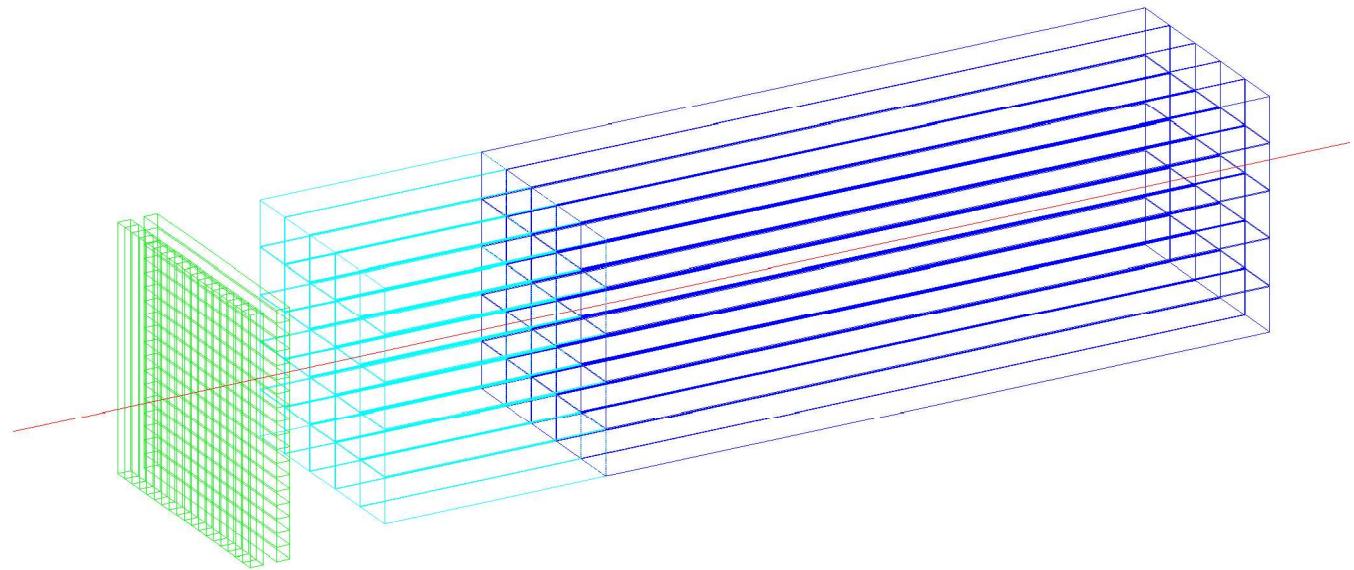
Full GEANT4 implementation of the DR calorimeter



# DUAL READOUT CALORIMETER



## CRYSTAL OPTION



### ▪ ECAL layer:

- PbWO crystals
- front segment 5 cm ( $\sim 5.4 X_0$ )
- rear segment for core shower
- (15 cm  $\sim 16.3 X_0$ )
- 10x10x200 mm<sup>3</sup> of crystal
- 5x5 mm<sup>2</sup> SiPMs (10-15 um)



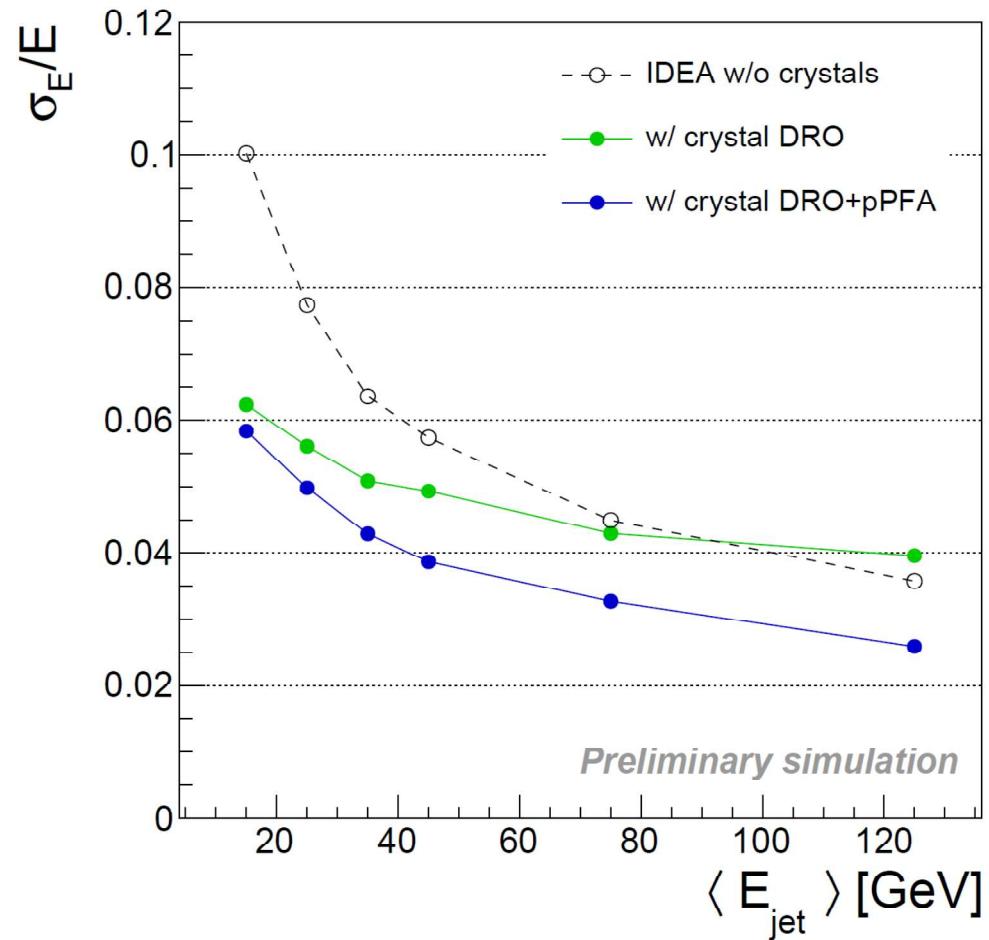
1x1x5 cm<sup>3</sup>  
PbWO

1x1x15 cm<sup>3</sup>  
PbWO

- ~20 cm PbWO<sub>4</sub>
- $\sigma_{EM} \approx 3\%/\sqrt{E}$
- DR w. filters
- Timing layer
- LYSO 20-30 ps
- PF for jets

## CRYSTAL OPTION

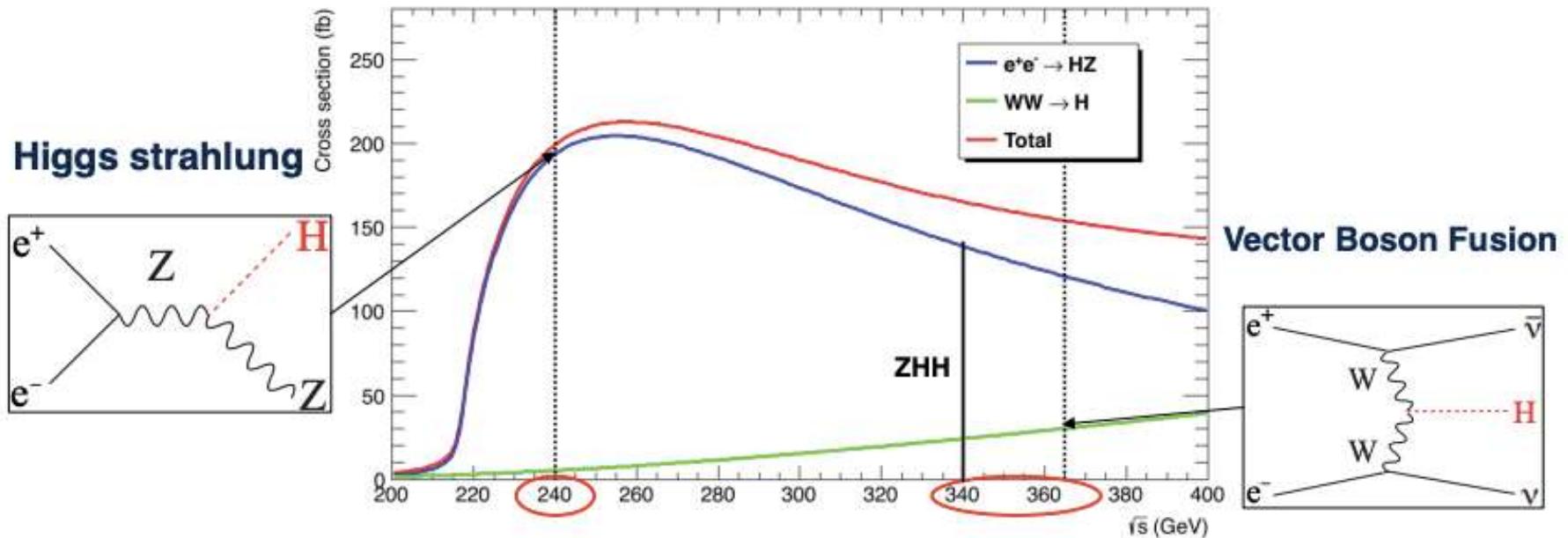
Jet resolution



3

# HIGGS PRODUCTION AT FCC-ee

## Higgs boson production through Higgs strahlung and VBF



- maximum ZH cross section value at  $\sqrt{s} = 255$  GeV
- luminosity drops with  $\sqrt{s}$  at constant ISR dissipation power

**maximum event production at  $\sqrt{s} = 240$  GeV**

- higher energy points available for other physics targets (top physics), but they can be used to improve Higgs measurements (in particular  $\Gamma_H$  and Higgs self-coupling)

# FCC-ee AS A HIGGS FACTORY AND BEYOND

Higgs provides a very good reason why we need both  $e^+e^-$  AND  $pp$  colliders

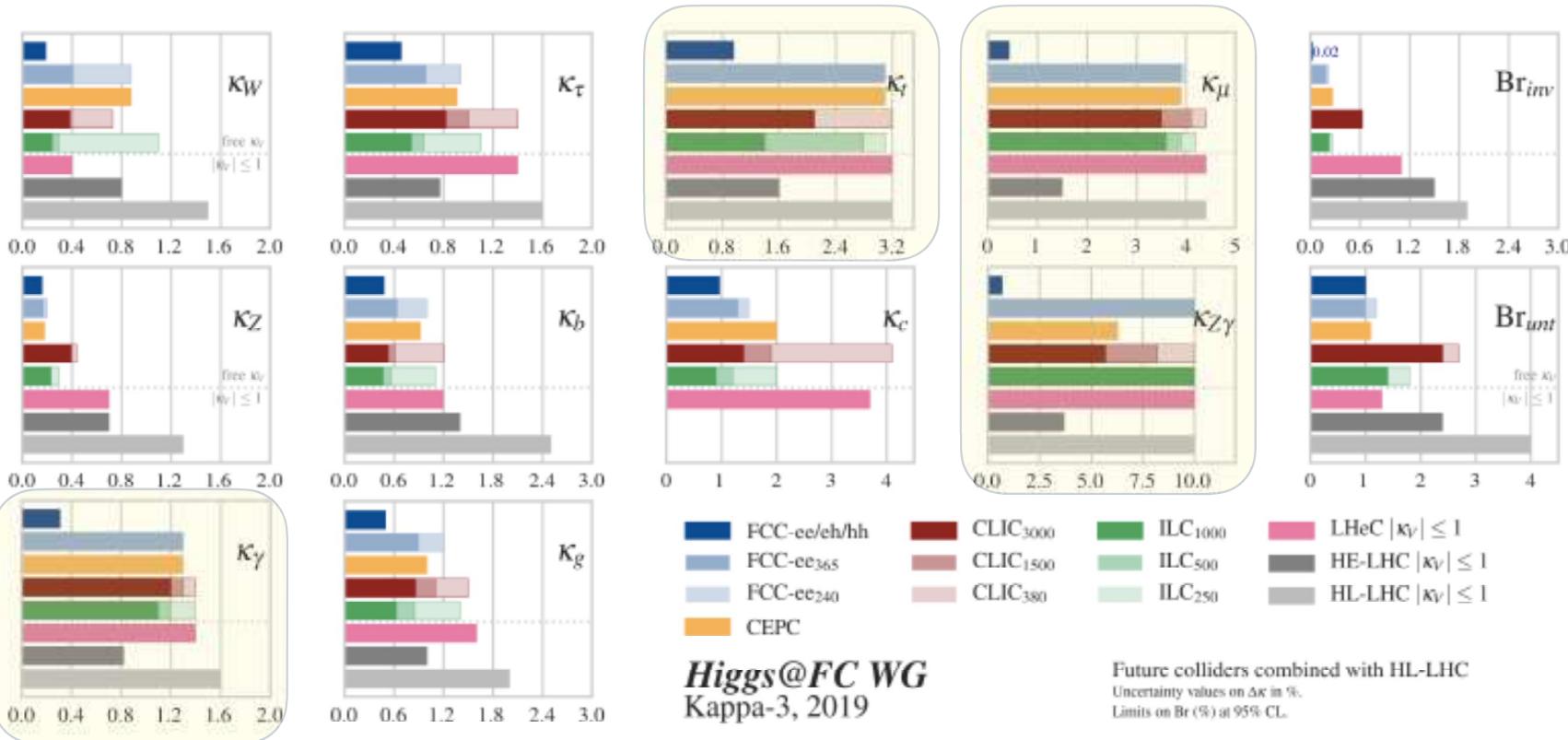
- FCC-ee measures  $g_{HZZ}$  to 0.2% (absolute, model-independent, standard candle) from  $\sigma_{ZH}$ 
  - $\Gamma_H, g_{Hbb}, g_{Hcc}, g_{H\tau\tau}, g_{HWW}$  follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over  $10^{10}$  Higgs bosons
  - (1<sup>st</sup> standard candle  $\rightarrow g_{H\mu\mu}, g_{H\gamma\gamma}, g_{HZ\gamma}, Br_{inv}$ )
  - FCC-ee measures top EW couplings ( $e^+e^- \rightarrow tt$ )
    - Another standard candle
  - FCC-hh produces  $10^8$   $ttH$  and  $2 \cdot 10^7$   $HH$  pairs
    - (2<sup>nd</sup> standard candle  $\rightarrow g_{Htt}$  and  $g_{HHH}$ )
- FCC-ee + FCC-hh is outstanding
  - All accessible couplings with per-mil precision; self-coupling with per-cent precision

Collider	HL-LHC	FCC-ee <sub>240 → 365</sub>	FCC-INT
Lumi ( $ab^{-1}$ )	3	$5 + 0.2 + 1.5$	30
Years	10	$3 + 1 + 4$	25
$g_{HZZ}$ (%)	1.5	0.18 / 0.17	0.17/0.16
$g_{HWW}$ (%)	1.7	0.44 / 0.41	0.20/0.19
$g_{Hbb}$ (%)	5.1	0.69 / 0.64	0.48/0.48
$g_{Hcc}$ (%)	SM	1.3 / 1.3	0.96/0.96
$g_{Hgg}$ (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{H\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11.	– / 10.	0.71/0.7
$g_{Htt}$ (%)	3.4	10. / 3.1	1.0/0.95
$g_{HHH}$ (%)	50.	44./33. 27./24.	2-3
$\Gamma_H$ (%)	SM	1.1	0.91
$BR_{inv}$ (%)	1.9	0.19	0.024
$BR_{EXO}$ (%)	SM (0.0)	1.1	1

FCC-ee is also the most effective way toward FCC-hh

# HIGGS COUPLINGS

- Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.



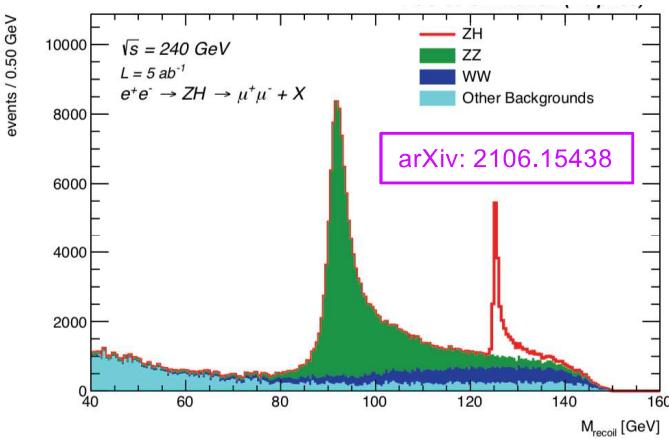
Yellow highlight  
for those  
couplings best  
measured with  
FCC-hh

# HIGGS FACTORY “CASE STUDIES”

- To have a concrete path toward the precision we plan to reach. With complete analysis and realistic detectors

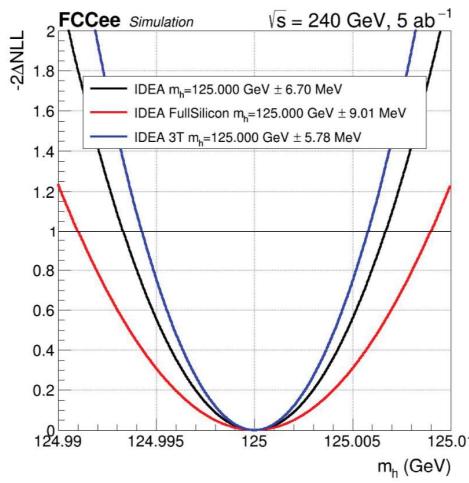
## Higgs mass and inclusive cross section measurement

### Recoil mass fit in $e^+e^- \rightarrow ZH$ with $Z \rightarrow \mu^+\mu^-$

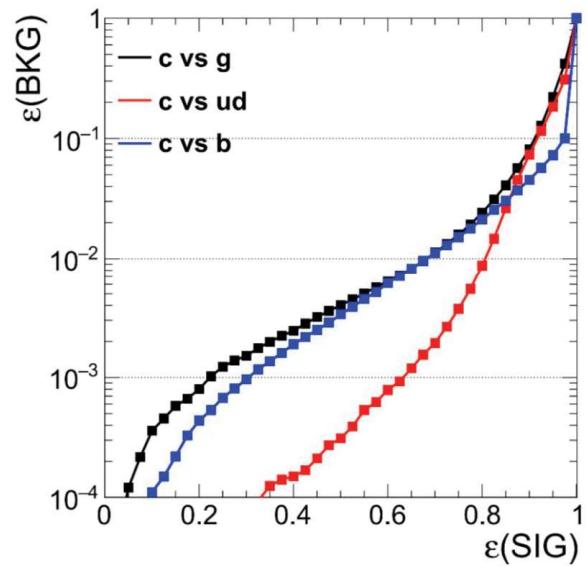


Gentle beamstrahlung  
→ limited mass tail

Light tracker much better  
Mag. Field of 3T helps a bit



## Flavour tagging

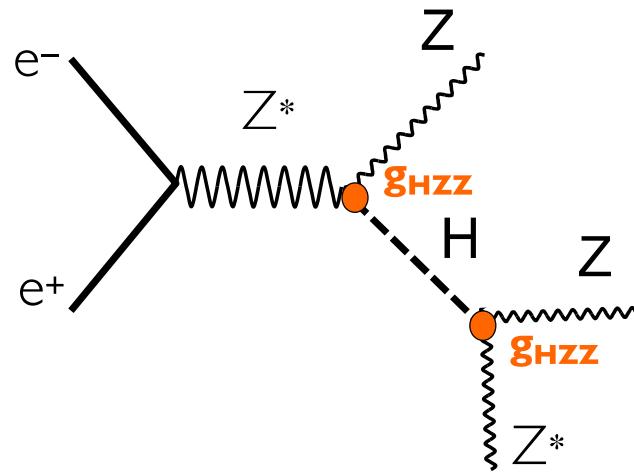


- Advanced flavour-tagging algorithm based on a Dynamic Graph Convolutional Neural Network.
- Very promising c-tagging
- Innovative developments on s-tagging too

## HIGGS WIDTH

- Model independent determination of the total Higgs decay width down to 1.3% with runs at  $\sqrt{s}=240$  and  $\sqrt{s}=365$  GeV

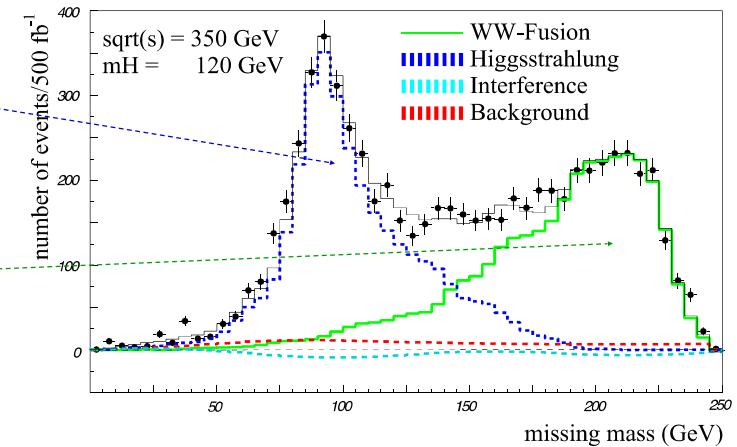
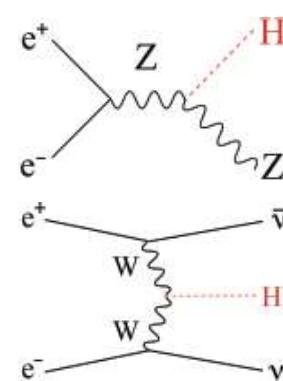
$e^-e^+ \rightarrow HZ$  &  $H \rightarrow ZZ$  at  $\sqrt{s} = 240$  GeV



- ❖  $\sigma_{HZ}$  is proportional to  $g_{HZZ}^2$
- ❖  $BR(H \rightarrow ZZ) = \Gamma(H \rightarrow ZZ) / \Gamma_H$  is proportional to  $g_{HZZ}^2 / \Gamma_H$ 
  - $\sigma_{HZ} \times BR(H \rightarrow ZZ)$  is proportional to  $g_{HZZ}^4 / \Gamma_H$
- ❖ Infer the total width  $\Gamma_H$

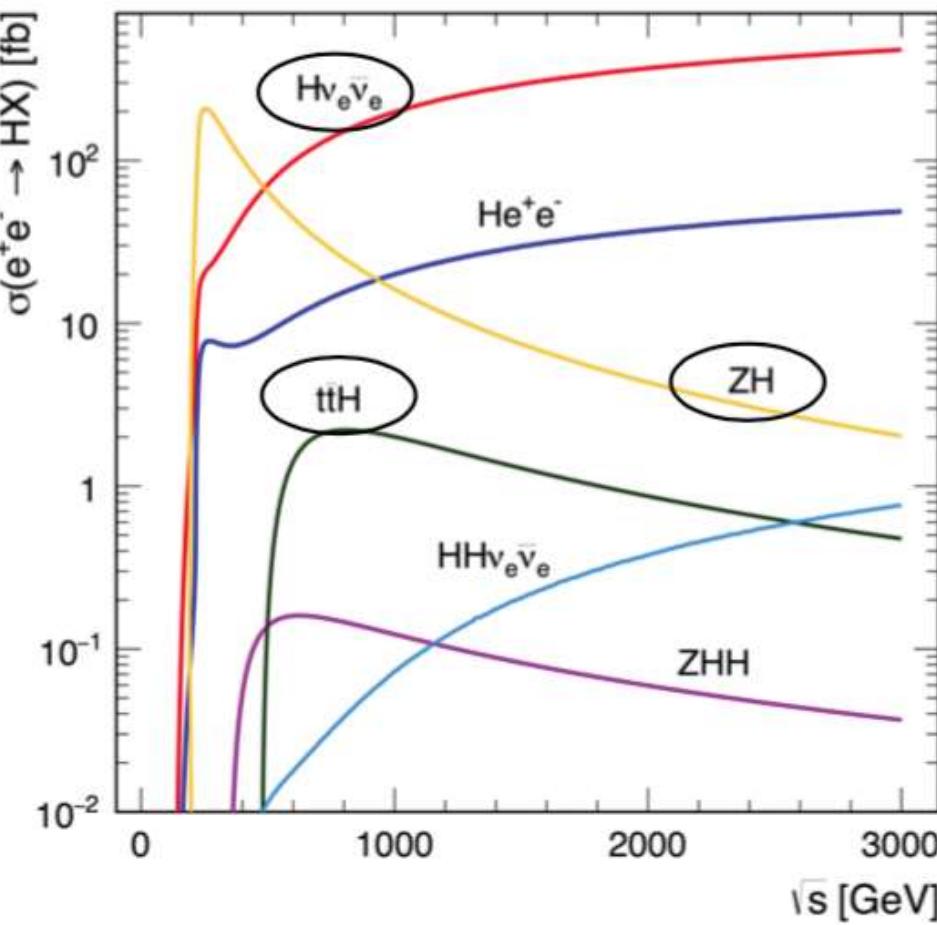
$\sqrt{s}=365$  not just for Top physics!

$WW \rightarrow H v\bar{v} \rightarrow b\bar{b}v\bar{v}$  at  $\sqrt{s} = 365$  GeV

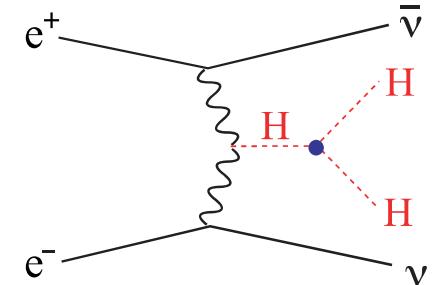
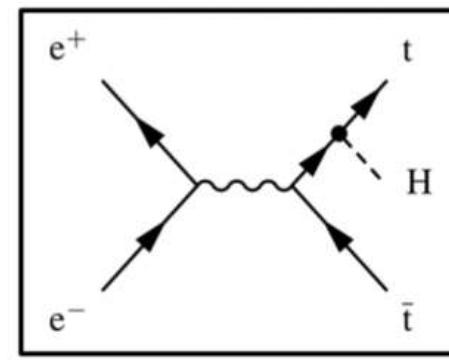


$$\Gamma_H \propto \frac{\sigma_{WW \rightarrow H}}{BR(H \rightarrow WW)} = \frac{\sigma_{WW \rightarrow H \rightarrow b\bar{b}}}{BR(H \rightarrow WW) \times BR(H \rightarrow b\bar{b})}$$

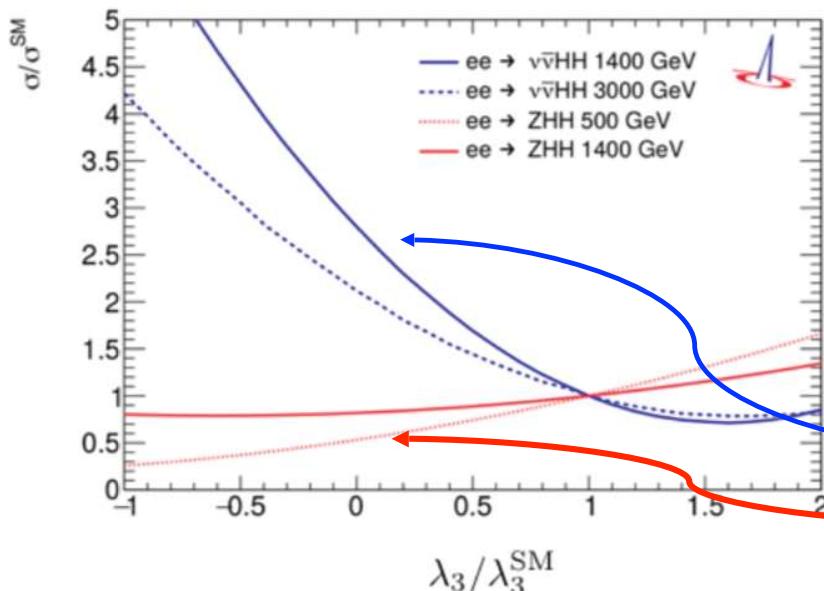
## HIGGS PRODUCTION AT HIGH ENERGY LEPTON COLLIDERS



- $t\bar{t}H$  production:  $e^+e^- \rightarrow t\bar{t}H$
- Accessible  $\sqrt{s} \geq 500$  GeV, maximum  $\approx 800$  GeV
- Direct extraction of top Yukawa coupling
- $ZHH$  and  $HHv_e\bar{v}_e$  production
- From  $\sqrt{s}=500$  GeV ( $ZHH$ ) and  $\approx 800$  GeV ( $HHv_e\bar{v}_e$ ), dual Higgs production
- Sensitivity to Higgs self coupling

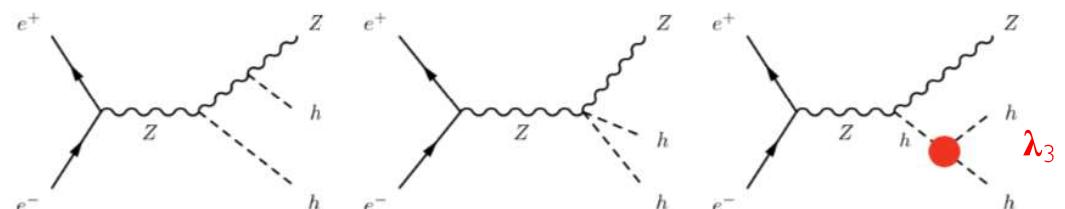


- Higgs self-coupling,  $\lambda_3$ , is a fundamental parameter of the SM whose value should be checked against prediction
- Essentially dictates the shape of the Higgs potential
- For  $\sqrt{s} \gtrsim 500$  GeV there is di-Higgs production

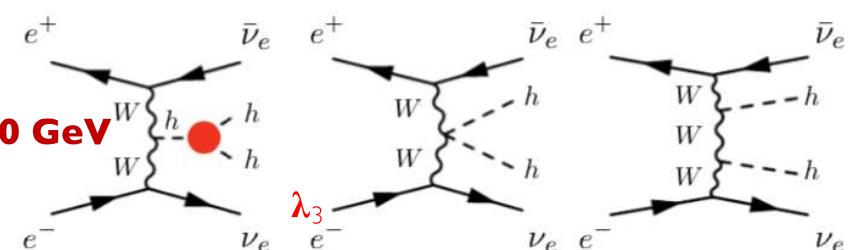


## HIGGS SELF-COUPLING, $\lambda_3$

From 500 GeV



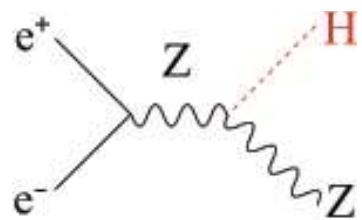
From  $\approx 800$  GeV



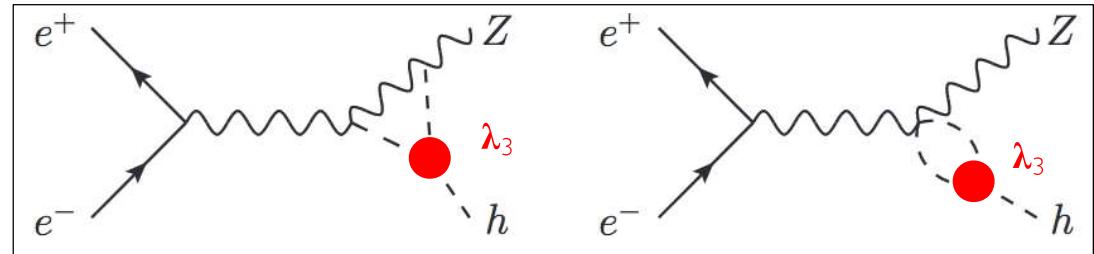
- In both cases, three interfering diagrams
  - ❖ Higgs self coupling,  $\lambda_3$ , extracted from fit to production cross section
    - At 1400 GeV: relatively strong dependence
    - At 500 GeV: weak(er) dependence

EVALUATION OF  $\lambda_{HHH}$  WITH SINGLE HIGGS PRODUCTION

arXiv:1312.3322



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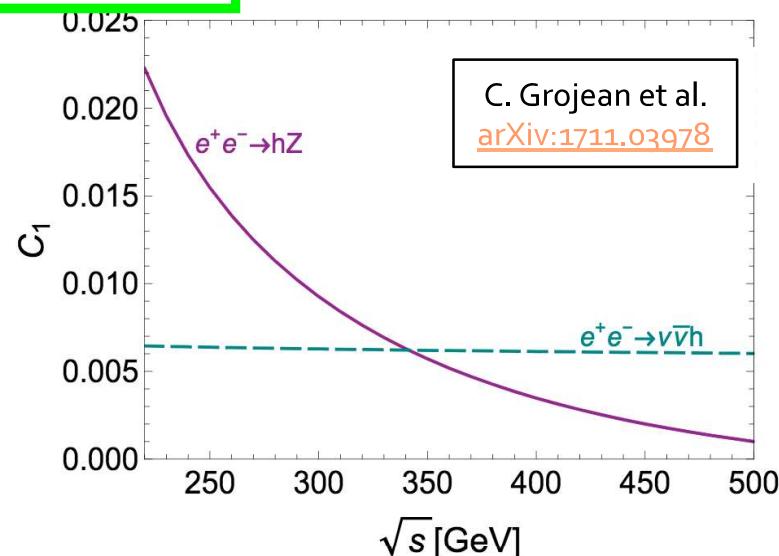
- At lower energies (CC,  $\sqrt{s} < 500 \text{ GeV}$ ), no production of Higgs pairs
- But, loops including Higgs self-coupling contribute to Higgs production cross section:
 
$$\delta_{\sigma}^{240} = 100(2\delta_Z + 0.014\delta_h) \%$$
  - up to 1.5% effect on  $\sigma_{ZH}$  @ $\sqrt{s}=240$ , but degeneracy  $\delta_H$  and  $\delta_Z$
  - cannot constrain  $\delta_H$  alone, would need assumption on  $\delta_Z$

## EVALUATION OF $\lambda_{\text{HHH}}$ WITH SINGLE HIGGS PRODUCTION

- ▶ Effect on  $\sigma_{\text{ZH}}$  and  $\sigma_{\text{VvH}}$  of Higgs self coupling ( $\lambda_3$  and hence  $\kappa_\lambda = \lambda_3 / \lambda_{3\text{SM}}$ ) depends on  $\sqrt{s}$
- ▶ Two energy points at  $\sqrt{s}=240$  and 365 lift the degeneracy between  $\delta_Z$  and  $\delta_h$
- ▶ Combinations of precision measurements of ZH associated production at different center of mass energies may be used to determine ellipse-plot constraints on the combined parameter space of  $\delta_Z$  and  $\delta_h$
- ▶ which could be used to set constraints on some strongly-coupled Higgs model

$$\Sigma_{\text{NLO}} = Z_H \Sigma_{\text{LO}} (1 + \kappa_\lambda C_1),$$

$C_1$  is a process-dependent coefficient that encodes the interference between the NLO amplitudes involving  $\kappa_\lambda$  and the LO ones

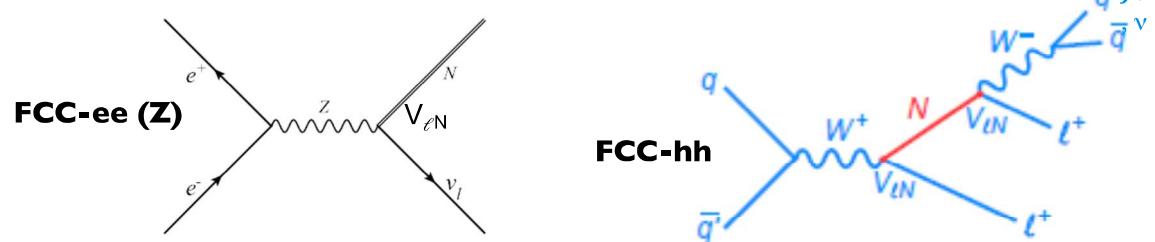


Precision on $\kappa_\lambda$	
FCC-ee	33 %
FCC-ee(4IP)	24 %
FCC(ee+hh)	5 %

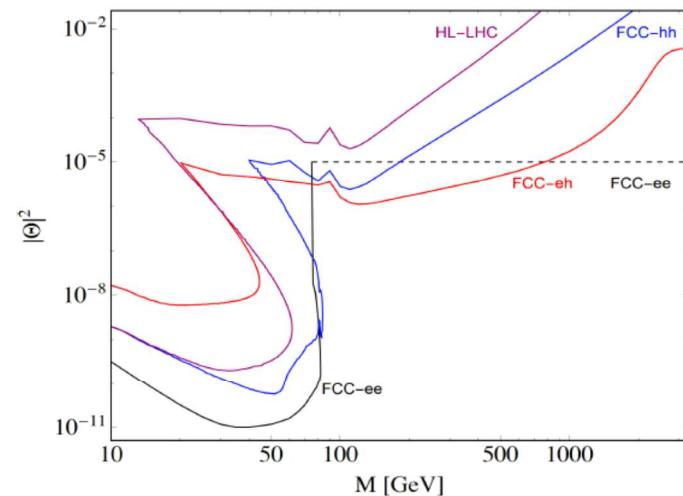
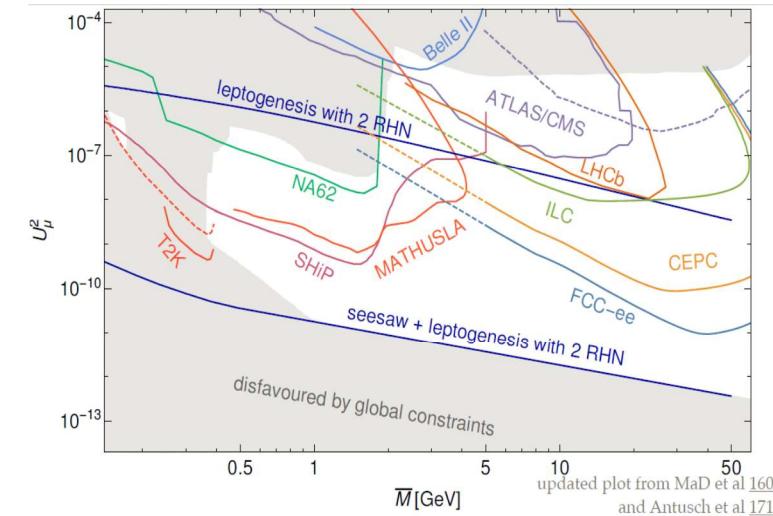
$\sqrt{s}=365\text{GeV}$  not just for Top physics!

# FCC SYNERGIES: FEEBLY INTERACTING PARTICLES

- Heavy Right-Handed Neutrinos
- Complete SM spectrum – and perhaps explain DM, BAU,  $\nu$  masses



- **FCC-ee sensitivity** (to mixing angle with LH  $\nu$ )
  - ◆ **EWPO:**  $\sim 10^{-5}$  up to very high masses
  - ◆ **Best, flavour-blind, sensitivity to  $\sum_\ell |V_{\ell N}|^2$  below 100 GeV**
- **FCC-hh sensitivity**
  - ◆ Sensitivity to  $V_{\ell 1 N} V_{\ell 2 N}$  with lepton charge and flavour
- **FCC-eh sensitivity**
  - ◆ Production in charge currents  $e p \rightarrow X N \rightarrow \ell W$
  - ◆ Sensitivity to  $V_{e N} V_{\ell N}$
- **Complementarity**
  - ◆ Discovery + complementary studies in overlap regions

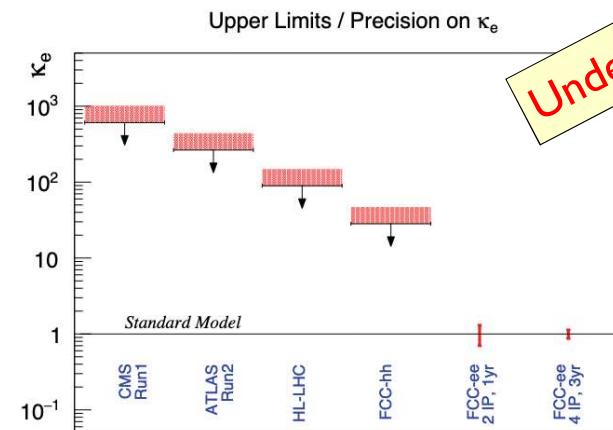


# ELECTRON YUKAWA COUPLING

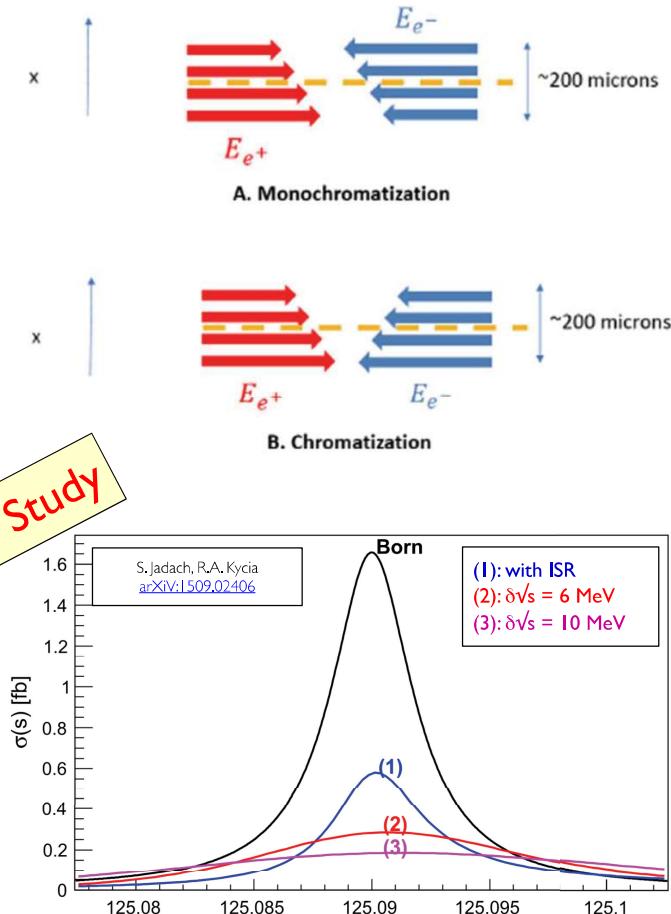
- Something unique: electron Yukawa coupling from  $e^+e^- \rightarrow H$
- One of the toughest challenges, which requires:
  - Higgs boson mass prior knowledge to a couple MeV
  - Huge luminosity (i.e., several years with possibly 4 IPs)
  - (Mono)chromatisatation:  $\Gamma_H$  (4.2 MeV)  $\ll \delta\sqrt{s}$  (100 MeV)
  - Continuous monitoring and adjustment of  $\sqrt{s}$
  - Different  $e^+$  and  $e^-$  energies (to avoid integer spin tune)
  - Extremely sensitive event selection against SM backgrounds
  - For all Higgs decay channels

Uncertainty at the SM level  
(IF everything works nominally)

Indicates whether the Higgs boson (also) gives mass to ordinary matter.

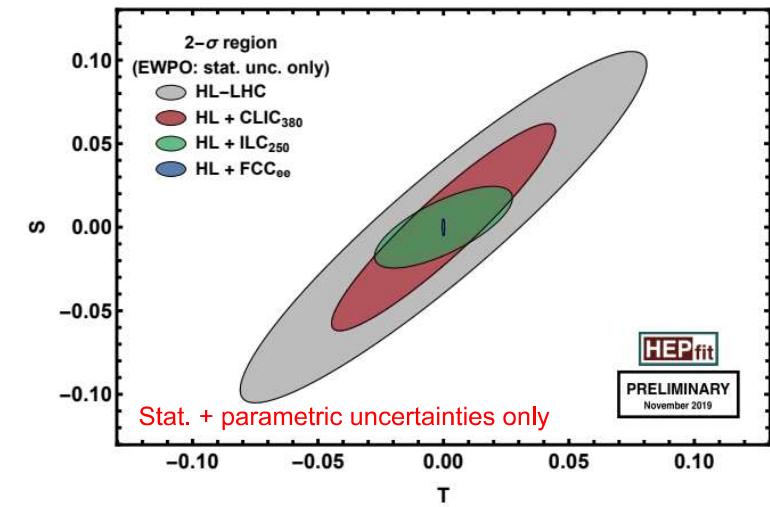
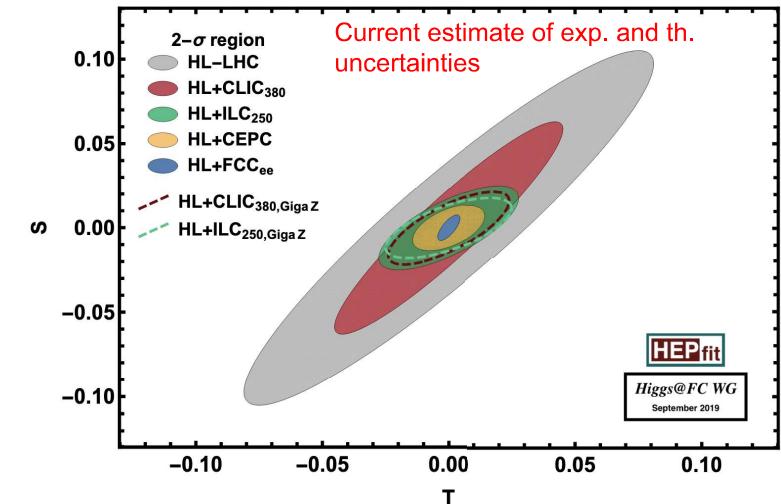


Very very challenging



# FCC-ee AS AN ELECTROWEAK FACTORY

- With highest luminosities at 91, 160 and 350 GeV
  - Complete set of EW observables can be measured
  - Precision ( $10^{-3}$  today) down to few  $10^{-6}$
  
- Precision unique to FCC-ee, with smallest parametric errors
  - Challenge: match syst. uncertainties to the stat. precision
    - A lot more potential to exploit with good detector design than the present treatment suggests
    - Theory work is critical and initiated
  - Precision = discovery potential (e.g., NP in Z/W propagators)



## SELECTED ELECTROWEAK QUANTITIES (FROM FCC-ee)

Orders of magnitudes reduction of statistical uncertainties

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
$m_Z$ (keV)	$91,186,700 \pm 2200$	5	100	From Z line shape scan Beam energy calibration
$\Gamma_Z$ (keV)	$2,495,200 \pm 2300$	8	100	From Z line shape scan Beam energy calibration
$R_\ell^Z (\times 10^3)$	$20,767 \pm 25$	0.06	0.2–1.0	Ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z) (\times 10^4)$	$1196 \pm 30$	0.1	0.4–1.6	From $R_\ell^Z$ above [43]
$R_b (\times 10^6)$	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [44]
$\sigma_{had}^0 (\times 10^3)$ (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement
$N_\nu (\times 10^3)$	$2991 \pm 7$	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{\text{eff}} (\times 10^6)$	$231,480 \pm 160$	3	2–5	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z) (\times 10^3)$	$128,952 \pm 14$	4	Small	From $A_{FB}^{\mu\mu}$ off peak [34]
$A_{FB}^{b,0} (\times 10^4)$	$992 \pm 16$	0.02	1–3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{\text{pol},\tau} (\times 10^4)$	$1498 \pm 49$	0.15	< 2	$\tau$ Polarisation and charge asymmetry $\tau$ decay physics
$m_W$ (MeV)	$80,350 \pm 15$	0.5	0.3	From WW threshold scan Beam energy calibration
$\Gamma_W$ (MeV)	$2085 \pm 42$	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W) (\times 10^4)$	$1170 \pm 420$	3	Small	From $R_\ell^W$ [45]
$N_\nu (\times 10^3)$	$2920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$m_{\text{top}}$ (MeV)	$172,740 \pm 500$	17	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\text{top}}$ (MeV)	$1410 \pm 190$	45	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	$1.2 \pm 0.3$	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{\text{CM}} = 365$ GeV run

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$\sigma_{\text{had}}^0 (\times 10^3) (\text{nb})$	$41,541 \pm 37$	0.1	4	Peak hadronic cross-section luminosity measurement

In this context would need from theory full 3-loop calculations for the Z pole and propagator EWK corrections and probably 2-loop for EWK corrections to the WW cross section. Matching these experimental precisions motivates a significant theoretical effort.

$\Gamma_W$ (MeV)	$2085 \pm 42$	1.2	0.3	From WW threshold scan Beam energy calibration
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$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	$1.2 \pm 0.3$	0.1	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$t\bar{t}Z$ couplings	$\pm 30\%$	0.5–1.5%	Small	From $E_{\text{CM}} = 365$ GeV run

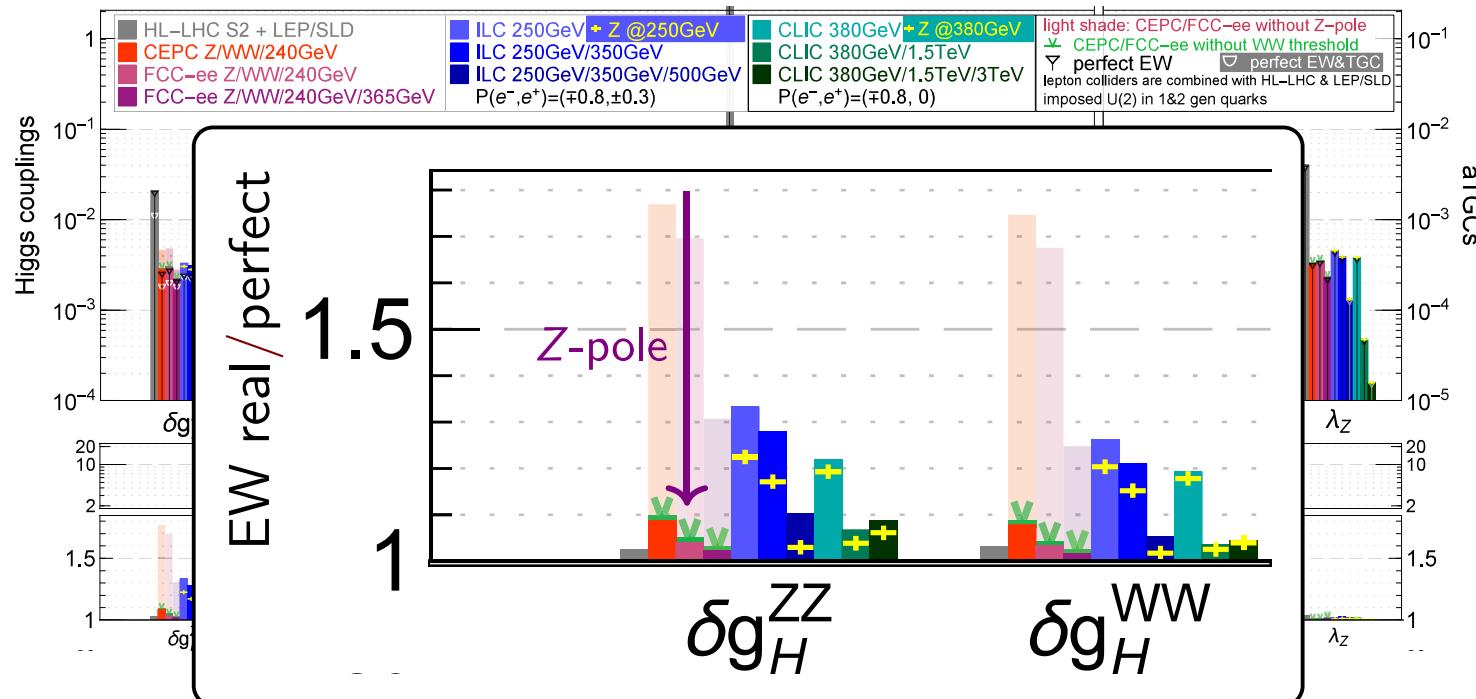
## NEUTRAL COUPLINGS AND EWK ANGLE

$$A_e = \frac{2g_{V_e}g_{A_e}}{(g_{V_e})^2 + (g_{A_e})^2} = \frac{2g_{V_e}/g_{A_e}}{1 + (g_{V_e}/g_{A_e})^2}$$

- $\sin^2 \theta_{eff}$  can be measured with  $5 \times 10^{-6}$  (at least) from:
  - Muon forward-backward asymmetry at pole  $A_{FB}^{\mu\mu}(m_Z)$  **assuming muon-electron universality**
    - uncertainty driven by knowledge of CM energy (point to point errors)
  - Tau polarization **without assuming lepton universality**
    - Tau polarization measures  $A_e$  and  $A_\tau$ , can input to  $A_{FB}^{\mu\mu} = \frac{3}{4} A_e A_\mu$  to measure separately  $e$ ,  $\mu$  and  $\tau$  coupling (with  $\Gamma_e, \Gamma_\mu, \Gamma_\tau$ )
      - Very large tau statistics and improved knowledge of parameters (BF, decay modeling).
      - Also use best decay channels,  $\tau \rightarrow p \nu \tau$ . Constraint on detector performance for  $\gamma/\pi^0$
      - Preliminary estimate to measure  $\sin^2 \theta_{eff}$  with  $6.6 \times 10^{-6}$  precision
  - Asymmetries  $A_{FB}^{bb}, A_{FB}^{cc}$  provide input to quark couplings (together with  $\Gamma_b, \Gamma_c$ )

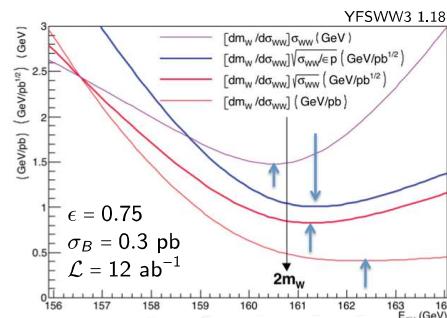
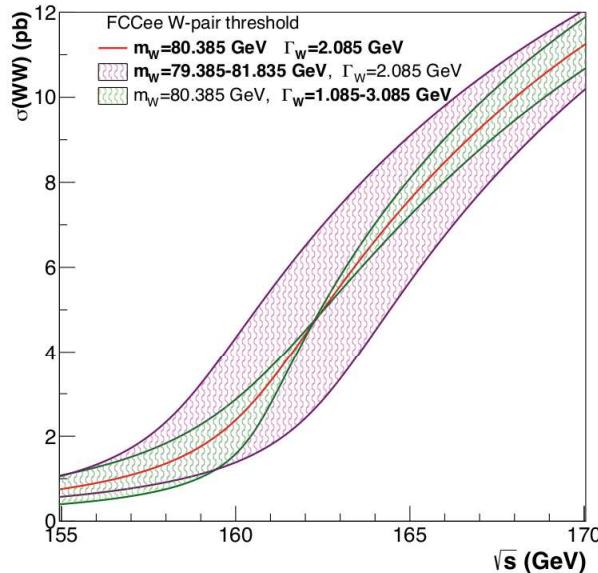
# IMPACT OF Z POLE RUN ON HIGGS

- Z-pole run and precise EWK observables have a big impact also on the Higgs effective couplings



15 EW param. also marginalized over / assumed perfectly constrained

# FCC AT THRESHOLD

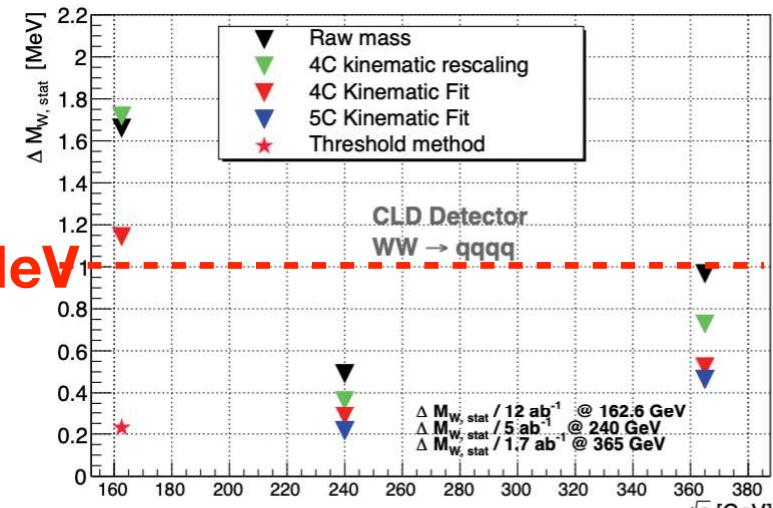


Optimal energy :  $E = 161.4 \text{ GeV}$   
 $\Delta M_W = 0.23 \text{ MeV}$

LEP :  $\Delta M_W = 210 \text{ MeV}$   
 $\mathcal{L} = 10 \text{ pb}^{-1}$

with  $E_1=157.1 \text{ GeV}$   $E_2=162.3 \text{ GeV}$   $f=0.4$   
 $\Delta m_W=0.62$   $\Delta \Gamma_W=1.5 \text{ (MeV)}$

# HOT TOPIC: W MASS AND WIDTH

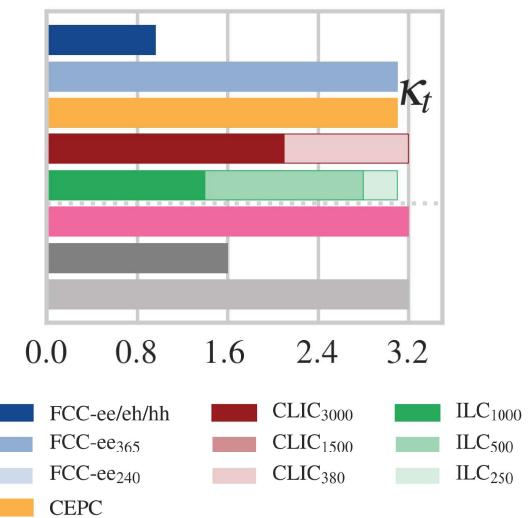
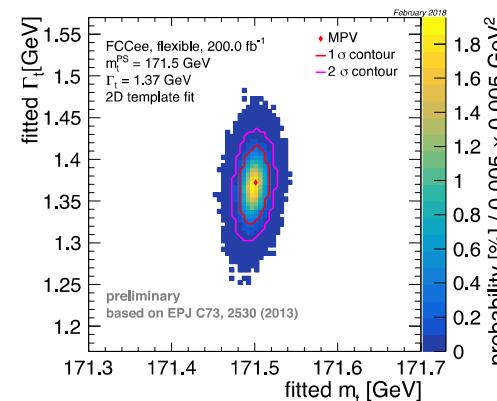
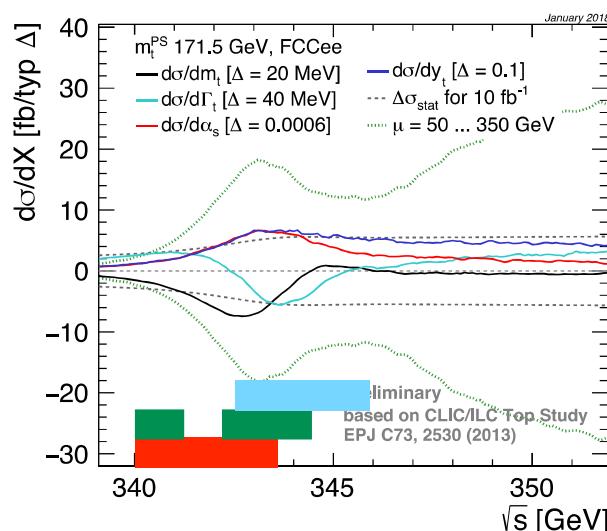


# ABOVE THRESHOLD

- Precise  $M(W)$  from threshold run
- $M(W)$  direct reconstruction from decay products useful/needed at any  $\sqrt{s}$ >threshold
- Competitive as statistical uncertainty but different challenges to be considered:
  - Event reconstruction, choice of jet algorithms
  - Lepton momentum scale and resolution
  - Kinematical fitting

# TOP PHYSICS AT FCC-ee

- Threshold region allows most precise measurements of top mass, width, and estimate of Yukawa coupling. Scan strategy can be optimized
- FCC-ee has some standalone sensitivity to the top Yukawa coupling from the measurements at thresholds for a 10% precision (profiting of the better as).
- But, HL-LHC result of about 3.1% already better (with FCC-ee Higgs measurements removing the model dependence)



- Run at 365 GeV used also for measurements of top EWK couplings (at the level of  $10^{-2}$ - $10^{-3}$ ) and FCNC in the top sector.

# THE INTENSITY FRONTIER - FLAVOR PHYSICS

- Enormous statistics  $10^{12}$  bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs ( $R_b, A_{FB}^{b,c}$ ) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g.,  $b \rightarrow s\tau\bar{\tau}$

Working point	Lumi. / IP [ $10^{34}$ cm $^{-2} \cdot$ s $^{-1}$ ]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab $^{-1}$ /year	2	
Z second phase	200	52 ab $^{-1}$ /year	2	150 ab $^{-1}$

Particle production ( $10^9$ )	$B^0$	$B^-$	$B_s^0$	$\Lambda_b$	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	800	220

**~15 times Belle's stat**

**Boost at the Z!**

Decay mode	$B^0 \rightarrow K^*(892)e^+e^-$	$B^0 \rightarrow K^*(892)\tau^+\tau^-$	$B_s(B^0) \rightarrow \mu^+\mu^-$
Belle II	$\sim 2\,000$	$\sim 10$	n/a (5)
LHCb Run I	150	-	$\sim 15$ (-)
LHCb Upgrade	$\sim 5\,000$	-	$\sim 500$ (50)
FCC-ee	$\sim 200\,000$	$\sim 1\,000$	$\sim 1\,000$ (100)

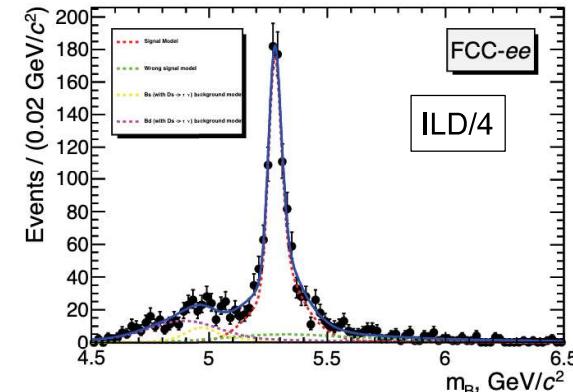
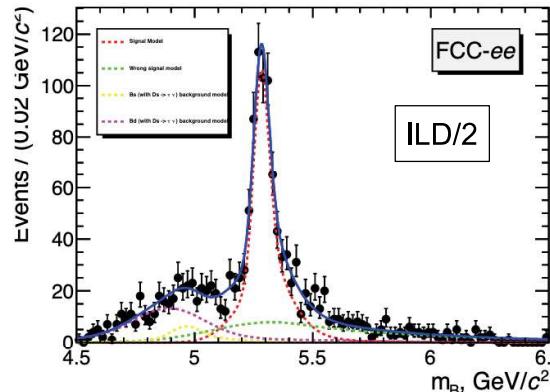
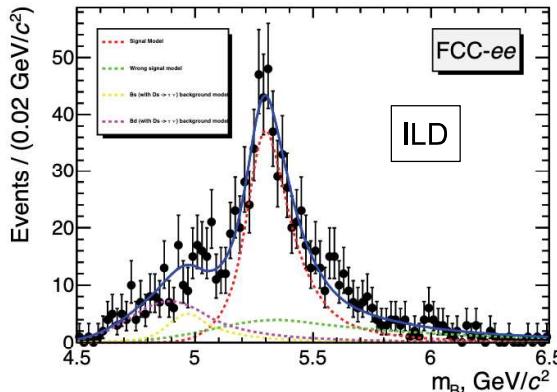
**Yields for flavor anomalies studies:**

**$b \rightarrow sll$  yields and  $B^0 \rightarrow K^{*0}\tau^+\tau^-$  **

**Full reconstruction possible**

# FLAVOR PHYSICS CASE STUDIES

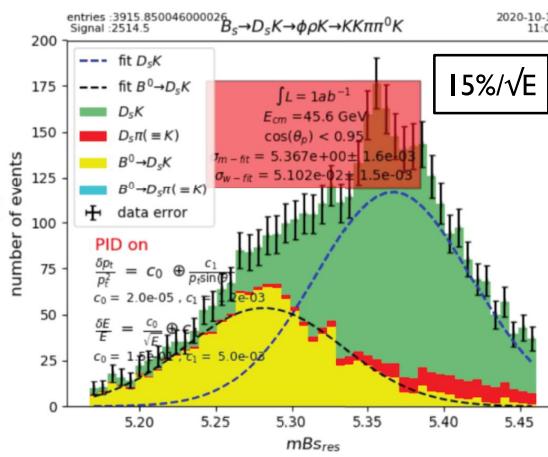
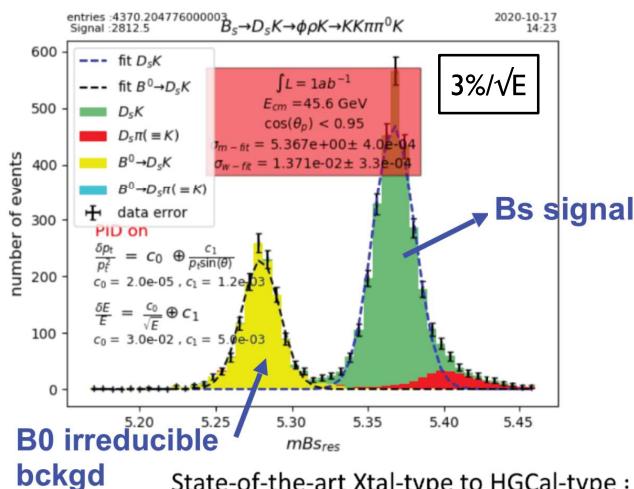
- $B^0 \rightarrow K^{*0}\tau^+\tau^-$  : need excellent Vertexing



A major background missing in these plots

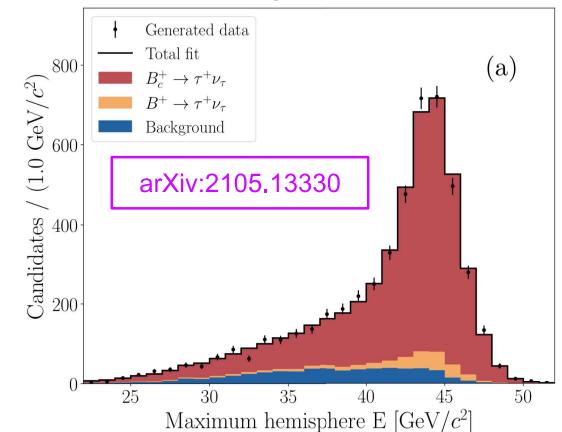
$$B^{*0} \rightarrow K^{*0} D_s D_s (D_s \rightarrow \pi\pi\pi^0\pi^0)$$

- $B_s \rightarrow D_s K$ , modes with neutrals : ECAL energy resolution prospects



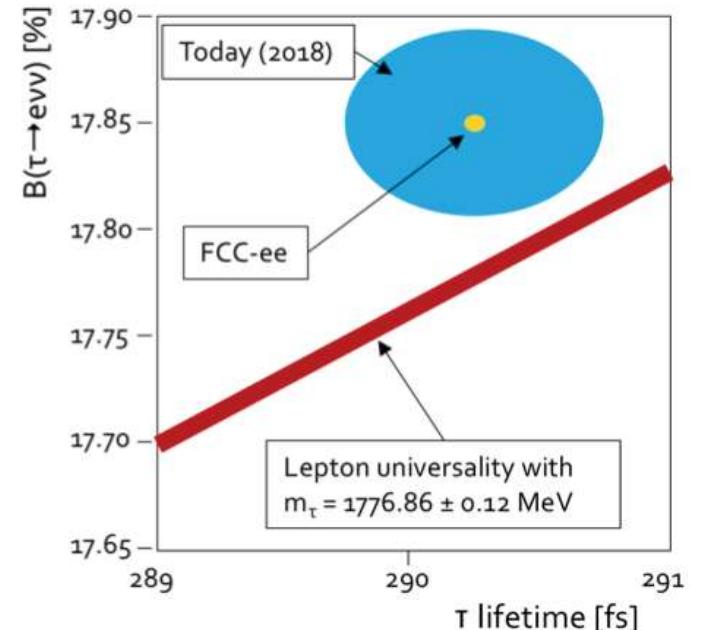
State-of-the-art Xtal-type to HGCal-type :  $\sigma(D_c^\pm(\phi\rho^\pm)K^\mp) \approx 14 \text{ MeV} \rightarrow 51 \text{ MeV}$

$B_c \rightarrow \tau\nu$  :



# THE INTENSITY FRONTIER - TAU PHYSICS

- Enormous statistics:  $1.7 \cdot 10^{11} \tau\tau$  events
- Clean environment, boost, vertexing
- Much improved measurement of tau mass, lifetime, BR's will be crucial for:
  - $\tau$ -based EWPOs ( $R_\tau$ ,  $A_{FB}^{\text{pol}}$ ,  $P_\tau$ )
  - Lepton universality violation tests
  - PMNS matrix unitarity
  - Constraints on Light-heavy neutrino mixing



## Detector Requirements

- Momentum resolution for Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions for lifetime measurement
- Tracker and ECAL granularity and e/ $\mu$ / $\pi$  separation: BR measurements, EWPOs

- Intensity frontier offers the opportunity to directly observe new feebly interacting particles below  $m(Z)$ . They could be also DM candidates.
- Signatures explored: photons and long lifetimes (LLP's).
  - Axion-like particles
  - Dark photons
  - Heavy Neutral Leptons

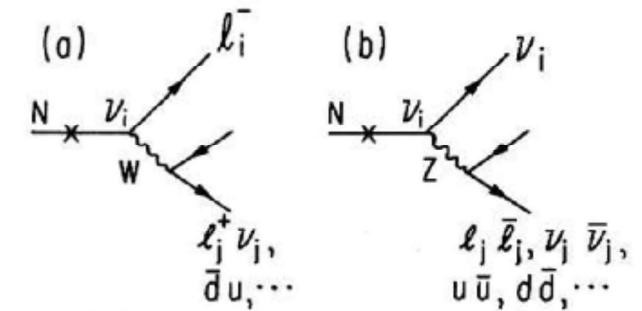
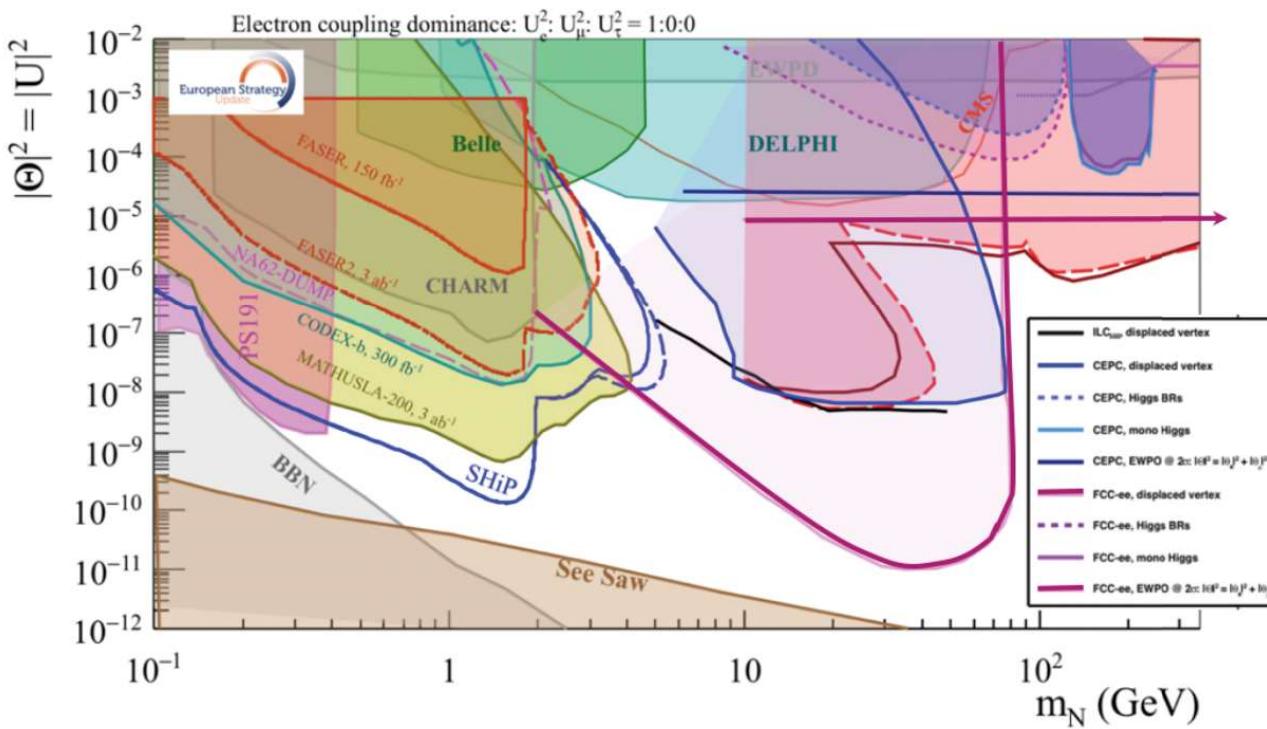
More “extravagant” signatures can be studied in the future profiting of the clean environment

### Detector Requirements

- Sensitivity to far-detached vertices ( $mm \rightarrow m$ )
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths  $\Rightarrow$  extended detector volume
- Full acceptance  $\Rightarrow$  Detector hermeticity

## BSM DIRECT SEARCHES - HEAVY NEUTRAL LEPTONS

- HNL more new studies in progress: “Snowmass white paper” in preparation.
- Test minimal type I seesaw hypothesis
- Together with  $\Delta M$  also tests the compatibility with leptogenesis

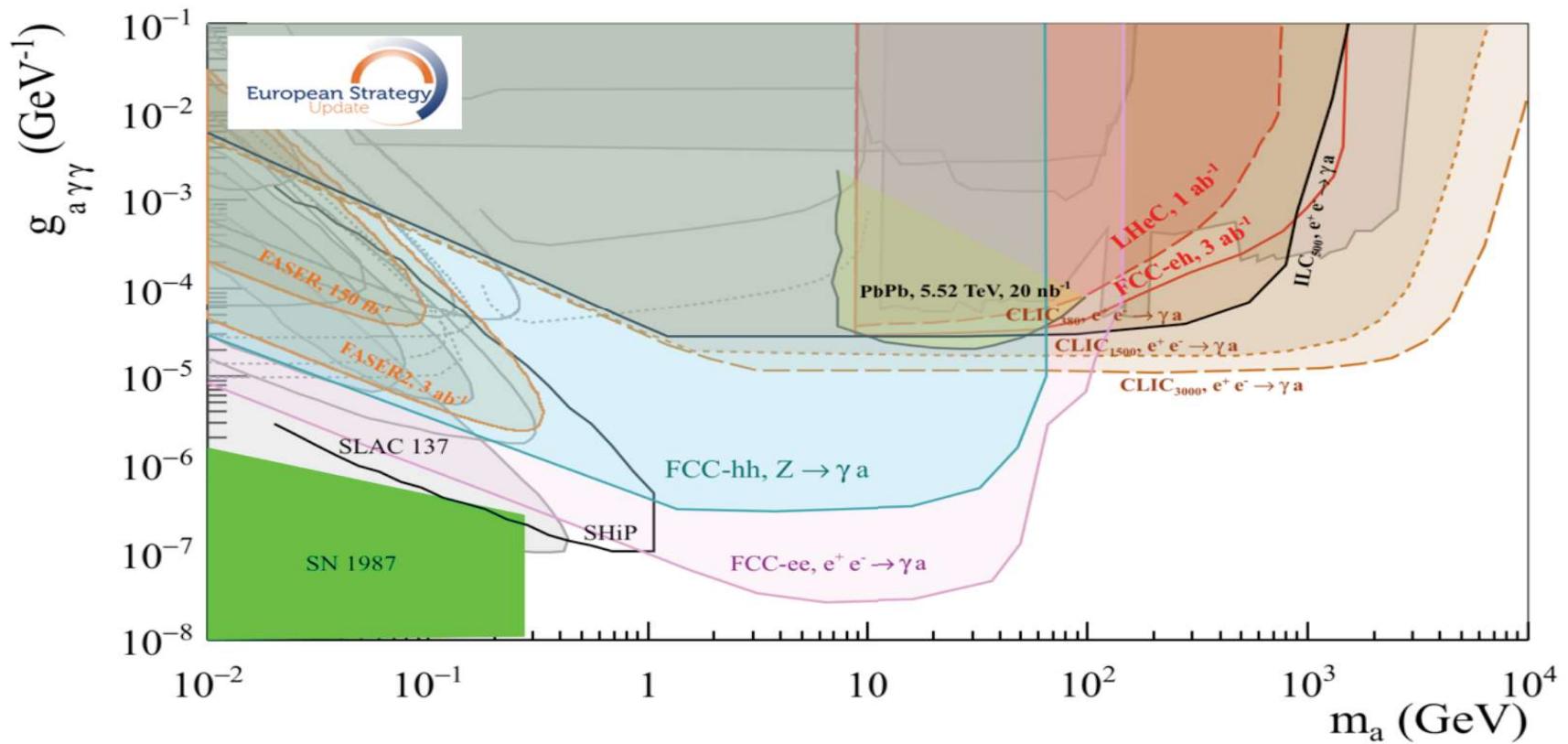


$$L \sim \frac{3 \text{ [cm]}}{|U|^2 \cdot (m_N \text{ [GeV]})^6}$$

$L \sim 1\text{m}$  for  $m_N=50\text{GeV}$  and  $|U|^2=10^{-12}$

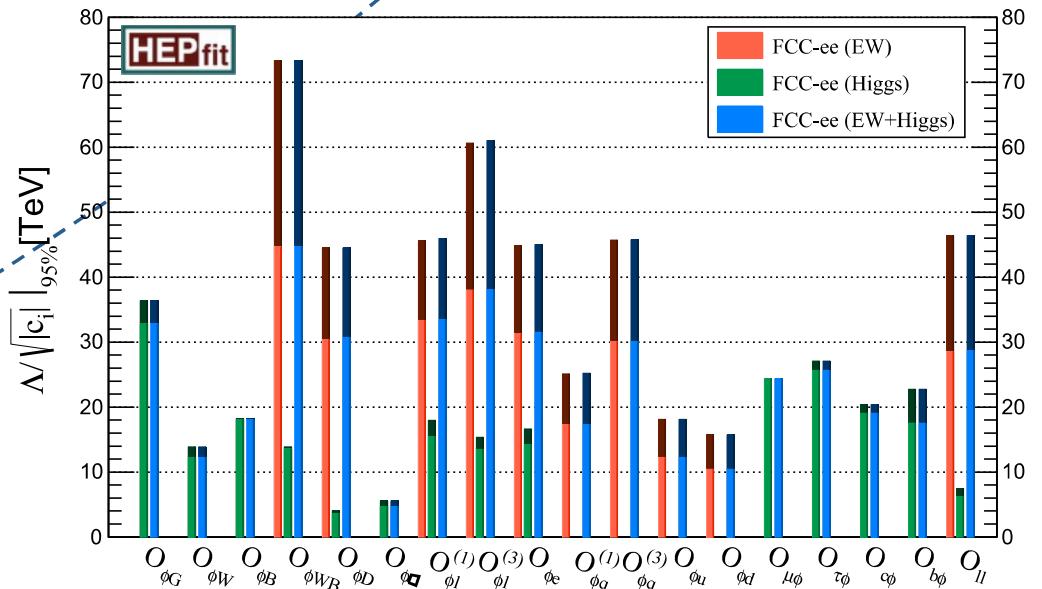
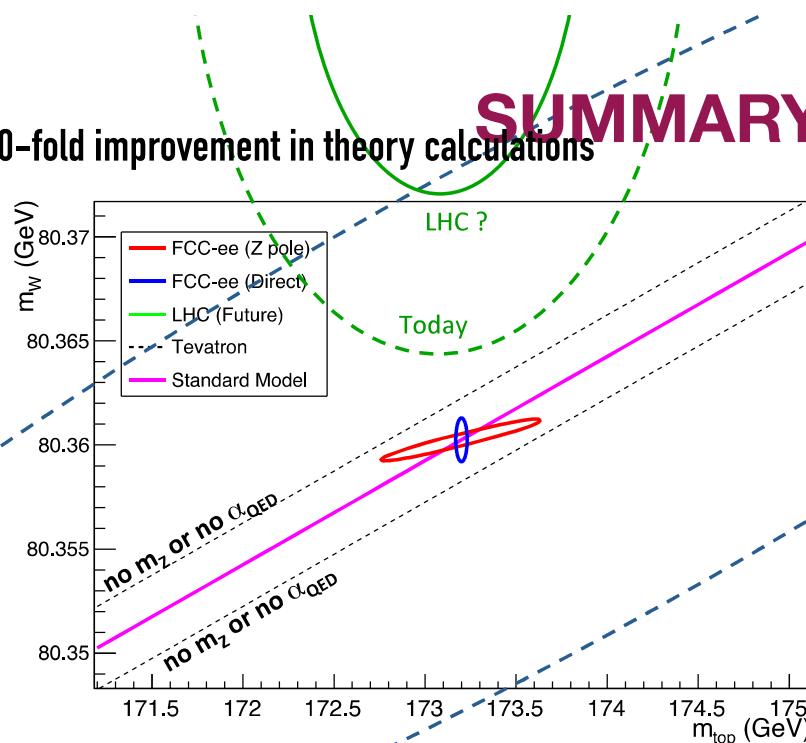
## BSM DIRECT SEARCHES - ALPS

- Similar situation for Axion-like-particles: luminosity is key to the game
- Complementarity with high energy lepton collider
- Fertile ground for development of innovative detector ideas!





# SUMMARY ON NEW PHYSICS SENSITIVITIES



- Fit to new physics effects parameterized by dim 6 SMEFT operators
- single operator fit can be informative
- model independent result only for global fit

What do we mean by “Sensitivity to NP up the scale of N TeV?” e.g.

$$\frac{c}{\Lambda^2} \sim \frac{g_{NP}^2}{M_{NP}^2} < 0.01 \text{ TeV}^{-2} \rightarrow M_{NP} > 10 g_{NP} \text{ TeV} \quad (\text{Weakly coupled NP})$$

$$(M_{NP} > 10 \text{ TeV} \quad (g_{NP} \sim 1))$$

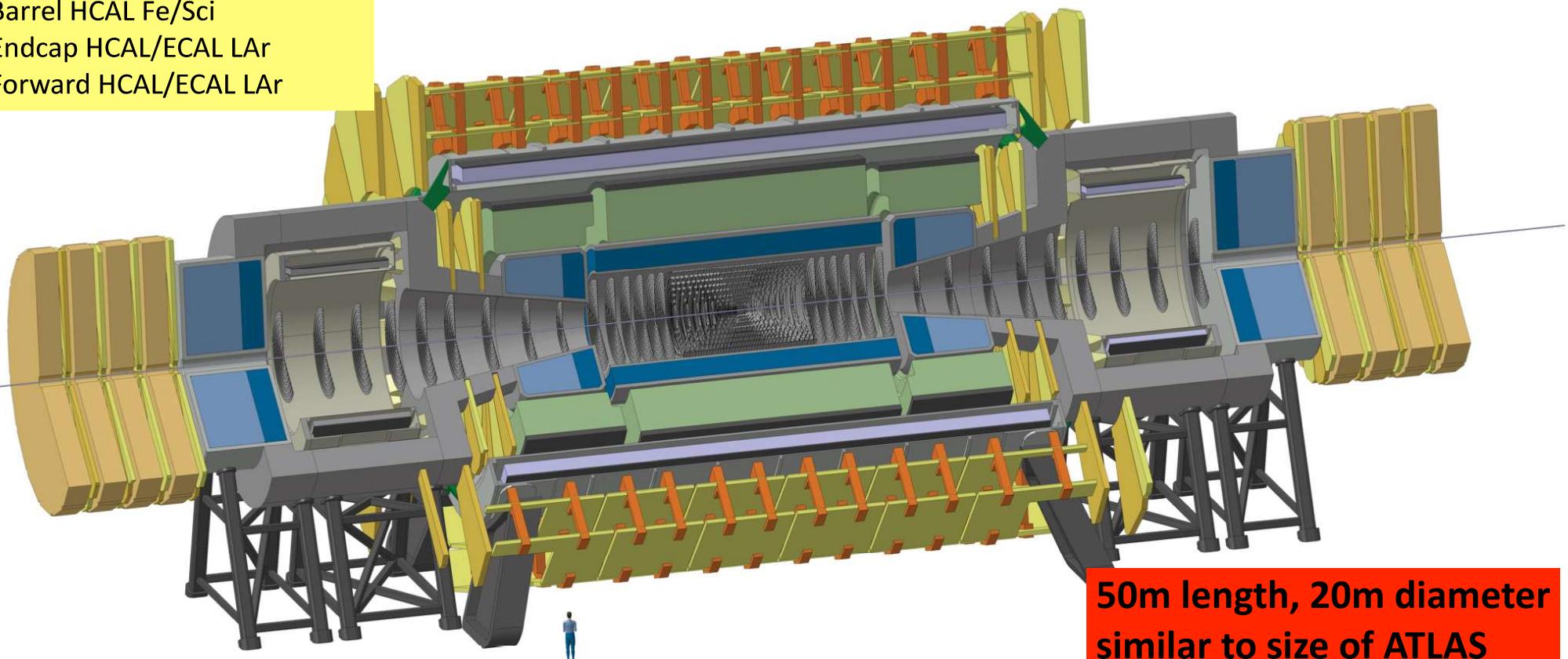
► Points to the physics to be studied with FCC-hh



# THE FCC-HH

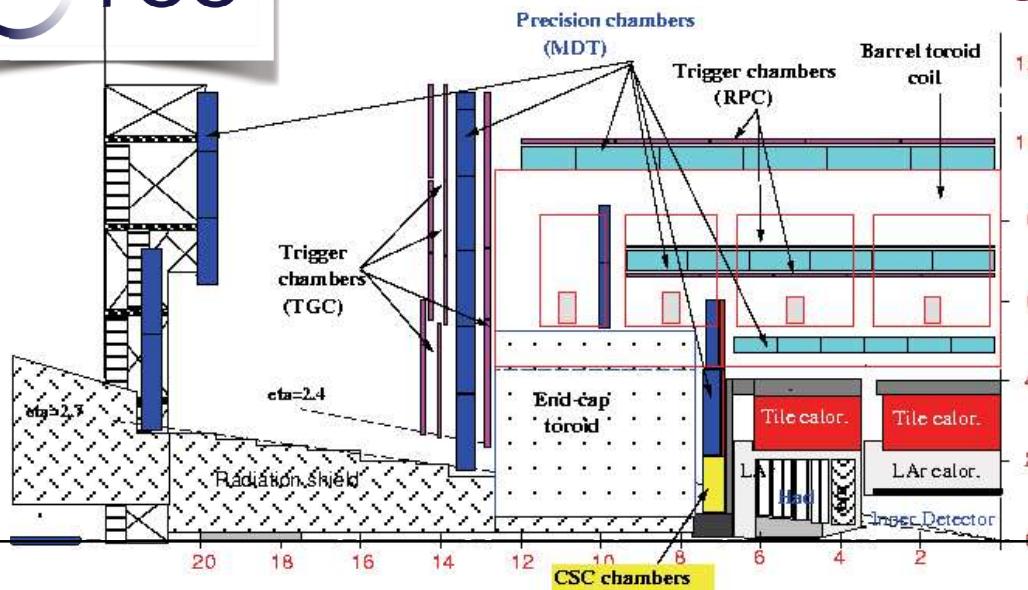
# FCC-hh REFERENCE DETECTOR

- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

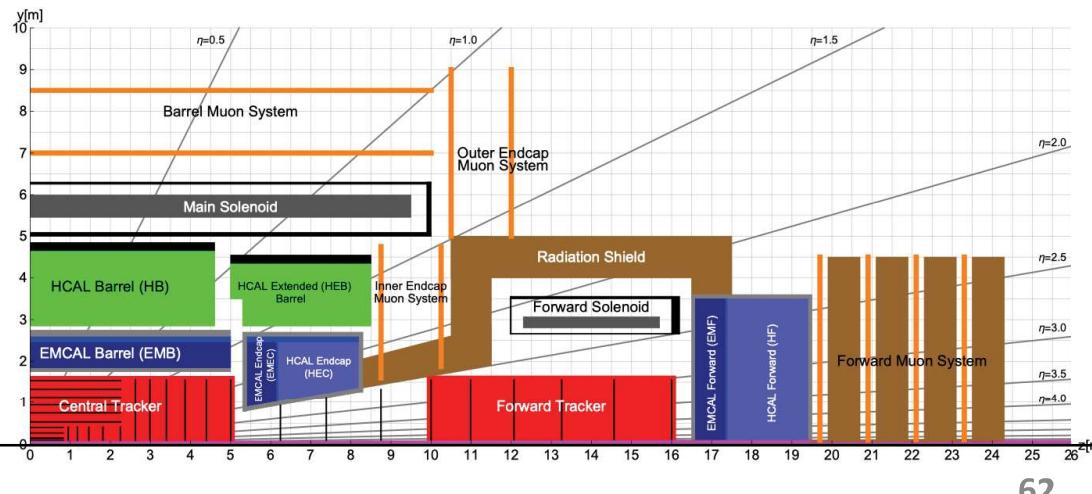
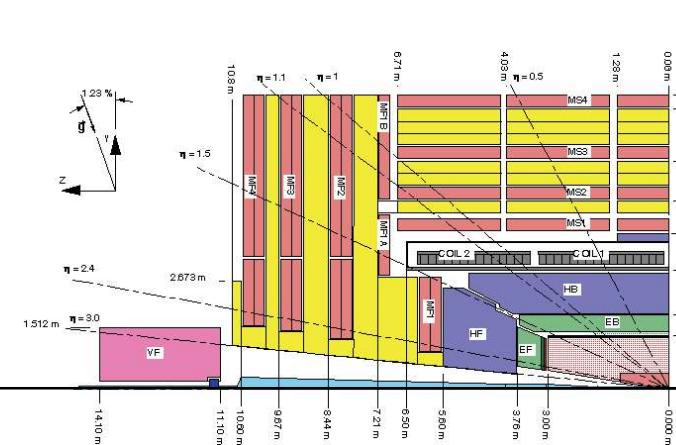
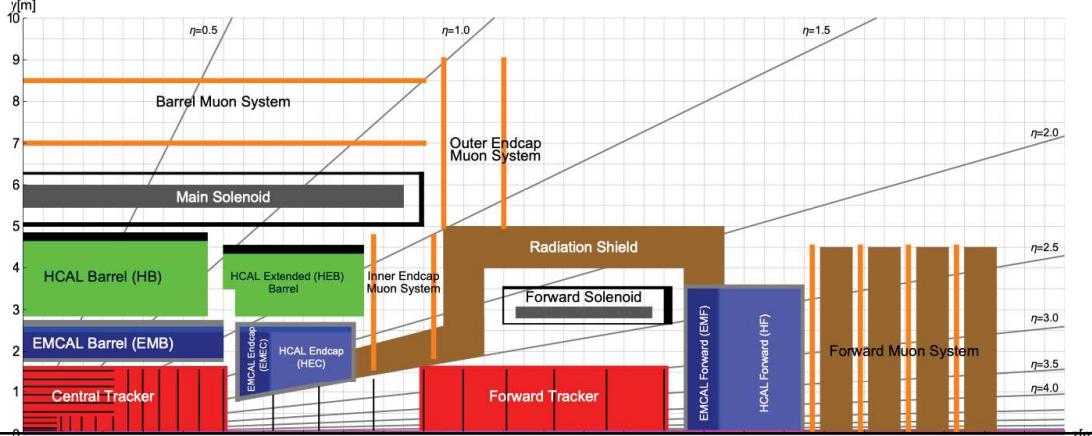


50m length, 20m diameter  
similar to size of ATLAS

FCC

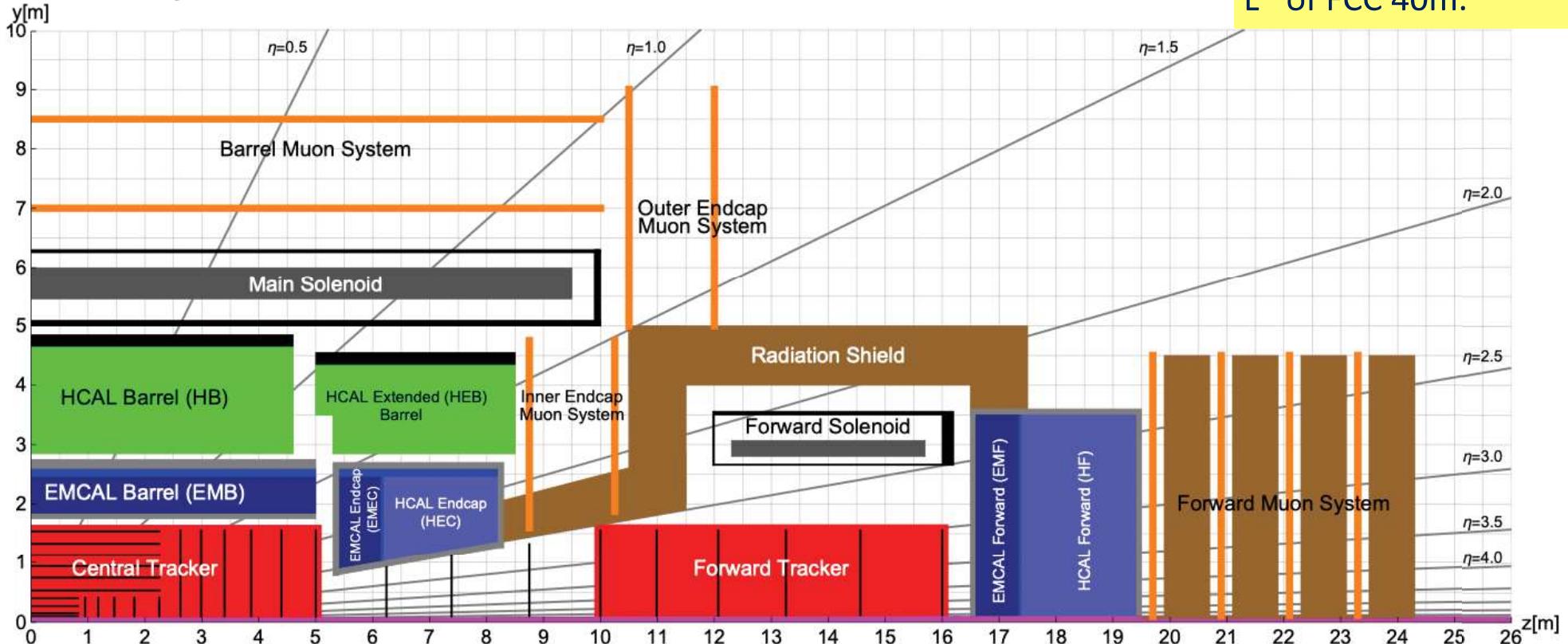


## COMPARISON TO ATLAS & CMS



# FCC-hh REFERENCE DETECTOR

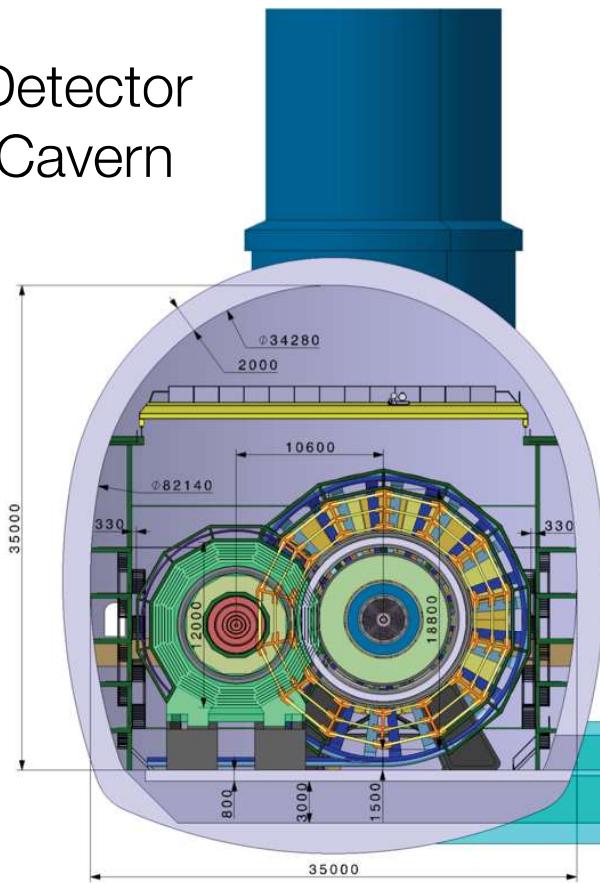
50m long, 20m diameter  
Cavern length 66m  
 $L^*$  of FCC 40m.



- 90% of 'heavy' physics will take place in  $\eta < 2.5$ .
- Increase of acceptance for precision spectroscopy and calorimetry from 2.5 at LHC to 3.8-4 for SM physics.

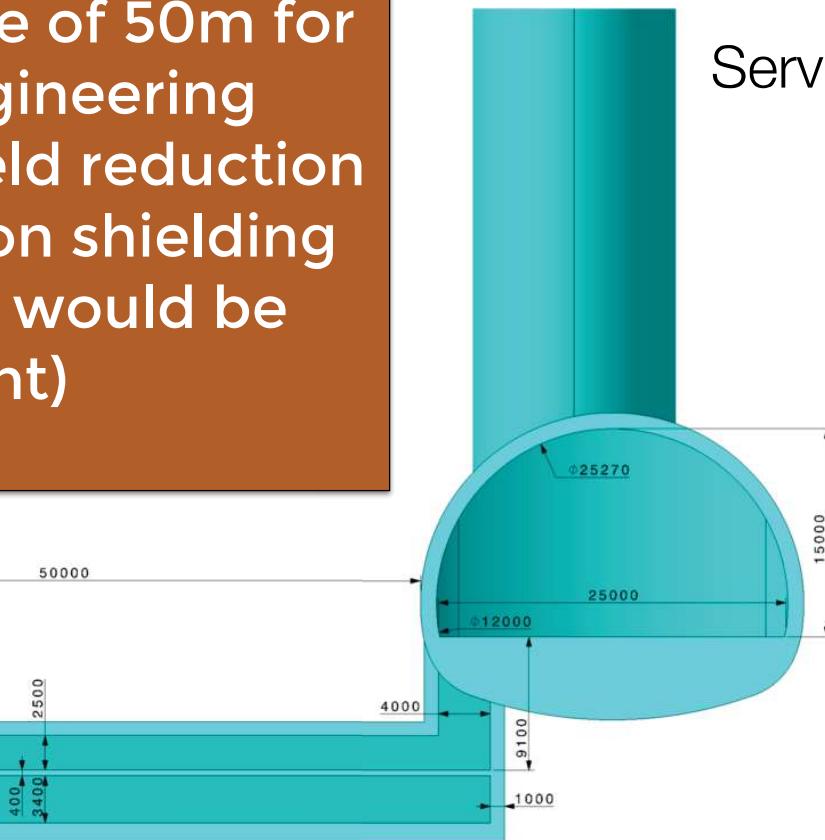
# FCC-HH REFERENCE DETECTOR CAVERN

Detector  
Cavern



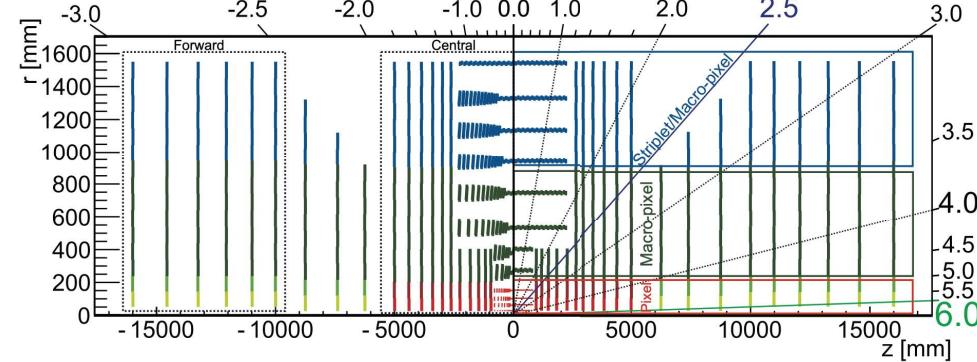
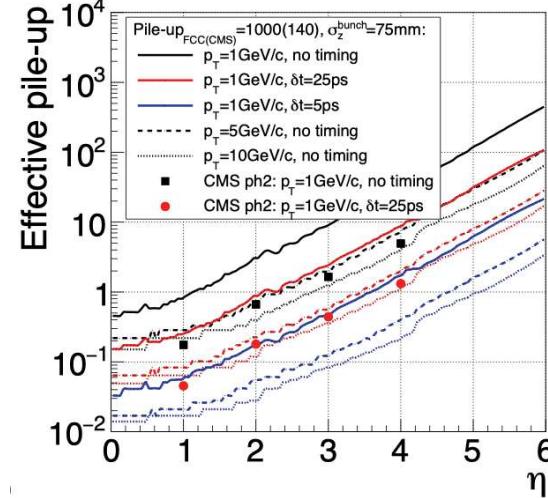
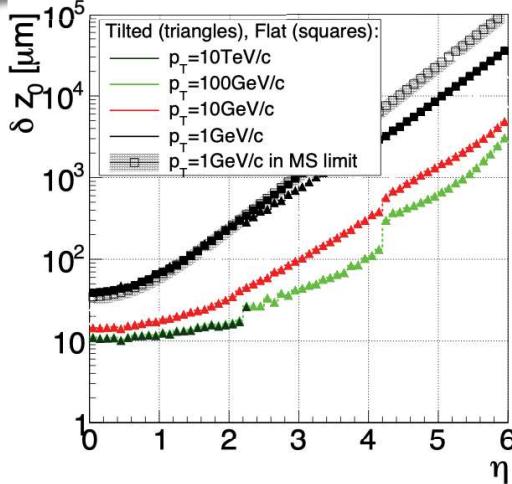
Distance of 50m for  
civil engineering  
stray field reduction  
Radiation shielding  
(10-15m would be  
sufficient)

Service Cavern





## PILEUP



Two tracker layout (tilted/flat)

► Average distance between vertices at  $z=0$ :

- 1mm for HL-LHC (140 pileup)
- 125um for FCC-hh (1000 pileup)

## ► As for HL-LHC, timing can help for vertex identification

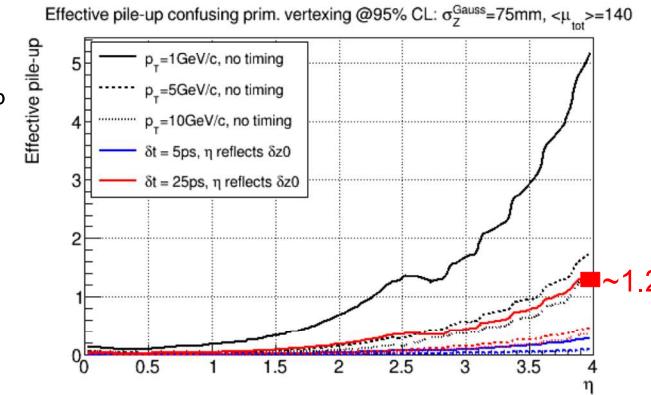
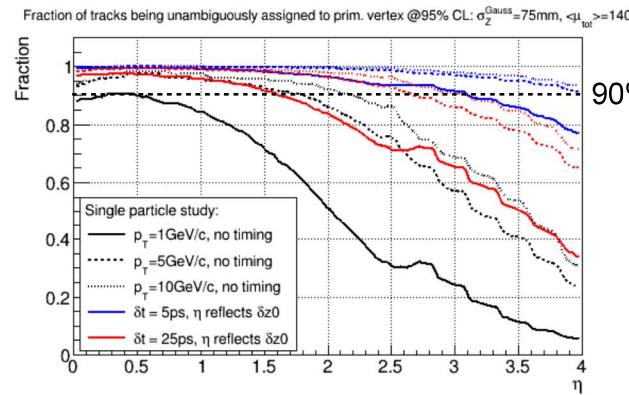
► Effective pileup: Number of vertices that a track of a given  $pT$  is compatible with at 95% CL.

- For a time resolution of 25ps, CMS can get to an effective pileup of 1 for 1 GeV/c tracks at  $\eta = 4$ .
- For an FCC detector the time resolution has to be at a level of 5ps to get to similar numbers.

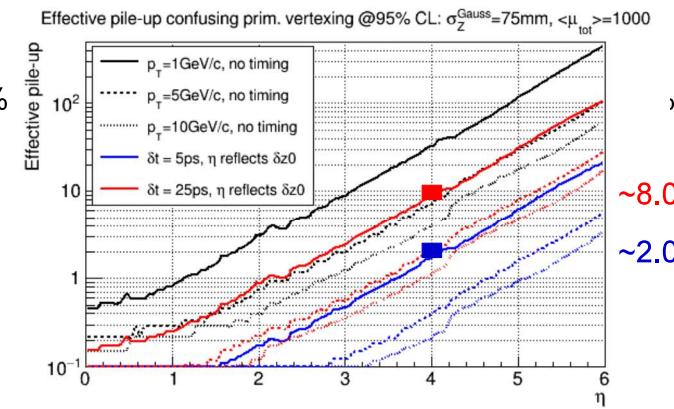
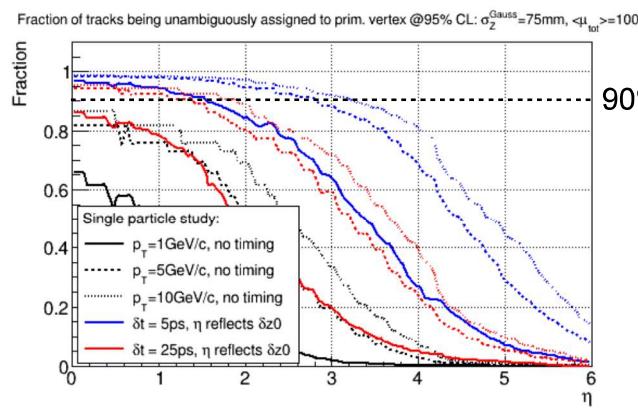
## ► The impact of pileup on a given physics analysis depends very much on the specific channels.

# HOW TO MITIGATE THE PILEUP? TIMING

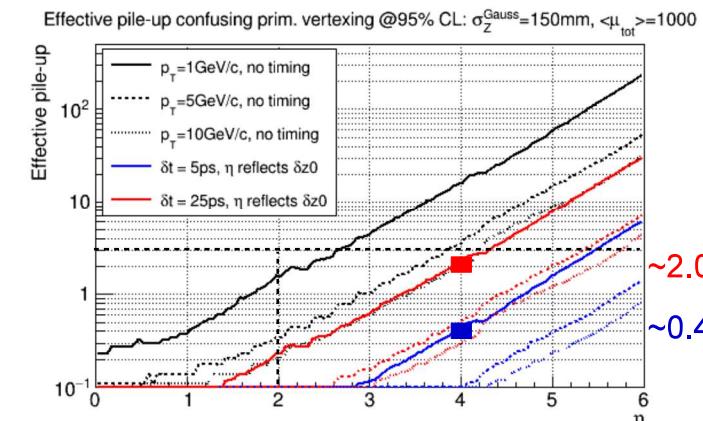
**HL-LHC scenario @ PU=140**  
**CMS Ph2 Upgr. tracker**



**FCC-hh @1000PU**



## Longer interaction region & timing



► **Higher statistics shifts the balance between systematic and statistical uncertainties.**

- It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the « systematics wall » of Low-stat measurements.
- We often talk about « precise » Higgs measurements.
- What we actually aim at is « sensitive » tests of the Higgs properties, where sensitive refers to the ability to reveal a BSM behaviour
- Sensitivity may not require extreme precision. Going after « sensitivity » rather than just precision opens itself new opportunities...

- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

$$\text{BR measurement: } \delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\text{TeV}}{\Lambda}\right)^2 \quad \Rightarrow \text{precision probes large } \Lambda$$

e.g.  $\delta O=1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV}$

$$\sigma(p_T > X): \quad \delta O \sim \left(\frac{Q}{\Lambda}\right)^2 \quad \Rightarrow \text{kinematic reach probes large } \Lambda$$

e.g.  $\delta O=15\% \text{ at } Q=1 \text{ TeV} \Rightarrow \Lambda \sim 2.5 \text{ TeV}$

## NUMEROLOGY FOR FCC-hh, 10ab<sup>-1</sup>, $\sqrt{s}=100$ TeV

- **$10^{10}$  Higgs bosons** =>  $10^4$ x today
- **$10^{12}$  top quarks** =>  $5 \cdot 10^4$  x today
  - => $10^{12}$  W bosons from top decays
  - => $10^{12}$  b hadrons from top decays
- => $10^{11}$   $t \rightarrow W \rightarrow \tau$
- few  $10^{11} t \rightarrow W \rightarrow$  charm hadrons

- precision measurements
- rare decays
- FCNC probes:  $H \rightarrow e\mu$

- precision measurements
- rare decays
- FCNC probes:  $t \rightarrow cV$  ( $V=Z,g,\gamma$ ),  
 $t \rightarrow cH$
- CP violation
- BSM decays ???

- rare decays  $\tau \rightarrow 3\mu, \mu\gamma, CPV$
- rare decays  $D \rightarrow \mu^+\mu^-, \dots CPV$

**Amazing potential, extreme detector and reconstruction challenges**

# What does it mean Standard Model at 100TeV?

---

- SM particles play multiples roles at a 100TeV collider
- in the context of BSM phenomena, new particles eventually decay to SM states
  - BSM interactions can modify production properties of SM particles. Observation of deviations in SM final states can probe BSM dynamics
- SM particles are then both SIGNAL and BACKGROUND for BSM
  - They can dilute and hide BSM signatures, but they are also necessary (think of trigger) to be able to select them
- SM processes are interesting per se. Huge rates at 100 TeV allow exploration of rare phenomena
- Finally SM processes are always the « standard candle » for detector calibration

# Parton Distribution Functions

---

- Accurate determination of PDF of the proton is essential to LHC physics. Even more at new higher-energy colliders
- $\sqrt{s}=100 \text{ TeV}$  will probe PDF in several currently unexplored regions:
  - ultra-low  $x$ ,  $x \leq 10^{-5}$
  - very large momentum transfer,  $Q^2 \geq (10 \text{ TeV})^2$
- In addition this is NOT a simple rescaling of the LHC physics as new phenomena will come up that were not present at lower energies.
- HL-LHC will help improve our knowledge compared to today, but it is difficult to predict also the technical improvement in the PDF calculations that will happen in the next 30 years.

# Top quark as a massless particle?

- At 100TeV collider particles like top appear as light as the bottom quark at the Tevatron  $\sqrt{s} \sim 2\text{TeV}$
- In case of a heavy scale, the gluon splitting in top-antitop pair receives an enhancement
- « Top PDFs » become relevant at the FCC

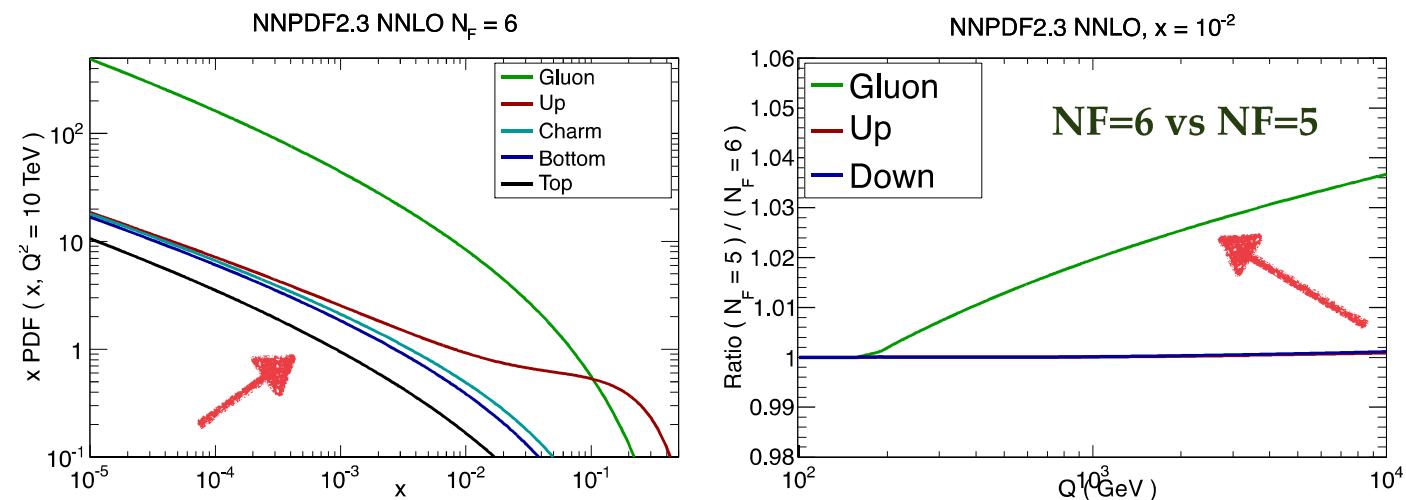


Fig. 11: Left plot: the top quark PDF compared with the other light partons, in the NNPDF2.3NNLO  $n_f = 6$  PDF set evaluated at  $Q = 10 \text{ TeV}$ . Right plot: Ratio between the gluon PDF in the  $n_f = 5$  and  $n_f = 6$  factorization schemes, as a function of the factorization scale  $Q$ .

- **Caveat: a simple treatment of top as massless does not work as well as for the other quarks even at FCC energies.**

# Production of gauge boson by « radiation »

- **New phenomenon!**
- Most likely mechanism to produce gauge boson in final states with multi-TeV jets is NOT LO QCD process of V recoiling against the jet:  $qg \rightarrow qV$
- It is a higher order process where another jet recoiling radiates off a V:  $qq \rightarrow qqV$
- Emission probability can be enhanced by 10%!

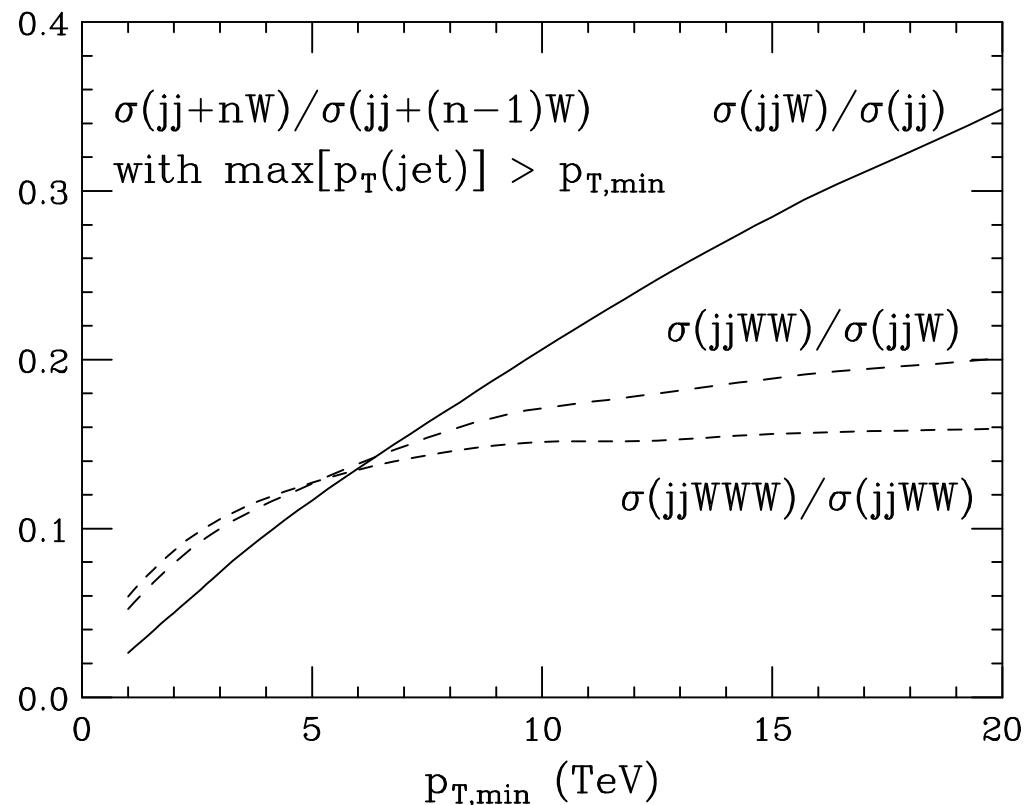
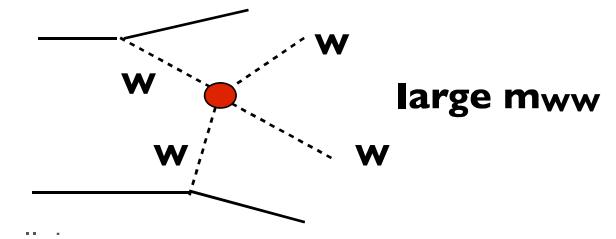
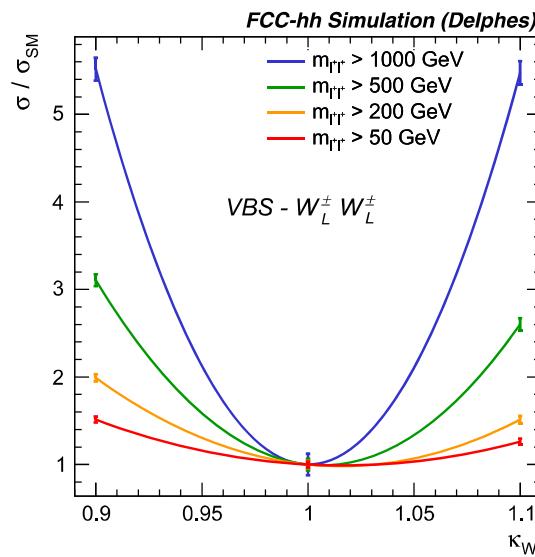
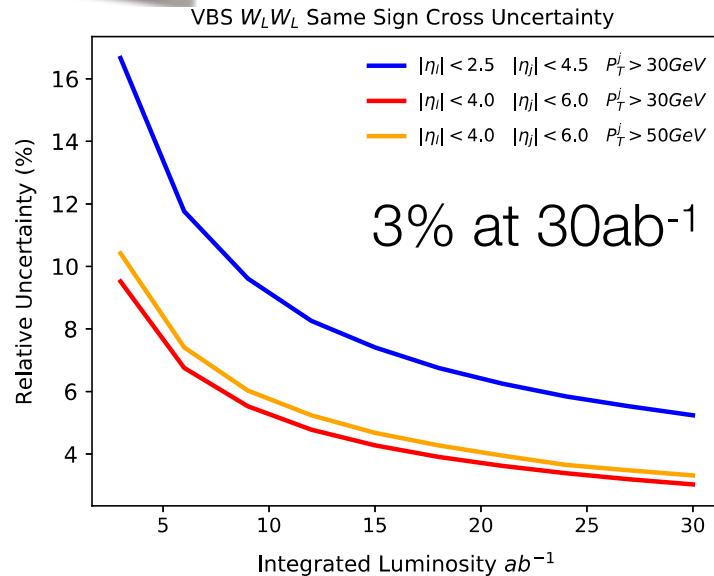


fig. 37: Emission probability for additional  $W$  bosons in dijet events at large  $p_T$ .

# FCC $W_L W_L$ SCATTERING (RELEVANT FOR VVH COUPLING)



Longitudinal component extracted from angular distribution of the two leptons

**Fig. 4.9** Left: precision in the determination of the scattering of same-sign longitudinal W bosons, as function of luminosity, for various kinematic cuts. Right: sensitivity of the longitudinal boson scattering cross section w.r.t. deviations of the WWH coupling from its SM value

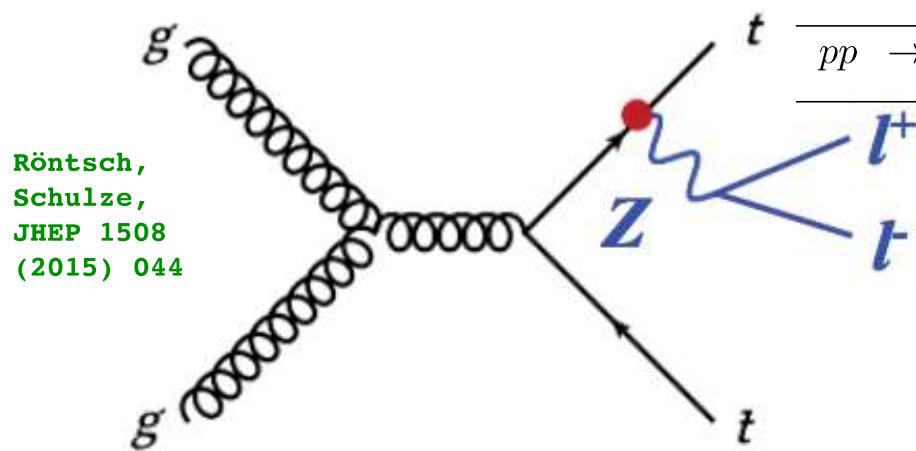
( $\kappa_W = 1$ ), for various selection cuts on the final-state dilepton invariant mass. The vertical bars represent the precision of the measurement, for  $30\text{ab}^{-1}$

**Table 4.5** Constraints on the HWW coupling modifier  $\kappa_W$  at 68% CL, obtained for various cuts on the di-lepton pair invariant mass in the  $W_L W_L \rightarrow HH$  process

$m_{l+l+}$ cut	$> 50\text{ GeV}$	$> 200\text{ GeV}$	$> 500\text{ GeV}$	$> 1000\text{ GeV}$
$\kappa_W \in$	[0.98, 1.05]	[0.99, 1.04]	[0.99, 1.03]	[0.98, 1.02]

# Associated production ttV @FCC-hh (1)

Associated production of top quarks and gauge bosons offer additional handles to study top properties



$$\mathcal{L}_{t\bar{t}Z} = e\bar{\psi}_t \left[ \gamma^\mu (C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu} q_\nu}{M_Z} (C_{2,V} + i\gamma_5 C_{2,A}) \right] \psi_t Z_\mu$$

FCC-pp

$\sigma$ LO	14TeV(fb)	100TeV(fb)	R
$pp \rightarrow t\bar{t}Z$	$1.99 \cdot 10^2 {}^{+10\%}_{-12\%} {}^{+3\%}_{-3\%}$	$5.63 \cdot 10^4 {}^{+9\%}_{-10\%} {}^{+1\%}_{-1\%}$	282
$pp \rightarrow t\bar{t}W^\pm$	$2.05 \cdot 10^2 {}^{+9\%}_{-10\%} {}^{+2\%}_{-2\%}$	$1.68 \cdot 10^4 {}^{+18\%}_{-16\%} {}^{+1\%}_{-1\%}$	82
<hr/>			
	$t\bar{t}\gamma$	$t\bar{t}W^\pm$	$t\bar{t}Z$
$\sigma$ (pb)	76.7	20.7	64.1
	$t\bar{t}WW$	$t\bar{t}W^\pm Z$	$t\bar{t}ZZ$
	1.34	0.21	0.20

NLO production cross-section

- **ttZ production via gg process increases more than ttW $^\pm$**

# Associated production ttV (2) - Anomalous EWK couplings

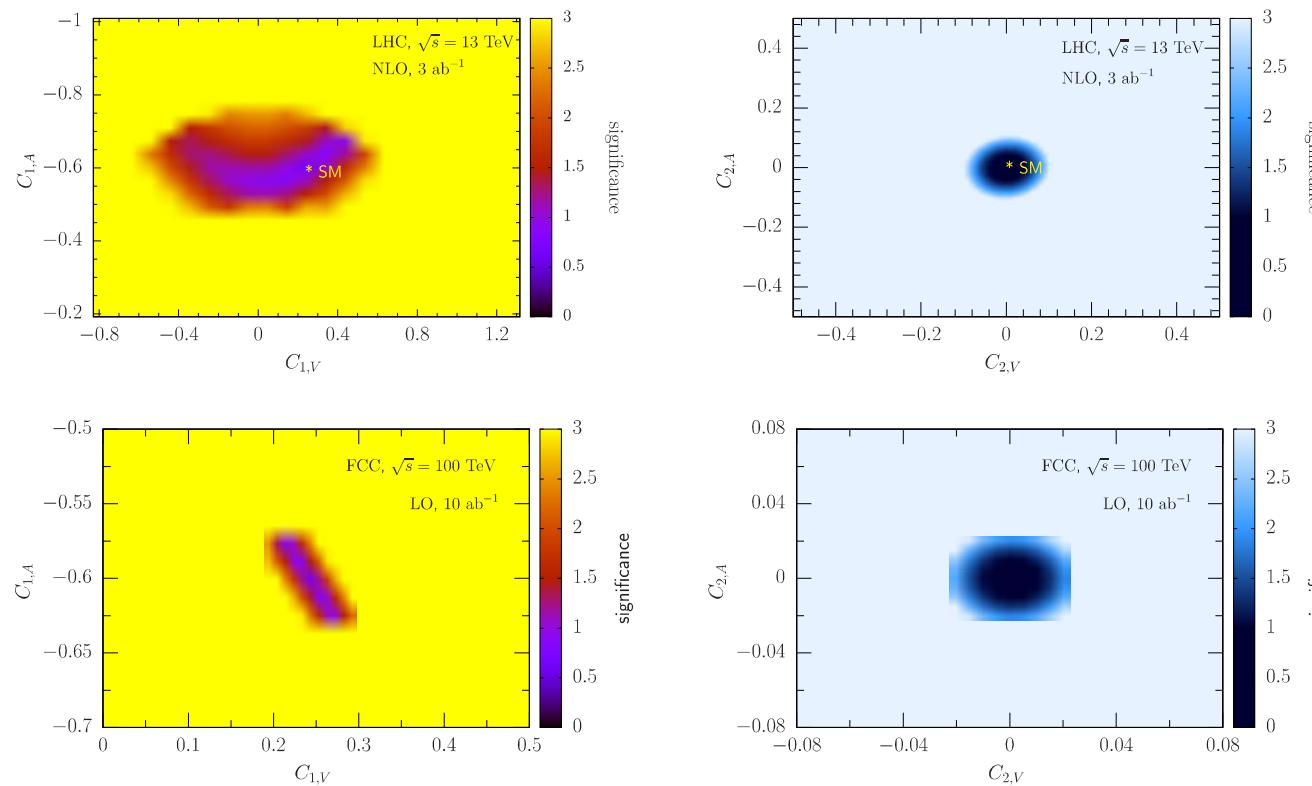
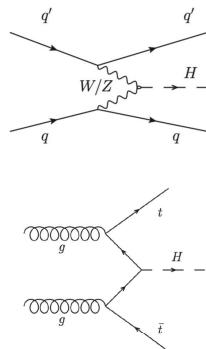


Fig. 169: Comparison of potential constraints on couplings  $C_{1/2,V/A}$  achievable at the LHC and FCC.  
For further details, see Refs. [469, 470].

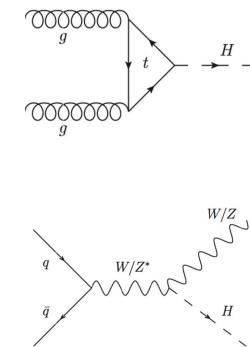
- **ttZ production via gg process increases more than ttW $^\pm$** 
  - ttZ and tty can be used for the measurement of the anomalous EW couplings  $C_{2,V/A}$  with comparable or better precision than at the FCC-ee.

Complementary:  
precision on SM coupling  
 $C_{1,V/A}$  from FCC-ee

# Single Higgs production @FCC-hh



	$\sigma(13 \text{ TeV})$	$\sigma(100 \text{ TeV})$	$\sigma(100)/\sigma(13)$
ggH (N <sup>3</sup> LO)	49 pb	803 pb	16
VBF (N <sup>2</sup> LO)	3.8 pb	69 pb	16
VH (N <sup>2</sup> LO)	2.3 pb	27 pb	11
tH (N <sup>2</sup> LO)	0.5 pb	34 pb	55



Expected improvement at FCC-hh:

- 20 billion Higgses produced at FCC-hh
- factor 10-50 in cross sections (and Lx10)
- reduction of a factor 10-20 in statistical uncertainties

$$\begin{aligned} N_{100} &= \sigma_{100 \text{ TeV}} \times 20 \text{ ab}^{-1} \\ N_8 &= \sigma_{8 \text{ TeV}} \times 20 \text{ fb}^{-1} \\ N_{14} &= \sigma_{14 \text{ TeV}} \times 3 \text{ ab}^{-1} \end{aligned}$$

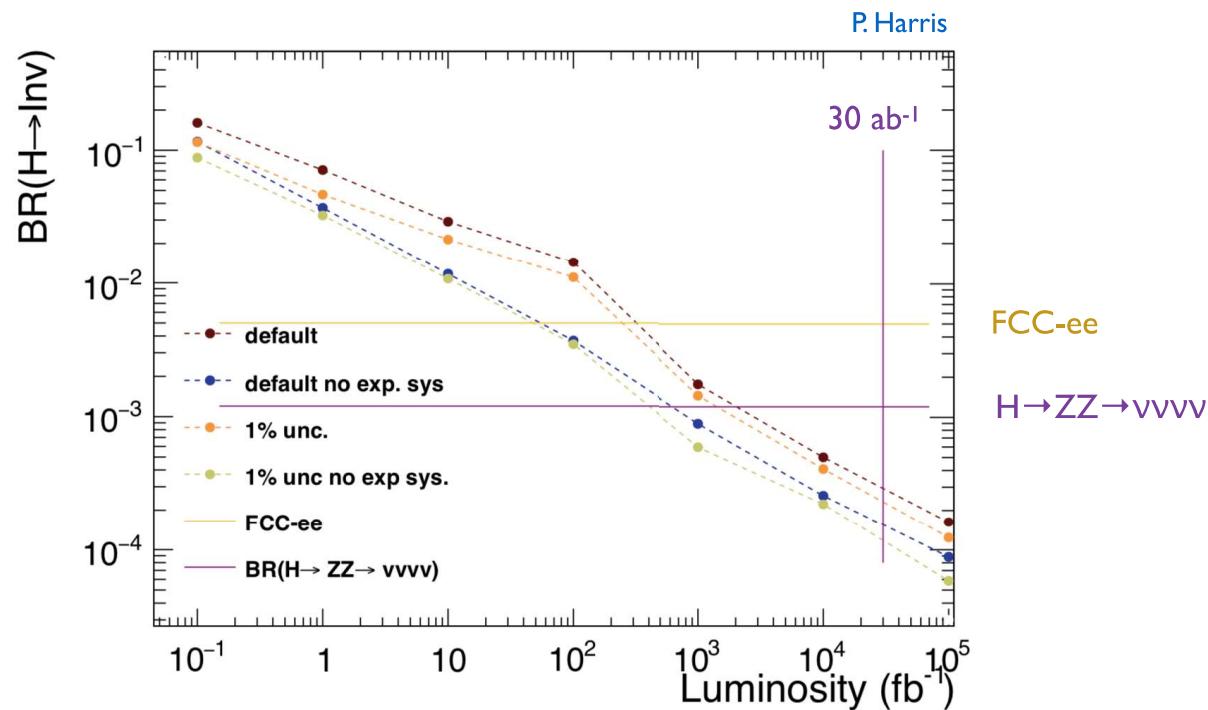
	$N_{100}$	$N_{100}/N_8$	$N_{100}/N_{14}$
gg $\rightarrow$ H	$16 \times 10^9$	$4 \times 10^4$	110
VBF	$1.6 \times 10^9$	$5 \times 10^4$	120
WH	$3.2 \times 10^8$	$2 \times 10^4$	65
ZH	$2.2 \times 10^8$	$3 \times 10^4$	85
tH	$7.6 \times 10^8$	$3 \times 10^5$	420

large statistics allows:

- for % - level precision in statistically limited rare channels ( $\mu\mu, Z\gamma$ )
- in systematics limited channel, to isolate cleaner samples in regions (e.g. @large Higgs  $p_T$ ) with :
  - higher S/B
  - smaller (relative) impact of systematic uncertainties

- Higgs invisible width can be measured in large missing- $E_T$  signatures
- Derive the  $BR(H \rightarrow \text{invisible})$  from a fit to the missing- $E_T$  spectrum
- Constrain background with data driven method using SM W/Z+jets
- $H \rightarrow 4\nu$ , with  $BR = 1.1 \times 10^{-4}$  can be seen after  $\sim 1\text{ab}^{-1}$

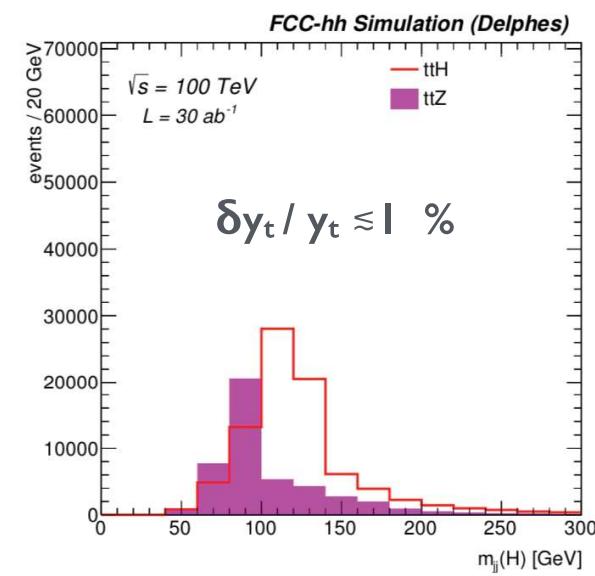
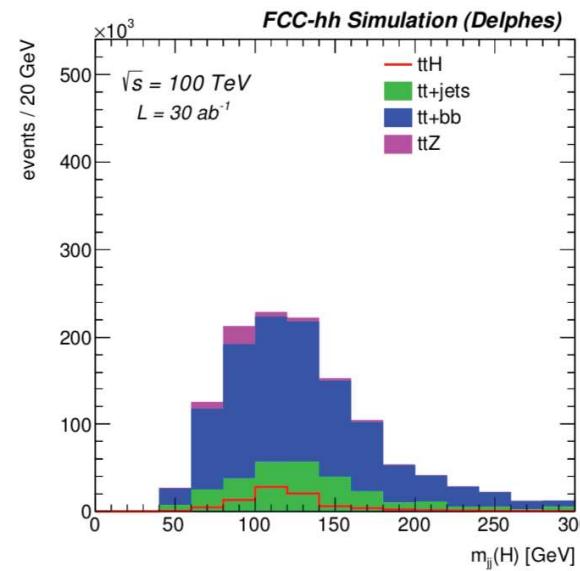
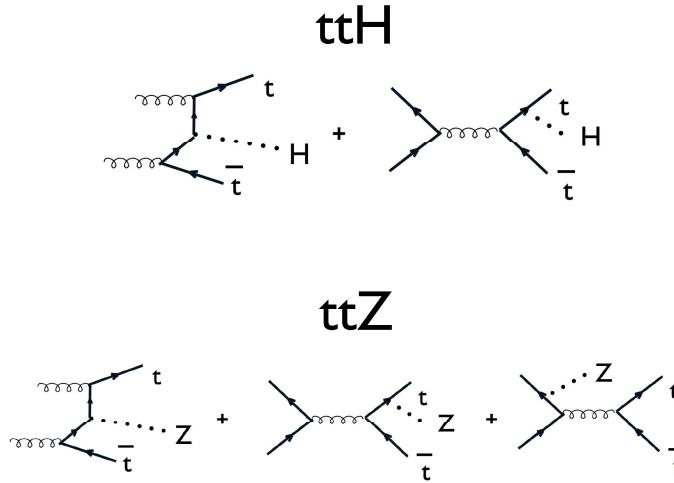
## H $\rightarrow$ INVISIBLE @FCC-hh



Sensitivity down to  $2 \times 10^{-4}$  with full statistics

## FCC SYNERGIES: TOP YUKAWA COUPLING AT FCC-hh

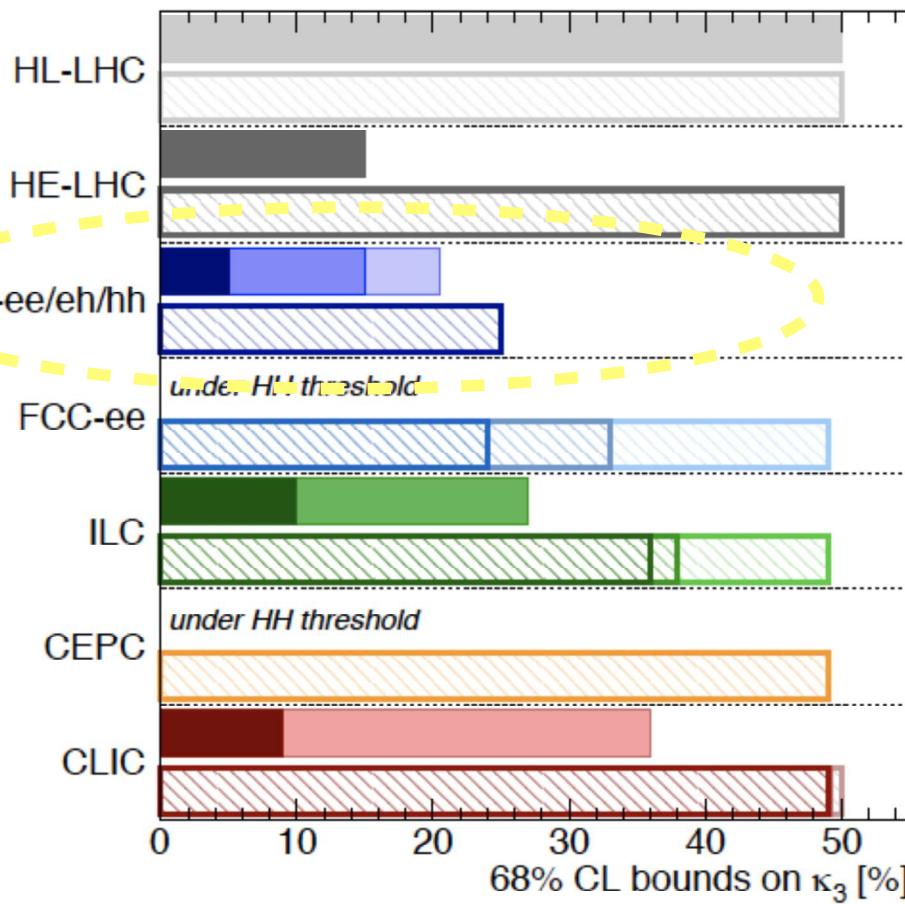
- Measure the production ratio  $\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$  in the boosted regime for  $H \rightarrow b\bar{b}$  and in the semi-leptonic top channel. Lumi, PDF, efficiency uncertainties cancel in the ratio
- Perform simultaneous fit of Z and H peak
- **Using  $g_{ttz}$  and  $k_b$  measured at 1% by FCC-ee.**
- **Top Yukawa can be measured at 1% and model independent at the FCC-hh**



- Run at 365 GeV used also for measurements of top EWK couplings (at the level of  $10^{-2}$ - $10^{-3}$ ) and FCNC in the top sector.

# FCC SYNERGIES: TRIPLE HIGGS COUPLING

Projected precision of  $\lambda_3$   
measurements



Higgs@FC WG November 2019

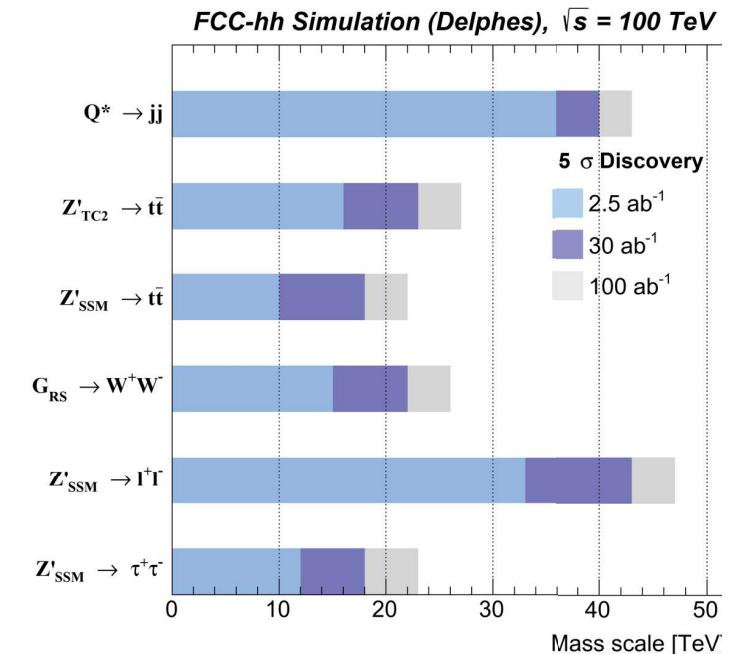
di-Higgs	single-Higgs
HL-LHC 50%	HL-LHC 50% (47%)
HE-LHC [10-20]%	HE-LHC 50% (40%)
FCC-ee/eh/hh 5%	FCC-ee/eh/hh 25% (18%)
LE-FCC 15%	LE-FCC n.a.
FCC-eh <sub>3500</sub> -17+24%	FCC-eh <sub>3500</sub> n.a.
FCC-ee <sub>365</sub> 48P	FCC-ee <sub>365</sub> 24% (14%)
	FCC-ee <sub>365</sub> 33% (19%)
	FCC-ee <sub>240</sub> 49% (19%)
ILC <sub>1000</sub> 10%	ILC <sub>1000</sub> 36% (25%)
ILC <sub>500</sub> 27%	ILC <sub>500</sub> 38% (27%)
	ILC <sub>250</sub> 49% (29%)
CEPC	CEPC 49% (17%)
CLIC <sub>3000</sub> -7%+11%	CLIC <sub>3000</sub> 49% (35%)
CLIC <sub>1500</sub> 36%	CLIC <sub>1500</sub> 49% (41%)
	CLIC <sub>380</sub> 50% (46%)

All future colliders combined with HL-LHC

FCC integrated  
program will measure  
 $\lambda_3$  to the 5% level

## FCC SYNERGIES: FCC-hh DIRECT DISCOVERY POTENTIAL

- Higher parton centre-of-mass energy →  
**A BIG STEP IN HIGH MASS REACH**
- Strongly coupled new particles, new gauge  
bosons ( $Z'$ ,  $W'$ ), excited quarks: up to 40 TeV!
- Extra Higgs bosons: up to 5-20 TeV
- High sensitivity to high energy phenomena,  
e.g.,  $WW$  scattering, DY up to 15 TeV

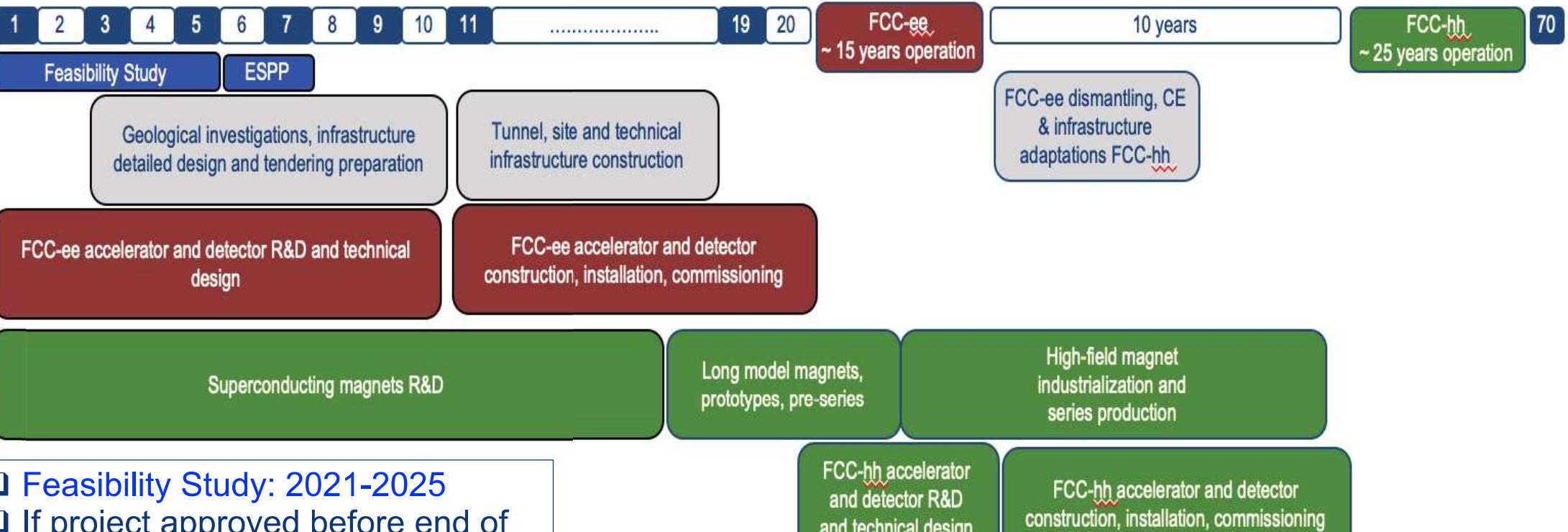


about x6 LHC mass reach at high mass, well matched to reveal the origin of deviations indirectly detected at the FCC-ee

# FCC FEASIBILITY STUDY

# TIMELINE OF THE FCC INTEGRATED PROGRAMME

F. Gianotti



- Feasibility Study: 2021-2025**
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

► The FCC is an ambitious project for the future of particle physics with concrete goals and deliverables to find the answers that we need from Nature!

## FUTURE COLLIDERS TAKE AWAY MESSAGE

**known knowns**

Standard  
Model

**known unknowns**

“known” new physics

**unknown knowns**

new physics modifies  
known physics

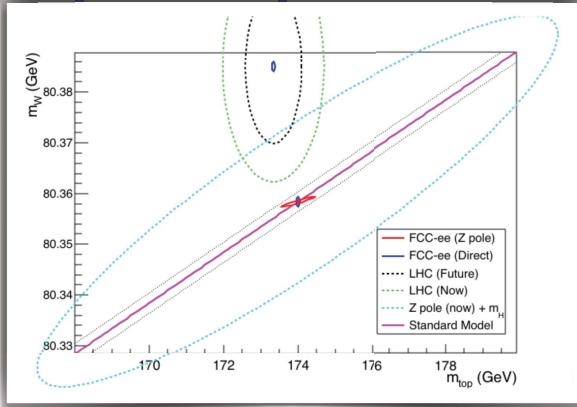
.....

and maybe we already  
measured it!

**unknown unknowns**

surprises

# FUTURE COLLIDERS TAKE AWAY MESSAGE



**known unknowns**

“known” new physics

**unknown knowns**

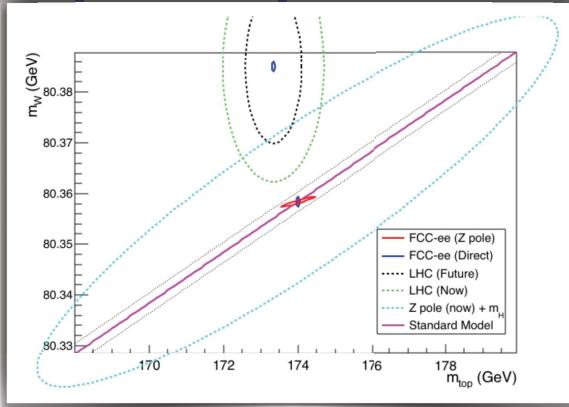
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**unknown unknowns**

surprises

# FUTURE COLLIDERS TAKE AWAY MESSAGE



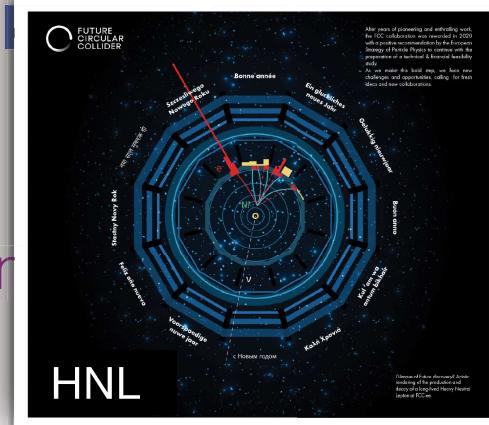
**unknown knowns**

new physics modifies  
known physics

.....

and maybe we already  
measured it!

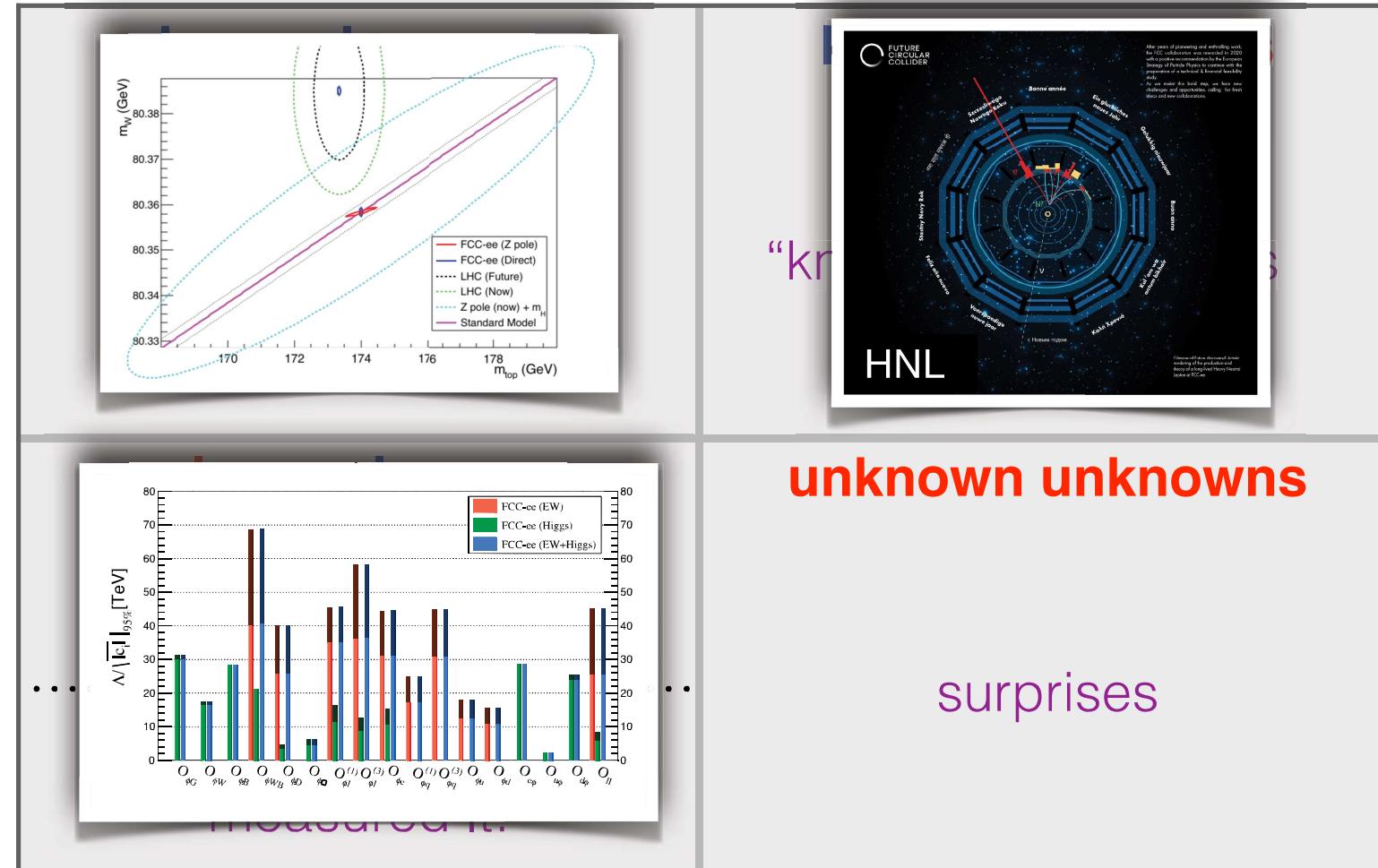
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**unknown unknowns**

surprises

# FUTURE COLLIDERS TAKE AWAY MESSAGE



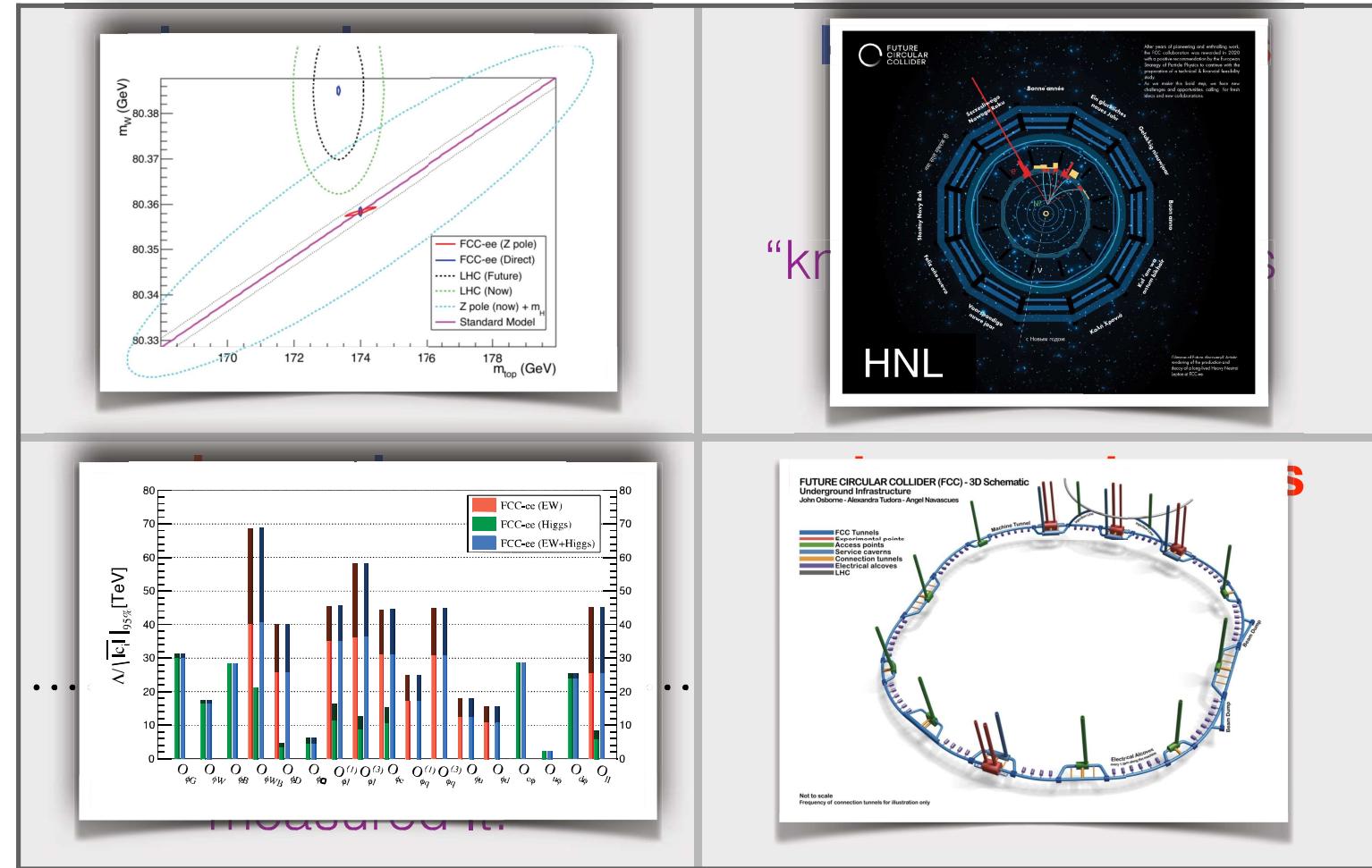
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HNL

unknown unknowns

surprises

# FUTURE COLLIDERS TAKE AWAY MESSAGE





# BACKUP

# FEASIBILITY STUDY GOALS AND ROADMAP TOWARDS FIRST e+e- COLLISIONS

## Highest priority goals:

Financial feasibility

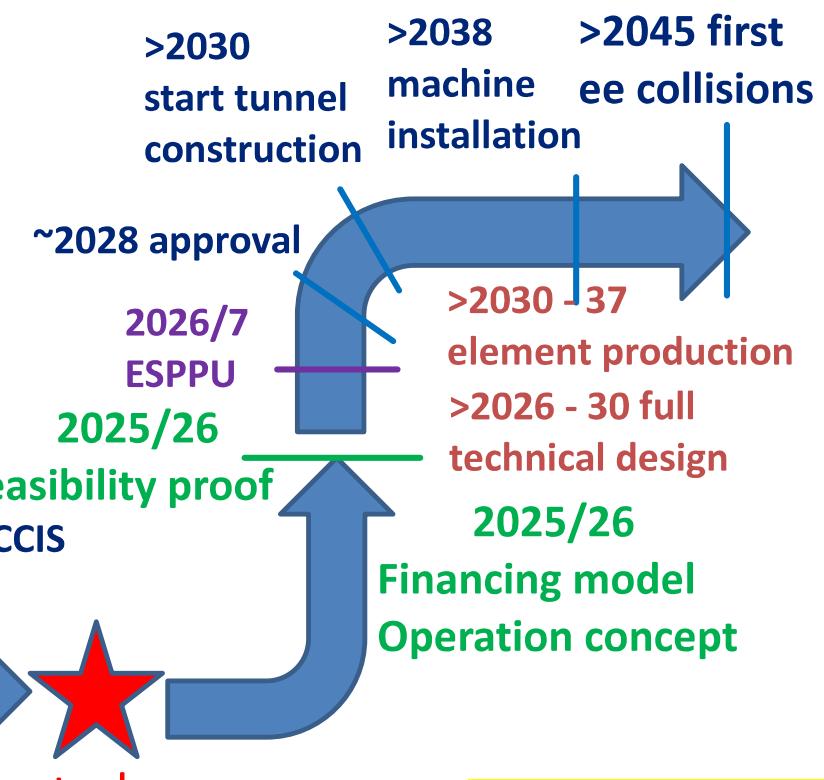
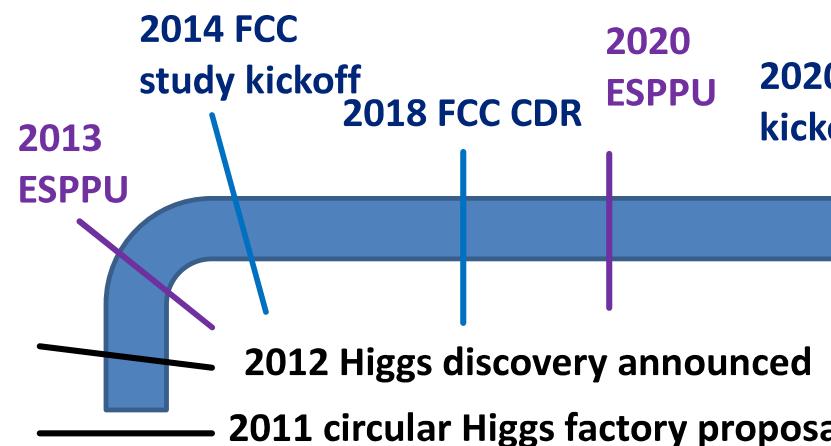
Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

## Technical and administrative feasibility of tunnel:

**no show-stopper for ~100 km tunnel**

Technologies of machine and experiments: **magnets; minimised environmental impact; energy efficiency & recovery**

Gathering scientific, political, societal and other support



2020-25  
FCC Feasibility Study  
FCCIS H2020 DS

# FEASIBILITY STUDY GOALS AND ROADMAP TOWARDS FIRST e+e- COLLISIONS

## Highest priority goals:

Financial feasibility

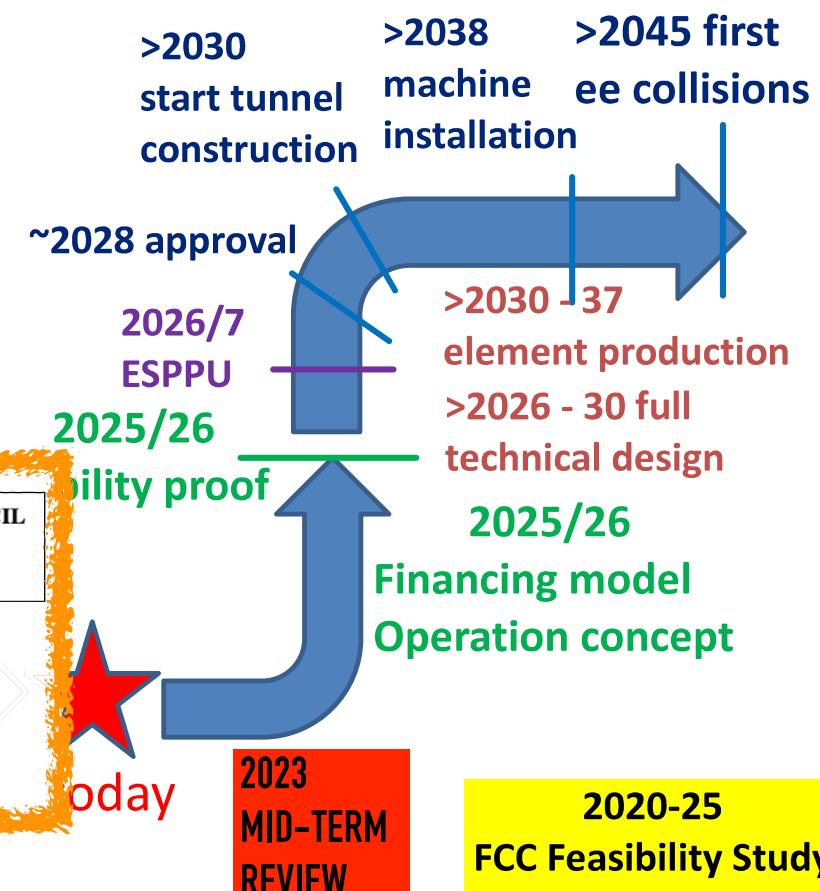
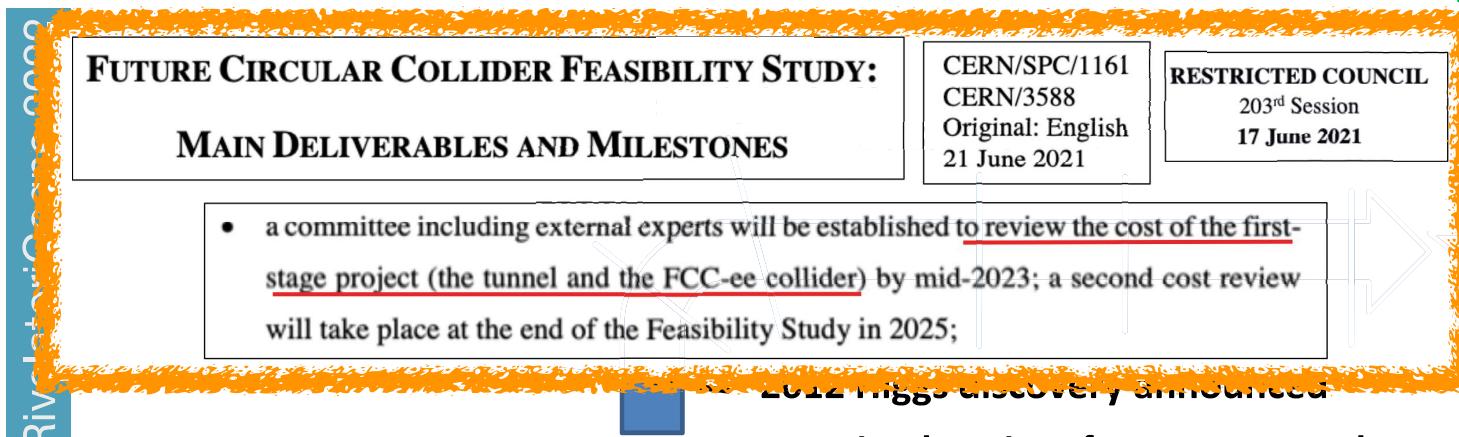
Fabiola Gianotti: "CERN vision and goals until next strategy update" FCCIS Kick-Off, 9 Nov. 2020

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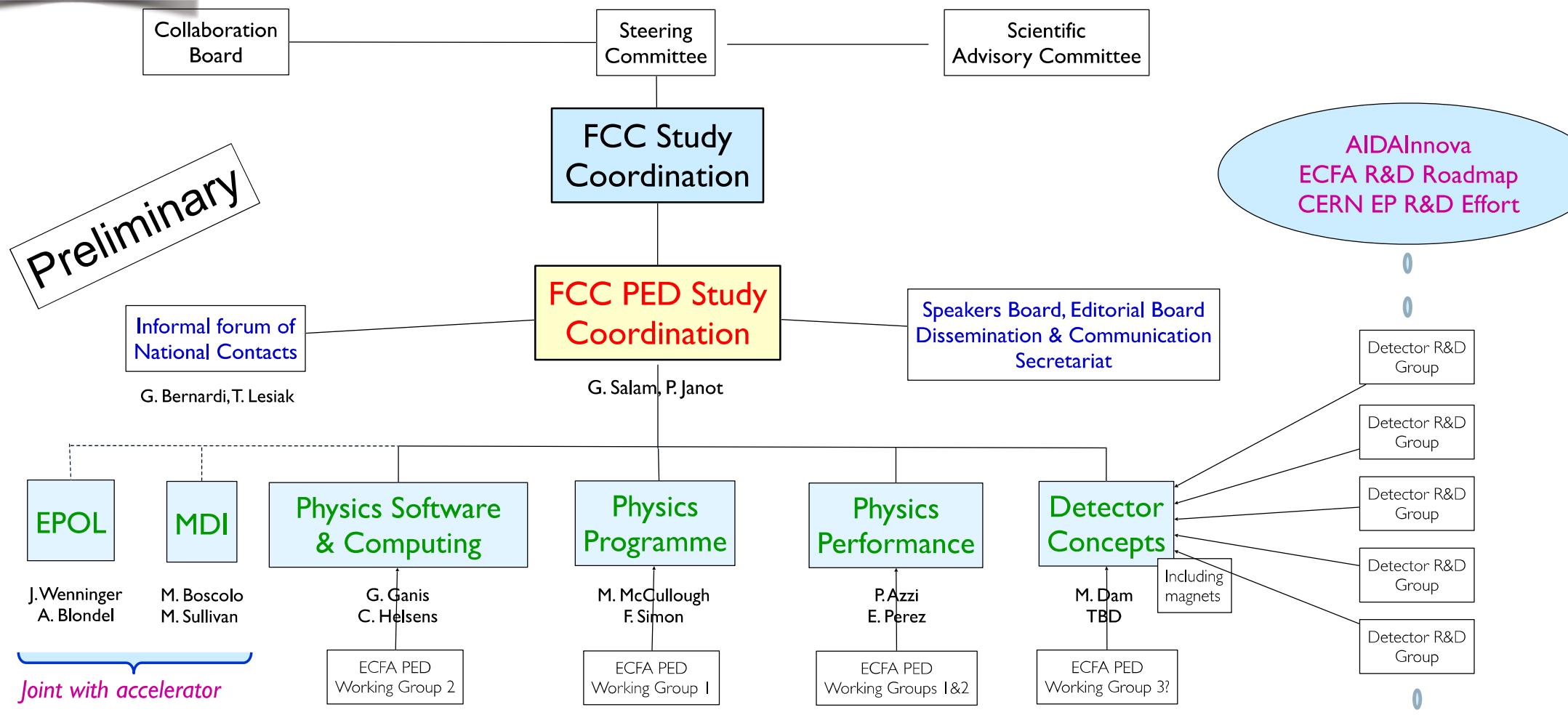
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Gathering scientific, political, societal and other support





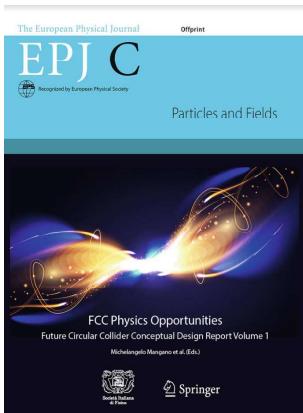
# PED ORGANISATION TO TACKLE THE CHALLENGES



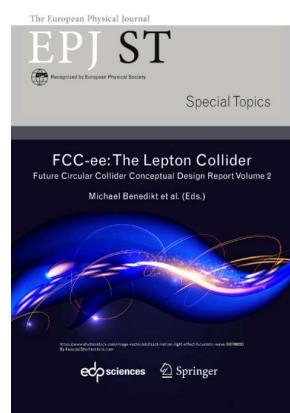


# FIND OUT MORE: SOME FCC DOCUMENTATION

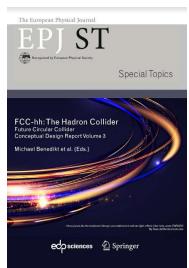
4 CDR volumes published in EPJ



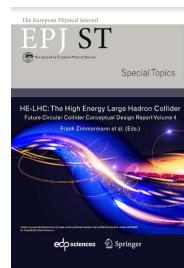
FCC Physics Opportunities



FCC-ee: The Lepton Collider



FCC-hh: The Hadron Collider



HE-LHC: The High Energy Large Hadron Collider



- Future Circular Collider - European Strategy Update Documents
  - (FCC-ee), (FCC-hh), (FCC-int)
- FCC-ee: Your Questions Answered
  - arXiv:1906.02693
- Circular and Linear e+e- Colliders: Another Story of Complementarity
  - arXiv:1912.11871
- Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders
  - arXiv:1901.02648
- Polarization and Centre-of-mass Energy Calibration at FCC-ee
  - arXiv:1909.12245
- EPJ+ Collection:
  - <https://www.epj.org/epjplus-news/2300-epj-focus-point-on-a-future-higgs-electroweak-factory-fcc-challenges-towards-discovery>
- FCC Week 2022:
  - <https://indico.cern.ch/event/1064327/timetable/>

# NEW OPPORTUNITIES CREATE NEW CHALLENGES

➤ EPJ+ special issue “A future Higgs and EW Factory: Challenges towards discovery”

<b>2</b>	<b>Introduction (2 essays)</b>		
2.1	Physics landscape after the Higgs discovery [1] . . . . .	3	
2.2	Building on the Shoulders of Giants [2] . . . . .	3	
<b>3</b>	<b>Part I: The next big leap – New Accelerator technologies to reach the precision frontier [3] (6 essays)</b>		
3.1	FCC-ee: the synthesis of a long history of $e^+e^-$ circular colliders [4] . . . . .	4	
3.2	RF system challenges . . . . .	4	
3.3	How to increase the physics output per MW.h? <b>MDI, <math>\sqrt{s}</math></b> . . . . .	4	
3.4	IR challenges and the Machine Detector Interface at FCC-ee [5] . . . . .	4	
3.5	The challenges of beam polarization and keV-scale center-of-mass energy calibration [6]	4	
3.6	The challenge of monochromatization [7] . . . . .	4	
<b>4</b>	<b>Part II: Physics Opportunities and challenges towards discovery [8] (15 essays)</b>		
4.1	Overview: new physics opportunities create new challenges [9] . . . . .	4	
4.2	Higgs and top challenges at FCC-ee [10] . . . . .	4	
4.3	Z line shape challenges : ppm and keV measurements [11] . . . . .	5	
4.4	Heavy quark challenges at FCC-ee [12] . . . . .	5	
4.5	The tau challenges at FCC-ee [13] . . . . .	5	
4.6	Hunting for rare processes and long lived particles at FCC-ee [14] . . . . .	6	
4.7	The W mass and width challenge at FCC-ee [15] . . . . .	6	
4.8	A special Higgs challenge: Measuring the electron Yukawa coupling via s-channel Higgs production [16] . . . . .	7	
4.9	A special Higgs challenge: Measuring the mass and cross section with ultimate precision [17] . . . . .	7	
<b>5</b>	<b>Part III: Theoretical challenges at the precision frontier [24] (7 essays)</b>		
5.1	Overall perspective and introduction . . . . .	4	
5.2	Theory challenges for electroweak and Higgs calculations [25] . . . . .	4	
5.3	Theory challenges for QCD calculations . . . . .	5	
5.4	New Physics at the FCC-ee: Indirect discovery potential [26] . . . . .	5	
5.5	Direct discovery of new light states [27] . . . . .	5	
5.6	Theoretical challenges for flavour physics [28] . . . . .	6	
5.7	Challenges for tau physics at the TeraZ [29] . . . . .	6	
<b>6</b>	<b>Part IV: Software Dev. &amp; Computational challenges (4 essays)</b>		
6.1	Key4hep, a framework for future HEP experiments and its use in FCC . . . . .	7	
6.2	Offline computing resources and approaches for sustainable computing . . . . .	7	
6.3	Accelerator-related codes and interplay with FCCSW . . . . .	7	
6.4	Online computing challenges: detector & readout requirements [30] . . . . .	7	

All 34 references in this Overleaf document:  
<https://www.overleaf.com/read/xcssxqyhtrgt>

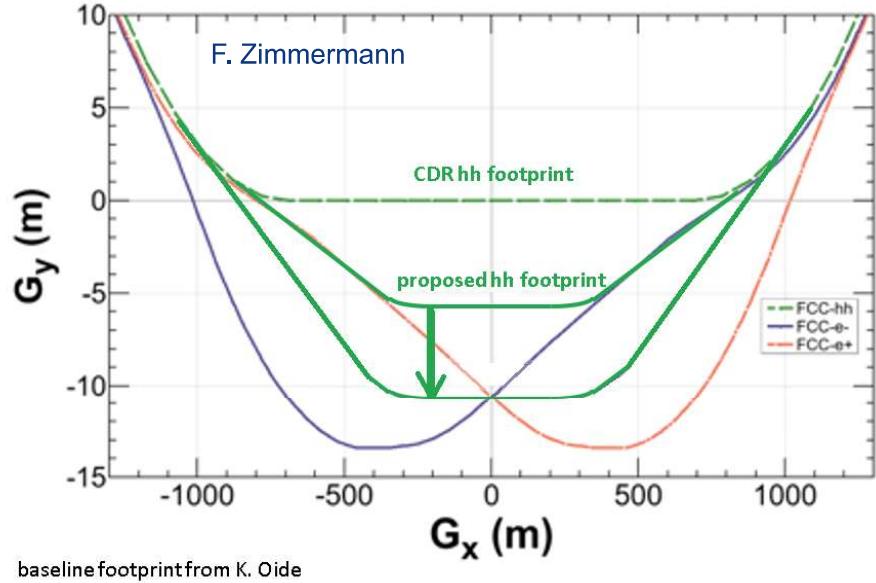
**Detector requirements  
& possible solutions**

**Theory  
challenges**

**Software and computing  
challenges**

**Challenges to match  
statistical precision**

# layout optimisation of high-luminosity insertions

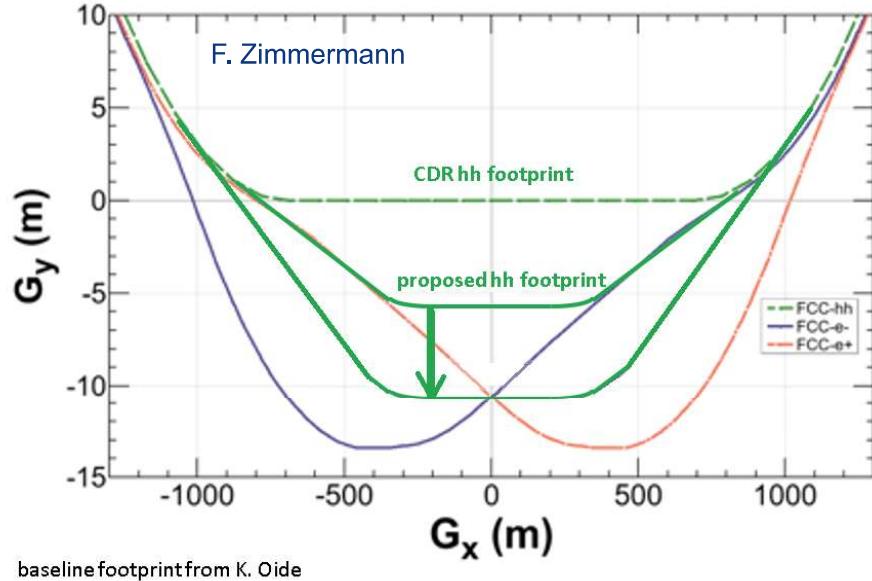


## From CDR

- Due to FCC-ee asymmetric IR layout, transverse displacement of IPs for FCC-ee and FCC-hh.
- FCC-hh footprint compatible with FCC-ee injector

Massimo Giovannozzi & Thys Risselada

# layout optimisation of high-luminosity insertions



Implementation of an improved layout with FCC-ee & FCC-hh IPs with same transverse positions

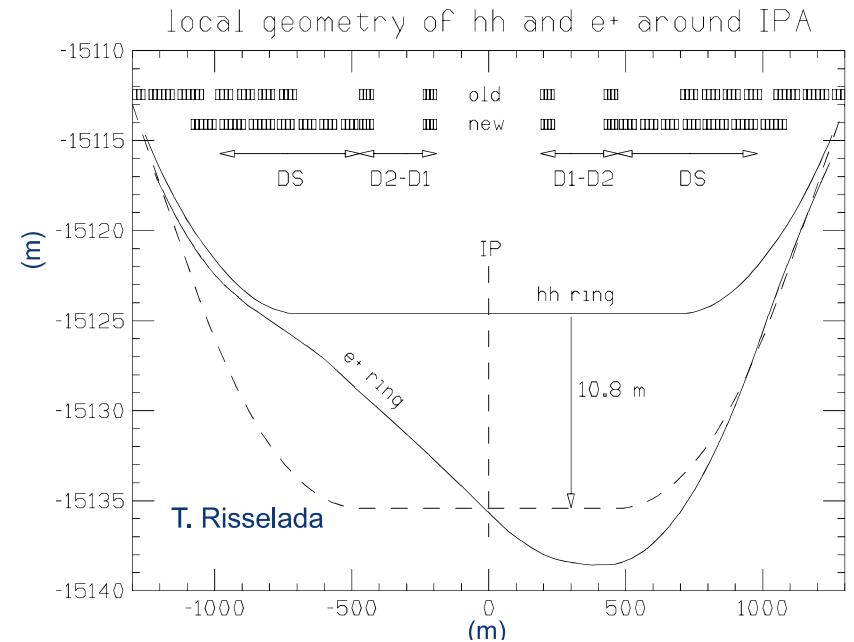
## Advantages:

- Transverse size of detector cavern reduced
- Tunnel width reduced over  $2 \times 500$  m
- Potential to re-use FCC-ee detector magnets for FCC-hh

## From CDR

- Due to FCC-ee asymmetric IR layout, transverse displacement of IPs for FCC-ee and FCC-hh.
- FCC-hh footprint compatible with FCC-ee injector

Massimo Giovannozzi & Thys Risselada



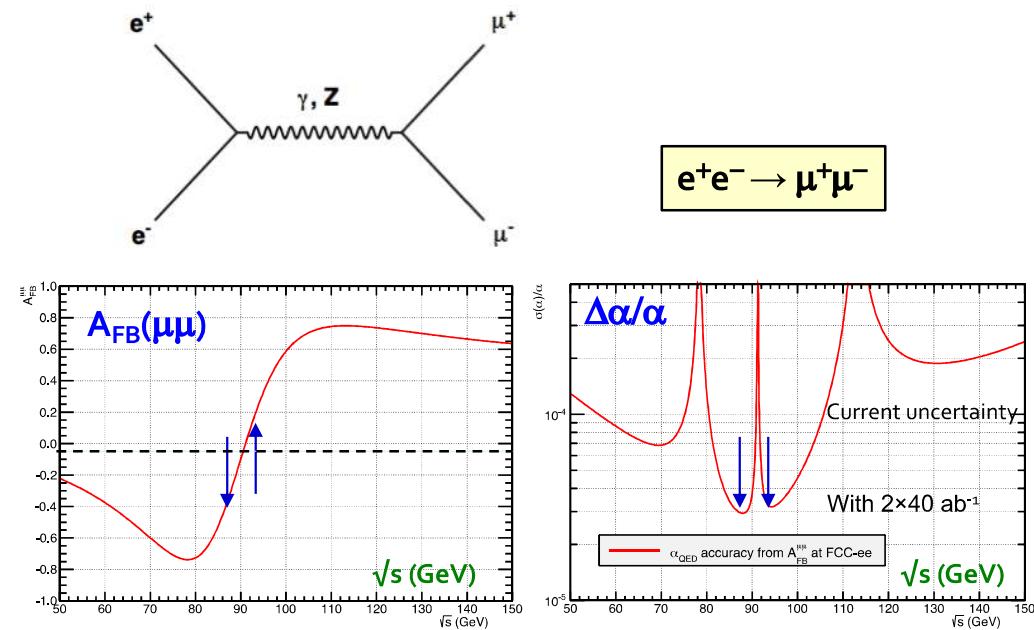
# ELECTROWEAK PRECISION MEASUREMENTS

## TeraZ ( $5 \times 10^{12} Z$ )

From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- $R_l$  = hadronic/leptonic width ( $\alpha_s(m_Z^2)$ , lepton couplings, precise universality test )
- peak cross section (invisible width,  $N_v$ )
- $A_{FB}(\mu\mu)$  ( $\sin^2\theta_{eff}$ ,  $\alpha_{QED}(m_Z^2)$ , lepton couplings)
- Tau polarization ( $\sin^2\theta_{eff}$ , lepton couplings,  $\alpha_{QED}(m_Z^2)$ )
- $R_b, R_c, A_{FB}(bb), A_{FB}(cc)$  (quark couplings)

- Boils down to measuring cross sections and asymmetries
- The dominant experimental uncertainties come from the beam energy knowledge

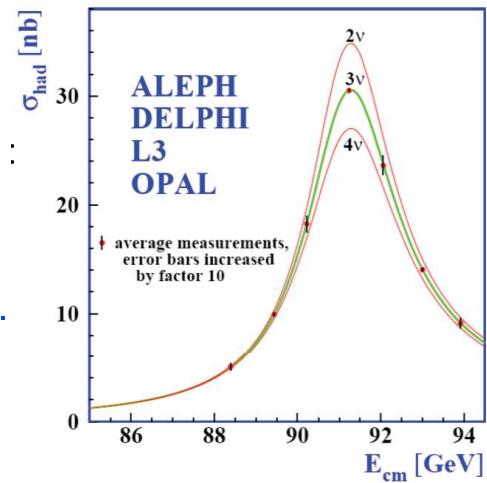
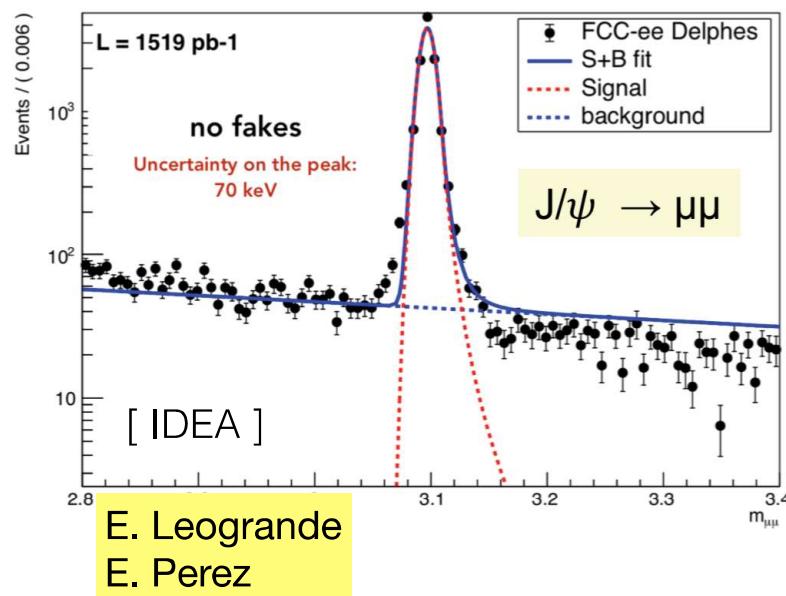


## Example: Determination of the Z width

**Key = Relative uncertainty of  $\sqrt{s}$  between the different energy points of the lineshape scan.**

Can be controlled via the direct measurement of  $M(\mu\mu)$  in di-muon events : compare the peak positions at the different  $\sqrt{s}$  points.

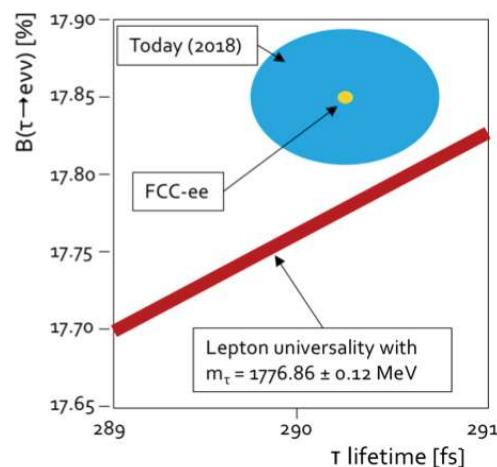
- $\sigma(M_{\mu\mu})$  : statistical potential to control relative  $\delta(\sqrt{s})$  to  $O(40 \text{ keV})$
- Requires the stability of the momentum scale, esp. of  $B$ , to that level, i.e.  $40 \text{ keV} / 90 \text{ GeV} < 10^{-6}$



In-situ, using the large statistics of well-known resonances, e.g.  $J/\psi \rightarrow \mu\mu$

First studies: Target seems within reach with an IDEA-like resolution (drift chamber as tracker)

Visible $Z$ decays	$3 \times 10^{12}$
$Z \rightarrow \tau^+\tau^-$	$1.3 \times 10^{11}$
1 vs. 3 prongs	$3.2 \times 10^{10}$
3 vs. 3 prong	$2.8 \times 10^9$
1 vs. 5 prong	$2.1 \times 10^8$
1 vs. 7 prong	< 67,000
1 vs 9 prong	?



## TERA-Z - TAU PHYSICS

CLFV  $Z$  decays:  
in SM  $< 10^{-50}$

Decay	Current bound	FCC-ee sensitivity
$Z \rightarrow e\mu$	$0.75 \times 10^{-6}$	$10^{-8}$
$Z \rightarrow \mu\tau$	$12 \times 10^{-6}$	$10^{-9}$
$Z \rightarrow e\tau$	$9.8 \times 10^{-6}$	$10^{-9}$

CLFV  $\tau$  decays:

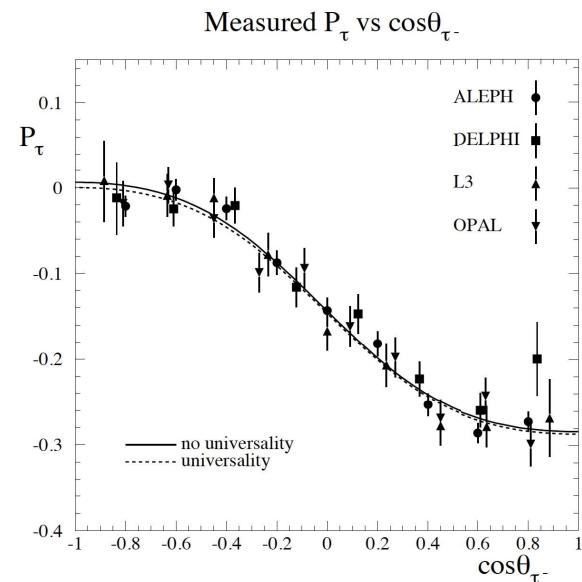
Decay	Current bound	FCC-ee sensitivity
$\tau \rightarrow \mu\gamma$	$4.4 \times 10^{-8}$	$2 \times 10^{-9}$
$\tau \rightarrow 3\mu$	$2 \times 10^{-8}$	$10^{-10}$

Property	Current WA	FCC-ee stat	FCC-ee syst
Mass [MeV]	$1776.86 \pm 0.12$	0.004	0.1
Electron BF [%]	$17.82 \pm 0.05$	0.0001	0.003
Muon BF	$17.39 \pm 0.05$	0.0001	0.003
Lifetime [fs]	$290.3 \pm 0.5$	0.005	0.04

## EXAMPLE: TAU POLARISATION

- Tau polarisation has a central role at the FCC-ee: crucial ingredient for  $A_e$ ,  $\sin^2\theta_{eff}$  at a circular collider
- Desired precision of few  $\times 10^{-6}$  on  $\sin^2\theta_{eff}$ , similar to that from  $A_{FB}^{\mu\mu}$  but model independent
- Very large tau statistics ( $\approx 1.5 \times 10^{11}$ ). Not only leptonic decays. Can profit of hadronic decays and choose the best channels (avoiding modelling issues).
- For instance use best decay channels such as  $\tau \rightarrow \rho v_\tau$

$$P_\tau(\cos \theta) = -\frac{\mathcal{A}_\tau(1 + \cos^2 \theta) + \mathcal{A}_e(2 \cos \theta)}{(1 + \cos^2 \theta) + \frac{4}{3}\mathcal{A}_{fb}(2 \cos \theta)}$$



Excellent benchmark for detector performance in  $\pi^0/\gamma$  separation

Often statistics limited  
 $5 \cdot 10^{12}$   $Z$  is a minimum

# FCC-ee AT THE INTENSITY FRONTIER

## Flavour physics programme

- Enormous statistics  $10^{12}$   $bb, cc$
  - Clean environment, favourable kinematics (boost)
  - Small beam pipe radius (vertexing)
1. Flavour EWPOs ( $R_b, A_{FB}^{b,c}$ ) : large improvements wrt LEP
  2. CKM matrix, CP violation in neutral B mesons
  3. Flavour anomalies in, e.g.,  $b \rightarrow s\tau\tau$

## Tau physics programme

- Enormous statistics:  $1.7 \cdot 10^{11} \tau\tau$  events
  - Clean environment, boost, vertexing
  - Much improved measurement of mass, lifetime, BR's
1.  $\tau$ -based EWPOs ( $R_\tau, A_{FB}^{\text{pol}}, P_\tau$ )
  2. Lepton universality violation tests
  3. PMNS matrix unitarity
  4. Light-heavy neutrino mixing

## Rare processes: Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below  $m_Z$

- Signature: long lifetimes (LLP's)
  1. Axion-like particles
  2. Dark photons
  3. Heavy Neutral Leptons



## FCC-ee AT THE INTENSITY FRONTIER

► ... which in turn provide specific detector requirements

More case studies lead to  
more detector requirements

### Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

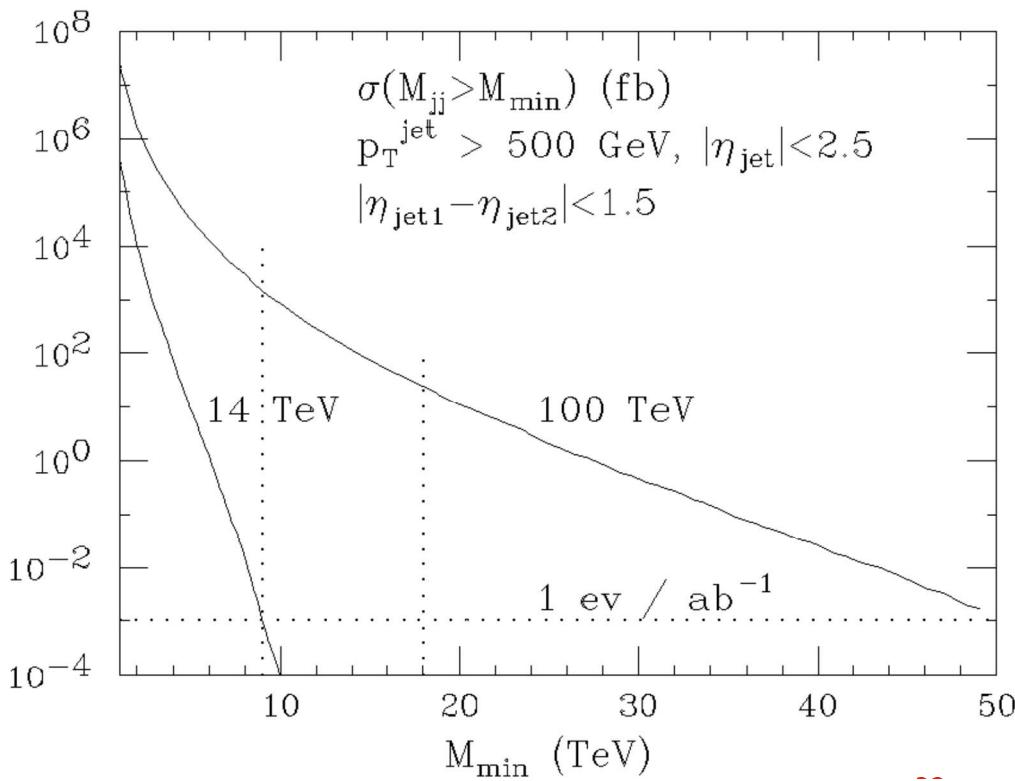
### Tau physics programme

- Momentum resolution  
Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions  
Lifetime measurement
- Tracker and ECAL granularity and e/ $\mu$ / $\pi$  separation  
BR measurements, EWPOs, spectral functions

### Rare processes: Feebly Coupled Particles

- Sensitivity to far-detached vertices ( $m m \rightarrow m$ )
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths  $\Rightarrow$  extended detector volume
- Full acceptance  $\Rightarrow$  Detector hermeticity

## DI-JET PRODUCTION AT LARGE MASS AT FCC-HH

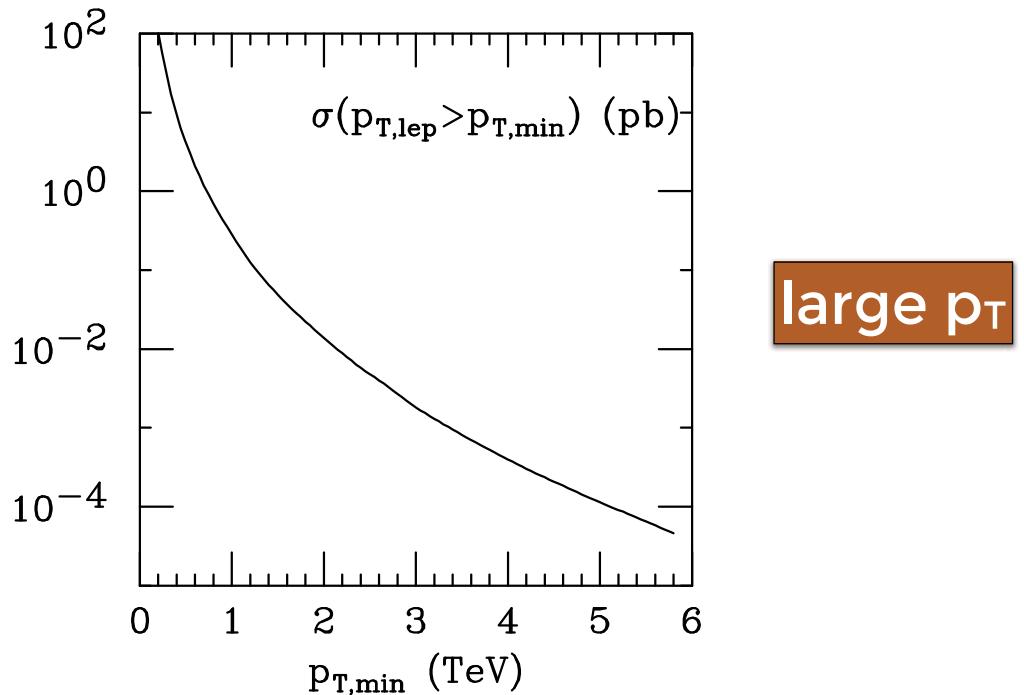
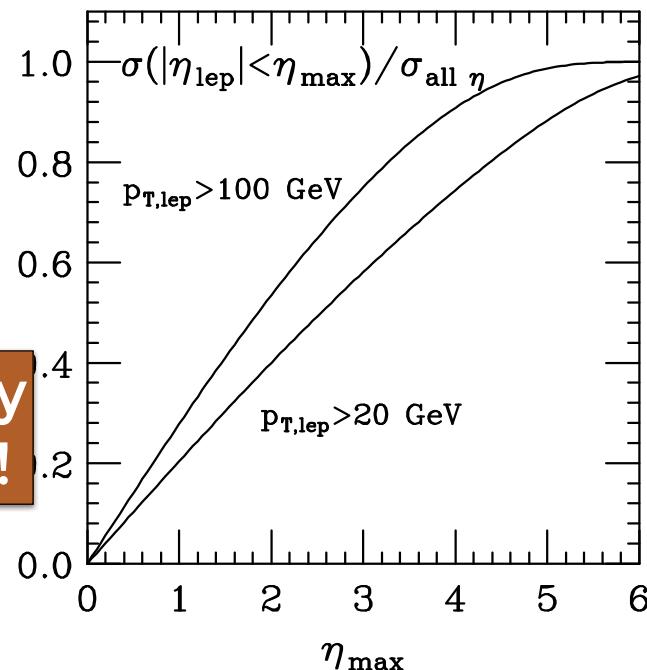


- 1 pb<sup>-1</sup> to recover sensitivity of HL-LHC ==> 1 day @  $10^{32}$
- 50 pb<sup>-1</sup> to recover 2x sensitivity of HL-LHC ==> 1 month @  $10^{32}$
- 1 fb<sup>-1</sup> to recover 3x sensitivity of HL-LHC ==> 1 year @  $2 \times 10^{32}$

## W AND Z PRODUCTION AT FCC-HH

- ▶ Production of W and Z bosons is an extremely important probe of EW and QCD dynamics
- ▶ The production rate of  $W^\pm(Z^0)$  bosons at 100 TeV is about  $1.3(0.4)\mu\text{b}$ . This corresponds to  $\mathcal{O}(10^{11})$  leptonic decays per  $\text{ab}^{-1}$ .

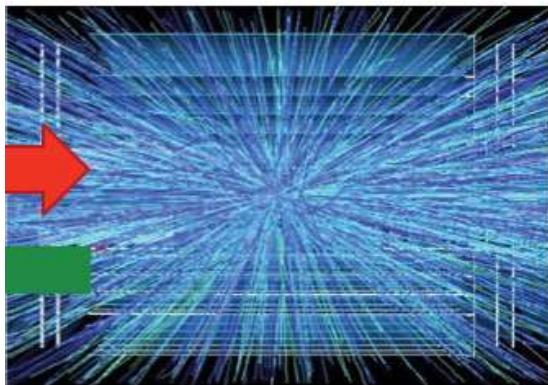
large rapidity distribution!



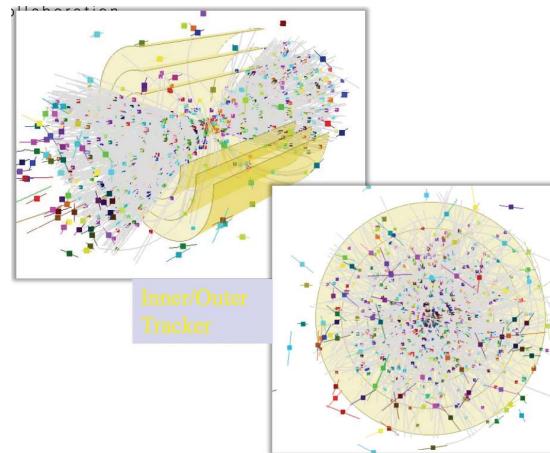
## BACKGROUNDS VS PRECISION

- Electron/muons are ELEMENTARY particles. No spectators. No PDF. The  $\sqrt{s}$  of the process is known. This LIMITS ULTIMATE PRECISION
- Various machines at high energy have processes that create noise and occupancy in the detector: analyses assume this will be OK

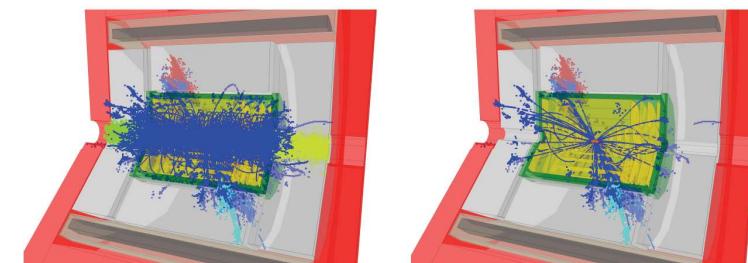
FCC-hh 100 TeV  
~1000 pileup



Muon Collider 10TeV  
Beam Induced Background

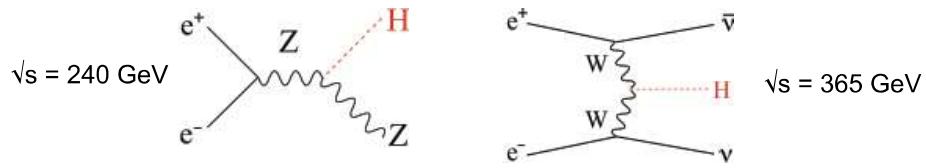


CLIC 3TeV  
Beamstrahlung Background



# FCC SYNERGIES: THE HIGGS BOSON

- The FCC integrated program (ee, hh, eh) has built-in synergies and complementarities
  - It will provide the most complete and model-independent studies of the Higgs boson

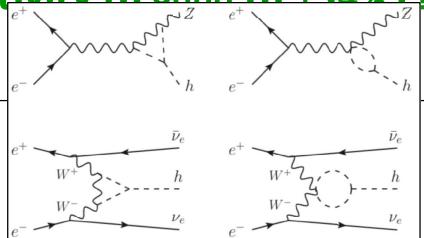


**FCC-ee provides  $10^6$  Hz +  $10^5$  WW  $\rightarrow$  H events**

Absolute determination of  $g_{HZZ}$  to  $\pm 0.17\%$

Model-independent determination of  $\Gamma_H$  to  $\pm 1\%$

- Fixed « candle » for all other measurements including those made at HL-LHC or FCC-hh
- Measure couplings to WW, bb, ττ, cc, gg, ... Even possibly the Hee coupling!
- First sensitivity to  $\sigma_{gg \rightarrow H}$  to  $\pm 34\%$  ( $\pm 21\%$  with 4IP)

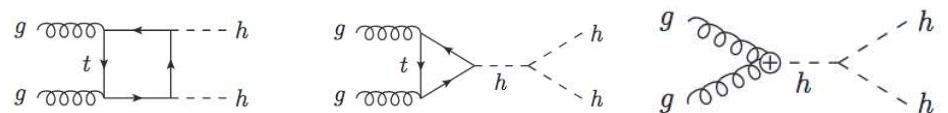


**FCC-hh provides  $3 \times 10^{10}$  Higgs bosons**

With this huge sample and using the FCC-ee candle

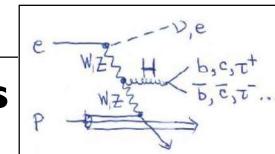
- Model-independent ttH coupling to  $< 1\%$  (HL-LHC and FCC-ee give  $\pm 2.6\%$ )
- Use  $\pm 1\%$  ttZ measurement at FCC-ee
- Rare decays: couplings to  $\mu\mu, \gamma\gamma, Z\gamma, \dots$
- Higgs self coupling  $g_{HHH}$  to  $\pm 3\%$

With double-Higgs production



**FCC-eh provides  $2.5 \times 10^6$  Higgs bosons**

With the FCC-ee candle, further improves on several measurements (e.g.,  $g_{HWW}$ )



# VERTEX DETECTOR: IDEA

Inspired by ALICE ITS based on MAPS technology, using the ARCADIA R&D program

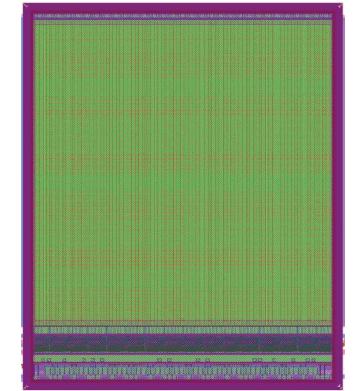
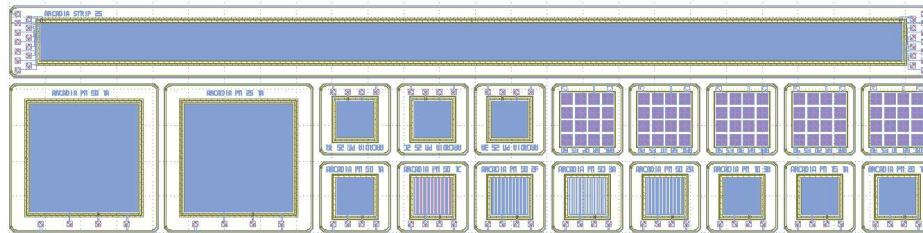
- ❑ Pixels  $20 \times 20 \mu\text{m}^2$

• Light

- ❑ Inner layers: 0.3% of  $X_0$  / layer
- ❑ Outer layers: 1% of  $X_0$  / layer

• Performance:

- ❑ Point resolution of  $\sim 3 \mu\text{m}$
- ❑ Efficiency of  $\sim 100\%$
- ❑ Extremely low fake rate hit rate



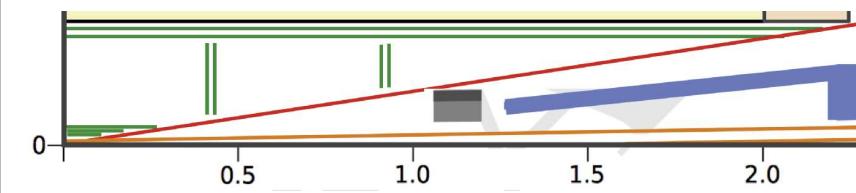
**5 MAPS layers:**

$$R = 1.7 - 2.3 - 3.1 \text{ cm}$$

$$\text{Pixel size: } 20 \times 20 \mu\text{m}^2$$

$$R = 32 - 34 \text{ cm}$$

$$\text{Pixel size: } 50 \times 100 \mu\text{m}^2$$

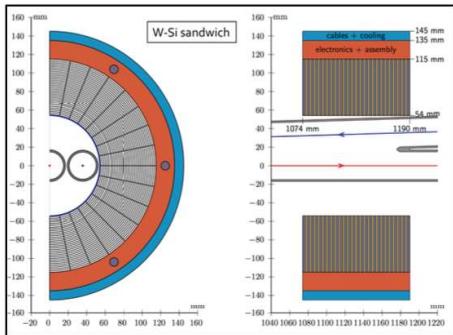


## Normalisation Issues

Ambitious goals:

- Absolute luminosity measurement to  $\lesssim 10^{-4}$
- Relative luminosity (energy-to-energy point) to  $\lesssim 10^{-5}$
- Inter-channel normalisation (e.g.  $\mu\mu$ /multi-hadronic) to  $\lesssim 10^{-5}$

### Luminosity Monitors (low angle Bhabha)



Dedicated presentation in MDI session tomorrow

- ◆ Many R&D/engineering challenges

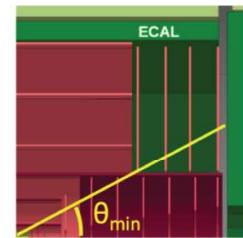
- Precision on acceptance boundaries to  $\mathcal{O}(1 \mu\text{m})$  !
- Mechanical assembly, metrology, alignment
- Physics rate of  $\mathcal{O}(100 \text{ kHz})$
- Readout at 50 MHz BX rate ?
- Power management / cooling
- Support / integration in crowded and complex MDI area

### Complementary lumi process: large angle $e^+e^- \rightarrow \gamma\gamma$

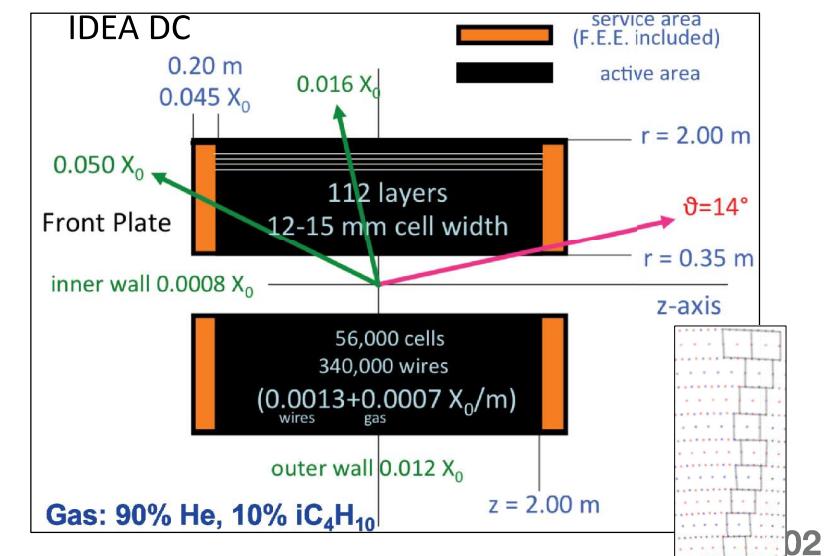
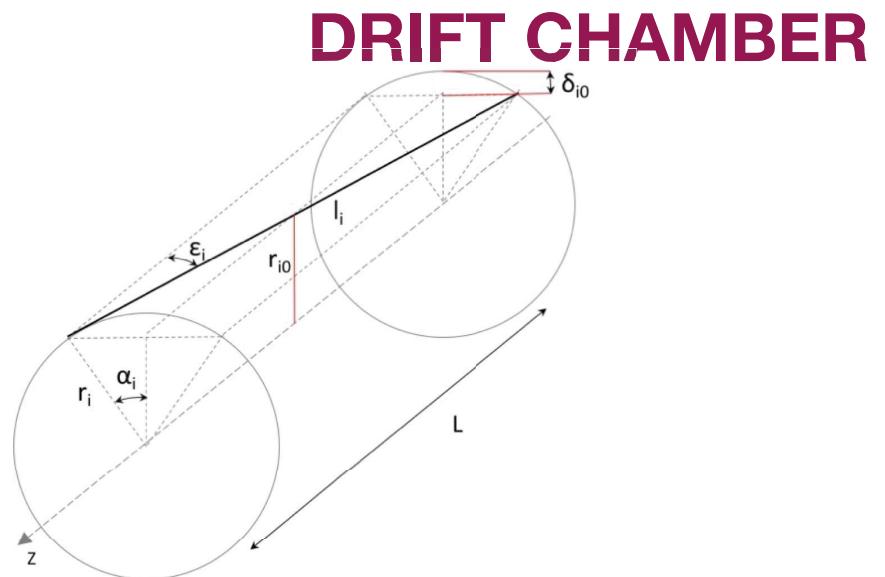
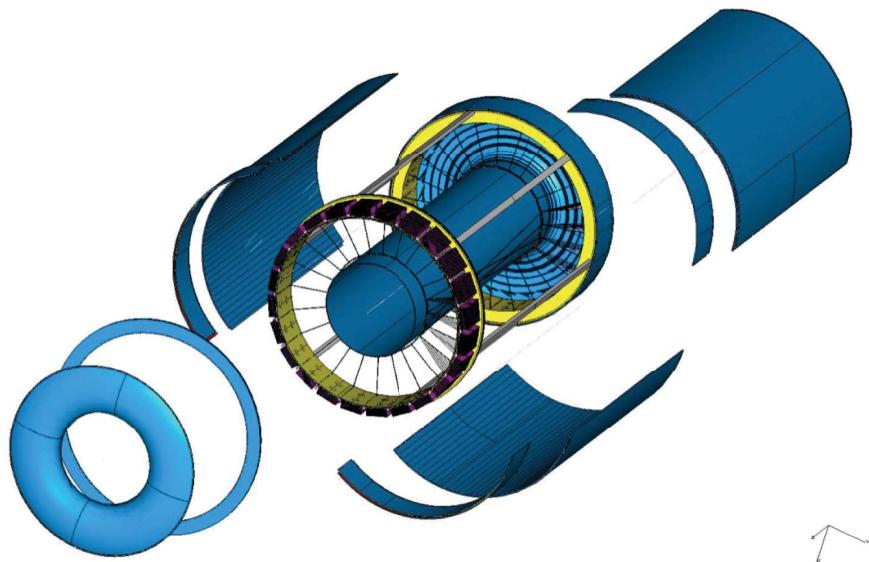
- $10^{-4} \Rightarrow$  control of acceptance boundary  $\delta\theta_{\min}$  to  $\mathcal{O}(50 \mu\text{rad})$
- Possible bckg:  $Z \rightarrow \pi^0\gamma \Rightarrow$  need to control  $\mathcal{B}(Z \rightarrow \pi^0\gamma)$  to  $10^{-7}$

### Acceptance of $Z \rightarrow \ell\ell$ to $10^{-5}$

- Control of acceptance boundary  $\delta\theta_{\min}$  to  $\mathcal{O}(50 \mu\text{rad})$
- No holes or cracks
- ◆ Possible implementation: Precisely machined pre-shower device in front of forward calorimeter
  - Note 1: IDEA concept already includes pre-shower + Si wrapper
  - Note 2: CM and detector systems differ by a  $\beta=0.015$  transverse boost



- IDEA: Extremely transparent Drift Chamber
  - Gas: 90% He – 10% iC<sub>4</sub>H<sub>10</sub>
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of  $X_0$  at 90°
    - ❖ Tungsten wires dominant contribution
  - 112 layers for each 15° azimuthal sector
  - max drift time: 350 ns





The  $\mu$ -RWELL is composed of only two elements:

- $\mu$ -RWELL\_PCB
- drift/cathode PCB defining the gas gap

$\mu$ -RWELL\_PCB = amplification-stage  $\oplus$  resistive stage  
 $\oplus$  readout PCB

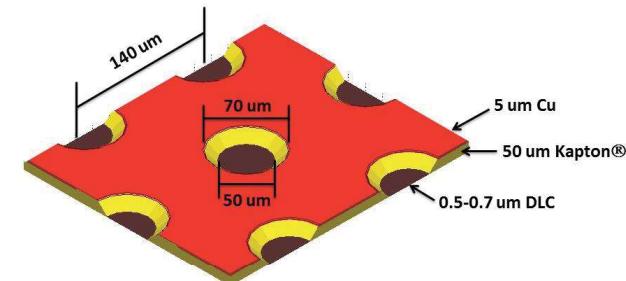
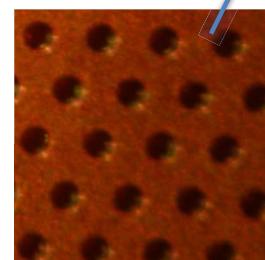
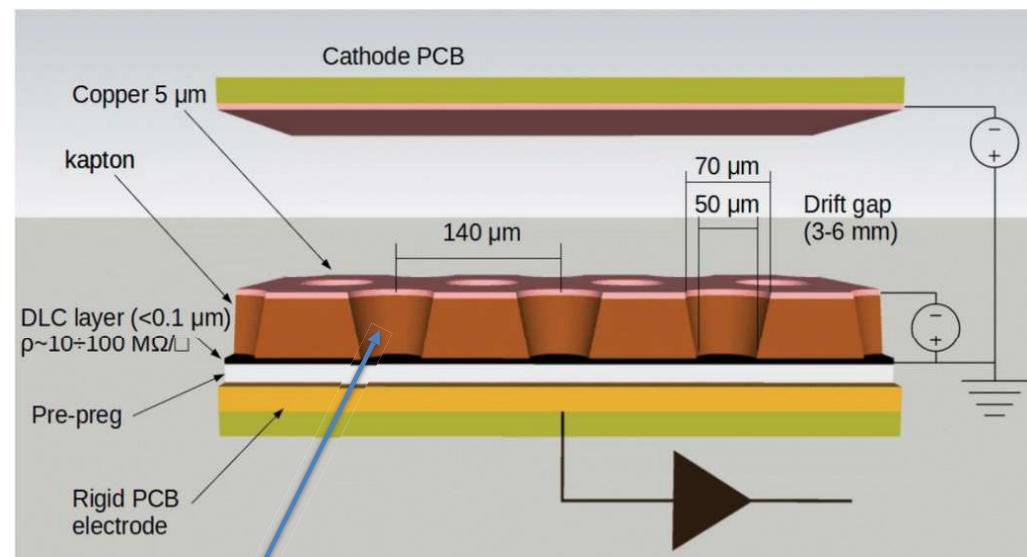
$\mu$ -RWELL operation:

- A charged particle ionises the gas between the two detector elements
- Primary electrons drift towards the  $\mu$ -RWELL\_PCB (anode) where they are multiplied, while ions drift to the cathode
- The signal is induced capacitively, through the DLC layer, to the readout PCB
- HV is applied between the Anode and Cathode PCB electrodes
- HV is also applied to the copper layer on the top of the kapton foil, providing the amplification field

(\*) G. Bencivelli et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015\_JINST\_10\_P02008)

## M-RWELL TECHNOLOGY

**INFN**  
 LNF BOLOGNA FERRARA TORINO  
Istituto Nazionale di Fisica Nucleare





FCC

## Preshower Detector

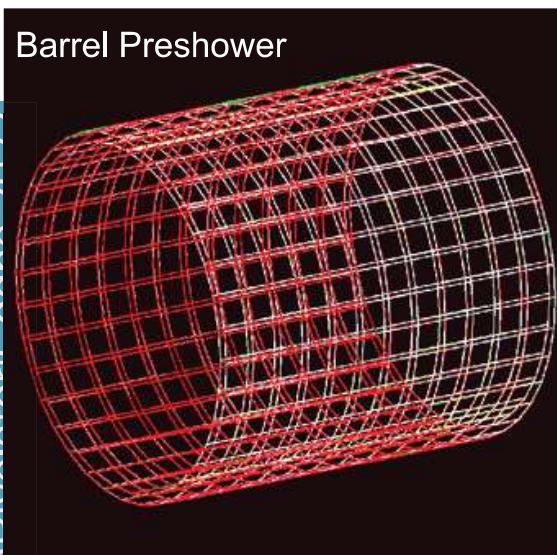
High resolution before the magnet  
to improve cluster reconstruction

Efficiency > 98%

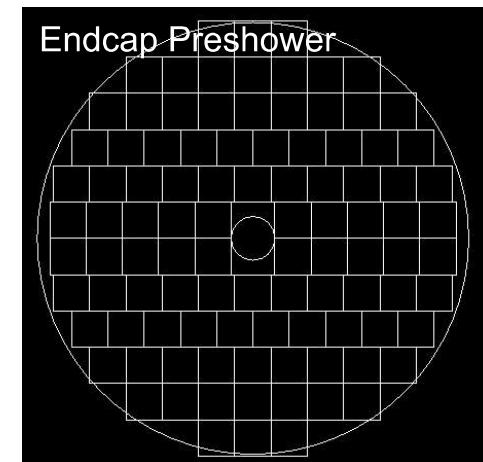
Space Resolution < 100  $\mu\text{m}$

Mass production

Optimization of FEE channels/cost



Similar design for  
the Muon detector



Similar design for  
the Muon detector

## **PRESHOWER AND MUON DETECTOR**

### Muon Detector

Identify muons and search for LLPs

Efficiency > 98%

Space Resolution < 400  $\mu\text{m}$

Mass production

Optimization of FEE channels/cost

### **Detector technology: $\mu$ -RWELL**

50x50  $\text{cm}^2$  2D tiles to  
cover more than 4330  $\text{m}^2$

### Preshower

pitch = 0.4 mm

FEE capacitance = 70 pF  
1.5 million channels

### Muon

pitch = 1.5 mm

FEE capacitance = 270 pF  
5 million channels