INFN
Istituto Nazionale di Fisica Nucleare


# *Calorimetry in High-Energy Physics*

*(lecture 2 of 2)*

*Roberto Ferrari*

*INFN – Sezione di Pavia*

# *Topics*

dual-readout calorimetry

particle flow and longitudinal segmentation

jets

readout and processing

… too much … must skip some parts

# *dual-readout calorimetry*

What:

correct hadronic energy measurements for $f_{em}$ fluctuations

How:

use two independent sampling processes

*with different sensitivity to em and non-em shower components*

to reconstruct $f_{em}$ event-by-event

*Scintillation light → S signal*

*Čerenkov light → C signal*

# *the math*

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

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

with $(h/e)_S$ and $(h/e)_C$ detector specific constants.

Solving the system, both E and $f_{em}$ can be reconstructed:

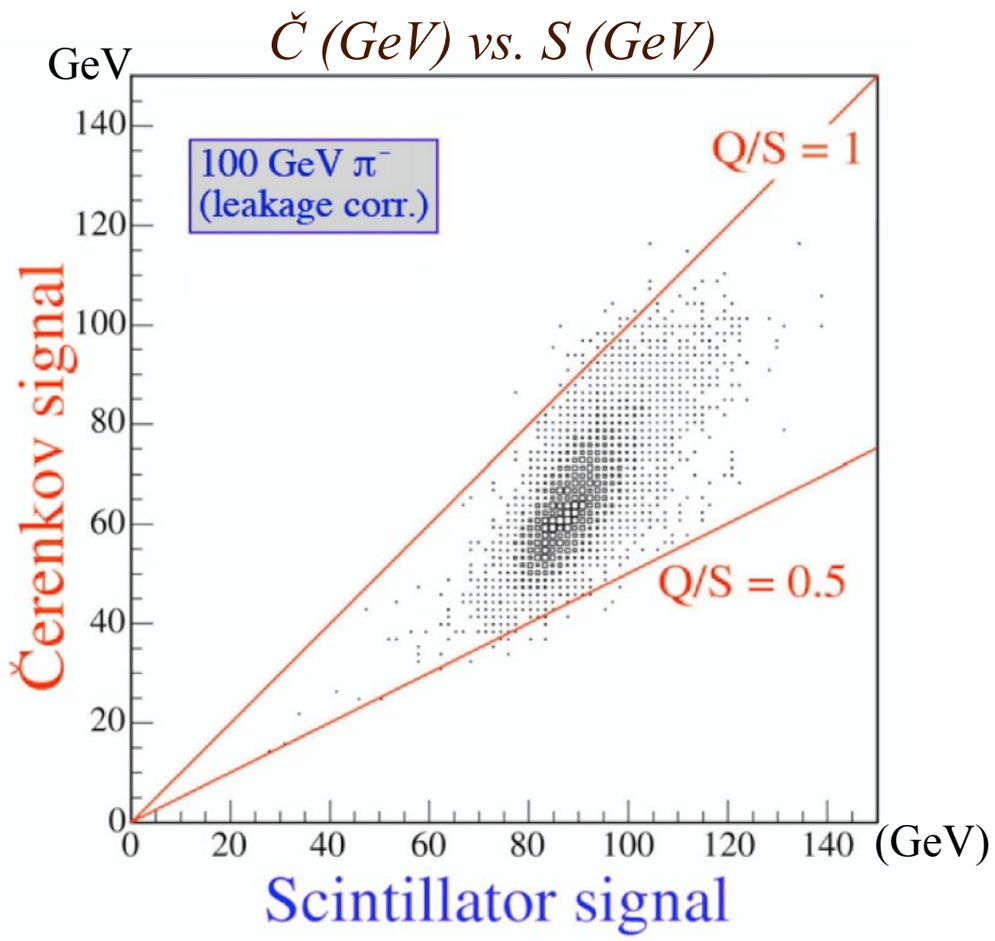
$$E = (S - \chi C) / (1 - \chi)$$

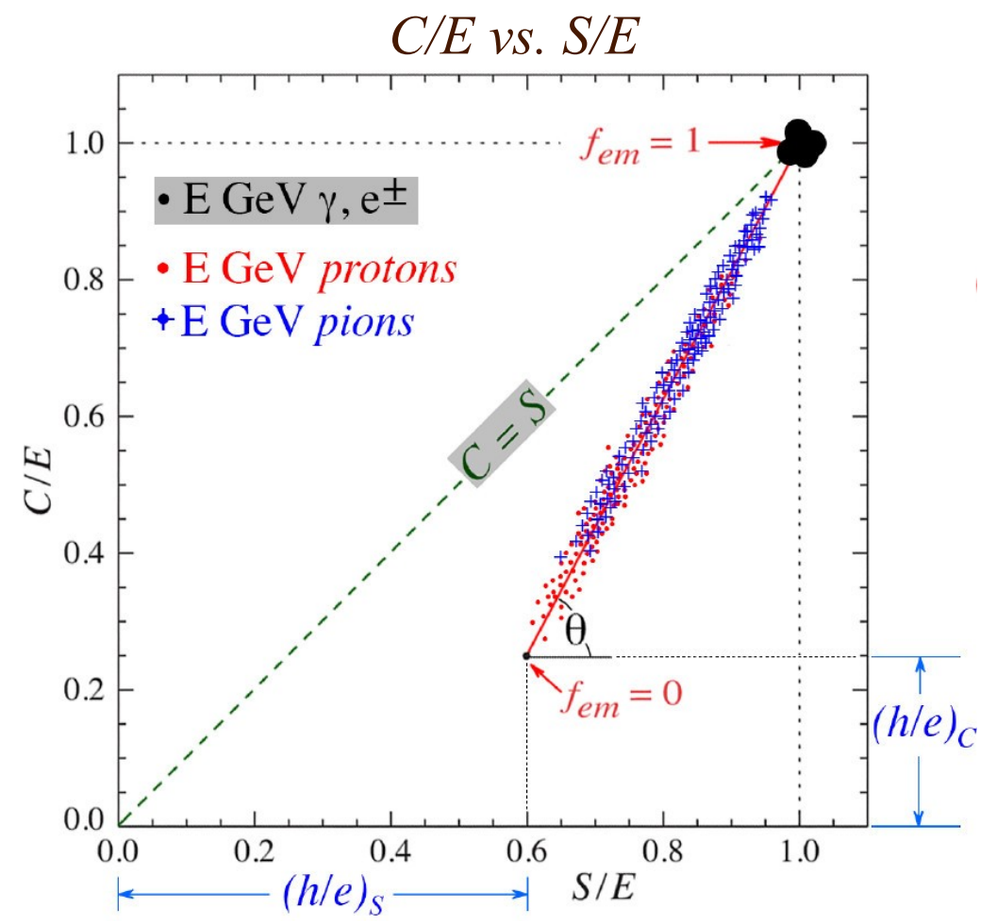
where:

$$\chi = (1 - (h/e)_S)\ / (1 - (h/e)_C)$$
$$= (E - S) / (E - C)$$

→ ***χ can be extracted from testbeam data***

# applying the d.r. approach




Hadronic data points (S, C) located around straight lines

$$E = \frac{S - \chi C}{1 - \chi}$$

*is universally valid*

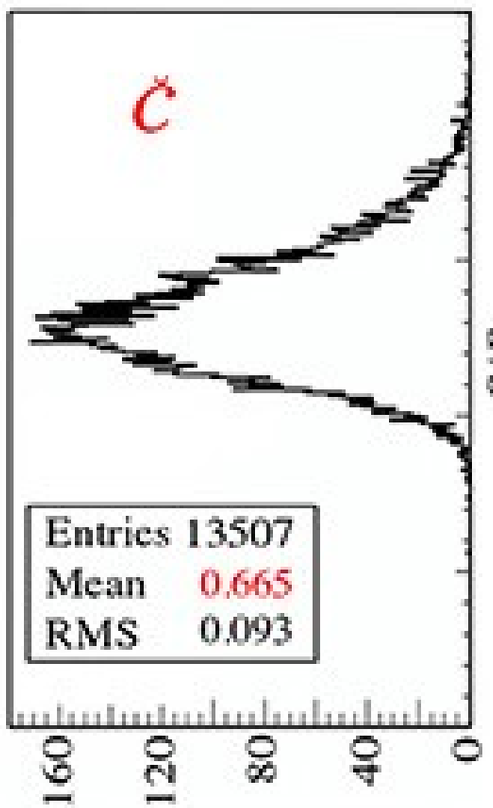
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

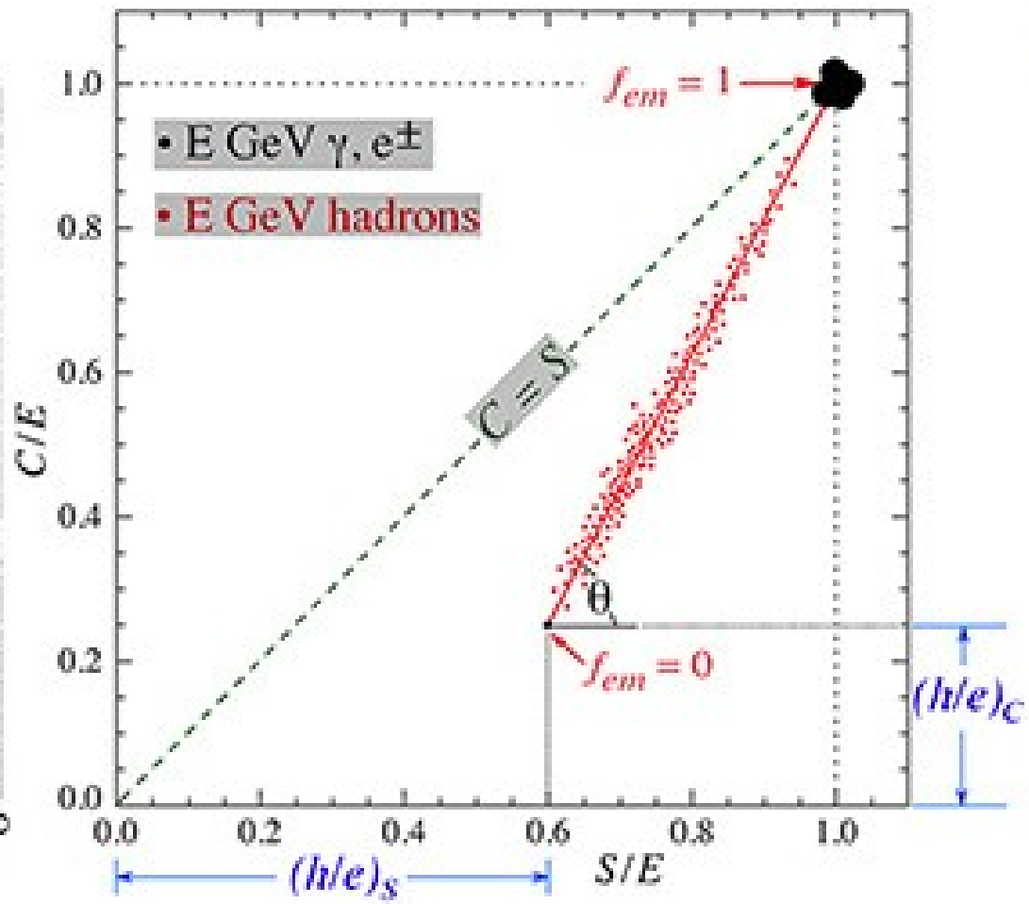
θ, χ independent of both:

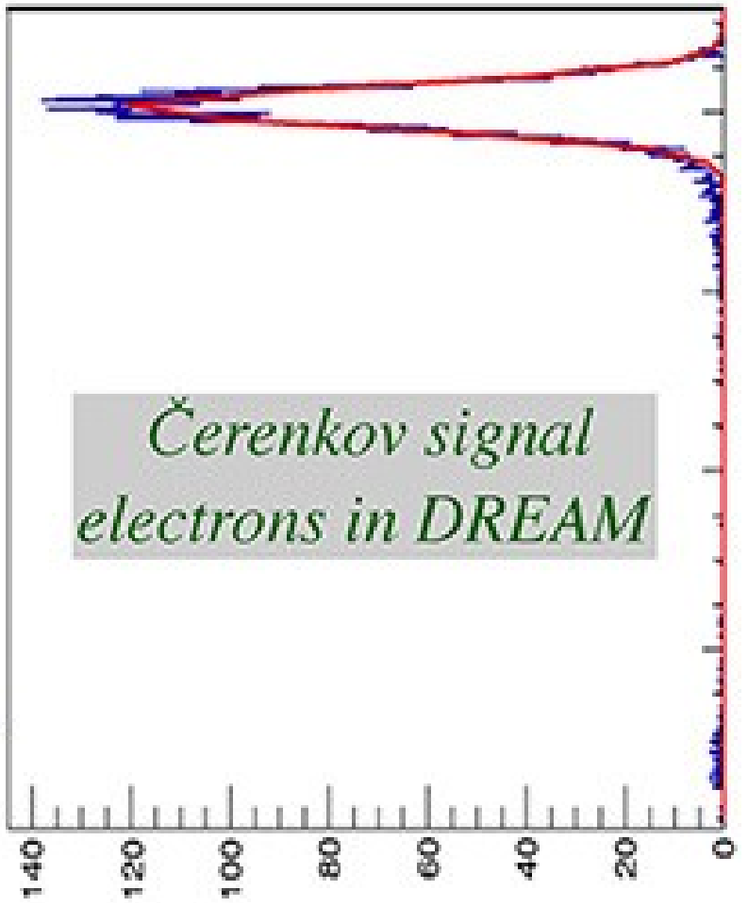
i) energy (!)

ii) type of hadron (!!)

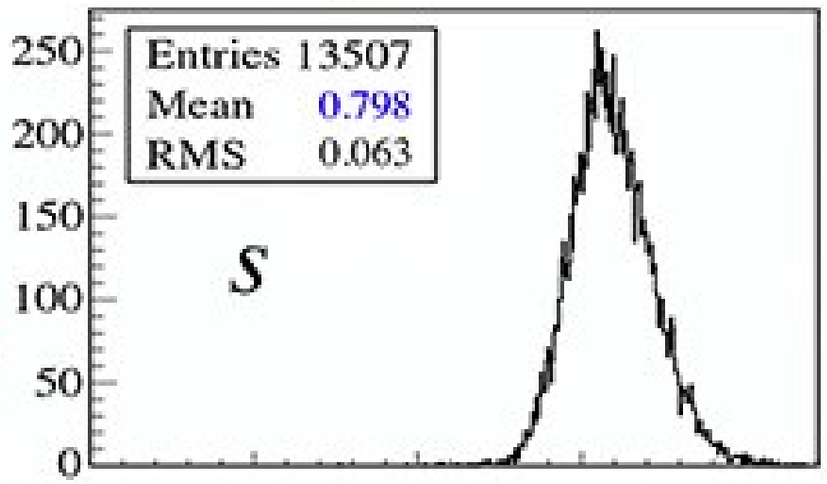
# *before d.r. corrections*



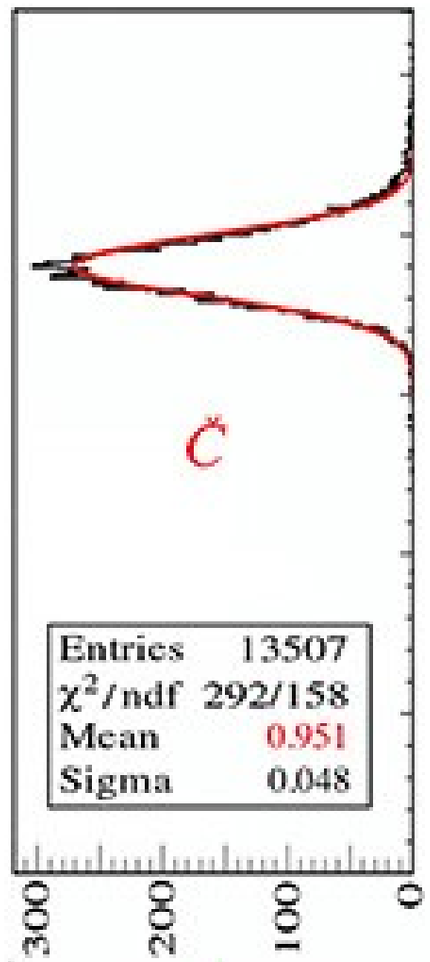



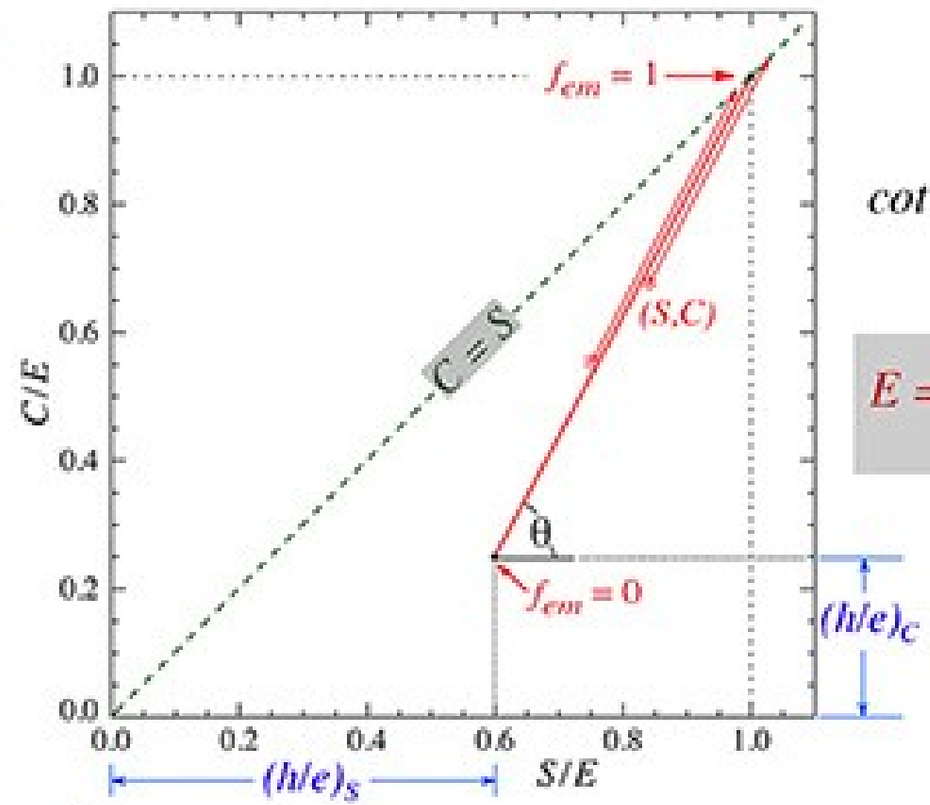




*200 GeV "jets" in DREAM*



# *with d.r. approach*

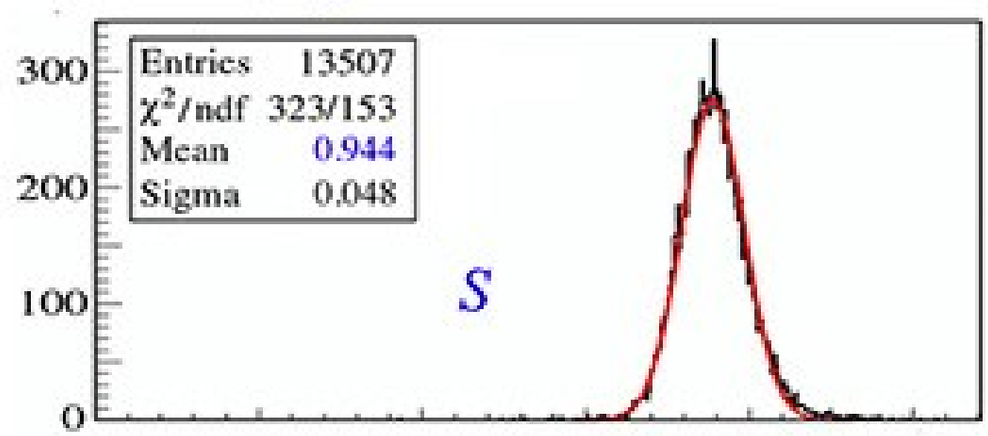



$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S-\chi C}{1-\chi}$$

*200 GeV "jets" in DREAM*

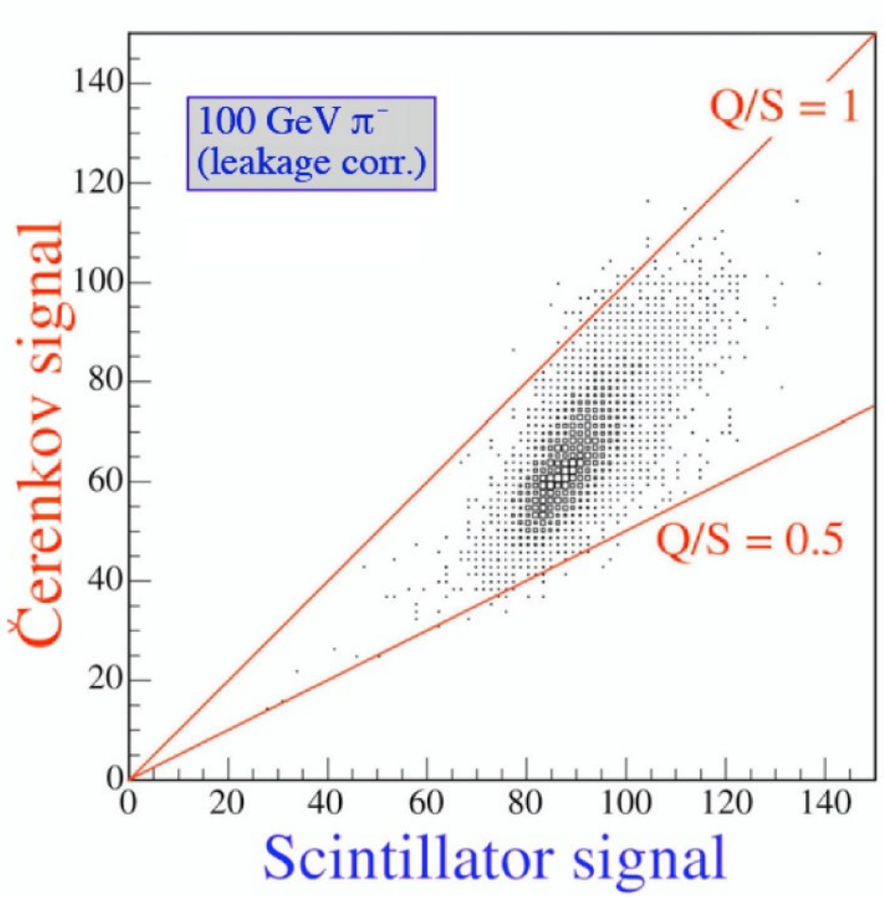


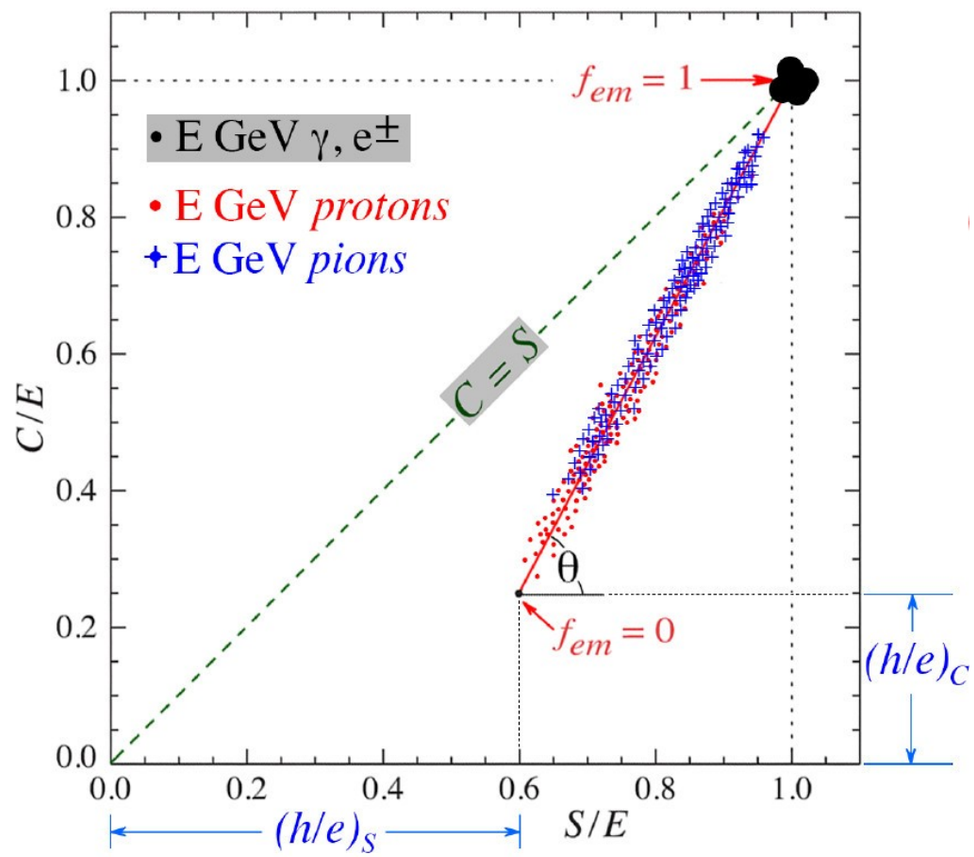
# *about χ parameter*

Range : $0 < \chi < 1$ $[\ (h/e)_C < (h/e)_S\ ]$

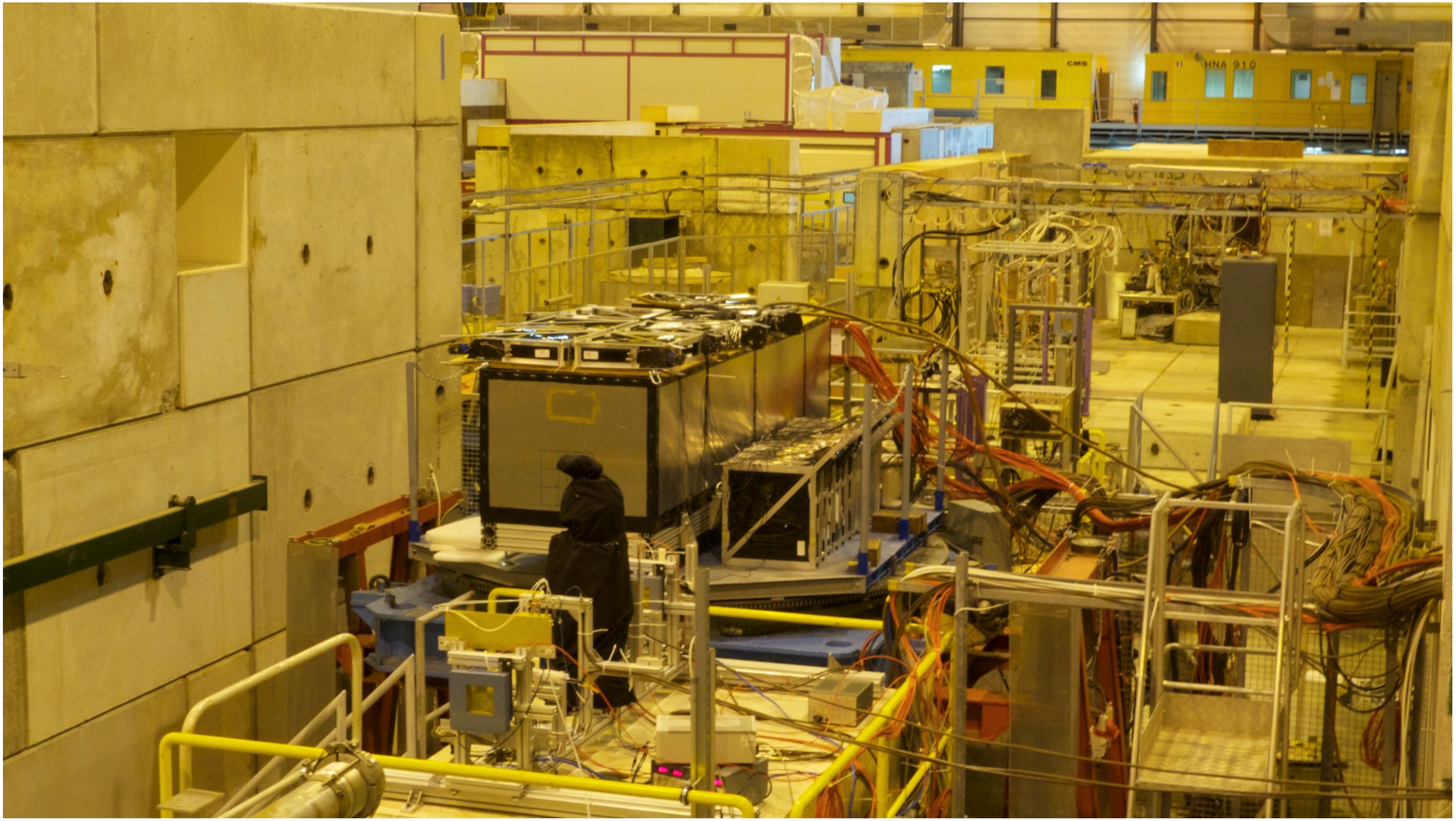
$(h/e)_S \rightarrow 1$ : $\chi \rightarrow 0$, $\theta \rightarrow 90°$, E better resolved

$(h/e)_C \rightarrow (h/e)_S$ : $\chi \rightarrow 1$, $\theta \rightarrow 45°$, E unresolved



# fibre-sampling dual-readout calorimeters



# the DREAM/RD52 collaboration

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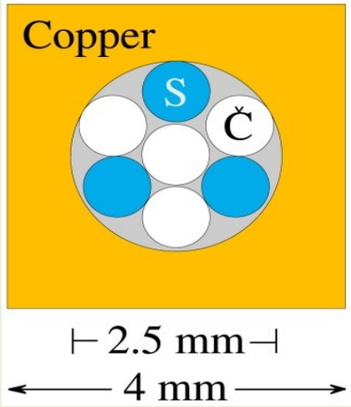
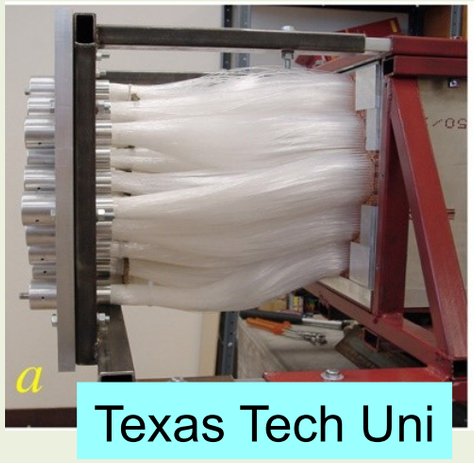
# fibre-sampling dual-readout calorimeters

2003
DREAM

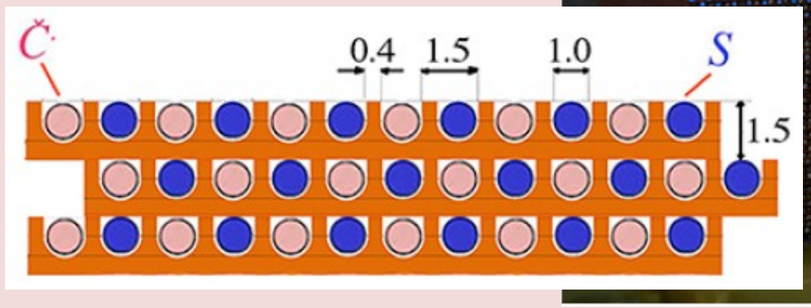
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%

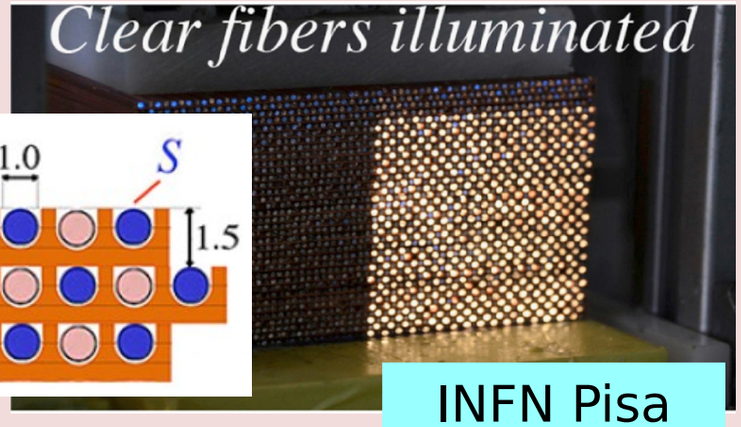



2012
RD52

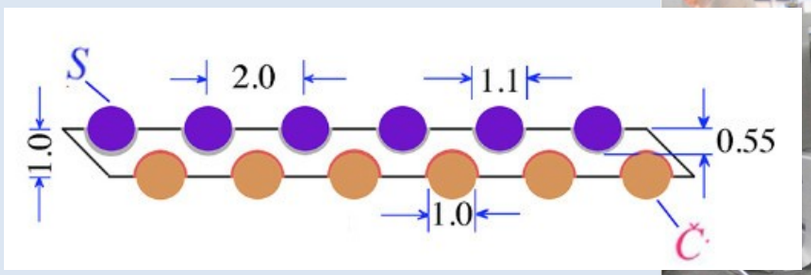
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm$^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 $\lambda_{int}$



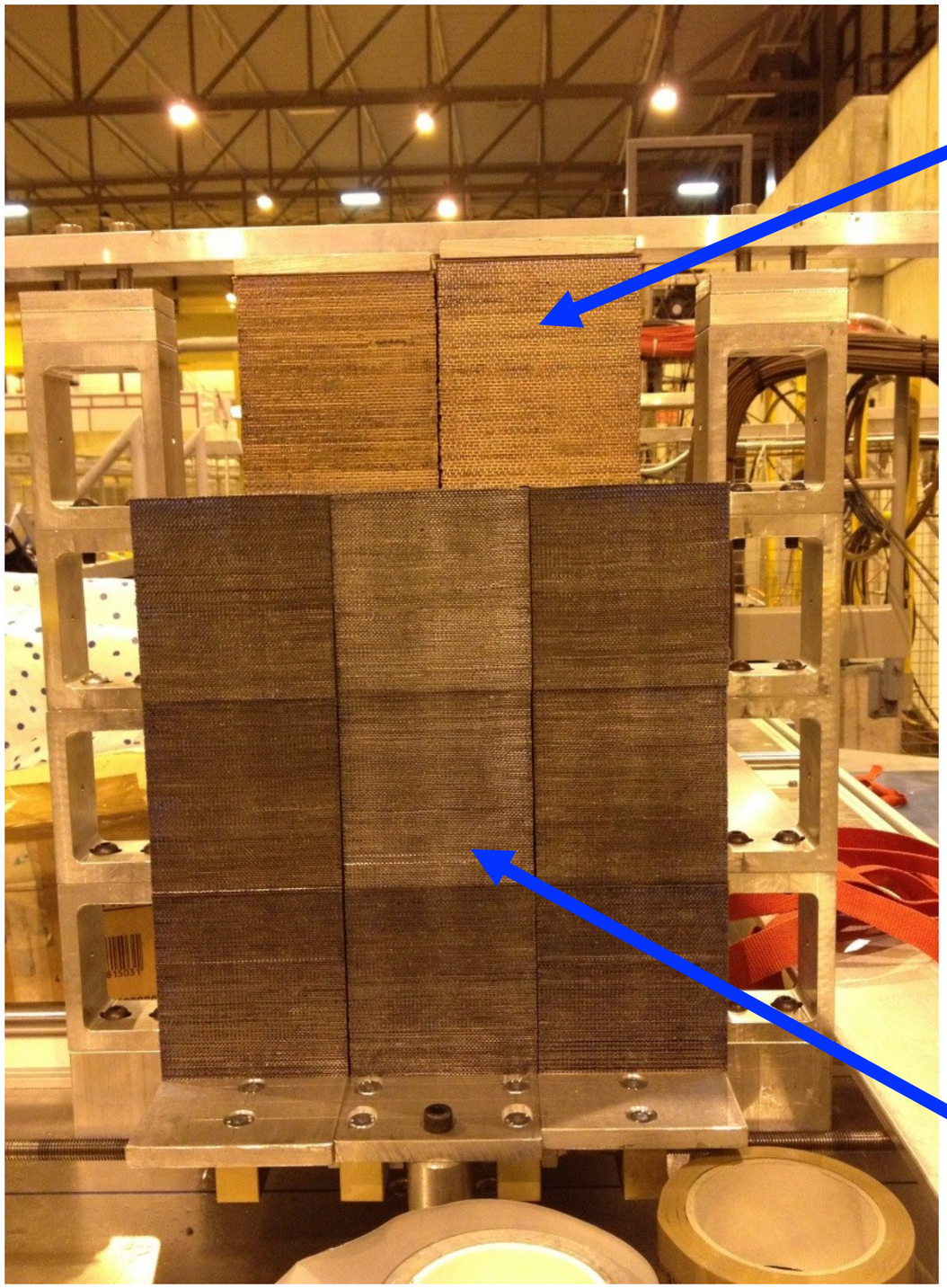




2012
RD52

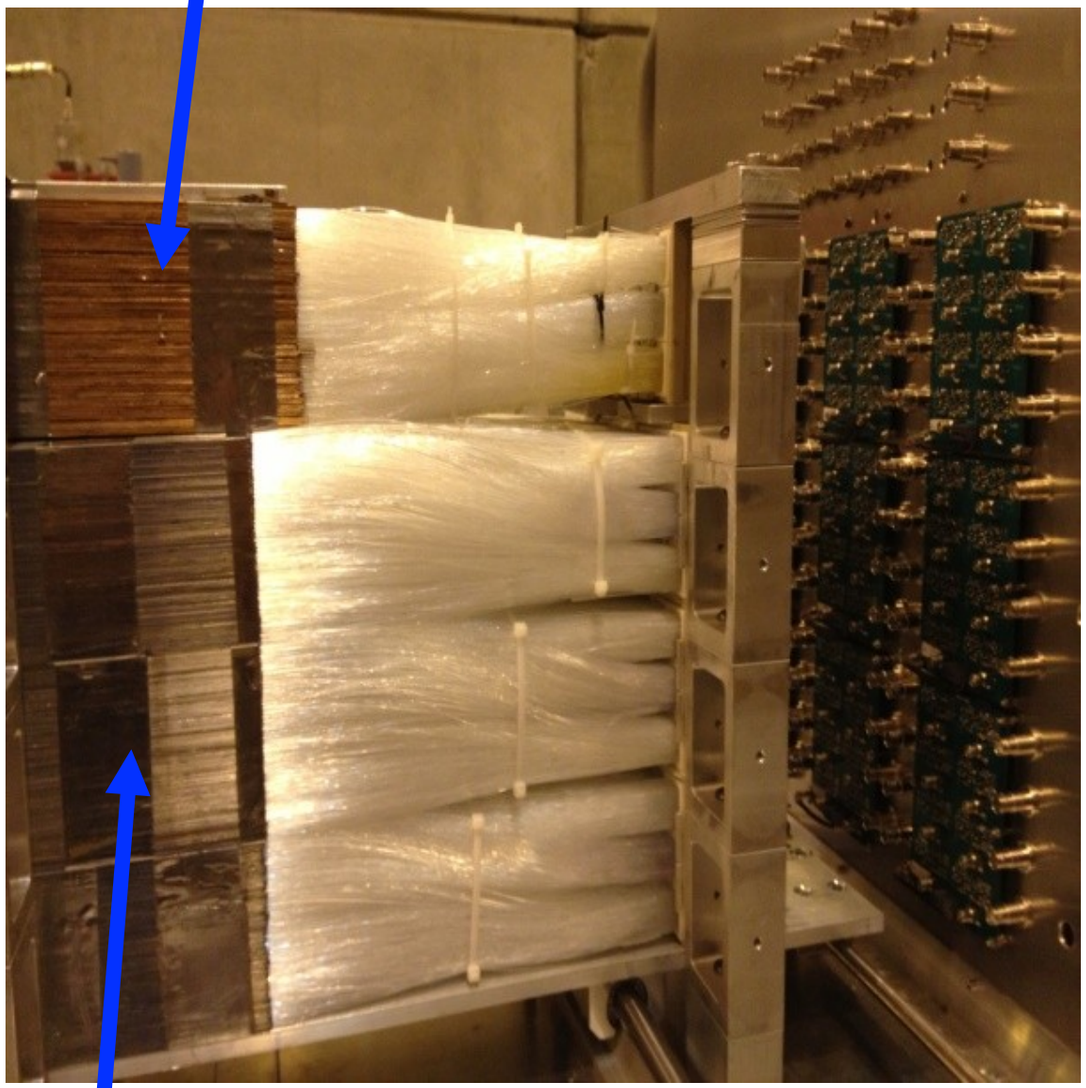
Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm$^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 $\lambda_{int}$




# RD52 dual-readout fibre calorimeters

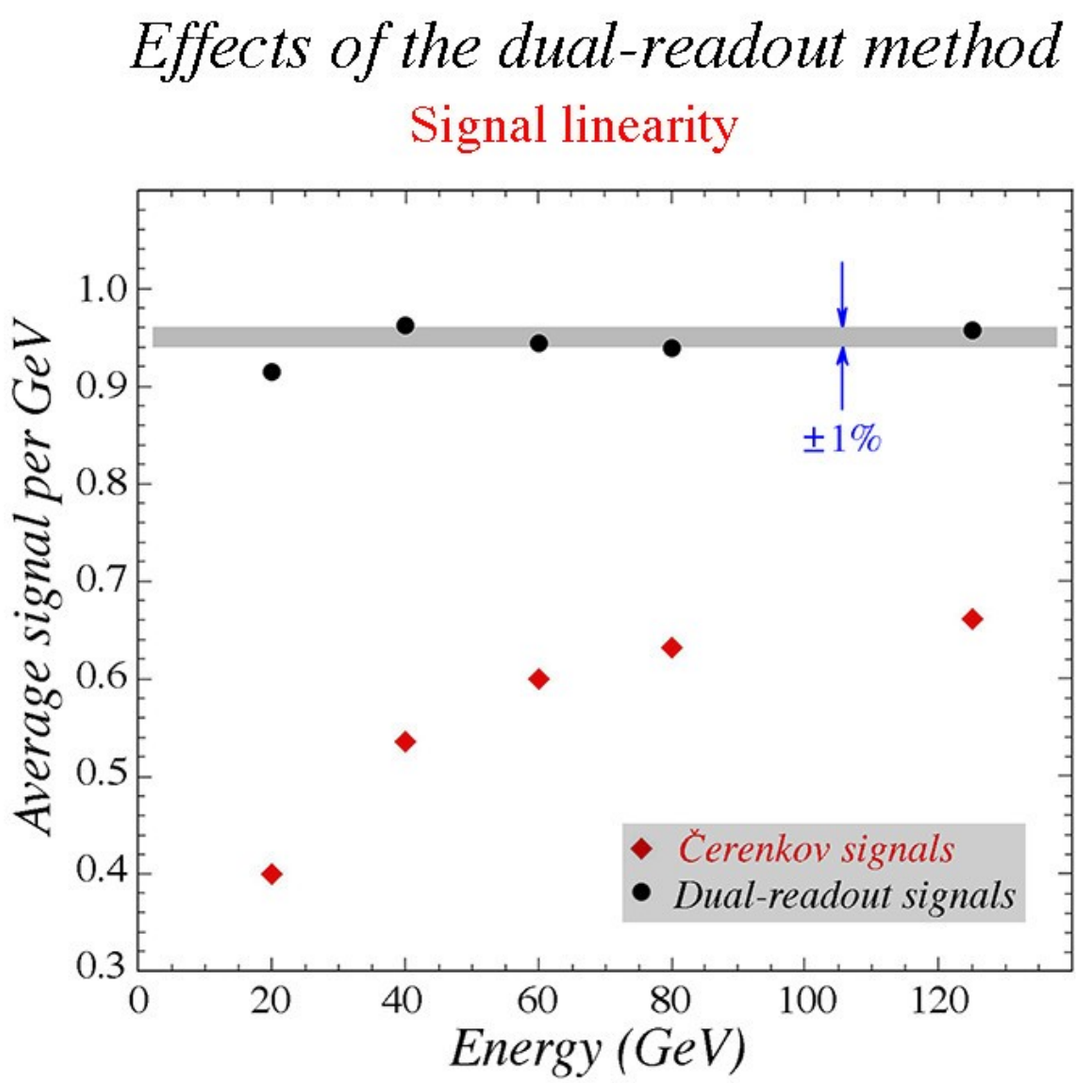


**2 Cu modules**

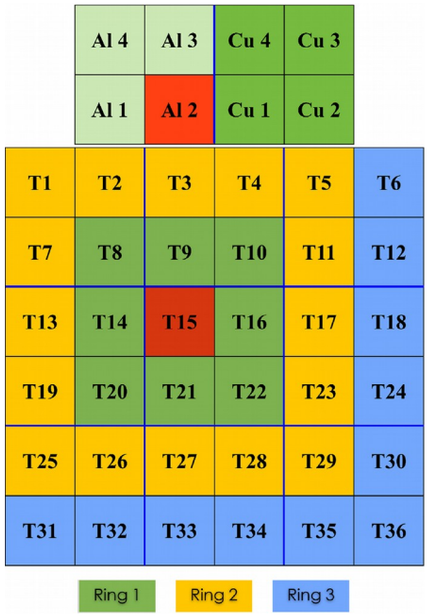


**Pb 3*3 matrix**

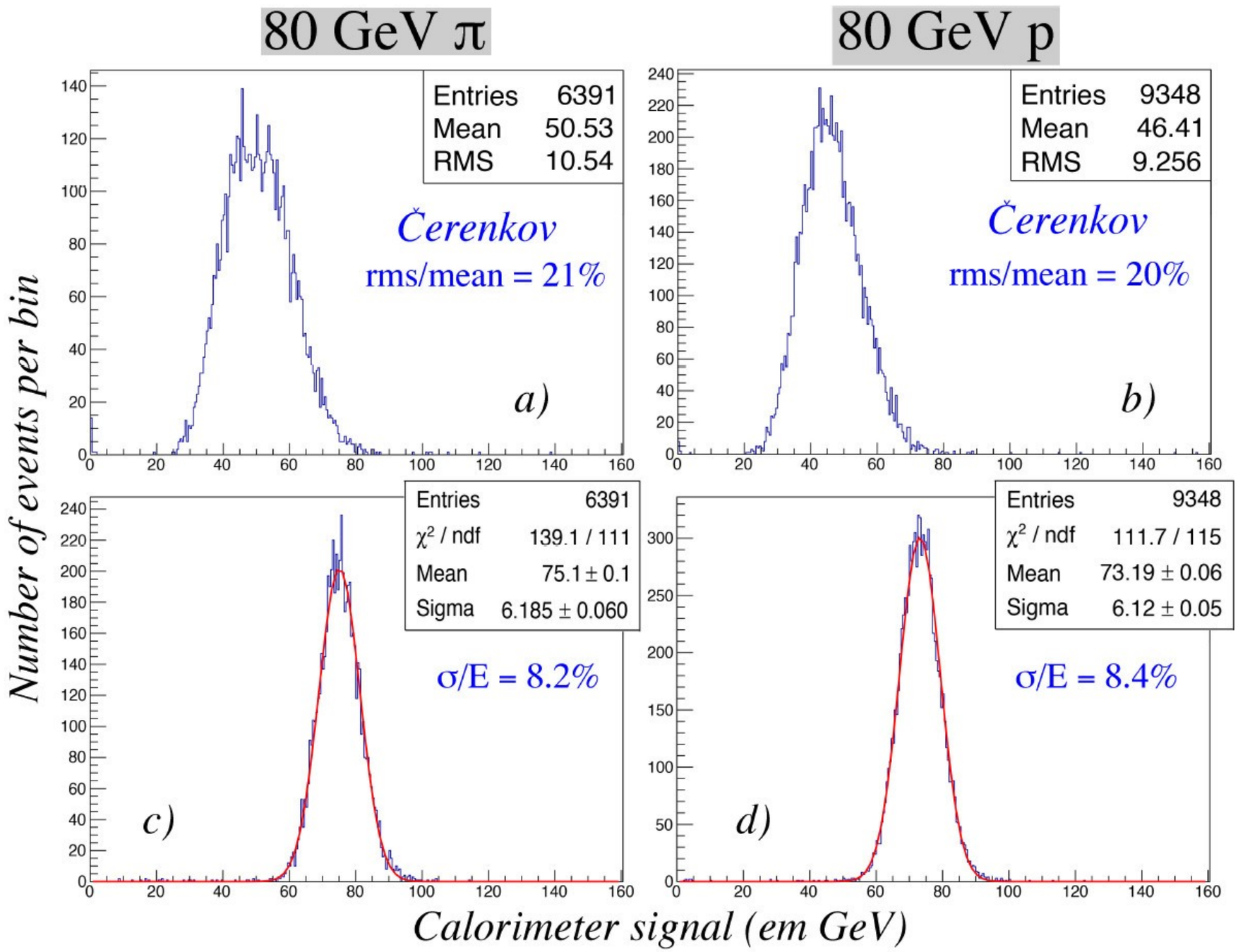
# d.r. at work (2)


Effects of the dual-readout method
Signal linearity
Average signal per GeV
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
±1%
Čerenkov signals
Dual-readout signals
0
20
40
60
80
100
120
Energy (GeV)

# d.r. at work (3)



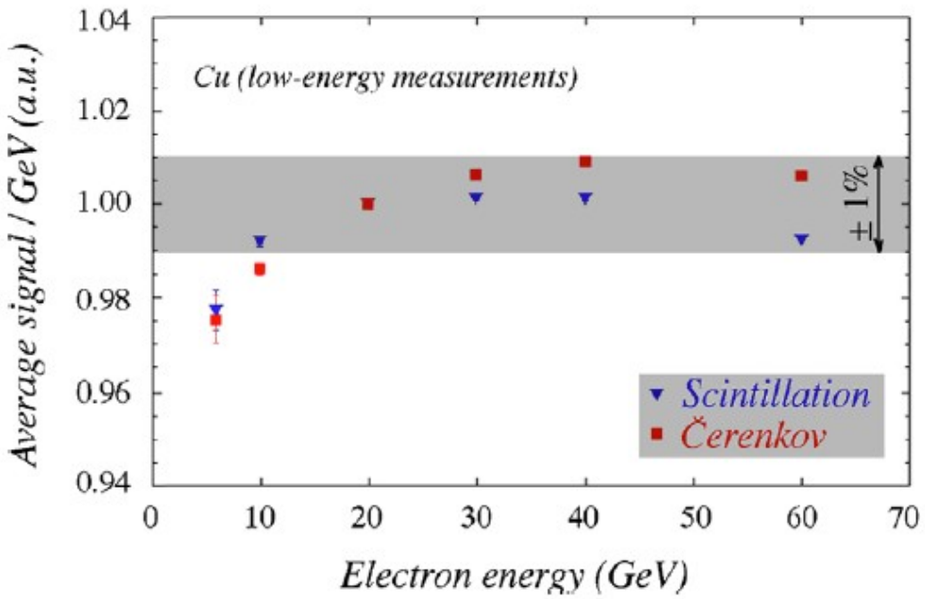

*NIM A 866 (2017) 76*

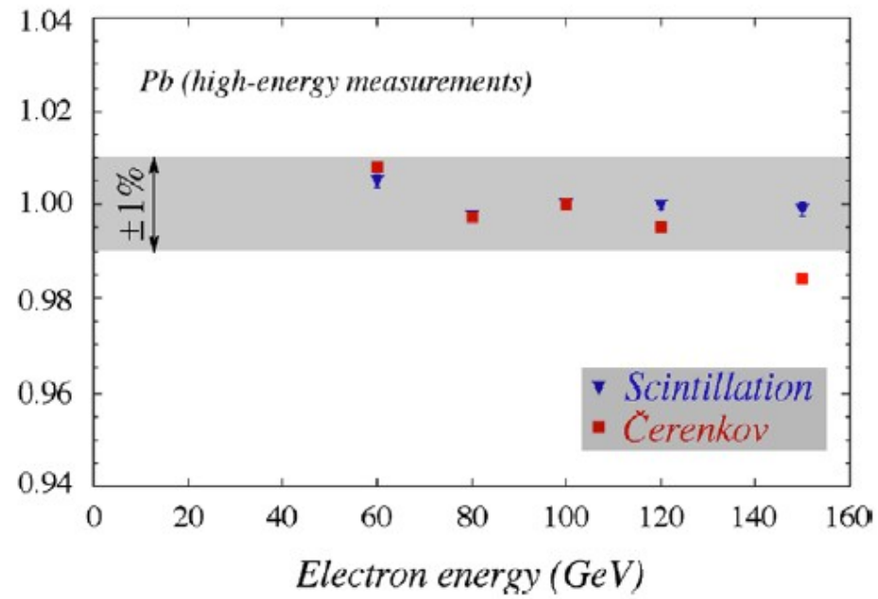


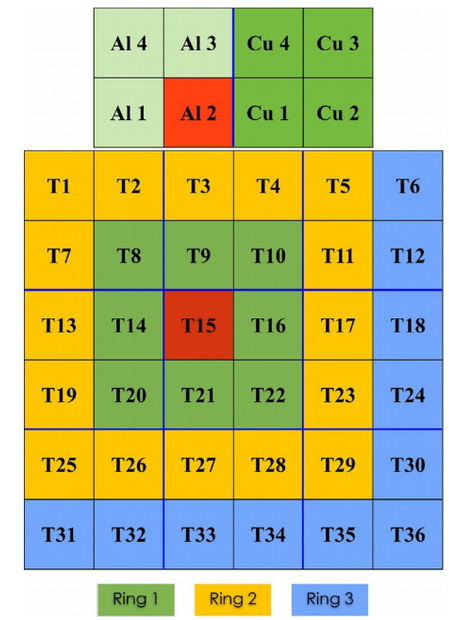
# em performance of RD52 calo.s

## Signal linearity

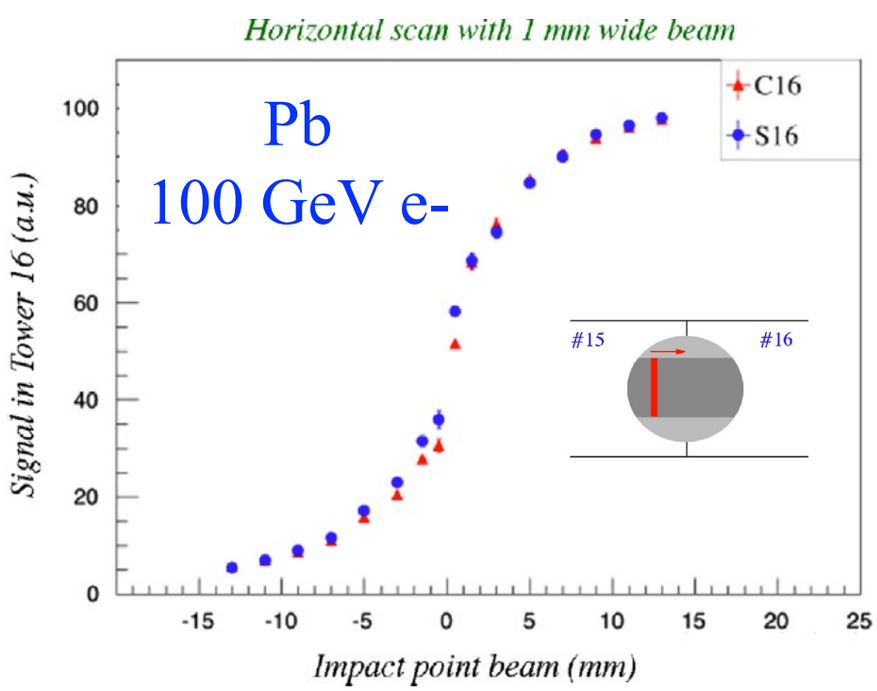
*NIM A 735 (2014) 130*

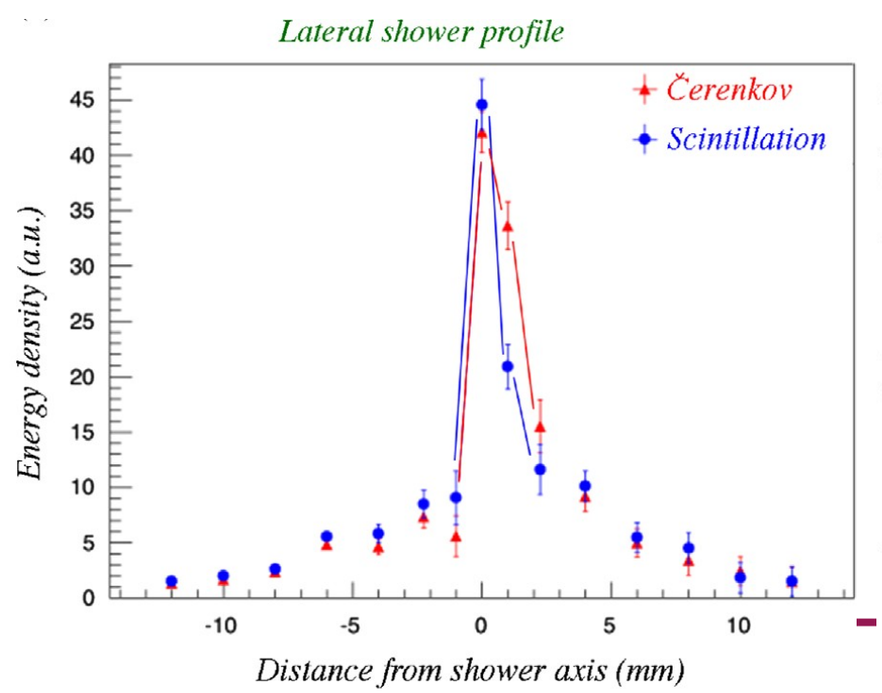


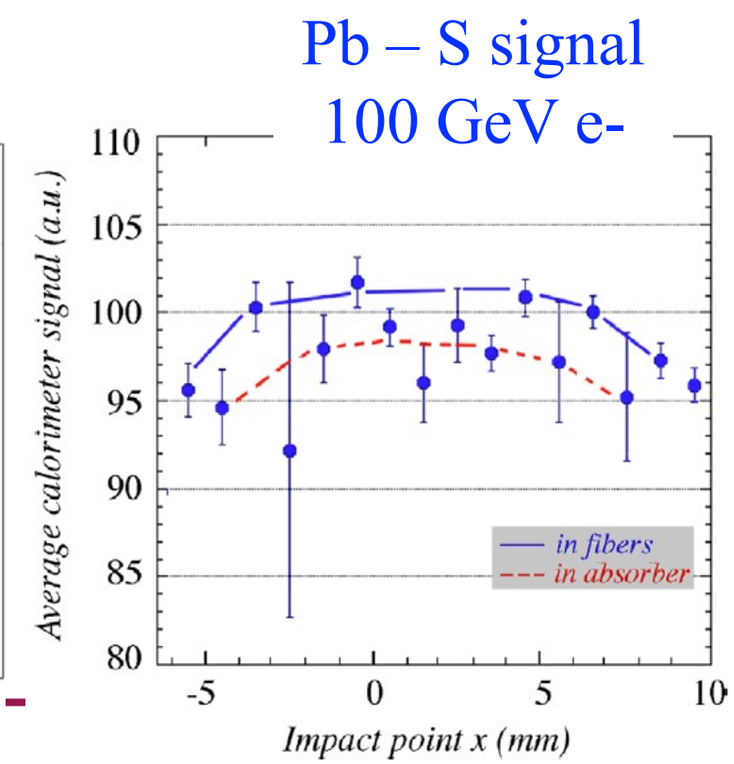




## Radial shower profile and response uniformity

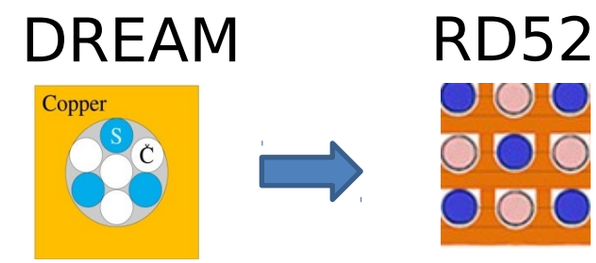


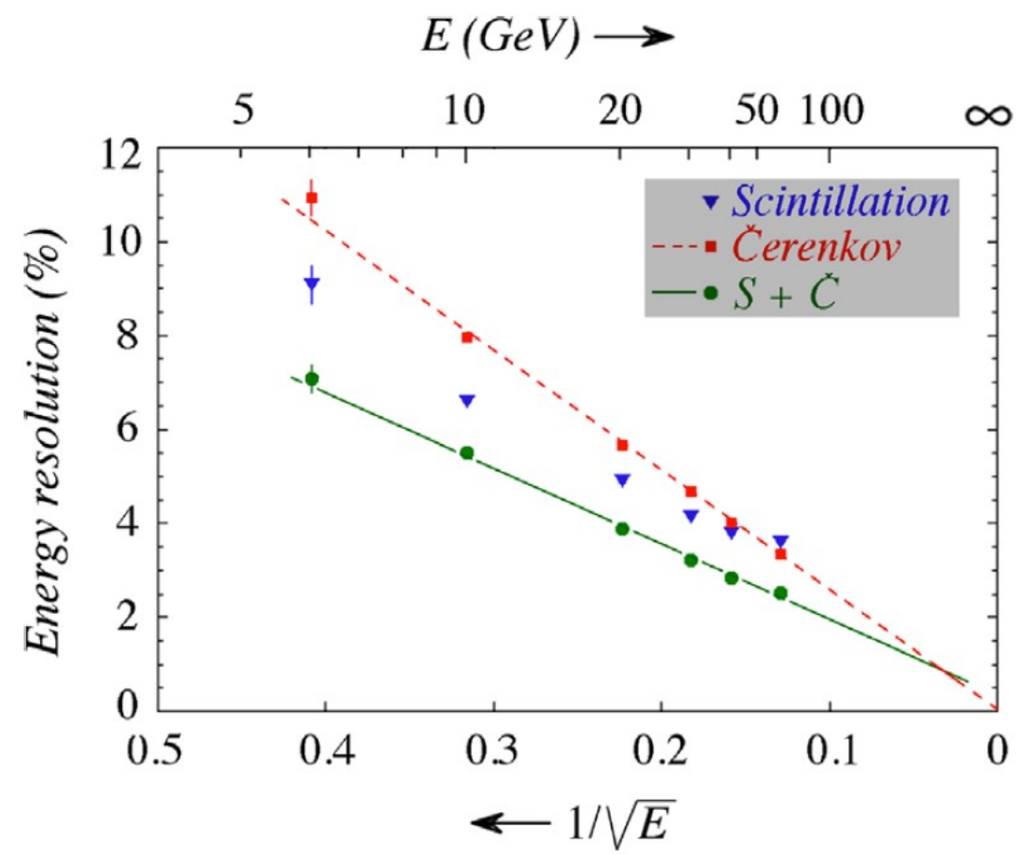
# em performance (copper)

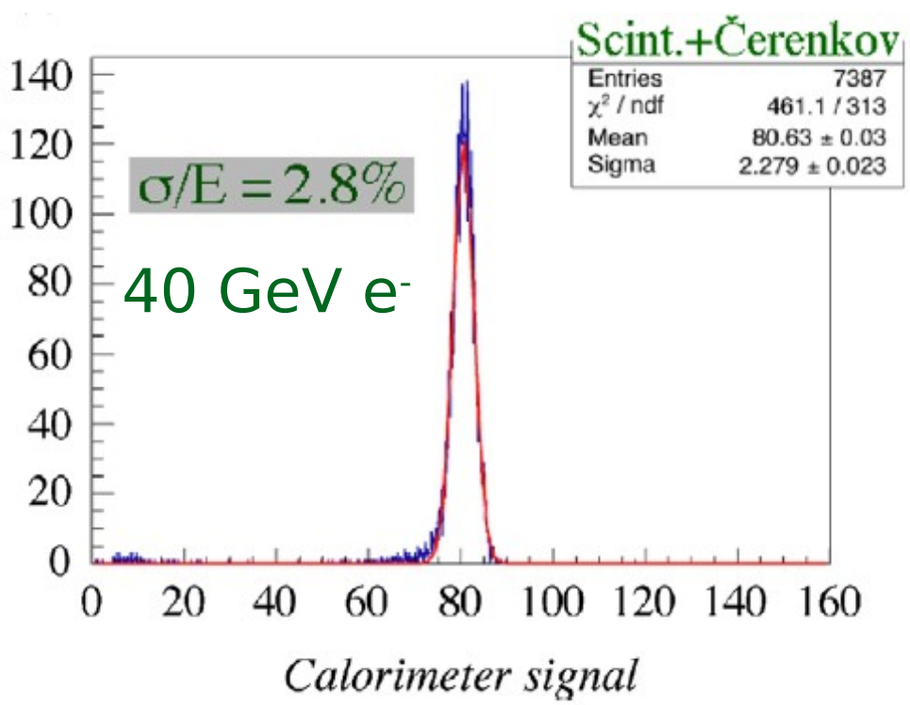
Č and S provide independent shower sampling → combine signals




*NIM A 735 (2014) 130*

→ improvement in resolution (doubled sampling fraction)



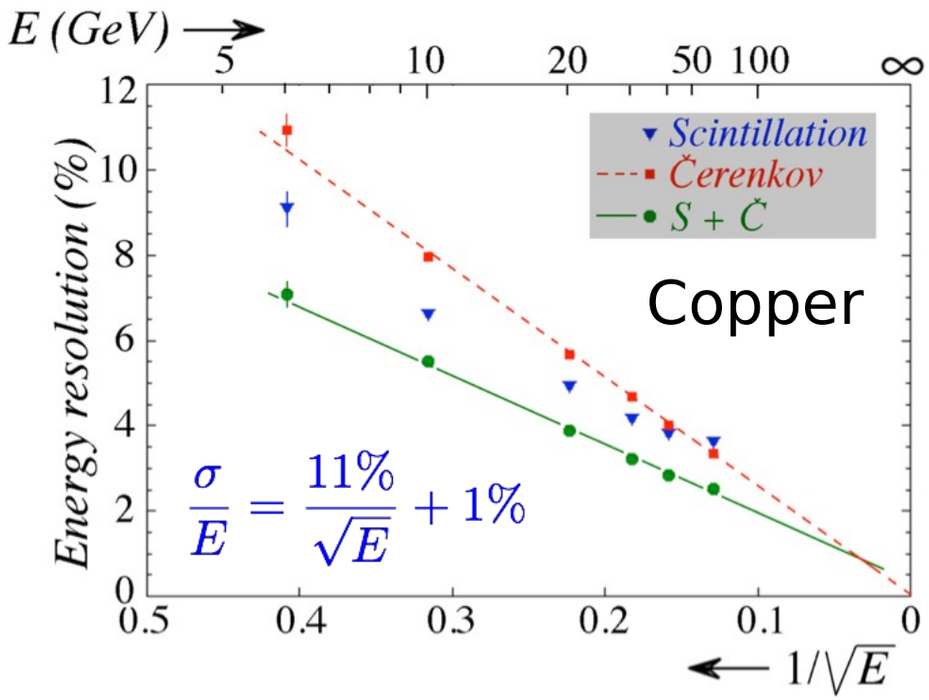



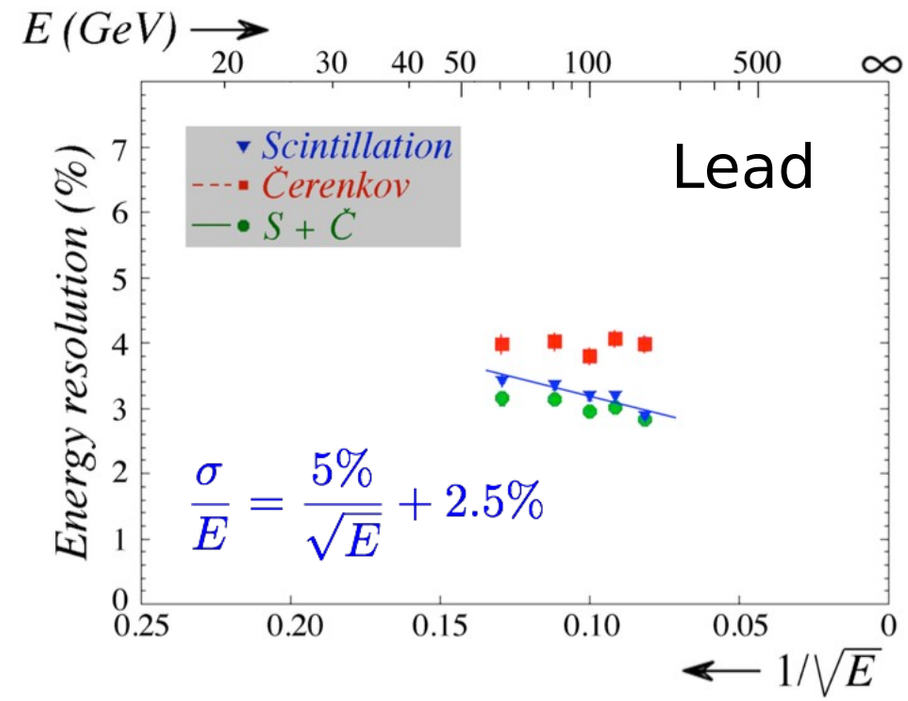

Constant term due to fluctuations in interaction point (only S). Disappears for larger angles

# em resolution

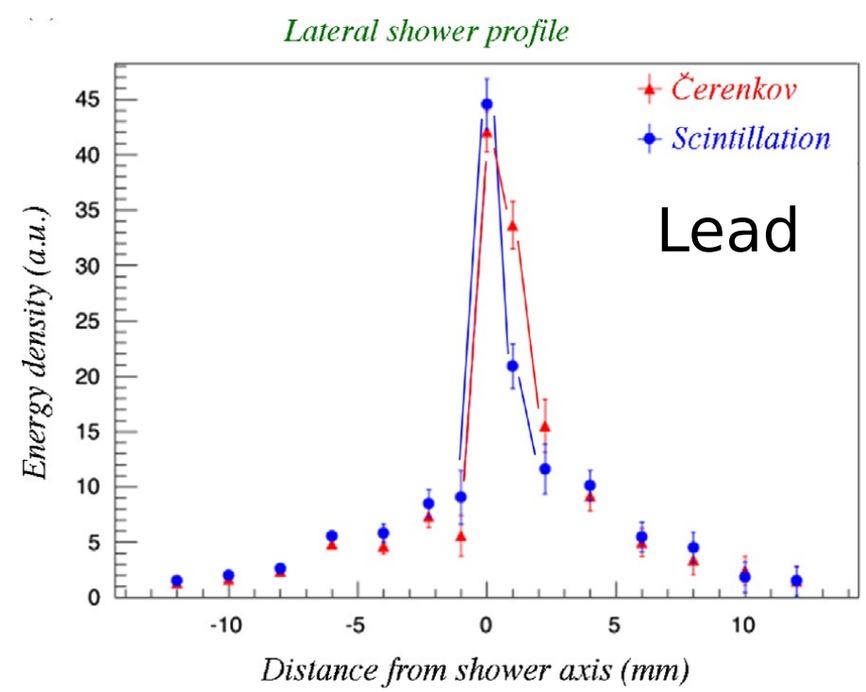
Electromagnetic Resolution

*~ 1% at 100 GeV*




~ 2 GeV resolution on $m_H$ in the γγ channel



# resolution parametrisation

Normally factorised into either 3 uncorrelated terms :

$$\sigma/E = a/\sqrt{E} \oplus b \oplus c/E$$

or assuming some correlation between first two terms :

$$\sigma/E = a/\sqrt{E} + b \oplus c/E$$

where :

a → stochastic term
b → constant term
(containment, cracks, non-uniformity, non-compensation … )
c → electronic noise

but more precise breakdowns are possible

for example lateral containment is better described by a $E^{-1/4}$ term

# resolution relevance ?

Few examples for next future (other than missing energy) :

invariant mass resolution :

$H \rightarrow \gamma\gamma$

→ both energy and spatial (angular) resolution of em calo

invariant mass resolution :

$H, Z \rightarrow \tau\tau$ (followed by $\tau \rightarrow \rho\nu$, $\rho \rightarrow \pi^{\pm}\pi^{0}$)
$H, Z, W \rightarrow jj$

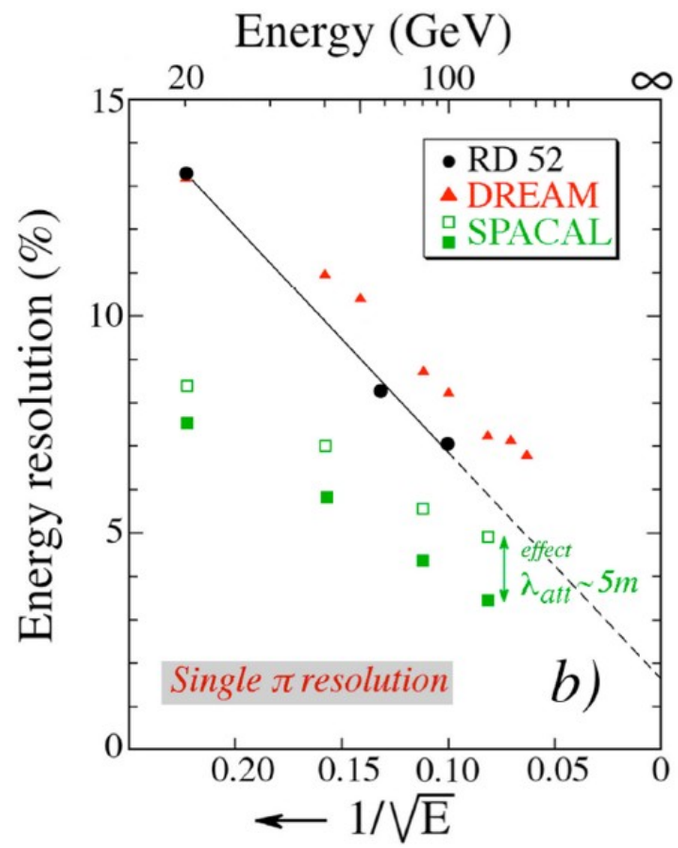
→ both energy and spatial (3D ?) resolution(s)

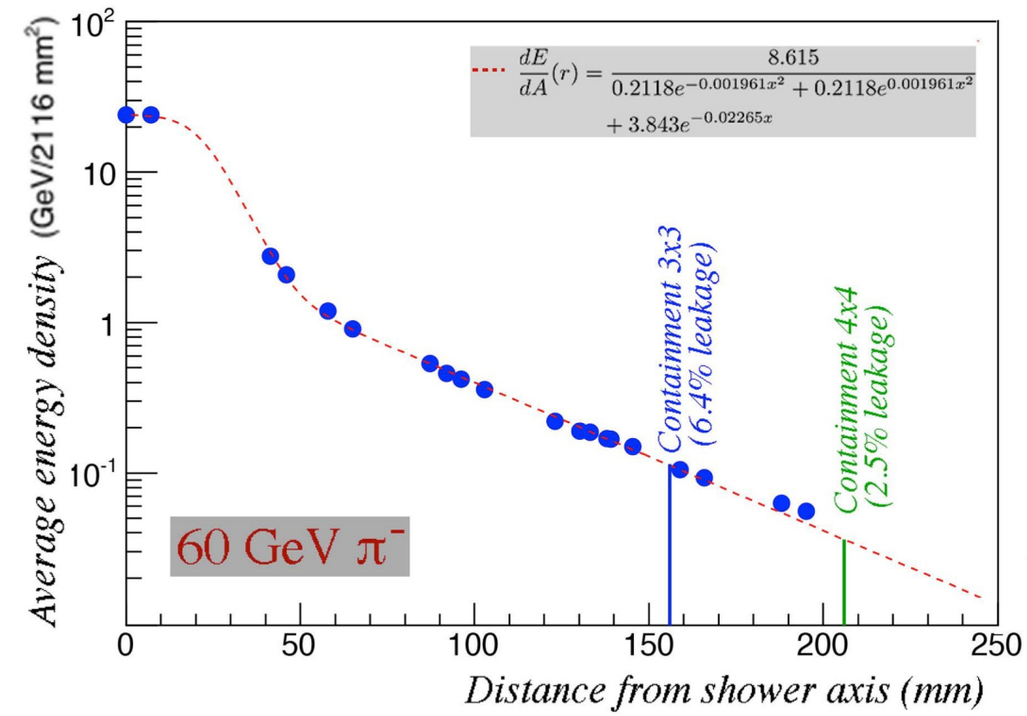
# single-particle hadronic resolution

Hadronic Resolution
(Pb Module)

$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

to be corrected for:
- light attenuation
- lateral leakage



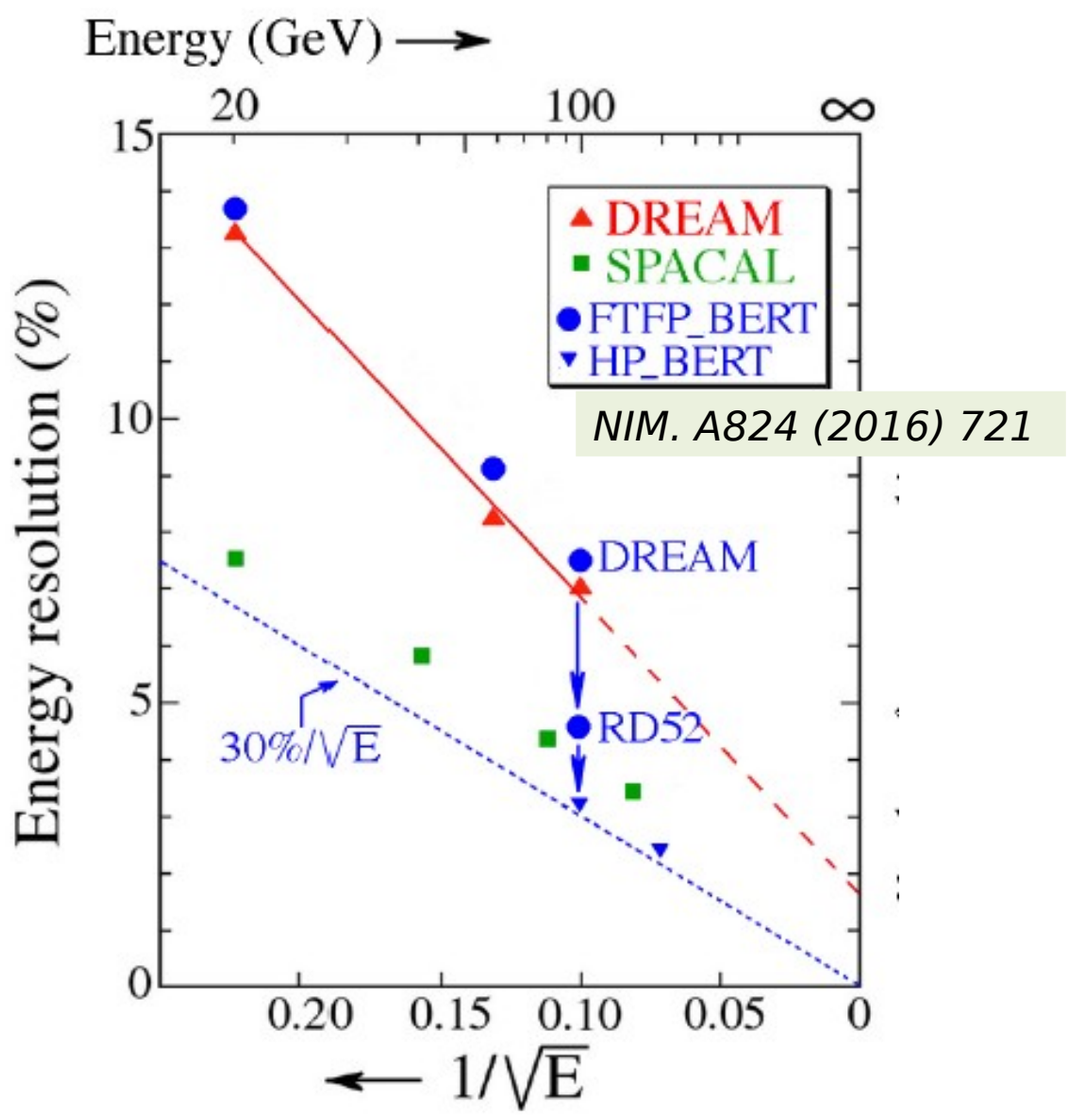

*jet energy resolution ~ few % at ~100 GeV*

*(4th Concept Detector LOI quotes 30%/√E for jets)*

*Jet resolution may improve coupled w/ tracking information (high granularity → "particle-flow")*

# Geant4 (preliminary) RD52 simulations

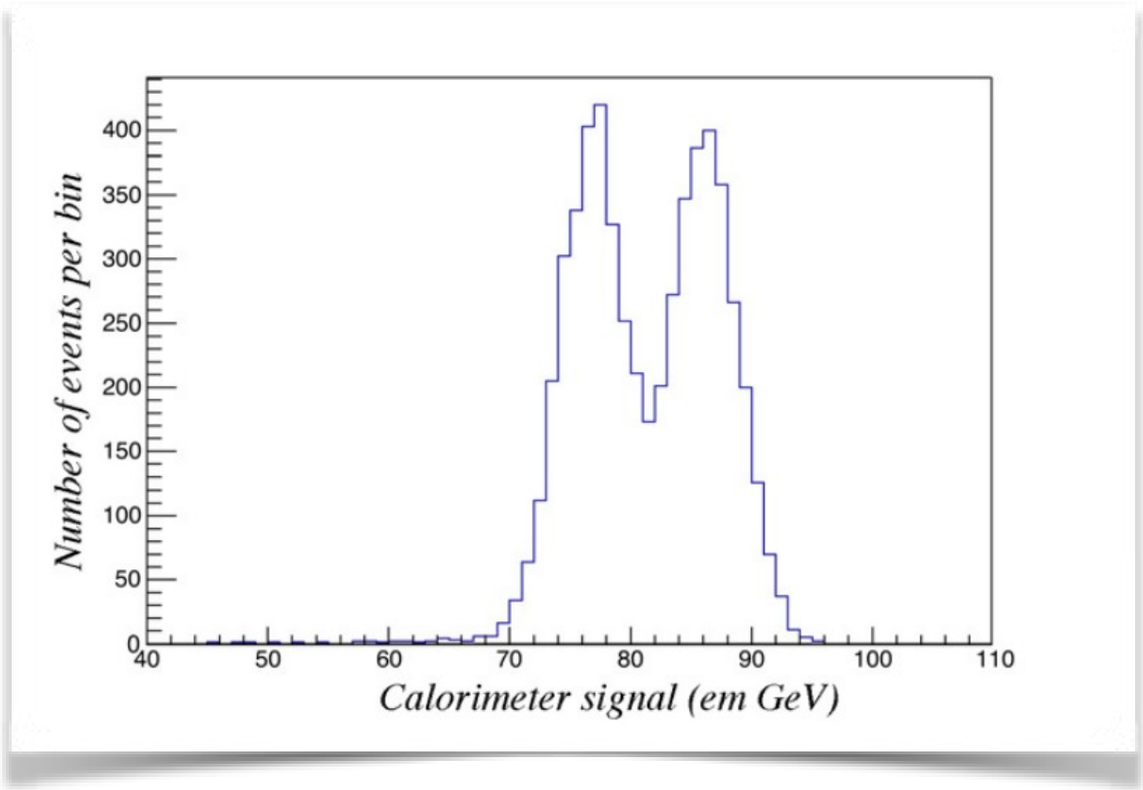
Hadronic Resolution




*NIM. A824 (2016) 721*

W/Z separation

[ H→WW / H→ZZ separation ]



# particle ID (electron/hadron separation)

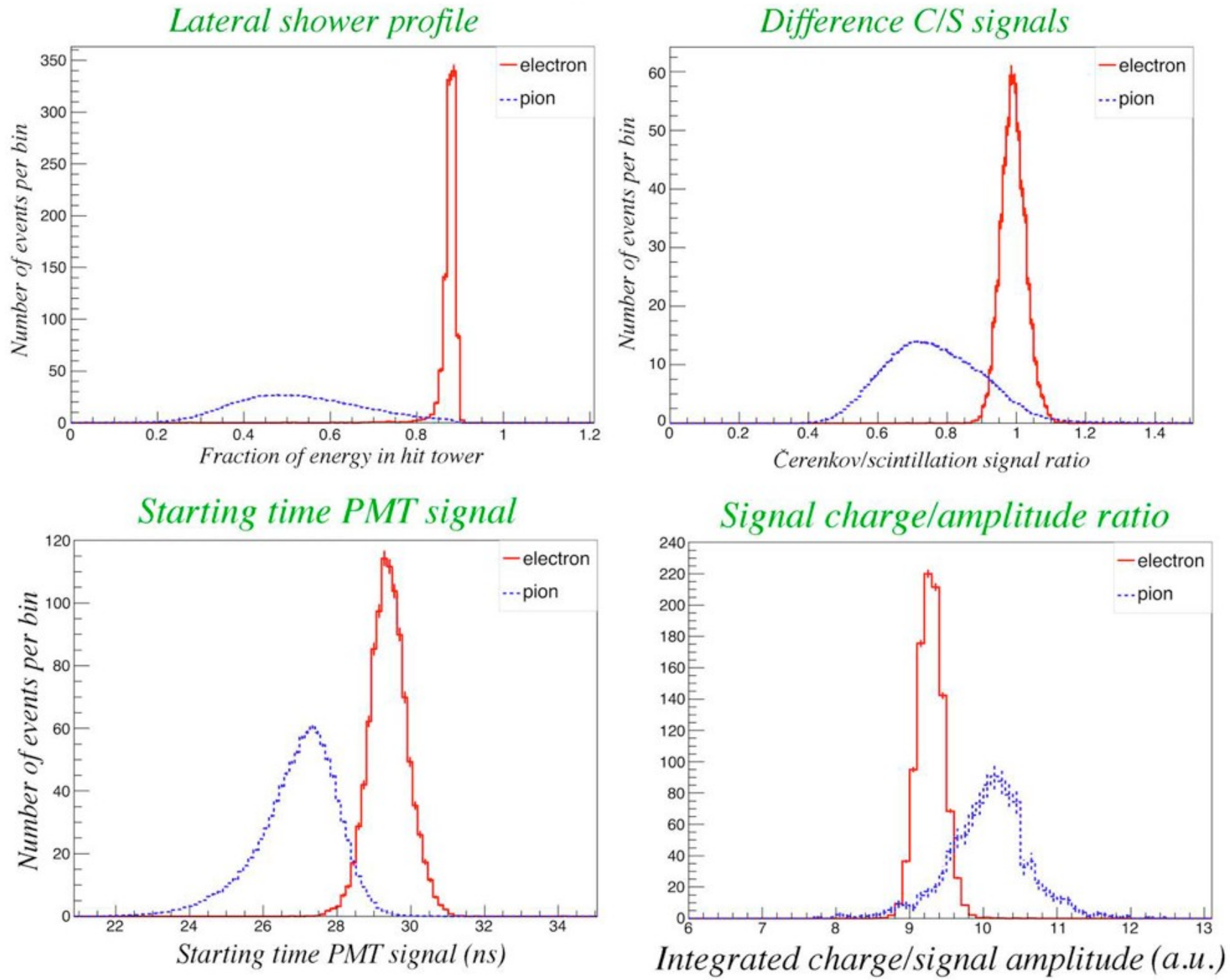
*RD52 lead calorimeter*

(60 GeV) $e^-$ vs. $\pi^-$

$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

*NIM A 735 (2014) 120*

*Methods to distinguish e/π in longitudinally unsegmented calorimeter*



# copper vs. lead

lead will have :

a) +60% in detector mass

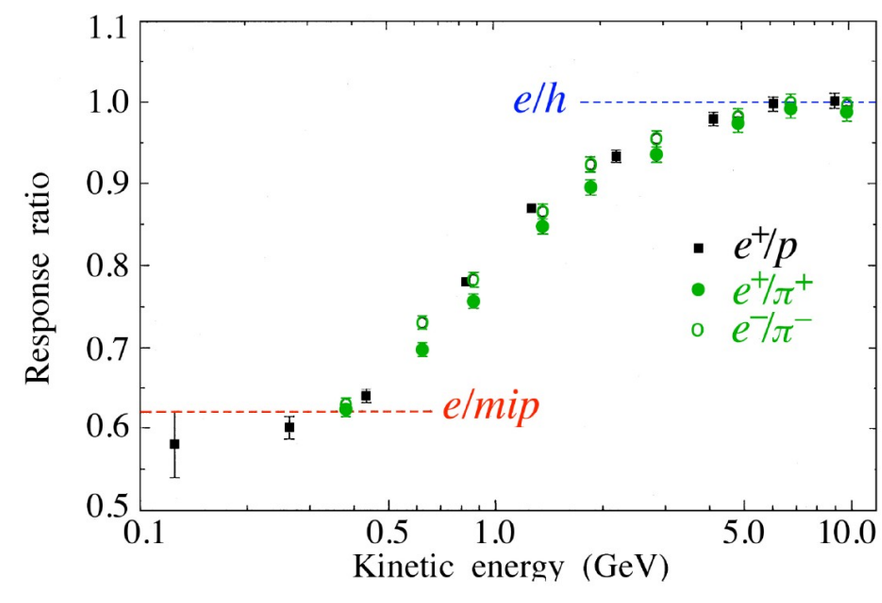
b) lower e/mip ratio :

→ lower Cherenkov light yield

→ loss of linearity for jets

e/mip :

~ 0.6 for lead
~ 0.9 for copper



# e/mip ratio

mip : minimum ionising particle → only ionisation

dE/dx (mip) :

lead ~ 12.6 MeV/cm → 7.15 MeV /$X_0$

copper ~ 12.7 MeV/cm → 18.0 MeV/$X_0$

( PMMA ~ 2.3 MeV/cm → 78.2 MeV/$X_0$ )

Moreover in high-Z absorbers :

$Z^5$ dependence of photoelectric effect

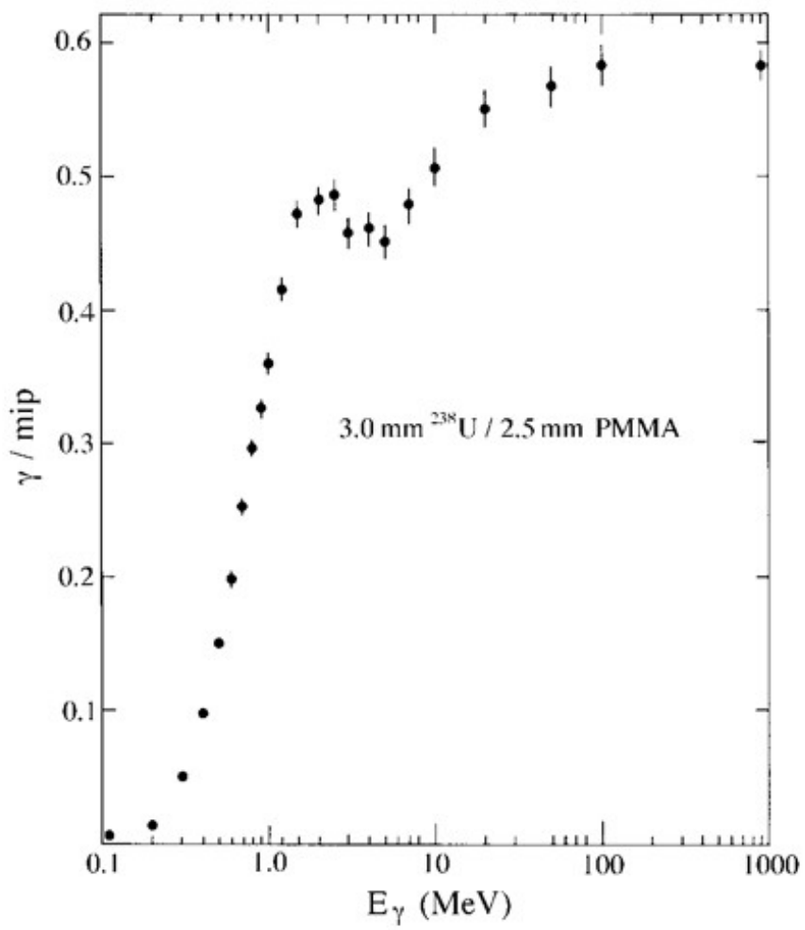
→ most soft-γ interact in absorber

photoelectrons have very short range

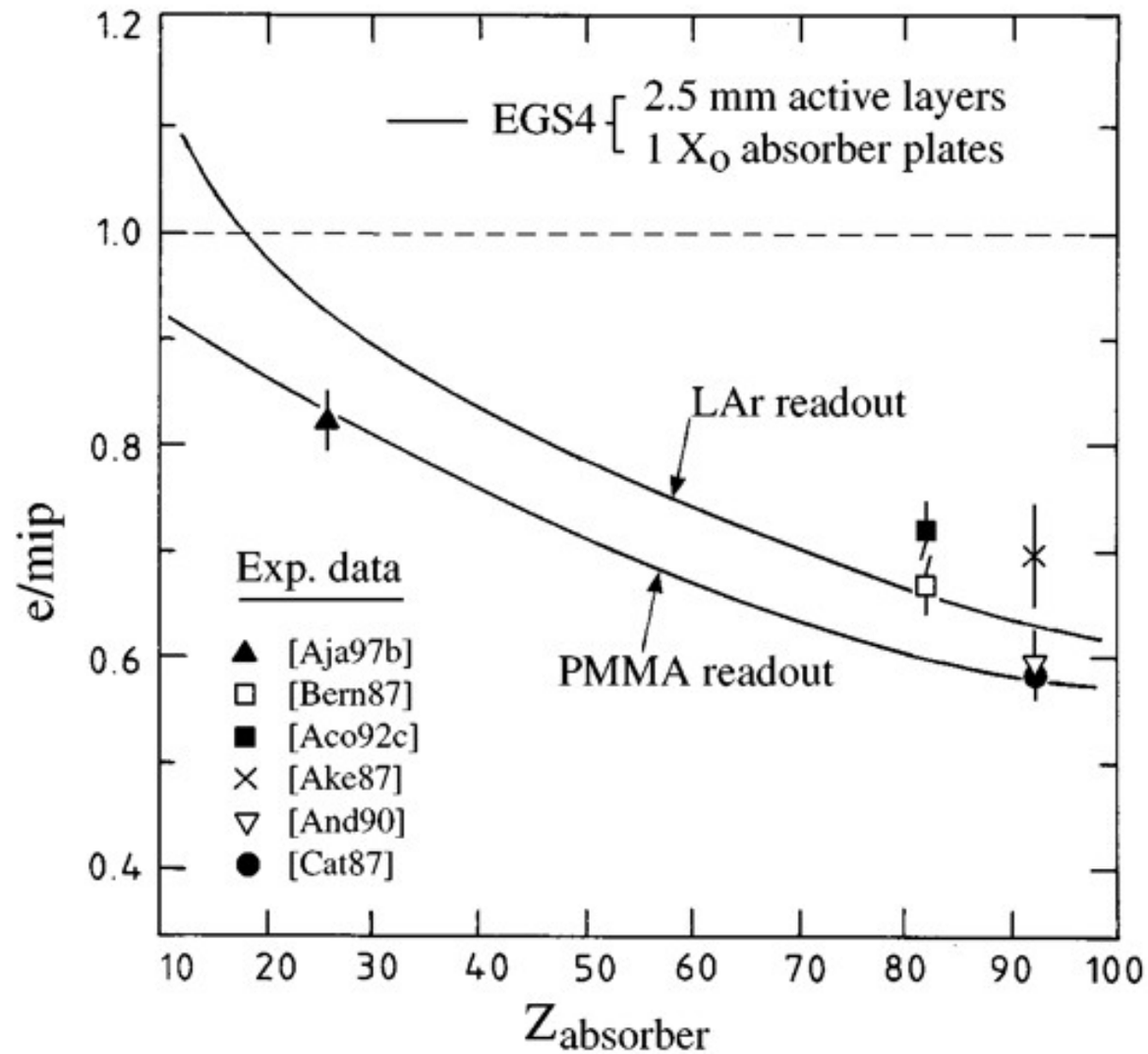
→ will contribute to signal only close to boundaries

→ *response to em showers suppressed wrt. mips*

# e/mip ratio

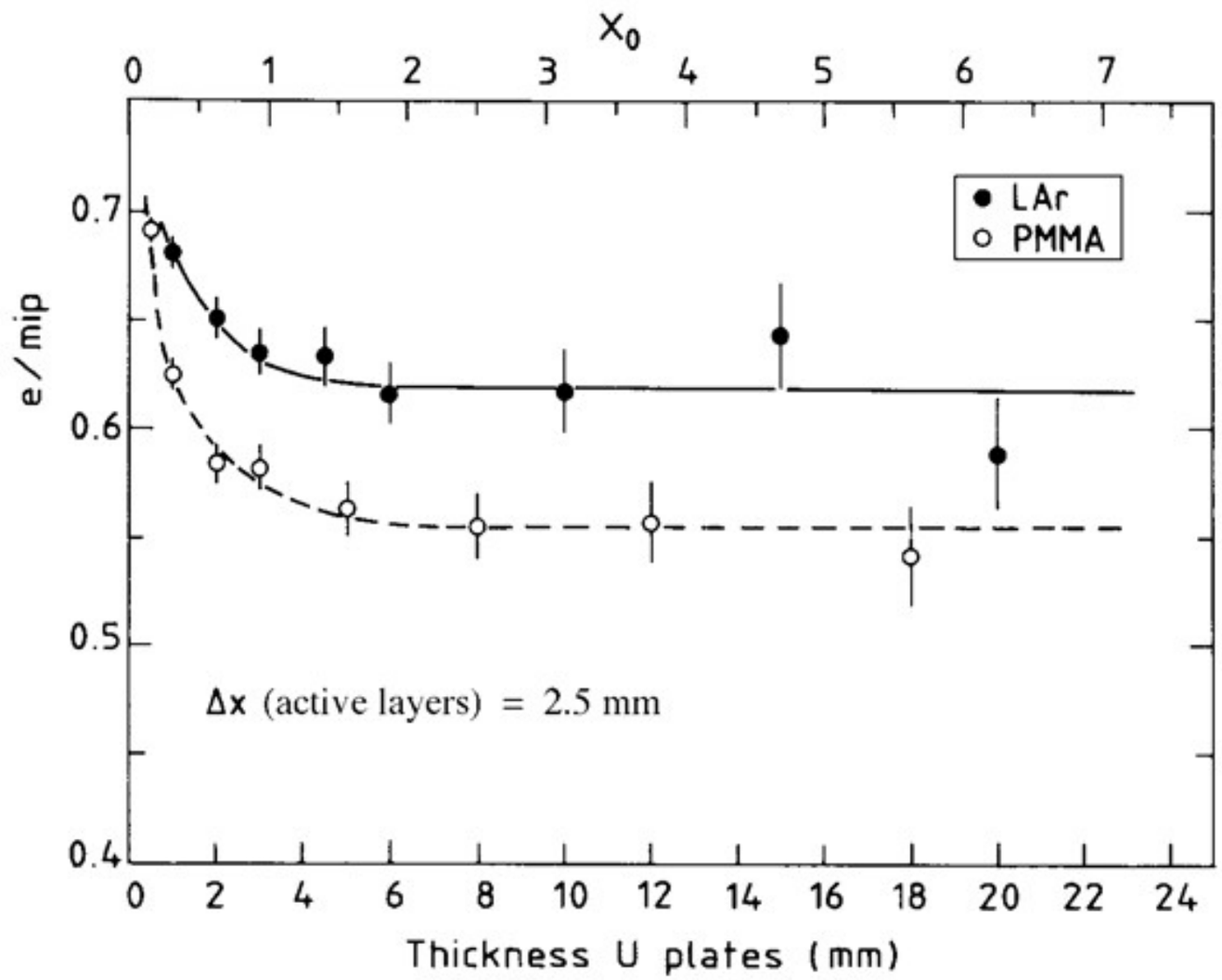



γ/mip ratio for
U (3 mm) / PMMA (2.5 mm)
sampling calorimeter




e/mip ratio with Z

# e/mip ratio




e/mip ratio as a function of absorber (U) plate thickness

# mip sampling fraction

analytically calculable … mip <dE/dx> values tabulated

e.g.:

LAr (2.5 mm depth) + U (3 mm depth)

LAr <dE/dx> = 2.105 MeV/cm

$2.105 \times 2.5 = 5.262$ MeV

U <dE/dx> = 20.49 MeV/cm

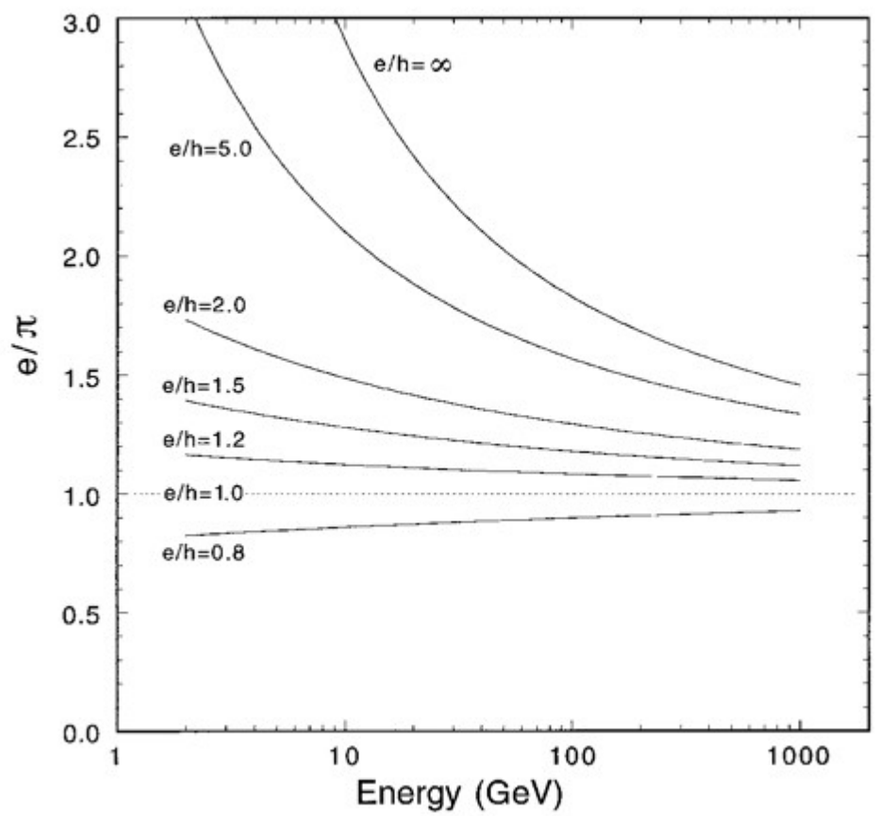
$20.49 \times 3 = 61.47$ MeV

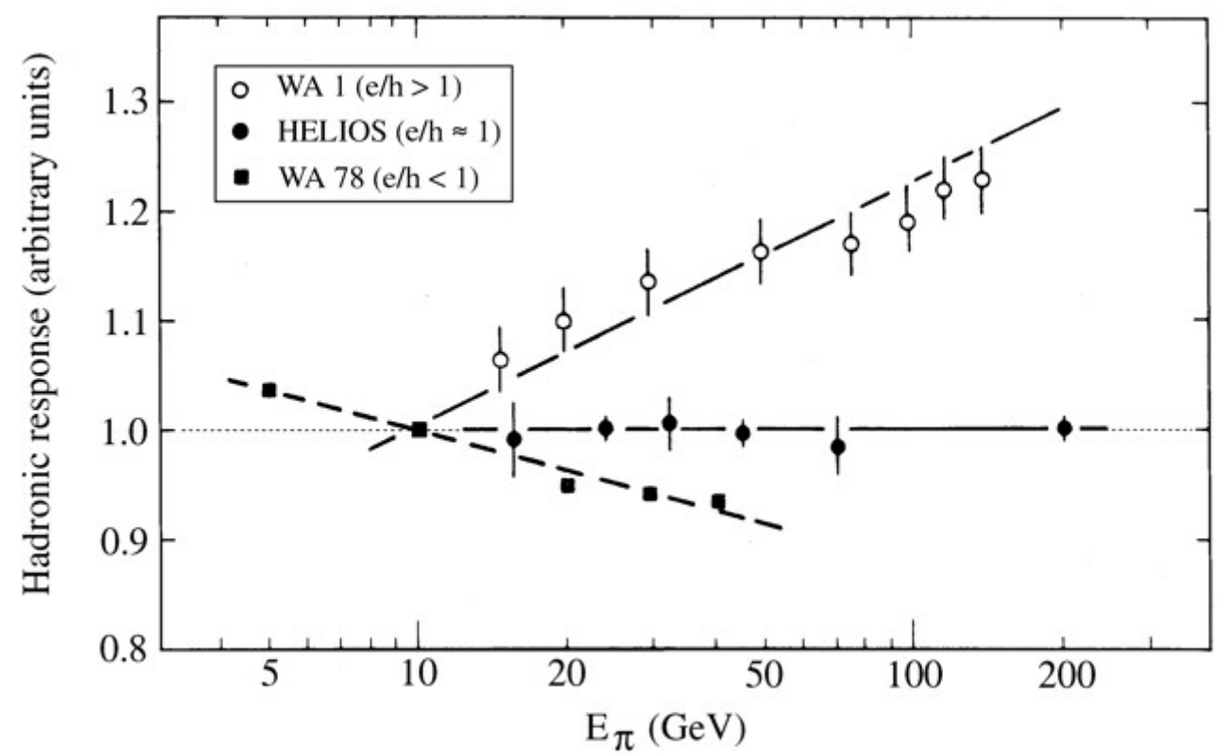
sampling fraction = 5.262 / (5.262 + 61.47) = 7.9%

# e/π ratio

calorimeter response to π : $\pi = f_{\mathrm{em}} \cdot e + (1 - f_{\mathrm{em}}) \cdot h$

$$\rightarrow \quad e/\pi = \frac{e/h}{1 - f_{\mathrm{em}}\left[1 - e/h\right]}$$

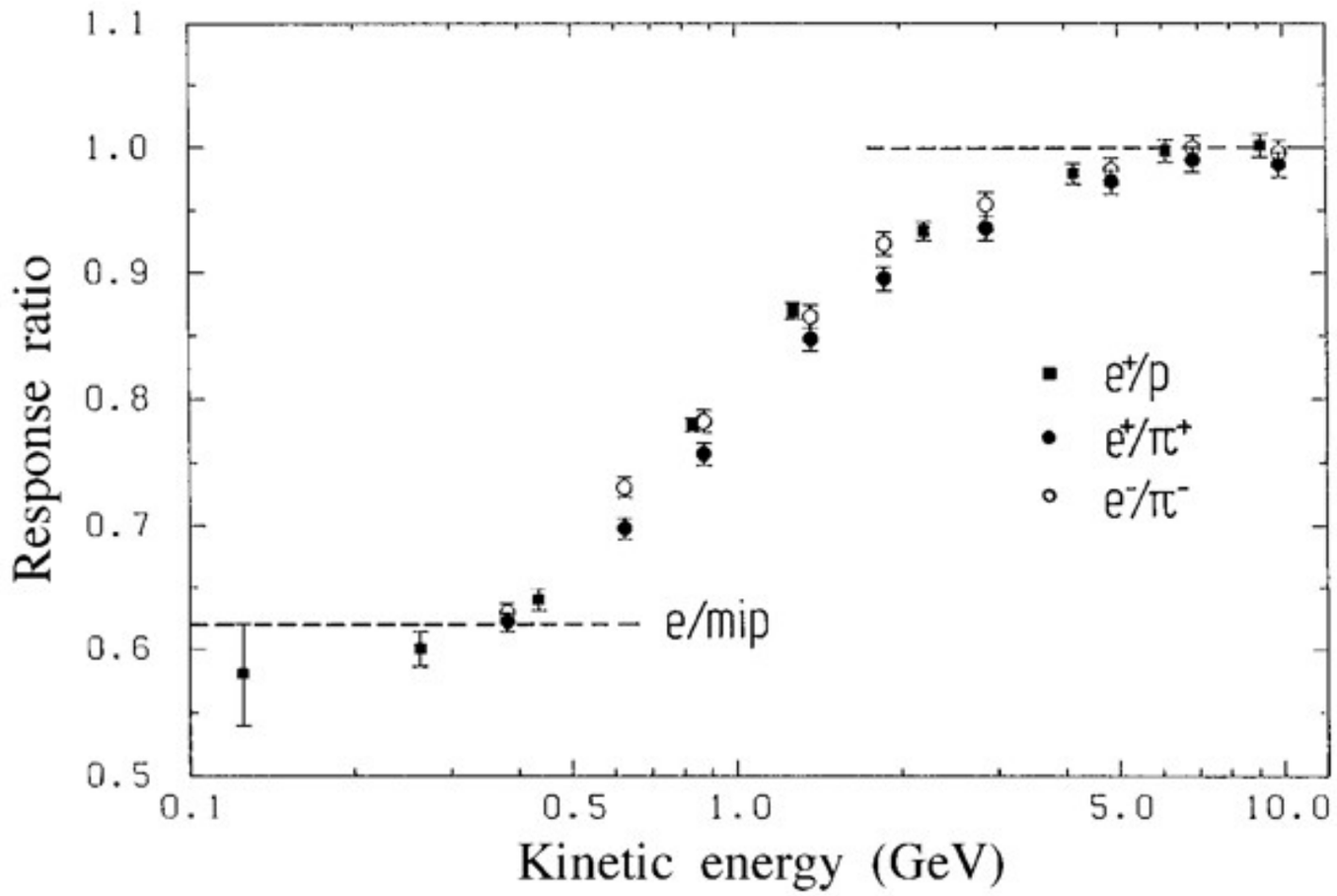



response to π as function of E

# low-energy hadrons

finally :




response of (compensating) ZEUS calorimeter to low-energy hadrons

# jets

Jets:

high-energy core
low-energy hadron tails

fluctuations among them
low-energy hadrons ~ mip.s

→ mip response must be considered

# transition to SiPM (single-fibre) readout

**SiPM + :**

- *compact readout (no fibres sticking out)*
- *longitudinal segmentation possible*
- *operation in magnetic field*
- *larger light yield (main limitation to Čerenkov signal)*
- *high readout granularity → particle flow "friendly"*
- *photon counting (calibration)*

**SiPM - :**

- *signal saturation (digital light detector)*
- *cross talk between Čerenkov and scintillation signals*
- *dynamic range*
- *instrumental effects (stability, afterpulsing, ...)*

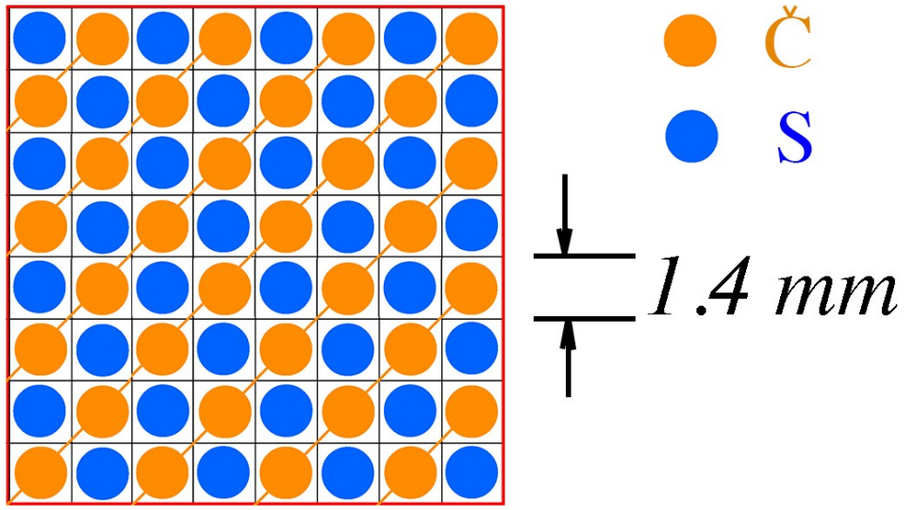
# RD52 SiPM module

*Brass module, dimensions: ~ 112 cm long, 12 x 12 mm$^2$*

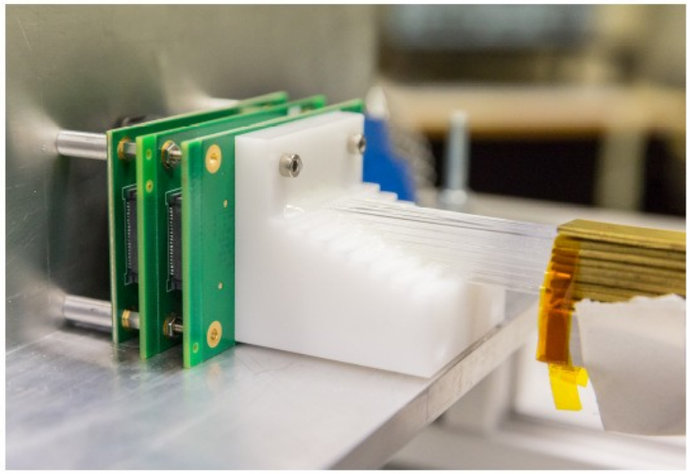
*32 (S) + 32 (Č) fibres*
*$X_0$ ~ 29 mm*
*$R_M$ ~ 31 mm*

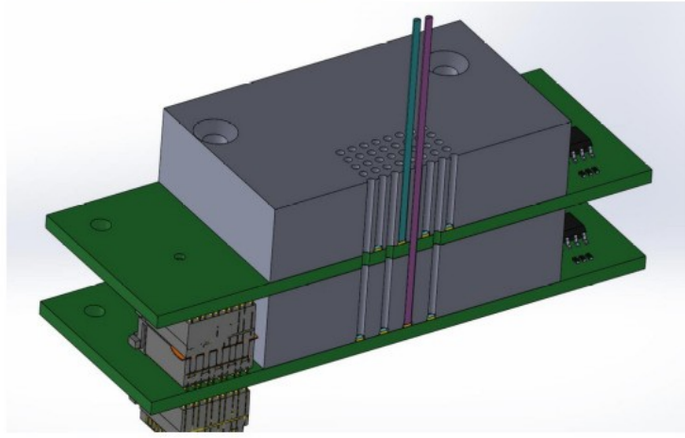
$\sim (0.4\ R_M)^2 \times 39\ X_0$

*shower cont. ~ 45%*
*$f_{sampl}$ ~ 5-6%*




*Light sensors (SiPM)*

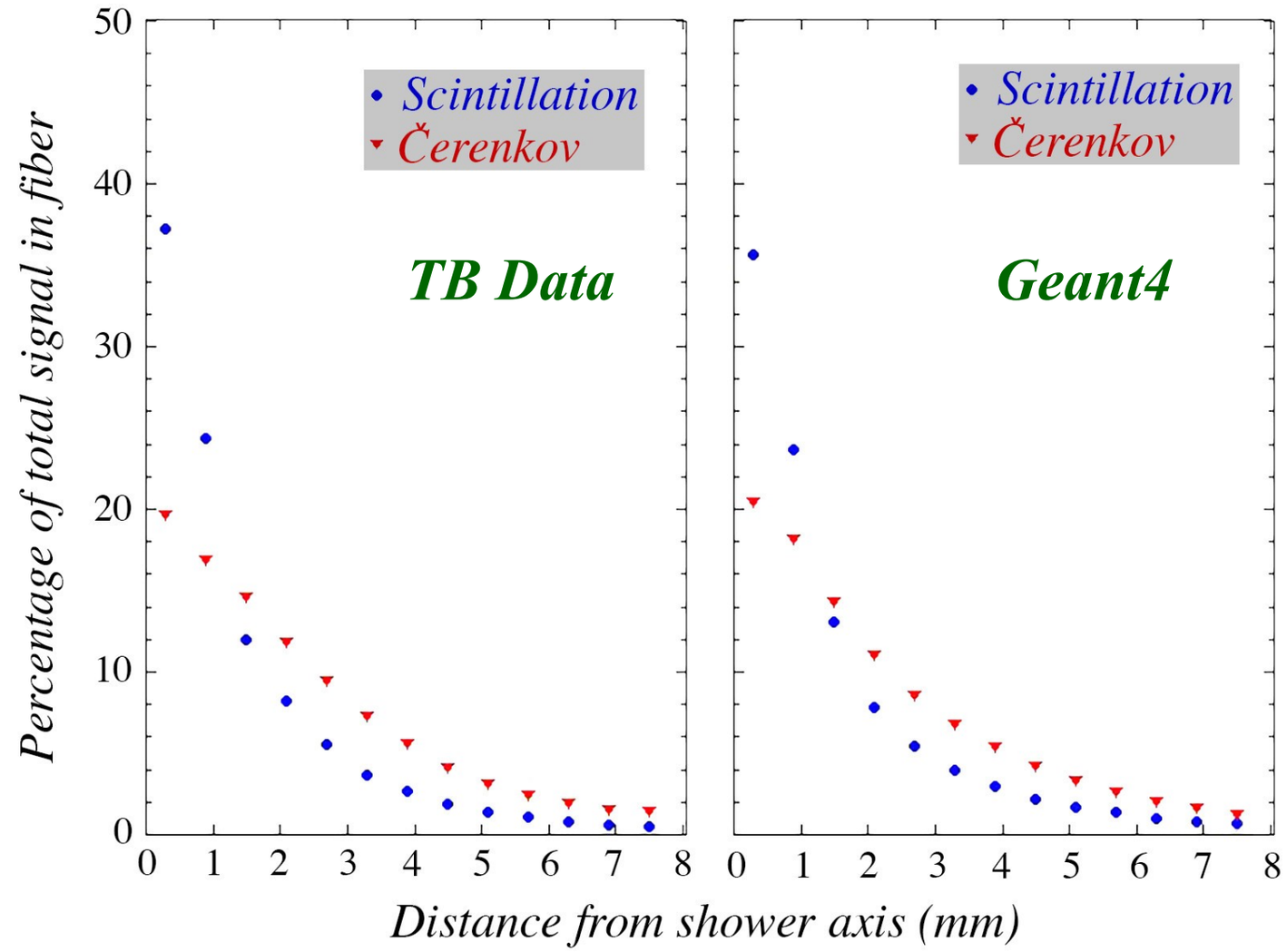




# lateral shower profile w/ SiPM

10 / 40 GeV $e^-$

$\theta, \Phi = 0°$

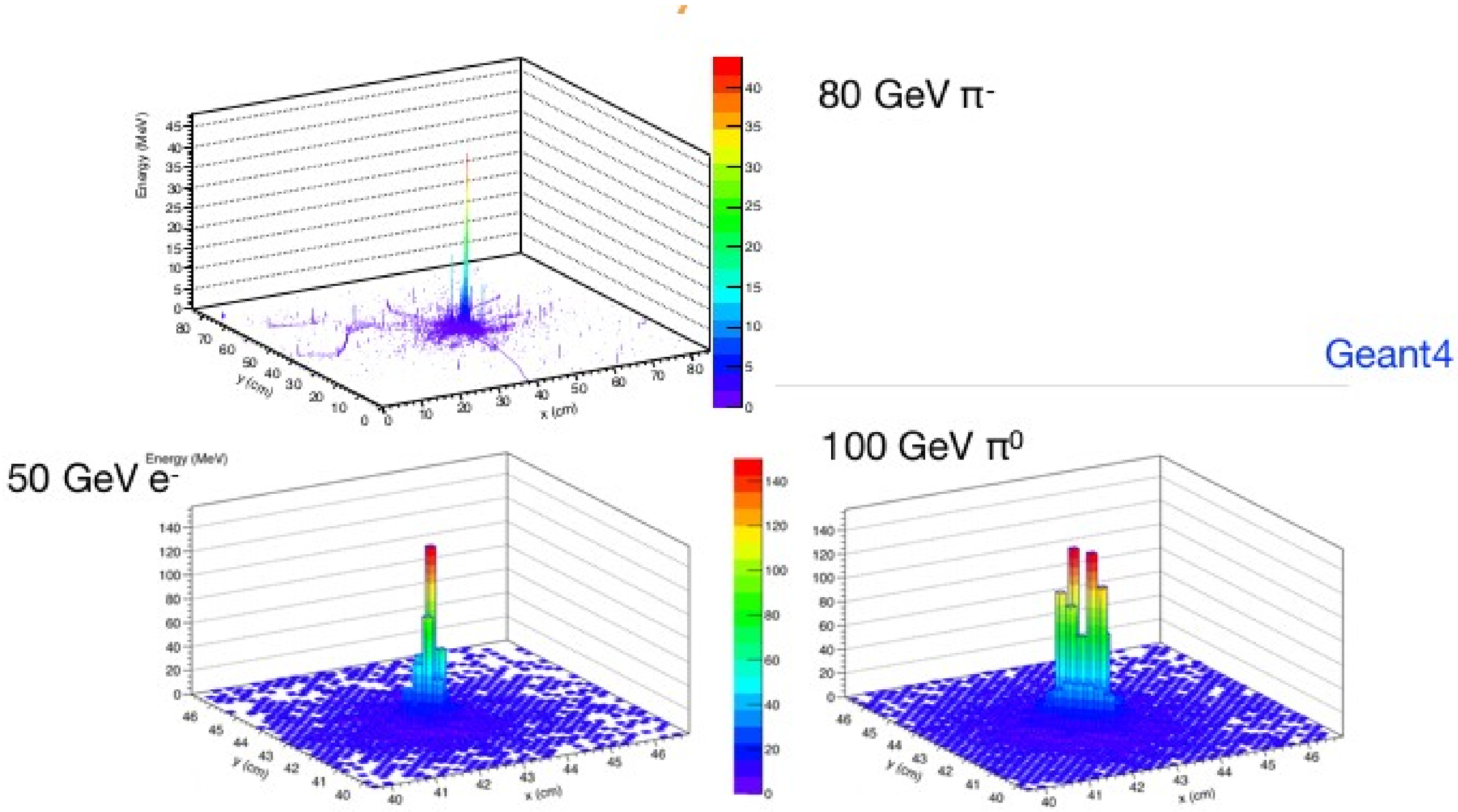



***em shower are very narrow:***

~10% (~50%) within ~1 (~10) mm from shower axis

→ fibre readout can easily provide (powerful) input to PFA

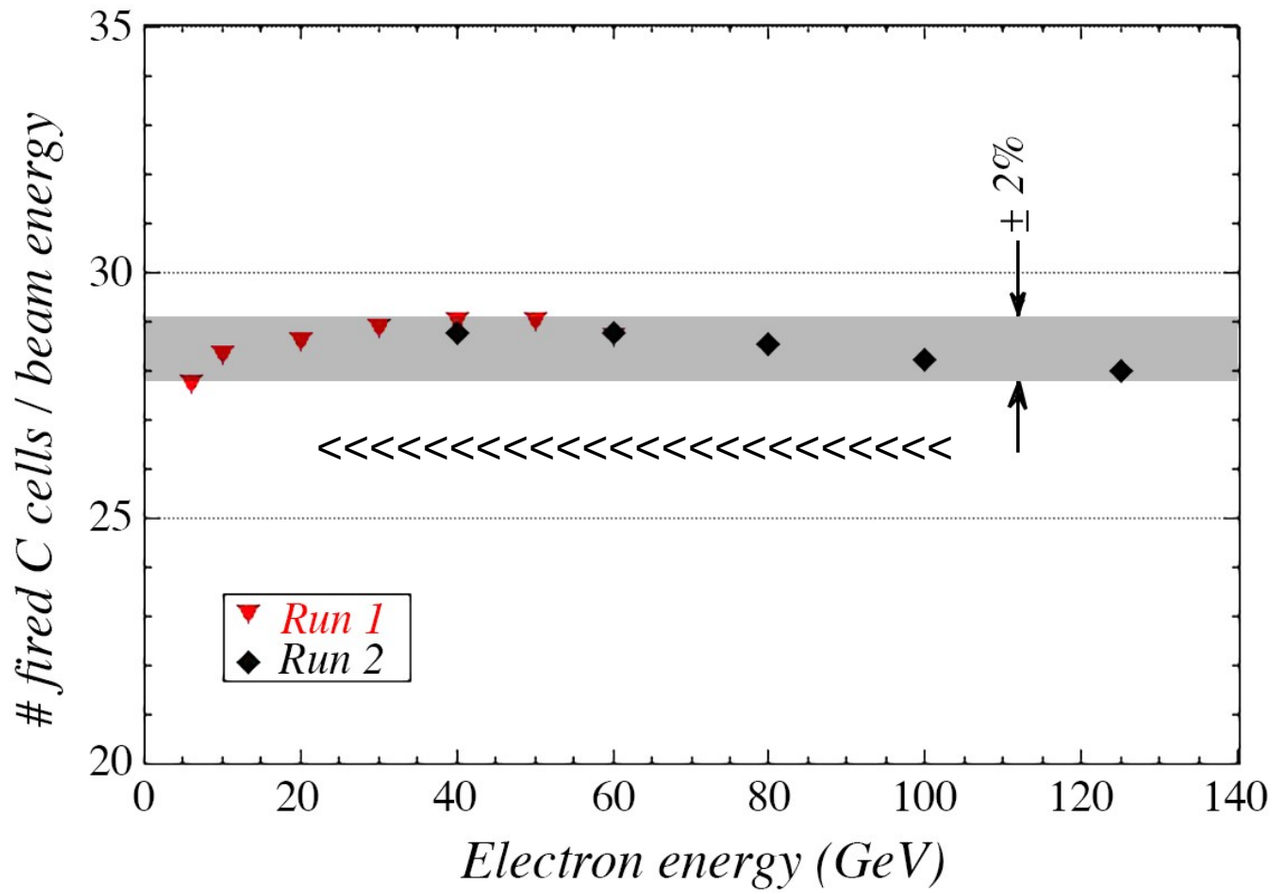
# 2D SiPM imaging




*Geant4 single-particle simulations*

# Cherenkov signal

Č signal/GeV vs. E




**~28.4 fired cells / GeV**

**⇒**

**~60 p.e. / GeV @ full containment**

# scintillation signal

## w/ scintillation light filtering:

attenuation factor ~ 77
(yellow filter)

*yellow filter → increase attenuation length*

### Signal linearity results from 2018 TB

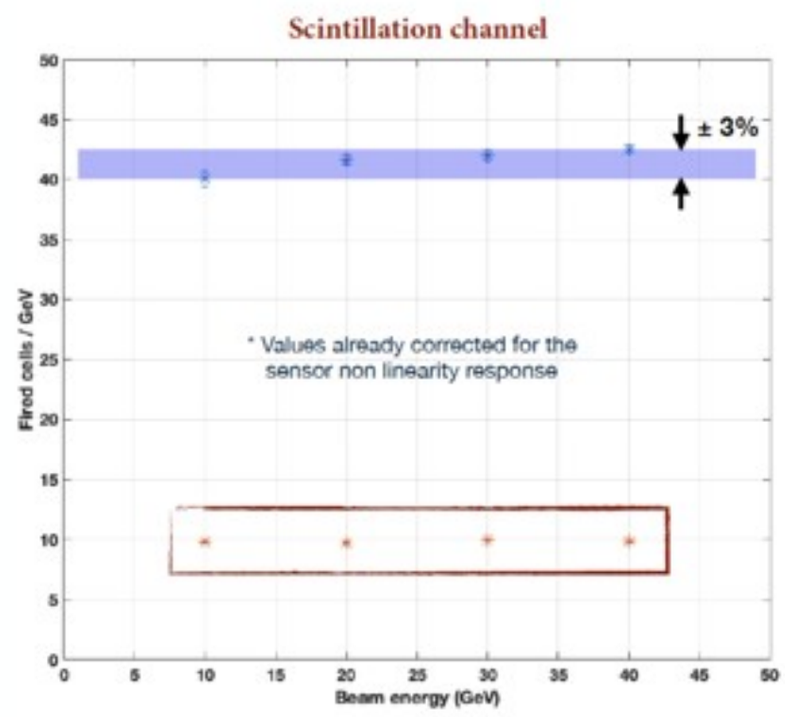
***Measurement conditions***:

$V_{op}$ = 5.5 $V_{ov}$ (57.5 V) and **PDE ~ 22% (S)**

Signal is linear from 10 to 40 GeV within 3%

Correcting for 45% e.m. energy containment: ~ ***93 Spe/GeV***

Stochastic term ~ ***10.9%***




To be checked with a simulation: sending electrons in the center of the module (4x4) with an angle: $-1 < \vartheta < 1$ mRad

Total: ***41.9 ± 0.1 Spe/GeV***

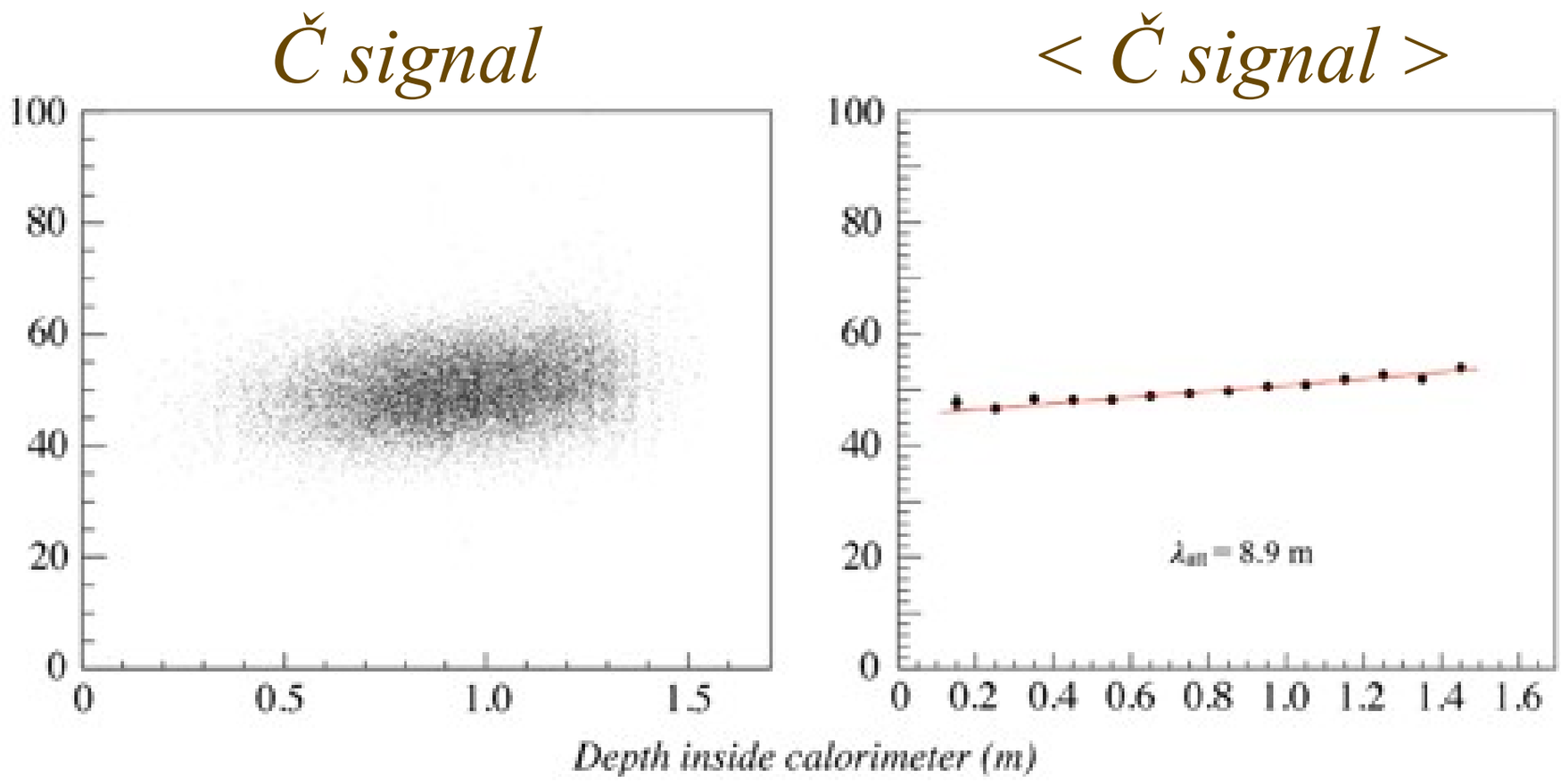
Hottest fibre: ***9.8 ± 0.1 Spe/GeV***

***No saturation*** effects: linear within ***1%***

# *... about attenuation length*

Two remarks:

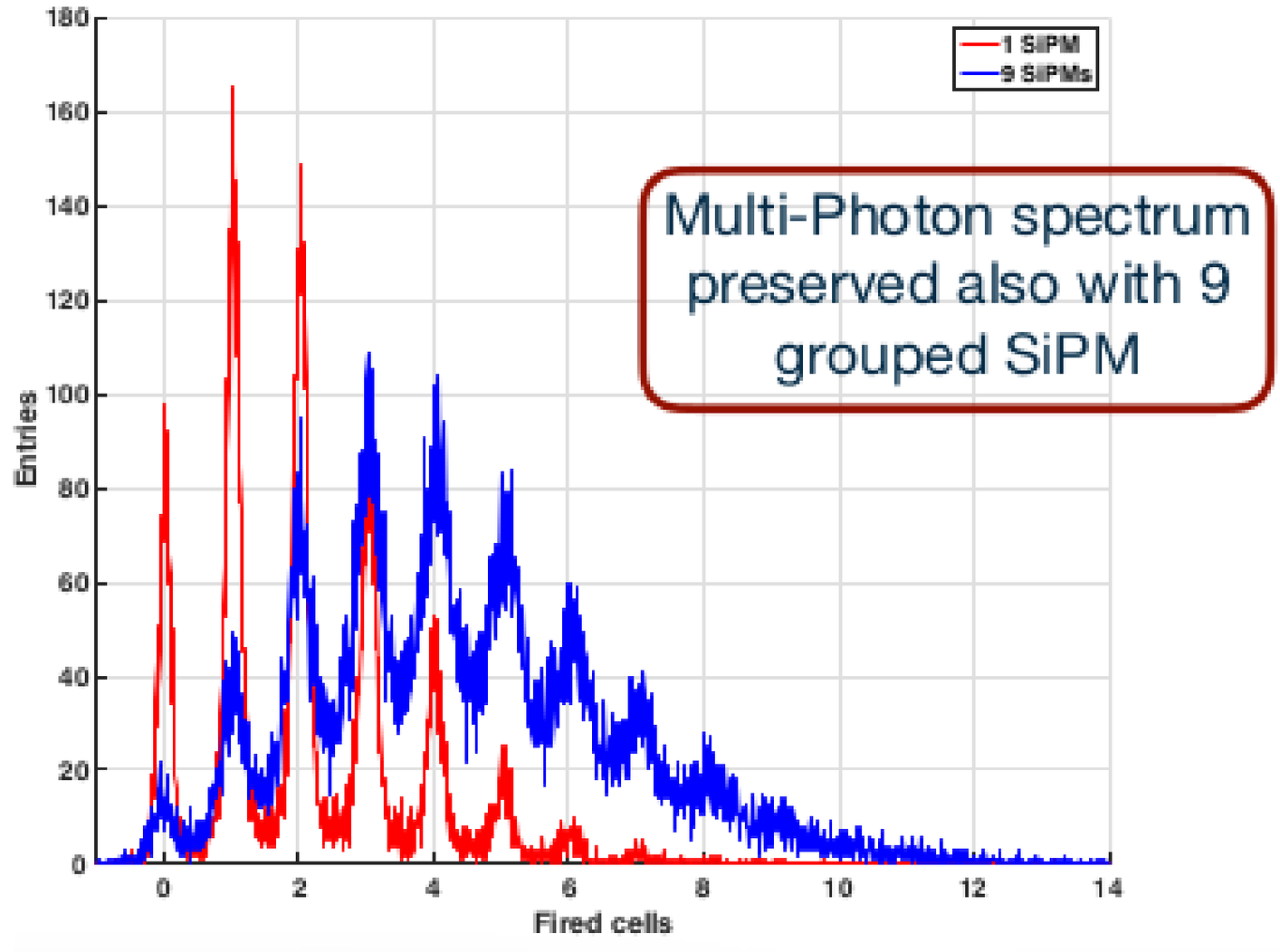
1) yellow filters increase attenuation length
2) timing measurement may allow for corrections, if needed



# readout granularity (channel grouping)

tune readout granularity by analogically grouping (i.e. adding) channels

tests done with
1, 2, 4, 6, 9 SiPM.s

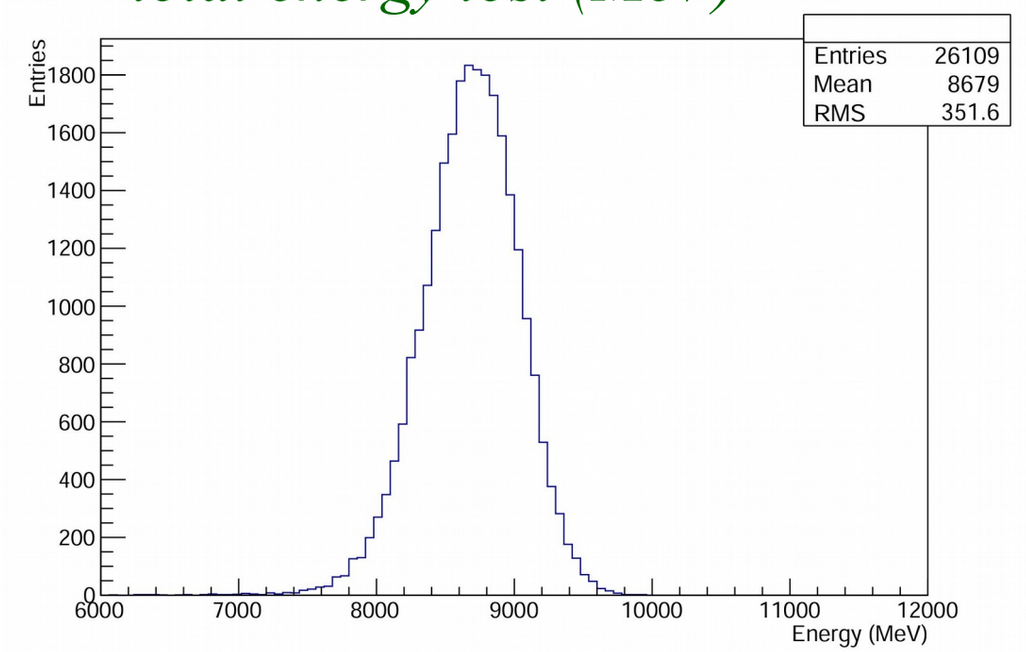



It works! May reasonably think at 2×2, 2×3, 2×4, 3×3 ...

# Geant4 - 20 GeV electron shower containment

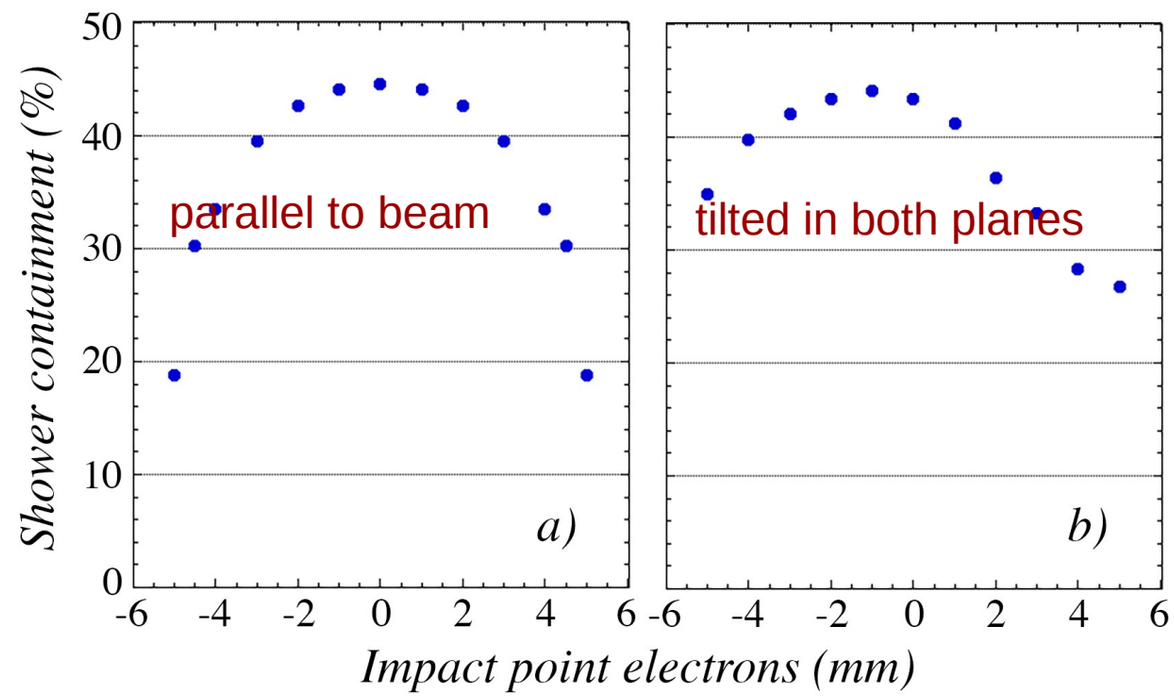
*RD52 testbeam module: 1.014 x 1.014 x 112.30 cm$^3$*

*total energy lost (MeV)*




*centered events: ~43% containment*

*containment .vs. impact point*




*e.m. calorimeter: 31.4 x 31.4 x 112.30 cm$^3$*

**containment > 99%**

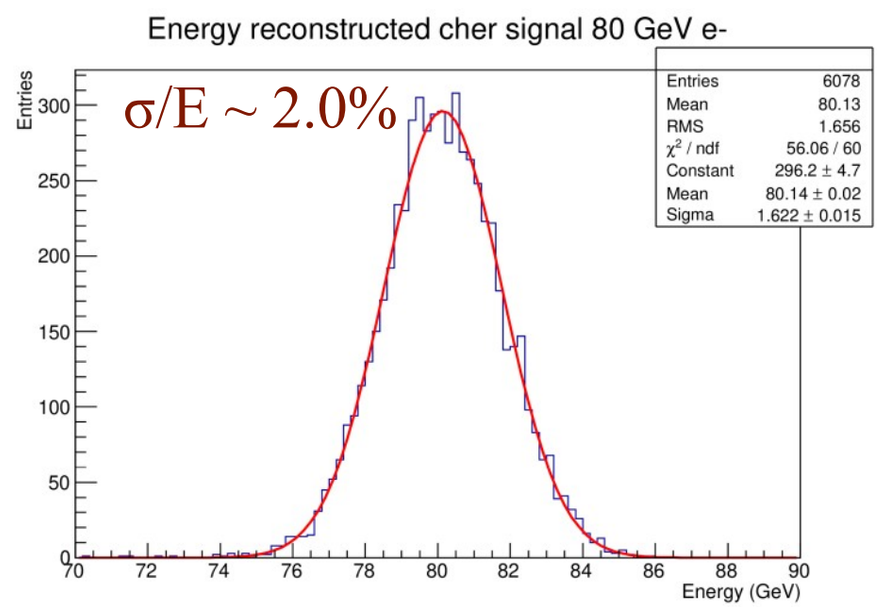
(all plots for copper unless specified differently)

# Geant4 - e.m. energy reconstruction (Cu)

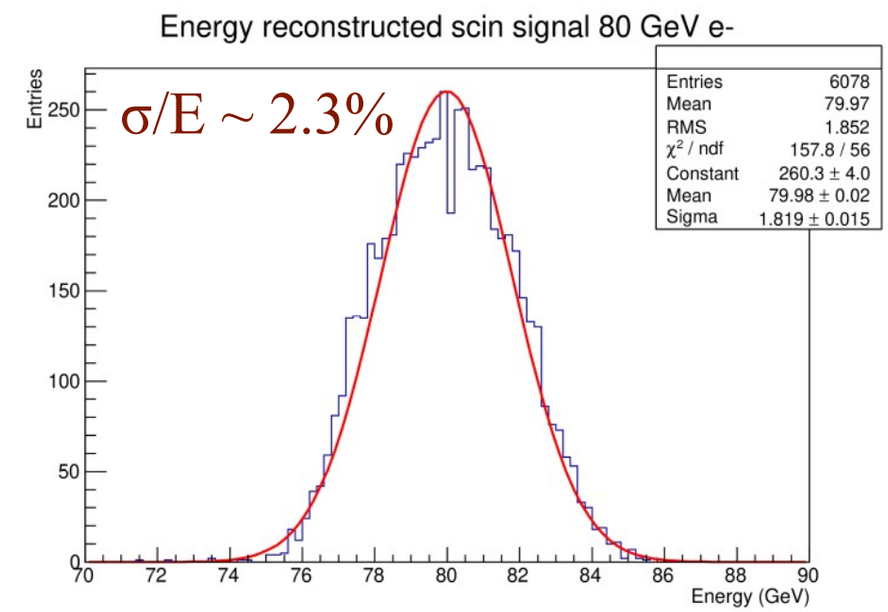
*e.m. calorimeter: 31.4 x 31.4 x 112.30 cm$^3$*

**containment >~99%**

Č only

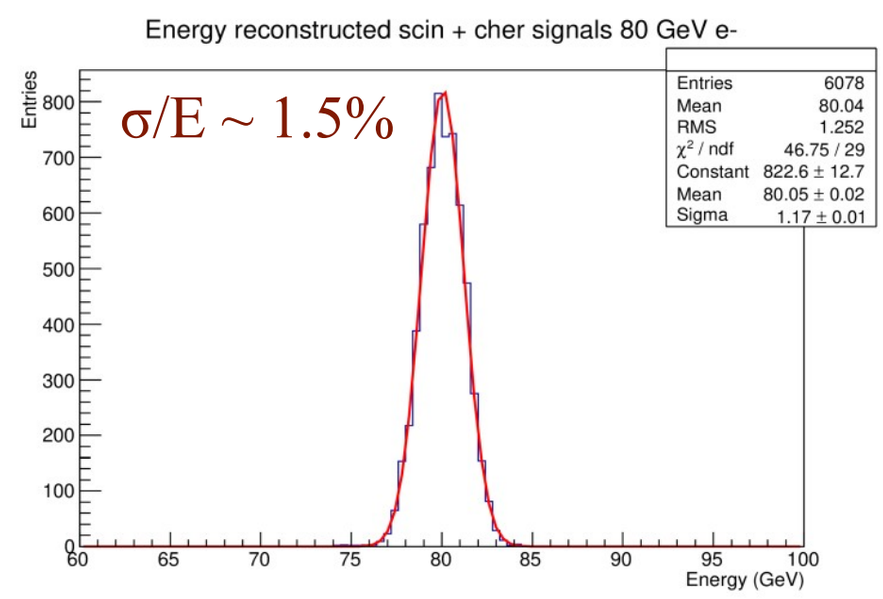



S only




*energy reconstructed 80 GeV electrons*

S+Č

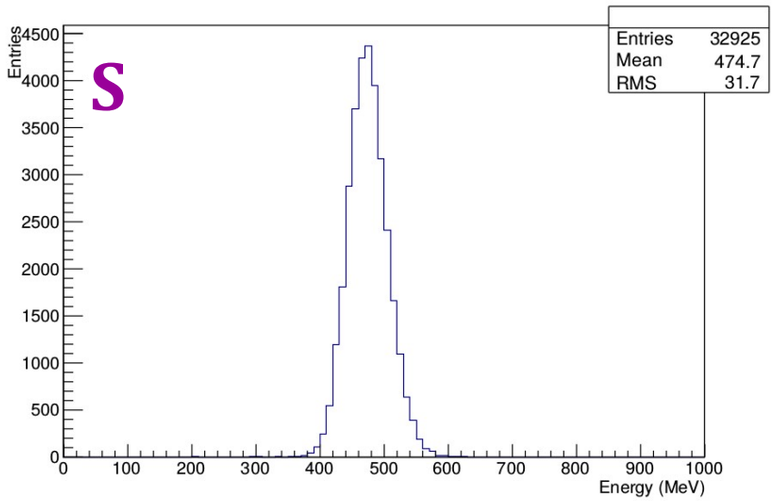


# Geant4 - sampling fraction (Cu)

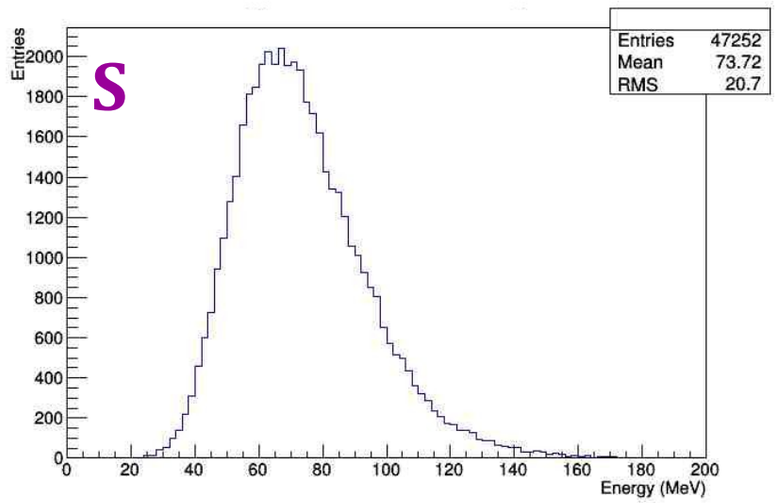
*e.m. calorimeter: 31.4 x 31.4 x 112.30 cm$^3$*

**containment >~99%**

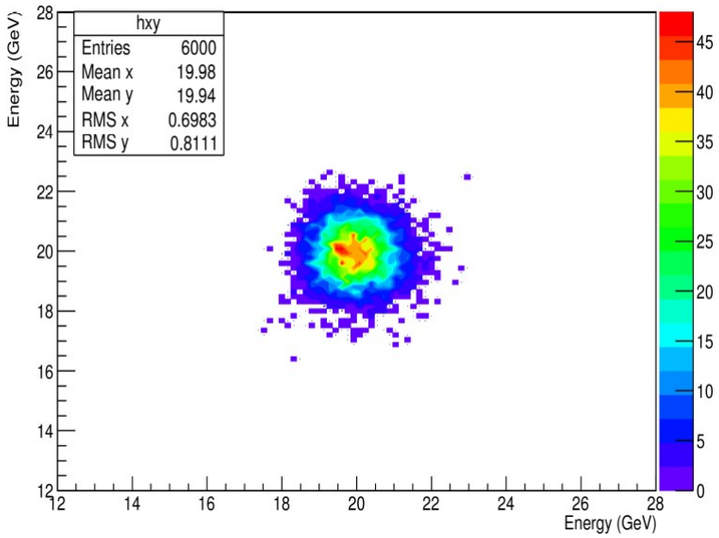
*E(MeV) S fibres: ~5.5%*



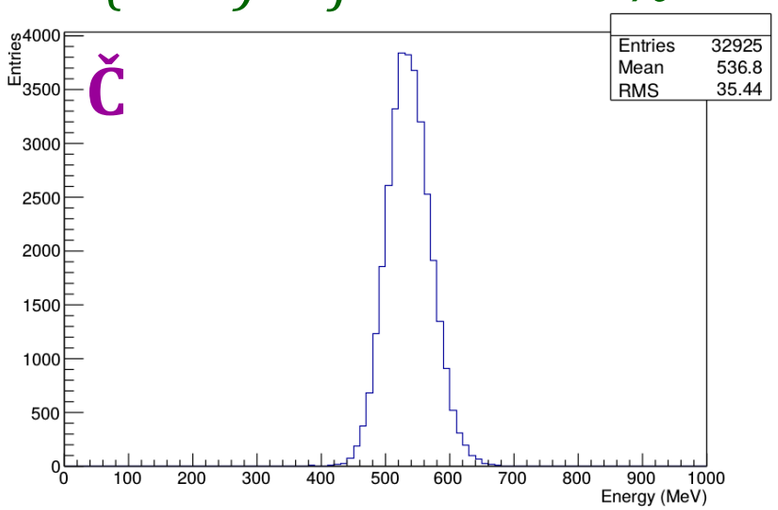

*E (MeV) in hottest fibre*



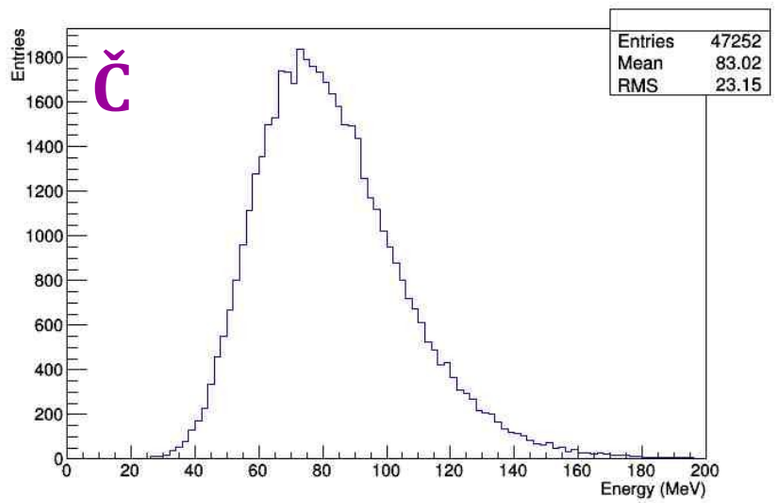

*C vs. S*




*E(MeV) in fibres: ~6.2%*




*E (MeV) in hottest fibre*

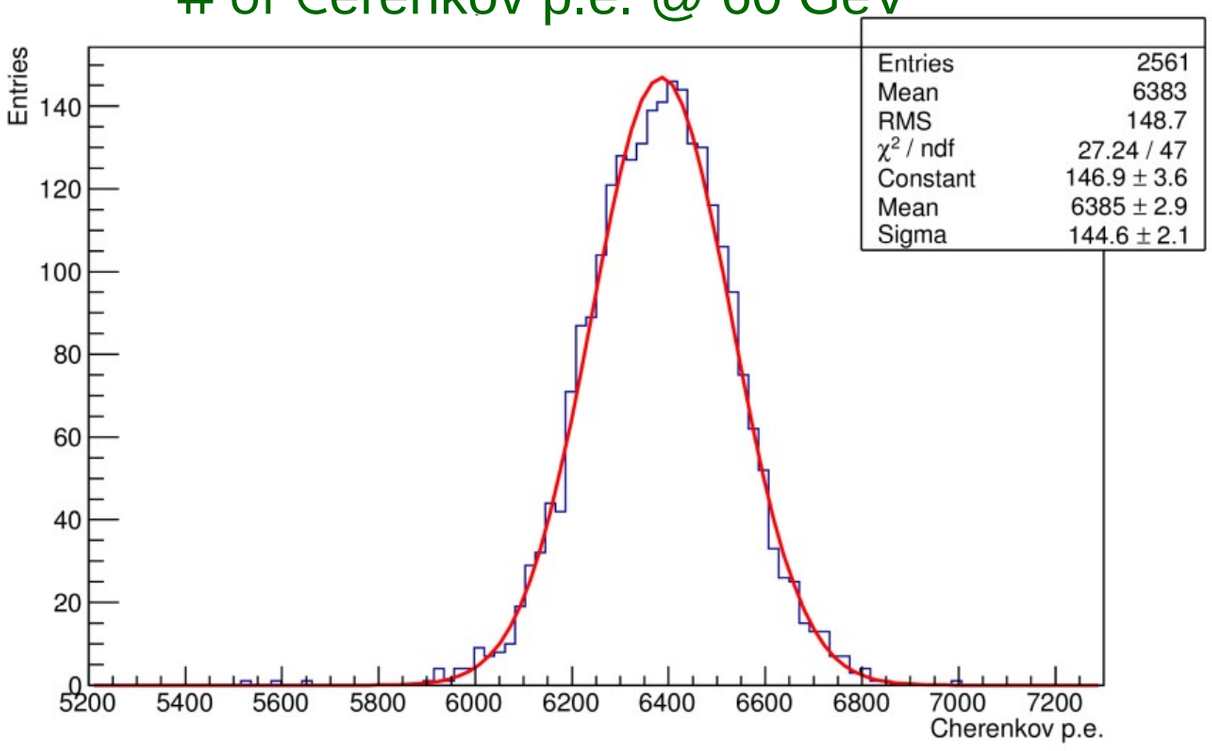


# Geant4 – e.m. performance (Cu)

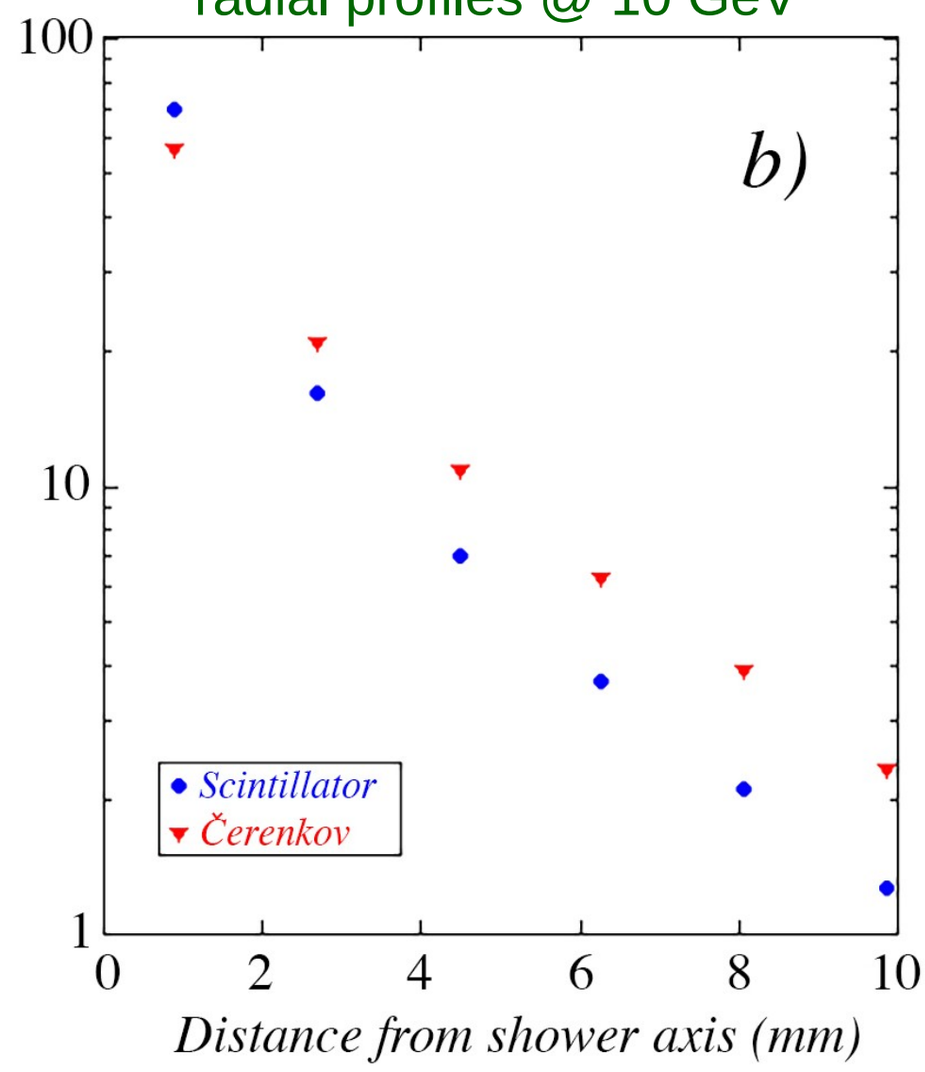
*e.m. calorimeter: 31.4 x 31.4 x 112.30 cm$^3$*

**containment >~99%**

# of Čerenkov p.e. @ 60 GeV

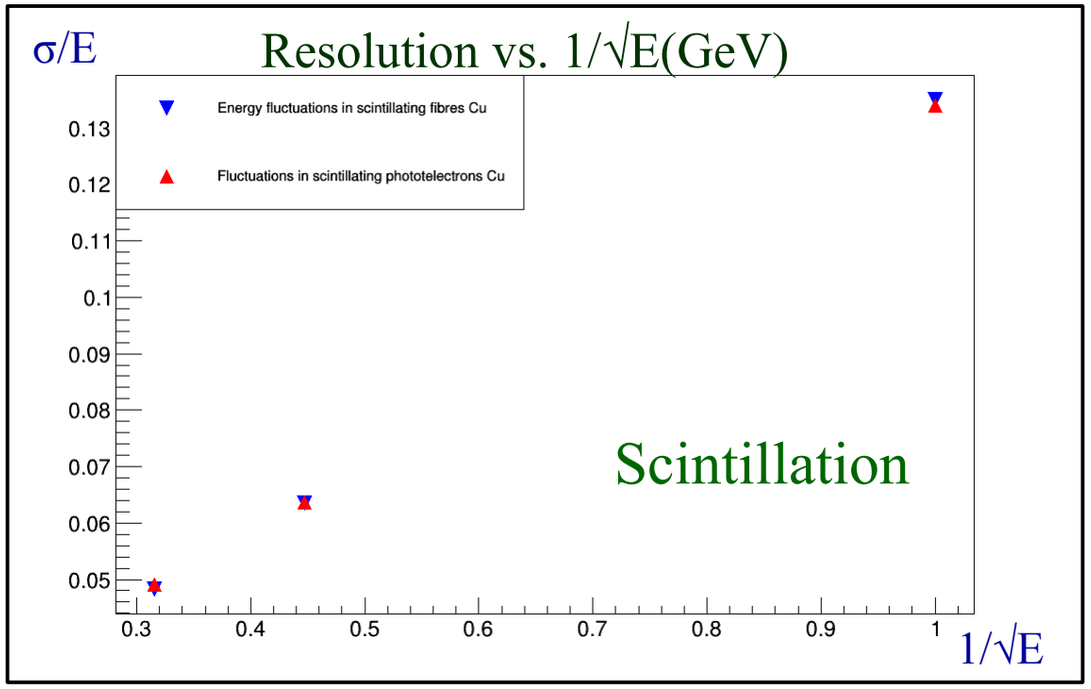


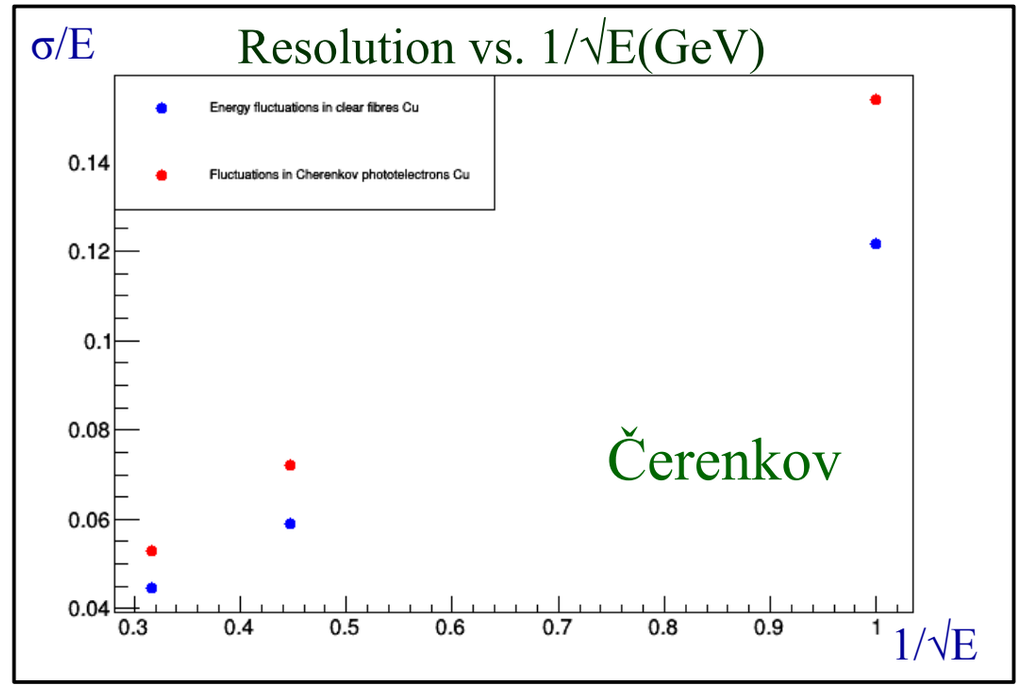

radial profiles @ 10 GeV



# Geant4 – signal fluctuations

*Energy deposition and p.e. number fluctuations*



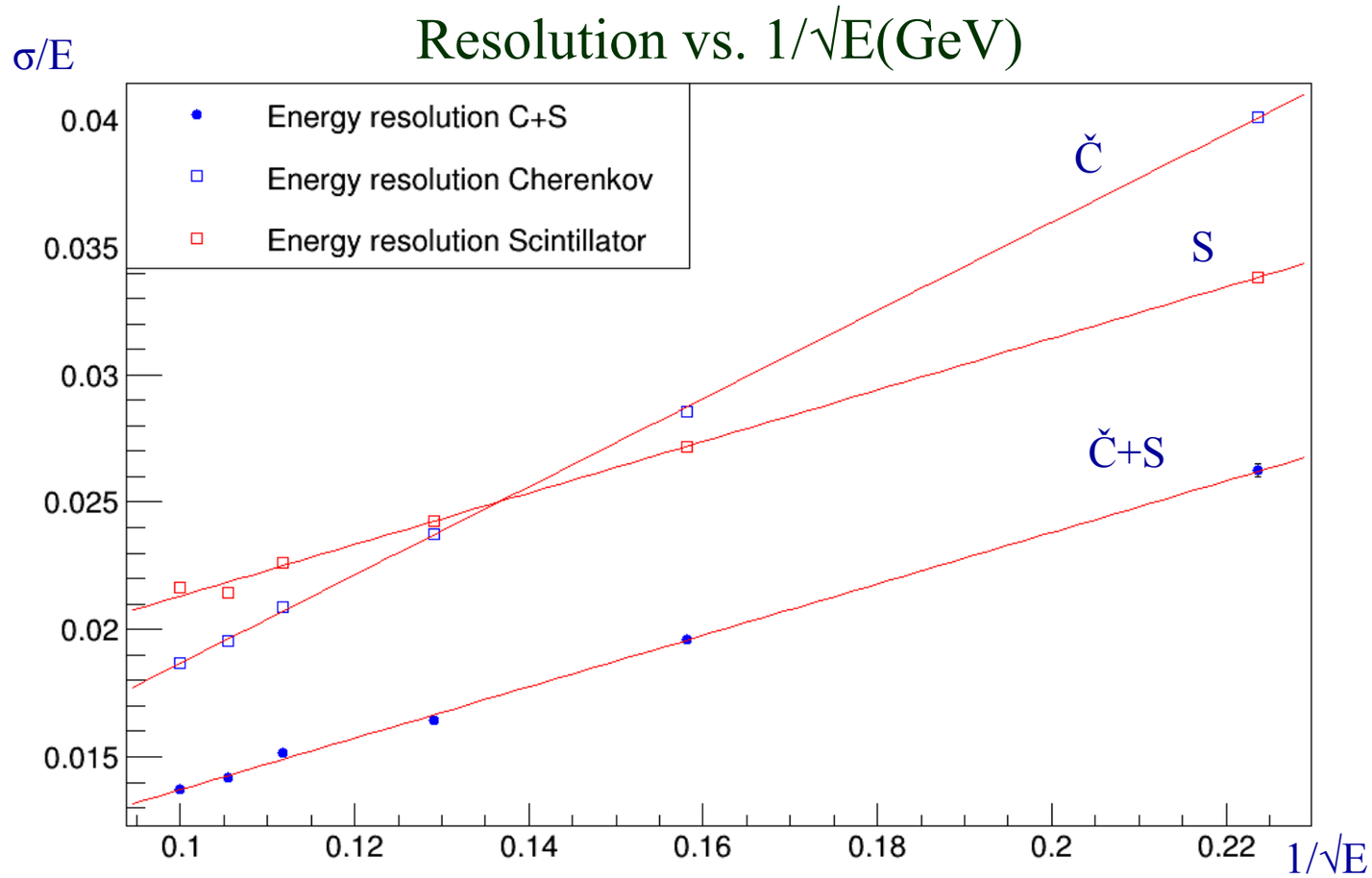

S: ~5500 p.e. / GeV
→ σ/E driven by fluctuations in en. depositions

Č: ~110 p.e. / GeV
→ σ/E driven by fluctuations in p.e. number

Sampling fluctuations contribution to resolution:

$$\frac{\sigma}{E} = 2.7\% \times \frac{\sqrt{1/0.113}}{\sqrt{E}} = \frac{8.0\%}{\sqrt{E}}$$

# Geant4 – e.m. resolution(s)




*S-only: 10.5/√E+1.1 (%)*

*Č-only: 17.9/√E (%)*

*(unweighted) average: 10.3/√E+0.3 (%)*

# Geant4 - hadronic shower simulations

*Dimensions:*

*71 x 71 units*

*1 unit:*

*1.014 x 1.014 x 250 $cm^3$ copper module*
*32 (S) + 32 (Č) fibres*
*SiPM readout*

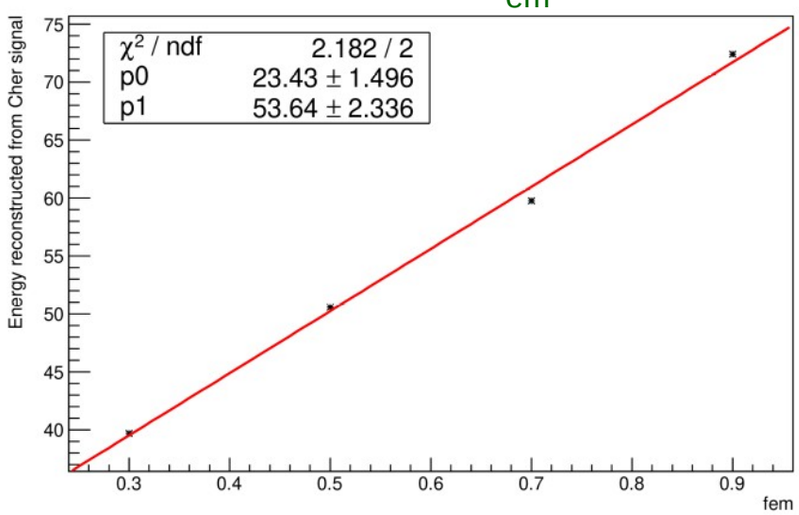
*Containment: ~99%*

*Calibration of both S and Č w/ 40 GeV $e^-$*

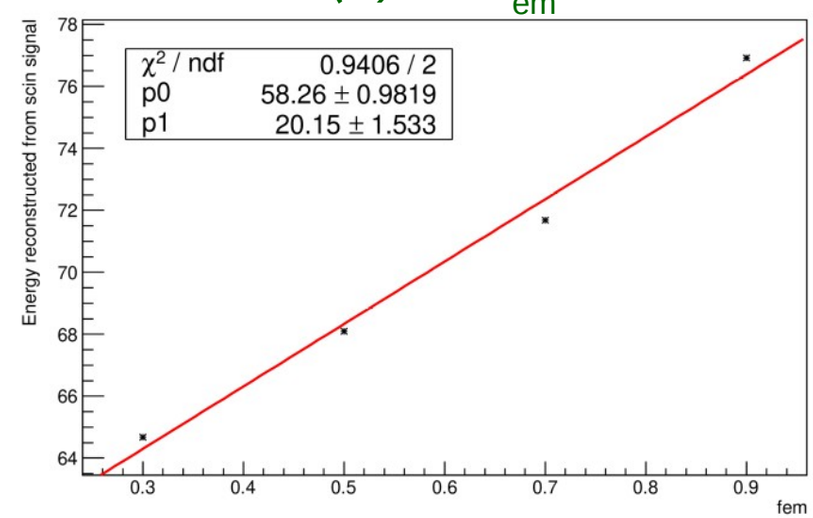
***** Preliminary results! *****

# Geant4 - hadronic performance (preliminary)

E(Č) vs. $f_{em}$

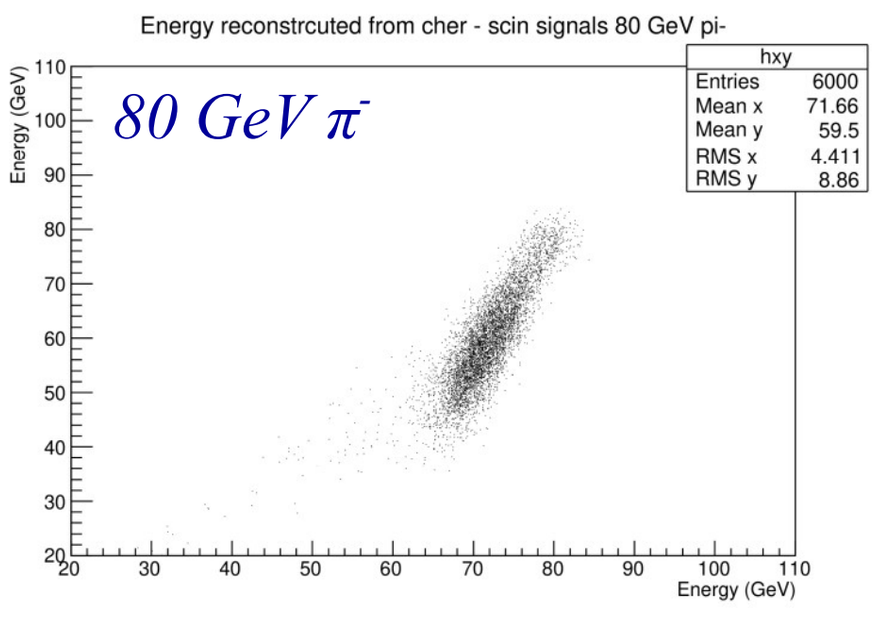



E(S) vs. $f_{em}$

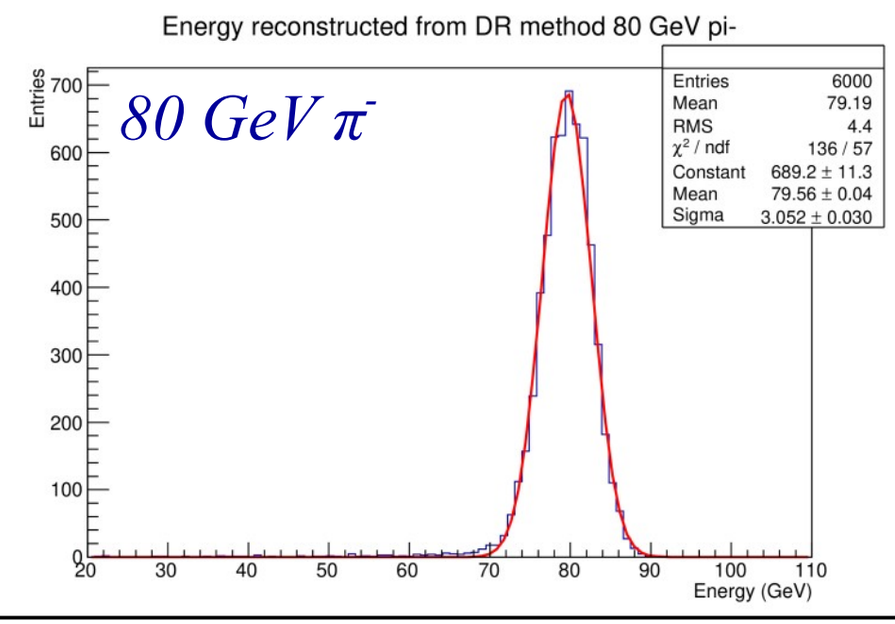



## *Copper*

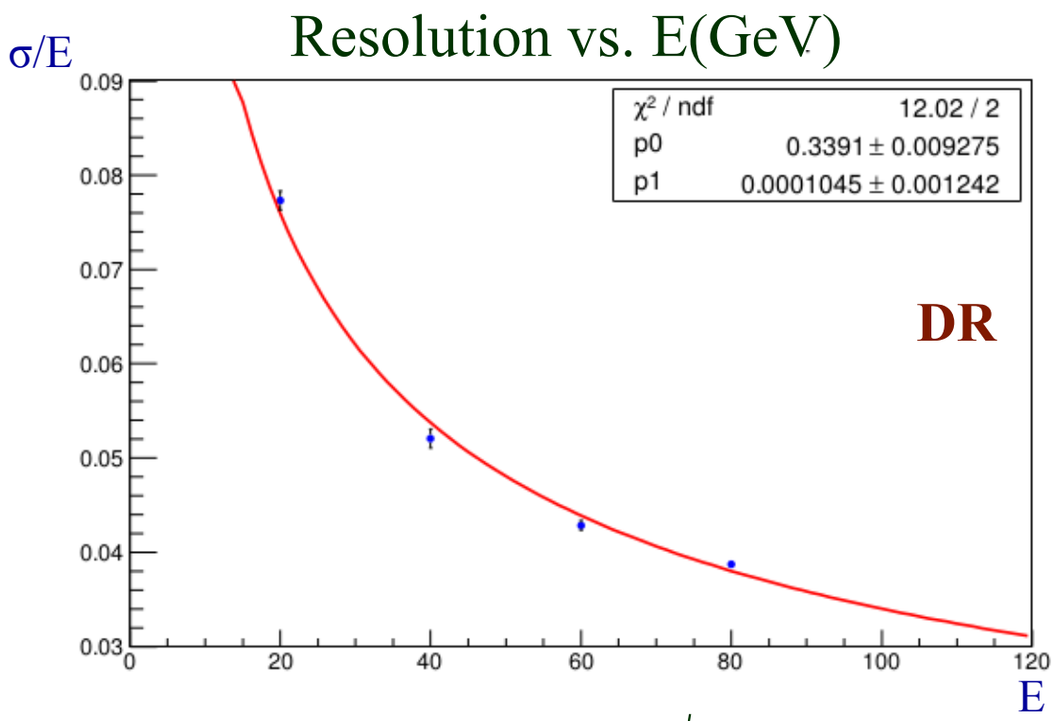
E(Č) vs. E(S)

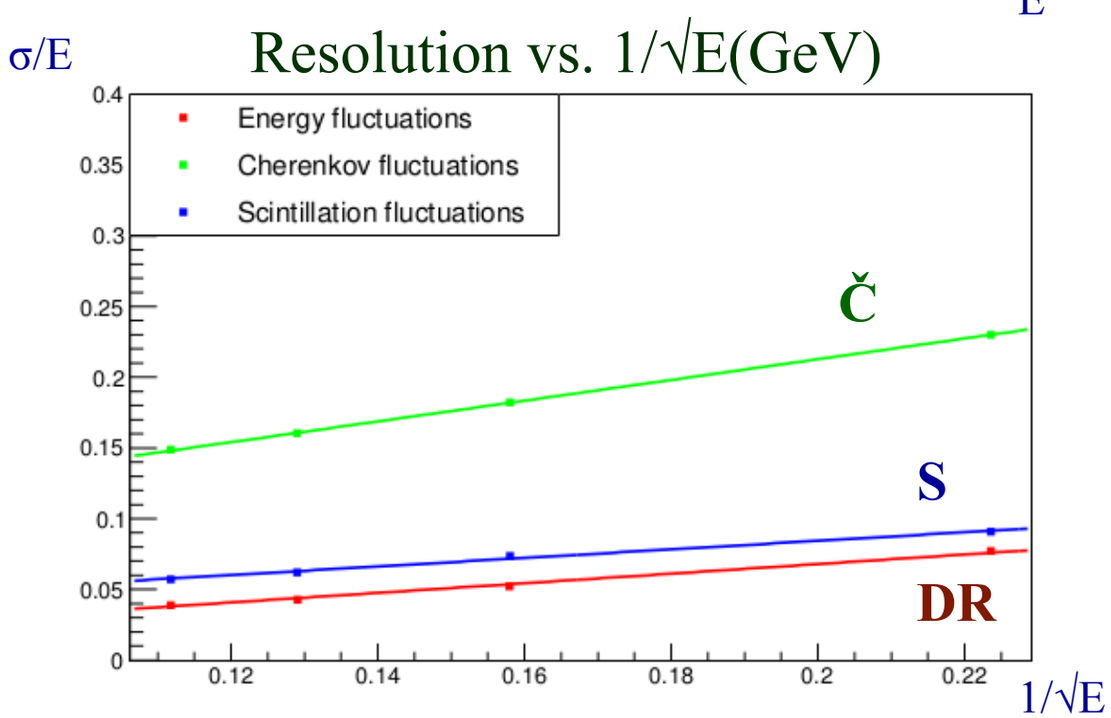



E (DR)



# Geant4 – Cu hadronic performance (preliminary)




*Č: ~73/√E + 6.6 (%)*
*S: ~30/√E + 2.4 (%)*

*DR: ~34/√E (%)*

*High-energy single-π resolutions:*

*σ/E(100 GeV) ~ 3.5%*
*σ/E(300 GeV) ~ 2.3%*
*σ/E(1000 GeV) ~1.7 %*

# many open issues ...

A non exhaustive list:

1) absorber (copper, lead, iron, ...)
2) longitudinal segmentation
3) alternative approaches (i.e. tiles vs. fibres)
4) front-end electronics (ASIC)
5) feature extraction
6) jets calibration and energy reconstruction

# absorber choice

absorber : active volume = 62 : 38

| | Iron | Brass (Cu260) | Lead |
|---|---|---|---|
| $\rho$ (gr/cm$^3$) | 5.31 | 5.71 | 7.46 |
| $\lambda_N$ (cm) | 23.7 | 23.3 | 24.7 |
| $\chi_0$ (cm) | 2.75 | 2.35 | 0.9 |
| $R_M$ (cm) | 2.48 | 2.38 | 2.32 |
| $\rho \times \lambda_N^3$ (kg) | 71 | 72 | 113 |
| $\lambda_N : \chi_0$ | 8.6 | 9.9 | 27.6 |

**Lead:**

(-) ~ 60% more mass

(+) a factor of ~ 3 in longitudinal separation of em and hadronic showers

# Geant4 – h/e and χ factors

$f_{em}$ = MC truth (total energy deposited by $e^+$ and $e^-$)
E = average contained energy
C, S = signals

either:

$$f_{em} \rightarrow 0 : C/E,\ S/E \rightarrow (h/e)$$

or:

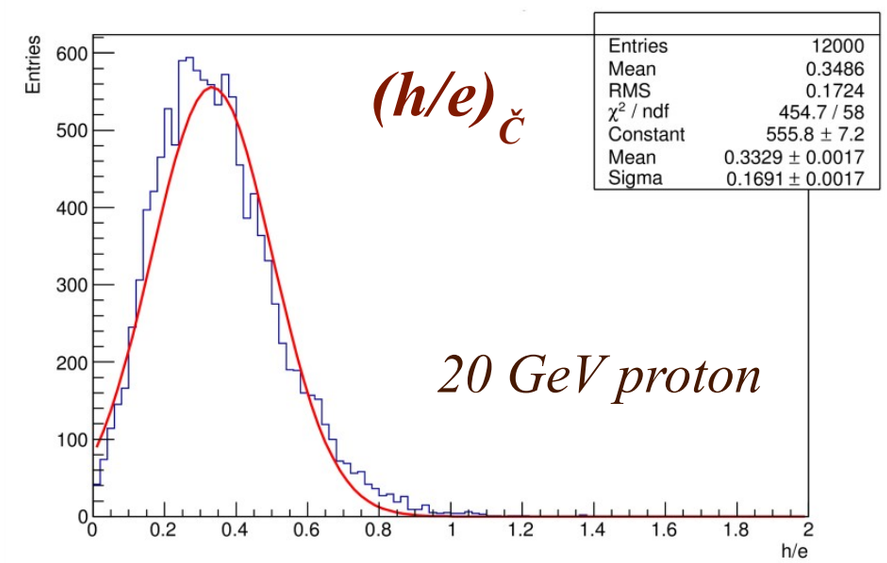
$$(h/e)_{Č} = (C/E - f_{em}) / (1 - f_{em})$$
$$(h/e)_{S} = (S/E - f_{em}) / (1 - f_{em})$$

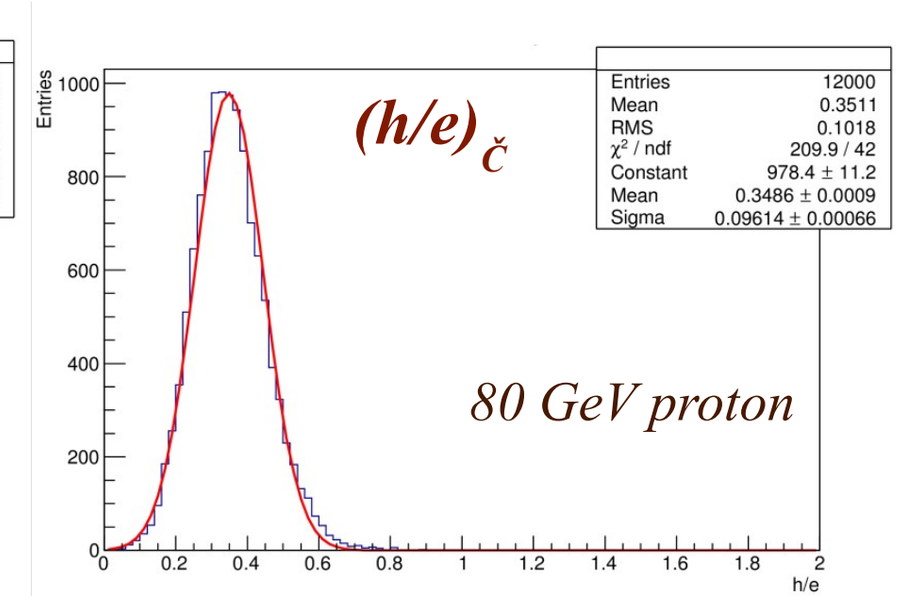
while:

$$\chi = (1 - (h/e)_{S}) / (1 - (h/e)_{Č}) = (E - S) / (E - C)$$

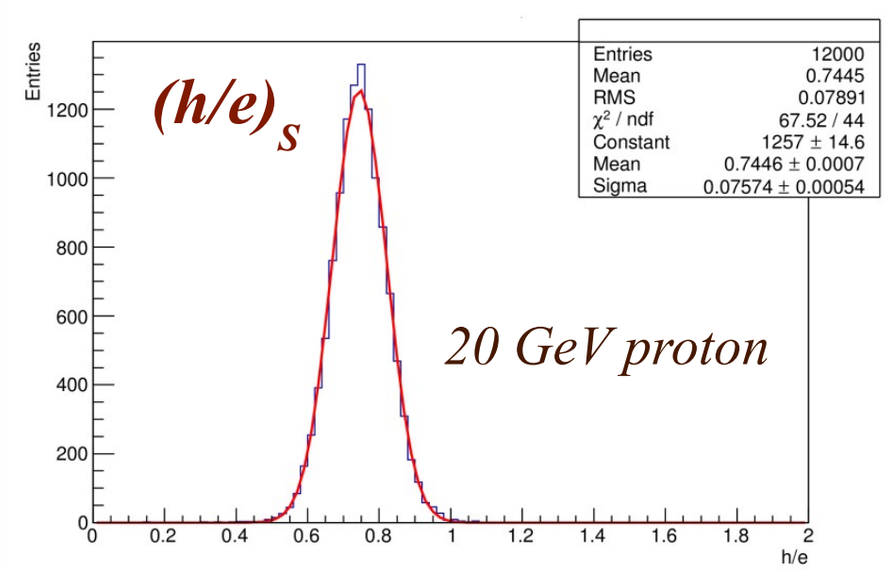
# Geant4 – h/e factors for Copper

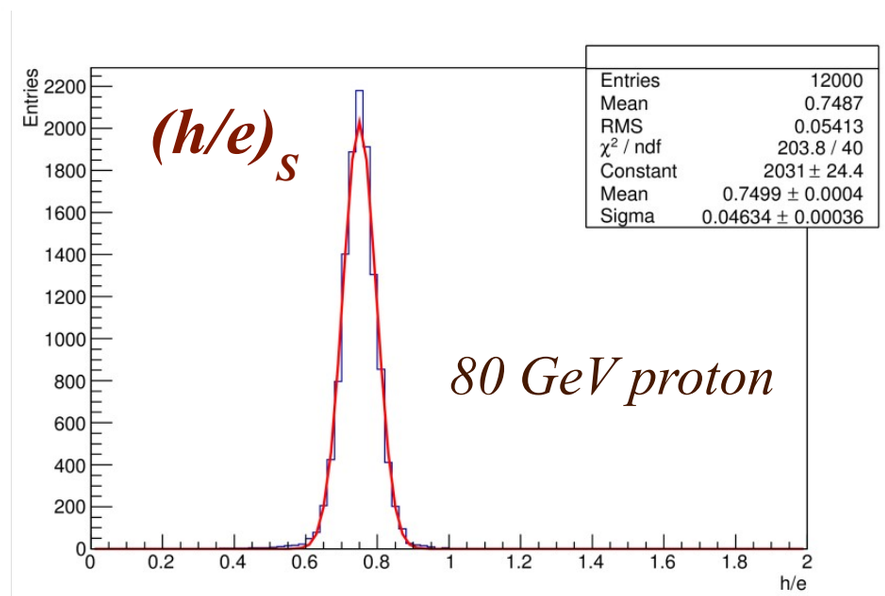
## *Copper*




$(h/e)_{Č} \approx 0.35$

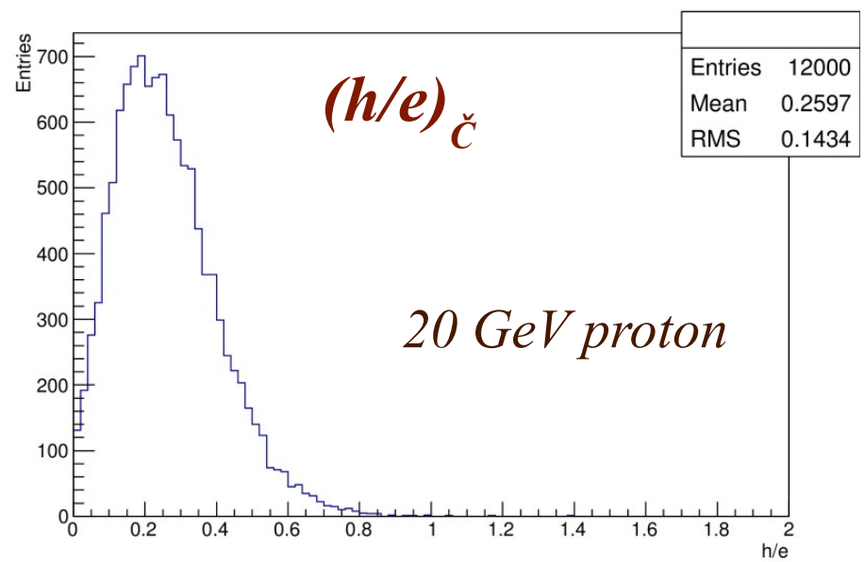


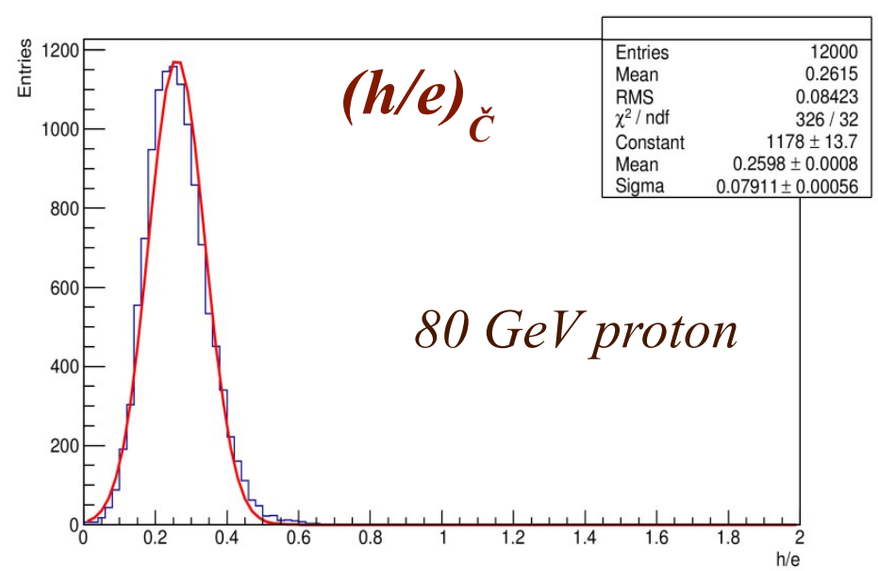




$(h/e)_{S} \approx 0.75$

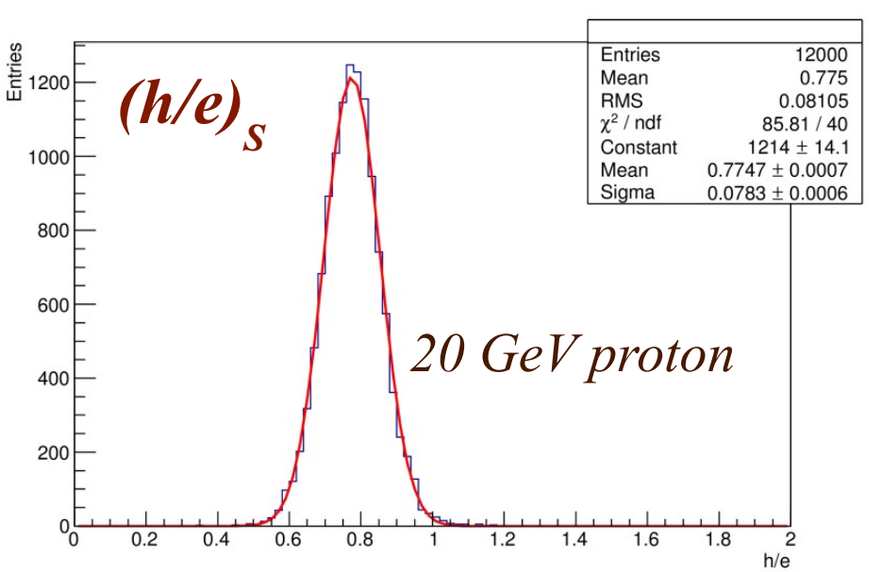
# Geant4 – h/e factors for Lead

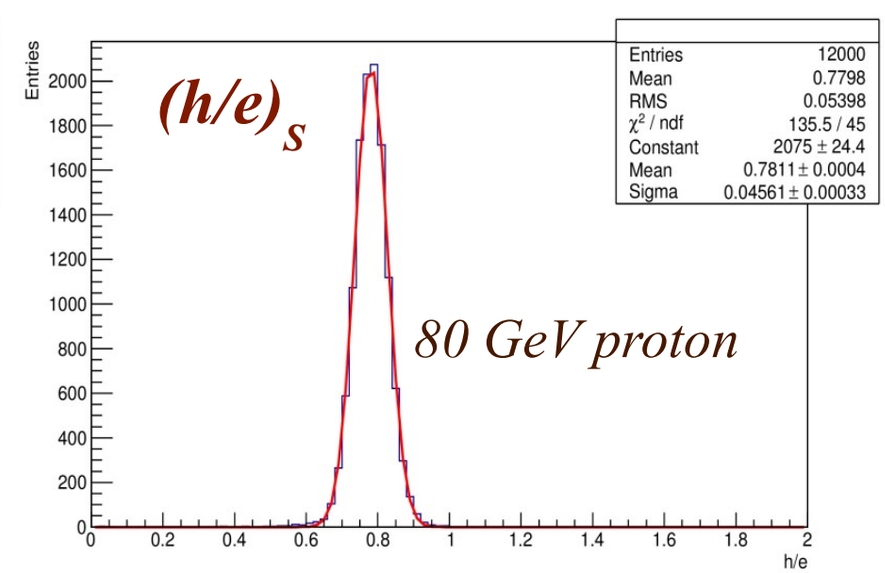
## *Lead*



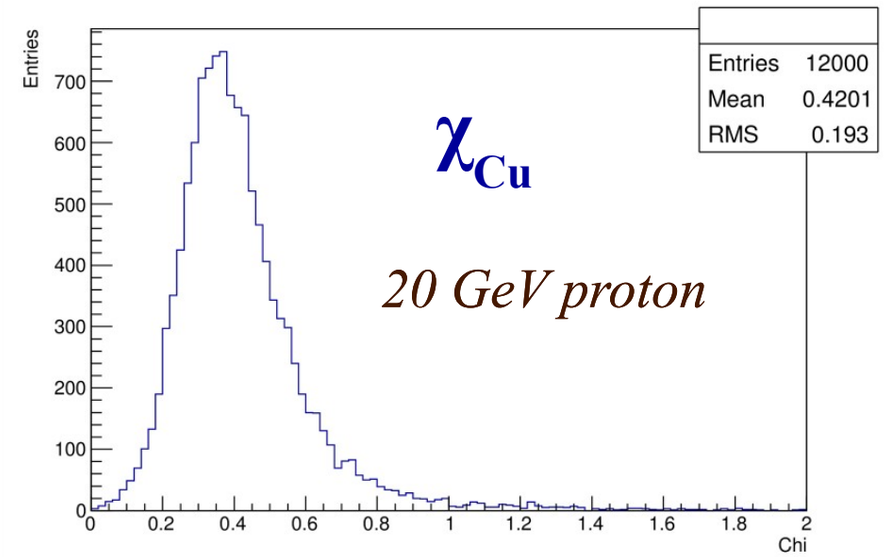

**$(h/e)_{Č} \approx 0.26$**



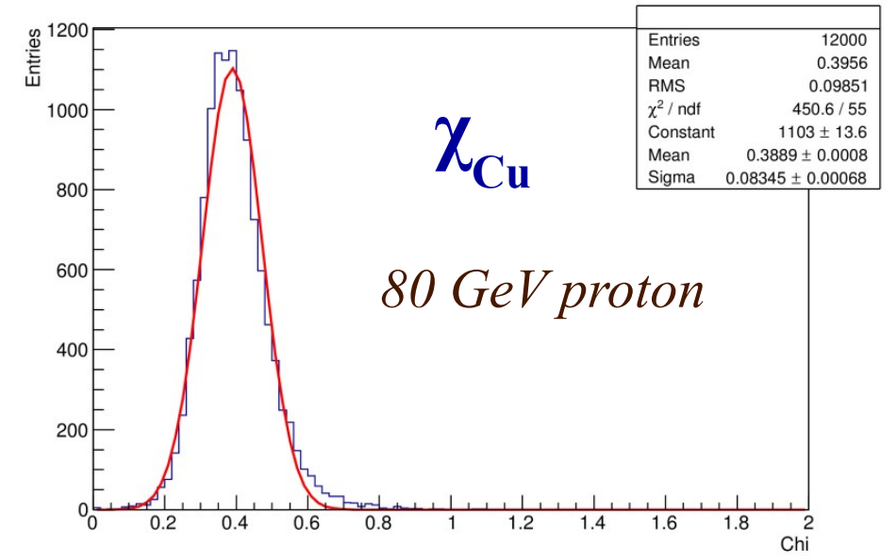

**$(h/e)_{S} \approx 0.78$**

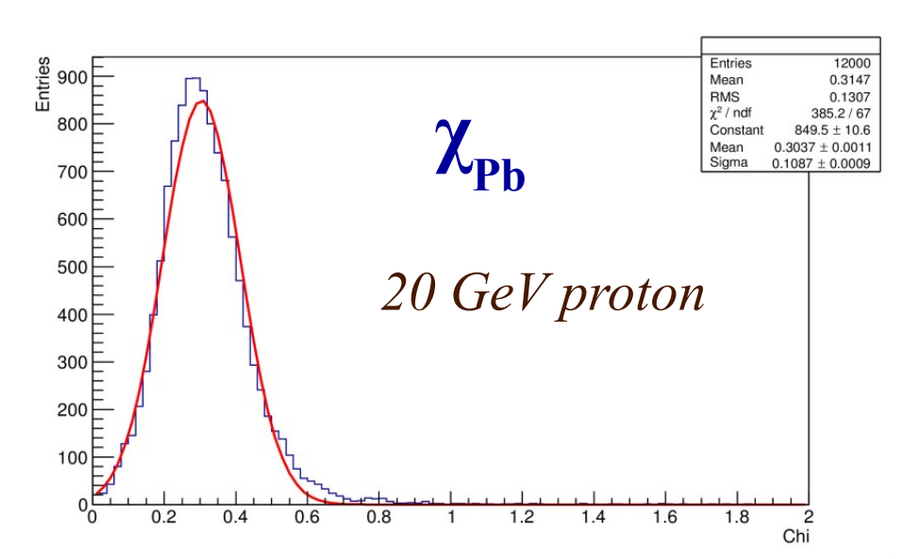
# Geant4 – χ factors for Copper and Lead




**Copper**

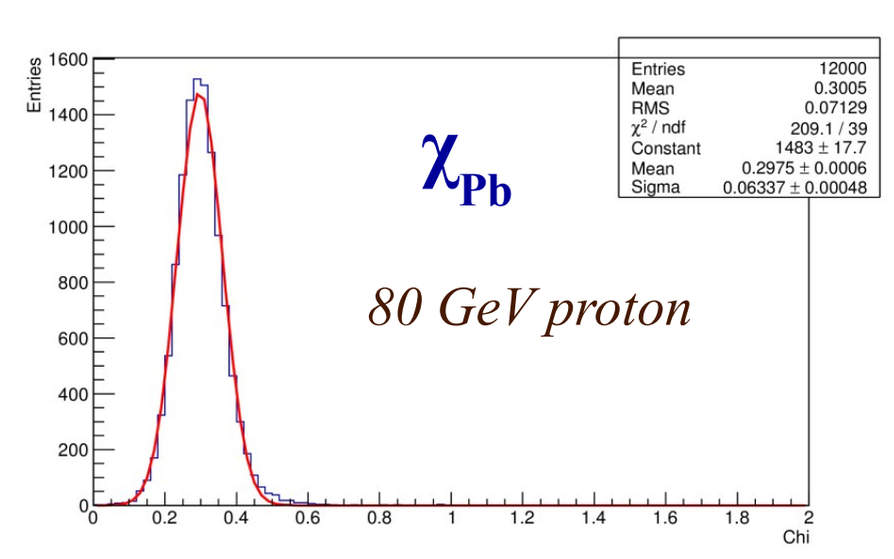
$\chi_{Cu} \approx 0.39$



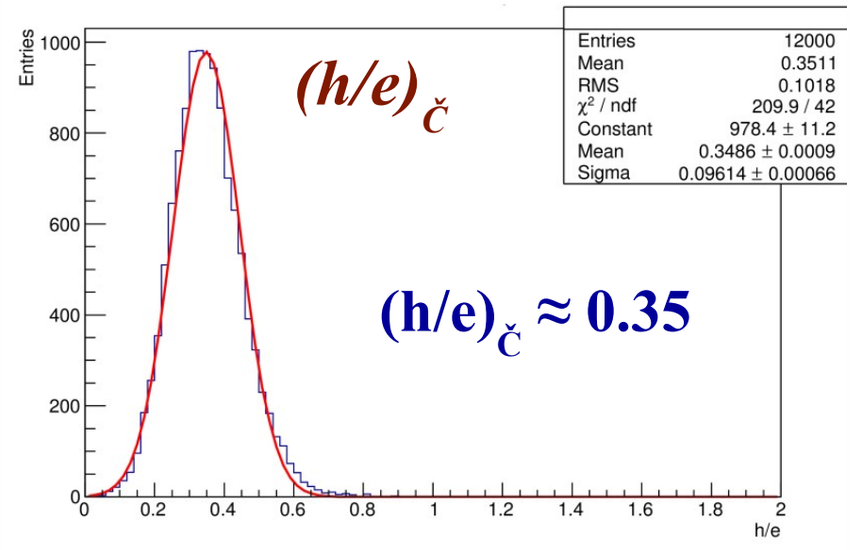



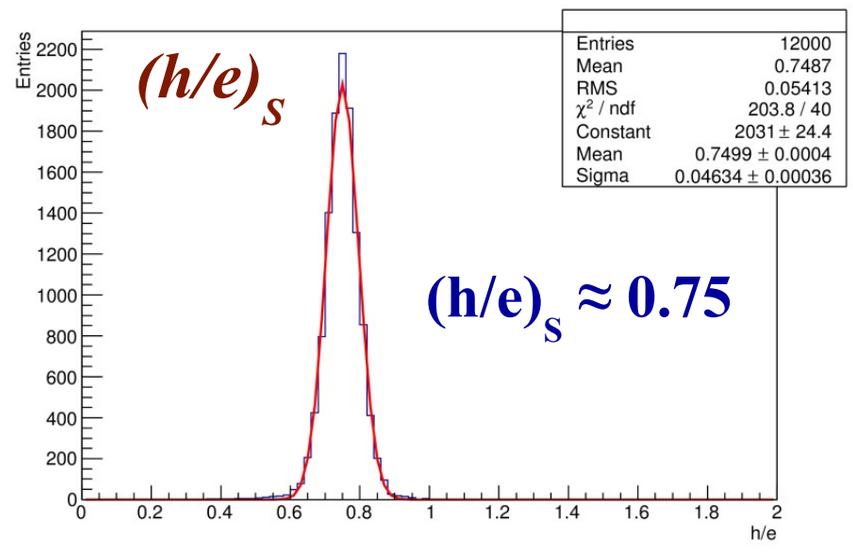

**Lead**

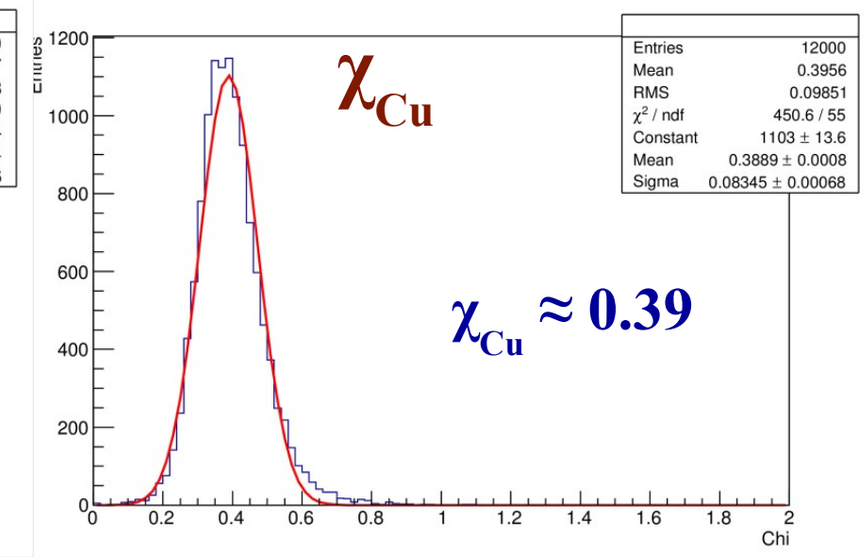
$\chi_{Pb} \approx 0.30$



# Geant4 – (h/e) and χ factors



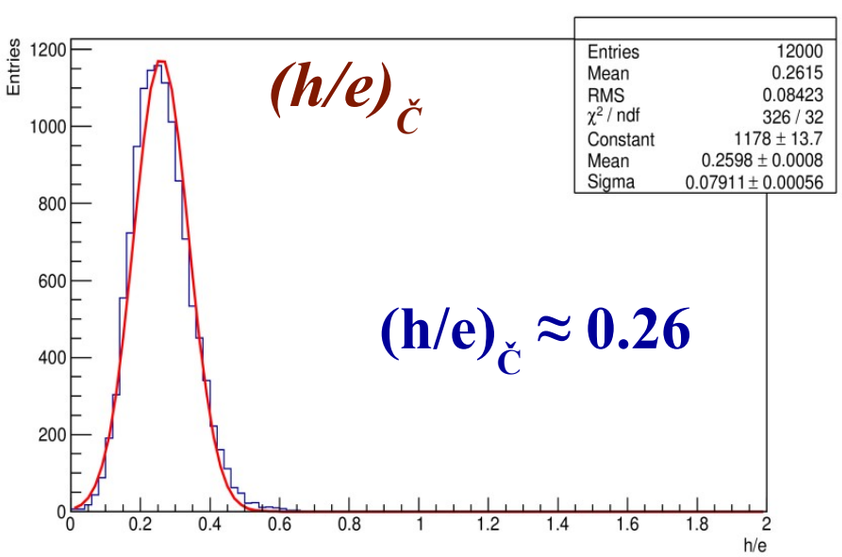



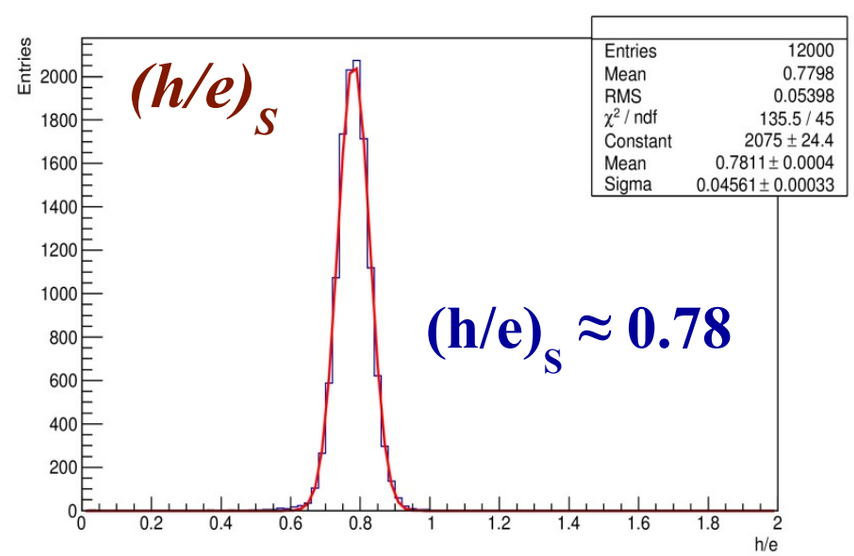



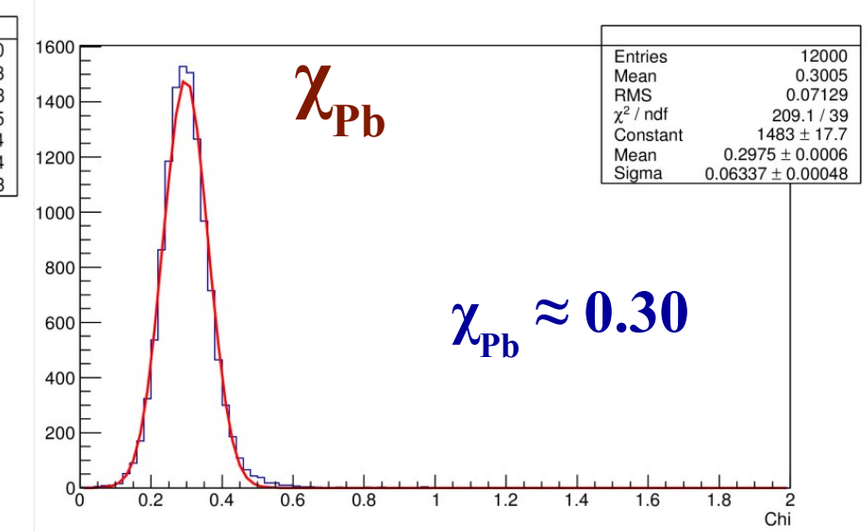

Copper →

*80 GeV protons in Copper ↑ & Lead ↓*

Lead →

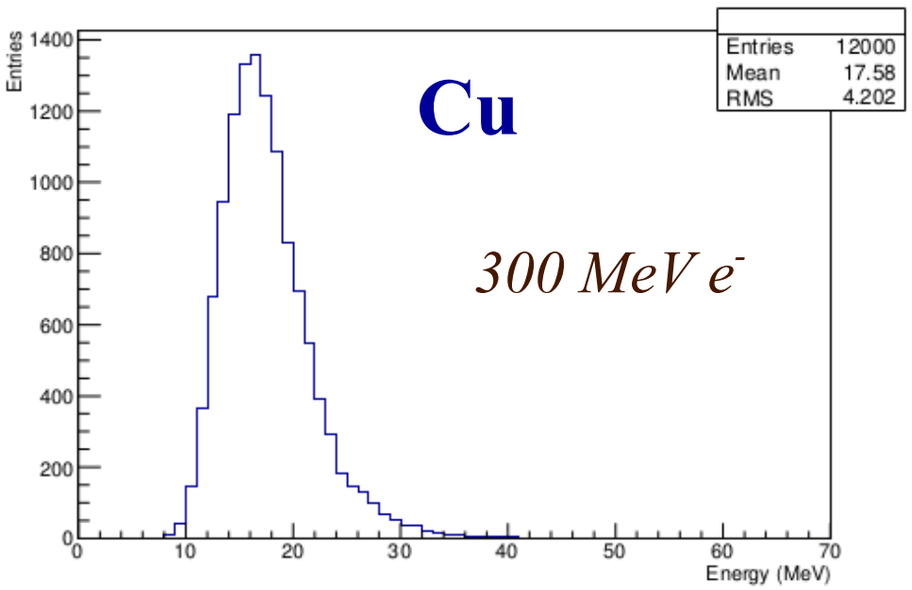


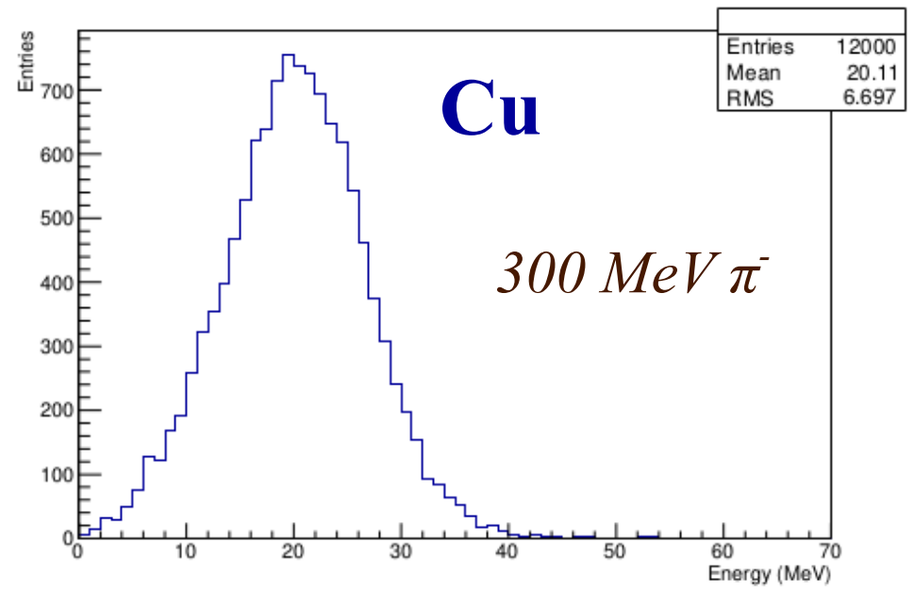



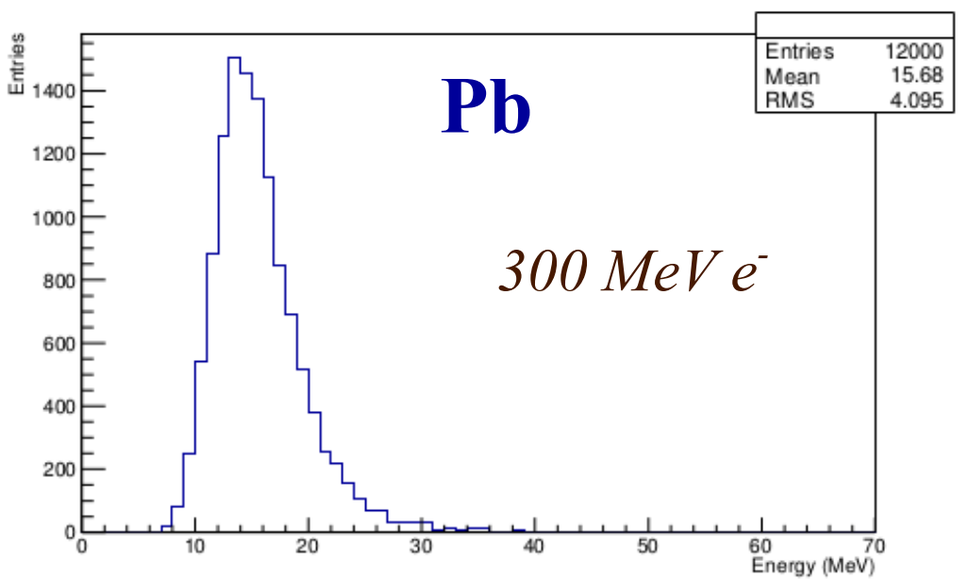



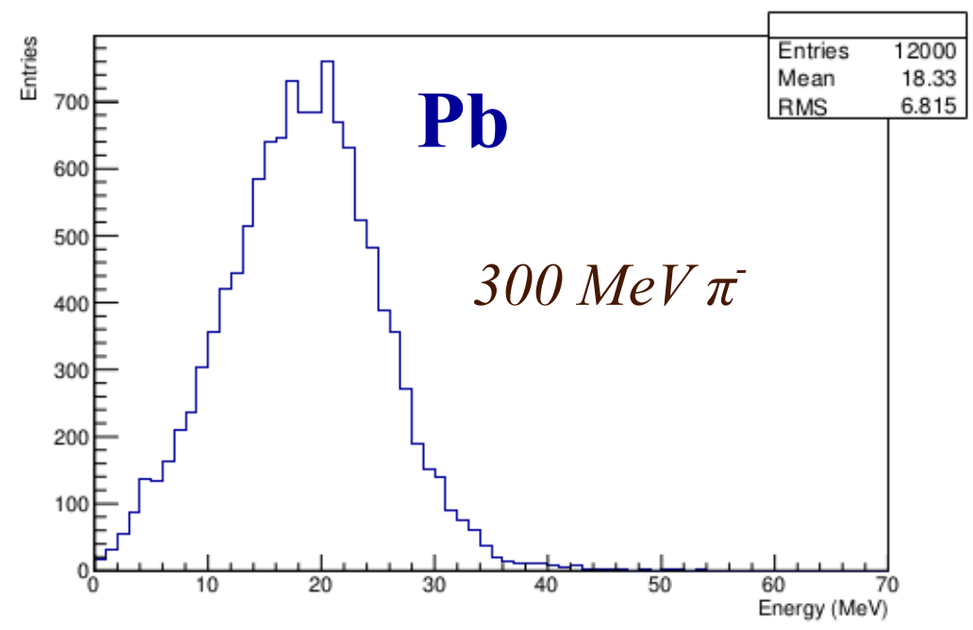
# low-energy performance - Copper vs. Lead

## *Energy deposited in scintillating fibres*



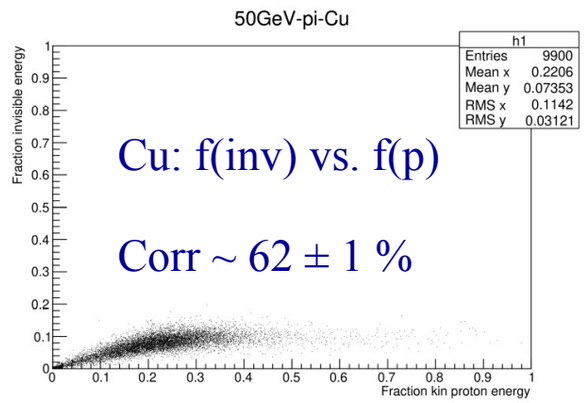



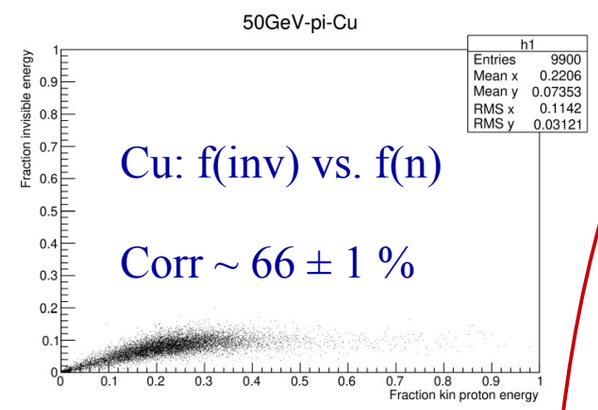



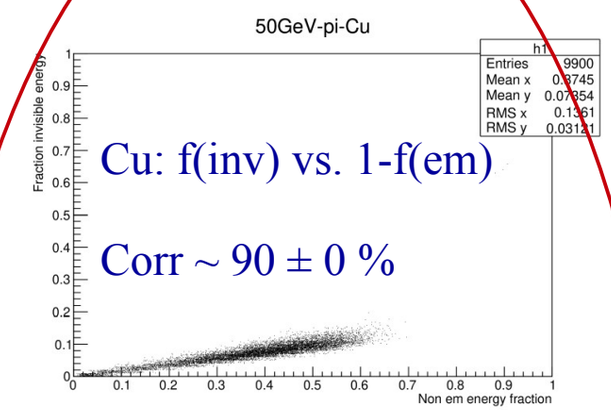
# invisible energy (50 GeV $\pi^-$) - correlations

$f(E)_{proton}$ → $f(E)_{neutron}$ → $1 - f_{em}$ →

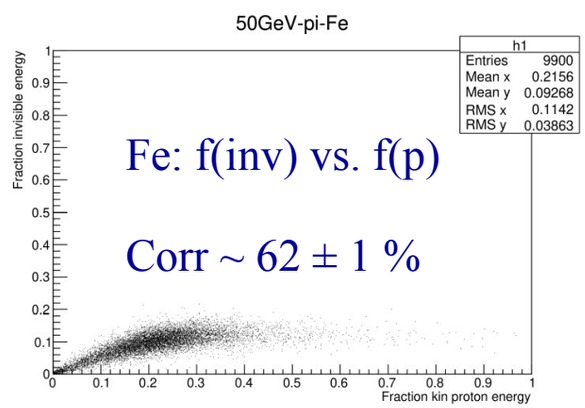
***Copper***

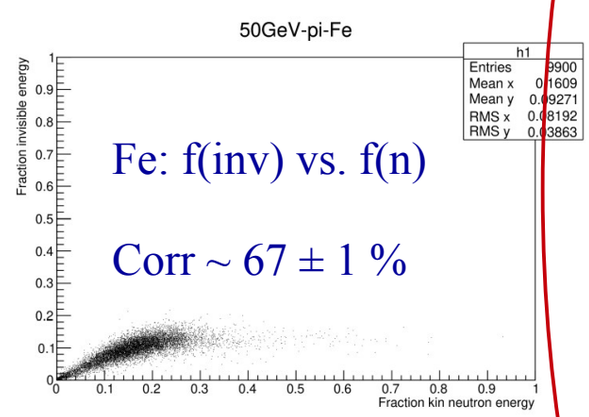


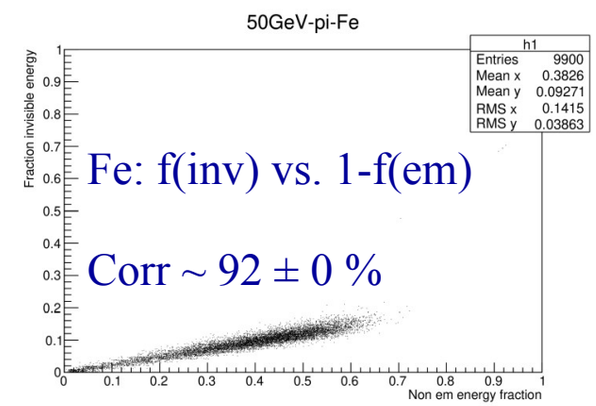



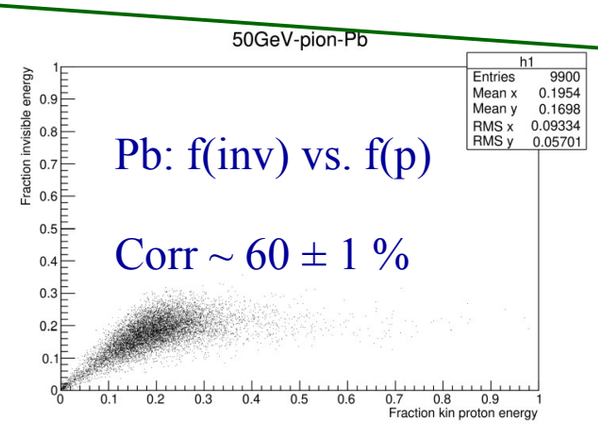

***Iron***

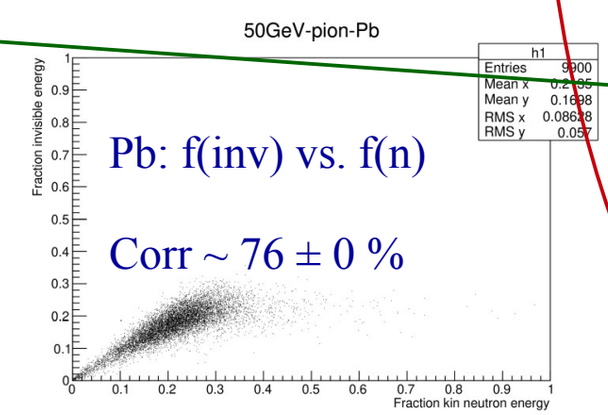


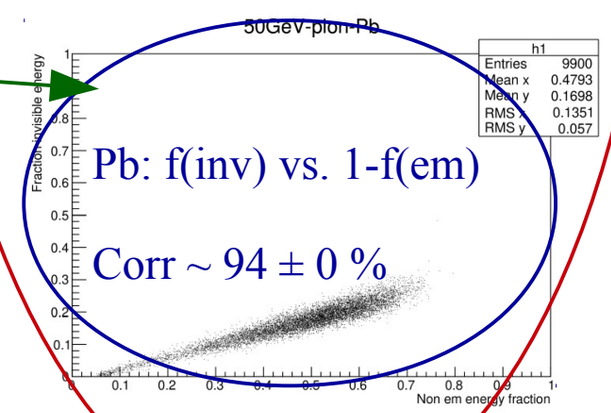




***Lead***

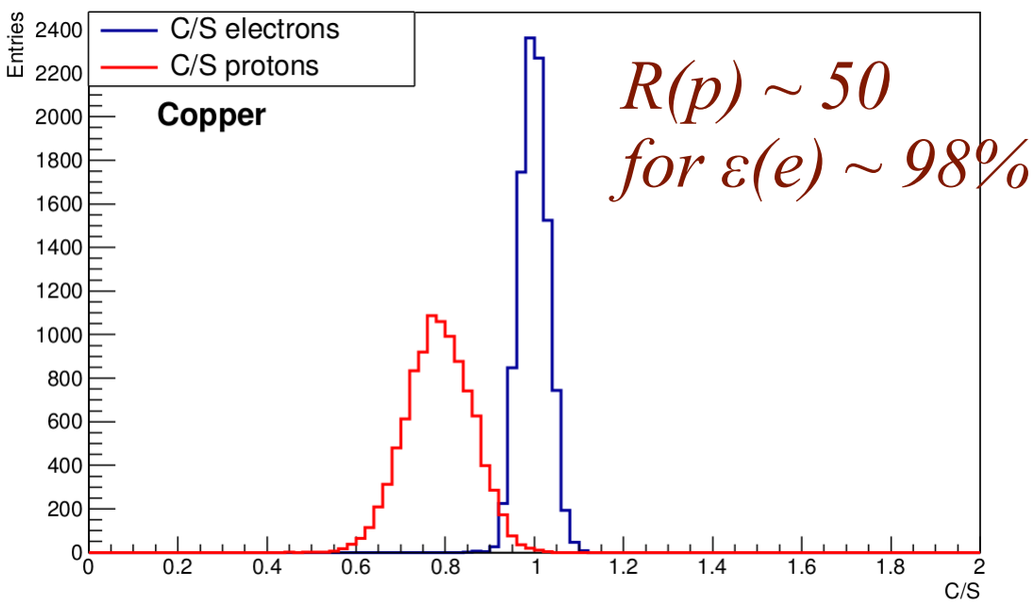


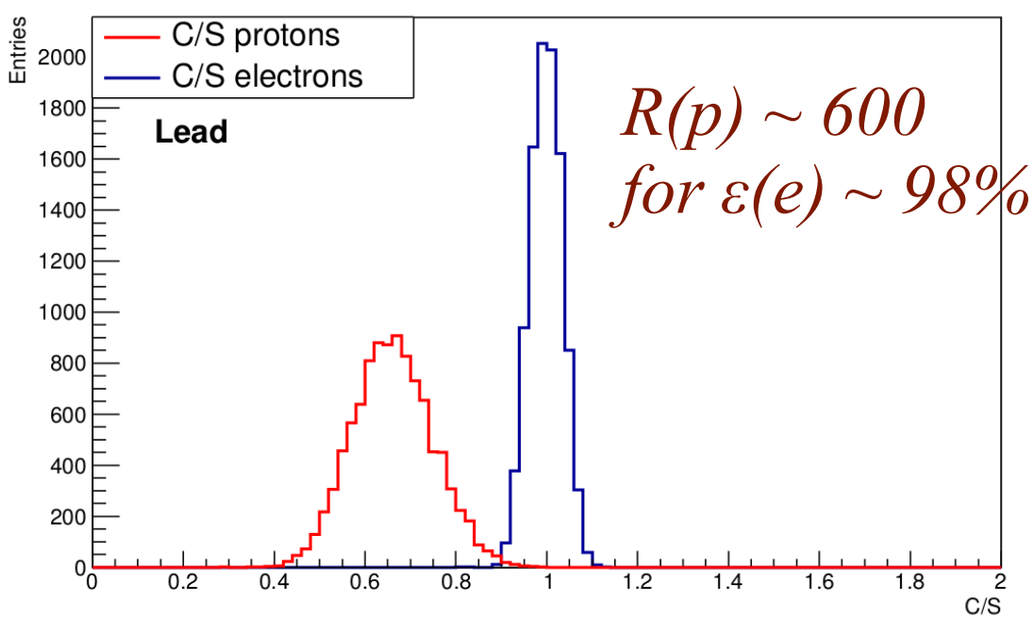



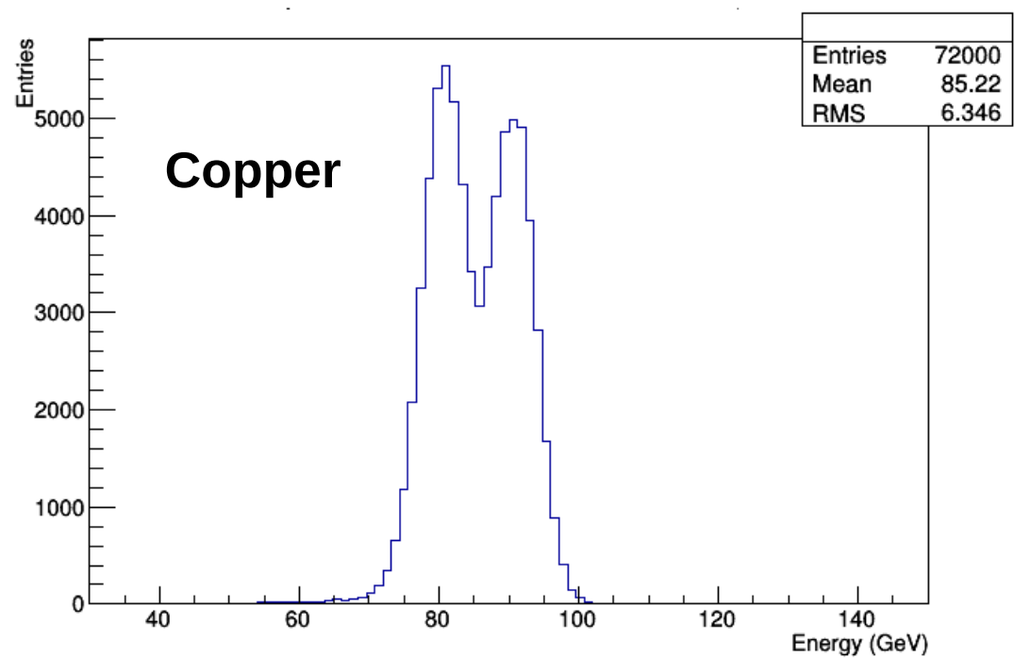
# particle Id & W/Z - copper vs. lead

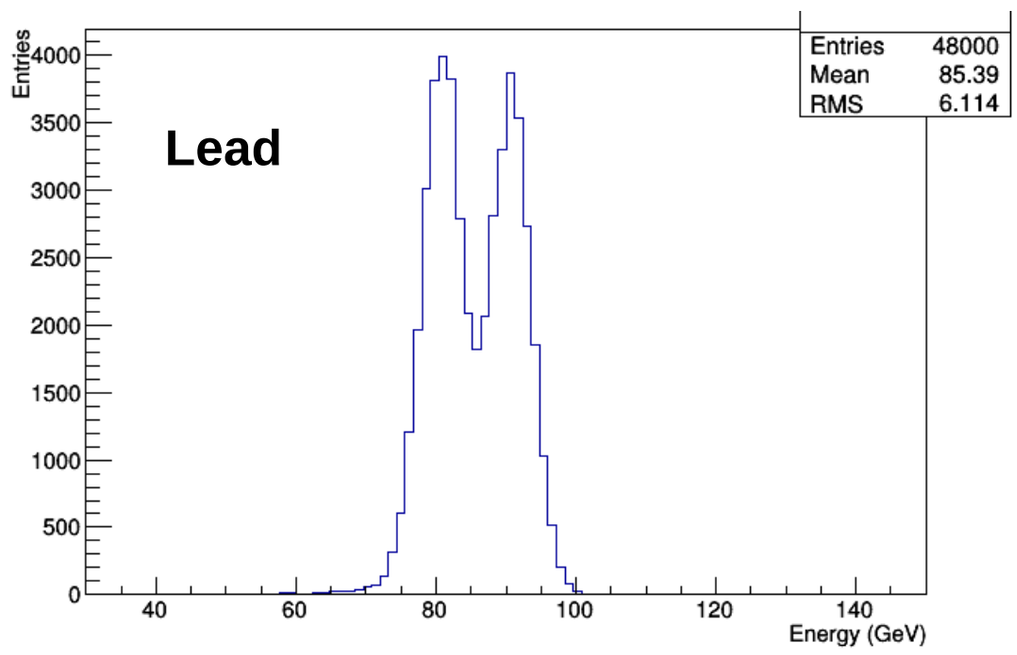
## *C/S ratio for 80 GeV e⁻ and p*




## *Multiple hadrons, 81 & 91 GeV*



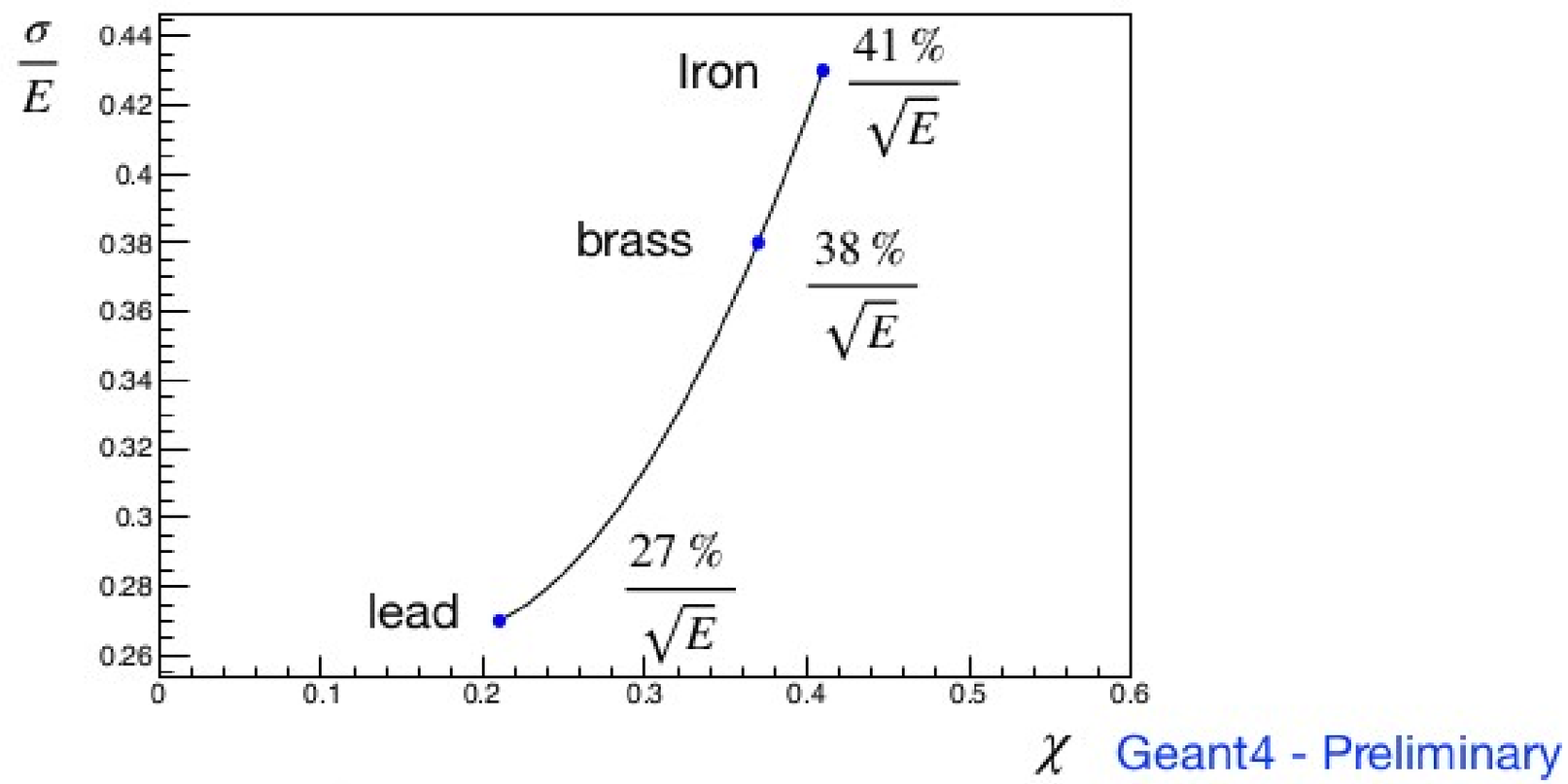
# impact on performance

hadronic performance
(dual-readout formula):

$$E = \frac{S - \chi C}{1 - \chi}$$

$$\chi = \frac{1 - (h/e)_s}{1 - (h/e)_c}$$

Hadronic resolution vs. χ




*χ : the lower the better ...*

em performance ~ almost unaffected
(dominated by sampling fluctuations)

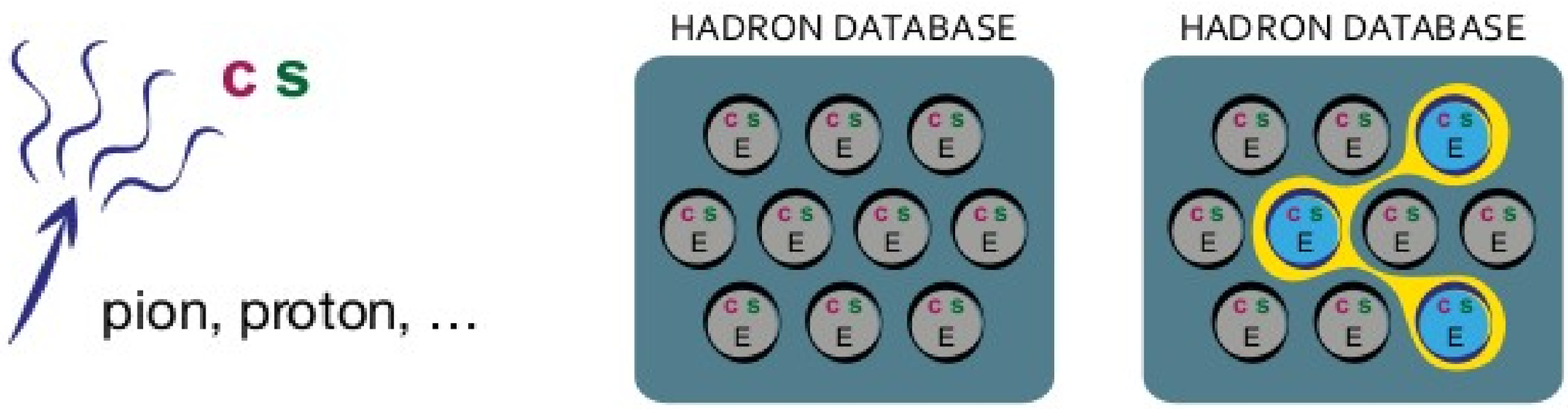
*take care: ideal, perfect, Geant4 detector*

# … a new way for energy reconstruction

## Machine Learning:

- create a calibration DB of events with C, S, E values
- search the closest (C, S) (really C/S) events → get E

→ *allows calibration with hadrons*



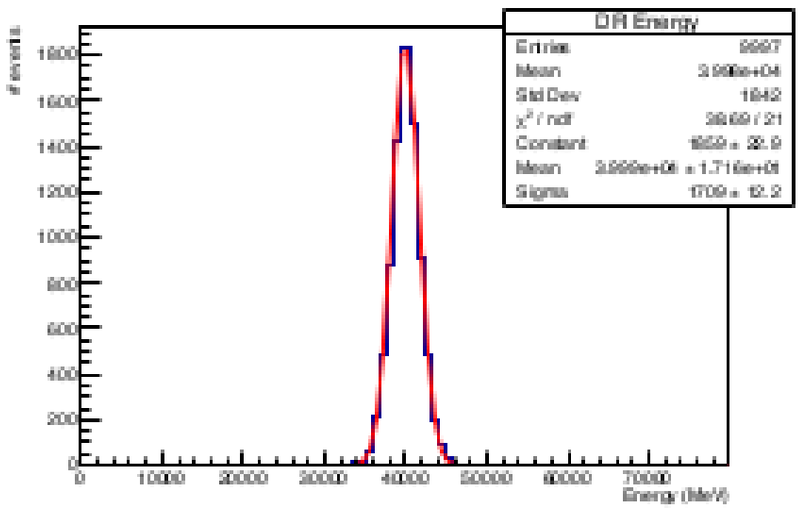

Reconstruct energy with:

$$E = \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{s_i}\times s + \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{c_i}\times c$$

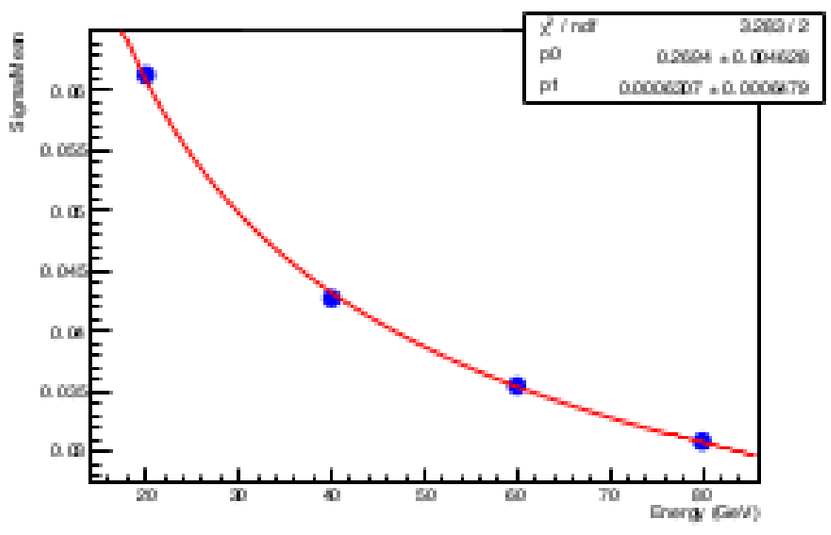
# DR vs. ML

Lead

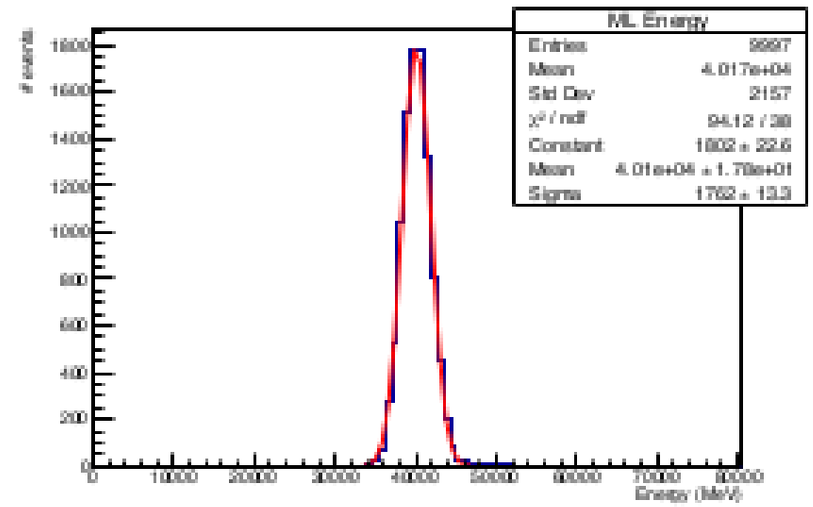
## DR



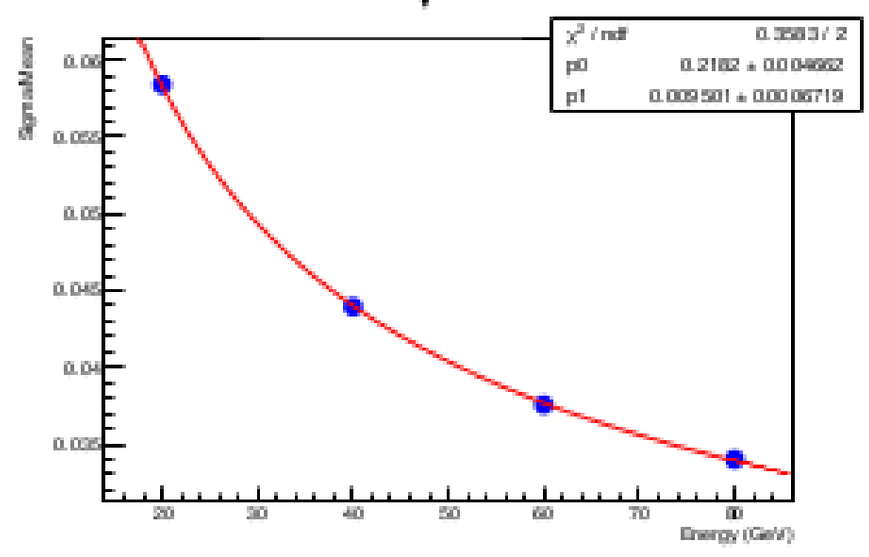

$$\frac{\sigma}{E} = \frac{27\,\%}{\sqrt{E}}$$




## ML




$$\frac{\sigma}{E} = \frac{22\,\%}{\sqrt{E}} \pm 0.9\,\%$$




Geant4 - Preliminary

# *ML performance*

## Hadronic resolution:

| | stochastic | constant |
|---|---|---|
| iron | 20 % | 2 % |
| brass | 22 % | 2 % |
| lead | 22 % | 1 % |
| tungsten | 23 % | 1 % |
| platinum | 23 % | 1 % |

*Geant4 – Very Very Preliminary*

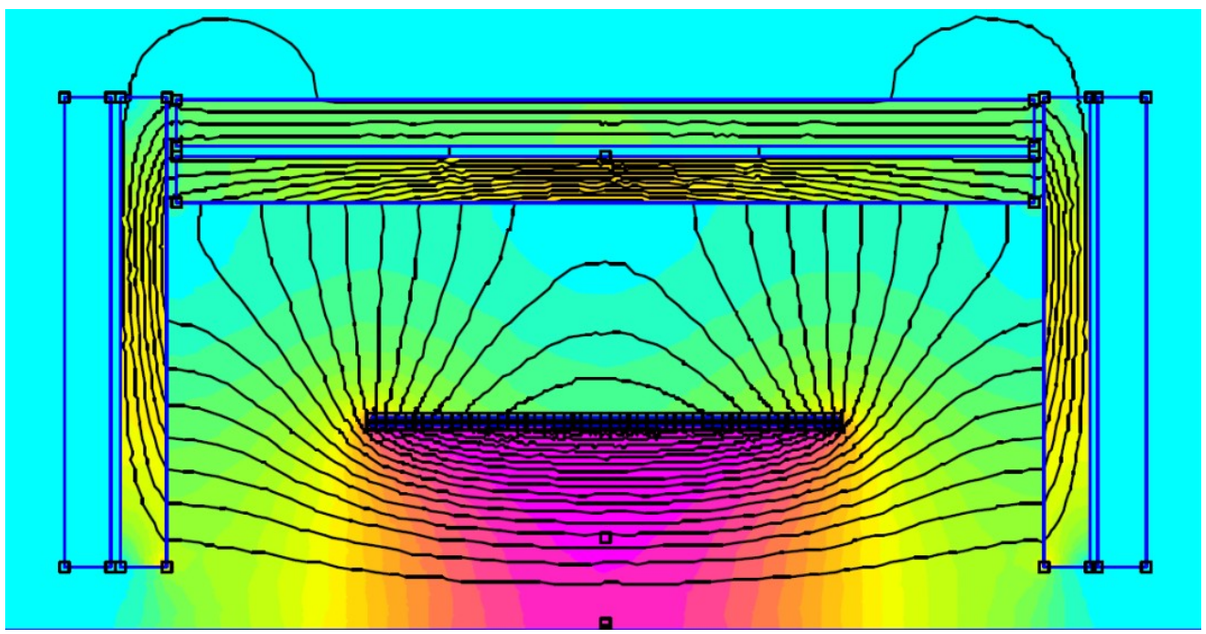
→ almost independent of absorber material

→ do NOT take too seriously absolute values !

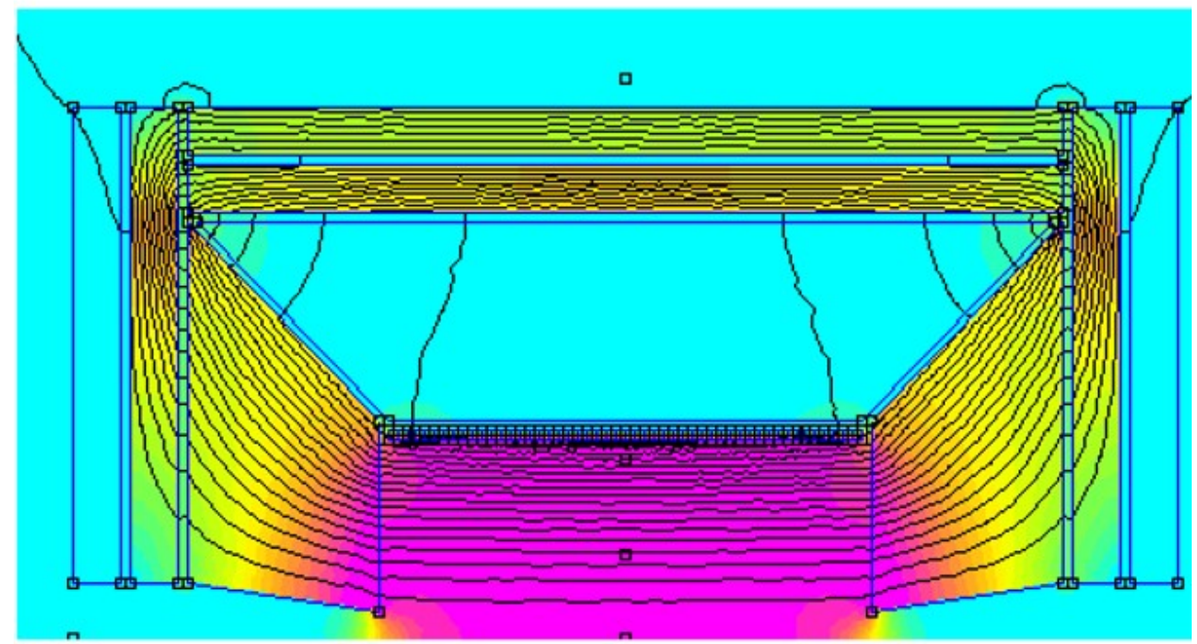
→ may provide a powerful tool for calibration and stability

# *last but not least ...*

## Magnetic field homogeneity → IRON



*Lead absorber*

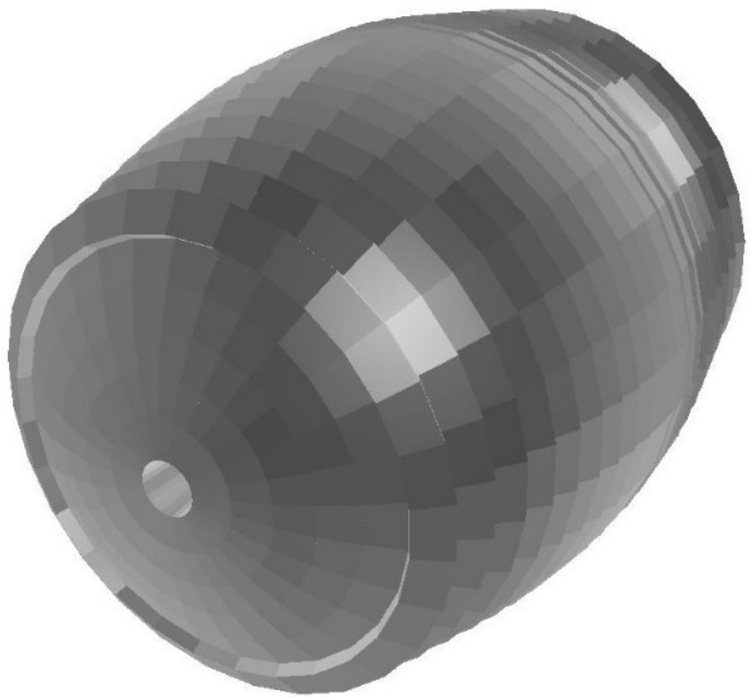


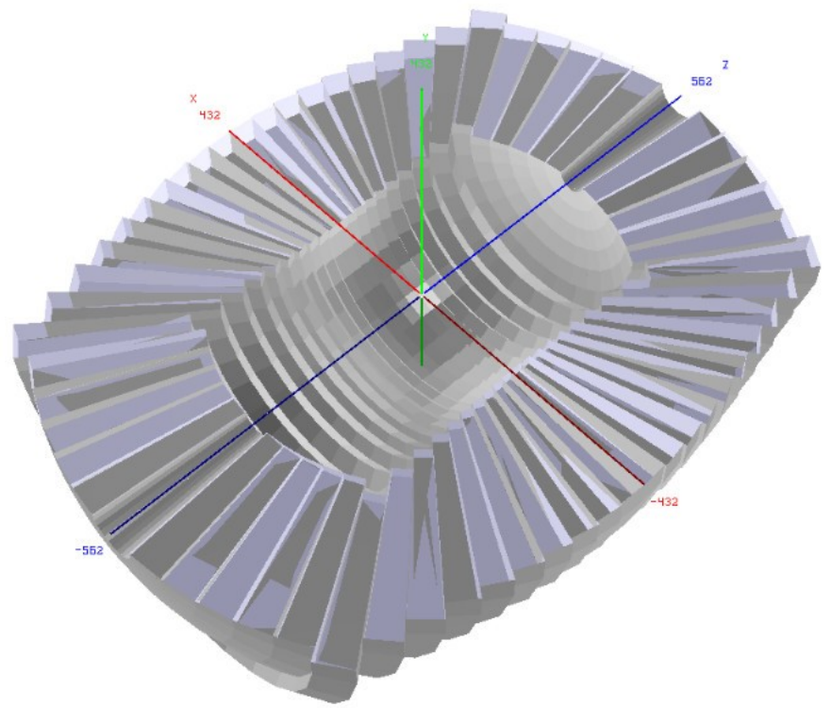
*→ forward with Iron*

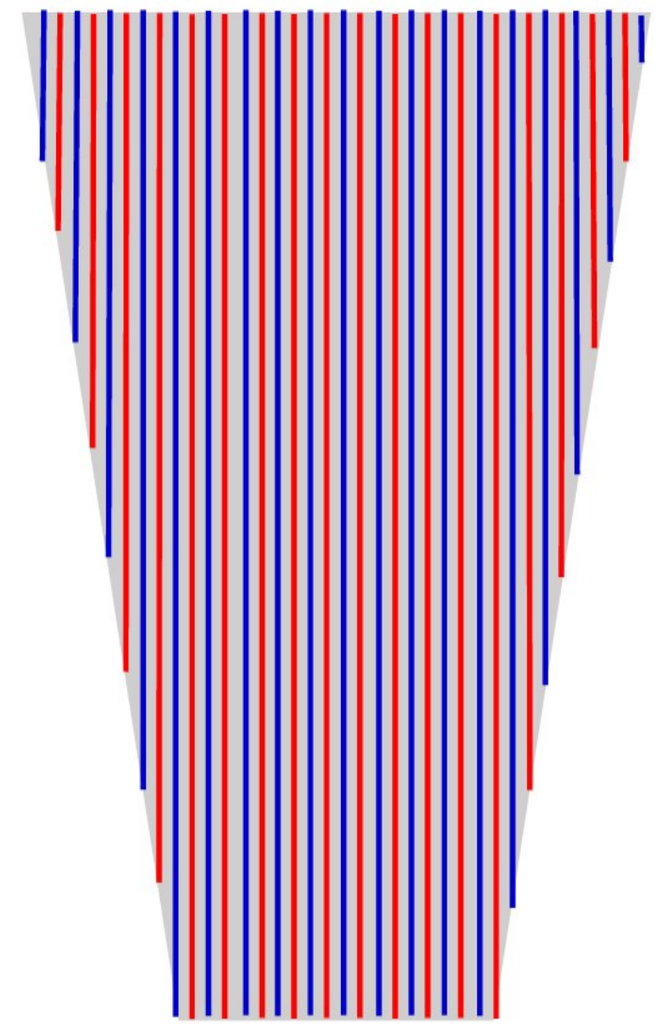
forward only → almost as good as with full iron

# 4π Simulations

*Dual-readout calorimeter description for CepC/FCCee simulation sw:*

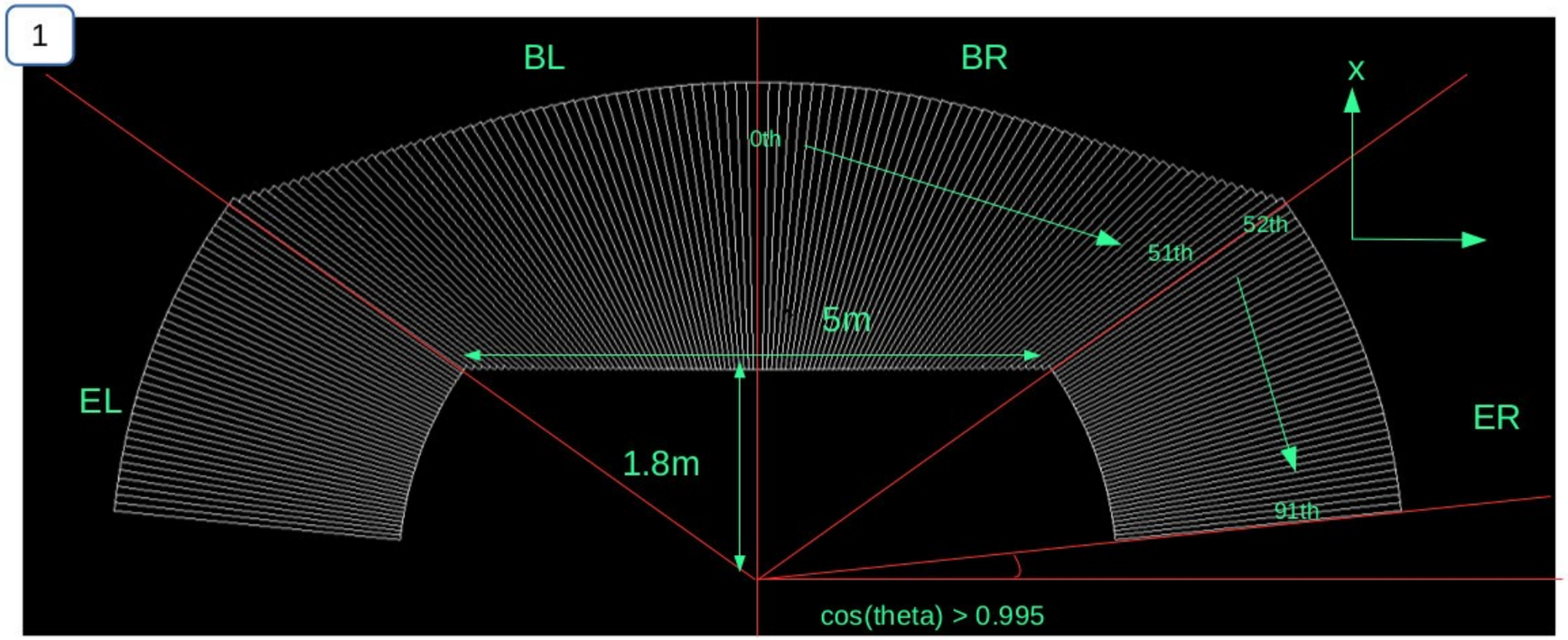


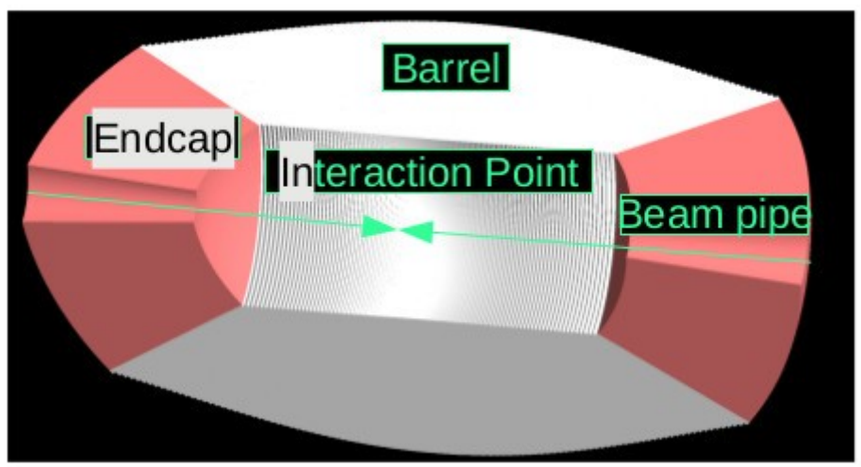


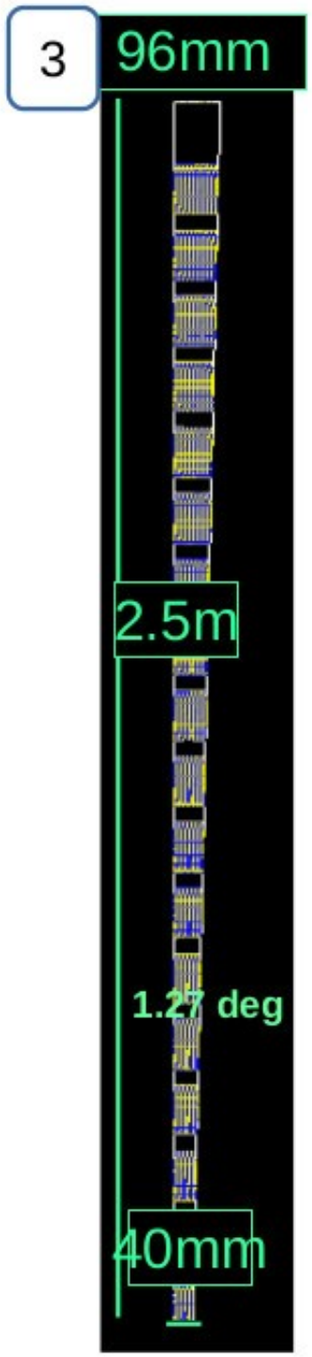



*a) full coverage*
*b) projective geometry*

# Wedge Geometry

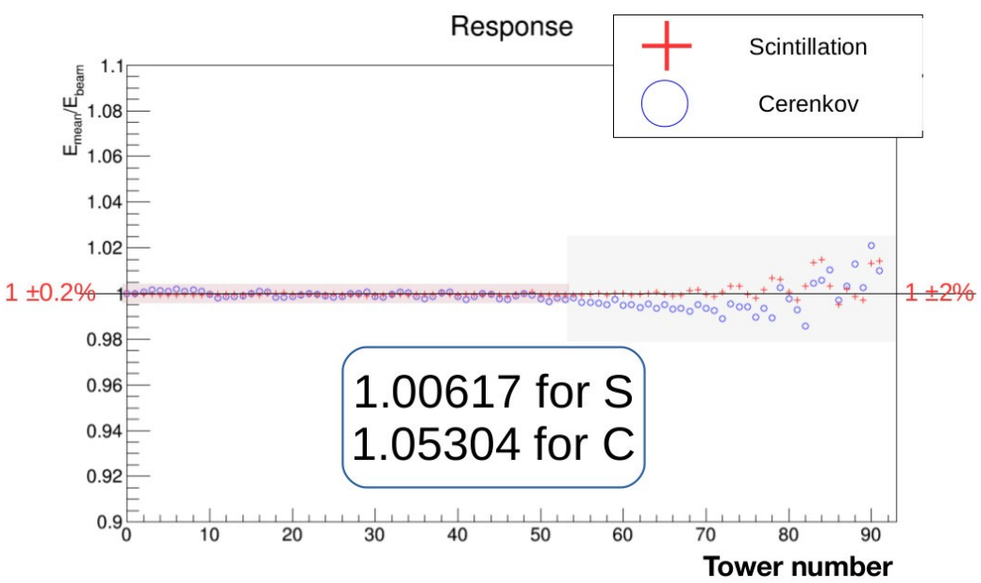


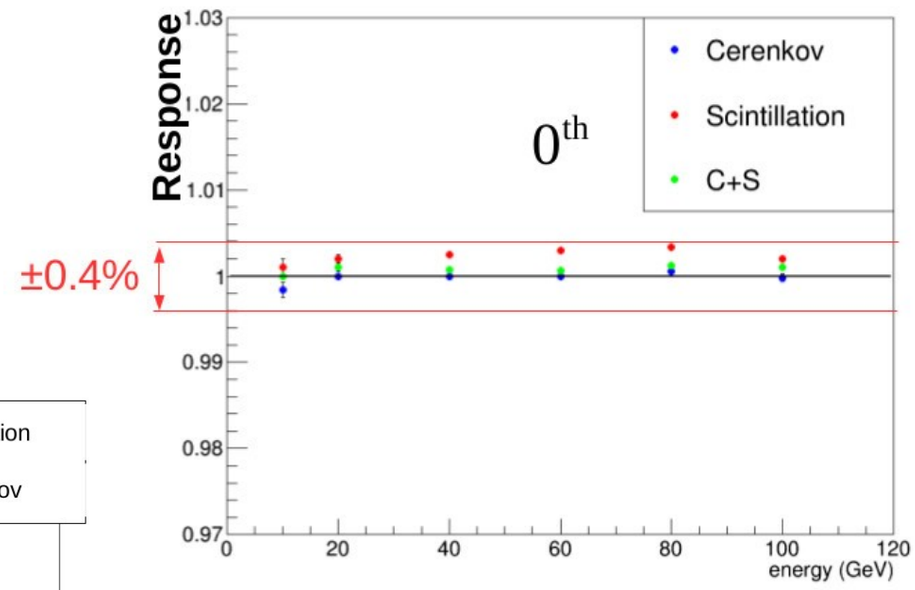



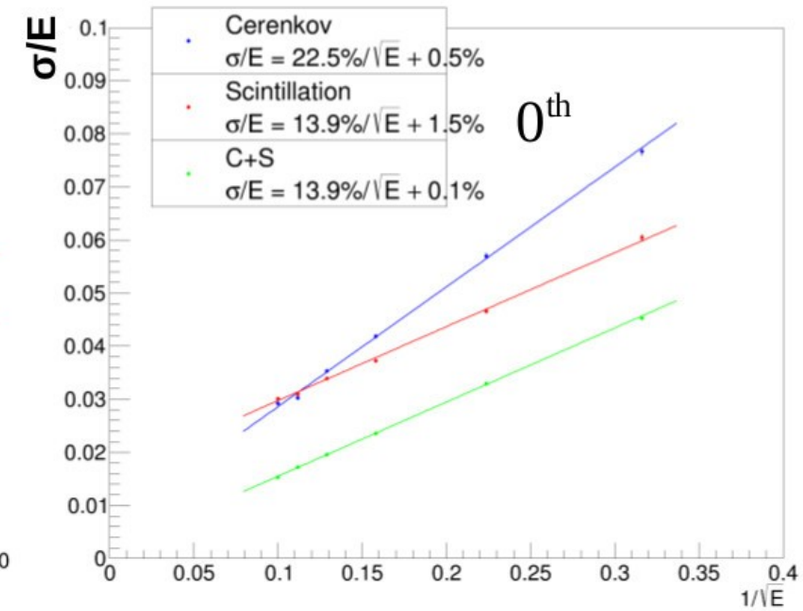




*Čerenkov light yield set to 30 p.e./GeV*
*Calibrated w/ 20 GeV $e^-$ beam @ [1°, 1.5°]*

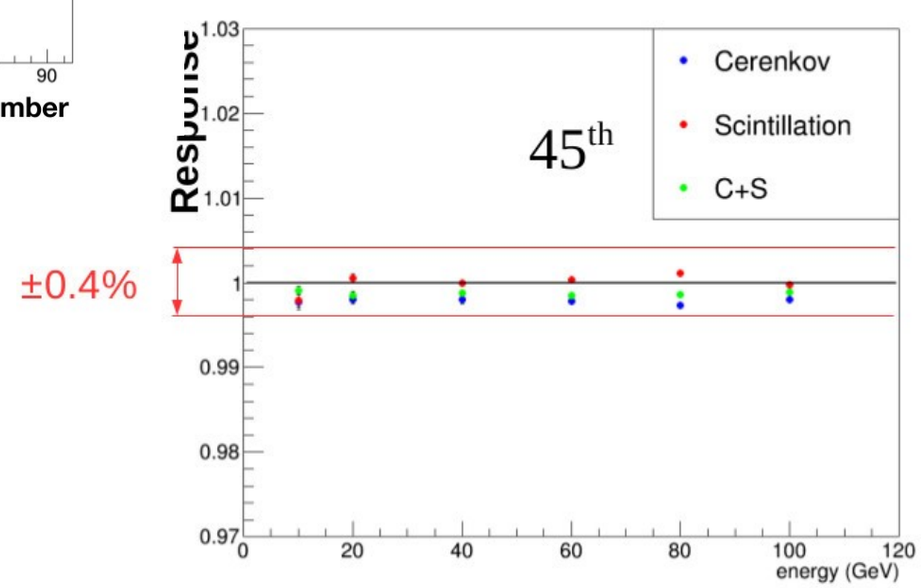
# *em* Performance

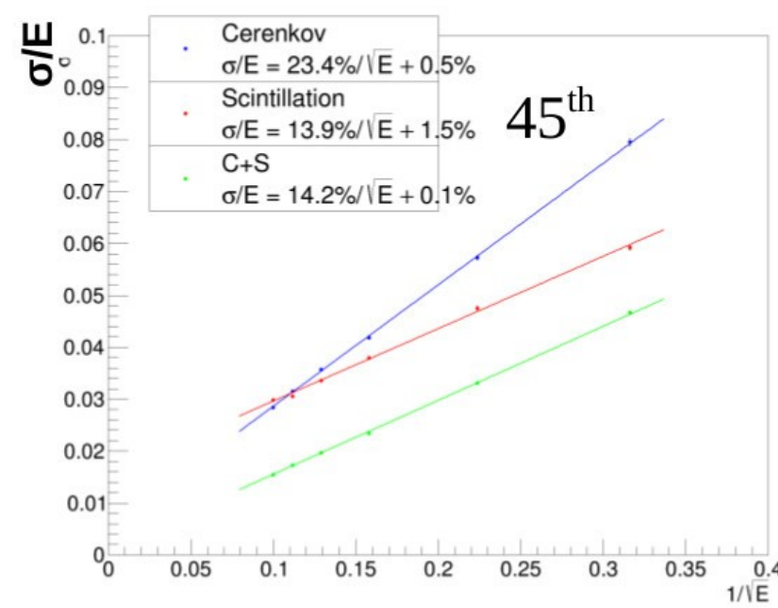



$$\sigma/E \sim 14.0\% / \sqrt{E} + 0.1\%$$



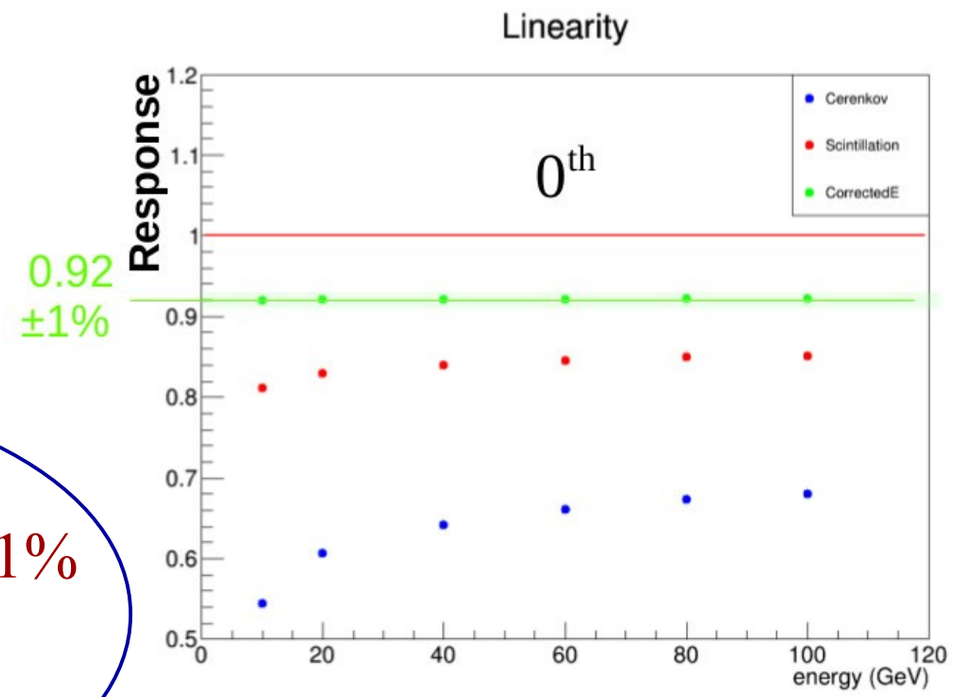
# *had* Performance

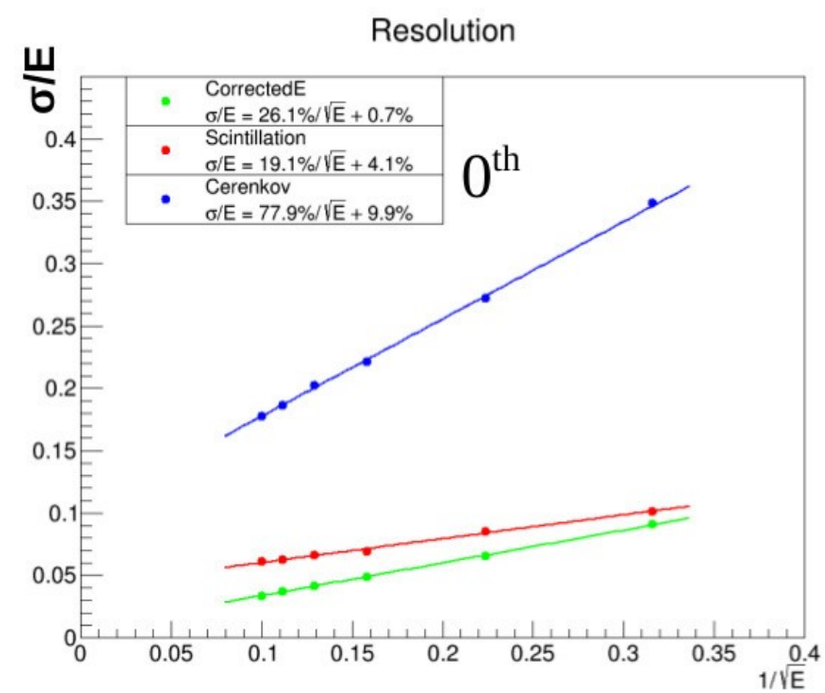
$$E = \frac{S - \chi C}{1 - \chi}$$

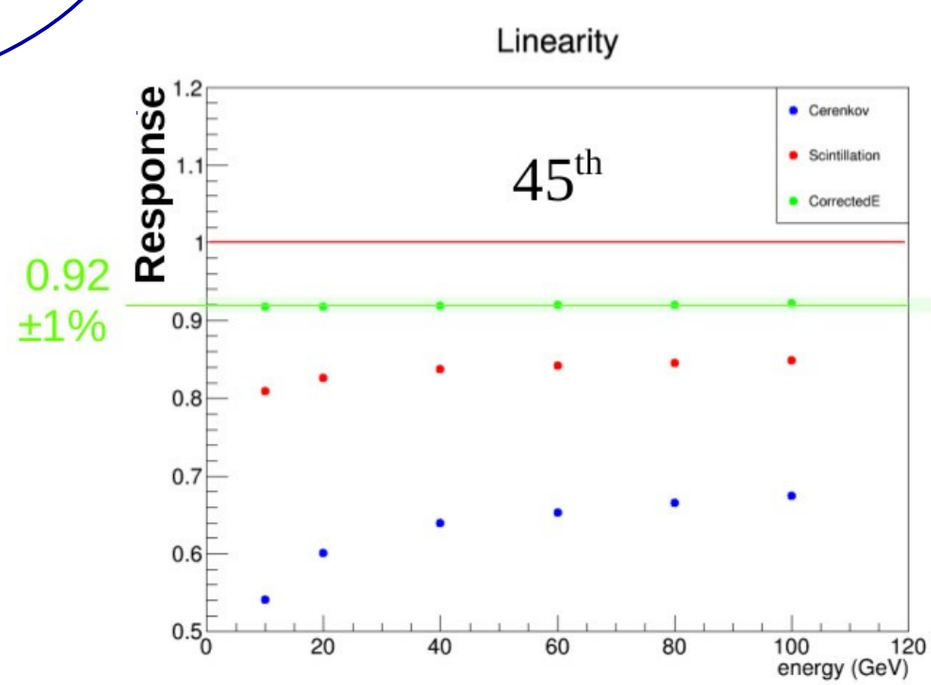
with $\chi = 0.29$

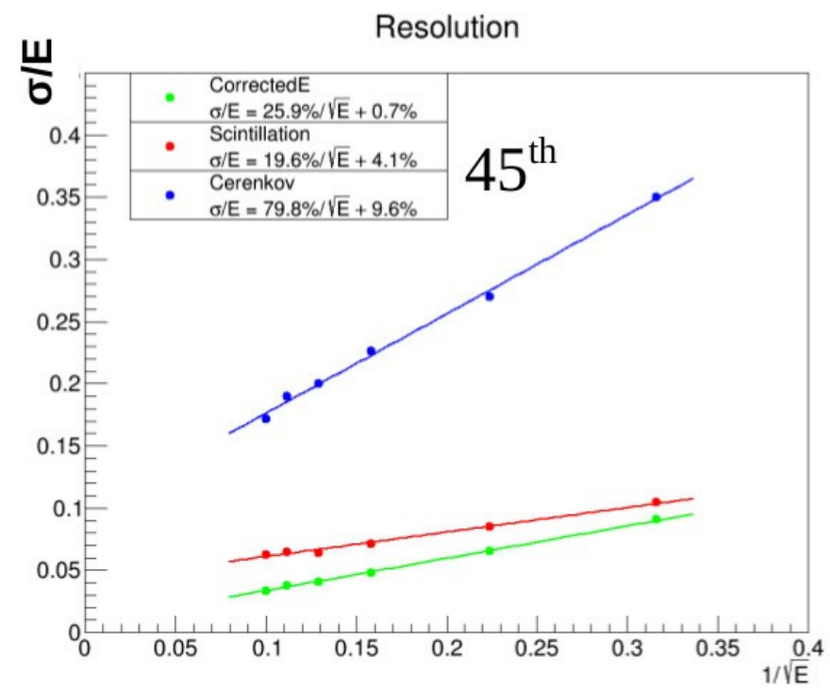
E(rec)/E(beam) ~ 92% ± 1%

σ/E ~ 26% / √E + 1%



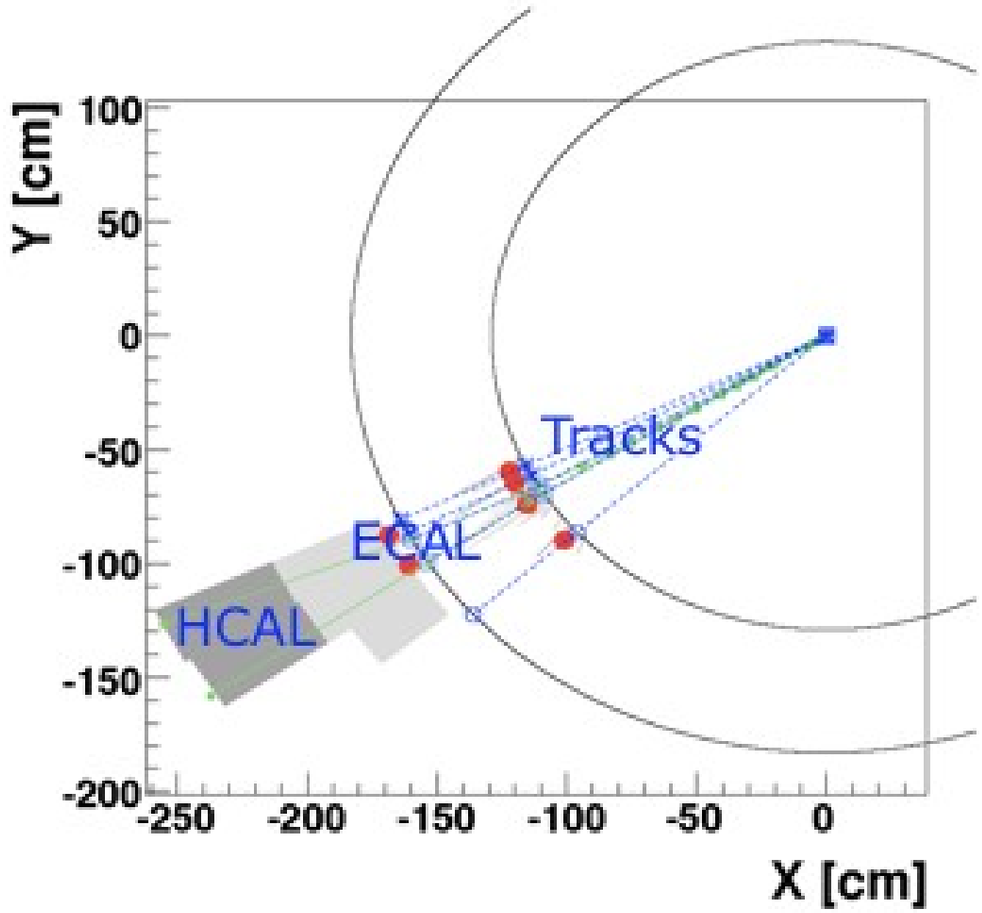
# *particle flow approach*

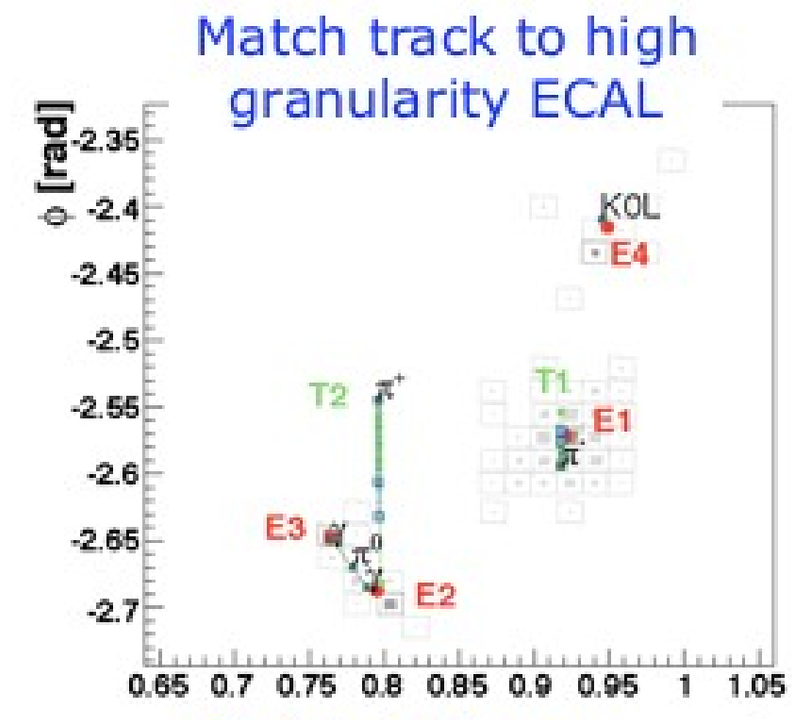
all (shower) particles and energy deposits tracked

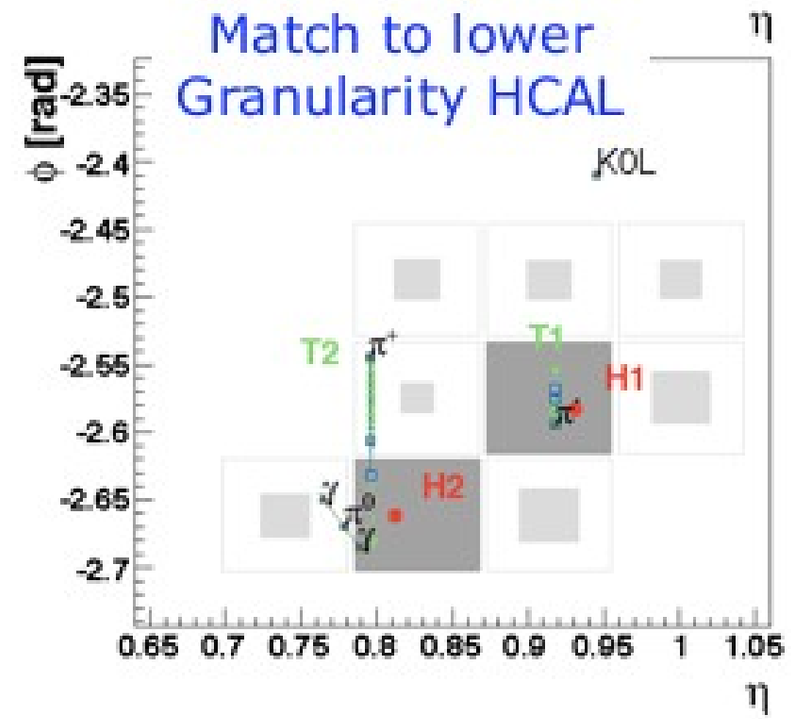
requires separation of em and hadronic shower deposits for jets (and τ-jets)

→ needs some longitudinal segmentation

# *particle flow ?*

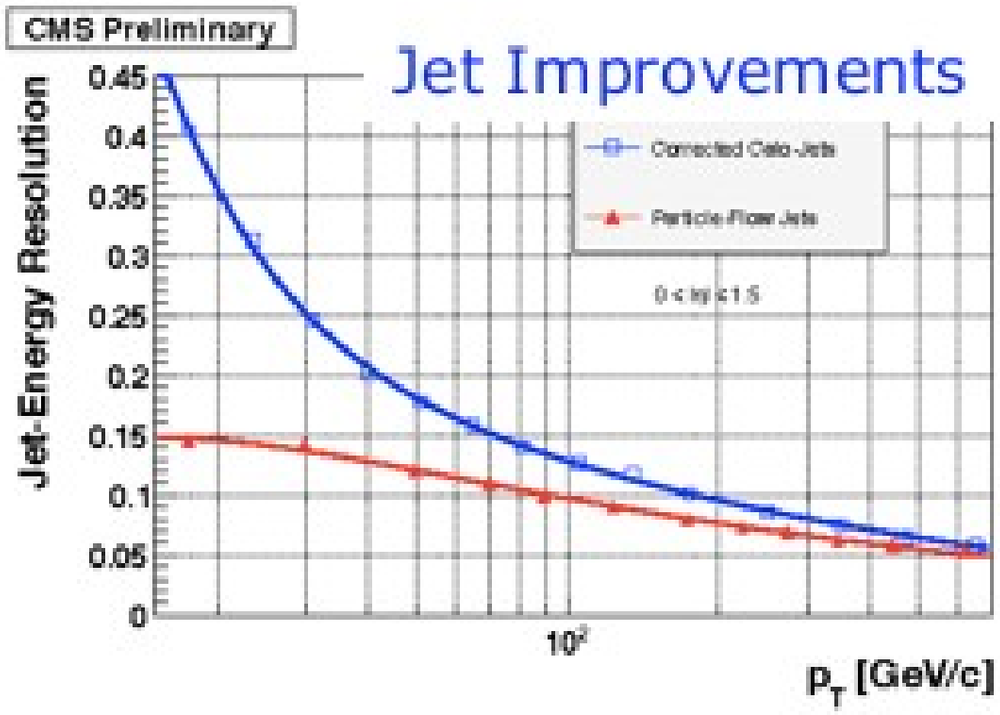


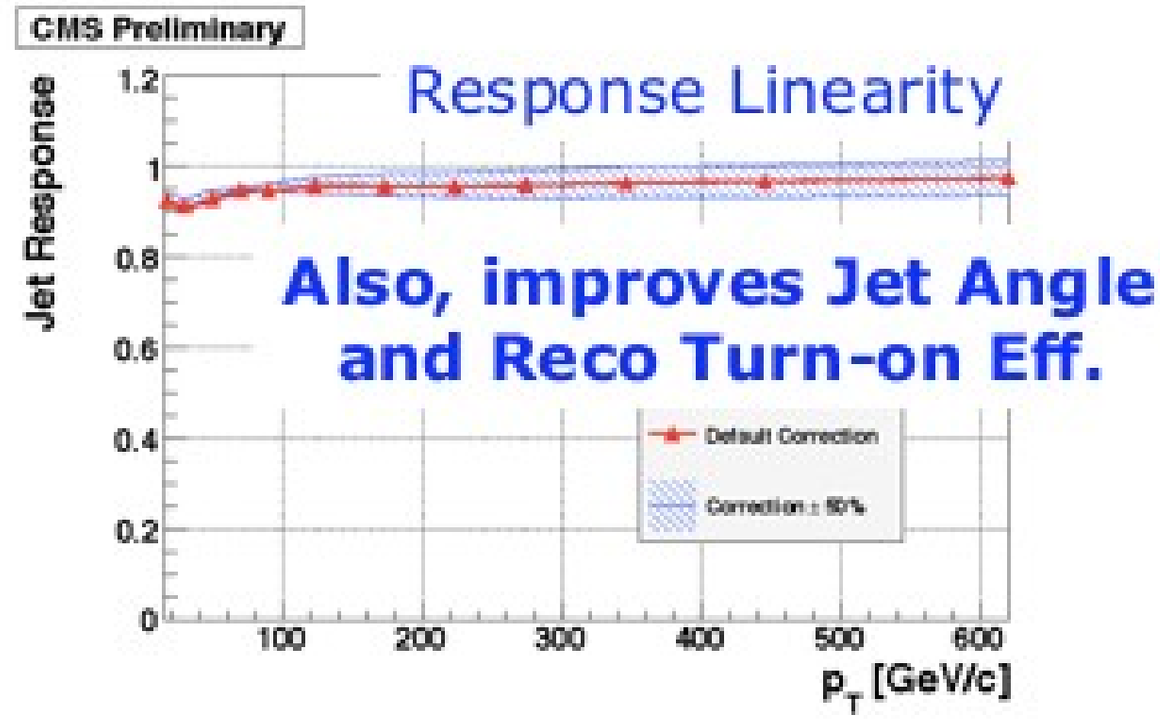



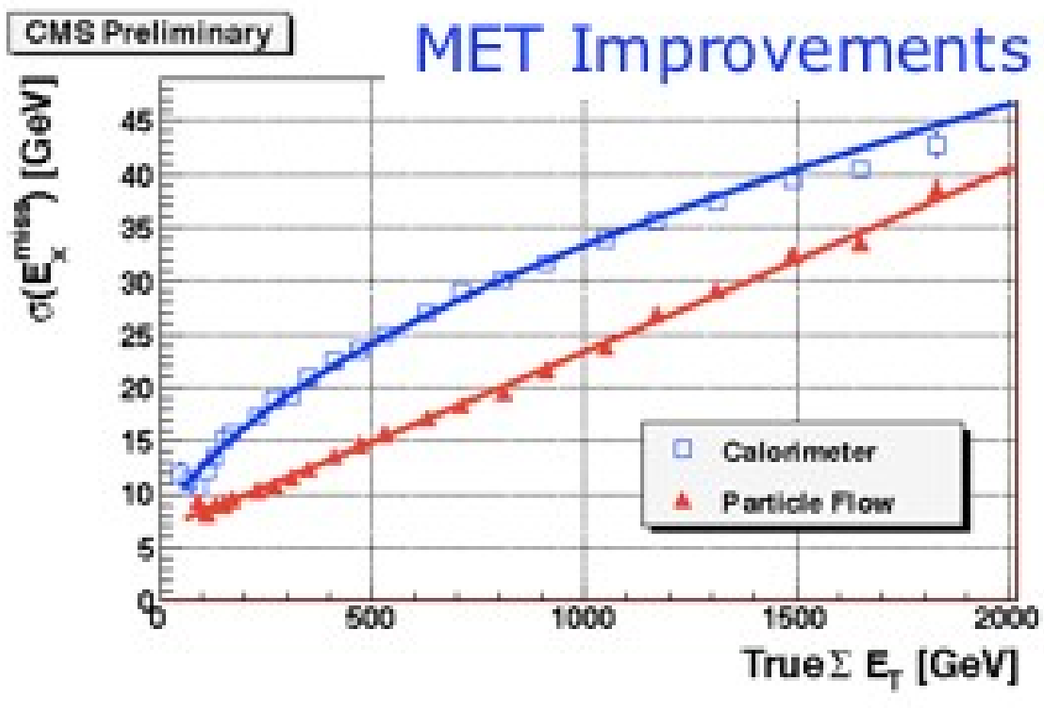



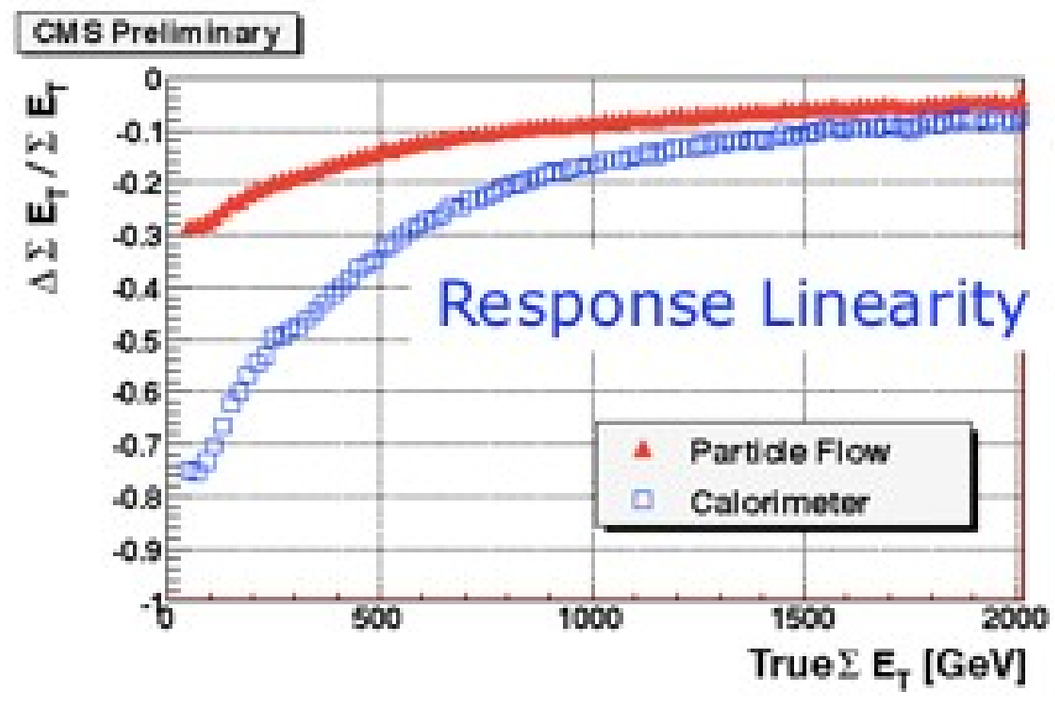

- high-precision tracking (and em calo)
- measure charged particle in tracker
- remove corresponding energy clusters
- calorimetry to only account for neutrals

# *particle flow*



# *d.r. calo longitudinal segmentation*

of course possible:

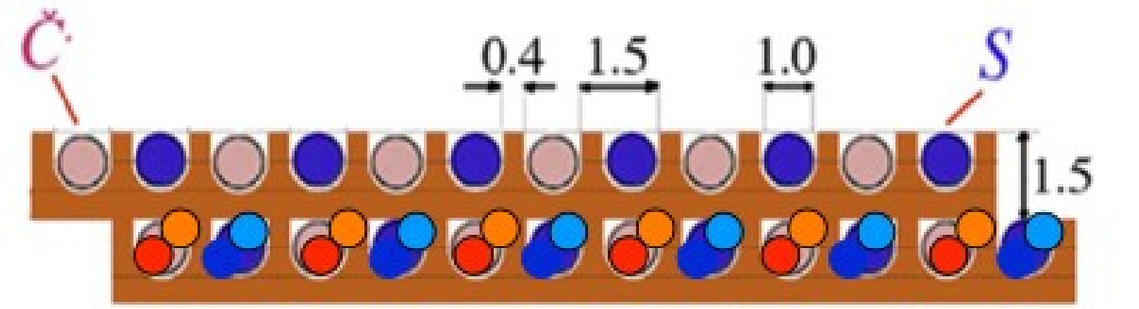
- one (lead ?) em compartment
- one (or more) (iron or copper ?) had comp.
- could be separately optimised

Drawbacks:

- complexity and cost
  (powering, cooling, readout, ...)

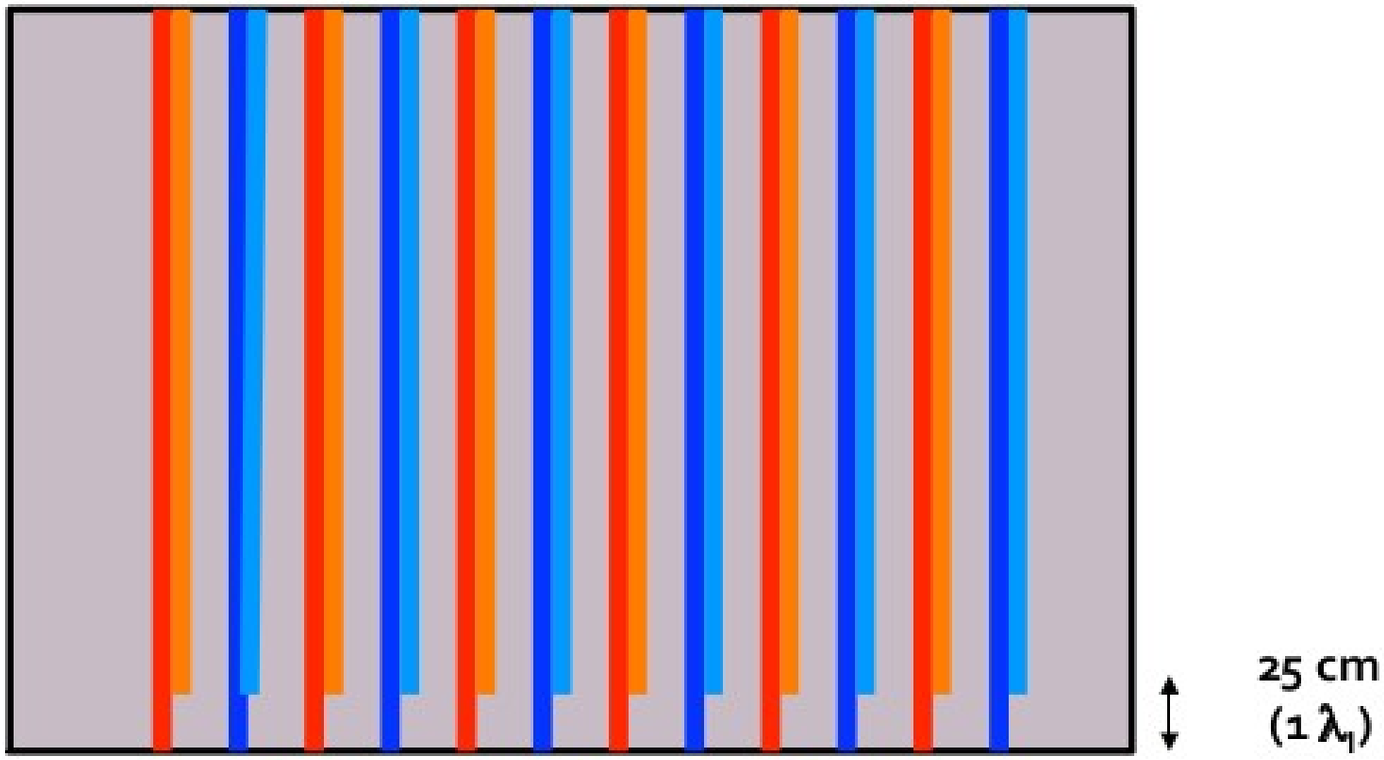
*alternative: fibres w/ 2-3 different lengths ?*

# *different-length (staggered) fibres ?*




*(at least) 4 kind of fibres:*

*S-short, S-long,*
*C-short, C-long*



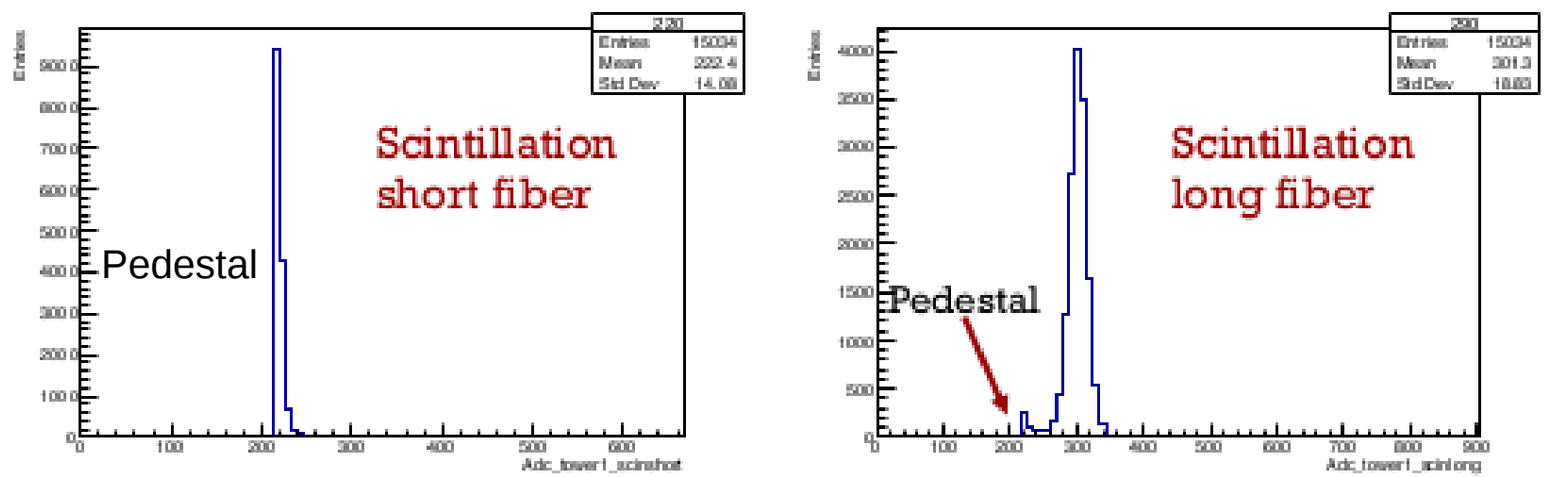

*short fibres → hadronic compartment(s)*

# 2018 staggered-fibre prototype

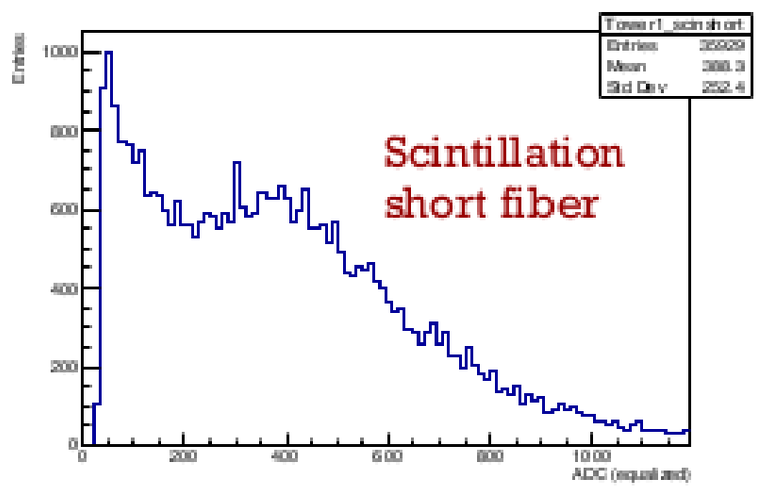
(9.3 × 9.3 × 250 cm$^3$) lead module → 4 towers → 16 readout signals

2018 testbeam:

20 GeV electron beam centred in tower 1




60 GeV pions centred in tower 1




The response of short fibers can only be studied with pions

# *tiles vs. fibres*

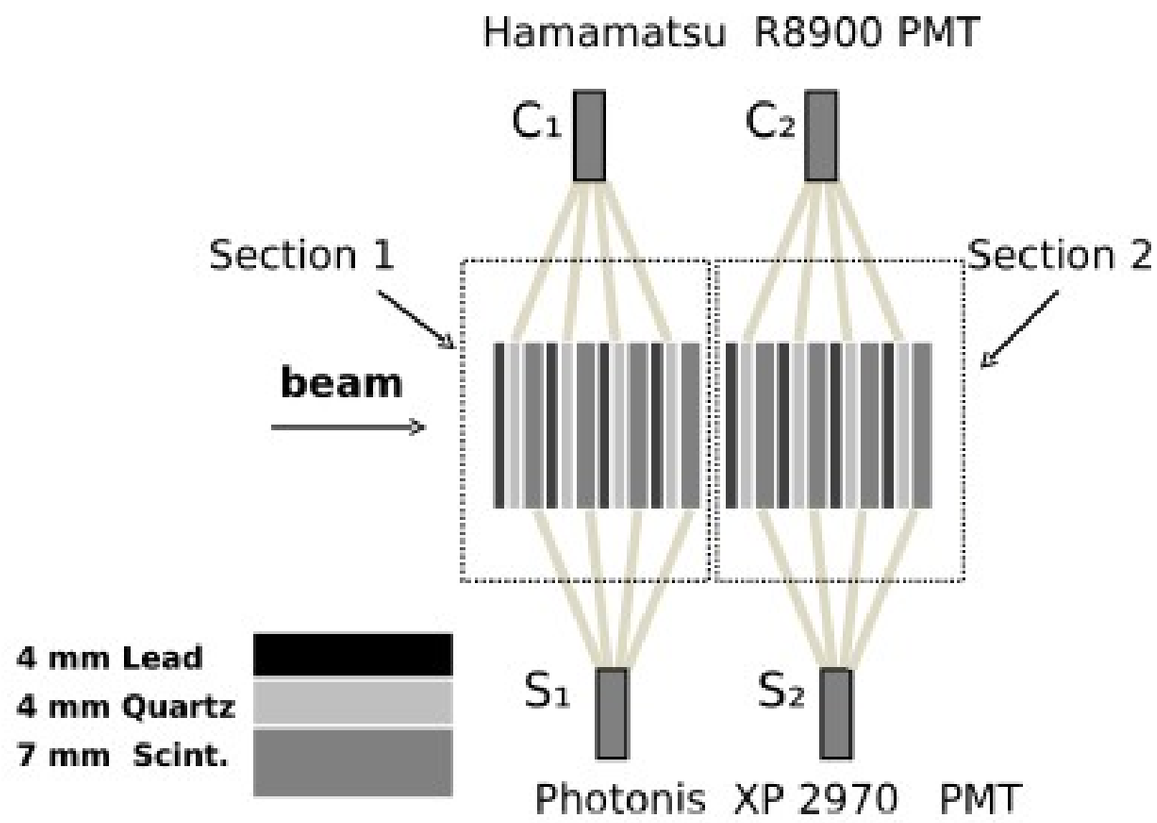
→ + tiles : fully tunable longitudinal segmentation
→ + tiles : no attenuation length issues
→ + tiles : no fibre-to-fibre fluctuation issues
→ + tiles : simpler and cheaper

→ + fibres : lateral segmentation
→ + fibres : highly homogeneous and compact
→ + fibres : higher sampling frequency
→ lower sampling fraction - $f_{samp}$
→ lower volume

$\sigma_{samp} \sim 2.7\% \times \sqrt{(d/f_{samp})}$ :

$\sigma_{samp} \sim 10\% \Leftrightarrow f_{samp} \sim 7\% \times d(mm)$

# RD52 tile prototype



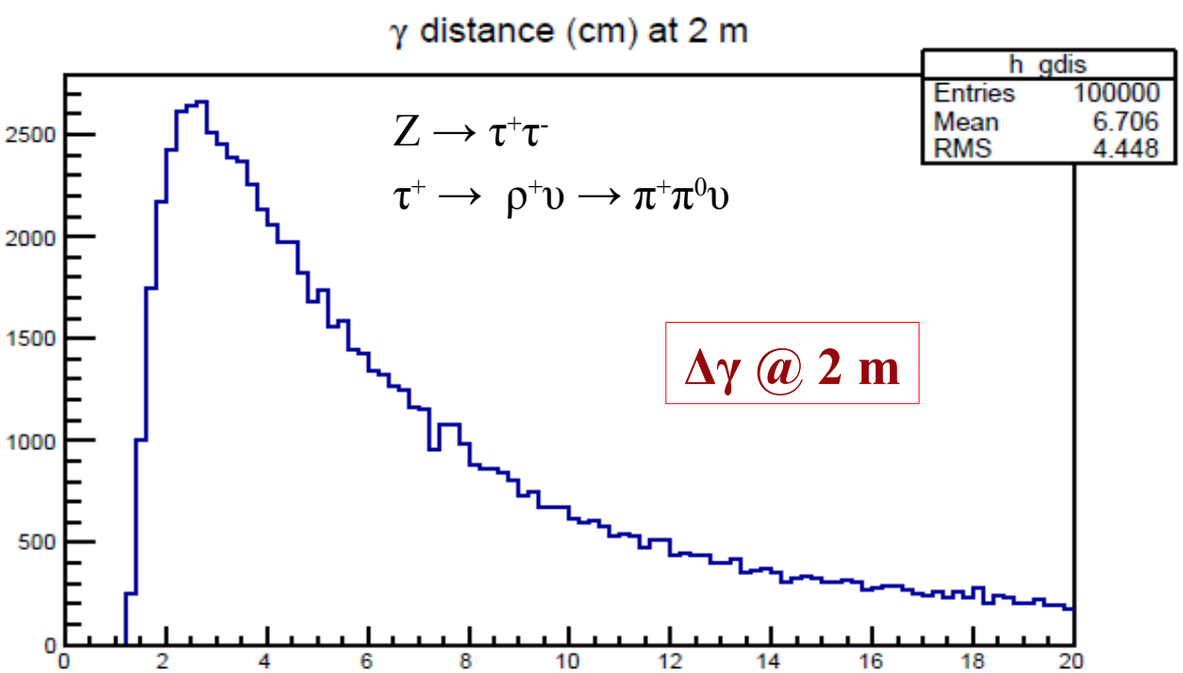

Č light yield ~ 50 p.e. / GeV … interesting … but …

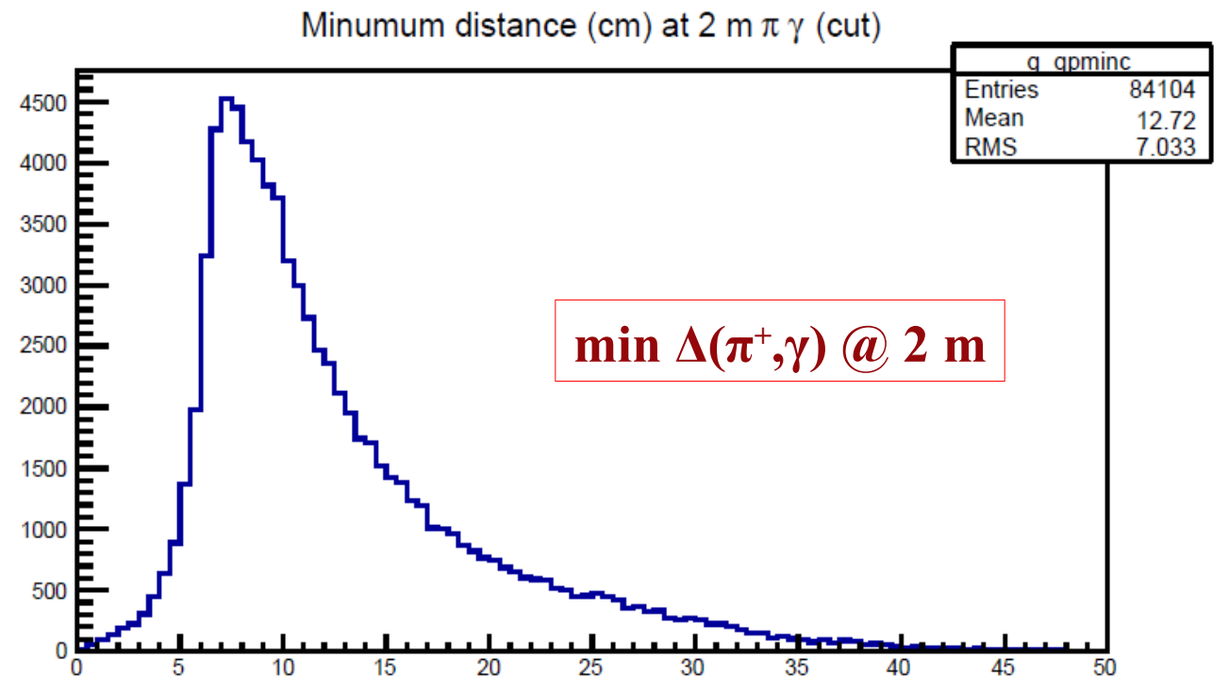
absorber : active volume = 27 : 73 = ~ 0.4
(vs. ~ 2 in RD52 lead matrix)

# *but …*

what the most probing benchmark for longitudinal segmentation ?

# the $\tau^{\pm} \rightarrow \rho^{\pm}\upsilon \rightarrow \pi^{\pm}\pi^{0}\upsilon$ case




*At a "naive" simulation, energy deposits look distinguishable*

*→ to be assessed w/ realistic detector simulations*

# *moreover … B field impact*

for B = 2 T , $R_{cal}$ = 2.5 m , charged particles will impact calorimeter with angle:

$$\alpha = R_{cal} / (2 \times R_{bend}) = \sim 2.5 / (2 \times P_T / 0.6)$$
$$= \sim 750 \text{ mrad} / P_T$$

10 GeV ($P_T$) charged tracks, after 60 cm, displaced by ~ 4.5 cm

→ issues only with neutral hadrons ($K_L$, n) ?

# *machine learning for jets*

Simplified jet model assuming:

fragmentation function

$$D(z) = (\alpha + 1)\frac{(1-z)^{\alpha}}{z}$$

$\alpha = 3$

$z =$ *jet energy fraction*

Jet composition

90 % *pion* 10 % *kaon*

30 % *neutral* 70 % *charged*

$$E = \frac{S - \chi C}{1 - \chi}$$

Electrons and gammas — **Yes**

Hard hadrons (undergoing nuclear interactions) — **Yes**

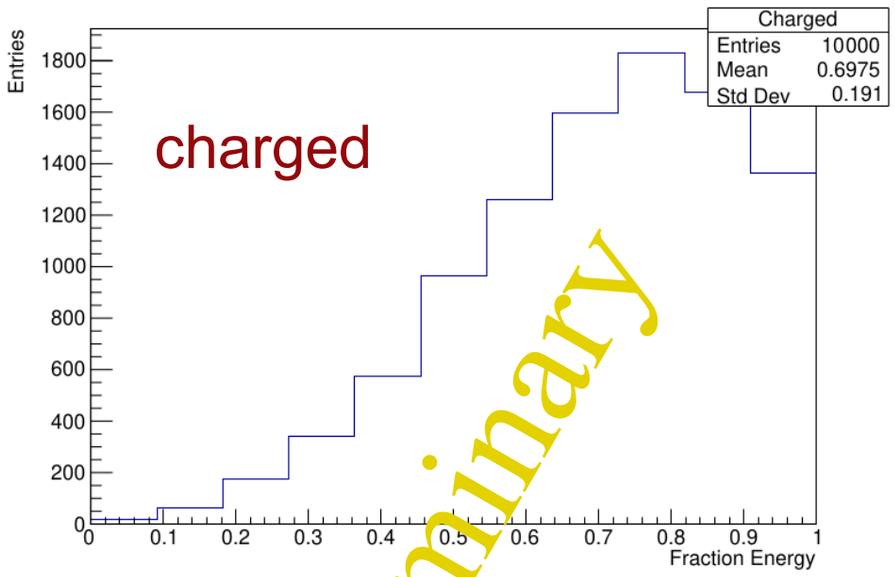
Soft hadrons (behaving like *mips*) — **? usually** $\frac{e}{mip} \neq 1$

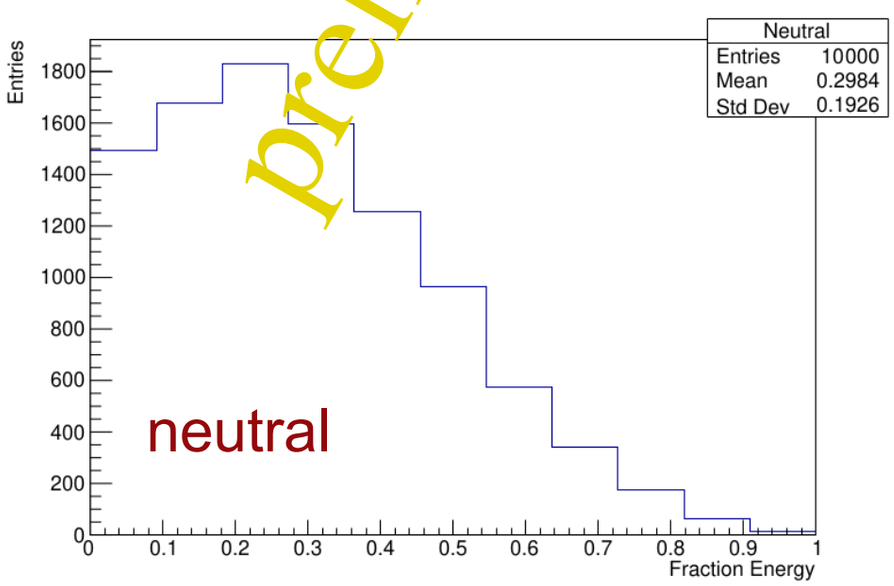
Does it reconstruct the correct energy for all the particles?

# *simplified jet structure*

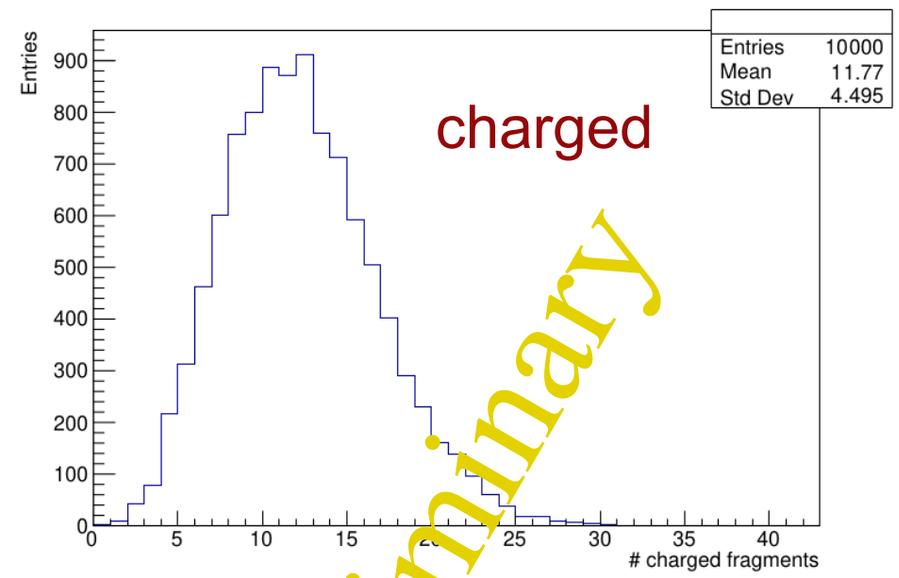
## *45 GeV Jets*

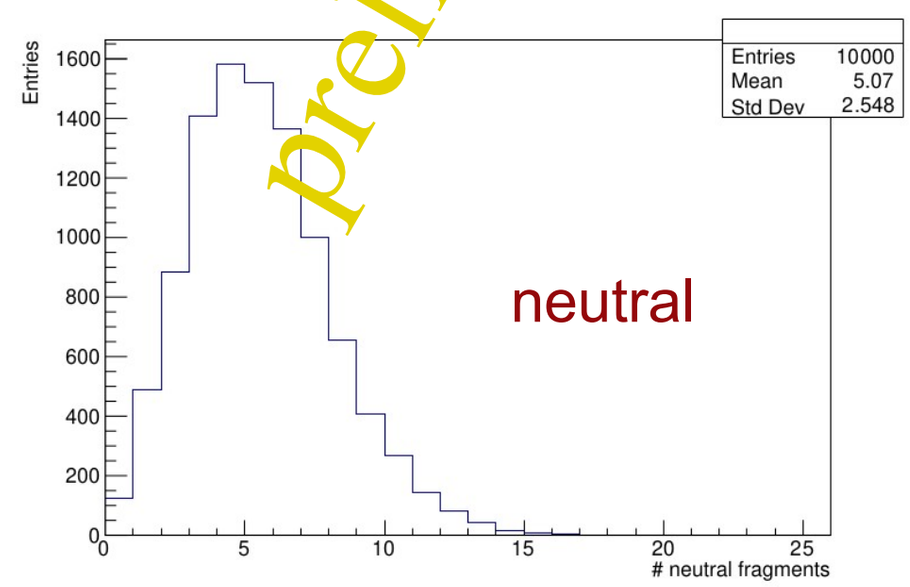
### Jet Energy Fraction




### Jet Multiplicity

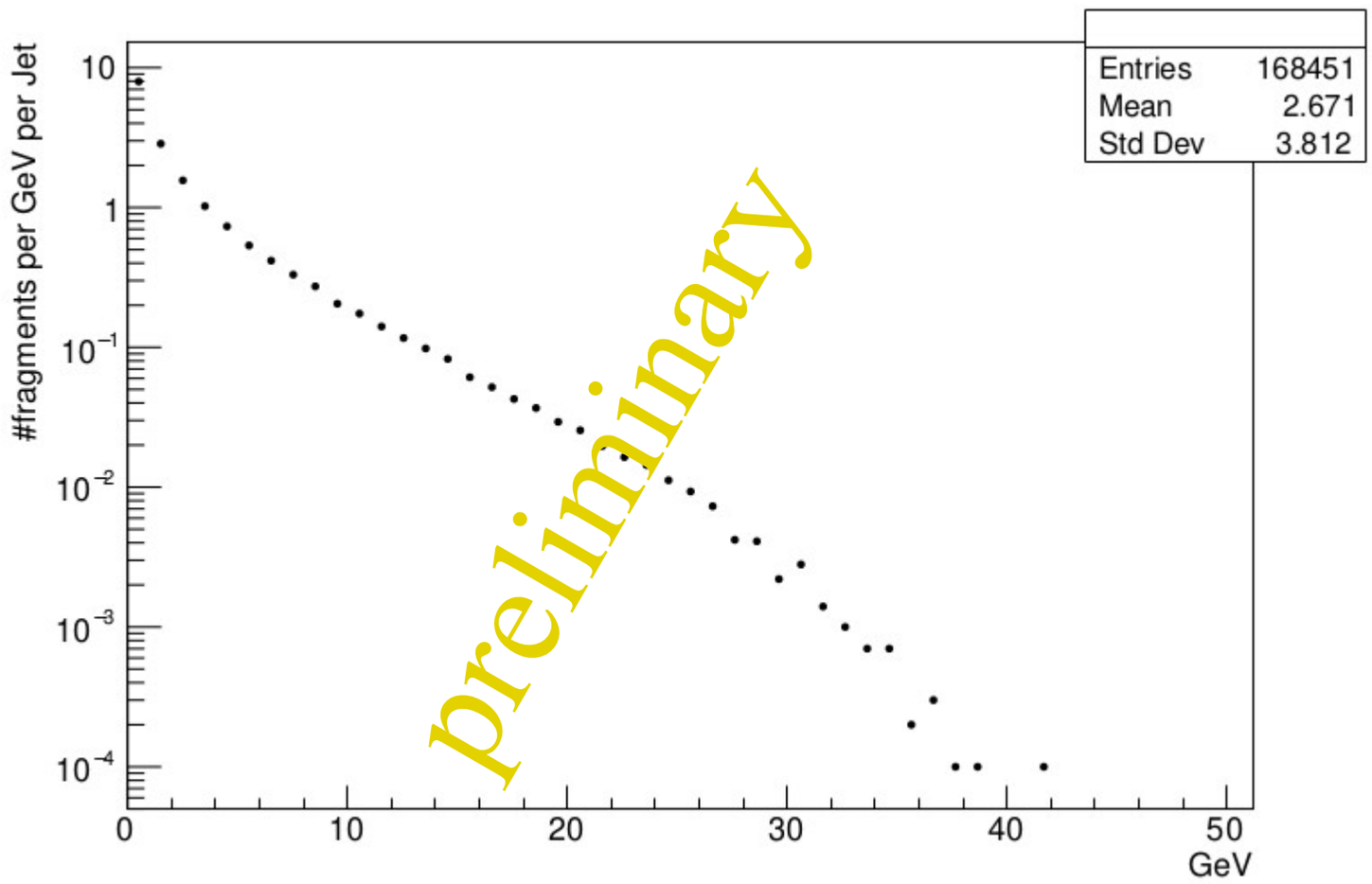


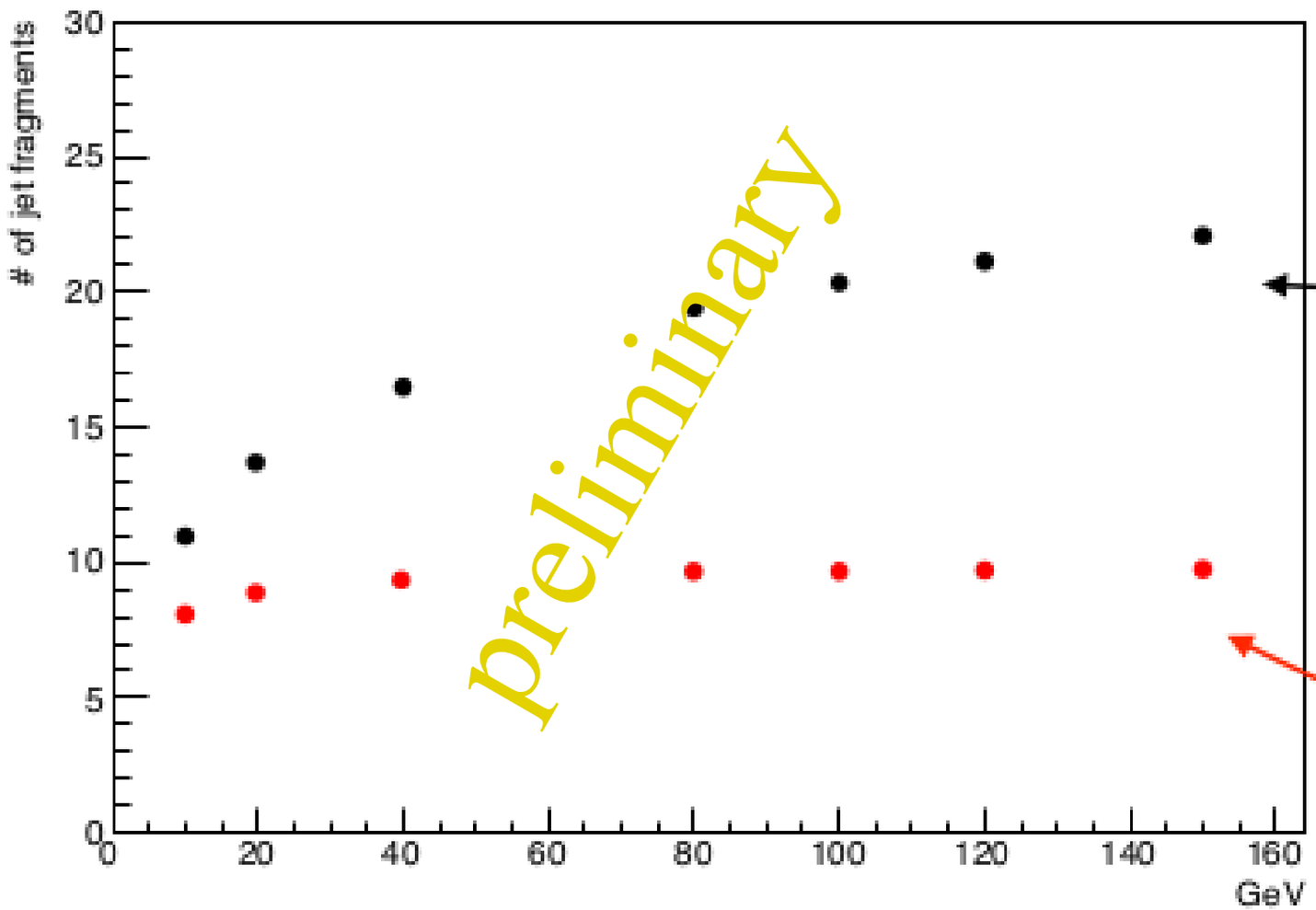
# *simplified jet structure*

## *45 GeV Jets*

### Number of fragments / GeV / Jet



# *simplified jet structure*



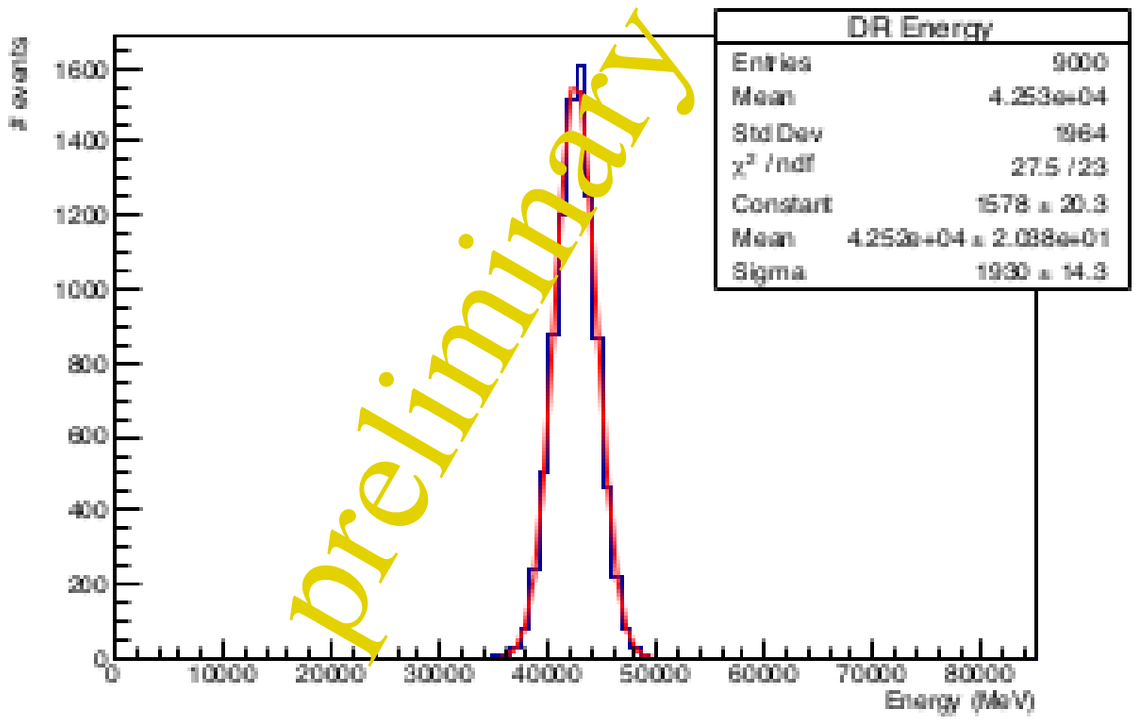

Average multiplicity vs. jet energy

Average number of fragments that is minimally needed to account for 90% of the jet energy vs. jet energy

The calorimeter has to deal with:
constant number of hard hadrons + increasing number of soft hadrons

# *reconstructed energy*

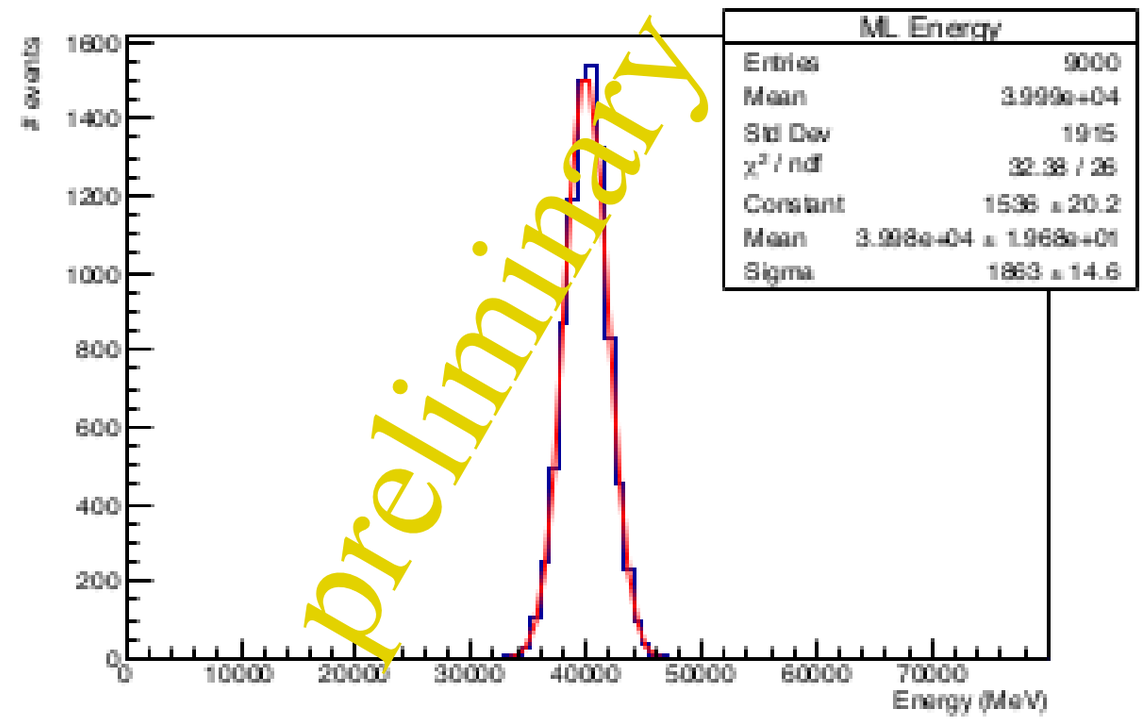
## DR method




With the classical approach the average reconstructed energy is slightly overestimated:

$$\frac{e}{mip} < 1$$

## Machine Learning

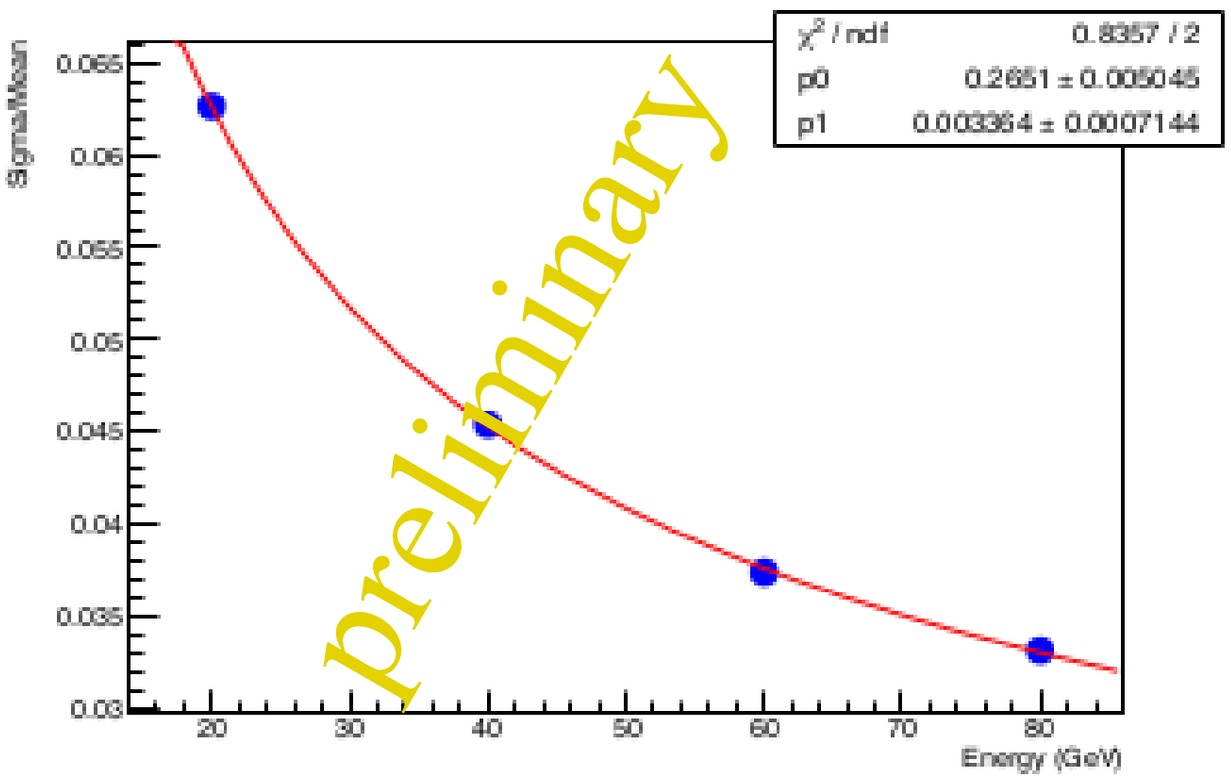



With machine learning
The energy is on average correctly reproduced:

Soft hadrons are present also in the trained database

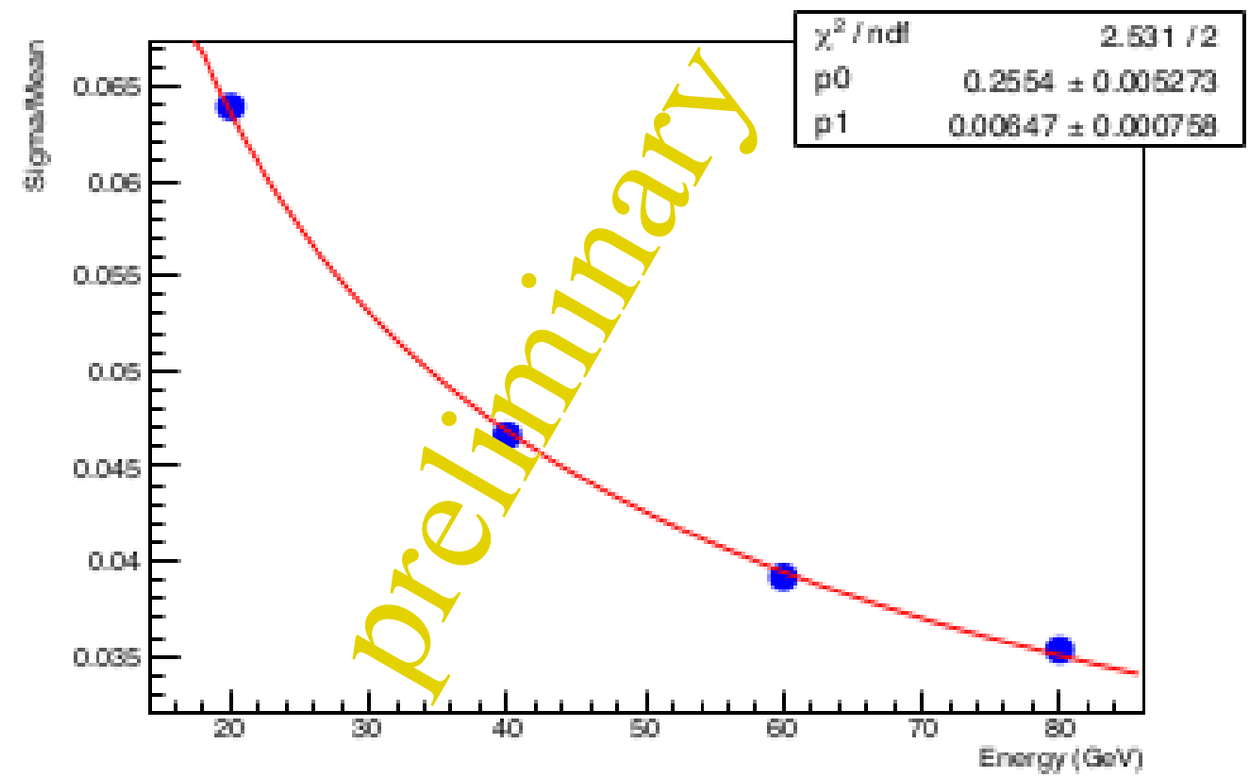
# *energy resolution*

## DR method




$$\frac{\sigma}{E} = \frac{26.5\,\%}{\sqrt{E}} + 0.3\,\%$$

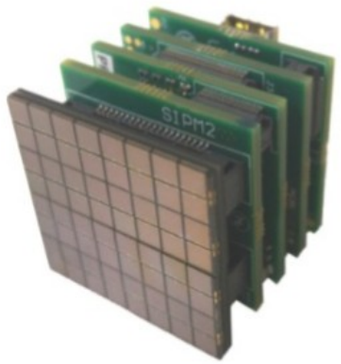
## Machine Learning

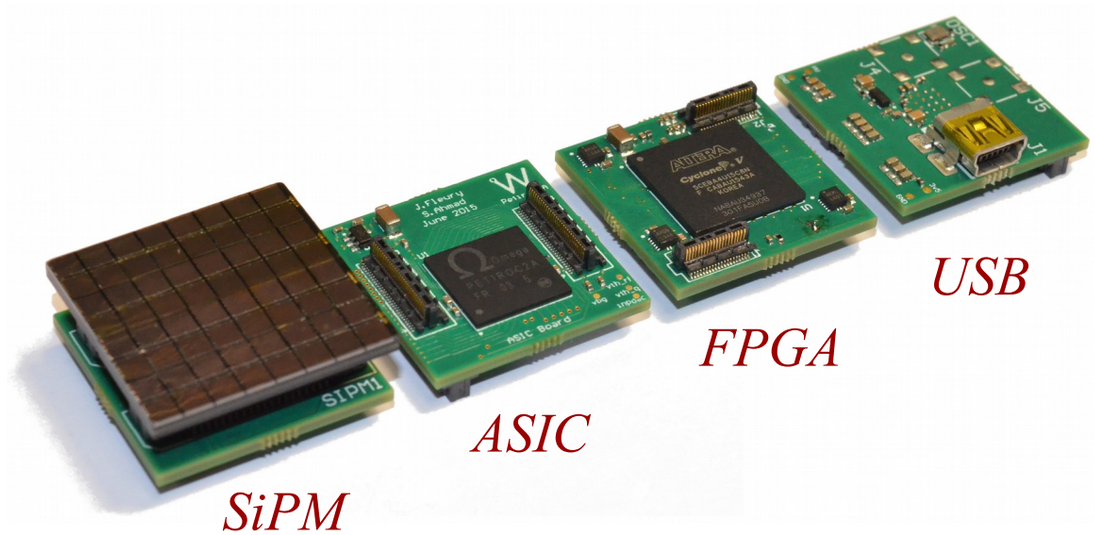



$$\frac{\sigma}{E} = \frac{25.5\,\%}{\sqrt{E}} + 0.6\,\%$$

# few words on front-end electronics

would like to get:






first step: ASIC

# *readout open ways*

Possible solutions:

a) analog charge integration : e.g. SPIROC

~ 2000 p.e. dynamic range
~ 100 ps time resolution

b) digital sampling : e.g. AARDVARC

10-15 Gs/s
< ~ 5 ps time resolution

it looks like an overkill

| AARDVARC Parameter | Specification |
|---|---|
| Process node | 130/65 nm |
| Channels | 4/8 |
| Sampling Rate | 10-15GSa/s |
| Storage Samples/ch | 32768 |
| Analog BW | >2GHz |
| Dynamic Range | 1.0 V |
| Time accuracy | <5 ps |
| Readout | Parallel/Fast Serial |
| ADC bits | 12 |
| Power/ch | 100 mW |

*[ $\Delta x \sim 5$ cm $\Rightarrow \Delta t \sim 100$ ps ]*

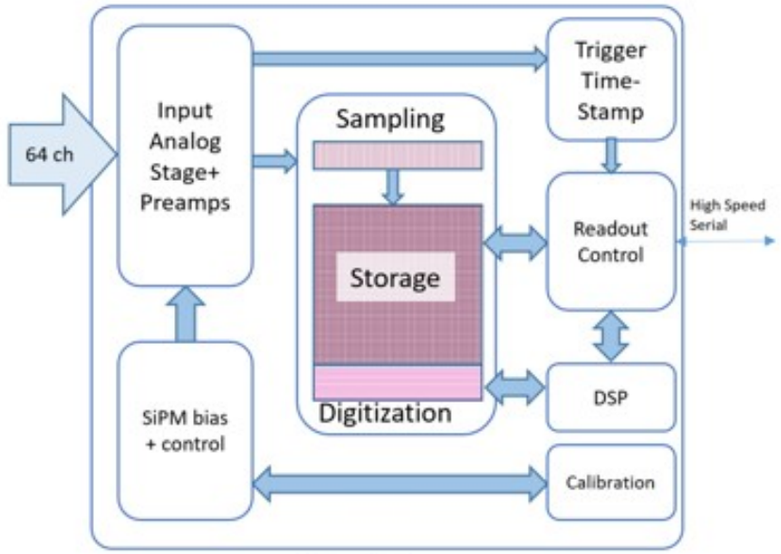
# … better tuned digital solution ?

**SiREAD**

**Silicon photomultiplier REadout, Automated calibration and Detection**

Nalu Scientific, LLC.
2800 Woodlawn Dr. Ste 298
Honolulu, HI 96822
info@naluscientific.com

Nalu Scientific
Data Acquisition Systems

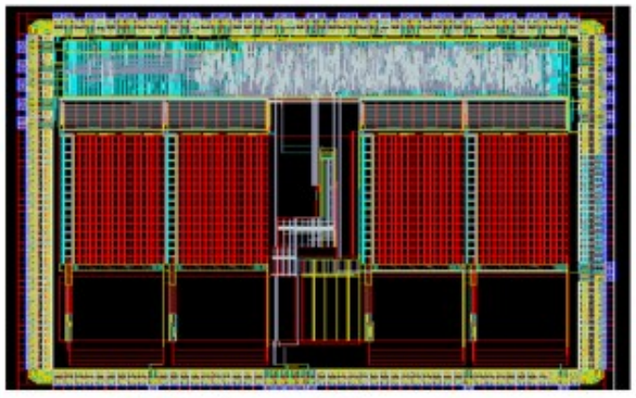



SiREAD block diagram

| SiREAD Parameter | Specifications |
|---|---|
| Channels | 64 |
| Sampling rate | 1-4 GSa/s |
| Storage samples/ch | 4096 |
| Analog bandwidth | 0.7-1.1 GHz |
| RMS voltage noise | <1mV |
| Dynamic range | 10-11 bits |
| Signal voltage range | 2.1 V |
| ADC on chip | 12 bits |
| Readout | Serial LVDS |
| Power consumption | 20-40 mW/ch |

**Key Features:**

- ✓ Giga-sample/sec full waveform sampling
- ✓ High density (64 channels)
- ✓ SiPM bias trim
- ✓ Deep buffer (4k Samples)
- ✓ Dead-timeless for kHz trigger rates
- ✓ User friendly: can operate using a CPU
- ✓ Low cost CMOS process, Low-power



SiREAD layout- 4 ch prototype

*declared to provide ~40-80 ps timing accuracy*

*[ $\Delta x \sim 5$ cm $\Rightarrow \Delta t \sim 100$ ps ]*

# *feature extraction*
## (FPGA real-time processor)

May likely provide :

a) total charge $Q_T$
b) starting time $T_S$
c) time over threshold ToT
d) peaking time $T_p$
e) peak value $V_p$
f) or maybe $Q_1$ $(T_1)$, $Q_2$ $(T_2)$, $Q_3$ $(T_3)$ …
(either single deposit or fixed time slices)

time structure carries information on longitudinal segmentation
(particularly true for Čerenkov signal)

*[ $\Delta x \sim 5$ cm $\Rightarrow \Delta t \sim 100$ ps ]*

# *Conclusions*

Many items lacking :

calibrations likely the most important (and critical)

But also :

homogeneous calorimeters
real (non-perfect) detector implementations
timing properties
trigger performance
active media
muon signals, light collection, photodetectors, radiation hardness,
...

a more rigorous approach to most issues (!)

# *Conclusions*

Apologies for that !

(fine … there is room for improvements)

reference :

Calorimetry
Energy Measurements in Particle Physics
R. Wigmans