Dual-Readout Calorimetry Simulations

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dual-readout calorimetry

What ?

Don’t spoil em resolution to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em} event-by-event

$\Longrightarrow$ *correct energy measurements for f_{em} fluctuations*

How ?

Exploit the fact that (e/h) values for scintillation light (S) and Čerenkov light (Č) production processes are (very) different

Why ?

Charged hadrons contribute to S but very marginally to Č

the principles

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

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

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

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

$\rightarrow$ *χ can be evaluated from calibration data*

χ , s , c $\rightarrow$ detector-specific parameters

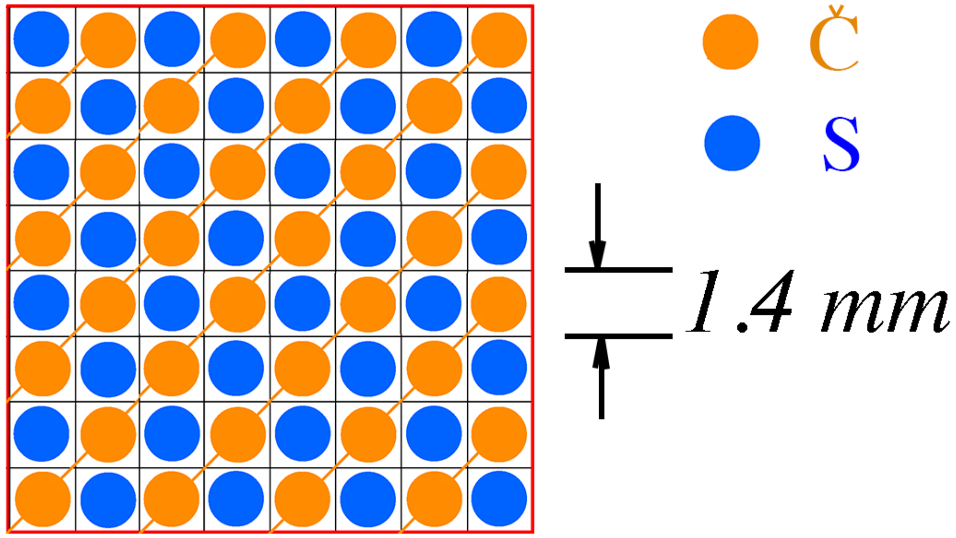
Geant4 simulations

Elementary unit:

brass (Cu260) matrix

~ 1 cm × 1 cm & 32 (S) + 32 (Č) fibres & SiPM readout

$R_M \sim 31$ mm & $X_0 \sim 29$ mm



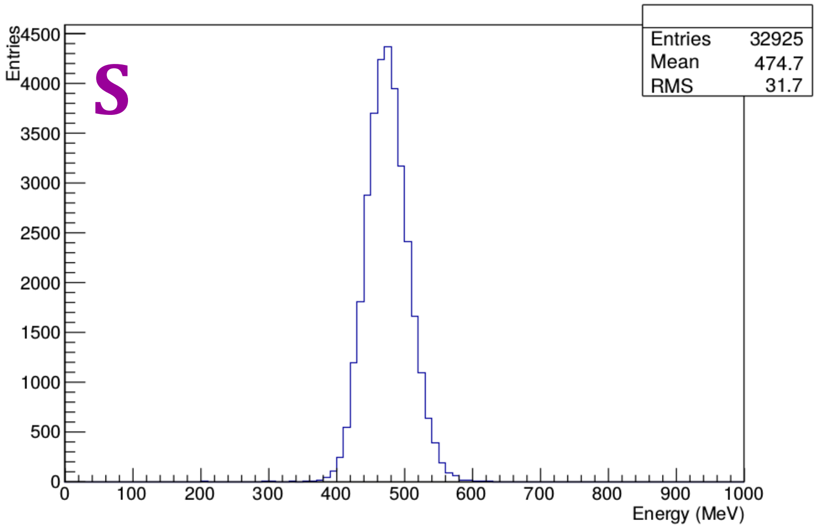
Electromagnetic performance

sampling fraction (Cu)

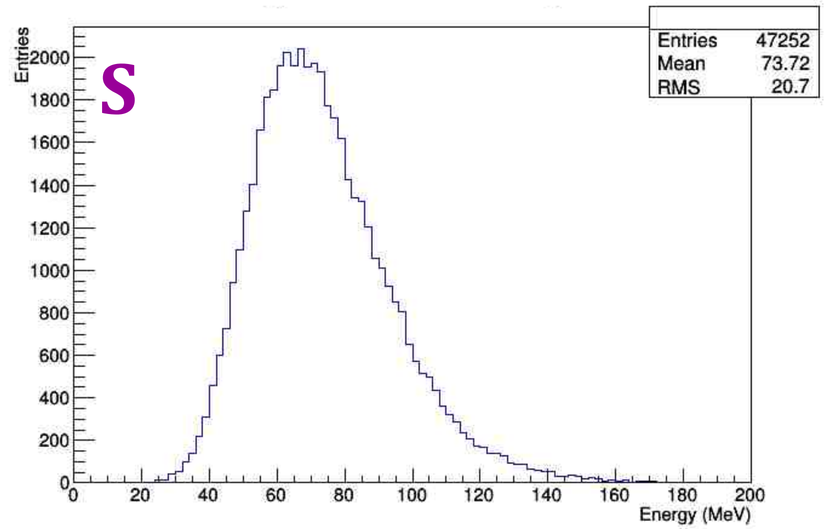
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

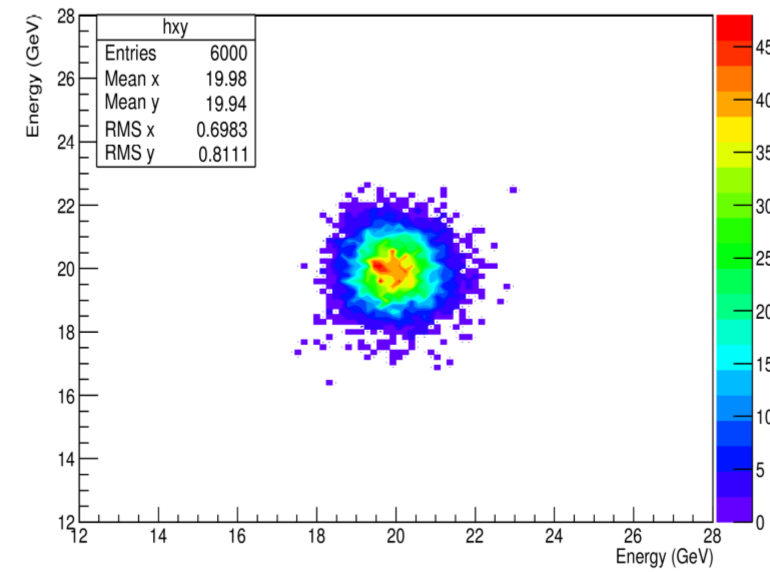
E(MeV) S fibres: ~5.5%



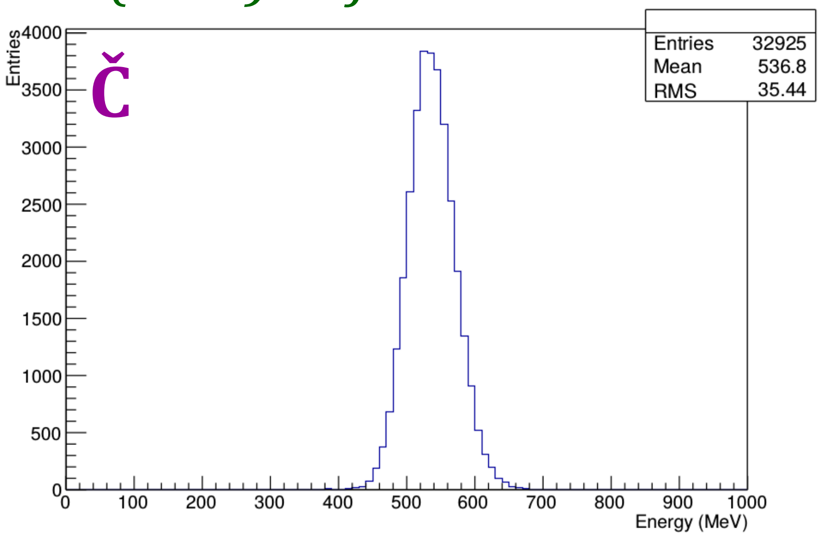
E (MeV) in hottest fibre



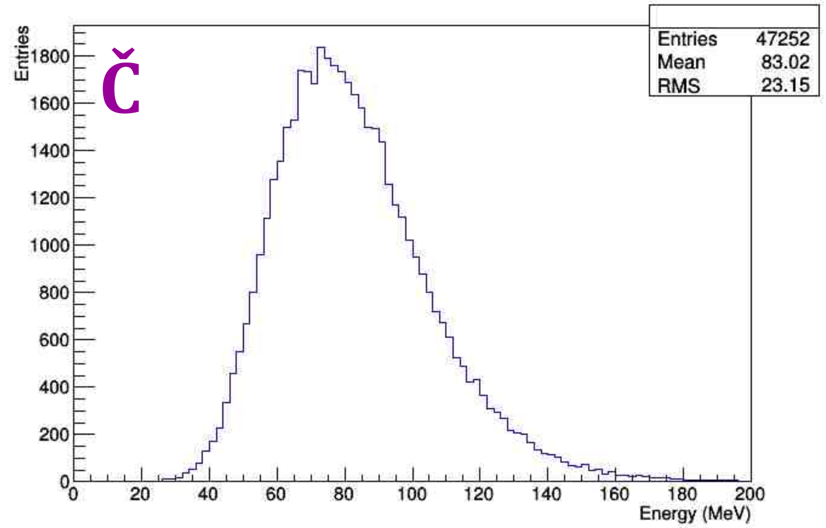
C vs. S



E(MeV) in fibres: ~6.2%

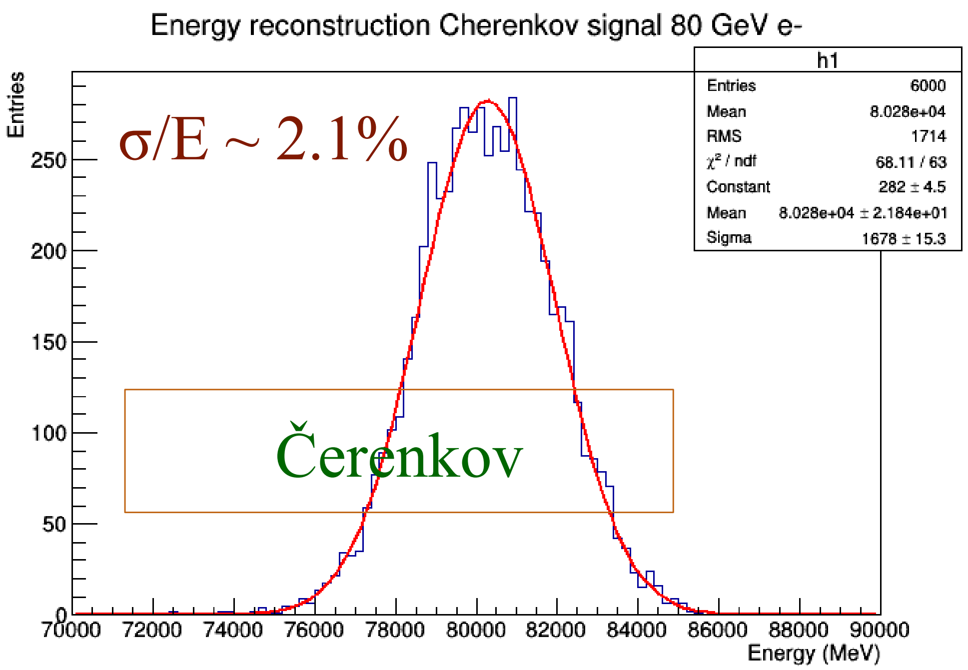


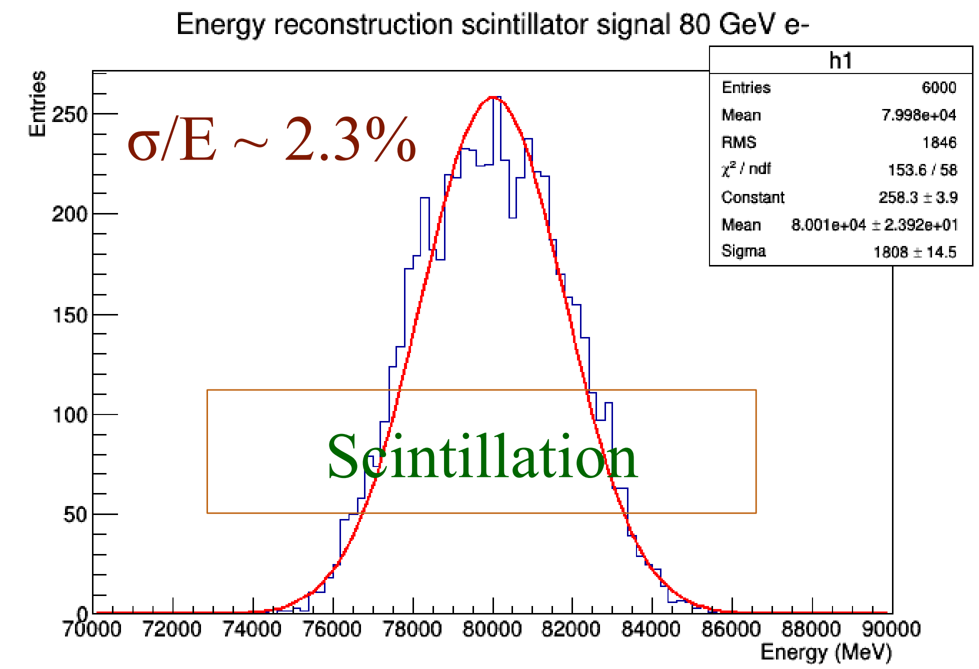
E (MeV) in hottest fibre

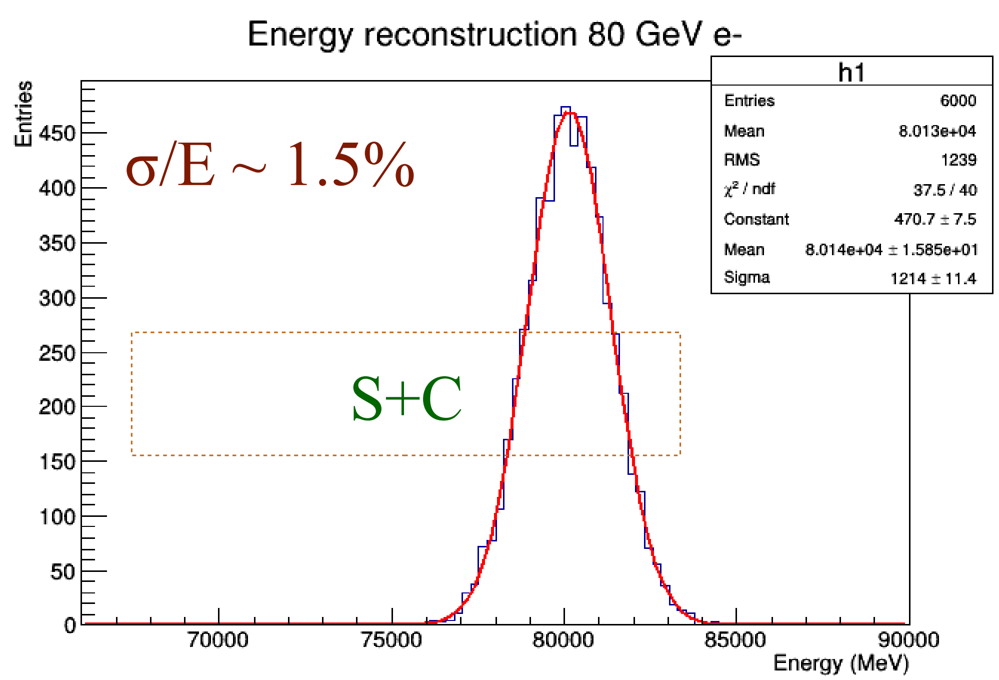


combined S+C resolution

80 GeV electrons

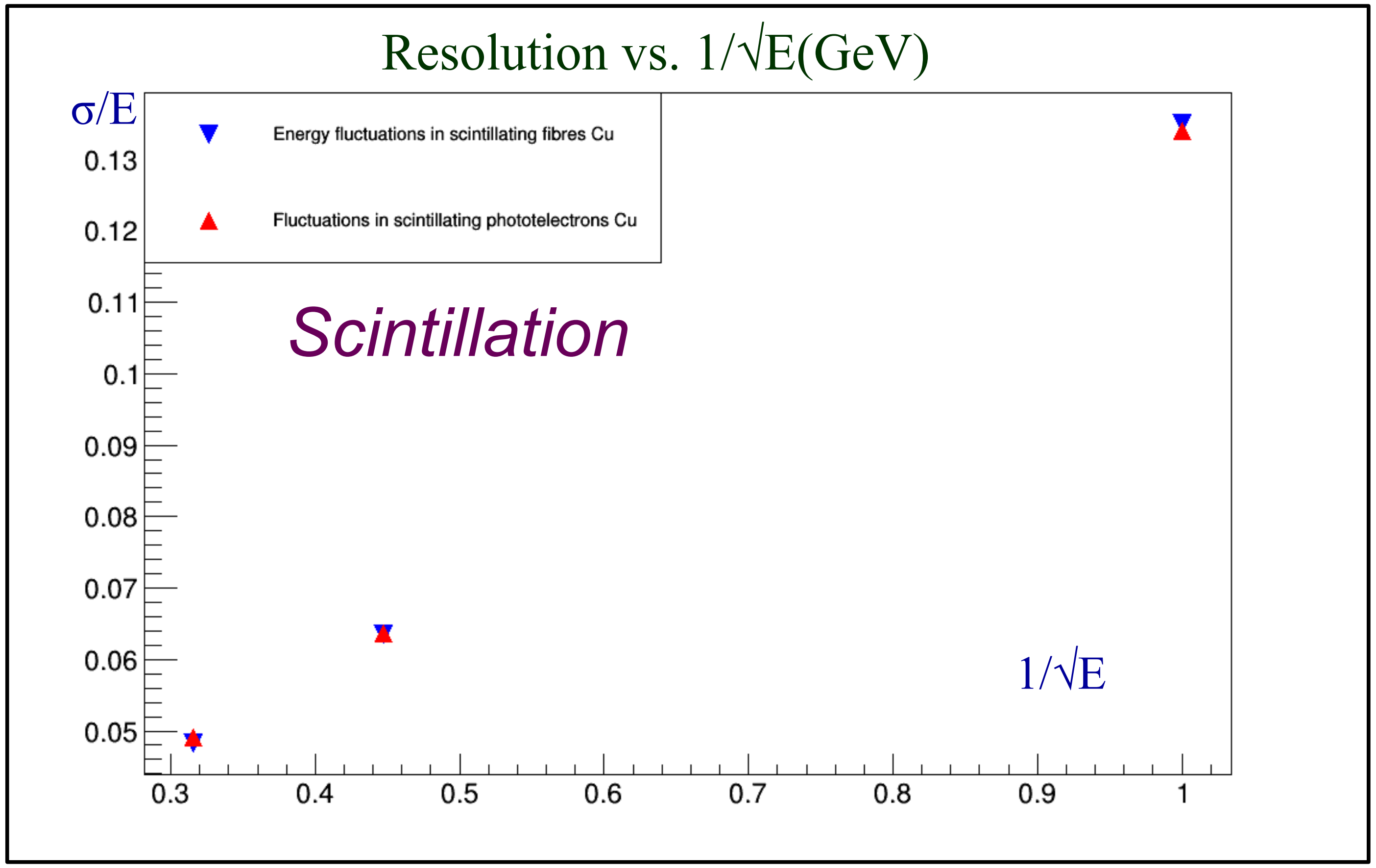


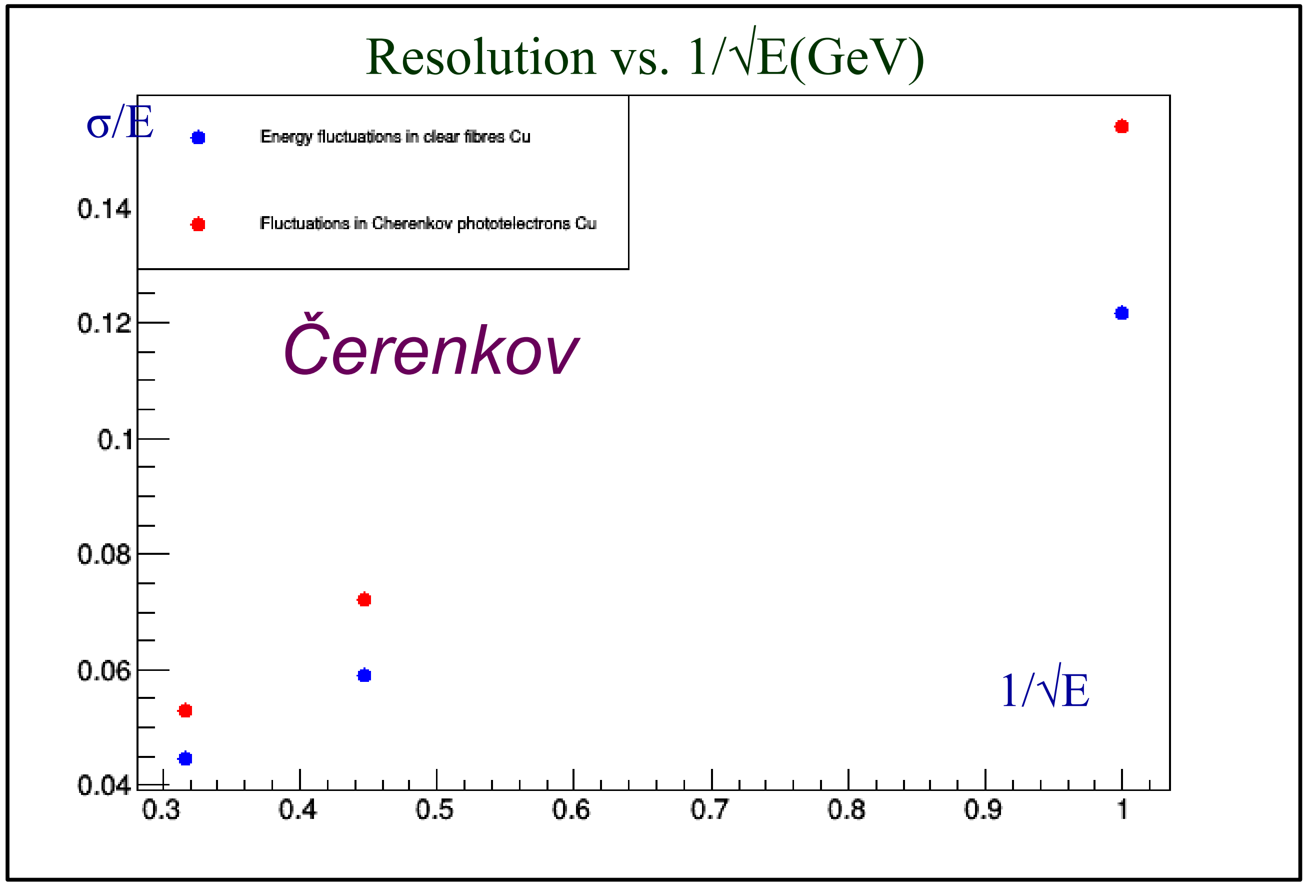




signal fluctuations

energy deposition and p.e. number fluctuations





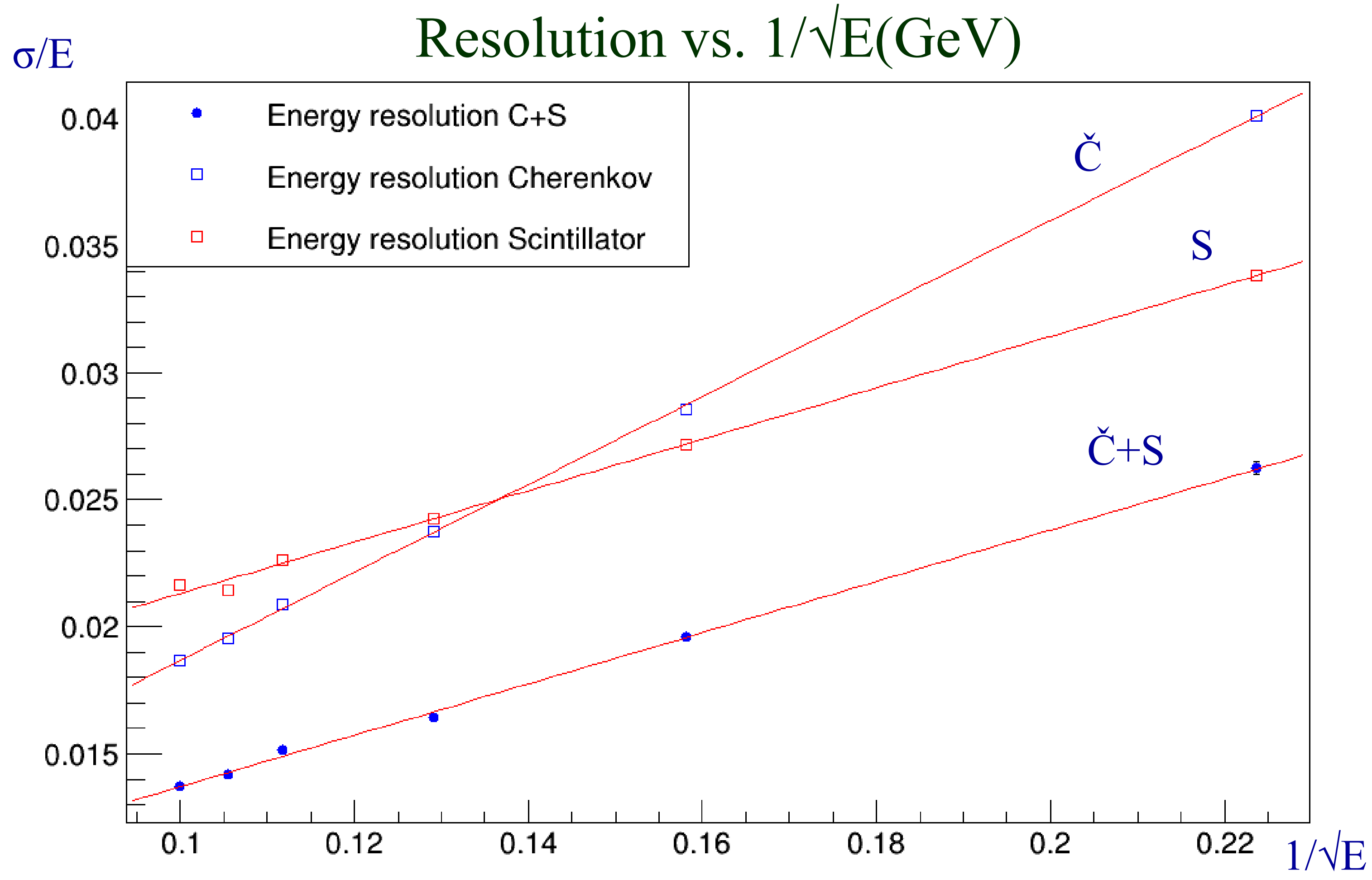
S: ~5500 p.e. / GeV → add filter ?

→ σ/E driven by en. depositions

Č: ~110 p.e. / GeV → add mirror ?

→ σ/E driven by p.e. number

e.m. resolution(s)

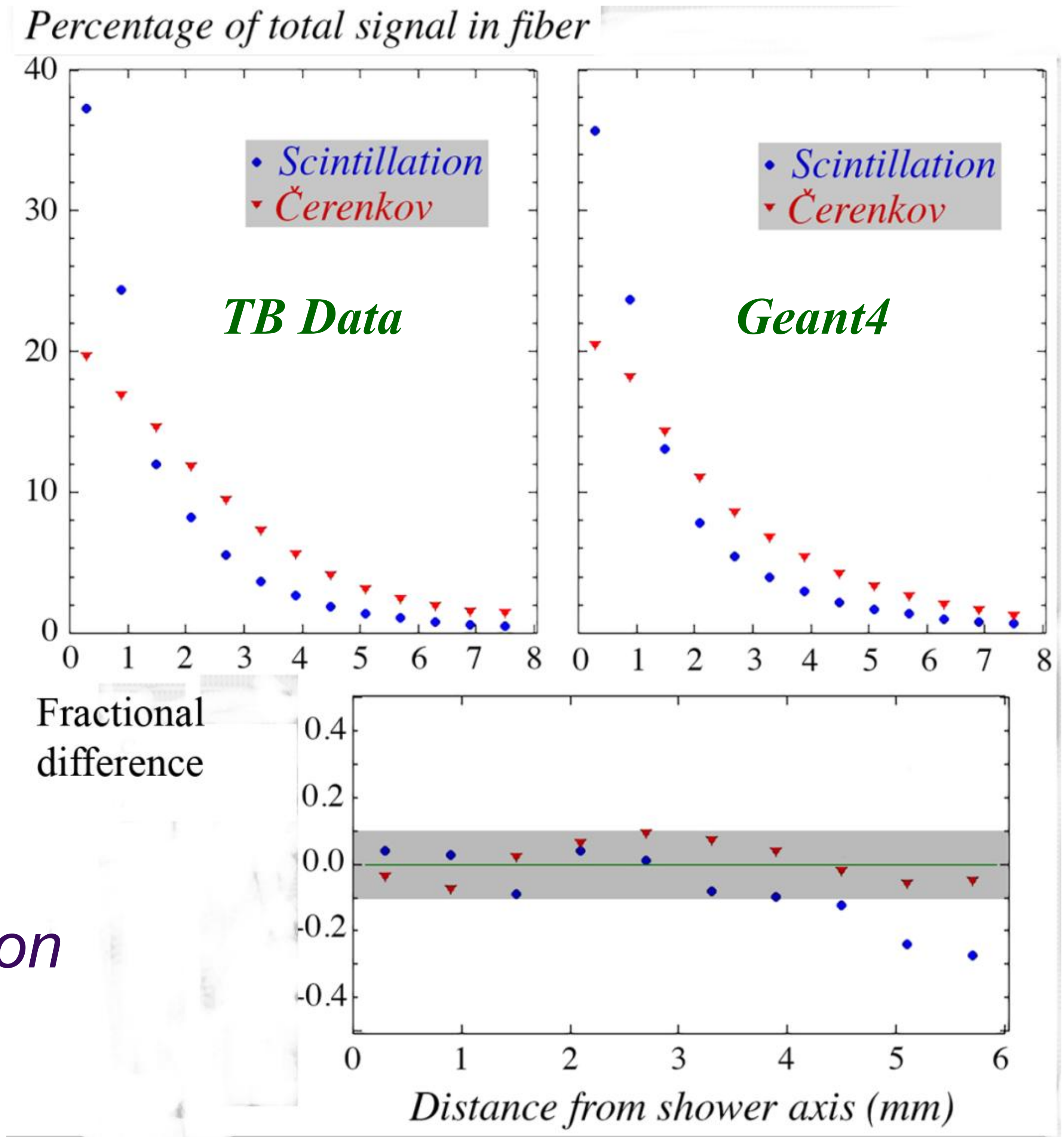


S-only: 10.5/√E+1.1 (%)

Č-only: 17.9/√E (%)

(unweighted) average: 10.3/√E+0.3 (%)

lateral shower profiles



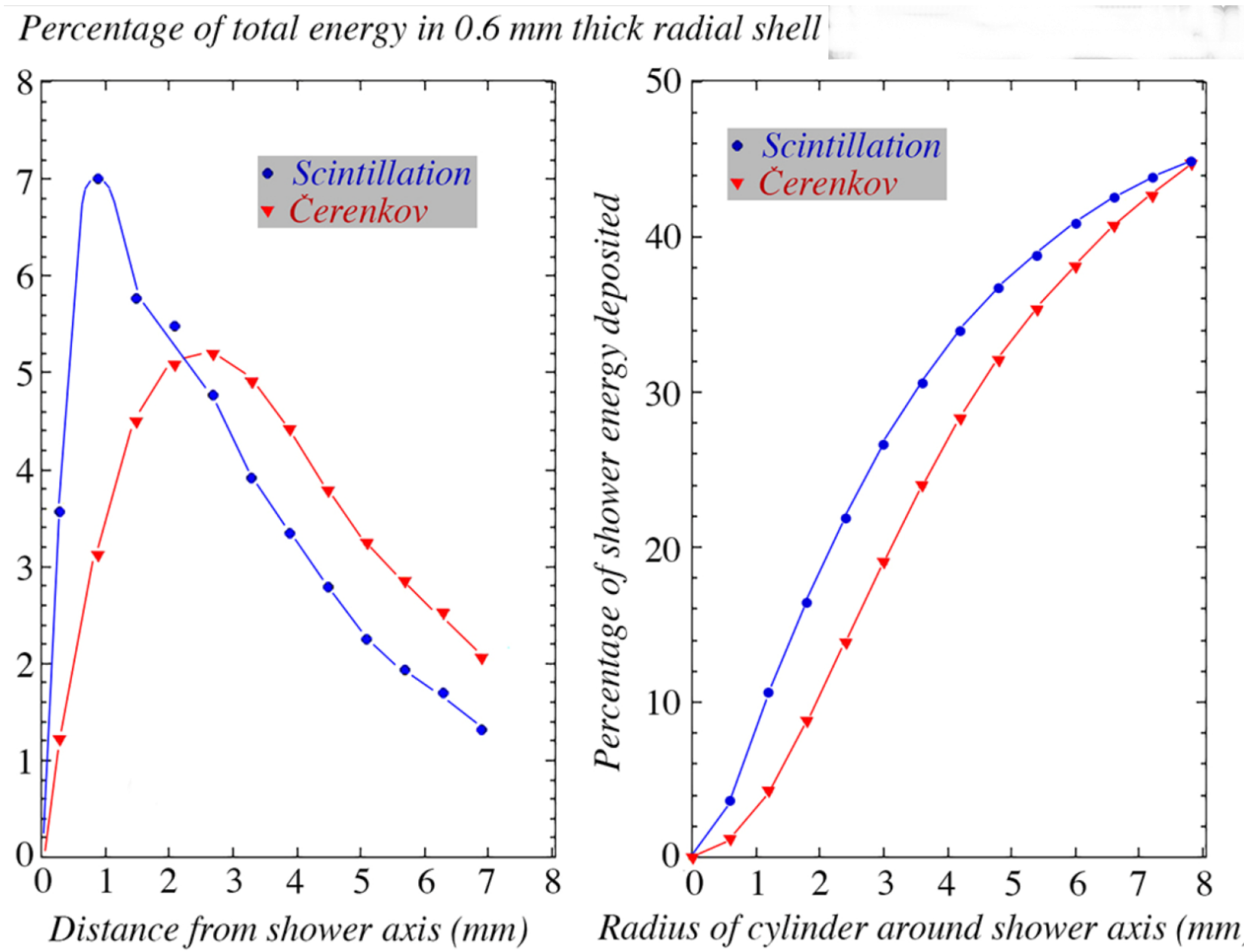
em shower very narrow

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

good for em shower identification

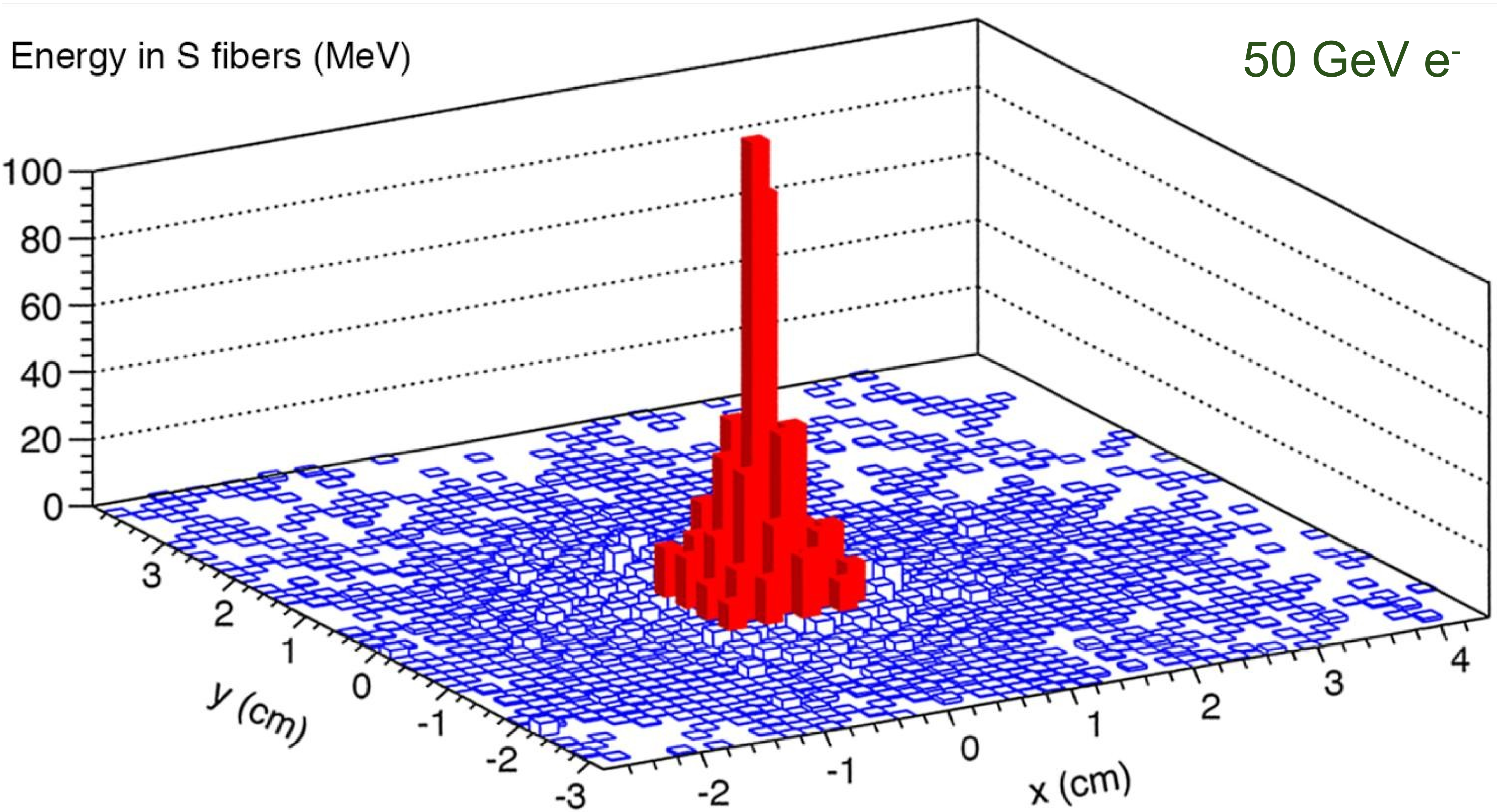
dynamic range issue

radial shower profiles



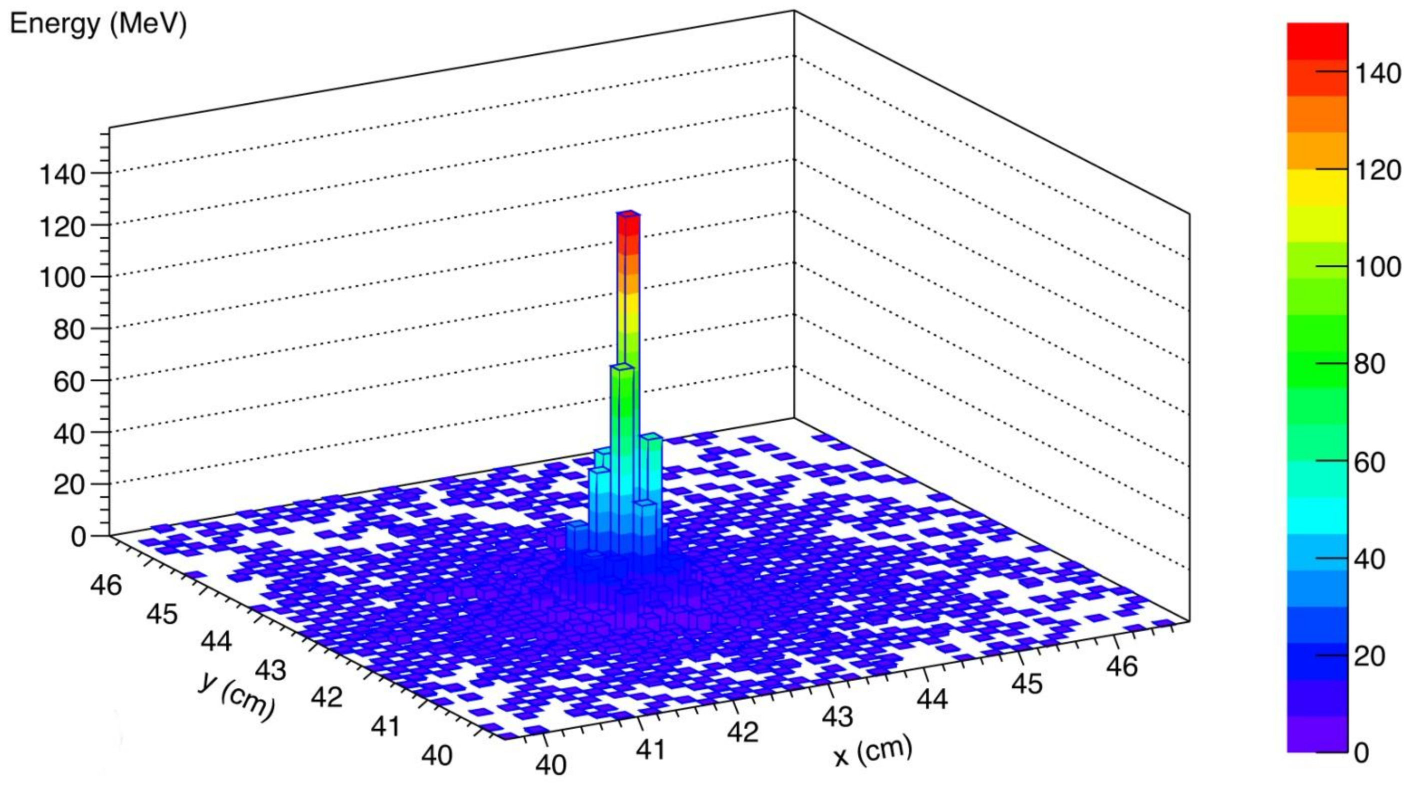
10% of shower energy deposited within 1 mm from shower axis, i.e. in a single fibre

shower profiles

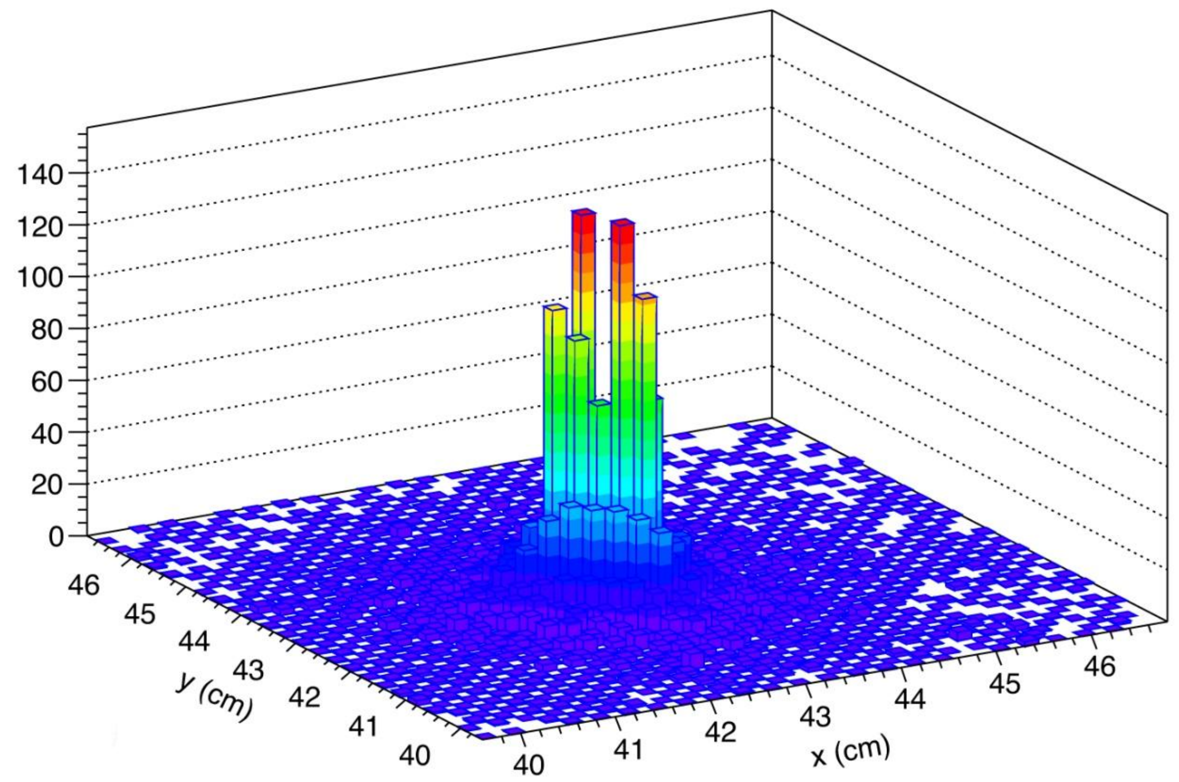


e/π^0 spatial separation

50 GeV e^-



100 GeV π^0



100 GeV π^0 decaying 2 m before the calorimeter

hadronic shower simulations

Dimensions:

71×71 units

1 unit:

$1.014 \times 1.014 \times 250\ cm^3$ copper module

32 (S) + 32 (Č) fibres

SiPM readout

Containment: ~99%

Calibration of both S and Č

w/ 40 GeV e^-

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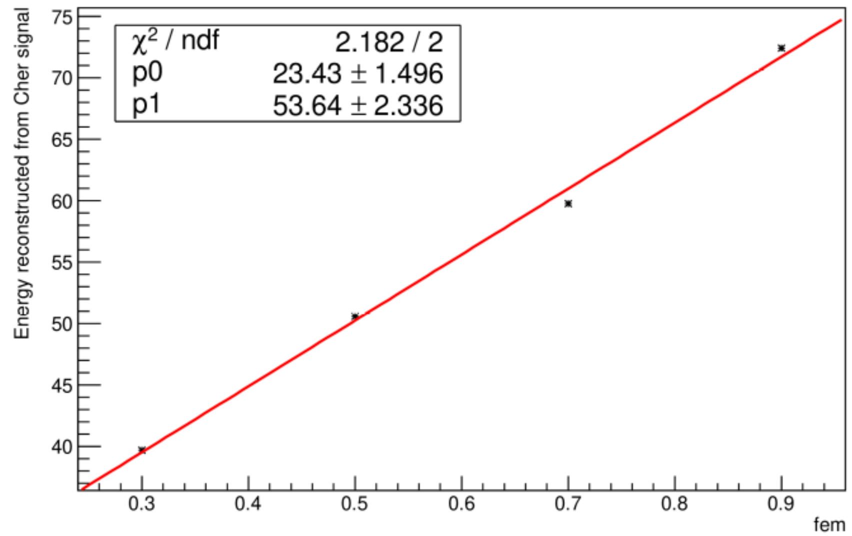
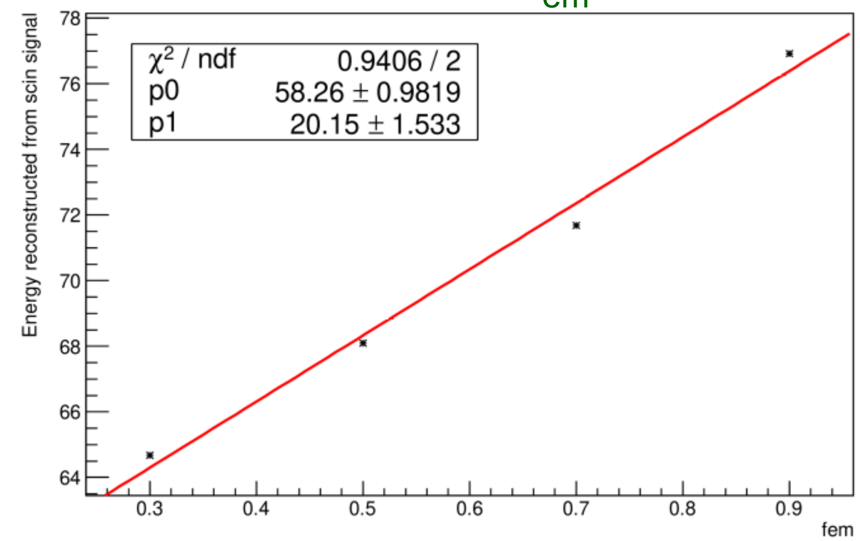
hadronic performance

E(Č) vs. f_{em}

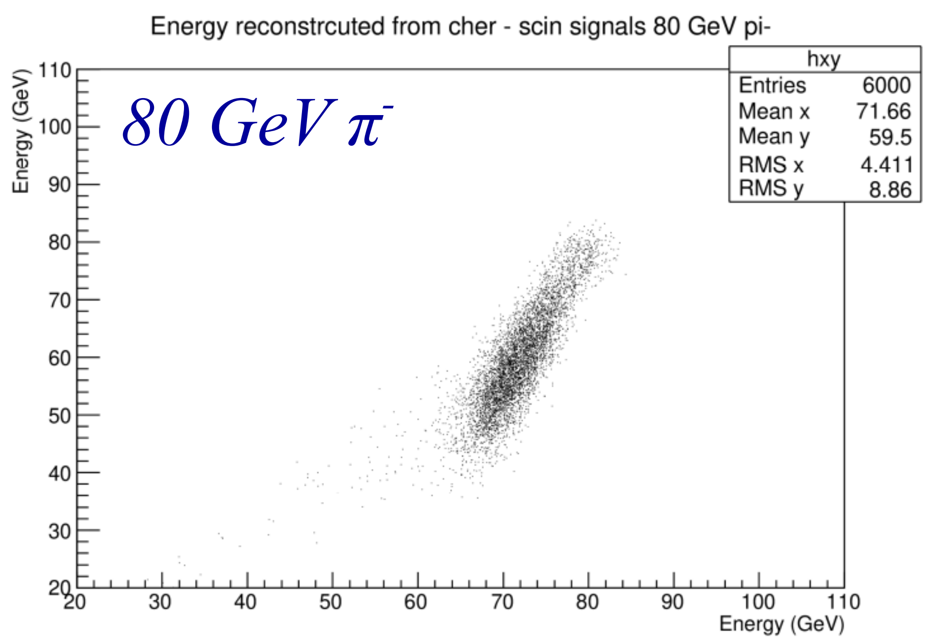


E(S) vs. f_{em}

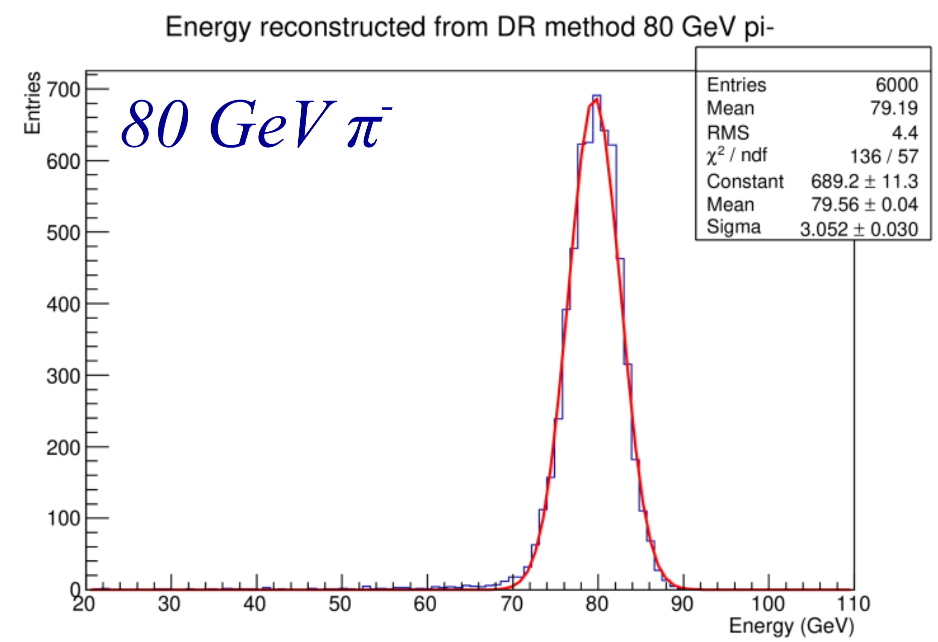


Copper

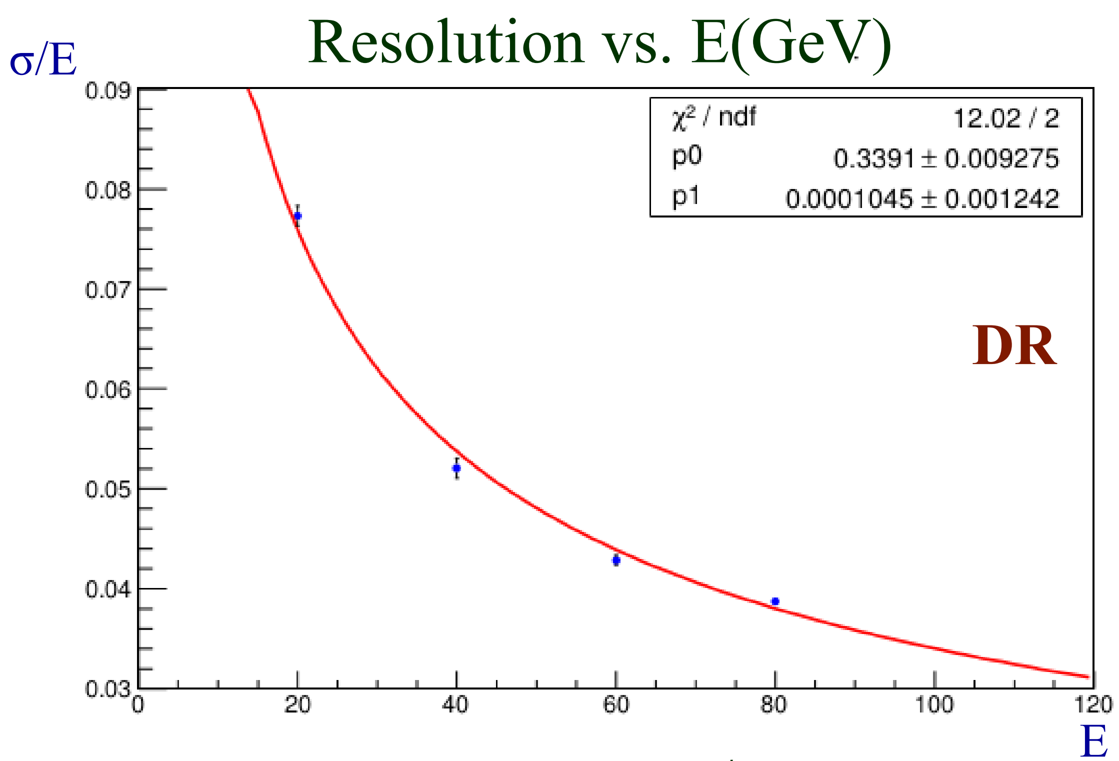
E(Č) vs. E(S)

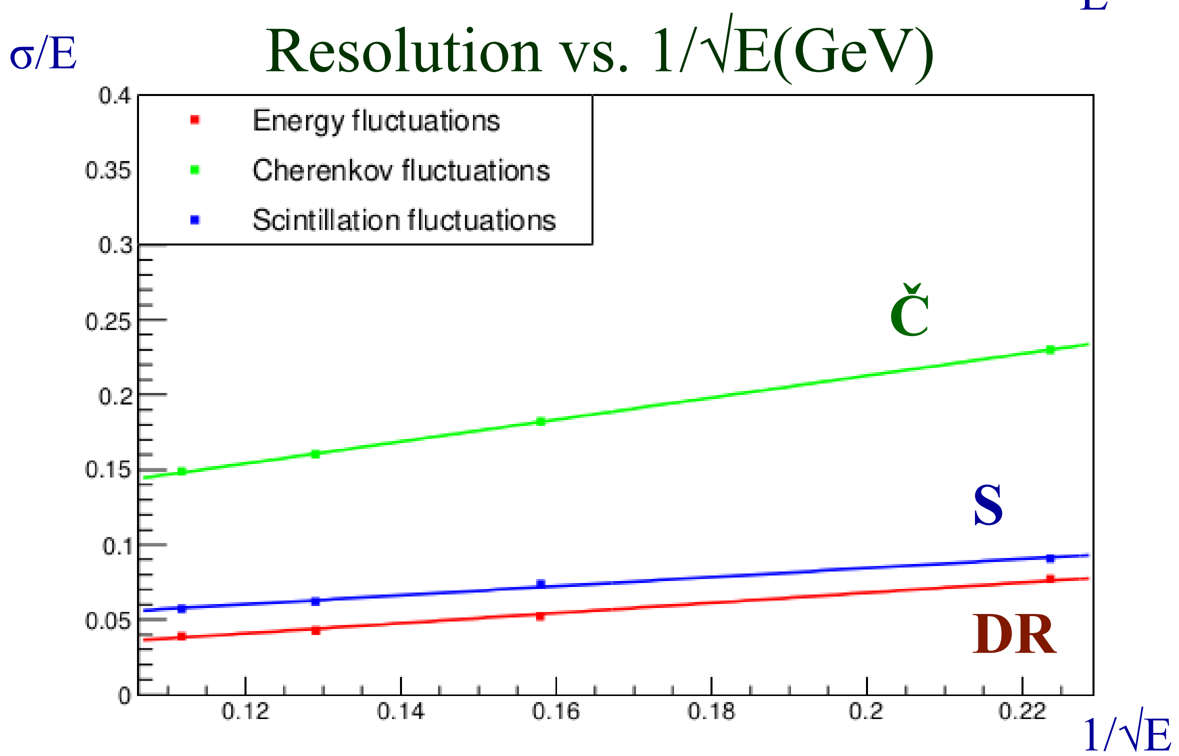


E (DR)



Cu hadronic performance





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

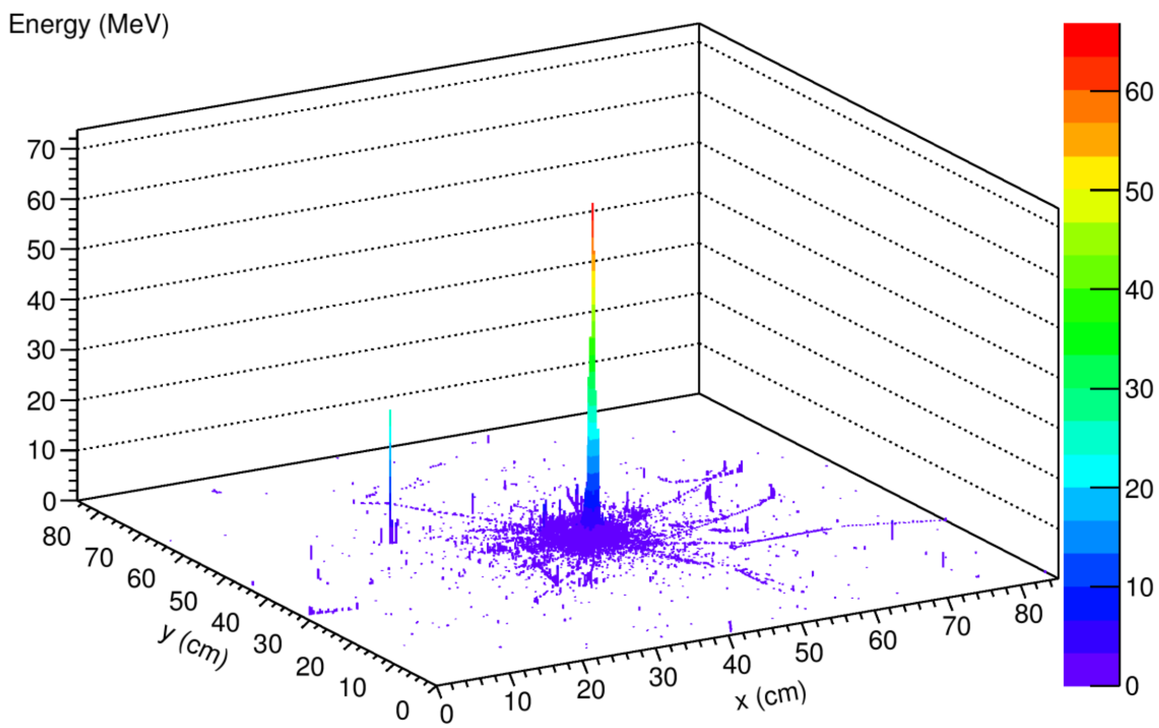
DR: ~34/√E (%)

High-energy single-π resolutions:

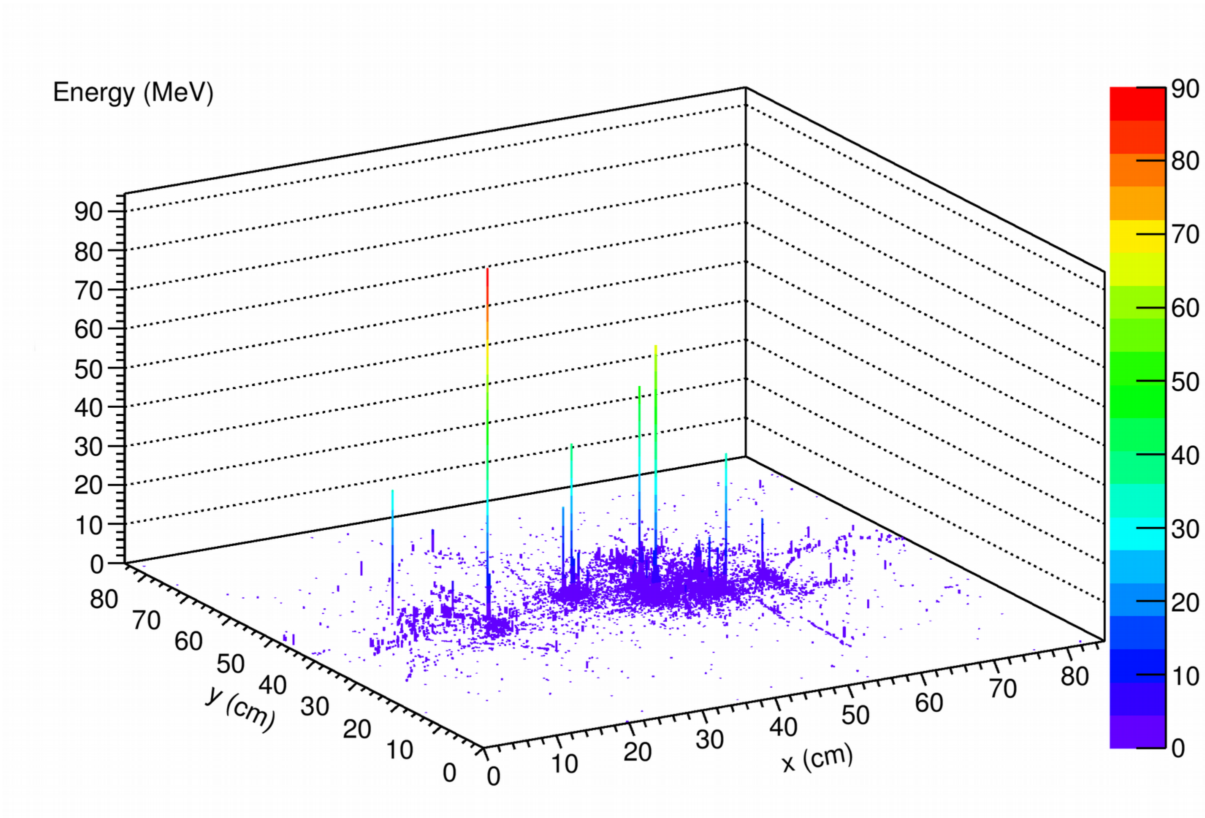
σ/E(100 GeV) ~ 3.5%
σ/E(300 GeV) ~ 2.3%
σ/E(1000 GeV) ~1.7 %

single hadron & jet profiles

80 GeV π



100 GeV jet



(h/e) and χ factors

f_{em} = MC truth (total energy deposited by e^+ and e^-)

E = average contained energy

C, S = signals

either:

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

or:

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

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

while:

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

copper vs. lead

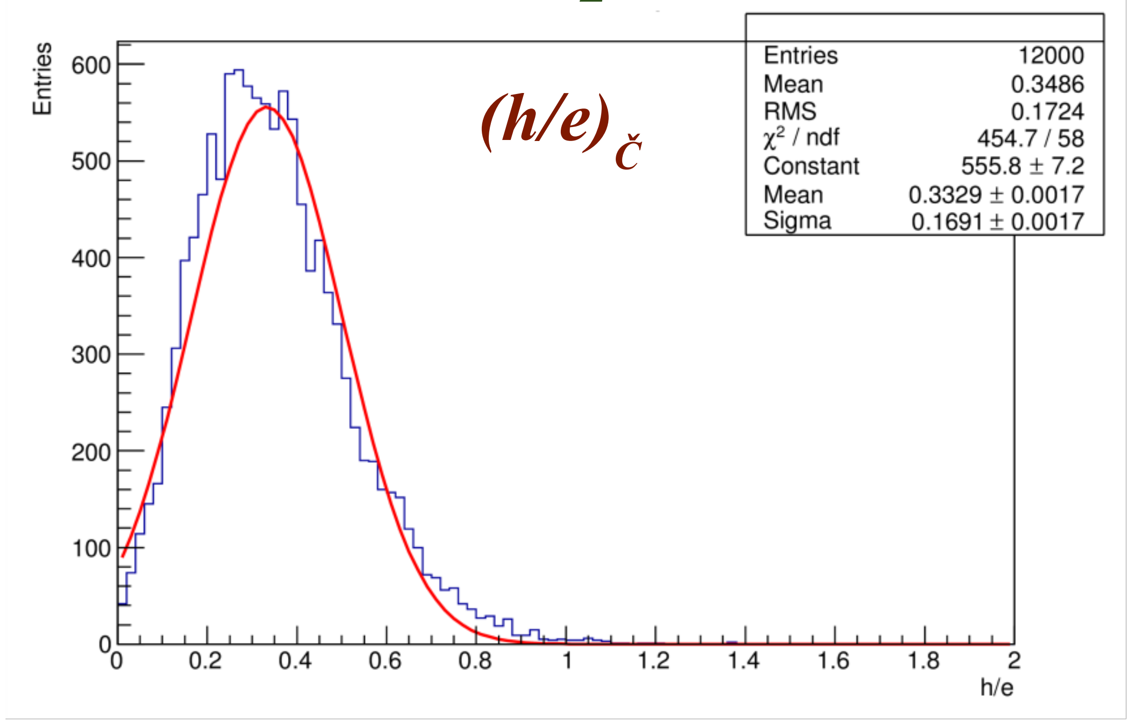
Copper	Lead
density = 8.96 gr/cm^3	density = 11.35 gr/cm^3
pion i.l. = 18.51 cm	pion i.l. = 19.93 cm
radiation l. = 1.436 cm	radiation l. = 0.5612 cm
Molière radius = 1.568 cm	Molière radius = 1.602 cm

volume ratio = $(19.93/18.51)^3 = 1.08^3 = 1.25$

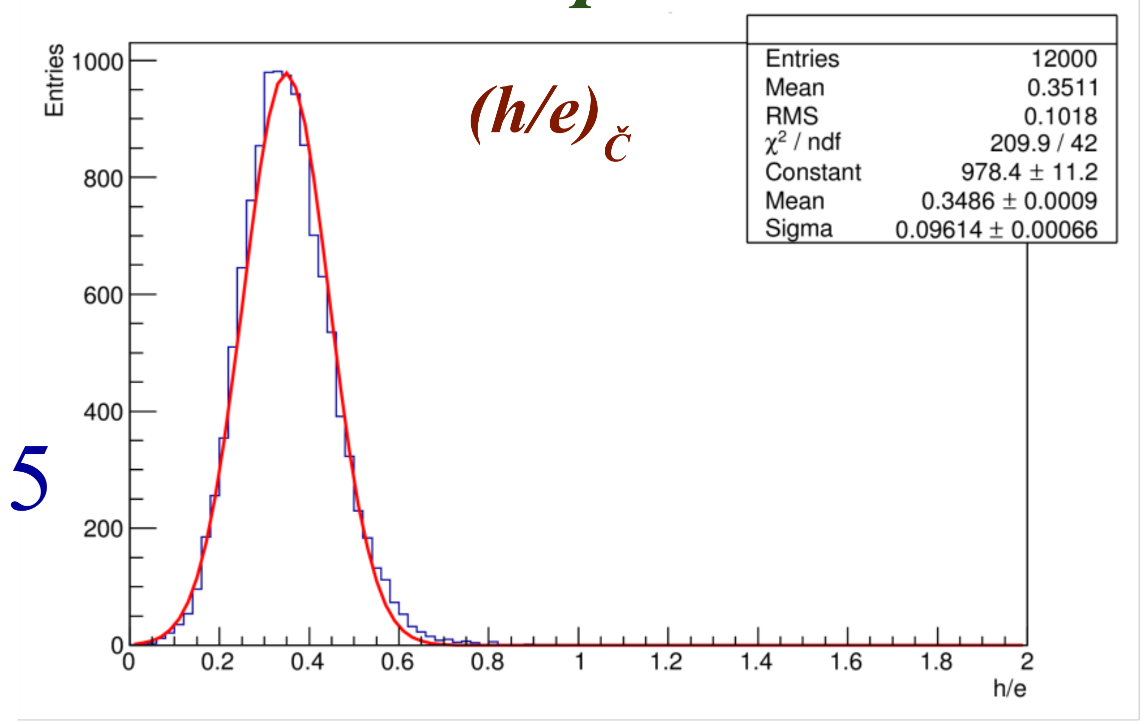
mass ratio = 1.25(11.35/8.96) = 1.58*

h/e factors for Copper

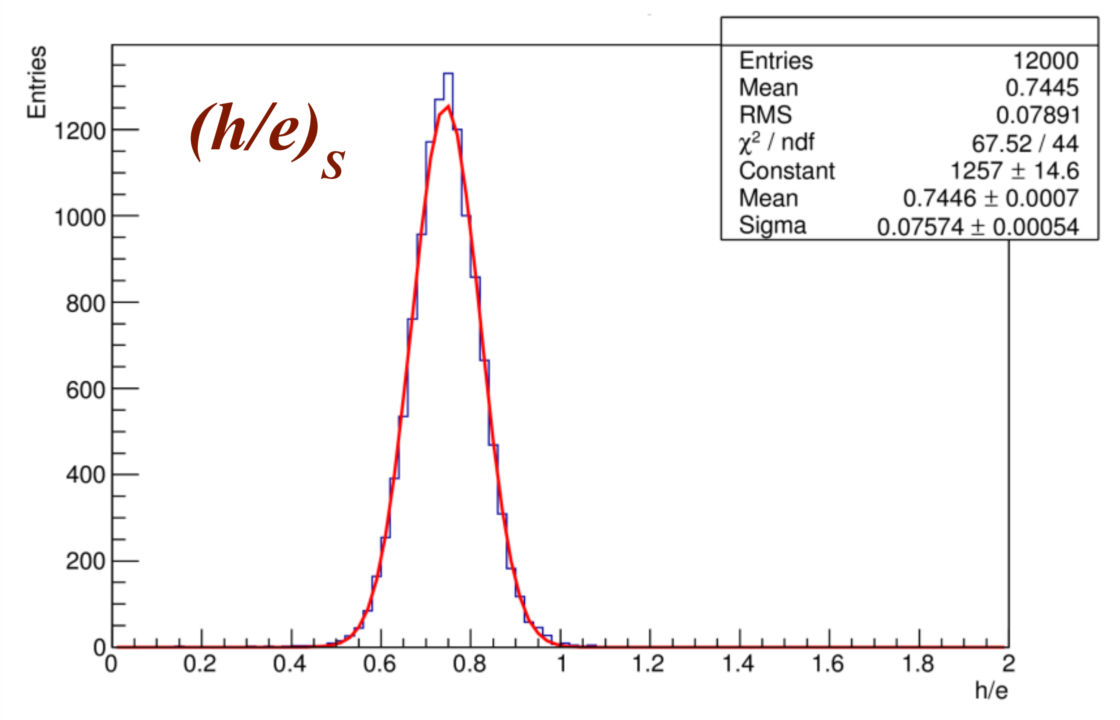
20 GeV proton

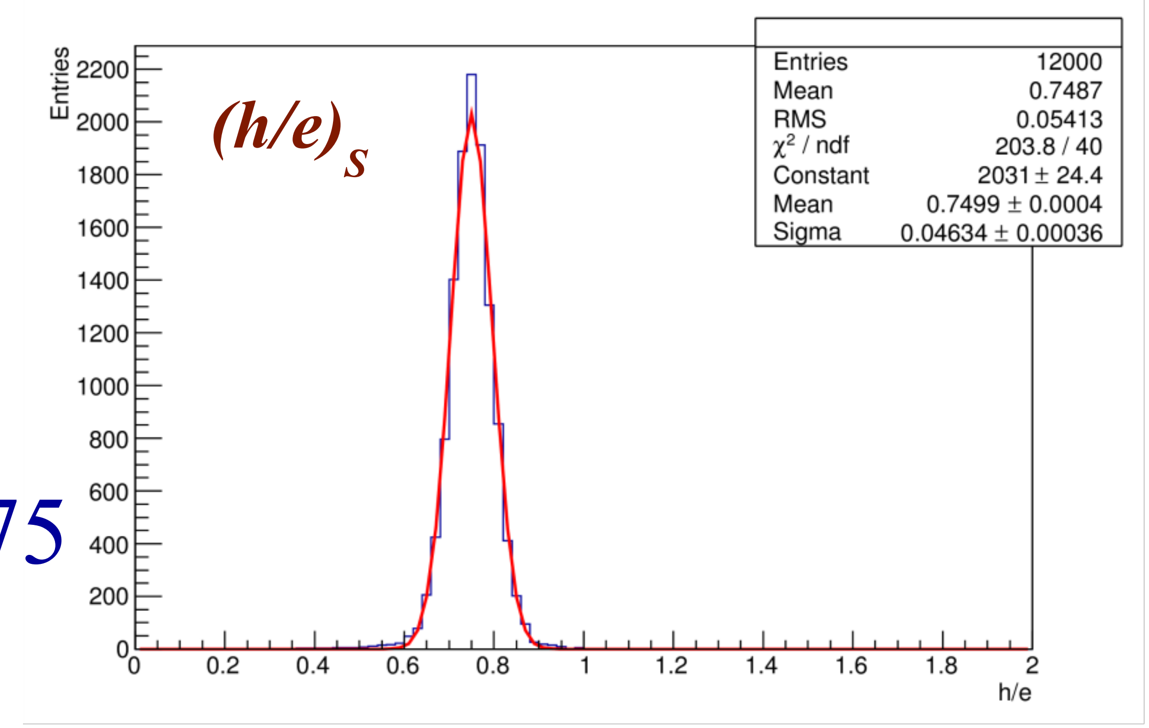


80 GeV proton



$(h/e)_{Č} \approx 0.35$

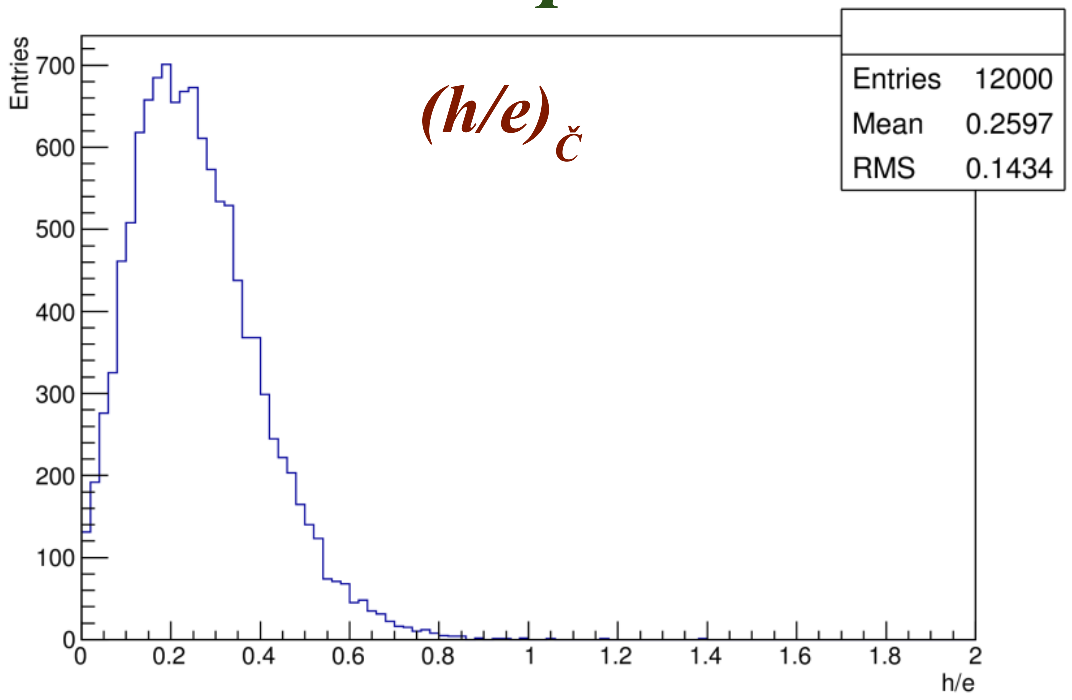




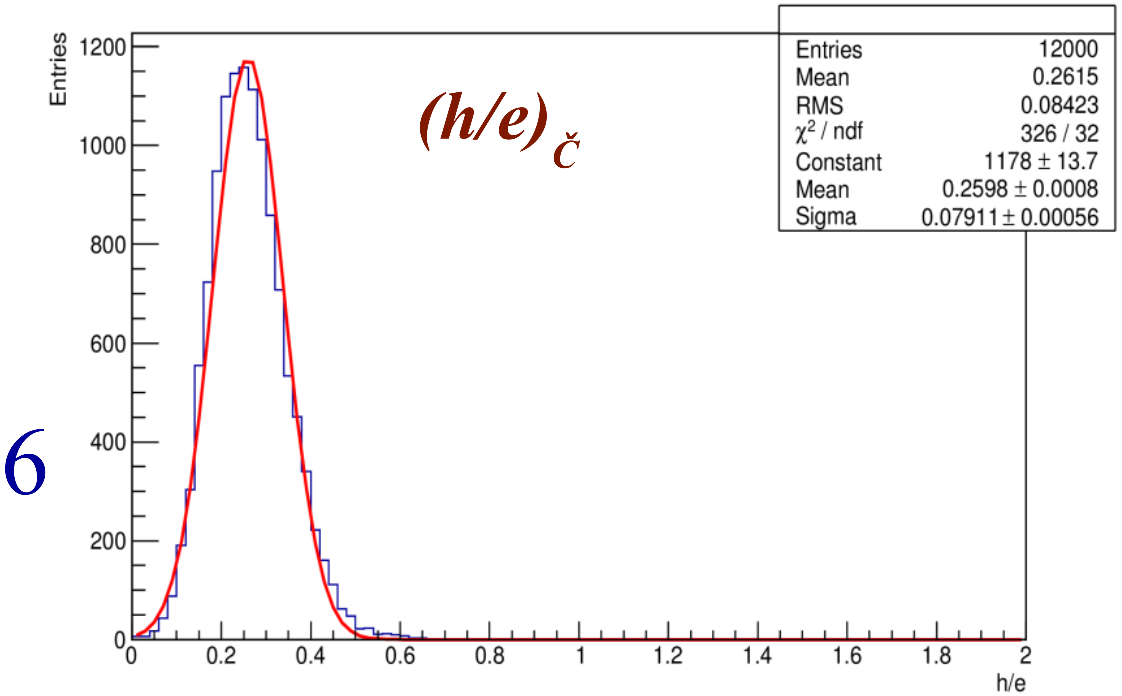
$(h/e)_{S} \approx 0.75$

h/e factors for Lead

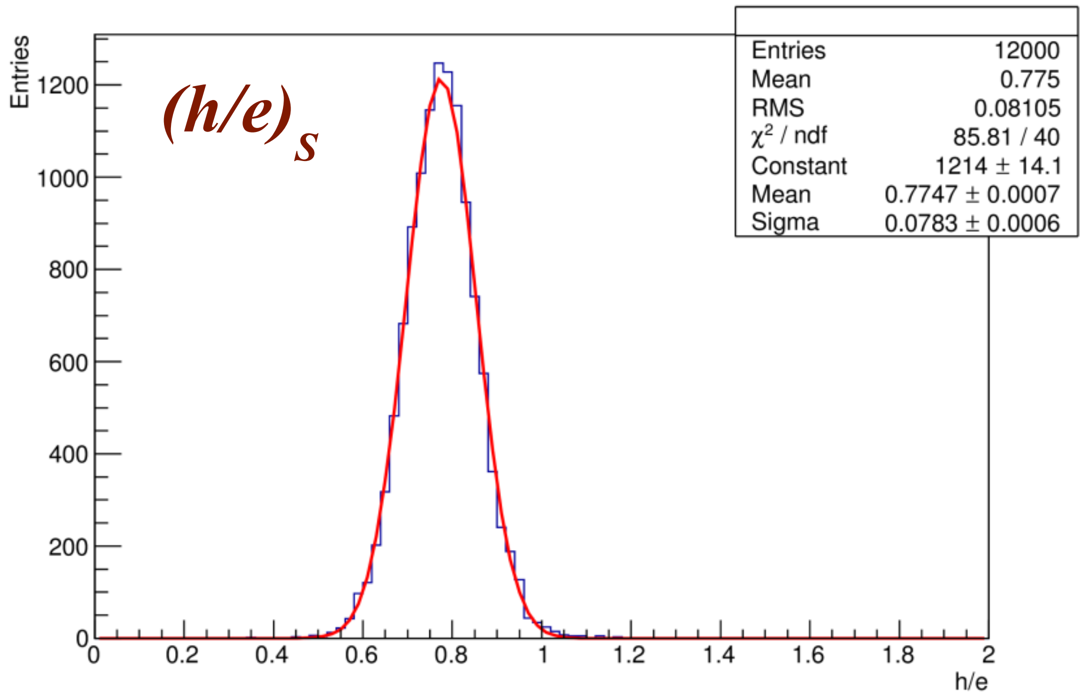
20 GeV proton



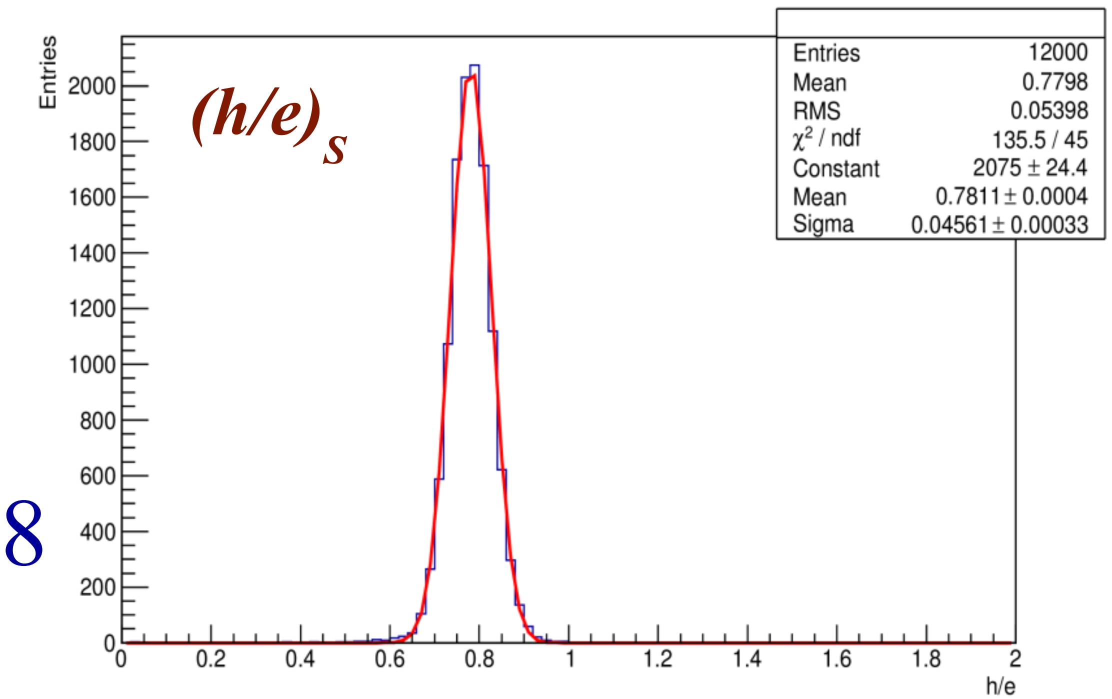
80 GeV proton



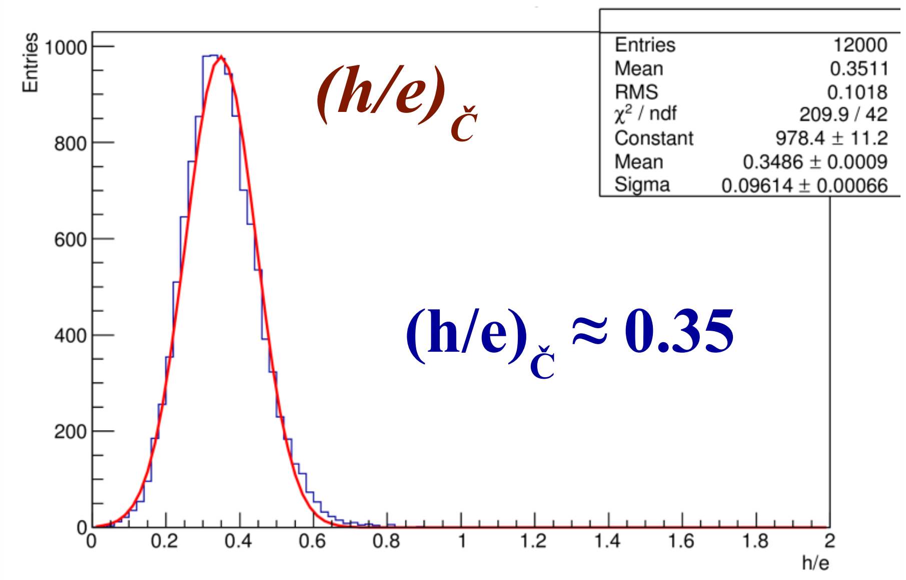
$$(h/e)_{Č} \approx 0.26$$

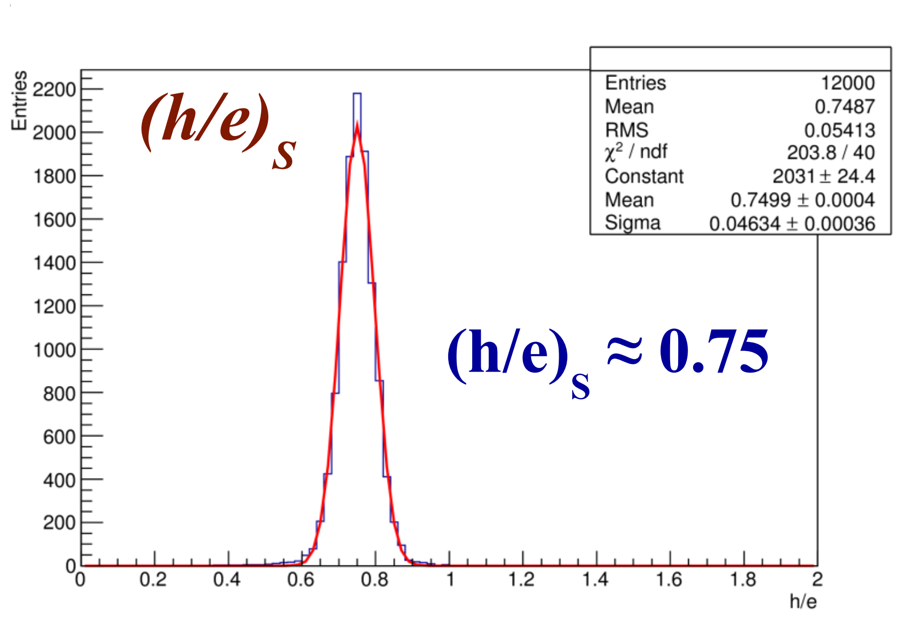


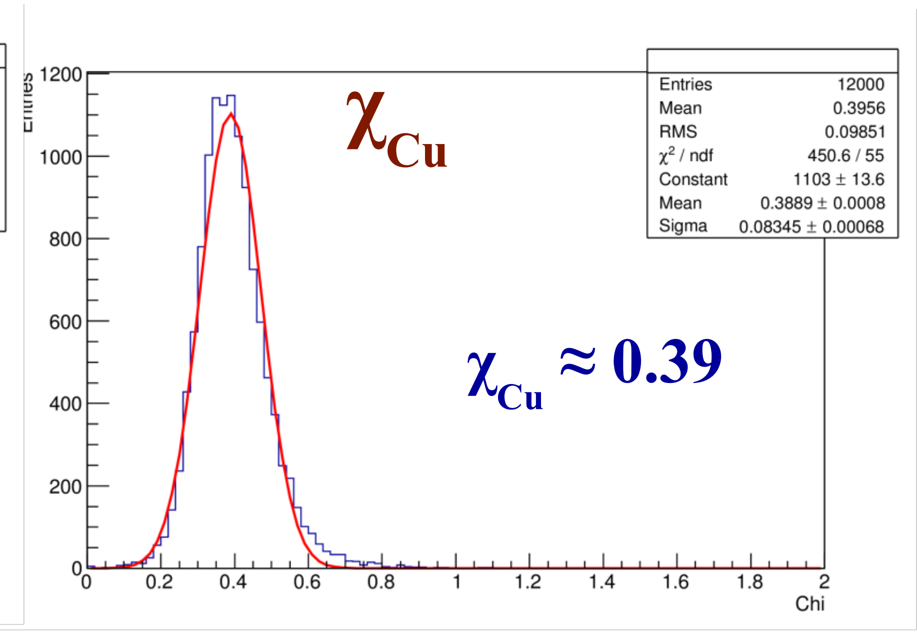
$$(h/e)_{S} \approx 0.78$$



(h/e) and χ factors



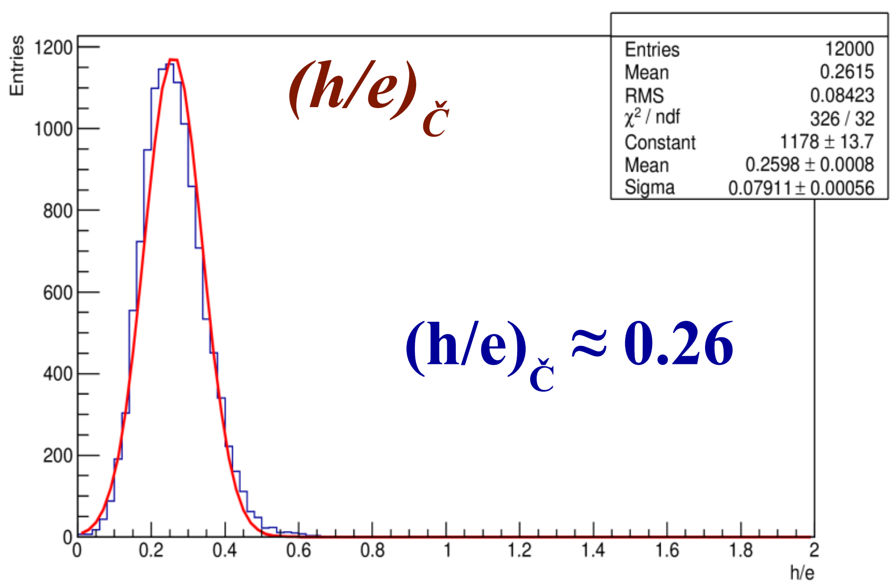


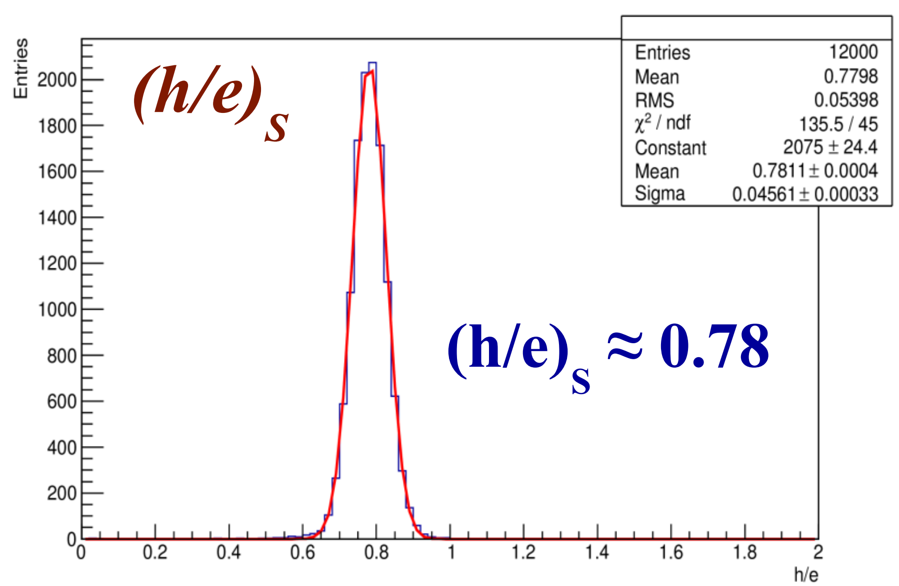


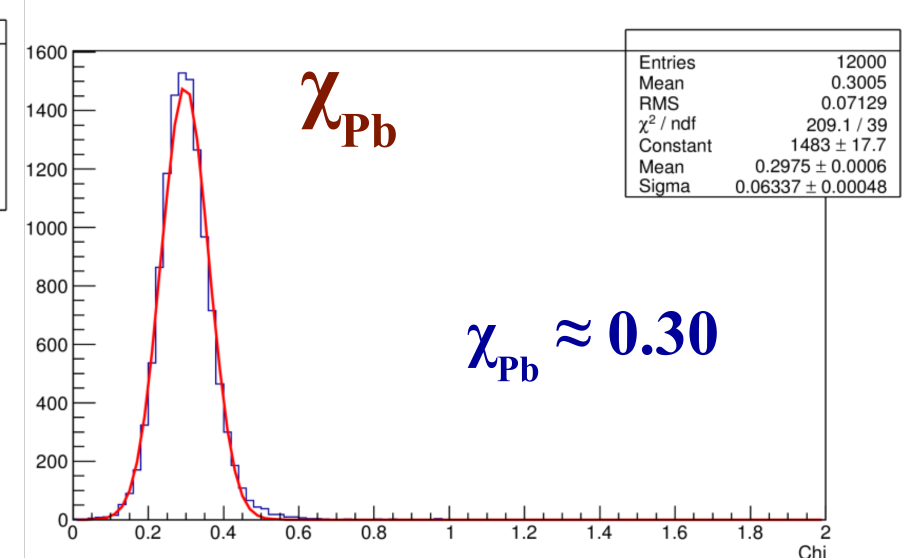
Copper →

80 GeV protons in Copper ↑ & Lead ↓

Lead →

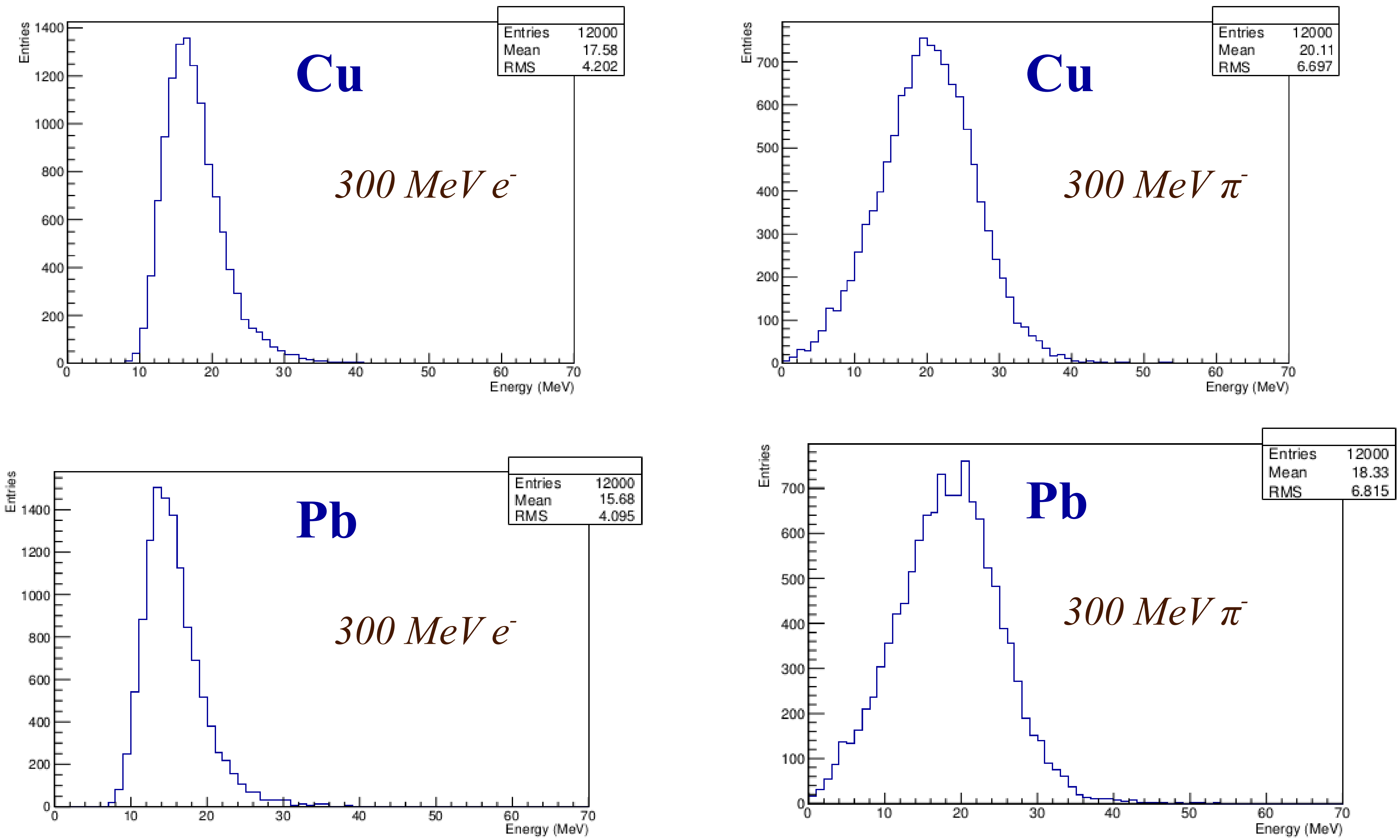




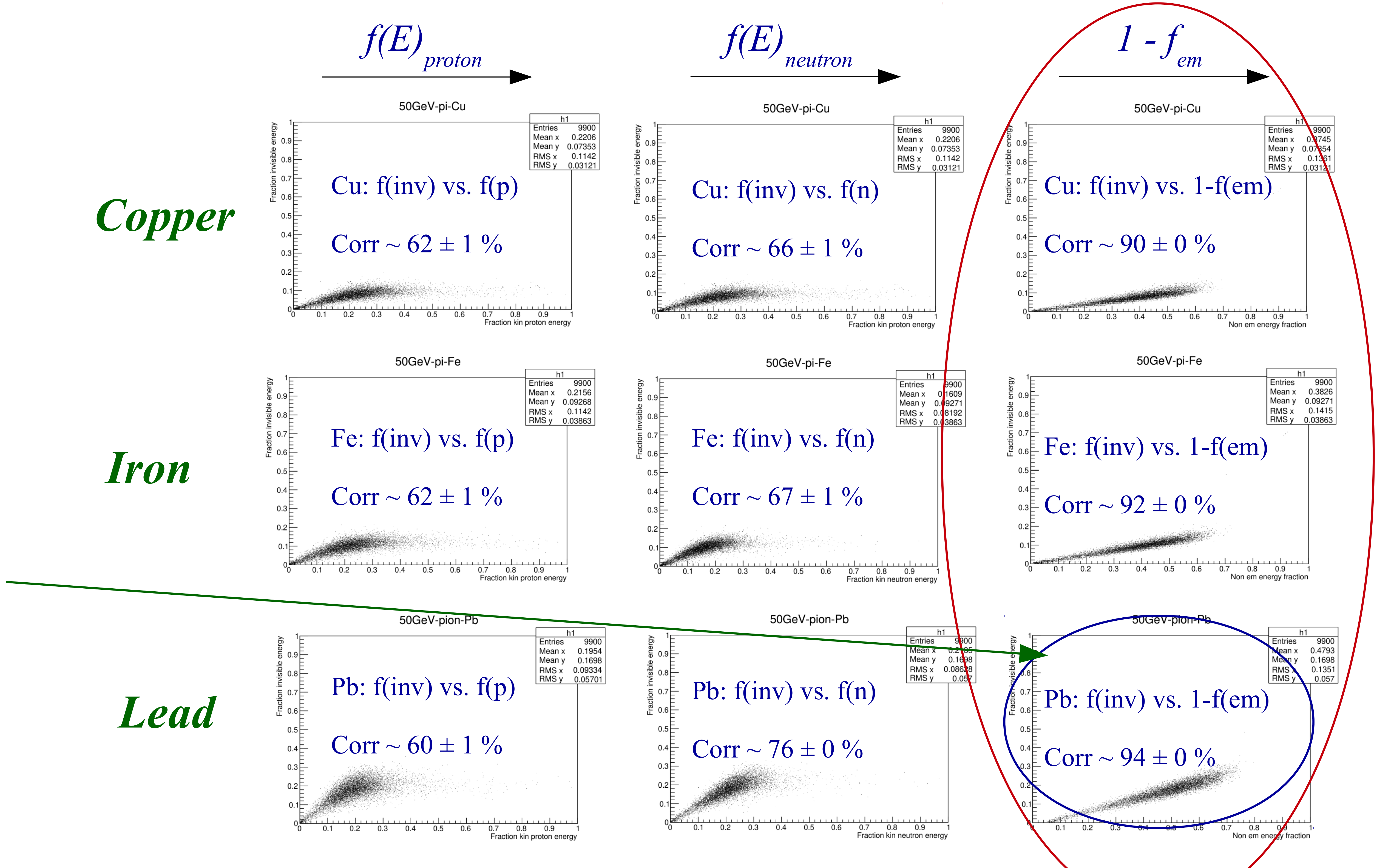


Low-energy performance - Copper vs. Lead

Energy deposited in scintillating fibres

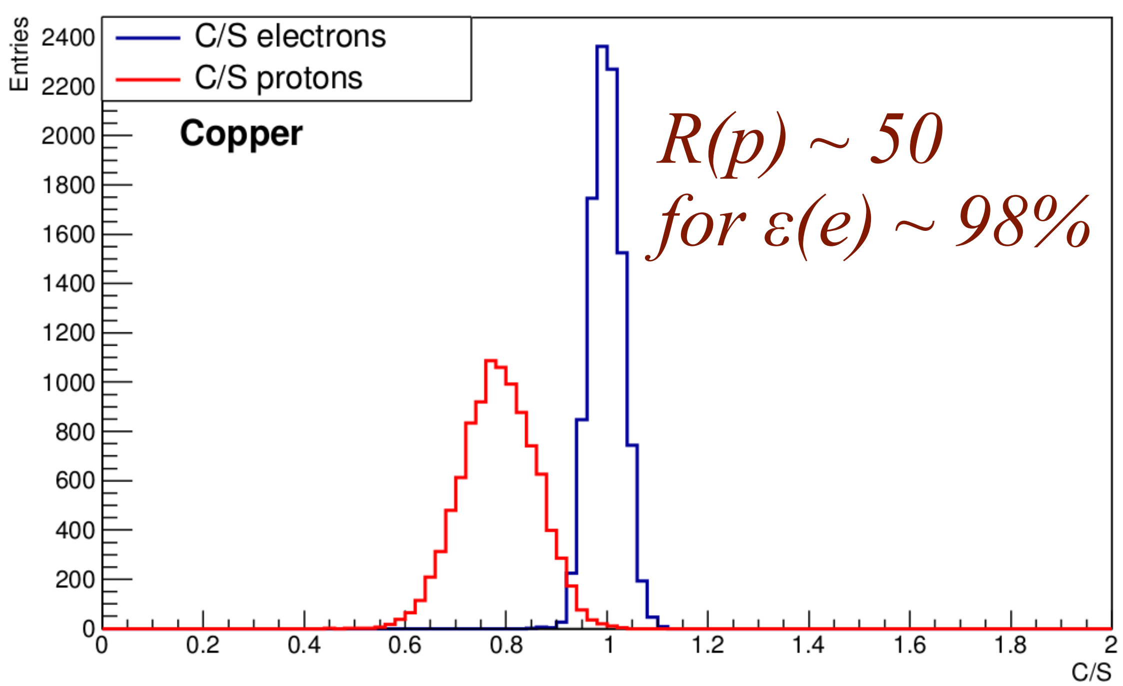


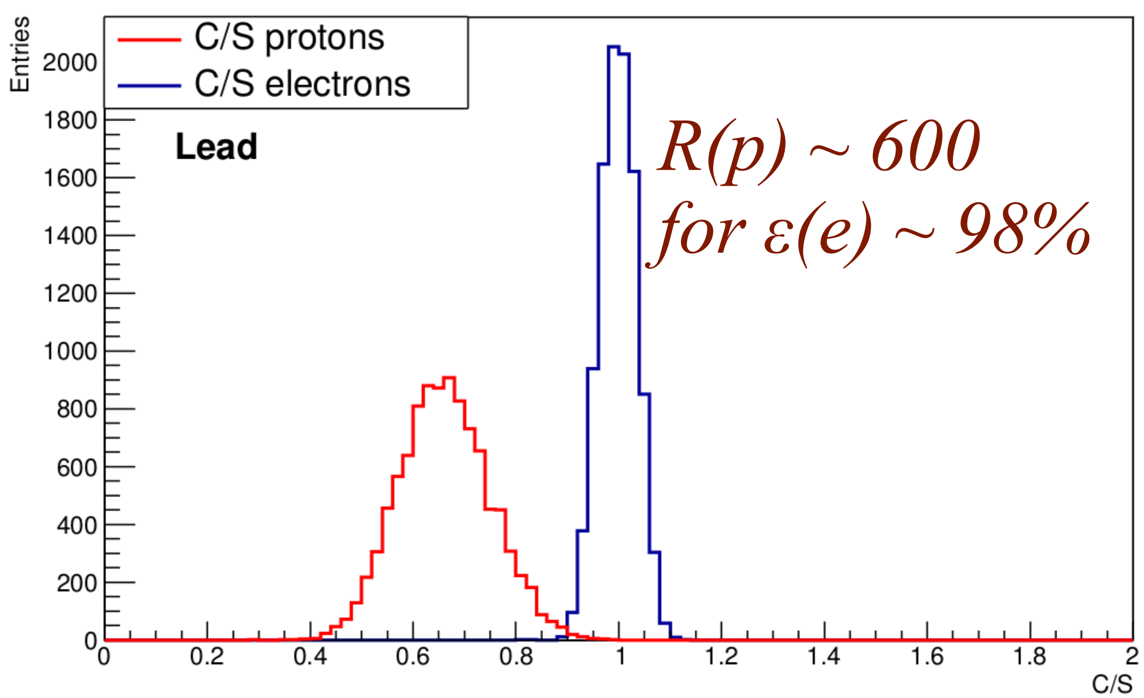
Invisible Energy (50 GeV π^-) - correlations



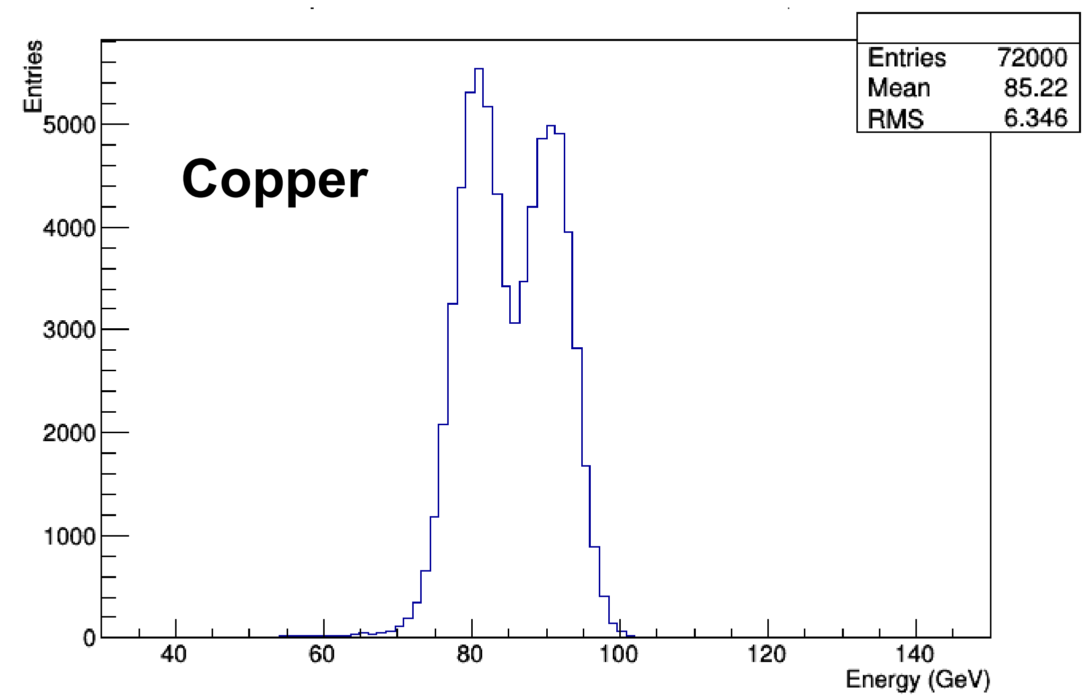
Particle Id & W/Z - Copper vs. Lead

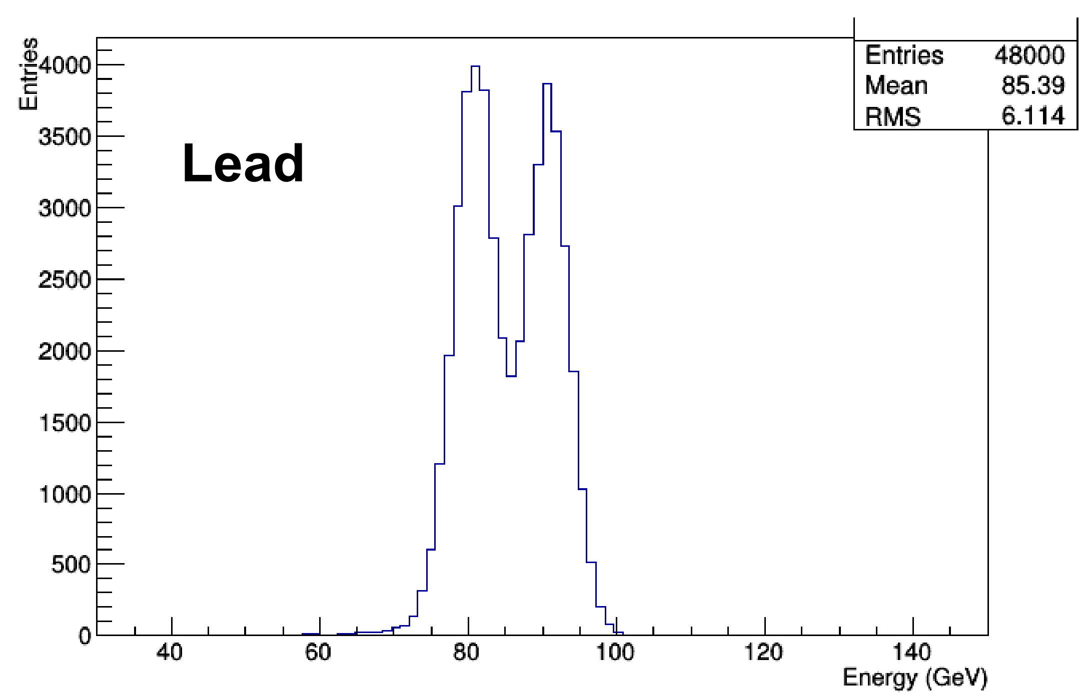
C/S ratio for 80 GeV e^- and p





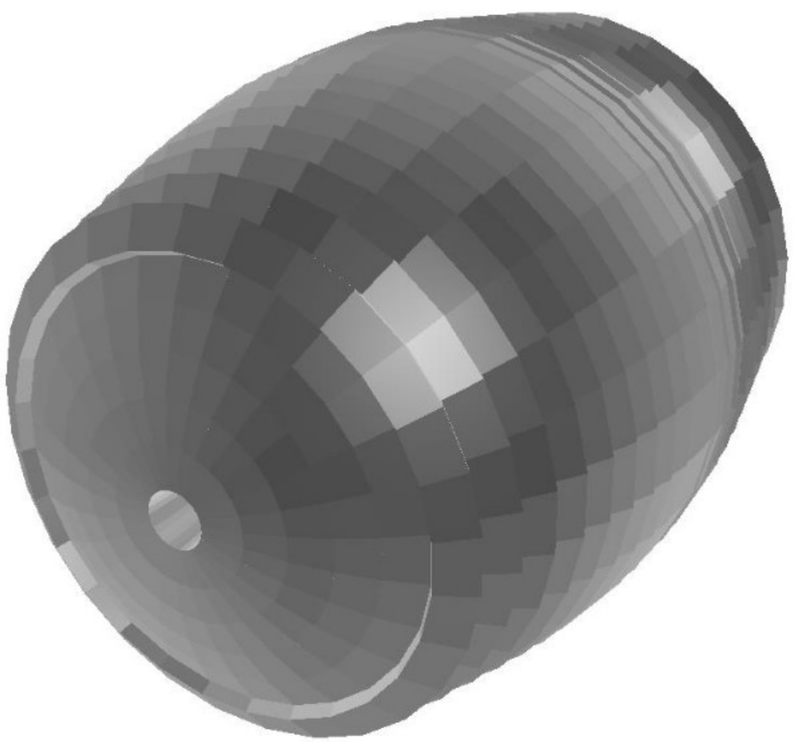
Multiple hadrons, 81 & 91 GeV

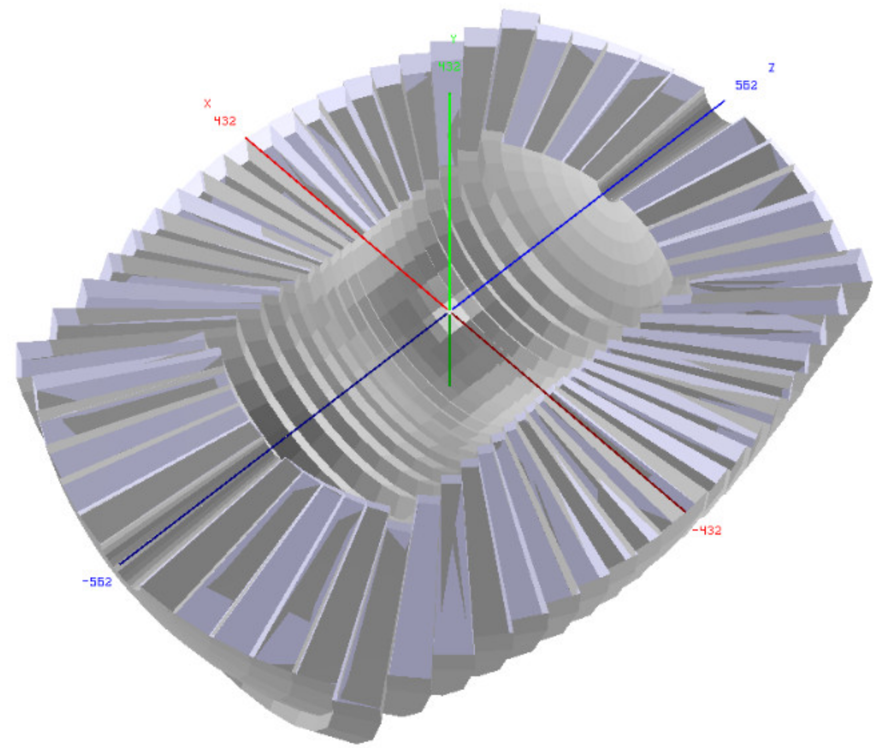


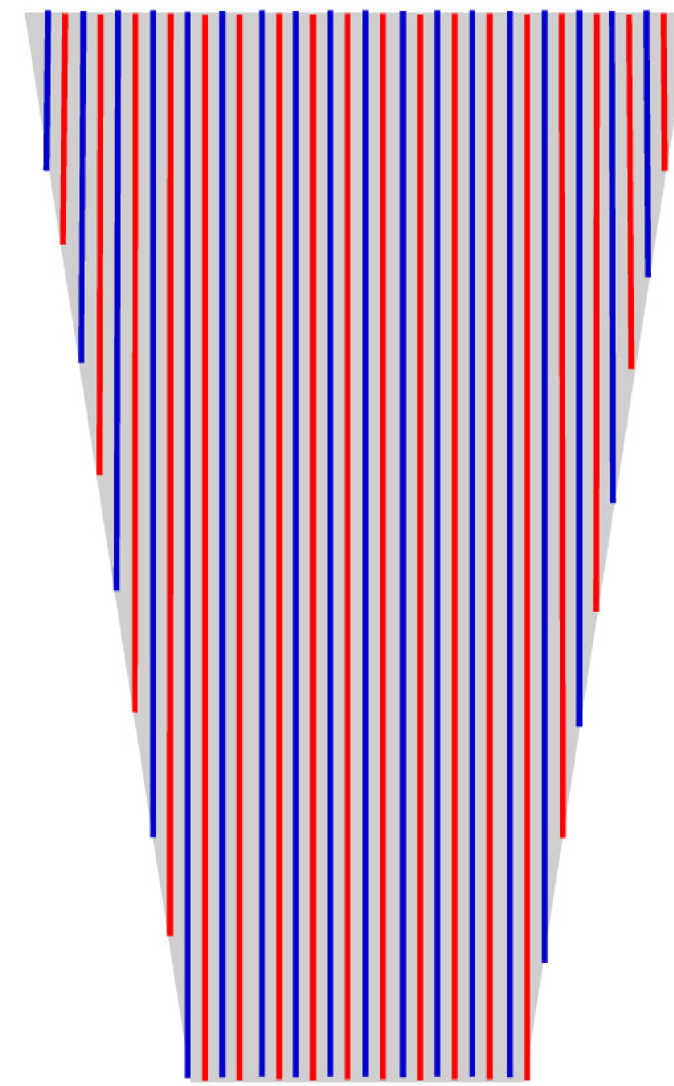


4π Simulations

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

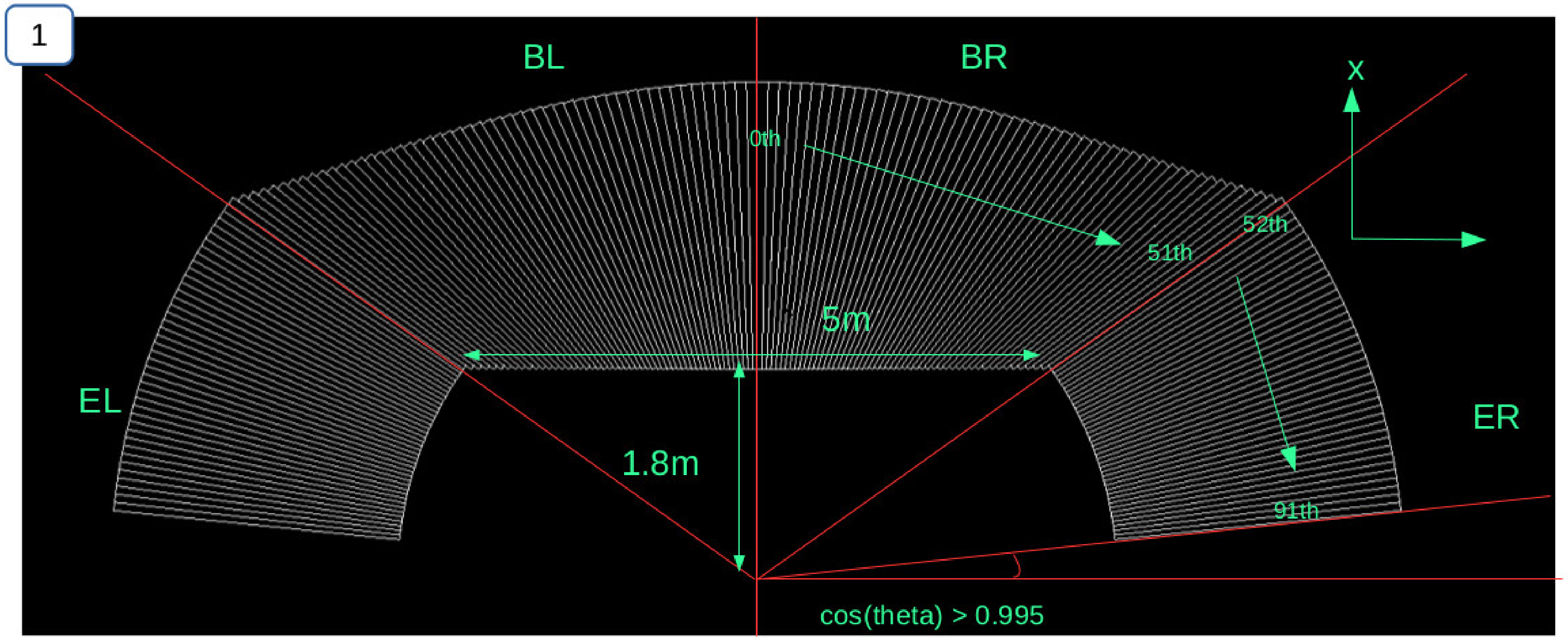


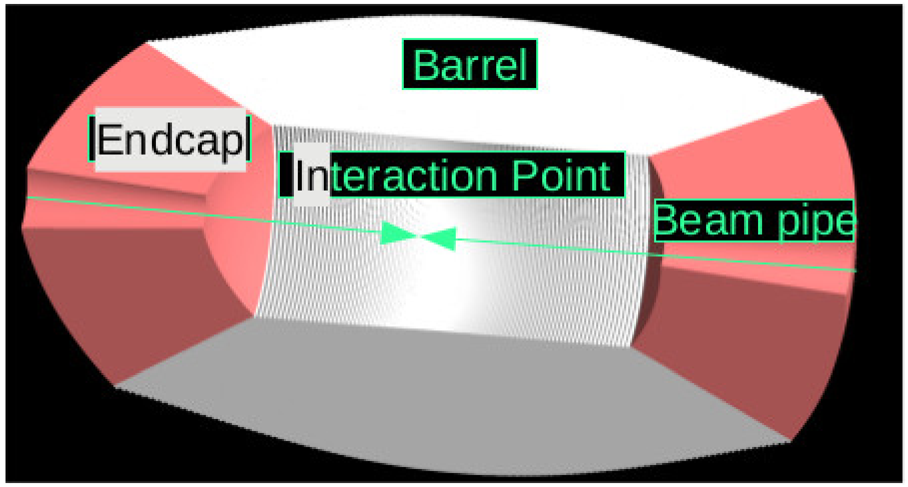


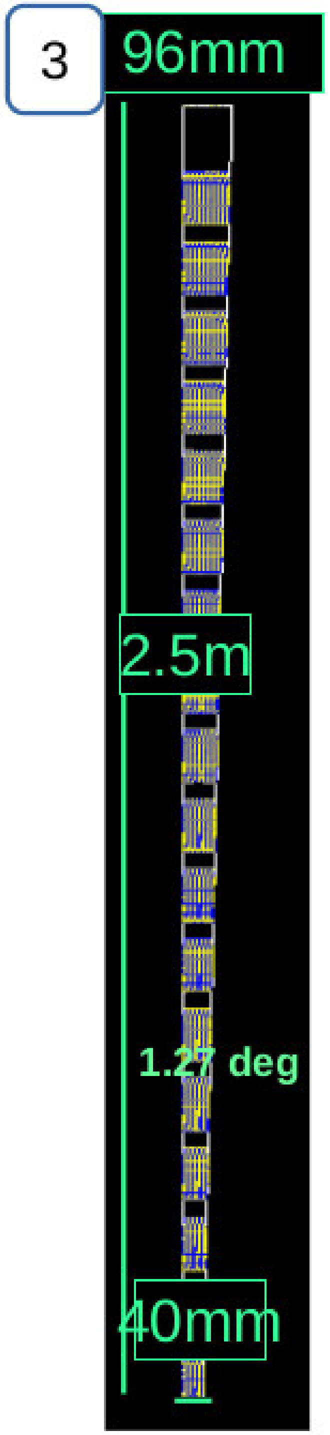


a) full coverage
b) projective geometry

Wedge Geometry

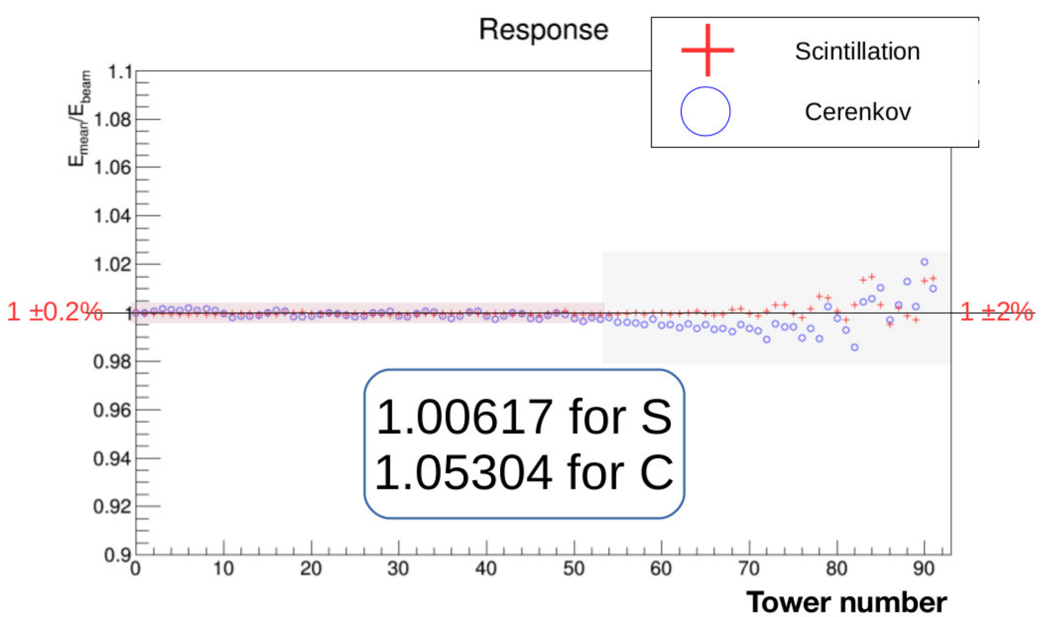


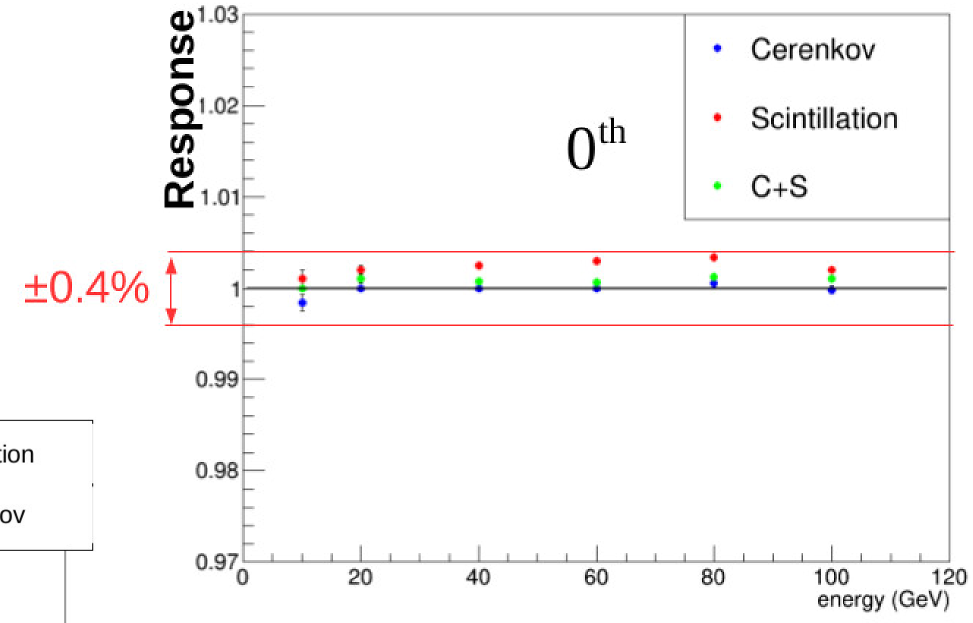


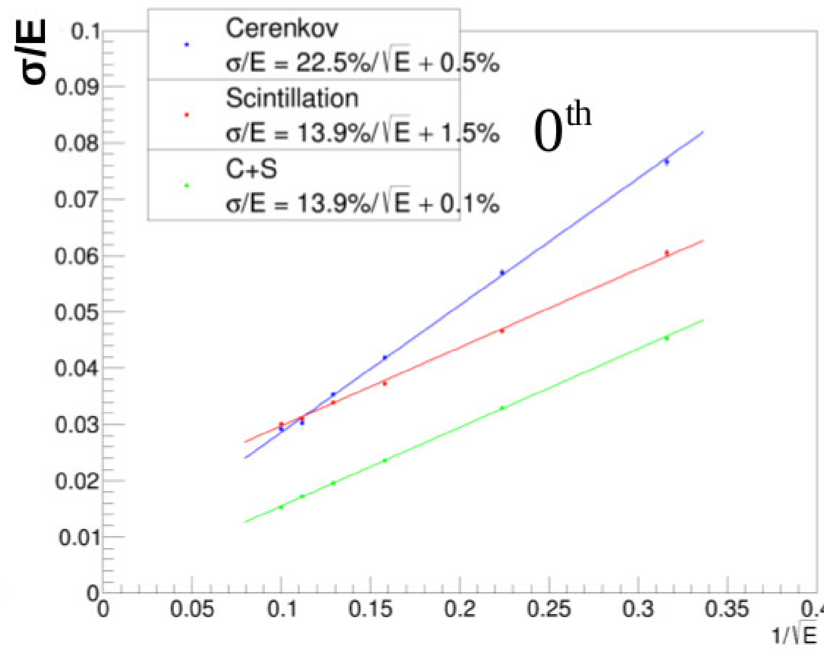


Čerenkov light yield set to 30 p.e./GeV
Calibrated w/ 20 GeV e⁻ beam @ [1º, 1.5º]

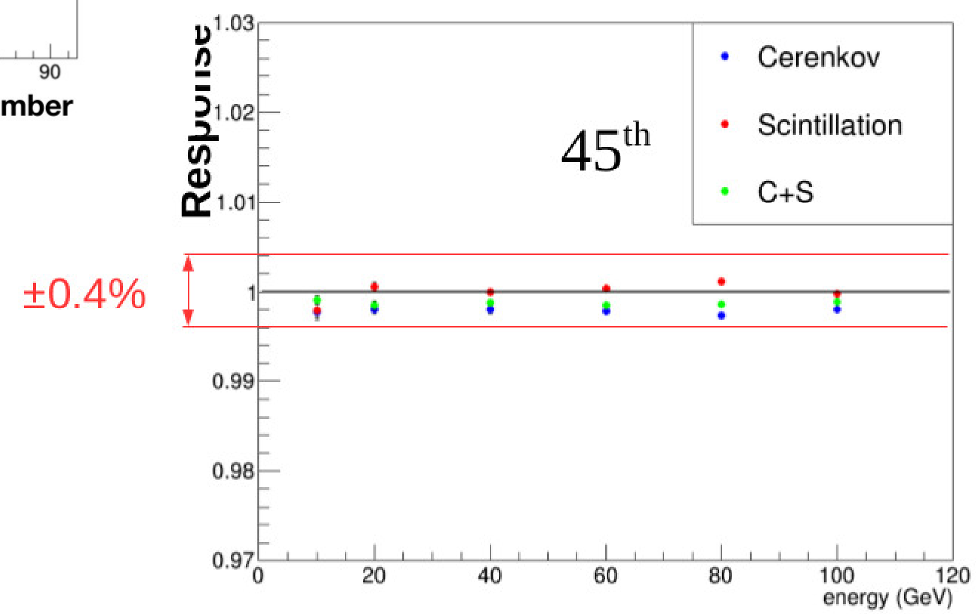
em Performance

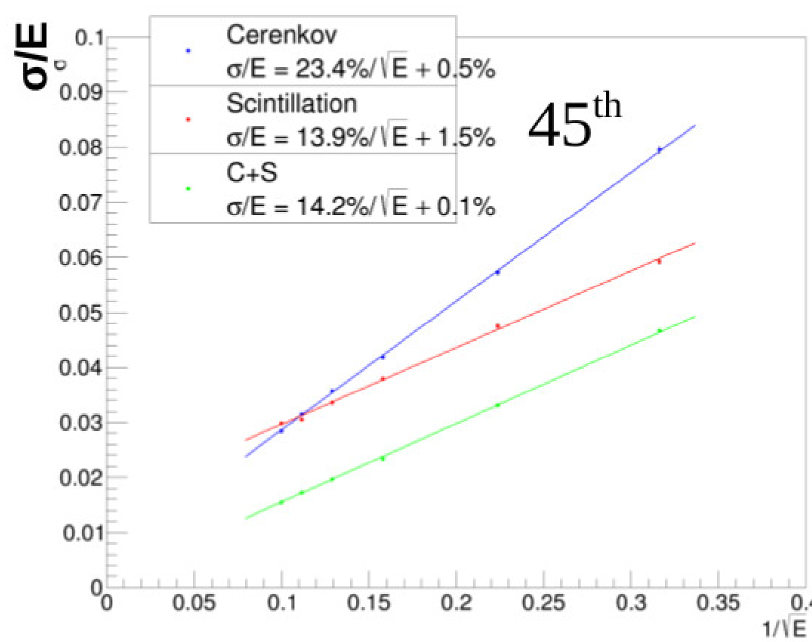






$\sigma/E \sim 14.0\% / \sqrt{E} + 0.1\%$





had Performance

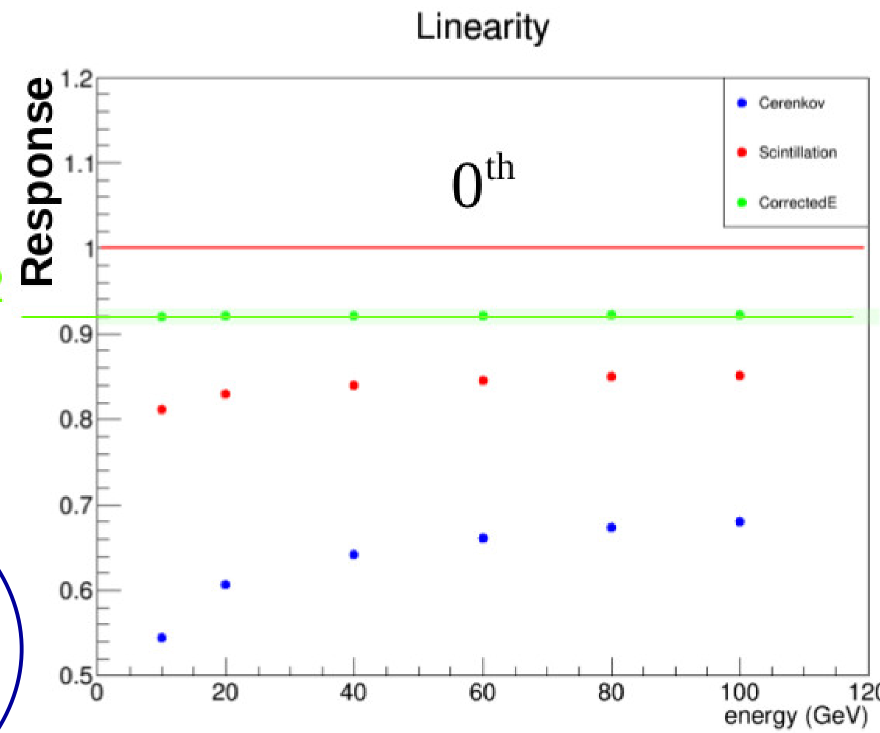
$$E = \frac{S - \chi C}{1 - \chi}$$

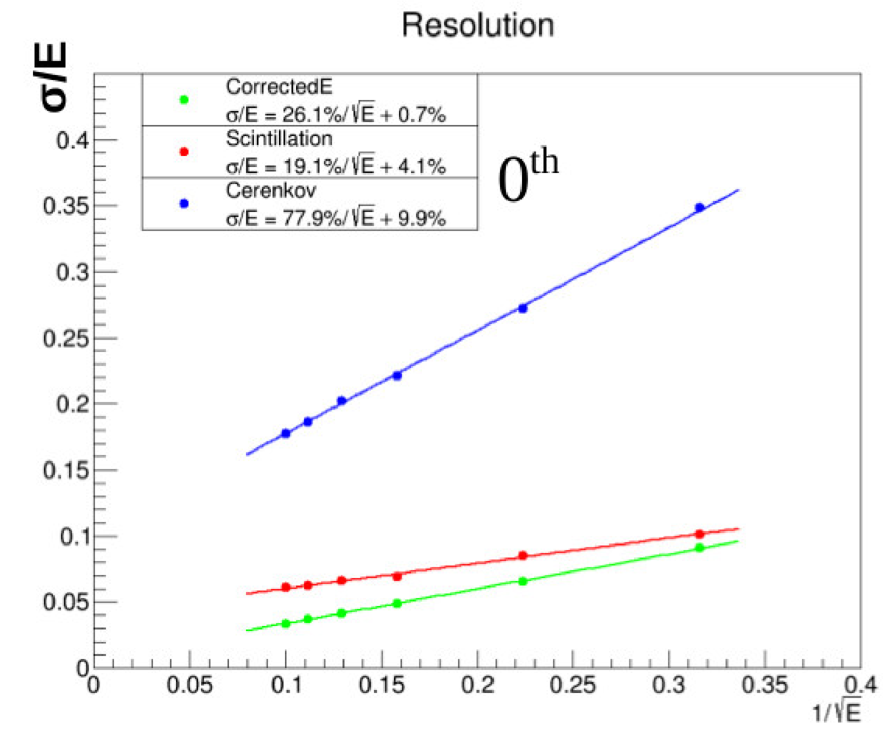
with $\chi = 0.29$

E(rec)/E(beam) ~ 92% ± 1%

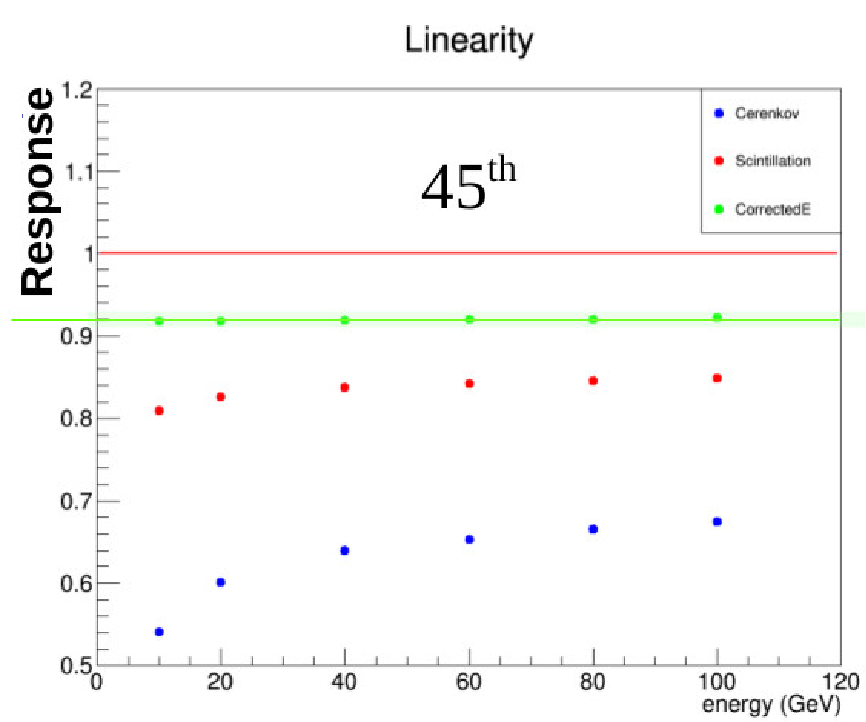
σ/E ~ 26% / √E + 1%

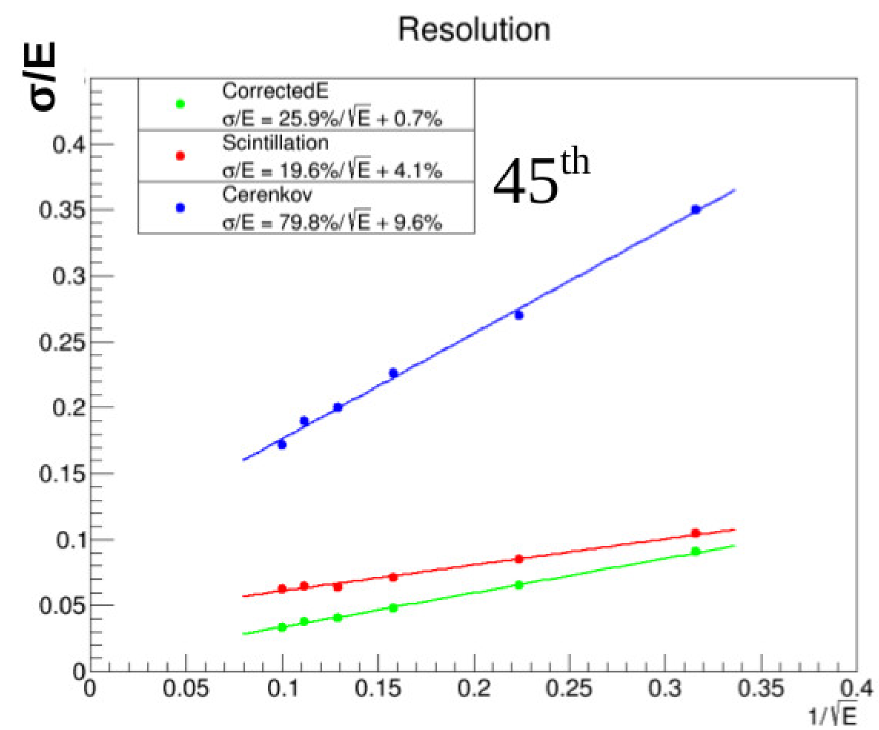
0.92
±1%





0.92
±1%





To be done ...

many issues still open/pending:

terminate Cu & Pb characterisation
resolution for jet
jet ($\tau \rightarrow$had) em/had component separation

+ impact of finite att. length $\rightarrow$ move from ideal detector

+ integrate in realistic 4π detector
$\rightarrow$ physics performance (W, Z, H, ...)!

+ VALIDATION w/ RD52 lead prototype

last but not least ...

address longitudinal segmentation issues ... 3 possible ways:

a) a real segmentation (em and had compartiments)

b) dual (displaced) fibre arrangement

c) timing (ToT, starting and falling time, peaking time)

+ implement particle flow algorithms

Conclusions

Geant4 simulations seem to prove that a dual-readout fibre-sampling calorimeter may provide, at the same time:

- e.m. resolution close to 10%/√E

- jet energy resolution ~ few % at ~100 GeV

- high performance in standalone e/h separation

for a cost effective solution for calorimetry at future e+e- colliders