Istituto Nazionale
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Dual-Readout Calorimetry

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dual-readout calorimetry

Need calorimetry:

many different and complex topics

no way to be exhaustive in a single lecture

→ just let me recap few concepts

Calorimeter role

calorimeters

massive detectors for both charged and neutral particles

→ *work as well for clusters of particles (i.e. jets)*

particles ~ totally "absorbed"

absorption process known as "shower development"

typically divided into:

a) electromagnetic ("em") calorimeters
b) hadronic ("had") calorimeters

last but not least, providing:

a) triggering
b) particle identification

calorimeters

Missing energy measurements :

4π (em & had) calorimetry coverage

["hermeticity"]

energy resolution

Normally factorised into 3 uncorrelated terms :

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

where :

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

but more accurate breakdowns possible

for example lateral containment better described by a $E^{-1/4}$ term
first and second term may have some correlations

resolution relevance ?

Few examples (other than missing energy) :

invariant mass resolution :

$H \rightarrow \gamma\gamma$

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

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

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

Shower modelling

electromagnetic (em) showers

development driven by em interactions :

→ clean & ~ simple

→ long-range

→ depend on atomic properties

→ atomic number & atomic scale (~10^{-10} m)

hadronic (had) showers

development driven by nuclear interactions :

→ complex & ~ hard

→ short-range

→ depend on nuclear properties

→ density of nuclei & nuclear scale (~10^{-15} m)

well known for about a century …

atom → football field (electron clouds anywhere)

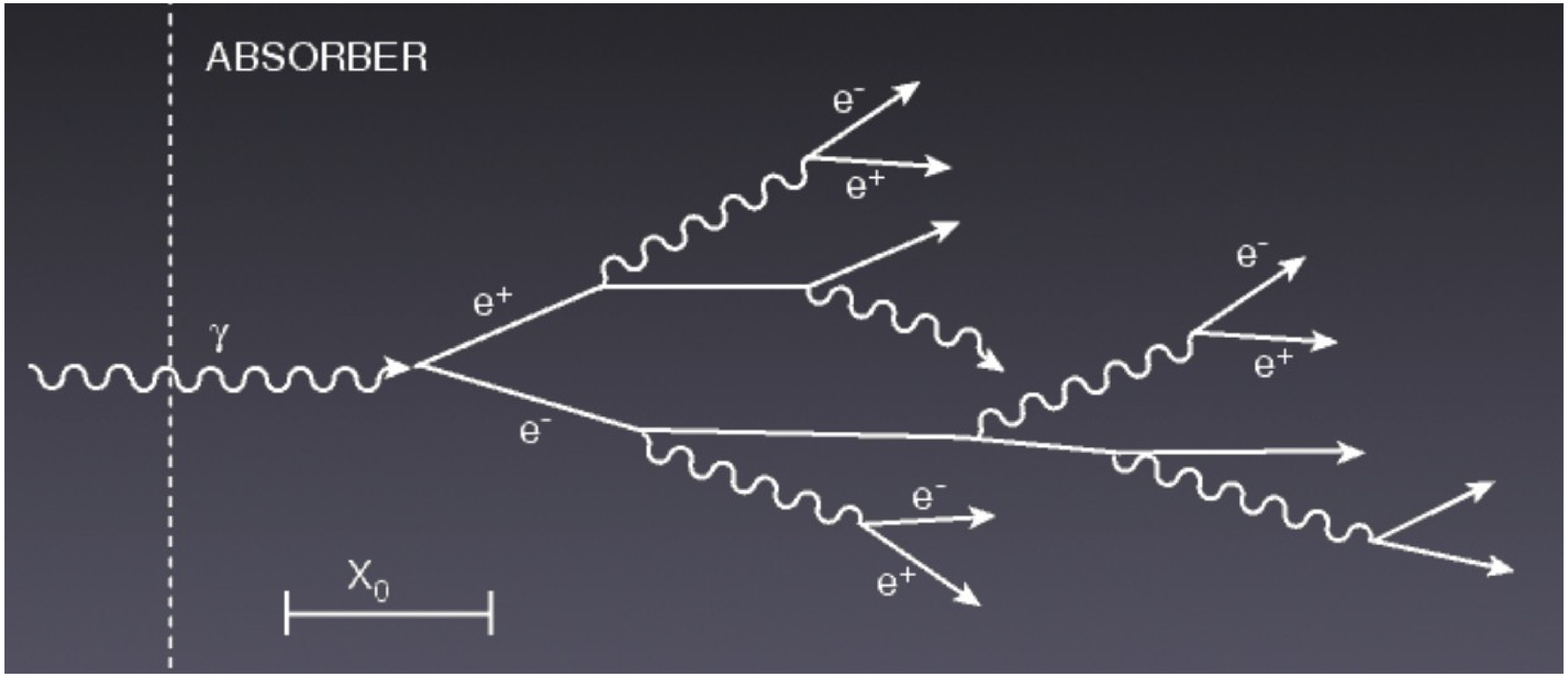
nucleus → 1 mm (static) sand grain at field center

→ *hadrons need to pass within ~10^{-15}m from nuclei to interact*

→ detectors (dimensions, materials) and performance
quite different

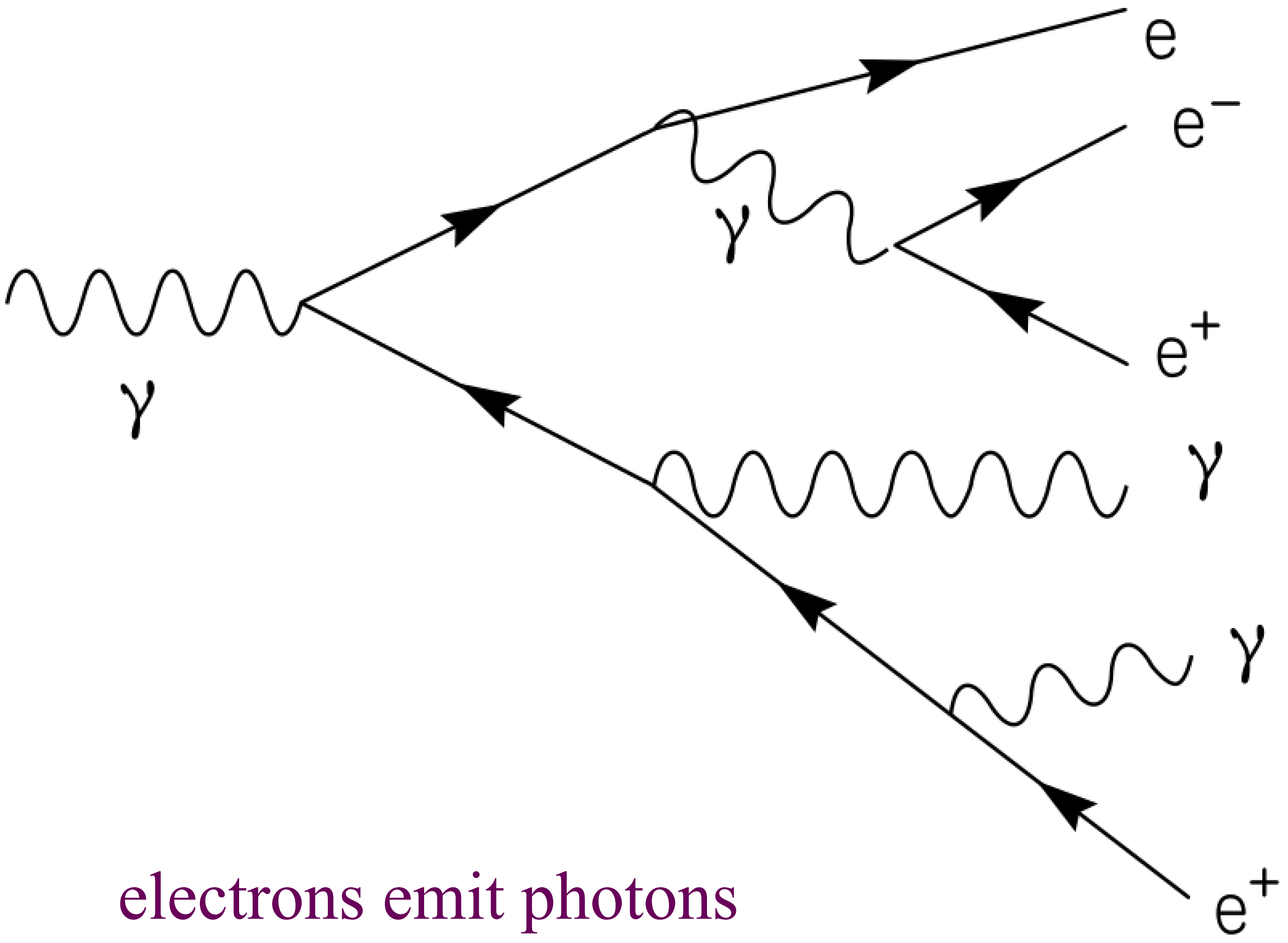
em showers

Cascade of (e^+,e^-,γ) → stochastic process w/ thousands particles



pair production, bremsstrahlung & ionisation

em showers



electrons emit photons
photons produce e^+e^- pairs

radiation length → X_0

X_0 : longitudinal development scale

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0}$$

1 X_0 : when <1-1/e> (~ 63.2%) of electron energy → brems.

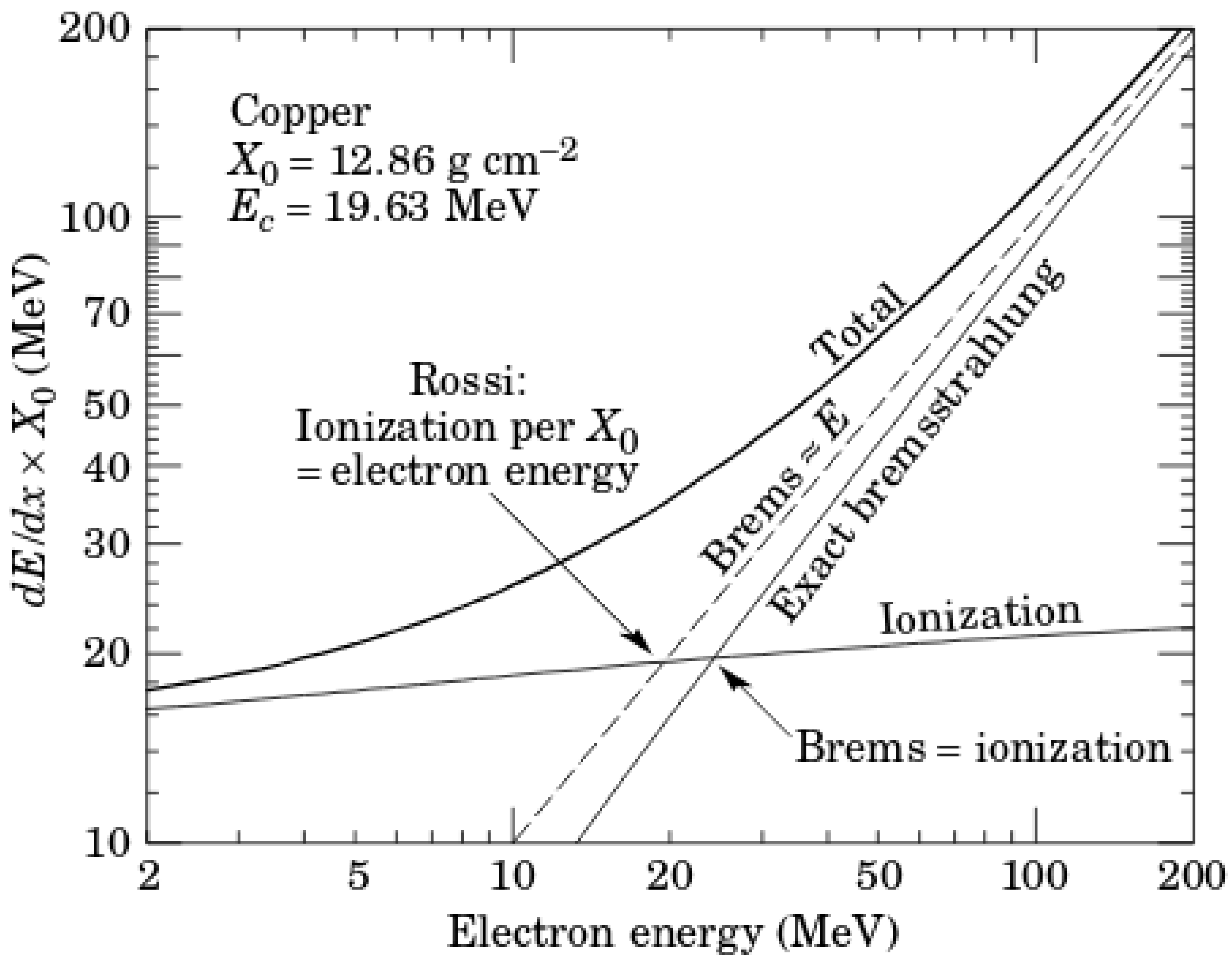
$$X_0 = \frac{1433\,A}{Z(Z+1)(11.4-\ln(Z))}\,\frac{\mathrm{g}}{\mathrm{cm}^2}$$

$$\boxed{X_0\ [\ \mathrm{g/cm^2}\ ] \sim Z^{-1}}$$

critical energy → E_c

E_c : when bremsstrahlung takes over ionisation

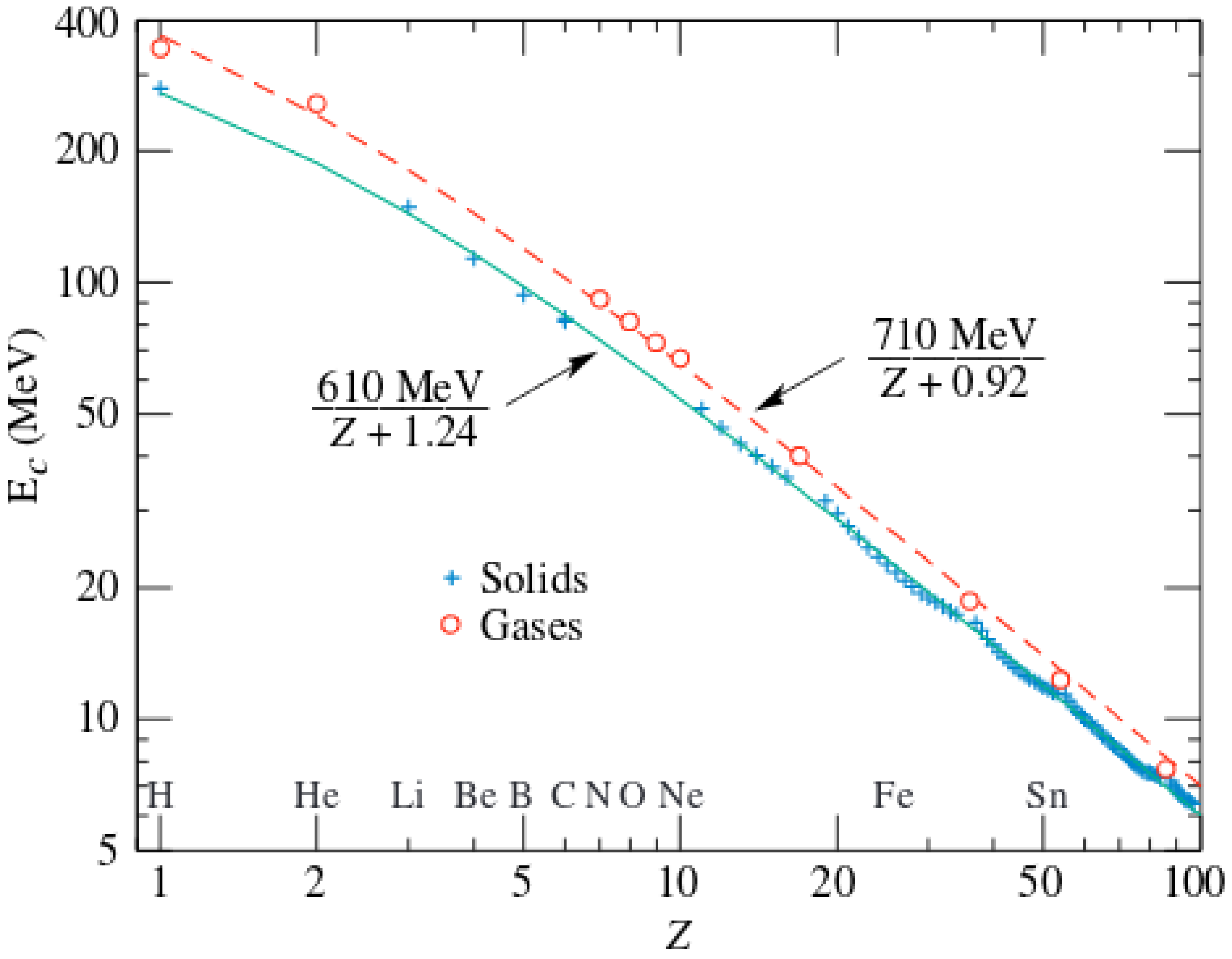
$$\boxed{\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{Ion}}$$



critical energy $\rightarrow E_c$

E_c : when bremsstrahlung takes over ionisation

$$\boxed{\left.\frac{dE}{dx}(E_c)\right|_{Brems} = \left.\frac{dE}{dx}(E_c)\right|_{Ion}}$$



$$\boxed{E_c\,[\,\mathrm{MeV}\,] \sim Z^{-1}}$$

Molière radius → R_M

lateral spread ~ driven by multiple scattering

R_M : radius of cylinder containing 90% of shower energy (95% in $2\times R_M$)

$$R_M = E_s \frac{X_0}{E_c}$$

where :

$$E_s = m_e c^2 \sqrt{4\pi/\alpha} = 21.2\ \mathrm{MeV}$$

→ R_M [g/cm^2] ~ independent of Z

compound materials

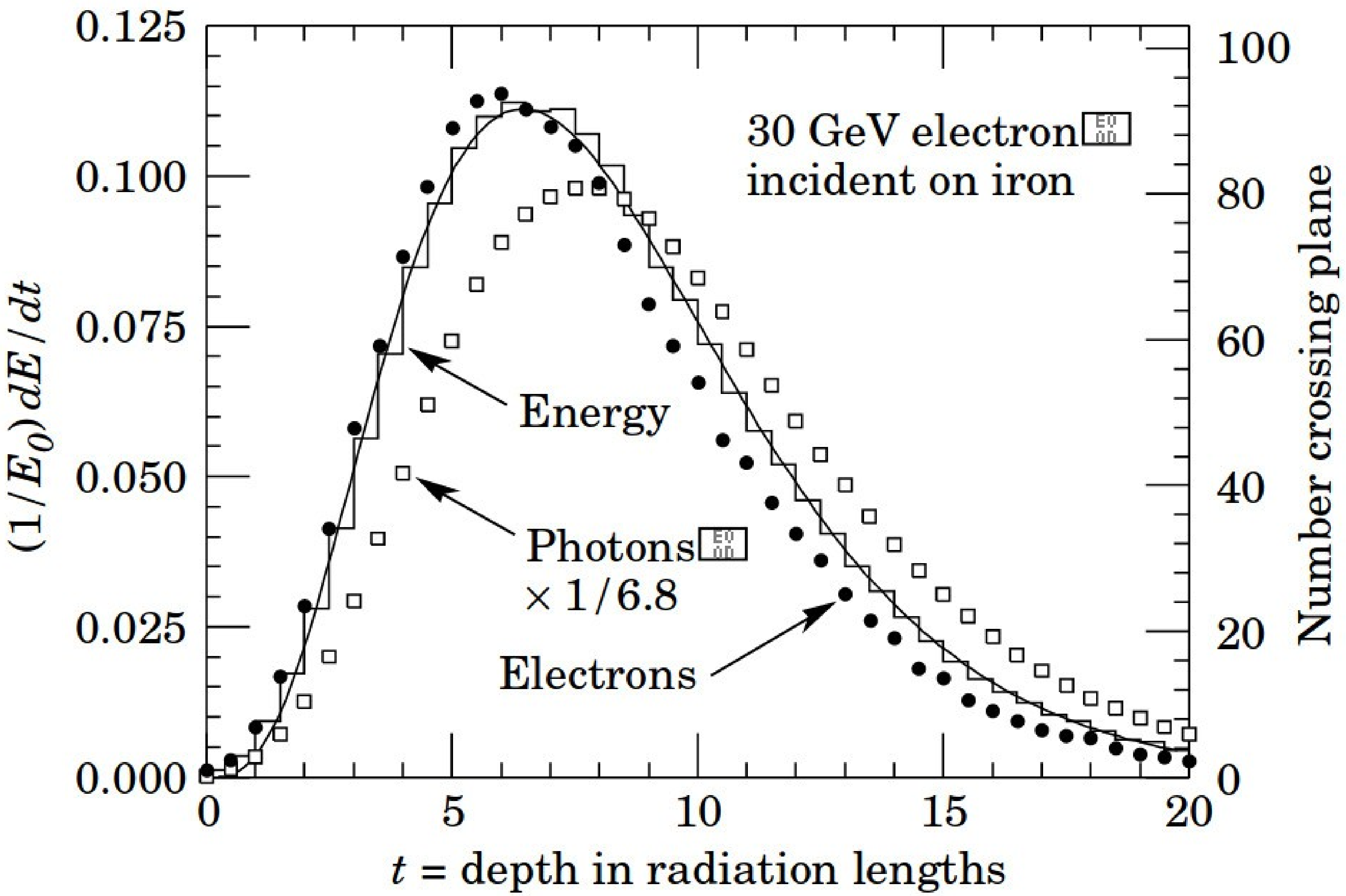
$$1/X_0 = \sum w_j/X_j$$

where : w_j = fraction by weight of j_{th} element

same for R_M :

$$\frac{1}{R_M} = \frac{1}{E_s}\sum \frac{w_j E_{cj}}{X_j} = \sum \frac{w_j}{R_{Mj}}$$

em shower development



1) fractional energy deposition per X_0

2) number of e and photons (E > 1.5 MeV) crossing planes

… one more parameter

shower maximum (shower depth):

where multiplication process ~ stops

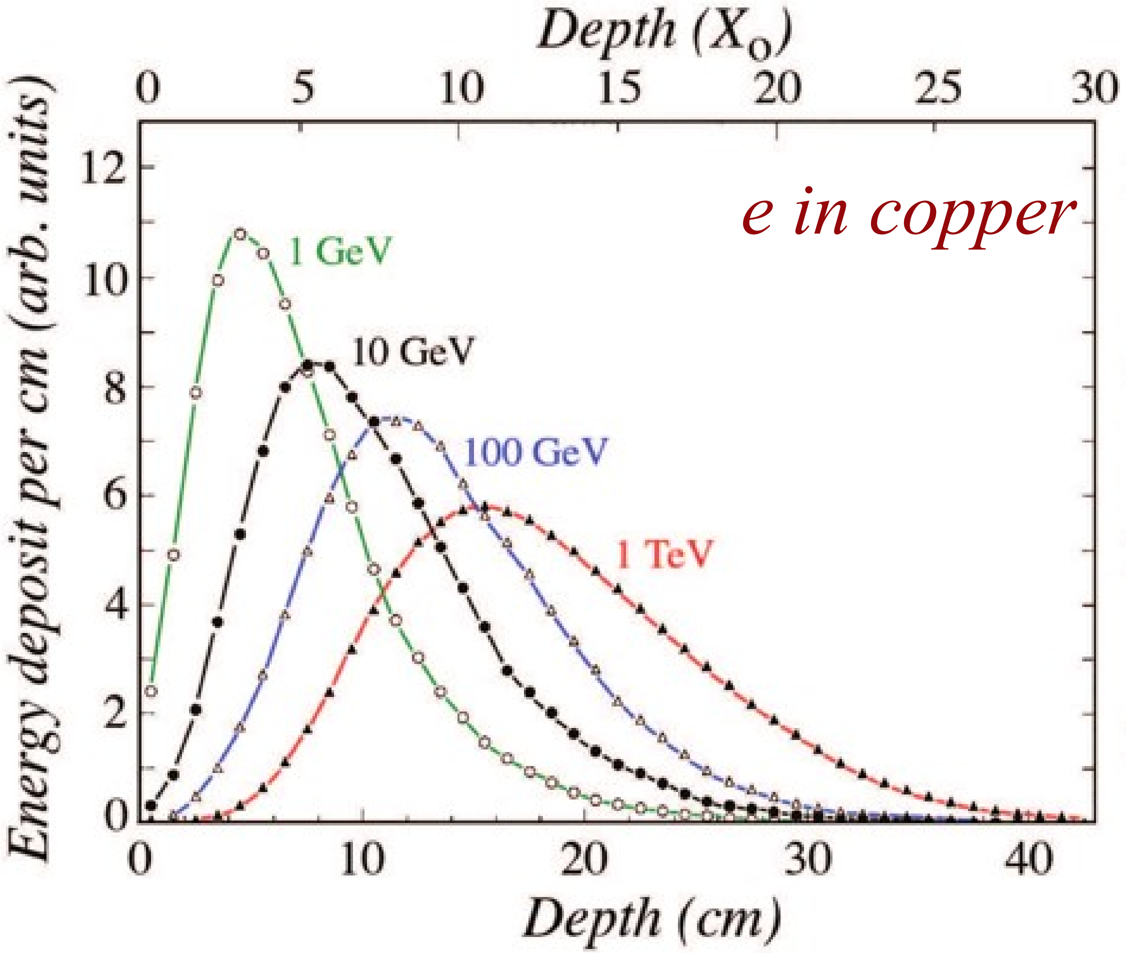
$$X = X_0 \frac{\ln(E_0/E_c)}{\ln 2}$$

X ~ 1 / Z , ~ log(E)

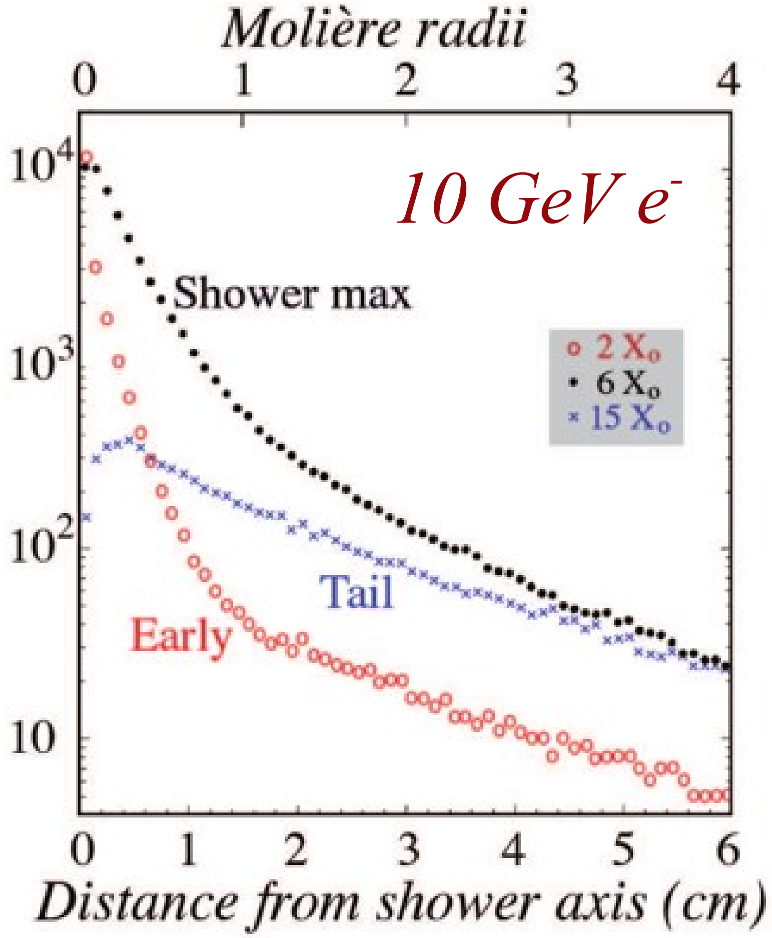
shower longitudinal dimension mildly grows as log(E)

shower development

longitudinal profiles

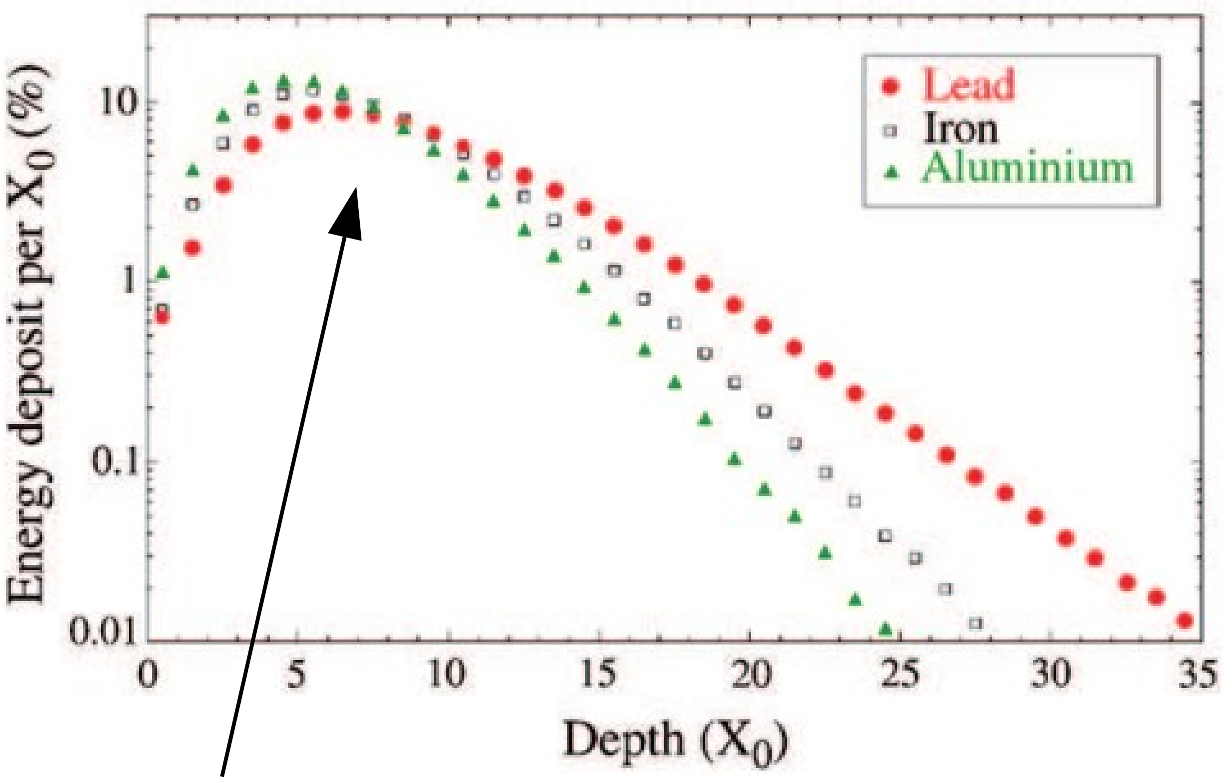


lateral profiles

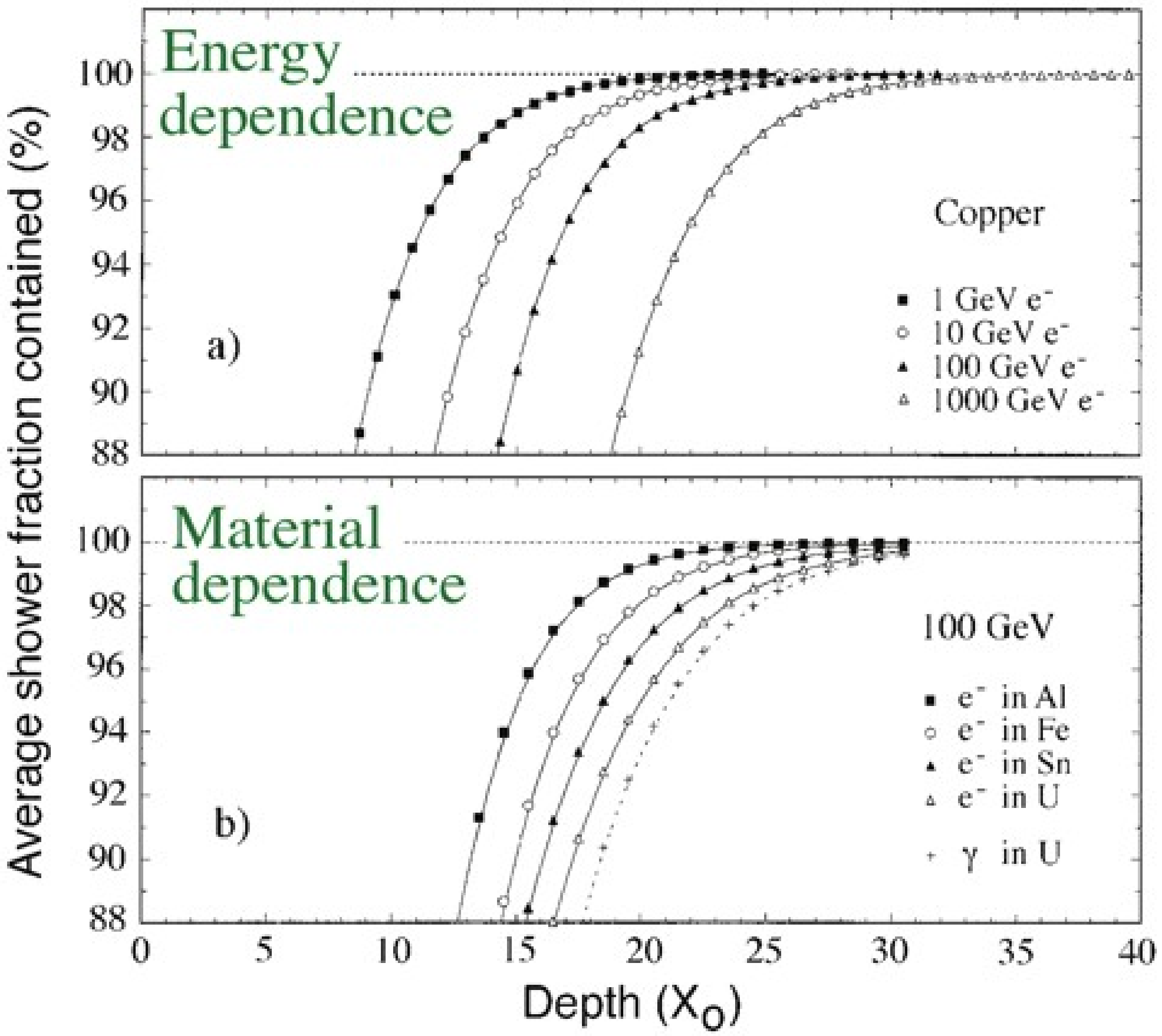


after shower maximum, lateral spread dominated by isotropic processes (Compton scattering, photelectric effect)

scaling violations



longitudinal profiles (10 GeV e$^-$)



as well, due to low-energy phenomena (Compton scattering, photoelectric effect) dominating after shower maximum

Detector response

energy response

total shower length L $\propto$ total energy = E

signal S (mainly due to low-energy particles) $\propto$ L $\propto$ E

$\rightarrow$ linearity

fluctuations :

a 40 GeV shower equivalent to 2 × 20 GeV showers

$\rightarrow$ independent fluctuations

$\rightarrow \sigma(E) \propto \sqrt{E}$

stochastic term :

$\sigma(E)/E = a/\sqrt{E}$ → improves as $E^{-½}$

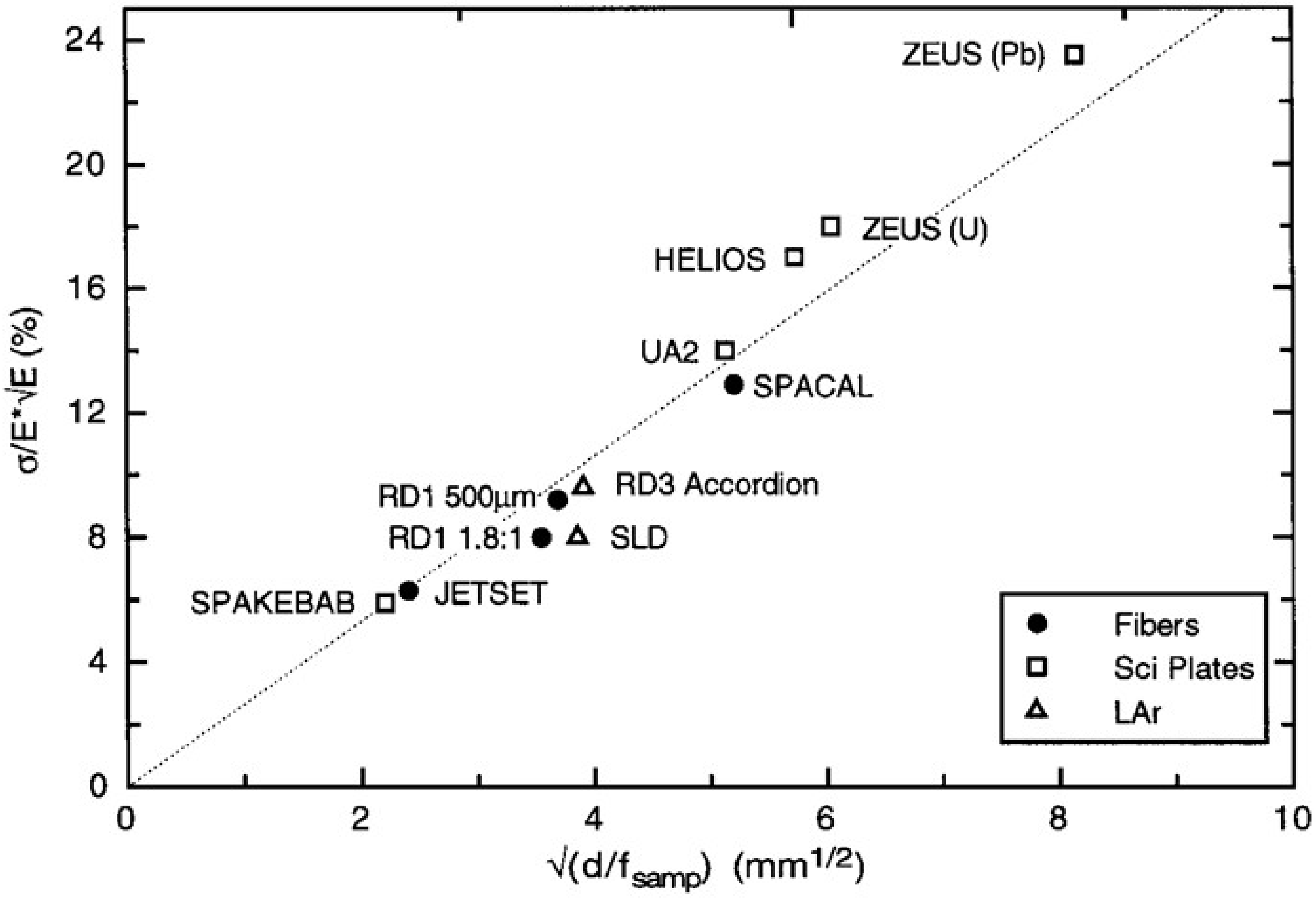
sampling calorimeters

usually sandwich of active (e.g. scintillator plates) and passive elements (e.g. lead plates)

→ impact on resolution ?

sampling fraction : fraction of energy lost in the active medium (by a minimum ionising particle)

sampling fluctuations



(rough) rule of thumb : $a_{\text{samp}} = 2.7\% \sqrt{d/f_{\text{samp}}}$

d [mm] = thickness of each active layer

em resolution ?

1) homogeneous: 100% of shower track sampled in active medium

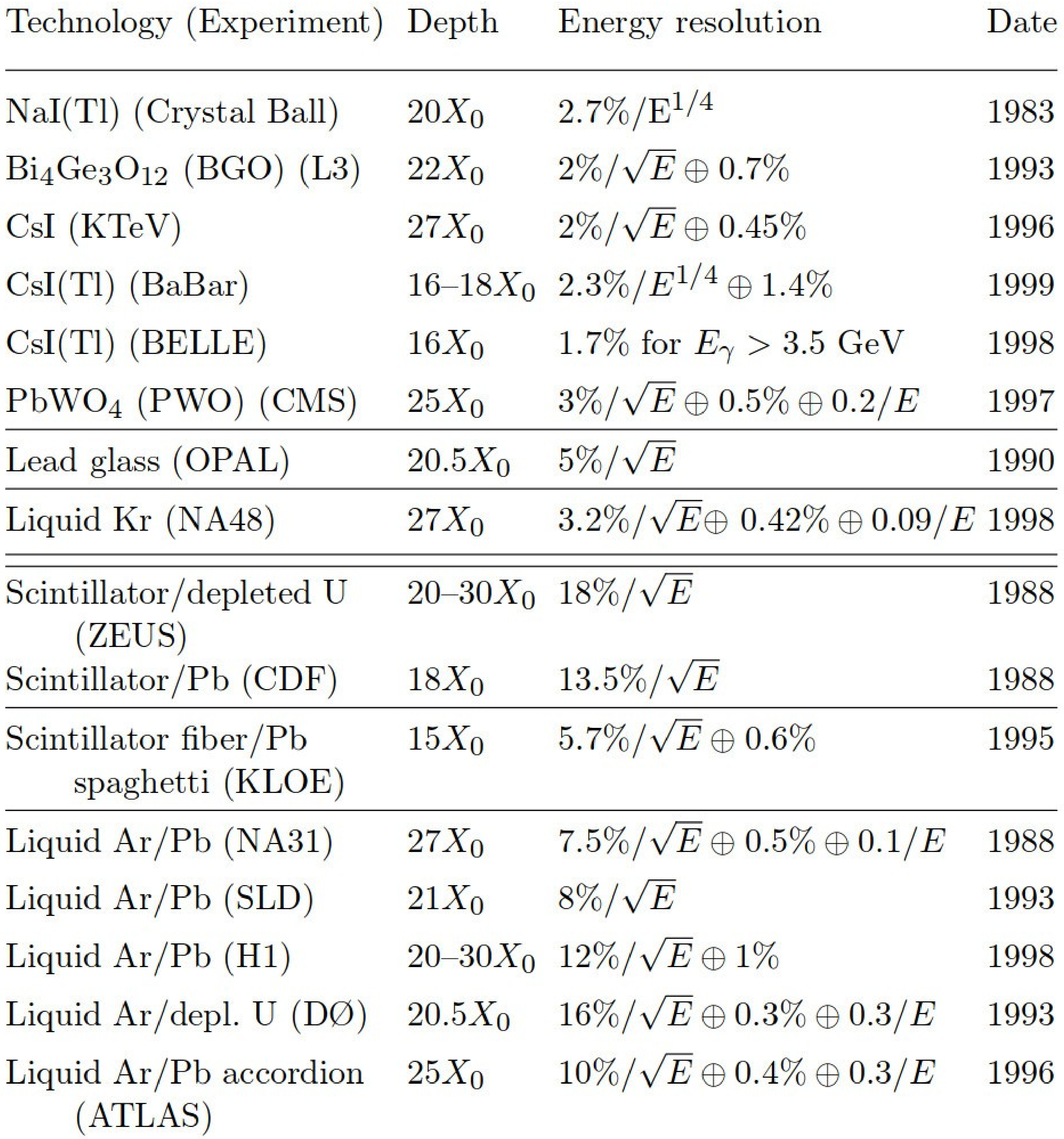
→ resolution $\sigma/E \sim O(1\%)/\sqrt{E(\mathrm{GeV})}$

2) sampling: only part (<~5%) of track sampled in active medium

→ resolution $\sigma/E \sim O(10\%)/\sqrt{E(\mathrm{GeV})}$

* “typical” values for high-energy physics

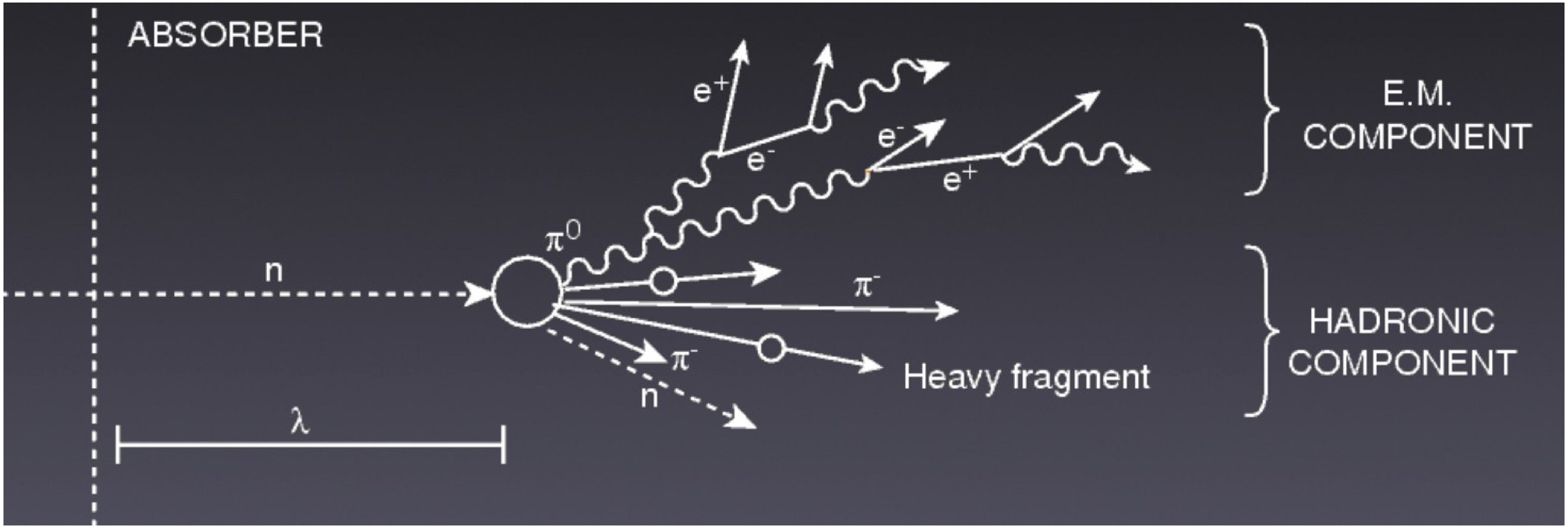
real em calorimeters



Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$\mathrm{Bi_4Ge_3O_{12}}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$\mathrm{PbWO_4}$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

hadronic calorimetry

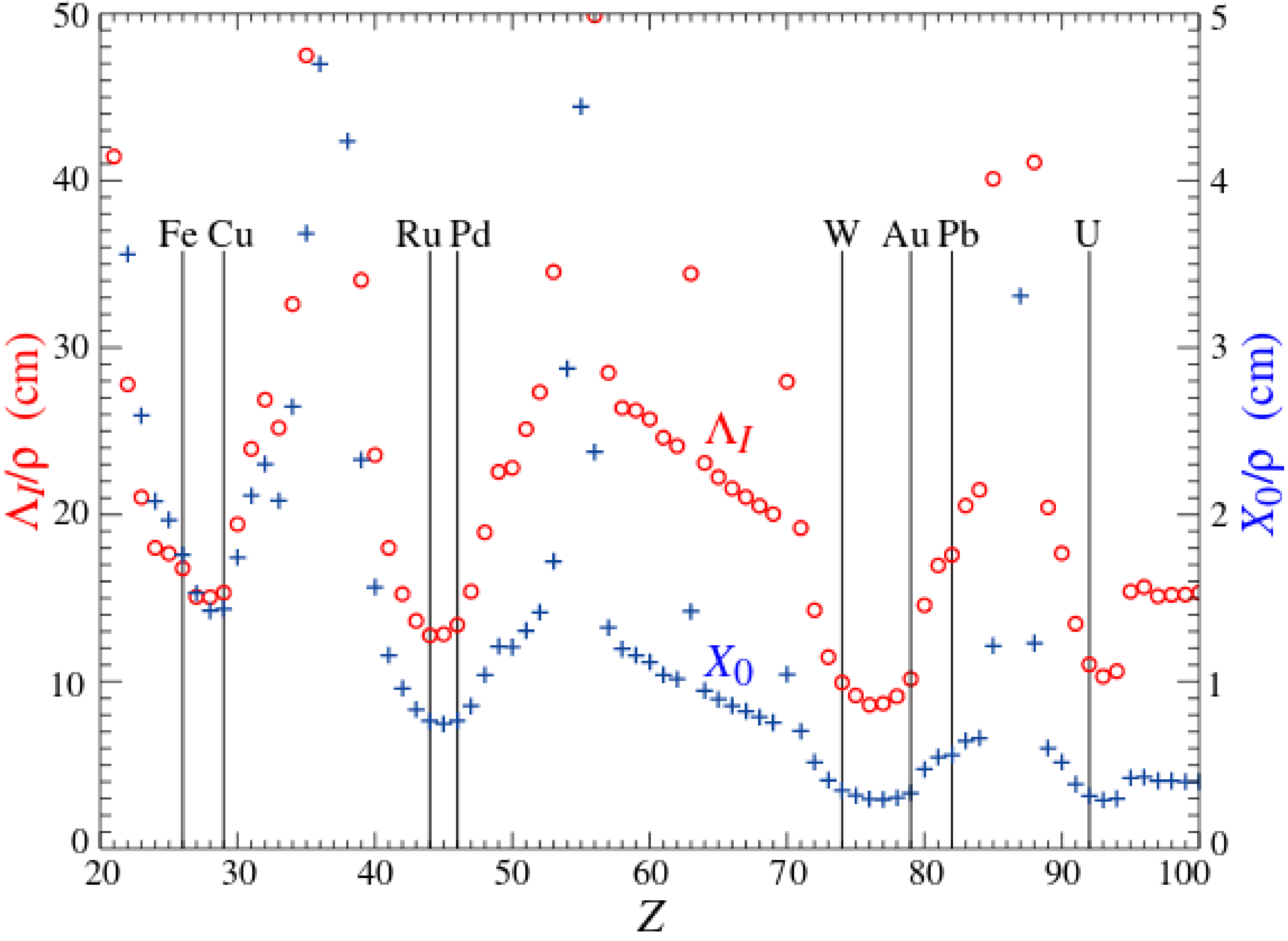
π^0, η^0 production → hadronic showers develop 2 main components:



h component: p, n, $\pi^{\pm}$, nuclear fission, … delayed photons, …

dimension scale : $\lambda_I \sim 35\ \mathrm{g/cm^2} \cdot A^{1/3}$

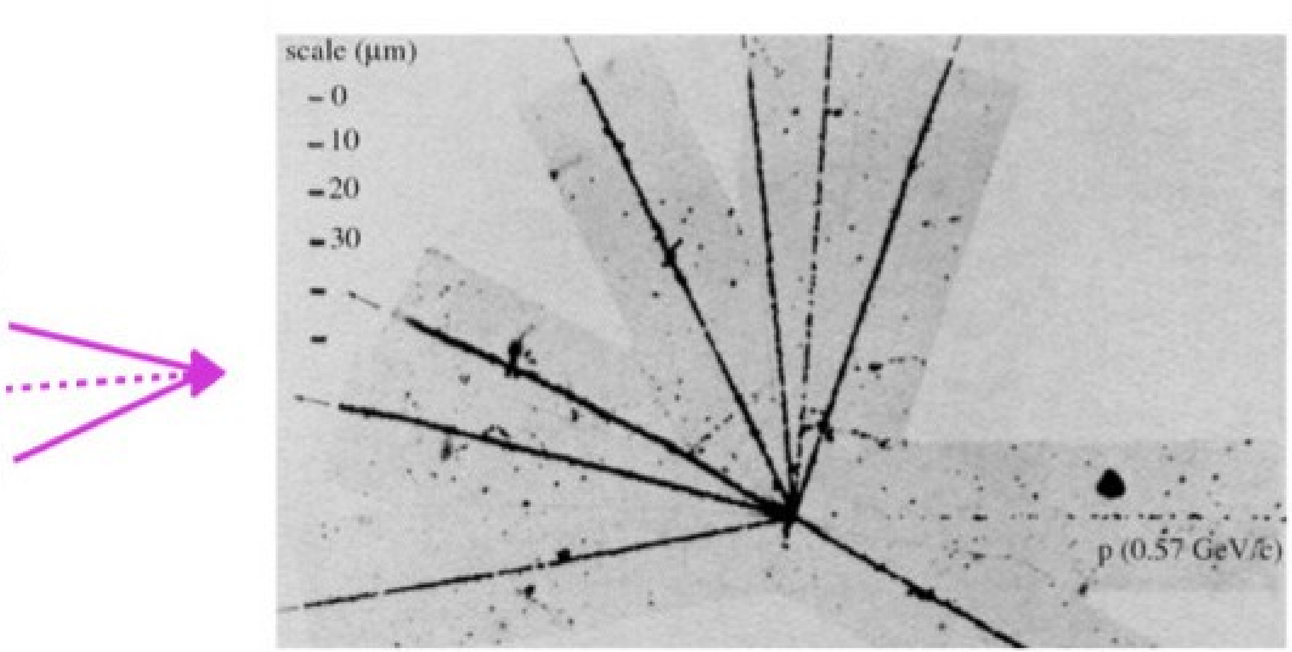
radiation vs. interaction length



→ a factor > ~10 in λ_I/X_0 ratio

hadronic shower components

- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons π±,K± (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)



many components w/ large fluctuations in relative yield

1. large non-gaussian fluctuations in energy sharing em/non-em
2. increase of em component with energy
3. large, non-gaussian fluctuations in "invisible" energy losses

electromagnetic fraction f_{em}

energy fraction carried by π^0 (mainly) and η^0

f_{em}, on average, *large and energy dependent*

fluctuations in f_{em} *large and non-poissonian*

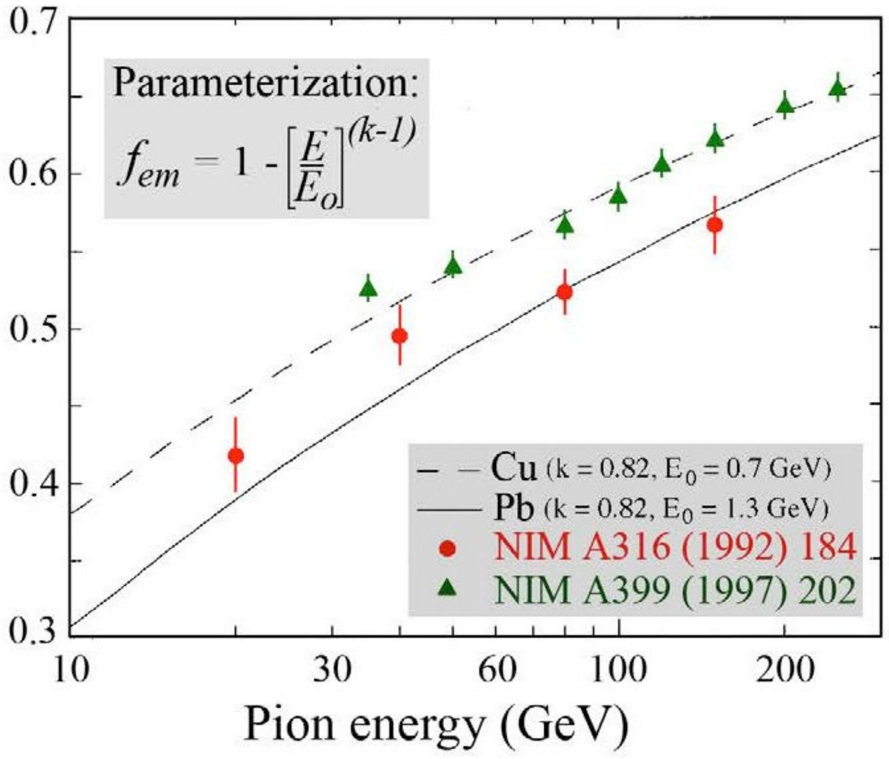
$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

←

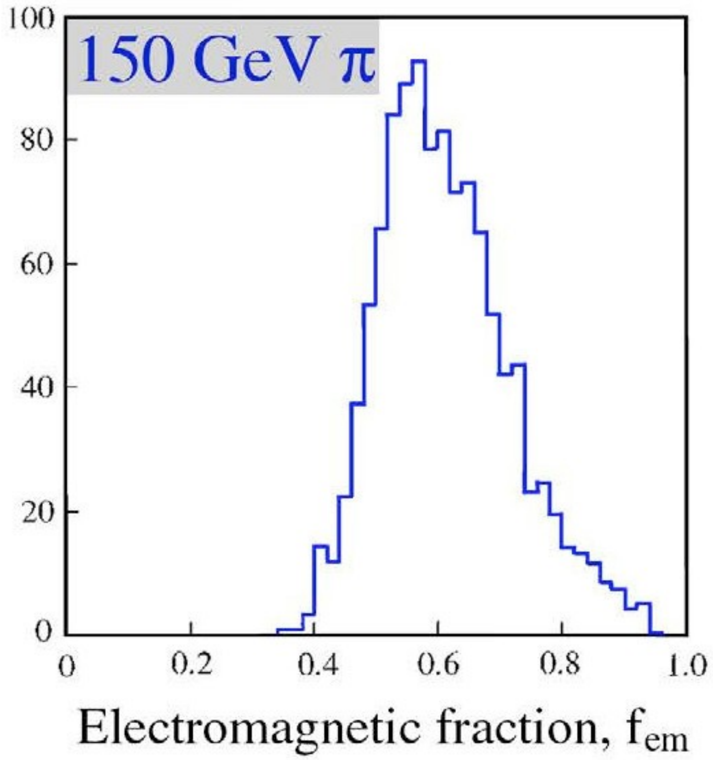
E_0 = average energy to produce a π^0

(k-1) related to average multiplicity

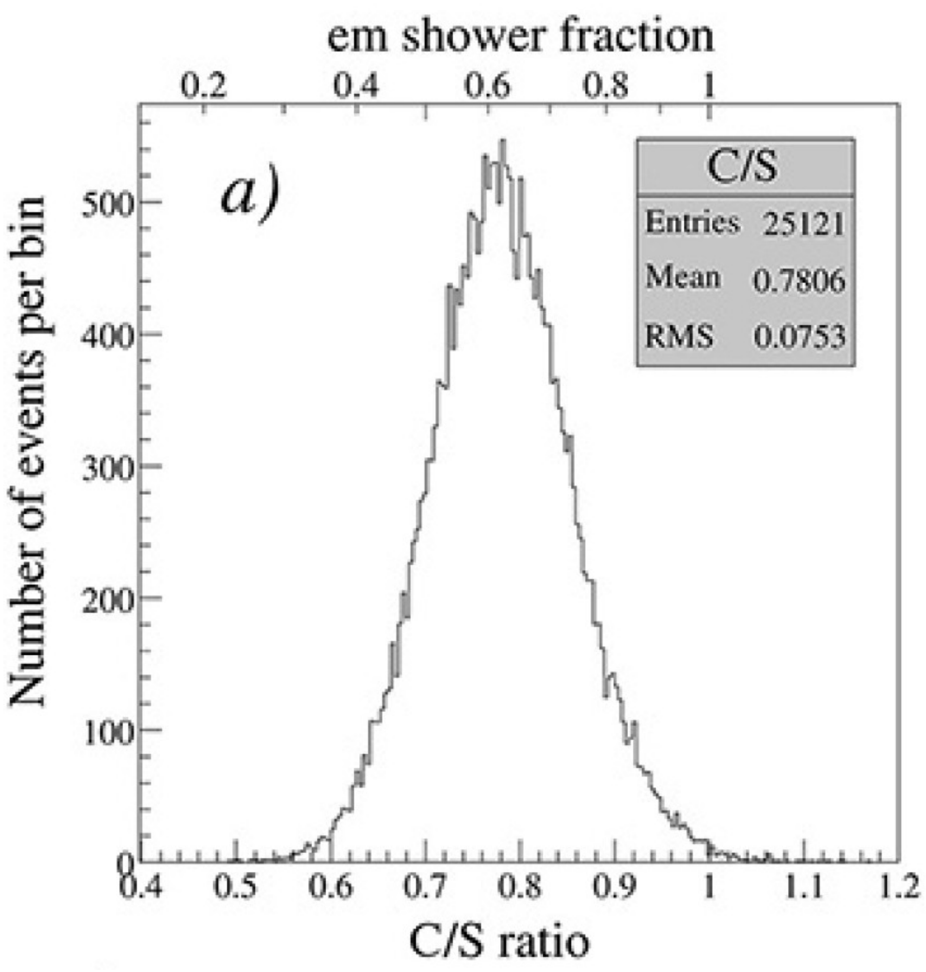
< f_{em} > vs. pion energy



f_{em} for 150 GeV pions

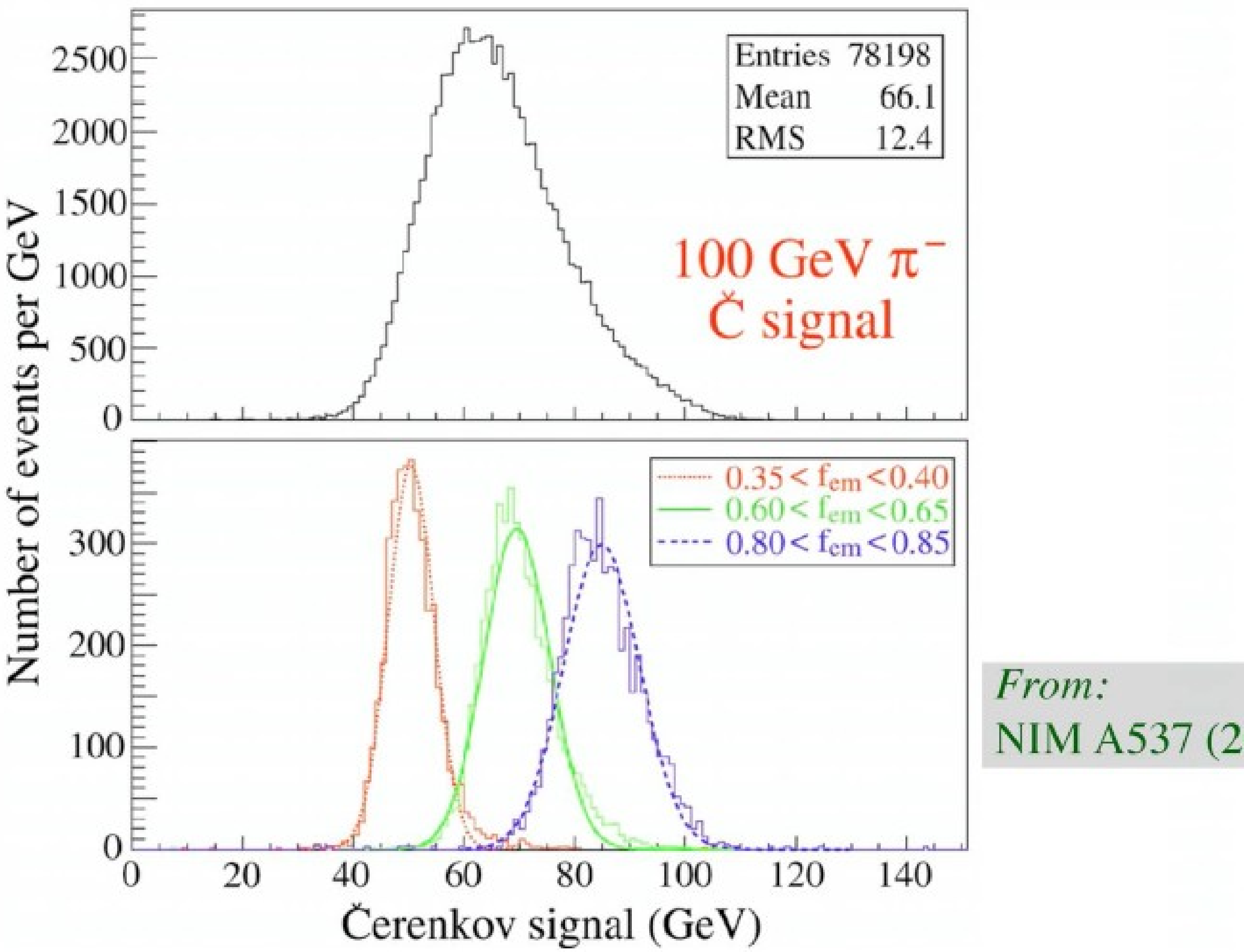


f_{em} fluctuations



$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$

DREAM: Effect of event selection based on f_{em}



From:
NIM A537 (2005) 537

invisible energy

- In nuclear reactions energy is lost (binding energy) to free protons and neutrons.
- Can’t provide any measurable signal (*invisible energy*)
- Accounts on average for about 30-40% of non-em shower energy

large event-by-event fluctuations limit resolution

Correlation between invisible energy and kinetic energy carried by released nucleons

Evaporation nucleons: soft spectrum, mostly neutrons (2-3 MeV)

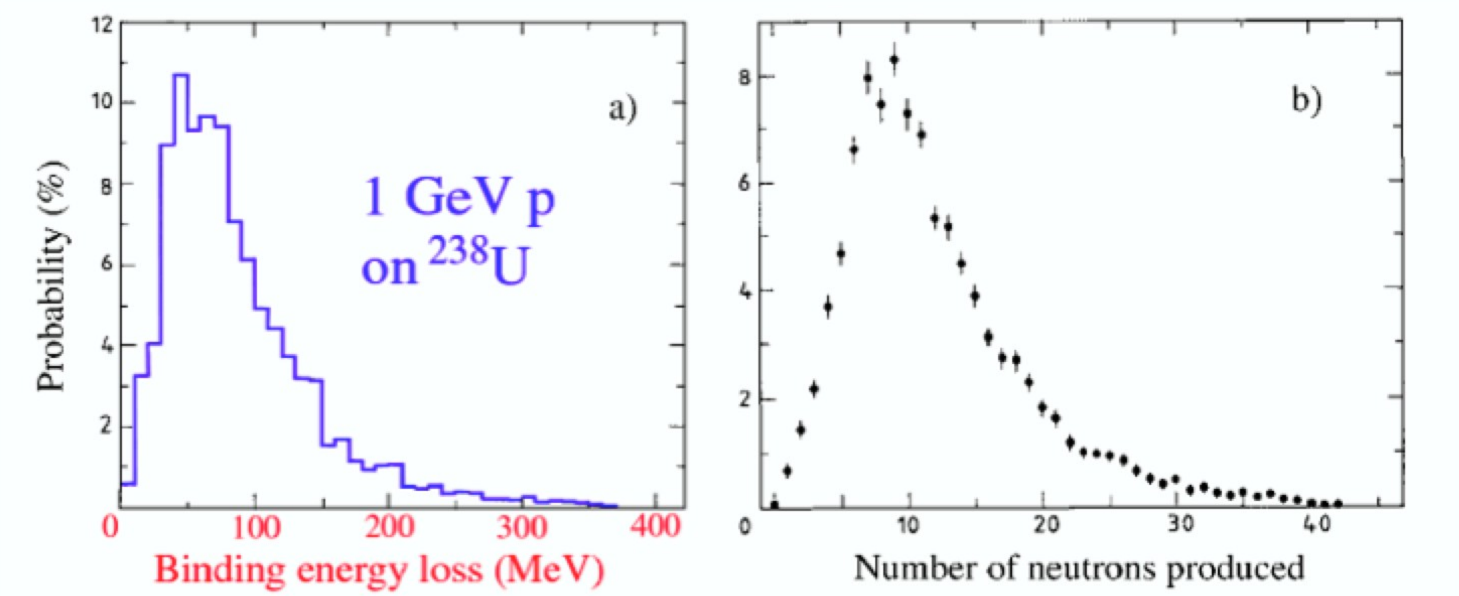
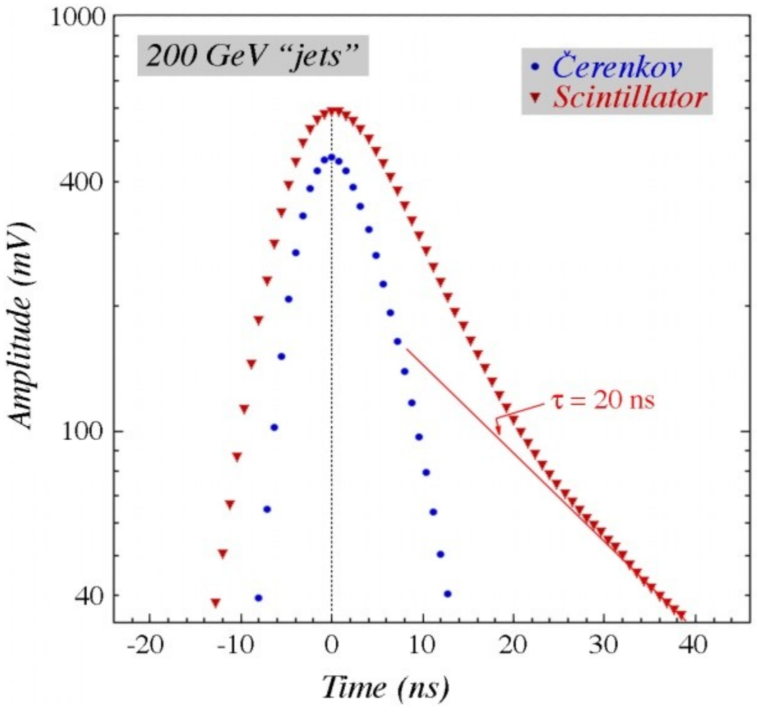


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (a), and the number of neutrons produced in such reactions (b). From [Wig 87].

invisible energy correlations

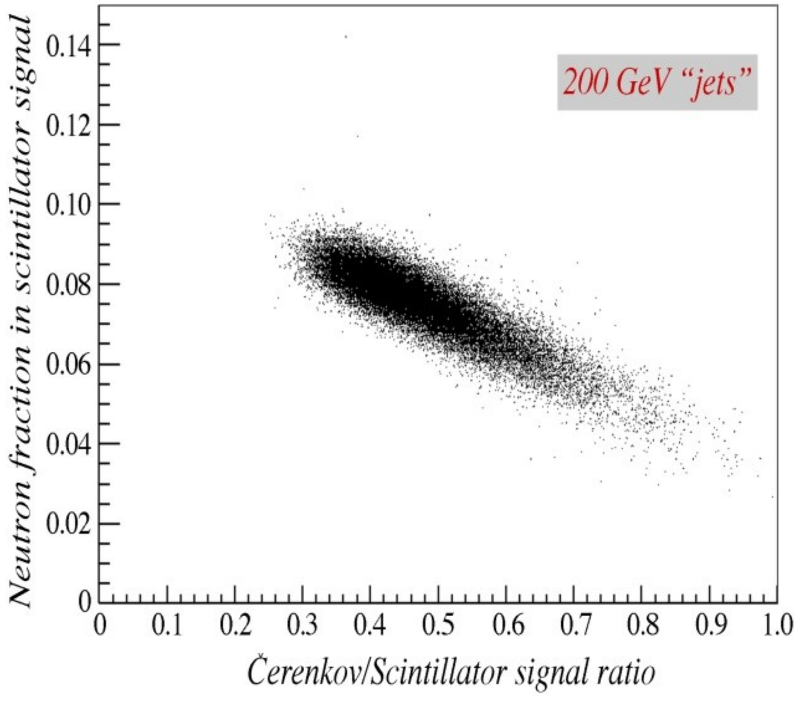
Measurement of the kinetic energy of neutrons - correlated to nuclear binding energy loss (invisible energy) - from signal time structure (DREAM)

Signal time structure

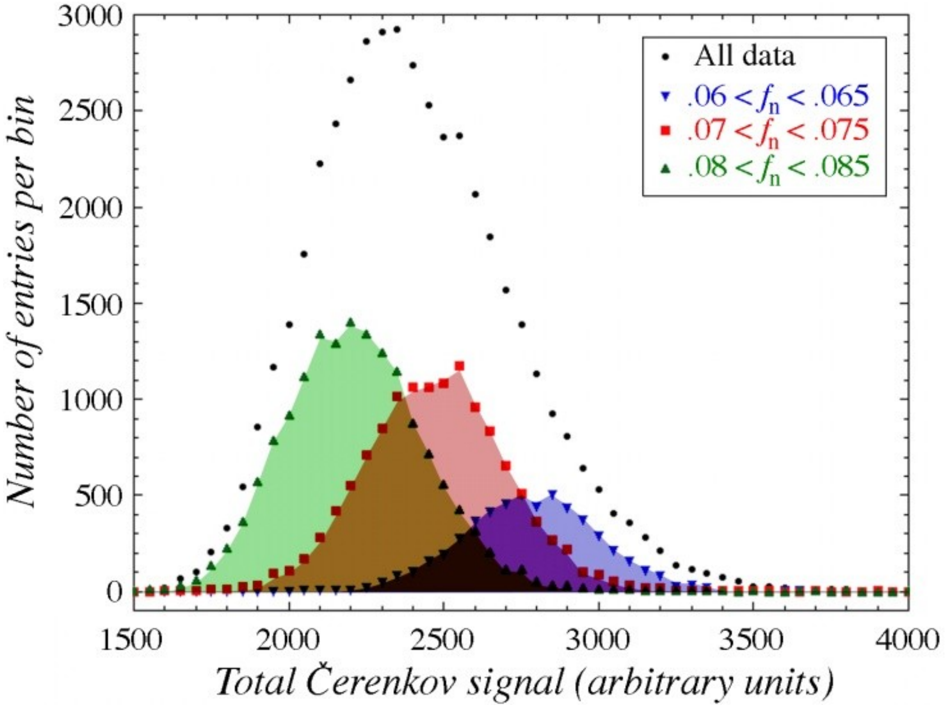


no tail in em showers

f_n anti-correlated to f_{em}



Probing the tot. signal distribution with f_n



detector response

Response:

detected signal per unit energy deposit

e.g. number of scintillating (or Cherenkov) p.e. / deposited GeV

Hadronic showers:

em component → response e
hadronic component → response h

what about the relative ratio e/h ?

compensation

e/h = 1 → compensating calorimeter

1) increase h → boost hadron response e.g. by adding hydrogen or by using Uranium, both acting as "neutron converters" → large integration volume and time

2) decrease e → decrease em sampling fraction (i.e. em performance) → tune active / passive material ratio

compensation pros & cons

- not a guarantee for high resolution
  - fluctuations in f_{em} are eliminated, but others may be very large
- has drawbacks
  - high-Z absorber required → small e/mip → non linearity @ low energy
  - low sampling fraction required → em resolution limited
  - relies on neutrons → integration over large volume and time

    SPACAL 30%/√E needed ~15 tonnes and ~50 ns

- high-res em and high-res hadron calorimetry mutually exclusive:
  - good jet energy resolution ⇒ compensation

    ⇒ small sampling fraction (~3%) ⇒ poor em resolution
  - good em resolution ⇒ high sampling fraction (100% crystals, 20% LAr)

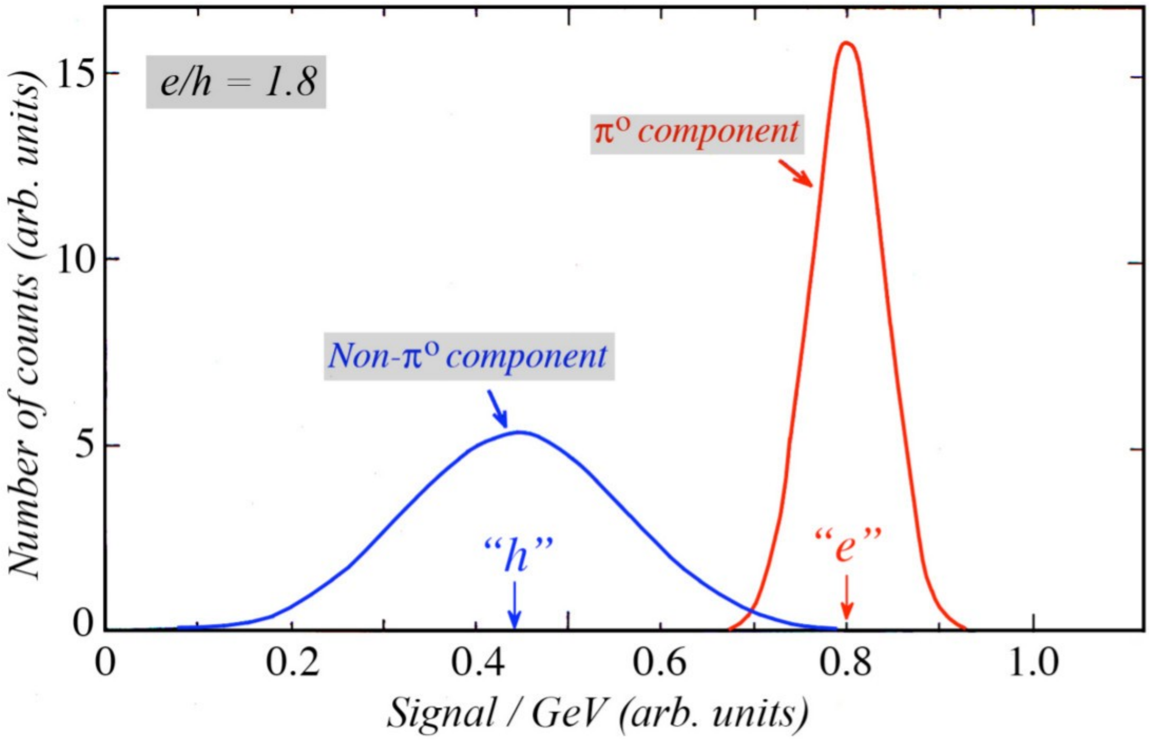
    ⇒ large non compensation ⇒ poor jet resolution

most general case

e ≠ h

e.g. (right plot):

only 1/1.8 ≈ 56% of non-π^o energy accounted by signal



Note:

e/h ratio: detector characteristic

typically, ~2 for crystals, in range 1-1.8 for sampling calorimeters

Nevertheless:

1) e/π depends on energy (*f_{em} depends on E and shower "age"*)

2) f_{em} different for π, K, p → response depends of particle type

scintillation

R(e) ≠ R(p) ≠ R(n) ≠ R(π) ≠ R(μ) ≠ R(jet)

a) invisible energy

b) different dE/dx

c) Birks' law

$$\frac{dL}{dx} = S\frac{\frac{dE}{dx}}{1 + k_B\frac{dE}{dx}}$$

e/mip ratio

mip : minimum ionising particle → only ionisation

dE/dx (mip) :

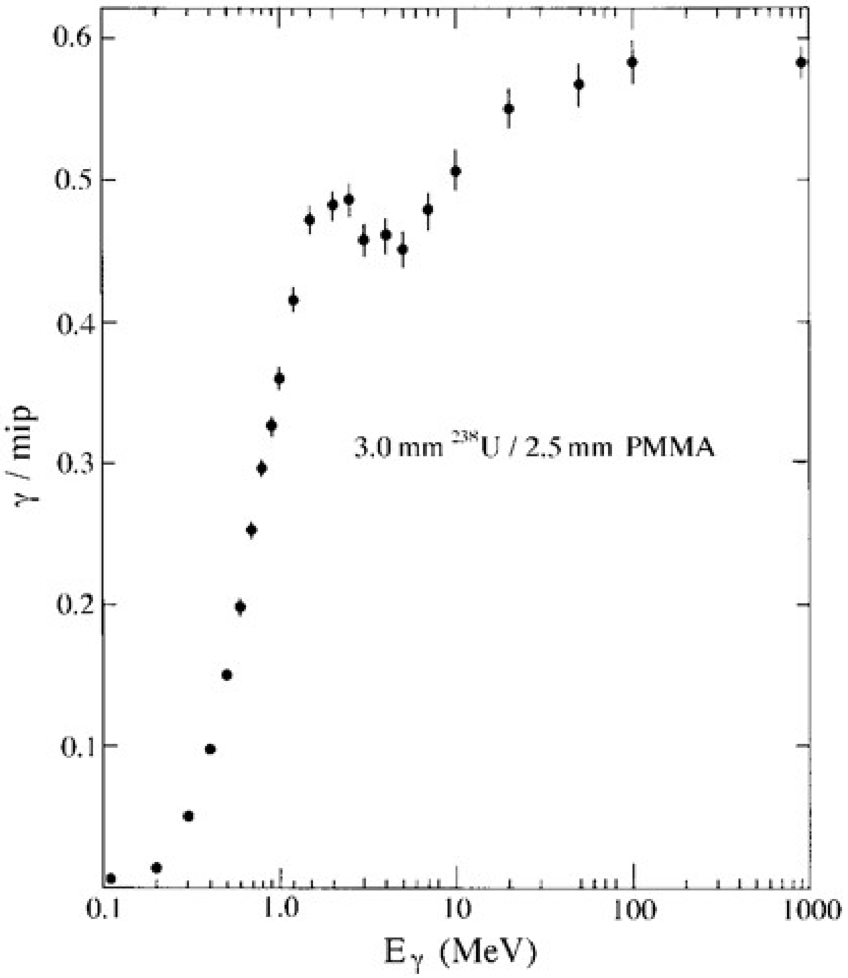
lead ~ 12.6 MeV/cm → 7.15 MeV /X_0
copper ~ 12.7 MeV/cm → 18.0 MeV/X_0
(PMMA ~ 2.3 MeV/cm → 78.2 MeV/X_0)

Moreover in high-Z absorbers :

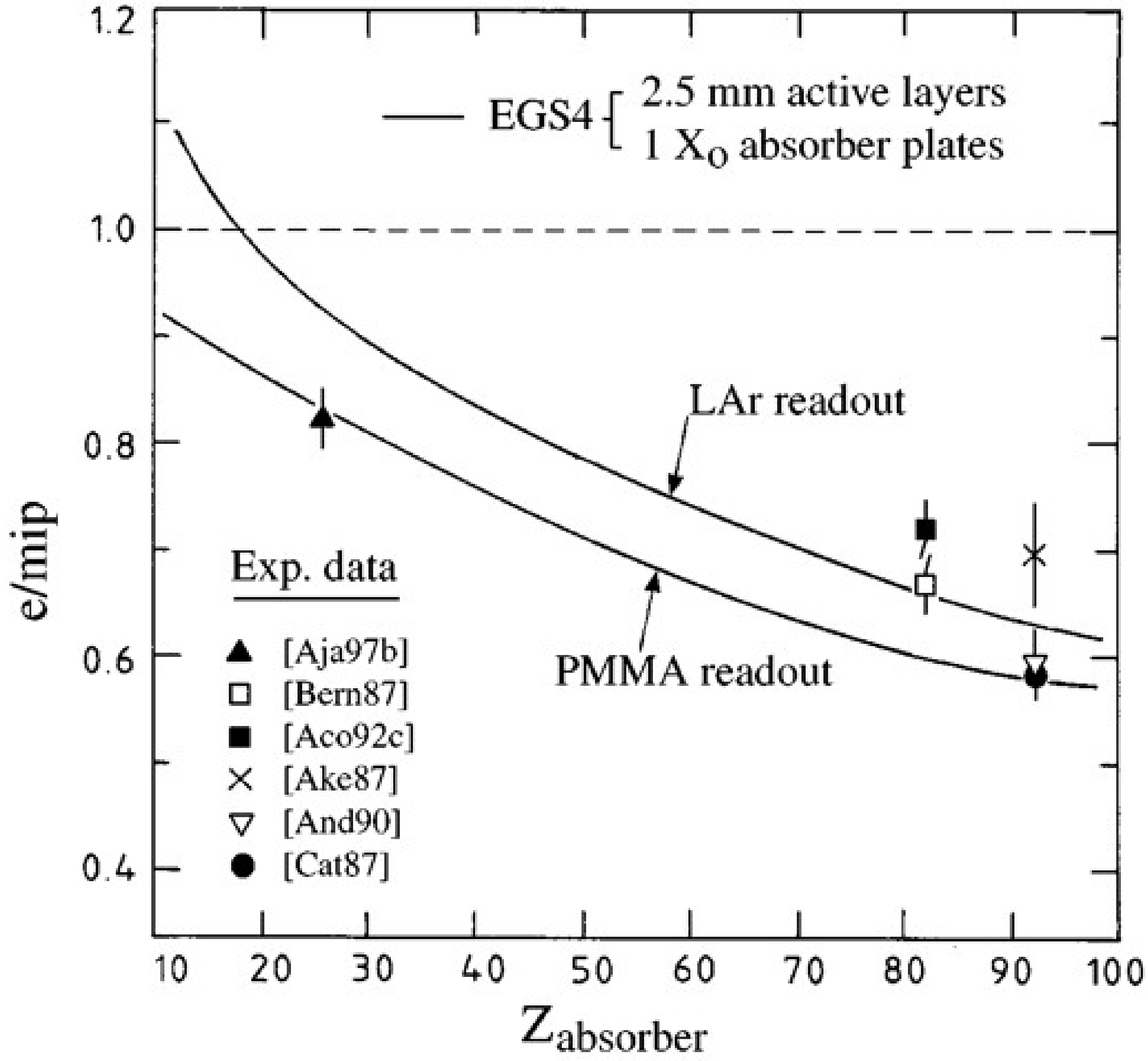
Z^5 dependence of photoelectric effect
→ most soft-γ interact in absorber
photoelectrons have very short range
→ will contribute to signal only close to boundaries

→ response to em showers suppressed wrt. mips

e/mip ratio



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

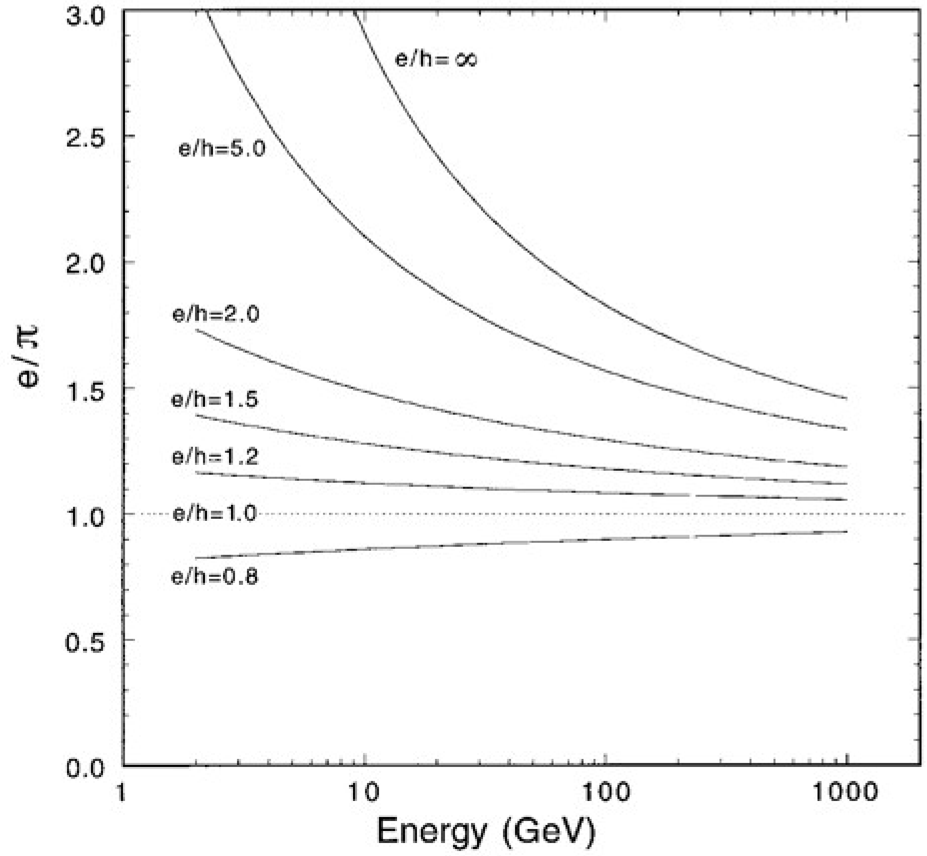


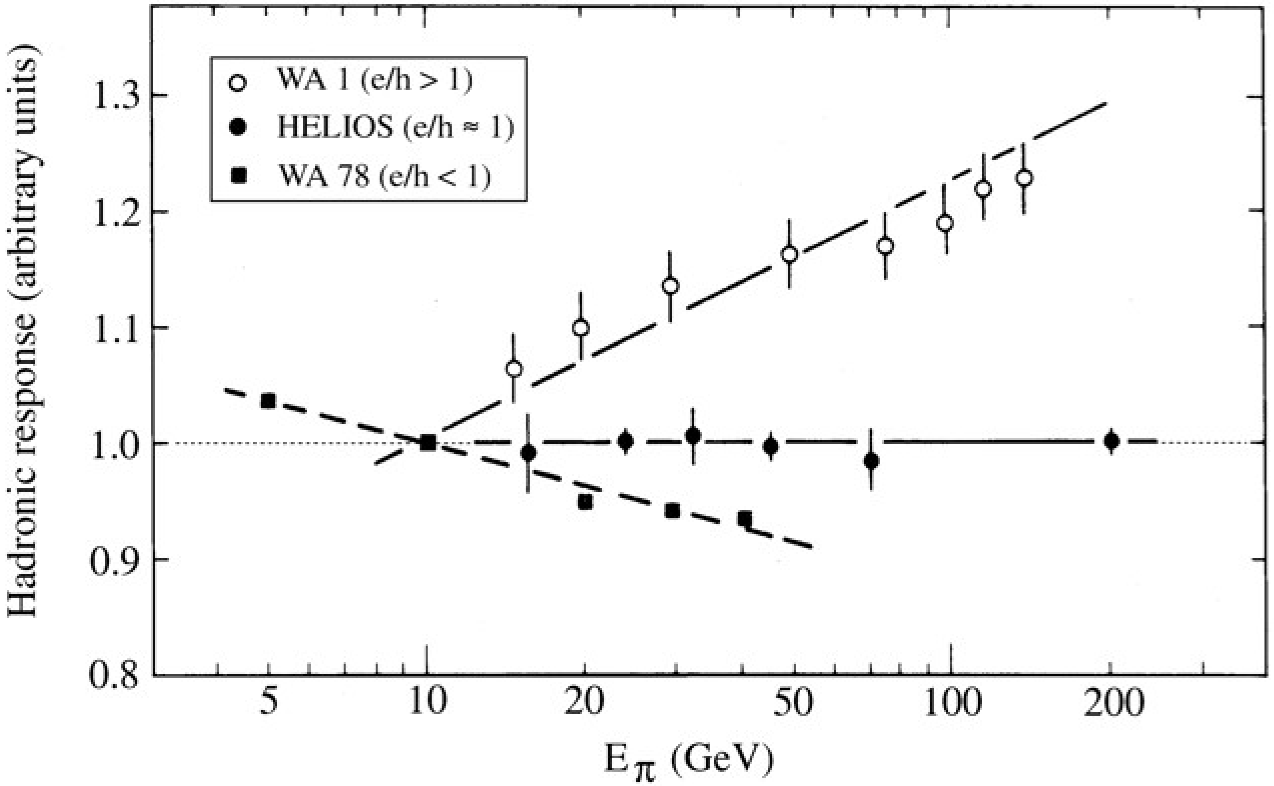
e/mip ratio with Z

e/π ratio

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

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

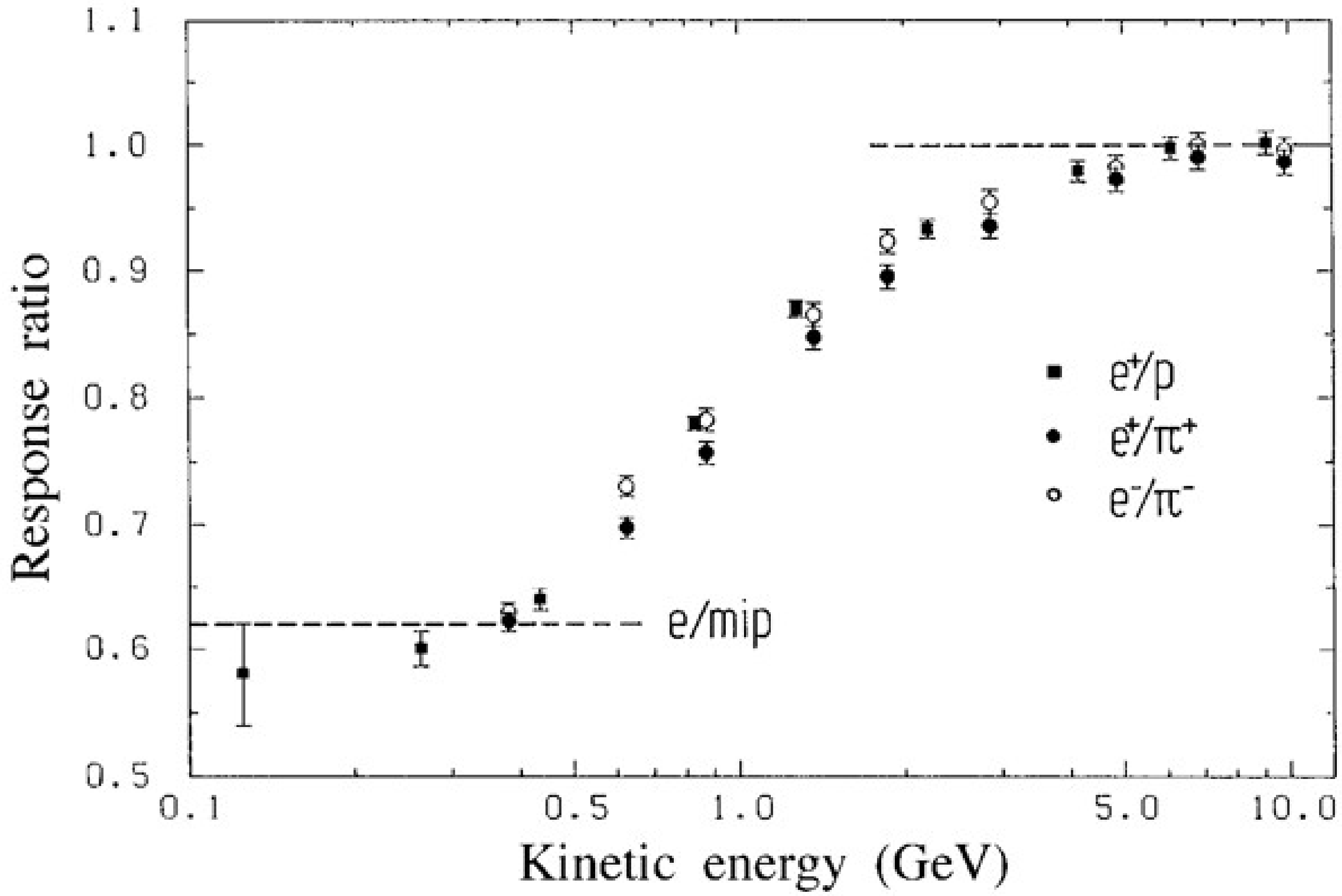




response to π as function of E

low-energy hadrons

finally :



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

jets

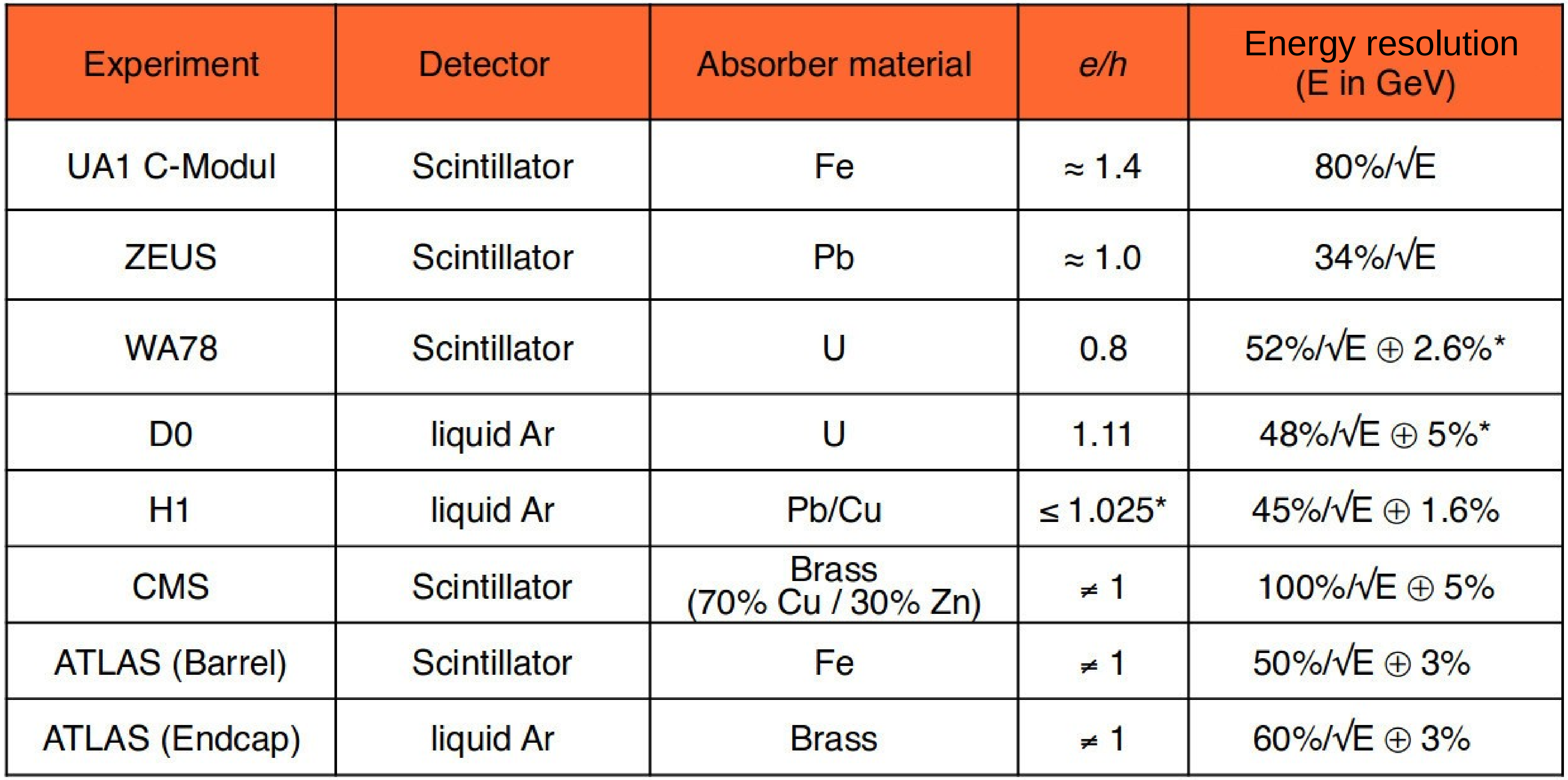
Jets:

high-energy core
low-energy hadron tails

fluctuations among them
low-energy hadrons ~ mip.s

→ mip response must be considered

real hadronic calorimeters



Experiment	Detector	Absorber material	*e/h*	Energy resolution (E in GeV)
UA1 C-Modul	Scintillator	Fe	≈ 1.4	80%/√E
ZEUS	Scintillator	Pb	≈ 1.0	34%/√E
WA78	Scintillator	U	0.8	52%/√E ⊕ 2.6%*
D0	liquid Ar	U	1.11	48%/√E ⊕ 5%*
H1	liquid Ar	Pb/Cu	≤ 1.025*	45%/√E ⊕ 1.6%
CMS	Scintillator	Brass (70% Cu / 30% Zn)	≠ 1	100%/√E ⊕ 5%
ATLAS (Barrel)	Scintillator	Fe	≠ 1	50%/√E ⊕ 3%
ATLAS (Endcap)	liquid Ar	Brass	≠ 1	60%/√E ⊕ 3%

* after software compensation

Dual-readout method

Dual-Readout (DR) 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

⟹ *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

working principles

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

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

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

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

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

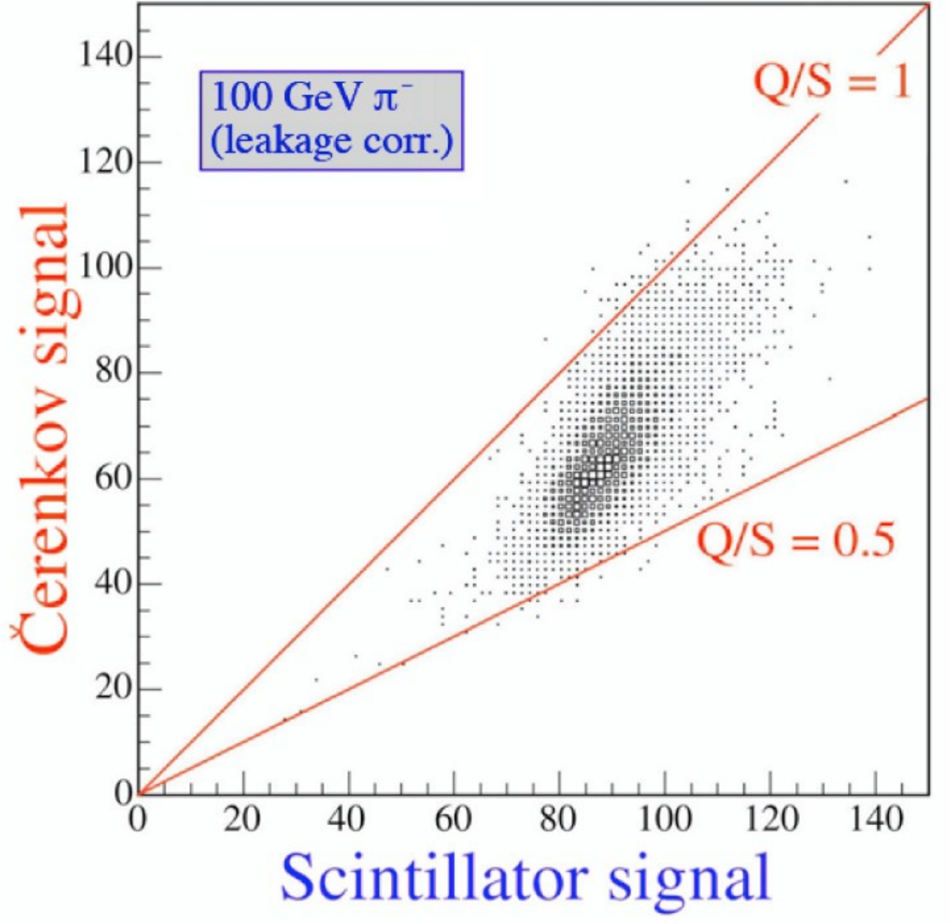
where:

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

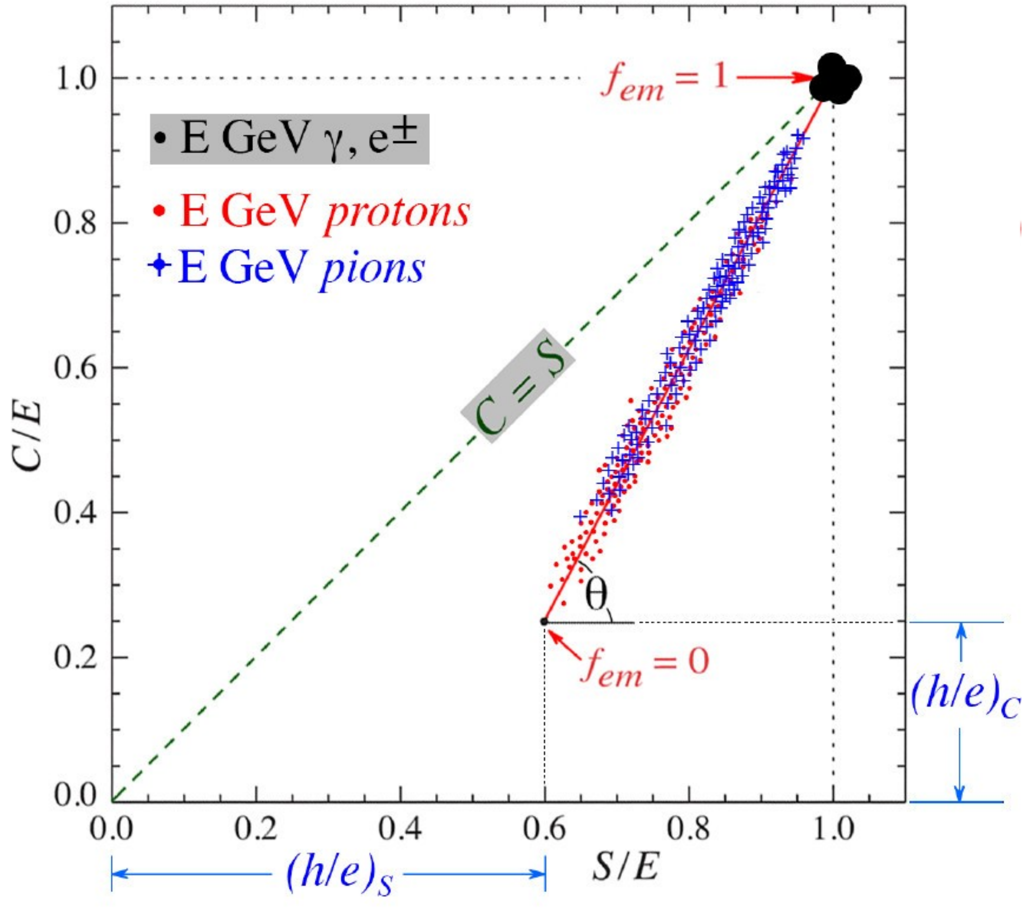
→ χ can be extracted from testbeam data

applying DR approach

Č (GeV) vs. S (GeV)



C/E vs. S/E



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

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

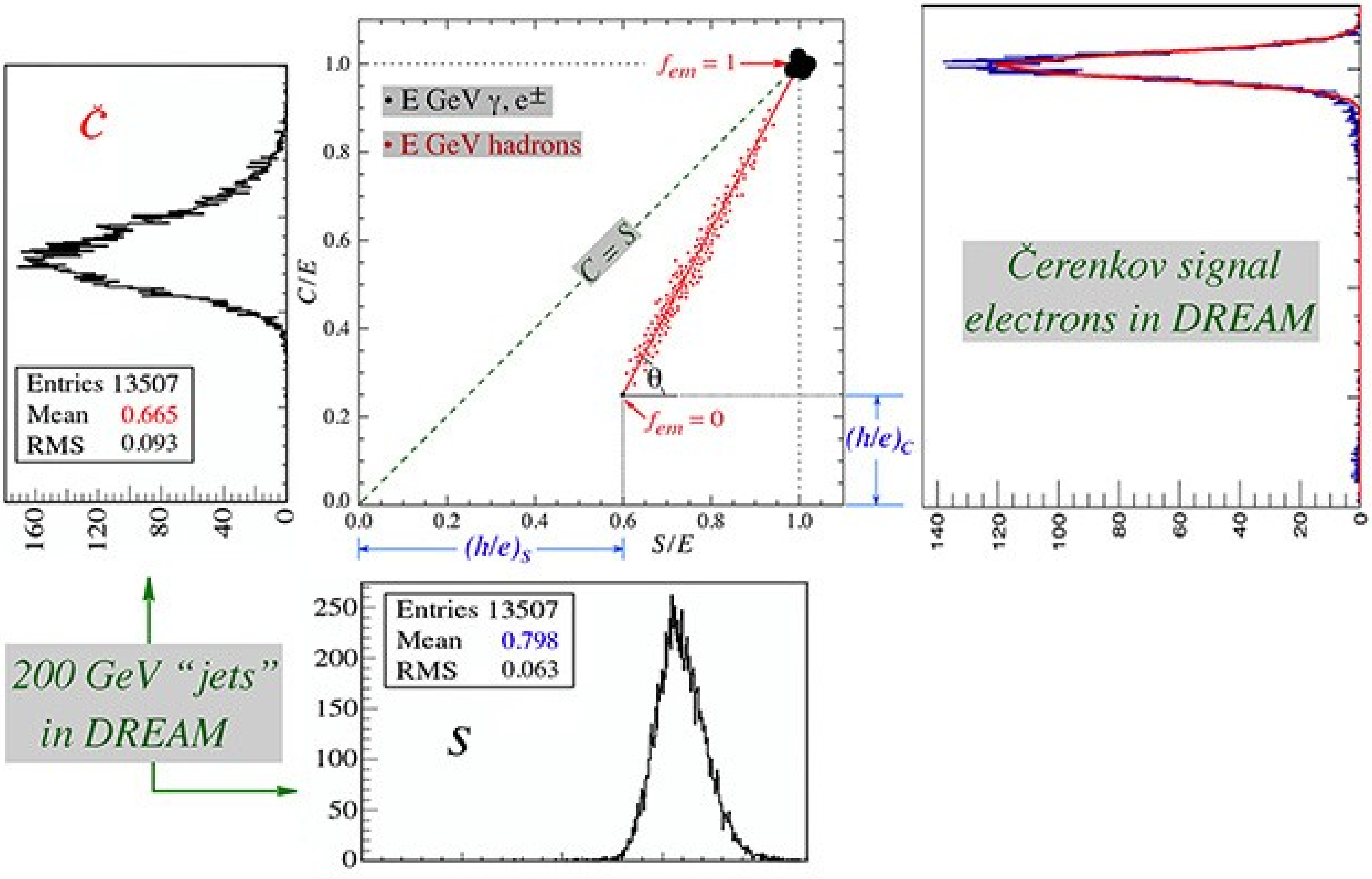
is universally valid

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

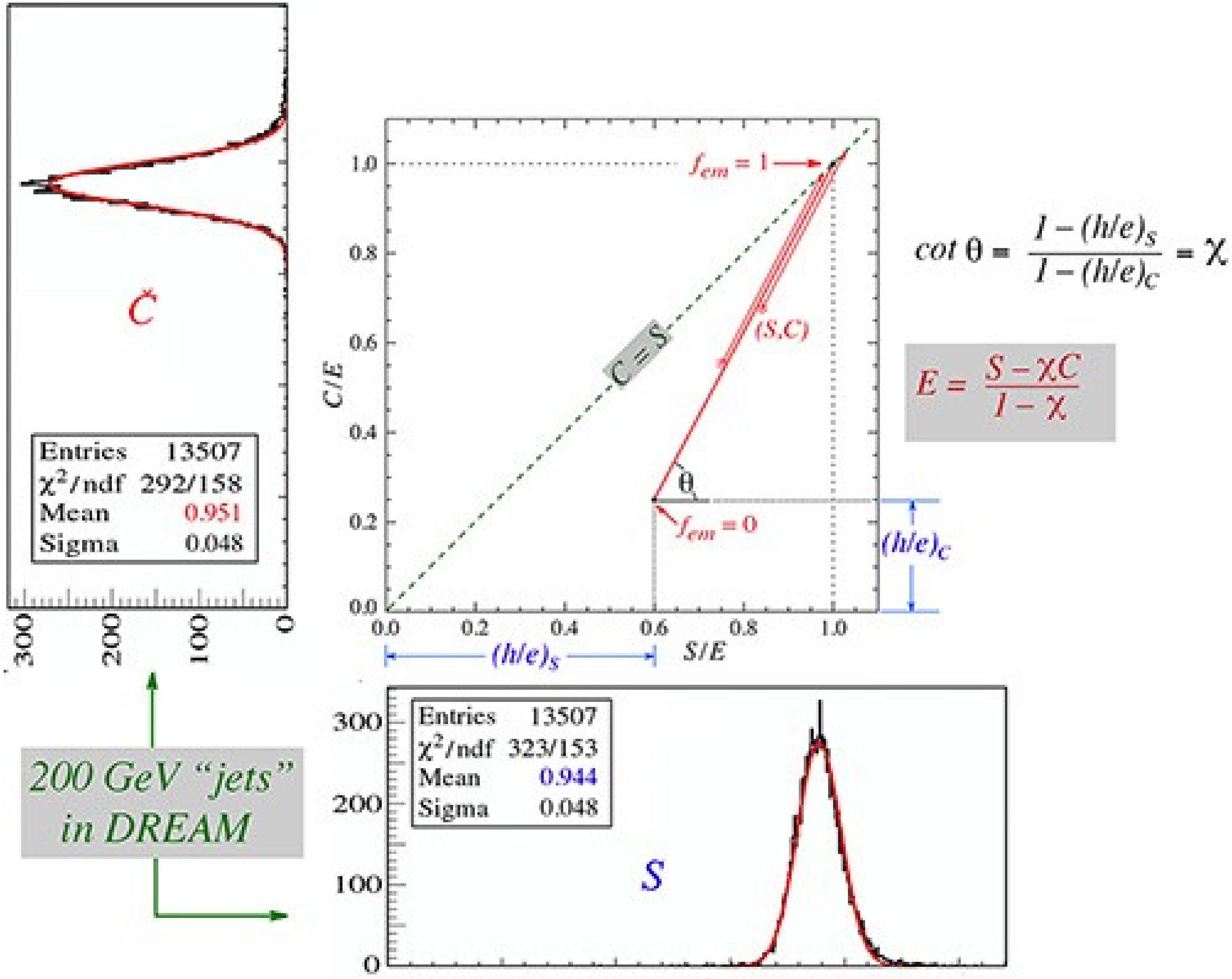
θ, χ independent of both:

- i) energy (!)
- ii) type of hadron (!!)

before DR corrections



with DR approach



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

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

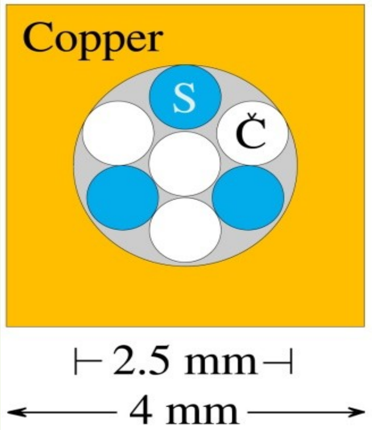
200 GeV "jets" in DREAM

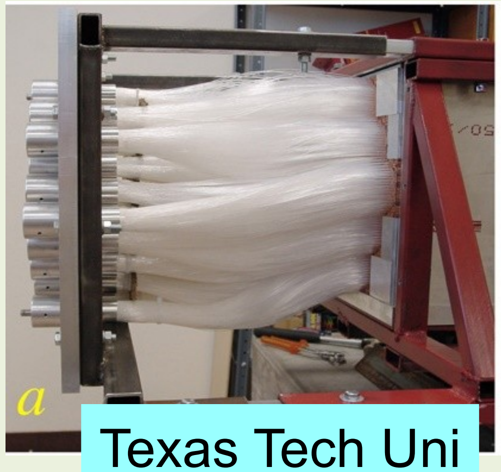
DREAM/RD52 prototypes

fibre-sampling dual-readout calorimeters

2003
DREAM

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

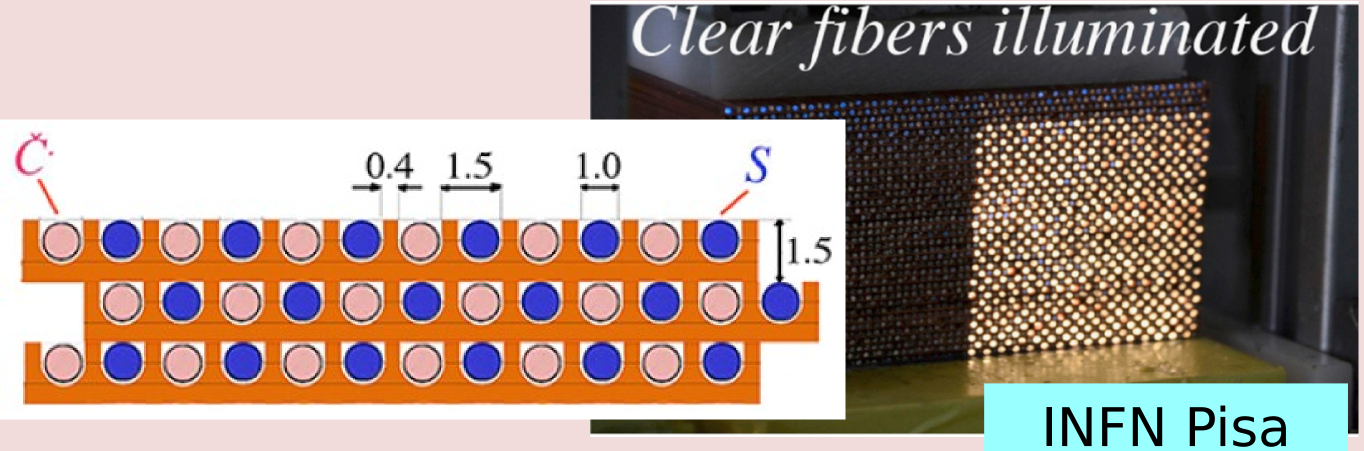




Texas Tech Uni

2012
RD52

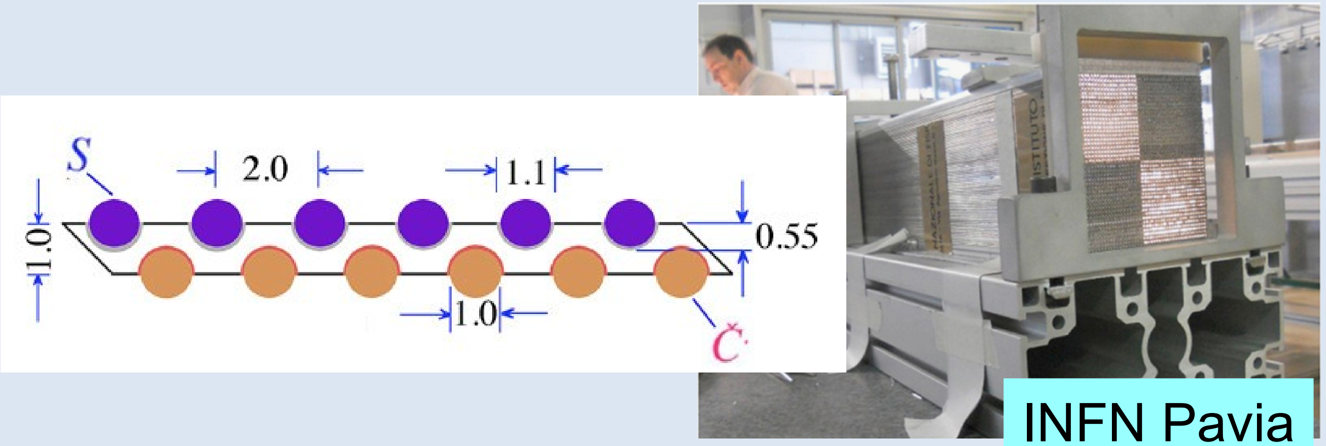
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

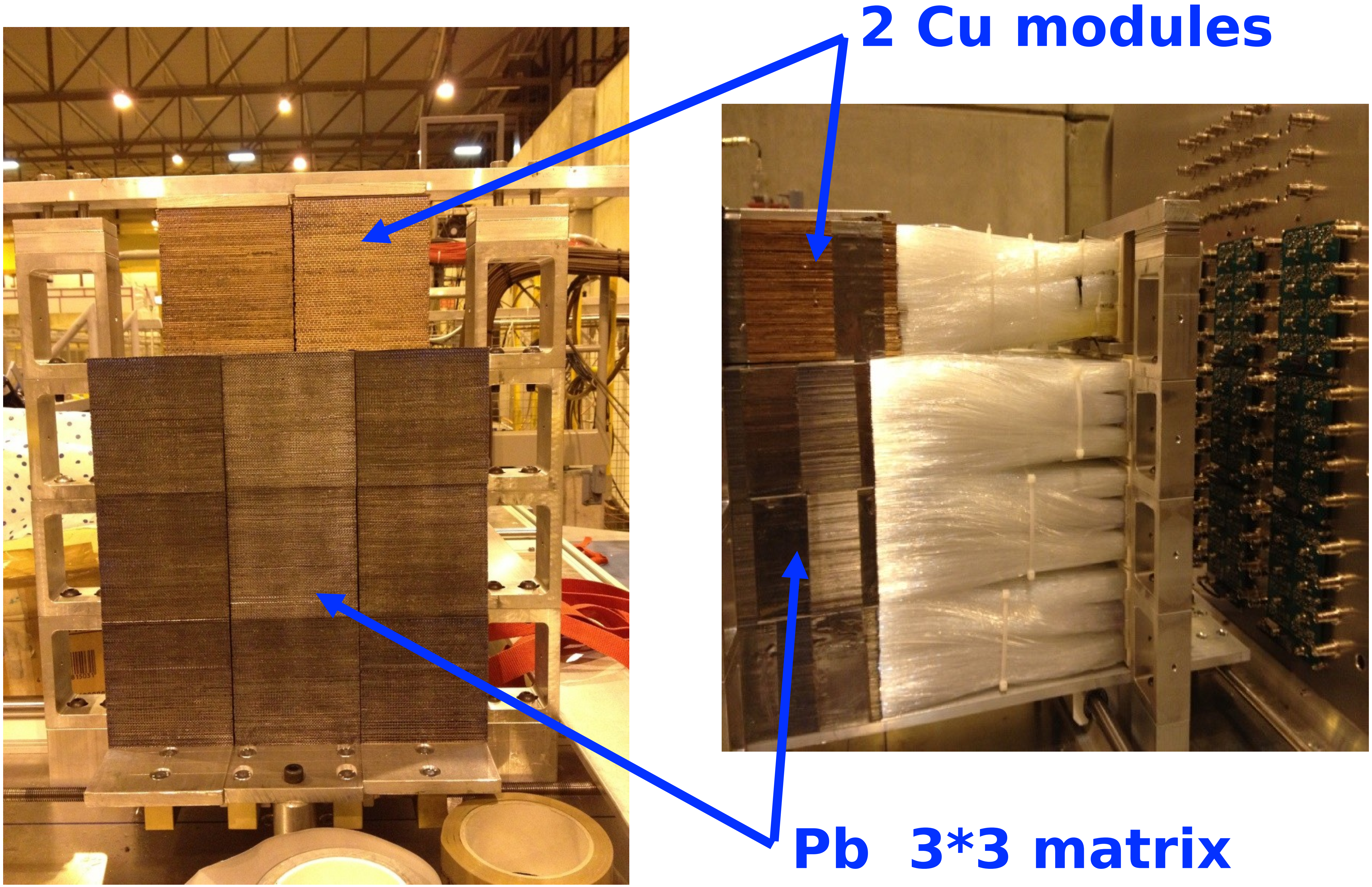
2012
RD52

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 λ_{int}



INFN Pavia

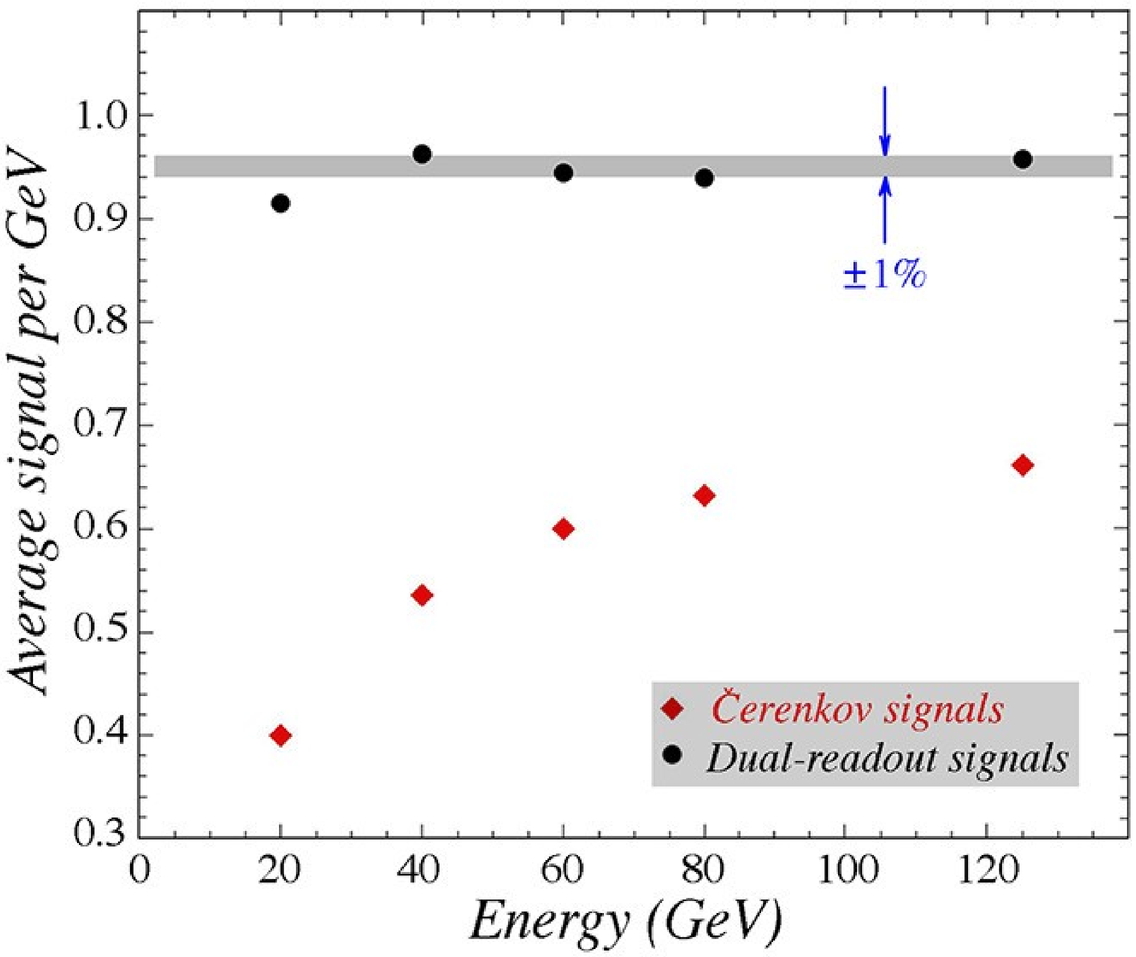
RD52 dual-readout fibre calorimeters



2 Cu modules

Pb 3*3 matrix

DR at work


Effects of the dual-readout method

Signal linearity

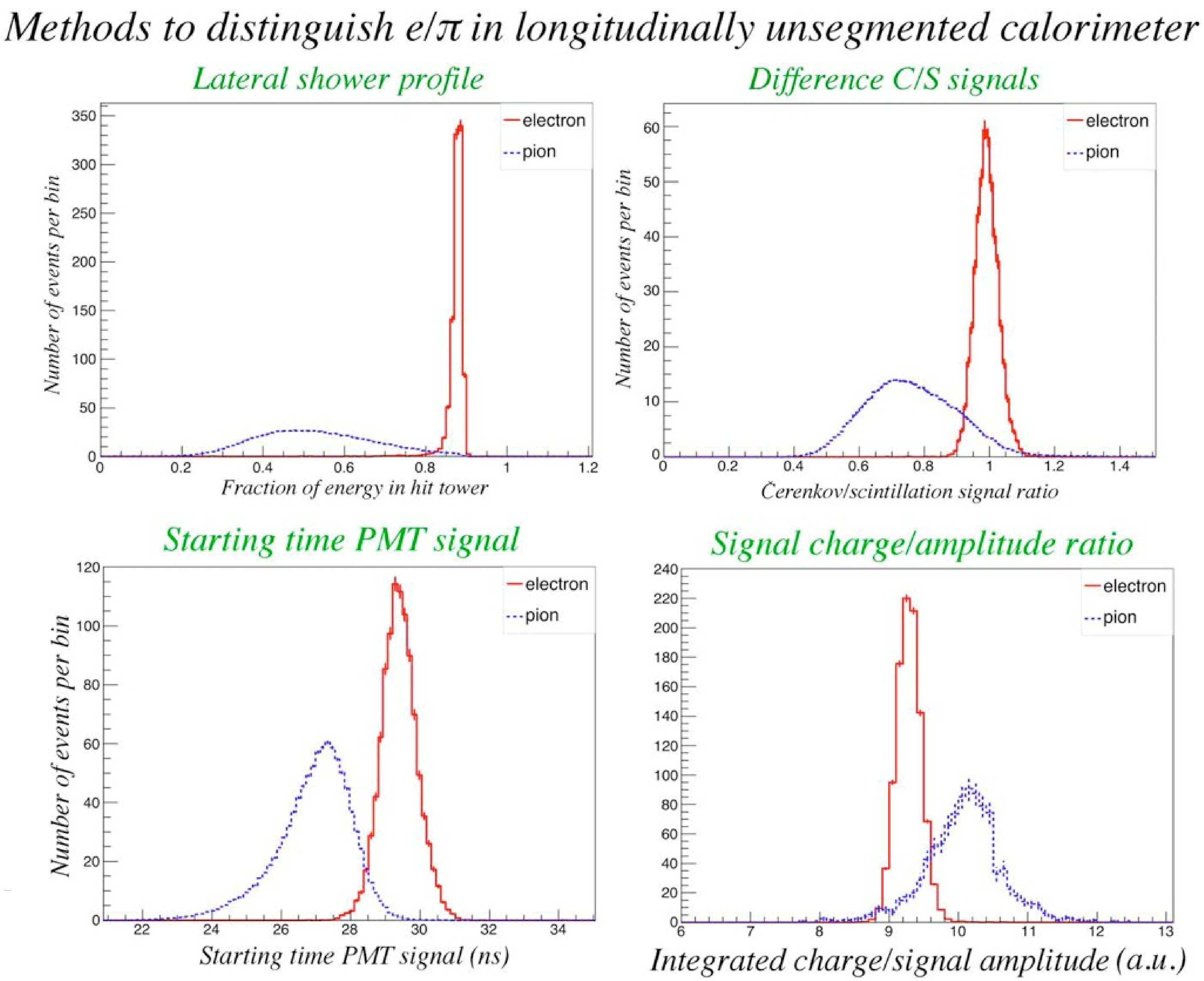
particle ID (electron/hadron separation)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

NIM A 735 (2014) 120



Methods to distinguish e/π in longitudinally unsegmented calorimeter

Lateral shower profile

Difference C/S signals

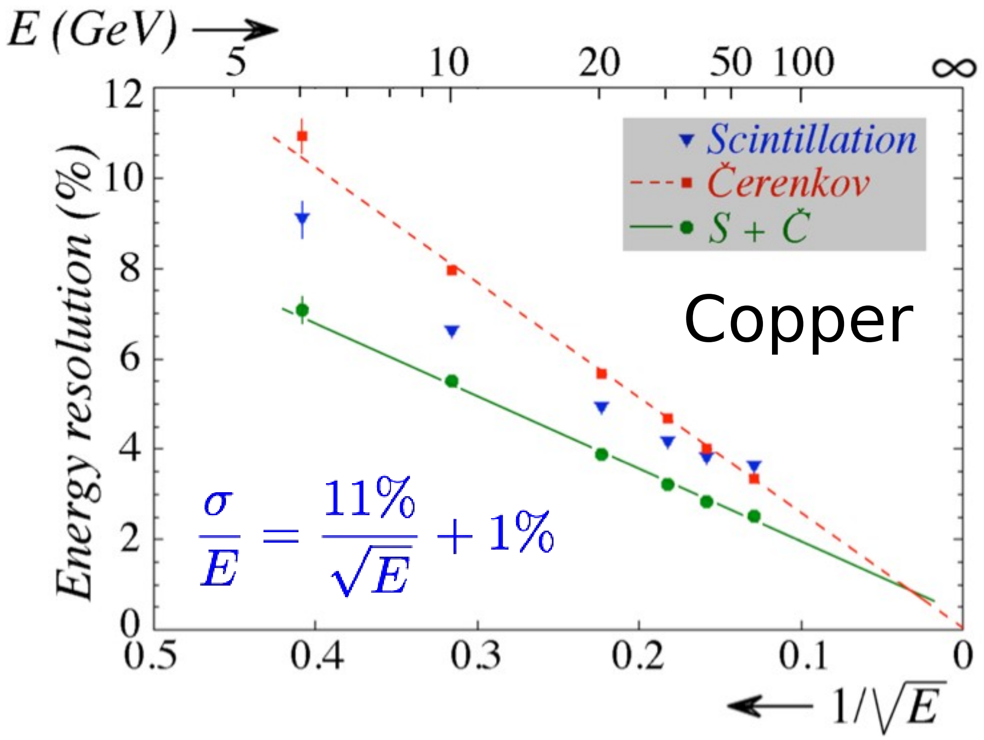
Starting time PMT signal

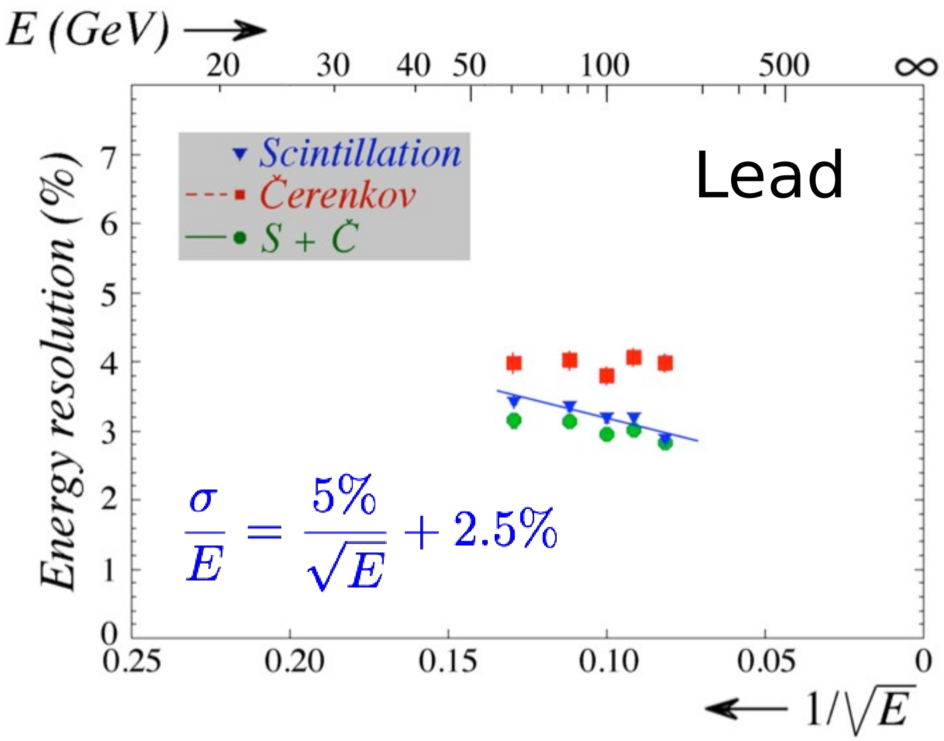
Signal charge/amplitude ratio

em resolution

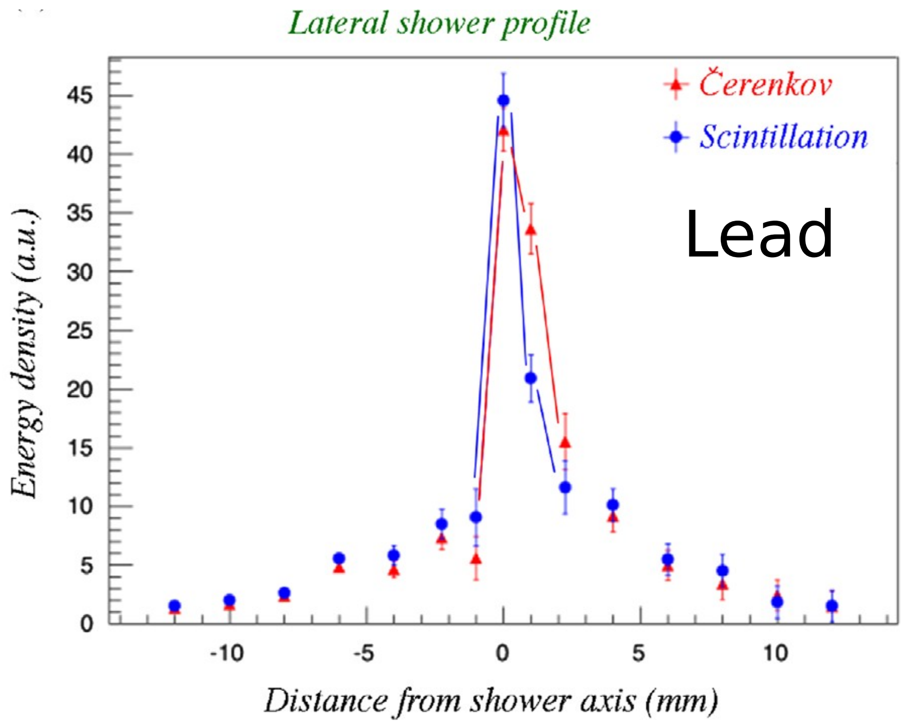
Electromagnetic
Resolution

~ 1% at 100 GeV





~ 2 GeV resolution on m_H in the γγ channel

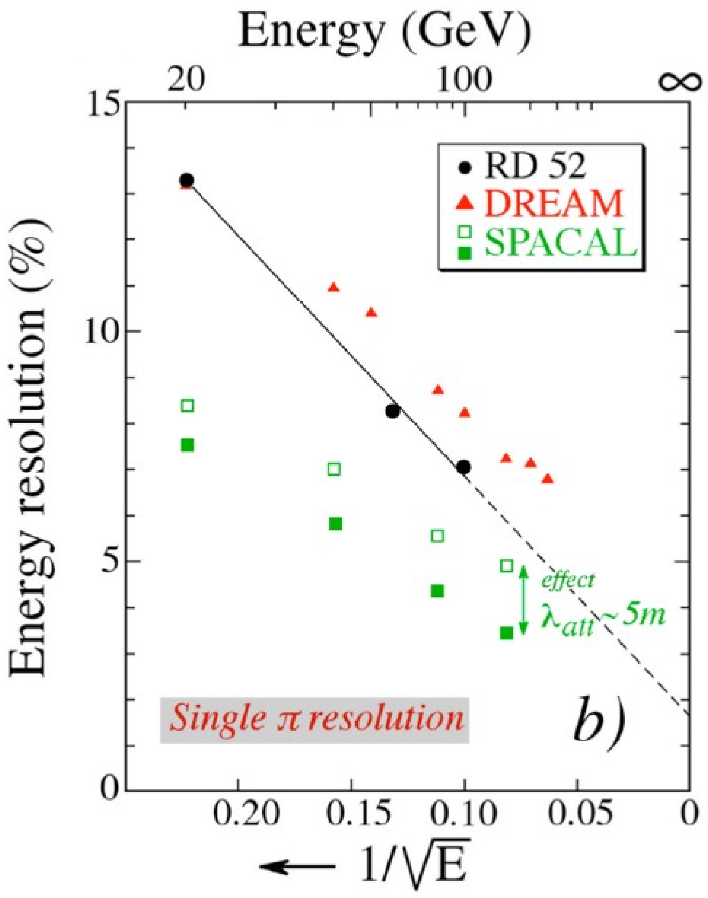


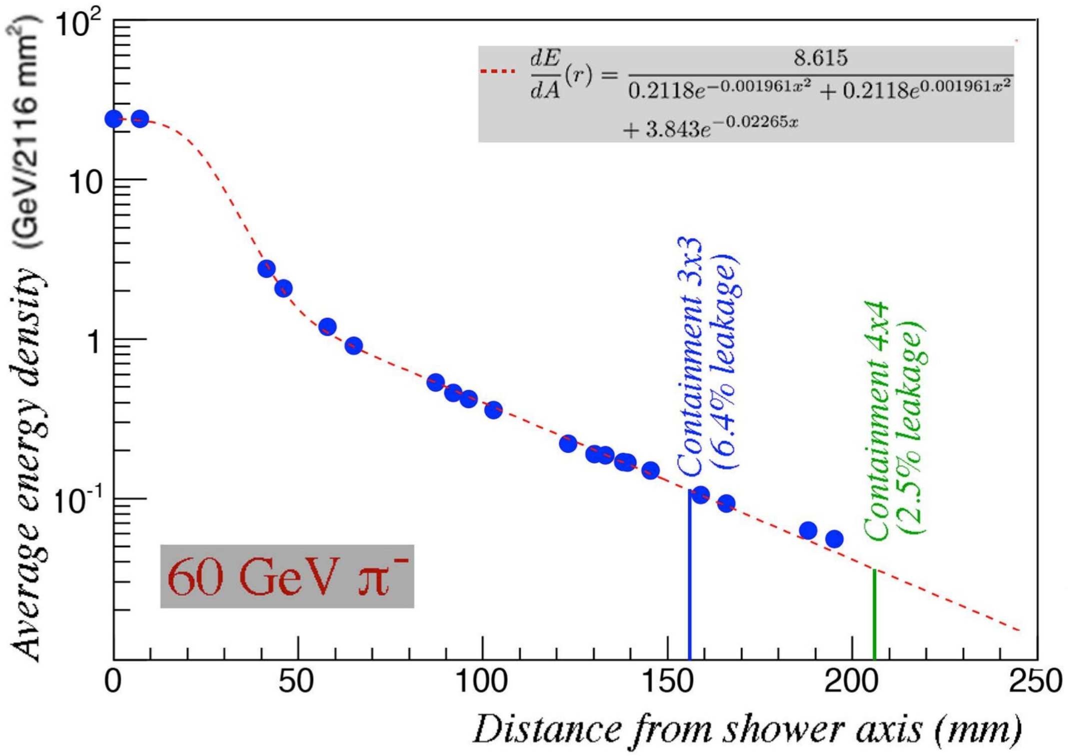
single-particle hadronic resolution

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 friendly")

Single-fibre readout

PMT → 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, ...)*

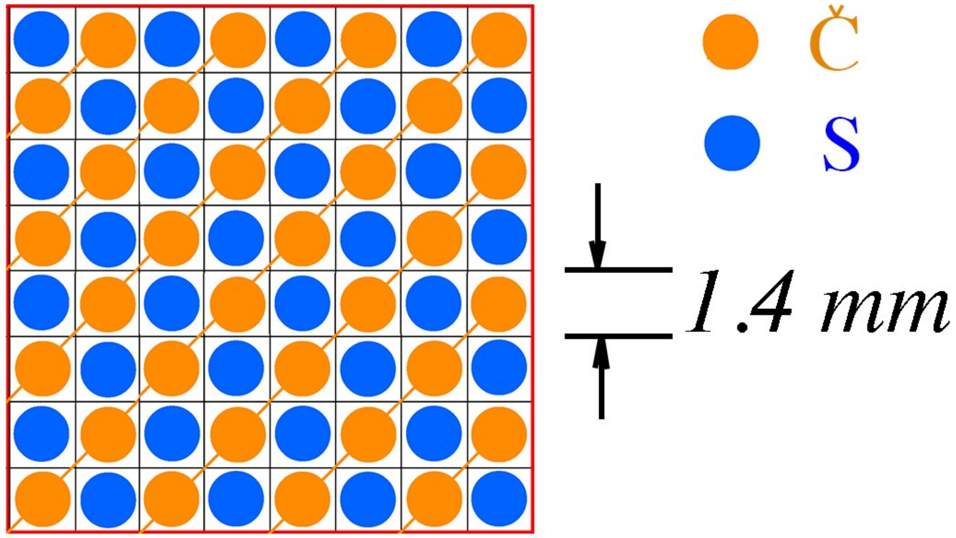
RD52 SiPM module

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

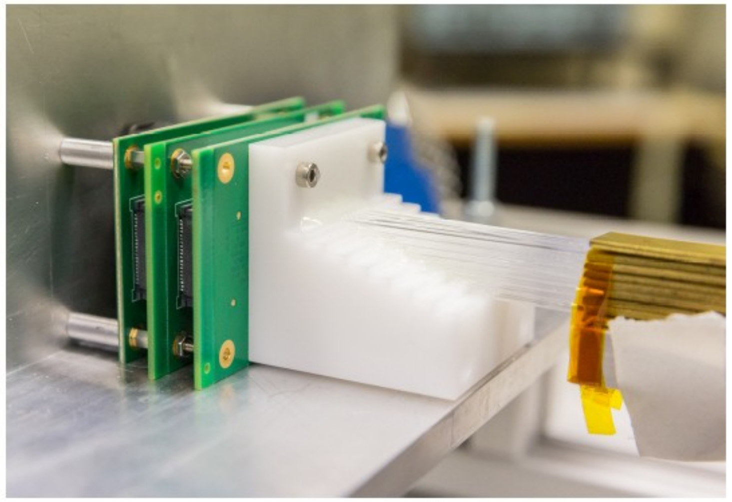
32 (S) + 32 (Č) fibres
$X_0 \sim 29$ *mm*
$R_M \sim 31$ *mm*

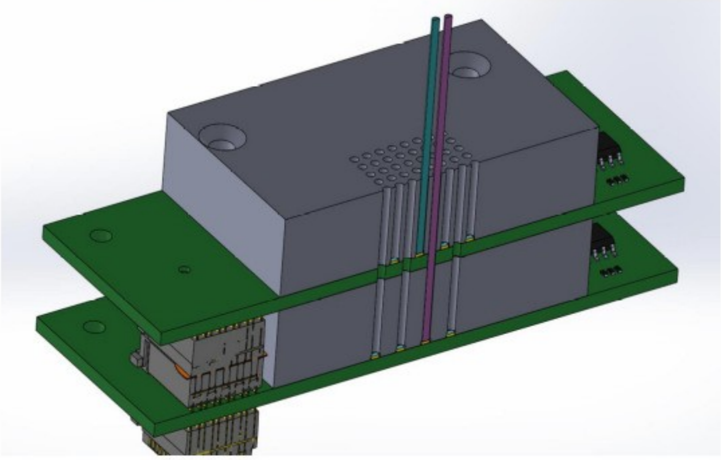
$\sim (0.4\ R_M)^2 \times 39\ X_0$

shower cont. ~ 45%
$f_{sampl} \sim 5\text{-}6\%$



SiPM light sensors

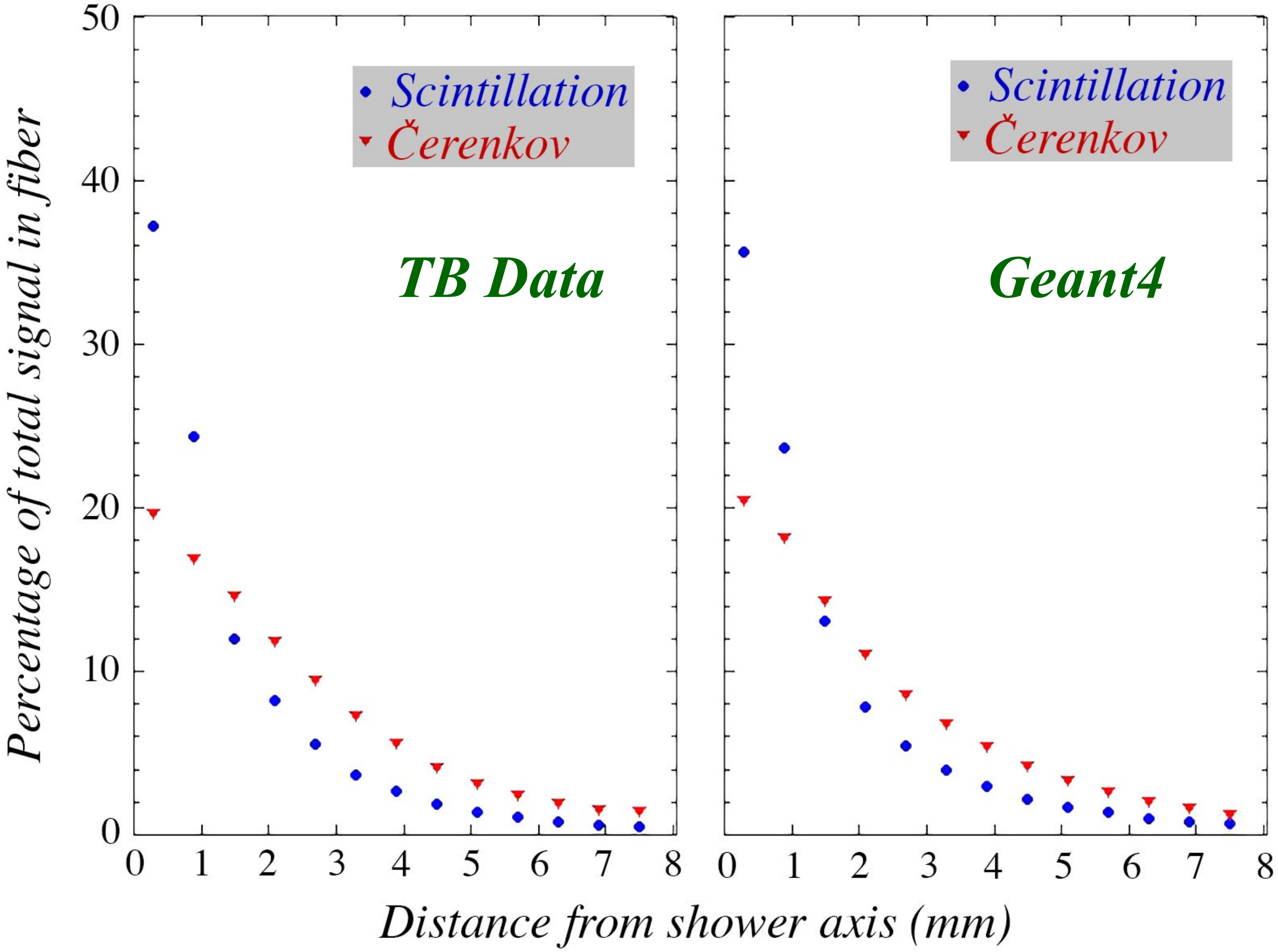




lateral shower profile w/ SiPM

10 / 40 GeV e$^-$

θ, Φ = 0°



em shower are very narrow:

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

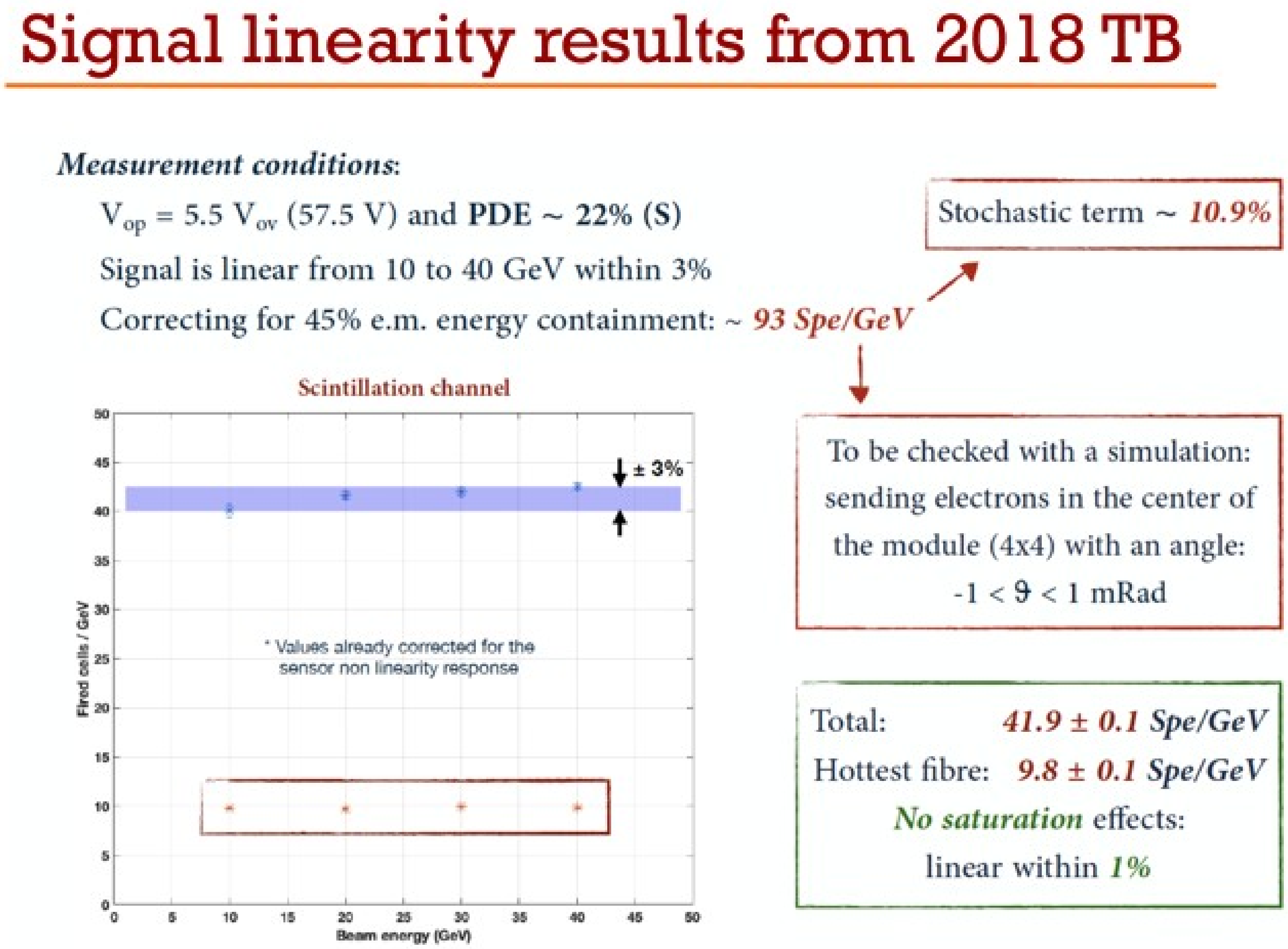
→ fibre readout can easily provide (powerful) input to PFA

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 < ϑ < 1 mRad

Scintillation channel

* Values already corrected for the sensor non linearity response

Total: ***41.9 ± 0.1 Spe/GeV***

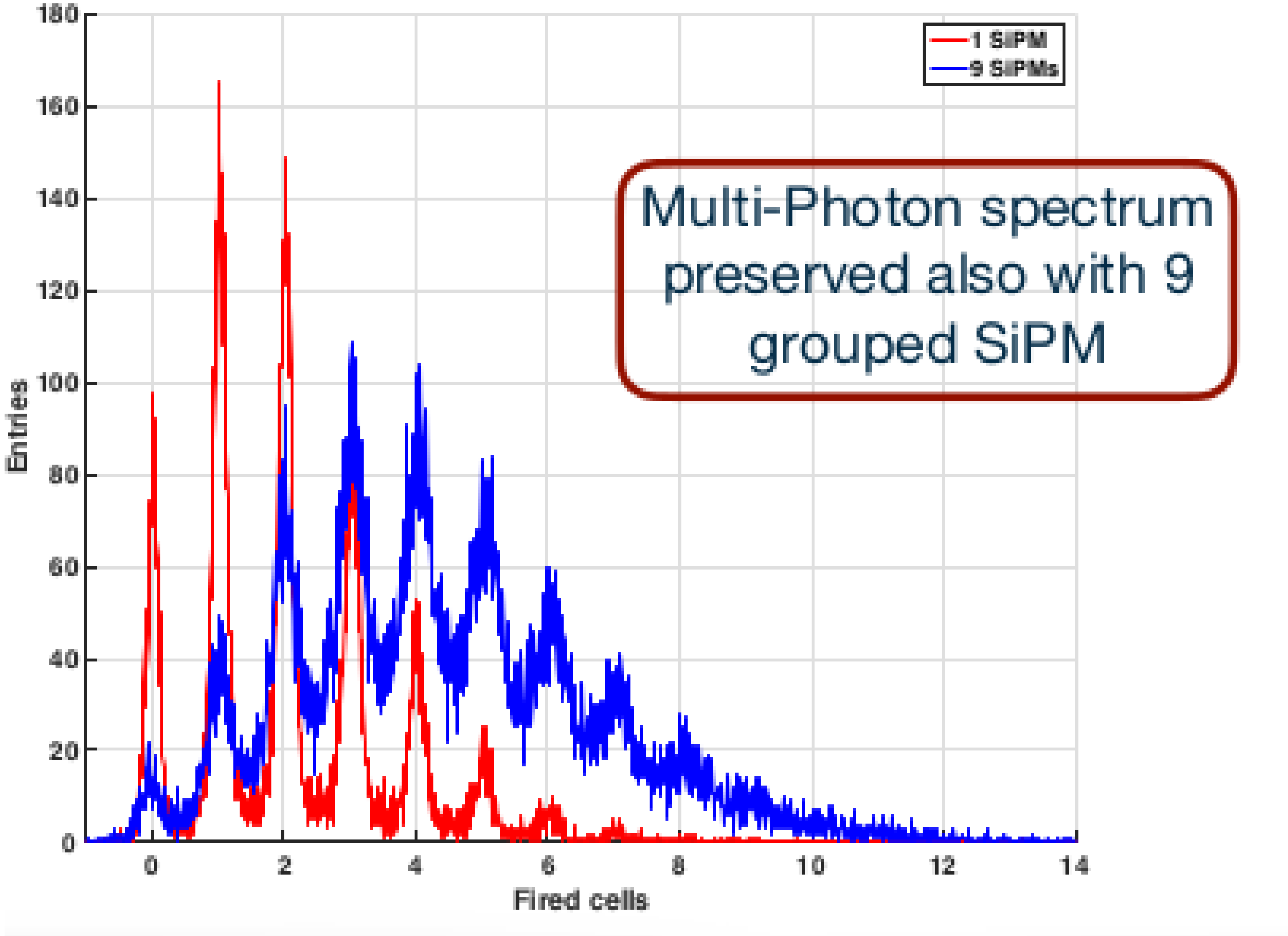
Hottest fibre: ***9.8 ± 0.1 Spe/GeV***

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

readout granularity (channel grouping)

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

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

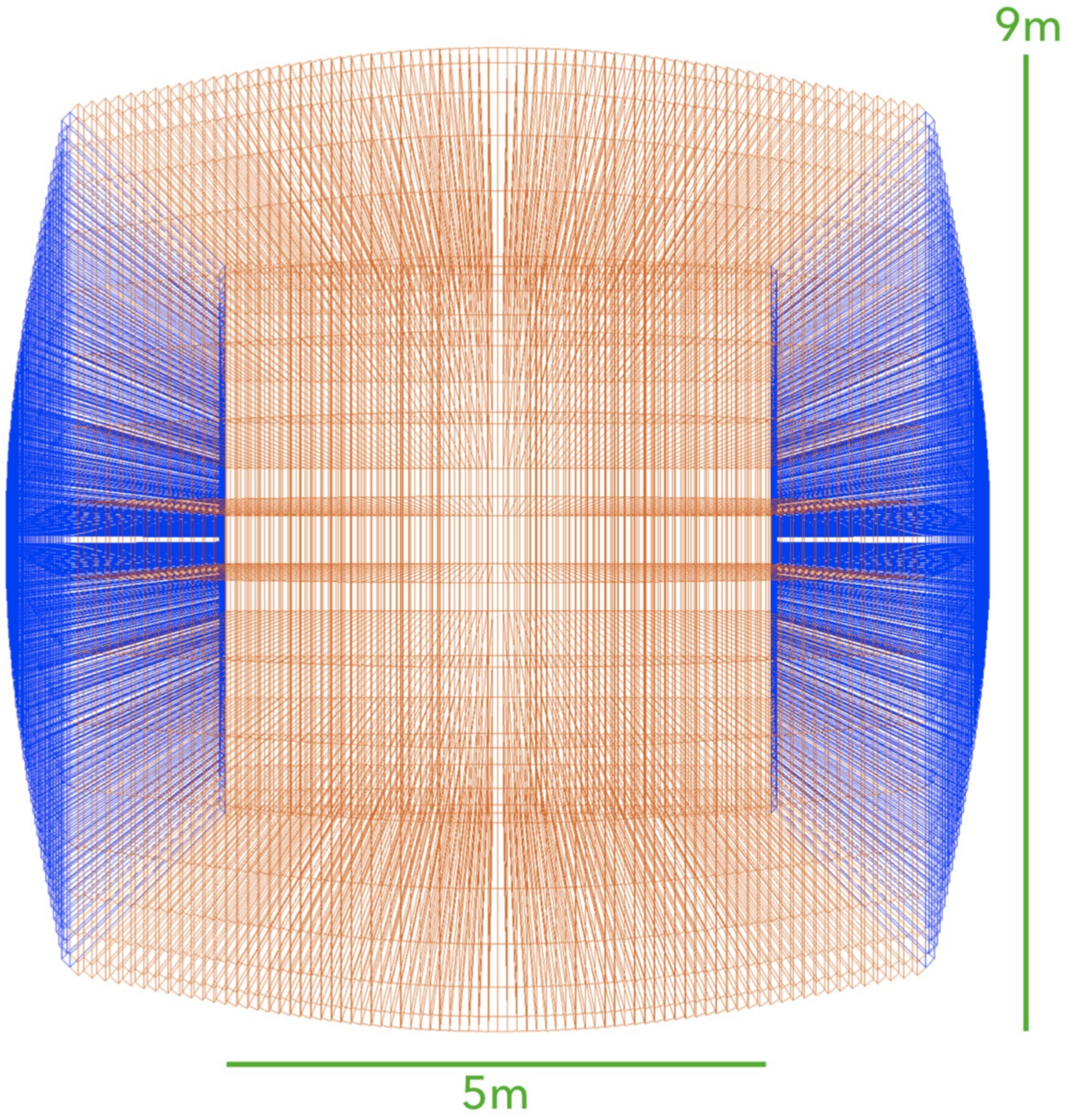


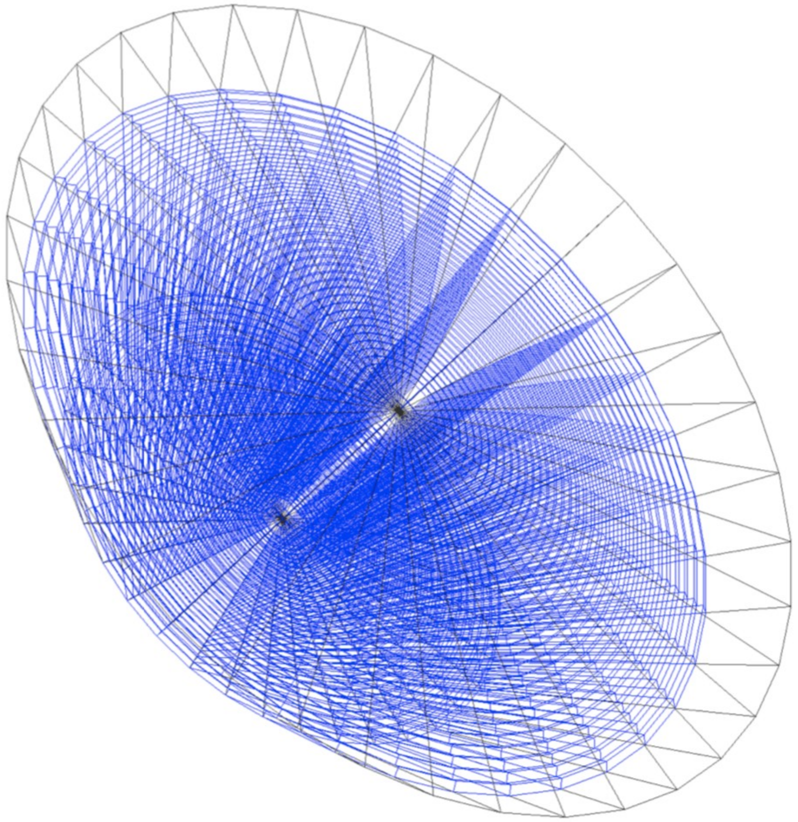
Multi-Photon spectrum preserved also with 9 grouped SiPM

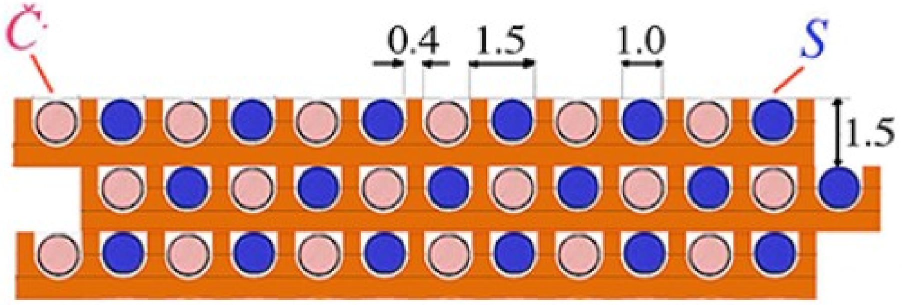
It works! May reasonably think at 2×2, 2×3, 2×4, 3×3 ...

G4 full simulations
em performance

(IDEA) 4π projective geometry



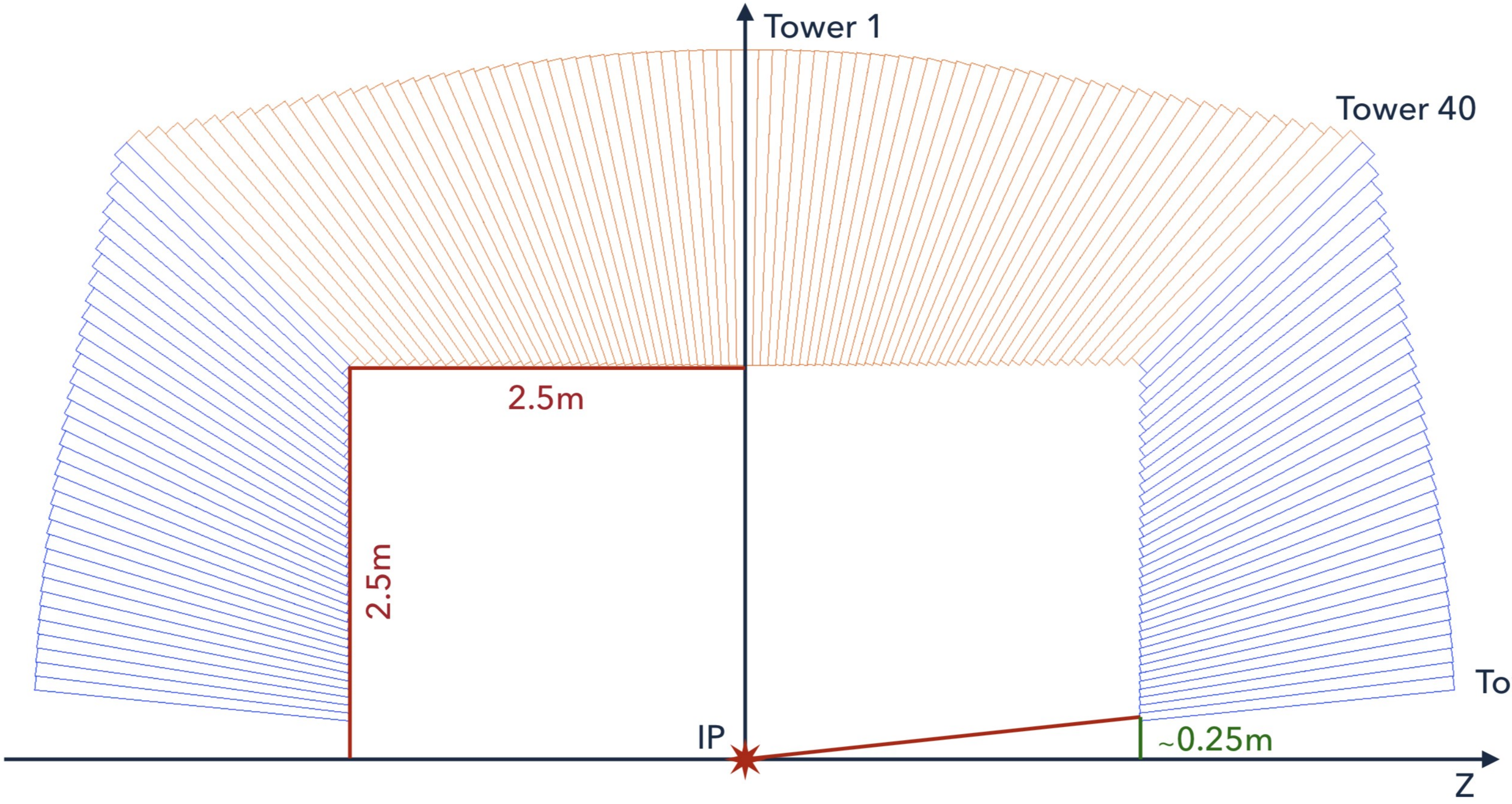




Copper + scintillating and Cherenkov fibers

IDEA detector layout

(IDEA) 4π projective geometry



75 projective elements x 36 slices

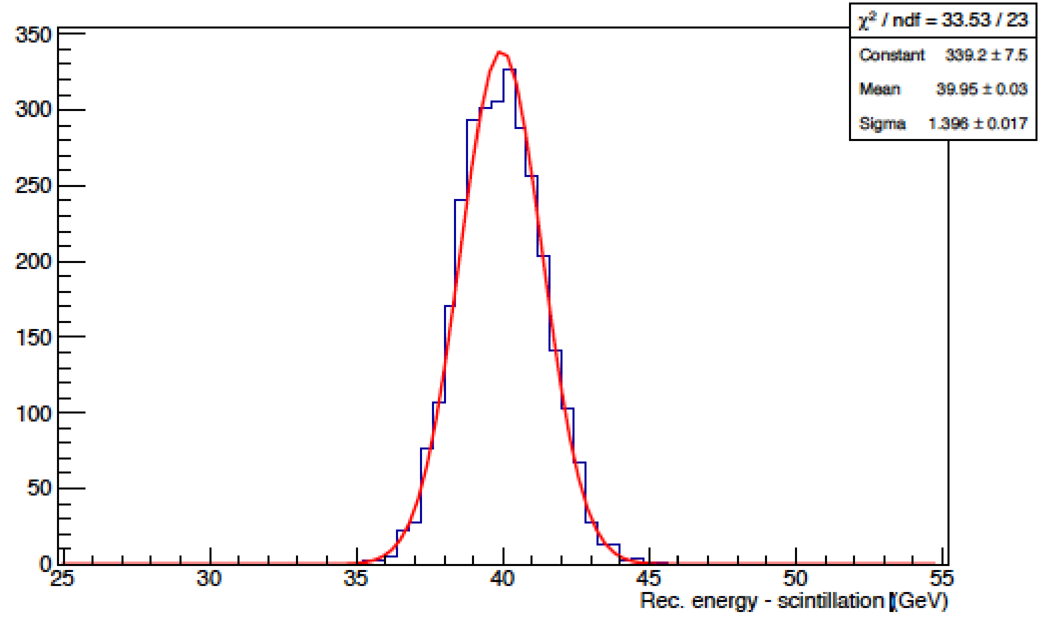
single-fibre readout: 130 M channels

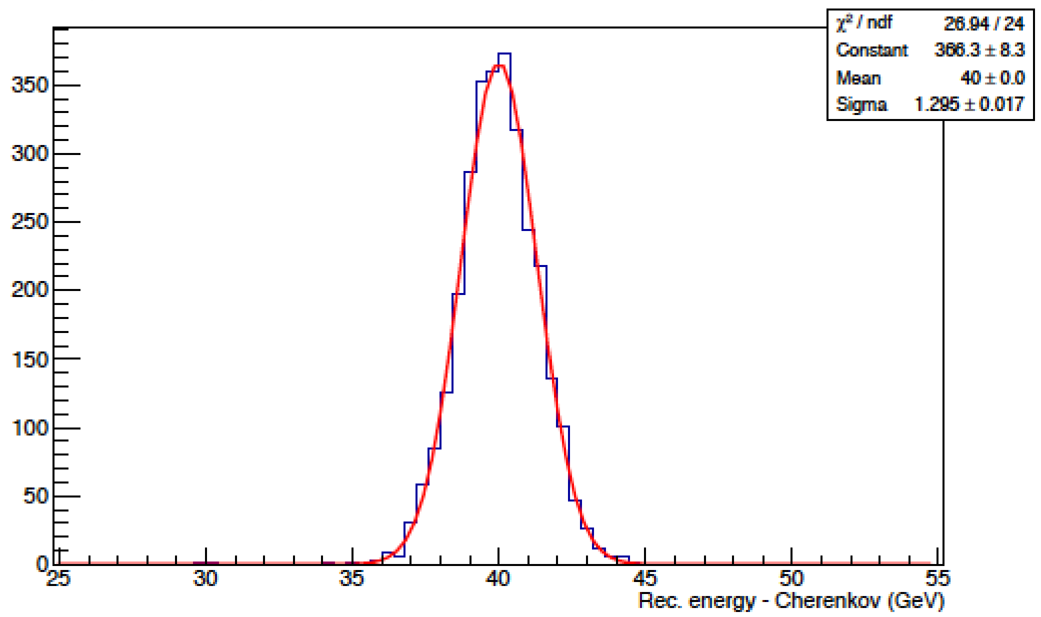
Tower size:

$$\Delta\theta = 1.125^\circ$$

$$\Delta\phi = 10^\circ$$

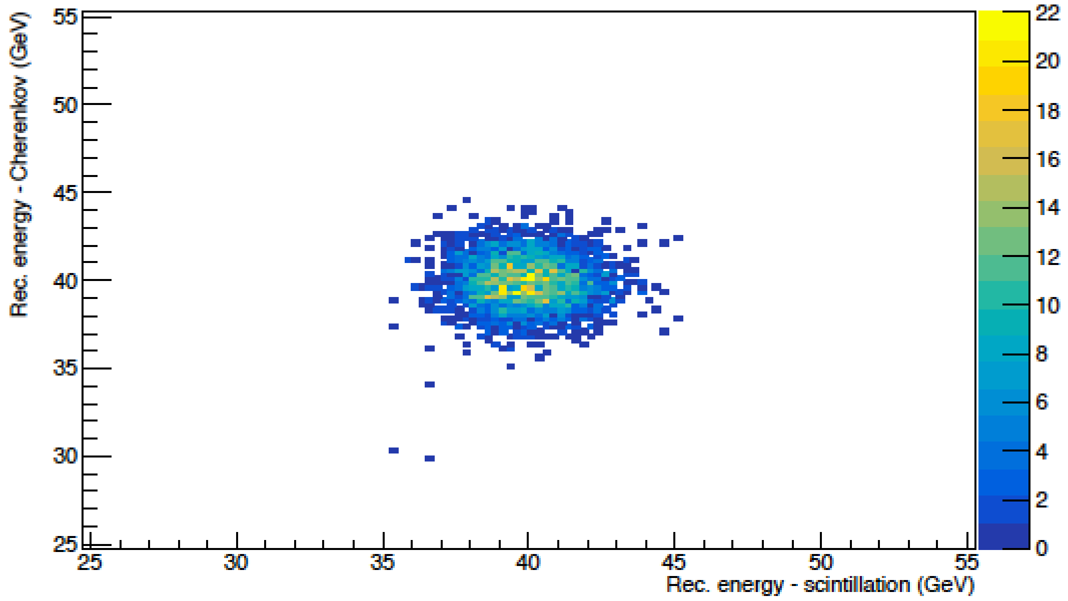
em performance: energy resolution


Scintillation

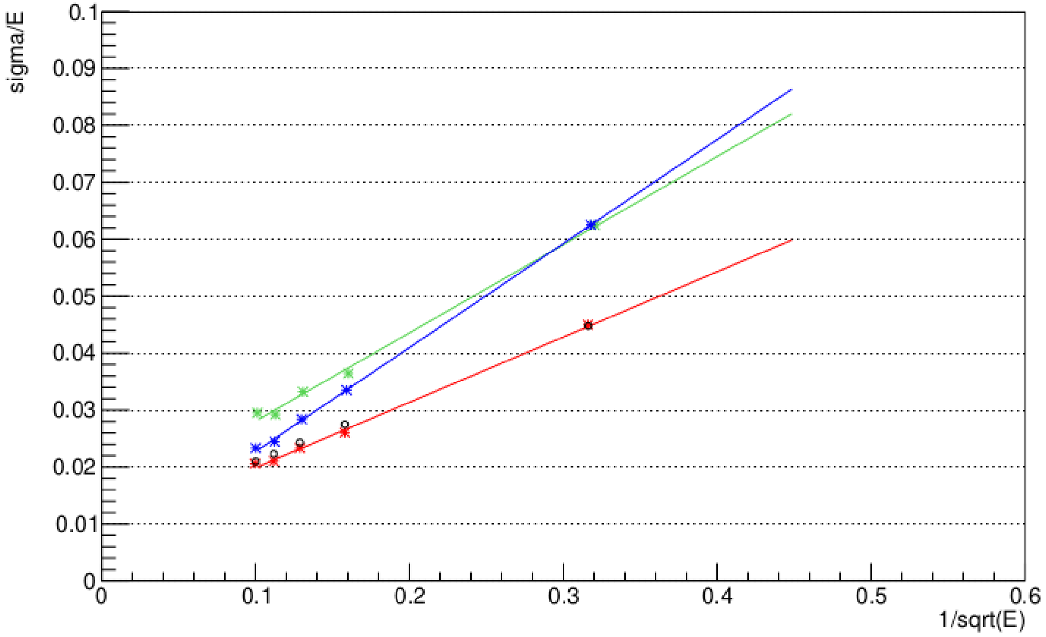

Cherenkov

Geant4
40 GeV e^-

$\theta = \varphi = 1.5°$



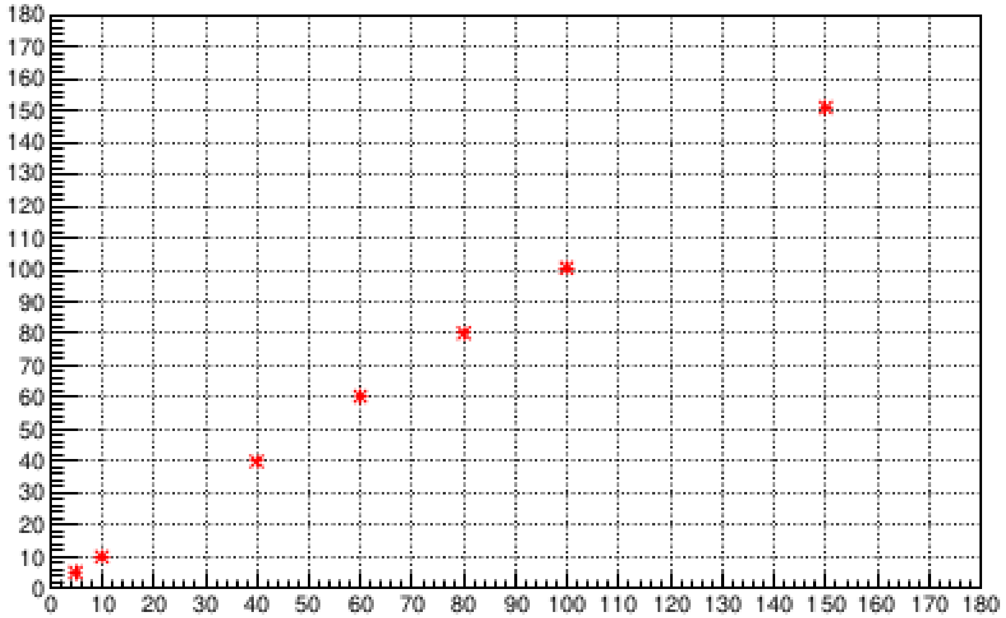
resolution & linearity

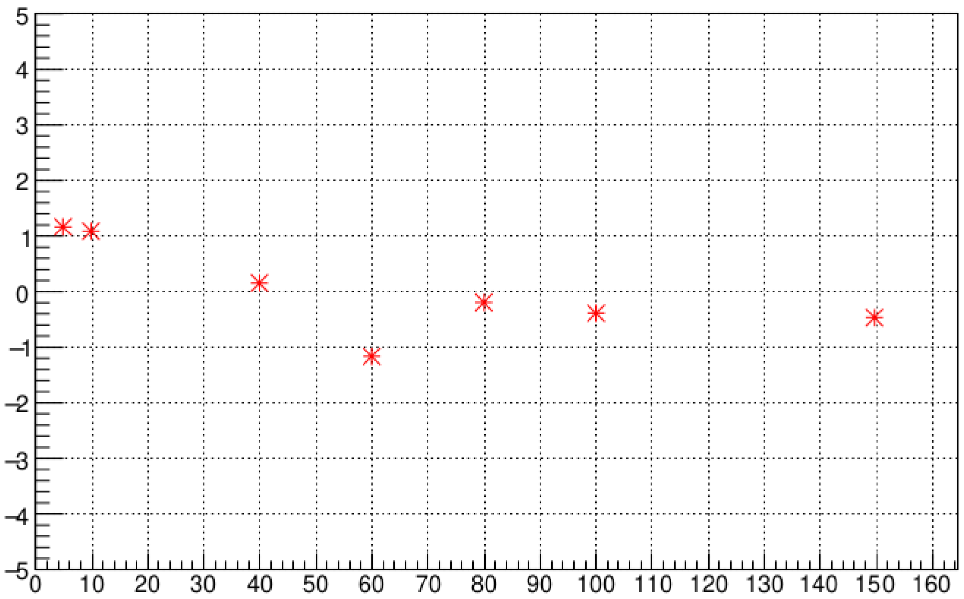


S → $$\frac{\sigma}{E} = \frac{15.5\%}{\sqrt{E}} + 1.2\%$$

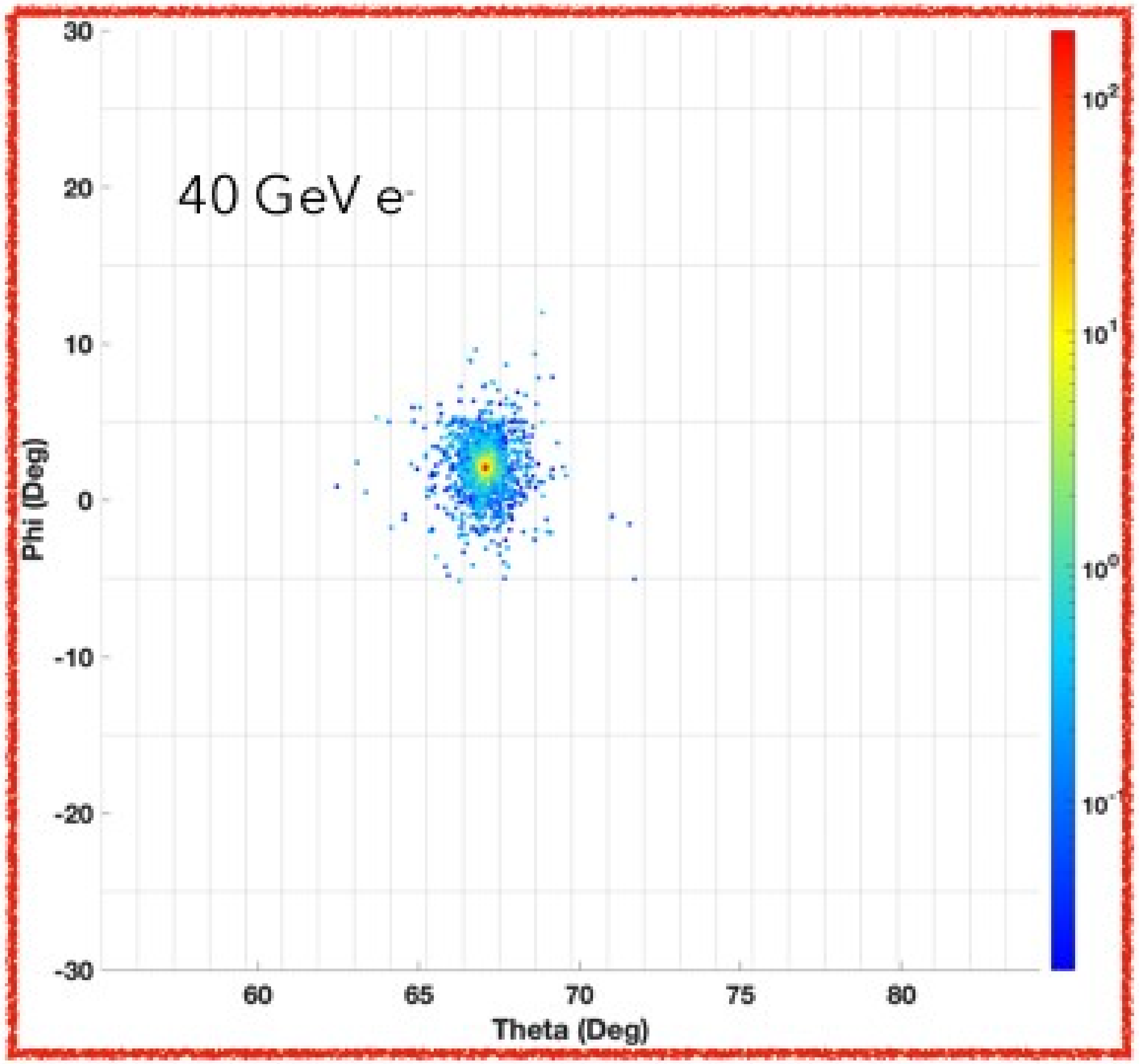
Č → $$\frac{\sigma}{E} = \frac{18.3\%}{\sqrt{E}} + 0.5\%$$

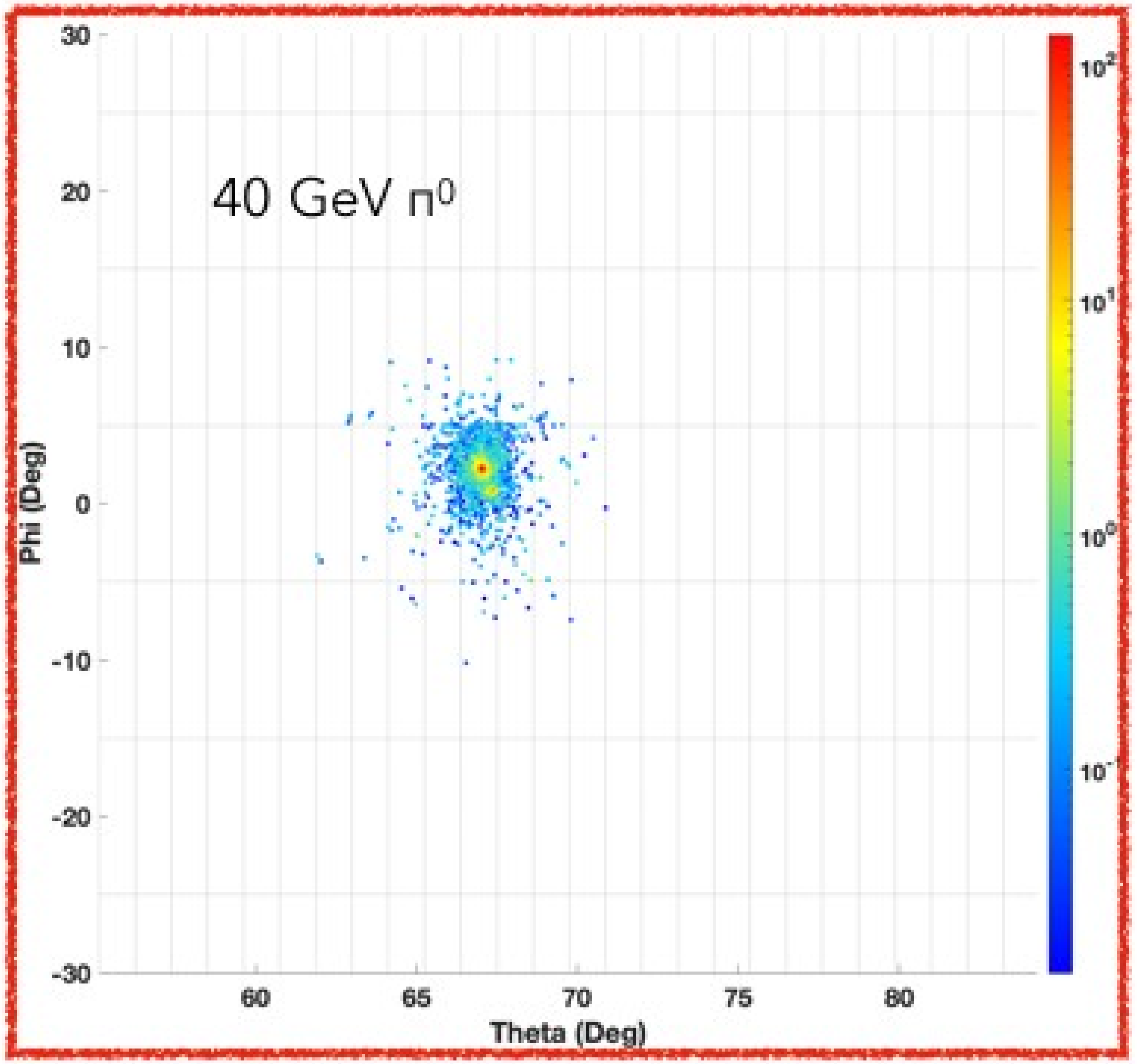
S + Č → $$\frac{\sigma}{E} = \frac{11.0\%}{\sqrt{E}} + 0.8\%$$



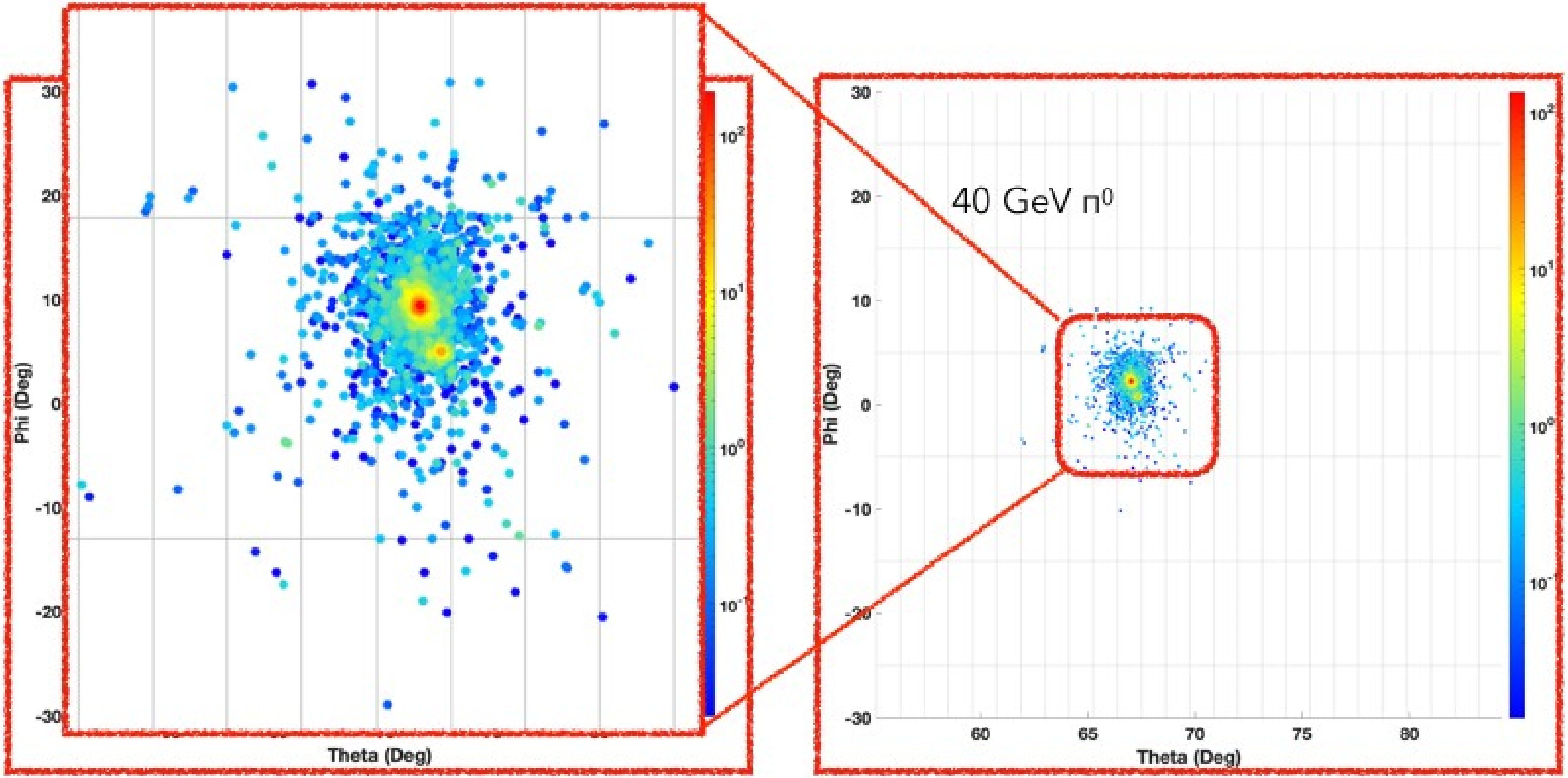


transverse granularity

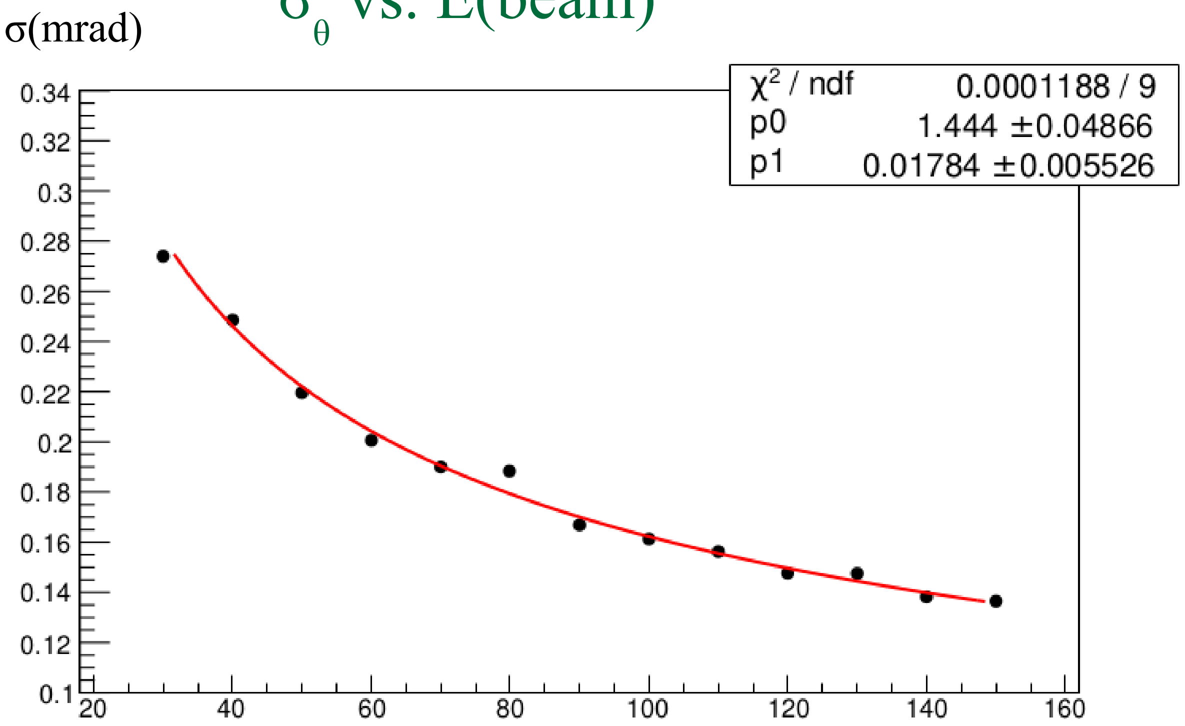


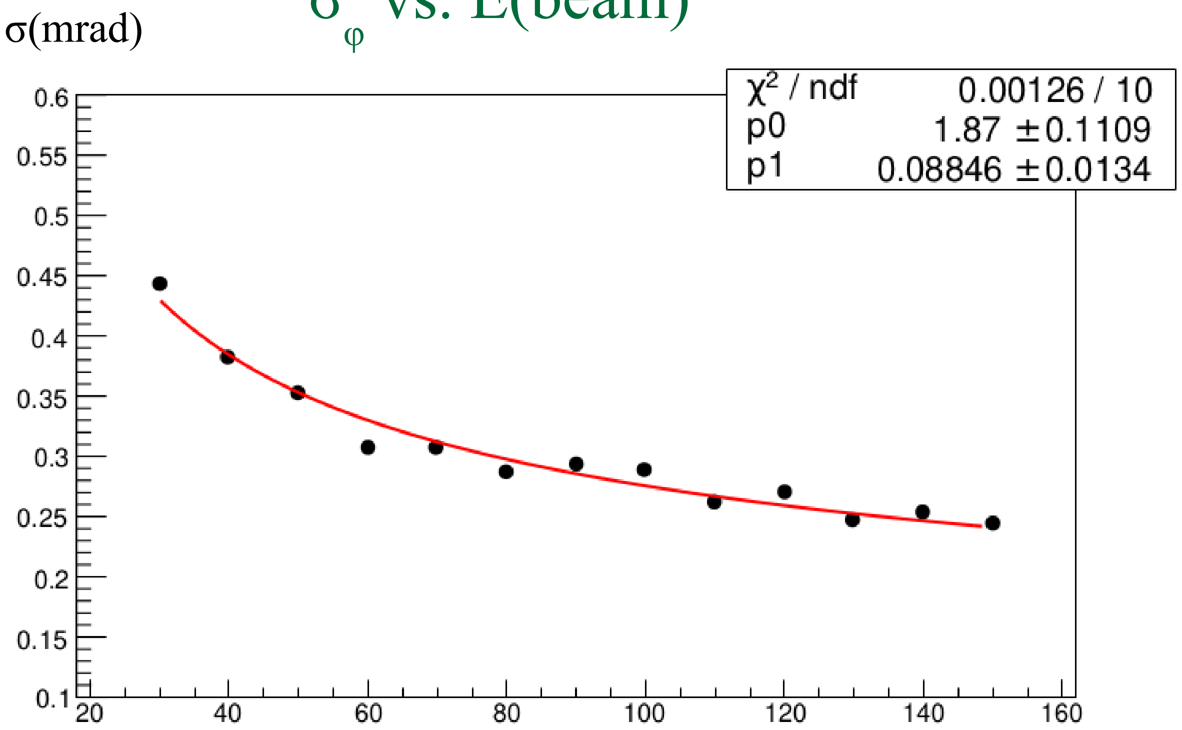


transverse granularity



angular resolution


σ_θ vs. E(beam)


σ_φ vs. E(beam)

$$\sigma_\theta = \frac{1.4\%}{\sqrt{E}} + 0.02 \quad \textit{(mrad)}$$

$$\sigma_\phi = \frac{1.8\%}{\sqrt{E}} + 0.09 \quad \textit{(mrad)}$$

G4 full simulations
hadronic performance

had performance

Caveat:

G4 modelling of nuclear interactions still not optimal

addressed through different physics lists

X factor estimate not yet reliable

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

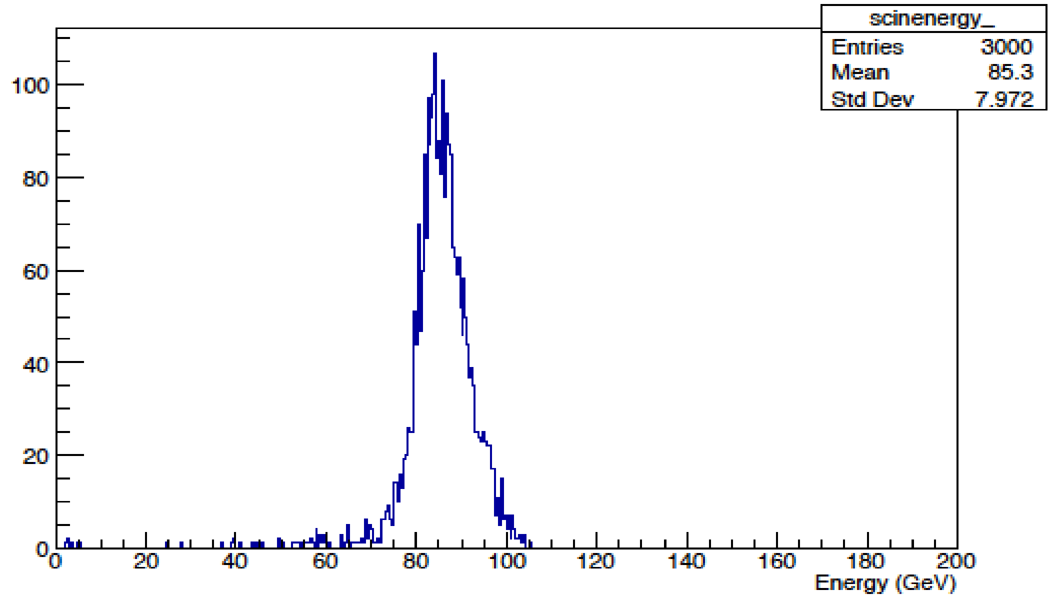
resolution and linearity critically depends on it

need valitation → hadronic size prototype

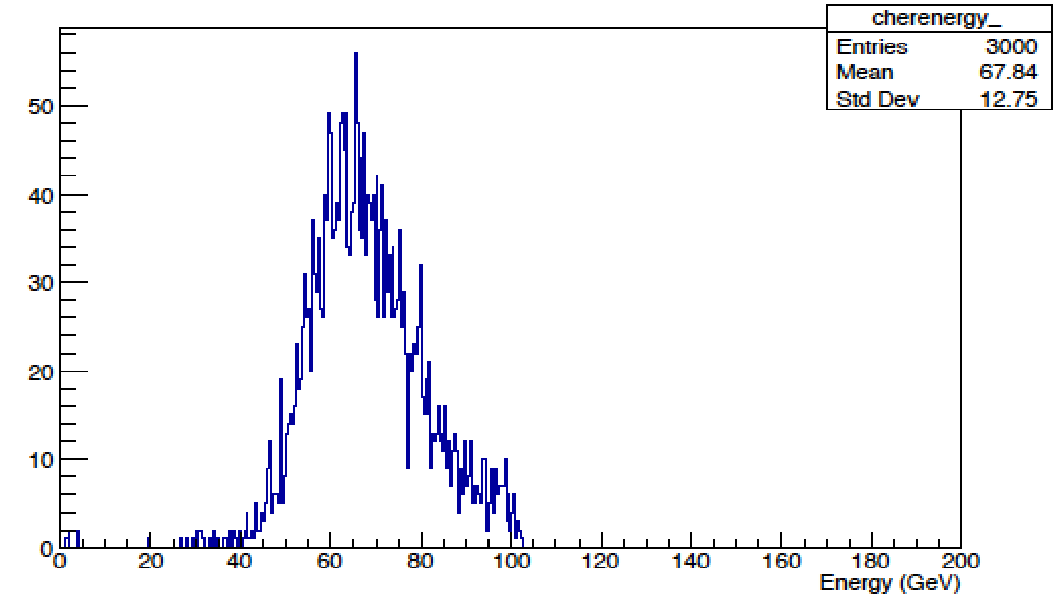
had performance: pion energy resolution

Geant4 100 GeV π (FTFP-BERT physics list)

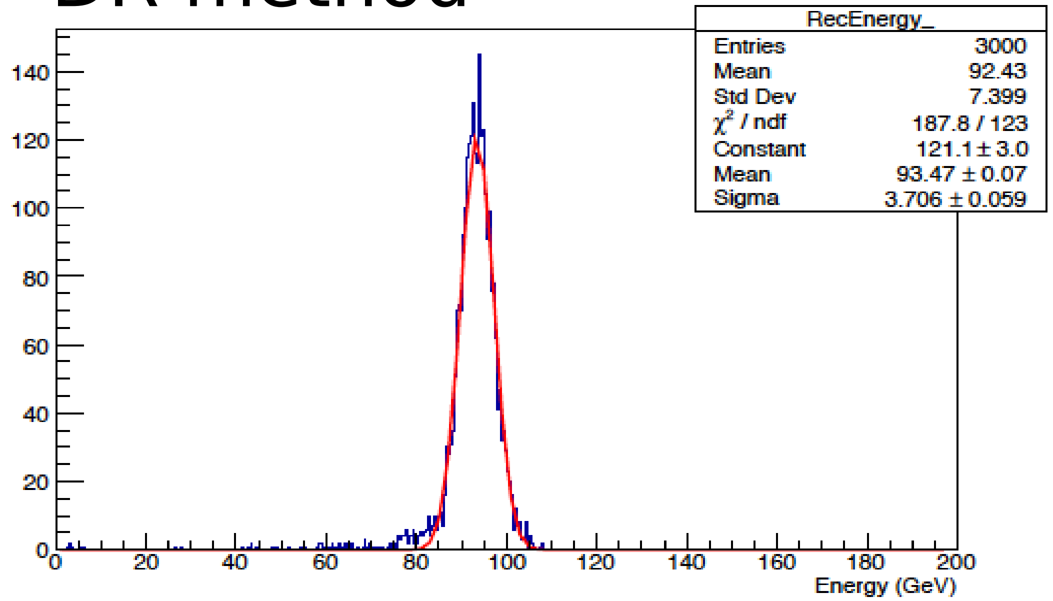
Scintillation

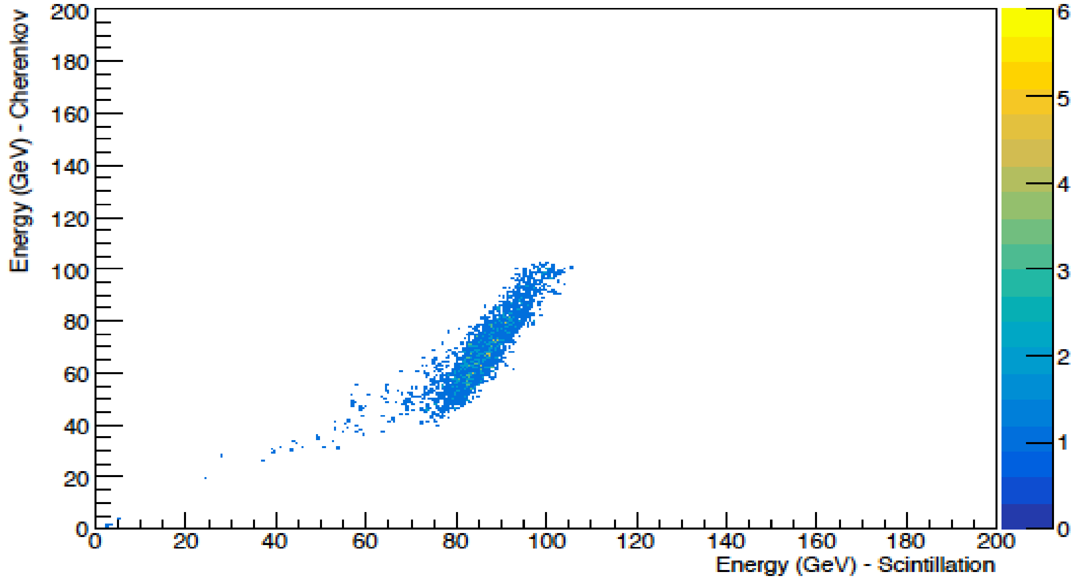


Cherenkov

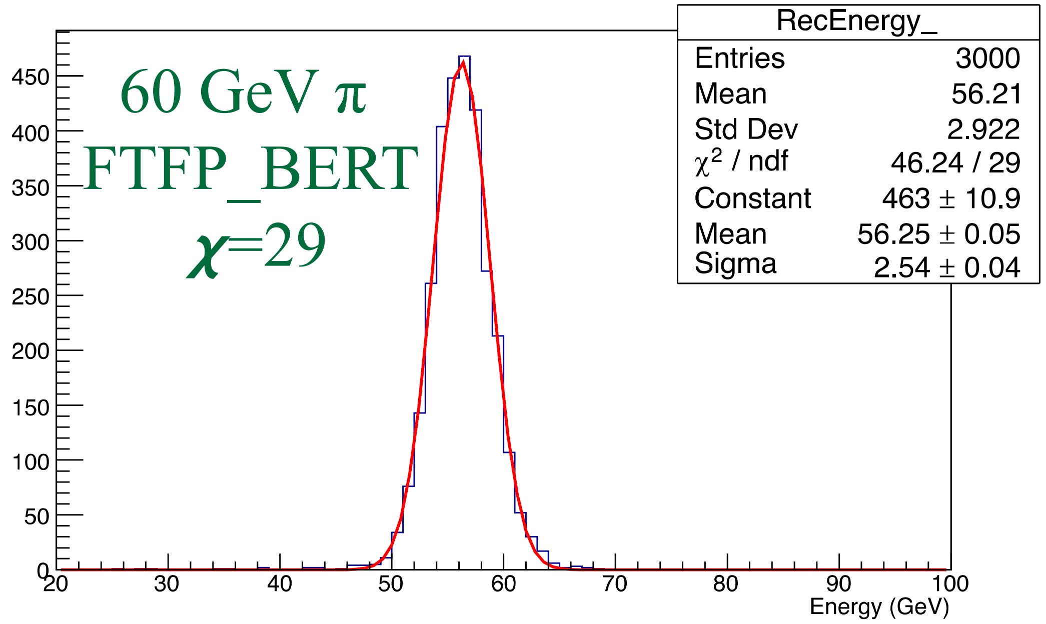


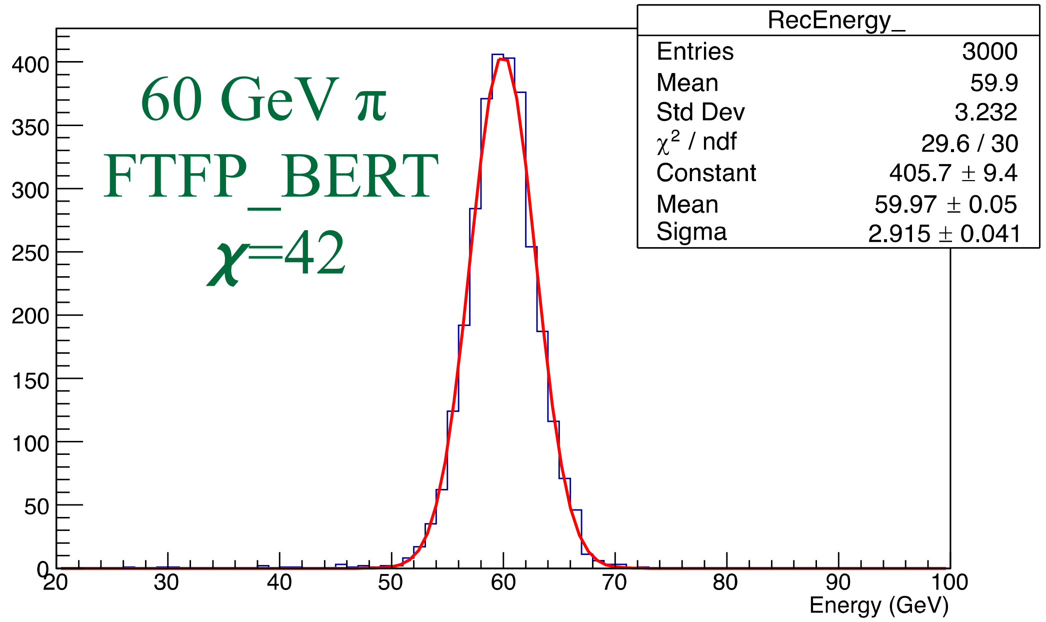
DR method

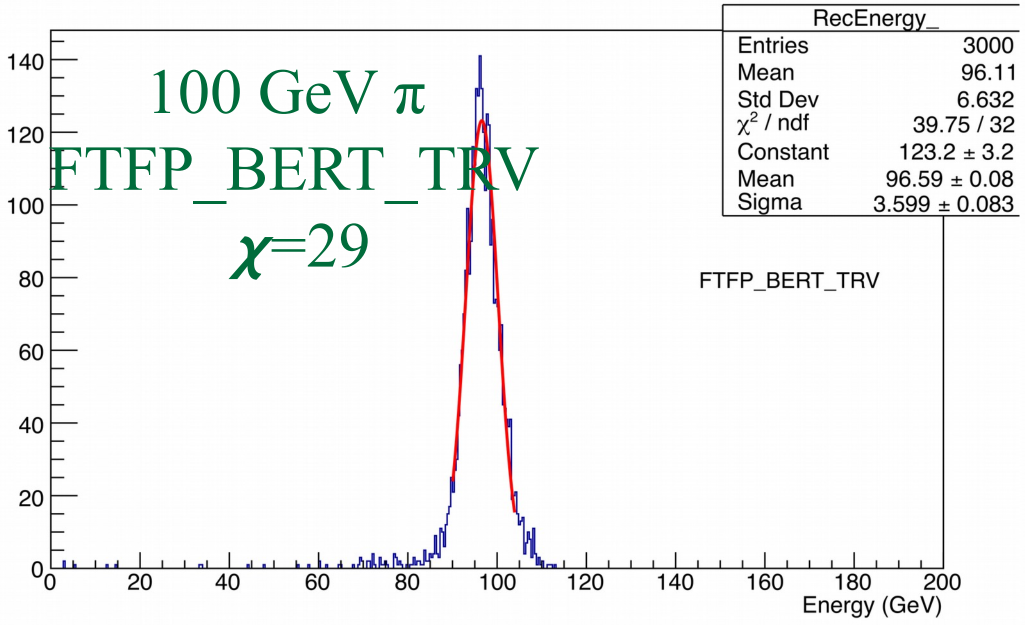


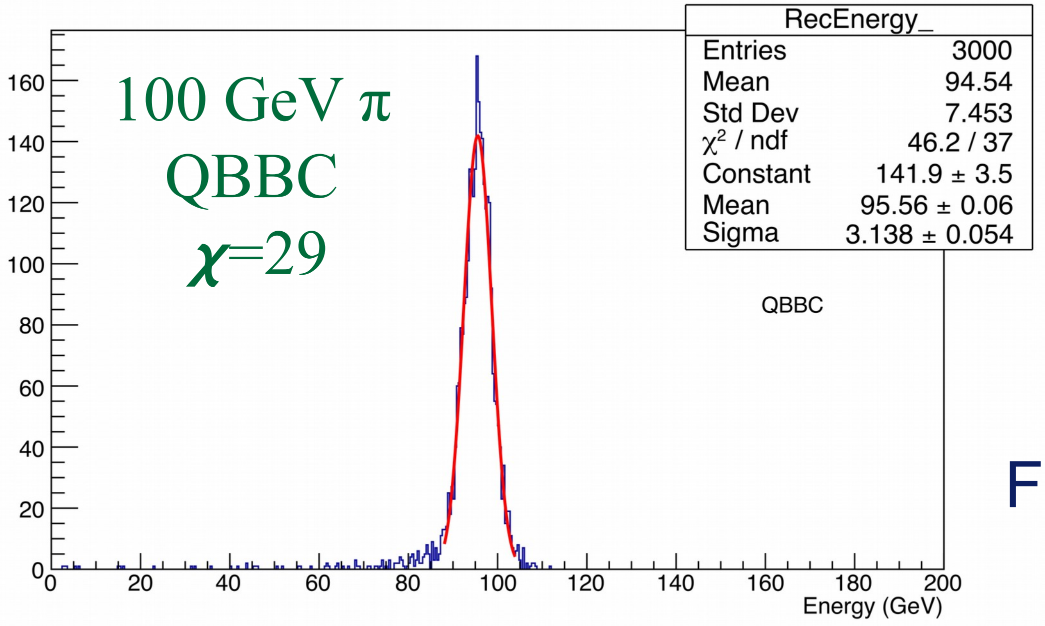


had performance: pion energy resolution


60 GeV π
FTFP_BERT
χ=29

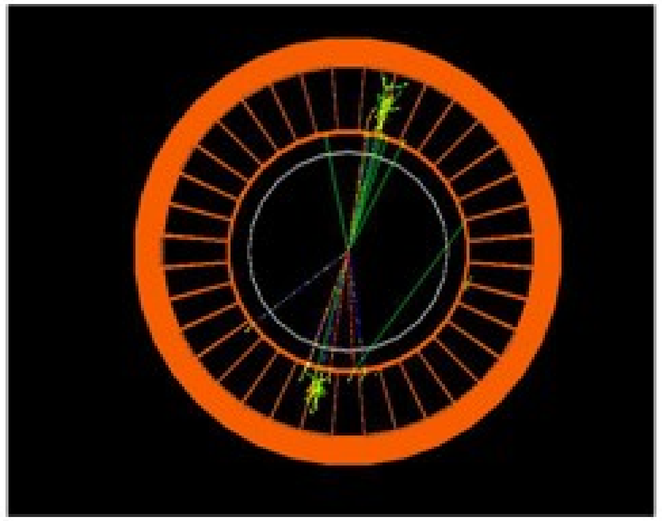

60 GeV π
FTFP_BERT
χ=42

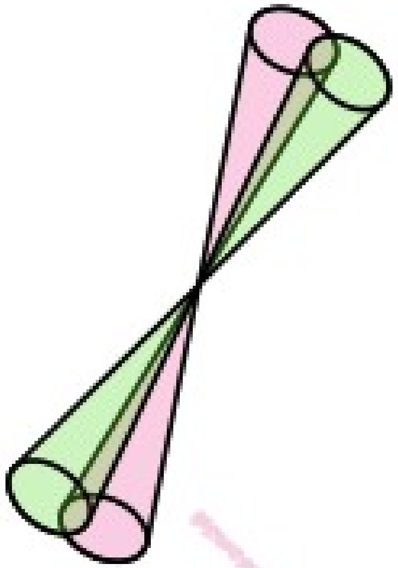

100 GeV π
FTFP_BERT_TRV
χ=29


100 GeV π
QBBC
χ=29

Promising prel.
results with
FTFP_BERT_TRV
and QBBC new
physics lists

$e^+e^- \rightarrow jj$

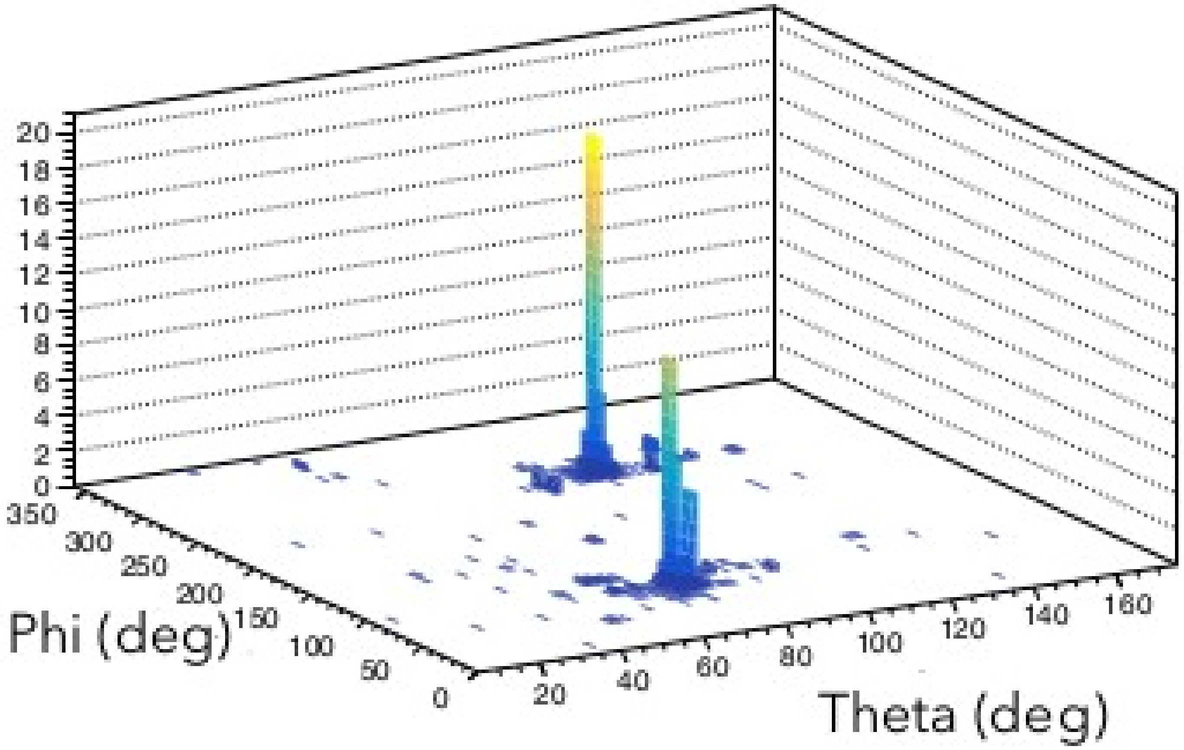


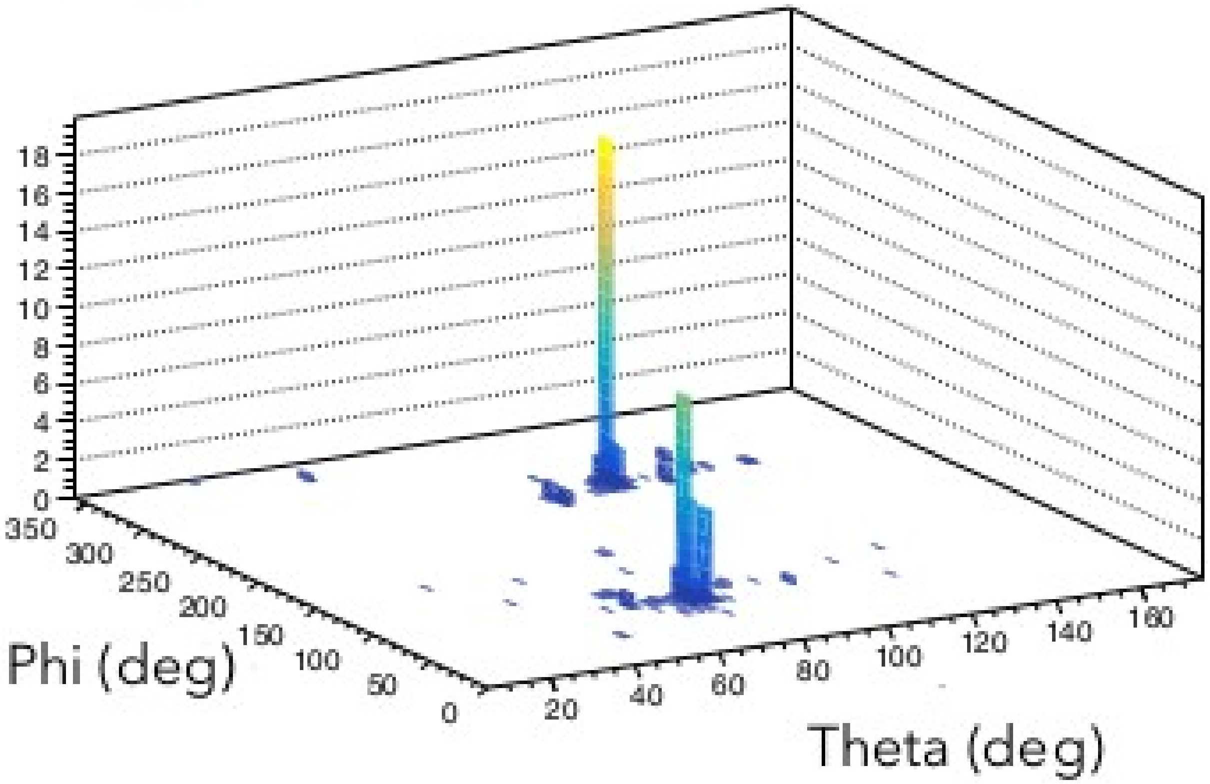


independent clustering on the two signals, using the (FASTJET) Durham kt algorithm

Scintillation signal (a.u.)

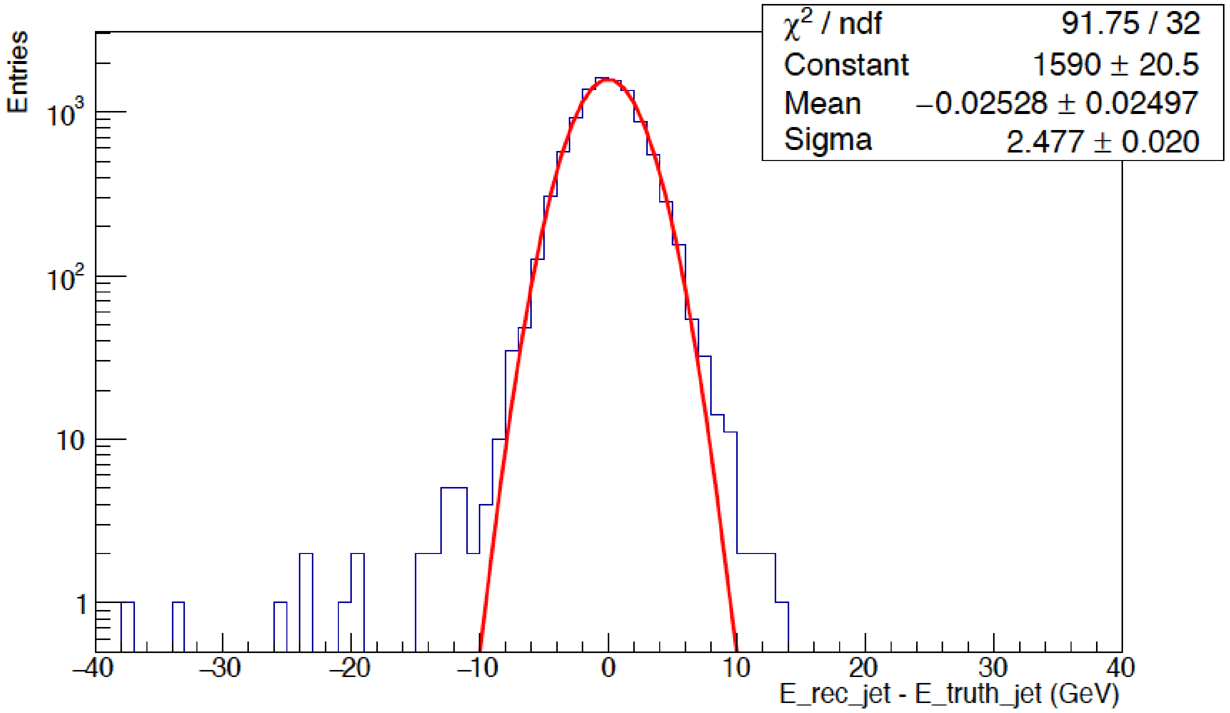
Cherenkov signal (a.u.)

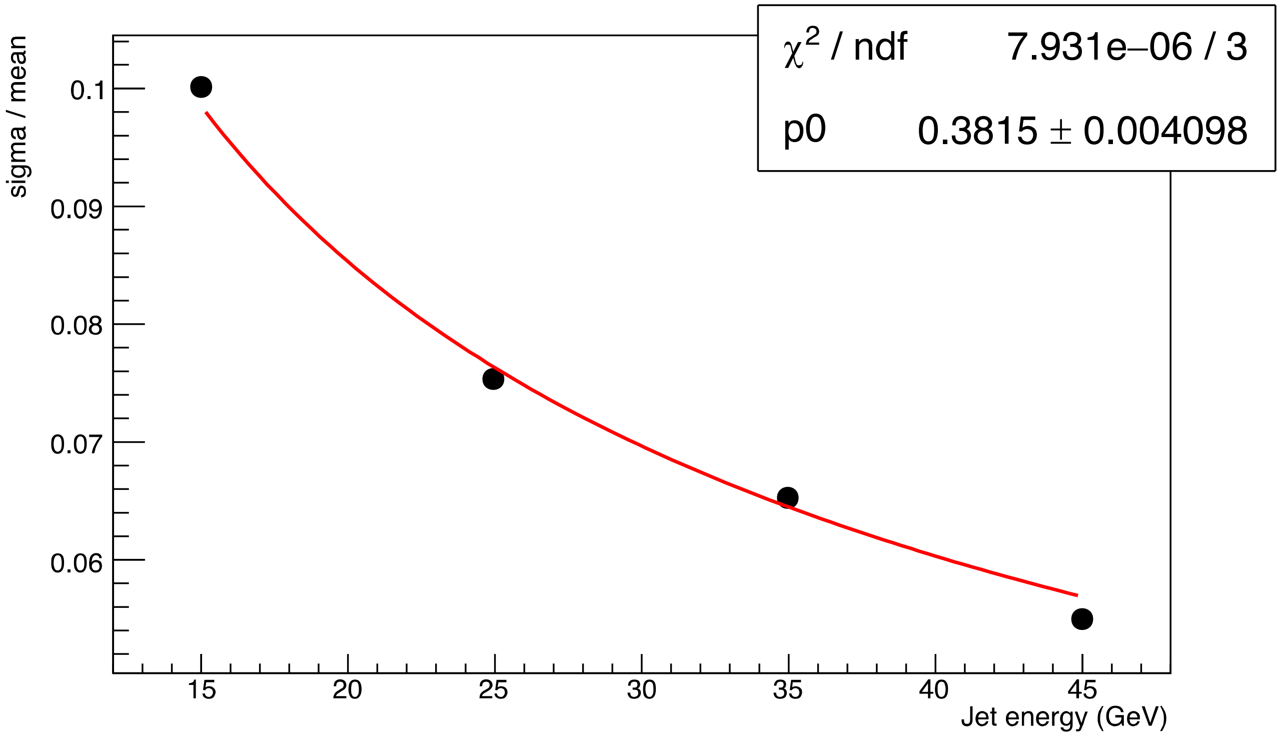




jet energy resolution

PYTHIA8 + GEANT4 + FASTJET





$$\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$$

2-jet Z/W/H final states

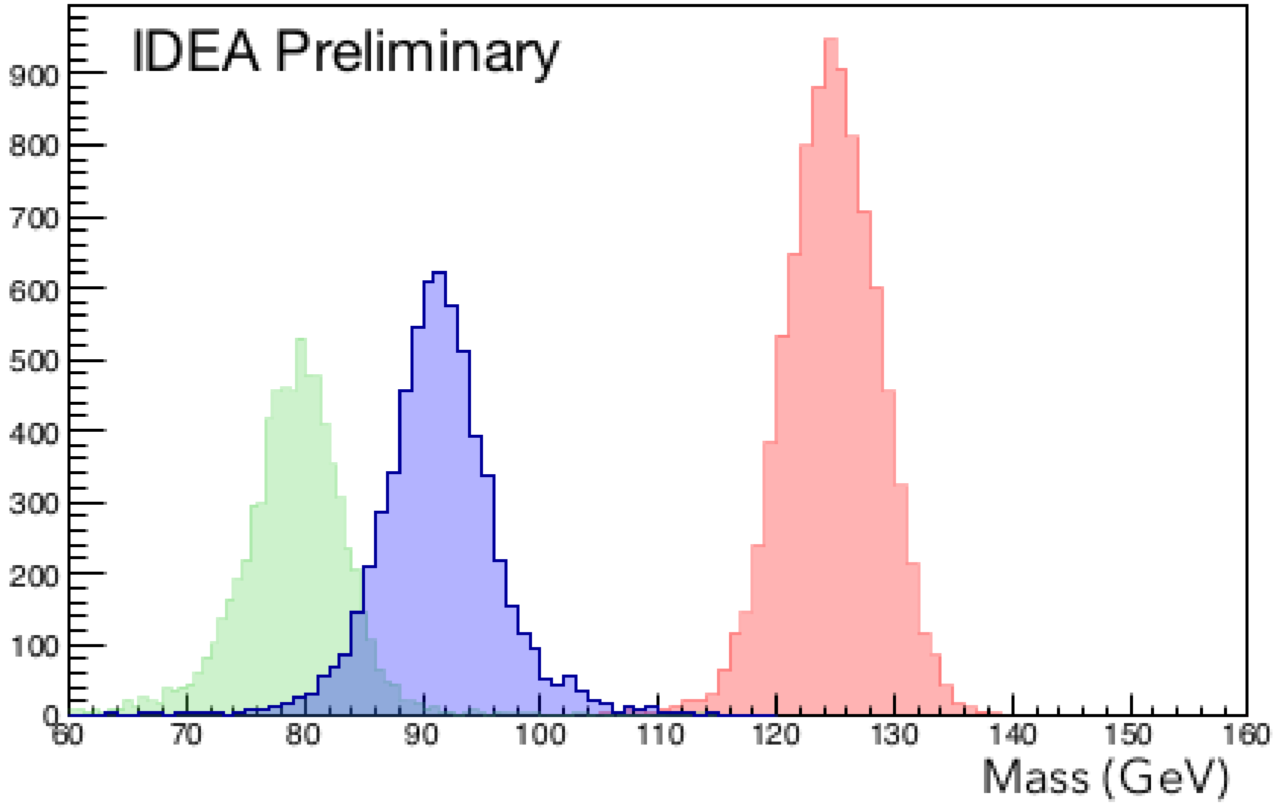
$$e^+e^- \rightarrow HZ \rightarrow \tilde{\chi}^0\tilde{\chi}^0 jj$$

$$e^+e^- \rightarrow WW \rightarrow \nu_\mu \mu jj$$

$$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$$

PYTHIA8 + GEANT4 + FASTJET

2j invariant mass



W	Average (GeV)	std
MC Truth	79.3	4.2
DR method	79.14	5.1

Z	Average (GeV)	std
MC Truth	91.24	4.32
DR method	91.32	5.43

G4 full simulations
particle identification

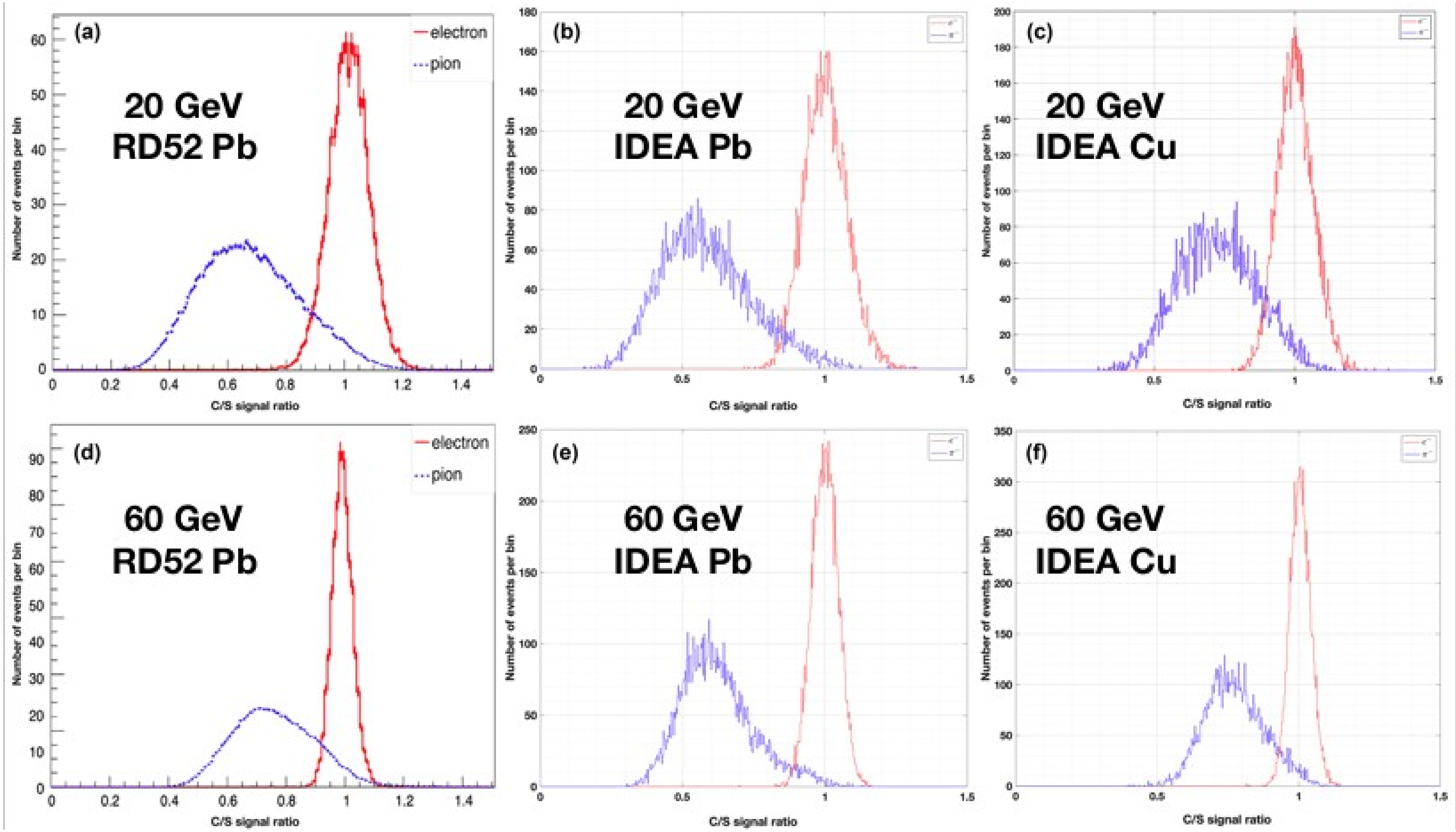
e/π separation

include time information in simulation
include scintillation decay time
simulate SiPM transfer function

estimate C/S, 95% radius, starting time (ToA)

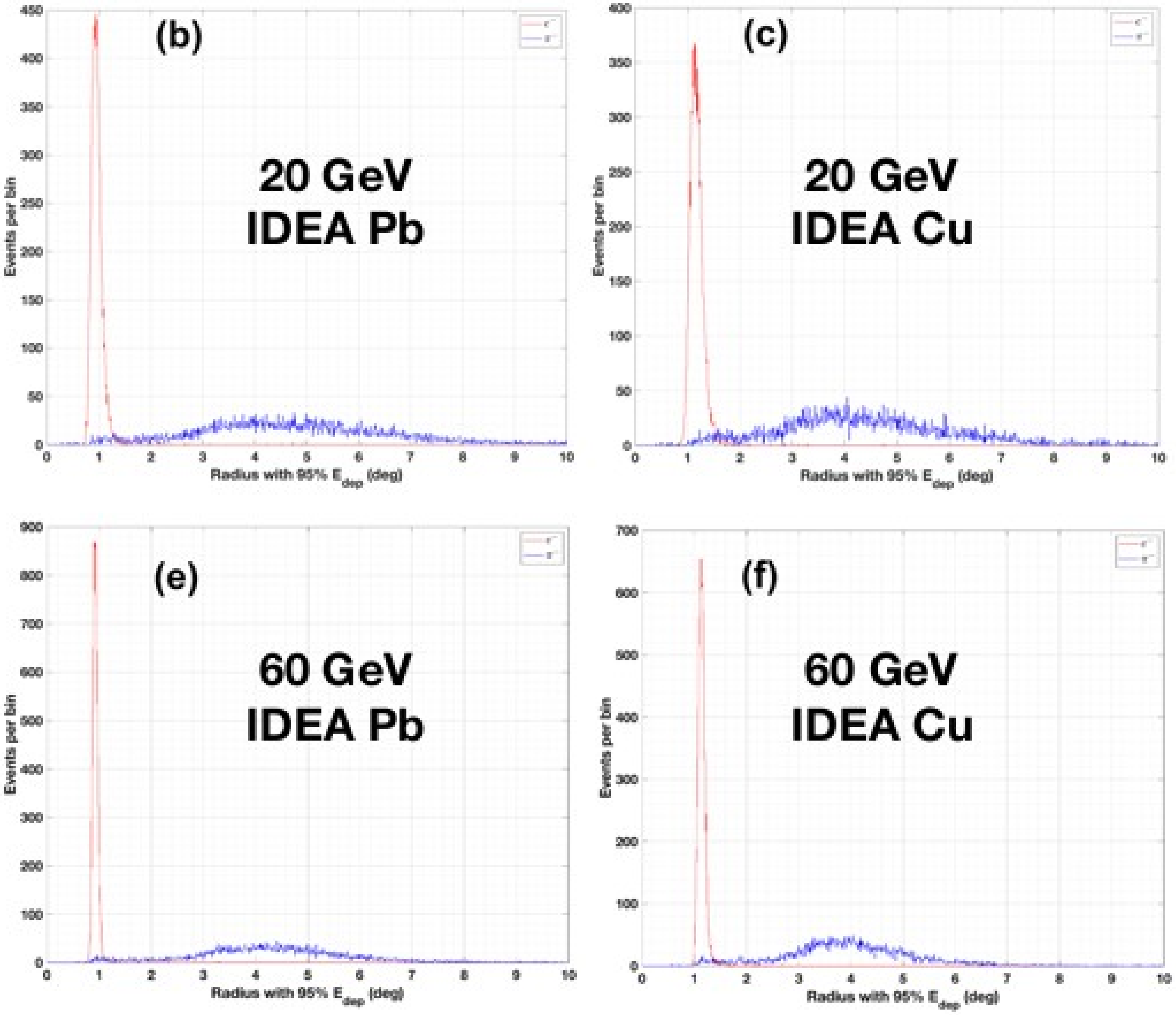
particle identification: C/S

Electron - pion separation



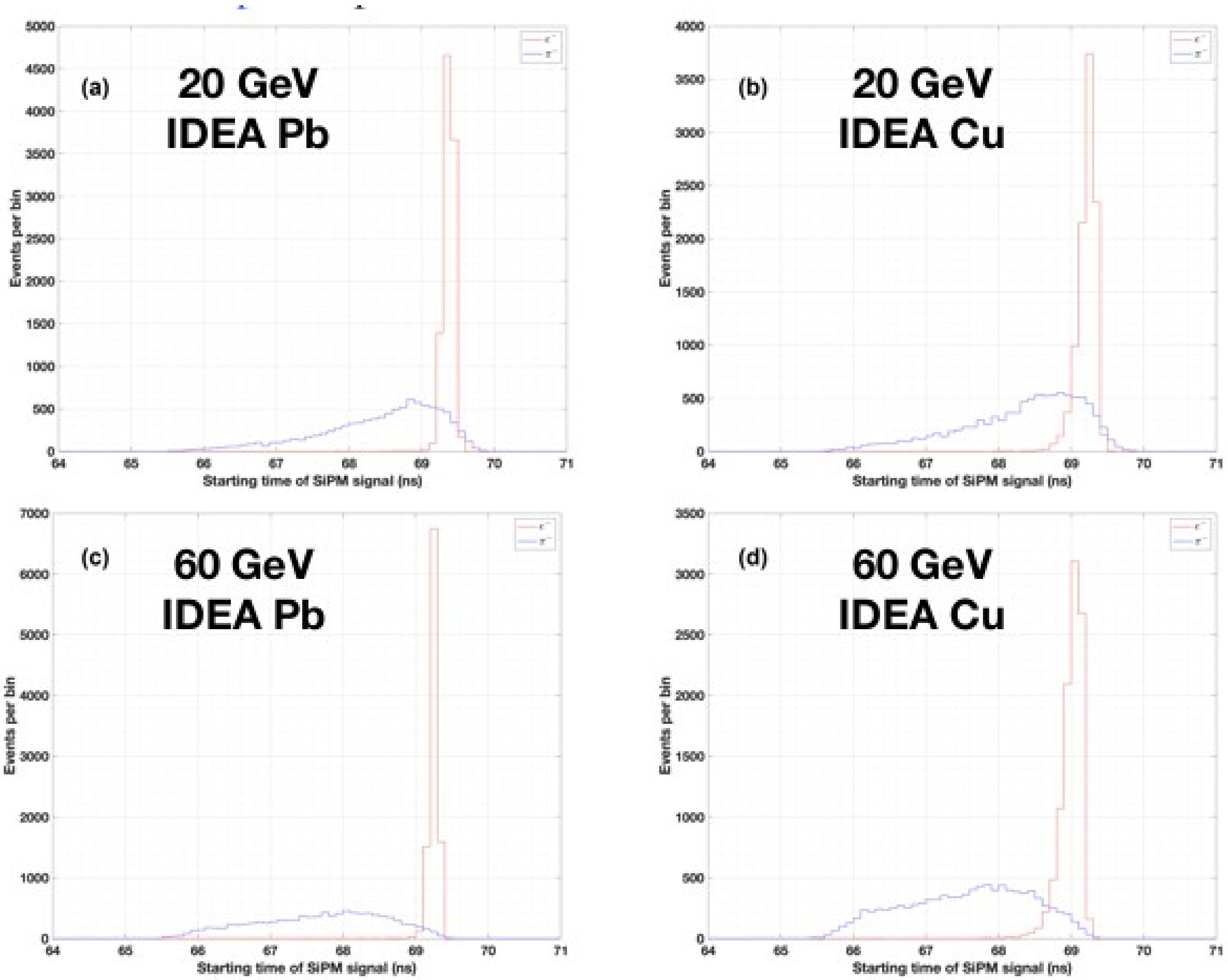
particle identification: 95% radius

Electron - pion separation

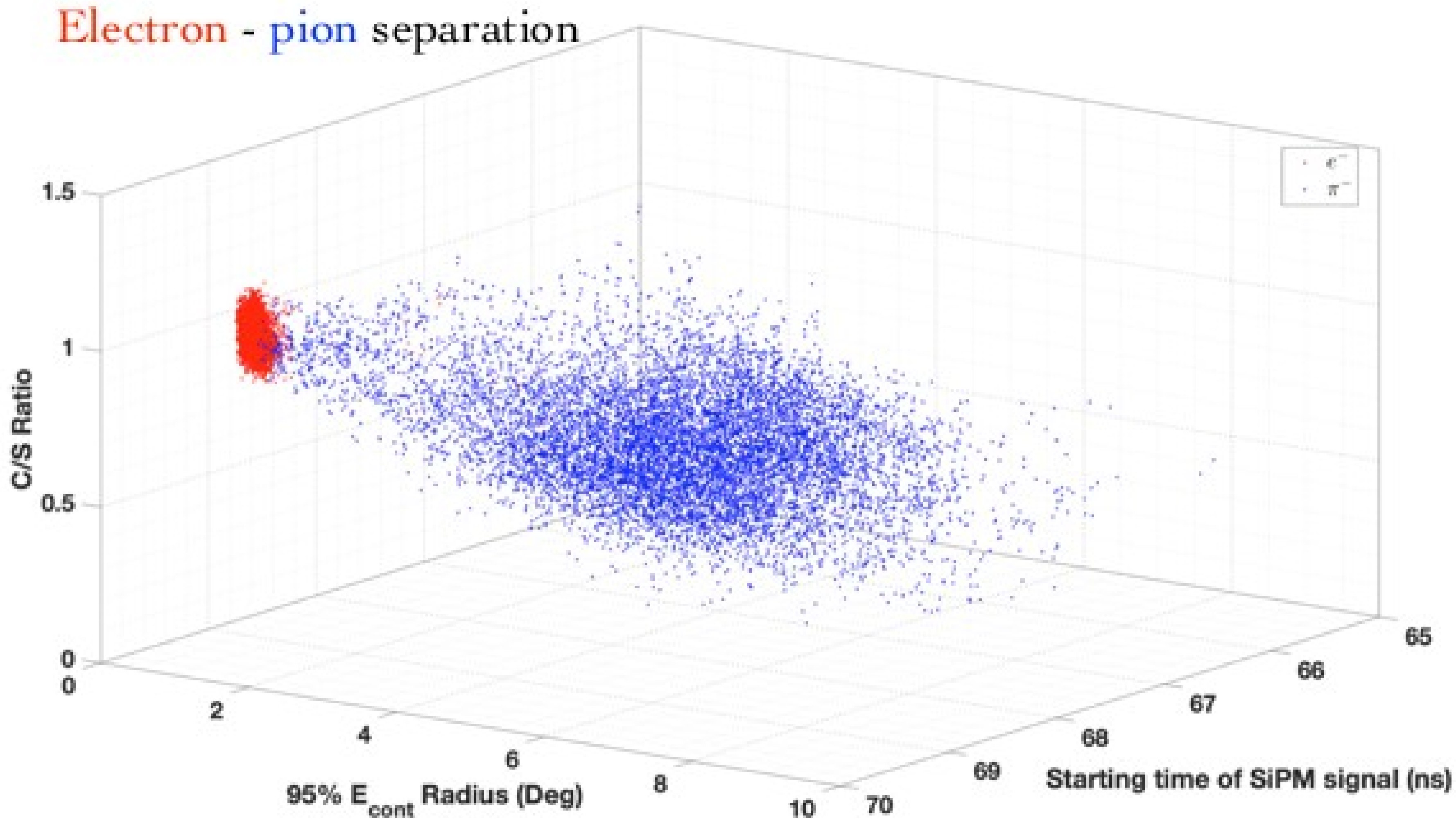


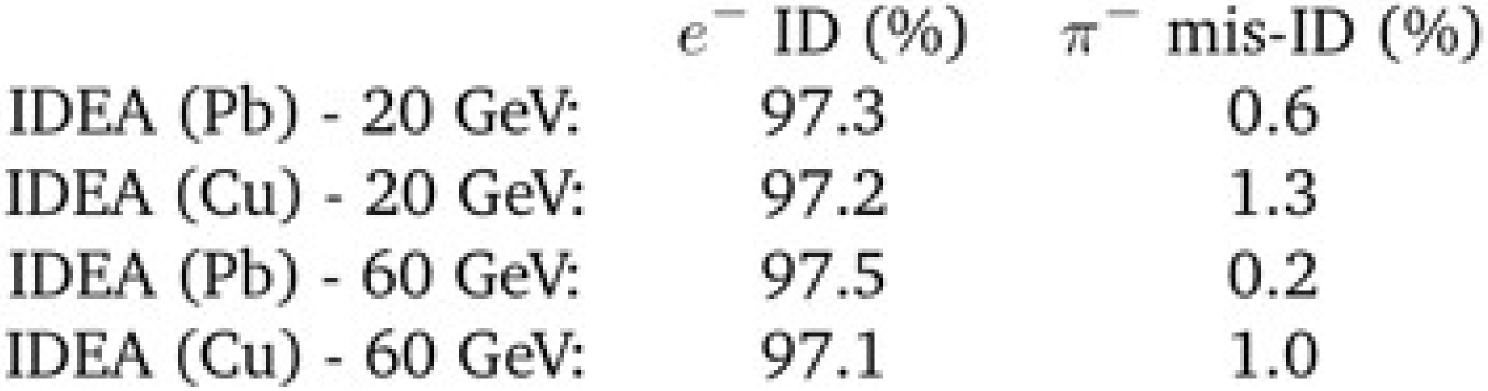
particle identification: SiPM ToA

Electron - pion separation



combined results





	e^- ID (%)	π^- mis-ID (%)
IDEA (Pb) - 20 GeV:	97.3	0.6
IDEA (Cu) - 20 GeV:	97.2	1.3
IDEA (Pb) - 60 GeV:	97.5	0.2
IDEA (Cu) - 60 GeV:	97.1	1.0

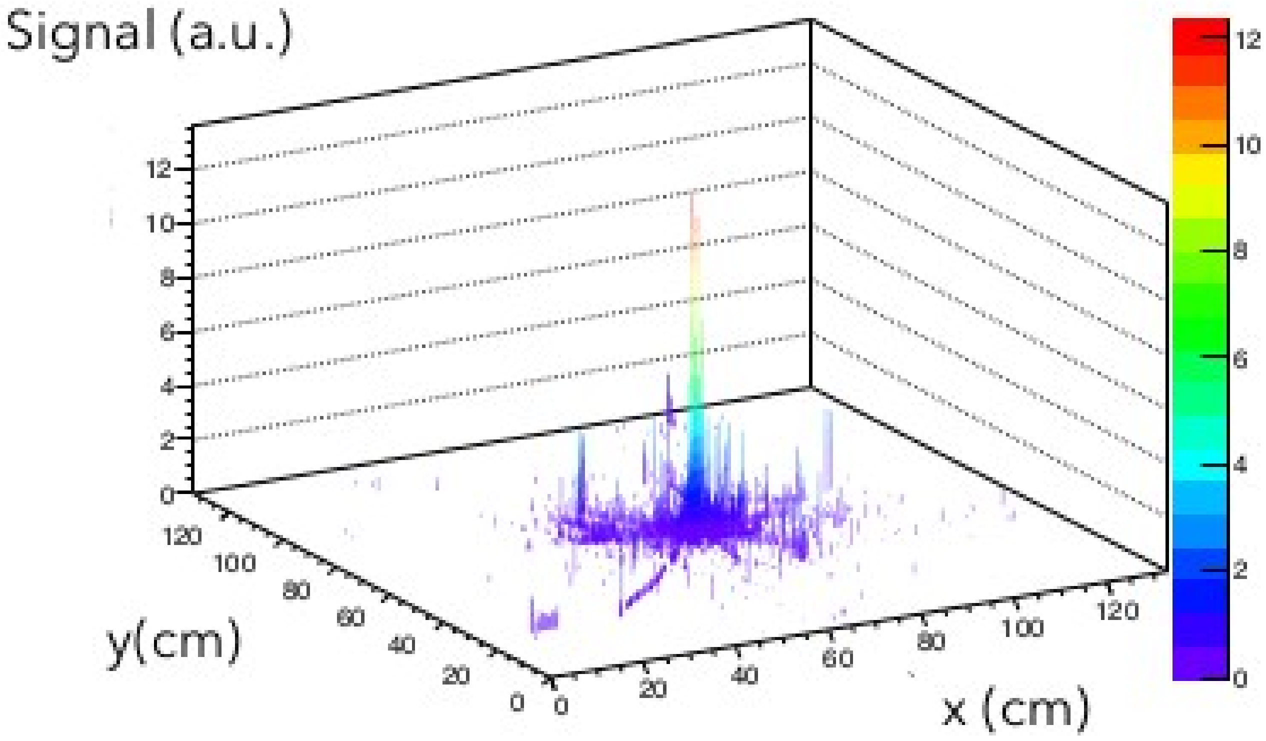
G4 full simulations
The Ultimate Weapon

deep learning applied to particle id

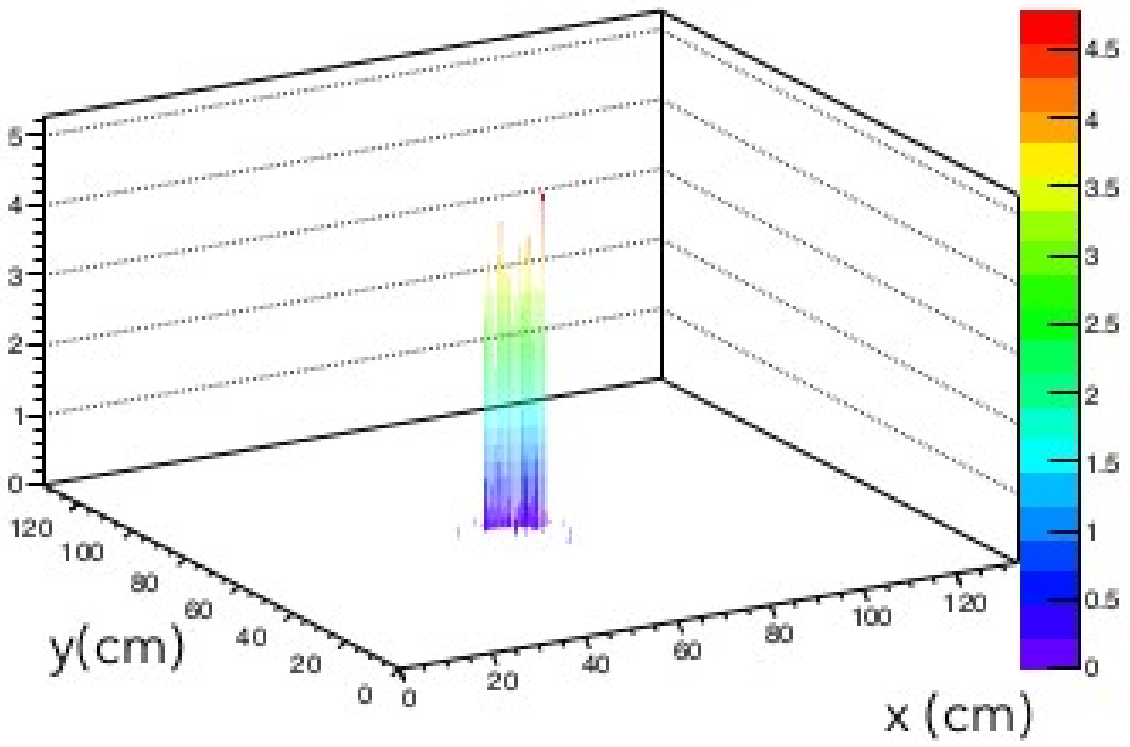
produced 6 samples of τ-decay final states with time information & SiPM transfer function

0	pi0 pi- nu_tau
1	e- anti_nu_e nu_tau
2	mu- anti_nu_mu nu_tau
3	pi- nu_tau
4	pi- pi- pi+ nu_tau
5	pi0 pi0 pi- nu_tau

$\tau^- \rightarrow \pi^- \nu_\tau$



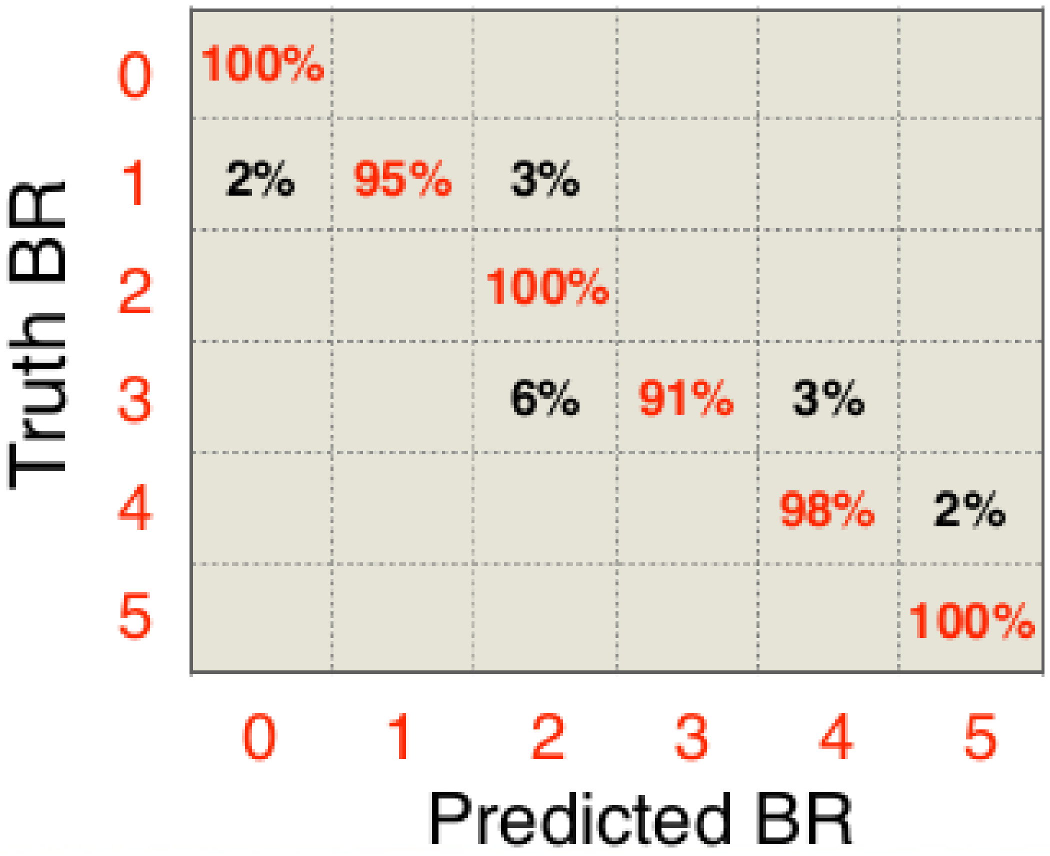
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$



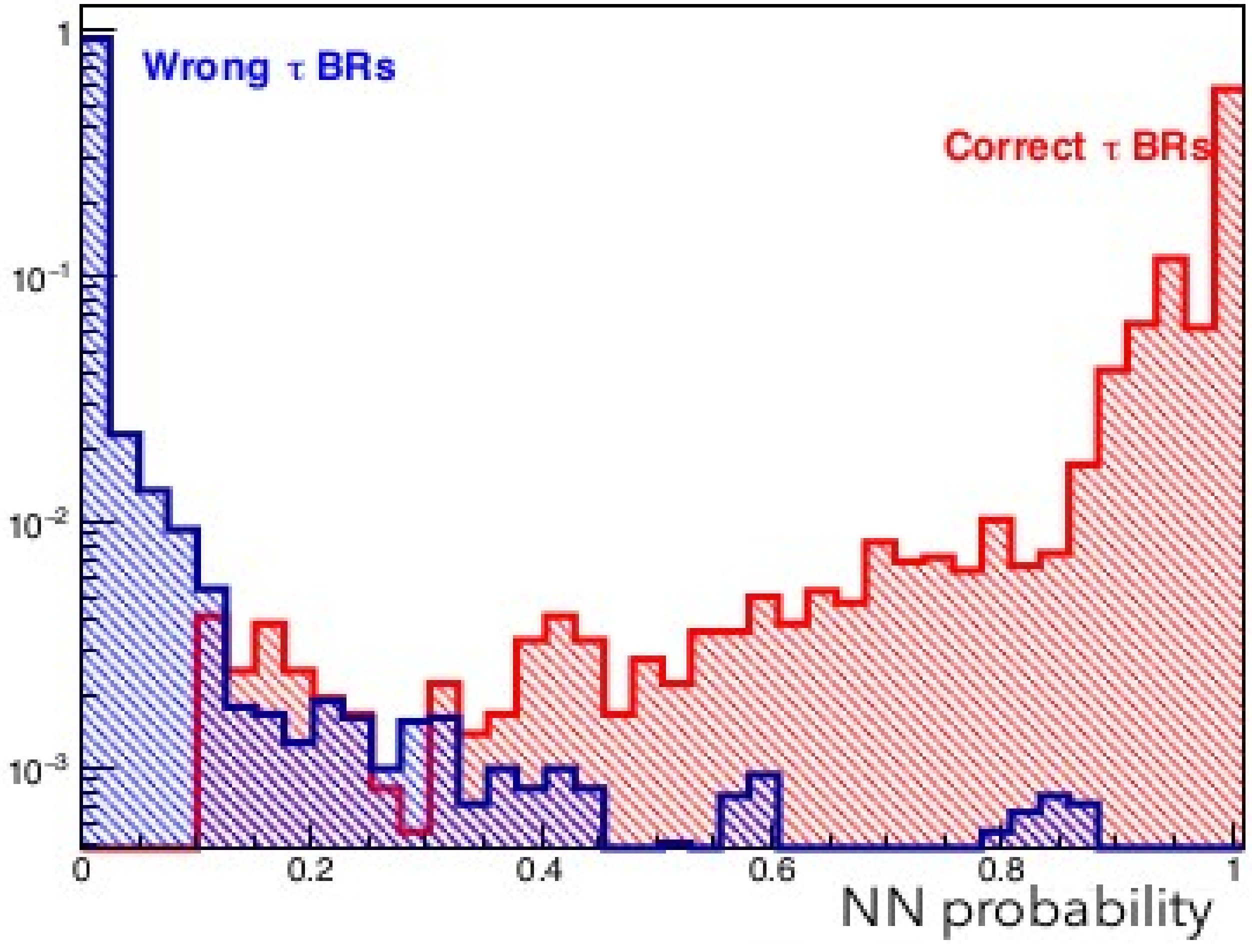
convolutional neural network results

- Signals from fibers in each 1.2×1.2 cm^2 module integrated to obtain 111×111 matrix
- 5 information: signal integral, signal height, peak position, time of crossing threshold, ToT
- Independently for scintillation and Cherenkov signals
- Each event → 111×111×10 tensor

- Average accuracy ~ 97.3%



Truth BR \ Predicted BR	0	1	2	3	4	5
0	100%					
1	2%	95%	3%			
2			100%			
3			6%	91%	3%	
4					98%	2%
5						100%



Conclusions

Dual-readout fibre-sampling calorimetry is a very promising technology to provide, at the same time:

- e.m. resolution of about 10%/√E
- jet energy resolution ~ few % at ~100 GeV
- excellent angular resolution
- high performance in particle identification

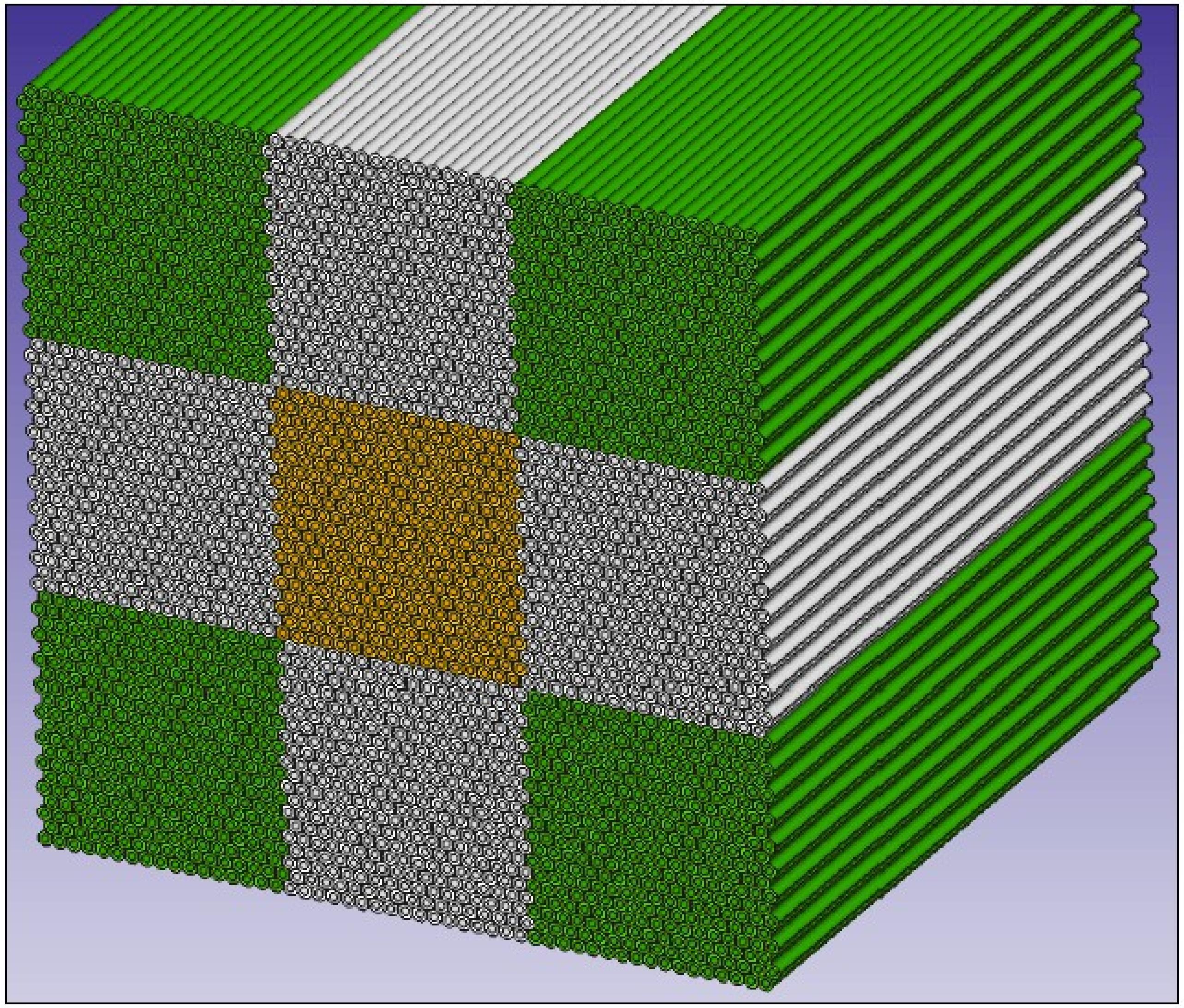
R&D ongoing to demonstrate it → Geant4 validation is an issue!

Next steps:

build a 10 cm x10 cm x 1 m prototype divided into 9 towers
16x20 capillary tubes per tower
readout of central tower with SiPMs, the others with PMTs

Conclusions

Dual-readout fibre-sampling calorimetry is a very promising technology t



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