INFN
Istituto Nazionale
di Fisica Nucleare

Dual-Readout Calorimetry @ HL e^+e^- Colliders

Roberto Ferrari
on behalf of the INFN RD_FA collaboration

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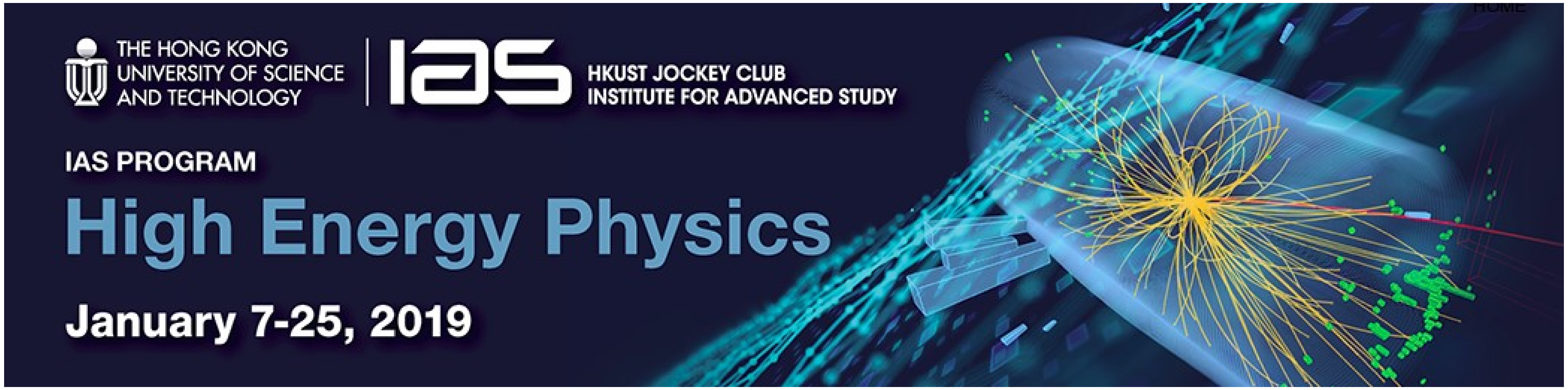


strategy (disclaimer)

- do not enter into details of dual-readout calorimetry

- target dual-readout fibre-sampling implementations

- briefly recap main old results

- stress on new results and open issues

recap (about 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:

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

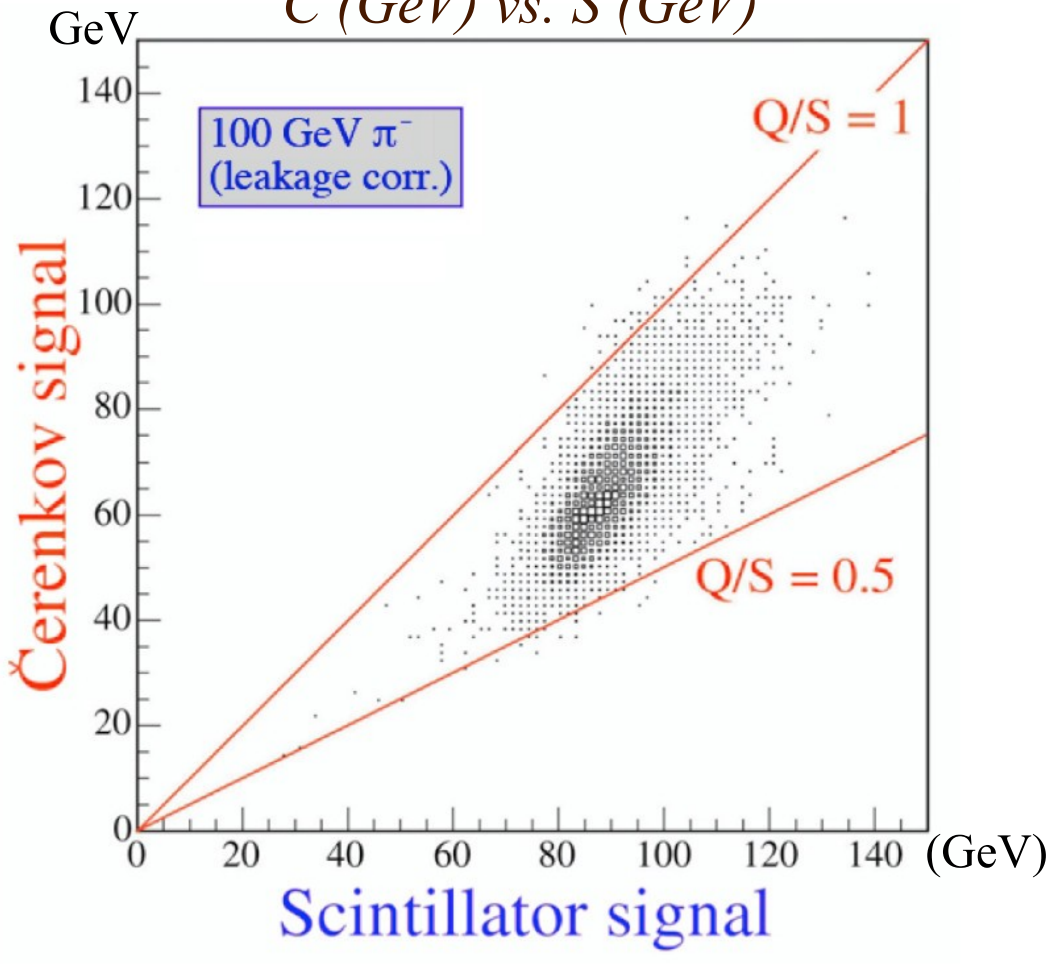
where:

$$\boxed{\begin{aligned} \chi &= (1 - (h/e)_S) \ / \ (1 - (h/e)_C) \\ &= (E - S) / (E - C) \end{aligned}}$$

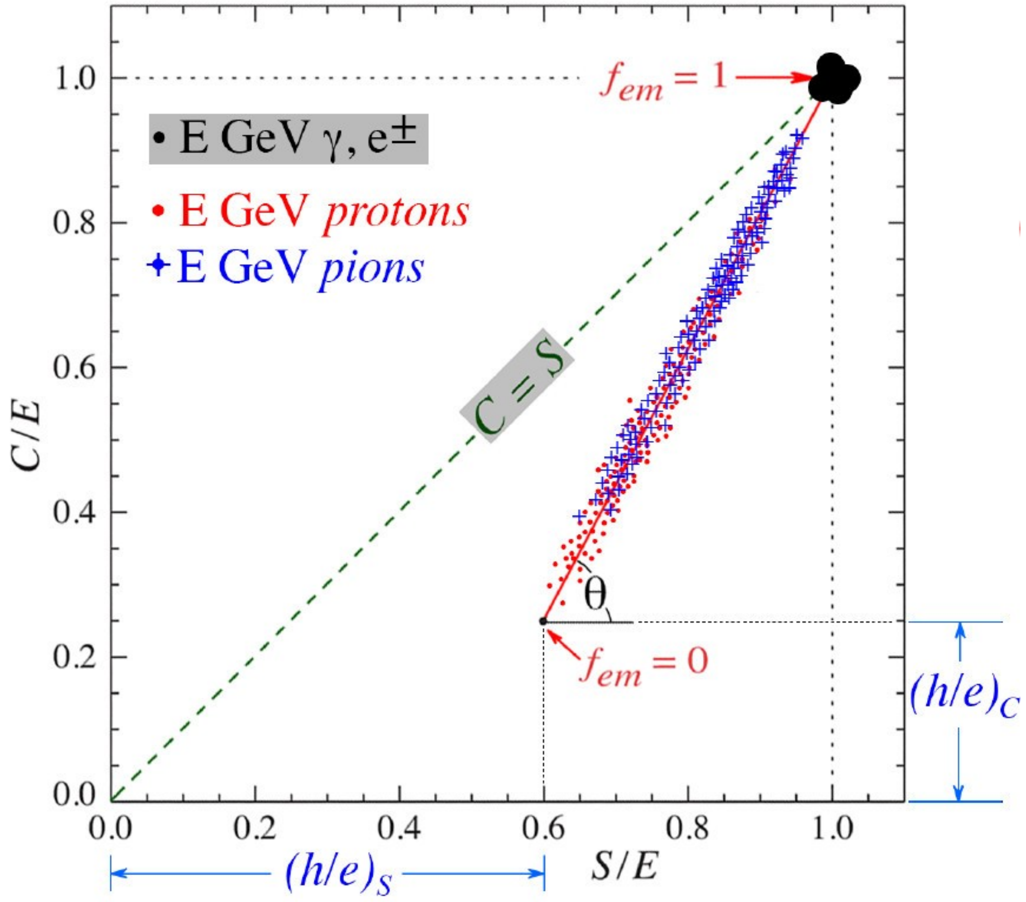
→ ***χ can be extracted from testbeam data***

The Alchemy

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:

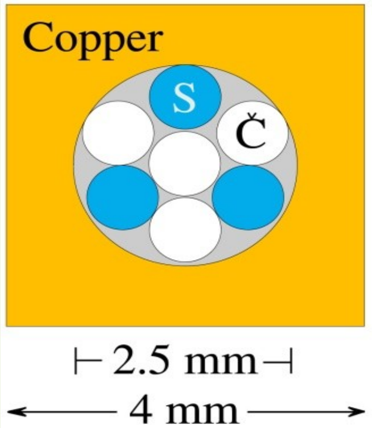
i) energy (!)

ii) type of hadron (!!)

fibre-sampling dual-readout calorimeters

2003
DREAM

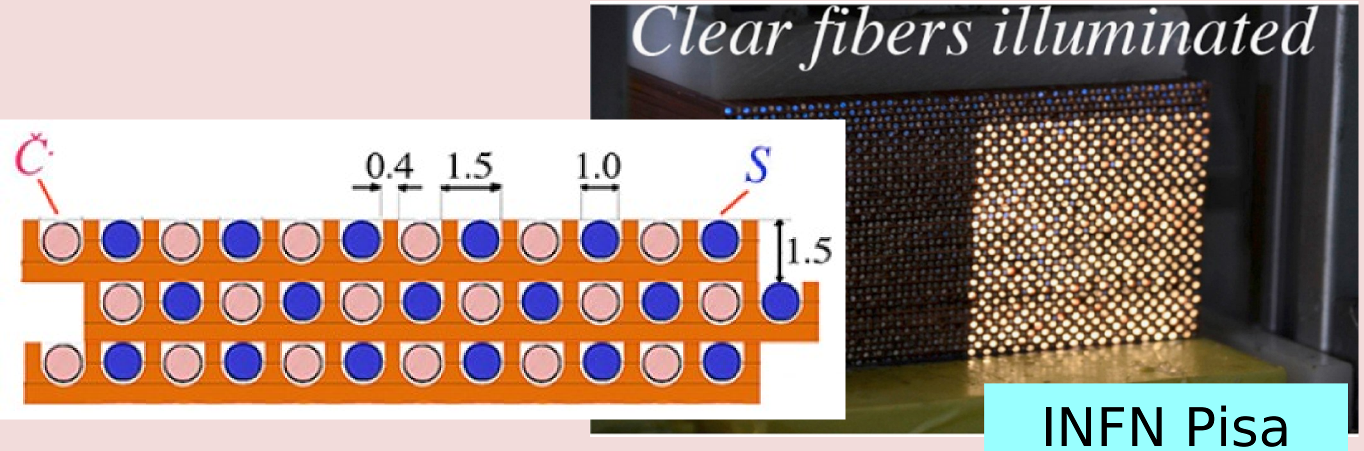
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%



Texas Tech Uni

2012
RD52

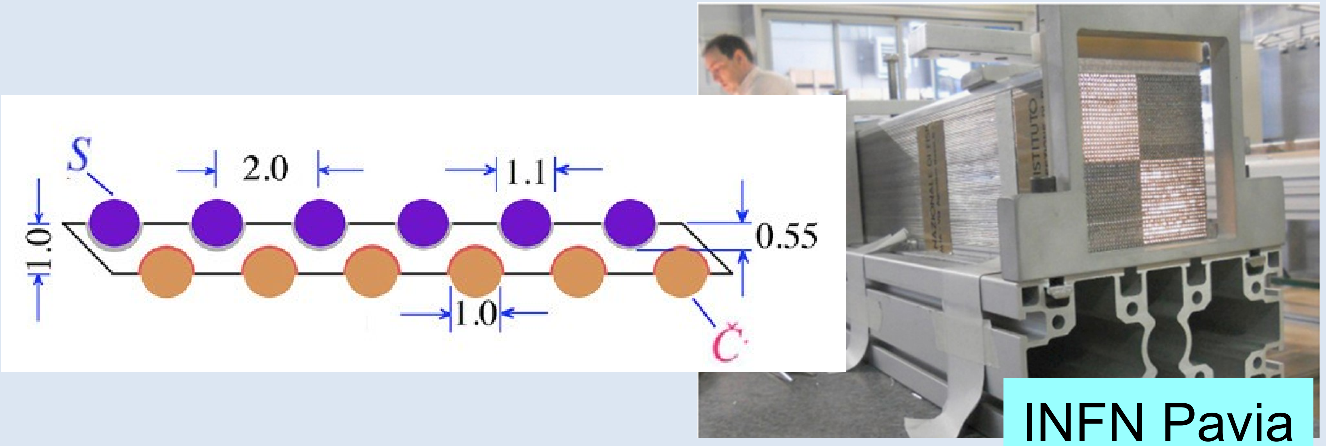
Cu, 2 modules → 8 towers
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

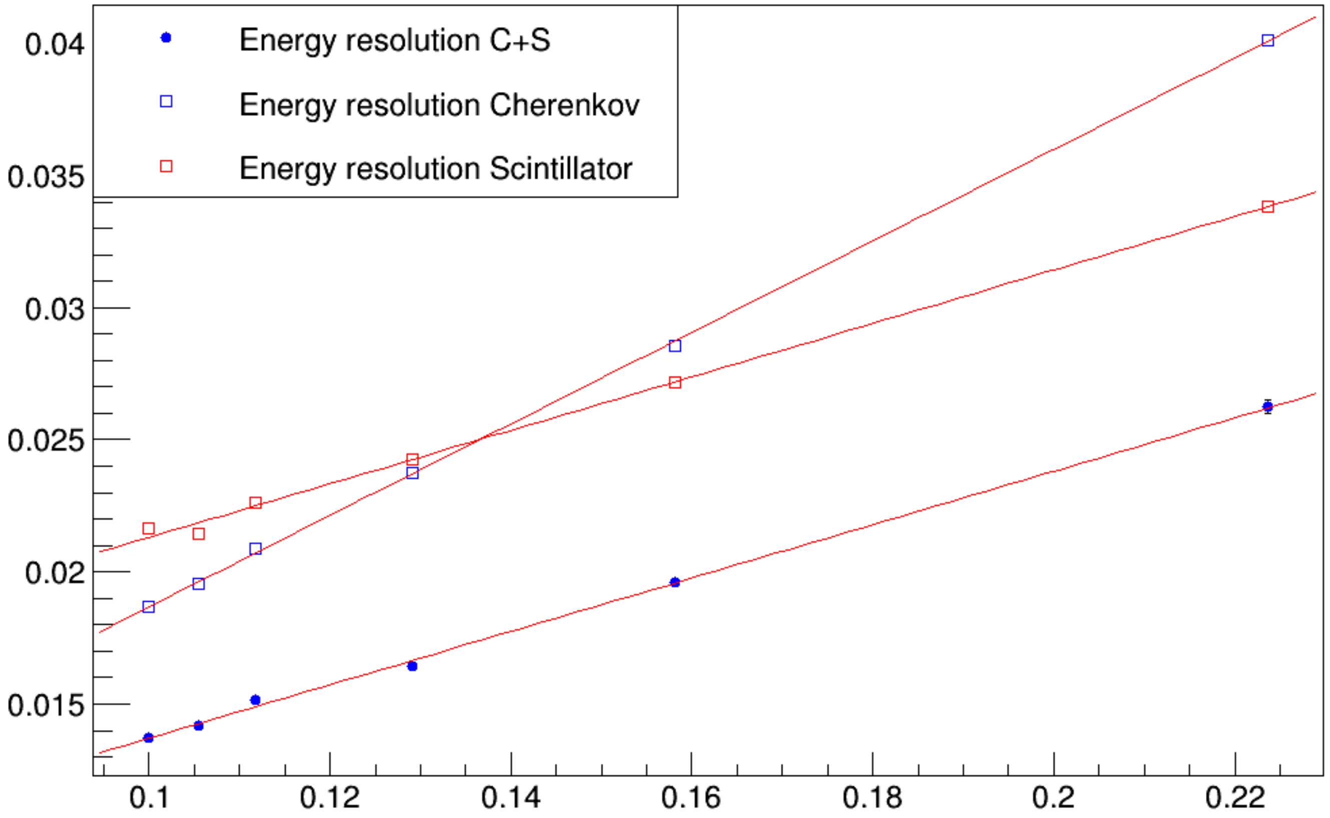
2012
RD52

Pb, 9 modules → 36 towers
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

em resolution (Geant4)



S-only: 10.5/√E+1.1 (%)

C-only: 17.9/√E (%)

(unweighted) average: 10.3/√E+0.3 (%)

(isolated) particle ID

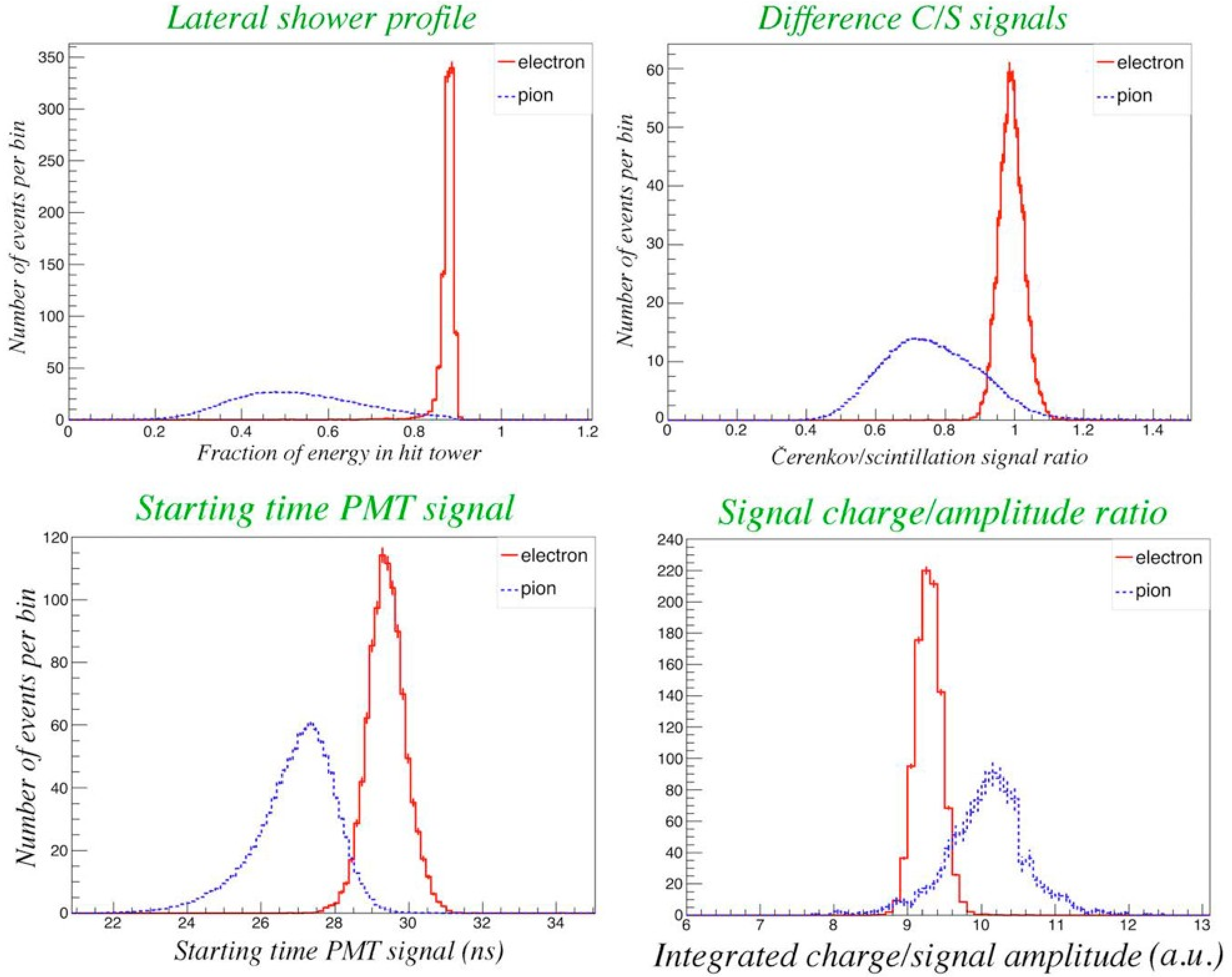
for single particles
look easy

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

Methods to distinguish e/π in longitudinally unsegmented calorimeter



Lateral shower profile — *Difference C/S signals* — *Starting time PMT signal* — *Signal charge/amplitude ratio*

Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

SiPM vs. PMT 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, ...)

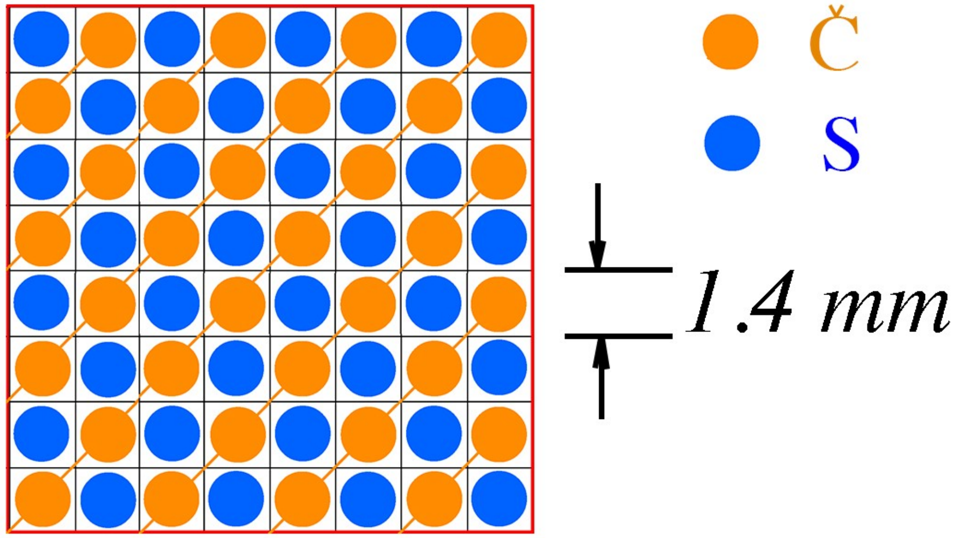
RD52 SiPM module

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

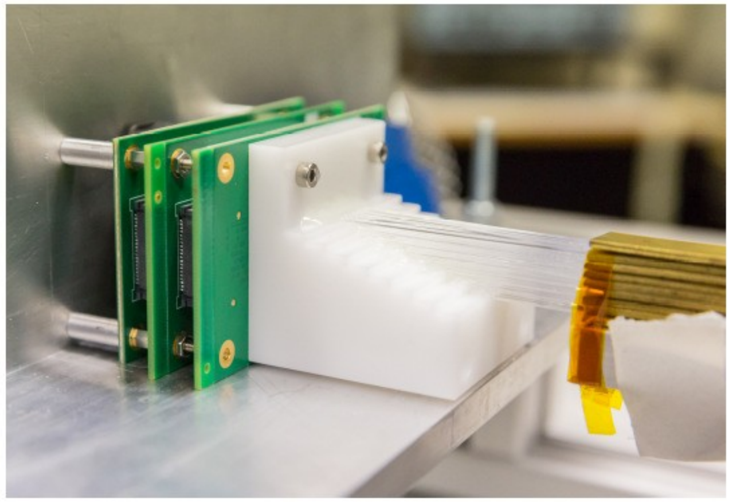
32 (S) + 32 (Č) fibres
$X_0 \sim 29$ *mm*
$R_M \sim 31$ *mm*

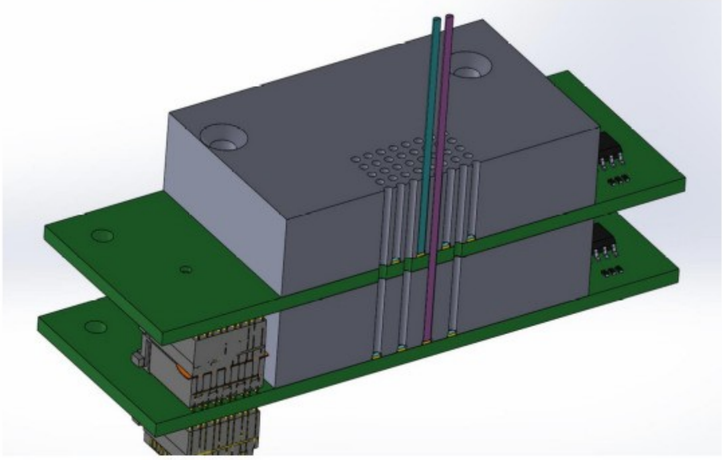
$\sim (0.4\ R_M)^2 \times 39\ X_0$

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



Light sensors (SiPM)

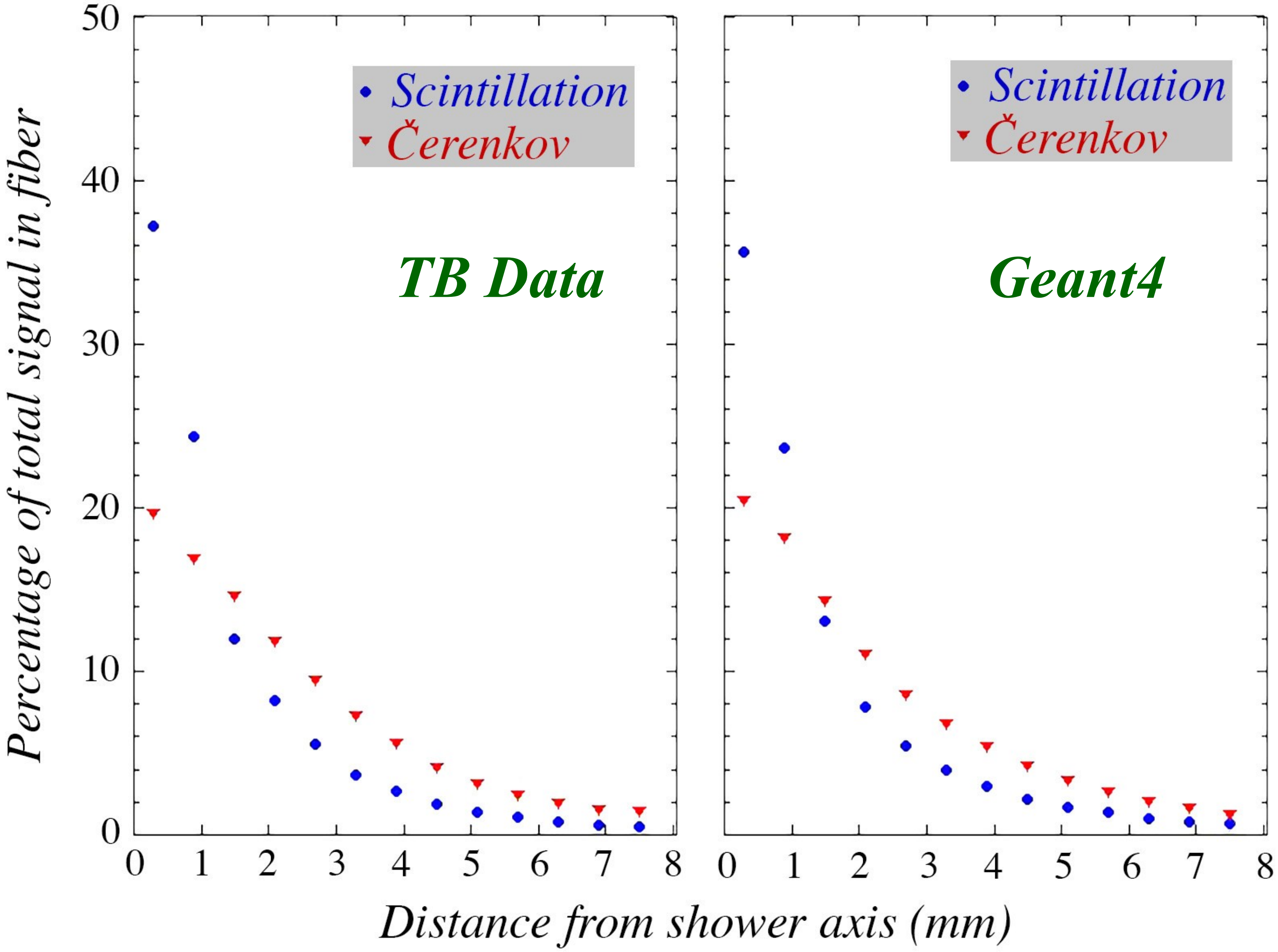




lateral shower profile w/ SiPM

10 / 40 GeV e^-

θ, Φ = 0°

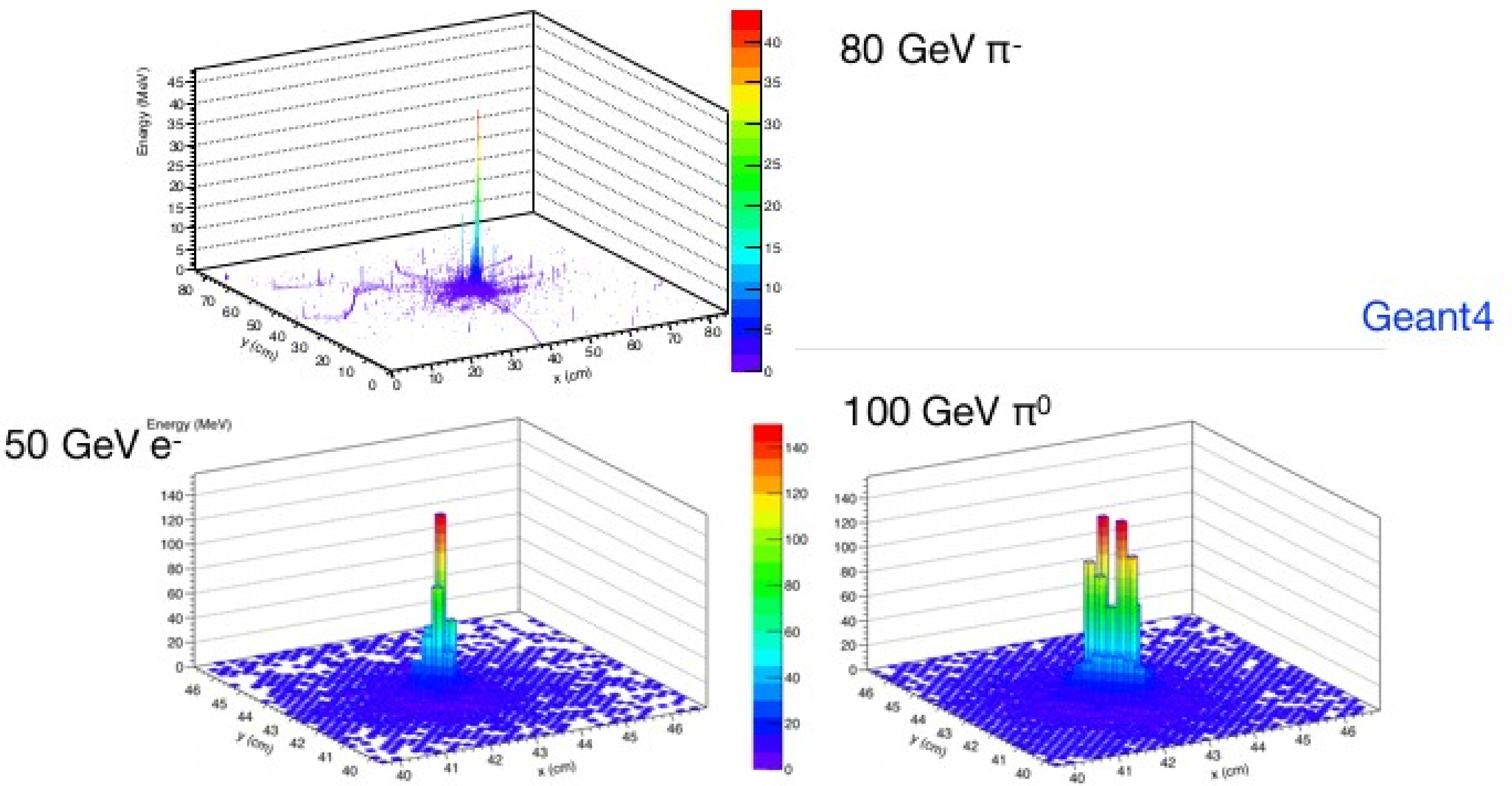


em shower are very narrow:

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

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

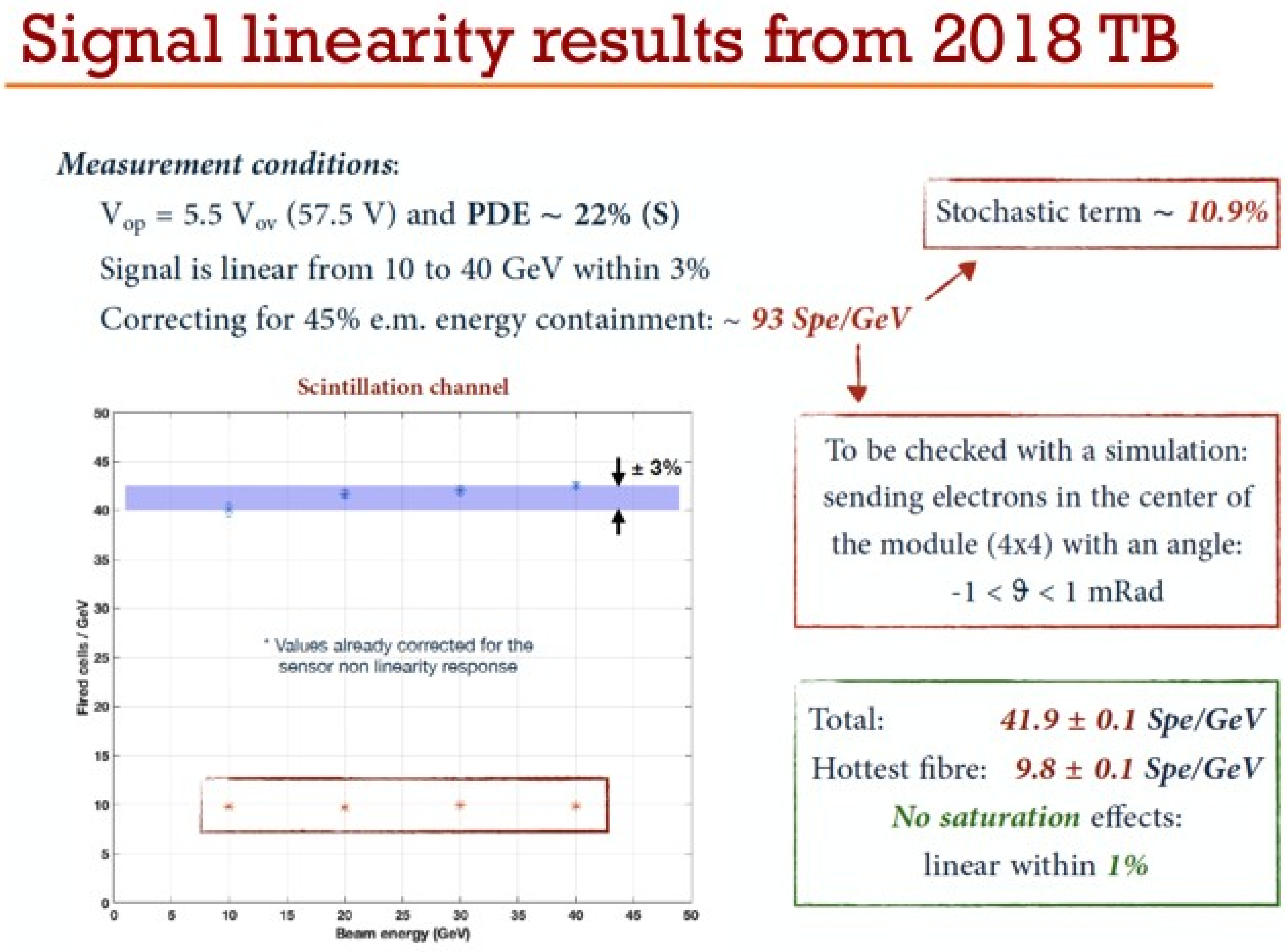
2D SiPM imaging



Geant4 single-particle simulations

SiPM response linearity

w/ scintillation light filtering:



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%***

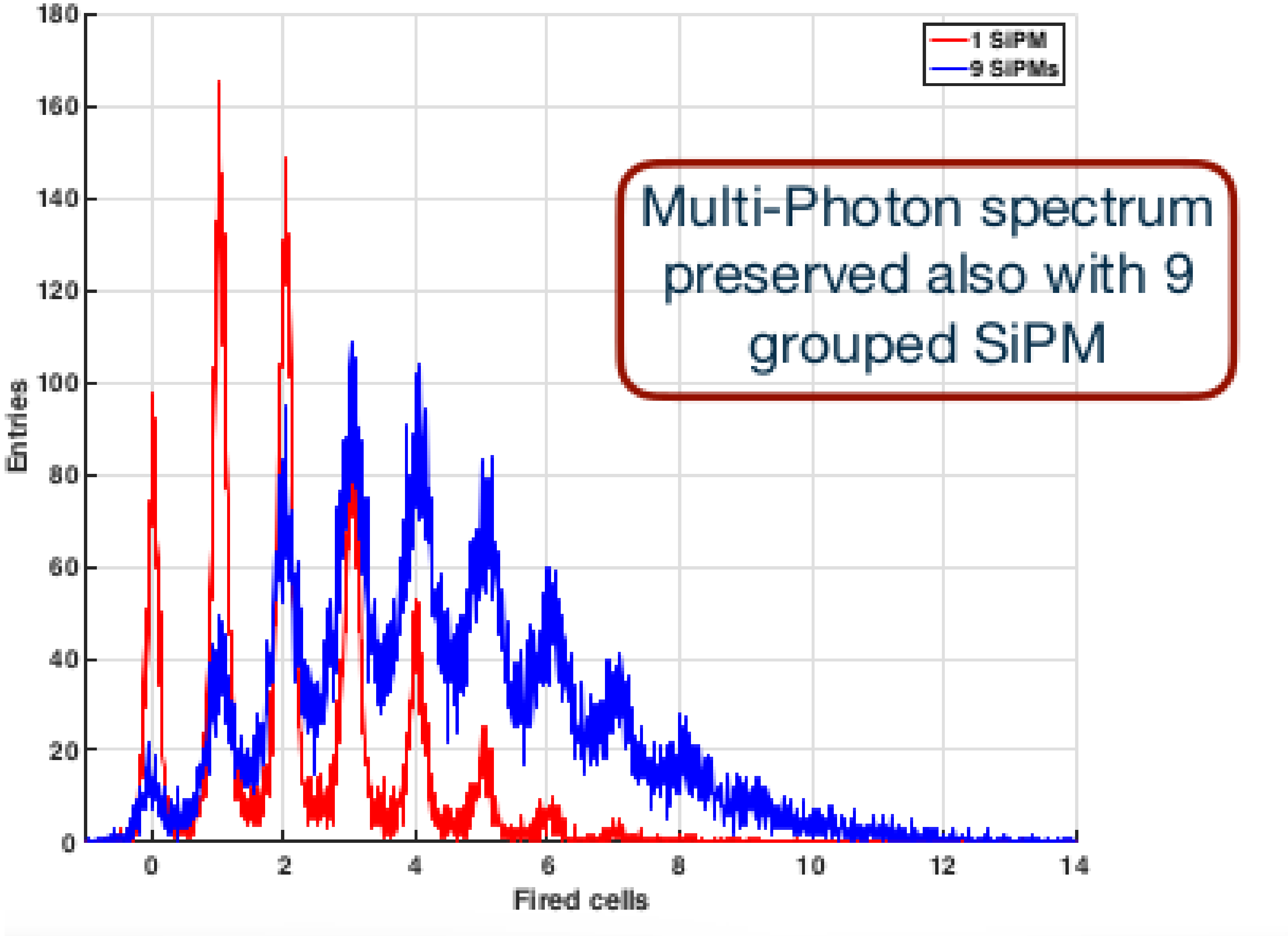
attenuation factor ~ 77
(yellow filter)

yellow filter → increase attenuation length

SiPM readout granularity (channel grouping)

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

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



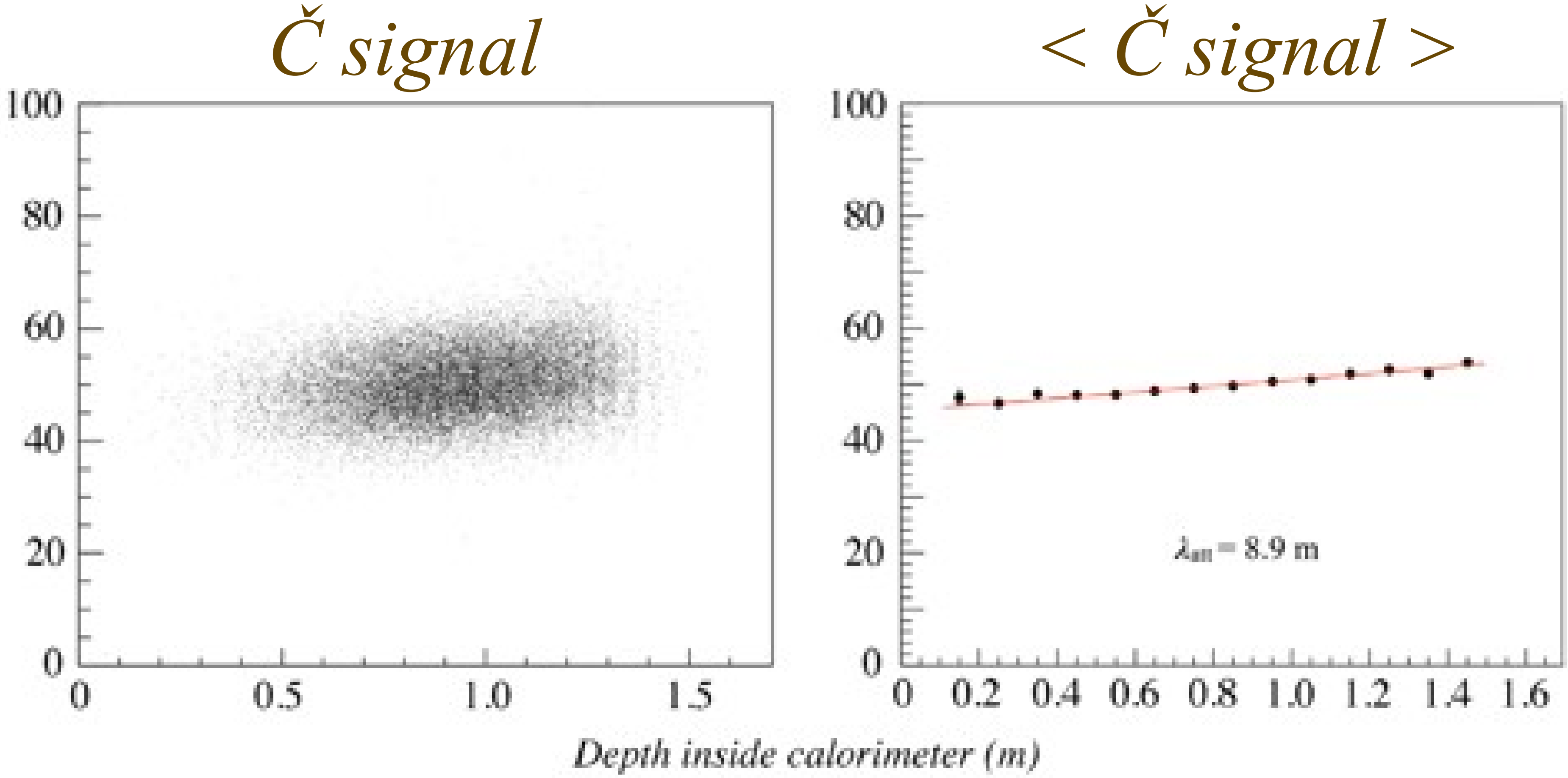
Multi-Photon spectrum preserved also with 9 grouped SiPM

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

… about attenuation length

Two remarks:

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



… more controversial issues

A non exhaustive list:

1) absorber
2) longitudinal segmentation
3) alternative approaches (i.e. tiles vs. fibres)
4) front-end electronics (ASIC)
5) feature extraction
6) machine learning for jets

Absorber Choice

absorber : active volume = 62 : 38

	Iron	Brass (Cu260)	Lead
ρ (gr/cm^3)	5.31	5.71	7.46
λ_N (cm)	23.7	23.3	24.7
χ_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:

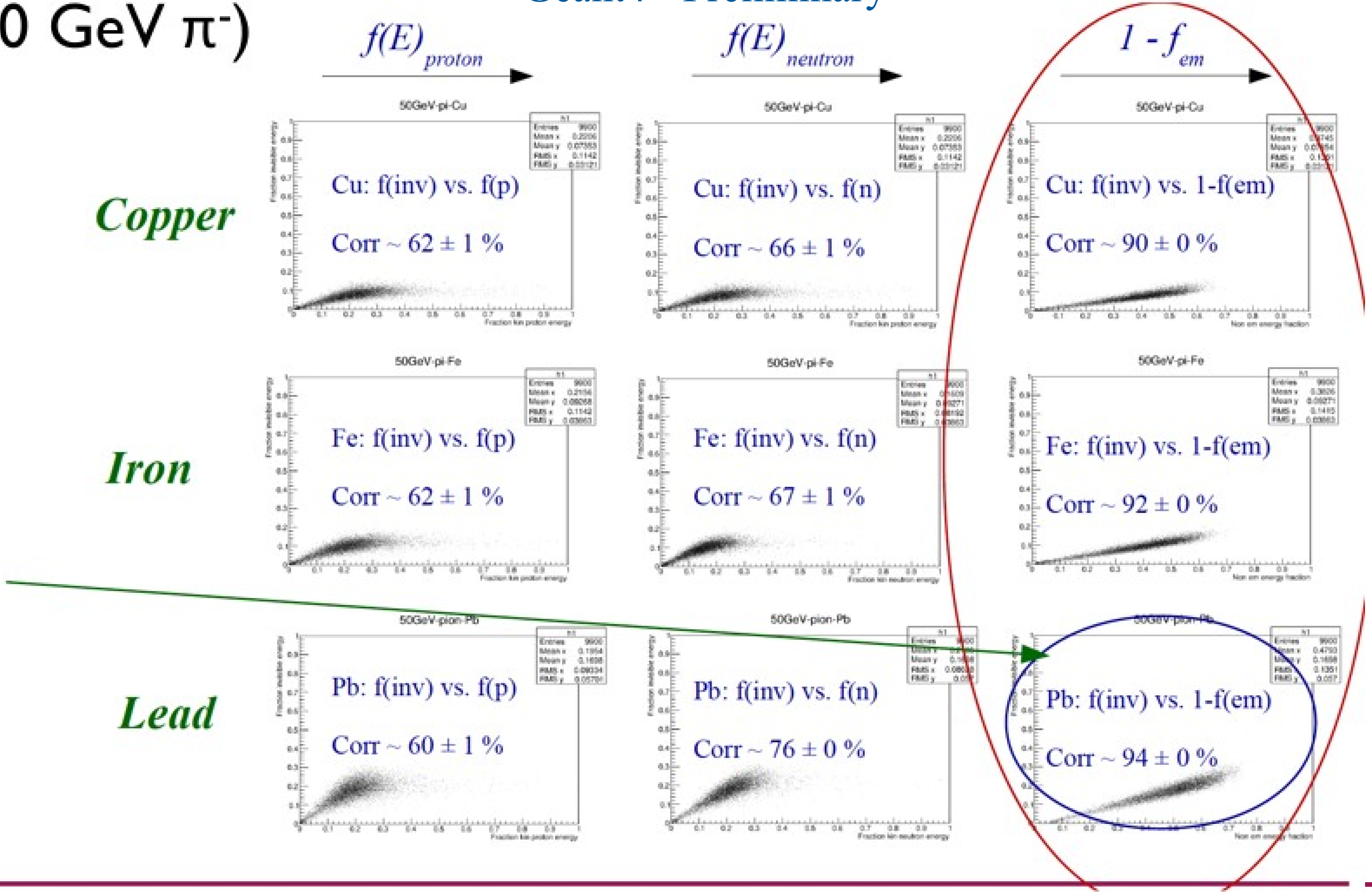
(-) ~ 60% more mass

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

Invisible Energy - Correlations

Geant4 - Preliminary

(50 GeV π^-)



Copper

Cu: f(inv) vs. f(p)

Corr ~ 62 ± 1 %

Cu: f(inv) vs. f(n)

Corr ~ 66 ± 1 %

Cu: f(inv) vs. 1-f(em)

Corr ~ 90 ± 0 %

Iron

Fe: f(inv) vs. f(p)

Corr ~ 62 ± 1 %

Fe: f(inv) vs. f(n)

Corr ~ 67 ± 1 %

Fe: f(inv) vs. 1-f(em)

Corr ~ 92 ± 0 %

Lead

Pb: f(inv) vs. f(p)

Corr ~ 60 ± 1 %

Pb: f(inv) vs. f(n)

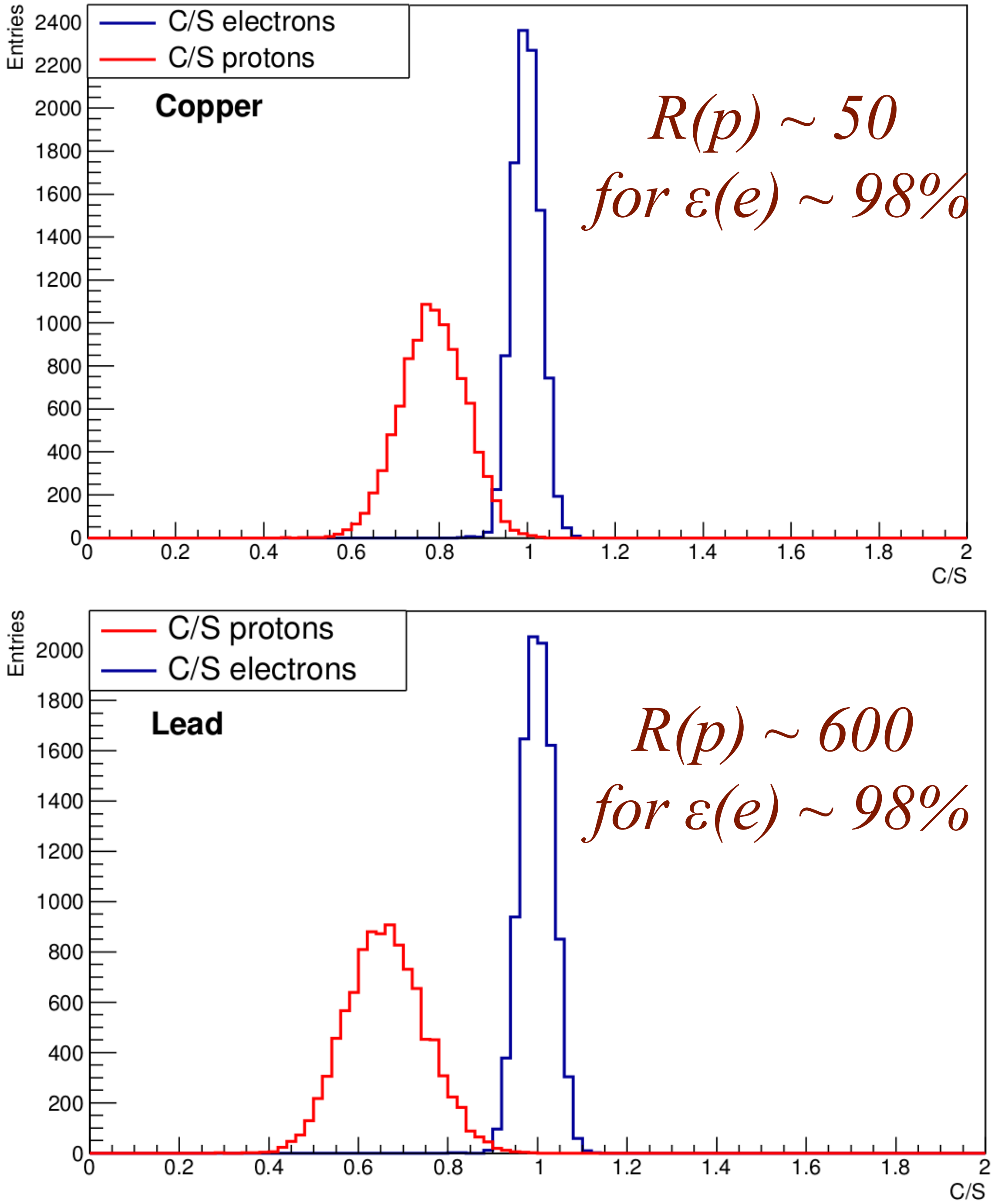
Corr ~ 76 ± 0 %

Pb: f(inv) vs. 1-f(em)

Corr ~ 94 ± 0 %

Particle Id & W/Z – Cu vs. Pb (Geant4)

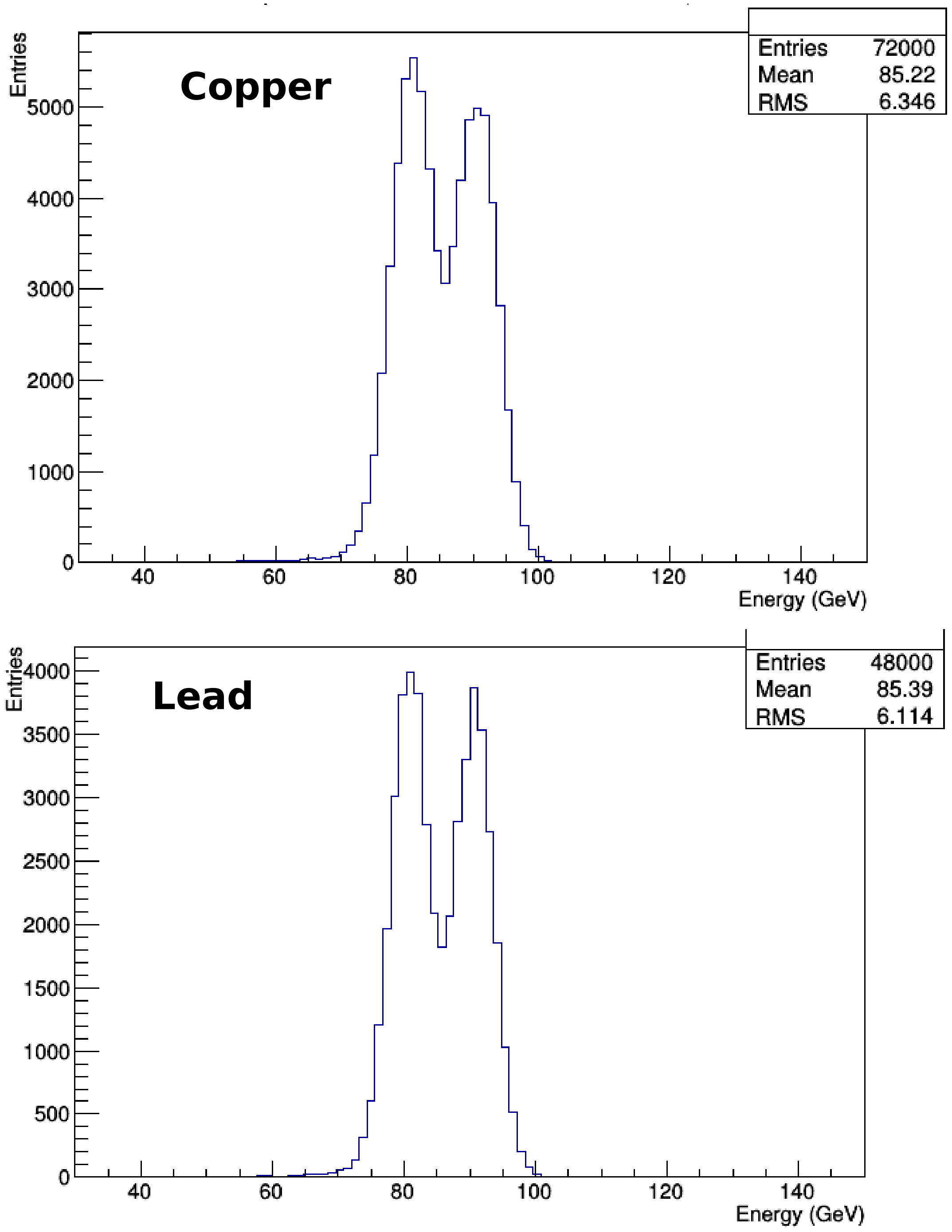
C/S ratio for 80 GeV e⁻ and p



R(p) ~ 50
for ε(e) ~ 98%

R(p) ~ 600
for ε(e) ~ 98%

Multiple hadrons, 81 & 91 GeV



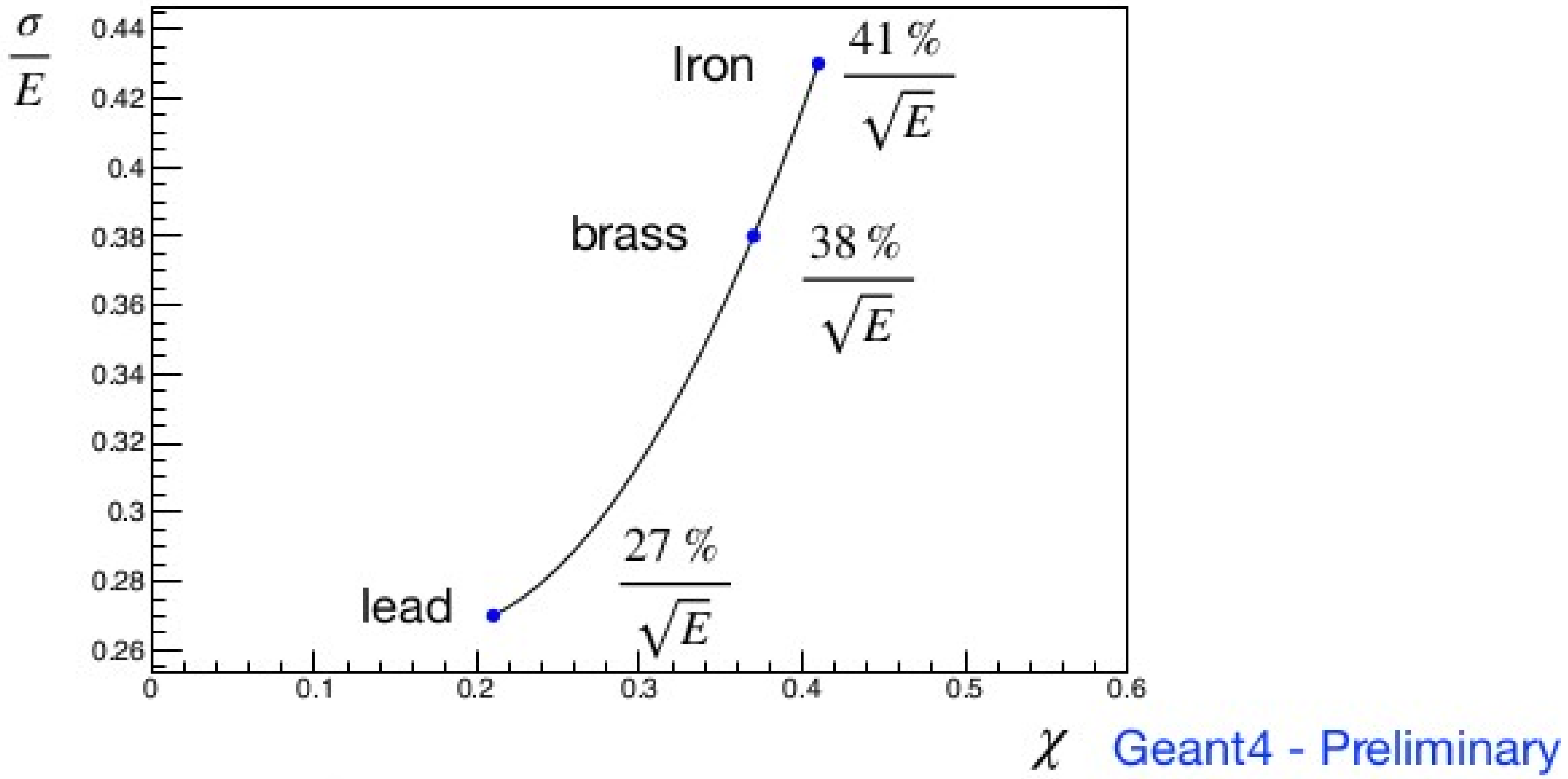
Impact on Performance

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



Geant4 - Preliminary

χ : the lower the better ...

em performance ~ almost unaffected
(dominated by sampling fluctuations)

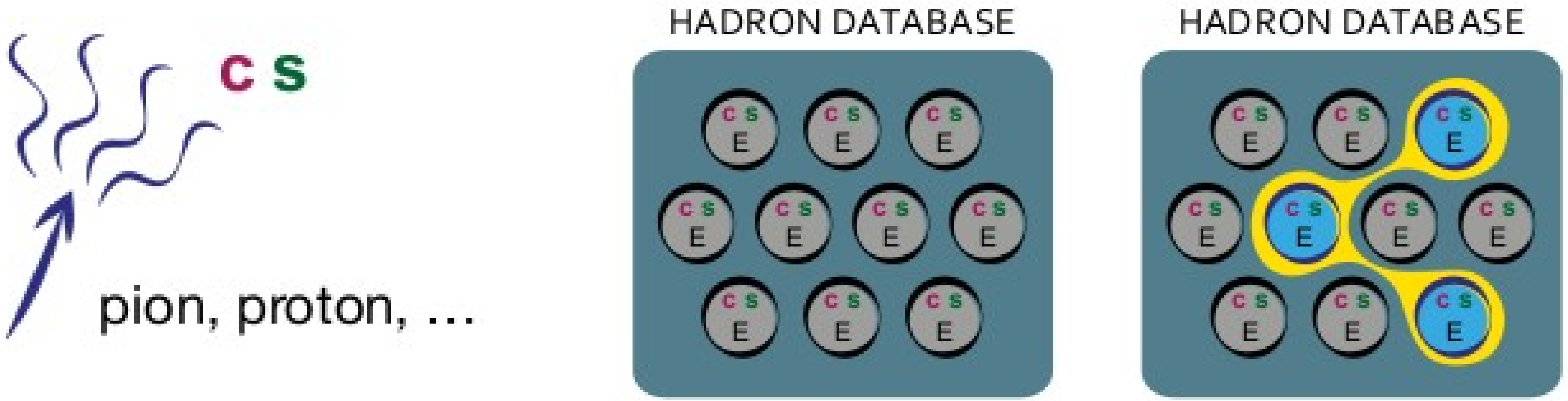
take care: ideal, perfect, Geant4 detector

… 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



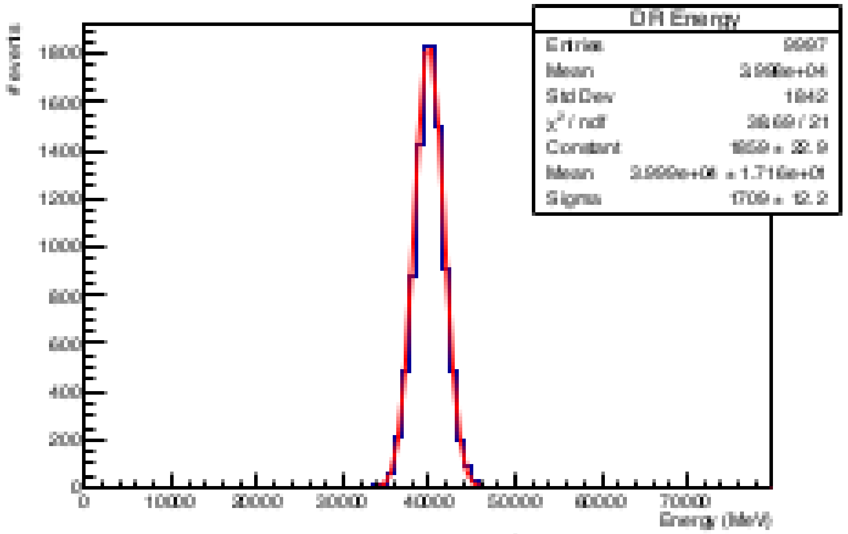
Reconstruct energy with:

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

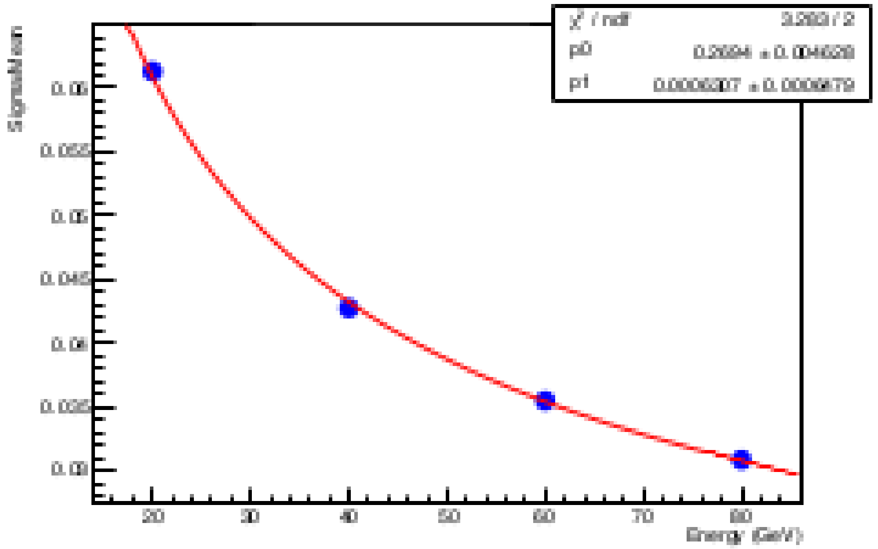
DR vs. ML

Lead

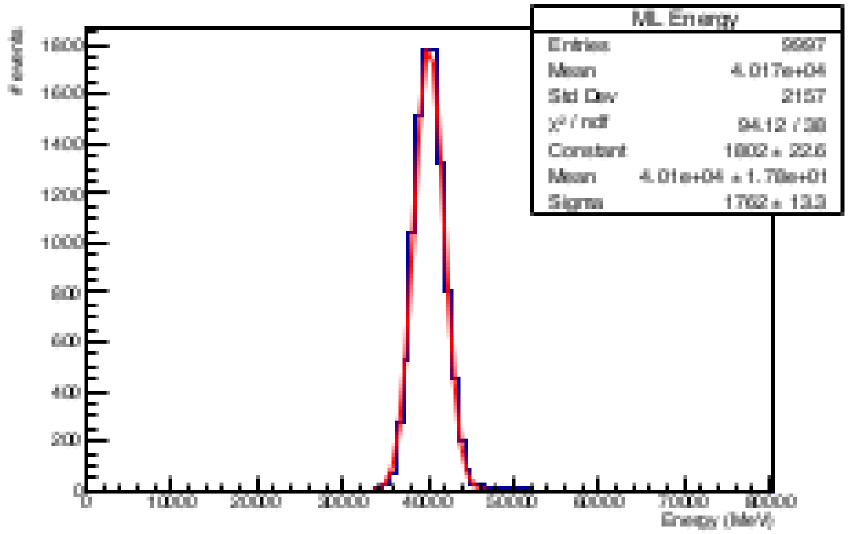
DR



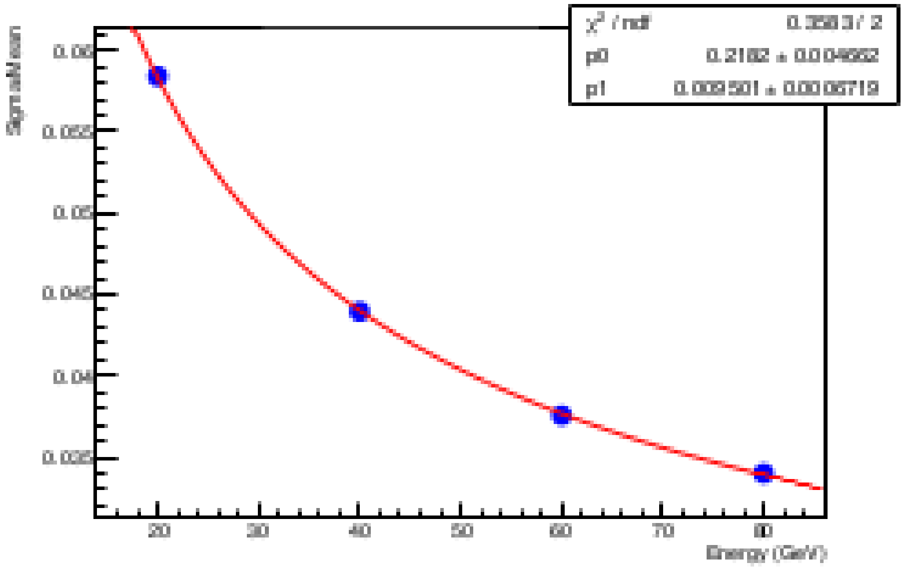
$$\frac{\sigma}{E} = \frac{27\,\%}{\sqrt{E}}$$



ML



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



Geant4 - Preliminary

ML performance

Hadronic resolution:

Geant4 – Very Very Preliminary

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

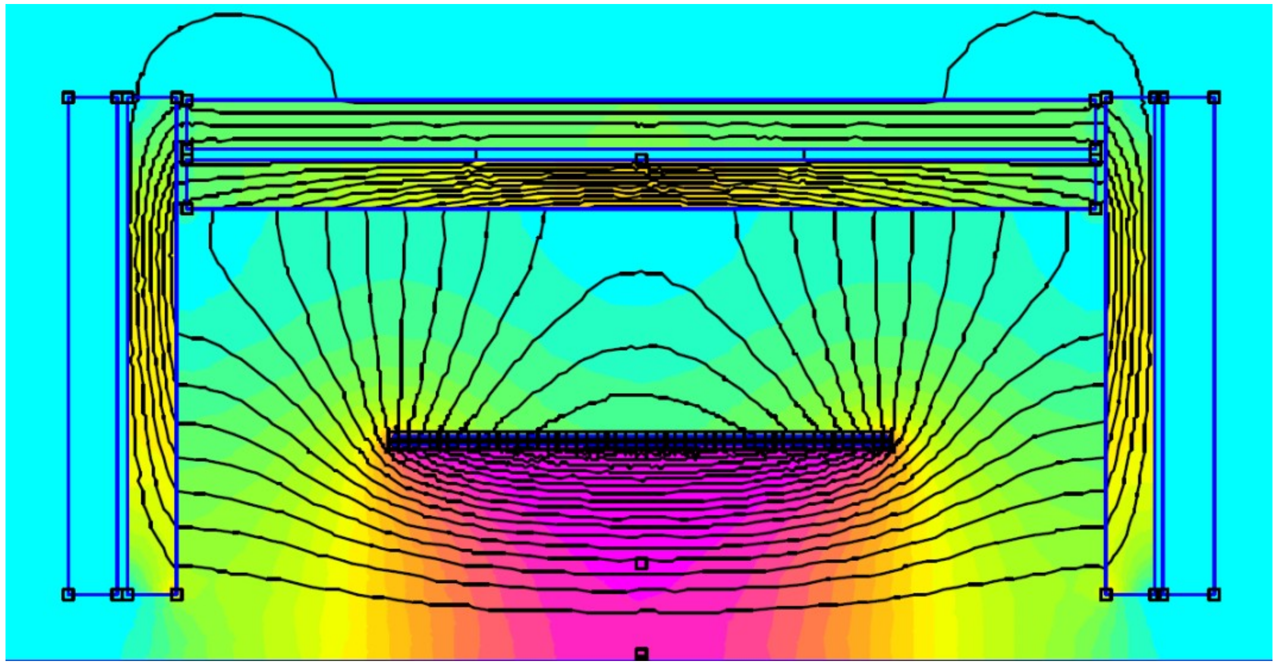
→ almost independent of absorber material

→ do NOT take too seriously absolute values !

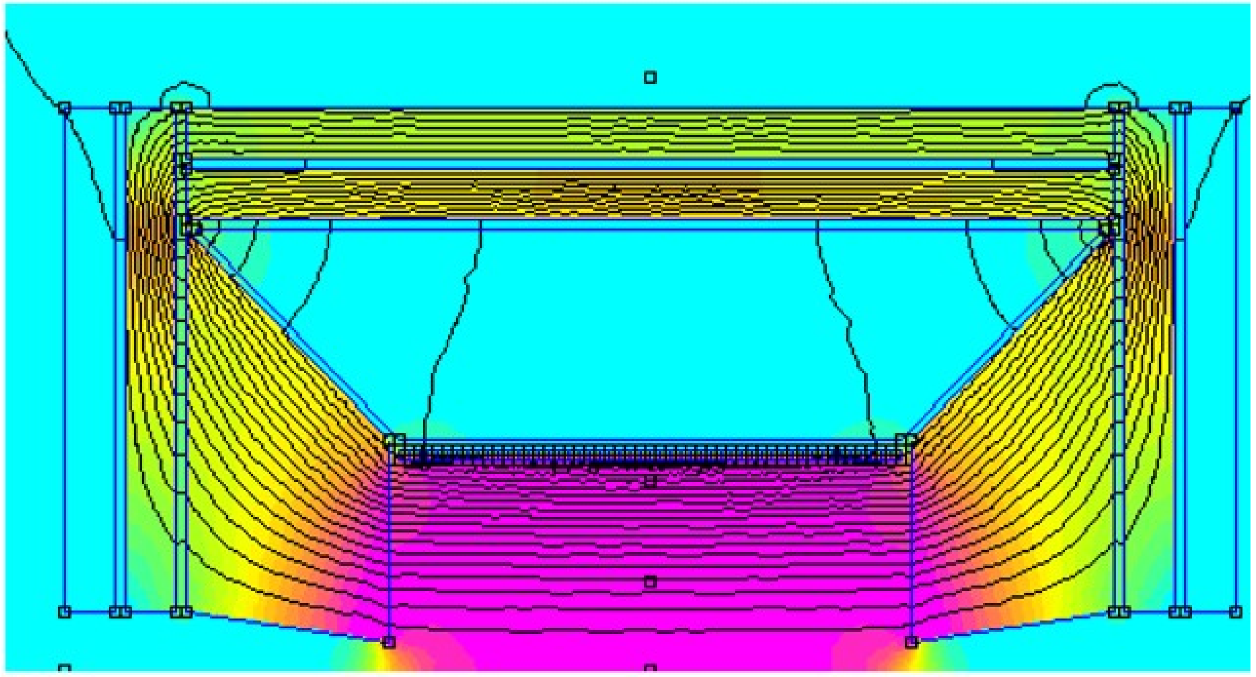
→ may provide a powerful tool for calibration and stability

last but not least ...

Magnetic field homogeneity → IRON



Lead absorber



→ forward with Iron

forward only → almost as good as with full iron

particle flow

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

→ longitudinal segmentation ?

longitudinal segmentation

Of course possible:

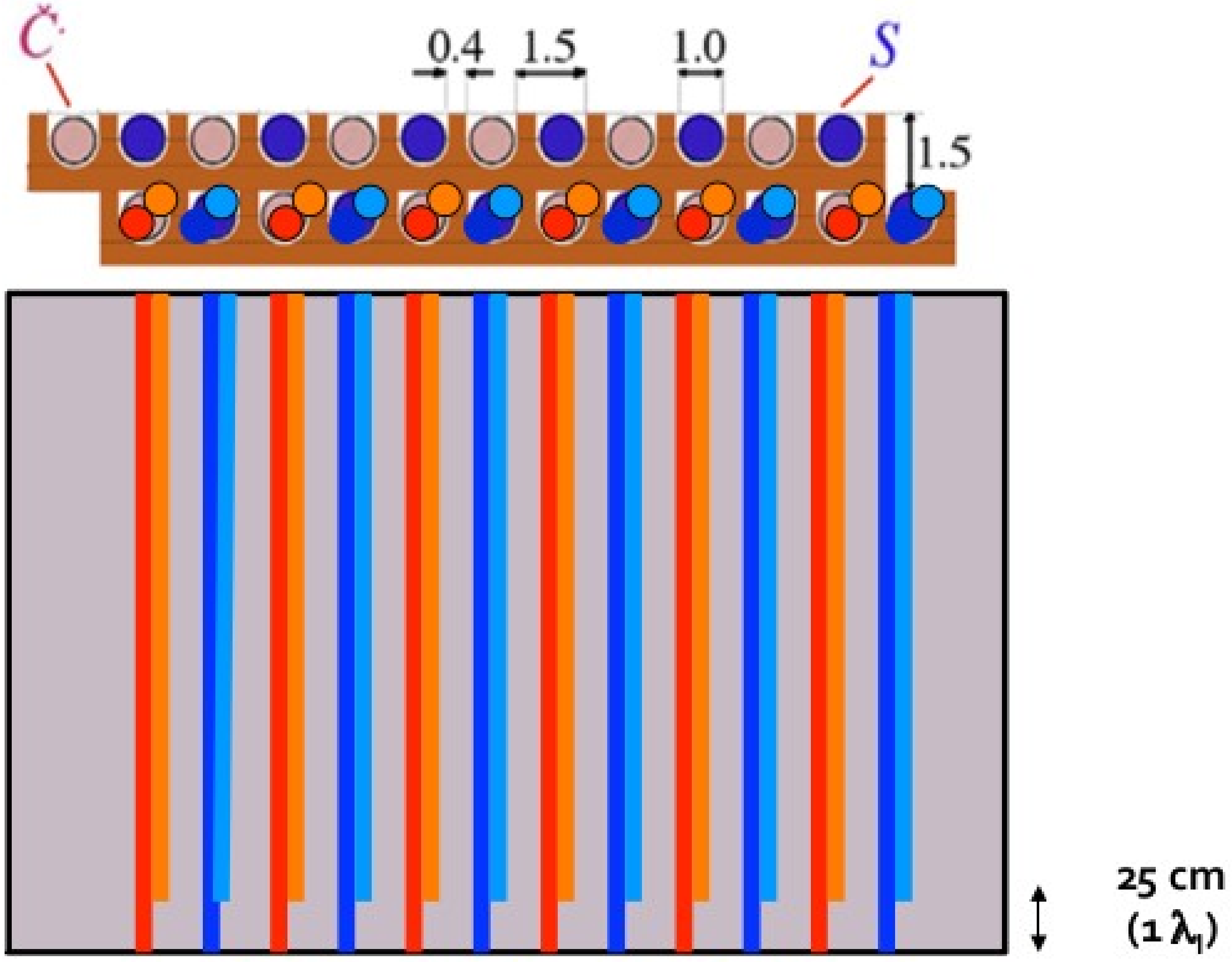
- one lead em compartment
- one (or more) iron had comp.
- may be separately optimised

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

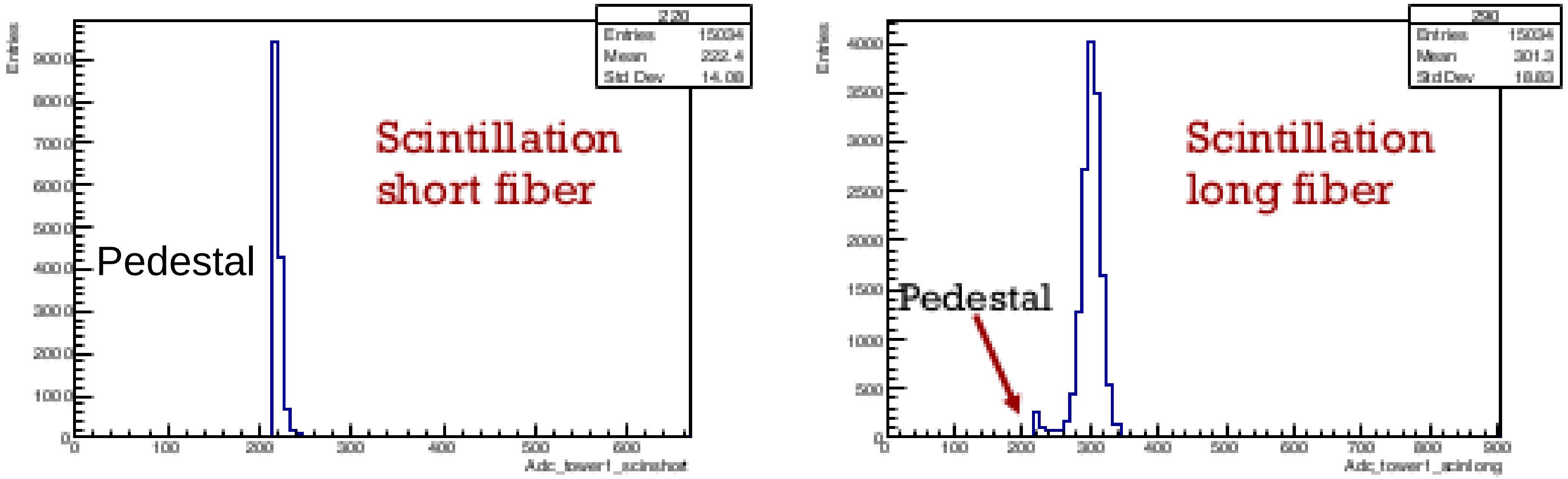
short fibres → hadronic compartment(s)

2018 staggered-fibre prototype

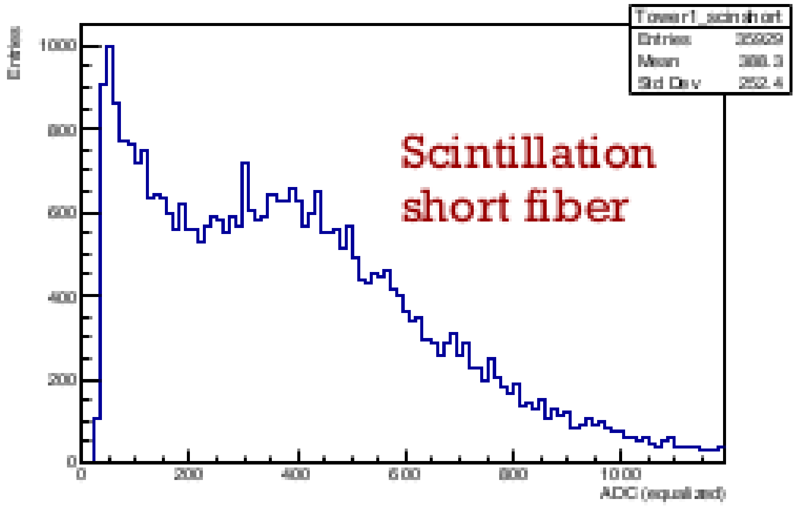
($9.3 \times 9.3 \times 250$ cm^3) lead module → 4 towers → 16 readout signals

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

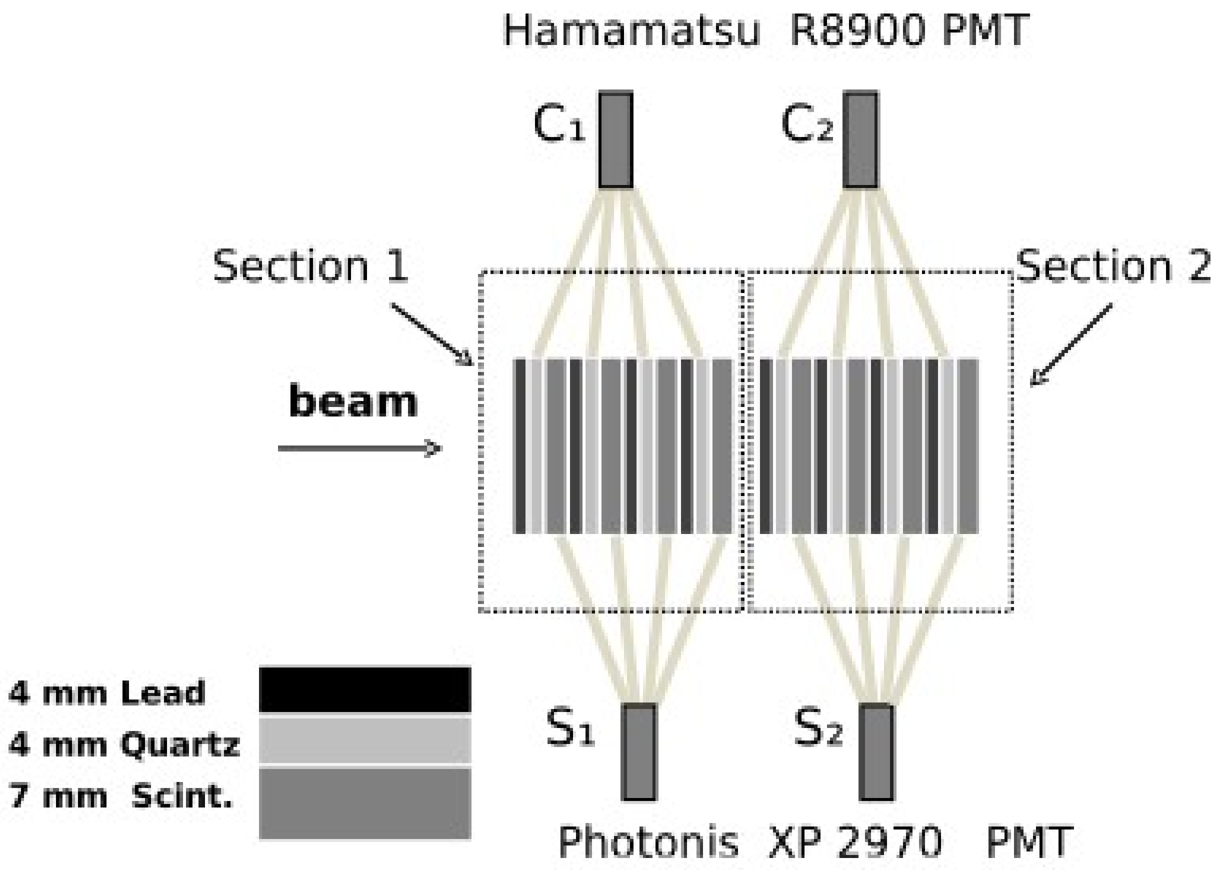
→ + tiles : fully tunable longitudinal segmentation
→ + tiles : no attenuation length issues
→ + tiles : no fibre-to-fibre fluctuation issues
→ + tiles : simpler and cheaper

→ + 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



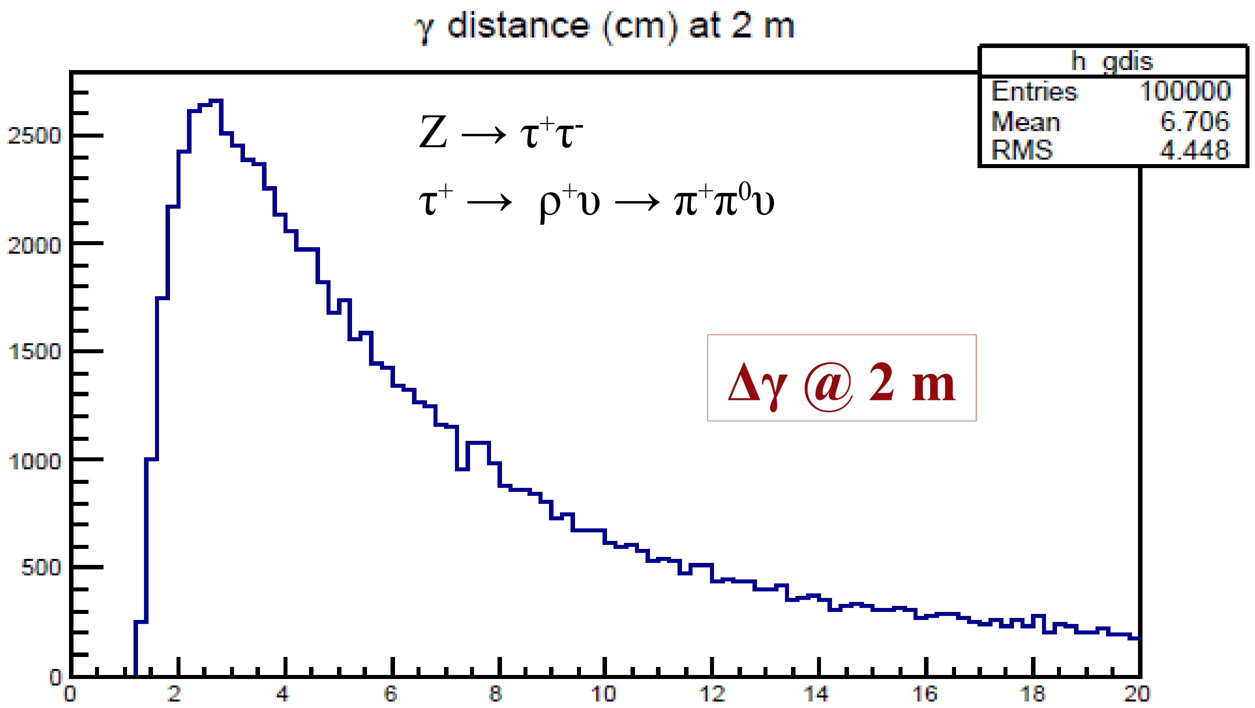
Č light yield ~ 50 p.e. / GeV … interesting … but …

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

but ...

what the most probing benchmark for longitudinal segmentation ?

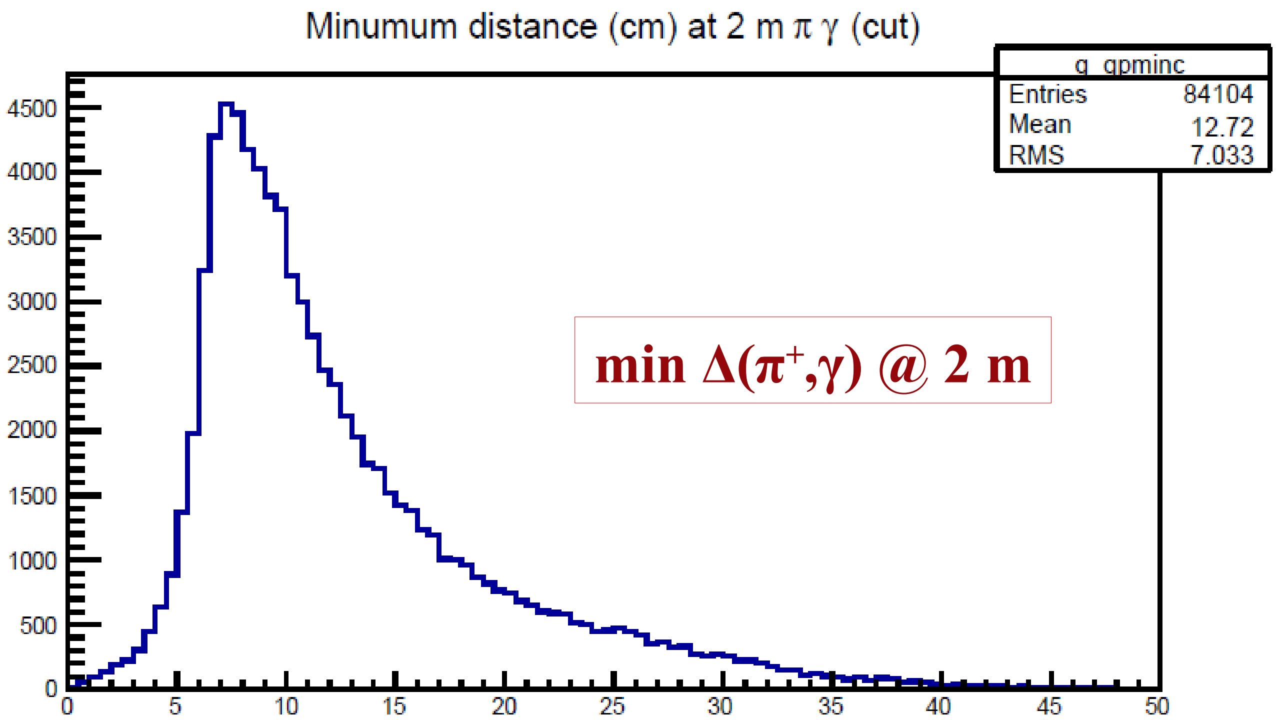
the $\tau^{\pm} \to \rho^{\pm}\upsilon \to \pi^{\pm}\pi^{0}\upsilon$ case



$Z \to \tau^{+}\tau^{-}$

$\tau^{+} \to \rho^{+}\upsilon \to \pi^{+}\pi^{0}\upsilon$

$\Delta\gamma$ @ 2 m



min $\Delta(\pi^{+},\gamma)$ @ 2 m

At a "naive" simulation, energy deposits look distinguishable

→ *to be assessed w/ realistic detector simulations*

nevertheless … B field impact

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

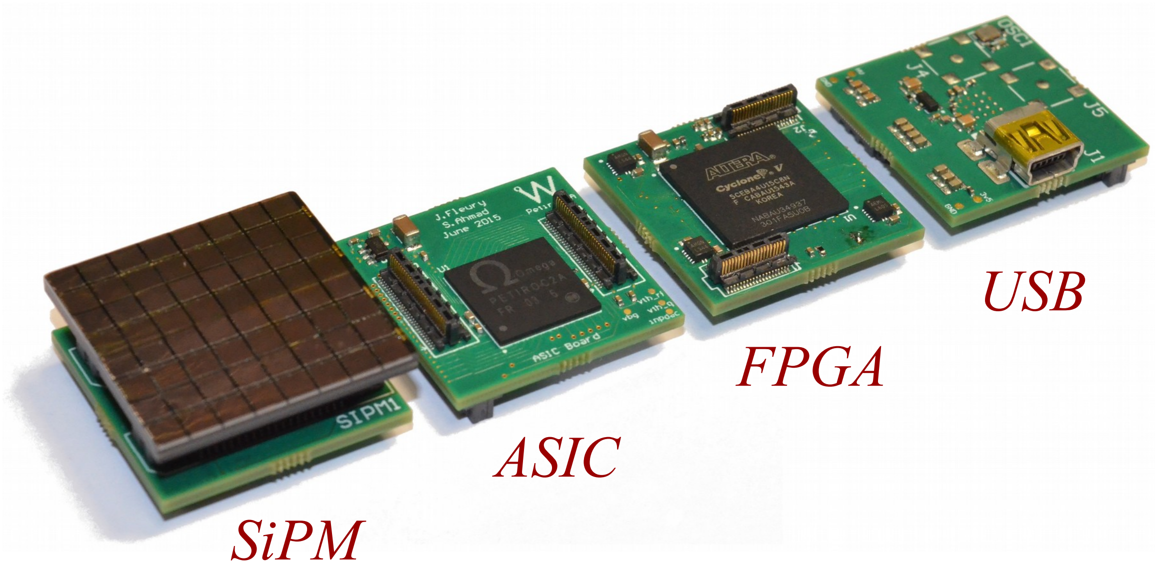
$$\alpha = R_{cal} / (2 \times R_{bend}) = \sim 2.5 / (2 \times P_T / 0.6)$$
$$= \sim 750 \text{ mrad} / P_T$$

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

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

front-end electronics

would like to get:



first step: ASIC

weeroc catalogue:

Chip	Detector	Ch	Polarity	Dyn Range	Specificities
SPIROC	SiPM	36	>0	10 fC - 300 pC	36 HV SiPM tuning (8 bits), Internal 12-bit ADC for charge and time measurement
EASIROC	SiPM	32	>0	10 fC - 300 pC	32 HV SiPM tuning (8 bits), 32 trigger outputs
CITIROC	SiPM	32	>0	10 fC - 300 pC	32 HV SiPM tuning (8 bits), 32 trigger outputs
PETIROC	SiPM	32	<0	100fC – 300 pC	32 HV SiPM tuning (8 bits), 32 trigger outputs, Internal 10-bit ADC for charge and time measurement (25 ps)
TRIROC	SiPM	64	Both	100 fC- 300 pC	64 HV SiPM tuning (8 bits), 64 trigger outputs, Internal 10-bit ADC for charge and time measurement (25 ps)

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

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

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

… better tuned digital solution ?

SiREAD

Silicon photomultiplier REadout, Automated calibration and Detection

Nalu Scientific, LLC.

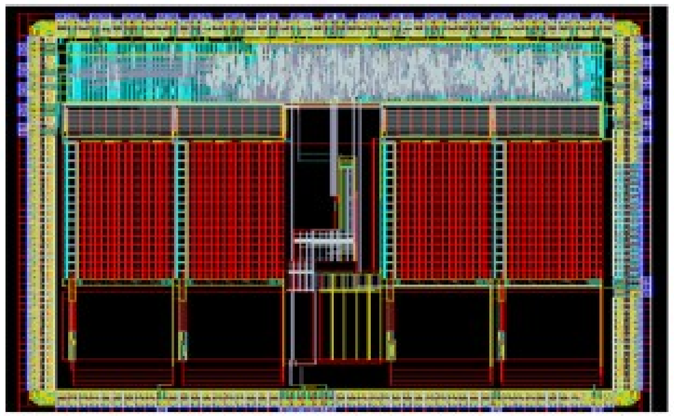
2800 Woodlawn Dr. Ste 298
Honolulu, HI 96822
info@naluscientific.com

Nalu Scientific
Data Acquisition Systems

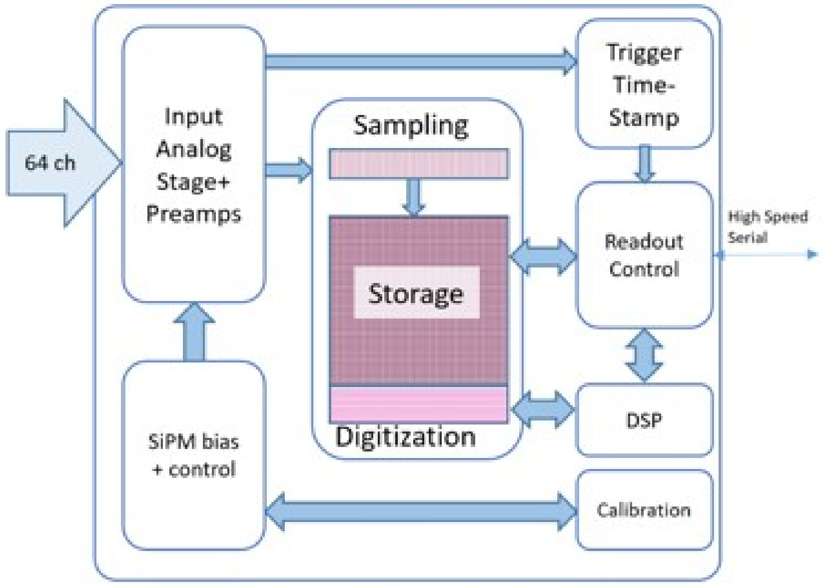
SiREAD Parameter	Specifications
Channels	64
Sampling rate	1-4 GSa/s
Storage samples/ch	4096
Analog bandwidth	0.7-1.1 GHz
RMS voltage noise	<1mV
Dynamic range	10-11 bits
Signal voltage range	2.1 V
ADC on chip	12 bits
Readout	Serial LVDS
Power consumption	20-40 mW/ch

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



SiREAD block diagram

declared to provide ~40-80 ps timing accuracy

[Δx ~ 5 cm ⇒ Δt ~ 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]

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**

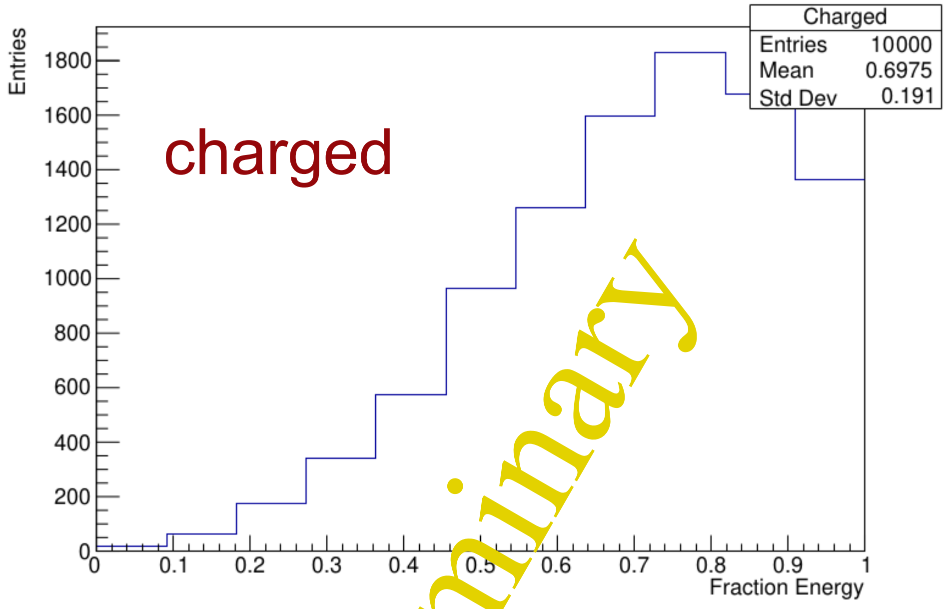
Soft hadrons
(behaving like *mips*) **? usually** $\frac{e}{mip} \neq 1$

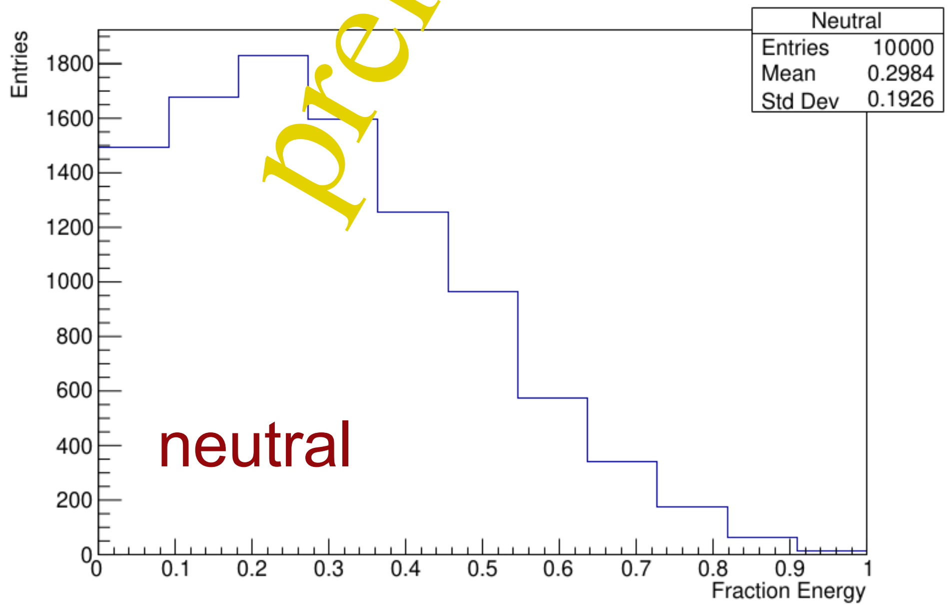
Does it reconstruct the correct energy for all the particles?

simplified jet structure

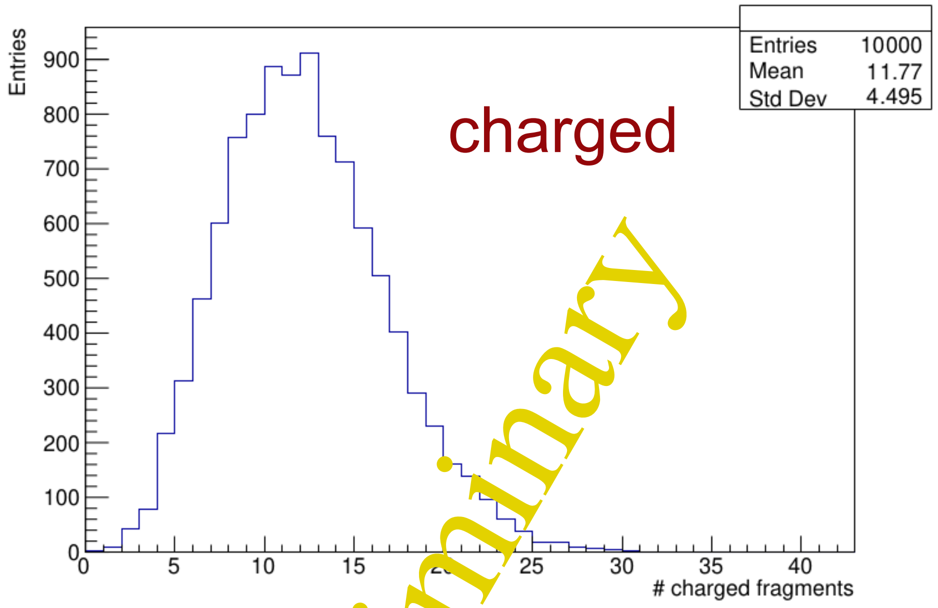
45 GeV Jets

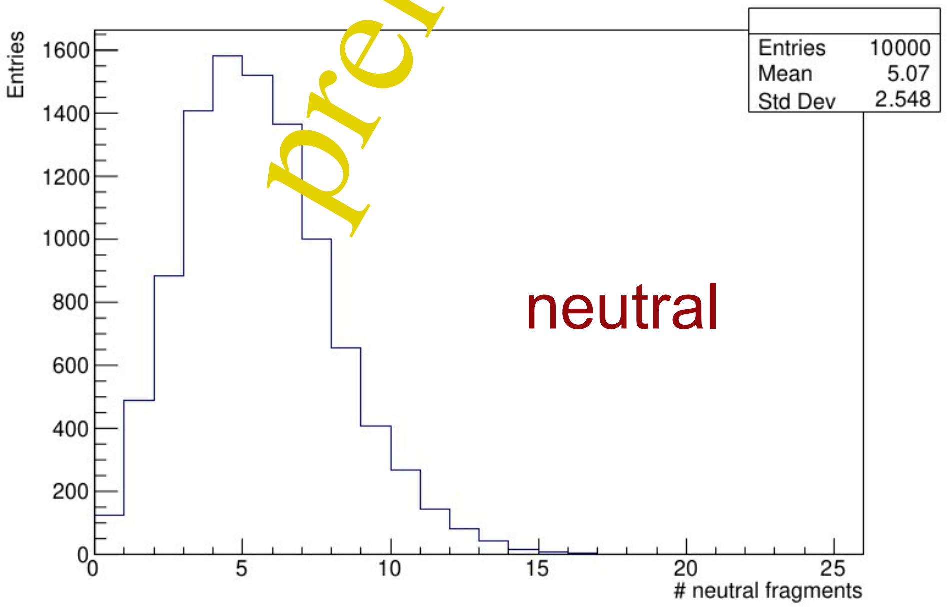
Jet Energy Fraction





Jet Multiplicity

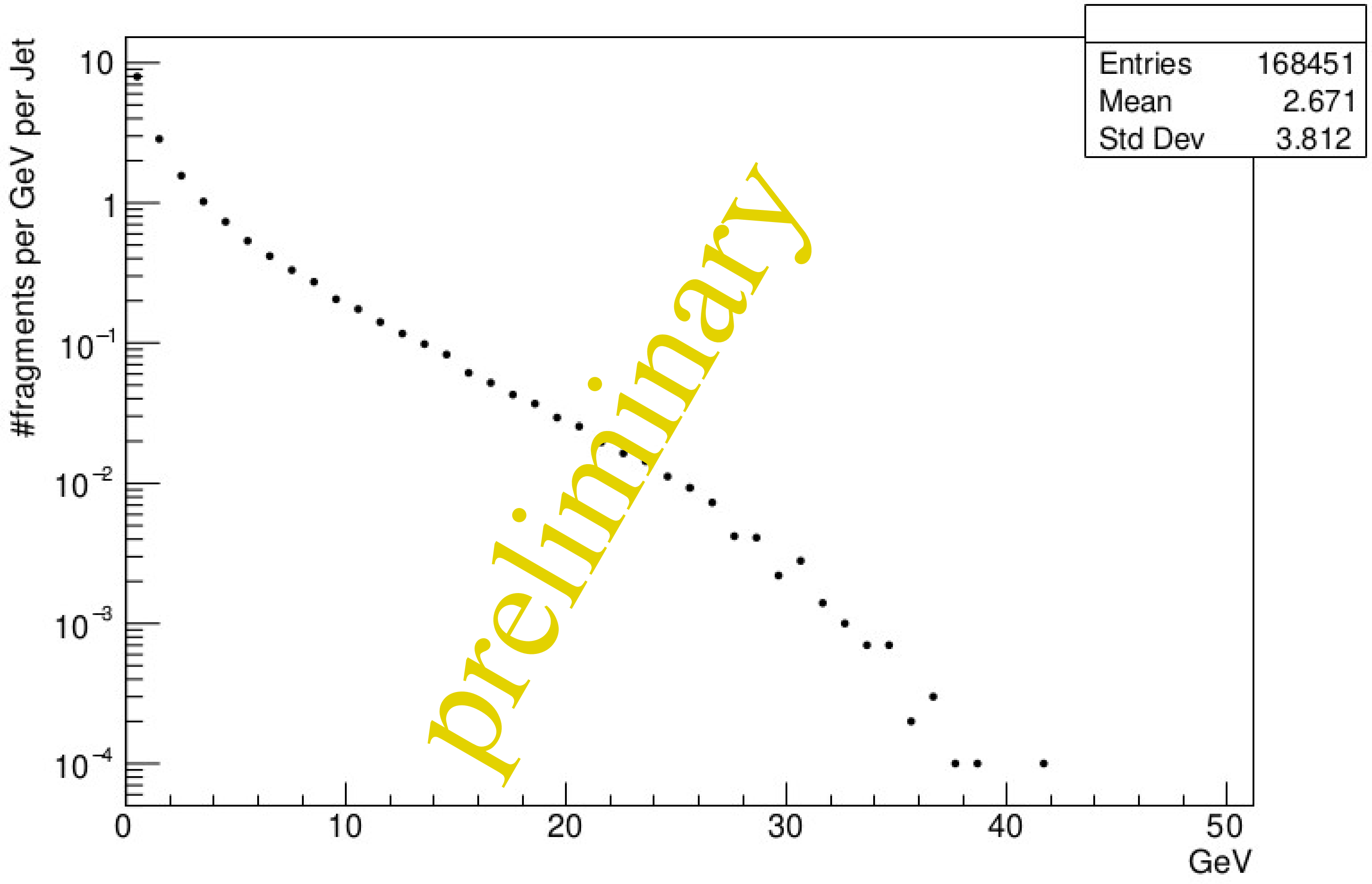




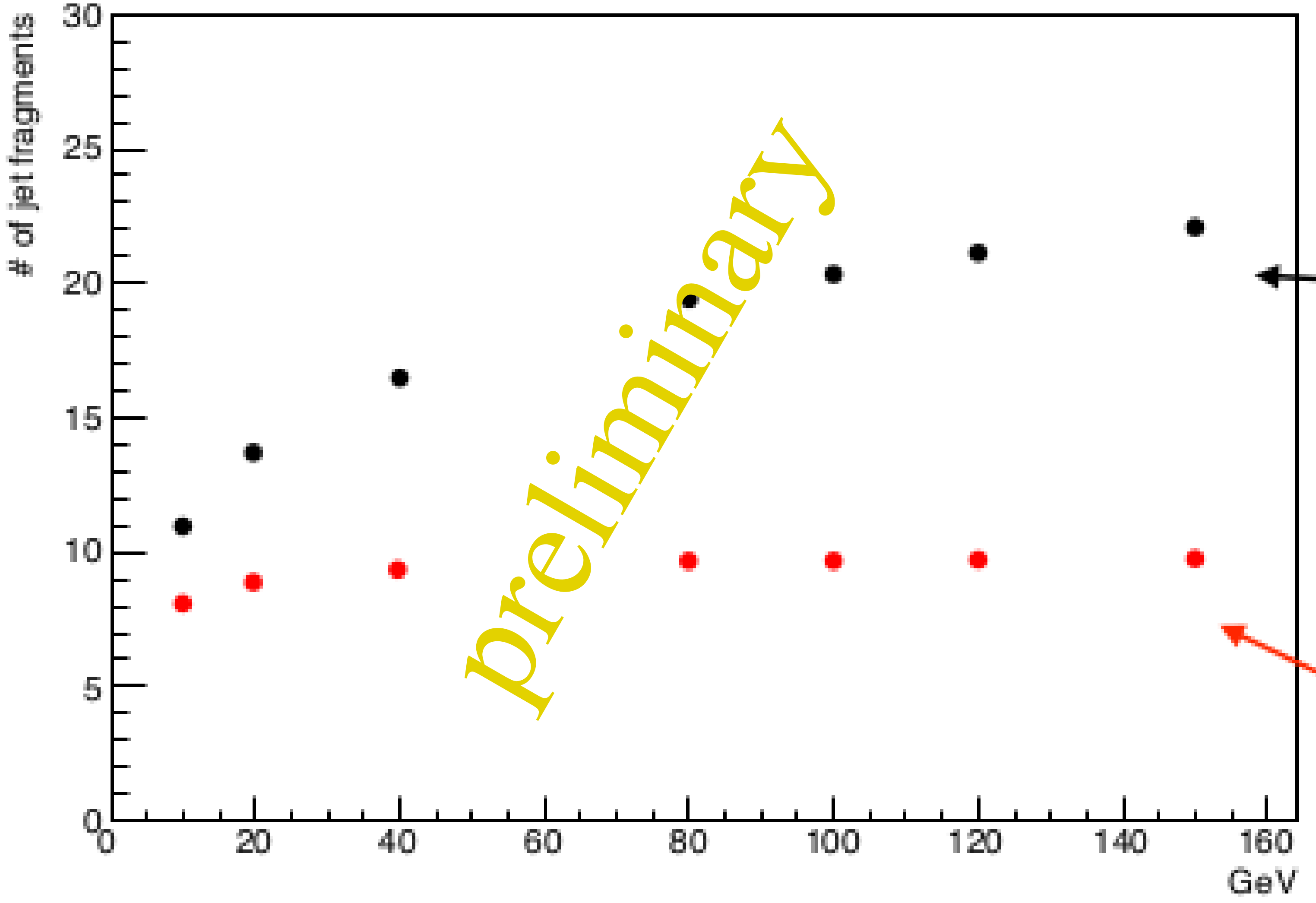
simplified jet structure

45 GeV Jets

Number of fragments / GeV / Jet



simplified jet structure



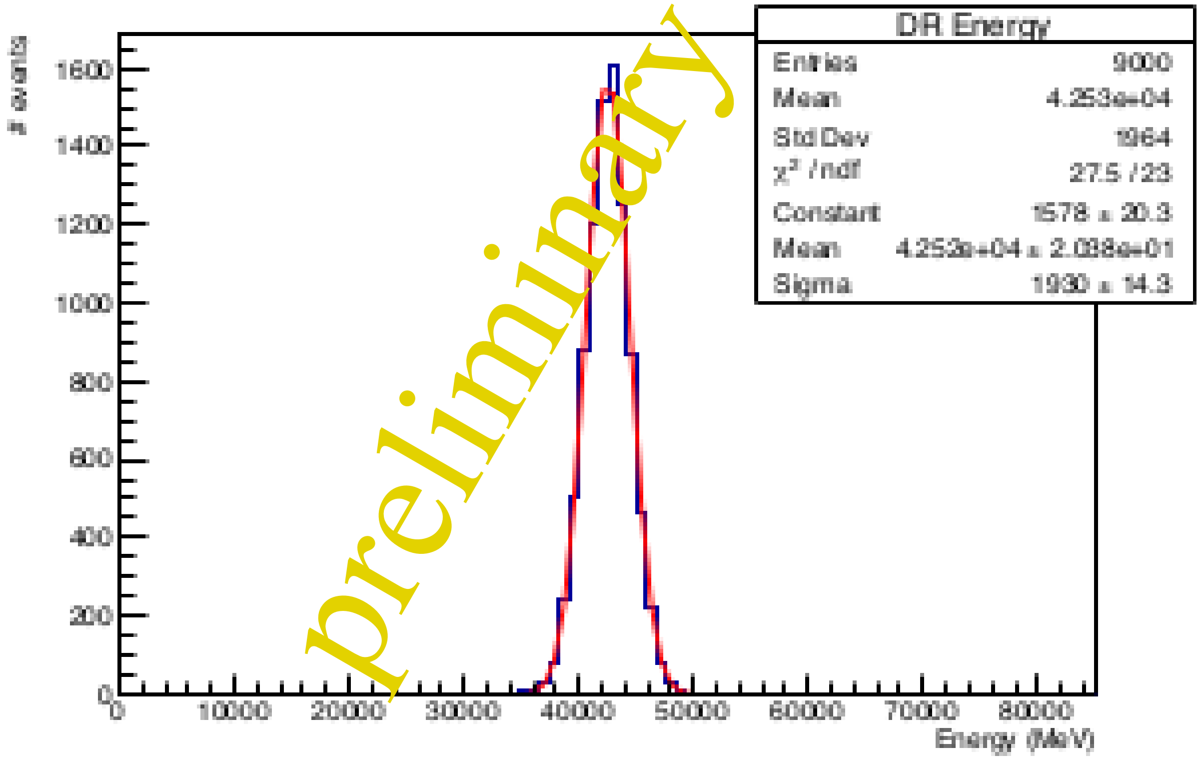
Average multiplicity vs. jet energy

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

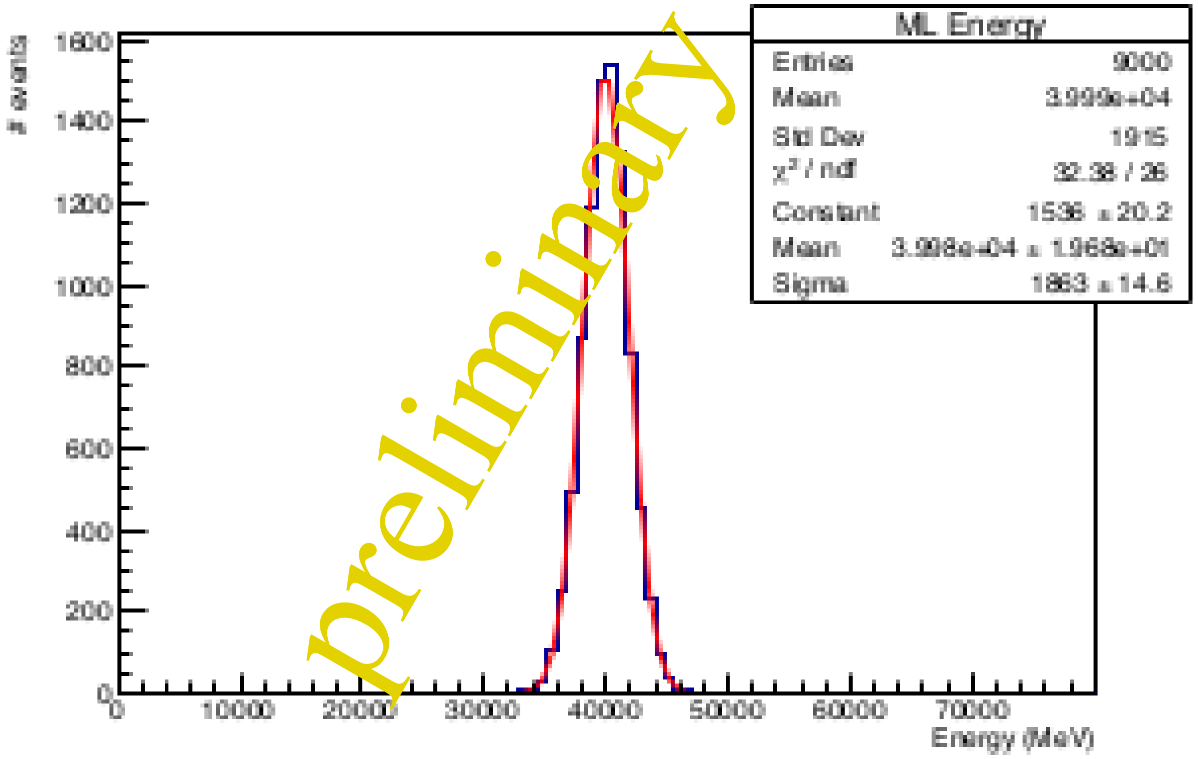
DR method



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

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

Machine Learning

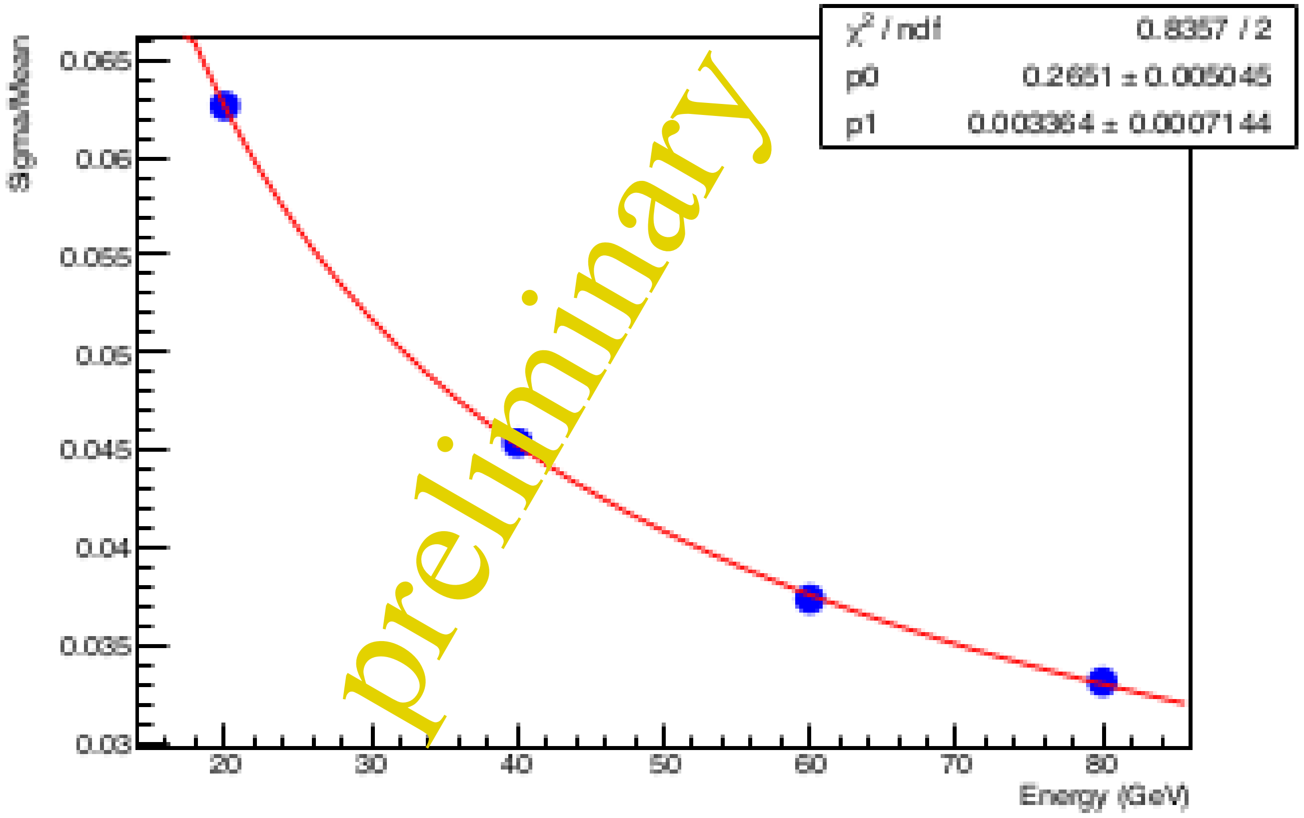


With machine learning
The energy is on average correctly reproduced:

Soft hadrons are present also in the trained database

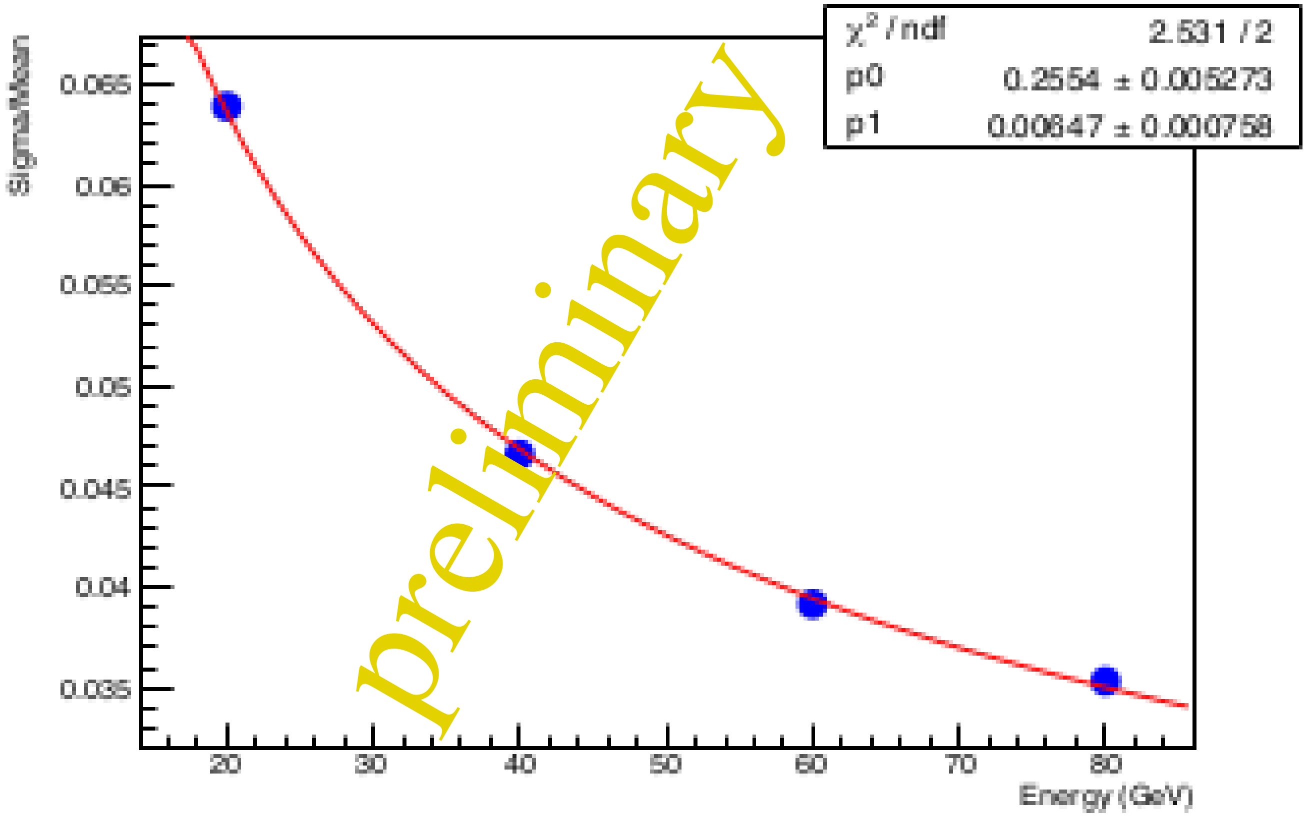
energy resolution

DR method



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

Machine Learning



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

Conclusions

Work is in progress over many fronts in order to assess the dual-readout performance @ e+e- colliders

Many open challenges exist but none looks really prohibitive, suitable solutions seem to be available

On the other hand, the final qualification test will require to have solved few more issues, not covered in this talk:

a) the need of a robust validation of Geant4 simulations with data
b) the construction of a ~ full-containment hadronic prototype
c) understanding and assessment of reliable mechanical production and assembly procedures

→ *planning to start addressing them asap …*