Dual-readout calorimeters inside a collider detector

John Hauptman, CEPC Workshop, EU Edition, Rome, 24-26 May 2018.

Outline of this talk

Perfect Detector (zero-mass tracker & infinite-mass calorimeter)

- no coil, no pre-shower, only minimal supports
- classic calorimeter: measure the particle energy losses inside a defined volume

Dual-readout latest experimental results (beam test data and simulations)

- direct robust calibration, low *systematics*, equal response to pions & protons, Gaussian, linear.
- Don Groom plot: understanding dual-readout with one plot.
- four-vector measurement of jets (from gluons & quarks from Ws and Zs)

B-fields without iron (cancel main *systematics* in low-mass detector, free space for new ideas)

- Cancel overall detector asymmetry systematics: B: 0-3.5T & B to -B
- Low-mass detector, reconfigurable, new ideas, e.g., Lead Glass Wall inside the Mark II detector

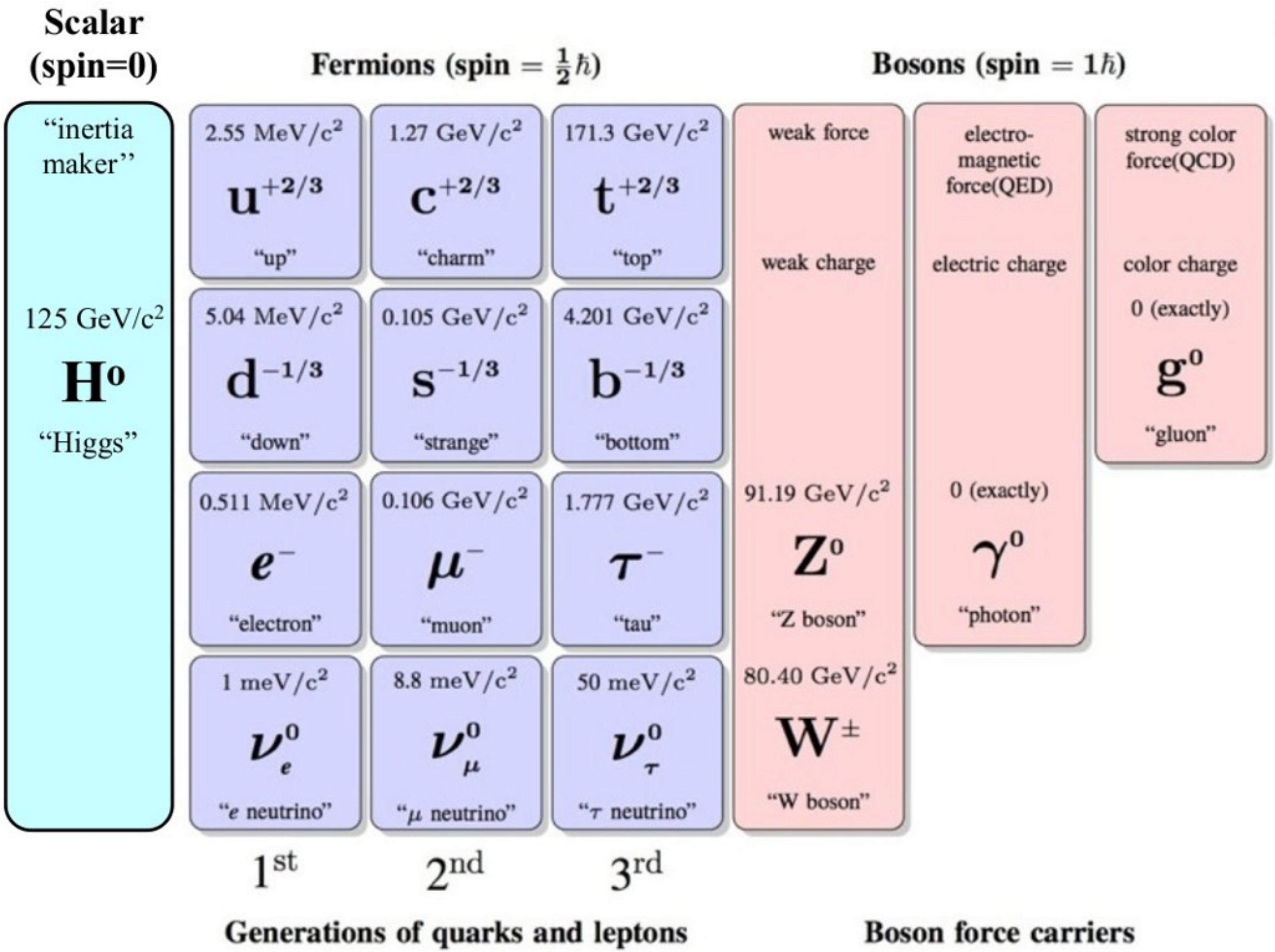
Calorimeter before the solenoidal coil (calibration, energy scale, and *systematics*)

- Thin solenoid is a one-time cost savings vs. 20 years of corrections and calibrations
- Pre-shower detector must be honestly tested on jets in beam tests

Unsolved problems for dual-readout calorimeter

- Rectangular modules into trapezoidal modules
- Photo-converter in a B-field (SiPMs)
- Forming copper absorber

"Dual-Readout Calorimetry," S.Lee, M.Livan, R.Wigmans
Rev. Mod. Phys. 90 (2018) 025002.
(arXiv:1712.0549 [physics.ins-det] 15 Dec 2017)



u, d, s, g $\longrightarrow$ jet

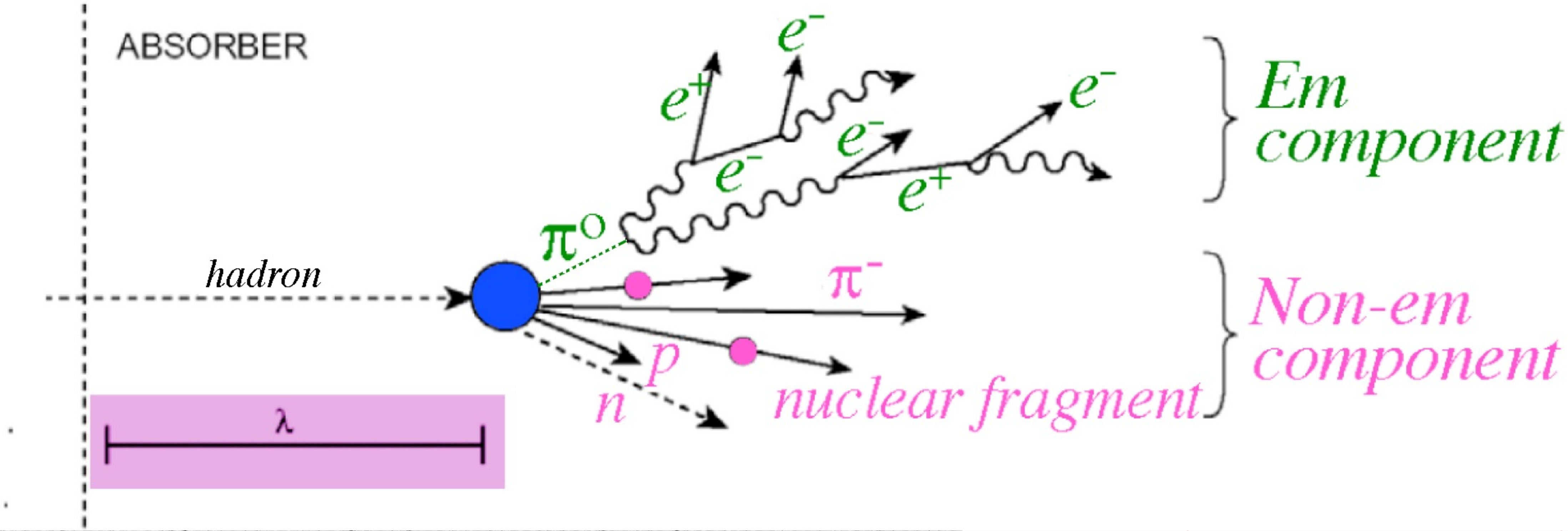
W, Z $\longrightarrow$ qq $\longrightarrow$ 2 jets

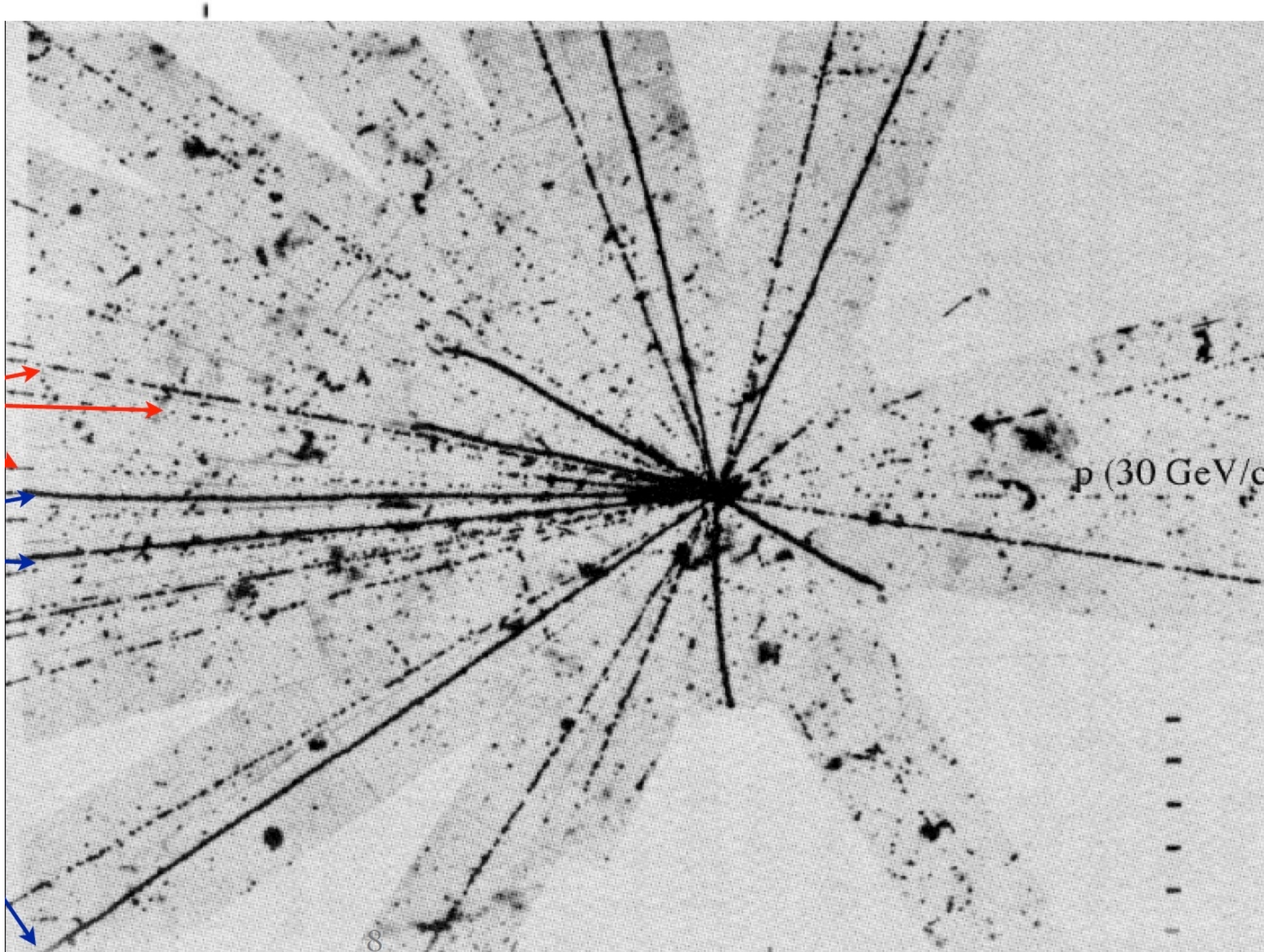
WW $\longrightarrow$ qqqq $\longrightarrow$ 4 jets (5C fit)

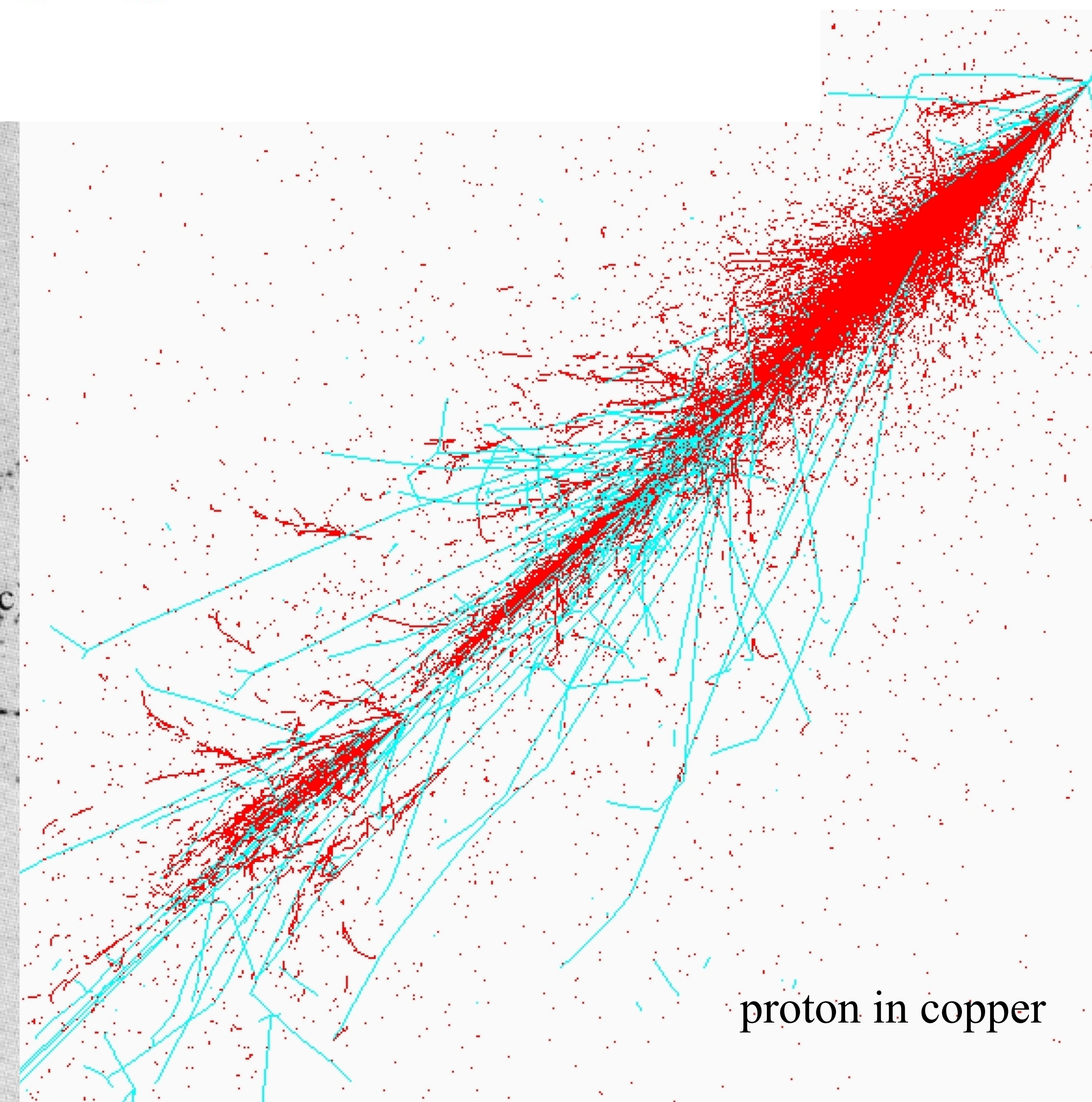
t $\longrightarrow$ Wb $\longrightarrow$ qqb $\longrightarrow$ 3 jets

H $\longrightarrow$ WW $\longrightarrow$ qqqq $\longrightarrow$ 4 jets

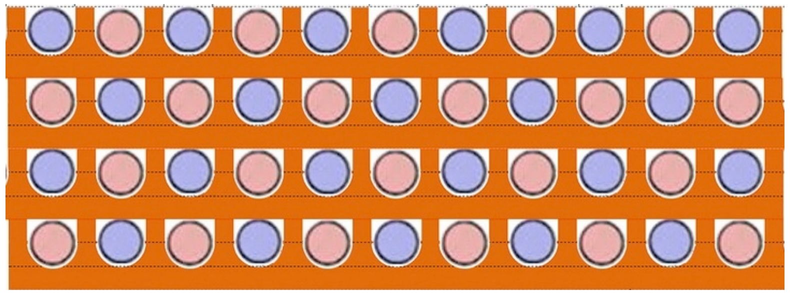
Why hadronic calorimetry is difficult







Dual-readout geometry: Cu



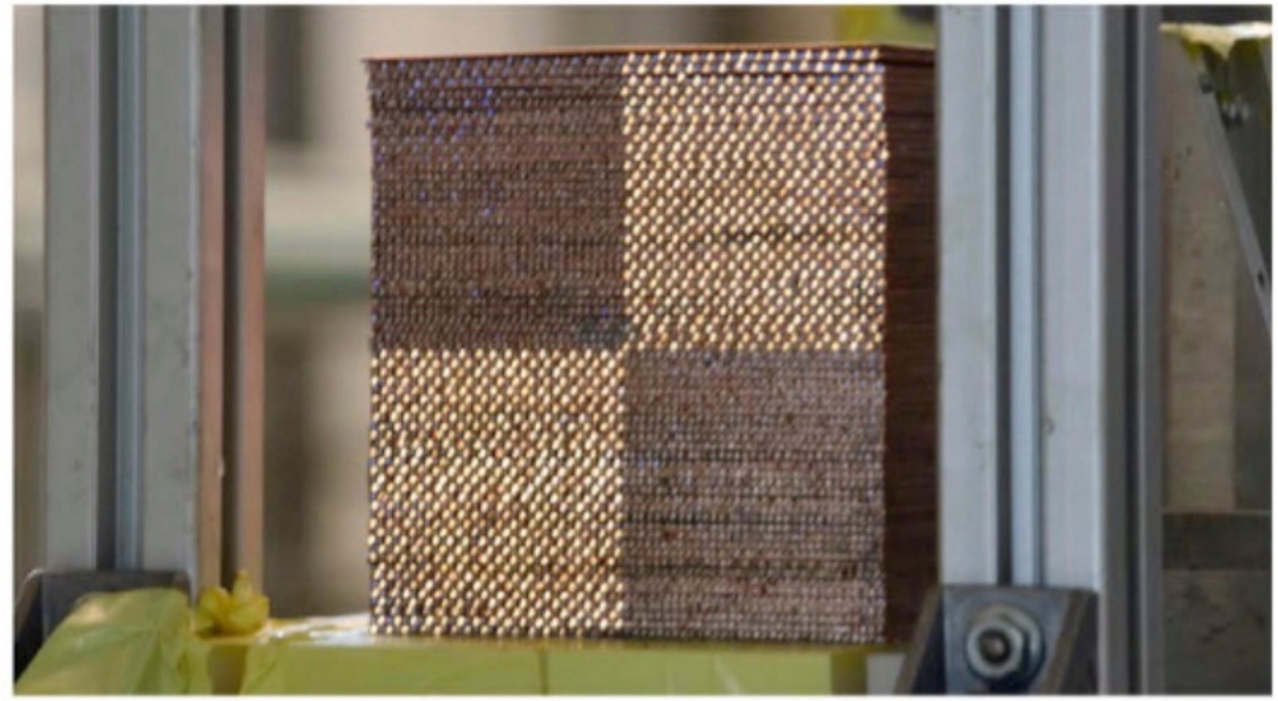
Copper ~ 1/2
S-fibers ~ 1/4
C-fibers ~ 1/4

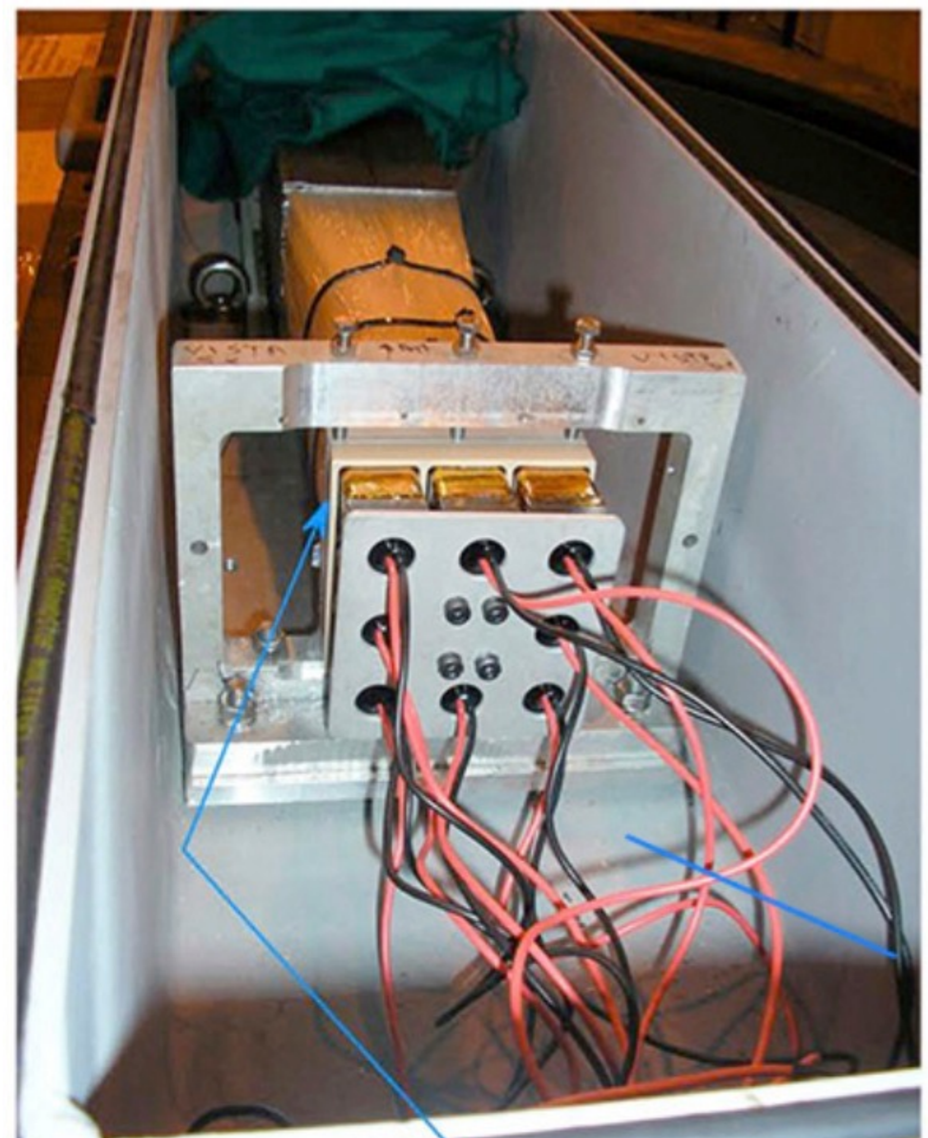
$$\lambda_{\rm Int}^{\rm Cu} = 137.3\ {\rm g/cm^2}$$

$$\lambda_{\rm Int}^{\rm Pb} = 199.6\ {\rm g/cm^2}$$

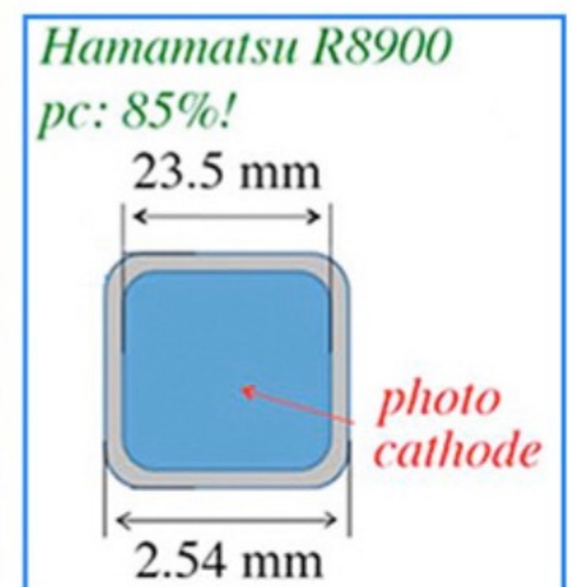
Cubic nucl. int. length:

$$(\lambda_{\rm Int}^{\rm Cu}/\lambda_{\rm Int}^{\rm Pb})^3 \approx 0.325$$





9.3 x 9.3 x 250 cm
150 kg
4 towers, 8 PMTs
2 x 2048 fibers



Dual-readout in one plot: D. Groom (LBNL, PDG)

$$S = E[f_{\rm em} + (1 - f_{\rm em}) \cdot \eta_S]$$

$$C = E[f_{\rm em} + (1 - f_{\rm em}) \cdot \eta_C]$$

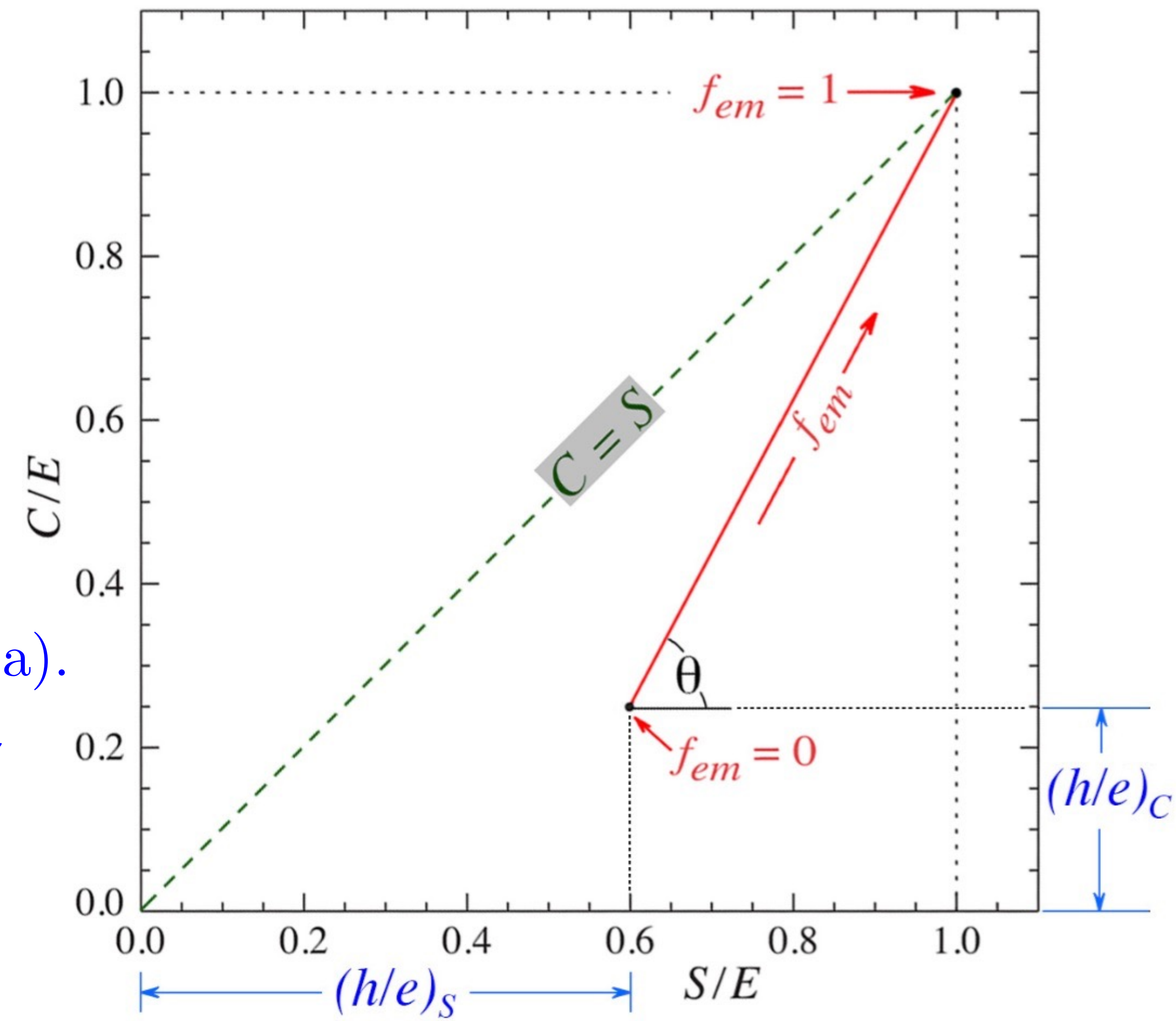
$\eta =< h/e >$ mean relative response of hadrons (h) to electrons (e) for S,C fibers in any copper/fiber geometry (determined directly from data).

Typically, $\eta_C \approx 0.2 \quad \eta_S \approx 0.7$

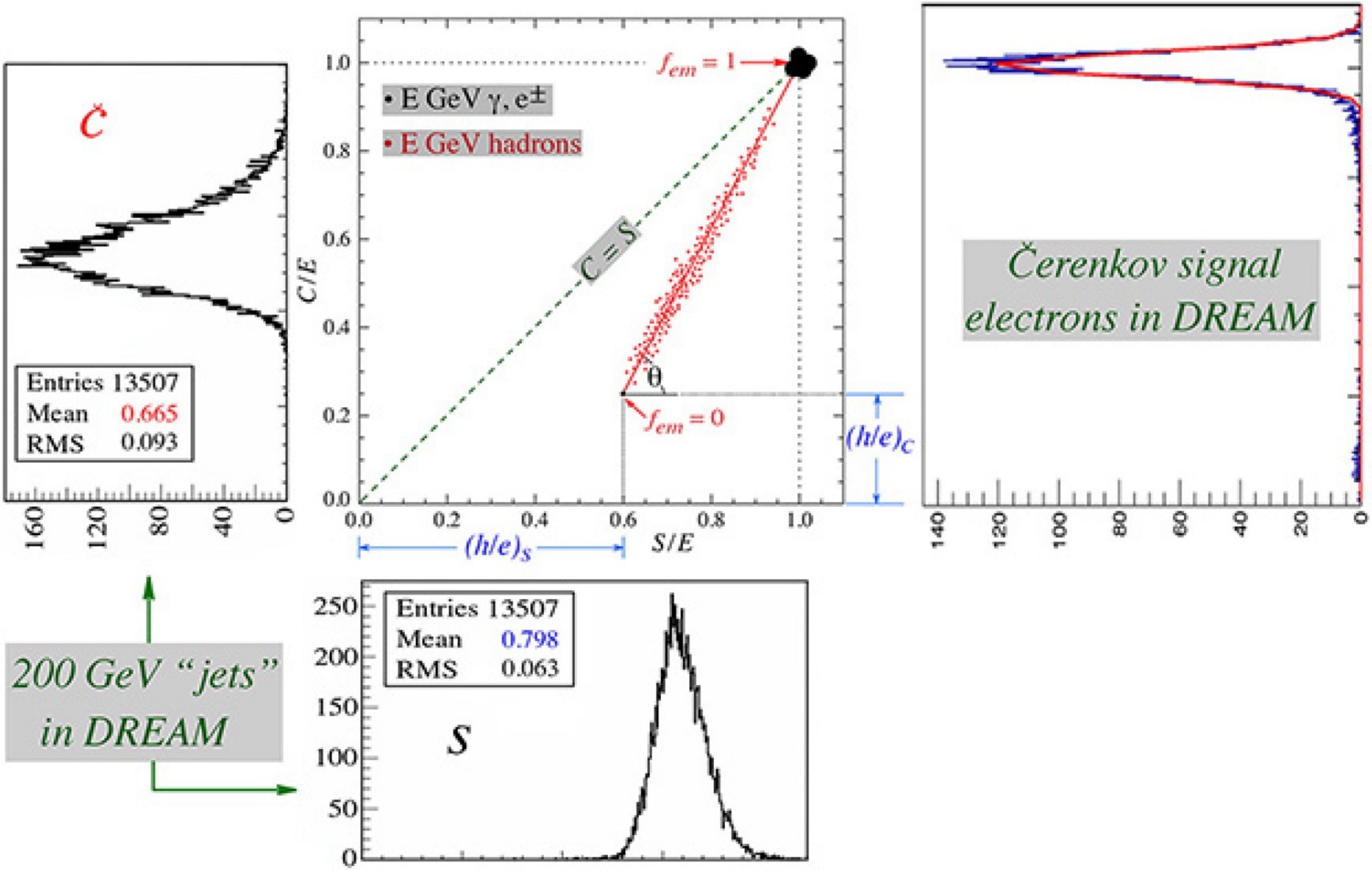
Dual-readout energy:

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

with $\xi = (1 - \eta_S)/1 - \eta_C)$



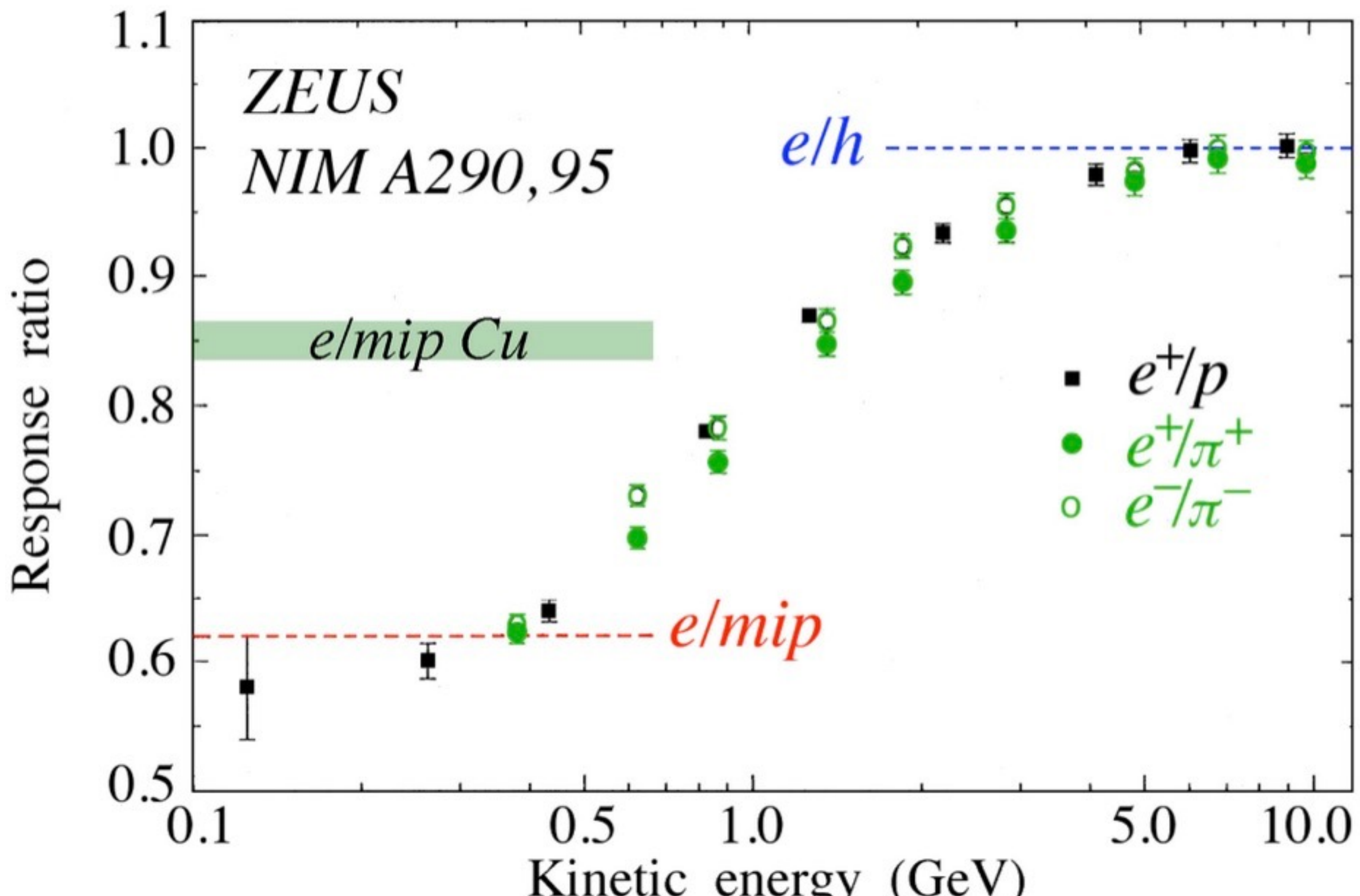
Why dual-readout yields good energy resolution



Hadronic calorimetry is complicated: *e/mip variation in response*

ZEUS energy resolution was worse for *jets* than for single pions.
This is the reason.

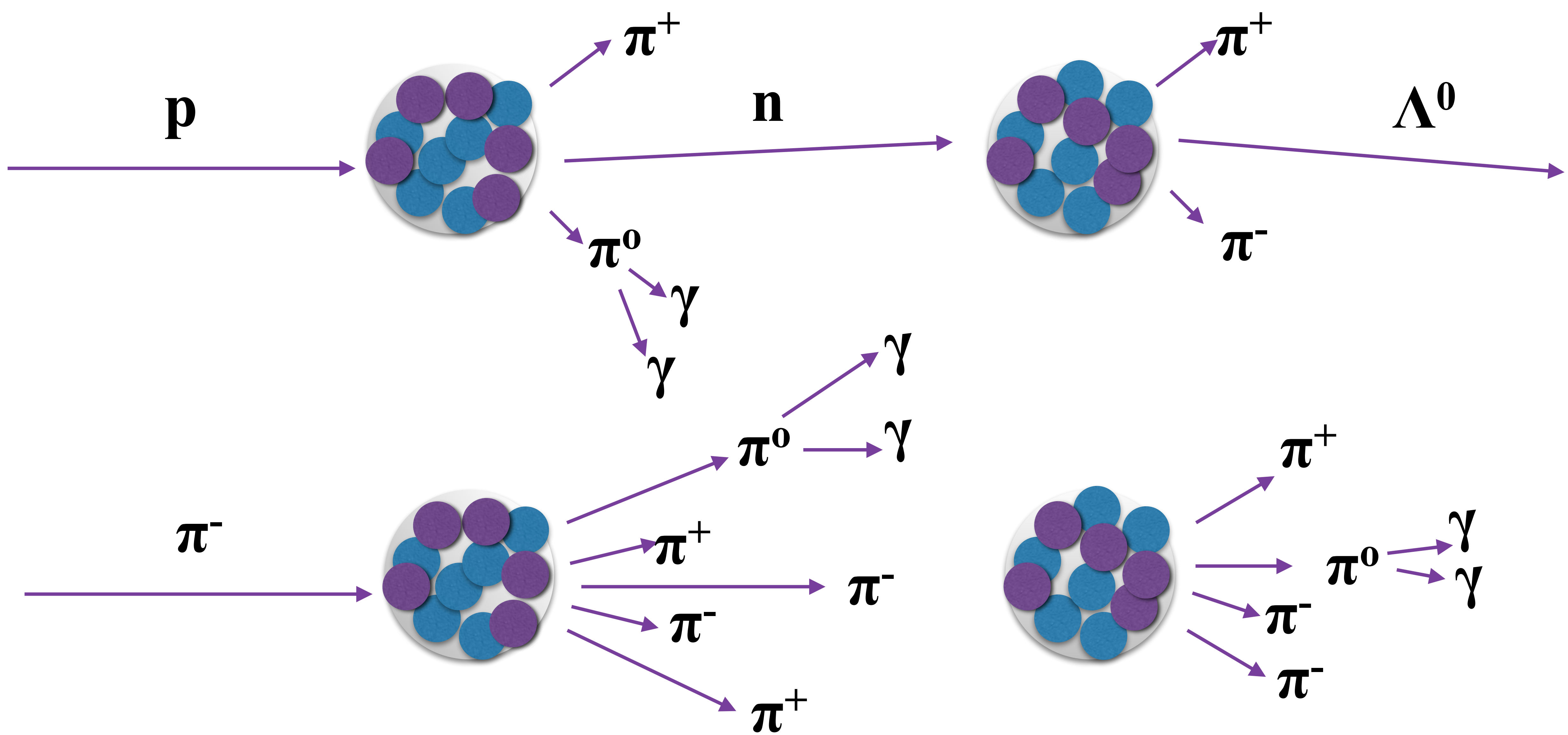
Correct jet energy track-by-track for variation in *e/mip* response (~1% of jet energy)



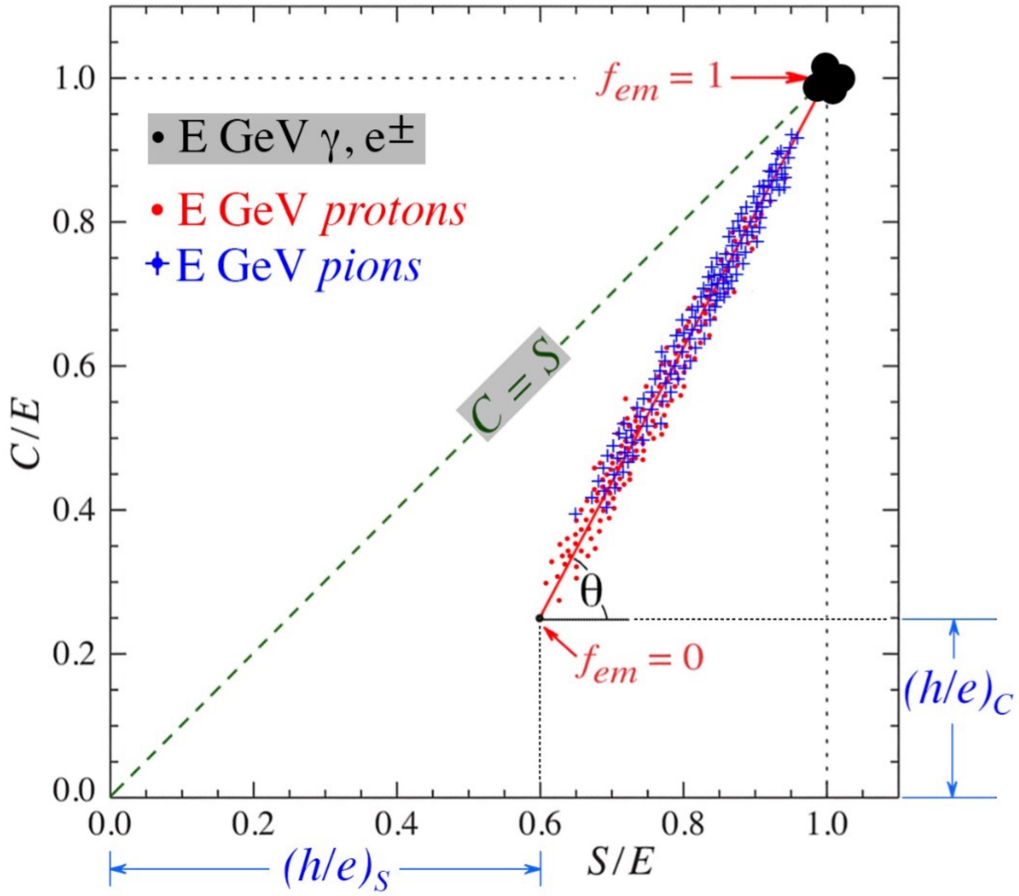
Hadronic calorimetry is complicated: *fluctuations in baryon content*

Baryon number conservation:

3-quark system maintains forward momentum, producing fewer pi-zeros.



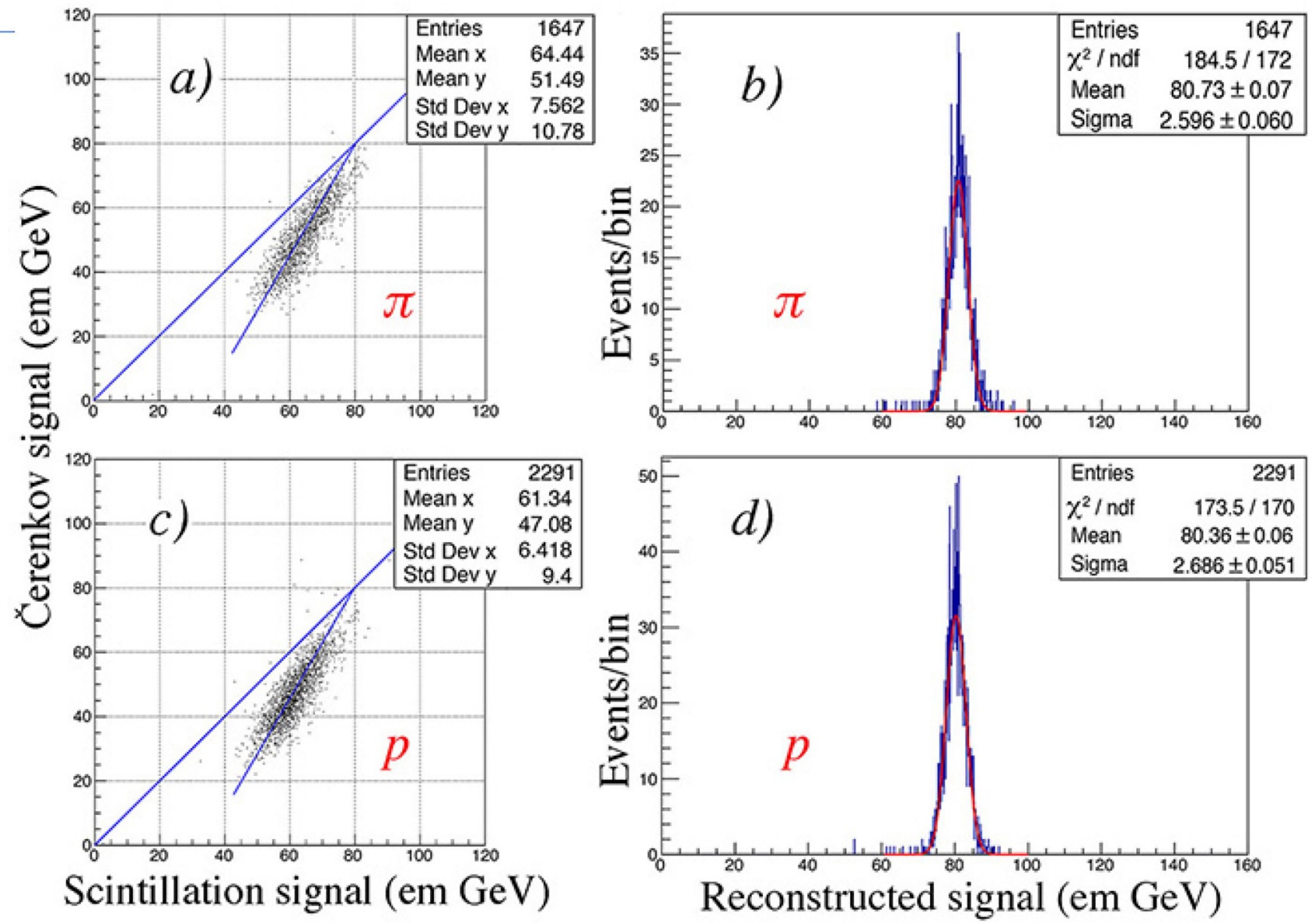
Calorimeter signal is larger for pions, more Gaussian for protons



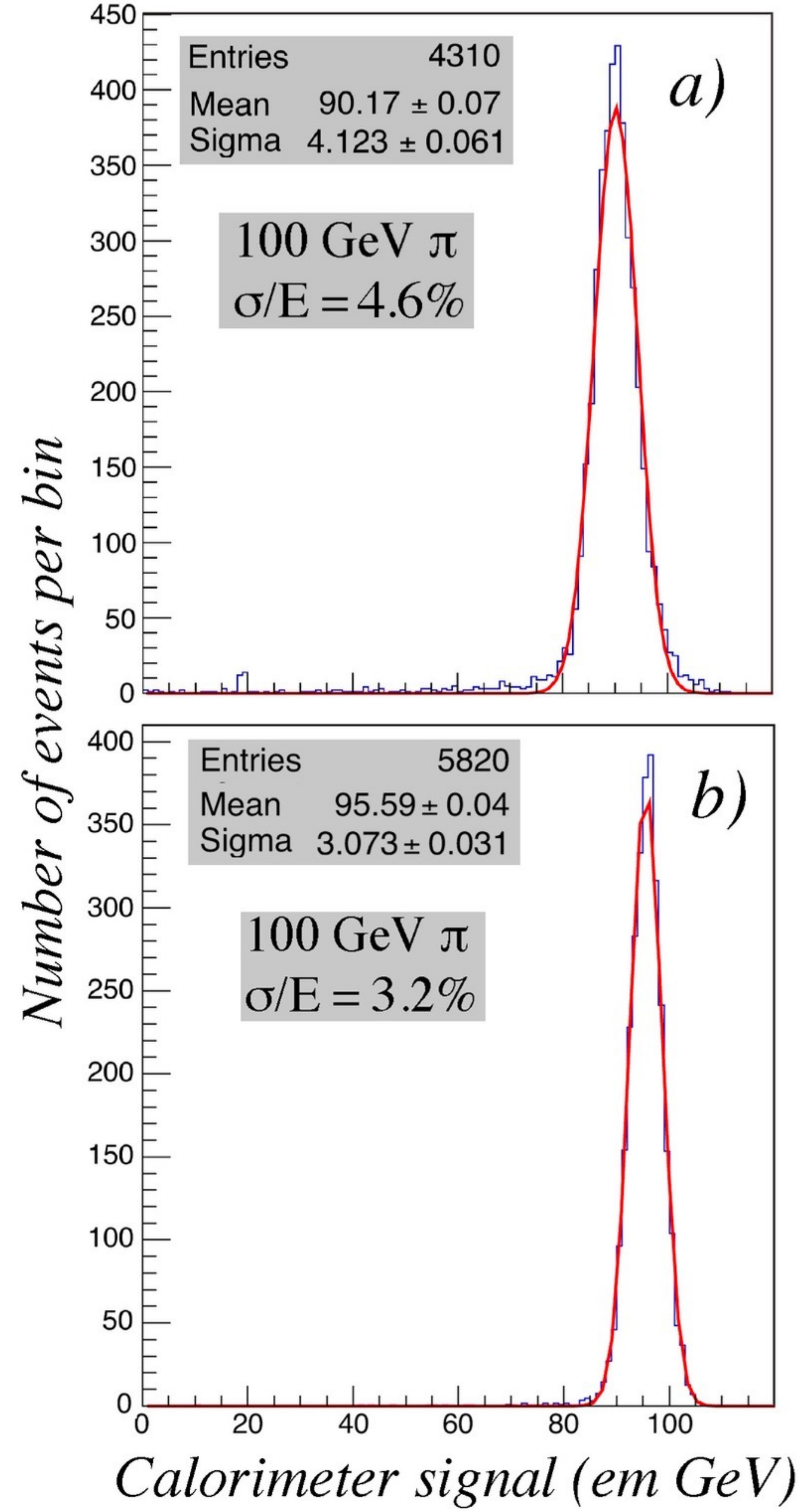
… fluctuations in baryon content

… but the dual-readout energies are the same

Protons populate lower Cerenkov signals than pions …



Hadronic calorimeters are complicated: *GEANT4 simulation*



FTFP_BERT

(usual LHC experiments)

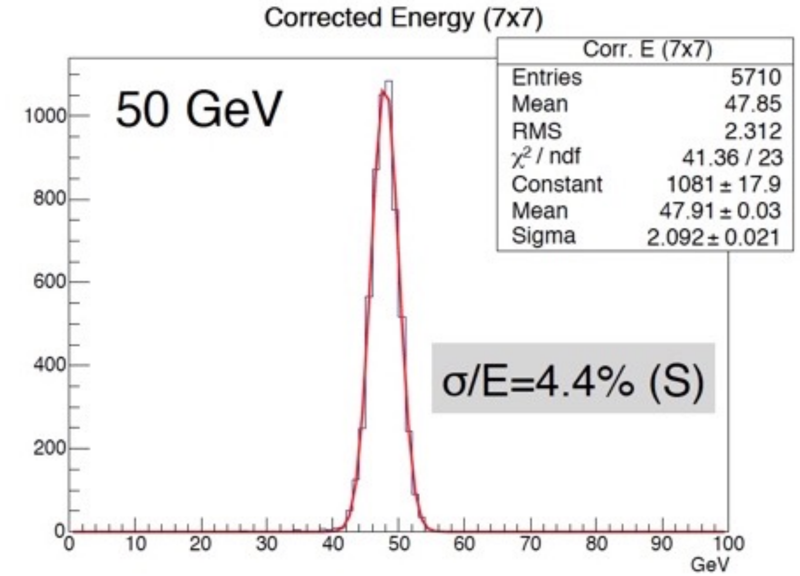
FTFP_BERT_HP

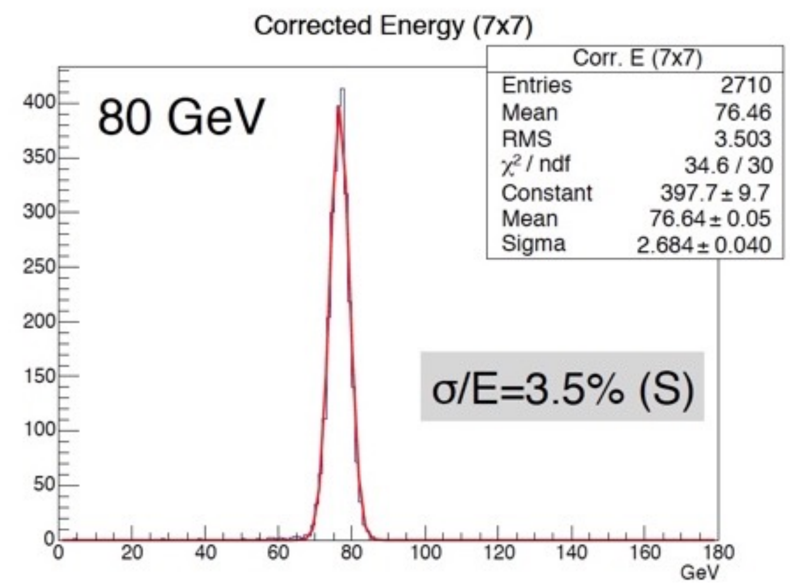
("high precision" treats neutrons more properly, which is critical for energy compensation in dual-readout calorimeters)

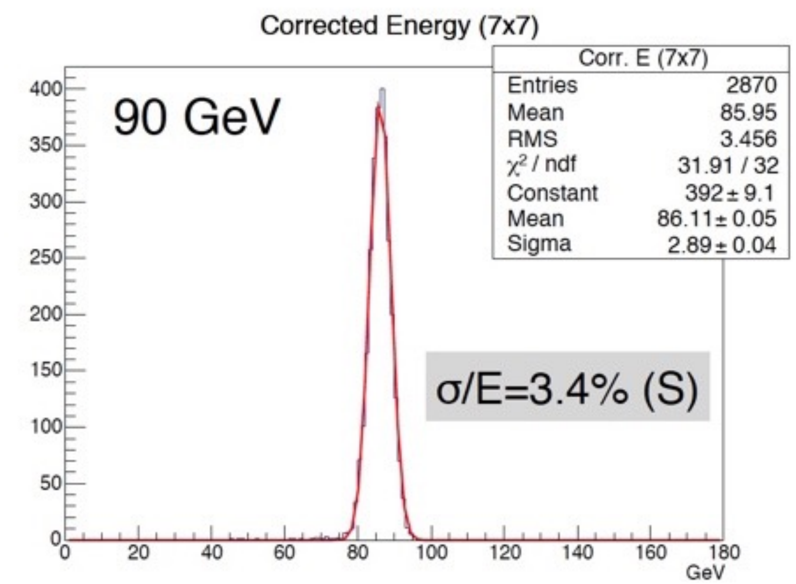
At 100 GeV: 4.6% → 3.2%

(65cm x 65cm, Gaussian, more to go - FLUKA?)

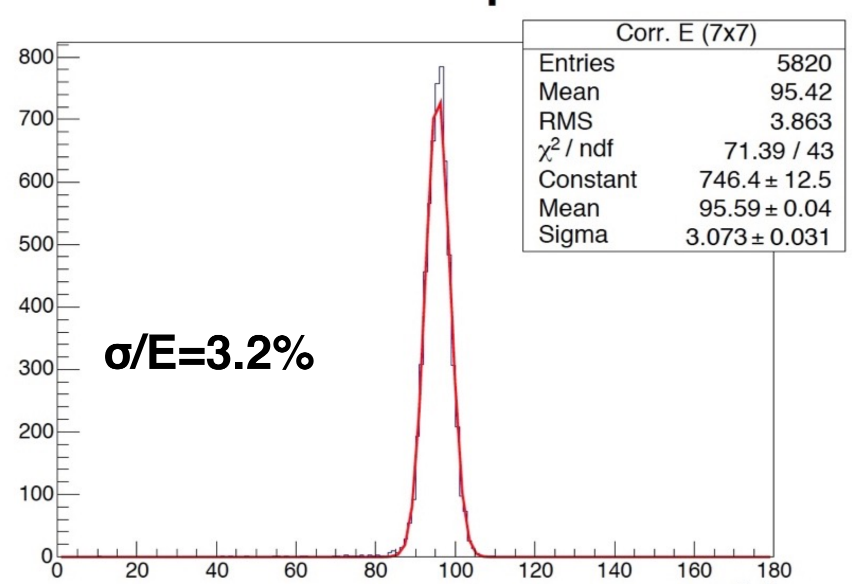
GEANT4
FTFP_BERT_HP simulation
of large copper dual-readout
module (65cm x 65cm)



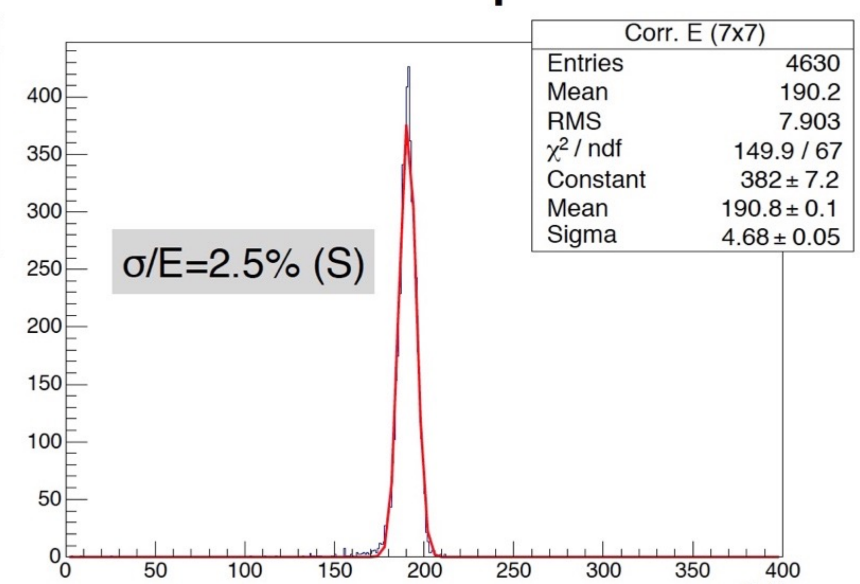




100 GeV pions



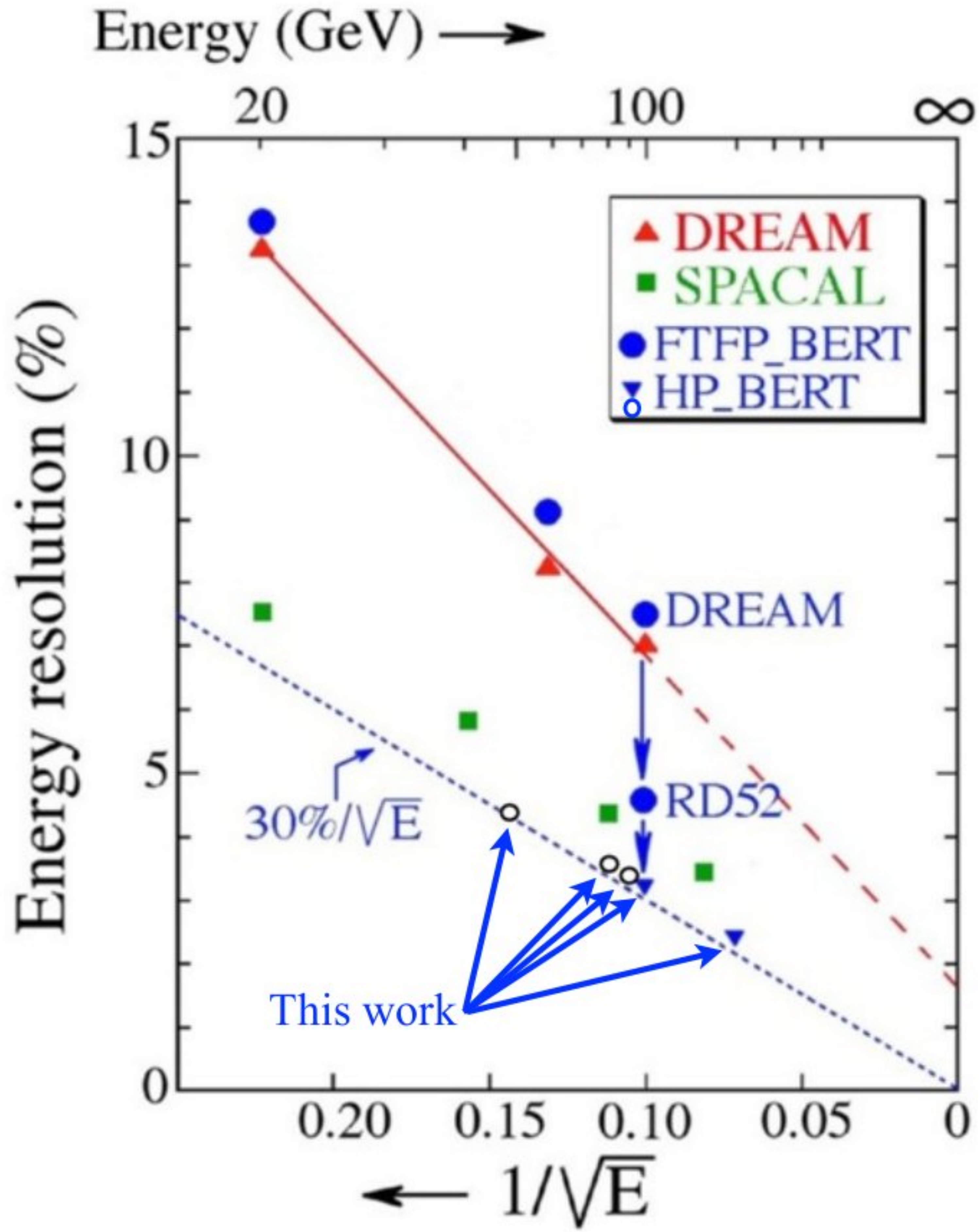
200 GeV pions



Dual-readout calorimeters
are getting close to 2%
energy resolution at high
energies ~300 GeV

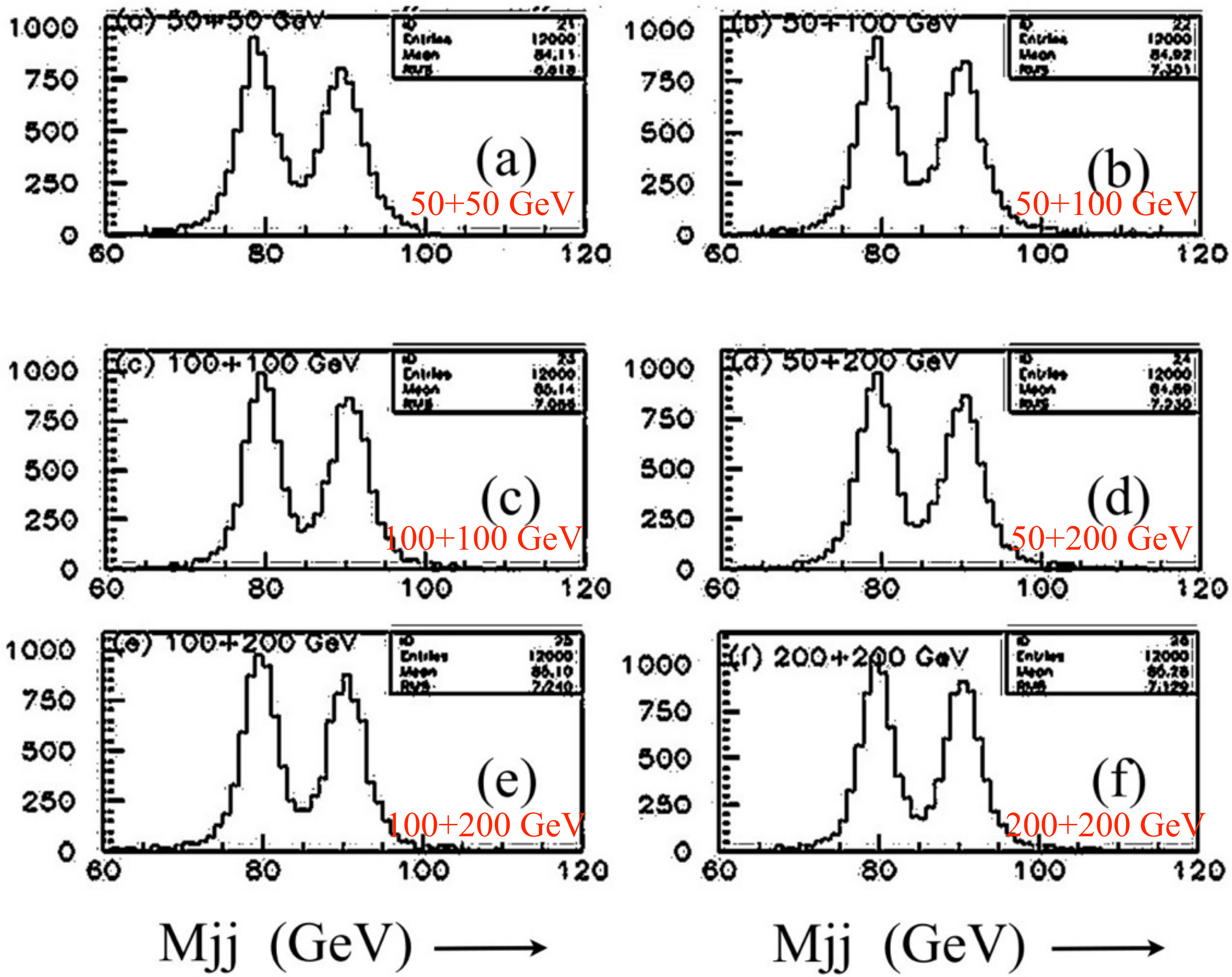
Compensating and dual-readout calorimeters.

The five points are from the FTFP_BERT_HP high-precision simulation of dual-readout at 50, 80, 90, 100 and 200 GeV π^-



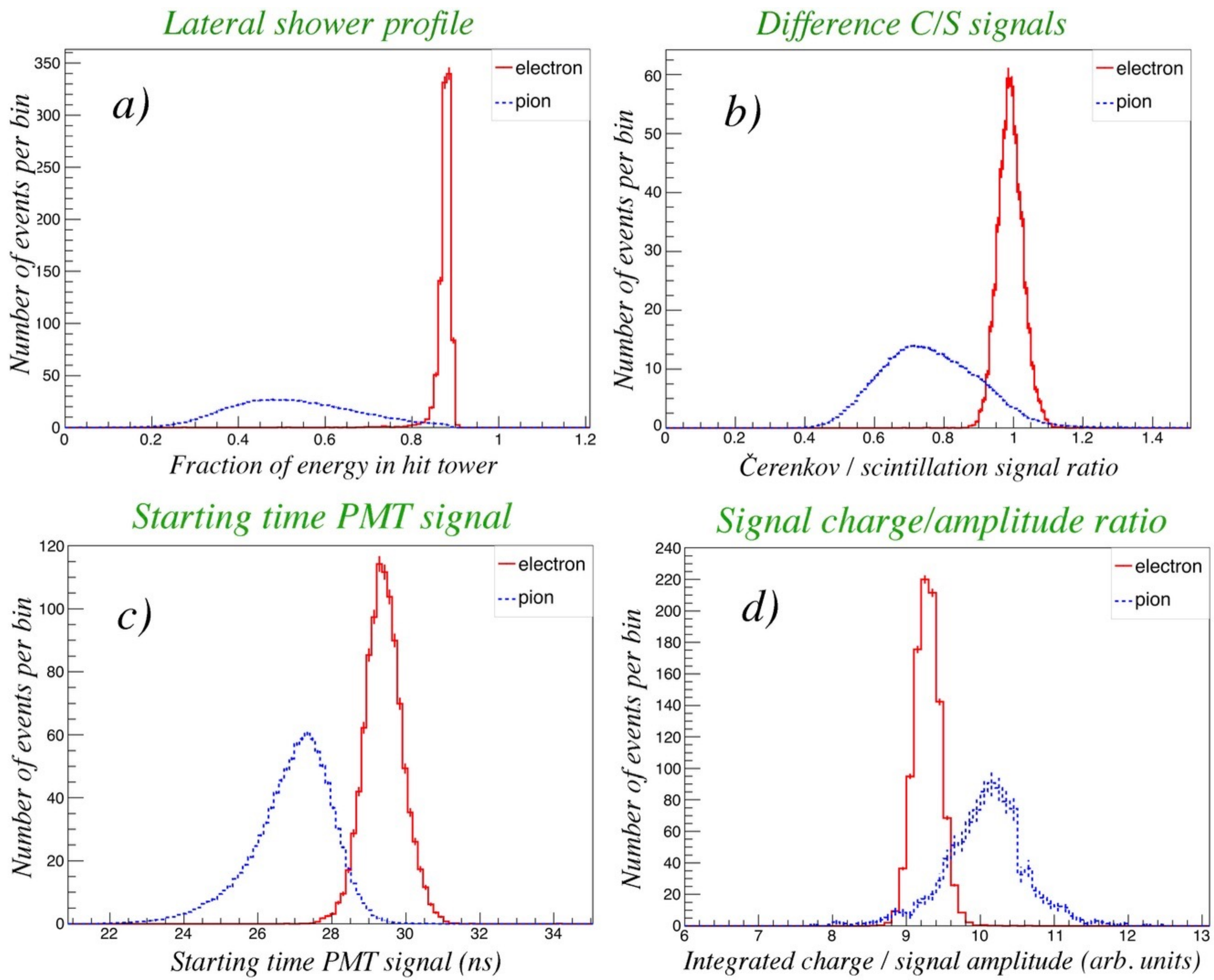
DREAM "interaction-jet" data at 50, 100, and 200 GeV; leakage suppressed; two beam particles set to W,Z Briet-Wigner mass; jet measurements from module data; overlap of jets not modeled.

Data-simulation of W and Z decays to quarks.



Particle ID: electron separation from pions

e^{-} - π^{-}
combined
separation
500:1

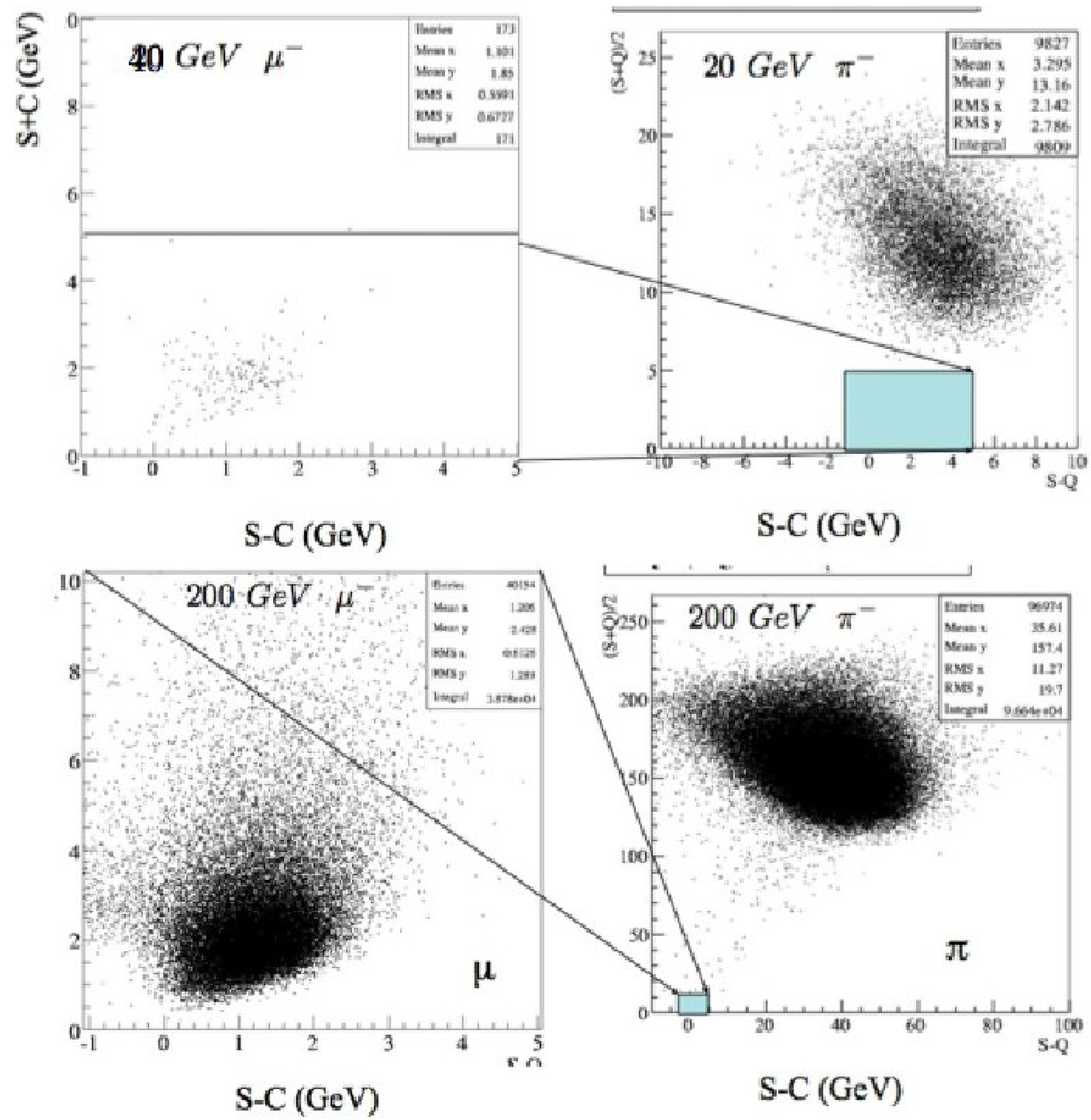


Particle ID: muon separation from pions   (original DREAM module data)

For a muon approximately aligned with the fibers, the Cerenkov signal is zero (outside numerical aperture)

S ~ *dE/dx* + radiation
C ~ 0 + radiation

Therefore,
(S-C) ~ *dE/dx ~ 1.1 GeV*
(S+C)/2 ~ pion energy



Particle ID: muon separation from pions (calorimeter + dual-solenoid)

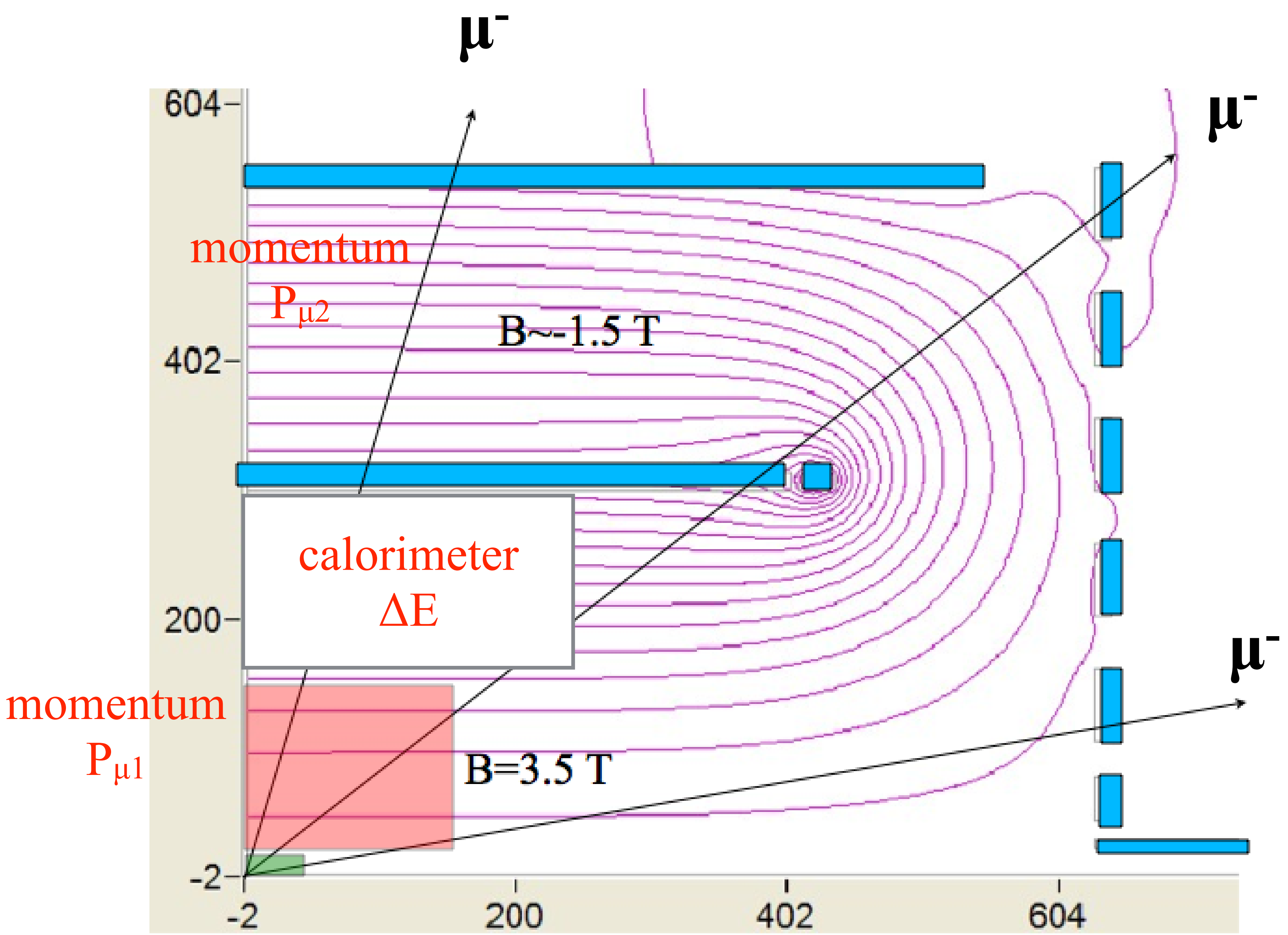
Energy conservation:

$P_{\mu 1} \sim \Delta E + P_{\mu 2}$

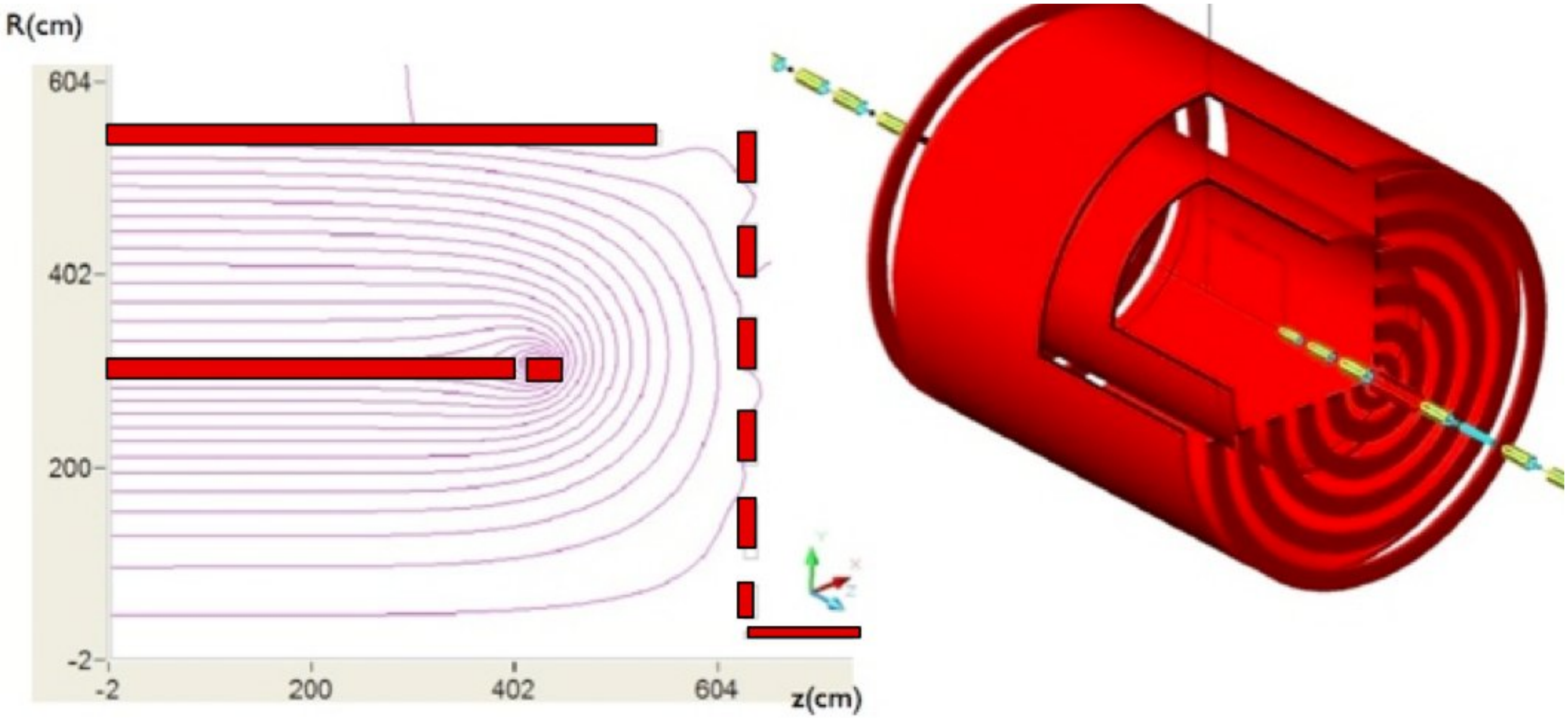
plus

(S-C) vs. (S+C)/2

yields a huge muon-pion discrimination.



Systematic cancellations:



Forward-backward quark asymmetries: cancel by varying and reversing B field

B = 3.5 T $\longrightarrow$ 0 T $\longrightarrow$ -3.5 T

Summary for dual-readout hadronic calorimetry

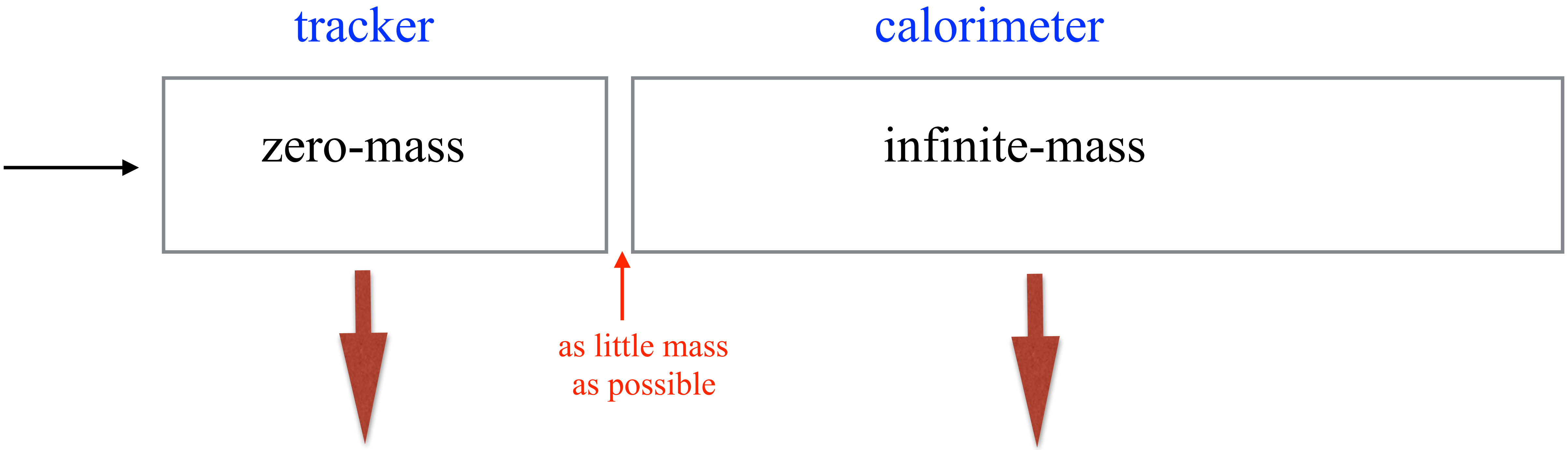
Unsolved problems

- We never built trapezoidal modules suited for a 4π detector, although the Pavia group (R. Ferrari, et al.) did so on RD1. A 'concept detector' was designed by the 4th group.
- SiPM studies underway (M. Caccia, et al., NIM paper)
- We formed two copper modules (F. Scuri, INFN Pisa), but did not succeed to build a large number at low cost.
- Tracker-calorimeter-coil or tracker-coil-calorimeter ?

Strengths we know (tested and published, NIM)

- Robust calibration with electrons only; Gaussian response function; linear mean response; good energy resolution.
- e^- and μ^- particle ID, "easy" to build.

Thank you for your attention.



He-based (?)
gaseous tracking

10 λ_{Int} deep copper
calorimeter

Beam crossing time
0.2 to 2.0
microseconds

$$\lambda_{\text{Int}}^{\text{Cu}} = 137.3\ \text{g/cm}^2 \quad \text{and} \quad \lambda_{\text{Int}}^{\text{Pb}} = 199.6\ \text{g/cm}^2$$

therefore a cubic nuclear interaction length is a factor of three smaller in Cu than in Pb:

$$(\lambda_{\text{Int}}^{Cu}/\lambda_{\text{Int}}^{Pb})^3 \approx 0.325$$

Thin silicon OK
(control Xo creep)

Classic calorimeter: measure particle energy losses in a defined geometrical volume.