Zero-degree High-Precision Hadronic Calorimetry

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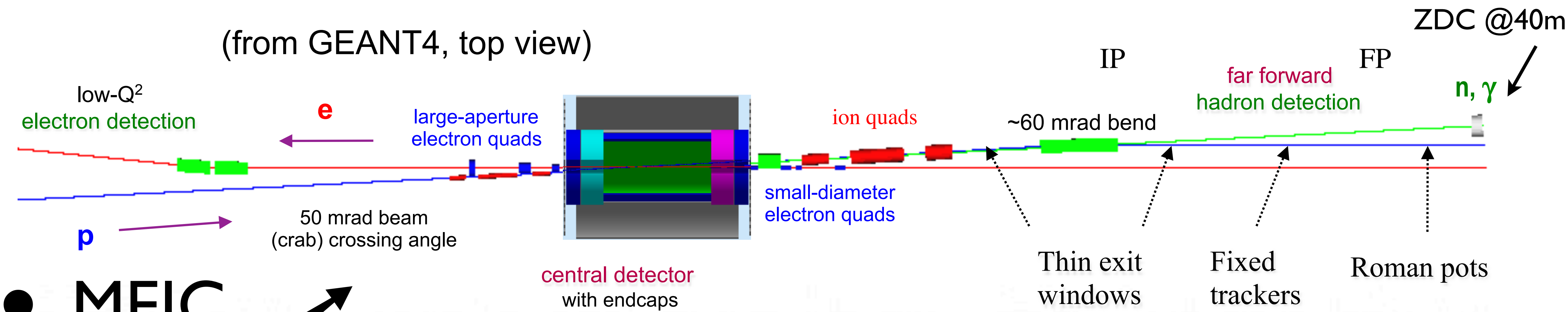
†RD52 Collaboration

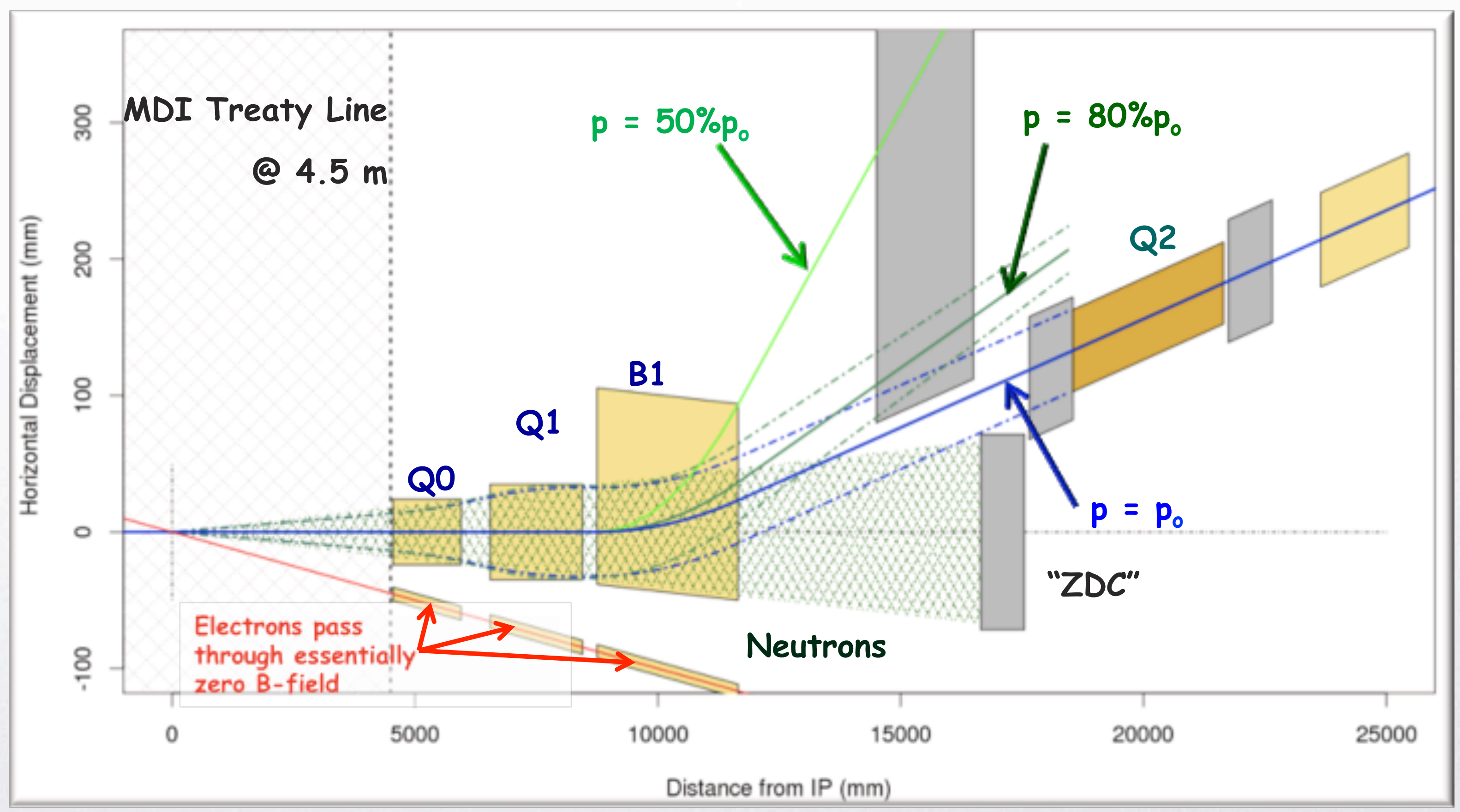
IP Layouts



- MEIC ↗

- eRHIC →

- ~1 m Ion beam to 0° line separation



Why 0°Calorimetry (ZDC)?

- e+p Baryonic Final State:
  - DIS target fragmentation/diffraction: *p(e,e'n)X, p(e,e'Δ)X*...
  - SIDIS: $e+p \rightarrow e'\, h+x + N+X$
    - Schweitzer, Strikman, & Weiss: arXiv 1210.1267
      χSB: Correlations between target- and current-jet fragmentation
  - Exclusive p(e,e'ρ^+n): Acceptance needed up to $p_\perp \gtrsim 1$ GeV/c
- Spectator neutrons from light nuclei:
  - Tag active nucleon momentum in D, ^{3,4}He
- Evaporation neutrons from medium-heavy nuclei:
  - Tag current-jet propagation length in nucleus event-by-event?
  - neutrons: [±2% total energy resolution ⊗ multiplicity] achievable

High performance important to physics program

ZDC Acceptance

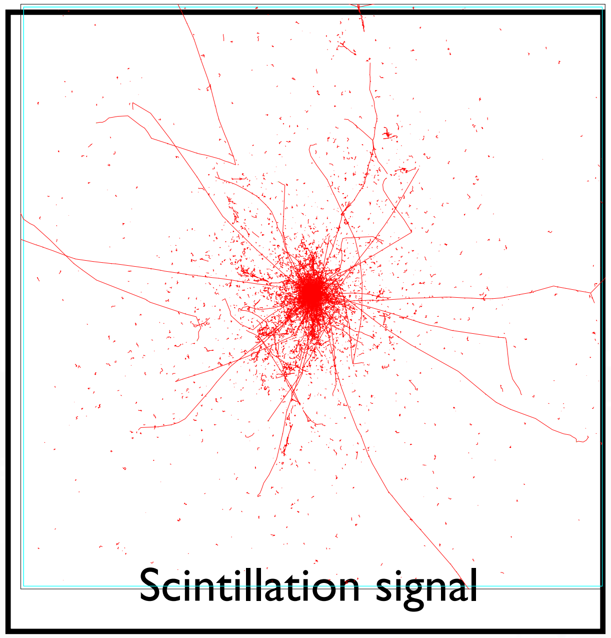
- SIDIS, Exclusive $p_{n\perp} \lesssim 1000$ MeV/c
- Spectator neutrons from light nuclei: $p_{\perp} \lesssim 200$ MeV/c
- Evaporation neutrons from heavy nuclei: $E_n < 10$ MeV ➜ $p_{n\perp} < 140$ MeV/c
- MEIC: ZDC ≤ 40 m from IP. Acceptance: $\theta_{n,\gamma} \lesssim 15$ mrad
  - $P(^AZ) = Z(100\ \text{GeV/c})$:
    - p-SIDIS, -Exclusive: $\theta_n < (1\ \text{GeV/c})/(100\ \text{GeV/c}) = 10$ mr
    - Light Nuclei spectators : $\theta_n < (0.2\ \text{GeV/c})/(50\ \text{GeV/c}) = 4$ mr
    - Heavy nuclei evaporation: $\theta_n < (0.140\text{GeV/c})/(40\ \text{GeV/c}) = 2.5$ mr
- eRHIC: ZDC ≤ 20 m from IP. Acceptance: $\theta_{n,\gamma} \lesssim 5$ mrad
  - $P(^AZ) = Z(250\ \text{GeV/c})$:
    - p-SIDIS, -Exclusive: $\theta_n < 1/250. = 4$ mr
    - Light Nuclei spectators : $\theta_n < 0.2/125. = 1.6$ mr
    - Heavy nuclei evaporation: $\theta_n < 0.14/100 = 1.4$ mr

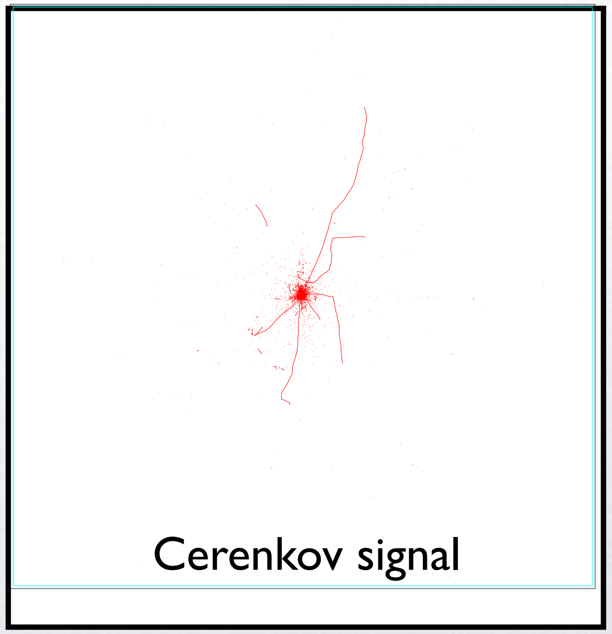
Dual Read-Out Calorimetry

- Sampling Calorimeter with separate readout of Cerenkov and Scintillation light. Fast (>1 GHz) pulse shape digitization (30+ NIM papers).
  - Event-by-event measurement of EM and hadronic parts of shower.
  - High spatial resolution of EM core of hadronic shower (Rayleigh criterion for separation $\leq$4 cm)
  - μ/π and n/γ particle I.D.
- Energy Resolution ~ $30\%/\sqrt{E}$ (GeV)

arXiv:0412123

Lateral Shower Spread





ZDC - Heavy Nuclei

- *eA* DIS: Neutron multiplicity and total energy:
  - Tag jet propagation length in nucleus event-by-event?
    - Count neutrons via isolation of EM shower cores
      - ~4 cm separation @ 40 m ➝ 1.0 mr (rms separation 2.5 mr)
    - Total energy of neutron evaporation:
      - Event with 10 neutrons, ~40 GeV each
        $[30\% / \sqrt{(400\ GeV)} + 1\%/\sqrt{N_n}\,] < 2.0\%$
- Charged particle multiplicity measured in far forward trackers

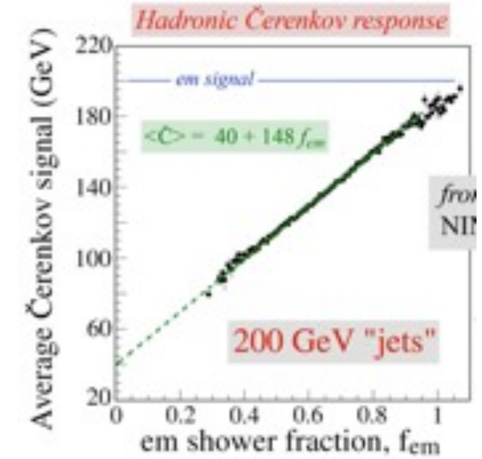
Exploratory Project ($32,100)

- What EIC specific aspects of Dual Readout Calorimetry require additional R&D?
  - Incorporate Dual Readout ZDC into detector/physics simulations
    - Spectator tagging theory/simulation funded by JLab LDRD
    - Extensive theory support for SIDIS, exclusive reactions
  - Synergy with CERN RD52 Collaboration
    - Two test runs in next fiscal year
    - Cluster separation: Analyze Monte-Carlo pileup of single particle data
    - n/γ separation and resolution:
      - n/γ simulation vs (π,p)/e data

High-precision neutron calorimeter: dual-readout for ZDC

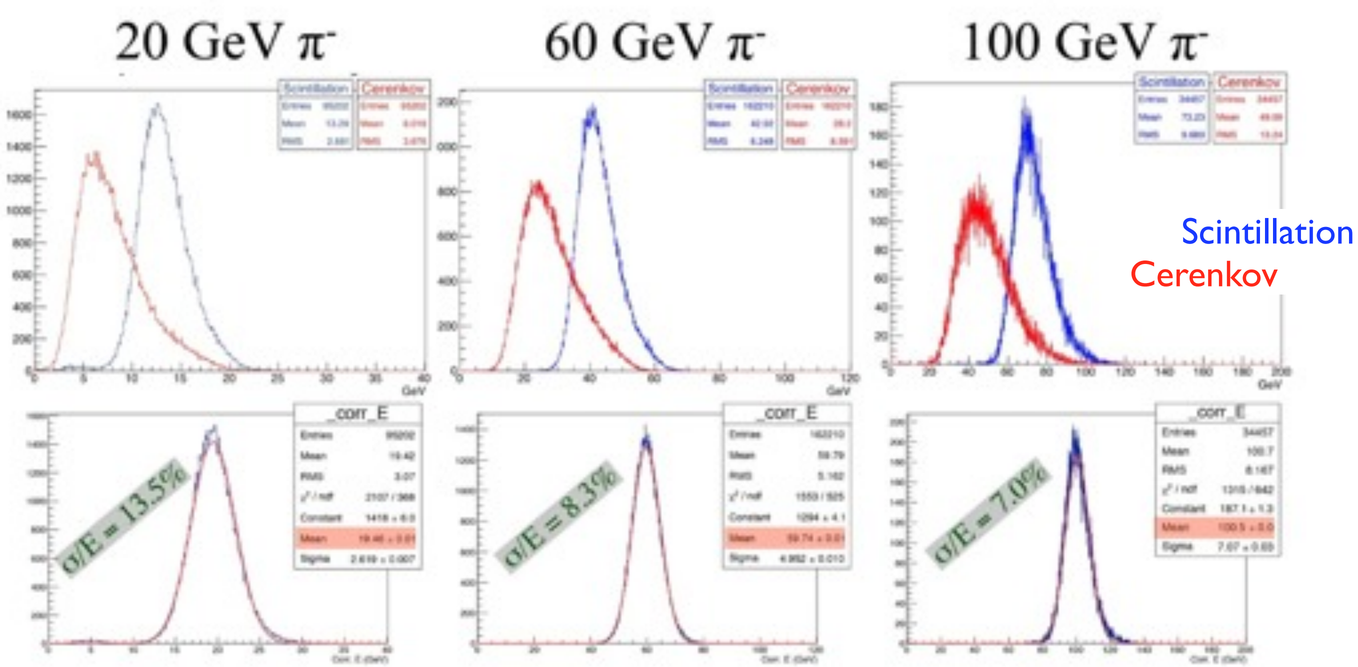
- measure every shower twice: scintillation and Cerenkov
- directly measures EM fraction, f_{em}
- set physical response averages, $\eta_C \sim (h/e)_C$ and $\eta_S \sim (h/e)_S$, then

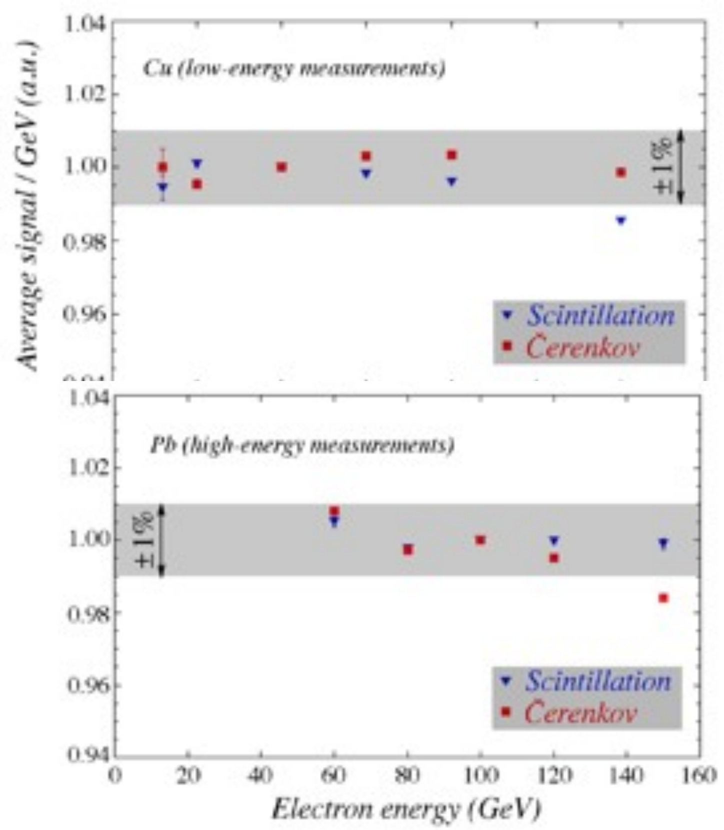
$$S = E\,[f_{em} + (1 - f_{em})\eta_s]$$
$$C = E\,[f_{em} + (1 - f_{em})\eta_c]$$



- calibrate with electrons in each channel - GeV/ADC

$$E = \frac{S - \chi C}{1 - \chi} \quad \textit{with} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = 0.45$$





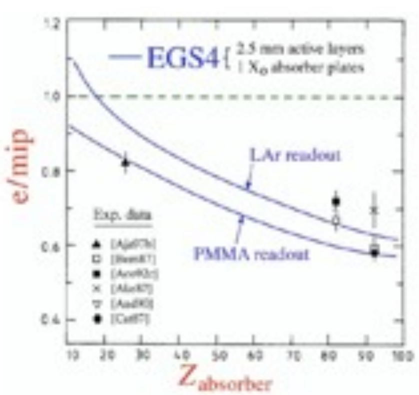
CERN project, RD52: 30 NIM papers on dual-readout

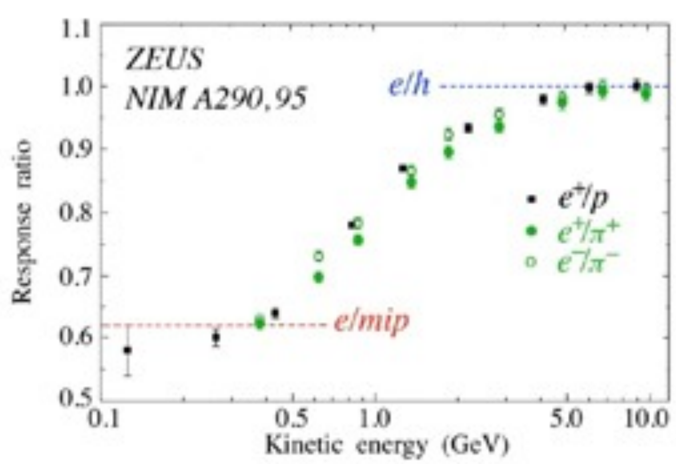
Cu modules, RD52:
Pisa x2 (tested)
Ames x16 (to be)

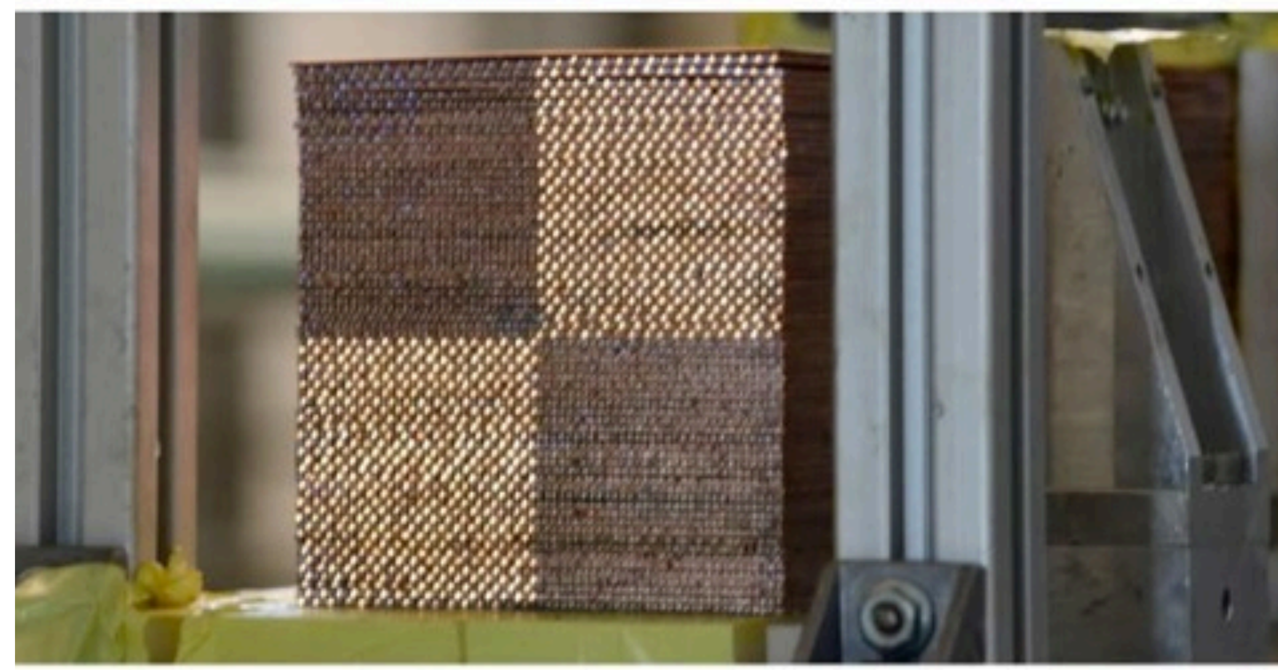
Pb modules, RD52:
Pavia x9

Absorber choice: Cu vs Pb

- *Detector mass: λ_{Cu} = 15.1 cm, λ_{Pb} = 17.0 cm*
  Mass $1\lambda^3$: Cu/Pb = 0.35
- *e/mip ⟶ Čerenkov light yield Cu/Pb ~ 1.4*
  (Showers inefficiently sampled in calorimeters with high-Z absorber)
- *Non-linearity at low energy in calorimeters with high-Z absorber*
  Important for jet detection

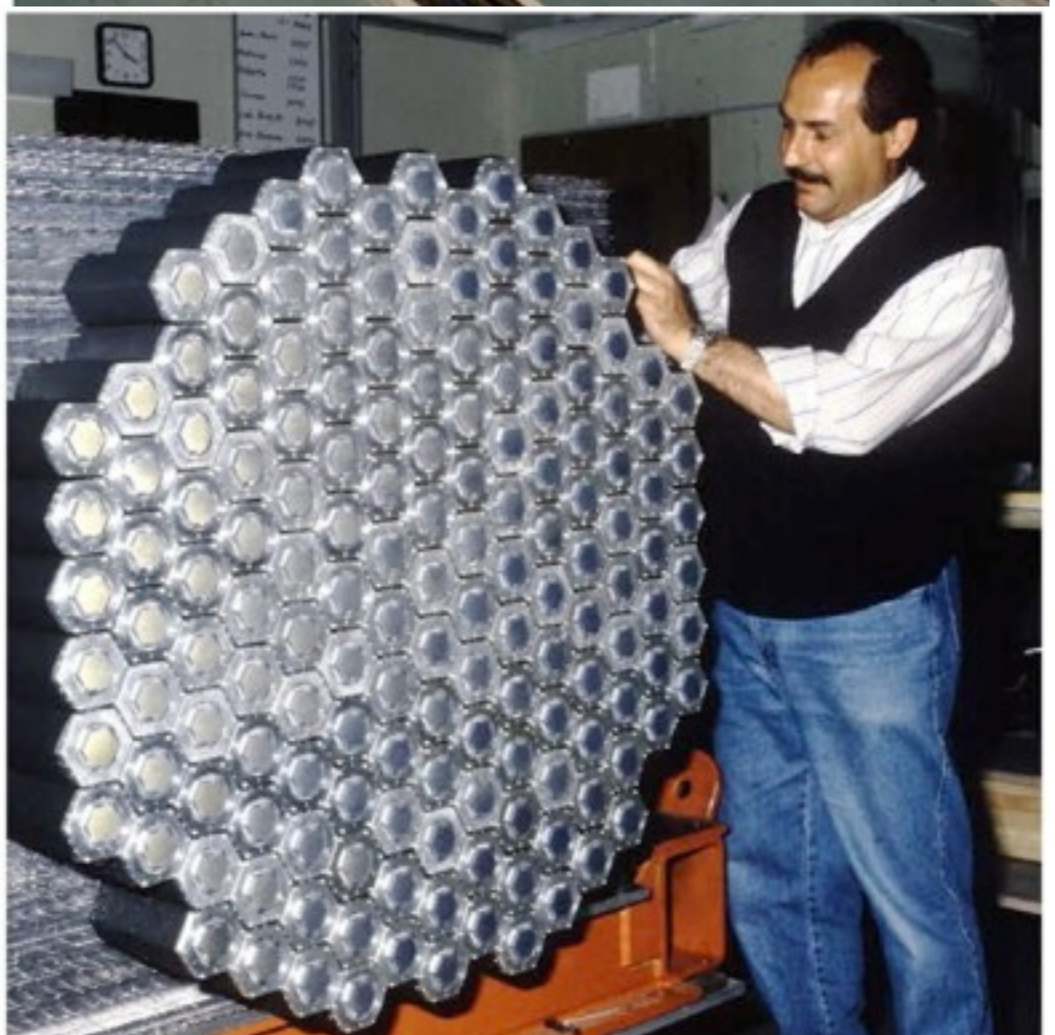




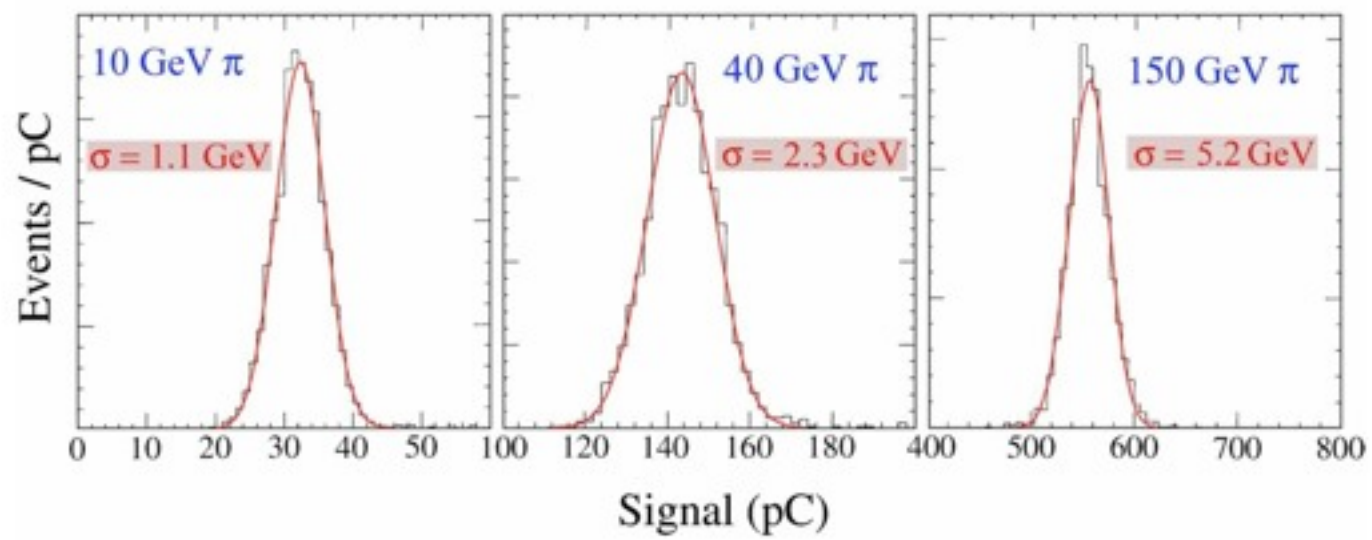


SPACAL 1989

Pb + scintillating fibers: 20 tons, long integration time



Hadronic signal distributions in a compensating calorimeter



from: NIM A308 (1991) 481

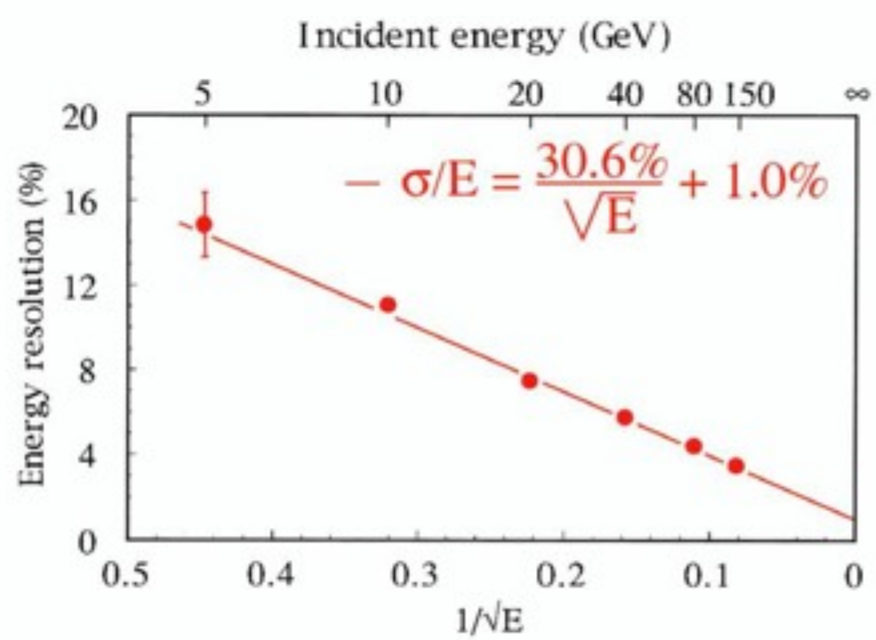
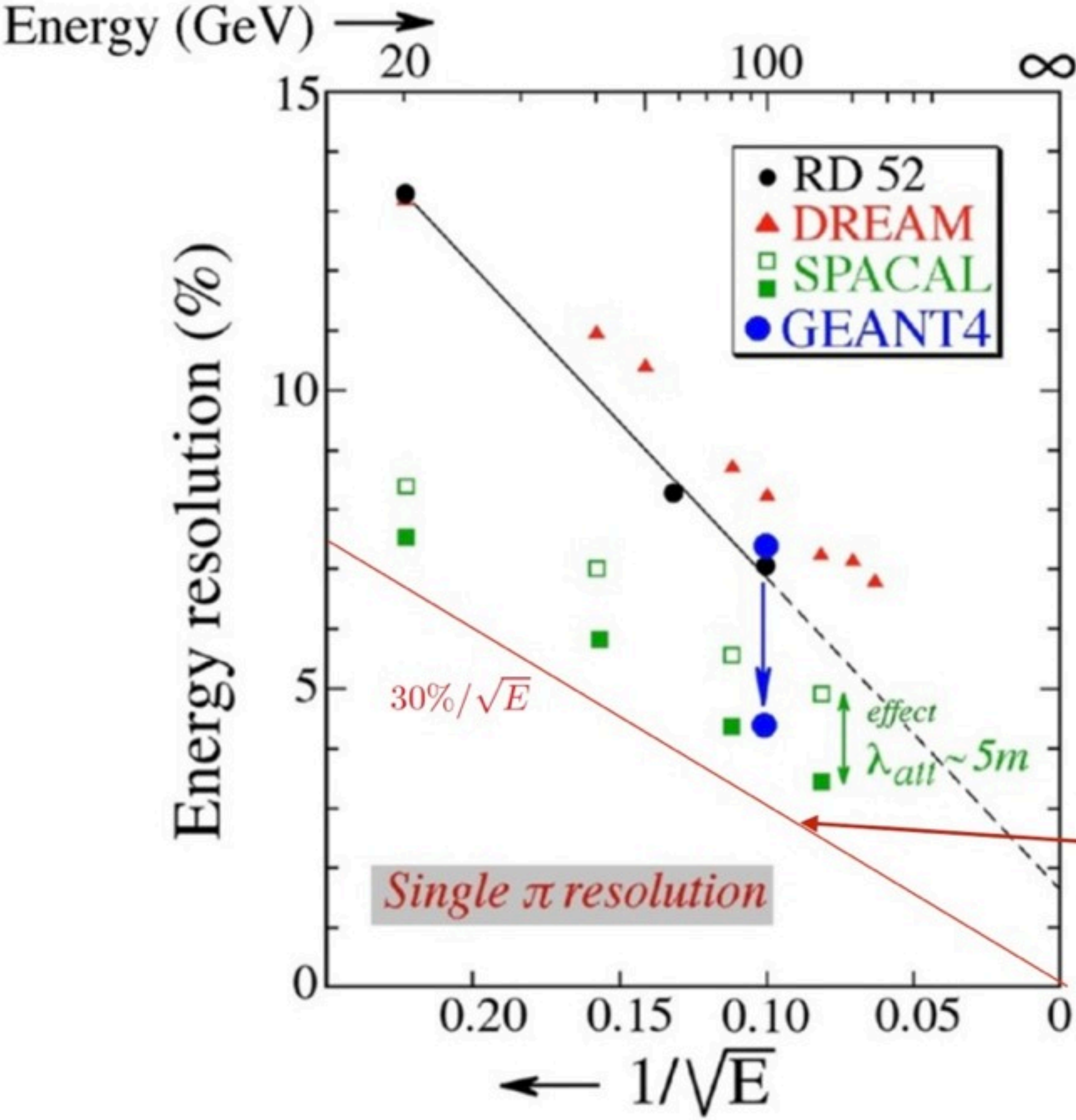


Figure 10: The hadronic energy resolution as a function of energy, for the compensating SPACAL *lead/plastic-scintillator calorimeter (sampling fraction 2%)*

NIM A308 (1991) 481



Comparison of four fiber modules; importance of attenuation and total absorbing mass.

Single π *maximizes* attenuation effects due to depth development fluctuations: gives ~2% constant term

at 100 GeV
$\sigma/E = 3\%$

RD52 plans and schedule (CERN):

- Dec. 2014 one-week test, *e*'s and π's
  study EM features of Cu & Pb modules

- Jul. 2015 two-week test of 2-ton Cu module,
  surrounded by 1.5-ton of Pb modules,
  plus 0.5-ton of neutron counters.

- the 2-ton Cu module is a close prototype for an ZDC

This request is for travel funds to support the Dec. 2014 and July 2015 beam tests by JLab and ODU physicists

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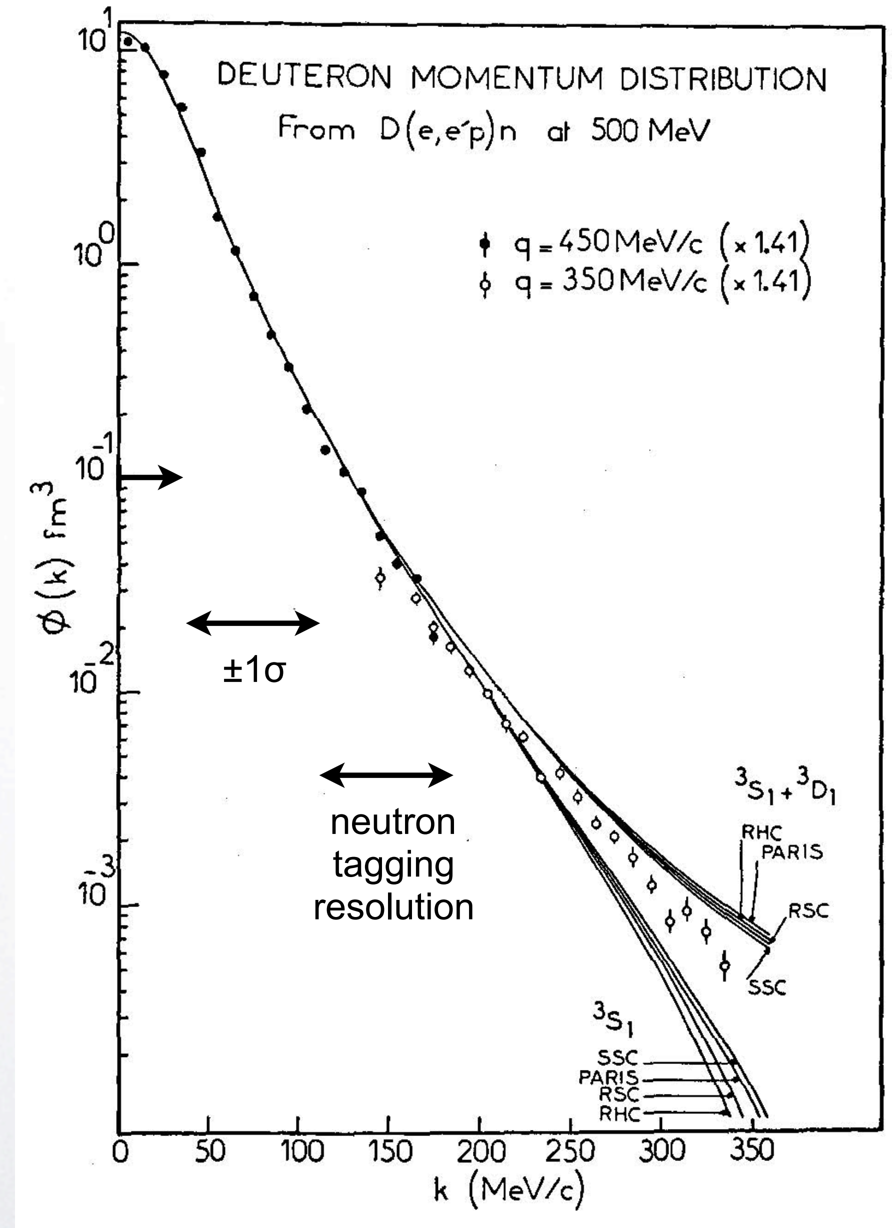
Backup slides

- neutron counting in ZDC
- proton-pion differences
- particle ID (electron-pion)
- leakage limited resolution

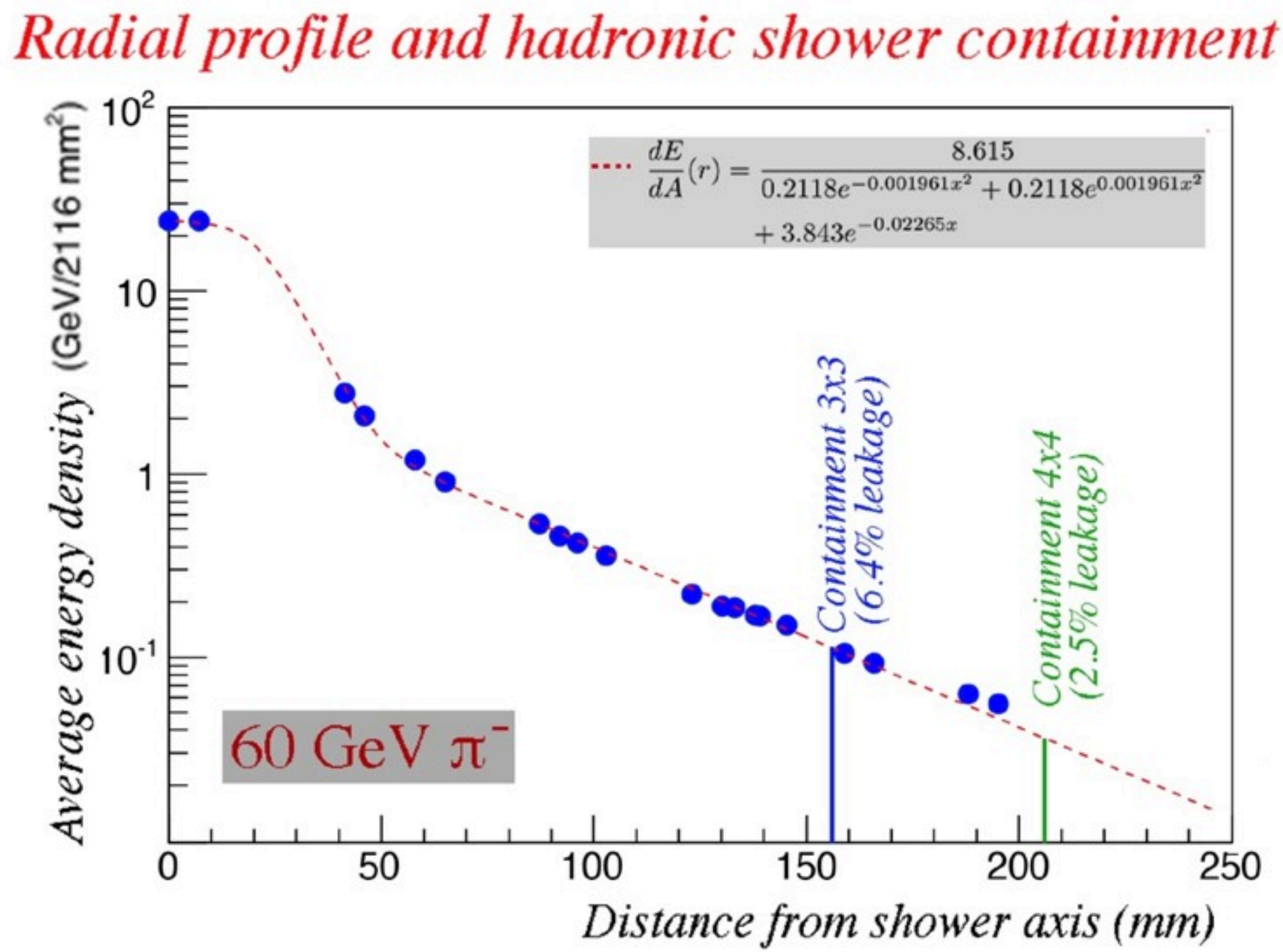
ZDC-Light Nuclei

- Spectator neutron tagging: Bound proton structure
  - DIS: D(*e,e'n_S*)X
  - Deep Virtual Exclusive: D(*e,e'n_S p γ*), D(*e,e'n_S p V*), ...
    - P_D = 100 GeV/c ➡ $p_n \approx$ 50 GeV/c
      - 30%/√E ➡ δp/p ≈ 4 %
      - Deuteron RestFrame δk ~ 0.04M



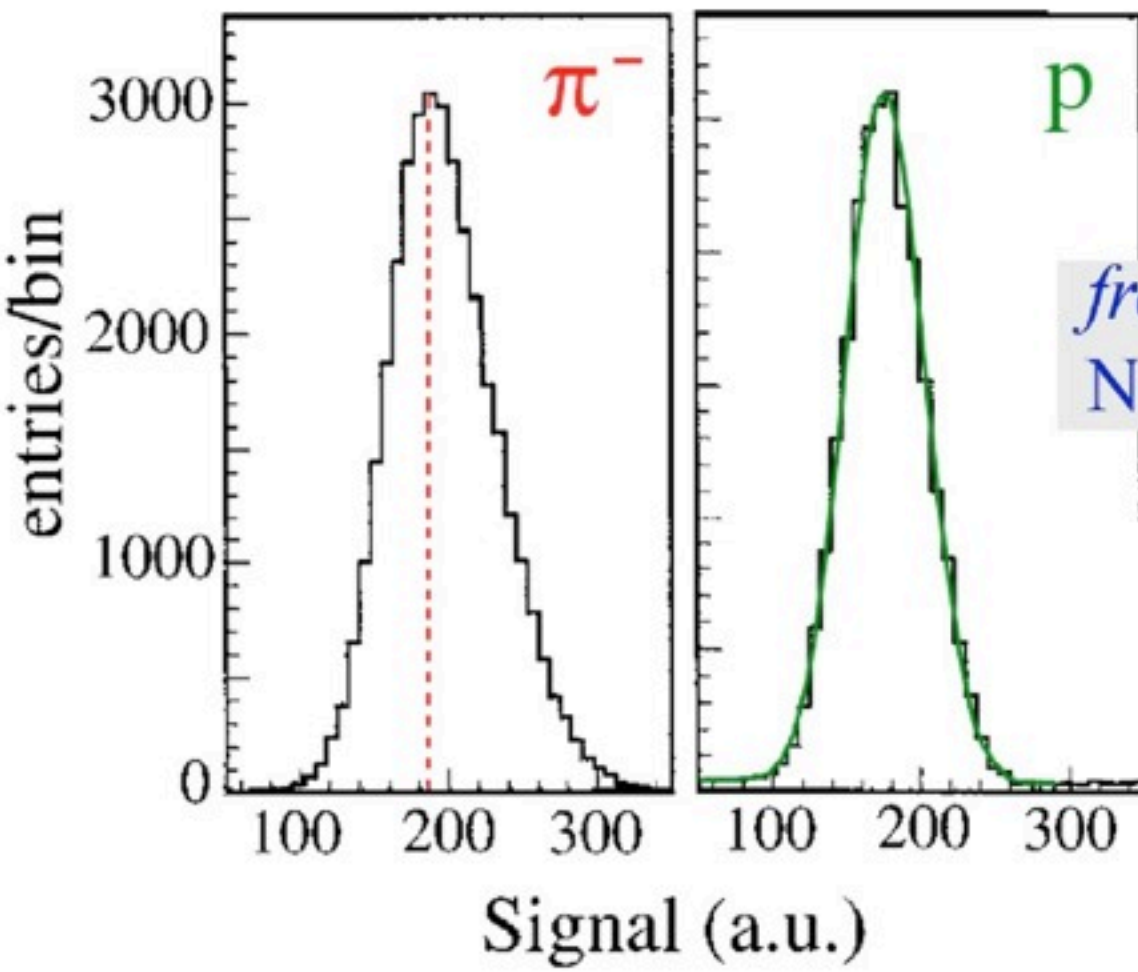
Monday, July 21, 2014

Counting neutrons: Rayleigh criterion at 4cm separation

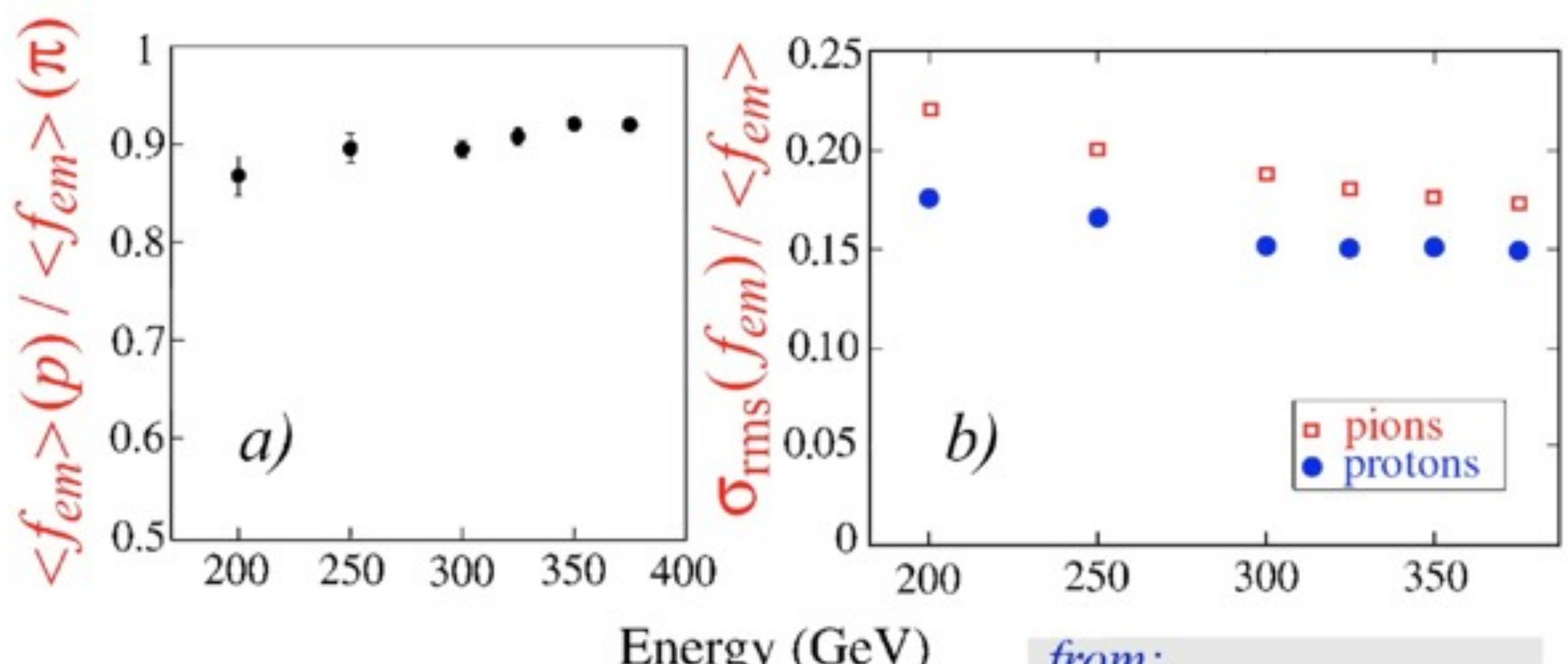


Proton-pion differences: may be useful in neutron tagging?

300 GeV showers in Cu



from:
NIM A408 (1998) 380

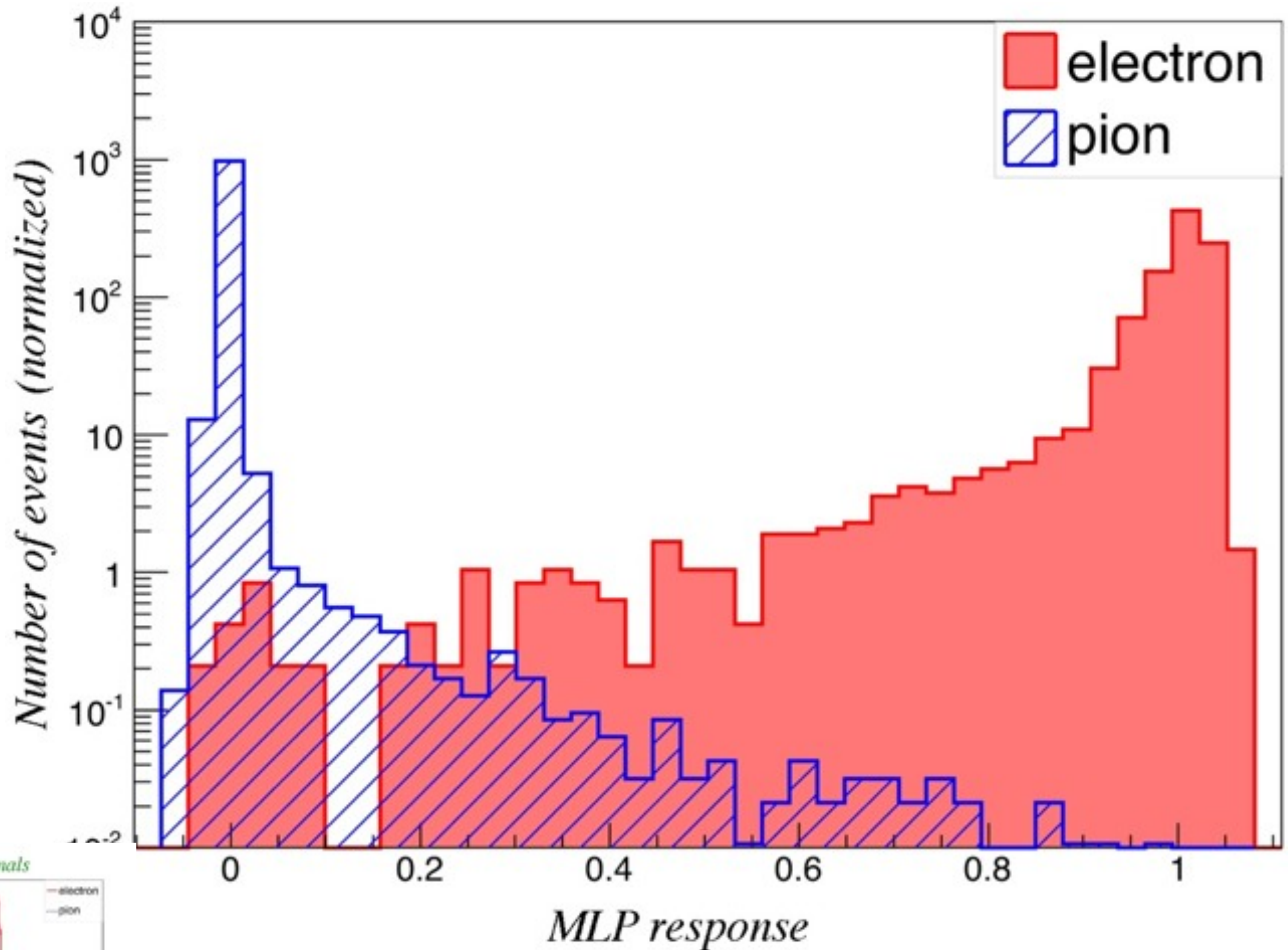


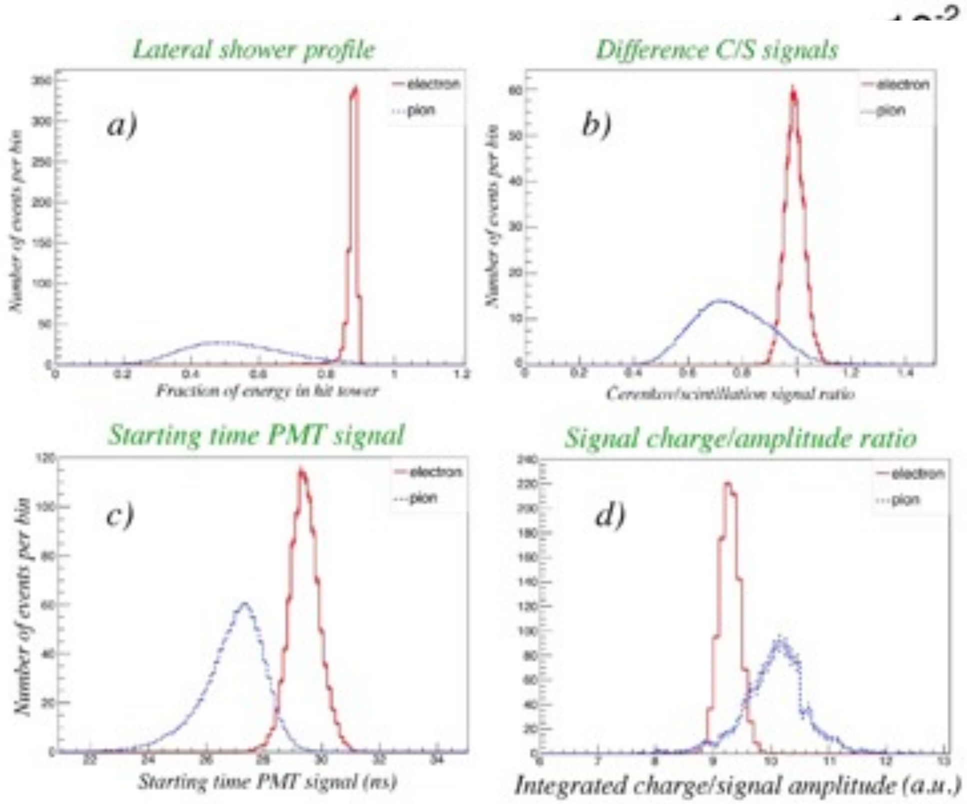
from:
NIM A408 (1998) 380

Particle ID:

e - π 99.8%

γ - n similar?





Based on four measures:

- lateral spread,
- C/S,
- longitudinal spread,
- time history

Direct energy resolution:

still limited by 4% leakage fluctuations. We are "building up" to 4 tons by next summer.