Dual-readout Calorimetry in ILC Detectors - *it's not too late*

The point of this 30 minutes is to show that dual-readout calorimeters

- are trivially calibrated with electrons at one energy
- are very nicely Gaussian in their response
- are linear to the highest tested energies
- have excellent hadronic energy resolution
- can be incorporated into a 4π collider detector
- provide numerous particle identifications

Even the small DREAM module achieves 4% energy resolution that is Gaussian and linear.

Remaining work for RD52 towards a 4π collider detector:

- directly achieve σ/E ~ 1-2% energy resolution (larger module, etc.)
- demonstrate that a fiber truncated pyramid works
- use SiPM readout (or another B-tolerant photo-converter; psec collab.)

These three items are approved and funded in our DoE proposal

I will discuss energy resolution, linearity,
4π geometry, SiPM readout, W, and particle ID.

John Hauptman, ILC & more, 16-17 May 2013, Villa del Grumello, Lake Como, Italy

The brief history of excellent hadronic calorimetry (it’s short):

SPACAL: first “compensating” calorimeter; Pb-scintillating fiber; 20 tonnes; EM resolution not so good; long integration time to achieve compensation

$\sigma/E \sim 30\% / \sqrt{E}$ “no if’s, and’s, or but’s” (beam module)

ZEUS: nearly compensating; U-scintillator;

$\sigma/E \sim 35\% / \sqrt{E}$ (beam module)

ATLAS: iron-scintillator

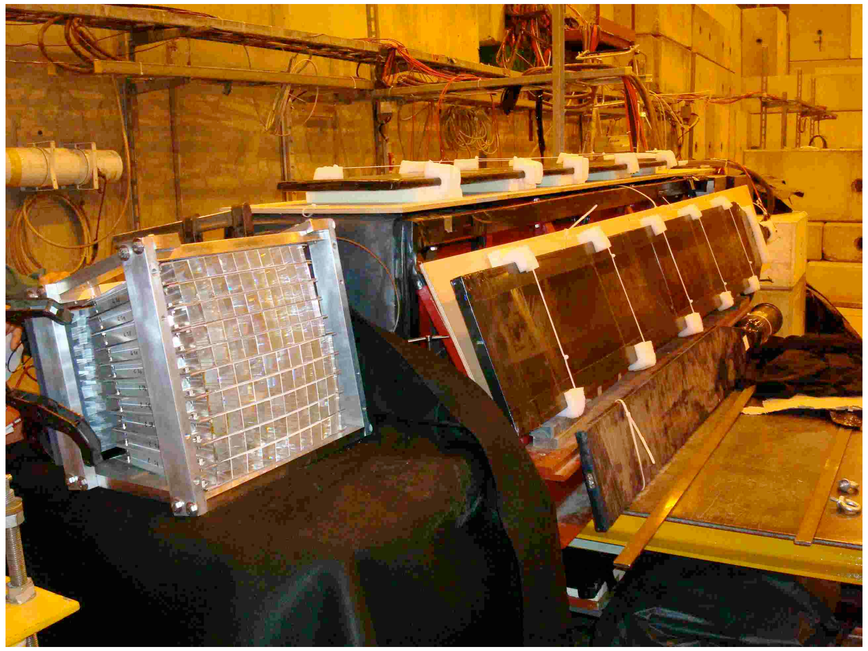
$\sigma/E \sim 50\% / \sqrt{E} \oplus 3\%$ (4π calorimeter)

DREAM/RD52 modules:

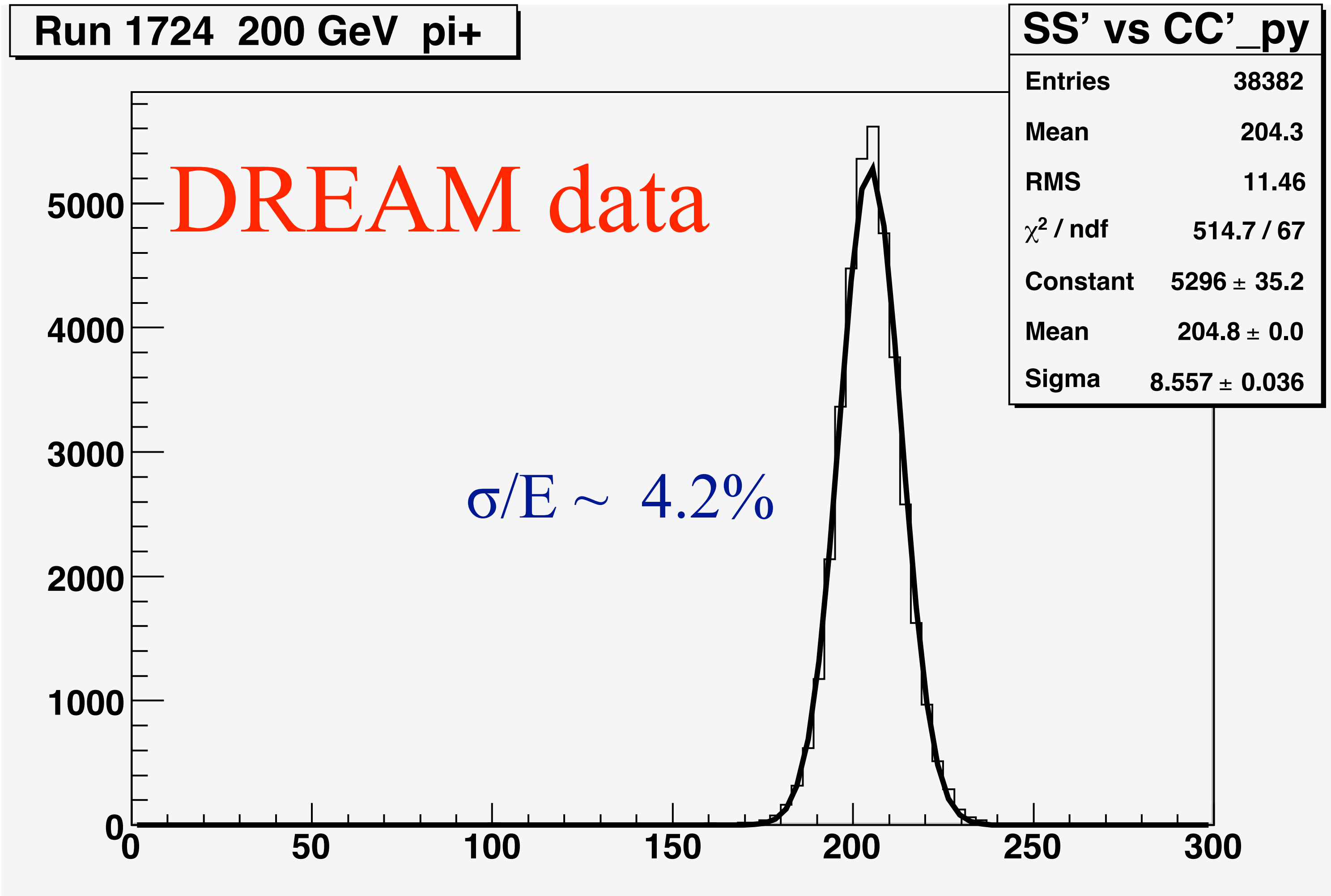
$\sigma \sim 4\%$ at 200 GeV π^+ (leakage limited) (beam module)

σ/E ~ 1-2%

BGO dual-readout +
DREAM fiber calorimeter

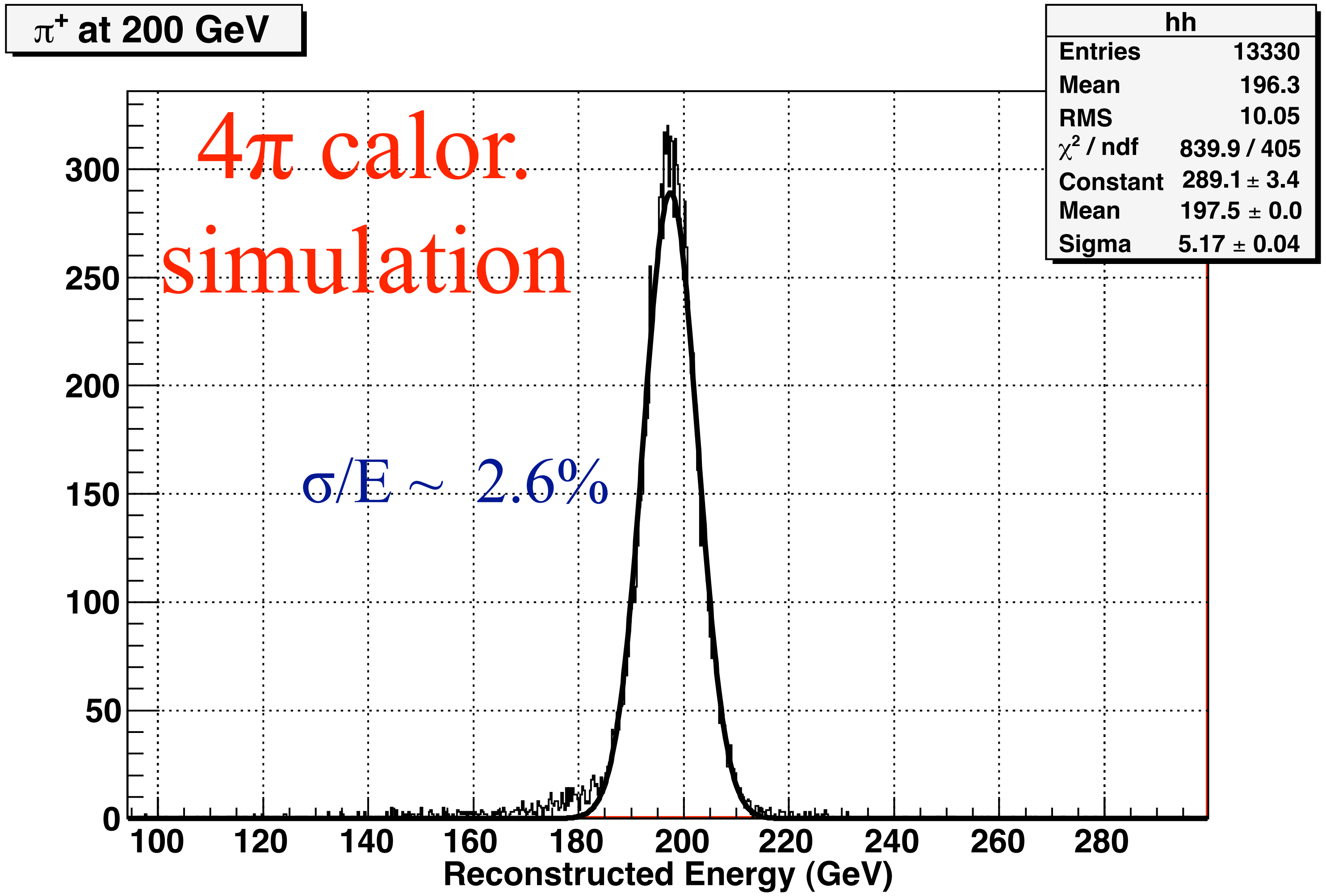


200 GeV π^+ CERN



DREAM data

σ/E ~ 4.2%



4π calor.
simulation

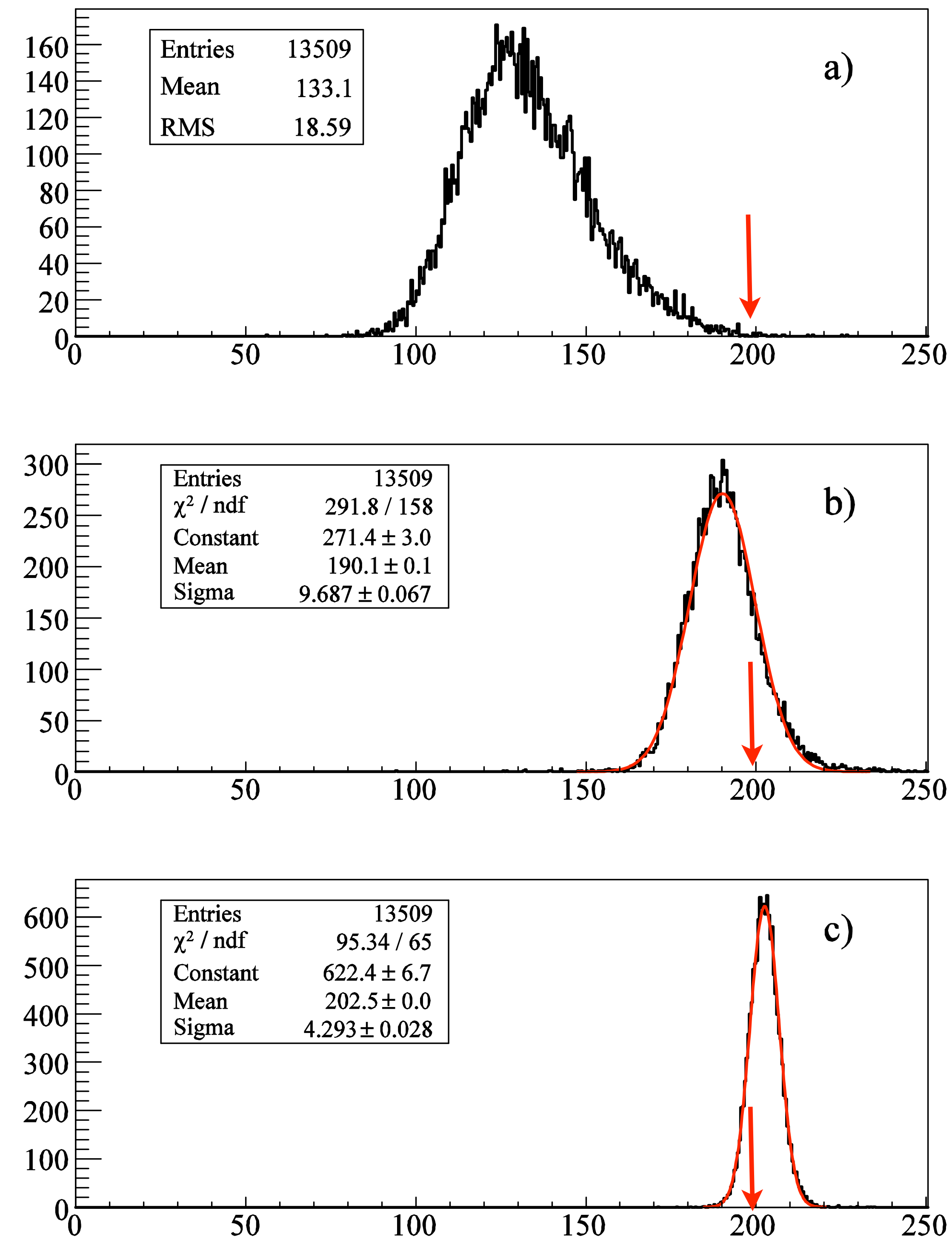
σ/E ~ 2.6%

Note: data are *cleaner* than simulation: no tails, no background.

Reason: the DREAM is perfectly rectilinear; simulation has projective towers.

σ/E ~ 1-2%

DREAM data: 200 GeV π^- energy response



Data NIM A537 (2005) 537.

Scintillating (S) fibers only

Dual-readout of S and Cerenkov (C)

$$f_{EM} \propto (C/E_{shower} - 1/\eta_C)$$

(4% leakage + neutron BE loss fluctuations, and limited by photoelectron statistics in C)

Dual-readout of S and C:

$$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$$

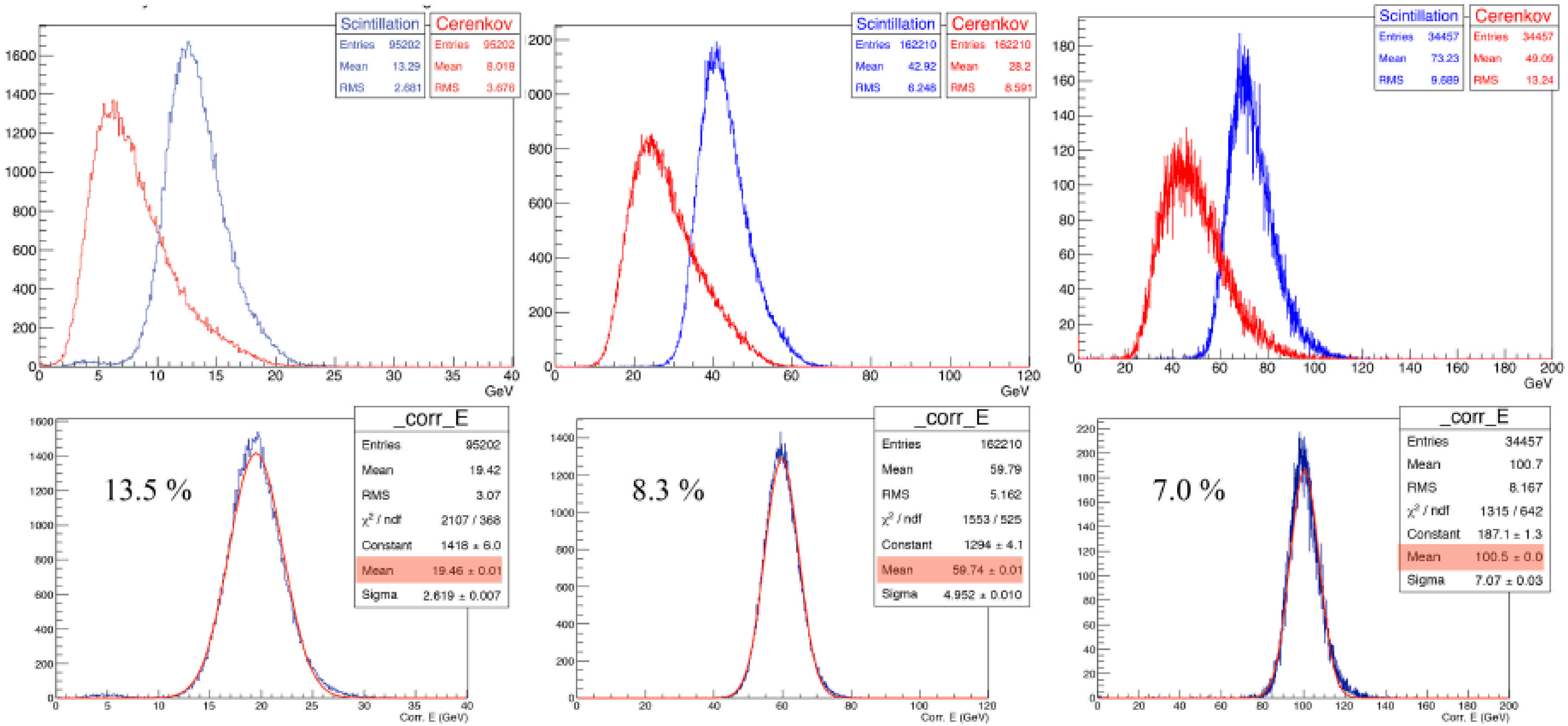
$$E = S / [f_{EM} + (1-f_{EM})\eta_S]$$

(suppresses leakage and BE fluctuations; optimum for DREAM geometry; σ/E ~ 20% /$\sqrt{}$E)

σ/E ~ 1-2%

Recent (Dec. 2012) RD52 test data: Gaussian, linear (single e^- calibration)

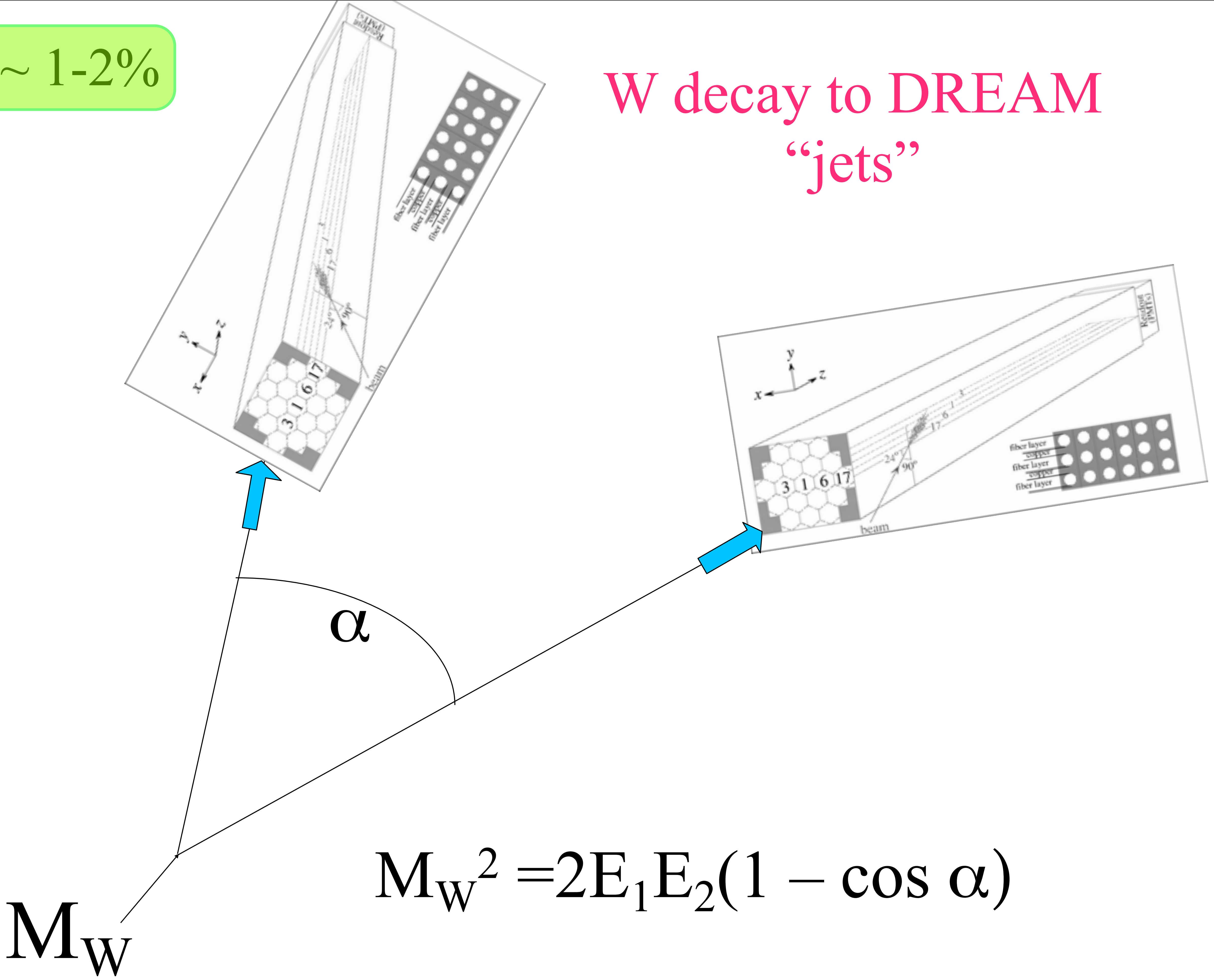
20 GeV π^- 60 GeV π^- 100 GeV π^-



Final resolution still dominated by leakage fluctuations

W decay to DREAM "jets"

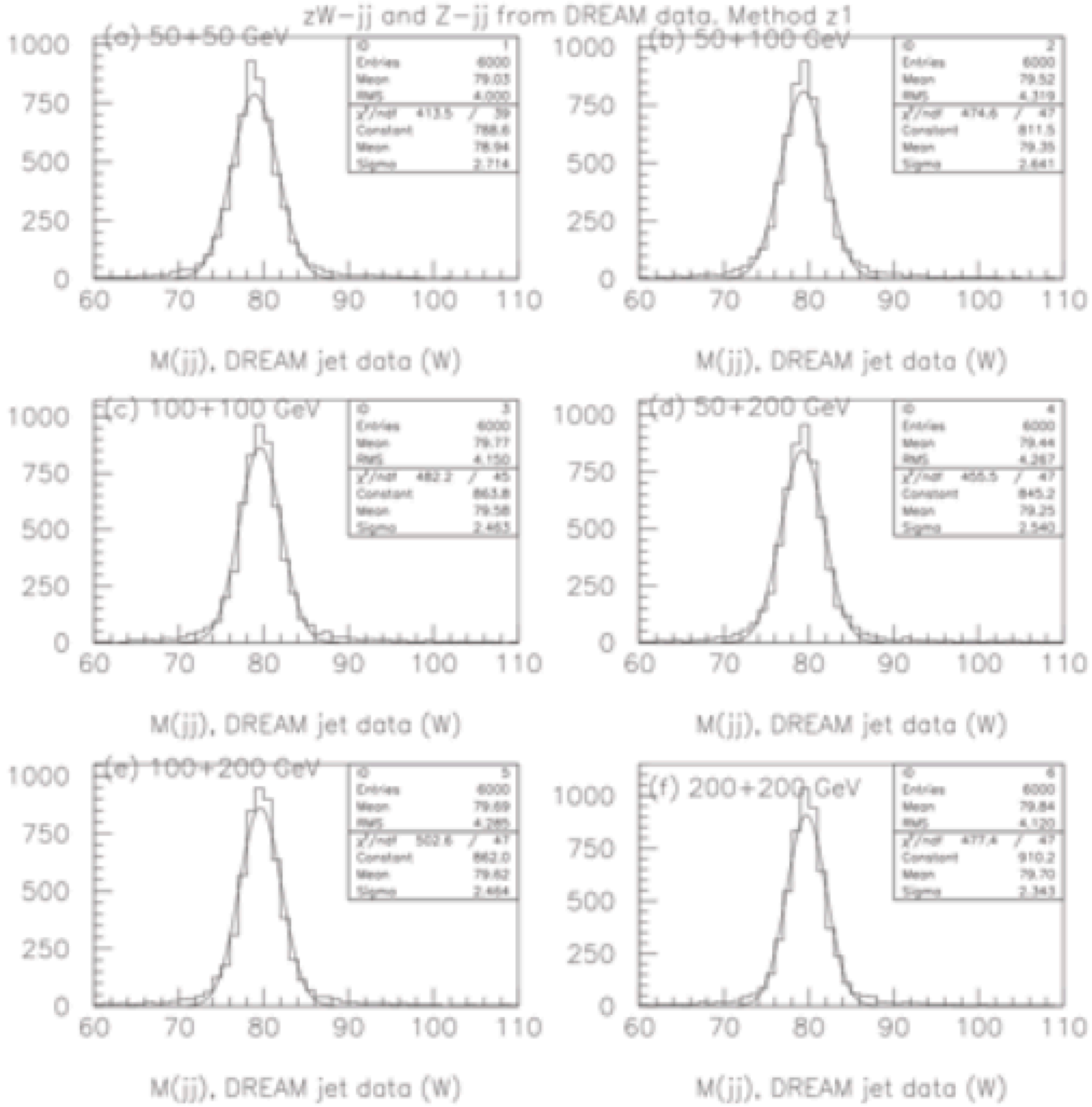
$\sigma/E \sim 1\text{-}2\%$



$$M_W^2 = 2E_1E_2(1 - \cos\alpha)$$

σ/E ~ 1-2%

W → "jet" + "jet" ("jets" are DREAM data events)

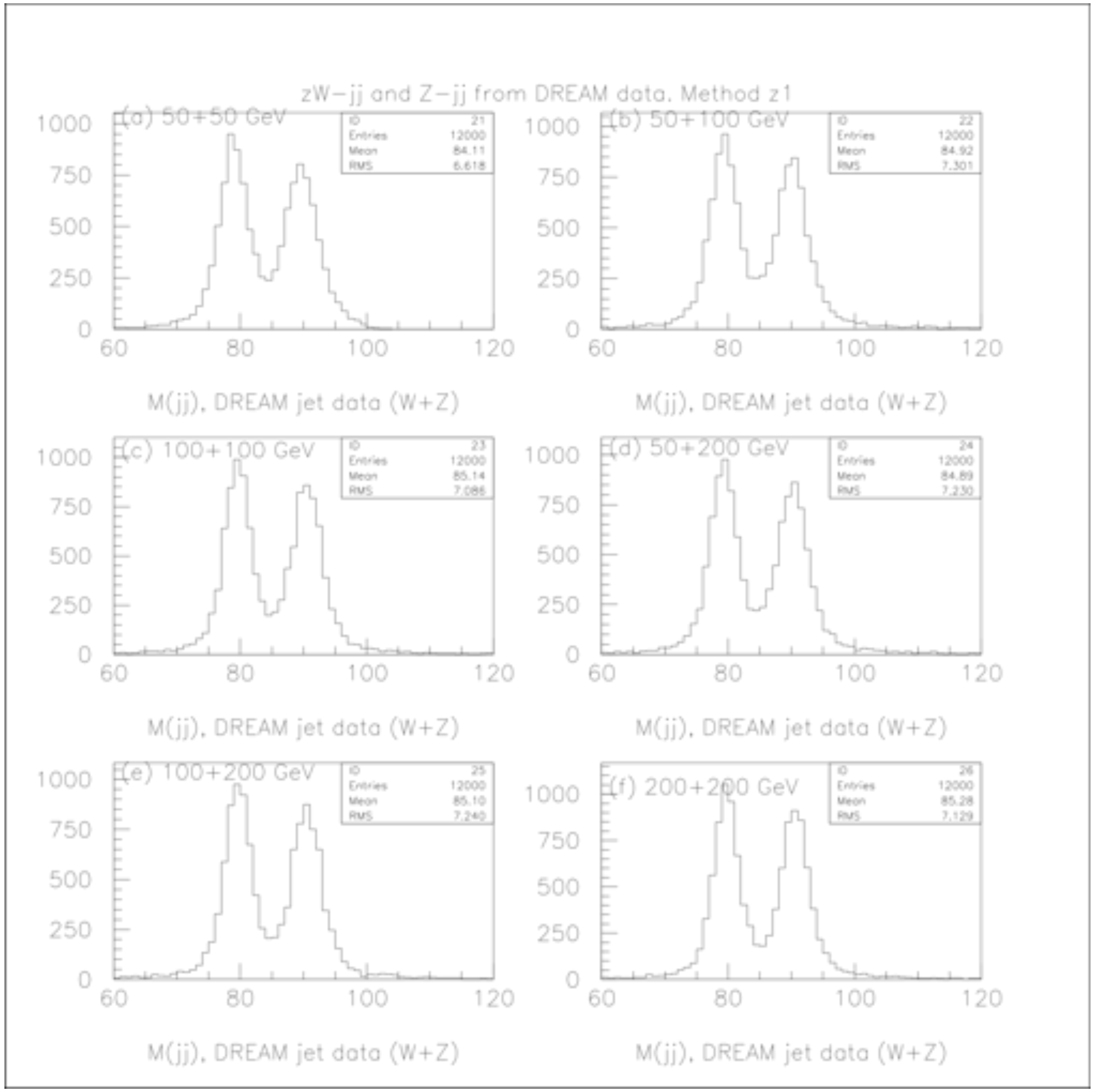


Procedure:

1. sample W Breit-Wigner
2. calculate α
3. align W quarks with beam hodoscope directions
4. take two data events for two beam files, ckomplete with (x,y) spatial and S,C measurement fluctuations
5. calculate and plot di-"jet" mass

$\sigma/E \sim$ 1-2%

same for the Z Breit-Wigner: superpose W and Z



two-jet Mass →

beam momentum files: (GeV/c)

50+50 50+100

100+100 50+200

100+200 200+200

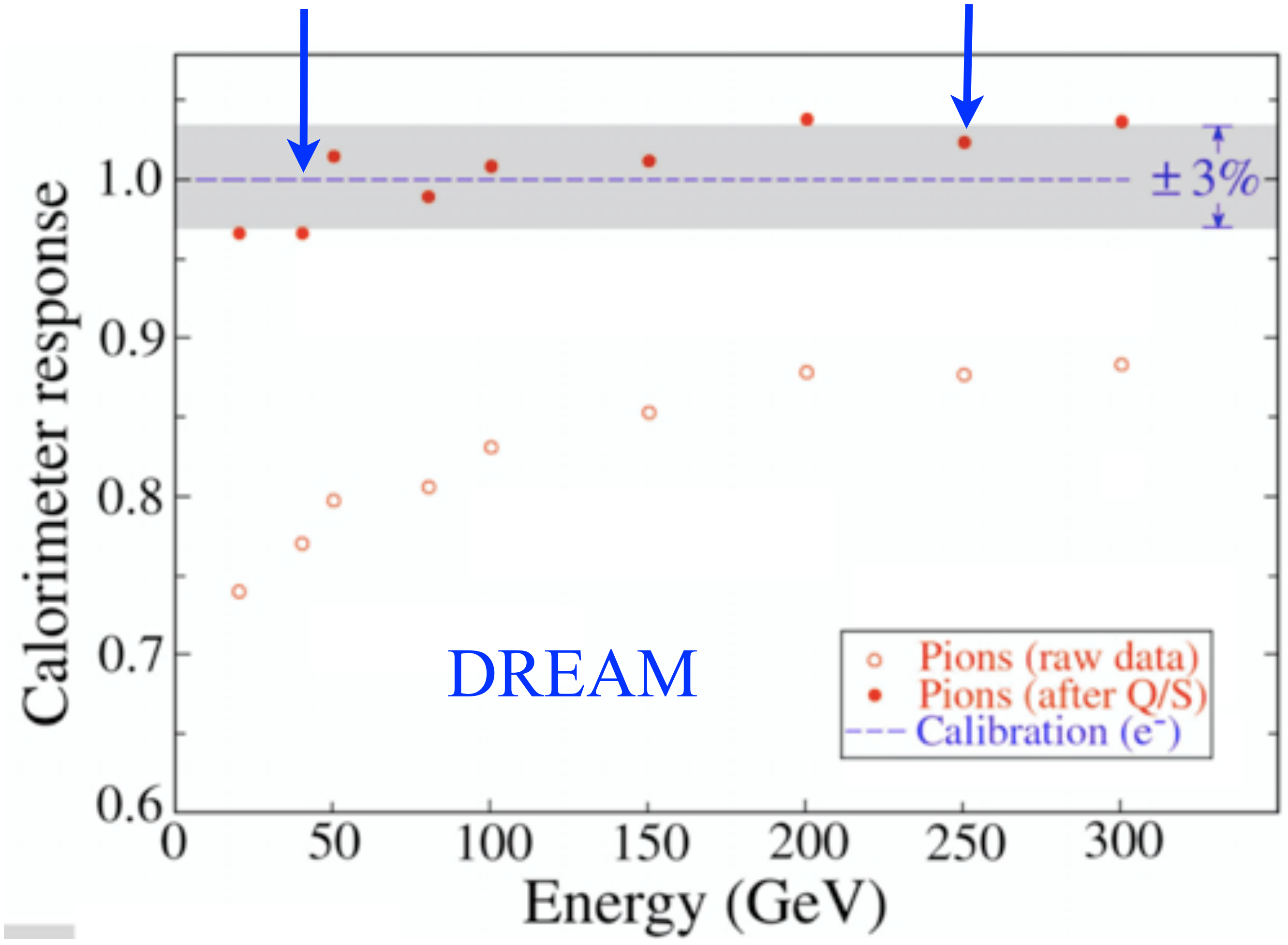
We will directly test the energy resolutions at E_{beam} = 80 GeV and 90 GeV in our next run.

Linearity

Hadronic energy linearity
over the whole SPS range, 20-300 GeV/c
(and, therefore, the whole ILC energy range)

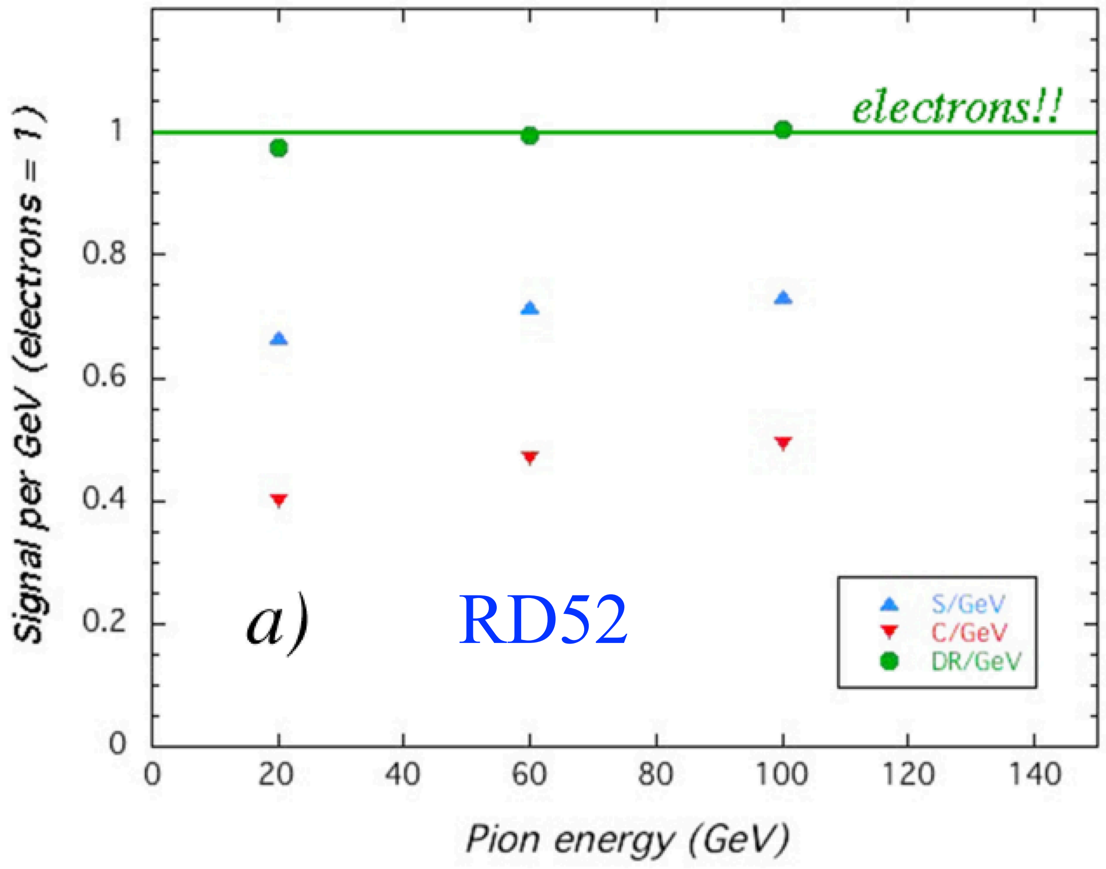
e- calibration point

250 GeV ILC beam



Data NIM A537 (2005) 537.

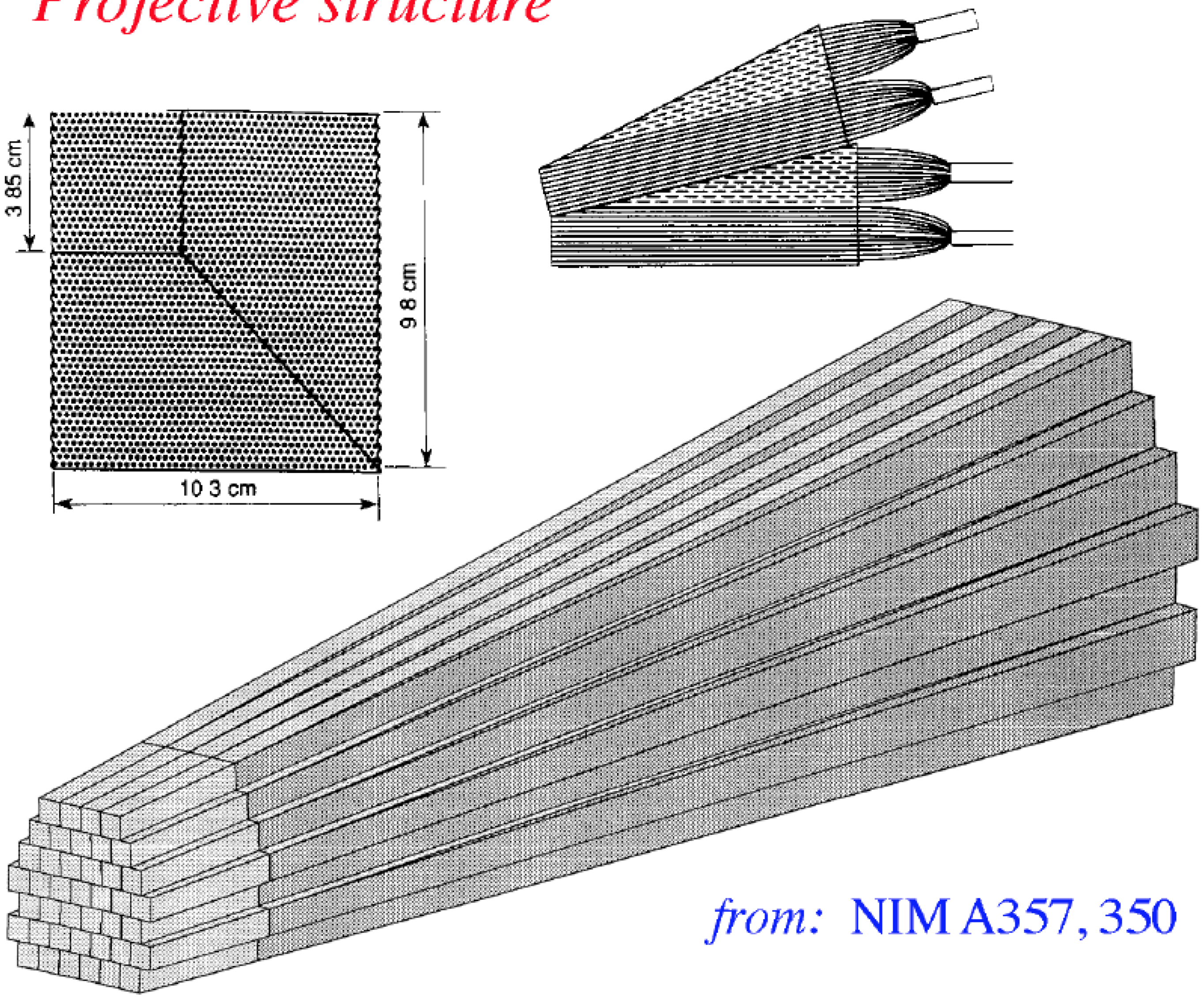
Electron energy scale well reproduced by DR!!



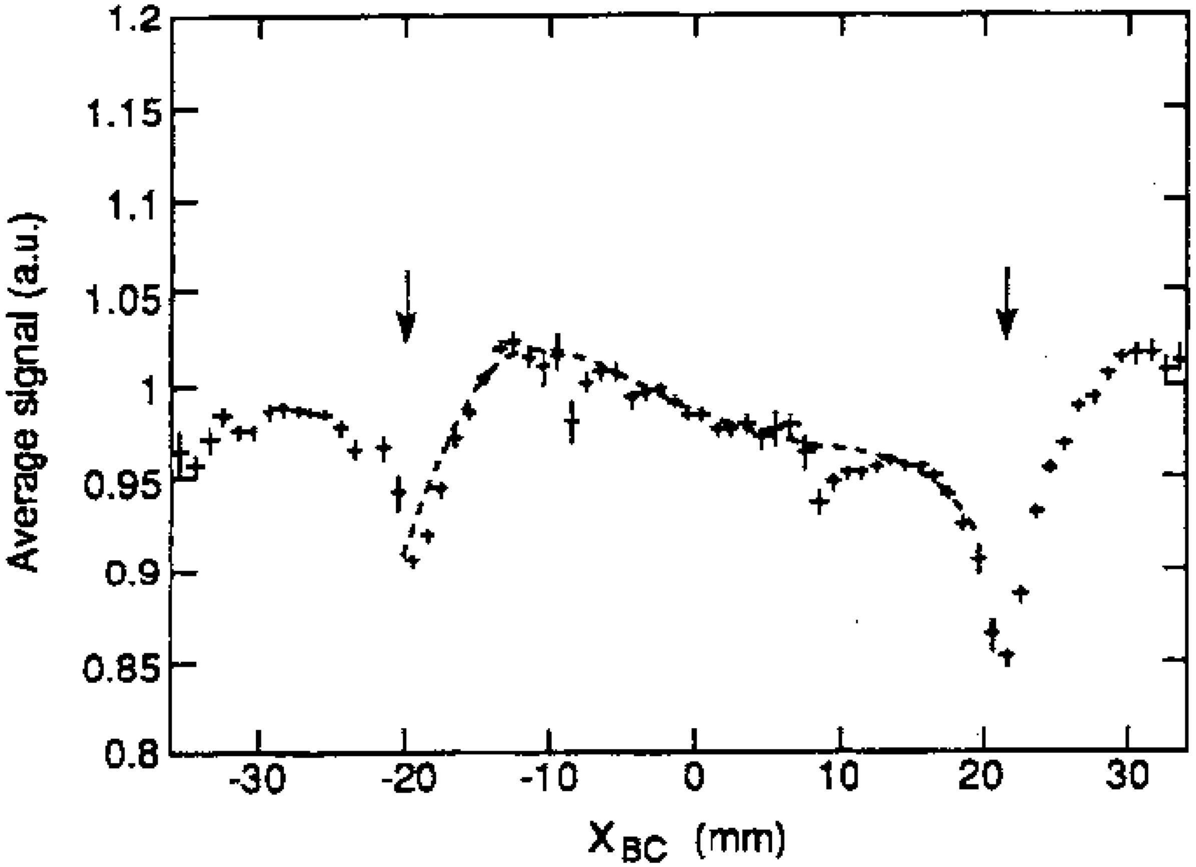
Nov-Dec CERN test 2012

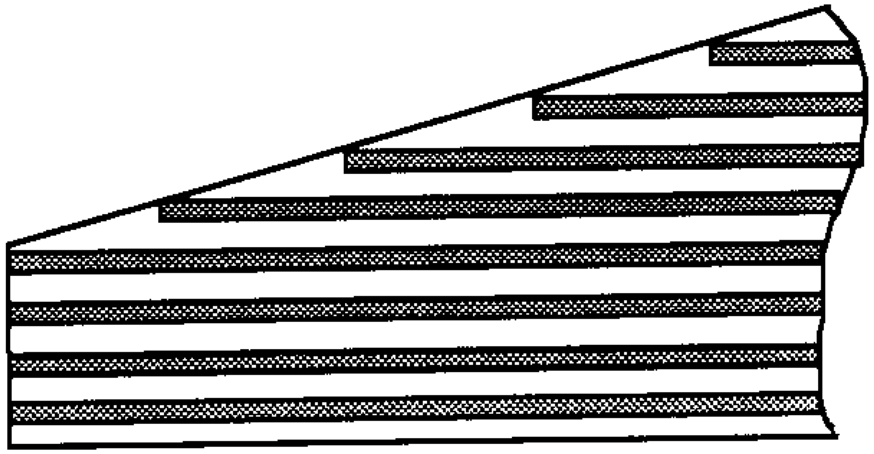
Geometry

Projective structure



from: NIM A357, 350



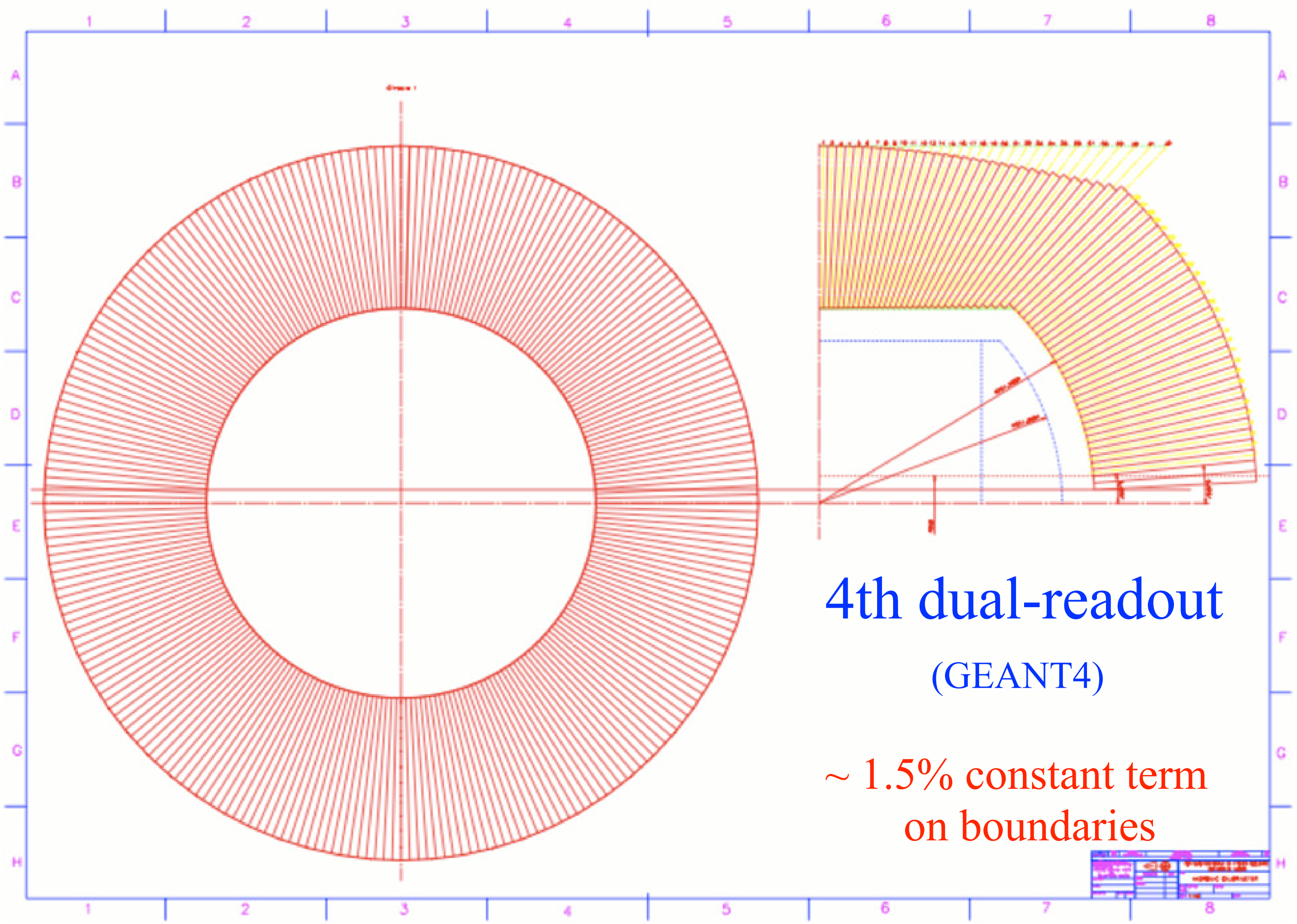


Geometry

From rectilinear module to 4π detector: RD52

(one of the goals of RD52)

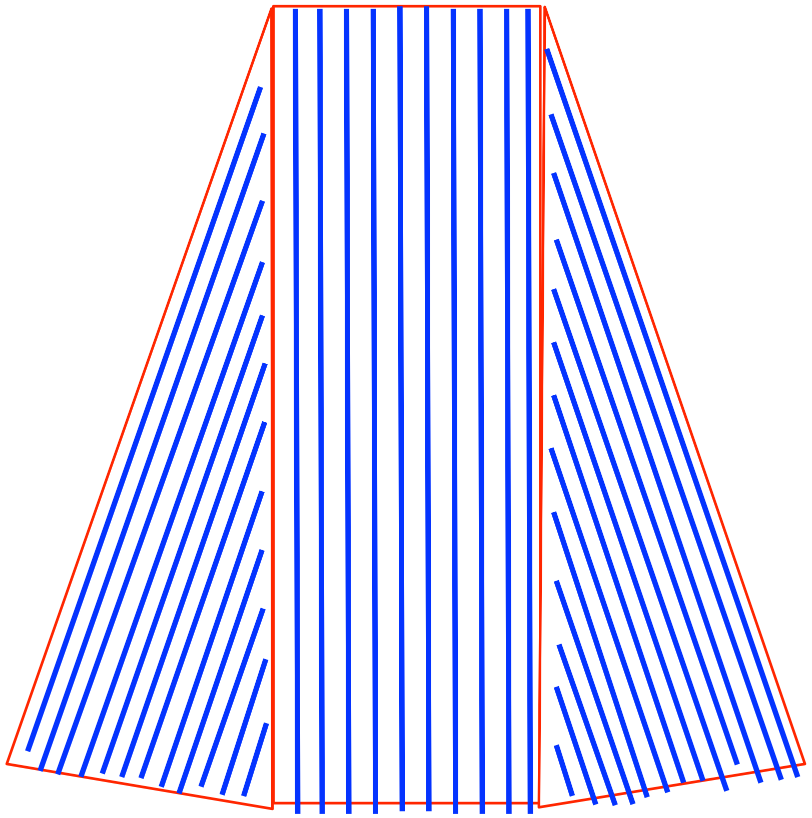
I prefer this fiber arrangement



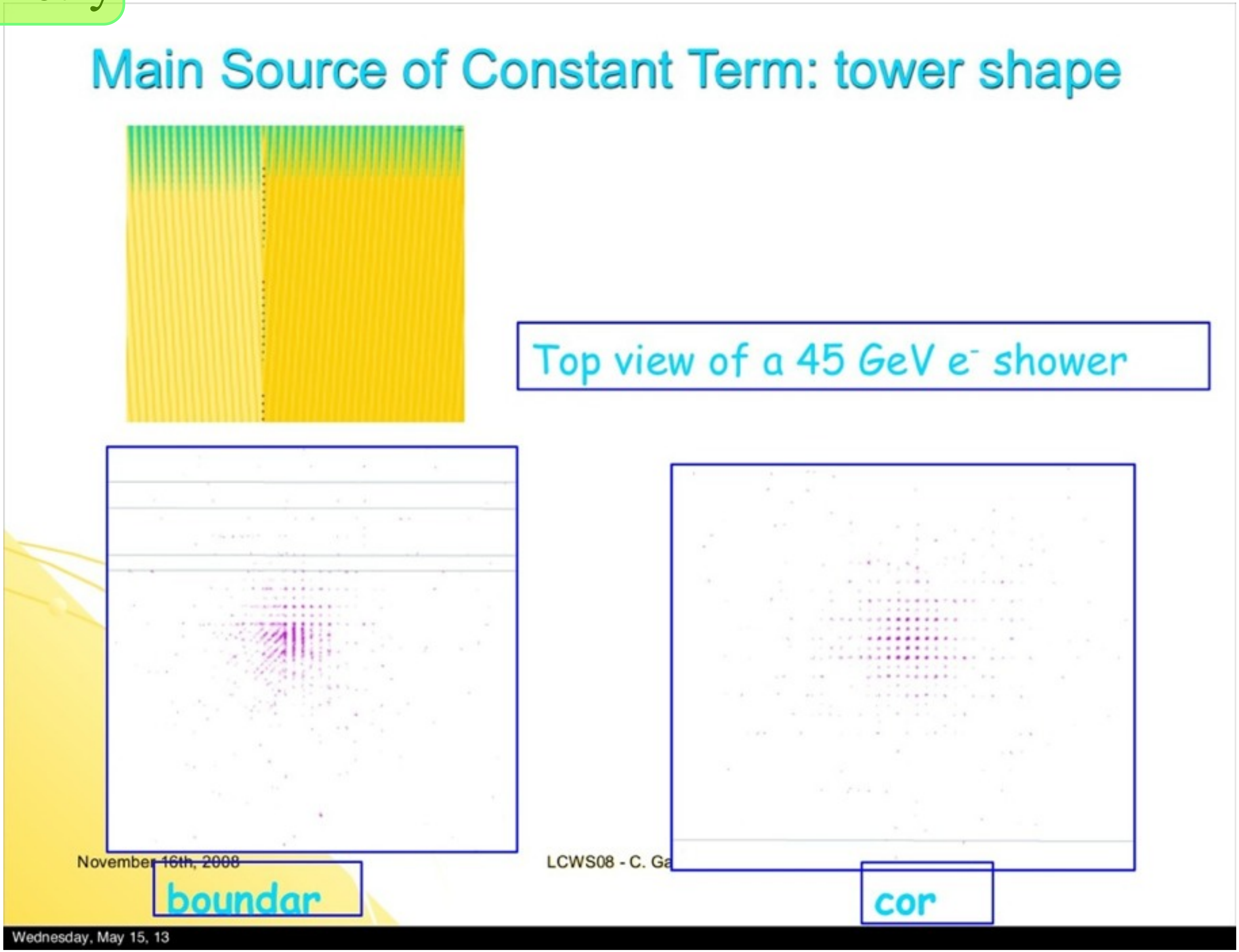
4th dual-readout

(GEANT4)

~ 1.5% constant term
on boundaries



Geometry



Main Source of Constant Term: tower shape

Top view of a 45 GeV e^- shower

boundar

cor

November 16th, 2008

LCWS08 - C. Ga

Wednesday, May 15, 13

B-field tolerant photo-converter

Best candidate is SiPM: we will test this on a small dual-readout module

Two solutions:

(1) silicon wafer with 1-mm SiPMs matched to the (x,y) positions of C fibers; pass-through holes for S fibers to second wafer.

(2) S fibers plug into a “light box” that mixes and collects S light; SiPM on edge picks up the light on successive bounces. Similar box gets the C light.

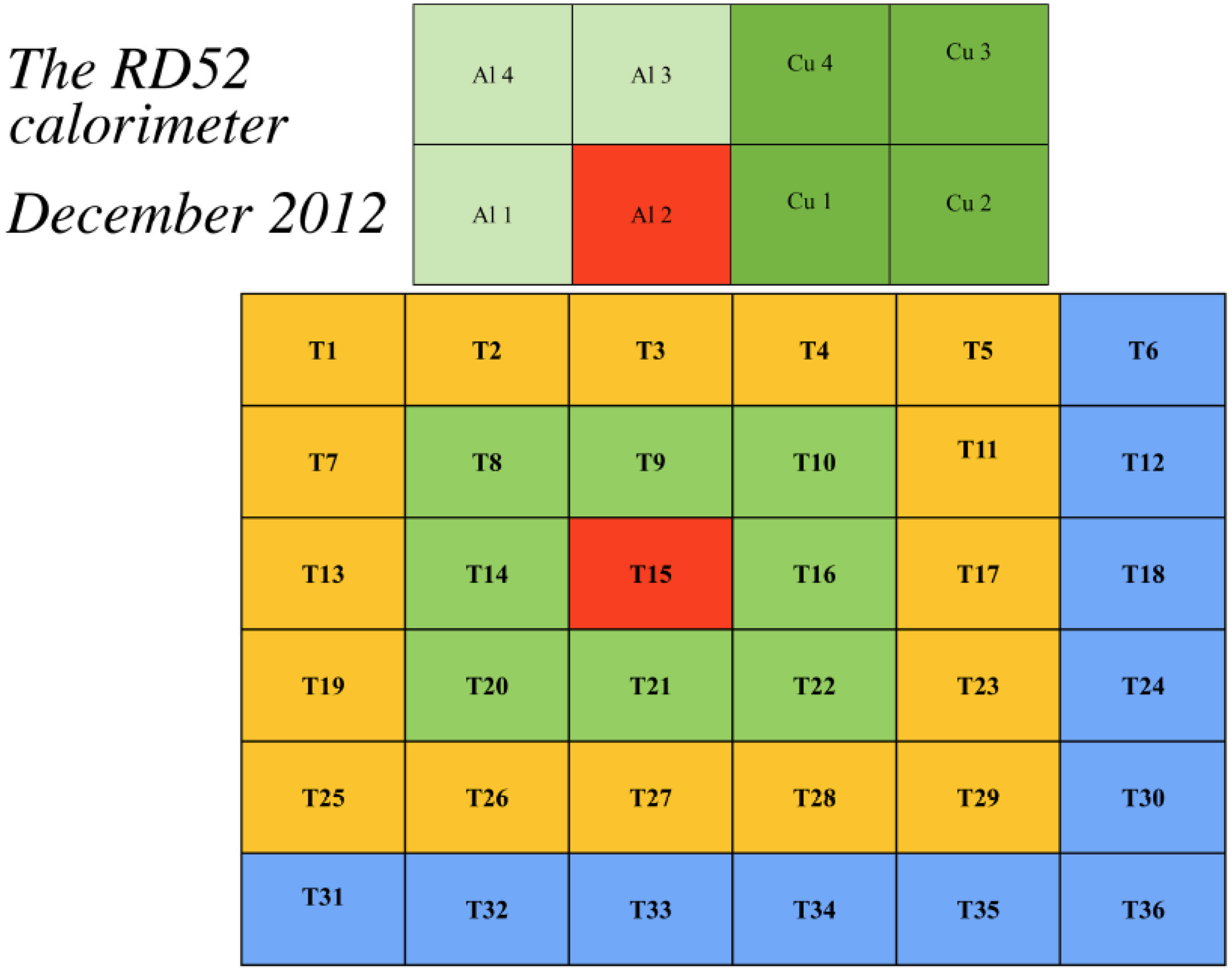
Two SiPM problems:

(1) noise rate near 1 MHz is a nuisance for calorimeters

(2) after-pulses look like neutrons

Pb → Cu → W   absorbers with dual-readout

- On RD52, the Pavia group has made 9 dual-readout modules (10cm x 10cm) with Pb absorber by extrusion.
- The Pisa group has made two modules with Cu absorber by milling.
- We are developing means to roll Cu into the RD52 absorber shape.
- Next step is to roll a W-Cu absorber. Funding not secured.



The RD52 calorimeter

December 2012

Al 4	Al 3	Cu 4	Cu 3
Al 1	Al 2	Cu 1	Cu 2

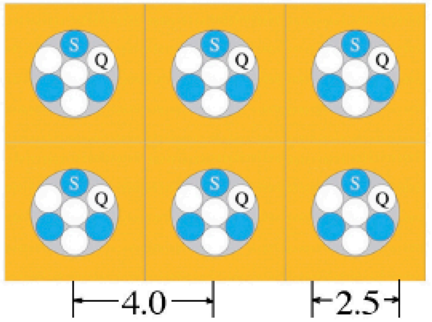
T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

Dual-readout calorimetry

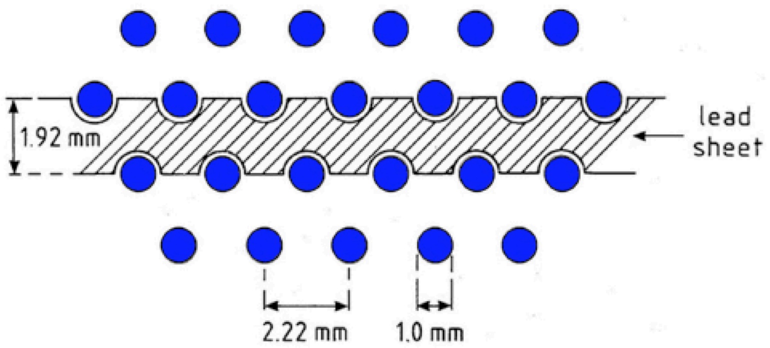
Fiber-impregnated
absorber volume

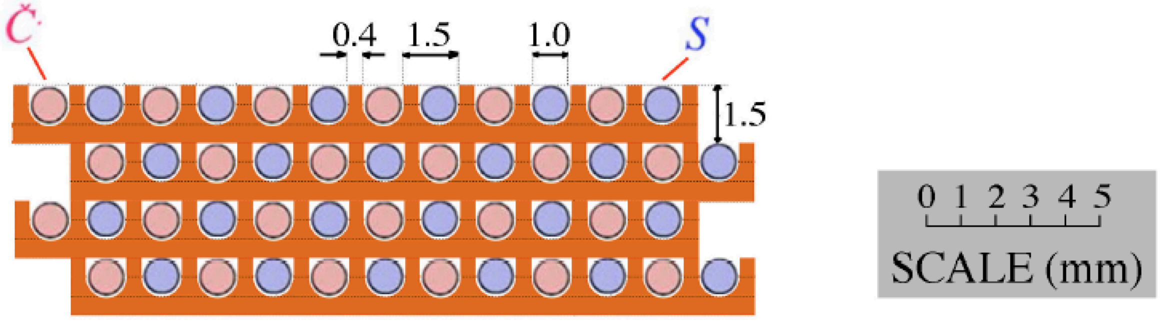
Sampling fraction & frequency

DREAM



SPACAL





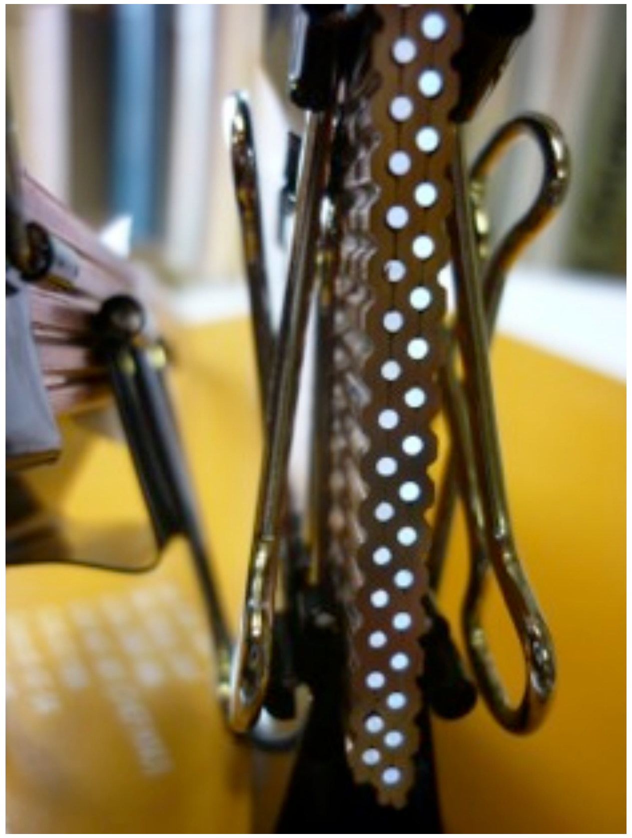
Fiber pattern RD52

Absorber thickness between sampling layers (Moliere radii):

SPACAL 0.071 *DREAM 0.099* *RD52 0.027*

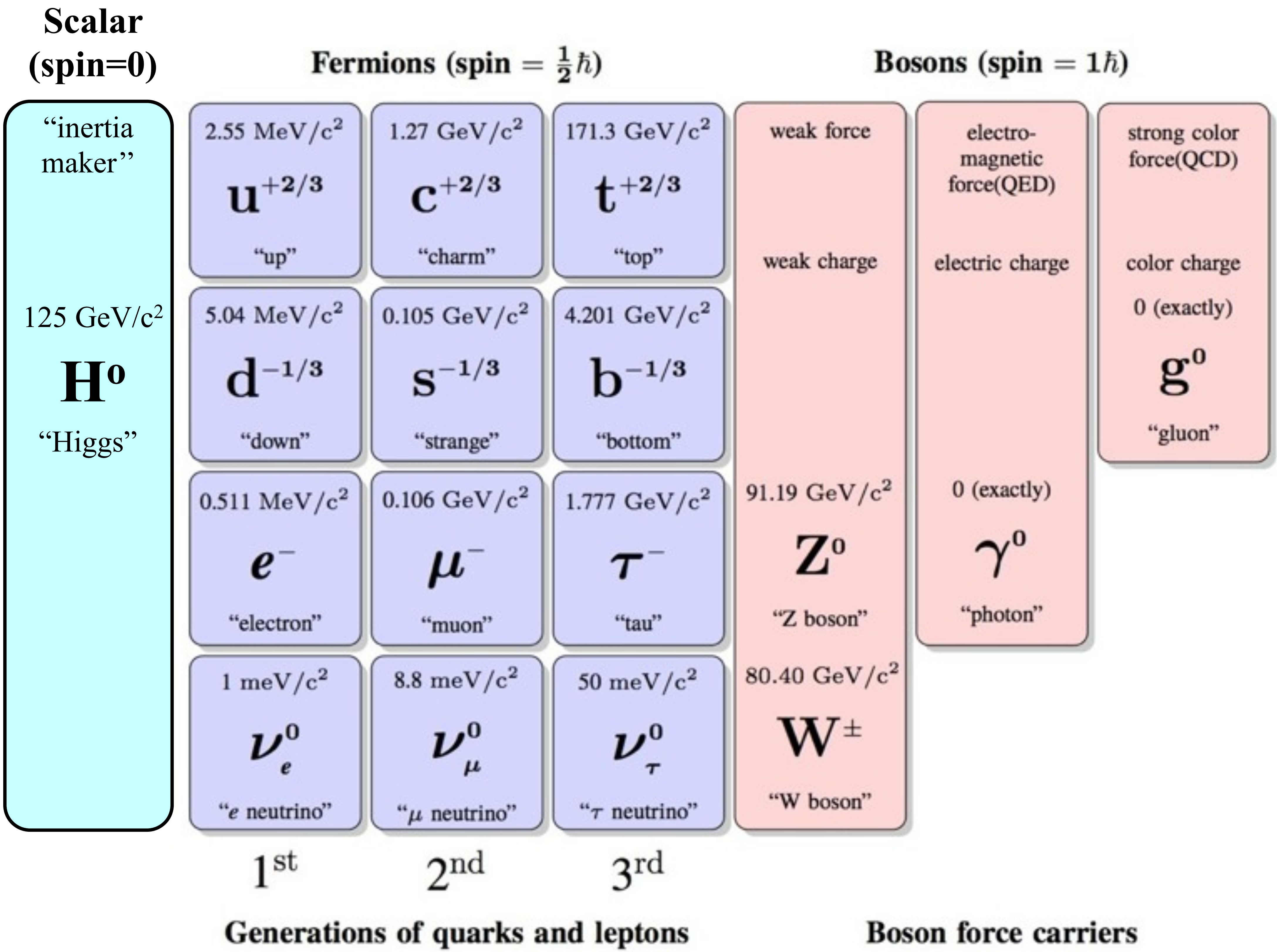
Pure Cu

Cu + Zn(10%)



Particle Identification

Measure these objects to 1-2%, and you can do anything.



Scalar (spin=0)	Fermions (spin $= \frac{1}{2}\hbar$)			Bosons (spin $= 1\hbar$)		
"inertia maker" 125 GeV/c^2 $\mathbf{H}^{\mathbf{o}}$ "Higgs"	2.55 MeV/c^2 $\mathrm{u}^{+2/3}$ "up"	1.27 GeV/c^2 $\mathrm{c}^{+2/3}$ "charm"	171.3 GeV/c^2 $\mathrm{t}^{+2/3}$ "top"	weak force weak charge	electro-magnetic force(QED) electric charge	strong color force(QCD) color charge 0 (exactly) g^0 "gluon"
	5.04 MeV/c^2 $\mathrm{d}^{-1/3}$ "down"	0.105 GeV/c^2 $\mathrm{s}^{-1/3}$ "strange"	4.201 GeV/c^2 $\mathrm{b}^{-1/3}$ "bottom"			
	0.511 MeV/c^2 e^- "electron"	0.106 GeV/c^2 μ^- "muon"	1.777 GeV/c^2 τ^- "tau"	91.19 GeV/c^2 Z^0 "Z boson"	0 (exactly) γ^0 "photon"	
	1 meV/c^2 ν_e^0 "e neutrino"	8.8 meV/c^2 ν_μ^0 "μ neutrino"	50 meV/c^2 ν_τ^0 "τ neutrino"	80.40 GeV/c^2 $\mathrm{W}^\pm$ "W boson"		
	1st	2nd	3rd			

Generations of quarks and leptons

Boson force carriers

Particle Identification

- 🔴 Achieved in test beam data
- 🟢 Achieved in cosmic mu test data
- 🔵 Achieved in simulation

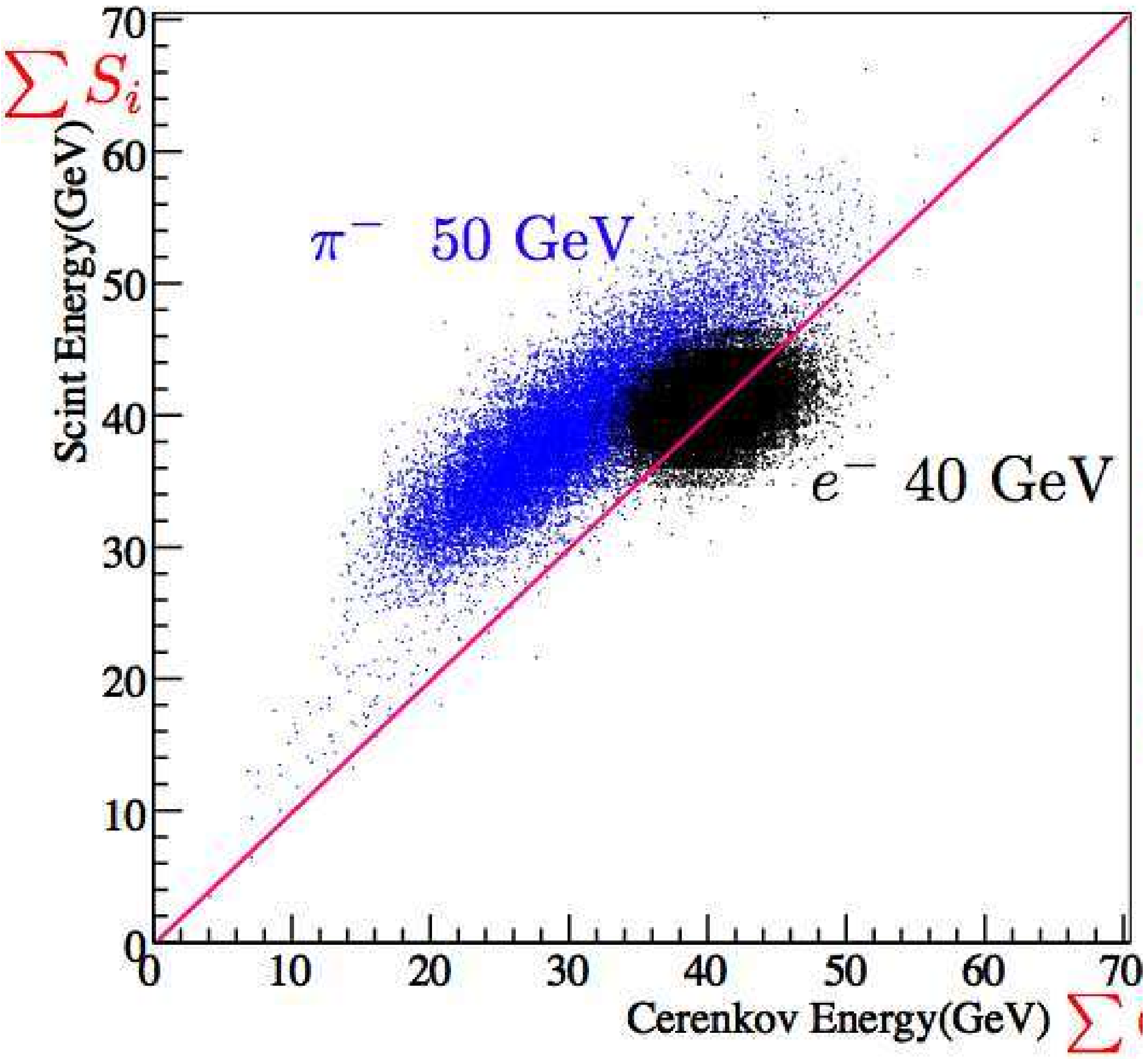
ID	Physical measurement	Partons/particles identified	Subsystems used	
1	C *vs.* S	$e^\pm$ *vs.* $\pi^\pm$ *vs.* $\mu^\pm$	S and C	🔴 🔵
2	$\chi^2 \sim \frac{1}{N}\Sigma_i^N[(C_i - S_i)/\sigma_i]^2$	EM *vs.* non-EM *vs.* "hadronic"	S_i and C_i channels	🔴
3	$(S - C)$ *vs.* $(S + C)$	μ *vs.* π	fiber S and C	🔴
4	$f_n \sim E_n/E_{\text{shower}}$ (MeV neutrons)	"hadronic" *vs.* non-"hadronic"	scintillating fibers $S_{pe}(t)$ long-time history	🔴 🔵
5	S_{pe} time duration	EM *vs.* non-EM *vs.* "hadronic"	S fibers time-history	🔴
6	dN/dx, specific ionization (cluster counting)	$e - \mu - \pi - K - p$ (few GeV region)	CluCou tracking	🟢
7	EM calor + tracking	$e - \gamma$	CluCou tracking + dual-readout calor's	
8	$p_{\text{track}} \approx E_{\text{calor}} + p_\mu$	μ *vs.* punch-through π	CluCou, calor, muon	
9	$\tau^\pm \to \rho^\pm\nu \to \pi^\pm\gamma\gamma$	τ *vs.* hadronic debris	BGO and fiber dual-reaout, CluCou	🔵
10	Time-of-flight (sub-ns)	massive SUSY object	Čerenkov pulses in BGO and fiber calorimeter	🔴
11	$W, Z \to jj$ mass	W, Z *vs.* QCD jj	CluCou, jet finding, dual-readout calor's	🔵

Basic dual-readout: Scintillation vs. Cerenkov

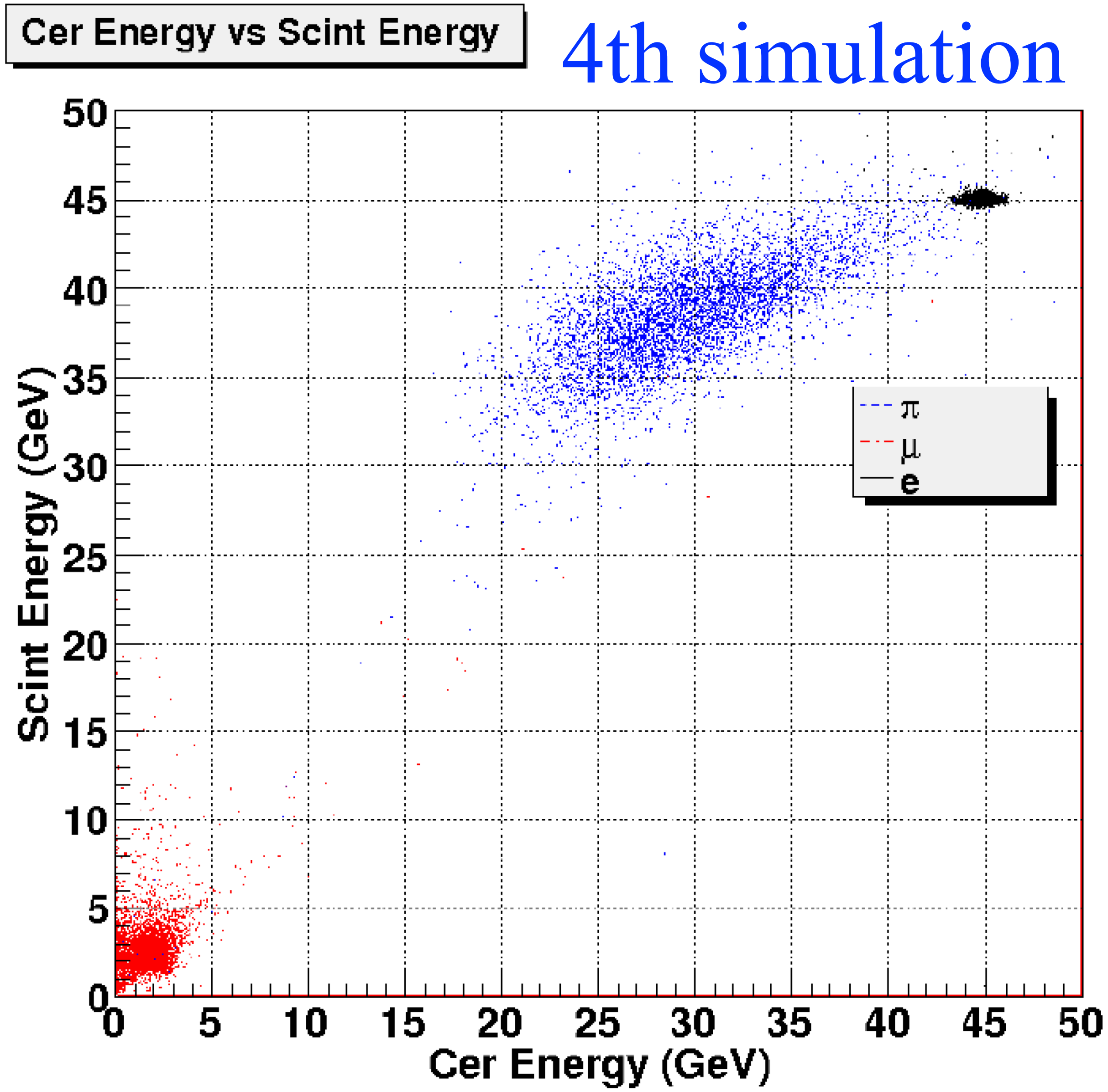
e-π-μ discrimination

$$S = E\,[f_{EM} + (1-f_{EM})\,\eta_S] \qquad \eta_S=(h/e)_S$$
$$C = E\,[f_{EM} + (1-f_{EM})\,\eta_C] \qquad \eta_C=(h/e)_C$$

DREAM module data



4th simulation

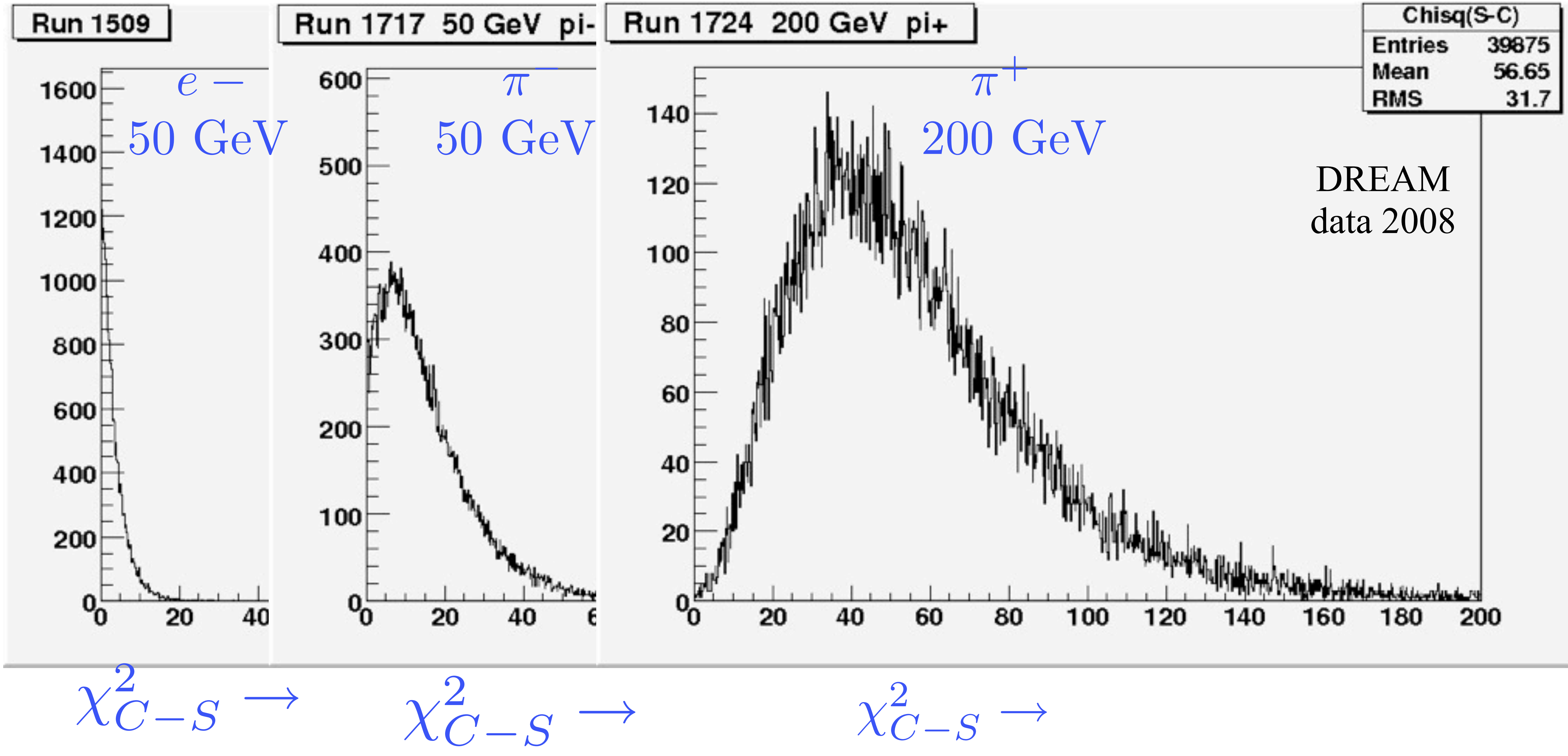


Dual-readout: (S-C) channel-by-channel

e-π discrimination

Chi-squared of S-C fluctuations among the channels of a shower:

$$\chi^2_{C-S} = \Sigma\left(\frac{S_k - C_k}{\sigma_k}\right)^2 \approx \Sigma_k \frac{(S_k - C_k)^2}{0.1(S_k + C_k)}$$

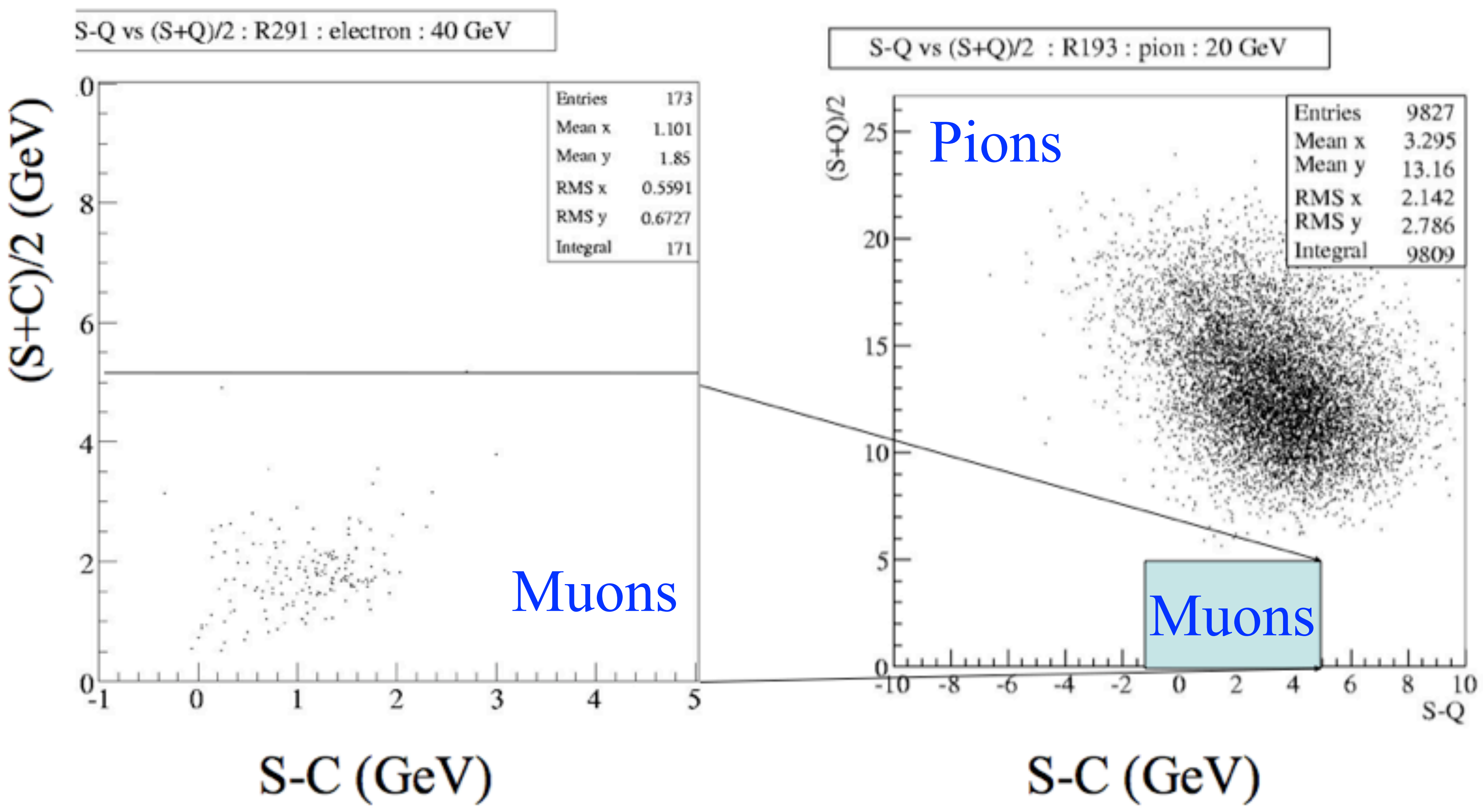


DREAM
data 2008

Dual-readout: unique ID for isolated muons

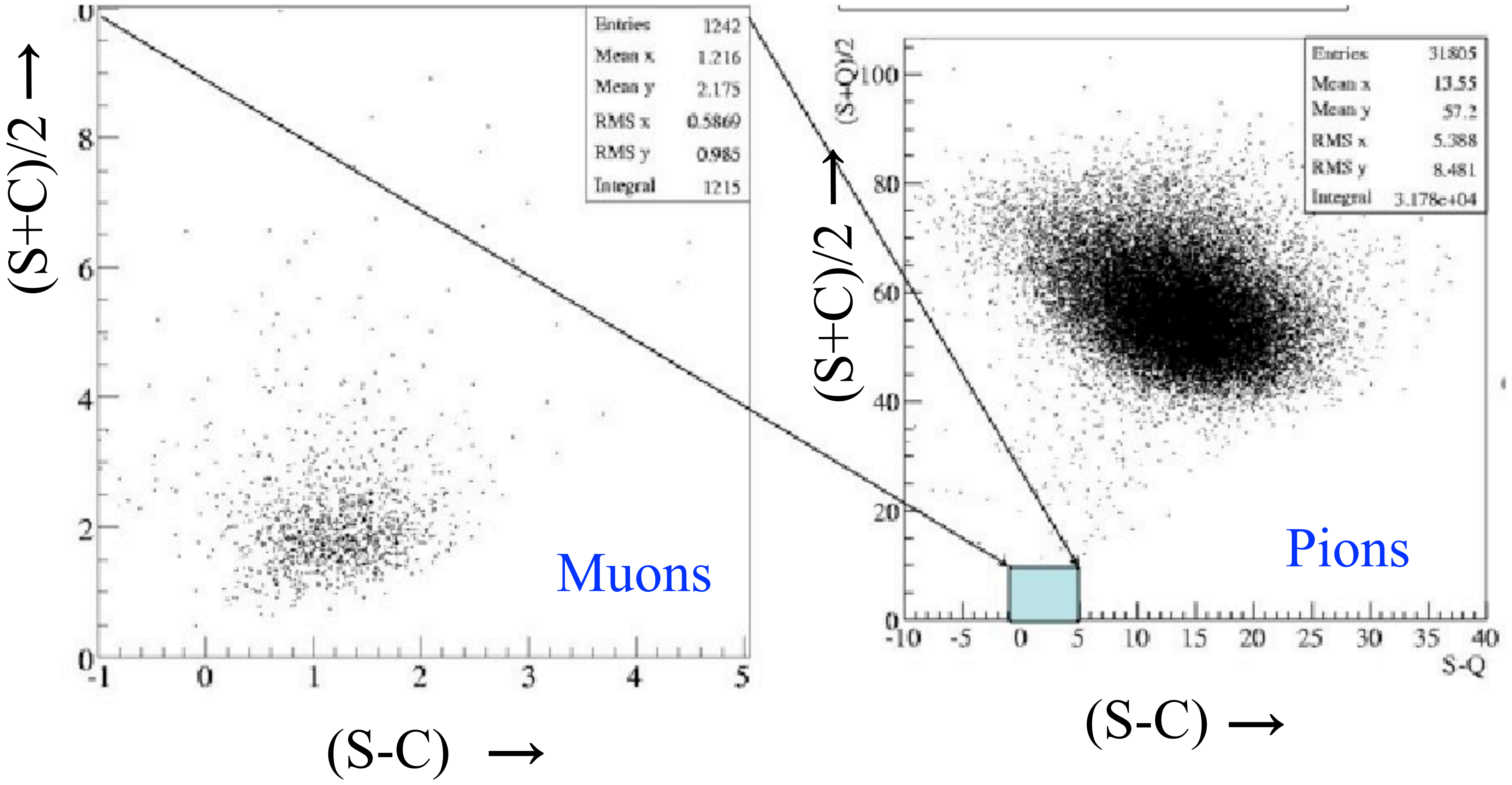
(Cerenkov angle > numerical aperture => zero Cerenkov signal)

Muons and Pions (20 GeV)



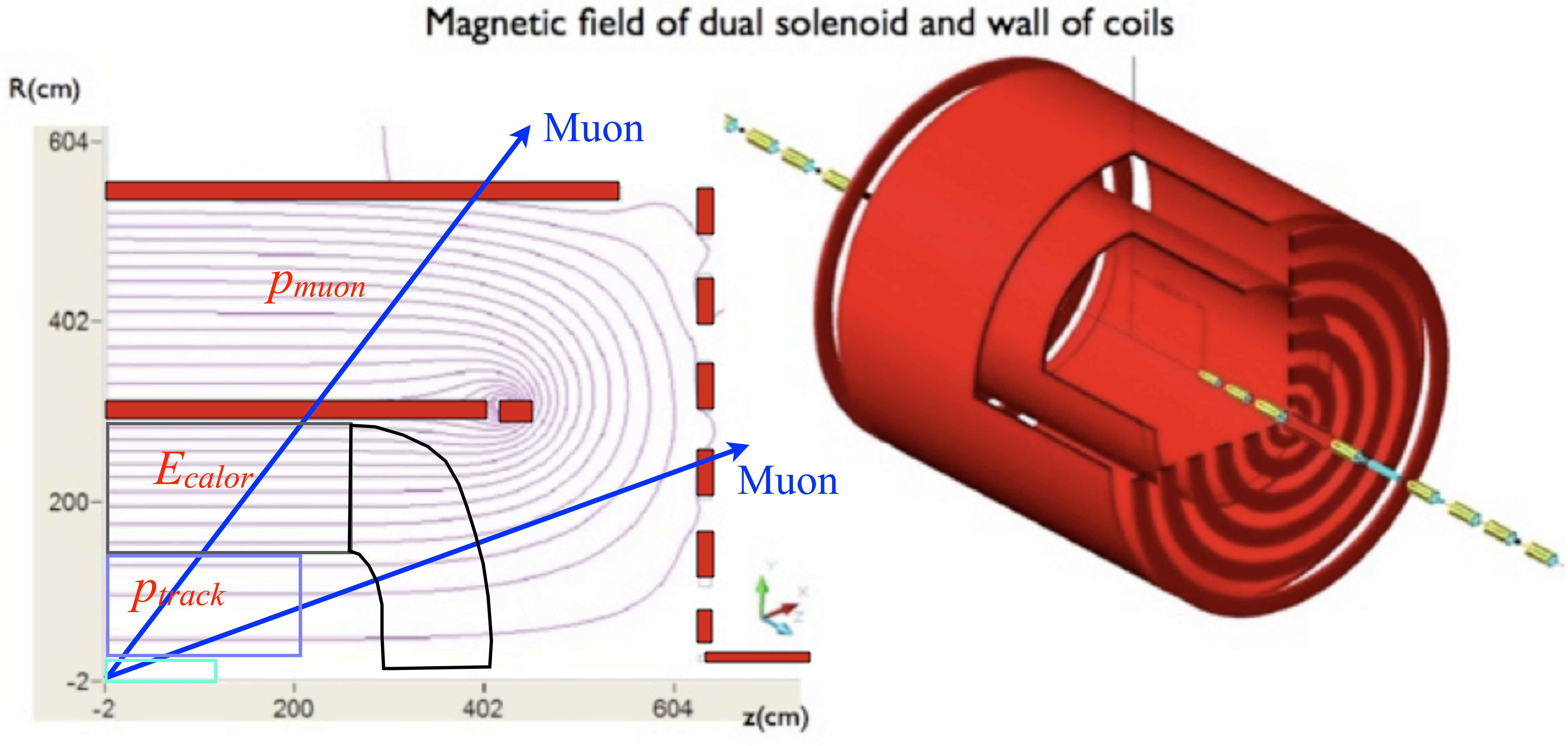
Dual-readout: unique ID for isolated muons

DREAM module, 80 GeV beam

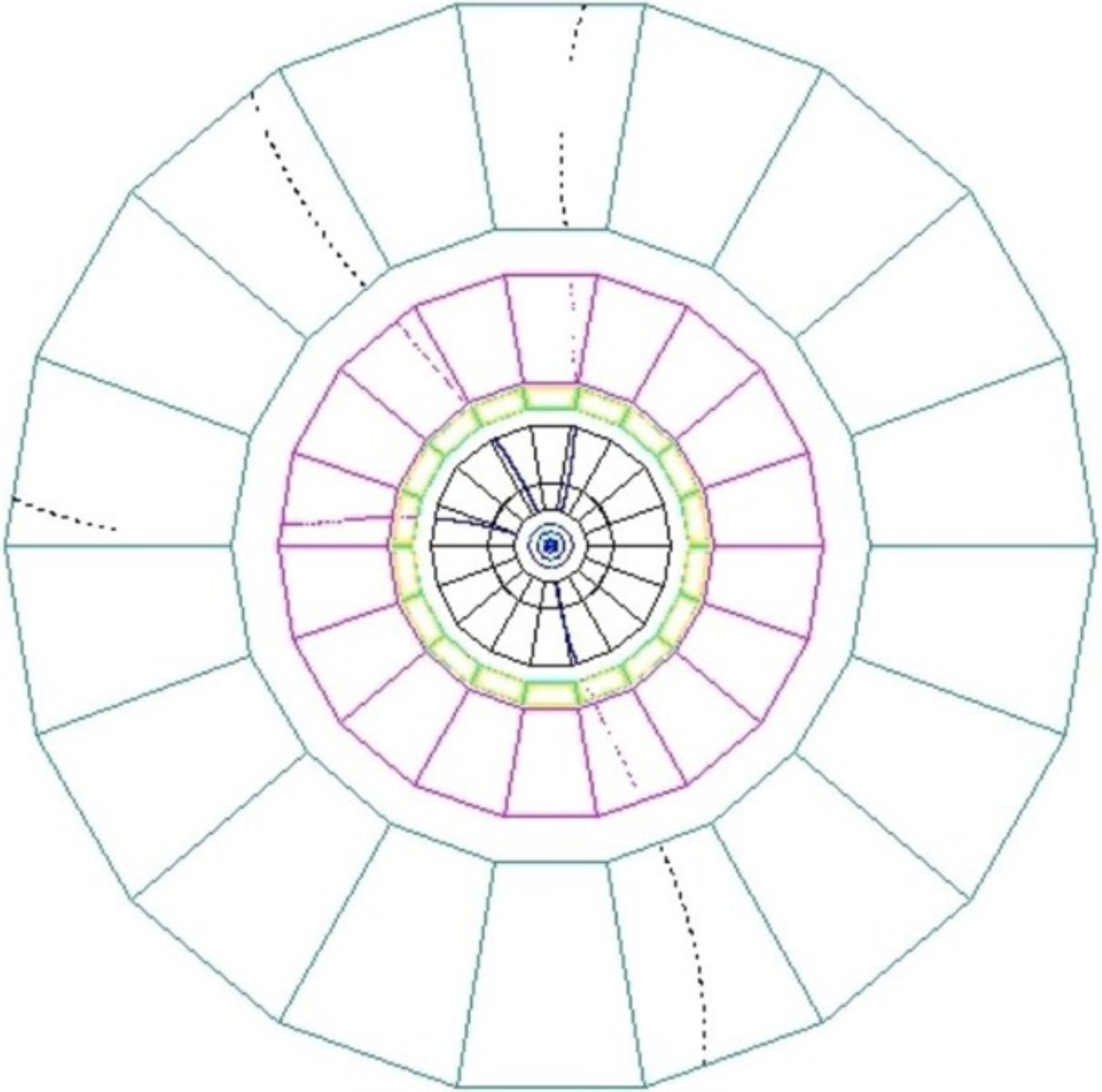


Muon ID by energy balance

$$p_{track} = E_{calor} + p_{muon}$$


Magnetic field of dual solenoid and wall of coils

Dual-readout: 5 GeV muons are clean with good acceptance



Muons are clean and
obvious;
Acceptance at 5 GeV
is good

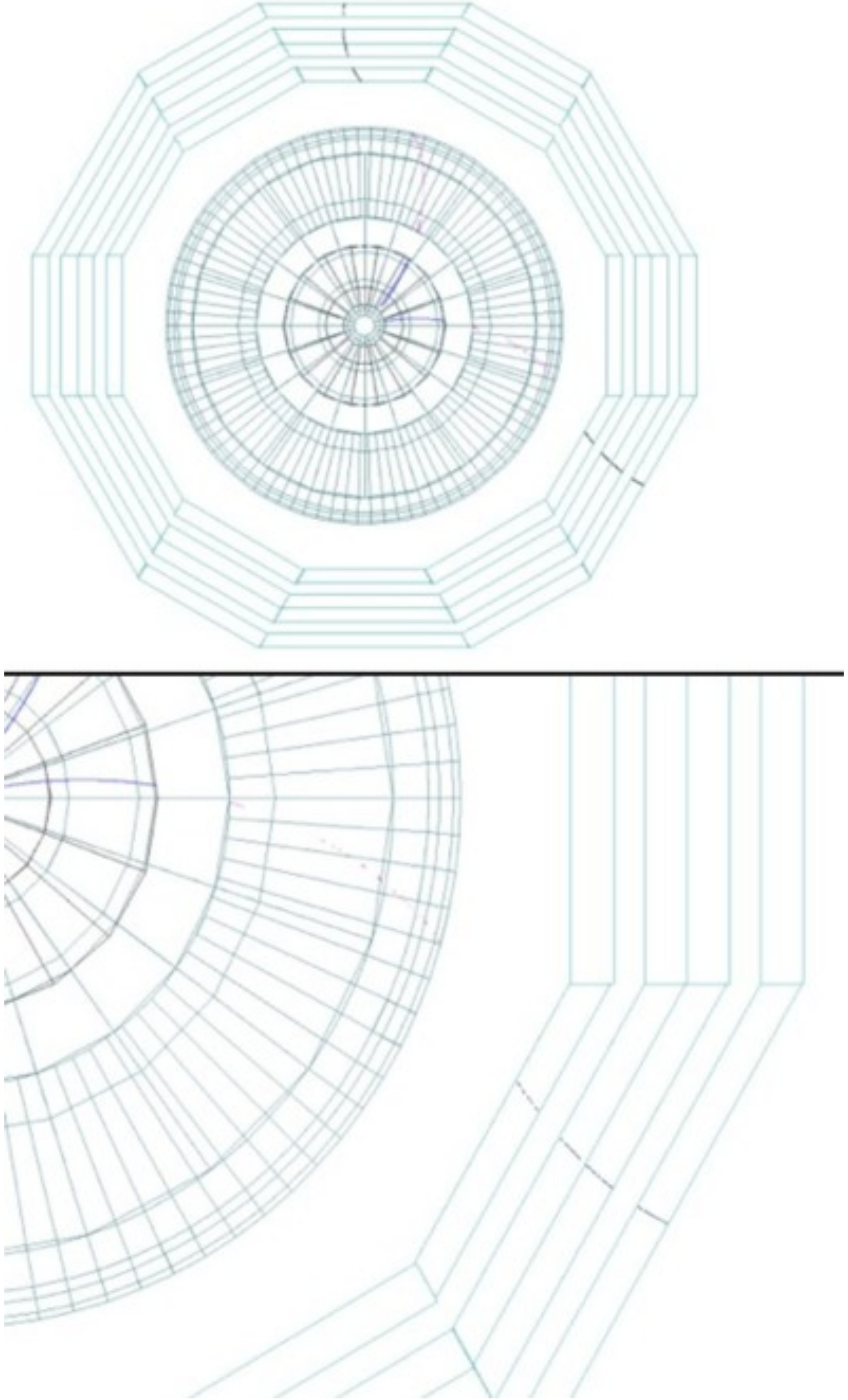
Dual-readout & CluClou

μ^+ and μ^- at 3.5 GeV/c

Muons are easy and obvious at 3.5 GeV/c.

We can push the muon acceptance down to 1 GeV/c.

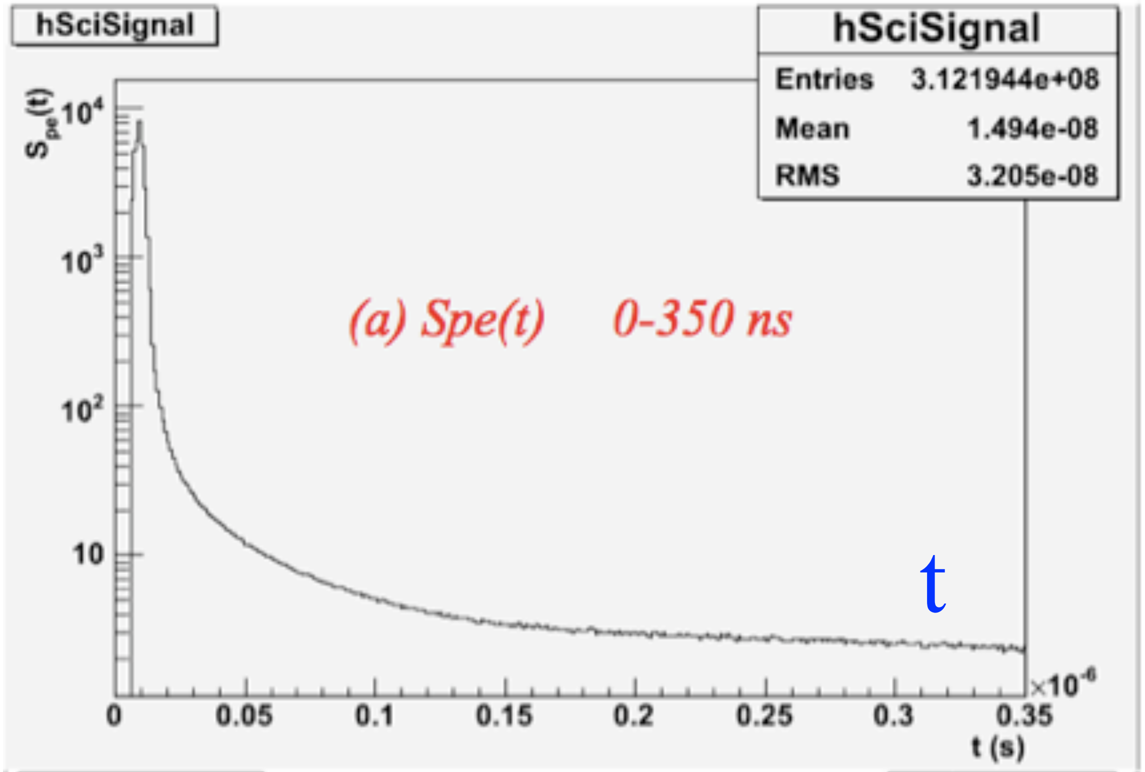
This will require fine coordination of CluCou and the dual-readout calorimeters.



Dual-readout: neutrons, calculate f_n from $S_{pe}(t)$ time-history

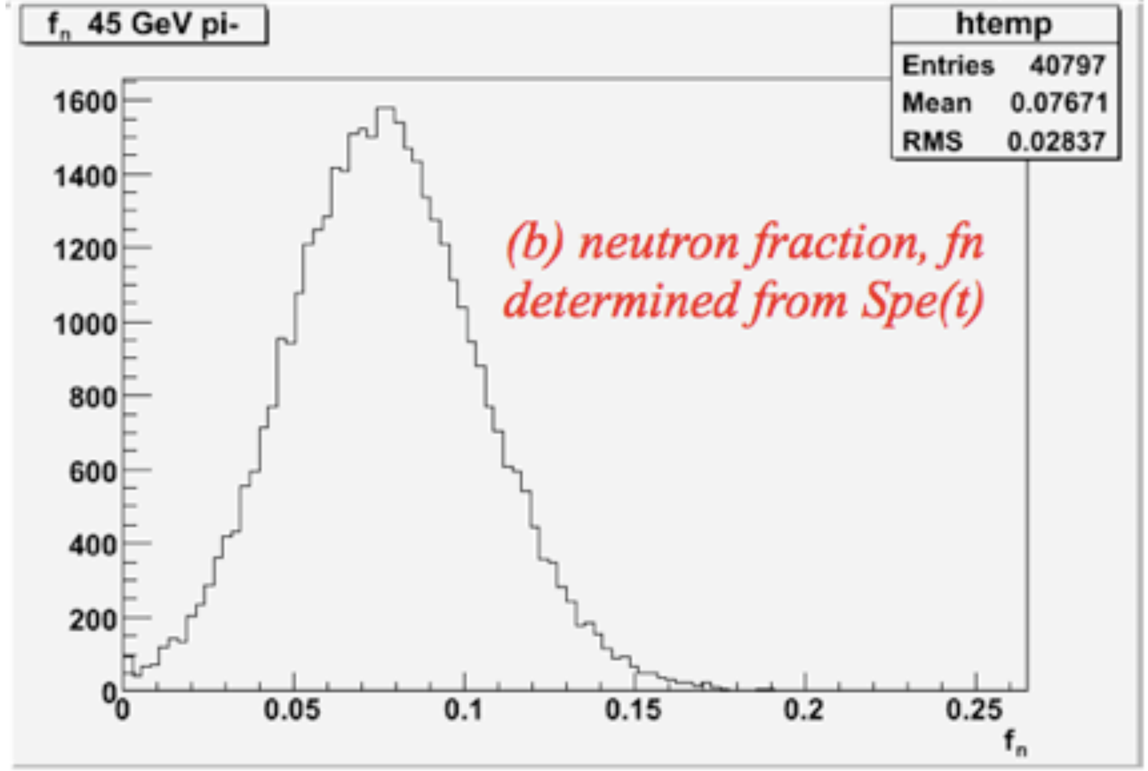
n tagging, simulation

Pavia CALOR08

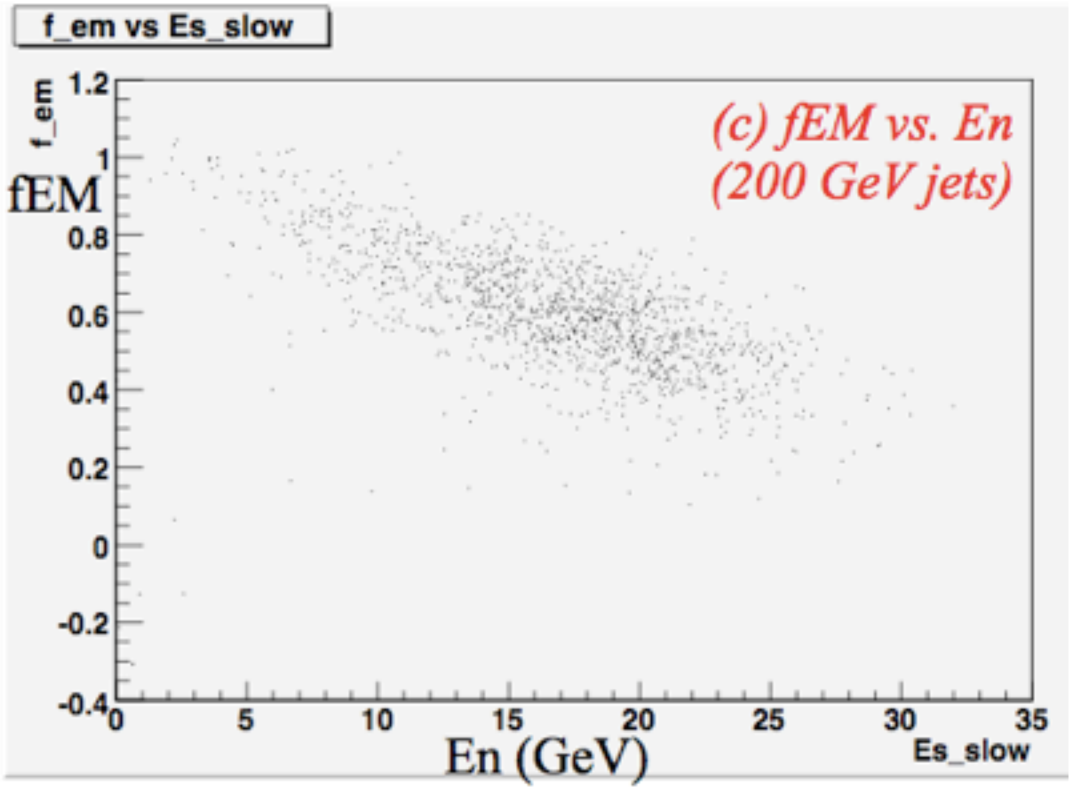


(a) Spe(t) 0-350 ns

We have a fair understanding of neutrons in both DREAM data and in the 4th detector.



(b) neutron fraction, fn determined from Spe(t)

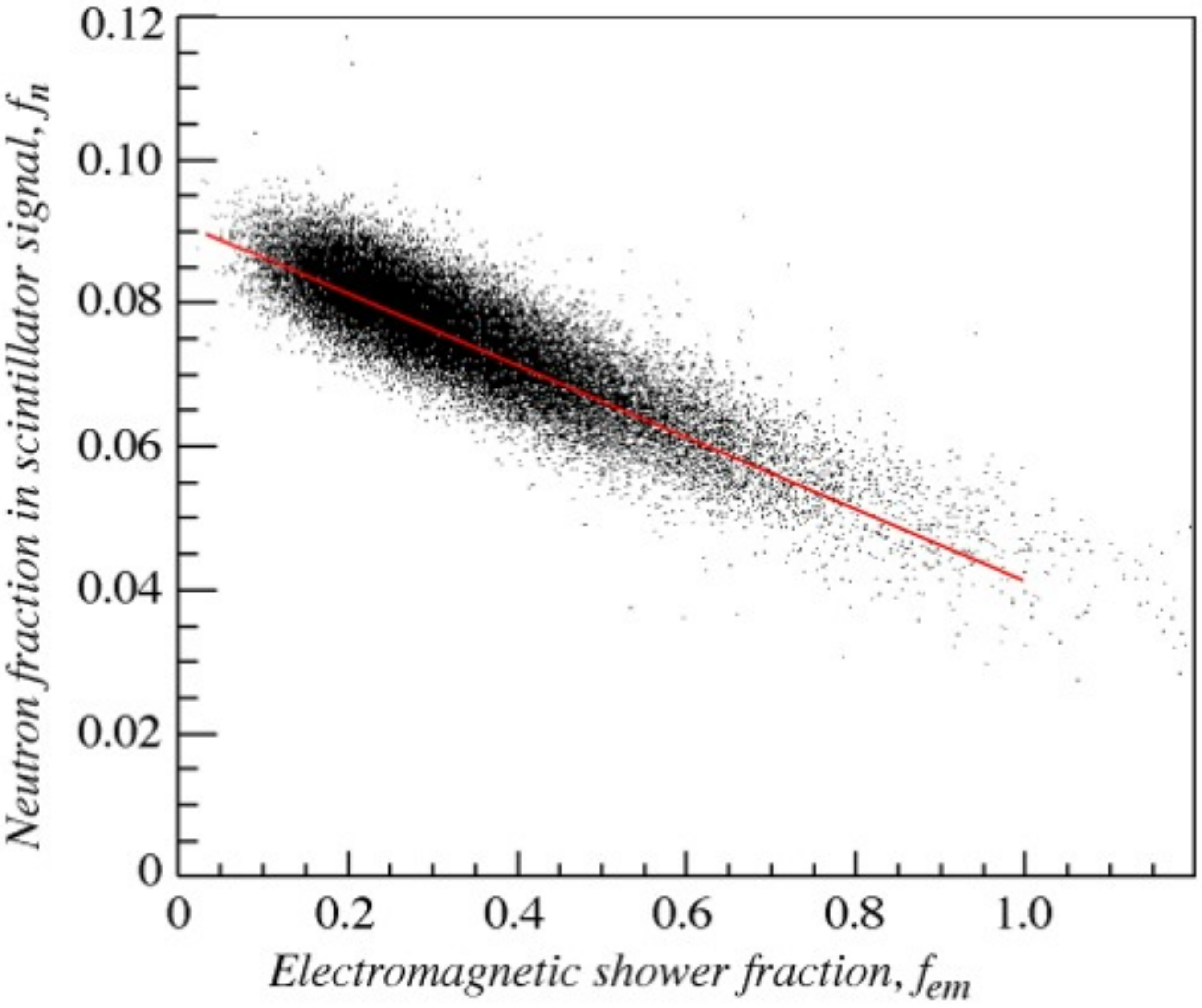


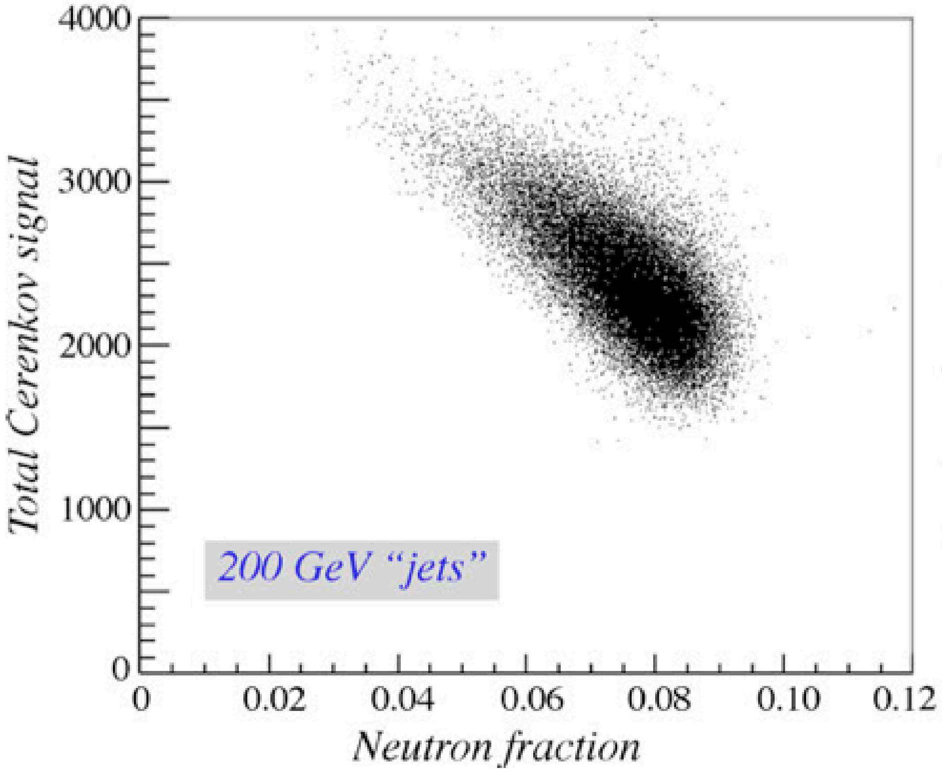
(c) fEM vs. En (200 GeV jets)

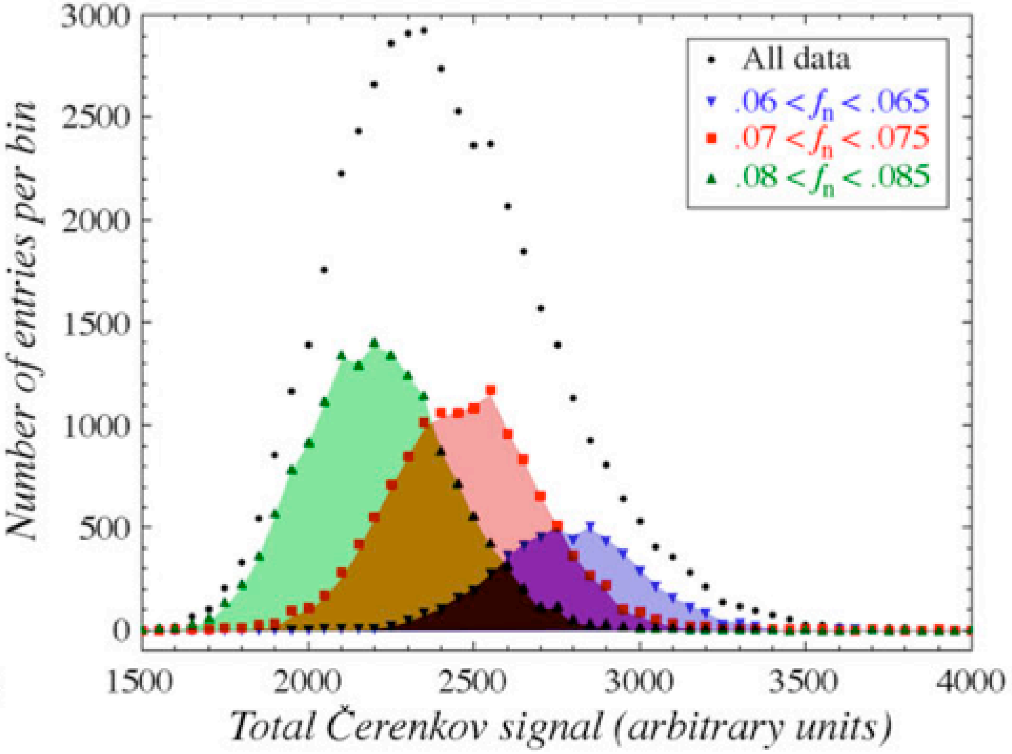
Dual-readout: neutron fraction, f_n

n tagging, DREAM data

- measured by time-history of scintillation light ("hadronic" ID)
- anti-correlated with the electromagnetic fraction



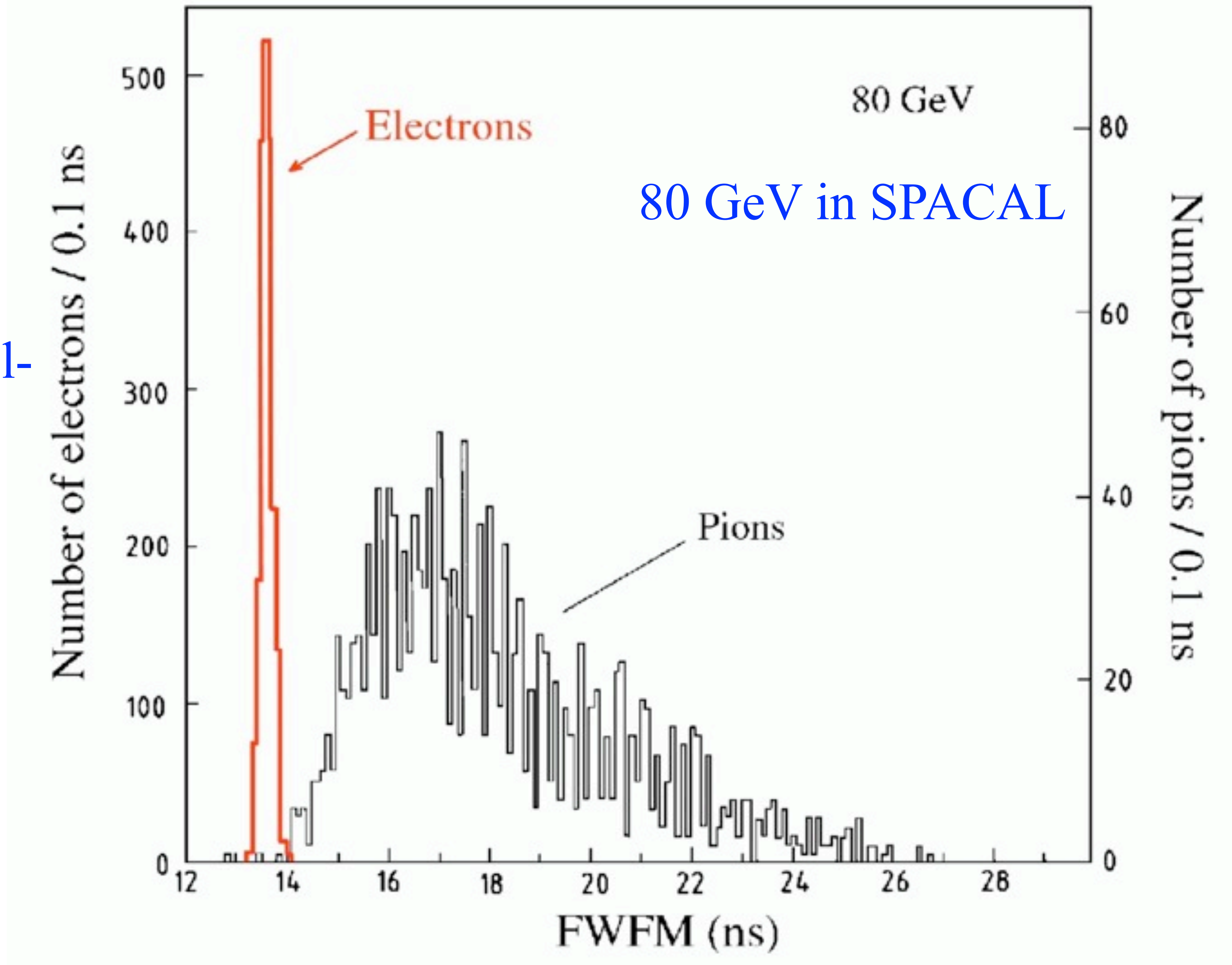




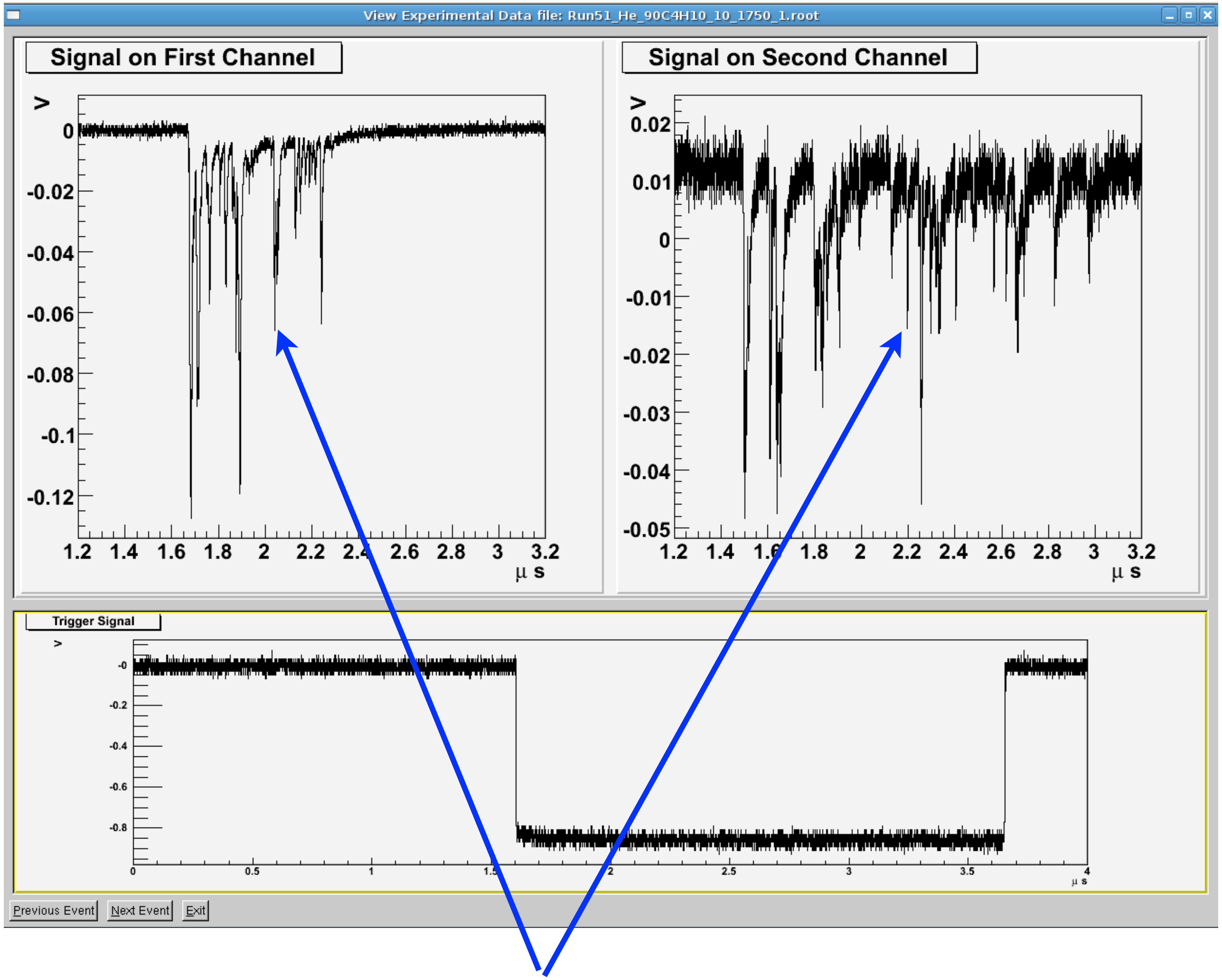
... also use this to improve the hadronic energy resolution.

Dual-readout: time-history differs for EM and hadronic objects

Distribution of pulse full-width at 1/5-maximum for electrons and pions



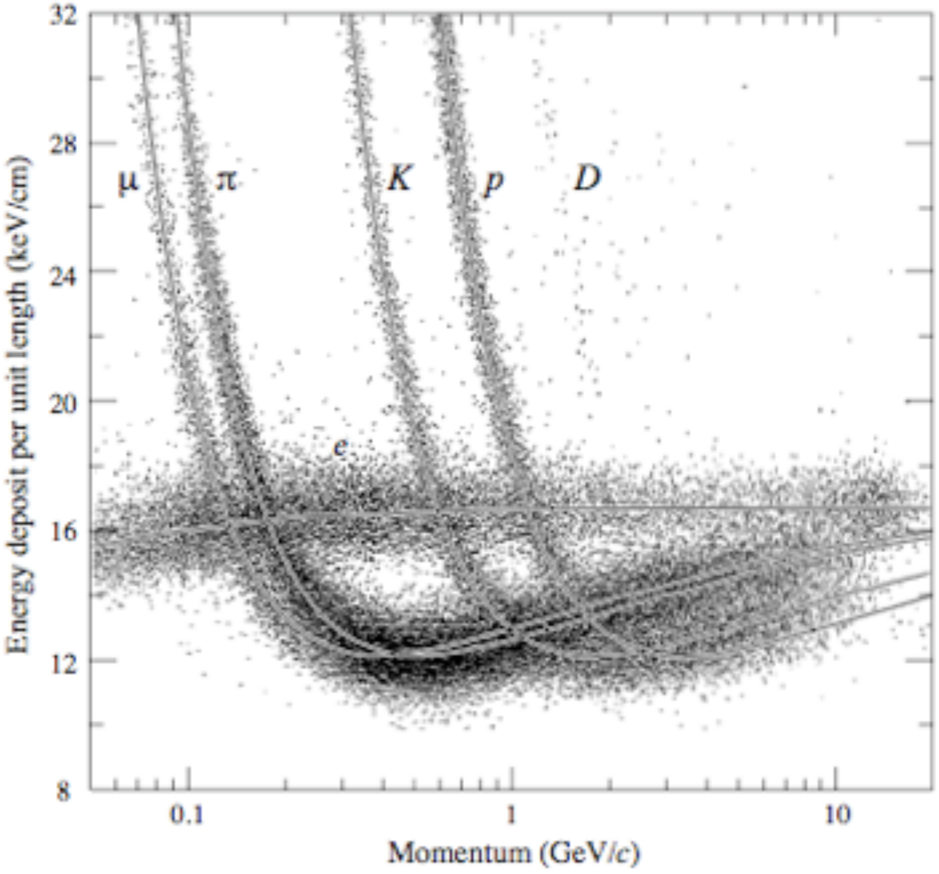
dE/dx by cluster-finding: *specific ionization resolution ~ 3%*



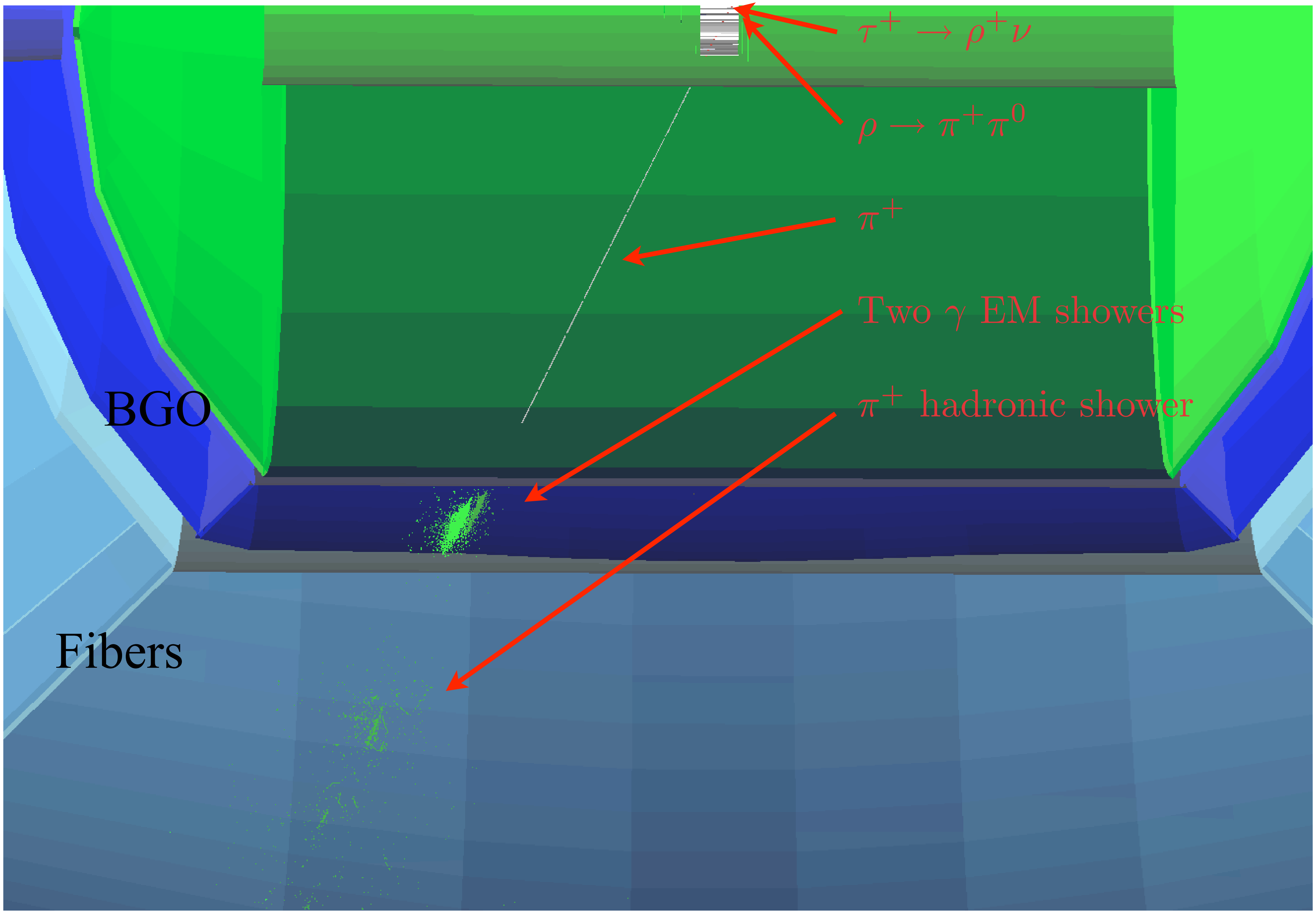
Measured CluCou clusters on two different wires: cluster count is Poisson (no Landau fluctuations), expect 3.5% measurement of specific ionization

TPC with ~6% dE/dx resolution

This TPC built by Dave Nygren, LBL, in 1970's, analyzed by Gerry Lynch.

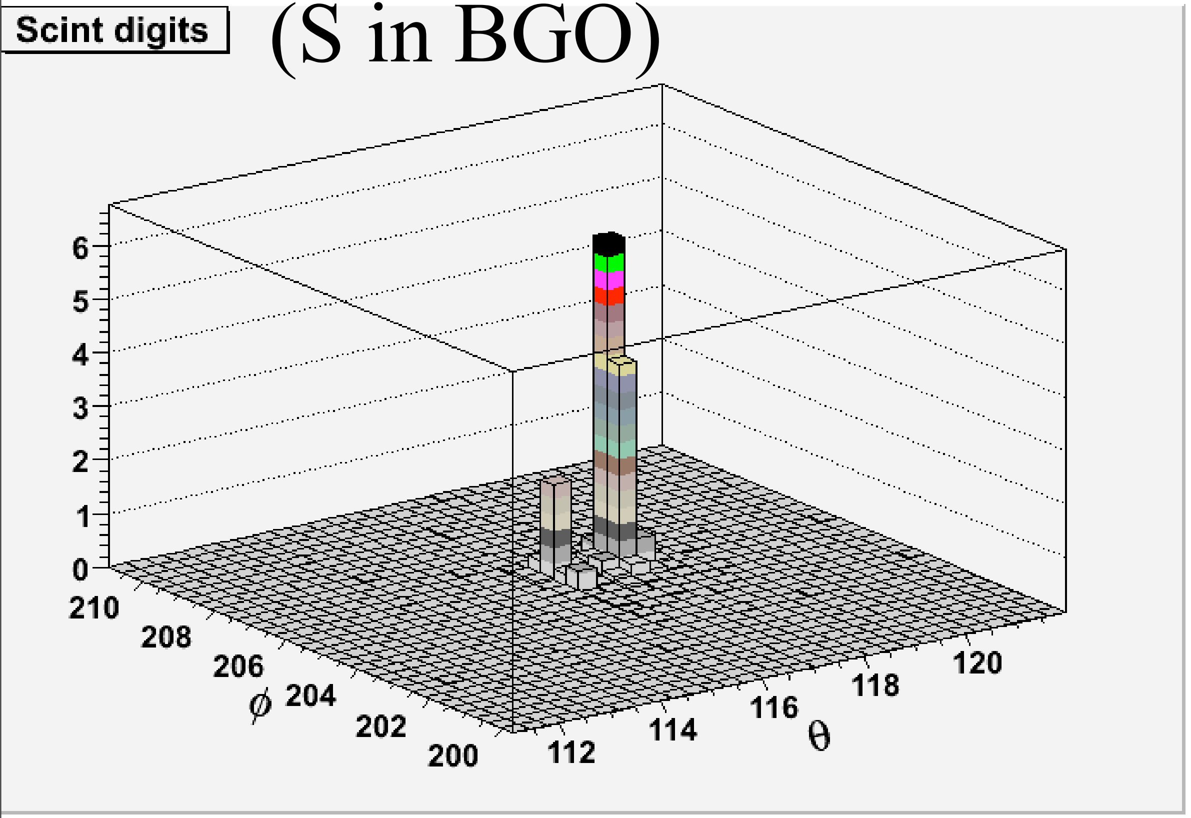


Tau ID with dual-readout

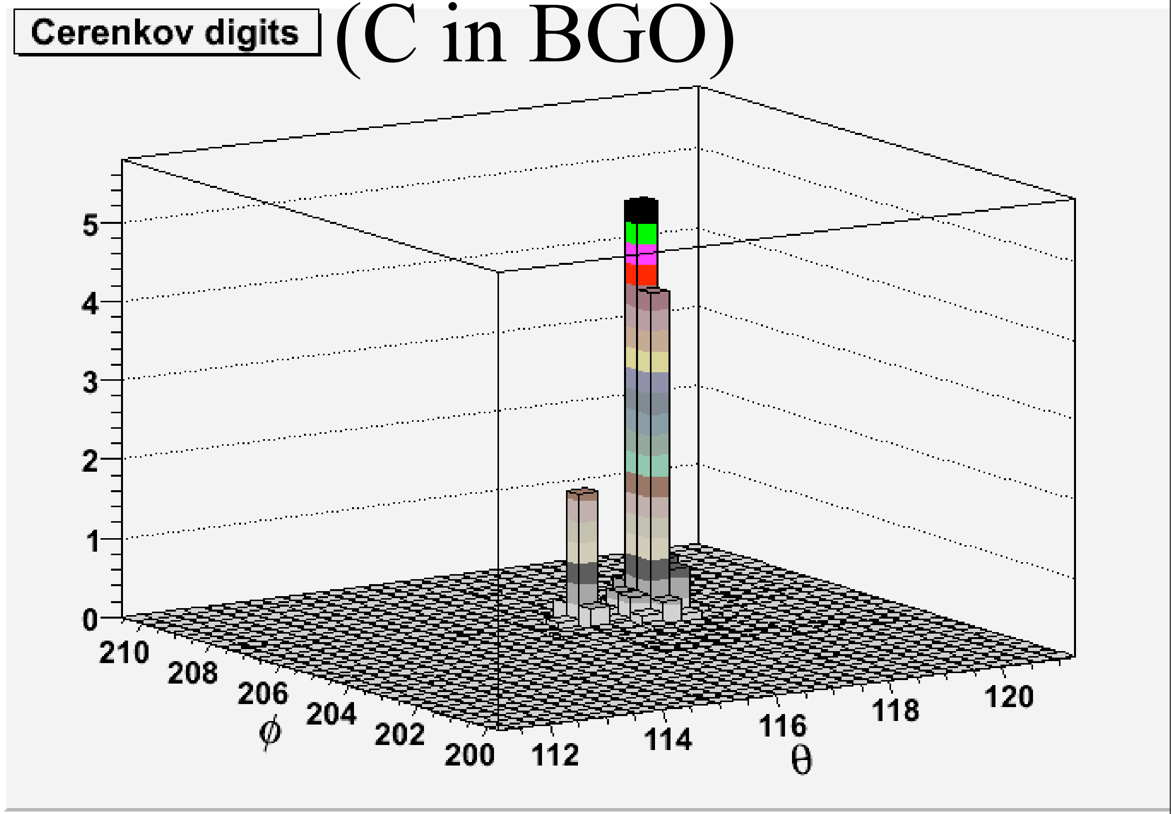


Tau ID with dual-readout

(S in BGO)



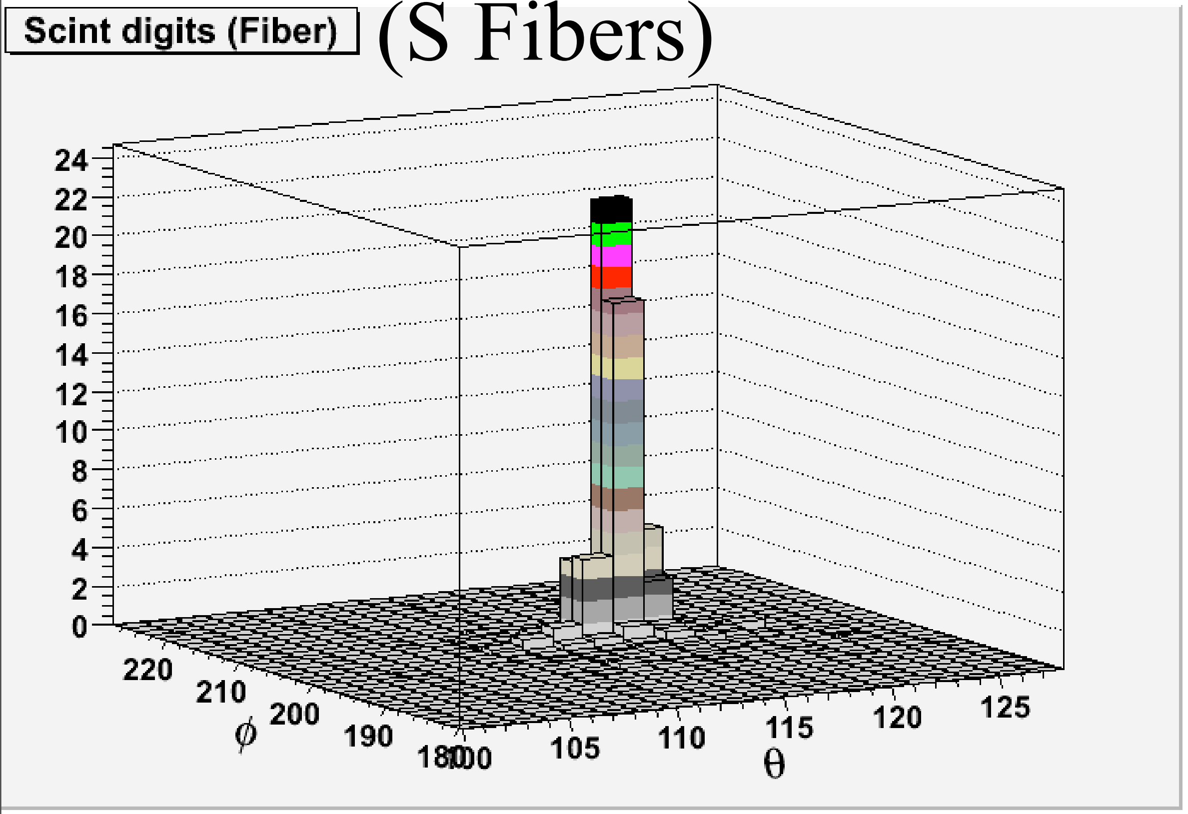
(C in BGO)



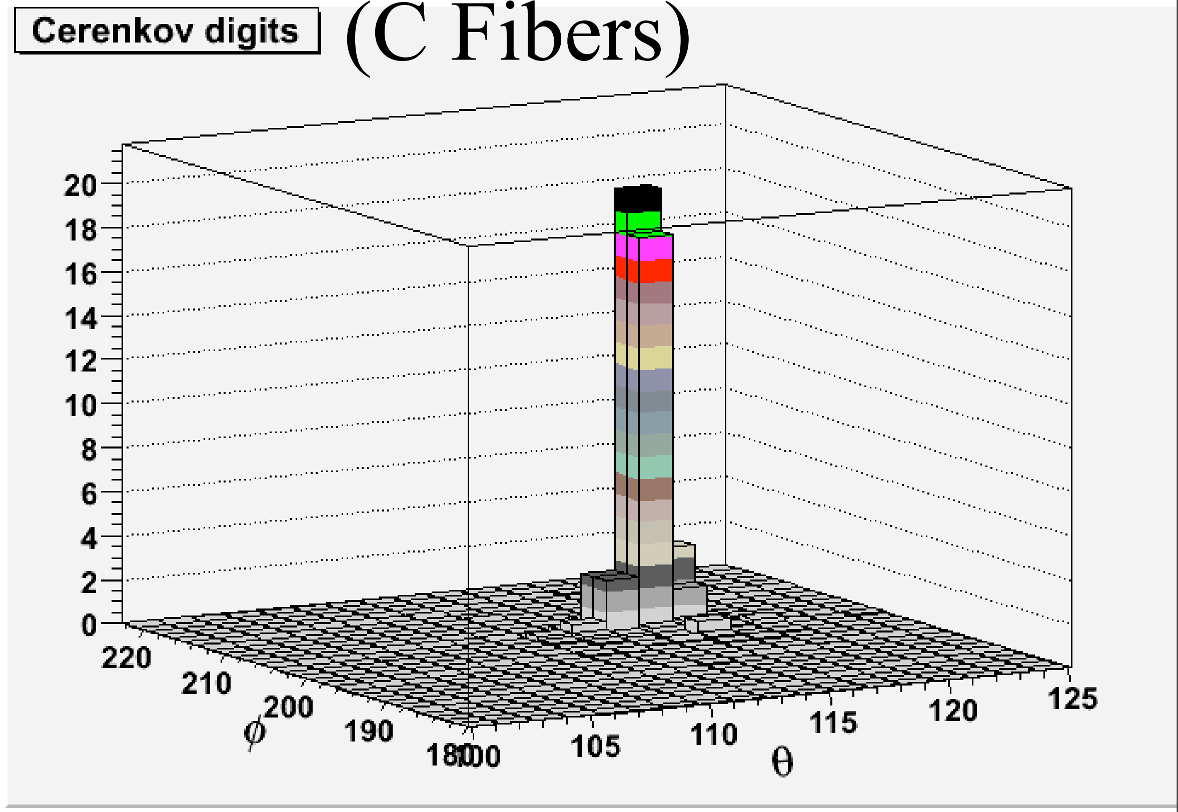
two
clear
photons

S~C
(EM)

(S Fibers)



(C Fibers)



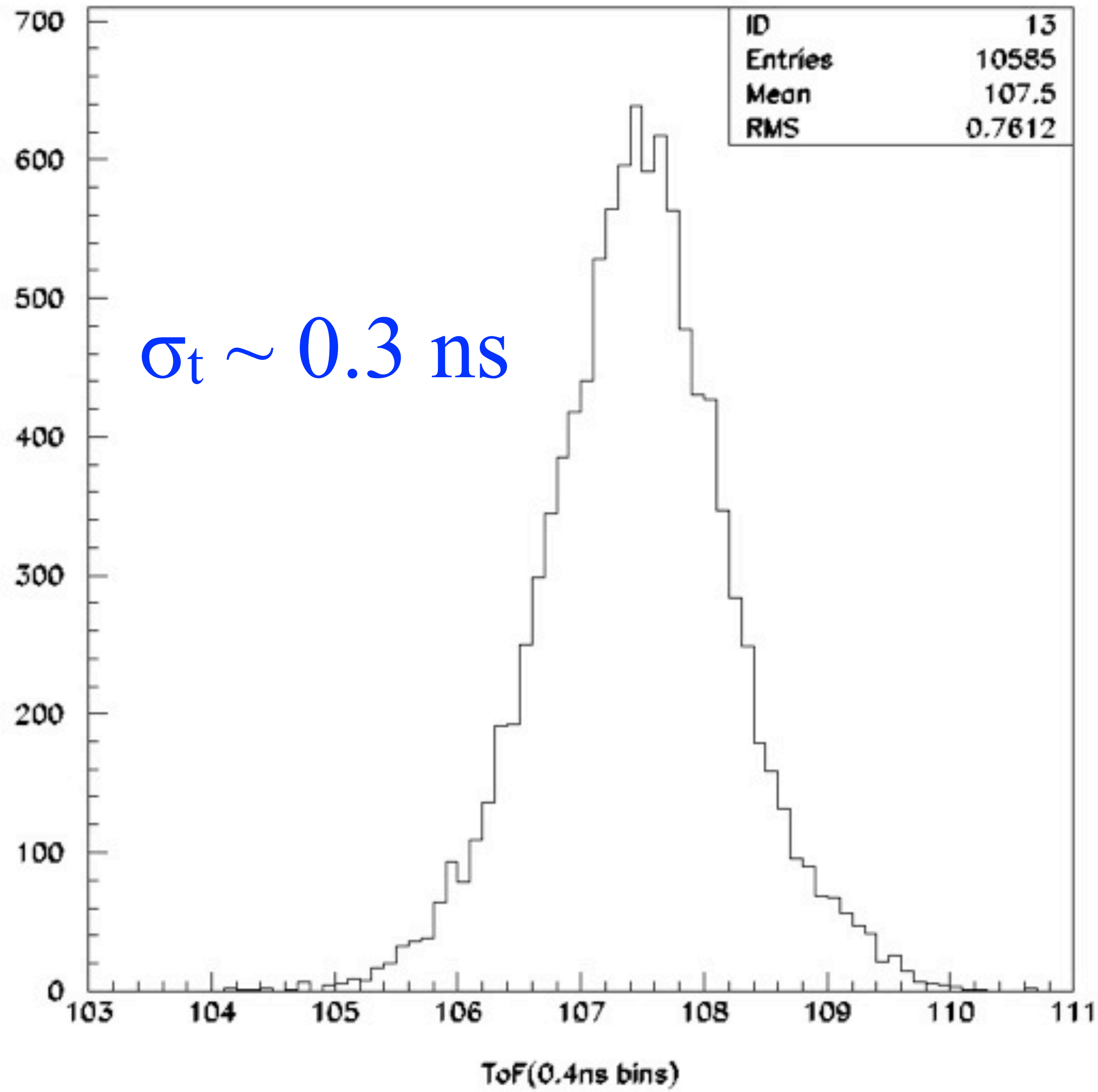
one
clear
shower

S-C
fluctuates

Time-of-flight with Cerenkov light in DREAM fibers

e^- at 50 GeV
fiber Cerenkov light
$\sigma_t \approx 0.30$ ns
Usable for EM decays
of massive long-lived
objects (SUSY, etc.)

We should work on this:
improve to 0.1ns: $\Delta z = 2$ cm

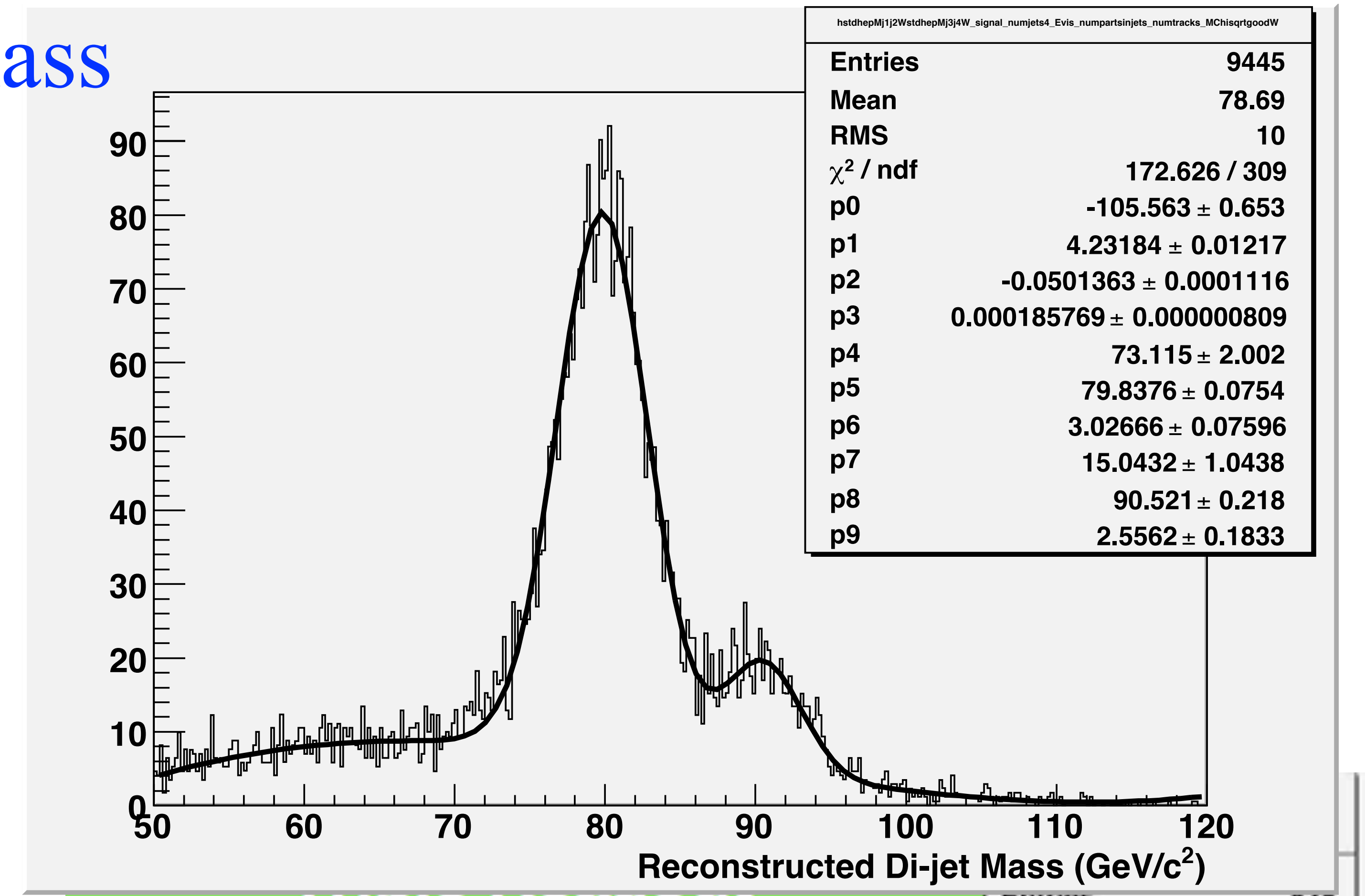


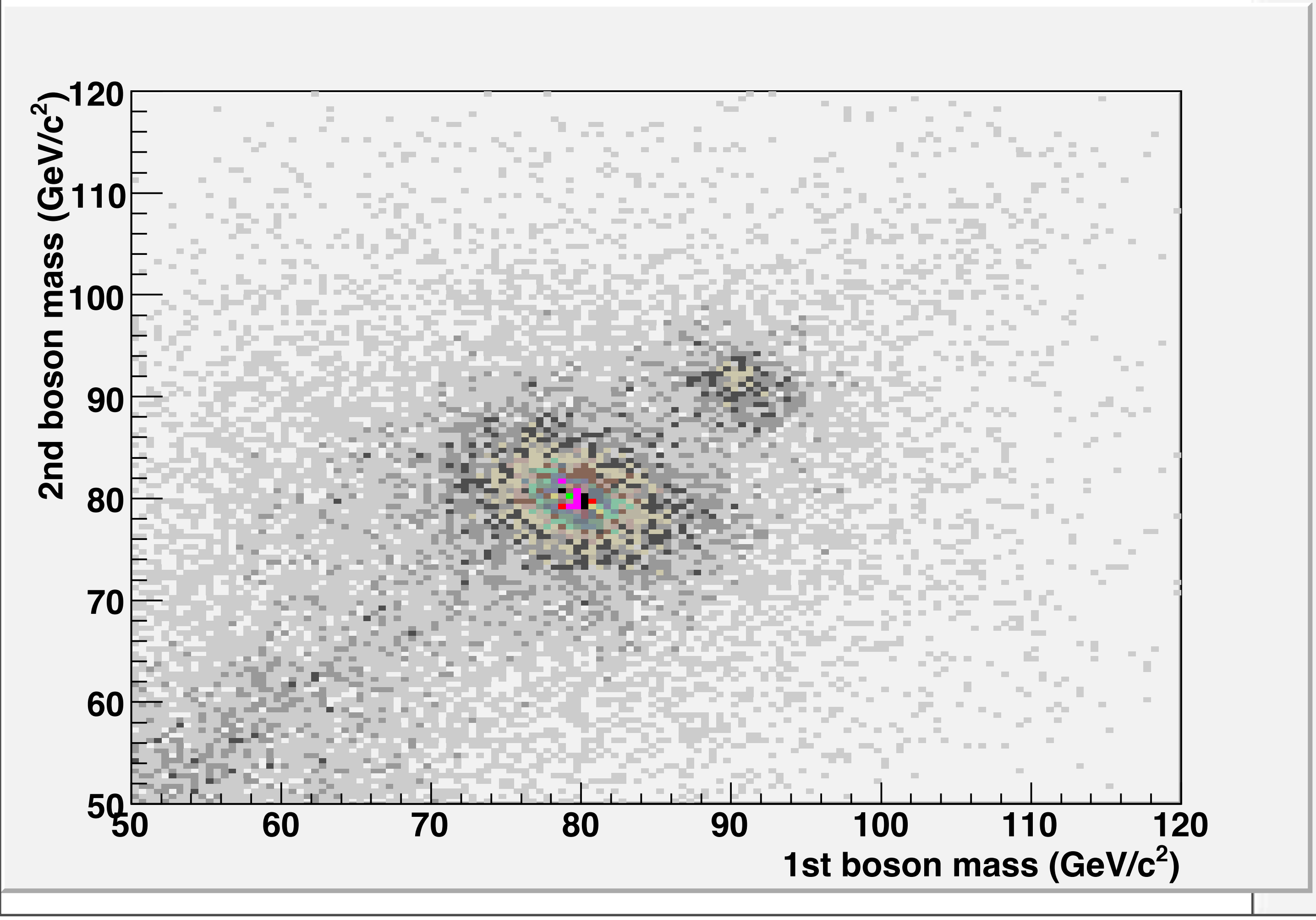
$\sigma_t \sim 0.3$ ns

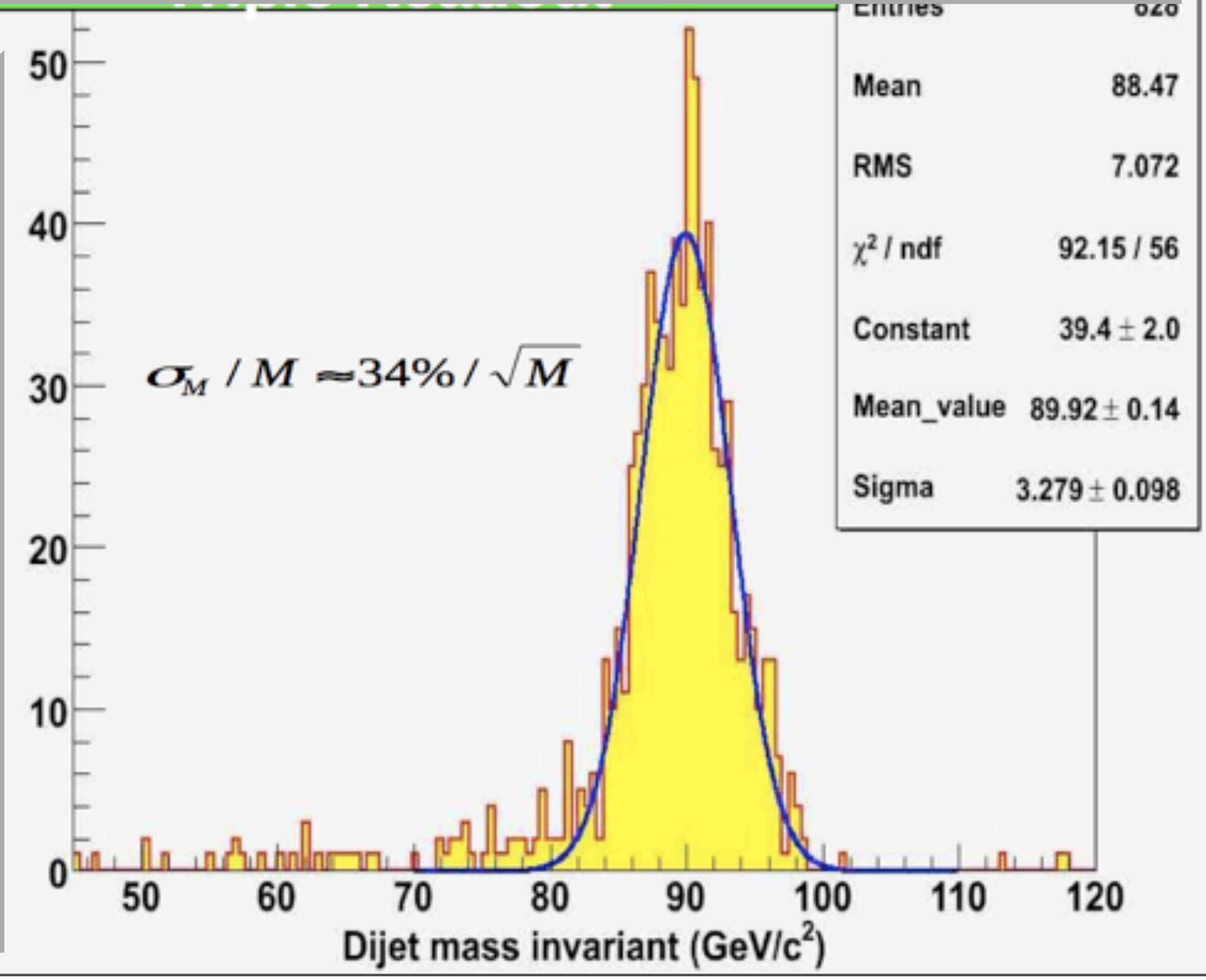
Dual-readout: *jet-jet* invariant mass

$$W \to jj$$
$$Z \to jj$$

$$e^+e^- \to W^+W^-\nu\bar{\nu}$$
$$e^+e^- \to Z^0Z^0\nu\bar{\nu}$$

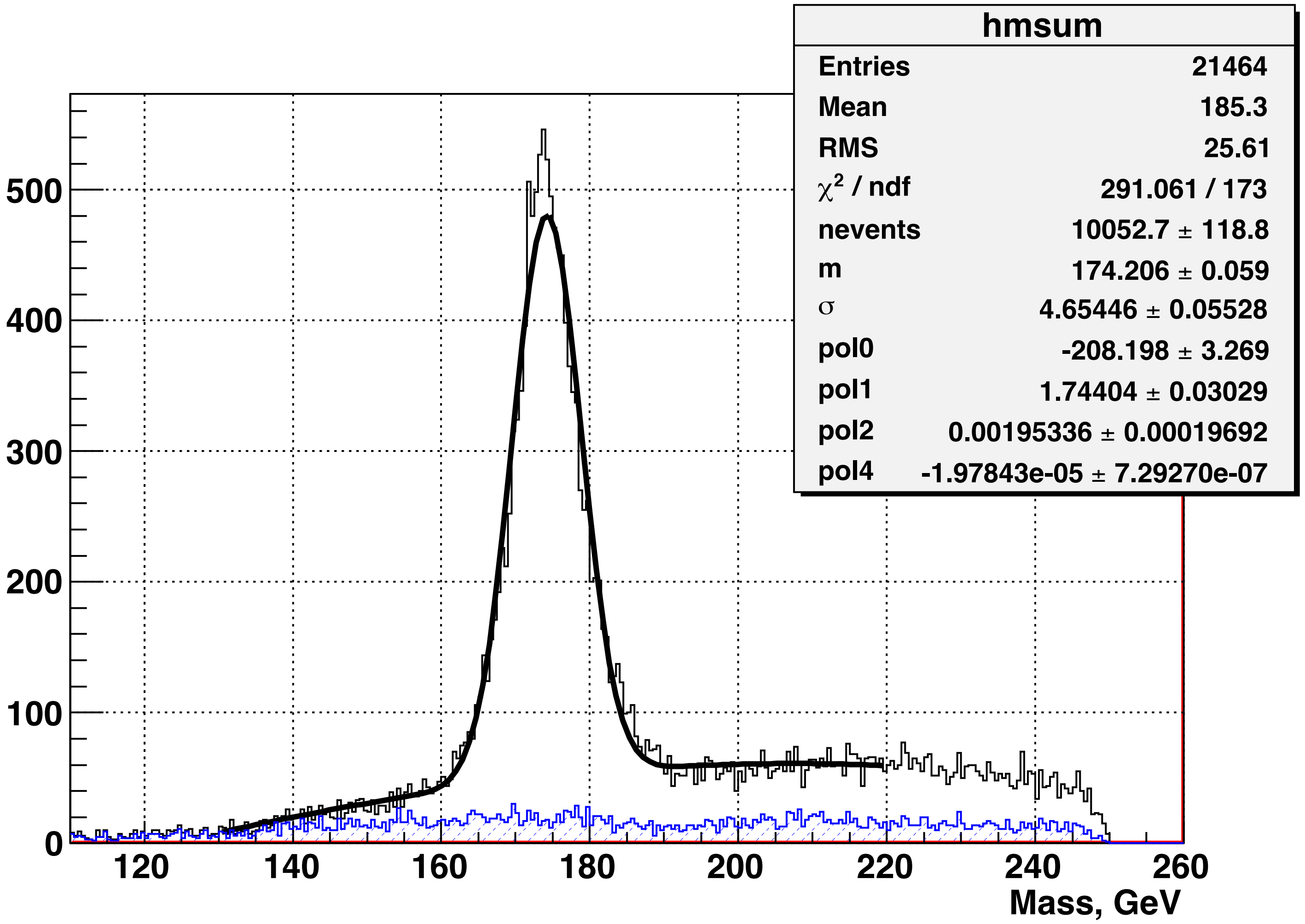






Dual-readout: *6-jet* invariant mass. top fit results

Fedor Ignatov,
Budker Institute



Mass ~ 174.206 +/- 0.059 GeV

σ_M ~ 4.65 +/- 0.055 GeV

The experimental resolution of the mass 2.7% corresponds to

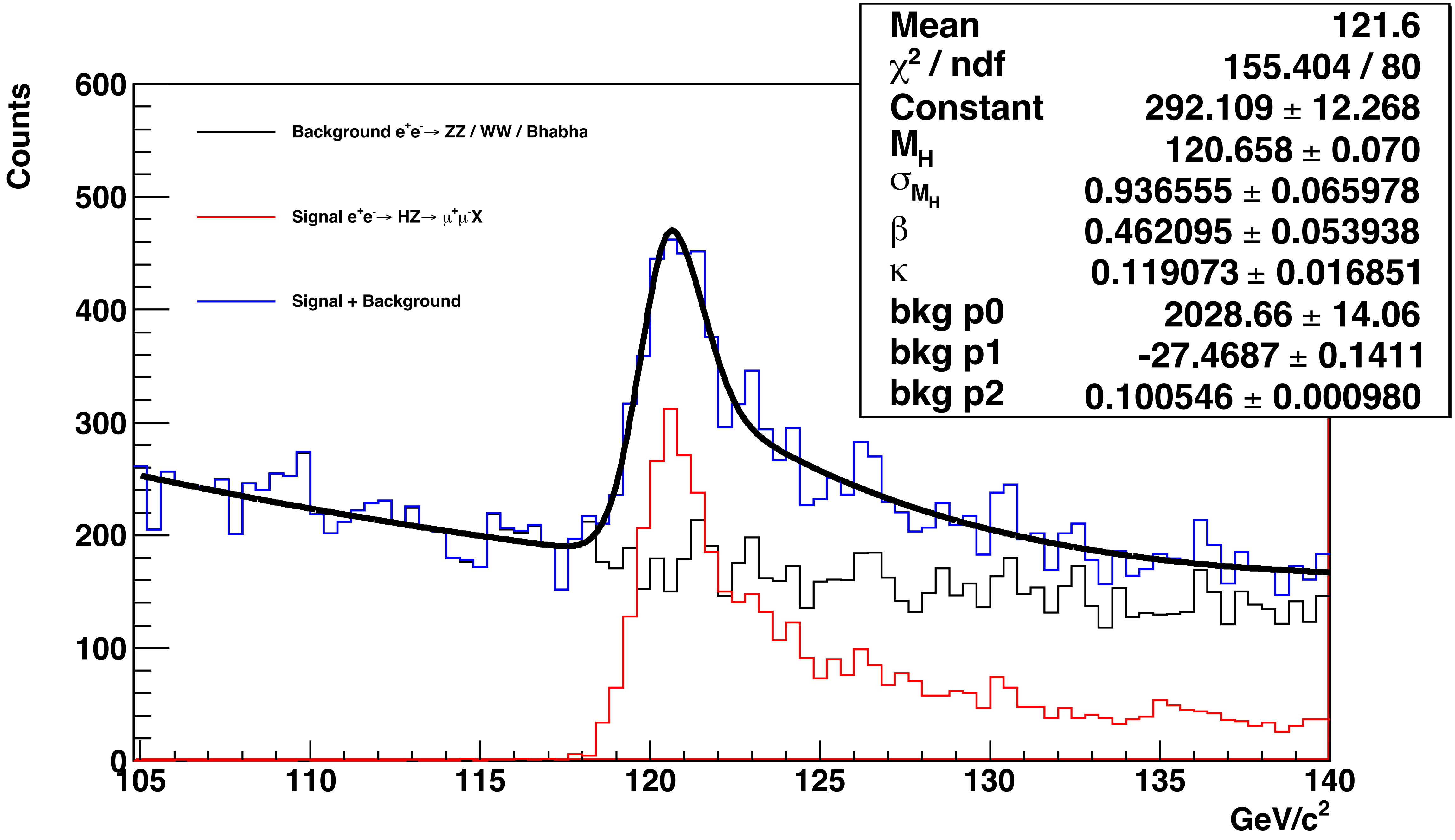
$\sigma_M/M \sim 35\% / \sqrt{M}$

which is very close to the expectations based on the DREAM dual-readout energy resolutions.

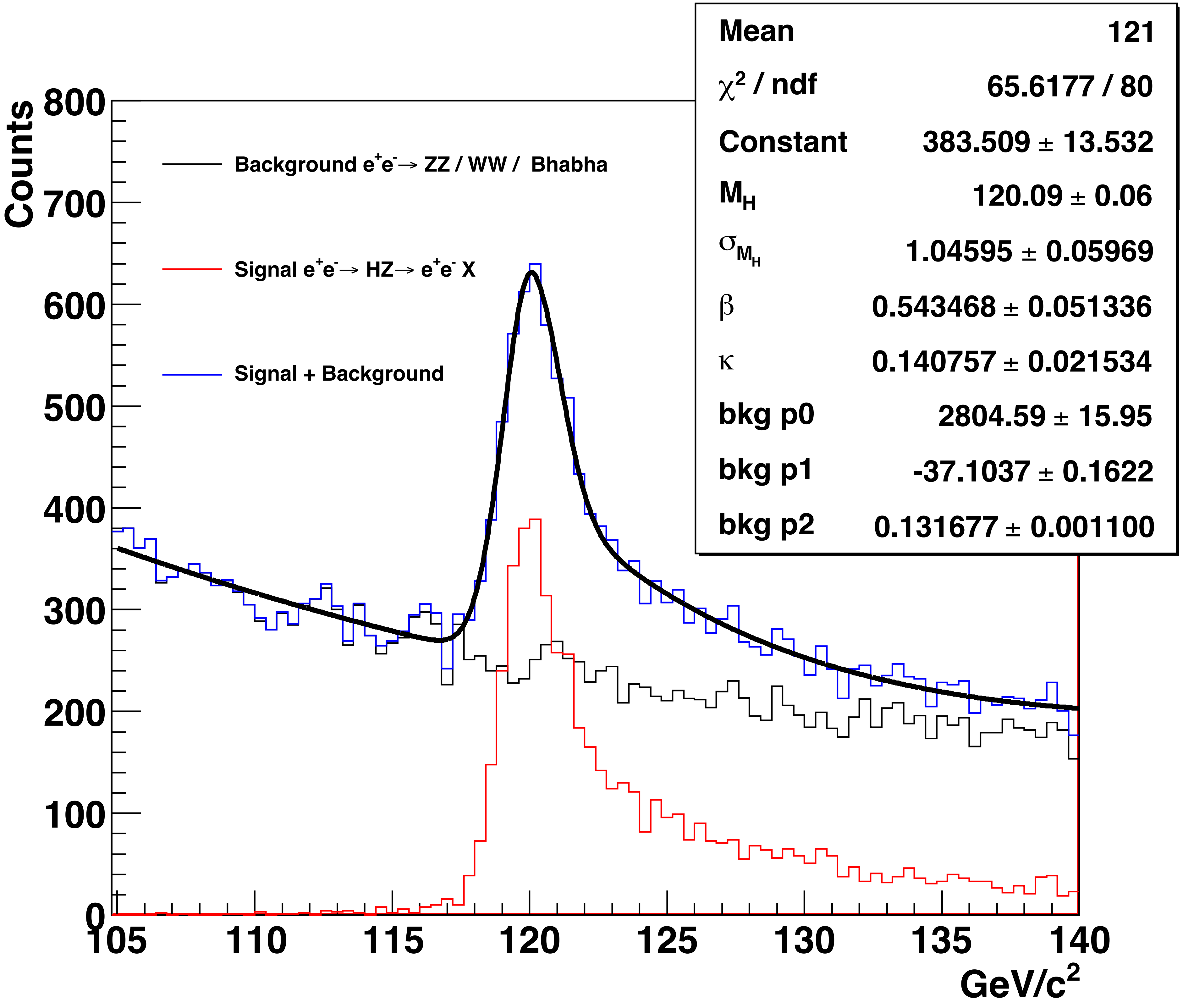
The overall top efficiency (probability to end up in the peak) is only 16% in this hurried study for the LoI. Needs more work on 6-jet selections and … *b*-tagging.

CluCou tracker: $\mu^+\mu^-$ invariant mass

Gianfranco Tassielli,
INFN, Lecce



Dual-readout & CluCou tracker: e^+e^- invariant mass



EM calorimeter really helps: sharper signal and lower backgrounds

Summary

(1) Dual-readout calorimeters are rich in particle ID measurements

- *Leptons: e, mu, tau (dual-readout) & neutrino (subtraction)*
- *Quarks: uds & t → Wb (dual-readout) c,b (tagging)*
- *Bosons: H, W, Z, and gamma (dual-readout)*
- *Hadrons: pi-zero (by mass), charged pi, K, p (by dE/dx)*

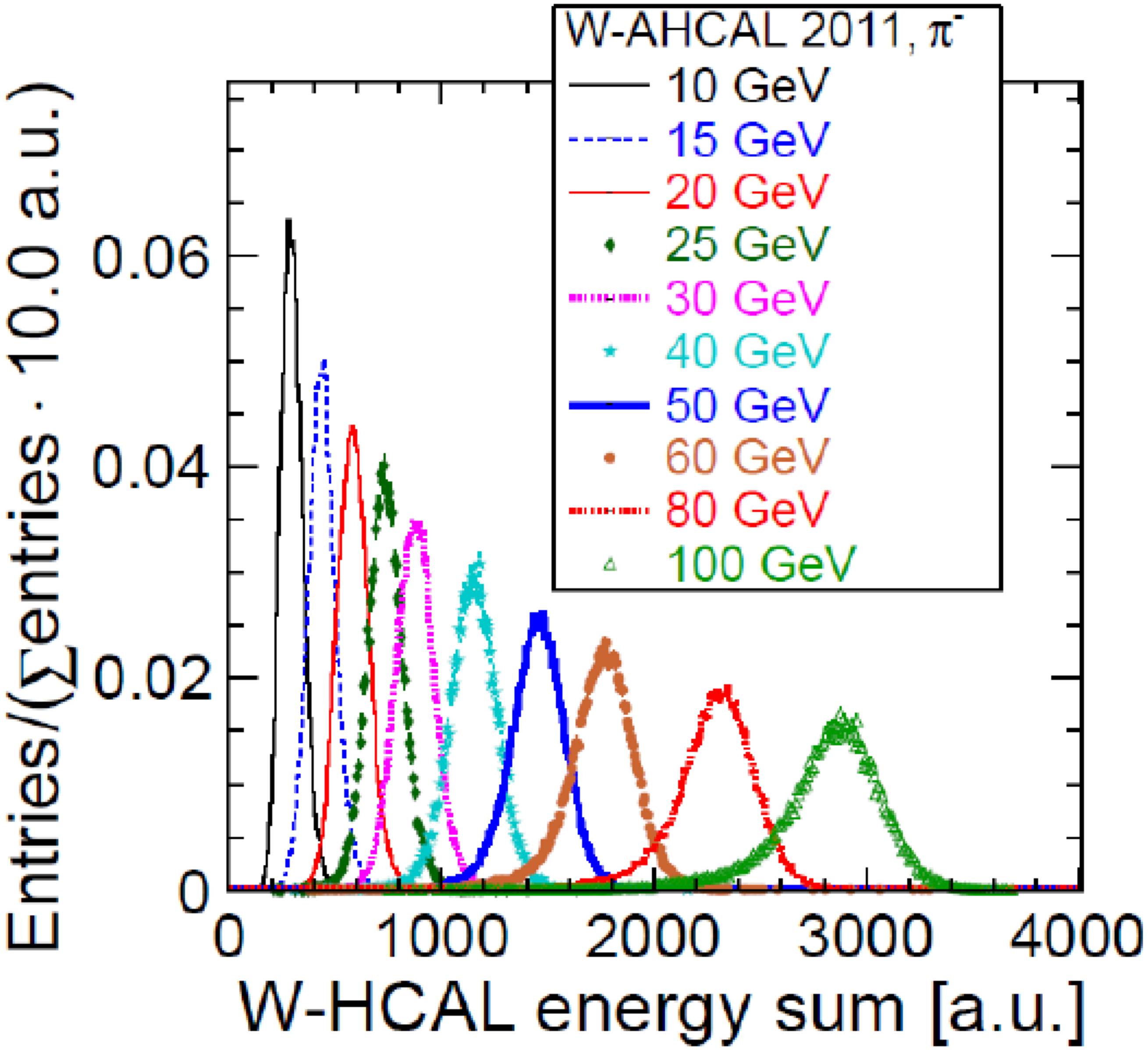
(2) Dual-readout calorimeters can be incorporated into *4π* detectors

(3) Dual-readout calorimeters would do good physics

Extras and spares (9)

Why I don't believe the CALICE calorimeters are going to work at a collider

CALICE W-AHCAL Test Beam 2011

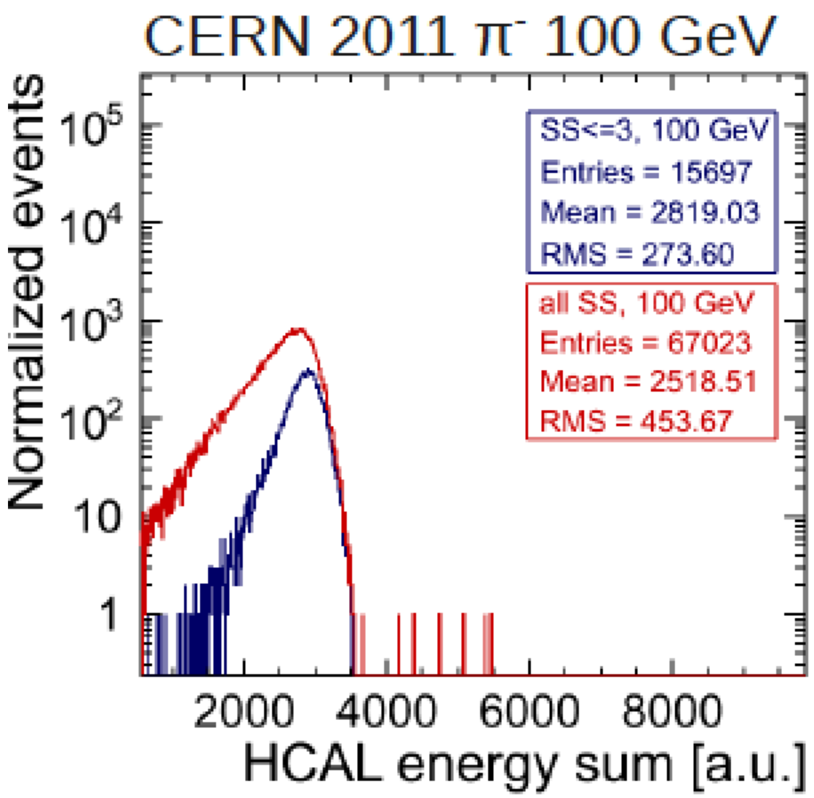


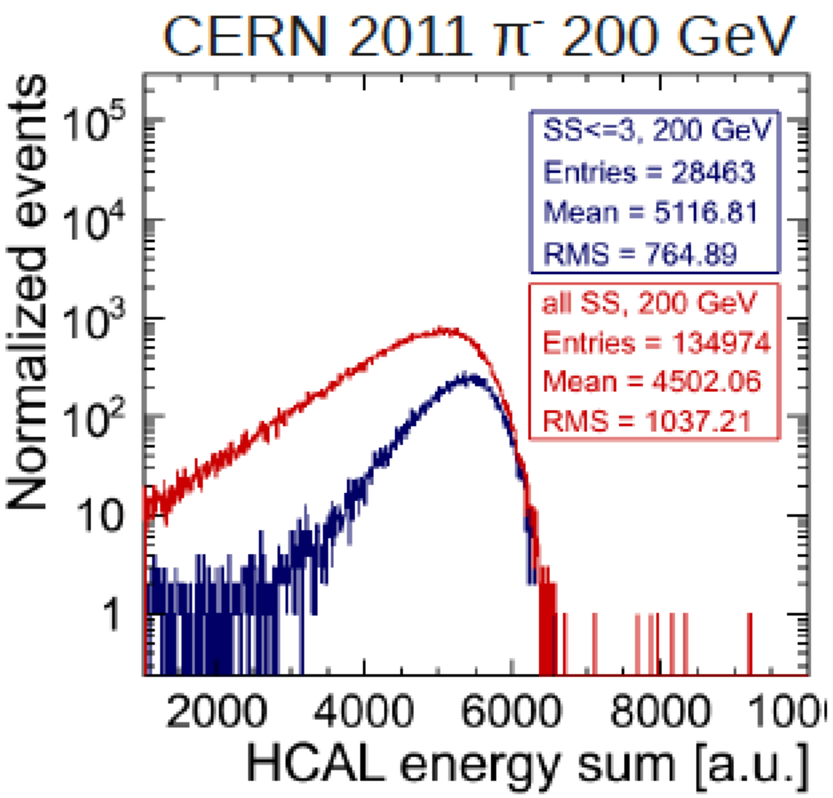
- W-AHCAL of 38 layers
- Only very small leakage effects are visible in W-AHCAL up to highest presented energies (here: $p_{beam} \leq 100$ GeV)
  - Selected only those events in which the shower starts in the first three layers of the W-AHCAL
- Leakage effects for very high energies $p_{beam} > 100$ GeV or for events with late shower start

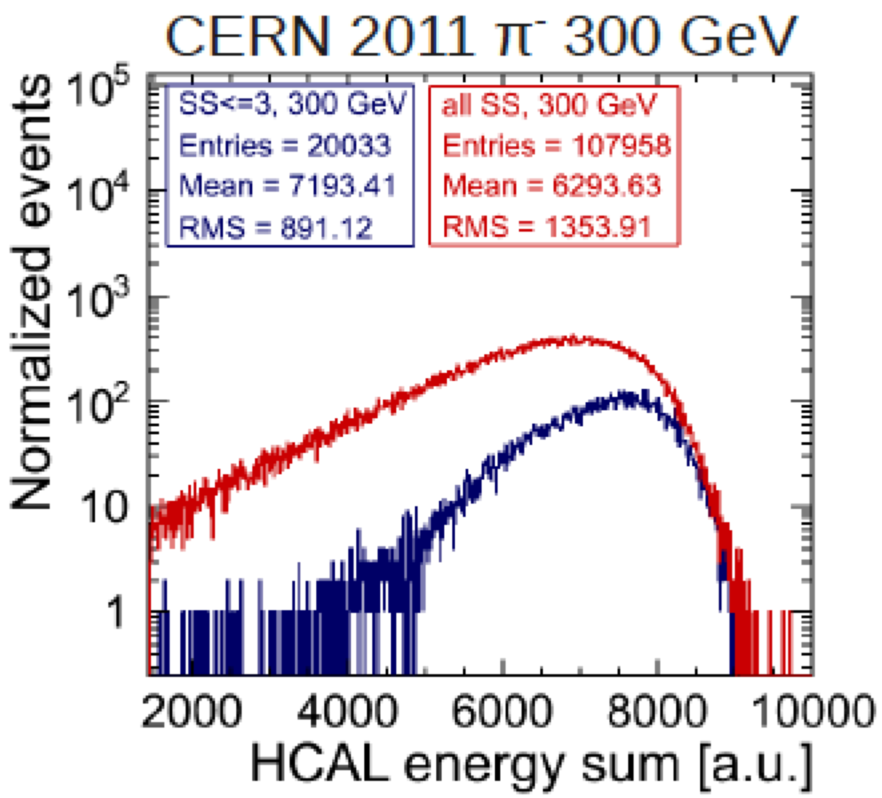
LCD Note 2013-002

W-AHCAL at High Energies

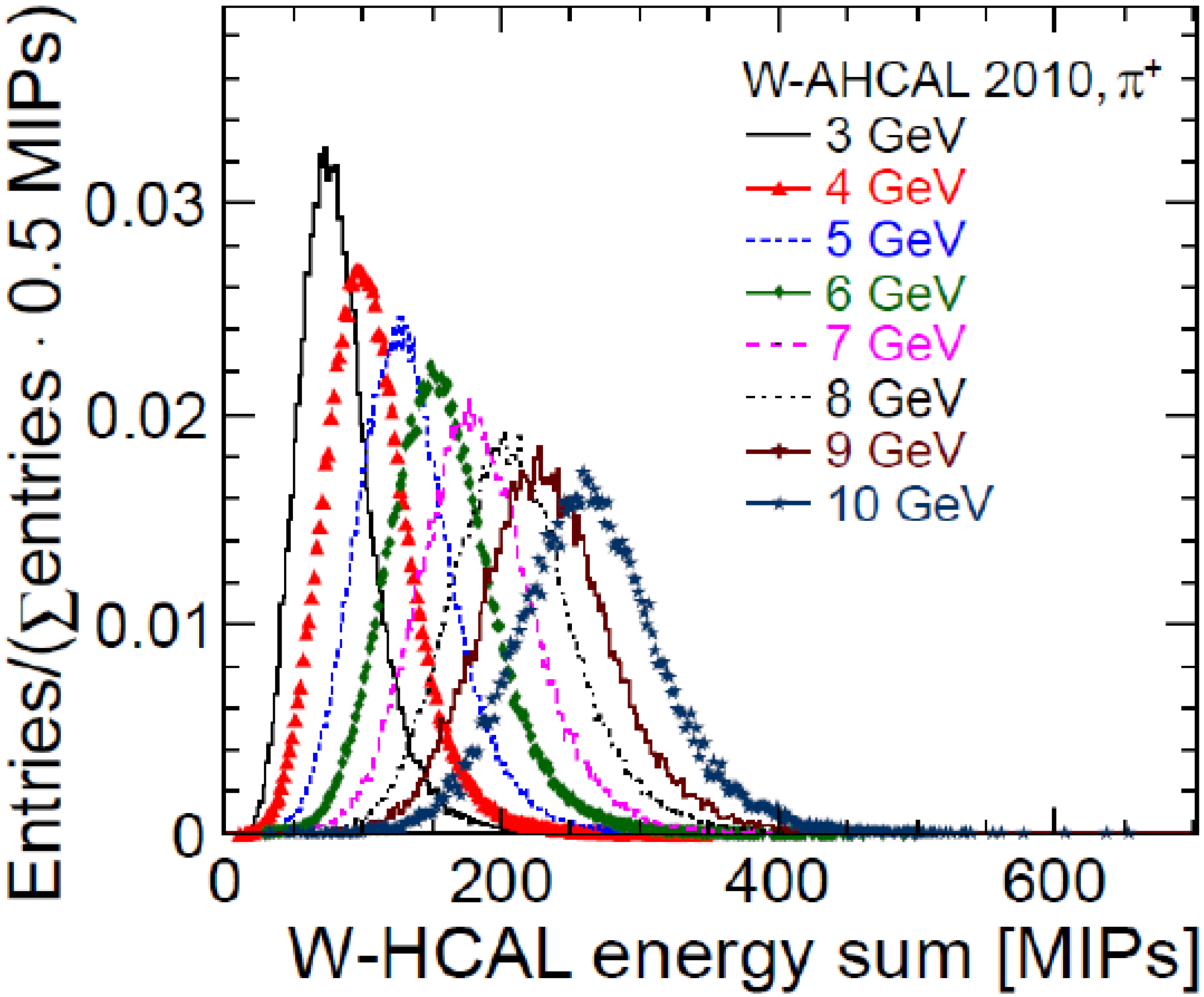
- Leakage effects grow
  - with increasing energy and
  - when accepting all showers no matter in which layer the shower starts
- W-AHCAL: Shower start ≤ 3
- W-AHCAL: All shower start layers


CERN 2011 π⁻ 100 GeV


CERN 2011 π⁻ 200 GeV


CERN 2011 π⁻ 300 GeV

CALICE W-AHCAL Test Beam 2010



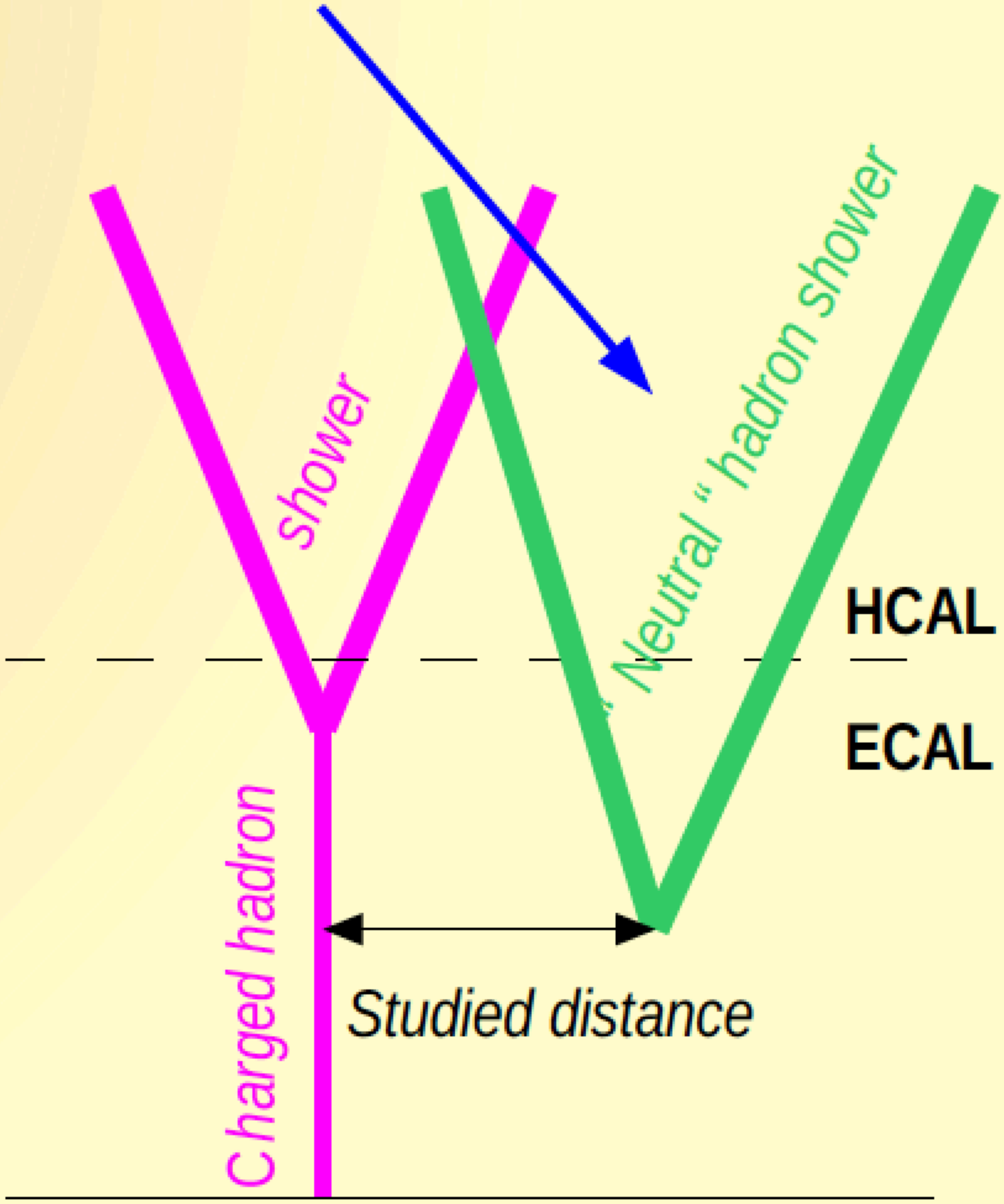
- Test beam with W-AHCAL at CERN PS at energies from 1 to 10 GeV
- W-AHCAL of 30 layers
- Clear pion peak at all energies in HCAL-only
- By selection, shower fully contained in W-AHCAL
  - Select events with shower start in very first W-AHCAL layers (≤3)

CALICE Analysis Note 036

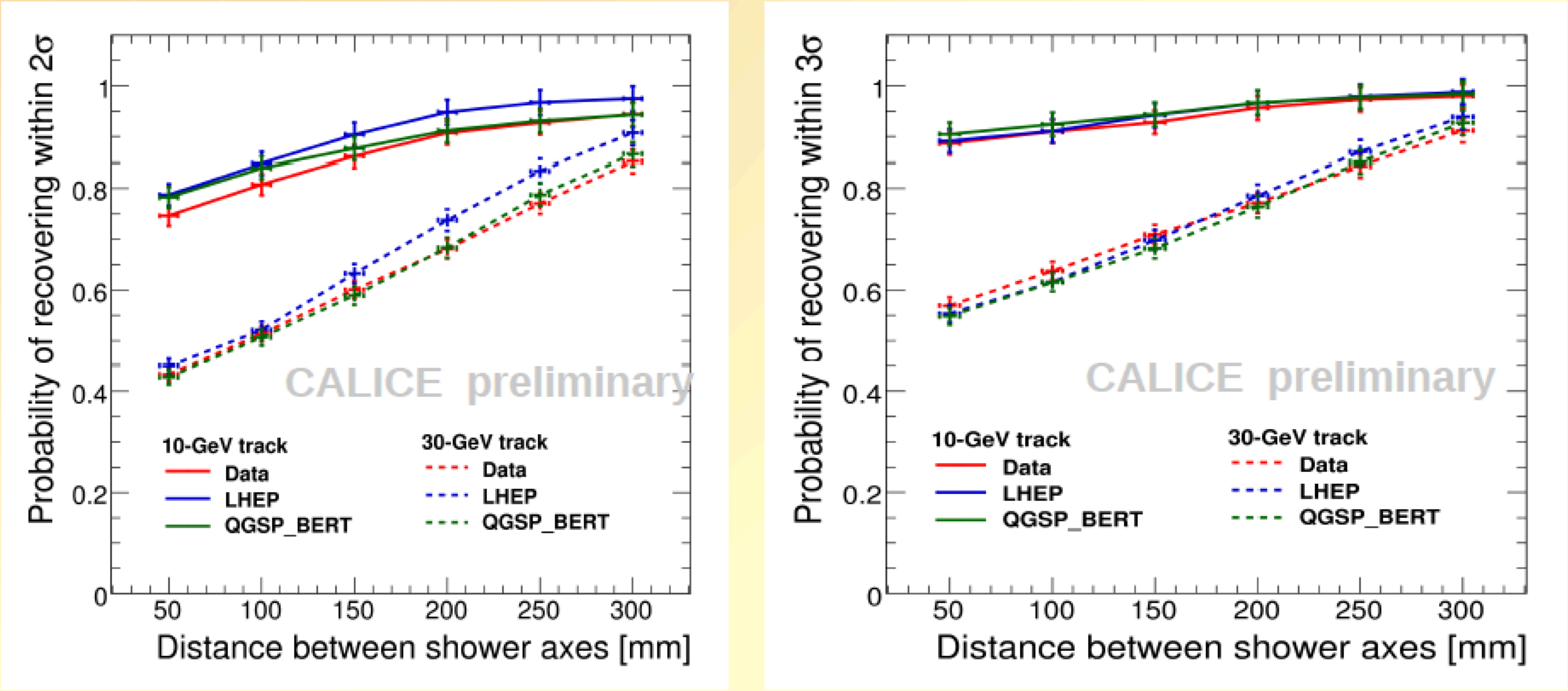
https://edms.cern.ch/file/1224616/1/can_note_14June2012.pdf

For one of the two events we move all hits at a studied transverse distance from their original position, keeping only hits placed behind the shower start. This event emulates a neutral hadron (e.g. neutron or K^{0}_{L}) shower

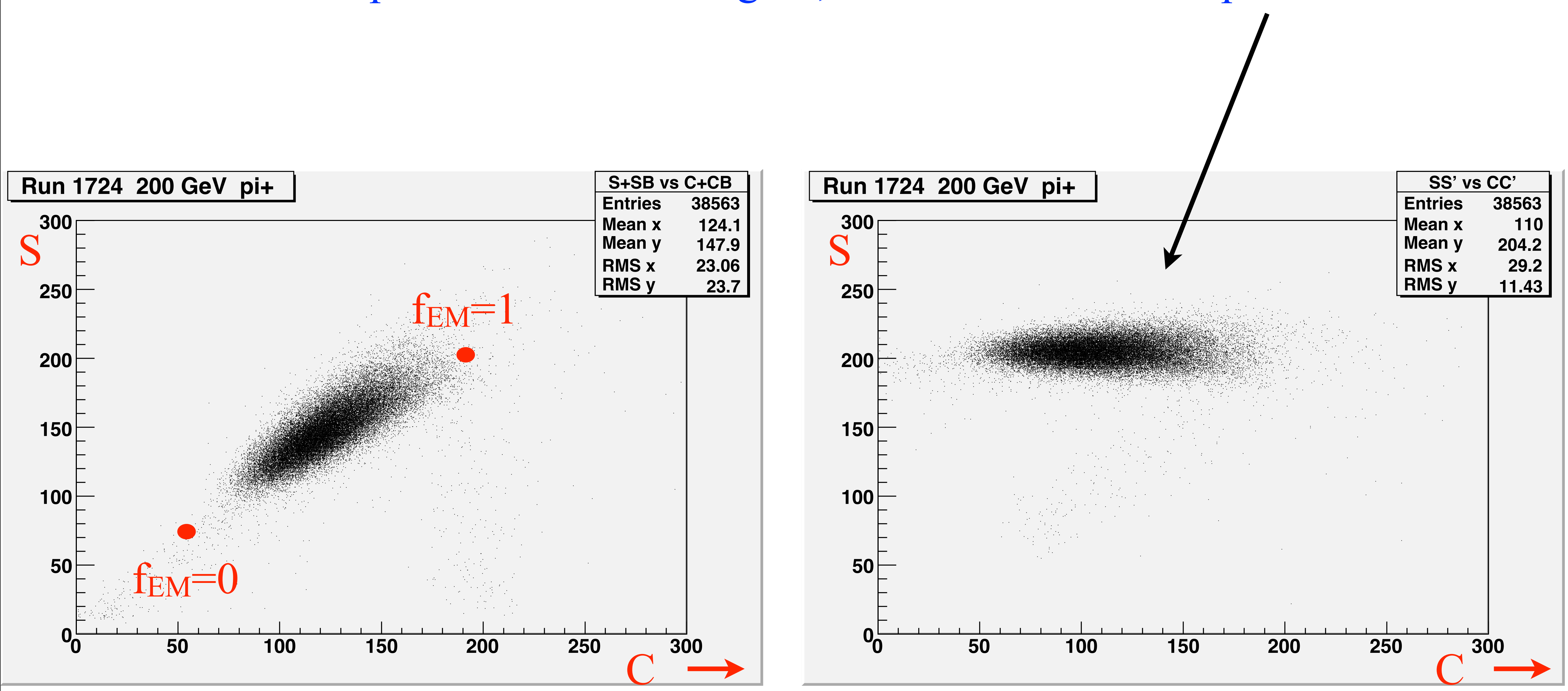
- To test PandoraPFA, we overlaid two events from different runs
- We used showers with 95% energy containment in ECAL and HCAL
- Beam smearing was corrected: every event was moved to zero XY position before mixing
- We mapped hits of both events to the top octant of the Large Detector Concept (LDC) geometry
- The structure of the CALICE prototype and the LDC are reasonably similar, the existing difference does not simplify the task for the program to disentangle sowers
- We studied distances between showers from 5 cm to 30 cm, typical for a 100 GeV jet



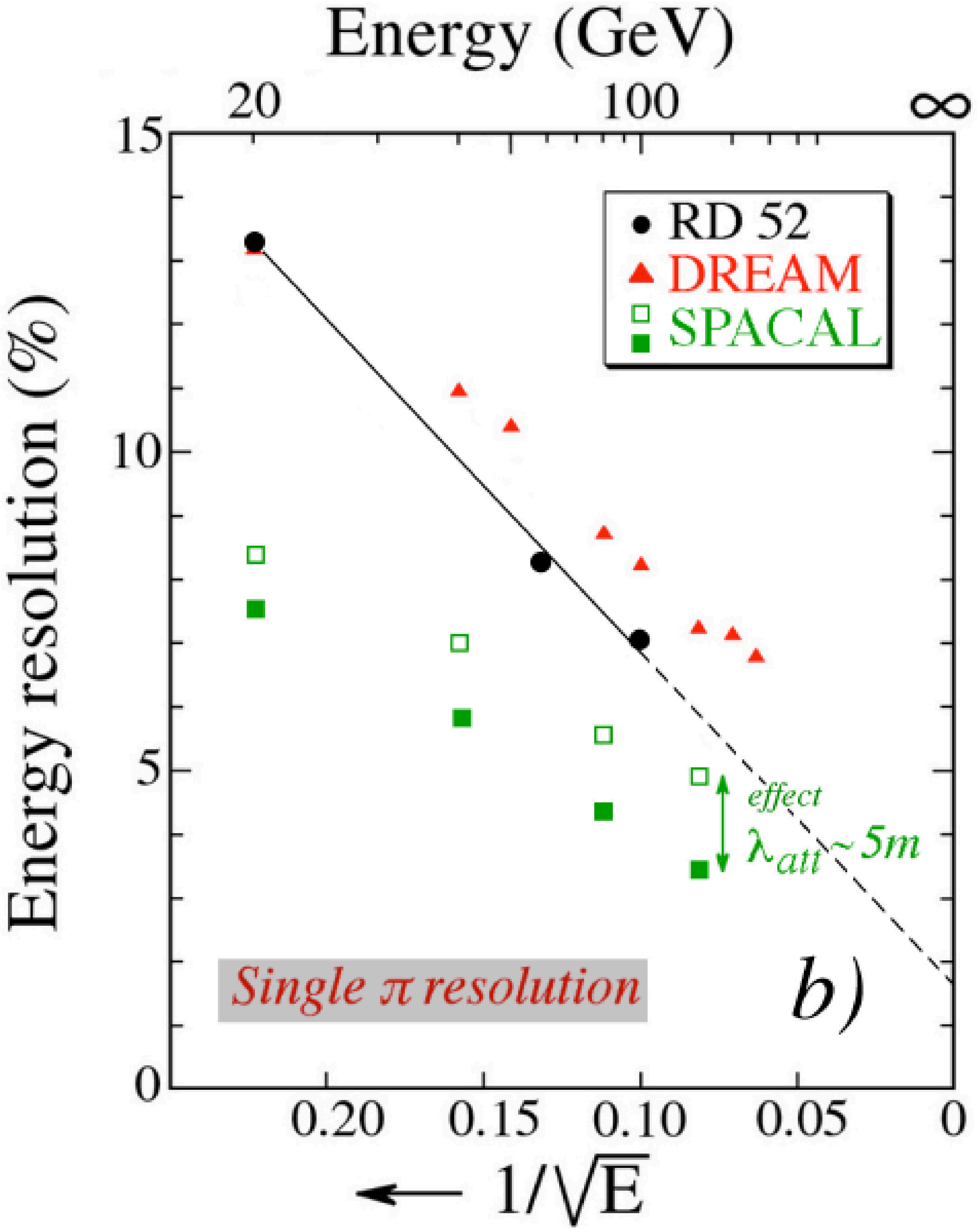
The probability to recover the 10 GeV neutral hadron energy within 2 (left) and 3 (right) standard deviations from its real energy versus the distance from the charged 10 GeV (continuous line) and 30 GeV (dashed line) pion for test beam data (red) and for both LHEP (blue) and QGSP_BERT (green) physics lists



Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves “compensation”.

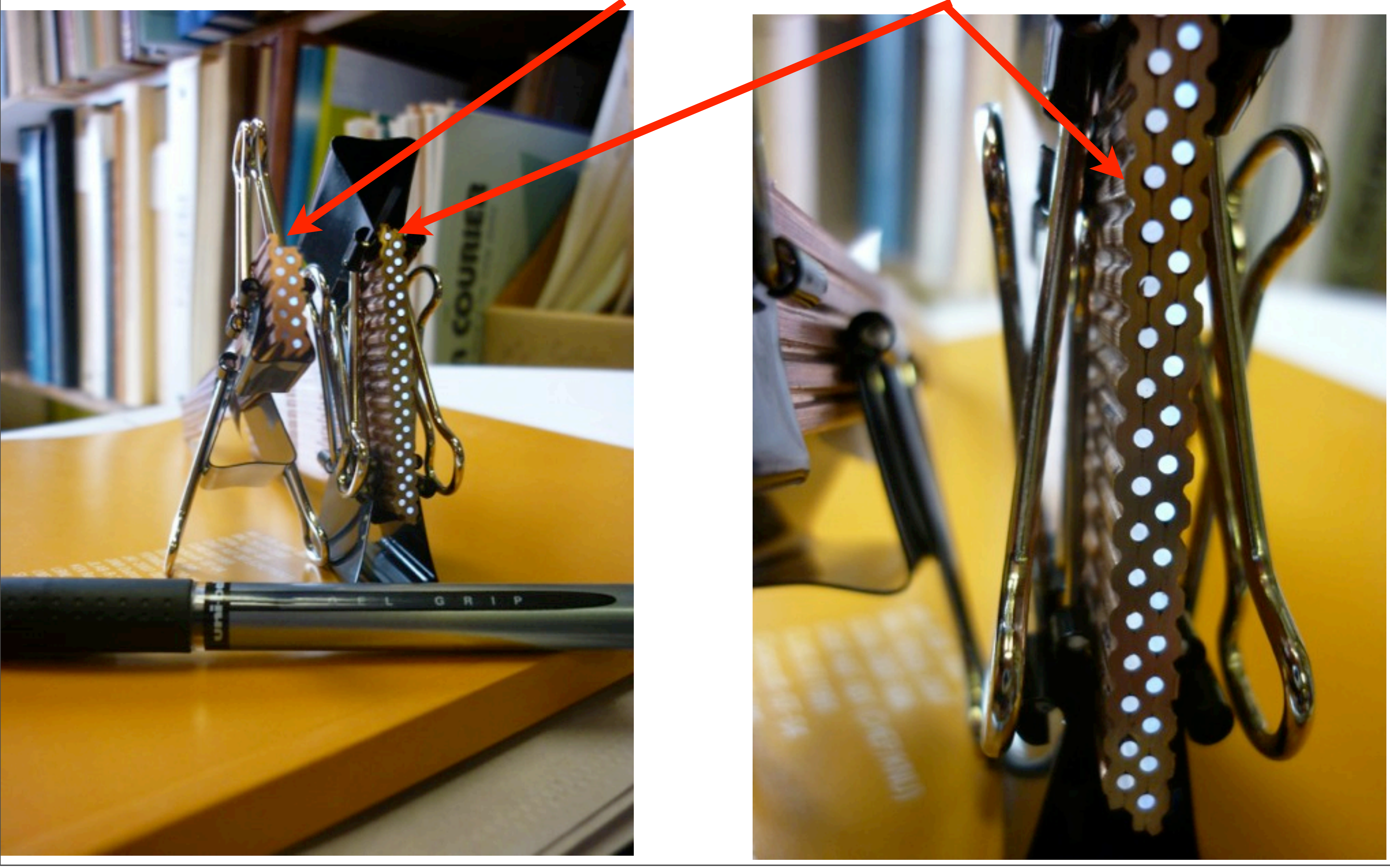


Why 1-2% hadron energy resolution at high energies is foreseen



Cu absorber with dual-readout

Pure Cu,   Cu + Zn(10%)



Geometry

From rectilinear module to 4π detector:

RD1, M. Livan, CERN-PPE/93-22 (Feb. 1993)