4th concept dual-readout calorimetry

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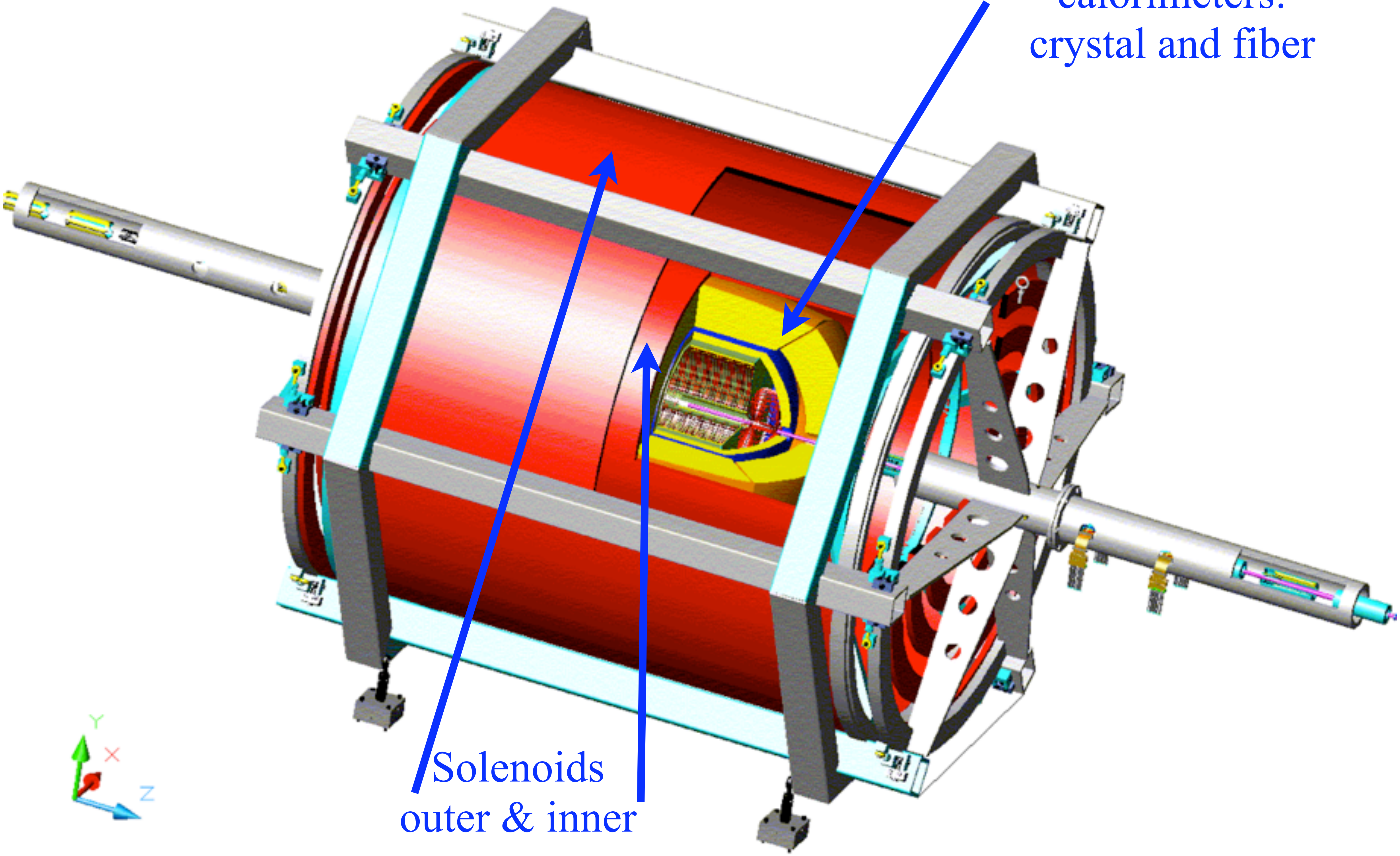
Data-driven and simulation-understood design of the 4th concept calorimeter configuration, and its consequent physics and particle identification capabilities.

The calorimeters are in the "usual place": after the tracker and before the B-field-defining solenoid

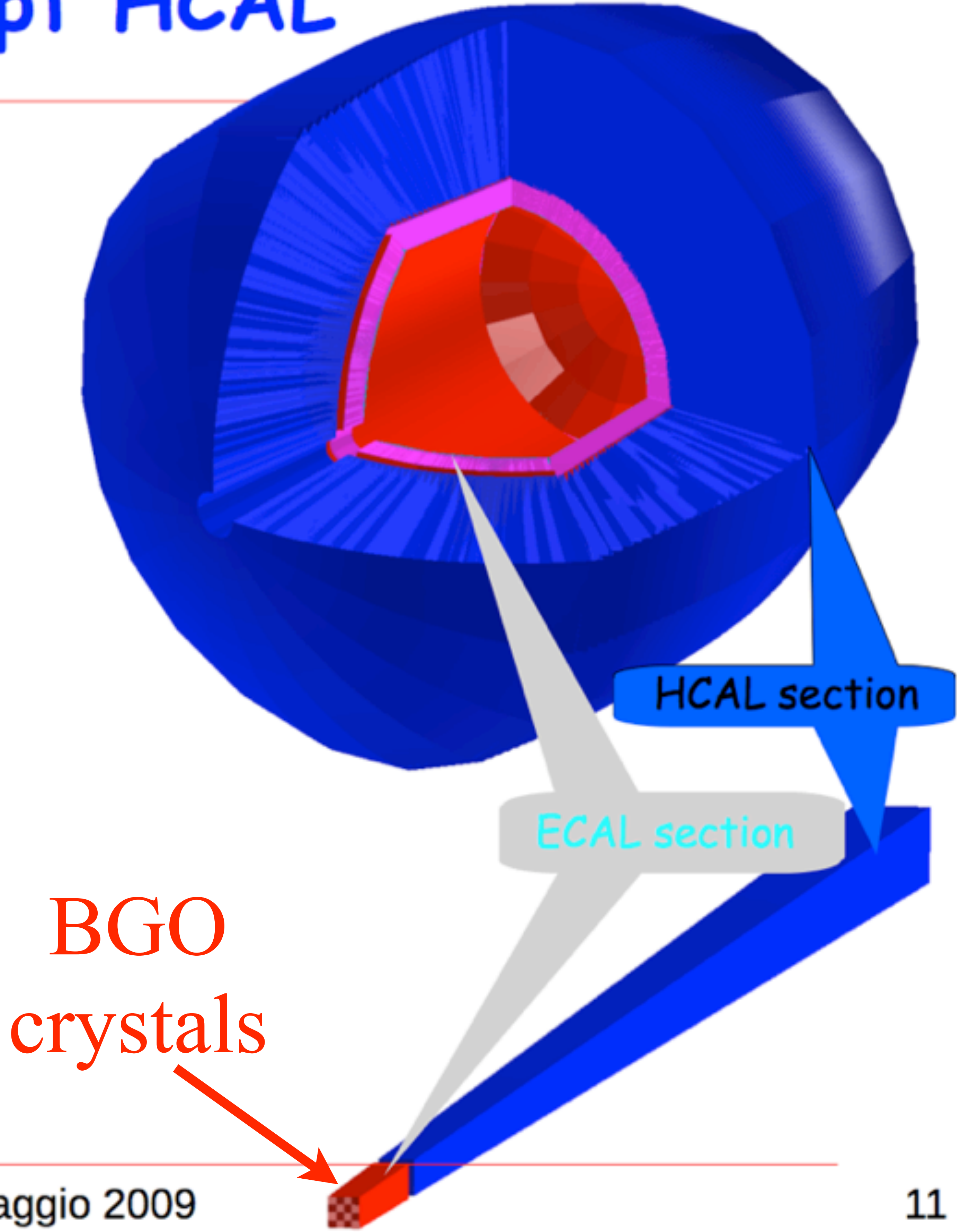


The 4th Concept HCAL

- Cu + scintillating fibers

  + Čerenkov fibers
- ~1.4° tower aperture angle
- 150 cm depth
- ~ 7.3 λ_{int} depth +1.2λ_{int}
- Fully projective geometry
- Azimuth coverage

  down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers



Dual-readout calorimetry: (measure EM fraction every event)

The problem

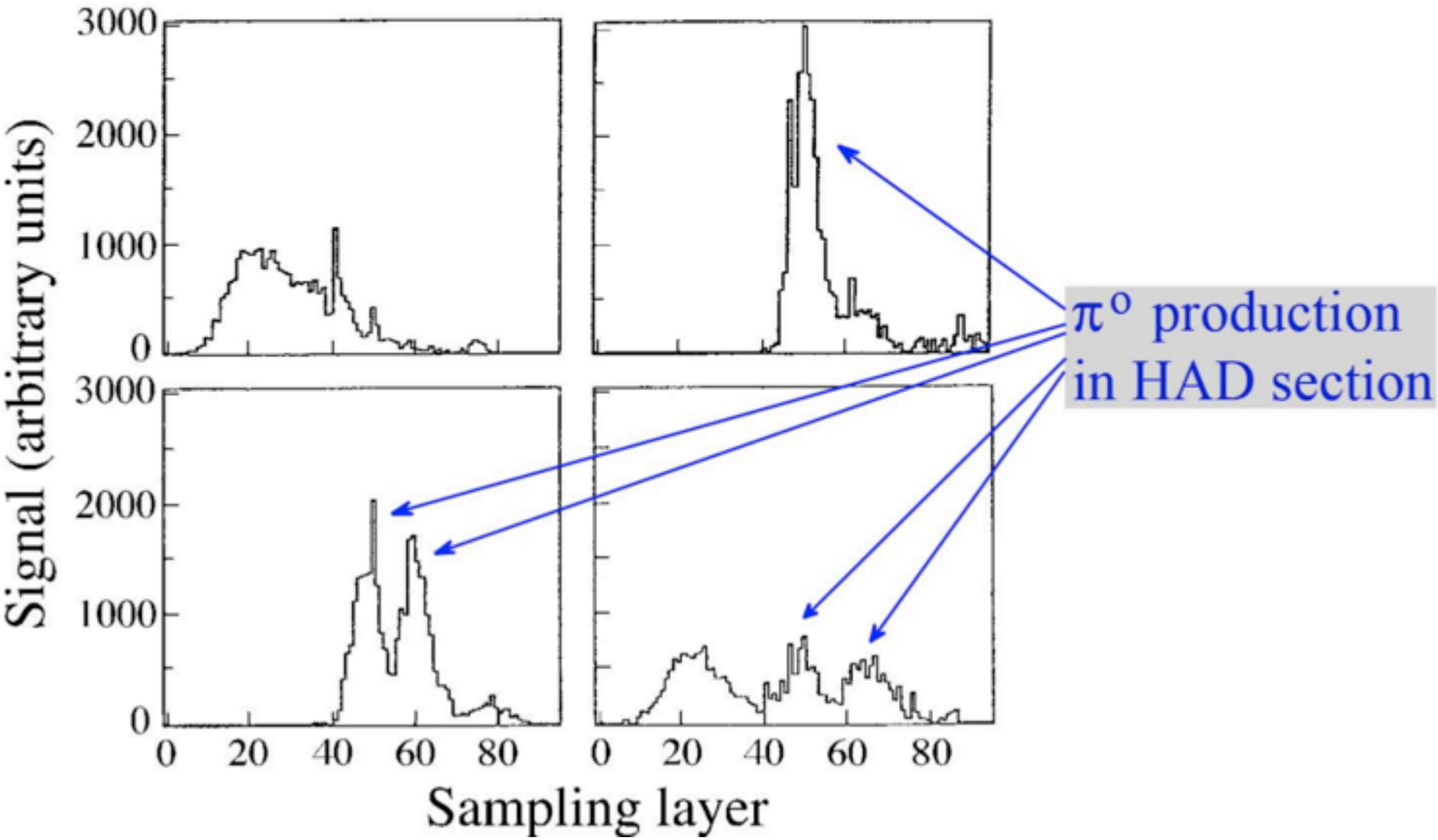
Hadronic showers consist of two very different components:

1. an EM part (*"e"*) from pi-zero and eta decays to photons,
2. a non-EM part (*"h"*) consisting of everything else,

and this non-EM part contributes less to the calorimeter signal than the EM part, $(e/h) > 1$, called "non-compensating". Fluctuations in the EM fraction lead to all the problems of hadronic calorimetry: poor energy resolution, non-linear response with energy, and non-Gaussian line shape.

270 GeV pi- beam →

(4 events)



π^o production in HAD section

One solution

Build a compensating calorimeter (*"e/h"* = *1*)

EM response (*"e"*) equals non-EM response (*"h"*)

This fixes the materials (*e.g.*, Pb and plastic scintillator) and their ratio.

Better solution

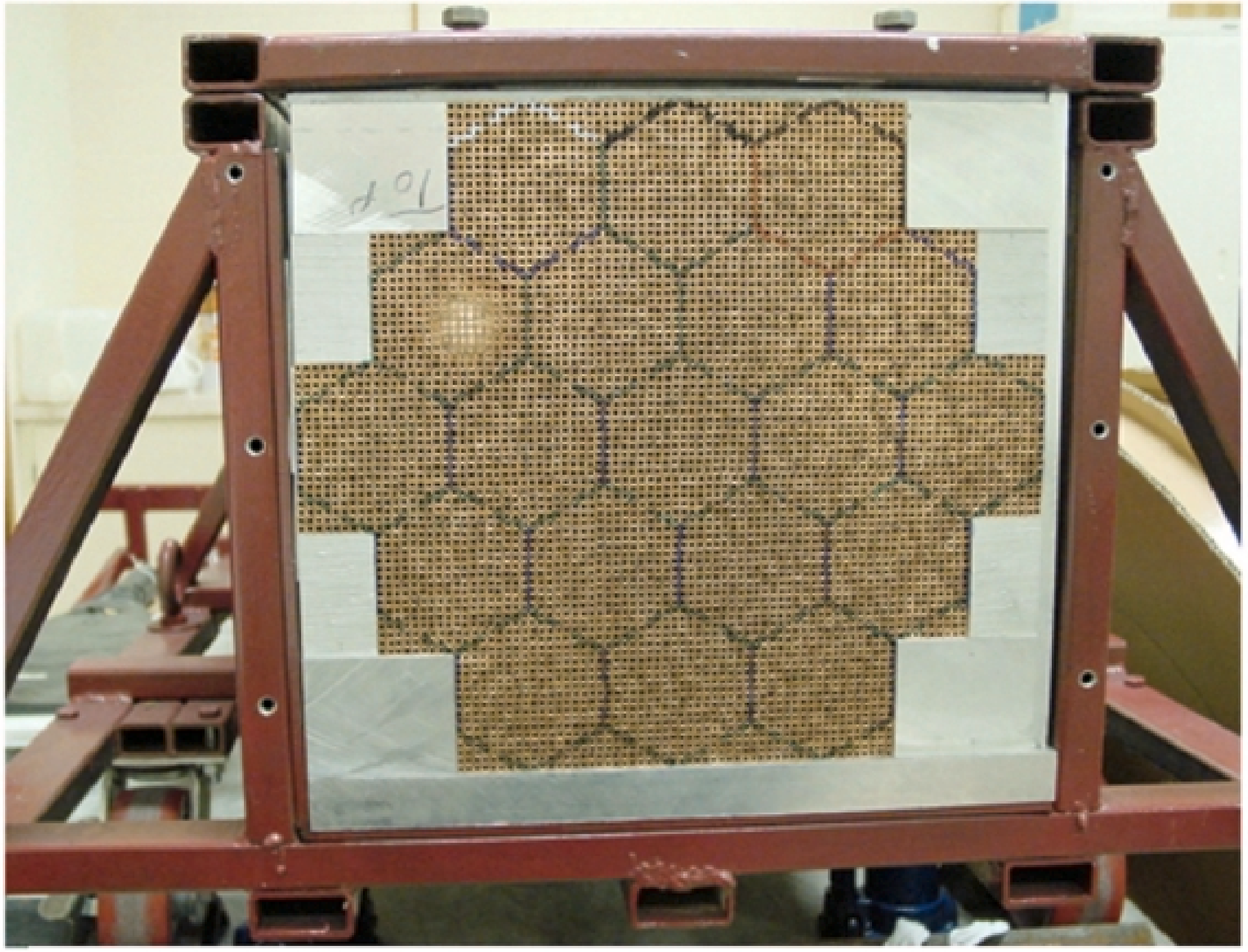
Measure both parts (*"dual"*) independently.

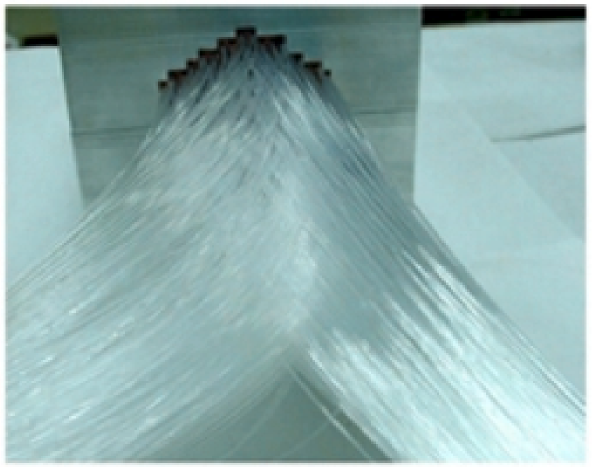
Choose whatever materials and ratios you like: Wigmans, Tucson CALOR conference (1997)

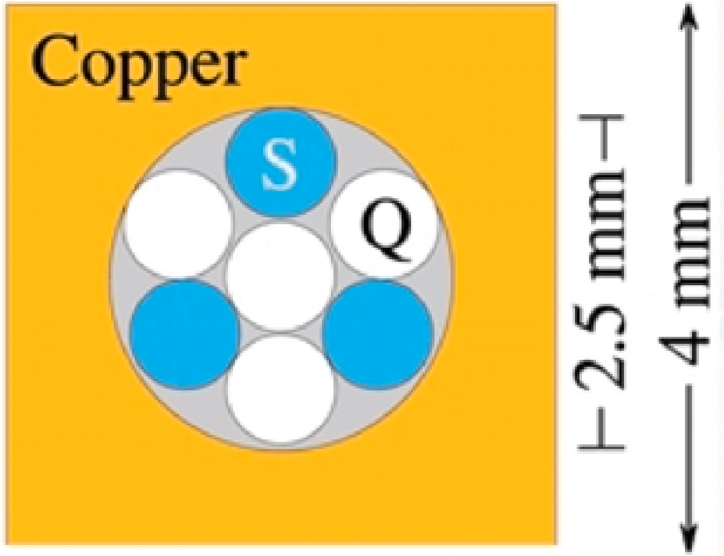
The “proof-of-principle” DREAM module

S = scintillating fibers
Q = quartz (clear) fibers

DREAM: Structure

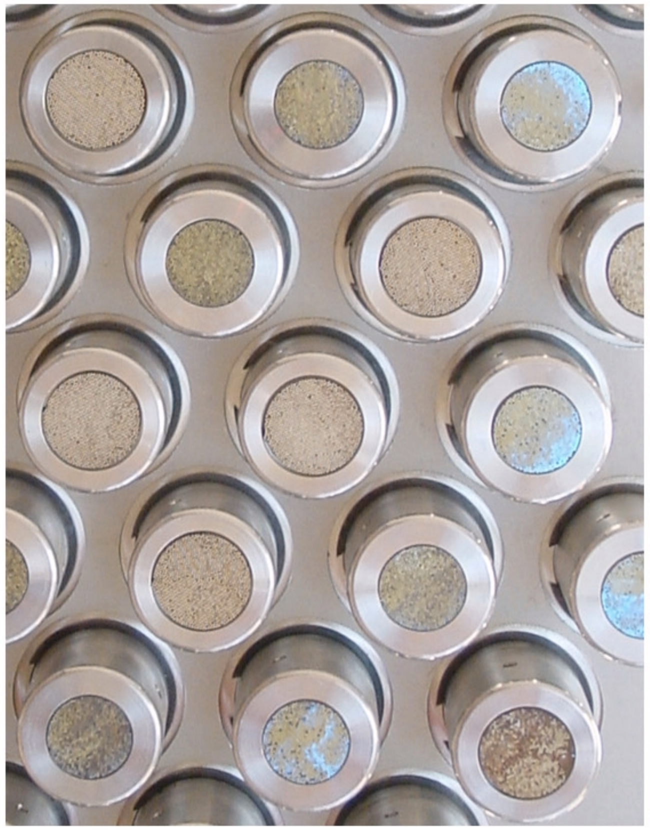


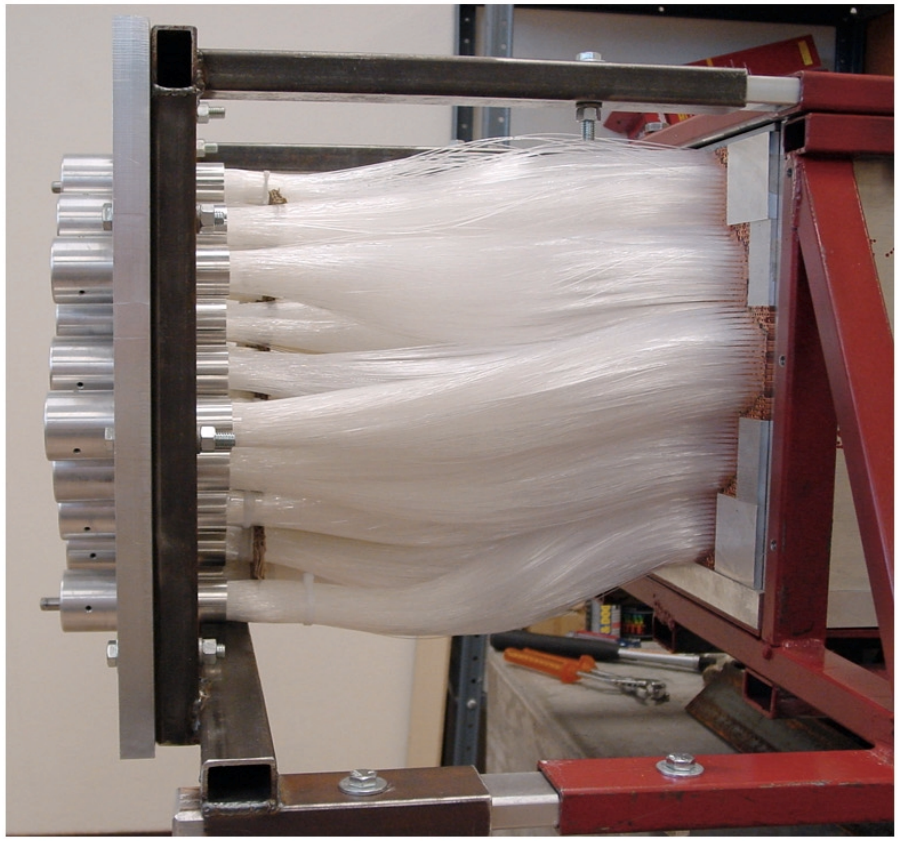




- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

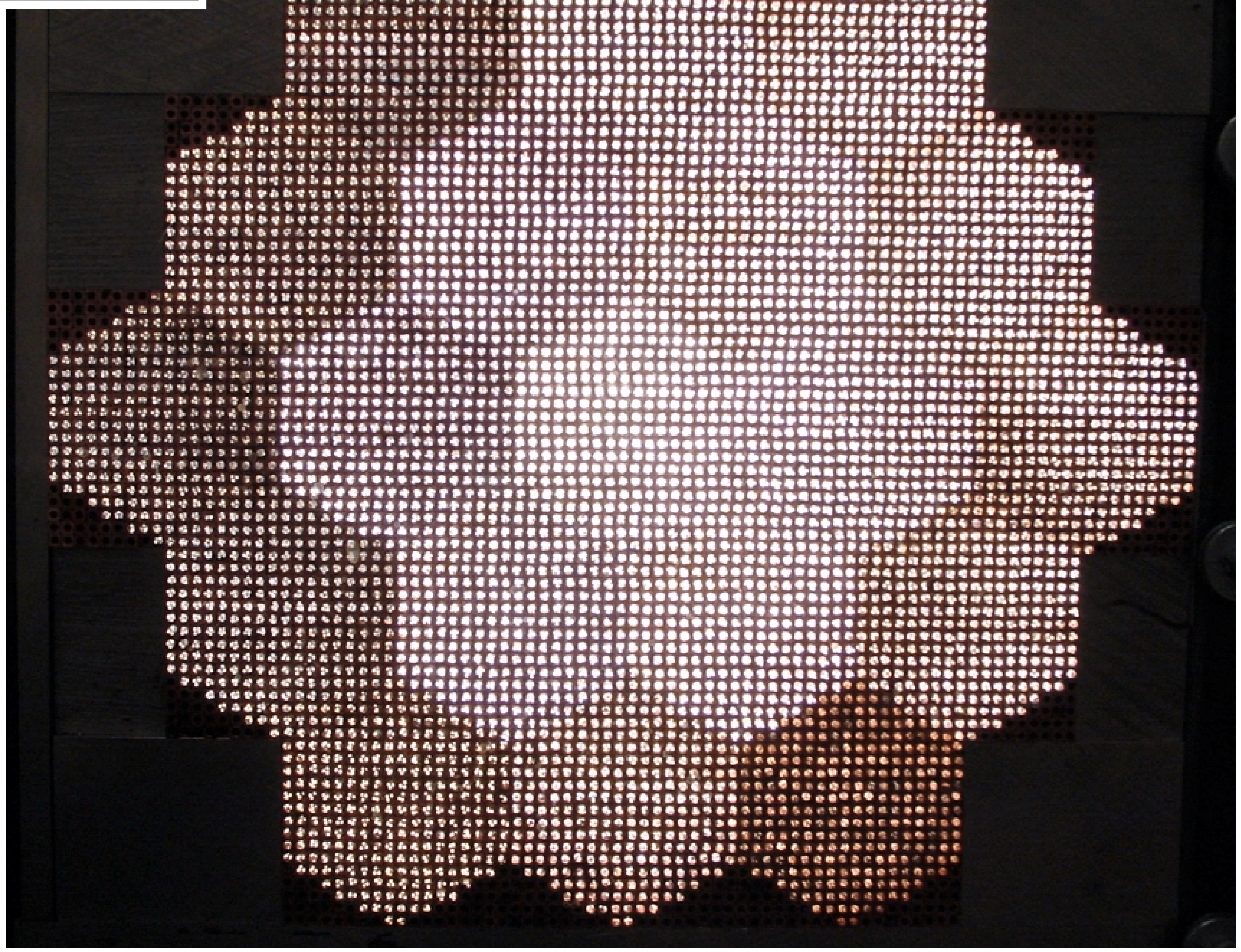
DREAM readout





Channel structure defined by bundled scintillation and Cerenkov fibers

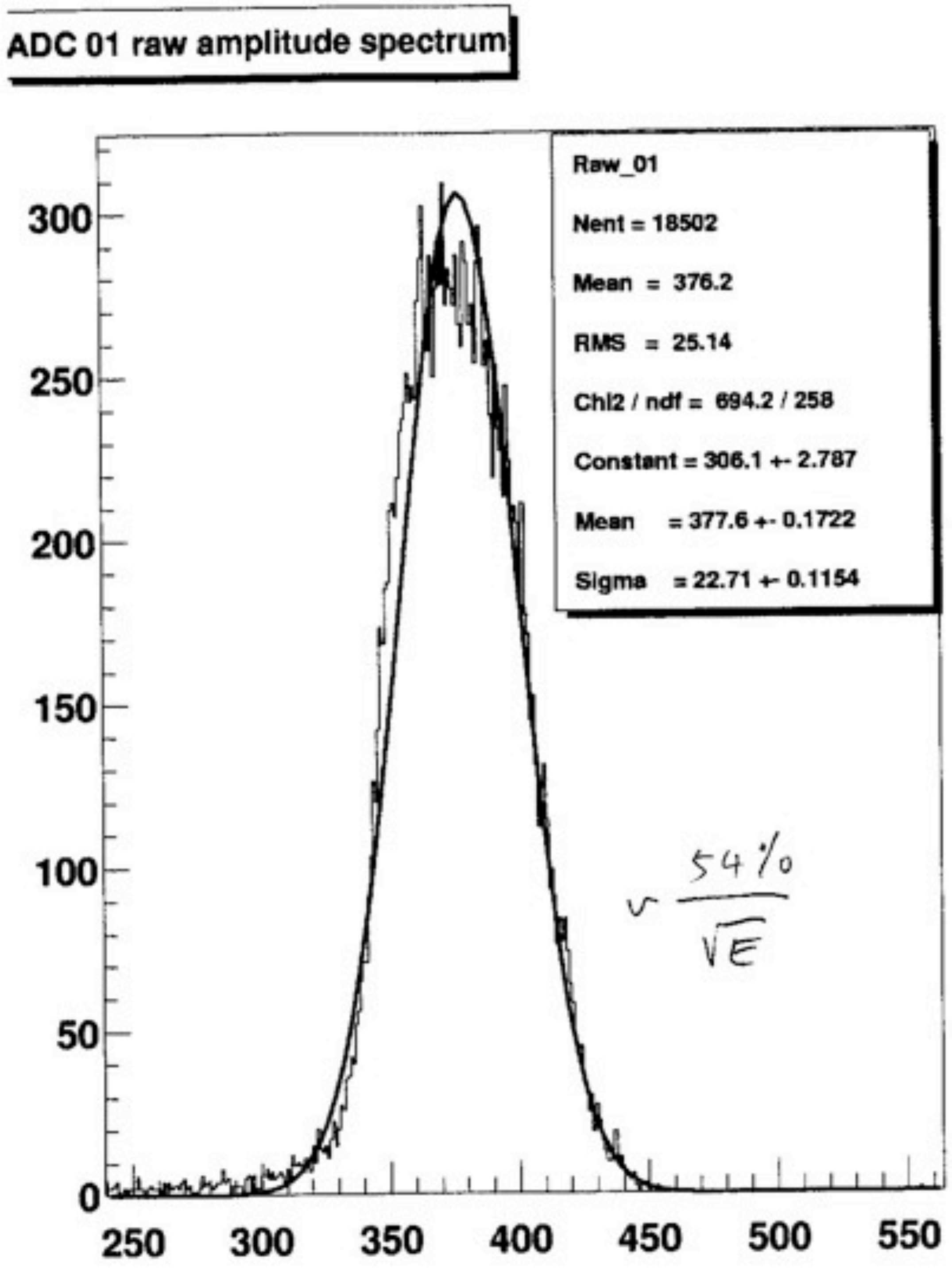
Shine light through module



2004 first SPS spill

FIRST SHOT!

SCINTILLATOR 80 GeV e^- (?) QUARTZ


ADC 01 raw amplitude spectrum

Raw_01

Nent = 18502

Mean = 376.2

RMS = 25.14

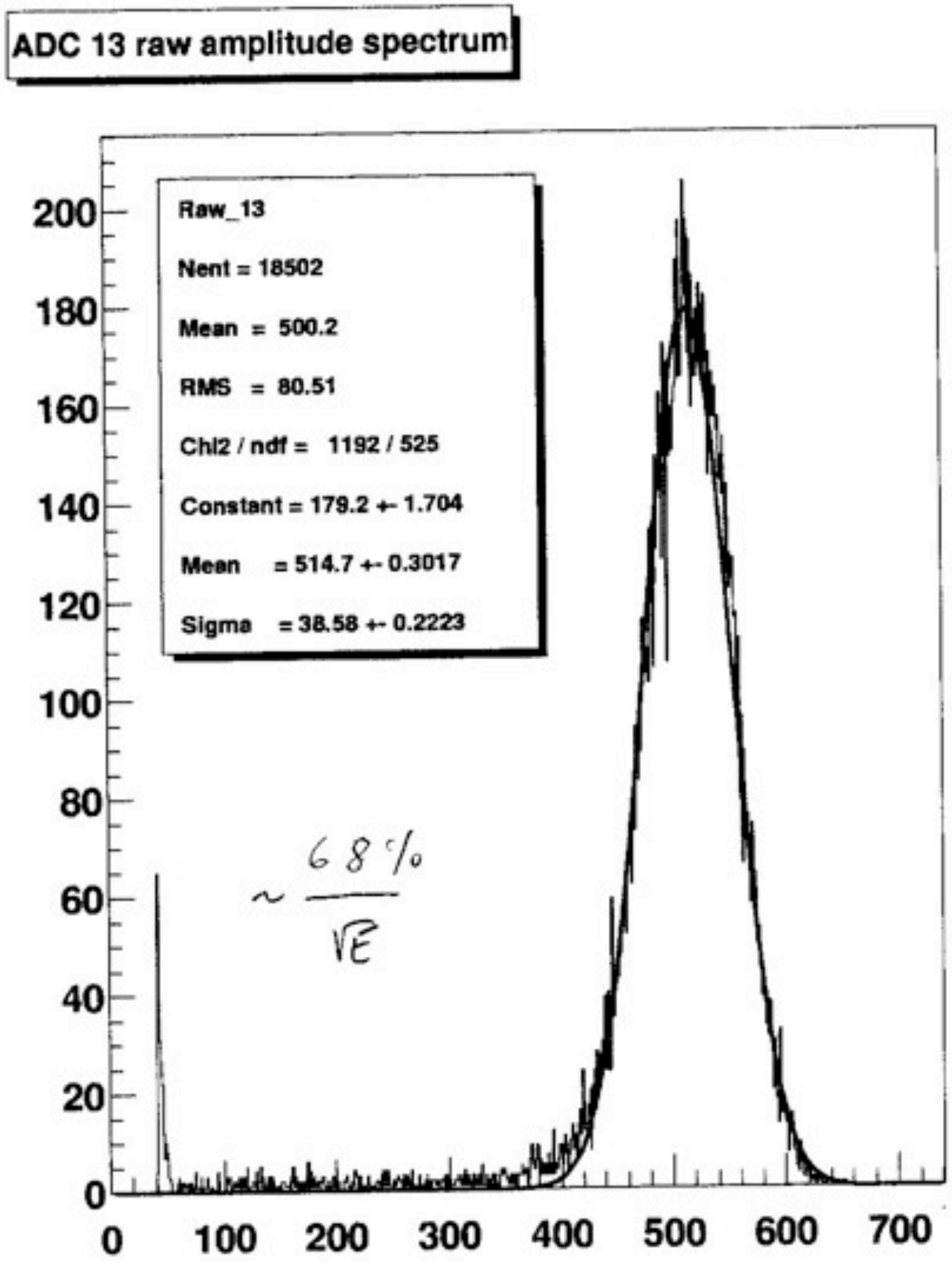
Chi2 / ndf = 694.2 / 258

Constant = 306.1 +- 2.787

Mean = 377.6 +- 0.1722

Sigma = 22.71 +- 0.1154

$\sim \frac{54\%}{\sqrt{E}}$


ADC 13 raw amplitude spectrum

Raw_13

Nent = 18502

Mean = 500.2

RMS = 80.51

Chi2 / ndf = 1192 / 525

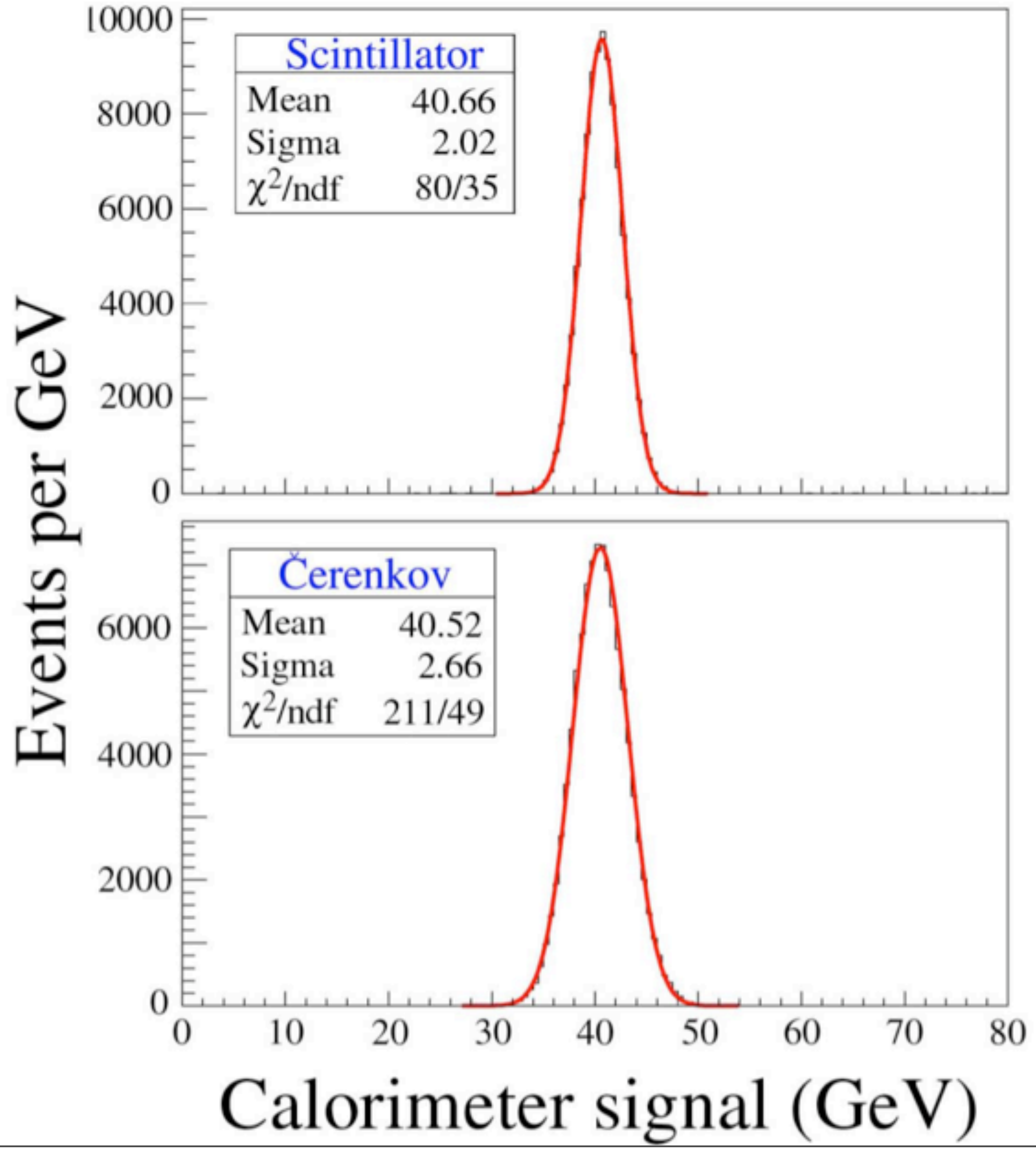
Constant = 179.2 +- 1.704

Mean = 514.7 +- 0.3017

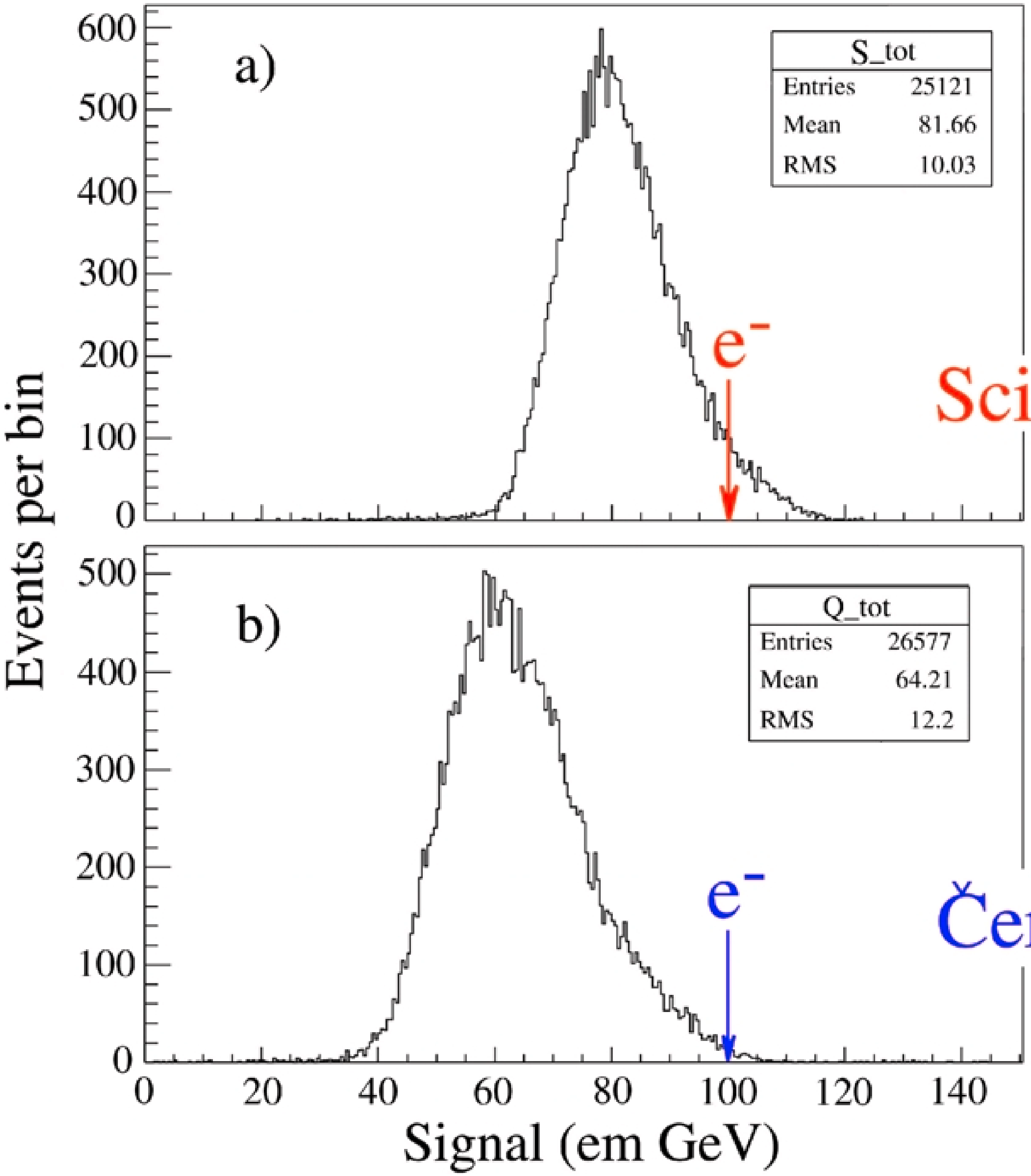
Sigma = 38.58 +- 0.2223

$\sim \frac{68\%}{\sqrt{E}}$

Calibrate with 40 GeV electrons: set GeV/ADC for both scintillation and Cerenkov to get <data> = 40 GeV



Response to 100 GeV negative pions: asymmetric, non-Gaussian, and wrong energy

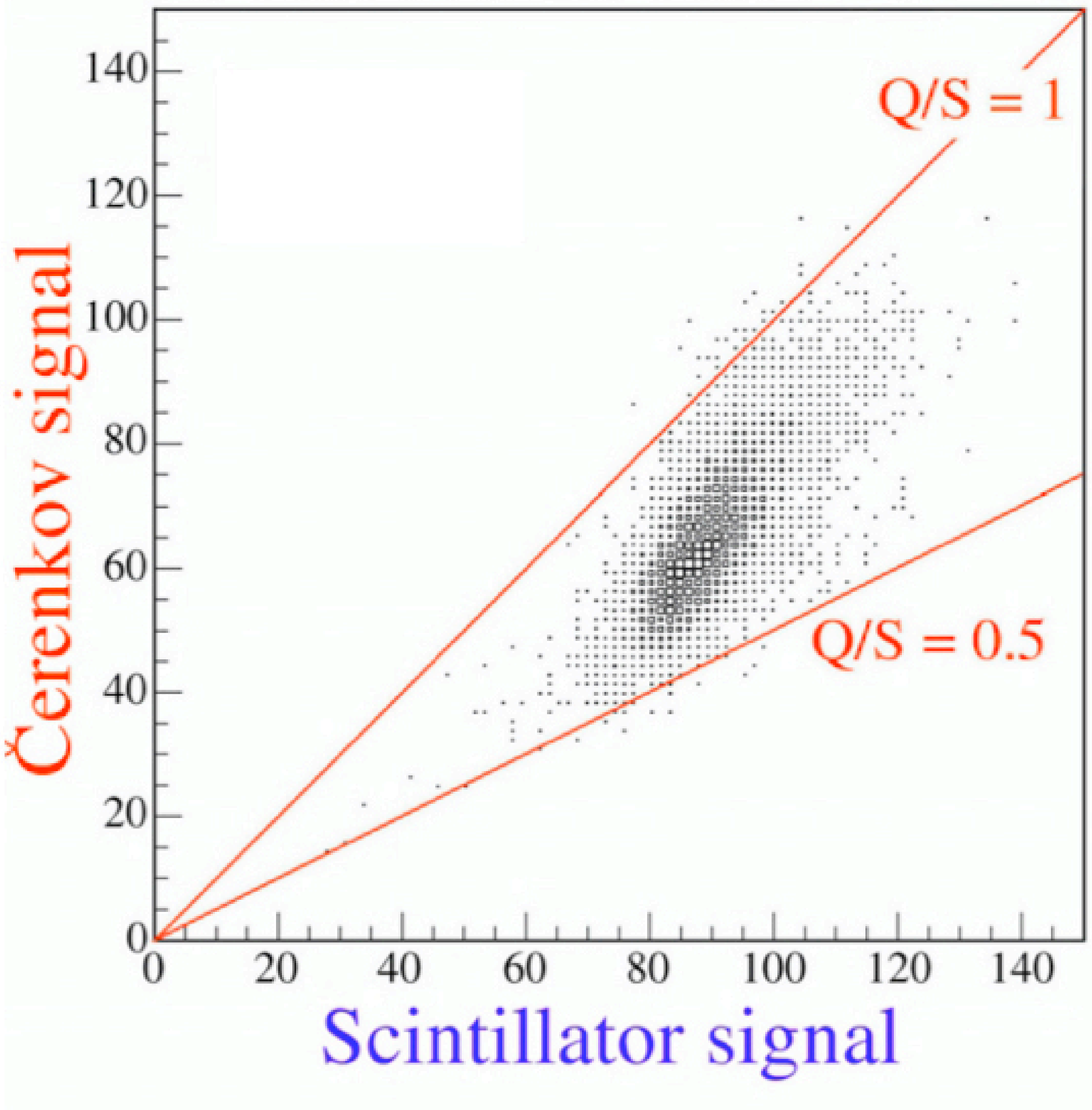


DREAM

Raw signals

(100 GeV π^-)

Basic dual-readout: "Hadron and Jet Detection with a Dual-Readout Calorimeter" NIM A537 (2005) 537-561.



$$Q = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_Q}(1 - f_{\mathrm{em}})\right] \quad (1)$$

$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right] \quad (2)$$

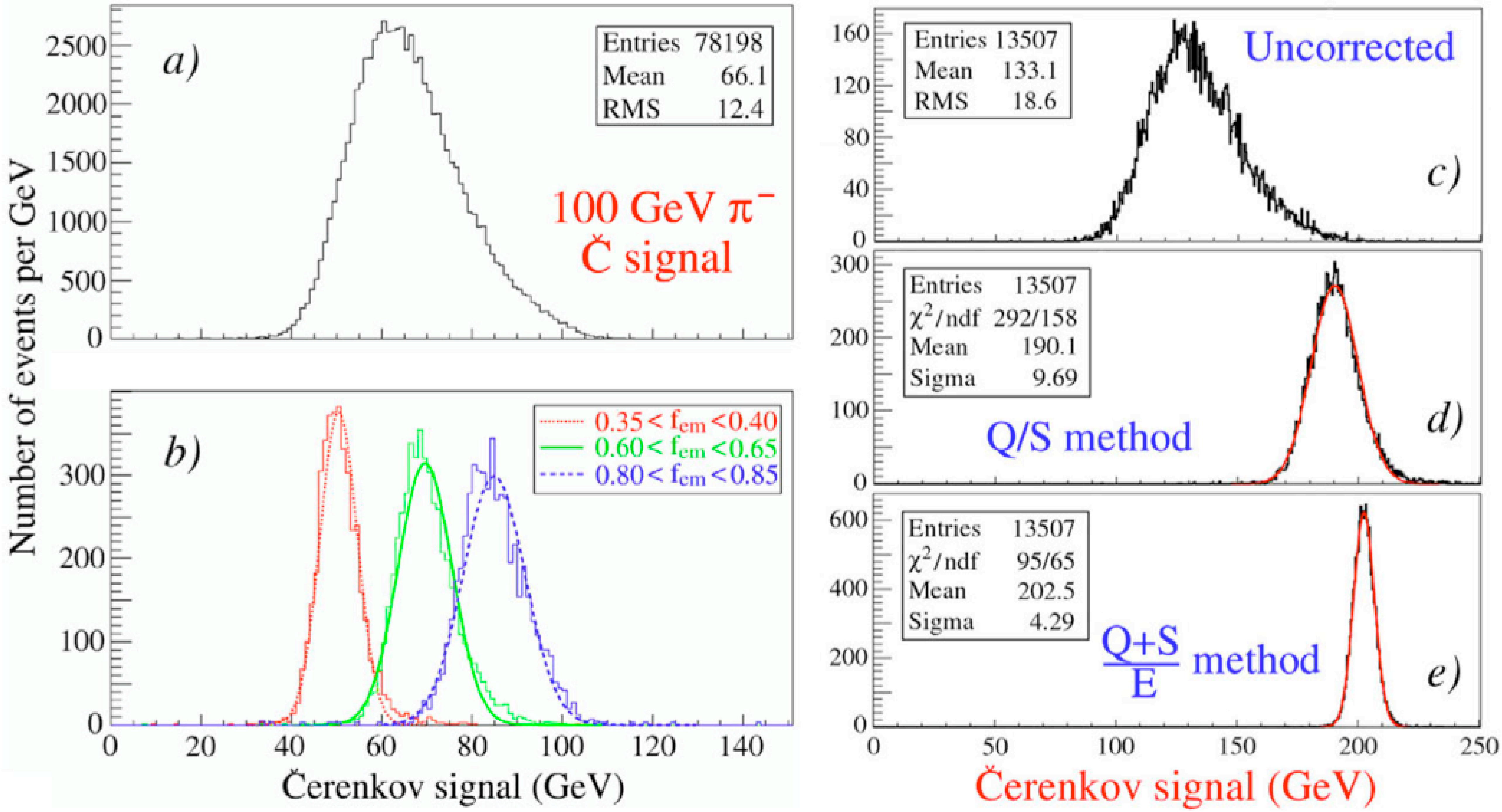
$e.g.$ If $e/h = 1.3\ (S),\ 4.7\ (Q)$

$$\boxed{\frac{Q}{S} = \frac{f_{\mathrm{em}} + 0.21\ (1 - f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\ (1 - f_{\mathrm{em}})}} \quad (3)$$

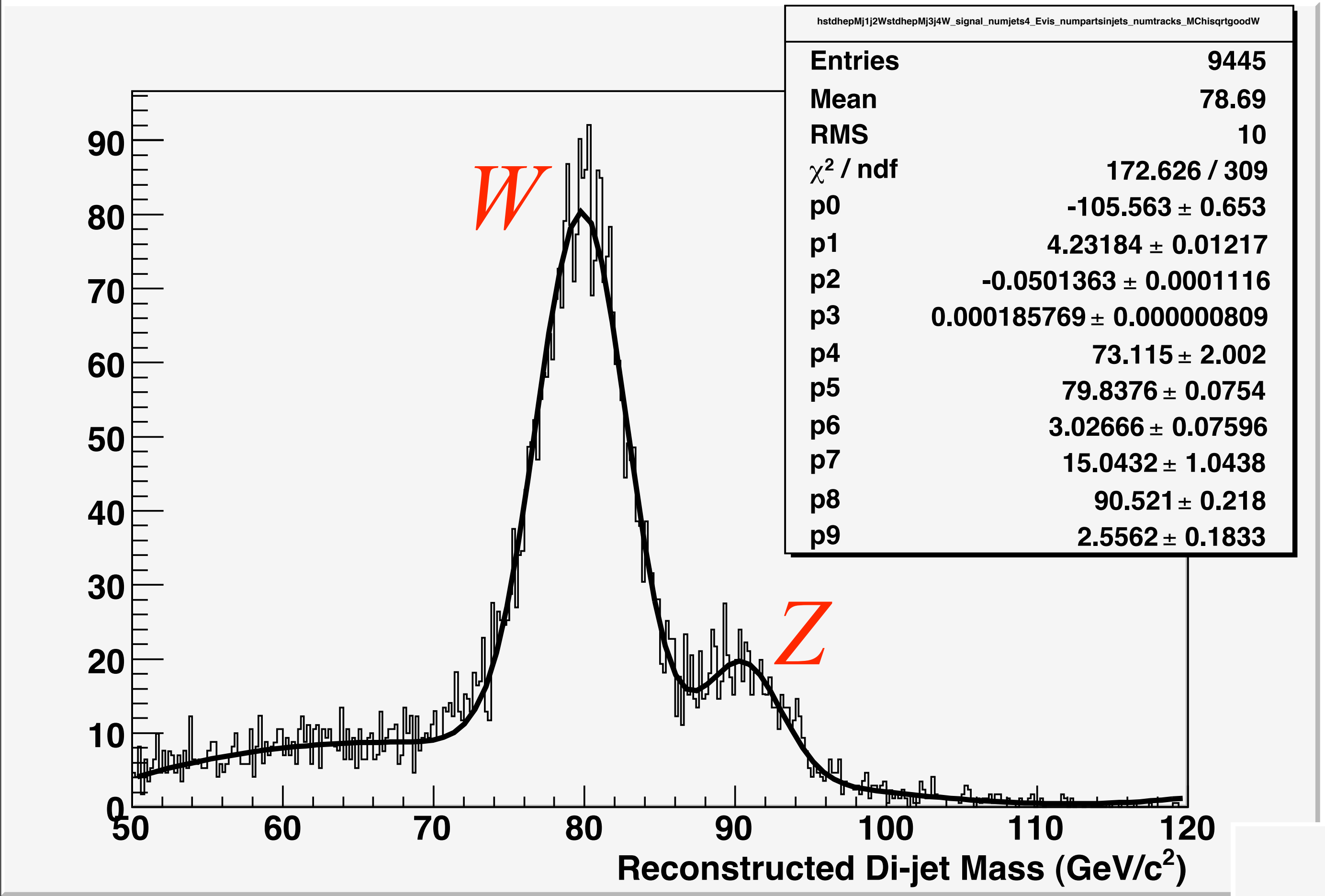
$$\boxed{E = \frac{S - \chi Q}{1 - \chi}} \quad (4)$$

with $\chi = \dfrac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

The asymmetric, non-Gaussian, broad, off-energy response function is the sum of narrow Gaussians !

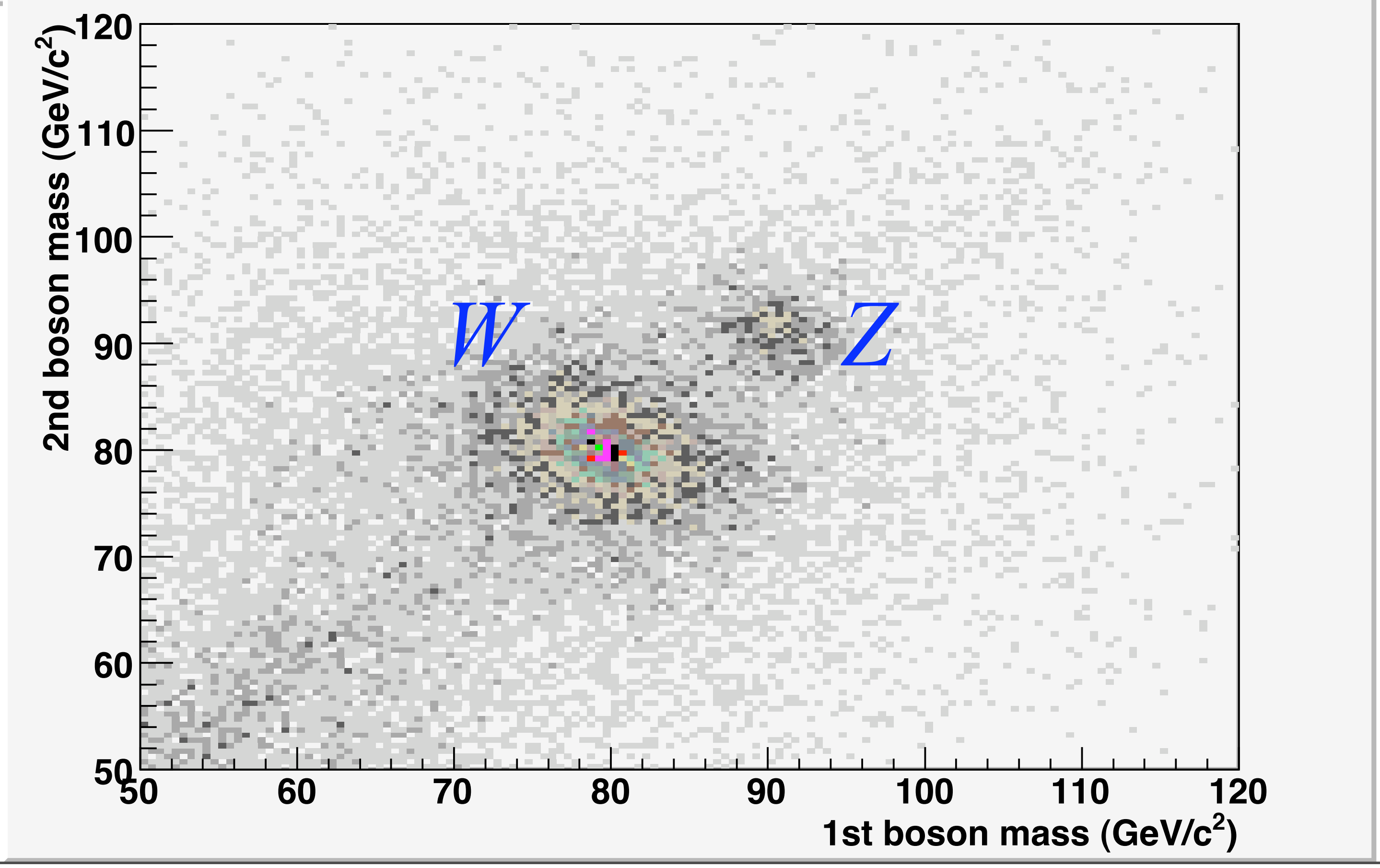


“Raw hadronic resolution” gives you W’s and Z’s



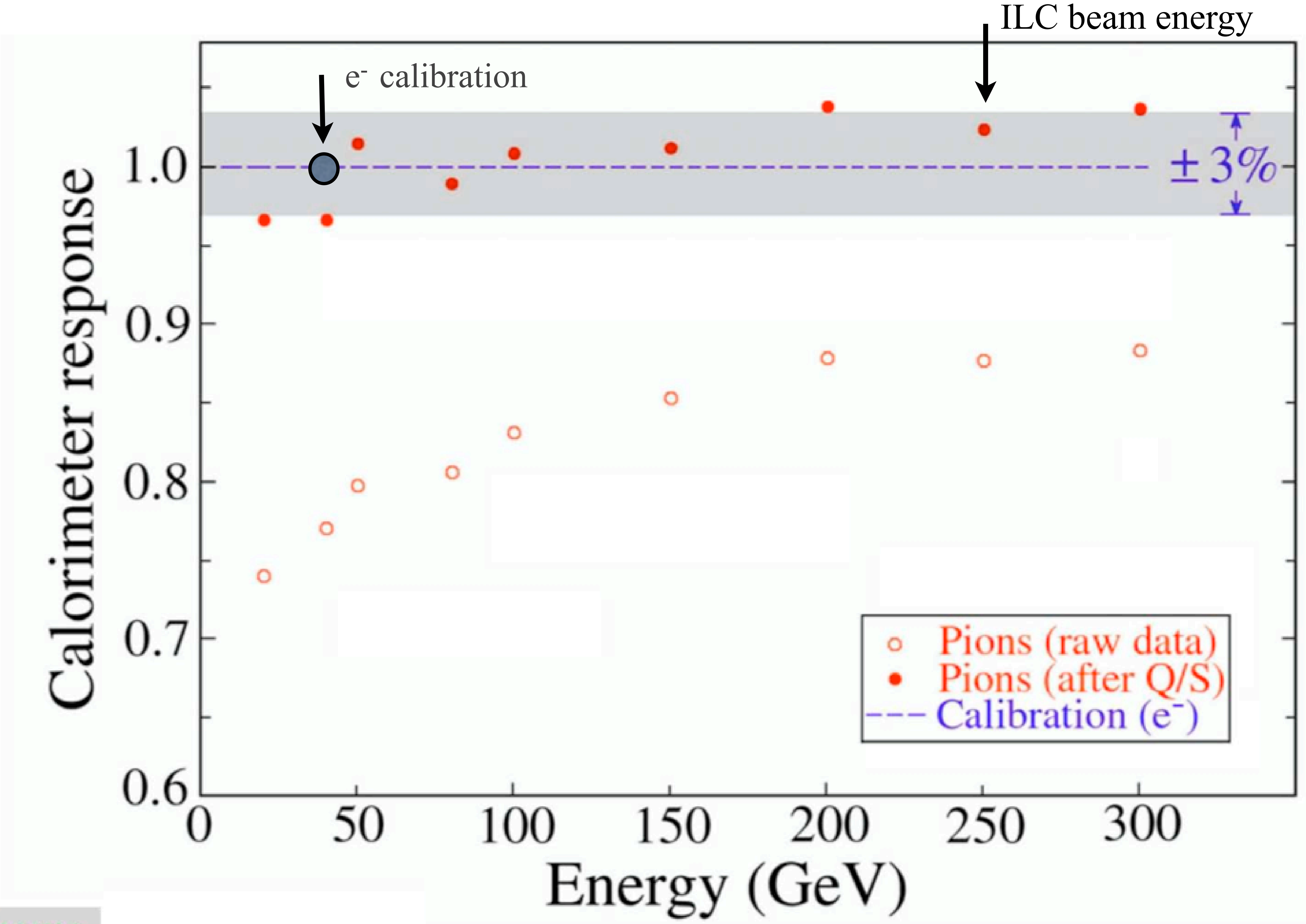
hstdhepMj1j2WstdhepMj3j4W_signal_numjets4_Evis_numpartsinjets_numtracks_MChisqrtgoodW

Entries	9445
Mean	78.69
RMS	10
χ^2 / ndf	172.626 / 309
p0	-105.563 ± 0.653
p1	4.23184 ± 0.01217
p2	-0.0501363 ± 0.0001116
p3	0.000185769 ± 0.000000809
p4	73.115 ± 2.002
p5	79.8376 ± 0.0754
p6	3.02666 ± 0.07596
p7	15.0432 ± 1.0438
p8	90.521 ± 0.218
p9	2.5562 ± 0.1833



From the SUSY pt. 5 analysis
by Anna Mazzacane

Hadronic response linearity



From:
NIM A537 (2005) 537

“Raw hadronic linearity” gives you:

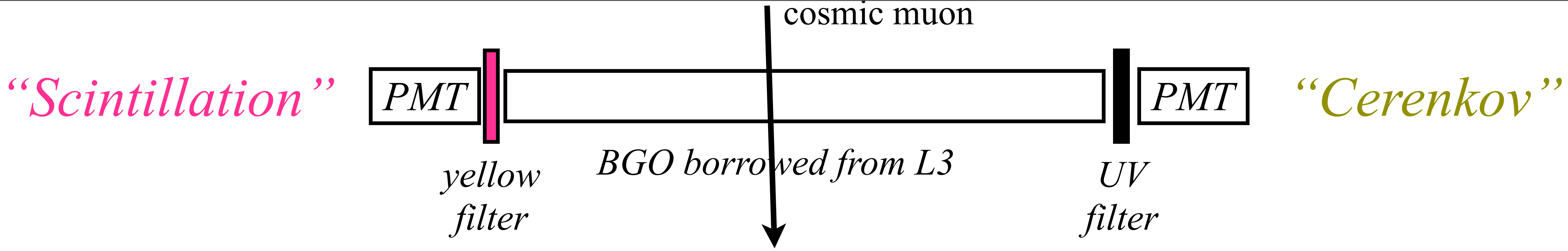
- “peace of mind” for physics above your calibration scale,
- more robust calibration using W and Z hadronic decays,
- much lower systematic uncertainties on jet energy scale, etc.
- high-mass and high-energy physics with high confidence

Fibers are great, but

- the EM resolution limited to 19%/√E due to the small numerical aperture of Cerenkov fibers.

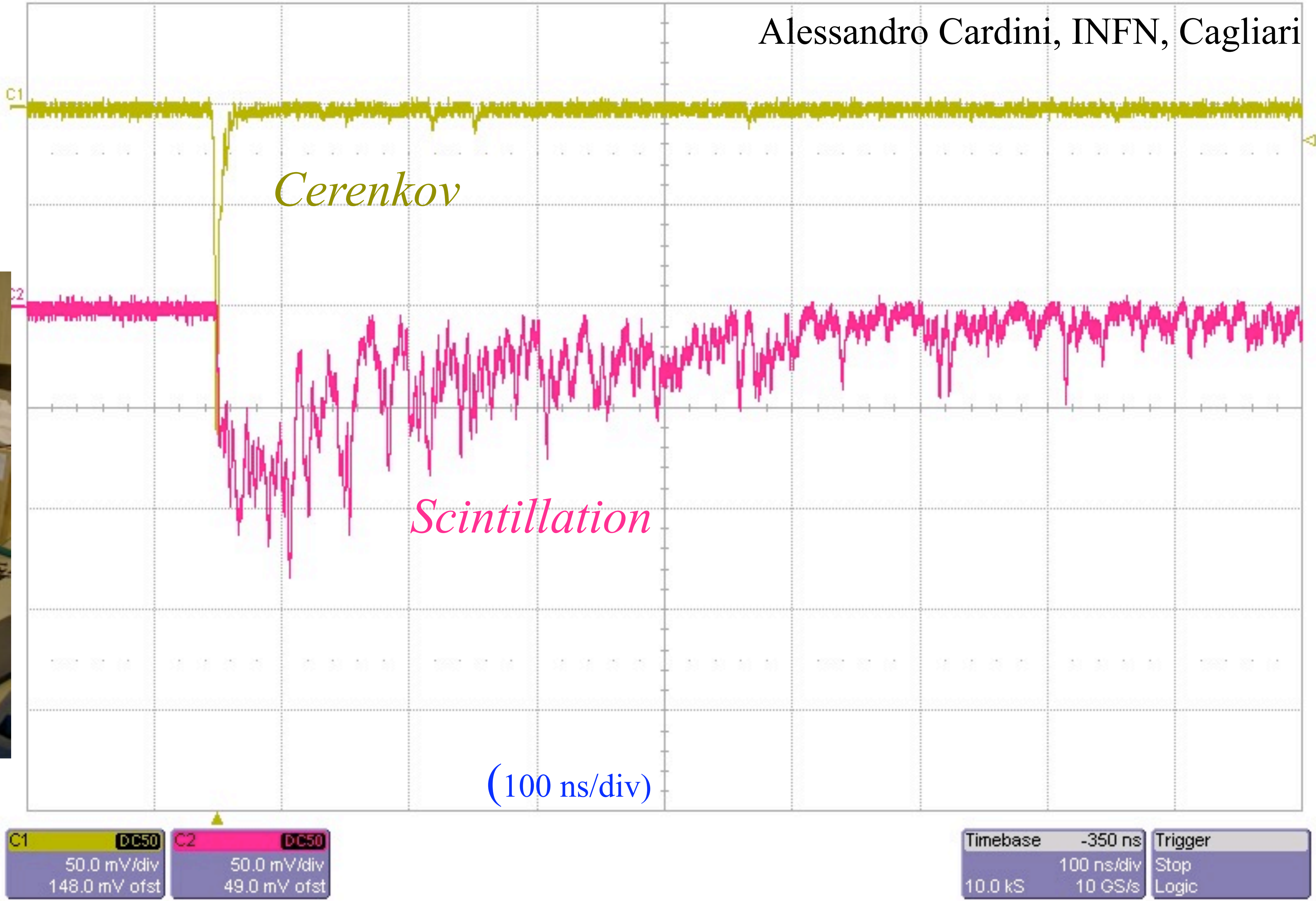
- Wigmans proposed crystals, and DREAM has tested many - PWO, PWO:Mo, PWO:Pr, BGO, BSO, and others. All work as dual-readout media.

- On 4th, we decided to put BGO crystals in front of the deep fiber module. This is a consequential decision, for many reasons.



BGO …

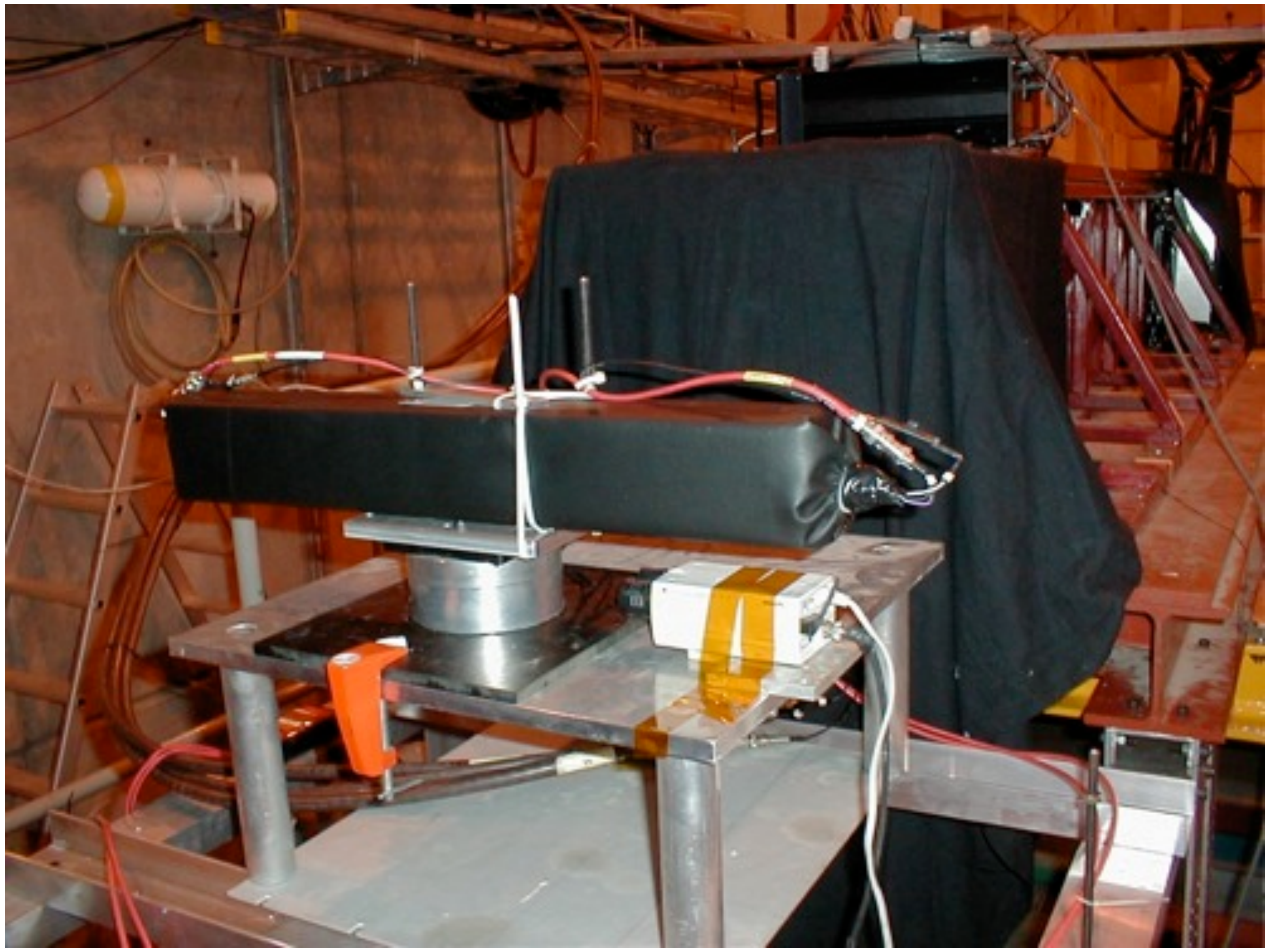
by time and wavelength


Alessandro Cardini, INFN, Cagliari

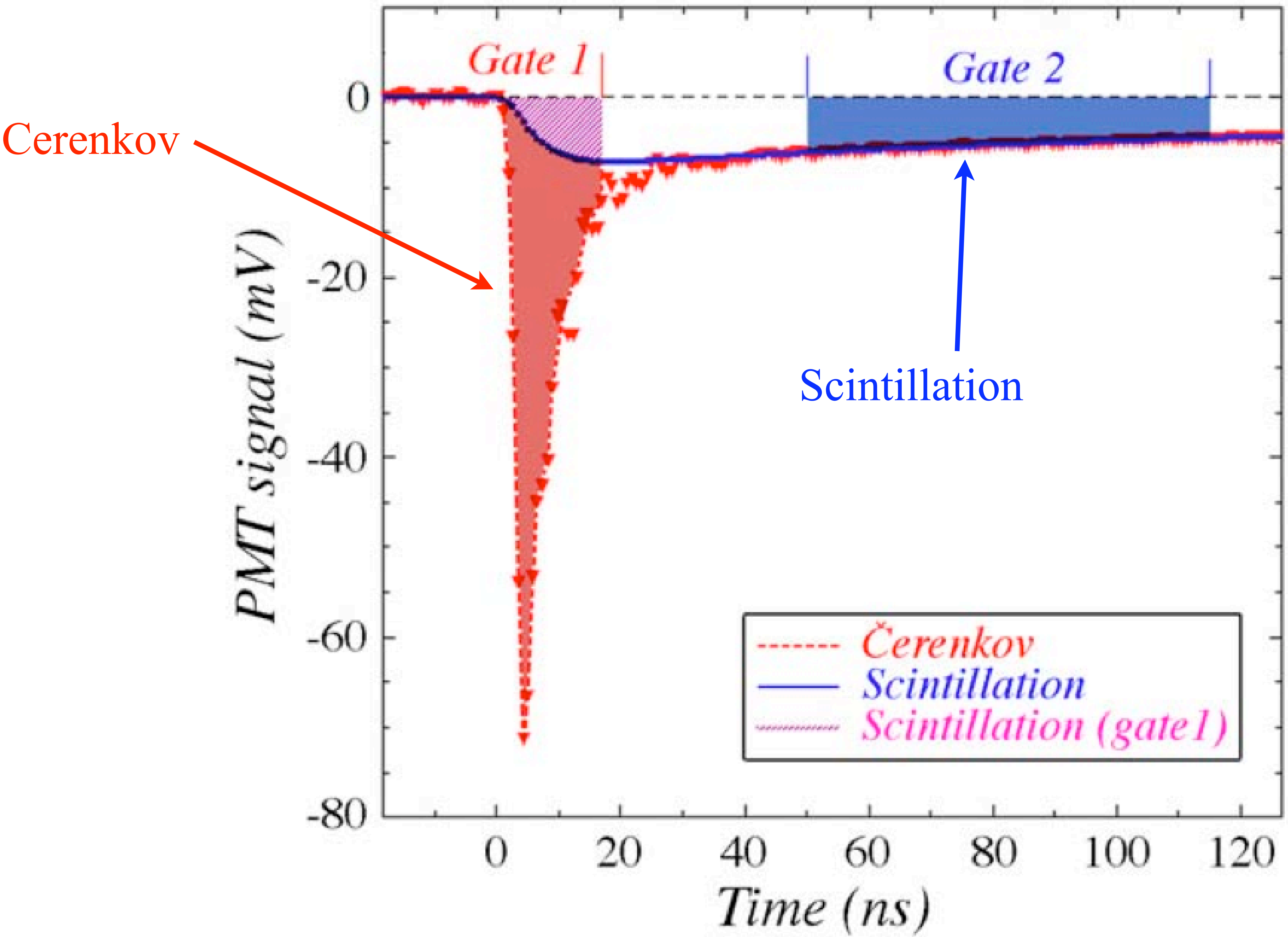
We can now do dual-readout in a single crystal ==> EM precision

Dual-readout of BGO crystals

BGO crystal, its housing, and in the beam in front of DREAM module



BGO crystal + one PMT + two gates



Cerenkov

Scintillation

CERN beam test of BGO array with DREAM module behind, surrounded by large scintillators to catch neutrons.

e, π, μ

20-300
GeV

Dual-Readout Calorimetry with a Full-Size BGO Electromagnetic Section

(published)

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Abstract

Beam tests of a hybrid dual-readout calorimeter are described. The electromagnetic section of this instrument consists of 100 BGO crystals and the hadronic section is made of copper in which two types of optical fibers are embedded. The electromagnetic fraction of hadronic showers developing in this calorimeter system is determined event by event from the relative amounts of Čerenkov light and scintillation light produced in the shower development. The benefits and limitations of this detector system for the detection of showers induced by single hadrons and by multiparticle jets are investigated. Effects of side leakage on the detector performance are also studied.

PACS: 29.40.Ka, 29.40.Mc, 29.40.Vj

Key words: Calorimetry, Čerenkov light, crystals, optical fibers

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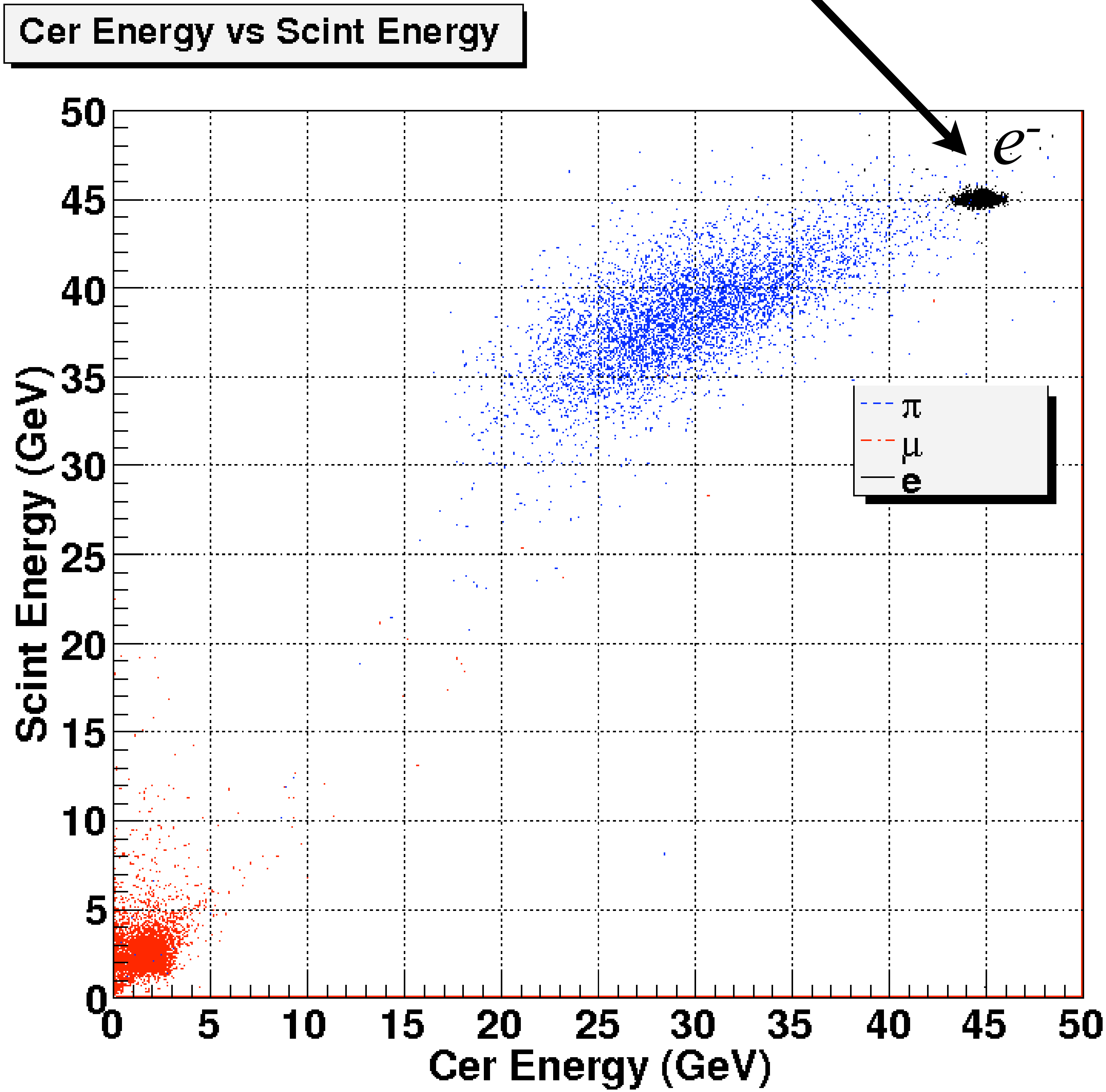
Combined crystal + fiber calorimeters:

Tested in beams of e, μ, π

Close to 4th

Crystal light-yield can give you: EM resolution

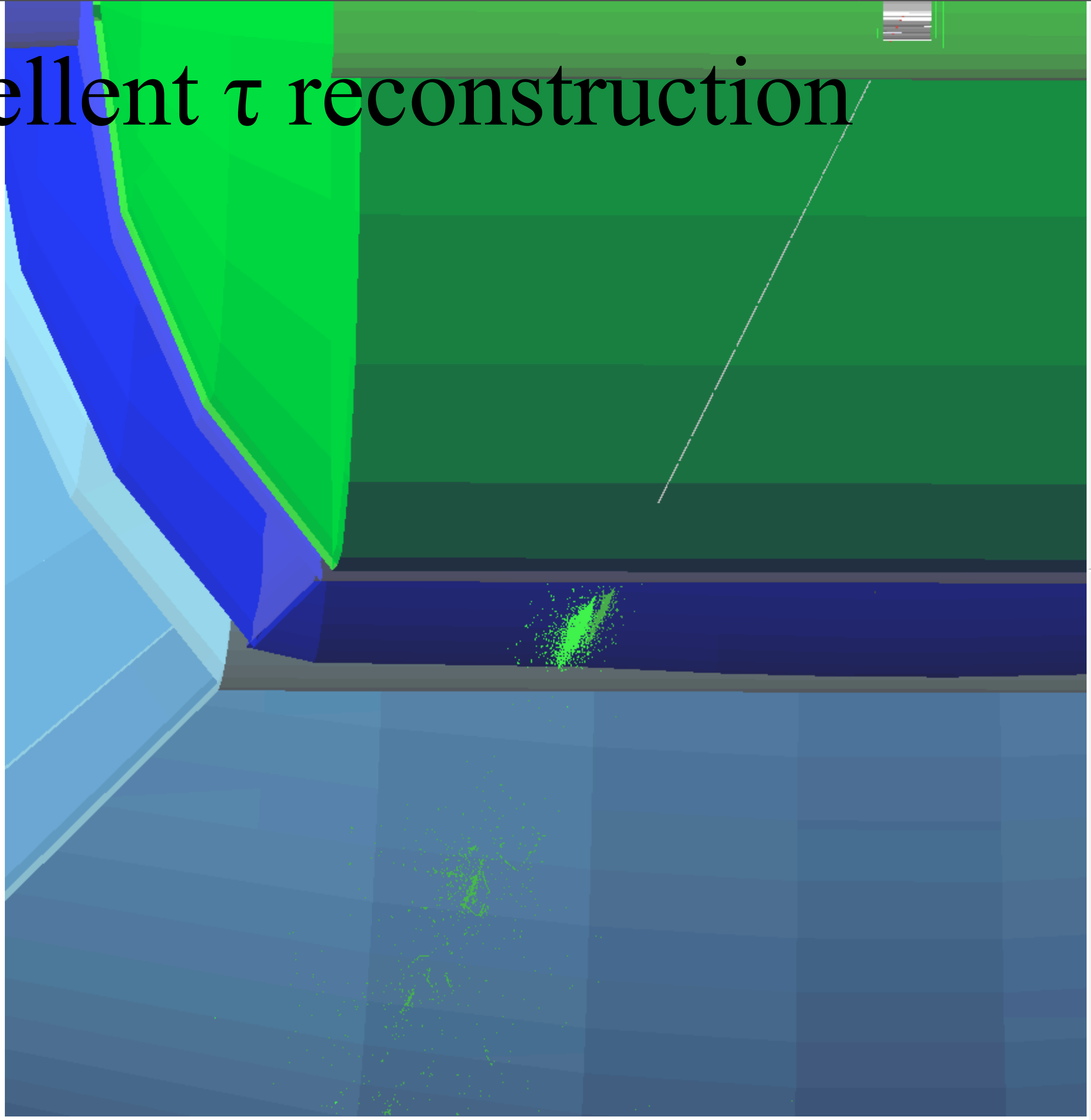


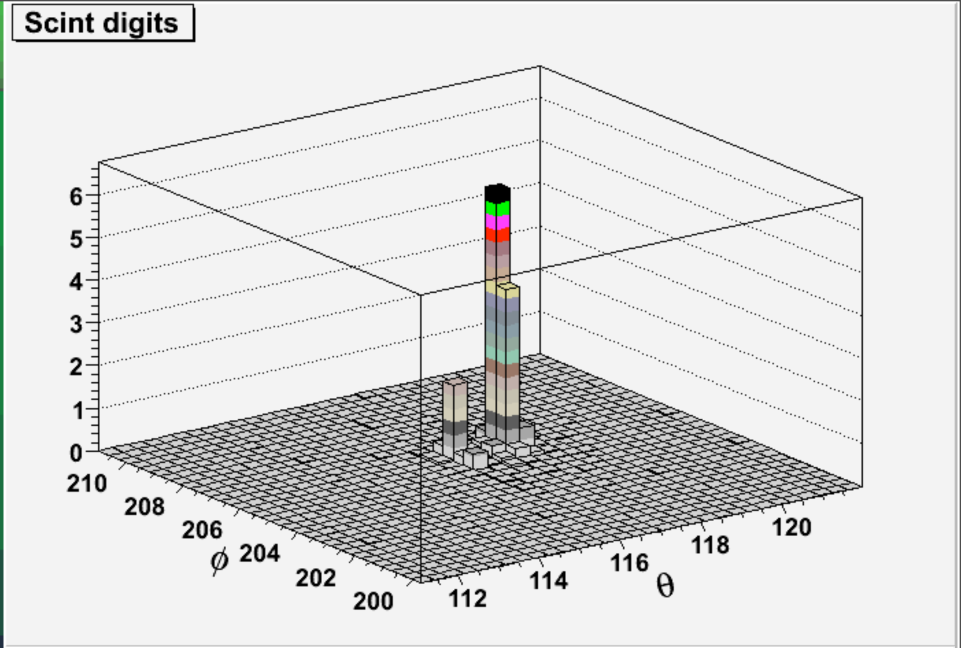
And, excellent τ reconstruction

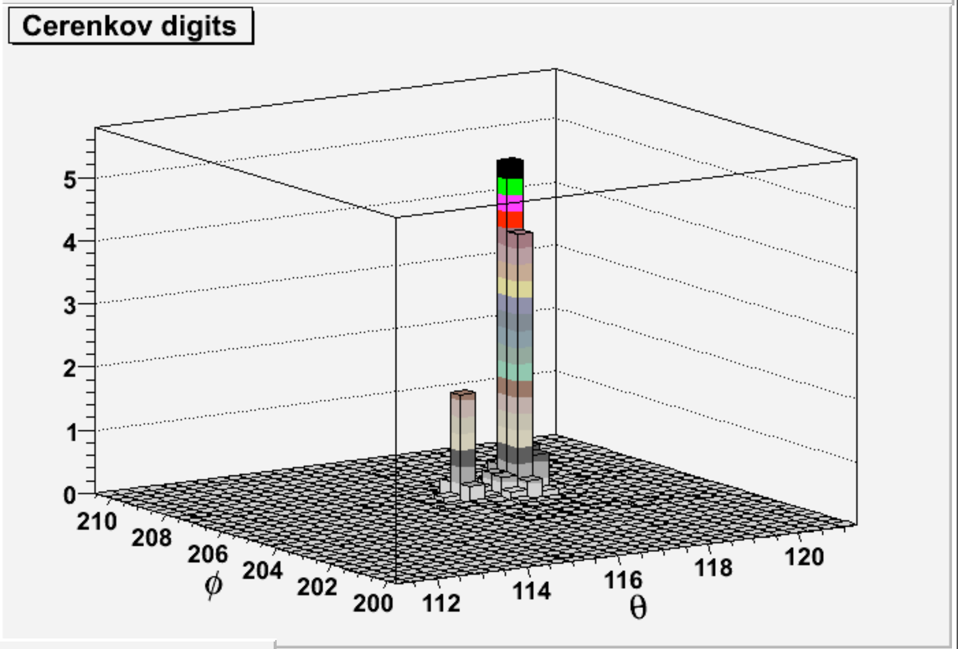
$\tau^+ \rightarrow \rho^+ \nu$

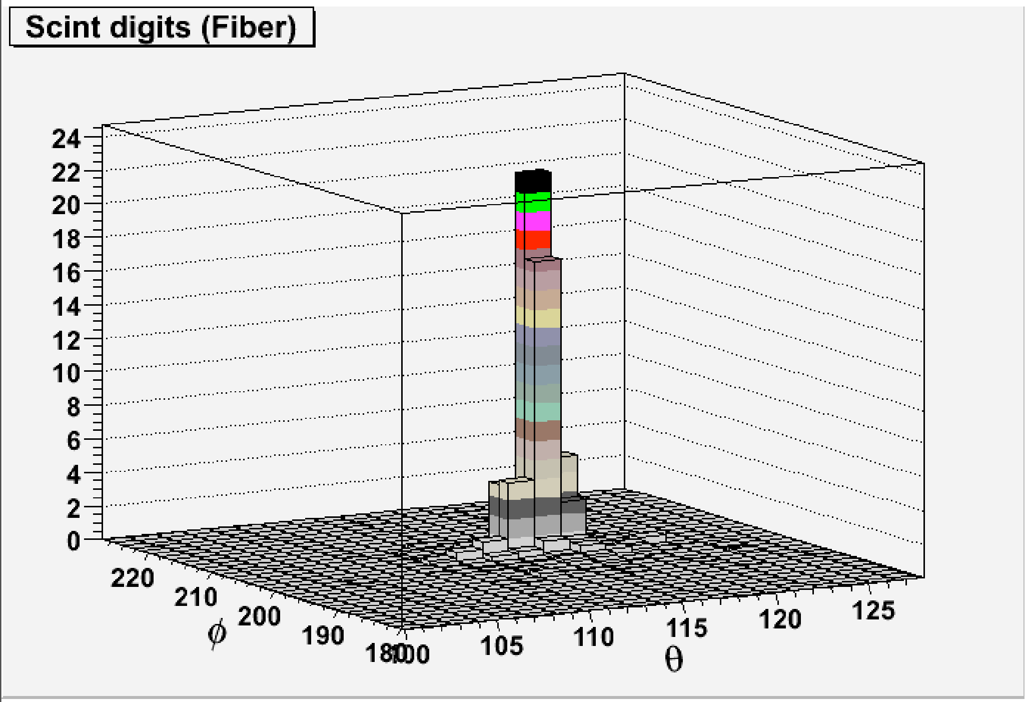
$\rho^+ \rightarrow \pi^+ \pi^0$

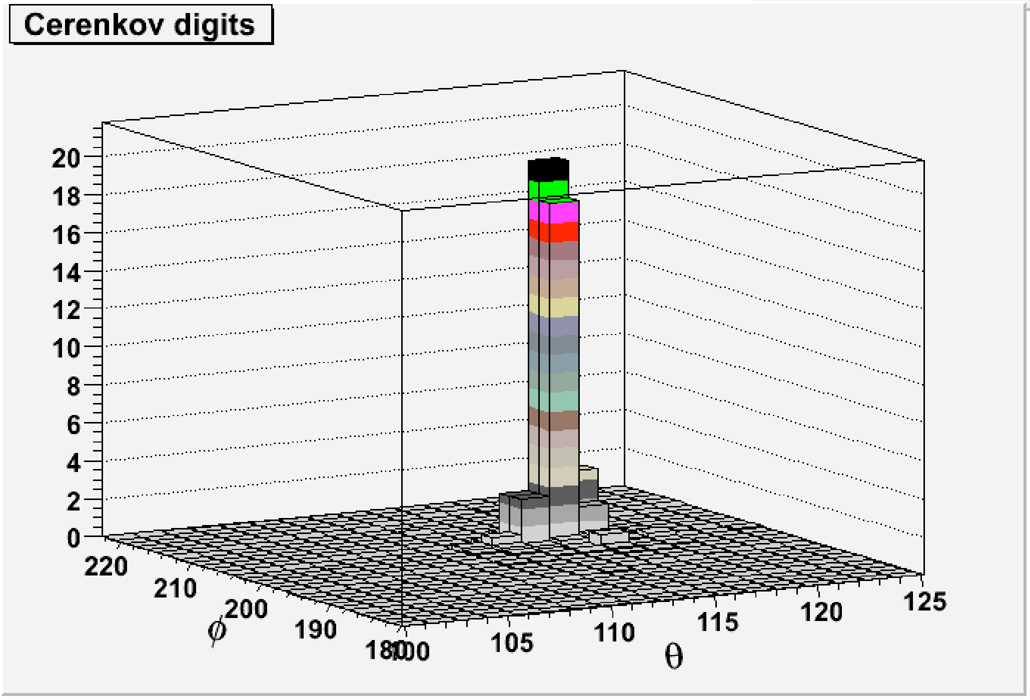
$\pi^0 \rightarrow \gamma\gamma$




Scint digits

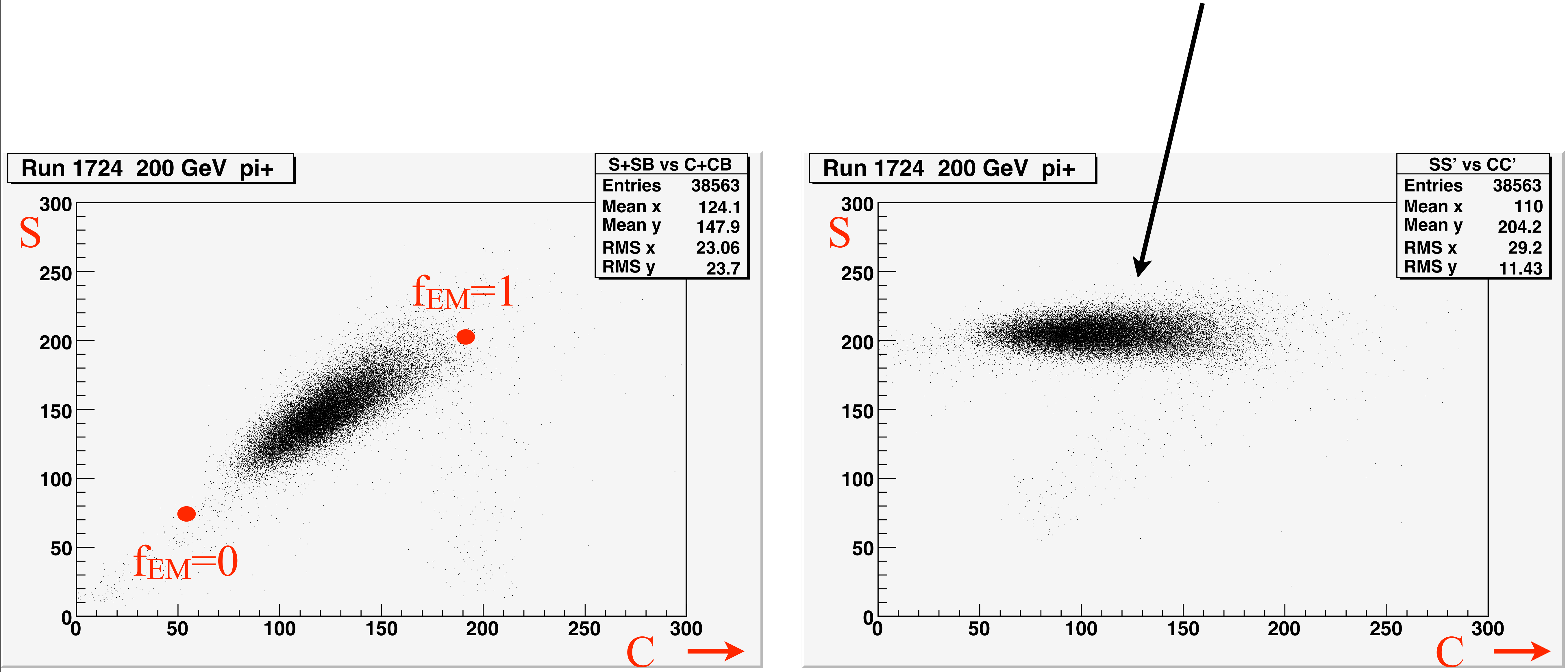

Cerenkov digits


Scint digits (Fiber)


Cerenkov digits

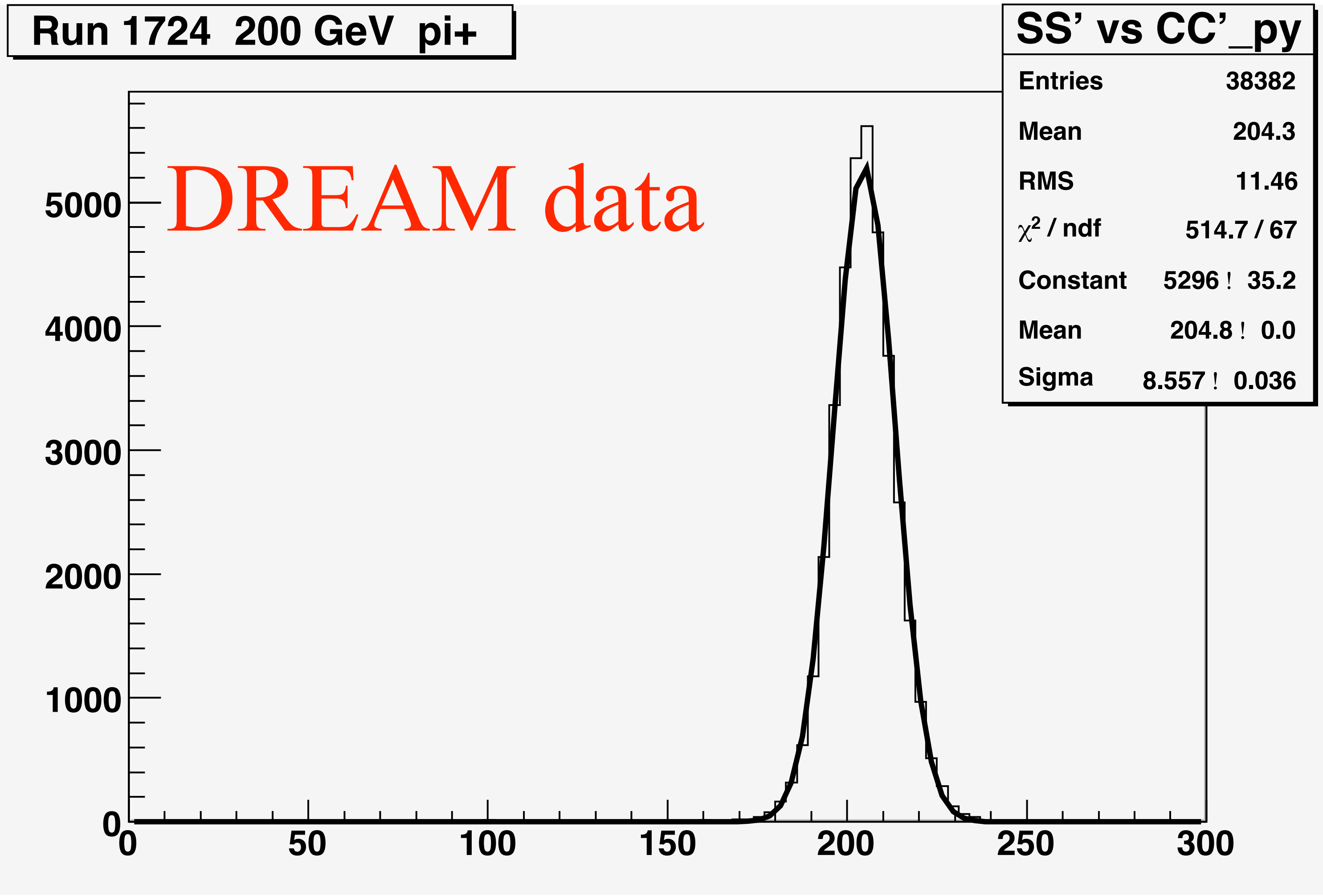
Calorimetric EM and hadronic identifications are excellent

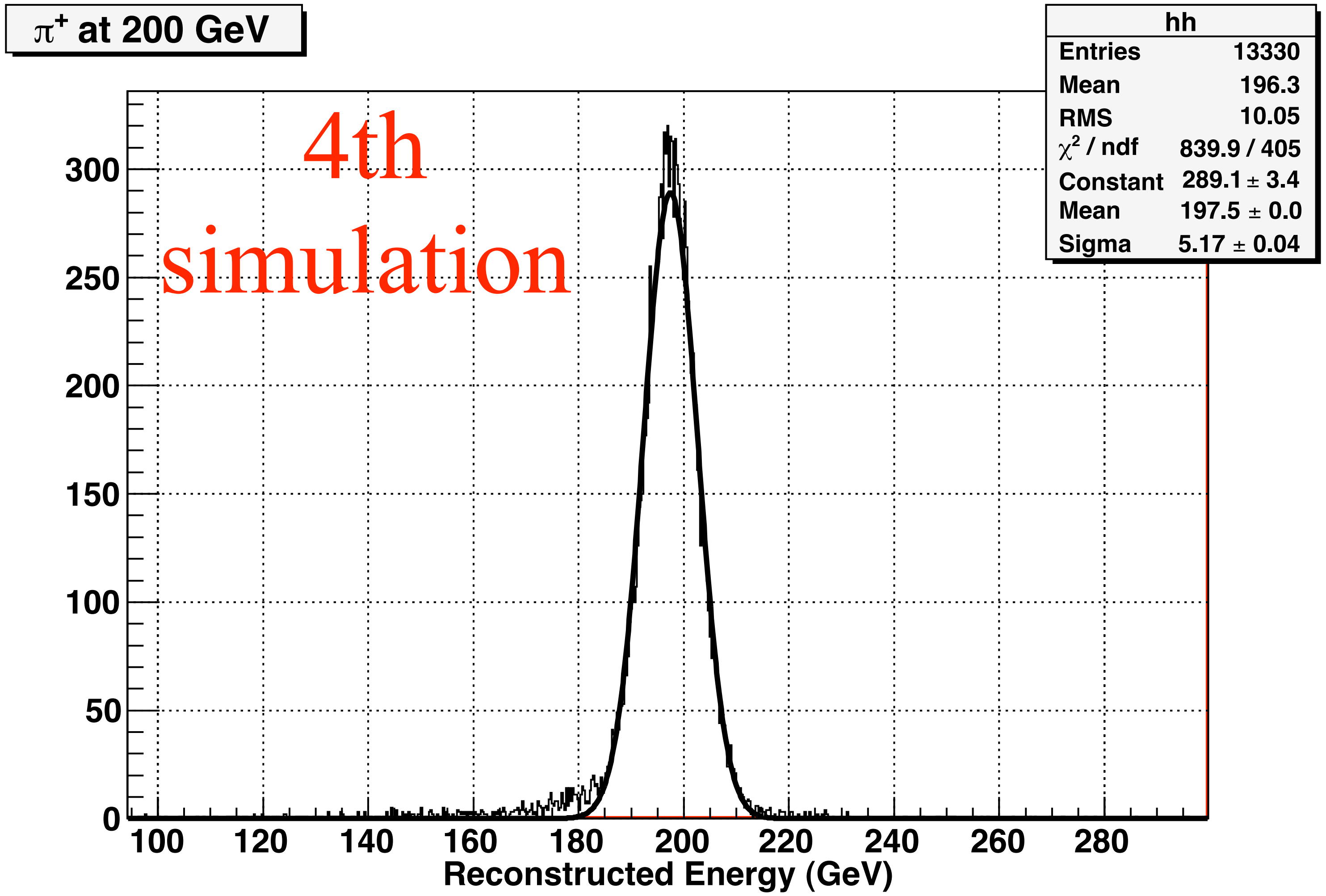
Next, combine BGO+DREAM. Total response to 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves “compensation”.



BGO+fiber calorimeter
200 GeV pion beam
DREAM data & 4th simulation

Gaussians fits include all data, no cuts, no selections, no fudging, you get to see the whole distribution





4th calorimetry, *in toto*

$$R(f_{em}) = f_{em} + \frac{1}{\eta}(1 - f_{em})$$

$$R = \frac{E_{RAW}}{E}$$

f_{em} = em fraction of the hadronic shower

η = em fraction in the fibers

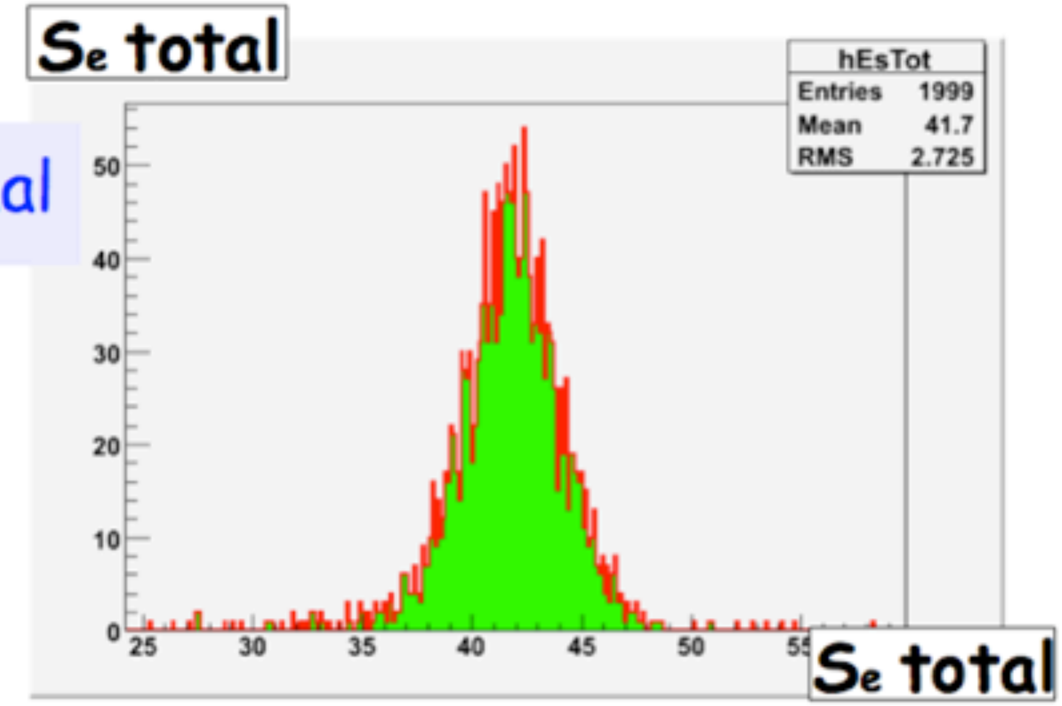
hadronic energy:

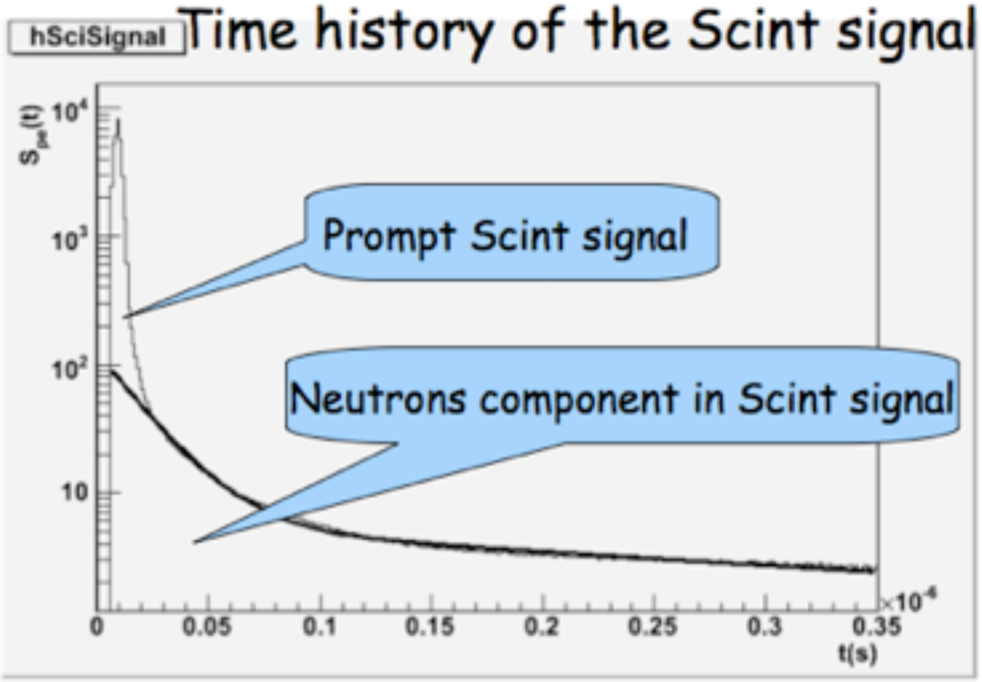
$$E_{Cal} = \boxed{\underbrace{\boxed{\frac{S_e - \lambda C_e}{1 - \lambda}}}_{\text{Dual Readout}} + \underbrace{\eta_n S n_e}_{\text{Triple Readout with time history}}}$$

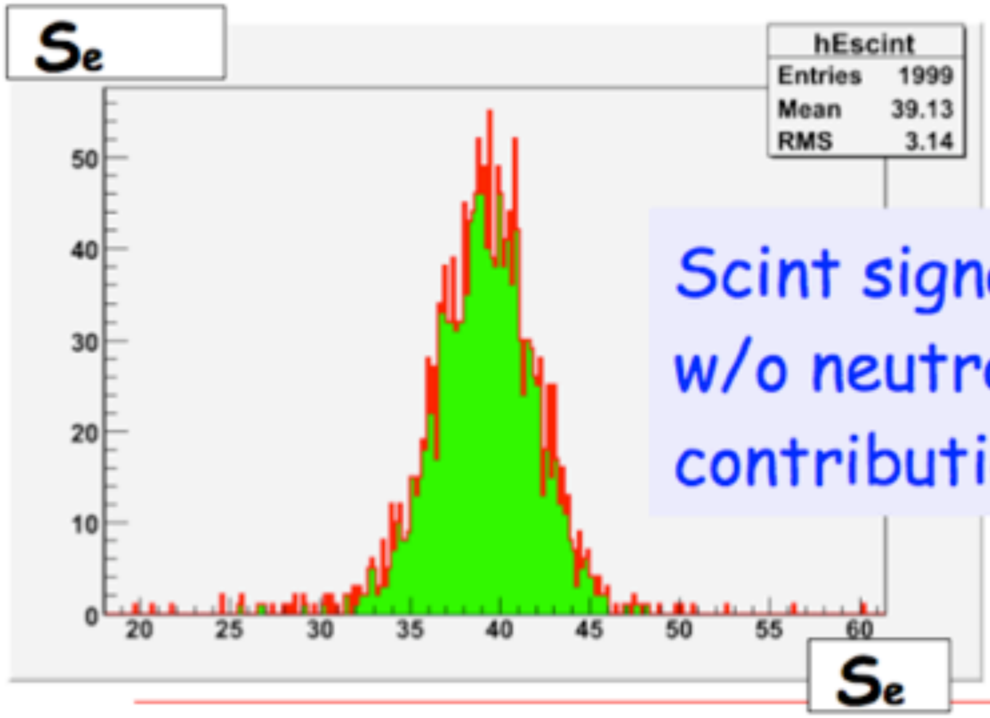
$$\lambda = \frac{1 - 1/\eta_S}{1 - 1/\eta_C}$$

Separation of the neutron component in the scintillation signal

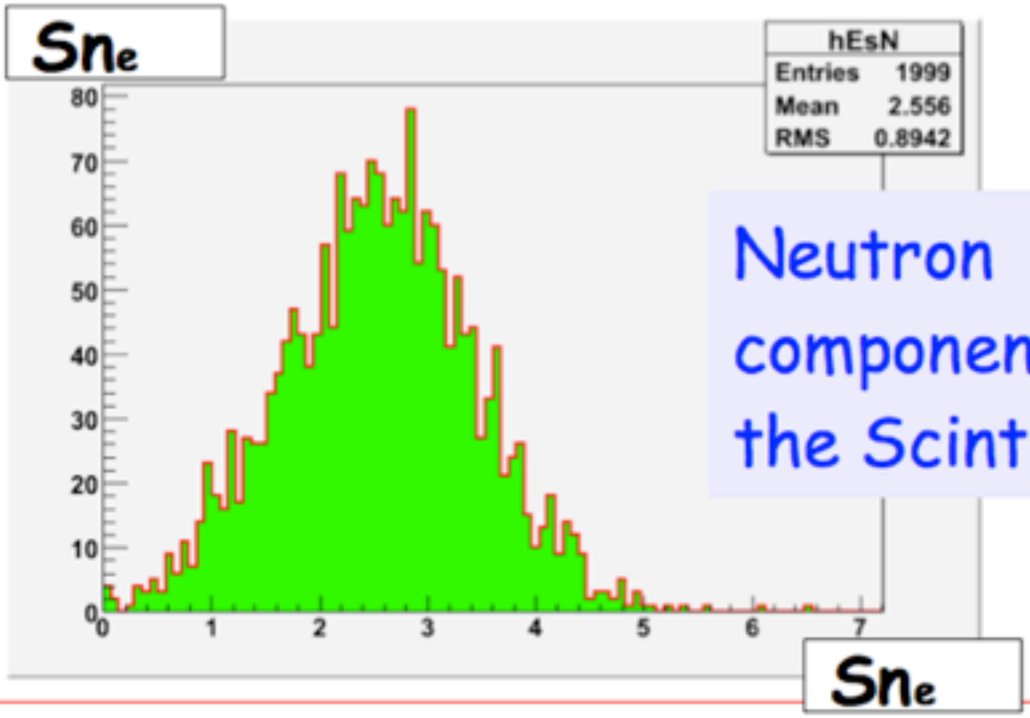
Full Scint signal







Scint signal w/o neutrons contribution



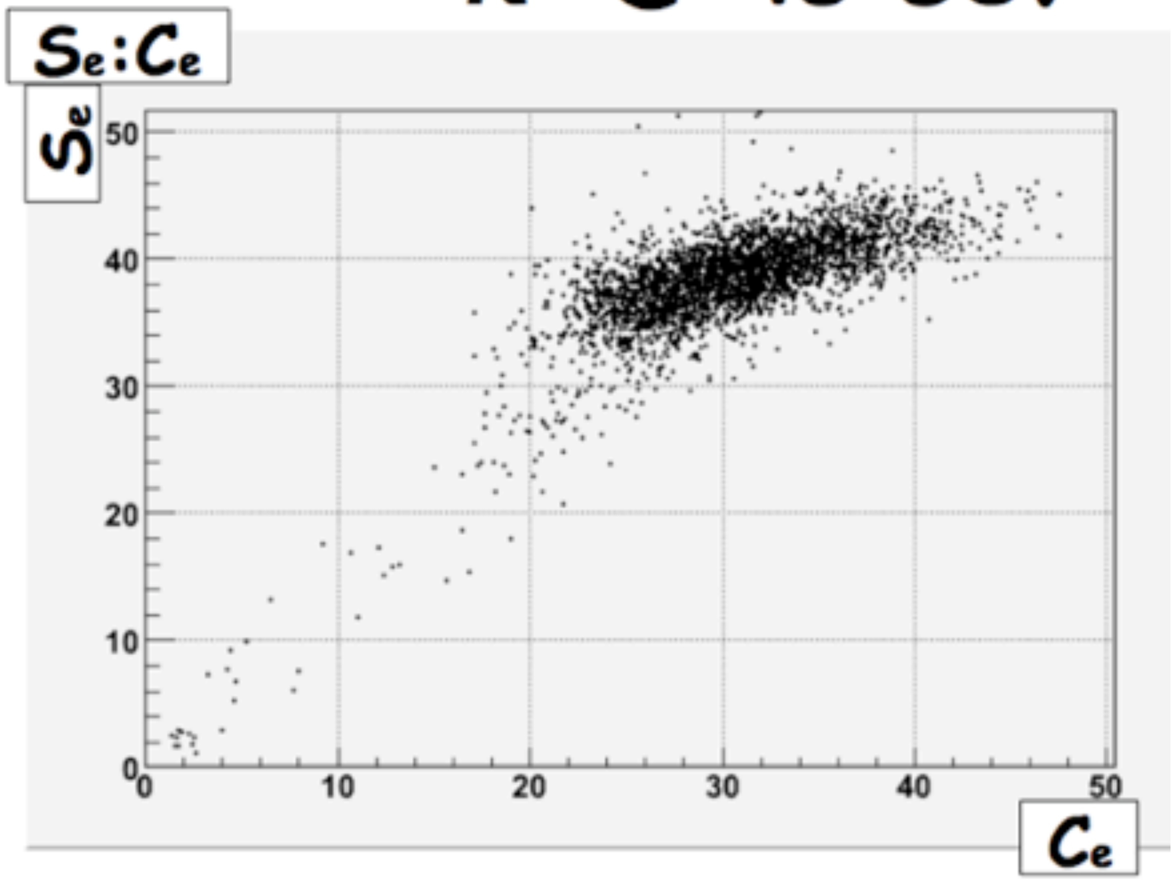
Neutron component in the Scint signal

Calibration at Z^0

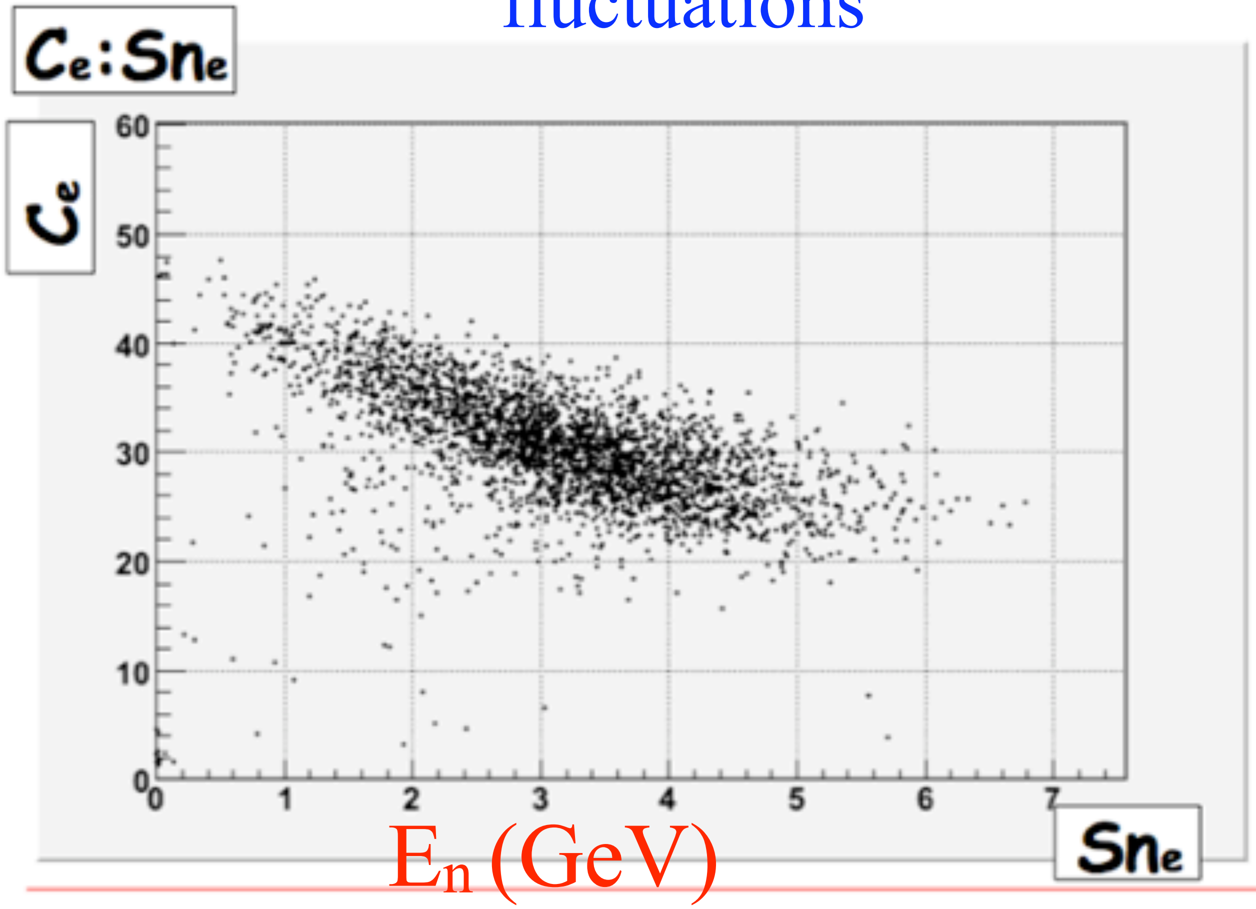
Scintillation vs. Cerenkov
EM fraction fluctuations

π^- @ 45 GeV

S_e versus C_e

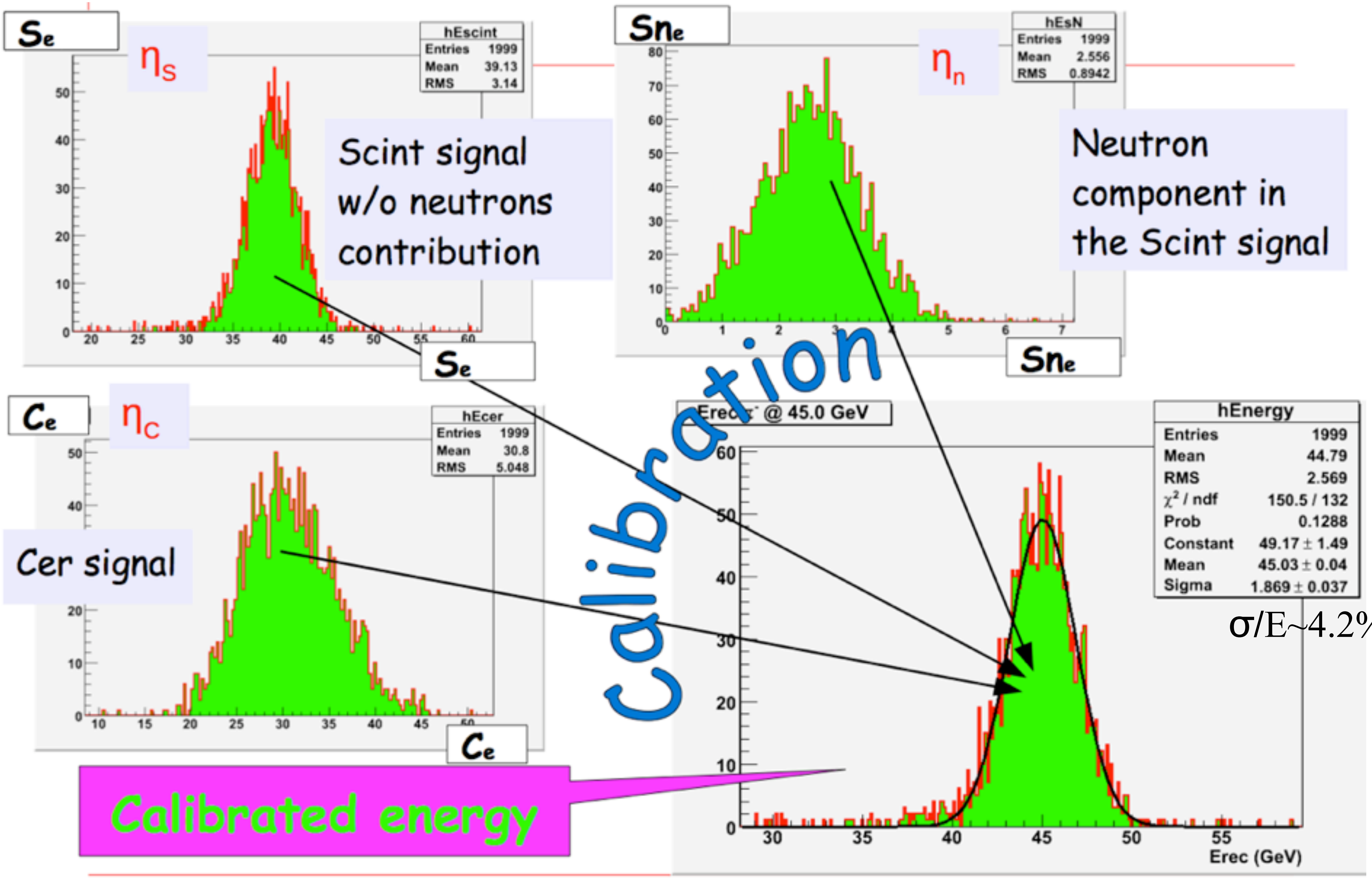


Cerenkov vs. E(neutrons)
binding energy loss
fluctuations



E_n (GeV)

C_e versus Sn_e



Scint signal w/o neutrons contribution

Neutron component in the Scint signal

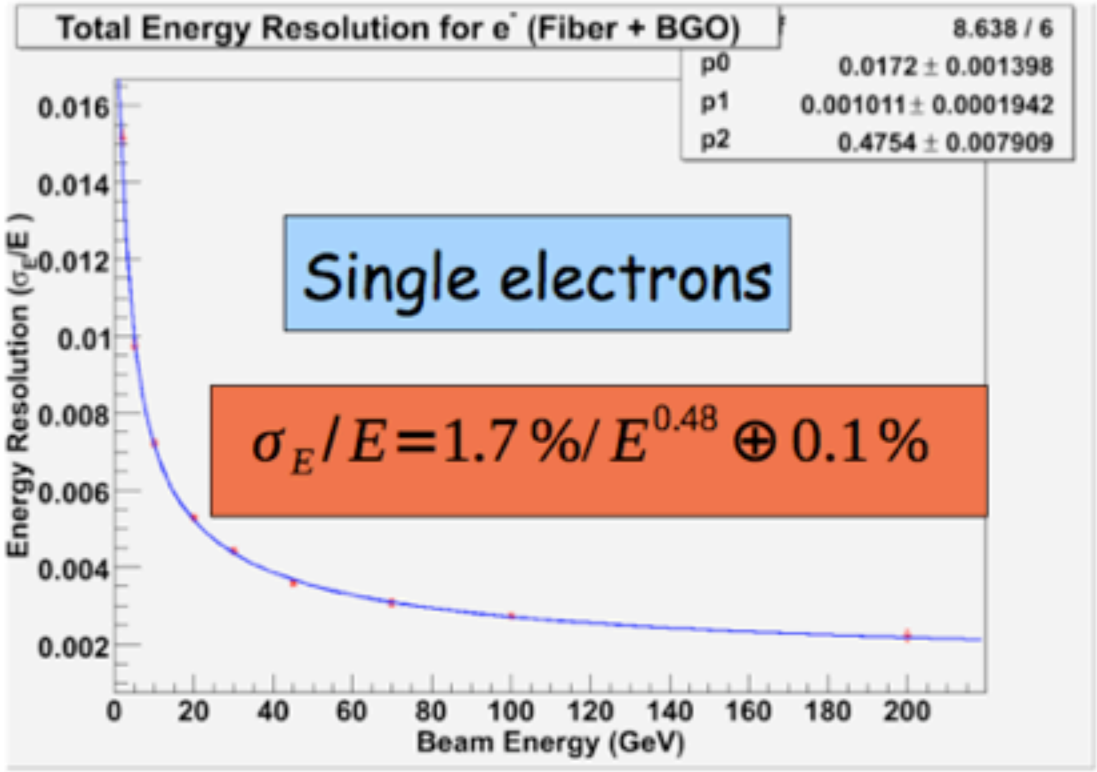
Cer signal

Calibration

Calibrated energy

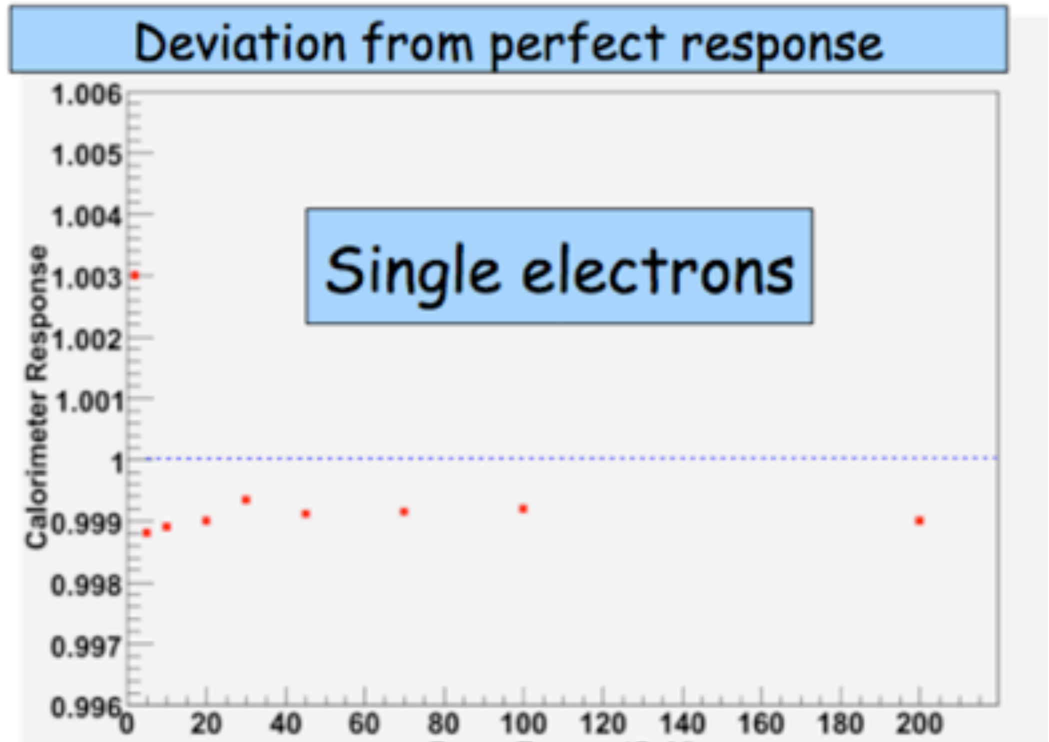
$\sigma/E \sim 4.2\%$

HCAL + ECAL resolution

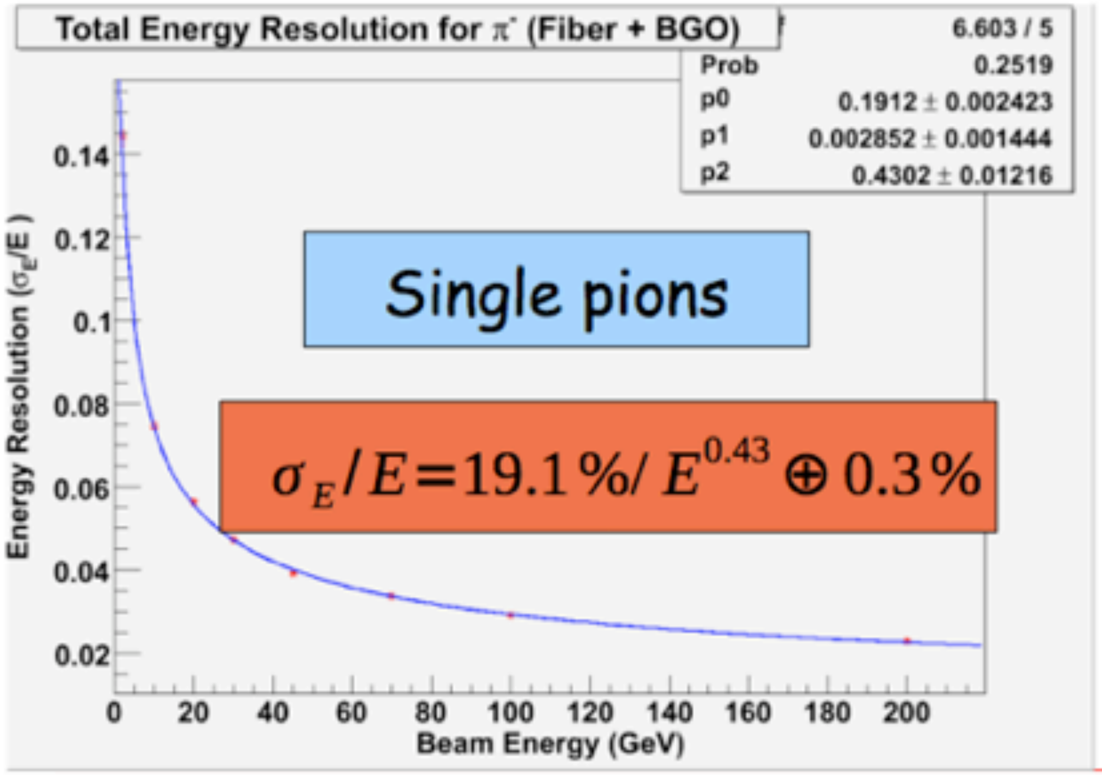


Single electrons

$$\sigma_E/E = 1.7\%/E^{0.48} \oplus 0.1\%$$

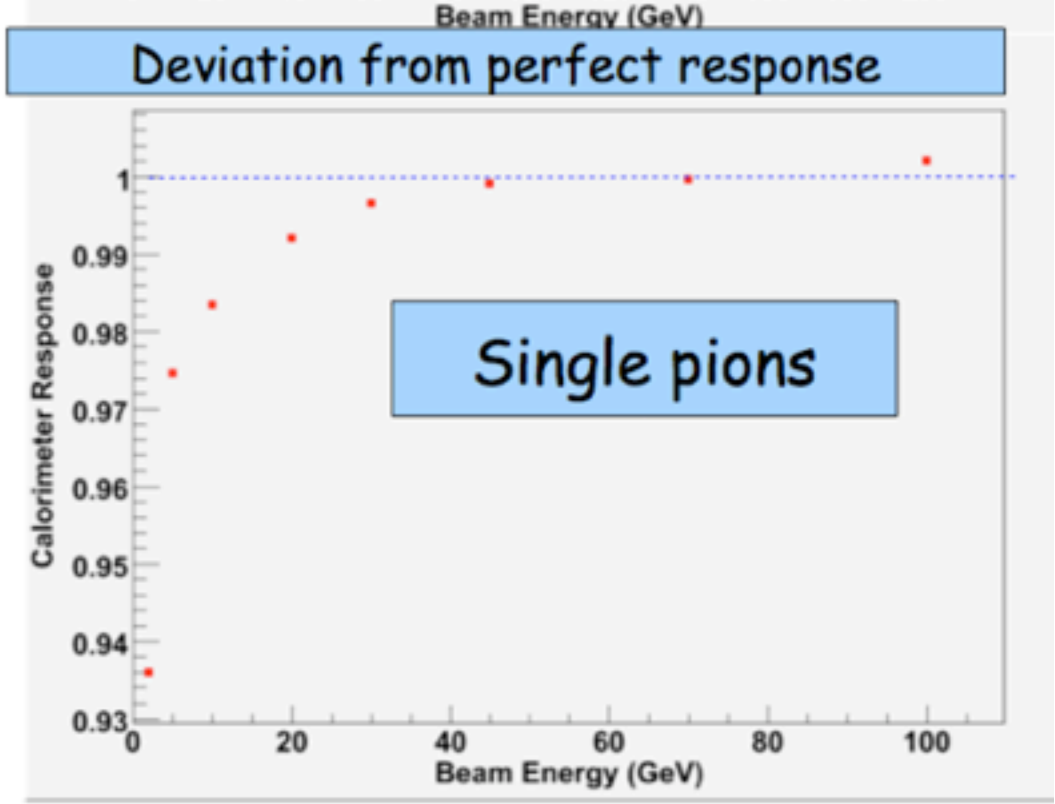


Single electrons



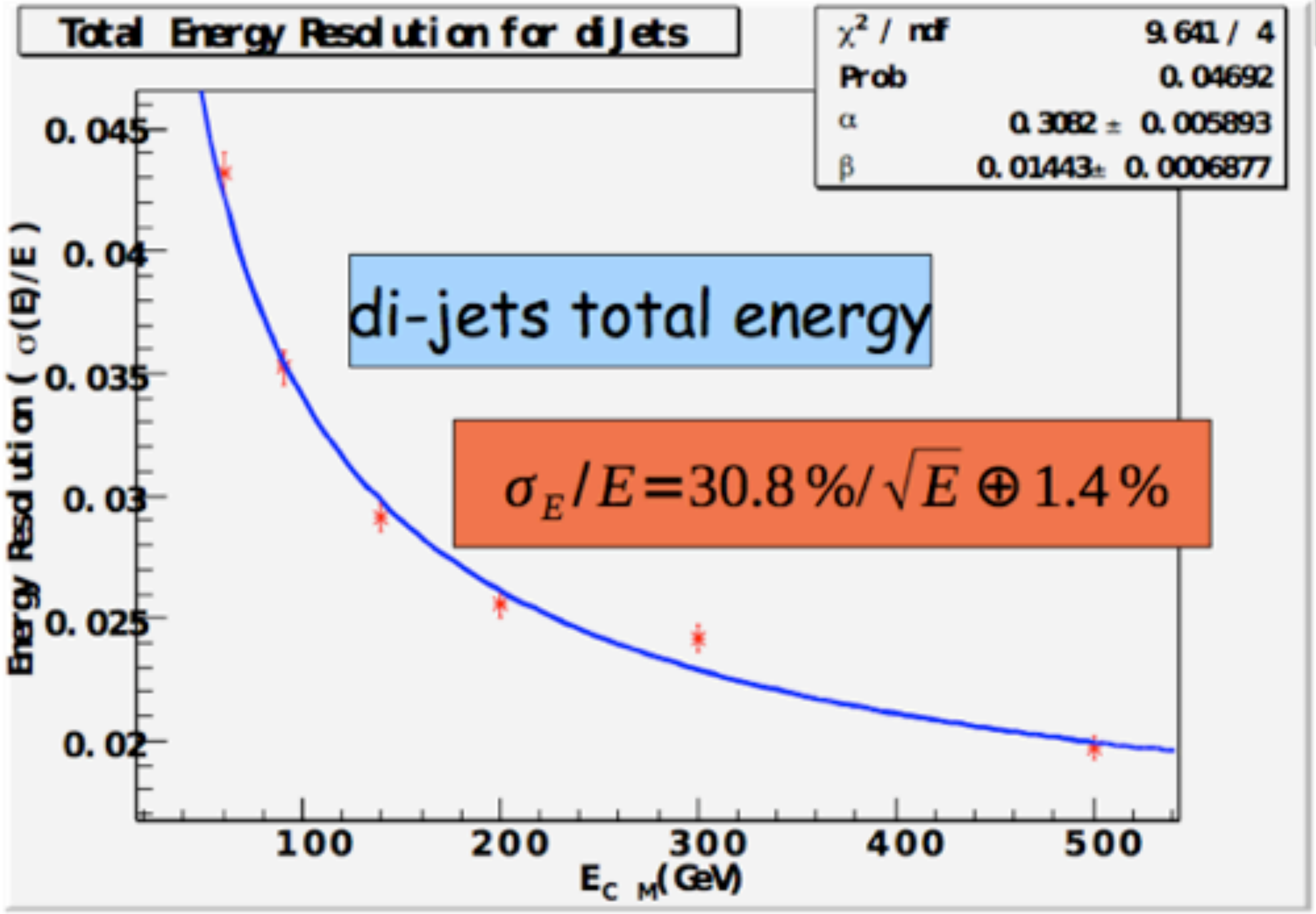
Single pions

$$\sigma_E/E = 19.1\%/E^{0.43} \oplus 0.3\%$$



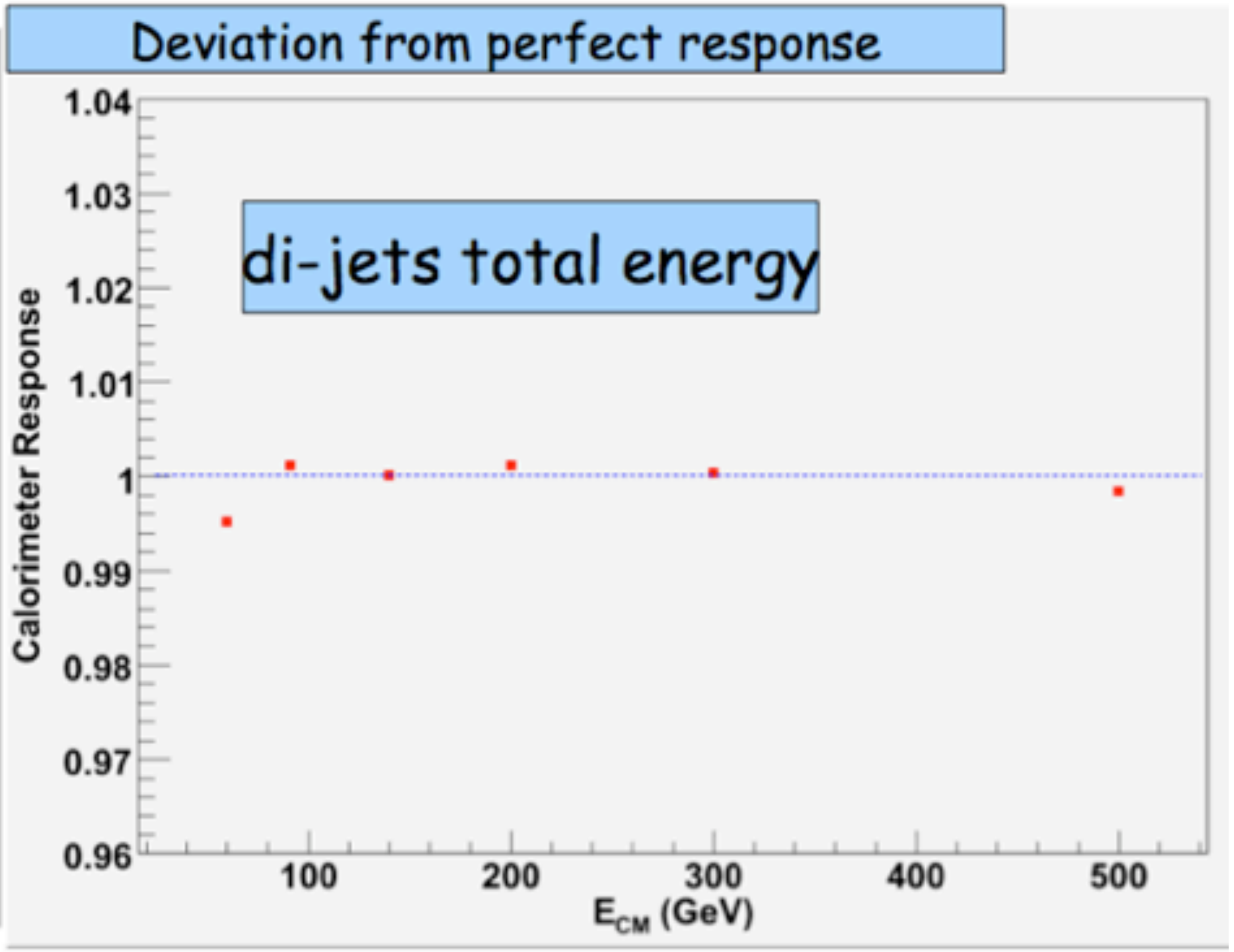
Single pions

HCAL + ECAL resolution



di-jets total energy

$$\sigma_E/E = 30.8\%/\sqrt{E} \oplus 1.4\%$$



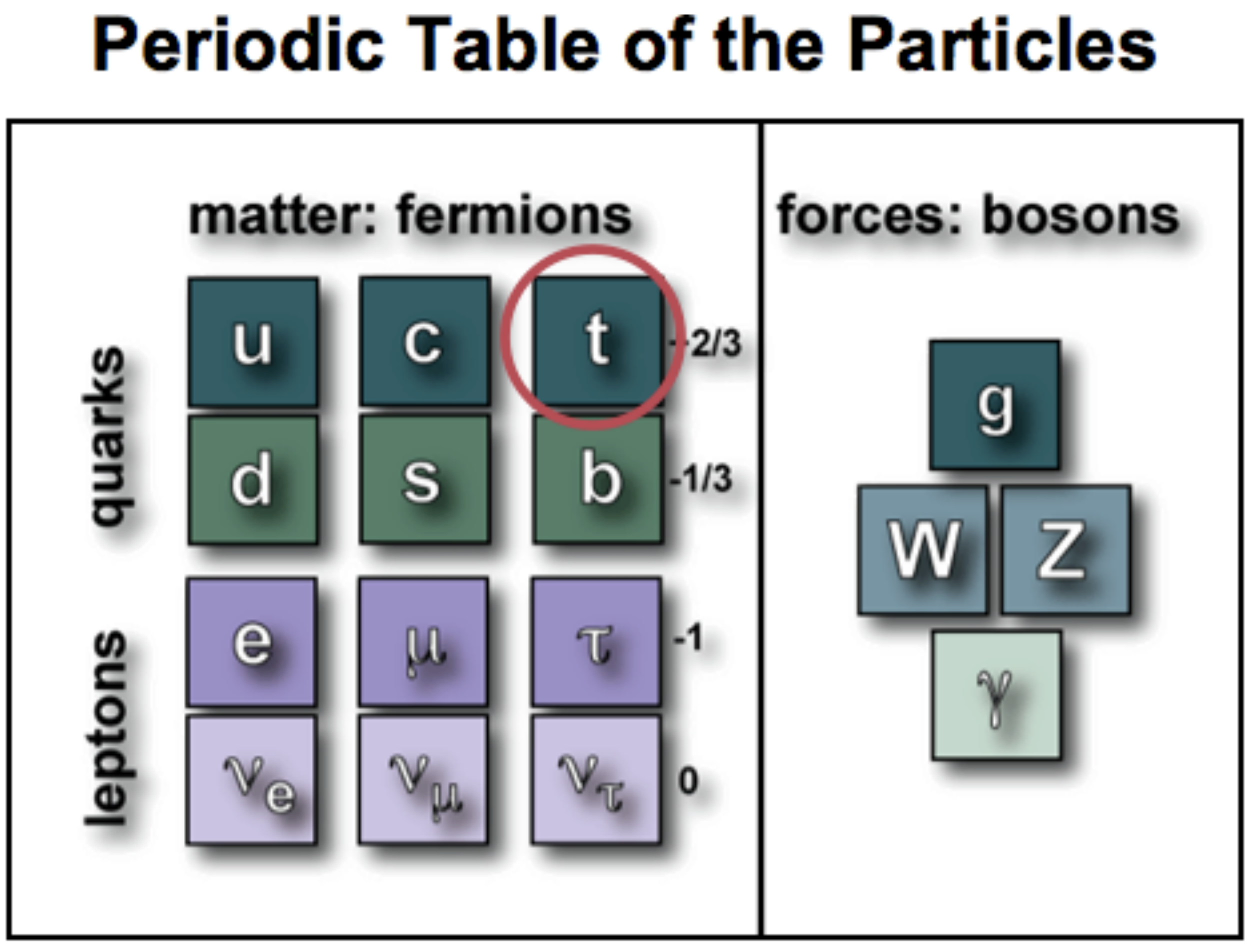
Deviation from perfect response

di-jets total energy

Triple readout ECAL + HCAL	Gaussian resolution stocastic term	constant term
e^-	$1.7\%/E^{0.48}$	0.1%
π^-	$19.1\%/E^{0.43}$	0.3%
di-jet	$30.8\%/\sqrt{E}$	1.4%

Particle Identification

(most of these are completely new
in high energy physics)



- *uds* quarks (jet energy resolution)
- *c,b* quarks (vertex tagging)
- *t* quark (reconstruction)

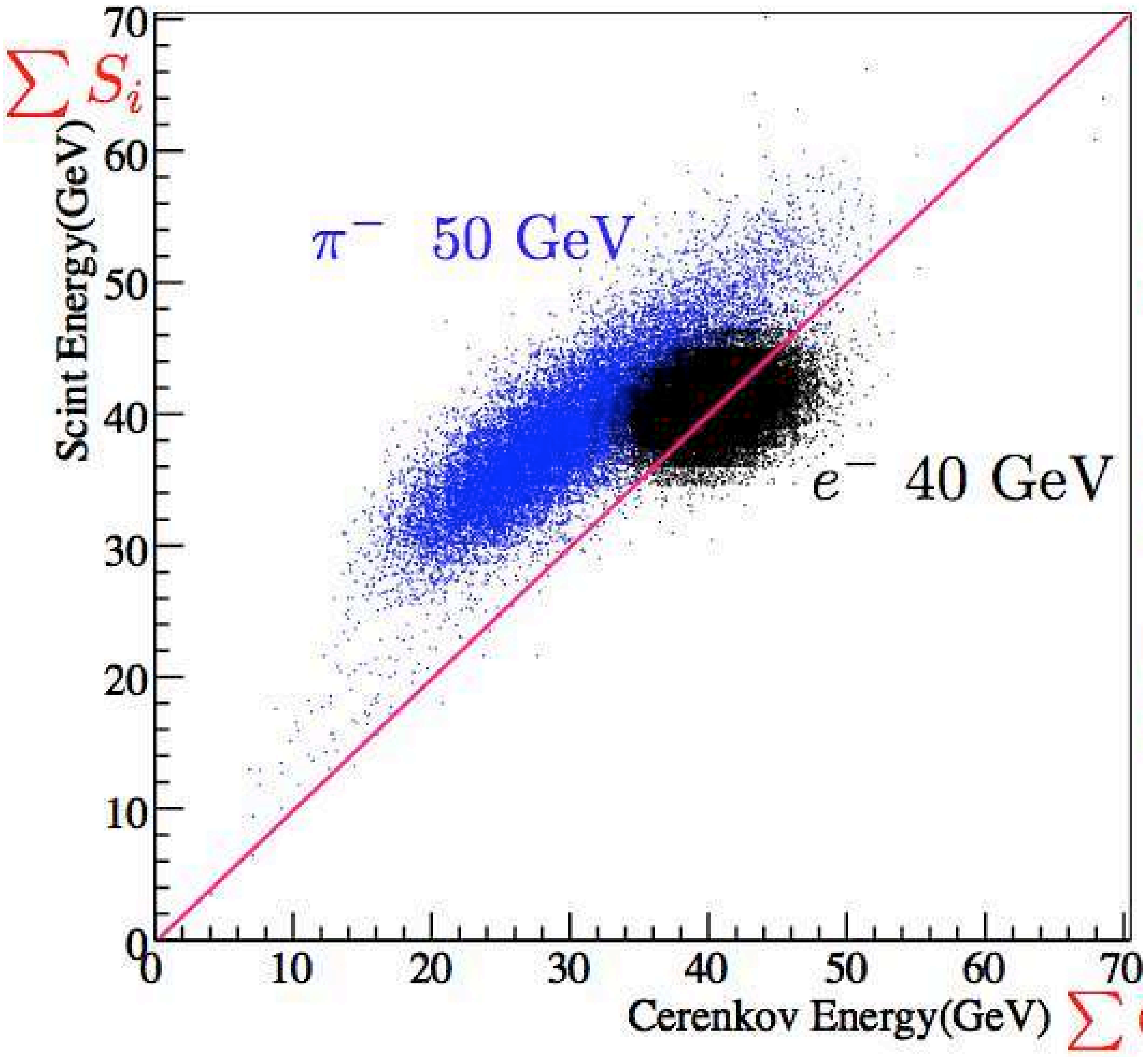
- *electron* (dual-readout)
- *muon* (dual-readout and iron-free field)
- *tau* (reconstruction)
- *neutrino* (by subtraction; resolution)

- *W,Z* (hadronic jet reconstruction)
- *photon* (BGO dual readout)
- *gluon* (jet energy resolution)

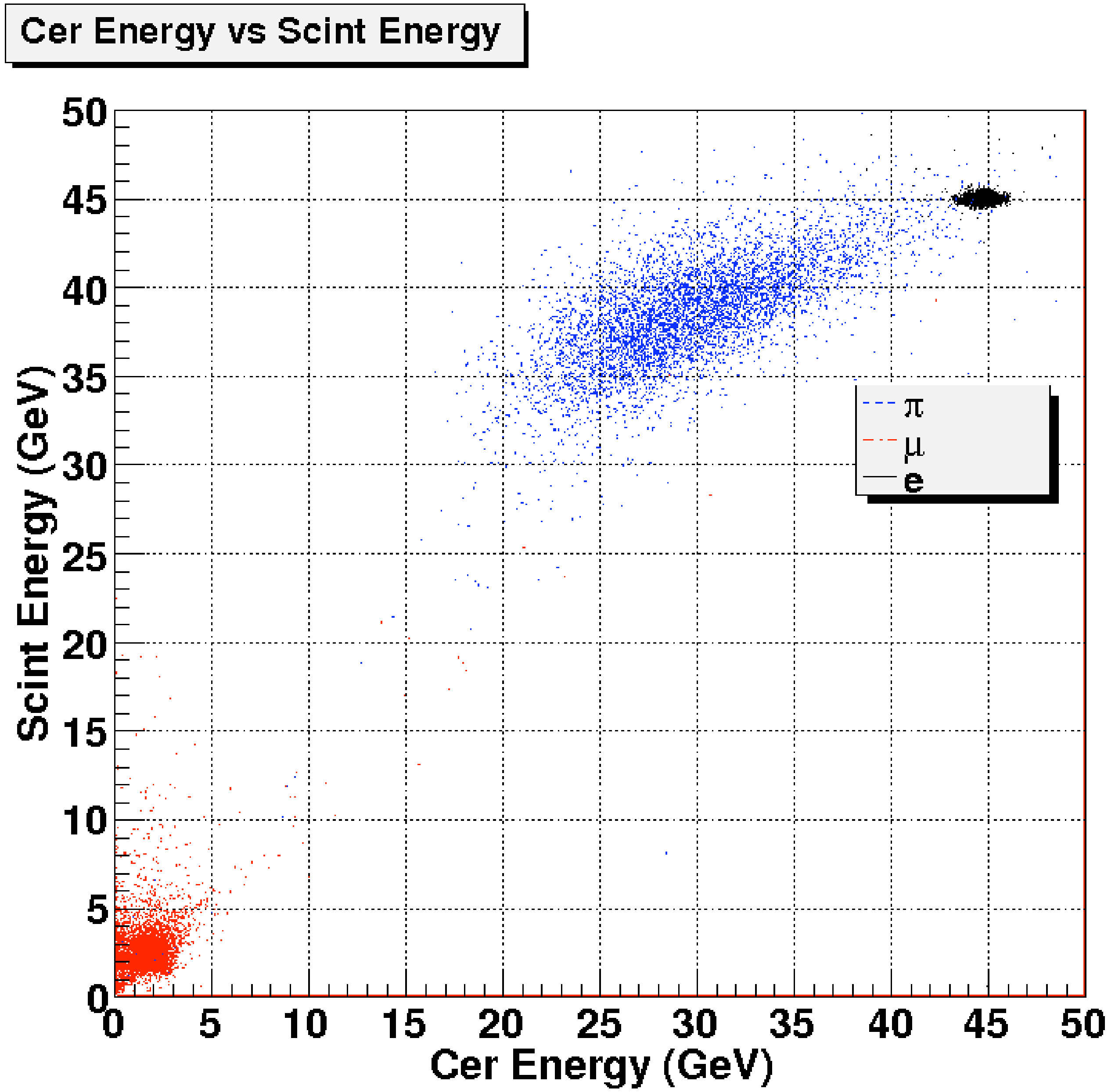
We think we can do it all.

(i) Immediate particle ID from the S vs. C plot

DREAM data

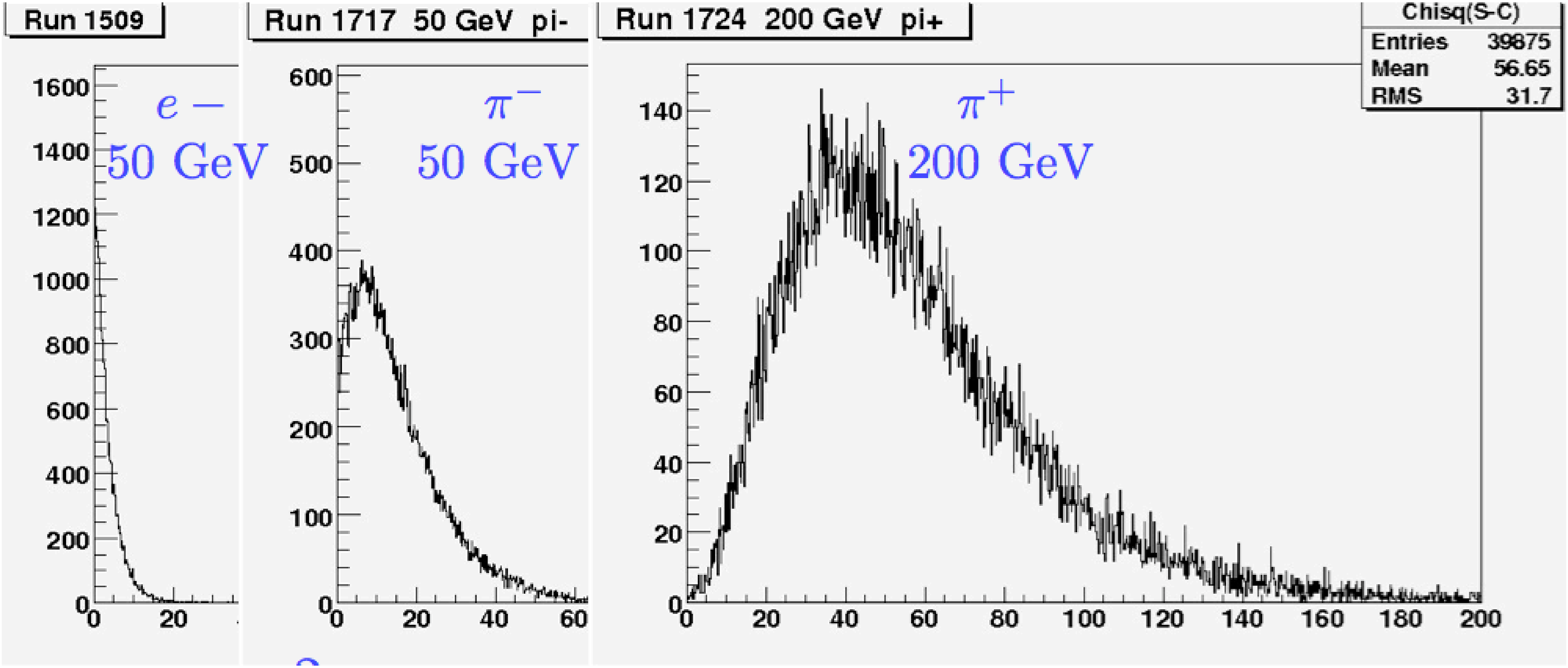


4th simulation (45 GeV)

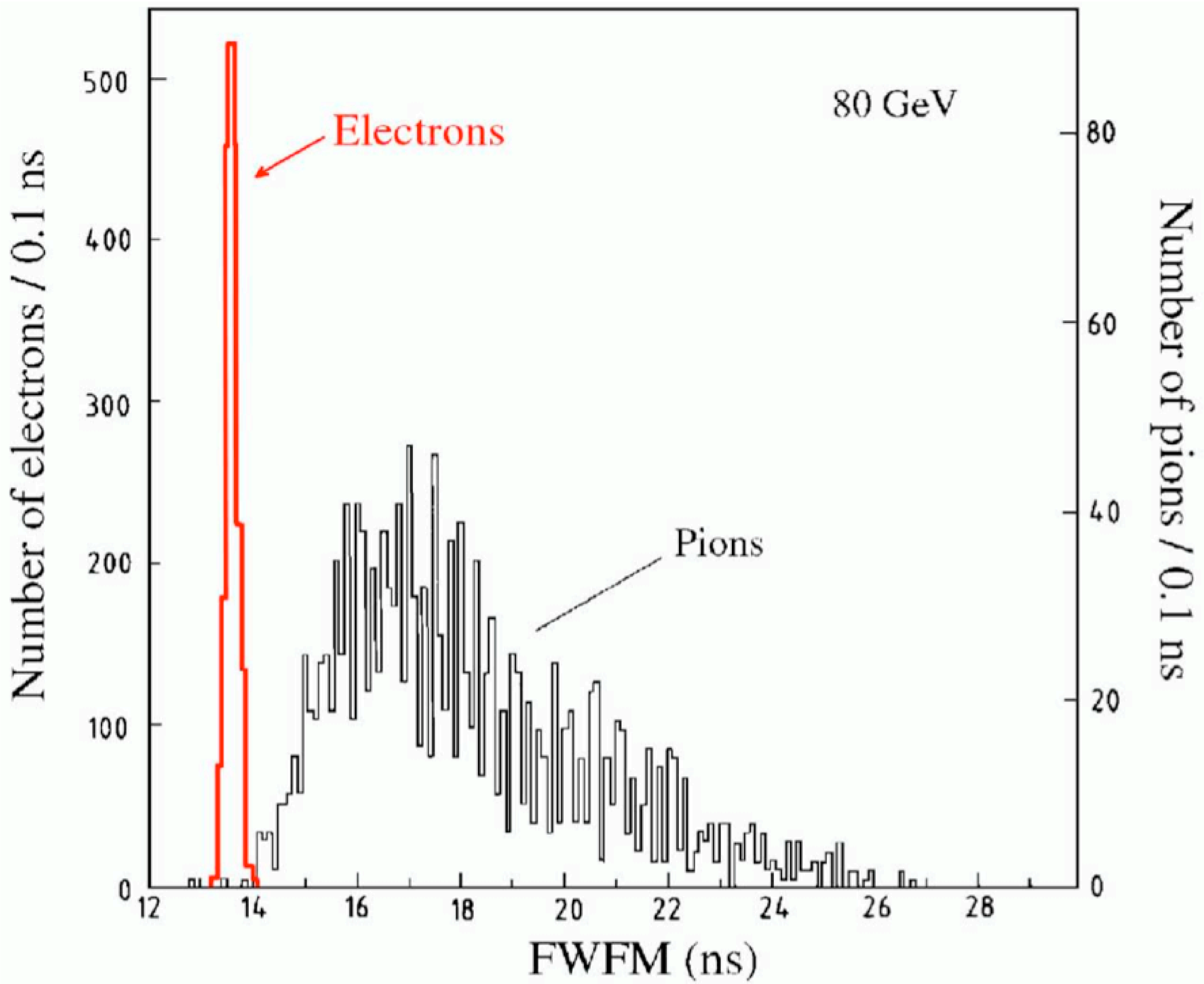


(ii) Further discrimination from the *fluctuations in S-C among the channels of a shower*

$$\chi^2 = \sum_k^N [\frac{(S_k - C_k)}{\sigma_k}]^2 \quad \sim 0 \text{ for } e^{\pm}, \text{ large for } \pi^{\pm}$$



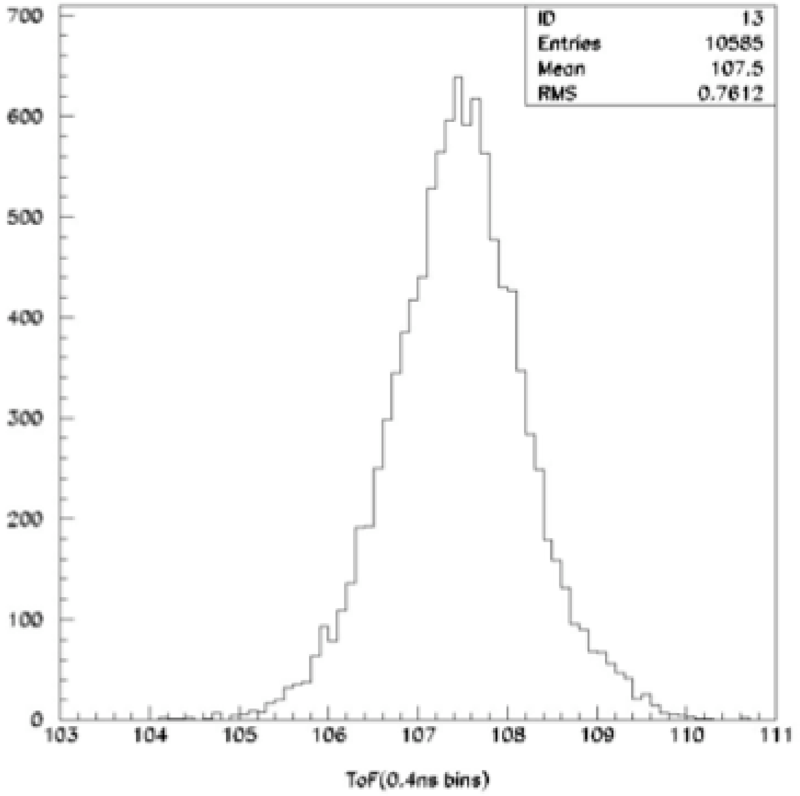
(iii) Time-history of scintillating fibers: duration of pulse at 1/5-maximum (SPACAL data)



(iv) Time-of-flight in Cerenkov fibers of DREAM

sigma ~ 0.3 ns

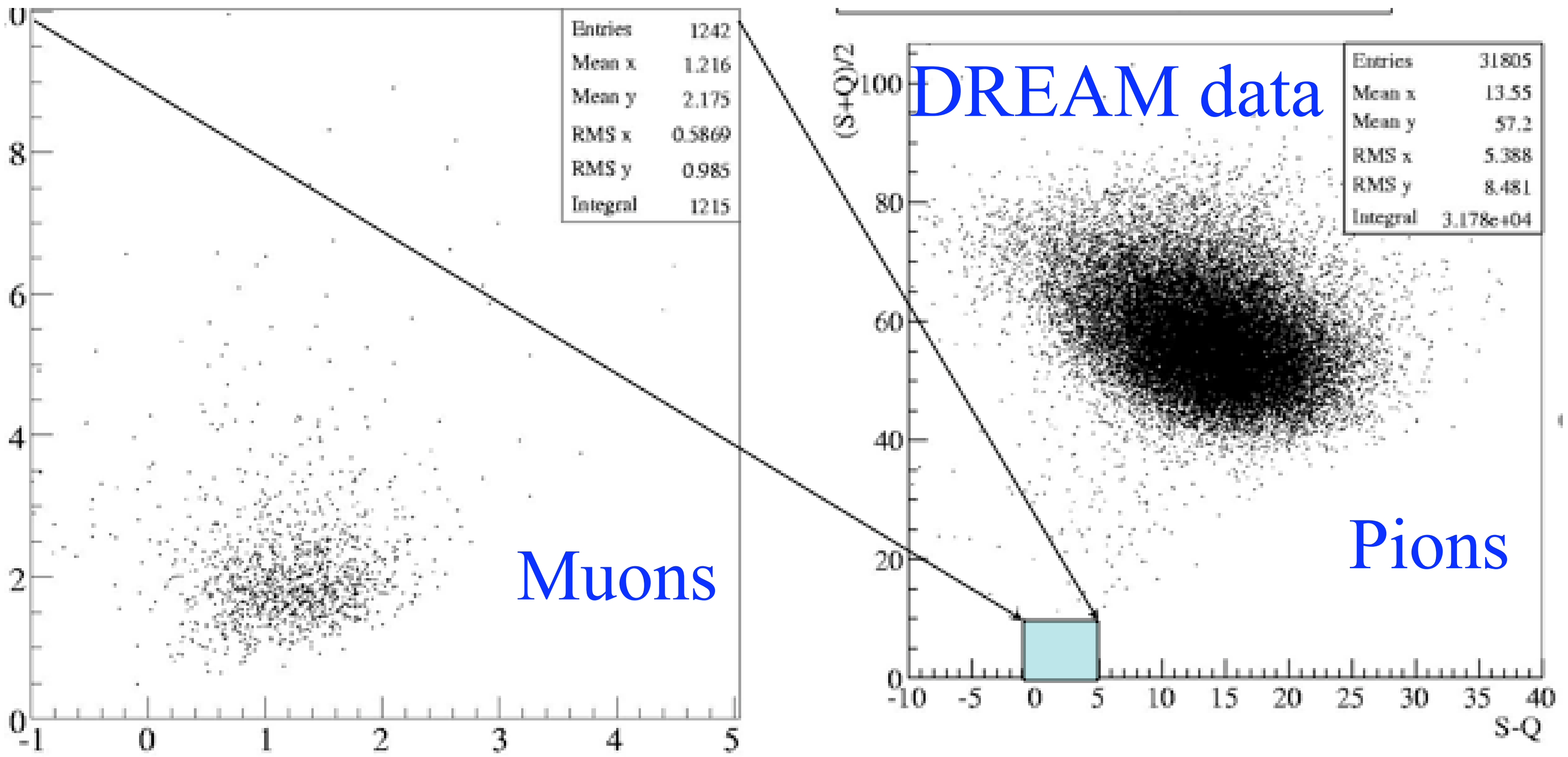
DREAM data



(v) Muon tagging in DREAM:

S-C ~ *dE/dx* (muons)

(S+C)/2 ~ Ebrems

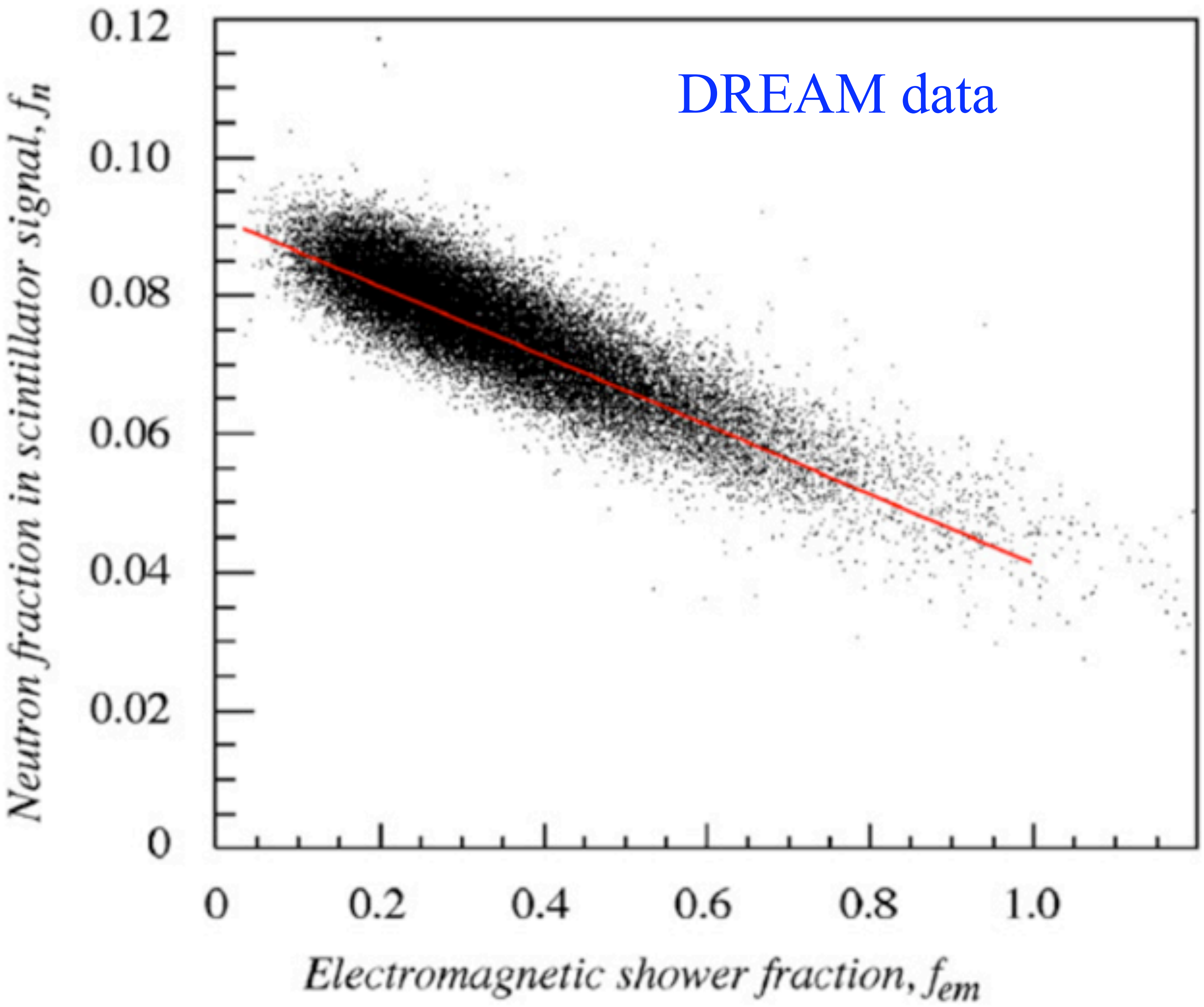


(vi) Neutron fraction *vs.* electromagnetic fraction: "hadronic" ID tag

Expected anti-correlation of

f_n (hadronic content) and

f_{EM} (electromagnetic content)

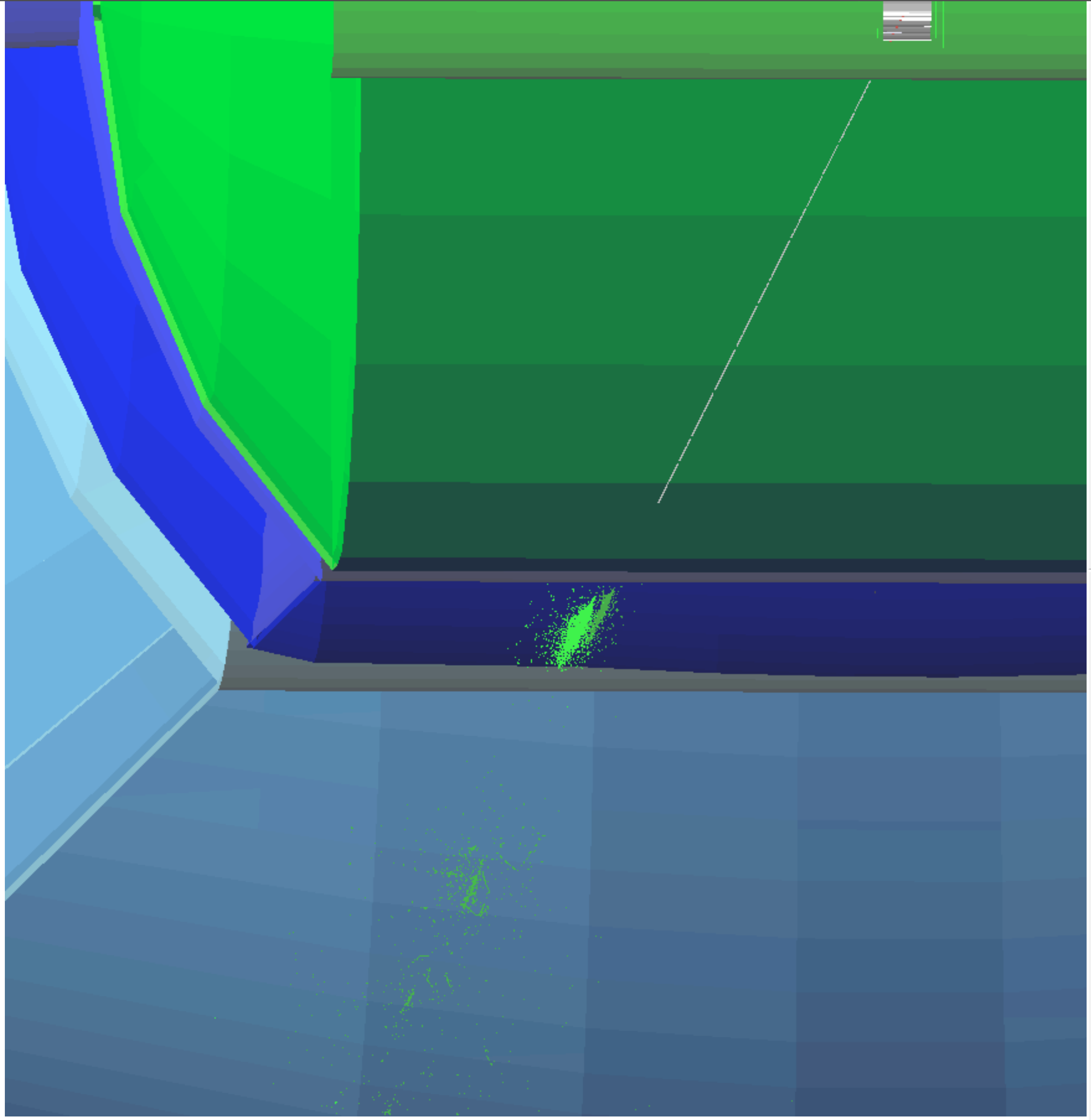


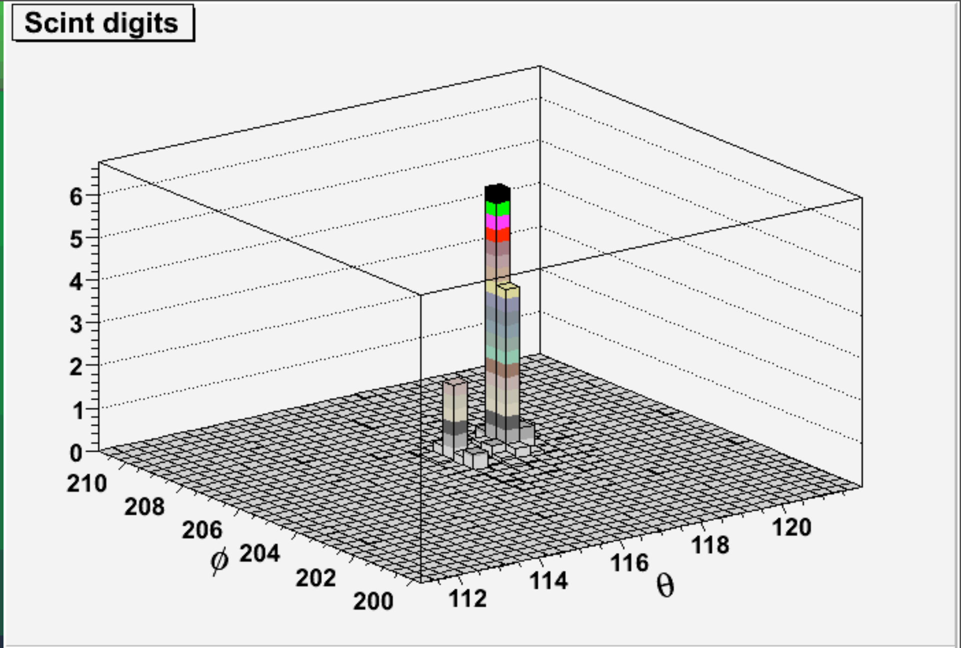
(viii)

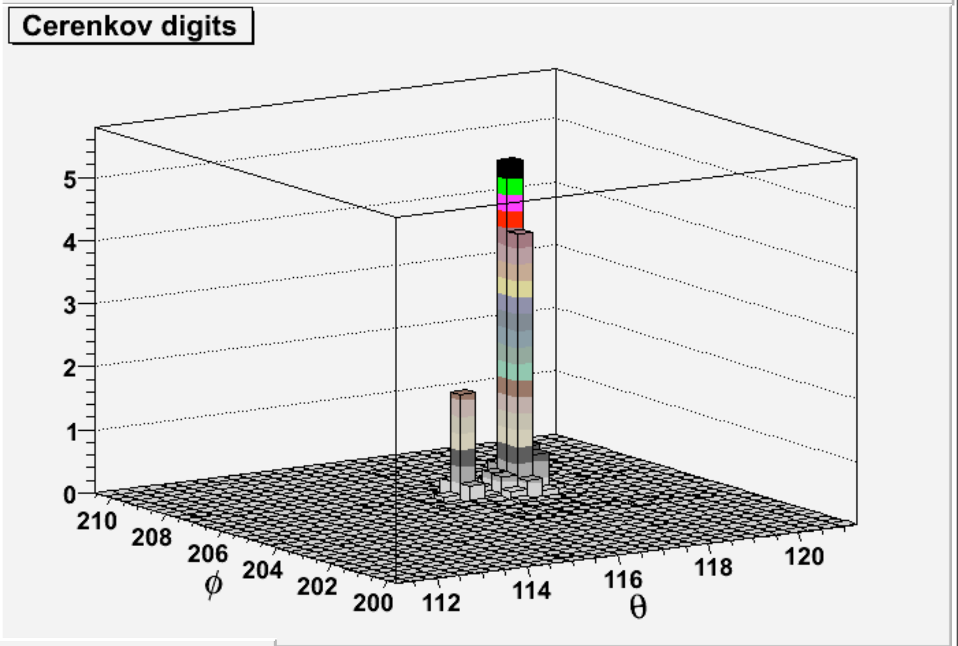
$\tau^{\pm}$ ID

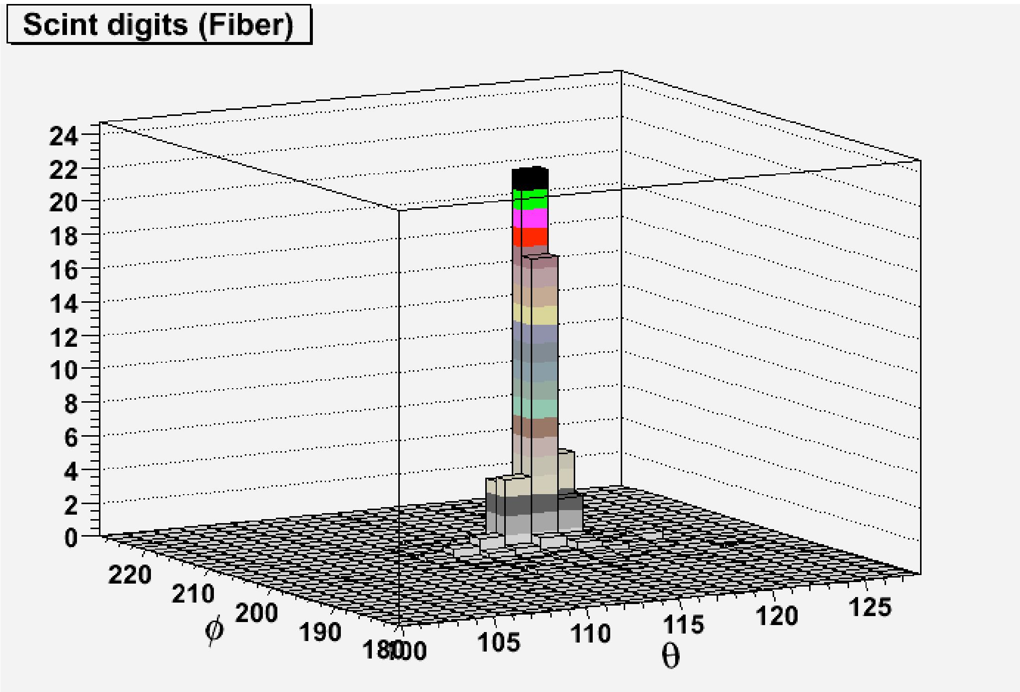
(for polarization)

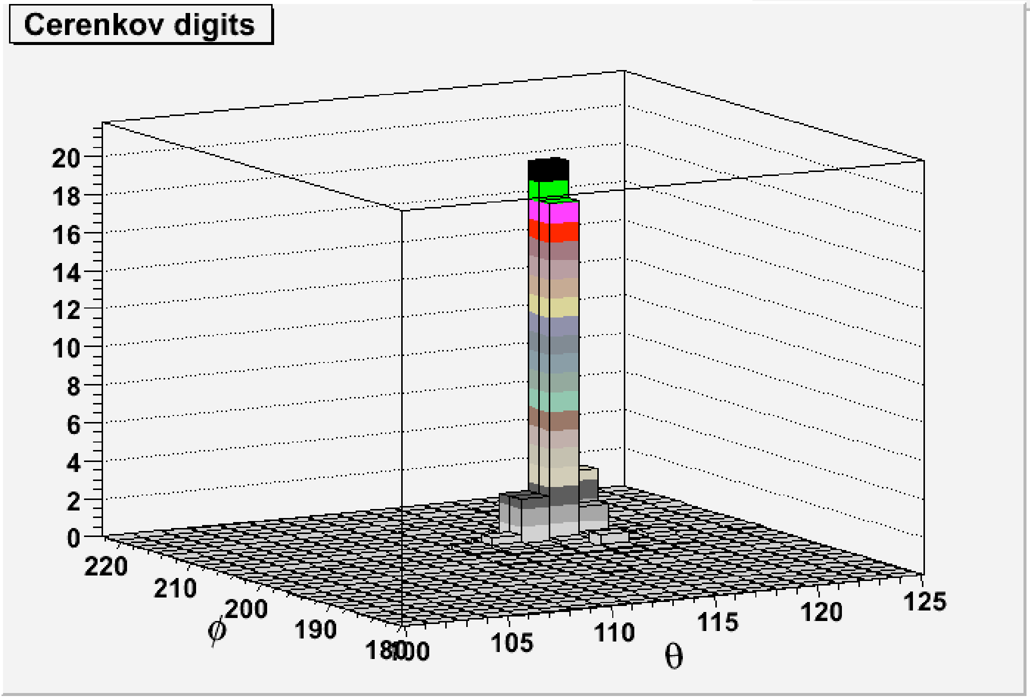
$$\tau^- \to \rho^- \nu$$
$$\to \pi^- \pi^0$$
$$\to \pi^- \gamma\gamma$$



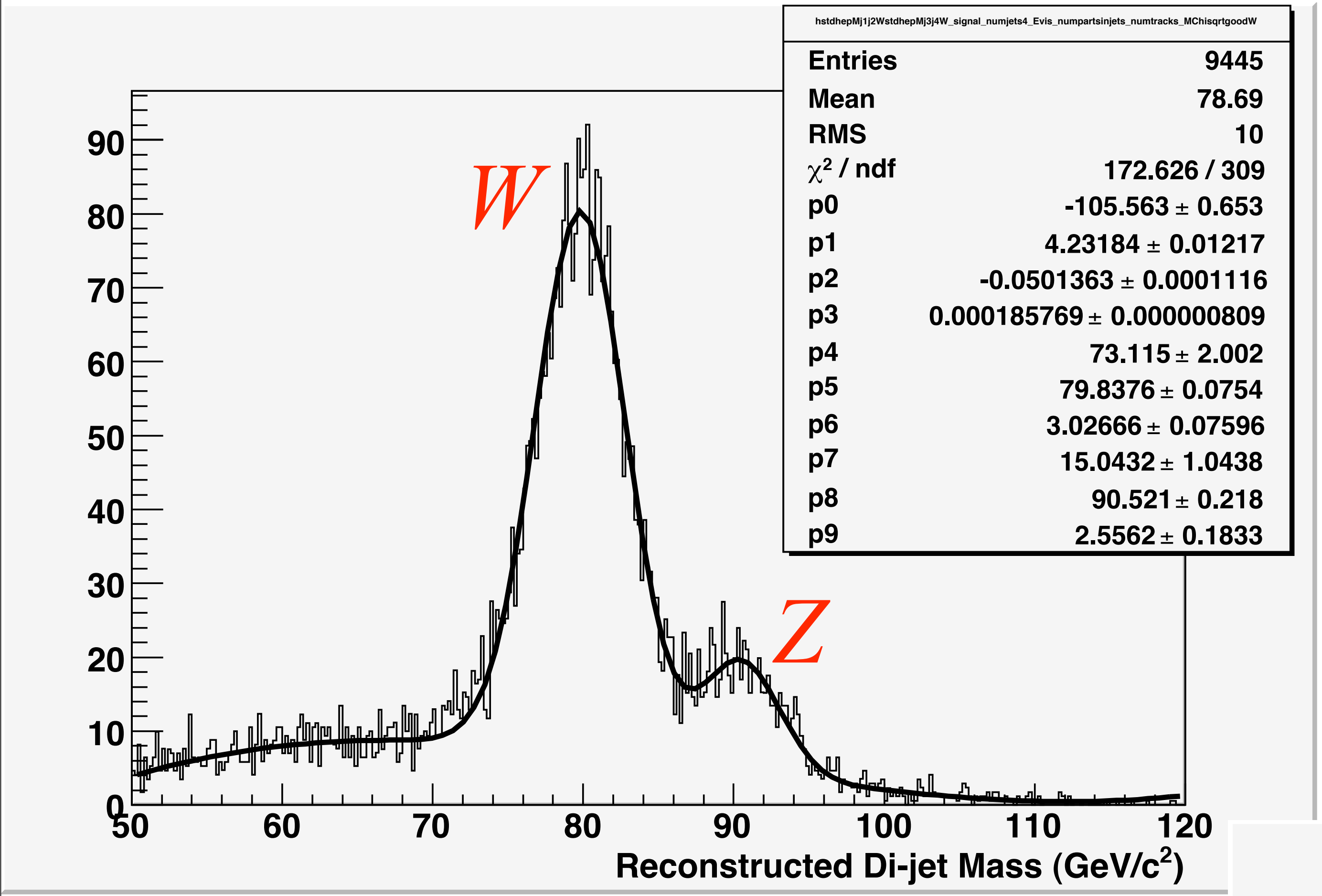

Scint digits


Cerenkov digits

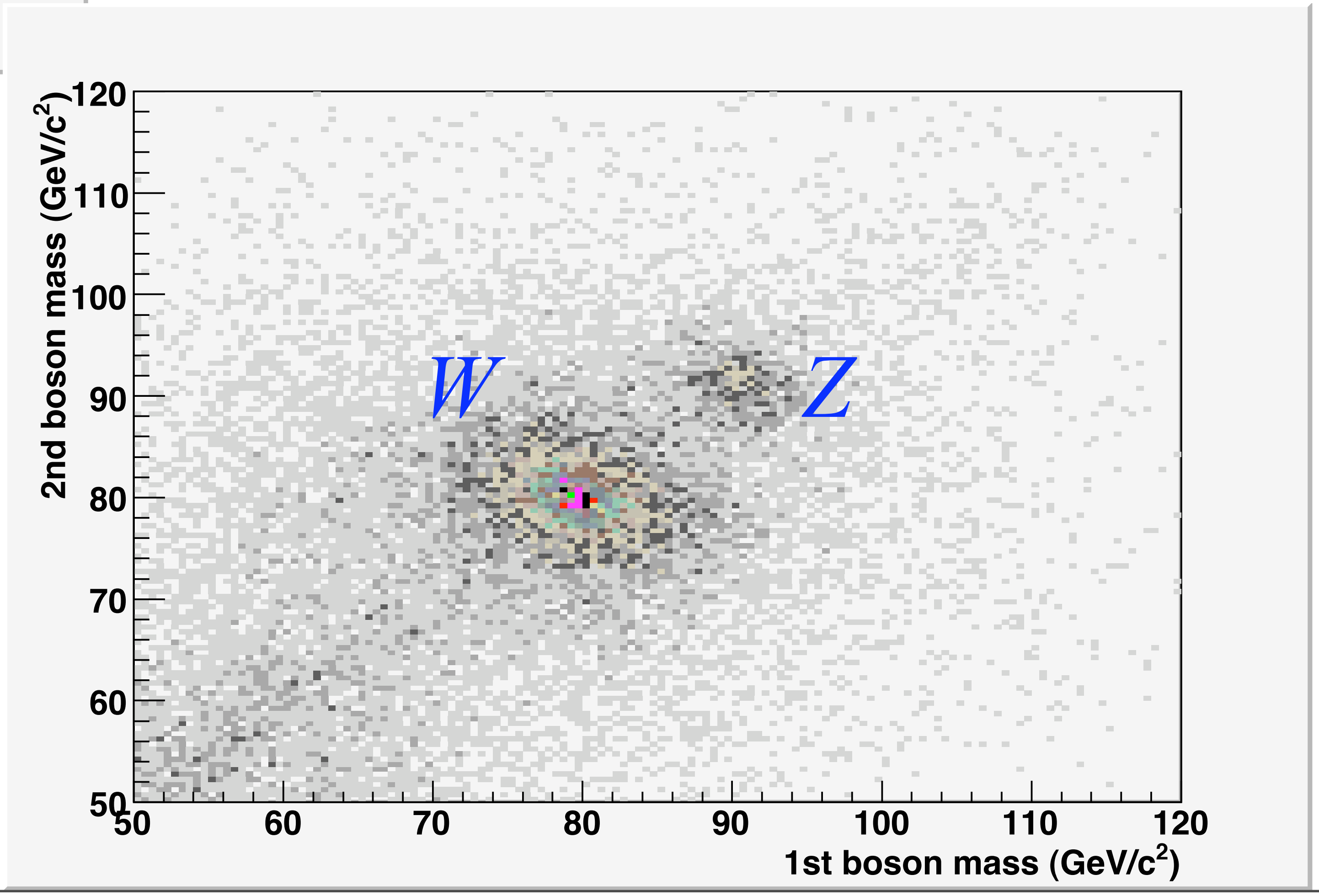

Scint digits (Fiber)


Cerenkov digits

(xi) W and Z mass measurement and discrimination



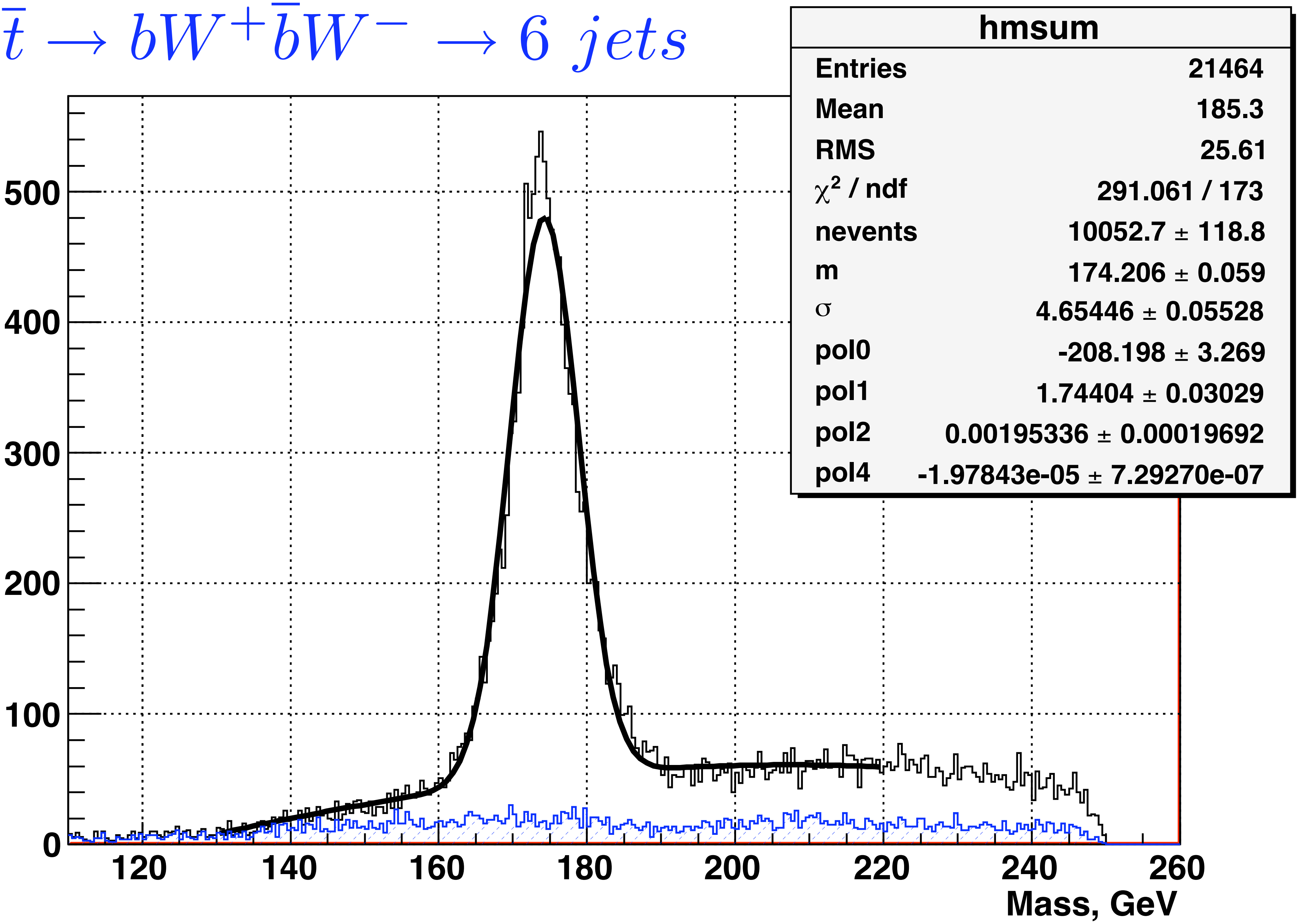
hstdhepMj1j2WstdhepMj3j4W_signal_numjets4_Evis_numpartsinjets_numtracks_MChisqrtgoodW	
Entries	9445
Mean	78.69
RMS	10
χ^2 / ndf	172.626 / 309
p0	-105.563 ± 0.653
p1	4.23184 ± 0.01217
p2	-0.0501363 ± 0.0001116
p3	0.000185769 ± 0.000000809
p4	73.115 ± 2.002
p5	79.8376 ± 0.0754
p6	3.02666 ± 0.07596
p7	15.0432 ± 1.0438
p8	90.521 ± 0.218
p9	2.5562 ± 0.1833



From the SUSY pt. 5 analysis
by Anna Mazzacane

(xii) top quark (all hadronic 6-jet channel)

$$e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^- \rightarrow 6\ jets$$

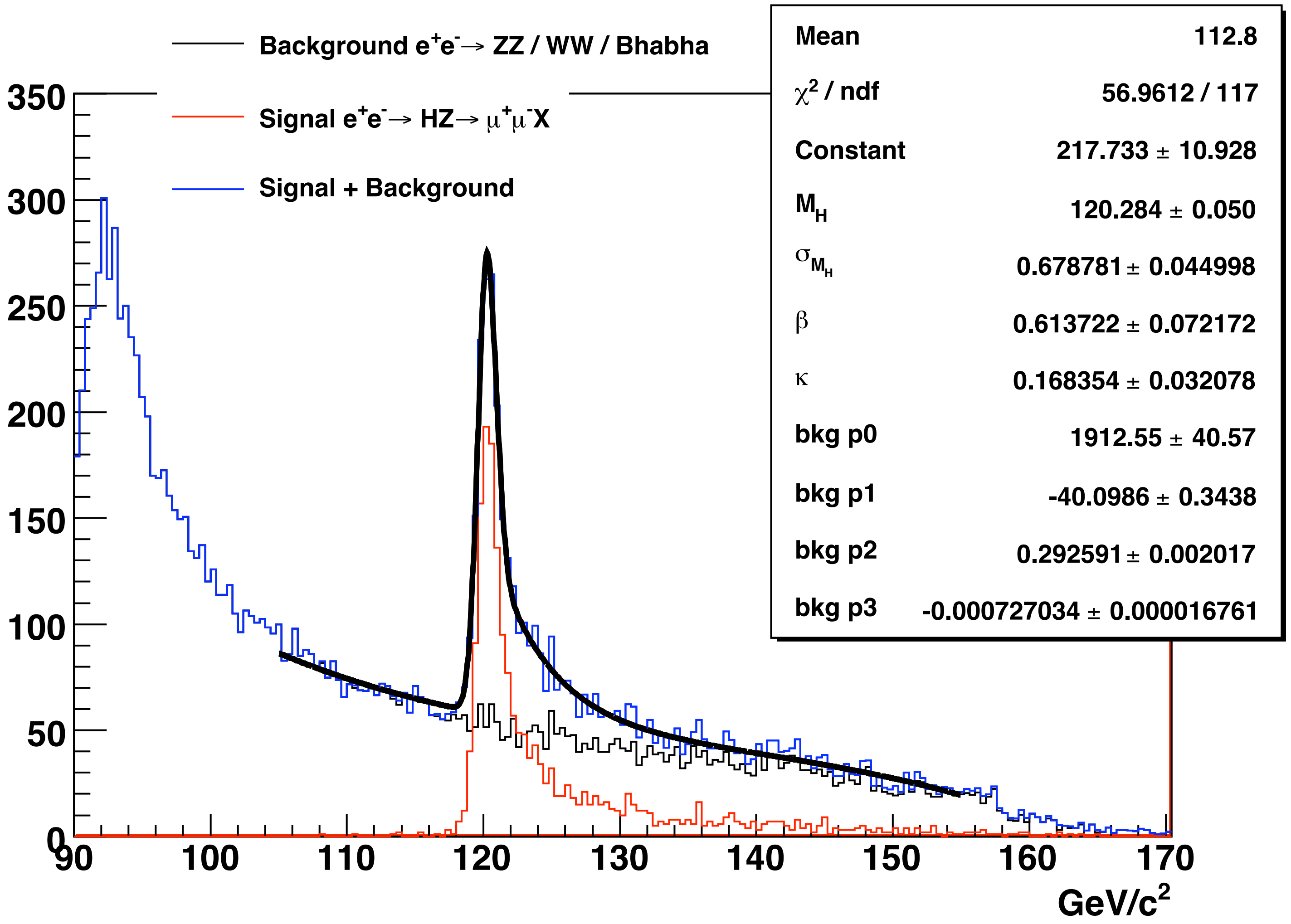


Fedor Ignatov (Budker Institute, Novosibirsk)

Flagship physics process: putative Higgs production

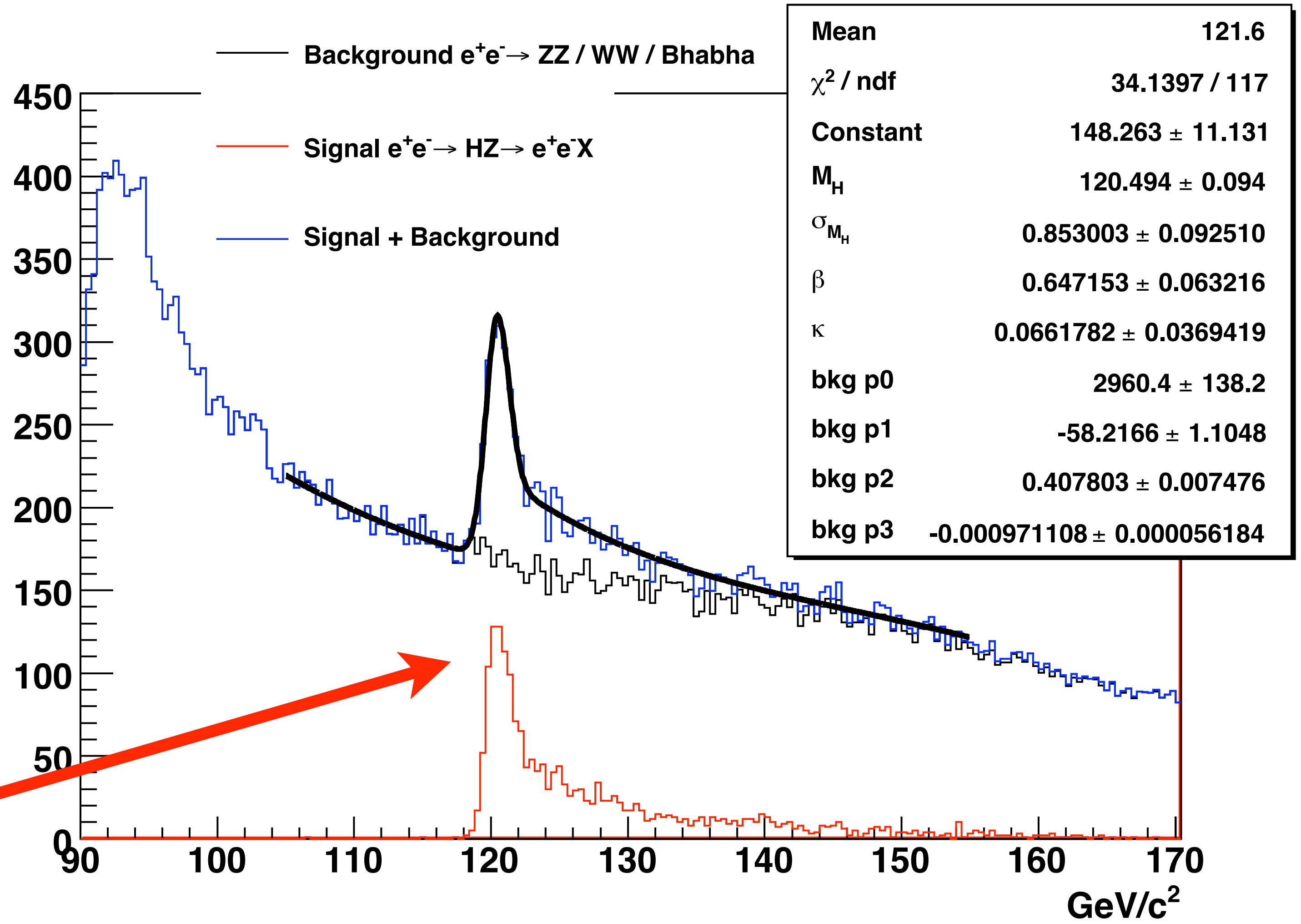
$$e^+e^- \to Z^0H^0 \to \ell^+\ell^- X \text{ at } \sqrt{s} = 250 \text{ GeV}$$

$\mu^+\mu^-$



Mass of X →

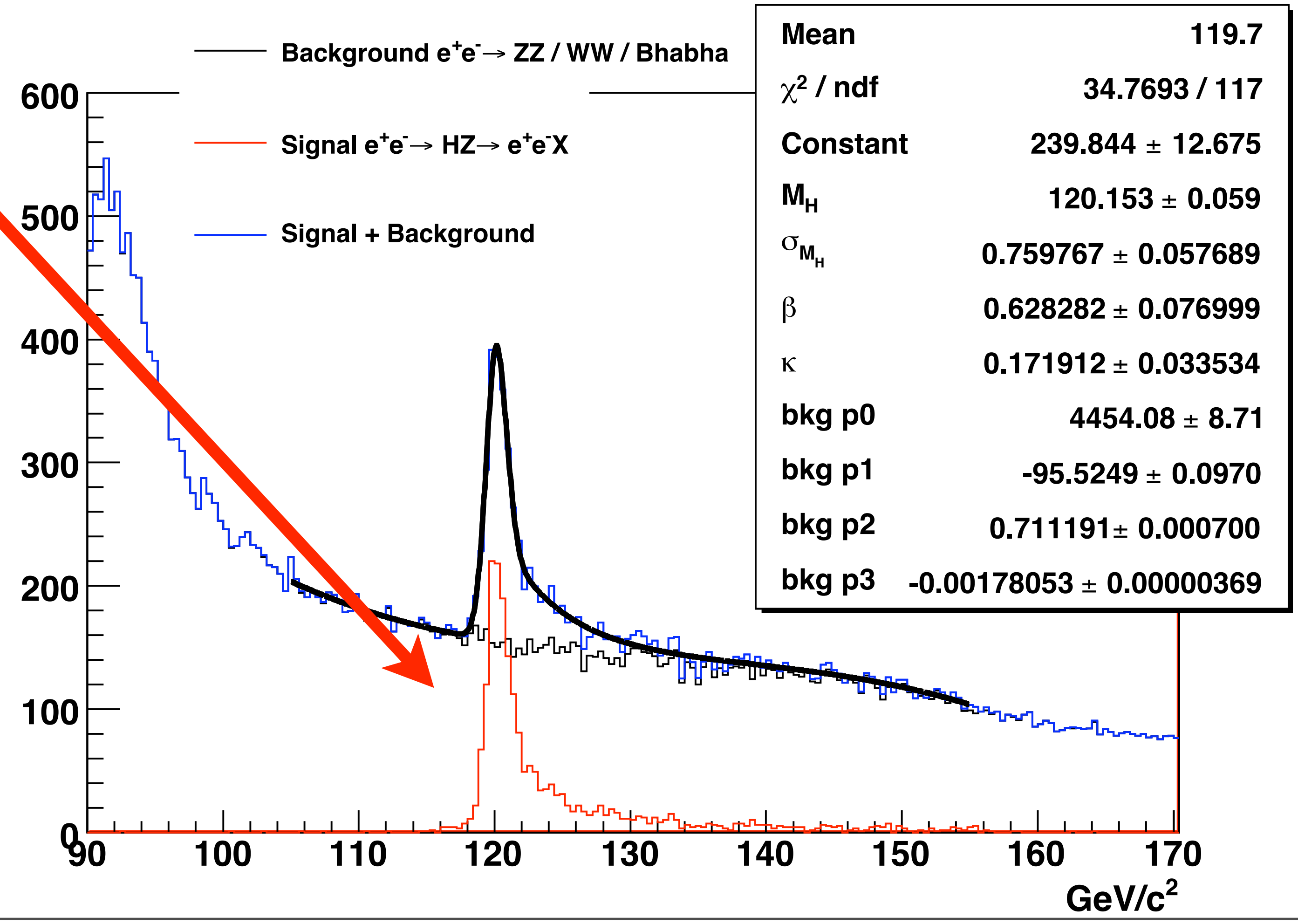
e^+e^-
(using tracking only)



Mean	121.6
χ^2 / ndf	34.1397 / 117
Constant	148.263 ± 11.131
M_H	120.494 ± 0.094
σ_{M_H}	0.853003 ± 0.092510
β	0.647153 ± 0.063216
κ	0.0661782 ± 0.0369419
bkg p0	2960.4 ± 138.2
bkg p1	-58.2166 ± 1.1048
bkg p2	0.407803 ± 0.007476
bkg p3	-0.000971108 ± 0.000056184

Crystal Calor improvement

e^+e^-
(tracking and calorimetry)



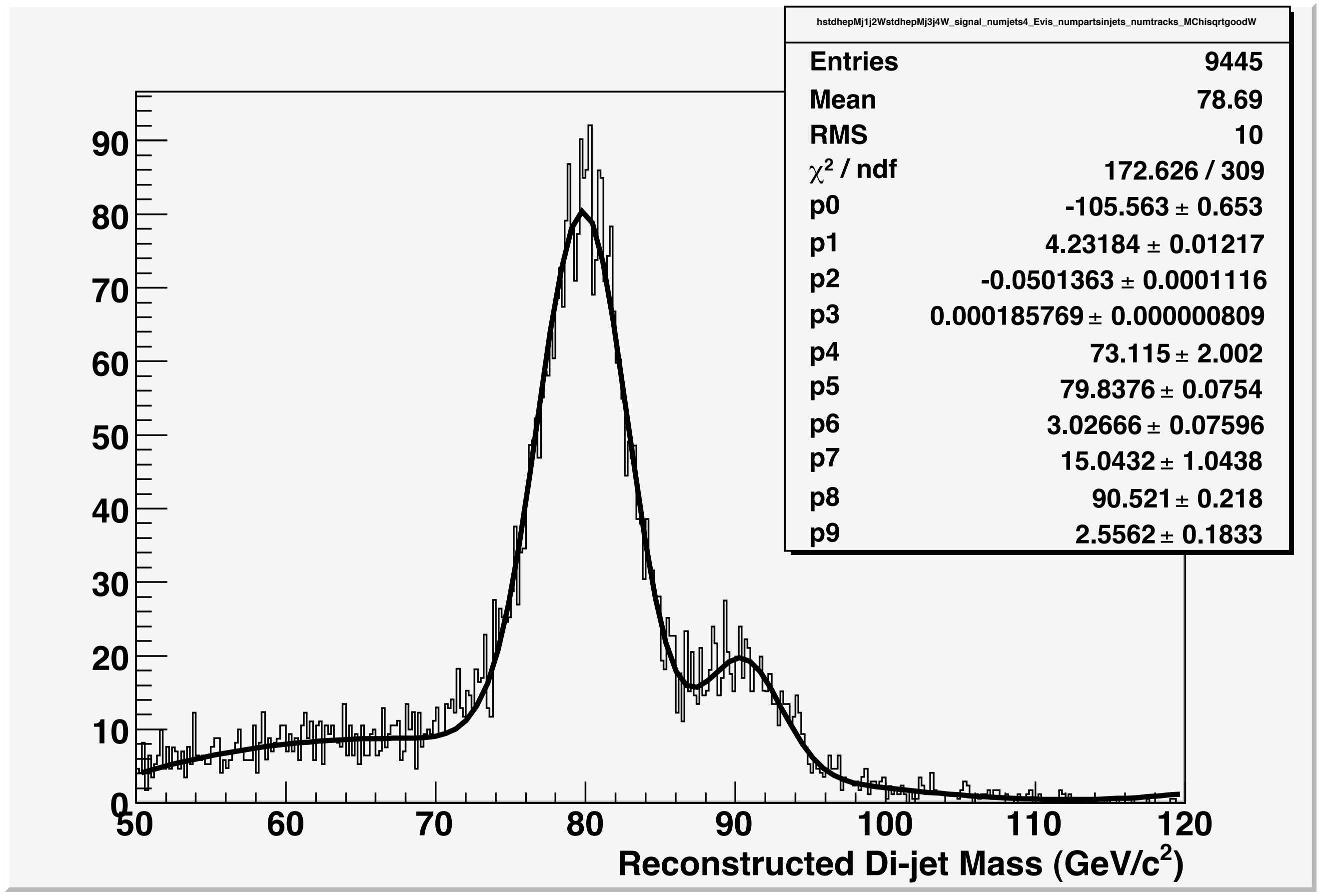
Mean	119.7
χ^2 / ndf	34.7693 / 117
Constant	239.844 ± 12.675
M_H	120.153 ± 0.059
σ_{M_H}	0.759767 ± 0.057689
β	0.628282 ± 0.076999
κ	0.171912 ± 0.033534
bkg p0	4454.08 ± 8.71
bkg p1	-95.5249 ± 0.0970
bkg p2	0.711191± 0.000700
bkg p3	-0.00178053 ± 0.00000369

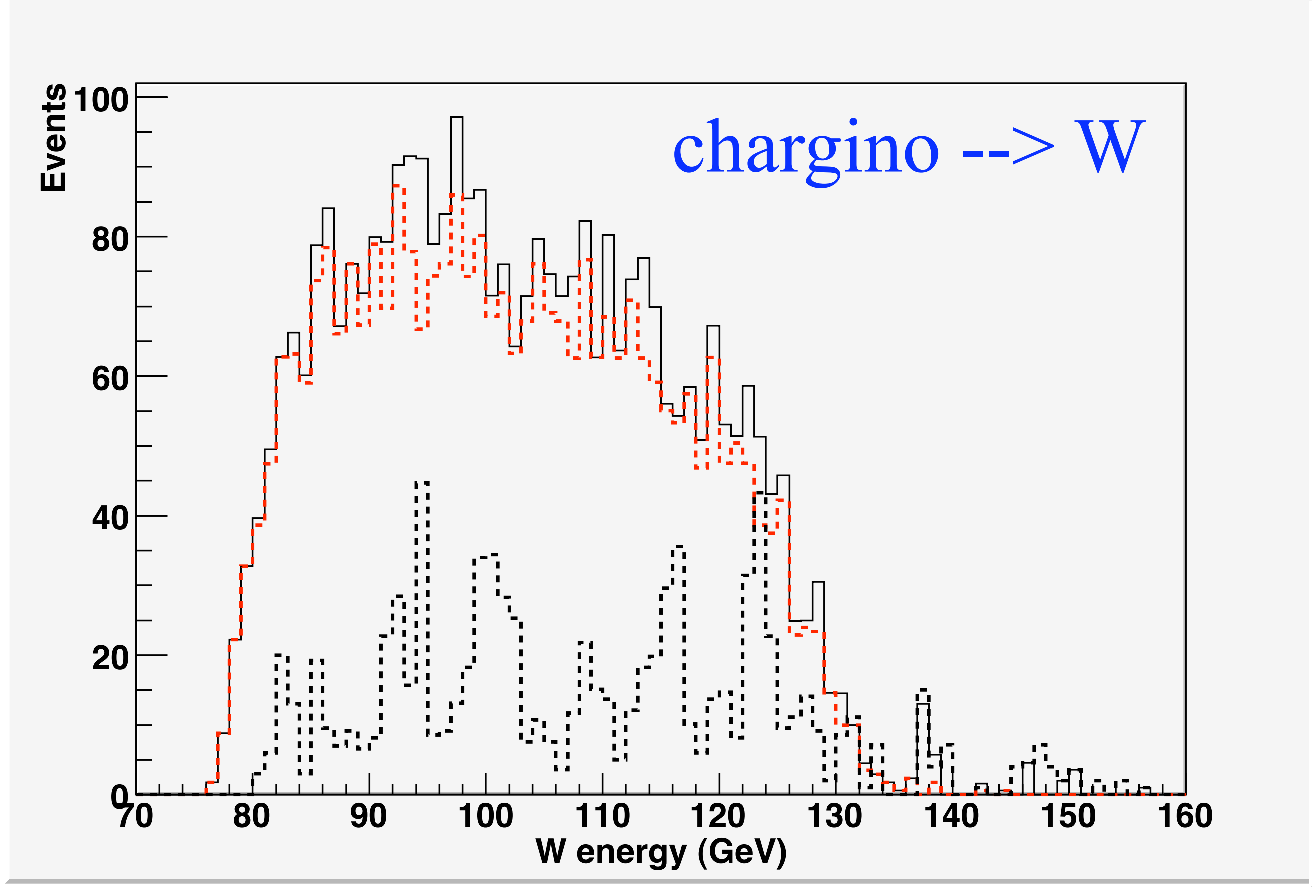
SUSY

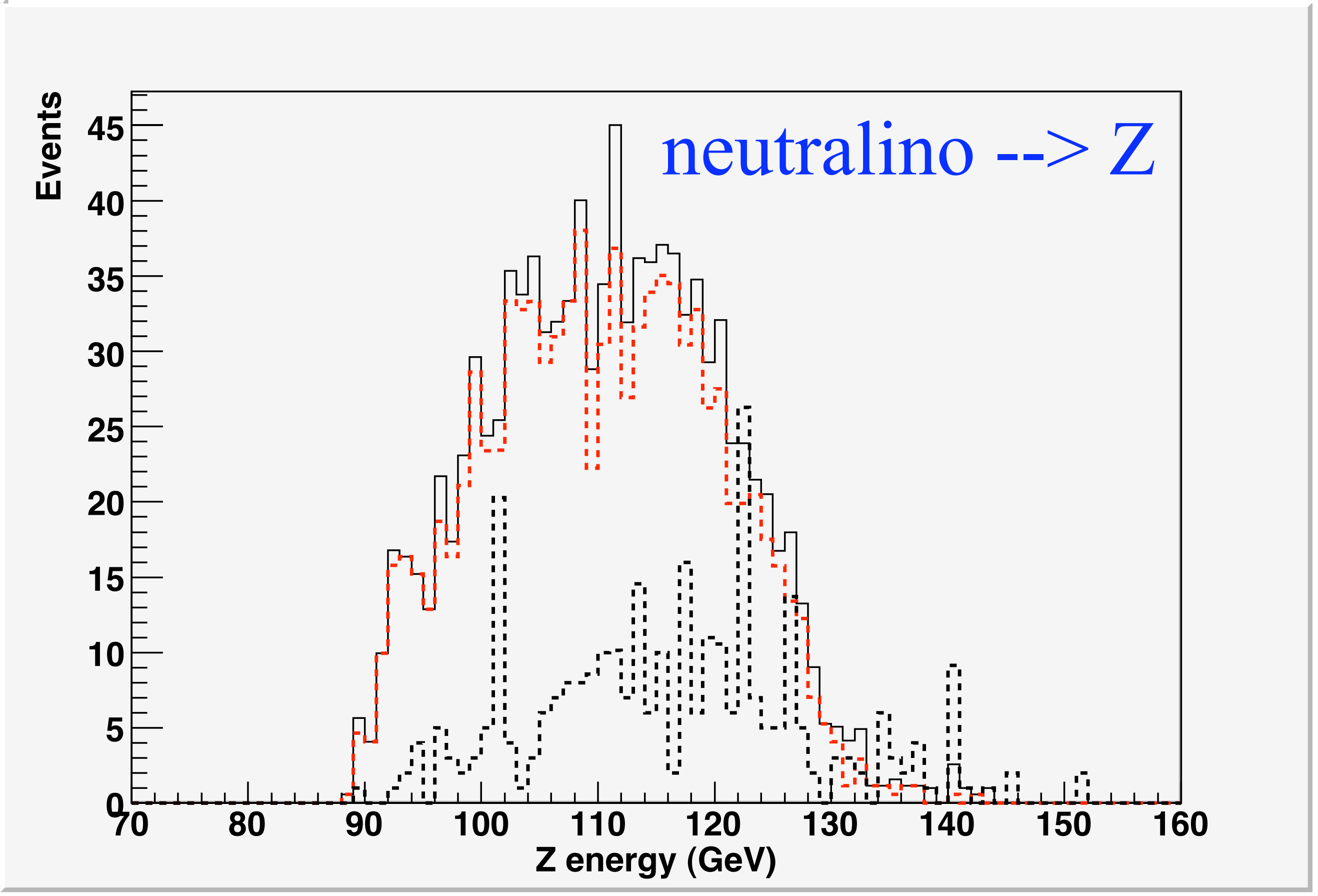
$$e^+e^- \rightarrow \chi_1^+\chi_1^- \rightarrow \chi_1^0\chi_1^0 W^+W^-$$

$$e^+e^- \rightarrow \chi_2^0\chi_2^0 \rightarrow \chi_1^0\chi_1^0 Z^0 Z^0$$

chargino mass resol = 2.8 GeV
neutralino mass resul = 2.5 GeV







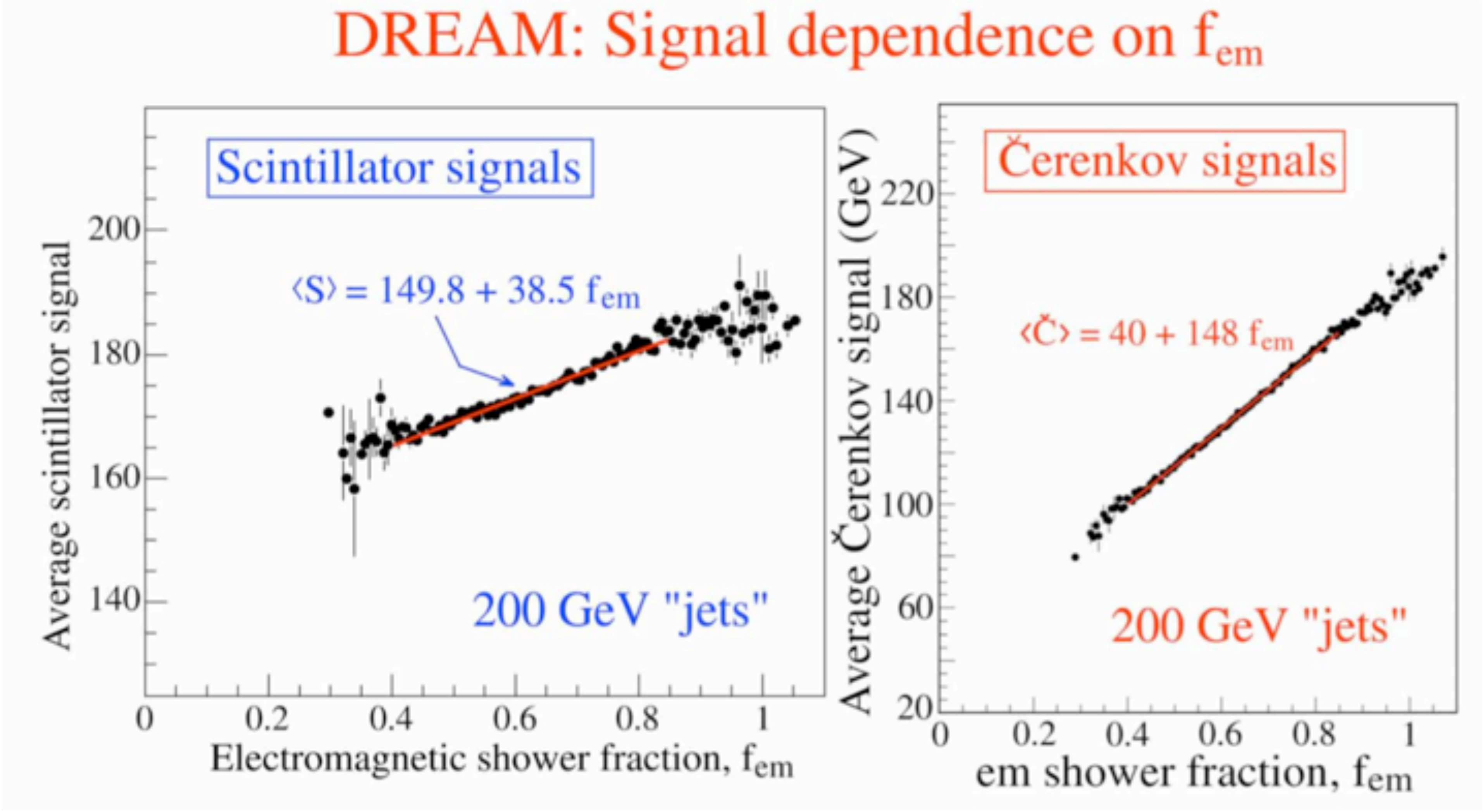
Summary:

“why we designed 4th calorimetry like this”

- we achieve 30%/√E resolution on jets
- we achieve L3-like resolution on EM objects
- we get time-of-flight at $\sigma \sim 0.3$ns for free from Ce fibers
- we get $\pi^0 \rightarrow \gamma\gamma$ from τ decay (for example)
- we get neutrons from time-history of Scint fibers
- we get a unique μ indentification
- we discriminate *e* and μ from π in multiple ways

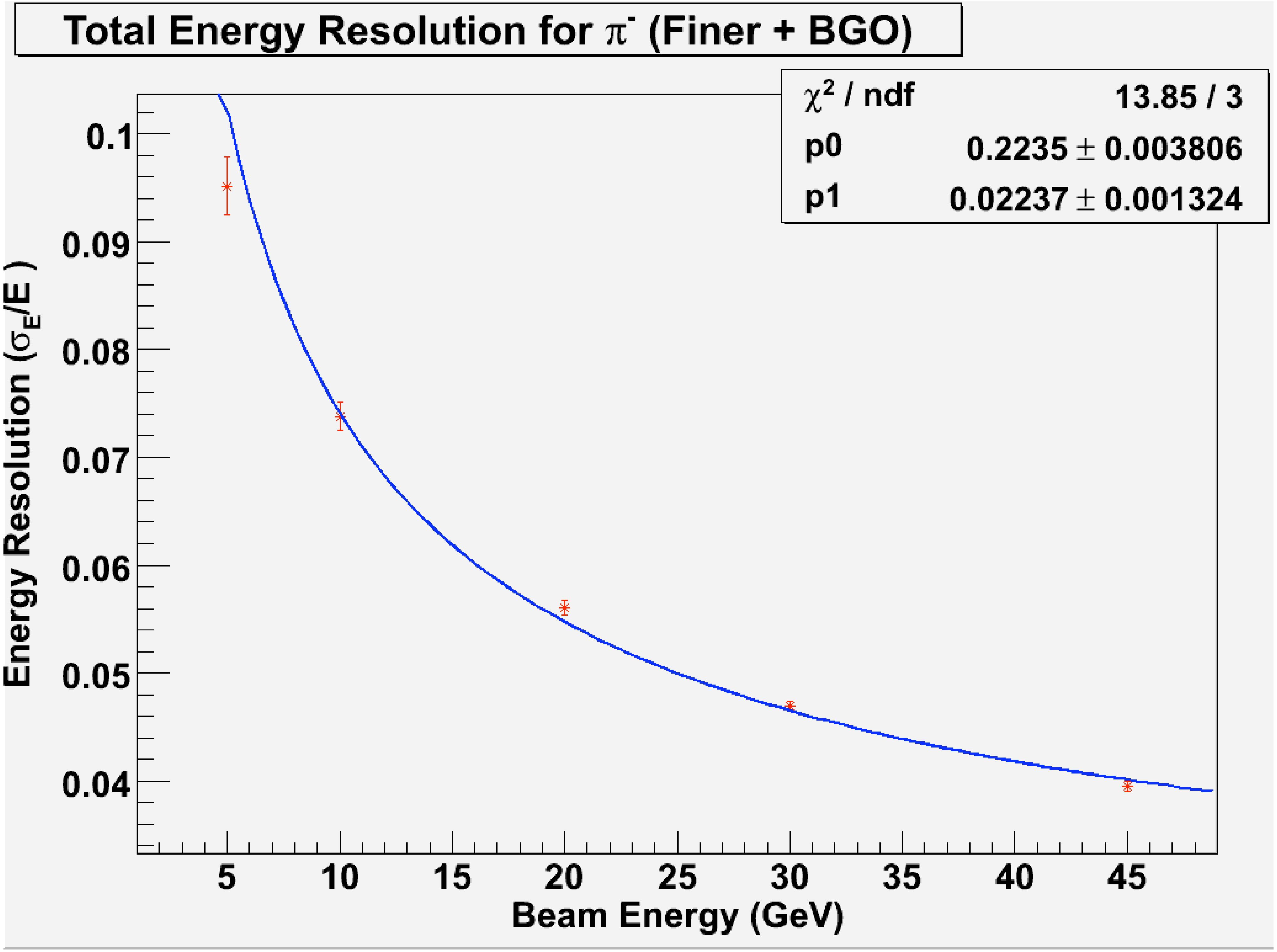
there are similar stories for tracking and magnetic field, but this is our calorimetry.

Spares



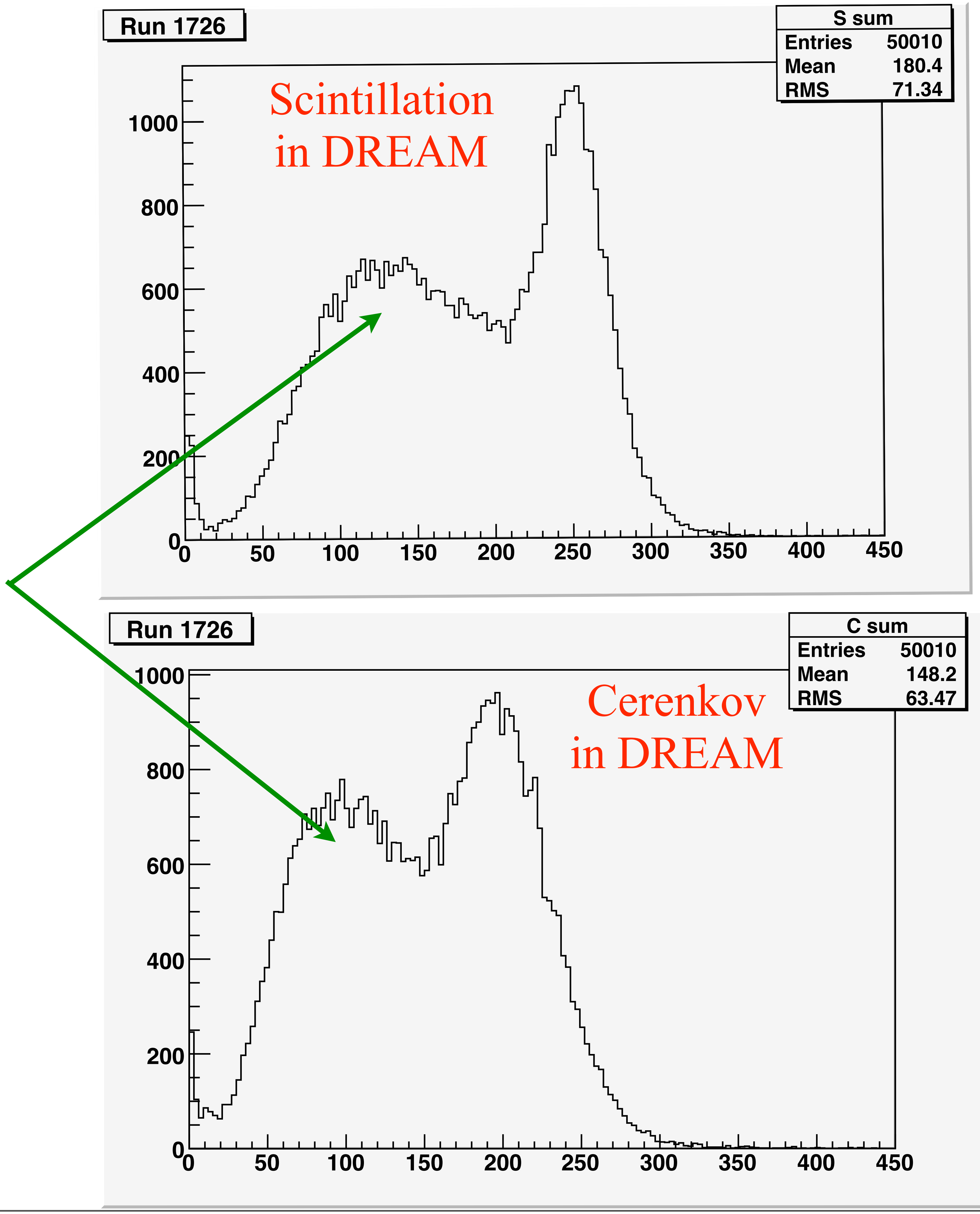
DREAM: Signal dependence on f_{em}

Simulated energy resolution for negative pions (in 4th configuration) of BGO+fiber



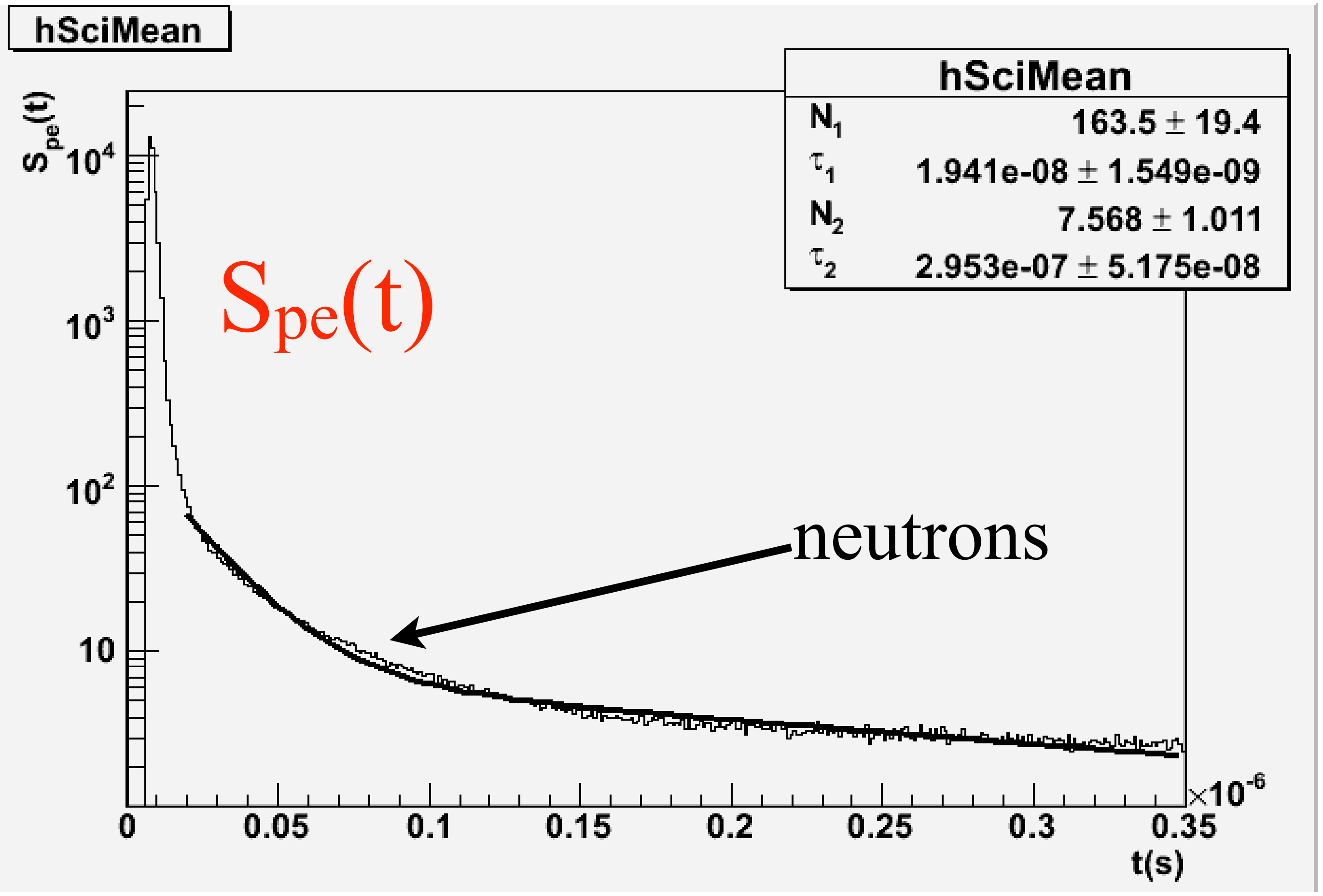
The BGO+DREAM calorimeter is a complicated beast. In my opinion, we can still do better with the analysis.

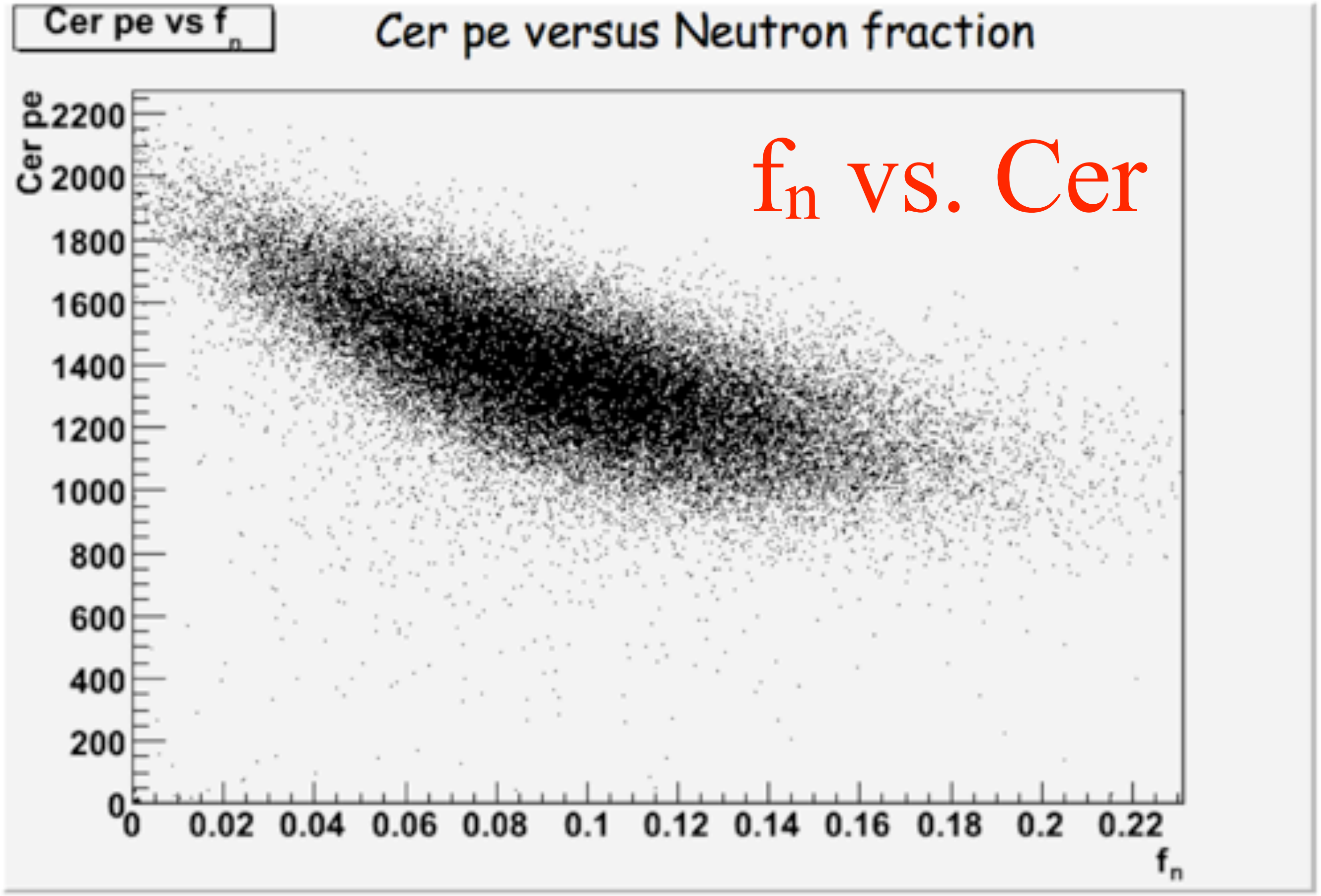
Pion interacted in BGO



In the 4th simulation, we do the same things:

I find good agreement, considering wide differences between 4th and the small DREAM module

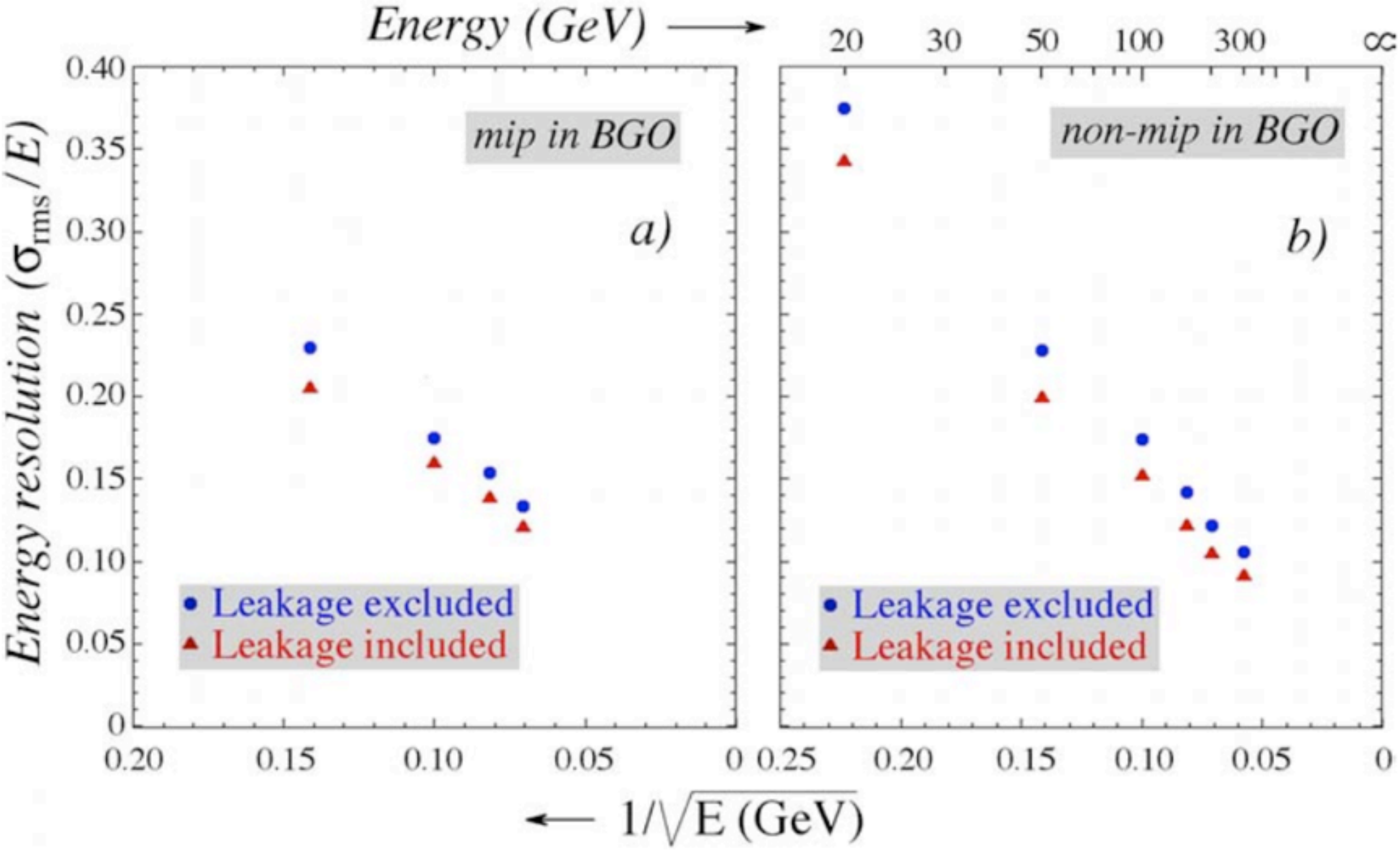




Leakage from DREAM

Energy resolution of DREAM module improved by 10-15% when leakage counters are included.

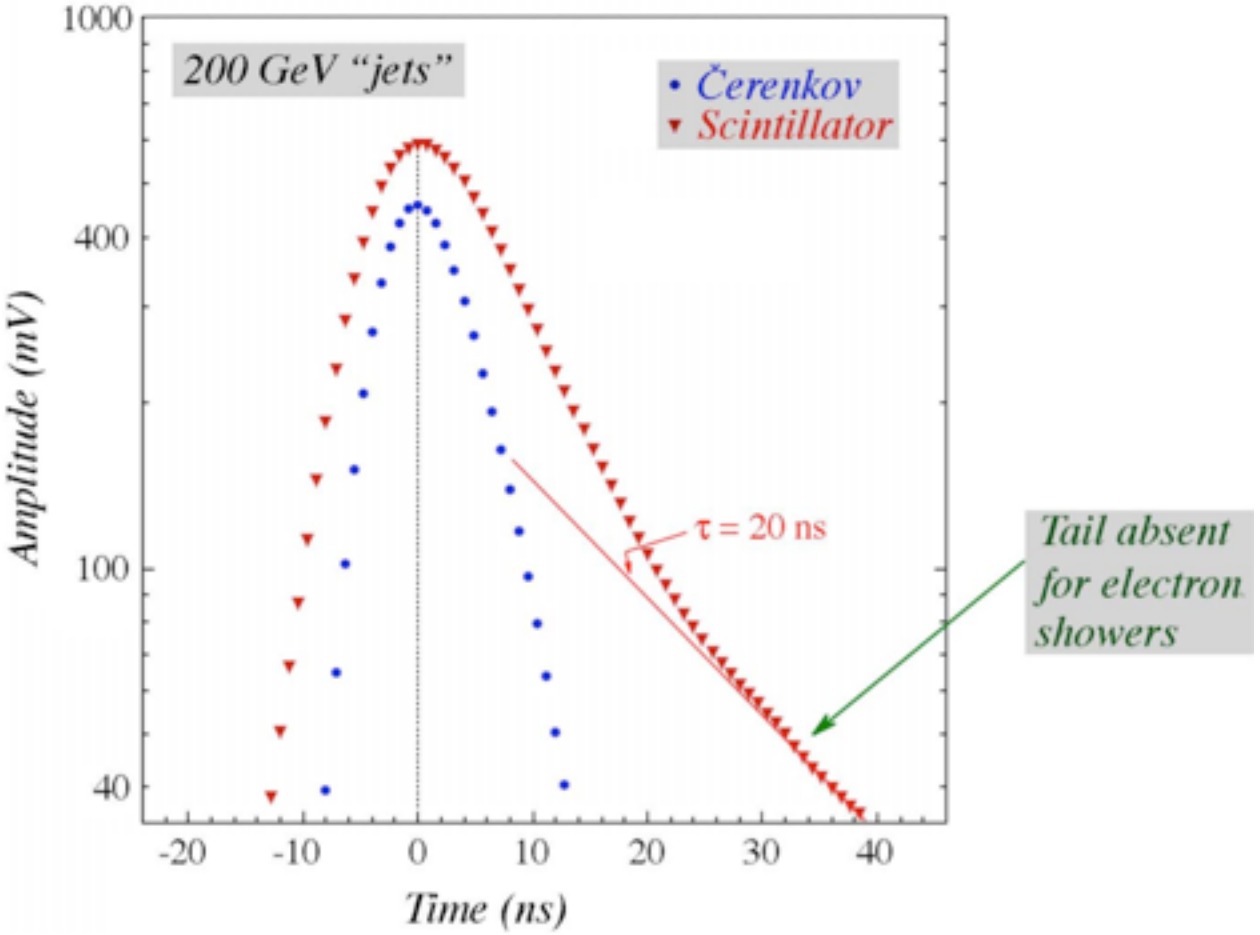
(these counters were very crude; try to do better next test)

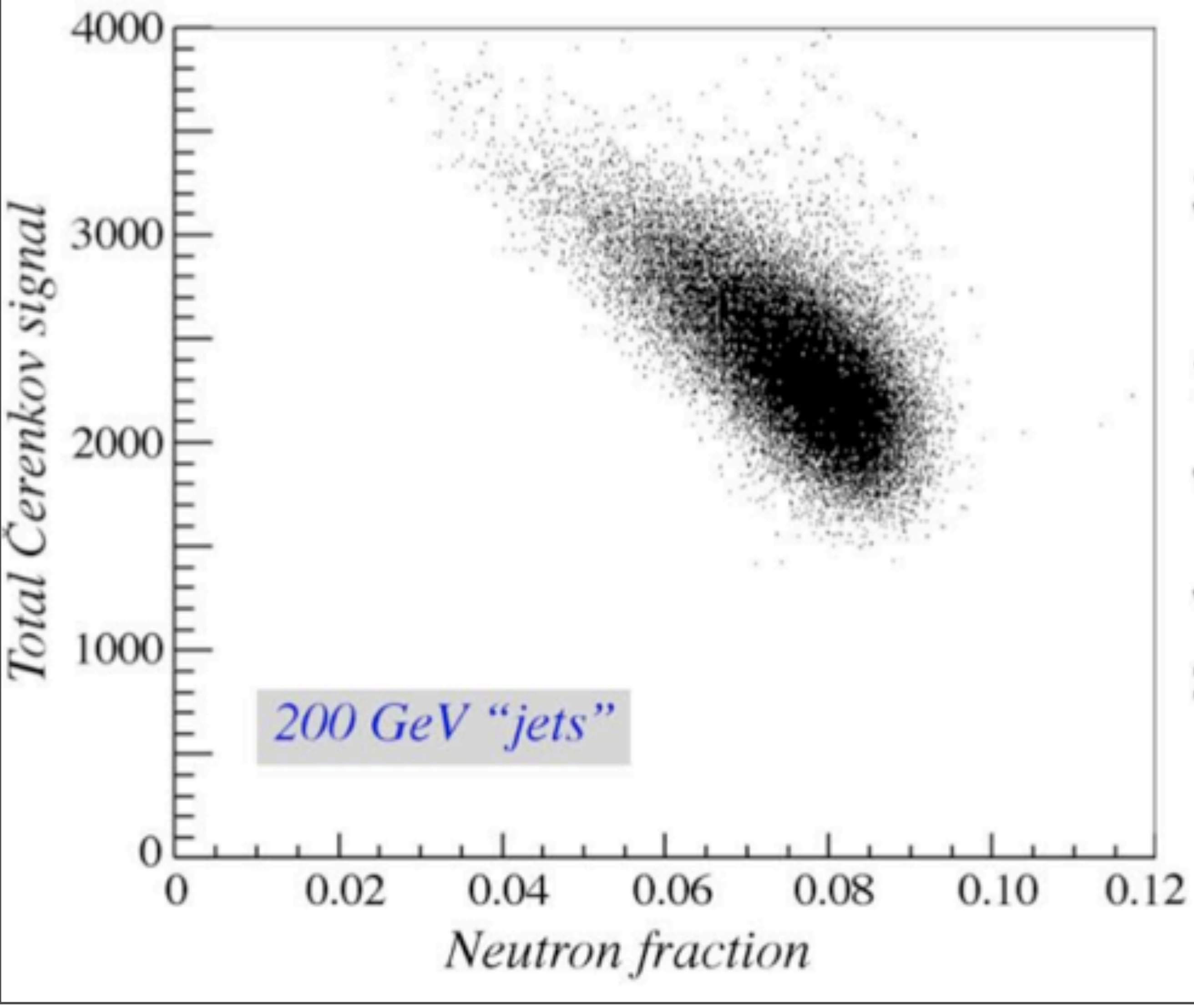


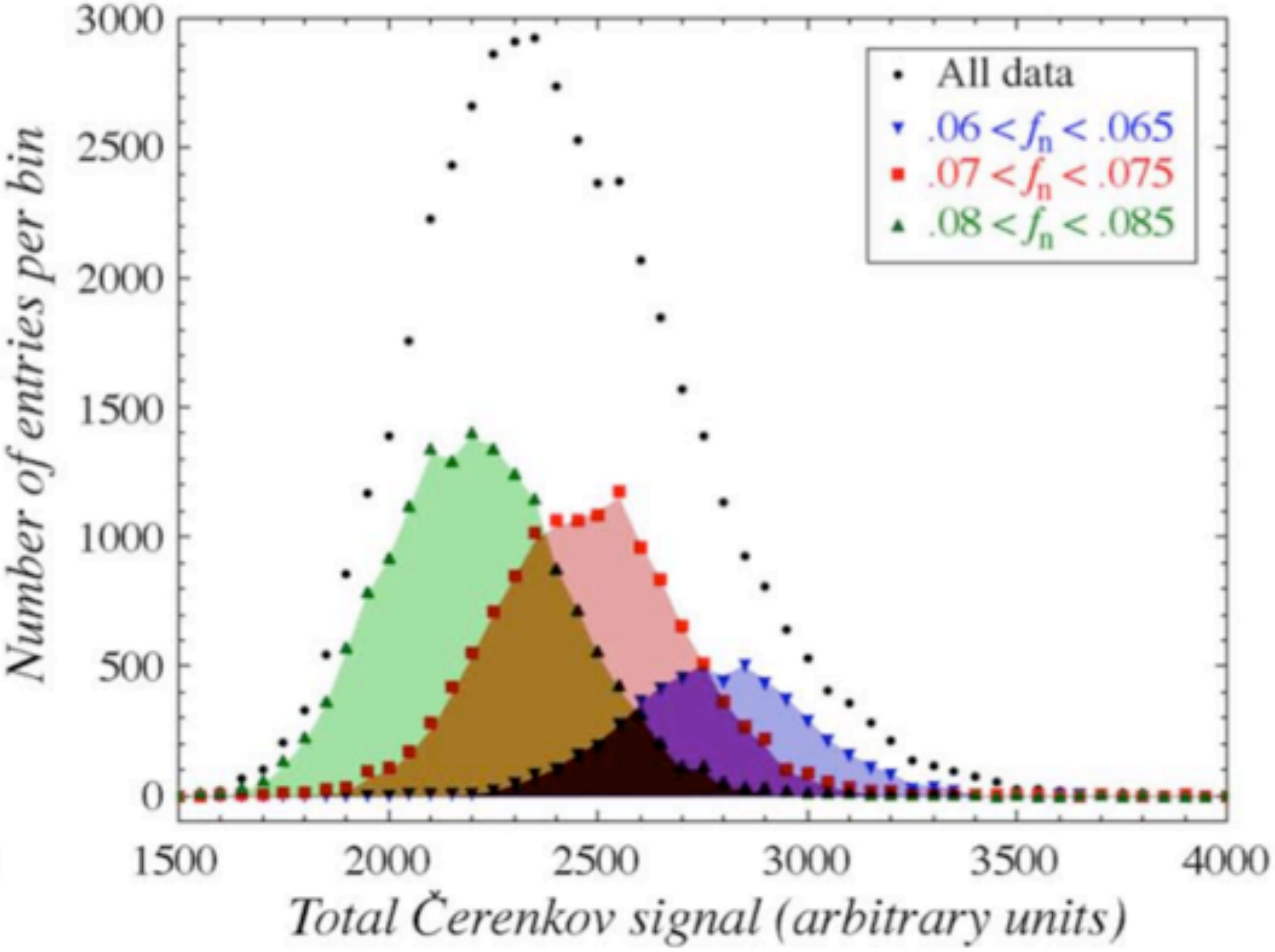
MeV neutrons

Neutron fraction, f_n, measured in scintillating fibers event-by-event:

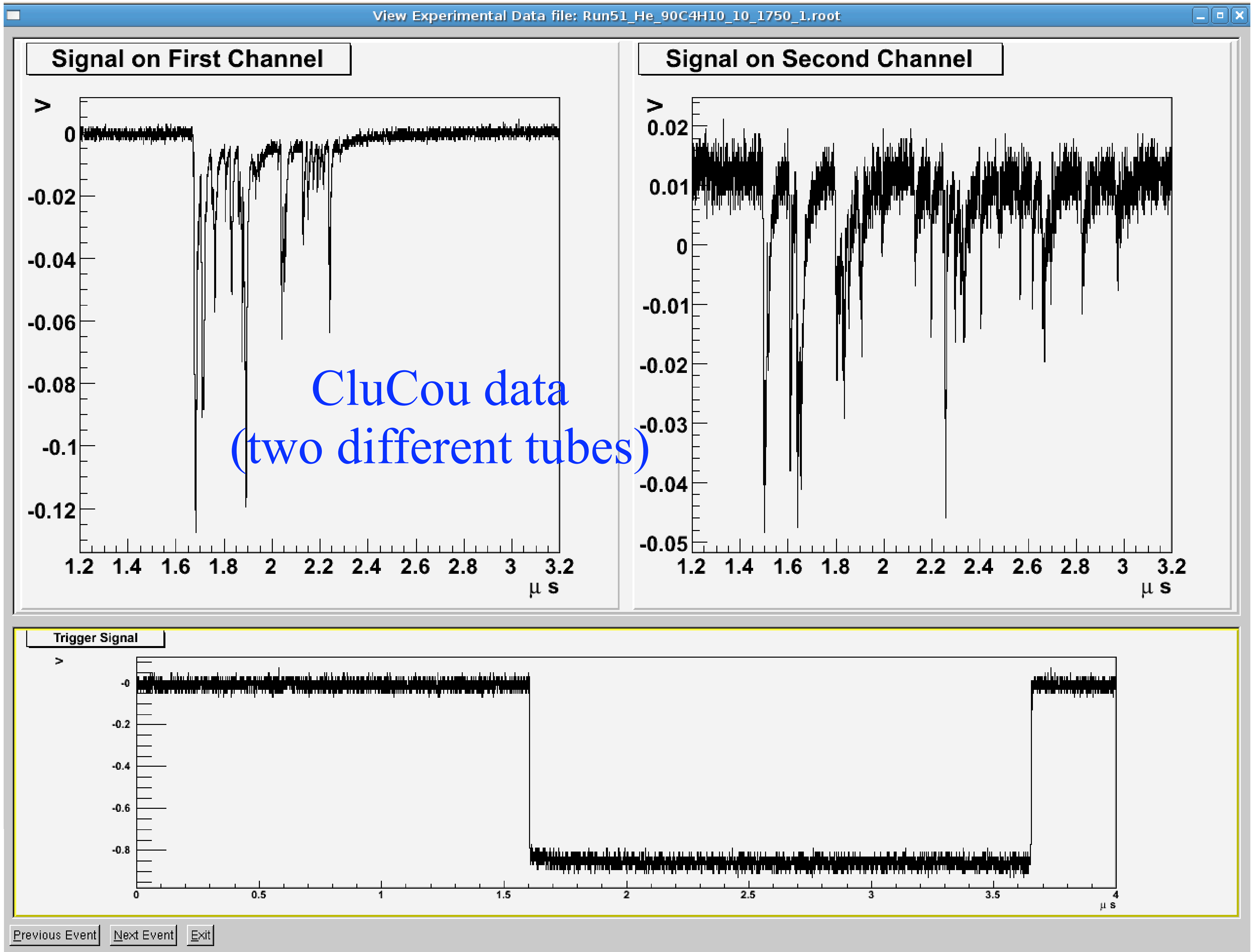
(1) improve energy resolution
(2) tag “hadronic” showers.



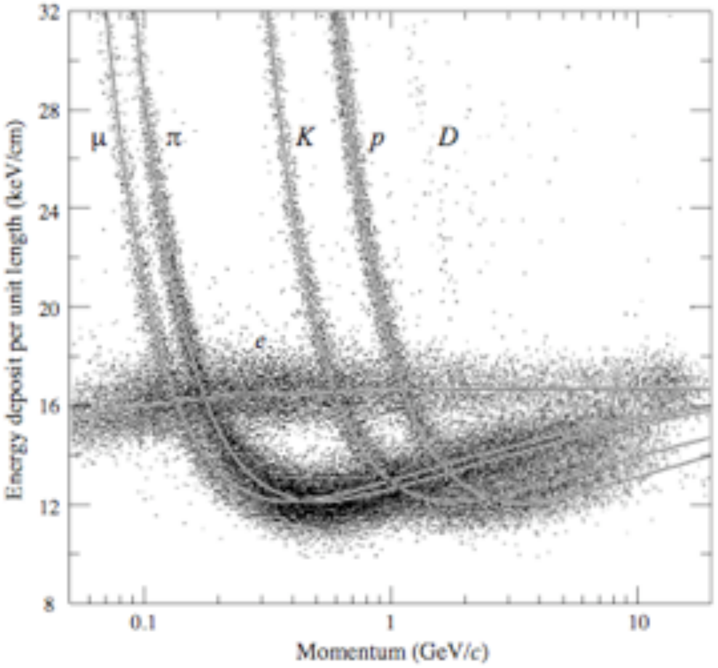




(vii) CluCou cluster-counting is Poisson: better *dE/dx* specific ionization resolution ~3% (no Landau tail)

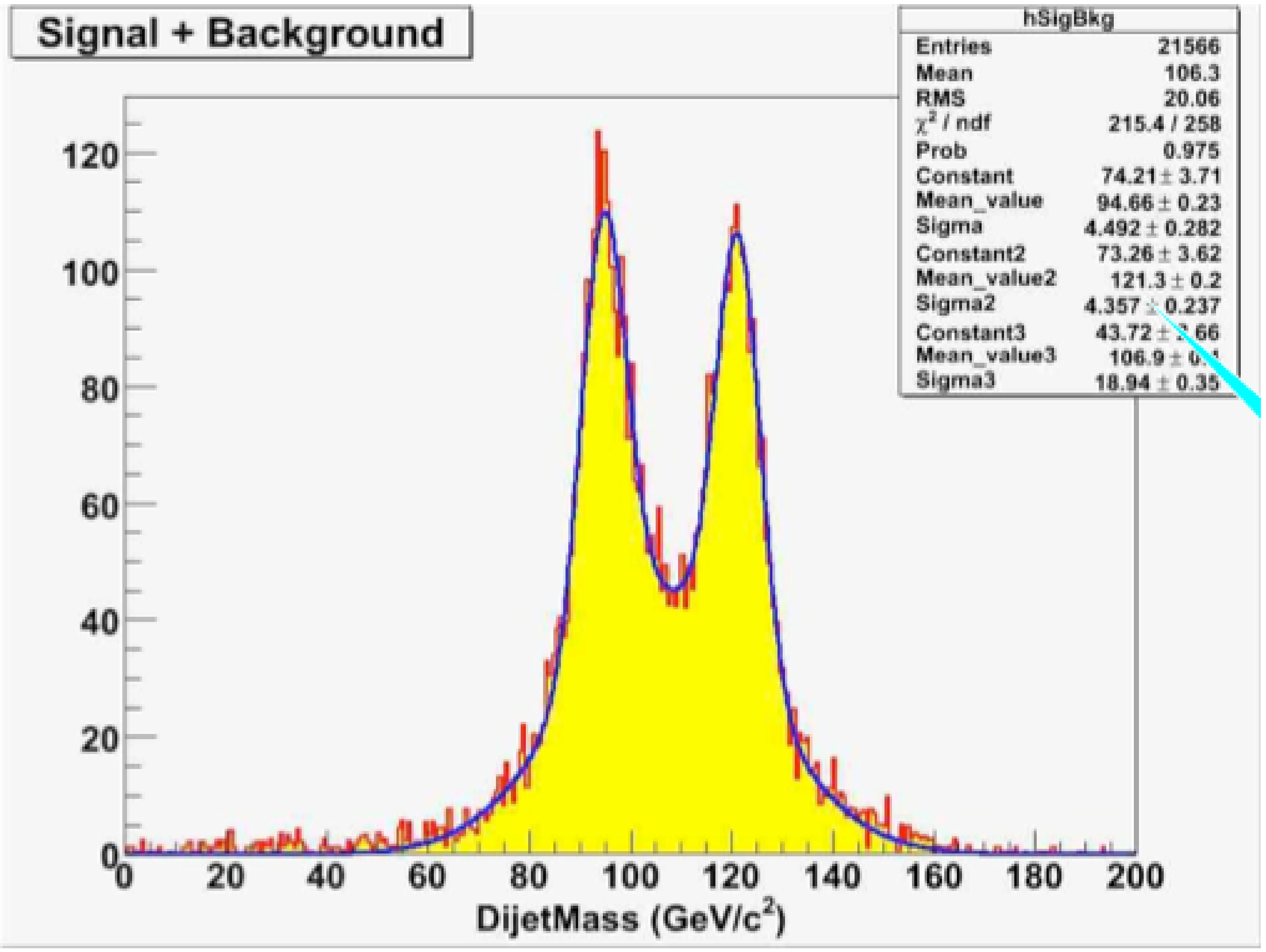


CluCou data
(two different tubes)

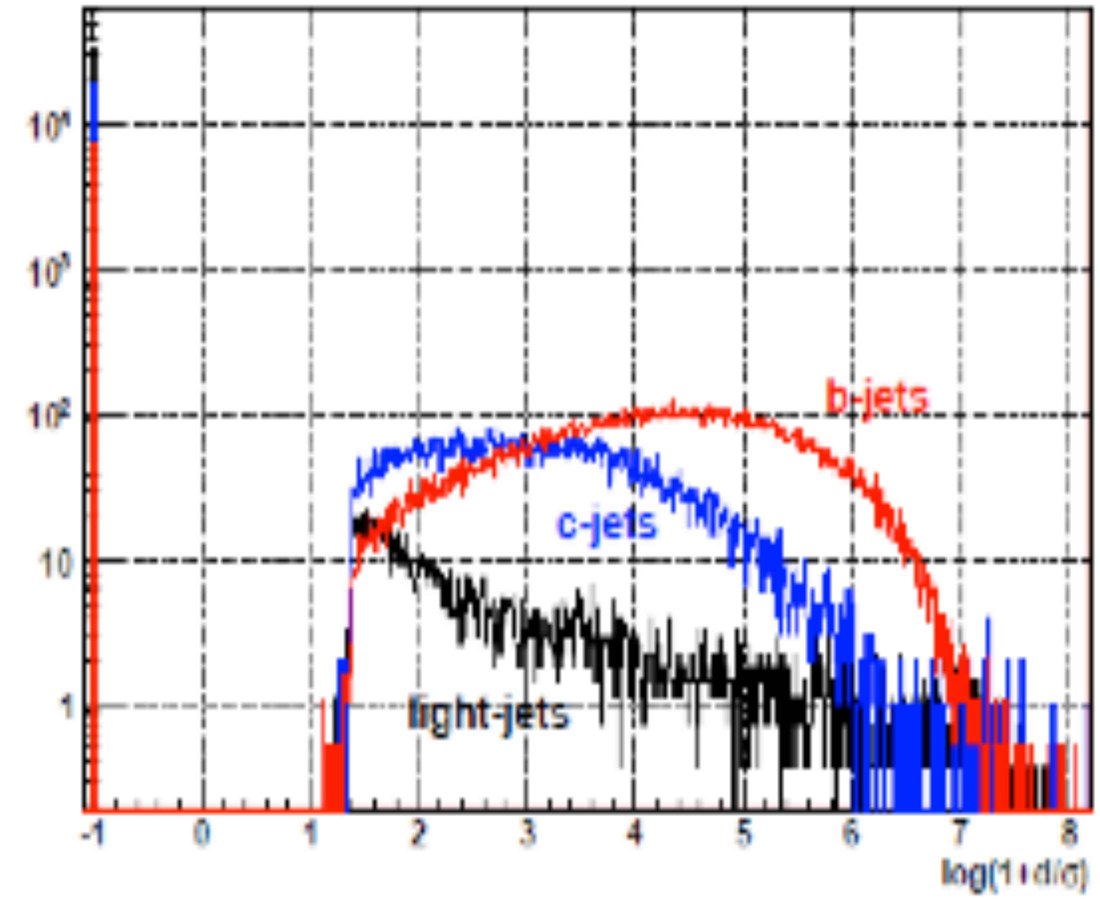


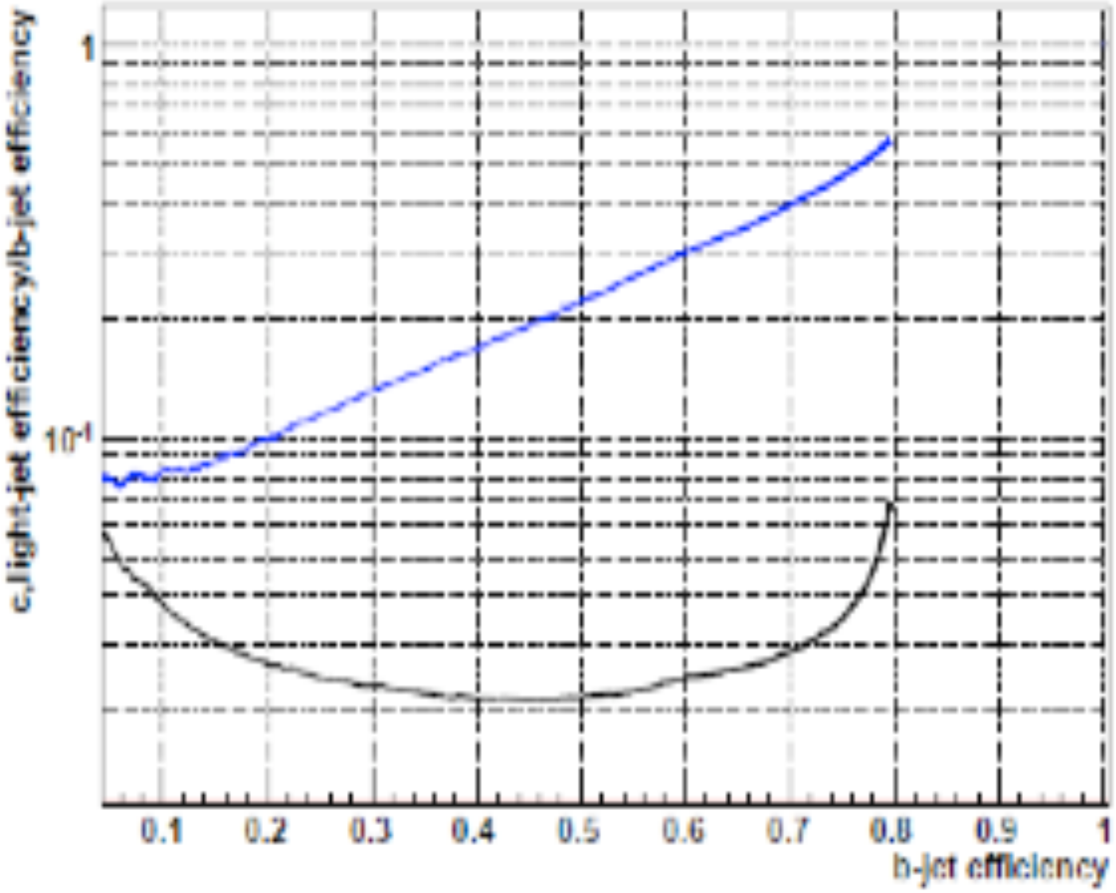
dE/dx resolution TPC LBL/PEP4
(using truncated mean ~6%)

(ix) Z --> jj mass resolution



(x) b,c quark tagging





BGO dual-readout from test beam
(calibrated on 10, 20, 30, 50, 100, 150, 200 GeV e-)