H and *t* Measurements at the ILC

Lederman, ~1970: hadron machines are broad band discovery engines.
A correct argument *against approving* SPEAR.
TG group, 1973-74: SPEAR group did not see the J/ψ for months

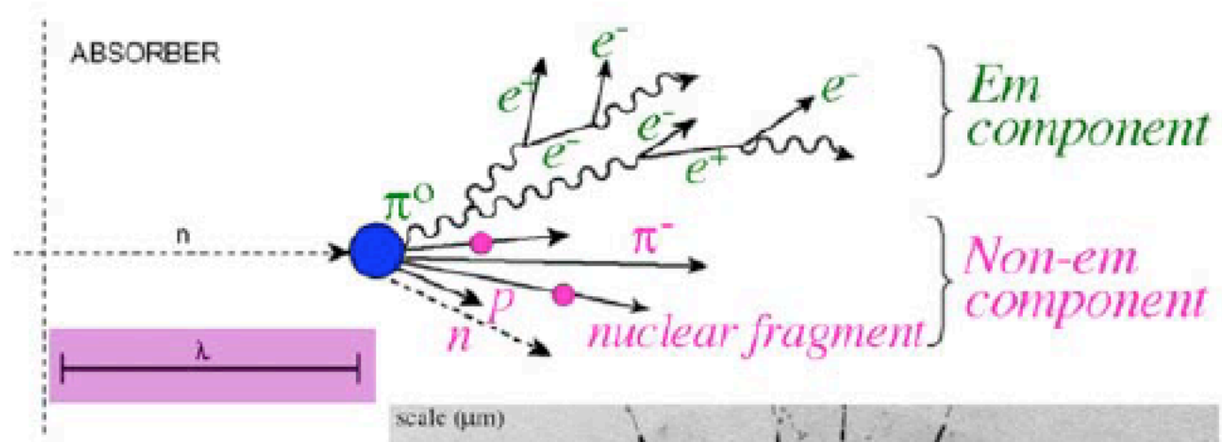
AGS	- J crude discovery	early 1974
SPEAR	- J/ψ precision meas's	late 1974
SppS	- *W, Z* crude discovery	1983
LEP	- *Z* precision measurements	1990
Tevatron	- *t* crude discovery	1995
LHC	- *H* crude discovery	2012
ILC	- *t,H* precision measurements	~2025

Compared to the already excellent LEP and SLC detectors, the ILC detectors must be
- better by a factor of 2 in hadronic calorimetry,
- better by a factor of 10 in tracking momentum resolution, and
- better by a factor of 10 in vertex definition and impact parameter resolution.

Hadronic calorimetry: factor of 2 better than LEP/SLC detectors

$\sigma/E \sim 60\% / \sqrt{E} \rightarrow 30\% / \sqrt{E}$ possible with dual-readout

DREAM (RD52) at CERN: measure the electromagnetic fraction, f_{EM}, and the neutron fraction, $f_{neutron}$, event-by-event, in a fiber calorimeter. Why?



→ Cerenkov light

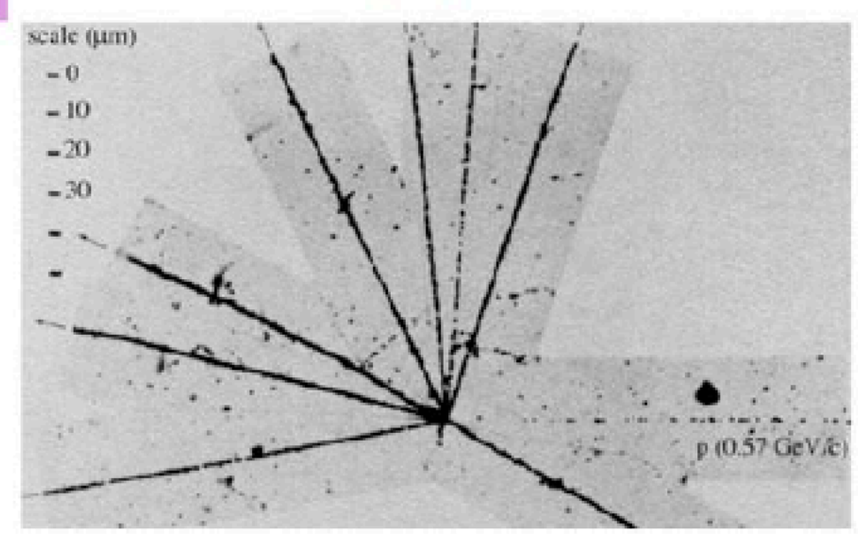
→ Scint. light

Electromagnetic component

- electrons, photons
- neutral pions → 2 γ

Hadronic (non-em) component

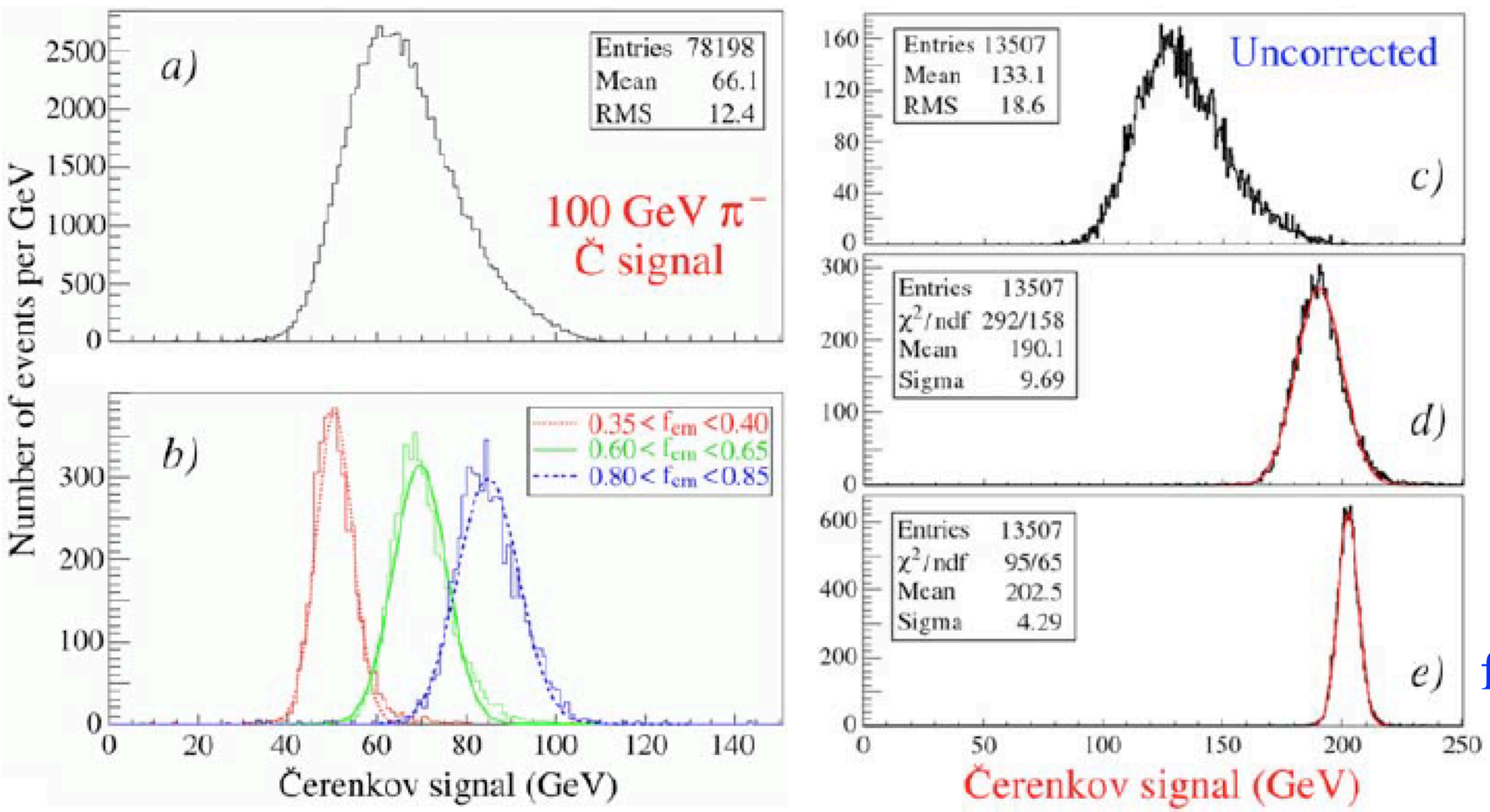
- charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
- nuclear fragments, p (25%)
- neutrons, soft γ's (15%)
- break-up of nuclei (*"invisible"*) (40%)



$$S = E\,[\; f_{EM} + (1 - f_{EM})\,\eta_S \;] \qquad \eta_S = (h/e)_S \sim 0.7$$

$$C = E\,[\; f_{EM} + (1 - f_{EM})\,\eta_C \;] \qquad \eta_C = (h/e)_C \sim 0.2$$

$$E = \frac{S - \chi C}{1 - \chi} \qquad \chi = \frac{1 - \eta_S}{1 - \eta_C} \qquad f_{EM} \sim C/E_{\text{shower}}$$



$f_{EM} \sim C/E_{beam}$

Tracking: factor of 10 better than LEP/SLC detectors

$\sigma/p^2 \sim$ few x 10^{-4} $(GeV/c)^{-1}$ $\rightarrow$ few x 10^{-5} $(GeV/c)^{-1}$ possible with …

Si strips	(SiD detector)	5 layers, $\sigma \sim 5\mu m$ per layer, but power pulsed at 5Hz in a 5T field
digital TPC	(ILD detector)	250 pts, 100μm per point, 3-dim pattern recognition, but massive end caps and positive ion loading
cluster-timing He-gas (4th)		150 pts, 50μm per point, particle ID by ~ *dN/dx,* ultra-low mass, but occupancy problems

My prejudice about tracking systems is that they all look good in a beam test, and all fail in different ways from different backgrounds, e.g., in high-rate environments.

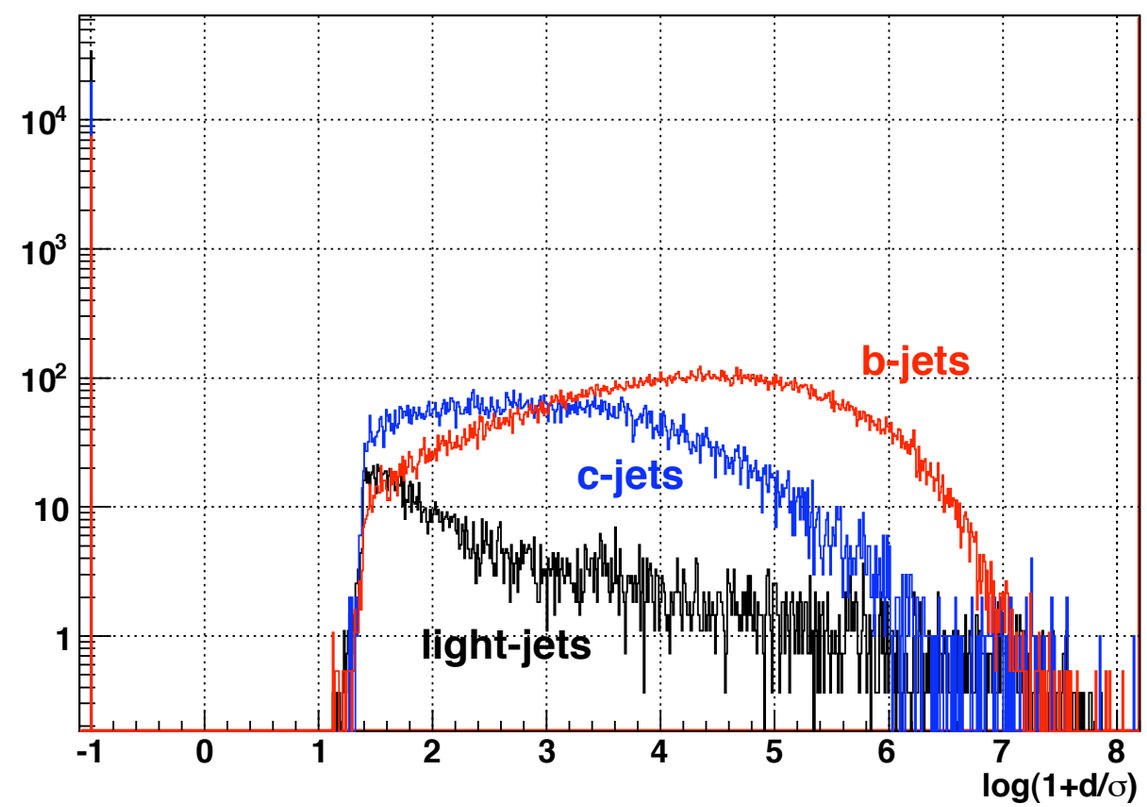
- 5-layer Si strips will have trouble catching Λ^0 and K^0 decays; the Lorentz forces during power pulsing may break bump bonds and induce mechanical harmonics.
- The TPC has a lot of mass and the positive ions (without an excellent gating grid) will flow back into the volume as sheets of charge, generating a radial E field.
- The He-gas drift chamber will have pile-up problems at high rates and low radius.

Vertex chamber: factor of 10 better impact parameter, *b*, resolution

$\sigma_b \sim 5\mu m \oplus 10\mu m / p \sin^{2/3}\theta \oplus 10\mu m / \sqrt{p}$ possible with 20μm x 20μm pixels

Several technologies are available, under intensive R&D (see Chris Damerell)

The distributions of the "impact parameter significance" - d/σ - with +1 added for display reasons, is shown for *b, c,* and *uds* jets.



Premium on precision, keep away from beams (2cm inner radius for 5T), low mass; must aid main tracker, must be stable, have low heat loading, etc.

“Benchmark processes” to assess detectors

The “benchmark” processes were chosen to stress different aspects of the detectors. The top reconstruction stressed hadronic calorimetry and jet reconstruction, and this Higgs problem stressed the tracking system precision.

$$e^+e^- \to Z^0H^0 \to e^+e^-X, \mu^+\mu^-X, \quad \sqrt{s} = 250 \text{ GeV}$$

$$e^+e^- \to Z^0H^0 \to \nu\nu X, \quad \sqrt{s} = 250 \text{ GeV}$$

$$e^+e^- \to Z^0H^0 \to Z^0 \to q\bar{q}, H^0 \to c\bar{c}, \quad \sqrt{s} = 250 \text{ GeV}$$

$$e^+e^- \to t\bar{t} \to W^+bW^-\bar{b} \to q\bar{q}bq\bar{q}\bar{b}, \quad \sqrt{s} = 500 \text{ GeV}$$

$$e^+e^- \to \tau^+\tau^-, \quad \sqrt{s} = 500 \text{ GeV}$$

$$e^+e^- \to \chi^+\chi^-/\chi_2^0\chi_2^0, \quad \sqrt{s} = 500 \text{ GeV}$$

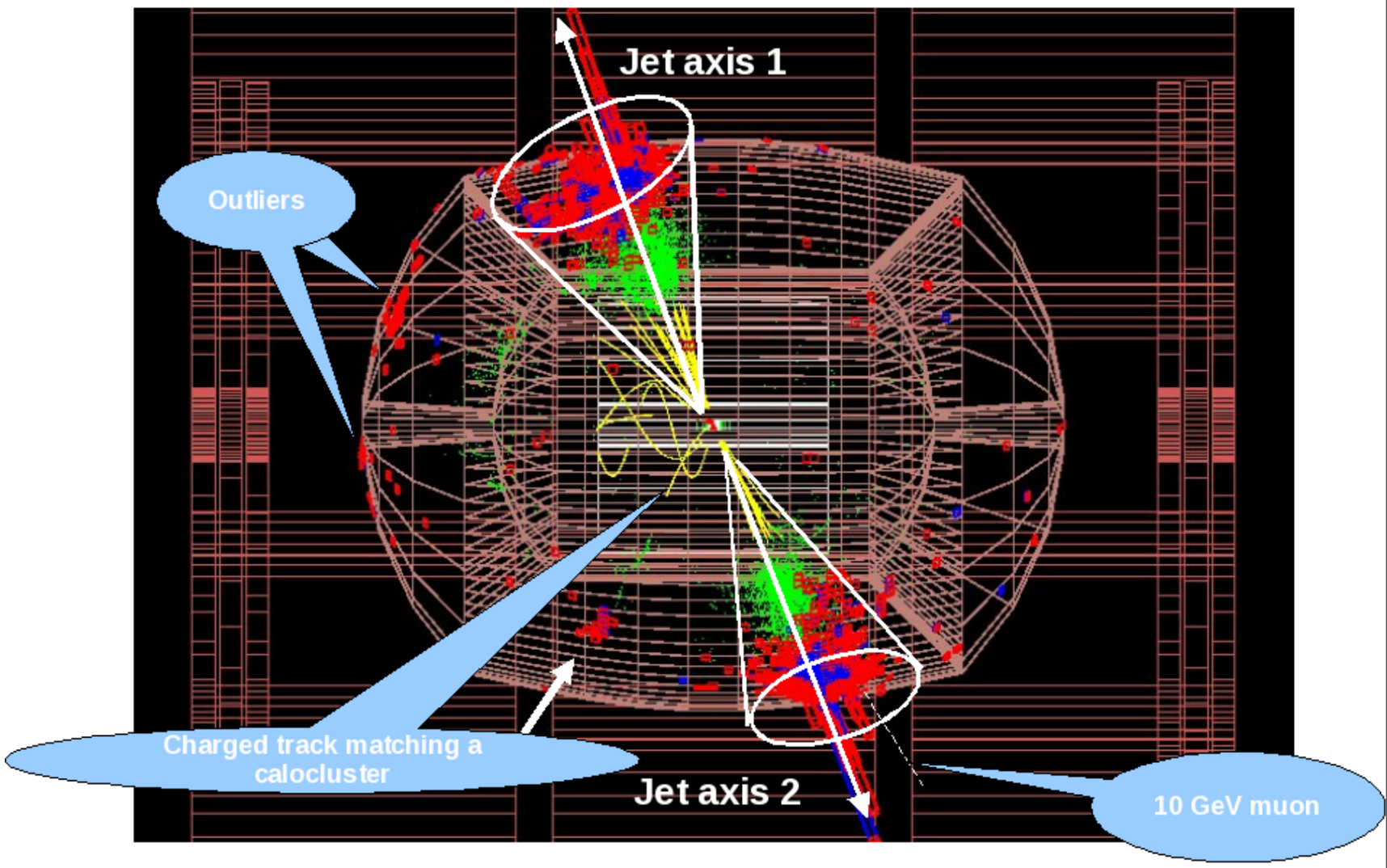
$$e^+e^- \to W^+W^-\nu\nu \quad \text{and} \quad Z^0Z^0\nu\nu$$

Top quark reconstruction in the 6-jet channel

$$e^+e^- \to t\bar{t} \to W^+bW^-\bar{b} \to 6\ jets \qquad \text{(bdu,bdu) \& (bsc,bsc)}$$

This excellent analysis by Fedor Ignatov, Budker Institute

- sample size: 63,283 events
- E_{CM} = 500 GeV
  L = 215 fb^{-1}
  M_t = 174 GeV
- include *4-jet* events (*csdu, cssc* scaled to L as background
- reconstruct jets (example of strategy with 2 jets)



- force 6 jets in each event by adjusting y_{cut}

- sort the 6 jets into two groups of 3 jets, while requiring that 2 of the 3 form a mass near the W mass. Best combination chosen by a combinatorial χ^2 test.

- do a full 7c kinematic fit:
  energy-momentum (4c)
  $M_{W1} = M_{W2} = 80.4$ GeV (2c)
  $M_t - M_{tbar} = 0$ (1c)

- in the end, choose best fit χ^2

- plot fitted M_t

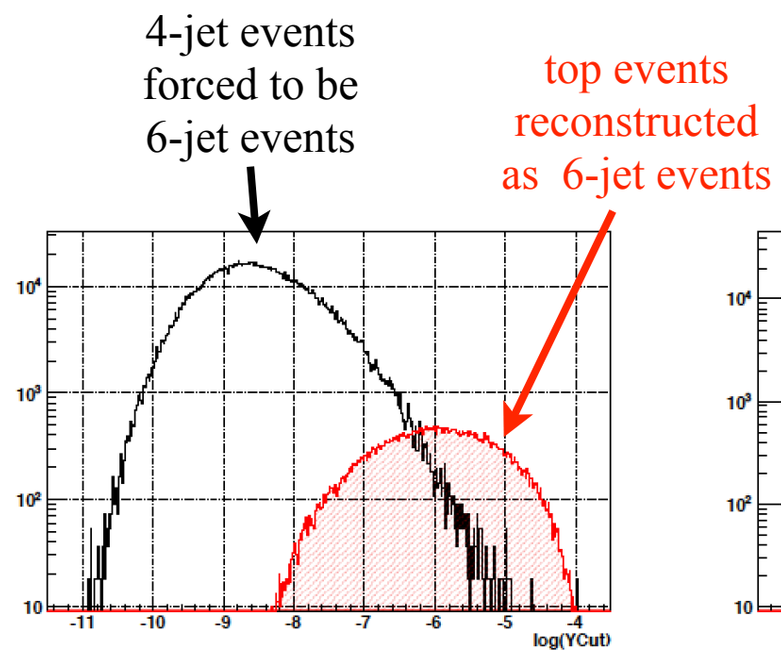


Figure 1: Distributions of log($ycut$) for signal events (filled area) and for SM 4-jets background

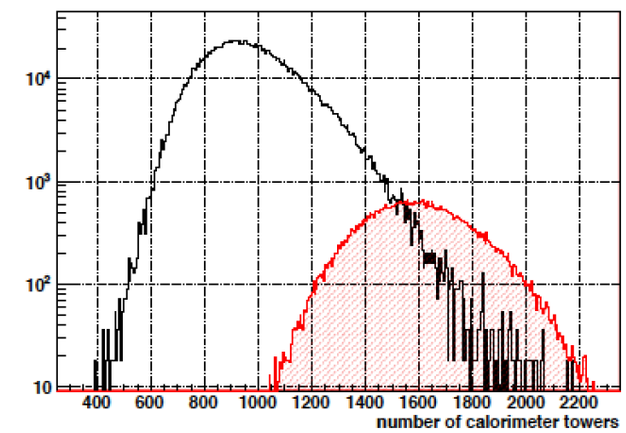


Figure 2: Distributions of number of calorimeter towers for signal events (filled area) and for SM 4-jets background

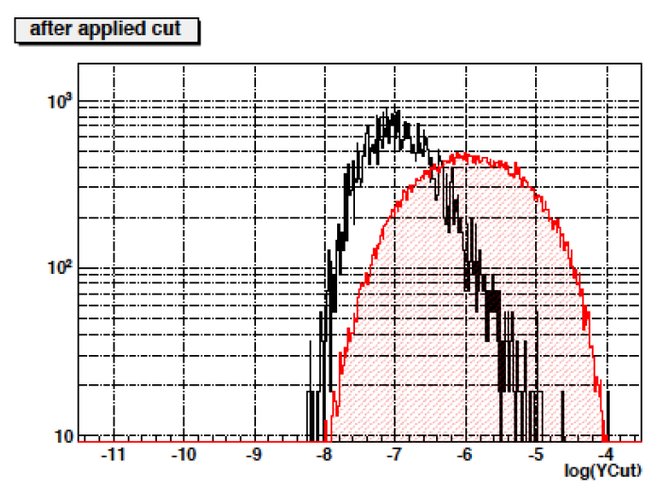


Figure 3: Distributions of log($ycut$) for signal events (filled area) and for SM 4-jets background after applied topological cut

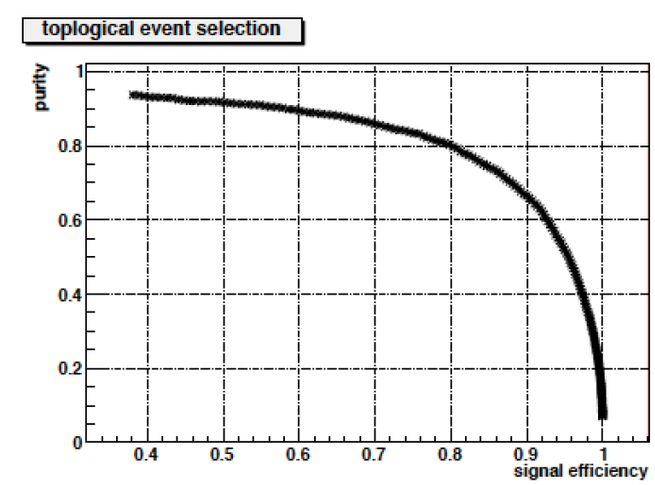
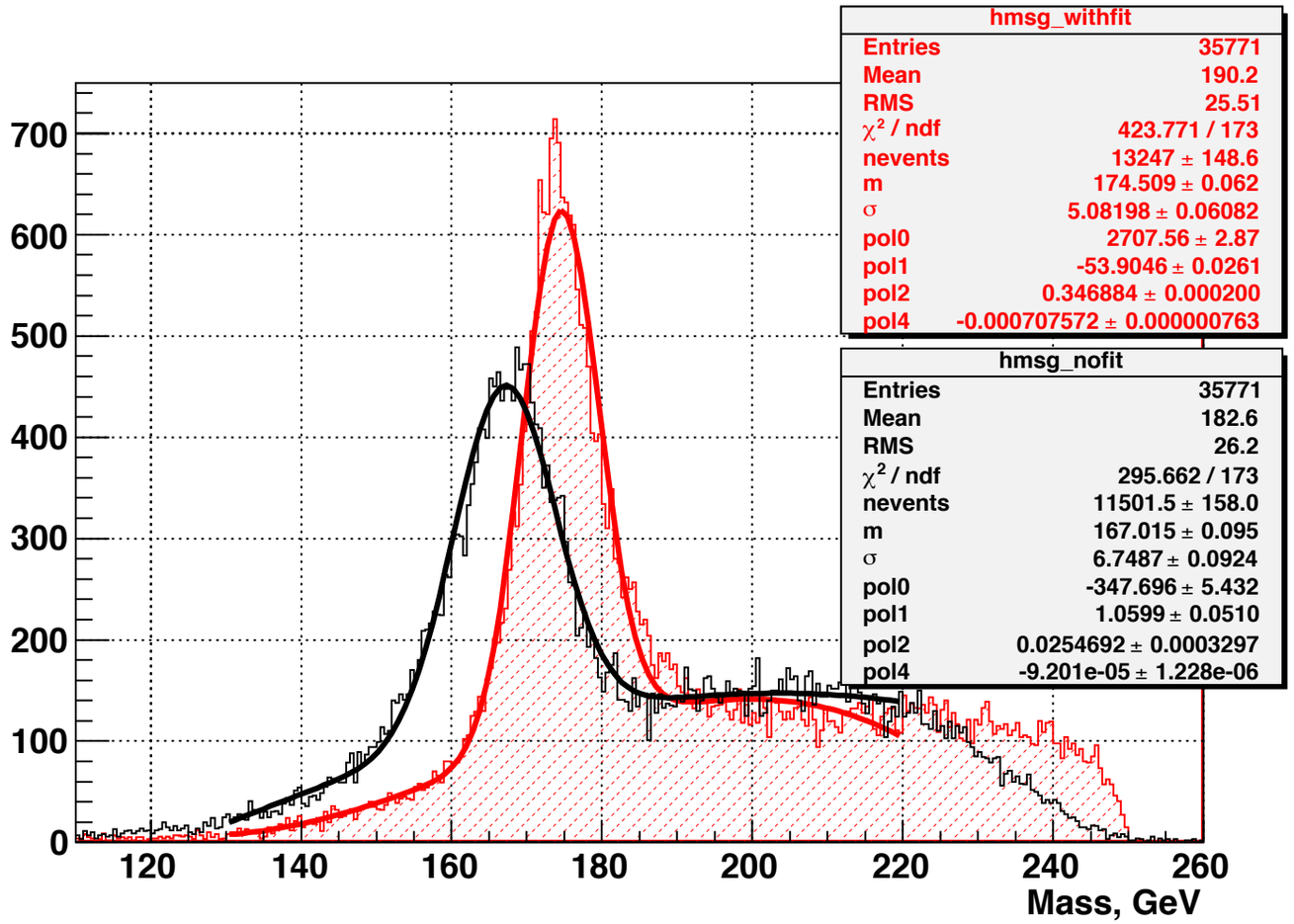


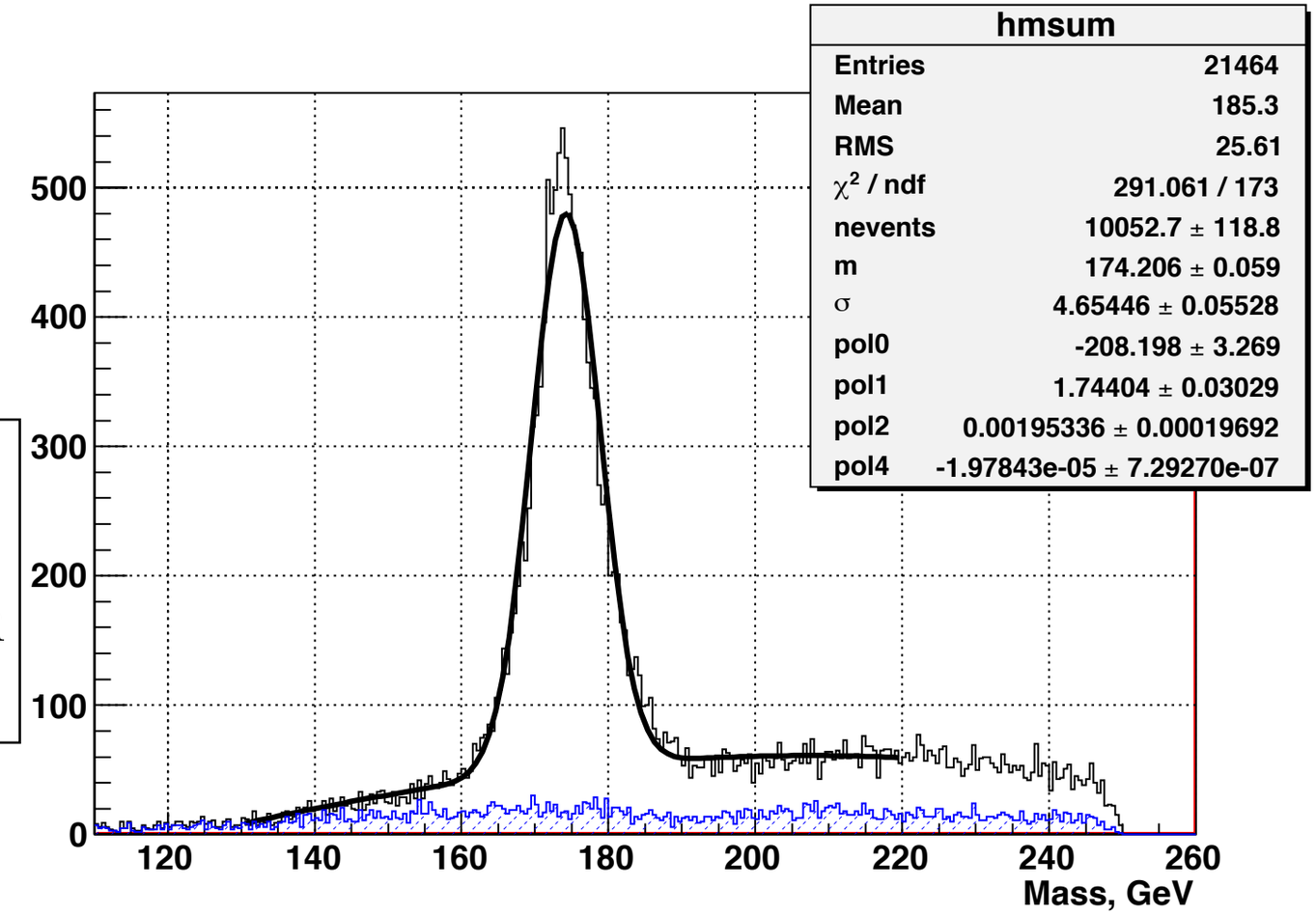
Figure 4: The purity of signal events versus efficiency of signal event selection



Six-jet mass

before kinematic fit

after fit (best χ^2 chosen)

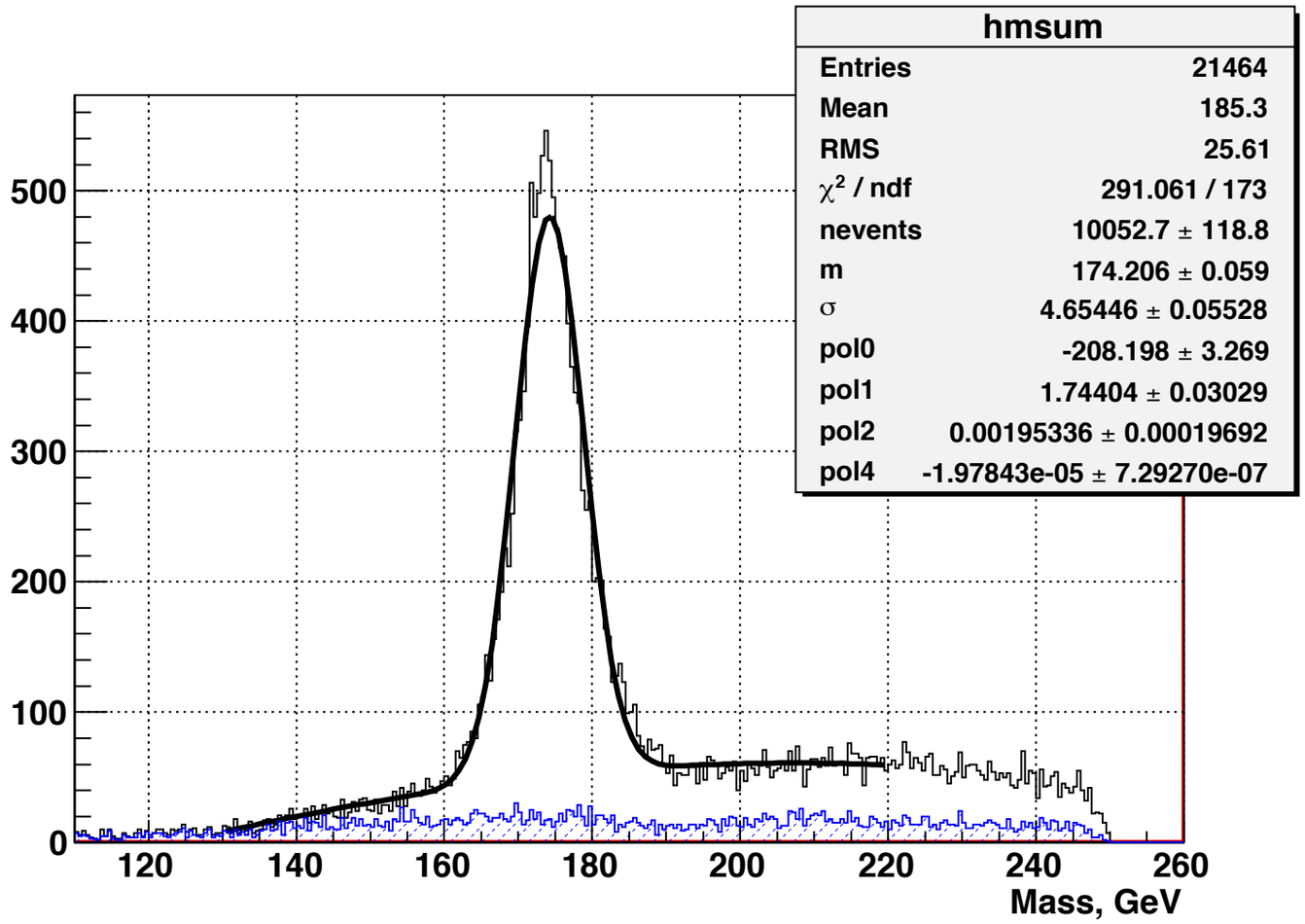


Six-jet mass + four-jet SM background

7c kinematic fit: $\chi^2/\mathrm{ndf} < 45/7$ selection

fit to mass distribution

Top fit results



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.

H reconstruction in the "bremsstrahlung" channel

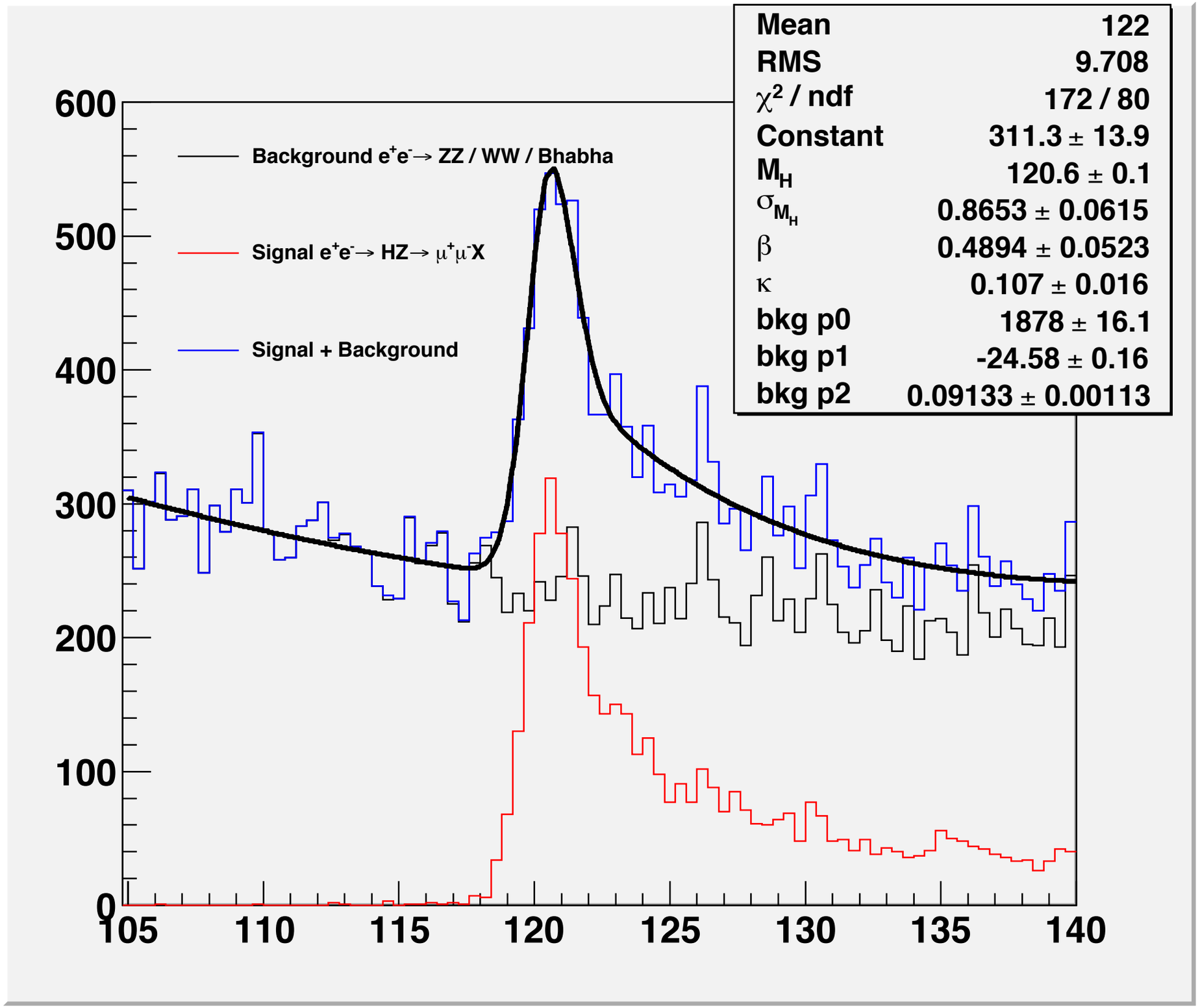
$$e^+e^- \to Z^* \to Z^0 H^0 \to \ell\bar{\ell} H^0 \qquad \ell = e^\pm, \mu^\pm$$

Analysis by Gianfranco Tassielli, INFN, Lecce

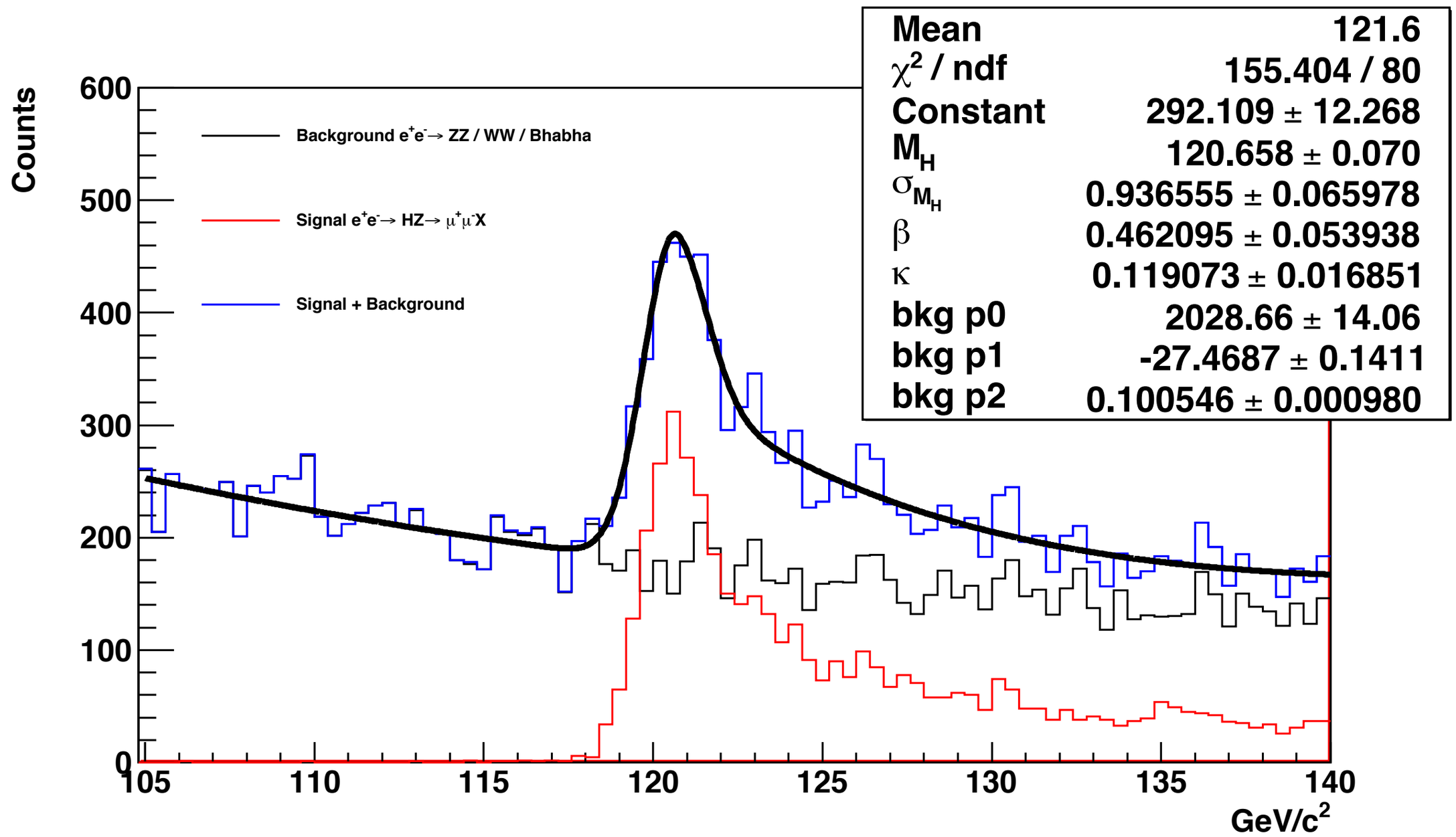
- Mass of Higgs taken to be 120 GeV, ILC CM energy is 250 GeV, and sample size is 500 fb^{-1}.
- This is a "missing mass" measurement: use the tracking system to measure the charged lepton pairs to high precision, then calculate the missing mass between the initial state four-vector and the lepton pair four-vector.
- For the electron pair case, one solves the problem both (1) with only the tracker, and (2) with the tracker plus the EM calorimeter.
- The physics backgrounds are

$$Z^0 \;\; Z^0 \to \ell^+\ell^- \; j \; j$$
$$W^+W^- \to \ell^+\ell^-$$
$$Bhabha \to \ell^+\ell^-$$

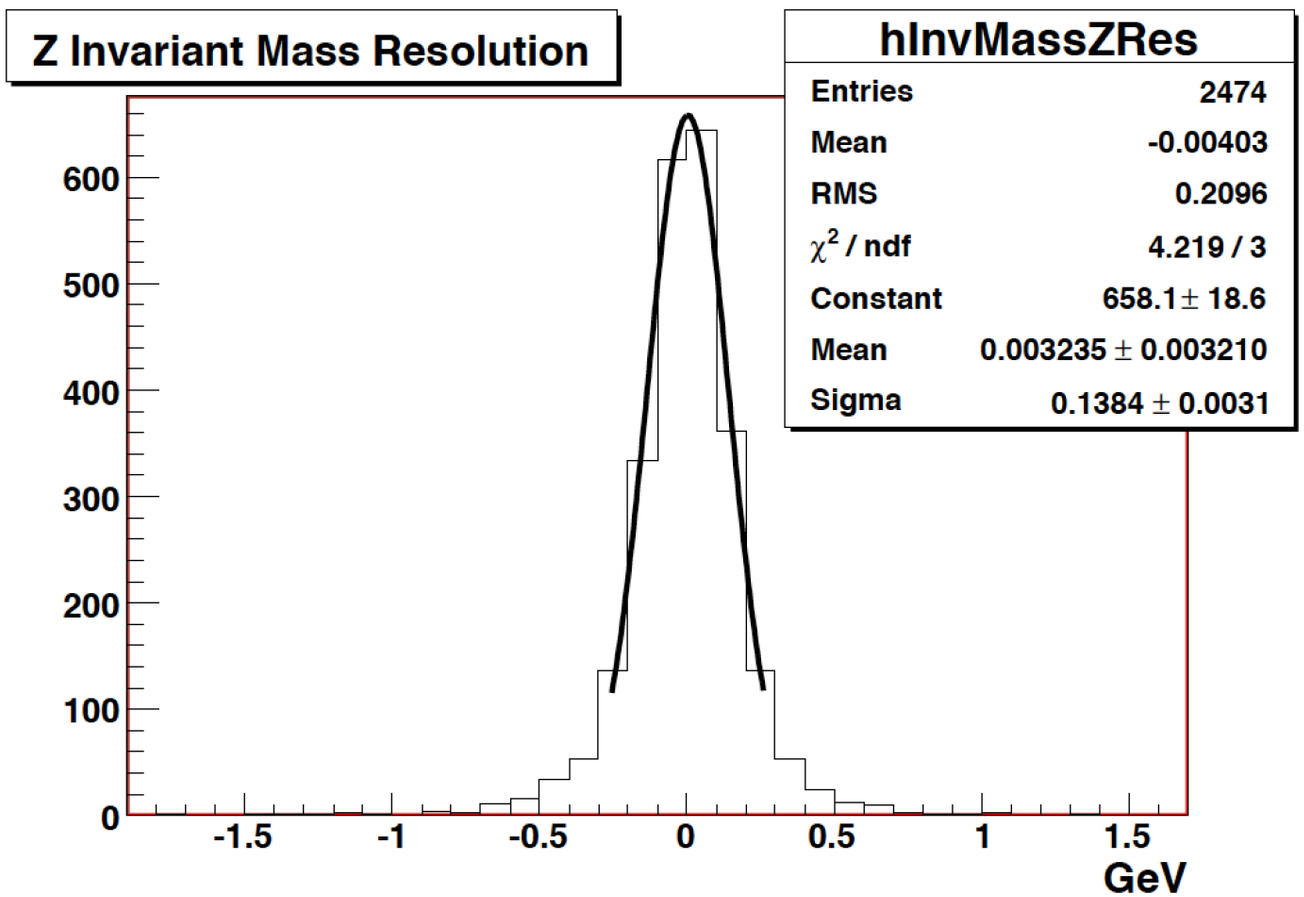
Muons: tracker



Muons: tracker



$Z \rightarrow \mu\mu$ mass resolution: consistent with momentum resolution



$\sigma_M \sim 0.138$ GeV

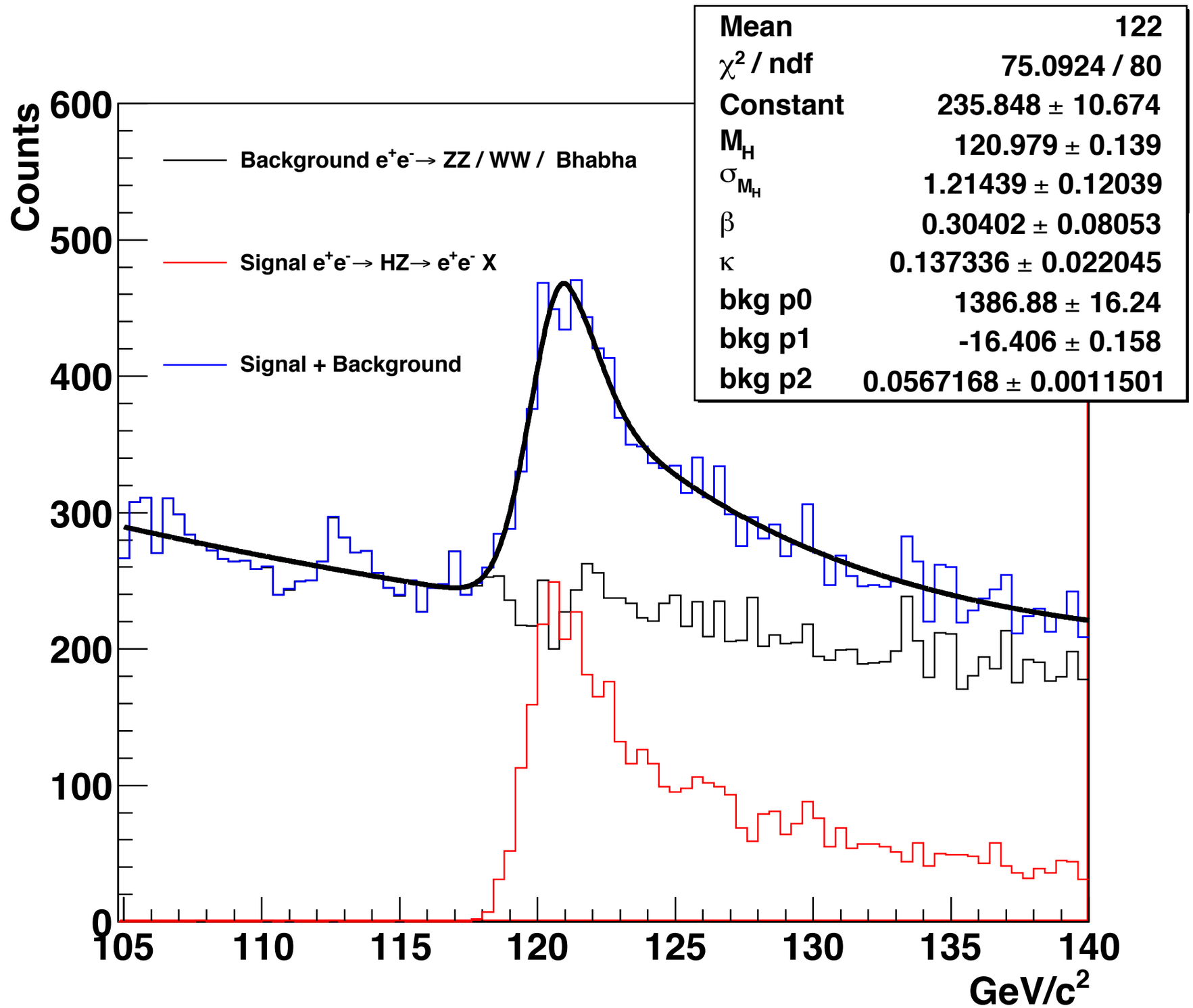
consistent with momentum resolution on both muons:

$\sigma_M \sim \sqrt{2}$ x few x 10^{-5} x $(45\ \text{GeV})^2$

~ 0.1 GeV

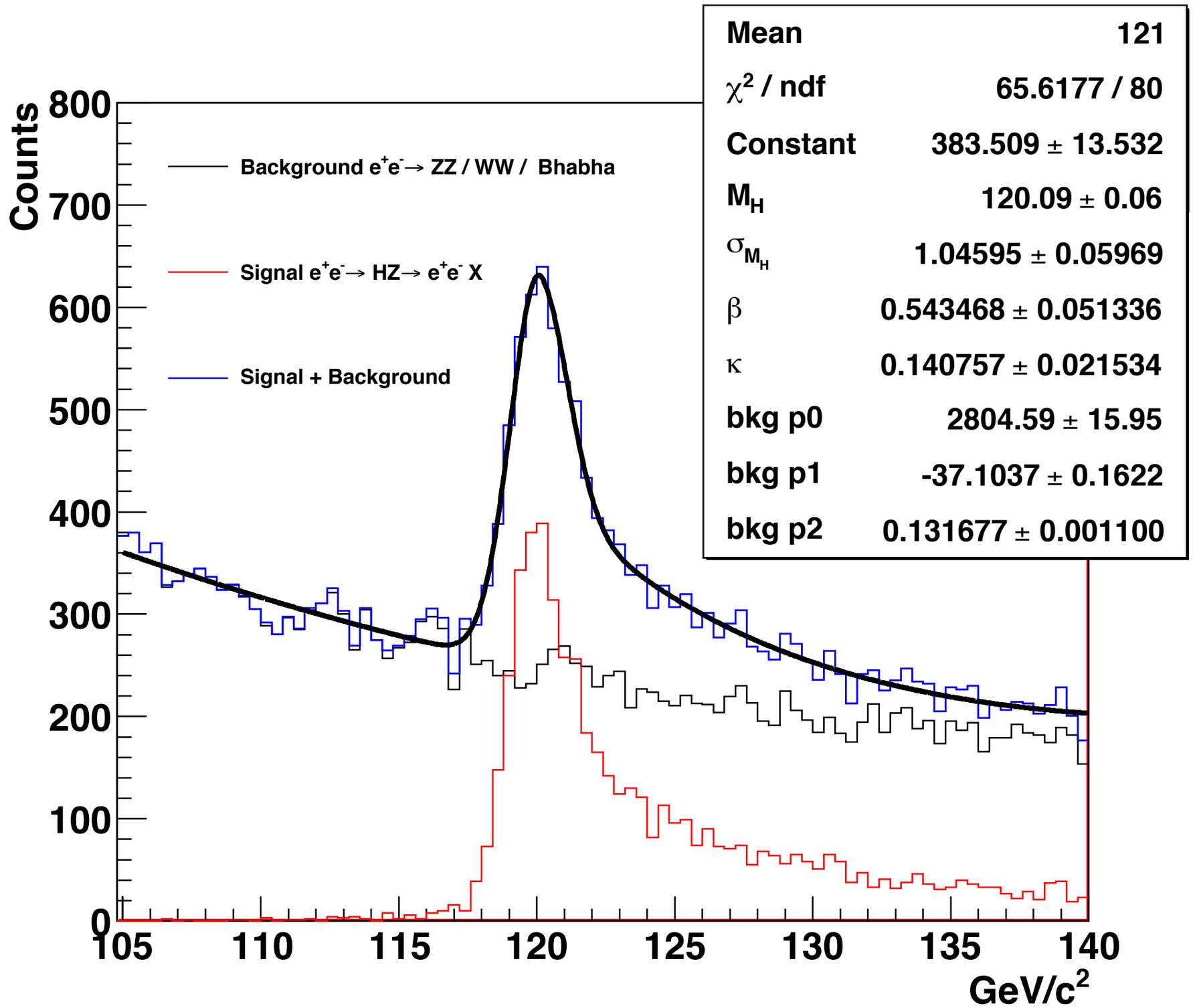
Electrons: tracker only

Suffers from electron bremsstrahlung in vertex and tracker.



Electrons: tracker plus calorimeter

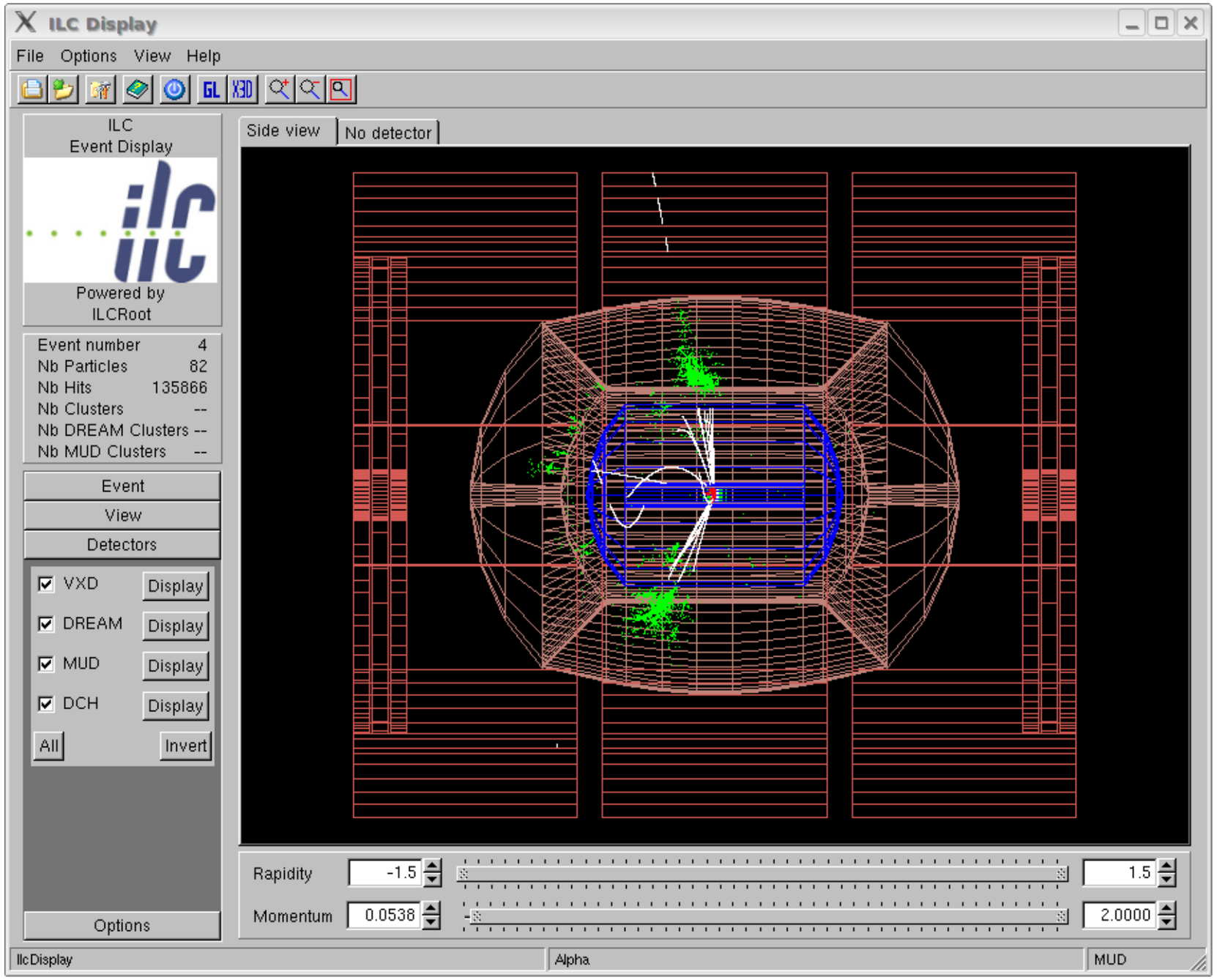
EM calorimeter really helps: sharper signal and lower backgrounds



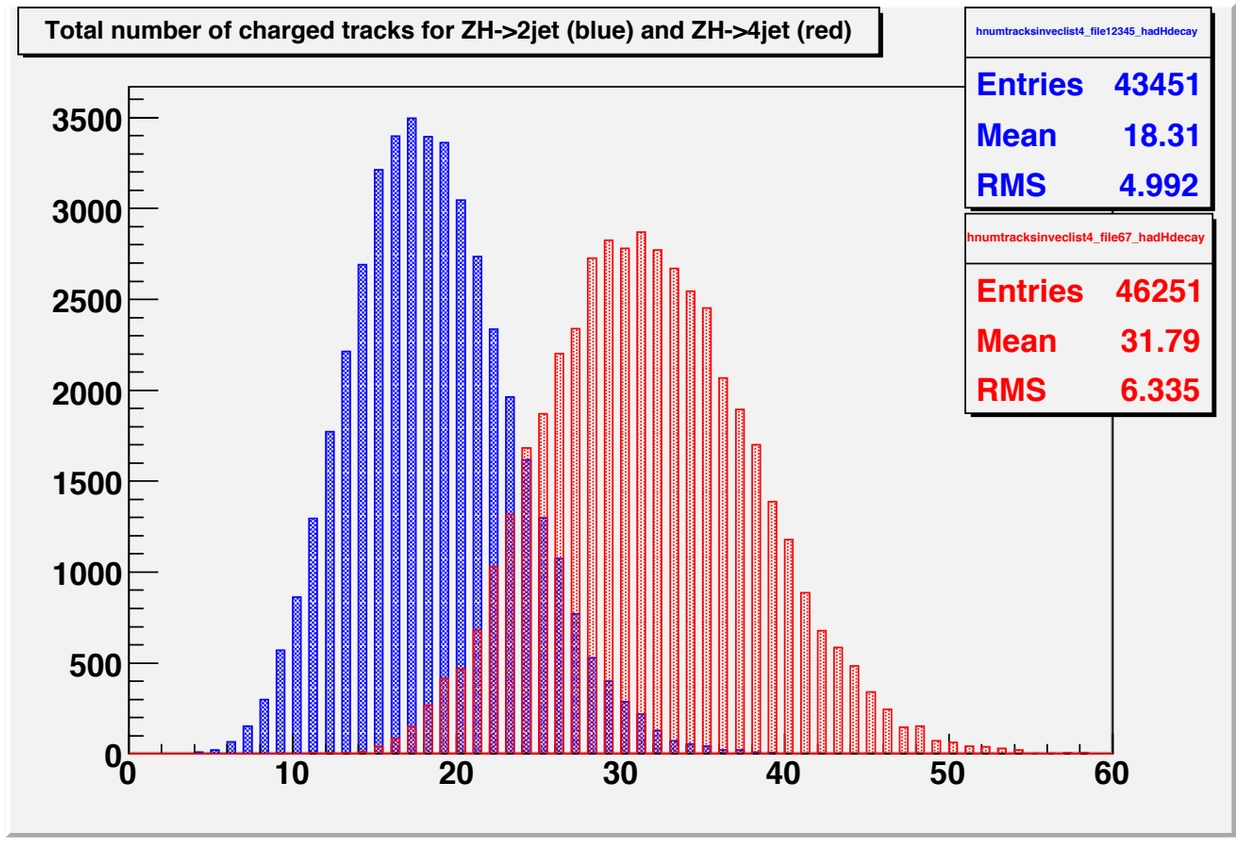
H direct reconstruction to charm quarks

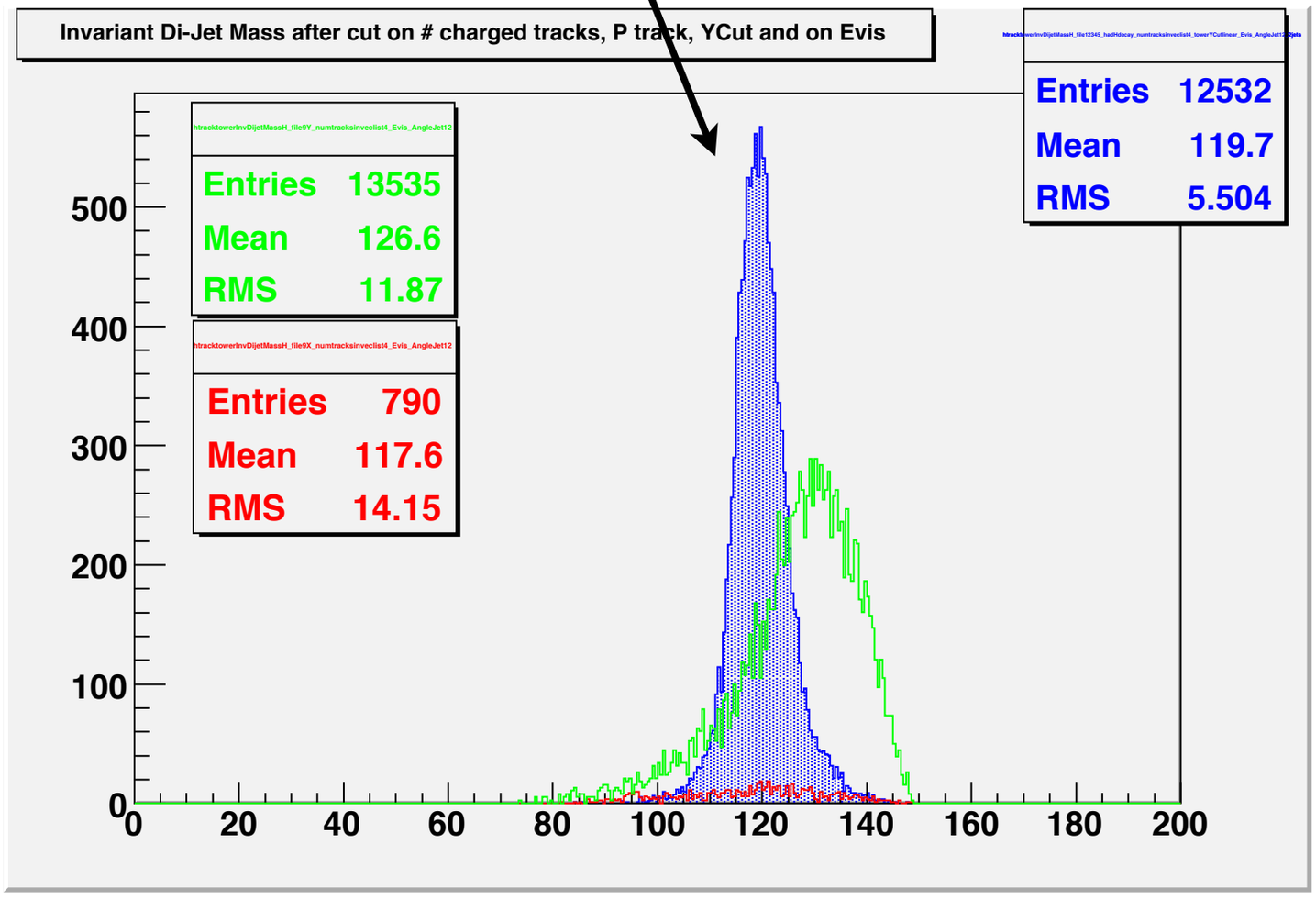
$$e^+e^- \rightarrow Z^0 H^0 \rightarrow \nu\bar{\nu}c\bar{c}$$

Simulated event with two charm-jets and a 45 GeV muon leaving one jet.



Selections on number of tracks, number of calorimeter towers, ycuts, etc., result is an H mass distribution

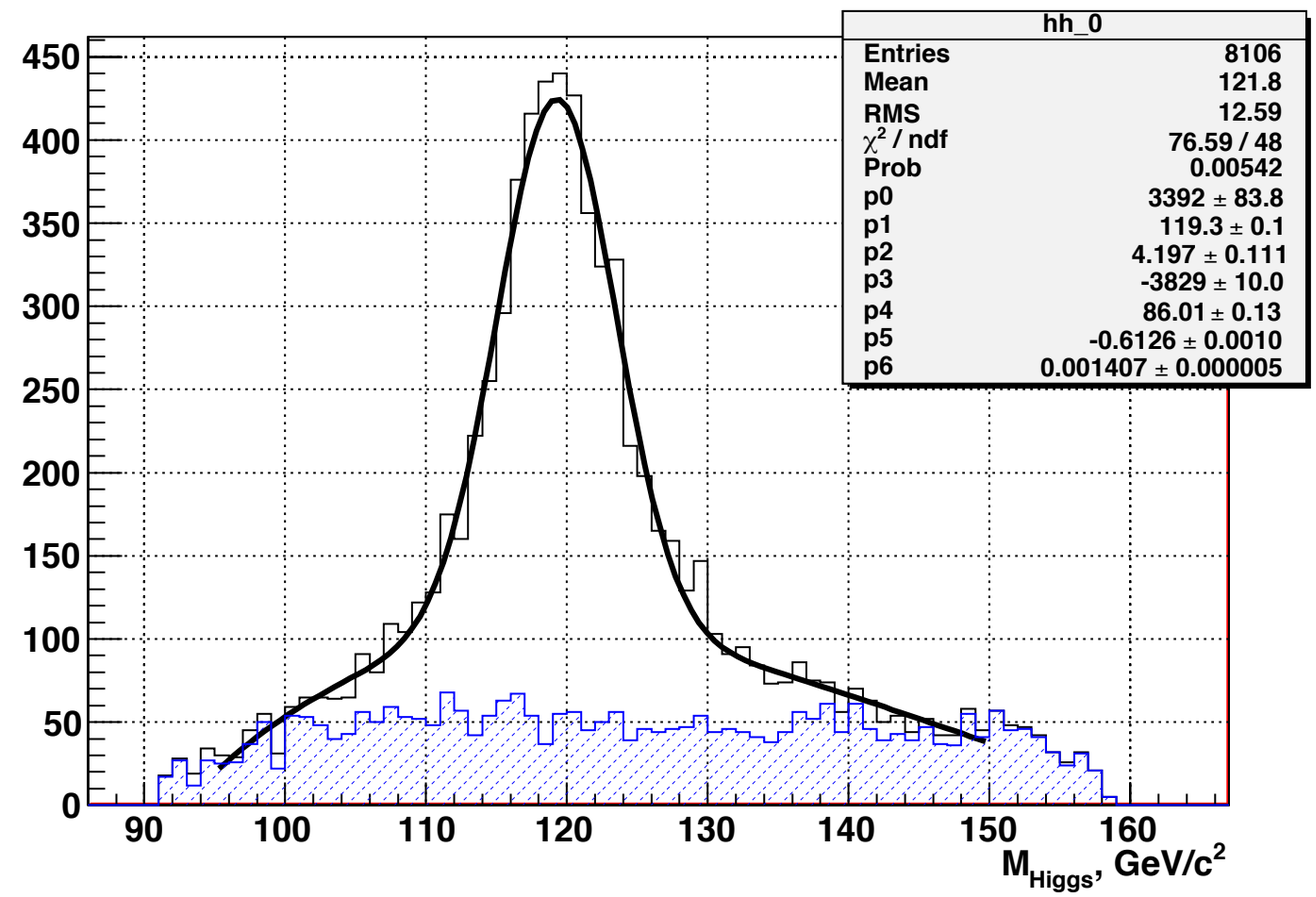




H direct reconstruction to bottom quarks

$$e^+e^- \rightarrow Z^0 H^0 \rightarrow jjb\bar{b}$$

H mass distribution after 5c fit



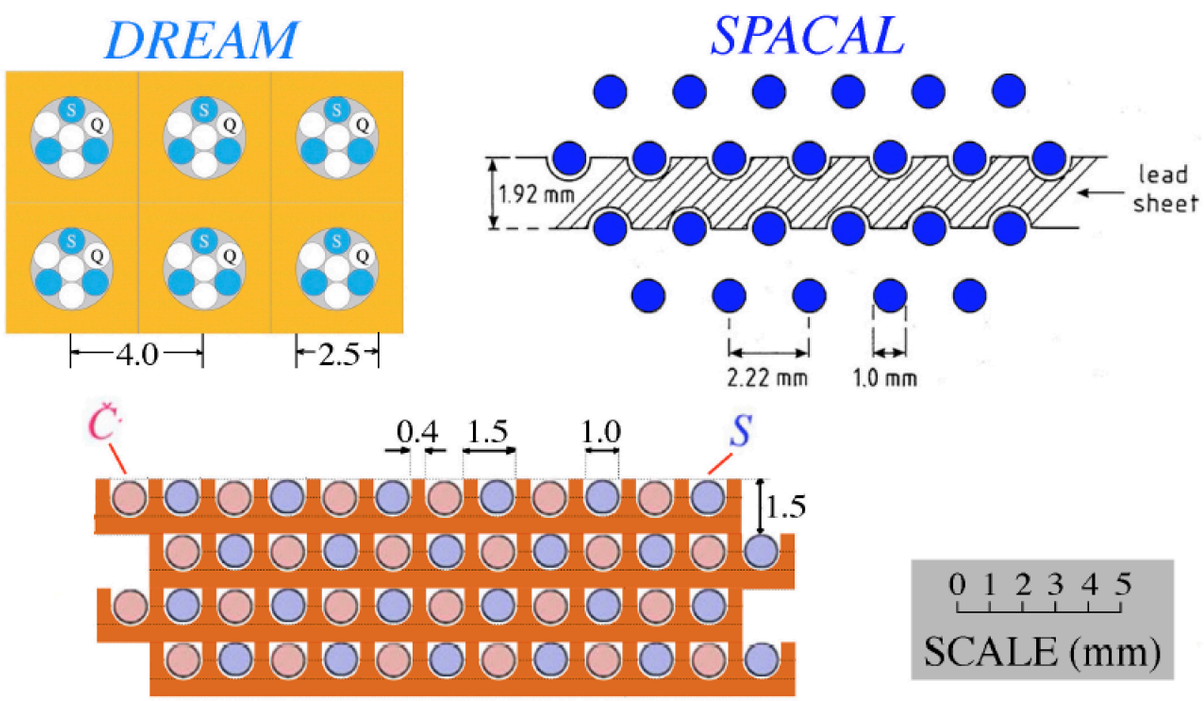
How do you get all this good stuff?

- dual-readout: hadronic calorimetry
- CluCou: nearly massless, cluster-counting tracking
- dual-solenoid: two magnetic field regions
- Muons: dual-readout
  dual momentum measurements
  conservation of energy
- particle ID on *every particle* of SM (actually, not used here)

Dual-readout calorimetry

Fiber-impregnated absorber volume

Sampling fraction & frequency



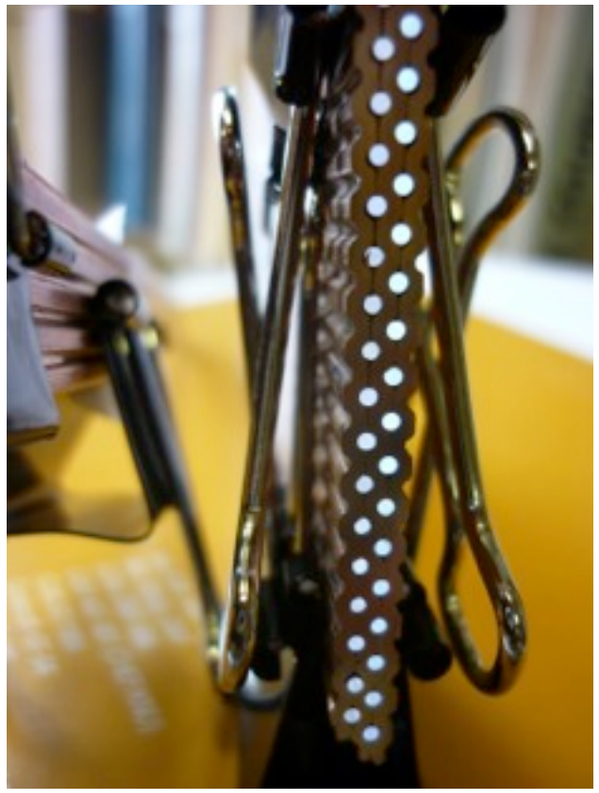
Fiber pattern RD52

Absorber thickness between sampling layers (Moliere radii):

SPACAL 0.071 *DREAM 0.099* *RD52 0.027*

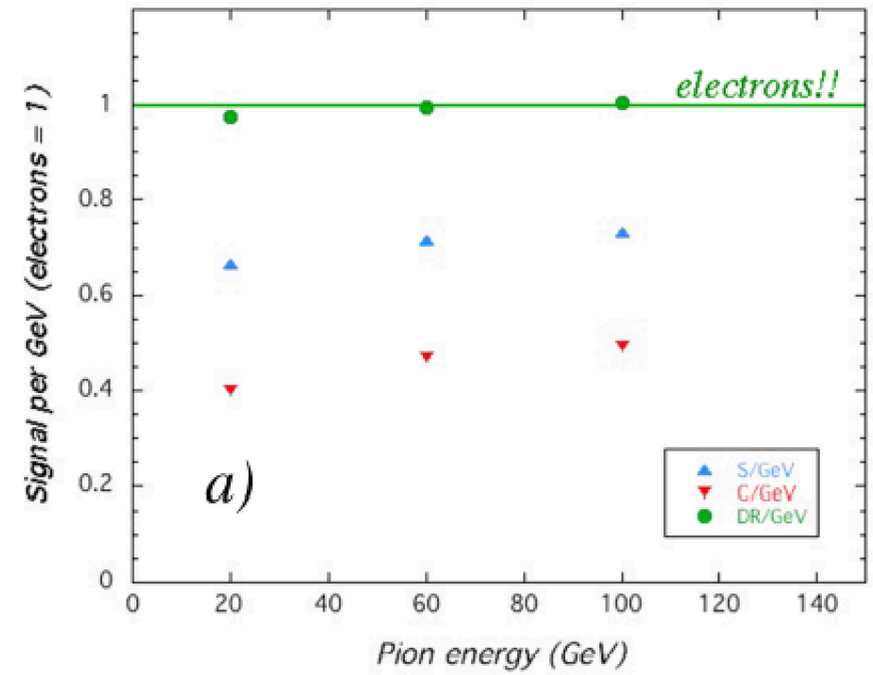
Pure Cu

Cu + Zn(10%)



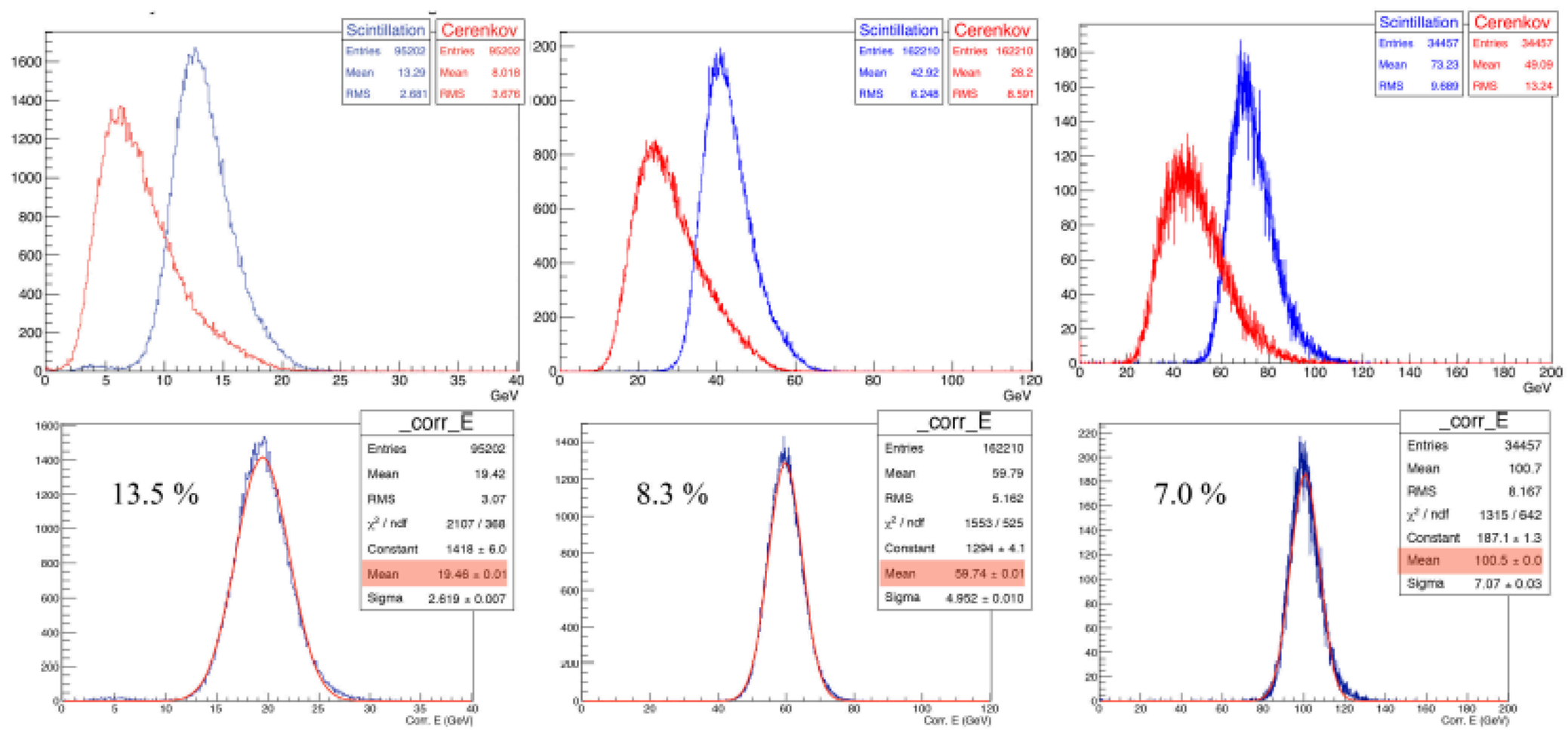
Dual-readout calorimetry

Electron energy scale well reproduced by DR!!



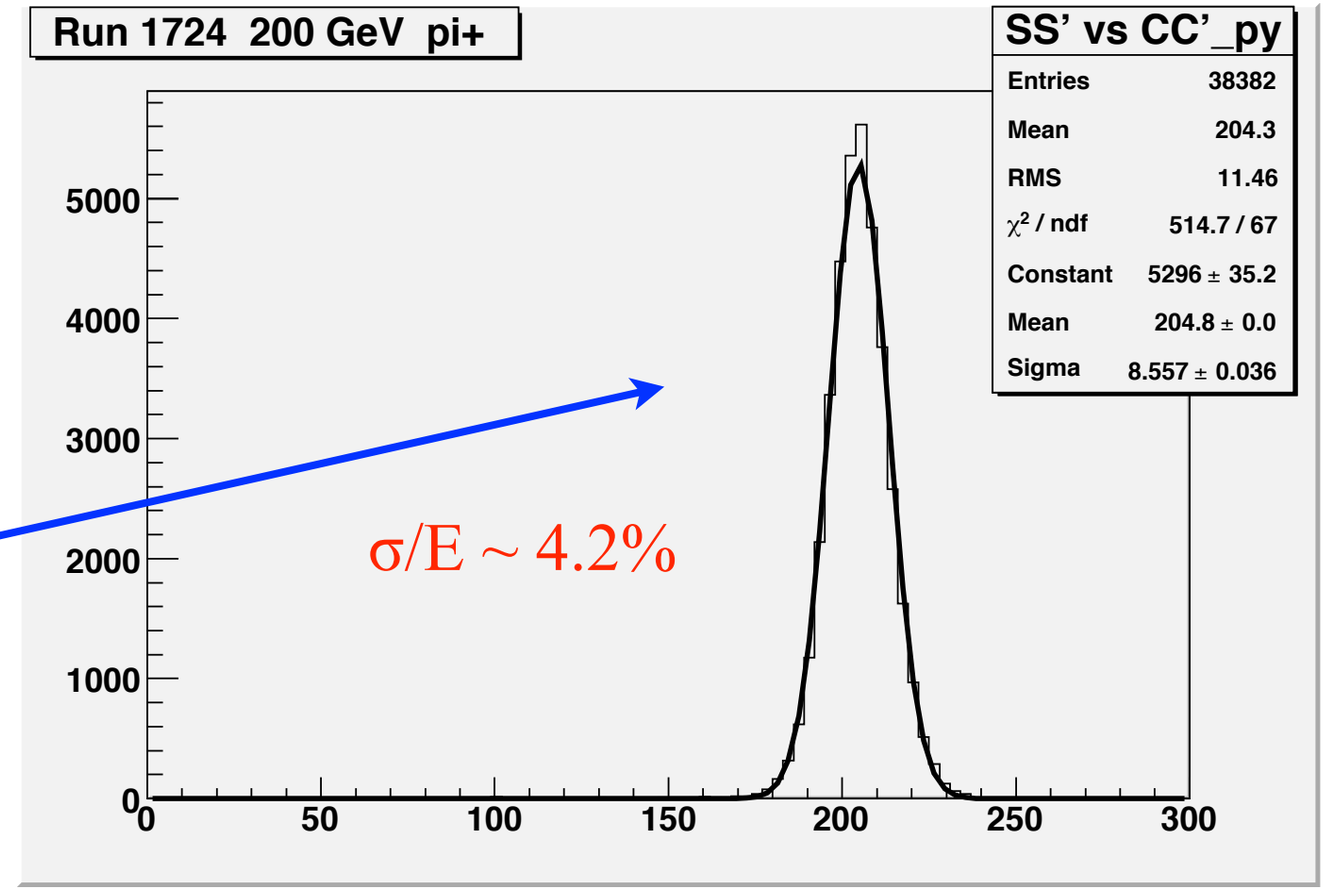
Energy resolution and linearity of our latest modules (on the way to 5 tons)

20 GeV π^- 60 GeV π^- 100 GeV π^-

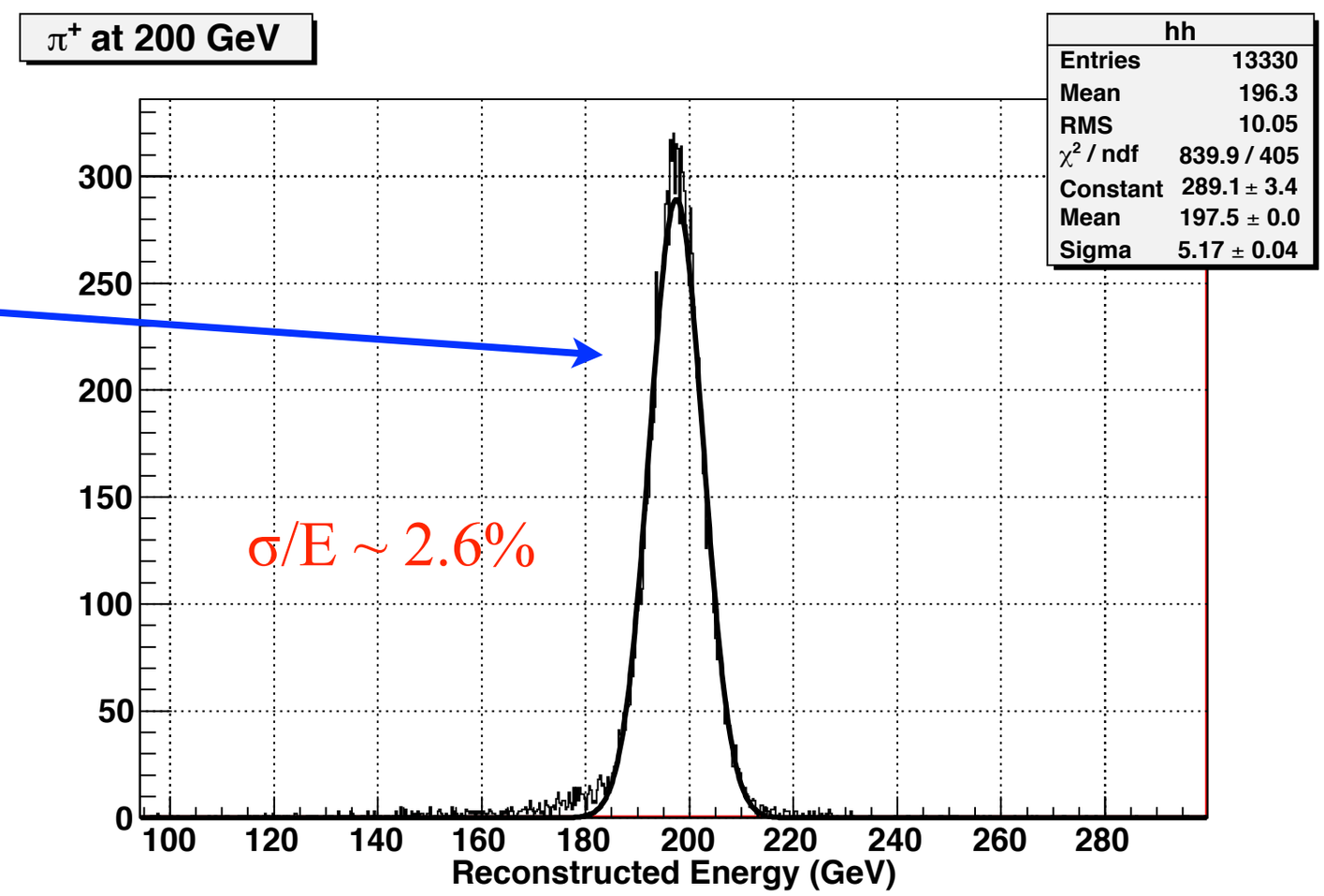


200 GeV π^+
(dual-readout)

DREAM data



4th simulation

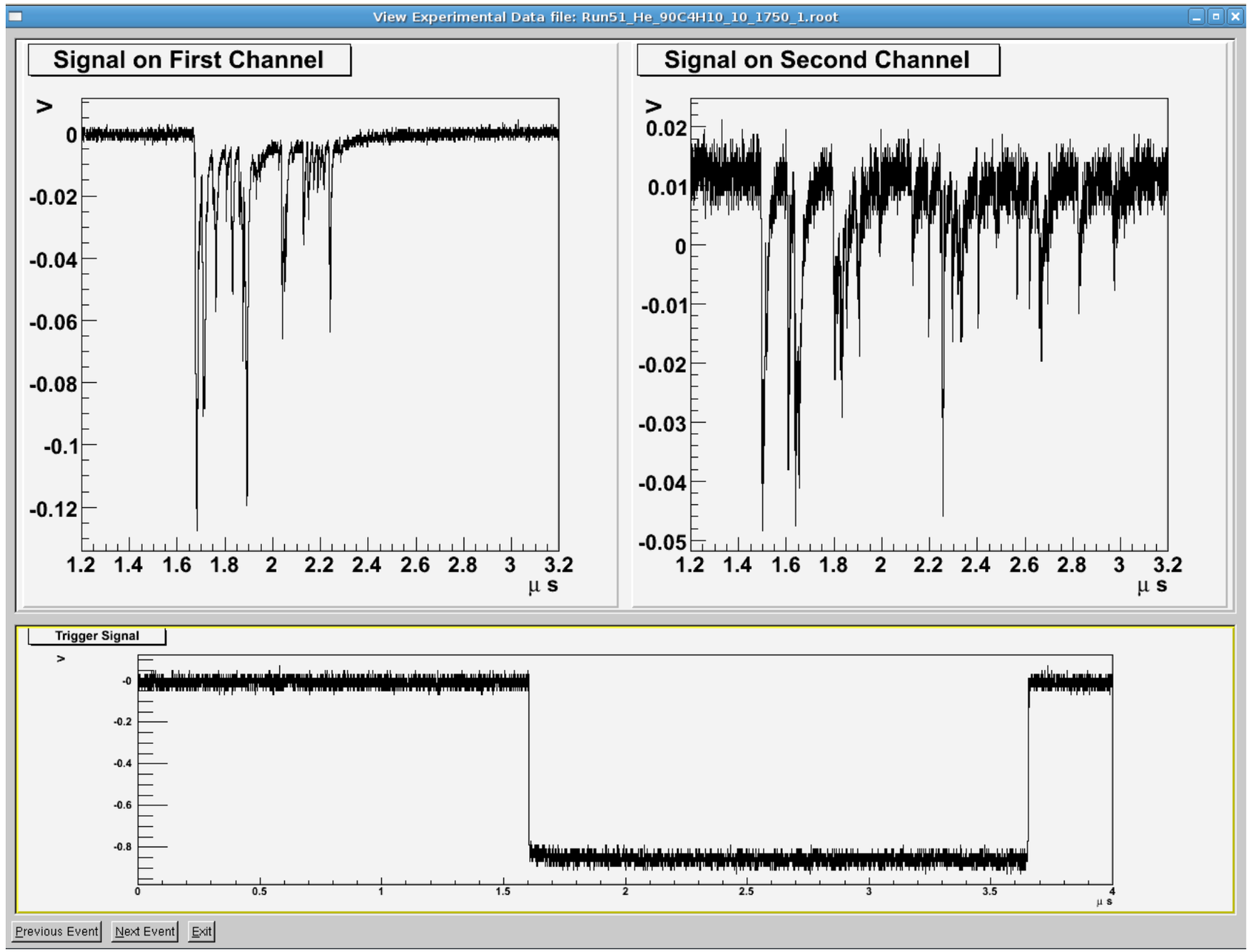


Cluster-counting-timing ultra-low-mass drift chamber

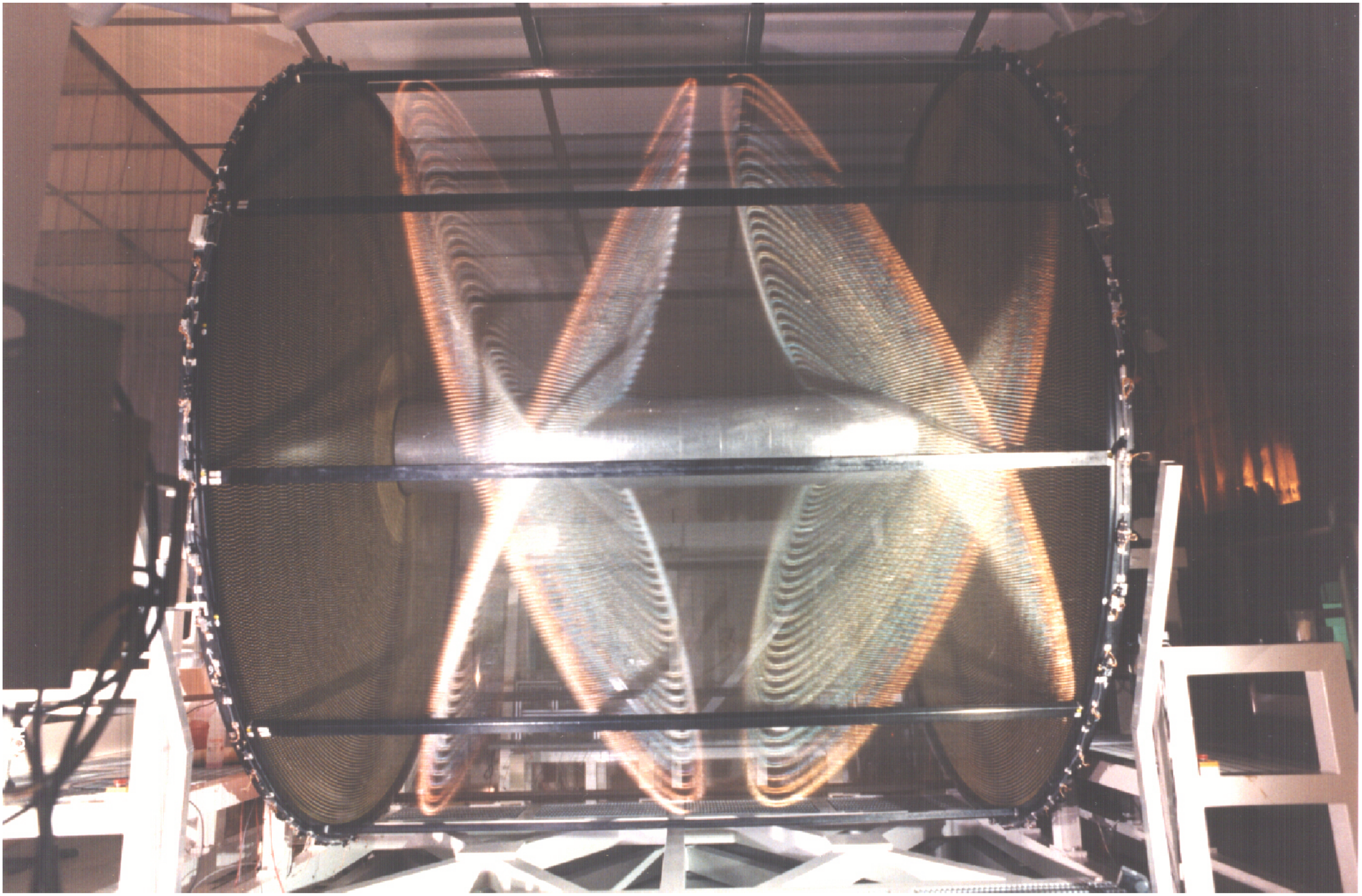
These are electron clusters avalanching on the sense wire. You see the Landau fluctuations.

This is the next step beyond Charpak; much better than the first cluster, or the first big cluster.

$\sigma \sim 40\mu m$ on ~150 pts.

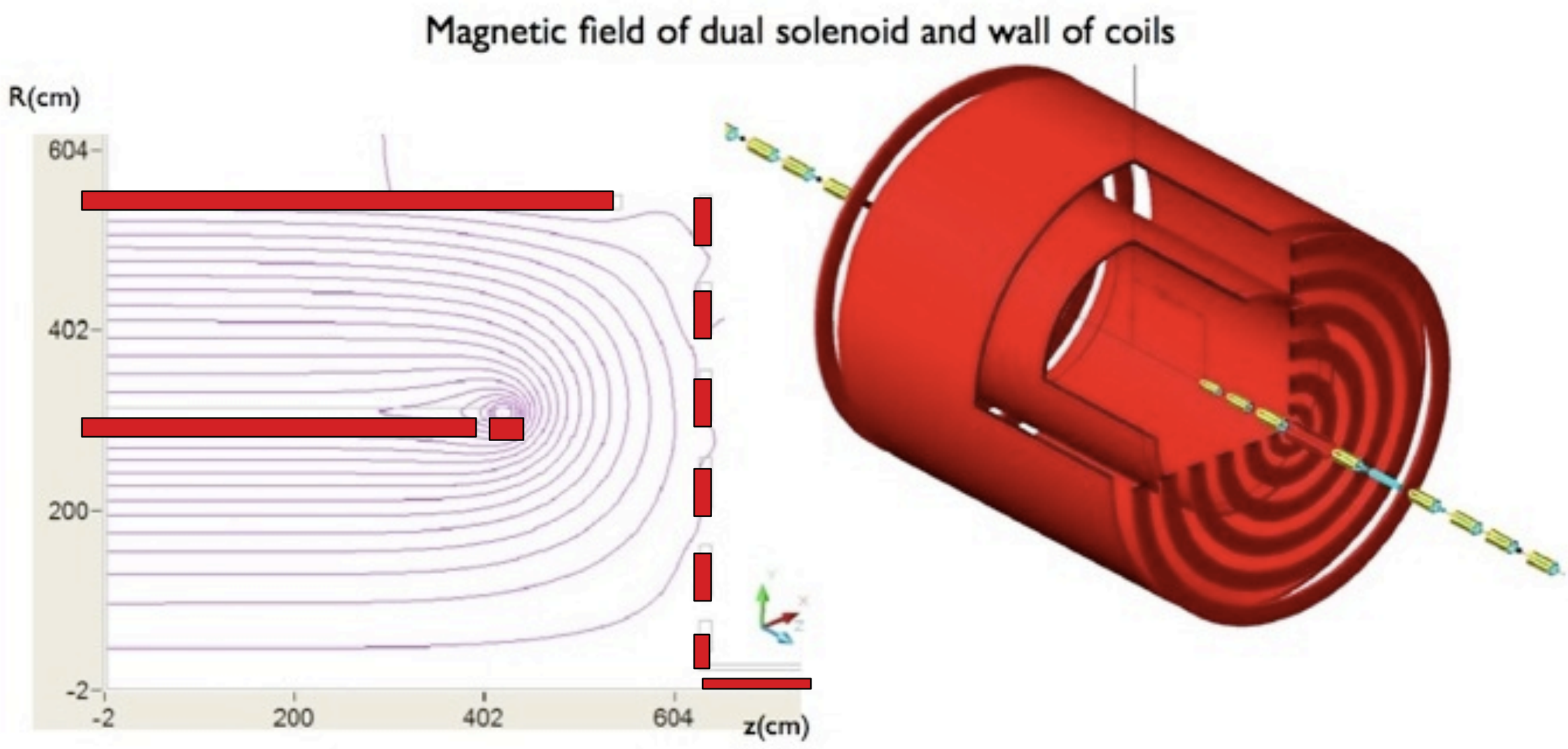


KLOE drift chamber - successful “prototype” for CluCou

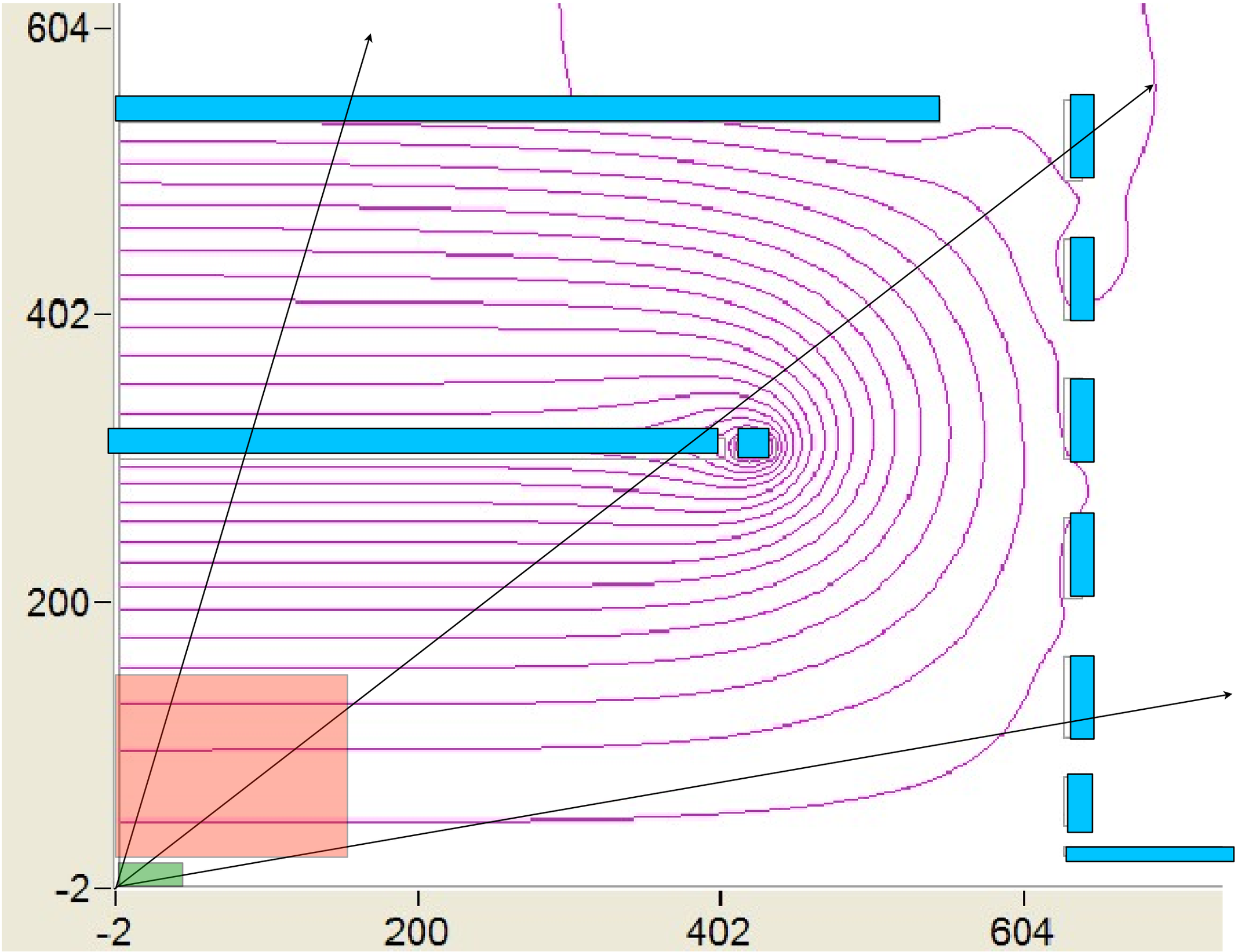


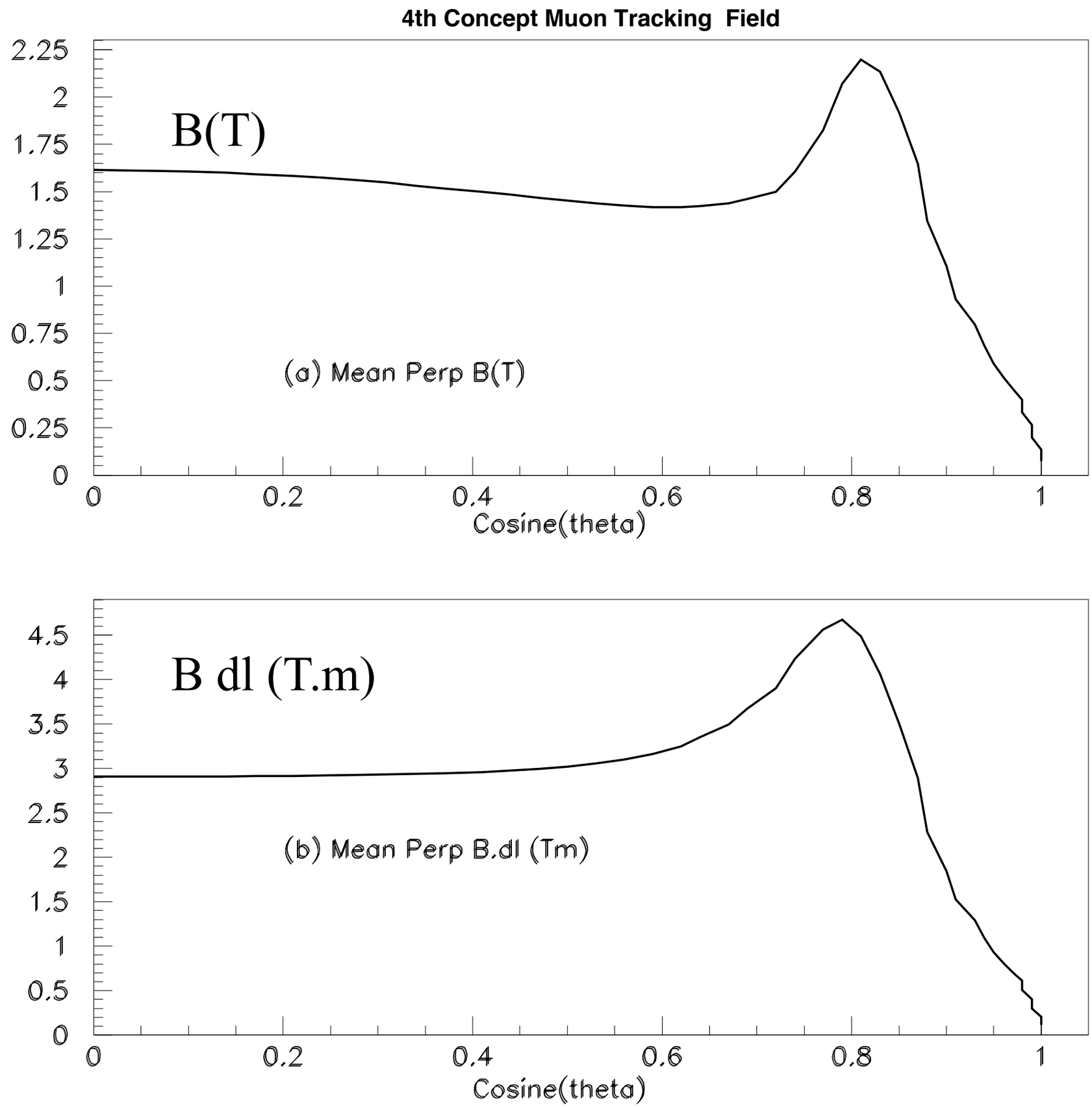
Dual-solenoid magnetic field

New magnetic field, new ``wall of coils'', iron-free: many benefits to muon detection and MDI, Alexander Mikhailichenko design



Muon measurements

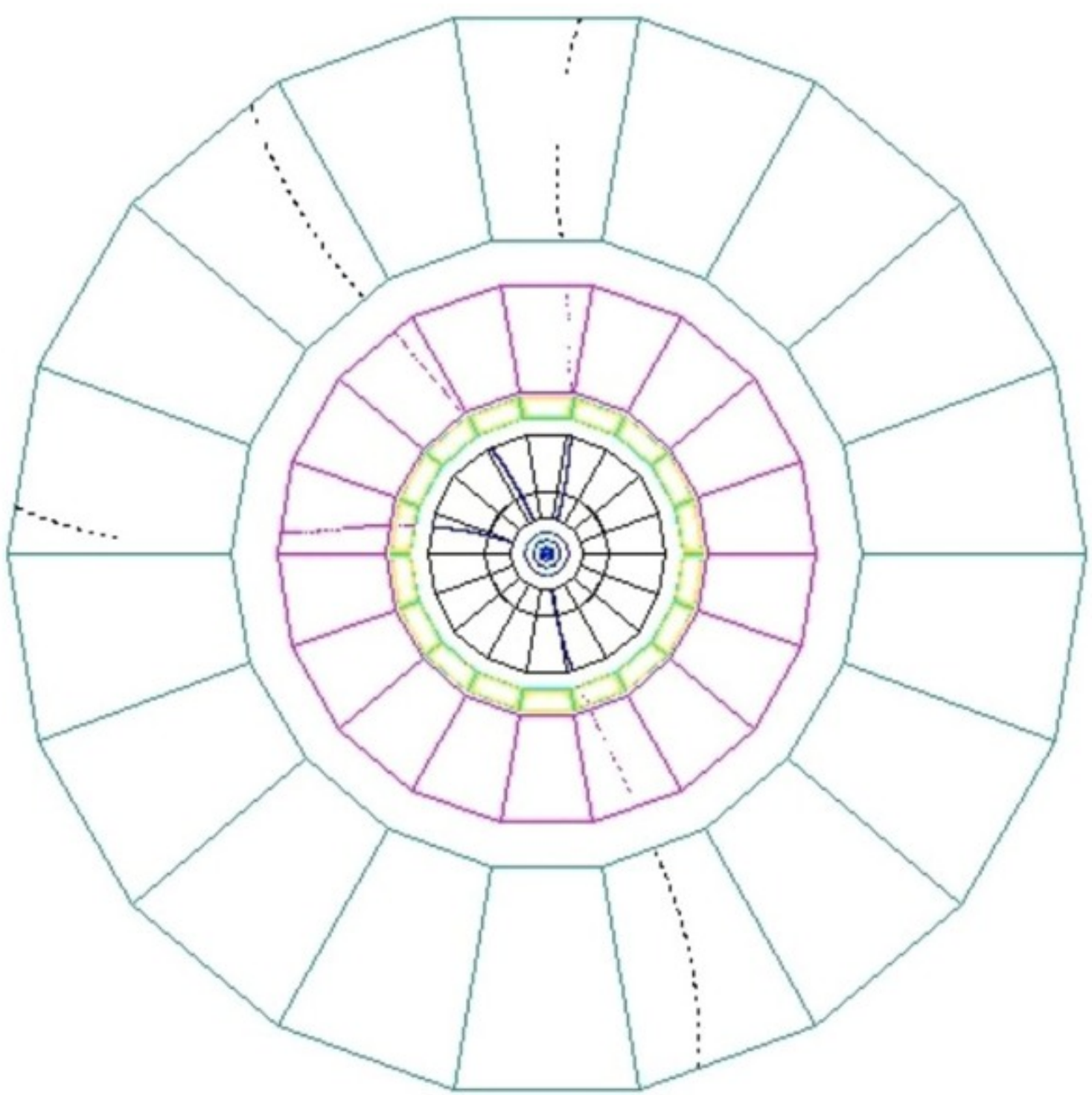




Dual solenoid

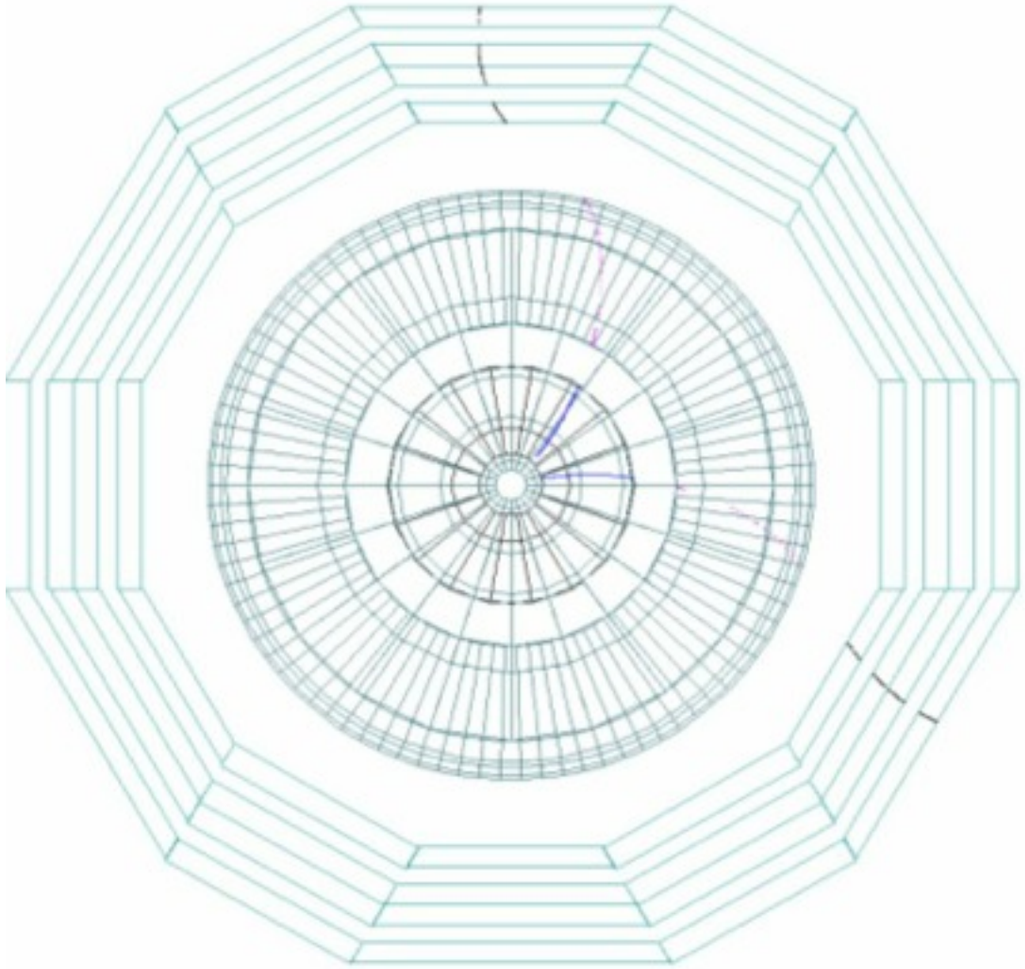
tracking along muon trajectories in the annulus between solenoids.

Four 5-GeV muons through detector as test



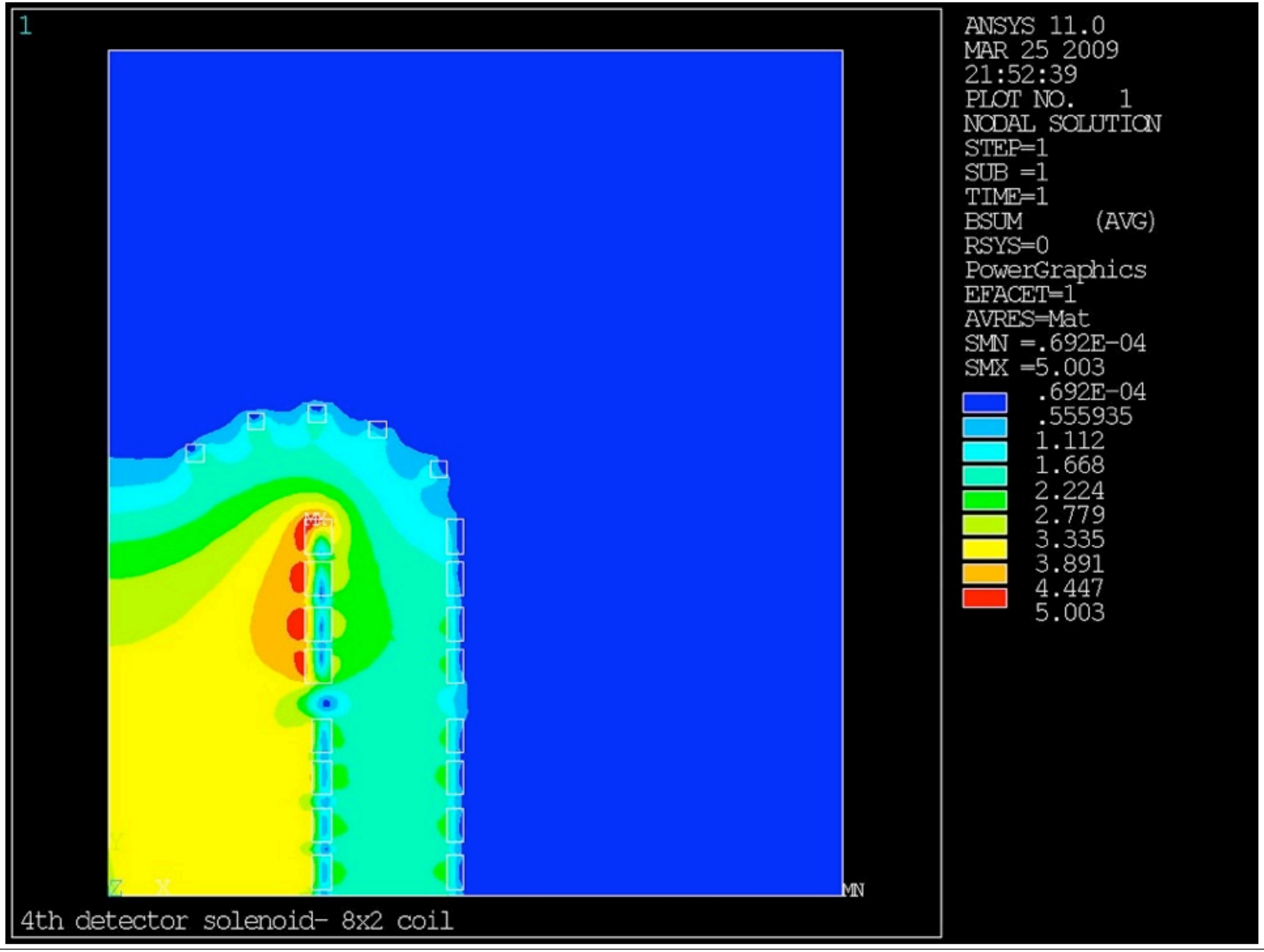
Muons are clean and obvious;
Acceptance at 5 GeV is good;
Momentum and energy measurements must add up for a real muon;
GEANT simulation in very good shape in a very short time;
Still, there is more fun work to do.

μ^+ and μ^- at 3.5 GeV/c



Muons are easy and obvious at 3.5 GeV/c.

We intend to push the acceptance for muons down to 1 GeV/c. This will require fine coordination of CluCou and the dual-readout BGO and fiber calorimeters.


1
ANSYS 11.0
MAR 25 2009
21:52:39
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BSUM (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =.692E-04
SMX =5.003
.692E-04
.555935
1.112
1.668
2.224
2.779
3.335
3.891
4.447
5.003
MN
4th detector solenoid- 8x2 coil

Muon dual-solenoid: Advantages

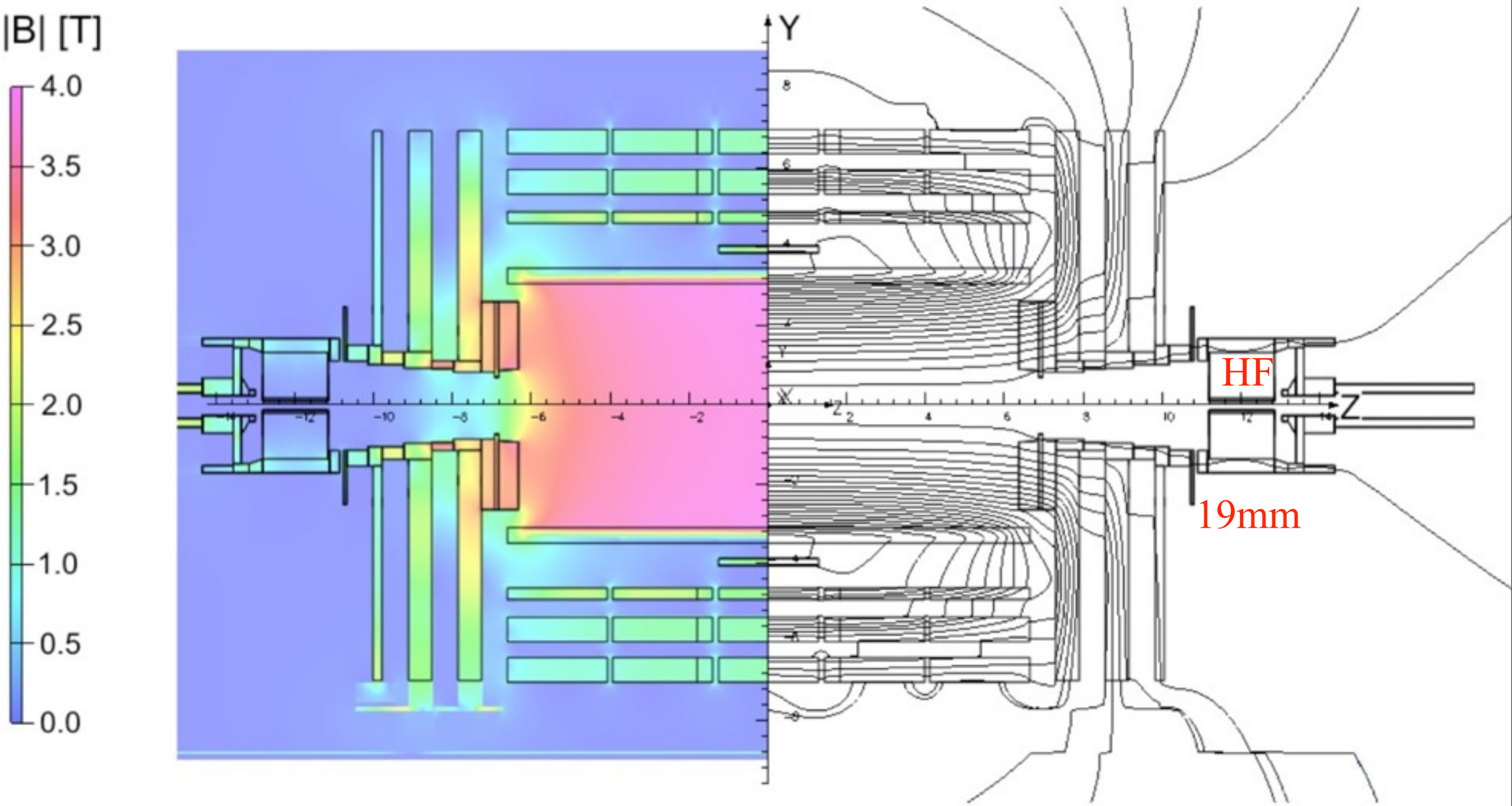
- Good momentum resolution: $\sigma/p^2 \sim 10^{-4}$ (GeV/c)$^{-1}$
- (Muons bent in Fe are fundamentally limited to

  $\sigma/p = 10\%/\sqrt{L}$, independent of momentum)
- Field is achievable, B is smooth in (θ,φ), and $\int Bdl$ is also smooth out to end of outer solenoid.
- ATLAS-like, but simpler.
- Excellent low momentum μ acceptance and efficiency
- Access to detector, flexibility for future physics
- Can control field on and around beam line.

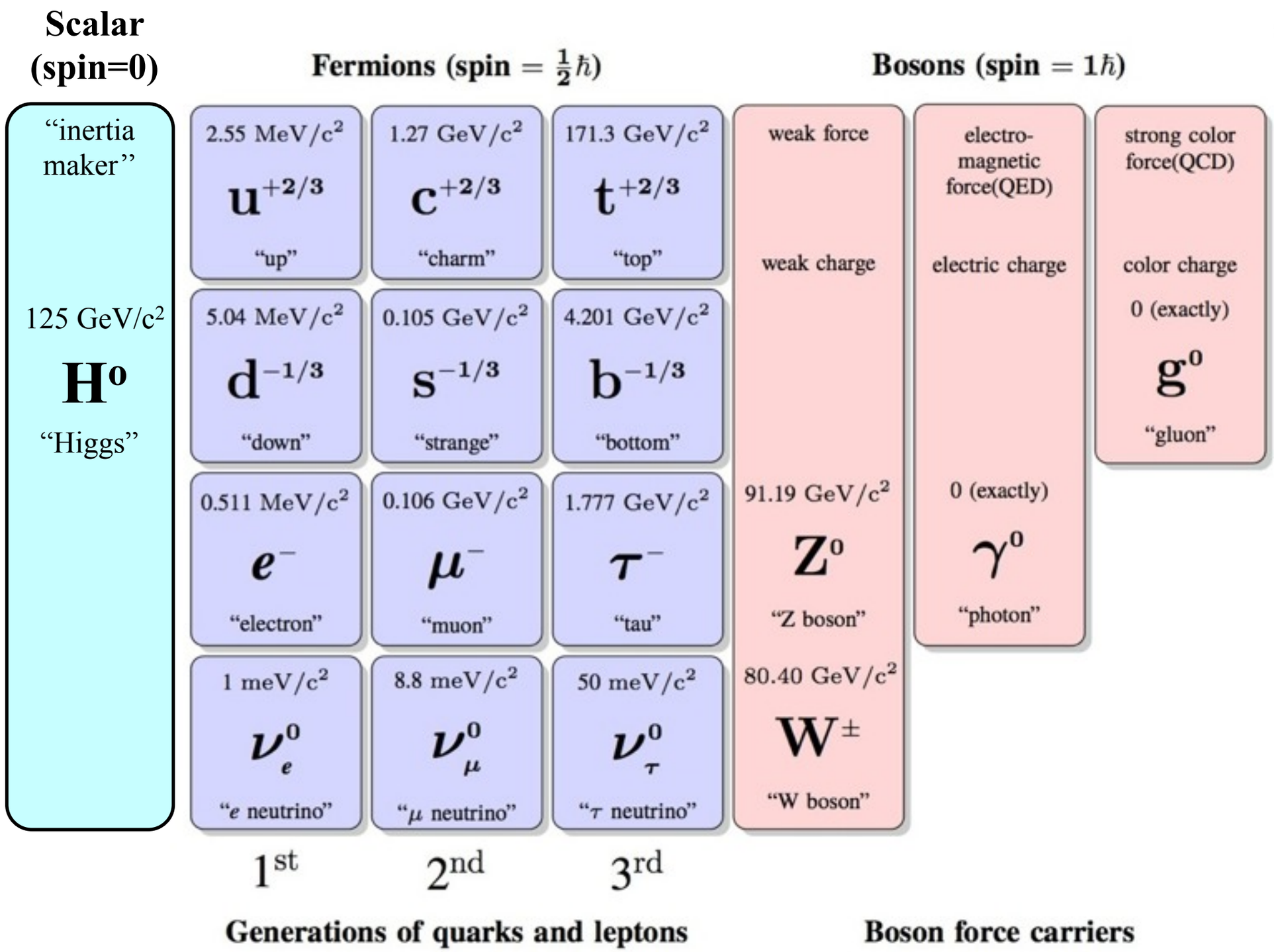
The Iron Age, circa 1995

B field map of CMS

Center of solenoid is 3.8T, iron saturates at 1.8T, therefore 2T of flux is free to find some unsaturated iron ... iron beams in the concrete floor, the elevator shafts, the HF calorimeters at z=11m.
SiD has a 5T field, so 3.2T has no energy advantage to stay inside iron ... big fringe field ~ 1kG at 1m.



Particle Identification: putting everything together



Achieved in test beam data

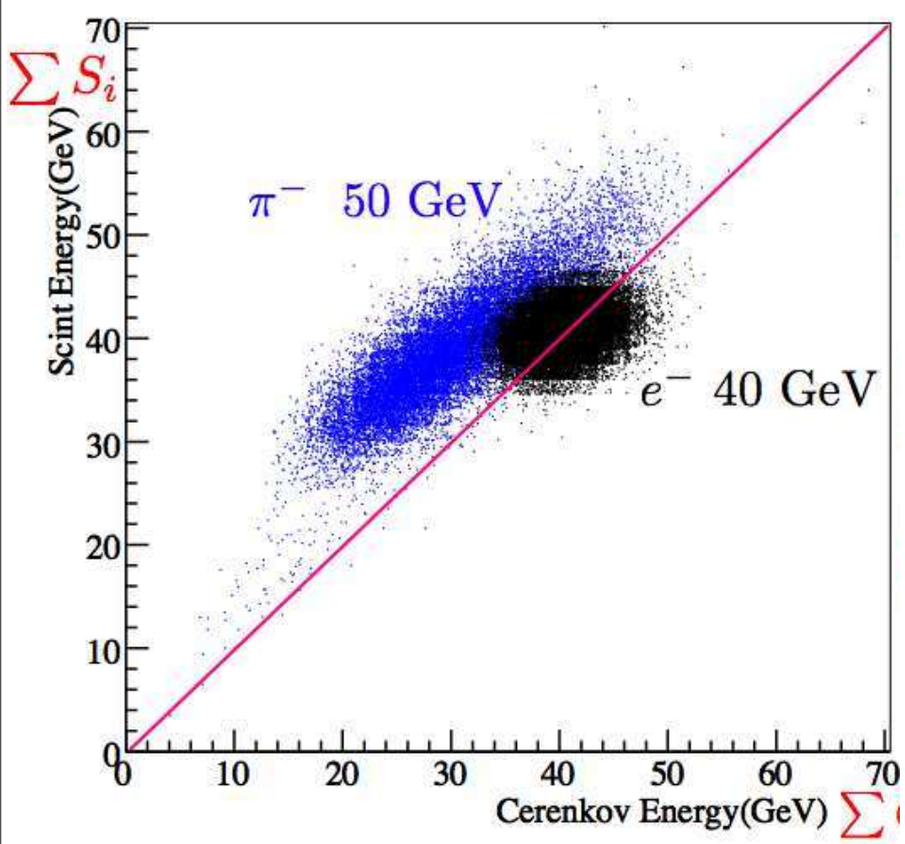
Achieved in cosmic mu test data

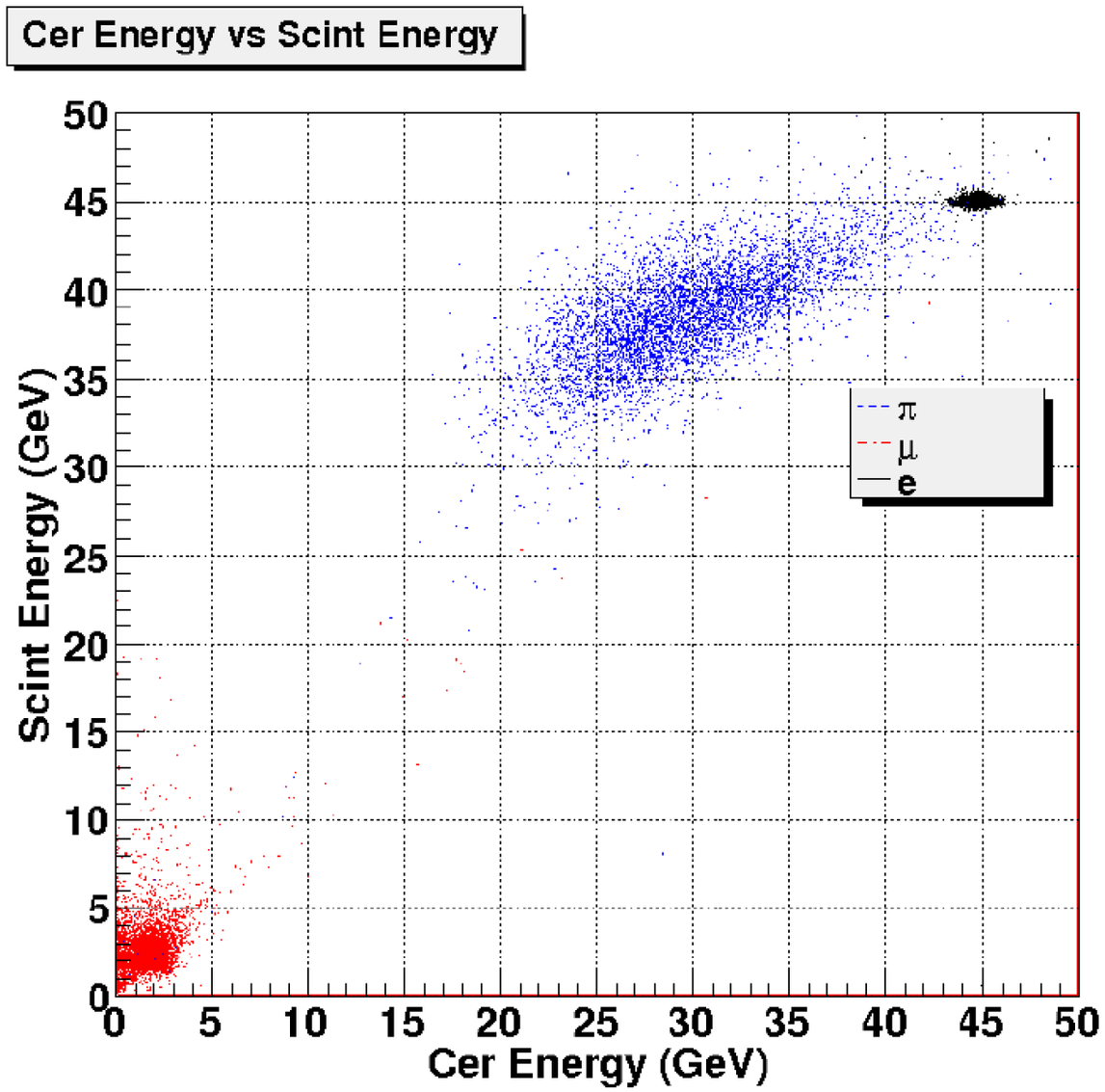
Achieved in ILCroot simulation and analysis

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

Dual-readout

e-π discrimination

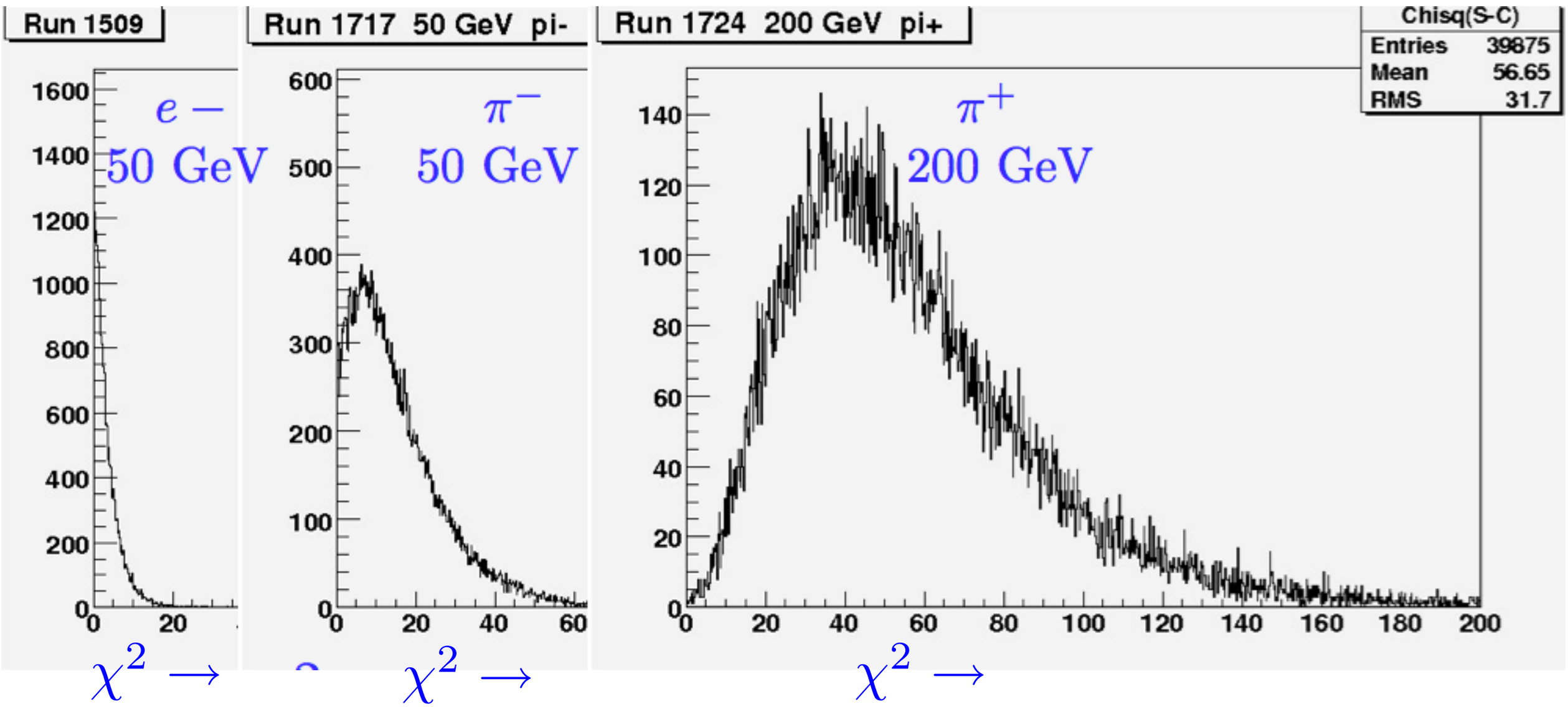




Dual-readout

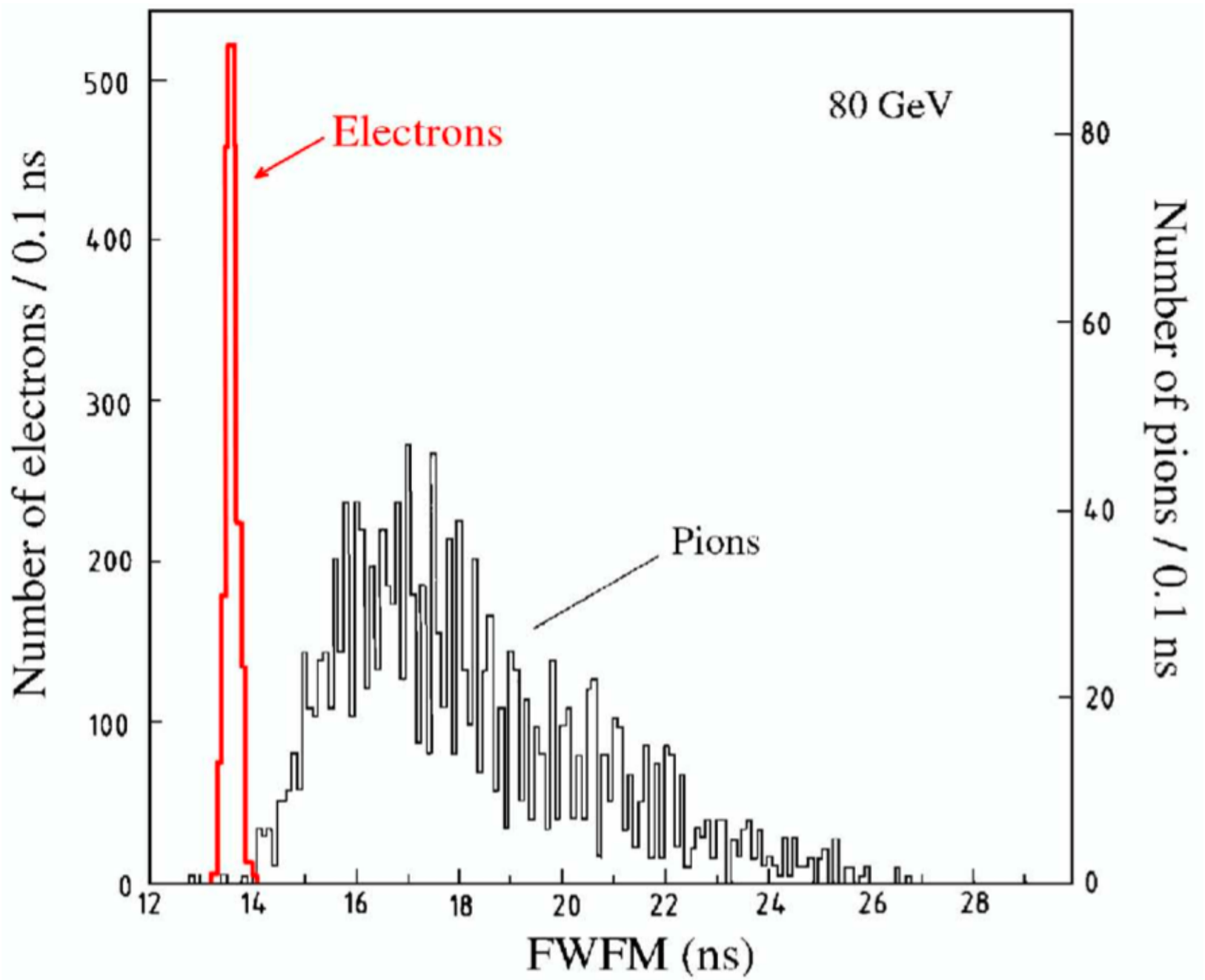
e-π discrimination

$$\chi^2 = \Sigma_k^N \left(\frac{S_k - C_k}{\sigma_k}\right)^2 \sim N \qquad \text{(for EM particles)}$$
$$>> N \qquad \text{(hadronic particles)}$$



Dual-readout

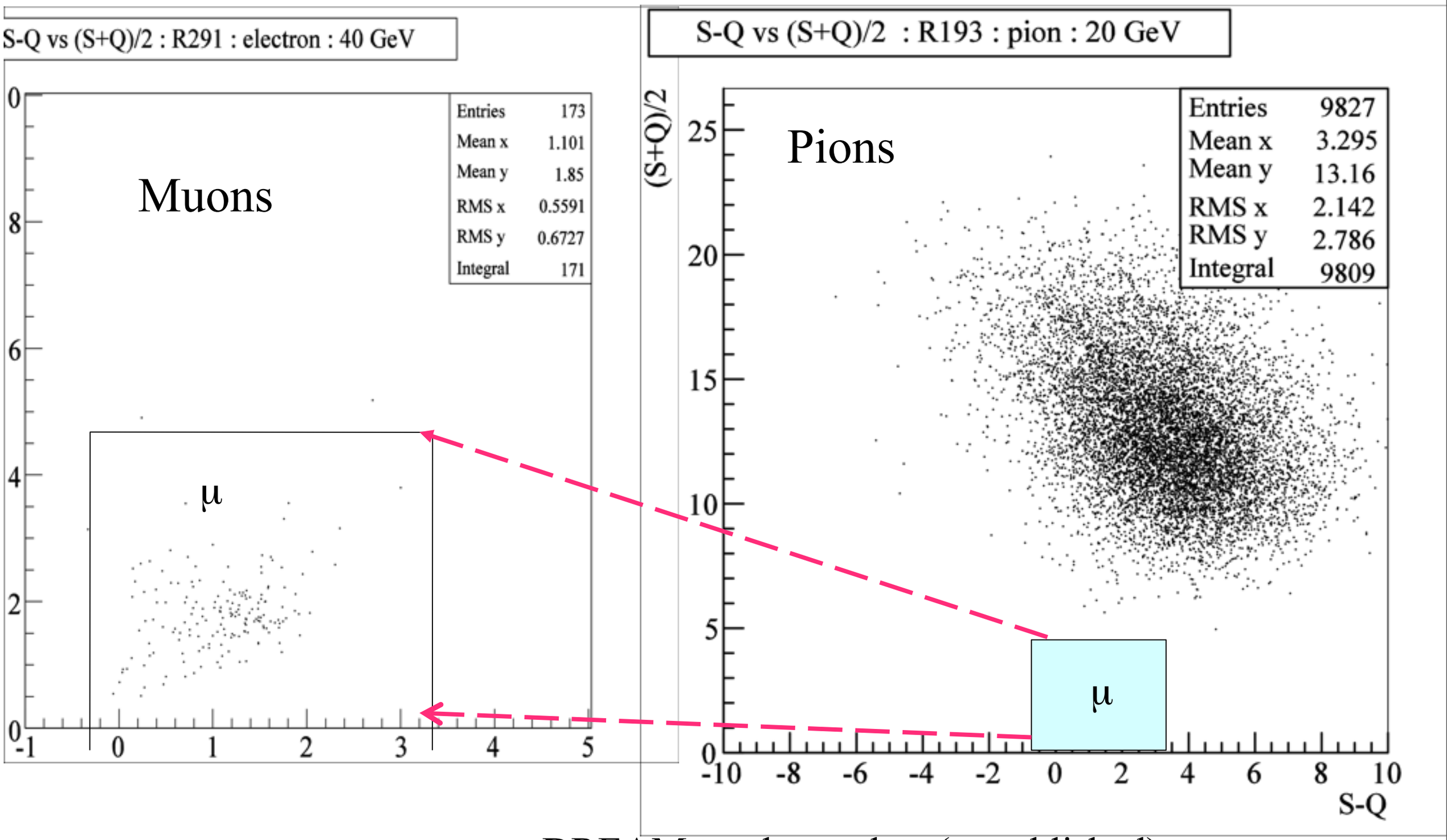
e-π discrimination



Dual-readout

μ-π discrimination

Separation of muons from pions at 20 GeV

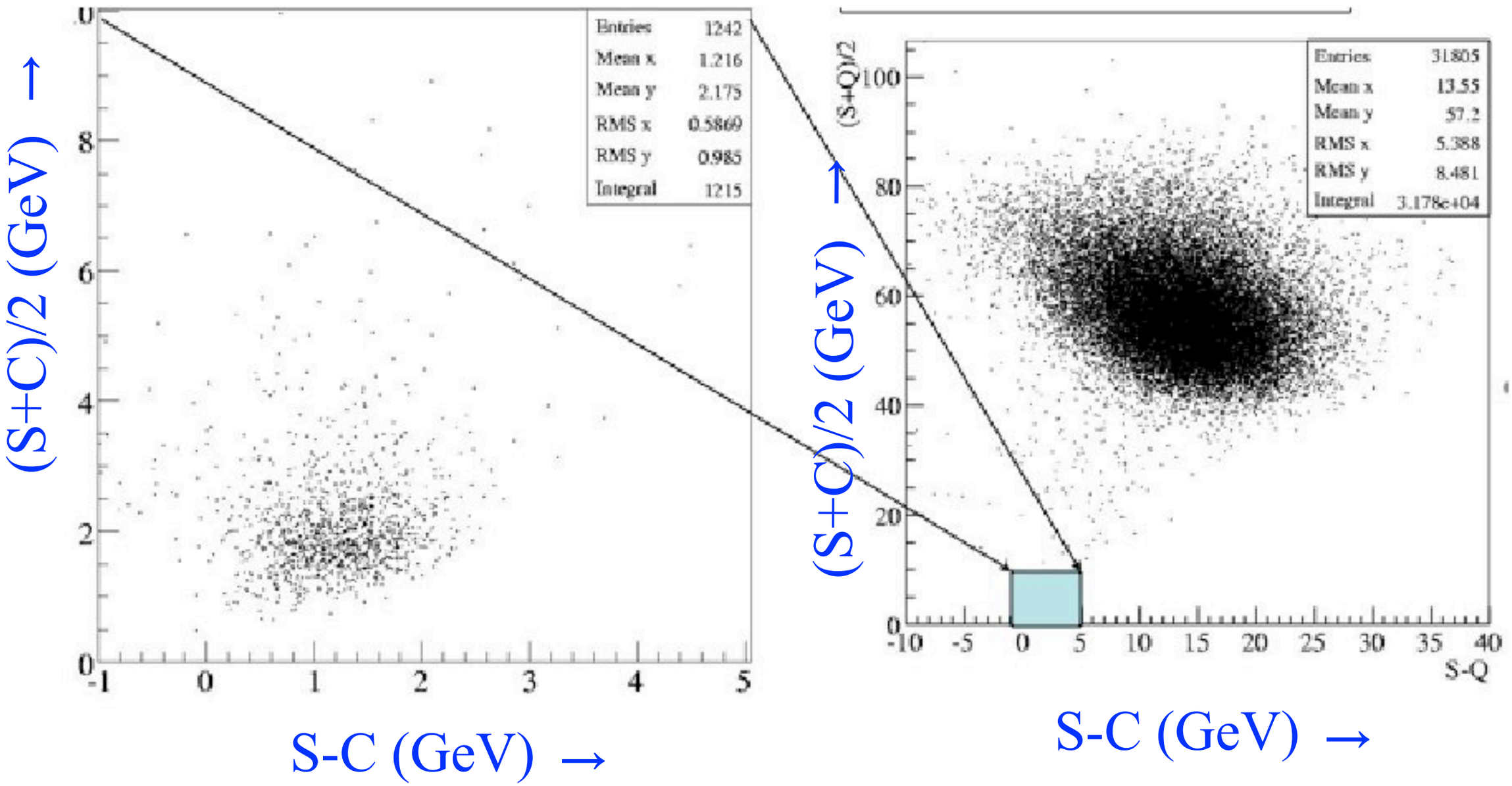


DREAM test beam data (unpublished)

Dual-readout

μ-π discrimination

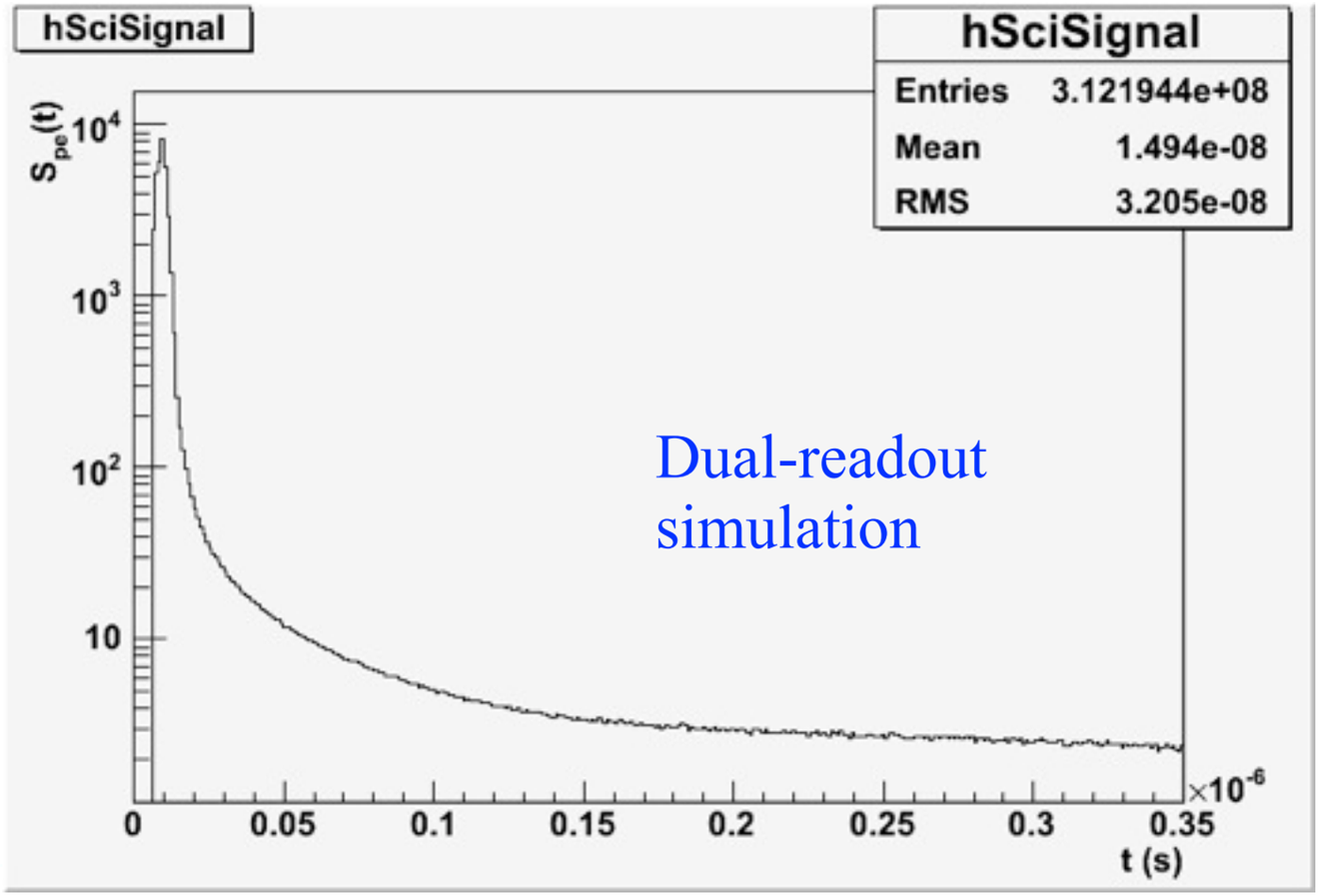
Separation of muons from pions at 80 GeV



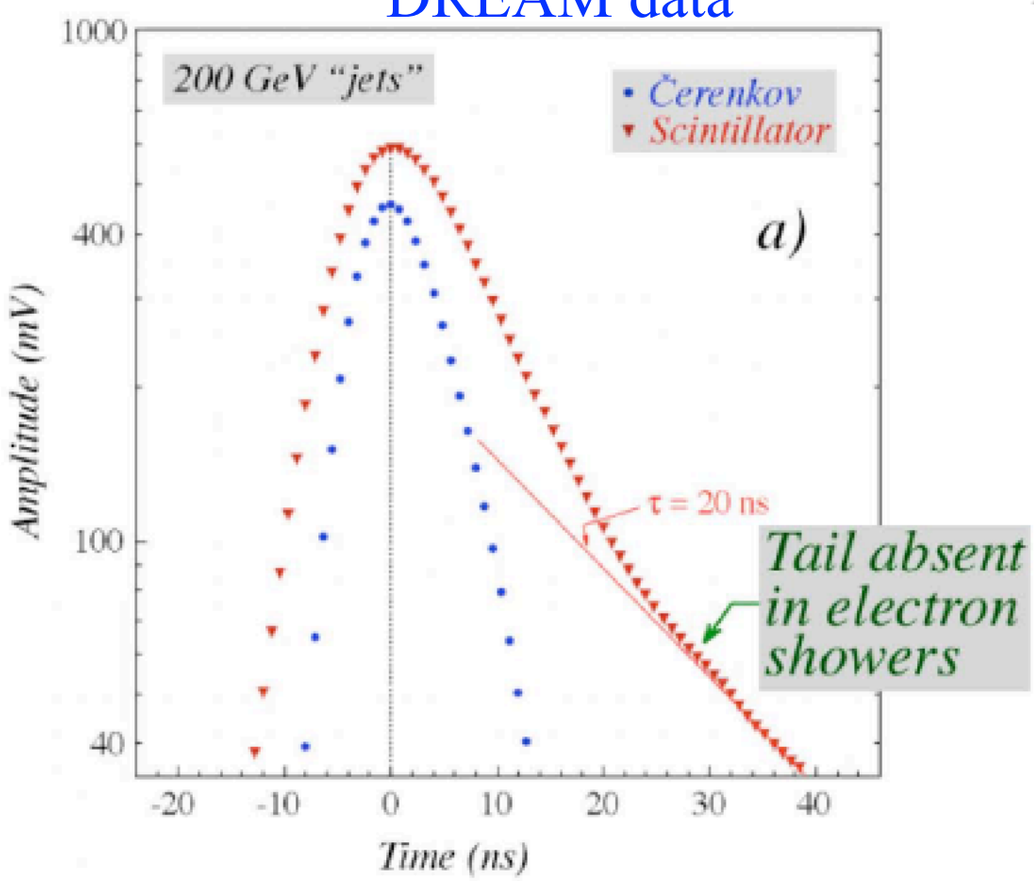
Dual-readout

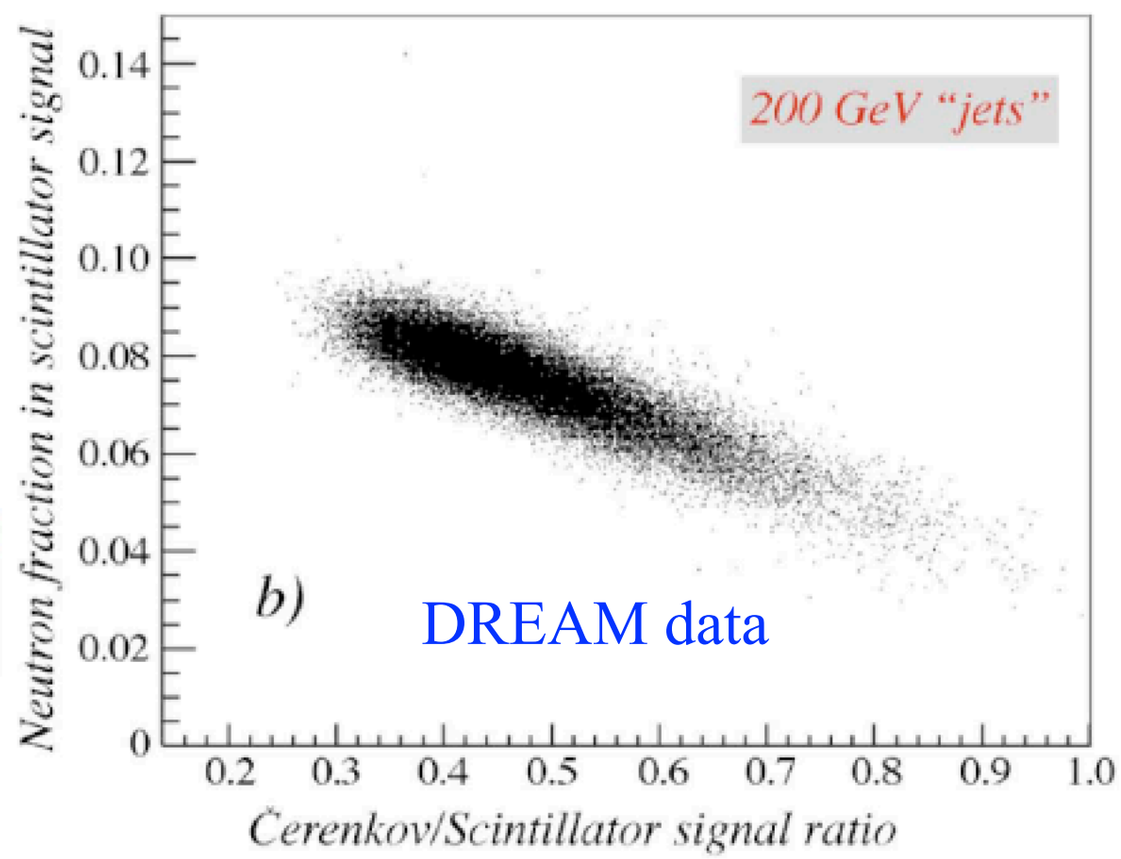
neutron-hadron tagging

$f_n \sim$ n-signal/E_{shower}



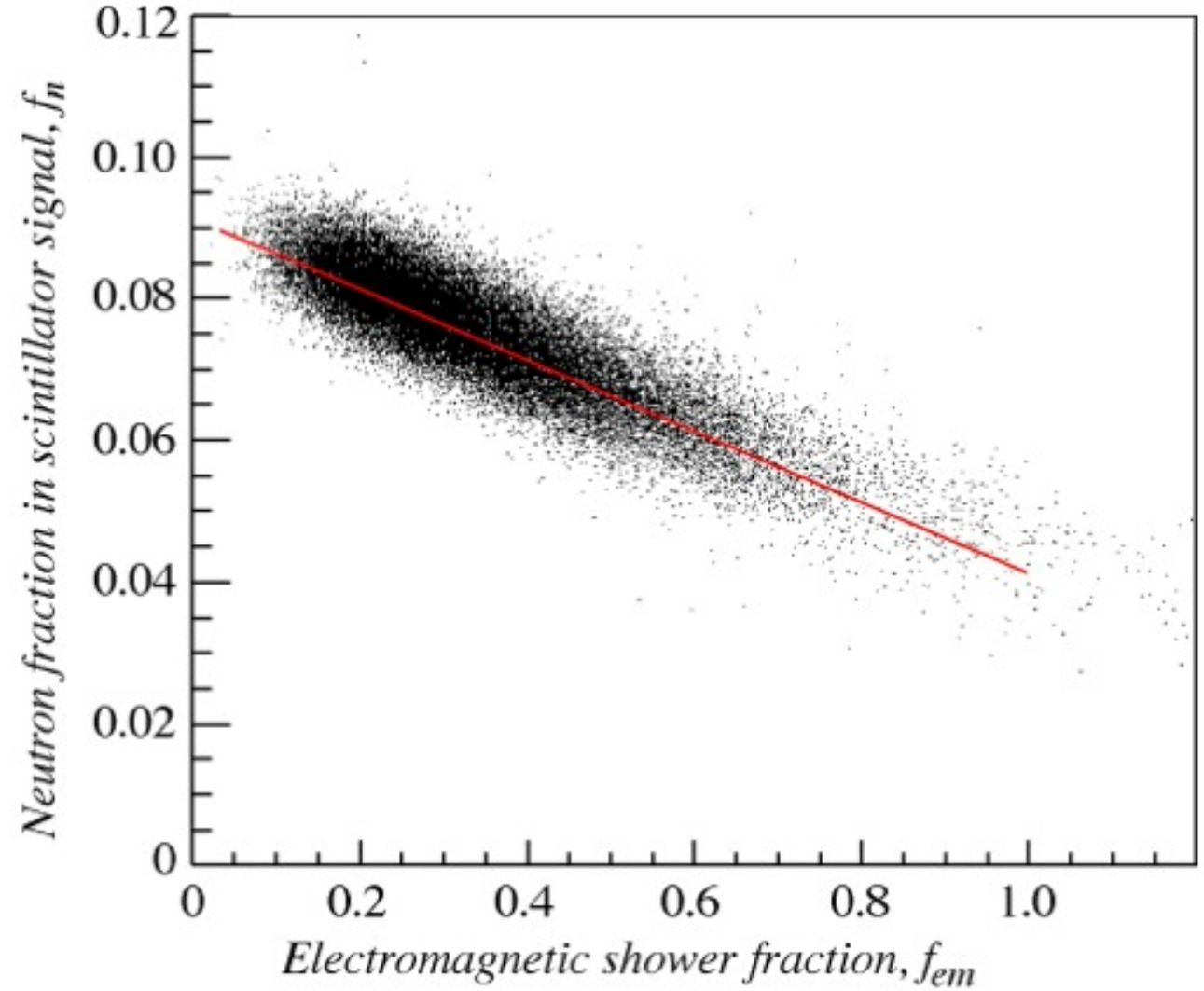
DREAM data

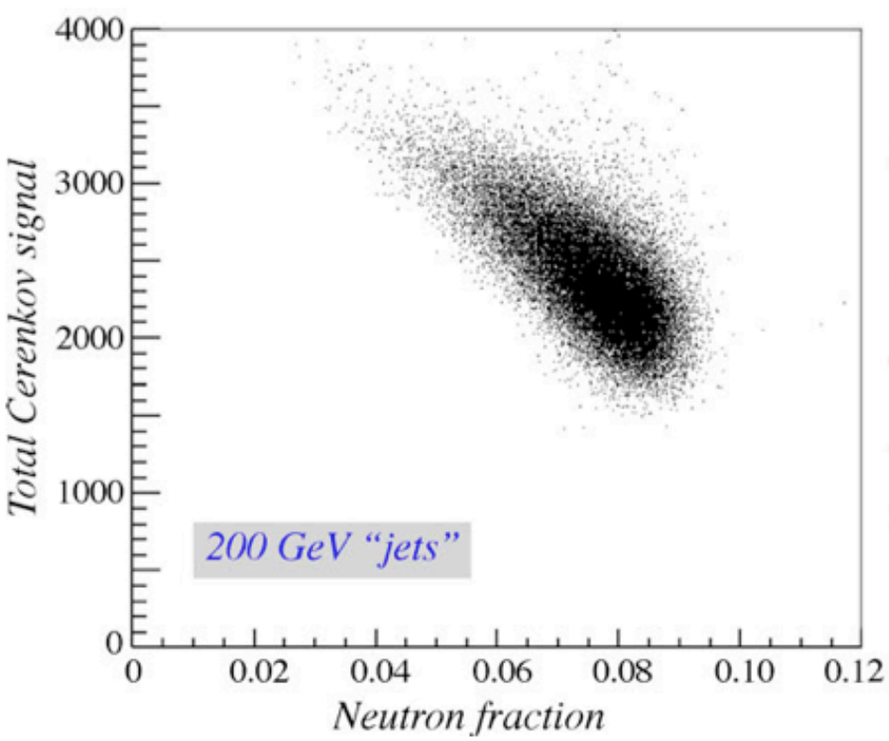


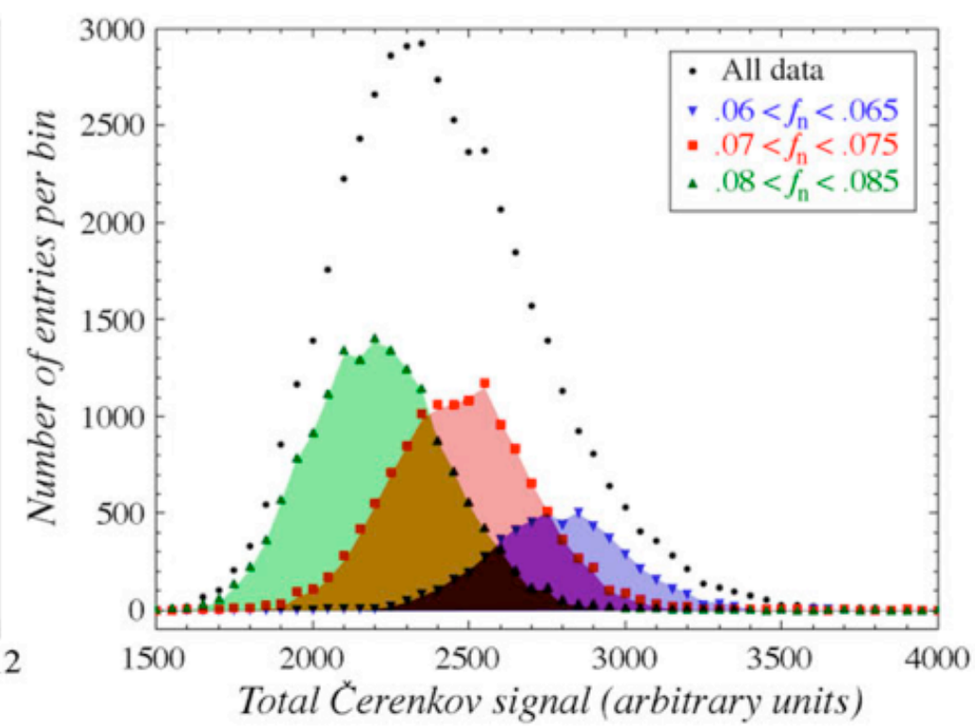


neutron fraction, f_n

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





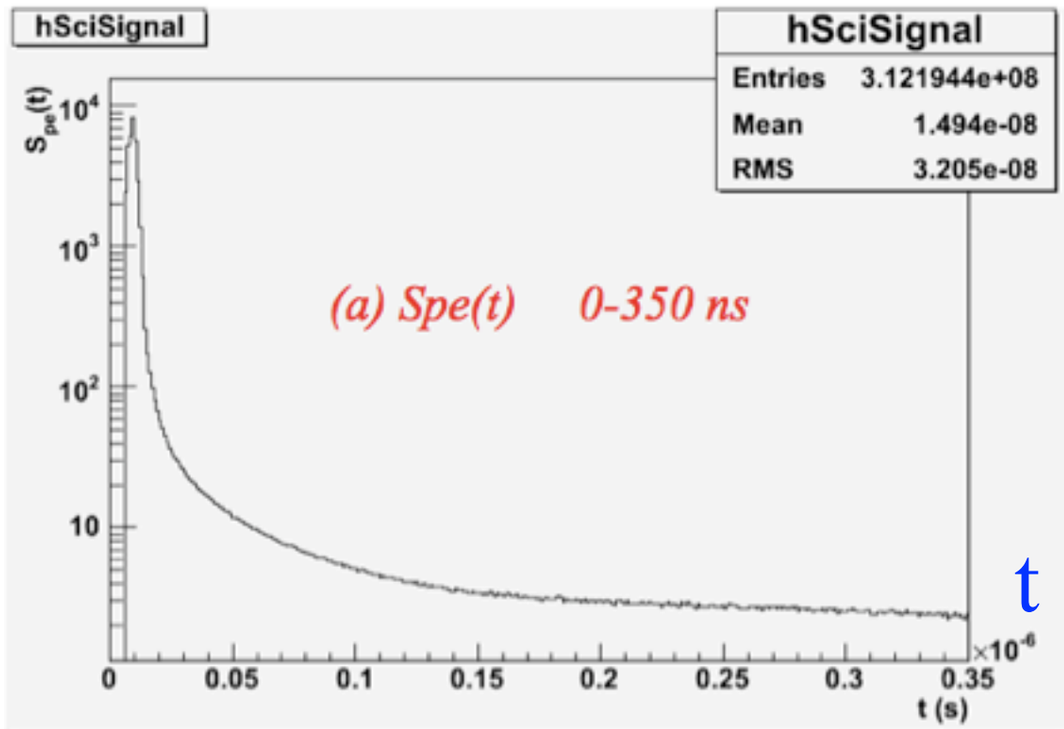


... also use this to improve the hadronic energy resolution.

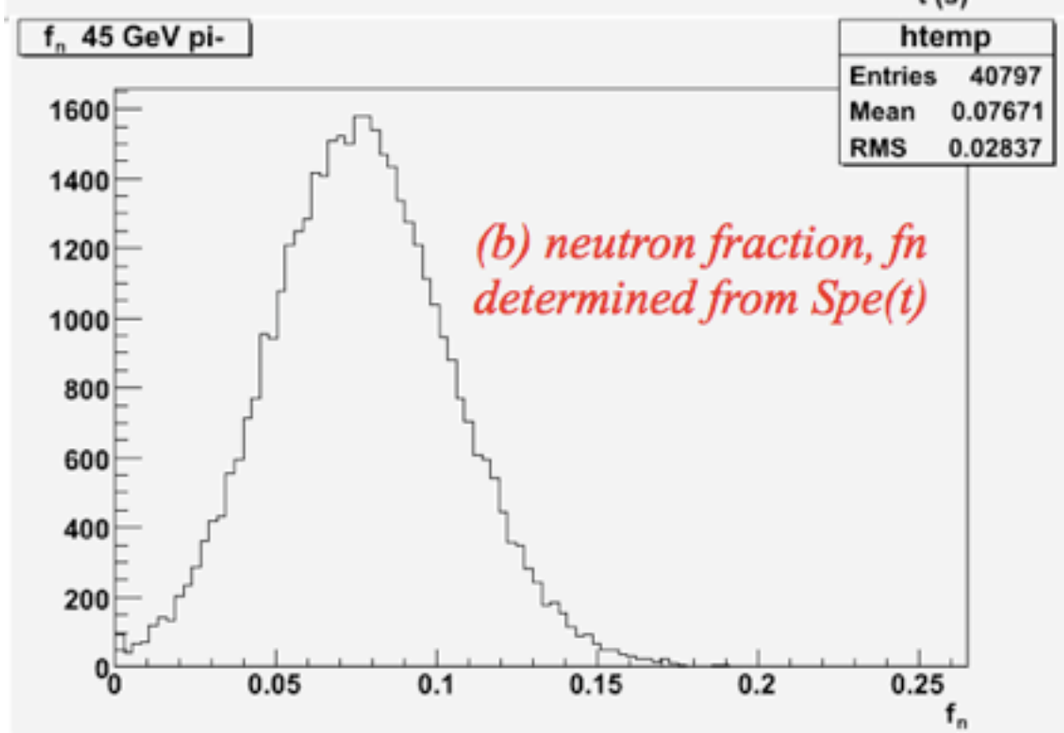
We also calculate f_n from $S_{pe}(t)$ time-history

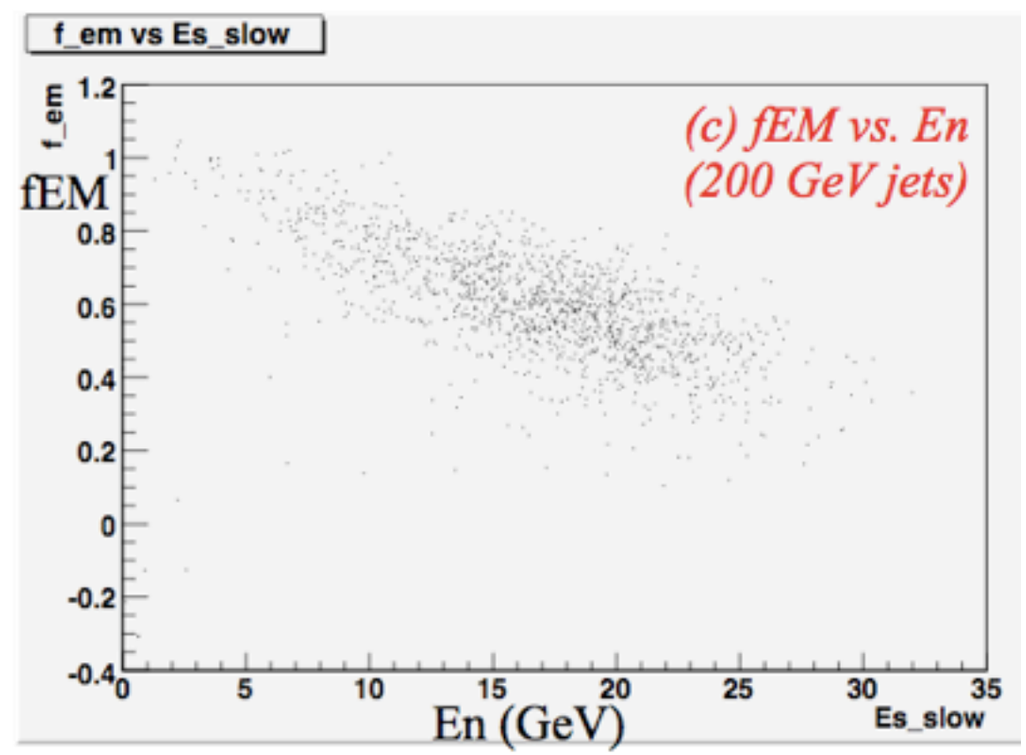
Pavia CALOR08

4th ILCroot V. Di Benedetto



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

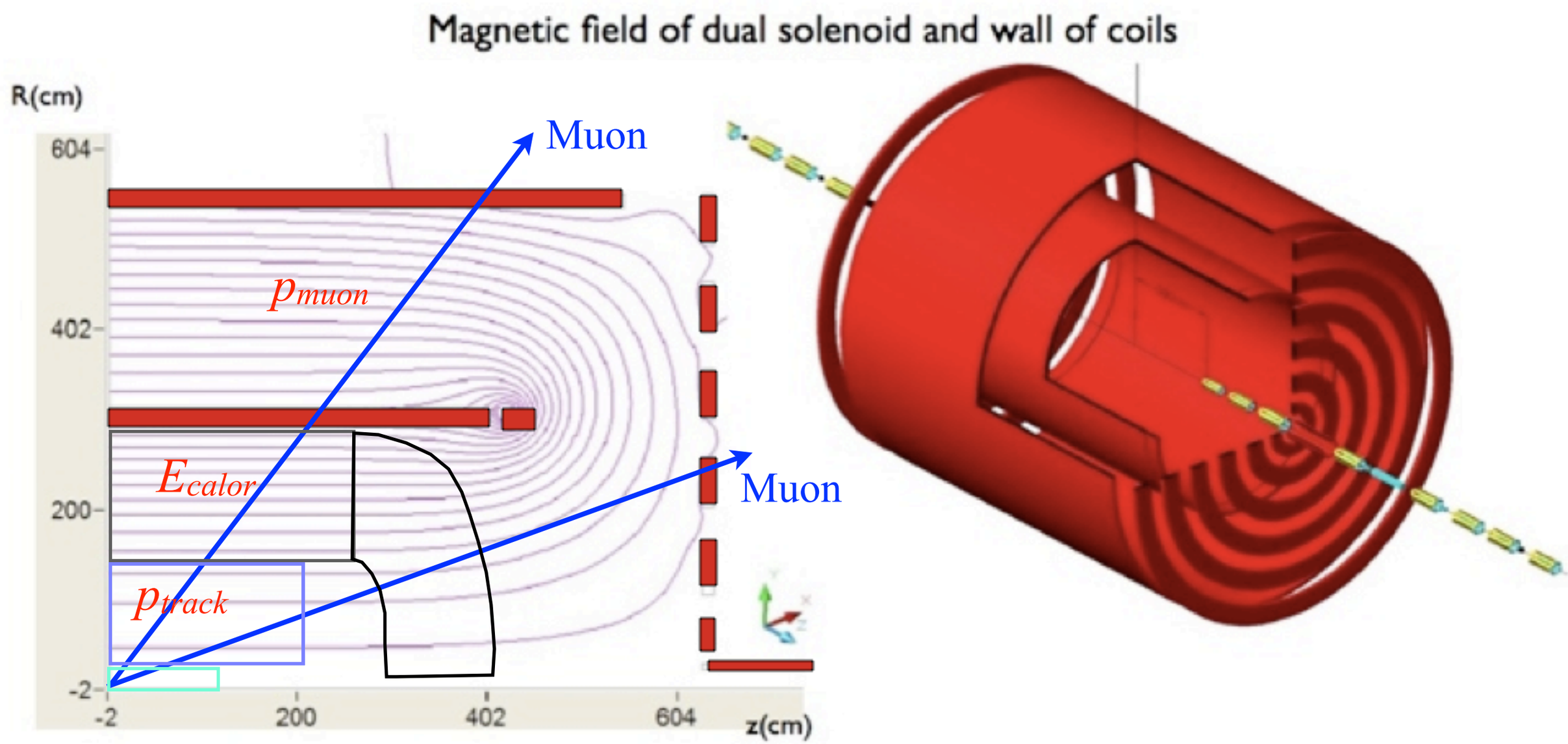




Dual-solenoid

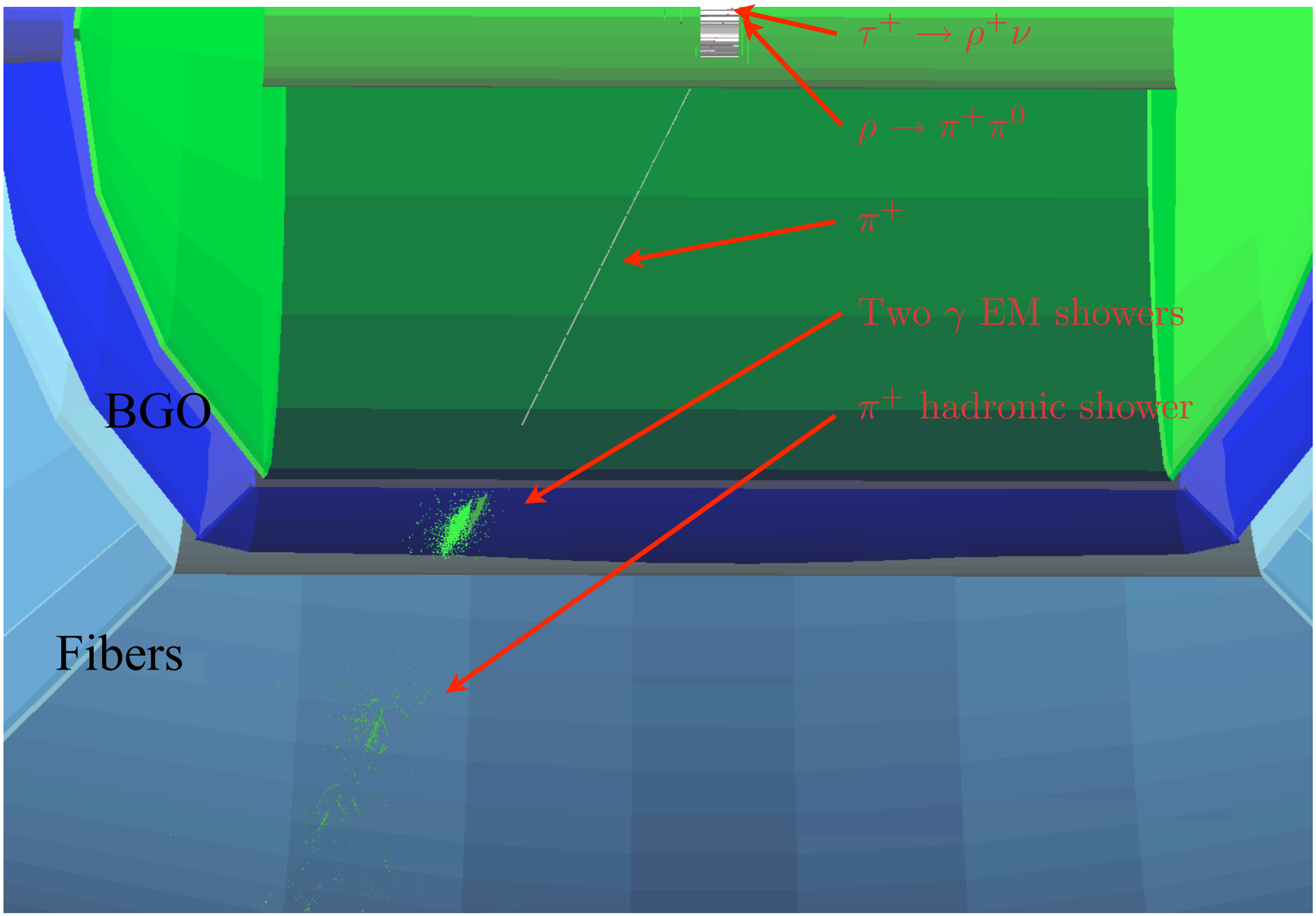
μ-π discrimination by energy balance

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

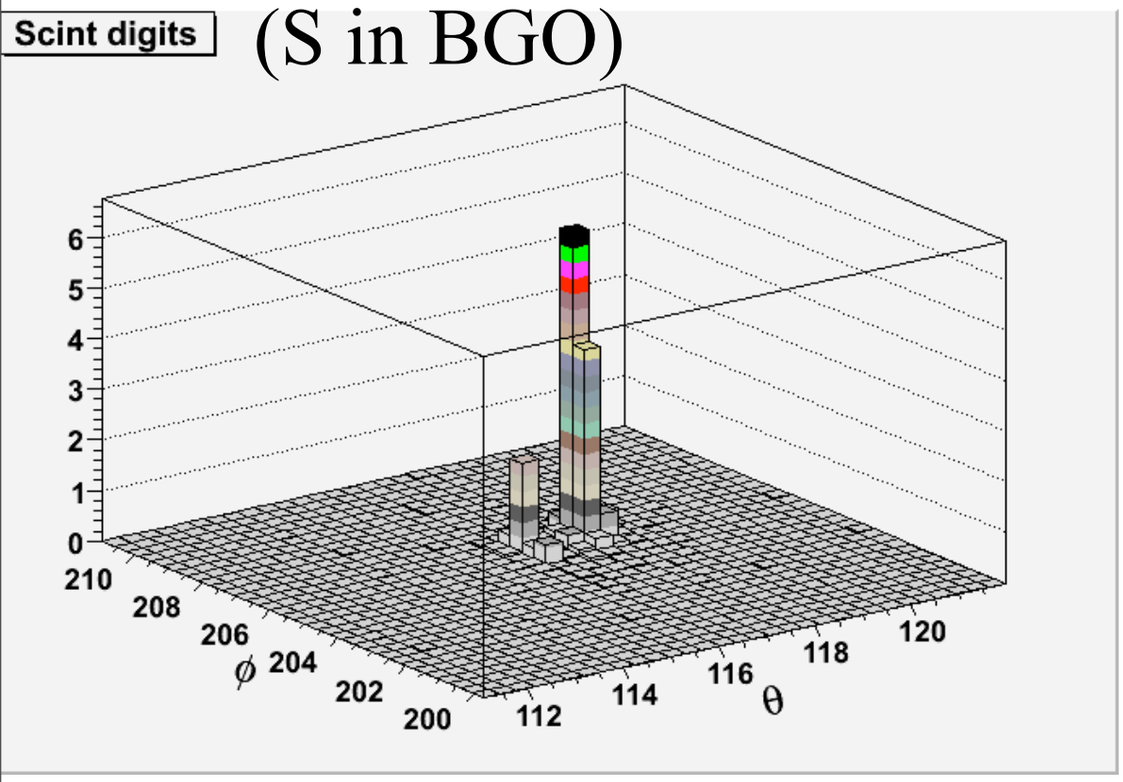


$\tau \rightarrow \rho\,\nu$

ρ is spin=1 … polarization analyzer

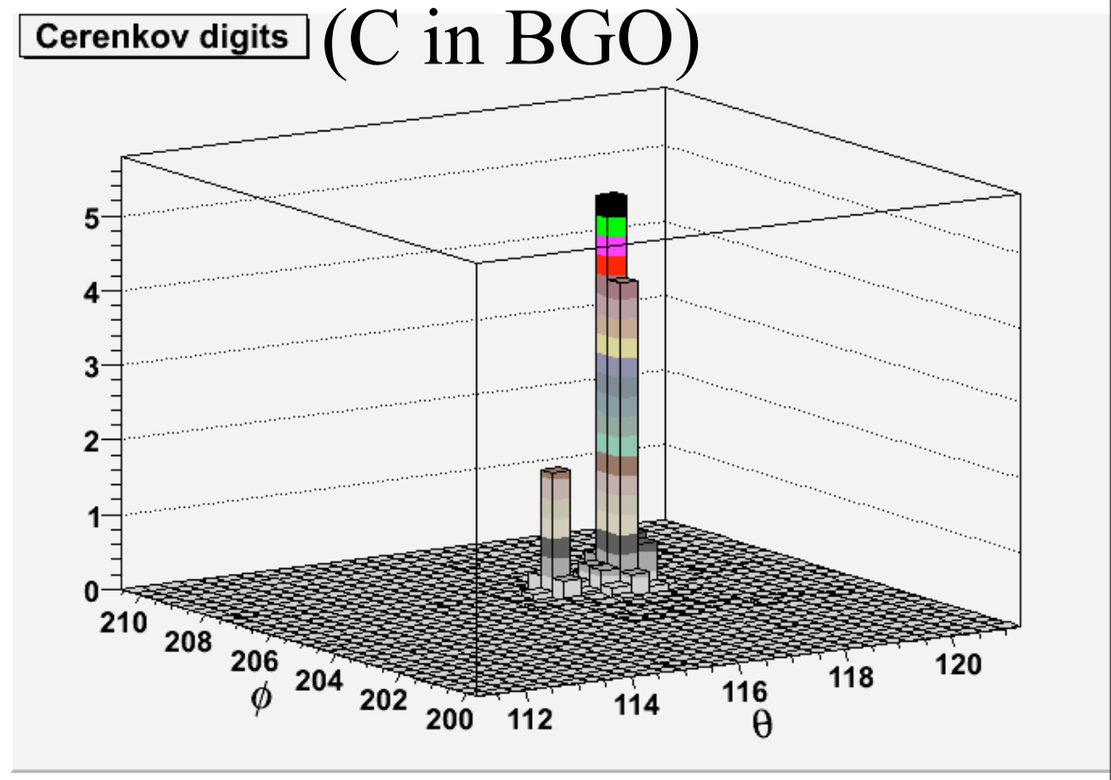


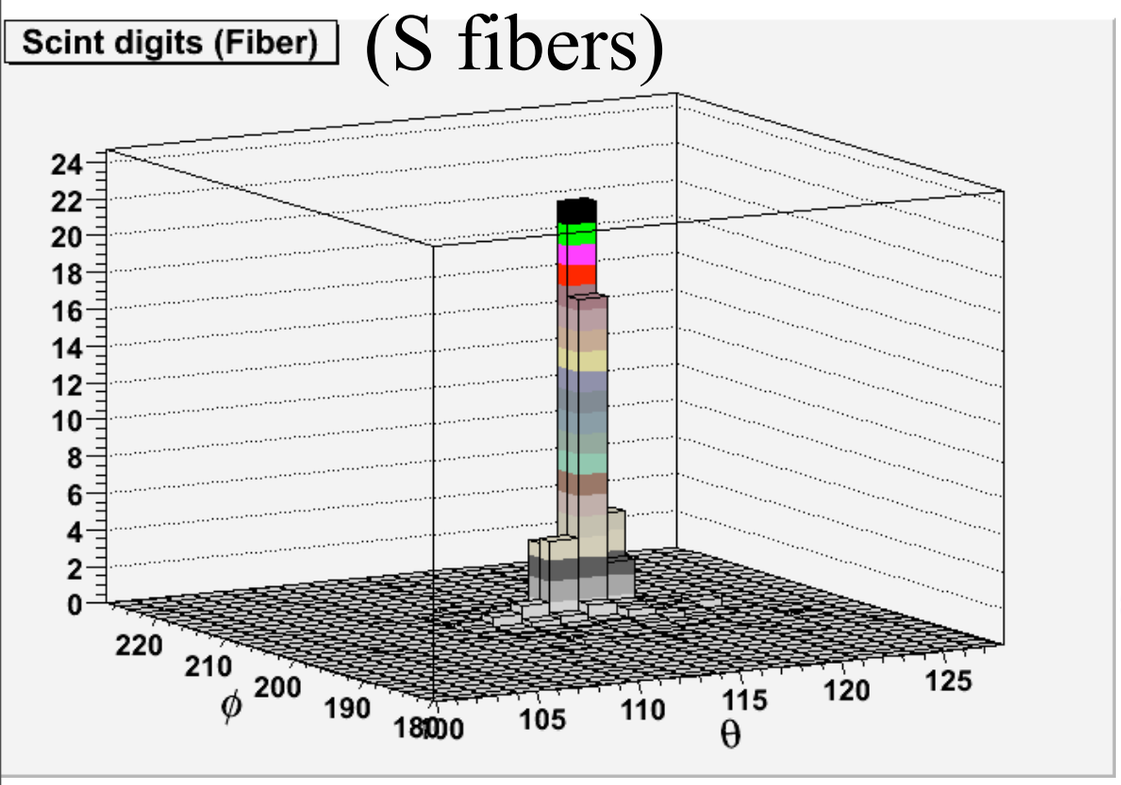
$\tau \rightarrow \rho \nu$



two clear photons

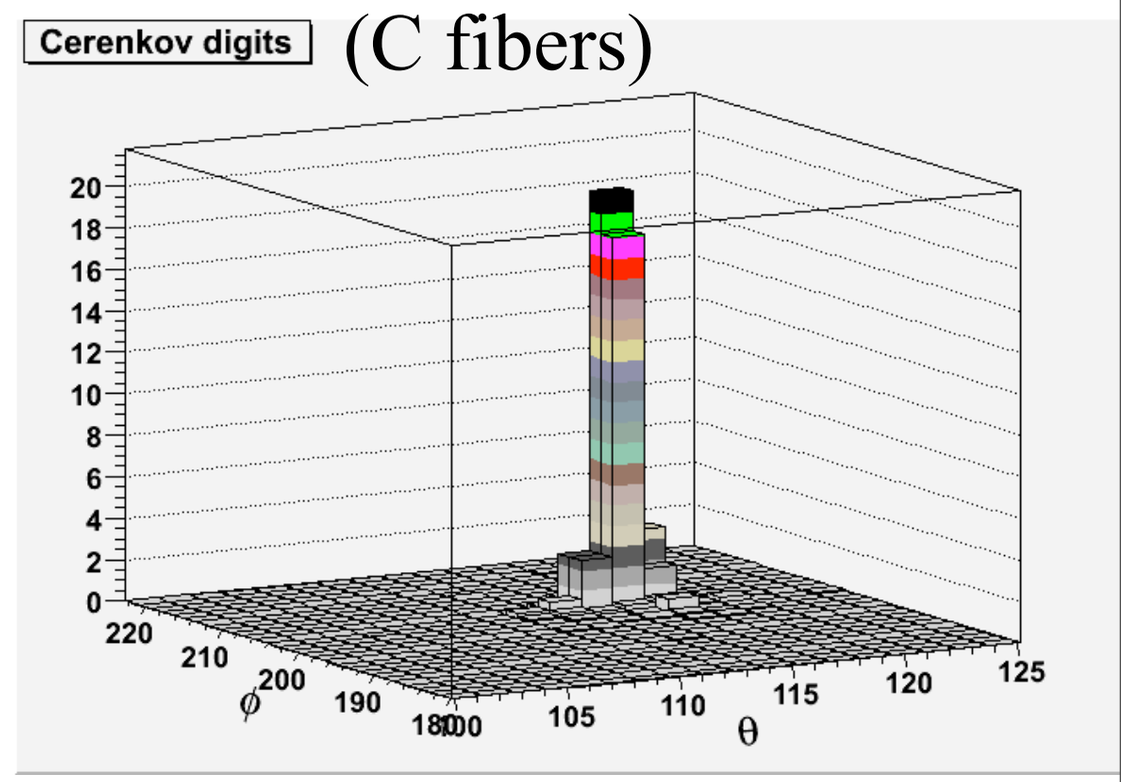
S~C (EM)





one clear shower

S>C (hadronic)

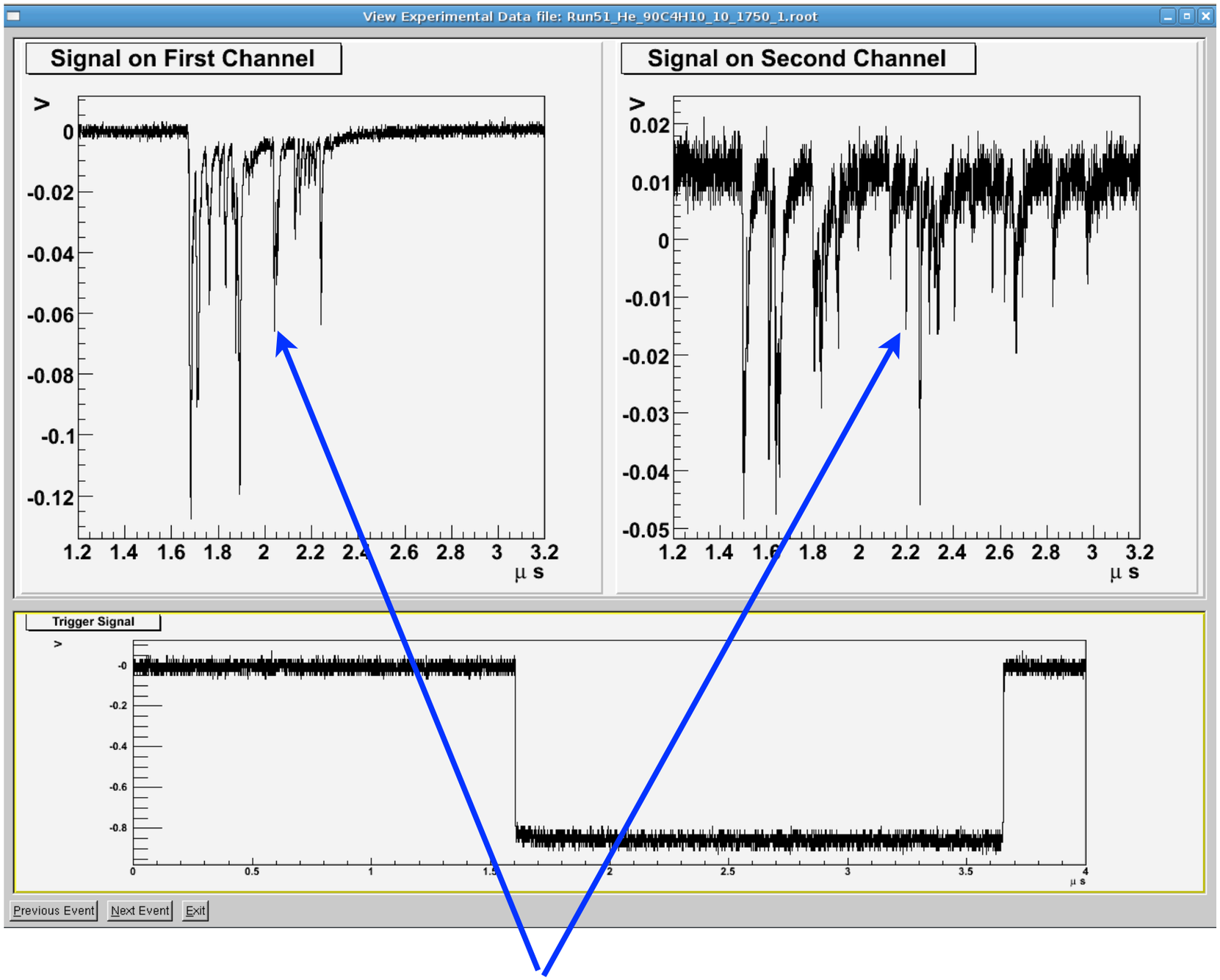


CluCou

μ-π-K-p tagging

dE/dx by cluster-finding:

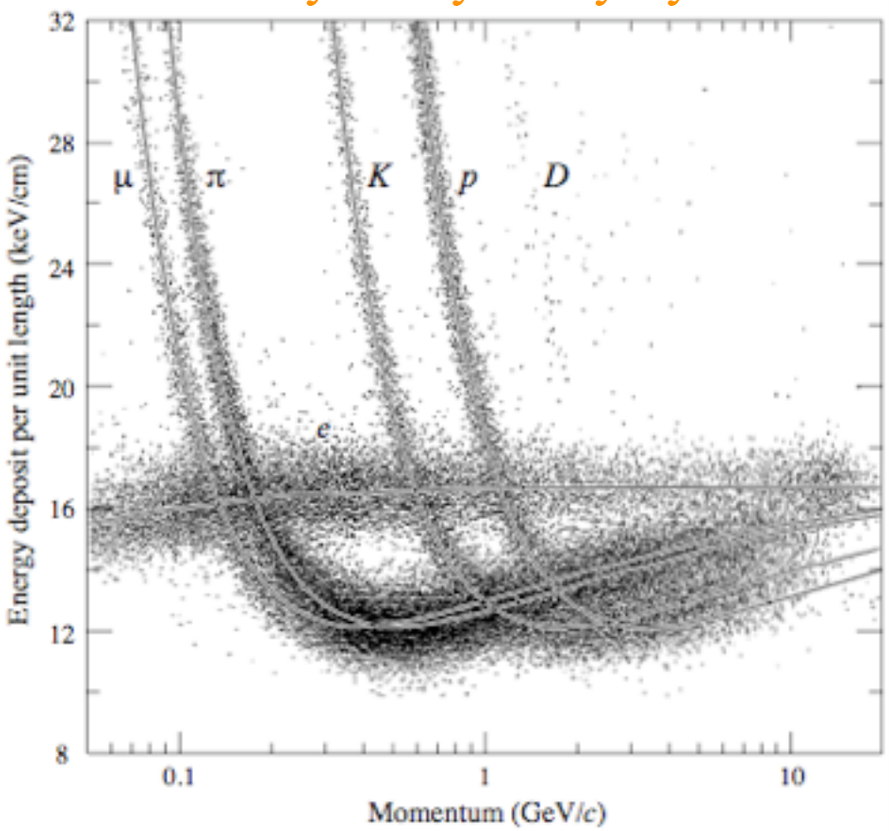
specific ionization ~ 3%



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

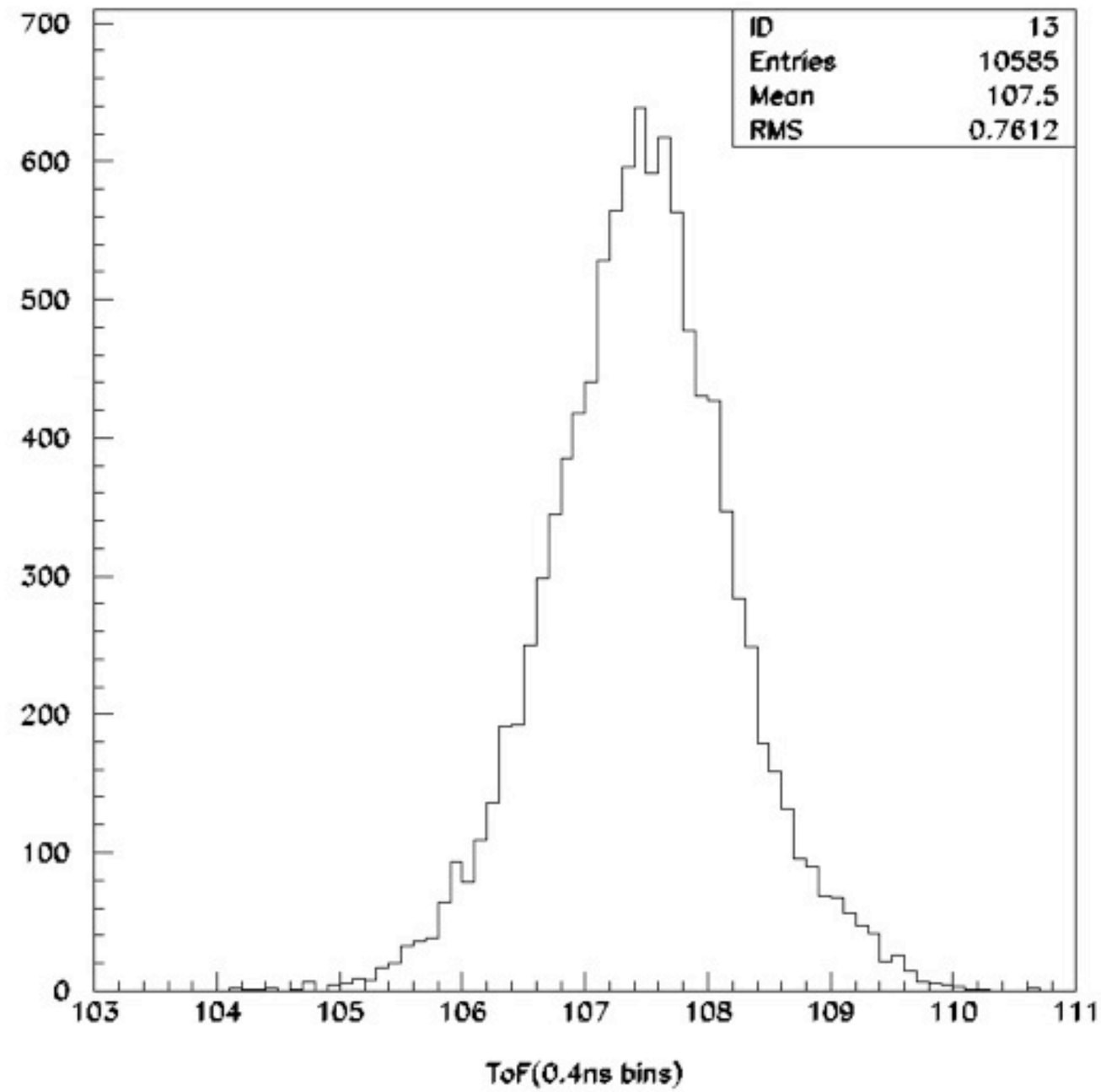
TPC with ~6% dE/dx resolution

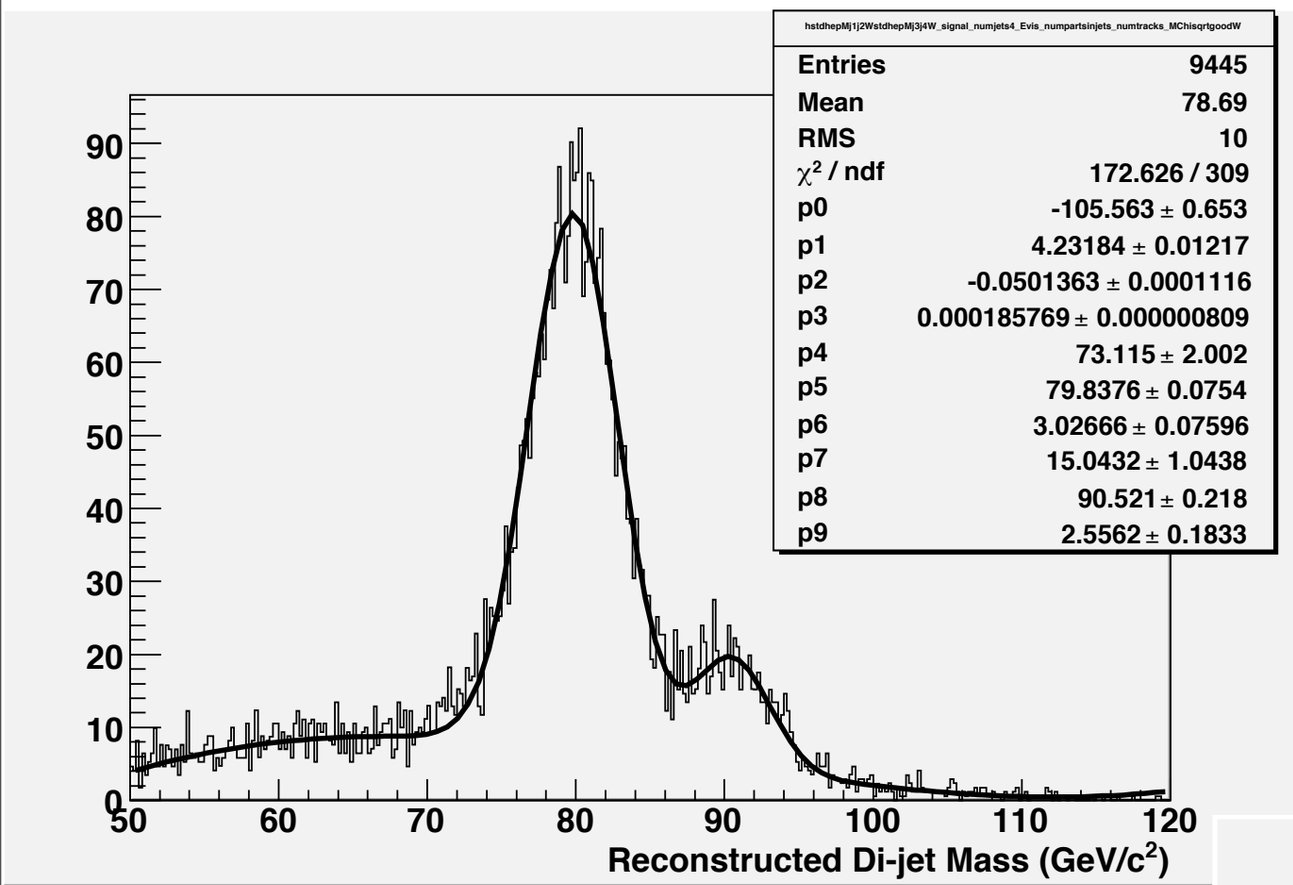
This TPC built by Dave Nygren, LBL, in 1970's, analyzed by Gerry Lynch.

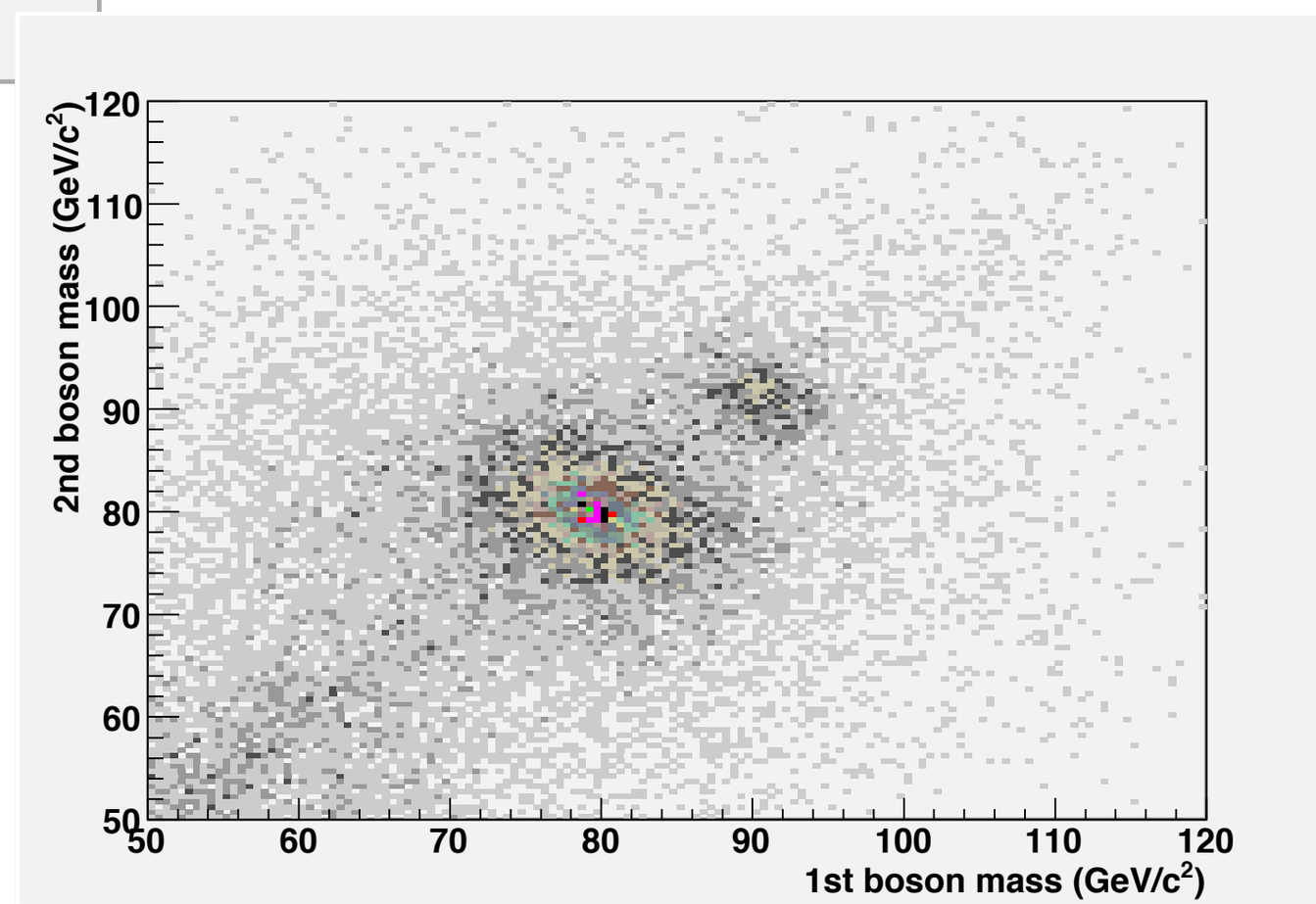


Time-of-flight of Cerenkov light in DREAM fibers

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



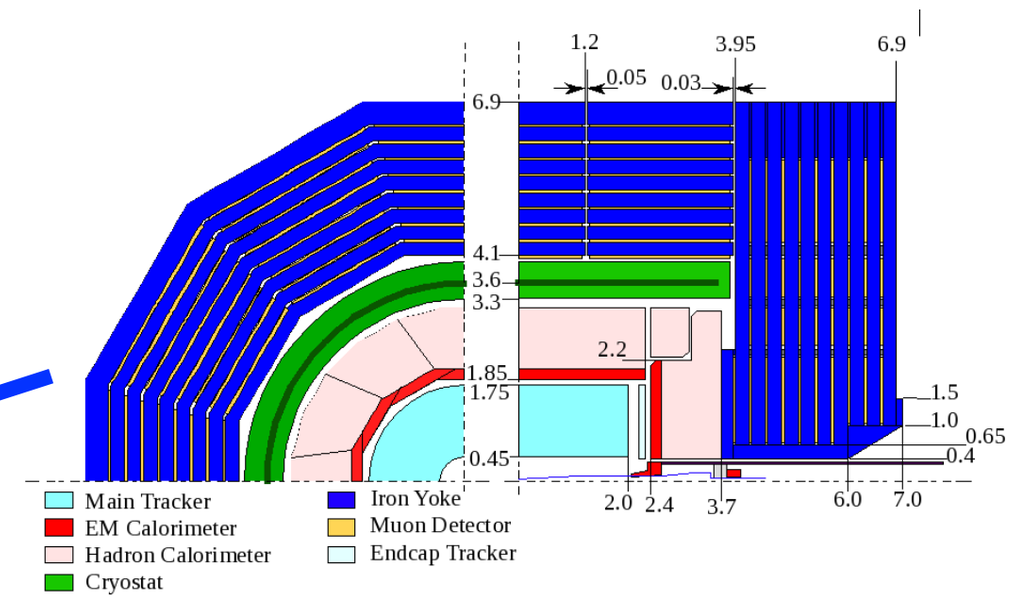

hstdhepMj1j2WstdhepMj3j4W_signal_numjets4_Evis_numpartsinjets_numtracks_MChisqrtgoodW
Entries 9445
Mean 78.69
RMS 10
χ² / ndf 172.626 / 309
p0 -105.563 ± 0.653
p1 4.23184 ± 0.01217
p2 -0.0501363 ± 0.0001116
p3 0.000185769 ± 0.000000809
p4 73.115 ± 2.002
p5 79.8376 ± 0.0754
p6 3.02666 ± 0.07596
p7 15.0432 ± 1.0438
p8 90.521 ± 0.218
p9 2.5562 ± 0.1833
Reconstructed Di-jet Mass (GeV/c²)


2nd boson mass (GeV/c²)
1st boson mass (GeV/c²)

The next seven frames are reasons why the dual-solenoid is a good idea for the ILC.

4th is "different" in almost every possible way (we are not trying to be different, or difficult)

- Flux return by a second solenoid (and therefore no iron mass) is a big deal.
  - 4th 1.5Kt
  - SiD 10 Kt
  - LDC 10 Kt
  - GLD 17 Kt



- As a consequence, almost every problem you can think of in the IR is easier; physics is better, too.
- "Self-shielding" solution (T. Sanami and A. Seryi) is discussed later.

"Iron Age" physics

- An iron yoke adds little to the magnetic environment, is not necessary for field uniformity, serves as only a crude pion filter, and ruins the momentum resolution on a muon.
- The iron may be good for hanging the calorimeter, but it also forecloses forever alterations, improvements and additions to the detector outside the calorimeter.
- Access and movement are more difficult, push-pull is more difficult, including supports and floor settling.
- It is not cheap: CMS iron is $35-75M.

Iron-free "basic principles"

Returning the flux with a second solenoid and the wall-of-coils

a) confines the field almost completely, no fringe field;

b) reduces detector-distorting forces associated with the field to almost zero;

c) allows a second muon momentum measurement and contributes to muon identification by energy matching;

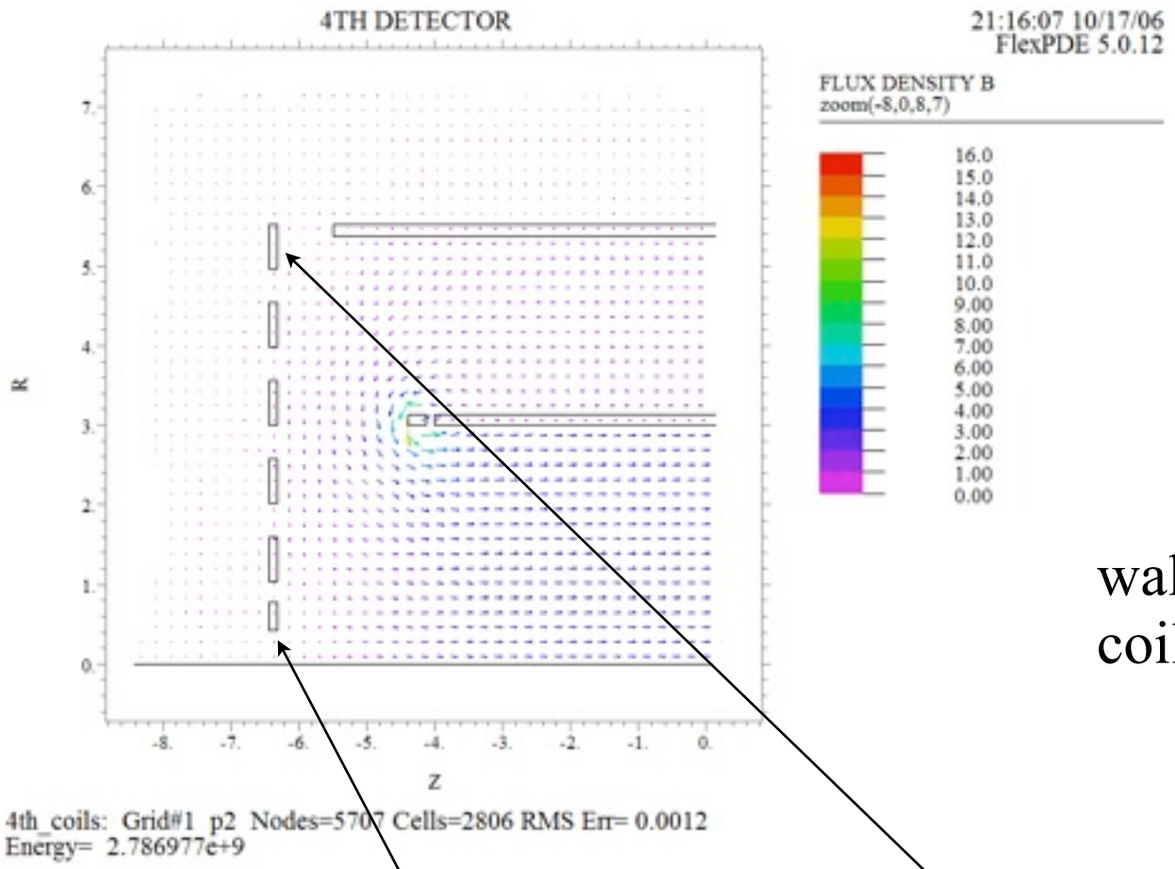
d) allows the cancellation of detector asymmetries in quark asymmetry measurements by B→ -B everywhere;

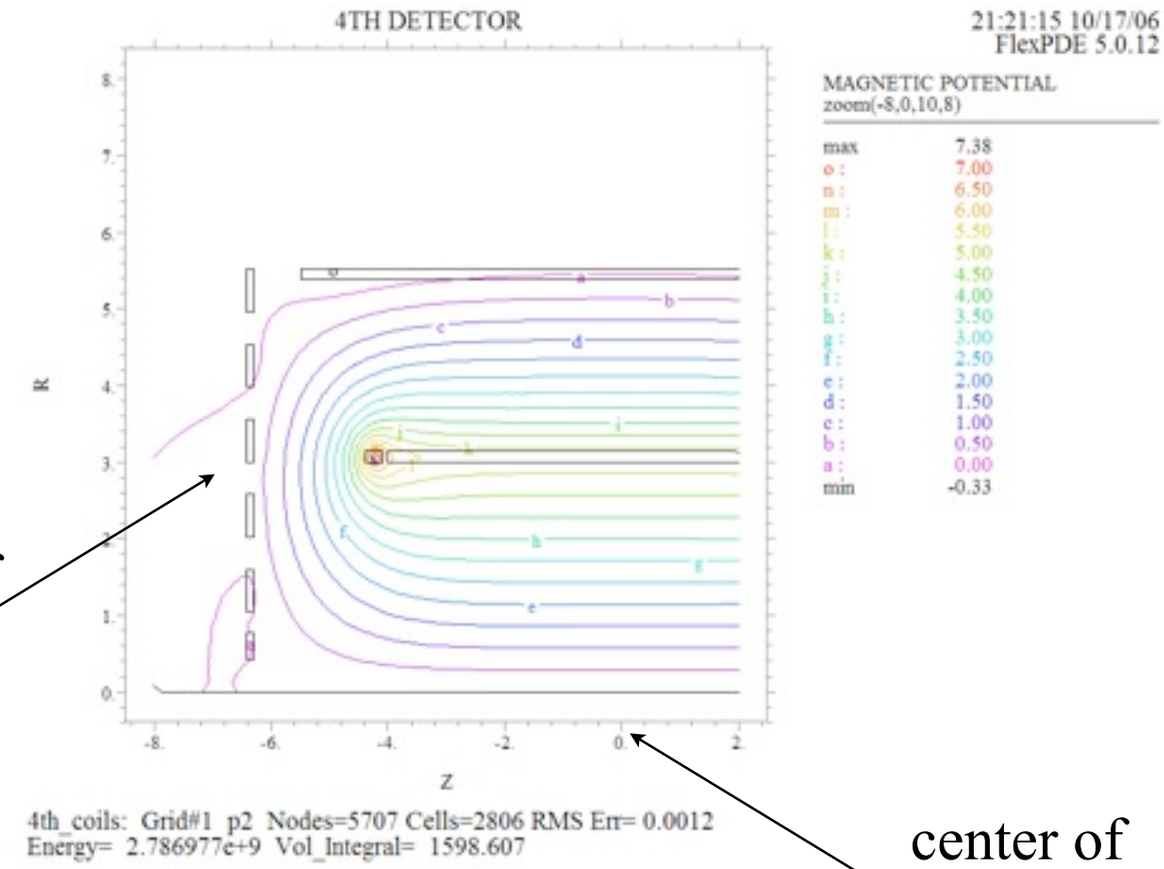
e) allows additions outside the calorimeter in future years (think Lead Glass Wall, or anti-neutron counters on the Magnetic Detector);

f) push-pull, repositioning, surveying are easier; and,

g) you have complete control of B on and near the beam.

Magnetic field configuration





wall of coils

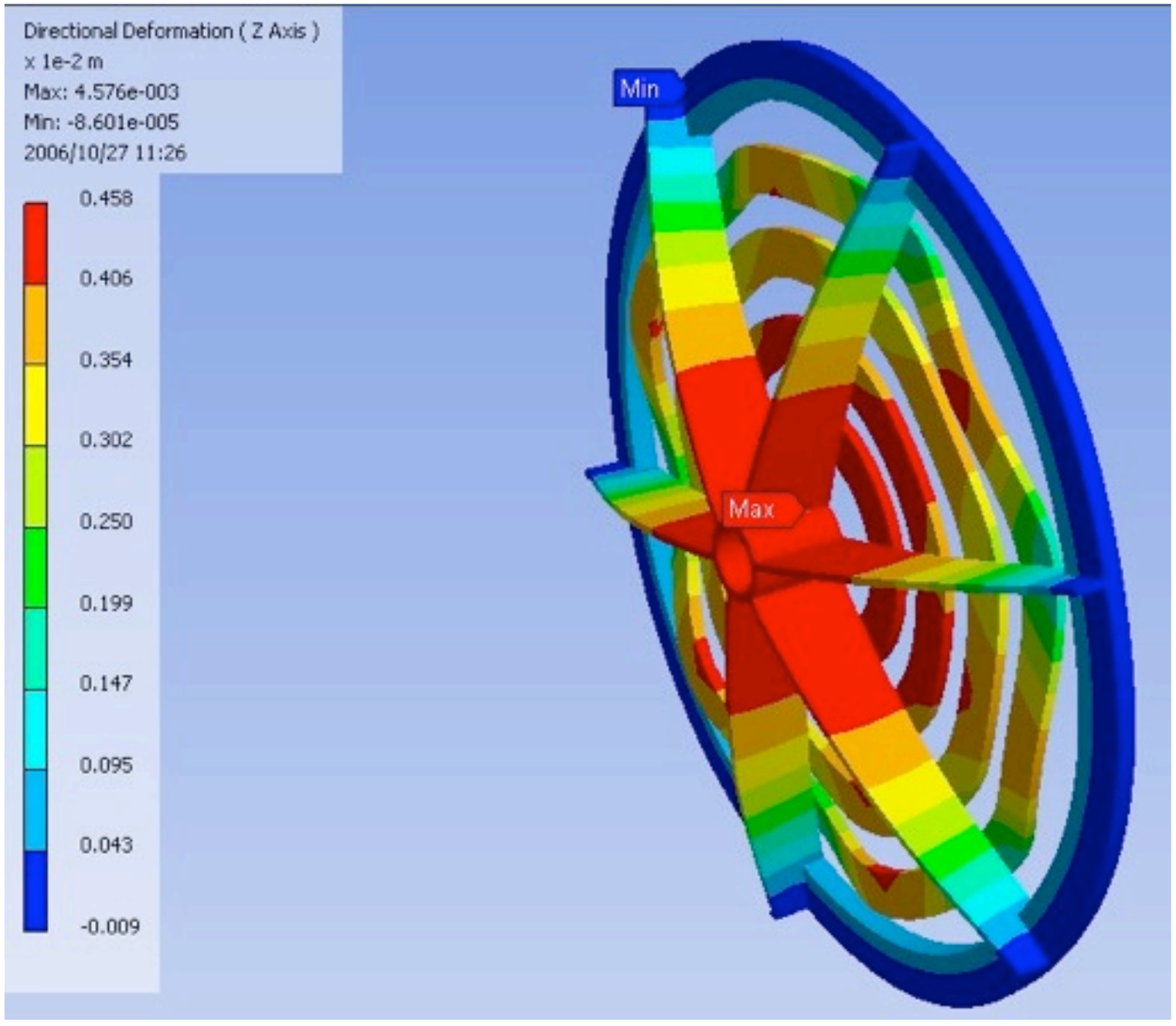
center of detector

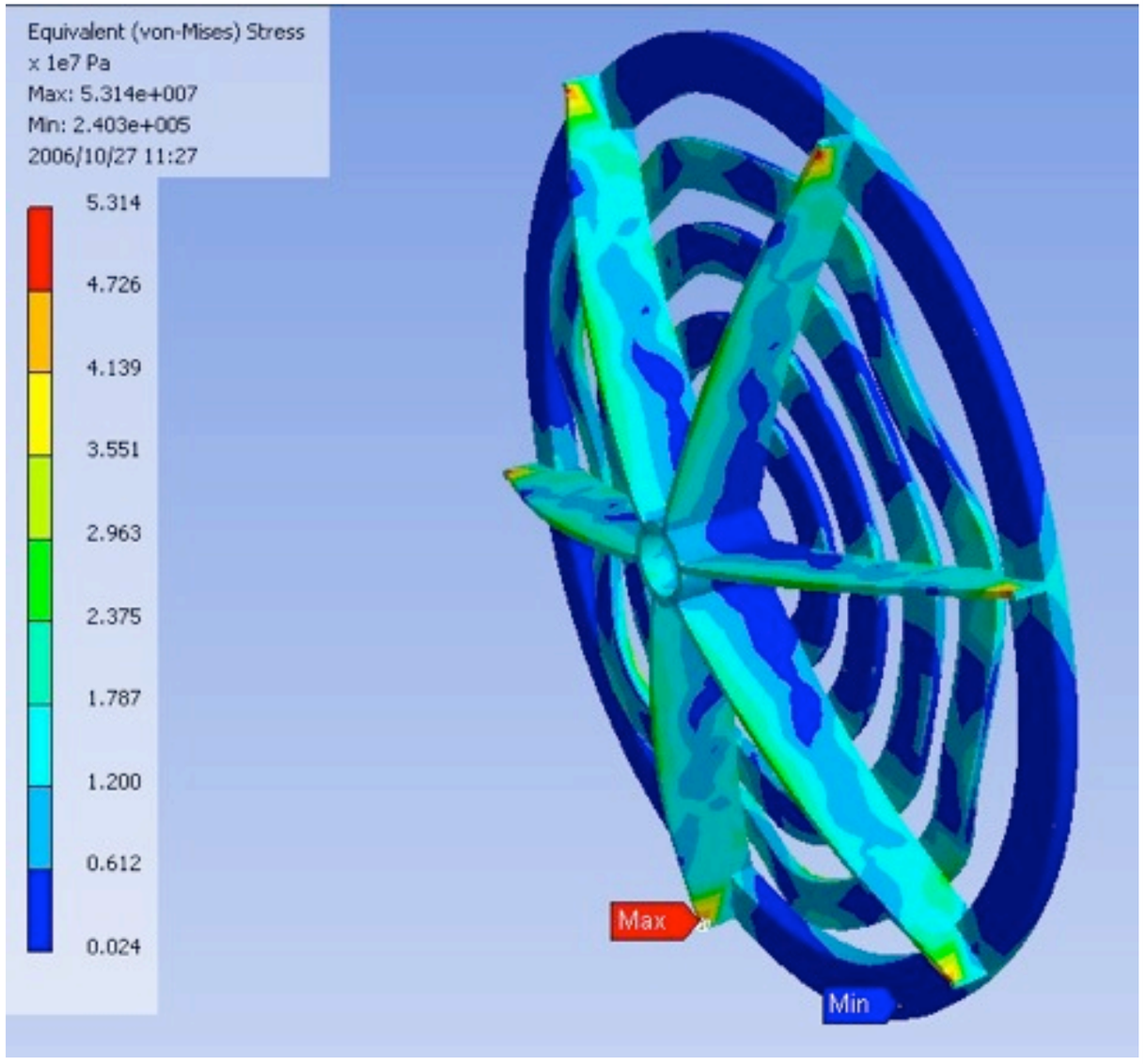
J(A/mm^2): 1; 8; 4.2; 3.3; 3.7; 1.7
Force(tons): 1.75; 102; 131; 135; 111; 10

- In a future optimization, all coils will have approximately the same current density
- Field outside the detector can be zeroed to any level required by a proper current distribution
- The coils can be fixed easily at the end plates

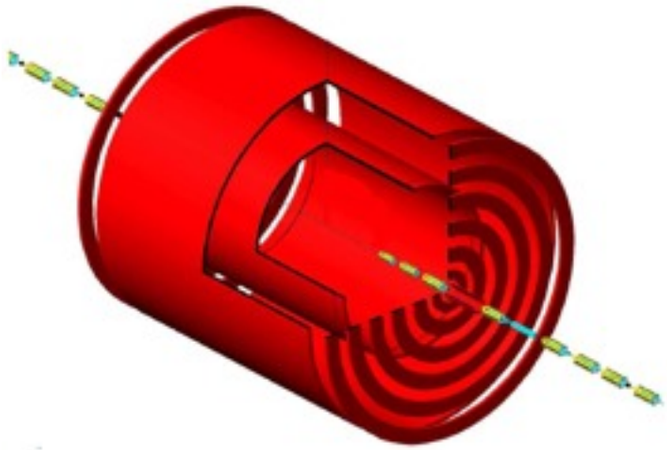
Deformations of end coils & support

Maximum deformation is in z, it is less that 5mm, and in the middle of the holder. Active movers and reinforcements can compensate this.





Calculated by V. Medjidzade; calculations carried out by B. Wands, also.



4th Concept Detector at Fermilab
19-20 October, 2006

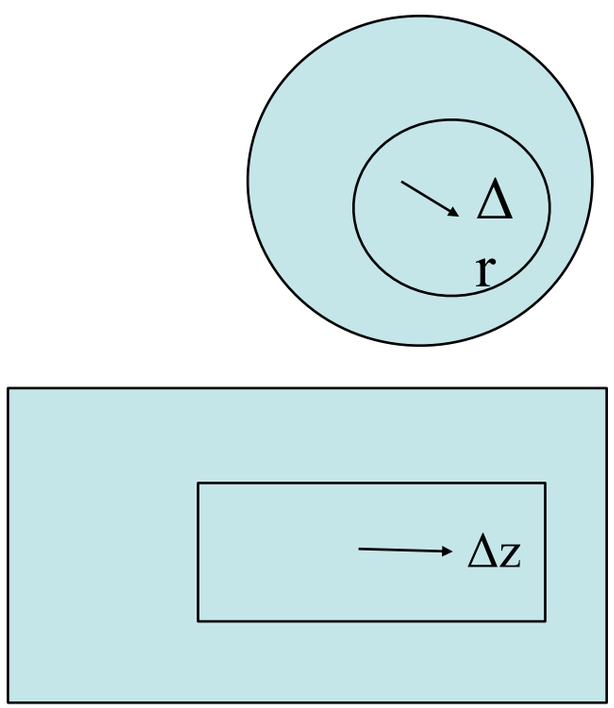
Fermilab
PPD/MD/Engineering Analysis Group

Magnets and Supports

Bob Wands October 20, 2006

Magnetic field analysis; coil technologies; preliminary structural calculations; modal analysis

- Stored energy 2.86 GJ
- Radial force is decentering ~ 0.4 t/mm
- Axial force is centering ~ 0.8 t/mm
- We need to relieve forces on coil ends
- Optimize, but no show stoppers
- Excellent note on conductor options, mechanics, support, remedies, solutions



Arguments and counter-arguments for iron vs. no-iron

Argument for no iron	Counter argument	Counter counter argument
Muon momentum is better measured in muon system	Doesn't matter; you can match to tracker momentum (AMiy)	Second measurement improves muon ID
Intra-detector distorting forces much reduced or non-existent	None ?	
Can reverse B and cancel detector asymmetries	Can achieve the same thing with Z--> mu mu events (JJar)	An independent check is essential and important
Allows additions and add-ons in later years	Unlikely to ever be done (JAle)	True; not many examples of this
Low mass: push-pull; (re-)positioning easier & cheaper	Not self-shielding	Can add concrete shielding walls; but it's not elegant
MDI advantages; complete control of B; no fringe field	Maybe not so (ASer)	To be discussed
Outer solenoid is easier than inner solenoid (~CMS)	Has to be built on-site due to size; expensive (P.Fabbricatore)	Both true; but maybe both can be ameliorated
Optical line-of-sight into detector: survey & alignment	Can align with Zs	... and lose luminosity; push-pull demands quick alignment

Summary

These are mostly new ideas in high energy physics, mostly tested, but none of them engineered and ready an actual detector.

On RD52, we will solve the problem of projective fibers; work on using SiPMs to avoid PMTs; and, seek the ultimate hadronic energy resolution.

Franco Grancagnolo (INFN, Lecce) continues to improve his cluster-counting and cluster-timing low-mass drift chamber.

Alexander Mikhailichenko and I will patent the dual-solenoid since it can be used effectively in MRI machines.

Extras:

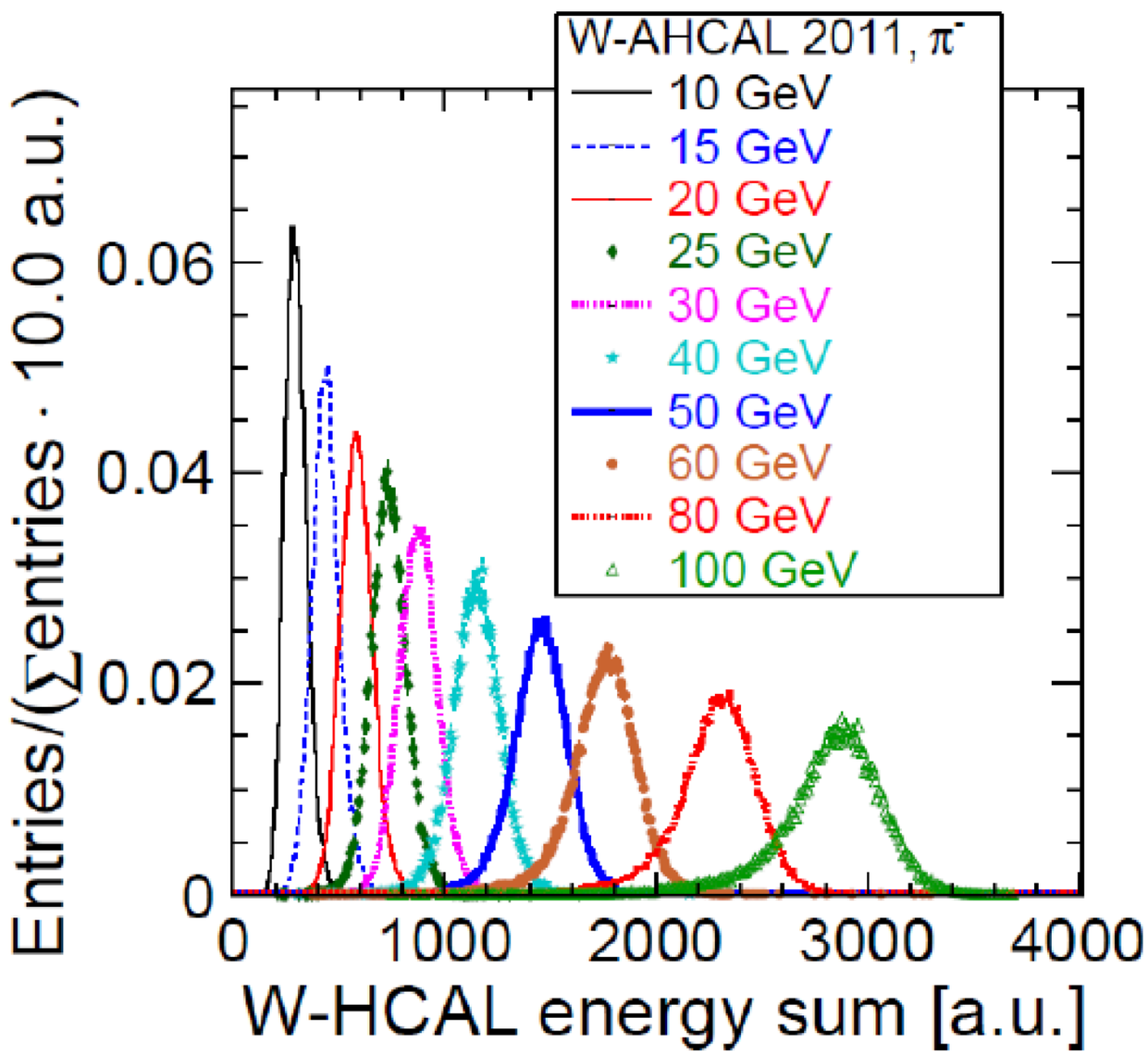
CALICE - why it will never work

4th jets - Higgs

DREAM - muons

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

CALICE W-AHCAL Test Beam 2011

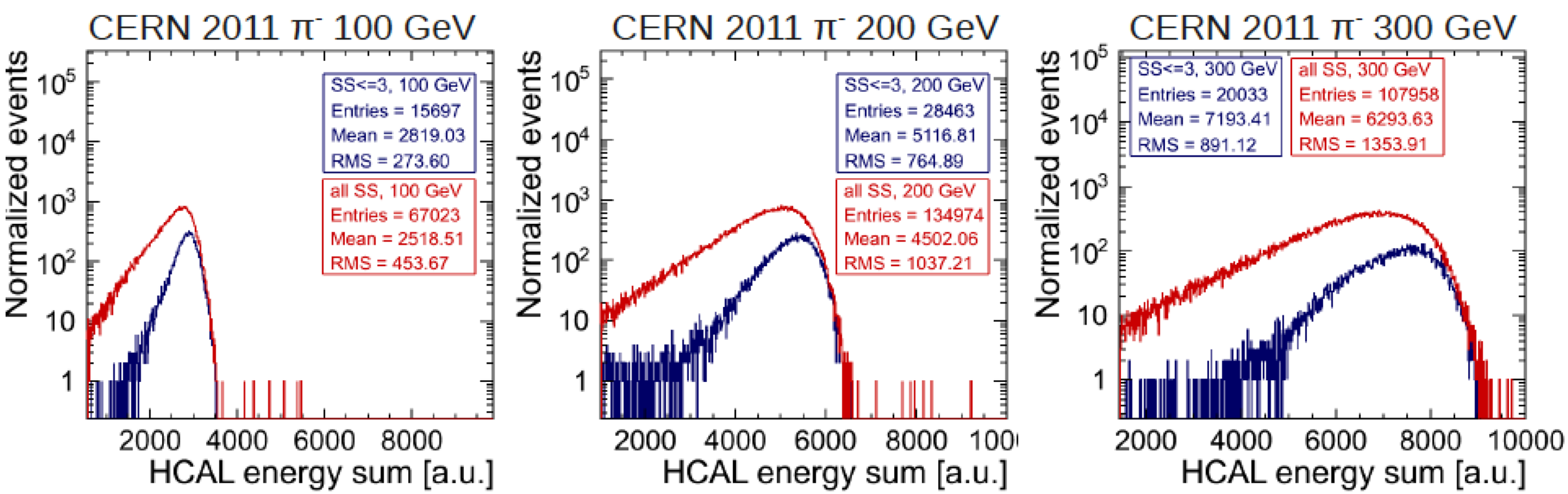


- W-AHCAL of 38 layers
- Only very small leakage effects are visible in W-AHCAL up to highest presented energies (here: $p_{beam} \leq 100$ GeV)
  - Selected only those events in which the shower starts in the first three layers of the W-AHCAL
- Leakage effects for very high energies $p_{beam} > 100$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

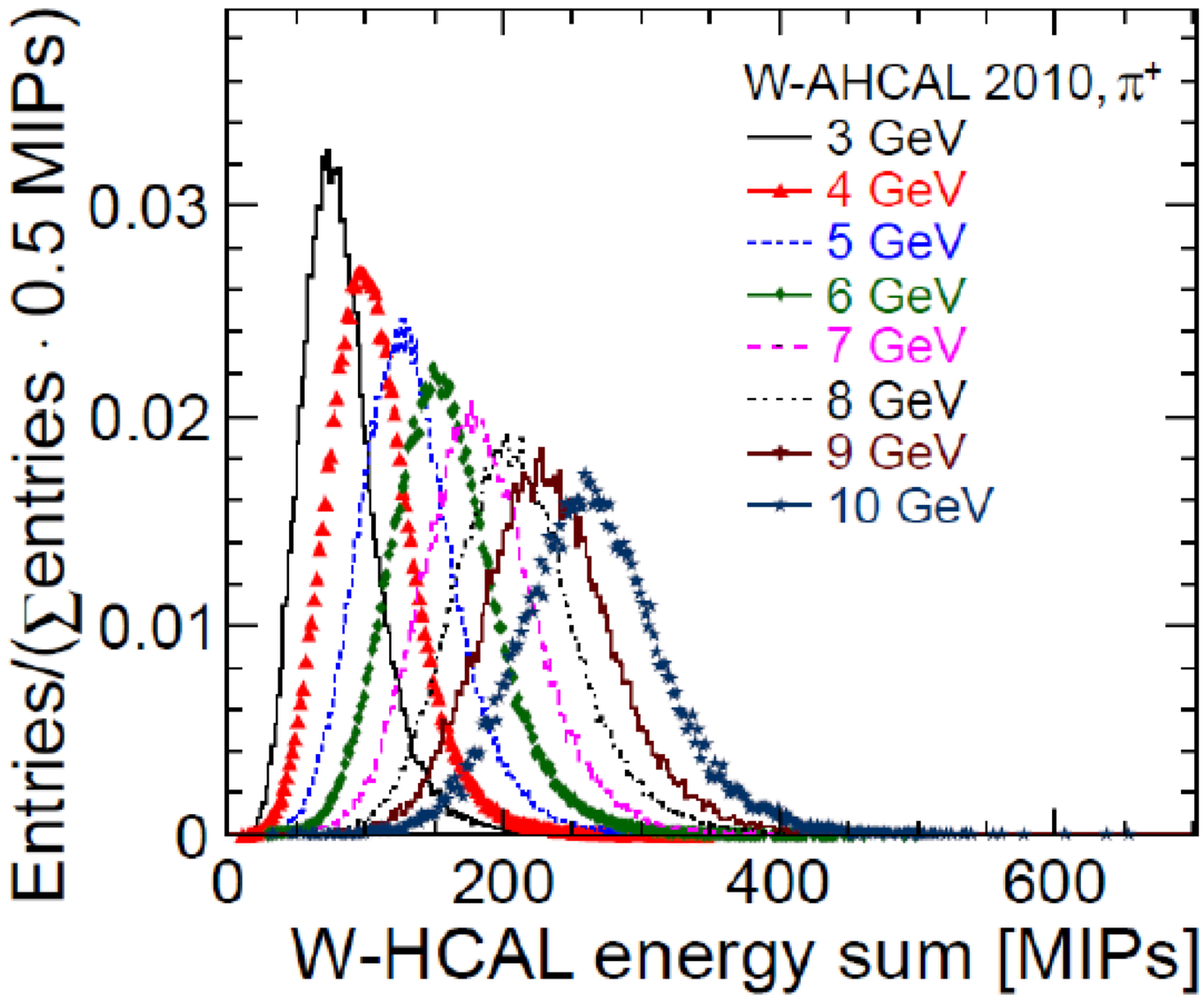
LCD Note 2013-002

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



CALICE W-AHCAL Test Beam 2010

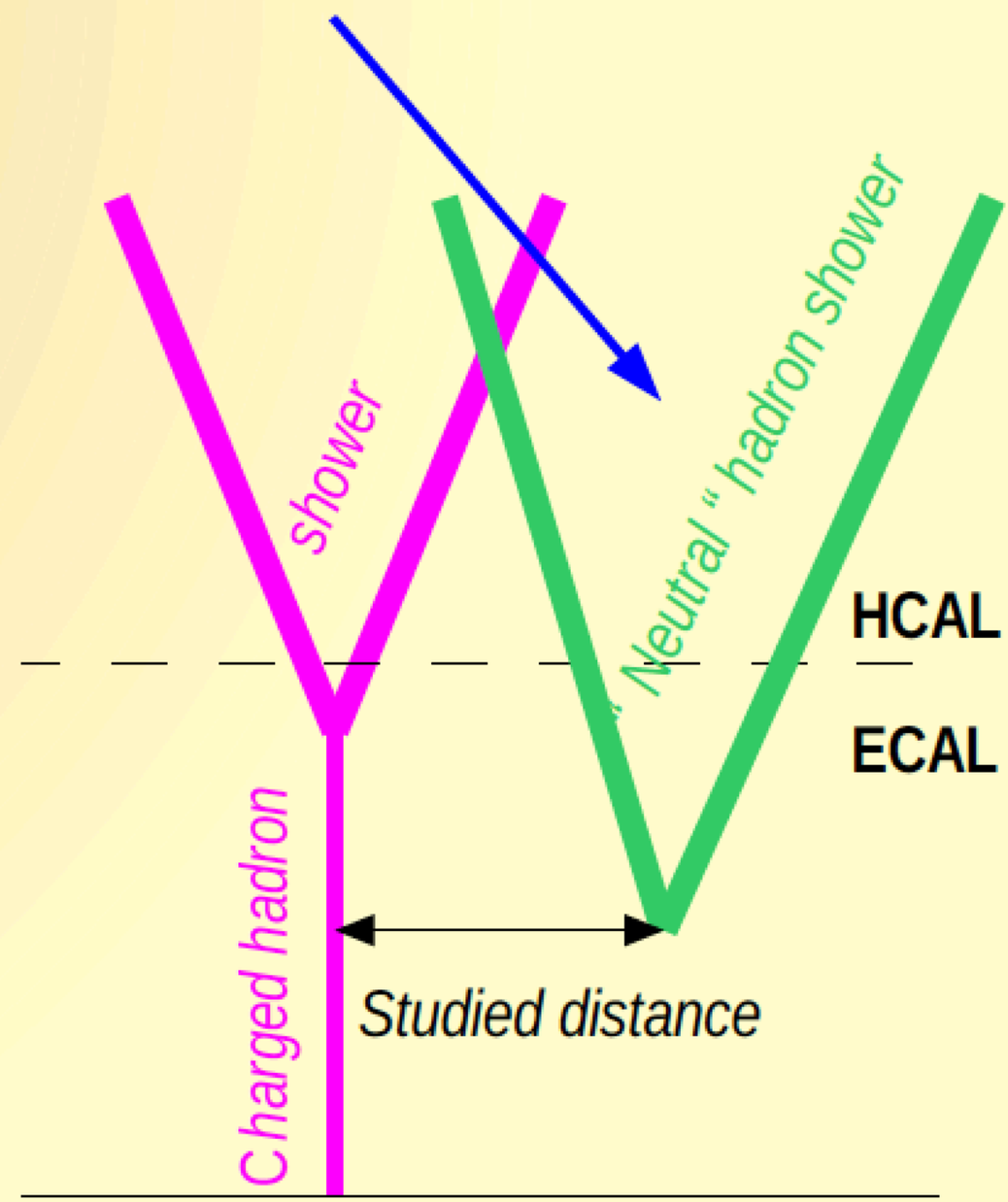


- Test beam with W-AHCAL at CERN PS at energies from 1 to 10 GeV
- W-AHCAL of 30 layers
- Clear pion peak at all energies in HCAL-only
- By selection, shower fully contained in W-AHCAL
  - Select events with shower start in very first W-AHCAL layers (≤3)

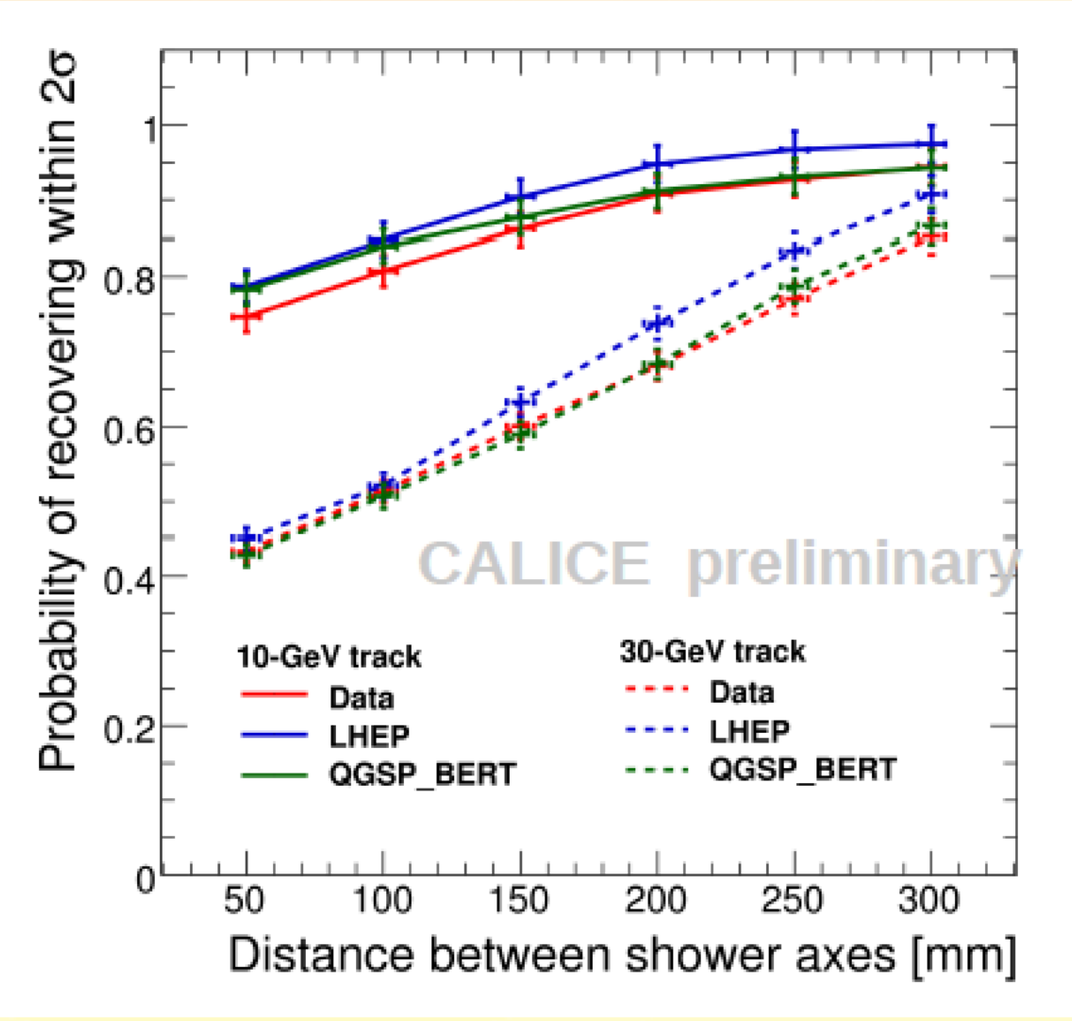
CALICE Analysis Note 036
https://edms.cern.ch/file/1224616/1/can_note_14June2012.pdf

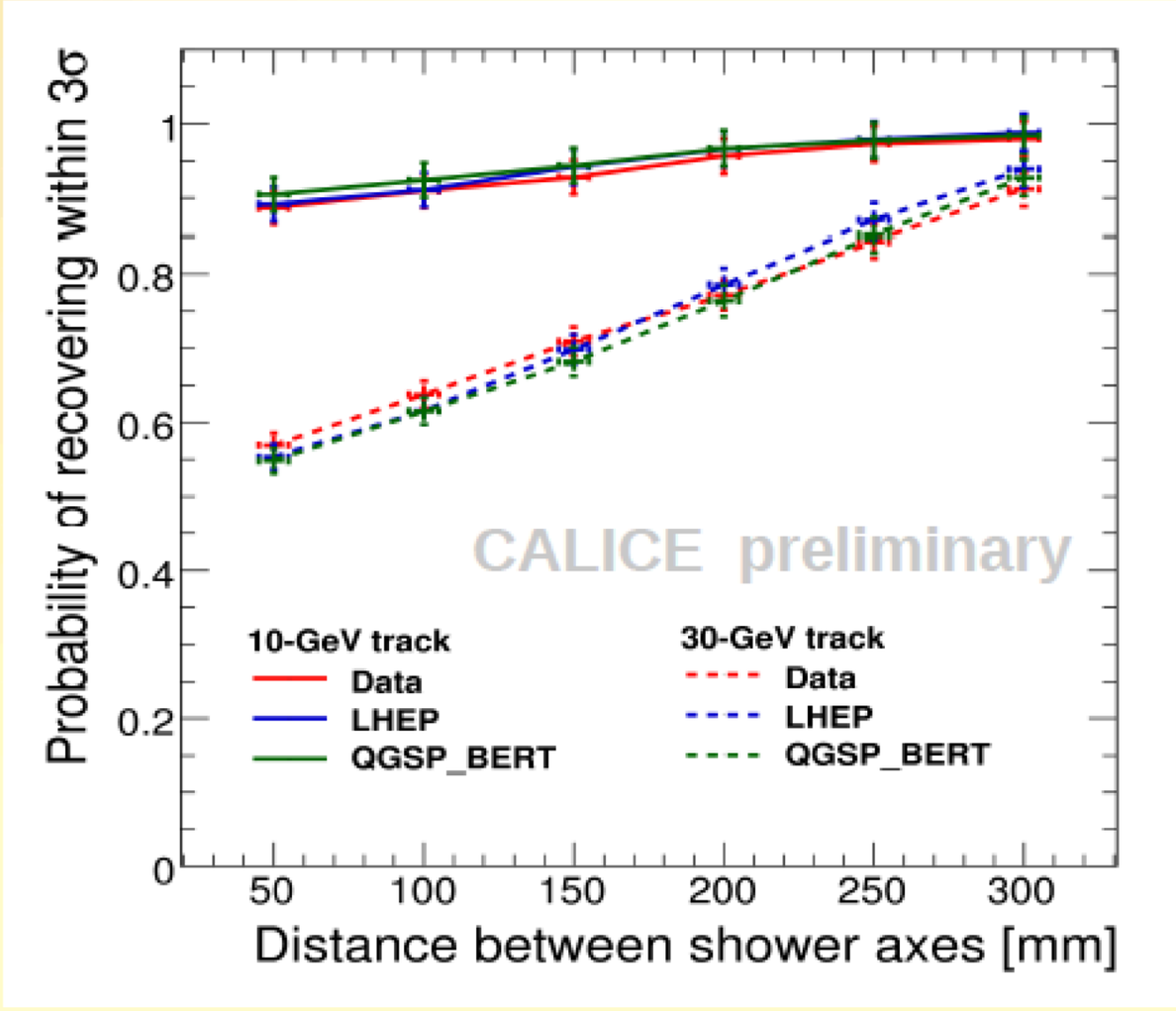
For one of the two events we move all hits at a studied transverse distance from their original position, keeping only hits placed behind the shower start. This event emulates a neutral hadron (e.g. neutron or K^{o}_{L}) shower

- 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



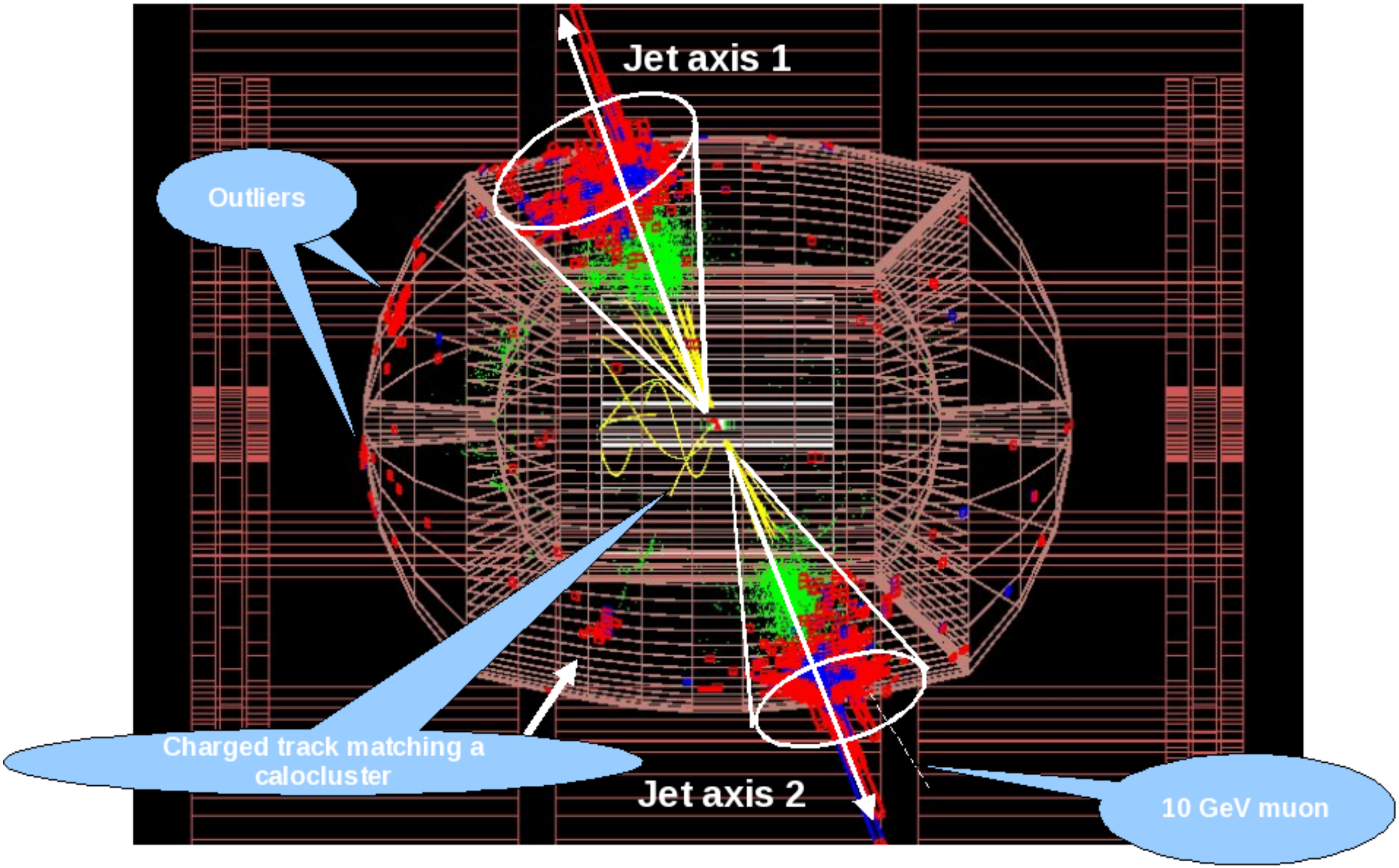
The probability to recover the 10 GeV neutral hadron energy within 2 (left) and 3 (right) standard deviations from its real energy versus the distance from the charged 10 GeV (continuous line) and 30 GeV (dashed line) pion for test beam data (red) and for both LHEP (blue) and QGSP_BERT (green) physics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

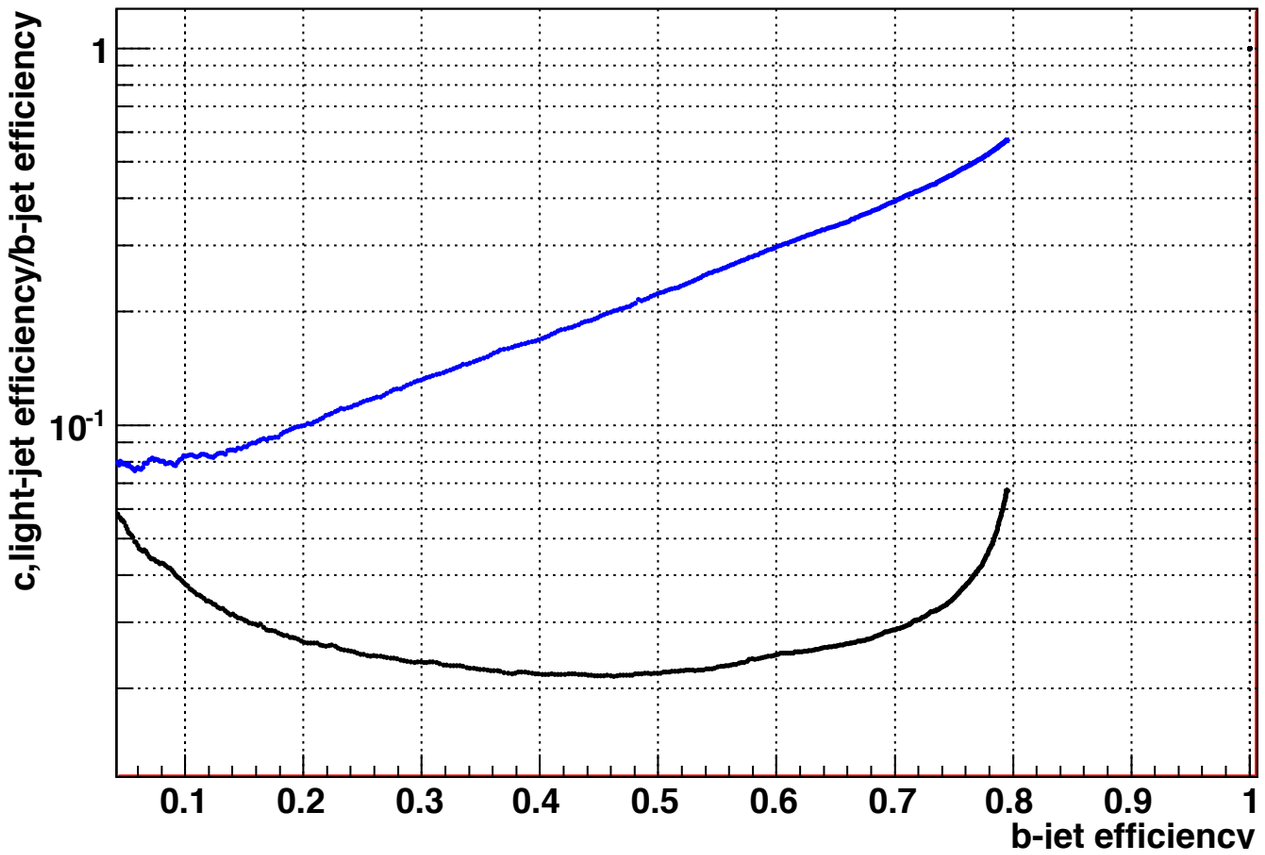


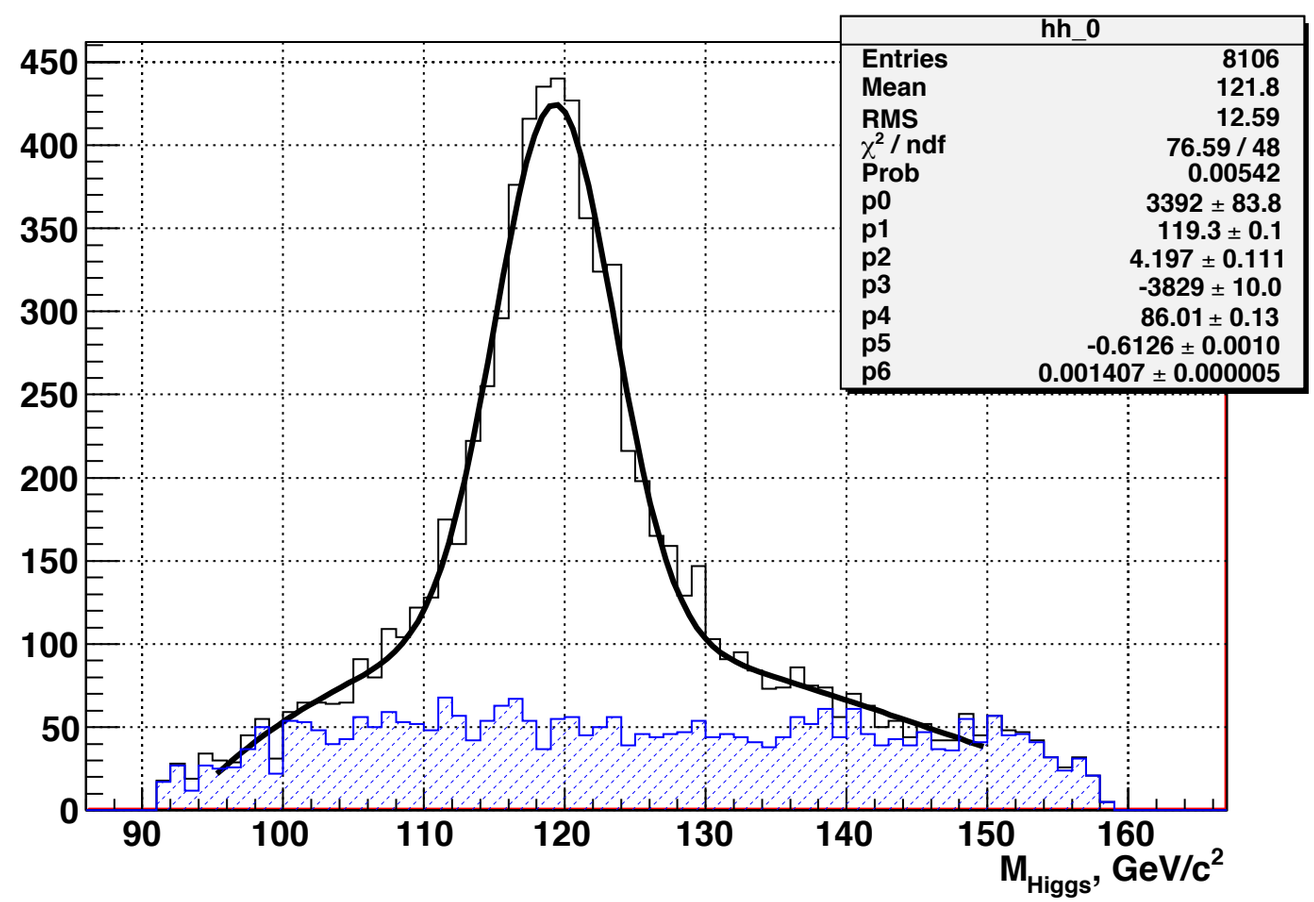


Abstract

The first precision measurements at a future ILC will be top quark pair production and Higgs production, which I will discuss in the context of the 4th Concept detector with its novel dual-readout calorimeters, nearly-massless tracking chamber, and new iron-free magnetic field configuration.

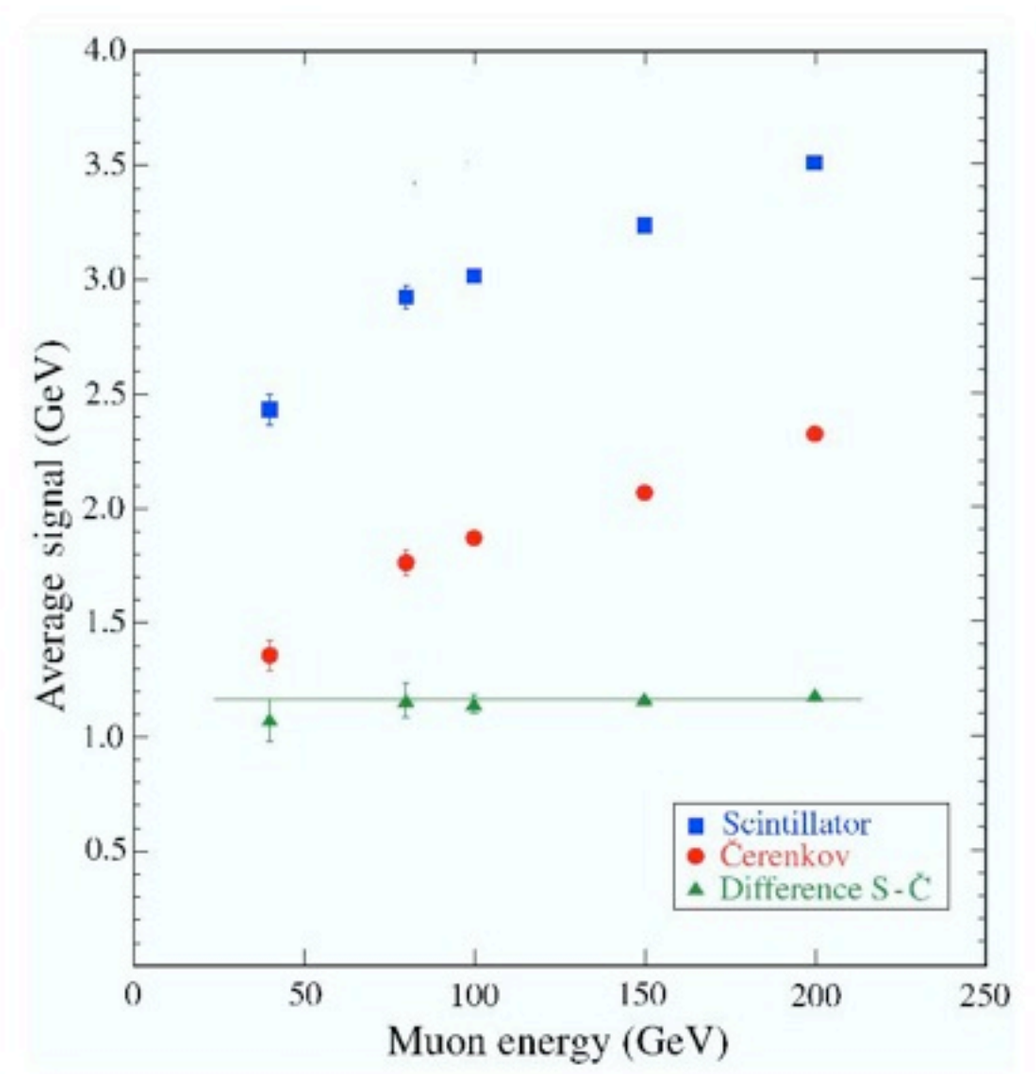

Jet axis 1
Outliers
Charged track matching a calocluster
Jet axis 2
10 GeV muon


c,light-jet efficiency/b-jet efficiency
1
10^{-1}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
b-iet efficiencv


hh_0
Entries 8106
Mean 121.8
RMS 12.59
χ^2 / ndf 76.59 / 48
Prob 0.00542
p0 3392 ± 83.8
p1 119.3 ± 0.1
p2 4.197 ± 0.111
p3 -3829 ± 10.0
p4 86.01 ± 0.13
p5 -0.6126 ± 0.0010
p6 0.001407 ± 0.000005
450
400
350
300
250
200
150
100
50
0
90
100
110
120
130
140
150
160
M_{Higgs}, GeV/c^2

Dual-readout

μ-π discrimination



Scintillation: ionization + bremsstrahlung + pair production

Cerenkov: bremsstrahlung + pair production

Difference S-C is ionization and is constant, independent of muon energy. This is a unique muon tag.