Detector Design Strategies

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Muon Collider Workshop
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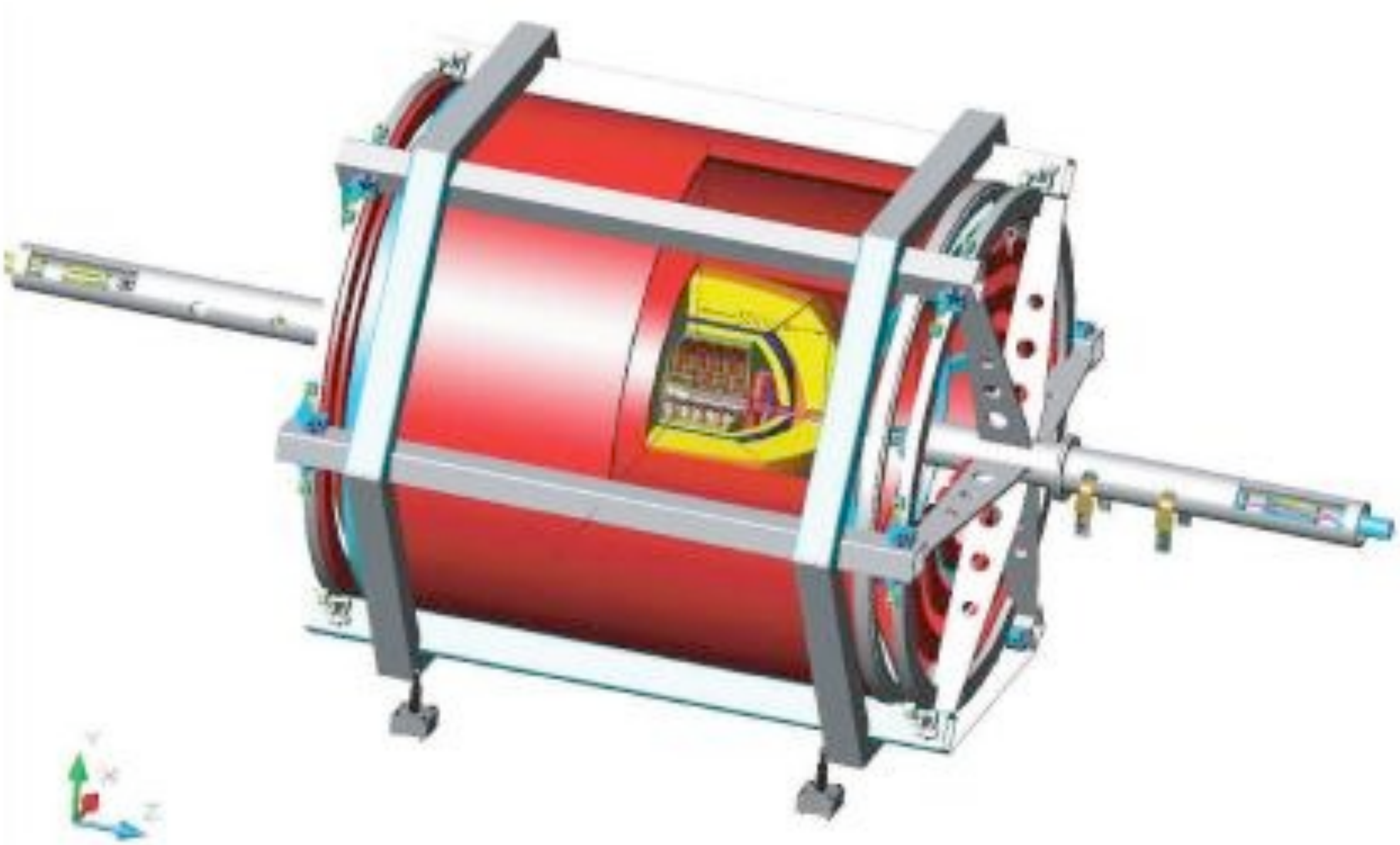
One eye on physics: *p & E resolutions, particle ID, physics backgrounds*

One eye on machine: *collision rates, machine backgrounds, timing, doses*

Perfect detector: *zero-mass tracking, infinite mass calorimeter, and sub-nanosecond timing of all detector elements*

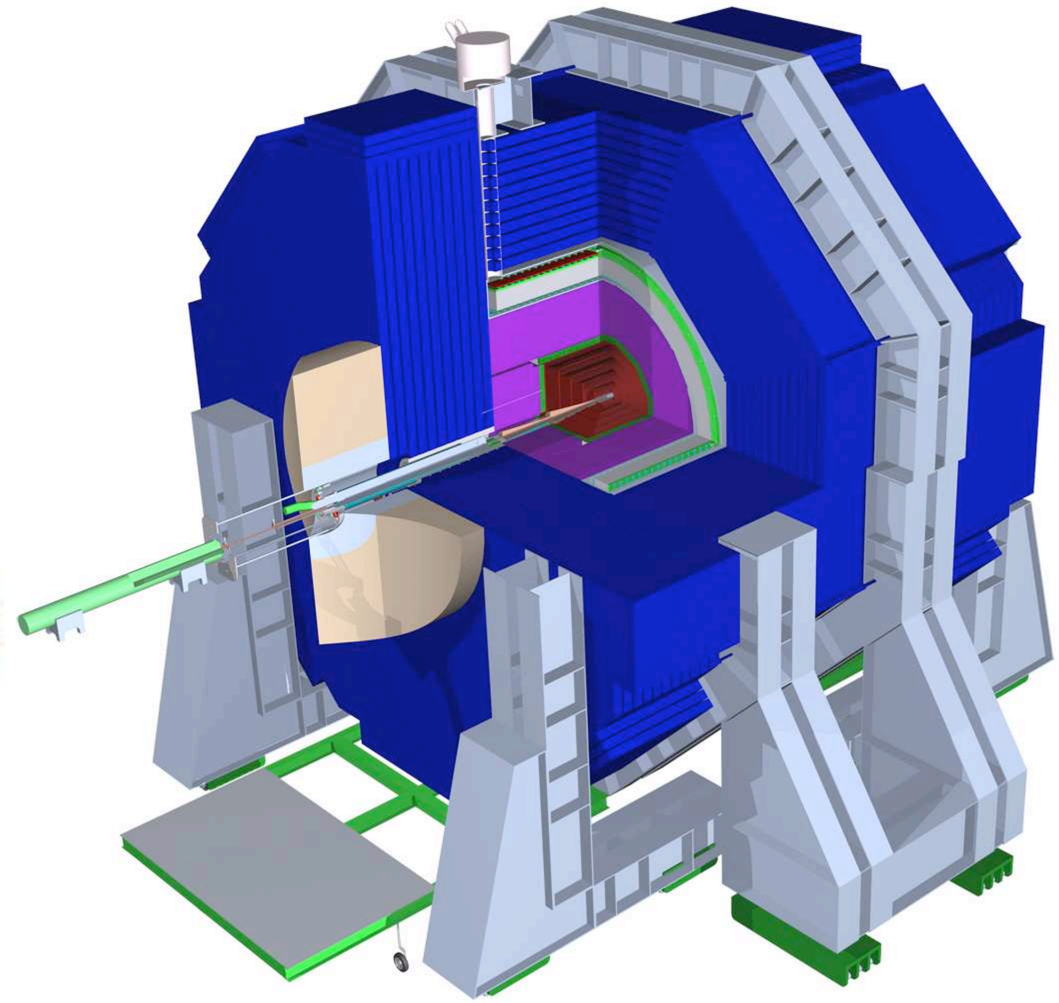
(Most detectors do not live up to their promises)

One detector



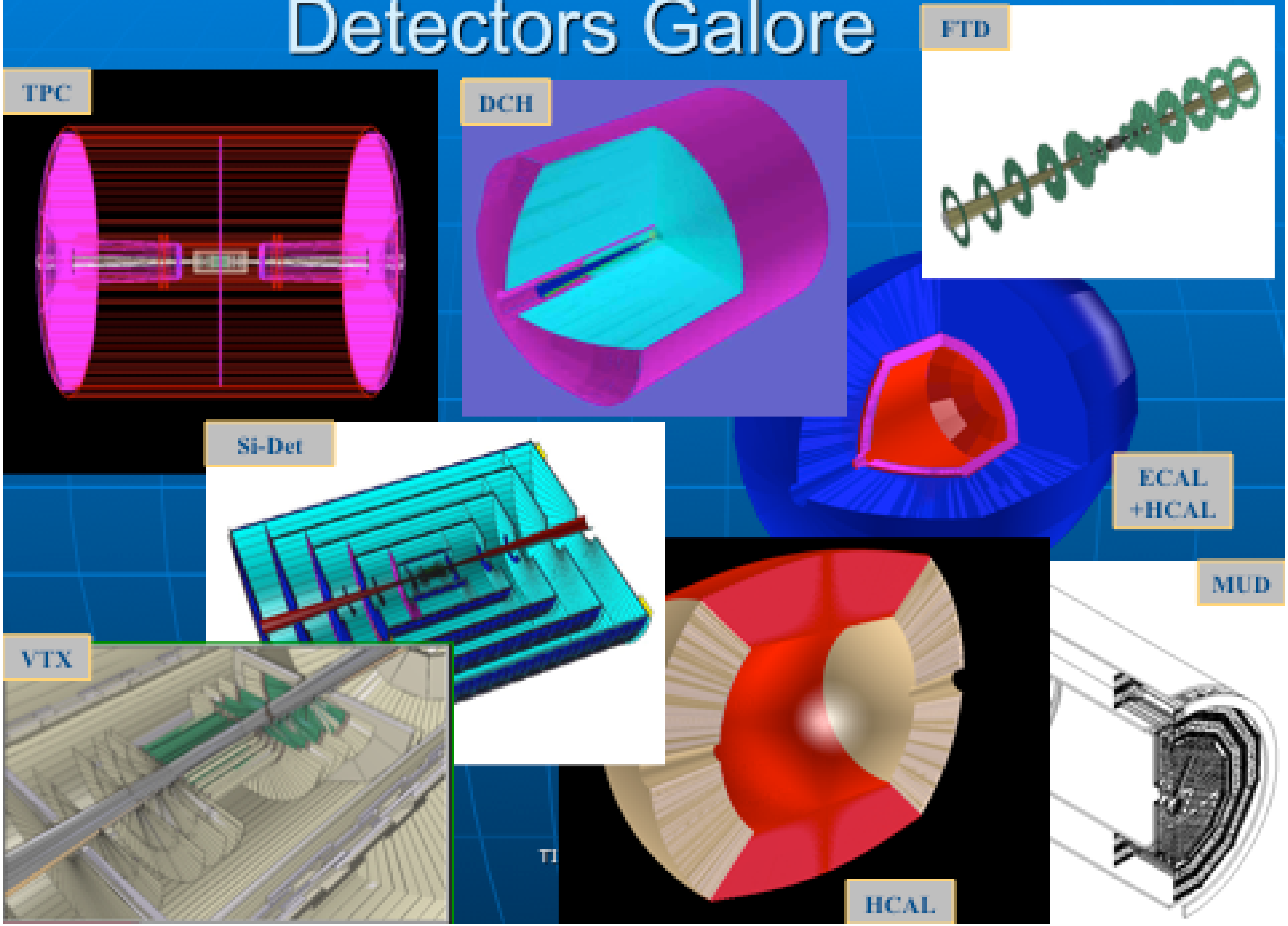
Another detector

31 March 2009



They are very different from each other. Detectors have a huge range.

Detectors Galore



See Corrado Gatto’s talk (some varieties of detectors we’ve studied)

Main requirements at a multi-TeV collider:

a. Best achievable Gaussian resolutions, σ, are obviously essential:
(physics precision) x (calibration) x (background rejection) ~ cube of σ

b. Physics $\mu^+\mu^- \rightarrow WW..\ \ ZZ...\ \ tt..\ \ ZH...$ demands

$\sigma_E / E \approx 30\% / \sqrt{E} \oplus small$ *[plus cm-scale lateral segmentation]*

$\sigma_p / p^2 \approx few\ x\ 10^{-5} \oplus ms\ (GeV/c)^{-1}$ *[tracking, keep material budget low]*

sub-nanosecond (2-5 GHz) time history [continuous volume interrogation]

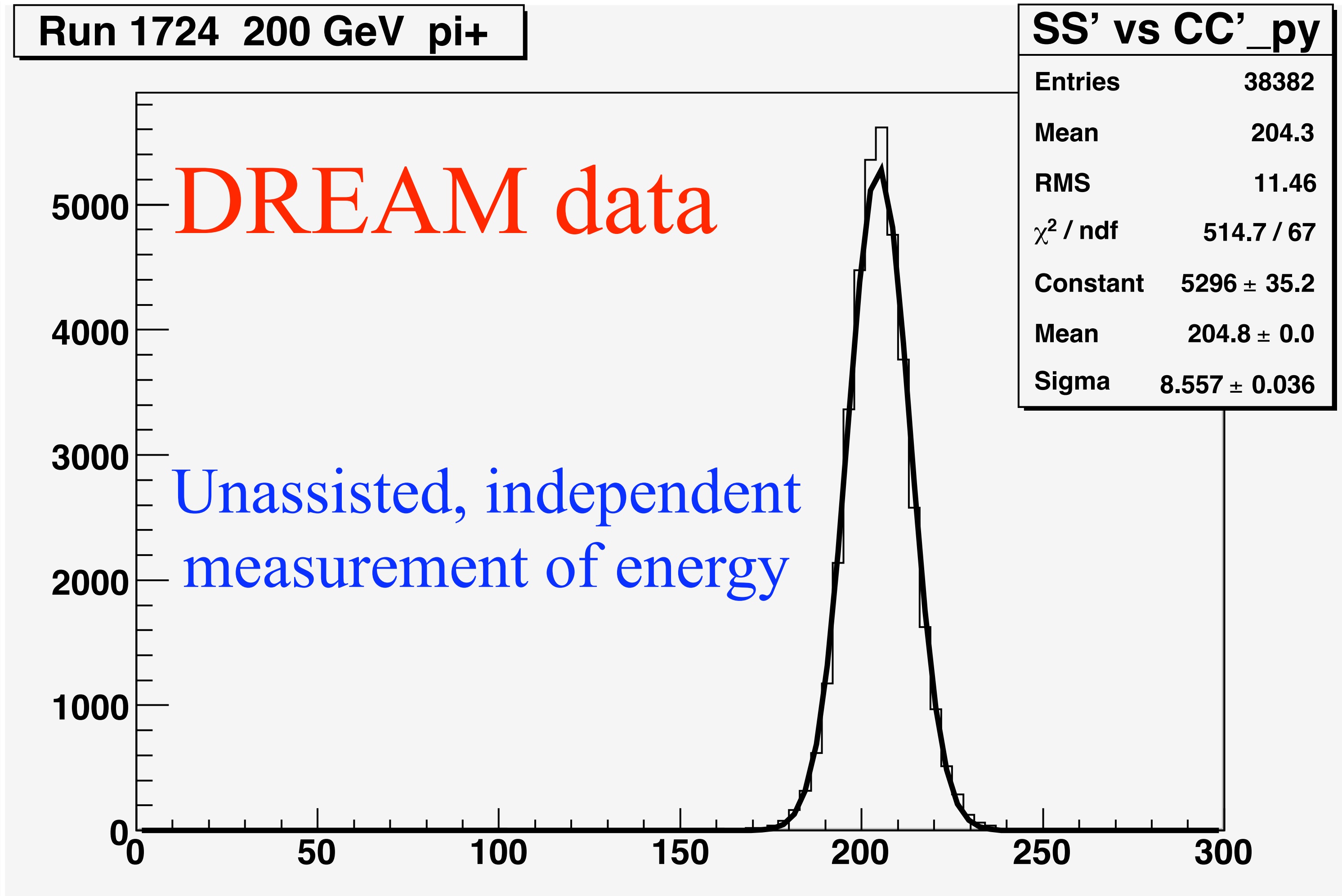
c. Particle identification ... assists everywhere (physics, calibration, background)

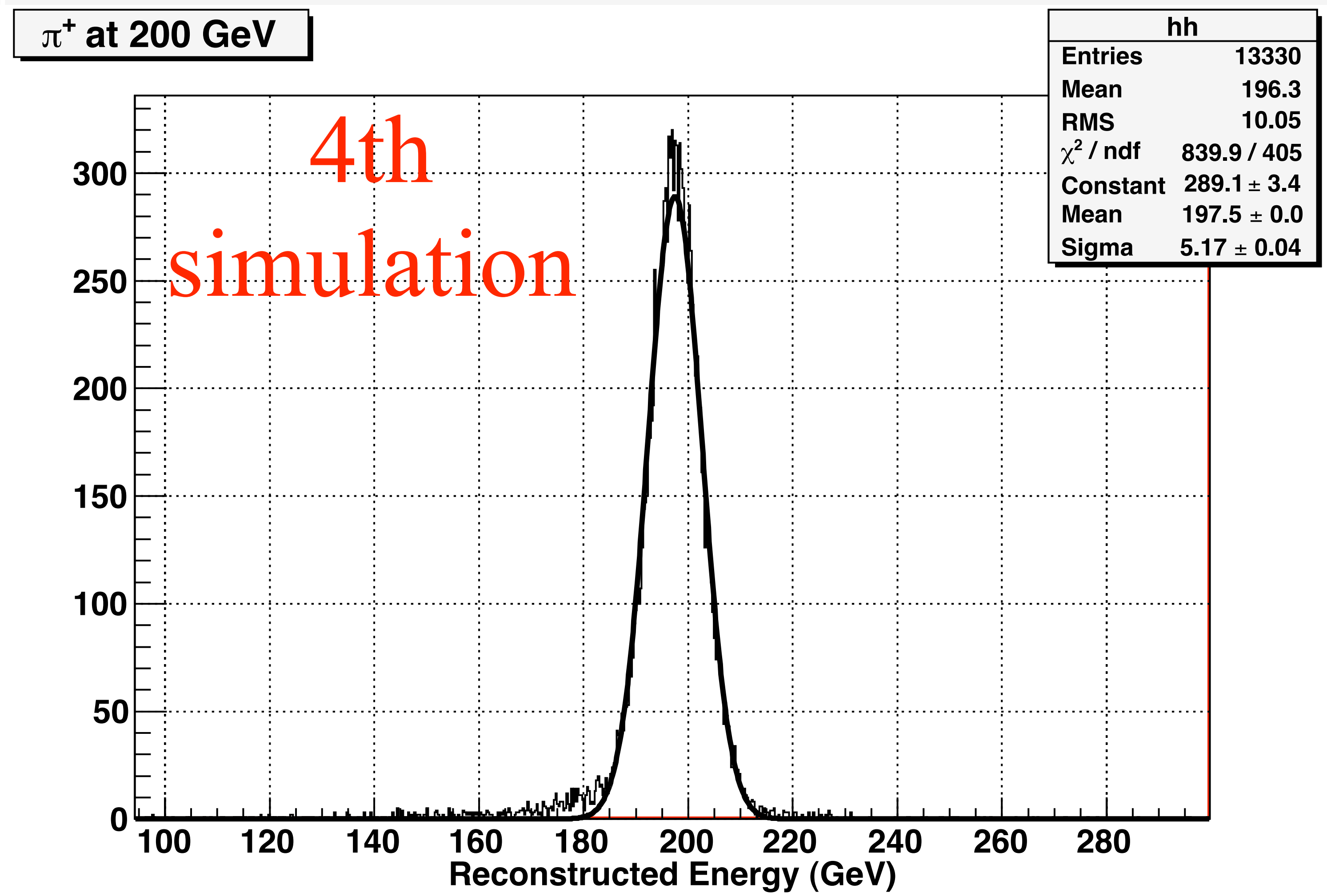
d. Pixel vertex radial standoff depends critically on machine backgrounds, but ought to achieve an impact parameter resolution of 5-10μm

(The 4th design has achieved these goals.)

$\sigma_E / E \approx 30\% / \sqrt{E} \oplus small$

BGO+fiber calorimeter
at 200 GeV

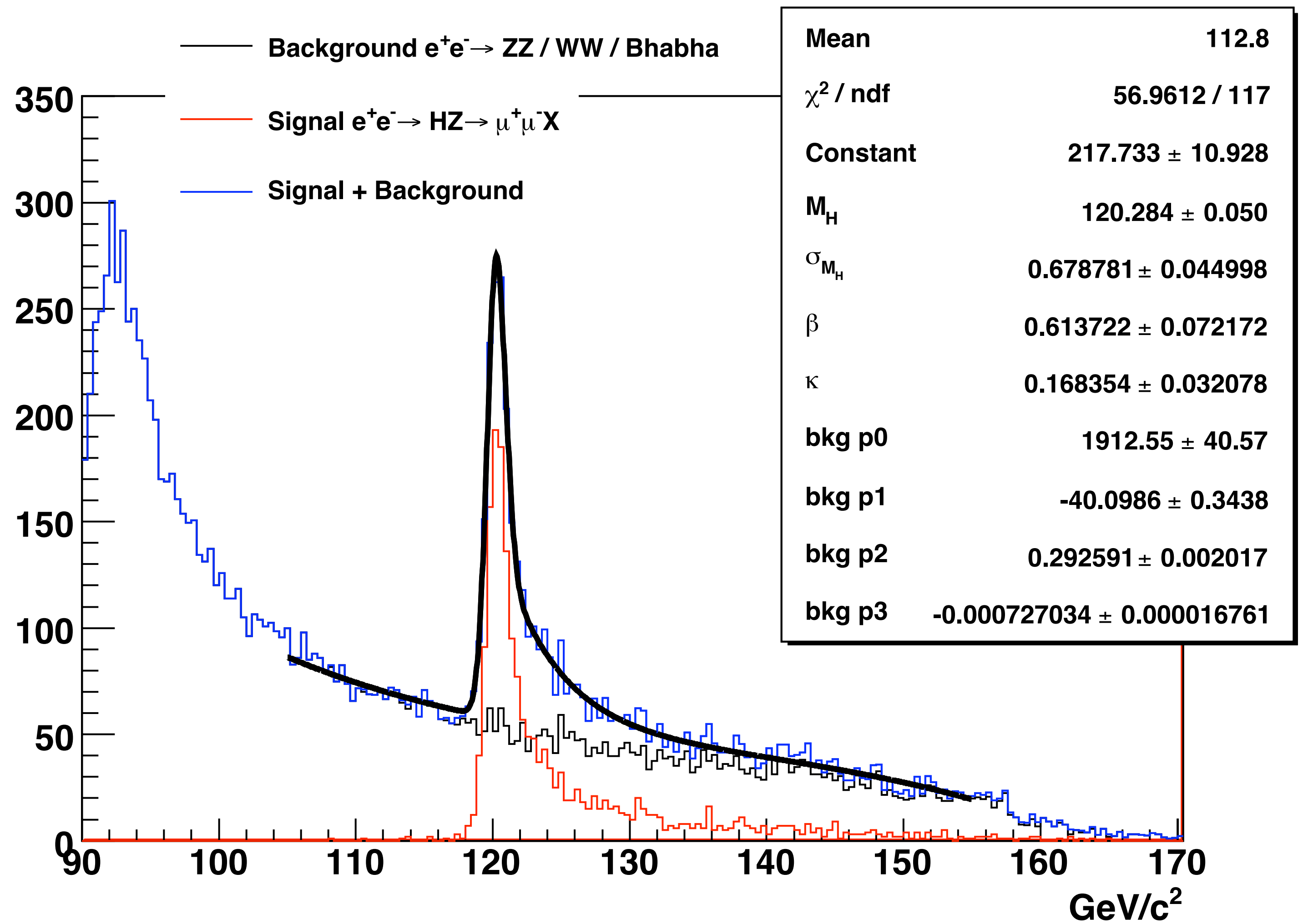




$\sigma_p / p^2 \approx$ *few x* $10^{-5} \oplus$ *ms* $(GeV/c)^{-1}$

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

$\mu^+\mu^-$



Mass of X

Six fundamental design principles:

(1) independence of detector subsystems

(2) particle identification

(3) auxiliary and ancillary detectors are unnecessary

(4) an iron-free detector is a big deal

(5) relative absence of dead-volumes within detector

(6) resistance to “engineering creep”

(1) Independence of each detector subsystem:

The calorimeter should function as a device to measure energies absorbed in specific volumes *without dependencies* on other subsystems such as tracking.

This criterion is exactly opposite to a PFA calorimeter in which this dependence is required.

The tracking system should measure and recognize patterns of contiguous spatial measurements as individual tracks *without depending* on a calorimeter or vertex chamber.

(a) Easy with “continuous” tracking throughout the volume, no need for a vertex starter-track or a calorimeter “stub”.
(b) It is always true that a high precision vertex chamber aids pattern recognition in an outer tracker, and every experiment will use this to advantage.
(c) Muon identification and measurement *necessarily* requires more than one system, but the basic measurements themselves should be as independent as possible.

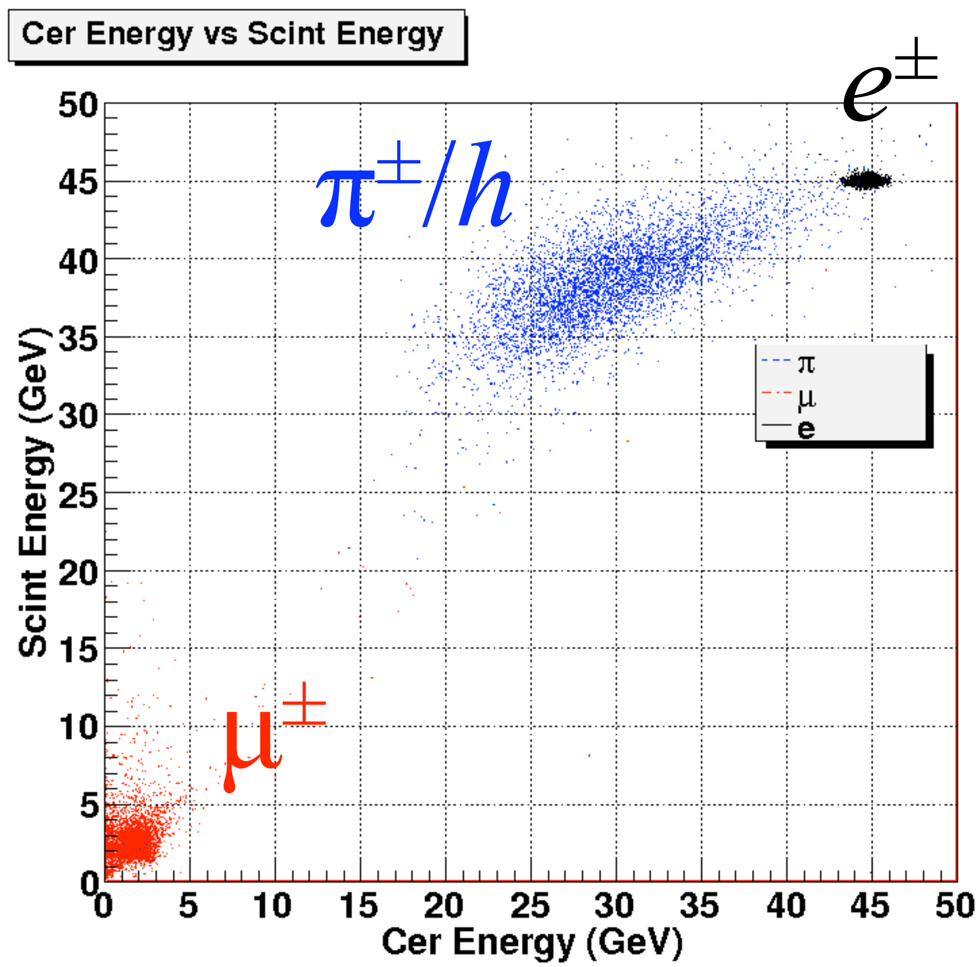
Bottom line: you should be able to turn off the B-field and tracker, and still do physics with the calorimeter. And, vice versa.

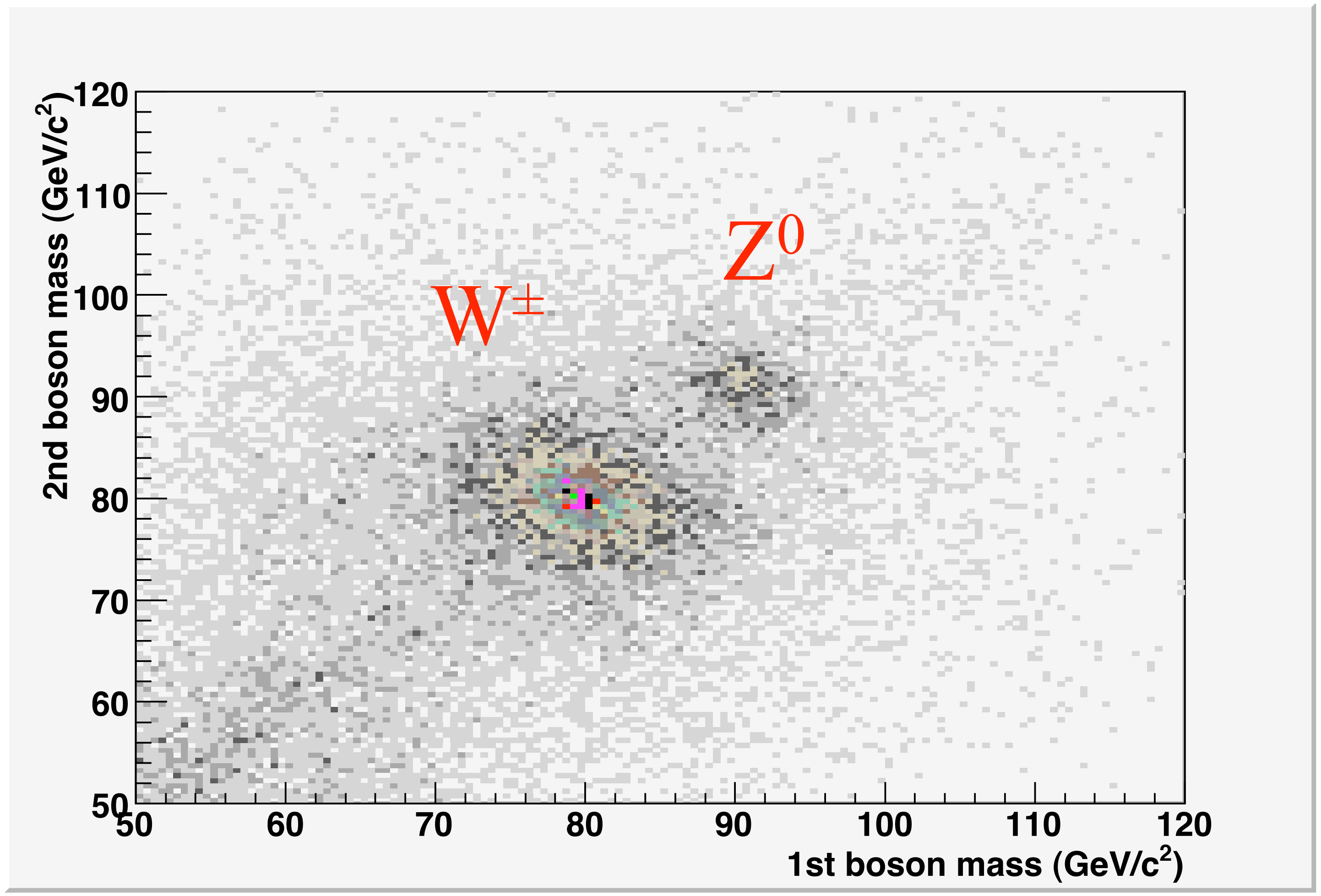
➡ *deficiencies in one system will not compromise another system*

(2) particle identification:

Crucial for physics at any future collider, for particles at both high and low momenta, and as many standard model partons as possible must be identified by direct measurements in independent detectors;

(The 4th detector makes direct measurements on *all* partons of the SM, e.g., e, μ, π, W and Z.





➡ *instrumental backgrounds become negligible with good pID*

(3) auxiliary or ancillary detectors are unnecessary:

Each detector subsystem (tracking, calorimeter, etc.) must be of sufficient capability that auxiliary or ancillary subsystems are unnecessary, *e.g.*,

• no “tail-catchers” to prop up a too-shallow calorimeter (4.5 λ_{INT} is too shallow);

• no “end-cap chambers” to re-measure tracks after too-massive end-plates;

• no “pre-shower detectors” to tag showers developing in too-massive detector materials before reaching the calorimeter;

• no “silicon blankets” or other multiple tracking devices to assist either the momentum resolution or pattern recognition;

• no “inter-detector chambers” to compensate for dead volumes; and,

• no multiple and different technologies for reasons of precision or measurement redundancy.

➡ *each new system is more cables, more material, less overall reliability*

(4) an iron-free detector is a big deal

We have introduced the dual-solenoid magnetic configuration to return the flux without iron, from which there are numerous advantages:

(a) no fringe field, avoids CMS problems;

(b) detector mass becomes about 2kt (instead of 10-20 kt);

(c) open detector for access and alignment/surveying, and air-core light paths for optical MONALISA alignments are easy;

(d) low mass means that everything in the IR (crane/floor loading/movement) is easier;

(e) high-precision track measurement after calorimeter in a tracking spectrometer;

(f) avoids huge ~25,000 tonne forces on pole tips which distort detector;

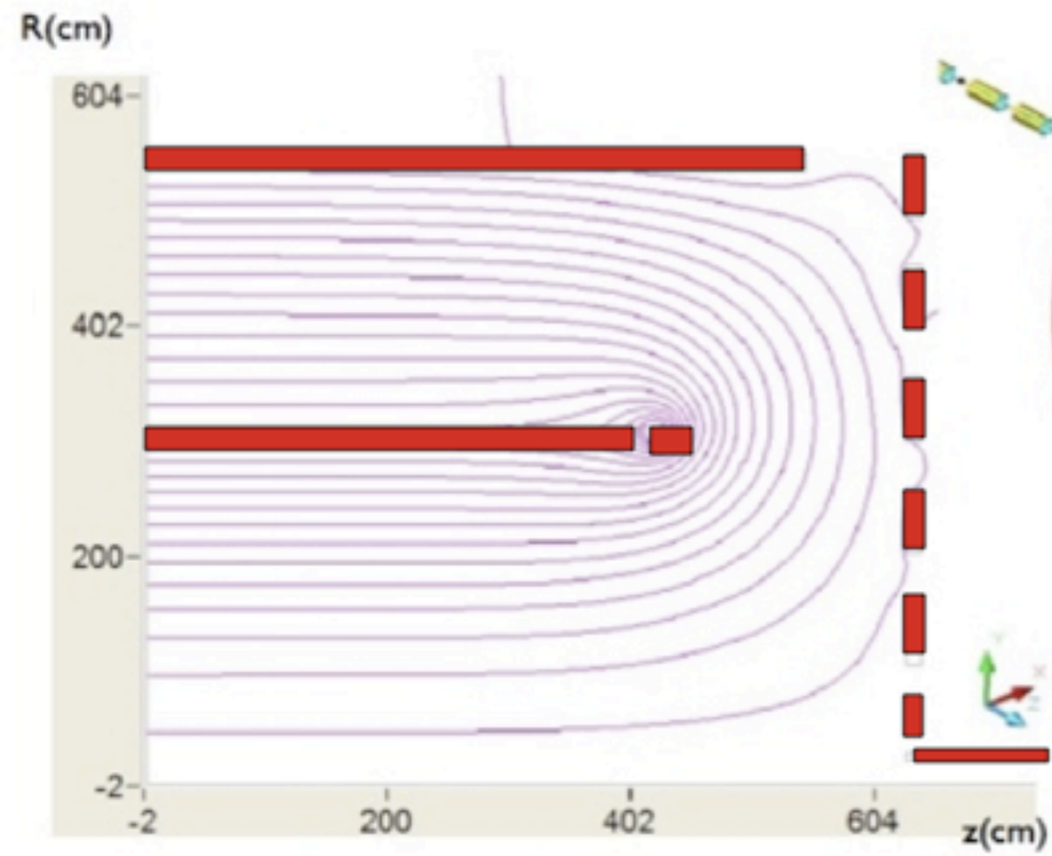
(g) all regions of the detector are available for measurements;

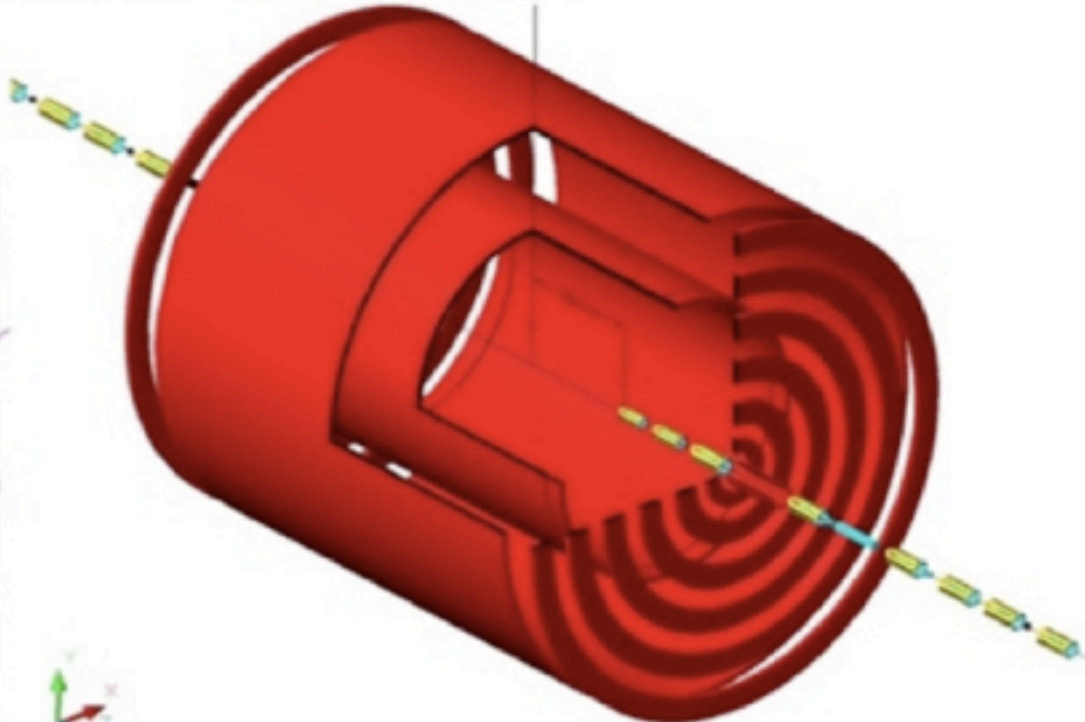
(h) final focus elements can be incorporated into detector for stability and beam control;

(i) can be easily disassembled, and new additions are easy to incorporate;

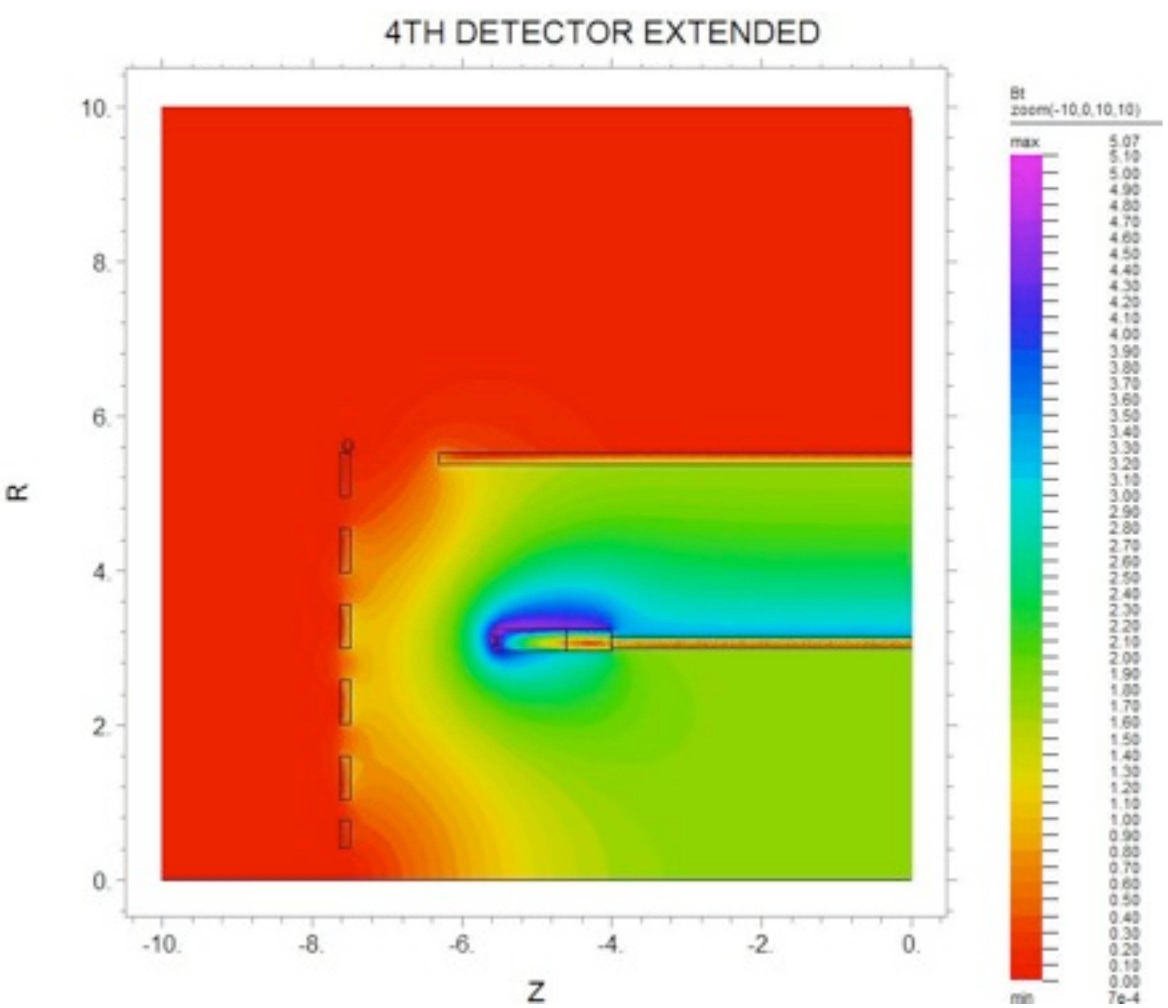
(j) one IR per detector means no push-pull and self-shielding not necessary.

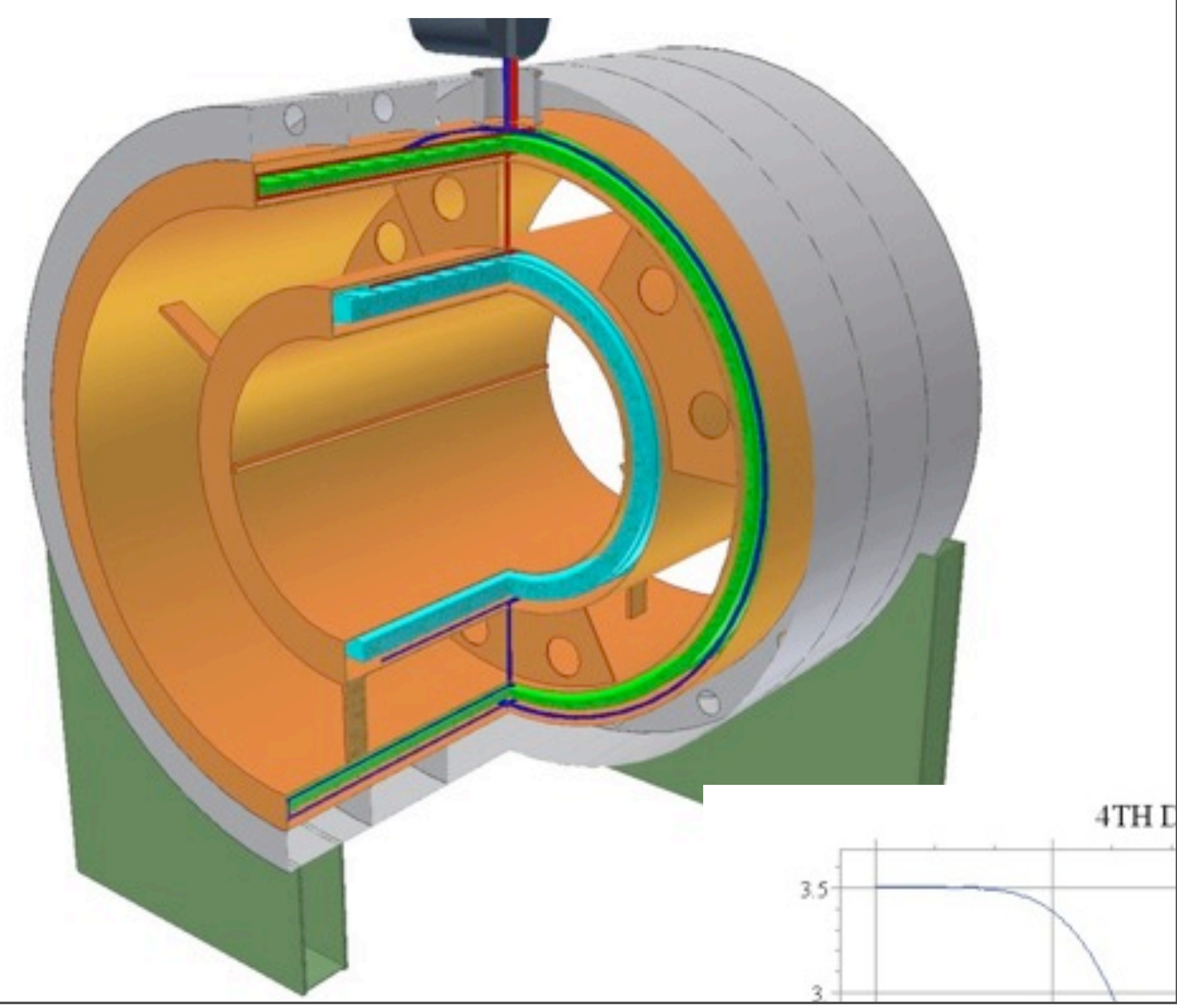
Magnetic field of dual solenoid and wall of coils





Alexander Mikhailichenko, Cornell LNS

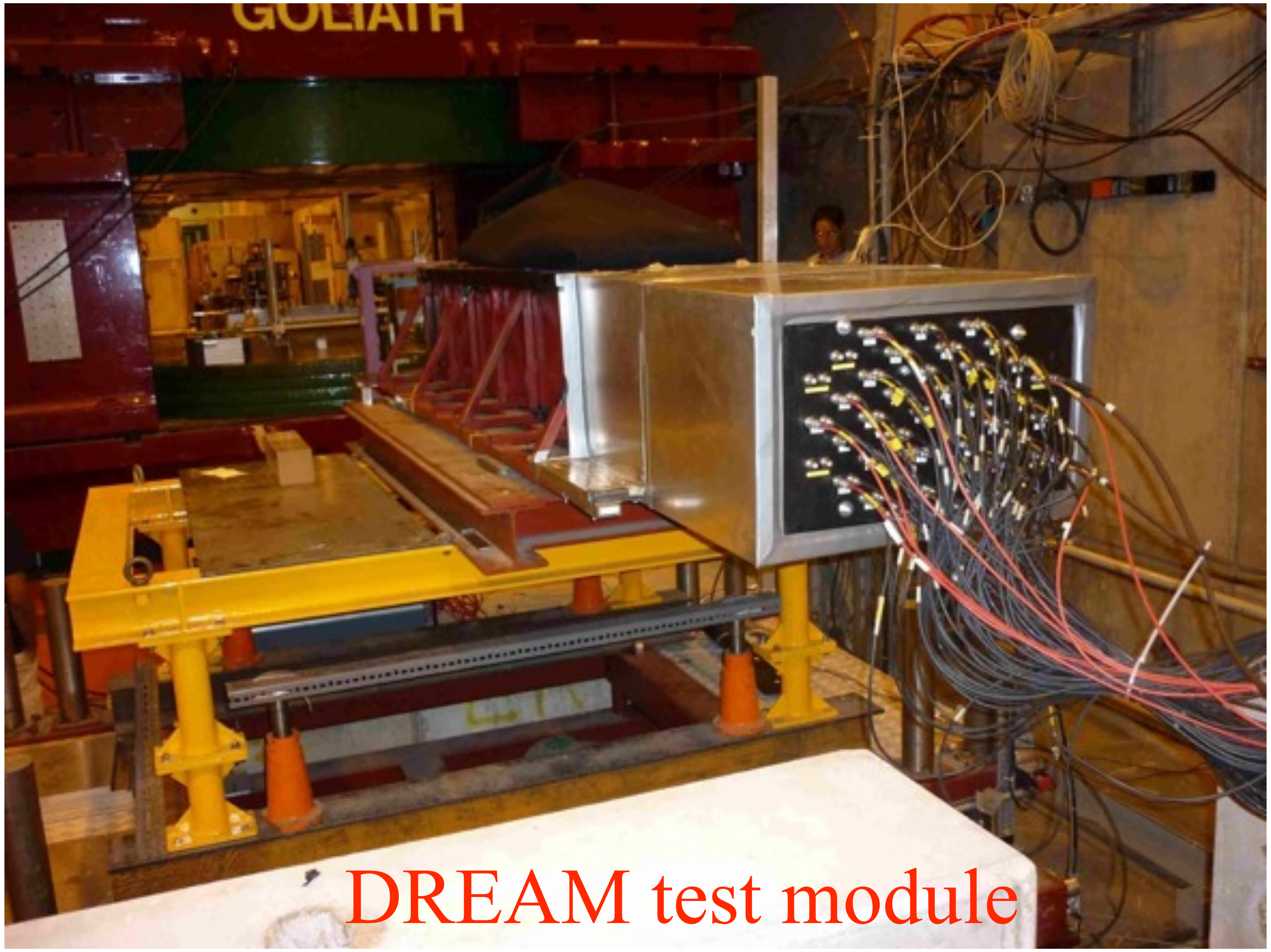




(5) relative absence of dead-volumes within the detector

This is an obvious statement, but avoiding dead material volumes for supports, cable-ways, etc., requires design foresight.

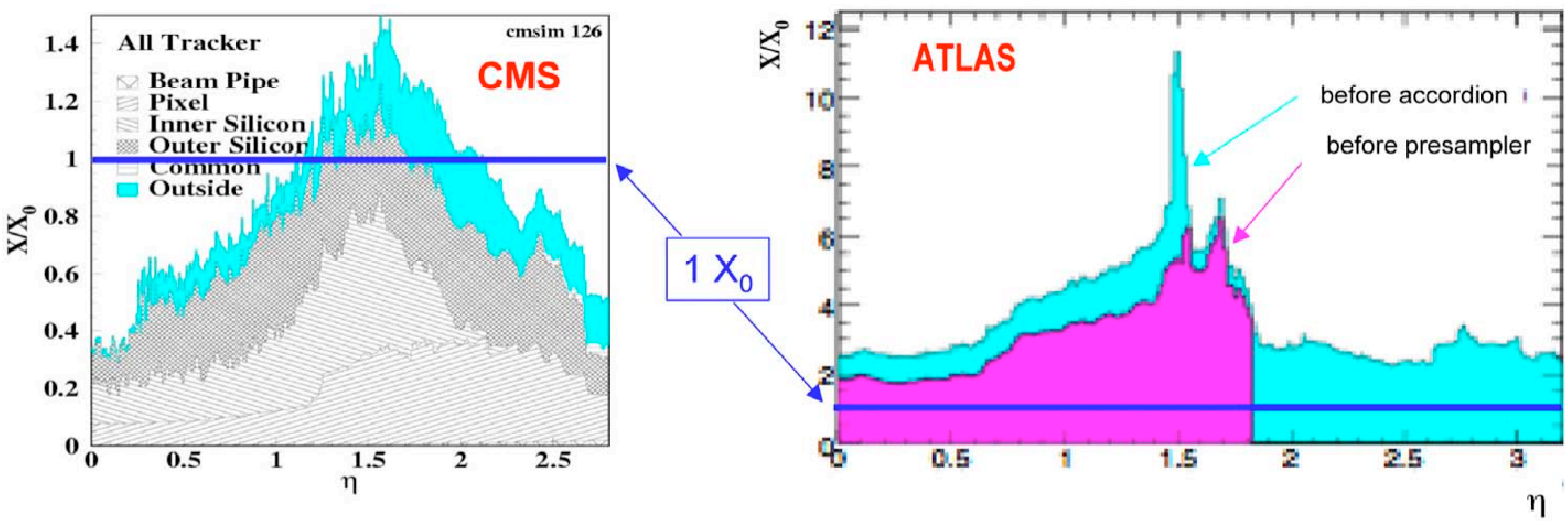
This is unavoidable for the support of massive instruments such as the calorimeter and the superconducting coils, but it is quite avoidable in calorimeters in which all readouts can be at the rear, and for light-weight tracking systems that do not require cooling or fragile supports within the tracking volume itself. Dual-readout fiber calorimeters are ideal for this, and an open-access detector without an iron *sarcophagus* allows calorimeter support from below (Bob Wands, Fermilab)



(6) resistance to “engineering creep” (for lack of a better term)

Well-laid plans and well-designed instruments are sometimes defeated in the end-game of building a big detector (often under funding and scheduling duress).

All big detectors undergo the successive transitions from ideas to physics prototypes, to beam tests, to engineering designs, to larger-scale prototypes, to system beam testing, to a large-scale industrial manufacturing stage, and finally to installation and *in situ* testing. During these stages of a big project, engineering necessities of tolerances, gravitational supports, and internal stand-offs and supports are almost *always solved by adding materials to the detector*. Good physics intentions are lost at this point.



Muon Collider detector design:

➡ be prepared for 4-6 TeV

precision track points (probably silicon pixels); calorimetry will dominate.

➡ must suppress $\mu \rightarrow e$ decay background

each 300 GeV $e^{\pm}$ that interacts starts a shower with
$N \sim 300$ GeV / $E_c \sim 10^5$ low energy $e^+/e^-/\gamma$. The MeV γ go everywhere.

Muon Collider specifically:
suppress $\mu \to e$ decay backgrounds

"Shower & Shield"

?

"Curl Up & Pass Through"

a. shield detector from debris of interacting decay *e*'s

b. 1996 Study (Steve Kahn)

c. hits in detector at acceptably low levels

d. #p/π/μ ~ 10^3 in tracker/bx

e. Need 20^0 tungsten cone inside detector; awkward for physics; may be source of tracker backgrounds

a. keep *e*'s inside beam pipe, as much as possible

b. 50T solenoid and ±200m straight sections

c. quads to focus diffuse *e*-disk

d. will require the talents of many people (Mokhov, Di Benedetto,

e. background tracks/bx not known

Five stages of protection (for "Curl Up & Pass Through")

- suppress e showers:
  keep decay electrons inside the beam pipe & dump them far from the detector

- shield debris of e's that do shower
  tungsten shields before detector, near beams (Steve Kahn, et al.)

- masks & collimators
  1996 study of beam line protection (Steve Kahn, et al.)

- for γ's and n's, an "invisible" detector
  ultra low-mass tracking system, CluCou, Franco Grancagnolo, low-mass Si

- "last resort" - reject using detector measurements
  spatial and time measurements (Steve Geer). If the 50T trick works, even a TPC can be used at a Muon Collider

- suppress *e* showers:

keep decay electrons inside the beam pipe: 50T small bore solenoid
➡ electron gyro radius is 3mm, so confined to 6mm radius beam pipe.

This will require the talents of many people:

i. 50T is already a problem to be solved (40T, 30T, ?)

ii. need ±200m straight sections

iii. the quads and sextupoles ought to be incorporated into a common cryostat with the solenoid

iv. how to confine (not over-focus) the electron cloud

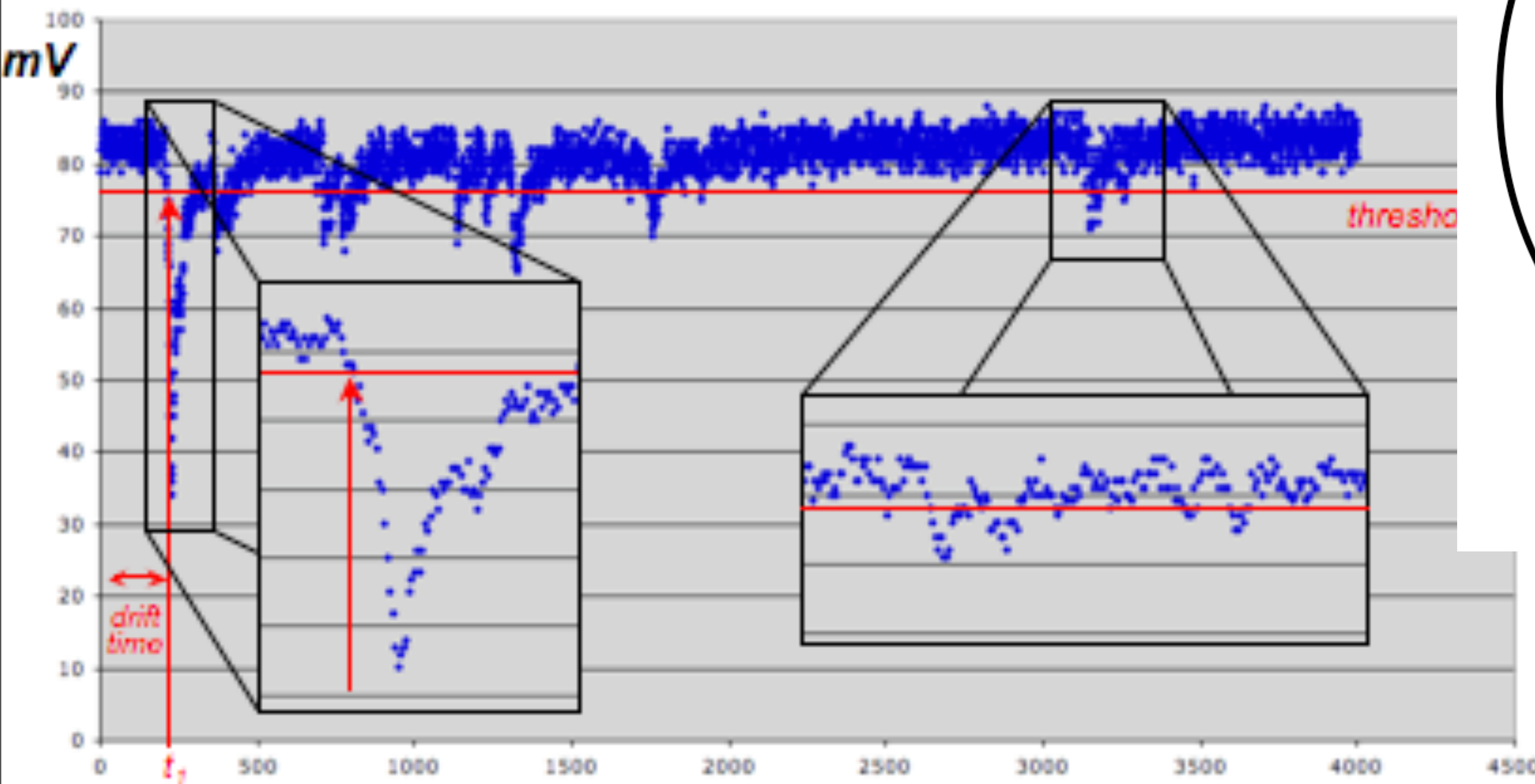
v. calculations of benefits to the detector are relatively easy compared to the machine issues

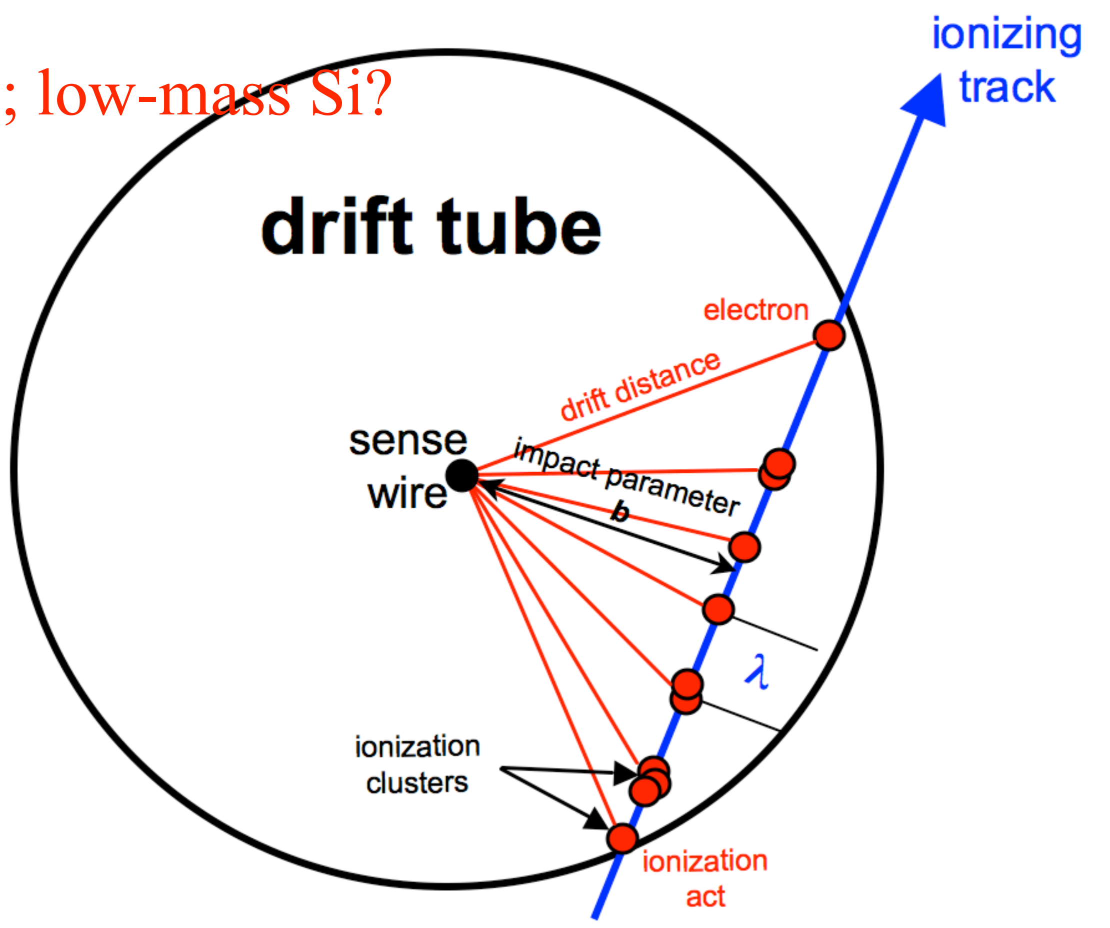
vi. maybe we will need an "intelligent absorber" in addition to the already intelligent masks of the 1996 design

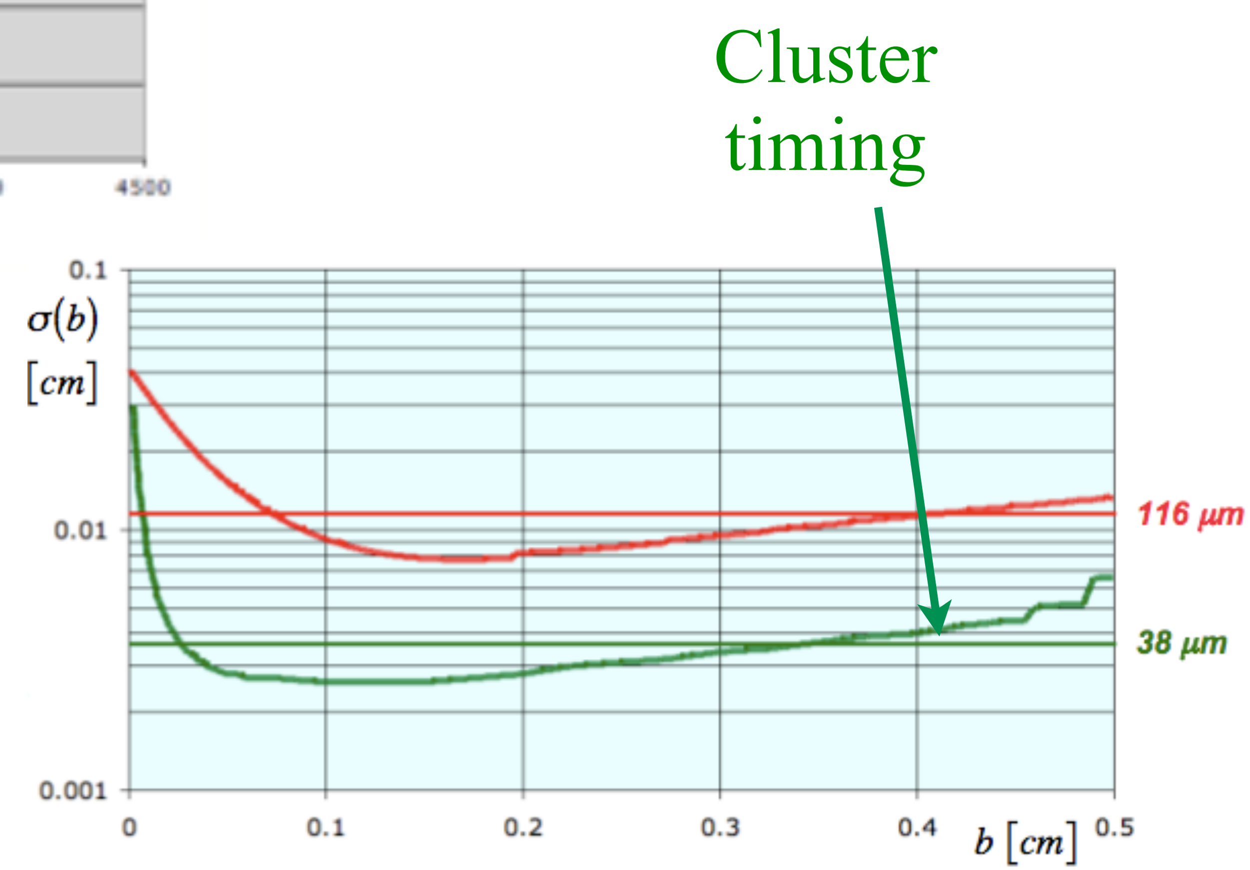
vii. the detector may need further spatial-time-directional rejection capabilities

- an "invisible" detector for γ's and *n*'s

ultra low-mass tracking system, CluCou, Grancagnolo; low-mass Si?





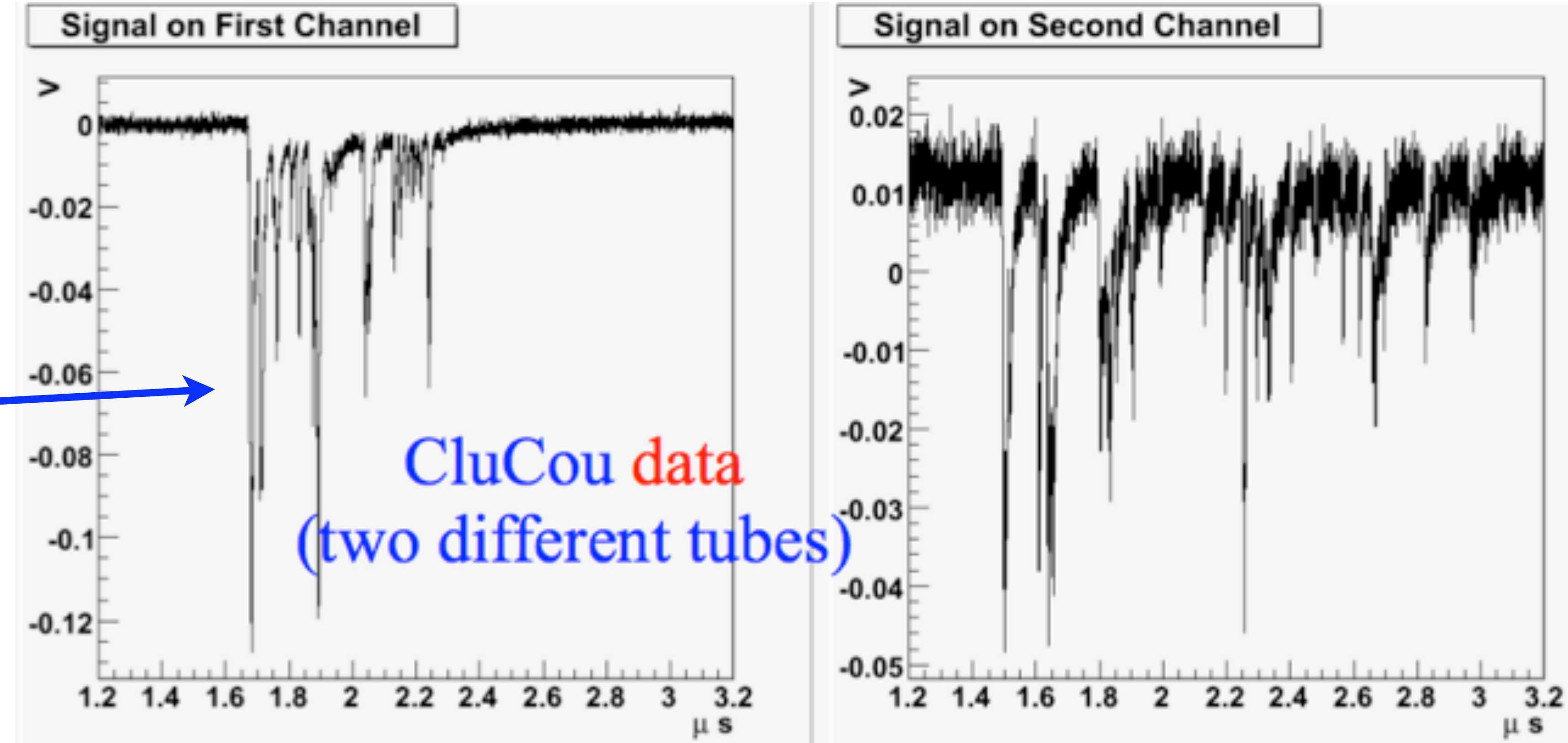


Ultra-low-mass (He gas) chamber, expect ~50 μm spatial resolution on each of 150 points on a track.

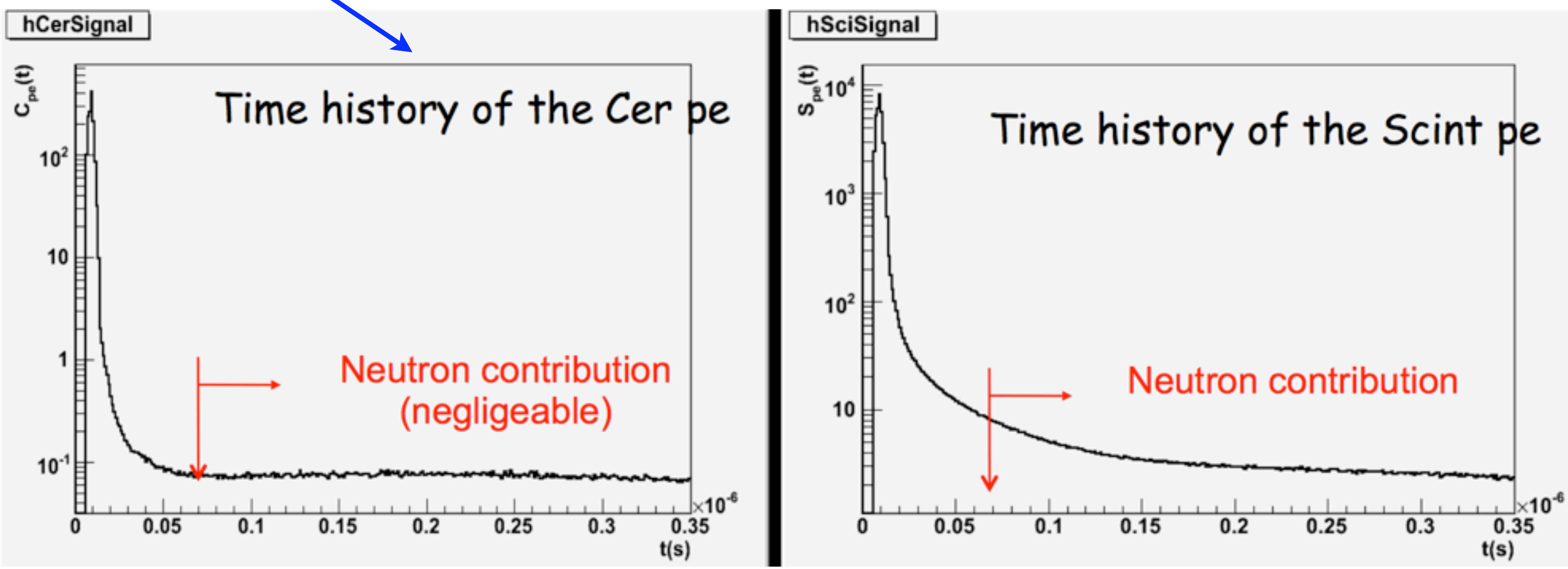
- "last resort" - reject using detector measurements ➡ time history every channel
  spatial and time measurements (Steve Geer)

sub-nanosecond sampling of entire detector volume:

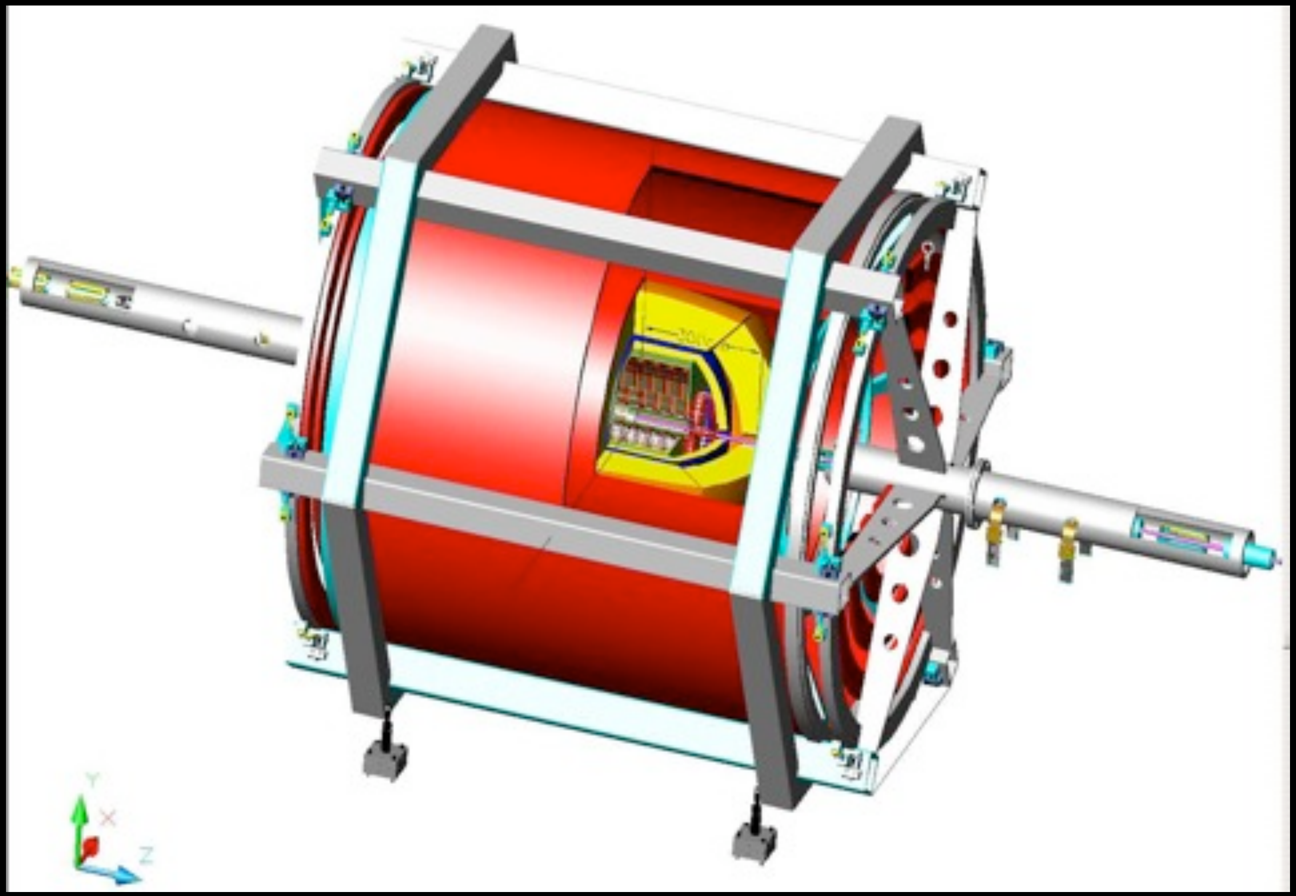
tracking & muon



calorimeter



An Dual Readout/Dual Solenoid Detector for Physics Studies at μCollider



Modification of 4th Concept Detector for 3 TeV Physiscs

1. Vertex Detector 20-micron pixels
2. Silicon Tracker (preliminary version)
3. Forward Tracker Disks (preliminary version)
4. Dual-readout calorimeter with time-history
5. Dual-solenoid with Muon Spectrometer

Replaces a Drift Chamber

The 4th Concept Collaboration

4th Letter of Intent

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Started @ Snowmass
8 / 2005

140 Members
33 Institutions
15 Countries

www.4thconcept.org

The 4th Concept Calorimeter

Hadronic Calorimeter

Cu + scintillating fibers + Ĉerenkov fibers

Fully projective layout

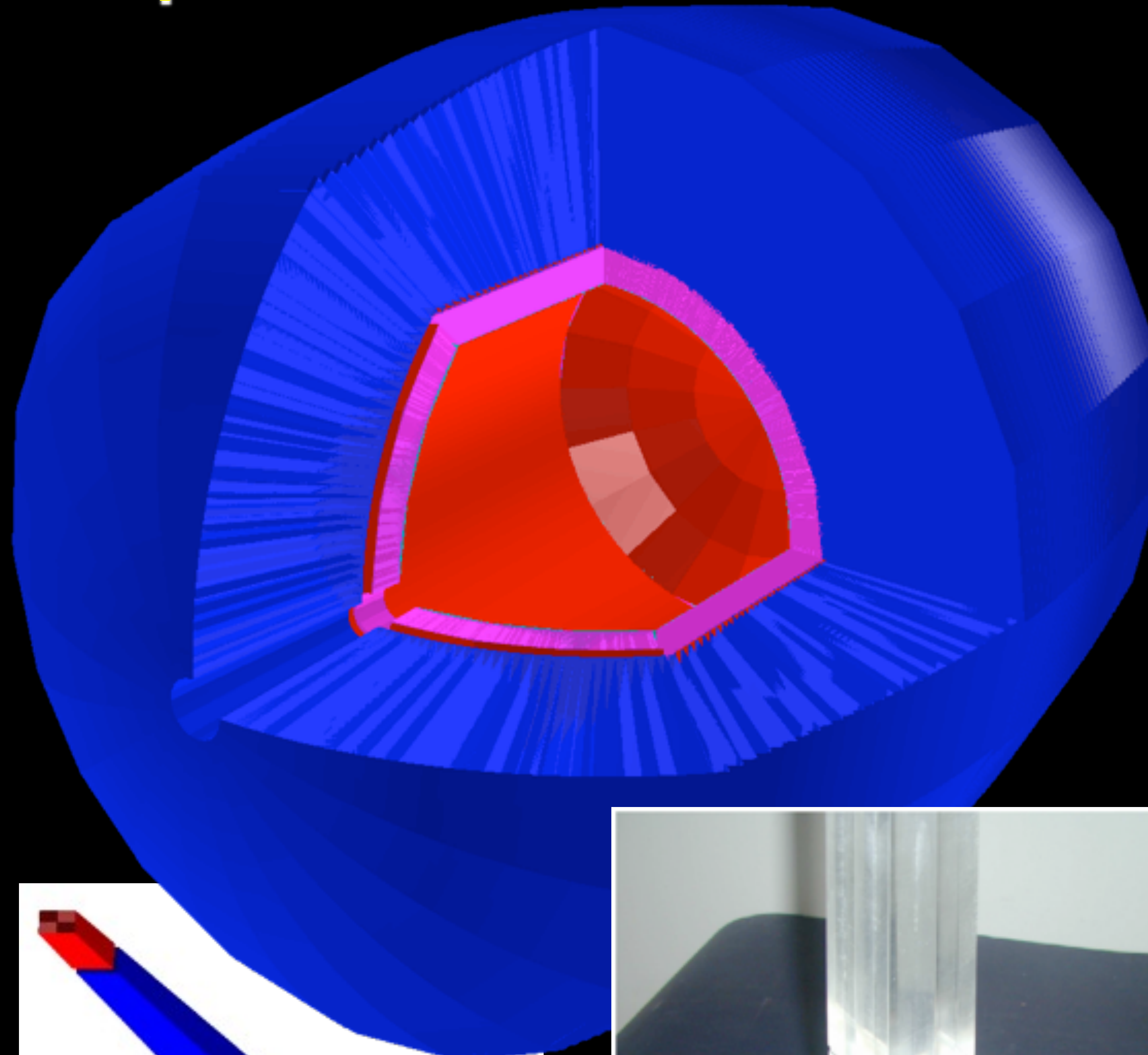
~1.4° aperture angle

~ 7.3 <λ_{int}> (Fibers)

Azimuth to 2.8°

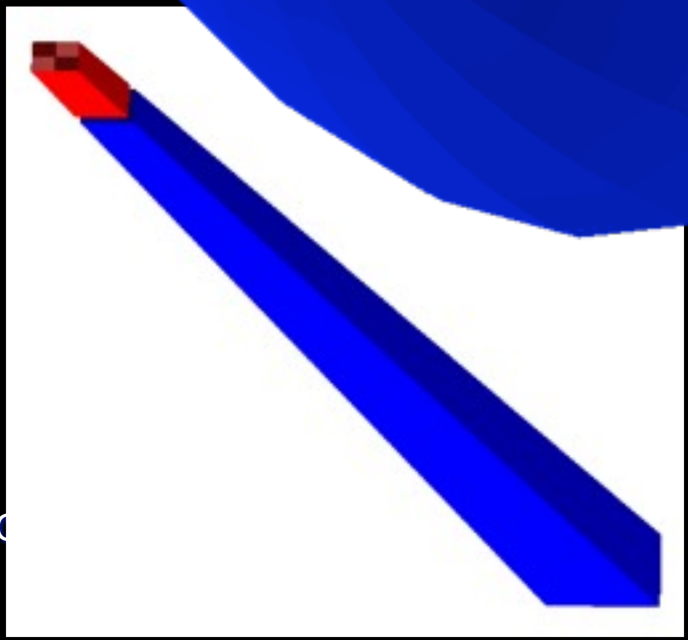
Barrel: 16384 cells

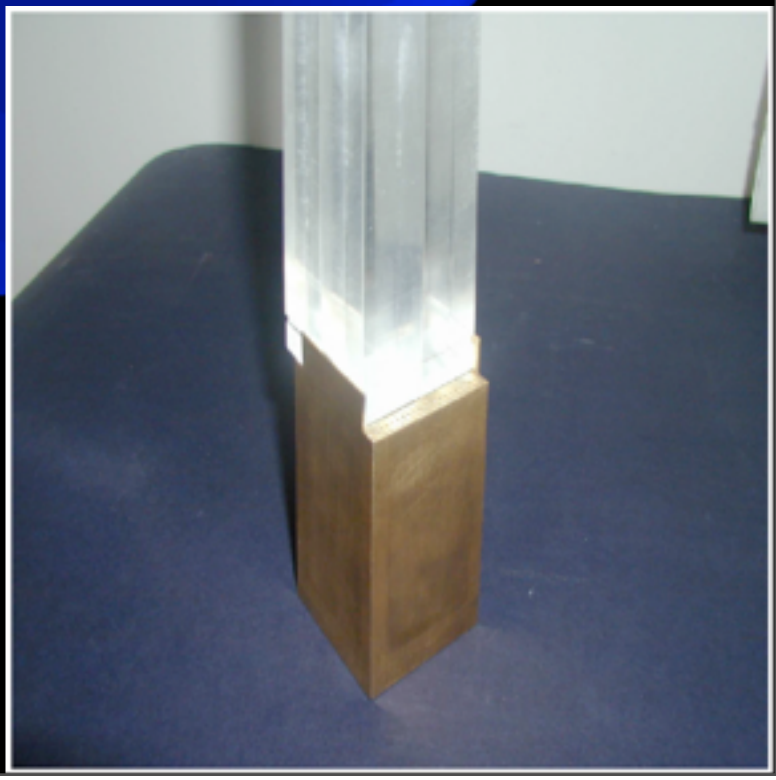
Endcaps: 7450 cells



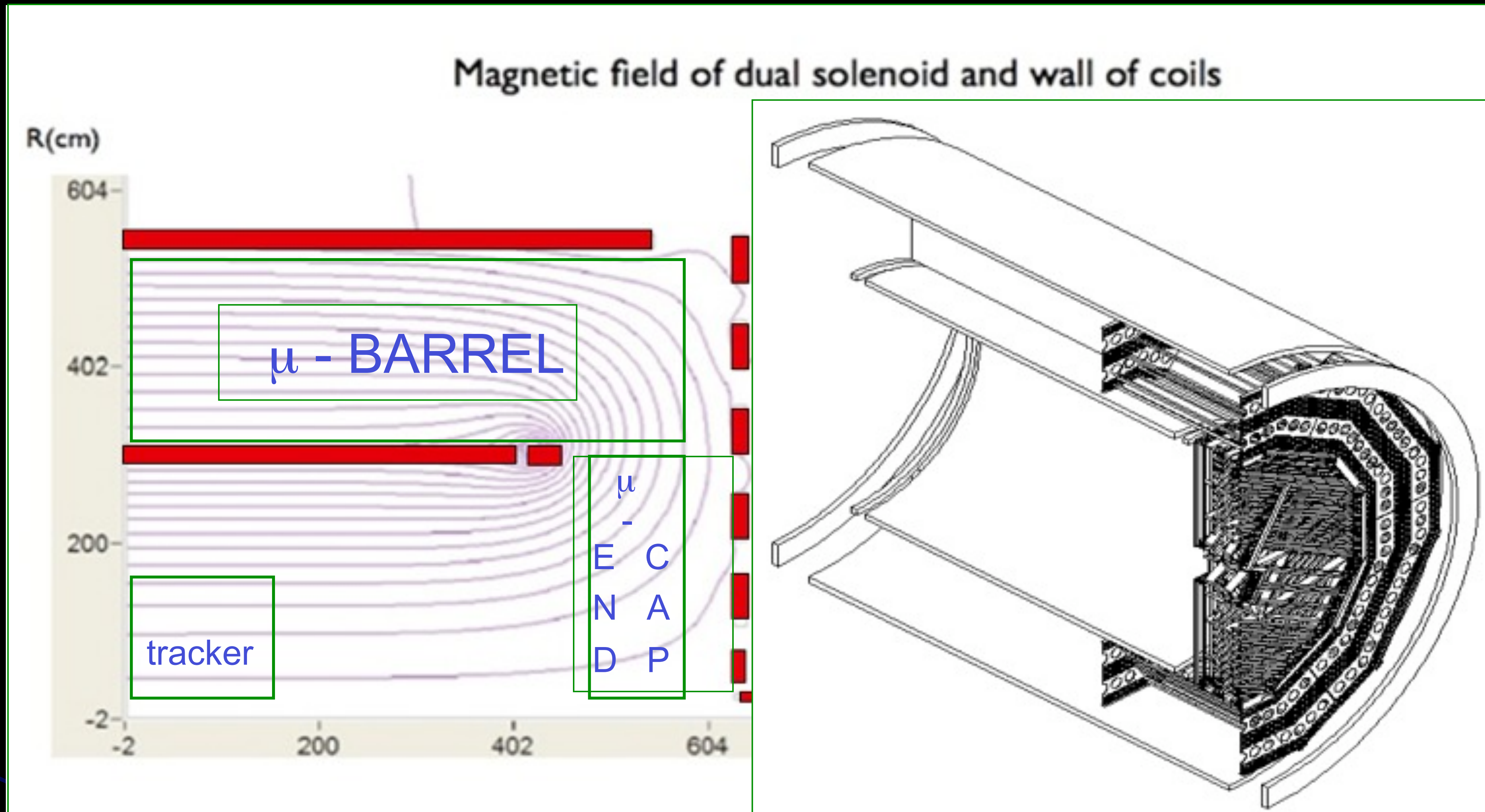
Electromagnetic Calorimeter

- BGO crystals for scintillating
- and Čerenkov light
- 2x2 crystals for each HCAL tower
- ~25 cm/22.7 Xo depth and ~ 1 λ_{int} depth
- Barrel: 65536 cells
- Endcaps: 29800 cells





Dual Solenoid B-field & Muon Spectrometer



radius 2.3 cm
filled with 90% He – 10% iC_4H_{10} @ NTP
gas gain few × 10^5
total drift time 2 μs
primary ionization 13 cluster/cm ⇒ ≈ 20 electrons/cm total
both ends instrumented with:

- > 1.5 GHz bandwidth
- 8 bit fADC
- > 2 Gsa/s sampling rate
- free running memory

for a

- fully efficient timing of primary ionization: cluster counting
- accurate measurement of longitudinal position with charge division
- particle identification with dN_{cl}/dx

Barel:

31500 tubes
21000 channels
840 cards

End caps:

8640 tubes
9792 channels
456 cards

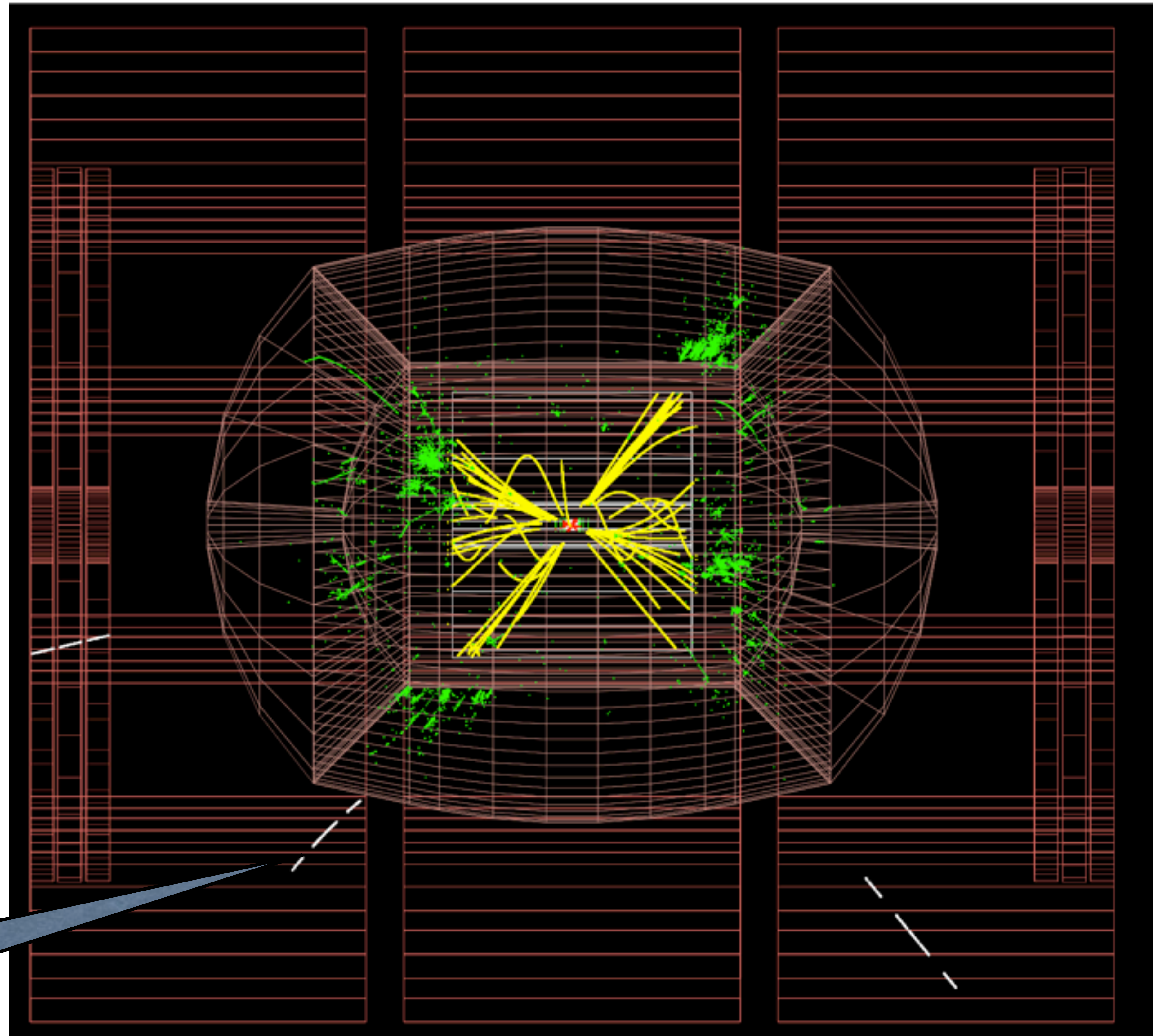
Total:

40140 tubes
30792 channels
1296 cards

Event Display in ILCroot

$e^+e^- \to H^oH^oZ^o$
$\to$ 4 jets
$+$ 2 muons

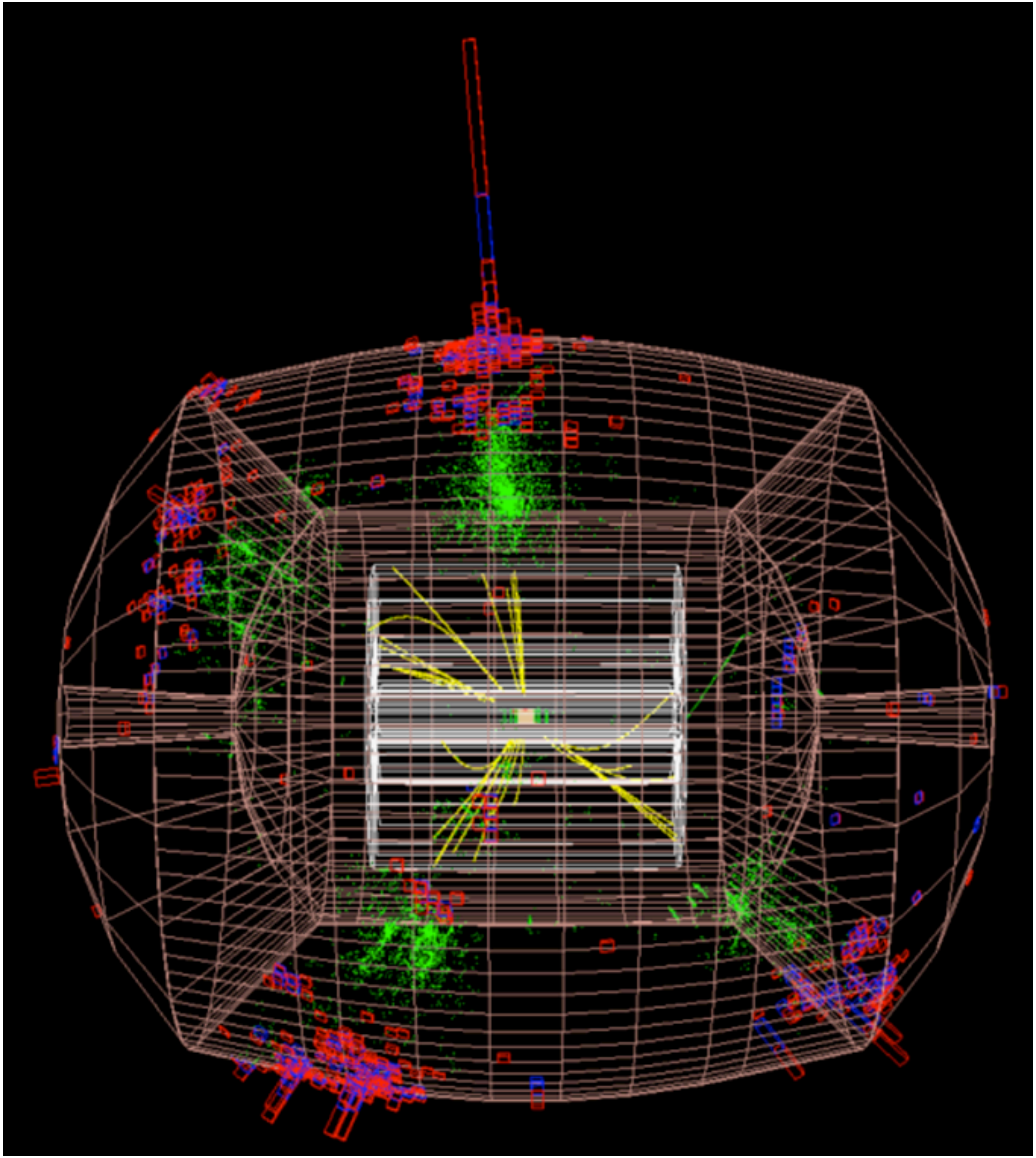
$E_{CM} = 500$ GeV



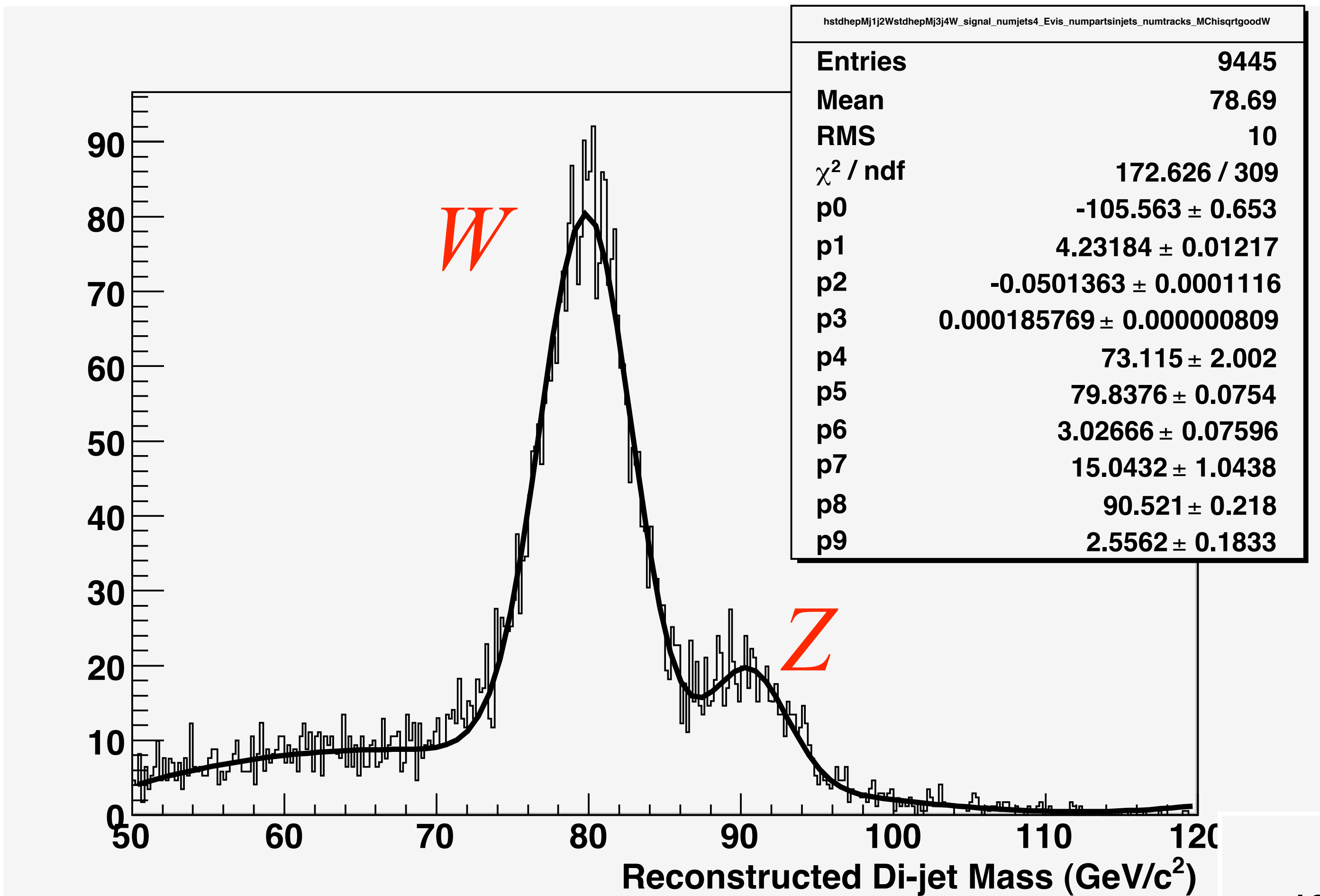
Low pt secondary muon

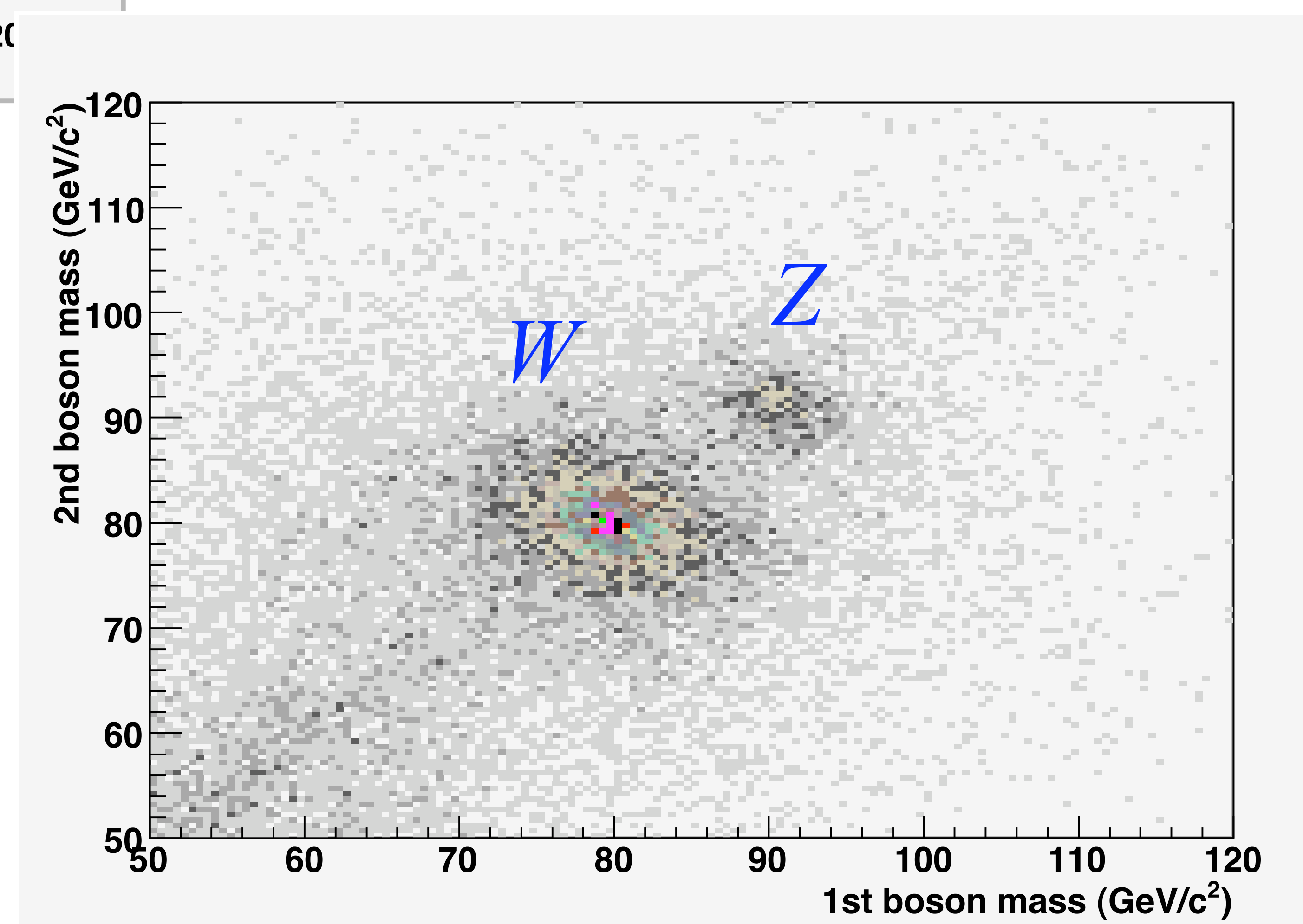
H^0Z^0 event

tracking &
calorimeters



W and Z mass measurement and discrimination

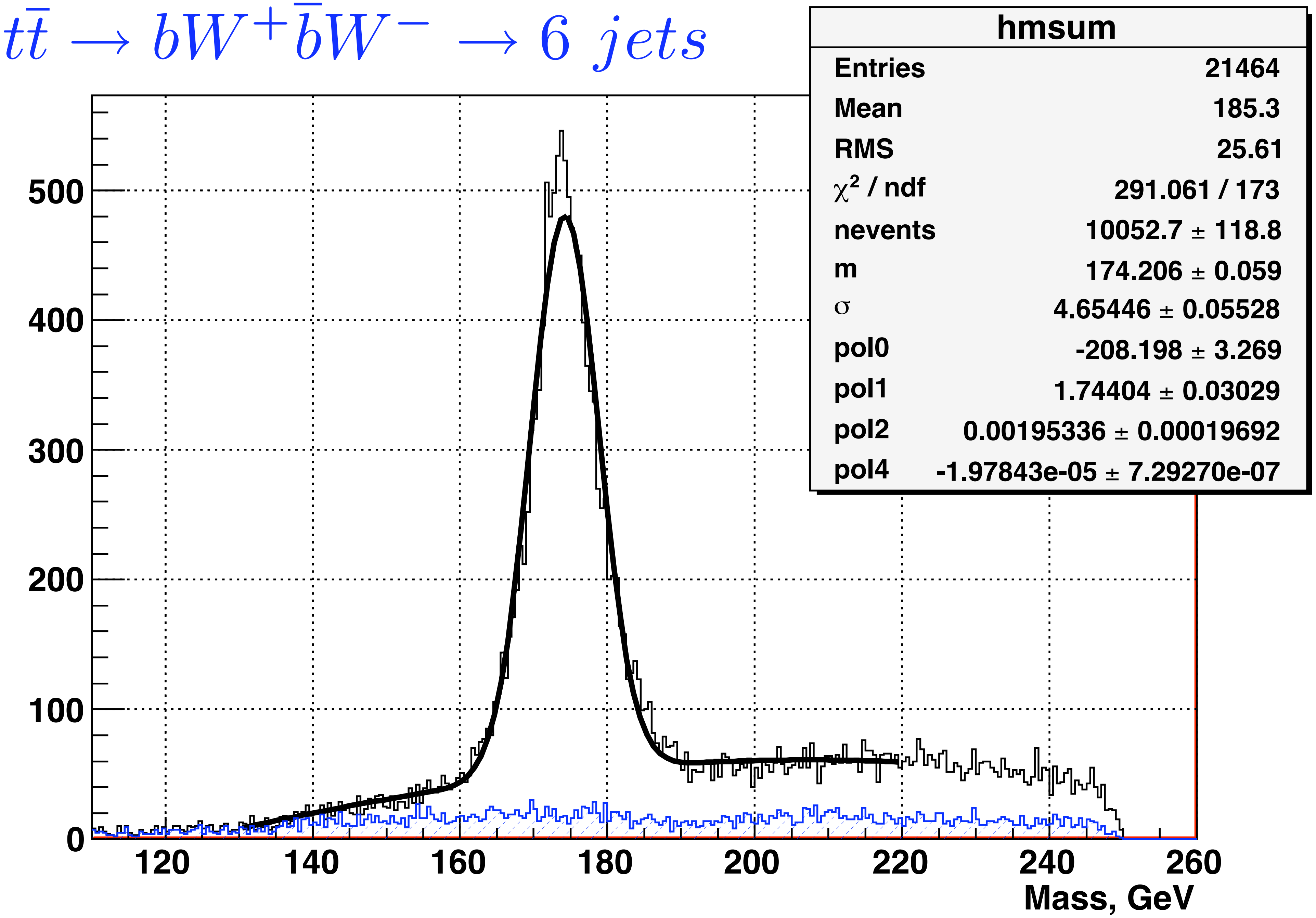




From the SUSY pt. 5 analysis
by Anna Mazzacane

top quark (all hadronic channel)

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



Fedor Ignatov (Budker Institute, Novosibirsk)

Summary

Calorimeter

Make it deep, ~10 λ_{INT}. No tail-catchers. Strictly uniform and well-defined volume sampling. The 4.5-5.5 λ_{INT} of the ILC calorimeters is a mistake, and worse for pions with 2/3 of the proton cross section, so effective interaction length depth is 3.0-4.0 λ_{INT}.

Tracking

Material budget X_0 is the danger. It worsens momentum resolution, worsens impact parameter tagging for *b,c* quarks, and forces photons to convert and electrons to bremsstrahlung inside the tracker volume. Silicon tracking has this risk. Lower mass gaseous trackers have their own problems: long-drift collects positive ions, and short-drift may have higher occupancies. *CluCou is the lowest-mass presently conceived tracking chamber, but may not survive MuX (we shall see)*

Time history

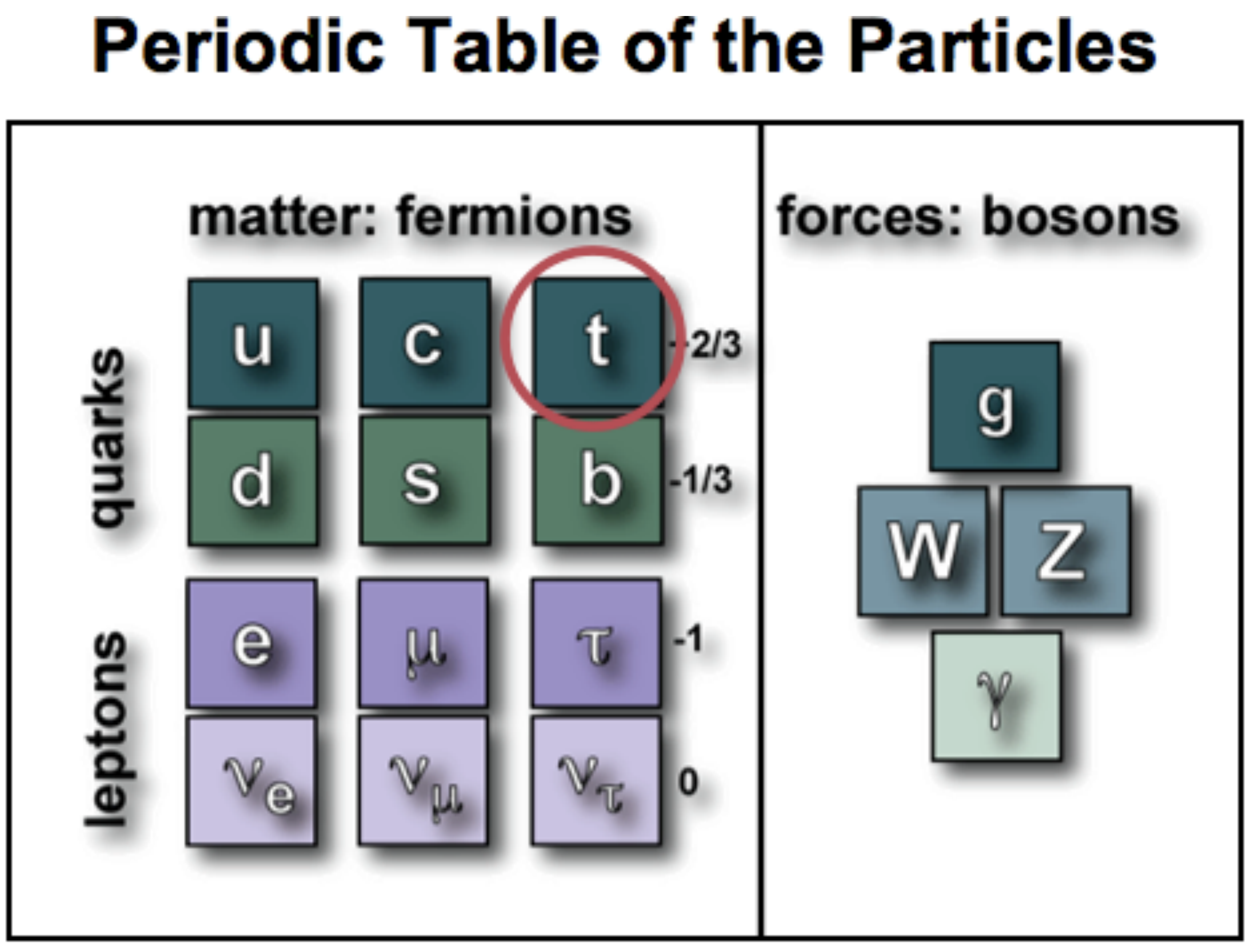
On 4th, we clock out everything with GHz or faster digitizers: 6-bits for CluCou clusters, and 14-bits for the dual-readout channels. This is very powerful for resolutions, pattern recognition, and background rejections. For the Muon Collider in particular, backgrounds will be in the wrong places with the wrong times.

Above all, this is all understood, in detail, by the Lecce group of Anna Mazzacane, Vito Di Benedetto, Gianfranco Tassielli, Marco Peccarisi, Corrado Gatto, and others.

If there's time, continue with particle identification:

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)

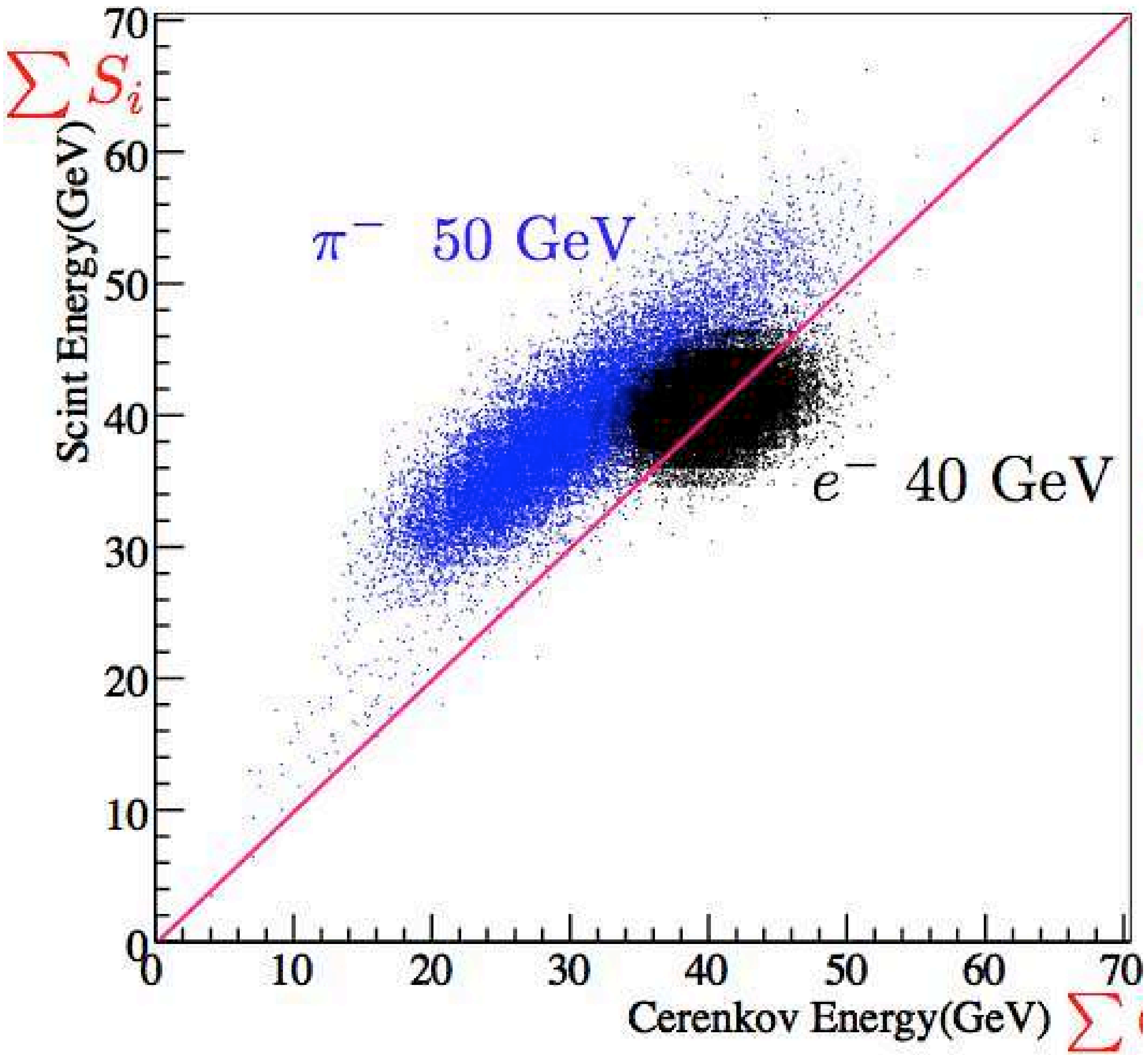
- *electron* (dual-readout)
- *muon* (dual-readout and iron-free field)
- *tau* (reconstruction)
- *neutrino* (by subtraction; resolution)

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

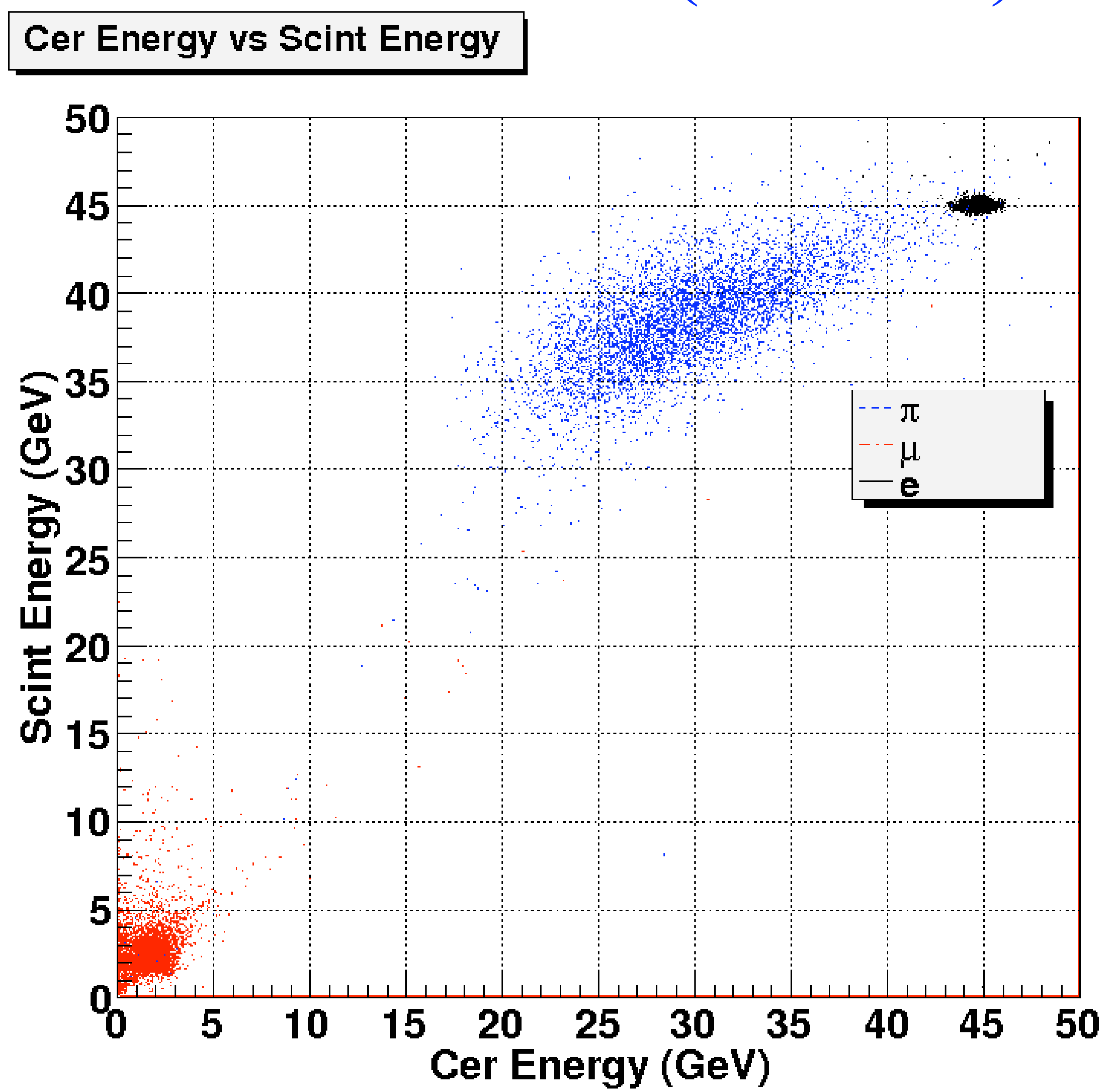
We think we can do it all.

Scintillation vs. Cerenkov → e - μ - π

DREAM fiber data

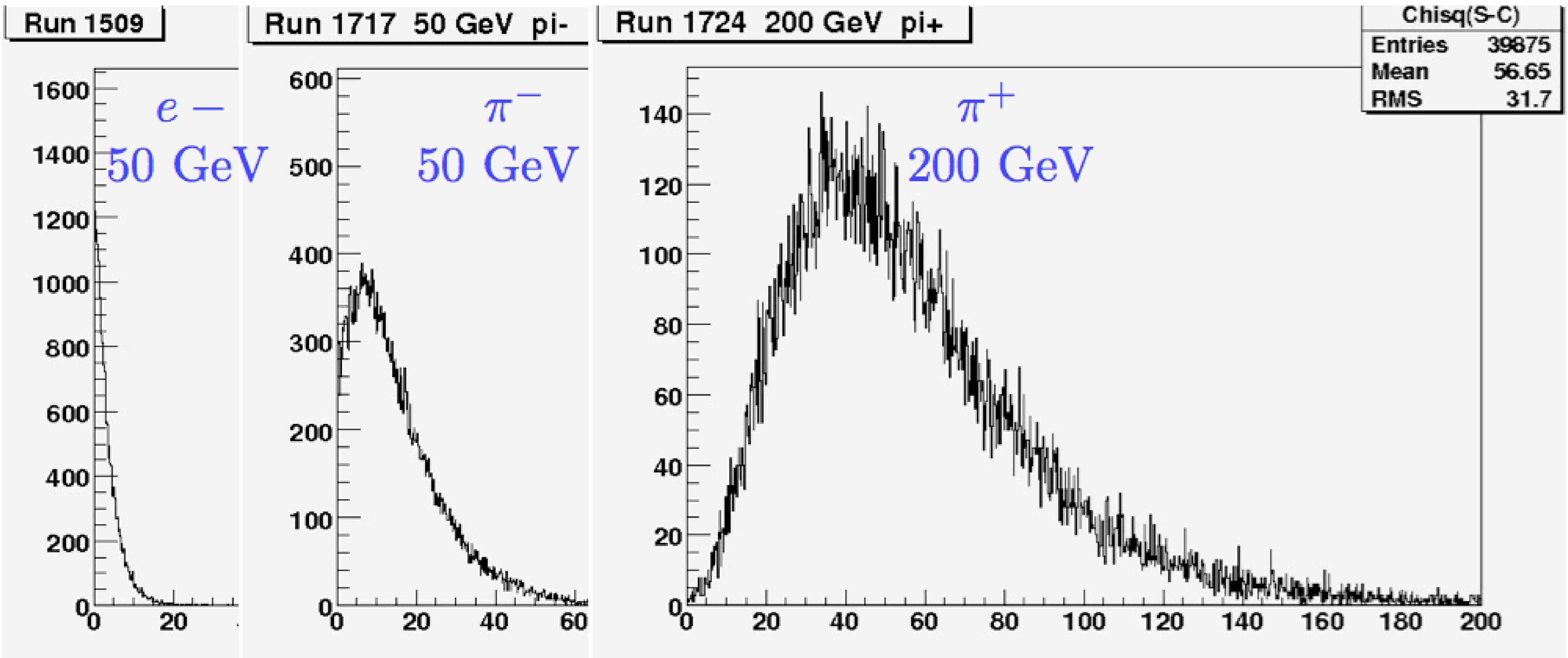


4th simulation (45 GeV)

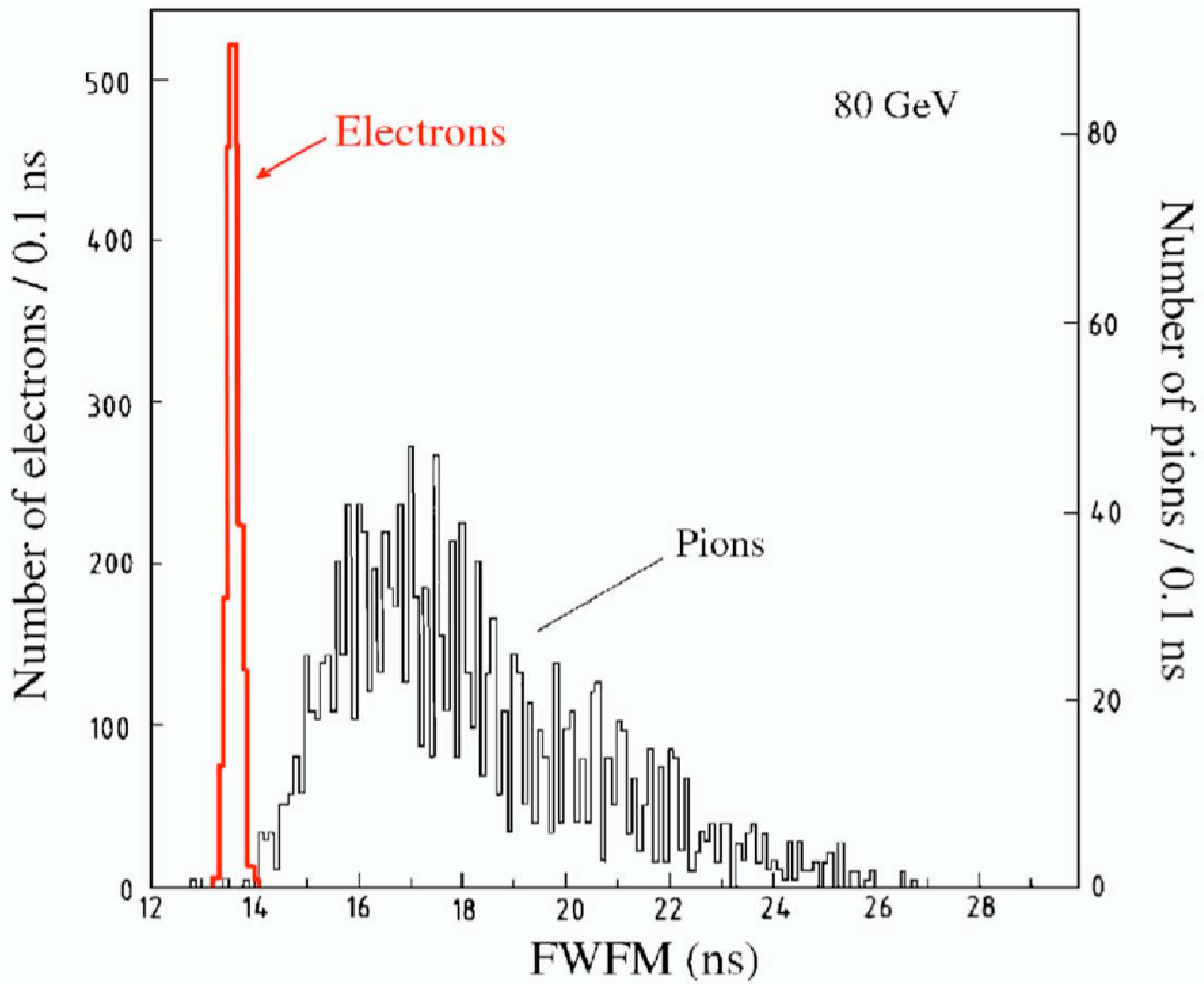


(ii) Further discrimination from the *fluctuations in S-C among the channels of a shower*

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



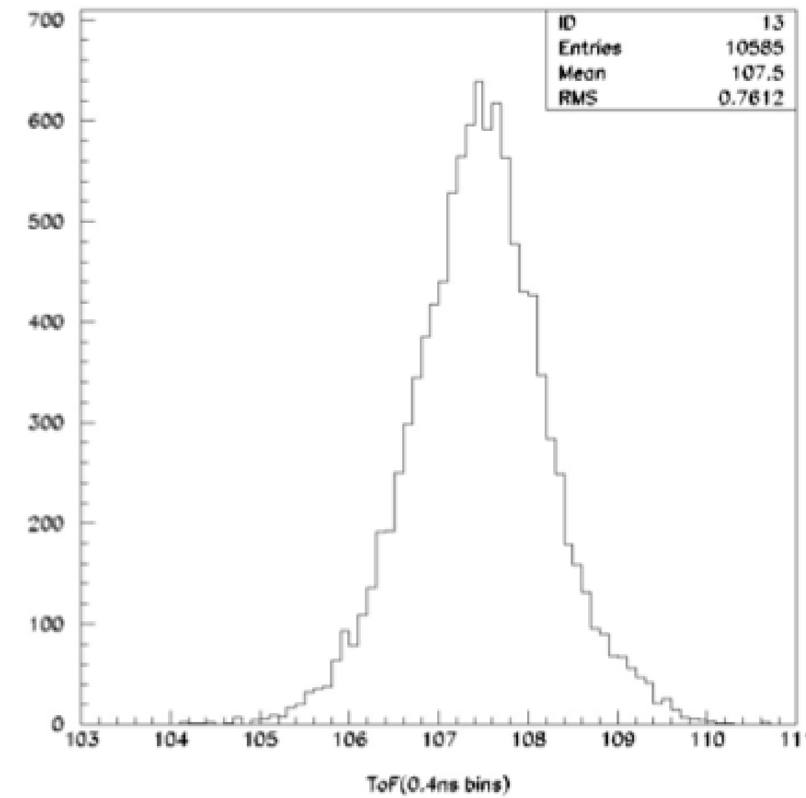
(iii) Time-history of scintillating fibers: duration of pulse at 1/5-maximum (SPACAL data)



Time-of-flight

(Cerenkov fibers)
$\sigma \sim 0.3$ ns

DREAM data

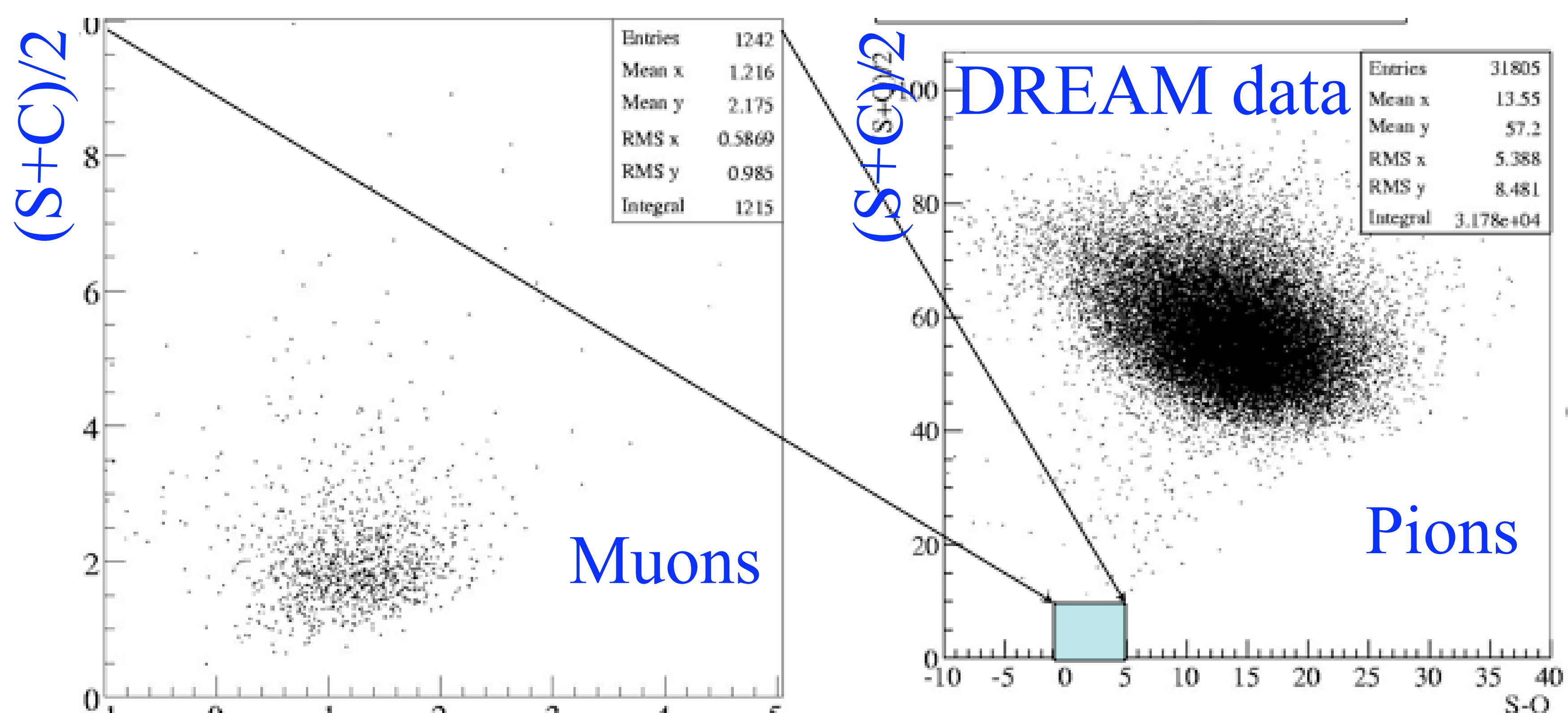


t (0.4 ns bins)

Muon tag (unique)

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

(S+C)/2 ~ E_{brems}



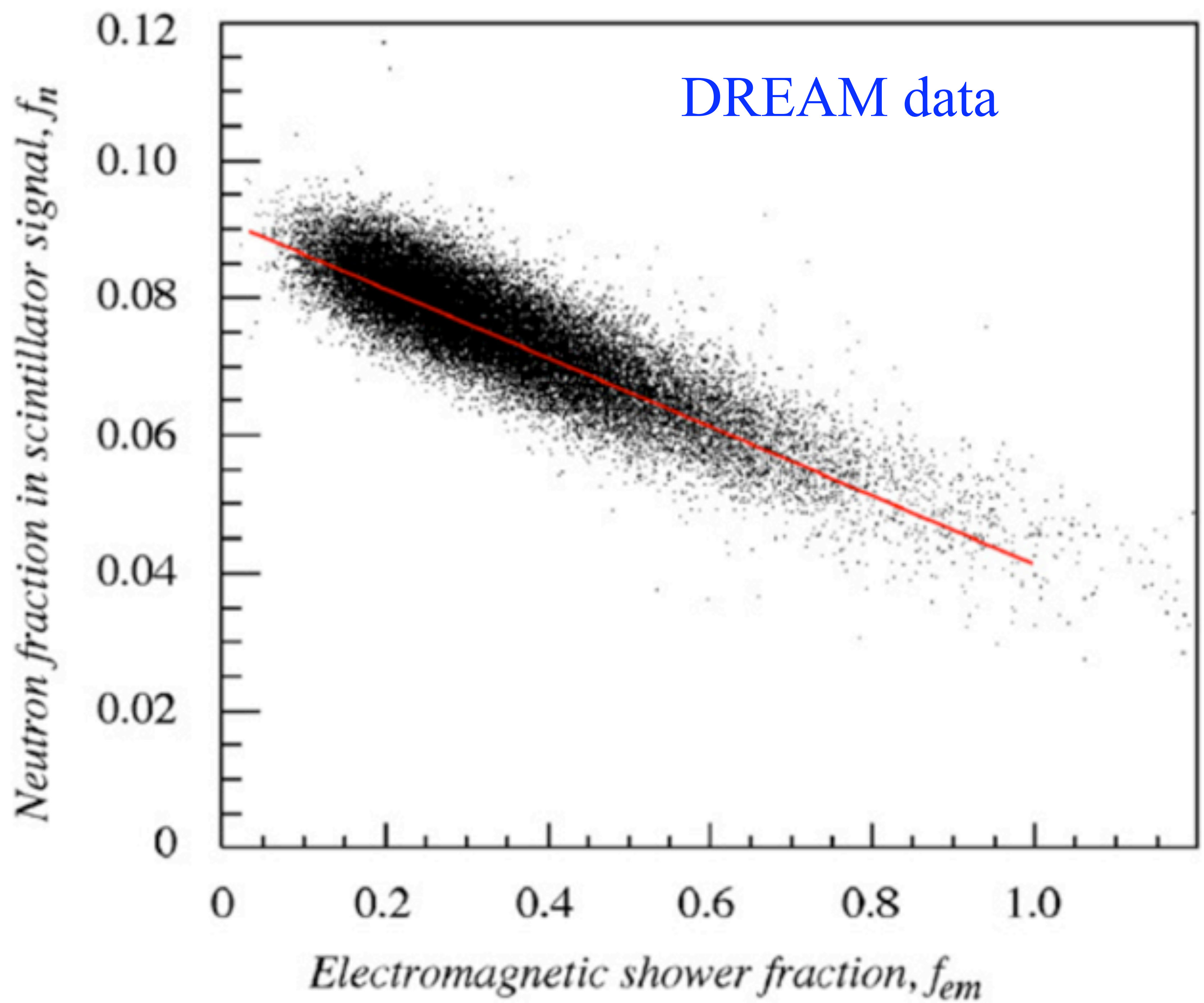
S-C S-C

Neutron fraction *vs.* electromagnetic fraction: "hadronic" ID tag

Expected anti-correlation of

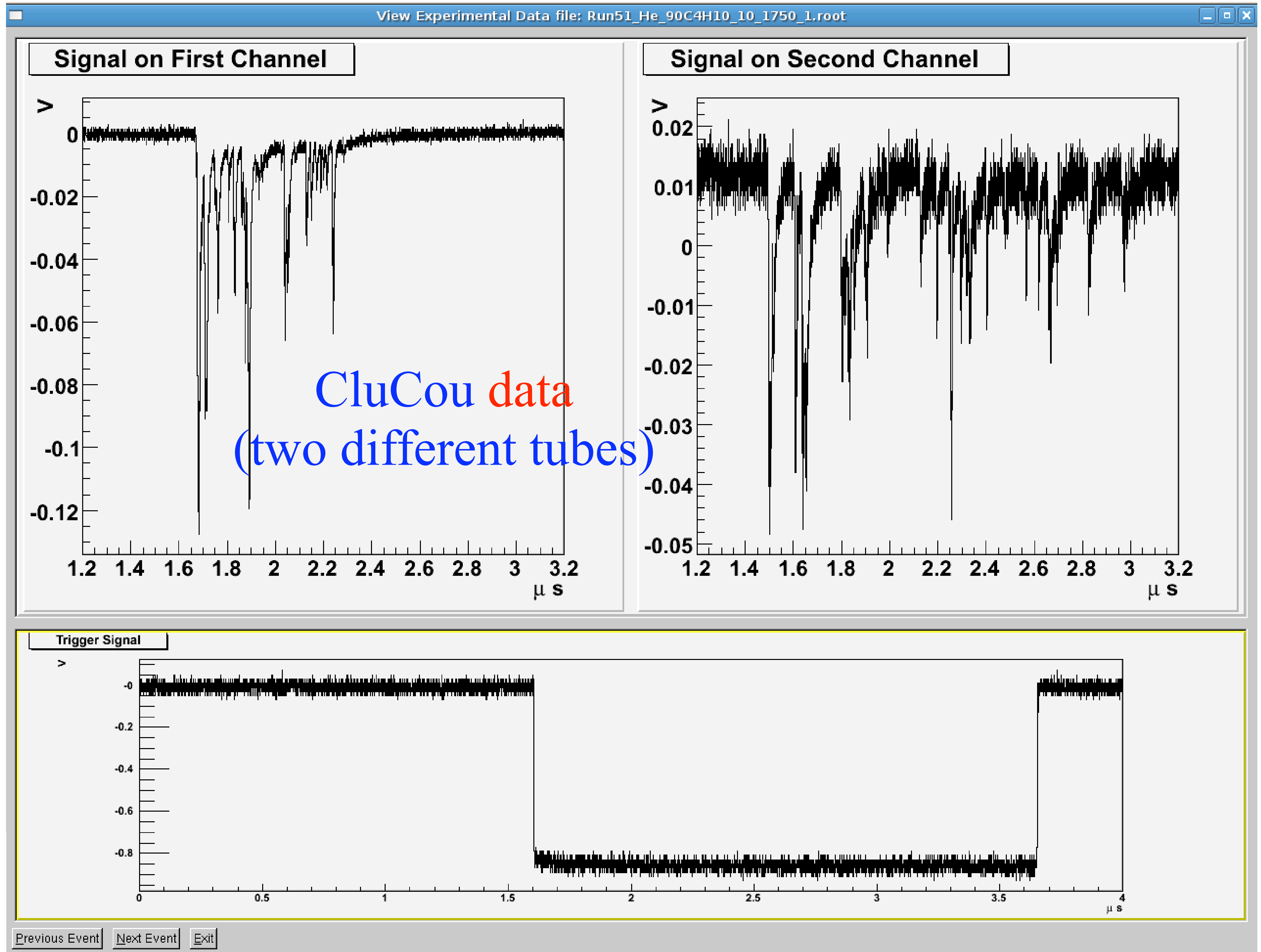
f_n (hadronic content) and

f_{EM} (electromagnetic content)

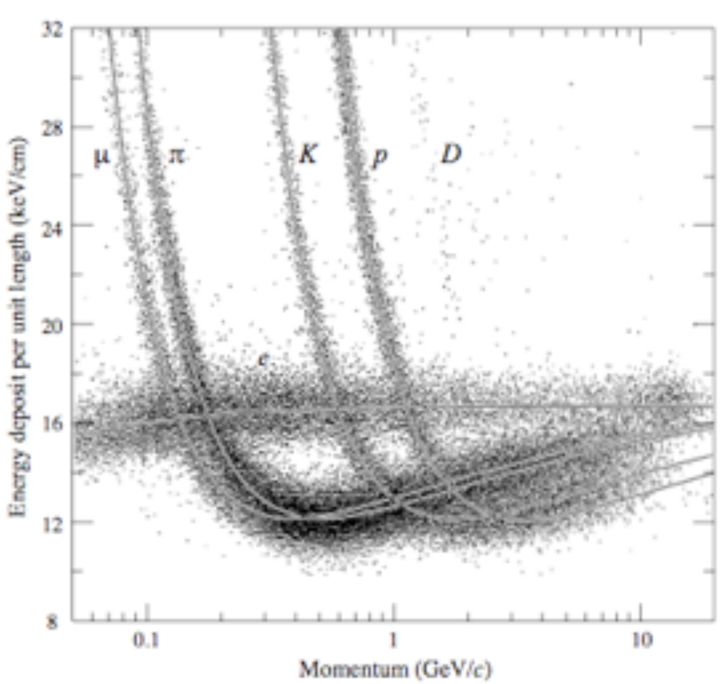


Cluster-timing

dN/dx is Poisson: better specific ionization resolution ~3% (no Landau tail)



CluCou data
(two different tubes)

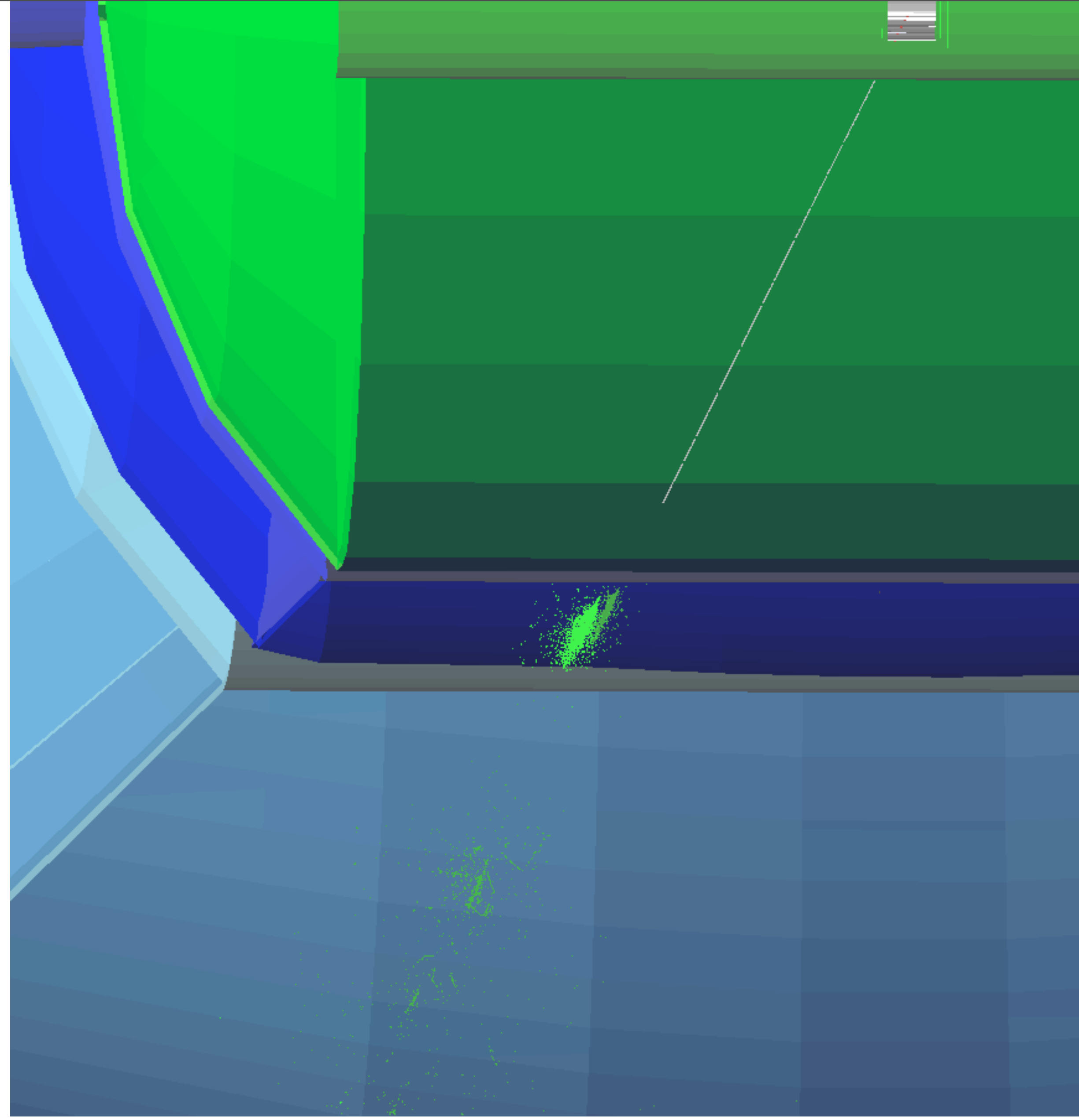


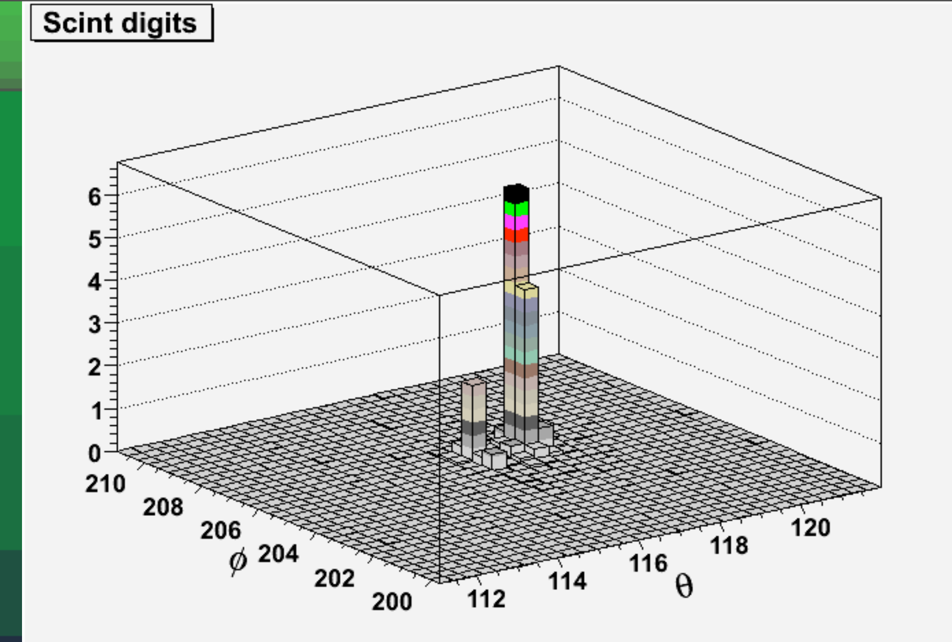
dE/dx resolution TPC LBL/PEP4 (data using truncated mean, resolution~6%)

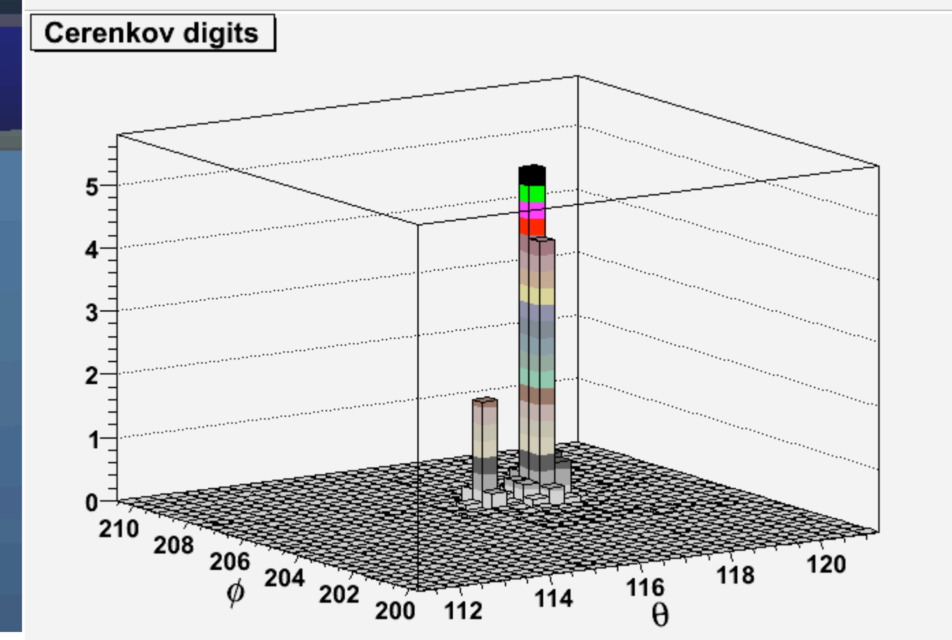
$\tau^{\pm}$ ID

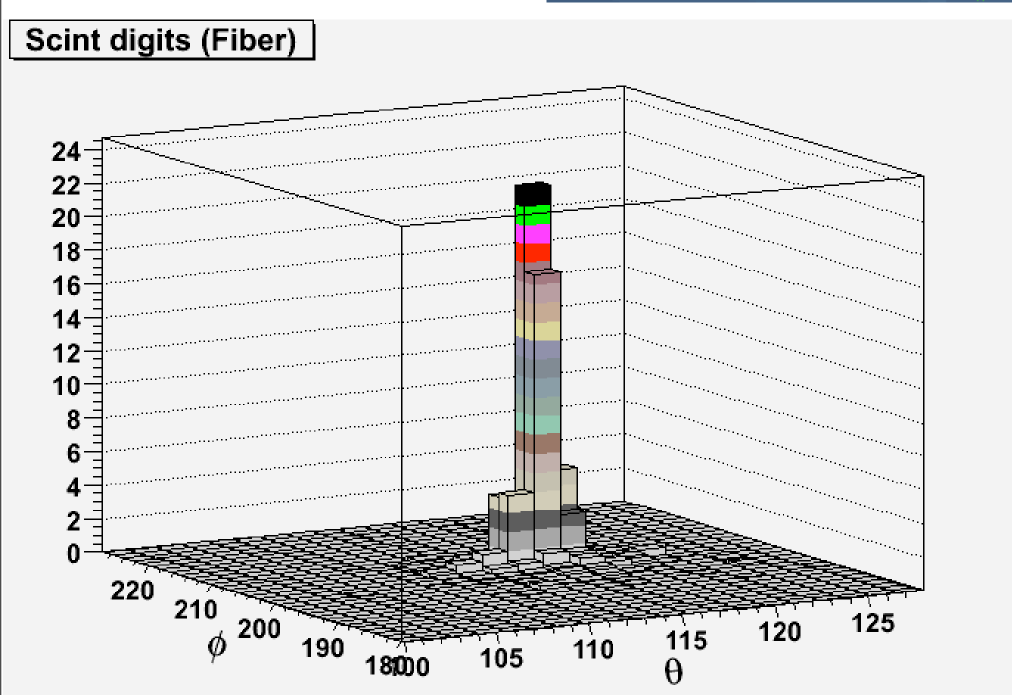
(for polarization)

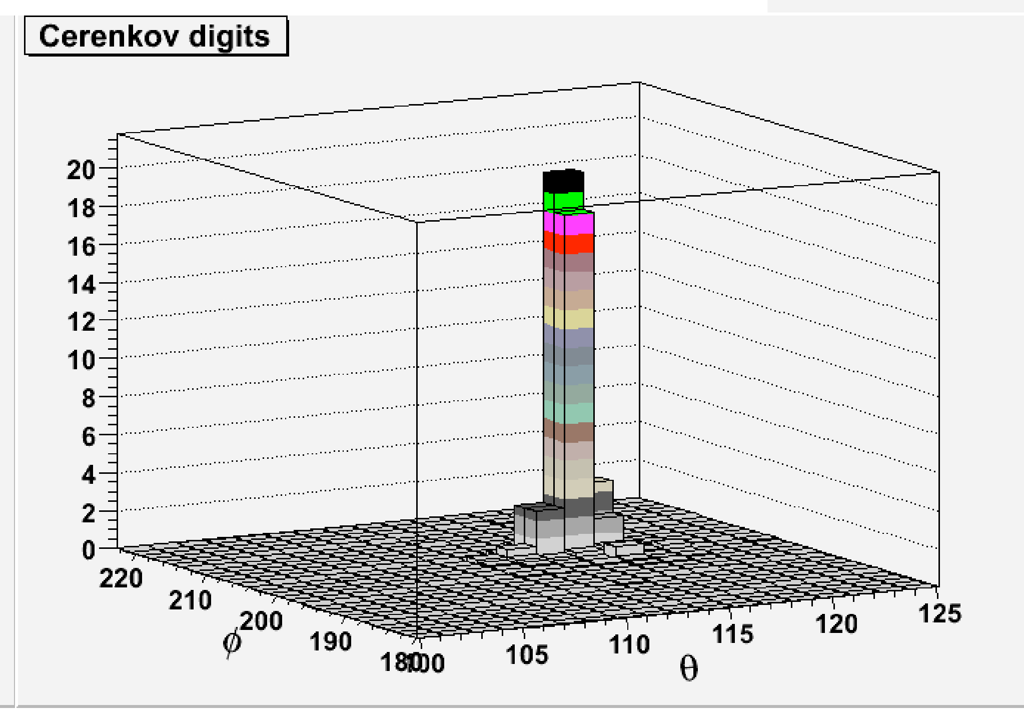
$$\tau^- \to \rho^- \nu$$
$$\to \pi^- \pi^0$$
$$\to \pi^- \gamma\gamma$$



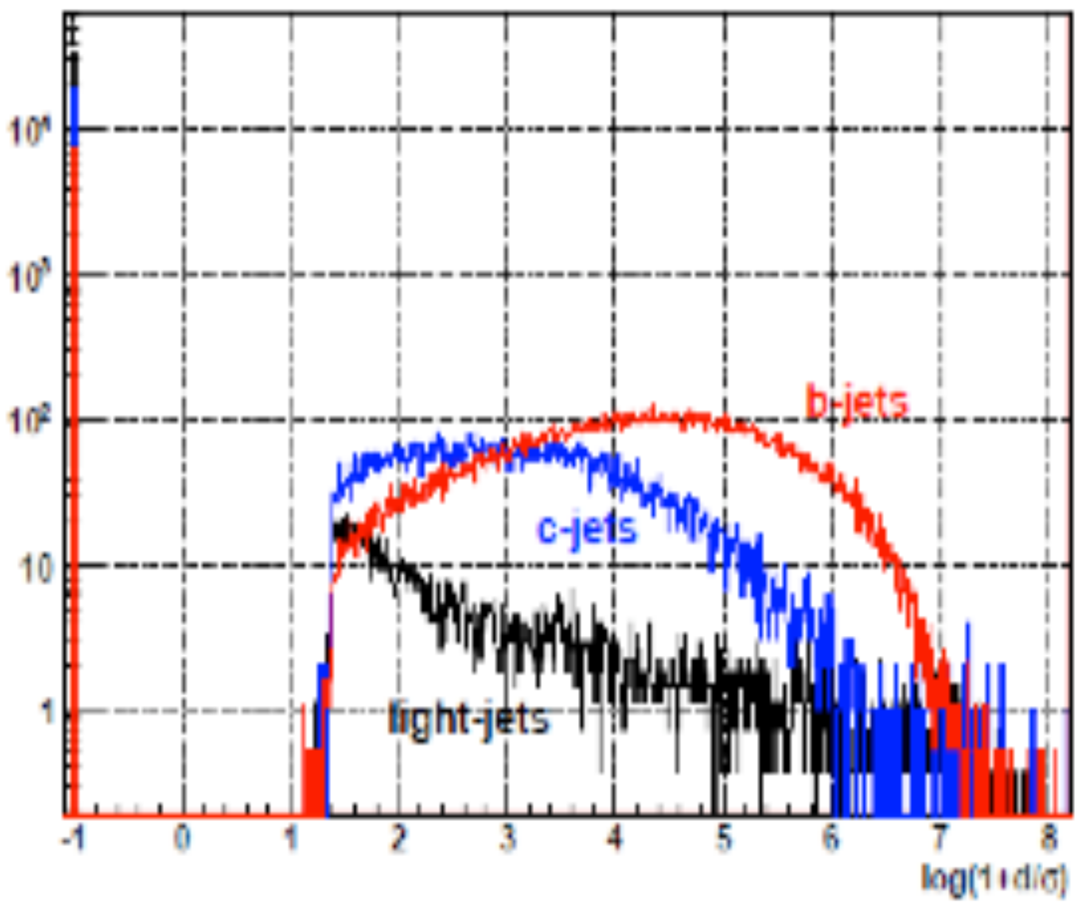


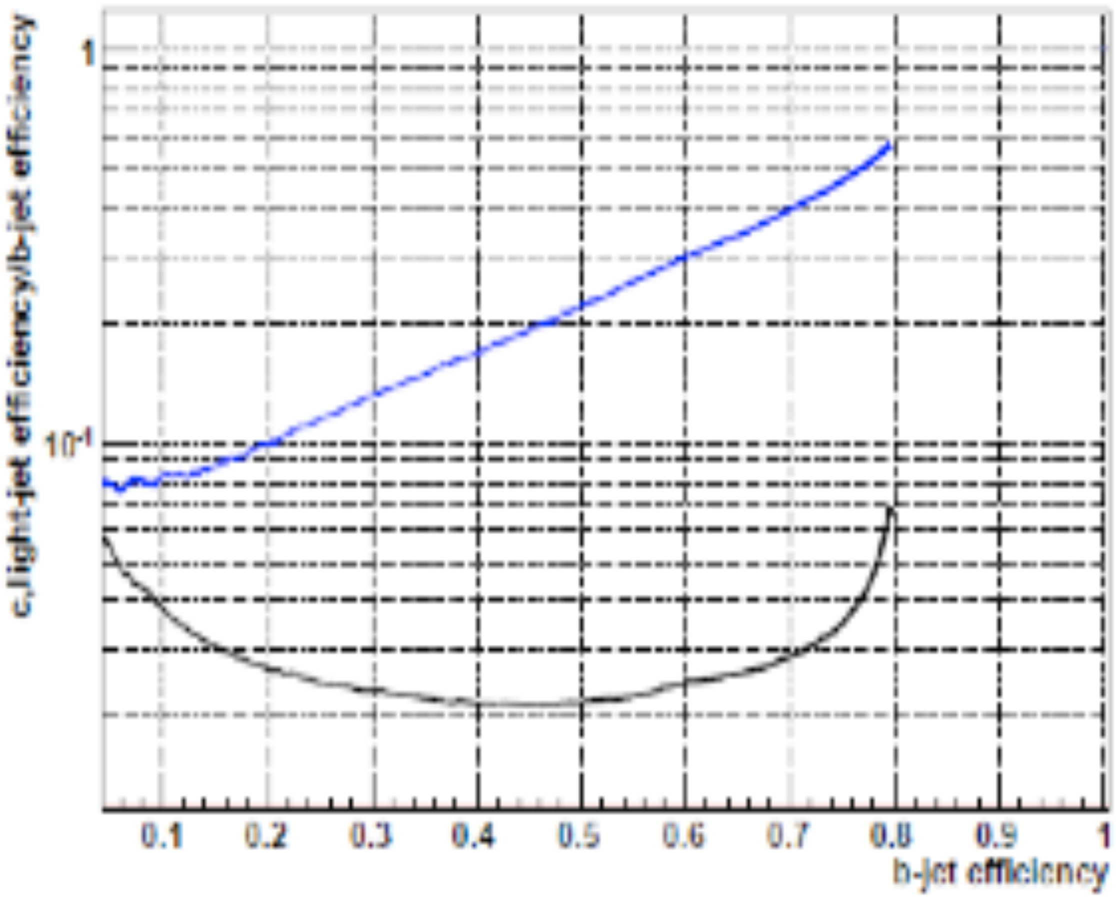






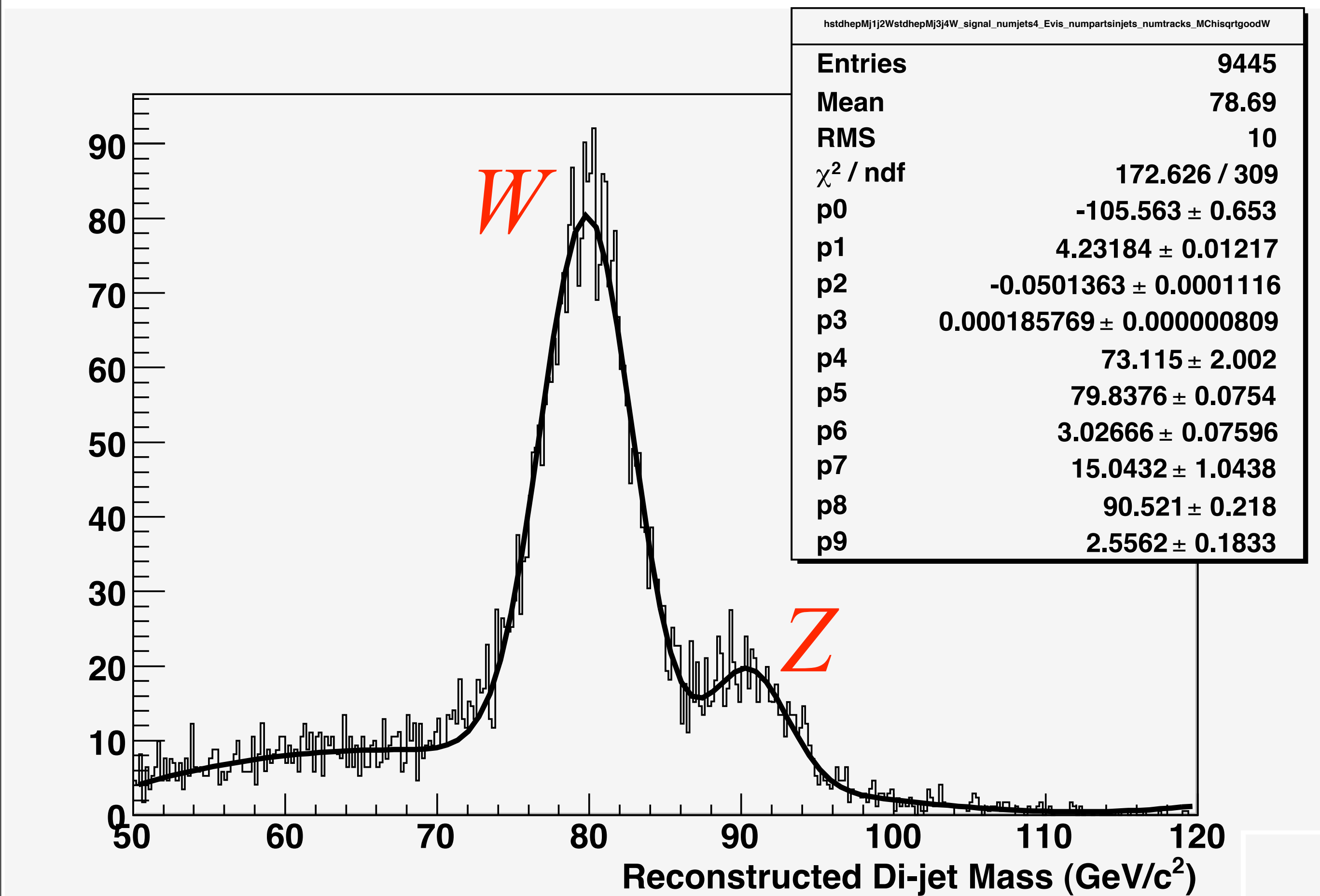
b,c quark tagging (by lifetime)

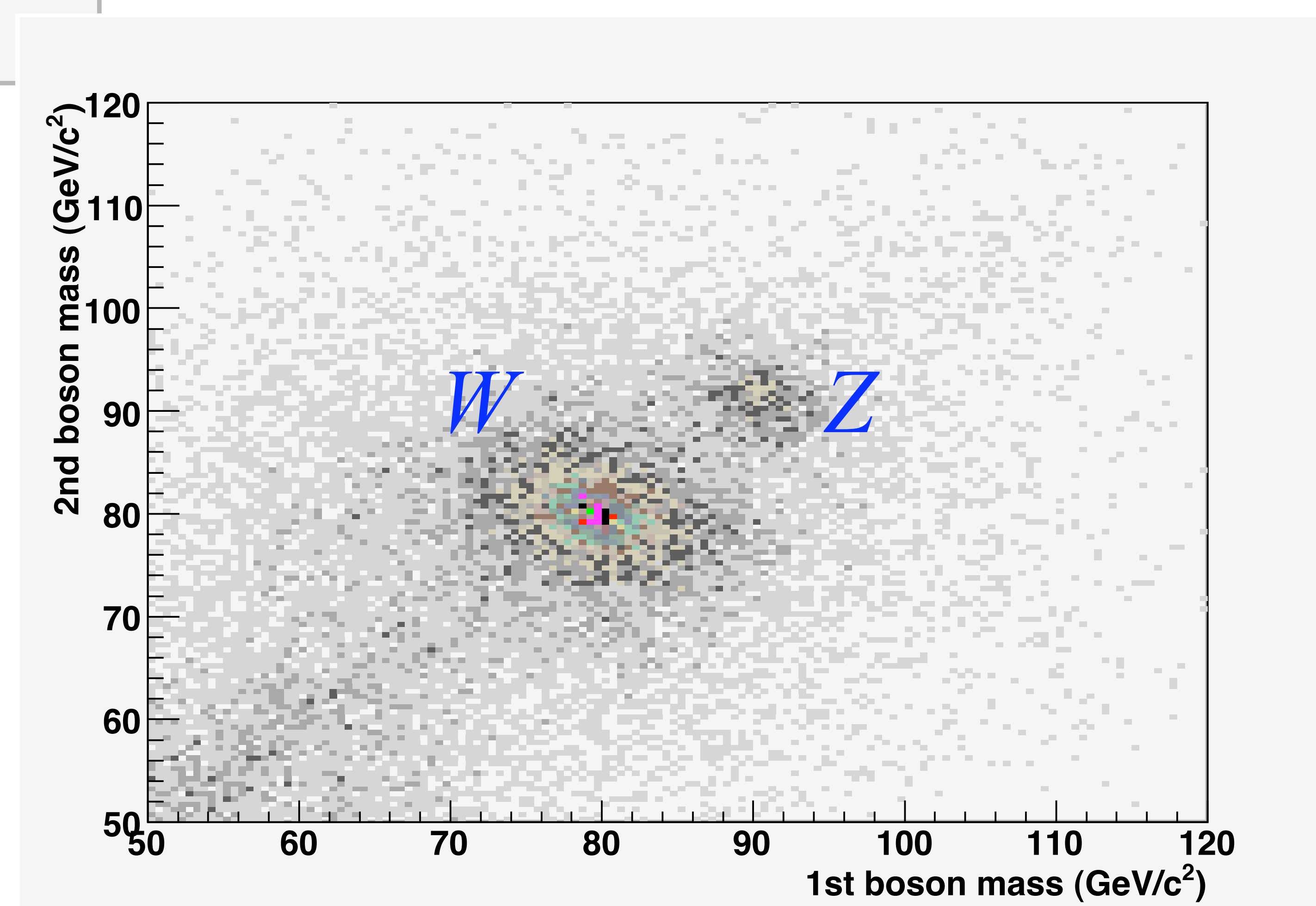




vertex impact parameter

W and Z mass discrimination (hadronic decays)

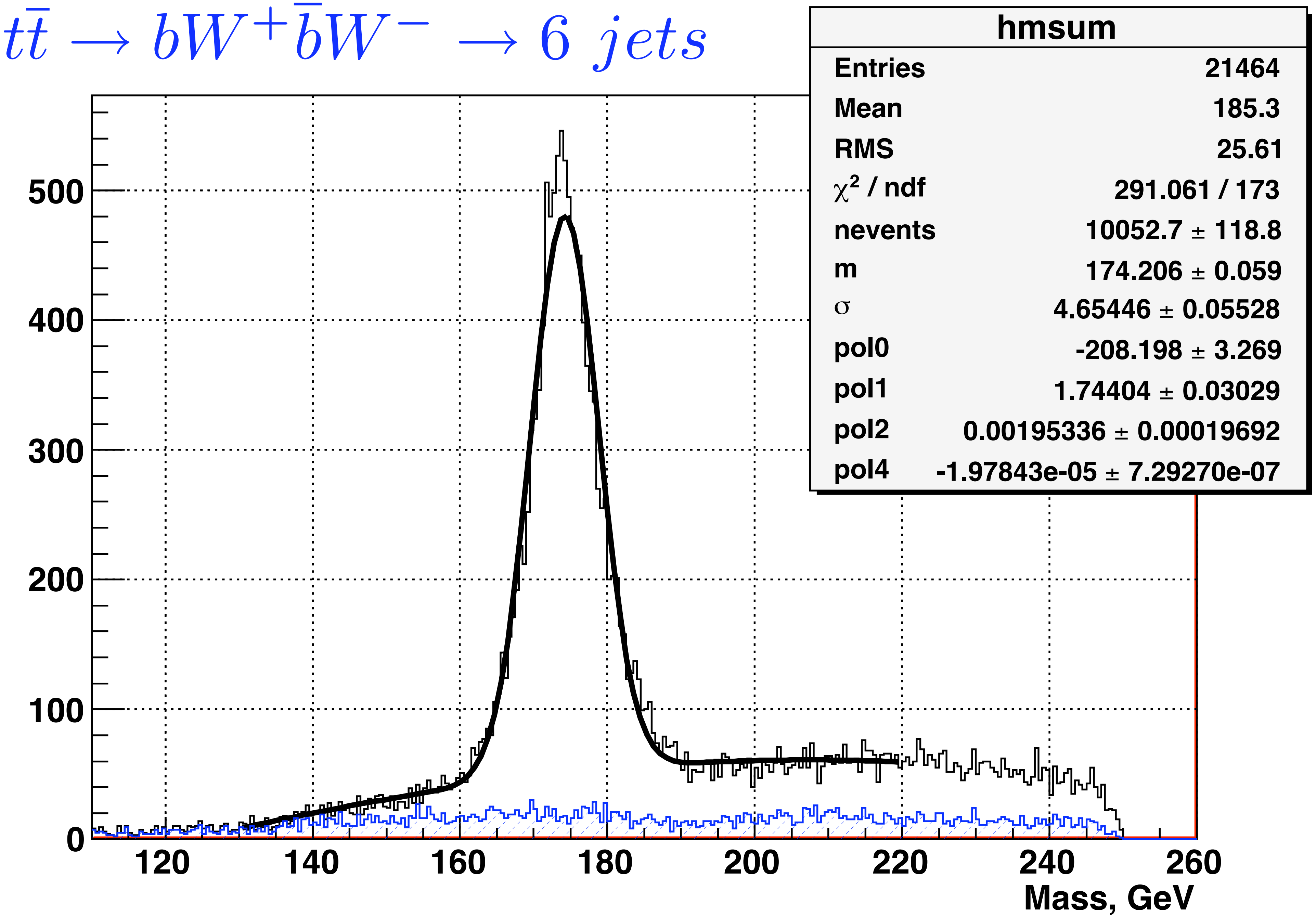




From the SUSY pt. 5 analysis
by Anna Mazzacane

top quark (all hadronic channel)

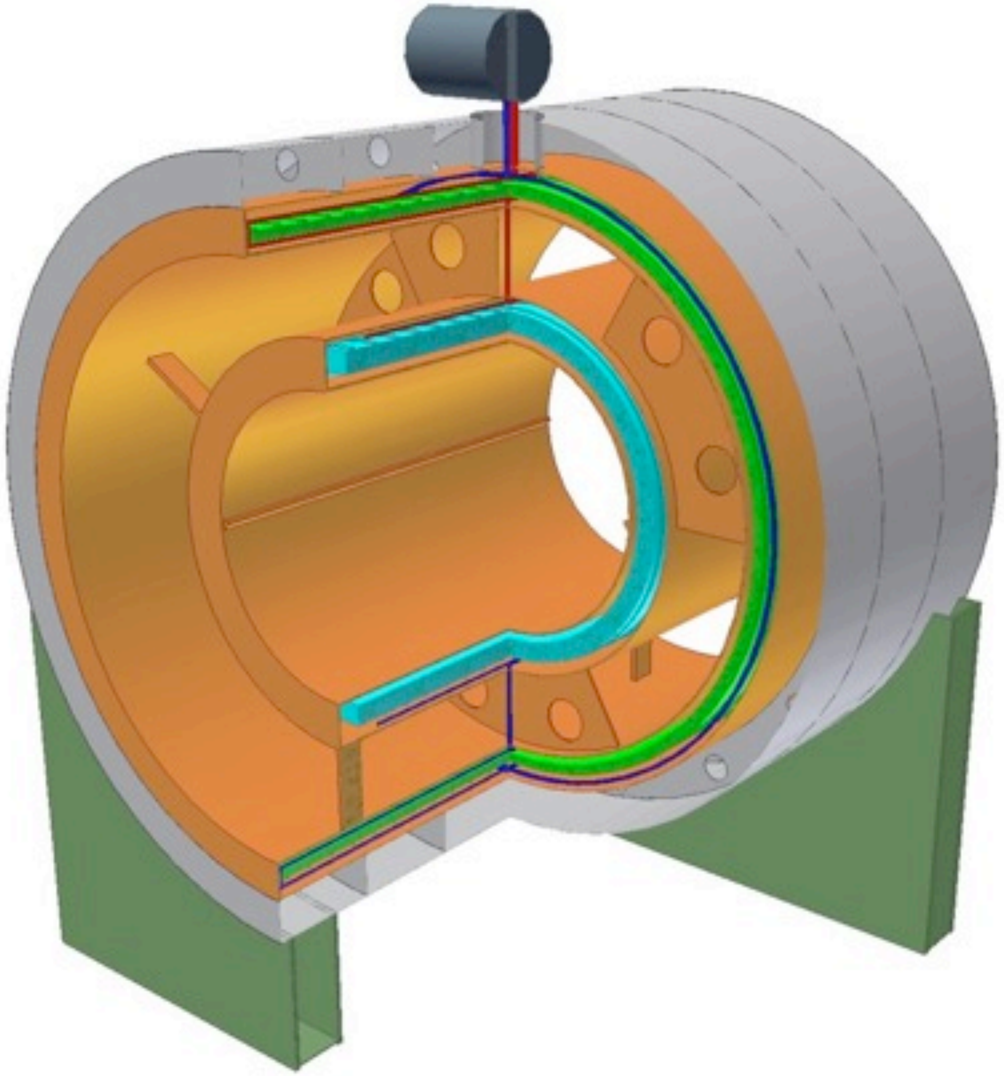
$$e^+e^- \to t\bar{t} \to bW^+\bar{b}W^- \to 6\ jets$$

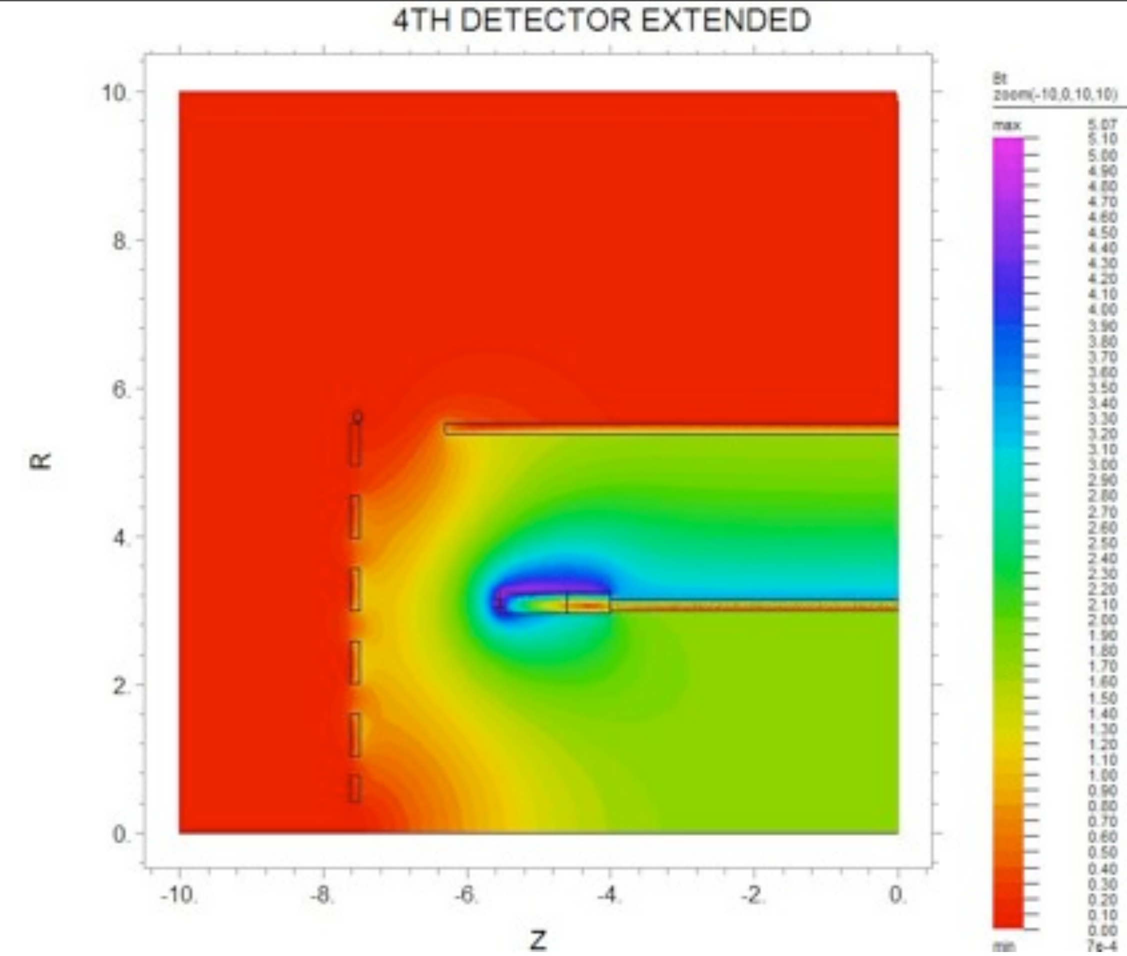


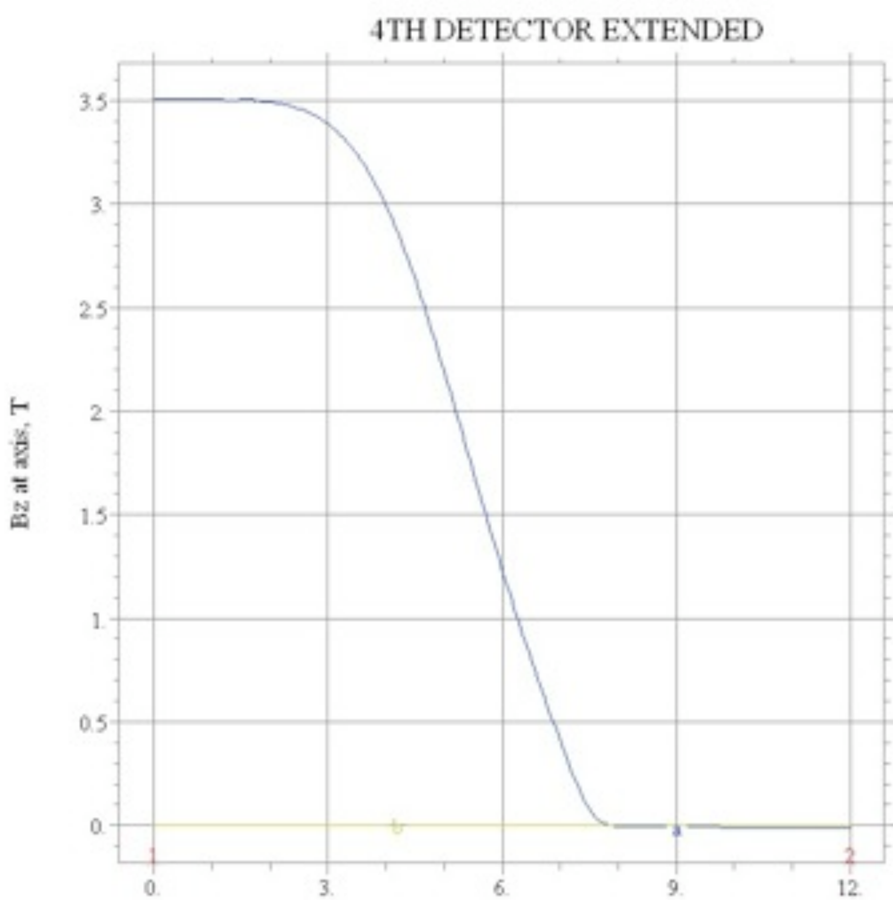
Fedor Ignatov (Budker Institute, Novosibirsk)

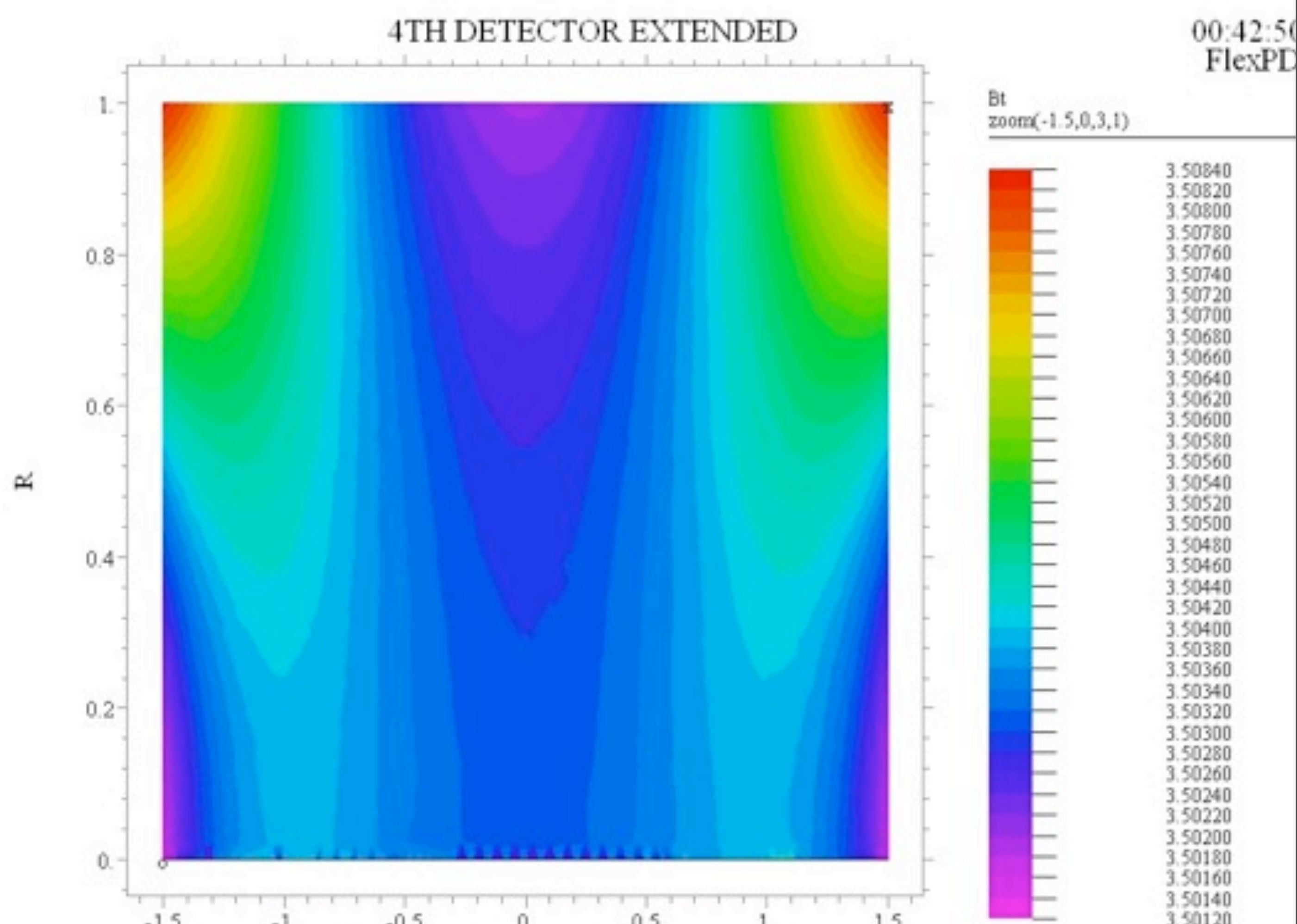
Summary

Spares

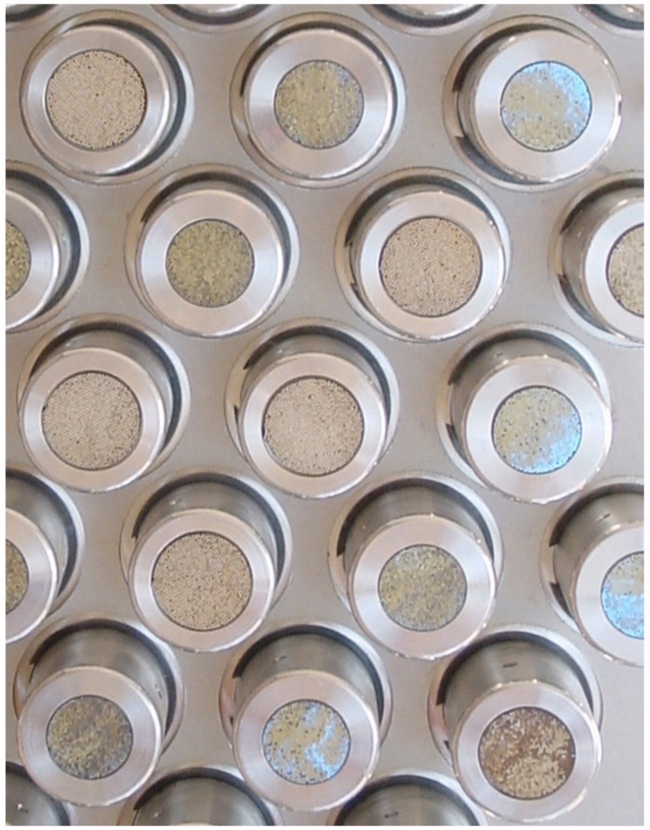


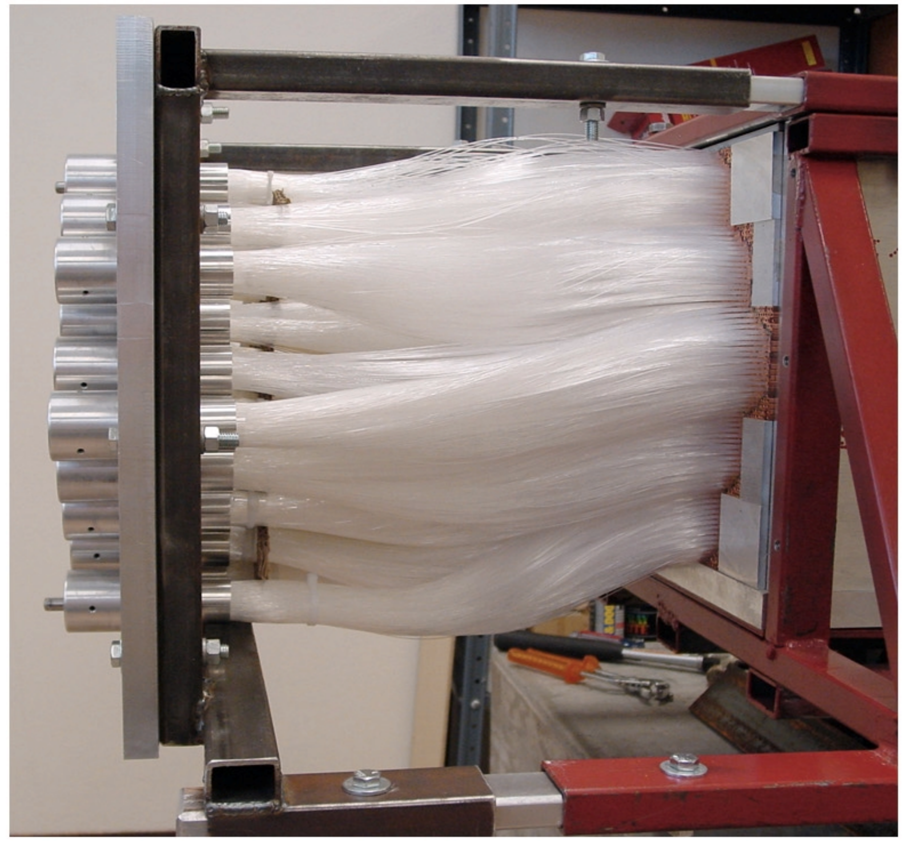

4TH DETECTOR EXTENDED
R
Z
Bt
zoom(-10,0,10,10)


4TH DETECTOR EXTENDED
Bz at axis, T

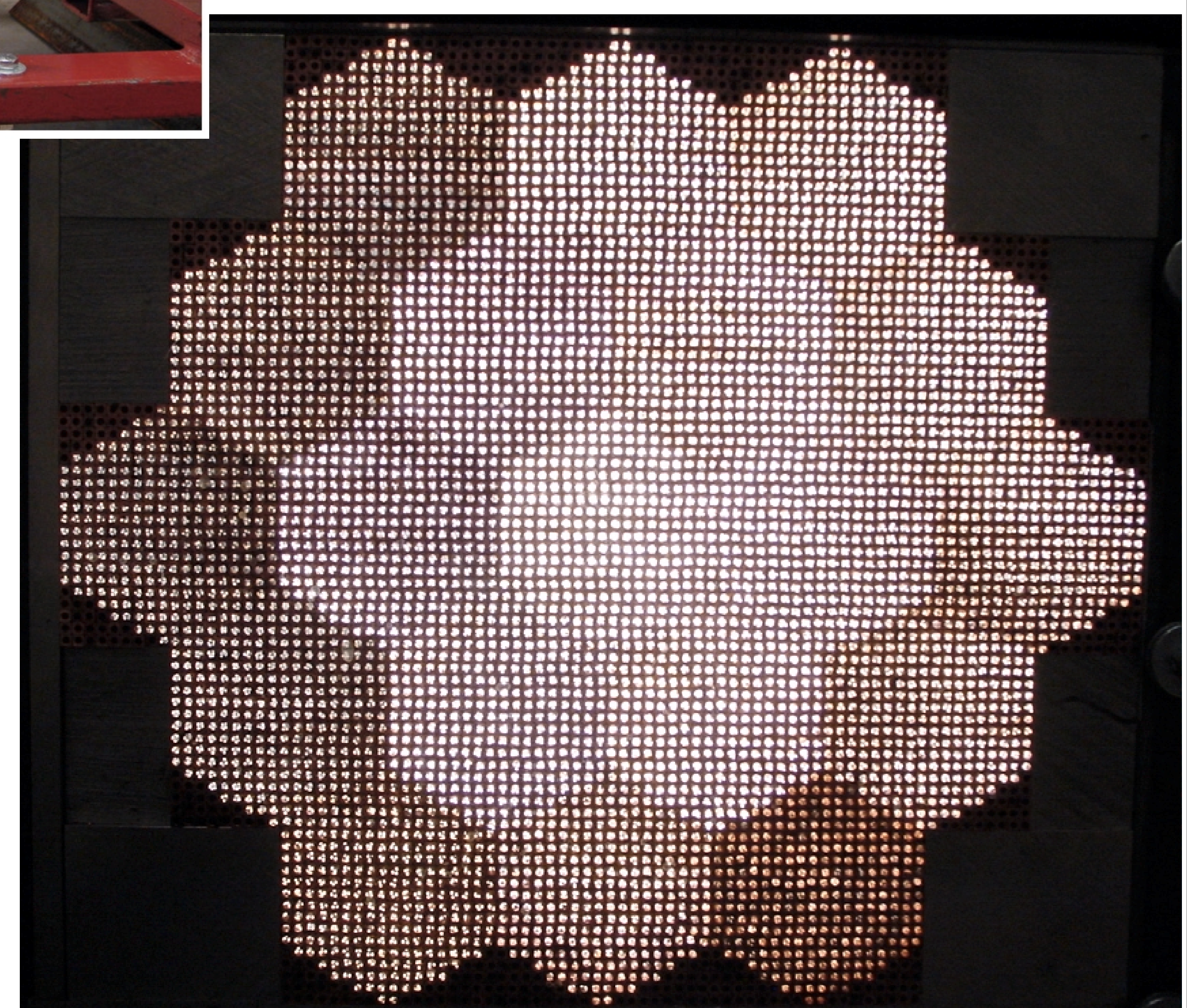

4TH DETECTOR EXTENDED
R
Bt
zoom(-1.5,0,3,1)

DREAM readout





Channel structure defined by bundled scintillation and Cerenkov fibers



Shine light through module

Crystals as dual-readout media

The DREAM collaboration has tested several crystals:

- $PbWO_4$ (“too fast, too blue, and too luminous”)
- $PbWO_4$:Pr
- $PbWO_4$:Mo
- BGO
- BSO (Bismuth sulfate)

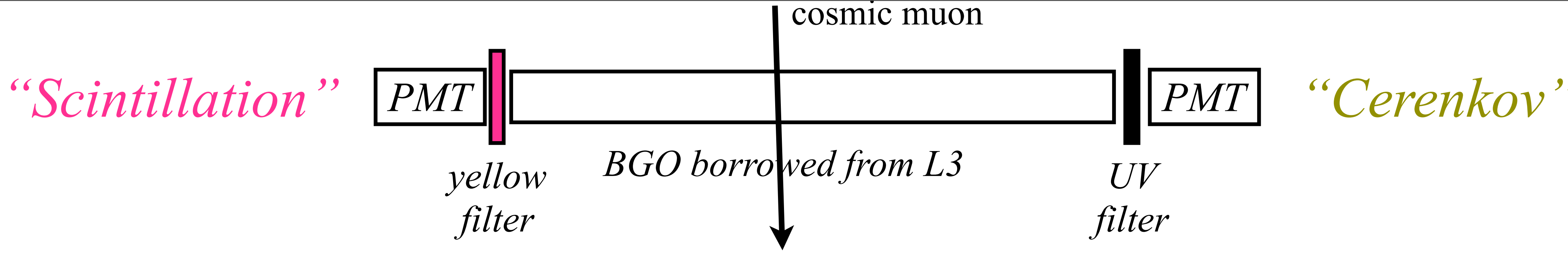
all work well (good reference: Silvia Franchino talk at TIPP09)

After the easy success with the DREAM module, we immediately began to think of improvements

- Cerenkov fiber pe statistics (~8pe/GeV) ... try crystals

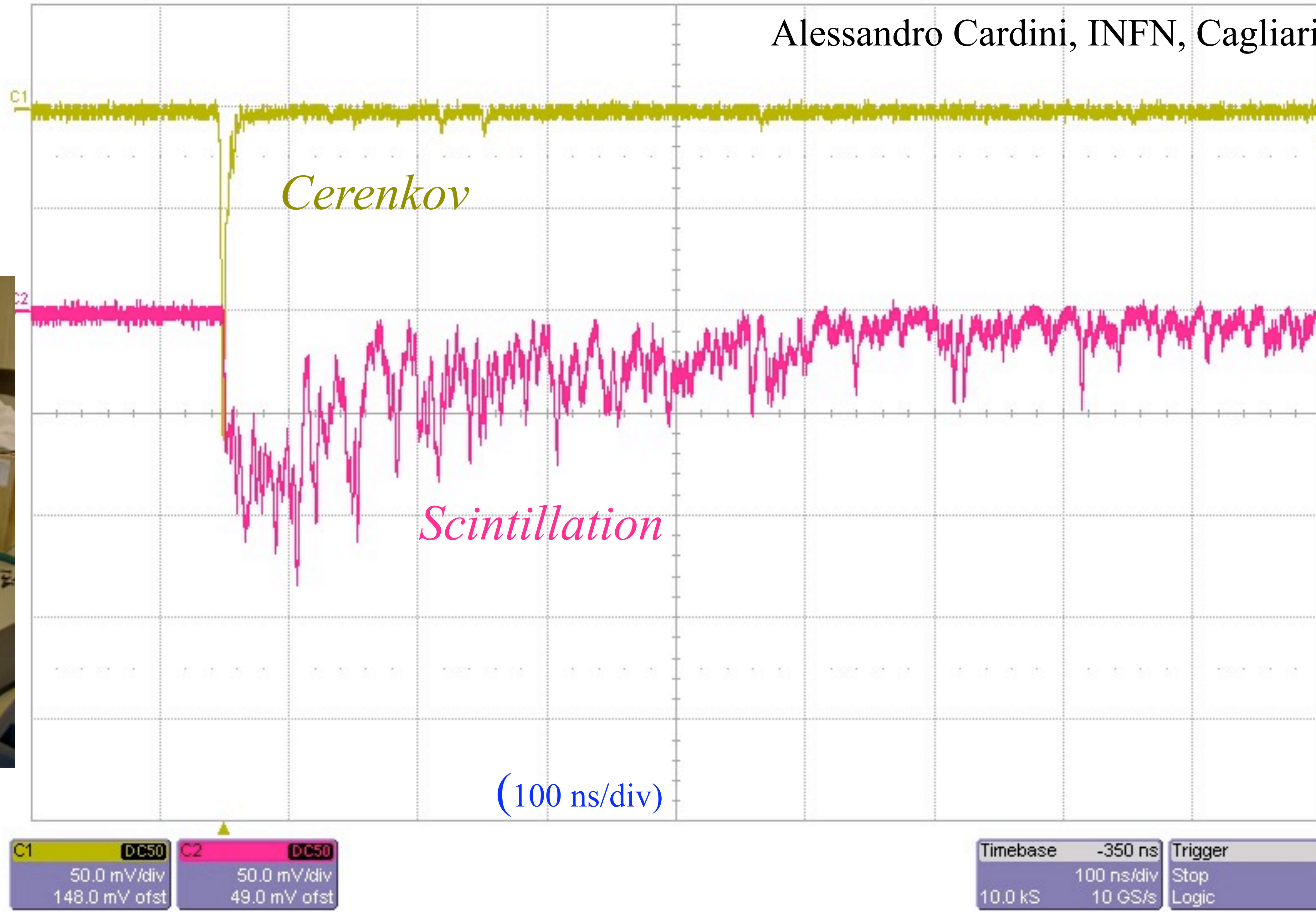
- next largest fluctuation is the BE losses in nuclear break-up, proportional to the MeV neutrons liberated in the shower ... measure $S_{pe}(t)$.

- leakage is only suppressed by more mass (and $), so make crude measurement of leakage (mostly neutrons).



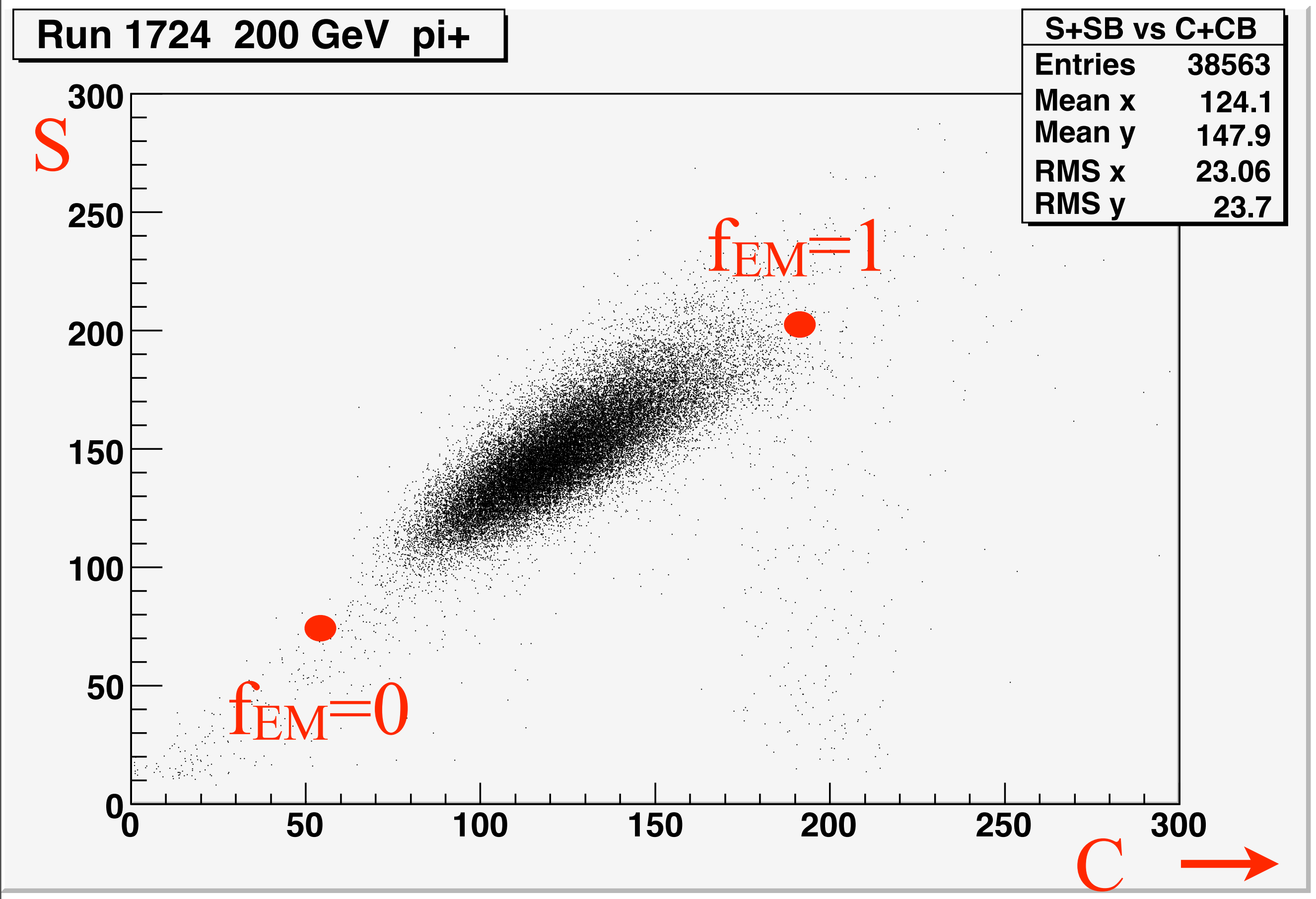
BGO ...

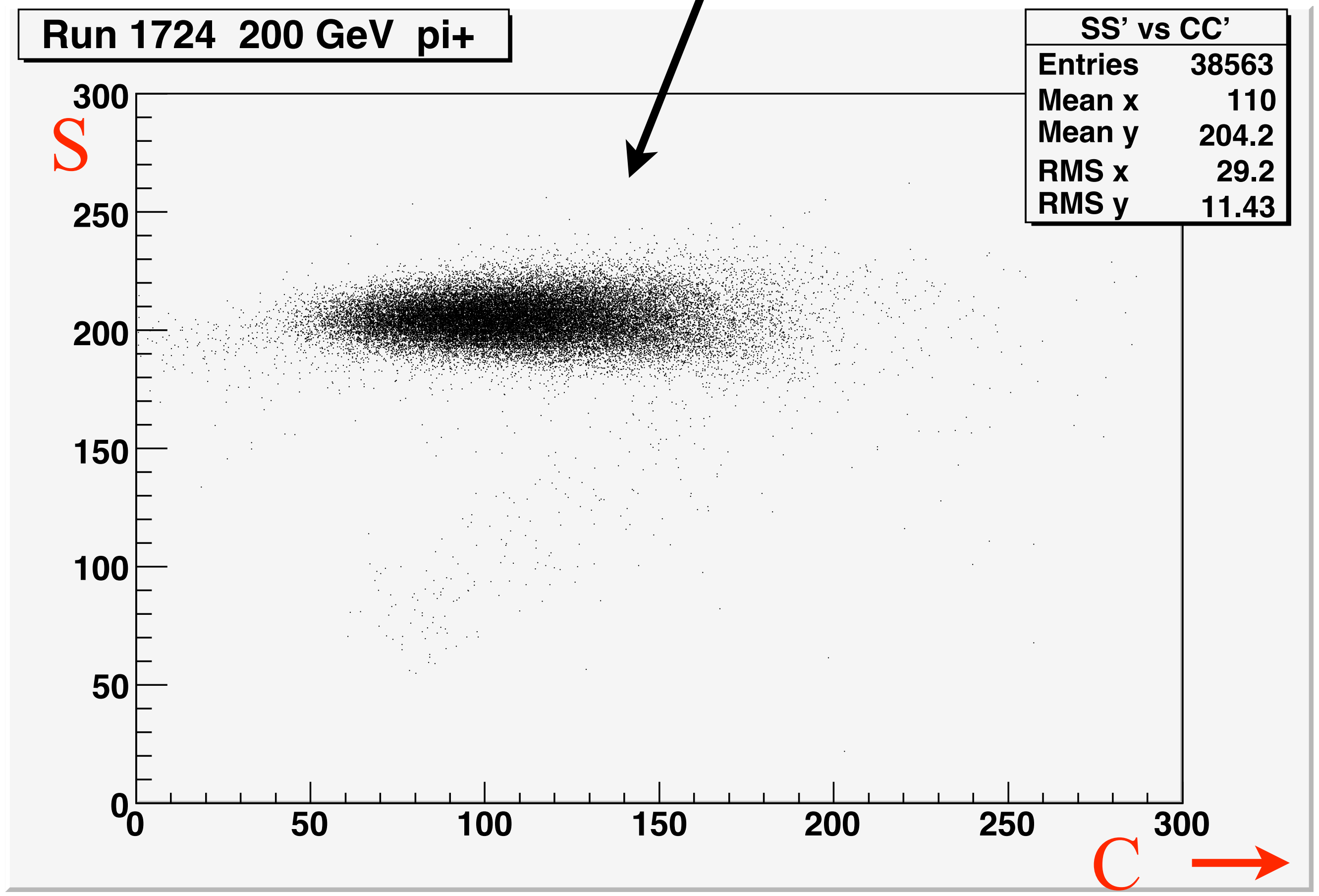
by time and wavelength



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

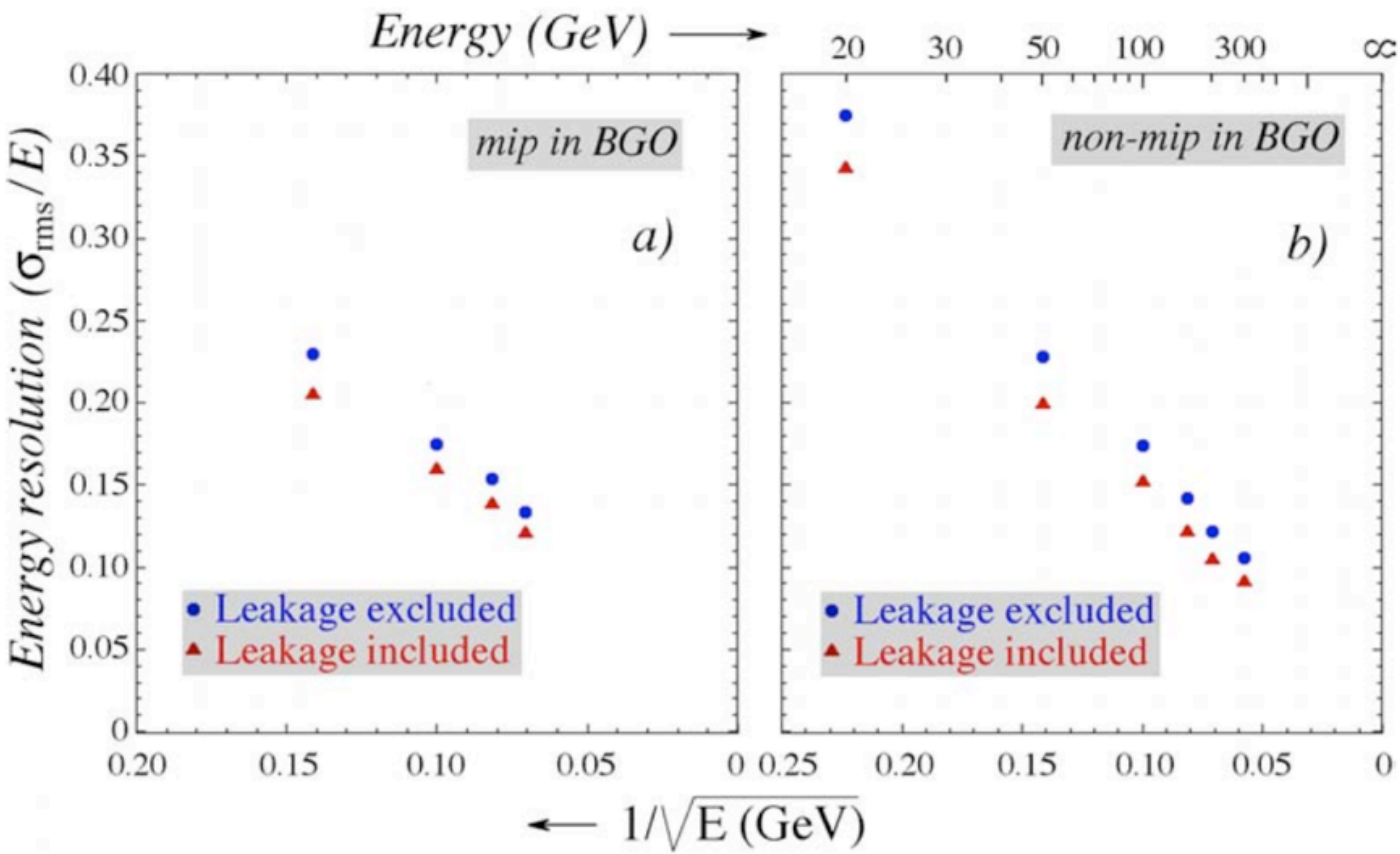
Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves "compensation".





Leakage from DREAM

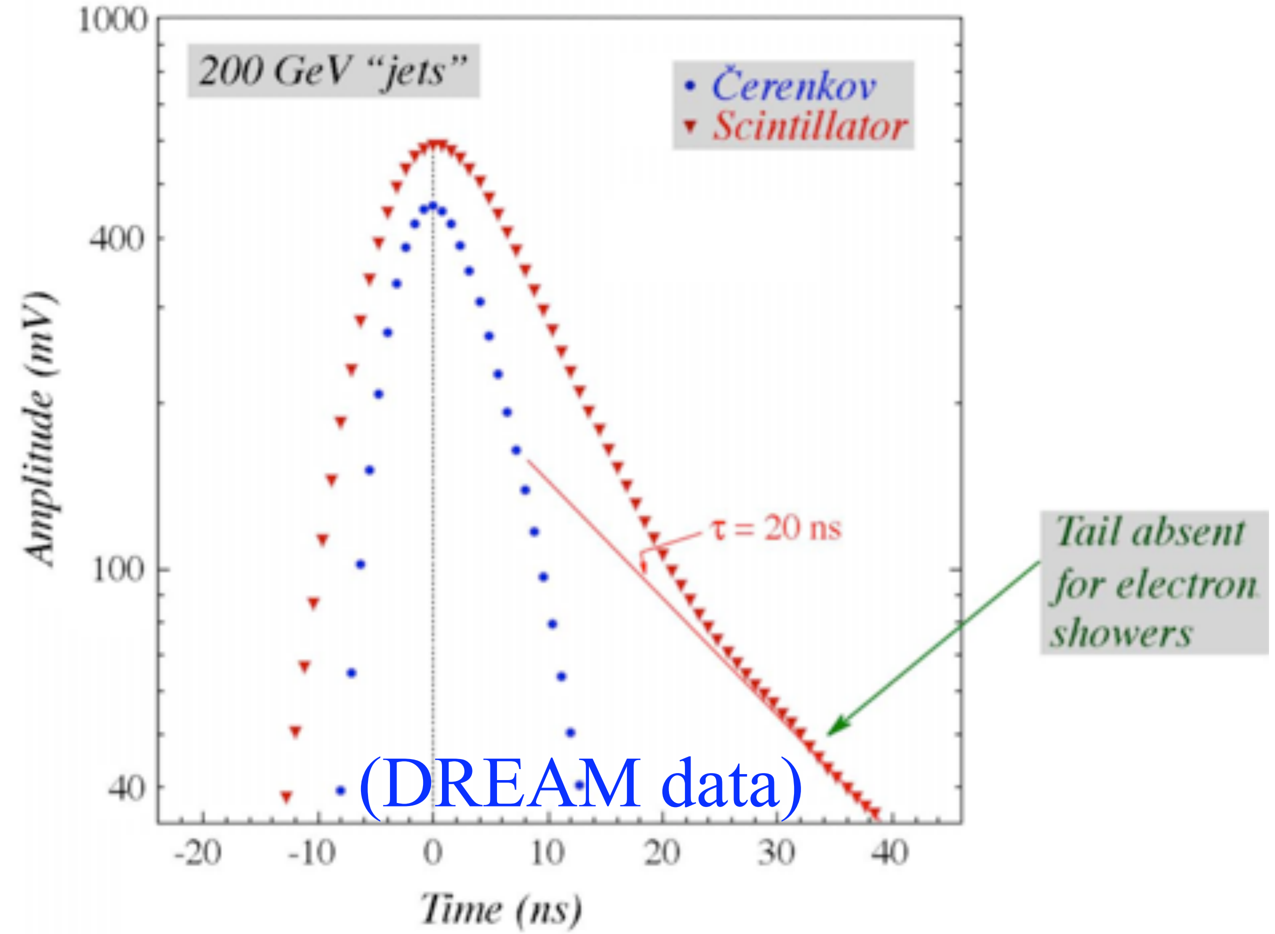
Energy resolution of DREAM module improved by 10-15% when simple leakage counters are included.

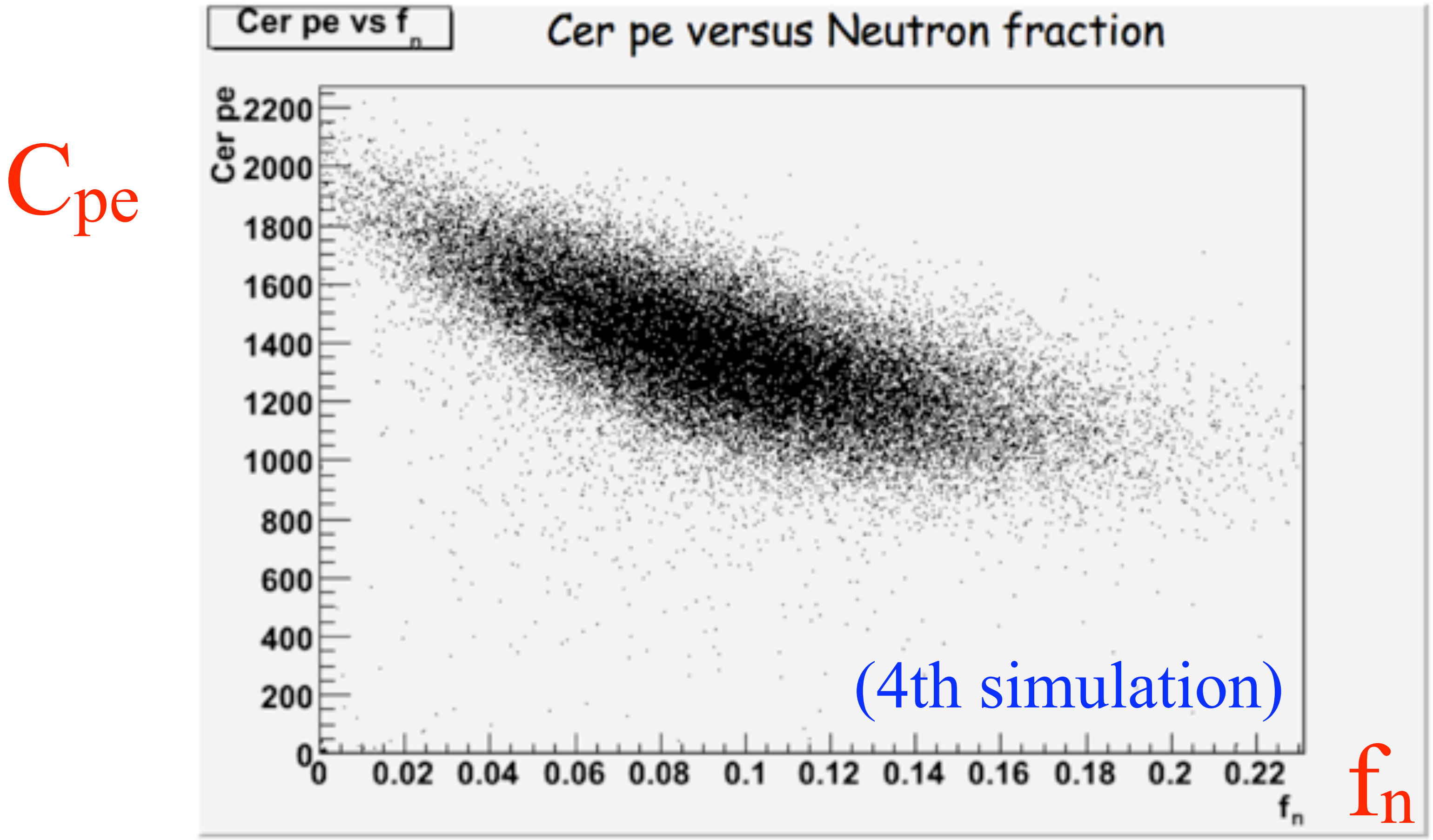


MeV neutrons

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

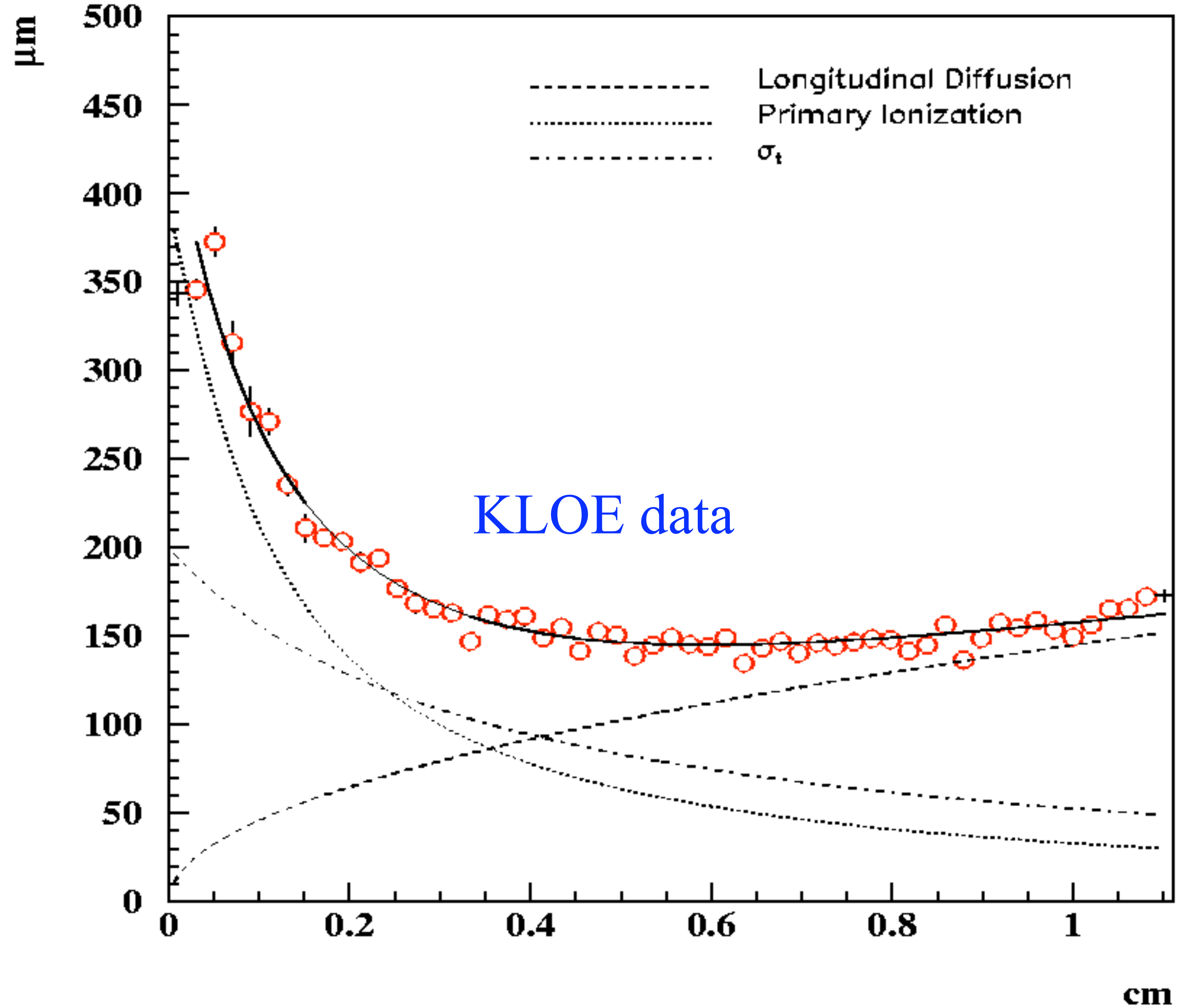
(1) improve energy resolution
(2) tag "hadronic" showers.





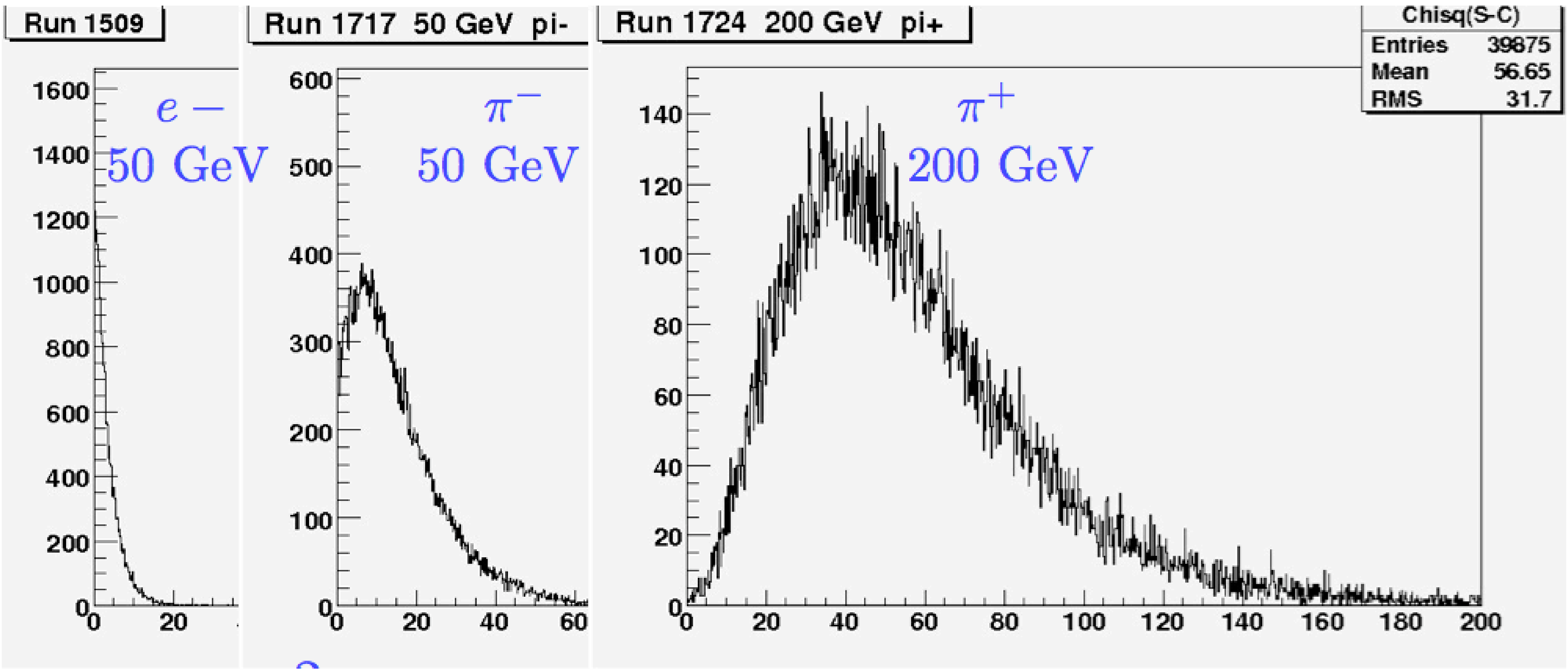
Cluster timing tracking chamber: (measure every cluster)

KLOE is a very well understood chamber

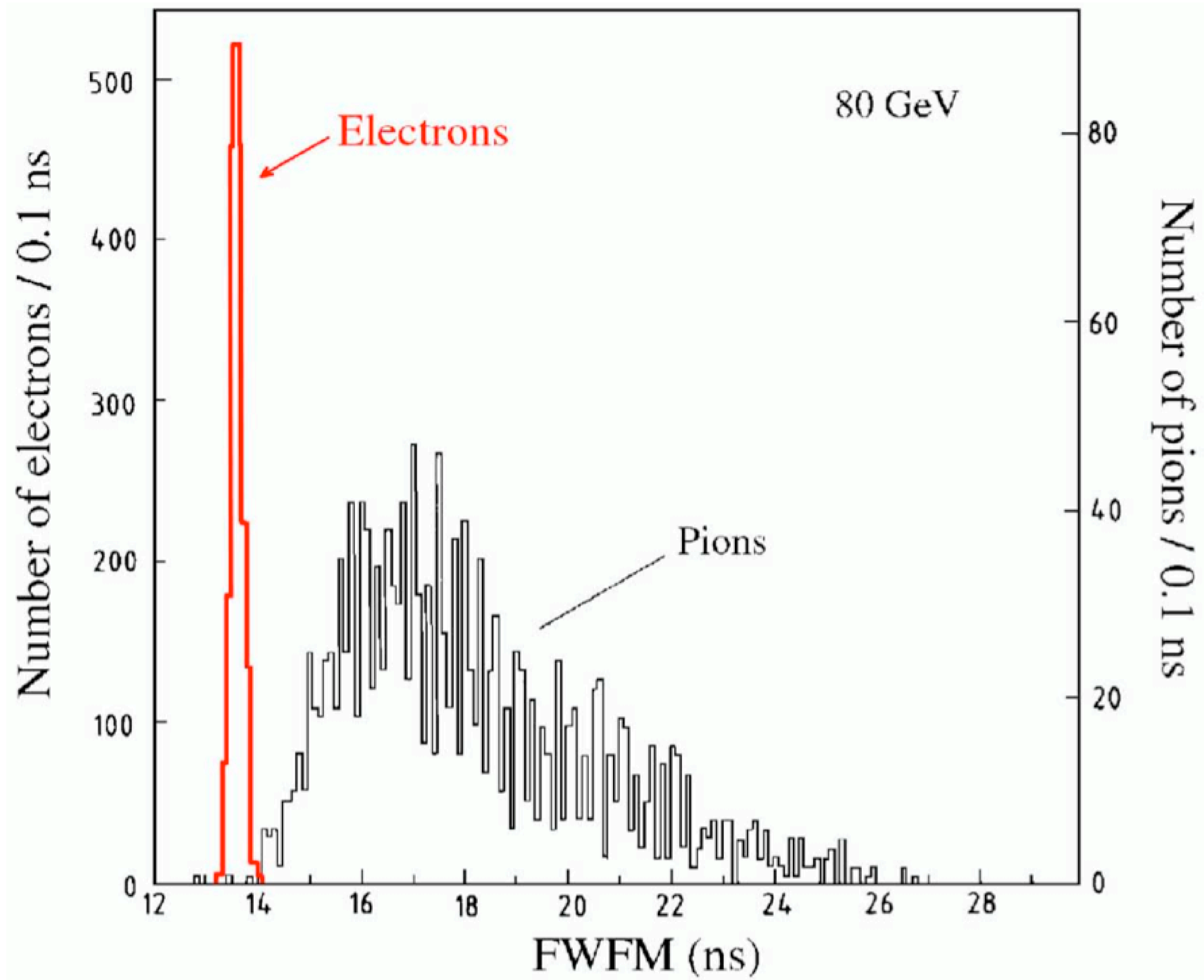


(ii) Further discrimination from the *fluctuations in S-C among the channels of a shower*

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



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

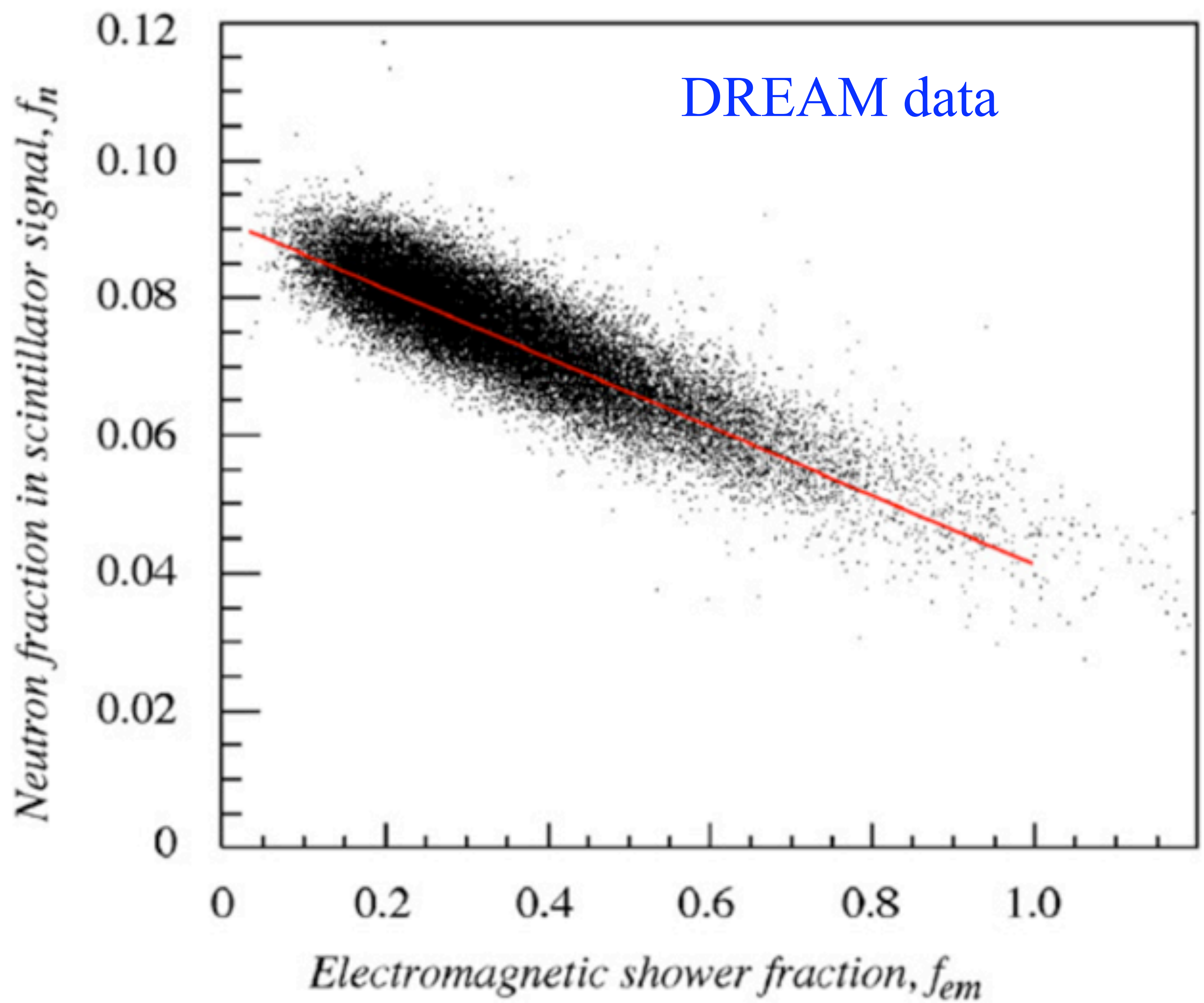


(vi) Neutron fraction *vs.* electromagnetic fraction: "hadronic" ID tag

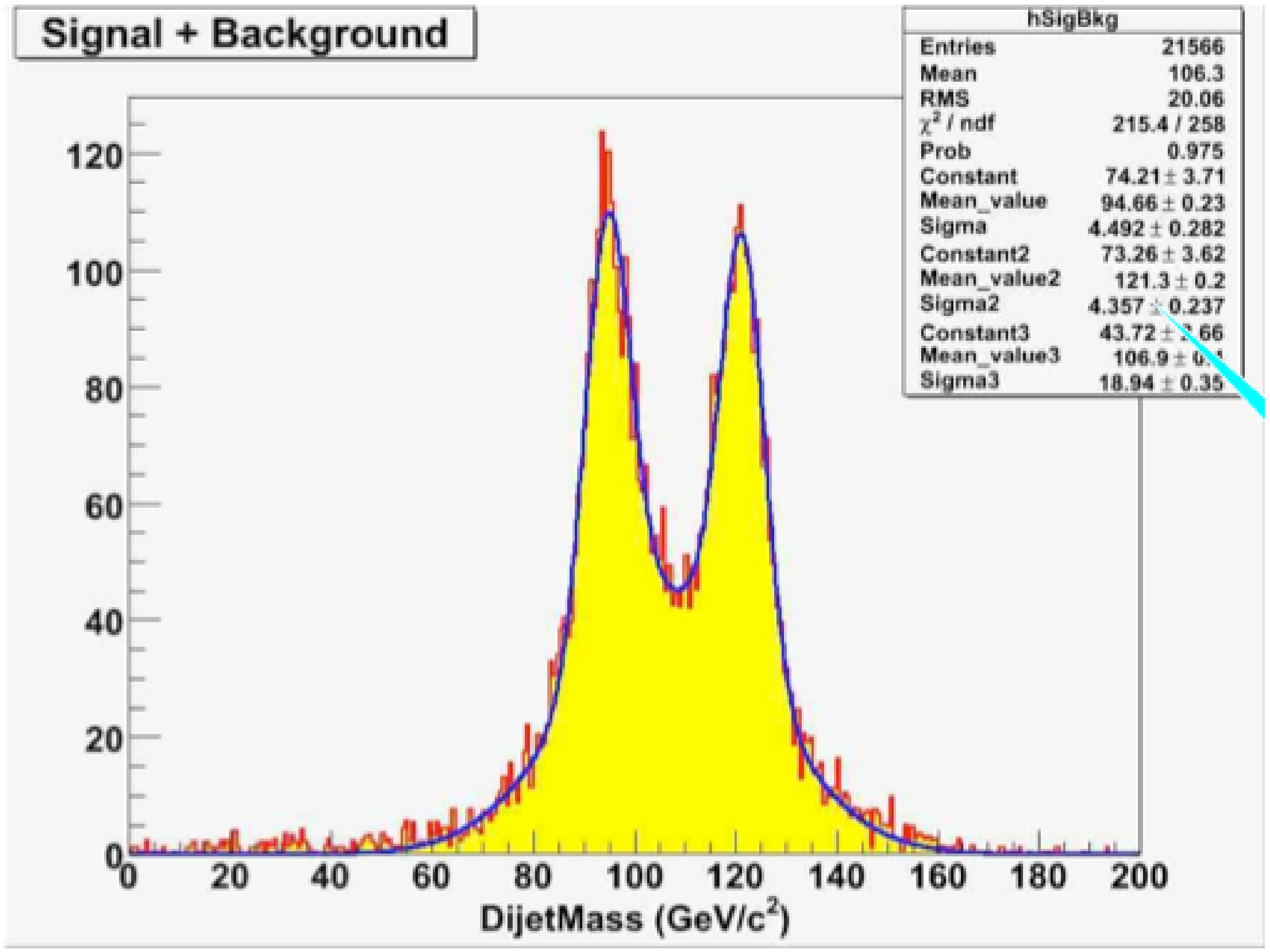
Expected anti-correlation of

f_n (hadronic content) and

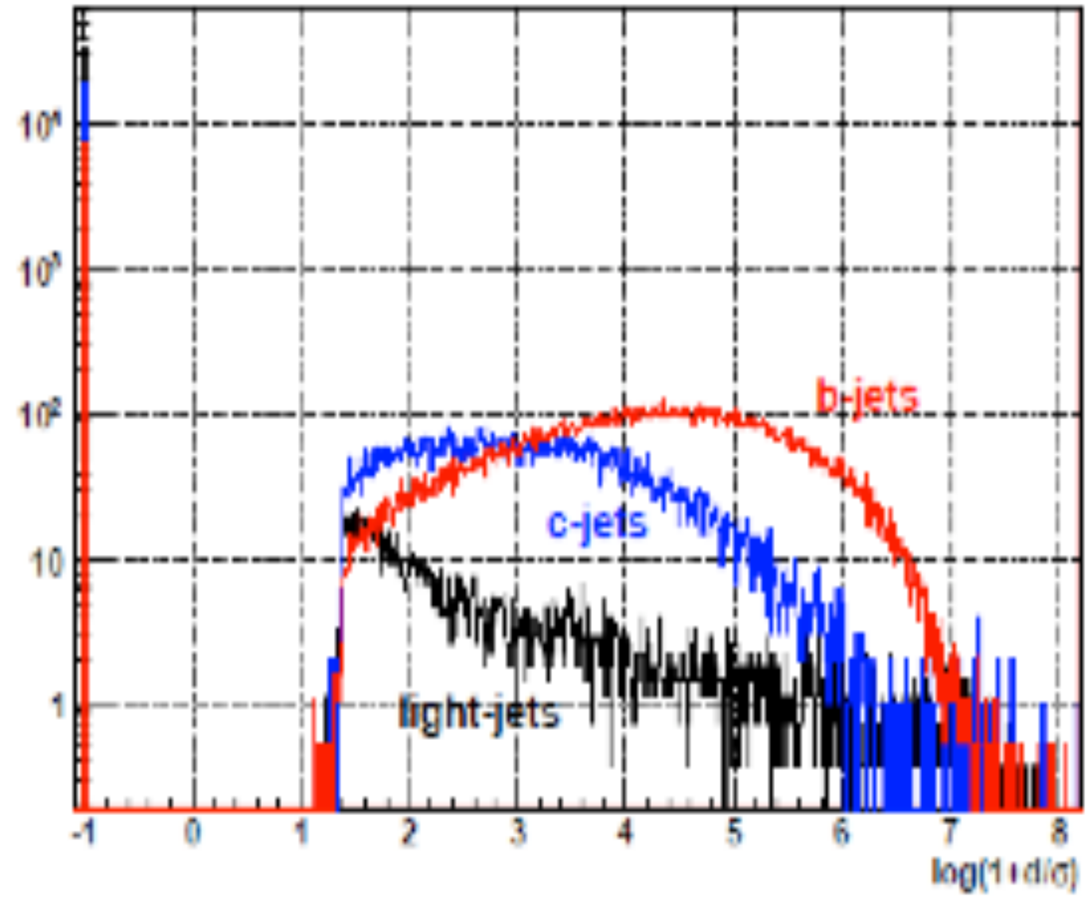
f_{EM} (electromagnetic content)

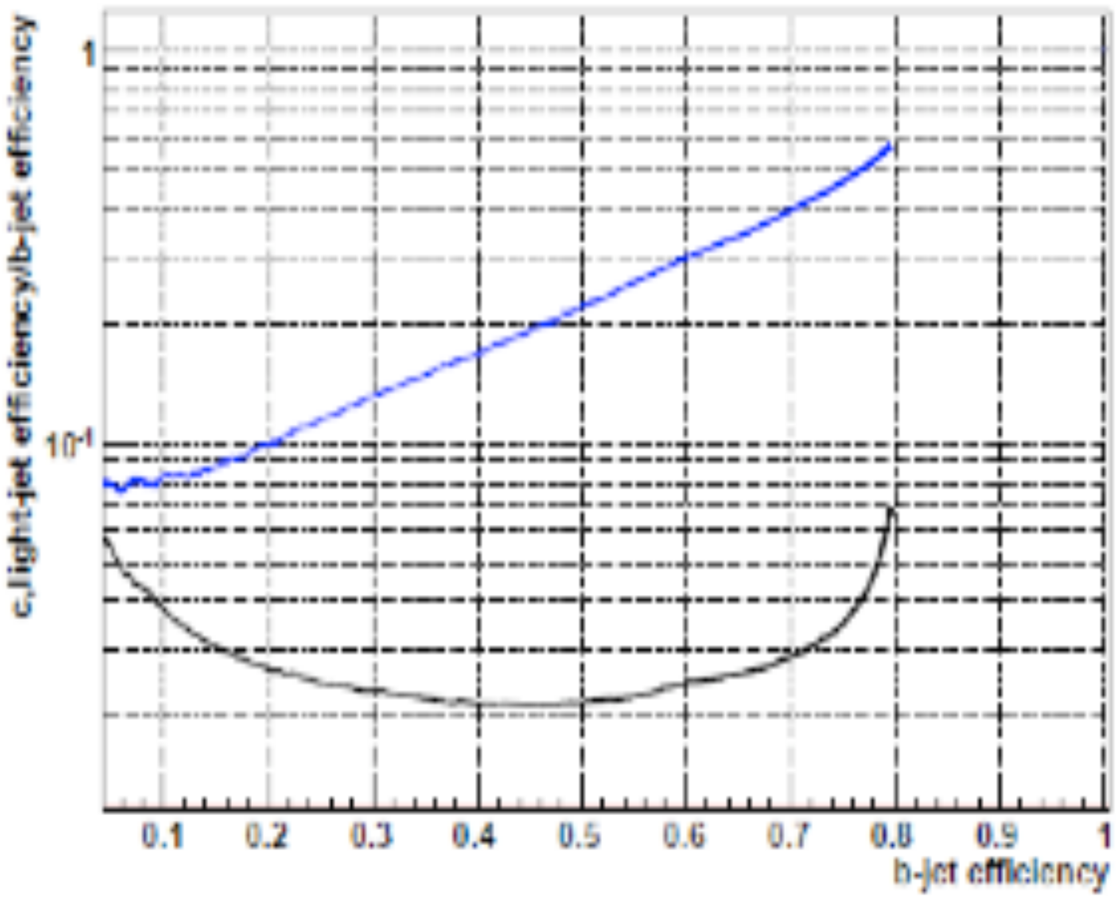


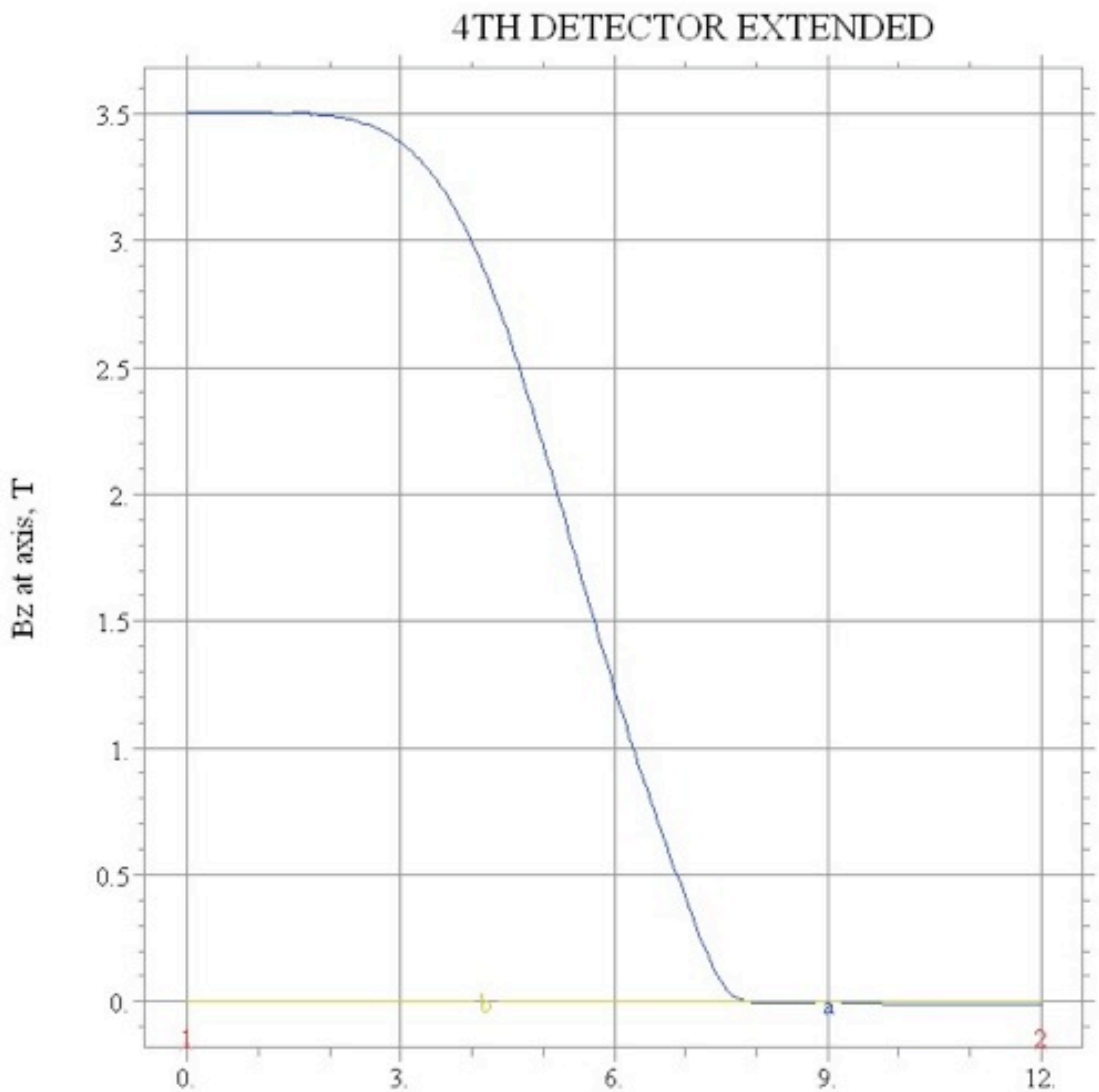
(ix) Z --> jj mass resolution



(x) b,c quark tagging

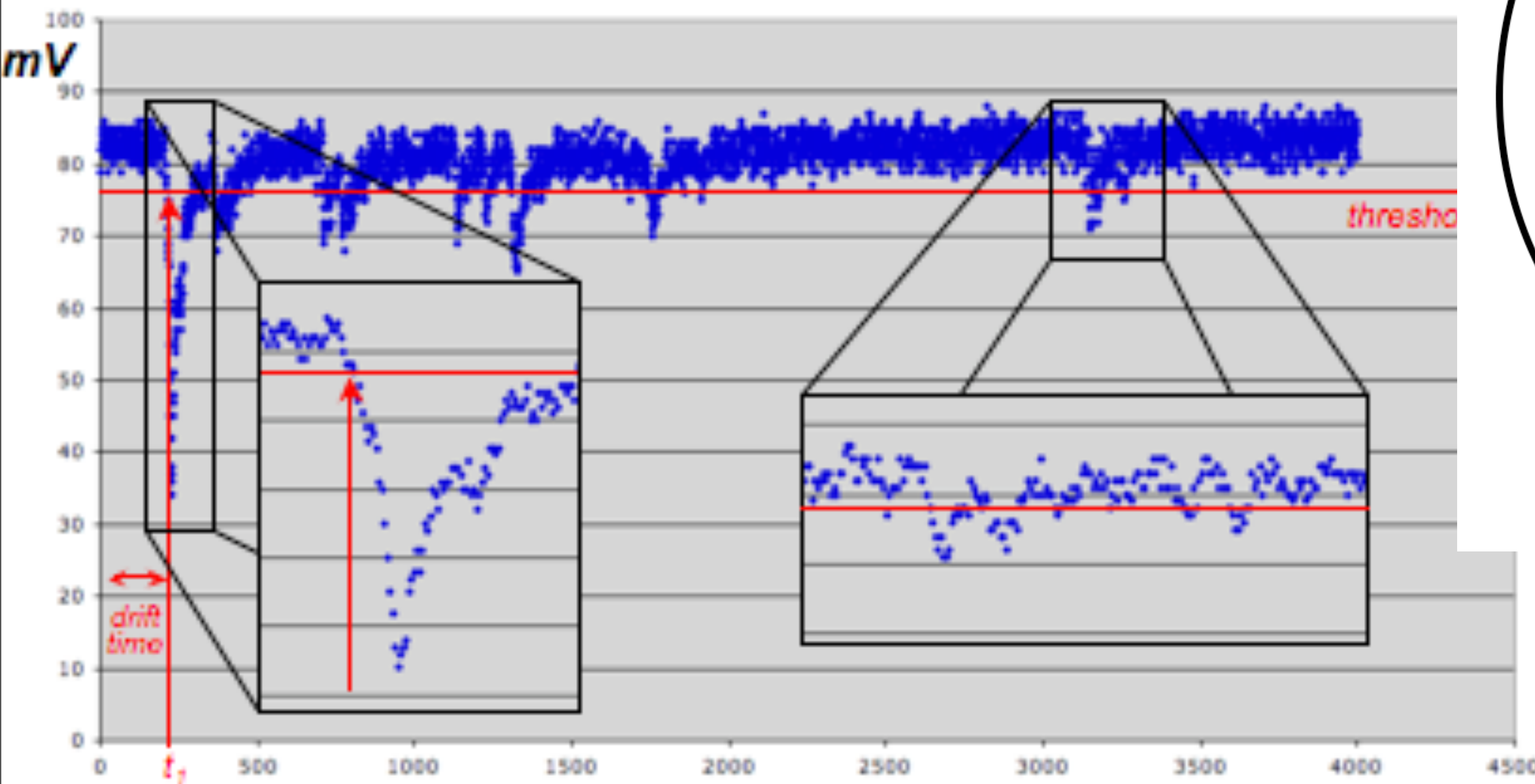


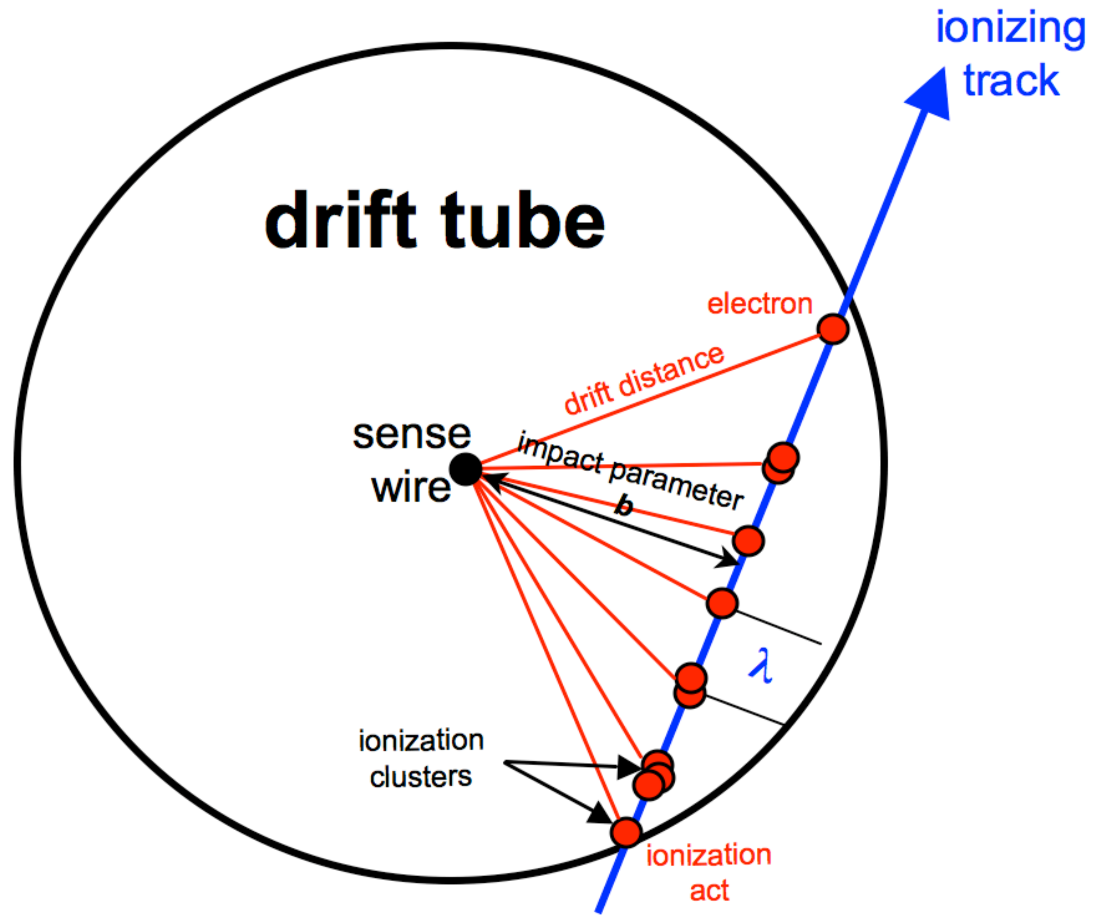



4TH DETECTOR EXTENDED
Bz at axis, T
3.5
3.
2.5
2.
1.5
1.
0.5
0.
0.
3.
6.
9.
12.
1
2
a
b

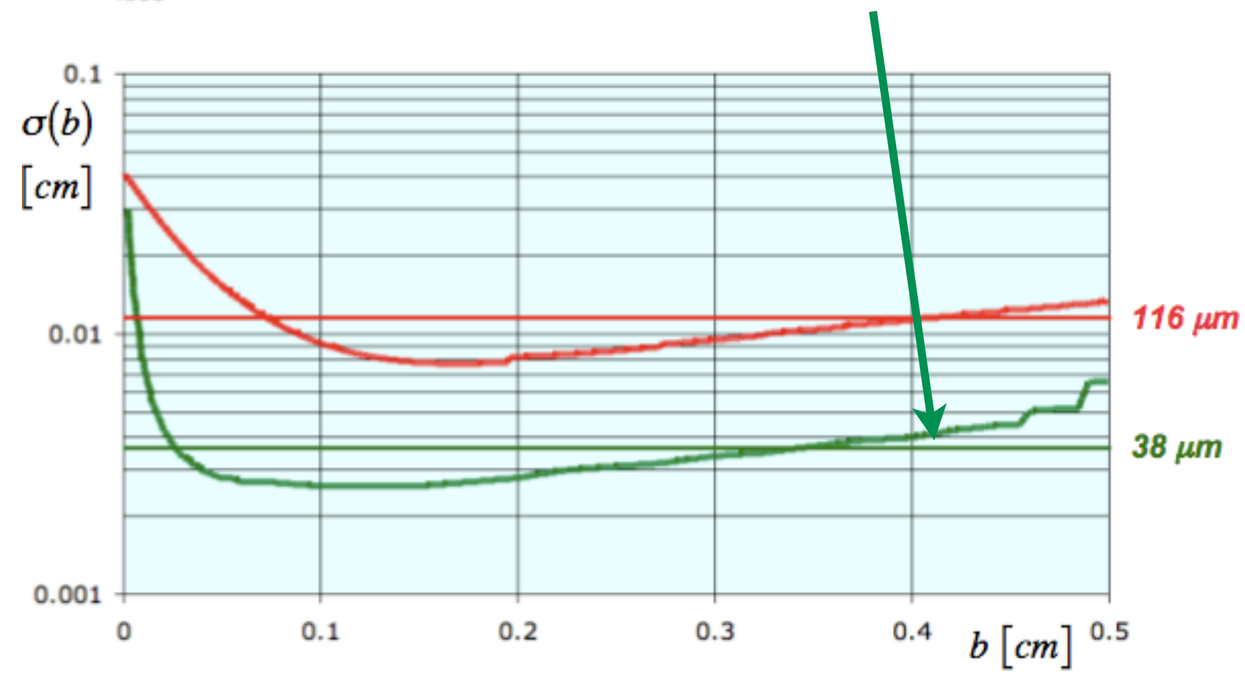
Cluster-timing (new, beyond Charpak)

of *every* electron cluster





Cluster timing

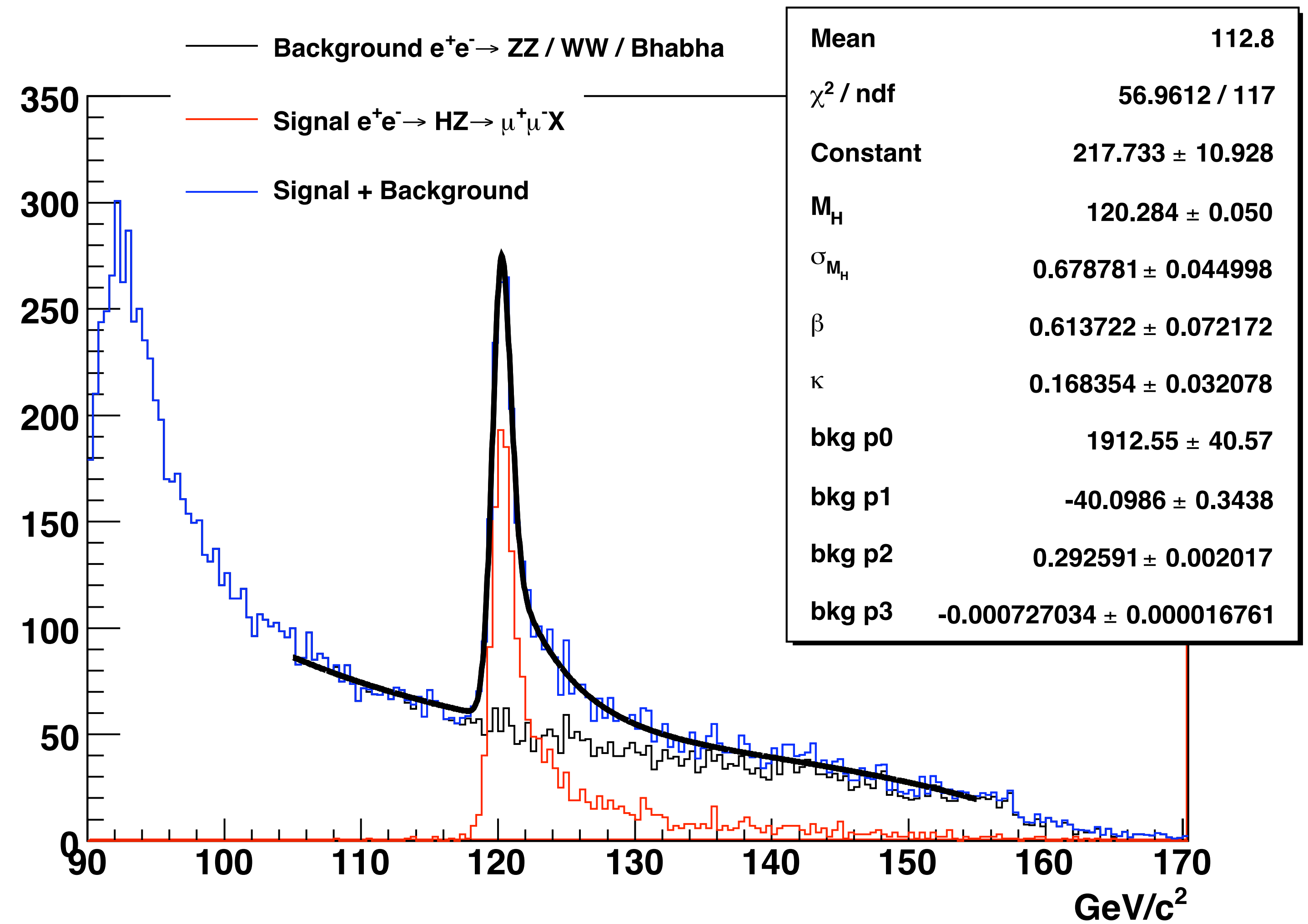


Ultra-low-mass chamber, expect ~50 μm spatial resolution on each of 150 points on a track.

Flagship physics process: putative Higgs production

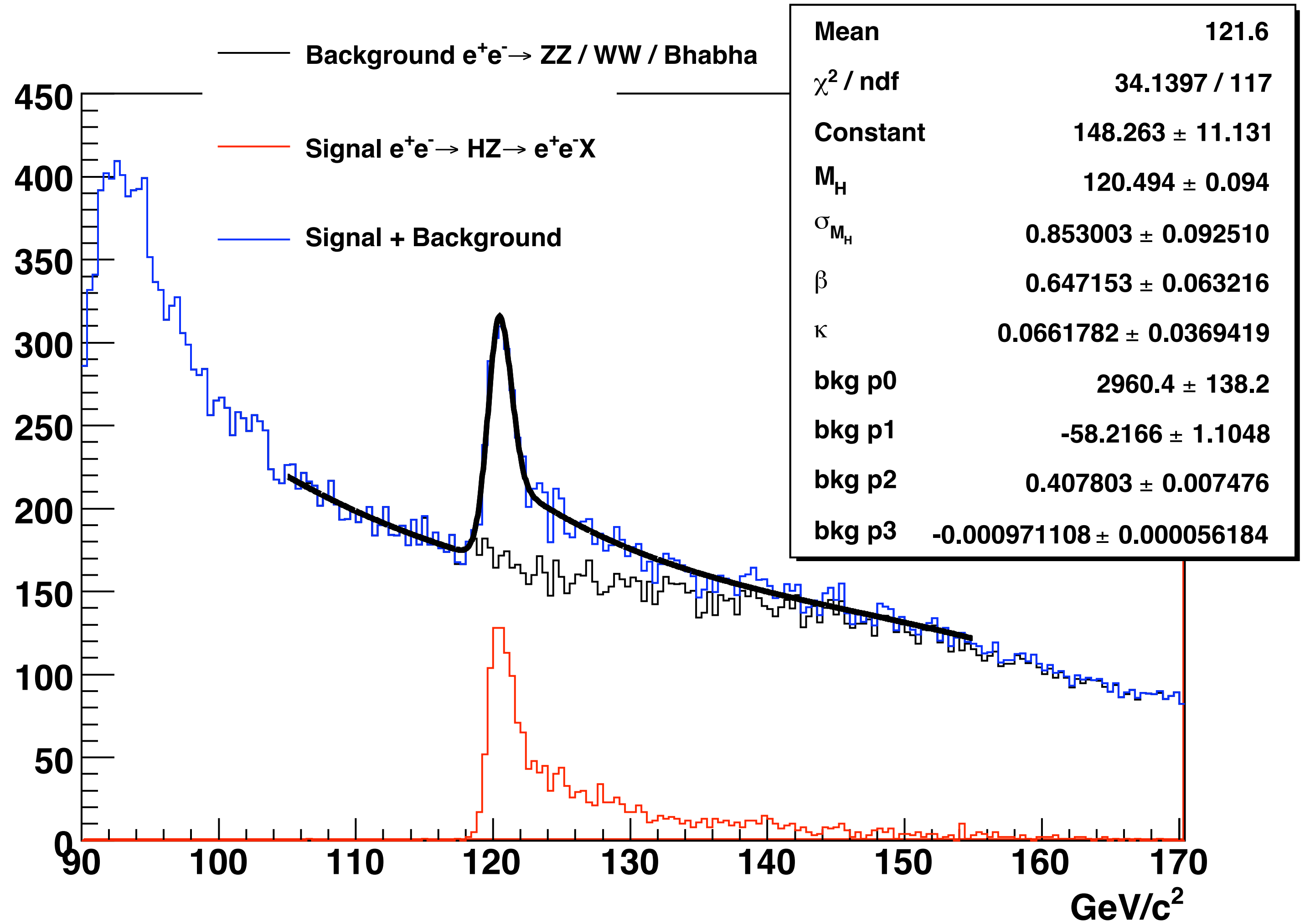
$$e^+e^- \to Z^0H^0 \to \ell^+\ell^-X \text{ at } \sqrt{s} = 250 \text{ GeV}$$

$\mu^+\mu^-$

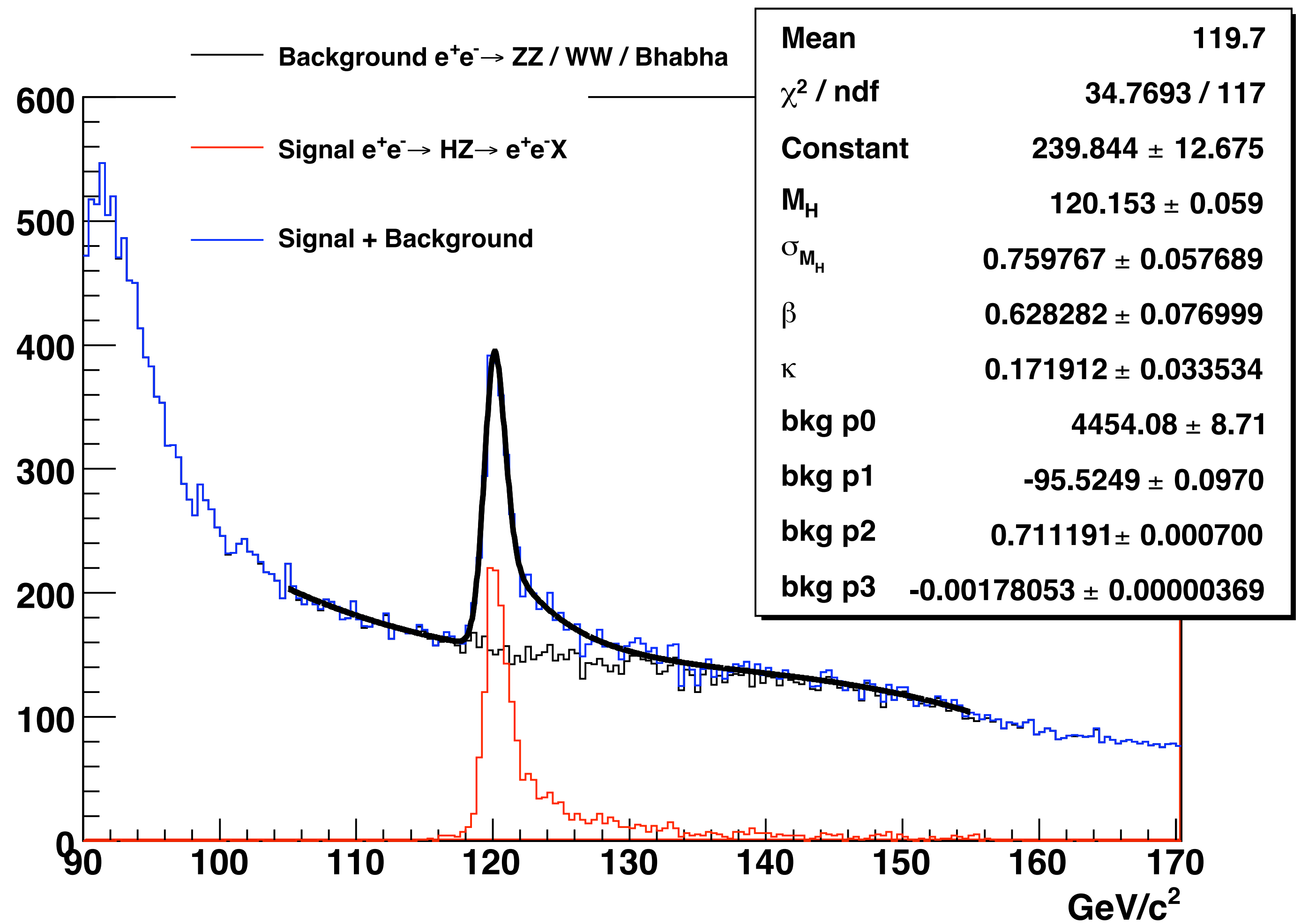


Mass of X

e^+e^-
(using tracking only)



e^+e^-
(tracking and calorimetry)

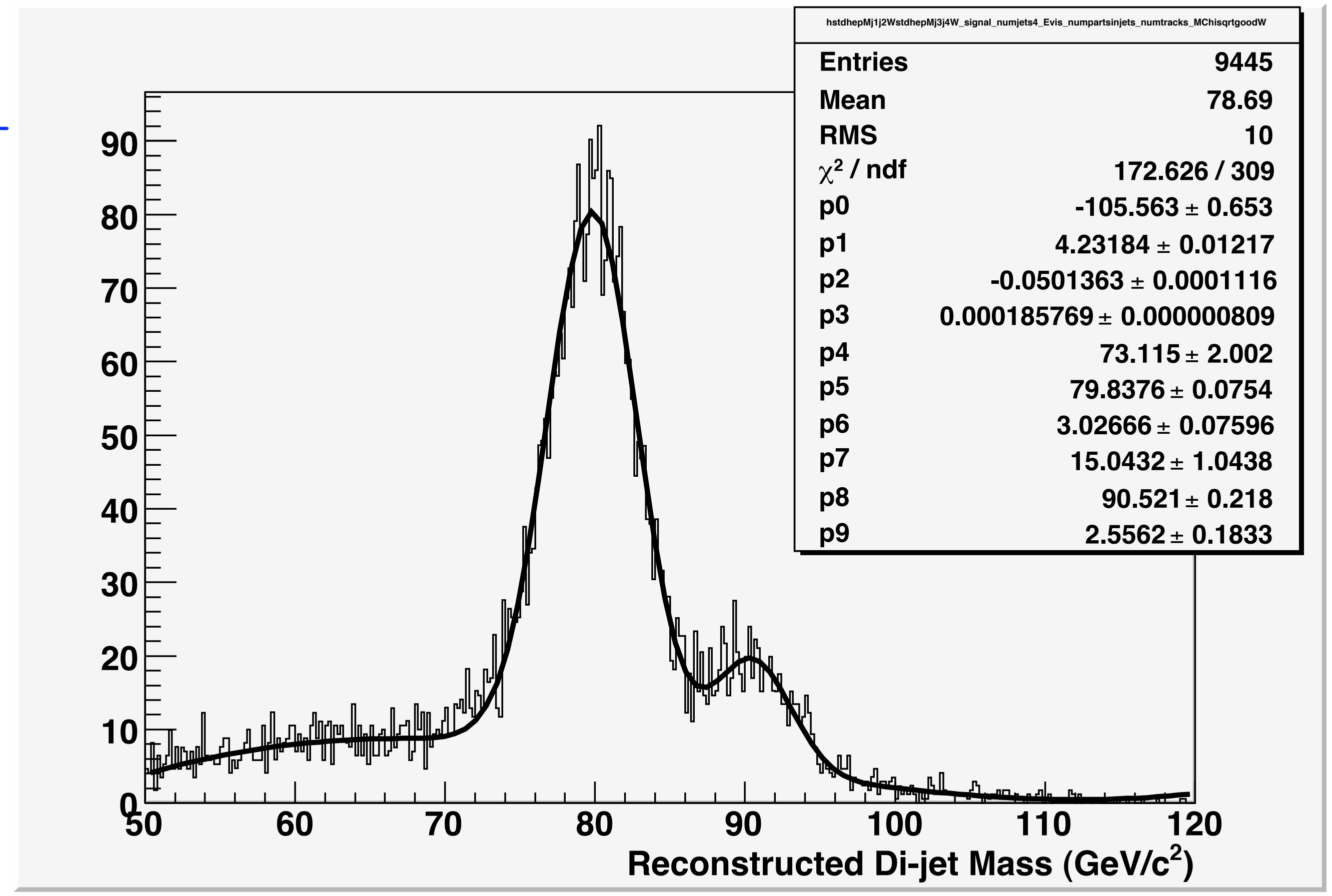


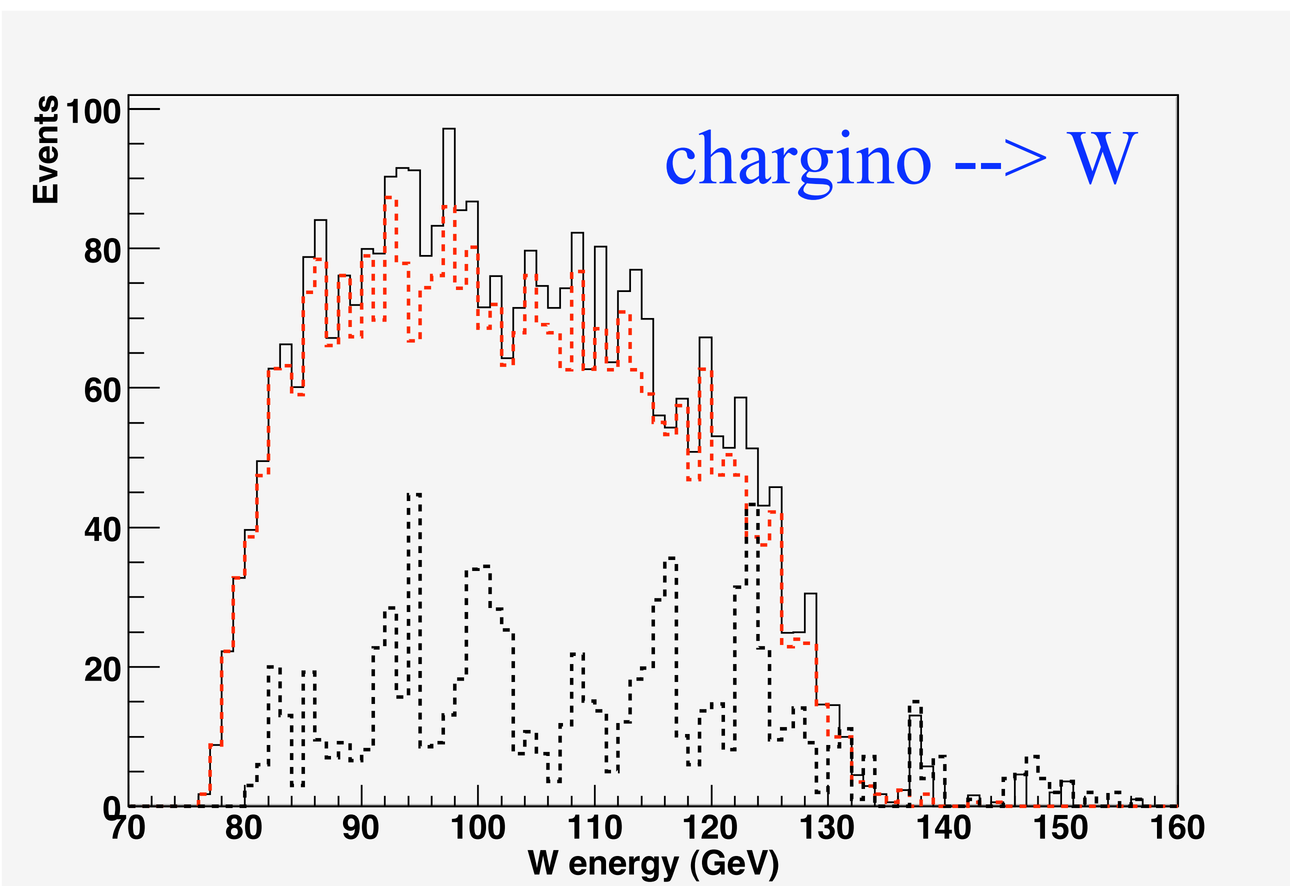
SUSY (supersymmetry):

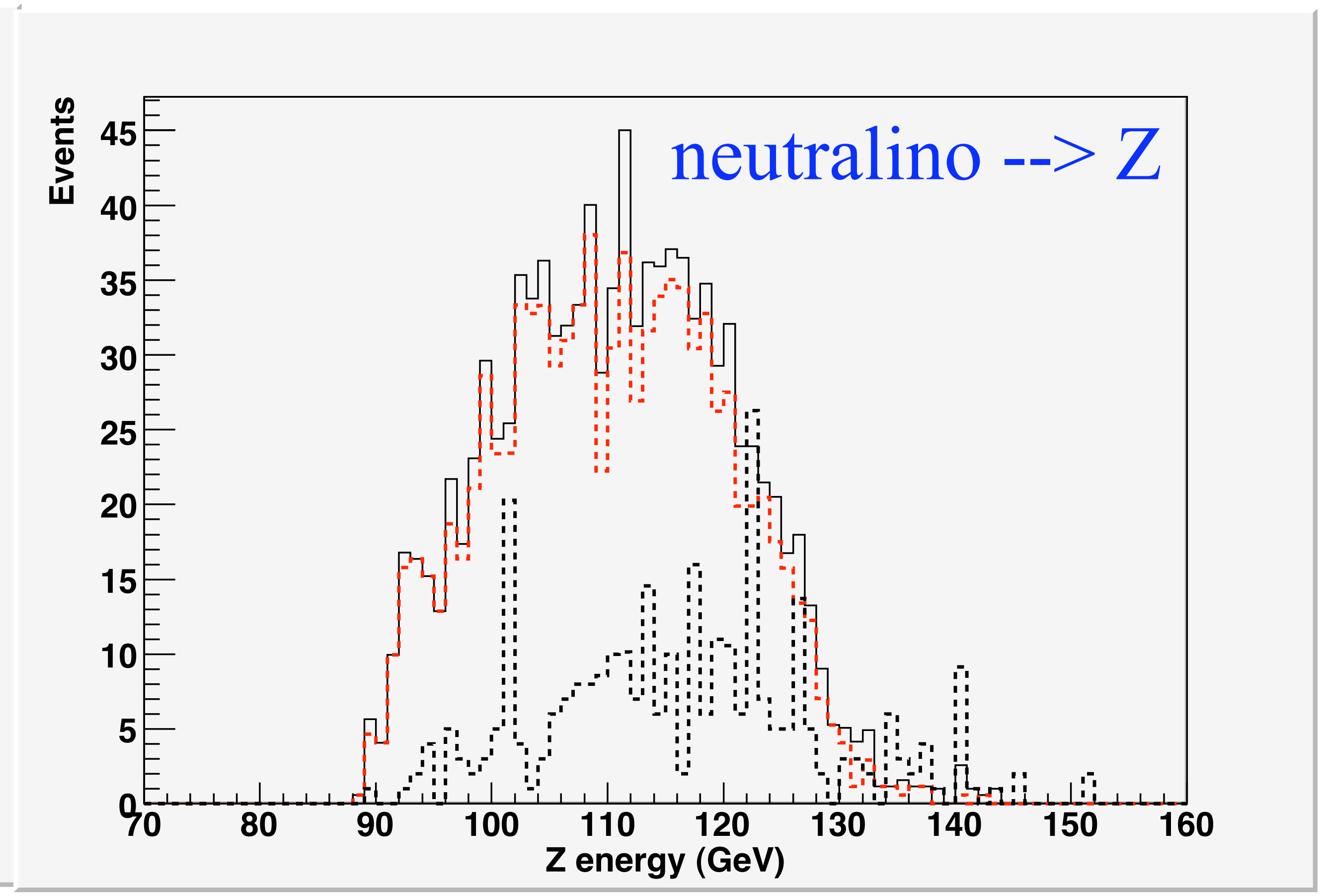
$$e^+e^- \rightarrow \chi_1^+\chi_1^- \rightarrow \chi_1^0\chi_1^0 W^+W^-$$

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

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







BGO+fiber
dual-readout calorimeter
at 200 GeV π^+