Dual-readout calorimetry and 4th for $\mu^+\mu^-$ and ν physics

John Hauptman
University of Mississippi, Oxford, NFMCC meeting
January 13-18, 2010

4th began as a small attempt to encourage the ILC detector community to look again at its calorimetry. At that time (August 2005) there were three concepts (SiD, LDC, and GLD) with *identical calorimeters*, simulated by the *same* code, and all of it based on *one idea, Particle Flow Analysis (PFA).* I suggested "a fourth" concept on encouragement from GP Yeh and Barry Barish. I am now writing a book for Wiley-Berlin on this subject.

Quickly, *a small number of excellent collaborators* joined:

- Alexander Mikhailichenko (LNS, Cornell) - machine, MDI, dual solenoids
- Richard Wigmans (DREAM, TTU) - calorimetry
- Franco Grancagnolo (INFN, Lecce) - tracking, software Corrado Gatto (Emi Cavallo, Vito Di Benedetto, Anna Mazzacane, Giusi Terracciano, Gianfranco Tassielli: *4 PhD theses)*

Four major innovations (& many particle identification measurements)

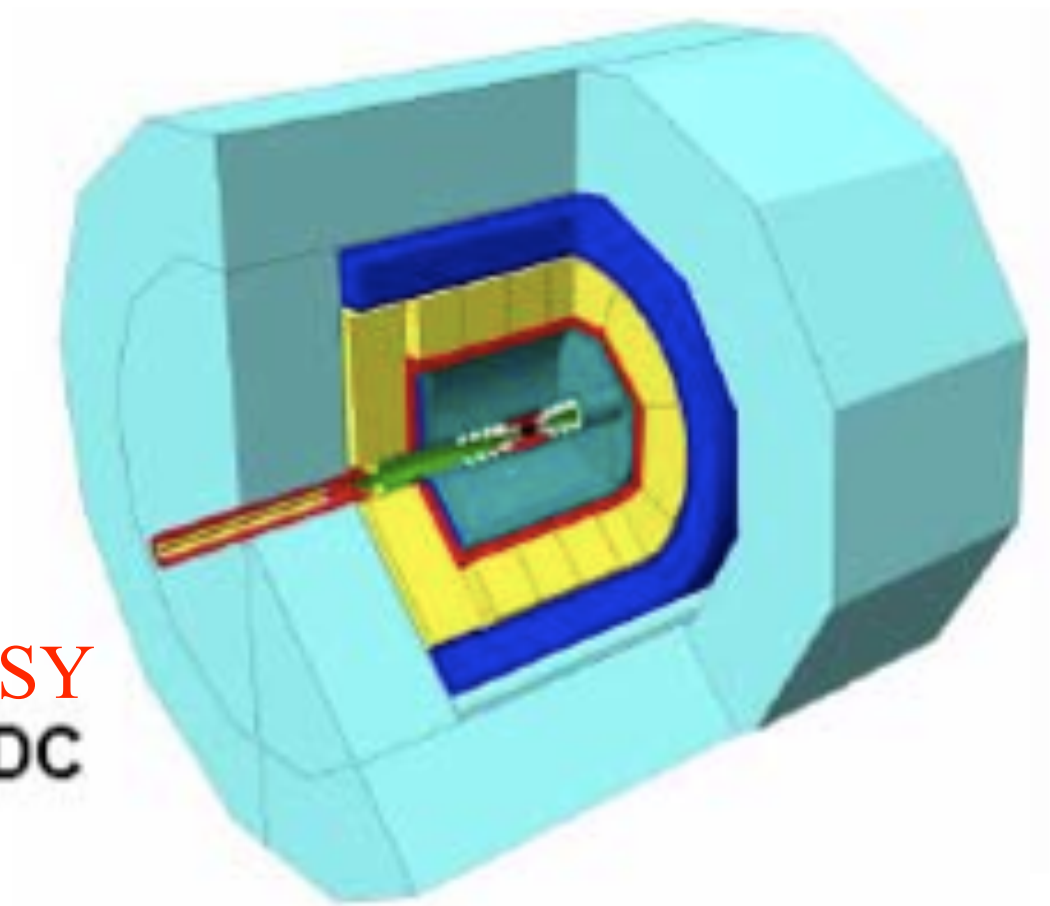
1. *dual-readout calorimeters*, both fiber and crystal;
2. low-mass *cluster-timing tracking* chamber; go to pixels (C. Damerell);
3. *dual-solenoid* to return the flux without iron; and,
4. *single final-focus* structure for detector+QF1+QD0

Letter of Intent: http://www.4thconcept.org/4LoI.pdf (140 people, 33 institutes/universities, 15 countries, 4 regions)

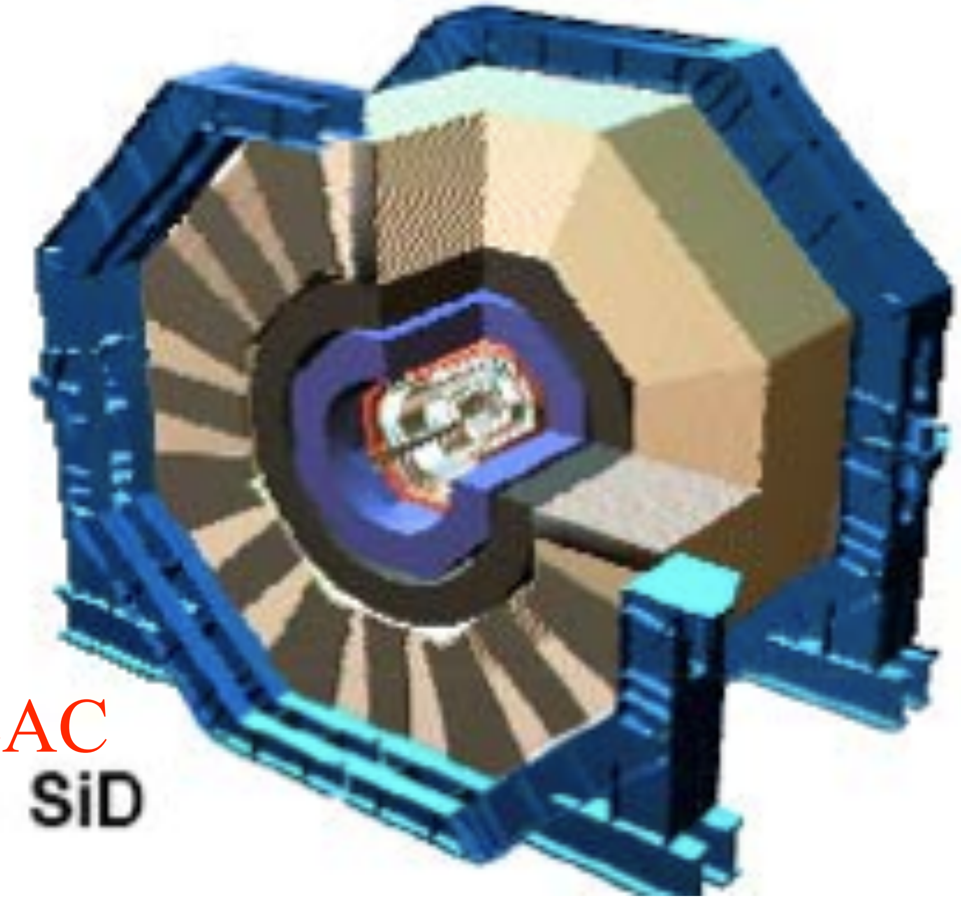
June'09: I asked Vito Di Benedetto to stay at Fermilab to work with Nikolai Mokhov on MARS+ILCroot.

Next → form an "executive board" to lead this detector & machine effort:
Alan Bross, Alexander Mikhailichenko, Nural Akchurin, Timofey Zolkin(?), John Hauptman,
Nikolai Mokhov, Steve Kahn, & send an email to us if you are interested in joining this board.

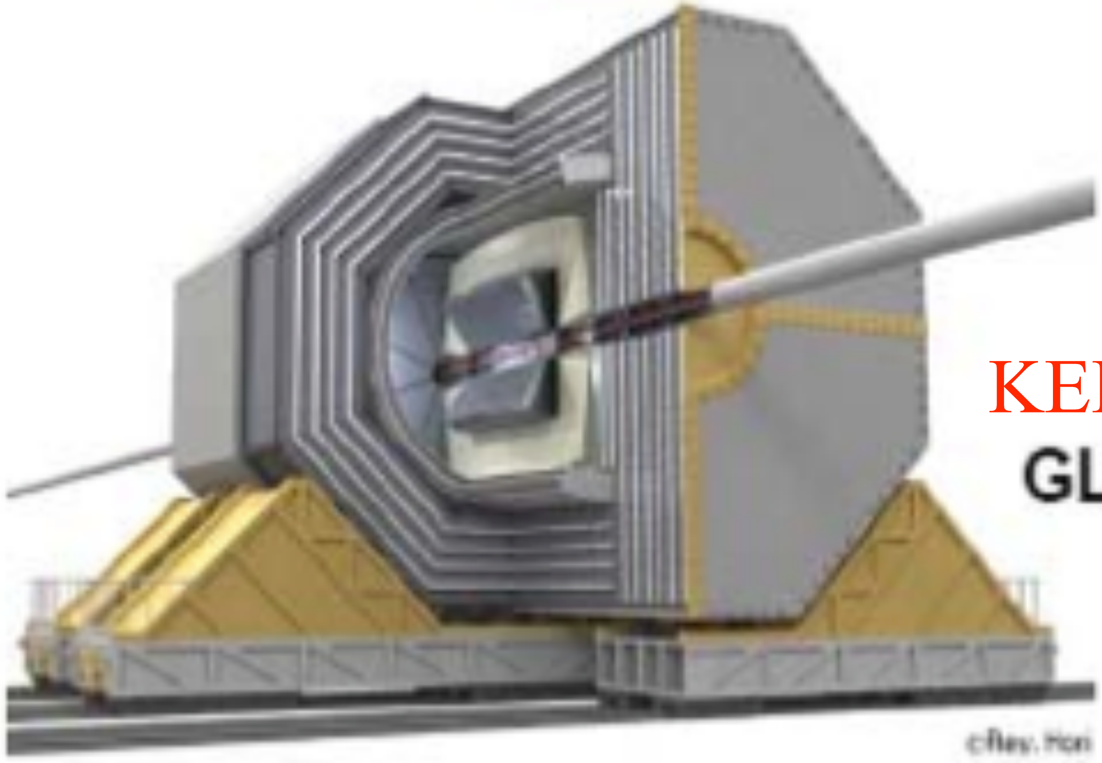
In the beginning, there were three ...



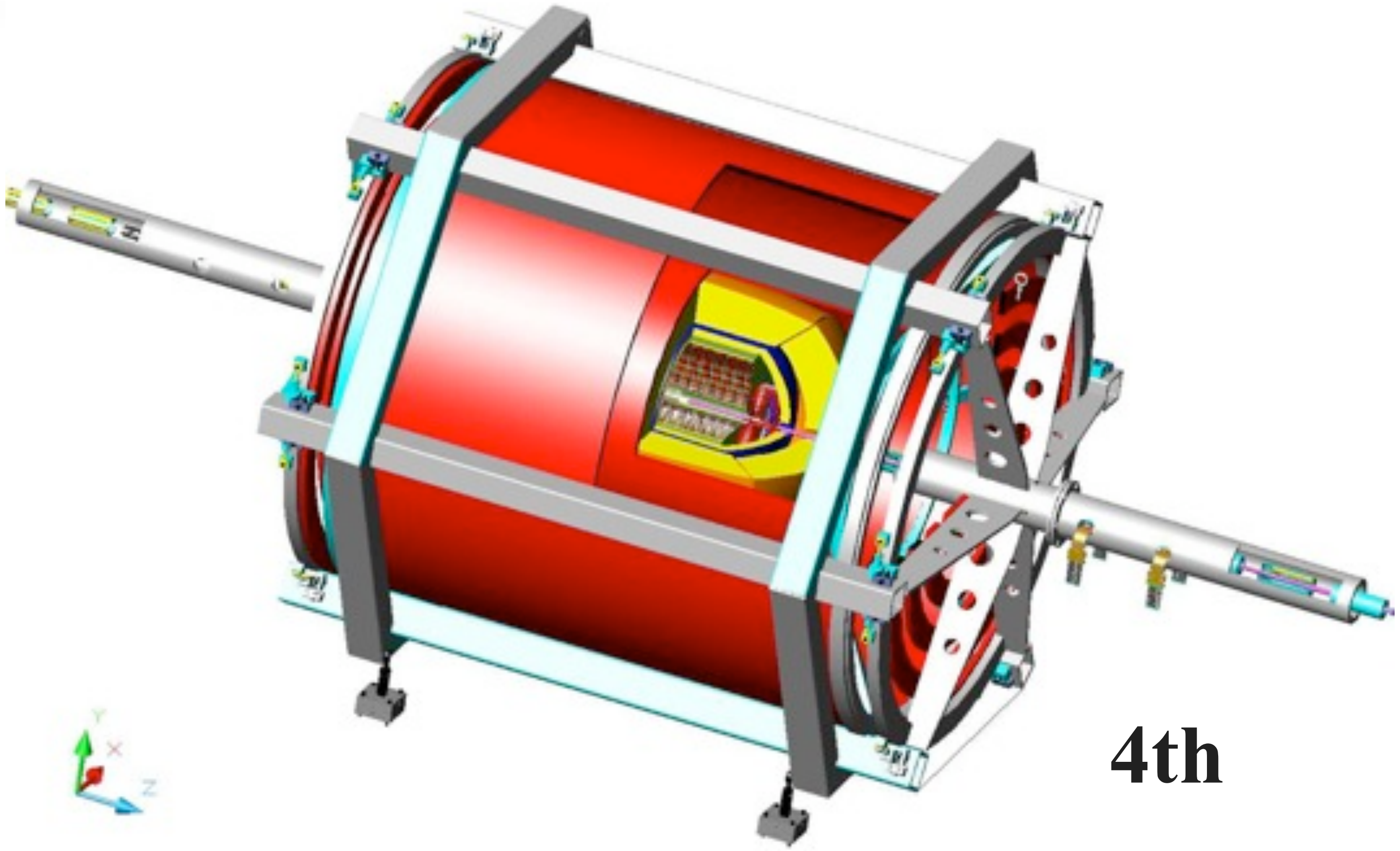
DESY
LDC



SLAC
SiD

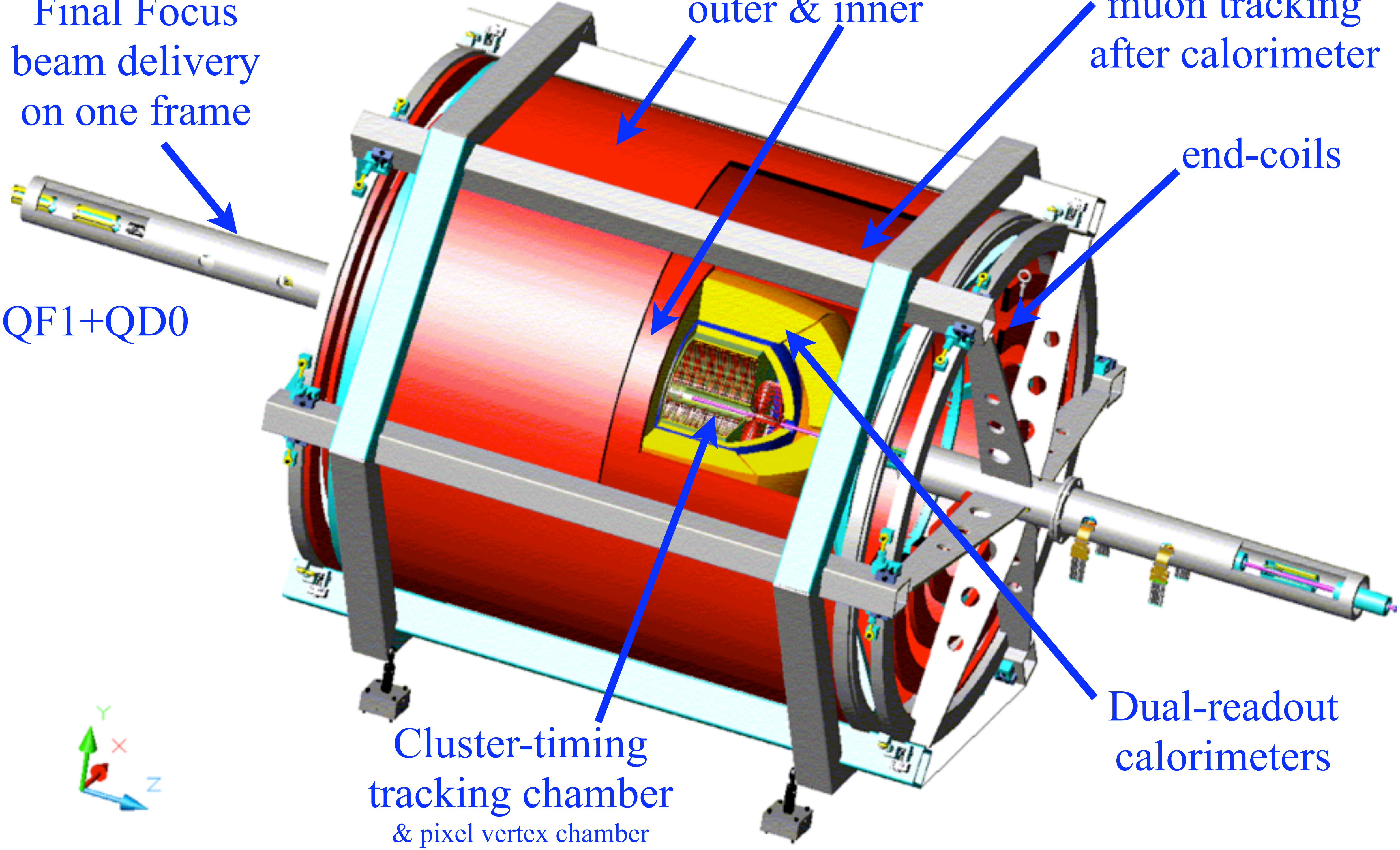


KEK
GLD



4th

4th detector



Final Focus
beam delivery
on one frame

QF1+QD0

Solenoids
outer & inner

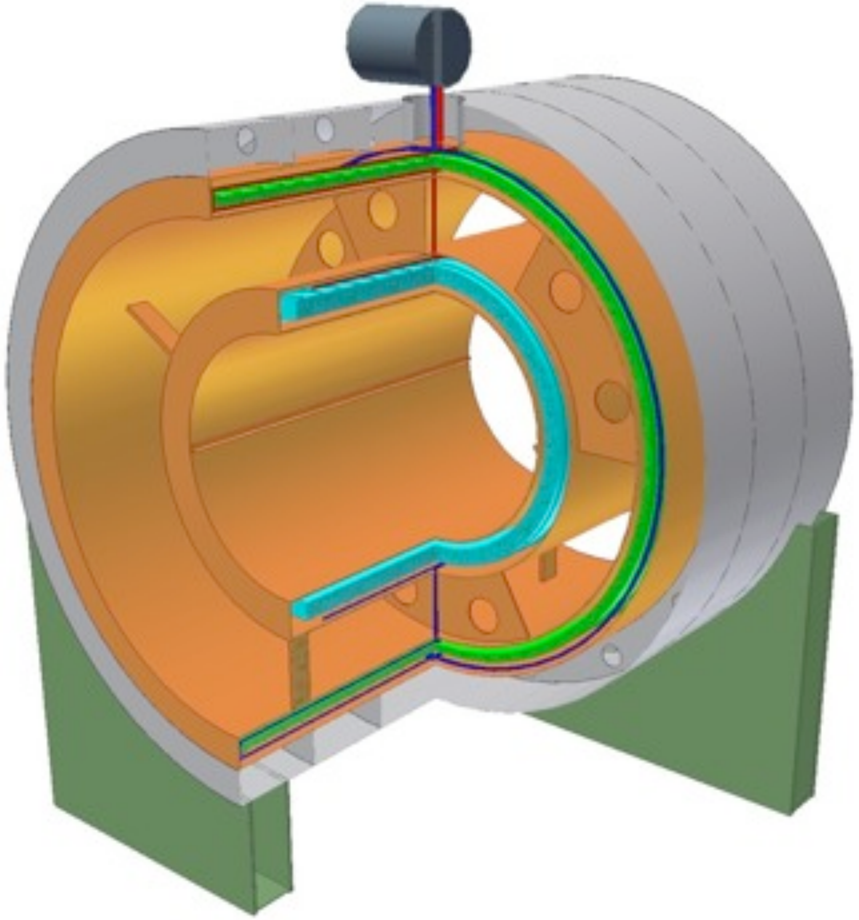
High-precision
muon tracking
after calorimeter

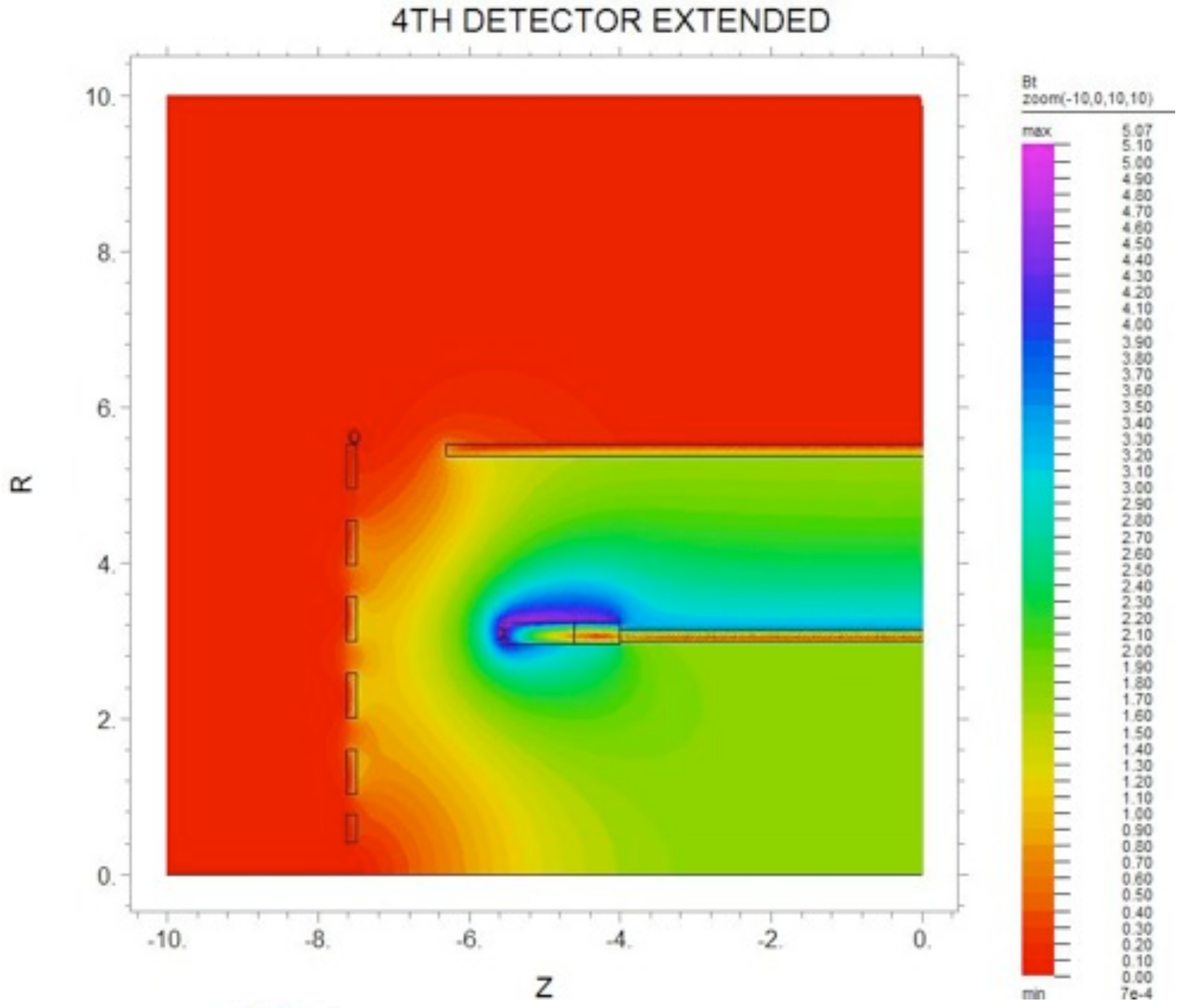
end-coils

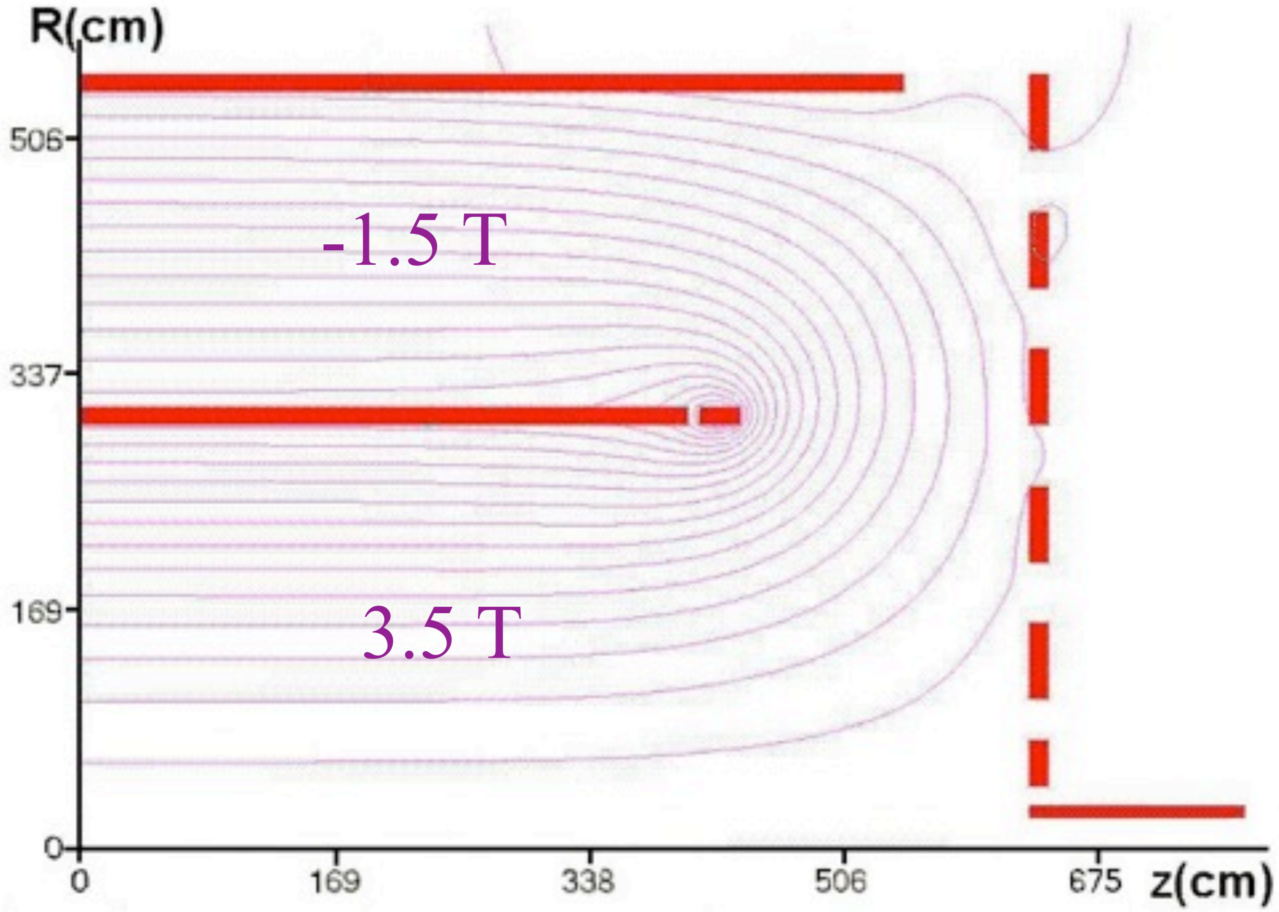
Dual-readout
calorimeters

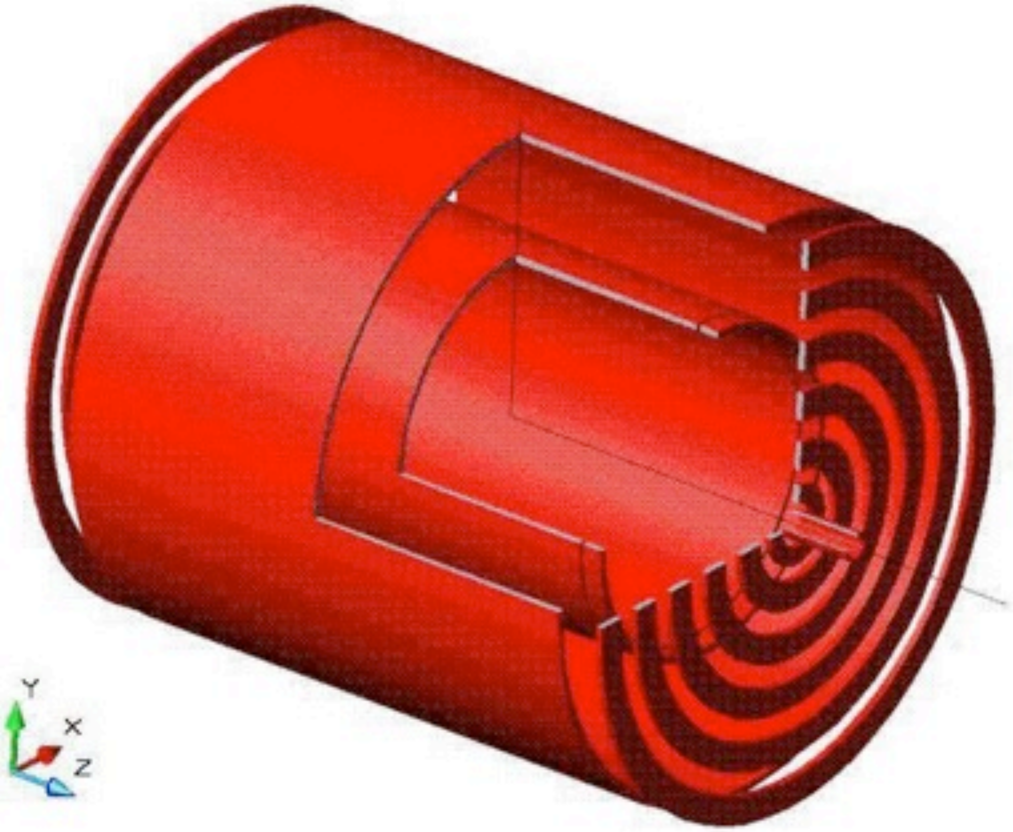
Cluster-timing
tracking chamber
& pixel vertex chamber

Dual-solenoids (completely new in HEP)





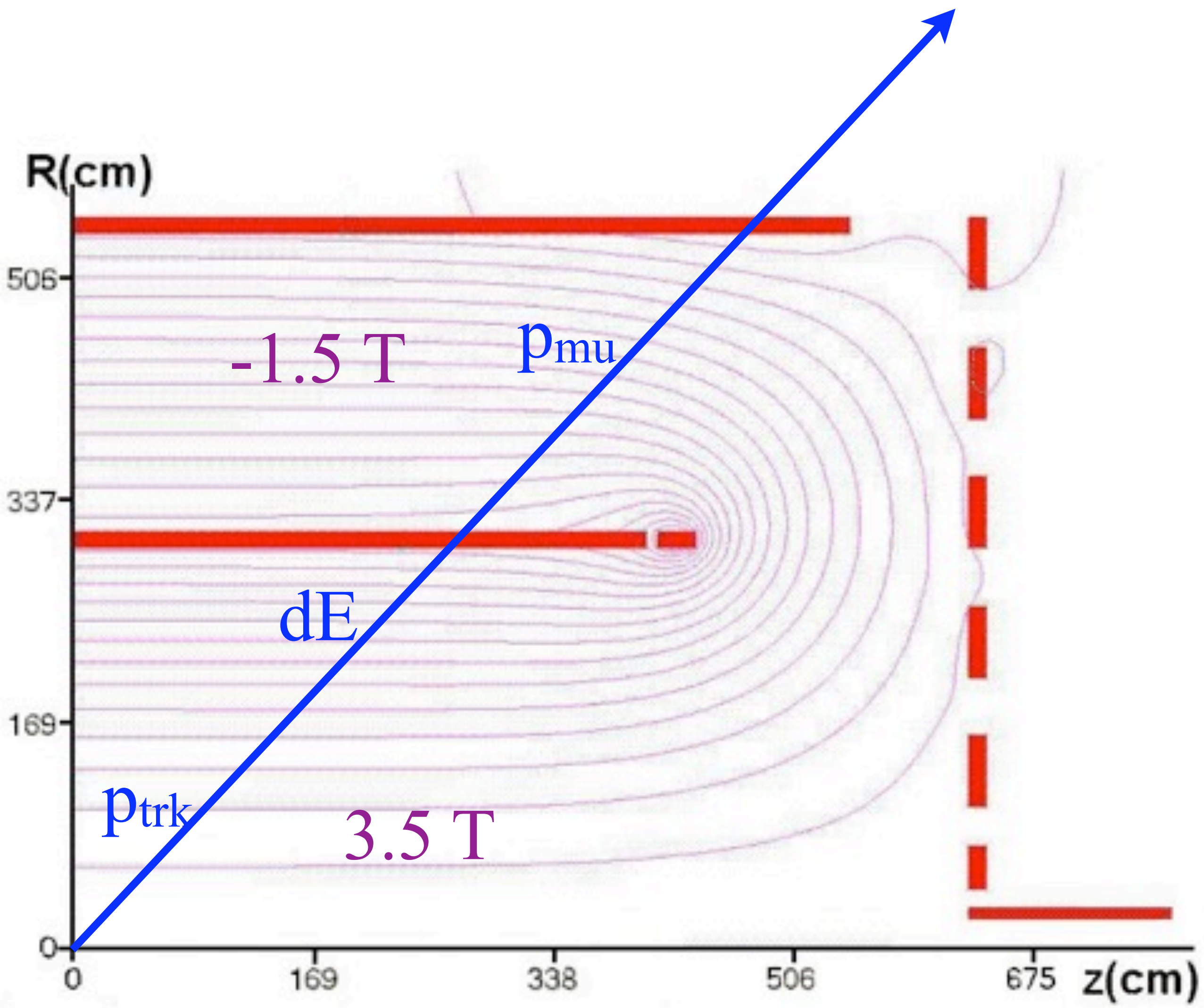


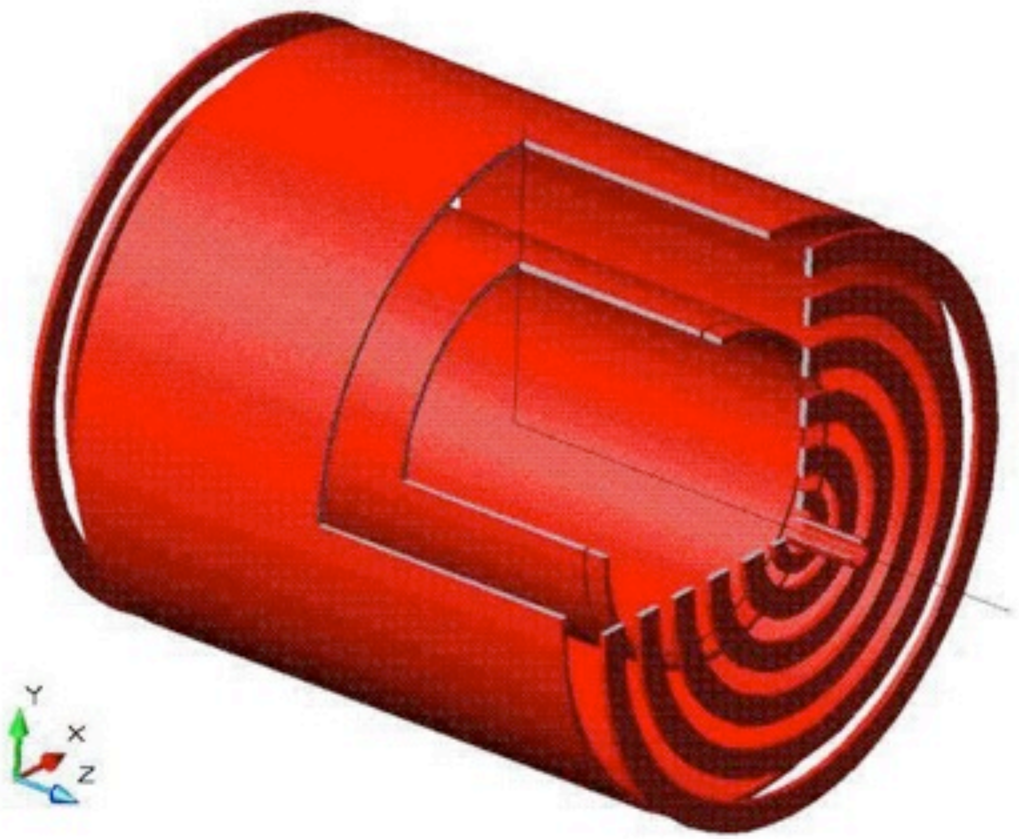


Dual-solenoids (A. Mikhailichenko, Cornell)

Muon measured with precision in every system:

- p_{trk} in central tracker
- dE bremsstrahlung in calorimeter
- p_{mu} in muon spectrometer





Dual-readout calorimetry (new in high energy physics)

- Electrons and photons (EM “electromagnetic” particles) are easy.
- Hadrons (protons, pions “strongly interacting” particles) are difficult due to large stochastic fluctuations between

  1. the EM part (“*e*”) from pi-zero and eta decays to photons
  2. the non-EM part (“*h*”) consisting of everything else

  and the fact that “*e*” response is larger than “*h*”.

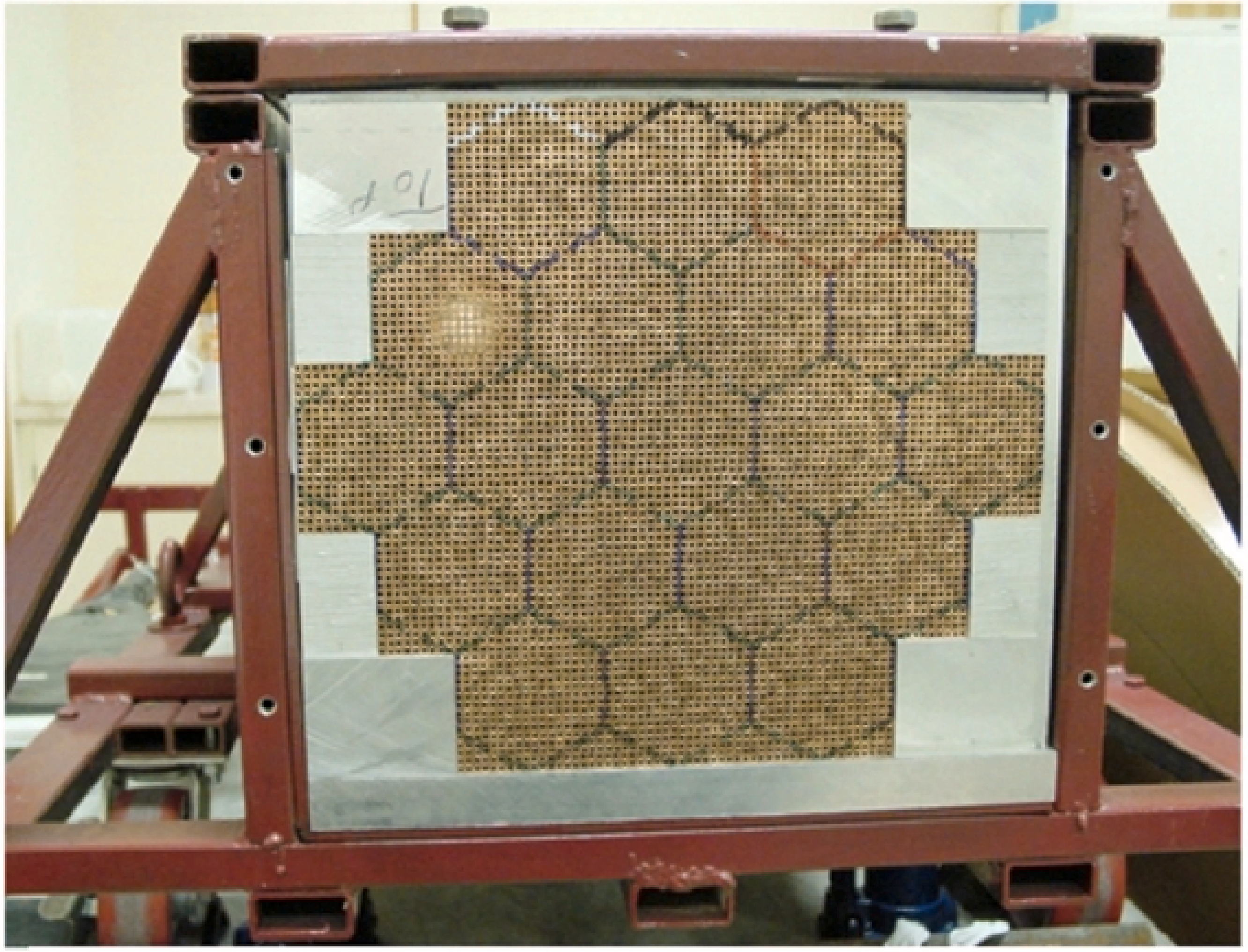
measure both ... “dual”

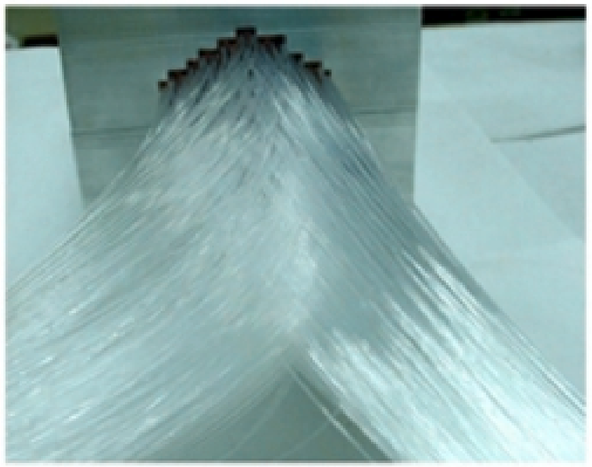
Relativistic electrons ($v > c/n$) generate Cerenkov light inside the clear fibers and the crystals; most other particles do not.

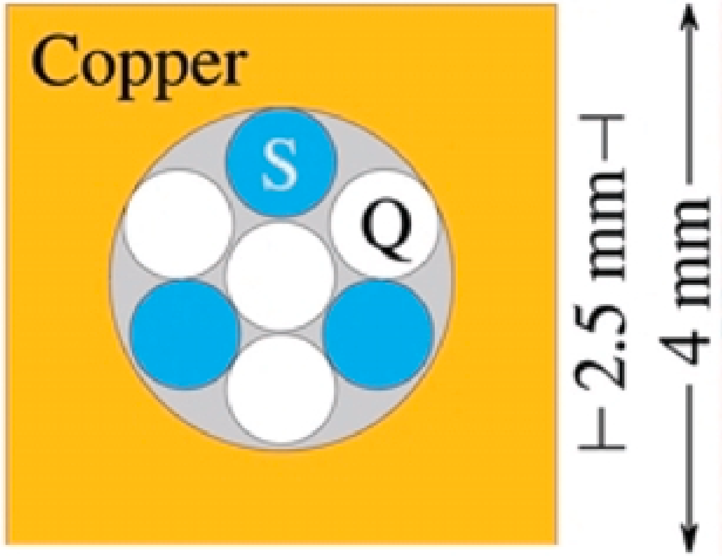
Fiber DREAM module: *proof-of-principle*

S = scintillating fibers
Q = quartz (clear) fibers

DREAM: Structure



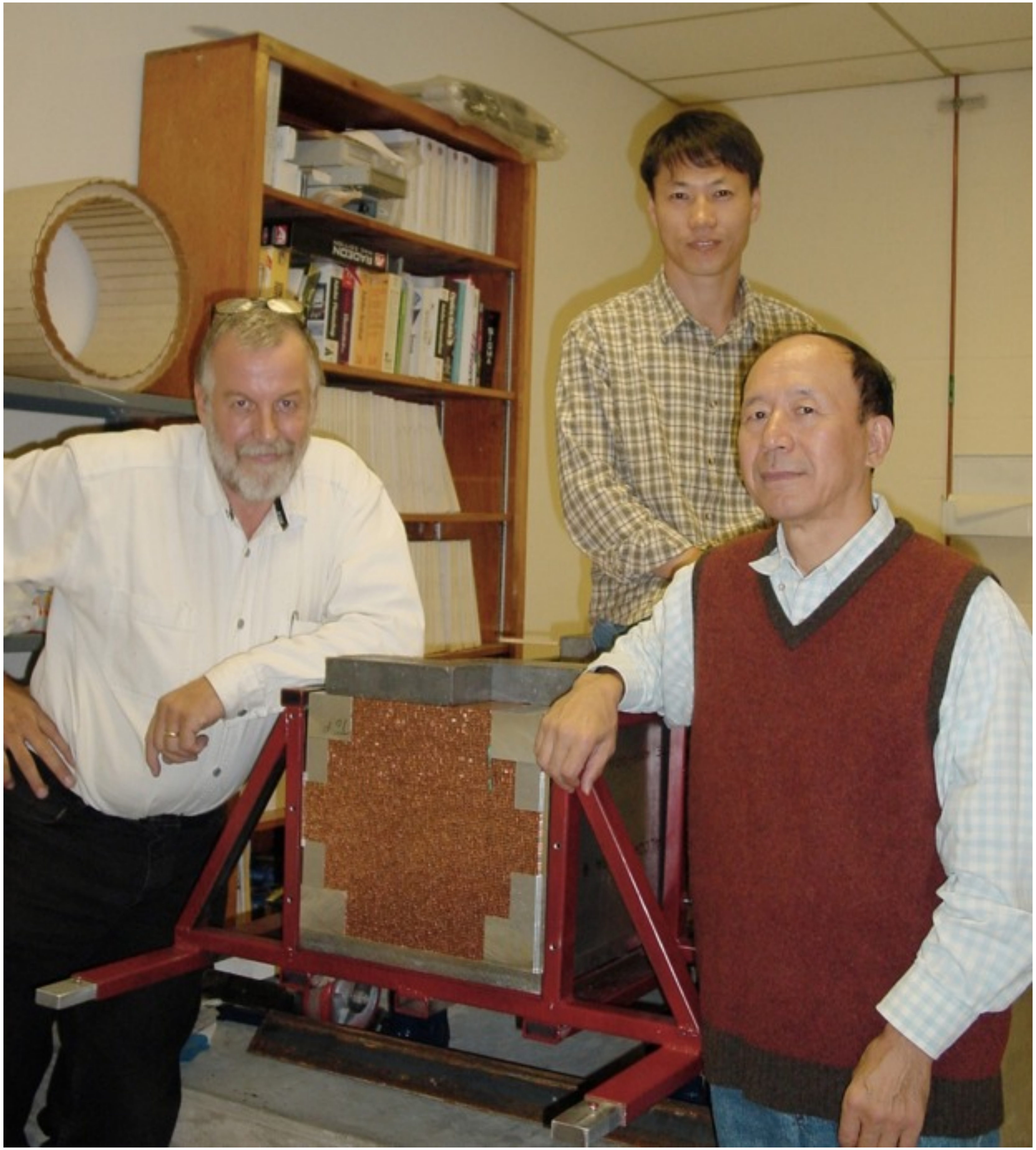




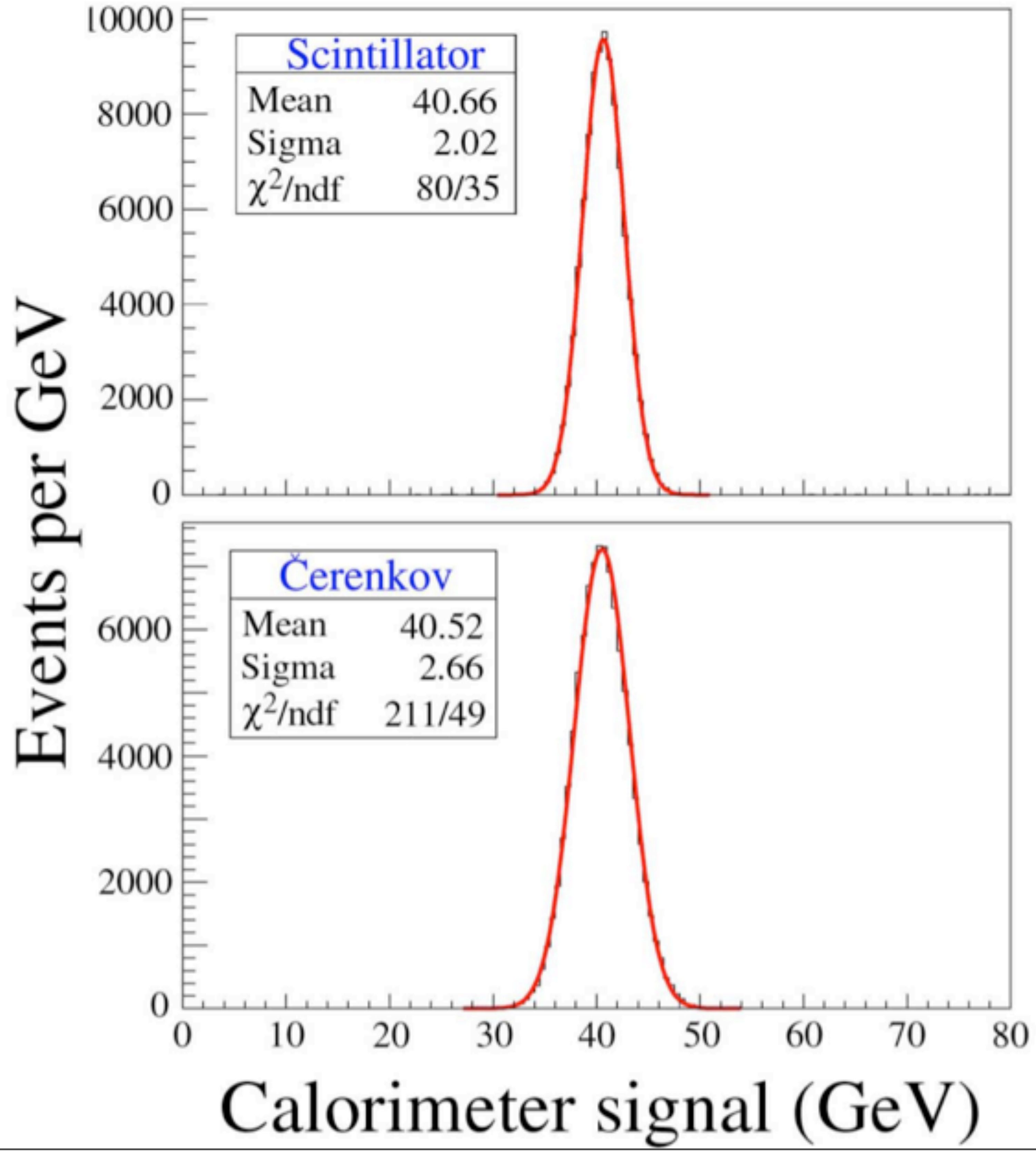
- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

Simply built, inexpensive, proof-of-principle DREAM module

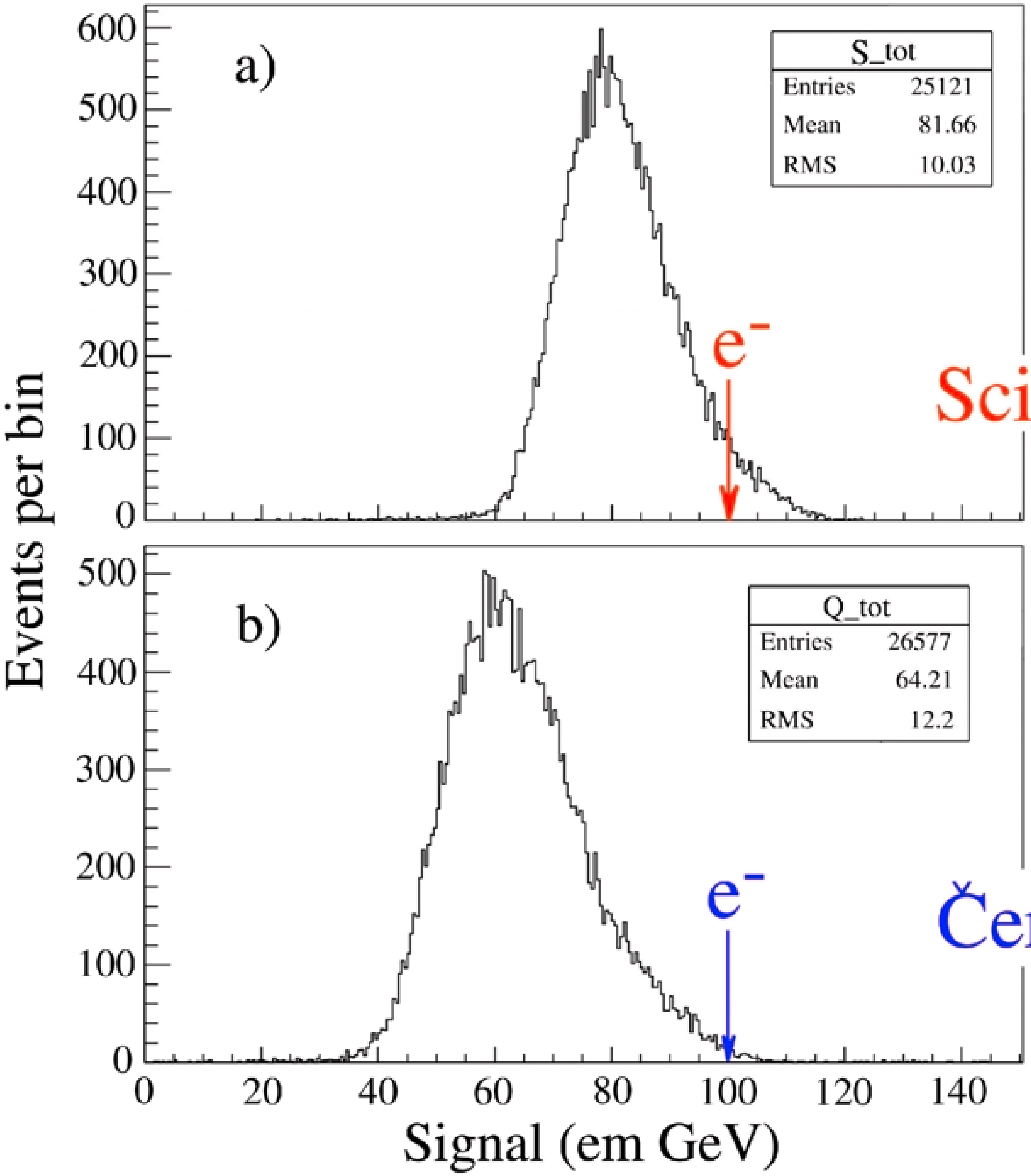
(built by Korean
housewives with silk
gloves in Lubbock, Texas)



Calibrate both signals with 40 GeV electrons



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



DREAM

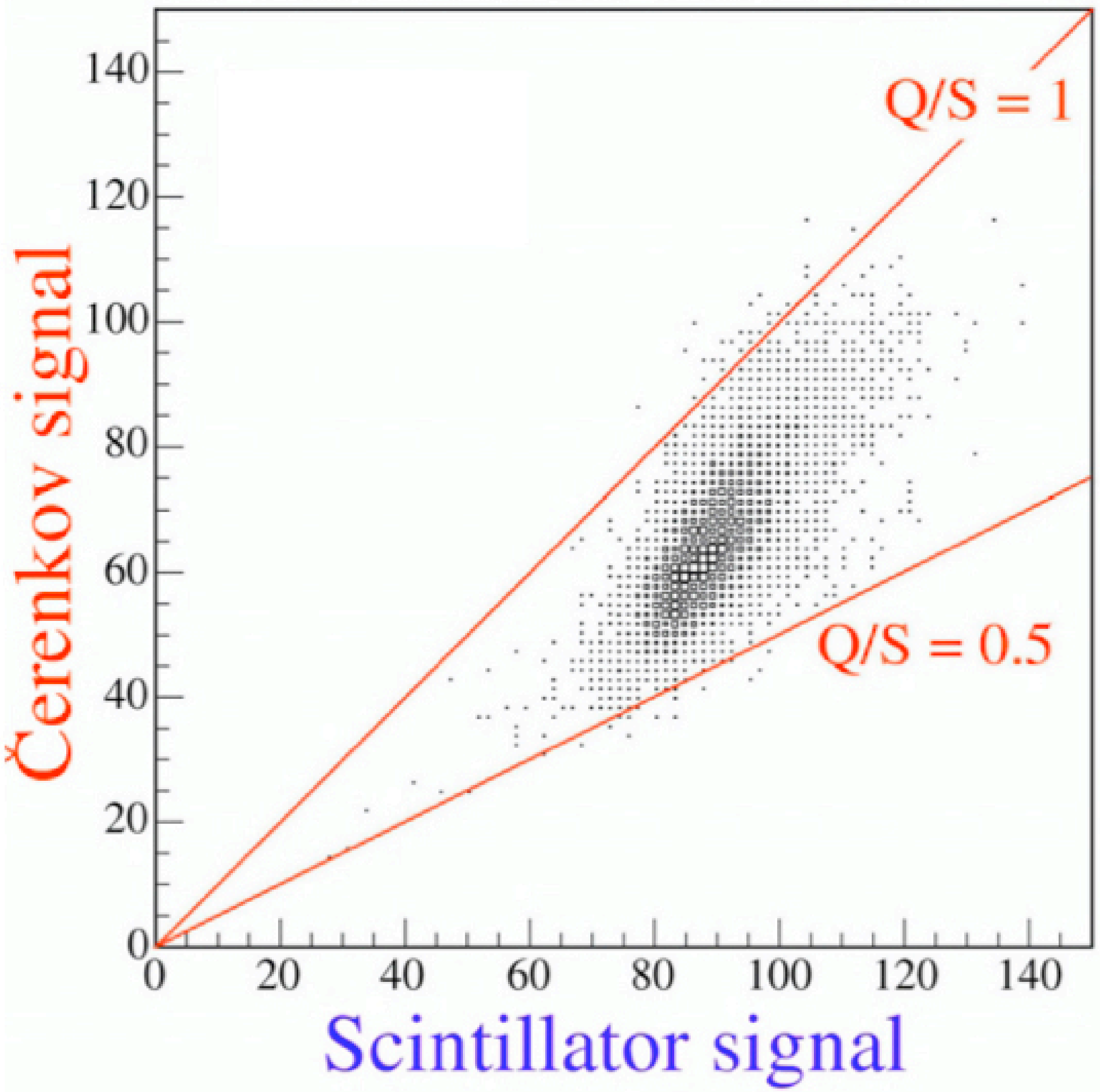
Raw signals

(100 GeV π^-)

Scintillator

Čerenkov

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



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

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

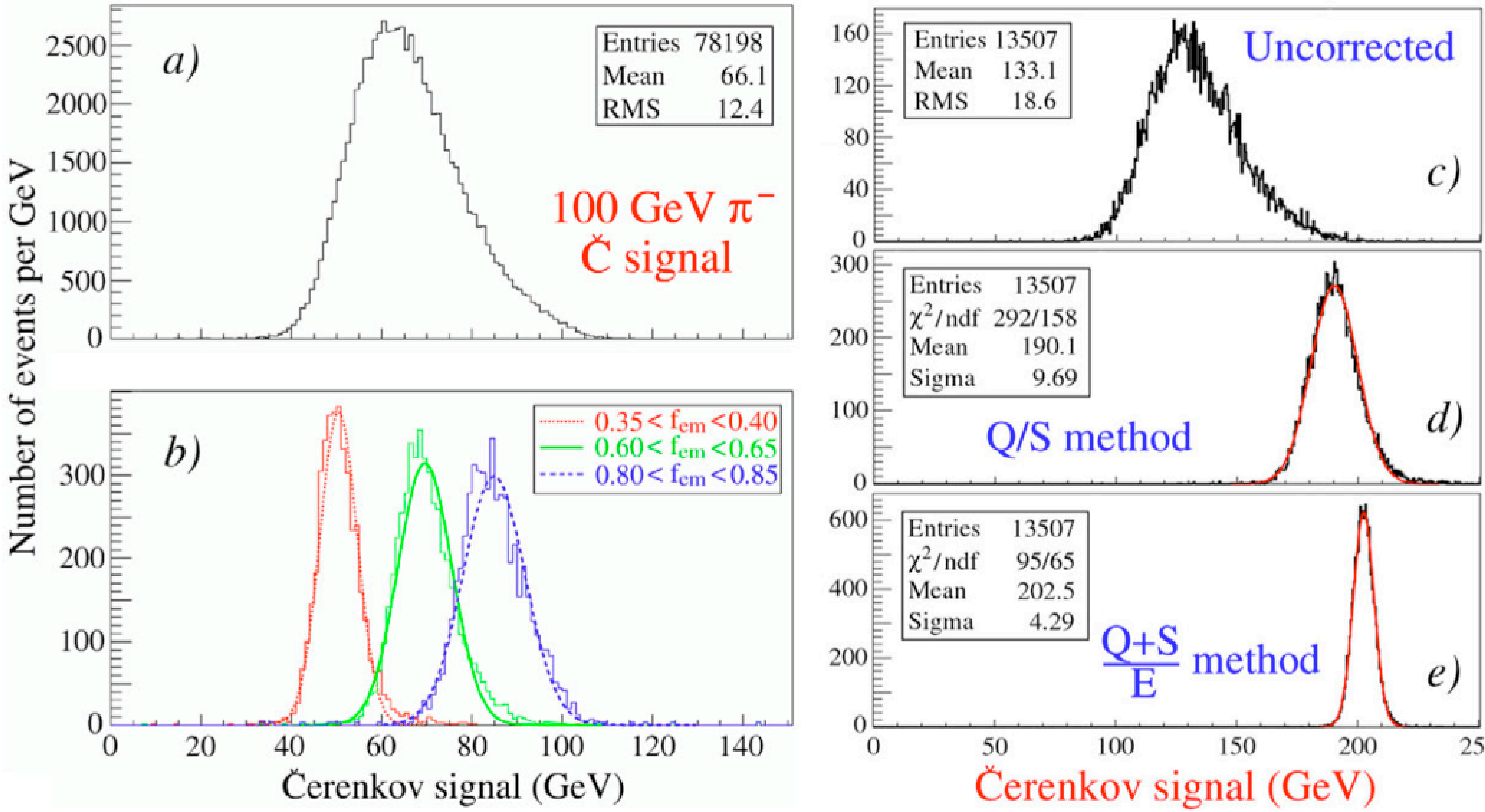
$e.g.$ If $e/h = 1.3$ (S), 4.7 (Q)

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

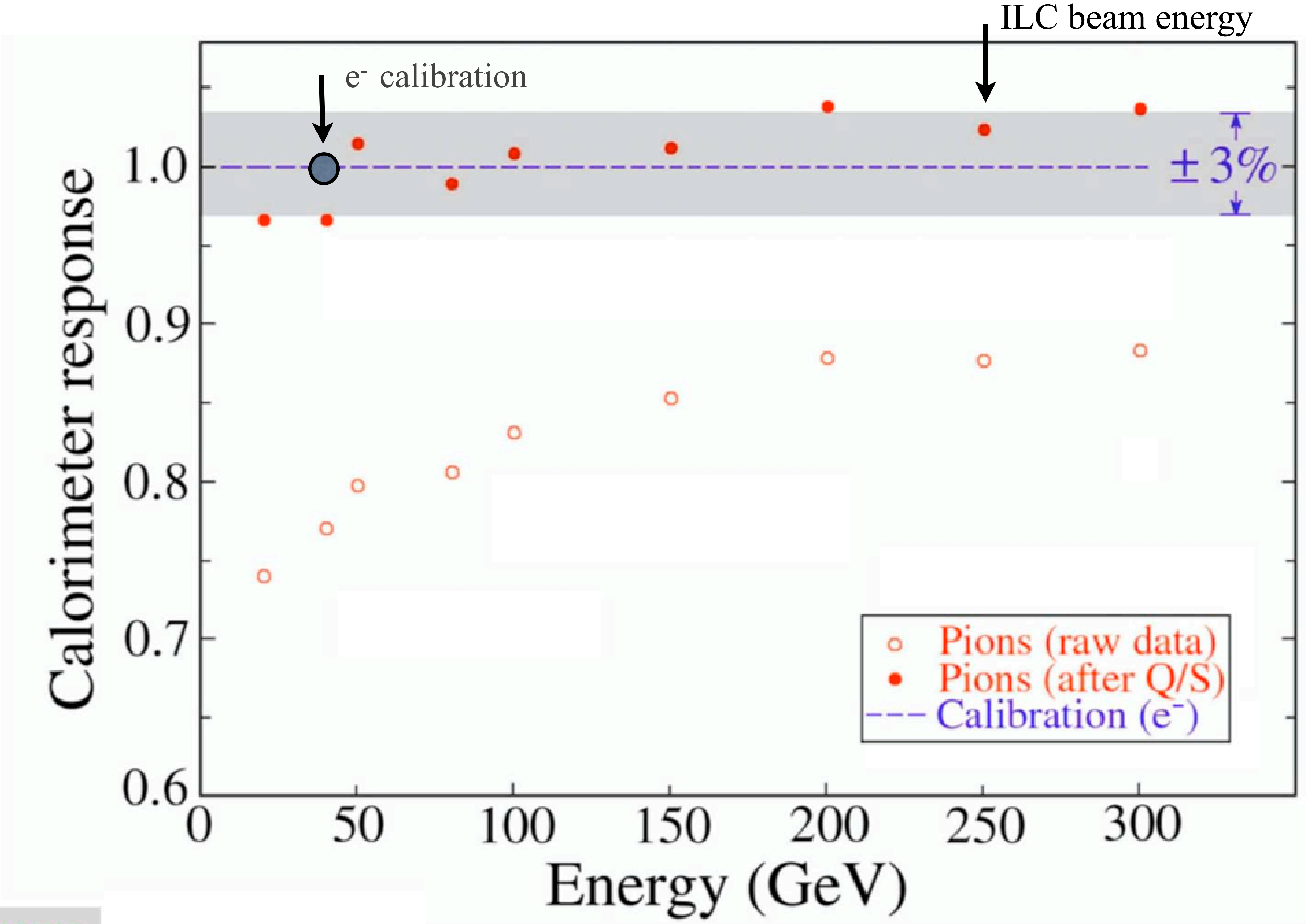
$$\boxed{E = \frac{S - \chi Q}{1 - \chi}} \quad (4)$$

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 !



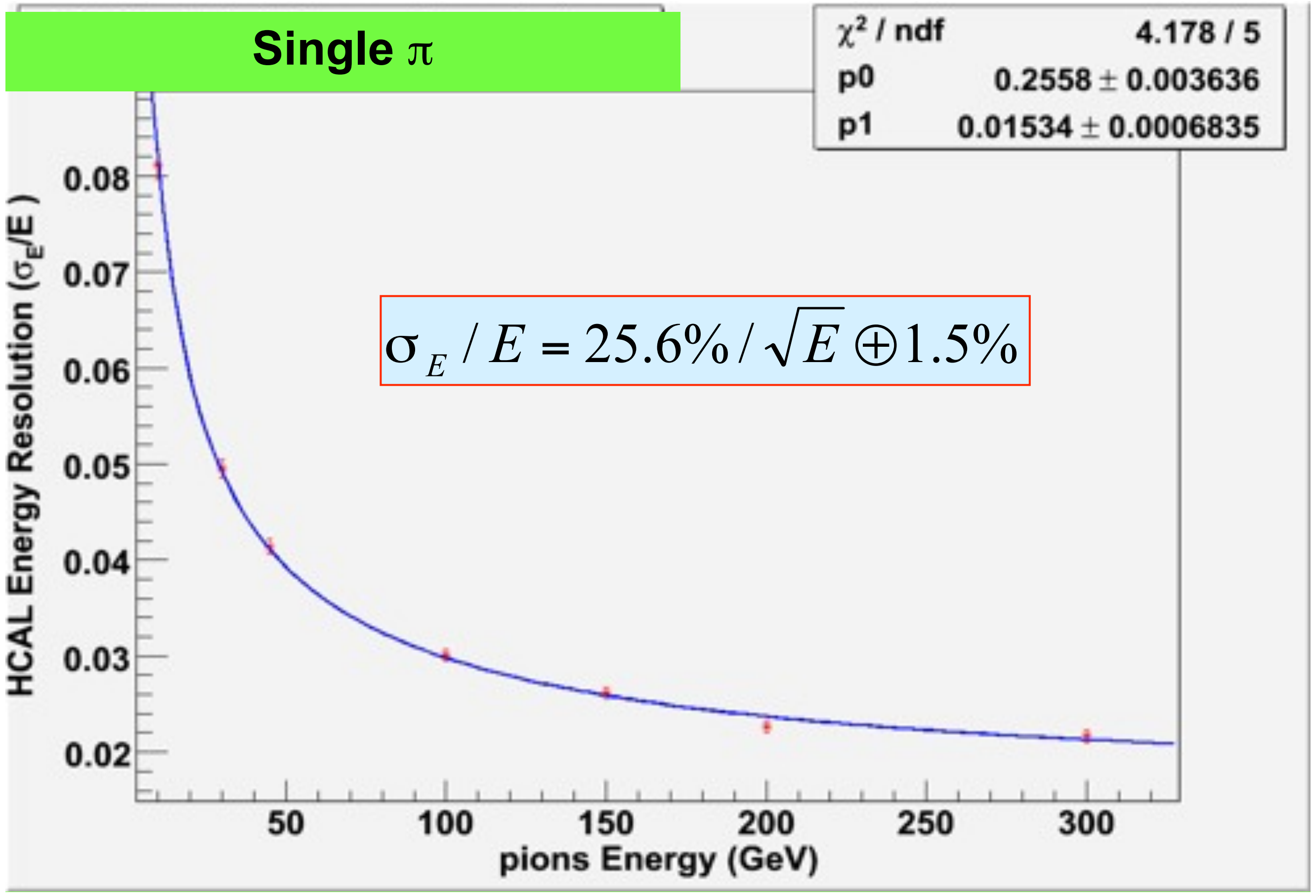
Hadronic response linearity



From:

NIM A537 (2005) 537

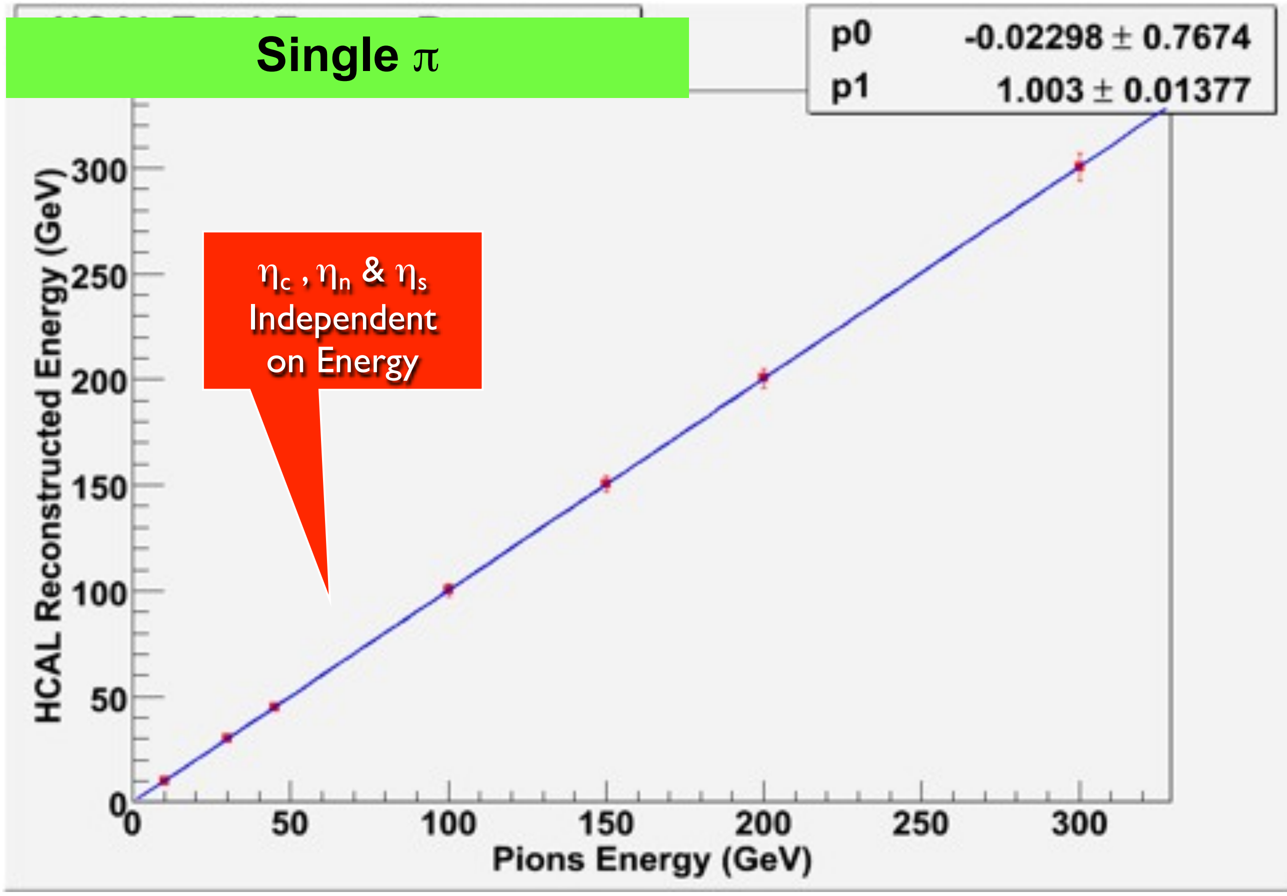
4th dual-readout simulation performance up to 1 TeV



Single π

χ^2 / ndf	4.178 / 5
p0	0.2558 ± 0.003636
p1	0.01534 ± 0.0006835

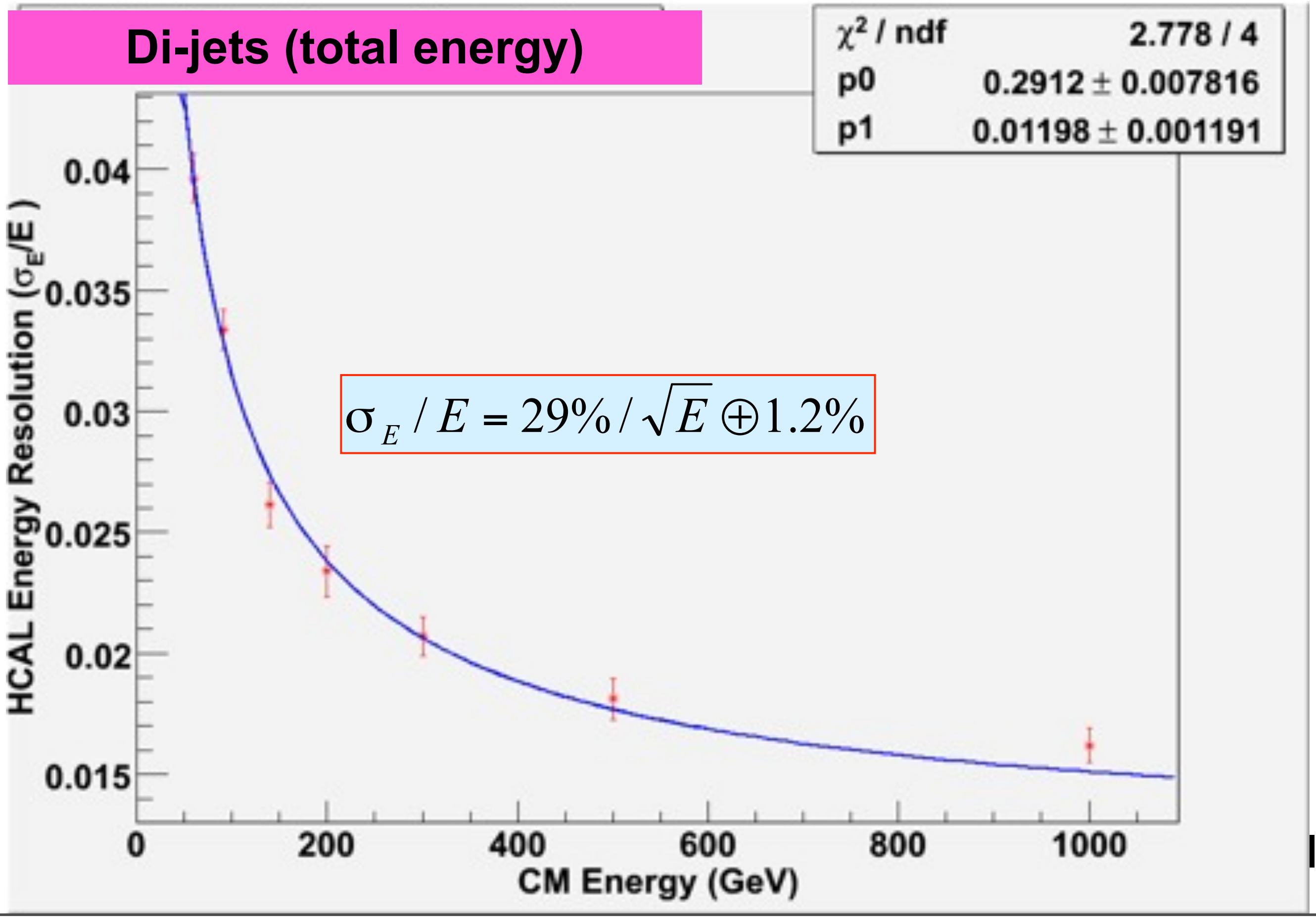
$$\sigma_E / E = 25.6\% / \sqrt{E} \oplus 1.5\%$$



Single π

p0	-0.02298 ± 0.7674
p1	1.003 ± 0.01377

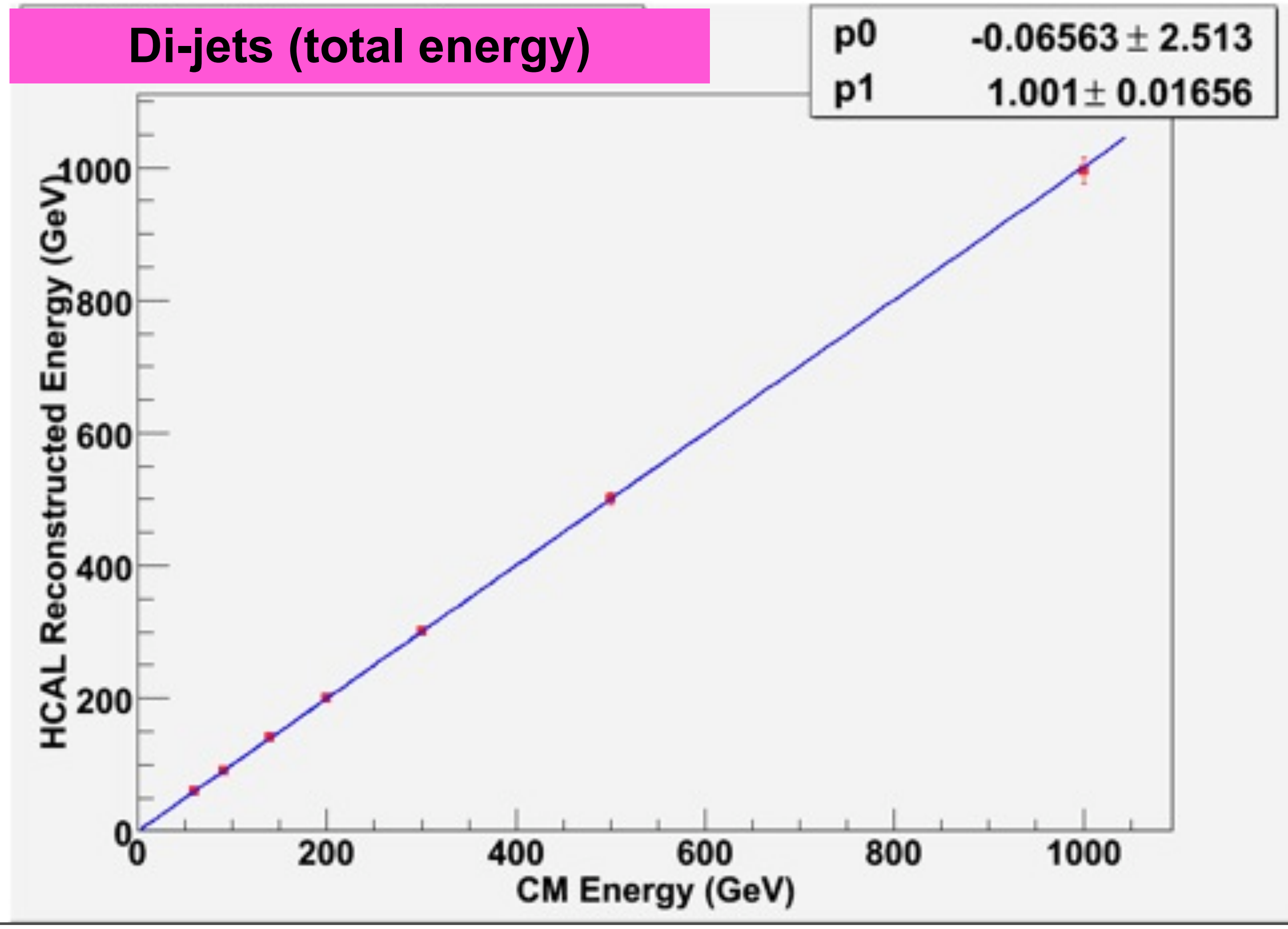
η_c , η_n & η_s Independent on Energy



Di-jets (total energy)

χ^2 / ndf	2.778 / 4
p0	0.2912 ± 0.007816
p1	0.01198 ± 0.001191

$$\sigma_E / E = 29\% / \sqrt{E} \oplus 1.2\%$$



Di-jets (total energy)

p0	-0.06563 ± 2.513
p1	1.001 ± 0.01656

Dual-readout of BGO crystals

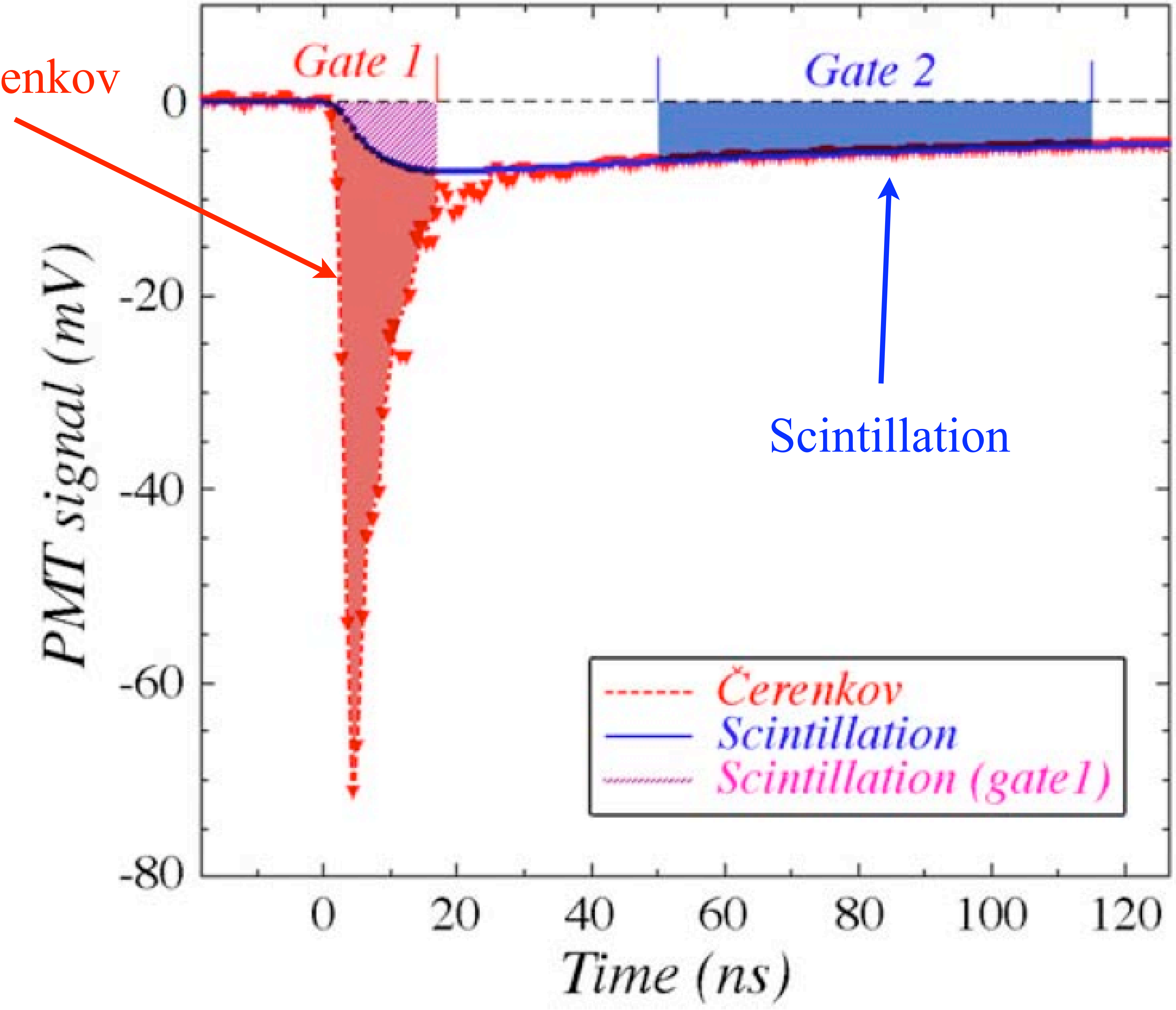
BGO crystal in its housing

and in the beam before DREAM

Seven papers in NIM on crystal measurements

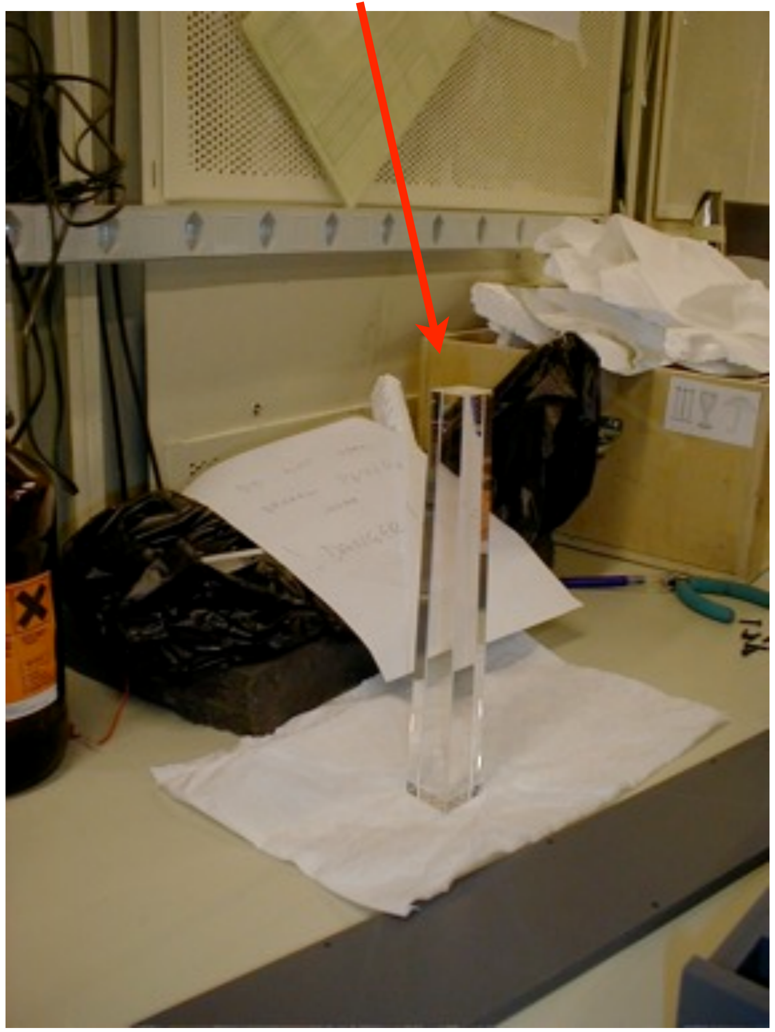
Crystal DREAM: *one PMT/crystal with time-history readout*

Cerenkov



Scintillation

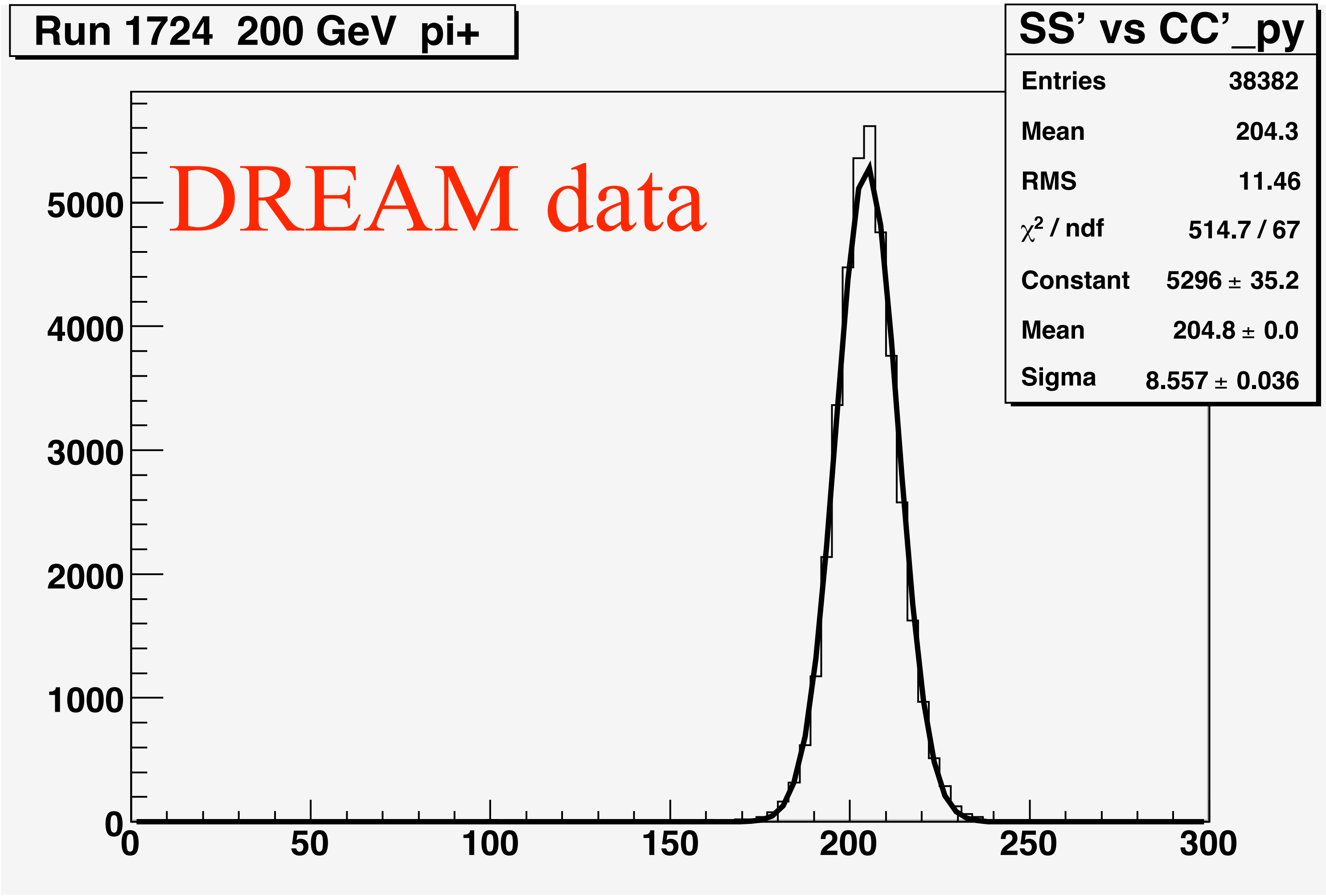
L3 BGO crystal

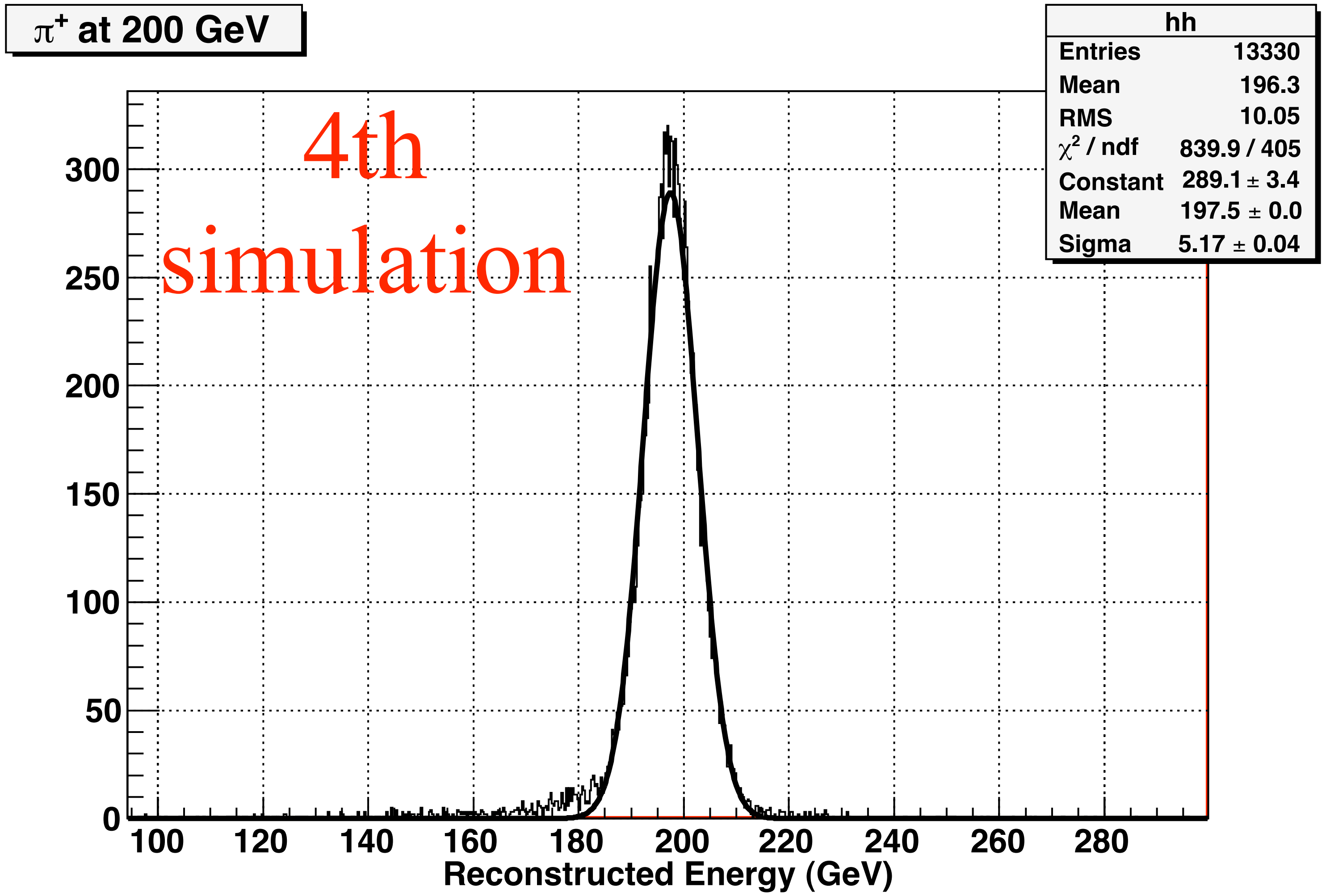


CERN beam test of BGO array + DREAM module (surrounded by large scintillators to catch neutrons)

electrons
pions
muons
“jets”

BGO+fiber calorimeter
at 200 GeV

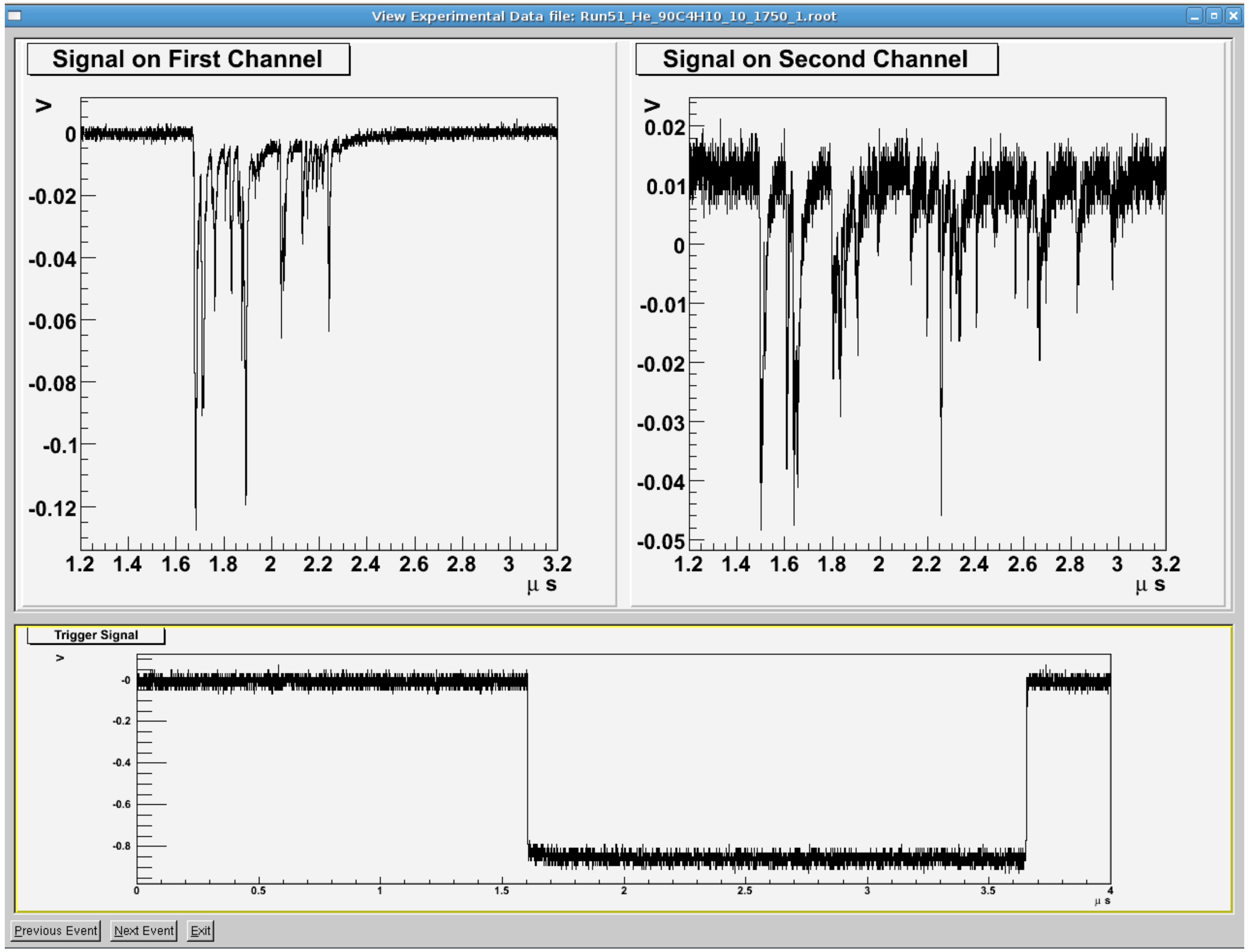


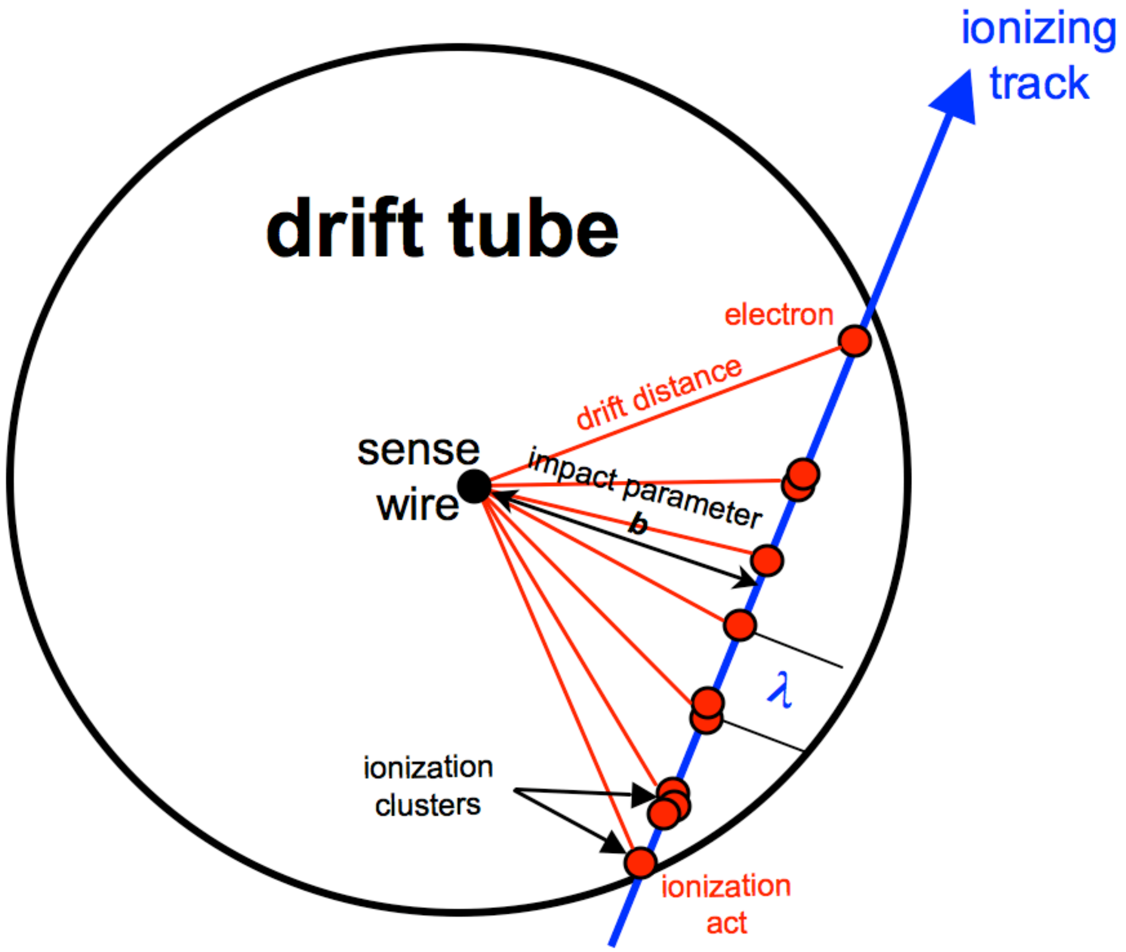


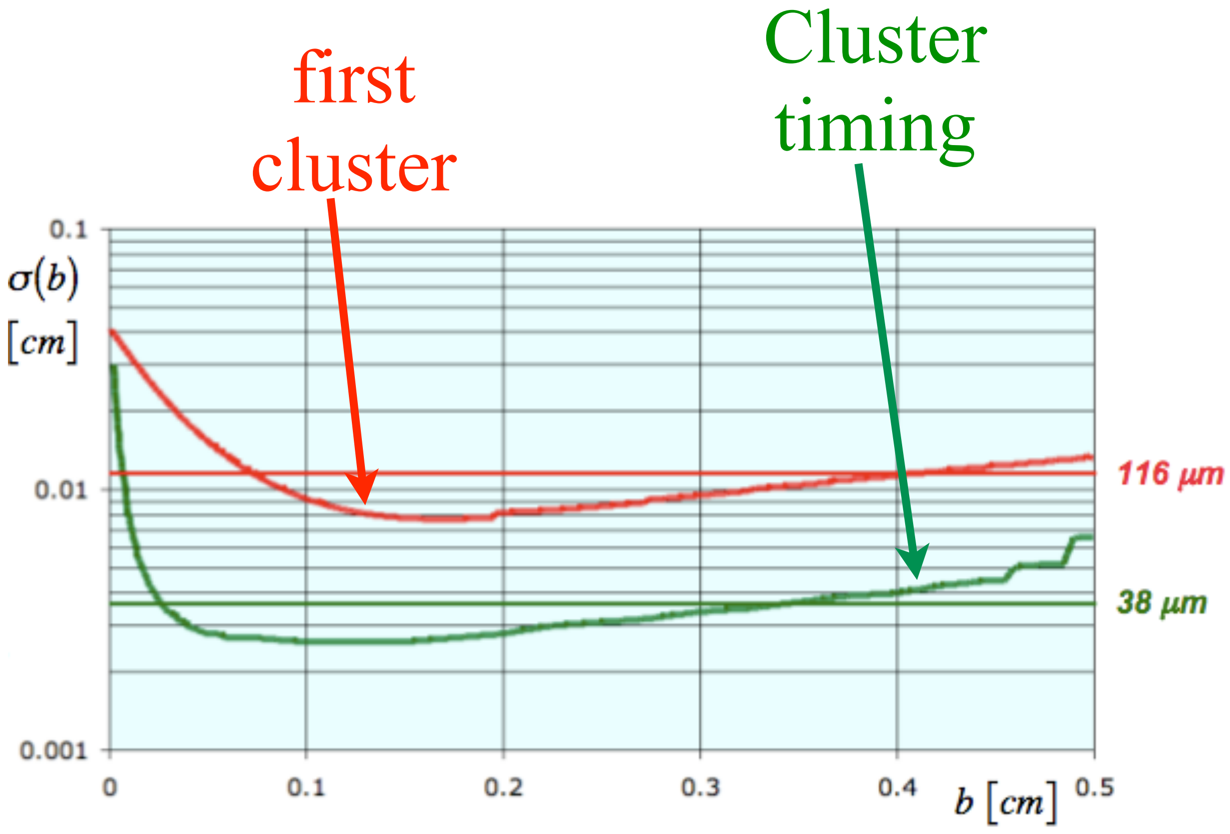
Cluster-timing

(new, beyond Charpak)

of *every* electron cluster



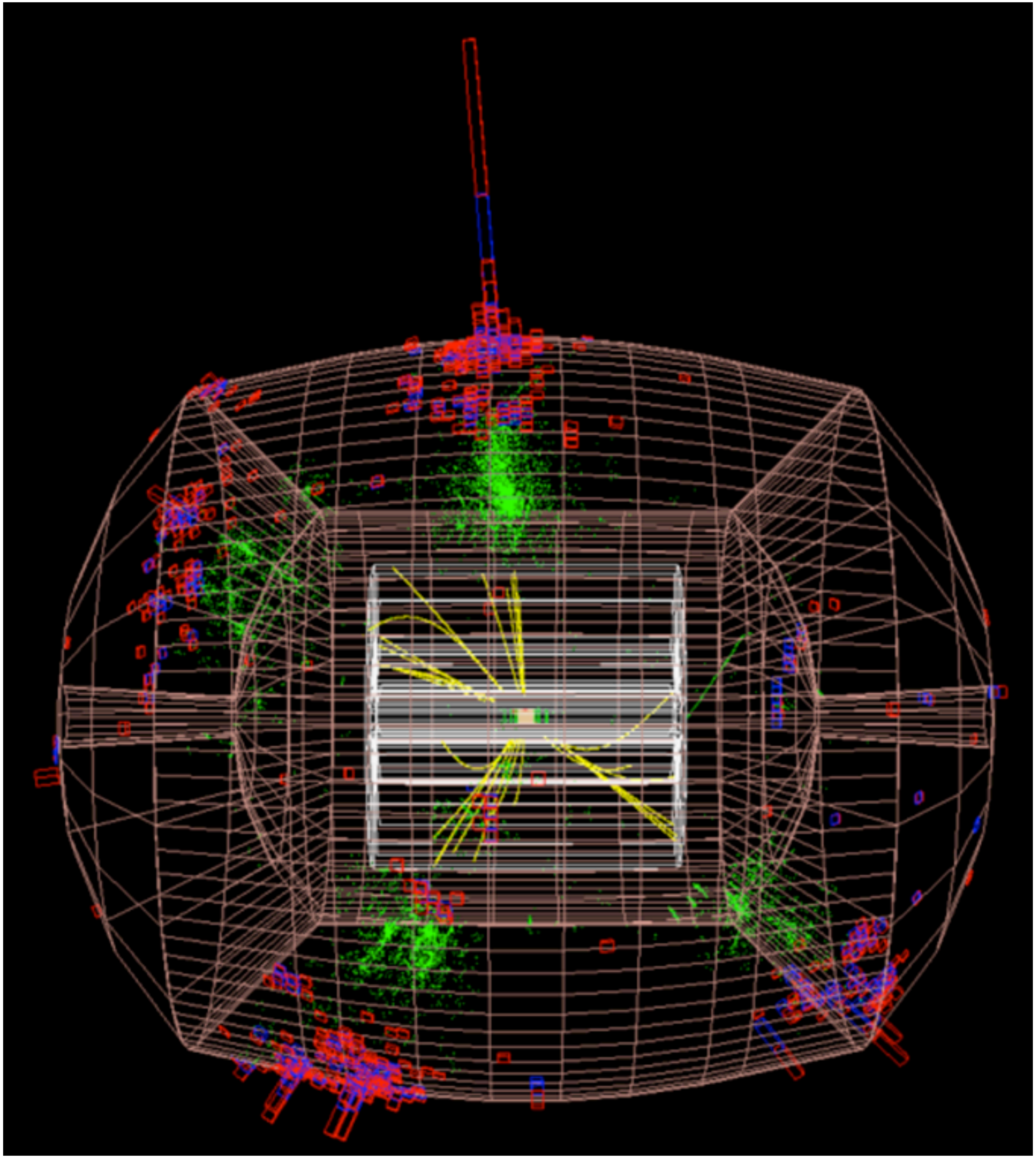




Ultra-low-mass chamber, expect ~50 μm spatial resolution on each of 150 points on a track.

H^0Z^0 event

(tracking & calorimeters)



Neutrino near detector: just make DREAM 100 meters long, segmented to include periodic magnetic momentum measurement volumes

Learn from KLOE and SPACAL!

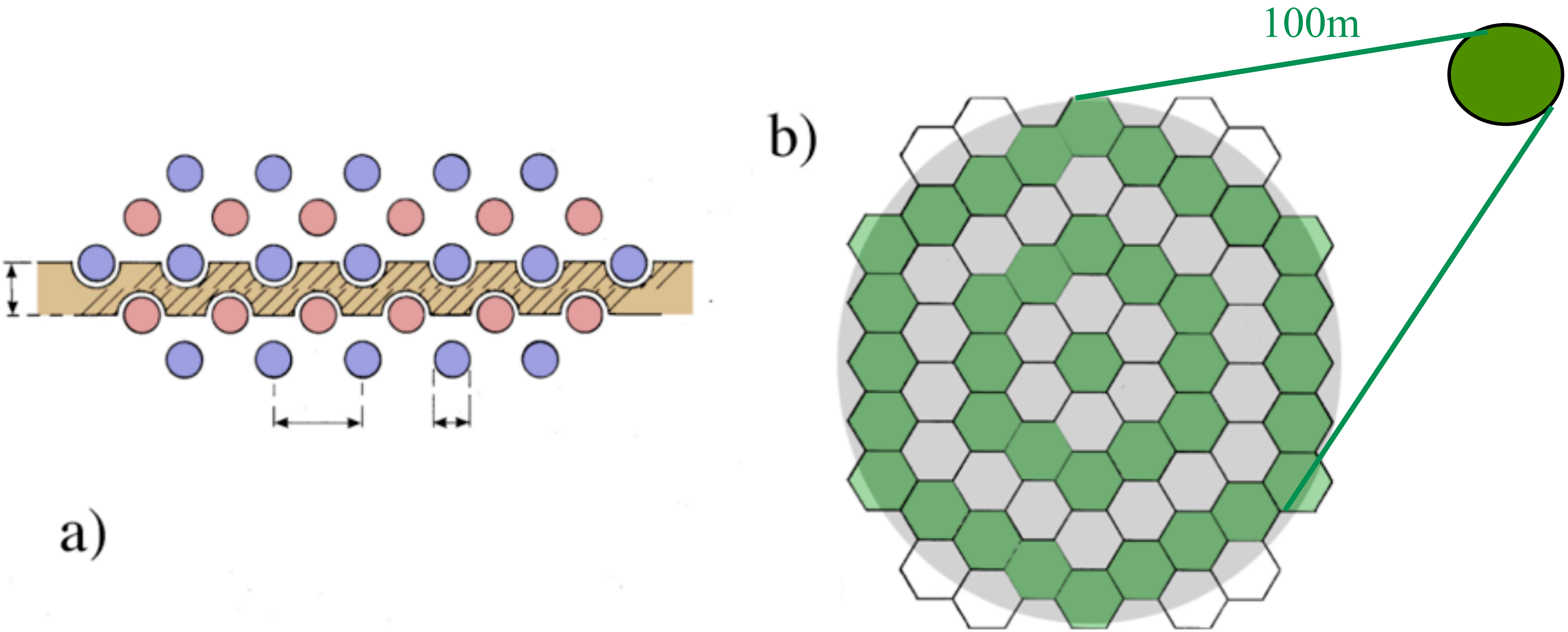


Figure 25: The pattern according to which the two types of fibers will be distributed inside the detector volume (a) and the tower structure of the proposed fiber calorimeter (b).

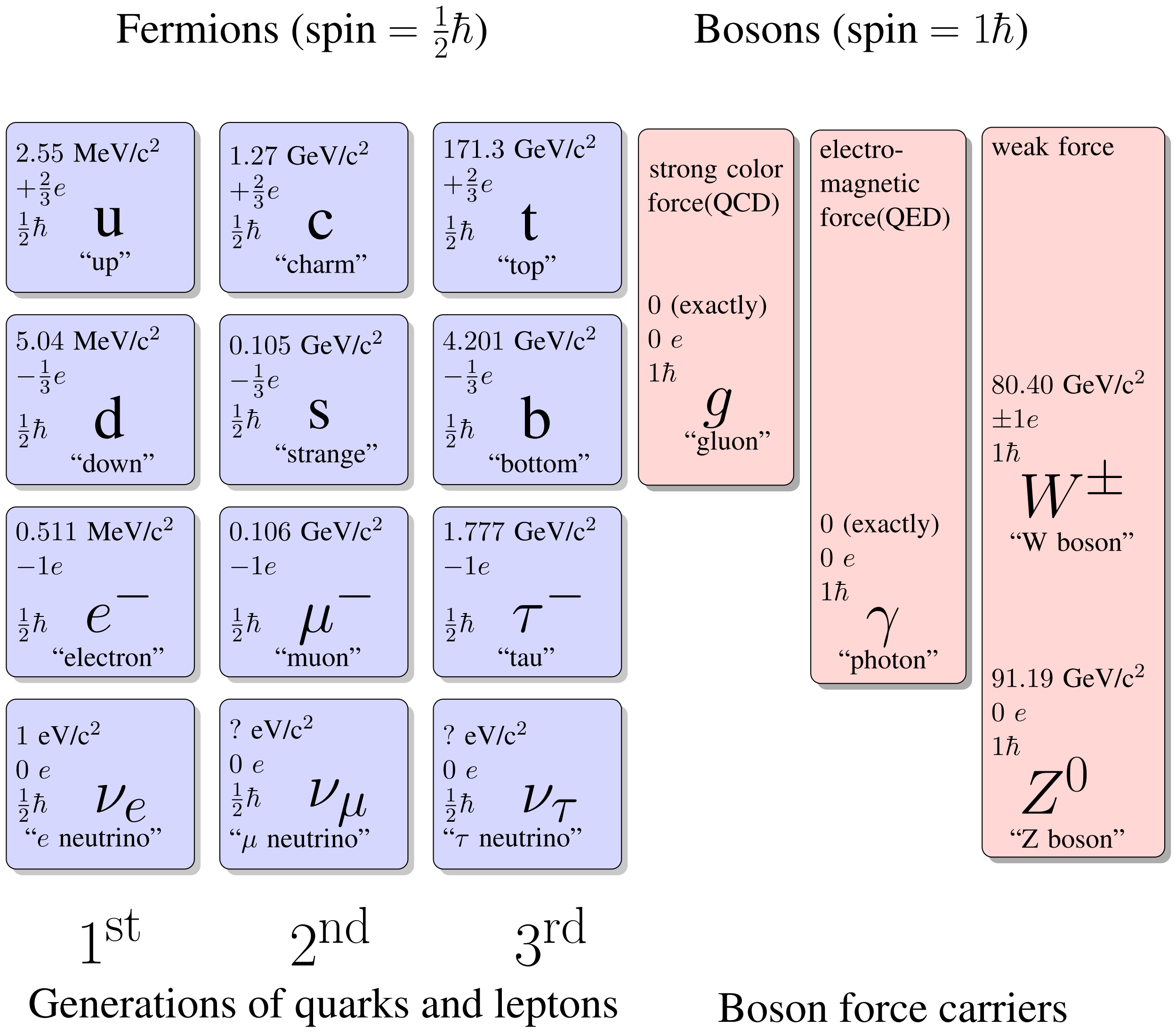
Particle Identification

(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)



Fermions (spin $= \frac{1}{2}\hbar$)

1^{st}	2^{nd}	3^{rd}
2.55 MeV/c^2 $+\frac{2}{3}e$ $\frac{1}{2}\hbar$ u "up"	1.27 GeV/c^2 $+\frac{2}{3}e$ $\frac{1}{2}\hbar$ c "charm"	171.3 GeV/c^2 $+\frac{2}{3}e$ $\frac{1}{2}\hbar$ t "top"
5.04 MeV/c^2 $-\frac{1}{3}e$ $\frac{1}{2}\hbar$ d "down"	0.105 GeV/c^2 $-\frac{1}{3}e$ $\frac{1}{2}\hbar$ s "strange"	4.201 GeV/c^2 $-\frac{1}{3}e$ $\frac{1}{2}\hbar$ b "bottom"
0.511 MeV/c^2 $-1e$ $\frac{1}{2}\hbar$ e^- "electron"	0.106 GeV/c^2 $-1e$ $\frac{1}{2}\hbar$ μ^- "muon"	1.777 GeV/c^2 $-1e$ $\frac{1}{2}\hbar$ τ^- "tau"
1 eV/c^2 0 e $\frac{1}{2}\hbar$ ν_e "e neutrino"	? eV/c^2 0 e $\frac{1}{2}\hbar$ ν_μ "μ neutrino"	? eV/c^2 0 e $\frac{1}{2}\hbar$ ν_τ "τ neutrino"

Generations of quarks and leptons

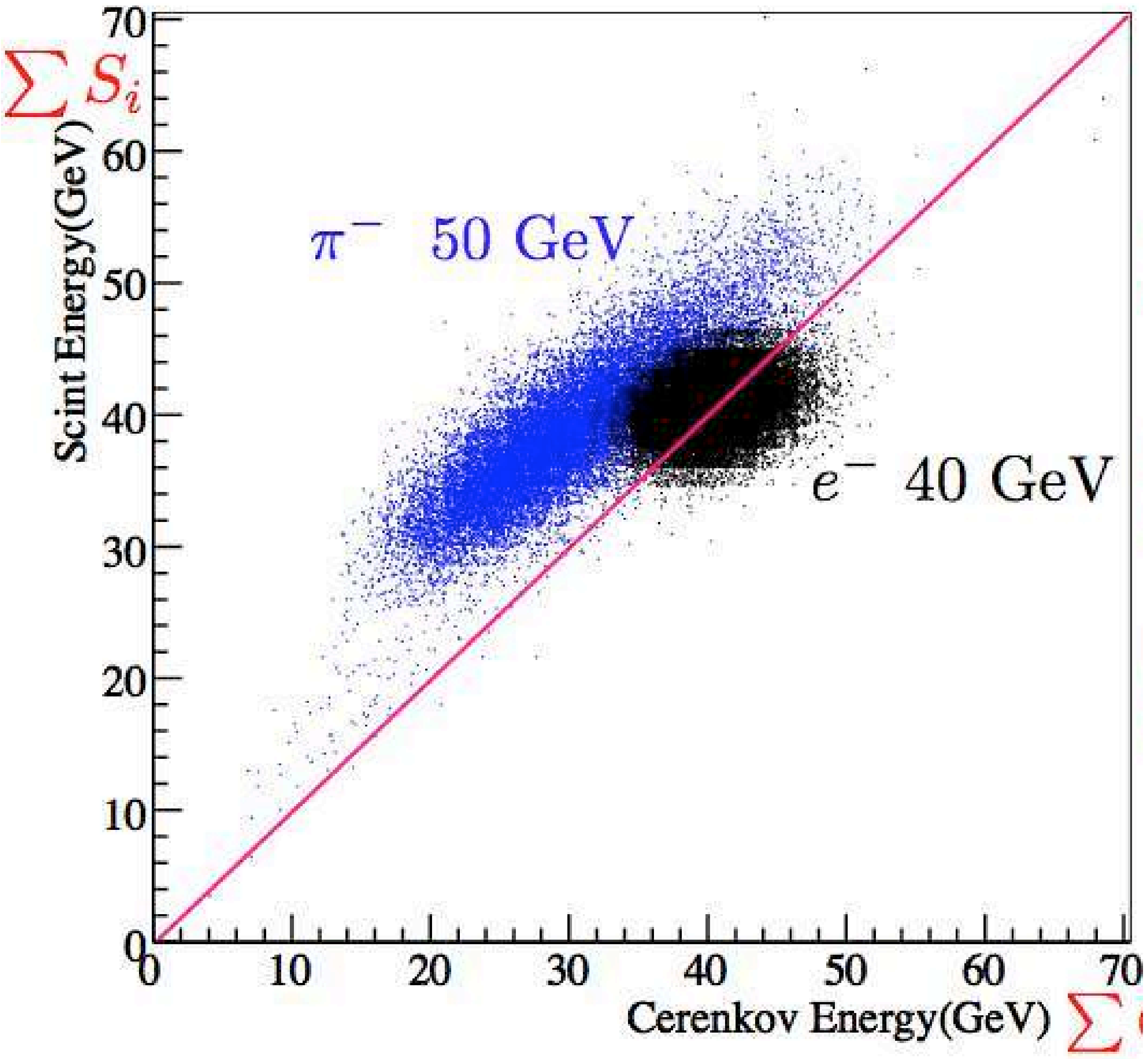
Bosons (spin $= 1\hbar$)

strong color force(QCD)	electro-magnetic force(QED)	weak force
0 (exactly) 0 e $1\hbar$ g "gluon"	0 (exactly) 0 e $1\hbar$ γ "photon"	80.40 GeV/c^2 $\pm1e$ $1\hbar$ $W^\pm$ "W boson" 91.19 GeV/c^2 0 e $1\hbar$ Z^0 "Z boson"

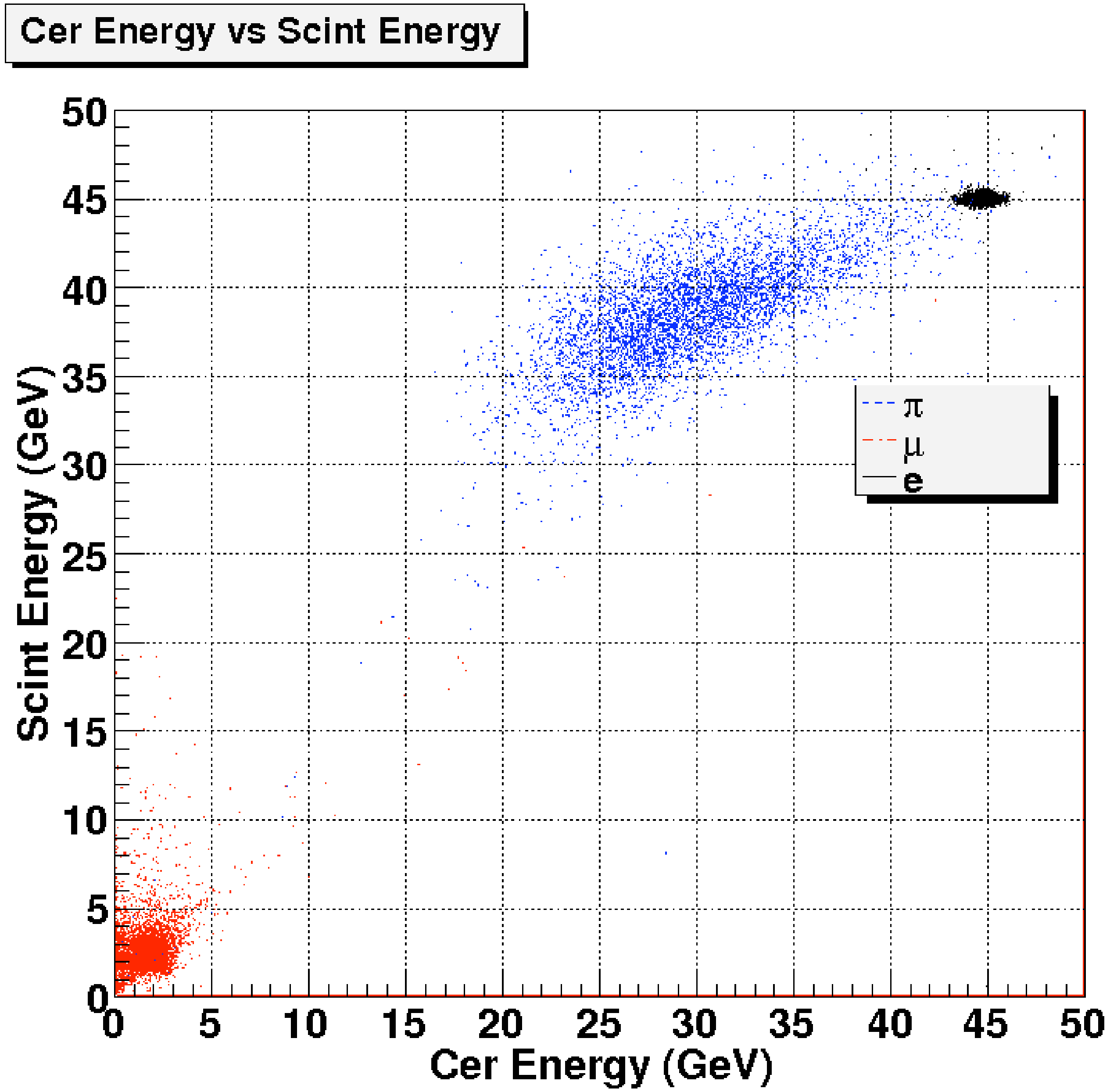
Boson force carriers

S *vs.* C → e - μ - $\pi^{\pm}$

DREAM data

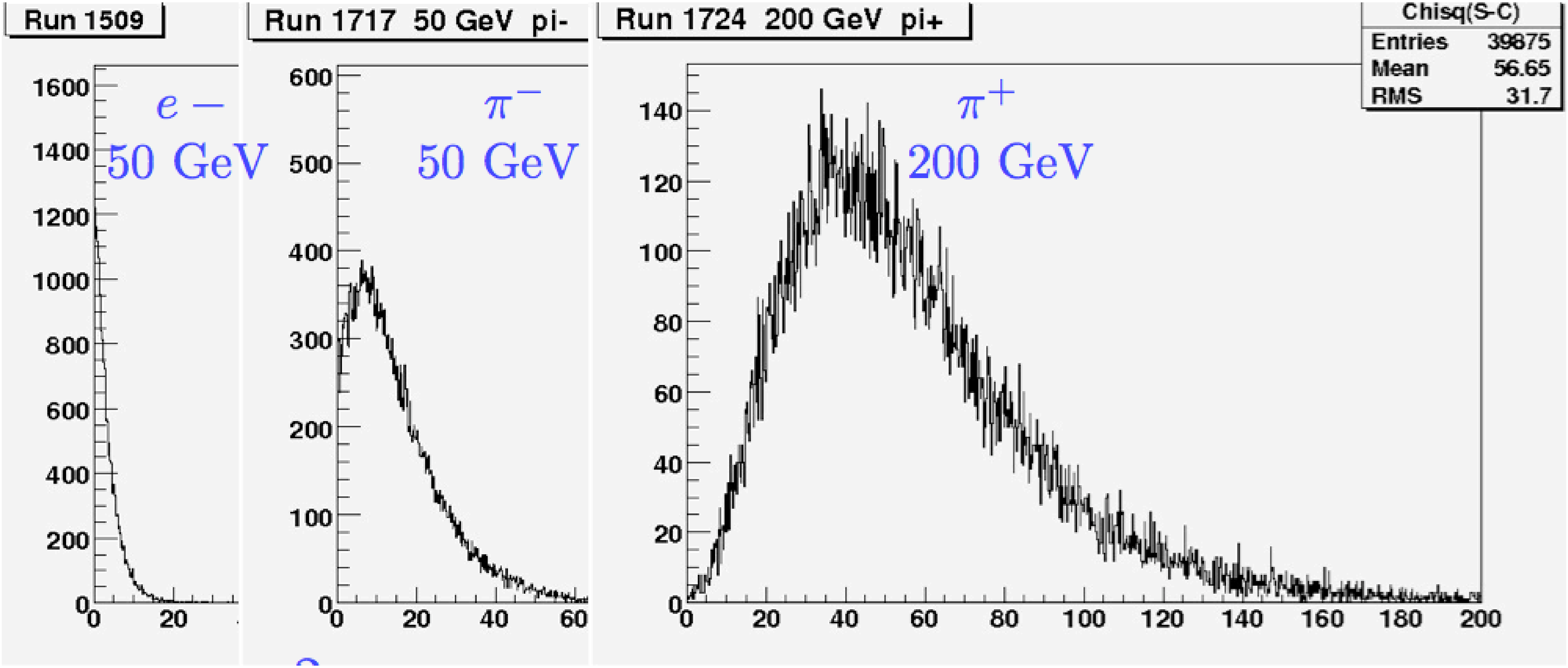


4th simulation (45 GeV)



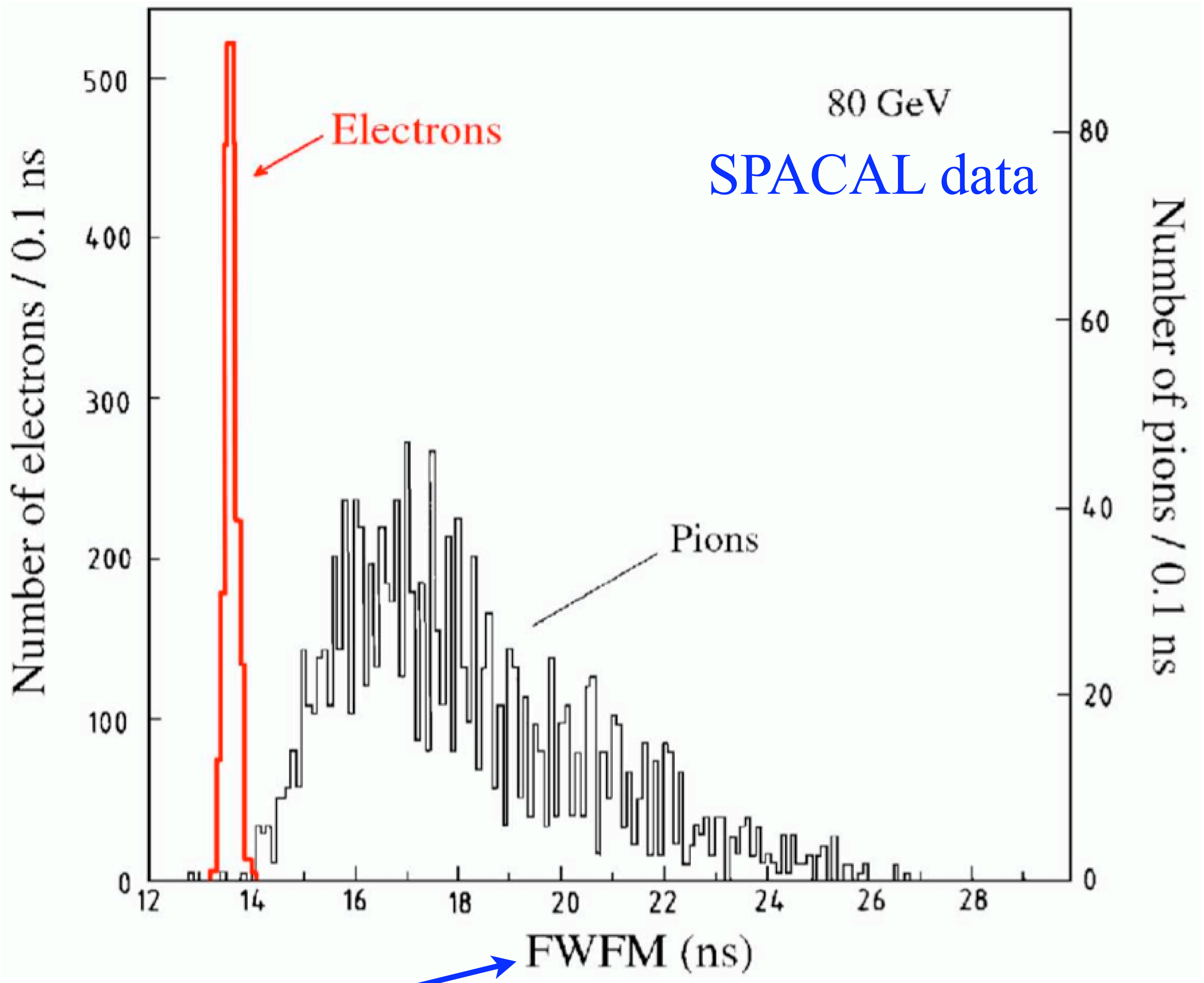
Fluctuations in *(S-C) among the channels of a shower* → *EM-hadron*

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



Time-history S(t) scintillating fibers

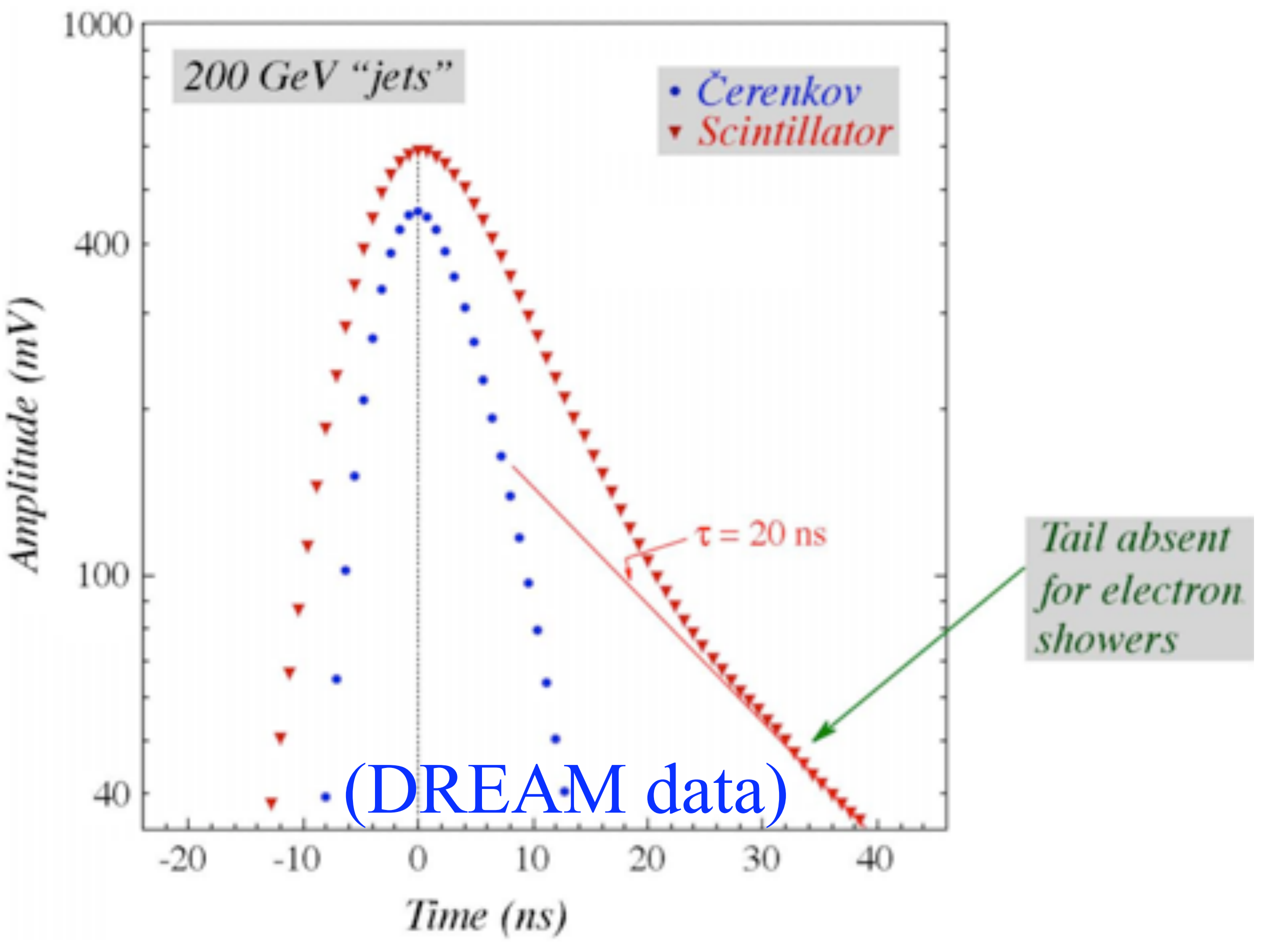
→ *e/γ - $\pi^{\pm}$/hadrons*



duration of pulse above 1/5-maximum

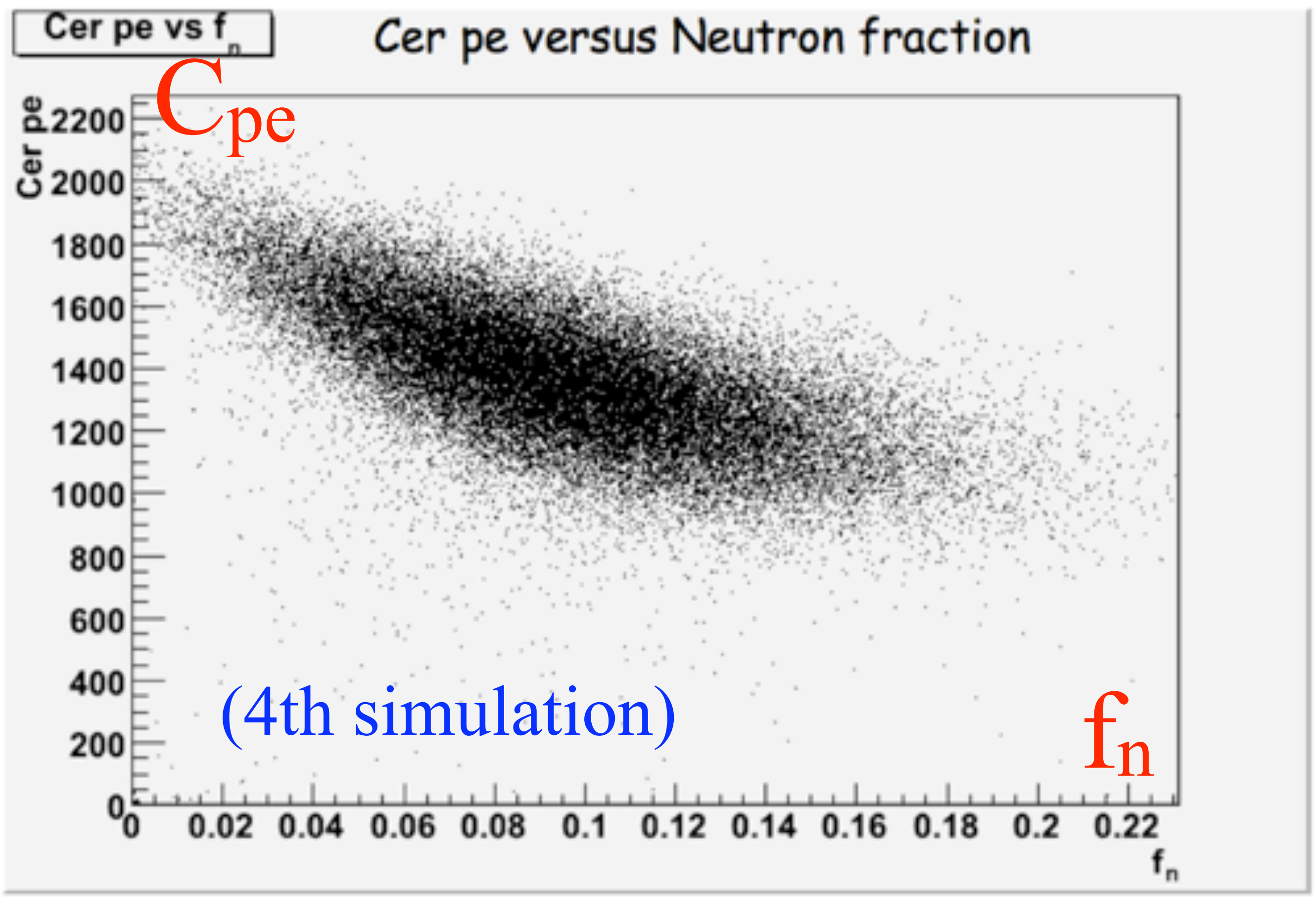
Time-history S(t) scintillating fibers

- MeV neutrons, and neutron fraction, f_n
- improve energy resolution, and ID “hadronic” showers

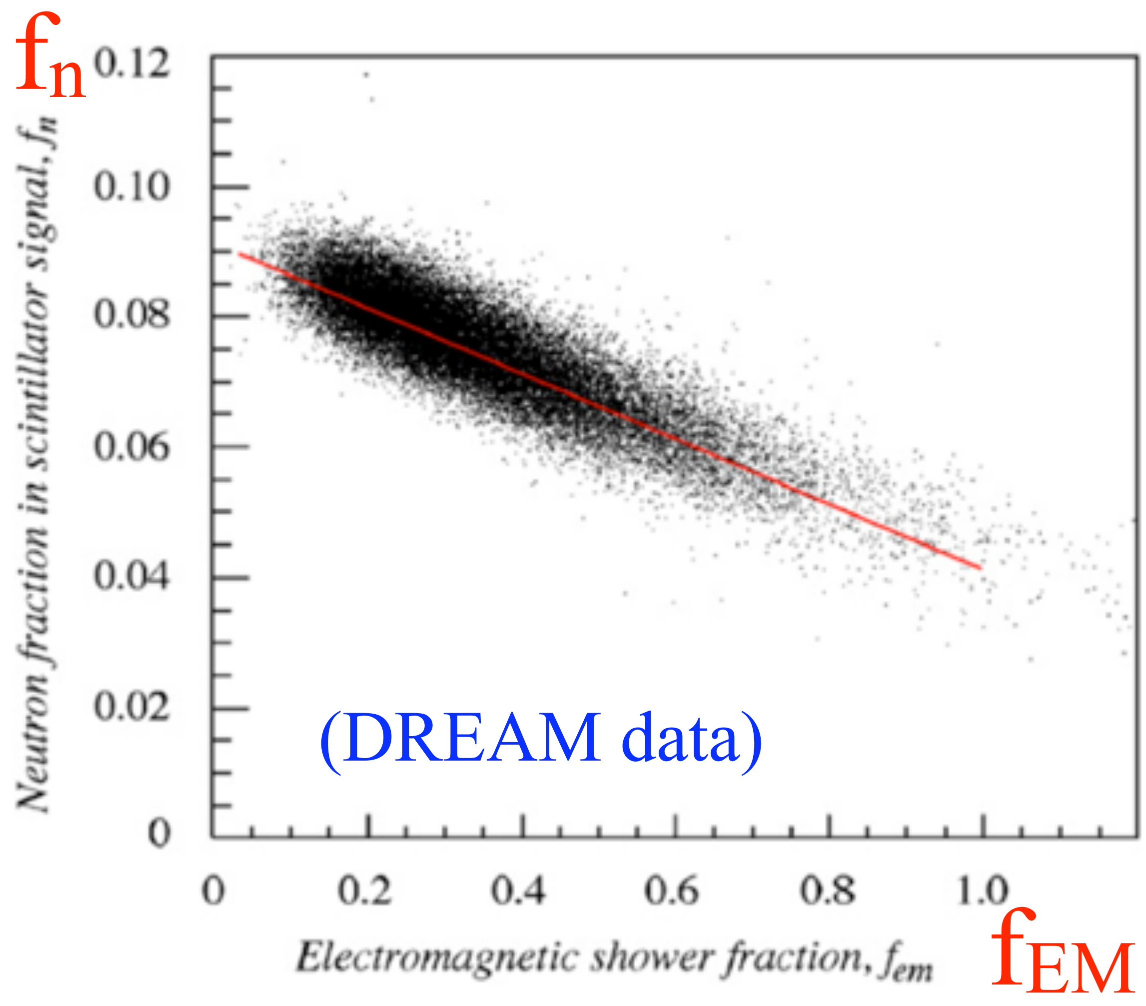


Tail absent for electron showers

(DREAM data)



(4th simulation)

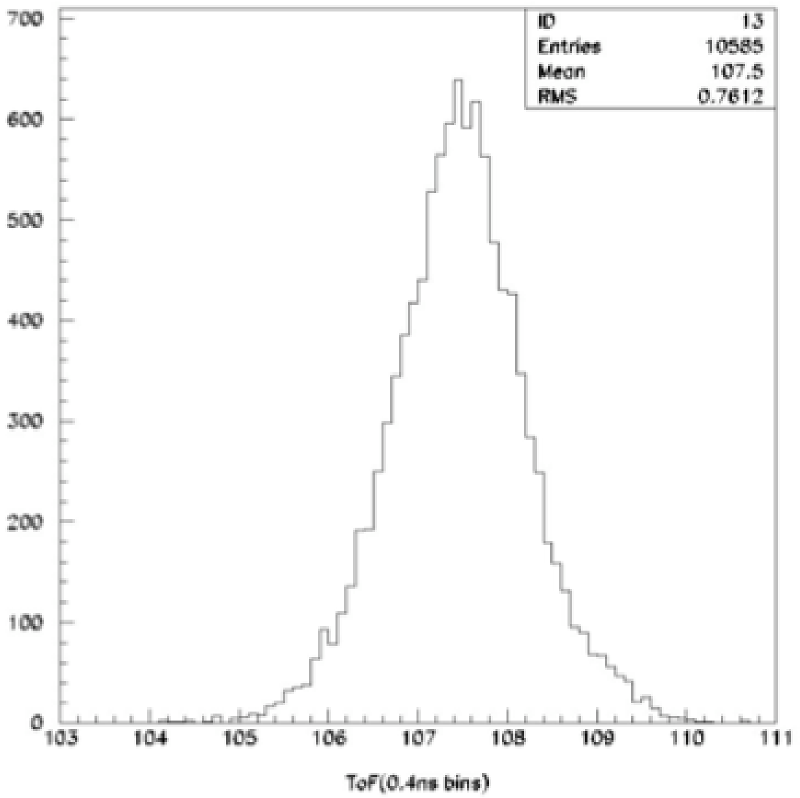


(DREAM data)

Time-of-flight

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

DREAM data

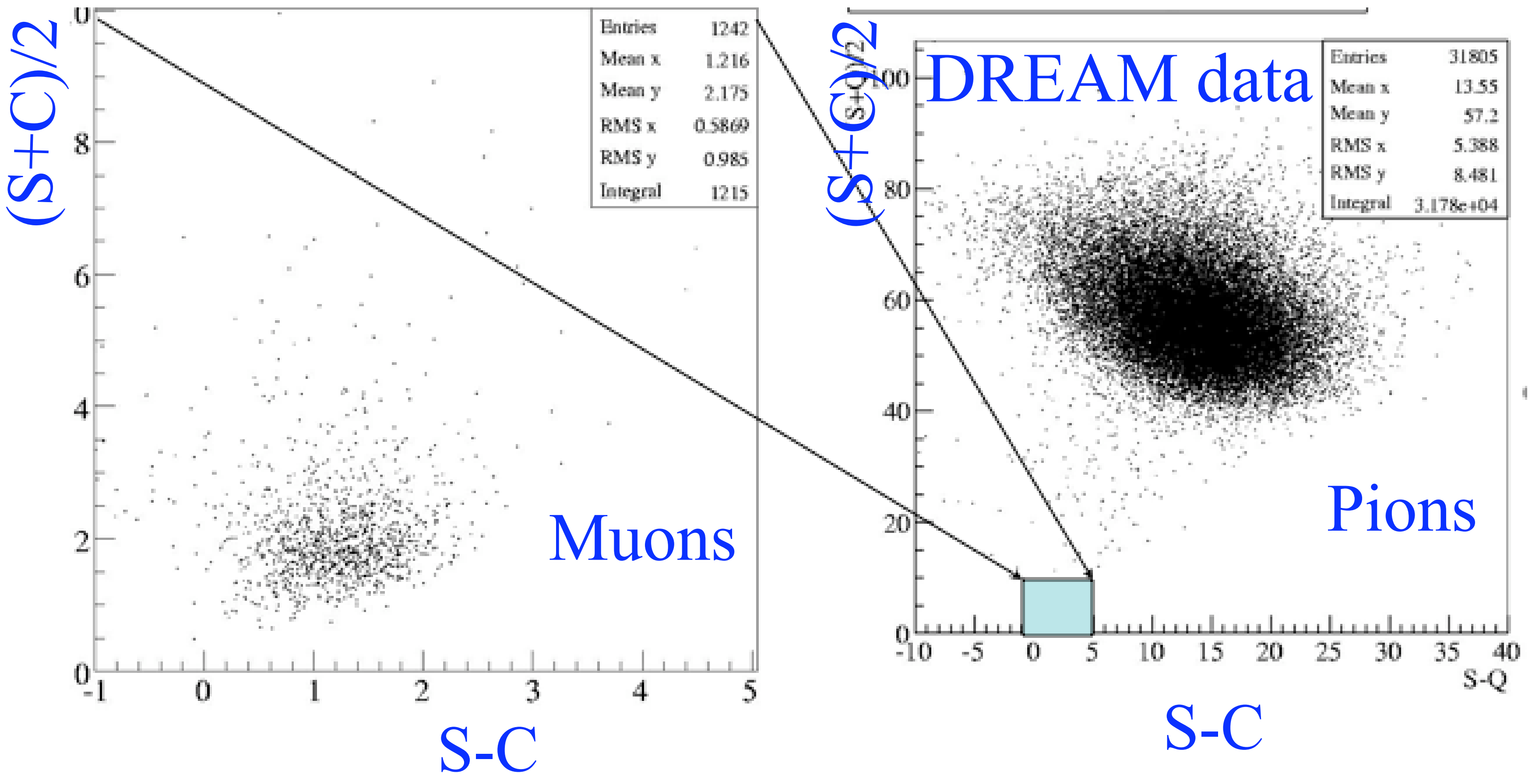


t (0.4 ns bins)

Muon tagging

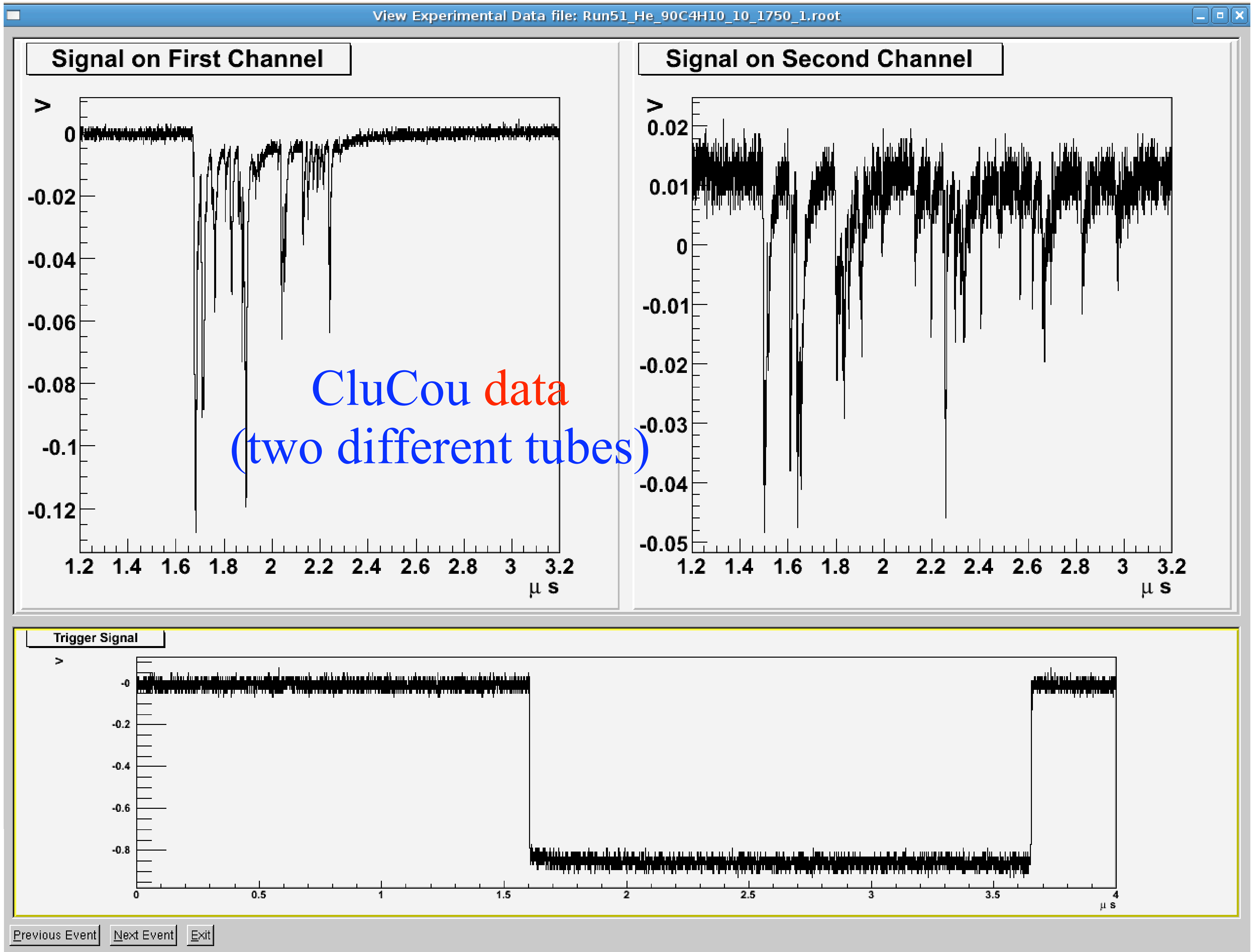
S-C ~ *dE/dx* (muons)

$(S+C)/2 \sim E_{brems}$

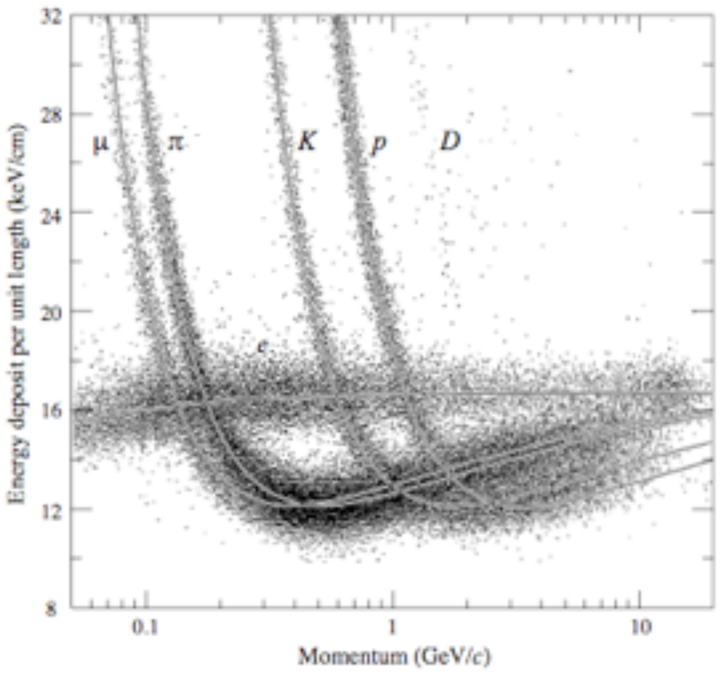


Cluster-timing

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



CluCou data
(two different tubes)

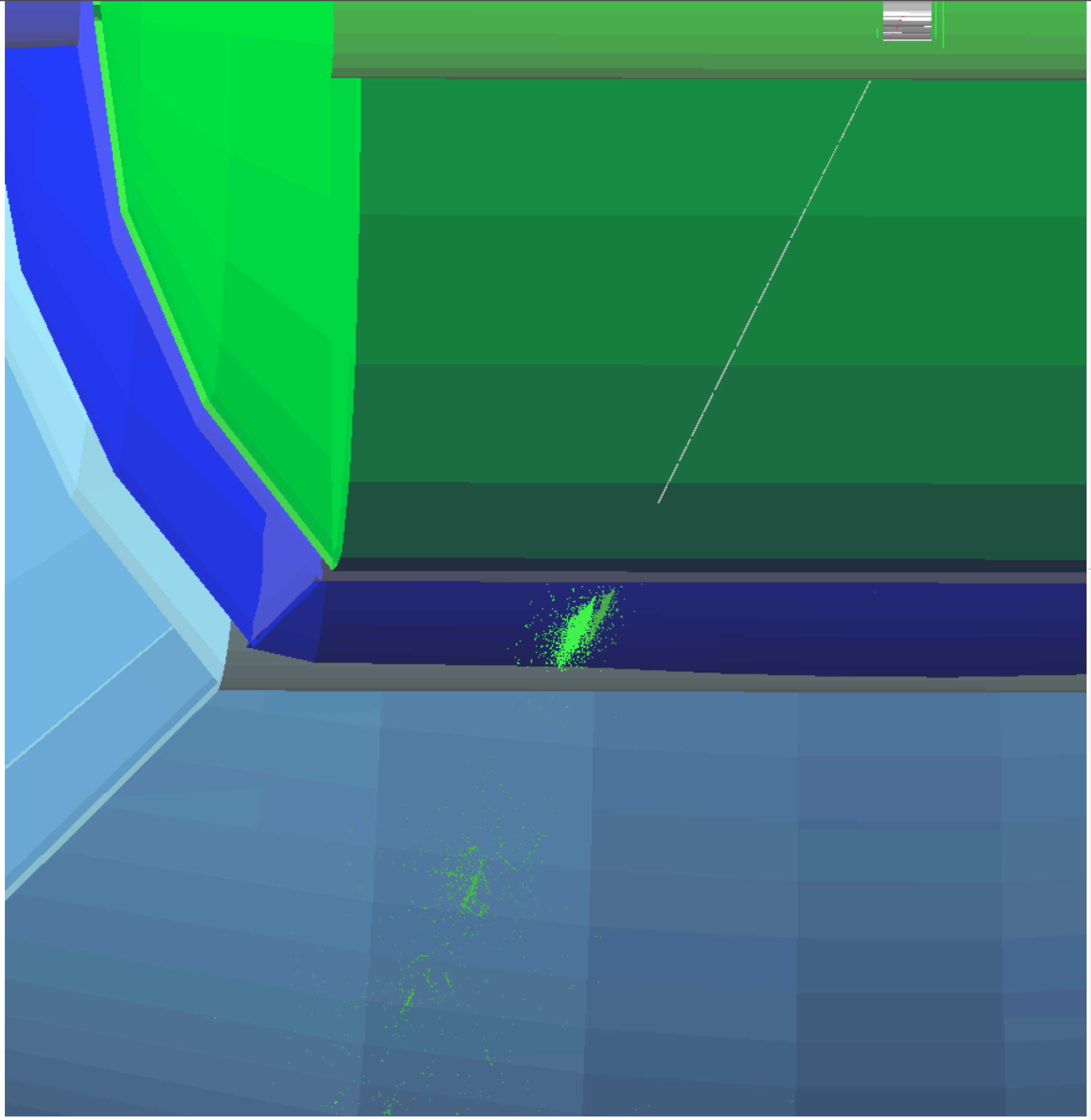


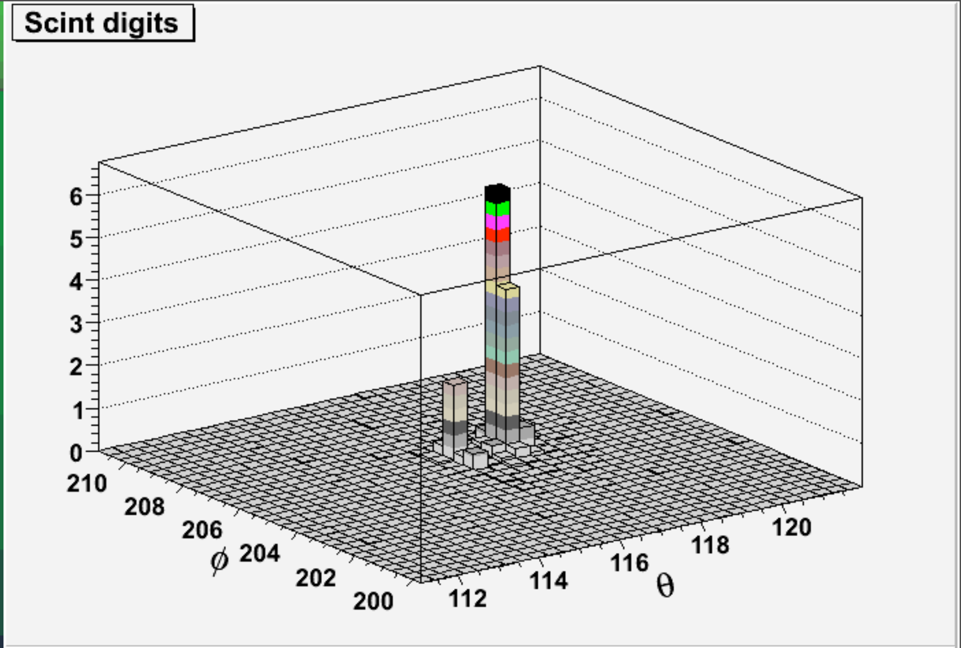
dE/dx resolution TPC LBL/PEP4 (data using truncated mean, resolution~6%)

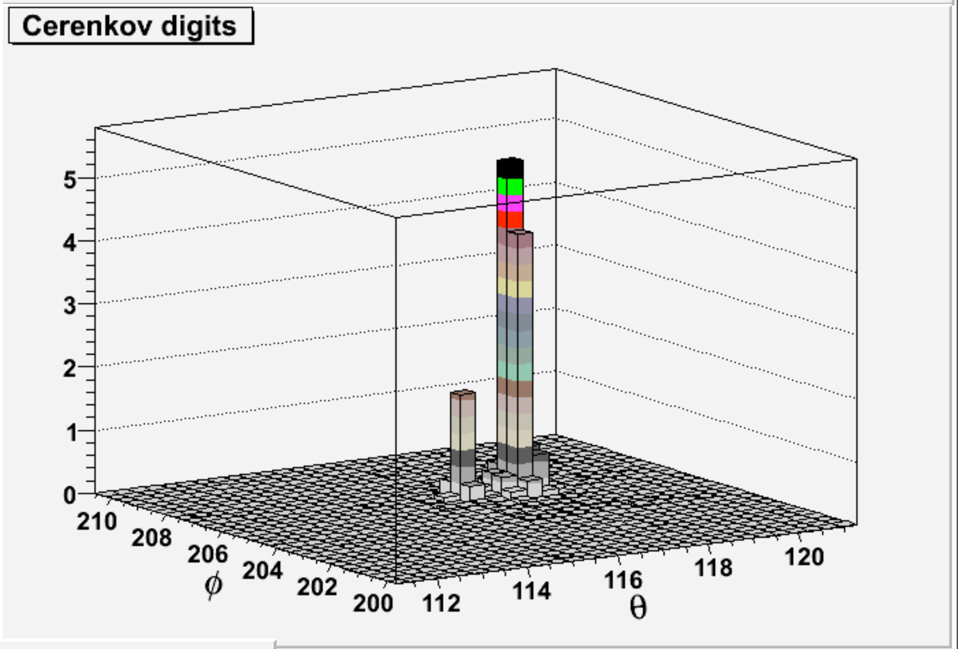
$\tau^{\pm}$ ID

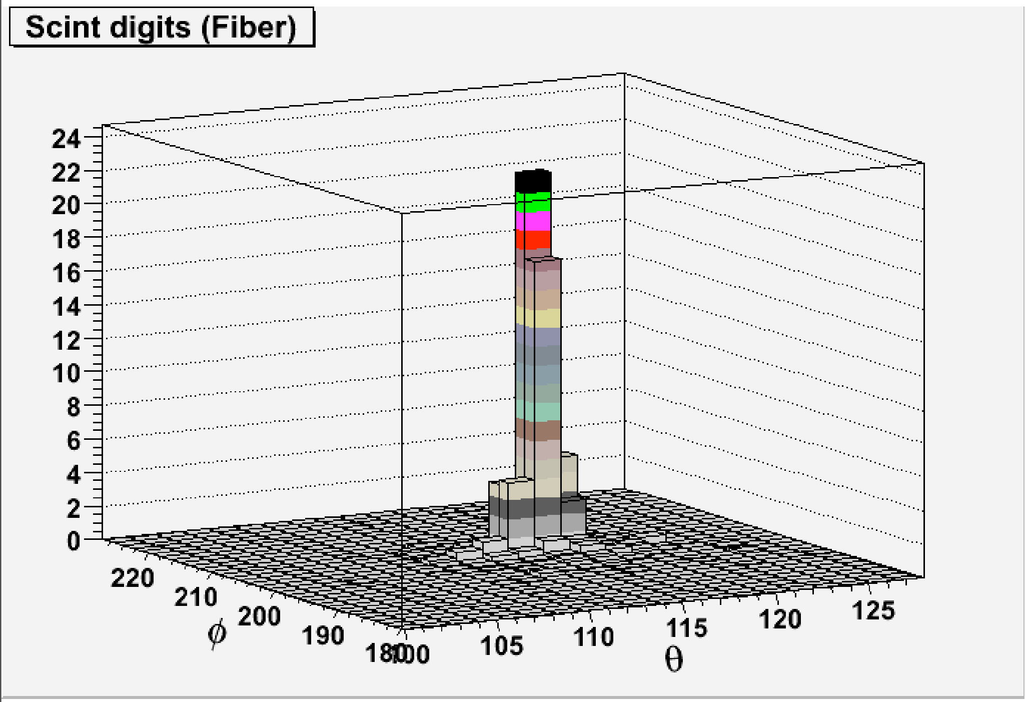
(for polarization)

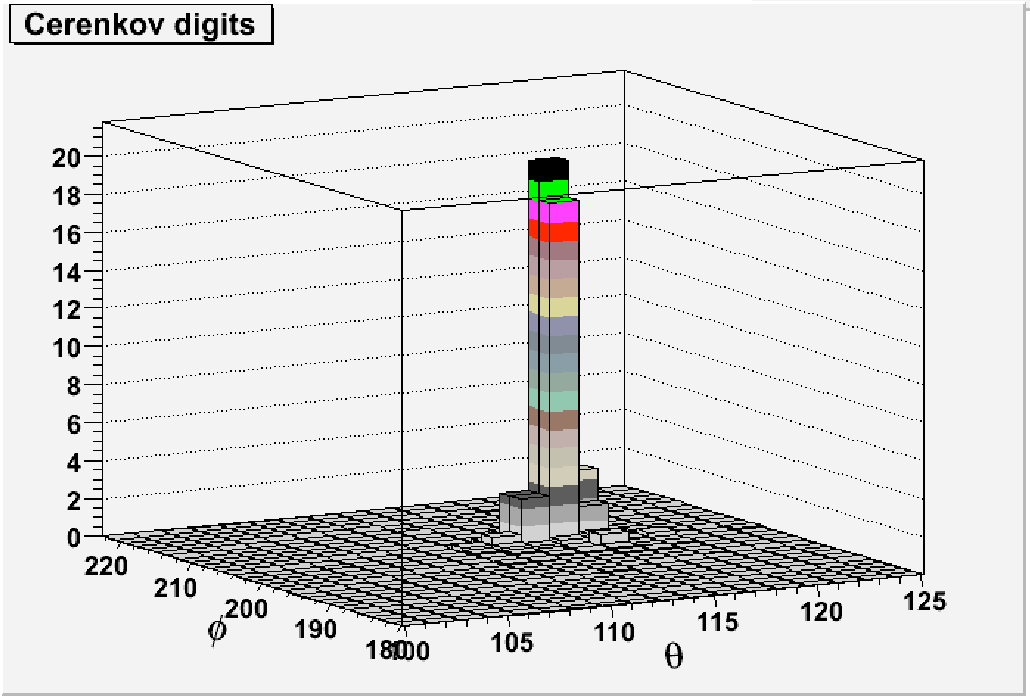
$$\tau^- \to \rho^- \nu$$
$$\to \pi^- \pi^0$$
$$\to \pi^- \gamma\gamma$$





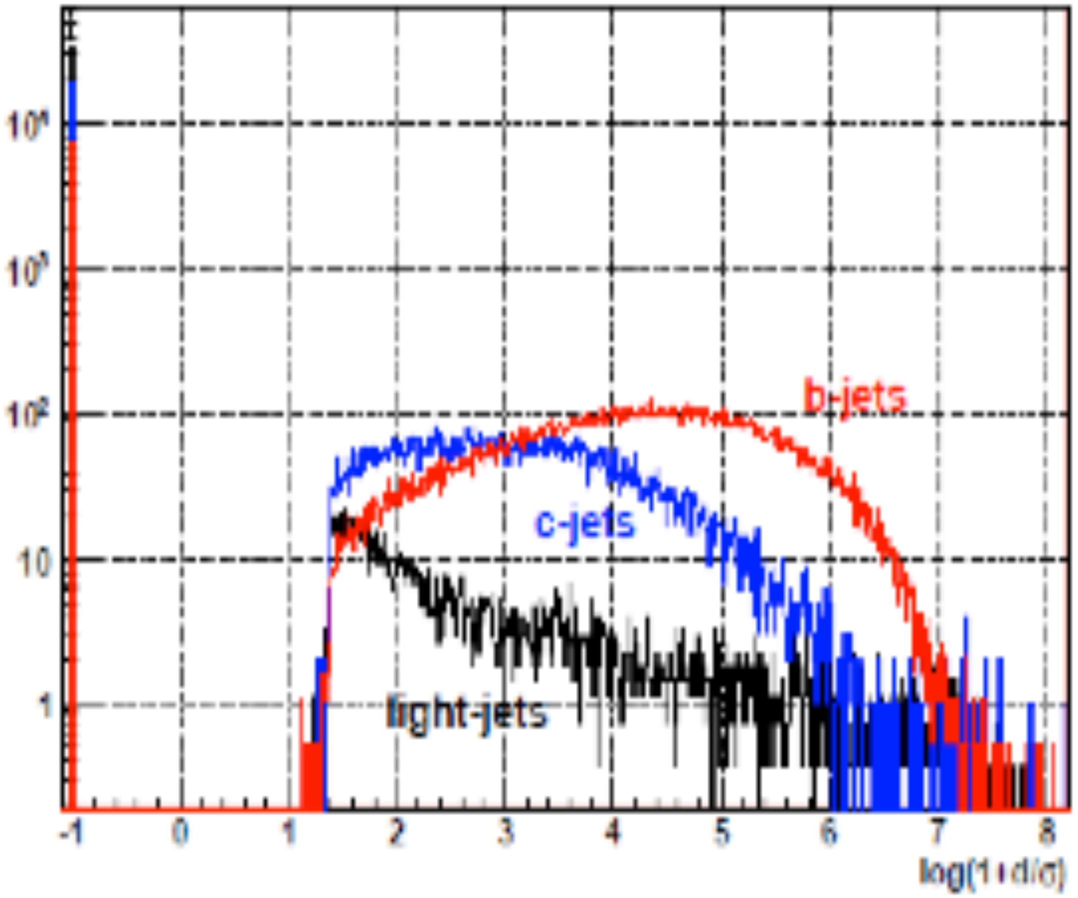




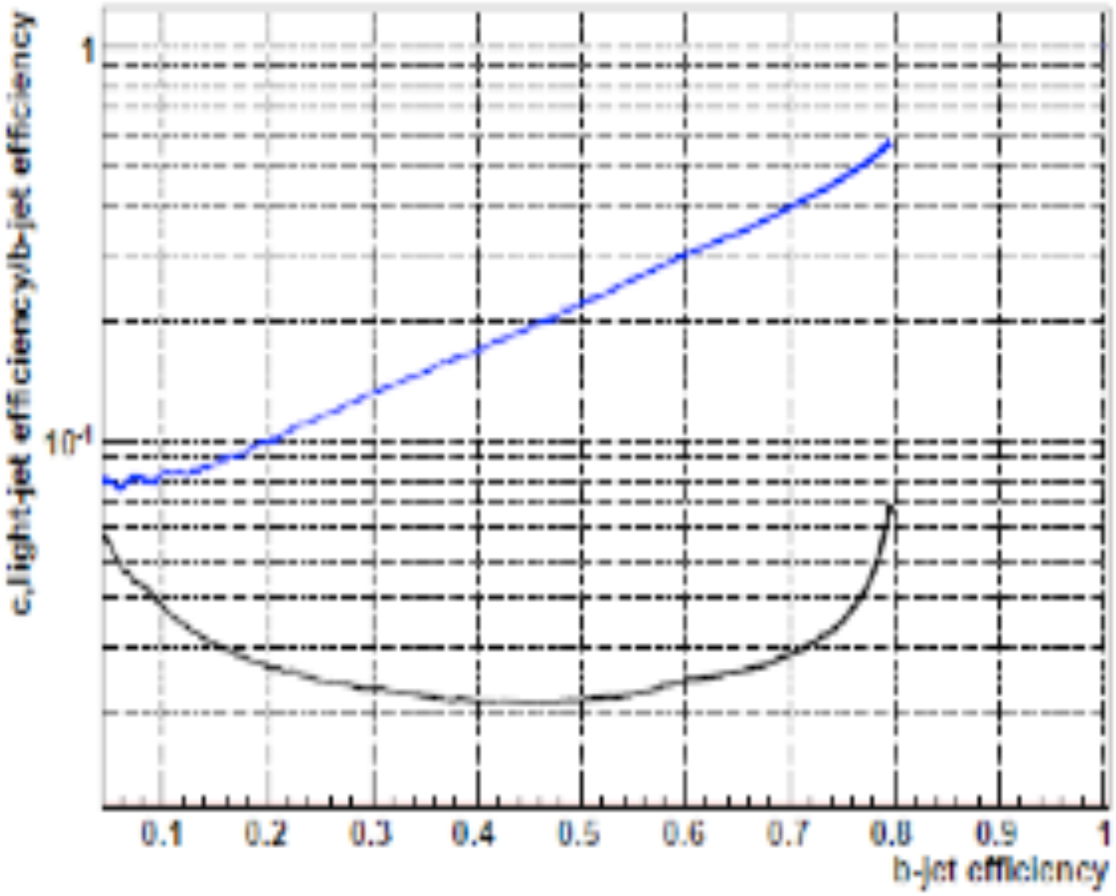


b,c quark tagging

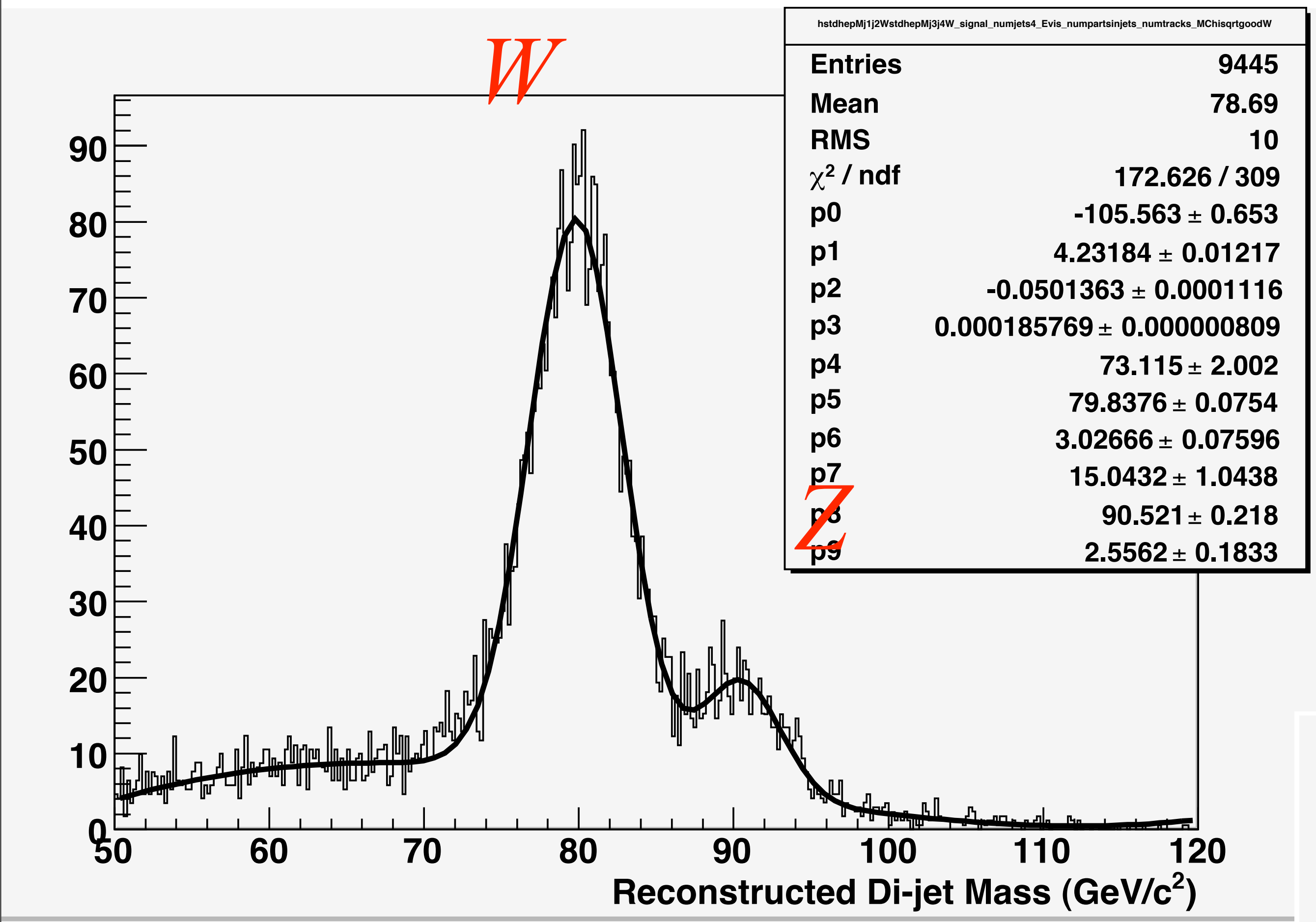
(by lifetime of B,D mesons)

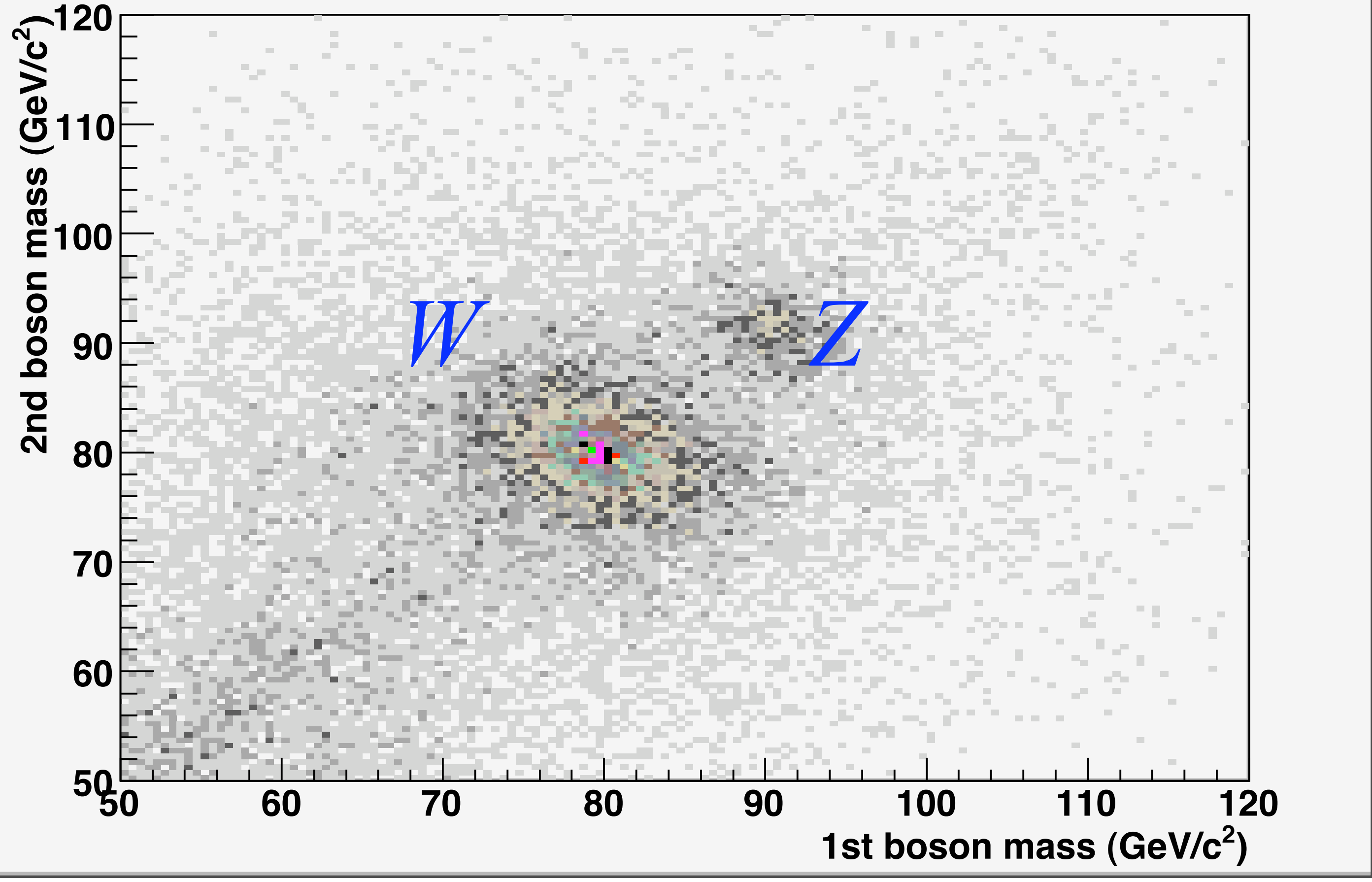


vertex impact parameter



W and Z mass measurement and discrimination

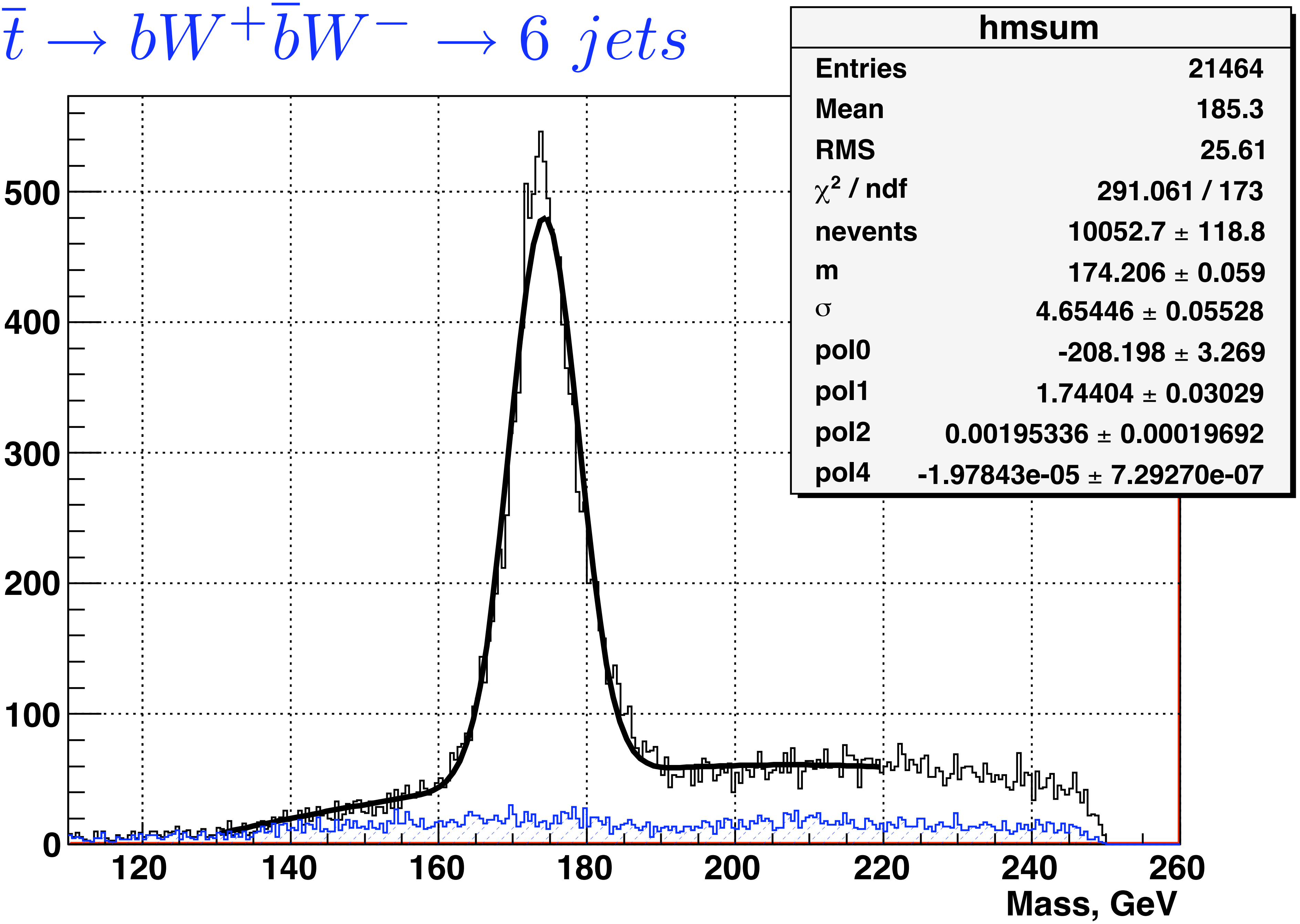




From the SUSY pt. 5 analysis
by Anna Mazzacane

top quark (all hadronic channel)

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



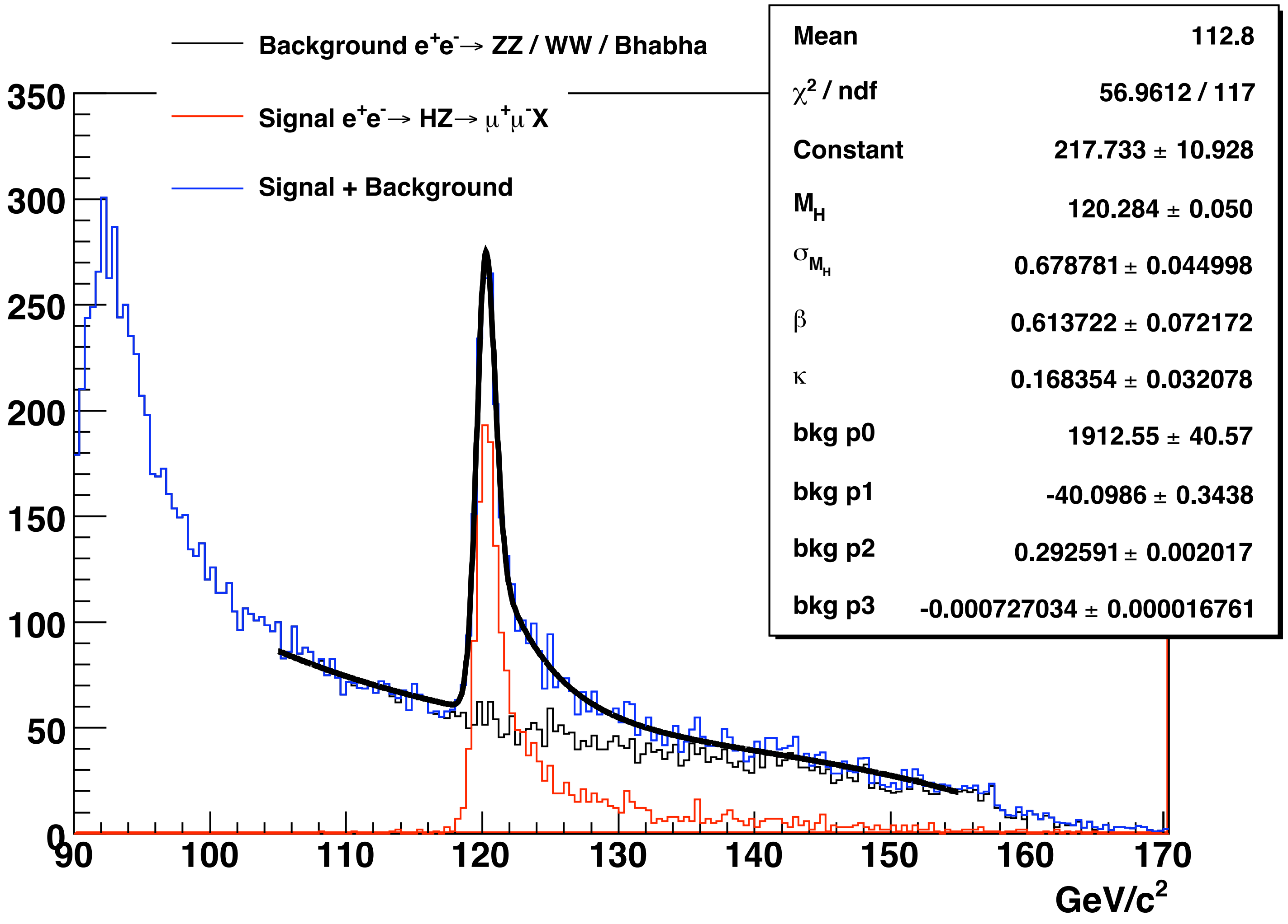
Fedor Ignatov (Budker Institute, Novosibirsk)

Physics processes

Flagship physics process: putative Higgs production

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

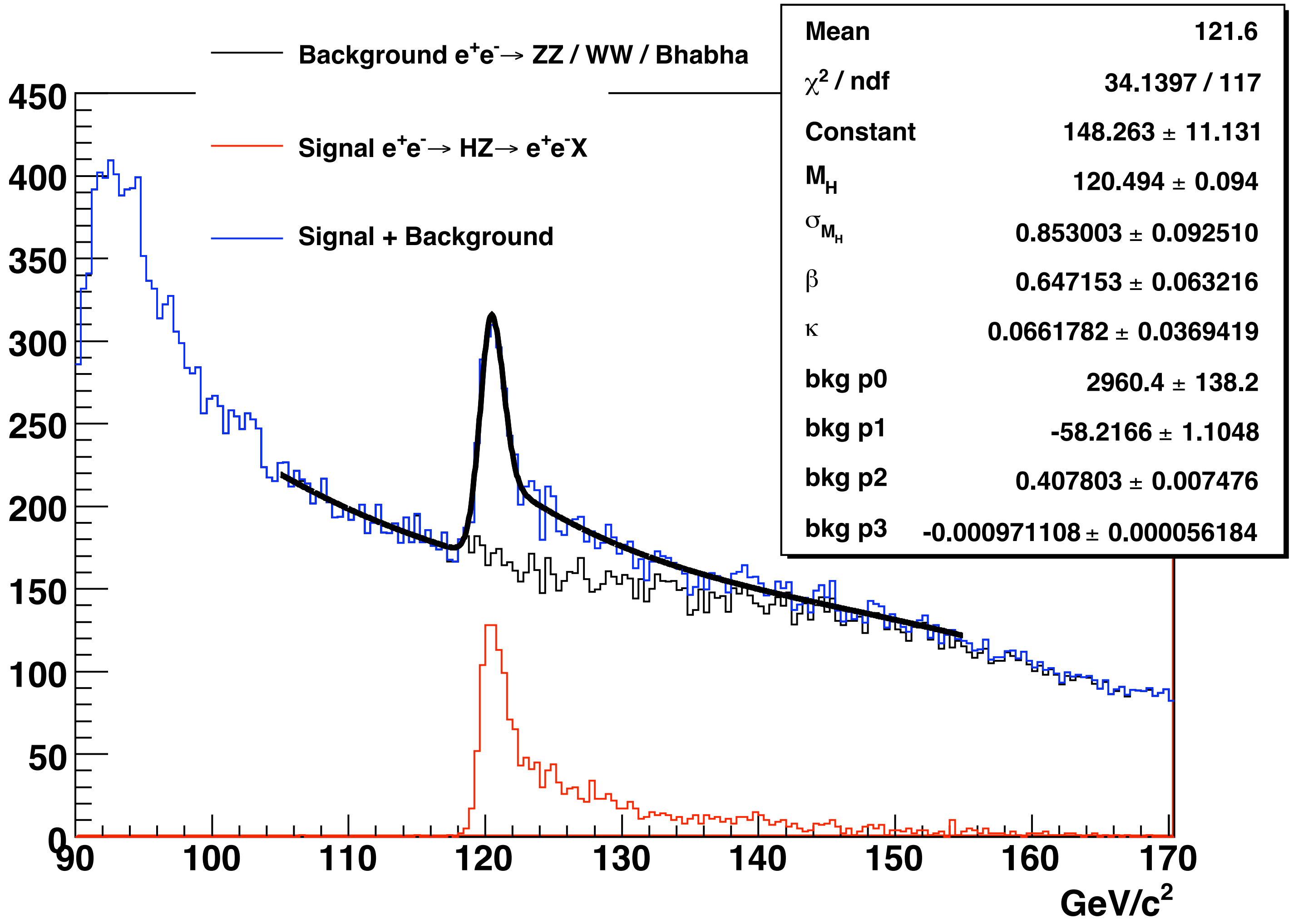
$\mu^+\mu^-$



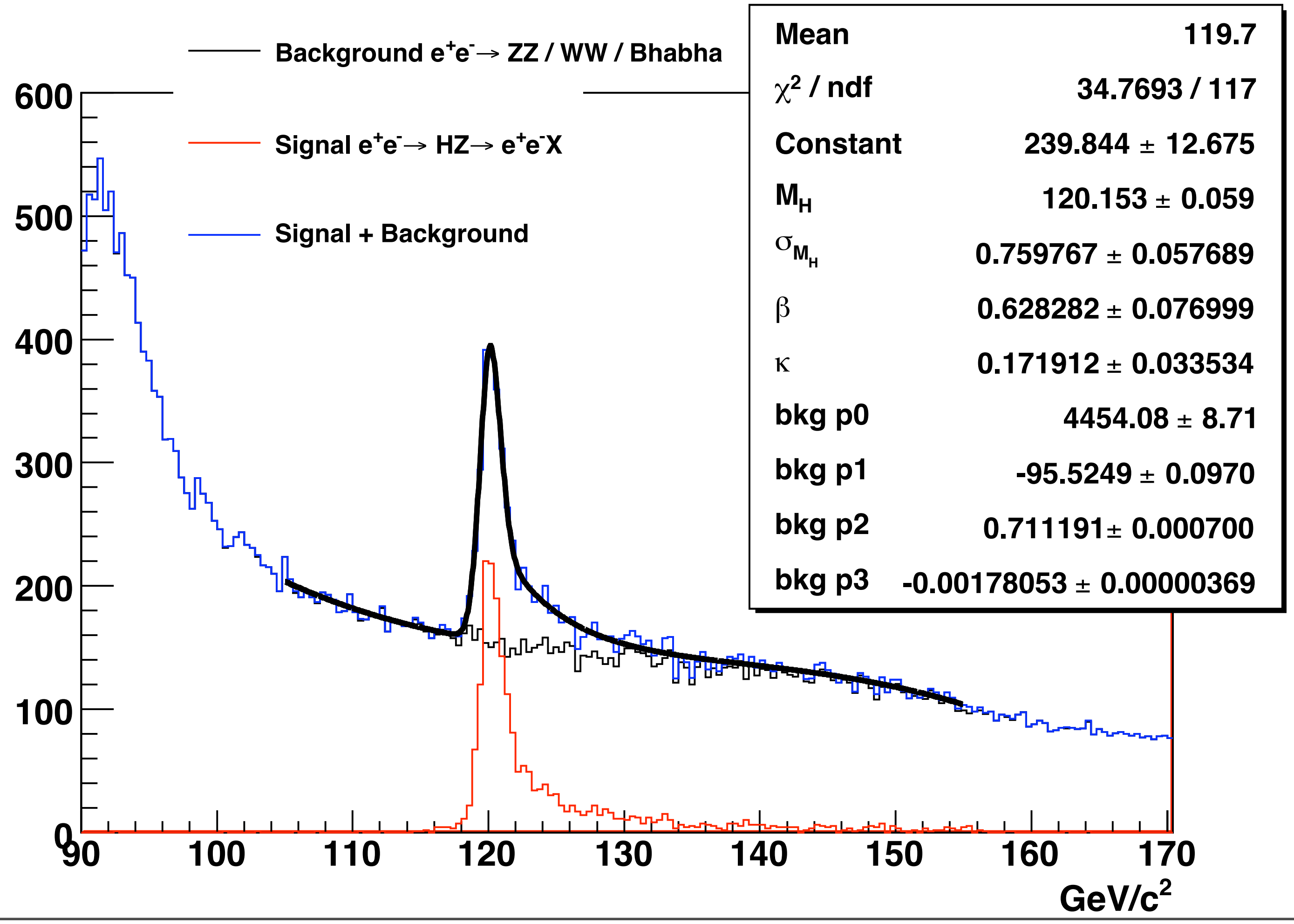
Mean	112.8
χ^2 / ndf	56.9612 / 117
Constant	217.733 ± 10.928
M_H	120.284 ± 0.050
σ_{M_H}	0.678781 ± 0.044998
β	0.613722 ± 0.072172
κ	0.168354 ± 0.032078
bkg p0	1912.55 ± 40.57
bkg p1	-40.0986 ± 0.3438
bkg p2	0.292591 ± 0.002017
bkg p3	-0.000727034 ± 0.000016761

Mass of X →

e^+e^-
(using tracking only)



e^+e^-
(tracking and calorimetry)



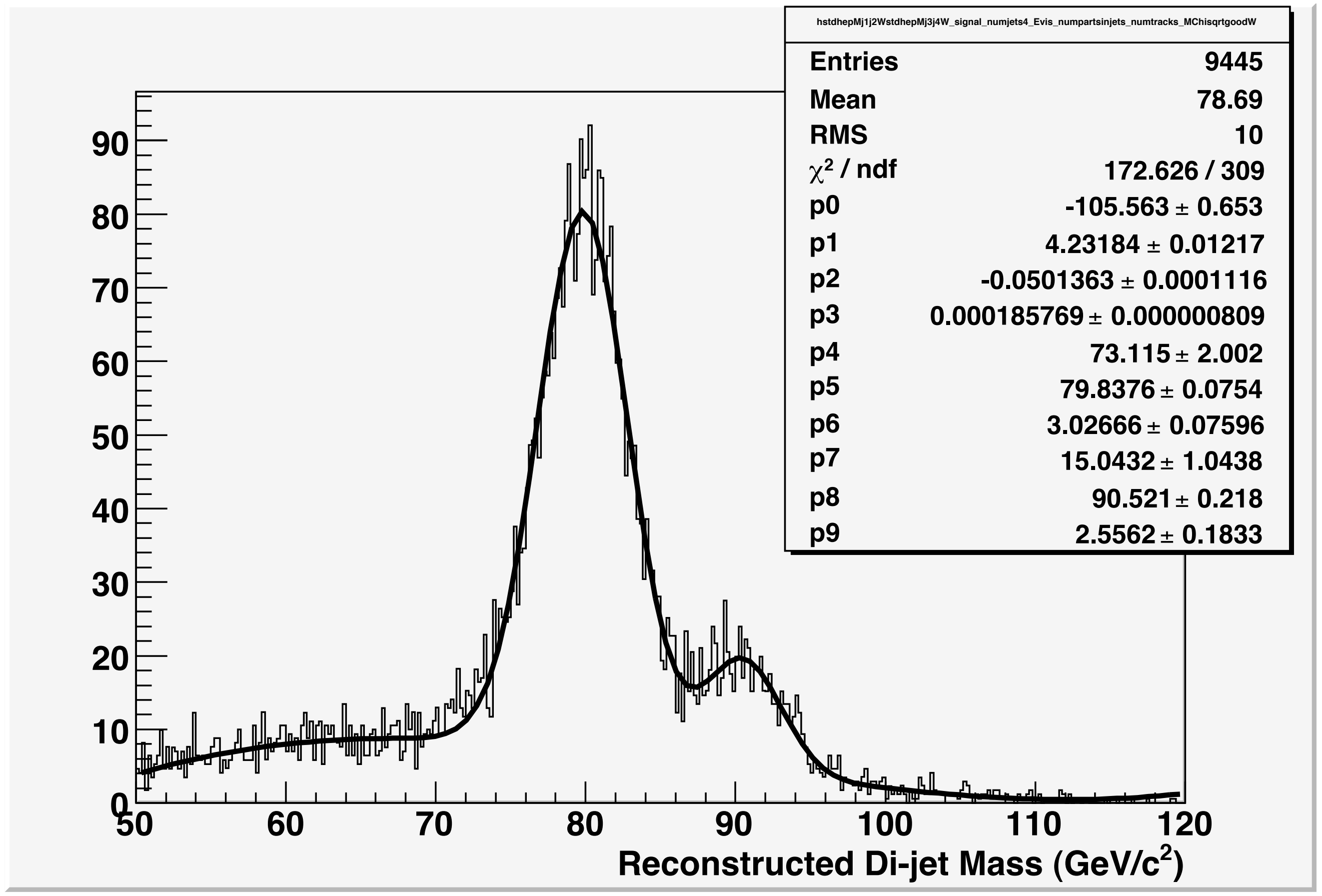
SUSY (supersymmetry):

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

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

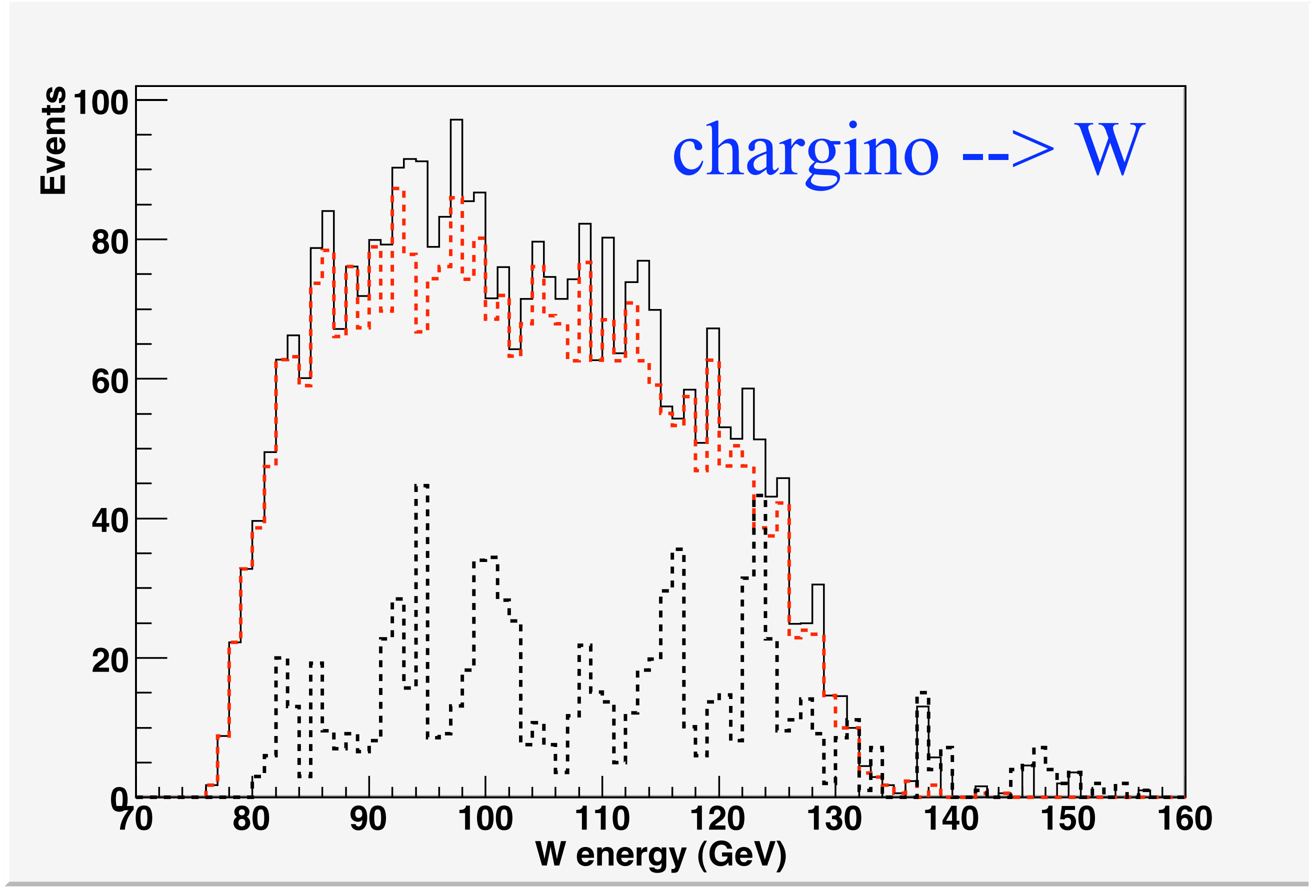
chargino σ_M ~ 2.8 GeV/c^2

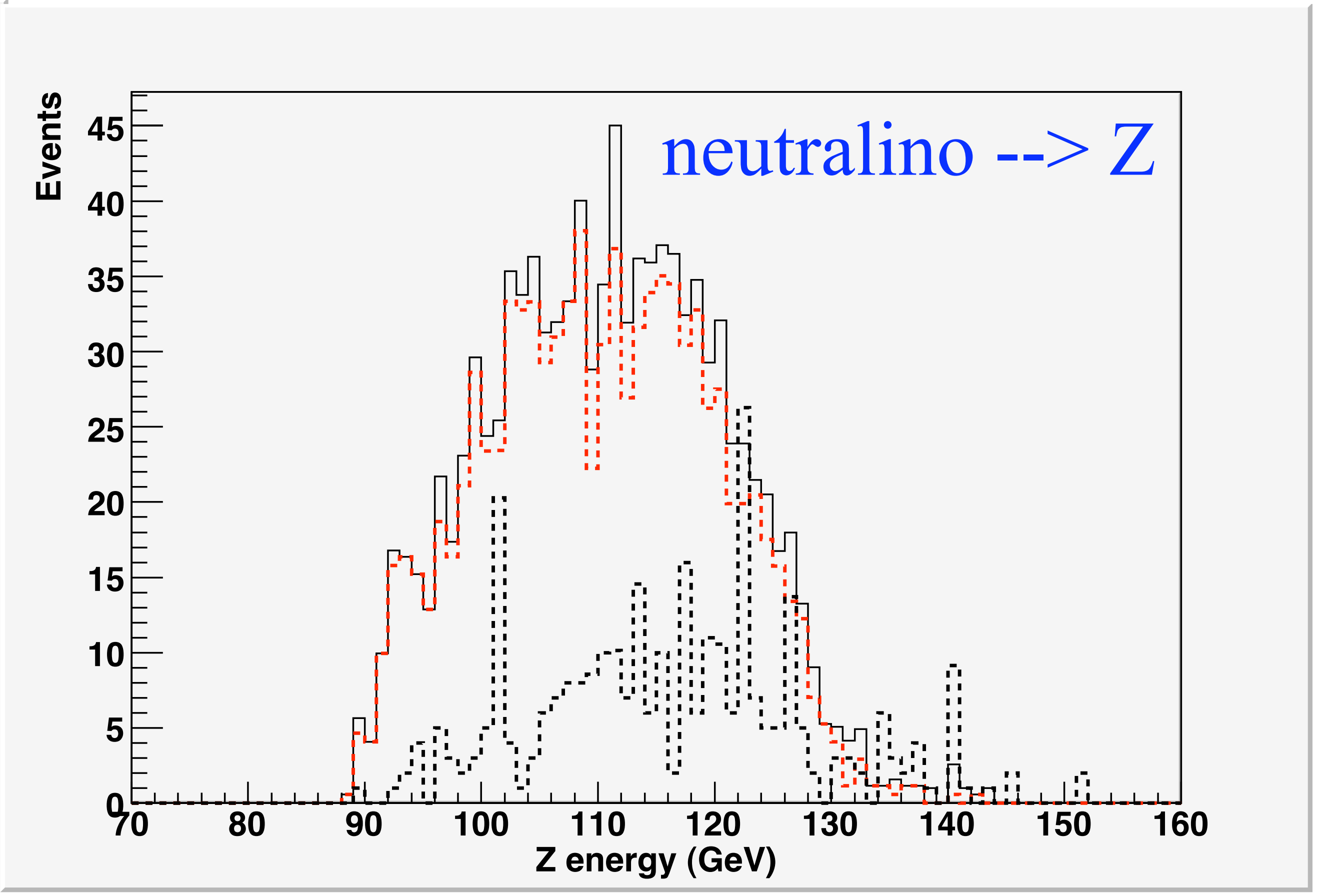
neutralino σ_M ~ 2.5 GeV/c^2



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

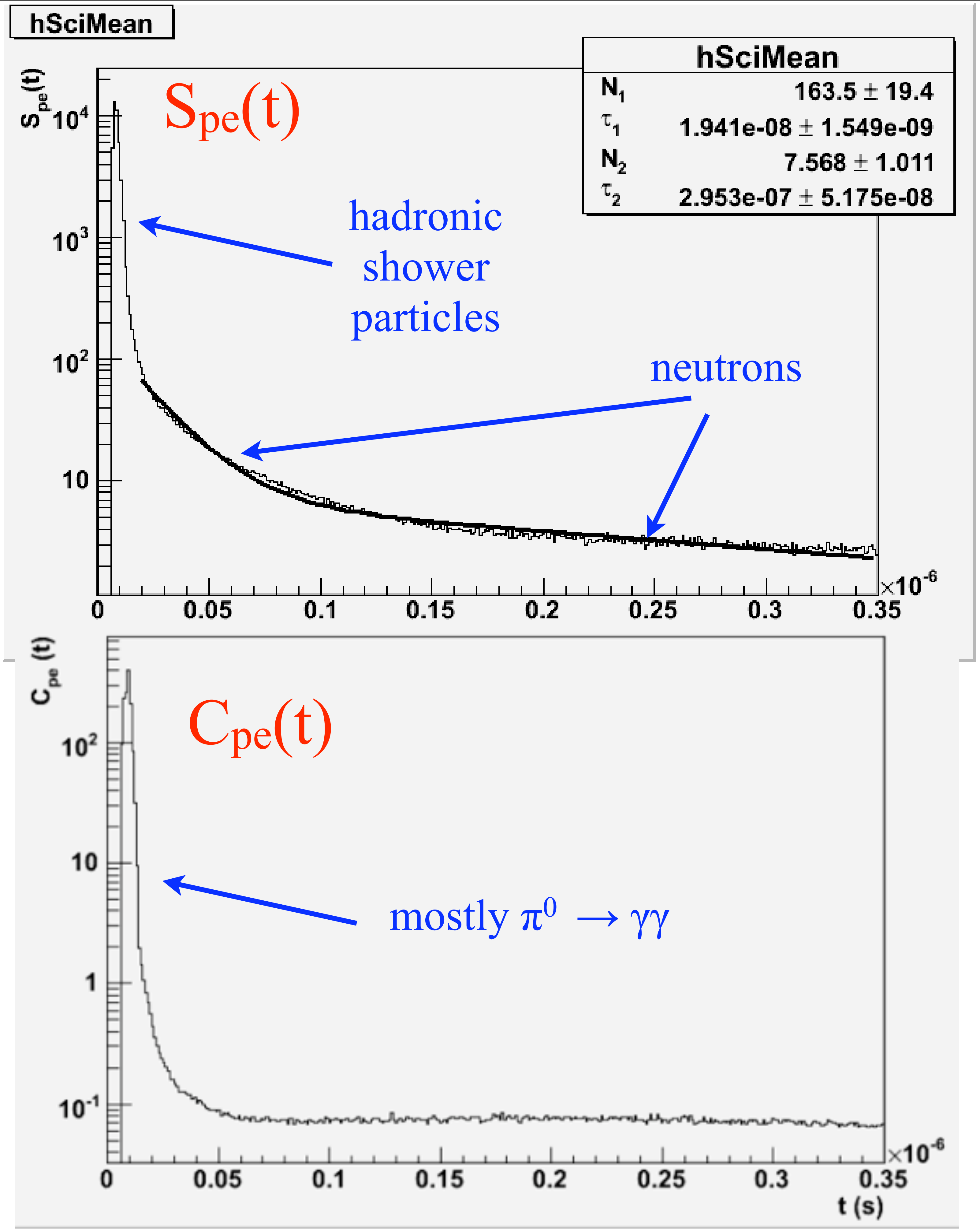




Bethe-Heitler background rejection
(in time domain)

Time-history of scintillating fibers: 1-5 GHz

(DRS4, Grancagnolo ASIC)



$S_{pe}(t)$

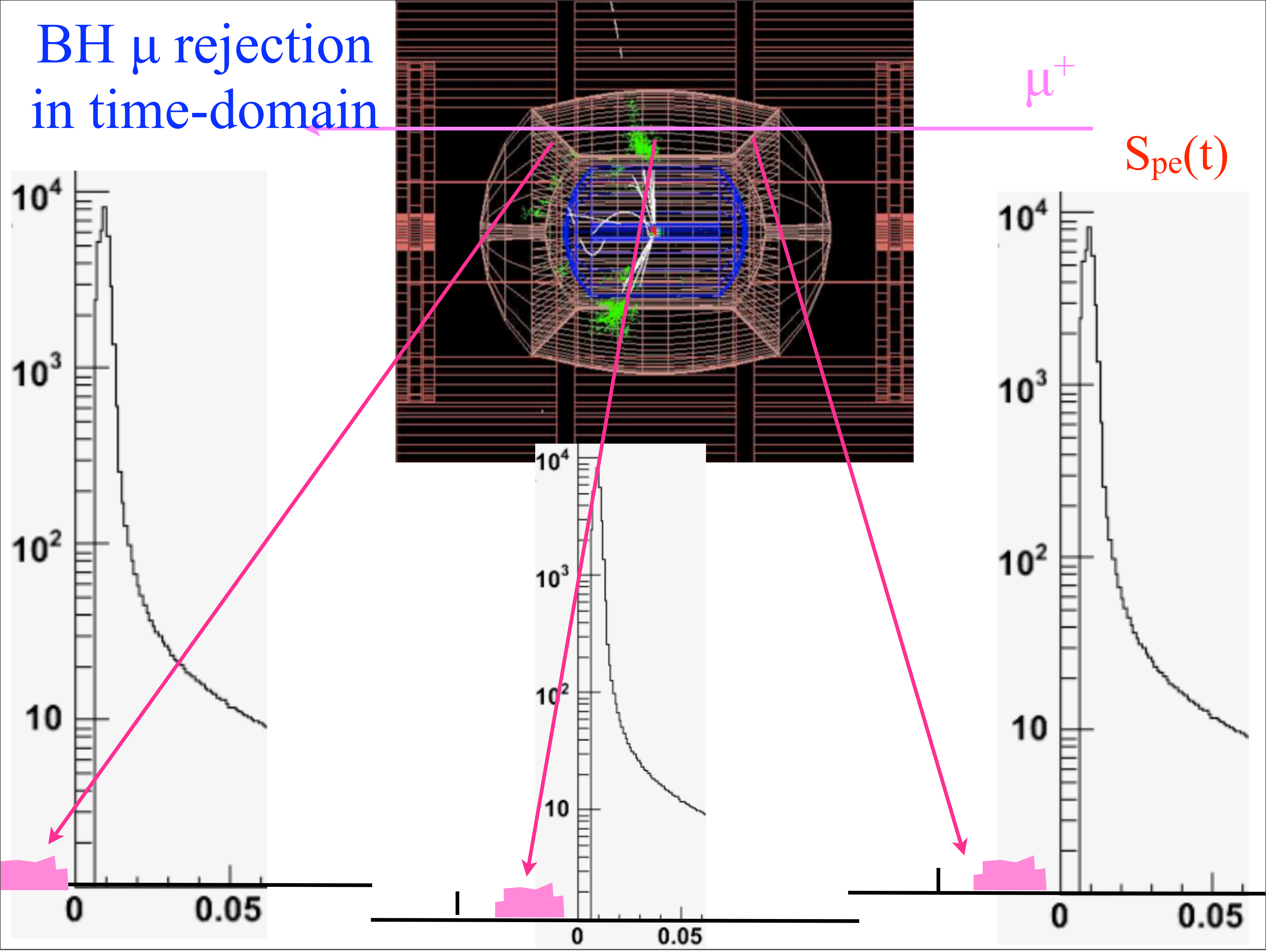
hadronic shower particles

neutrons

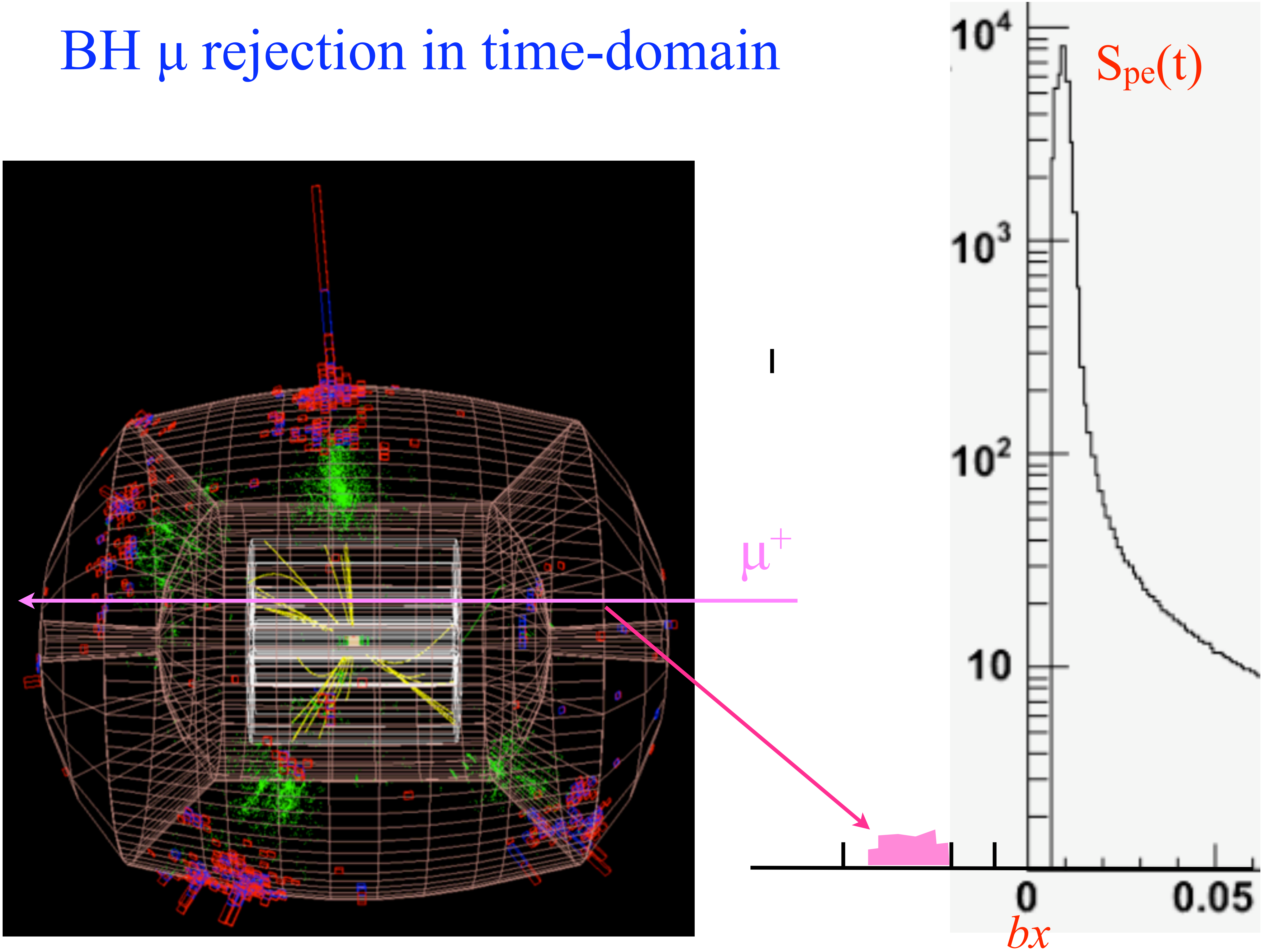
$C_{pe}(t)$

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

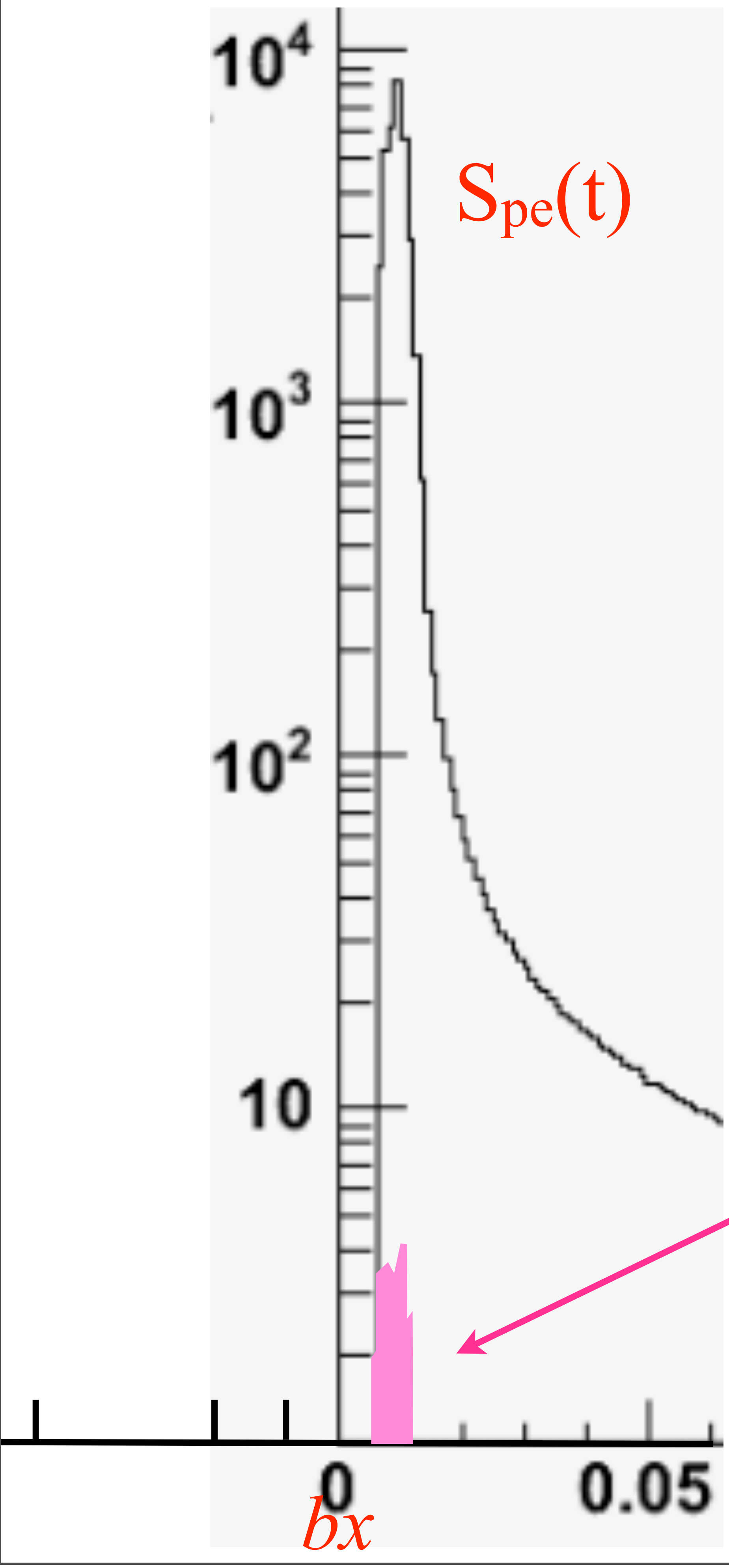
BH μ rejection in time-domain

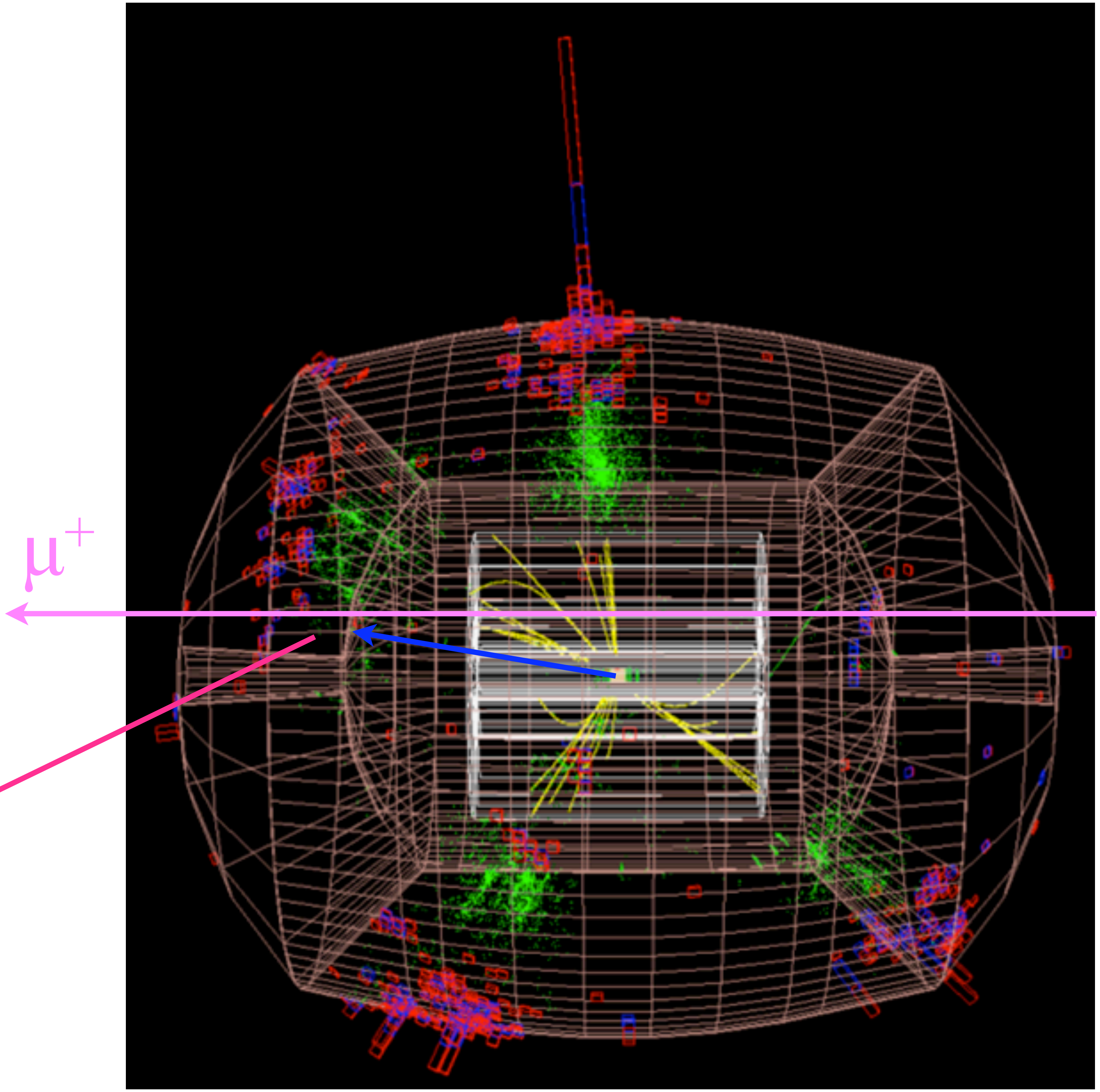


BH μ rejection in time-domain



BH μ rejection in time-domain

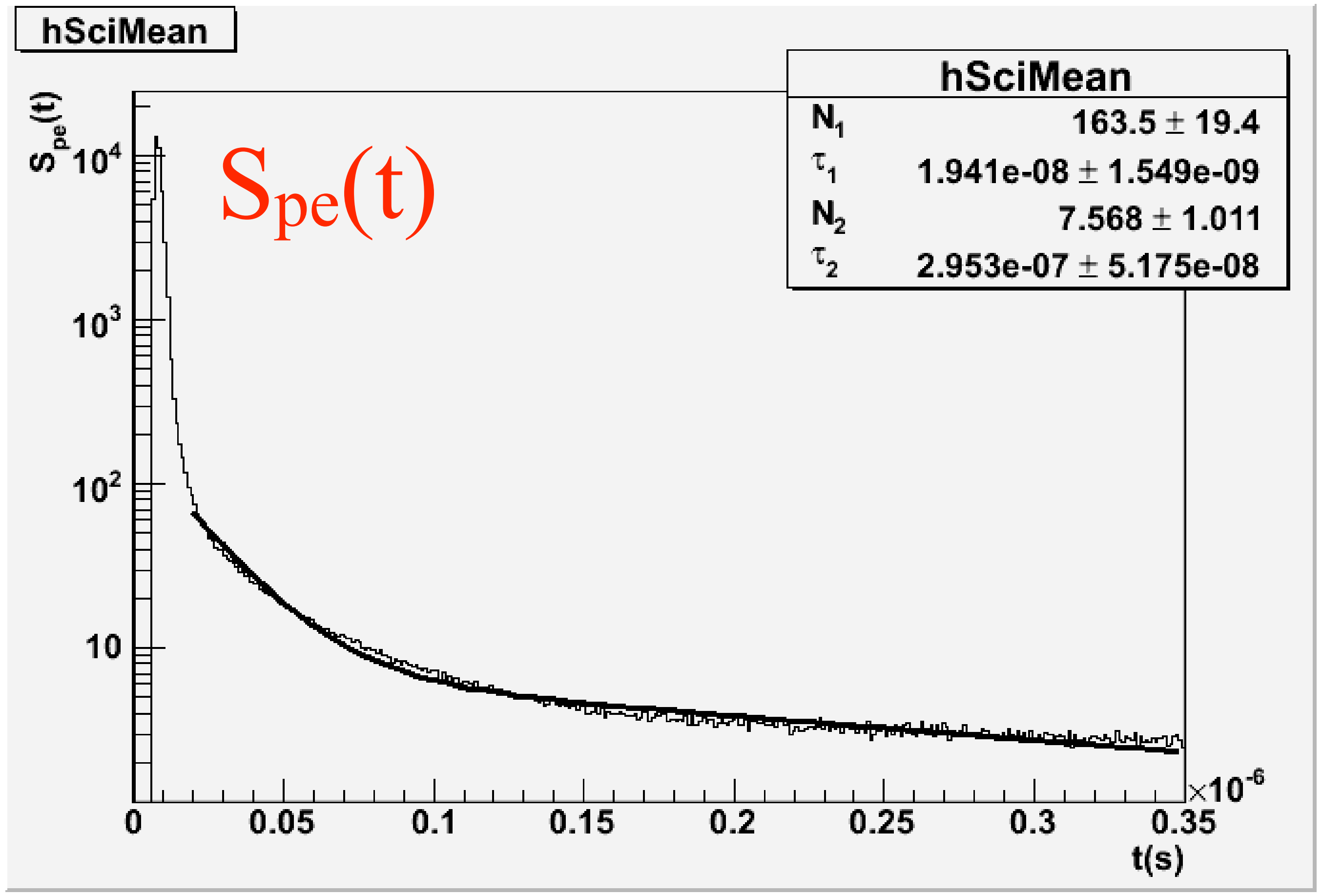




Time-history is very powerful: every volume in 4th is clocked out at 1 GHz, or faster

- particle IDs
- background rejections (plural)
- one t_0 and one pedestal (or baseline)
- depth segmentation is 5-10 cm

Far better than a physical segmentation, which is expensive, with many t_0's and pedestals, and is difficult to calibrate.

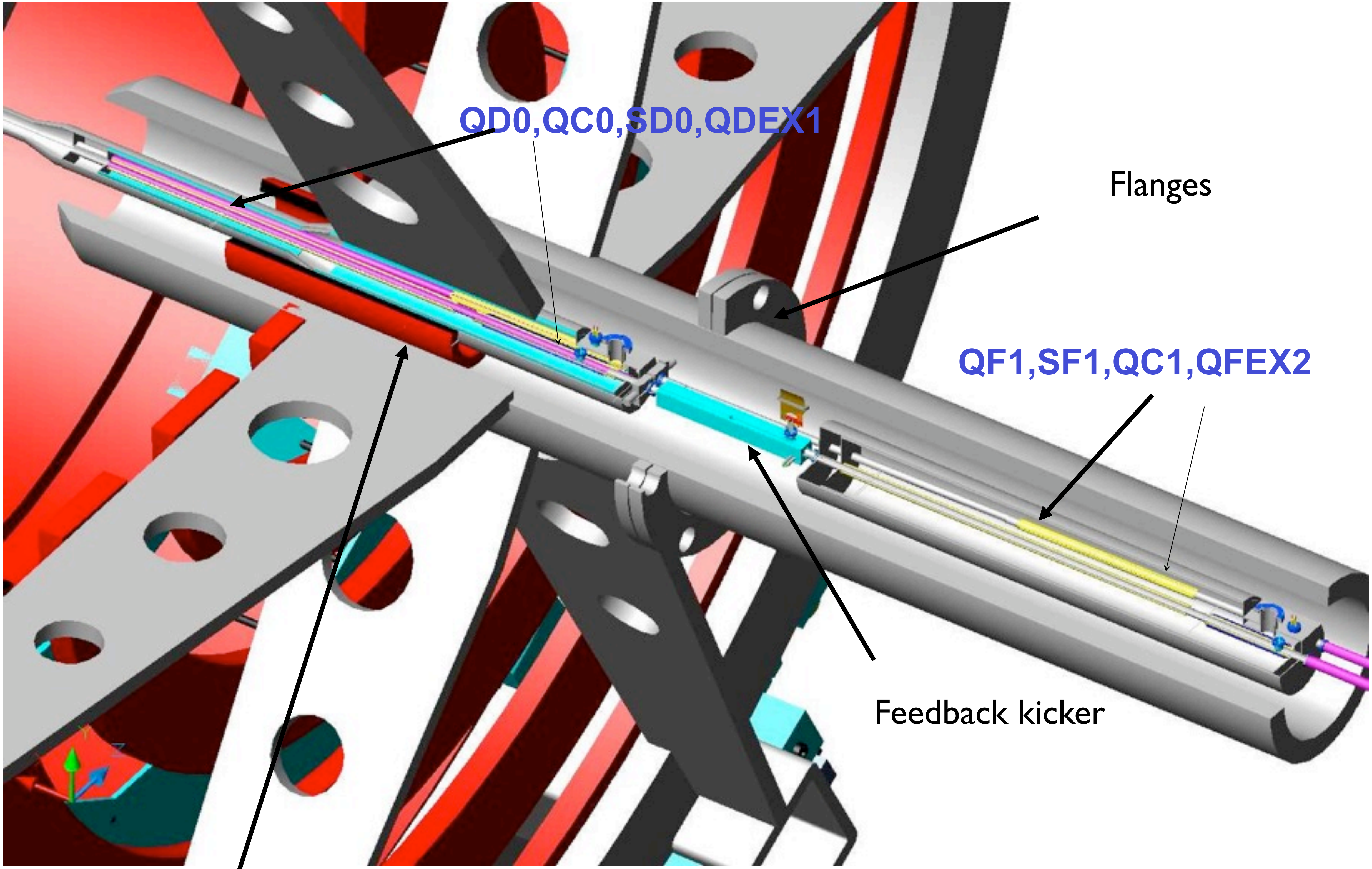


Summary

- 4th is a novel detector, we will publish it, and optimize & design for the Muon Collider. It is perfectly OK as a strawman detector.
- multi-TeV objects demands higher spatial precision and smaller measurement volumes, i.e., pixels for tracking (Chris Damerell). This is *terra incognita.*
- R&D for (1) large solenoids, (2) more dual-readout tests including a "99% containment module" to be tested at CERN in ~ 2 years, and (3) fast digitizers.
- we need an "executive board" of machine physicists, detector people, and others to lead 4th.

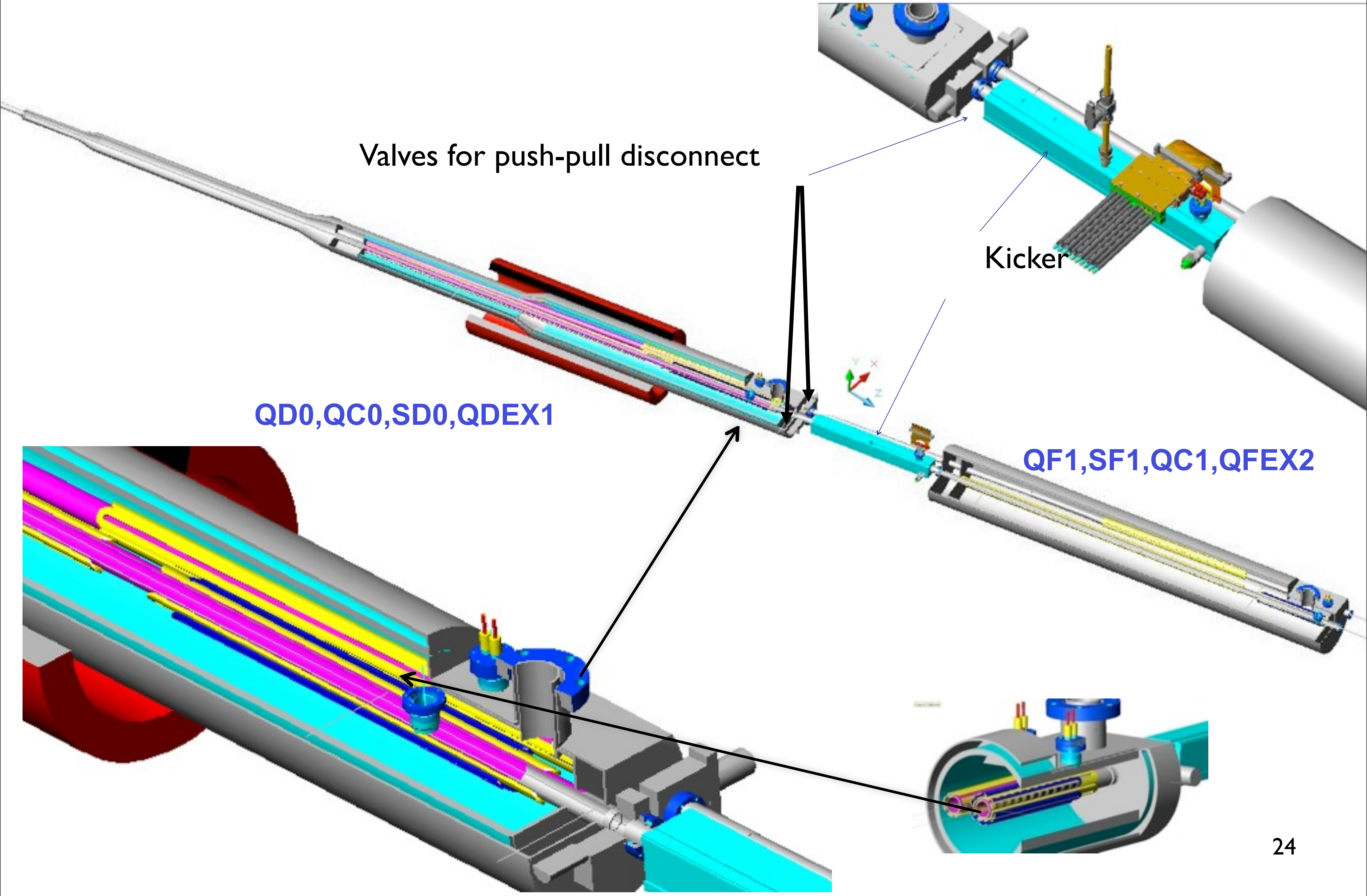
Spares

14 mrad crossing angle optics fragment



Each quad could be moved mechanically + trim coils

FINAL DOUBLET (IN/OUT), SEXTUPOLES FOR 14 mrad CROSSING ANGLE

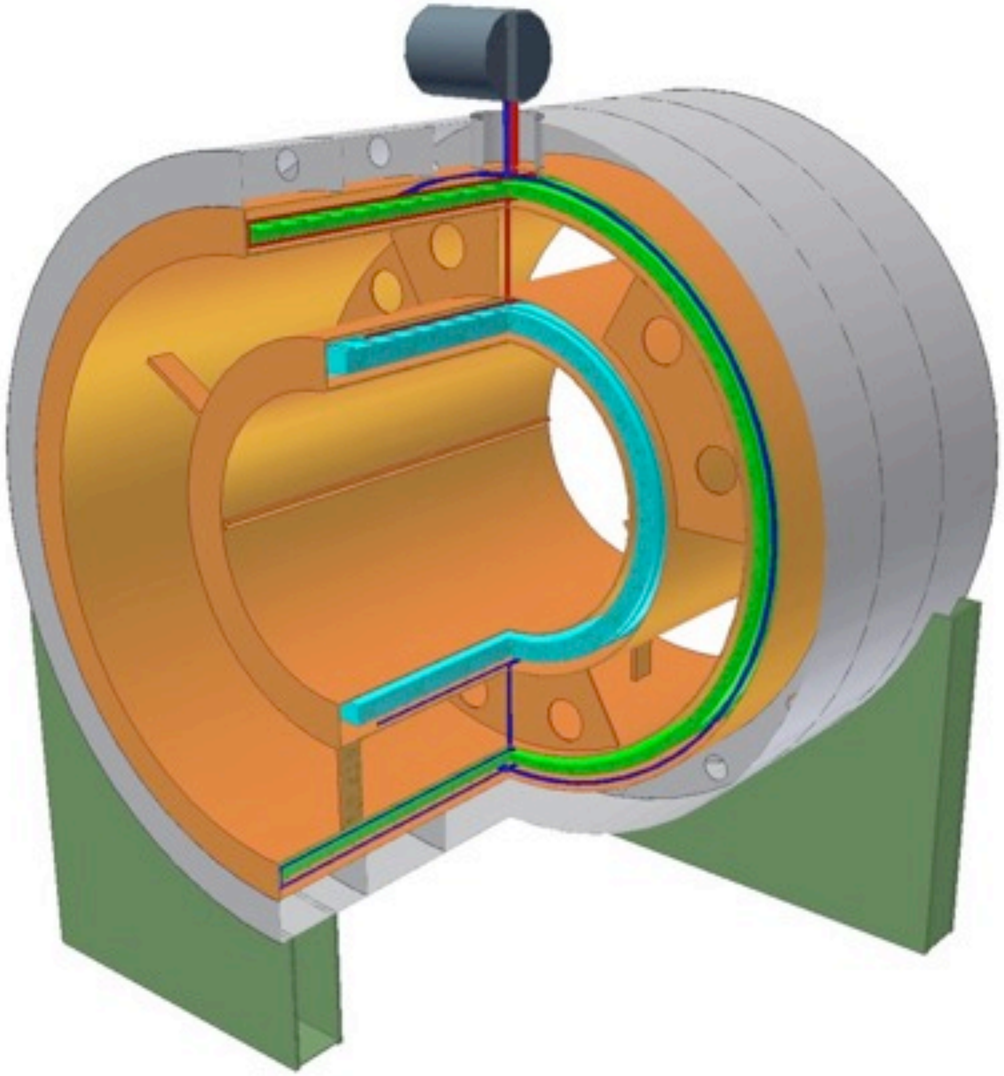


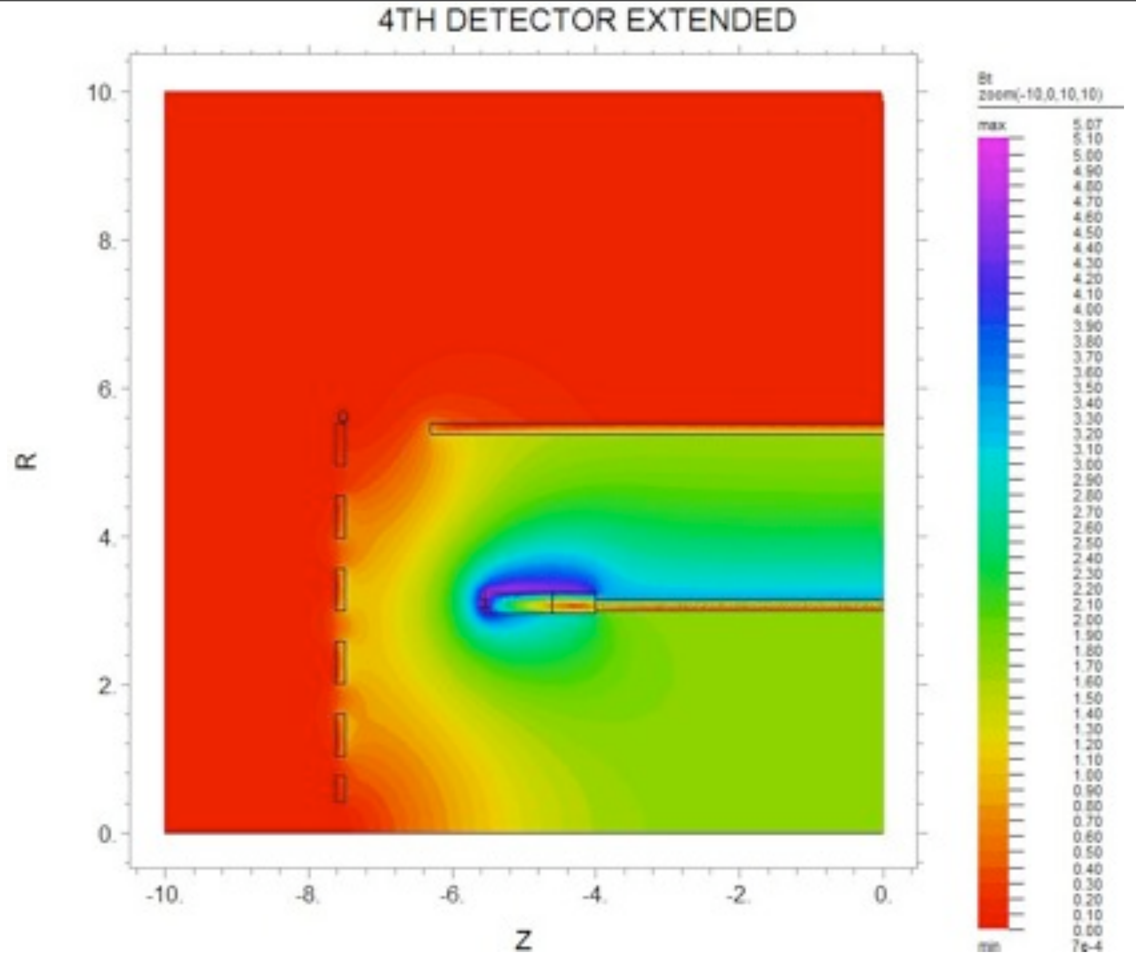
Valves for push-pull disconnect

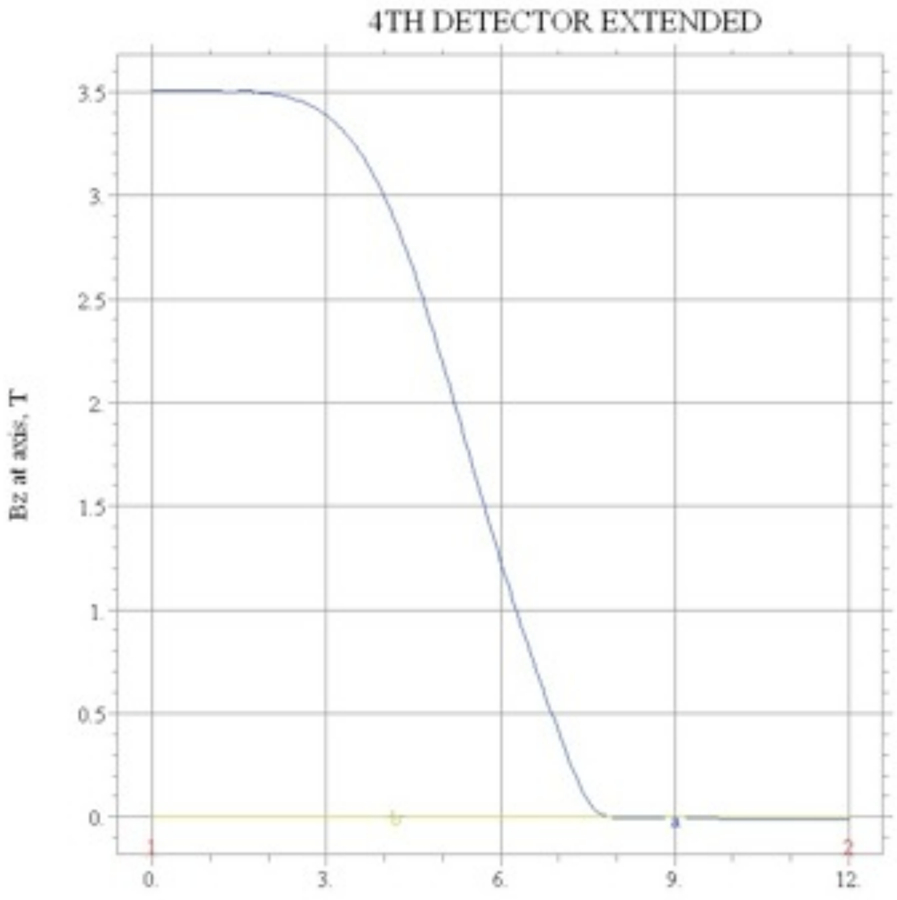
Kicker

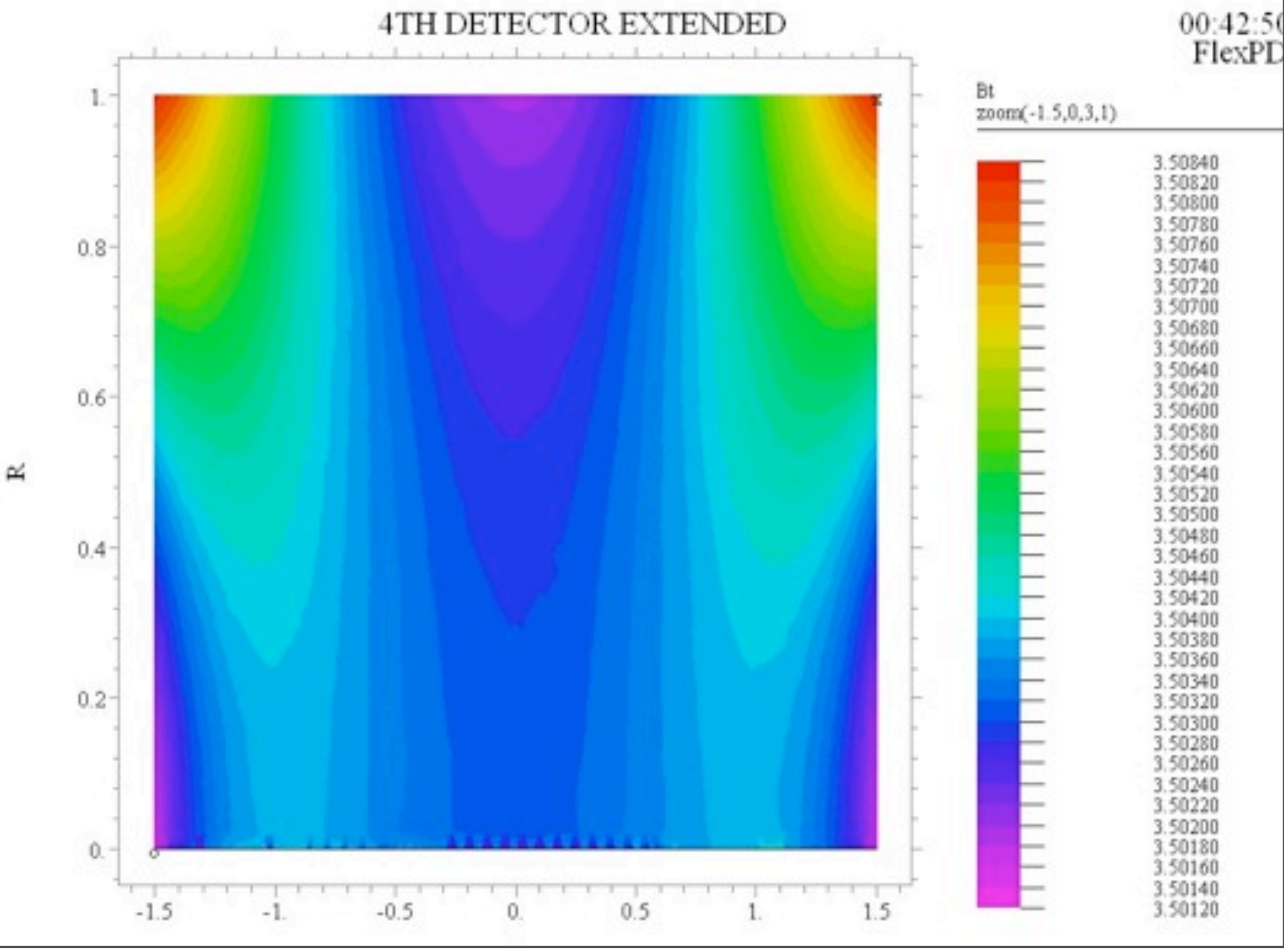
QD0,QC0,SD0,QDEX1

QF1,SF1,QC1,QFEX2

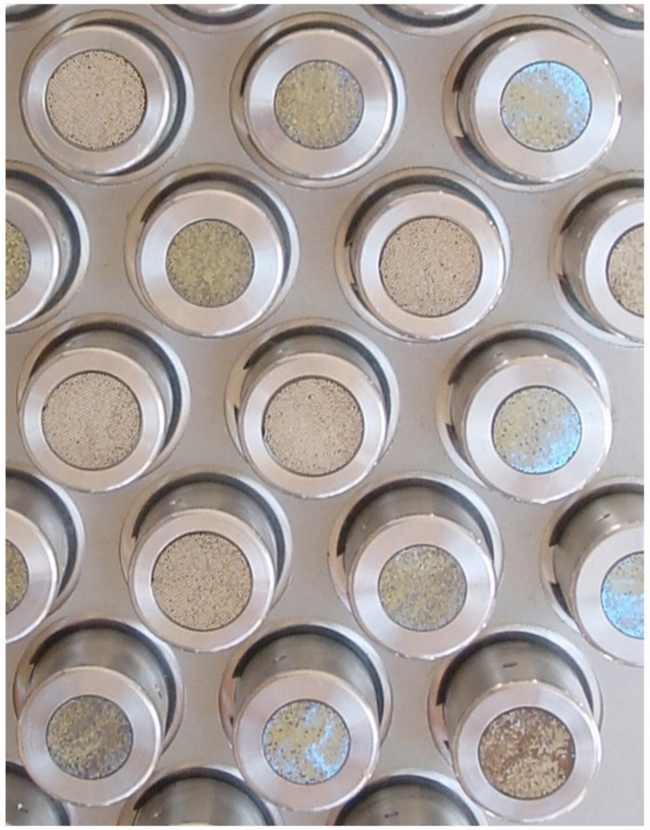


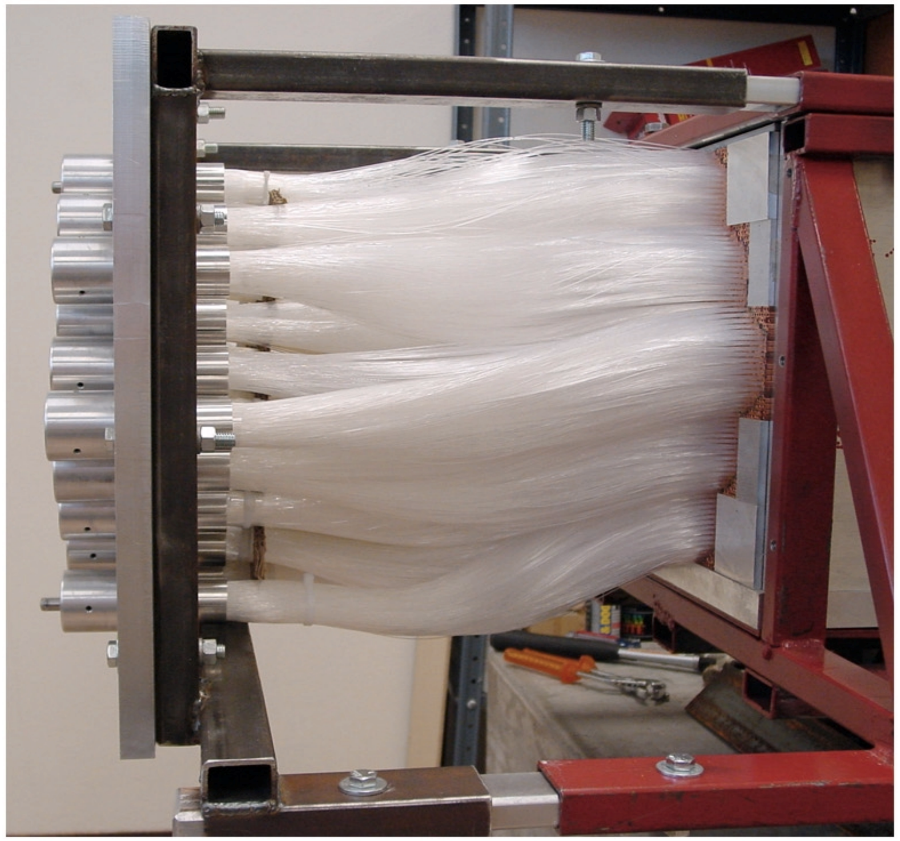

4TH DETECTOR EXTENDED
R
Z
10.
8.
6.
4.
2.
0.
-10.
-8.
-6.
-4.
-2.
0.
Bt
zoom(-10,0,10,10)
max
5.07
5.10
5.00
4.90
4.80
4.70
4.60
4.50
4.40
4.30
4.20
4.10
4.00
3.90
3.80
3.70
3.60
3.50
3.40
3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
min
7e-4


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

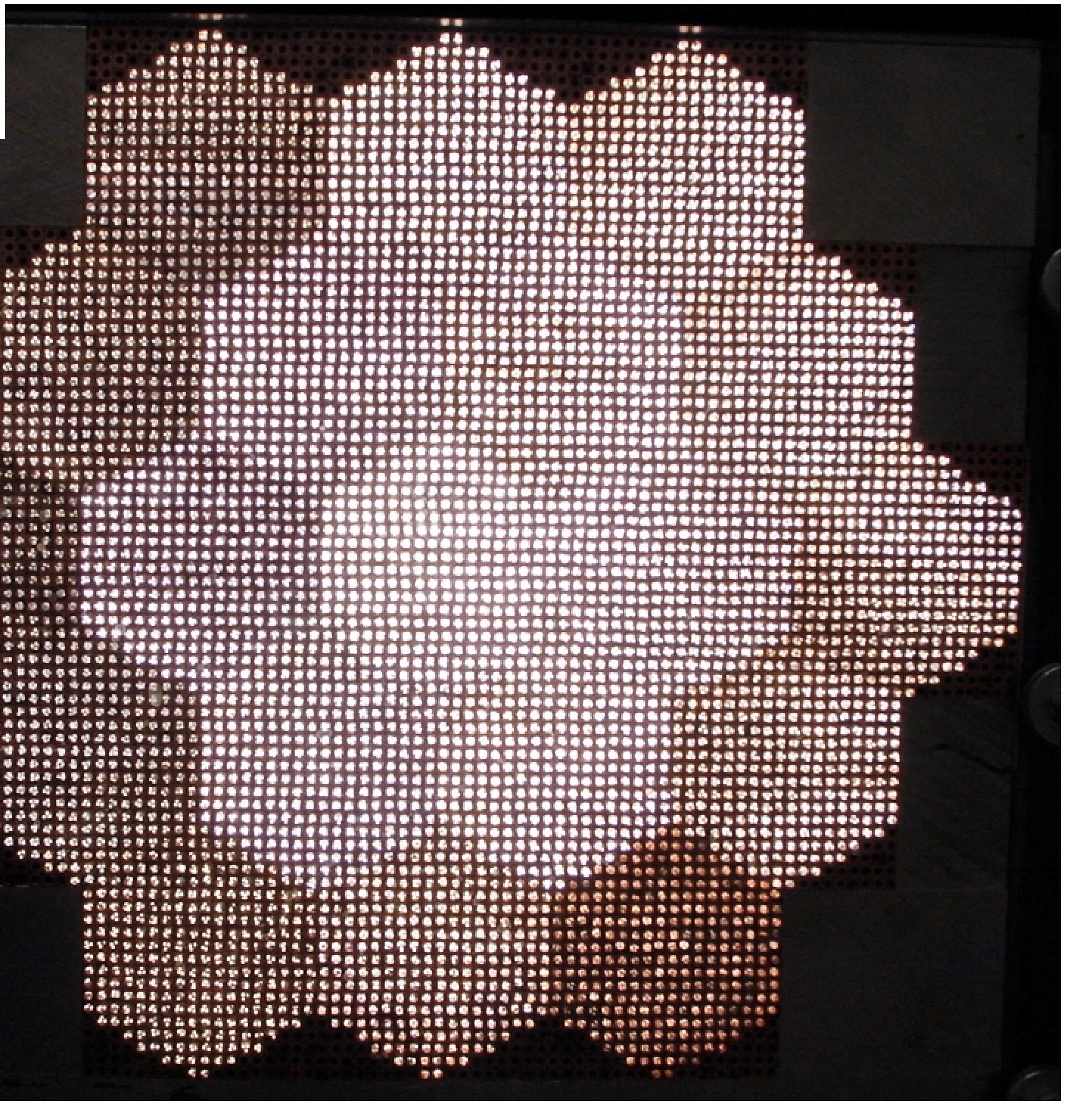

4TH DETECTOR EXTENDED
00:42:5
FlexPD
R
1.
0.8
0.6
0.4
0.2
0.
-1.5
-1.
-0.5
0.
0.5
1.
1.5
Bt
zoom(-1.5,0,3,1)
3.50840
3.50820
3.50800
3.50780
3.50760
3.50740
3.50720
3.50700
3.50680
3.50660
3.50640
3.50620
3.50600
3.50580
3.50560
3.50540
3.50520
3.50500
3.50480
3.50460
3.50440
3.50420
3.50400
3.50380
3.50360
3.50340
3.50320
3.50300
3.50280
3.50260
3.50240
3.50220
3.50200
3.50180
3.50160
3.50140
3.50120

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)

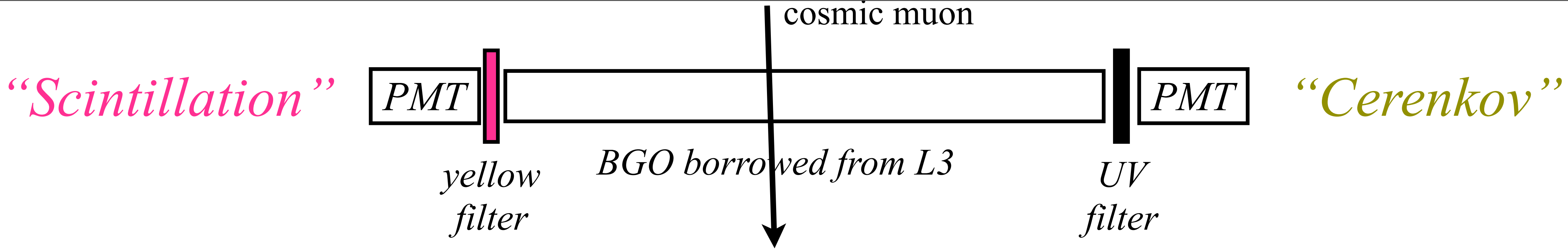
all work well (good reference: Silvia Franchino talk at TIPP09)

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

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

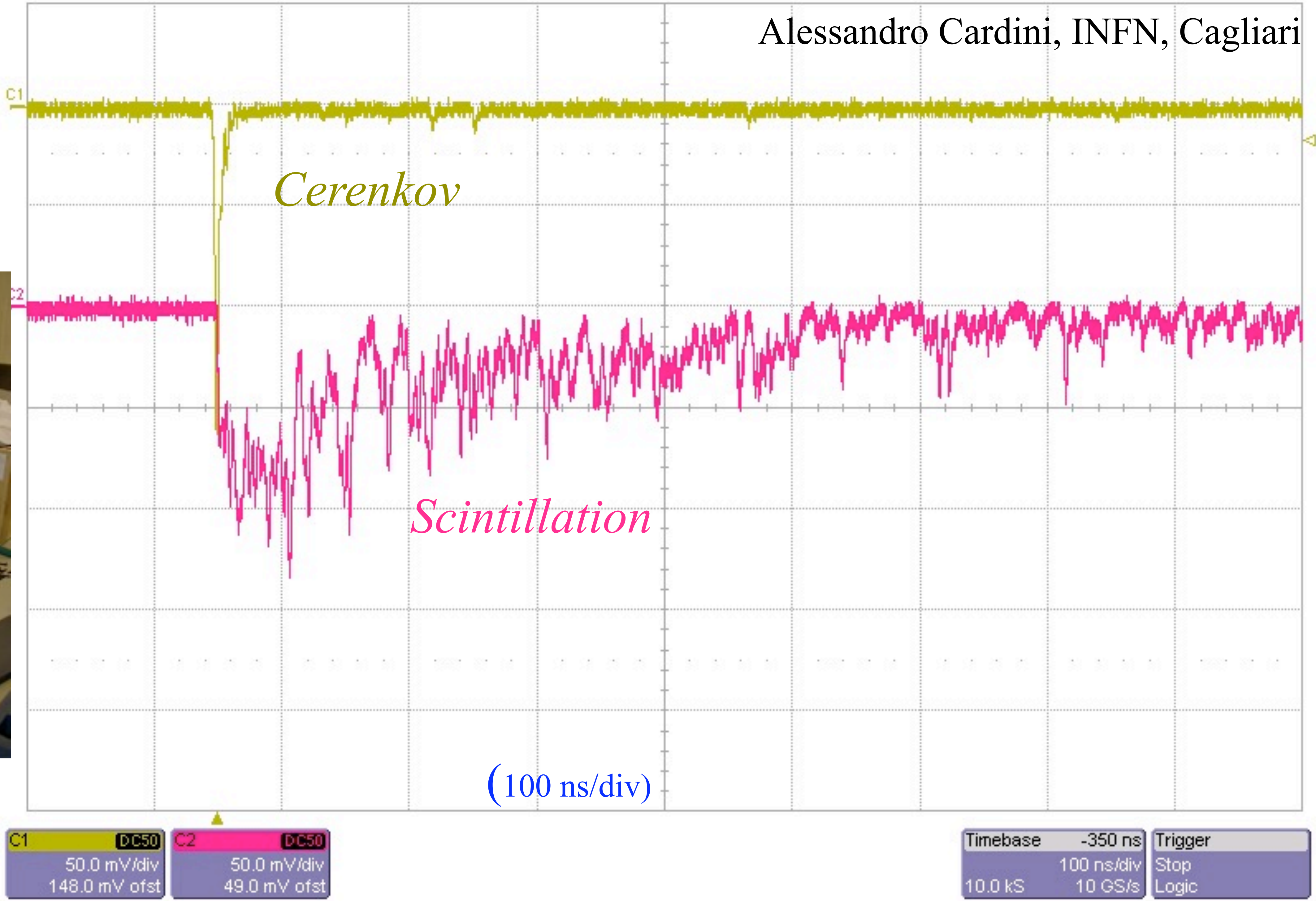
- next largest fluctuation is the BE losses in nuclear break-up, proportional to the MeV neutrons liberated in the shower ... measure $S_{pe}(t)$.

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



BGO …

by time and wavelength



Alessandro Cardini, INFN, Cagliari

C1 DC50
50.0 mV/div
148.0 mV ofst

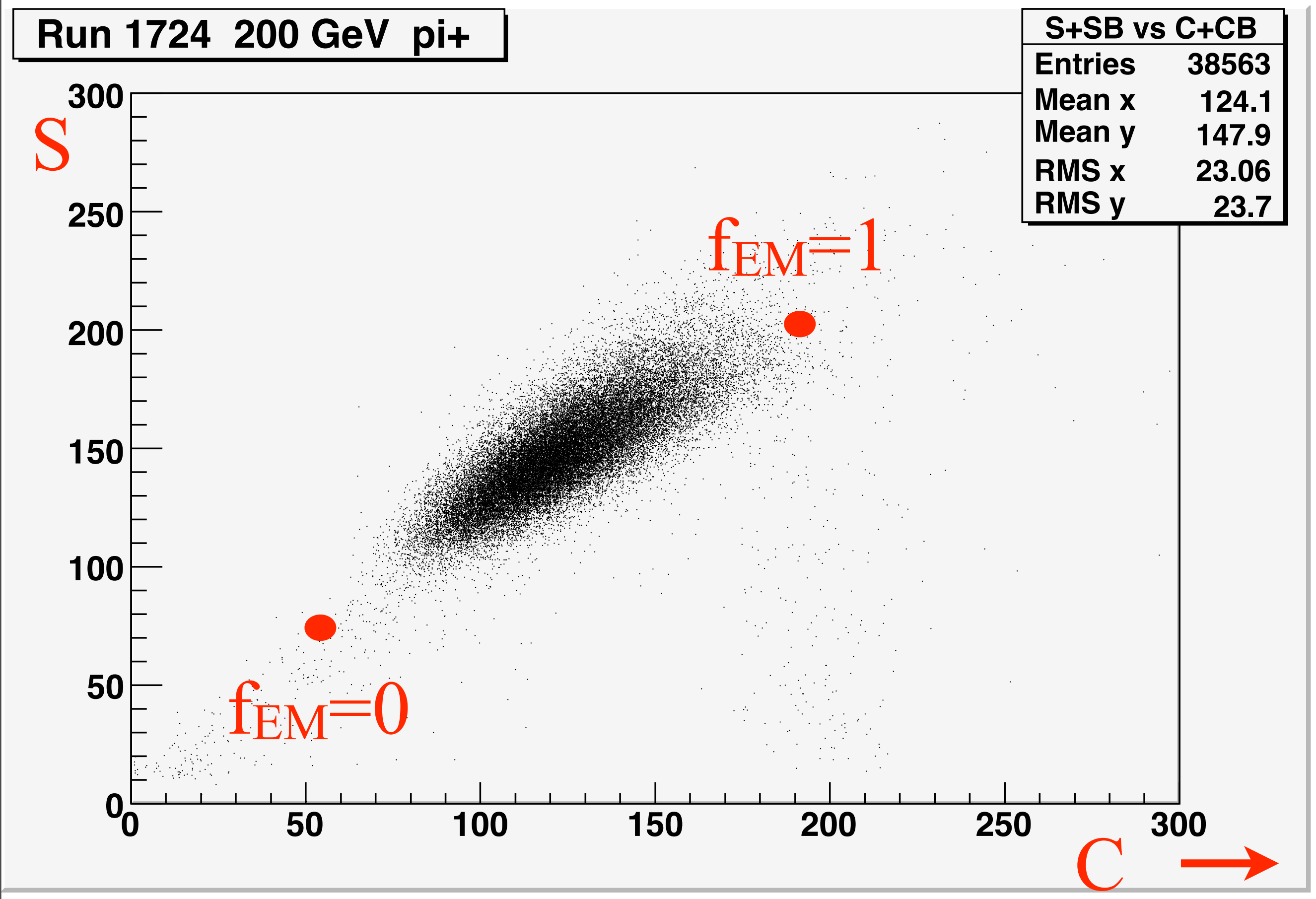
C2 DC50
50.0 mV/div
49.0 mV ofst

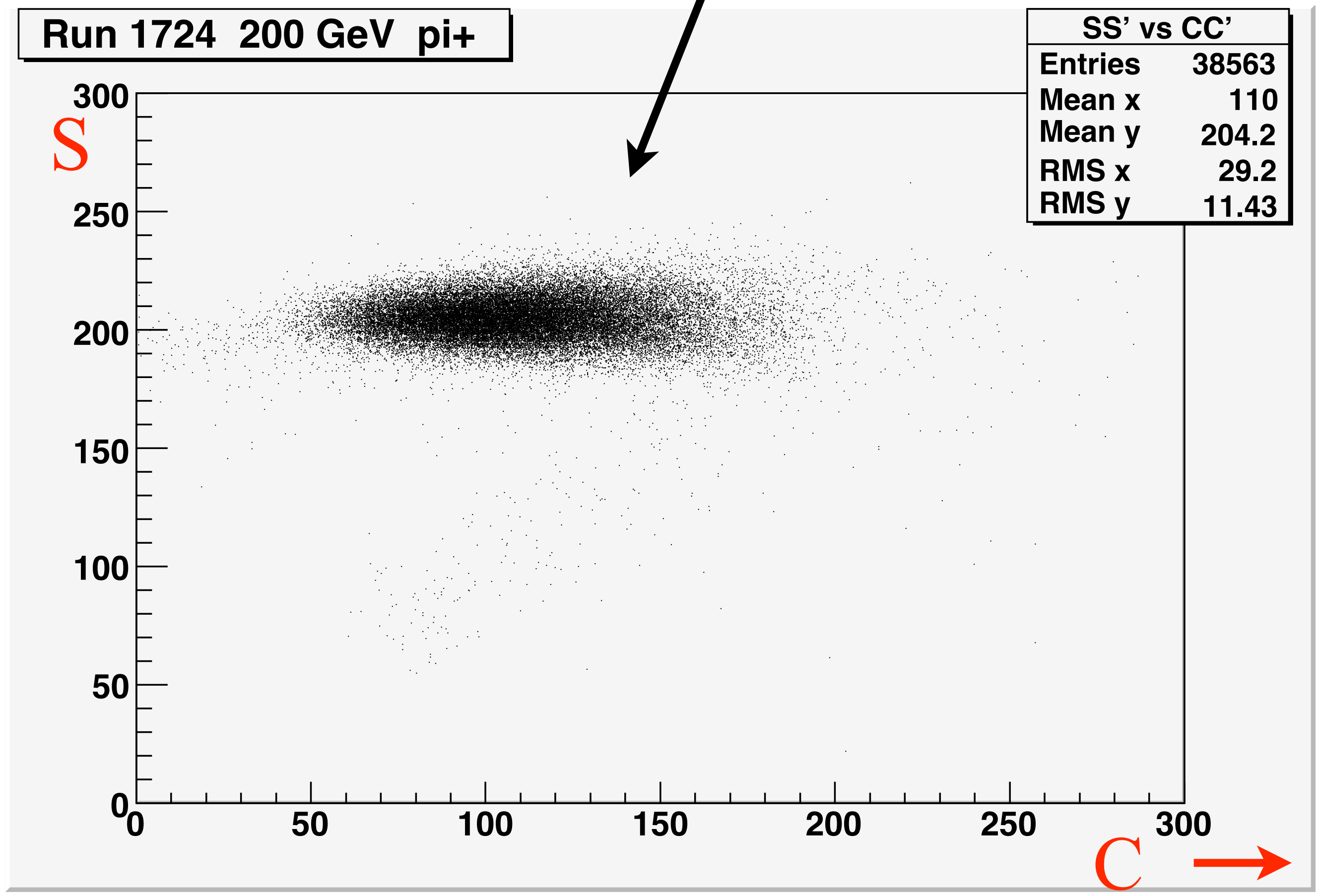
Timebase -350 ns
100 ns/div
10.0 kS 10 GS/s

Trigger
Stop
Logic

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

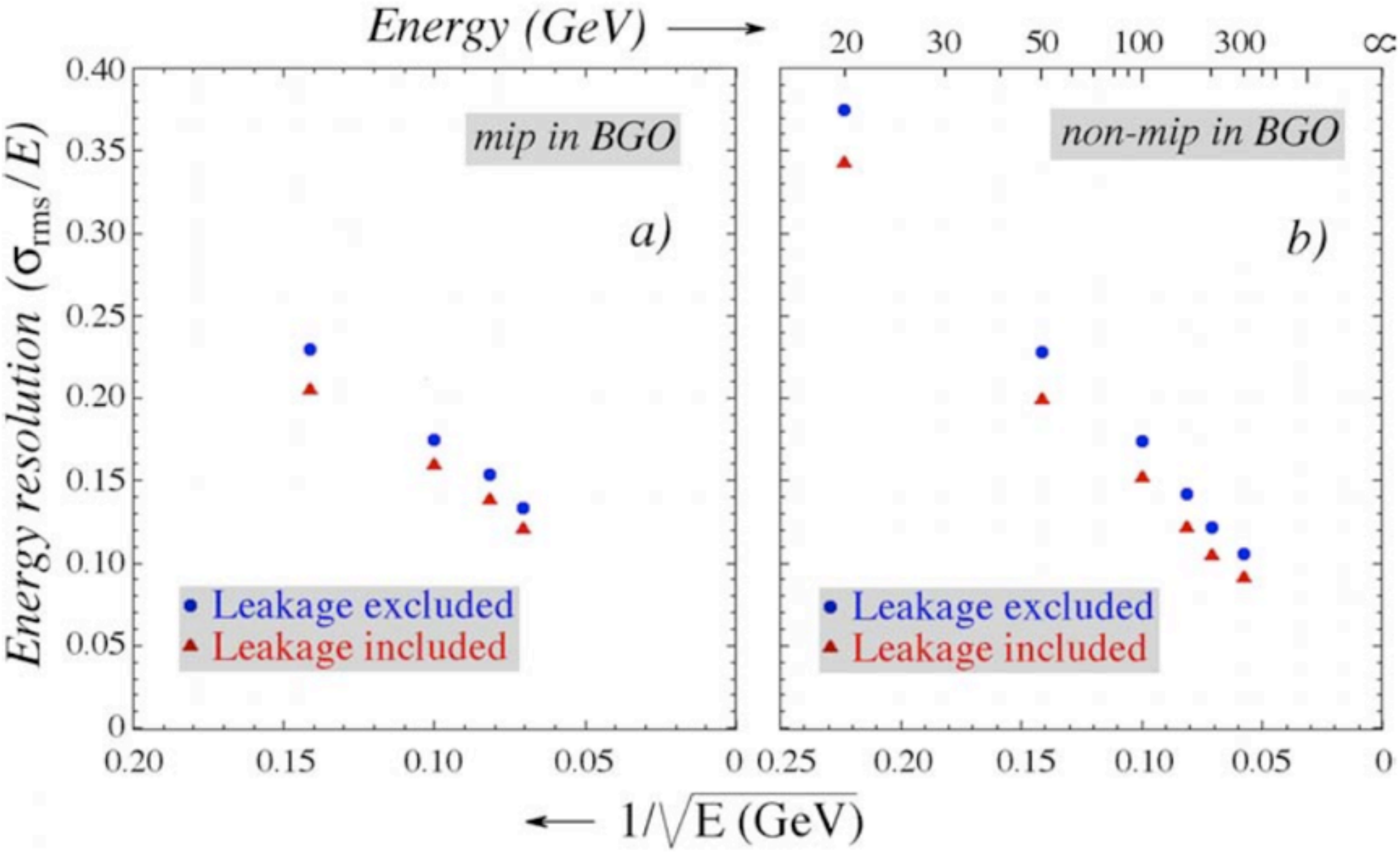
Dual-readout in the BGO+DREAM configuration for 200 GeV pi+. Measuring C allows a simple rotation of this figure, which achieves “compensation”.





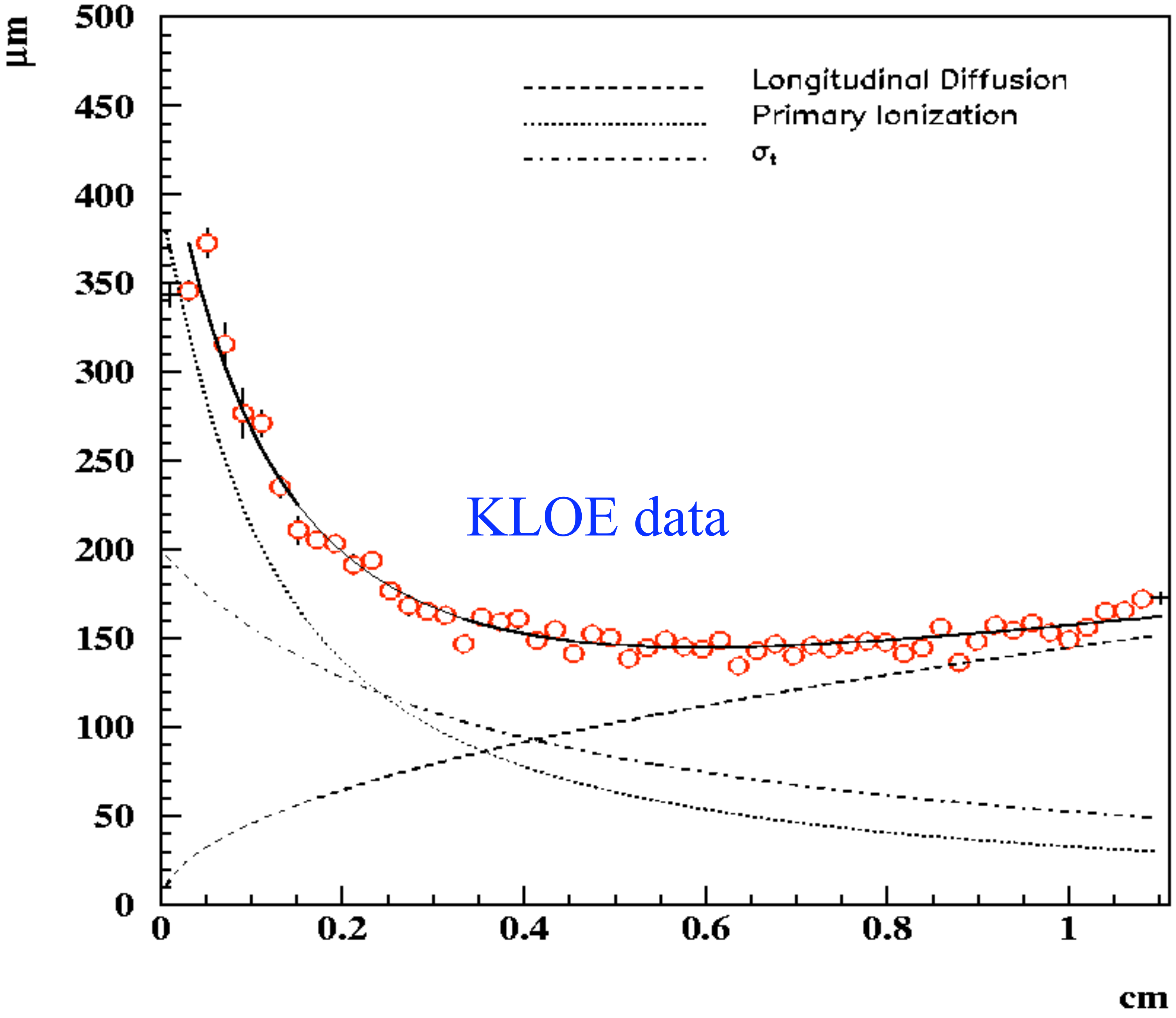
Leakage from DREAM

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



Cluster timing tracking chamber: (measure every cluster)

KLOE is a very well understood chamber

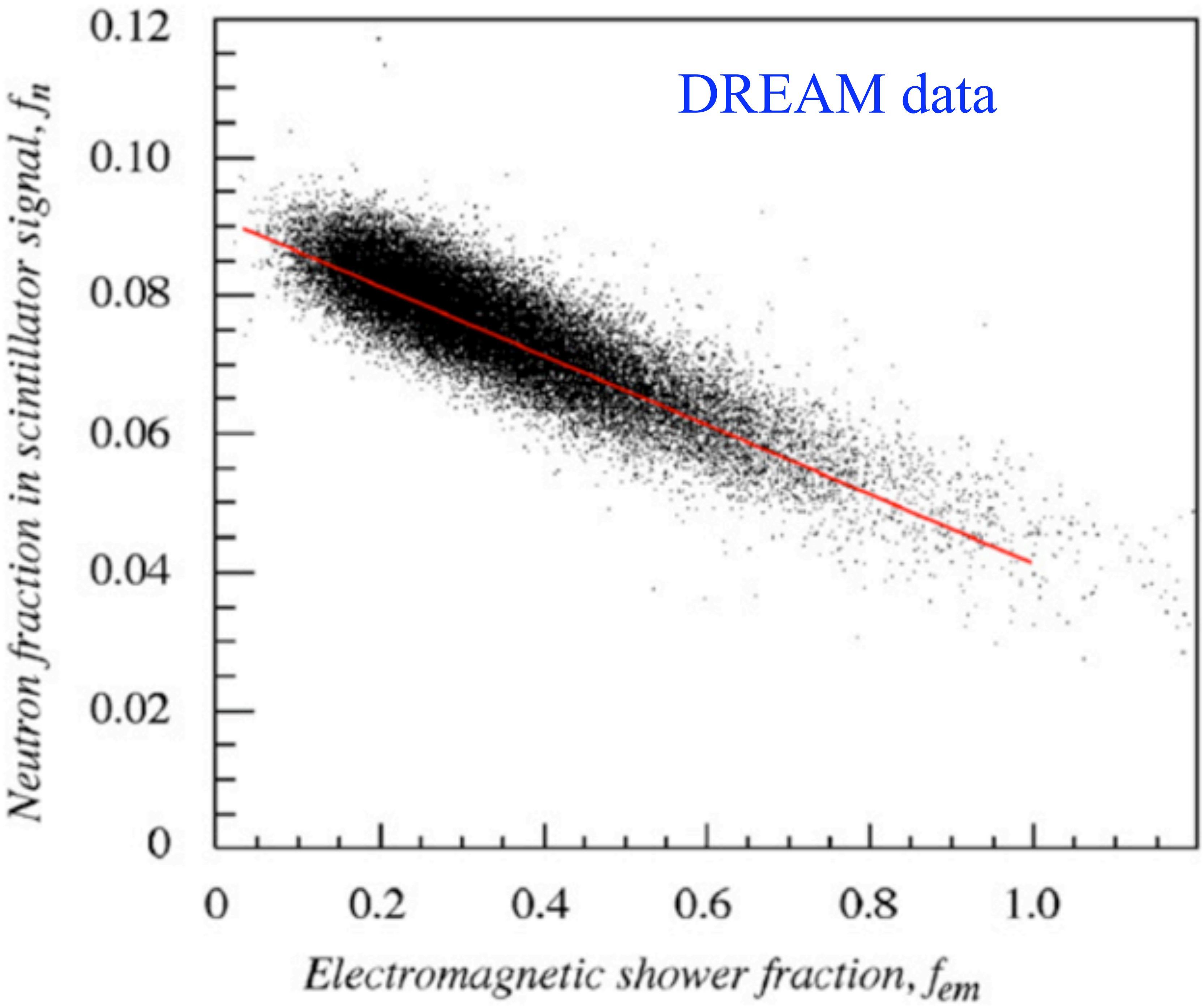


(vi) Neutron fraction *vs.* electromagnetic fraction: “hadronic” ID tag

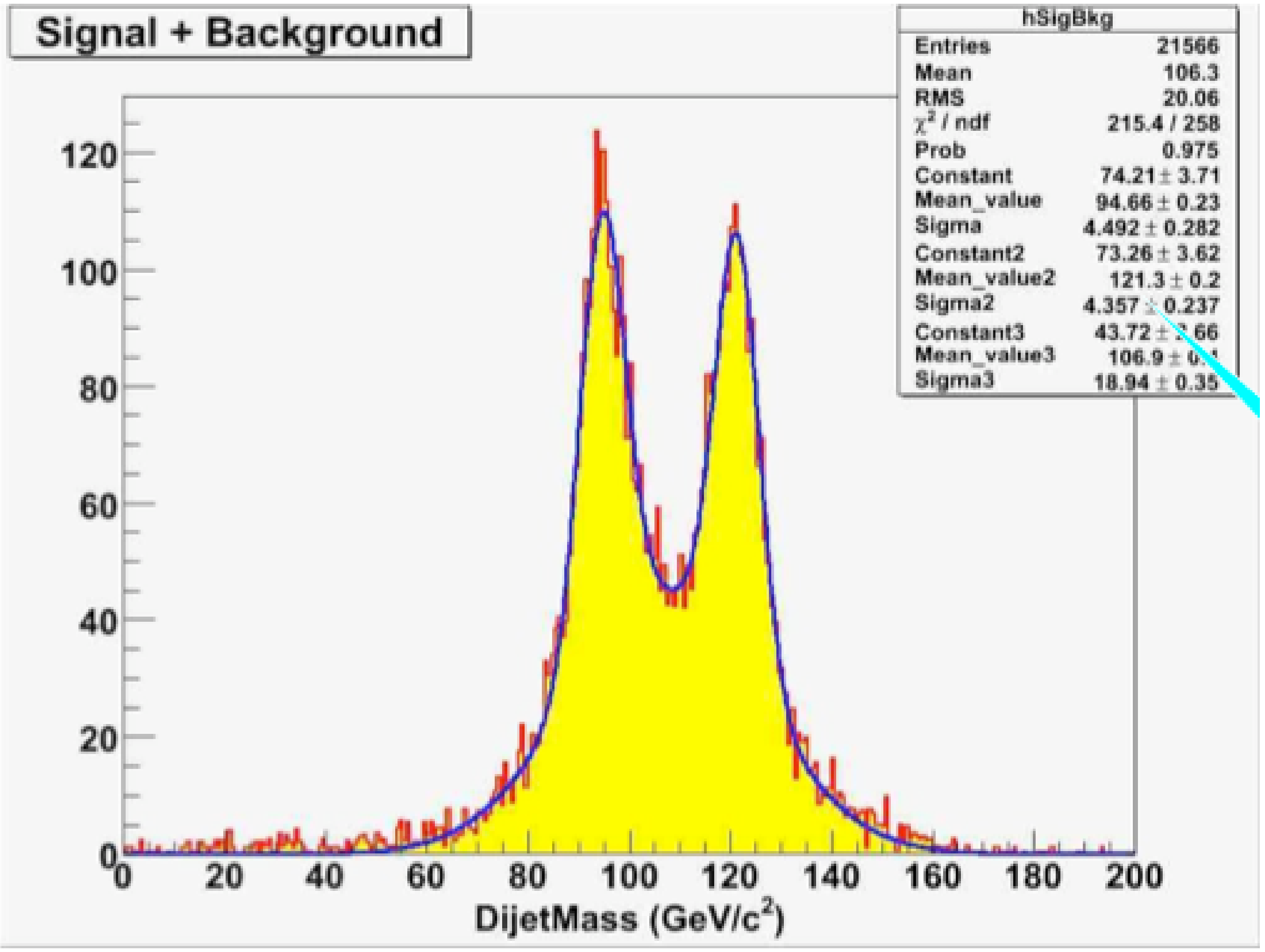
Expected anti-correlation of

f_n (hadronic content) and

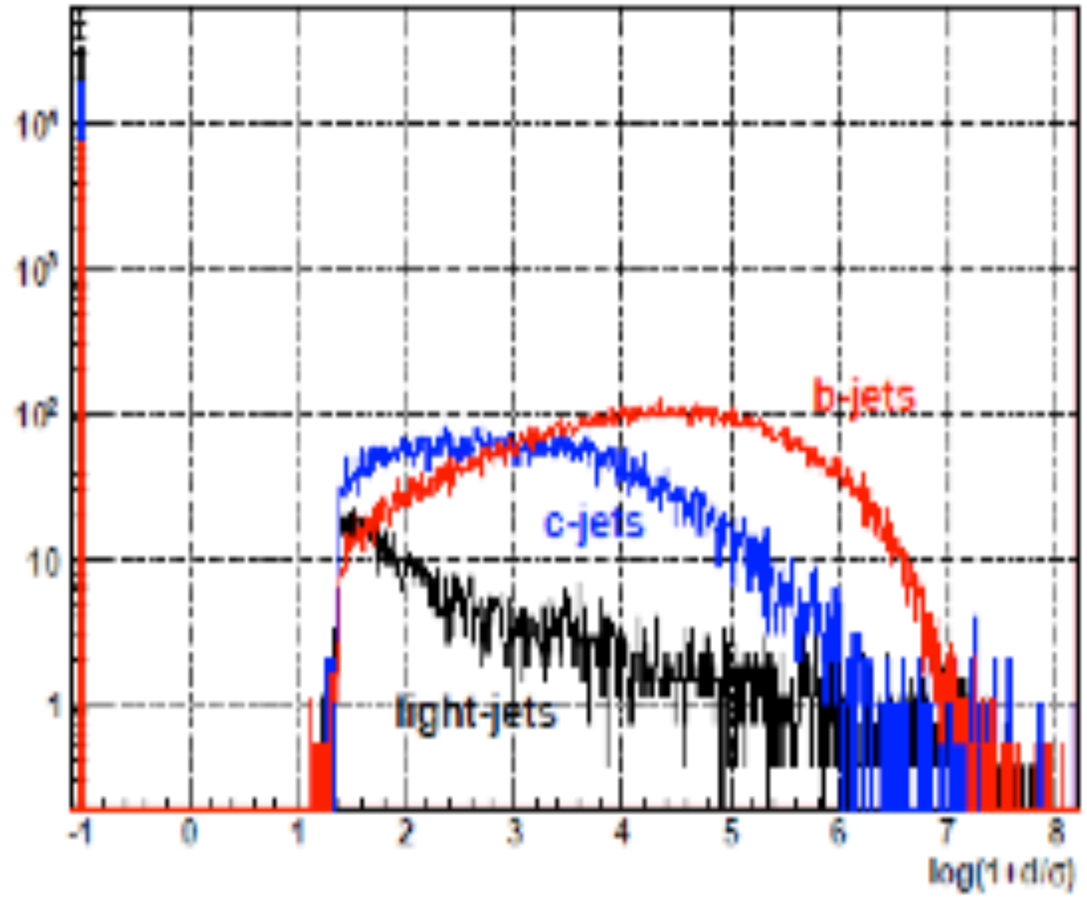
f_{EM} (electromagnetic content)

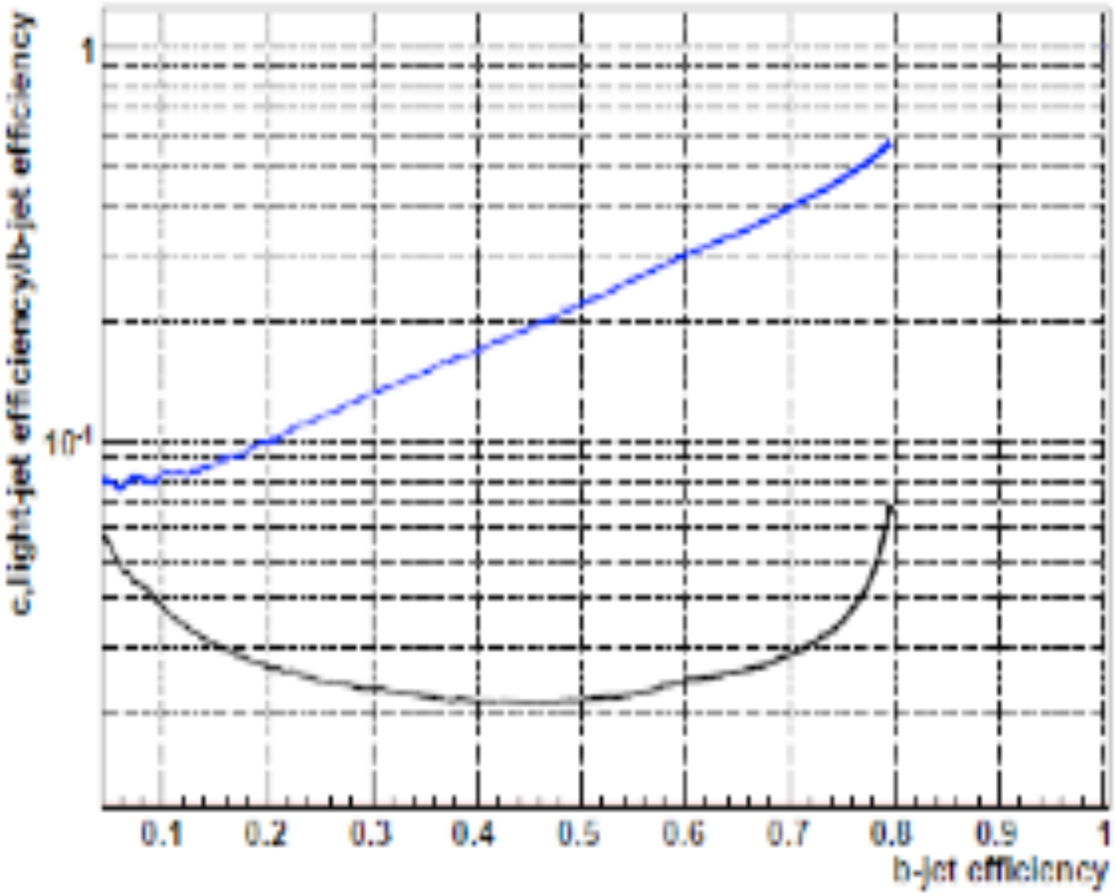


(ix) Z --> jj mass resolution



(x) b,c quark tagging





Summary of 4th:

- many ideas, data, beam tests, calculations and detailed simulations of physics performance;
- excellent particle ID;
- funding $155K;
- Letter of Intent is finished (with appendices) at www.4thconcept.org/4LoI.pdf;
- we are actually ready for an EDR, primarily because we have multiple successful beam tests and have made our scientific and technical decisions; and,
- book contract with Wiley on the design, physics and building of big experiments.