The Evolution of Lepton Collider Detectors

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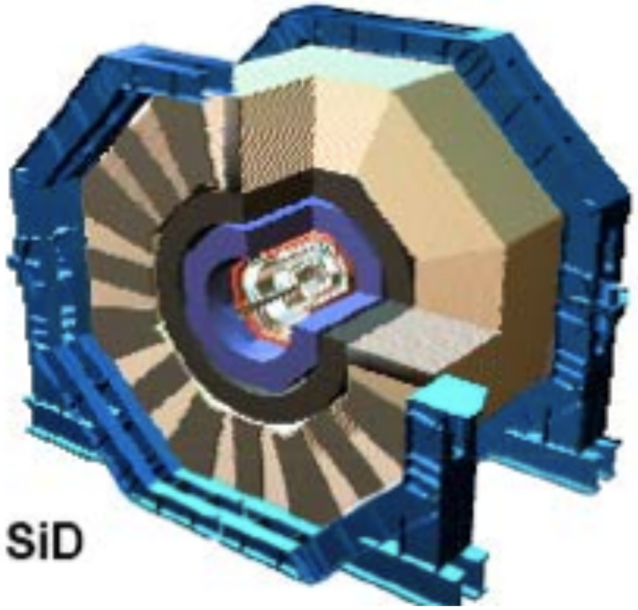
STORI11 “Storage Rings”
9-12 October 2011

This is about the *detectors*,
not the machines or the physics.



> *“Now I see. The experimentalist connects the nut and the bolt to the Feynman diagram.”*
>
> \- Sung Keun Park (student)

Parallel to the evolution of the machines, their detectors have evolved driven by two terms:

(1) the current realizations or expectations for physics:

- “can we see collisions?” [Ada]
- “can we check QED?” [Adone]
- “the photon couples to everything” [SPEAR, Richter, 1971]
- searches and studies: c, τ, b, t, Z, H

(2) the available technologies

for tracking:

- two scintillators in coincidence
- spark chambers, first optical then electronic
- MWPCs
- drift chambers
- TPCs, at PEP, LEP, sophisticated ILC/ILD TPCs
- silicon strips/pixels

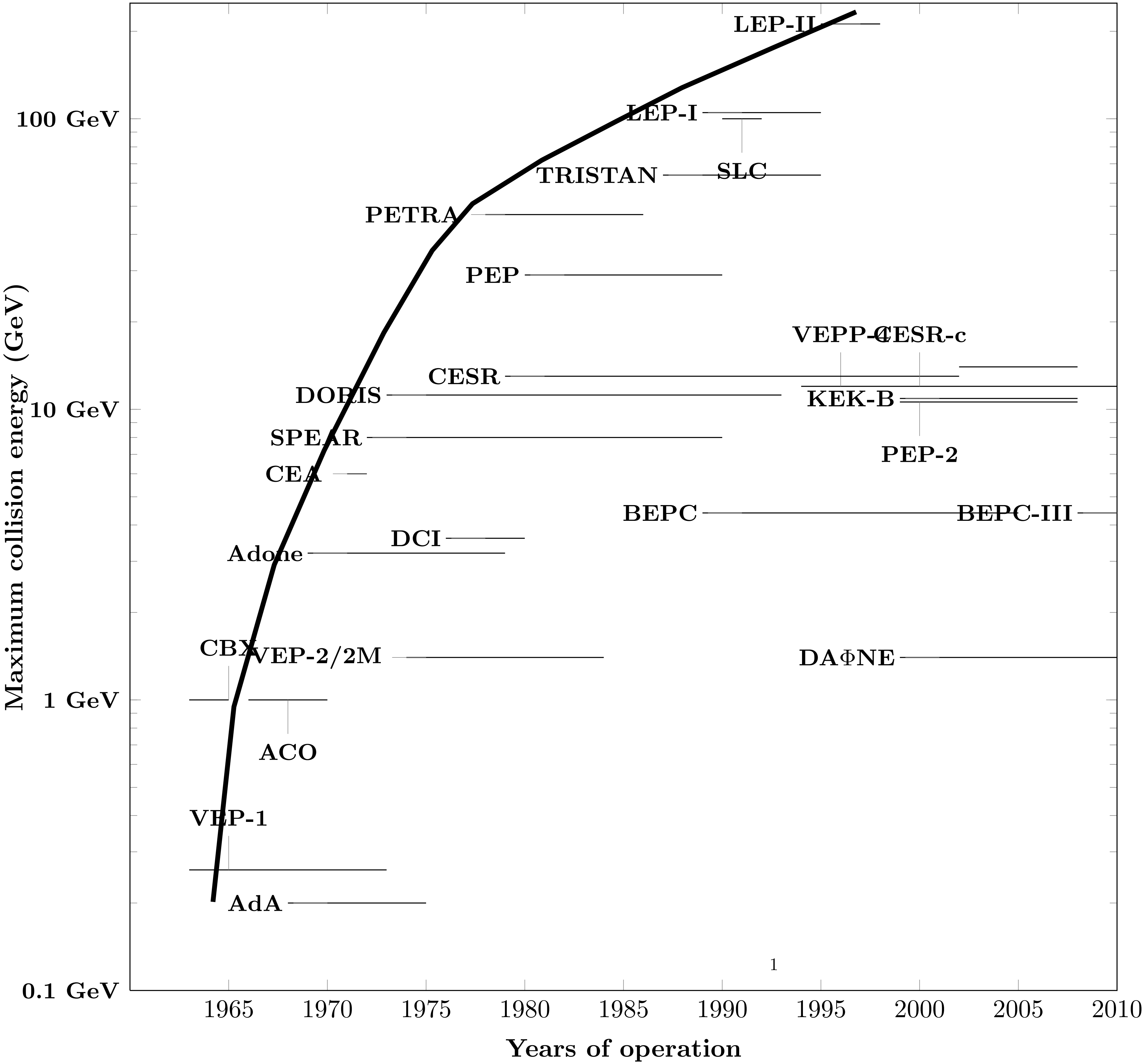
and for calorimetry:

- two scintillators in coincidence
- “dagwood” calorimeters: LAr/gas/scint/PFA
- dual readout calorimeters

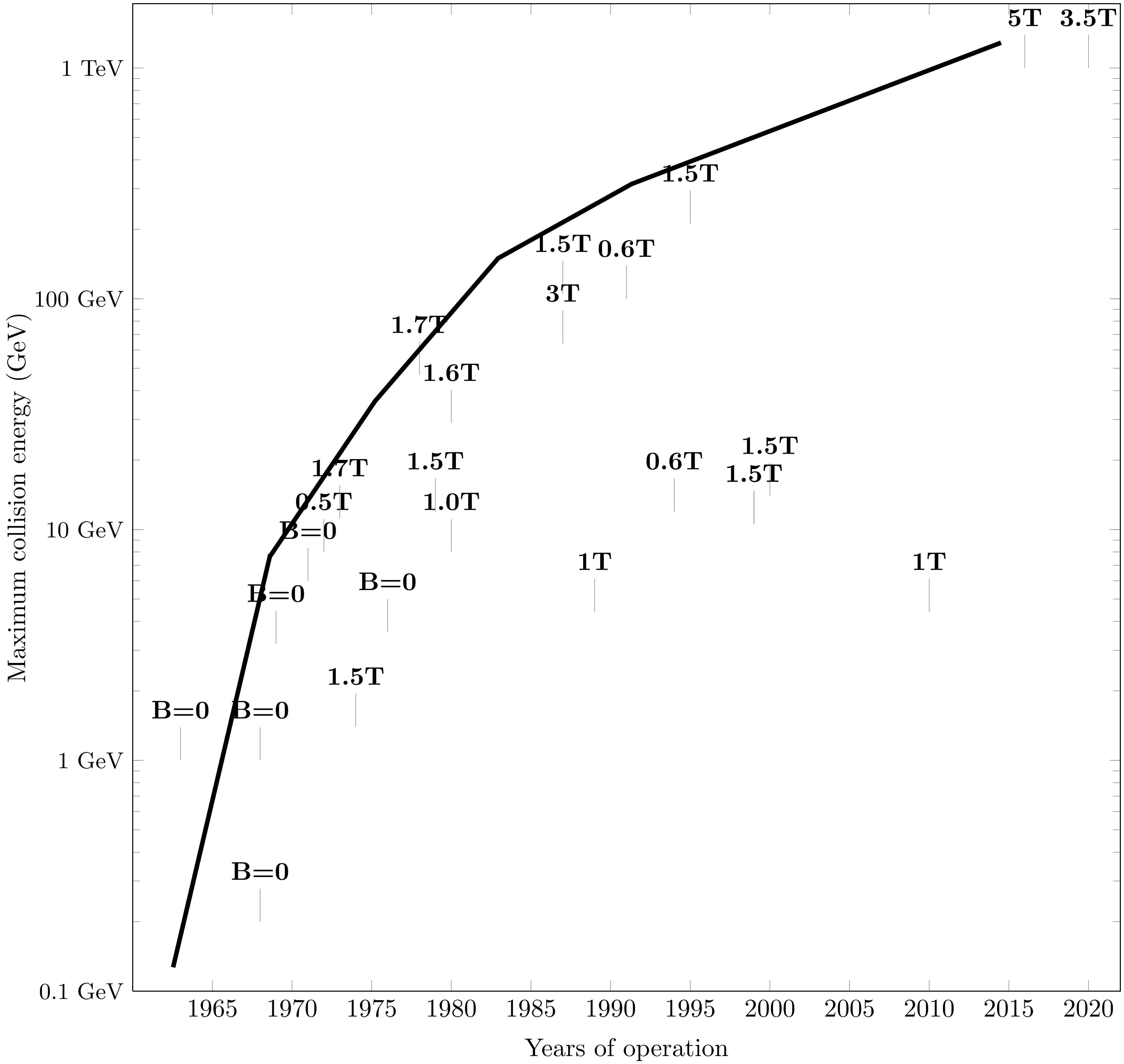

Dagwood sandwich

machine	exp	“vision”	B	p	pID	EM	Had	..
CBX, ‘63	$e^+e^- \to X$	QED	0	-	-	∞	∞	
ACO,’66	$e^+e^- \to X$	QED	0	-		∞	∞	
AdA, ’68	$e^+e^- \to X$	QED	0	-		∞	∞	
Adone, ’69	$e^+e^- \to X$	QED	0			∞	∞	
CEA, ’71	$e^+e^- \to X$	QED	0	-	-	∞	∞	
SPEAR, ’72	Mark 1	$e^+e^- \to \gamma^*$	.5T	SC	-	100%	∞	
	Mark 2	b, t	0.45T	DC		10%	∞	
	Mark 3	c, τ	1.0T	DC		10%	∞	
’75	DELCO	c	.5T	PWC	e	∞	∞	
DORIS, ’73	ARGUS	c, b				10%	∞	
	CrystalBall	$\to \gamma$	0T	PWC	$e\gamma$	2%	∞	
	DASP	c	0 T	DC		10%	∞	
	PLUTO	c, b	1.7T	...		10%	∞	
VEP-2, ’74	OLYA	...						
	CMD-3	c, τ	1.5T	DC				
	SND	ud, c, τ	1.35T	DC				
	KEDR	..	0.6T	DC	$\mu e \pi K$	5%	∞	
PETRA, ’78	JADE	t	0.45T			4%	∞	
	Mark-J	t	0T			2%	∞	
	PLUTO	t	1.7T			20%	∞	
	TASSO	t	0.5T			15%	∞	
CESR, ’79	CUSB	c	0.44T	DC		2%	∞	
	CLEO-n	b	1.5T	DC	$\mu e \pi K p$	2%	∞	
PEP, ’80	Mark2	”	0.45T	DC	μe	10%	∞	
	HRS	”	1.6T	DC	μe	20%	∞	
	MAC	”	.6T	DC	μ	30%	∞	
’82	TPC	t, b, c	1.5T	TPC	$\mu e \pi K$	40%	∞	
TRISTAN, ’87	TOPAZ ...	t	1.2T	TPC	$\mu e \pi K p$	20%	∞	
	VENUS	t	0.75T	DC		20%	∞	
	AMY	t	3.0T	DC		30%	∞	
LEP I, ’89	ALEPH	Z	1.5T	TPC	$\mu e \pi K p$	10%	100%	
	DELPHI	Z	1.2T	TPC	$\mu e \pi K p$	20%	200%	
BEPC, ’89	BES-n	c, τ	1.0	DC		2%	∞	
SLC, ’90	Mark-2, SLD	Z^0	0.6T	DC	μe	10%	100%	
VEPP-4, ’94	KEDR	b	0.6T	DC	$\mu e \pi K$	4%	∞	
DAΦNE, ’99	KLOE	CP				8%	∞	
PEP2, ’99	BaBar	b	1.5T	DC	$\mu e \pi K p$	3%	∞	
KEK2, ’99	Belle	b	1.5T	DC	$\mu e \pi K p$	3%	∞	
VEPP-2000	SND	udc	1.35T	DC		3%	∞	
	CMD-3	udc	1.5T			5%	∞	
ILC, 2015	ILD	W, Z, H	3.5T	TPC	$\mu e \pi K p W Z$	20%	35%	
CLIC, 2020	SiD	W, Z, H	5.0T	Si	$\mu e W Z$	20%	35%	
μColl, 2030	4th	W, Z, H	3.5T	DC	$\mu e \pi K p W Z$	10%	29%	

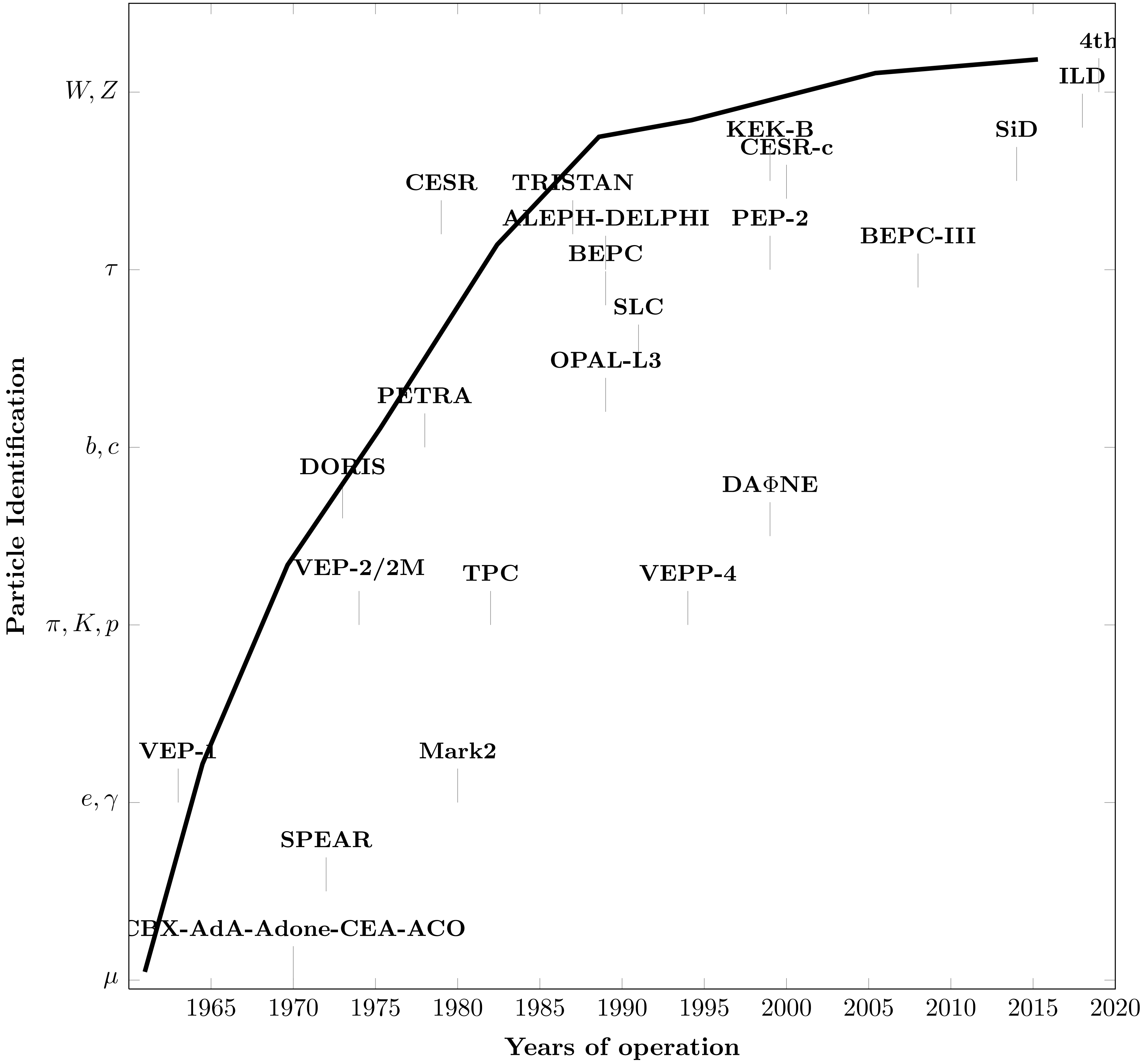
Some numbers, not all correct to be sure; for the ILC, SiD and ILD were “validated”, but 4th was not, by the advisory committee IDAG.


LEP-II
LEP-I
SLC
TRISTAN
PETRA
PEP
VEPP-4
CESR-c
CESR
DORIS
KEK-B
PEP-2
SPEAR
CEA
BEPC
BEPC-III
DCI
Adone
CBX
VEP-2/2M
DAΦNE
ACO
VEP-1
AdA
1
100 GeV
10 GeV
1 GeV
0.1 GeV
Maximum collision energy (GeV)
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Years of operation

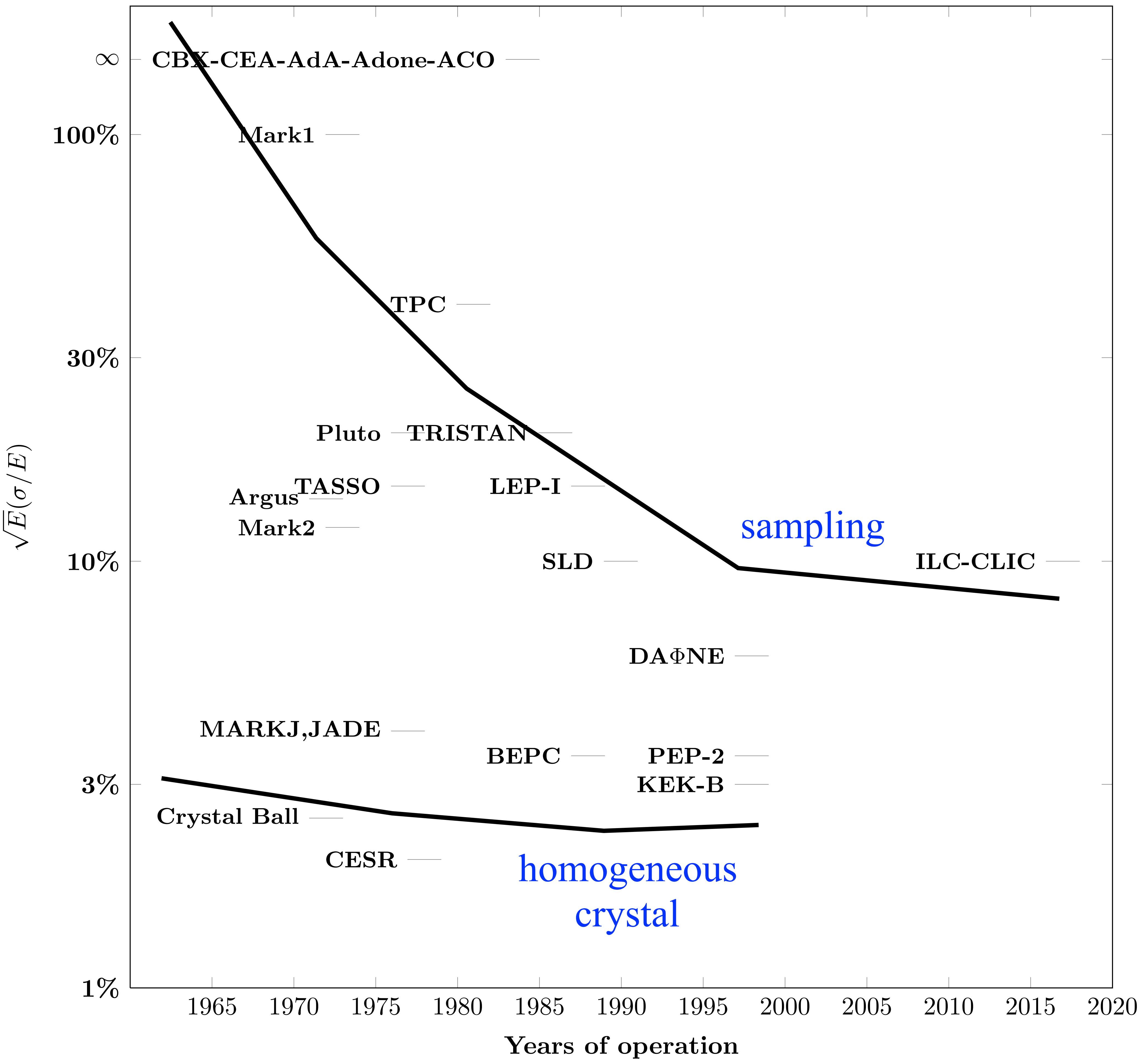
B(T)


5T
3.5T
1 TeV
1.5T
1.5T
0.6T
100 GeV
3T
1.7T
1.6T
1.5T
1.5T
1.7T
1.5T
0.6T
1.5T
0.5T
1.0T
B=0
10 GeV
1T
1T
B=0
B=0
1.5T
B=0
B=0
1 GeV
B=0
0.1 GeV
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Maximum collision energy (GeV)
Years of operation

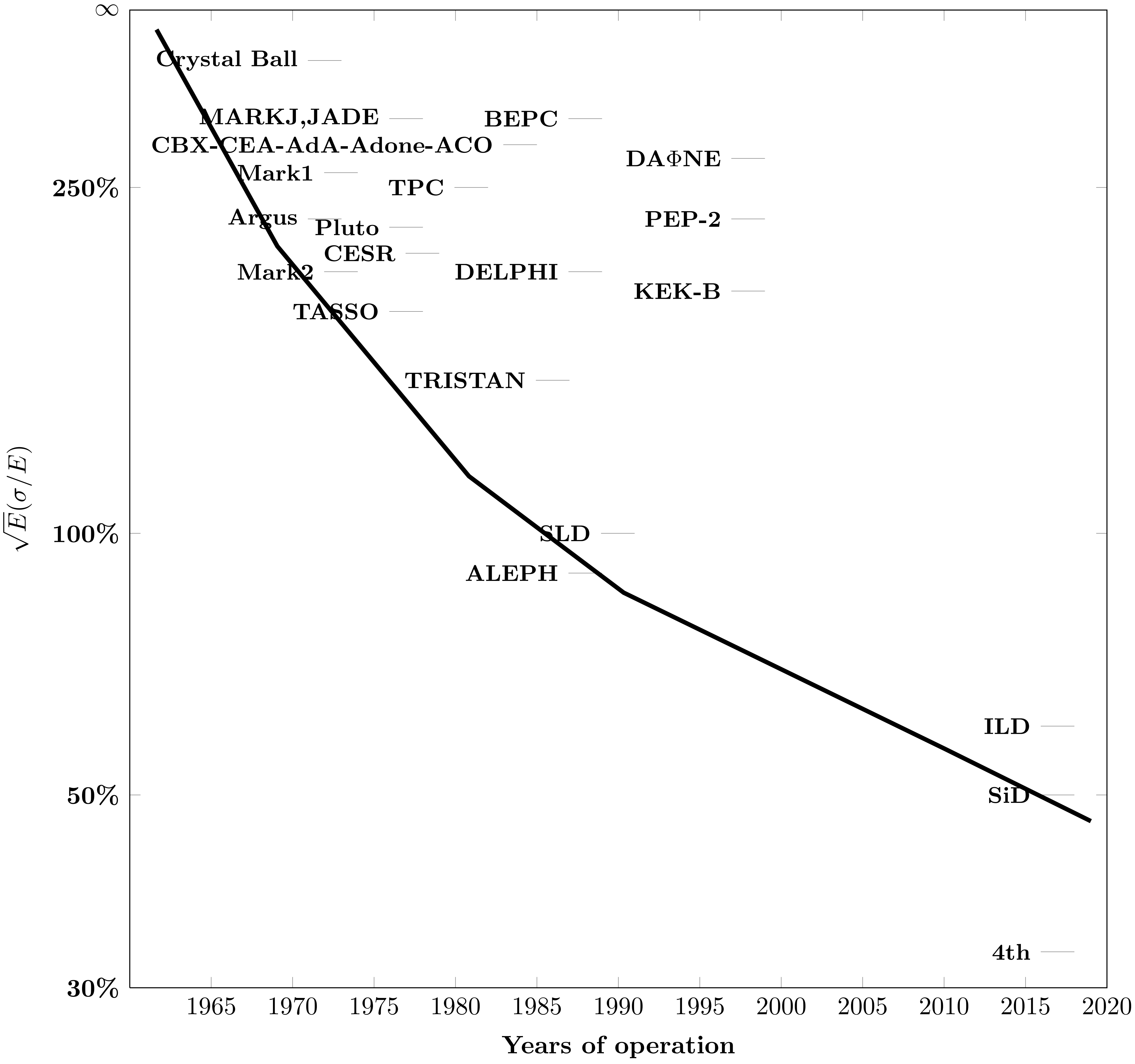
Particle identification:



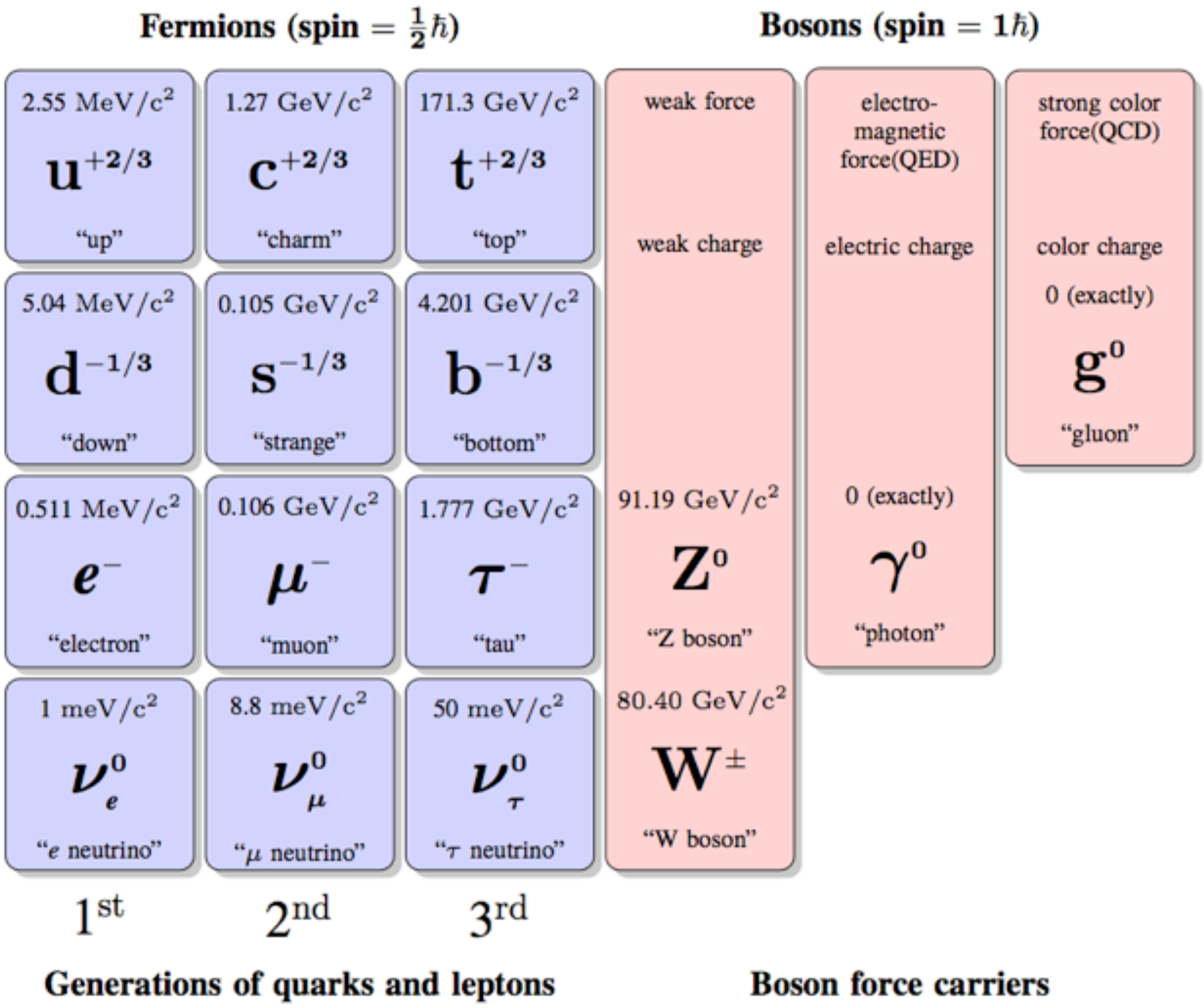
Electromagnetic calorimetry: stochastic term



Hadronic calorimetry: stochastic term



The next detector must measure and identify *all quarks, leptons and gauge bosons*



Fermions (spin = $\frac{1}{2}\hbar$)			**Bosons (spin = $1\hbar$)**		
2.55 MeV/c² $\mathbf{u}^{+2/3}$ "up"	1.27 GeV/c² $\mathbf{c}^{+2/3}$ "charm"	171.3 GeV/c² $\mathbf{t}^{+2/3}$ "top"	weak force weak charge	electro-magnetic force(QED) electric charge	strong color force(QCD) color charge
5.04 MeV/c² $\mathbf{d}^{-1/3}$ "down"	0.105 GeV/c² $\mathbf{s}^{-1/3}$ "strange"	4.201 GeV/c² $\mathbf{b}^{-1/3}$ "bottom"			0 (exactly) $\mathbf{g}^0$ "gluon"
0.511 MeV/c² e^- "electron"	0.106 GeV/c² μ^- "muon"	1.777 GeV/c² τ^- "tau"	91.19 GeV/c² $\mathbf{Z}^0$ "Z boson"	0 (exactly) γ^0 "photon"	
1 meV/c² ν_e^0 "e neutrino"	8.8 meV/c² ν_μ^0 "μ neutrino"	50 meV/c² ν_τ^0 "τ neutrino"	80.40 GeV/c² $\mathbf{W}^\pm$ "W boson"		
1st	2nd	3rd			

Generations of quarks and leptons **Boson force carriers**

This is to be contrasted with all previous lepton collider detectors that addressed, for example, *c* and τ, or *b*, or *Z*, ...

ALEPH: Steinberger pre-collaboration meetings

"We had open meetings about once a week ... at which all important design features .. were ... decided."

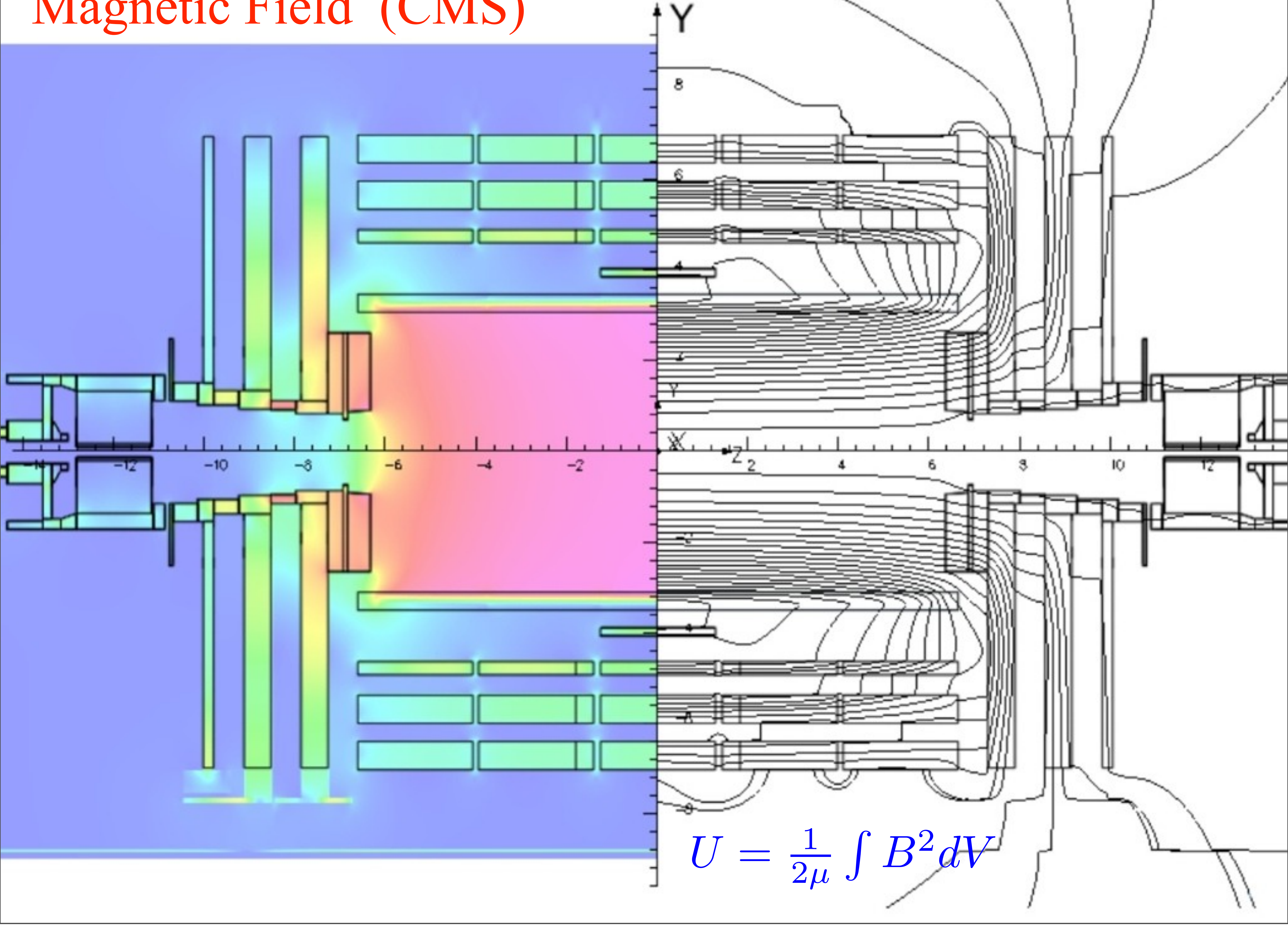
- "The *magnetic field* should be a superconducting solenoid with 1.5 Tesla ... a technical challenge."
- "The *main tracking* should be ... a TPC."
- "The *electromagnetic calorimeter* should be optimized for spatial rather than energy resolution ... for particle identification."
- "The *hadron calorimeter* should use the iron return yoke."
- "The detector naturally consists of a 'barrel' and two 'end caps'."

Magnetic Detector: Richter

"While SPEAR was being designed, we were ... thinking about the [detector]. In the 1965 SPEAR proposal, we had described two different kinds of detectors: the first, a *non-magnetic detector* that would have looked only at particle multiplicities and angular distributions, with ... crude particle-identification ...; the second, a *magnetic detector* that could add accurate momentum measurement ..."

Proceeding in the order of Steinberger ... Magnetic field, Tracking, EM calorimetry, Hadronic calorimetry, and overall Geometry

Magnetic Field (CMS)



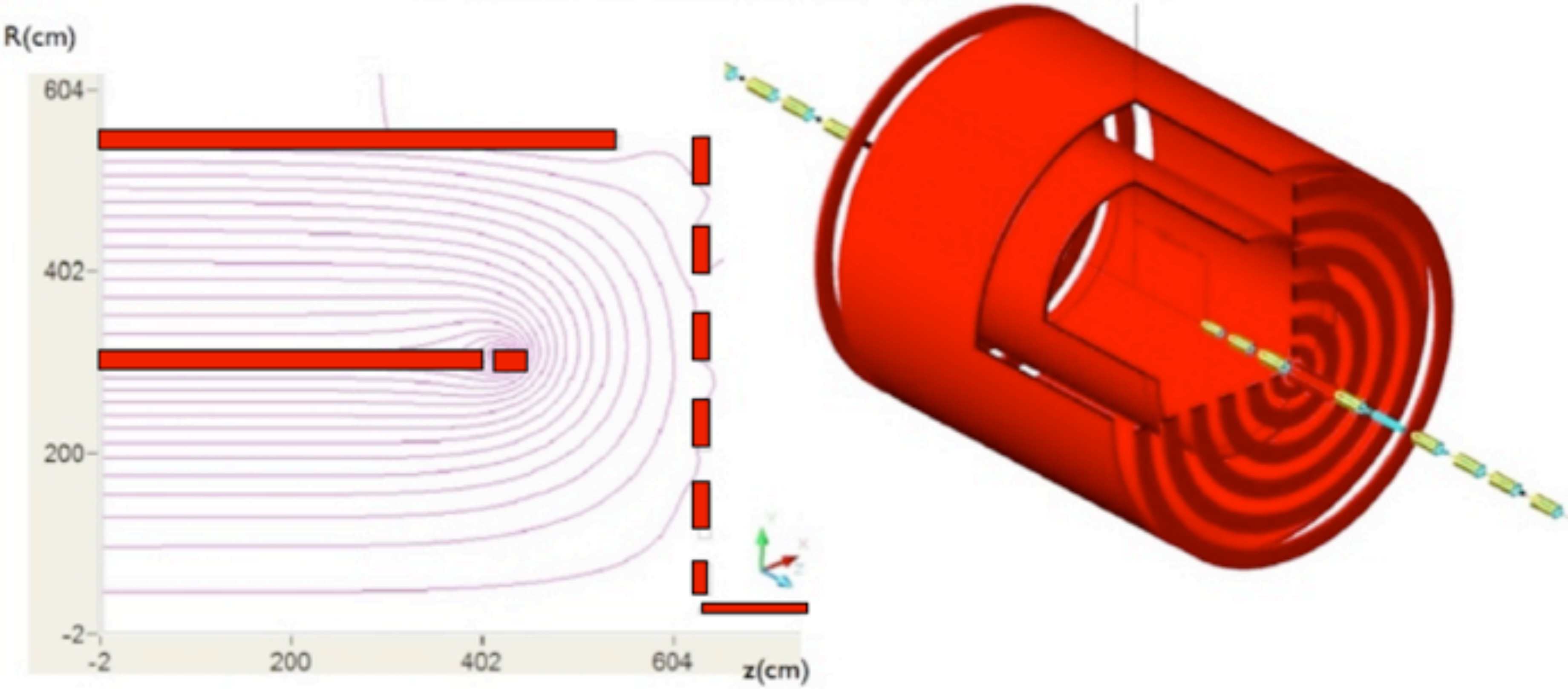
$$U = \frac{1}{2\mu} \int B^2 dV$$

The CMS solenoid and muon system is the standard for almost all detectors, and follows from the SPEAR Magnetic Detector.

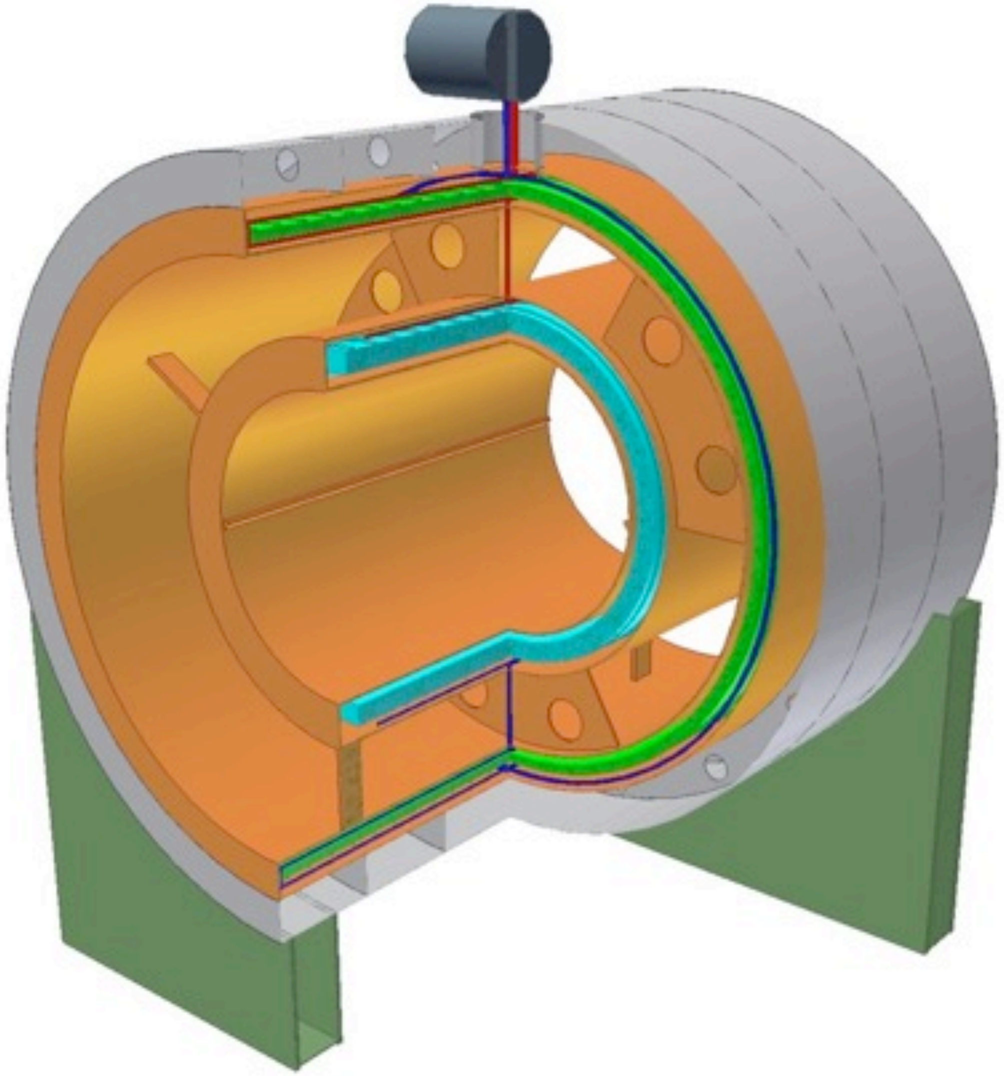
The lepton detectors at the ILC have a solenoidal field for tracking, but the iron return yoke is unnecessary: the flux can be returned by an outer solenoid.

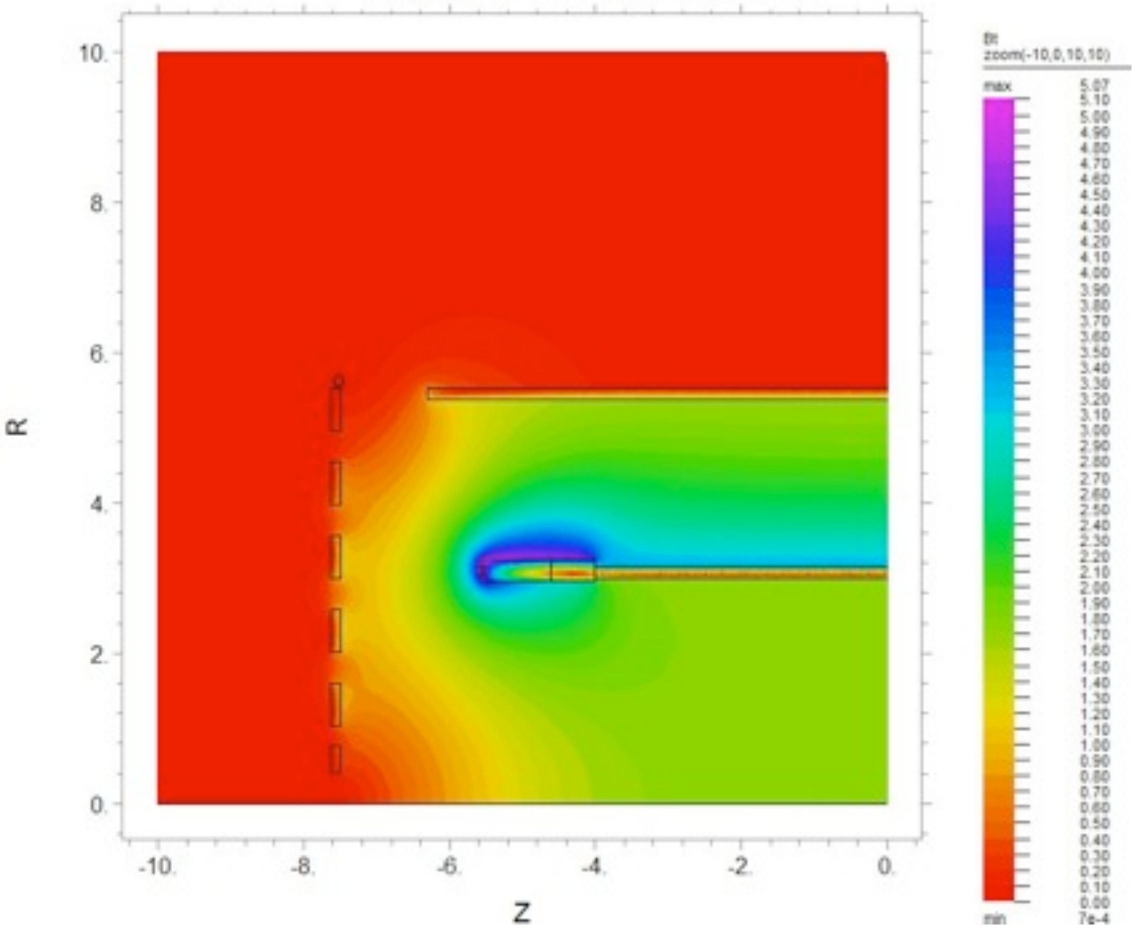
New magnetic field, new ``wall of coils", iron-free:
many benefits to muon detection and MDI,
Alexander Mikhailichenko design

Magnetic field of dual solenoid and wall of coils

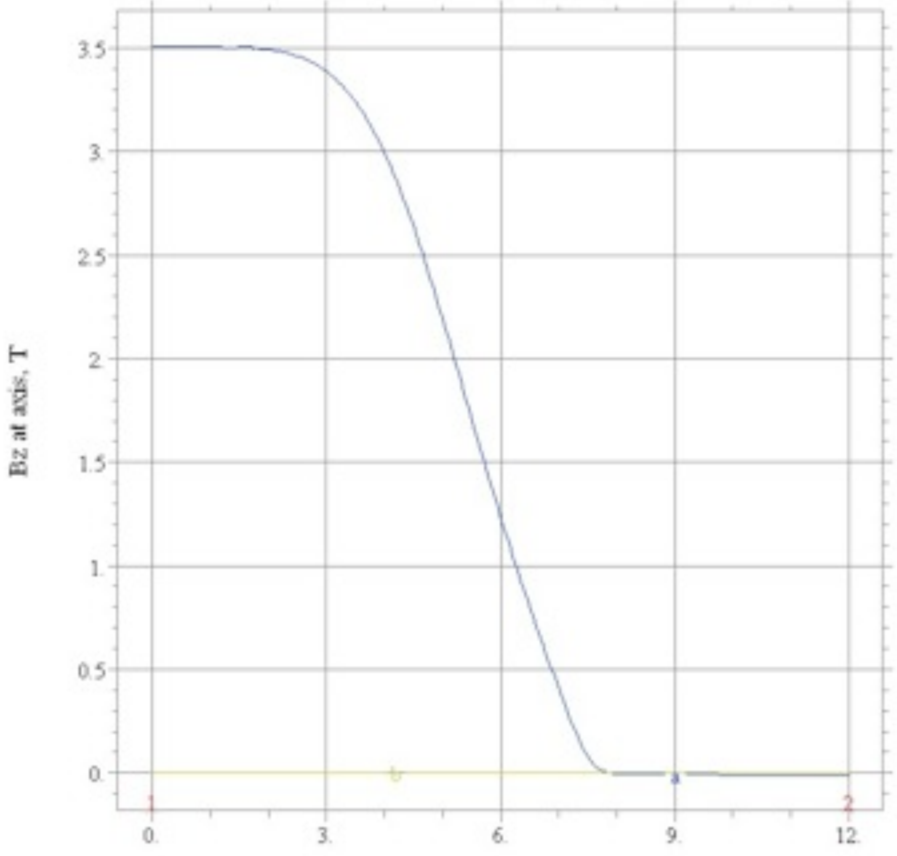


MAGNETIC DISCUSSION

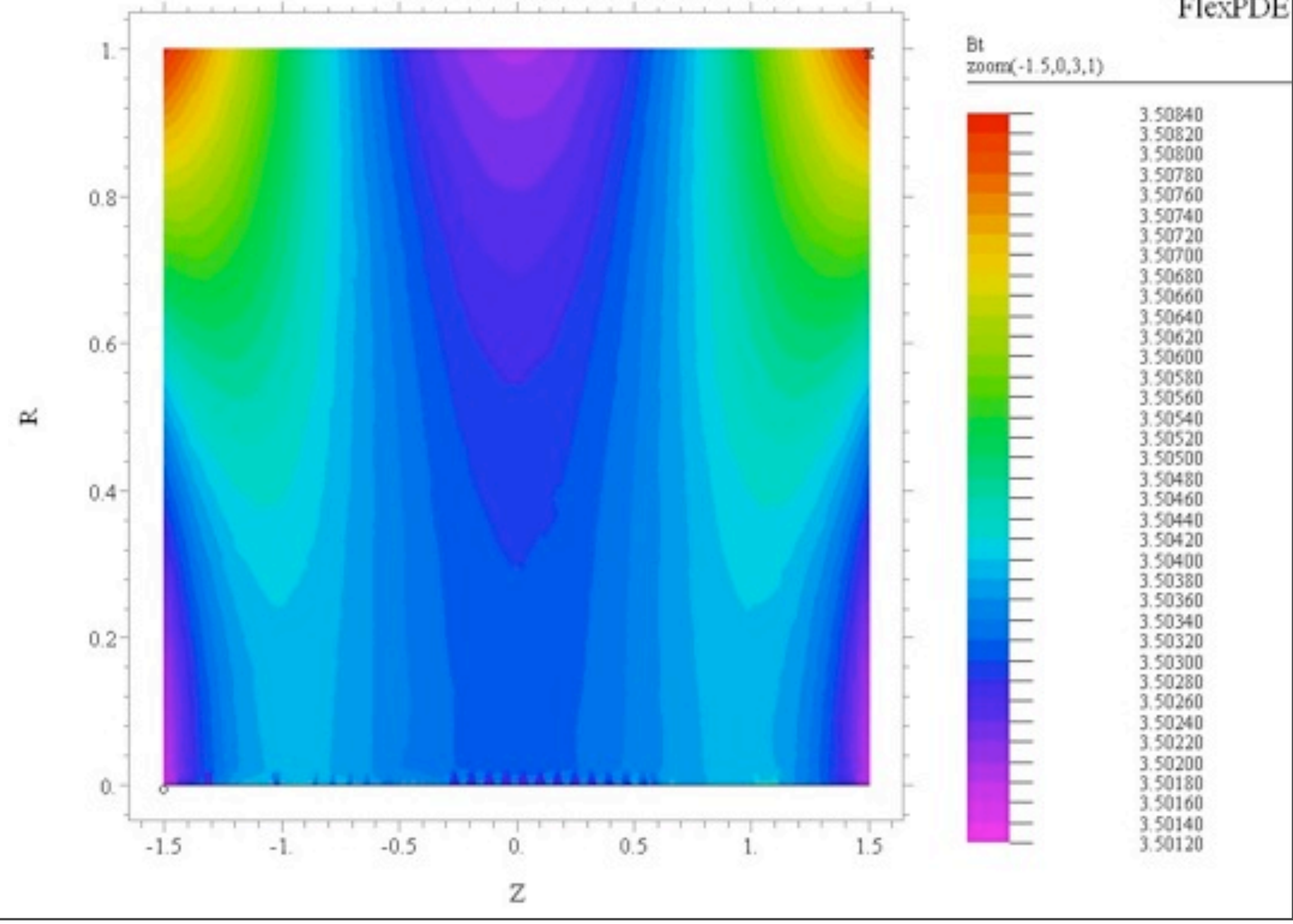




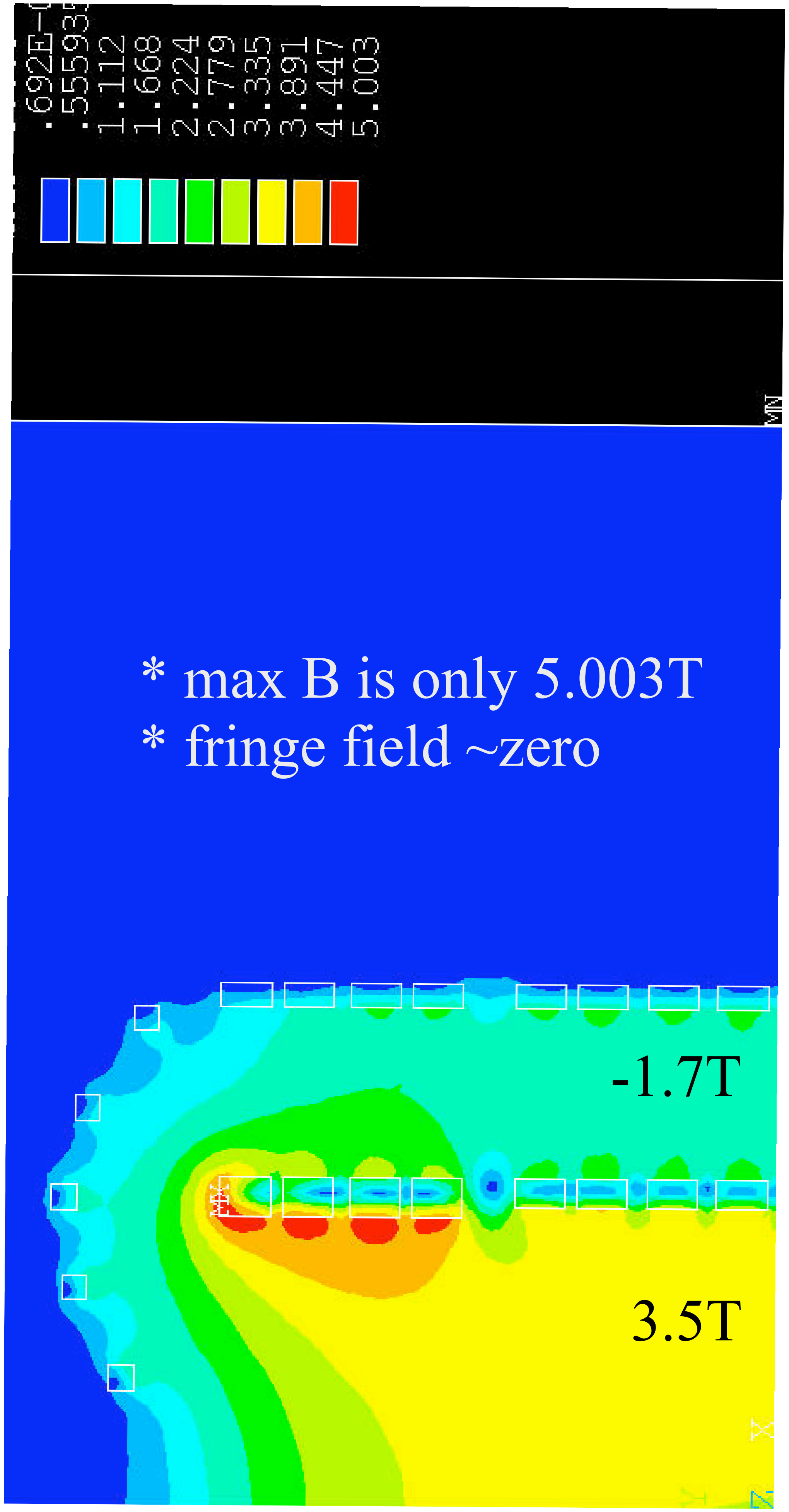
4TH DETECTOR EXTENDED



4TH DETECTOR EXTENDED



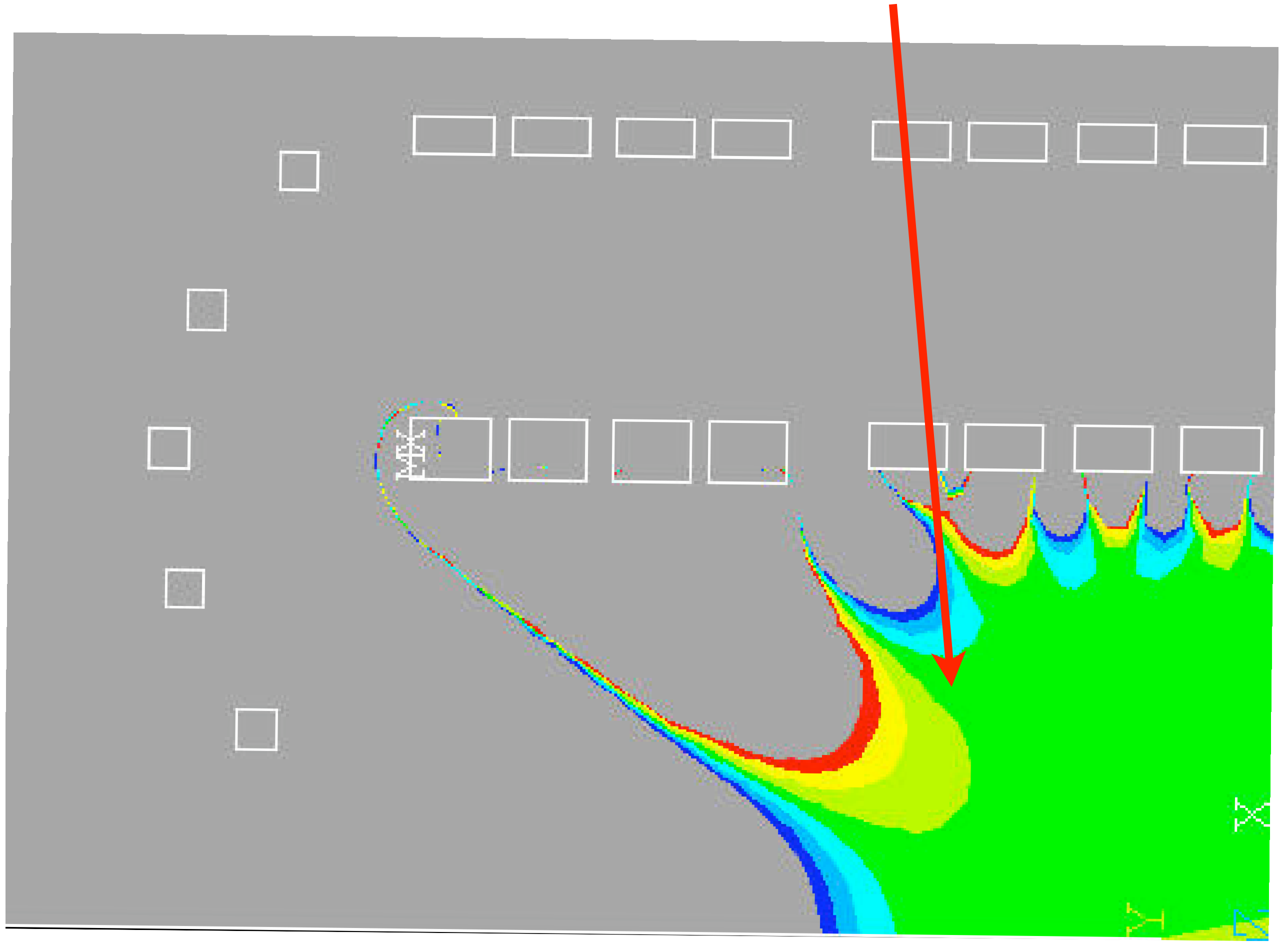
The turns can be lumped, not rectilinear



- max B is only 5.003T
- fringe field ~zero

M. Wake (KEK) solutions,
compared to Mikhailichenko’s,
means there is a continuum of
interesting solutions available.

Tracking field quality is excellent:
each color is dB/B=0.001



Dual solenoids: scientific advantages

- no iron: cheaper, more flexible detector; outer coil is big but easier than inner.
- precision measurement of muons outside calorimeter and inner solenoid.
- can reverse B field: cancel detector asymmetries in precision *b,c* asymmetry measurements; can run at B=0
- can insert specialized detectors in the annulus between the solenoids for new searches, new ideas, ...
- exceedingly flexible: can move calorimeter in *z*, do intra-detector surveying, re-configuration of detector, etc., no iron sarcophagus
- can insert a toroid to measure small angle tracks ...
- 15 kt lower mass, all mechanical problems in the IR are easier
- zero fringe field solves many problems, including stray fields on magnetic elements of the final focus

Tracking

For big colliders, there are three possibilities among the three ILC contenders:

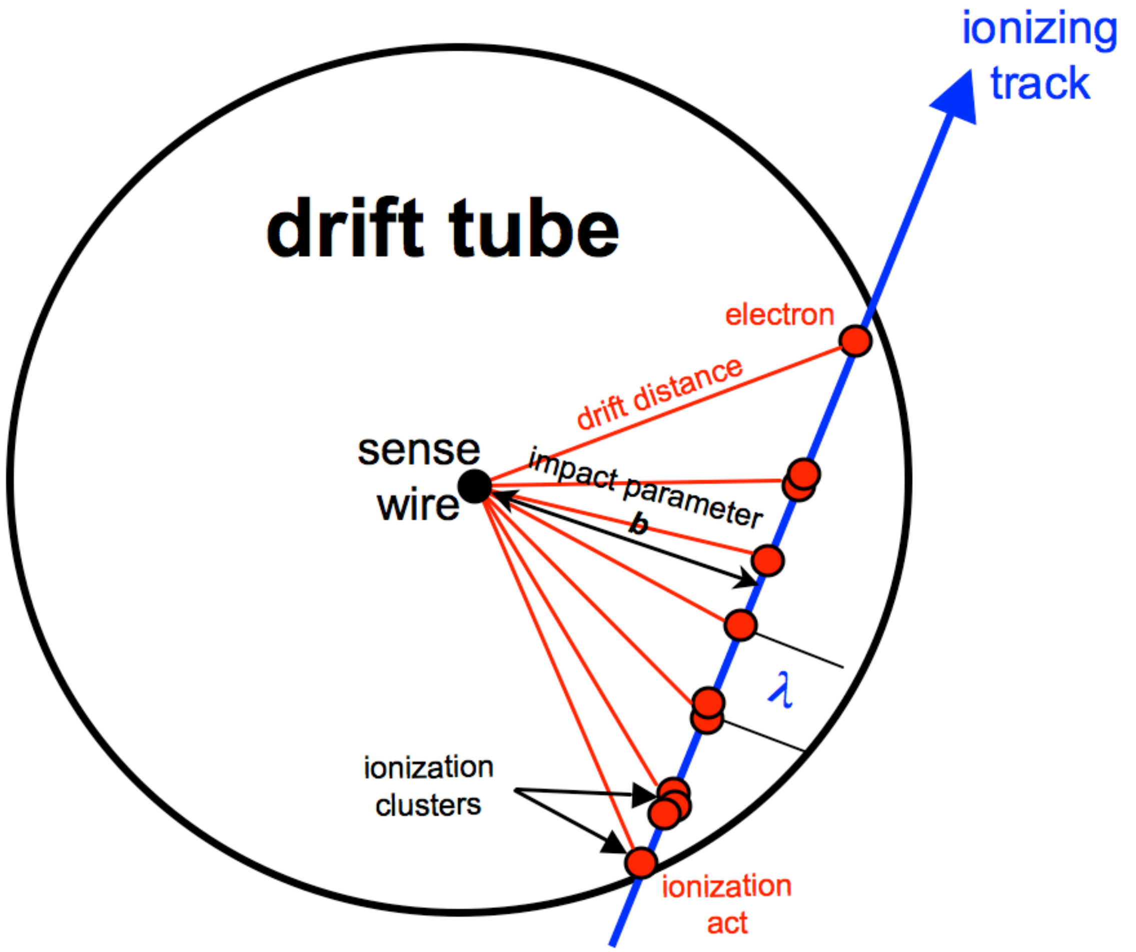
- all-silicon, 5-planes, 5-microns:
  - exceptional spatial resolution,
  - but only a few points on tracks and requires cooling

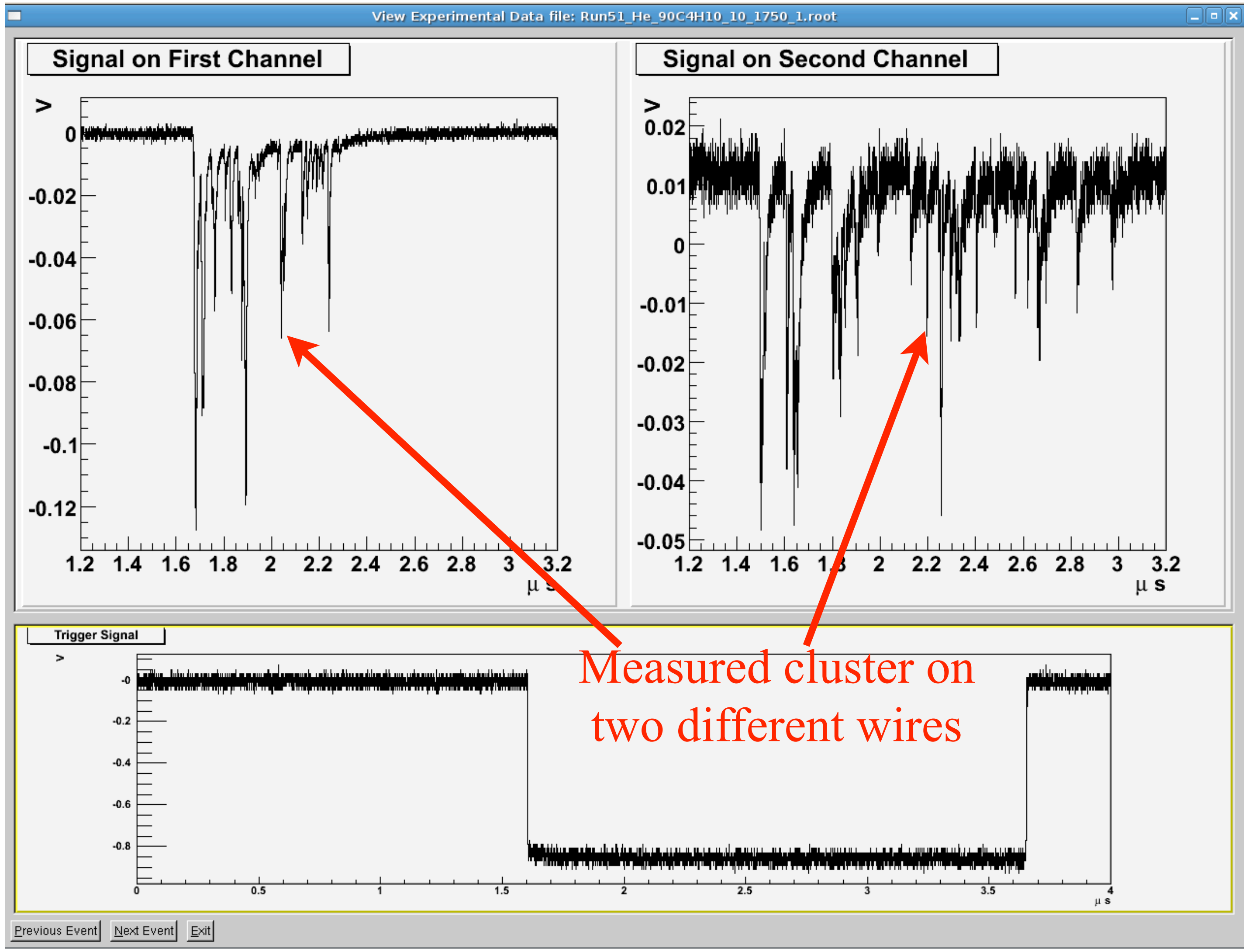
- a high-performance TPC:
  - spectacular spatial detail,
  - but slow and high-mass medium

- a KLOE-like drift chamber with cluster-timing:
  - “transparent” to x-ray debris in IR
  - spatial precision to 40 μm
  - *dN/dx* specific ionization particle ID to 3.5%

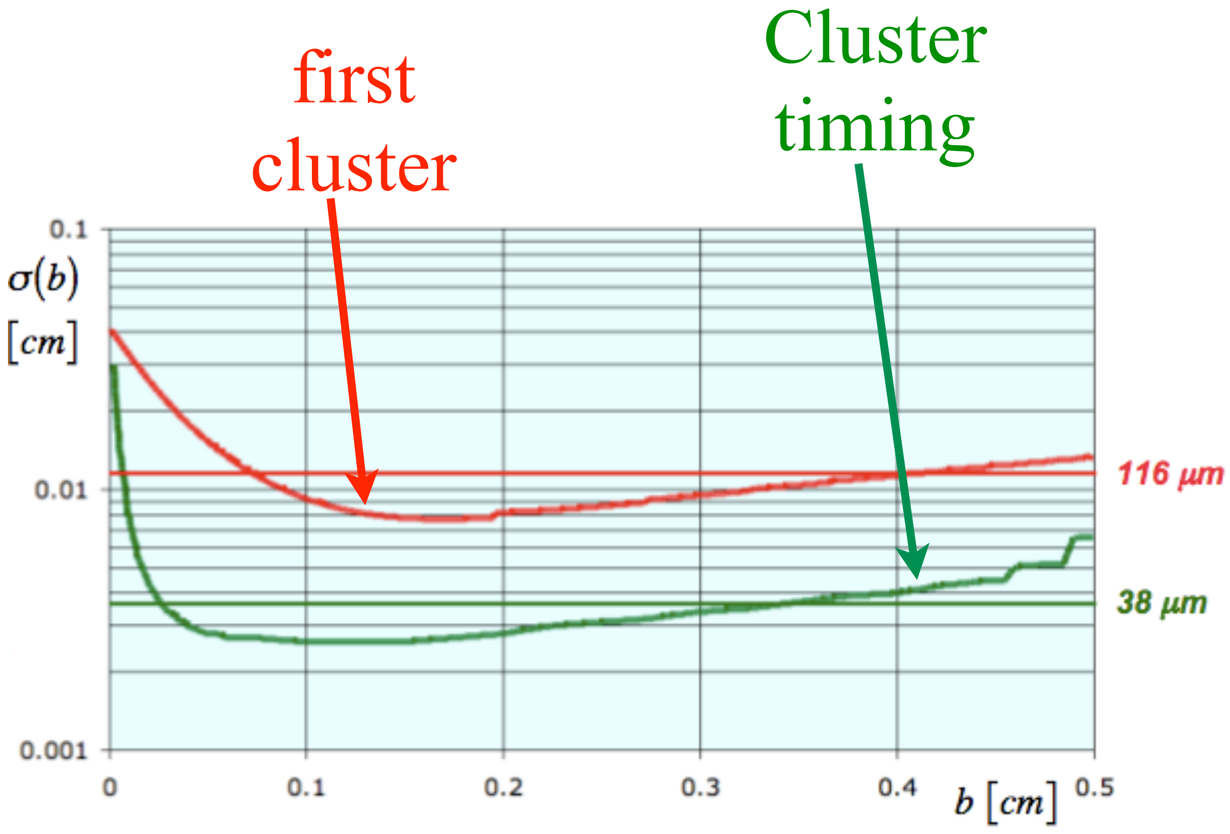
Cluster-timing (new, beyond Charpak)

of *every* electron cluster




View Experimental Data file: Run51_He_90C4H10_10_1750_1.root

Measured cluster on two different wires


first cluster

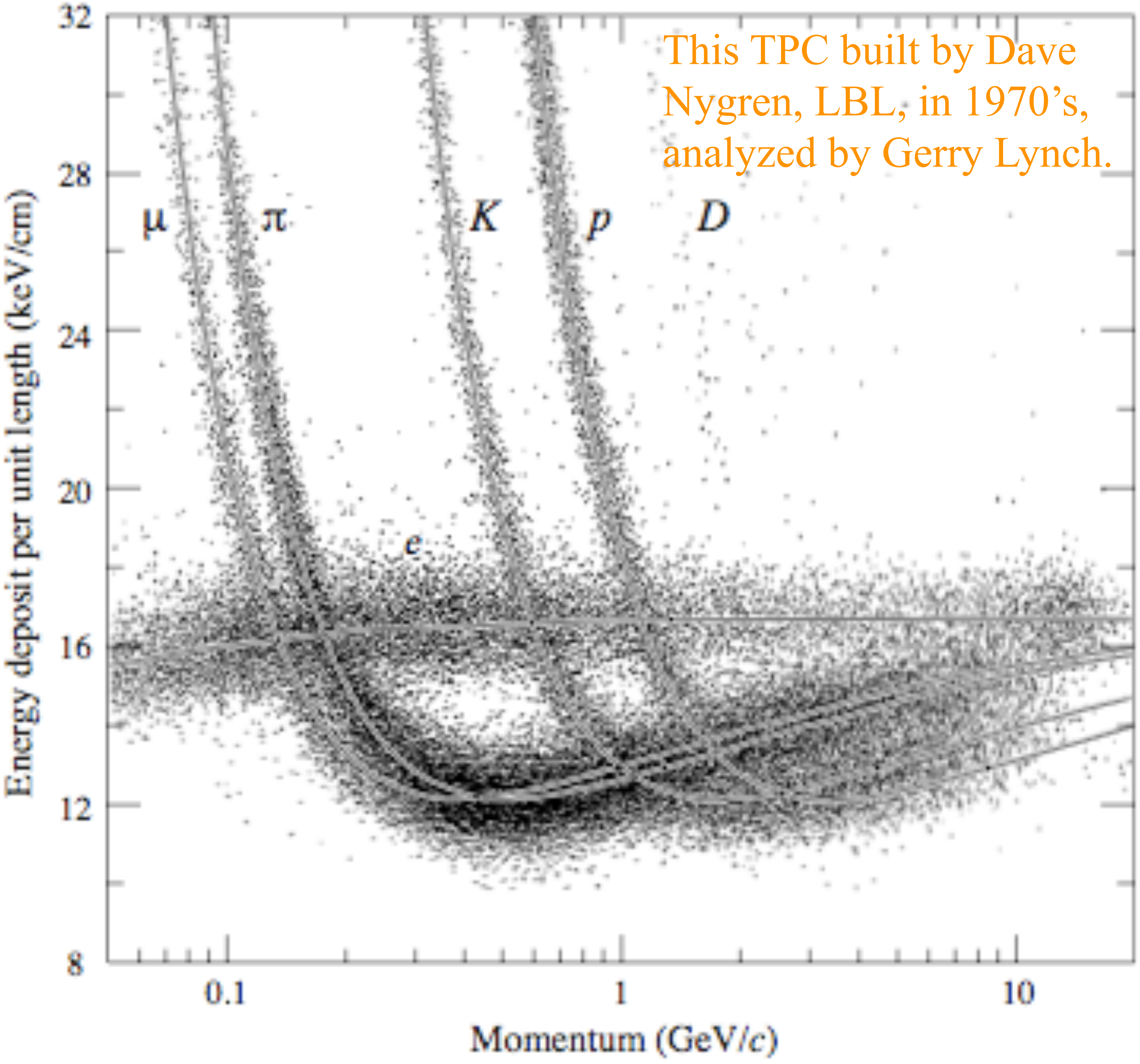
Cluster timing

Ultra-low-mass chamber, expect ~40 μm spatial resolution on each of 150 points on a track.

KLOE-like drift chamber with cluster-timing electronics

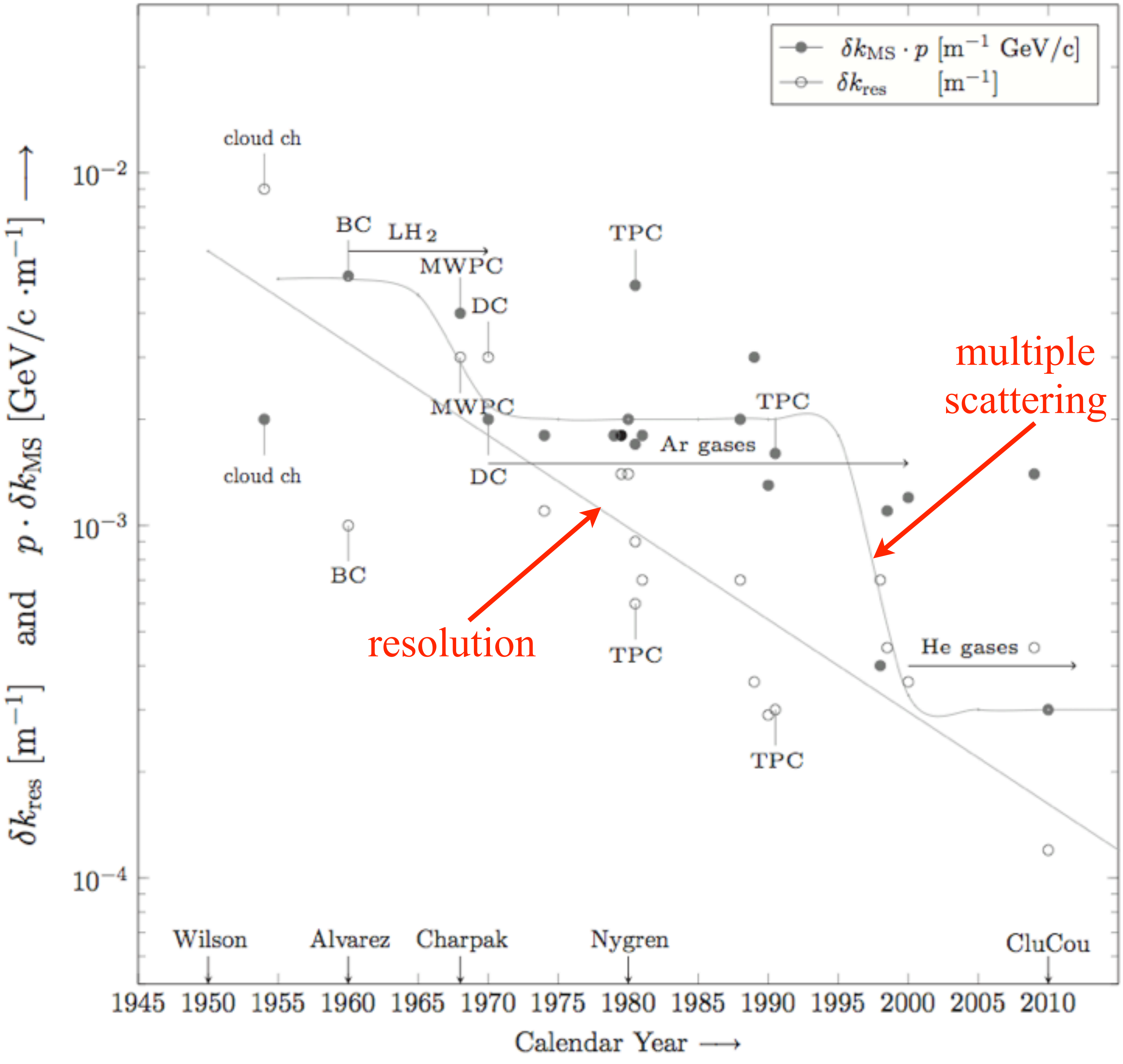
Cluster counting is Poisson (no Landau fluctuations), expect 3.5% *dN/dx* measurement of specific ionization

TPC with ~6% *dE/dx* (world record) using truncated mean on 180 samples



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

Evolution of the curvature uncertainties in tracking chambers; F. Grancagnolo



multiple scattering

resolution

EM calorimetry

Many “easy” excellent solutions demonstrated
in current experiments: CsI, PWO, LSO.
There is nothing more I can add.

Hadronic calorimetry

A much more difficult and contentious problem. Expensive and not fully understood, even by major practitioners.

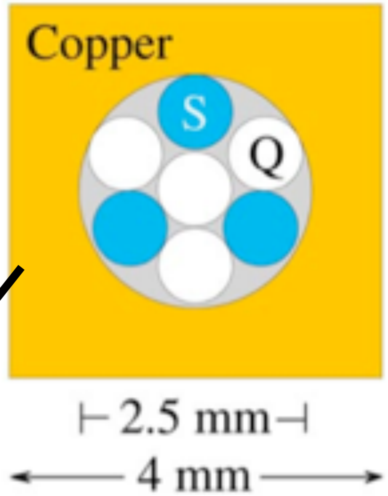
There are two major R&D efforts today, "particle flow" calorimetry and the other on "dual-readout" calorimetry. I will discuss only dual-readout since I believe it will prevail as the better choice for high-precision detectors of the future.

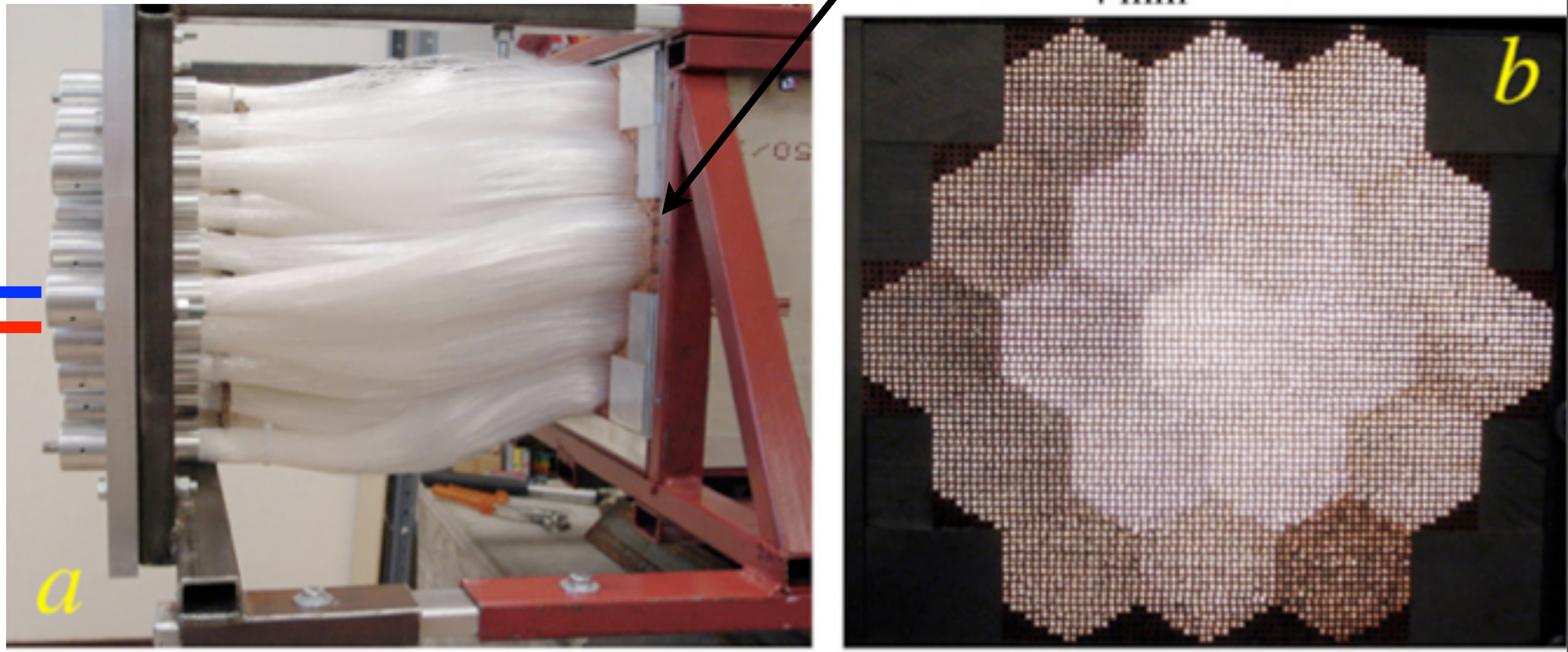
Best single reference on dual-readout is the proposal to the SPS Council:

"Dual-Readout Calorimetry for High-Quality Energy Measurements,"
R. Wigmans, DREAM Collaboration, CERN-SPSC-2010-012,
SPSC-M-771, 31 March 2010.

The *simple* proof-of-principle DREAM module

These extruded tubes are just stacked up to make the module



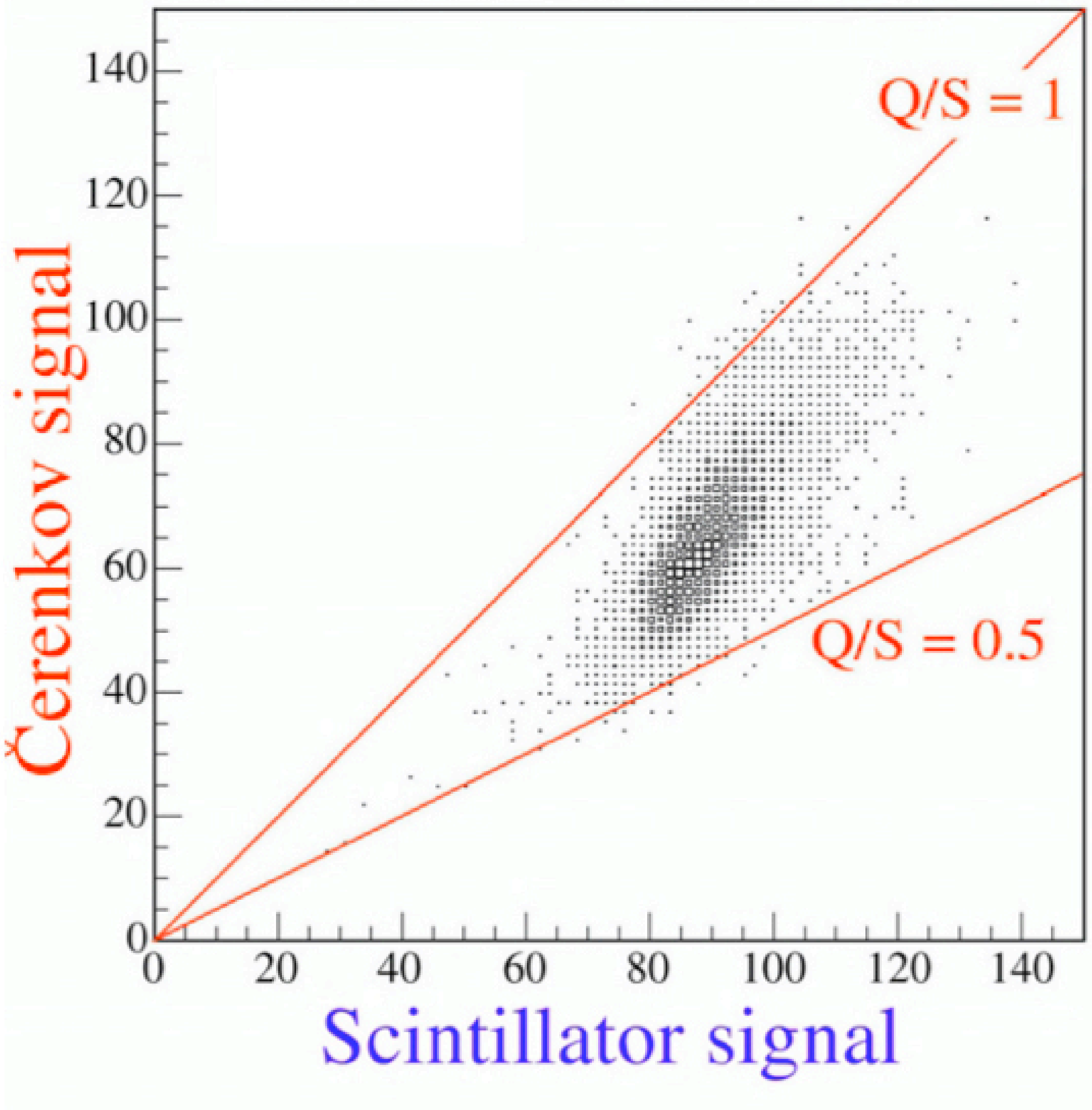


Scintillation fibers see all charged

Cerenkov fibers mostly see relativistic electrons
f_{EM} = EM fraction

Fluctuations in the EM fraction are responsible for almost all of the problems of hadronic calorimetry: measurement of f_{EM} event-by-event solves these problems.

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



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

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

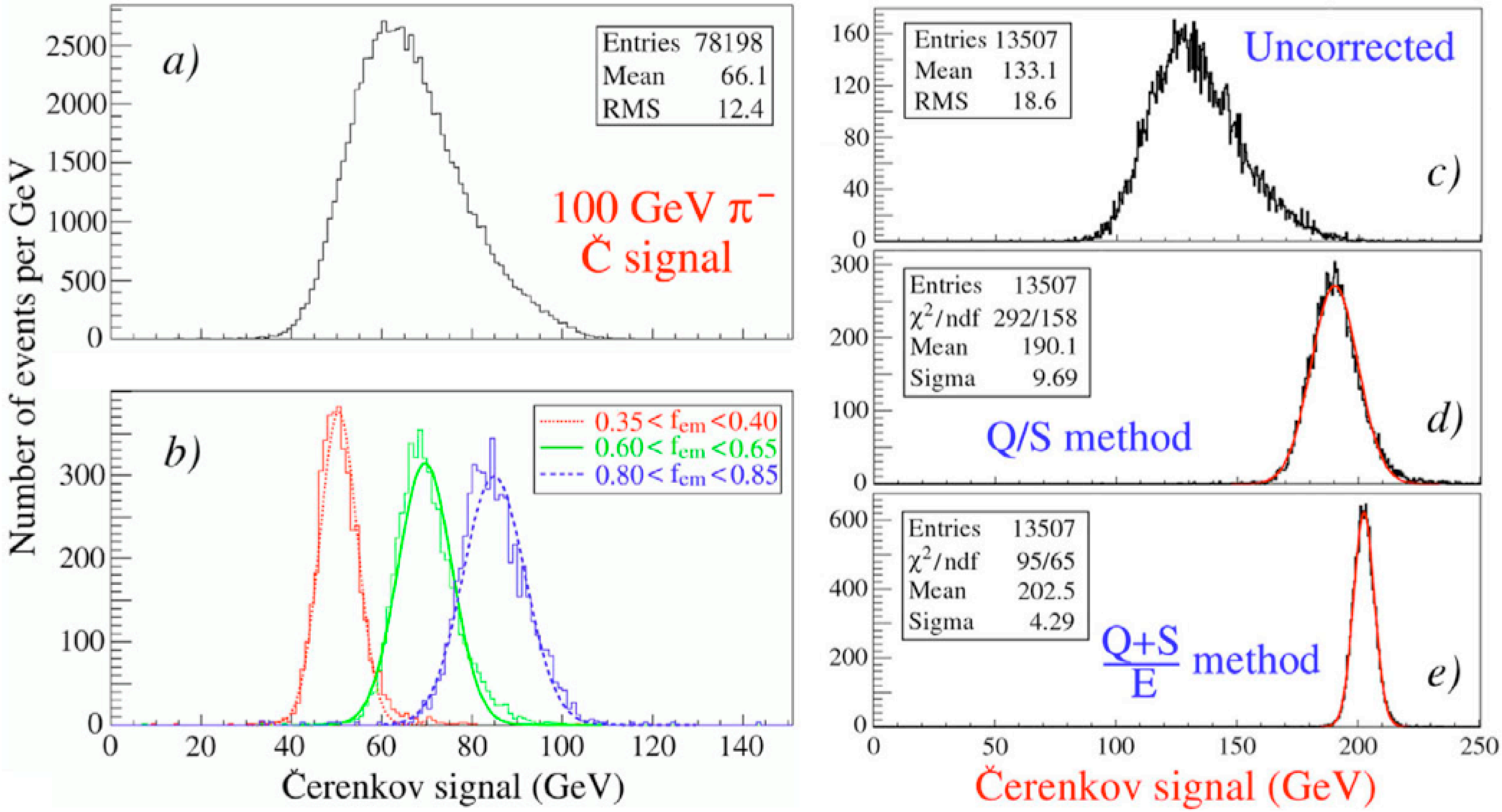
$e.g.$ If $e/h = 1.3$ (S), 4.7 (Q)

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

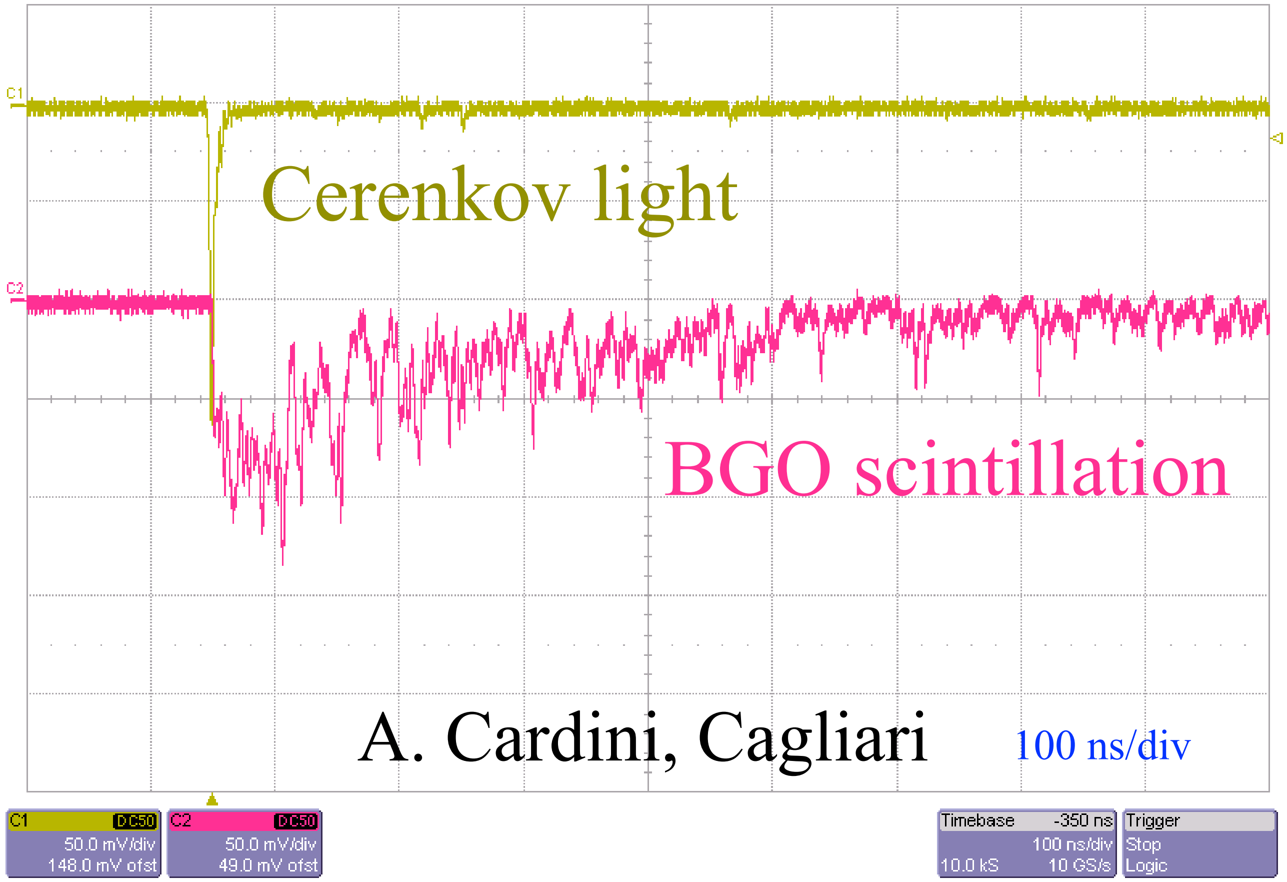
$$\boxed{E = \frac{S - \chi Q}{1 - \chi}} \quad (4)$$

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 !



Dual readout in BGO crystals

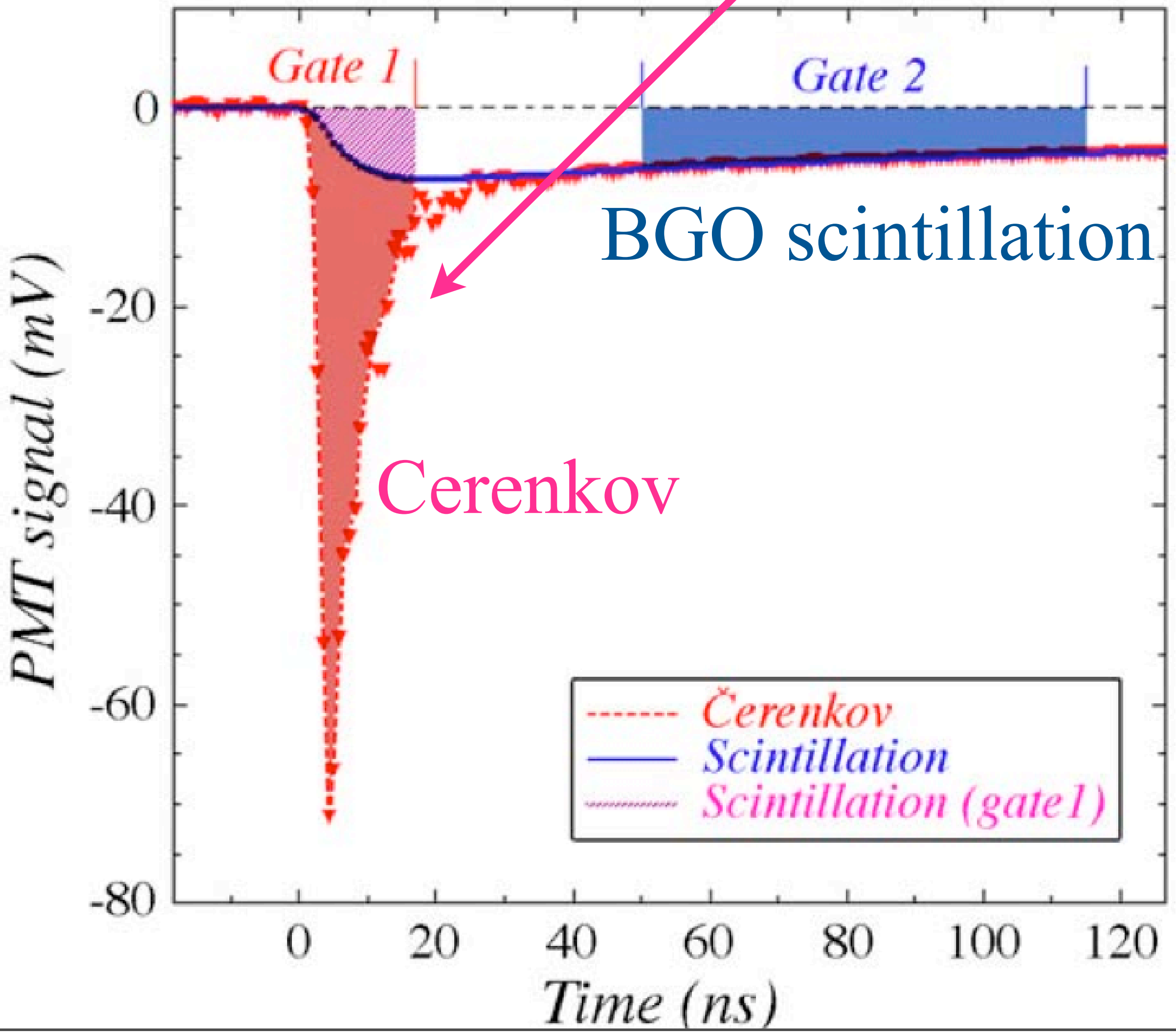


A. Cardini, Cagliari

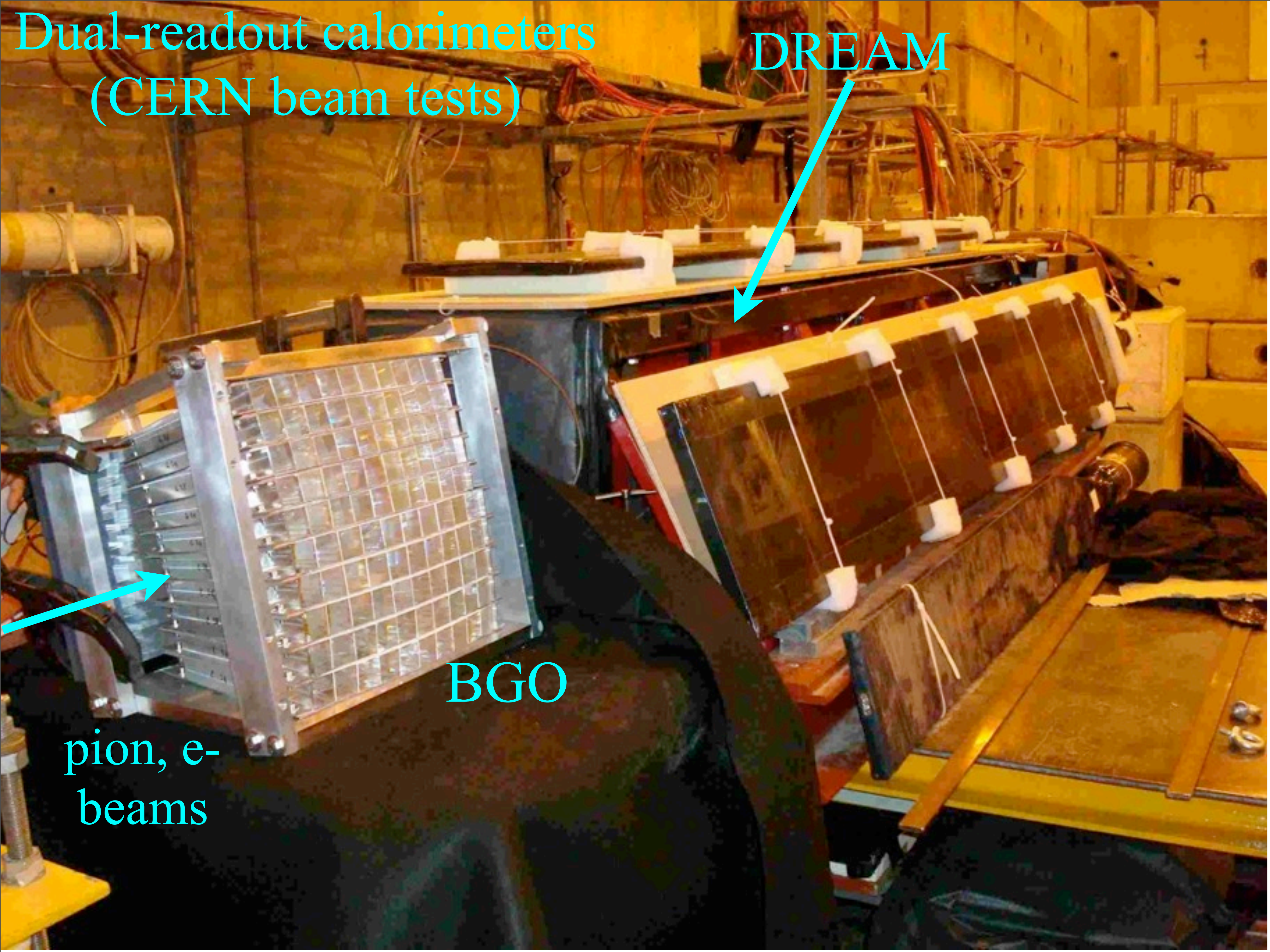
Single cosmic muon
(2 PMTs)

L3 BGO
crystal

e^- beam, 1PMT



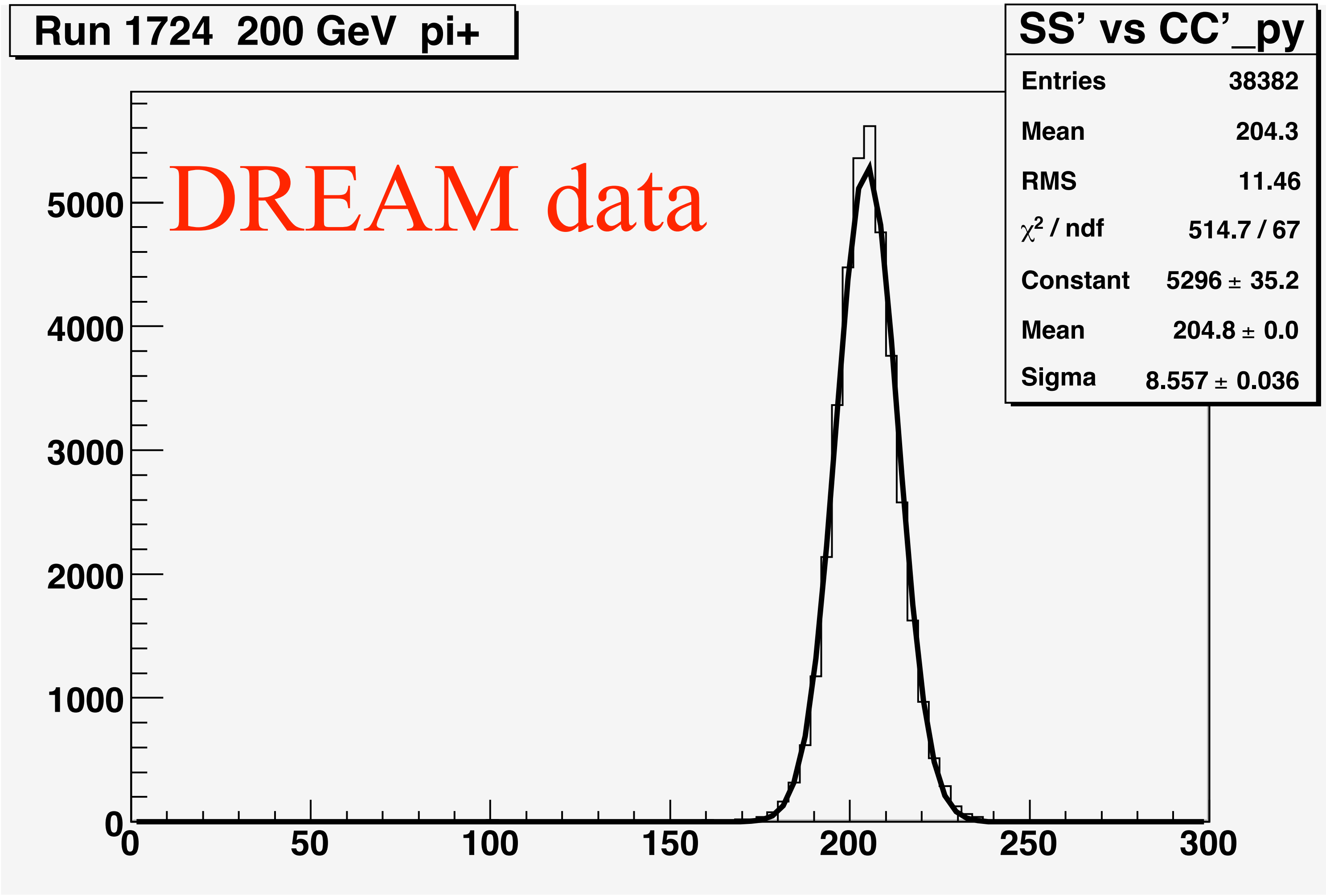
Dual-readout calorimeters (CERN beam tests)

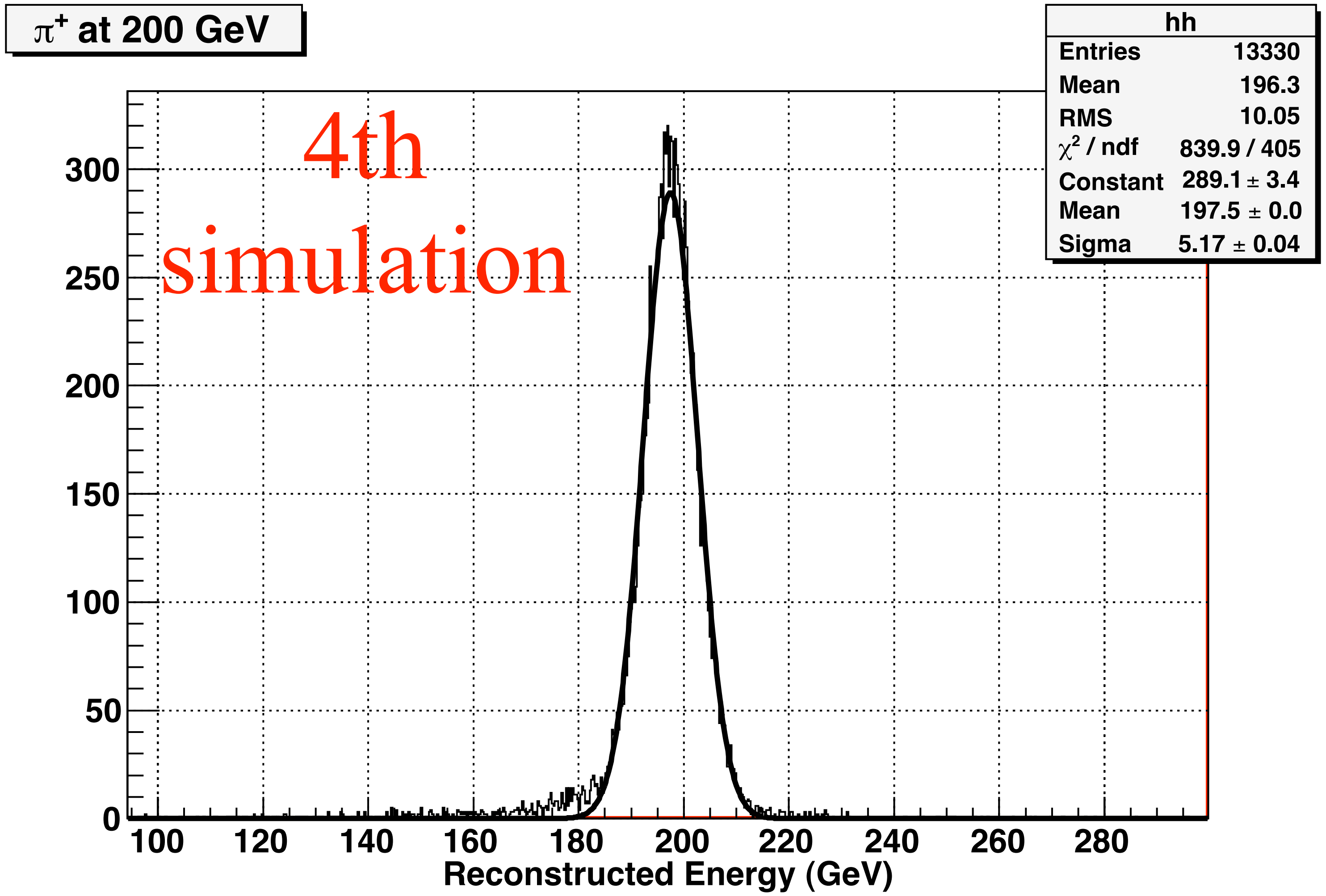


The DREAM Collaboration (Cagliari, CERN, Cosenza, Iowa State, Pavia, Pisa, Rome, Texas Tech)

(Will answer K. Hara's question.)

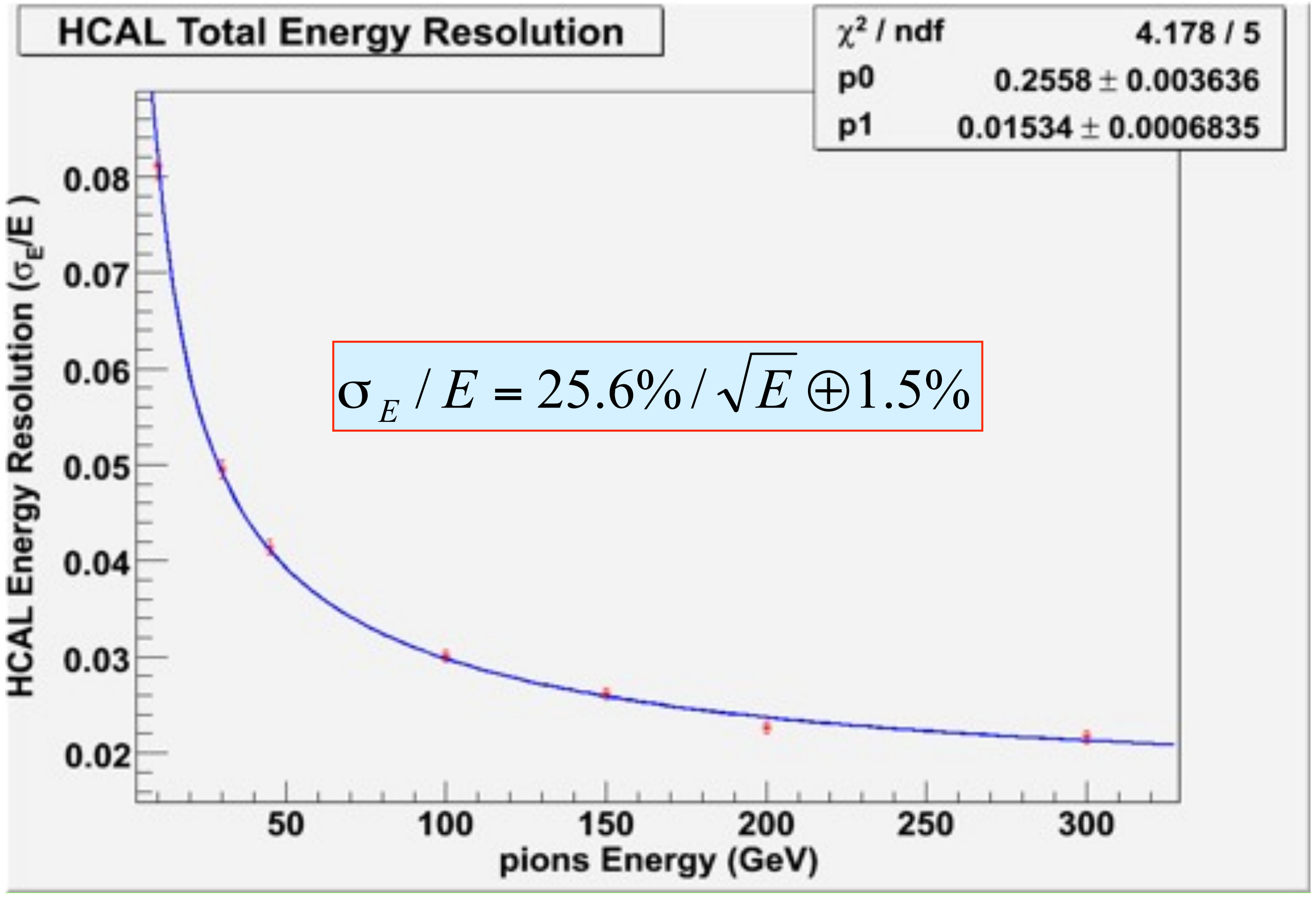
BGO+fiber calorimeter
at 200 GeV





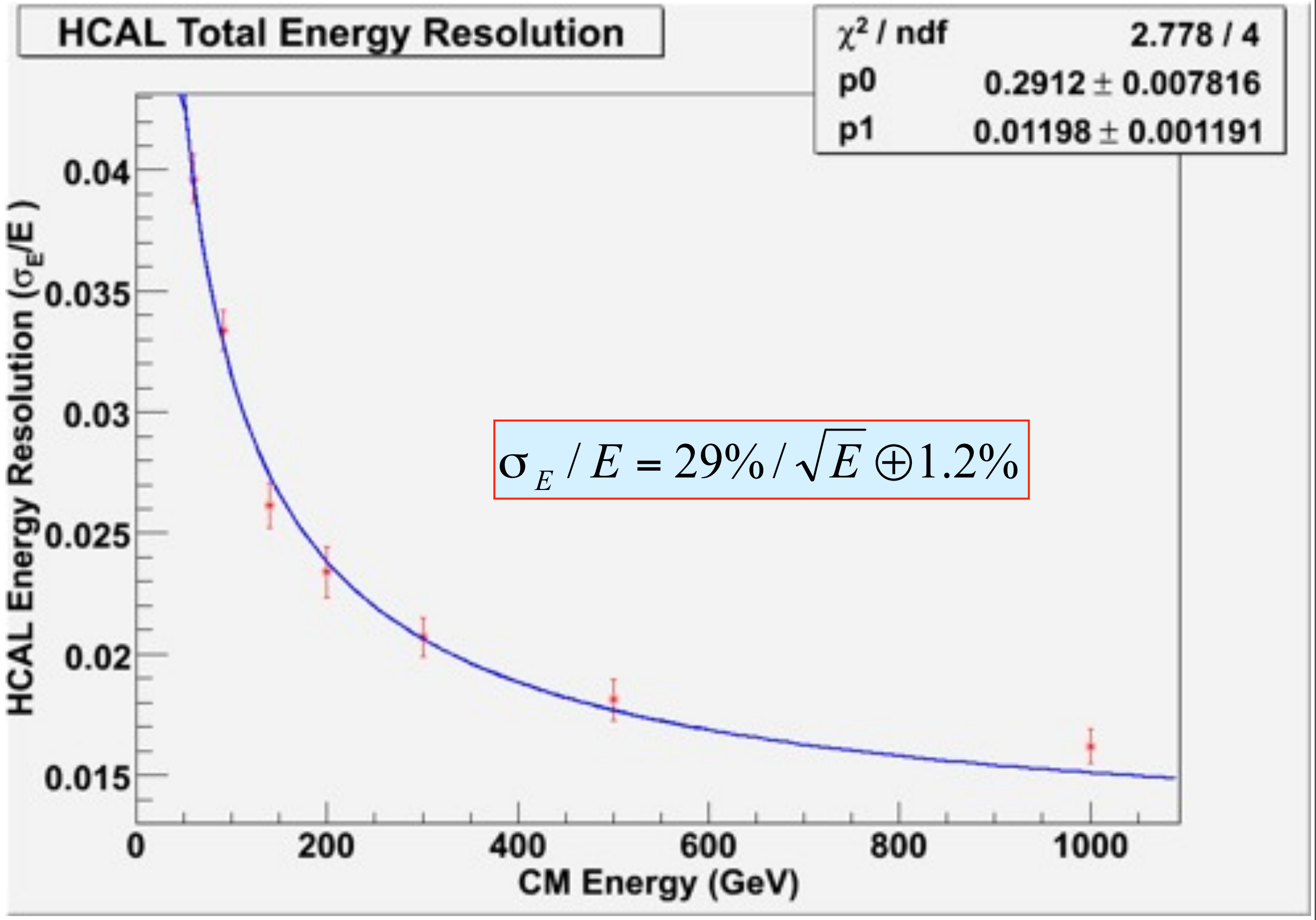
4th dual-readout simulation performance up to 1 TeV

Single π



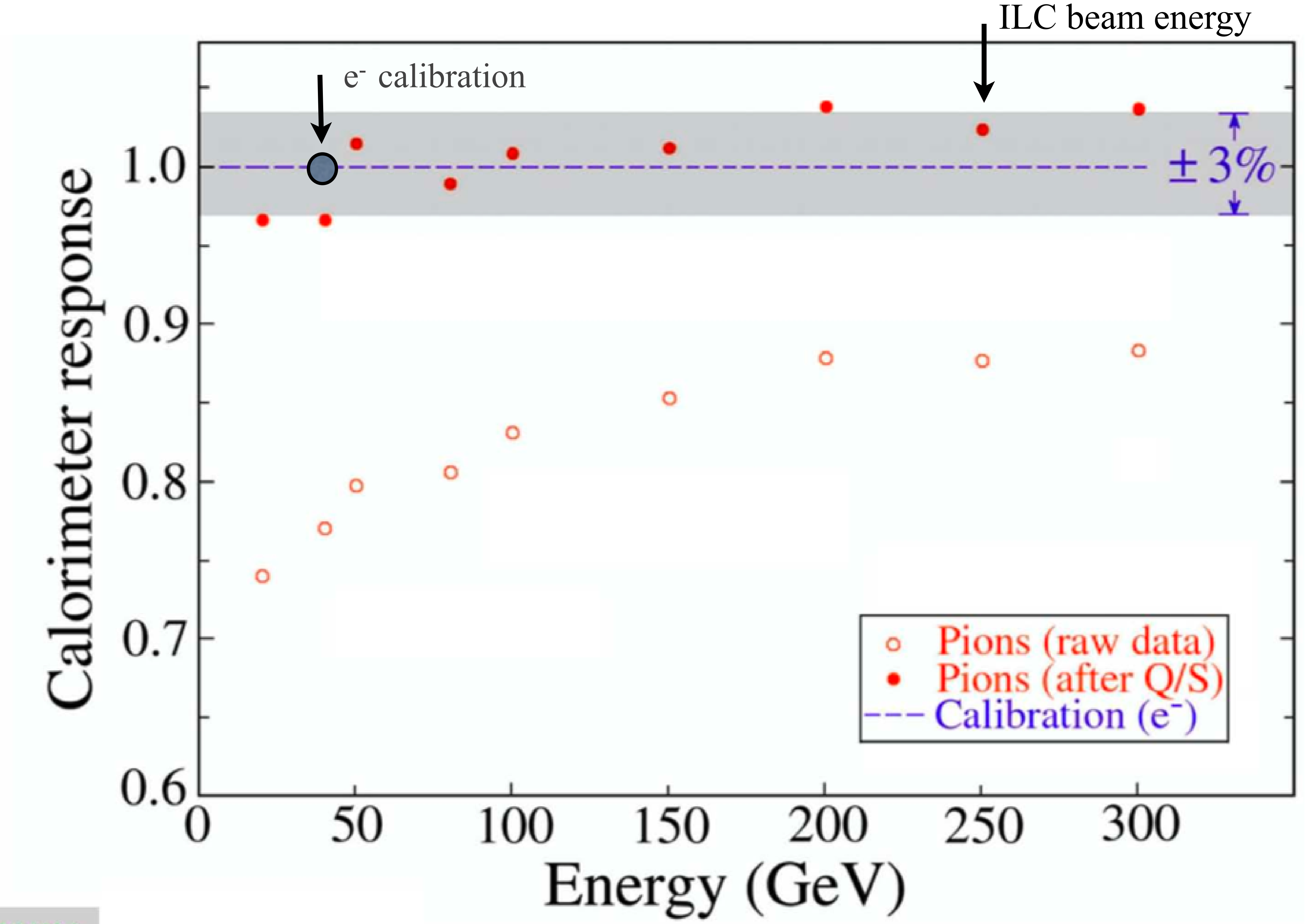
$$\sigma_E / E = 25.6\% / \sqrt{E} \oplus 1.5\%$$

Di-jets (total energy)



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

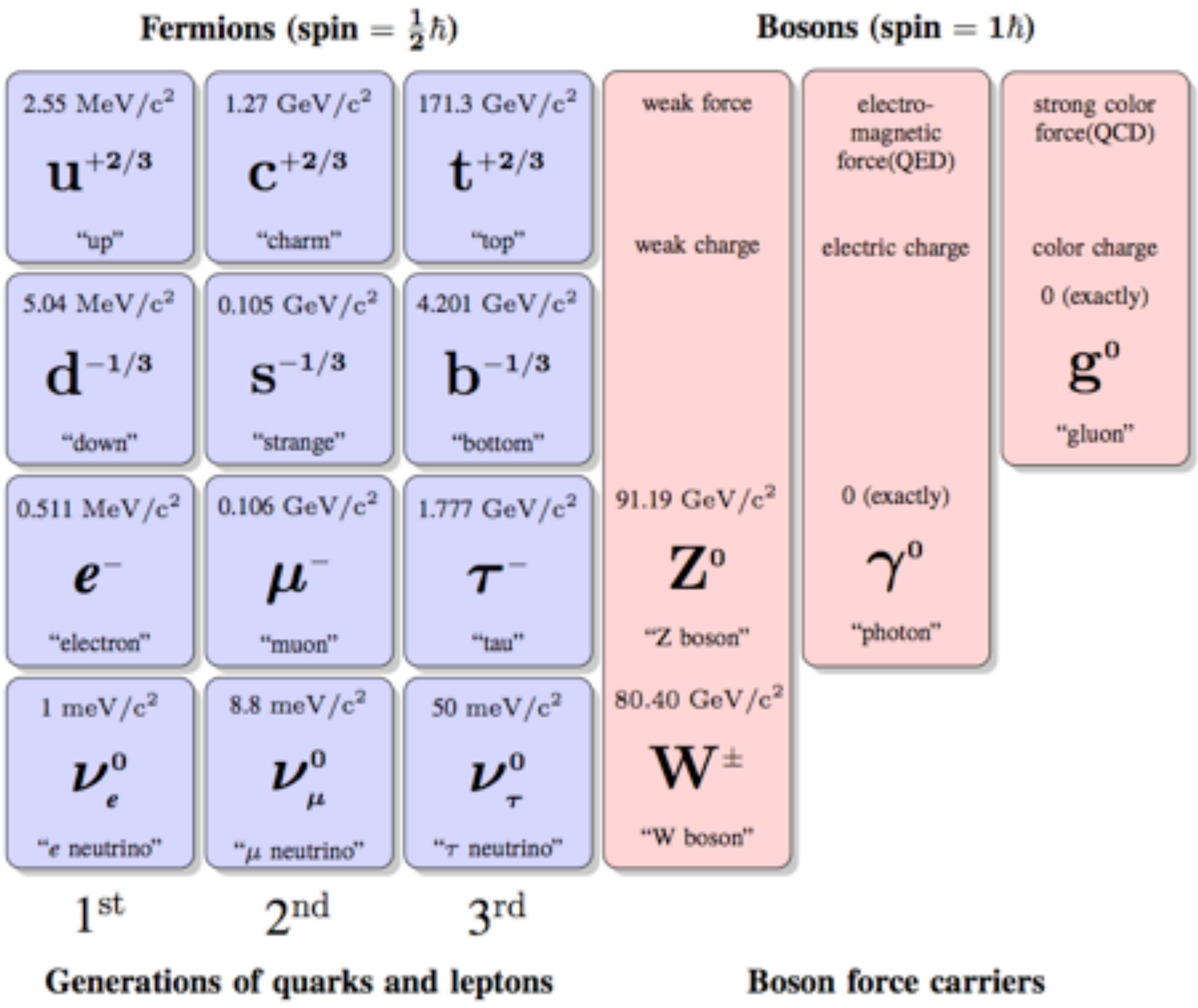
Hadronic response linearity



From:
NIM A537 (2005) 537

Particle Identification

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



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1 meV/c² ν_e^0 "e neutrino"	8.8 meV/c² ν_μ^0 "μ neutrino"	50 meV/c² ν_τ^0 "τ neutrino"	80.40 GeV/c² $W^\pm$ "W boson"		
1st	2nd	3rd			

Generations of quarks and leptons **Boson force carriers**

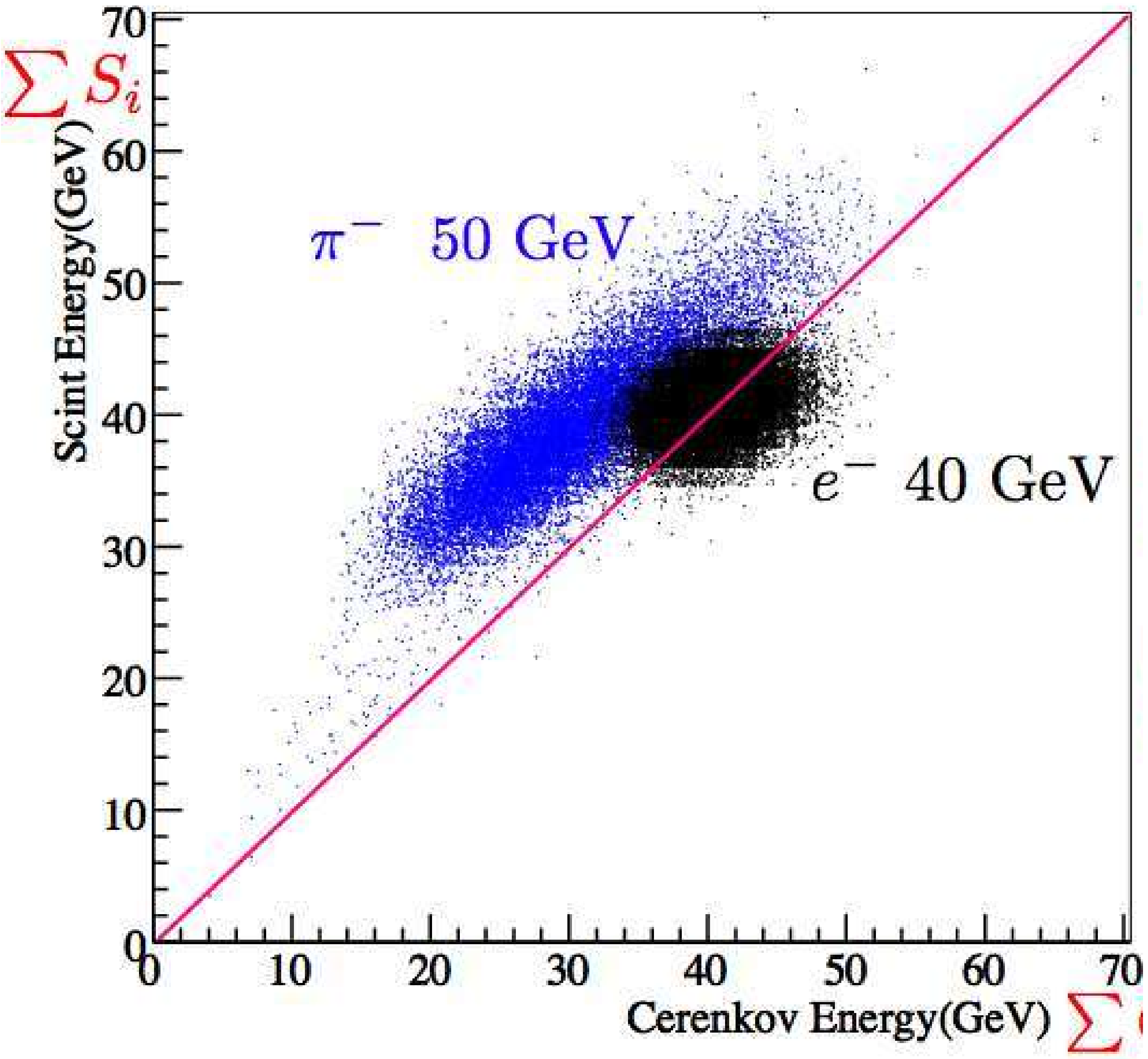
- *uds* quarks (jet energy resolution)
- *c,b* quarks (vertex tagging)
- *t* quark (reconstruction)

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

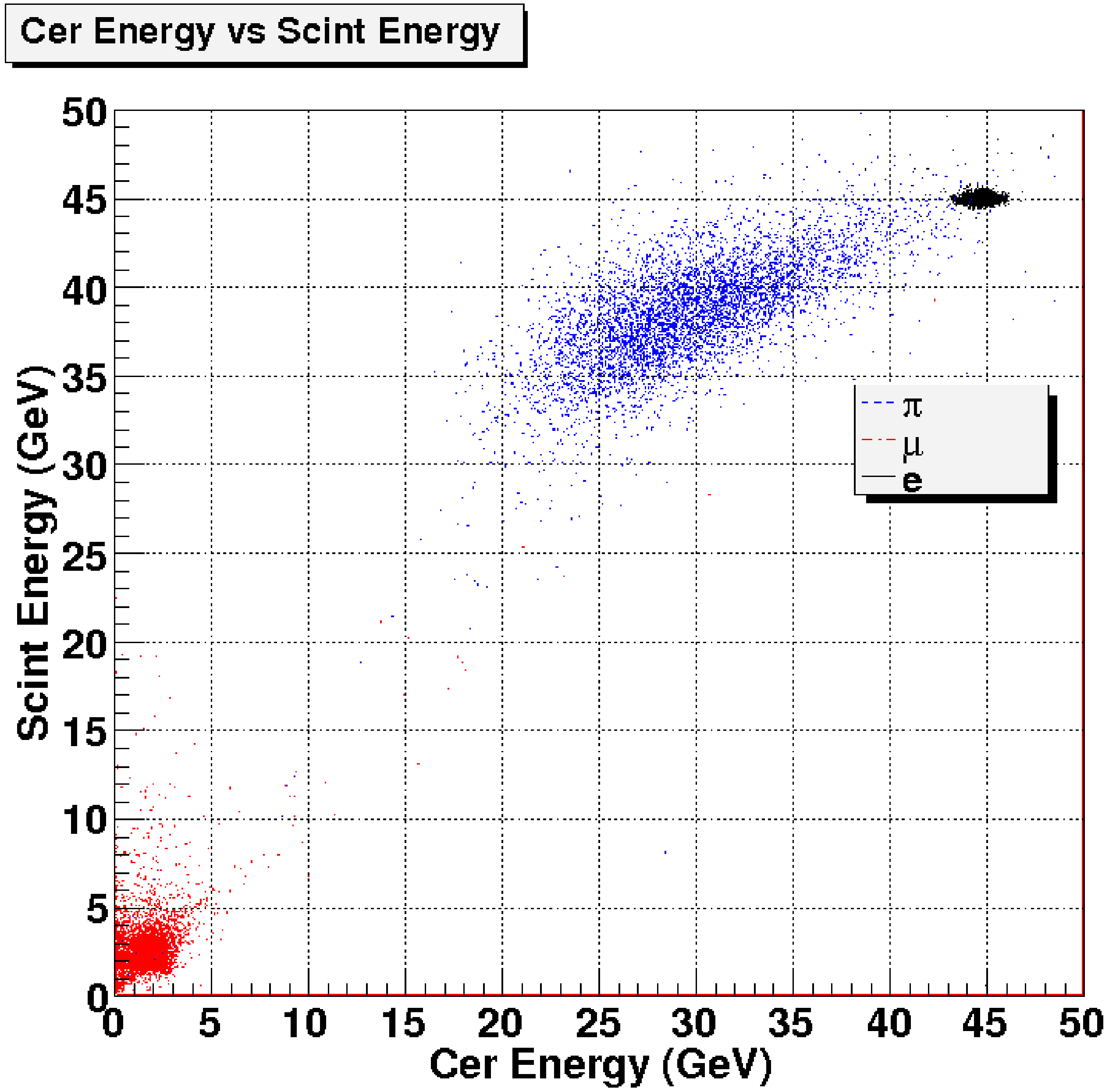
- *W,Z* (hadronic jet reconstruction)
- *photon* (BGO dual readout)
- *gluon* (jet energy resolution)

S *vs.* C → e - μ - $\pi^{\pm}$

DREAM data

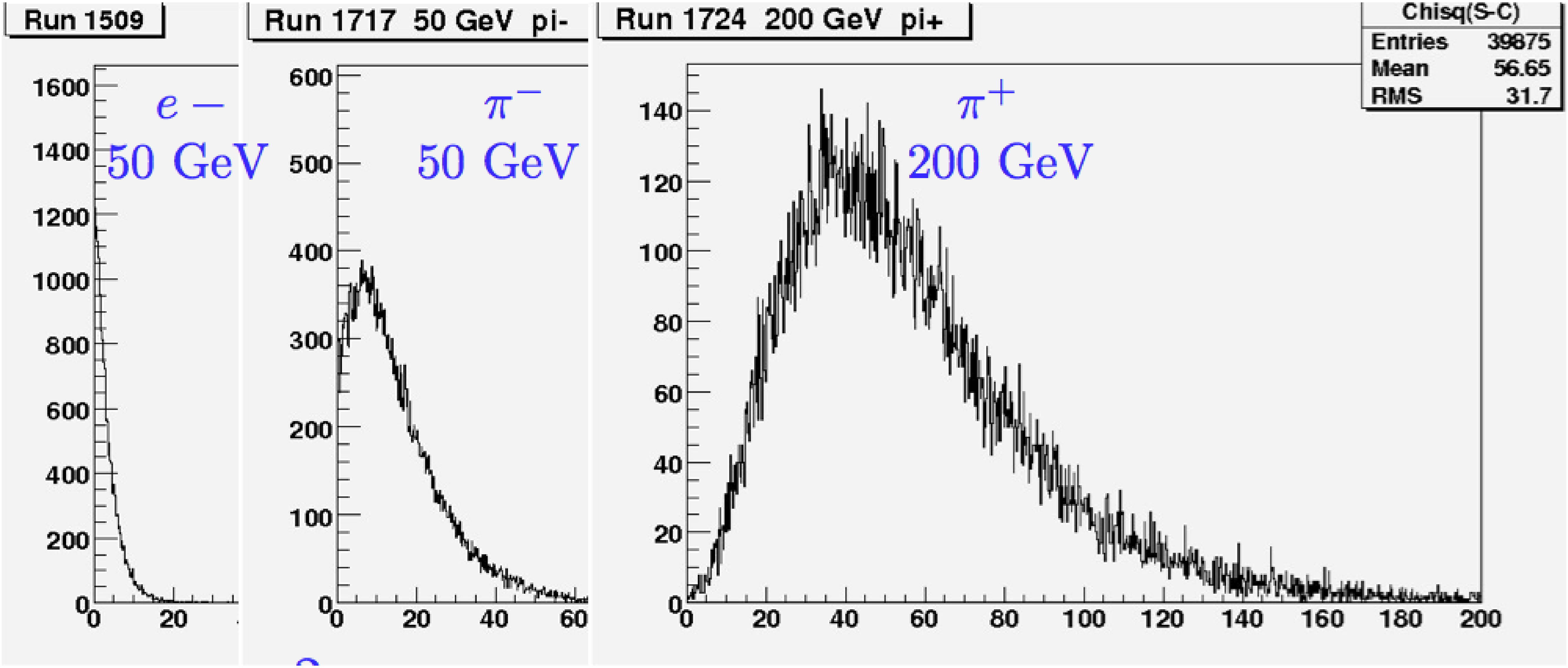


4th simulation (45 GeV)



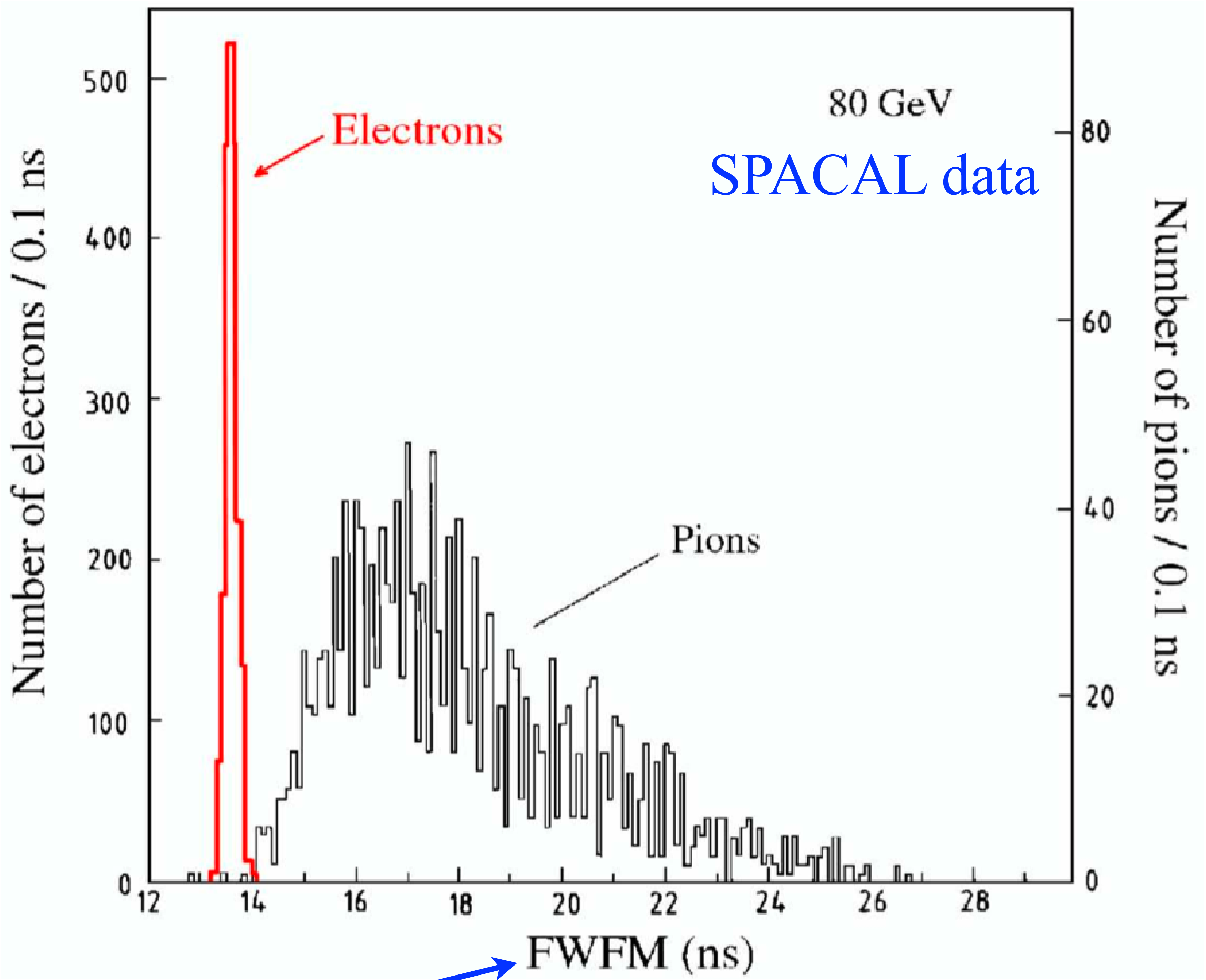
Fluctuations in *(S-C) among the channels of a shower* → *EM-hadron*

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



Time-history S(t) scintillating fibers

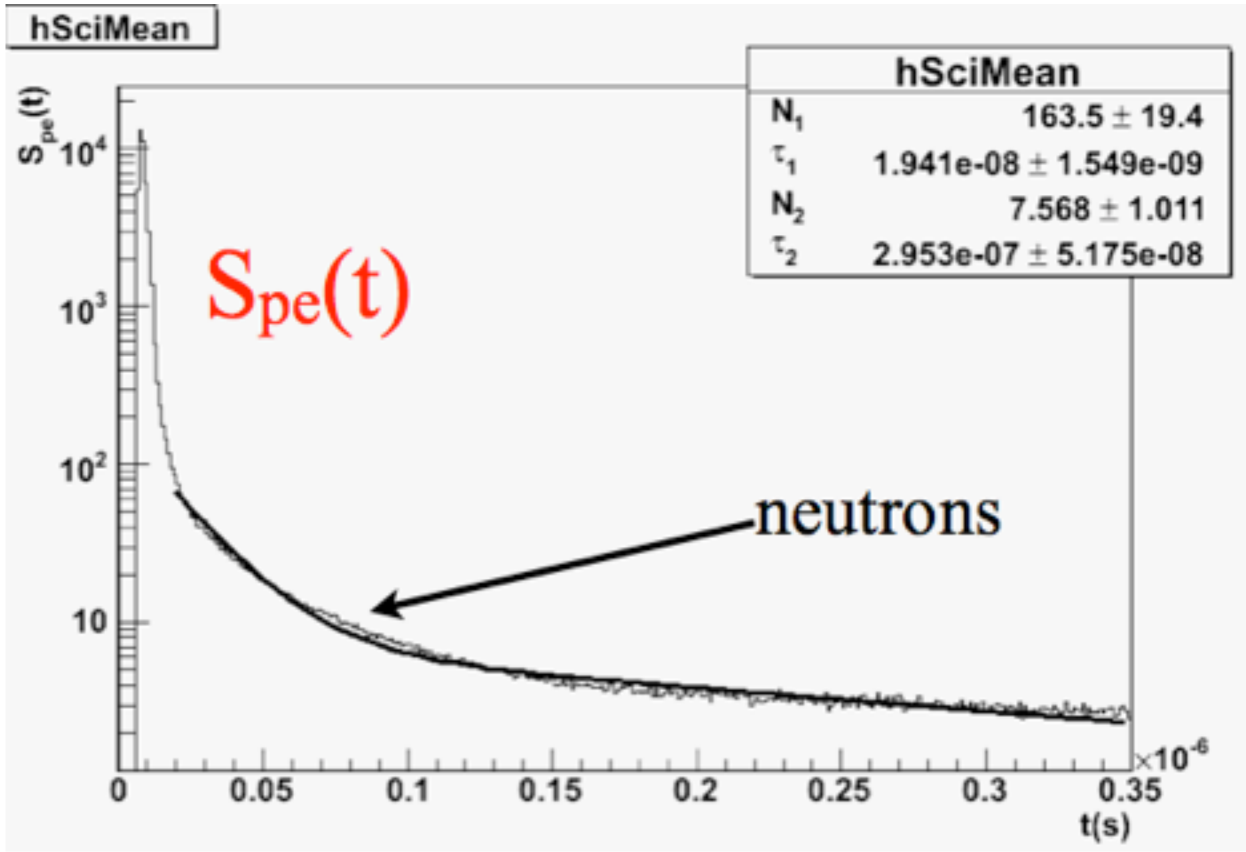
→ *e/γ - π^±/hadrons*

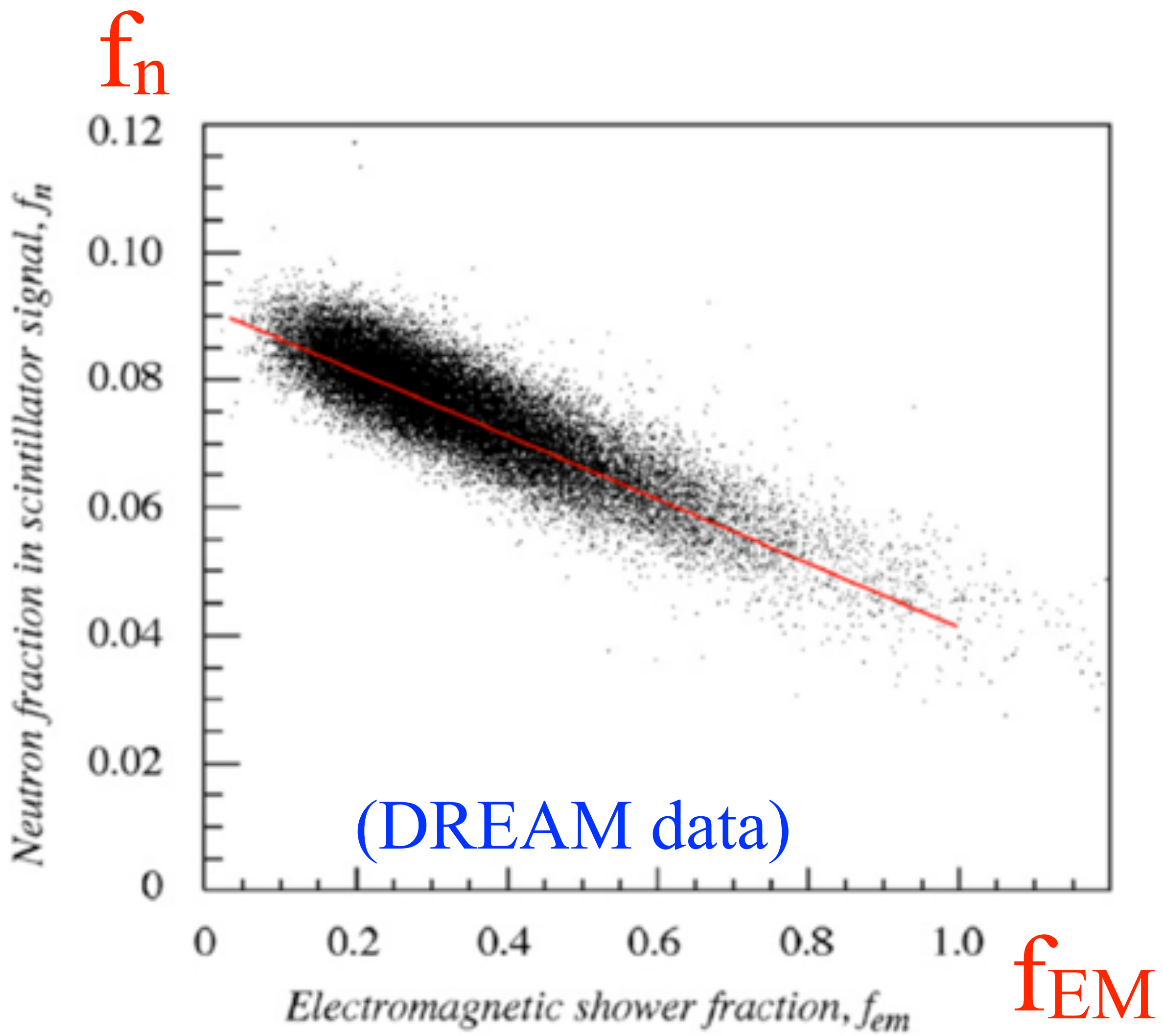


duration of pulse above 1/5-maximum

Time-history S(t) scintillating fibers

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

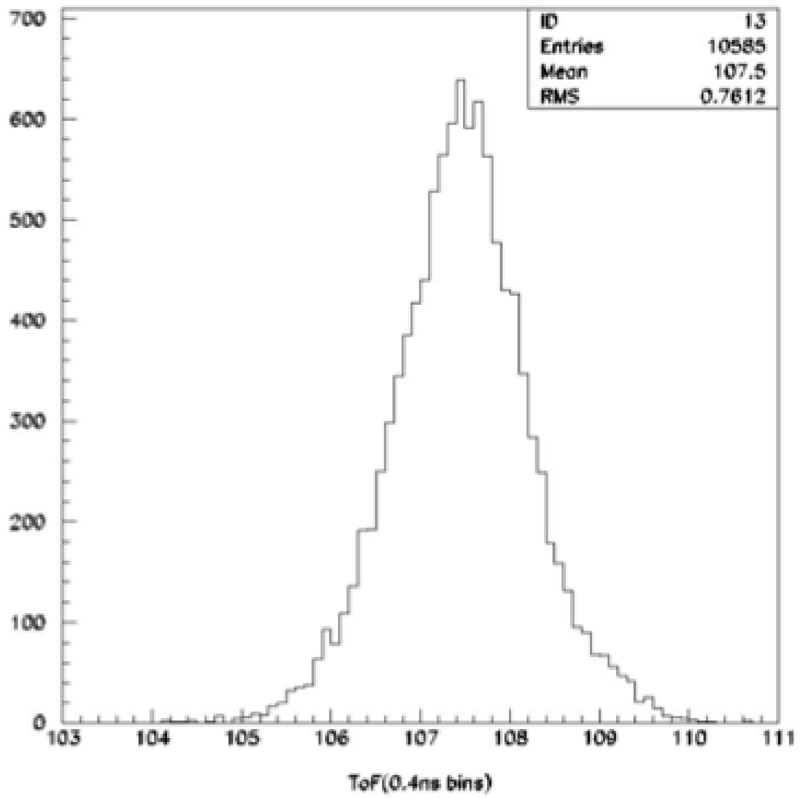




Time-of-flight

(Cerenkov fibers)
σ ~ 0.3 ns

DREAM data

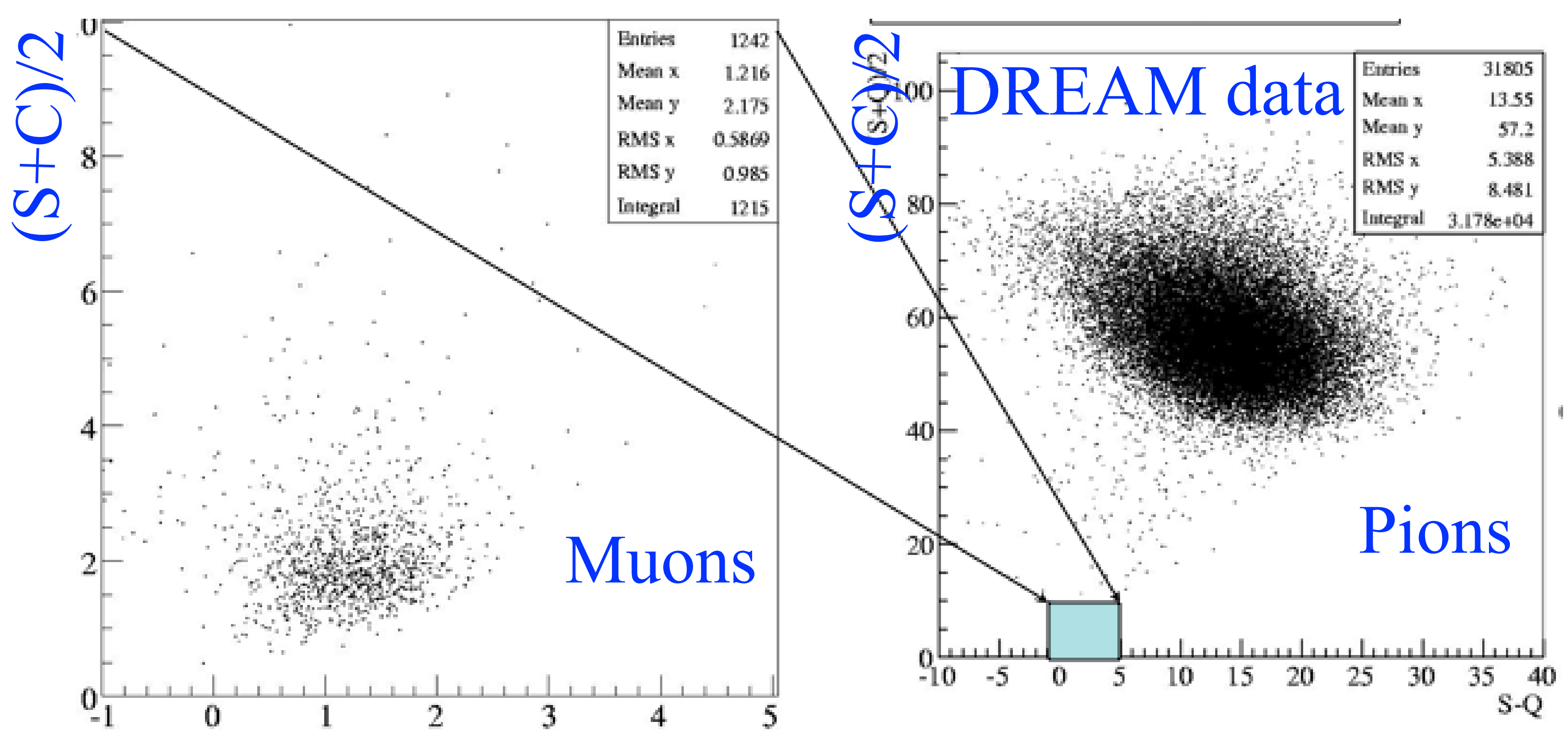


t (0.4 ns bins)

Muon tagging

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

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

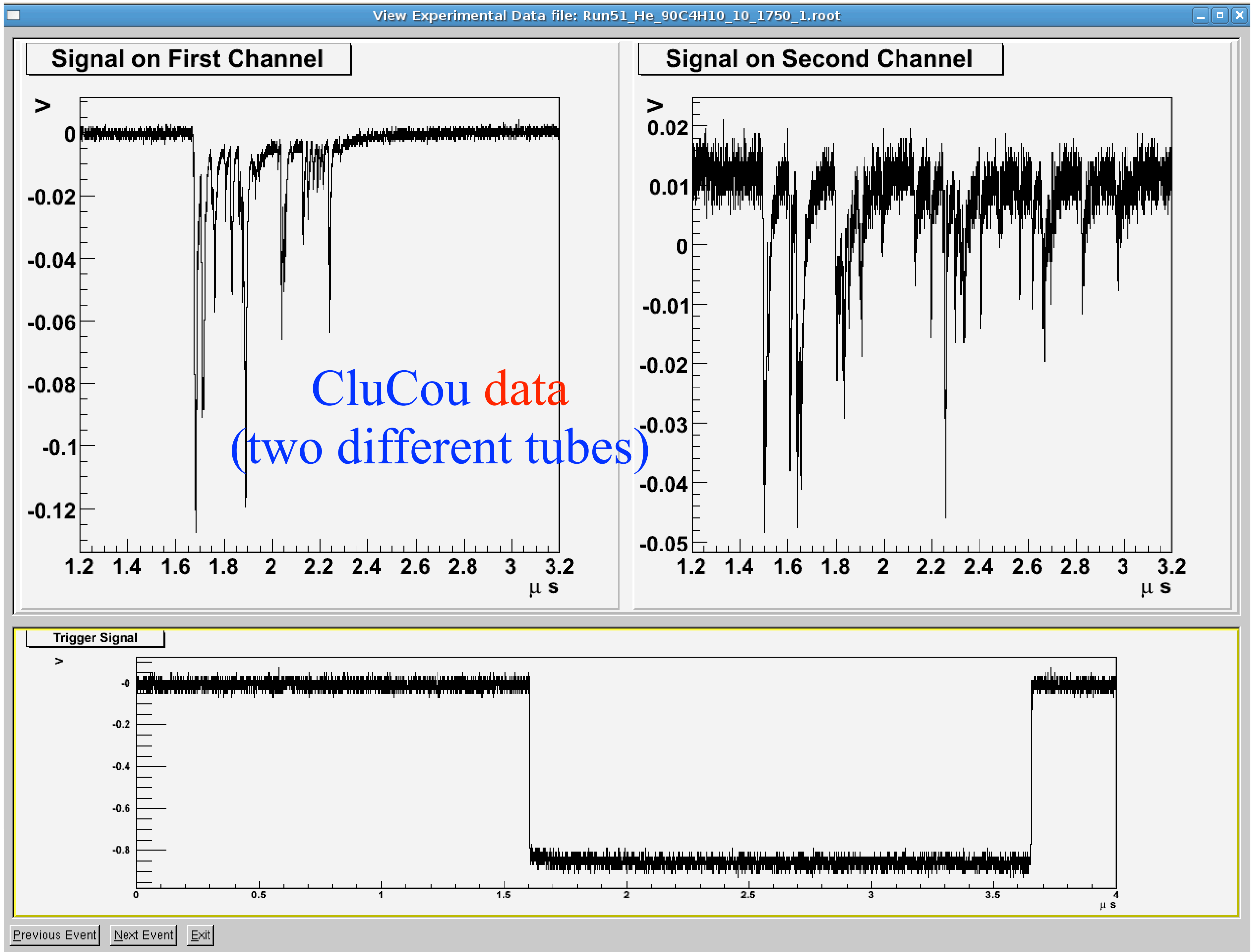


S-C

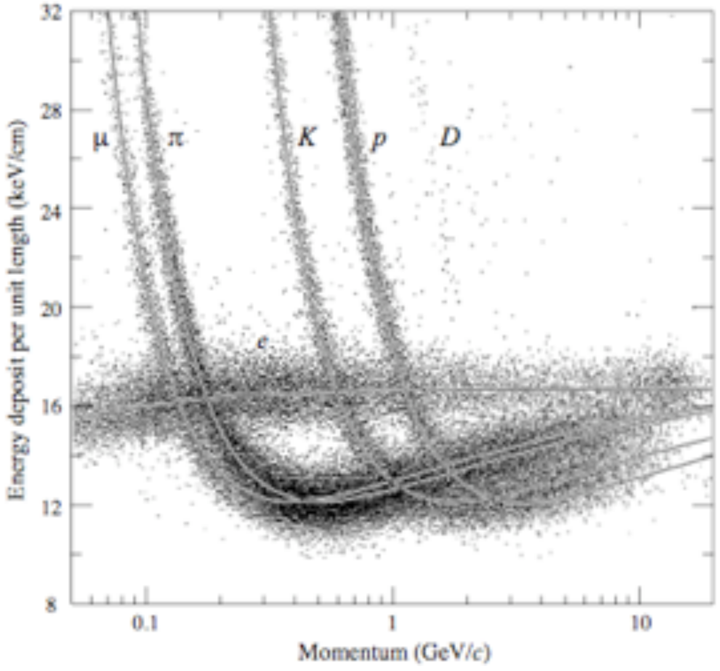
S-C

dN/dx by cluster-counting

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



CluCou data
(two different tubes)

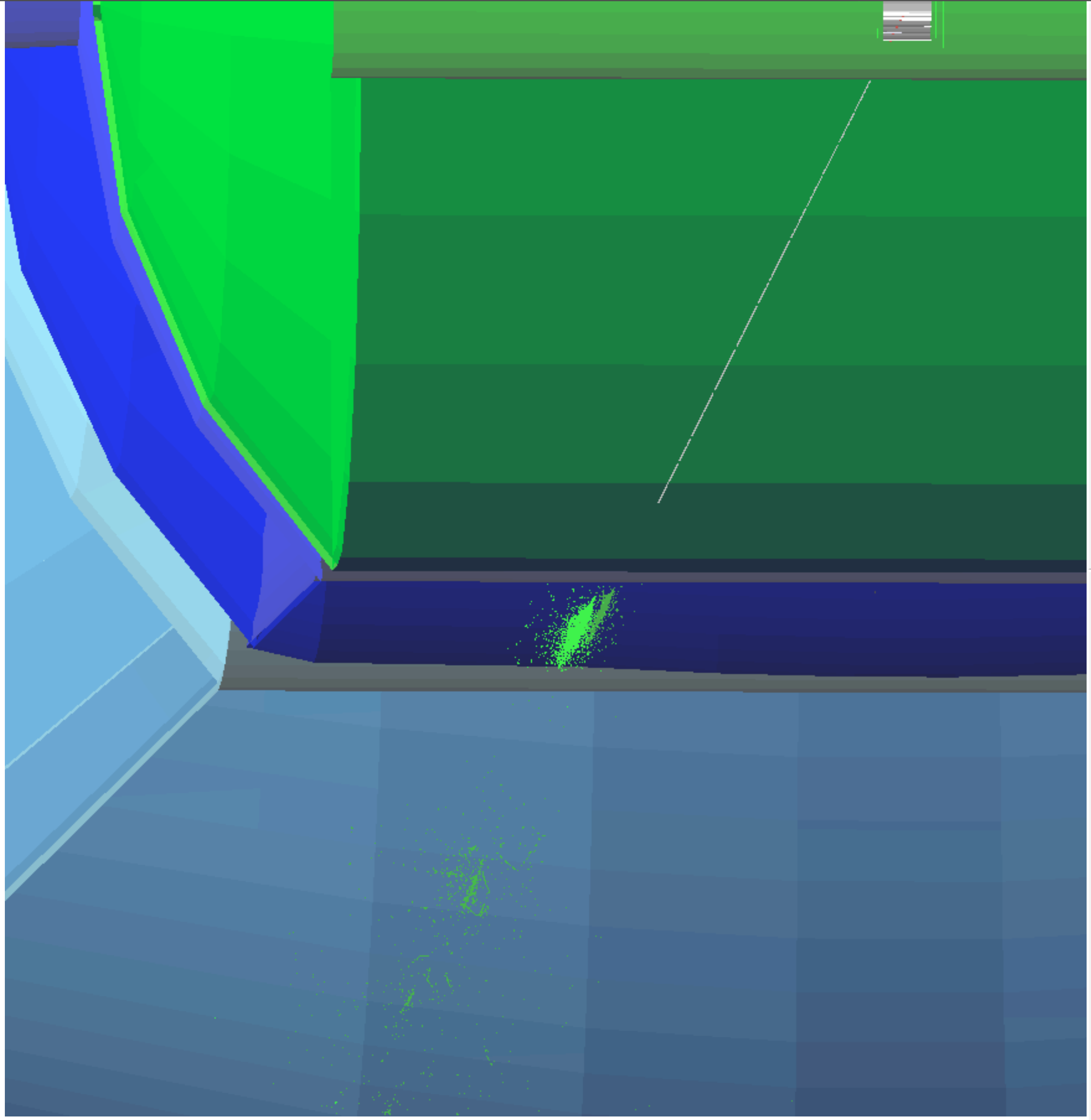


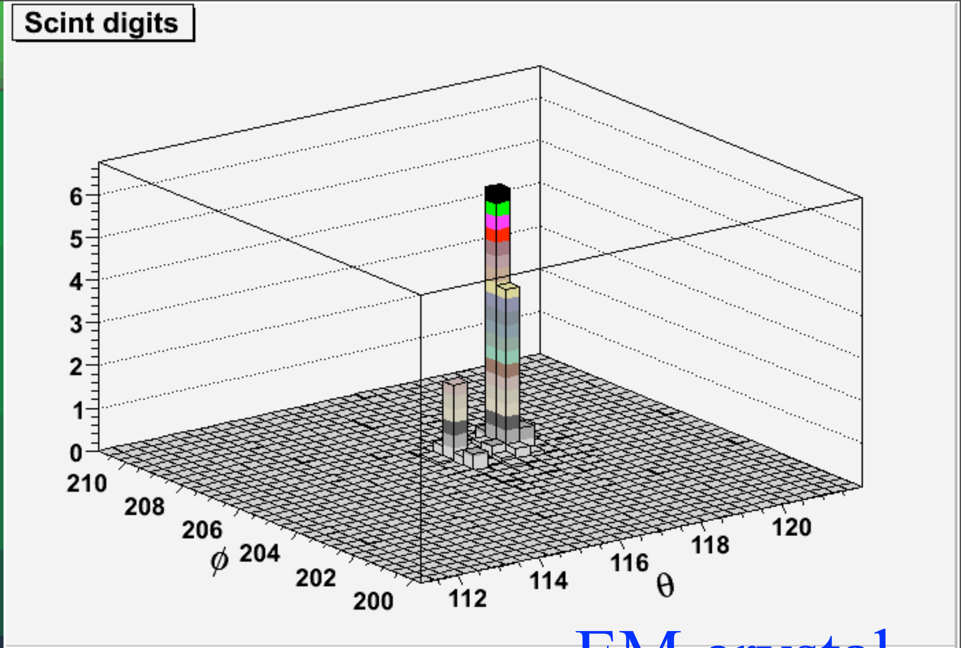
dE/dx resolution TPC LBL/PEP4 (data using truncated mean, resolution~6%)

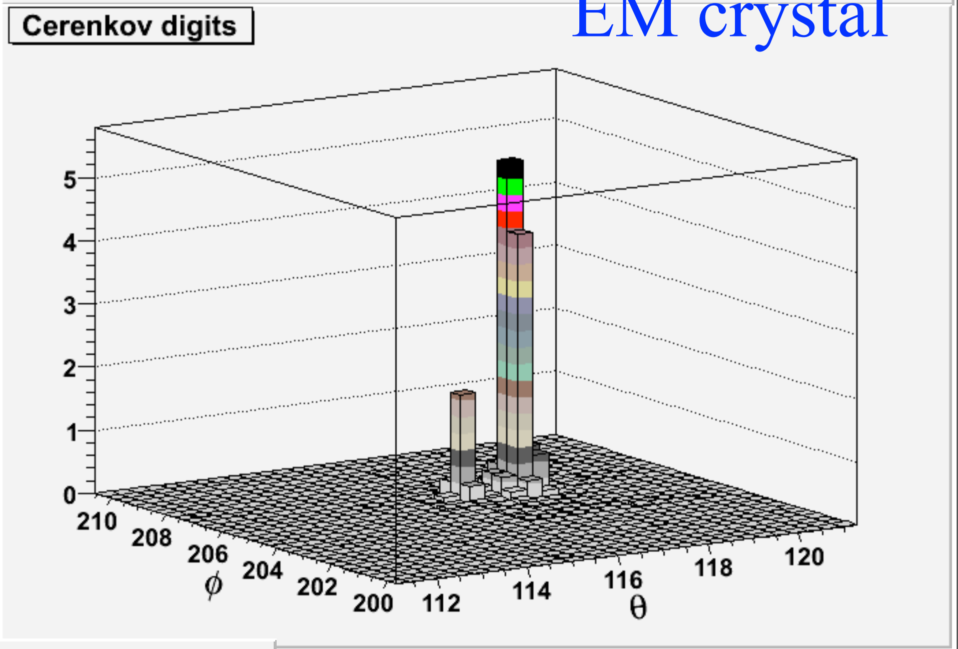
$\tau^{\pm}$ ID

(for polarization)

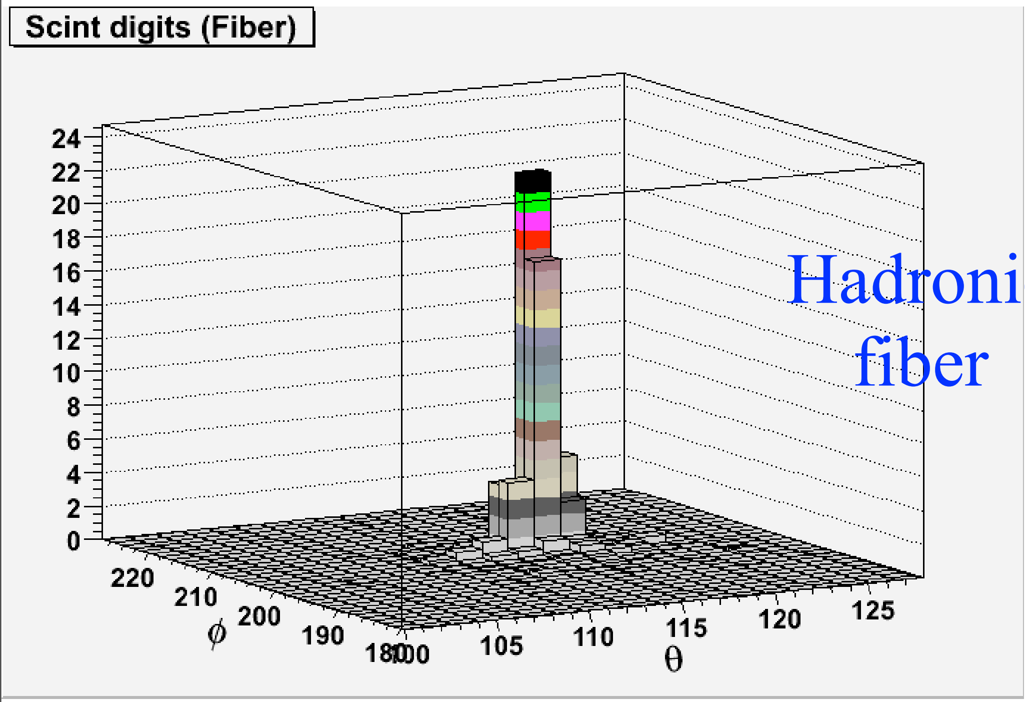
$$\begin{aligned}\tau^- &\to \rho^- \nu\\ &\to \pi^- \pi^0\\ &\to \pi^- \gamma\gamma\end{aligned}$$

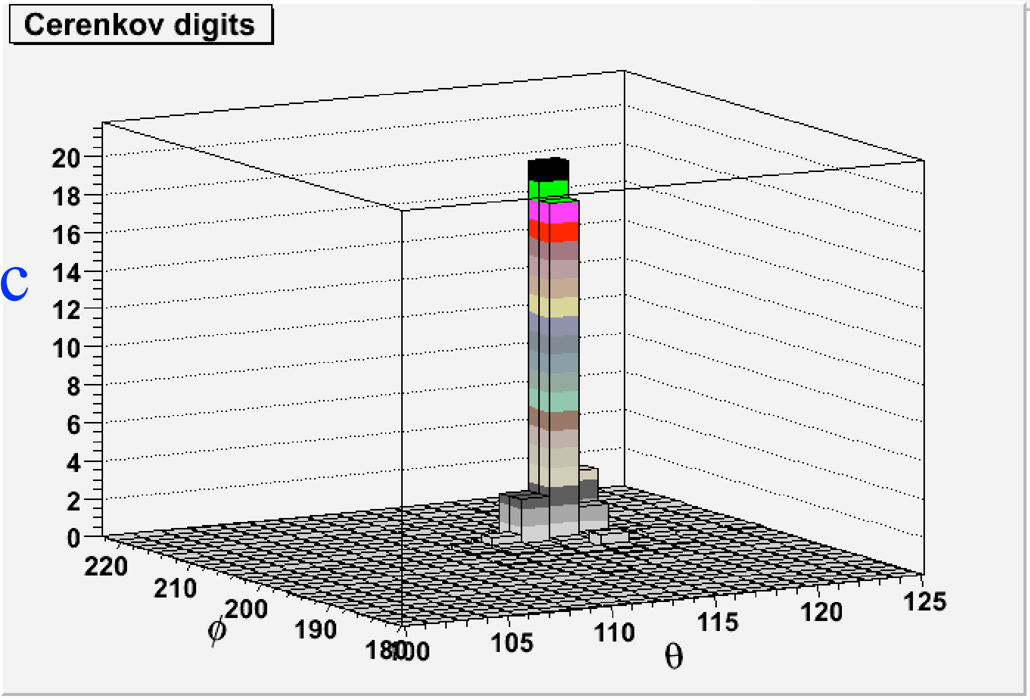






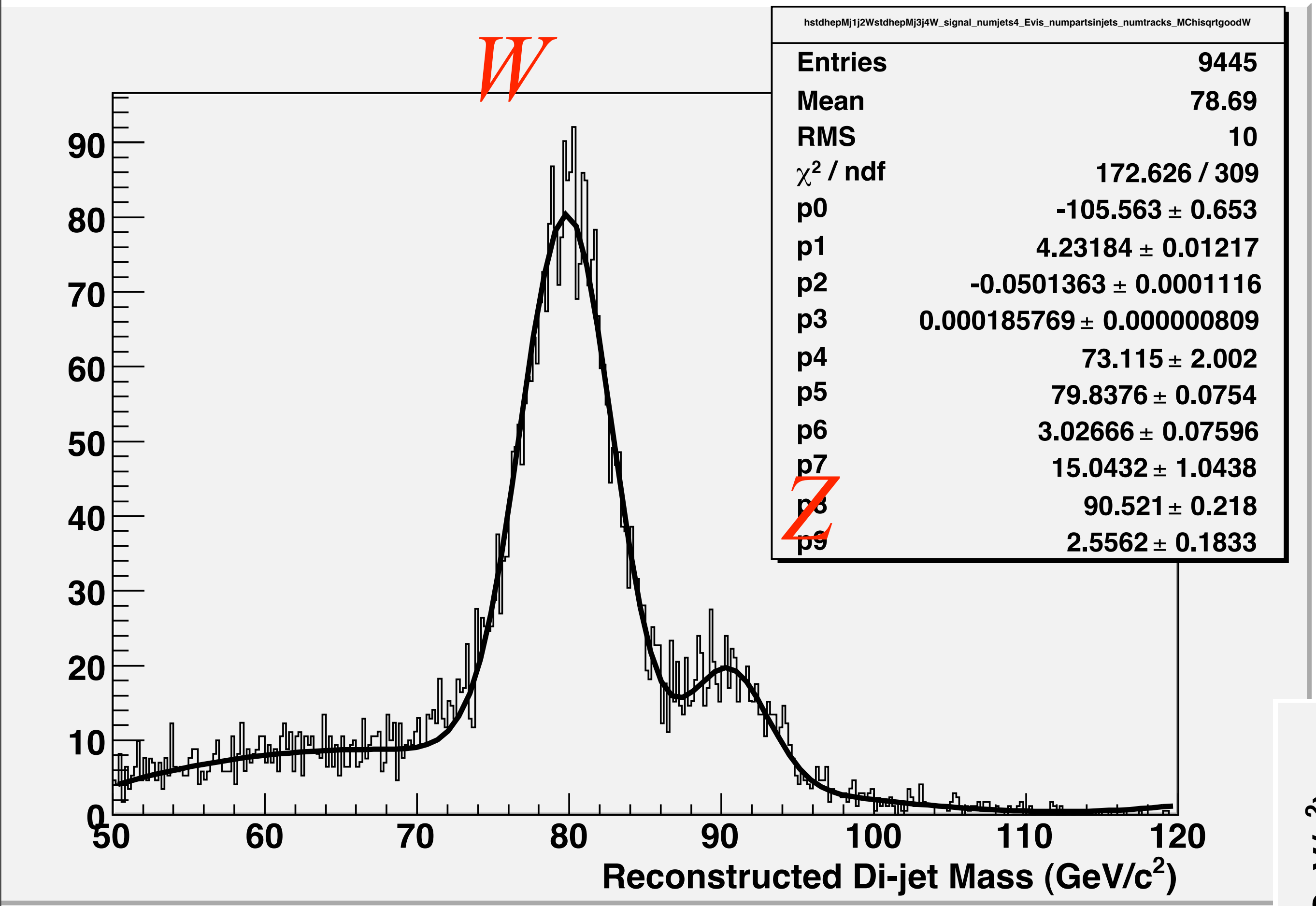
EM crystal





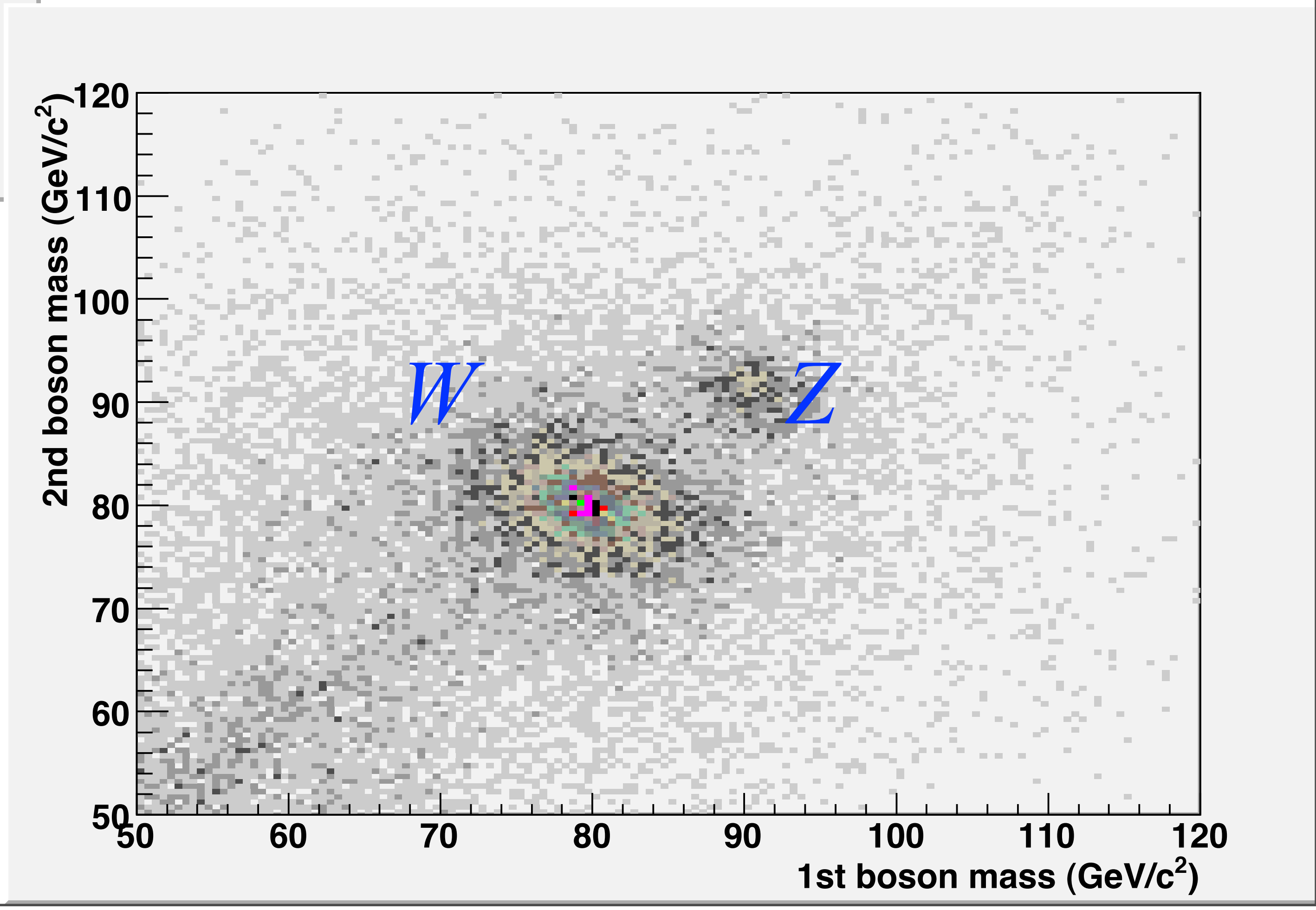
Hadronic fiber

W and Z mass measurement and discrimination



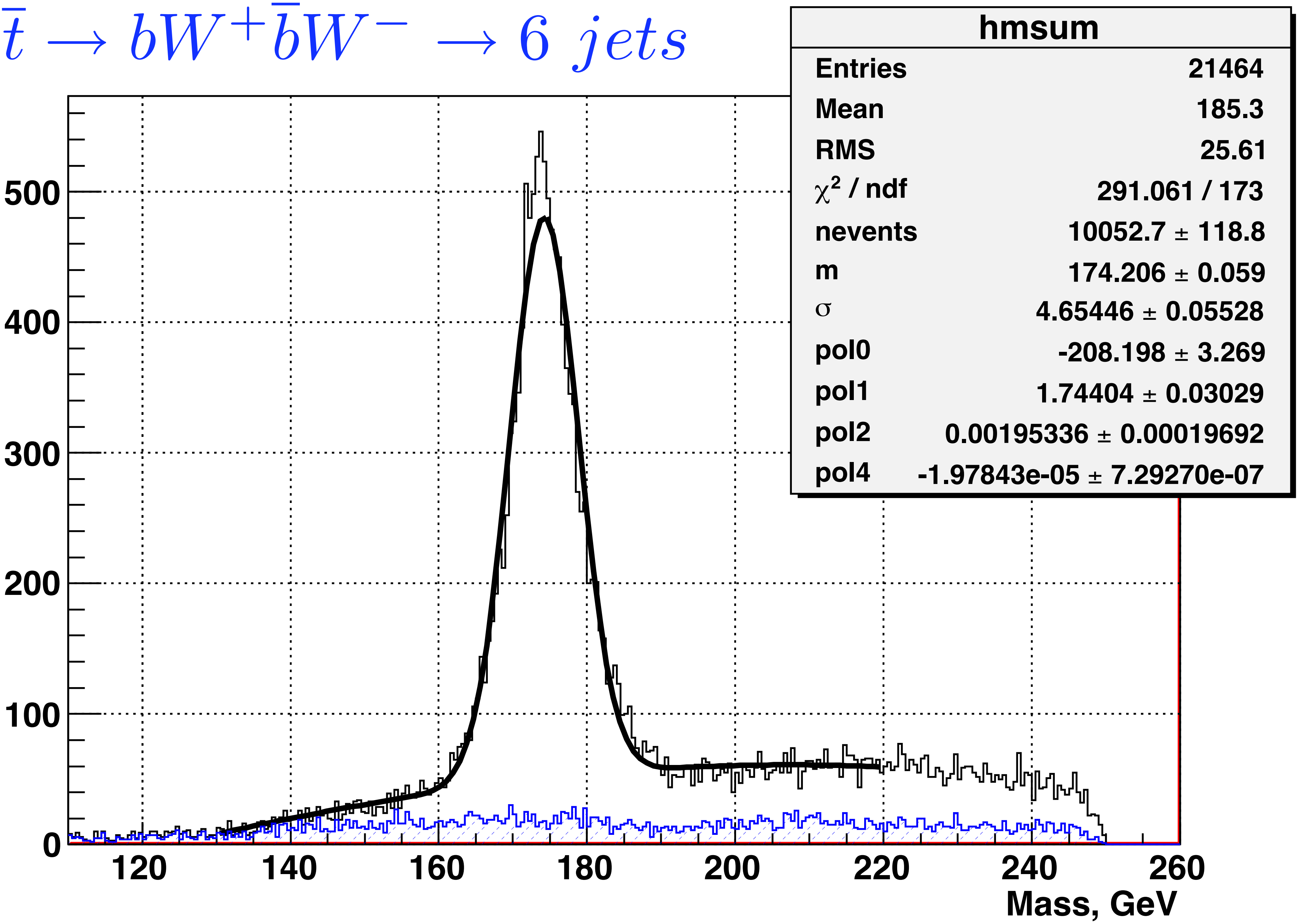
hstdhepMj1j2WstdhepMj3j4W_signal_numjets4_Evis_numpartsinjets_numtracks_MChisqrtgoodW

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



top quark (all hadronic channel)

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

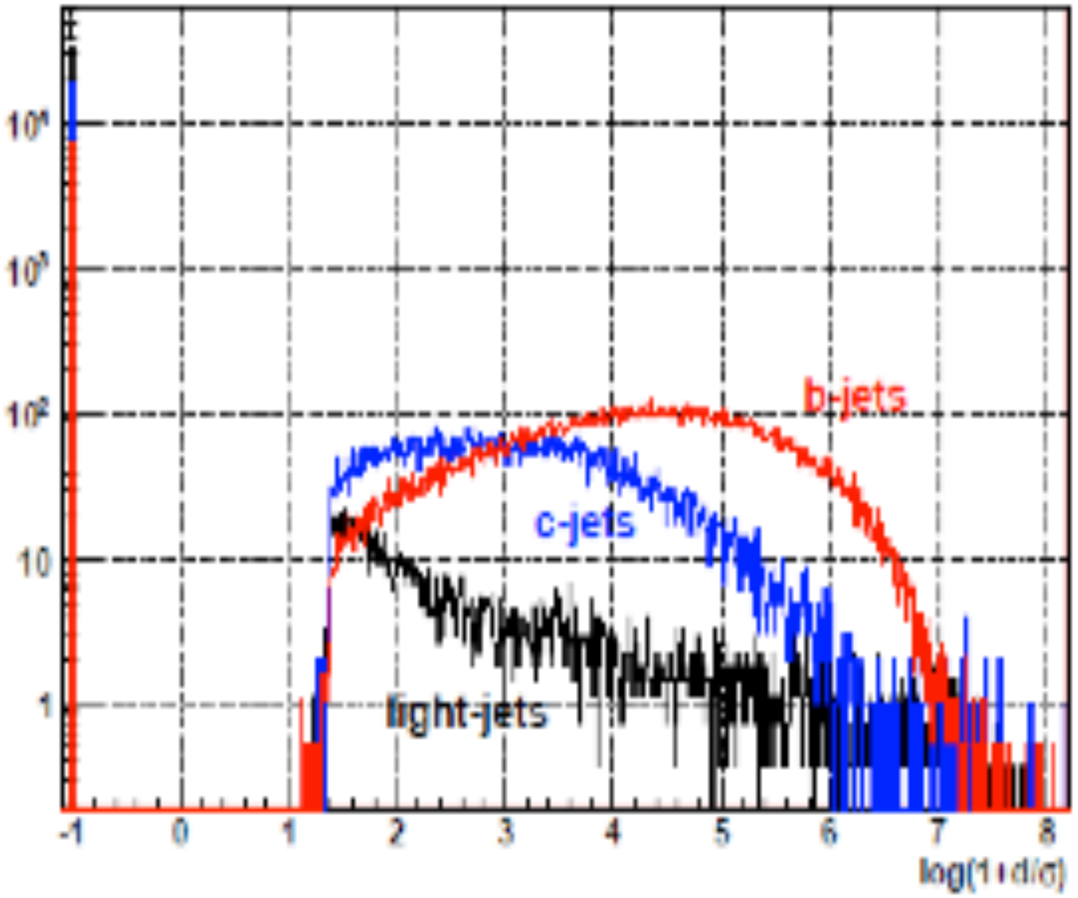


hmsum	
Entries	21464
Mean	185.3
RMS	25.61
χ^2 / ndf	291.061 / 173
nevents	10052.7 ± 118.8
m	174.206 ± 0.059
σ	4.65446 ± 0.05528
pol0	-208.198 ± 3.269
pol1	1.74404 ± 0.03029
pol2	0.00195336 ± 0.00019692
pol4	-1.97843e-05 ± 7.29270e-07

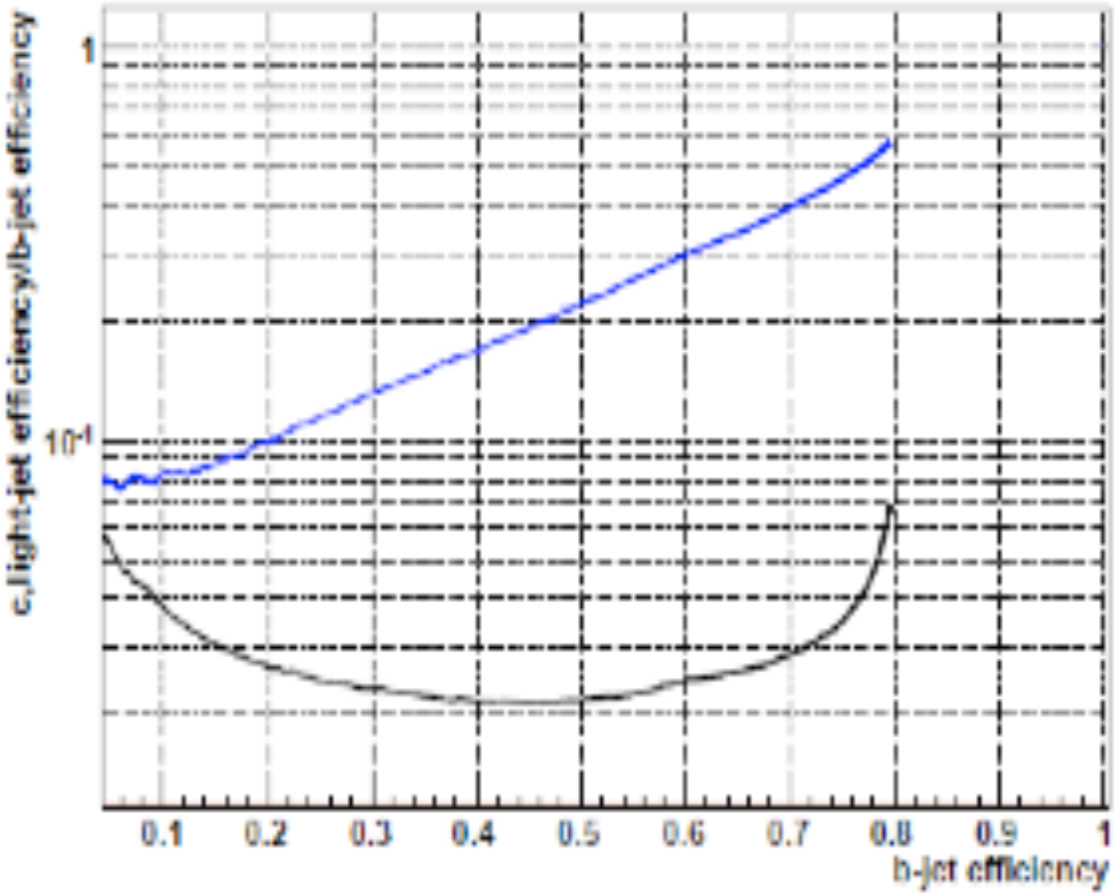
Fedor Ignatov (Budker Institute, Novosibirsk)

b,c quark tagging (by lifetime of B,D mesons in silicon pixel vertex chamber)

(Fedor Ignatov, Budker Institute)

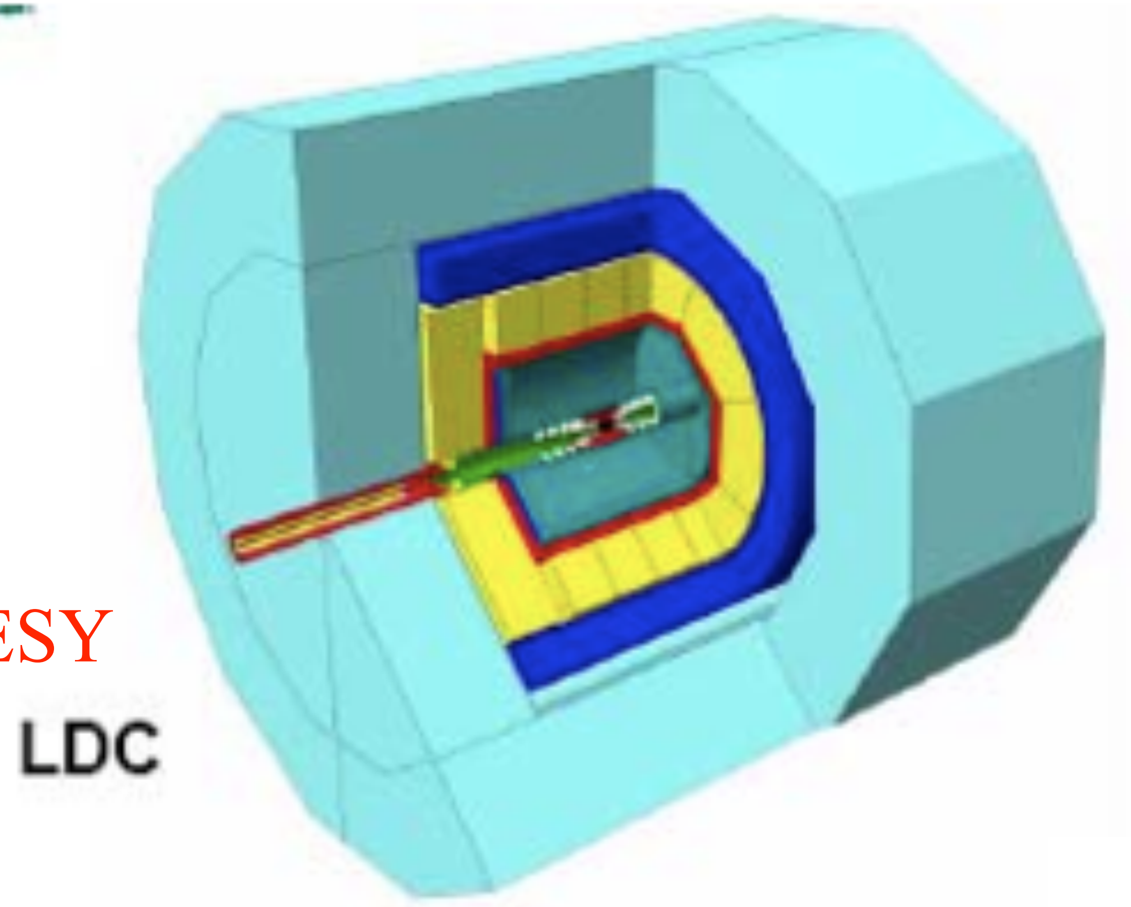


vertex impact parameter

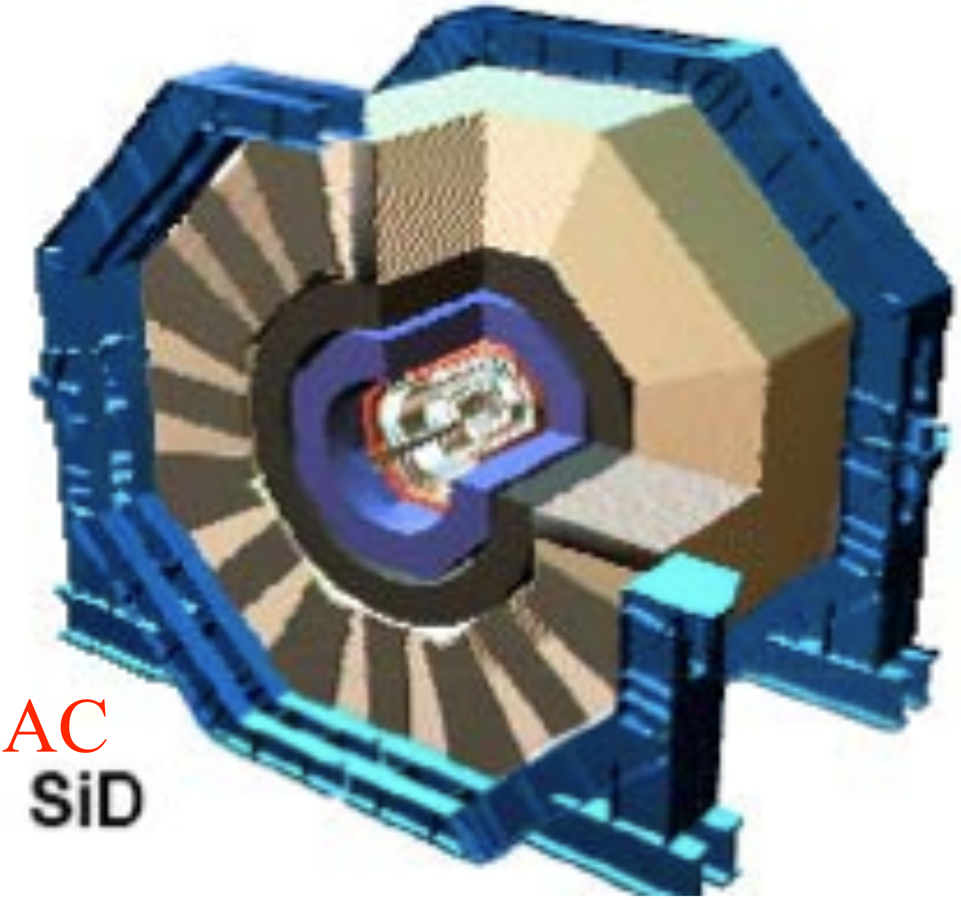


Geometries

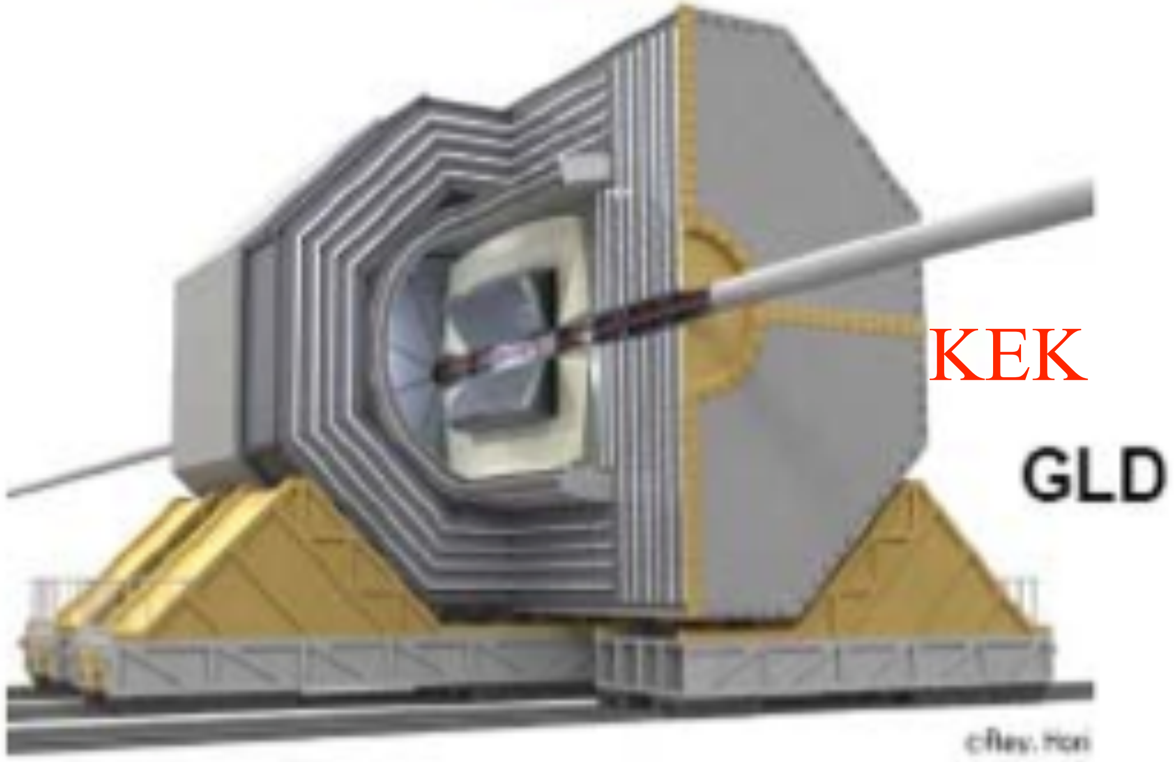
DESY

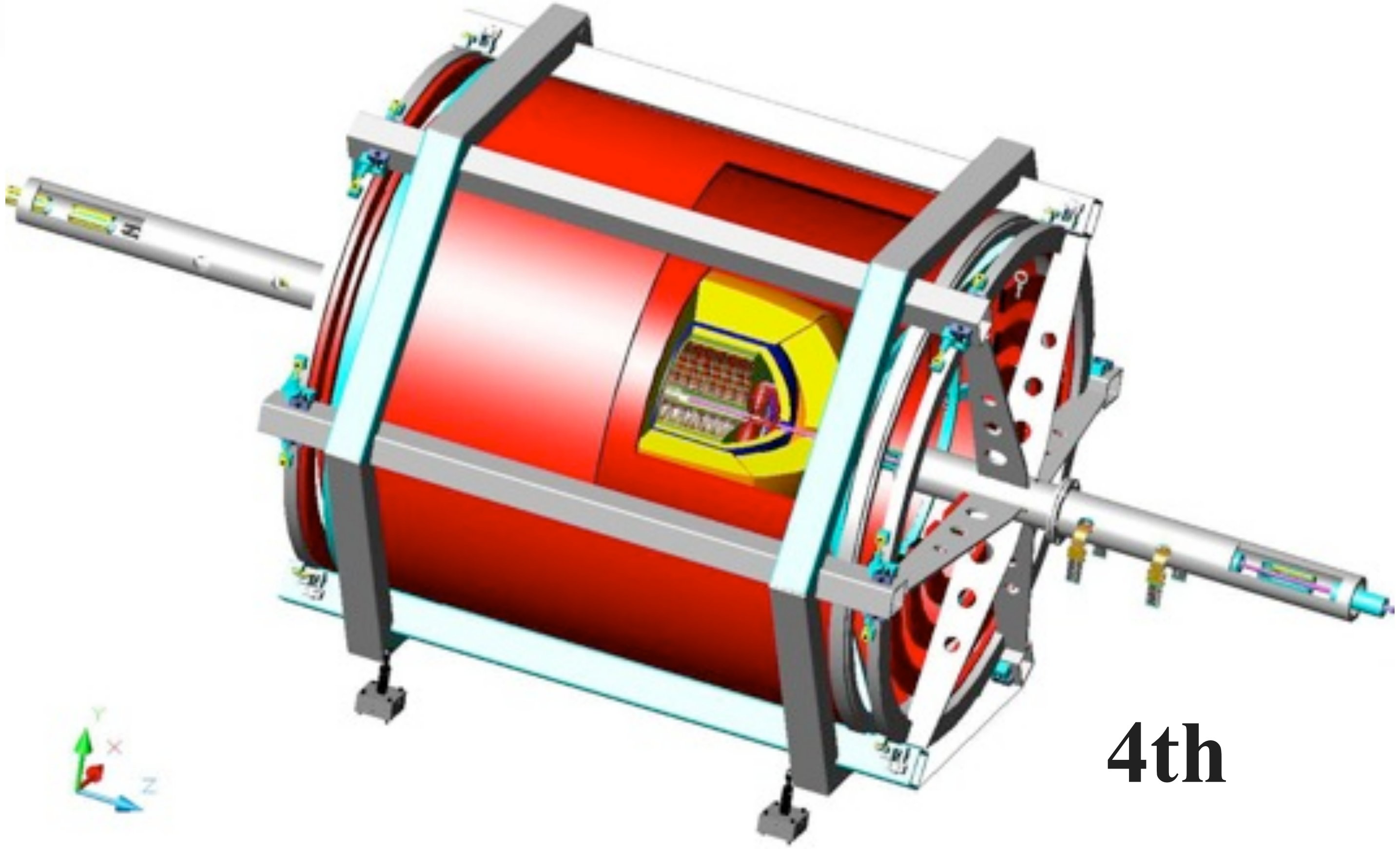


SLAC



KEK





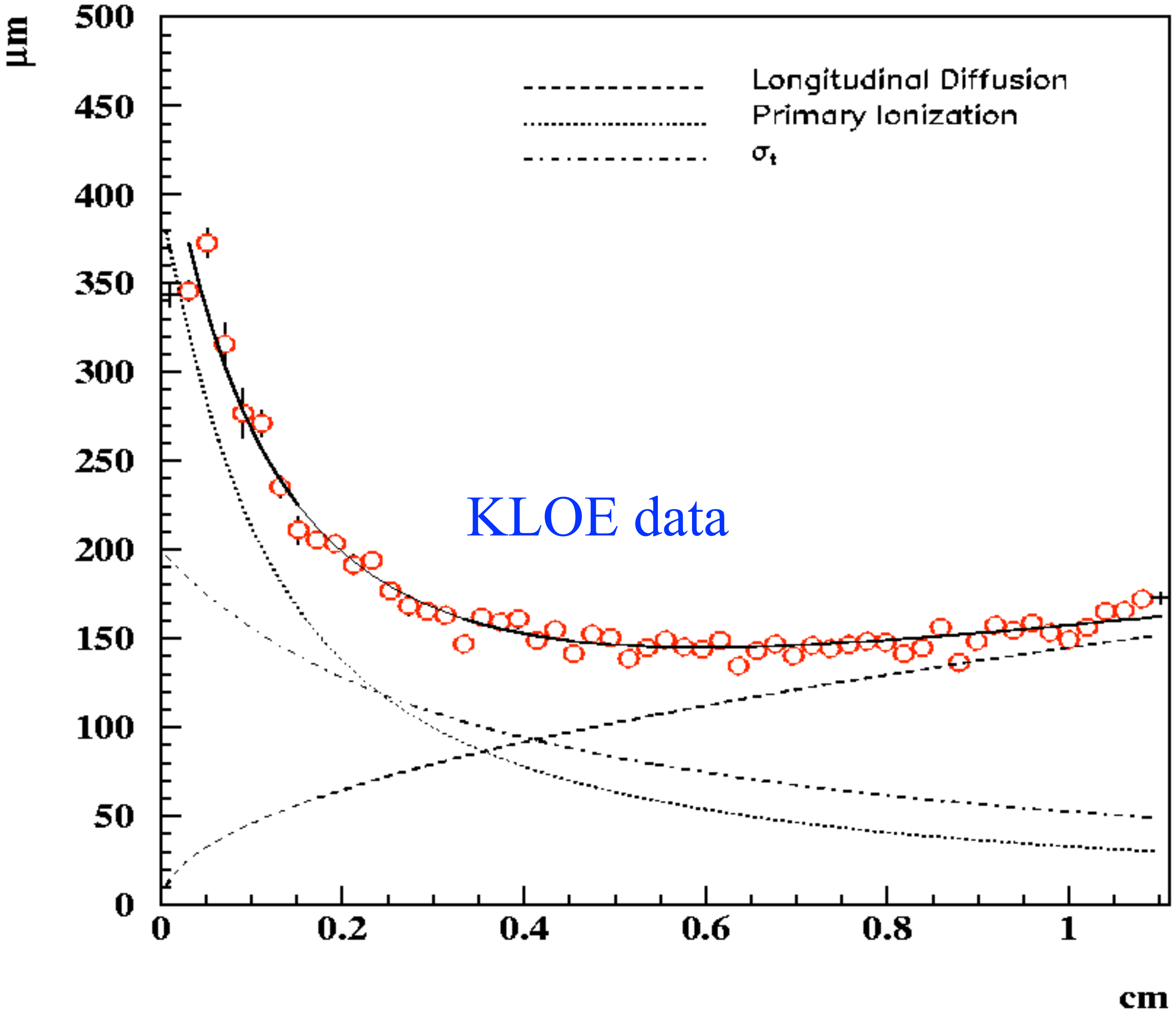
4th

Summary

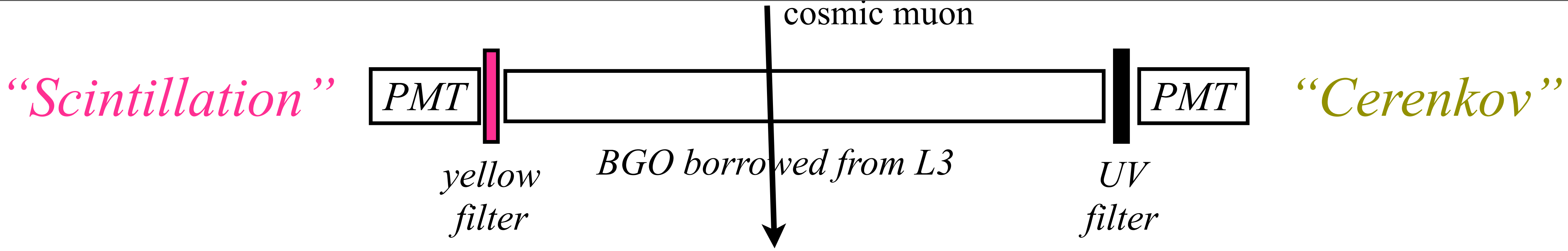
A big detector is a technically and socially complex instrument that takes more than 10 years to design and build, and will likely run in colliding beams for 10-20 years. The next big detector (e.g., for the International Linear Collider, CLIC, or a Muon Collider) must be near-perfect. There are active R&D efforts in tracking, calorimetry, silicon pixels, and DAQ.

Cluster timing tracking chamber: (measure every cluster)

KLOE is a very well understood chamber

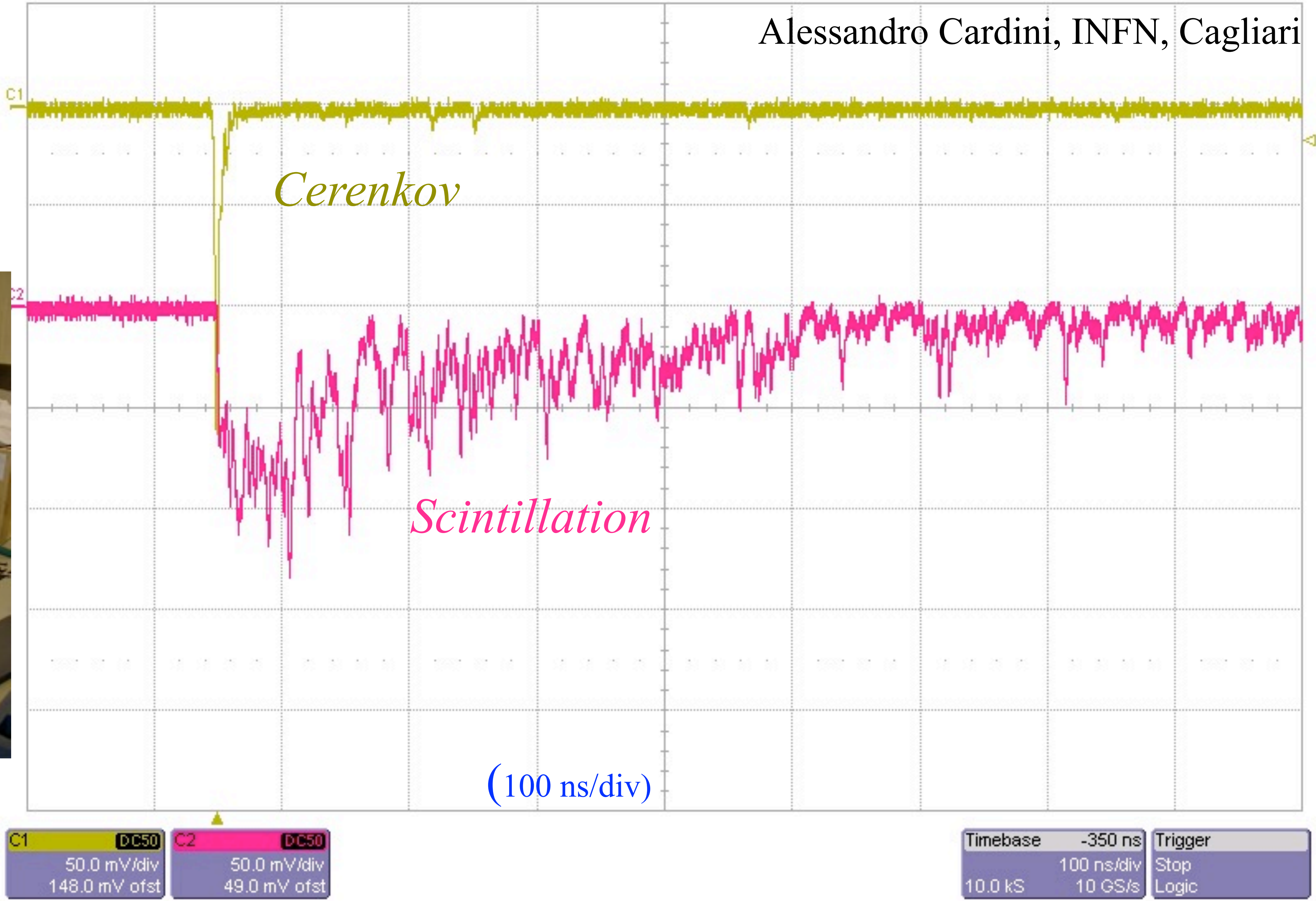


KLOE data

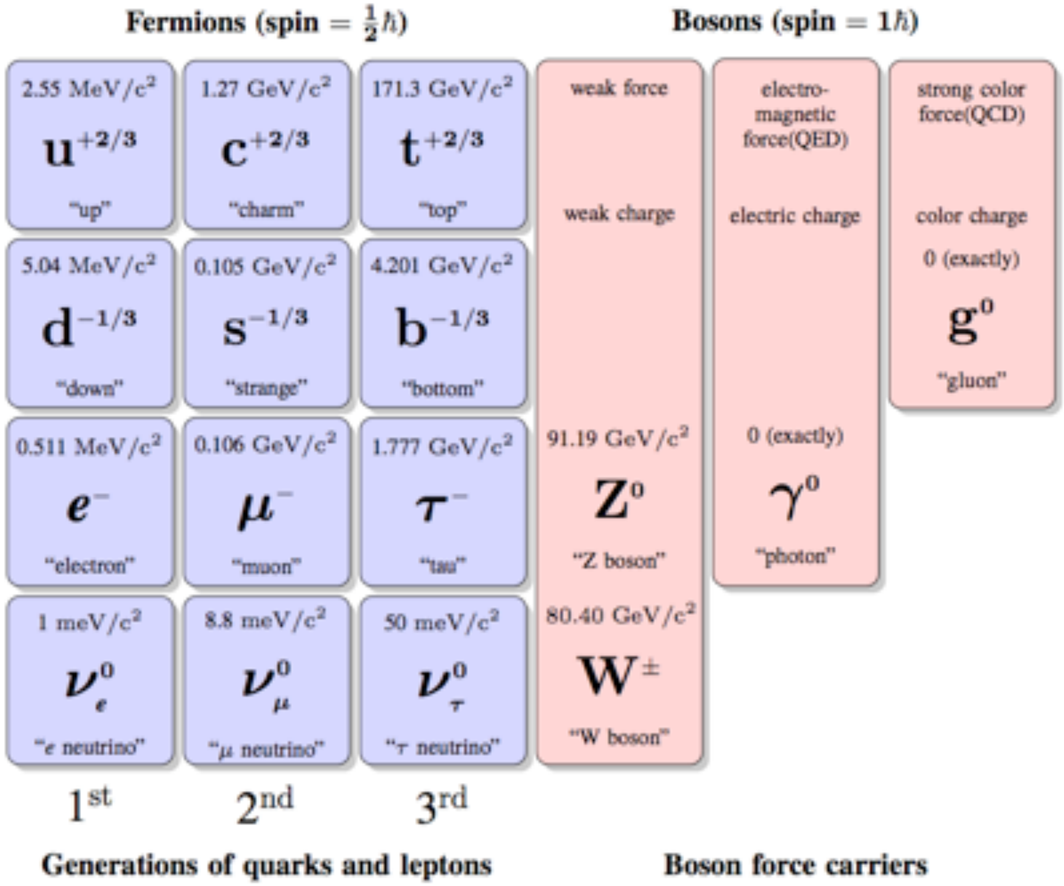


BGO ...

by time and wavelength

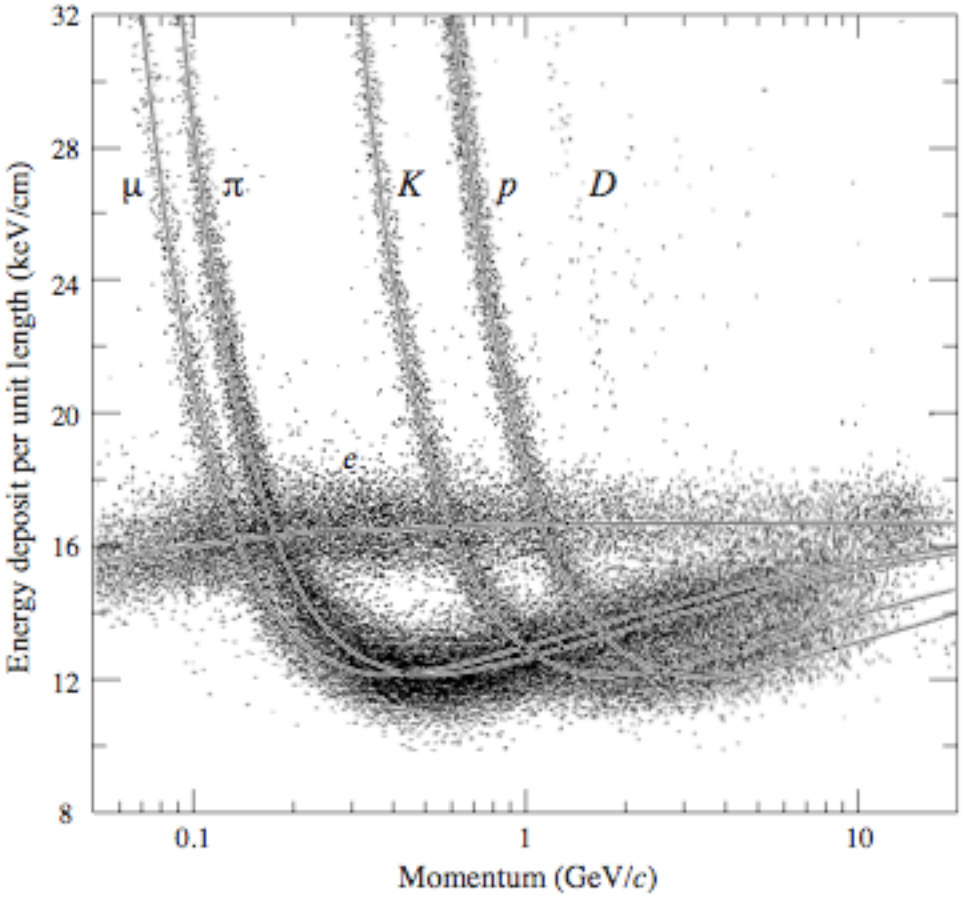

Alessandro Cardini, INFN, Cagliari

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

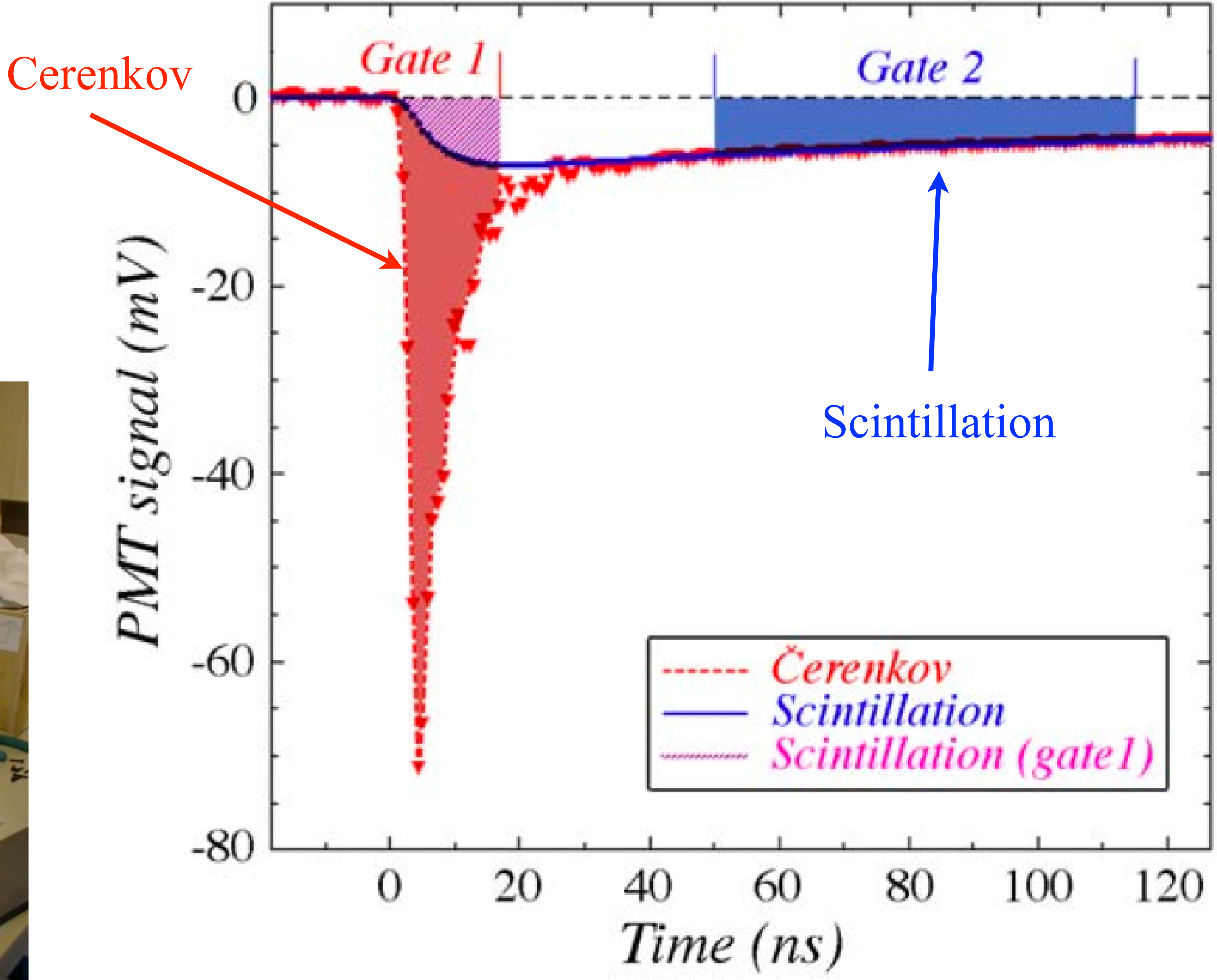


Fermions (spin = $\frac{1}{2}\hbar$)			Bosons (spin = $1\hbar$)		
2.55 MeV/c^2 $\mathbf{u}^{+2/3}$ "up"	1.27 GeV/c^2 $\mathbf{c}^{+2/3}$ "charm"	171.3 GeV/c^2 $\mathbf{t}^{+2/3}$ "top"	weak force weak charge	electro-magnetic force(QED) electric charge	strong color force(QCD) color charge
5.04 MeV/c^2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

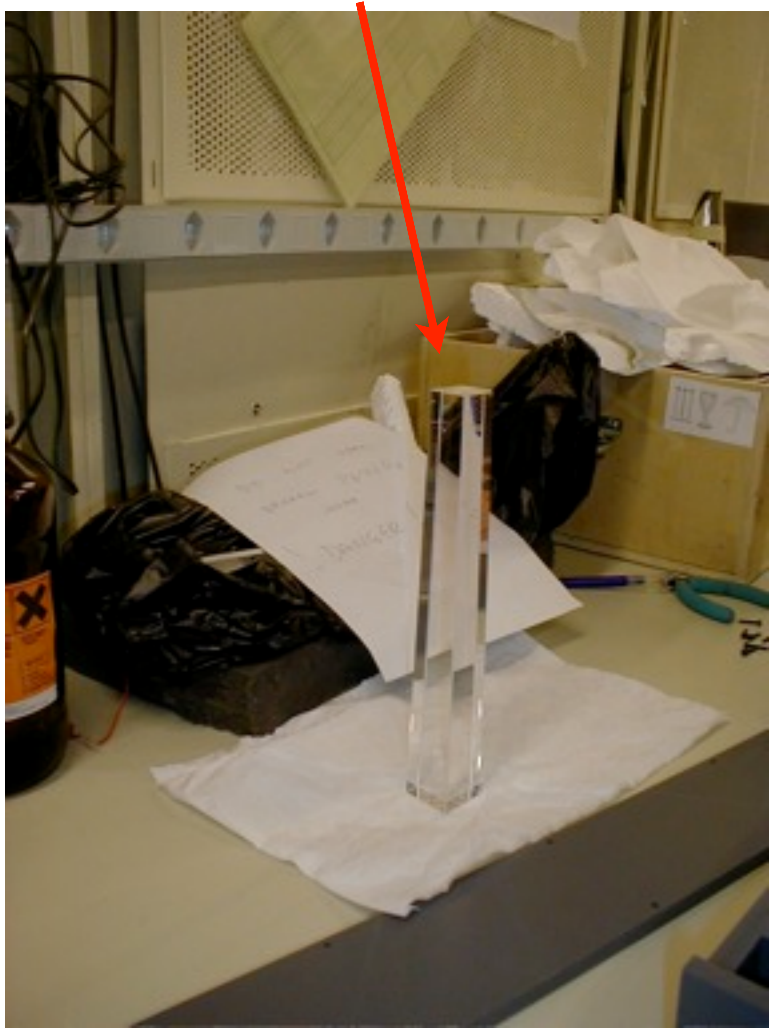
Generations of quarks and leptons **Boson force carriers**


Energy deposit per unit length (keV/cm)
32
28
24
20
16
12
8
0.1
1
10
Momentum (GeV/c)
μ
π
K
p
D
e

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

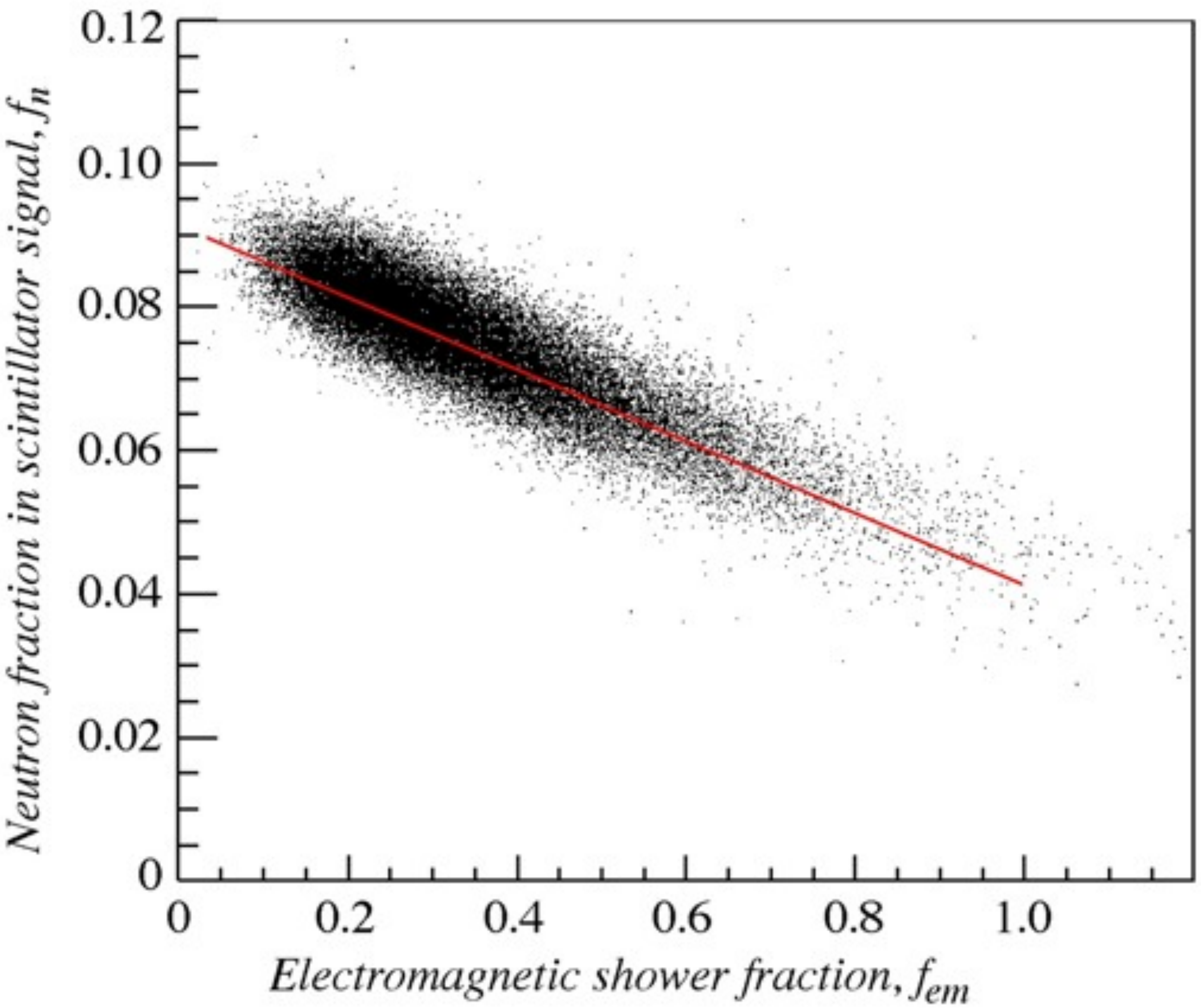


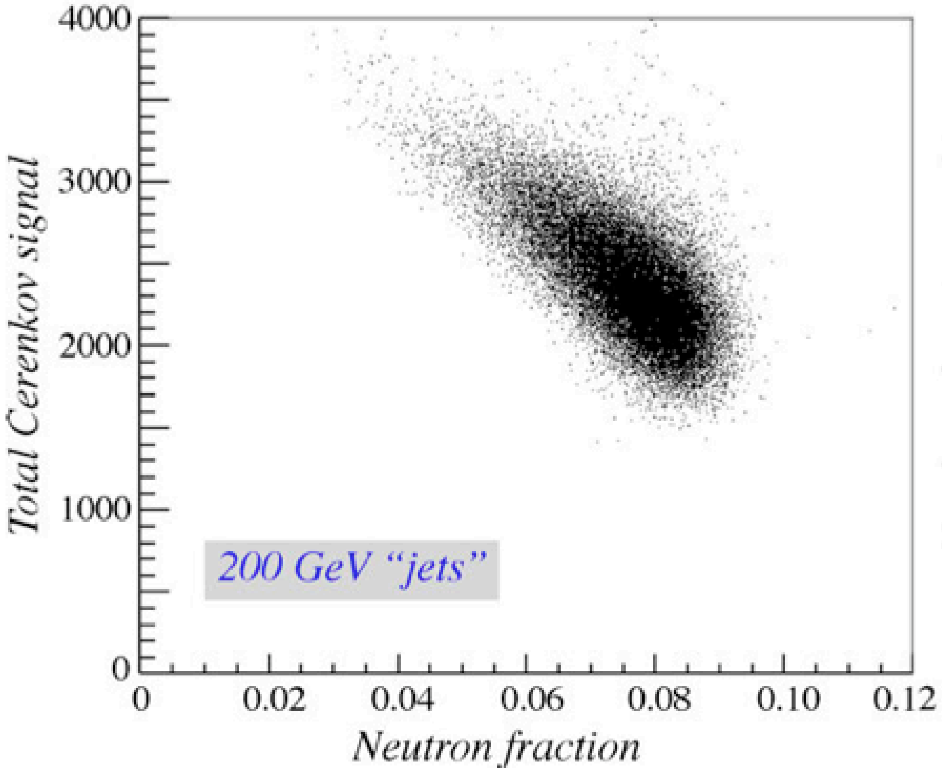
L3 BGO crystal

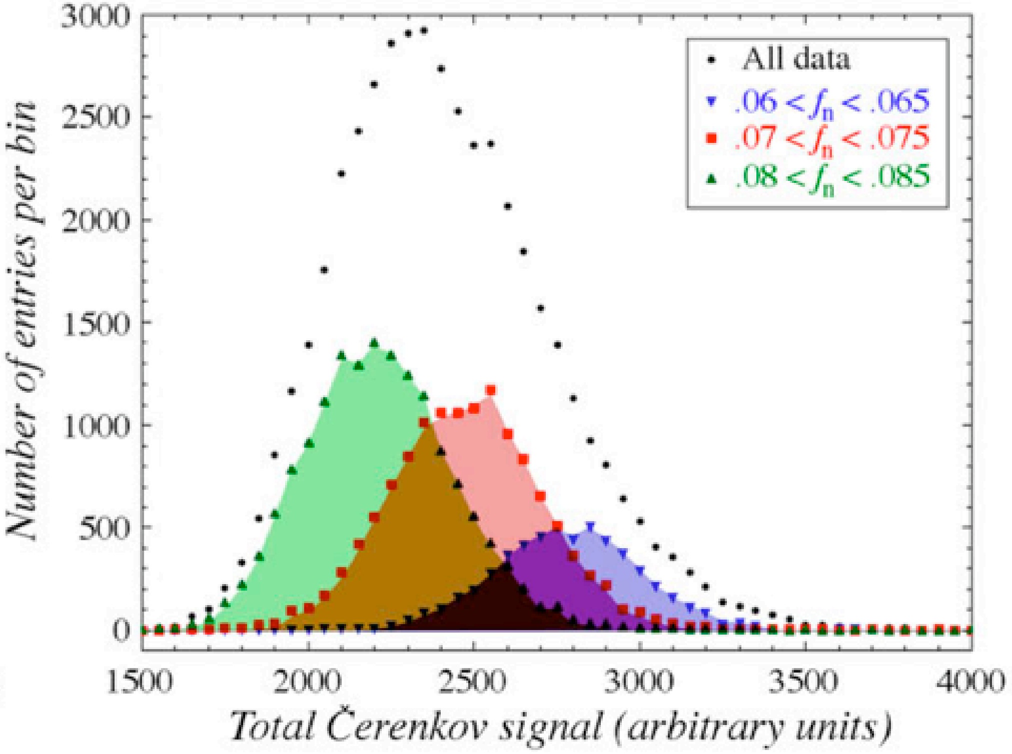


4. neutron fraction, f_n

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





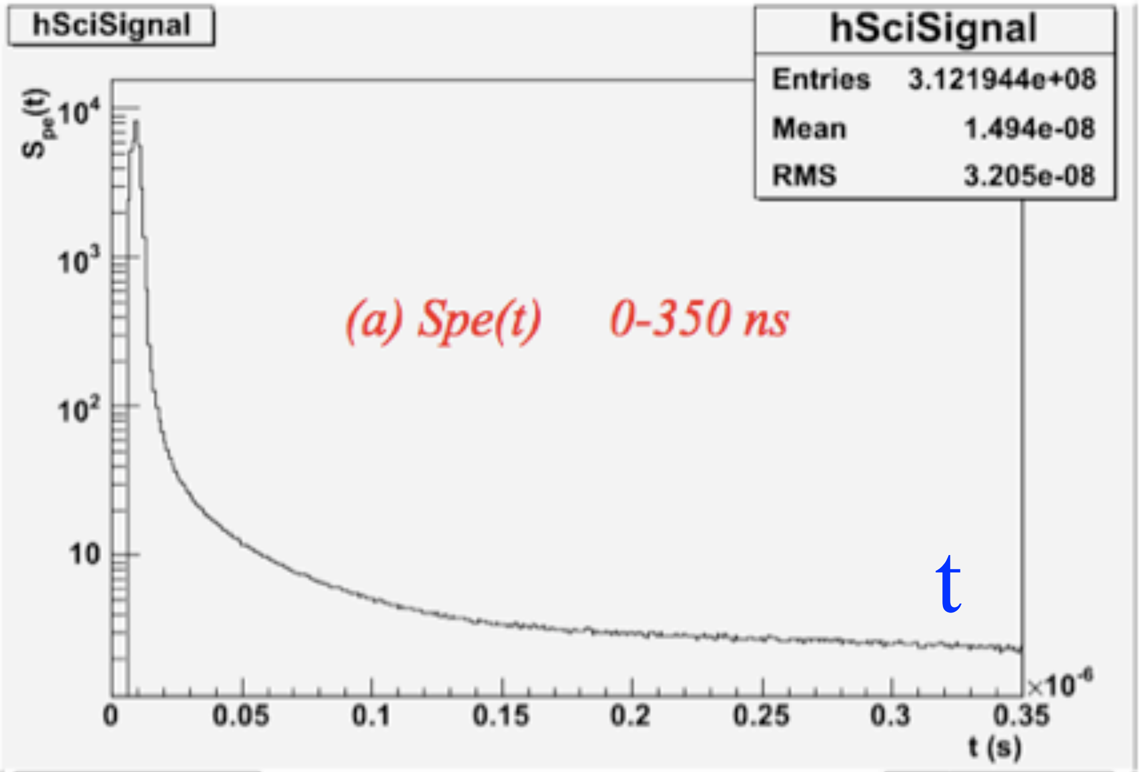


... also use this to improve the hadronic energy resolution.

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

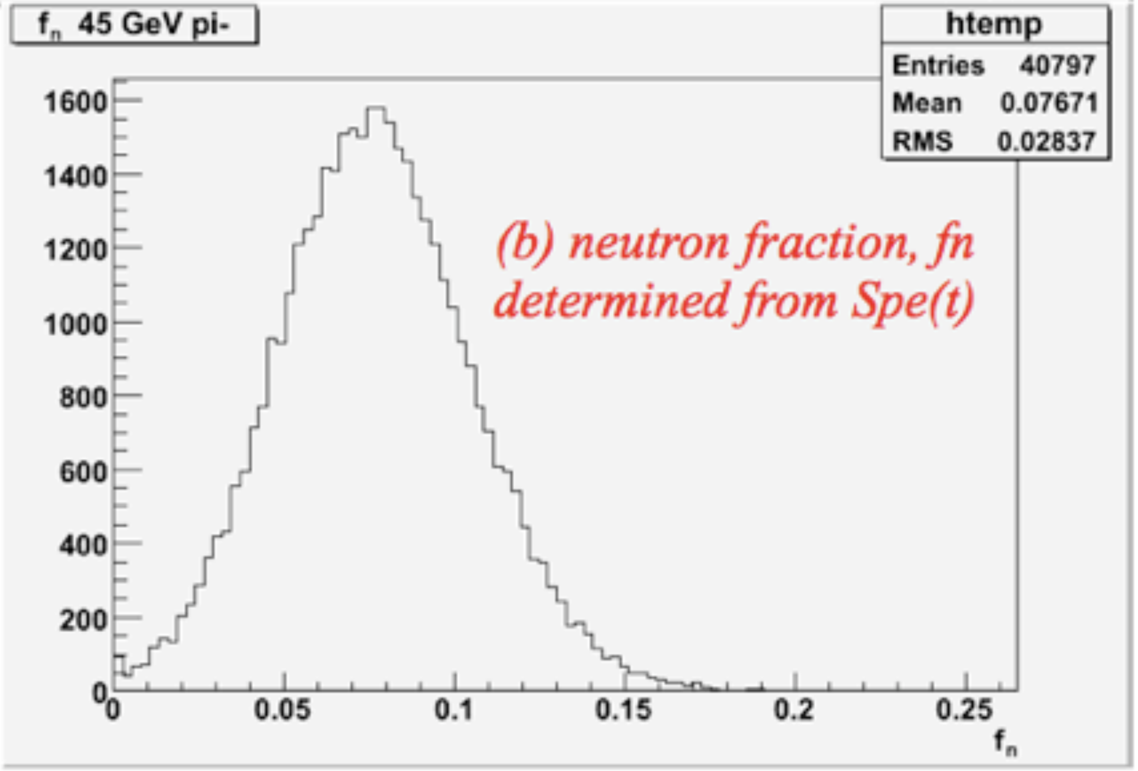
Pavia CALOR08

4th ILCroot V. Di Benedetto

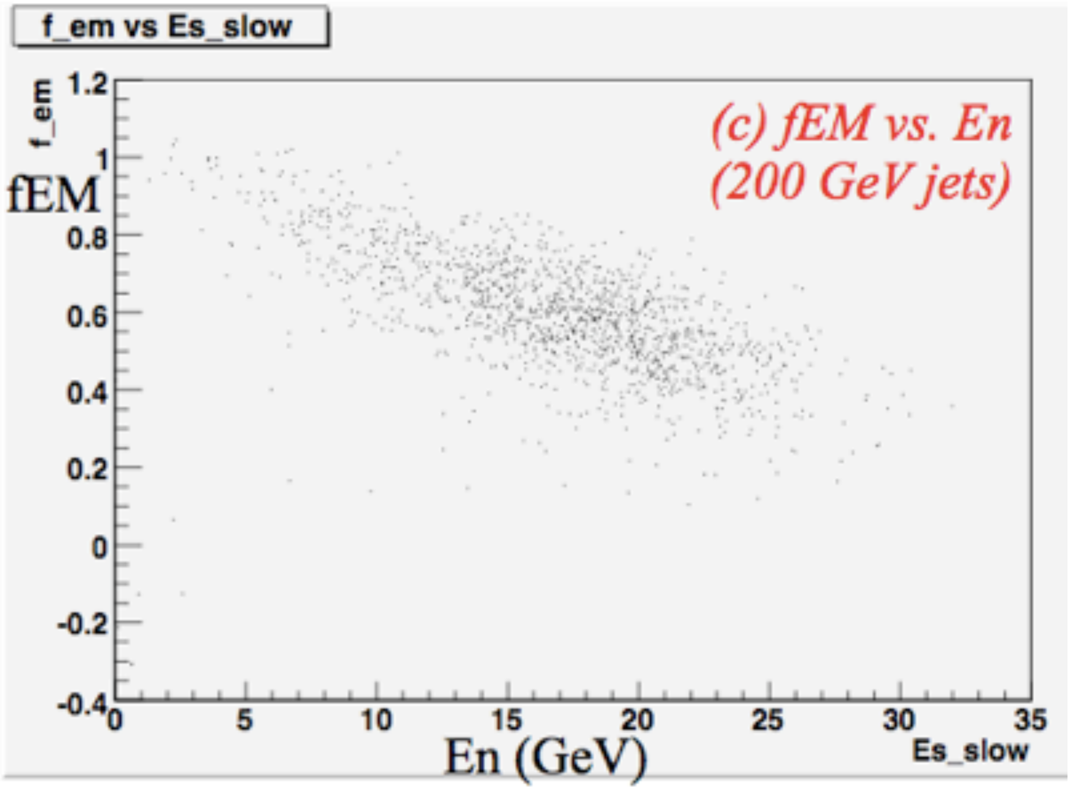


(a) Spe(t) 0-350 ns

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



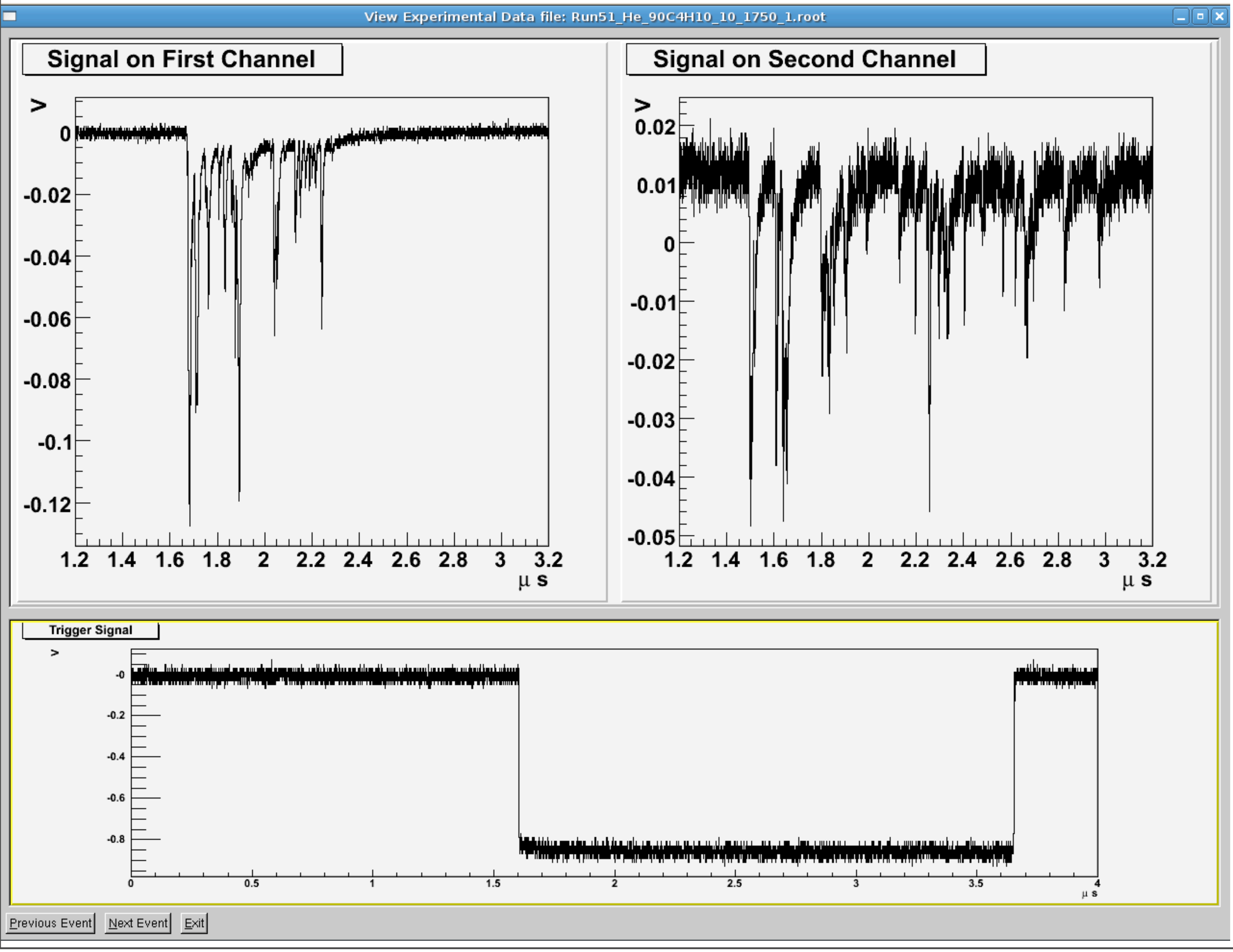
(b) neutron fraction, fn determined from Spe(t)



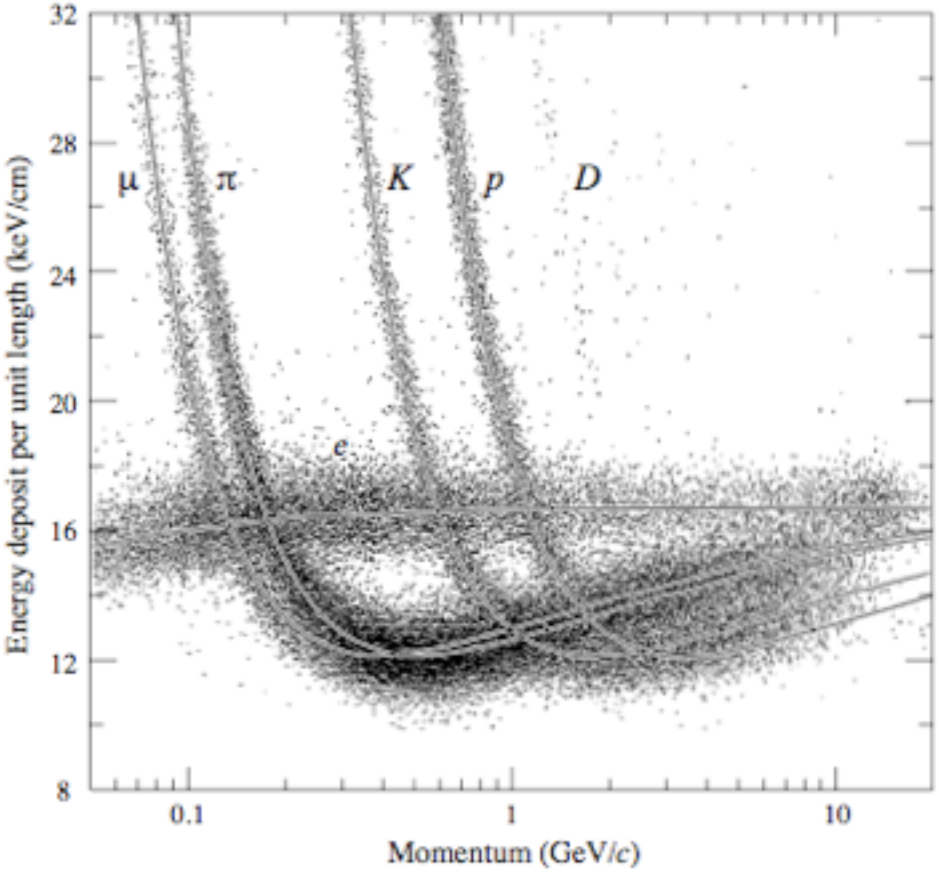
(c) fEM vs. En (200 GeV jets)

dN/dx by cluster-counting: *specific ionization resolution ~ 3.5%*

π - K - p identification



TPC with ~6%
dE/dx resolution



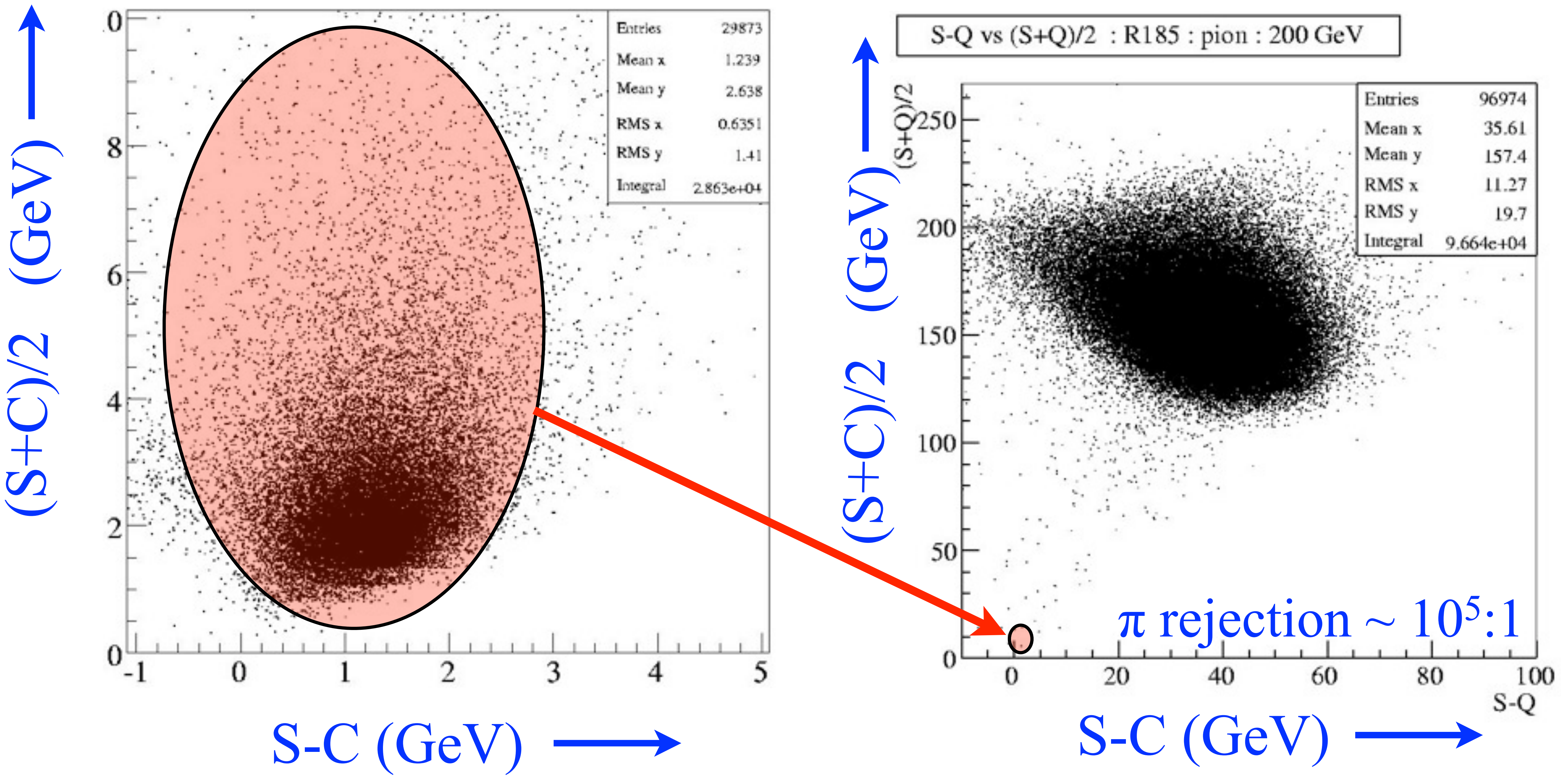
μ vs. π dual-readout: $\theta_{\mathrm{Cher}} > \theta_{\mathrm{num.\ aperture}}$

(S~*dE/dx+brems* & *C~brems)*

S-C ~ *dE/dx* ~ 1.1 GeV (in DREAM) for μ

200 GeV μ^-

200 GeV π^-

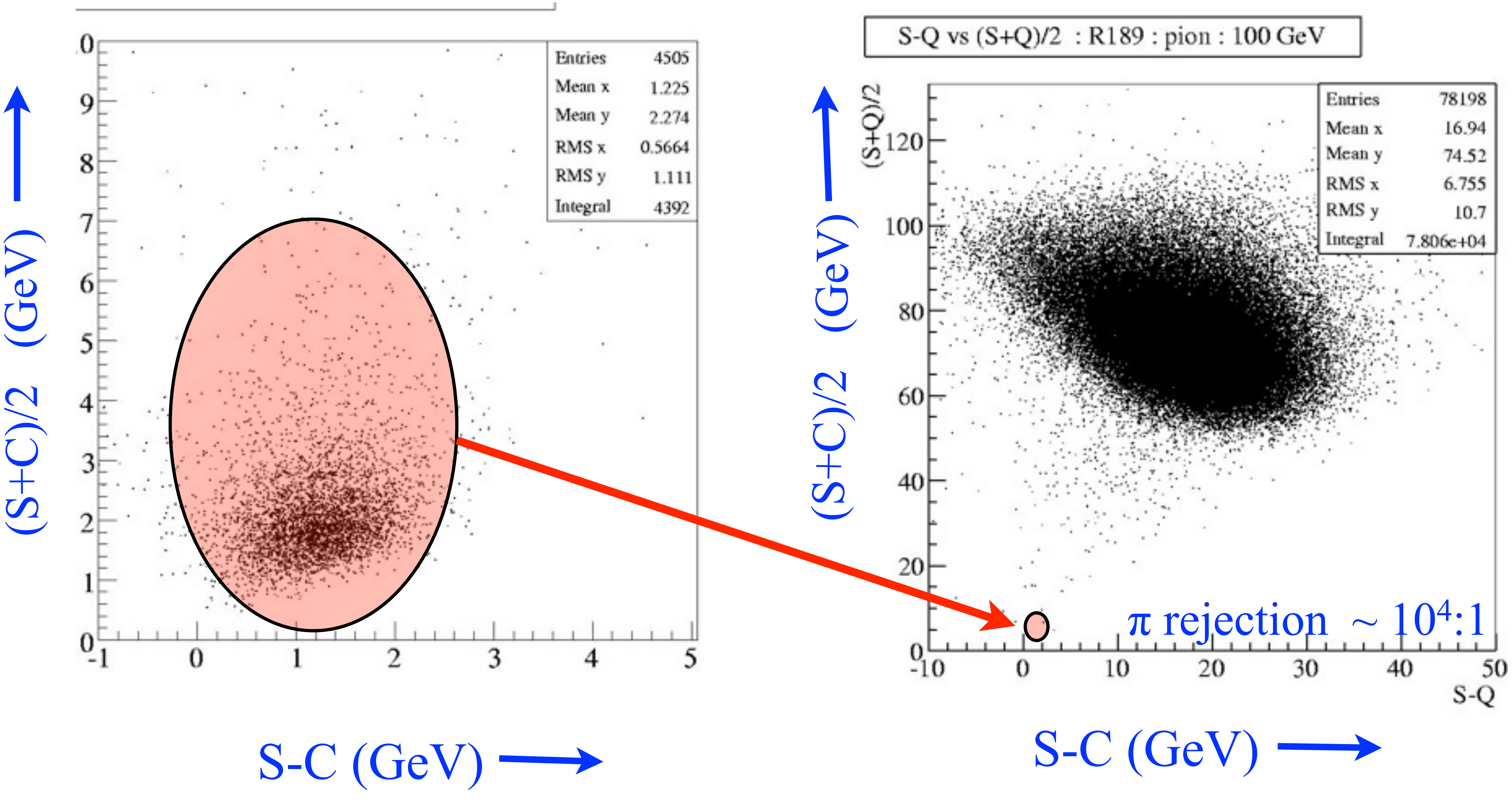


π rejection ~ 10^5:1

μ vs. π dual-readout: $\theta_{Cher} > \theta_{num.\ aperture}$

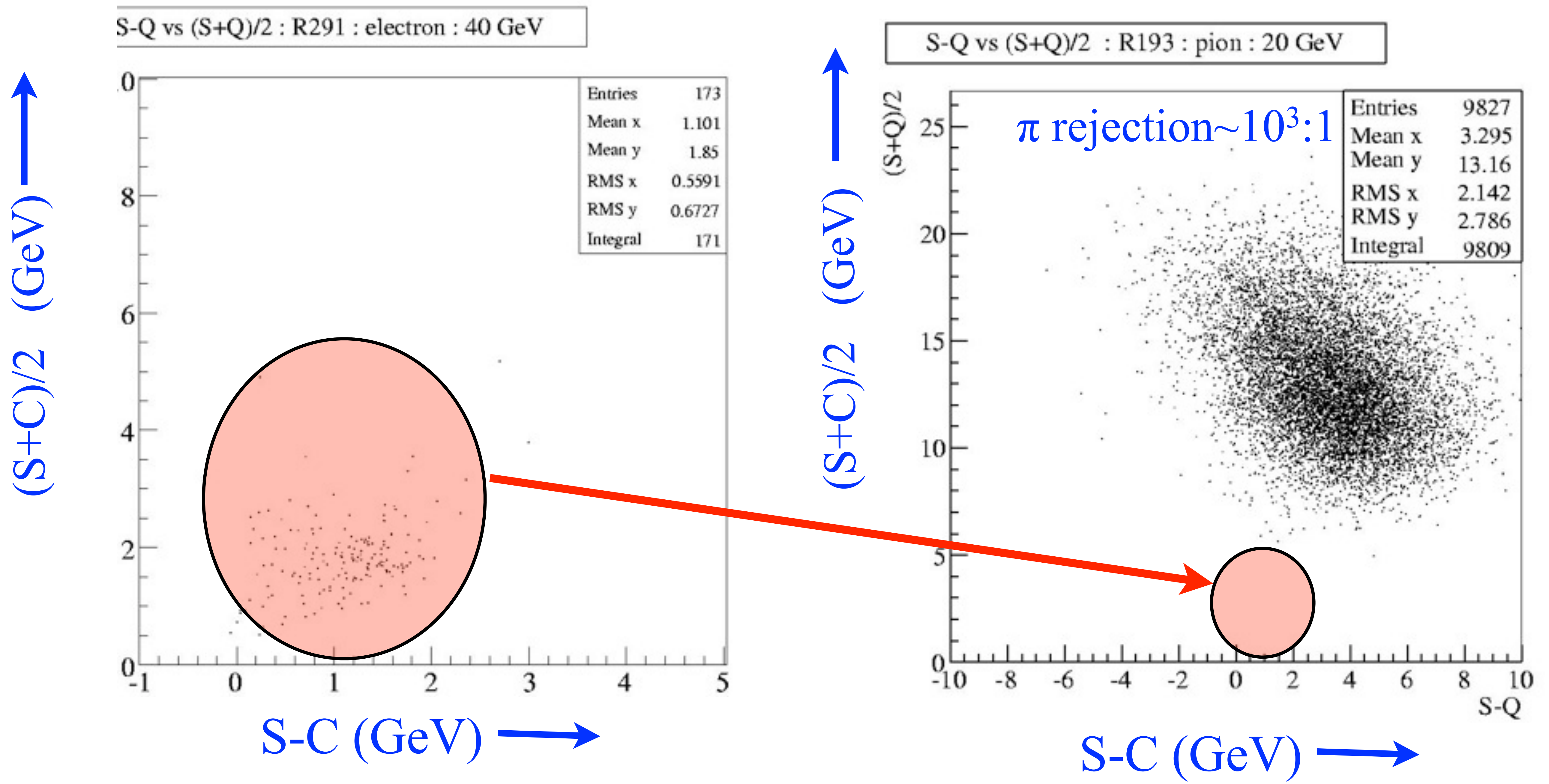
100 GeV μ^-

100 GeV π^-



μ vs. π   dual-readout: $\theta_{\mathrm{Cher}} > \theta_{\mathrm{num.\ aperture}}$

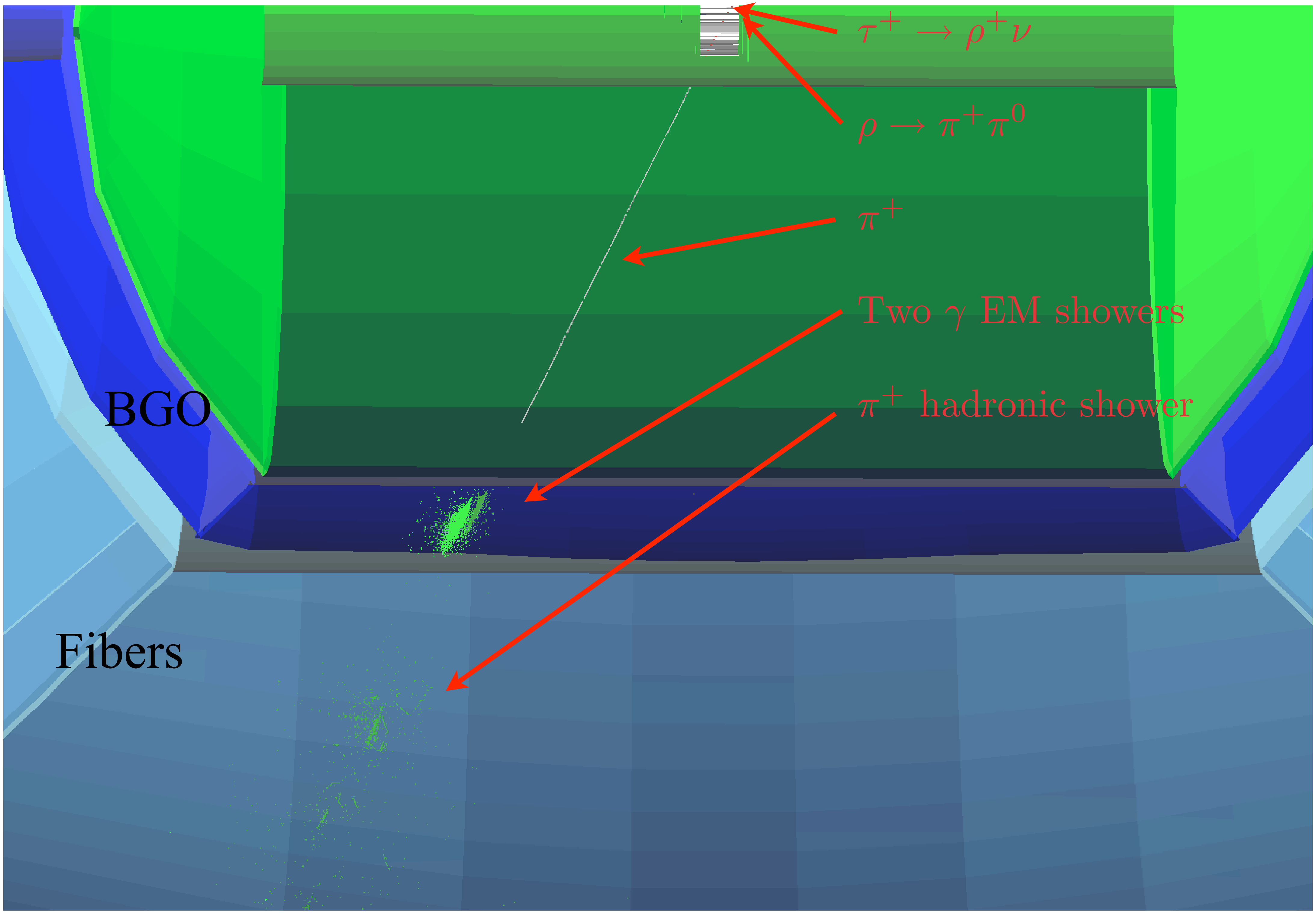
40 GeV μ^- 20 GeV π^-



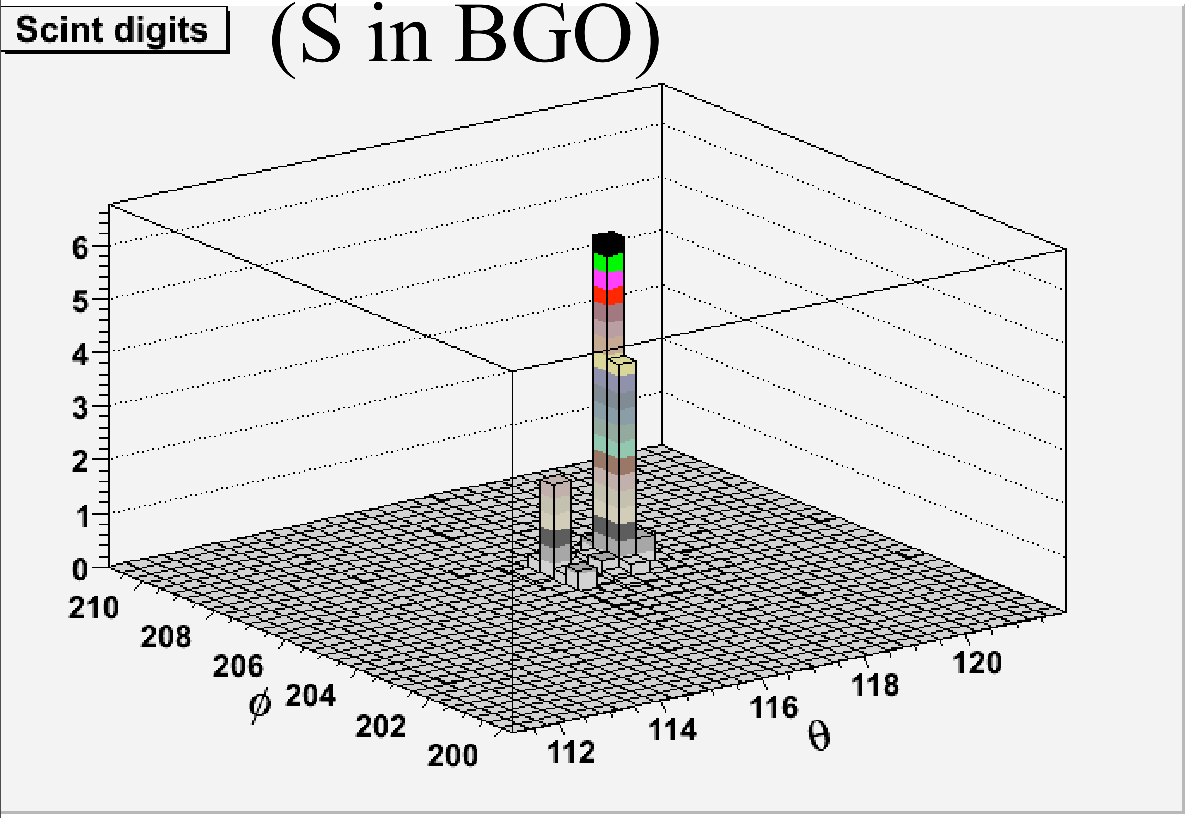
π rejection~10^3:1

9. Tau ID by reconstruction of pi-zero and charged pion

(result from V. Di Benedetto, INFN, Lecce)

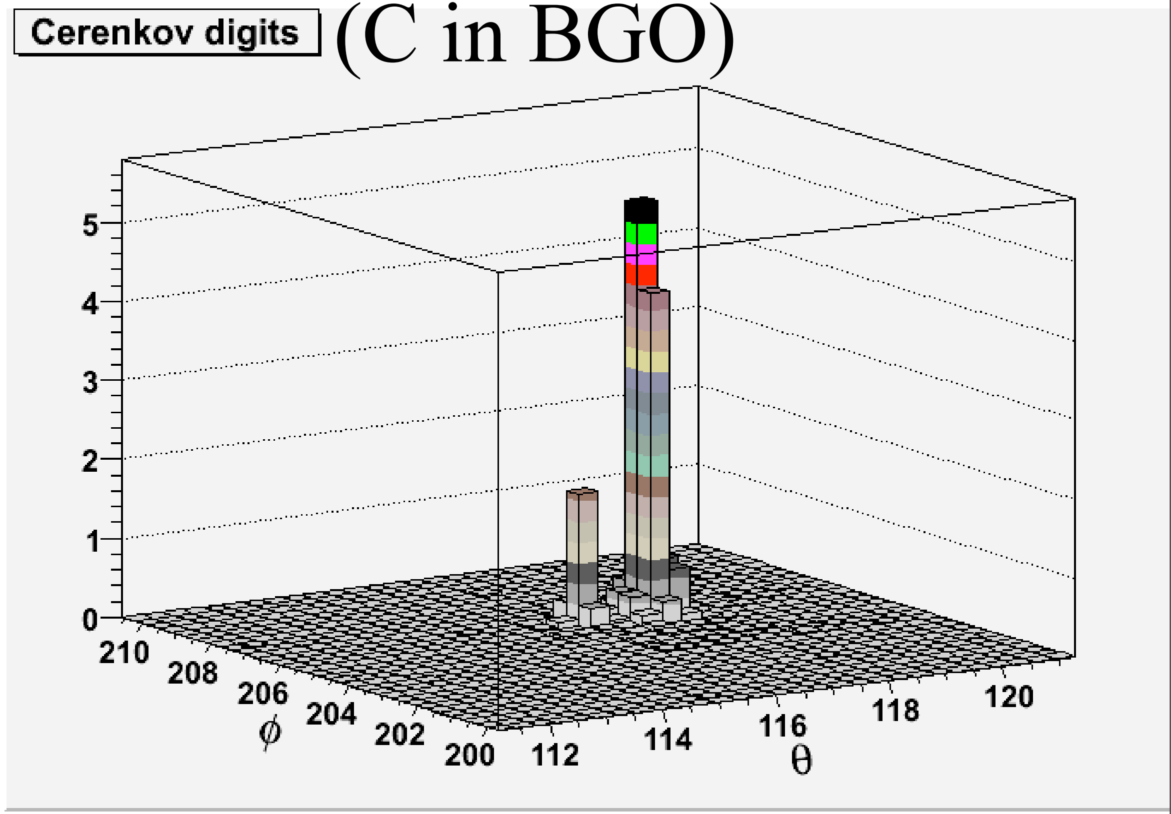


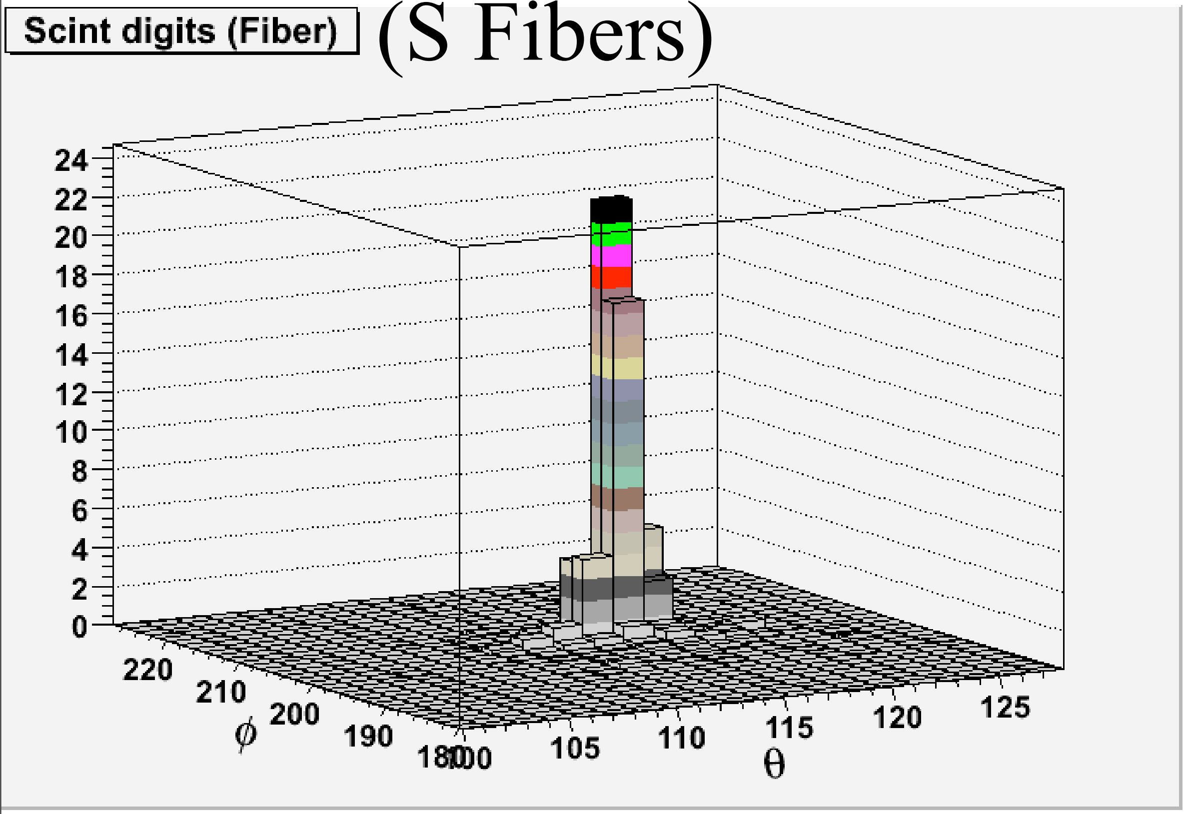
9. (continued)


(S in BGO)

two
clear
photons

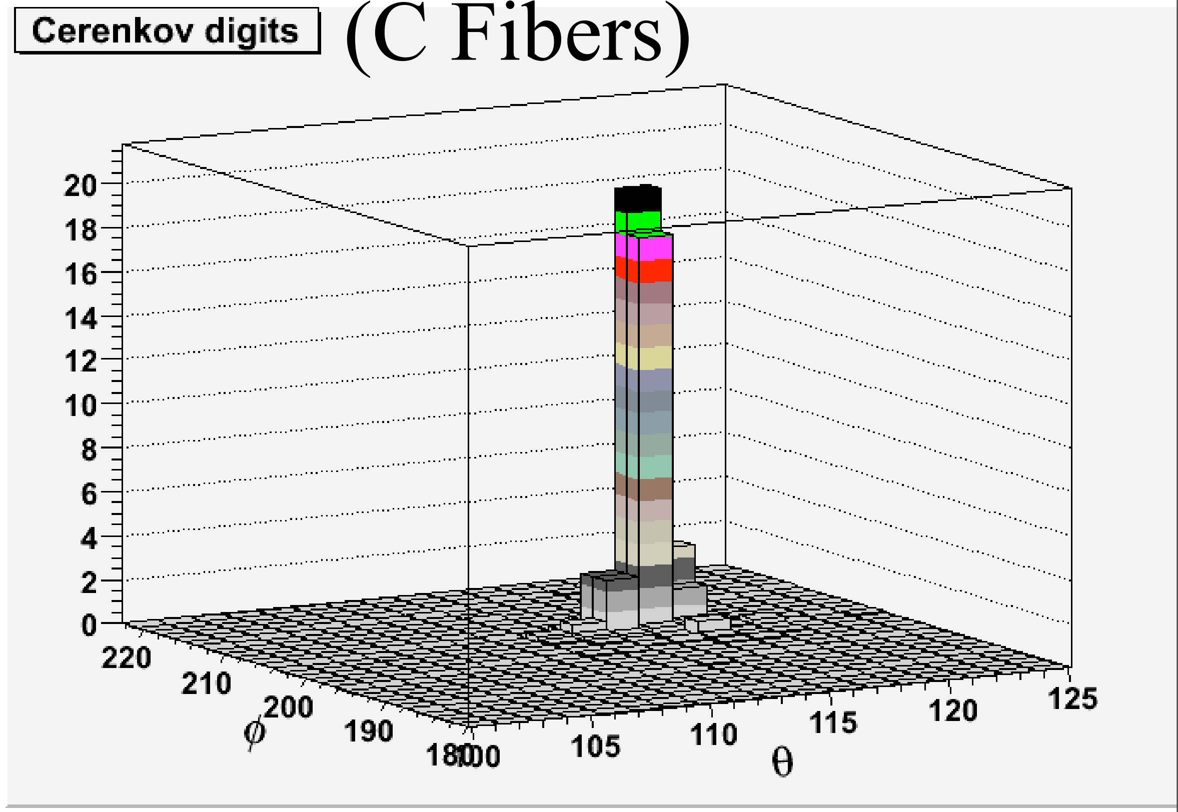
S~C
(EM)


(C in BGO)


(S Fibers)

one
clear
shower

S>C
(hadronic)


(C Fibers)

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

Generations of quarks and leptons

Boson force carriers