American Linear Collider Physics Group

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Calorimetry for a LC

Detector Development with PFAs

ECAL Optimizaton

HCAL Optimizaton

Demo – PFA Performance in a LC Detector

A Particle-Flow Jet Detector

Jets :

charged pions, photons, K_L^0/n -> *>95% of jet energy*

other hadrons/leptons/neutrinos -> few %

Need a detector sensitive only to charged pions (+ other charged particles)

= Tracker

Need a detector sensitive only to photons

= ECAL -> try to force hadron showers into the HCAL (longitudinal segmentation), fine granularity for separation of showers

Need a detector sensitive only to neutral hadrons

= HCAL -> longitudinal segmentation and fine granularity for separation of charged/neutral hadron showers

ECAL Requirements for Particle-Flow

-> Need a dense calorimeter with optimal separation between the starting depth of EM and Hadronic showers. If λ_I / X_0 is large, then the *longitudinal separation* between starting points of EM and Hadronic showers is large

-> For electromagnetic showers in a dense calorimeter, the transverse size is small

- -> small r_M (Moliere radius)
- -> If the transverse segmentation is of size r_M, get optimal *transverse separation* of electromagnetic clusters.

W/Si for LDC, SiD   Pb/Scintillator for GLD

Some ECAL Issues :

-> range cut optimizaton in GEANT4 – dense absorber/thin active layer transition . . . CALICE ECAL Test Beam results to answer?

-> ECAL thickness – containment of EM showers

HCAL Optimization for Particle FLow

A comparison of various absorbers and readout types for a LC HCAL. It includes the following types of analyses :

1) Single particle analyses

used to understand calibration issues and techniques, test understanding of generator processes, input for various calculations, e.g. perfect PFA (see below)

2) e+e- -> Z -> qqbar

simple events that allow simple analyses using energy sums - eliminates jet algorithm dependencies when testing PFA algorithms

3) PFAs

Perfect PFA - 2 types, one based on single particle resolution for photons and neutral hadrons, one based on actual contributions to the overall energy sum resolution at the Z Pole assuming perfect calorimeter hit ID.

“Real” PFA - True photon hits from MC, determination of charged hadron interaction layer (layer of first showering) and analysis of E/P for iterative cones starting at the interaction layer to get calorimeter showers associated with charged hadrons, various treatments of leftover hits as the neutral contribution

Calorimeter Absorber Optimization

1) PFA optimization - beginning of hadron showers separated (longitudinally) from beginning of EM showers . . .

$\mathcal{P}(e,\gamma) = 1 - C_{e,\gamma}\, e^{-x/X0}$ $\quad C_{e,\gamma} = (1, 7/9)$

$\mathcal{P}(h) = 1 - C_h\, e^{-l/\lambda I}$ $\quad C_h = 1$

So, in first layers of calorimeter, want $\mathcal{P}(e,\gamma) \gg \mathcal{P}(h)$

-> $x/X_0 \gg l/\lambda_I$

-> λ_I/X_0 should be as large as possible

Dense, Non-magnetic

Material	λ_I (cm)	X_0 (cm)	λ_I/X_0
W	9.59	0.35	27.40
Au	9.74	0.34	28.65
Pt	8.84	0.305	28.98
Pb	17.09	0.56	30.52
U	10.50	0.32	32.81

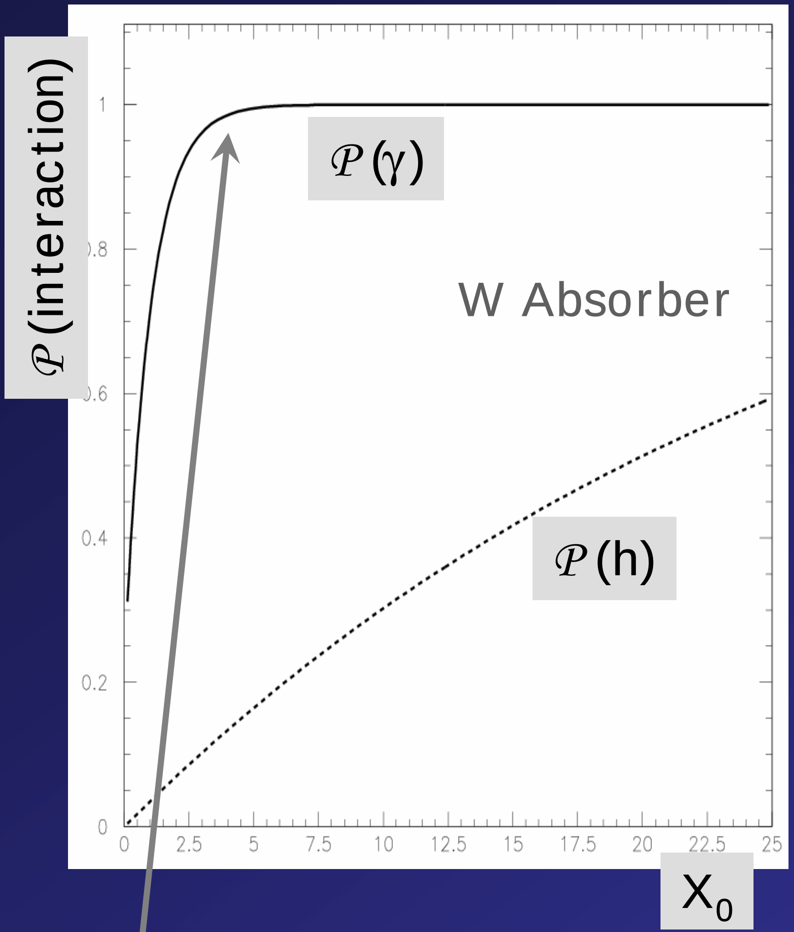
Less Dense, Non-magnetic

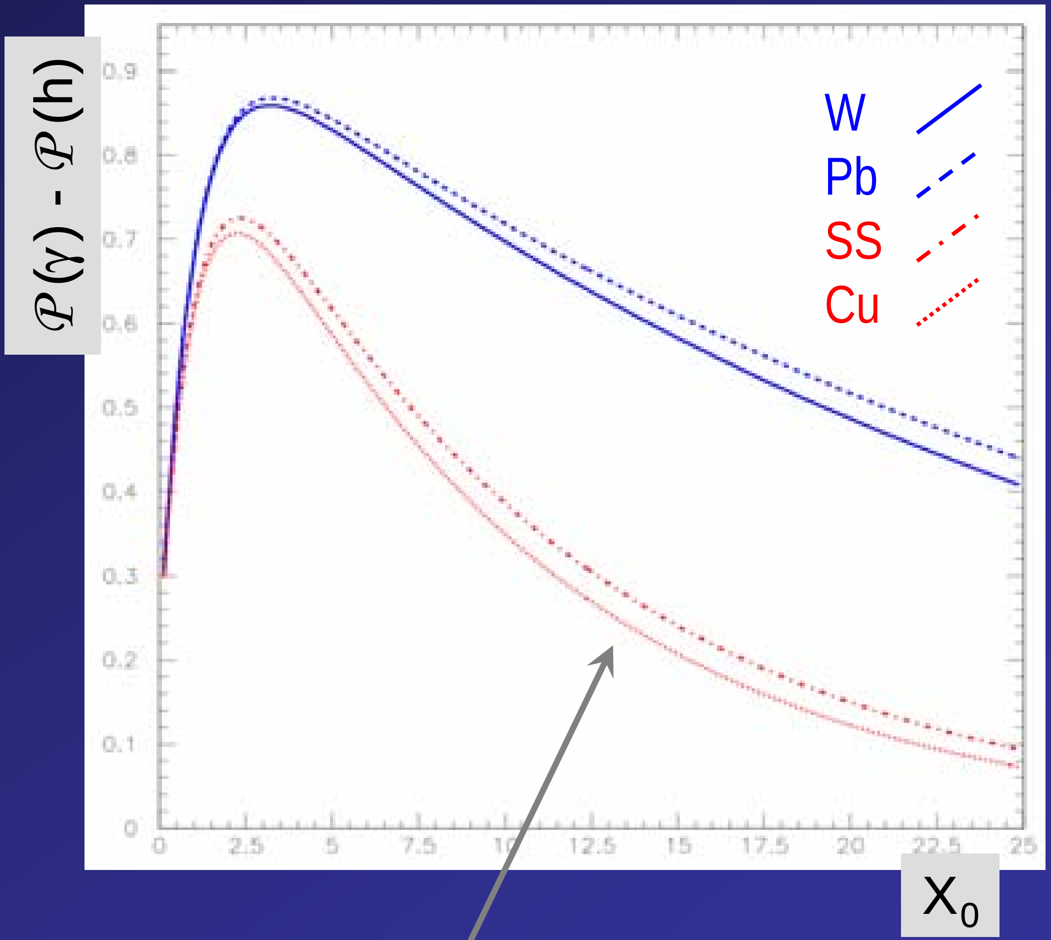
Material	λ_I (cm)	X_0 (cm)	λ_I/X_0
Fe (SS)	16.76	1.76	9.52
Cu	15.06	1.43	10.53

. . . Use these for ECAL

* Note ~X2 difference in λ_I for W/Pb – important for HCAL later

Shower Probabilities in ECAL (25 X_0)



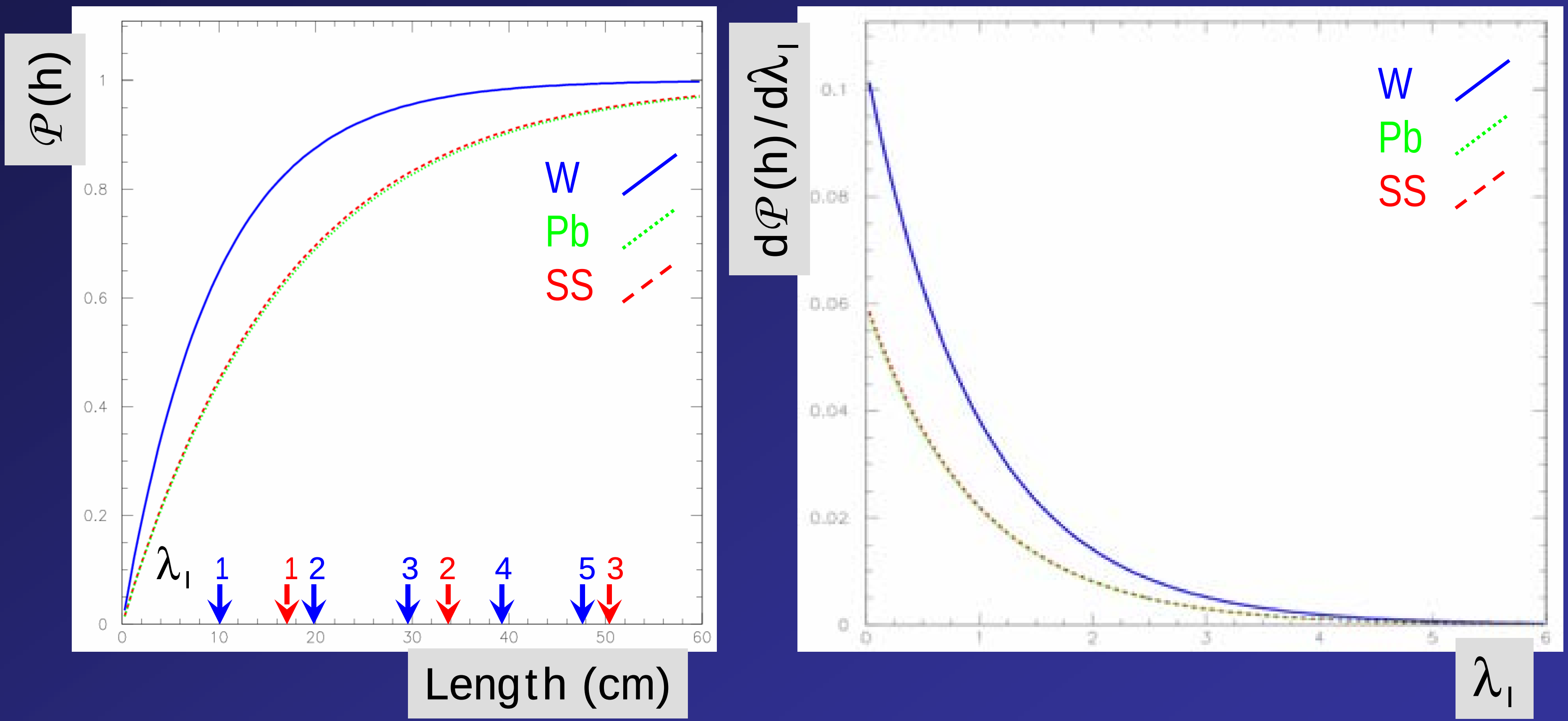


𝒫(γ) reaches ~100% while 𝒫(h) still <20%

-> W,Pb probability differences >> SS,Cu

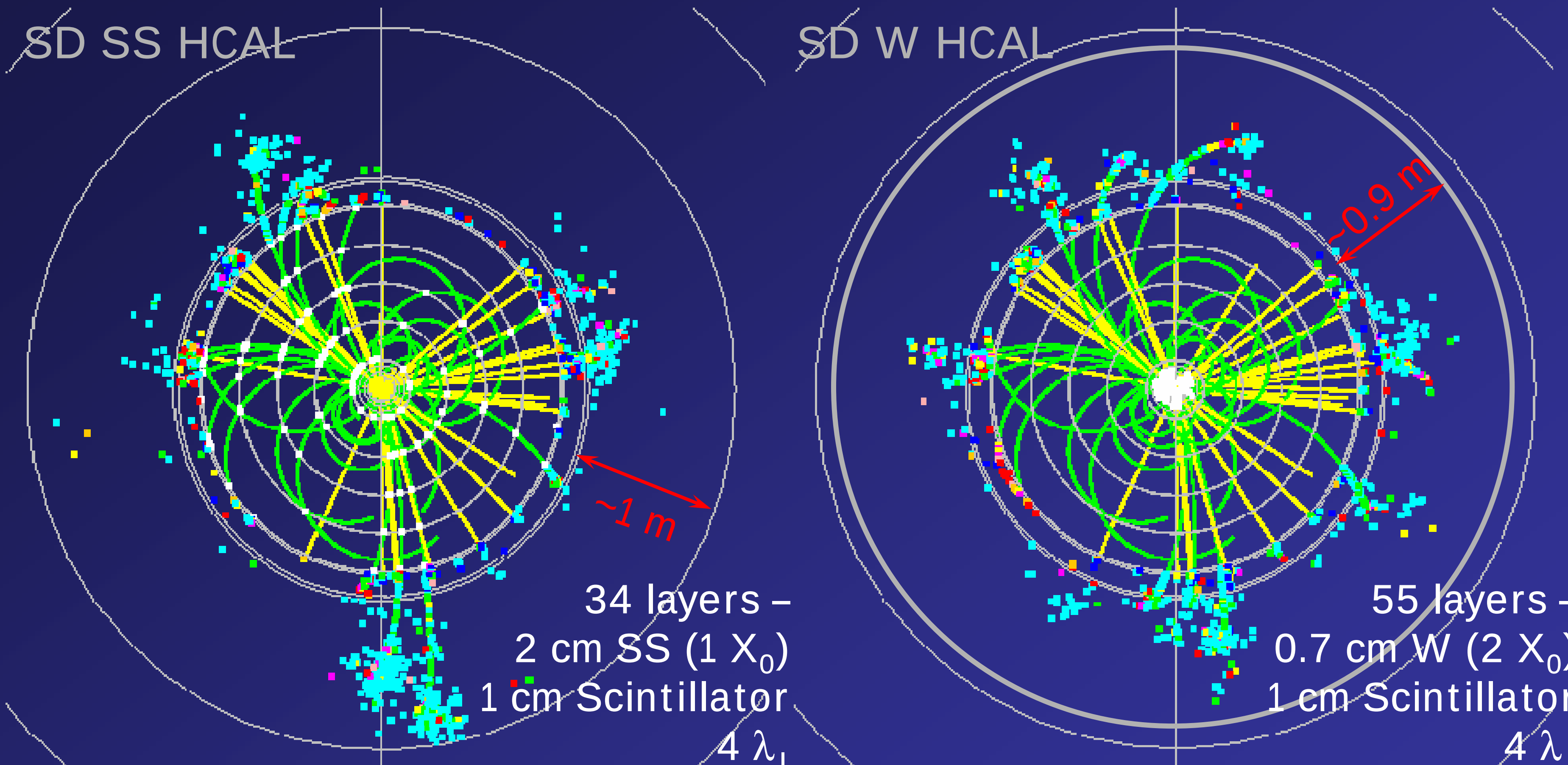
-> better shower separation in dense material

2) Once $\mathcal{P}(e,\gamma)$ -> 1 and γ's are fully contained (end of ECAL), want $\mathcal{P}(h)$ -> 1 as fast as possible . . .



. . . W performs better than SS and Pb for HCAL

Z jets in SS/W HCAL – Absorber Comparison



Same event - different shower shape in W compared to SS?

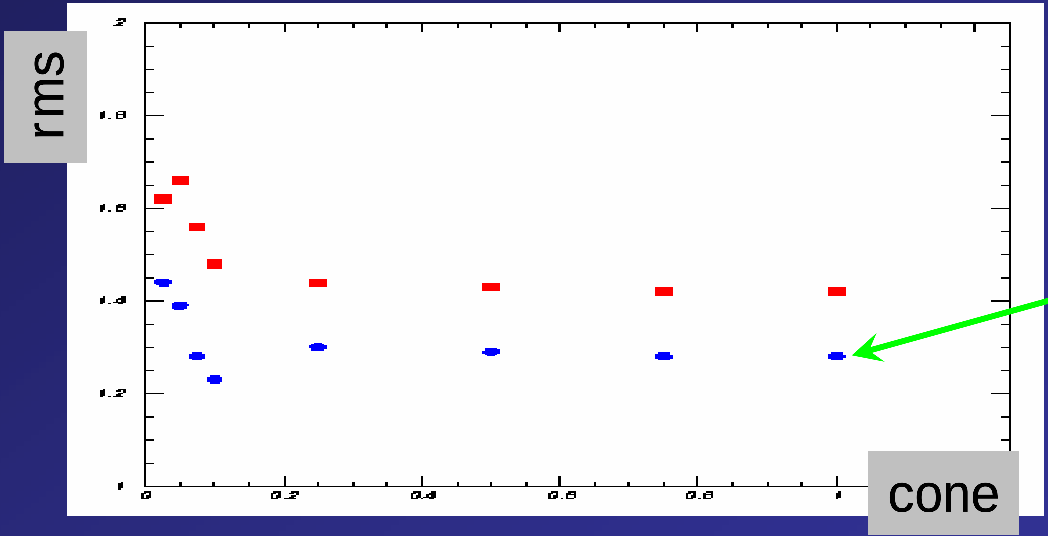
3) And, hadron showers should be as compact as possible . . .

SS Single 5 GeV π

cone	mean (GeV)	rms	σ/mean	$\chi2$
.025	2.07	1.62	.79	10.61
.05	2.96	1.66	.51	4.51
.075	3.63	1.56	.38	2.74
.10	4.08	1.48	.31	2.56
.25	4.76	1.44	.25	2.49
.50	4.85	1.43	.25	2.42
.75	4.86	1.42	.25	2.25
1.00	4.87	1.42	.25	2.45

W Single 5 GeV π

cone	mean (GeV)	rms	σ/mean	$\chi2$
.025	1.92	1.44	.78	9.36
.05	2.94	1.39	.41	4.29
.075	3.59	1.28	.31	2.42
.10	4.01	1.23	.25	2.35
.25	4.64	1.30	.23	2.70
.50	4.77	1.29	.23	2.50
.75	4.79	1.28	.23	2.41
1.00	4.80	1.28	.23	2.40



Energy in fixed cone size :
- -> means ~same for SS/W
- -> rms ~10% smaller in W

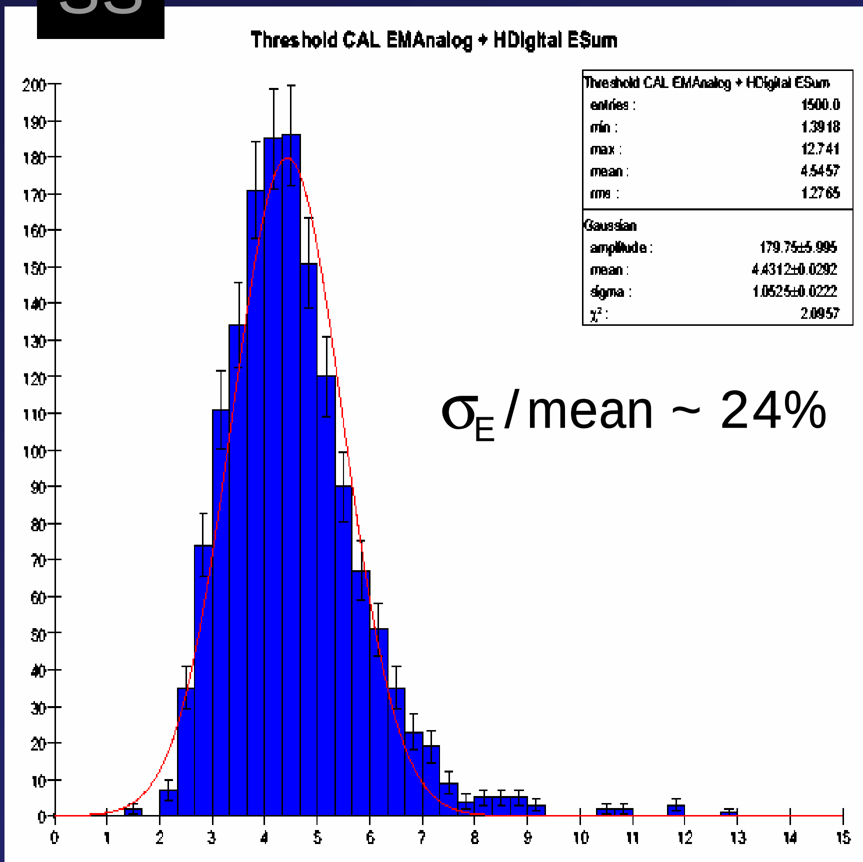
Tighter showers in W

. . . W looks like the best choice for HCAL

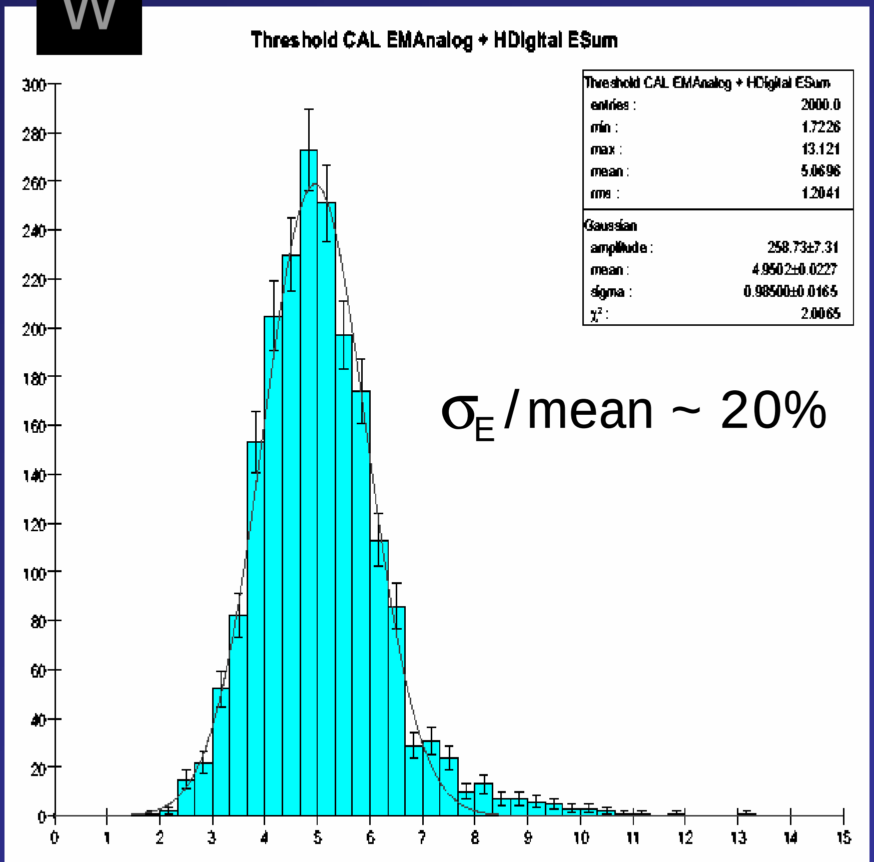
4) Energy resolution comparisons for SS, W . . .

Single 5 GeV Pion

SS



W



Energy measurement in calorimeter – Analog ECAL, Digital HCAL

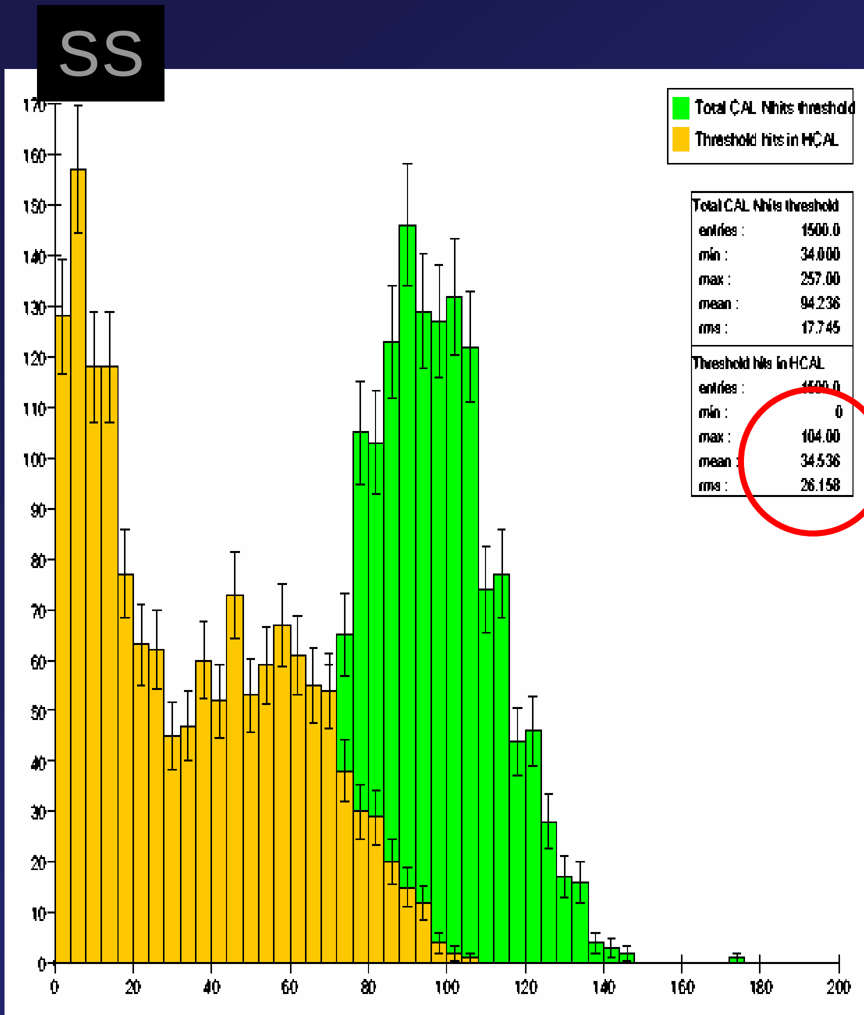
-> σ/ mean smaller in W HCAL

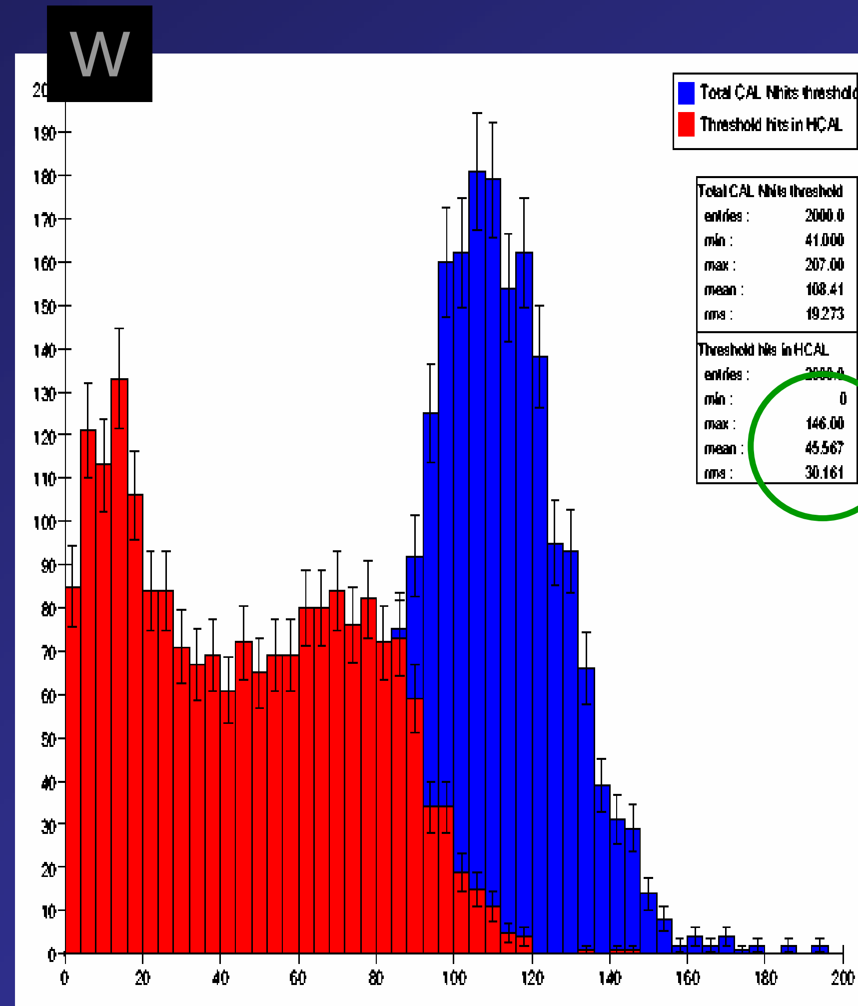
-> same behavior for analog HCAL

W – 2 X_0 sampling

SS – 1 X_0 sampling

Single 5 GeV Pion – Number of hits (1/3 mip thresh)





More hits in W HCAL than in SS

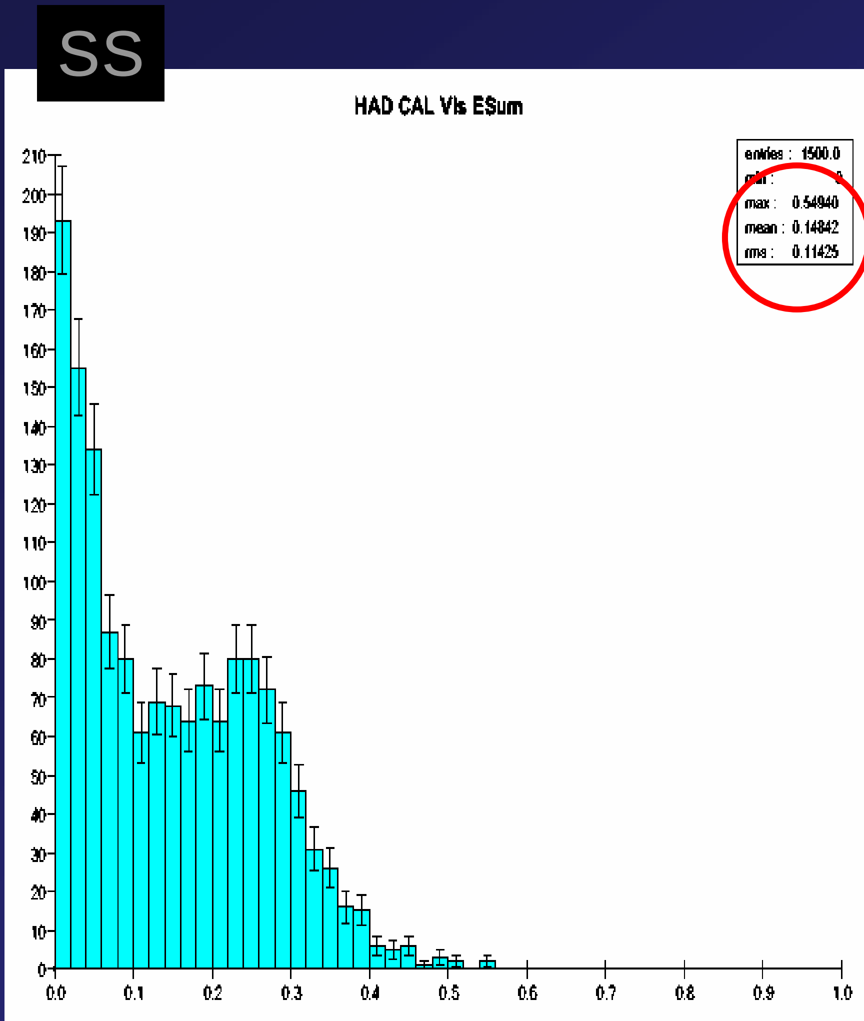
-> 30% more hits in the HCAL for W

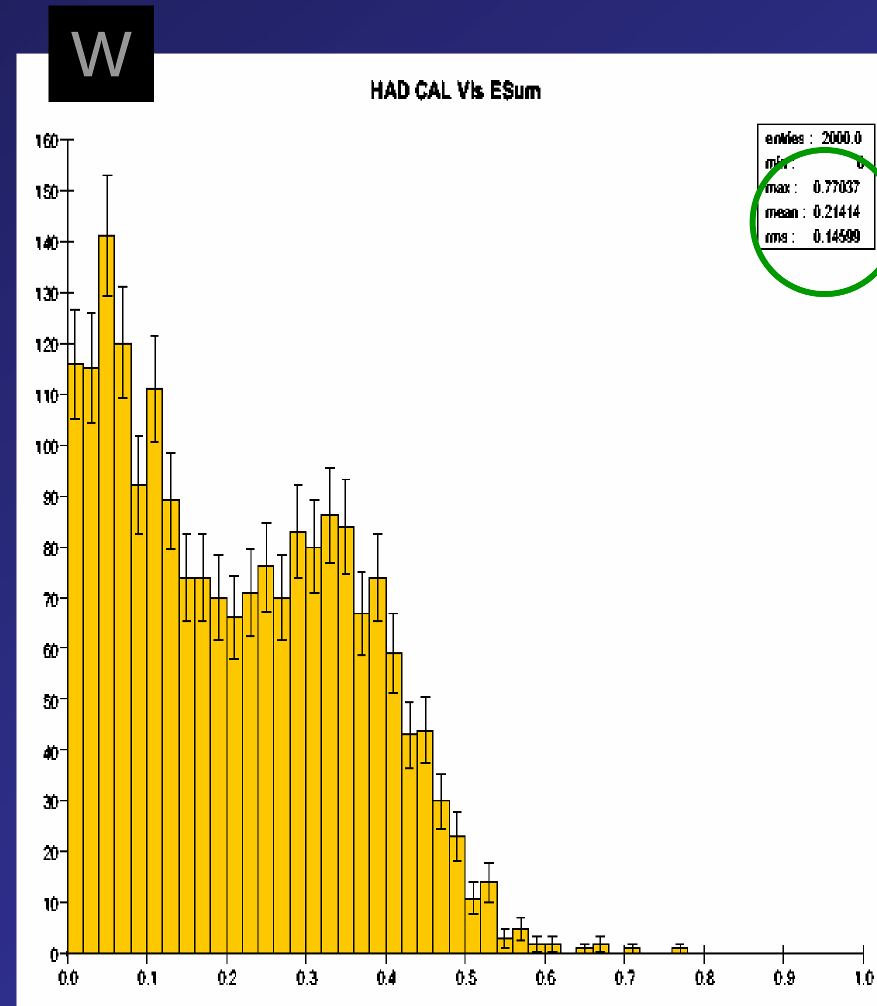
-> <u>better digital resolution for W!</u>

W – 2 X_0 sampling

SS – 1 X_0 sampling

Single 5 GeV Pion – Visible Energy in HCAL





More visible energy in W HCAL

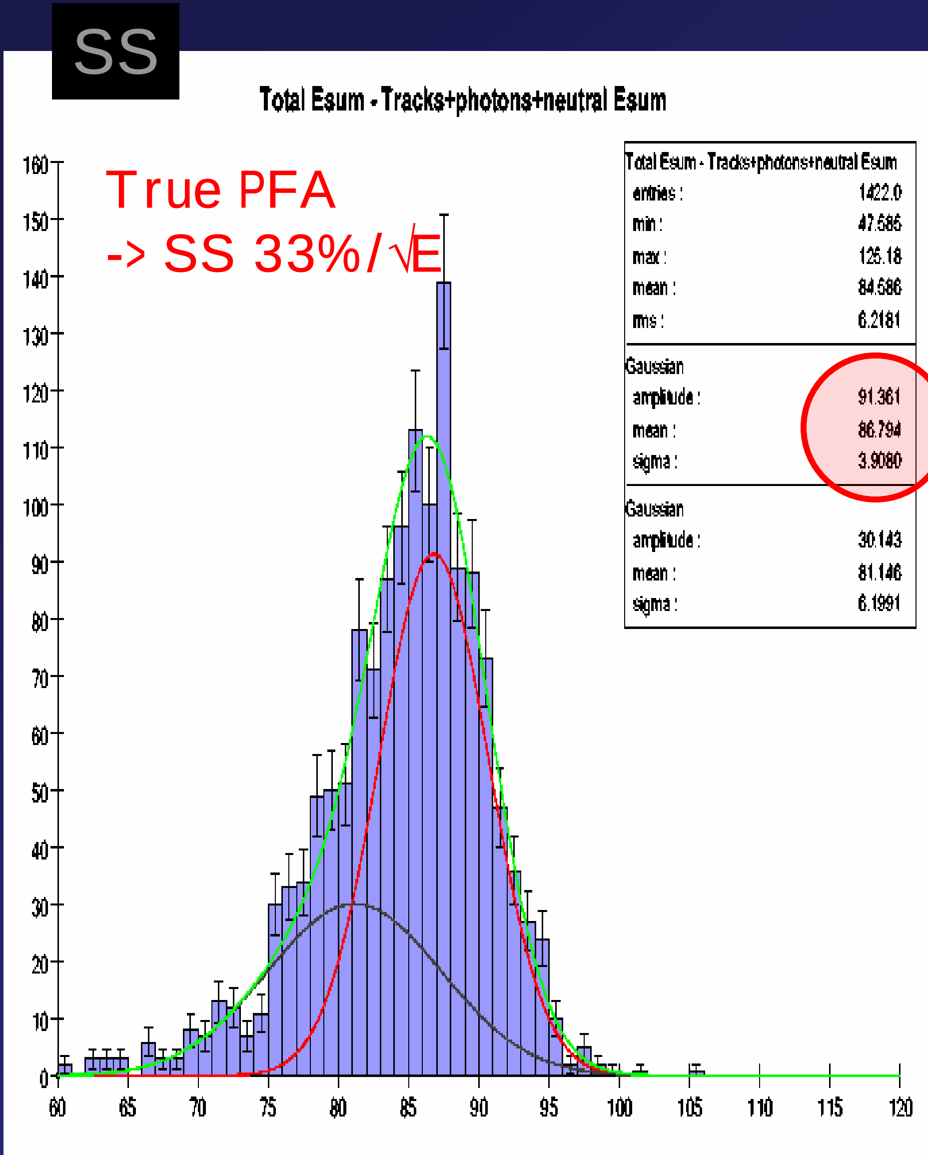
-> <u>better analog resolution in W</u>

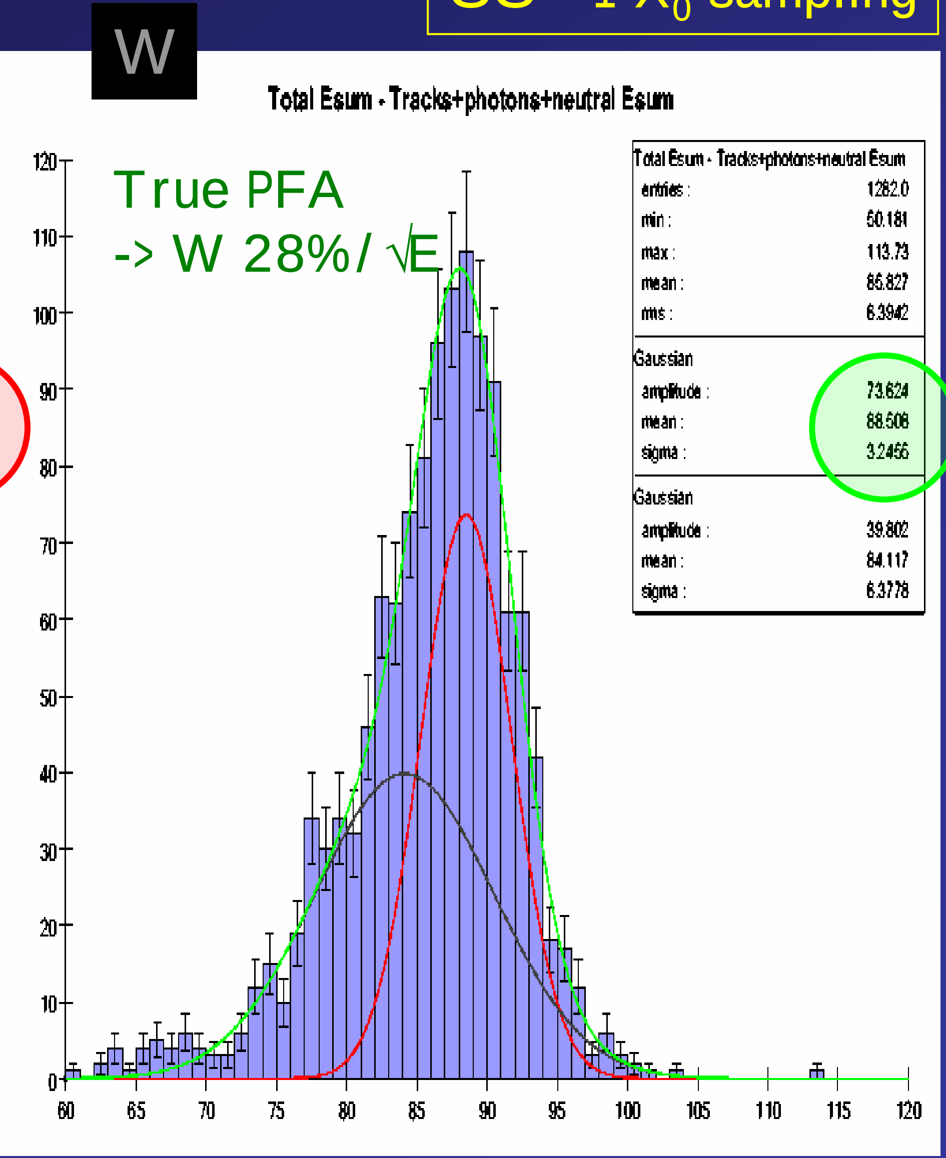
W – 2 X_0 sampling

SS – 1 X_0 sampling

e+e- -> Z (jets) – PFA performance Fits

W – 2 X_0 sampling
SS – 1 X_0 sampling



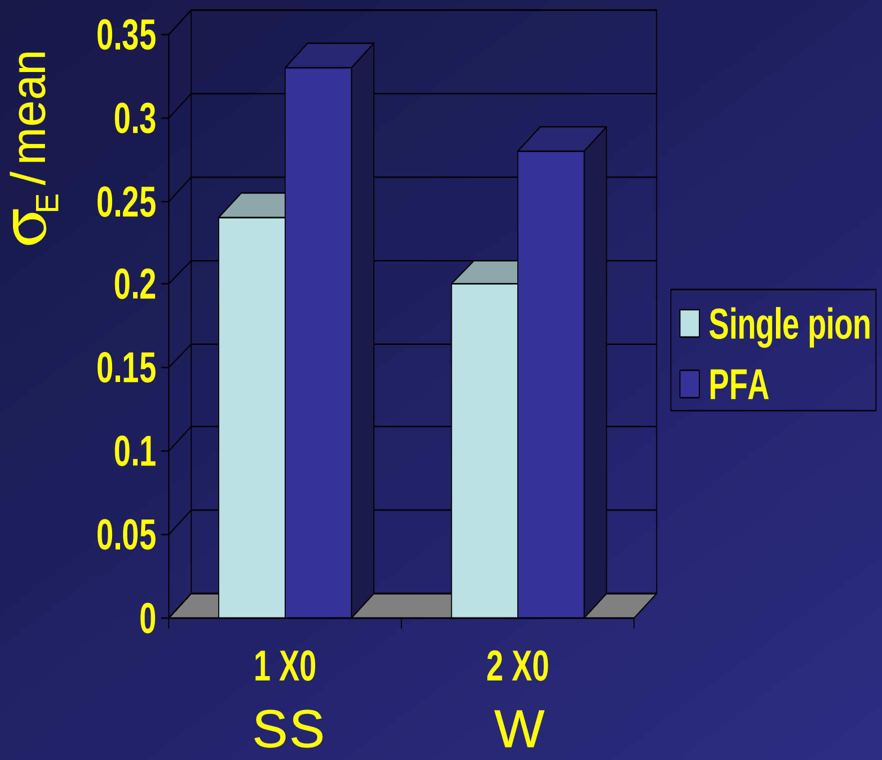


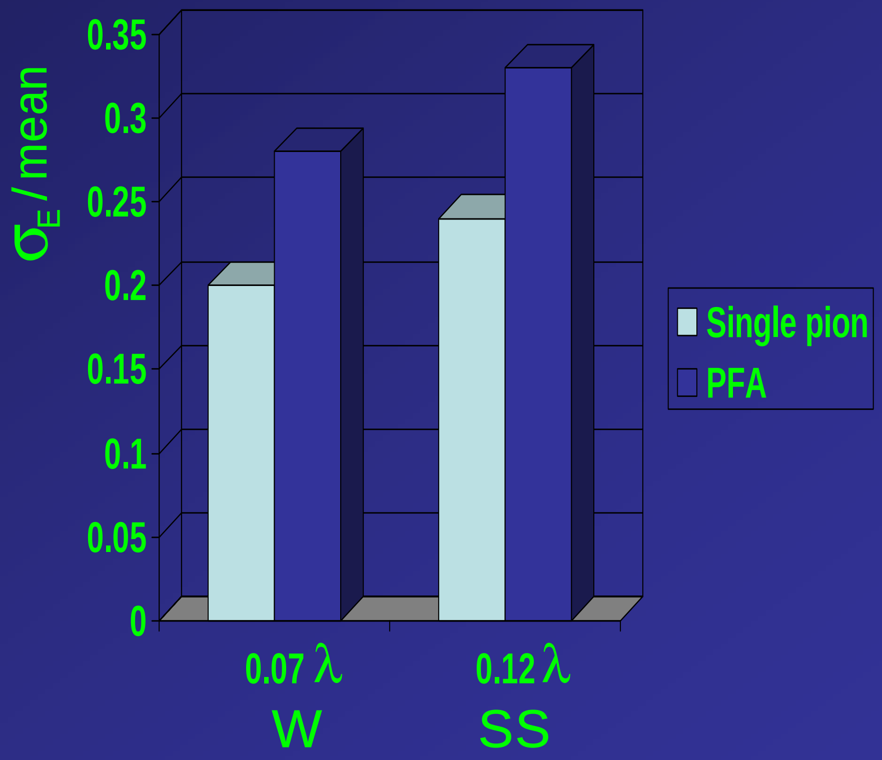
Better PFA performance with the W HCAL for conical showers . . .

however, simple iterative cone reconstructs smaller fraction of events*

W – 2 X_0 sampling
SS – 1 X_0 sampling

Single particle, PFA resolution comparison results . . .





σ_E/mean ↓, X_0 ↑ !   Coarser X_0 sampling gives better σ_E!?

σ_E/mean ↓, λ_I ↓   Finer λ_I sampling gives better σ_E

. . . W looks like the best choice for HCAL

-> hadron E resolution depends on λ_I, not X_0

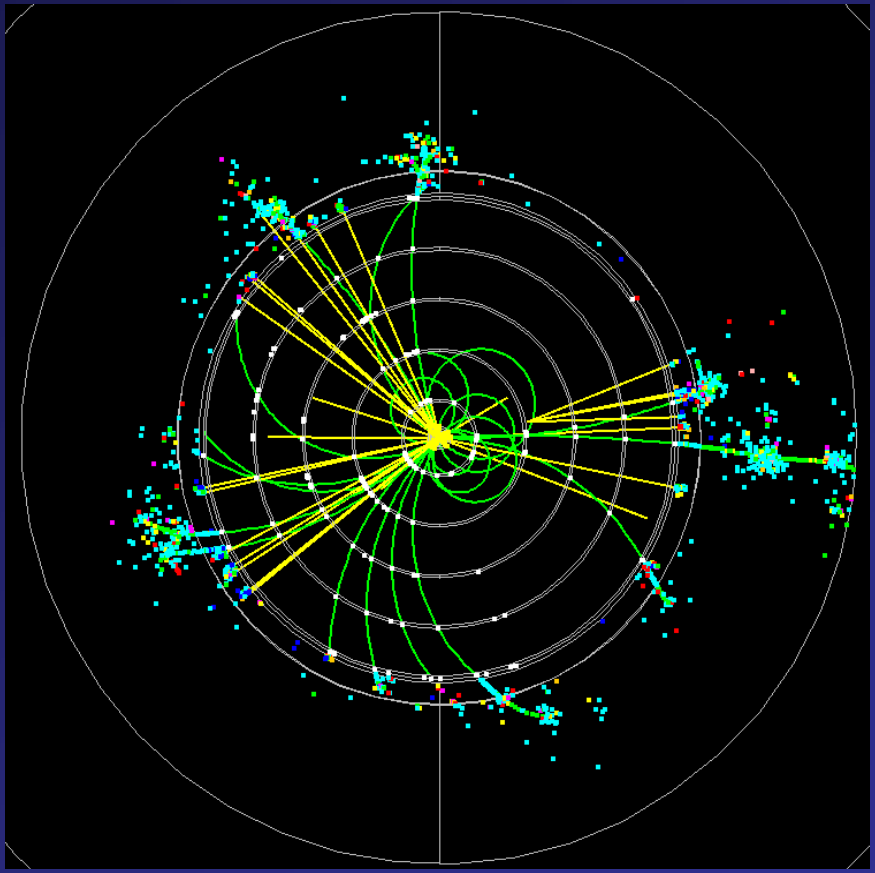
HCAL Readout Optimization

Dense HCALs (W absorber) - 4 λ_I in ~82.5 cm IR -> OR

SDFeb05 SCI HCAL

55 layers of 0.7 cm W/0.8 cm Scin.

Sampling fraction ~6%

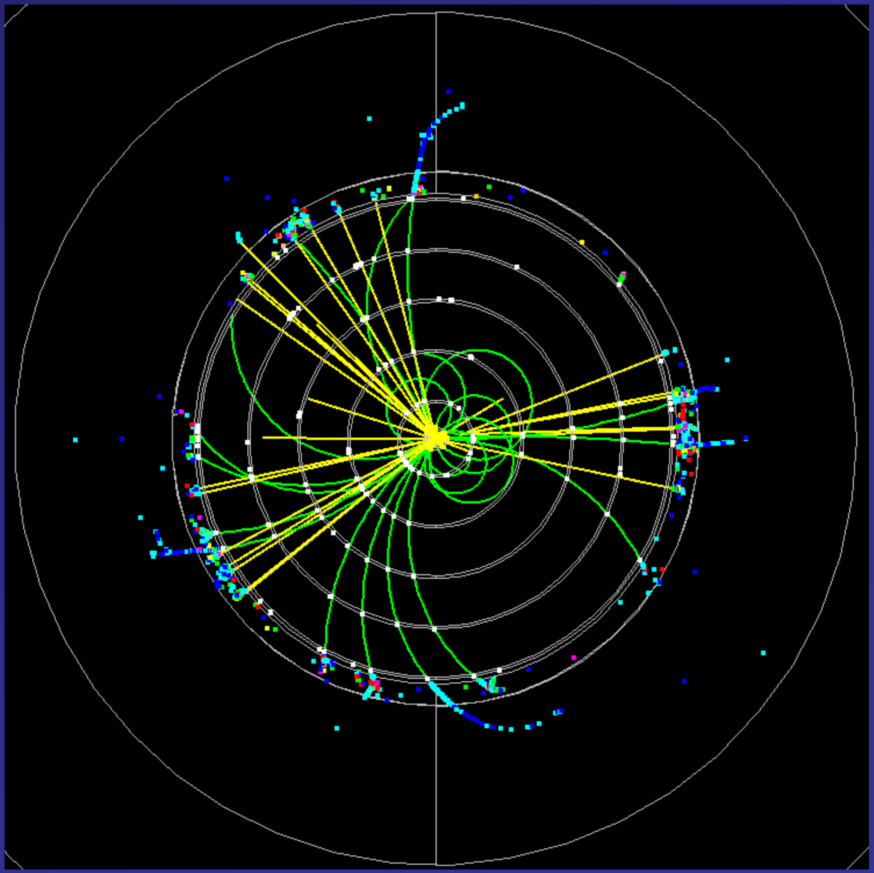


SDFeb05 RPC HCAL

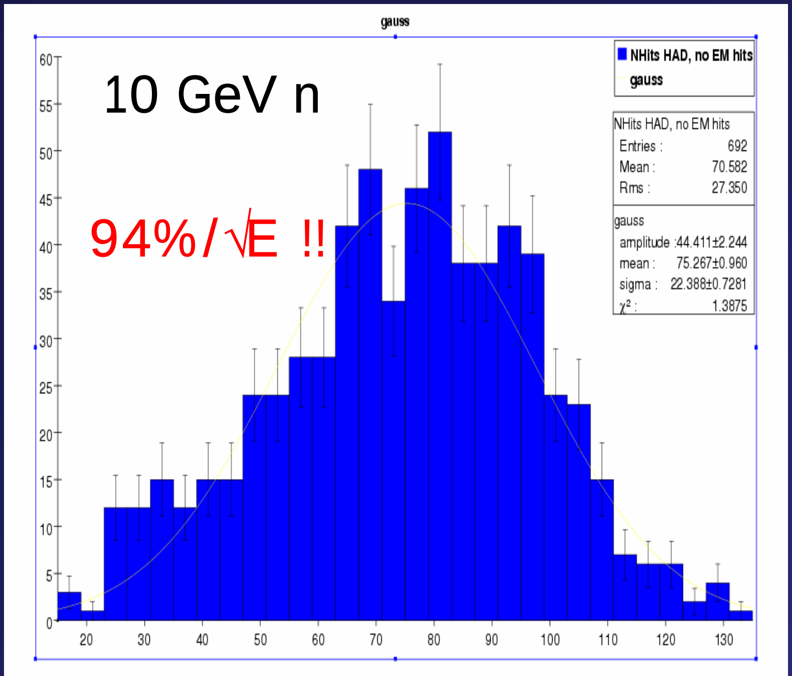
55 layers of 0.7 cm W/0.8 cm RPC

1.2 mm gas gap

Sampling Fraction ~0.0025%!!!



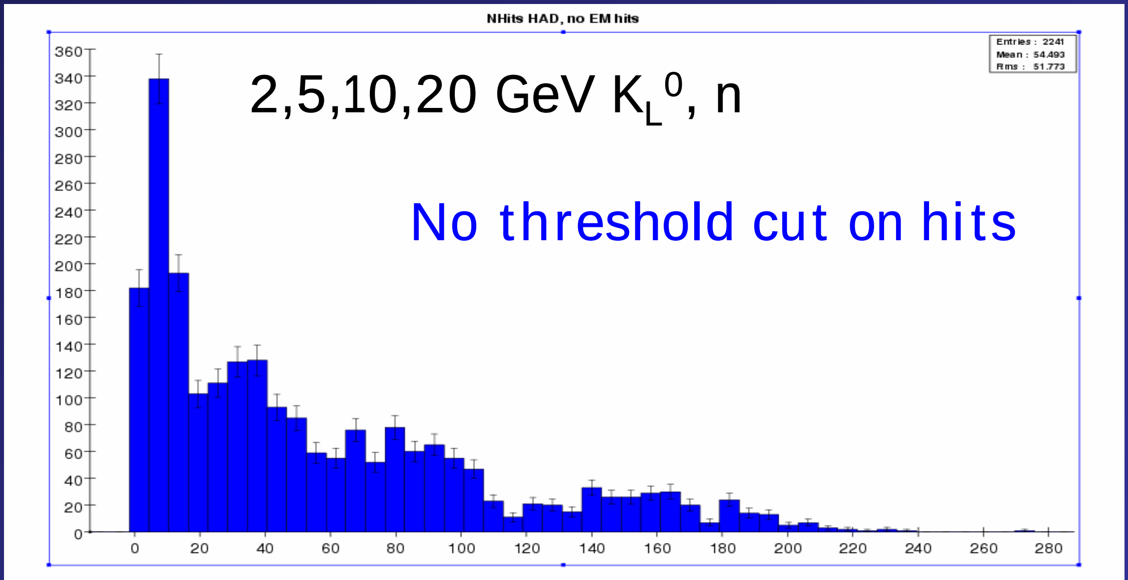
SiD SS/RPC HCAL



Hits for 2,5,10,20 GeV Neutrals

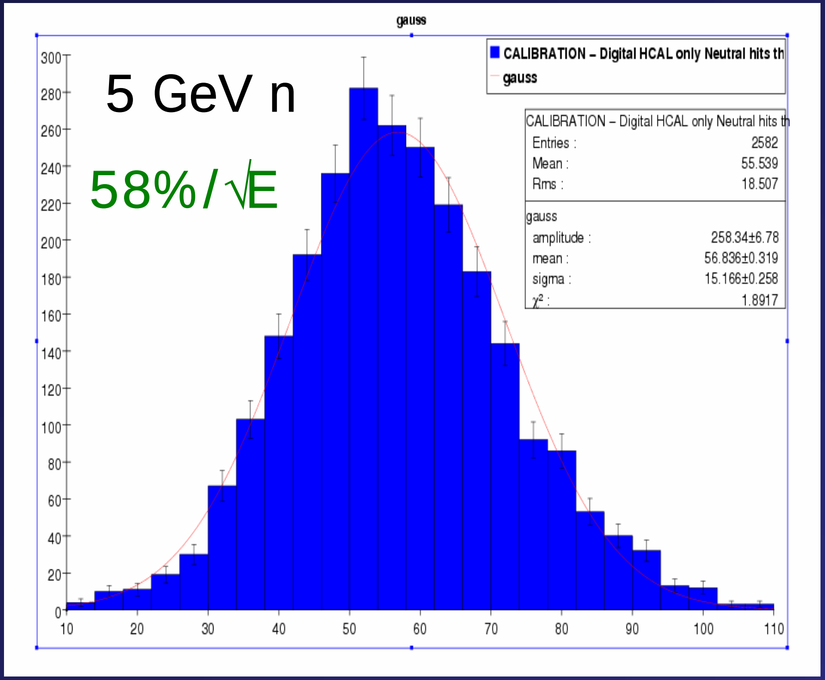
	2 GeV	5 GeV	10 GeV	20 GeV
Mean	8.6	33.7	75.3	144.3
σ	5.6	12.2	22.4	41.5
σ/mean	0.65	0.36	0.30	0.29

-> Fit Result : $76\%/\sqrt{E} \oplus 21\%$!



Average ~6.5 hits/GeV

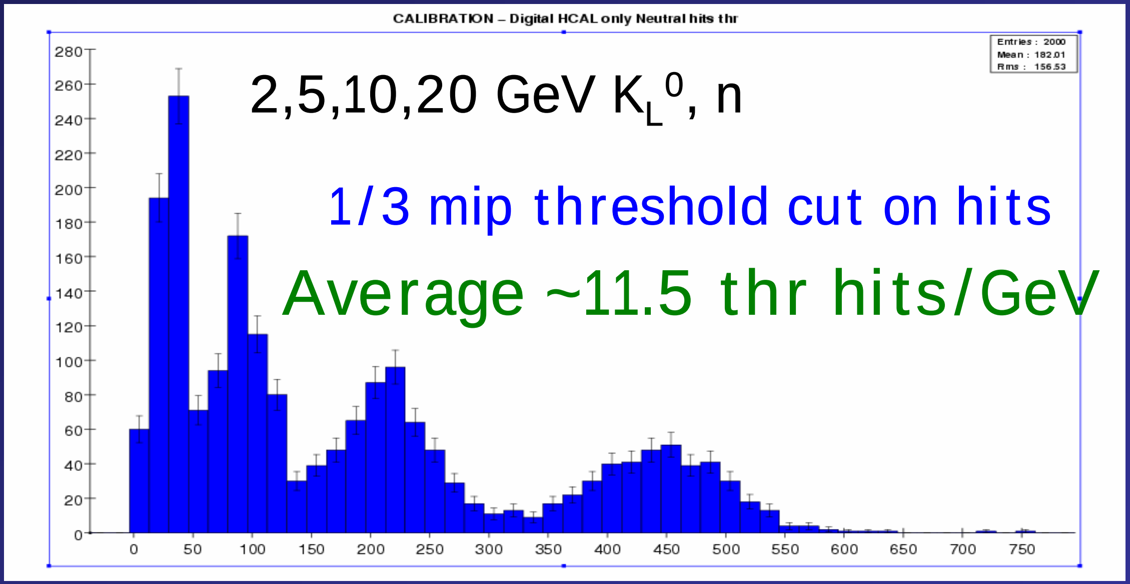
SDFeb05 W/Scin HCAL

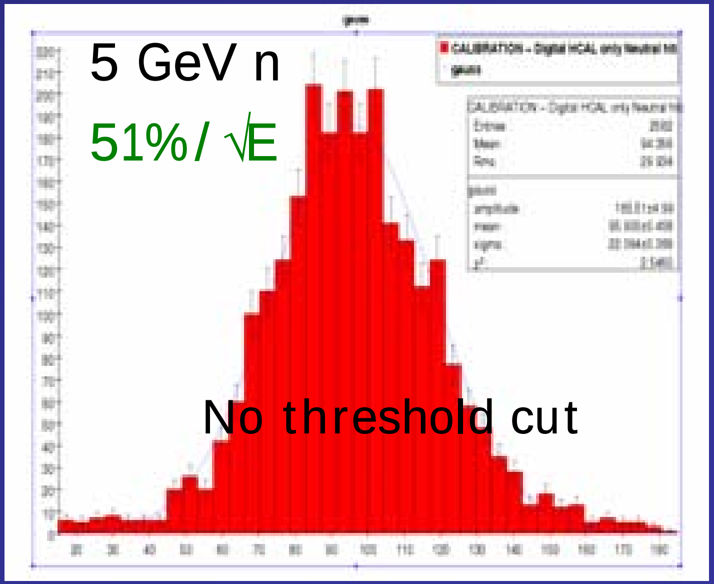


Hits for 2,5,10,20 GeV Neutrals

	2 GeV	5 GeV	10 GeV	20 GeV
Mean	18.6	56.8	126.9	253.5
σ	7.7	15.2	26.6	41.3
σ/mean	0.41	0.27	0.21	0.16

-> Fit Result : 56%/ √E ⊕ 11%



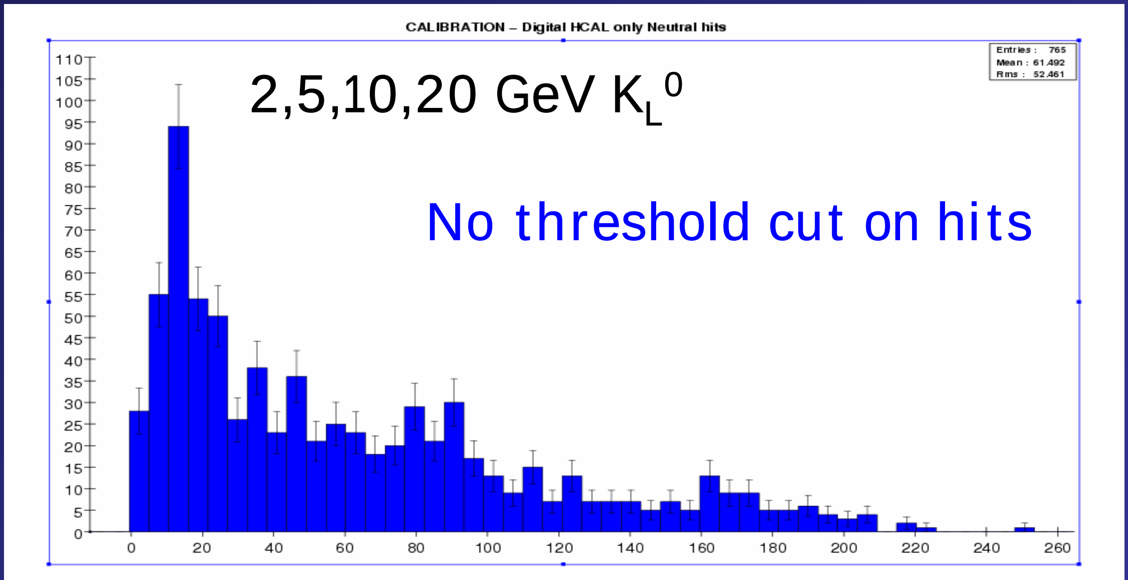


SDFeb05 W/RPC HCAL

Hits for 2,5,10,20 GeV Neutrals

	2 GeV	5 GeV	10 GeV	20 GeV
Mean	14.1	41.8	85.4	154.8
σ	6.4	13.6	19.6	43.3
σ/mean	0.45	0.33	0.23	0.28

-> Fit Result : $54\%/\sqrt{E} \oplus 21\%$



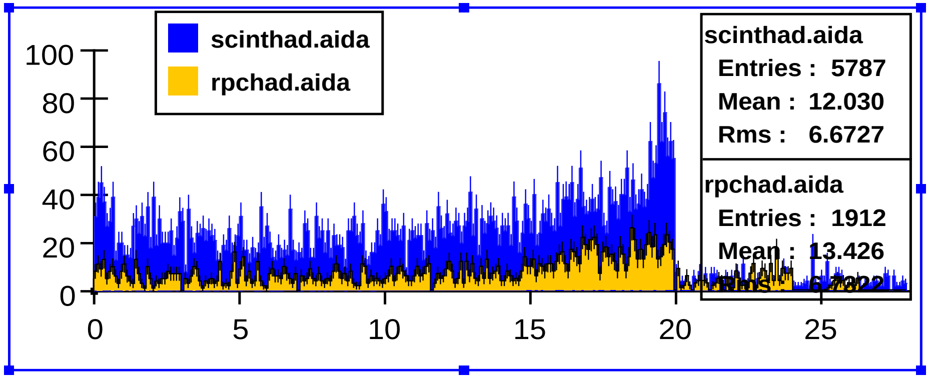
Average ~7.9 hits/GeV

Origin of hits in Scintillator/RPC from G4

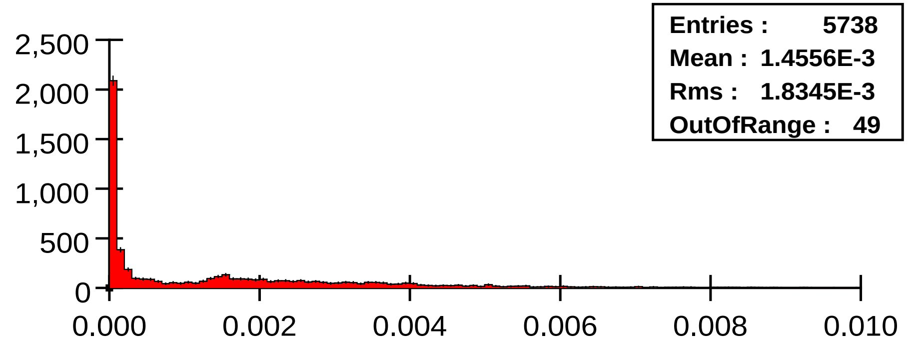
Ron Cassell

- For each hcal hit, select particle producing it.
- If neutral (explanation), find R of endpoint.
- If charged, trace parentage back to neutral, and find R of vertex of particle created from neutral.
- Plot r = radial distance from beginning of layer

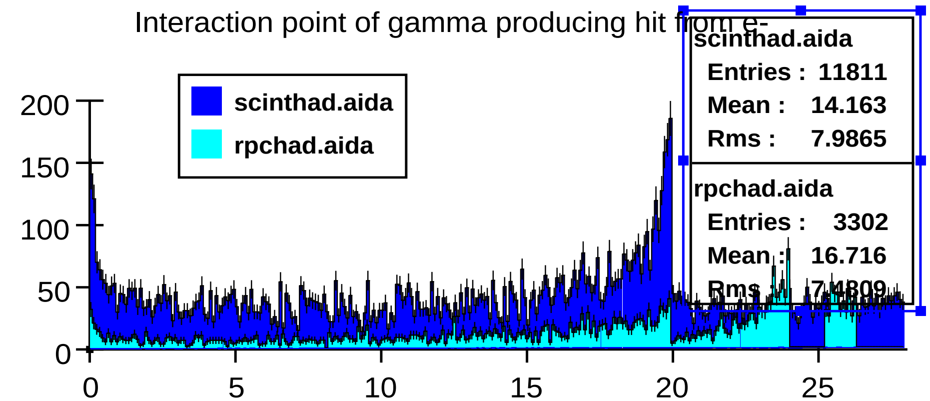
Interaction point of gamma producing hit from e+



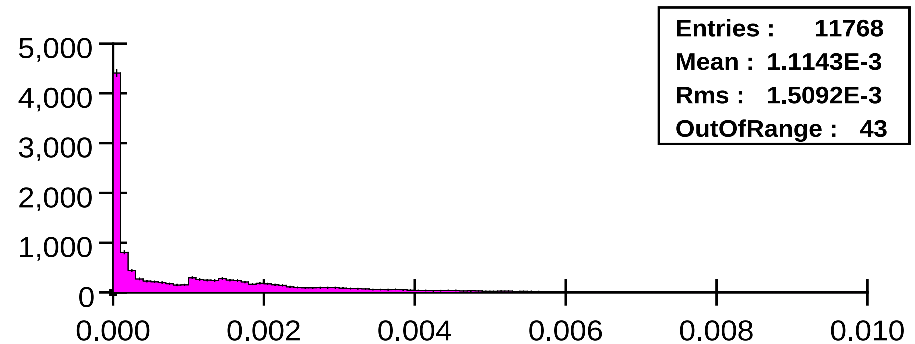
gamma producing hit from e+: Hit energy



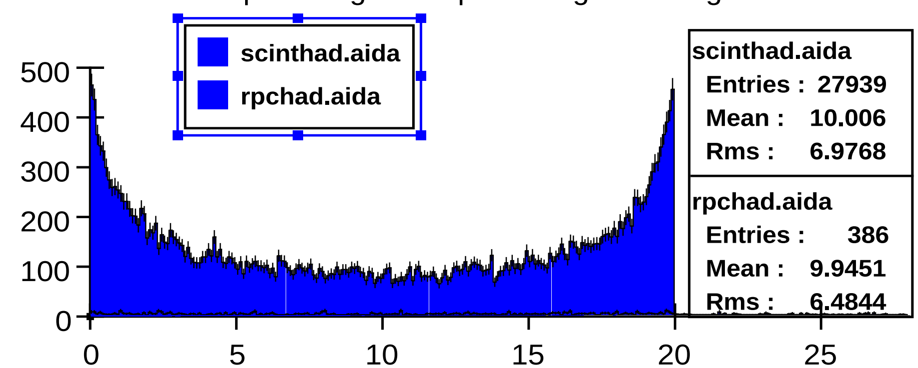
Interaction point of gamma producing hit from e-



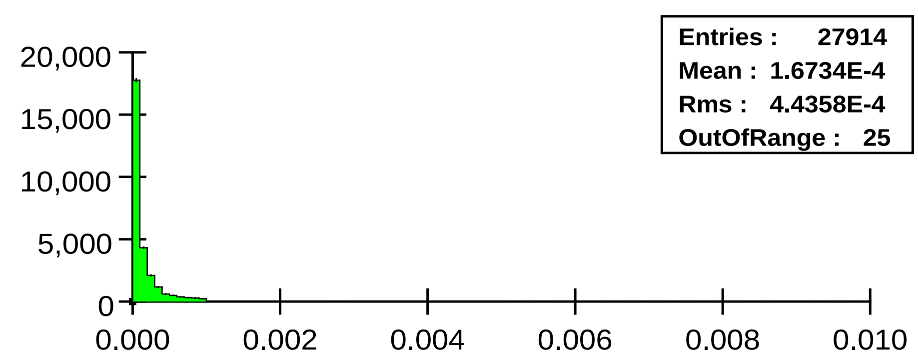
gamma producing hit from e-: Hit energy

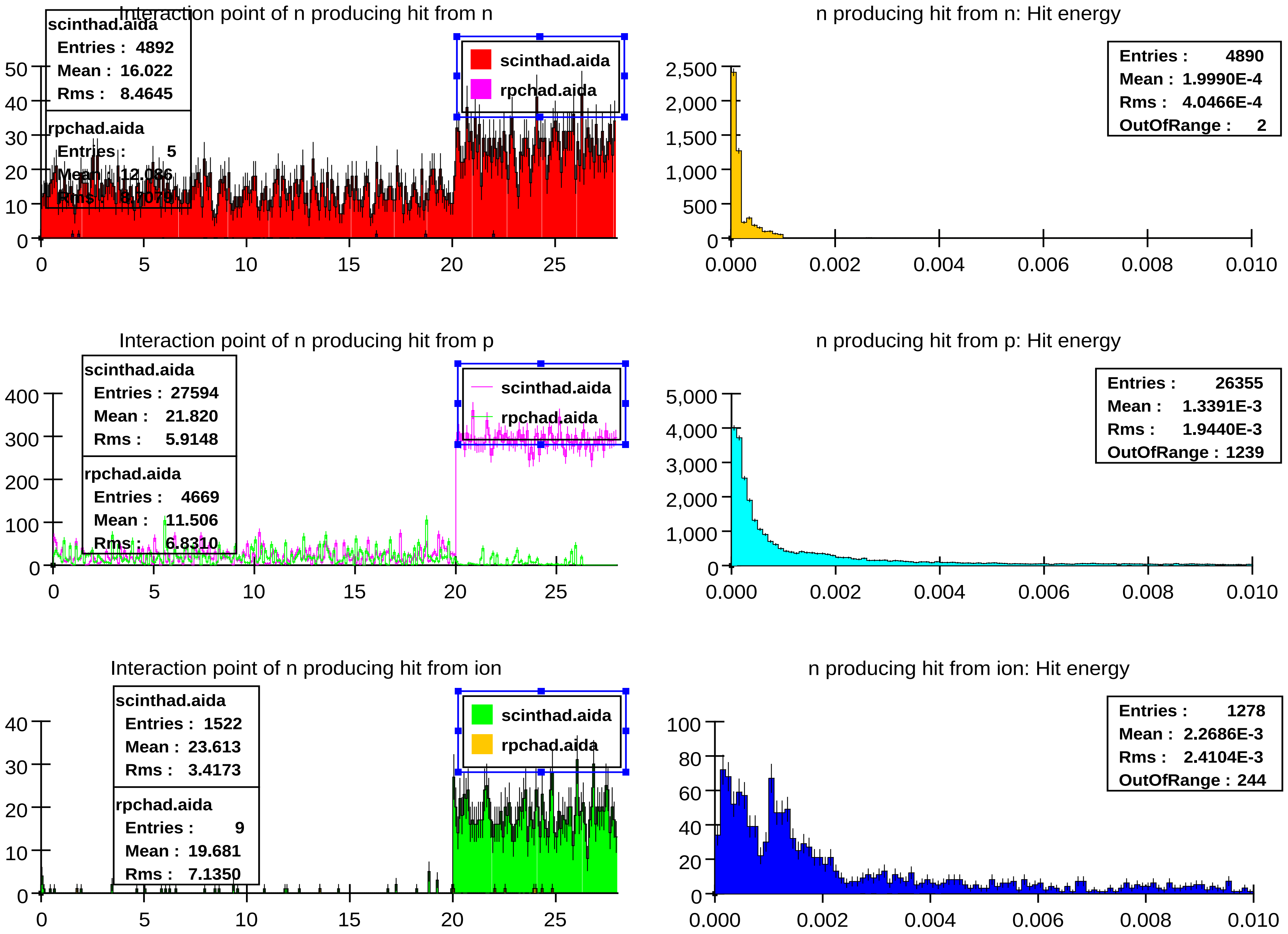


Interaction point of gamma producing hit from gamma

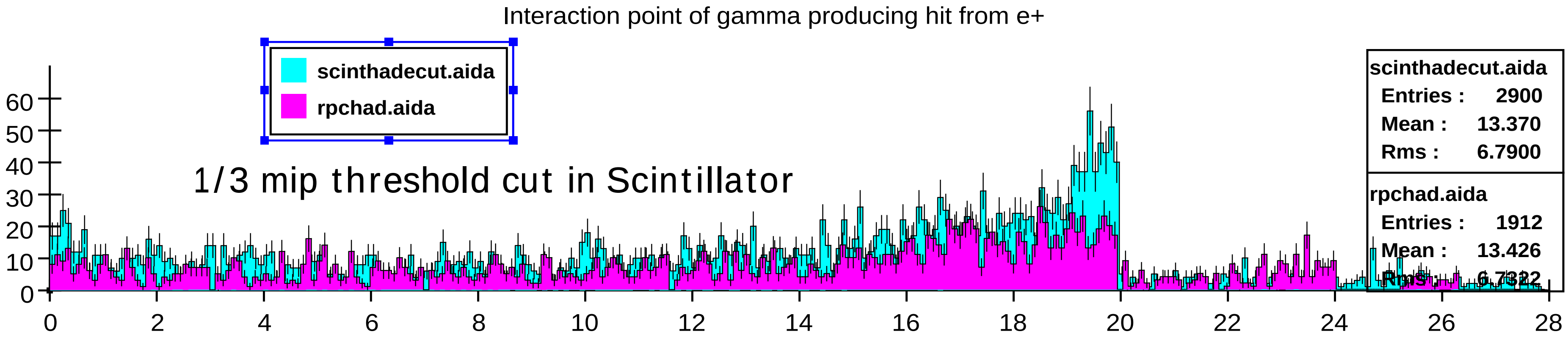


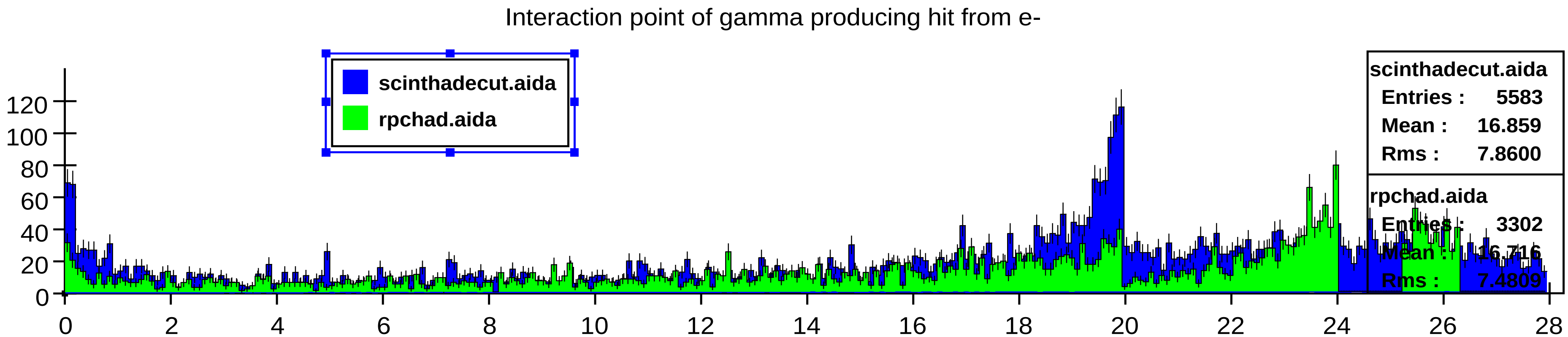
gamma producing hit from gamma: Hit energy





Interaction point of n producing hit from n
scinthad.aida
Entries : 4892
Mean : 16.022
Rms : 8.4645
rpchad.aida
Entries : 5
Mean : 12.086
Rms : 8.7079
scinthad.aida
rpchad.aida
n producing hit from n: Hit energy
Entries : 4890
Mean : 1.9990E-4
Rms : 4.0466E-4
OutOfRange : 2
Interaction point of n producing hit from p
scinthad.aida
Entries : 27594
Mean : 21.820
Rms : 5.9148
rpchad.aida
Entries : 4669
Mean : 11.506
Rms : 6.8310
scinthad.aida
rpchad.aida
n producing hit from p: Hit energy
Entries : 26355
Mean : 1.3391E-3
Rms : 1.9440E-3
OutOfRange : 1239
Interaction point of n producing hit from ion
scinthad.aida
Entries : 1522
Mean : 23.613
Rms : 3.4173
rpchad.aida
Entries : 9
Mean : 19.681
Rms : 7.1350
scinthad.aida
rpchad.aida
n producing hit from ion: Hit energy
Entries : 1278
Mean : 2.2686E-3
Rms : 2.4104E-3
OutOfRange : 244


Interaction point of gamma producing hit from e+
scinthadecut.aida
rpchad.aida
1/3 mip threshold cut in Scintillator
scinthadecut.aida
Entries : 2900
Mean : 13.370
Rms : 6.7900
rpchad.aida
Entries : 1912
Mean : 13.426
Rms : 6.7322


Interaction point of gamma producing hit from e-
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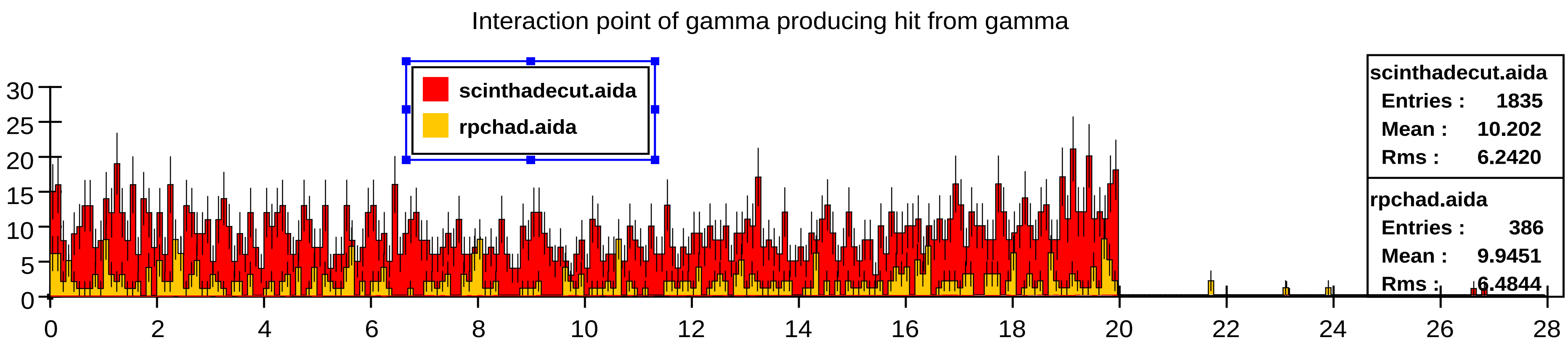
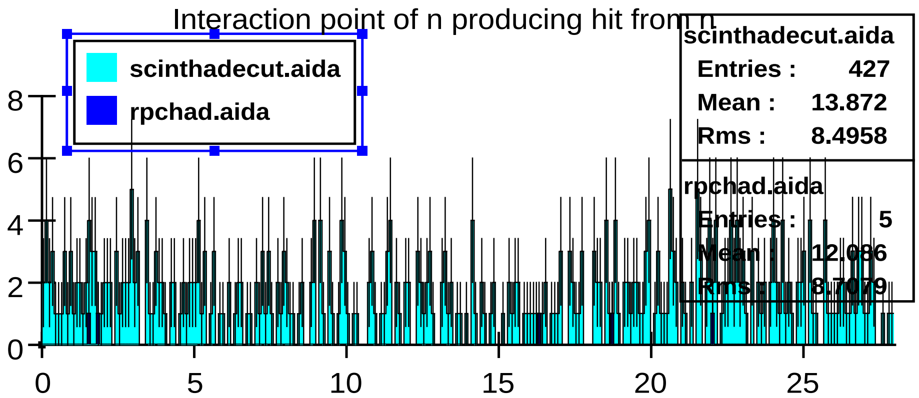
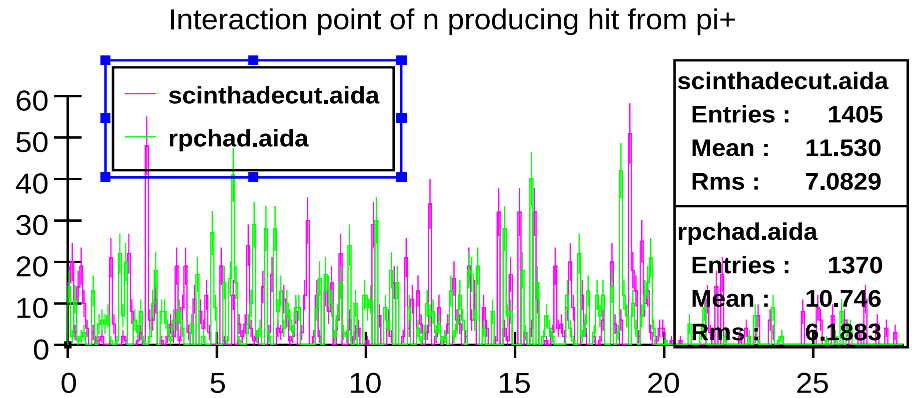
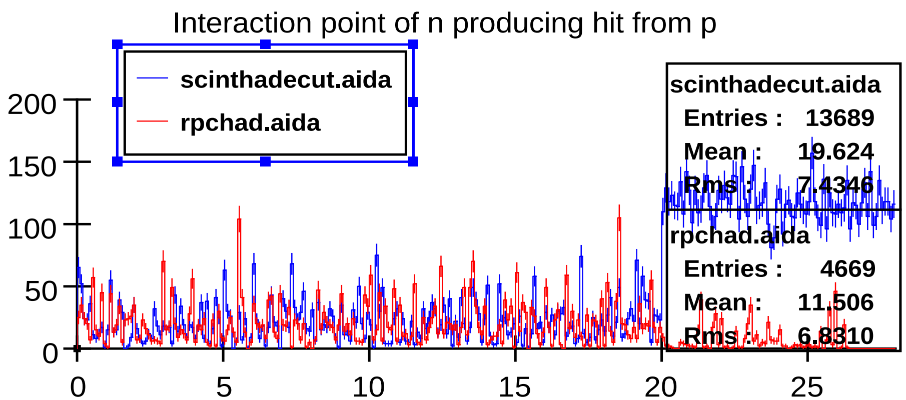
rpchad.aida
scinthadecut.aida
Entries : 5583
Mean : 16.859
Rms : 7.8600
rpchad.aida
Entries : 3302
Mean : 16.716
Rms : 7.4809


Interaction point of gamma producing hit from gamma
scinthadecut.aida
rpchad.aida
scinthadecut.aida
Entries : 1835
Mean : 10.202
Rms : 6.2420
rpchad.aida
Entries : 386
Mean : 9.9451
Rms : 6.4844


Interaction point of n producing hit from n
scinthadecut.aida
rpchad.aida
scinthadecut.aida
Entries : 427
Mean : 13.872
Rms : 8.4958
rpchad.aida
Entries : 5
Mean : 12.086
Rms : 8.7079
0 2 4 6 8
0 5 10 15 20 25


Interaction point of n producing hit from pi+
scinthadecut.aida
rpchad.aida
scinthadecut.aida
Entries : 1405
Mean : 11.530
Rms : 7.0829
rpchad.aida
Entries : 1370
Mean : 10.746
Rms : 6.1883
0 10 20 30 40 50 60
0 5 10 15 20 25


Interaction point of n producing hit from p
scinthadecut.aida
rpchad.aida
scinthadecut.aida
Entries : 13689
Mean : 19.624
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rpchad.aida
Entries : 4669
Mean : 11.506
Rms : 6.8310
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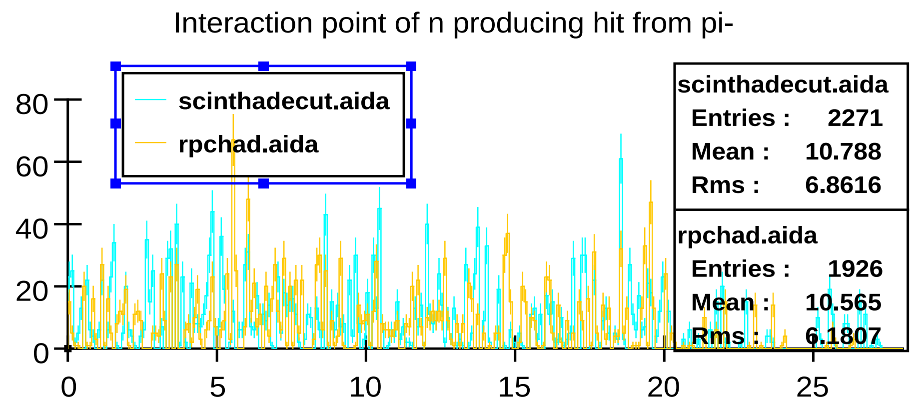
0 5 10 15 20 25


Interaction point of n producing hit from pi-
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rpchad.aida
scinthadecut.aida
Entries : 2271
Mean : 10.788
Rms : 6.8616
rpchad.aida
Entries : 1926
Mean : 10.565
Rms : 6.1807
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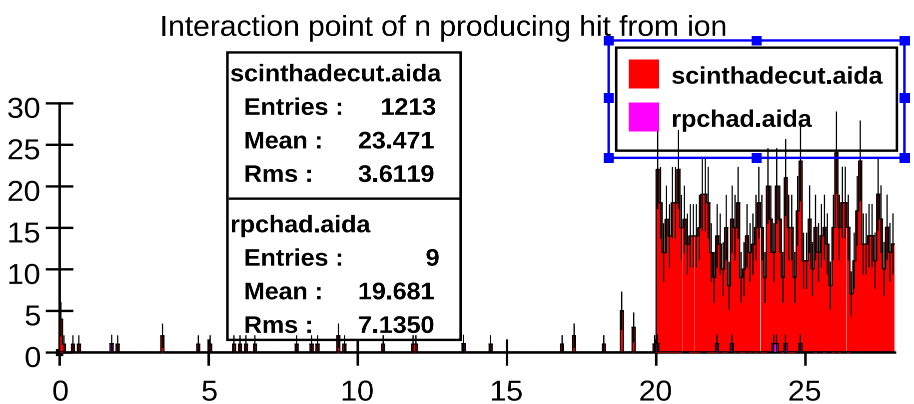
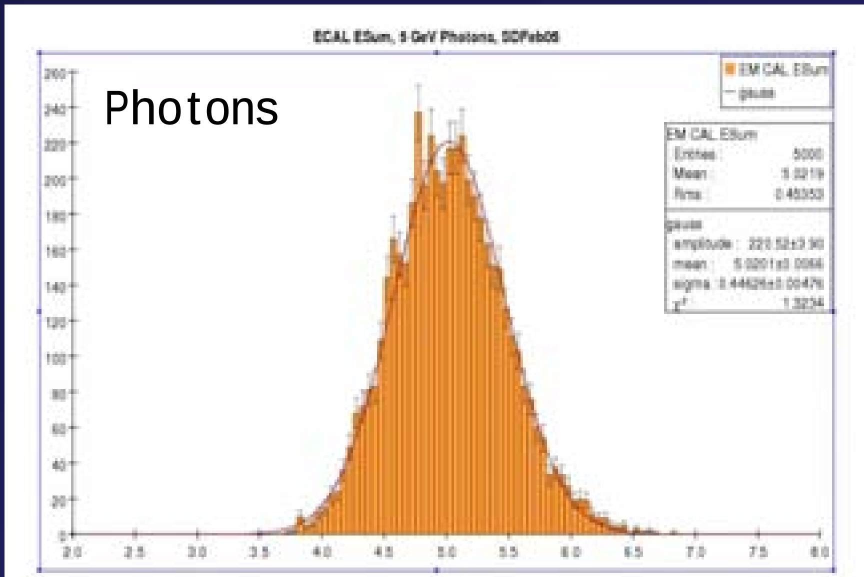
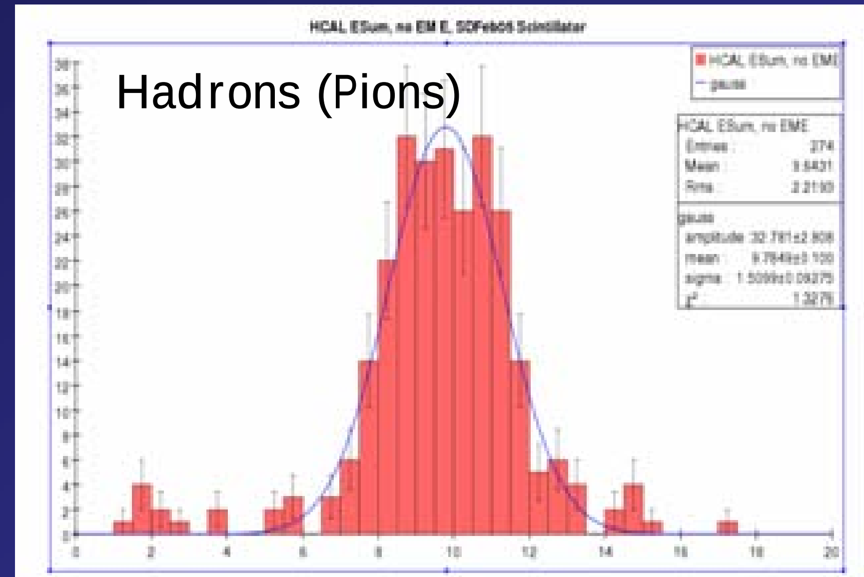
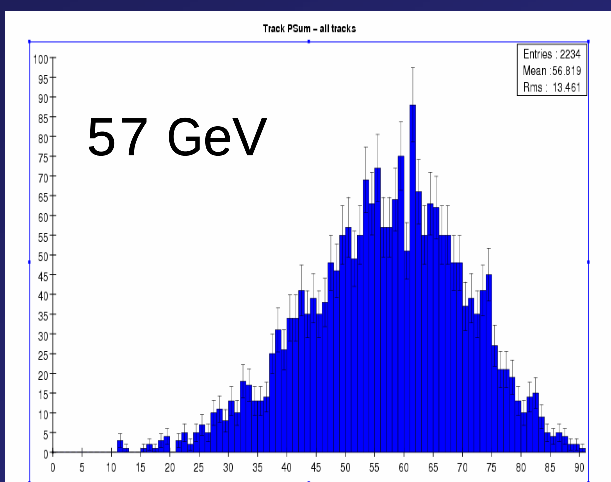
0 5 10 15 20 25

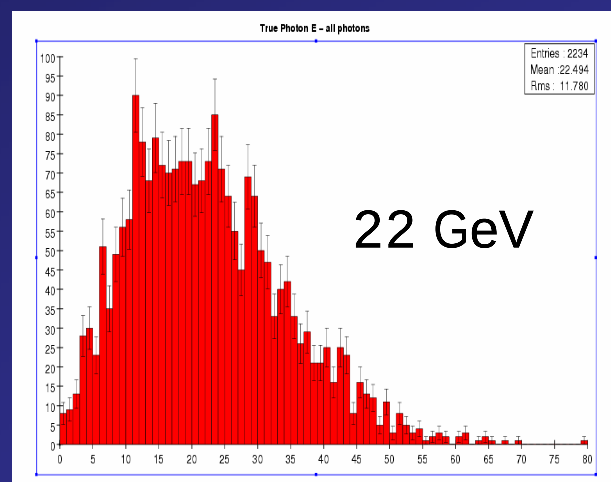

Interaction point of n producing hit from ion
scinthadecut.aida
Entries : 1213
Mean : 23.471
Rms : 3.6119
rpchad.aida
Entries : 9
Mean : 19.681
Rms : 7.1350
scinthadecut.aida
rpchad.aida
0 5 10 15 20 25 30
0 5 10 15 20 25

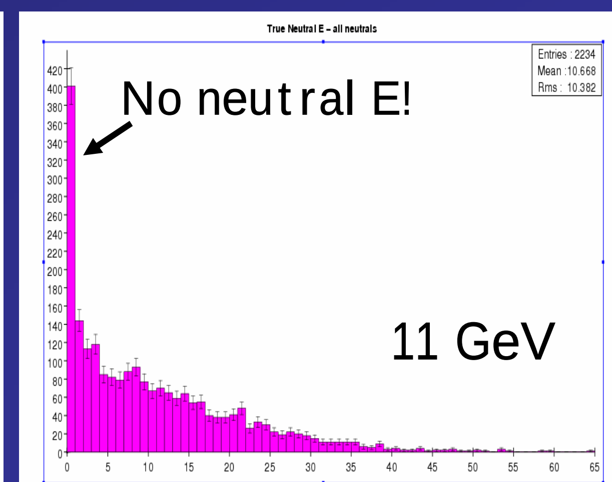
Analytic Perfect PFA – SDFeb05 Detector Model











Photon resolution = $\sqrt{22.5} \times .199 = 0.94$ GeV

Neutral H resolution = $\sqrt{10.7} \times .48 = 1.57$ GeV

-> PPFA = $19\%/\sqrt{E}$

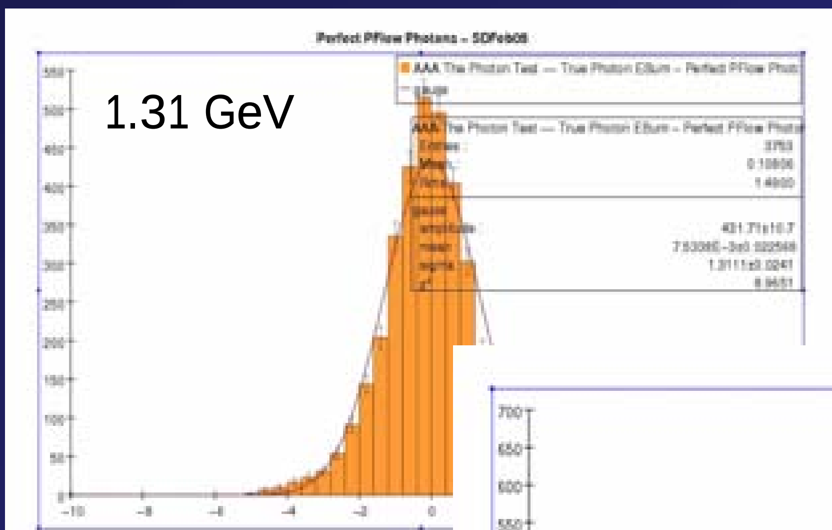
PFA Development – Definitions and Preparation

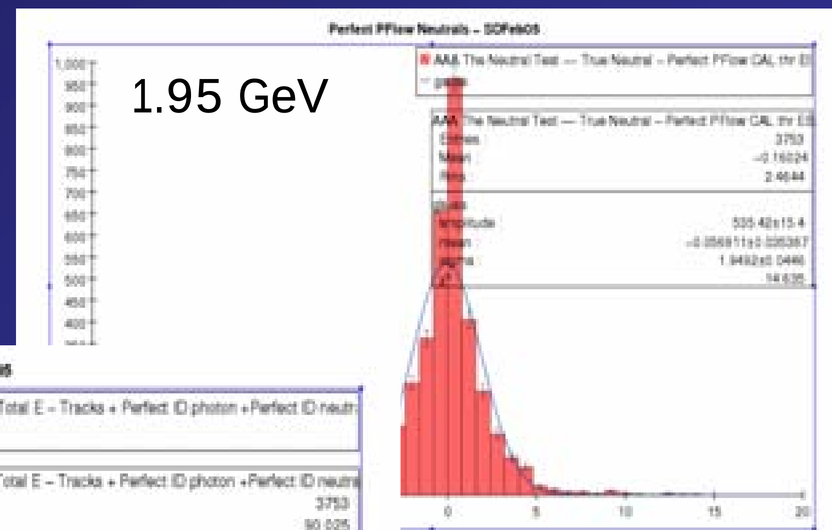
3) Perfect PFA with Detector Effects at Z Pole

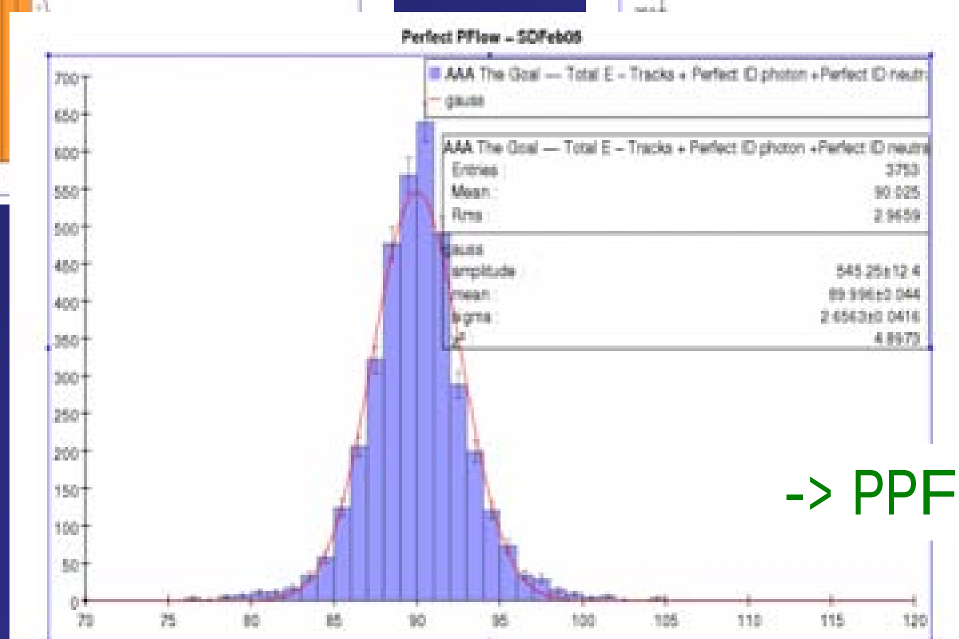
Equal to 2a)?

Better than 30%/√E?

4) Now ready for PFA development ------→ DEMO







-> PPFA = 28%/√E

Summary of Observations

1) Hadron showers are more compact in an HCAL with a denser absorber (e.g., W) compared to SS (Fe).
   -> better separation of charged/neutral showers
   -> a dense HCAL is more compact in R, allowing savings on the magnet cost (presumably $\propto BR^2$ or B^2R^2)
   -> smaller HCAL, more compact showers – PFA performance not compromised

2) Scintillator readout in digital mode (even with threshold cut) produces more "hits" than gas (RPC) digital readout for neutrons.
   -> better resolution in a Scintillator HCAL for neutral contribution in a PFA
   -> comes from neutron-proton elastic scattering, knocking the proton out of H atoms in the Scintillator
   -> need H in readout material to detect neutrons

Generalization of Observations

1) A compact calorimeter should be made of a dense absorber and a solid (or maybe liquid) active medium – like W/Scintillator

2) For the LC, assuming calorimetry designed to use PFAs, the HCAL is a *neutron detector*, therefore, should contain H in the active layer

3) A gas HCAL seems to be more suited for a larger detector, since gains in performance all seem to increase R (thinning the absorber, adding layers of H, increasing the gas thickness, etc.)

So, a plan for LC calorimeter development and optimization could be :

ECAL – W/Si because of PFA requirements

HCAL :

1) Compact Detector (CDC) – - - W/Scintillator

2) Large Detector (LDC) – - - W/RPC

3) Huge Detector (GLD) – - - SS/RPC