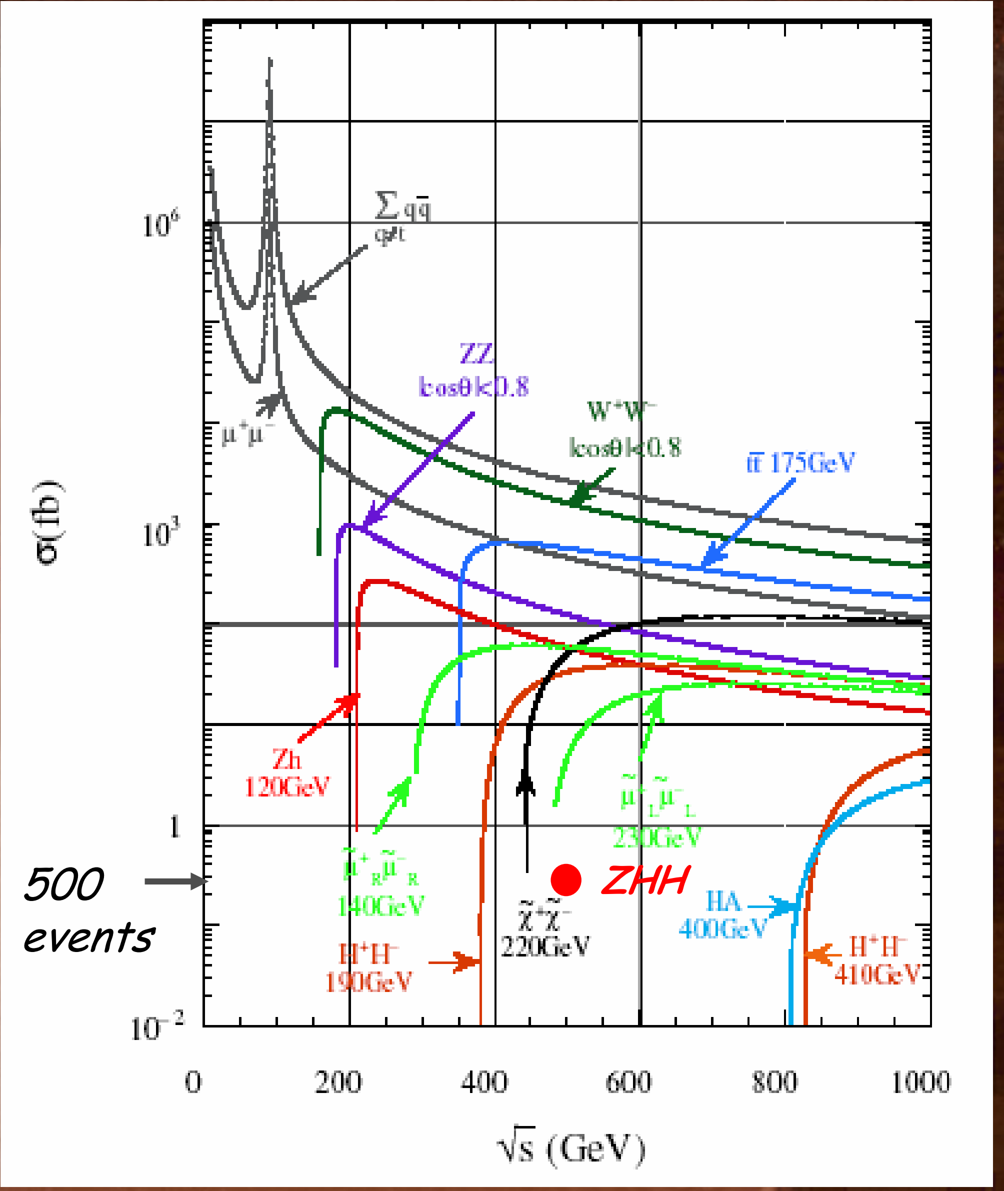
Particle Flow Development for Detector Optimization

- What is a Particle Flow Detector?
- Recent Progress in PFA Development
- Some things we have learned
- PFA Template

Stephen Magill
Argonne National Laboratory

Precision Physics at the ILC

- e^+e^- : clean but sometimes complex events
- often statistics limited
- final states with heavy bosons **W, Z, H**
- can't ignore hadronic decay modes (80% BR) -> **multi-jet events**
- in general no kinematic fits

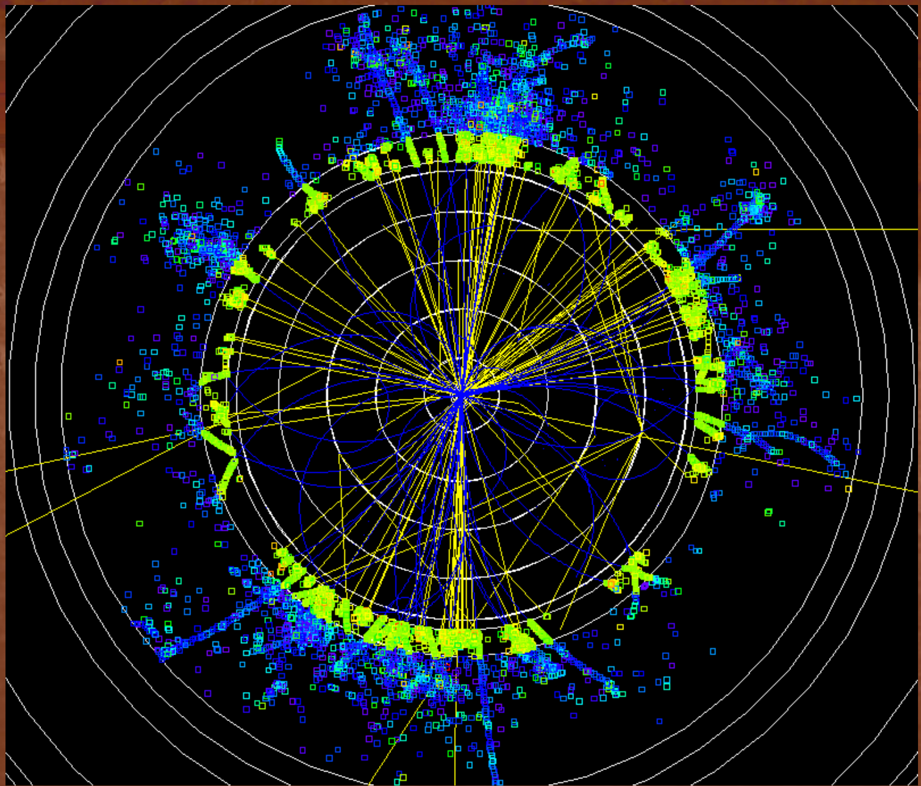


A Particle Flow Detector

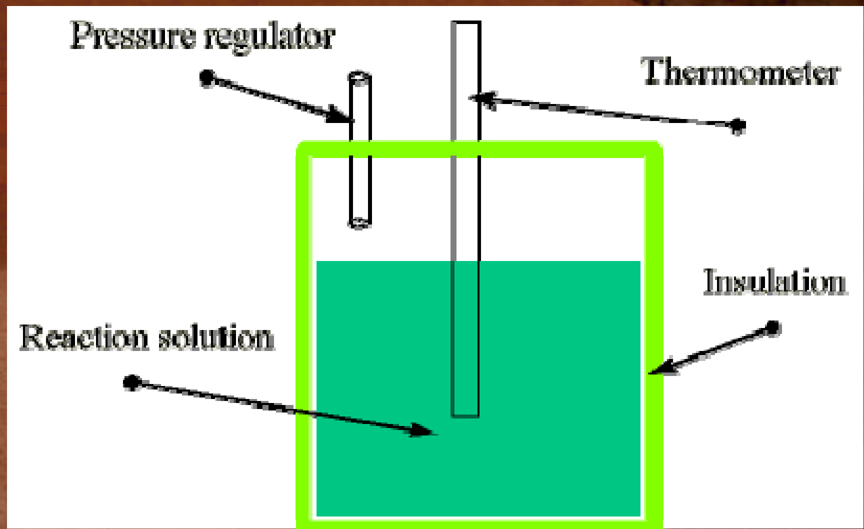
PFA Goal : *1 to 1 correspondence between measured detector objects and particle 4-vectors -> best jet (parton) reconstruction (energy and momentum of parton)*

-> combines *tracking* and *3-D imaging calorimetry* :

Particle Flow Calorimetry



Traditional Calorimetry



Emphasis – particle reconstruction vs E measurement in a volume

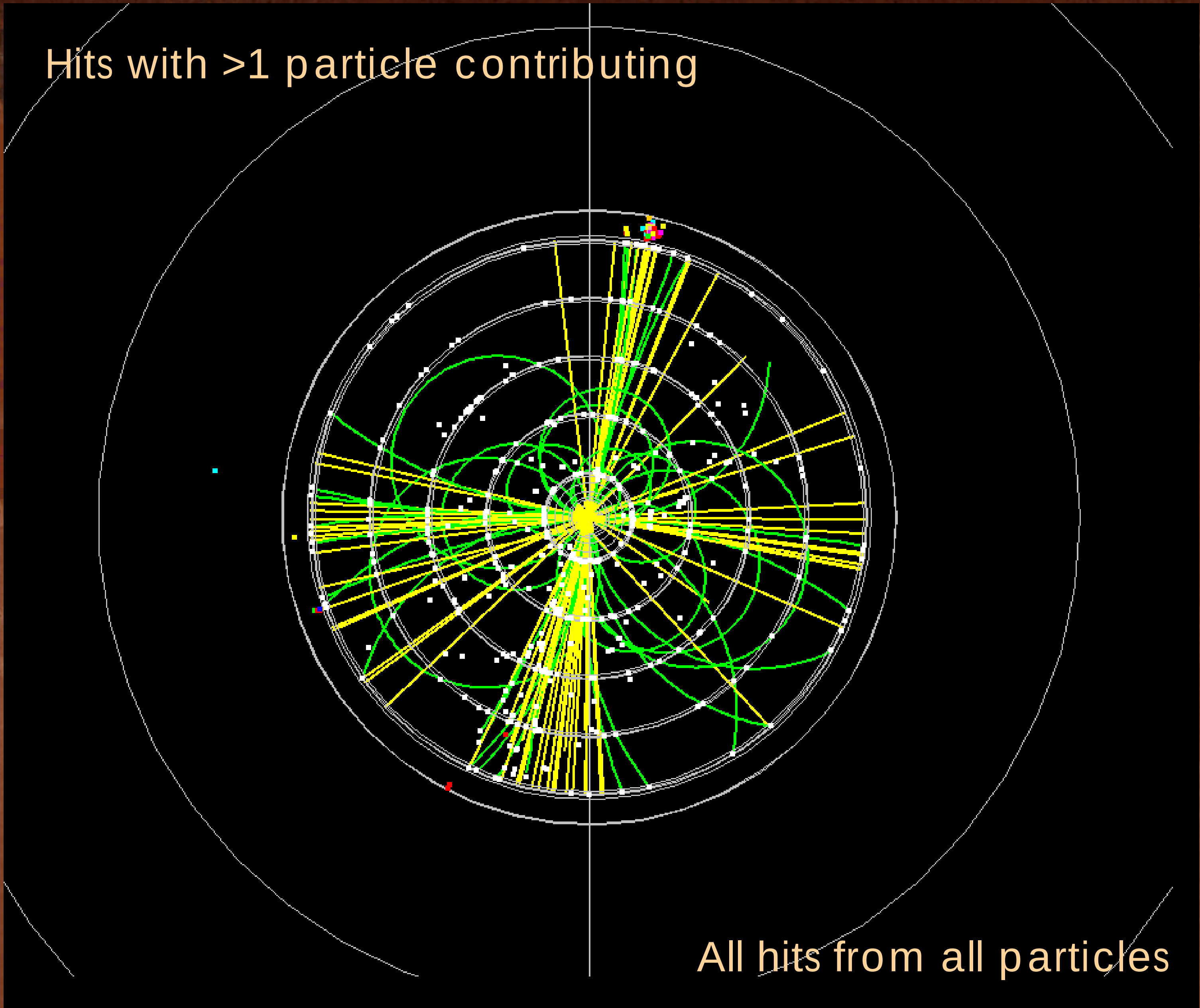
Tracking :

- good tracking for charged particles (~60% of jet E)
  -> σ_p (tracking) <<< σ_E for photons or hadrons in CAL
  -> Si Strip Tracker

Calorimetry :

- good EM Calorimetry for photon measurement (~25% of jet E)
  -> σ_E for photons < σ_E for neutral hadrons
  -> dense absorber for optimal longitudinal separation of photon/hadron showers –> Si/W Sandwich ECAL
- good separation of neutral and charged showers in E/HCAL
  -> CAL objects == particles
  -> 1 particle : 1 object -> small CAL cells
  -> SS or W RPC digital CAL, SS or W Scintillator Analog CAL
- adequate E resolution for neutrals in HCAL (~10% of jet E)
  -> σ_E < minimum mass difference, e.g. $M_Z - M_W$
  -> still largest contribution to jet E resolution . . .
  -> as long as mistakes don't dominate

Occupancy Event Display



SiD Variant

Si Tracker

W/Si ECAL

SS/RPC HCAL

Jet E Resolution – Confusion Term

Example PFA Construction – mips, photons, charged hadrons, neutral hadrons

	mips	photons	Ch. hadrons	Neu. hadrons
mips	σ_{mip}	$\sigma_{mip\gamma}$	σ_{mipch}	σ_{mipnh}
photons	$\sigma_{\gamma mip}$	σ_{γ}	$\sigma_{\gamma ch}$	$\sigma_{\gamma nh}$
Ch. hadrons	σ_{chmip}	$\sigma_{ch\gamma}$	σ_{ch}	σ_{chnh}
Neu. hadrons	σ_{nhmip}	$\sigma_{nh\gamma}$	σ_{nhch}	σ_{nh}

-> Replace mips, charged hadron showers with tracks

-> mip γ, neutral hadron confusion small

So, $\sigma_E^2 = \sigma_\gamma^2 + \sigma_{nh}^2 + \sigma_{conf}^2$

where $\sigma_{conf}^2 = \sigma_{chnh}^2 + \sigma_{\gamma ch}^2 + \sigma_{\gamma nh}^2$ (6 terms)

Where we are in PFA Development?

Recent Progress in development of tools for PFA

-> Cal calibration methods – standardized method concentrating on photons, neutral hadrons

-> PFA Template

Complete PFA analyses - Z-Pole and Beyond

-> Have achieved resolutions approaching PFA resolution goal of ~30%/√E

-> Have achieved results with non-dominant confusion term

-> Detector variant comparisons have begun

Standardization of Calorimeter Calibration

- EM calorimeter treated as 2 detectors: double the absorber in last 10 layers
- Endcaps treated separately from barrel
- For each detector, 6 subdetector sampling fractions
- Sampling fractions calculated minimizing delta(neutral energy sum)**2 at Zpole
- Results put in detector files, allowing estimate of cluster energy without identification

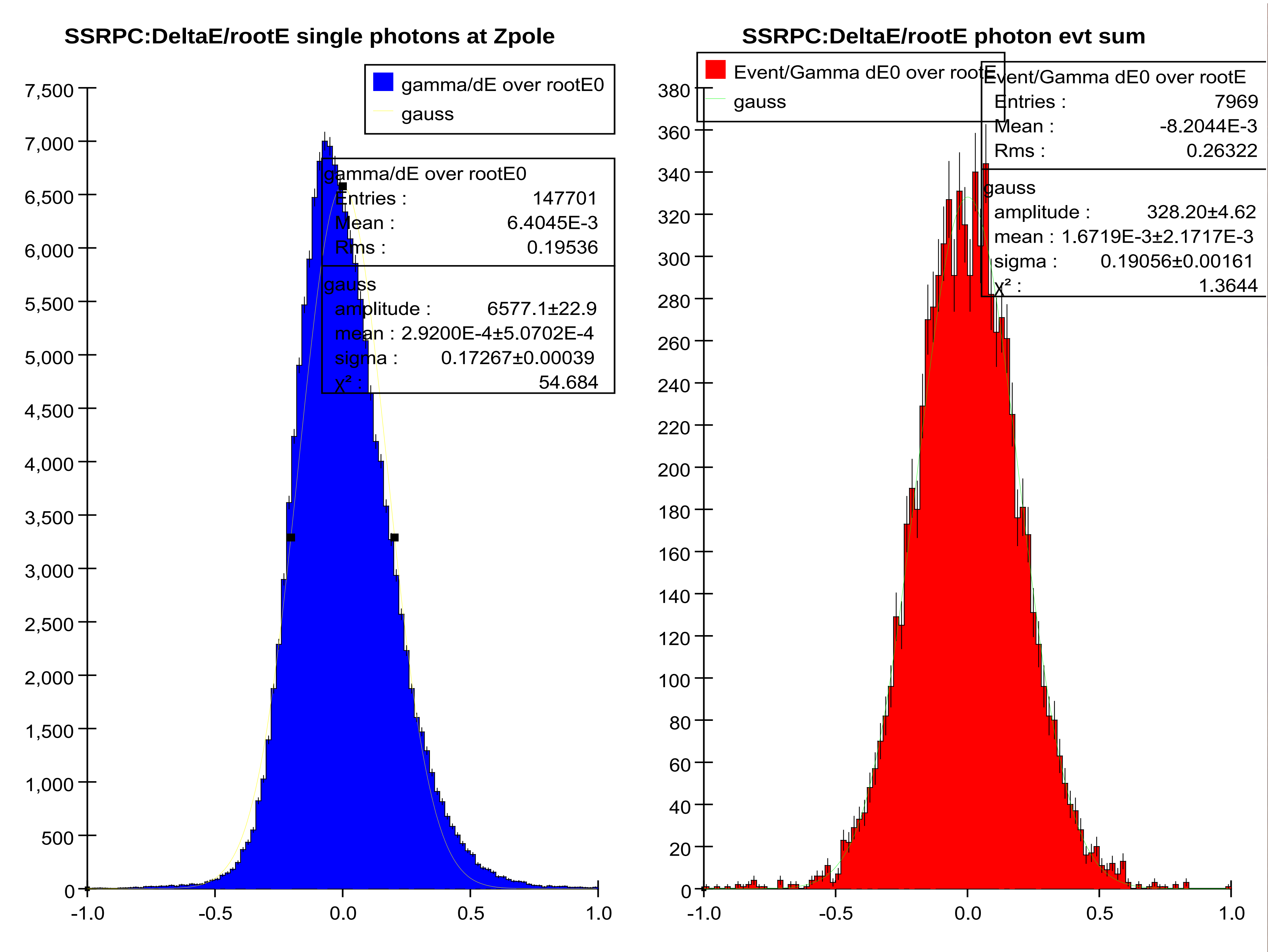
Photons

- Response reasonably linear
- Calculate linear and constant term for each of 6 subdetectors for each detector, minimizing delta(photon energy sum)**2 at the Zpole

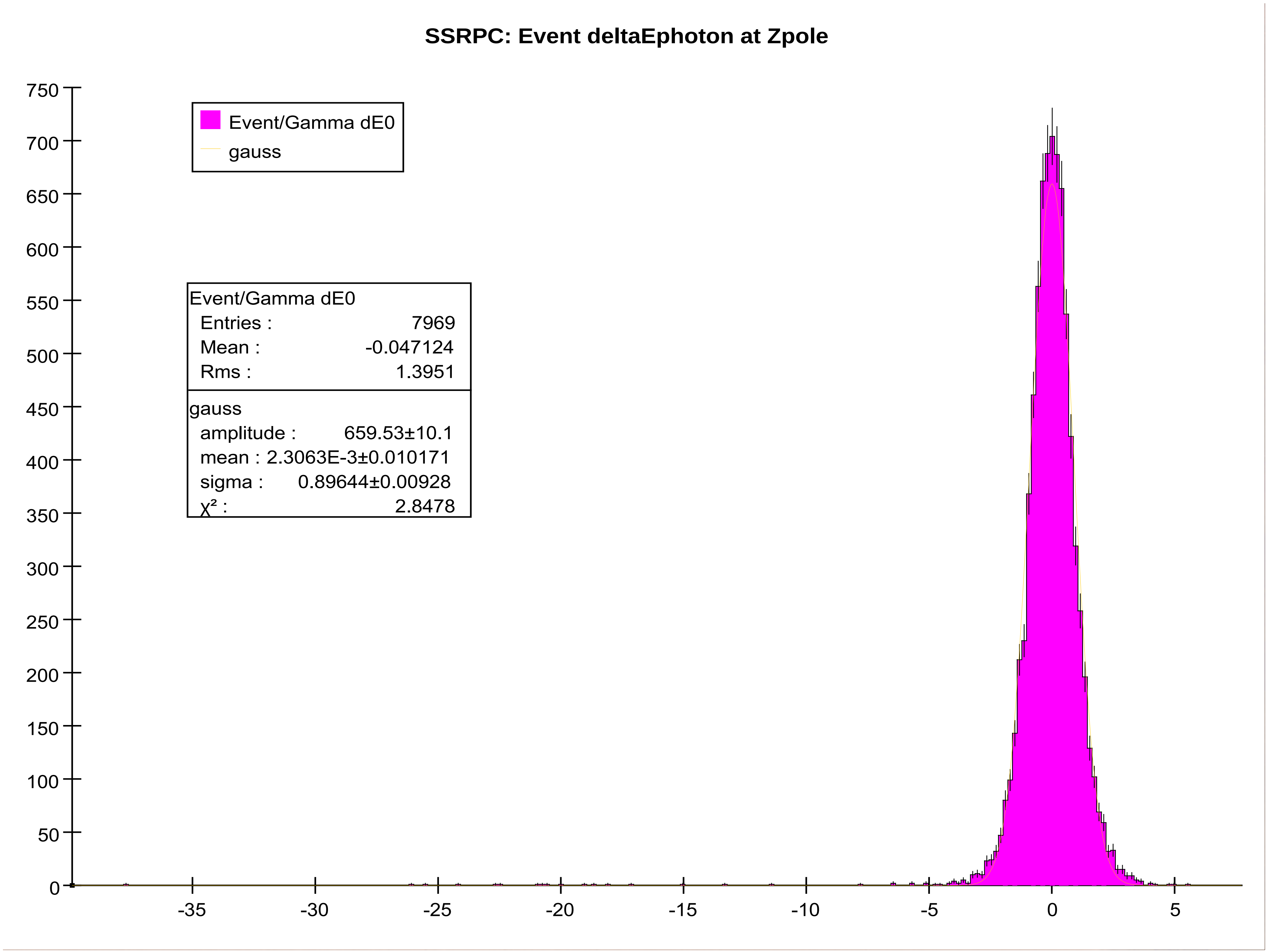
Neutral Hadrons

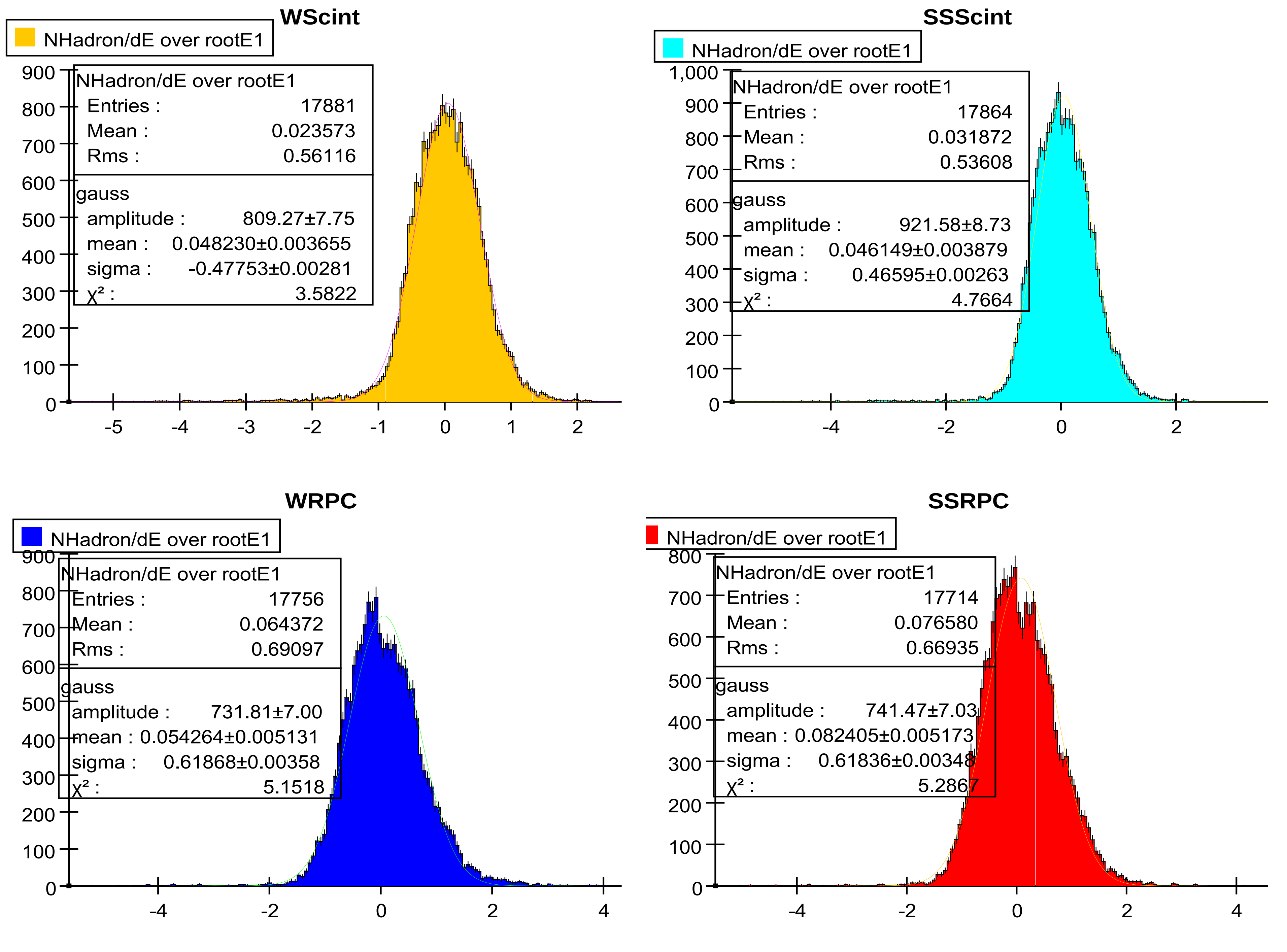
- For each detector, for each subdetector, map out response for isolated detector at 17 energy points and 3 angles, for k0L, n, nbar
- Average responses assuming 2k0L+1n+1nbar

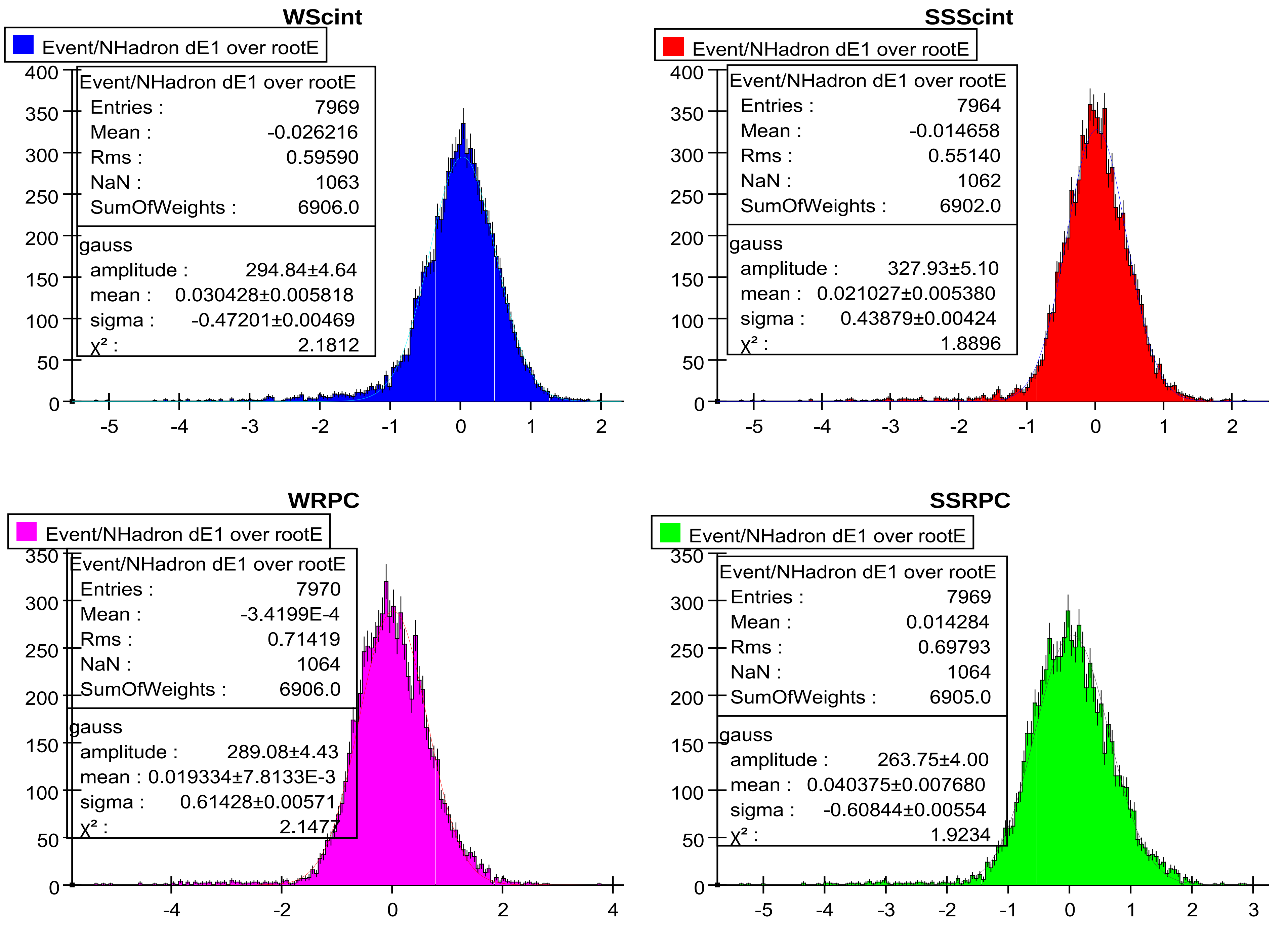
R. Cassell, SLAC

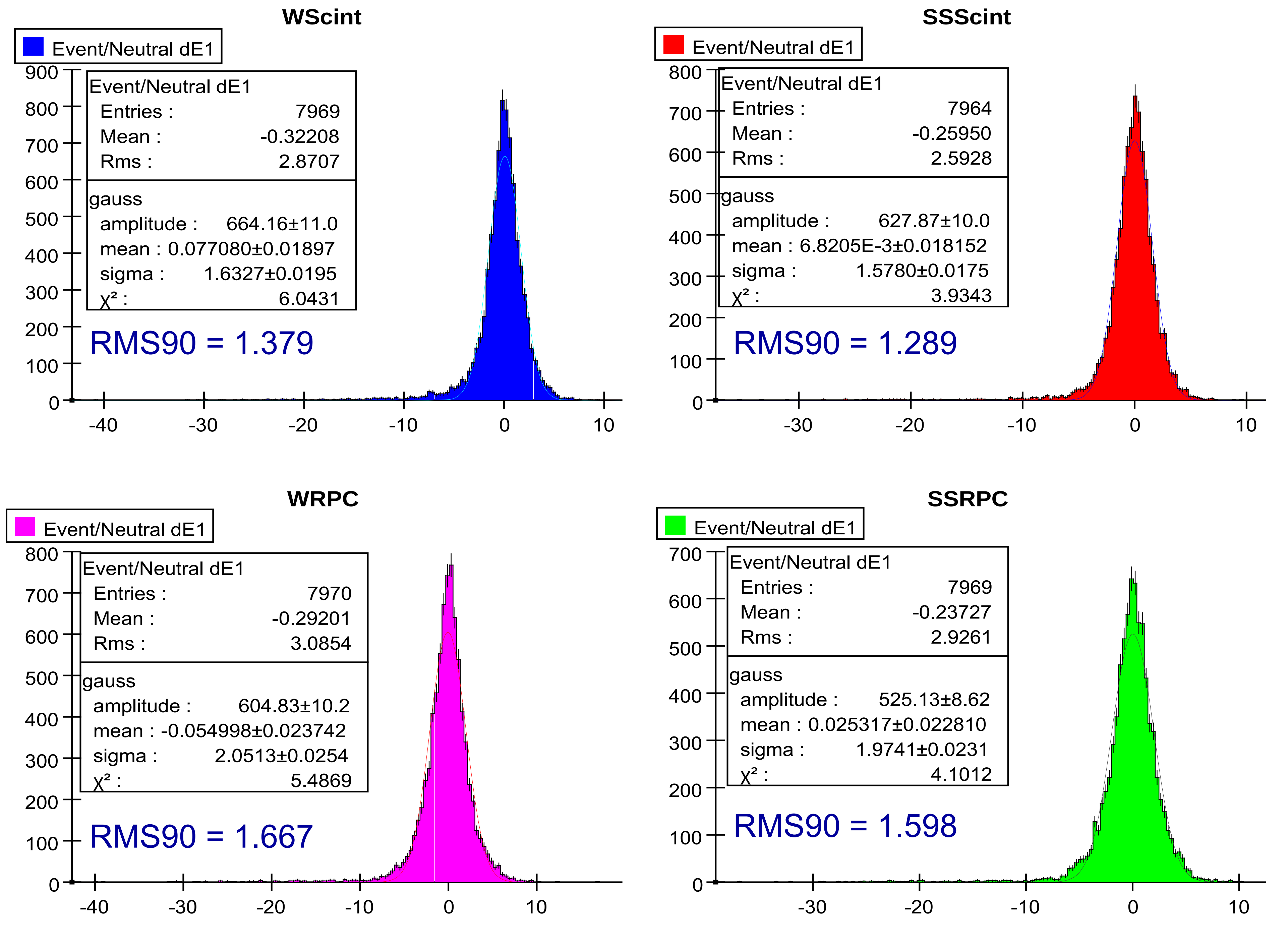


SSRPC:DeltaE/rootE single photons at Zpole
gamma/dE over rootE0
gauss
gamma/dE over rootE0
Entries : 147701
Mean : 6.4045E-3
Rms : 0.19536
gauss
amplitude : 6577.1±22.9
mean : 2.9200E-4±5.0702E-4
sigma : 0.17267±0.00039
χ² : 54.684
SSRPC:DeltaE/rootE photon evt sum
Event/Gamma dE0 over rootE
gauss
Event/Gamma dE0 over rootE
Entries : 7969
Mean : -8.2044E-3
Rms : 0.26322
gauss
amplitude : 328.20±4.62
mean : 1.6719E-3±2.1717E-3
sigma : 0.19056±0.00161
χ² : 1.3644


SSRPC: Event deltaEphoton at Zpole
Event/Gamma dE0
gauss
Event/Gamma dE0
Entries : 7969
Mean : -0.047124
Rms : 1.3951
gauss
amplitude : 659.53±10.1
mean : 2.3063E-3±0.010171
sigma : 0.89644±0.00928
χ² : 2.8478
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-35
-30
-25
-20
-15
-10
-5
0
5


WScint
NHadron/dE over rootE1
NHadron/dE over rootE1
Entries : 17881
Mean : 0.023573
Rms : 0.56116
gauss
amplitude : 809.27±7.75
mean : 0.048230±0.003655
sigma : -0.47753±0.00281
χ² : 3.5822
SSScint
NHadron/dE over rootE1
NHadron/dE over rootE1
Entries : 17864
Mean : 0.031872
Rms : 0.53608
gauss
amplitude : 921.58±8.73
mean : 0.046149±0.003879
sigma : 0.46595±0.00263
χ² : 4.7664
WRPC
NHadron/dE over rootE1
NHadron/dE over rootE1
Entries : 17756
Mean : 0.064372
Rms : 0.69097
gauss
amplitude : 731.81±7.00
mean : 0.054264±0.005131
sigma : 0.61868±0.00358
χ² : 5.1518
SSRPC
NHadron/dE over rootE1
NHadron/dE over rootE1
Entries : 17714
Mean : 0.076580
Rms : 0.66935
gauss
amplitude : 741.47±7.03
mean : 0.082405±0.005173
sigma : 0.61836±0.00348
χ² : 5.2867

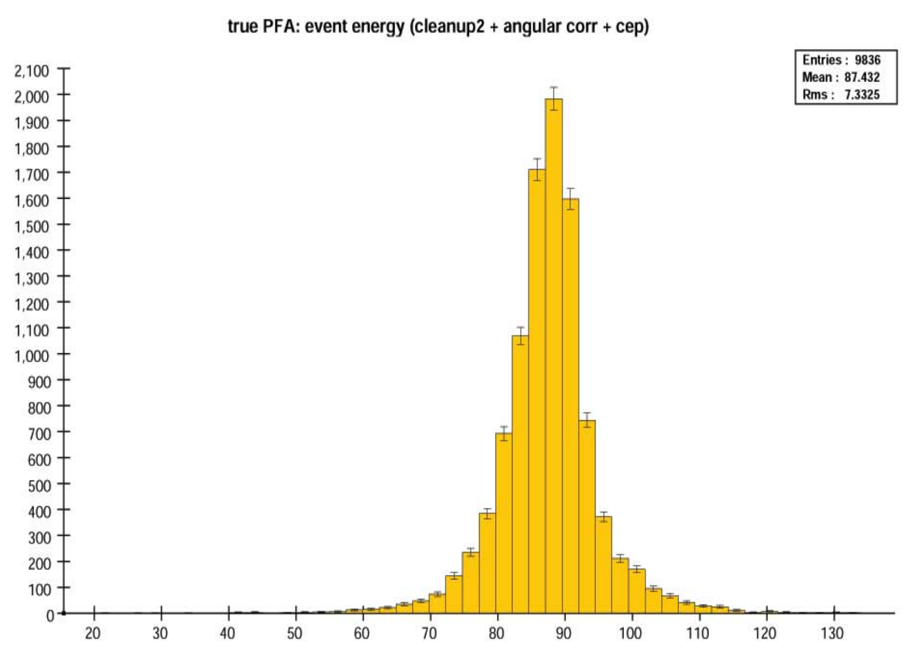

WScint
Event/NHadron dE1 over rootE
Event/NHadron dE1 over rootE
Entries : 7969
Mean : -0.026216
Rms : 0.59590
NaN : 1063
SumOfWeights : 6906.0
gauss
amplitude : 294.84±4.64
mean : 0.030428±0.005818
sigma : -0.47201±0.00469
χ² : 2.1812
SSScint
Event/NHadron dE1 over rootE
Event/NHadron dE1 over rootE
Entries : 7964
Mean : -0.014658
Rms : 0.55140
NaN : 1062
SumOfWeights : 6902.0
gauss
amplitude : 327.93±5.10
mean : 0.021027±0.005380
sigma : 0.43879±0.00424
χ² : 1.8896
WRPC
Event/NHadron dE1 over rootE
Event/NHadron dE1 over rootE
Entries : 7970
Mean : -3.4199E-4
Rms : 0.71419
NaN : 1064
SumOfWeights : 6906.0
gauss
amplitude : 289.08±4.43
mean : 0.019334±7.8133E-3
sigma : 0.61428±0.00571
χ² : 2.1477
SSRPC
Event/NHadron dE1 over rootE
Event/NHadron dE1 over rootE
Entries : 7969
Mean : 0.014284
Rms : 0.69793
NaN : 1064
SumOfWeights : 6905.0
gauss
amplitude : 263.75±4.00
mean : 0.040375±0.007680
sigma : -0.60844±0.00554
χ² : 1.9234

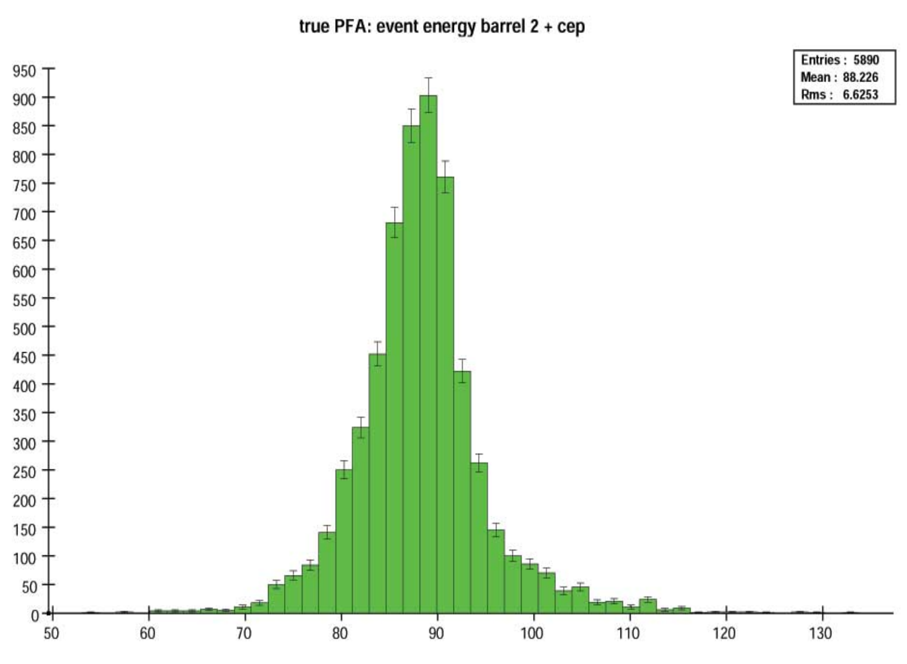


WScint
Event/Neutral dE1
Event/Neutral dE1
Entries : 7969
Mean : -0.32208
Rms : 2.8707
gauss
amplitude : 664.16±11.0
mean : 0.077080±0.01897
sigma : 1.6327±0.0195
χ² : 6.0431
RMS90 = 1.379
SSScint
Event/Neutral dE1
Event/Neutral dE1
Entries : 7964
Mean : -0.25950
Rms : 2.5928
gauss
amplitude : 627.87±10.0
mean : 6.8205E-3±0.018152
sigma : 1.5780±0.0175
χ² : 3.9343
RMS90 = 1.289
WRPC
Event/Neutral dE1
Event/Neutral dE1
Entries : 7970
Mean : -0.29201
Rms : 3.0854
gauss
amplitude : 604.83±10.2
mean : -0.054998±0.023742
sigma : 2.0513±0.0254
χ² : 5.4869
RMS90 = 1.667
SSRPC
Event/Neutral dE1
Event/Neutral dE1
Entries : 7969
Mean : -0.23727
Rms : 2.9261
gauss
amplitude : 525.13±8.62
mean : 0.025317±0.022810
sigma : 1.9741±0.0231
χ² : 4.1012
RMS90 = 1.598

PFA at Z-pole: sidaug05_np

Lei Xia, ANL





No cut

Mean 87.4 GeV
RMS 7.33 GeV
RMS90 4.56 GeV
[49%/sqrt(E)]

Barrel event (cos(theta[Q]) < sqrt(2)/2)

Mean 88.2 GeV
RMS 6.63 GeV
RMS90 4.28 GeV
[46%/sqrt(E)]

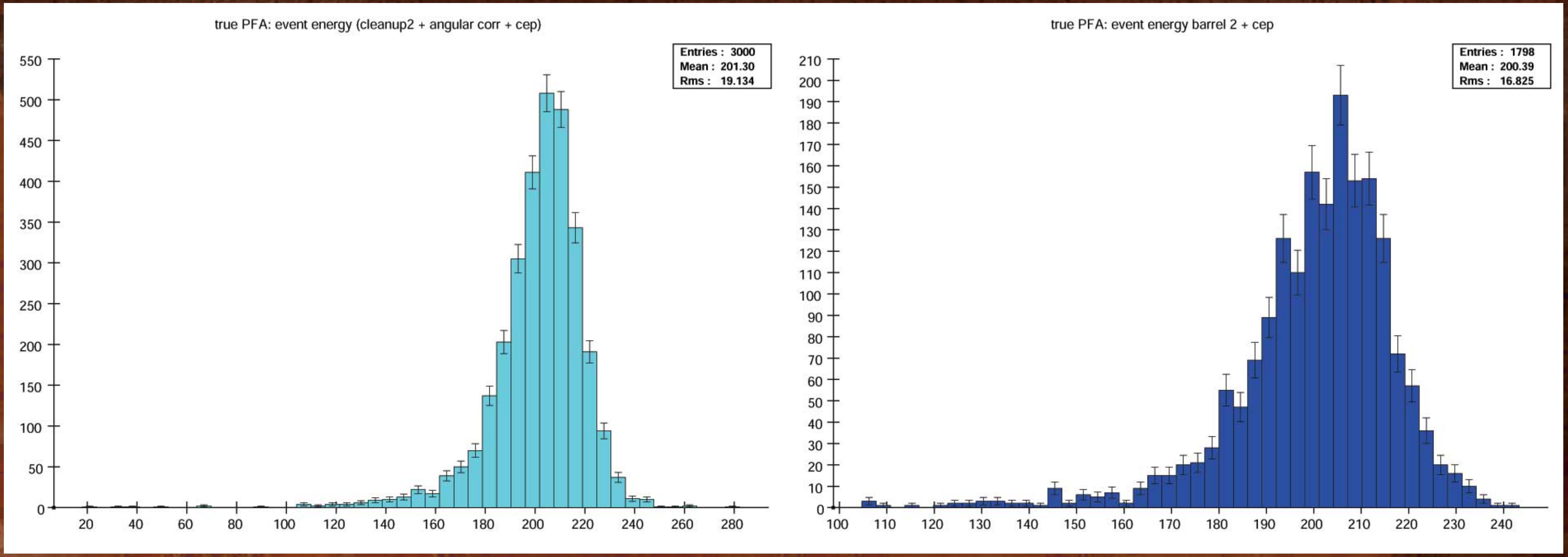
Detector model: SiDaug05_np (non-projective cells)

PFA: no change from Vancouver, *except adding E/P check*

parameters for clustering, etc. are not tuned yet...

30 layer ECAL, SS/RPC HCAL

PFA Results - 200 GeV E_{cm}



No cut

Mean 201.3 GeV
RMS 19.1 GeV
RMS90 11.6 GeV
[82%/sqrt(E)]

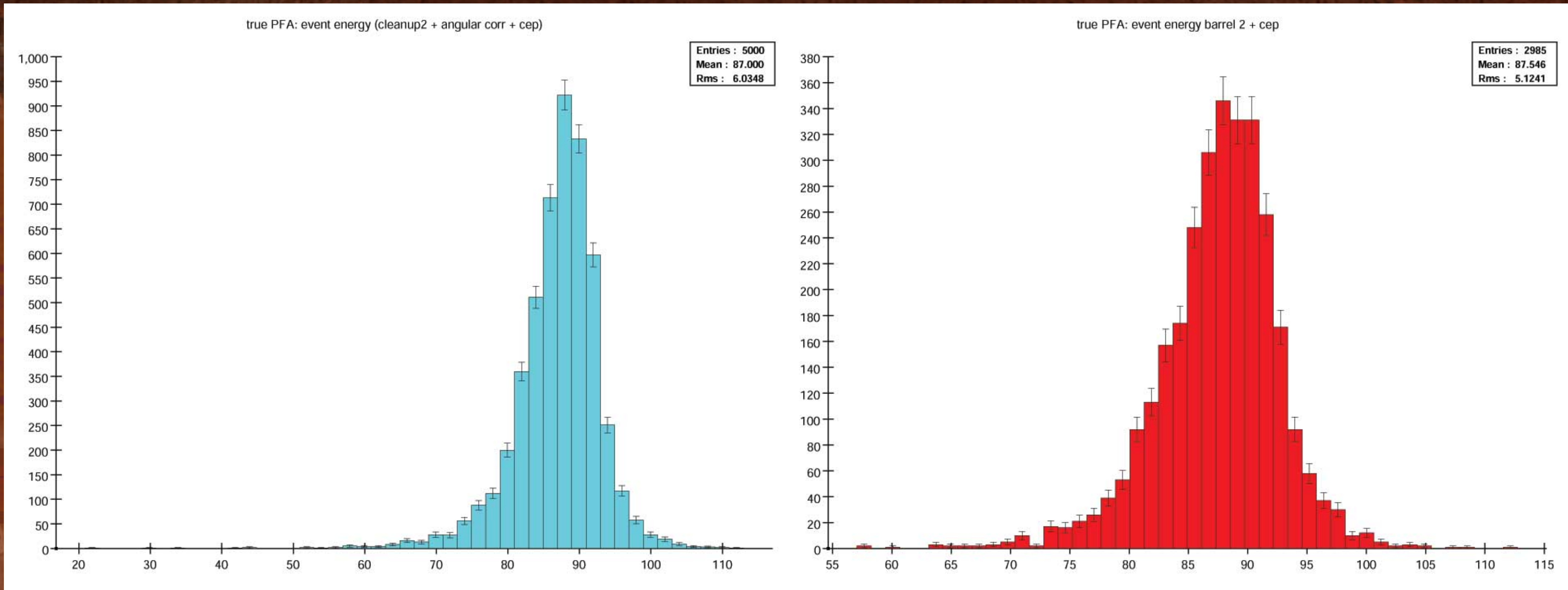
Barrel event (cos(theta[Q]) < sqrt(2)/2)

Mean 200.4 GeV
RMS 16.8 GeV
RMS90 10.9 GeV
[77%/sqrt(E)]

PFA need to be tuned/modified for higher energy

Much better performance should be possible

PFA Results - Back to Z-pole: sidaug05_np



No cut

Mean 87.0 GeV
RMS 6.03 GeV
RMS90 3.81 GeV
[41%/sqrt(E)]

Barrel event (cos(theta[Q]) < sqrt(2)/2)

Mean 87.5 GeV
RMS 5.12 GeV
RMS90 3.54 GeV
[38%/sqrt(E)]

Got it last night – so, very preliminary!

PFA Results – Detector, E_{cm} Comparisons

Comparing different detectors

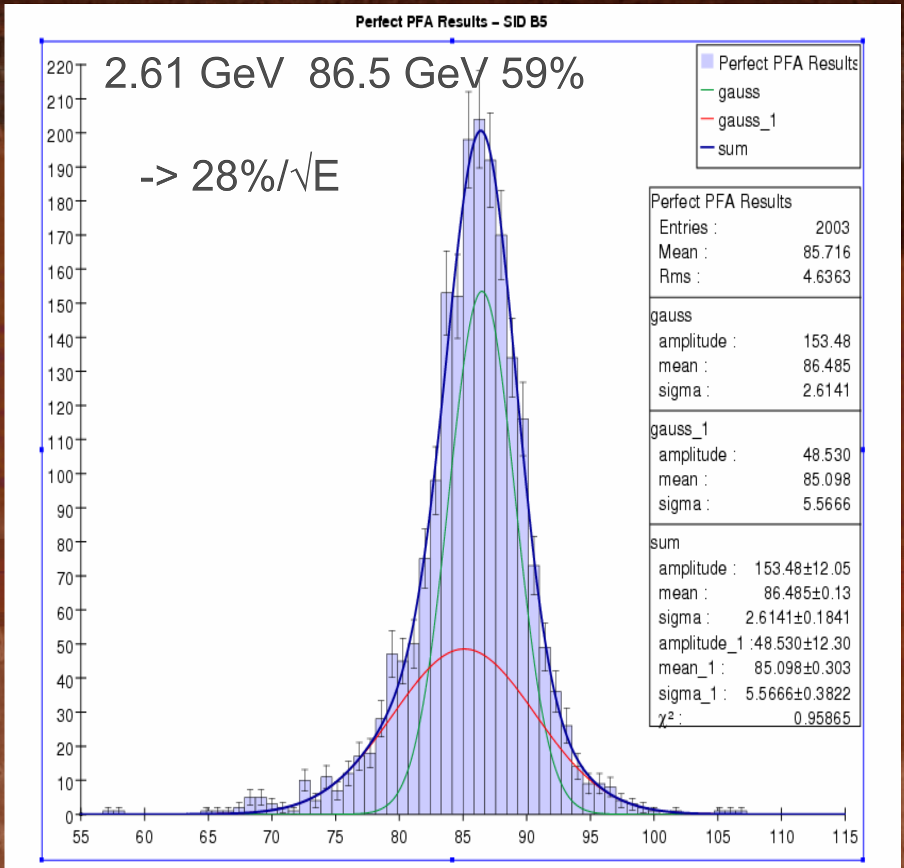
Detector	CM energy (GeV)	Jet energy (GeV)	Correcting for missing energy: rms90 (GeV)	Correcting for missing energy: m90 (GeV)	Not correcting for missing energy: rms90 (GeV)	Not correcting for missing energy: m90 (GeV)	Corrected for missing energy
sidaug05	91	45.5	4.42	91.65	4.53	90.22	46%/√E
sidaug05	200	100	8.33	202.69	9.44	200.73	59%/√E
sidaug05	500	250	20.52	501.66	27.75	491.89	92%/√E
sidaug05_ scinthcal	91	45.5	3.86	90.89	3.93	89.76	40%/√E
acme0605	91.0	45.5	3.95	91.55	4.20	90.40	41%/√E
acme0605	200	100	8.21	206.39	9.36	204.40	57%/√E
acme0605	500	250	24.06	510.19	30.34	501.67	107%/√E

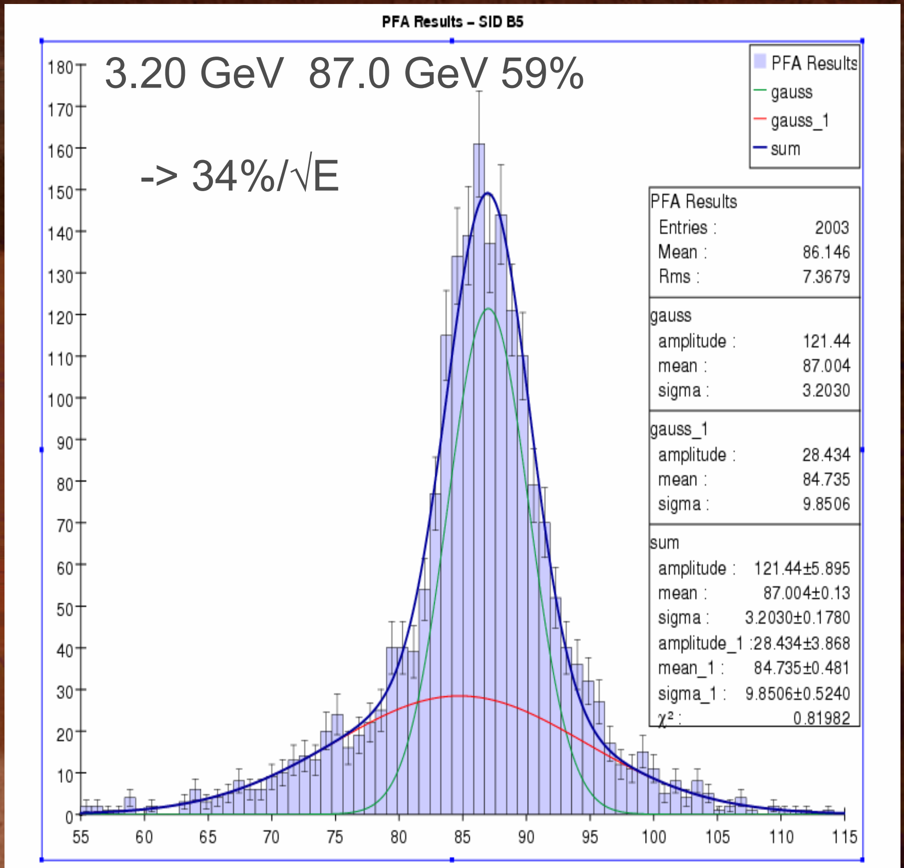
Lots of missing energy at high Ecm

Below 4GeV with scintillator at Z-pole!

M. Charles, Iowa

PFA Results – Taming the Confusion Term





SiD Detector Model
Si Strip Tracker
W/Si ECAL, IR = 125 cm
4mm X 4mm cells
SS/RPC Digital HCAL
1cm X 1cm cells
5 T B field (CAL inside)

Average confusion contribution = 1.9 GeV < neutral hadron resolution contribution of 2.2 GeV

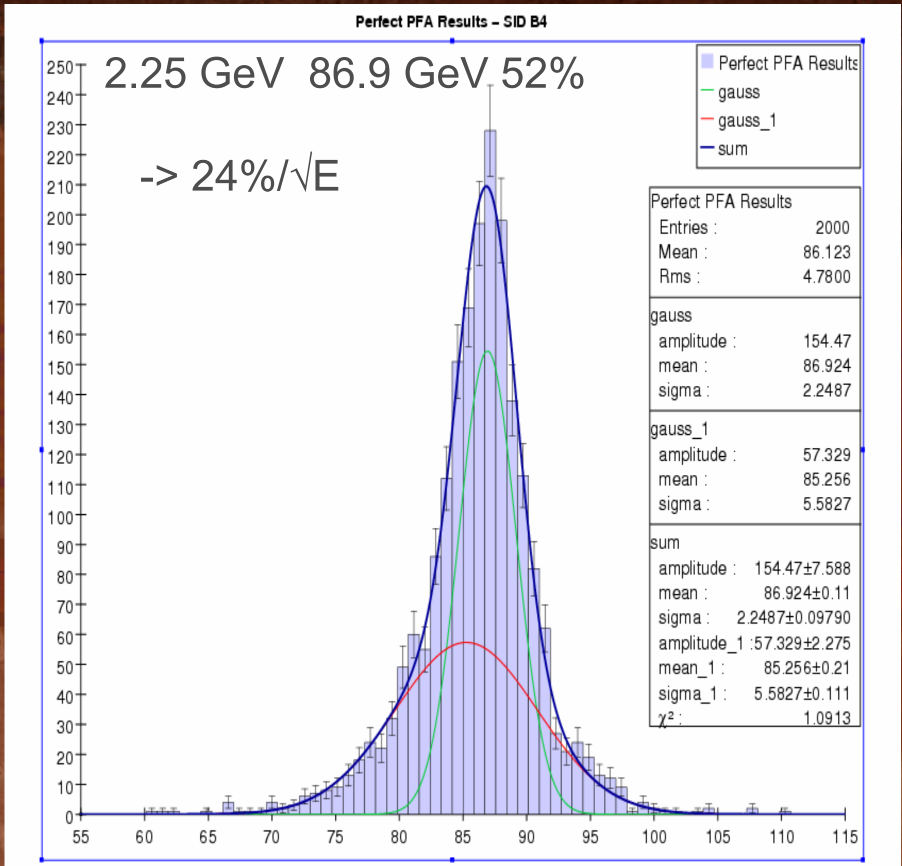
-> PFA goal!*

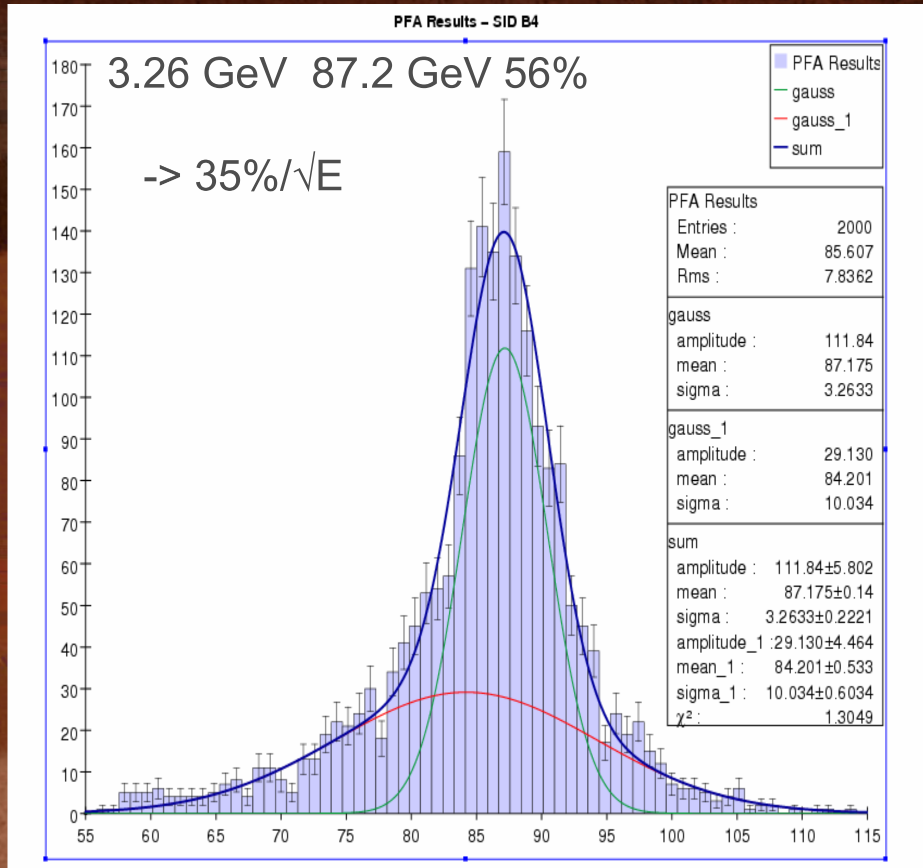
ANL/SLAC

* other 40% of events!

Detector Comparisons with PFAs

Vary B-field





SiD SS/RPC - 5 T field

Perfect PFA σ = 2.6 GeV

PFA σ = 3.2 GeV

Average confusion = 1.9 GeV

SiD SS/RPC - 4 T field

Perfect PFA σ = 2.3 GeV

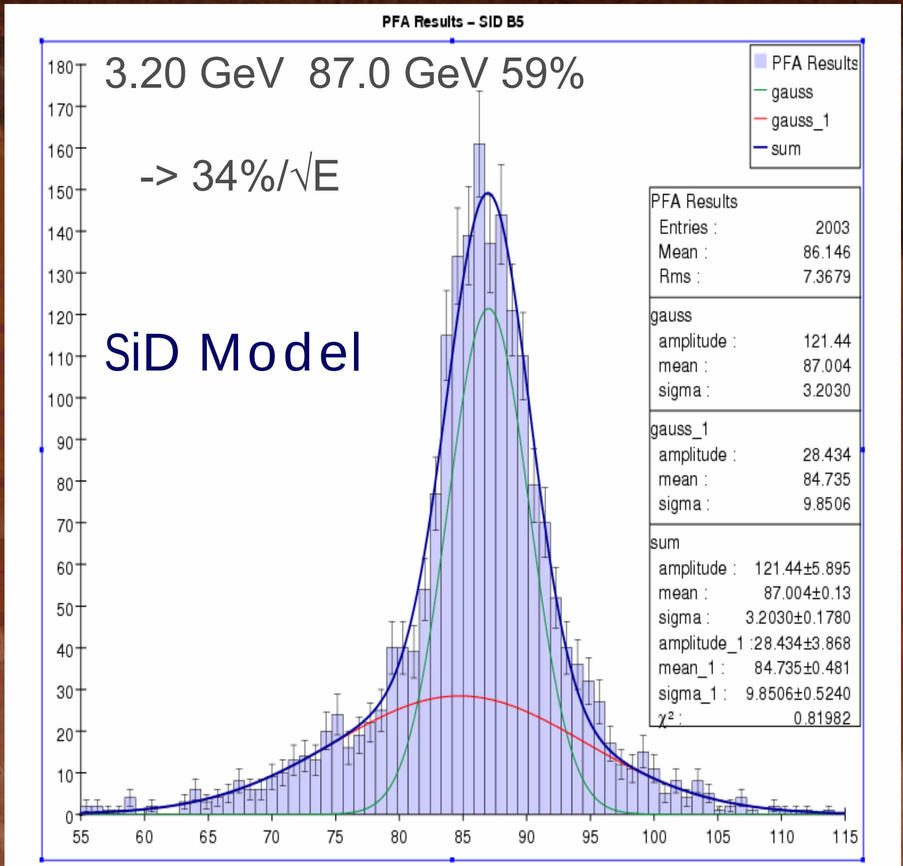
PFA σ = 3.3 GeV

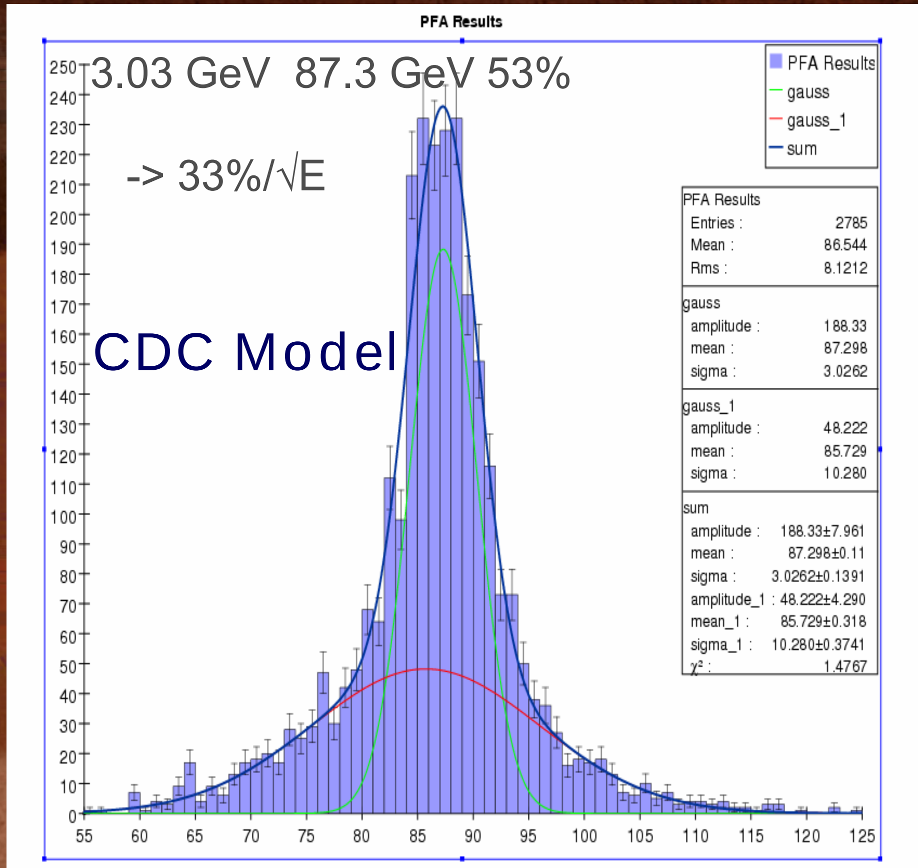
Average confusion = 2.4 GeV

-> Better performance in larger B-field

Detector Optimized for PFA?

Vary ECAL IR





SiD -> CDC 150

- ECAL IR increased from 125 cm to 150 cm
- 6 layers of Si Strip tracking
- HCAL reduced by 22 cm (SS/RPC -> W/Scintillator)
- Magnet IR only 1 inch bigger!
- Improved PFA performance w/o increasing magnet bore

Summary of some things we have learned so far . . .

Calibration will rely on both test beam and simulation

- -> Neutrals in test beam?
- -> Low energy particles

Track/Shower matching helped by E/p

- -> ANL/SLAC, Xia, Charles, Pandora

Need to tune PFA for E_{cm}, detector model, physics?

Neutral shower = charged shower – mips

- -> common clustering alg?
- -> fragment association algorithms
- -> Test beam implications

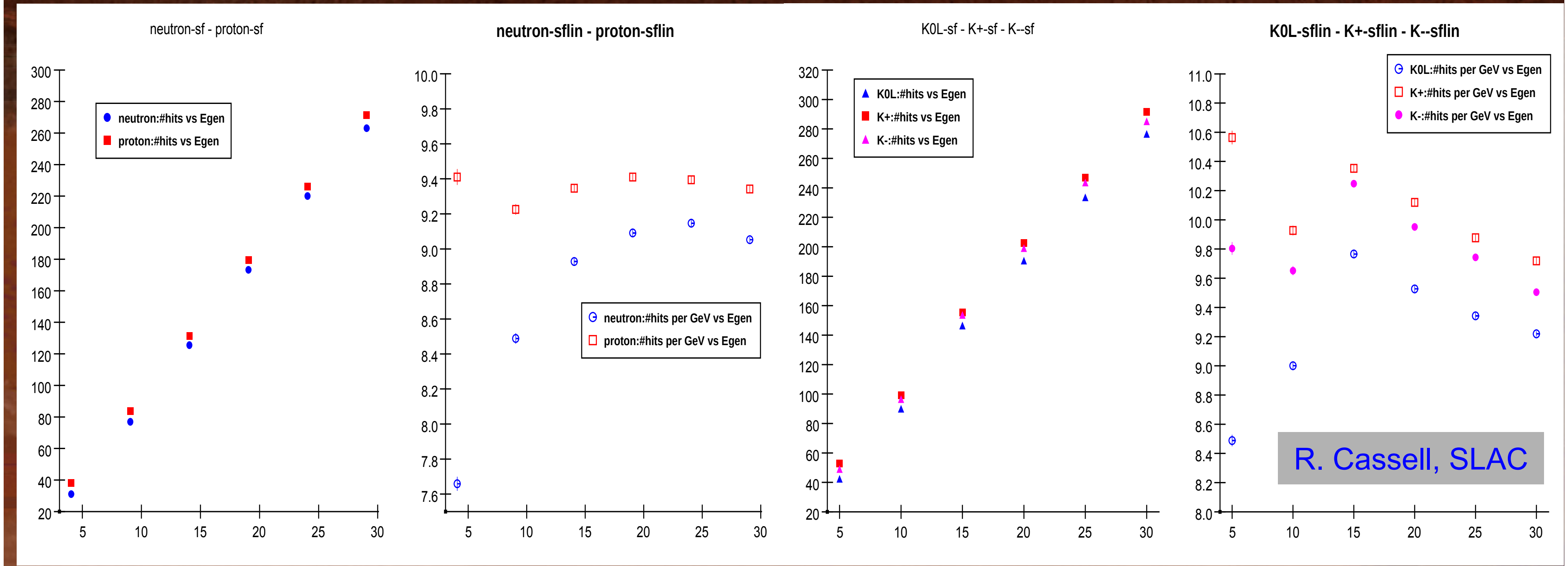
Use of multiple clustering algorithms

- -> photon ID example

Different algorithms for each particle type – modular PFA

- -> PFA Template

Comparison of Charged/Neutral Hadron Hits



-> linearity of response

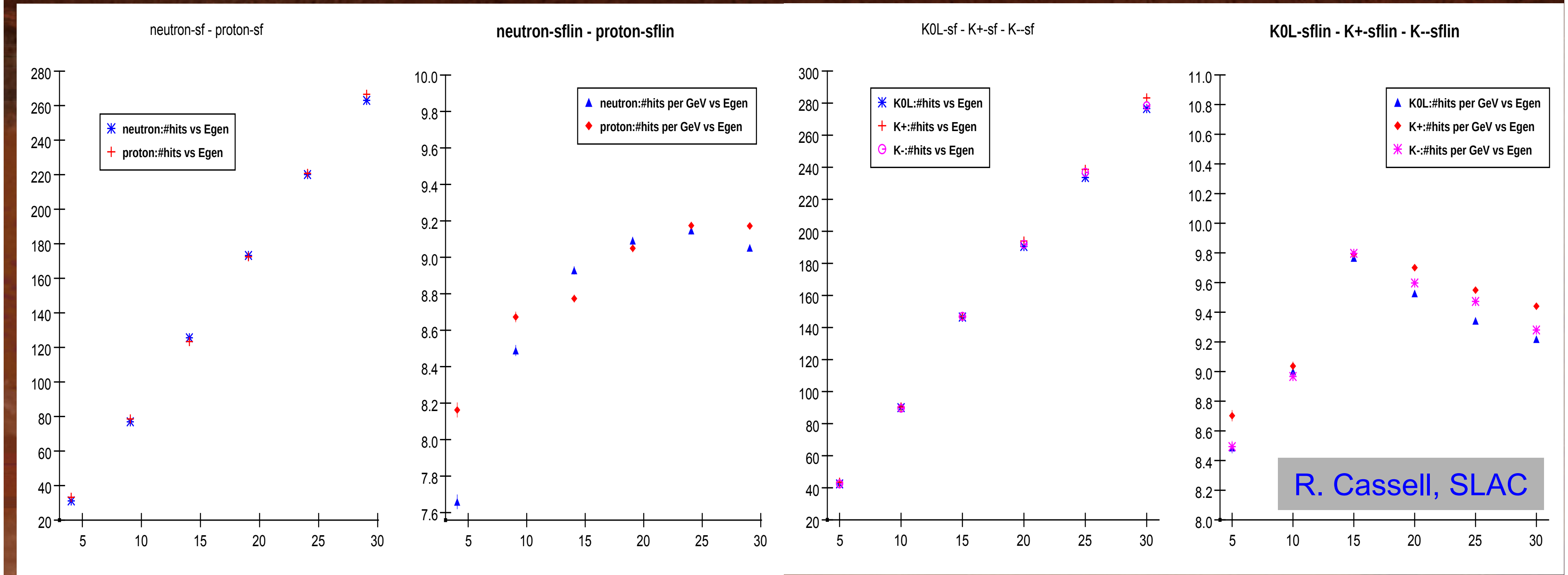
-> charged hadrons generate slightly more hits than neutral

-> calibration (#hits/GeV) different, especially at low energy

Mips before showering – charged hadrons lose ~25 MeV per layer in SSRPC isolated detector. (Normal incidence)

Try to correct by weighting N hits (N = # of layers traversed before interacting) by .25

Charged(Mip correction)/Neutral Hadron Hits



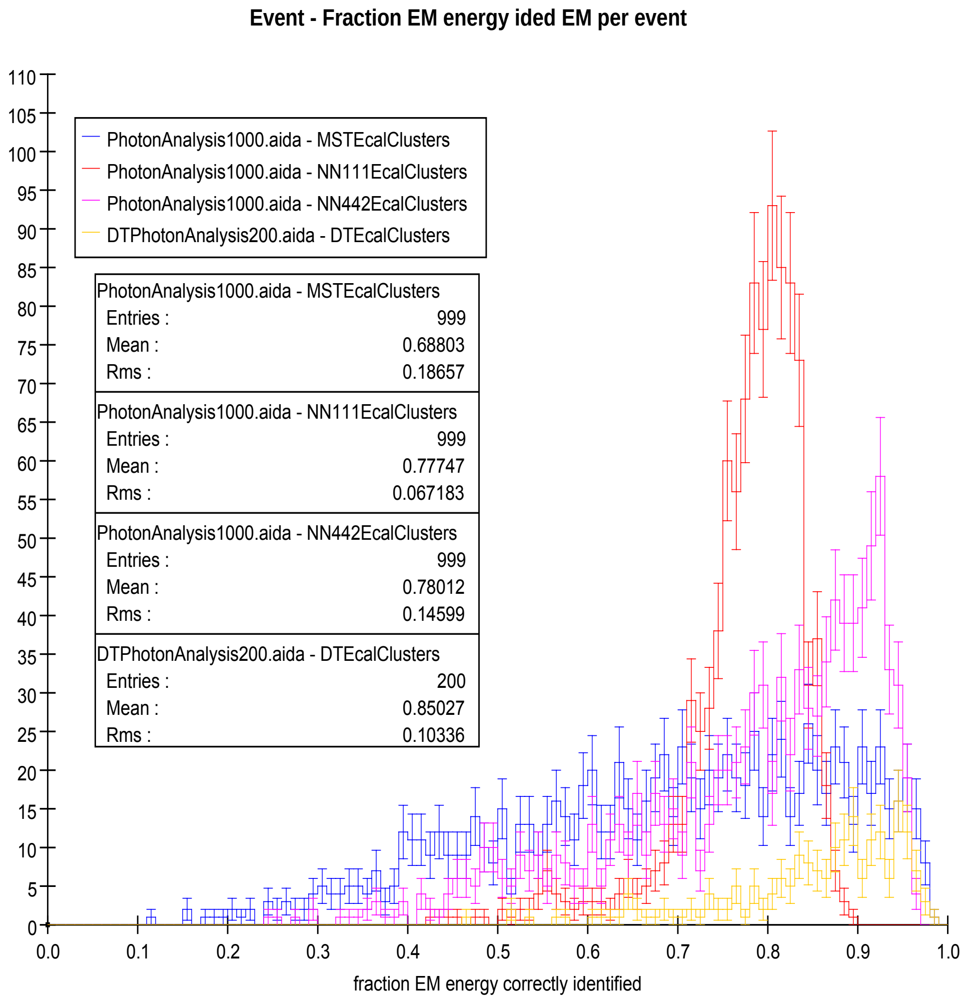
-> account for mip trace properly
-> after weighting, #hits charged ~ #hits neutral
-> shower calibration (#hits/GeV) now very similar

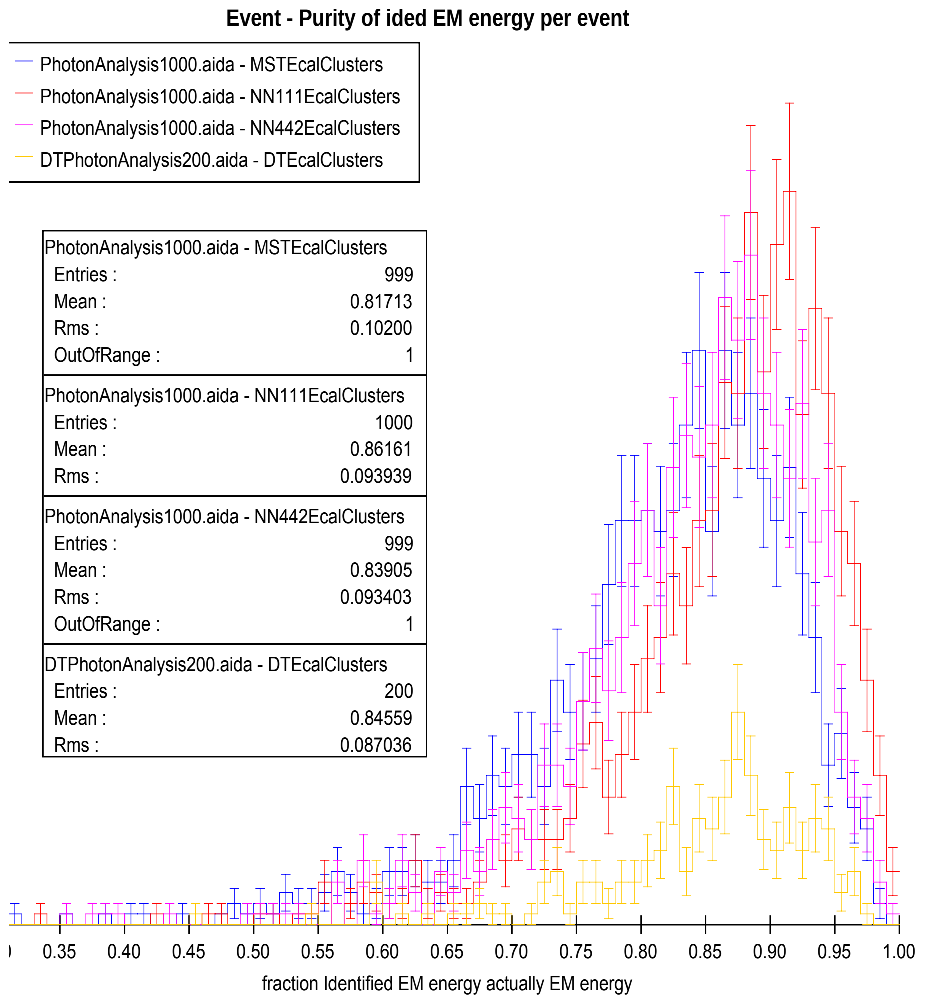
In PFA, find mips first attached to extrapolated tracks, then can cluster remaining hits with same calibration (#hits/GeV) for charged and neutral hadrons*

* remember, this is simulation!

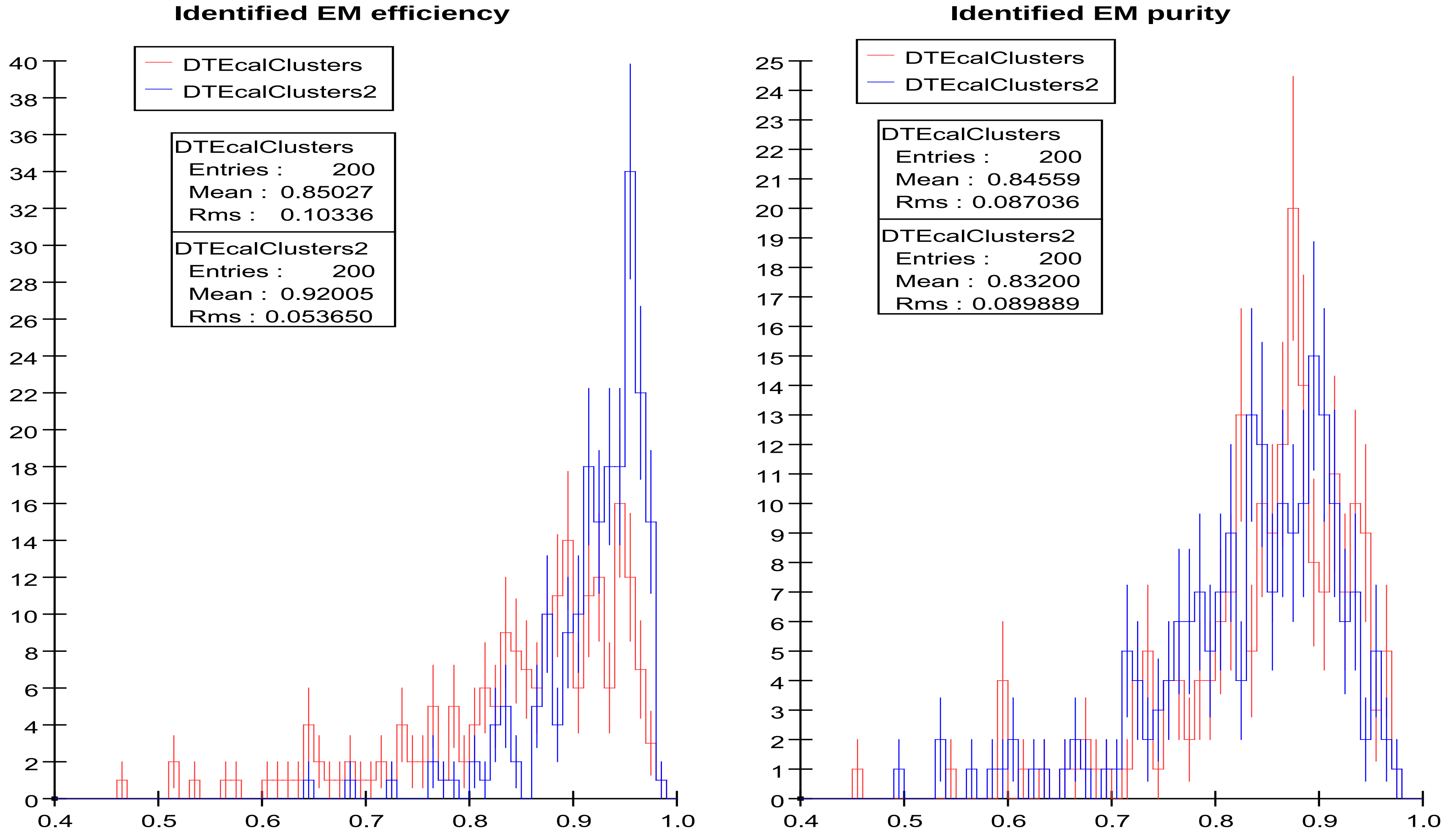
Photon ID – Efficiency, Purity for Cluster Algs

R. Cassell, SLAC





Use DT for Energy, NN(1,1,1) for ID



PFA Template – Imminent Release

DigiSim (NIU digitization program – threshold, timing cuts, noise, etc)

Event Filter -> select regions, other cuts

Perfect PFA Calculation -> "perfect" detector objects

Collection A to HitMap A conversion (package UIowa)

Track/Mip Trace Algorithm -> Associated Mip Clusters, modified HitMap

HitMap B to Collection B conversion (package UIowa)

Clusterer for ECAL hits (input: Collection B, output: clusters)
Photon ID Algorithm -> Photons, modified HitMap

HitMap C to Collection C conversion

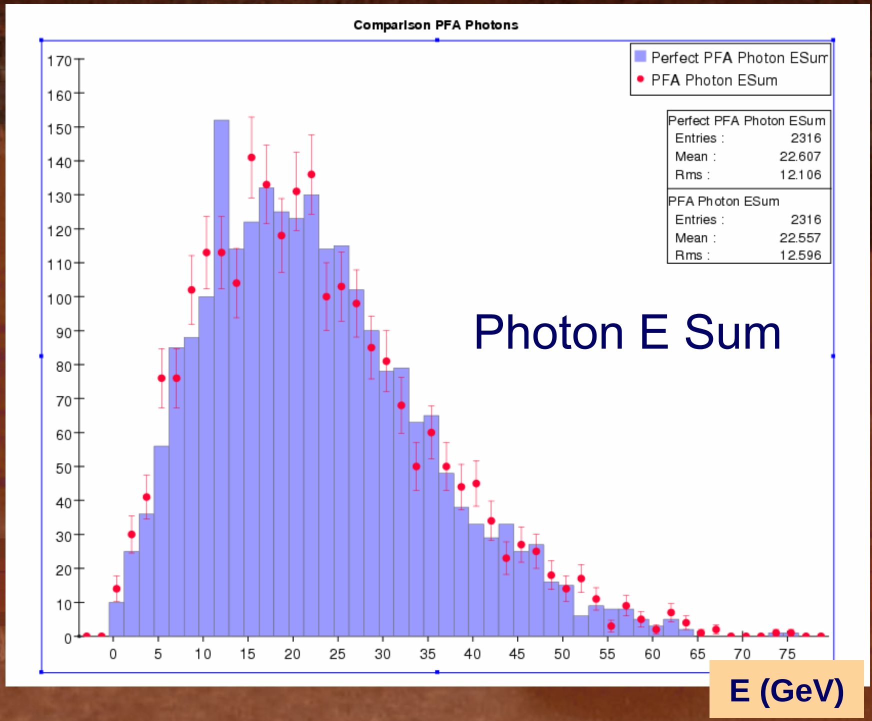
Clusterer for ECAL, HCAL hits (input: Collection C, output: clusters)
Track/Shower Association Algorithm -> Charged Hadrons, modified HitMap

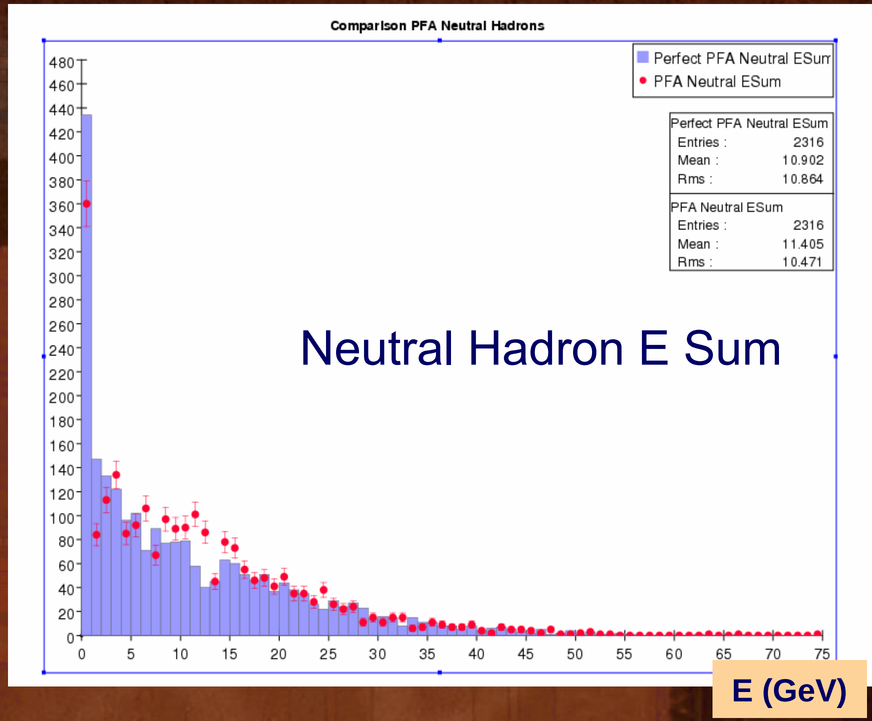
HitMap D to Collection D conversion

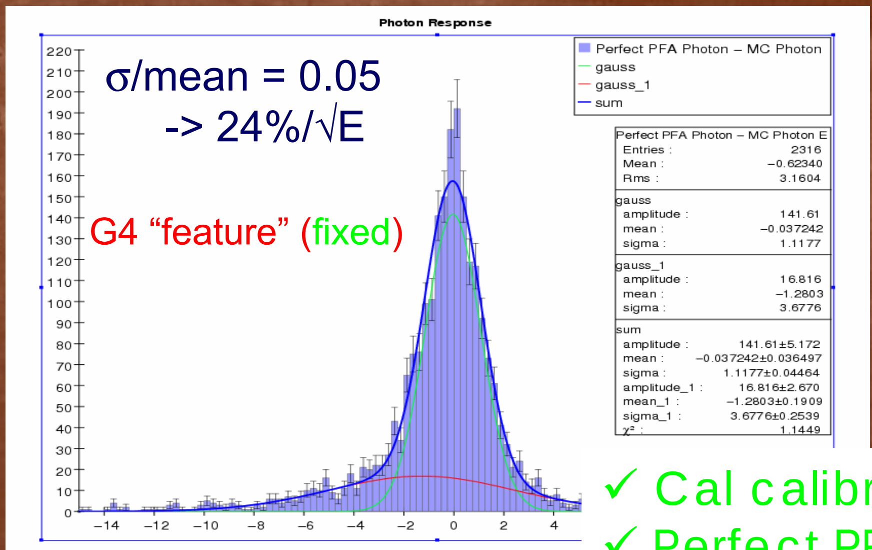
Clusterer for ECAL, HCAL hits (input: Collection D, output: clusters)
Neutral Hadron ID Algorithm -> Neutral Hadrons, modified HitMap

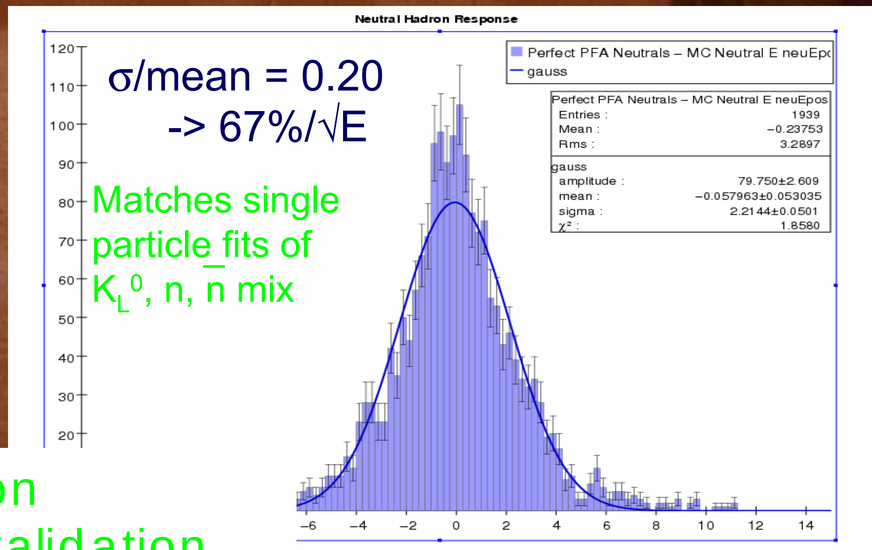
Post-processor (input: HitMap E, output: ?)

PFA Module Comparisons









✓ Cal calibration

✓ Perfect PFA validation

Summary

At ZPole :

- *Have approached desired jet energy resolution of ~30%/√E*
- *Have achieved $\sigma_{confusion} < \sigma_{neutral\ hadron}$ in PFA energy sum*

Have developed huge collection of tools necessary for both PFA development and detector optimization :

- Flexible, fast full simulation packages
- Full reconstruction capabilities
- Standard Calorimeter calibration procedures
- Standardized algorithm comparison tools
- Modular, standardized PFA Template

Next Steps :

- Move from energy sums to dijet mass – PFA jet reconstruction
- Move to physics events at 500 GeV CM
- Use PFAs for detector optimization at 500 GeV

e^+e^- -> ttbar -> 6 jets @500 GeV CM