The PFA Approach to ILC Calorimetry

Steve Magill - ANL

Calorimeter R&D Review
LCWS DESY
May 31, 2007

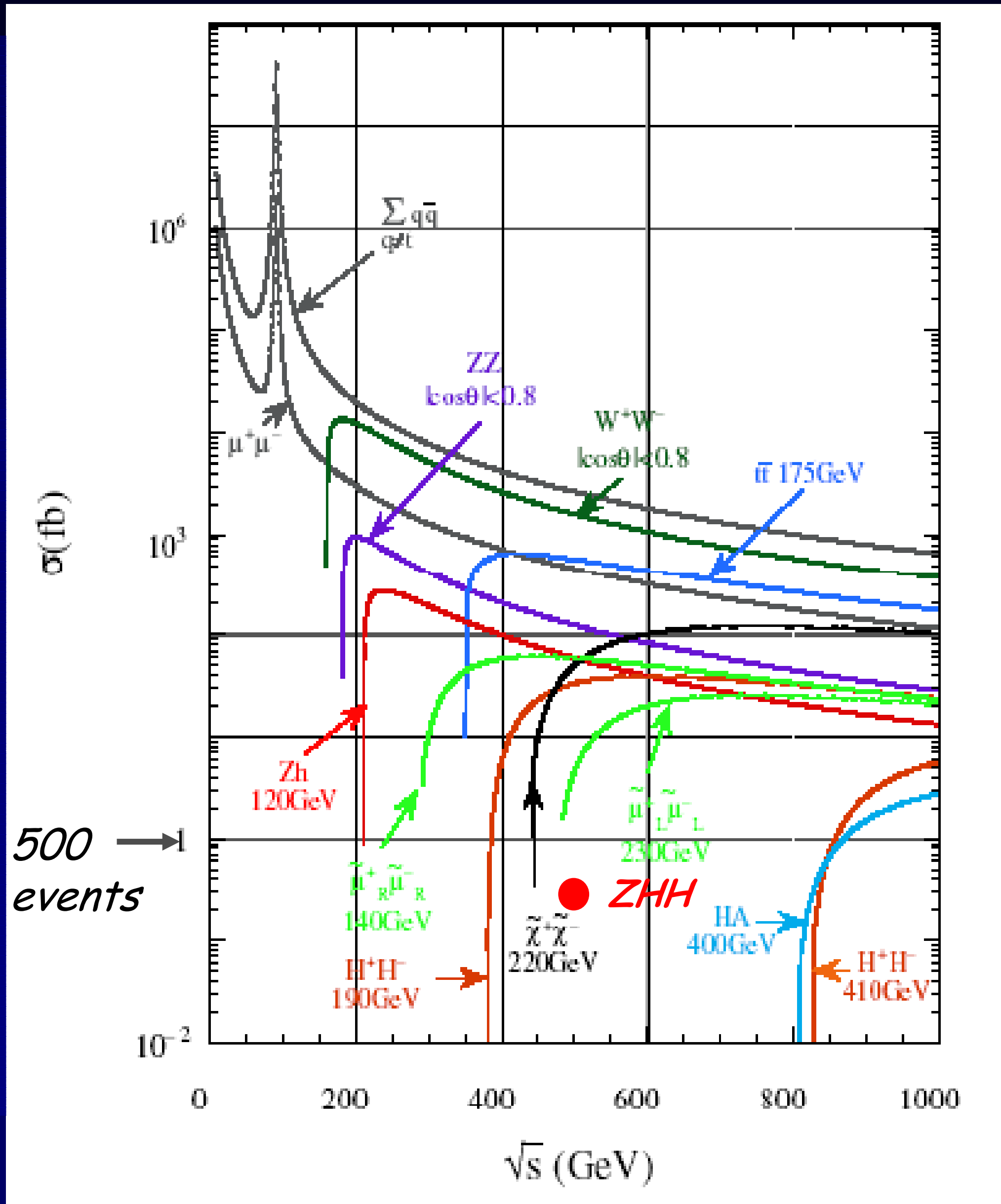
- Multi-jet Events at the ILC
  - PFA Approach
  - PFA Goals
- PFA Requirements on ILC Calorimetry
- PFA-motivated Detector Models
- PFA Results
  - Energy Sums
  - Dijet Mass
  - Detector Optimization
- Simulations and Test Beams
- Summary

The PFA results shown in this talk are made possible and brought to you by :

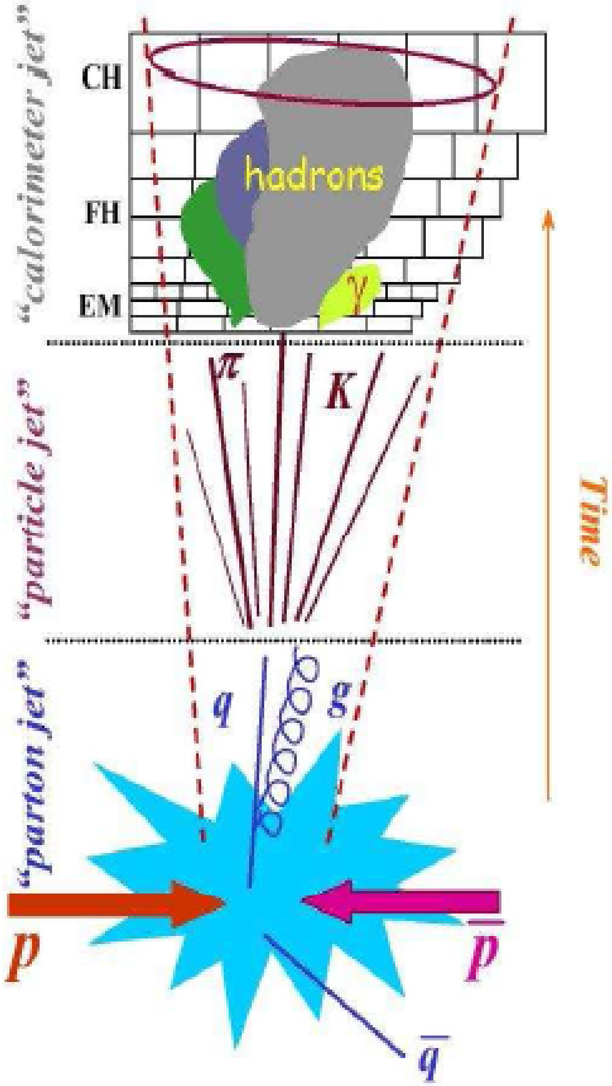
Ron Cassell, SLAC
Mat Charles, University of Iowa
Norman Graf, SLAC
Mark Thomson, Cambridge University
Graham Wilson, Kansas Uiversity
Lei Xia, ANL
SM, ANL

Precision Physics at the ILC

- e^+e^- : background-free but can be complex multi-jet events
- Includes final states with heavy bosons *W, Z, H*
- But, statistics limited so must include hadronic decay modes (~80% BR) -> *multi-jet events*
- In general no kinematic fits -> full event reconstruction



Parton Measurement via Jet Reconstruction



- Calorimeter jet
  - Interaction of hadrons with calorimeter.
  - Collection of calorimeter cell energies.
- Particle jet
  - After hadronization and fragmentation.
  - Effect of hadronization is soft $\Rightarrow$ allows comparison between particle and parton jets.
- Parton jet
  - Hard scattering.
  - Additional showers.

From J. Kvita at CALOR06

Cal Jet -> *large correction* -> Particle Jet -> *small correction* -> Parton Jet

The Particle Flow Approach to Jet Reconstruction

PFA Aim : *1 to 1 correspondence between measured detector objects and particle 4-vectors*

-> Detector Jet == Particle Jet

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

- good tracking for charged particles (~60% of jet E)
  -> σ_p (tracking) <<< σ_E for photons or hadrons in CAL
- good EM Calorimetry for photon measurement (~25% of jet E)
  -> σ_E for photons < σ_E for neutral hadrons
- good separation of neutral and charged showers in E/HCAL
  -> CAL objects == particles
  -> 1 particle : 1 object -> small CAL cells
- adequate E resolution for neutrals in HCAL (~13% of jet E)
  -> σ_E < minimum mass difference, e.g. $M_Z - M_W$
  -> still largest contribution to jet E resolution

Jet Energy Resolution – “Perfect” PFA

- Jet energy resolution
  $\sigma^2(E_{jet}) = \sigma^2(ch.) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Excellent tracker :
  $\sigma^2(ch.) << \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Perfect PFA : $\sigma^2(conf.) = 0$
- $\sigma^2(E_{jet}) = A_\gamma^2 E_\gamma + A_h^2 E_{h0} = w_\gamma A_\gamma^2 E_{jet} + w_{h0} A_h^2 E_{jet}$
  $\sigma(E_{\gamma,h})/E_{\gamma,h} = A_{\gamma,h}/\sqrt{E_{\gamma,h}}$

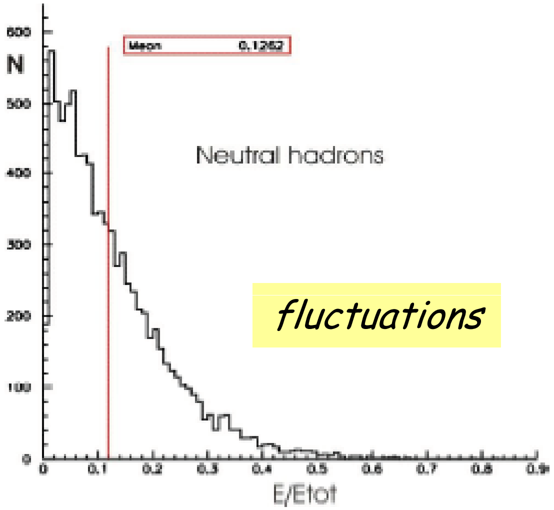
Typically $w_\gamma = 25\%$; $w_{h0} = 13\%$

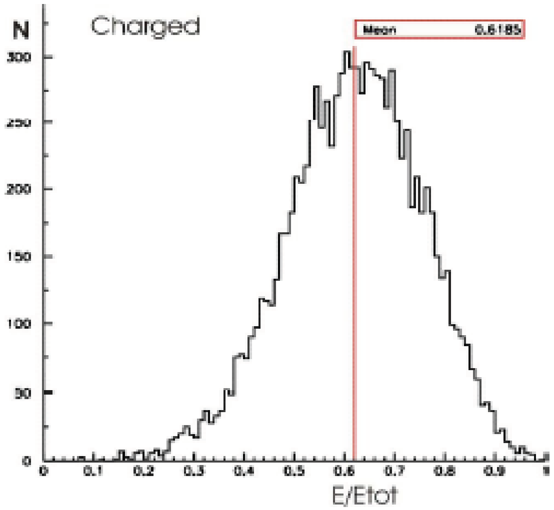
$A_\gamma = 15\%$; $A_{h0} = 35\%$

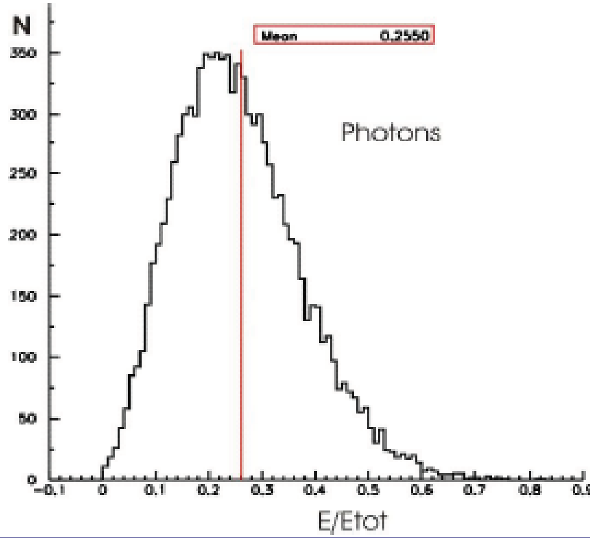
=> $\sigma(E_{jet})/E_{jet} = 15\%/\sqrt{E_{jet}}$

$A_\gamma = 15\%$; $A_{h0} = 60\%$

=> $\sigma(E_{jet})/E_{jet} = 23\%/\sqrt{E_{jet}}$

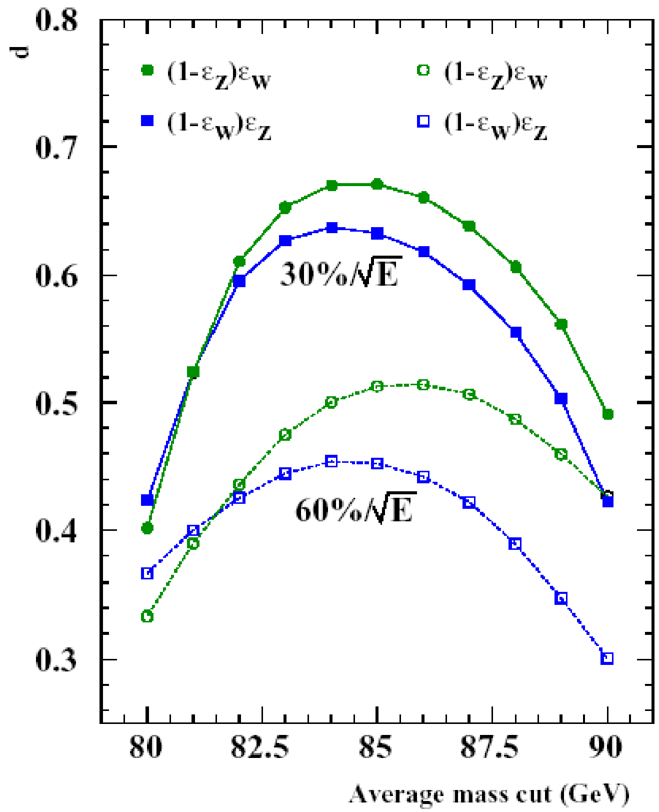




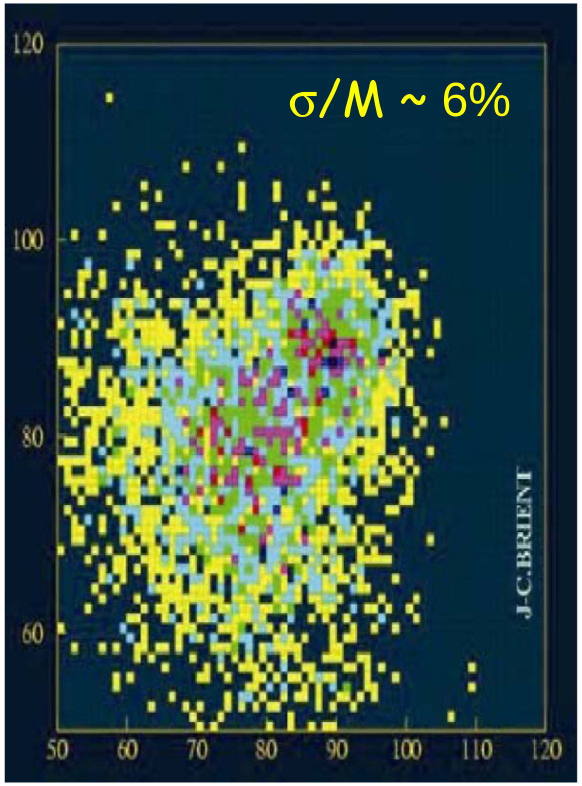


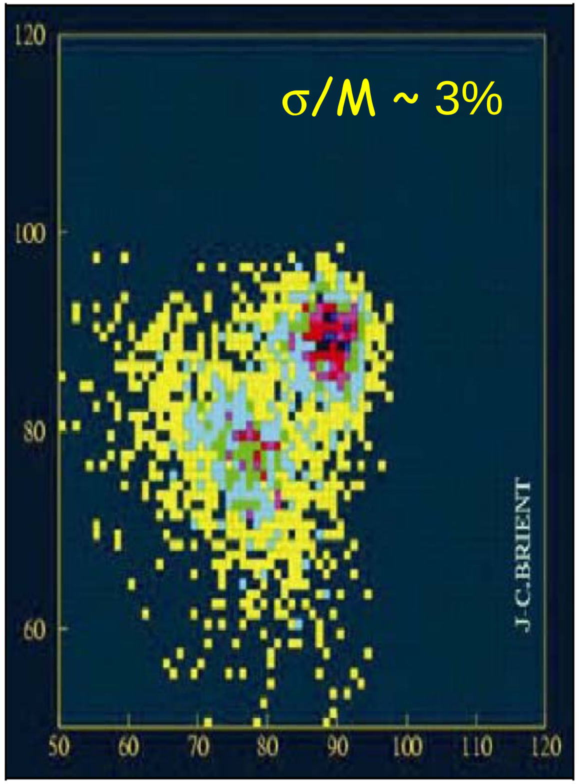
PFA Goal – Particle-by-Particle W, Z ID

- Want $m_Z - m_W = 3\sigma_m$ (dijets)
  -> dijet mass resolution of ~3.5 GeV or ***3-4% of the mass***
- Better resolution increases the ***useable luminosity*** – or decreases running cost



Dijet masses in WW and ZZ events





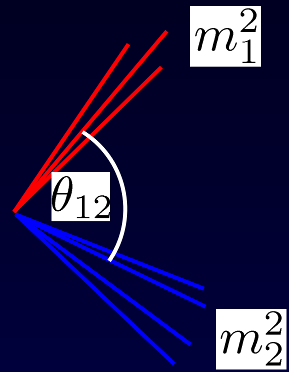
*Dilution factor vs cut : **integrated luminosity equivalent***

102 GeV Higgs?!!

PFA Goal – Jet Energy Resolution Dependence

★ **For a pair of jets have:**

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$



★ **Assuming a single jet energy resolution of**

$$\sigma_E/E = \alpha(E)/\sqrt{E(\mathrm{GeV})}$$

$$\Rightarrow \sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\mathrm{GeV})}$$

+ term due to θ_{12} uncertainty

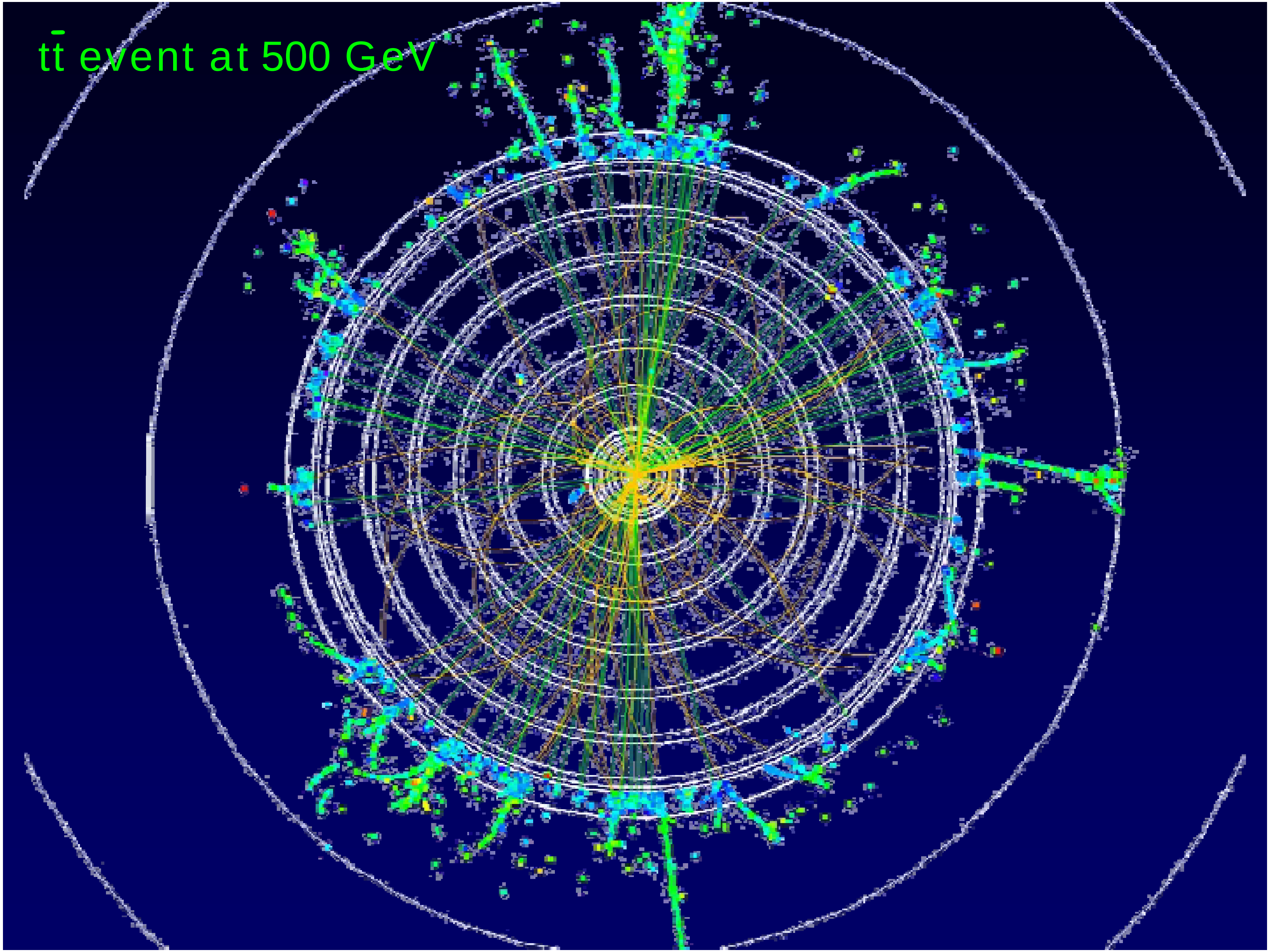
★ **For a Gauge boson mass resolution of order** $\Gamma_{\mathrm{W/Z}}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027 \Rightarrow \sim 3\%$$

$$\Rightarrow \boxed{\alpha(E_j) < 0.03\sqrt{E_{jj}(GeV)}}$$

E_{jj}/GeV	$\alpha(E_j)$
91	< 29 %
200	< 42 %
360	< 57 %
500	< 67 %

Jet energy resolution requirement depends on energy →


$t\bar{t}$ event at 500 GeV

The PFA Approach and Detector Design

PFA key -> complete separation of charged and neutral hadron showers

-> hadron showers NOT well described analytically, *fluctuations dominate*

-> average approach -> E resolutions dominated by fluctuations

-> shower reconstruction algorithms -> sensitive to fluctuations on a *shower-by-shower basis* -> better E resolution - PFA approach

Requires a calorimeter designed for optimal 3-D hadron (and photon) shower reconstruction :

-> granularity << shower transverse size (number of "hits")

-> segmentation << shower longitudinal size ("hits")

-> digital or analog readout?

-> dependence on inner R, B-field, etc.

uses optimized PFA to test detector model variations

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 effective r_M (Moliere radius) -> dense absorber + thin readout gap

-> If the transverse segmentation is of size r_M or smaller, get optimal *transverse separation* of electromagnetic clusters.

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

. . . use these for ECAL

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

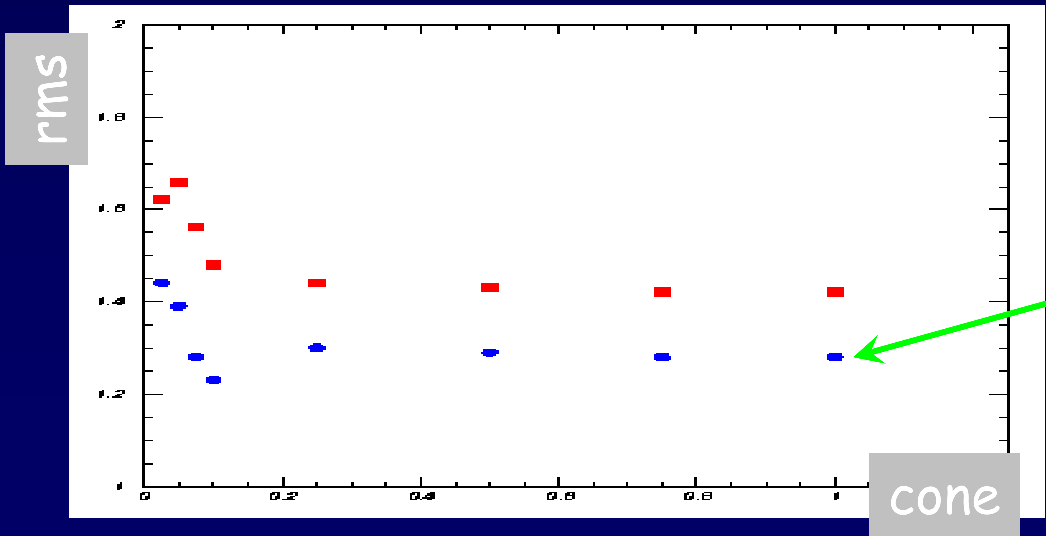
HCAL Requirements for Particle-Flow

SS — Single 5 GeV π

cone	mean (GeV)	rms	σ/mean	$\chi 2$
.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	$\chi 2$
.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

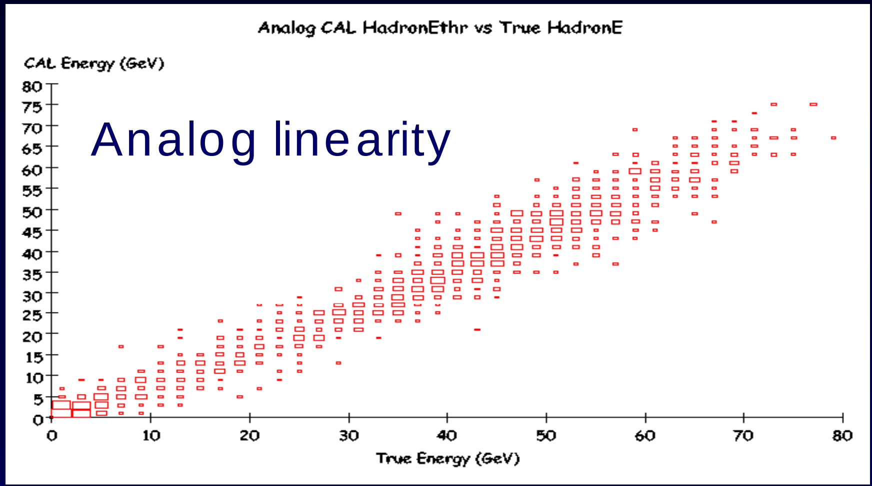
Tighter showers in W

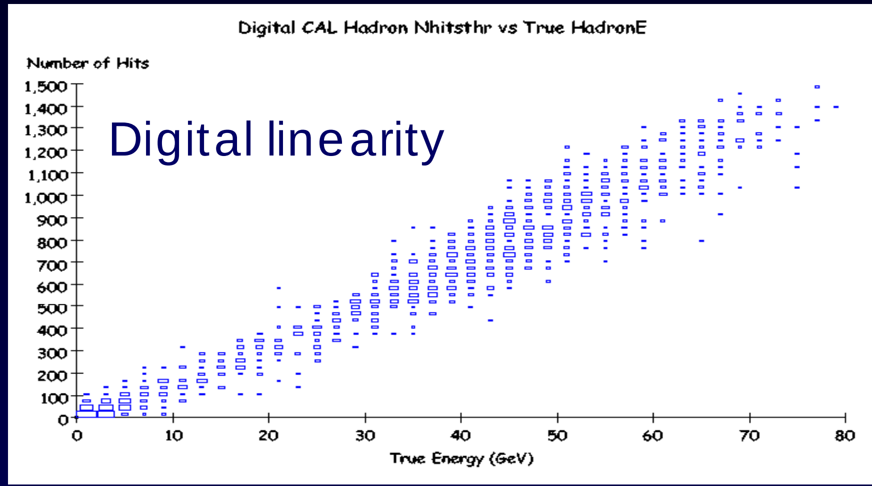
. . . dense HCAL as well?

-> 3-D separation of showers

Digital HCAL?

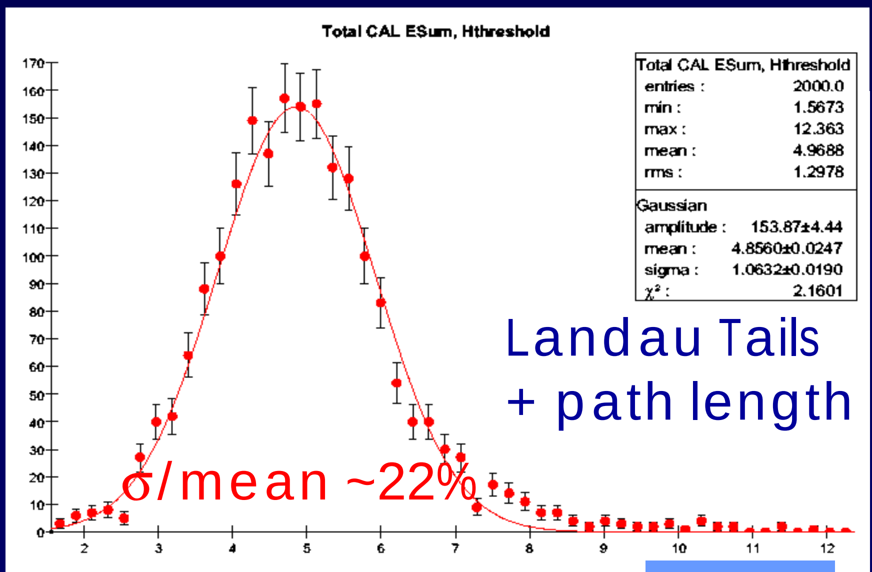
GEANT 4 Simulation of SiD Detector (5 GeV π^+)
-> sum of ECAL and HCAL analog signals - Analog
-> number of hits with 1/3 mip threshold in HCAL - Digital



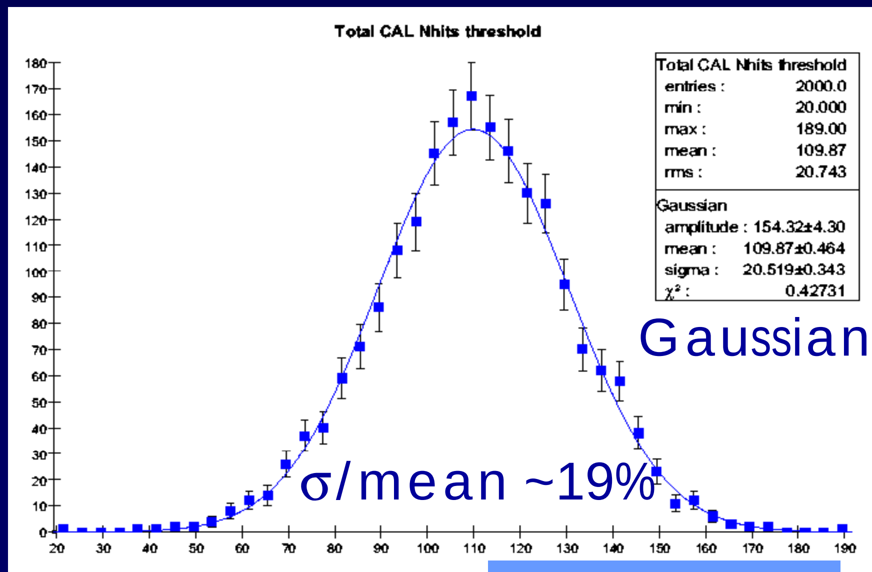


Analog

Digital

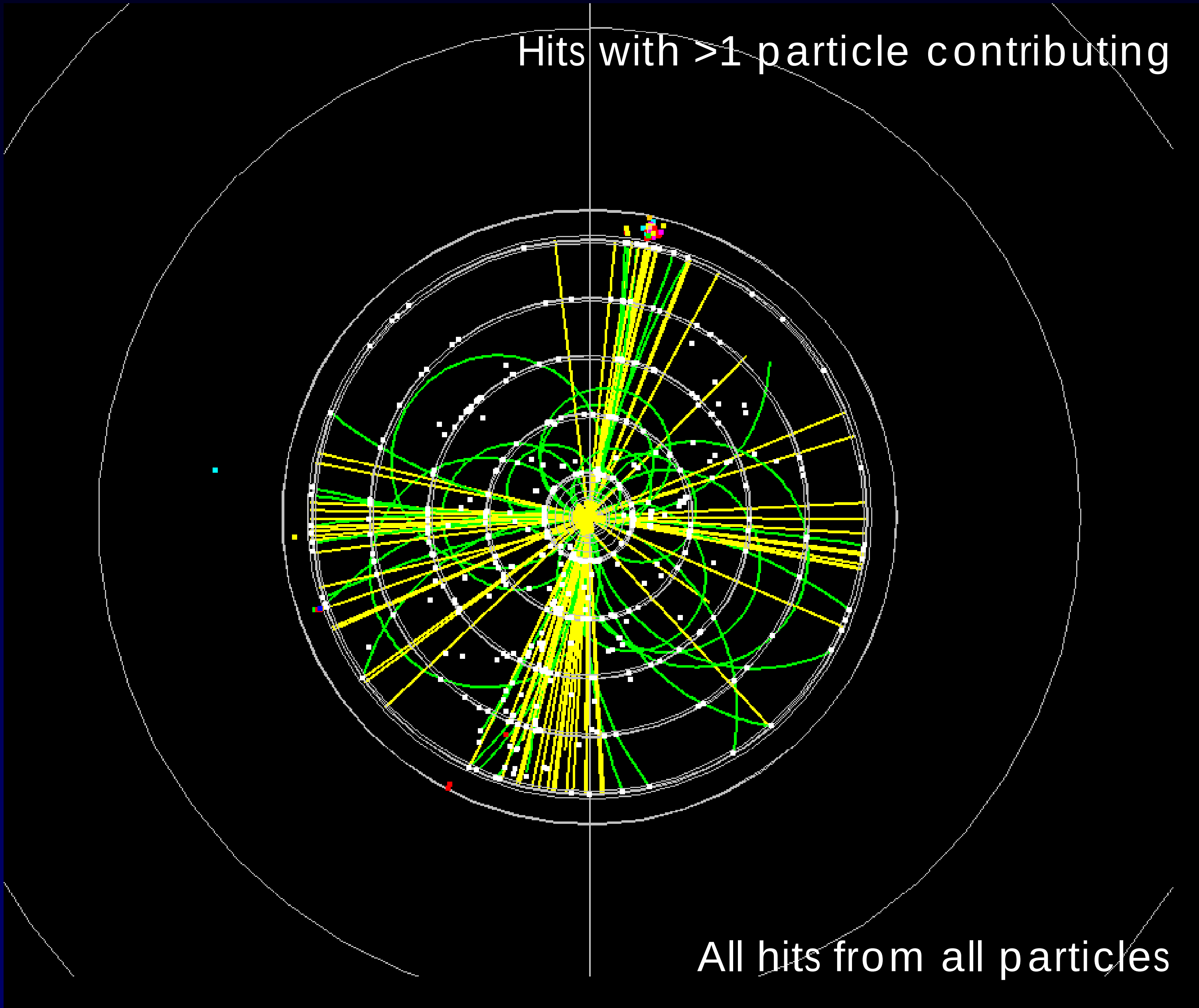


E (GeV)



Number of Hits

Occupancy Event Display

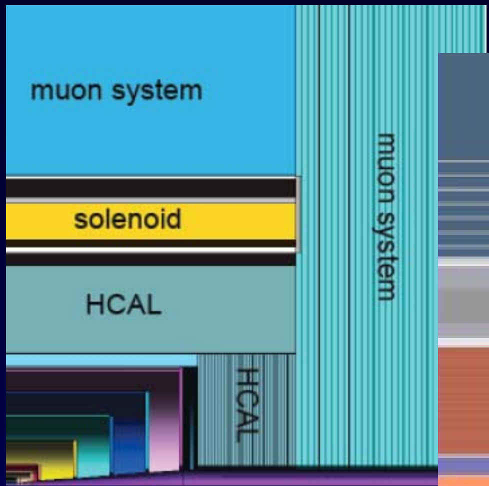


PFA-Motivated Detector Models

a la T. Yoshioka

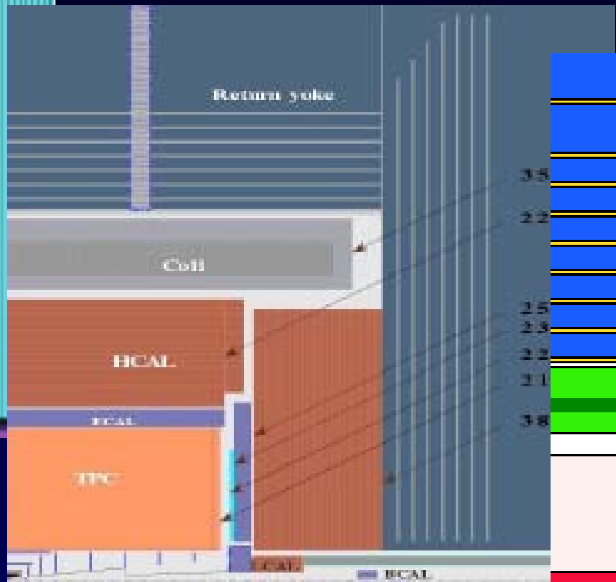
B-field

SiD



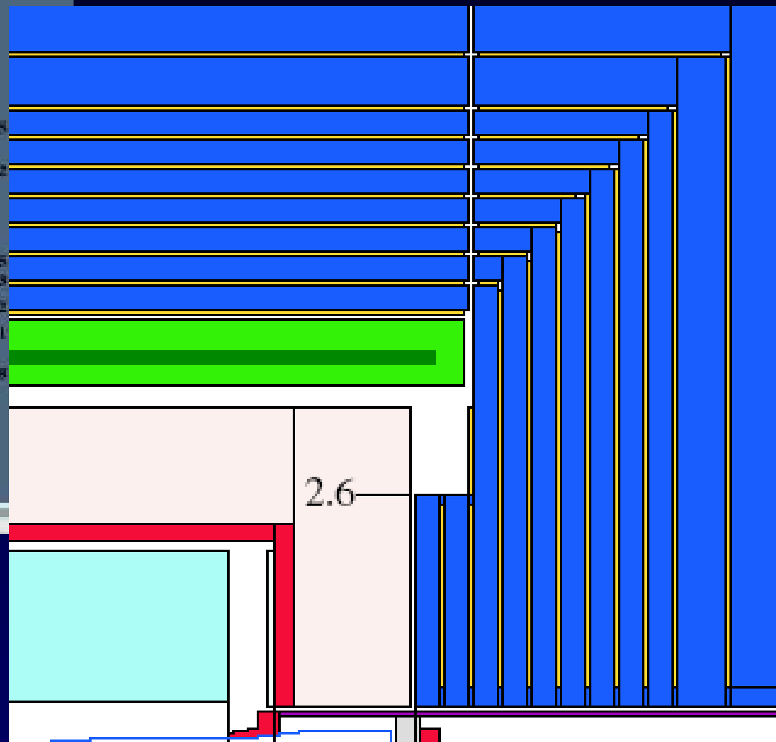
5 Tesla B-field
Si Strip/Disks Tracking
W/Si ECAL, IR = 125 cm
SS/RPC Digital HCAL

LDC



4 Tesla B-field
TPC Tracking
W/Si ECAL, IR = 160 cm
SS/Scin Analog HCAL

GLD



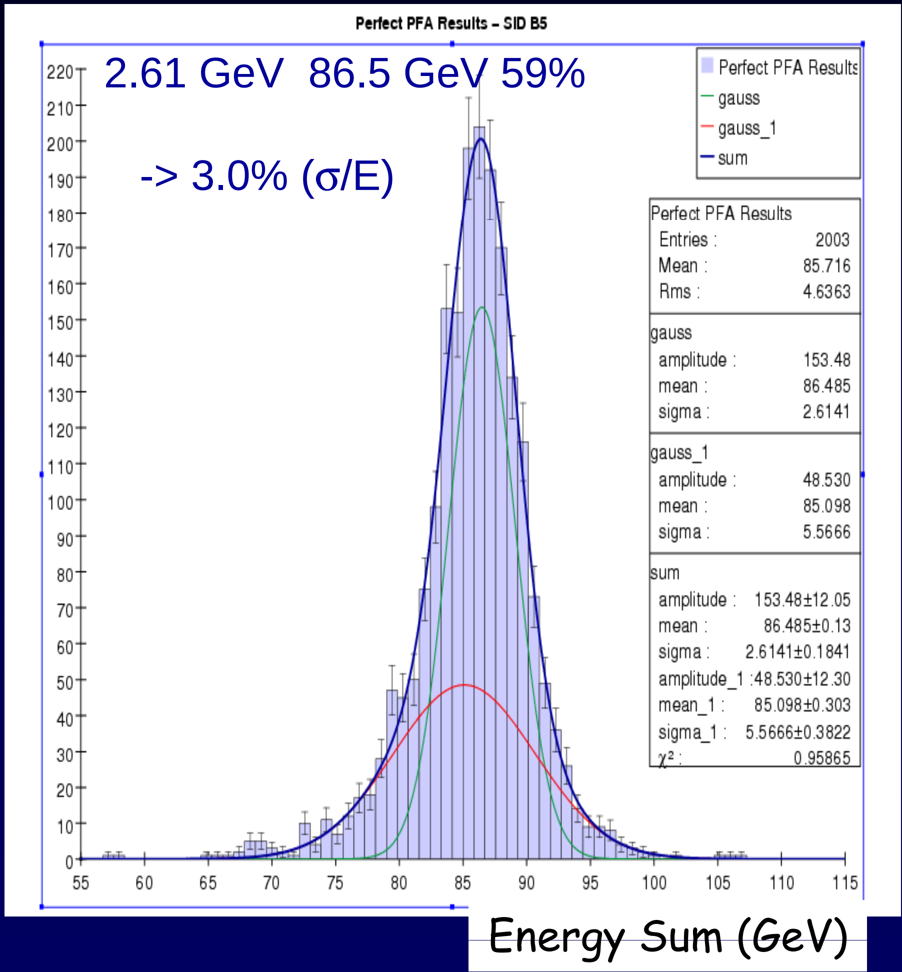
3 Tesla B-field
TPC Tracking
W/Scin ECAL, IR = 210 cm
Pb/Scin Analog HCAL

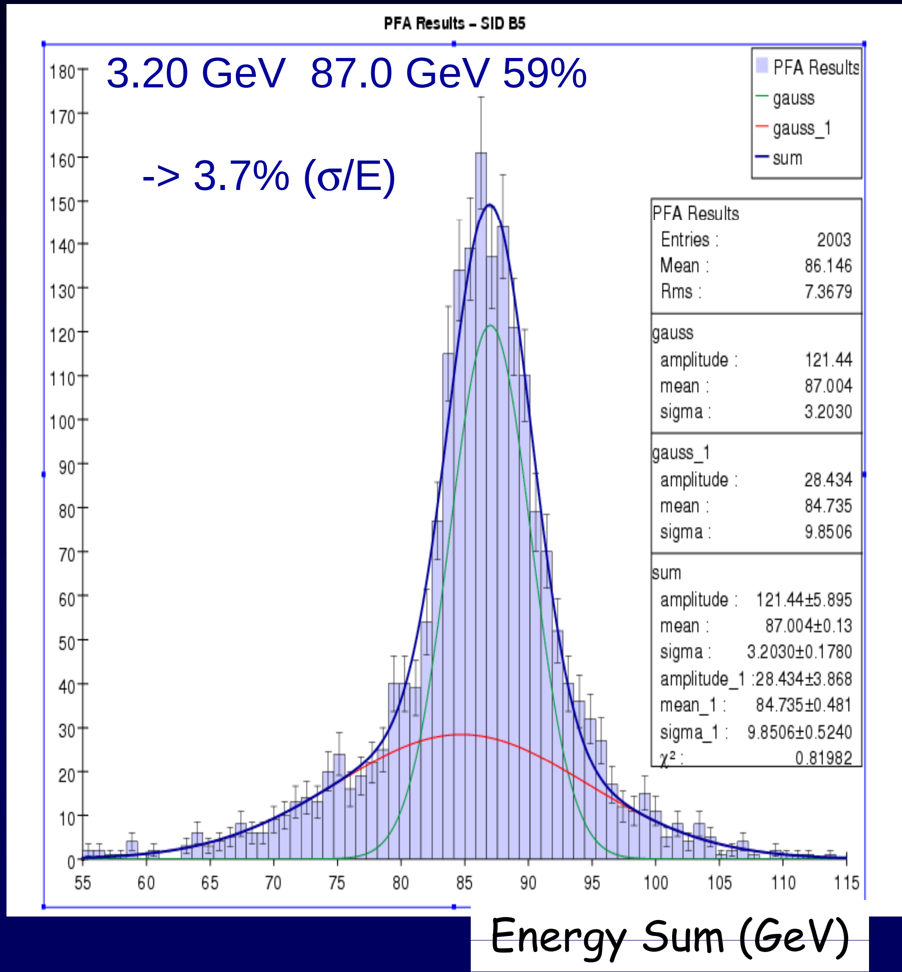
Radius

Common features :
Large B-field (3-5 Tesla) with calorimeter inside
-> Suppresses beam backgrounds in detector
-> Separates charged hadrons
State-of-the-Art tracking (TPC, Si-Strips)
Dense (W), fine-grained (Si pixels, Scin strips) ECAL
Highly granular and segmented HCAL (SS, Pb, W)
digital (gas) and analog (scintillator) readouts
Muon Systems outside of coil

PFA Results at Z Pole in SiD

SiD SS/RPC HCAL

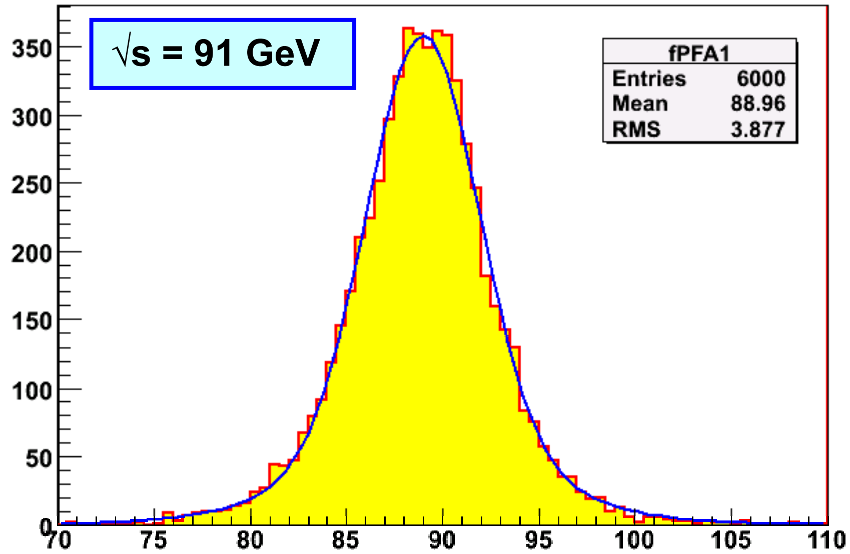




Average total confusion contribution = 1.9 GeV (central peak)
<~ Neutral hadron resolution contribution of 2.2 GeV (Perfect PFA)

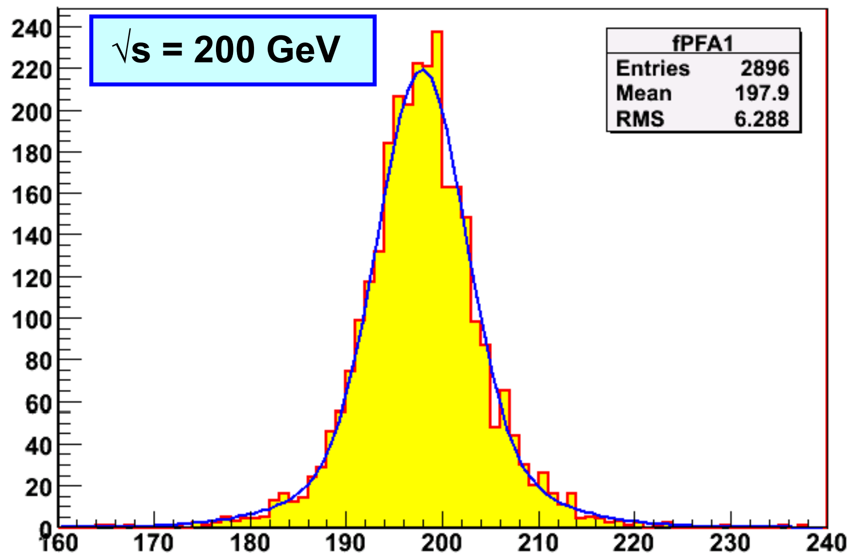
PFA Results on qqbar

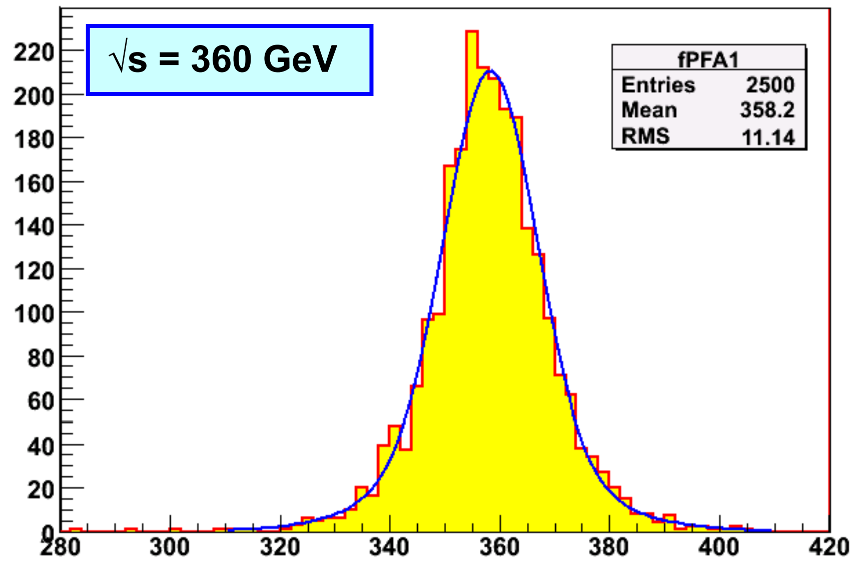
LDC SS/Scin HCAL



E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\|\cos\theta\|<0.7$
45 GeV	0.295
100 GeV	0.305
180 GeV	0.418
250 GeV	0.534

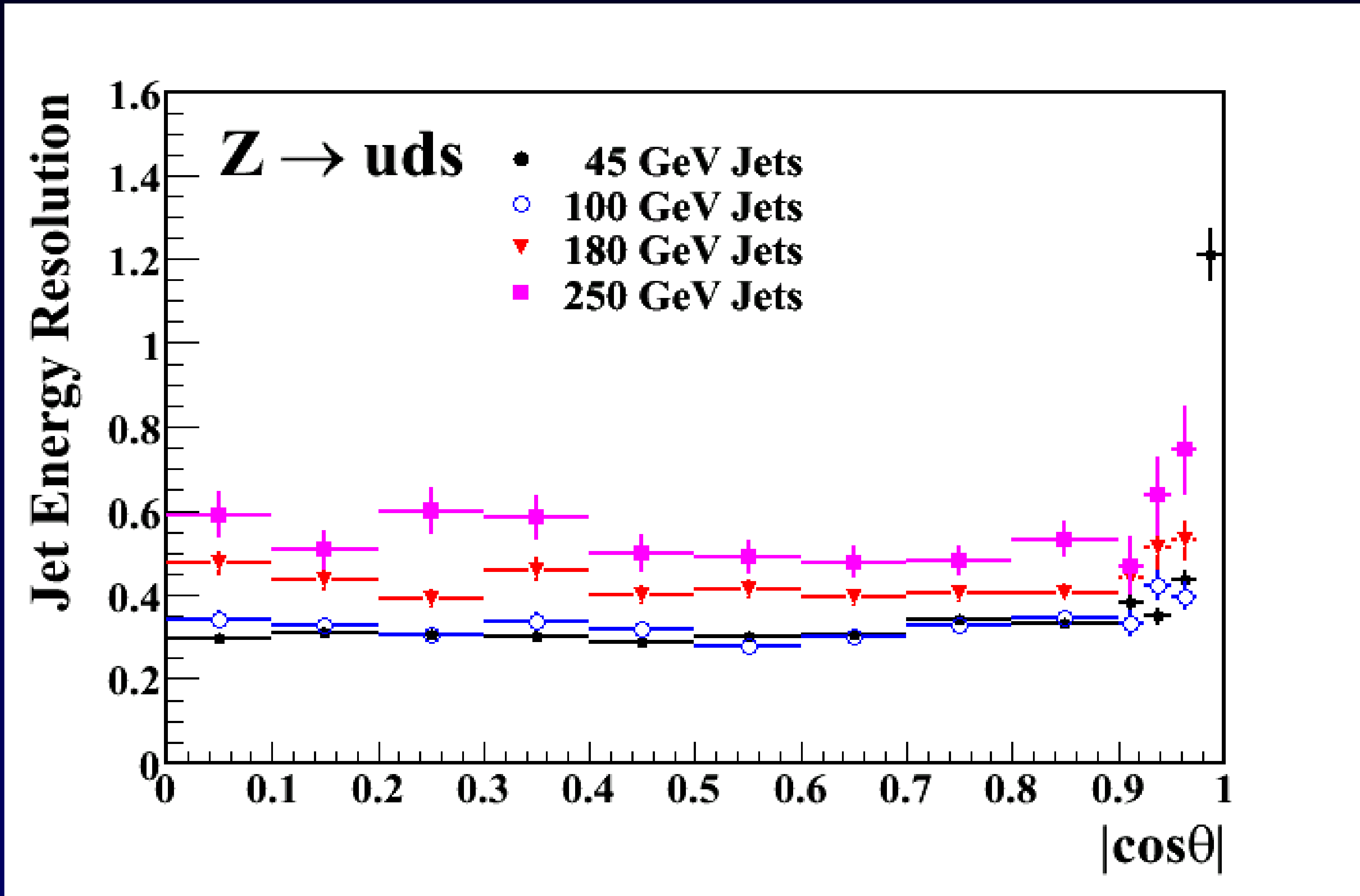
rms90





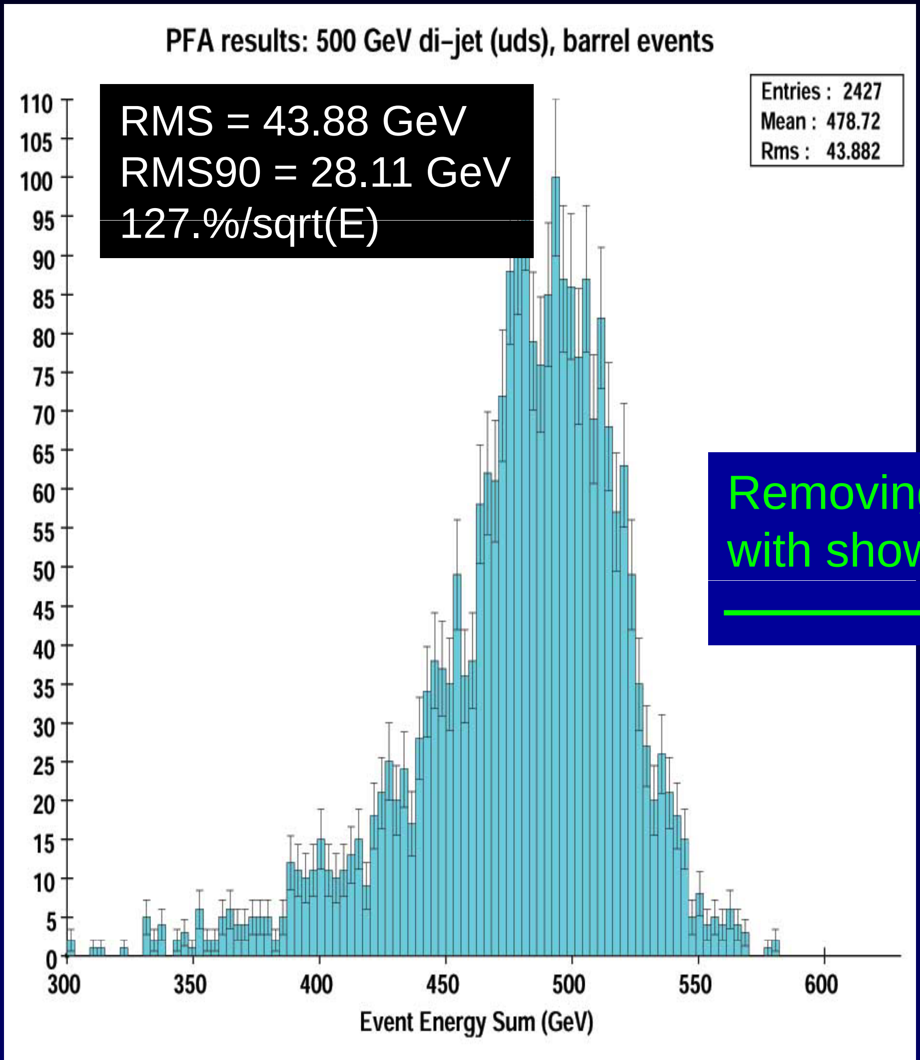
PFA Results - Angular Dependence

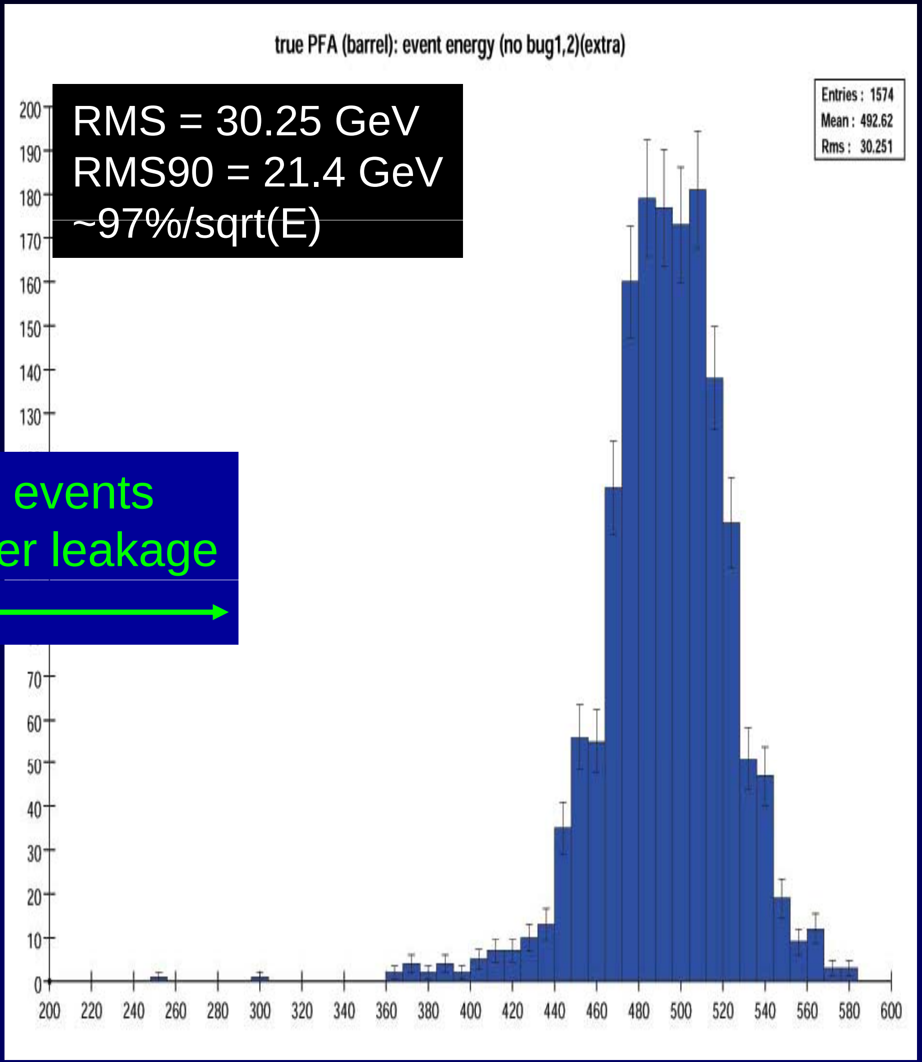
LDC SS/Scin HCAL



- Fairly flat until beam pipe affects result
- Evidence for shower leakage at $\cos\theta = 0$?

PFA Results : Central (Barrel) Results for qqbar





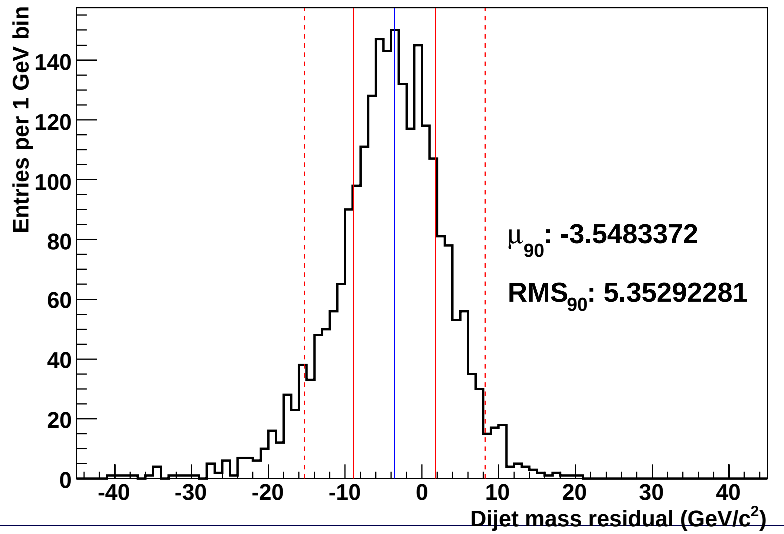
Removing events with shower leakage

- Shower leakage affects PFA performance at high energy
- Use hits in the muon detectors to estimate shower leakage?

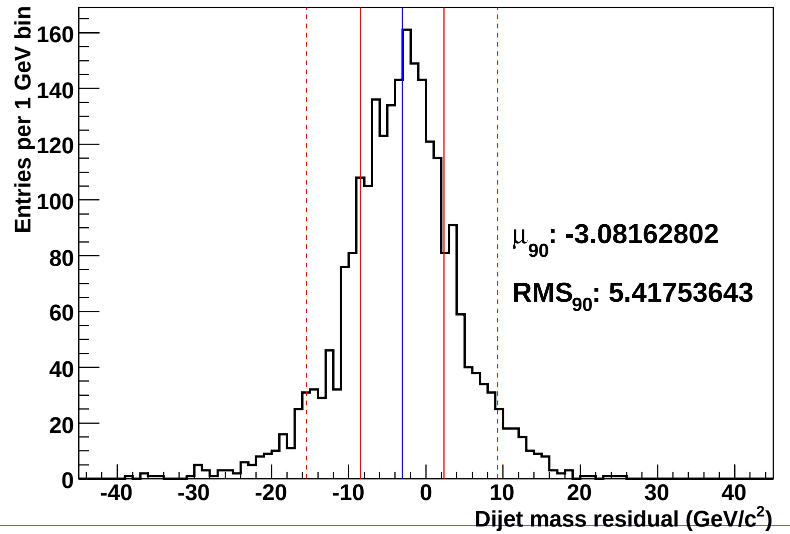
SiD SS/RPC HCAL

PFA Results : Dijets from e^+e^- -> ZZ at 500 GeV

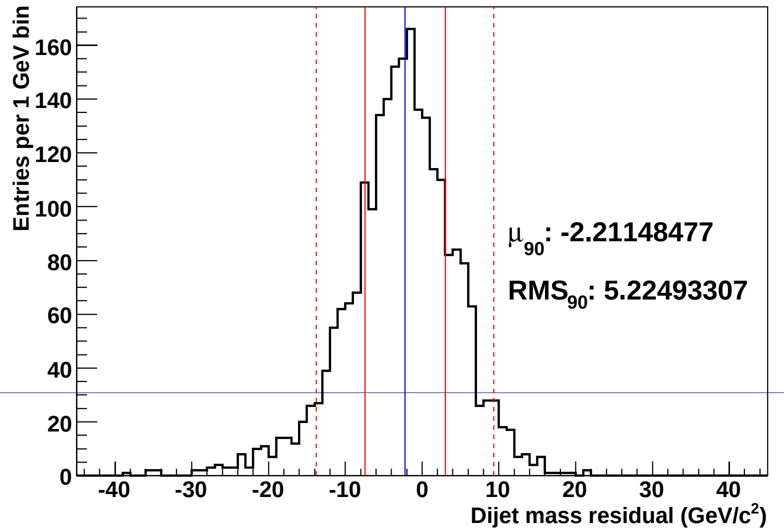
SiD W/Scin HCAL



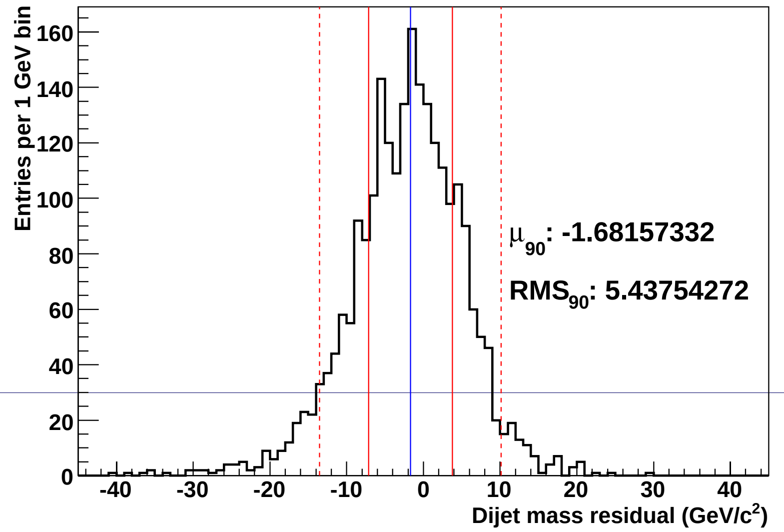
SiD W/RPC HCAL



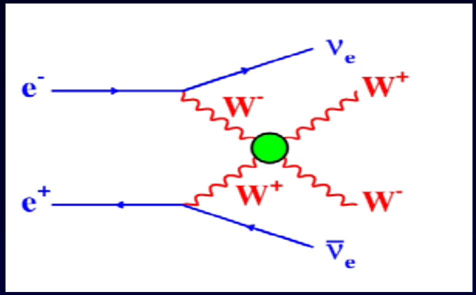
SiD SS/Scin HCAL

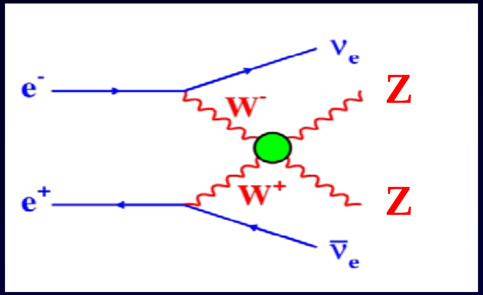


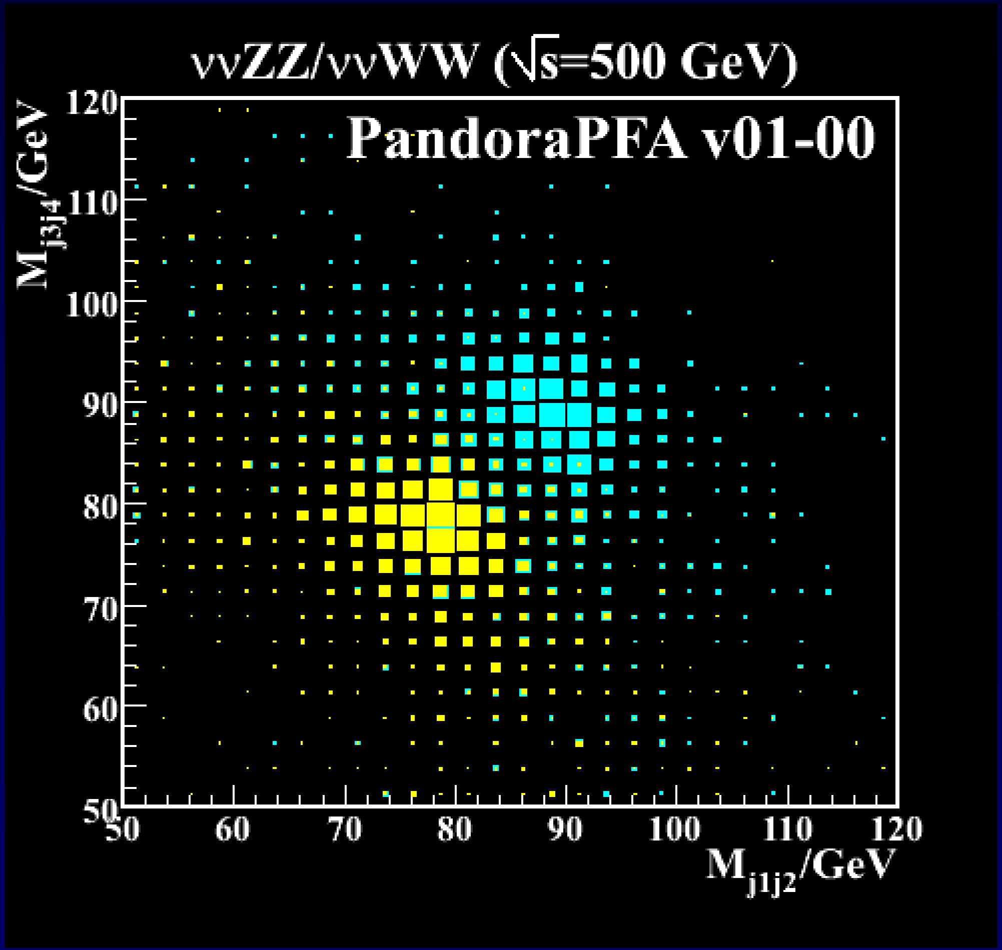
SiD SS/RPC HCAL

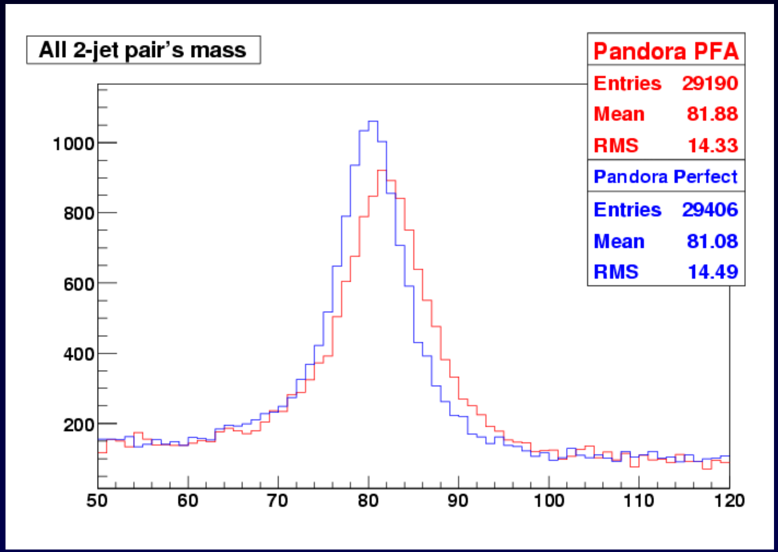


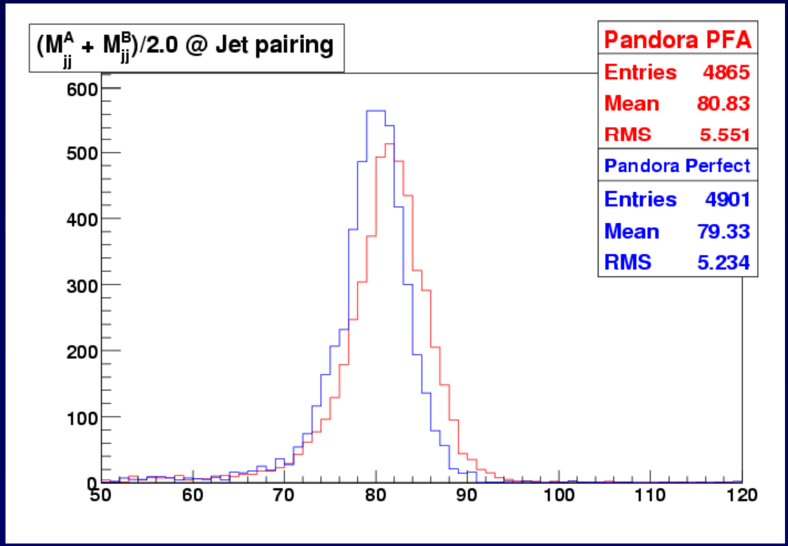
W,Z Separation in Physics Events with PFA











LDC SS/Scin HCAL

Detector Optimization Studies with PFAs

Ultimately : Optimise performance vs. cost

★ **Main questions (the major cost drivers):**
- **Size : performance vs. radius (IP to ECAL)**
- **Granularity (longitudinal/transverse): ECAL and HCAL**
- **B-field : performance vs. B**

★ **To answer them use MC simulation + PFA algorithm**
- **Need a good MC simulation**
- **Need realistic PFA algorithm**
  (*want/need results from multiple algorithms*)

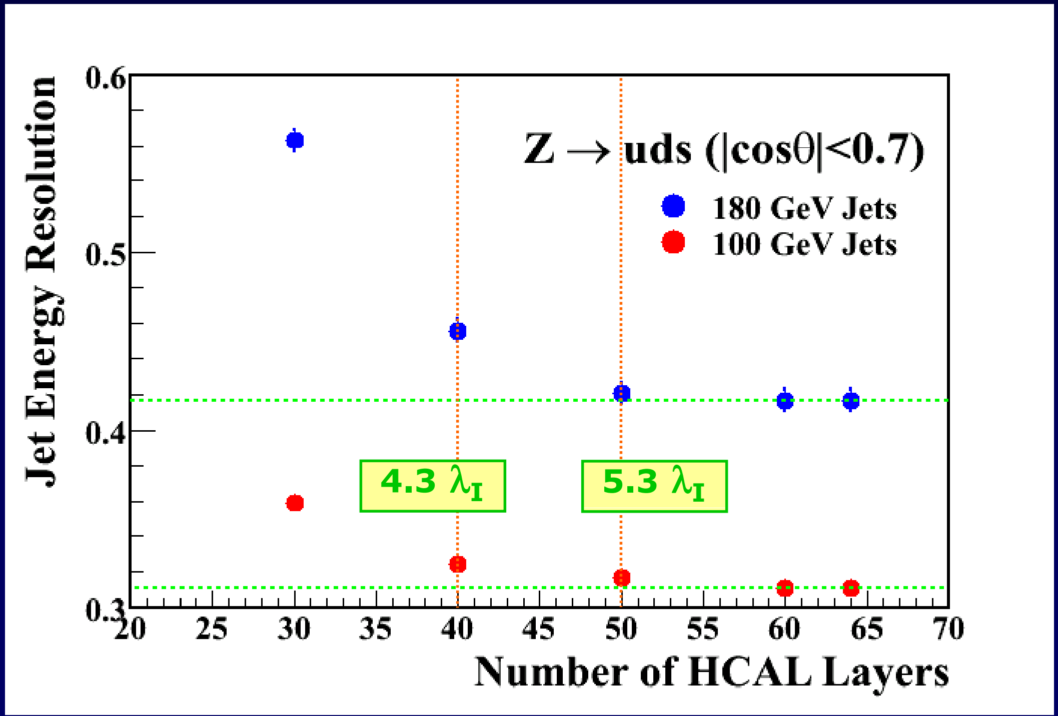
Developed PFA Template -> interchange of PFA code

Caveat Emptor

★ **These studies are interesting but not clear how seriously they should be taken**
- **how much is due to the detector**
- **how much due to imperfect algorithm**

HCAL Depth and Transverse segmentation

- Investigated HCAL Depth (interaction lengths)
  - Generated $Z \rightarrow uds$ events with a large HCAL (63 layers)
    - approx 7 λ_I
  - In PandoraPFA introduced a configuration variable to truncate the HCAL to arbitrary depth
  - Takes account of hexadecagonal geometry

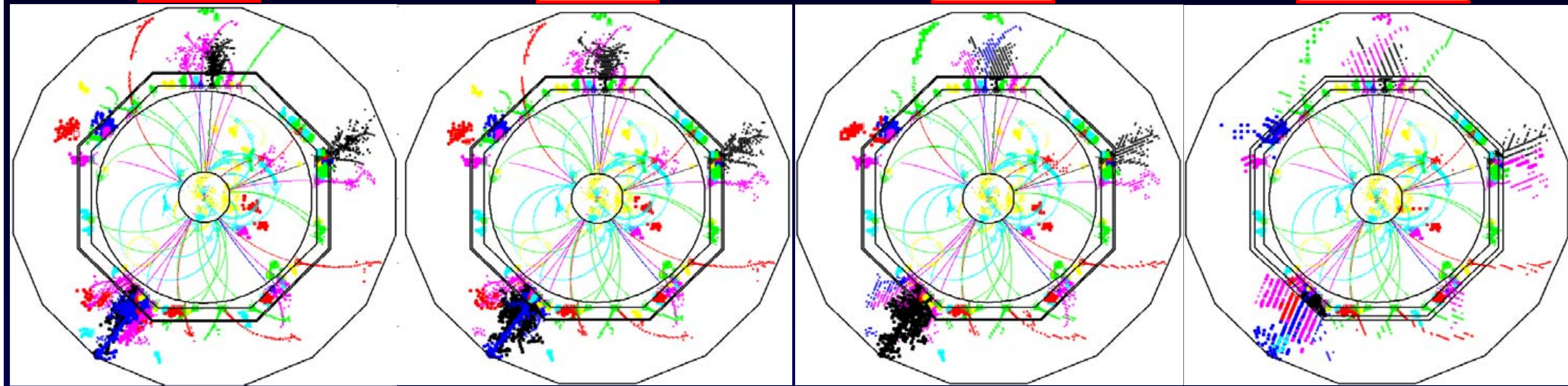


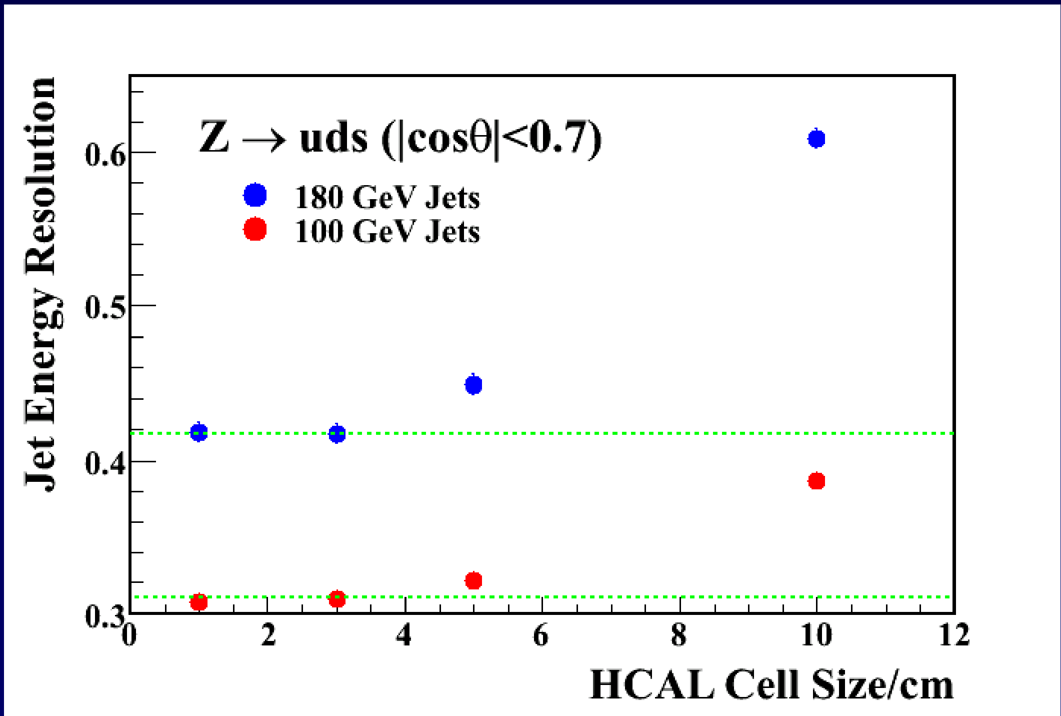
- HCAL leakage is significant for high energy
- Argues for ~ 5 λ_I HCAL

NOTE: no attempt to account for leakage – i.e. using muon hits - this is a worse case

✶ Analogue scintillator tile HCAL : change tile size 1x1 → 10x10 mm^2

1x1 | 3x3 | 5x5 | 10x10





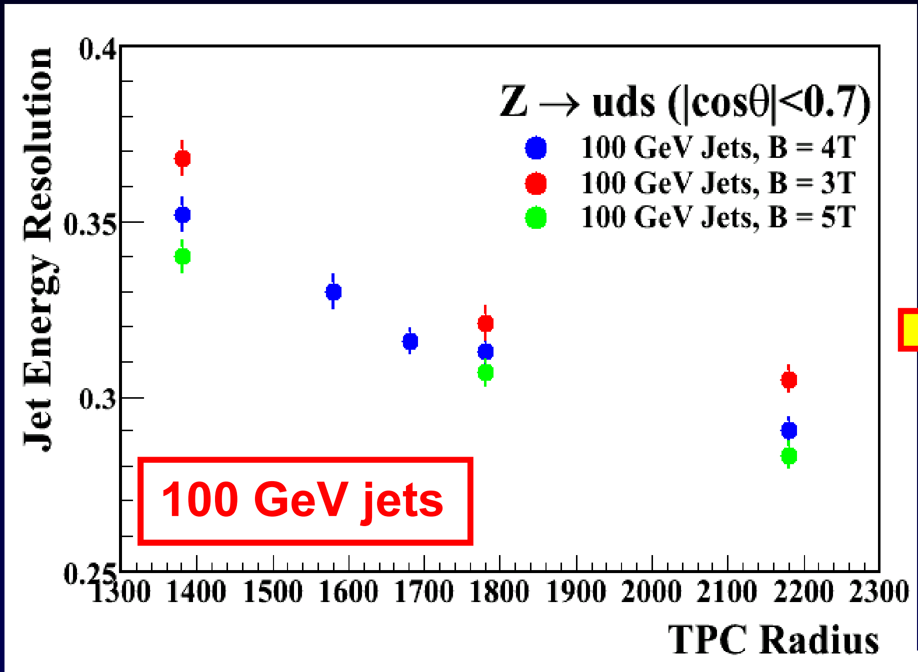
"Preliminary Conclusions"

- 3x3 cm^2 cell size
- No advantage → 1x1 cm^2
  - physics ?
  - algorithm artefact ?
- 5x5 cm^2 degrades PFA
  - Does not exclude coarser granularity deep in HCAL

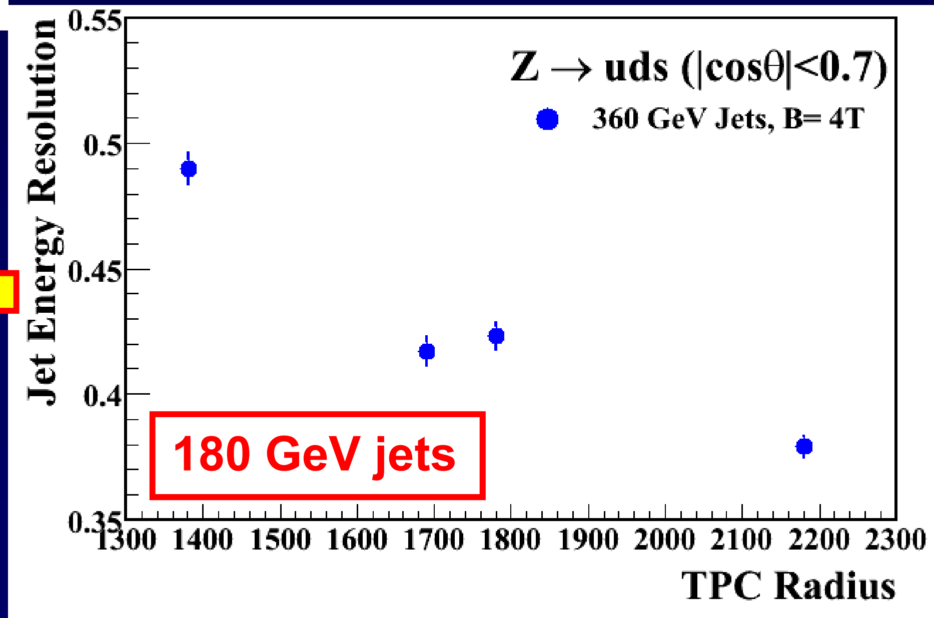
LDC SS/Scin HCAL

PFA Results : CAL Radius and Detector B-field

LDC SS/Scin HCAL



Radius more important than B-field



Radius more important at higher energies

B-field studies on the way…

Simulations and Test Beams

PFA + Full Simulations -> LC detector design

- new and unique approach to calorimeter design
- requires reconstruction of single particles, BUT in the context of jets
    - -> particle fragmentation in cal layers (Hadron Shower Models)
    - -> fluctuations in parton hadronization (QCD)
- relies on correct! simulation of individual hadron showers

  AND
- proximity with other simulated particles in a QCD jet

Test Beam Contributions to Simulation :

1) Shower Model Comparisons – formation of G4 Physics List
“thick” target data – *CAL prototypes*

2) Shower Model Tuning
“thin” target data – particle production diff cross sections vs E, angle, etc. – dedicated experiment – *MIPP (Fermilab)*

Correct simulation of hadron showers ultimately requires 2)

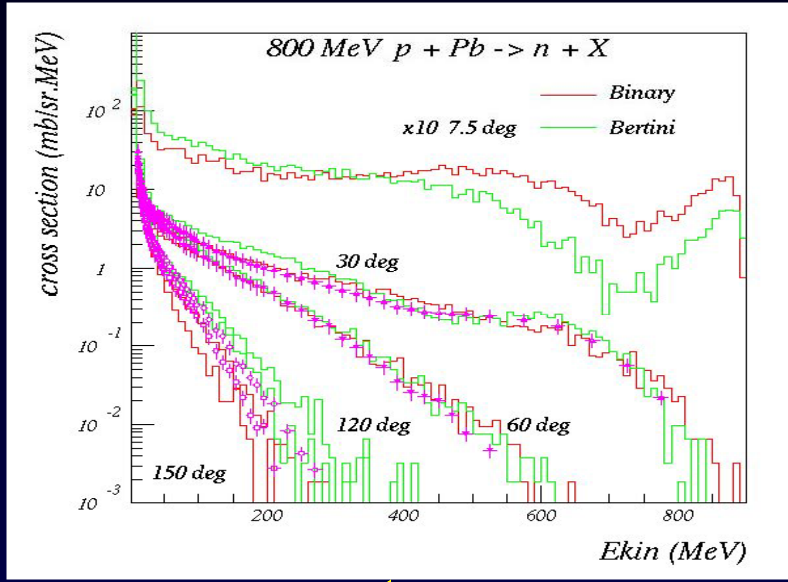
Hadron Shower Models - Cal Prototypes in Test Beams

LCPhys vs LHEP in G4

LCPhys – Bertini Cascade Model

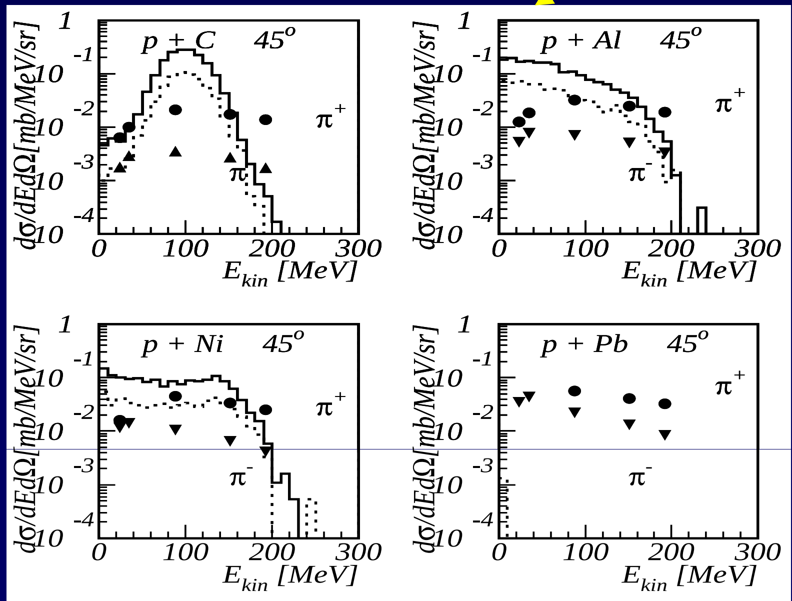
LHEP – Phenom Models, LEP

	LCPhys	LHEP
π+/-	Bertini Cascade 0-9.9 GeV LEP 9.5-25 GeV QGSP 12 GeV – 100 TeV	G4LEPion+/-Inelastic 0-55 GeV G4HEPion+/-Inelastic 25-100 TeV
p	Bertini Cascade 0-9.9 GeV LEP 9.5-25 GeV QGSP 12 GeV – 100 TeV	G4LEProtonInelastic 0-55 GeV G4HEProtonInelastic 25-100 TeV
pbar	LEP 0-25 GeV QGSP 20 GeV – 10 TeV	LEP 0-25 GeV HEP 20 GeV – 100 TeV
KL0	Bertini Cascade 0-13 GeV QGSP 12 GeV – 100 TeV	G4LEKaonZeroLInelastic 0-25 GeV G4HEKaonZeroInelastic 20-10 TeV
n	Bertini Cascade 0-9.9 GeV LEP 9.5-25 GeV QGSP 12 GeV – 100 TeV	G4LENeutronInelastic 0-55 GeV G4HENeutronInelastic 25-100 TeV
nbar	LEP 0-25 GeV QGSP 12 GeV – 10 TeV	LEP 0-25 GeV HEP 20 GeV – 100 TeV



Cascade Models

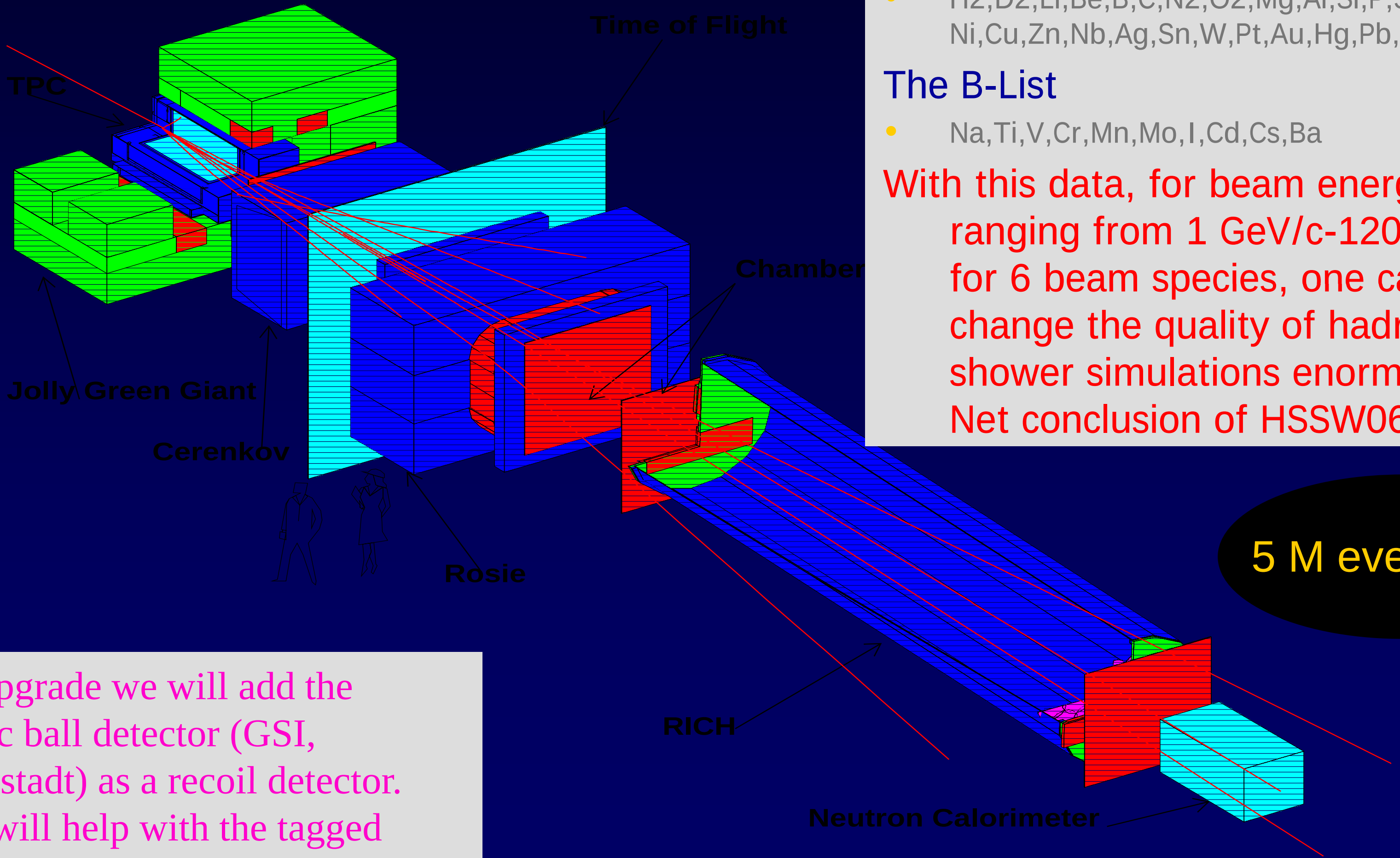
LEP



Hadron Shower Model Tuning – MIPP Upgrade

MIPP

Main Injector Particle Production Experiment (FNAL-E907)



The A-List

- H2,D2,Li,Be,B,C,N2,O2,Mg,Al,Si,P,S,Ar,K,Ca,Fe, Ni,Cu,Zn,Nb,Ag,Sn,W,Pt,Au,Hg,Pb,Bi,U

The B-List

- Na,Ti,V,Cr,Mn,Mo,I,Cd,Cs,Ba

With this data, for beam energies ranging from 1 GeV/c-120 GeV/c for 6 beam species, one can change the quality of hadronic shower simulations enormously—Net conclusion of HSSW06.

5 M events/day

For upgrade we will add the plastic ball detector (GSI, Darmstadt) as a recoil detector. This will help with the tagged neutrons

MIPP Experiment and Upgrade -Status

- MIPP E907 took data in 2005 is busy analyzing 18 million events—Results expected soon.
- MIPP Upgrade proposal P-960
  - was deferred in October 2006 till MIPP publishes existing data
  - Obtains new collaborators-(10 additional institutions have joined)
- MIPP Upgrade will speed up DAQ by a factor of 100 and will obtain data on 30 nuclei. This will benefit hadronic shower simulator programs enormously—See Dennis Wright’s talk at the ILC test beam workshop.
- MIPP Upgrade will provide tagged neutral beams for ILC calorimeter usage.

Tagged neutron and K-long beams in MIPP

The MIPP Spectrometer includes high statistics neutron and K-long beams generated on the LH2 target that can be tagged by constrained fitting

-> neutron and K-long momenta can known to better than 2%

-> energy of the neutron (K-long) can be varied by changing the incoming proton(K^+) momentum in the following reactions :

$$pp \rightarrow pn\pi^+$$

$$K^+p \rightarrow pK_L^0\pi^+$$

$$K^-p \rightarrow pK_L^0\pi^-$$

$$\overline{p}p \rightarrow \overline{n}\pi^- p$$

See R.Raja-MIPP Note 130.

Expected tagged neutral rates/day of running

Beam Momentum (GeV/c)	Proton Beam (# p/day)	K+ Beam (# K_L/day)	K- Beam (# K_L/day)	Antiproton Beam (# anti-n/day)
10	20532	4400	4425	6650
20	52581	9000	9400	11450
30	66511	12375	14175	13500
60	47069	15750	14125	13550

An expression of support from the ILC community will help speed up the approval process.

Summary

Jet reconstruction will be crucial to our understanding of physics at the ILC.

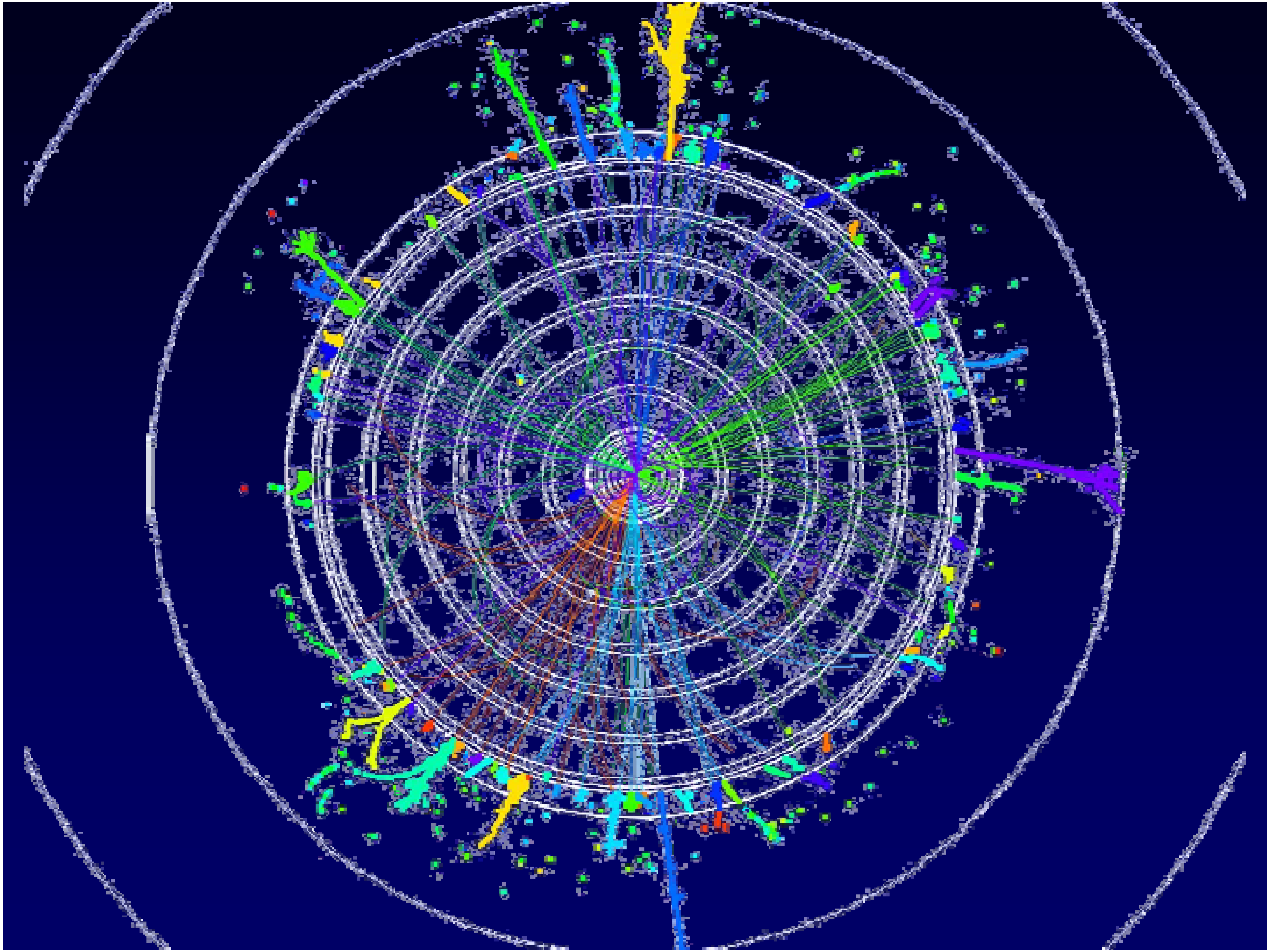
To live up to its potential as a precision instrument for the physics of the future, an ILC detector must include hadronic decays of massive particles in physics analyses as well as leptonic modes

-> The PFA approach to jet reconstruction is seen as a way to use the components of an ILC detector in an optimal way, achieving unprecedented mass resolution from dijet reconstruction.

PFA development is an R&D project itself, and much progress has been made in efforts parallel to the those in detector hardware.

PFAs are beginning to show that they do, indeed, result in much improved jet reconstruction for simulated events and jets that are expected at the ILC.

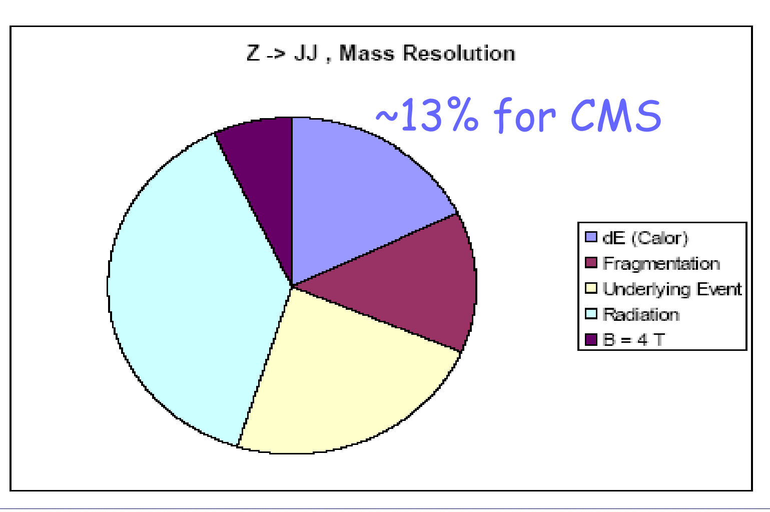
Dependencies on various detector parameters are now being studied, which will ultimately influence our choice of technologies for ILC detector component design – in particular the calorimeters.



Backup Slides

PFAs for LC Detectors?

Much "cleaner" environment for jets in e+e- collisions than in ppbar - at the LHC, jet E resolution is dominated by contributions from underlying events and final state gluon radiation



Without large UE and FSR contributions, CAL resolution dominates

-> An obvious goal – W/Z ID with dijet mass measurement?

Current calorimeters - $\sigma_M \sim 9$ GeV at Z-Pole

PFA potential improvement - $\sigma_M \sim 3$ GeV

-> in addition to leptonic decay modes, can use >80% of hadronic decays as well

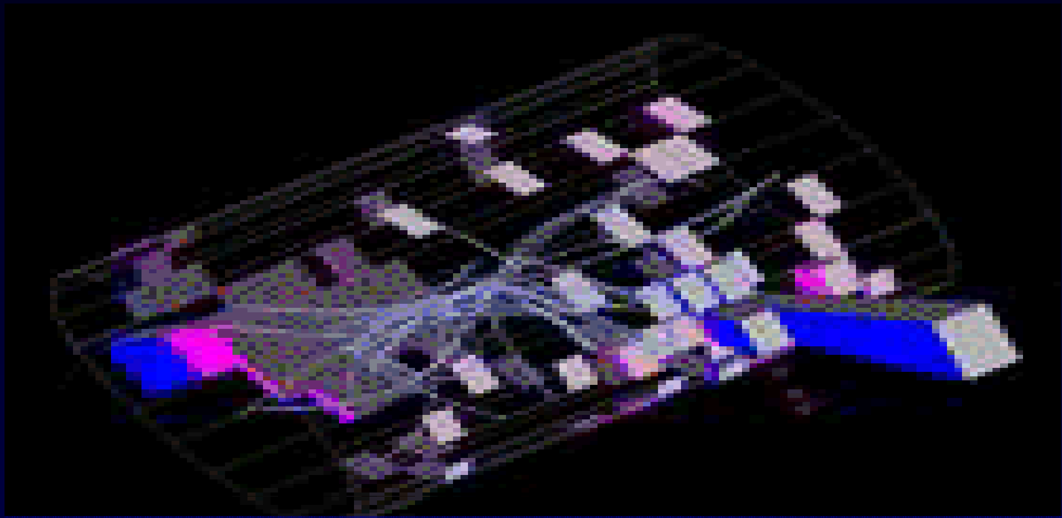
PFA vs Compensation?

Hardware compensation – for high energy particles (ZEUS $35\%/\sqrt{E}$ for π > ~3 GeV) but for jets resolution degrades.

Software compensation - requires knowledge of the particle type and/or particle energy, + reliance on shower and/or jet models

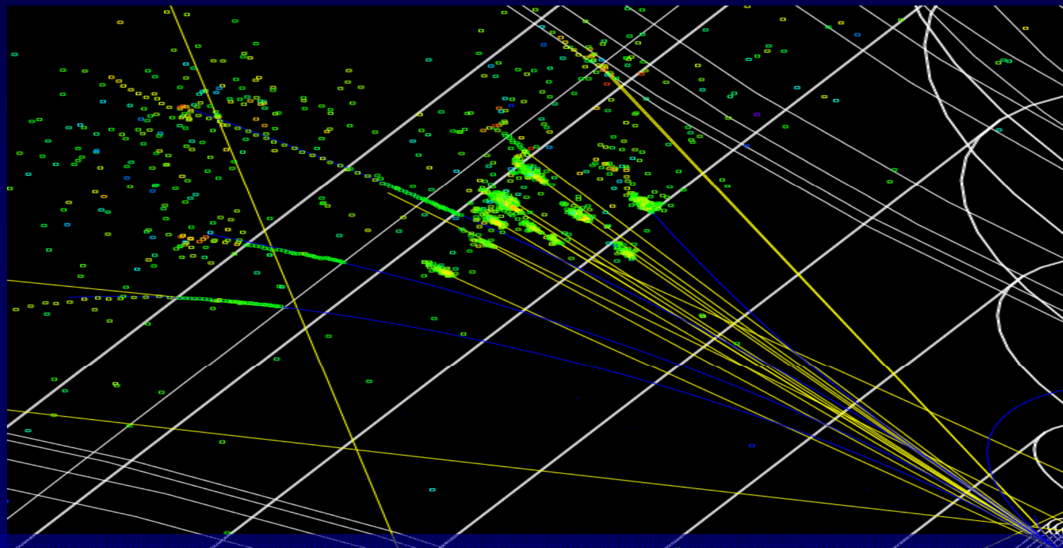
Particle Flow works as long as $\sigma_{\text{"mistakes"}} < \sigma_E$ of neutral hadrons (10%)

Dijet event in CDF Detector



ppbar -> qqbar -> hadrons + photons -> large calorimeter cells
traditional jet measurement

One jet in Z -> qqbar event in a LC Detector



Z -> qqbar -> hadrons + photons = small 3D cal cells
PFA jet measurement