Particle Flow Algorithm Performance

Mat Charles
The University of Iowa

Overview

- The why, what & how of PFA
- PFA implementations
- Some physics studies

Why are we studying PFA?

- What are our goals right now?
  - Establish that the baseline detector designs can do the physics
  - Understand which design choices have a big effect (dσ/d$)
  - Optimize detector designs for physics performance (given overall constraints)
  - ... leading up to the technology choices
- PFAs are a means to accomplish these goals.

What is the objective of PFA?

To produce lists of reconstructed final-state particles good enough to use in physics benchmarking & analysis without using generator truth information (cheating).

This immediately throws up questions:

- Physics benchmarking: Which channels? What figure of merit?
- Good enough: How good is that?
- Without cheating: What do we do in the meantime?
- Final-state particles: A whole other can of worms...
- How realistic does our detector model need to be? (e.g. readout digitization, noise, machine background, ...)

Assumptions strongly affect performance; different assumptions make it non-trivial to compare different PFAs.

Why multiple PFAs?

- In short: You can't factorize σ_{conf}(detector, algorithm)
- Comparisons of detector designs
  - In general, PFA tuned on one won't be optimal on another
  - This gets worse as PFAs become more sophisticated
  - Major retuning/recoding if detectors are very different
- Redundancy -- multiple approaches are healthy
  - It's not obvious what will work and what won't
  - Approaches that work well for one physics measurement may be lousy for another
  - ... but important to be willing & able to share ideas
- Incompatible code bases (sad but true)

What PFAs are there?

There are many:

In Europe:

- Mark Thomson (PandoraPFA)
- Alexei Raspereza (Wolf)
- Oliver Wendt (TrackBasedPFA)

In Asia:

- Tamaki Yoshioka et al

In North America:

- Mat Charles
- Steve Magill
- Lei Xia (Density-based)
- NIU (Directed tree)

... plus more components at various stages of integration:

- Photon finders and identifiers (e.g. H-matrix)
- Muon finders
- π^0 reconstruction
- Calibration
- Tools (e.g. DigiSim, template)
- ...

What is the current PFA performance?

Short answer:

- Most PFAs do OK at the Z-pole but have not yet been proven at higher energies.
- Major exception is PandoraPFA, which is excellent at Z-pole and scales moderately well to higher energies.

Longer answer: see upcoming slides...

How do we measure performance?

We can't want to run a full physics analysis for every incremental change -- use more-or-less standard shorthands instead:

- Energy sum for events with u/d/s jets (quoting rms_{90})
- Dijet mass residuals for $Z \rightarrow$ uu/dd/ss (quoting rms_{90})
- Caveats: differences in energy, $\cos\vartheta$ cut, missing E, ...

Current philosophy: $dm/m \sim dE_{jet}/E_{jet} \sim$ 3-4% will give adequate W/Z separation. But bear in mind:

- Energy sum ≠ dijet mass ≠ physics performance (beware especially error propagation with rms_{90})
- Risk of over-focusing on these and ignoring things that don't contribute much (e.g. b/c jets, muon ID, jet-finding...)

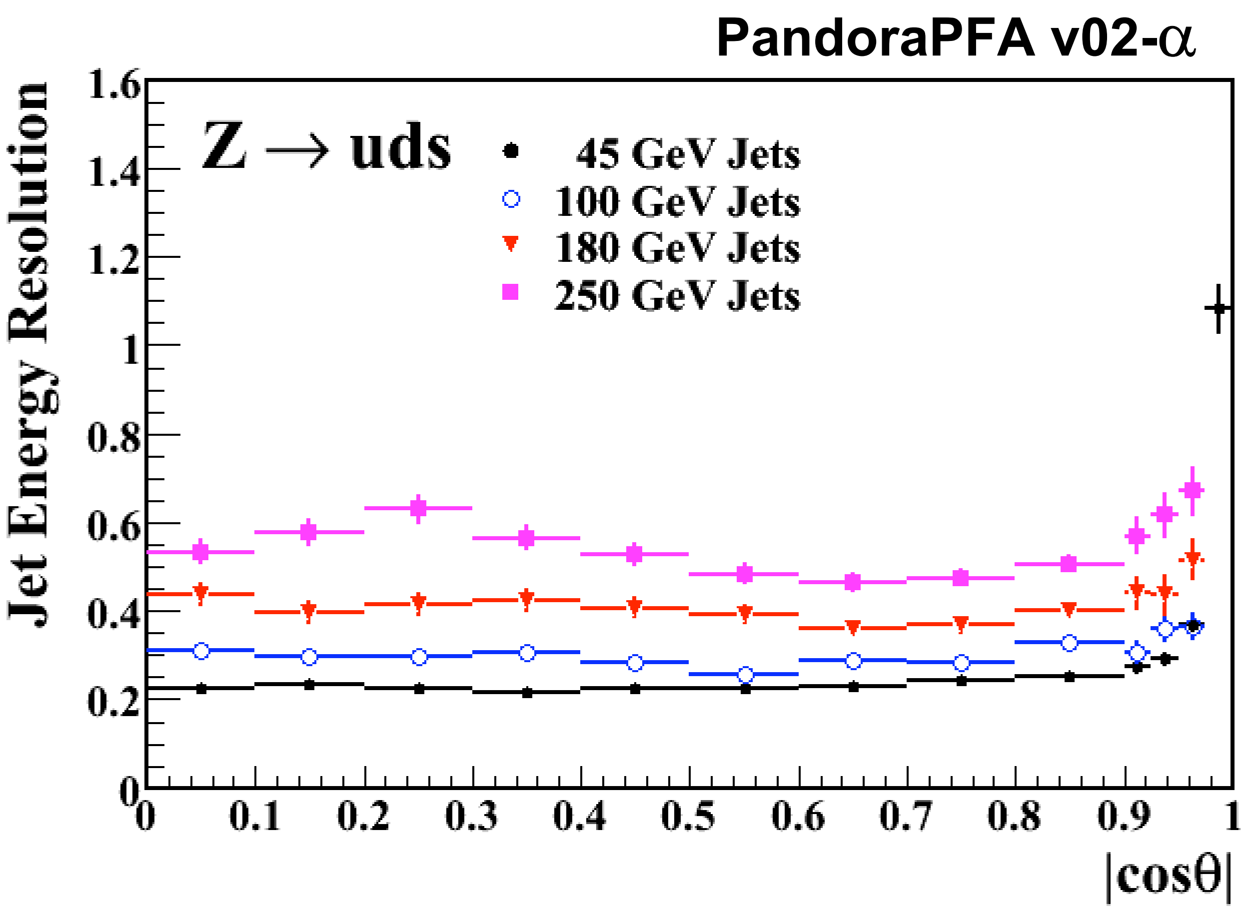
PandoraPFA

Mark Thomson (Cambridge)

A detailed and highly tuned algorithm that uses several clustering steps looking at internal topology of showers, well-known and beloved by all. Results shown for LDC00.

PandoraPFA v02-α

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.227	3.4 %
100 GeV	0.287	2.9 %
180 GeV	0.395	2.9 %
250 GeV	0.532	3.4 %



Excellent performance at low E, approaching perfect pattern recognition. Decent at high E, but Mark aims to do better.

PandoraPFA

Mark Thomson (Cambridge)

Older version of code than shown on previous slide

Configuration	n/sqrt(E)	Jet energy
LDC00Sc	30.5	45
LDC00Sc 5T	31.2	45
LDC00Sc 30 layer ECAL	32.4	45
LDC00Sc Sid-ish 4T	32.6	45
LDC00Sc Sid-ish 5T	32.0	45
LDC00Sc Sid-ish 6T	33.8	45
LDC00Sc	36.7	100
LDC00Sc Sid-ish 4T	42.7	100
LDC00Sc Sid-ish 5T	41.0	100
LDC00Sc Sid-ish 6T	39.8	100

Marcel Stanitzki **Errors ± 0.2-0.3**

100 GeV Numbers very preliminary

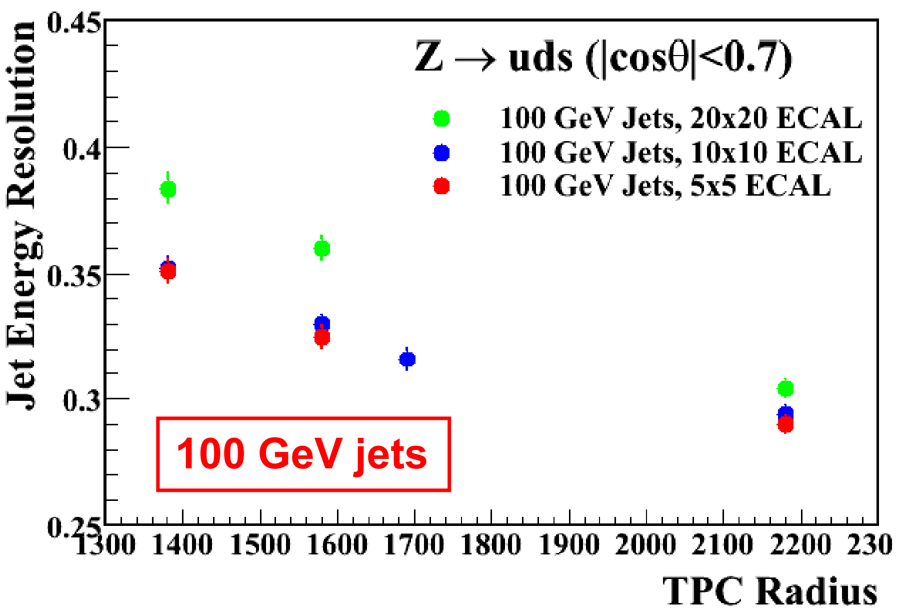
What about other detector configurations?

[Careful: not tuned for these!]

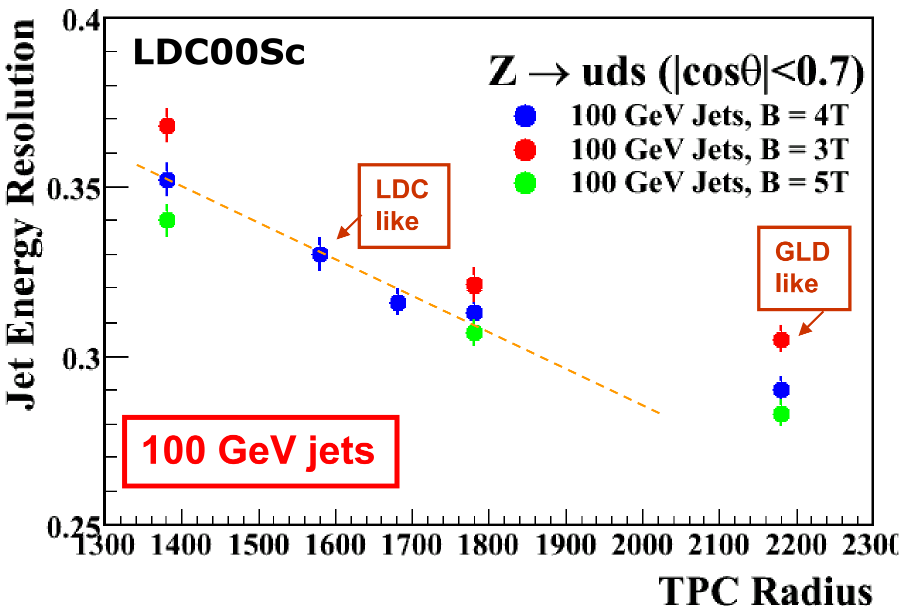
Results look reasonable at nearby points in parameter space, at least for $E_{jet} \lesssim 100$ GeV.

(In particular, LCD-style detector with 125cm ECAL radius + 5T B-field at Z-pole approaches 30%/√E.)

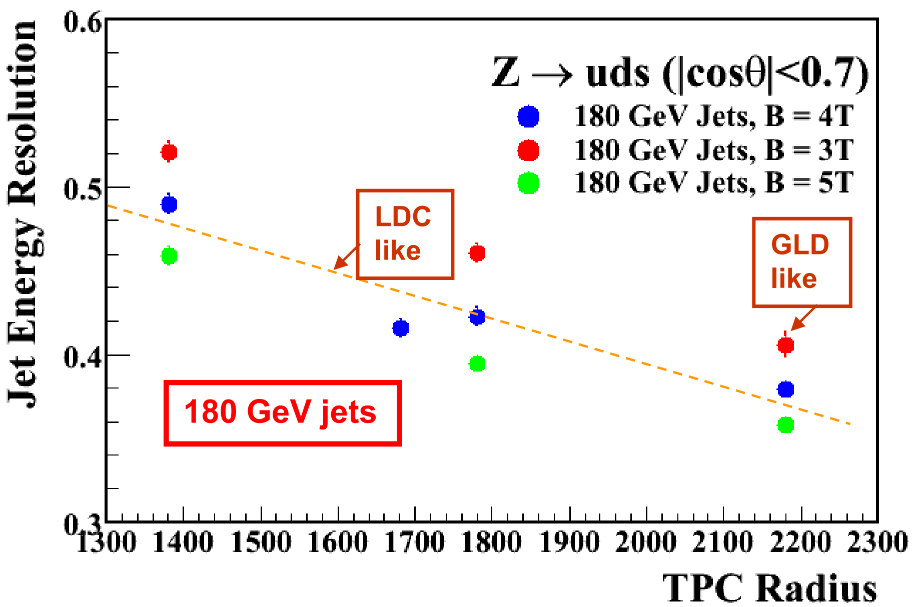
Mark Thomson



Varying ECAL segmentation



Varying geometry (100 GeV)



Varying geometry (180 GeV)

Round-up of other PFAs

Table idea stolen from Lei Xia (ANL)

rms$_{90}$ of energy sum [GeV]

rms$_{90}$ of dijet mass residuals [GeV]

PFA/Group	Detector	uds dijet 91 GeV	uds dijet 200 GeV	uds dijet 360 GeV	uds dijet 500 GeV	ZZ 500 GeV
PandoraPFA	LDC00	2.2	4.1	7.5	11.9	
Wolf	LDC00	5.1				
TrackBasedPFA	LDC00	3.9				
ANL(1)+SLAC	SiD	3.2/9.9 [dbl gaus]				
ANL(2)	sidaug05_np	3.3	9.1		27.6	
Iowa	sid01					5.6
NIU	sidaug05_tcmt	3.9/11.0 [dbl gaus]				
GLD	GLD	2.8	6.4	12.9	19.0	
Needed for dM/M = 3%		1.9	4.2	7.6	10.6	2.7
Needed for dM/M = 4%		2.6	5.7	10.2	14.1	3.6

Thoughts on performance

PFA is a hard problem. Implementations are improving but most are not there yet.

- PandoraPFA is in the best shape by far right now.
- Caution: As things get more realistic, you have to run just to stay in the same place.

Viability of PFA approach has been proven

- With PandoraPFA for LDC with cheated tracks
- ... and changing (r_{ECAL} to 125cm and B to 5T), for $E_{jet} \lesssim 100$ GeV [arguably 180]
- Expect $\sigma_{conf}(RPC) \lesssim \sigma_{conf}(Scint)$, but should verify.

Now we need to bring alternate PFAs up to the same performance level!

A word on detector benchmarking

There are three stages:

- First, achieve minimum acceptable performance on generic figure of merit with at least one PFA on baseline design. This validates that the concept is OK for physics.
- Second, vary the detector design within the region of parameter space for which the PFA is well-tuned (or can be returned), using generic figure of merit.
- Third, use a suite of full physics studies to see the real performance variation at a small number of points.

You cannot advance beyond step 1 until your PFA is performing very well. Otherwise you are tuning on the weaknesses of your algorithm rather than the strengths of your detector.

Physics studies

Now starting to see many real physics analyses comparing PFA outputs -- this is fantastic! I applaud both the trail-blazing analysts & the PFA developers.

Some recent studies (not exhaustive):

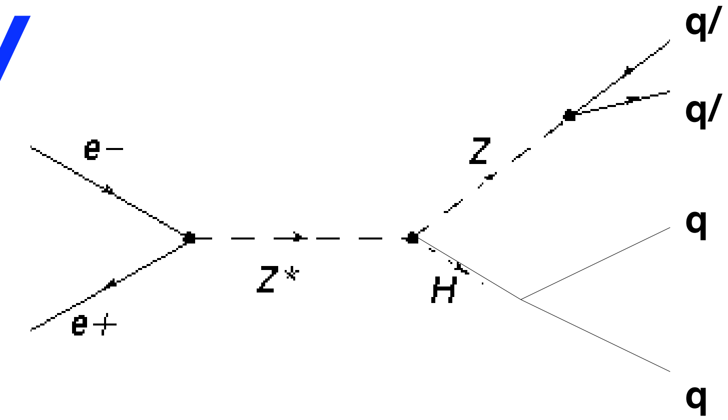
- Higgstrahluhng -- K. Wichmann (DESY)
- WW scattering -- W. Yan & D. Ward (Cambridge)
- ZZH -- M. Faucci Giannelli et al (RHUL)

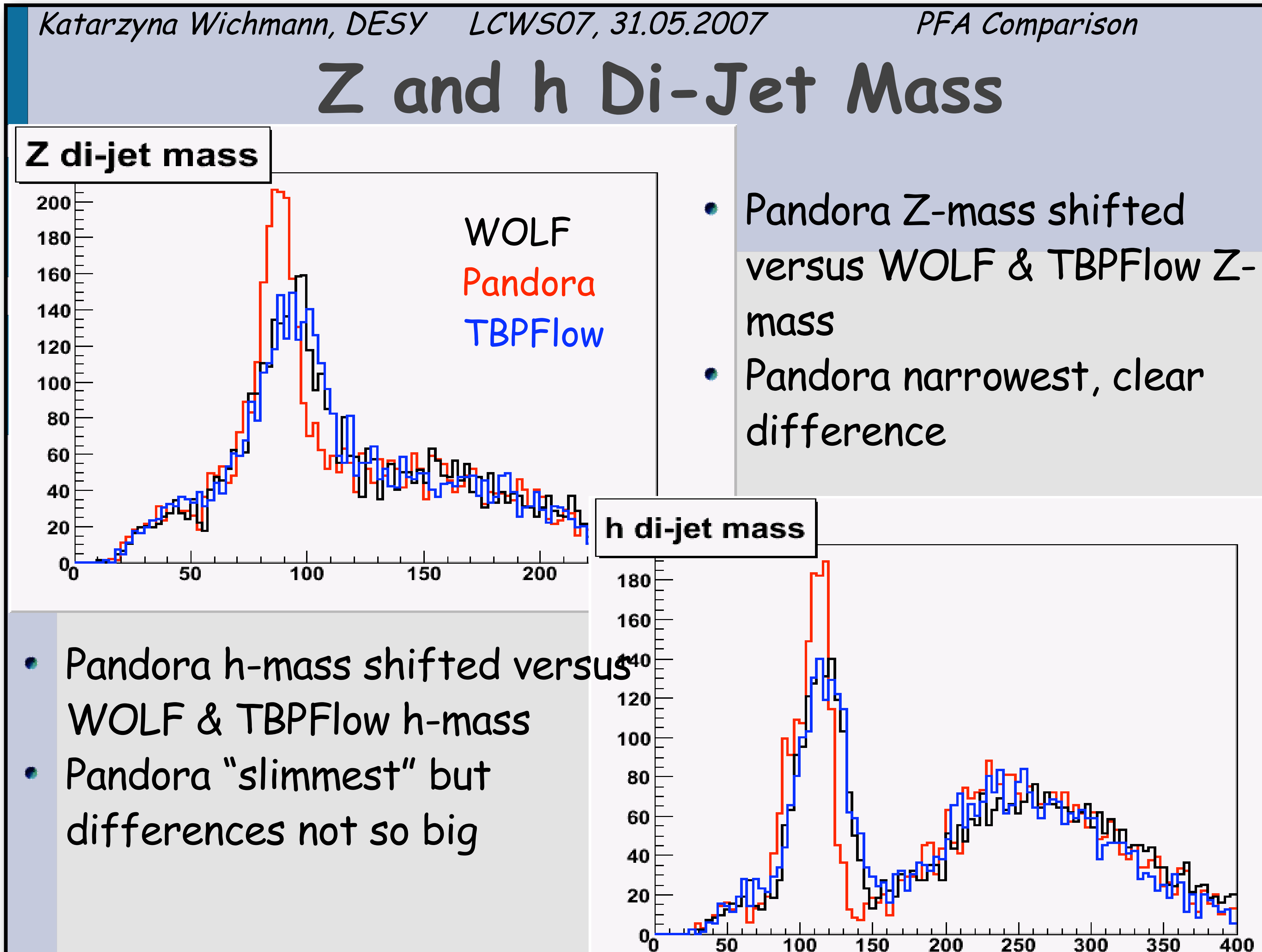
... and work on PFA output ongoing elsewhere too, e.g. H. Zhao (UMiss) + T. Barklow (SLAC).

Higgstrahlung study

Katarzyna Wichmann (DESY)

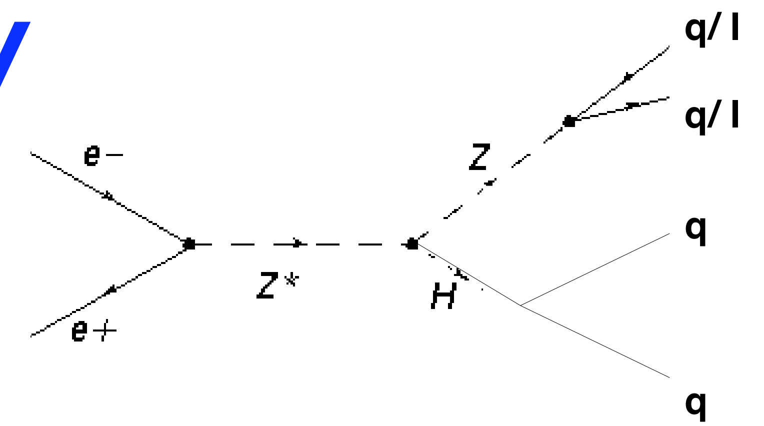
Shown here: $e^+e^- \rightarrow Z^* \rightarrow ZH, Z \rightarrow qq$,
$H \rightarrow qq$ [mostly bb], m_h = 120 GeV @ 500 GeV on LDC00





Higgstrahlung study

Katarzyna Wichmann (DESY)



Shown here: $e^+e^- \rightarrow Z^* \rightarrow ZH, Z \rightarrow qq,$
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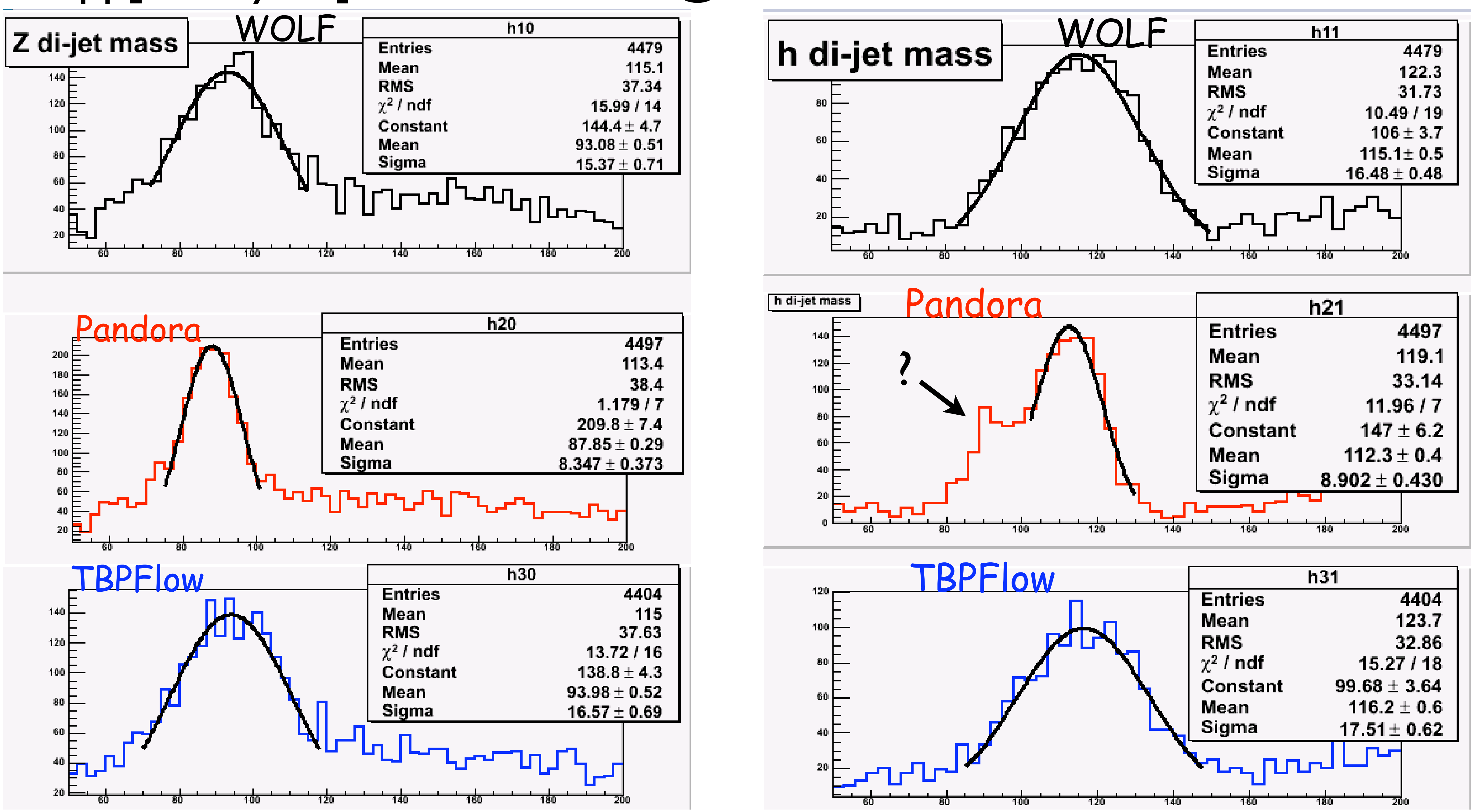


Resolution ~ 8-9 GeV for Pandora, 15-17 GeV for Wolf/TBP

WW scattering

Wenbiao Yen, David Ward (Cambridge)

PandoraPFA
Wolf
Perfect

See slides from CALICE UK meeting, 20 Sep for full details.

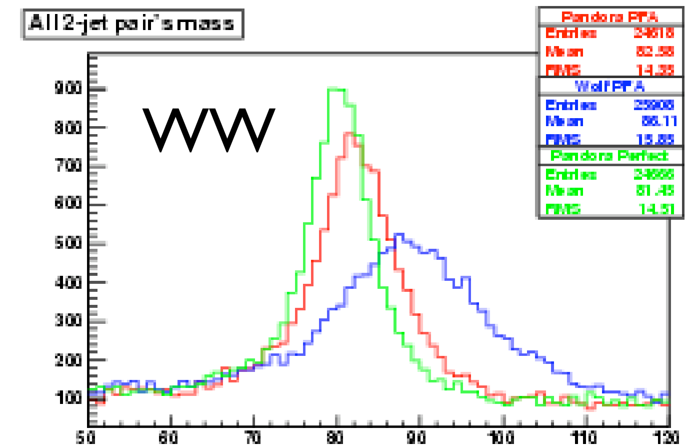
Very nice, detailed search for anomalous couplings α_4 & α_5 from EW chiral Lagrangian.

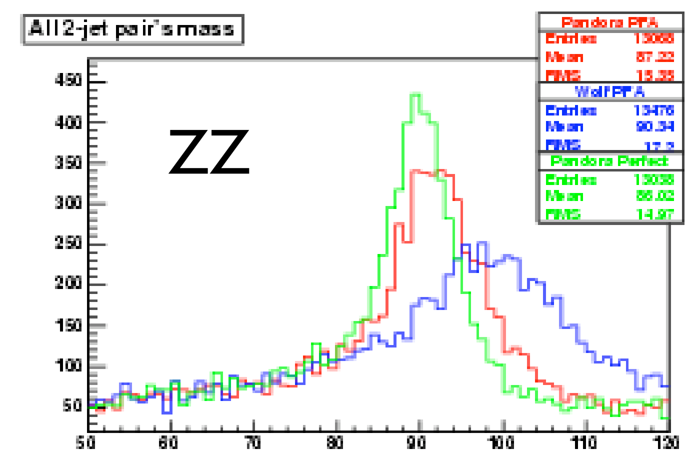
Uses cocktail of processes generated at 800 GeV with 40%/80% polarized beams, luminosity equivalent to 500 - 1000 fb^{-1}.

Event selection based on:

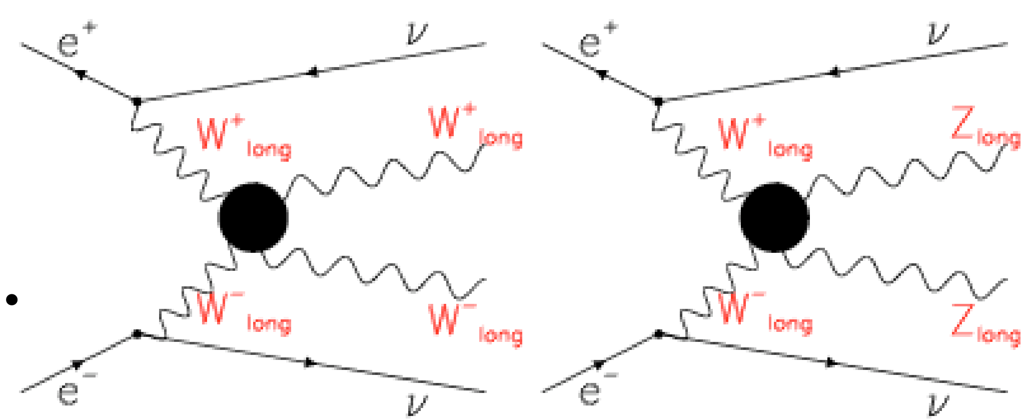
- large missing mass (neutrinos)
- significant visible transverse energy
- cuts on reconstructed W, Z mass

PandoraPFA & Wolf tested for selection; Pandora used for main analysis (next slide).



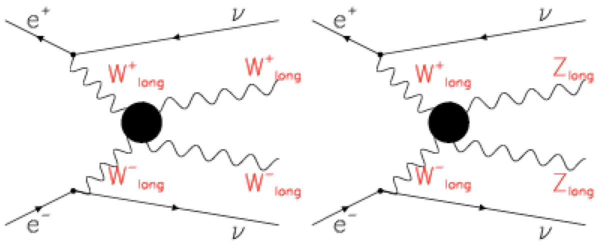


Signal events ($\nu\nu WW$, $\nu\nu ZZ$)



WW scattering

Wenbiao Yen, David Ward (Cambridge)

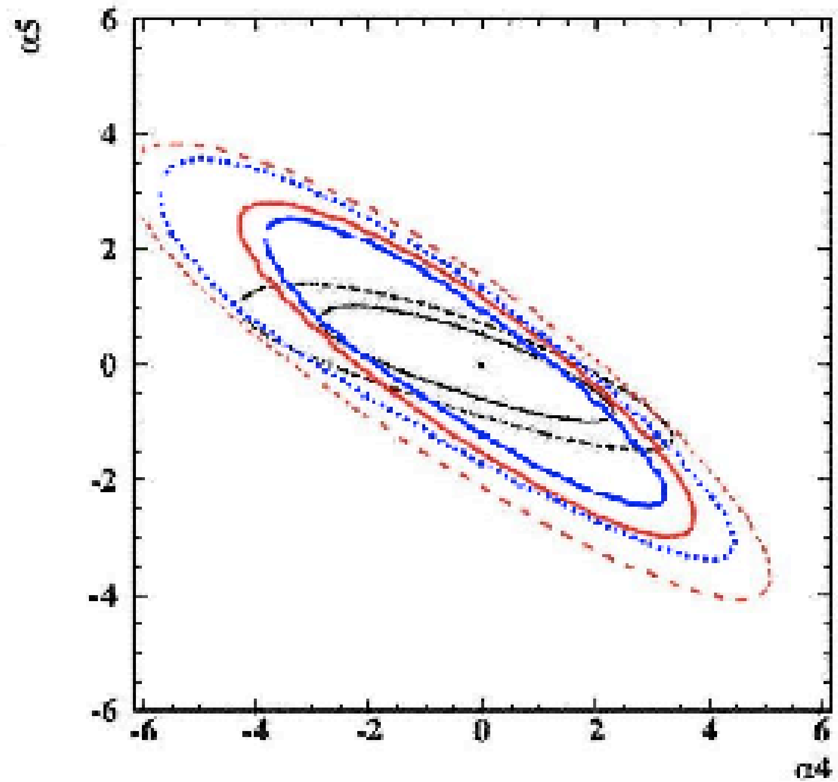


See slides from CALICE UK meeting, 20 Sep for full details.

Likelihood from combined WW/ZZ

Expected 1σ, 2σ contours on couplings if no signal for:

- Full analysis on PFA output
- Recent fast MC study



- **Blue: results on LDC00Sc detector model**
- **Red: Predrag Krstonosic's results @ LCWS 2005 on TESLA fast simulation**
- **Black: LC-PHSM-2001-038 on TESLA fast simulation**

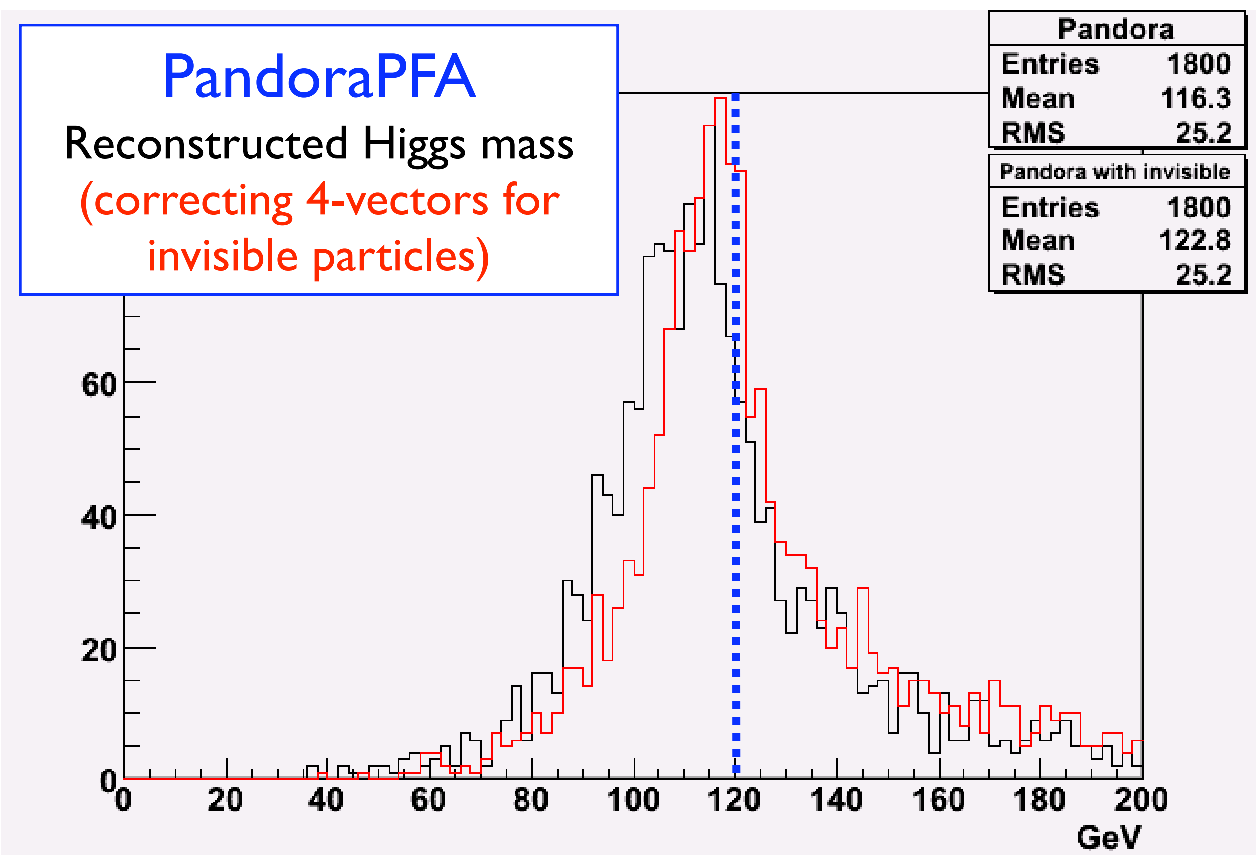
$e^+e^- \to ZHH$ study

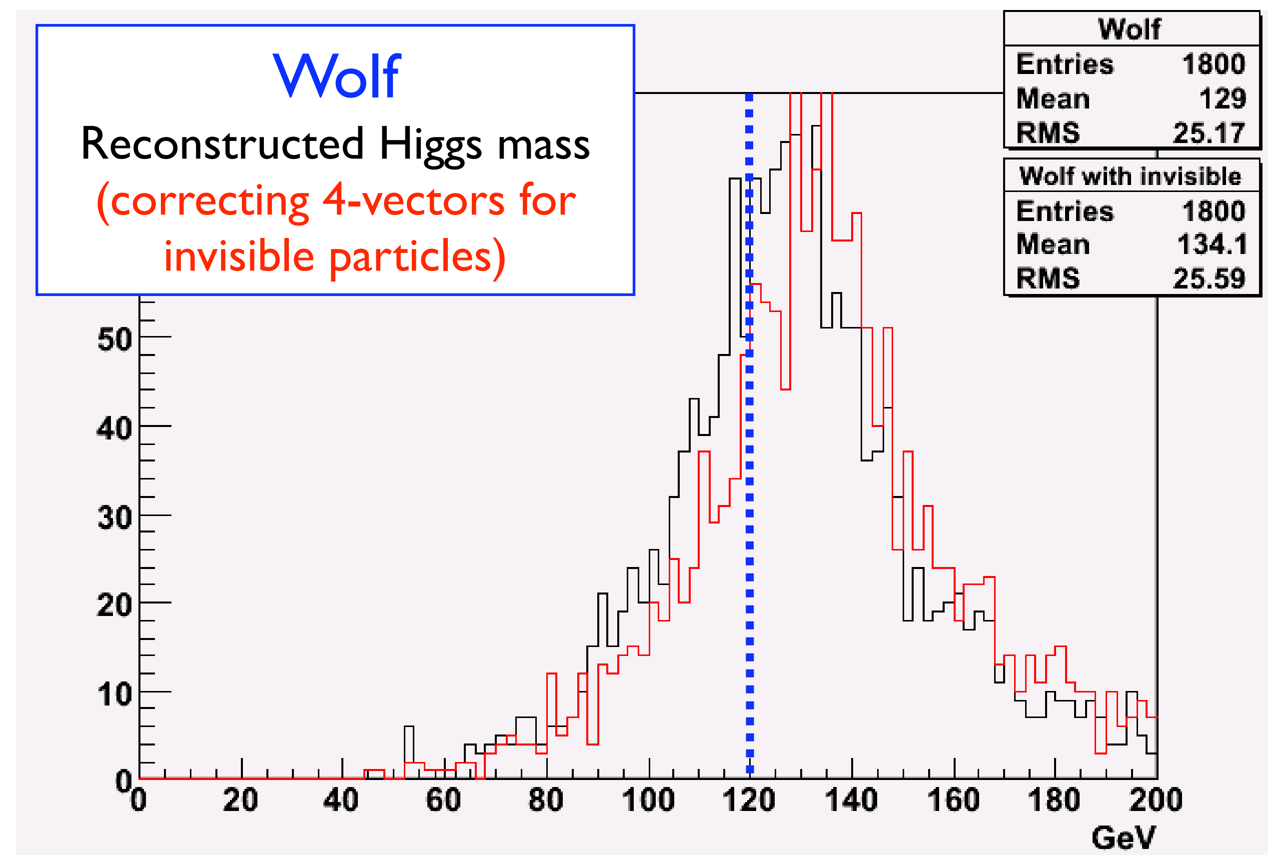
Michele Faucci Giannelli, Fabrizio Salvatore, Mike Green, Tao Wu (RHUL)

Looking at $e^+e^- \to Z(e^+e^-/\mu^+\mu^-)\, H(bb)\, H(bb)$ @ 500 GeV events.

4 jets per event... pick combination that minimizes $D^2 = (M_{ij} - M_H)^2 + (M_{kl} - M_H)^2$

(Plots below shown for $Z \to e^+e^-$ on LDC01Sc)





Performance for $Z \to \mu^+\mu^-$ comparable but a little worse due to pion mis-ID

Performance for LDC00Sc comparable but a little worse for electrons due to extra material.

See LC-PHSM-2007-003 for more details

Conclusions

- Multiple full physics studies -- great to see this!
- Milestone: PandoraPFA has proved that PFA is viable
  - ... though there is more work to do for high-energy jets
  - Performance still good scaling to SiD size & B-field
  - Scaling to 1TeV machine?
- Other PFAs need to catch up
  - Especially for SiD! Can show that general concept is viable with Pandora, but cannot optimize yet. This is critical.
  - Progress is held back by serious shortage of [wo]manpower.
  - Timescale to prepare for the LOIs is tight.
  - No proven alternative to PFA for SiD right now.

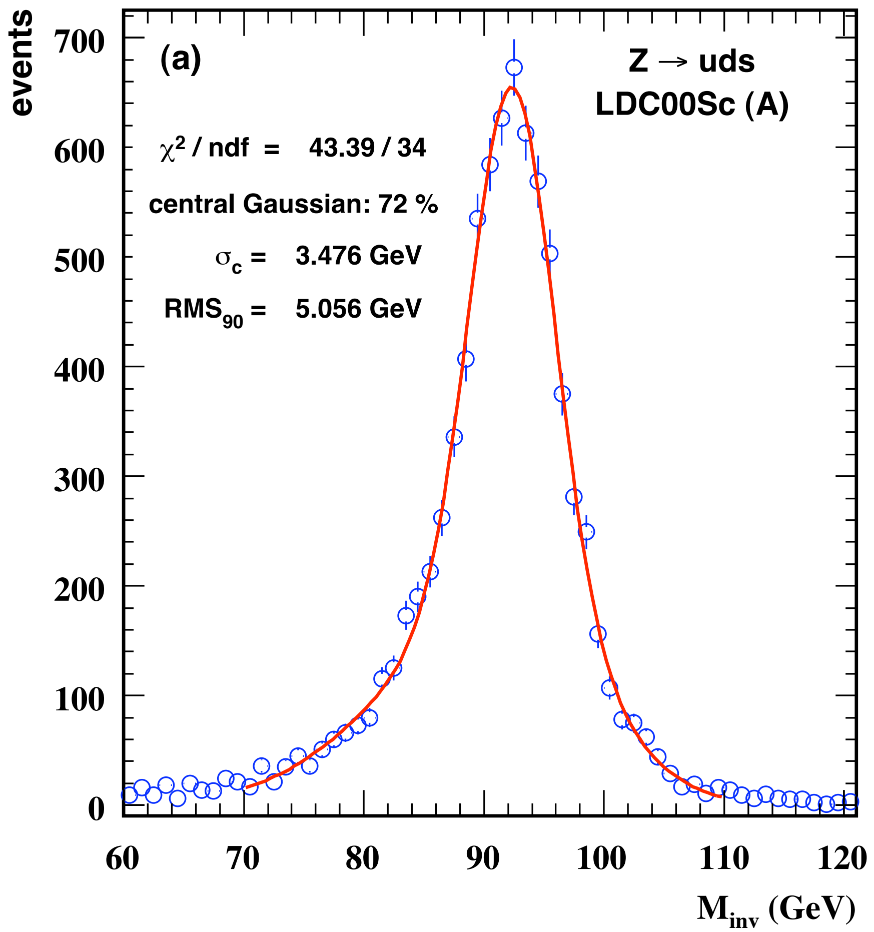
Extra material

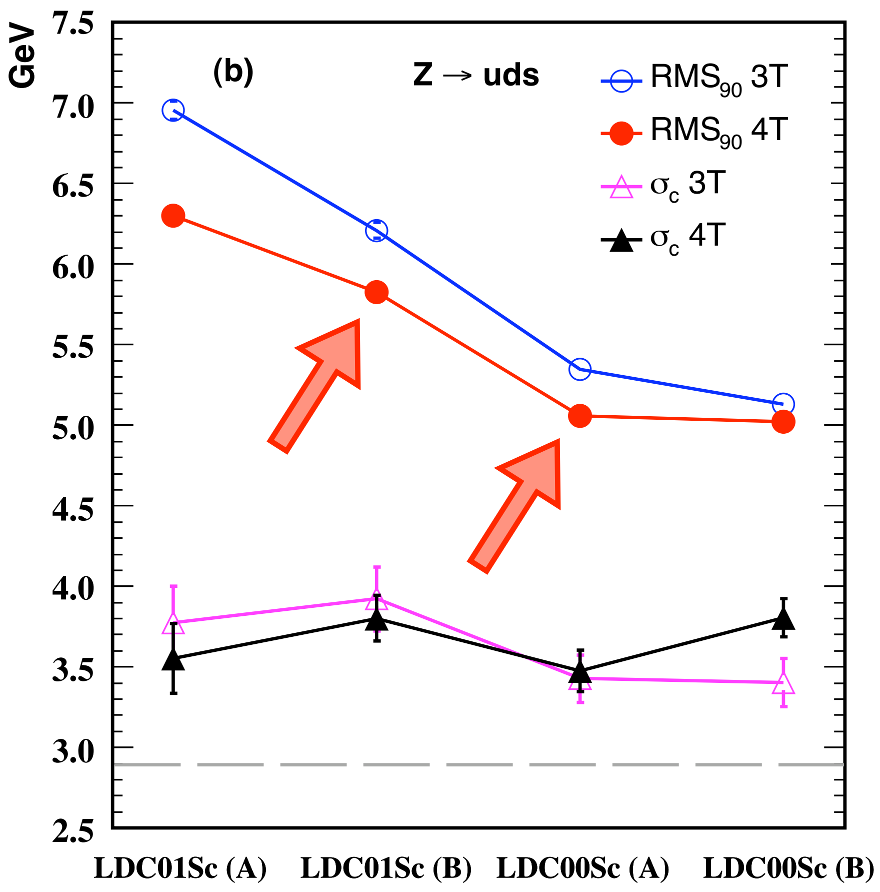
Wolf

Alexei Raspereza (DESY)

Geometrical clustering based purely on spatial information, treating hits as digital.

LC-DET-2007-001





rms$_{90}$ ~ 5--6 GeV for Z-pole LDC

(53%/√E for LDC00)

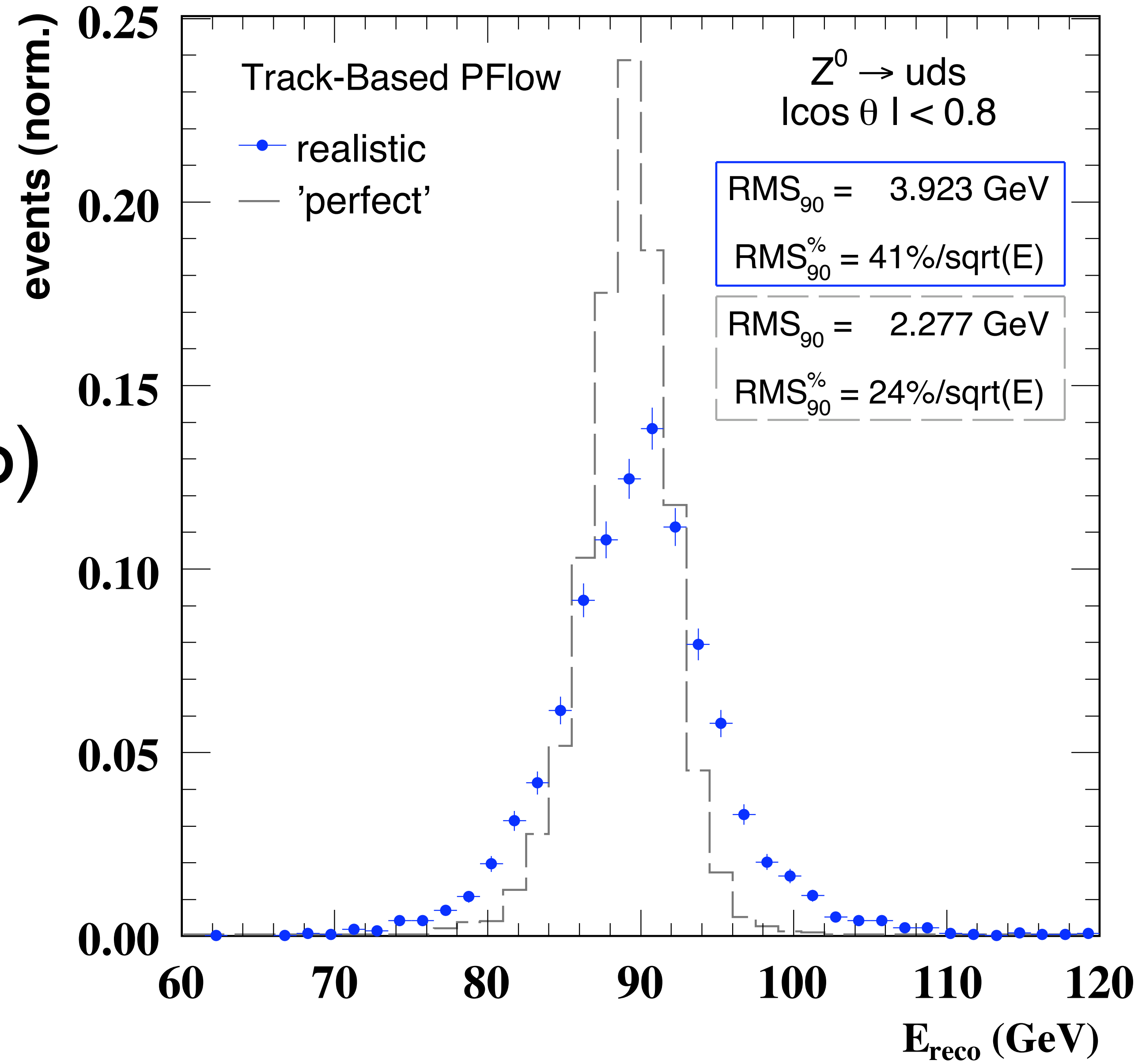
model variation	LDC01Sc (A)	LDC01Sc (B)	LDC00Sc (A)	LDC00Sc (B)
R_{TPC} (mm)	1380	1580	1690	1890
L_{TPC} (mm)	2000	2200	2730	2930

TrackBasedPFA

Oliver Wendt (DESY/Hamburg)

Reconstruction in stages:

- Photons
- Tracks (seeds for next step)
- MIP stubs (seeds for next step)
- Micro-clusters
- Merge to form final charged clusters, constrained by E/p
- Neutral hadrons



$rms_{90} = 41\%/\sqrt{E}$ at Z-pole for LDC00Sc.

PFA at Iowa

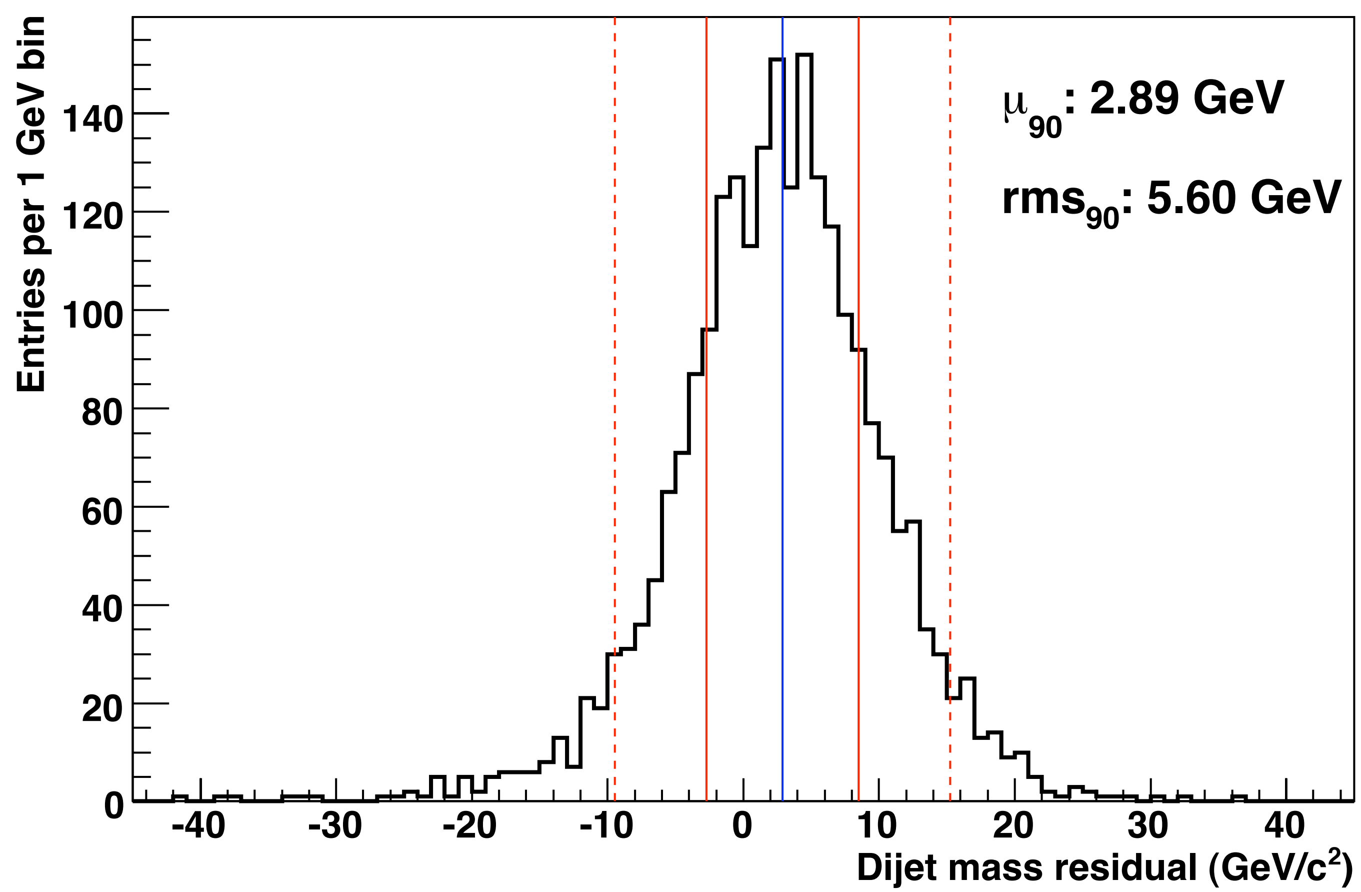
Mat Charles (U. Iowa)

Reconstruction in stages:

- Photon-finding & ID (H-matrix)
- Find MIP segments, dense clumps
- Build skeletons of hadronic showers from MIPs & clumps (linking based on proximity & likelihood selector)
- Match tracks; break up skeletons with >1 track
- Merge fragments/secondaries
- E/p check (discard track if failed)

Dijet mass residuals for
$e^+e^- \rightarrow Z(\nu\nu)\ Z(qq)$ @ 500 GeV:

rms_{90} = 5.6 GeV for sid01
(125cm ECAL, 5T, Steel/RPC HCAL)



Includes components by Ron Cassell (SLAC), Norman Graf (SLAC), Graham Wilson (Kansas), Steve Magill (ANL)

PFA at Argonne (1)

Steve Magill (ANL)

Reconstruction in stages:

- Photon-finding & ID (H-matrix)
- Extrapolate tracks to ECAL
- Follow MIP trail of isolated hits
- Switch to nearest-neighbour clusterer once shower starts
- Add clusters until E/p consistent with 1

[plots from Tue talk to be added]

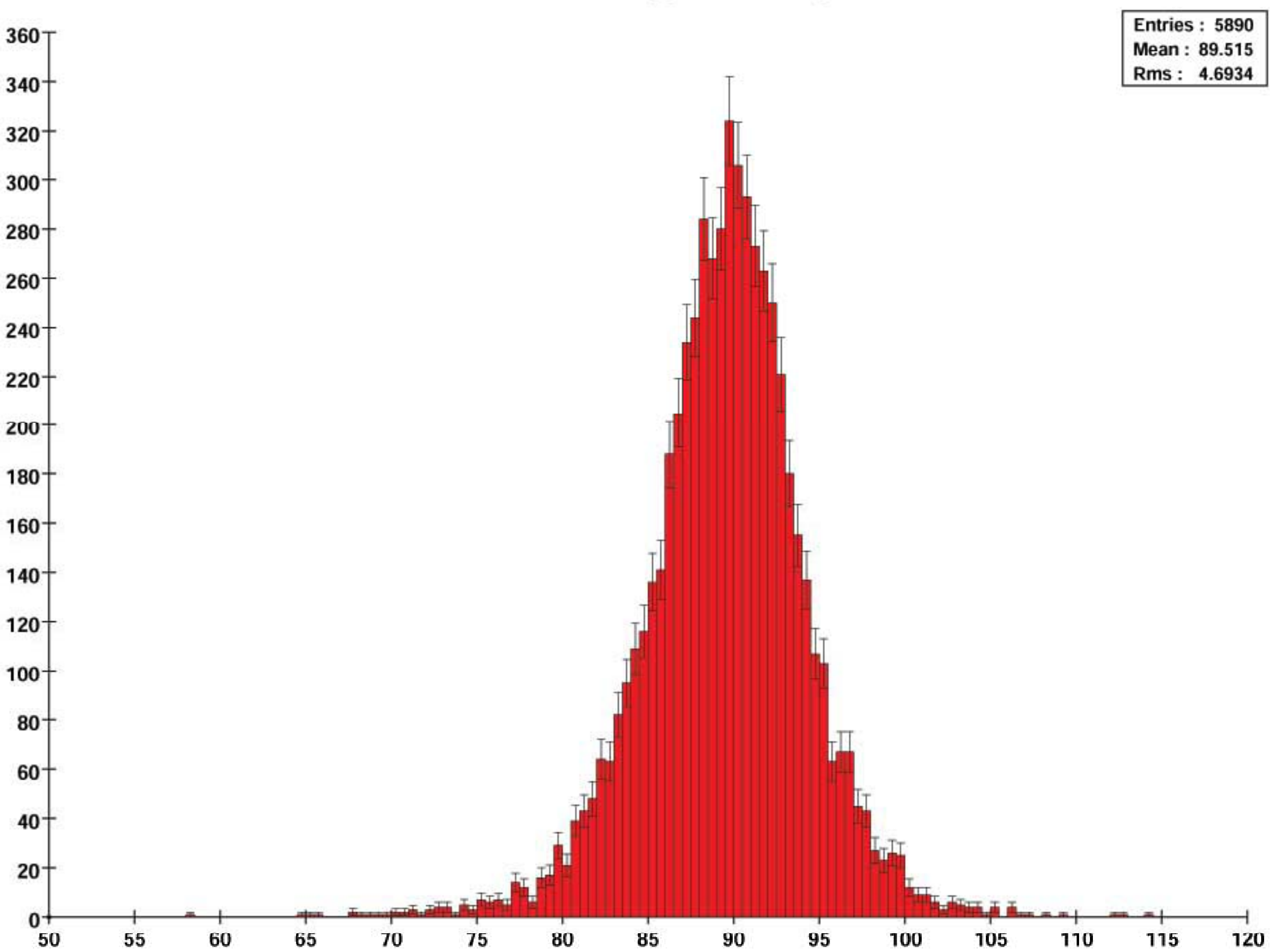
Includes components by Ron Cassell (SLAC), Norman Graf (SLAC), Graham Wilson (Kansas)

PFA at Argonne (2)

Lei Xia (ANL)

Again, reconstruction in stages:

- Form CAL clusters based on local hit density & separation
- Identify photon clusters (H-matrix)
- Match tracks & apply E/p correction
- Identify primary neutrals vs fragments; discard fragments



Does very nicely at Z-pole!

For |cos(ϑ)|<1/√2, Z-pole, sidaug05_np:
mean = 89.52 GeV
RMS = 4.69 GeV
rms90 = 3.32 GeV (35.1%/√E)

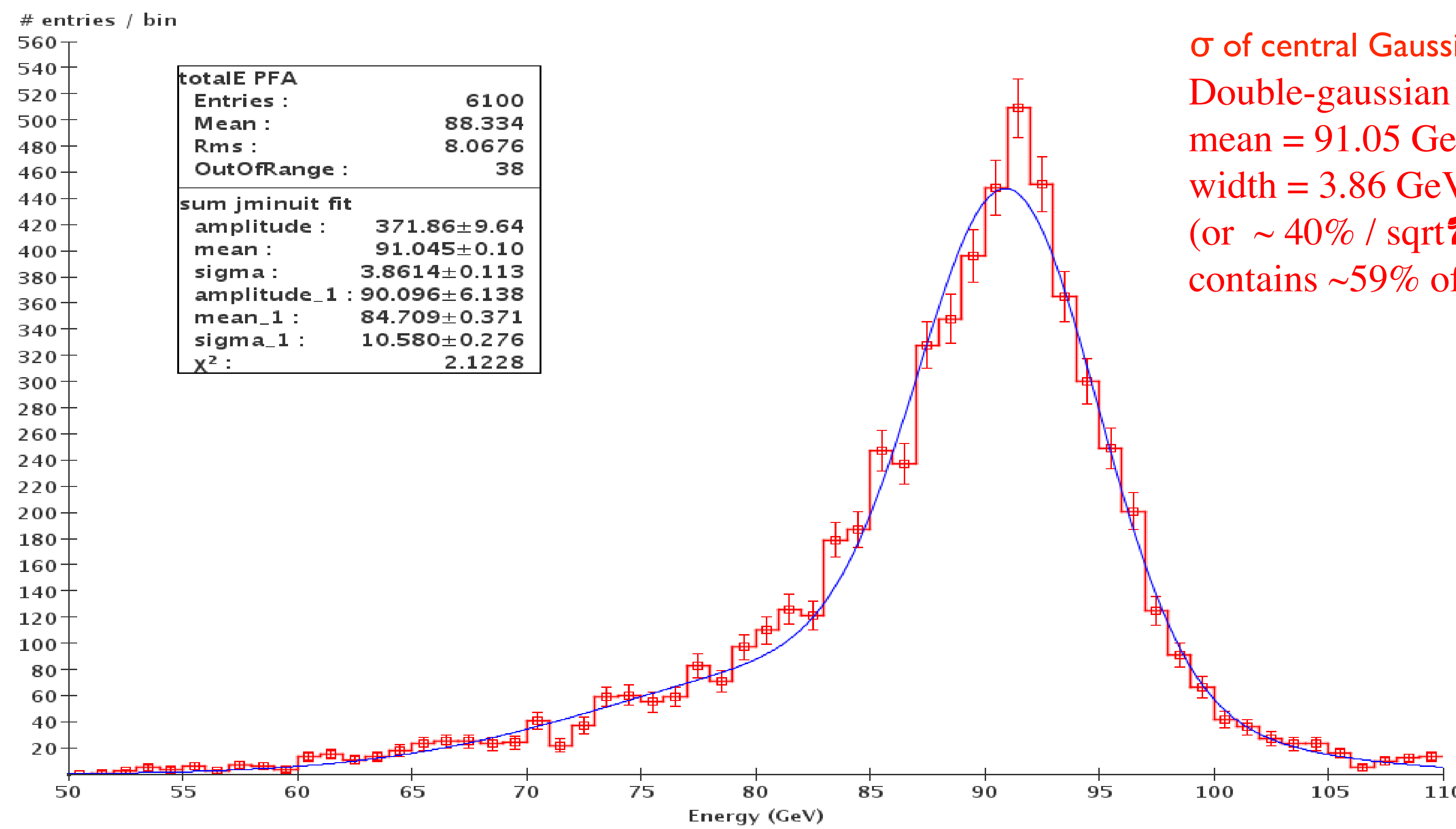
Performance also tested with energy sums at higher energies.

- 67%/√E at 200 GeV
- 127%/√E at 500 GeV

PFA at NICADD/NIU

Dhiman Chakraborty, Guilherme Lima, Vishnu Zutshi (NICADD/NIU)

- Main clustering routine based on local hit density gradient (“directed tree”)
- Photon ID (H-matrix)
- Track matching
- Merge clusters into showers
- Discard fragments



σ of central Gaussian in Double-gaussian fit
mean = 91.05 GeV
width = 3.86 GeV
(or ~ 40% / sqrt☎E))
contains ~59% of events

Z-pole events on sidaug05_tcmt

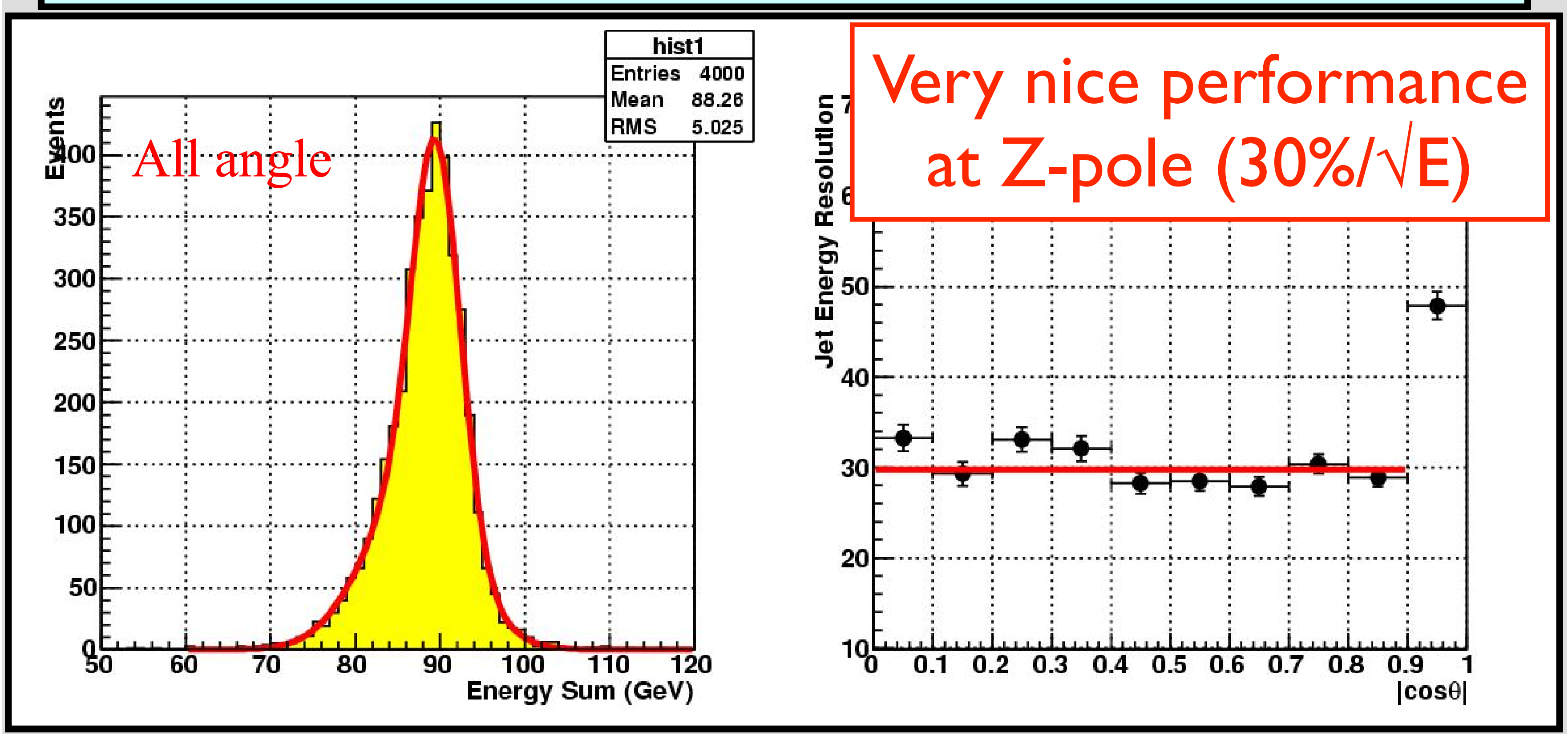
Algorithm has been on hold during test-beam work; group plans to get resume PFA development soon.

PFA for GLD

Tamaki Yoshioka (Tokyo) & GLD

- Photon-finding (likelihood selector)
- Charged hadron reco (pick up cells in tube around track)
- Find neutral hadrons & satellites/fragments (separate with likelihood selector)

- Z → uds @ 91.2GeV, tile calorimeter, 1cm x 1cm tile size



Performance tested vs several detector parameters

Ecm	3 Tesla	4 Tesla	5 Tesla
91.2	29.8±0.4	28.4±0.3	28.6±0.3
350	68.7±1.1	58.5±1.0	55.5±0.9

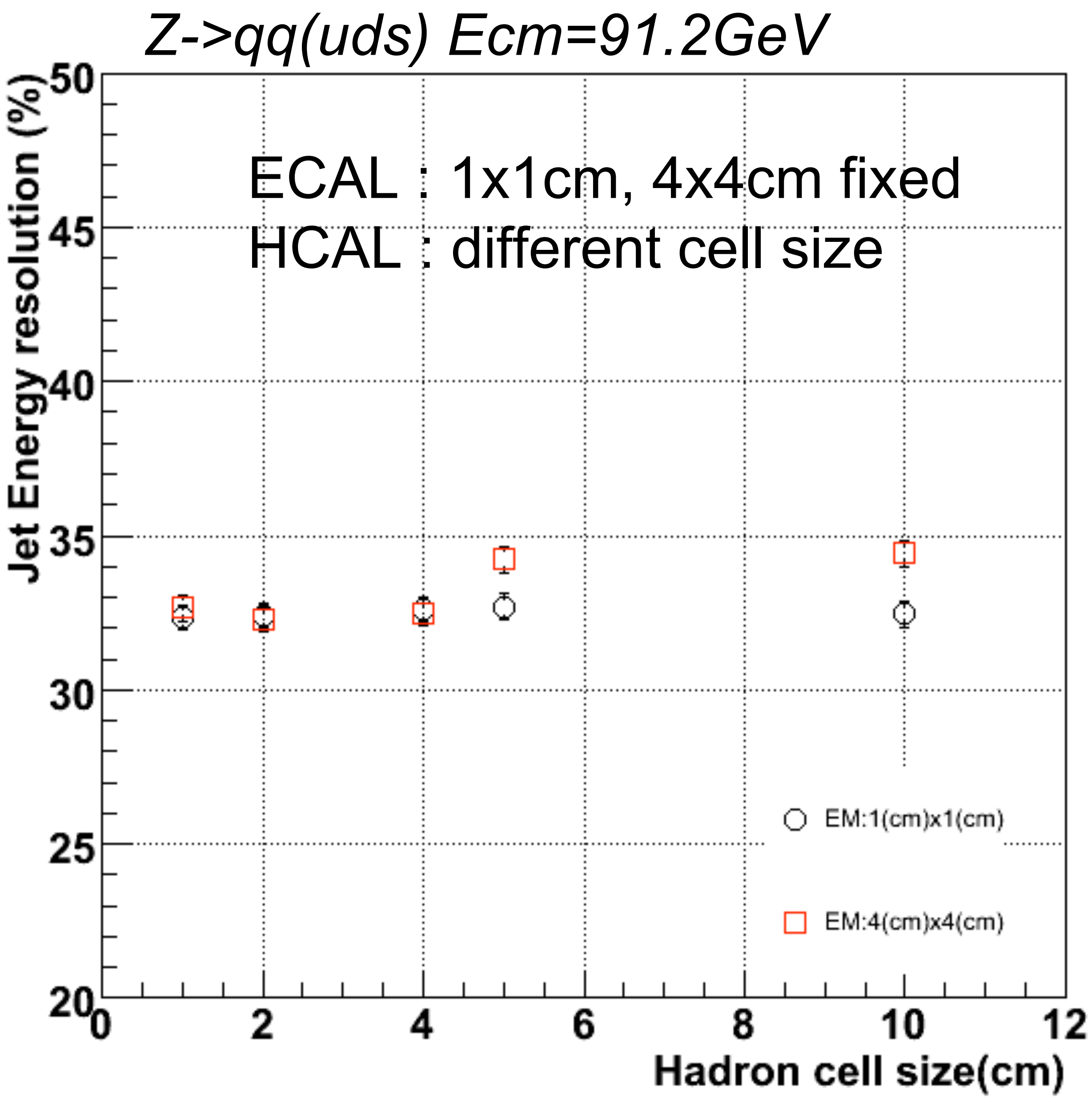
Ecm	140 cm	180 cm	210 cm
91.2	37.9±0.4	35.0±0.4	29.8±0.4
350	93.4±1.5	81.0±1.3	68.7±1.1

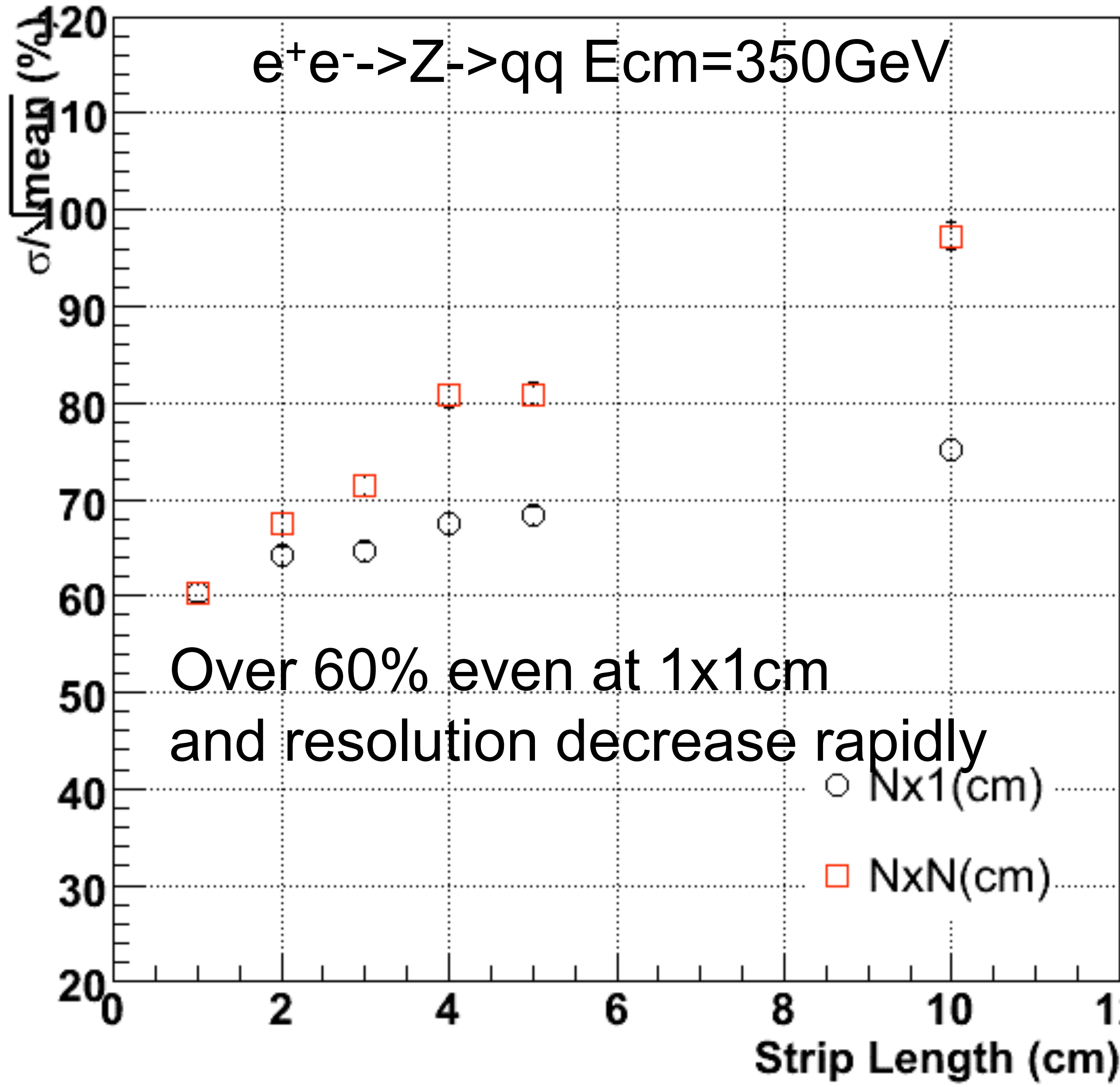
Ecm	4.0 λ_0	5.0 λ_0	5.7 λ_0
91.2	37.9±0.4	35.0±0.4	29.8±0.4
350	93.4±1.5	81.0±1.3	68.7±1.1

PFA for GLD

Hiroaki Ono (Niigata) & ACFA-Sim-J

Tests of performance with different ECAL, HCAL segmentations





Not much effect at Z-pole

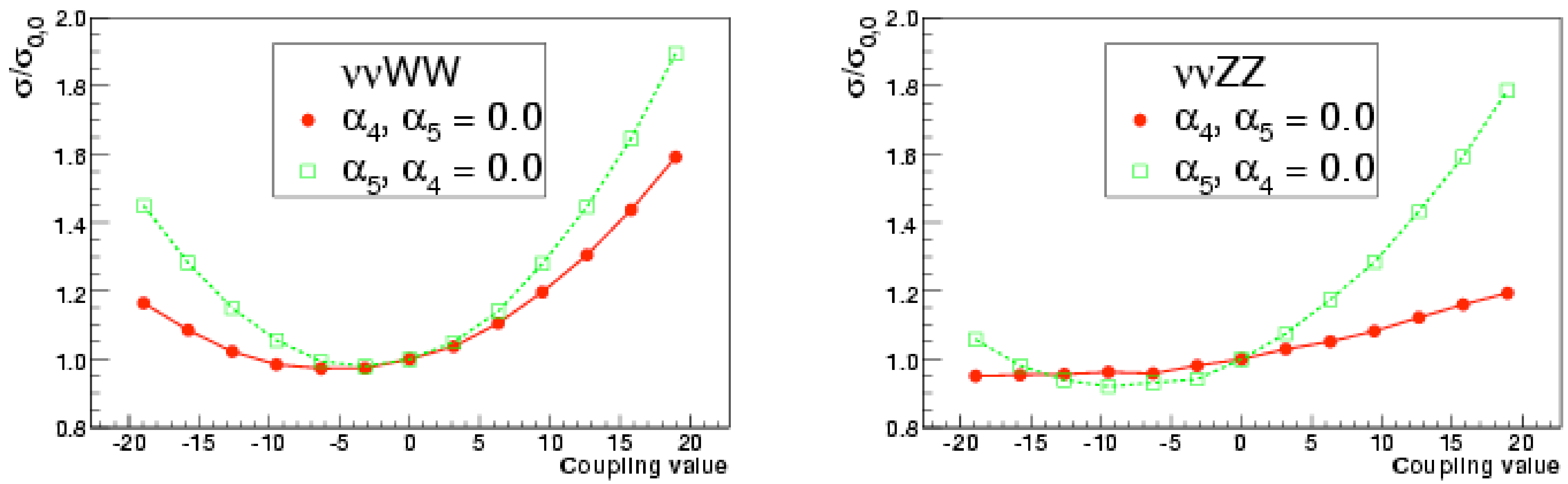
Dramatic effect at 350 GeV

WW scattering sensitivity

See slides from CALICE UK meeting, 20 Sep for full details. [Wenbiao Yen]

WW/ZZ signal

- WW/ZZ Signal events
  - $147.0 < m^1_{qq} + m^2_{qq} < 171.0$ GeV: WW
  - $171.0 < m^1_{qq} + m^2_{qq} < 195.0$ GeV: ZZ
  - $|m^1_{qq} - m^2_{qq}| <= 20.0$ GeV
  - $m_{\nu_e \bar{\nu}_e} >= 100.0$ GeV



- $\nu\nu WW$ events are more sensitive than $\nu\nu ZZ$ events
- α_5 is more sensitive than α_4