PFA Jet Energy Measurements

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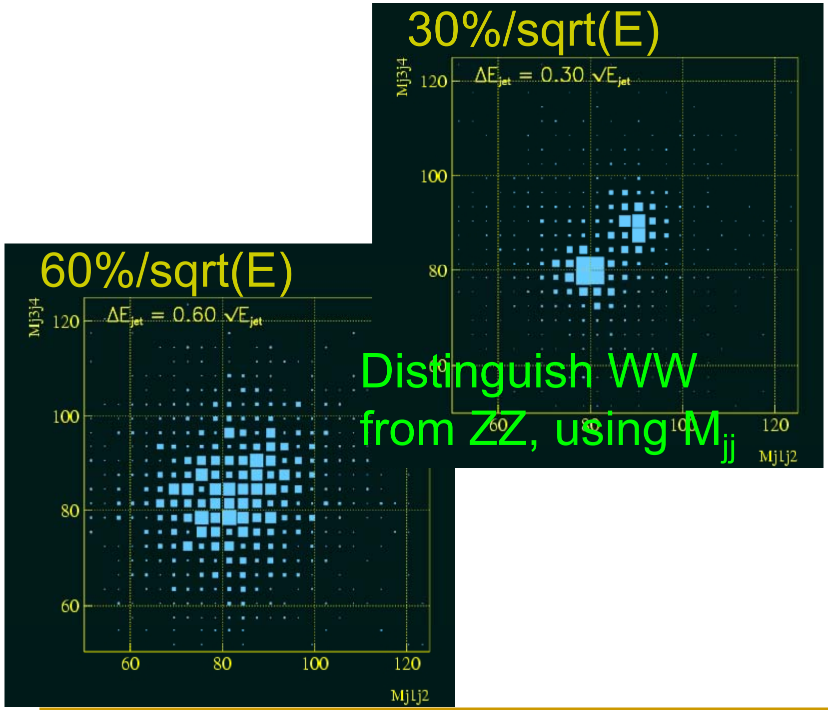
ILC requires precise measurement for jet energy/di-jet mass

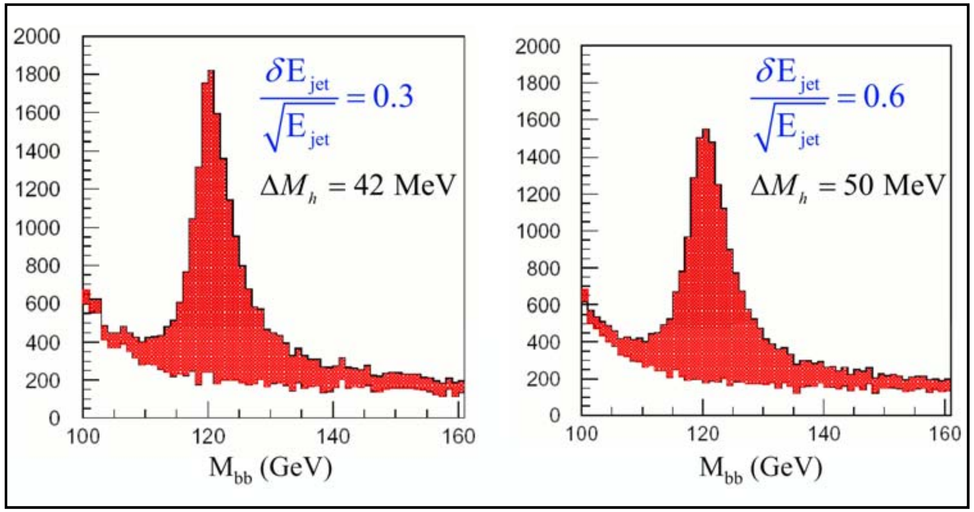
Process	Vertex	Tracking		Calorimetry		Fwd		Very Fwd	Integration					Pol.
	σ_{IP}	$\delta p/p^2$	ϵ	δE	$\delta\theta,\ \delta\phi$	Trk	Cal	θ^e_{min}	δE_{jet}	M_{jj}	ℓ-Id	V^0-Id	$Q_{jet/vtx}$	
$ee \to Zh \to \ell\ell X$		x									x			
$ee \to Zh \to jjbb$	x	x	x			x				x	x			
$ee \to Zh, h \to bb/cc/\tau\tau$	x		x							x	x			
$ee \to Zh, h \to WW$	x		x		x				x	x	x			
$ee \to Zh,\ h \to \mu\mu$	x	x									x			
$ee \to Zh,\ h \to \gamma\gamma$				x	x		x							
$ee \to Zh, h \to invisible$			x			x	x							
$ee \to \nu\nu h$	x	x	x	x			x			x	x			
$ee \to tth$	x	x	x	x	x		x	x	x		x			
$ee \to Zhh,\ \nu\nu hh$	x	x	x	x	x	x	x		x	x	x	x	x	x
$ee \to WW$										x			x	
$ee \to \nu\nu WW/ZZ$						x	x		x	x	x			
$ee \to \tilde{e}_R\tilde{e}_R$ (Point 1)		x						x			x			x
$ee \to \tilde{\tau}_1\tilde{\tau}_1$	x	x						x						
$ee \to \tilde{t}_1\tilde{t}_1$	x	x							x	x		x		
$ee \to \tilde{\tau}_1\tilde{\tau}_1$ (Point 3)	x	x			x	x	x	x	x					
$ee \to \tilde{\chi}^0_2\tilde{\chi}^0_3$ (Point 5)									x	x				
$ee \to HA \to bbbb$	x	x								x	x			
$ee \to \tilde{\tau}_1\tilde{\tau}_1$			x											
$\chi^0_1 \to \gamma + \not{E}$					x									
$\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 + \pi^\pm_{soft}$			x					x						
$ee \to tt \to 6\ jets$	x		x						x	x	x			
$ee \to ff\ [e, \mu, \tau; b, c]$	x		x				x		x		x		x	x
$ee \to \gamma G$ (ADD)				x	x			x						x
$ee \to KK \to f\bar{f}$		x									x			
$ee \to ee_{fwd}$						x	x	x						
$ee \to Z\gamma$		x		x	x	x	x							

- At LEP, ALEPH got a jet energy resolution of ~60%/sqrt(E)
  - Achieved with Particle Flow Algorithm (Energy Flow, at the time) on a detector not optimized for PFA
  - Significantly worse than 60%/sqrt(E) if used current measure (rms90, for example)
- This is not good enough for ILC physics program, we want to do a lot better!

ILC goal for jet energy resolution

- ILC goal: distinguish W, Z by their di-jet invariant mass
  - Well know expression: jet energy resolution ~ 30%/sqrt(E)
  - More realistic goal for high (>100 GeV) jet energies: flat 3-4% resolution
  - Combine the two: 30%/sqrt(E) up to 100 GeV (E_j or M_{jj}) and 3-4% above
- Most promising approach: **Particle Flow Algorithm (PFA) + detector optimized for PFA** (← a whole new approach!)





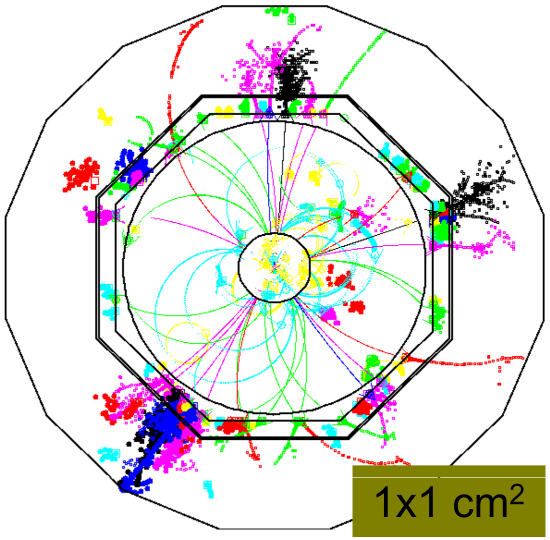
$e^+e^- \rightarrow ZH \rightarrow qqbb$ @ 350GeV, 500fb-1
M_{jj} of two b-jets for different jet energy resolution.
→ **40% luminosity gain**

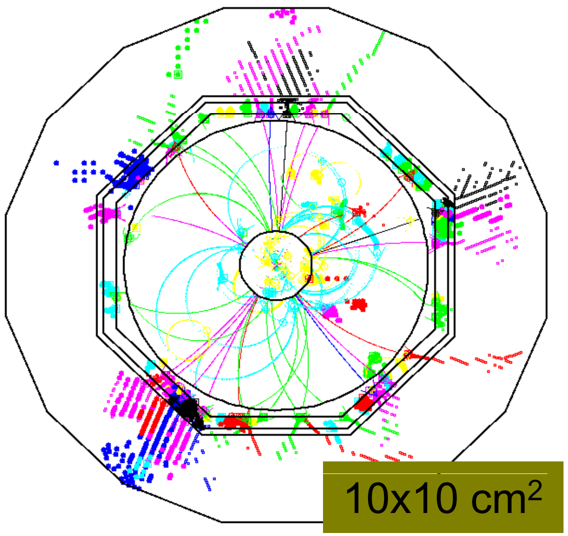
PFA: introduction

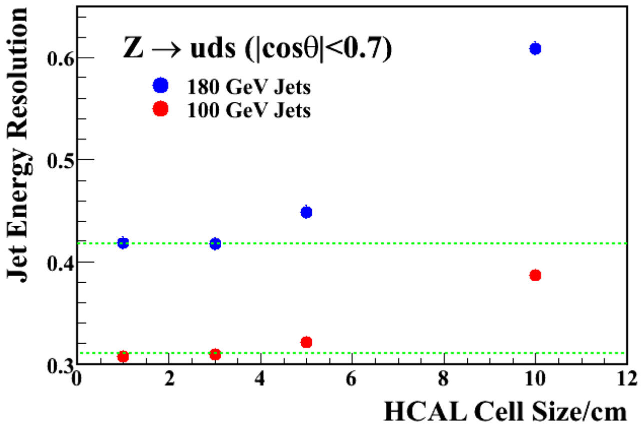
- Measure jets in the PFA way…

Particles in Jets	Fraction of jet energy	Measured with
Charged	65%	Tracker, negligible uncertainty
Photon	25%	ECal, 15%/ √ E
Neutral hadron	10%	ECal + HCal, ~50-60%/ √ E

- Clear separation of the 3 parts is the key issue of PFA
  - Charged particle, photon and neutral hadron: all deposit their energy in the calorimeters
  - Maximum segmentation of the calorimeters is needed to make the separation possible
  - Calorimeter optimized for PFA is very different from traditional ← a lot of R&D needed!







From Mark Thomson, LCWS'07

Same multi-jet event with different HCal segmentation

PFA development is a major R&D issue

- Several really good PFA's are needed
  - PFA approach need to be validated by ≥ 1 real algorithms
  - PFA with required performance is a major tool for detector design:
    - PFA is the tool to assess a detector's performance
    - PFA is the tool to optimize detector design
    - But we need to be sure that we are not fooled by a poor PFA
      - Need to push PFA performance to its practical limit
      - Need to optimize PFA for each detector configuration and physics process
      - >1 independent PFA's will help to remove algorithm artifact
  - Realization of a really good algorithm turns out to be (much) more difficult than many of us expected
    - Need to get all individual steps right (and there are many of them!)
    - Progress occurs through iterations (smart developer + a lot of time are needed!)
- PFA development needs a reliable (hadron) shower simulation
  - Calorimeter test beam program will provide critical shower shape data to select/tune simulation
  - PFA study need to figure out a set of important shower parameters that affects PFA performance

PFA: contributors

- Many US groups contribute to the PFA development

	Simulation infrastructure	Common tools	Individual algorithm	Complete PFA
ANL		√	√	√
Iowa		√	√	√
Kansas			√	
NIU	√		√	√
SLAC	√	√	√	√

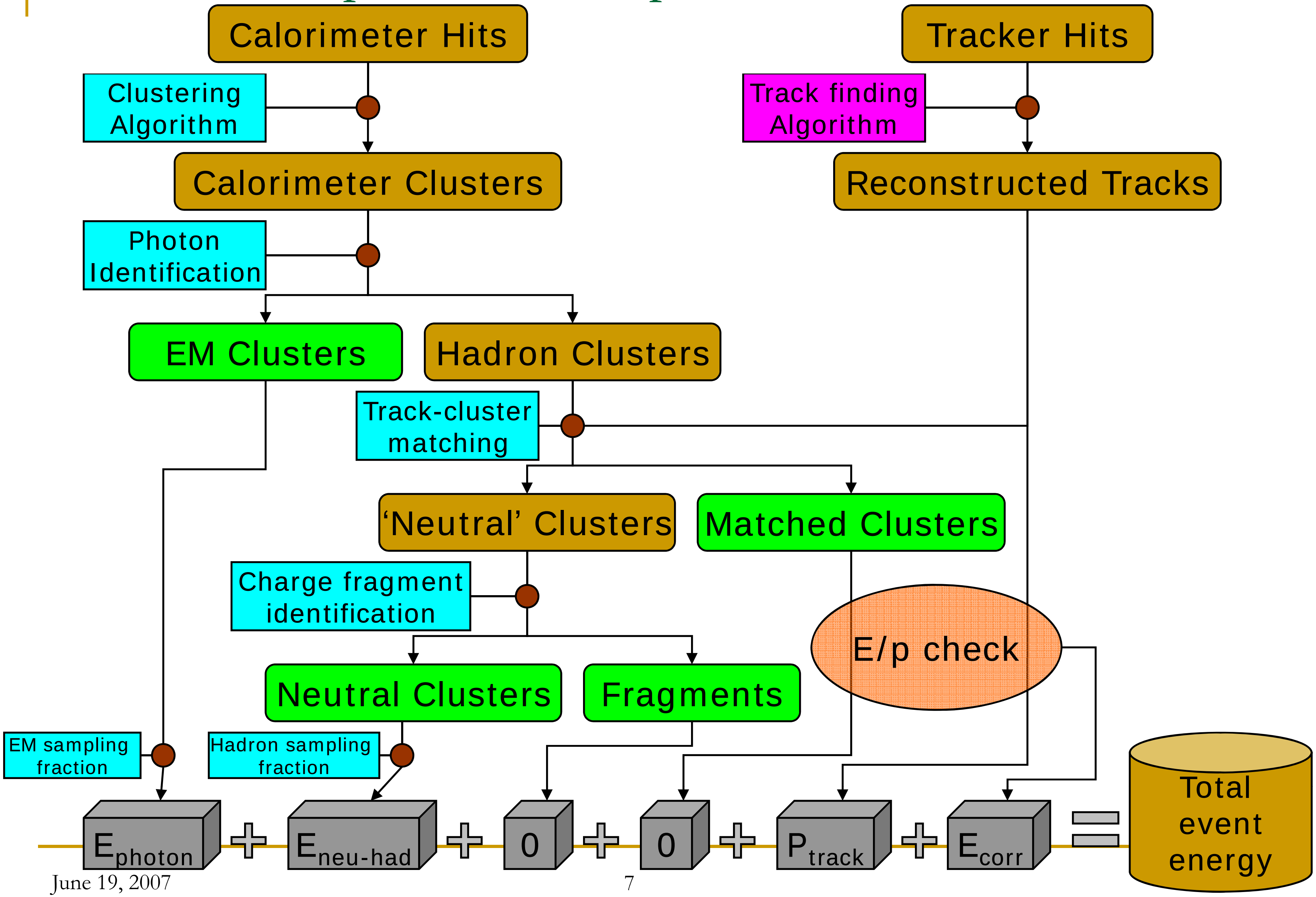
- Currently, there are 4 fully implemented PFA's developed by US efforts

	Dijet 91GeV	Dijet 200 GeV	Dijet 500 GeV	ZZ 500 GeV
ANL(I)+SLAC	√			√
ANL(II)	√	√	√	
Iowa	√	√	√	√
NIU	√			

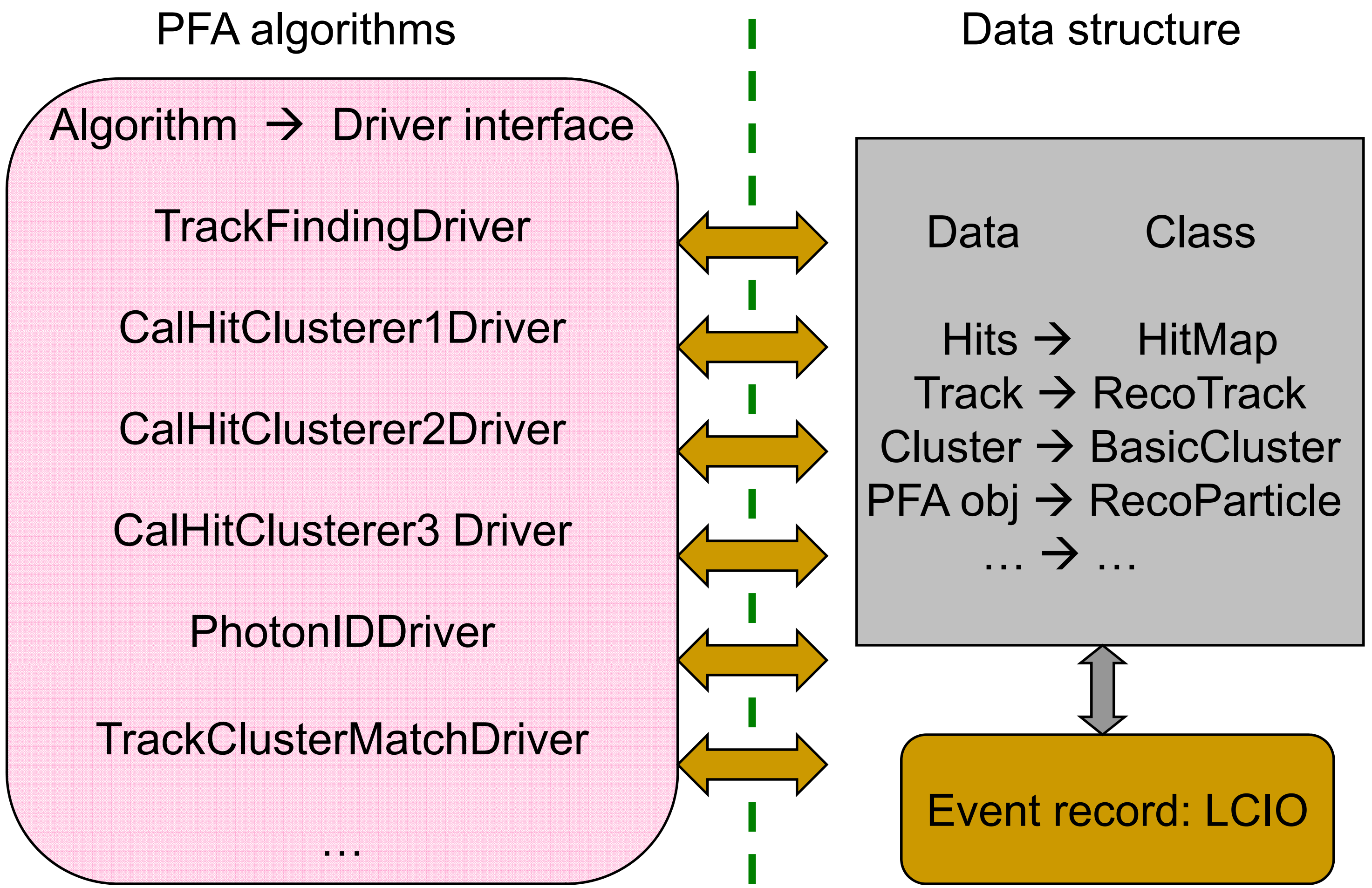
√: current focus

- Other efforts for PFA development
  - Pandora PFA, GLD PFA, Wolf PFA, Track based PFA, etc.

PFA: an example of a real implementation



Some highlights: PFA template (SLAC+IOWA+ANL)

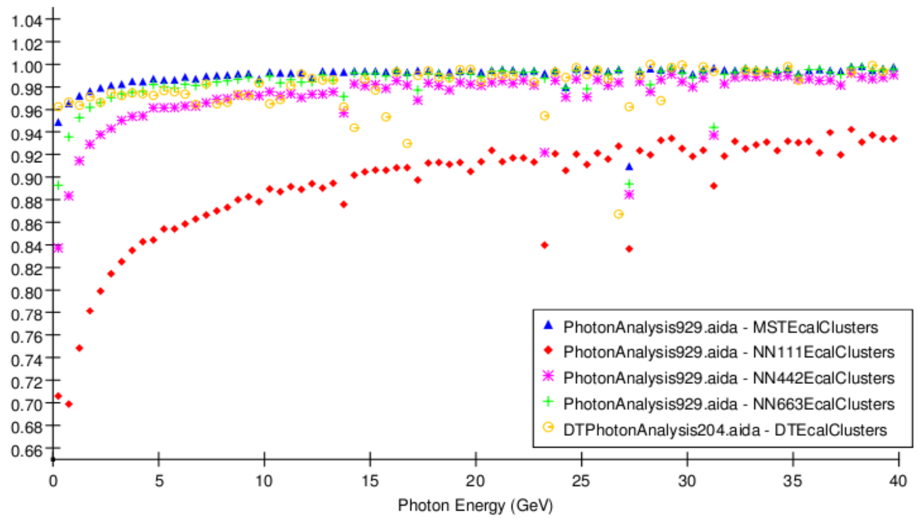


- Enables e.g. algorithm substitution, CAL hit/cluster accounting
- A number of available common tools can be easily used from the template
- Ref: https://confluence.slac.stanford.edu/display/ilc/lcsim+PFA+guide

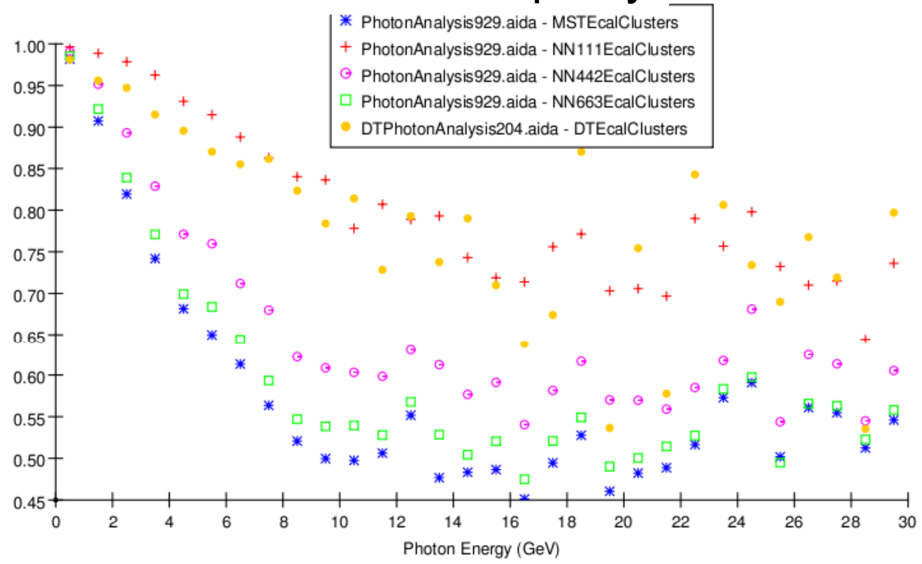
Some highlights: directed tree clustering algorithm (NIU)

- Cal-only clustering developed at NIU
- Hit selection: E > E_{MIP} / 4, and time < 100ns (applied before the clustering)
- Studied by Ron Cassell (SLAC)
  - Directed tree cluster has the best efficiency + purity for photon showers, among all tested clustering algorithms

Photon efficiency

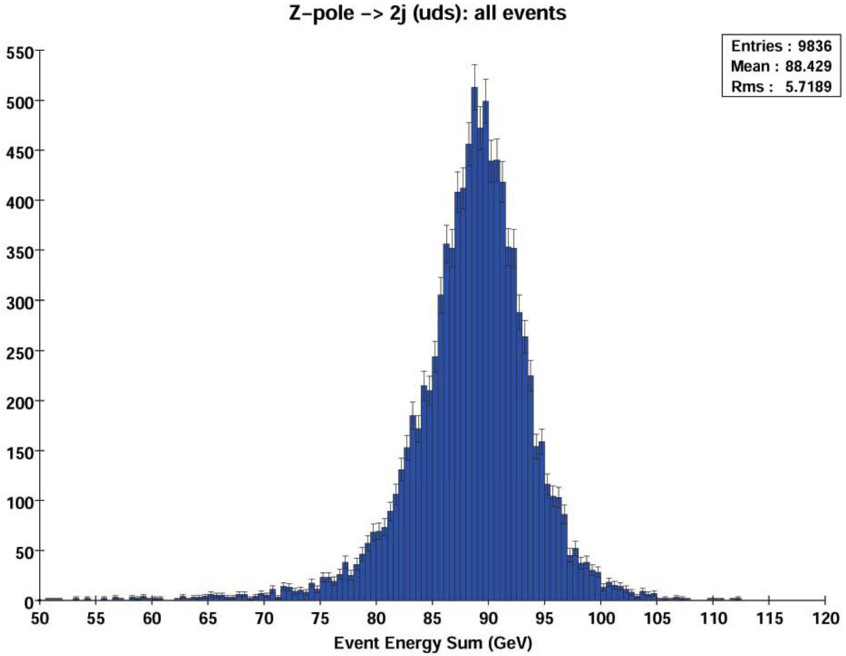


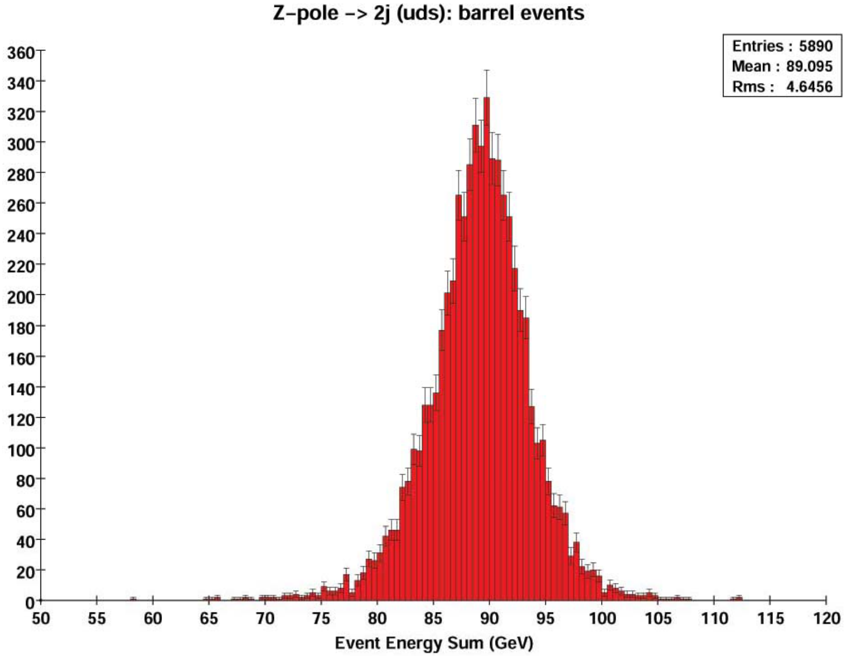
Photon cluster purity



PFA performance: $e^+e^- \rightarrow$ qqbar(uds) @ 91GeV (ANL)

(rms90: rms of central 90% of events)





All events, no cut

Mean	88.43 GeV
RMS	5.718 GeV
RMS90	3.600 GeV
	[38.2 %/sqrt(E)]

Barrel events (cos(theta[Q]) < 1/sqrt(2))

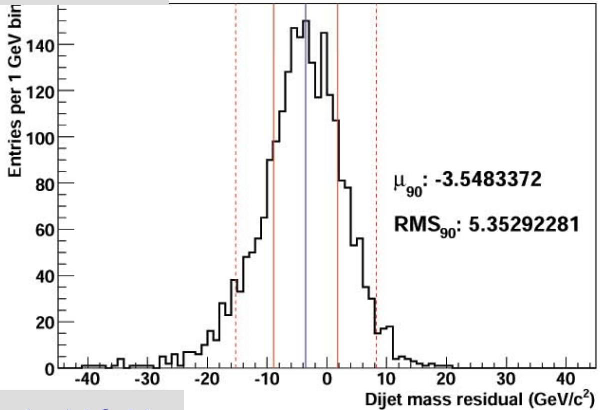
Mean	89.10 GeV
RMS	4.646 GeV
RMS90	3.283 GeV
	[34.7 %/sqrt(E)]

Still not quite 30%/sqrt(E) yet, but very close now

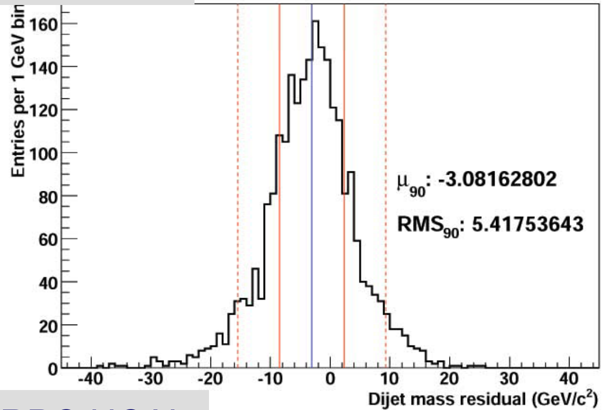
PFA performance: $e^+e^- \rightarrow ZZ$ @ 500GeV (IOWA)

- $Z_1 \rightarrow$ nunubar, $Z_2 \rightarrow$ qqbar (uds)
- Di-jet mass residual = (true mass of Z_2 - reconstructed mass of Z_2)
  - μ_{90}: mean of central 90% events
  - rms_{90}: rms of central 90% events

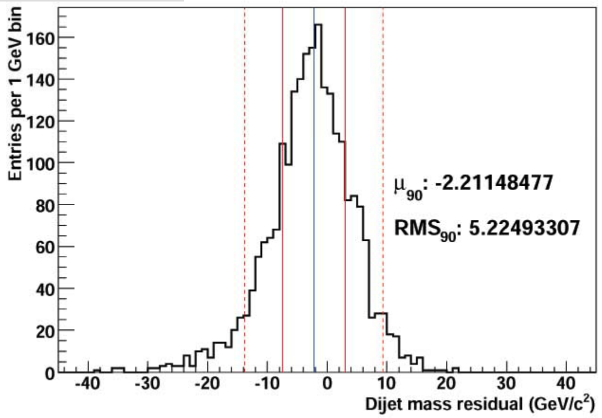
SiD W/Scin HCAL



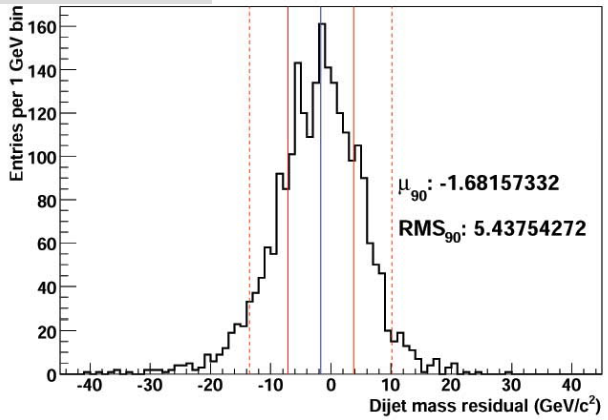
SiD W/RPC HCAL



SiD SS/Scin HCAL



SiD SS/RPC HCAL



PFA performance: summary

rms_{90}(GeV)	Detector model	Tracker outer R	Cal thickness	Shower model	Dijet 91GeV	Dijet 200GeV	Dijet 360GeV	Dijet 500GeV	ZZ 500GeV[b]
ANL(I)+SLAC	SiD	1.3m	~5 λ	LCPhys	3.2/9.9[a]				
ANL(II)					3.3	9.1		27.6	
Iowa									5.2[c]
NIU					3.9/11.[a]				
PandoraPFA*	LDC	1.7m	~7 λ	LHEP	2.8	4.3	7.9	11.9	___
GLD PFA*	GLD	2.1m	5.7 λ	LCPhys	2.8	6.4	12.9	19.0	___
30%/sqrt(E)	___	___	___	___	2.86	4.24	5.69	6.71	(?)
3%					1.93	4.24	7.64	10.61	(?)
4%					2.57	5.67	10.18	14.14	(?)

* From talks given by Mark Thomson and Tamaki Yoshioka at LCWS'07

a) 2 Gaussian fit, (central Gaussian width/2nd Gaussian width)

b) $Z_1 \rightarrow$nunubar, $Z_2 \rightarrow$qqbar (uds)

c) Di-jet mass residual [= true mass of Z2 - reconstructed mass of Z2]

- A fair comparison between all PFA efforts is NOT possible at the moment
- PandoraPFA (M. Thomson) achieved ILC goal in some parameter space
- US efforts: 30%/sqrt(E) or 3-4% goal has not been achieved yet, but we made a lot of progress during the last few years and we are much closer now

What's still missing? (and future plan)

- A really good PFA
  - We made a lot of progress, but we still need to push our PFA performance further, especially at high CM energies
  - We need to find good PFA for all the physics processes we are interested in:
    - ZZ → qqνν/qqqq, ZH, ttbar, …
- Dependence of PFA performance on hadron shower models
  - Is shower simulation critical for PFA performance? (most likely yes!)
  - Is there a set of shower parameters that we can tune according to data, to guarantee a realistic PFA reconstruction?
- After getting a really good PFA
  - Start detector model comparison and optimization
    - B-field variations
    - ECAL IR variations
    - HCAL technology/parameter variations
    - Detector concept comparisons
- An extremely ambitious plan is to have all these done by the end of 2007

- But the biggest missing item is manpower
  - Most of PFA developers can only work on it part-time, with current support level
  - A significant increase in effort/support is needed to assure timely PFA development

Summary

- US PFA effort has made a lot of progress
  - Significantly improved PFA performance
  - Completed common tools and PFA template
- Current focus is to push PFA performance to its practical limit, especially at high CM energies
  - Try to achieve ILC goal for jet energy resolution
  - Collaborate with calorimeter test beam effort to verify simulation
  - Get ready for detector comparison/optimization
- Short of manpower is currently the biggest problem in PFA development
  - Need significant increase of support