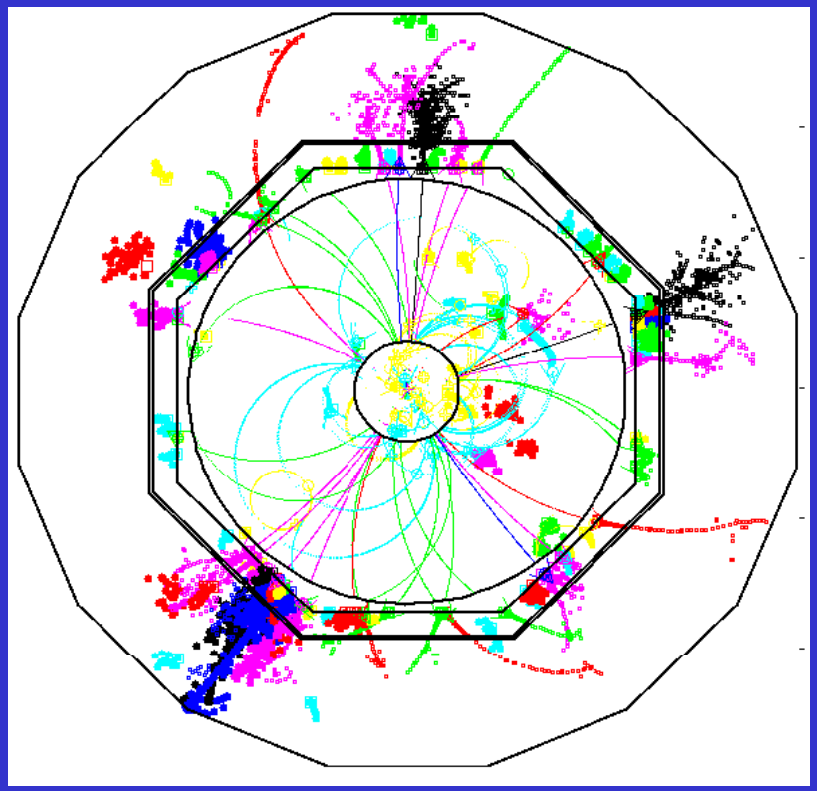
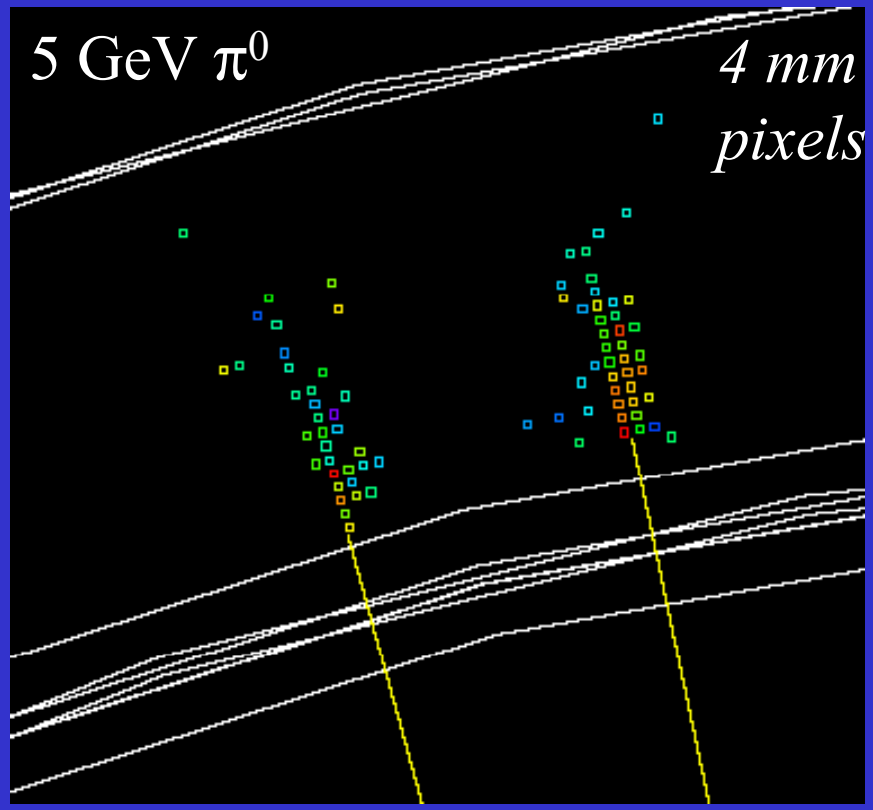
Investigation of ECAL Concepts Designed for Particle Flow





Graham W. Wilson, University of Kansas

ILC Calorimetry R&D Review, DESY Hamburg, June 2007

Outline

- Personnel
- Basic Philosophy
- Principal physics driven design criteria
- Brief orientation to previously reported work
- Highlights of current research
  - Calibration strategies and measuring EM interactions
  - Photon reconstruction and π^0 fitting for jet energy
  - Applying fast timing techniques to ILC ?

Personnel

- **Graham Wilson, Faculty**
- **Carsten Hensel, Postdoc (mostly DØ, no direct funding for ILC)**
- **David File, Grad student (and EE)**
- **Shantanu Dikshit, Grad student**
- Matt Treaster, Master's student
- Darius Gallagher, Master's student
- Eric Benavidez, UG student
- Jonathan van Eenwyk, UG student
- Stephen Floor, Chris Patrick, Matt Richard (Semester design project students)

Basic Philosophy

- ECAL for an ILC detector will almost certainly be a sampling calorimeter with readout of each individual layer, and fine transverse cell size.
  - Abundance of information.
  - Want best design for physics at a justifiable overall cost.
- Evaluate performance of different approaches to "precision" sampling EM calorimetry.
- Investigate novel ideas, enabled by the typical detector design, and current R&D with potential to deliver new capabilities.
  - Some of the traditional calorimeter design principles may be moot.
- Not currently committed to a particular technology choice: studying both Si and scintillator related issues
  - Interested in participating in test-beam efforts but would like to have adequate resources to make a valued contribution.

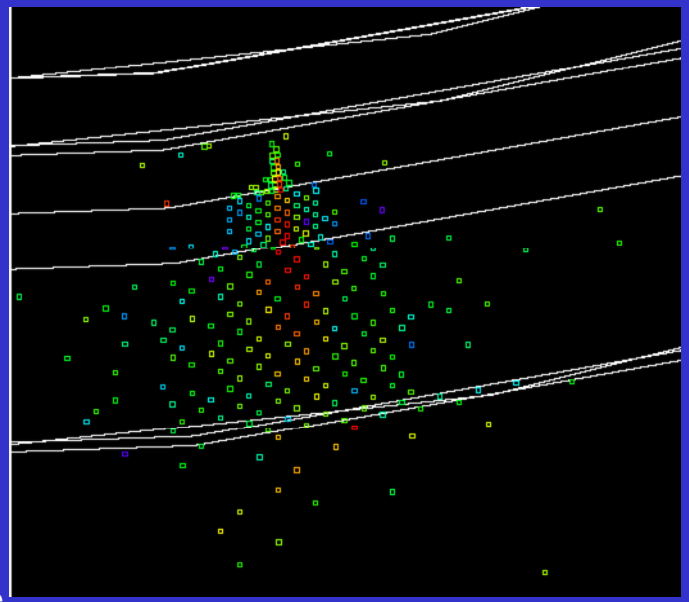
Example: frankyaug05

A radially staggered buildable analog calorimeter with exquisite granularity, with no cost optimization using Tungsten. B = 3T.

With M. Thomson.
Acknowledgements to N. Graf

(W was cheaper in 05..)

	R(m)	Nlayers	X0	Active	Cell-size (mm)
EM Barrel 1:	2.10	10	0.5	Si	2.5 × 2.5 × 0.32
EM Barrel 2:	2.13	10	0.5	Si	10 × 10 × 0.32
EM Barrel 3:	2.16	20	0.5	Sc	20 × 20 × 2
HCAL:	2.255	50	2.0	Sc	40 × 40 × 2



50 GeV photon

Choices made based on then current R&D work, driven by making a sensible, robust design with aggressive performance and minimizing Silicon area in a GLD-scale detector.

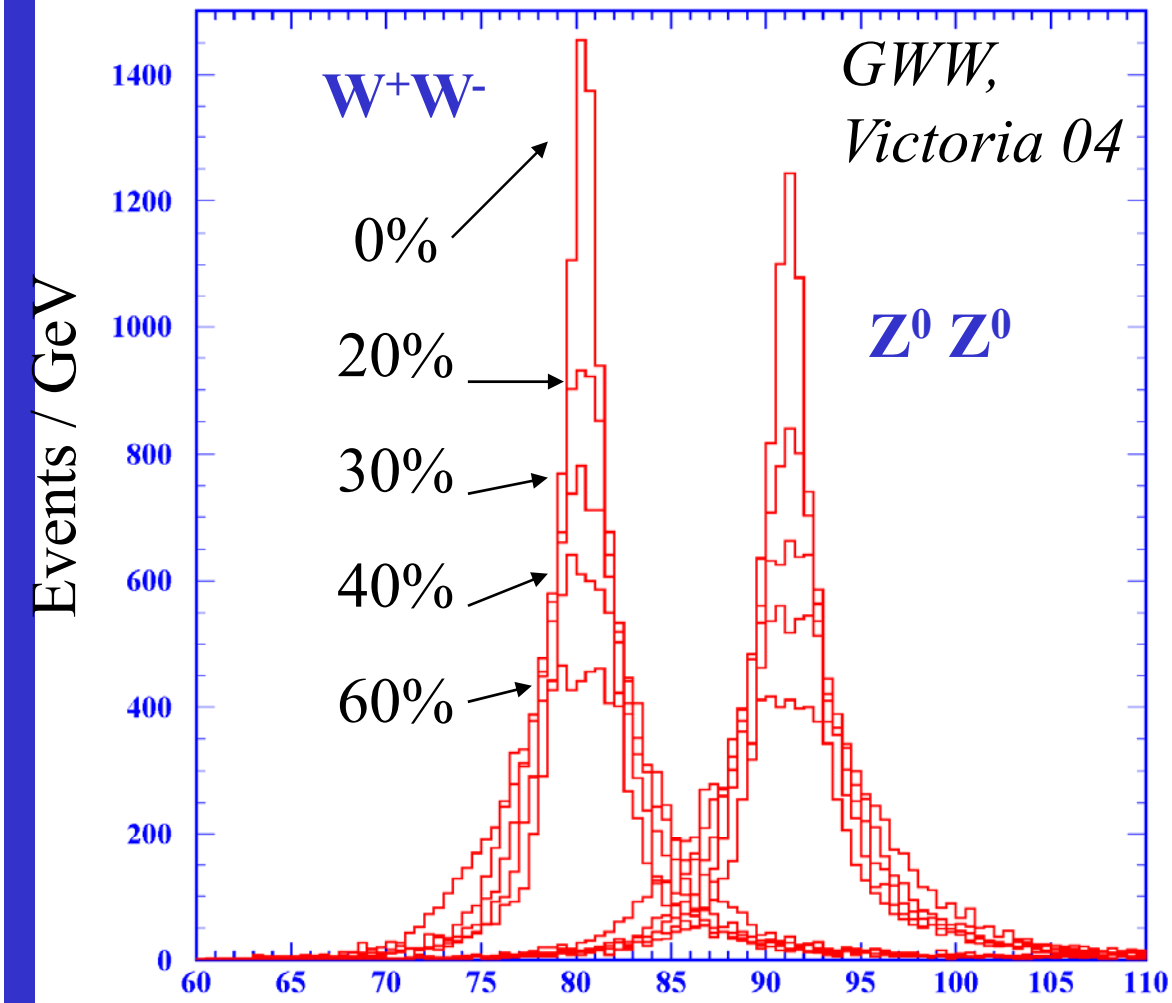
Expect: $\sigma_E/E = 11\%/\sqrt{E}$ at low energy

Principal physics design criteria

- Hermeticity
  - Lots of ν's from W, Z.
  - Sensitivity to some SUSY possibilities critically linked to hermetic design to smallest possible angle.
  - Emphasis on electro-magnetic hermeticity.
- Particle Flow

- Design suited to general purpose e^+e^- experiment
  - Particle flow may be the main driver of the overall detector concept, but eg. intrinsic EM resolution should not be forgotten.
  - Eg. fast timing.

Di-jet mass distribution vs E_{jet} resolution



No kinematic fits, just direct measurement

Average di-jet mass (GeV)

Comparing $e^+e^- \rightarrow WW$ and

$e^+e^- \rightarrow ZZ$ at $\sqrt{s}$=300 GeV

$\langle E_{jet} \rangle$ = *75 GeV*

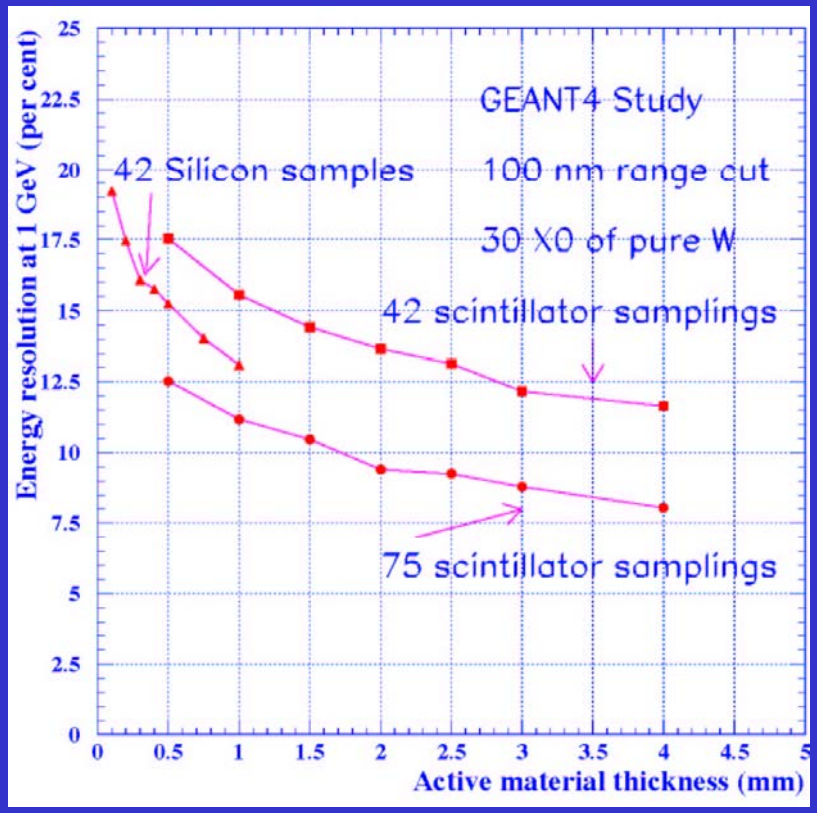
(hadronic decays only, assume WW:ZZ = 1:1 for illustration)

Reality = 7:1 !

$\sigma(E_{jet})$ = xx%$\sqrt{E_{jet}}$(GeV)

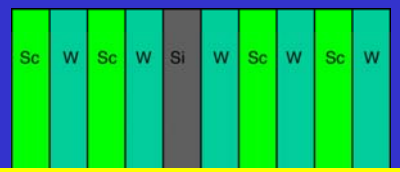
30%$\sqrt{E_{jet}}$ is a good target. Physics (Γ_w=2 GeV) may demand even more !

EM Resolution Considerations



Want many layers, low cost, compact, excellent granularity

(Old) studies of hybrid structures:



HY75	HY135	HY42
• 1.4mm W plates	• 0.778mm W plates	• 2.5 mm W plates
• 15 layers Si	• 15 layers Si	• 14 layers Si
• 60 layers of 1.5mm Scint.	• 120 layers of 1mm Sc	• 28 layers of 2 mm Sc
• 4 layers ganged (30 pe/mip) (if 5pe/mip/mm)	• 8 layers ganged (40 pe/mip)	• 2 layers ganged (20 pe/mip)
• 15 super-layers each with mip-detection	• 15 super-layers	• 14 super-layers

E res :	10.4%/√E	7.7%/√E	14.3%/√E
Moliere radius :	19.3 mm	21.4 mm	16.5 mm

33% of the Silicon cost

(SDMar01 30X_0 W : 15.4%/√E, 15.5 mm)

Montpellier, 14 Nov 03 Graham W. Wilson 24

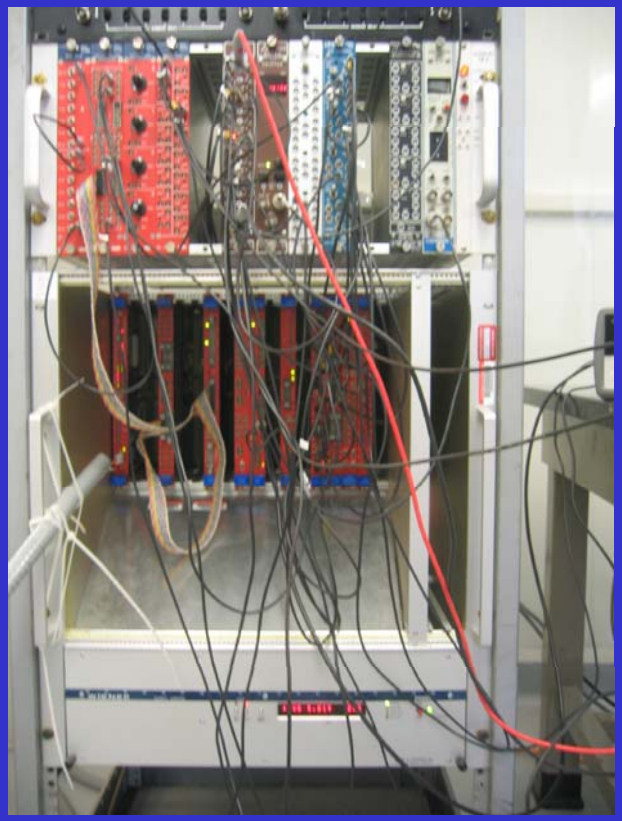
Si-Sc. correlations used to improve resolution.

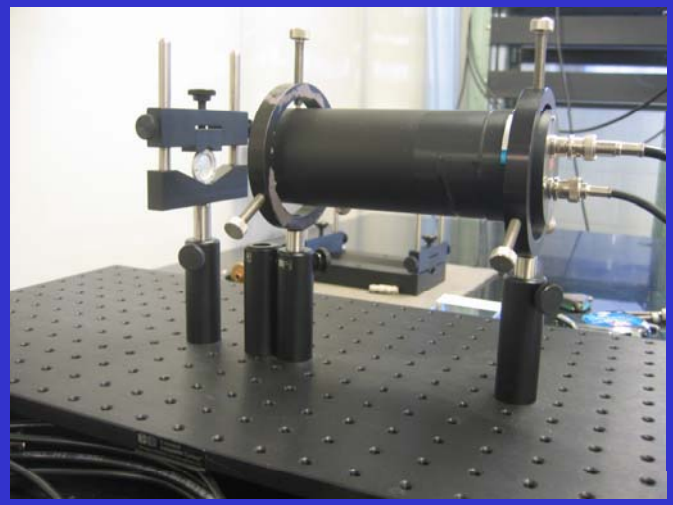
Mechanical design likely to be difficult.

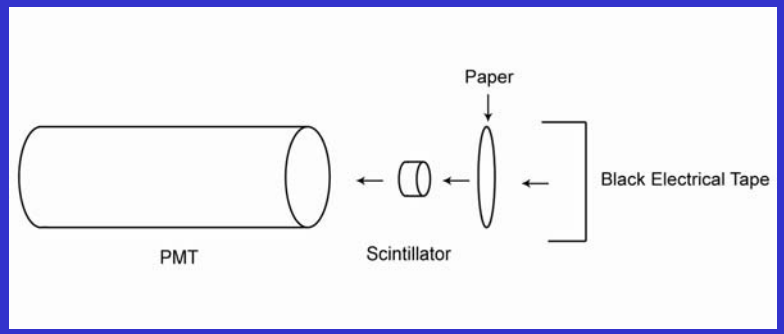
Developing Lab

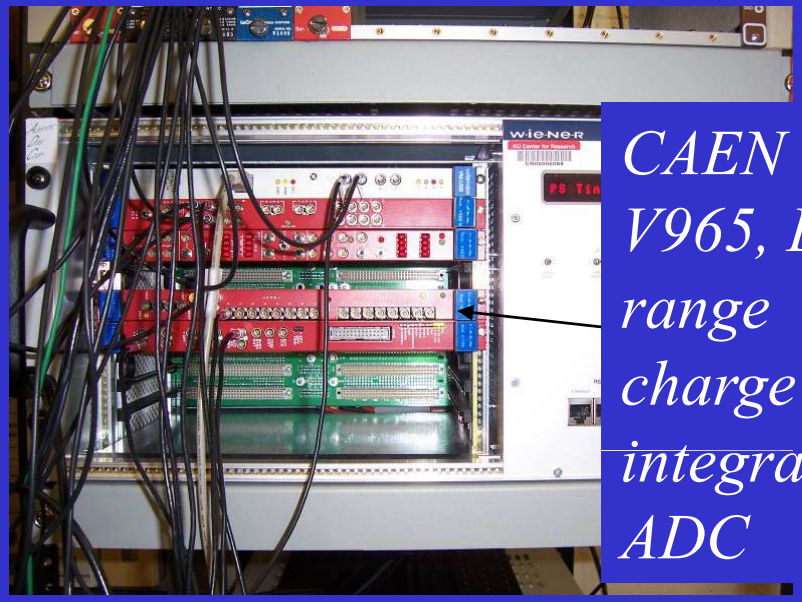
- Aims:
  - Develop in-situ ability to appreciate technical feasibility of different approaches.
  - Test single planes of detectors well before going to test-beam.
  - Test simulation of particle interactions with matter with available tools.
  - Train and motivate students in research, particularly detectors, DAQ and electronics. (This sells well with NSF … we need to get them more engaged in ILC science…)

Lab Measurements with Sources and Cosmics





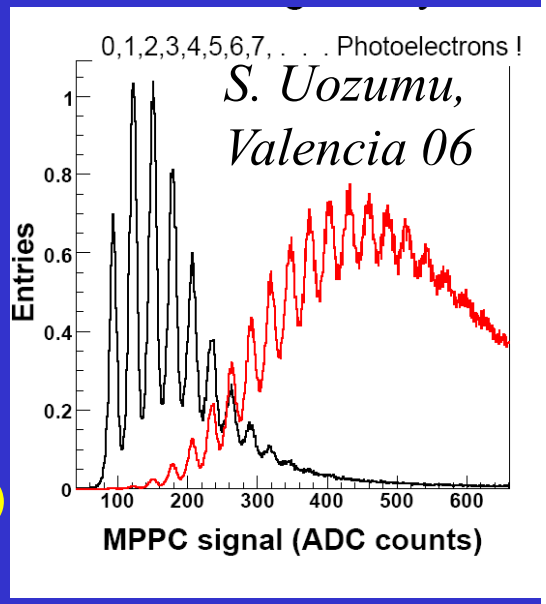




CAEN V965, Dual range charge integrating ADC

Calibration strategy ?

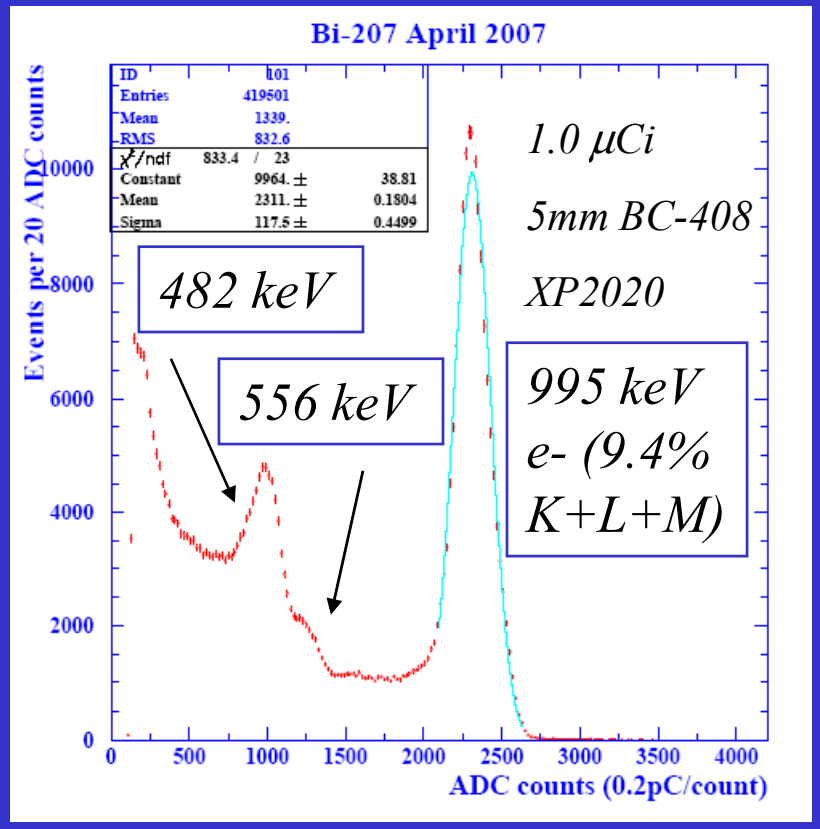
- Typical detector designs have MANY cells.
- Essential physics calibration is ADC → deposited energy
- In the Si-PM era, pe → ADC calibration is straightforward (modulo saturation).
- In thin active media, like ECAL Scintillator, calibration with sources may be an attractive, high statistics way to deal with non-uniformities, saturation, material thickness etc.
  - Current thinking is centered on procedures which could certainly be carried out during production, and maybe also in situ. (especially if push/pull is realized !)
  - Following plots are data with a conventional PMT setup (self-triggered) aimed at commissioning ability in a well defined setup before going on to applying to technologies suitable for ILC such as thin tiles.
  - Should also investigate **time** resolution and calibration, and material budget control techniques (also for tracker).
  - Can check low energy EM interaction detector response simulation.

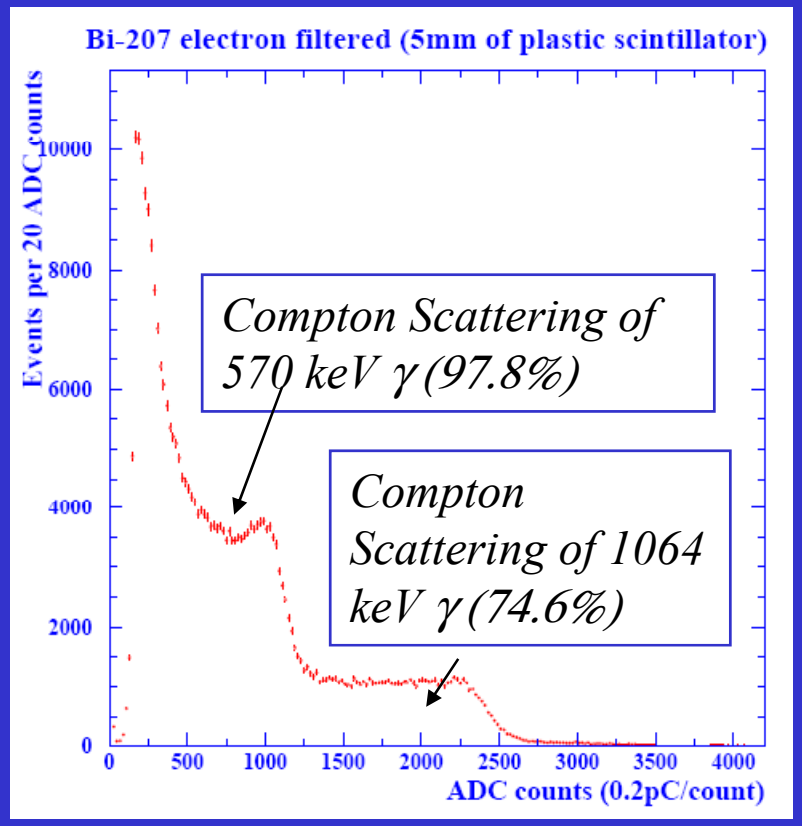


Exploring Calibration Strategies

Bi-207 with Al mylar window: internal conversion electrons.

All plots are data with 5mm BC-408 scintillator.

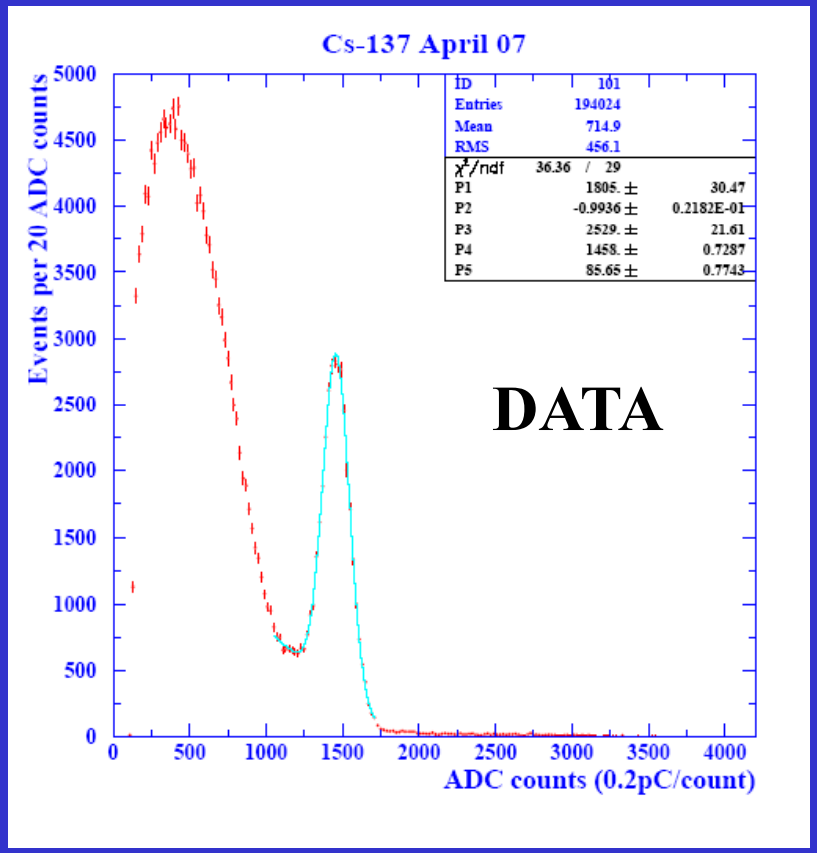


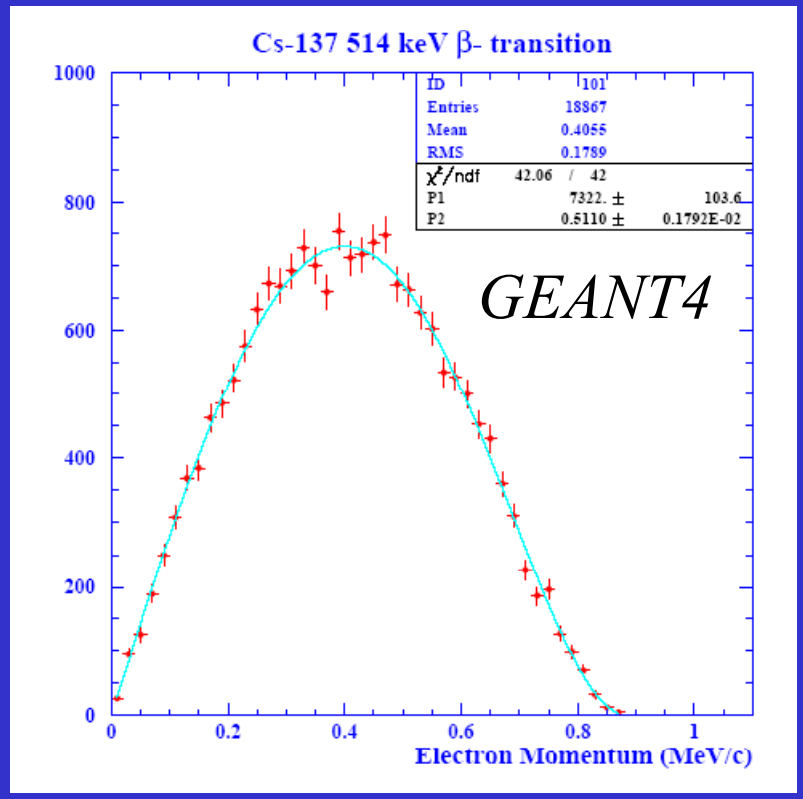


Absorption peak σ_E/E = 5.5%. (intrinsic splitting: 3.3%). Energy scale stat. error of < 0.01% !

Energy loss in upstream material, leads to the 482 keV e^- peak overlapping with 570 keV Compton edge (393 keV)

Cs-137





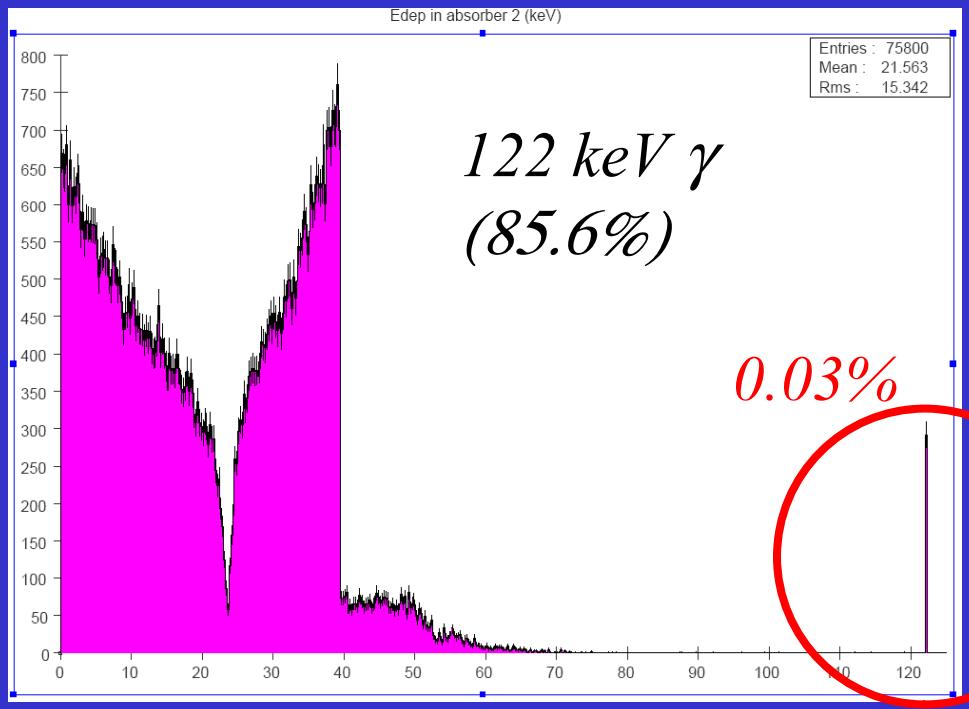
γ: 662 keV (85.1%)

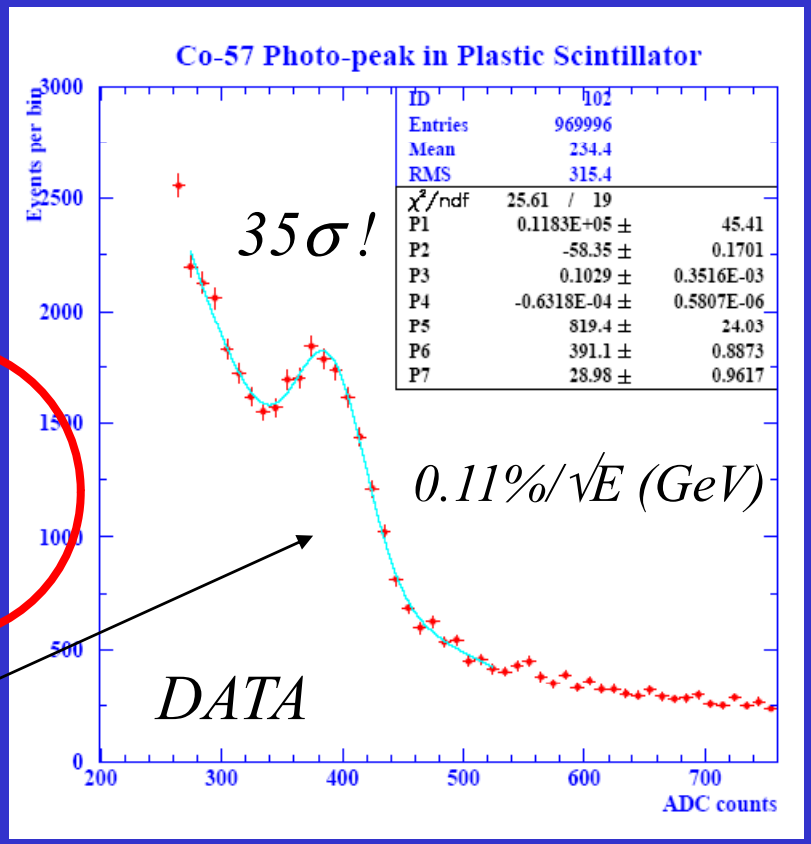
e^- : 624 (7.7%), 656 (1.4%)

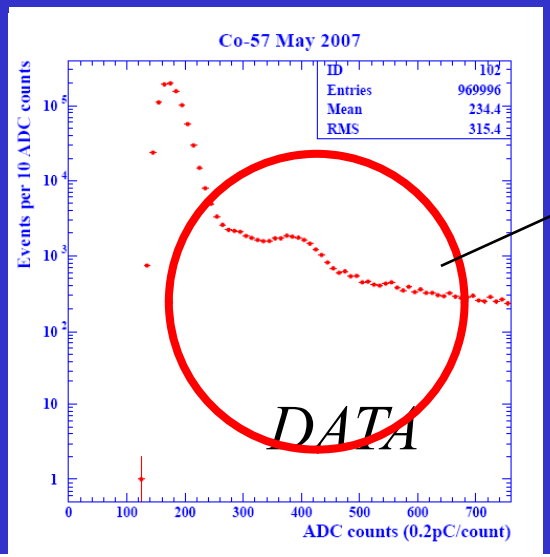
β_1: 514 keV endpoint (94.4%)

β_2: 1176 keV endpoint (5.6%)

Co-57 ($t_{1/2}$=272 d)



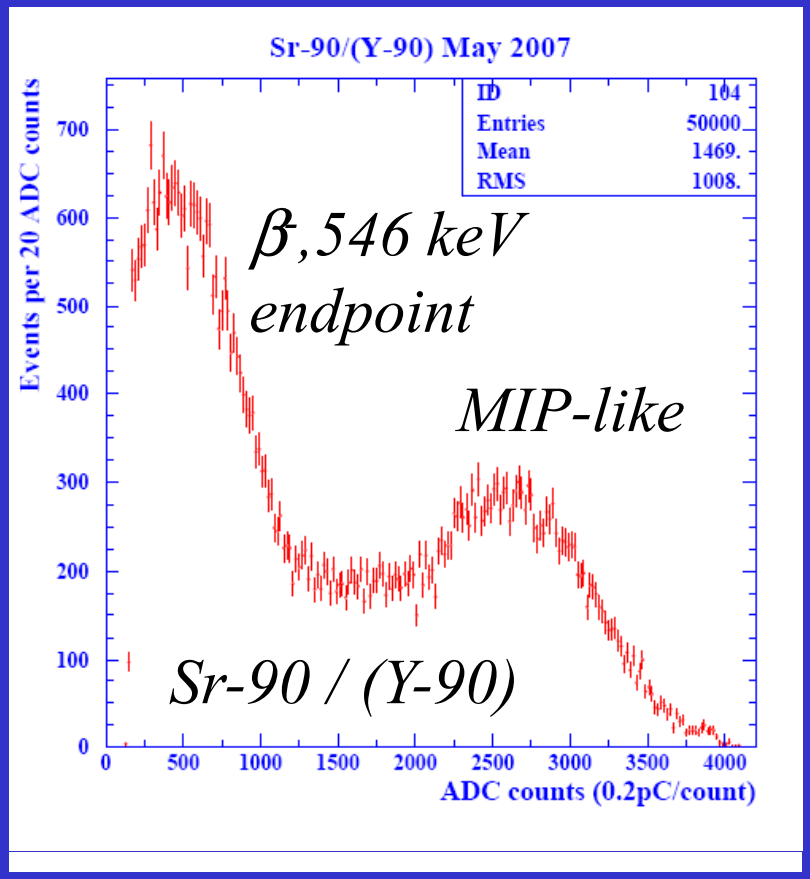


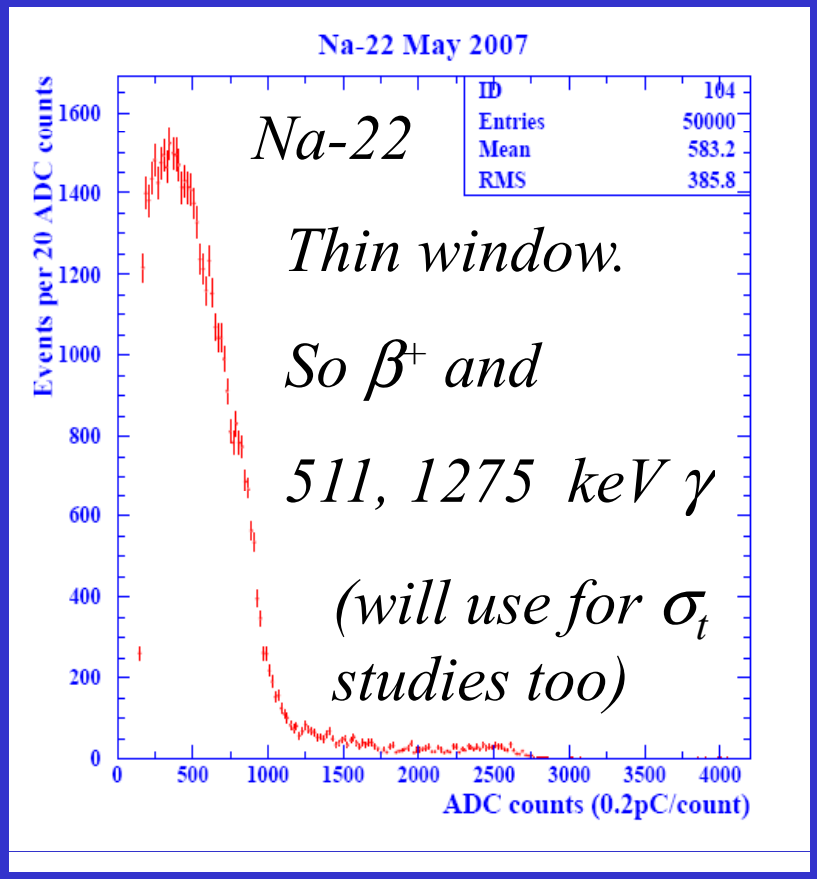


Full-energy peak corresponding to 0.1 MIP.

Lower energies (eg. Am-241, 60 keV) with higher full-energy efficiency could be interesting. (Or Pb-loaded scintillator ...)

Check response to various EM particles





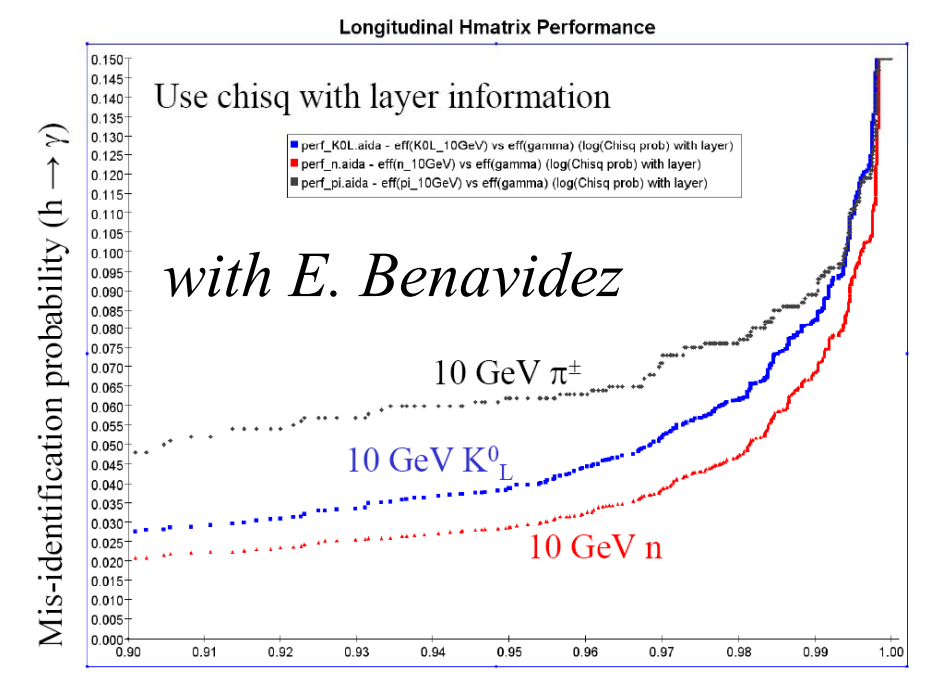
Relativistic electrons

Positrons and gammas

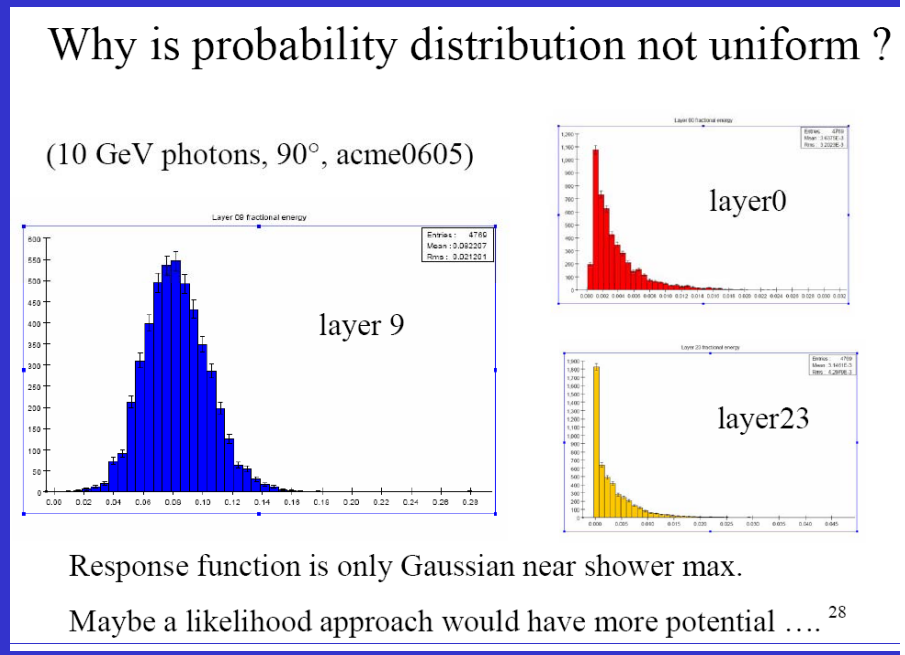
Photon / neutral hadron separation

Use covariance matrix of the energies measured per layer to discriminate photons from neutral hadrons. (H-matrix method initially developed by N. Graf)

Uses SiD-like acme0605 detector (20+10 layers). In the US software framework which promises flexibility in studying various detector designs

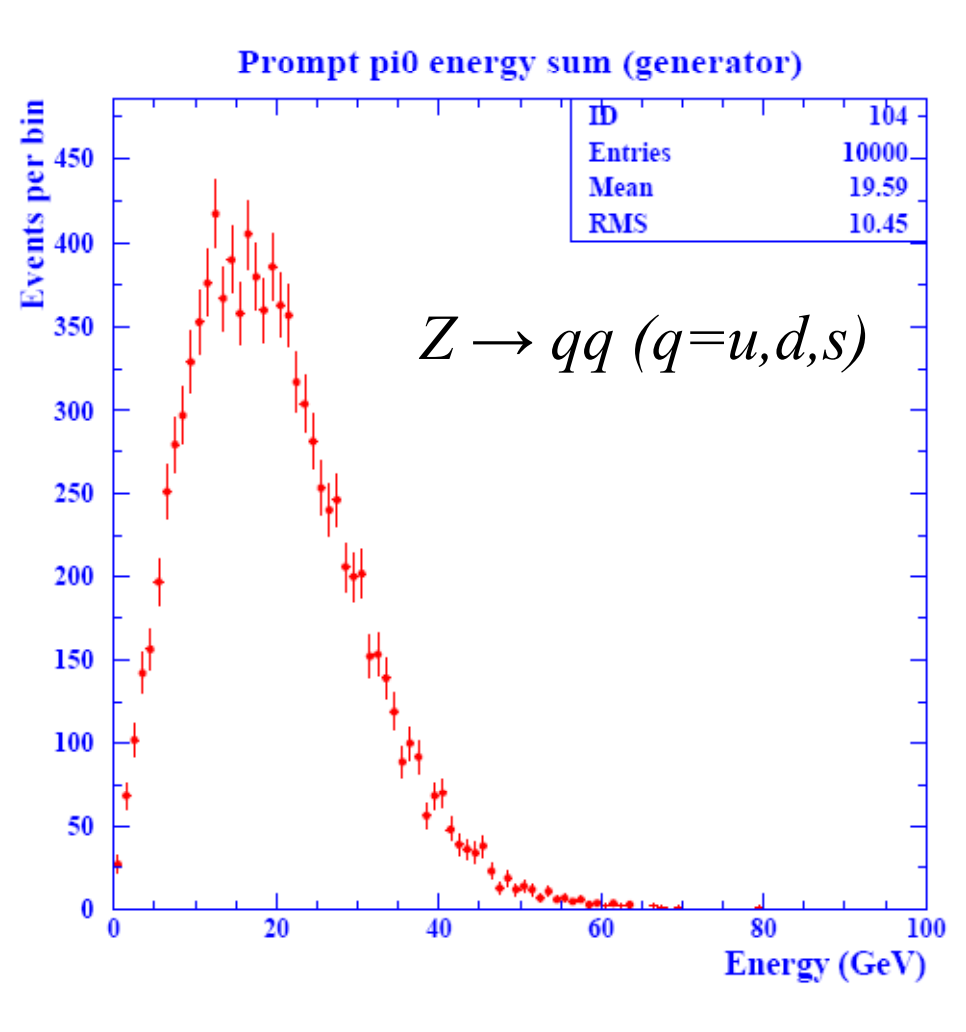


Efficiency for 5 GeV γ



Note: more coherence on software frameworks would help somebody like me contribute effectively to LDC, GLD and SiD.

Prompt EM energy component of jets



Dominated by π^0's.

Defined as prompt if they are produced within 10 cm of the IP.

*On **average**, with 16%/√E EM energy resolution, the intrinsic EM resolution contribution to the jet energy is 0.71 GeV corresponding to 7.4%/√Ejet.*

Can potentially reduce this contribution using π^0 mass constraint. May drive ultra-fine position resolution (eg. MAPS) and/or lead to an option of saving some Silicon layers.

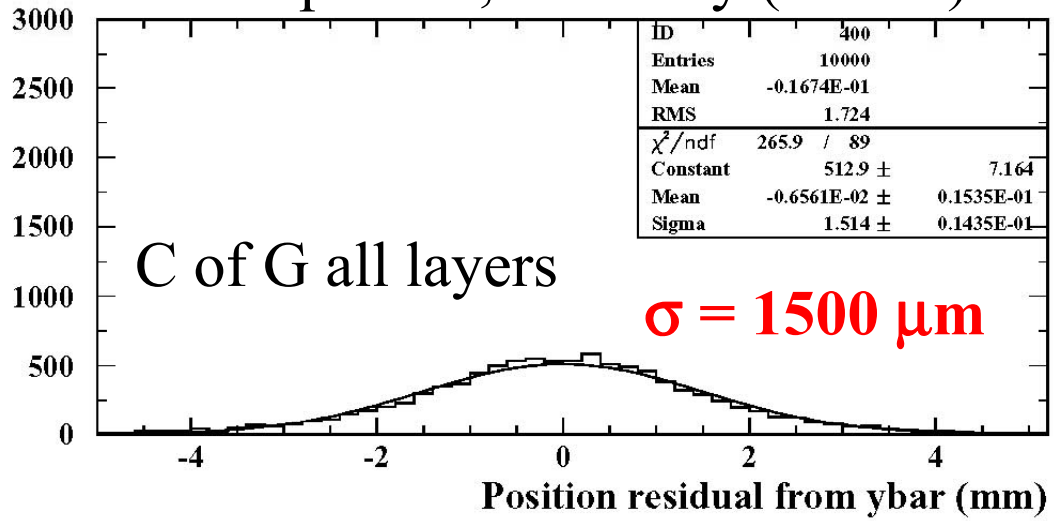
Position resolution from simple fit

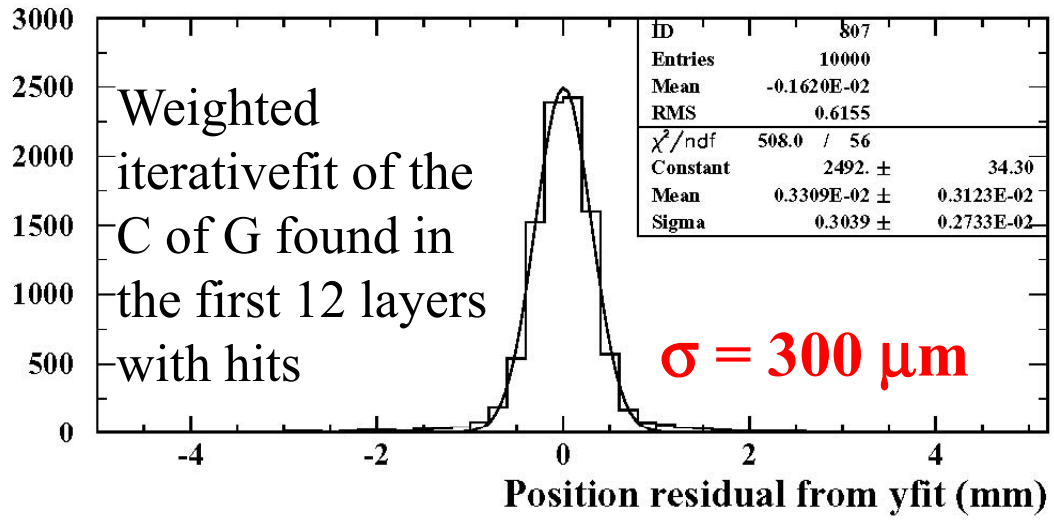
Key: measure the shower really well near the conversion point ($\gamma \rightarrow e^+e^-$)

*2004 study with 1mm*1mm Si pixels (pre-MAPS I thought this was unbuildable ...) and 42 layers with sampling every 5/7 X_0*

Position resolution does indeed improve by a factor of **5** *in a realistic 100% efficient algorithm!*

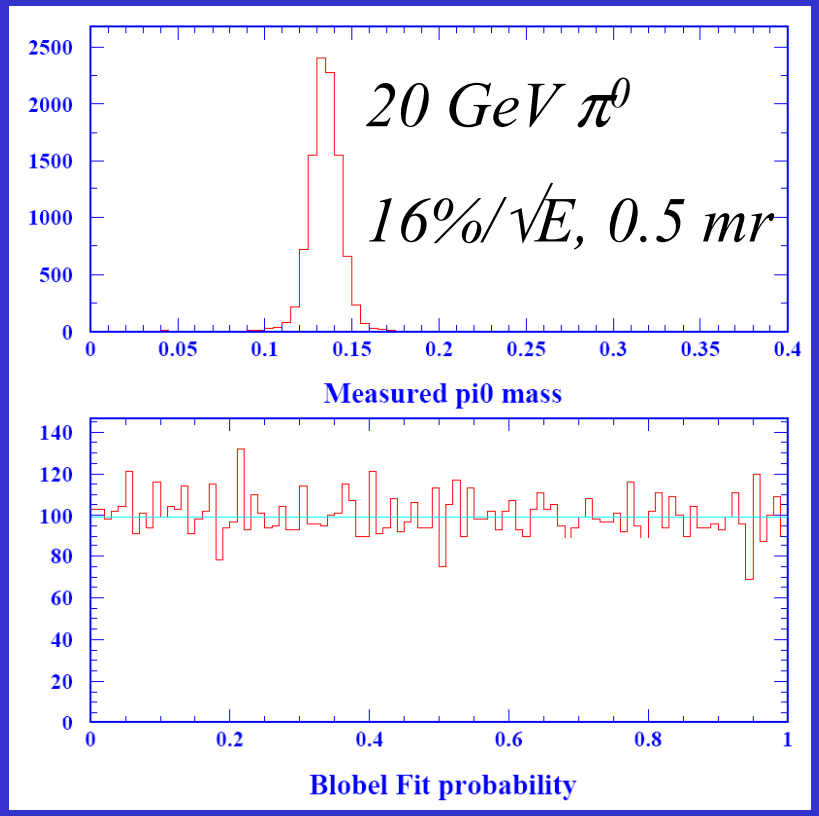
1 GeV photon, G4 study (GWW)

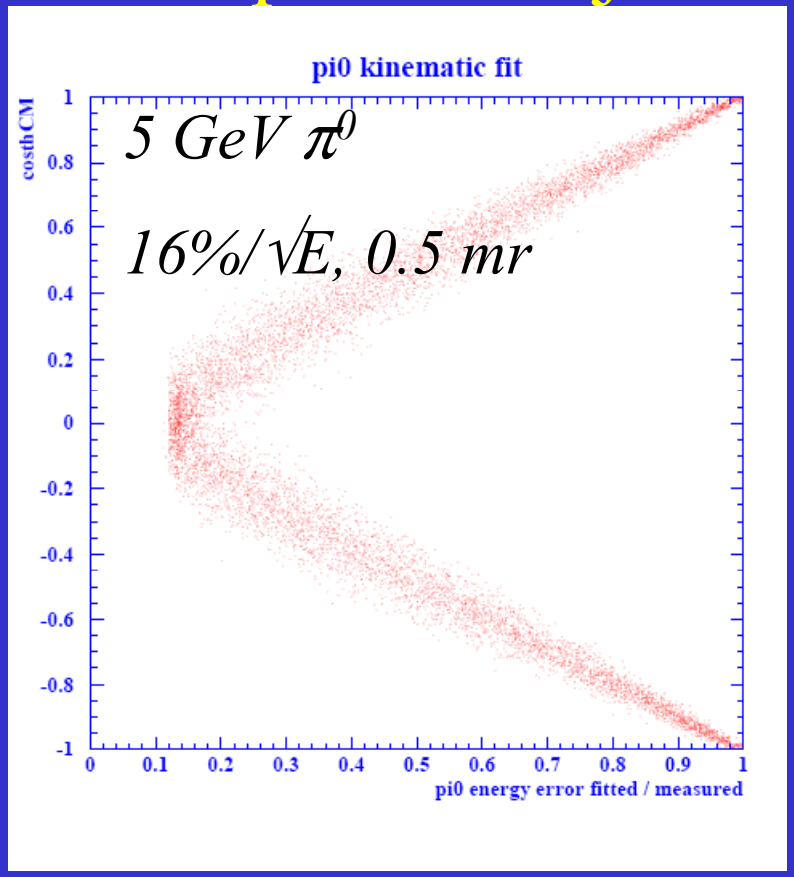




Still just d/√12 !

Comprehensive study of applying mass-constrained fit for π^0's to improve the energy resolution of the *prompt* EM component of jets





See talk at Valencia meeting for more details. Proof of principle of the intrinsic potential per π^0.

NOTE: Not only does the resolution improve, the resolution is known per pair

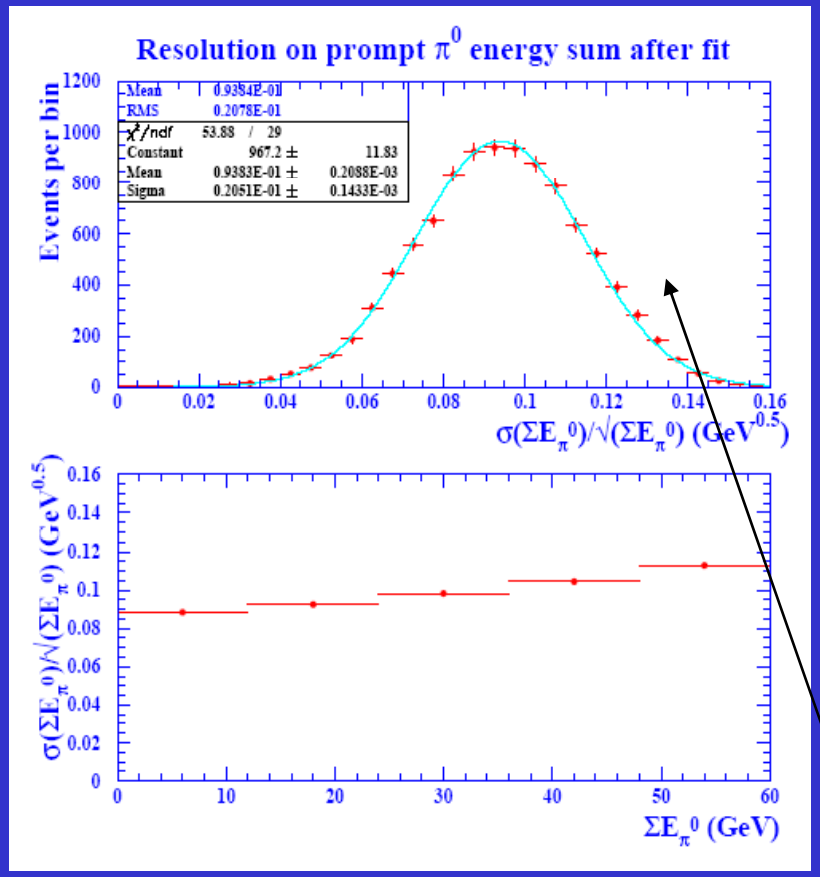
Practical Implementation for Hadronic Events

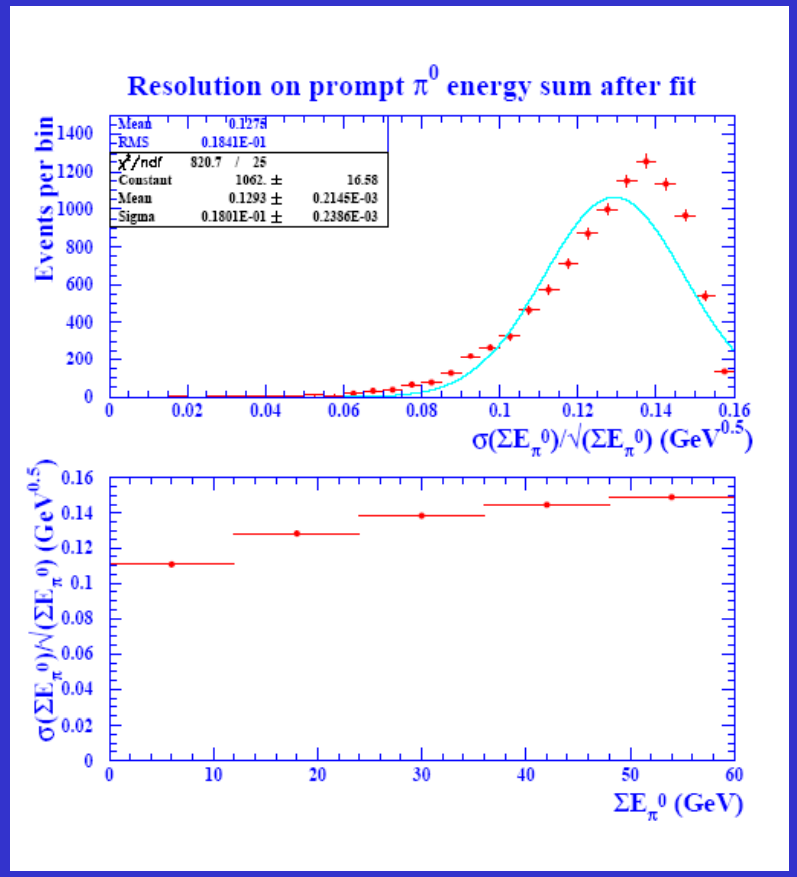
- 1. Assume perfect pairing of photons to π^0s.
  - Estimate improvement.
  - Study implications for detector.
- 2. Implement an assignment algorithm which associates sibling photon pairs to parent π^0s.
  - Now have a first implementation which can probably be improved considerably. Lots of work still to do here.
- 3. Implement in the context of full simulation of a particular detector model.
  - Need to care about photon calibration, resolution functions, purity, efficiency etc. (Clermont-Ferrand group, is working on this aspect for LDC). See P. Gris talk, work by C. Carloganu.

Applying mass-constraint to Z → hadrons

Assumes ***perfect pairing*** *of sibling photons to parent* π^0

(currently restrict to prompt π^0*s defined as originating within 10 cm of IP)*





16%/√E, $\Delta\psi_{12}$*=0.5mr*

16%/√E, $\Delta\psi_{12}$*=8mr*

Potential to improve resolution on average to 9.4%/√E

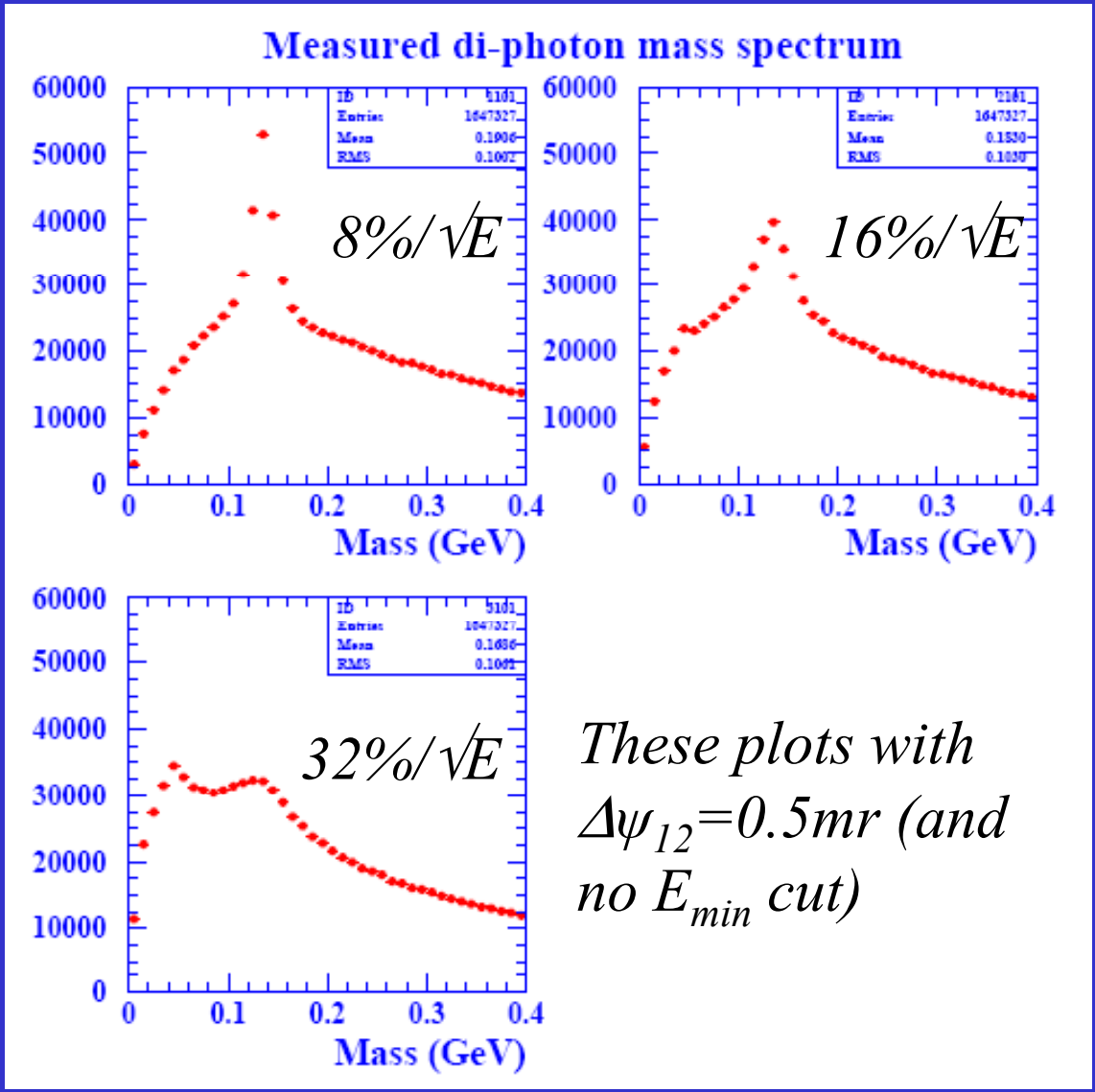
Summary on potential with perfect pairing

ECAL Energy Resolution (%)	No fit	Fit (0.5 mrad)	Fit (2 mrad)	Fit (8 mrad)
8.0	8.0	4.9	5.8	6.8
16.0	16.0	9.4	10.7	12.7
32.0	32.0	18.3	19.9	23.4

Table 1: *Average normalized fractional energy resolution (%) on the total prompt π^0 energy in light-quark Z events with and without kinematic fitting for different assumptions on the ECAL energy resolution stochastic term, and the di-photon opening angle resolution assuming perfect pairing in the kinematic fit. Errors are less than 0.1%.*

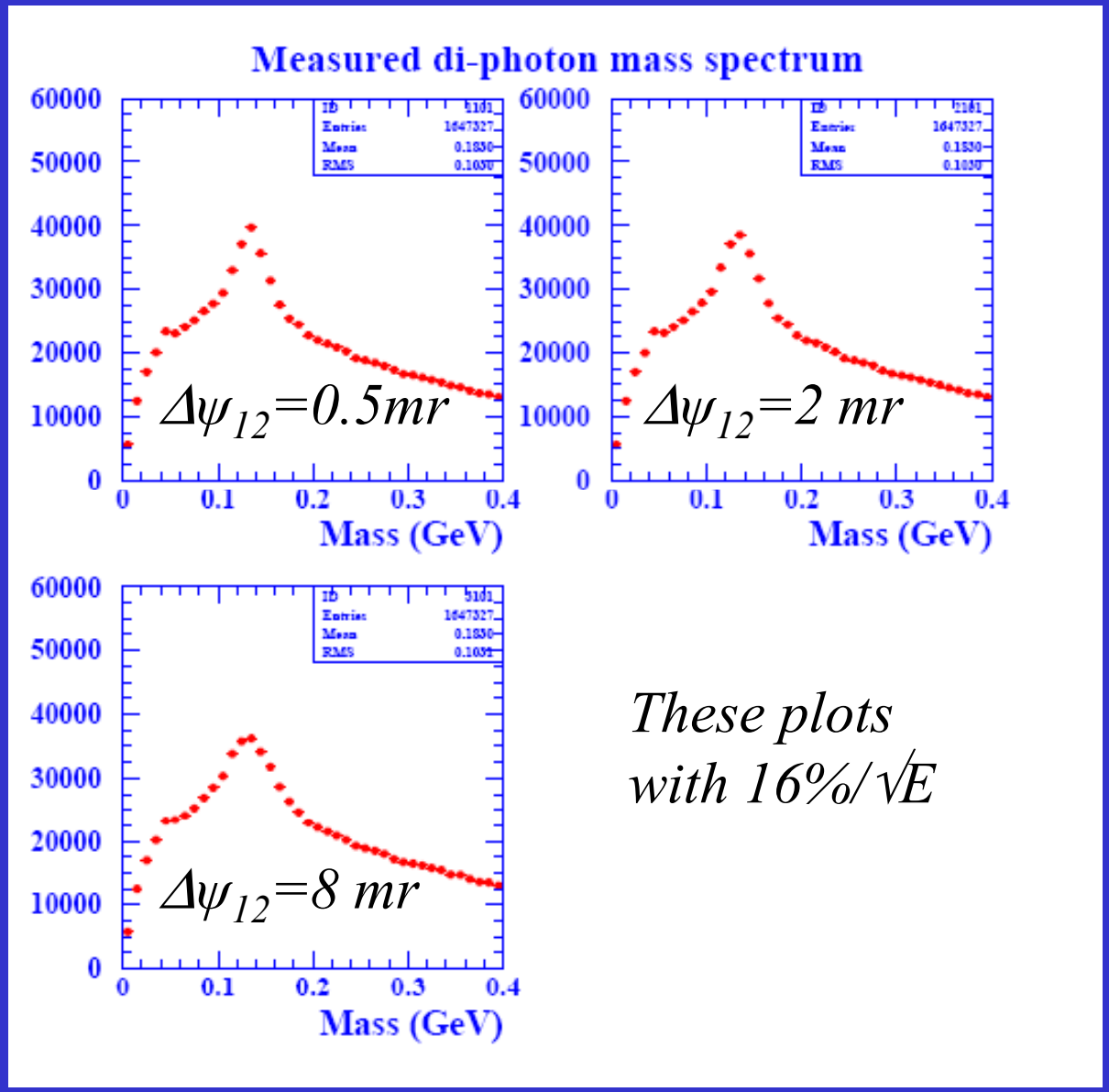
Include (vast) combinatorics

$\langle n_{\pi 0} \rangle = 8.6$



These plots with $\Delta\psi_{12}$=0.5mr (and no E_{min} cut)

Same, but vary opening angle resolution



Assignment Algorithm

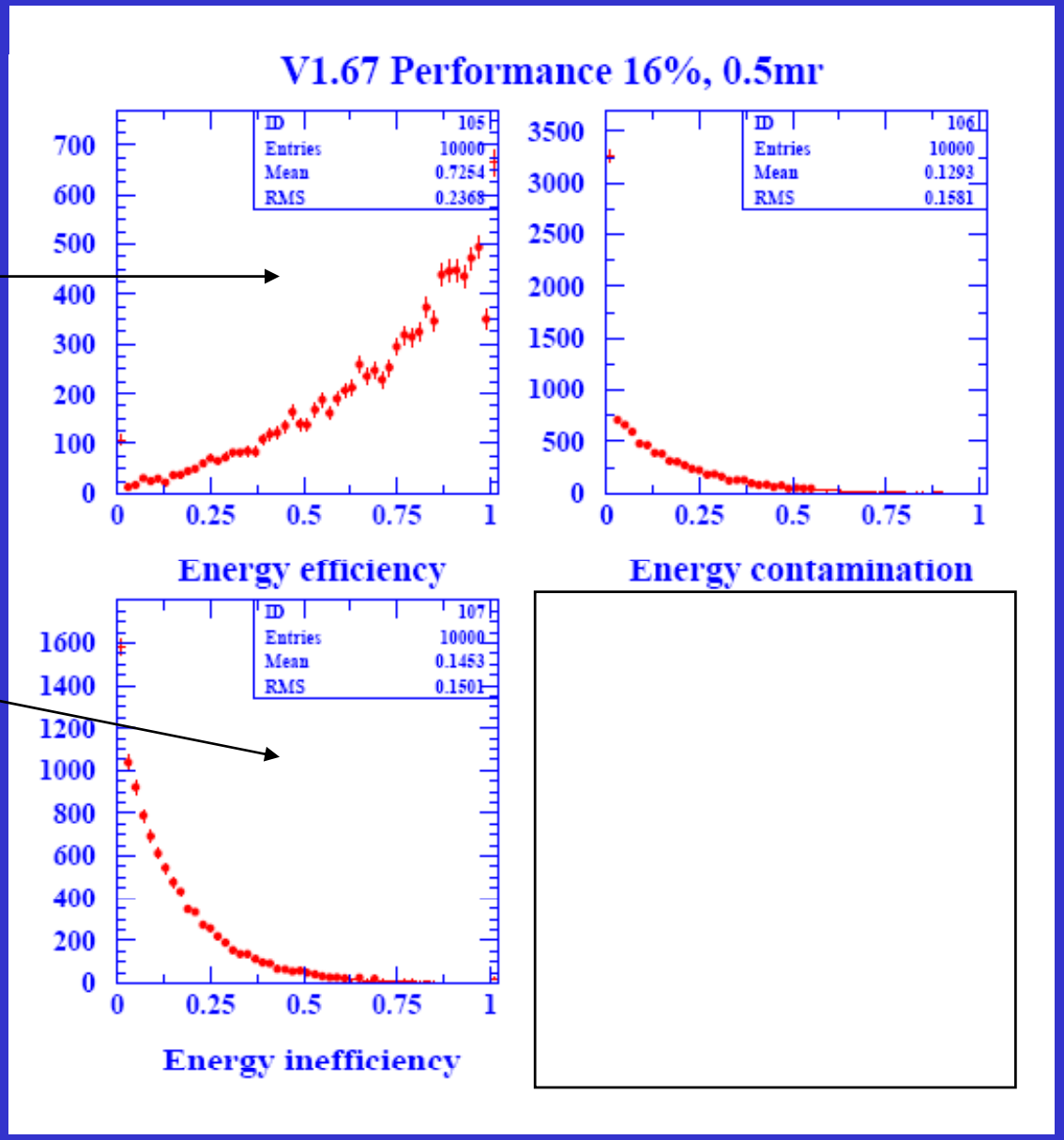
- Very basic so far. (Snap-shot)
- $E_\gamma > 0.1$ GeV
- $p_{fit} > 1\%$
- Form $\chi^2_{mass} = [(m - m(\pi^0))/0.07]^2 \rightarrow p_{mass}$
- Use a discriminant, $D = p_{fit}\, p_{mass}\, E_{\pi 0} / \sigma_m$
- Using energy sorted photons, assign photons to pairings if they have the highest D for both photons.
- Unassigned photons, contribute with their normal measured energy.
- Performance may be strongly dependent on the actual combinatorics.
- Have also looked into a more global method of assignment using assignment problem methodology. Currently pondering how to enforce one-to-one assignment, while taking advantage of N^3 rather than N! scaling of standard techniques.

Performance

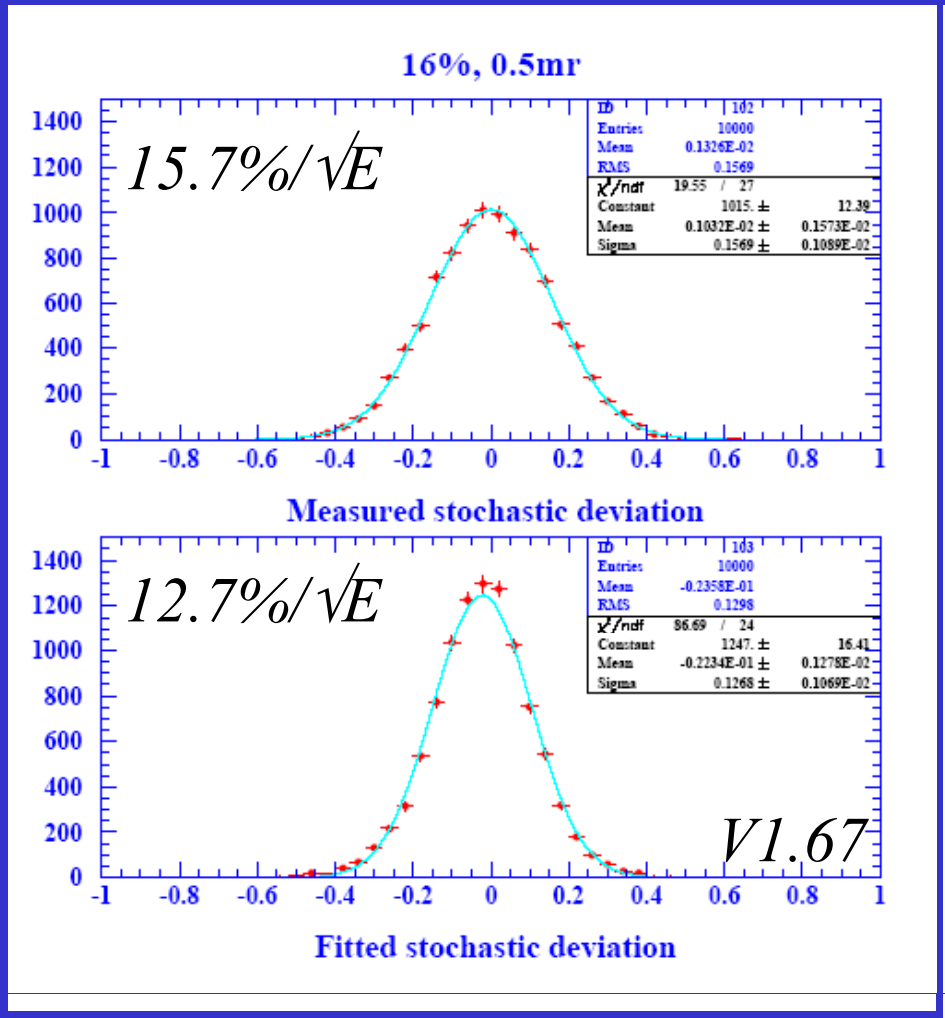
Fraction of prompt π^0 energy correctly fitted, ε_c

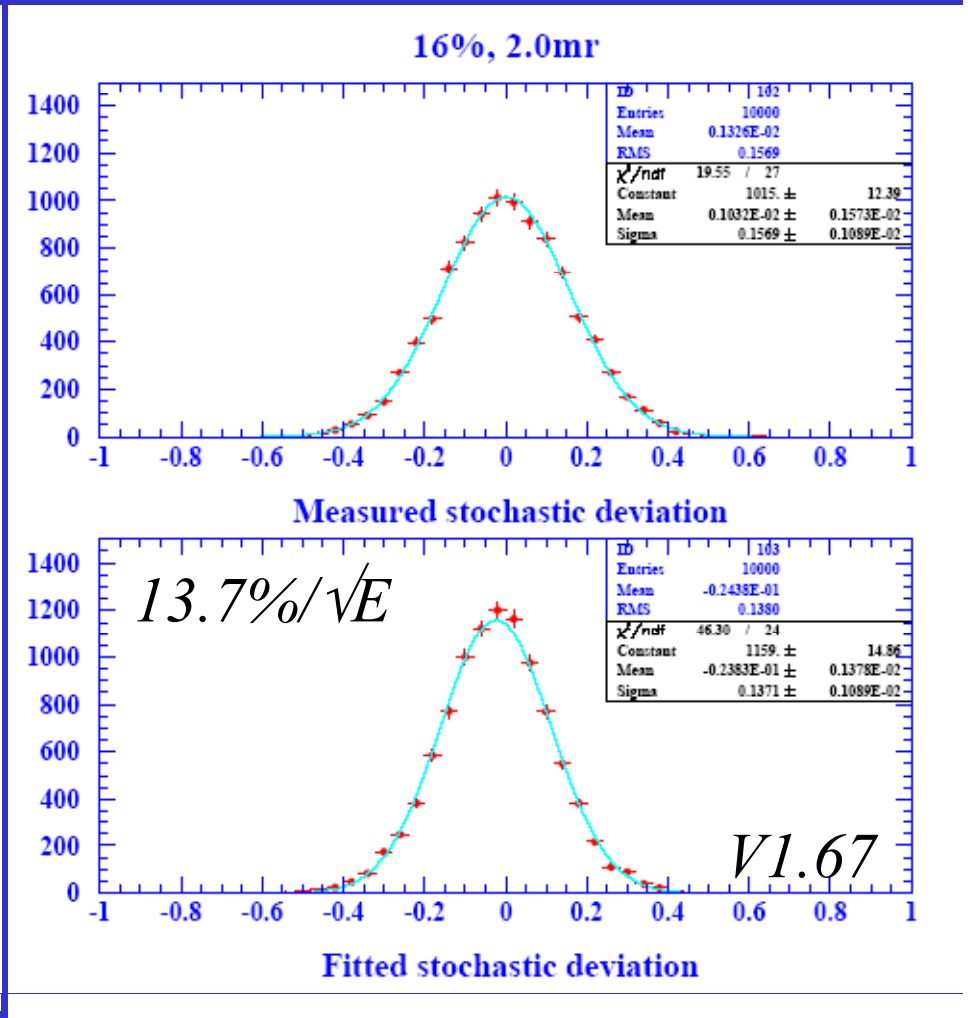
Fraction of prompt π^0 energy wrongly fitted, ε_W

Fraction of prompt π^0 energy unfitted, ε_{UF}



Results (10k Z events)

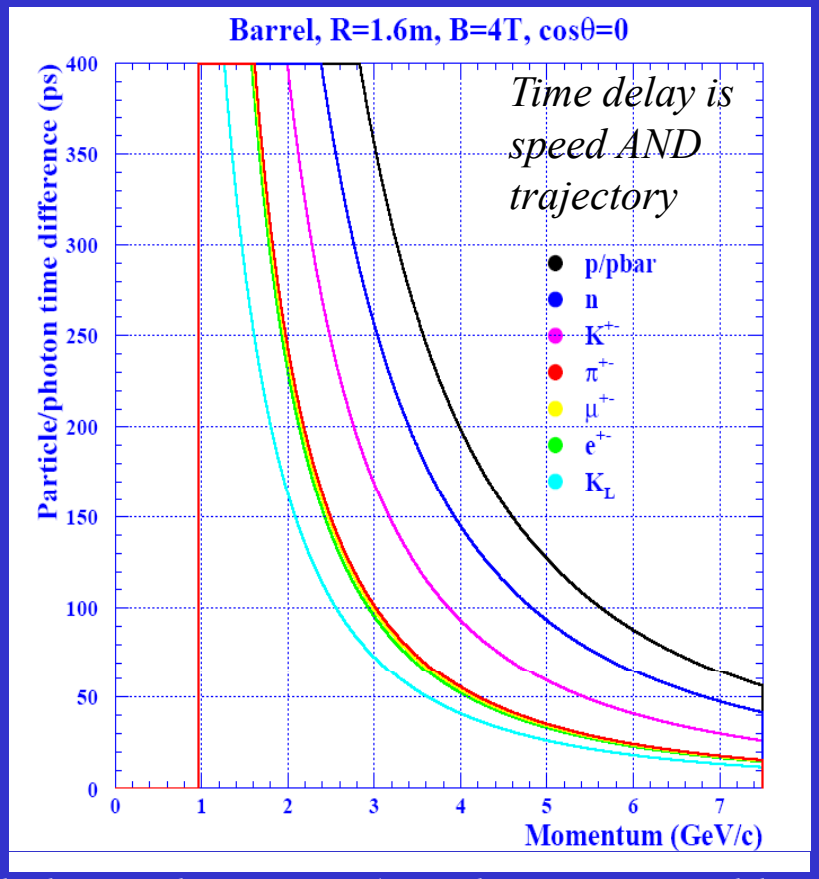


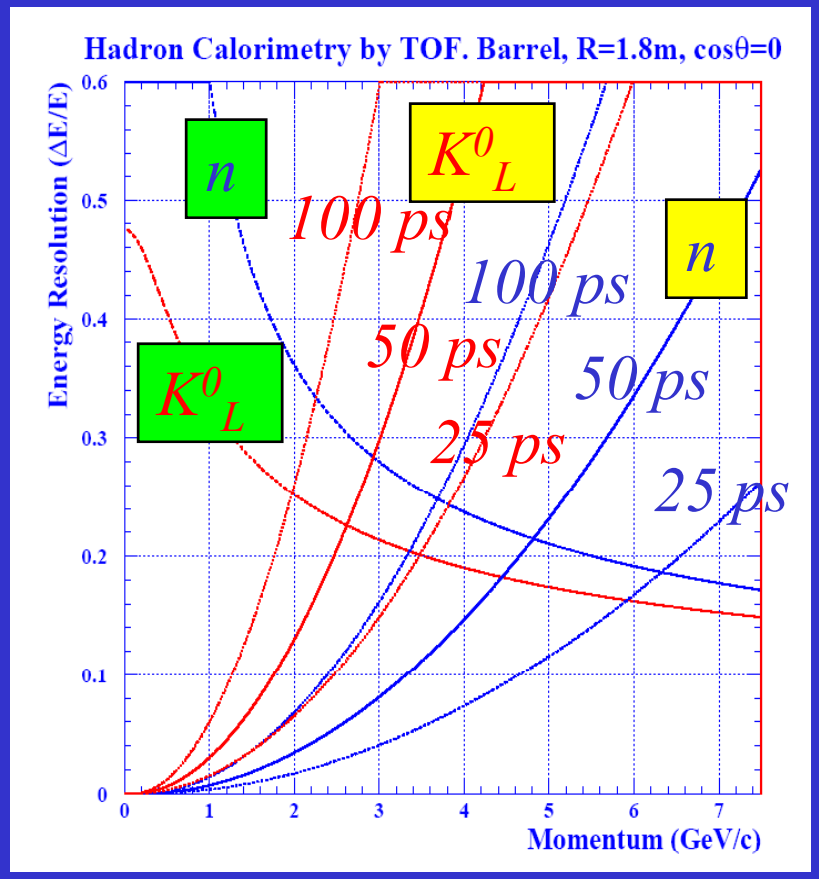


Fast Timing / Temporal Calorimetry

Idea: time resolution at below the 100 ps level is easily achievable with dedicated detectors. Can it be applied in a useful way in an ILC detector ?

Can TOF help measure neutral hadrons at low p ?





Can help resolving γ/π. (PID by TOF possible – but redundant with dE/dx in a TPC-based detector). Resolve confusion.

HCAL (LDC DOD) *TOF*

Possible Detectors ?

- State-of-the-art: MCP-PMT, σ_t = 5 ps measured using Cerenkov light in 10mm quartz, K. Inami et al, NIM A 560 (2006) 303.
  - Also see emerging "fast-timing" initiatives. (Fritsch, LeDu)
- Cerenkov layers – also designed for C-based compensation.
- Ultra-fast scintillator pads with direct-coupled thin B-field tolerant photo-detectors tiled in a few layers through the calorimeter ??
  - Eg. quenched scintillators with FWHM of 400 ps per γ. (BC-422Q)
  - Will do time resolution studies with this.
- RPCs, Peskov
- Scintillating fibers.

Summary

- I believe ILC calorimetry is fertile ground for novel and interesting approaches to full bubble-chamber like reconstruction of events in the context of the PFA approach.
- EM calorimeter contribution to the jet energy resolution can plausibly be considerably improved using π^0 mass constraint.
- Encourage you to help support efforts like this which help build constructively on existing R&D with a view to getting the best physics out of the ILC independent of particular detector technology bias and specific detector design concept.

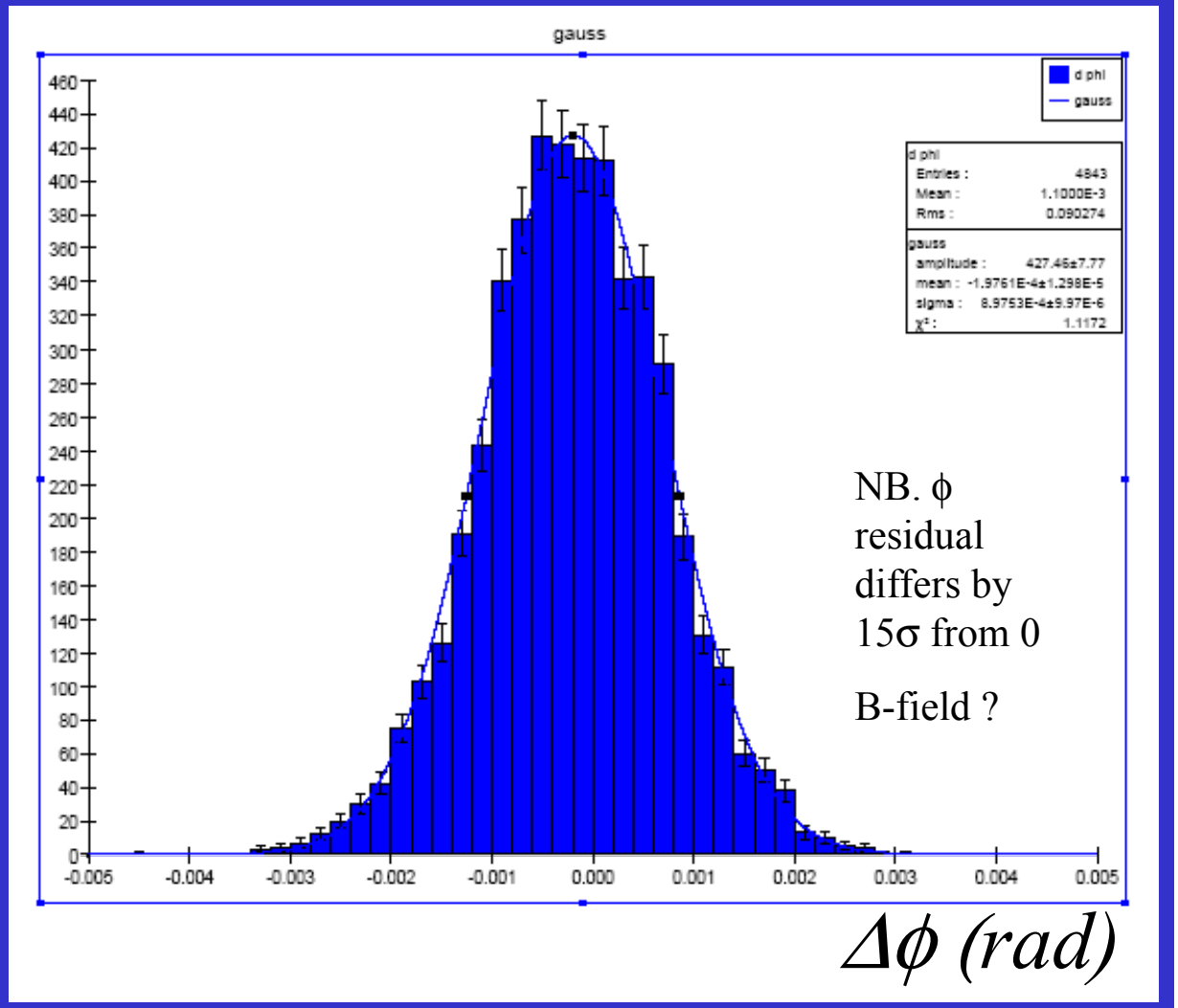
Backup Slides

Angular Resolution Studies

5 GeV photon at 90°, sidmay05 detector (4 mm pixels, R=1.27m)

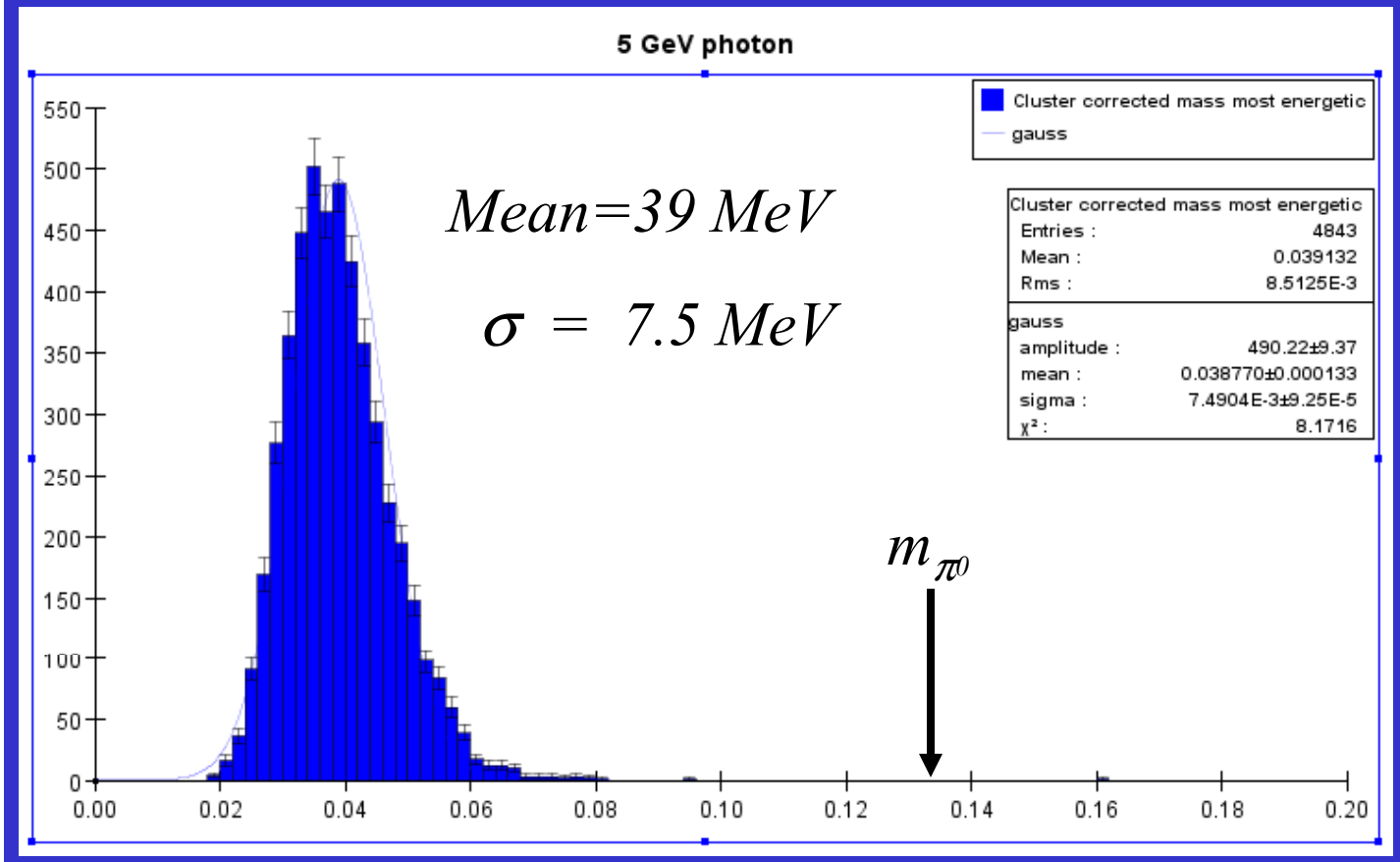
Phi resolution of 0.9 mrad *just* using cluster CoG.

=> θ_{12} resolution of 2 mrad is easily achievable for spatially resolved photons.



NB. Previous study (see backup slide), shows that a factor of 5 improvement in resolution is possible at fixed R using longitudinally weighted "track-fit".

Cluster Mass for Photons



Cluster Mass (GeV)

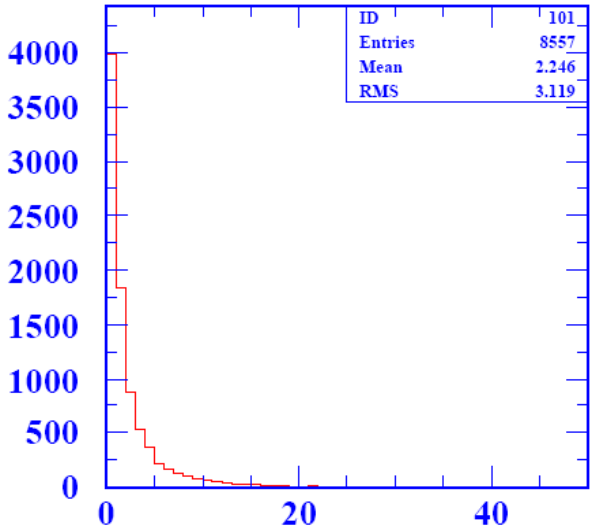
Of course, photons actually have a mass of zero.

The transverse spread of the shower leads to a non-zero cluster mass calculated from each cell.

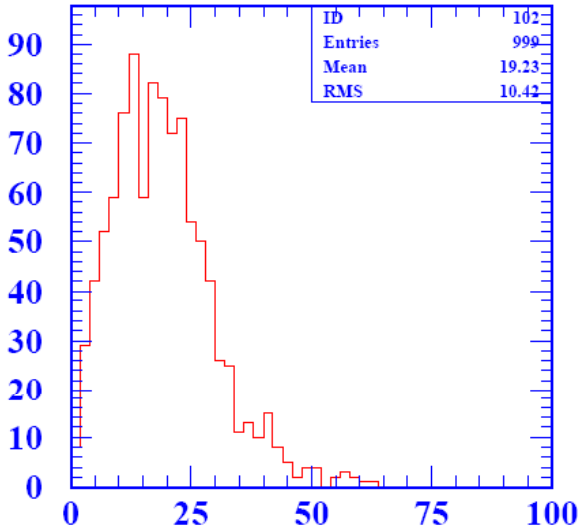
Use to distinguish single photons from merged π^0's.

Performance depends on detector design (R, R_M, B, cell-size, ...)

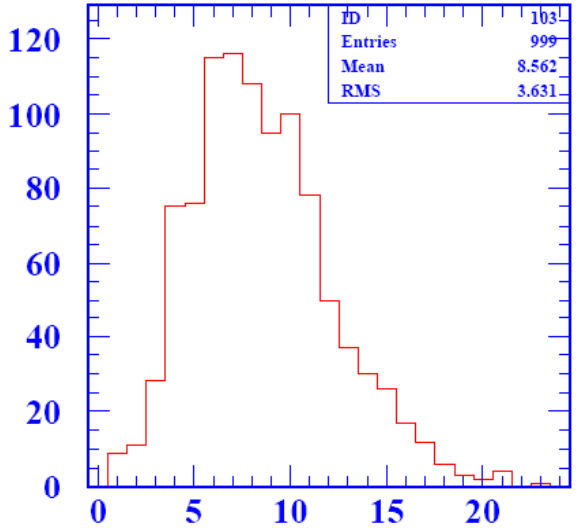
Z to uu, dd, ss at 91 GeV



Prompt pi0 energy spectrum



Prompt pi0 event energy

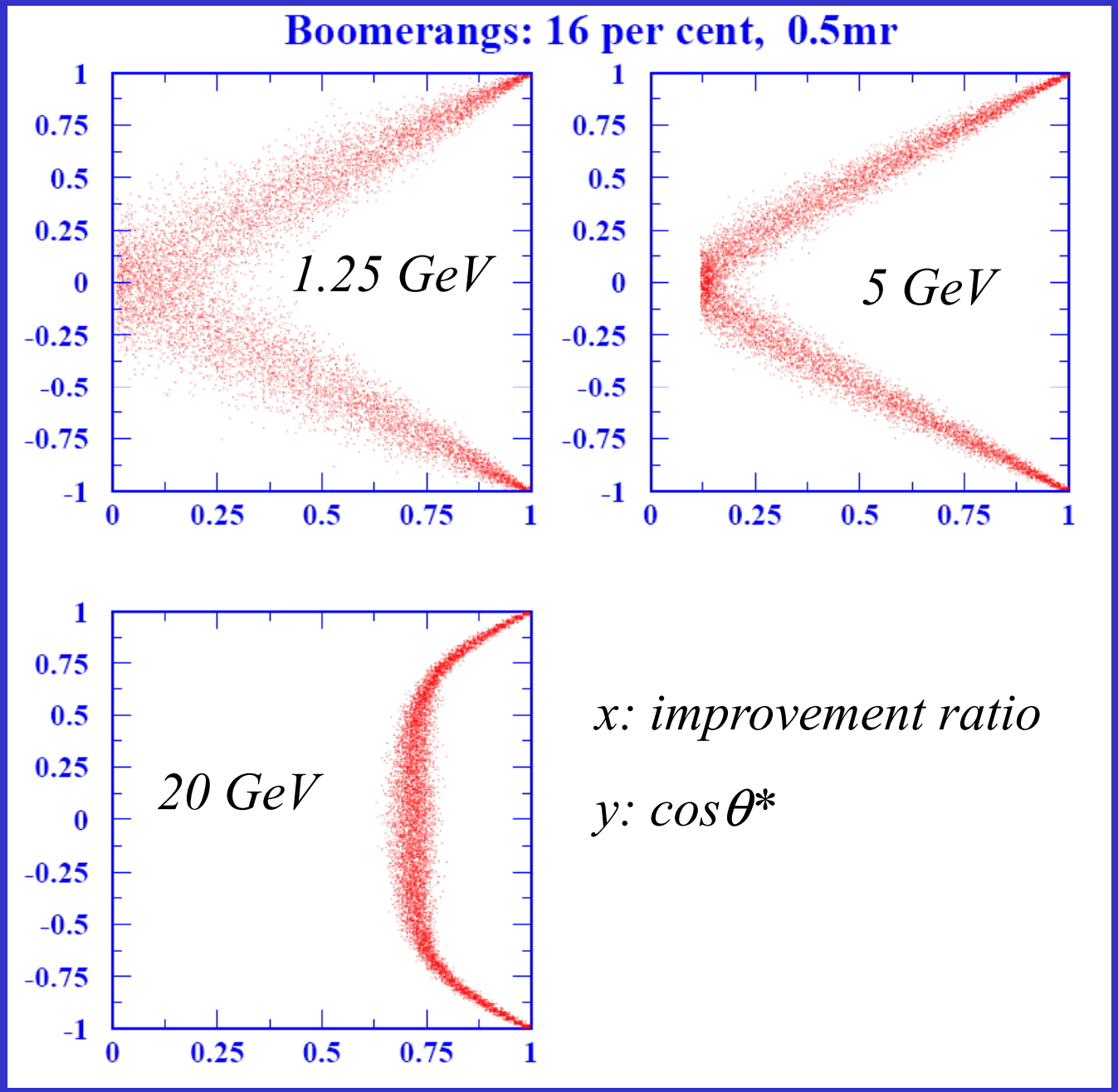


Prompt pi0 count

On average 19.2 GeV (21.0%)

NB generator has ISR and beamsstrahlung turned off.

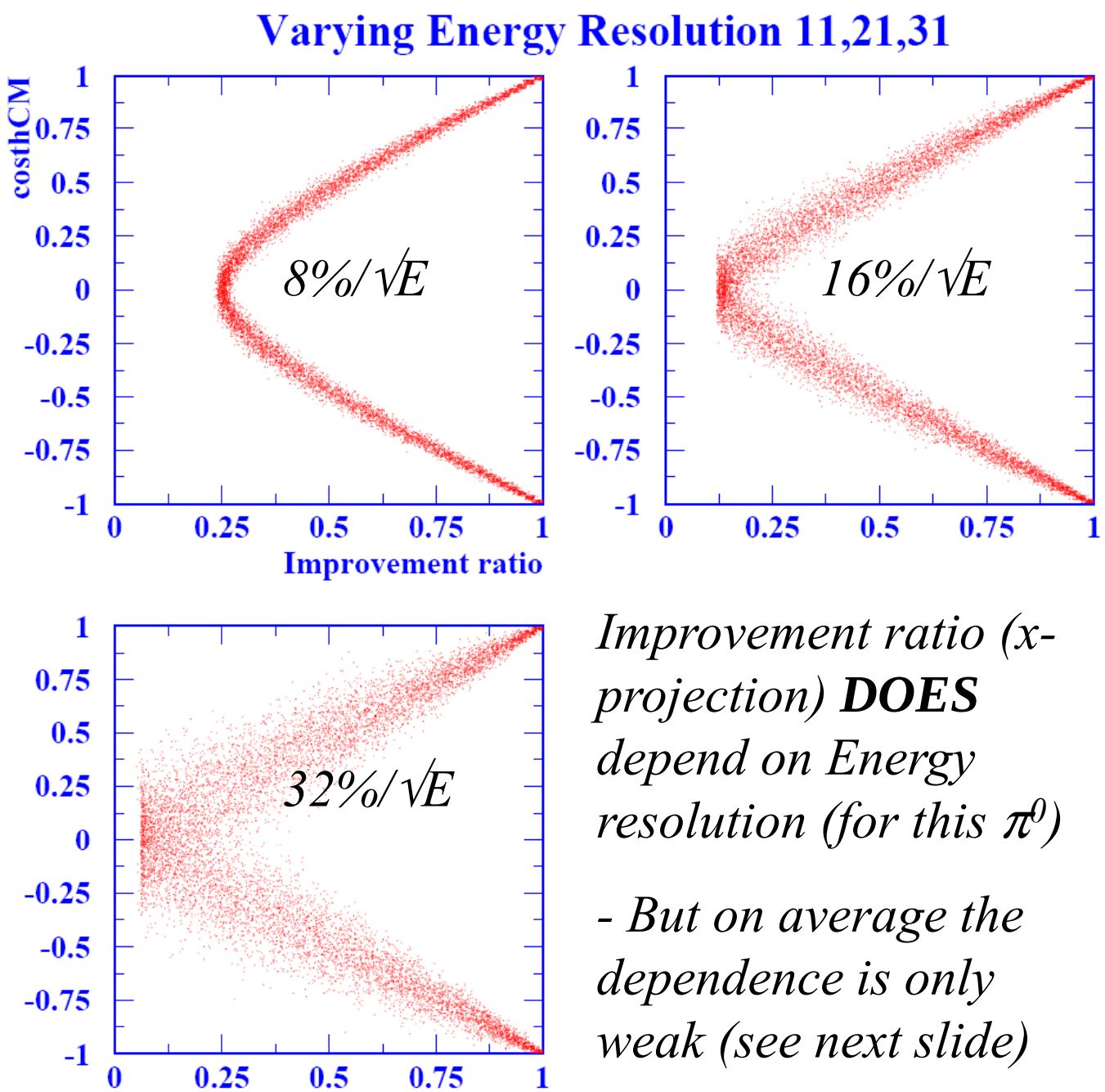
Dependence on π^0 energy



x: improvement ratio

y: $\cos\theta^*$

5 GeV π^0



Improvement ratio (x-projection) ***DOES*** *depend on Energy resolution (for this π^0)*

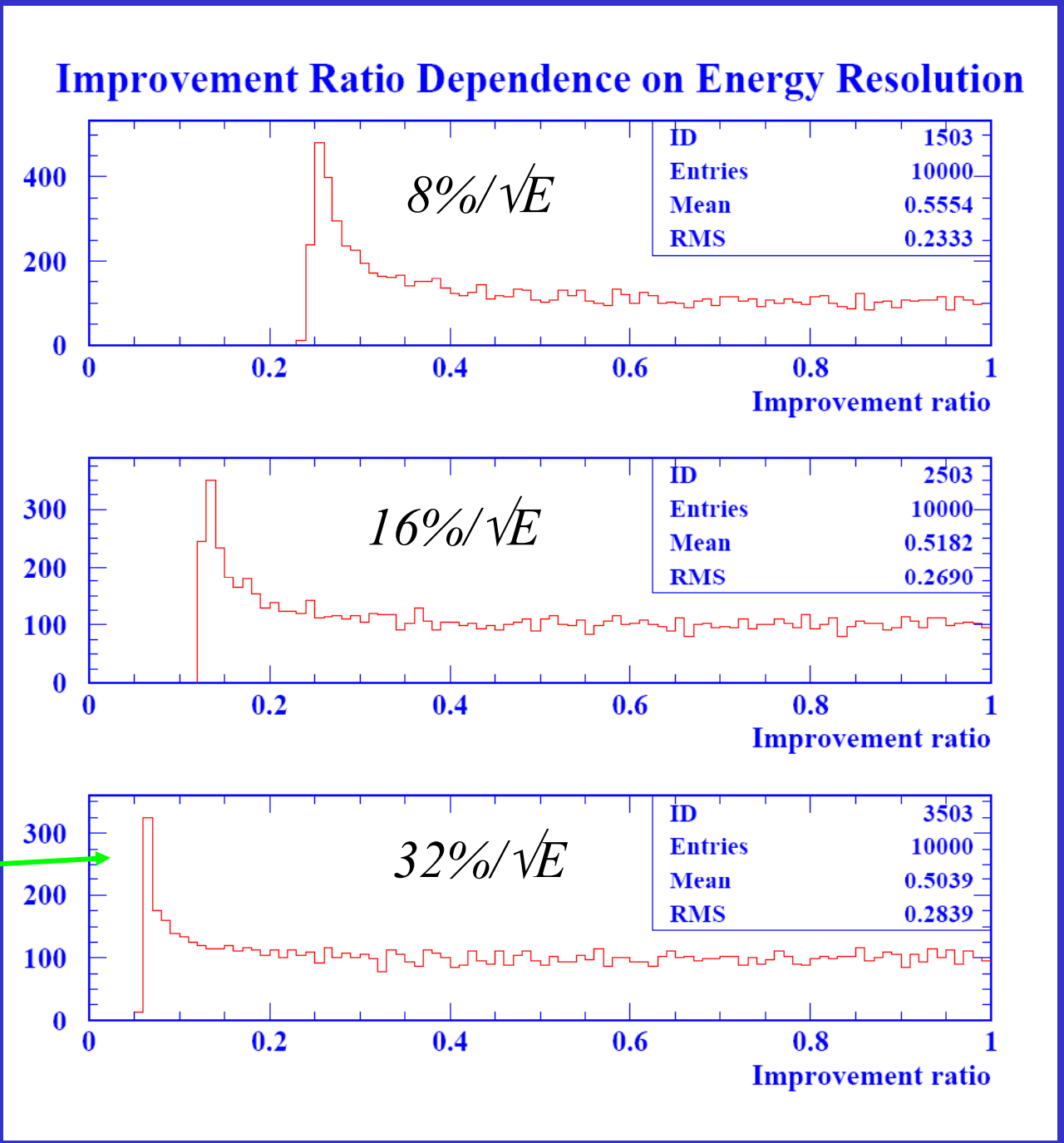
- But on average the dependence is only weak (see next slide)

This slide has been corrected from that presented at Vancouver

5 GeV π^0

Average improvement factor not highly dependent on energy resolution.

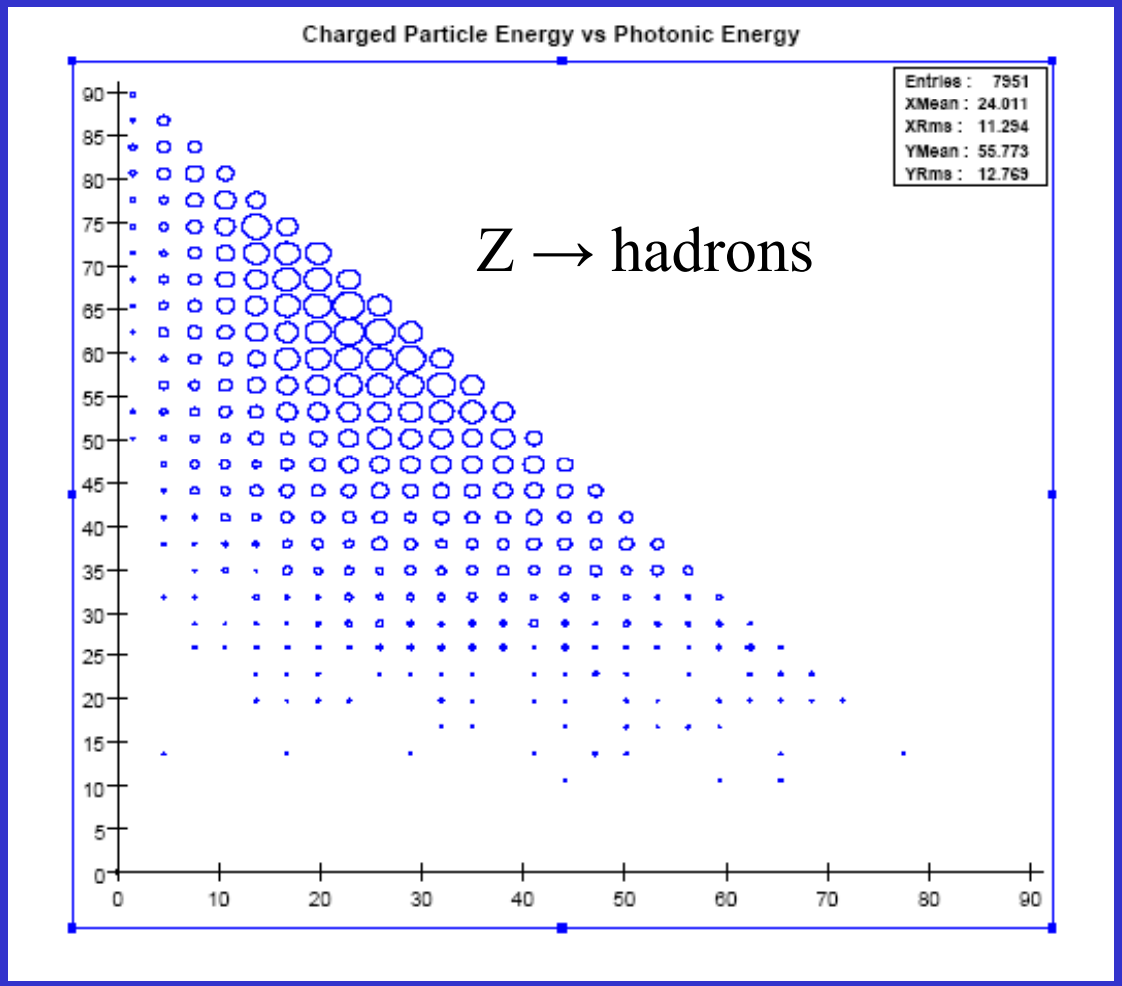
BUT the maximum possible improvements increase as the energy resolution is degraded.



PFA "Dalitz" Plot

Also see: http://heplx3.phsx.ku.edu/~graham/lcws05_slacconf_gwwilson.pdf

"On Evaluating the Calorimetry Performance of Detector Design Concepts", for an alternative detector-based view of what we need to be doing.



On average, photonic energy only about 30%, but often much greater.

γ, π^0, η^0 rates measured at LEP

	Experimental results				JETSET	HERWIG
	OPAL	ALEPH [6]	DELPHI [9]	L3 [10–12]	7.4	5.9
photon						
x_E range	0.003-1.000	0.018-0.450				
N_γ in range	16.84 ± 0.86	7.37 ± 0.24				
N_γ all x_E	20.97 ± 1.15				20.76	22.65
π^0						
x_E range	0.007-0.400	0.025-1.000	0.011-0.750	0.004-0.150		
N_{π^0} in range	8.29 ± 0.63	4.80 ± 0.32	7.1 ± 0.8	8.38 ± 0.67		
N_{π^0} all x_E	9.55 ± 0.76	9.63 ± 0.64	9.2 ± 1.0	9.18 ± 0.73	9.60	10.29
η						
x_E range	0.025-1.000	0.100-1.000		0.020-0.300		
N_η in range	0.79 ± 0.08	0.282 ± 0.022		0.70 ± 0.08		
N_η all x_E	0.97 ± 0.11			0.91 ± 0.11	1.00	0.92
N_η $x_p > 0.1$	0.344 ± 0.030	0.282 ± 0.022			0.286	0.243

Consistent with JETSET tune where 92% of photons come from π^0's.

Some fraction is non-prompt, from K^0_S, Λ decay

9.6 π^0 per event at Z pole

2. π^0 Kinematic Fitting

- For simplicity used the following measured experimental quantities:

  E_1 (Energy of photon 1)

  E_2 (Energy of photon 2)

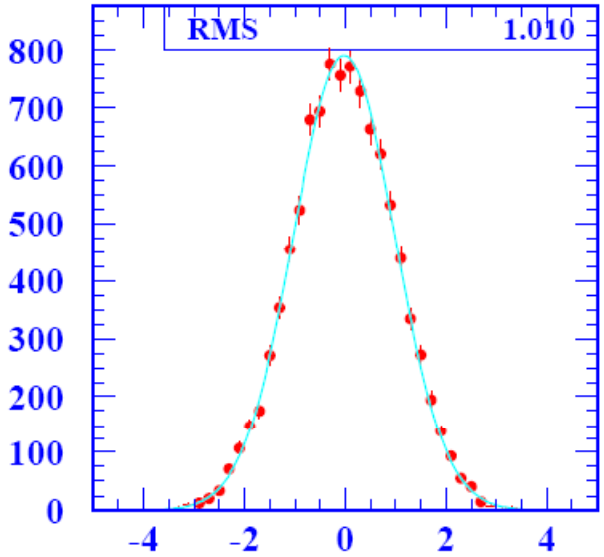
  ψ_{12} (3-d opening angle of photons 1 and 2)

- Fit uses
  - 3 variables, $\mathbf{x} = (E_1,\ E_2,\ 2(1 - \cos\psi_{12}))$
  - a diagonal error matrix

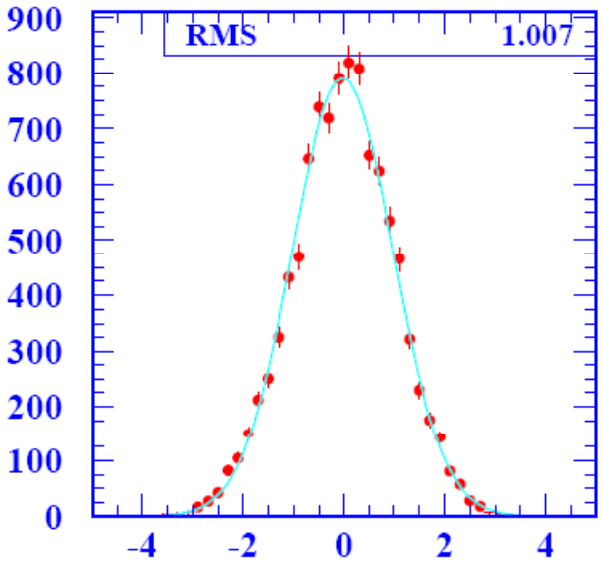
    (assumes individual γ's are completely resolved and measured independently)
  - and the constraint equation

    $m_{\pi^0}^2 = 2\, E_1\, E_2\, (1 - \cos\psi_{12}) = x_1\, x_2\, x_3$

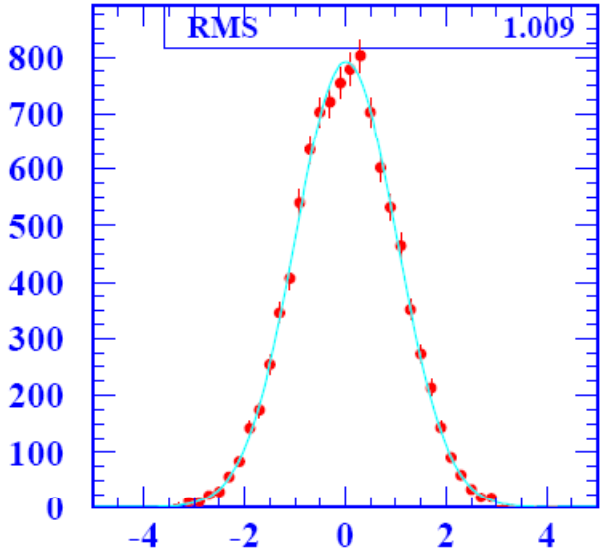
Pull distributions



Measured pi0 energy pull cf gen



Fitted pi0 energy pull cf gen



Fitted pi0 energy Pull cf measured

=> You should also be able to believe the errors on the fitted energies of each π^0