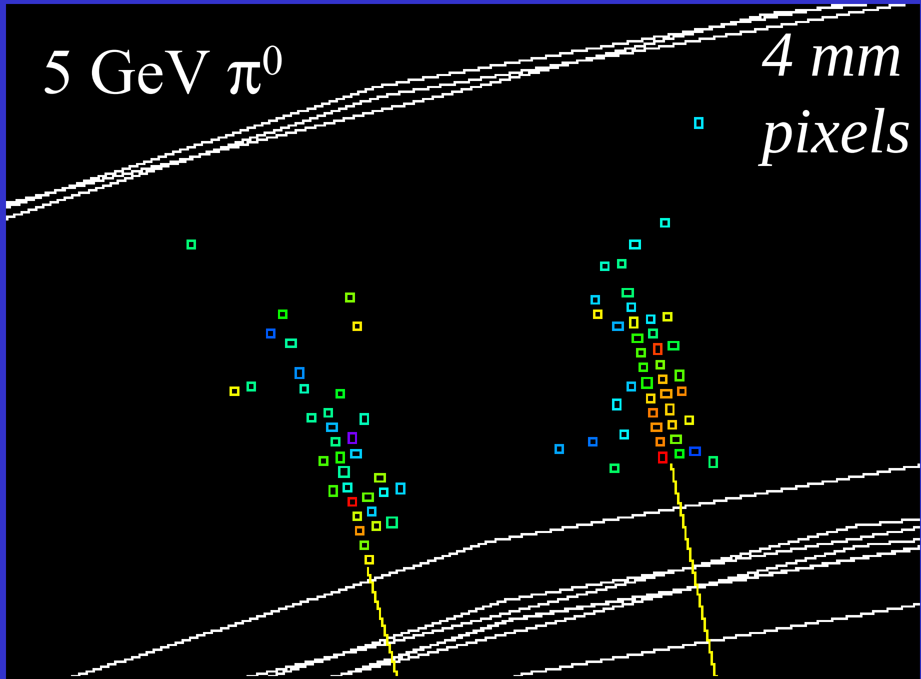
Investigating π^0 Kinematic Fits



EM calorimeters under consideration for ILC have unprecedented potential for photon position resolution.

Can this be used to measure π^0 energies very well ?

R also relevant

Also see talks at Snowmass 05 and Vancouver 06.

1. π^0's and particle flow
2. π^0 kinematic fitting
3. Improvements in π^0 energy resolution
4. Applying to hadronic jets

Graham W. Wilson, University of Kansas

1. π^0's and Particle Flow

- Particle Flow
  - Charged particles => TRACKER => 62%
  - **Photons => ECAL => 26%**
  - Neutral hadrons => HCAL => 12%

- Photons
  - Prompt Photons (can assume vtx = (0,0,0))
    - **π^0 (About 95% of the photon energy content at the Z)**
    - η, η' etc.
    - Lone photons (eg. $\omega \rightarrow \pi^0 \gamma$)
  - Non-prompt Photons
    - $K^0_S \rightarrow \pi^0 \pi^0$
    - $\Lambda \rightarrow \pi^0 n$
- So, as you know, most photons do come from prompt π^0's, we do know the π^0 mass, and they interact in well understood ways !

Issues

- A) Proof of Principle *for the Intrinsic potential* of a 1-C constrained fit to m(π^0) for a single **isolated** π^0 with two spatially separated photons.
  - Can we get a fitter that works, and does it buy us anything in principle ? (Emphatic YES)
  - What detector parameters / design issues does it point to ?

- B) Practical *implementation* in the context of hadronic jets.
  - Major issue: combinatorics (9.6 π^0 per event at the Z). Algorithm for choosing appropriate pairings.
  - Relatively small background from non-prompt photons can presumably be discriminated against using cluster pointing.
  - Details of photon reconstruction in jets.
    - Need to understand errors and minimize biases

Proof of Principle (A) is now completed and very encouraging.

First steps towards assessing the potential in the context of B).

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

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

π^0 mass resolution

- Can show that for $\sigma_E/E = c_1/\sqrt{E}$ that
  $\Delta m/m = \mathbf{c_1} /\sqrt{[(1-a^2)\, E_{\pi^0}]} \oplus 3.70\, \boldsymbol{\Delta\psi_{12}} E_{\pi^0} \sqrt{(\beta^2-a^2)}$
  where $a = \beta \cos\theta^* = (E_1-E_2)/E_{\pi^0}$

So the mass resolution has 2 terms :

i) depending on the EM energy resolution (c_1)

ii) depending on the opening angle resolution ($\boldsymbol{\Delta\psi_{12}}$)

The relative importance of each depends on (E_{π^0}, a)

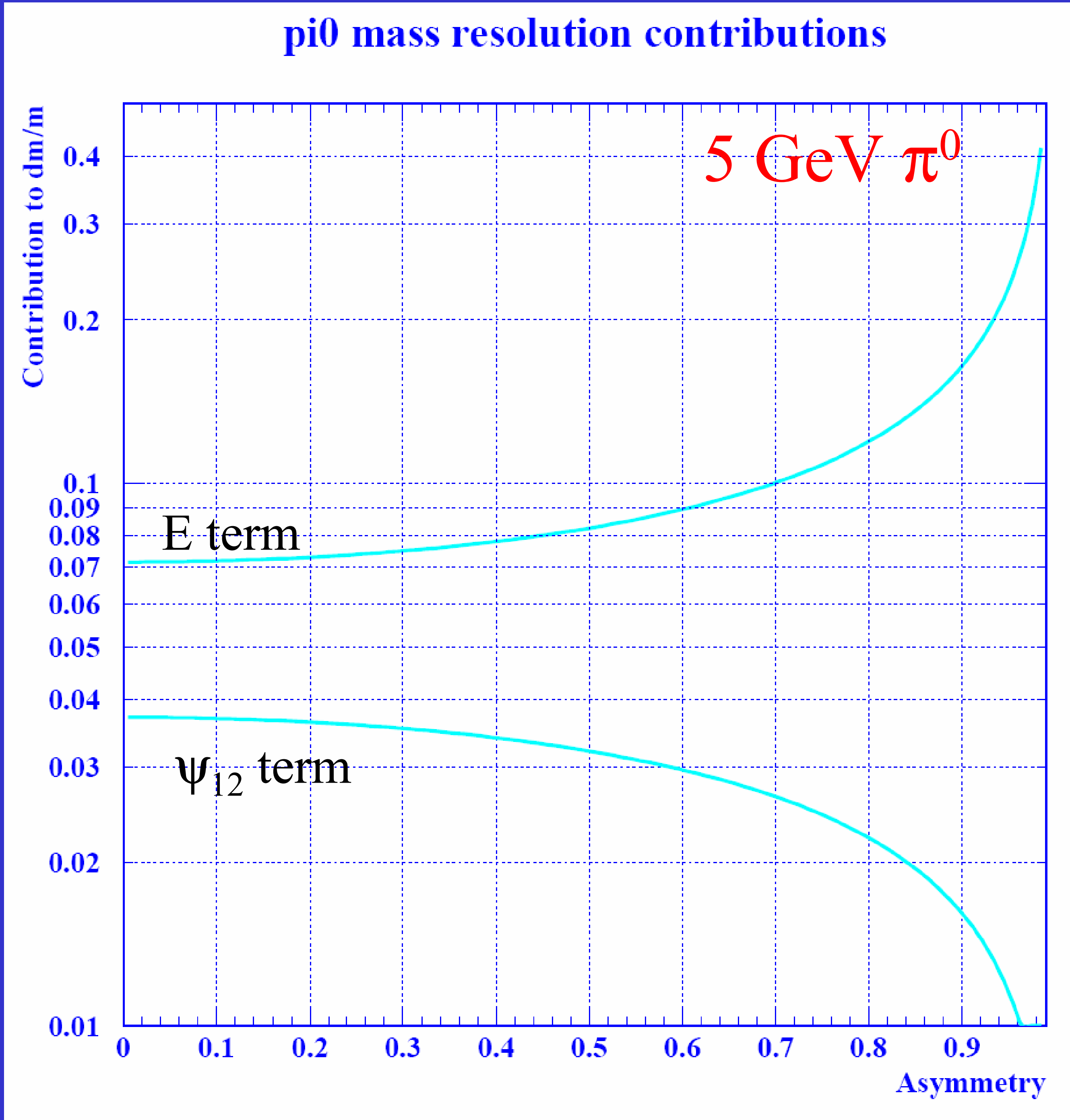
π^0 mass resolution

Plots assume:

$c_1 = 0.16$ (SiD)

$\Delta\psi_{12} = 2$ mrad

For these detector resolutions, 5 GeV π^0 mass resolution dominated by the E term



Recent Improvements

- Blobel numerical fitter in DP in addition to analytic fit (both F77 for now)
  - consistent
- Technical details
  - $\cos\theta^* = (1/\beta)\,(E_1 - E_2) / E_{\pi^0}$
  - Error truncation for low energies : avoid –ve energies …
  - Using simulated error rather than measured error
  - Now have ***perfect*** probability and pull distributions
- Error propagation after kinematic fit
  - Demonstration that for each π^0 in the event, we could not only improve the π^0 energy resolution but would also **know the error**.

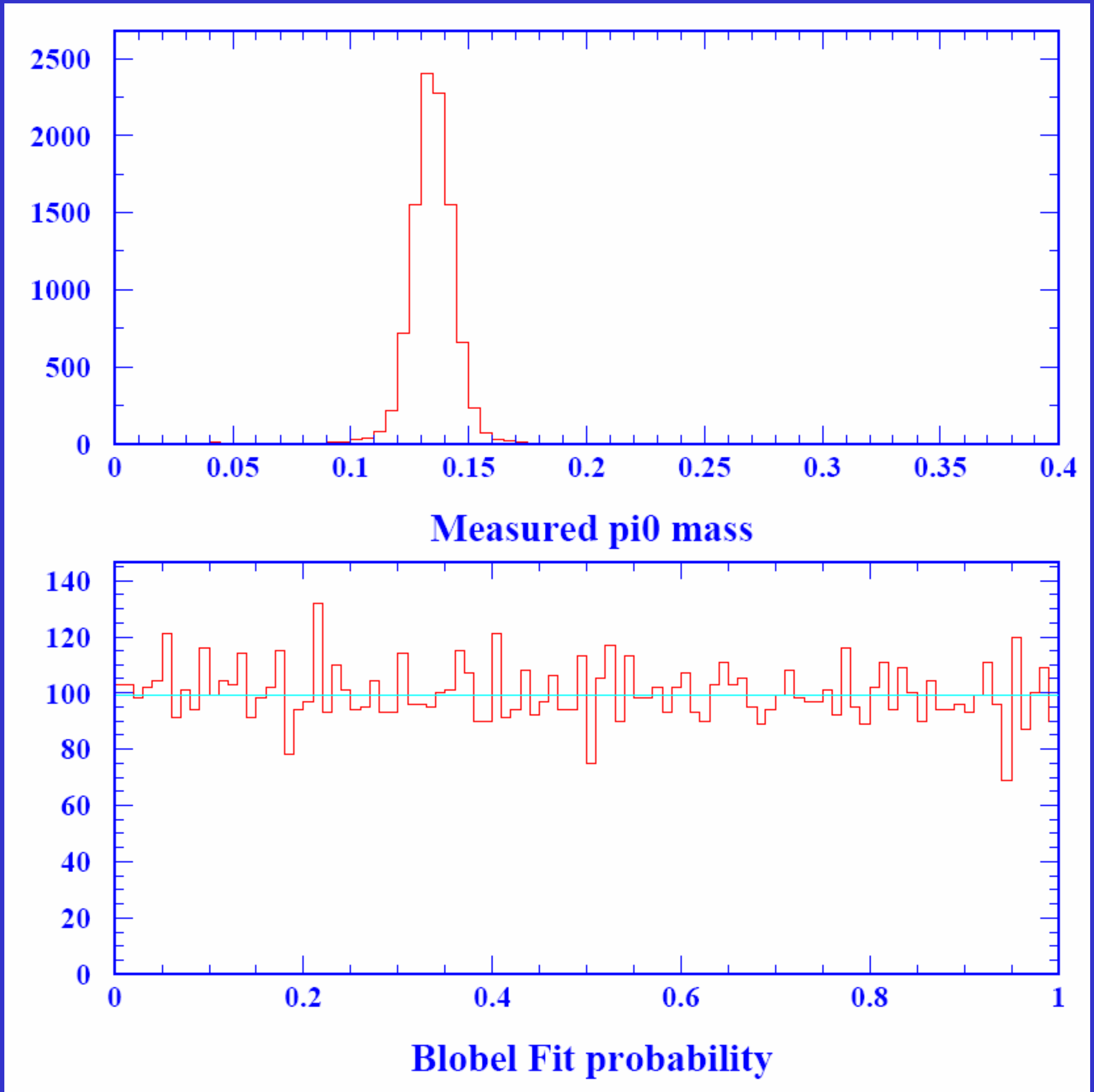
20 GeV π^0

Use single π^0 toy MC with Gaussian smearing for studies.

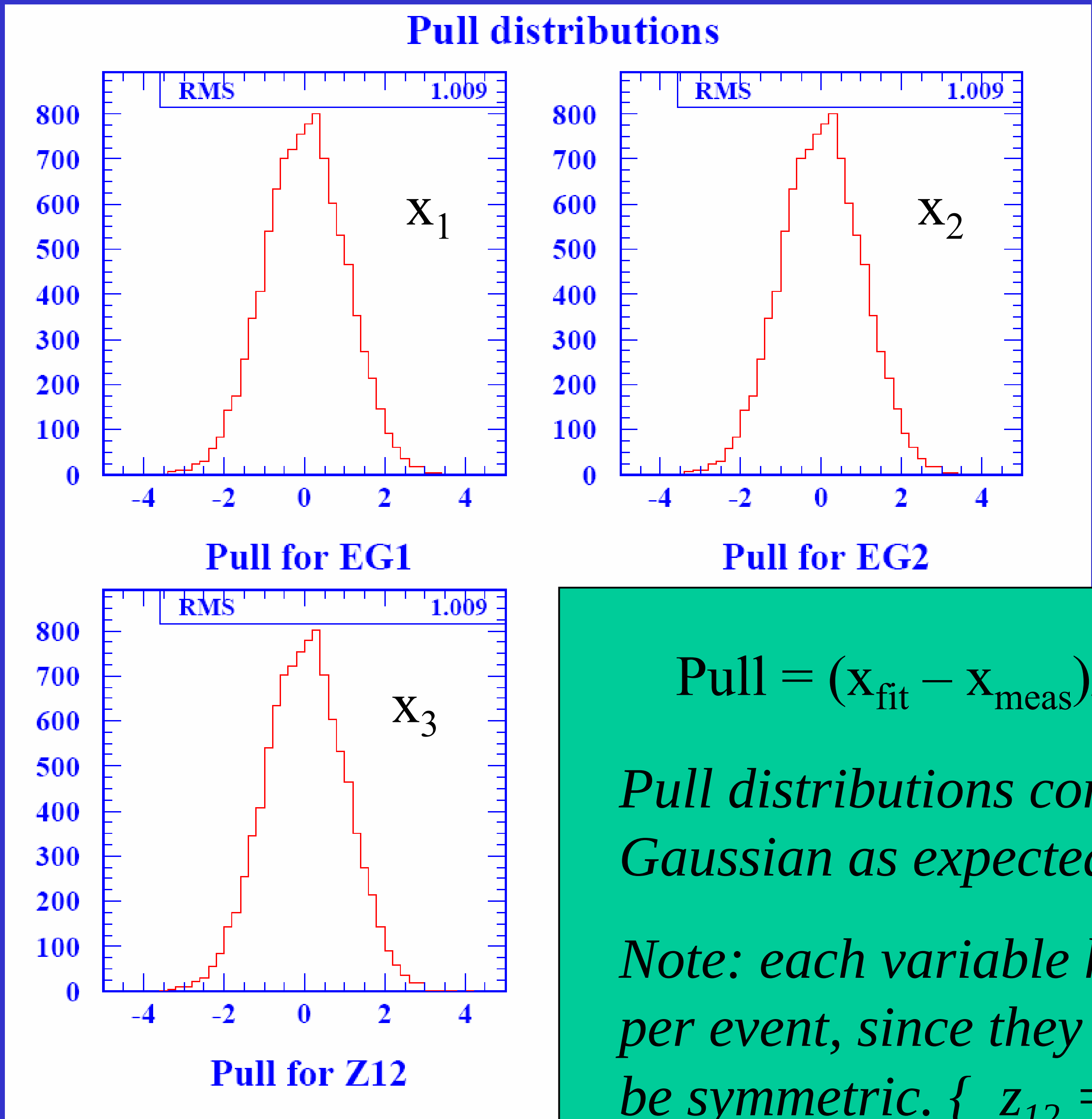
Energy resolution per photon $=16\%/\sqrt{E}$.

Error on ψ_{12}=0.5 mrad.

These resolutions used unless otherwise stated.



A rare thing: a really flat probability distribution !!!

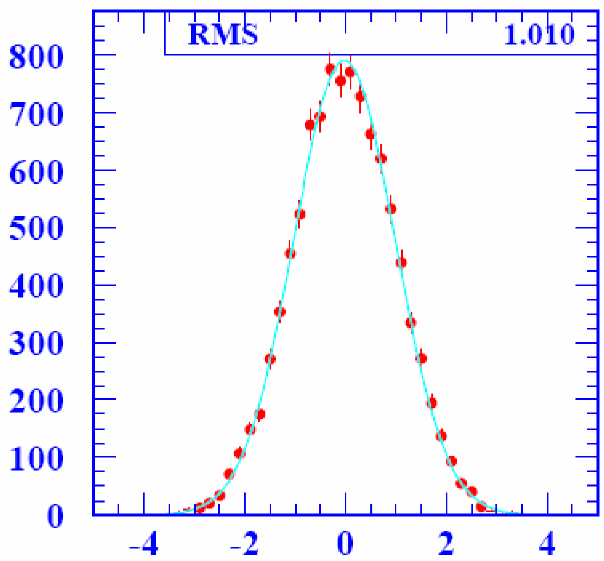


$$\text{Pull} = (x_{fit} - x_{meas})/\sqrt{(\sigma_{meas}^2 - \sigma_{fit}^2)}$$

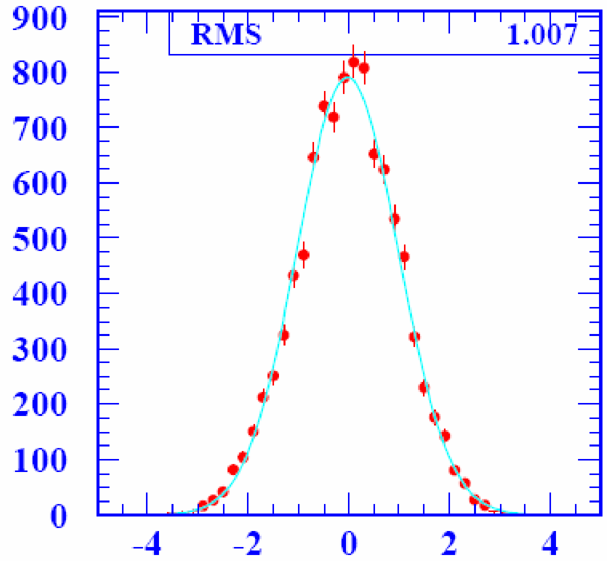
Pull distributions consistent with unit Gaussian as expected.

Note: each variable has an identical pull per event, since they were constructed to be symmetric. { $z_{12} = 2(1-\cos\psi_{12})$ }

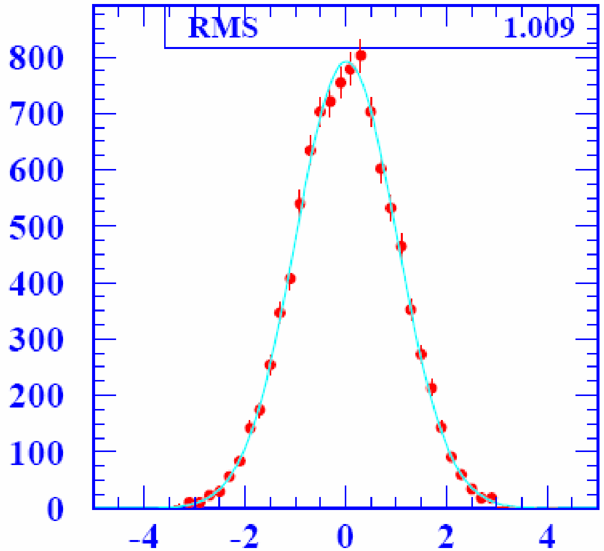
Pull distributions



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

3. Results on π^0 Energy Resolution Improvement

For the Proof of Principle study there are:

Two relevant π^0 kinematic parameters:

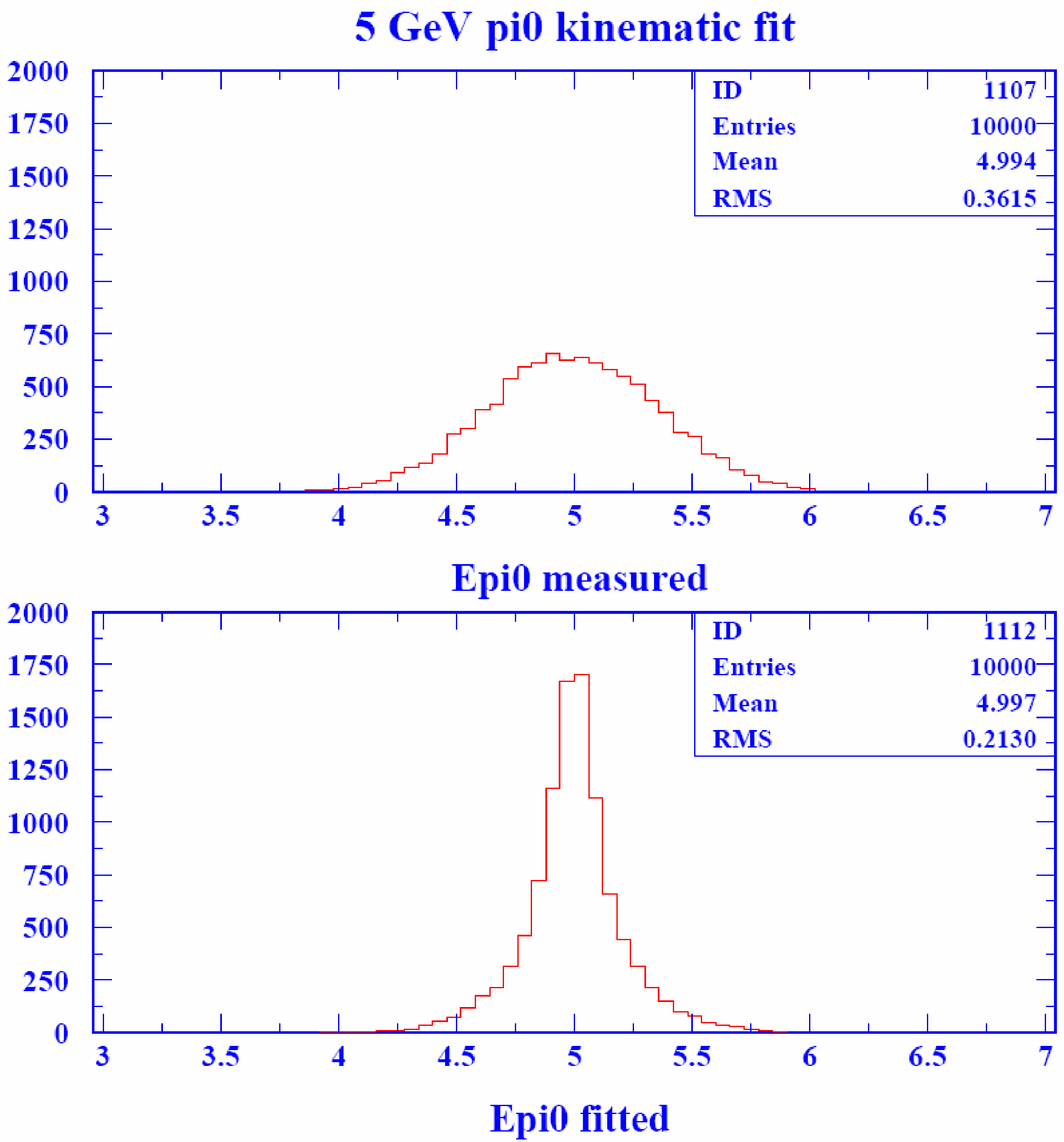
i) $E(\pi^0)$

ii) $\cos\theta^*$ (cosine of CM decay angle)

And two relevant detector parameters:

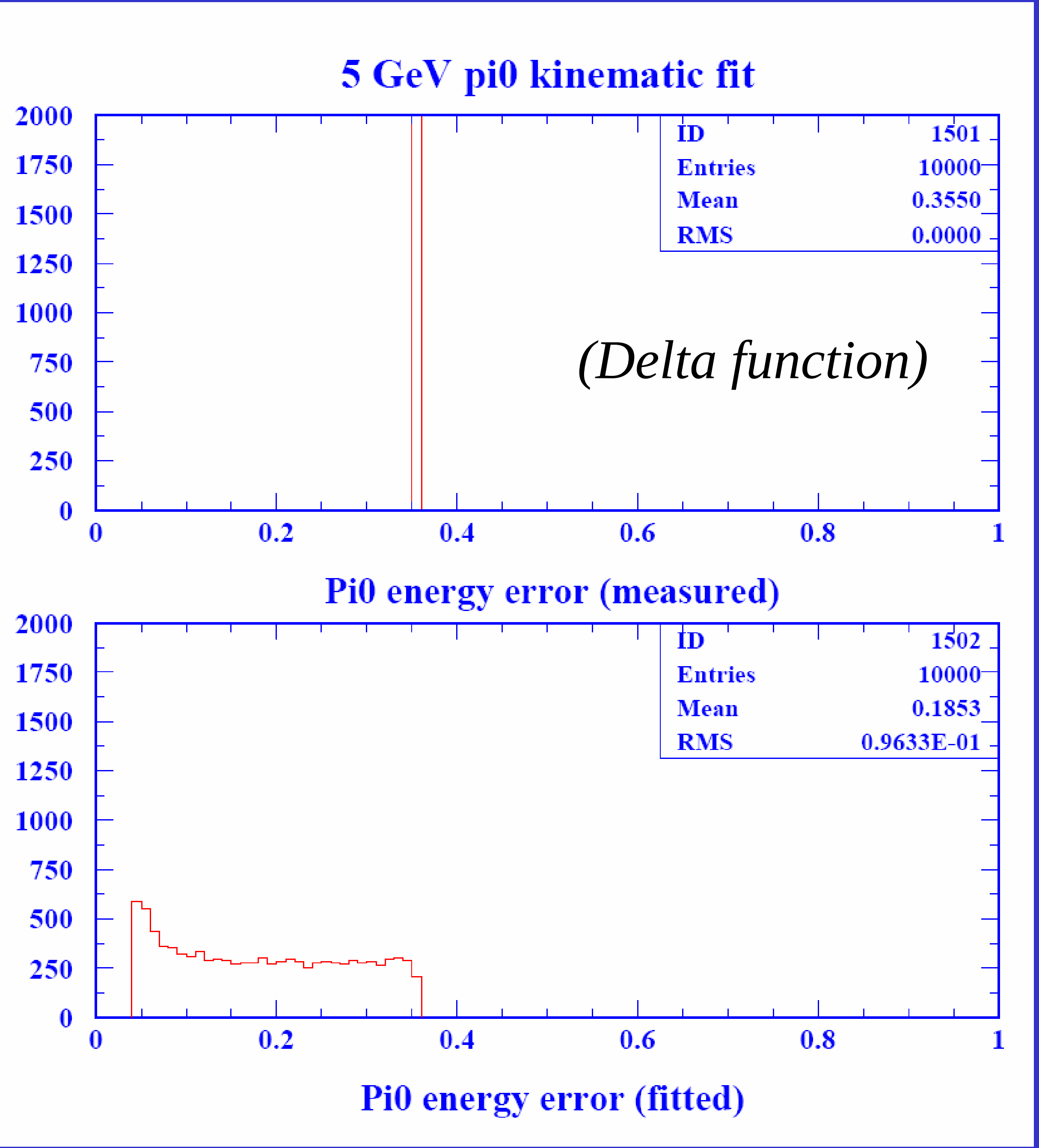
i) Photon fractional energy resolution ($\Delta E/E$)

ii) Opening angle resolution ($\Delta\psi_{12}$)



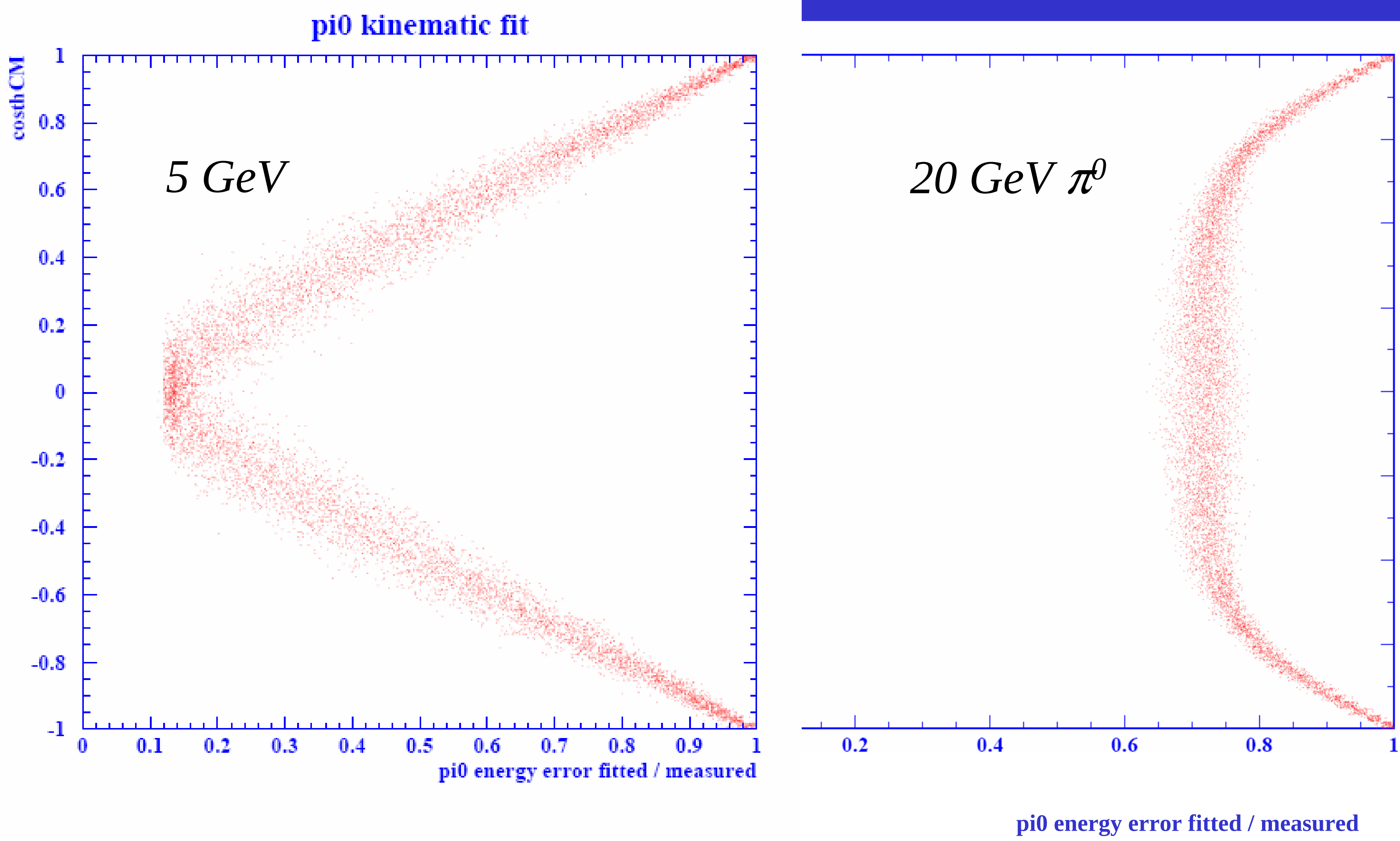
DRAMATIC IMPROVEMENT

But this plot is not really a good representation of what is going on.

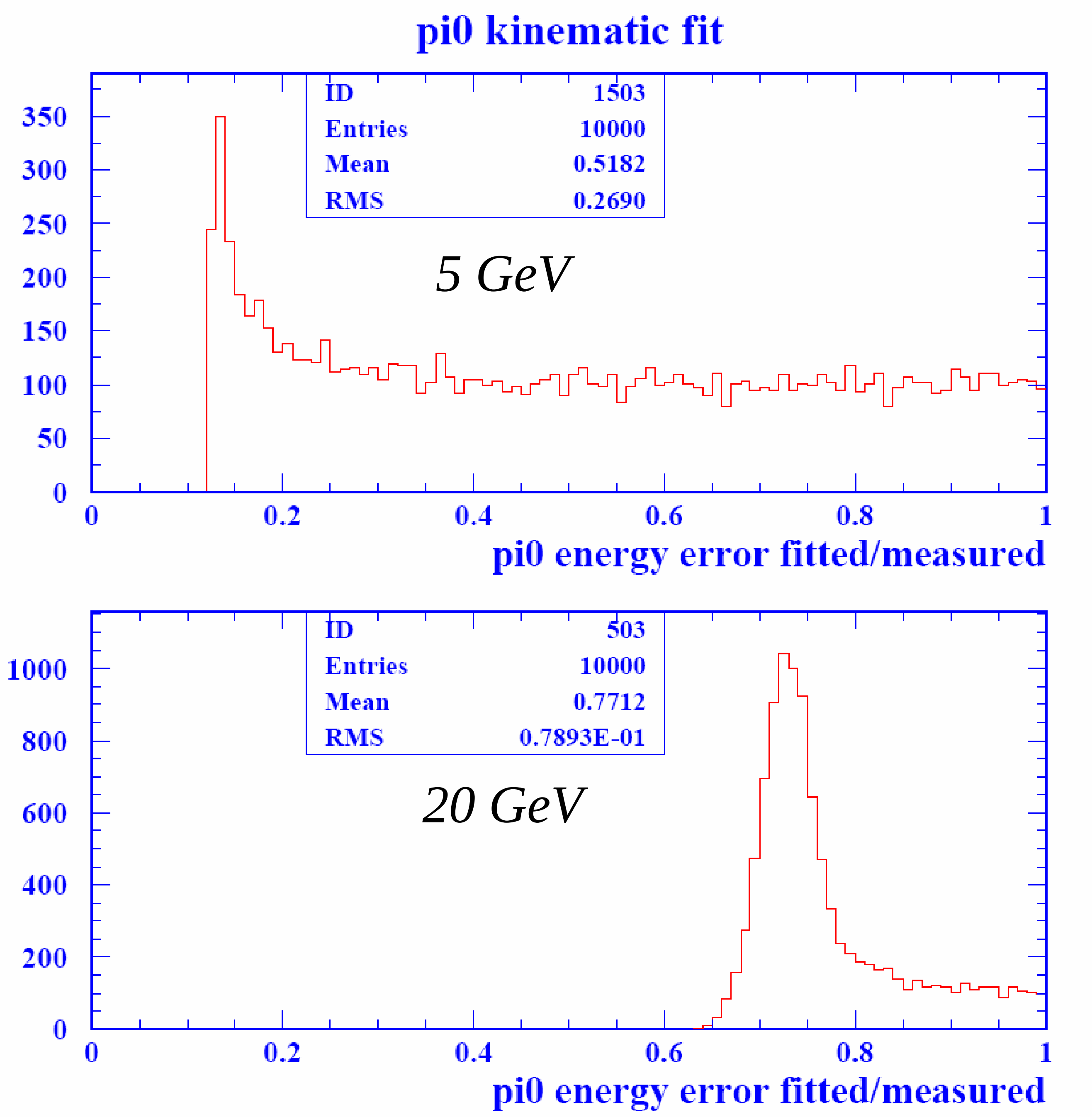


From now on, will use the π^0 energy error ratio (fitted/measured) as the estimator of the improvement.

Call this the improvement ratio.



Very strong dependence of fit error on cosθ*.
Symmetric decay (cosθ*=0) is best

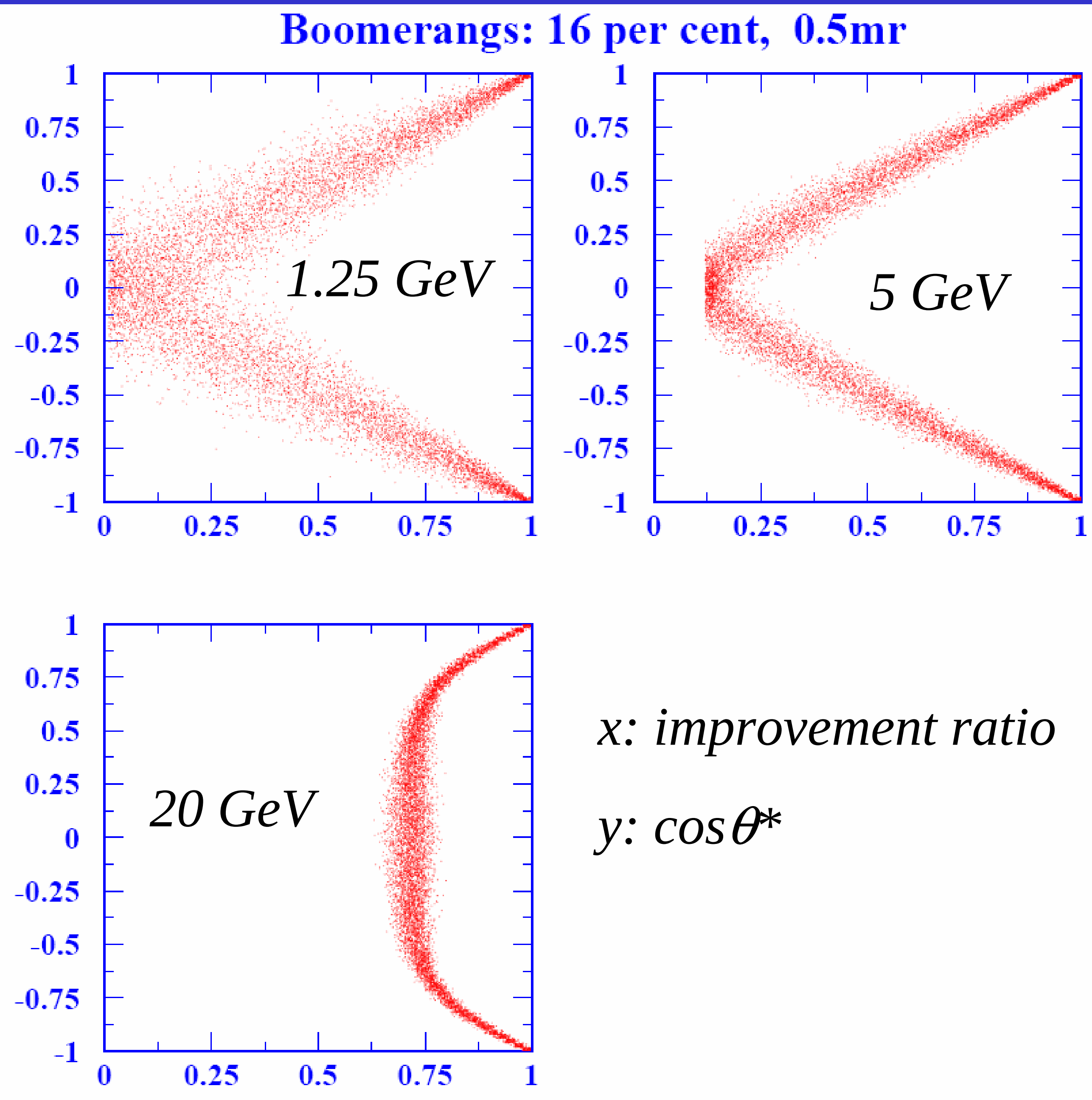


Improvement by up to a factor of 7 !

On average, factor of 2.

Improves by a factor of 1.3 on average.

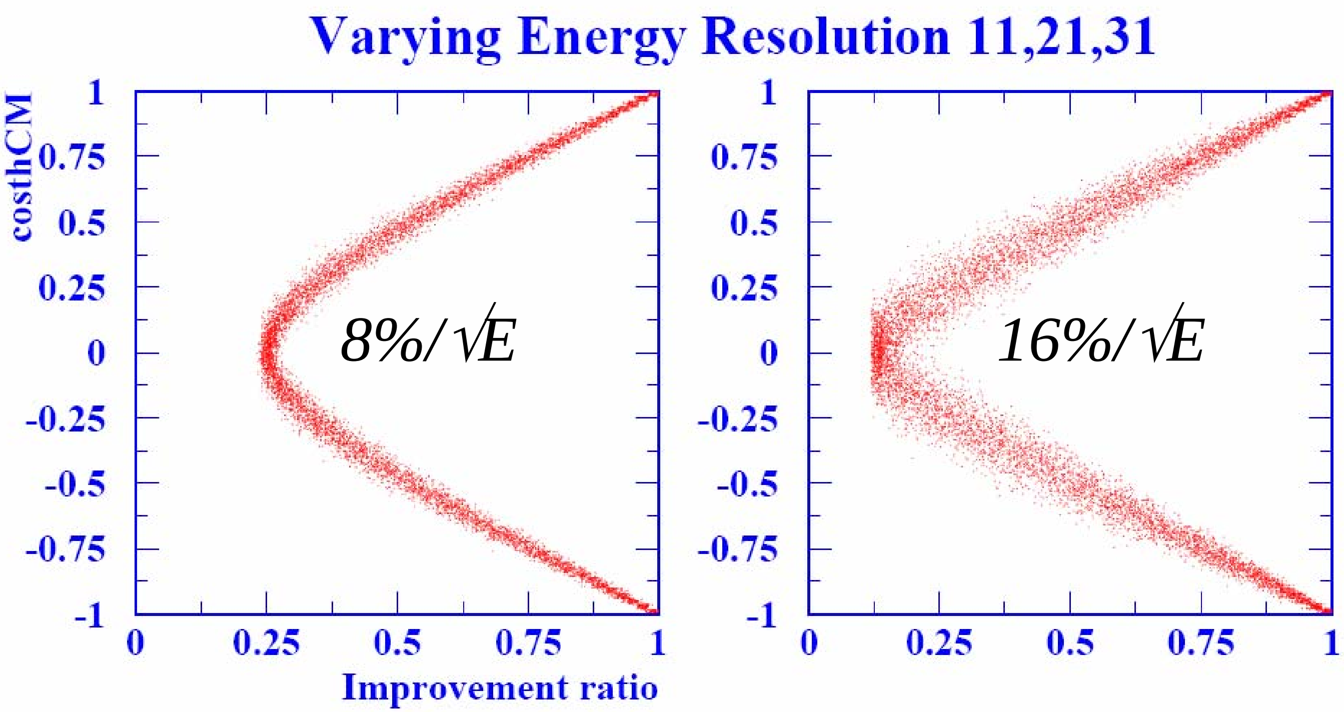
Dependence on π^0 energy

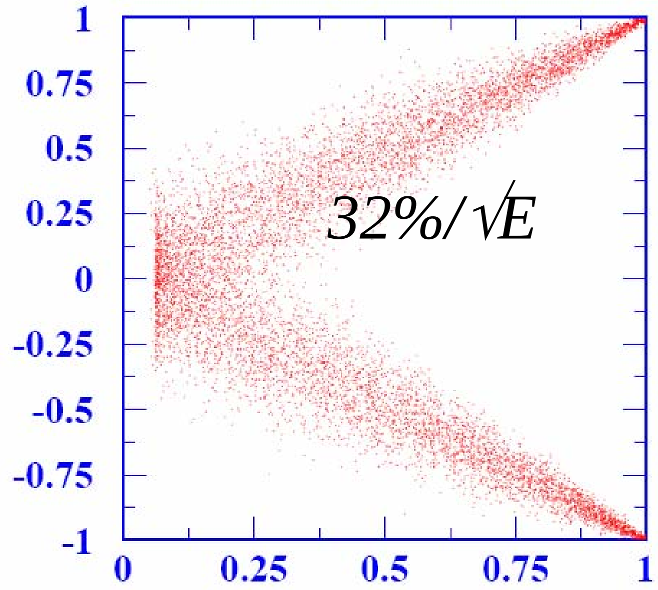


x: improvement ratio

y: $\cos\theta^*$

5 GeV π^0





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

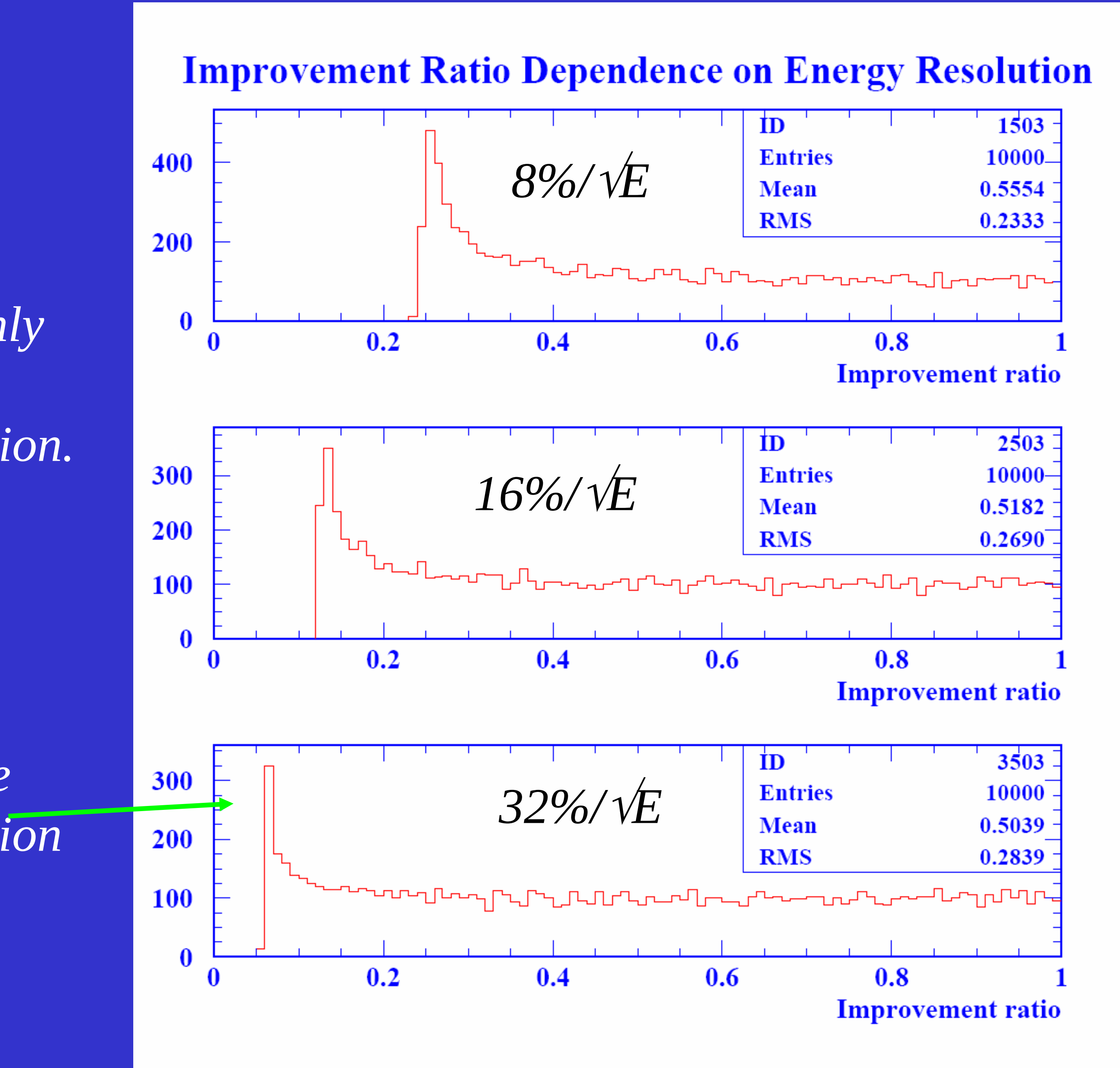
- But on average the dependence is only weak (see next slide)

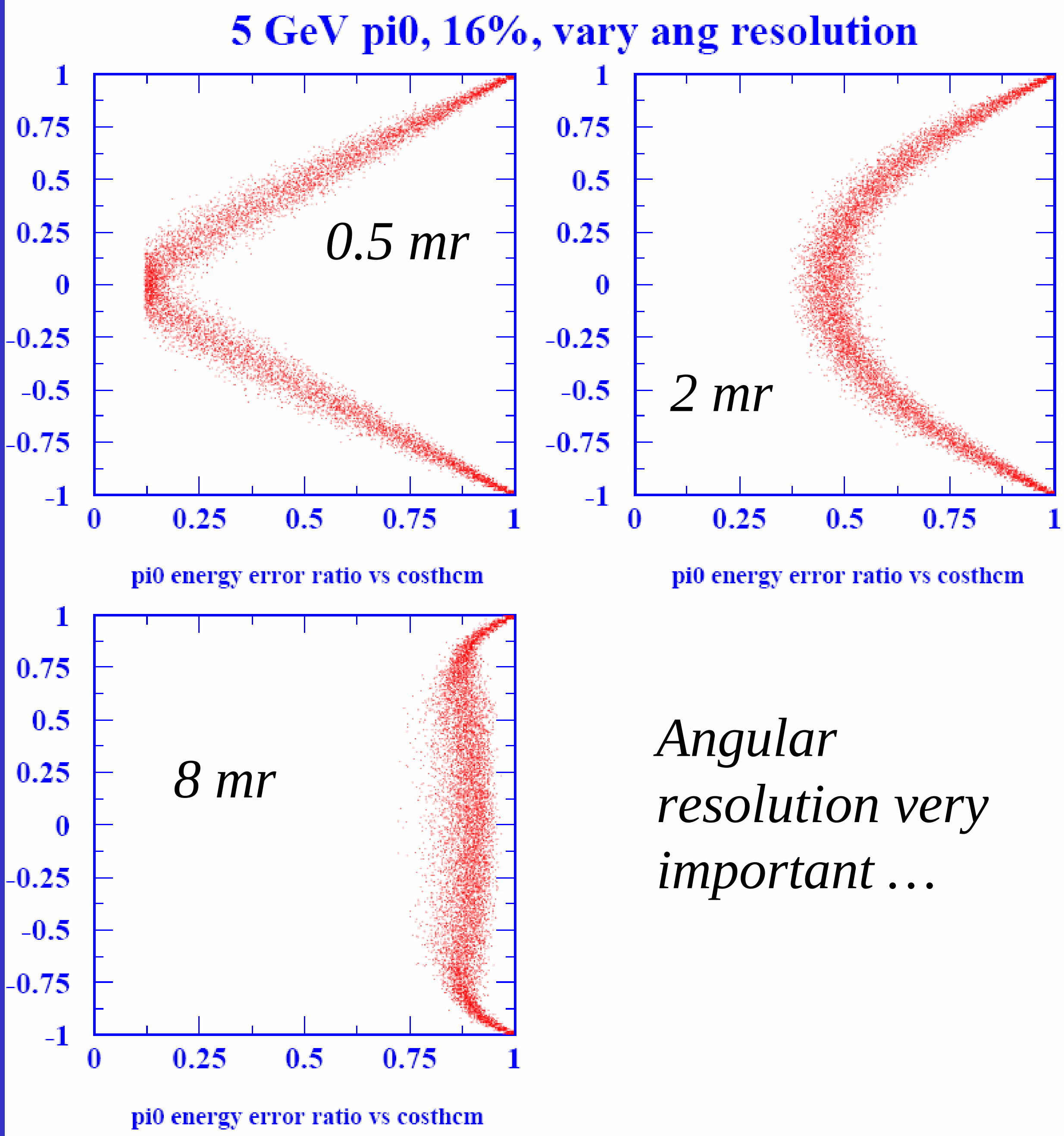
This slide has been corrected from that presented at Vancouver

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.

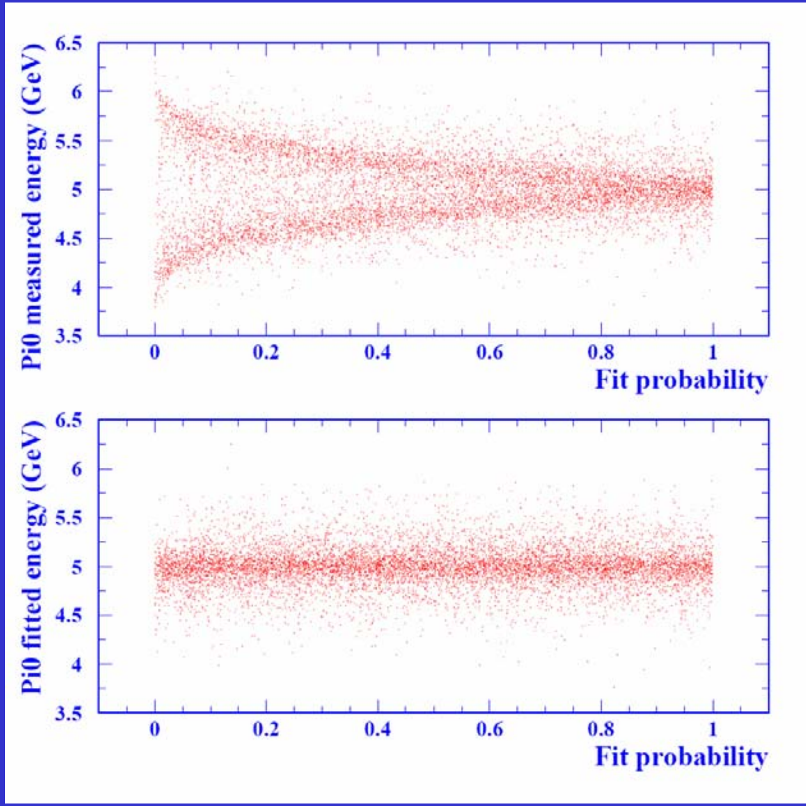




Angular resolution very important …

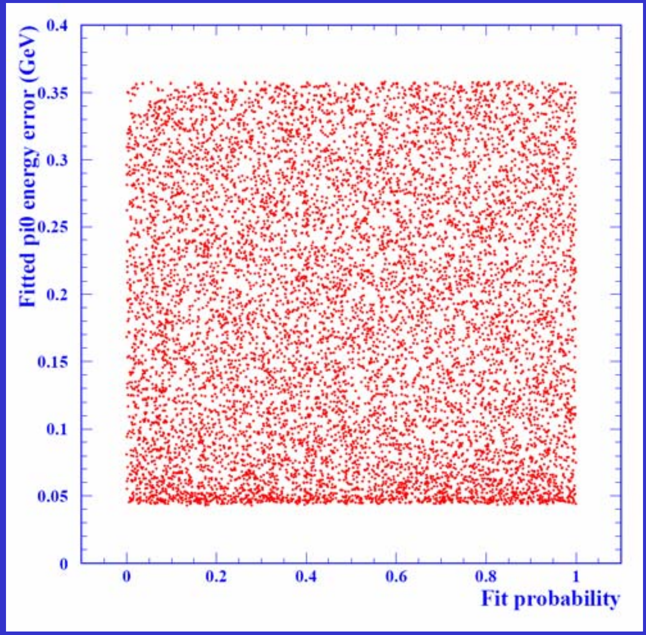
What's going on ?

5 GeV π^0, c_1=16%, $\Delta\psi_{12}$=0.5mr

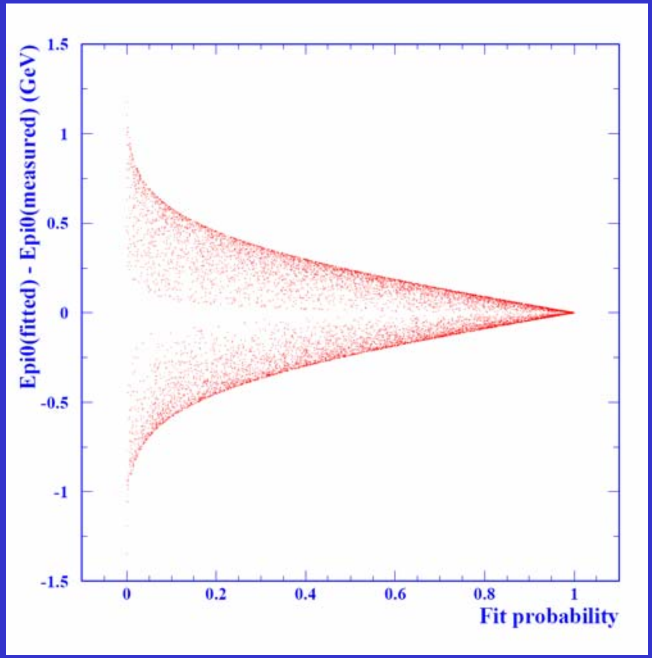


$E_{\pi 0}$ changes most when p_{fit} small.

(NB the constraint is correct, so low p_{fit} corresponds to π^0's where typically the energy has fluctuated substantially)



Error on π^0 energy is independent of p_{fit}



Hard edges correspond to low $|\cos\theta^*|$

Kinematic Fitting Summary

- Proof of principle of kinematic fit for π^0 reconstruction done.
  - Kinematic fit infrastructure now a solid foundation.
  - Well understood errors on each π^0.
- Potential for a factor of two improvement in the energy resolution of the EM component of hadronic jets.

4. Towards applying to hadronic jets

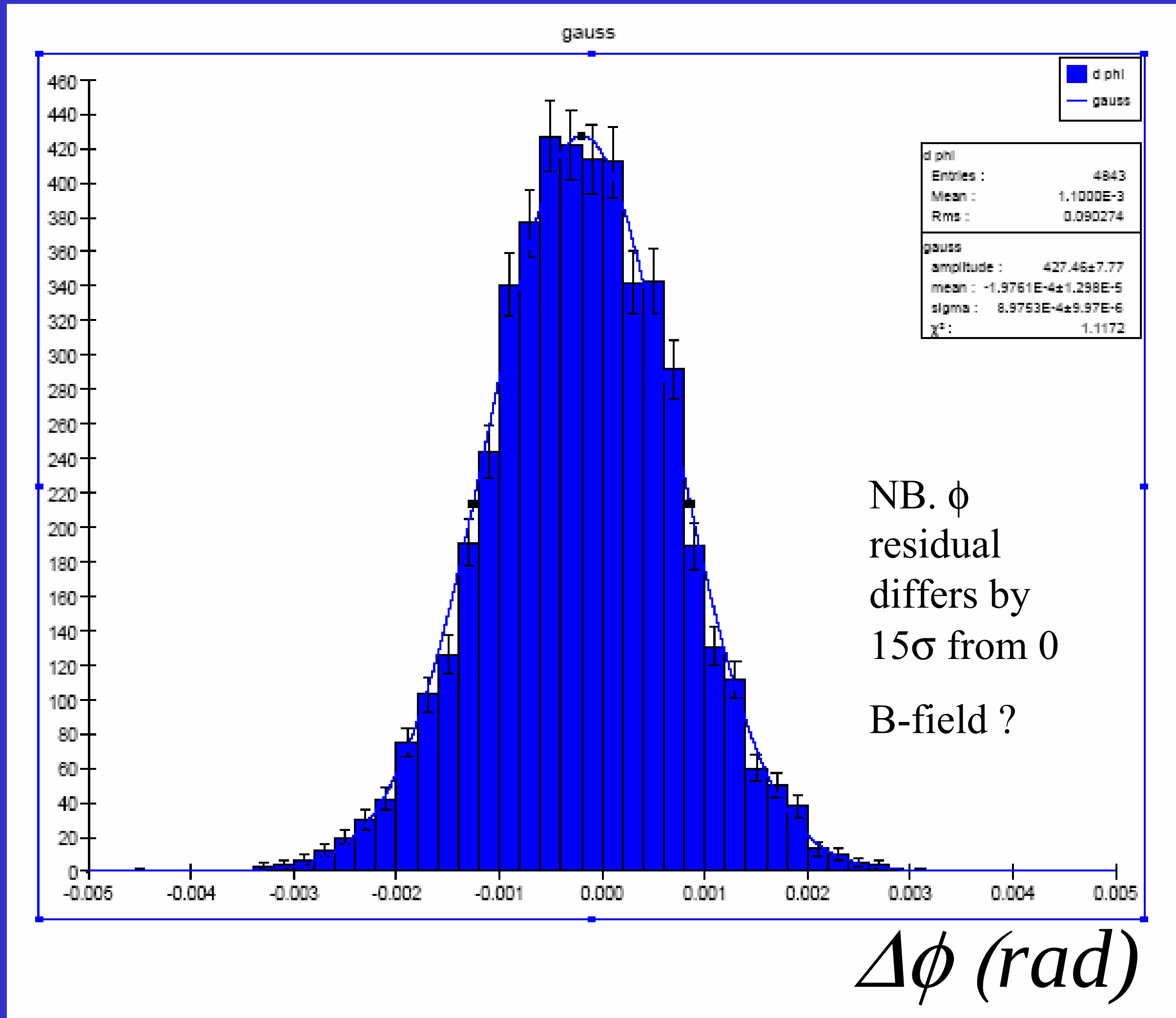
- Detector response
- Characterize the multi-photon issues in $Z \rightarrow uu, dd, ss$ events.
  - Define prompt photons as originating within 10 cm of the origin
    - (NB differs from standard $c\tau < 10$ cm definition)

Angular Resolution Studies

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

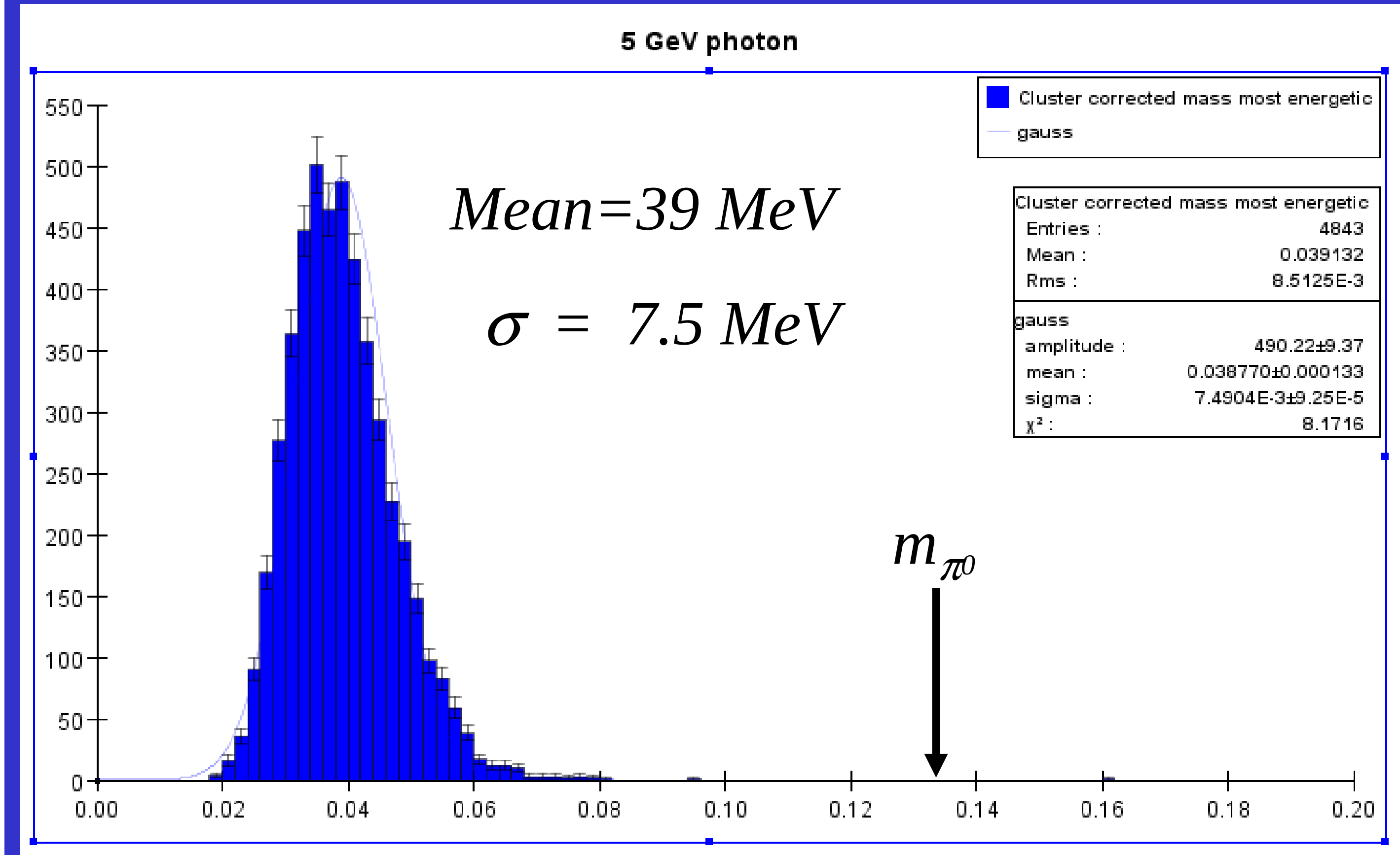
Phi resolution of 0.9 mrad *just* using cluster CoG.

=> 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



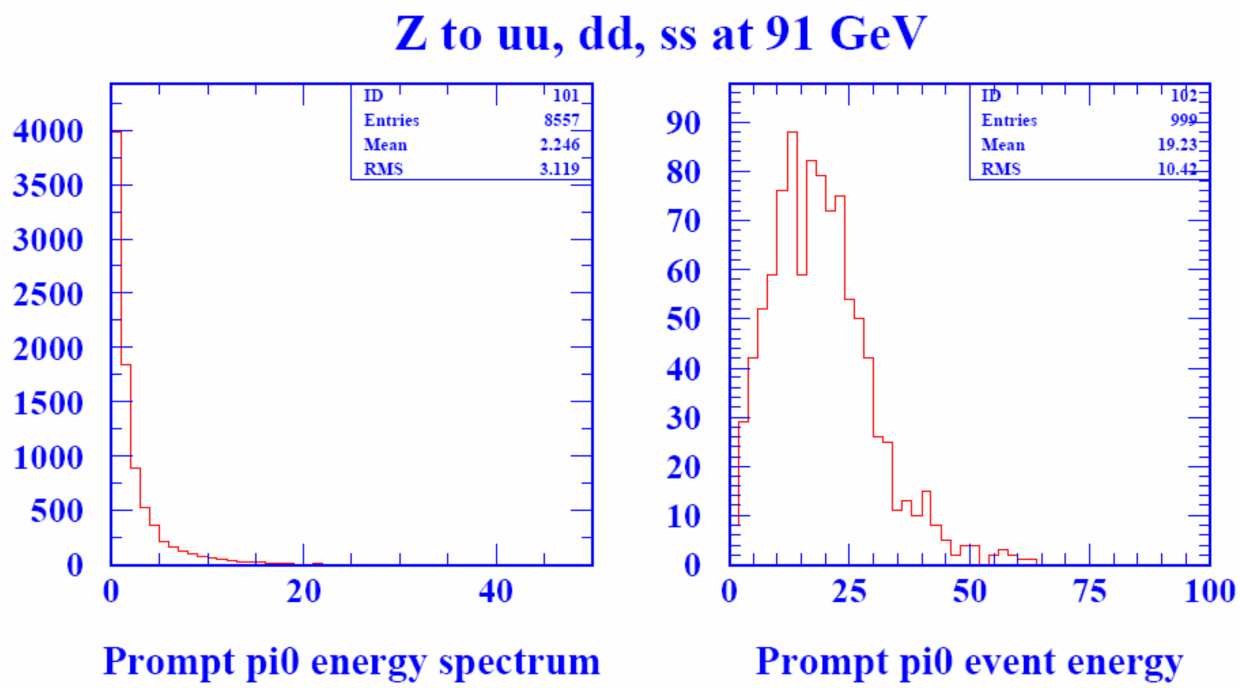
Cluster Mass (GeV)

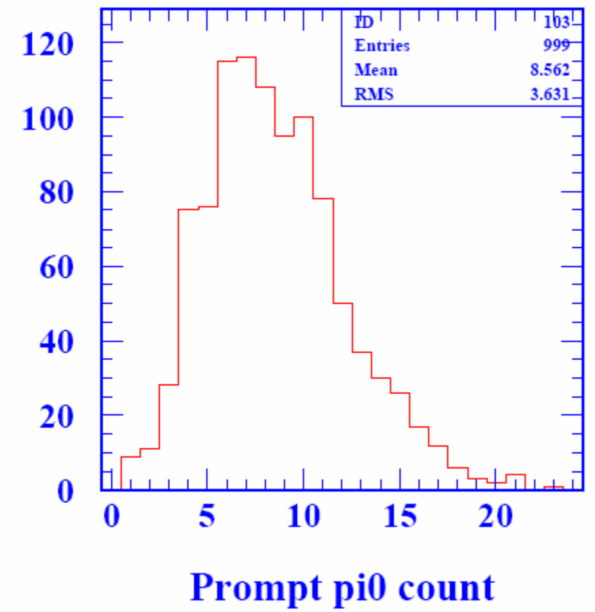
Of course, photons actually have a mass of zero.

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.

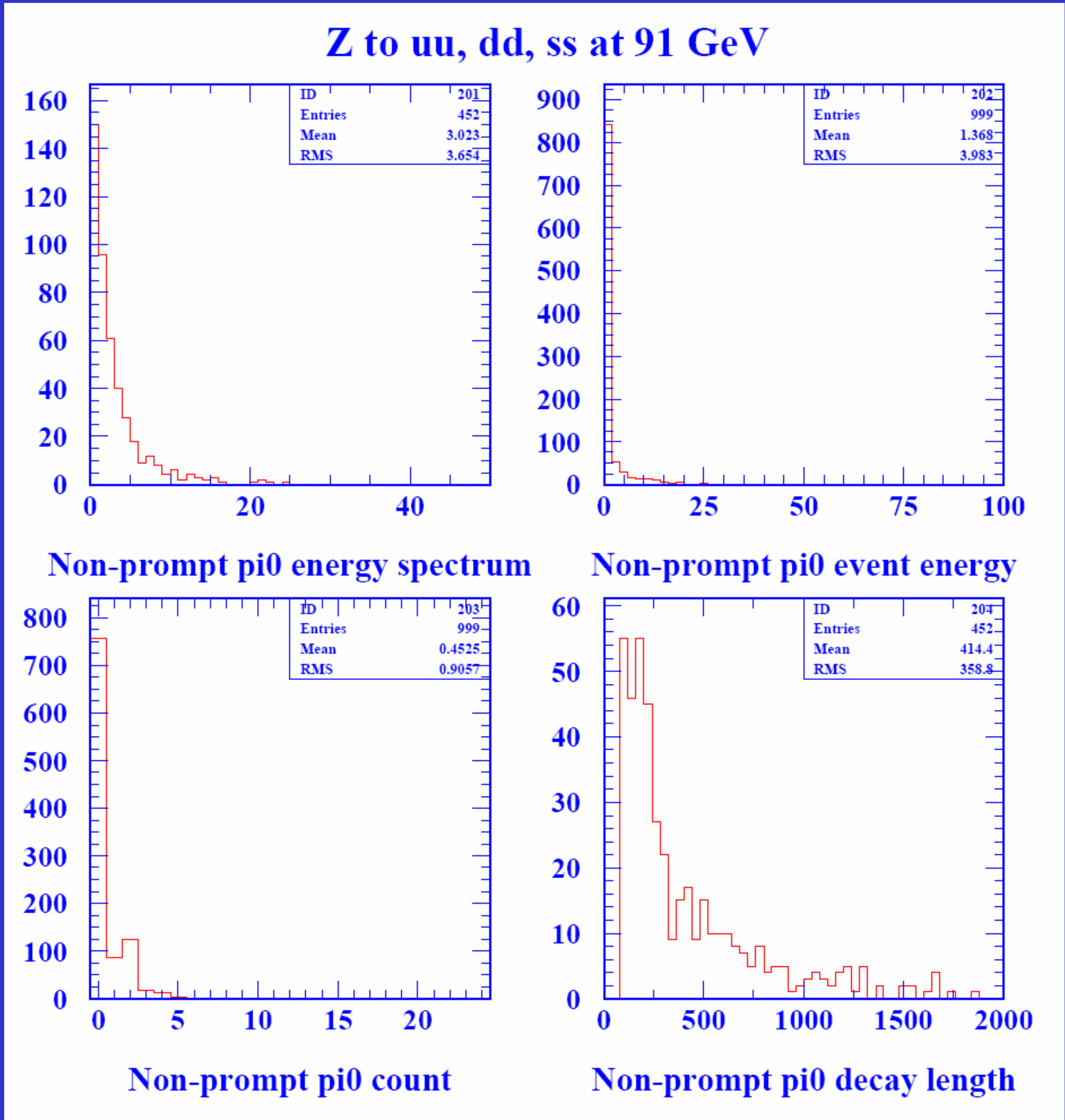
Performance depends on detector design (R, R_M, B, cell-size, …)





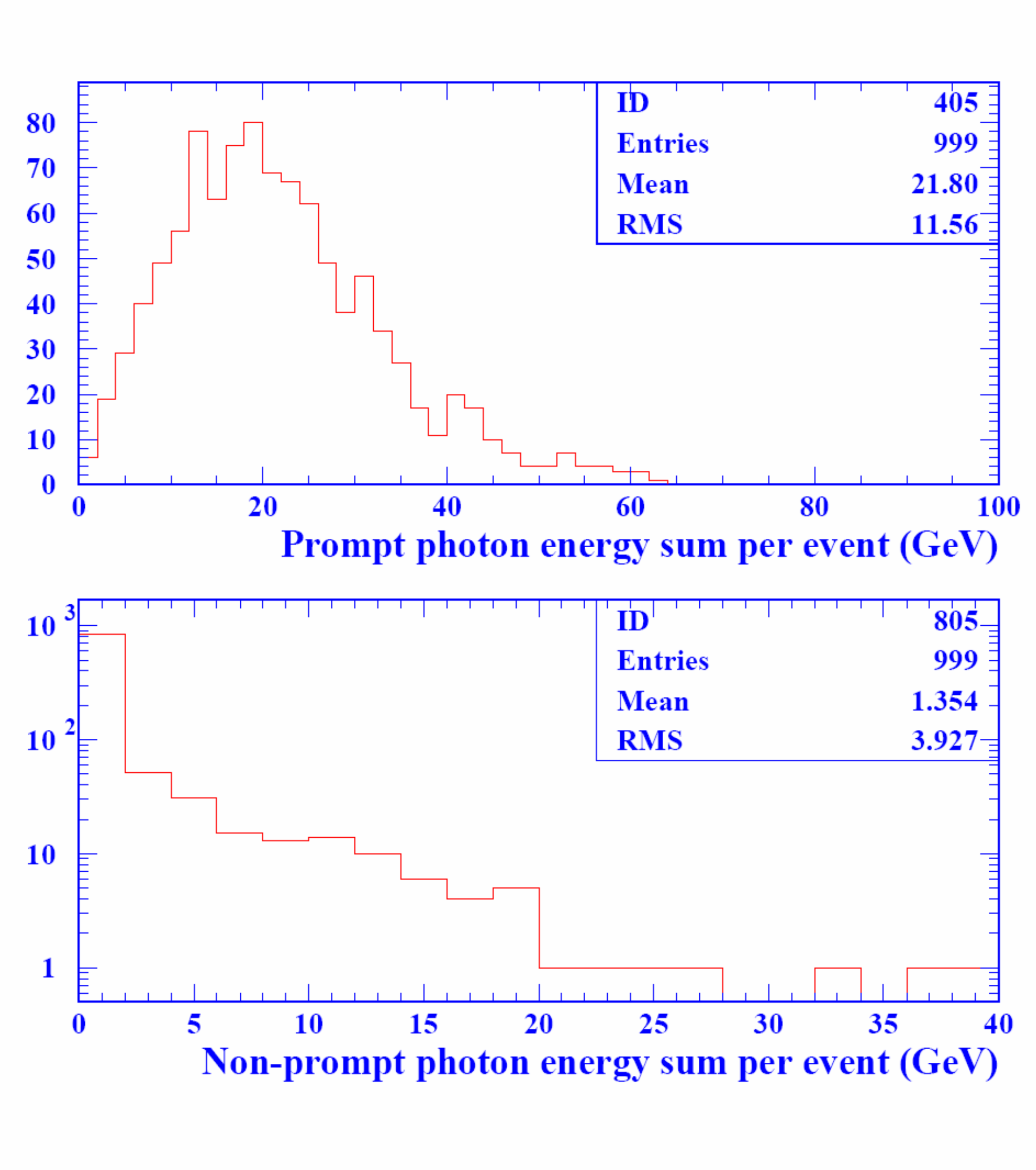
On average 19.2 GeV (21.0%)

NB generator has ISR and beamstrahlung turned off.



On average, 1.4 GeV (1.5%)

Photon Accounting



cf 19.2 GeV from prompt π^0

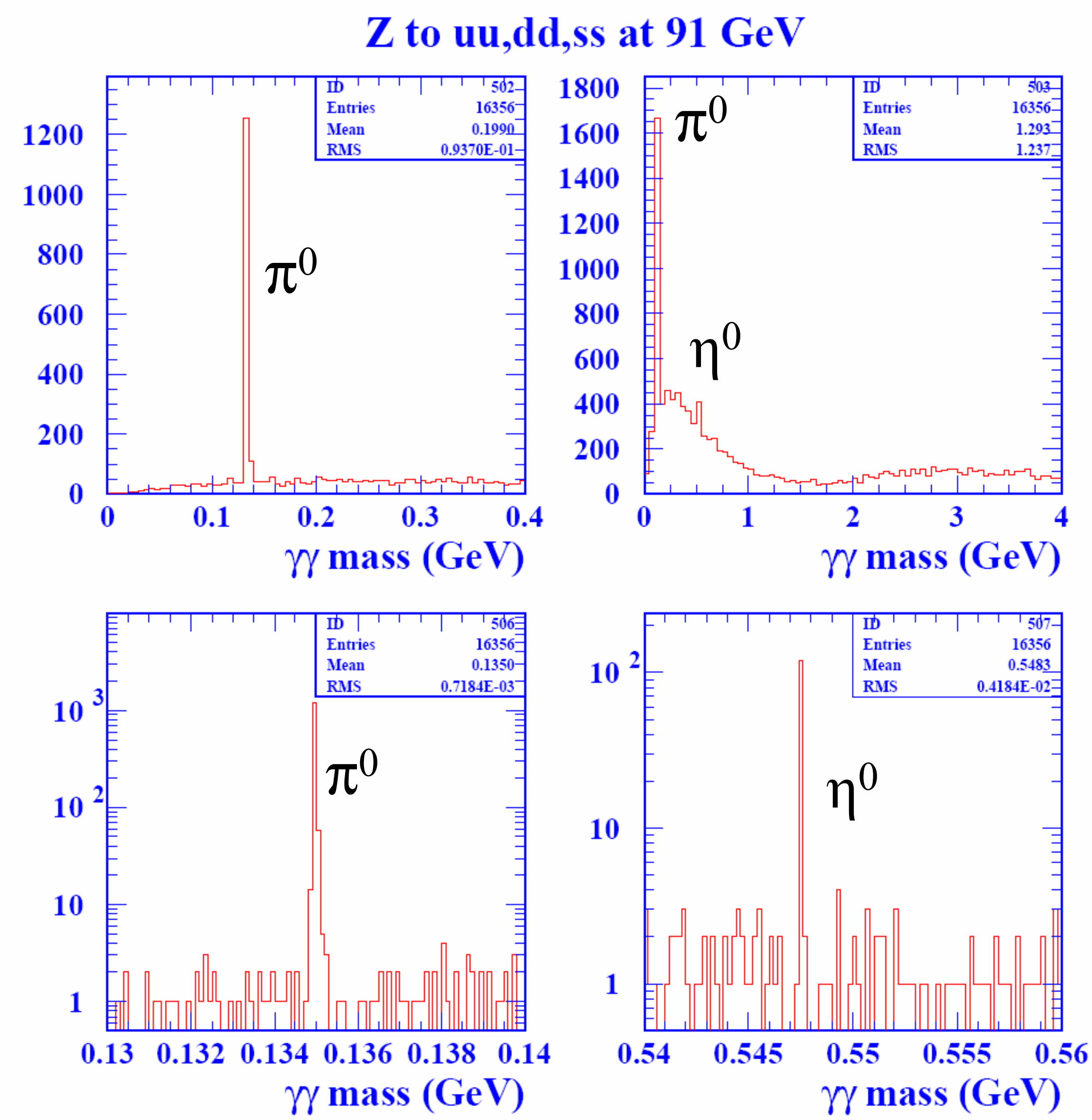
Intrinsic *prompt* photon combinatorial background in $m_{\gamma\gamma}$ distribution assuming perfect resolution, and requiring $E_\gamma > 1$ GeV.

With decent resolution, the combinatoric background looks manageable:

0.09 combinations / 10 MeV/event (π^0),

0.06 combinations/10 MeV/event (η).

Especially if one adopts a strategy of finding the most energetic and/or symmetric DK ones first.



Next step: play with some algorithms

Conclusions and Outlook

- Kinematic fitting works.
- Excellent angular resolution for photons may lead to much improved resolution on EM component of hadronic jets (and knowledge of the error).
- Immediate plans (with a reliable internet connection!):
  - Implement pairing and fitting algorithm in hadronic events assuming unperturbed photon response.
- Measuring very well some jets (those without neutral hadrons), and knowing the resolution, could be advantageous in some physics analyses.

Backup Slides

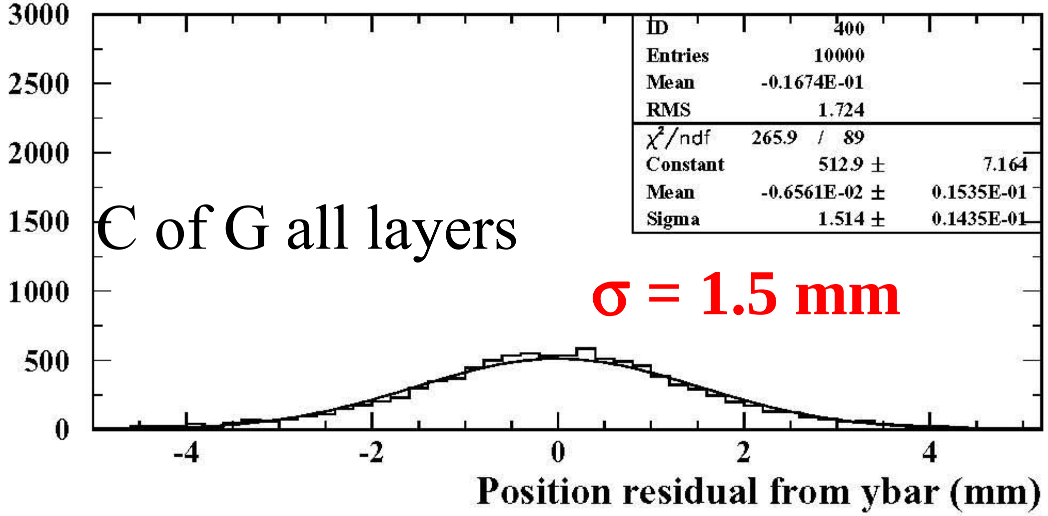
Position resolution from simple fit

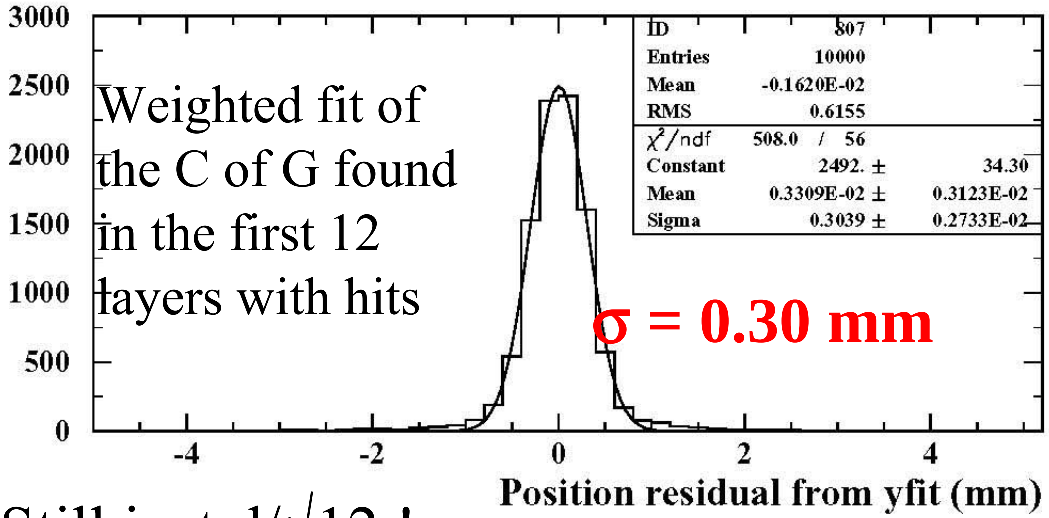
Neglect layer 0 (albedo)

Using the first 12 layers with hits with E>180 keV, combine the measured C of G from each layer using a least-squares fit (errors varying from 0.32mm to 4.4mm). Iteratively drop up to 5 layers in the "track fit".

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

1 GeV photon, G4 study (GWW)



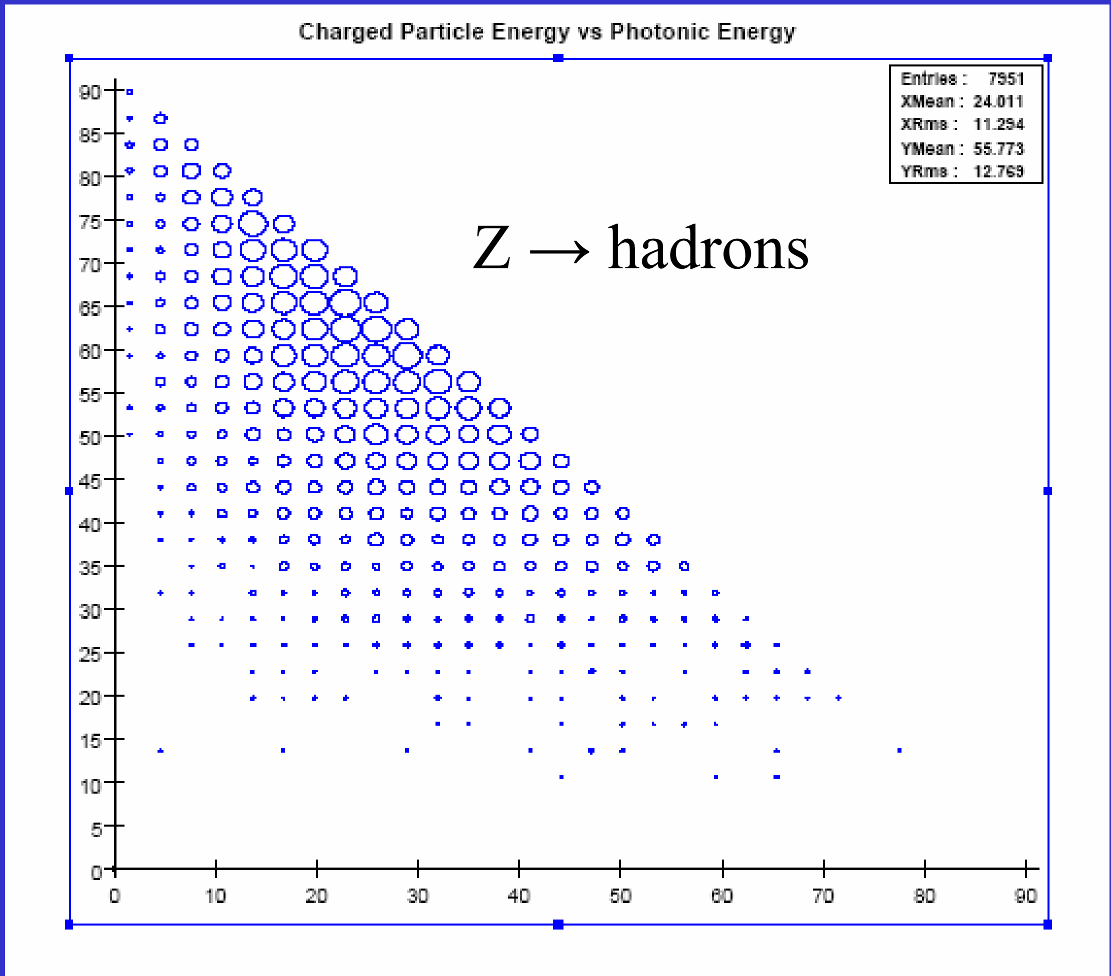


Still just d/√12 !

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 7.4	HERWIG 5.9
	OPAL	ALEPH [6]	DELPHI [9]	L3 [10–12]		
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

Investigating π^0 Kinematic Fits

- Standard technique for π^0's is to apply the mass constraint to the measured $\gamma\gamma$ system.
- Setting aside for now the combinatoric assignment problem in jets, I decided to look into the potential improvement in π^0 energy measurement.
- In contrast to "normal ECALs", the Si-W approach promises much better measurement of the $\gamma\gamma$ opening distance, and hence the opening angle at fixed R. This precise $\theta_{\gamma\gamma}$ measurement therefore potentially can be used to improve the π^0 energy resolution.
- How much ?, and how does this affect the detector concepts ?

Methodology

- Wrote toy MC to generate 5 GeV π^0 with usual isotropic CM decay angle ($dN/d\cos\theta^* = 1$).
- Assumed photon energy resolution (σ_E/E) of 16%/$\sqrt{E}$.
- Assumed γ–γ opening angle resolution of 2 mrad.
- Solved analytically from first principles, the constrained fit problem under the assumption of a diagonal error matrix in terms of (E_1, E_2, $2(1-\cos\theta_{12})$), and with a first order expansion.
  - Note. $m^2 = 2\, E_1\, E_2\, (1 - \cos\theta_{12})$
- π^0 kinematics depends a lot on $\cos\theta^*$. Useful to define the energy asymmetry, $a \equiv (E_1-E_2)/(E_1+E_2) = \beta \cos\theta^*$.