Research on Neutral Pion Reconstruction with the forward electromagnetic calorimeter at STAR/RHIC

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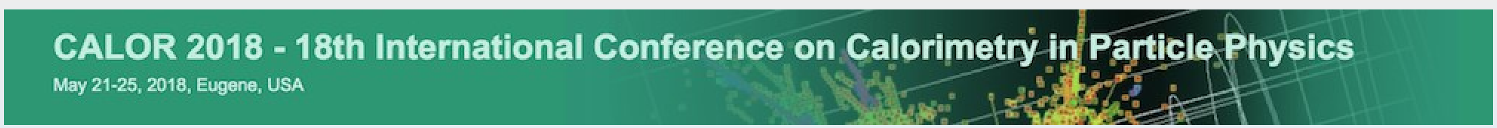

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STAR

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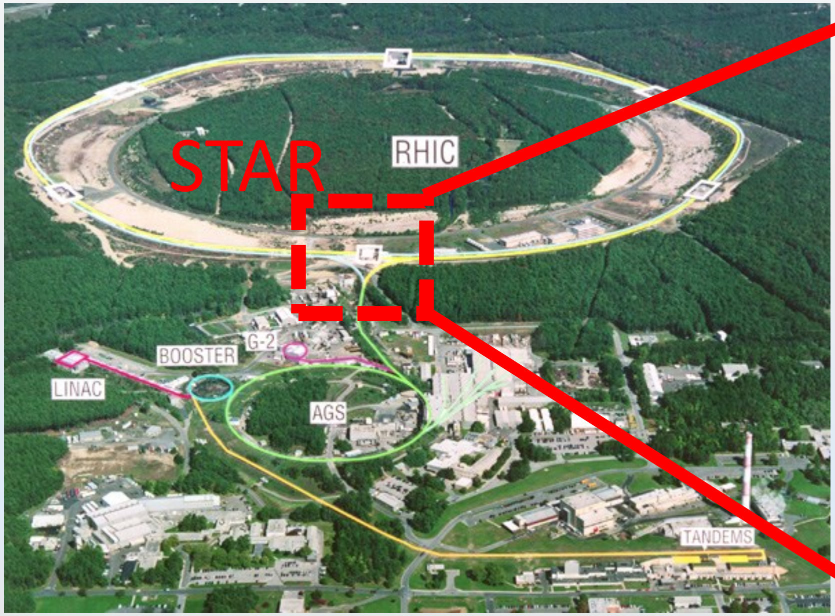
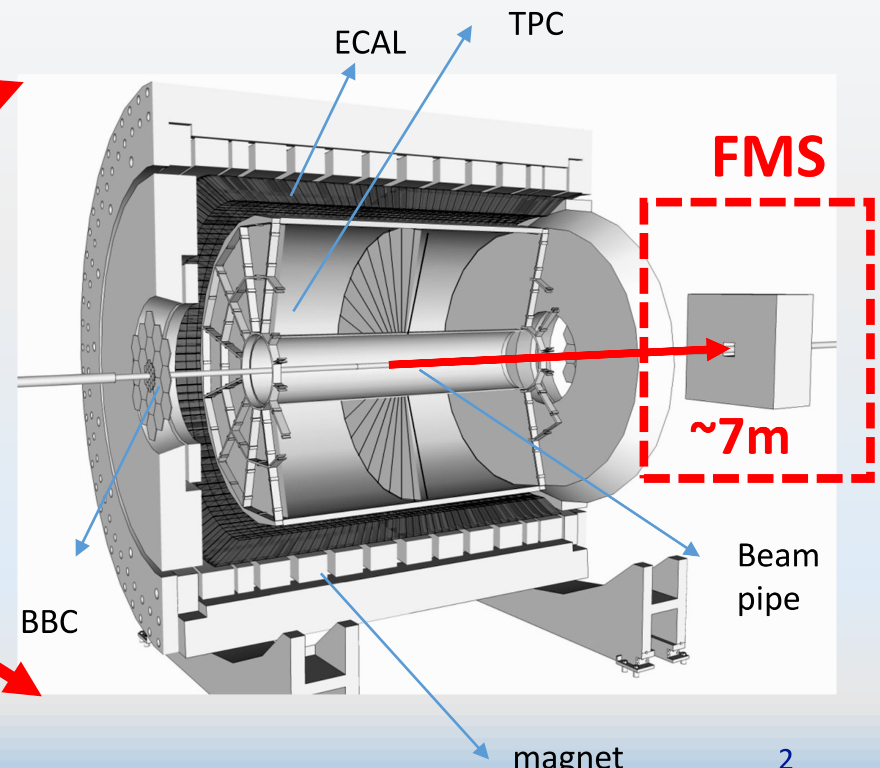
STAR @ RHIC

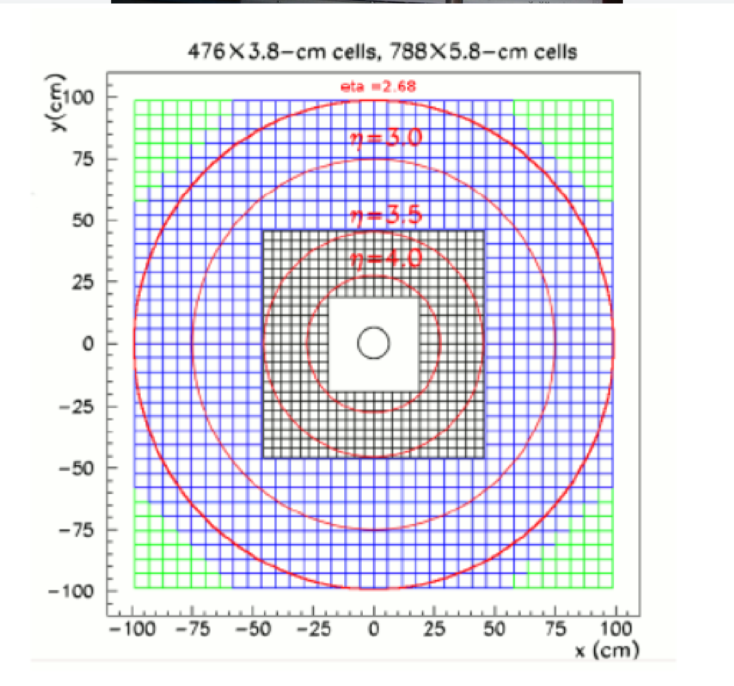
- The *Relativistic Heavy Ion Collider* at BNL provides a unique opportunity to study the internal structure of nucleon, because it is the world's only polarized proton collider.
- The *Solenoidal Tracker At RHIC*
- Electromagnetic Calorimetry : BEMC, EEMC, FMS
  - **2008:** Forward Meson Spectrometer(FMS) $2.6 < \eta < 4.0$
- TPC, Time-of-Flight, Muon detectors, Beam-Beam Counters, …..



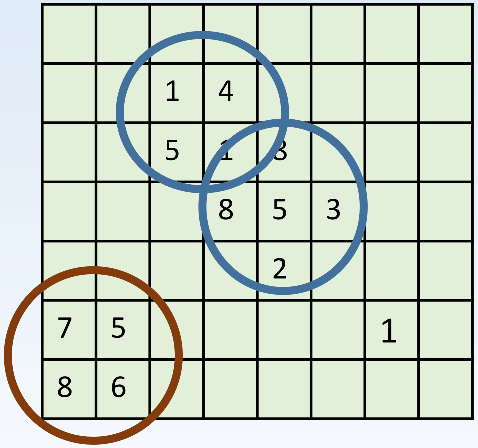


FMS

- Electromagnetic Calorimeter (FMS) made out of lead glass.
  - Non-projective
  - Ideal way to detect photons from π^0 – decays
  - Large rapidity 2.6 to 4.0
  - 1264 blocks of 2 sizes: 3.8cm /5.8cm also with different length and material
- forward rapidity
  - Access to low and high x $x \sim \frac{2p_T}{\sqrt{s}} e^{\pm y}$
- many scientific opportunities by measuring
  - γ, π^0, J/Ψ, Drell-Yan
  - 2015 and 2017 upgraded to add a pre- and post-shower



Photon Reconstruction



2 photons (overlap) cluster

1-photon cluster

Forming Clusters using highest energy tower as seed

Clusters are categorized based on size as

1-photon cluster → Fit to get energy and position

2-photon (overlap) cluster → Try 1st fit. Total Energy and direction in x-y plane are fixed. Fit to get position of the pion, opening angle and energy separation → Try 2nd fit. Use 1st fit as input. Position and energy is not fixed.

For ambiguous cluster, try both

validation

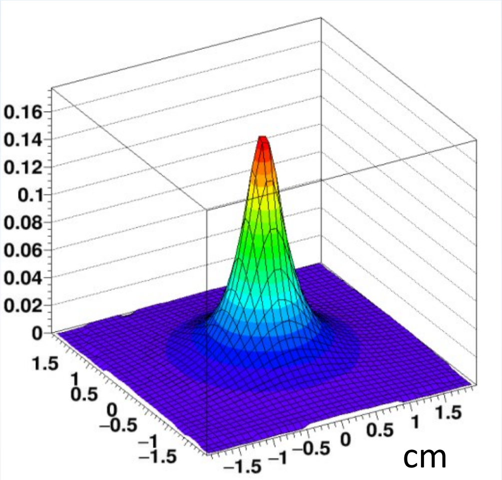
A FMS point/photon candidate is born

Shower shape fitting

x & y are distance from the cell to the photon candidate, G(x,y) represent energy deposition of this point to the cell

$$G(x,y) = F(x+\frac{d}{2}, y+\frac{d}{2}) - F(x-\frac{d}{2}, y+\frac{d}{2}) - F(x+\frac{d}{2}, y-\frac{d}{2}) + F(x-\frac{d}{2}, y-\frac{d}{2})$$

$$F(x,y) = \frac{1}{2\pi}\sum_{i=1}^{3} a_i \left[\arctan\left(\frac{x}{b_i}\right) + \arctan\left(\frac{y}{b_i}\right) + \arctan\left(\frac{xy}{b_i\sqrt{b_i^2+x^2+y^2}}\right)\right]$$

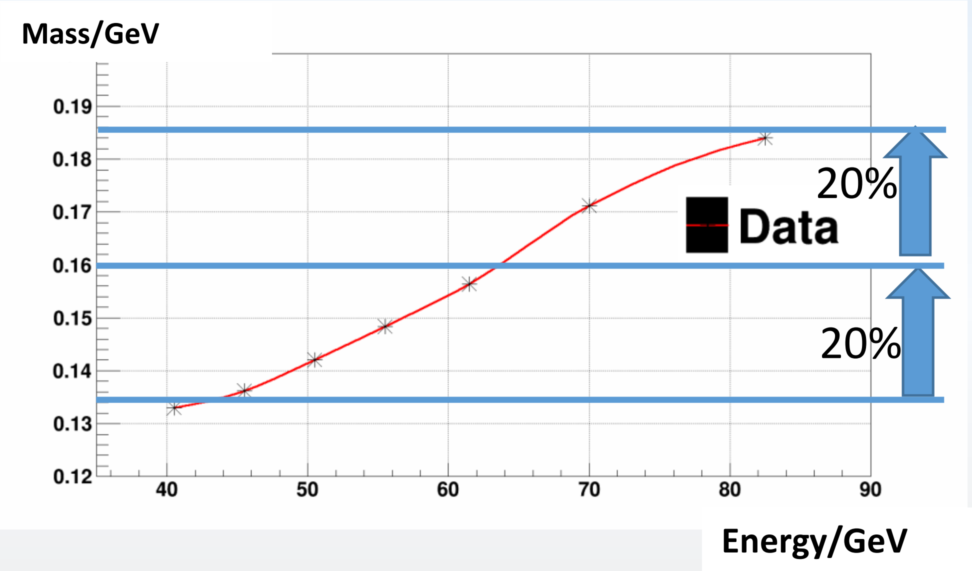


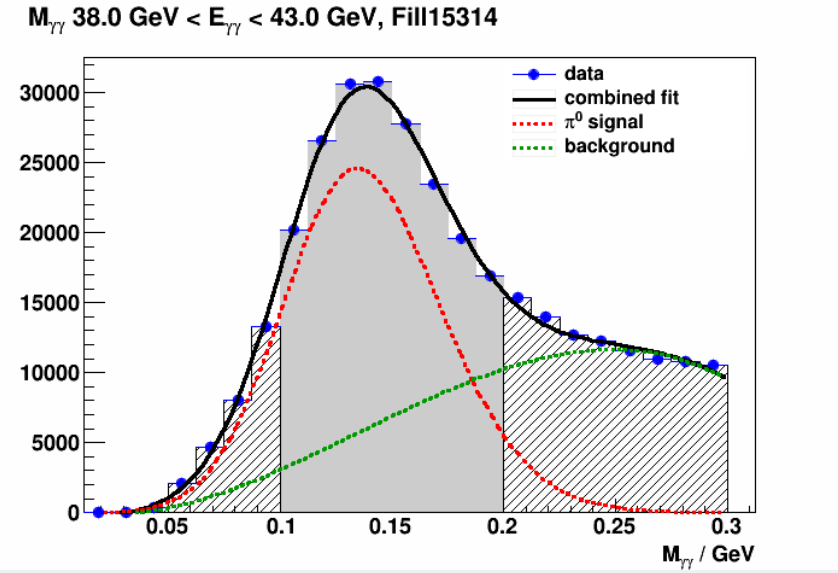
Integral form of shower shape function, a_is and b_is are pre-defined parameters

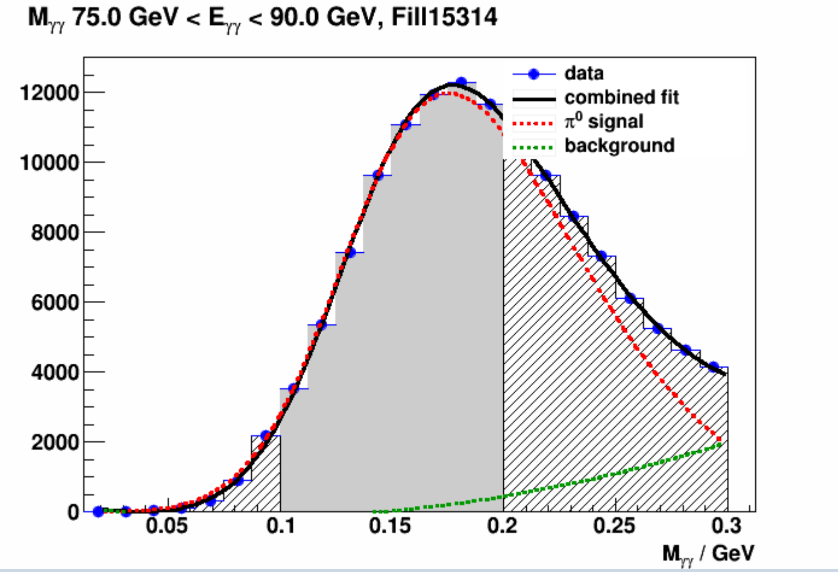
- ❑ By fitting the shower shape, one can determine the point position. The form of the shower shape is shown above.
- ❑ Reconstruct π^0 using combination of all points using

$$M_{\gamma\gamma} = \sqrt{2 * E_1 * E_2 * (1 - \cos(\theta))}$$

Difficulties encountered







Large pion mass shift at high energy:
Pushing to high energy, the position of the π^0 mass peak increases significantly, which makes it hard to fit and and get a correct signal/background ratio.
A big disadvantage to estimate uncertainty.

Possible Explanations

$$M_{\gamma\gamma} = \sqrt{2 * E_1 * E_2 * (1 - \cos(\theta))} \approx \sqrt{E_1 * E_2} * \theta = E_{total} * \sqrt{1/2 * (1 - Z_{\gamma\gamma}^2)} * \theta$$

$$Z_{\gamma\gamma} = \frac{E_1 - E_2}{E_1 + E_2}$$

Energy

- Errors during data recording
- Energy scale is biased by the detector
- Calibration
- Separation of overlap photons

Opening angle

- Collision vertex distribution
- Incident angle and shower maximum
- parameterization of shower shape
- Algorithm of reconstruction

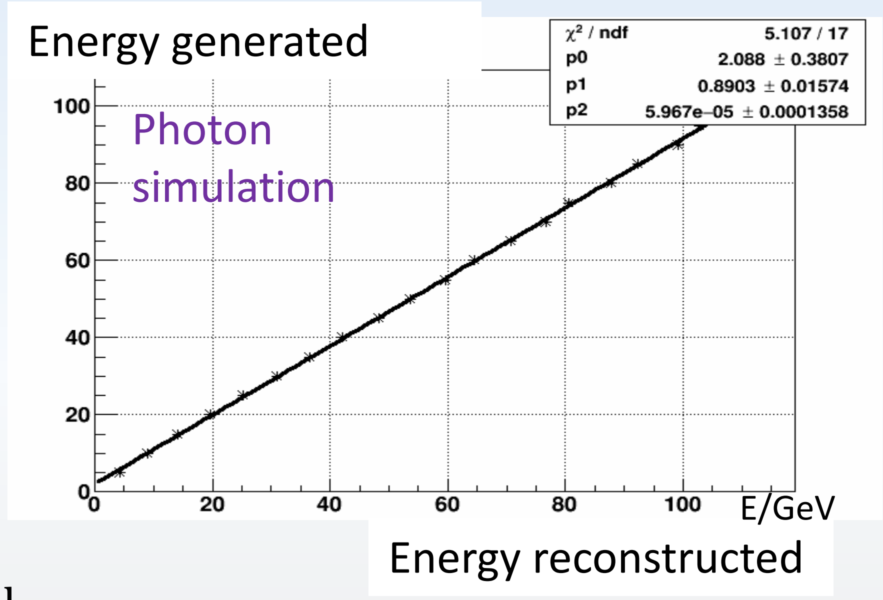
Since calibration is done via π^0 mass, all factors could also influence the calibration which make it more complicated

Energy response of the detector

The amount of Cherenkov light loss varies with the photon energy due to the transparency of the lead glass which can be affected by radiation damage.

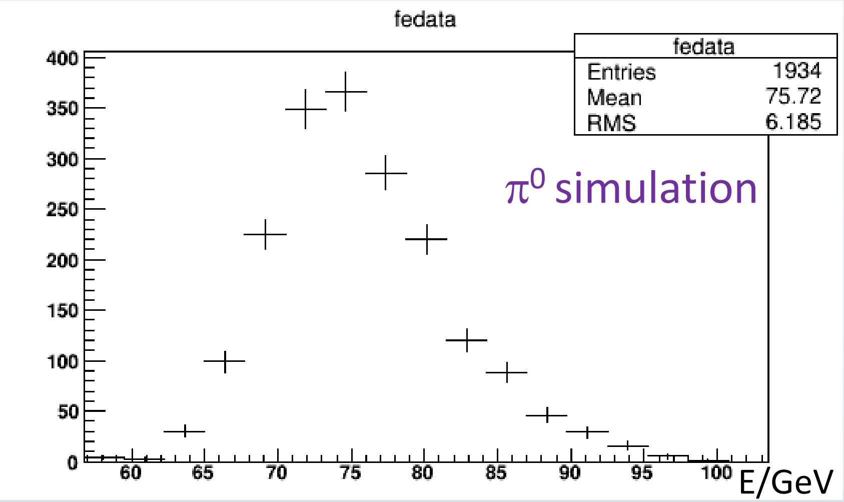
In simulation, we use a depth related energy modulation to model this effect.

$$E = E_{deposite} * e^{-\Lambda(L-z)} \quad \Lambda = 0.04 \text{ for small cell}$$



Simulation test of 75GeV π^0 .

The average π^0 energy shows good relation to the photon energy



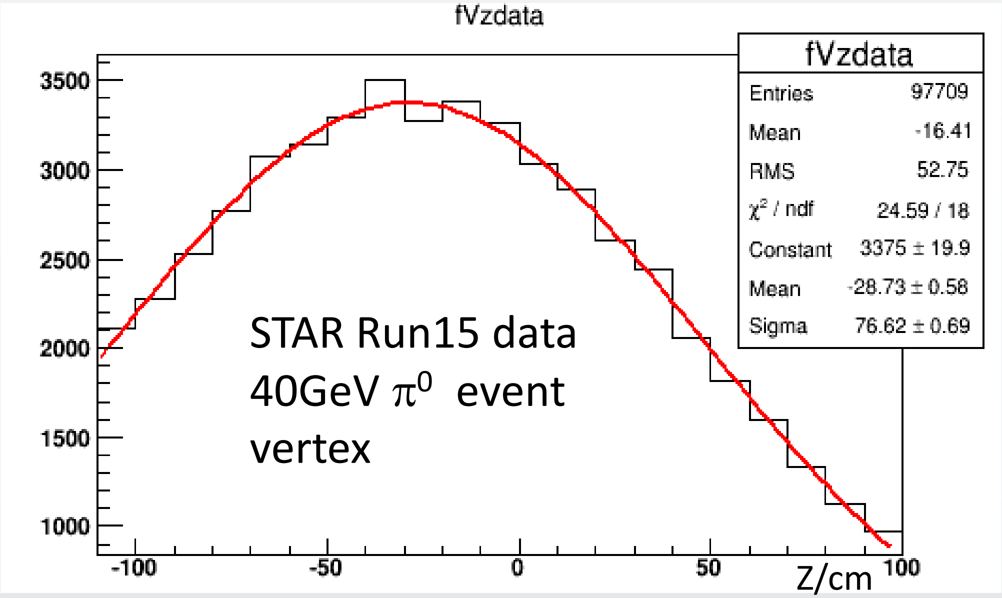
Opening angle

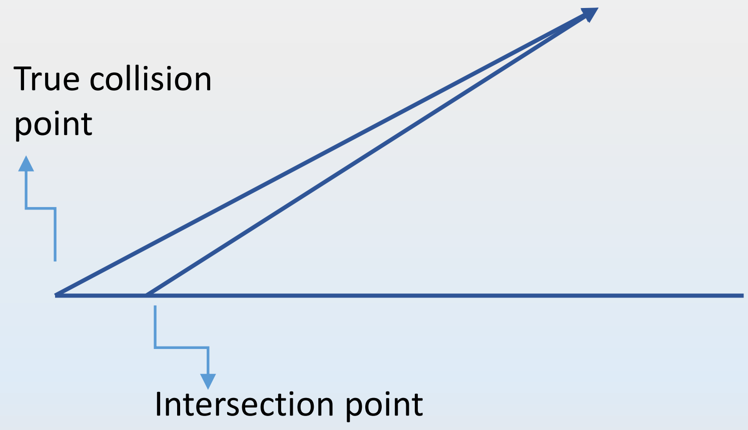
Longitudinal Vertex position:

Vertex information is provided by Beam-Beam Counters

35cm shift of the vertex approximately over/under-estimates the opening angle by 5%. (7m from IR to FMS)

The wide distribution makes it important to account for it in the calculation.





Incident angle

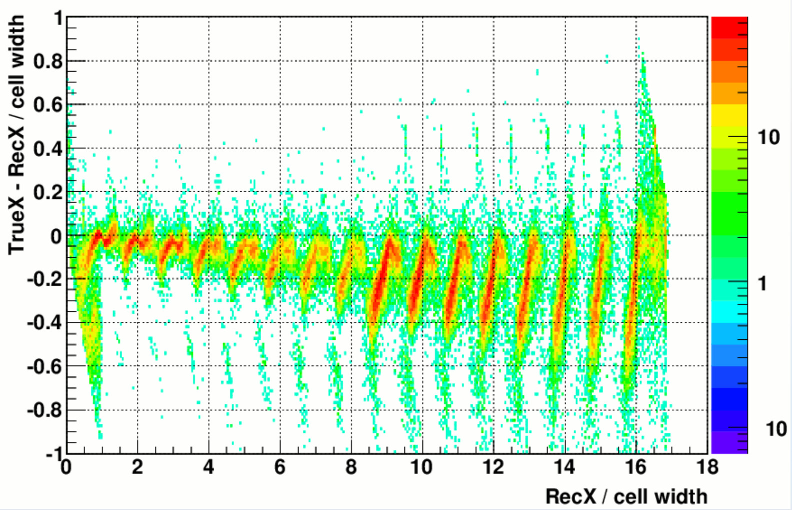
Use the incident angle to create an asymmetric shower shape.

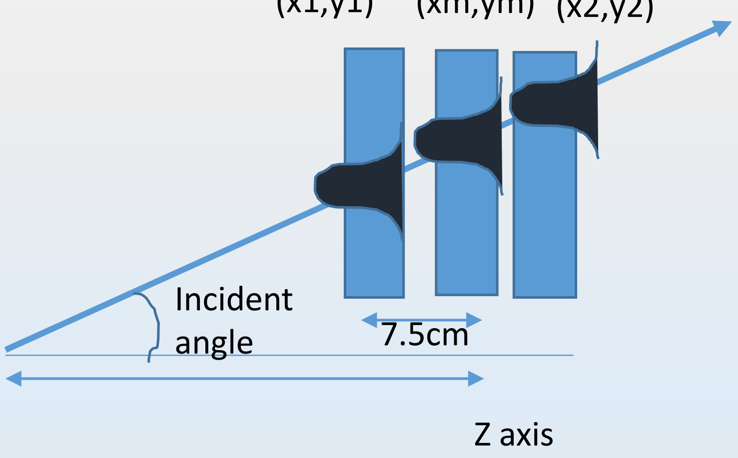
This gives a much better positioning of the FMS points

→ Reduces possible bias, which could be as large as 1/5 of the cell width for outer cells,

→ Suboptimal solution could contribute 3~4% to the opening angle.

Bias in symmetric shower shape: from simulation

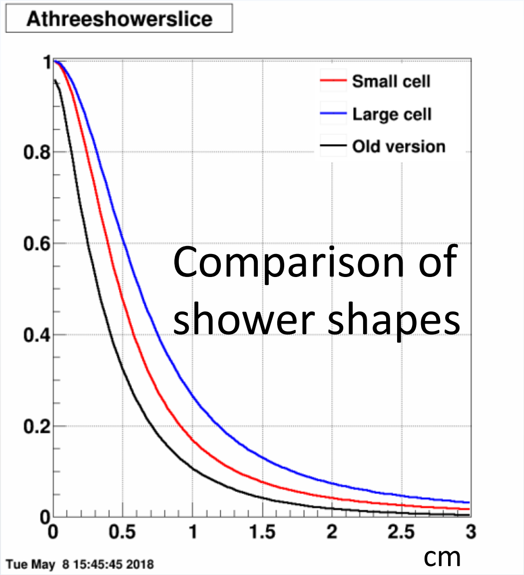


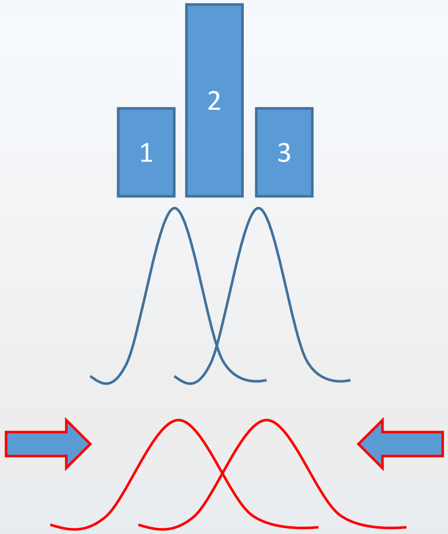


Algorithm & parameter

We found that a wider shower shape leads to smaller opening angles.

Right now the fitting parameters are extracted from a parameterized shower shape from paper.





Narrow shower shape

More energy deposited in outer cells for wider version

$$E_{noAtt}(e,z,r) = z^{\mathrm{A}(e)} * \mathrm{e}^{-\frac{\mathrm{z}}{\Lambda(e)}} * \frac{e^{-\frac{r}{\mathrm{M}(z,e)}}}{\mathrm{M}(z,e)}, \mathrm{M}(z,e) = 0.039 * \sqrt{e^{z/\Psi(e)}}$$

$$E_{Att}(e,z,r) = e^{-\beta(Z_{max}-z)} * E_{noatt}$$

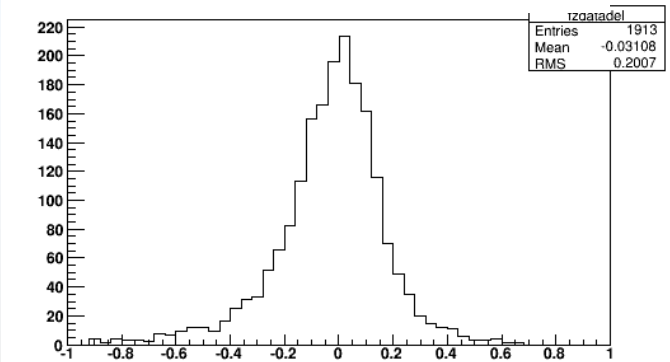
A. De Angelis (1988). Three-dimensional parametrization of photon-initiated high energy showers.

Result: π^0 only simulation

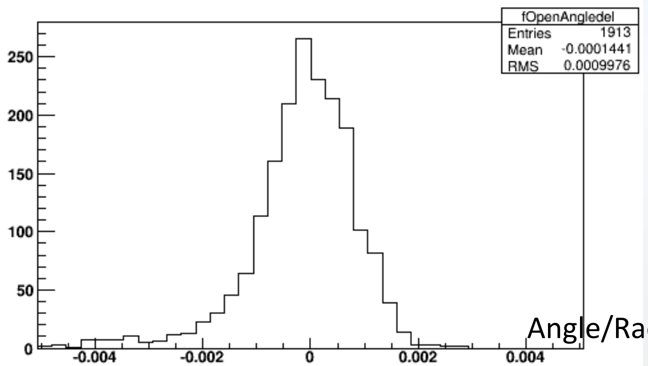
Results after all corrections and improvements are applied

Test sample: 75GeV π^0 at fixed position on FMS

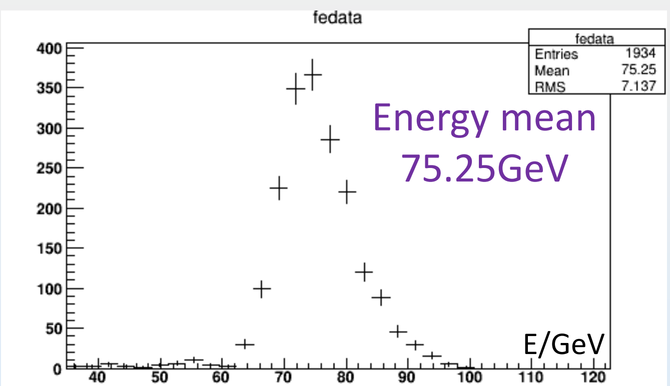
δ $Z_{\gamma\gamma}$ mean : 0.03



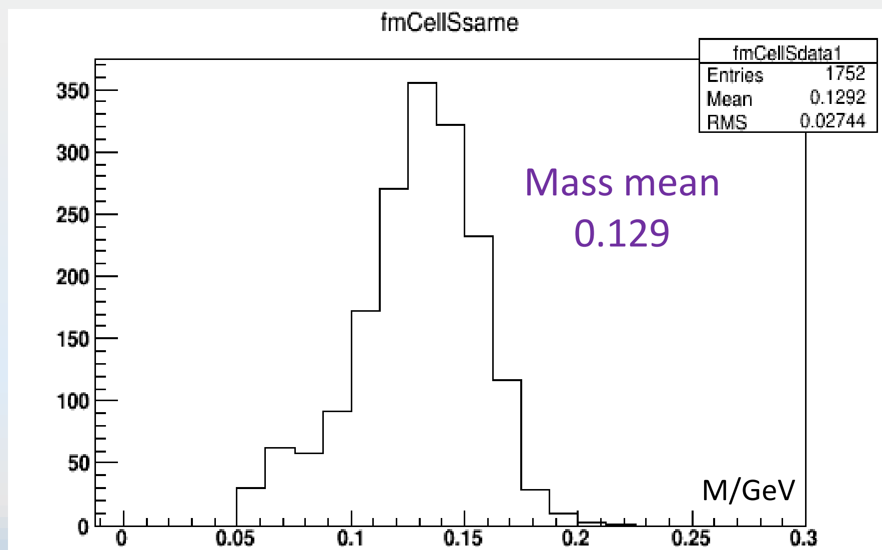
δ opening angle mean : -0.00014



δ =generated - Reconstructed



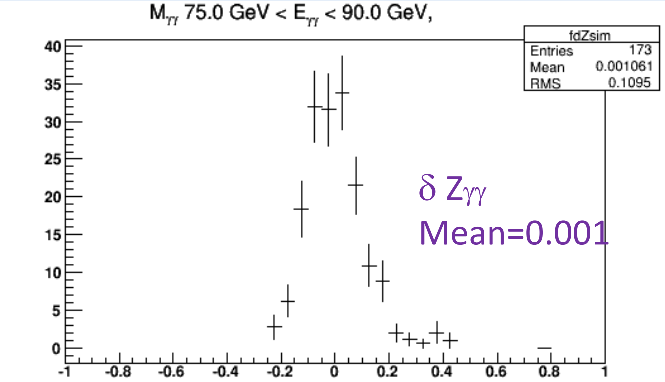
Energy mean 75.25GeV

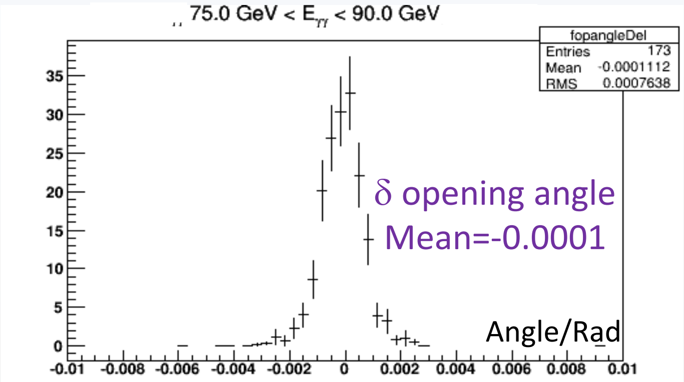


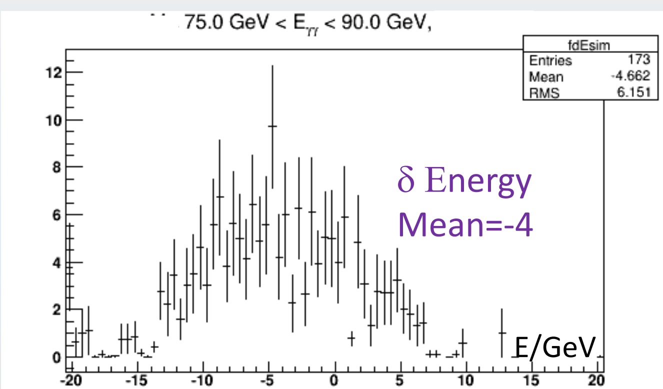
Mass mean 0.129

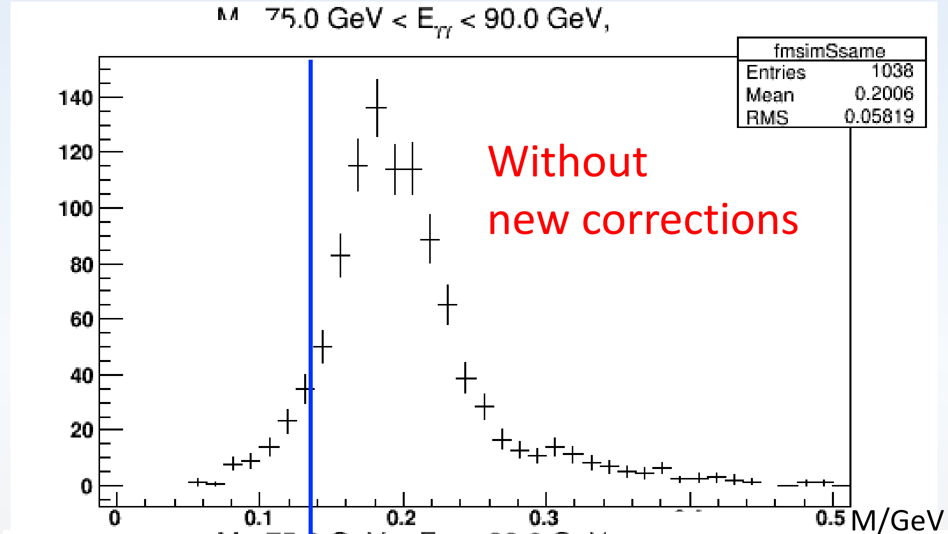
simulation for pp √s= 500 GeV

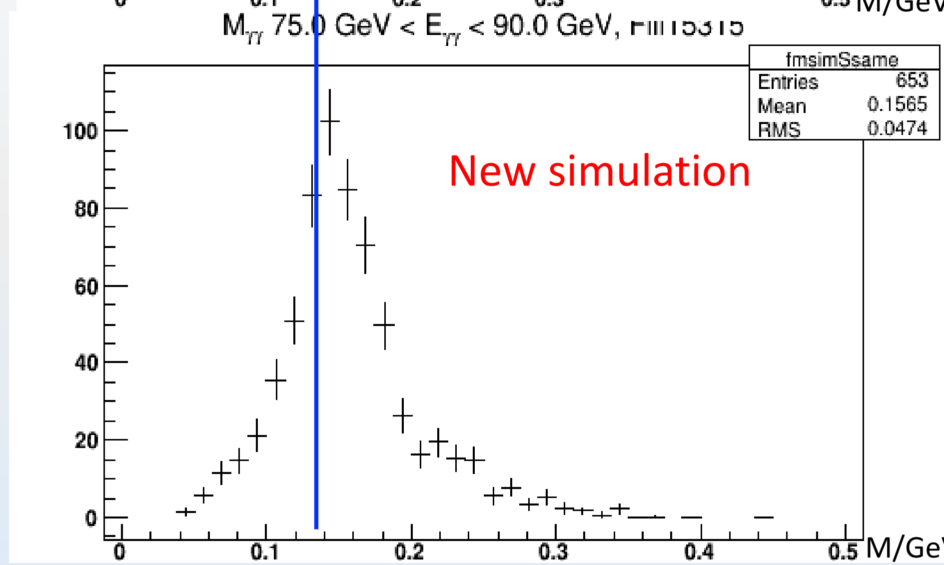
Pythia event generator +Geant 3











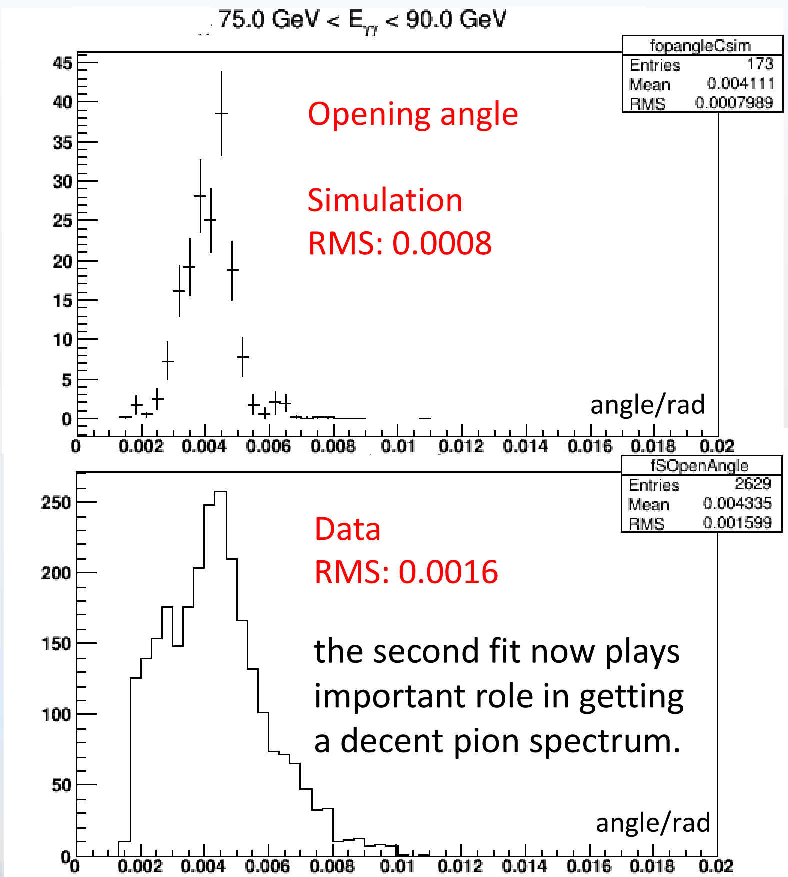
There are particles that cannot be separated from the pion signal

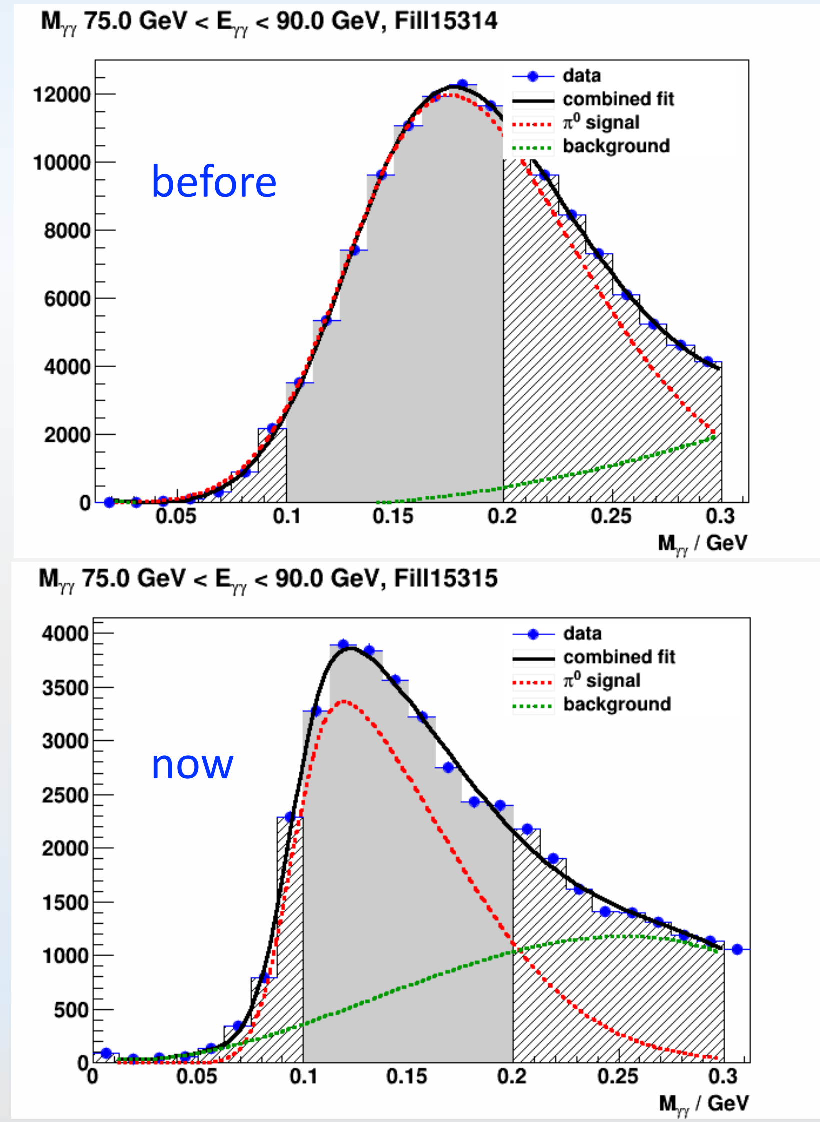
→ additional energy contribution

Result: 500 GeV p-p collision Data

Comparison between data and simulation

Resolution is worse in data. It ends up hitting the opening angle lower limit more, which makes the spectrum more skewed in data.





Summary

- The π^0 mass peak reconstructed by the STAR forward electromagnetic calorimeter (FMS) is strongly energy-dependent.
- The following corrections and modifications have been introduced in the π^0 reconstruction
  - Collision vertex correction
  - Non-linear energy correction
  - Shower shape parameters and fitting process
  - Shower shape form based on Incident angle
- Research has been done to understand the bias. After corrections and modifications, both simulation and data sample show a largely improved π^0 mass peak.

Backup

Adjusting the $D_{\gamma\gamma}$ lower limit

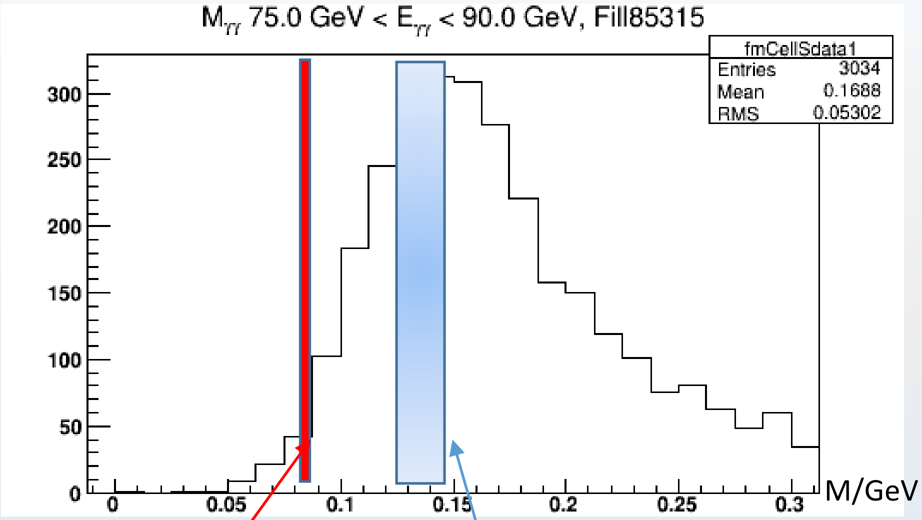
Reconstruction Algorithm and its related parameter originally came from different detector, which aimed at lower photon / π^0 energy region.

At high energy, where the opening angle is small, the old routine could fail.

The most important one is the fitting limit of the opening angle when fitting overlap photons.

Now simply use the half cell width as the lower limit.

The half cell width as lower limit is considered the new limit in the calculation



The calculated limit biased the opening angle

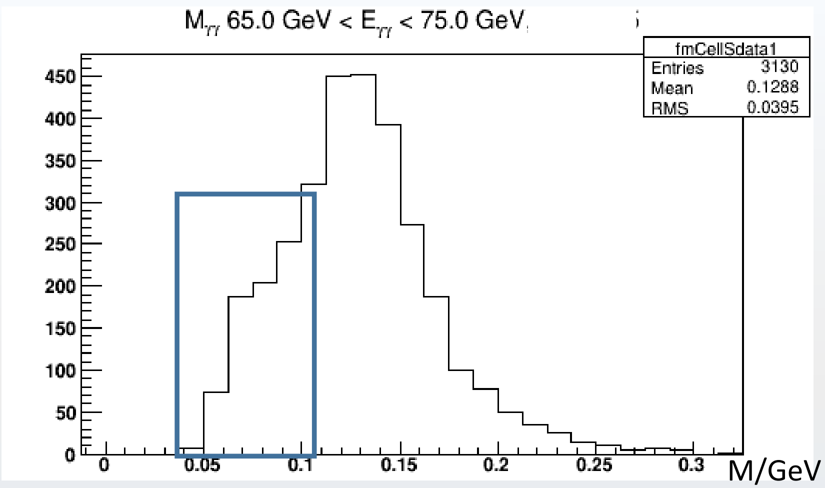
Half cell width limit

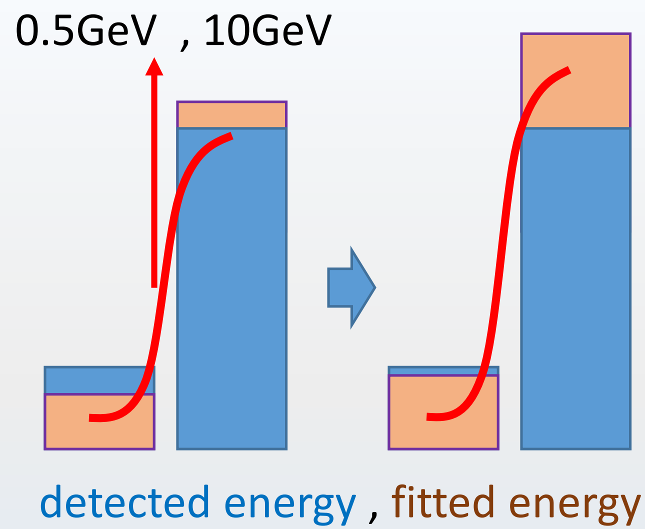
The old calculated limit

The 2nd fit

The 2nd fit originally is designed to get better precision of energy and position when fitting overlap photons.

- Now it is also useful to smooth the bump caused by opening angle lower limit.





- During the 2nd fit, the energy of each fitted photon has to be fixed.

Due to imperfections in the cell weighting (considerably too high weight for low energy cells), the fit is biased to increase the total energy to get a lower chi^2.