Towards Jet Specific Energy Resolution: Investigating $\pi^0$ Kinematic Fits

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

Can this be used to measure $\pi^0$ energies very well and by extension hadronic jets?

Also see talks 2005-2007 on $\pi^0$ KF basics and initial forays into applying to hadronic events.

(latest: ALCPG07 for more details.)

Graham W. Wilson and Brian van Doren
Develop *jet specific energy resolution* formalism.

Take advantage of knowledge of jet energy errors jet per jet.

Non-Gaussian resolution function is not a cardinal sin – it is a potentially exploitable feature.

Will eventually need detailed understanding at individual event level inside PF algorithms.

As a first step, take advantage of error knowledge on the fitted photon component (under the \( \pi^0 \) mass hypothesis).

May be most useful in the near-term in the “no-confusion” limit.

\[
E_{\text{jet}} = E_{\text{ch}} + E_{\gamma} + E_{\text{NH}}
\]
**Possible 1 TeV benchmark?**

Single $W$ study at $\sqrt{s} = 1$ TeV

\[ W \rightarrow q \, q \]

(jets are not so energetic)

**Example (New) Physics Analysis**

**W mass fit from hadronic system**

<table>
<thead>
<tr>
<th>ID</th>
<th>681</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>4714</td>
</tr>
<tr>
<td>Mean</td>
<td>90.29</td>
</tr>
<tr>
<td>RMS</td>
<td>3.763</td>
</tr>
<tr>
<td>UDBLW</td>
<td>99.90</td>
</tr>
<tr>
<td>UFBW</td>
<td>61.88</td>
</tr>
</tbody>
</table>

\[ \sqrt{s}/\text{jet} = 34.61 \, \pm \, 38 \]

\[ P1 = 0.184 \pm 0.05 \, \pm \, 0.070 \pm 0.06 \]

\[ P2 = 86.18 \, \pm \, 0.23 \pm 0.01 \]

\[ P3 = 2.120 \, \pm \, 0.07 \pm 0.01 \]

**Fast Simulation (Gaussian smearing)**

\[ \sigma(E) = 1.1 \, \sigma_{\text{rms}}(E) \]

Is this useful for physics? Example $m_W$.

**WPHACT v2.0.2 generator**

Use ILD jet energy resolution parametrization with $\alpha = 0.1 \, \sigma_{\text{rms}}$.

Potentially very useful! (Especially, if the really challenging requirements on jet energy scale and calibration can be met!)
Absolute Jet Energy Scale

• One self-contained approach for PFA could be bottom-up using known particle masses.
  - Momentum scale ($J/\psi$)
  - Photon scale ($\pi^0$)
  - $K^0_L$ scale ($\phi$)
  - n scale ($\Sigma$)
  - nbar scale ($\Sigma$)

• Probably unrealistic as the only method.
  - But may point to the need for substantial statistics at the Z.
$\pi^0$ Kinematic Fitting
**π^0**’s and Particle Flow

- **Particle Flow**
  - Charged particles  => TRACKER  => 62%
  - **Photons**  => ECAL  => 28%
  - Neutral hadrons  => HCAL  => 10%

- **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. ω → π^0 γ)
  - Non-prompt Photons
    - K^0_S → π^0 π^0
    - Λ → π^0 η

- 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!
- So, for correctly paired photons, π^0 mass constraint is reasonable, and we have shown that the improvement in estimating E_{π0} can be sizeable.
Detector Resolution

- Both ILD and SiD envisage compact EM calorimeters capable of very precise angular measurements readout every X0 or so.
- Examples:
  - Si-W
    - (13 mm² cells at R=1.27 m (SiD)
    - (25 mm² cells at R=1.85 m (ILD)
    - (50 µm x 50 µm pixels – MAPS option)
  - Can identify the photon conversion point in the ECAL with resolution typical of the pixel size largely independent of the photon energy.
- Resolutions in the 0.5 mrad range per projection for 1 GeV photons is at hand (assuming photon is prompt).
Working on a paper documenting and extending the foundations of earlier studies. Emphasis is on a generic detector for a wide range of resolution assumptions. Mainly treating the single $\pi^0$ case using smeared Monte Carlo.

Applying mass-constrained fits to the energy reconstruction of di-photon resonances with high granularity calorimeters

G. W. Wilson$^a$ and B. van Doren$^a$

$^a$Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA
E-mail: gwwilson@ku.edu

ABSTRACT: Mass-constrained fits to correctly matched pairs of photons are investigated and the improvements in di-photon energy resolution are quantified for the ubiquitous $\pi^0$ for a range of $\pi^0$ energies, center-of-mass decay angles, and assumptions on photon energy and angular resolution.
$\pi^0$ Kinematic Fitting I

- For simplicity, (old 3-variable studies) used the following measured experimental quantities:
  - $E_1$ (Energy of photon 1)
  - $E_2$ (Energy of photon 2)
  - $\psi_{12}$ (3-d opening angle of photons 1 and 2)

- Fit using
  - 3 variables, $x = (E_1, E_2, 2(1 - \cos \psi_{12}))$
  - a diagonal error matrix
    - (assumes individual $\gamma$’s are completely resolved and measured independently)
  - and the constraint equation
    - $m_{\pi^0}^2 = 2E_1 E_2 (1 - \cos \psi_{12}) = x_1 x_2 x_3$
The new 6-variable study uses \((E, \theta, \phi)\) for each photon.

Still a diagonal error matrix.

Implementations:

- 3 variable: analytic
- 3 variable: Blobel F77 fitter
- 6 variable: Blobel F77 fitter
- 6 variable: MarlinKinFit (Brian)

6-variable advantages:

- More realistic angular resolution implementation
- Assess improvements in \(\pi^0\) direction

Have been able to cross-check all four with identical inputs.
Energy Smearing and Detection Threshold

- Previously had used Gaussian energy smearing.
  - $\sigma_E/E = \alpha/\sqrt{E}$
  - Non-negligible probability of negative energy.
- Elected to smear the photon energies using a Compound Poisson distribution (reasonably physically motivated as a model of branching processes).
- Impose a minimum detection threshold at $E (\text{GeV}) > 2 \alpha^2$
- For $\alpha=0.16$, $E_{\text{min}} = 0.05 \text{ GeV}$
Smearing the Photon Angular Resolution

Photons are assumed to be prompt. So angular resolution is equivalent to position resolution in the ECAL for this application.

Photons are smeared independently in “x” and “y” by Gaussians with width of eg. $\sigma = 0.5\text{mrad}$ independent of energy.

Rayleigh distribution with $\sigma = 0.5\text{mrad}$

$\text{Err}(\psi_{12}) = \sqrt{2} \sigma$ (previous thinking: $\text{Err}(\psi_{12}) = 2 \sigma$ !)

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVTLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>4000</td>
<td>0.2406E-01</td>
<td>0.7100</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVTLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>4000</td>
<td>0.2406E-01</td>
<td>0.7100</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

$\chi^2$/d.o.f $= 94.84 / 85$

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVTLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>4000</td>
<td>0.2406E-01</td>
<td>0.7100</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>UDELW</th>
<th>OVTLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>202</td>
<td>4000</td>
<td>0.2406E-01</td>
<td>0.7100</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Example Fit

4 GeV $\pi^0$, 16%/\sqrt{E}$, 0.5mr (default assumptions unless stated otherwise)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured</th>
<th>3-variable fit</th>
<th>6-variable fit</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>2.468 ± 0.253</td>
<td>2.385 ± 0.192</td>
<td>2.385 ± 0.192</td>
<td>-0.504</td>
</tr>
<tr>
<td>$E_2$</td>
<td>1.679 ± 0.196</td>
<td>1.605 ± 0.130</td>
<td>1.605 ± 0.130</td>
<td>-0.504</td>
</tr>
<tr>
<td>$2(1 - \cos \psi_{12})$</td>
<td>$(4.765 \pm 0.0985) \times 10^{-3}$</td>
<td>$(4.759 \pm 0.0977) \times 10^{-3}$</td>
<td>-0.504</td>
<td></td>
</tr>
<tr>
<td>$\theta_1$ (mrad)</td>
<td>1608.36 ± 0.50</td>
<td>1608.37 ± 0.50</td>
<td>0.504</td>
<td></td>
</tr>
<tr>
<td>$\theta_2$ (mrad)</td>
<td>1619.11 ± 0.50</td>
<td>1619.10 ± 0.50</td>
<td>-0.504</td>
<td></td>
</tr>
<tr>
<td>$\phi_1$ (mrad)</td>
<td>2196.86 ± 0.50</td>
<td>2196.84 ± 0.50</td>
<td>-0.504</td>
<td></td>
</tr>
<tr>
<td>$\phi_2$ (mrad)</td>
<td>2128.60 ± 0.50</td>
<td>2128.62 ± 0.50</td>
<td>0.504</td>
<td></td>
</tr>
<tr>
<td>$m_{\pi^0}$ (MeV)</td>
<td>140.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_{E_1E_2}$</td>
<td>-0.9683</td>
<td>-0.9683</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\pi^0}$</td>
<td>4.147 ± 0.320</td>
<td>3.990 ± 0.074</td>
<td>3.990 ± 0.074</td>
<td></td>
</tr>
<tr>
<td>$\chi^2/\nu$</td>
<td></td>
<td>0.2543/1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{\text{fit}}$ (%)</td>
<td></td>
<td>61.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Note: the 3 and 6-variable fits are equivalent in terms of energy variables)
Pull Distributions
Fit Probability

<table>
<thead>
<tr>
<th>pfit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>96835</td>
</tr>
<tr>
<td>Mean</td>
<td>0.5027</td>
</tr>
<tr>
<td>RMS</td>
<td>0.289</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
<td>114.6 / 99</td>
</tr>
<tr>
<td>Prob</td>
<td>0.1358</td>
</tr>
<tr>
<td>$p0$</td>
<td>967.2 ± 3.1</td>
</tr>
</tbody>
</table>
π⁰ Angle Improvements

Modest improvements at this energy, but note that this feeds through combinatorically with all other particle pairs in hadronic mass estimates.
$4 \text{ GeV } \pi^0$

**Graphs:**
- **ep0m**
  - Entries: 96834
  - Mean: 4.001
  - RMS: 0.3203

- **ep0f**
  - Entries: 96834
  - Mean: 4.008
  - RMS: 0.1822

- **errp0f**
  - Entries: 96834
  - Mean: 0.0808
  - RMS: 0.04103

- **invvar**
  - Entries: 96834
  - Mean: 114.3
  - RMS: 15.4

**Note:** $16\% / \sqrt{E}$
4 GeV $\pi^0$ ($\cos\theta^* = 0.25$)

Use mean and RMS of this distribution in following plots for fixed values of $\cos\theta^*$

16%/\sqrt{E}
Fitted $\pi^0$ Energy Resolution

Use rms of fitted $\pi^0$ energy distribution.

$\pi^0$s are generated at fixed $\cos \theta^*$ values

![Graph showing fitted energy resolution vs. $\cos \theta^*$ for different angular resolutions.](image-url)
Fitted $\pi^0$ Energy Resolution

Use rms of fitted $\pi^0$ energy distribution.

$\pi^0$s are generated at fixed $\cos \theta^*$ values
Fitted $\pi^0$ Energy Bias

Bias < 0.3%
Weighted Mean

• We can also try and use the π⁰ specific energy resolution.

• As an exercise, look at weighting by the fitted energy error of each π⁰ in a mono-energetic sample with the usual weight factor of $σ_i^{-2}$.

• In this case, we can define an effective resolution per π⁰, $σ_* \equiv \sqrt{(1/\langle σ_i^{-2} \rangle)}$, (and also scale this stochastically too).
4 GeV $\pi^0$

**ep0m**
- Entries: 96834
- Mean: 4.001
- RMS: 0.3203

**err0f**
- Entries: 96834
- Mean: 0.0808
- RMS: 0.04103

16%/$\sqrt{E}$

**ep0f**
- Entries: 96834
- Mean: 4.008
- RMS: 0.1822

**invvar**
- Entries: 96834
- Mean: 114.3
- RMS: 154
Averaging over all $\cos \theta^*$

Quite an improvement on the apparent statistical error on this “observable”
$\pi^0$ specific energy resolution

Use fitted error on each $\pi^0$ to form weighted average for an ensemble of mono-energetic $\pi^0$s.
$\pi^0$ specific energy resolution

Large ensemble

Weighted mean has a bias of around 0.25%

Chi$^2$/dof small, but not acceptable.

Why?
\[ \pi^0 \] fit pathology

The fit always adjusts the energies of both photons upwards or downwards according to the measured mass deviation from \( m(\pi^0) \).

Sometimes this can lead to a “wrong” fit with small errors

**Example (\( p_{\text{fit}} = 0.5\% \))**

<table>
<thead>
<tr>
<th>( E1 ) (GeV)</th>
<th>( E2 ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>1.2</td>
</tr>
<tr>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>1.9</td>
<td>1.7</td>
</tr>
</tbody>
</table>
$Z^0$

$16\%/\sqrt{E}, 0.5\text{mr}, \text{perfect pairing}$

Calculate error on the sum of the fitted $\pi^0$ energies and scale stochastically

Potential of energy resolution of around $9.2\%/\sqrt{E}$ on average
Next Steps

- Finalize current studies and complete write-up.
- Implement on simulated single $\pi^0$'s
  - Need appropriate clustering, calibrated ECAL and errors.
  - Expect to put some emphasis on low energy photons.
  - While the ILD ECAL is not over-designed for this application, doing “real” simulation studies again will be an important complement to this more conceptual work, and will enable studies in the PFA framework.
  - To get the full benefit – need some more segmented ECAL layers (e.g. MAPS or analog Si-strips). MAPS based ECAL layers are well matched to this application!
- Re-visit (and write up) “matching problem” – pairing up photons in hadronic events.
  - (Old results $16%/\sqrt{E} \rightarrow 12%/\sqrt{E}$) (9.4%)
Conclusions and Outlook

• Kinematic fitting works
  – Detector designs should take advantage.

• Excellent angular resolution for photons can lead to much improved resolution on EM component of hadronic jets (and knowledge of the error).

• Measuring very well some jets (those without neutral hadrons), and knowing the resolution, will be advantageous in some physics analyses.
Backup Slides
\( \pi^0 \) mass resolution

- Can show that for \( \sigma_E/E = c_1/\sqrt{E} \) that
  \[
  \Delta m/m = c_1/\sqrt{[(1-a^2) E_{\pi^0}]} \oplus 3.70 \Delta\psi_{12}E_{\pi^0} \sqrt{(\beta^2-a^2)}
  \]
  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 \( (\Delta\psi_{12}) \)

The relative importance of each depends on \( (E_{\pi^0}, a) \)
$\pi^0$ mass resolution

Plots assume:

$c_1 = 0.16$ (SiD)

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

For these detector resolutions, 5 GeV $\pi^0$ 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 $\pi^0$ in the event, we could not only improve the $\pi^0$ energy resolution but would also know the error.
Use single $\pi^0$ toy MC with Gaussian smearing for studies.

Energy resolution per photon = 16%/√E.

Error on $\psi_{12}$ = 0.5 mrad.

These resolutions used unless otherwise stated.

A rare thing: a really flat probability distribution !!!
Pull = \frac{(x_{\text{fit}} - x_{\text{meas}})}{\sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{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}) \}
You should also be able to believe the errors on the fitted energies of each $\pi^0$
3. Results on $\pi^0$ Energy Resolution Improvement

For the Proof of Principle study there are:

Two relevant $\pi^0$ 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 ($\Delta \psi$)
DRAMATIC IMPROVEMENT

But this plot is not really a good representation of what is going on.
From now on, will use the $\pi^0$ 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.
5 GeV

On average, factor of 2.

Improves by up to a factor of 7!

20 GeV

Improves by a factor of 1.3 on average.
Dependence on $\pi^0$ energy

Boomerangs: 16 per cent, 0.5mr

$x$: improvement ratio

$y$: $\cos \theta^*$
Improvement ratio (x-projection) DOES depend on Energy resolution (for this π0)

- But on average the dependence is only weak (see next slide)
Average improvement factor not highly dependent on energy resolution. BUT the maximum possible improvements increase as the energy resolution is degraded.
5 GeV π0, 16%, vary angle resolution

Angular resolution very important ...
What’s going on?

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

Error on $\pi^0$ energy is independent of $p_{\text{fit}}$

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

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

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

• Proof of principle of kinematic fit for $\pi^0$ reconstruction done.
  – Kinematic fit infrastructure now a solid foundation.
  – Well understood errors on each $\pi^0$.

• 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.

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

NB. $\phi$ residual differs by 15$\sigma$ from 0 B-field?

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”.

$\Delta\phi \ (rad)$
Cluster Mass for Photons

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.

Cluster Mass (GeV)

Mean = 39 MeV

σ = 7.5 MeV

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

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

Cluster corrected mass most energetic
Entries: 4943
Mean: 0.039132
Rms: 8.5125E-3

Gauss
amplitude: 490.22±8.37
mean: 0.038776±0.000133
sigma: 7.4904E-3±9.25E-5
χ^2: 6.174
On average 19.2 GeV (21.0%)
On average, 1.4 GeV (1.5%)
Photon Accounting

cf 19.2 GeV from prompt $\pi^0$
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 ($\pi^0$),

0.06 combinations/10 MeV/event ($\eta$).

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

Next step: play with some algorithms
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)

Position residual from ybar (mm)

C of G all layers

\[ \sigma = 1.5 \text{ mm} \]

Position residual from yfit (mm)

Weighted fit of the C of G found in the first 12 layers with hits

\[ \sigma = 0.30 \text{ mm} \]

Still just \( \frac{d}{\sqrt{12}} \)!
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, π0, η0 rates measured at LEP

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>photon xE range</td>
<td>0.003-1.000</td>
<td>0.018-0.450</td>
<td></td>
<td></td>
<td>20.76</td>
<td>22.65</td>
</tr>
<tr>
<td>Nγ in range</td>
<td>16.84 ± 0.86</td>
<td>7.37 ± 0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nγ all xE</td>
<td>20.97 ± 1.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π0 xE range</td>
<td>0.007-0.400</td>
<td>0.025-1.000</td>
<td>0.011-0.750</td>
<td>0.004-0.150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nπ0 in range</td>
<td>8.29 ± 0.63</td>
<td>4.80 ± 0.32</td>
<td>7.1 ± 0.8</td>
<td>8.38 ± 0.67</td>
<td>9.60</td>
<td>10.29</td>
</tr>
<tr>
<td>Nπ0 all xE</td>
<td>9.55 ± 0.76</td>
<td>9.63 ± 0.64</td>
<td>9.2 ± 1.0</td>
<td>9.18 ± 0.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>η xE range</td>
<td>0.025-1.000</td>
<td>0.100-1.000</td>
<td></td>
<td>0.020-0.300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nη in range</td>
<td>0.79 ± 0.08</td>
<td>0.282 ± 0.022</td>
<td></td>
<td>0.70 ± 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nη all xE</td>
<td>0.97 ± 0.11</td>
<td></td>
<td></td>
<td>0.91 ± 0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nη x_p &gt; 0.1</td>
<td>0.344 ± 0.030</td>
<td>0.282 ± 0.022</td>
<td></td>
<td>0.286</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Consistent with JETSET tune where 92% of photons come from π0’s. Some fraction is non-prompt, from K^0_S, Λ decay

9.6 π0 per event at Z pole