# Inclusive Neutral Pion Cross Section Measurement with the STAR Endcap Electromagnetic Calorimeter

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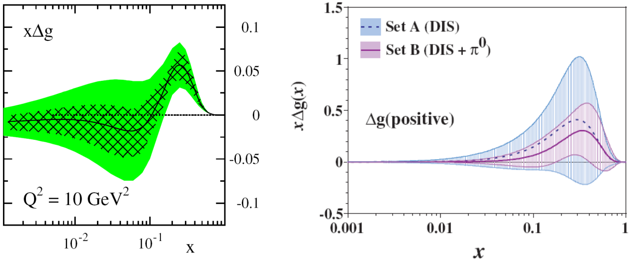
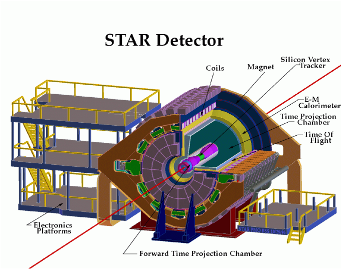
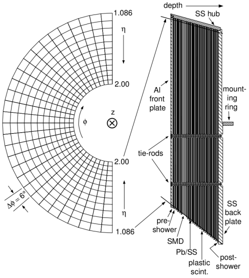
# Motivation: $\Delta g(x)$ and pQCD

- The gluon helicity distribution is one contributor to the total nucleon spin.
- While initially measured via (SI)DIS, measuring $A_{LL}$ in inclusive $pp \to \pi^0 + X$
  - Provides complimentary access, both kinematically and in relation to partonic sub-processes
  - Has significant effects on global $\Delta g(x)$ fits
    - DSSV: de Florian, *et al.*, Phys. Rev. **D** 80 (2009), Phys. Rev. Lett. 101 (2008) *(left plot)*
    - Hirai & Kumano, arXiv:0808.0413 [hep-ph] *(right plot)*
- The global fits of $\delta g(x)$ are poorly constrained at $x < 0.1$.
- How to reach $\Delta g(x)$ at lower $x$?
  - Measure $A_{LL}$ farther forward ($\eta$ in 1-2), i.e. the STAR endcap electromagnetic calorimeter (EEMC)
- First step: measure $pp \to \pi^0 + X$ cross section and compare with pQCD.
- $\pi^0$ mesons are also a background to the prompt photon + jet, another channel to access $\delta g(x)$

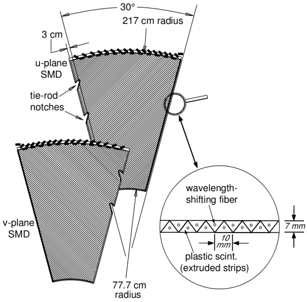


# STAR's Endcap Electromagnetic Calorimeter



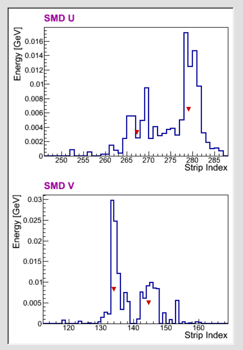

- Scintillating strip SMD
  - $\phi$ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Full $\phi$ coverage–no gaps
- Resolution of a few mm




- Lead/scintillator sampling EM calorimeter
- Covers $1.09 < \eta < 2$ over full azimuth
- 720 optically isolated projective towers ($\approx 22X_0$)
- 2 pre-shower, 1 post-shower layers, and an additional shower max. detector (SMD)

# Particle Reconstruction

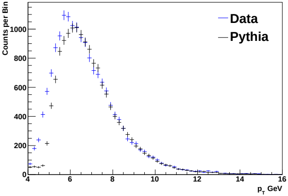
- EM Particle ($\gamma$, $e^\pm$, etc.) Reconstruction Procedure
  1. Identify clusters in the $u$ and $v$ strips
  2. Determine which $u$ and $v$ clusters to associate with incident particles
  3. Compute energy of incident particle using the towers.
- SMD clusters are found by
  - Smoothing the histogram using the method of J. Tukey (`TH1::Smooth`).
  - Identify clusters as a strip above an energy threshold, with $\pm 3$ strips having monotonically decreasing energy.
  - Cluster position is set to energy-weighted mean position
- We expect cluster to be larger than $1 \pm 3 = 7$ strips, but
  - Expect central strip position & energy to be sufficiently correlated to cluster position & energy.
  - Correlation increased by smoothing
- SMD response in fairly clean $\pi^0$ candidate (data) event is plotted on the right.
  - Blue histograms show energy response per strip.
  - Inverted red triangles represent clusters, drawn at x=mean, y=10% cluster energy.



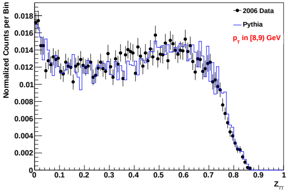

- General reconstruction difficulties include
  - Upstream material: $\pi^0$ opening angle on the same order as opening angle for $\gamma \to e^+e^-$
  - Single particle sometimes looks like two particles, and vice versa

# Data/Monte Carlo Comparison

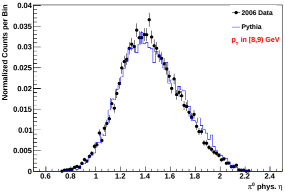
## $\pi^0$ $p_T$



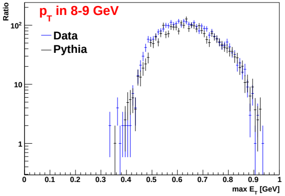

## $\pi^0$ $Z_{\gamma\gamma}$



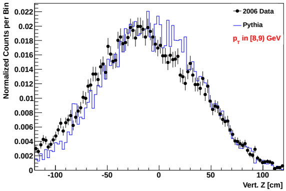

## $\pi^0$ Physical $\eta$




## $E_{T,max}/E_{T,3x3}$

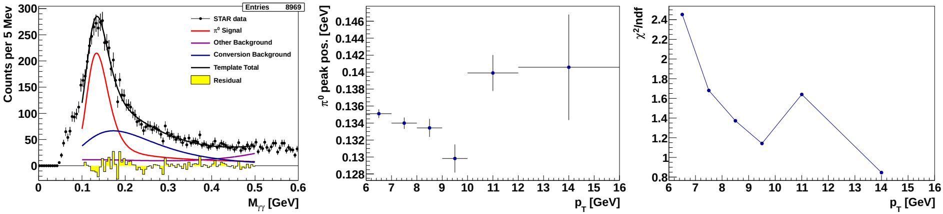



## Vertex $Z$




- Plots shown for $\pi^0$ $p_T$ in 8-9 GeV
- Pythia tune 329, “Pro-pT0”
- Agreement generally good for $\pi^0$ $p_T > 5$ GeV
- Sampled lumi. of 8.3 $\text{pb}^{-1}$

# Background Subtraction




- There exist a variety of backgrounds, both due to physics and reconstruction; for example,
  - $\gamma \to e^+e^-$ conversions, and $\pi^0$ candidate could be $\gamma e^+$, $\gamma e^-$, $e^+e^-$, etc.
  - Reconstructing the wrong number of photons in an event
- Sufficient to use three template functions to model signal + background
  - $\pi^0$ signal, direct conversion background, all other backgrounds
- Template function parameters fixed by fitting functions to reconstructed Pythia Monte Carlo.
- Normalizations of the templates and an energy scale factor determined by fitting template functions to the data

$$f_T(M_{\gamma\gamma}) = \sum_{i=1}^{3} w_i f_i(M_{\gamma\gamma}/\alpha)$$

# Computing the Cross Section

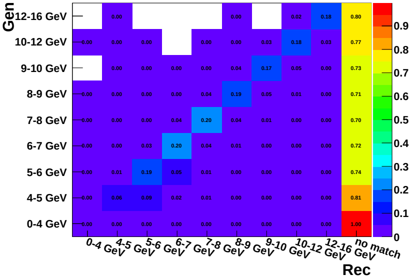
- The unfolded number of $\pi^0$s per $p_T$ bin is computed as

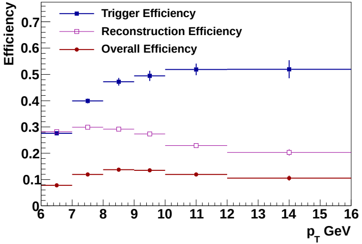
$$N_i^{(\pi^0)} = \sum_j S_{i,j}^{-1} f_j \, s_j \, N_j^{(\text{raw})}$$

  - $S$ is the smearing matrix
  - $f$ accounts for smearing outside the $p_T$ range
  - $s$ is the signal fraction
  - $N^{(\text{raw})}$ is the raw number of counts in the $\pi^0$ peak window.
- The cross section is computed as

$$E\frac{d^3\sigma}{d\boldsymbol{p}^3} = \frac{1}{2\pi}\frac{1}{\Delta\eta}\frac{1}{\Delta p_T}\frac{1}{\langle p_T\rangle}\frac{1}{\epsilon}\frac{1}{\text{B.R.}}\frac{N^{(\pi^0)}}{\mathcal{L}}$$

- Physical $\eta$ is in $(0.8, 2.0)$, thus $\Delta\eta = 1.2$.
- The $p_T$ bin width, $\Delta p_T$, varies between 1 and 4 GeV.
- The total efficiency $\epsilon$ is the product of the trigger and reconstruction efficiencies.
- The branching ratio for $\pi^0 \to \gamma\gamma$ is 0.98798 (PDG)

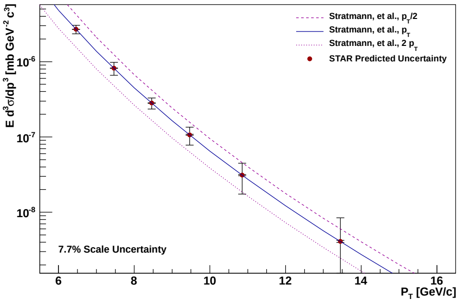


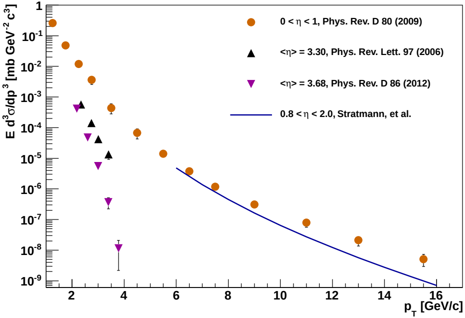



# Systematics

- The statistical uncertainty is the Poisson uncertainty on the raw number of counts
- The following $p_T$ dependent systematic uncertainties are included in the analysis
  - On the signal fraction
    - Uncertainty on template function parameters, energy scale and signal weight
    - Uncertainty related to choice of fit range
  - On the background subtracted number of $\pi^0$s
    - Uncertainty related to fit residual, related to accuracy of template shapes
  - On the unfolded number of $\pi^0$s
    - Uncertainty on the smearing matrix $S$ and factor $f$ (related to Monte Carlo statistical uncertainty)
    - Uncertainty related to added additional lower $p_T$ bins
  - On the final cross section
    - Uncertainty on $\langle p_T \rangle$, assuming EEMC resolution is $\delta E/E = 0.16/\sqrt{E}$
    - Uncertainties on reconstruction and trigger efficiencies (related to Monte Carlo statistical uncertainty)
    - Overall energy scale uncertainty of 3%—dominant systematic uncertainty
- All uncertainties are propagated analytically

# Predicted Cross Section Uncertainties




- Theory curve from private communication with Marco Stratmann
  - Uses CTEQ65M distribution functions and DSS fragmentation function
  - Does not include propagated uncertainty on distribution and fragmentation functions
- Points plotted at central value of theory curve, but with predicted statistical and systematic uncertainties
  - Inner horizontal lines mark statistical uncertainty (barely visible)
  - Total error bar is combined statistical and systematic uncertainty.
- Experimental uncertainties are on the order of the theoretical uncertainty
- New results will be in an unexplored phase space region.
  - Investigation underway to divide EEMC data into multiple $\eta$ bins

# Conclusions and Outlook

- Results will represents first $pp \rightarrow \pi^0 + X$ cross section within this $\eta$ range
  - Internal discussions regarding publication schedule are ongoing.
- Additionally, the $A_{LL}$ analysis is equally advanced
  - Not shown today as exists preliminary version, shown at SPIN 2008
  - Major improvement over older results is the background subtraction procedure.
  - Ready to be included in the cross section paper.
- Transverse data also being analyzed for the $\pi^0$ $A_N$.
- Thus far only 200 GeV data from one year analyzed
  - Several more years of data to analyze
  - More recent years have higher integrated luminosity and less upstream material
  - Data available for both $\sqrt{s}$ at 200 GeV and 500 GeV.
  - Just need to finalize some details regarding the simulations.
- The STAR EEMC is also sensitive to other final states, such as prompt photons and $\eta$'s
- The cross section result is opening the door for many STAR EEMC results to come.