Forward Neutral Pion Cross Section and Spin Asymmetry Measurements at STAR

S. Gliske, for the
STAR Collaboration

Argonne National Laboratory

XI International Workshop on
Deep-Inelastic Scattering and Related Subjects

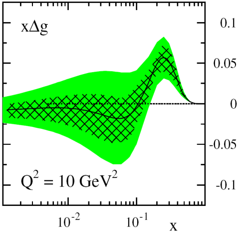
Marseille, France

April 23rd, 2013

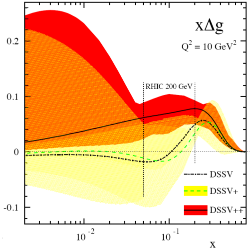
Motivation: $\Delta g(x)$ and pQCD

- The gluon helicity distribution is one contributor to the total nucleon spin.
- While initially measured via (SI)DIS, measuring A_{LL} in polarized $pp \to \pi^0 + X$
  - Provides complimentary access, both kinematically and in relation to partonic sub-processes
  - Has significant effects on global $\Delta g(x)$ fits
- The global fits of $\Delta g(x)$ are poorly constrained at $x < 0.05$.
- How to reach $\Delta g(x)$ at lower x?
  - Measure A_{LL} farther forward (η in 1-2), i.e. the STAR endcap electromagnetic calorimeter (EEMC)
  - Main subprocess is now gq scattering, with small x of the gluon.
- First step: measure $pp \to \pi^0 + X$ cross section and compare with pQCD.
- π^0 mesons are also a background to the prompt photon + jet, another channel to access $\Delta g(x)$

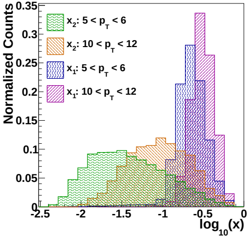
DSSV, PRD 80 (2009), PRL 101 (2008)



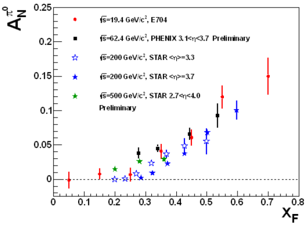
DSSV+/DSSV++, arXiv:1304.0079

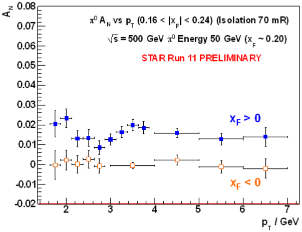


π^0s in STAR EEMC Acceptance



Transverse Spin Asymmetry A_N

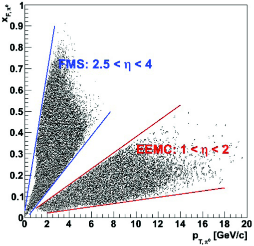




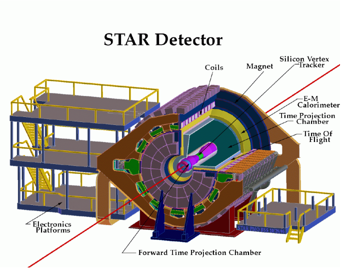
- Non-zero A_N for $x_F > 0$ observed over wide energy range.
- Includes contributions from leading twist Sivers and Collins effects or higher twist effects.

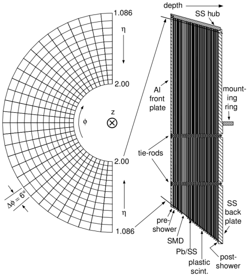
- A_N expected to
  - Increase with x_F
  - Go to zero in the limit of $p_T \to 0$
  - Scale as $1/p_T$ at high p_T.
- STAR EEMC has larger dynamic range in p_T and covers an unmeasured (p_T, x_F) region
  - $5 < p_T < 12$ GeV, $0.06 < x_F < 0.27$, and $0.8 < \eta < 2.0$
- A_N will be small due to small x_F, but may show p_T dependence.

STAR $\sqrt{s} = 200$ GeV

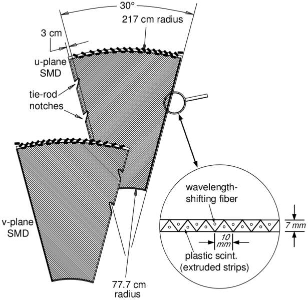


STAR's Endcap Electromagnetic Calorimeter





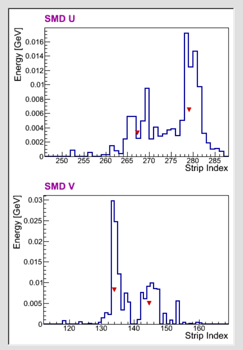
- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Full ϕ coverage–no gaps
- Resolution of a few mm



- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- 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)
- Trigger involves thresholds on the maximum tower energy and the 3×3 patch of surrounding towers.

Particle Reconstruction

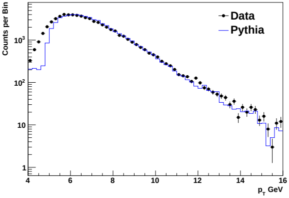
- EM Particle (γ, $e^{\pm}$, etc.) Reconstruction Procedure
  1. Identify clusters in the u and v strips
  2. Determine which u and v clusters to associate with incident particles
  3. Compute energy of incident particle using the towers.
- SMD clusters are found by
  - Smoothing the histogram using the method of J. Tukey (`TH1::Smooth`).
  - Identify clusters as a strip above an energy threshold, with ± 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 π^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.



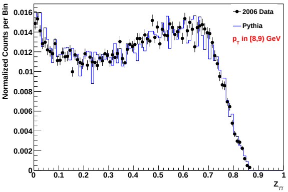
- General reconstruction difficulties include
  - Upstream material: π^0 opening angle on the same order as opening angle for $\gamma \to e^+e^-$
  - Single particle sometimes looks like two particles, and vice versa

Data/Monte Carlo Comparison

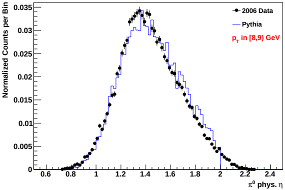
$\pi^0\ p_T$



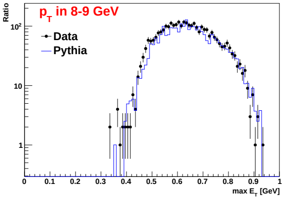
$\pi^0\ Z_{\gamma\gamma}$



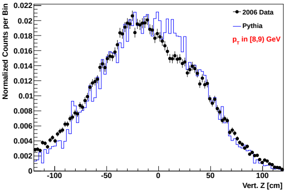
π^0 Physical η



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



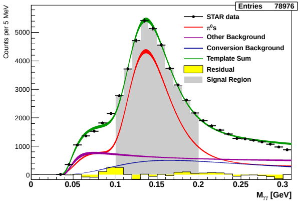
Vertex Z

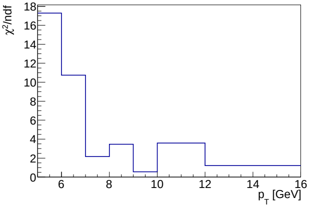


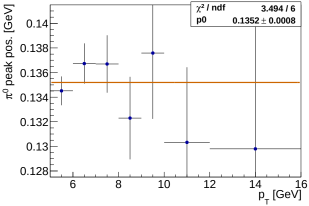
- Plots shown for $\pi^0\ p_T$ in 8-9 GeV
- Pythia tune 329, "Pro-pT0"
- Agreement generally good for $\pi^0\ p_T > 6$ GeV
- $5 < p_T < 6$ GeV usable, but has higher systematic uncertainty
- Sampled lumi. of 8 pb^{-1}

Background Subtraction

$7 < p_T < 8$ GeV







- There exist a variety of backgrounds, both due to physics and reconstruction; for example,
  - $\gamma \to e^+e^-$ conversions, and π^0 candidate could be γe^+, γe^-, e^+e^-, etc.
  - Reconstructing the wrong number of photons in an event
- Sufficient to use three template functions to model signal + background
  - π^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

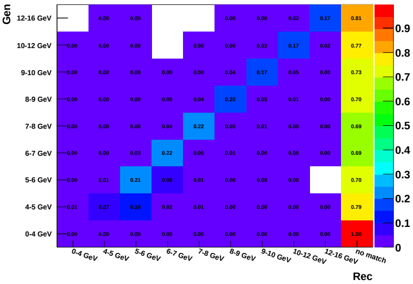
- The unfolded number of π^0s per p_T bin is computed as

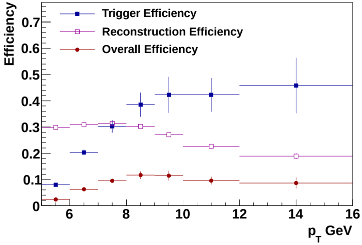
$$N_i^{(\pi^0)} = \sum_j S_{i,j}^{-1} \, f_j \, s_j \, N_j^{(\mathrm{raw})}$$

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

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

- Physical η is in $(0.8, 2.0)$, thus $\Delta\eta = 1.2$.
- The p_T bin width, Δp_T, varies between 1 and 4 GeV.
- The total efficiency ϵ is the product of the trigger and reconstruction efficiencies.
- The branching ratio for $\pi^0 \to \gamma\gamma$ is 0.98823 (PDG)

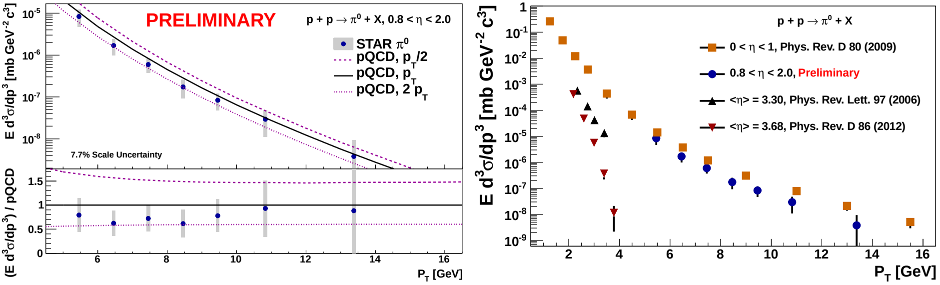




Cross Section Uncertainties

- 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 on integrals to determine the fraction within the signal (peak) region
    - Uncertainty based on the fit residual, related to accuracy of template shapes
  - On the unfolded number of π^0s
    - Uncertainty on the smearing matrix S and factor f (related to Monte Carlo statistical uncertainty)
    - Uncertainty related to effectiveness of accounting for "smeared in" background
  - 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

Cross Section Preliminary Results



- 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 Lafferty-Wyatt points, by fitting entire result to an exponential.
  - Error bars indicate statistical uncertainty (barely visible)
  - Error boxes indicate systematic systematic uncertainty.
- Experimental uncertainties are on the order of the theoretical scale uncertainty.
- Result covers an unmeasured region of phase space
  - It is observed that the cross section for $0.8 < \eta < 2.0$ is not much different than that for $0 < \eta < 1$.

Analysis for Longitudinal Spin Asymmetries

- The raw asymmetries are computed from number of π^0 candidates within $0.1 < M_{\gamma\gamma} < 0.2$ GeV.

$$A_{L,B} = \frac{1}{\langle P_B \rangle}\left(\frac{N^{++}+N^{+-}-N^{-+}-N^{--}}{N^{++}+N^{+-}+N^{-+}+N^{--}} - \frac{L^{++}+L^{+-}-L^{-+}-L^{--}}{L^{++}+L^{+-}+L^{-+}+L^{--}}\right),$$

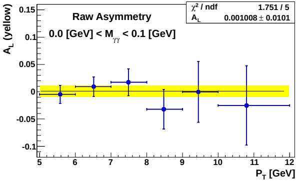
$$A_{L,Y} = \frac{1}{\langle P_Y \rangle}\left(\frac{N^{++}-N^{+-}+N^{-+}-N^{--}}{N^{++}+N^{+-}+N^{-+}+N^{--}} - \frac{L^{++}-L^{+-}+L^{-+}-L^{--}}{L^{++}+L^{+-}+L^{-+}+L^{--}}\right),$$

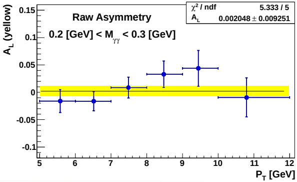
$$A_{LL} = \frac{1}{\langle P_B P_Y \rangle}\left(\frac{N^{++}-N^{+-}-N^{-+}+N^{--}}{N^{++}+N^{+-}+N^{-+}+N^{--}} - \frac{L^{++}-L^{+-}-L^{-+}+L^{--}}{L^{++}+L^{+-}+L^{-+}+L^{--}}\right),$$

- Luminosity weighted polarizations are $\langle P_B \rangle = 0.56$, $\langle P_Y \rangle = 0.59$, and $\langle P_B P_Y \rangle = 0.33$.
- Asymmetries corrected for background using

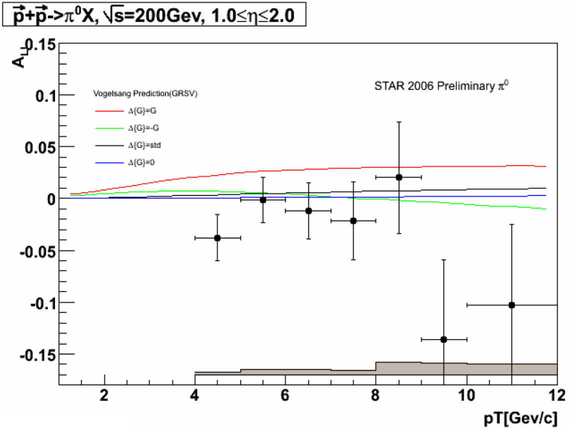
$$A^{sig} = \frac{1}{s}\left(A^{raw} - (1-s)A^{bkg}\right),$$

- Background asymmetries are estimated from mass sideband regions and are observed to be within 1σ of zero with $\sigma \approx 0.01$.



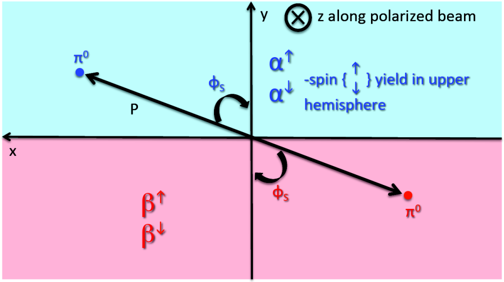


Preliminary Results for Longitudinal Spin Asymmetries



- Preliminary results shown at SPIN'08 use older procedures
  - Significant time invested in improving simulations, reconstruction code, and background subtraction procedure.
- Main message unchanged
- Systematics well under control
- First measurement in this η range
- Consistent with predictions
- May have some impact due to lower Bjorken-x coverage
- Additional statistics already recorded at STAR during other running years.
  - Need effort verifying and improving simulations for the other years.

Transverse Spin Asymmetry A_N Analysis



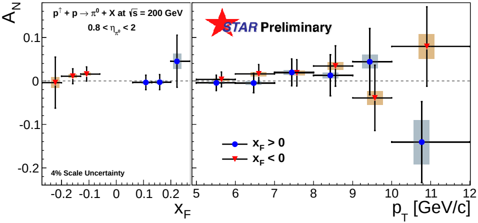
- Raw asymmetry

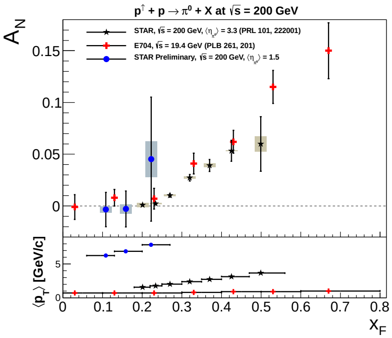
$$\mathcal{E}(\phi) = \frac{\sqrt{\alpha^\uparrow \beta^\downarrow} - \sqrt{\alpha^\downarrow \beta^\uparrow}}{\sqrt{\alpha^\uparrow \beta^\downarrow} + \sqrt{\alpha^\downarrow \beta^\uparrow}}$$

- Fit $\mathcal{E}(\phi)$ to $p_0 + \varepsilon \sin\phi$

- The background is subtracted from ε using same procedure as for longitudinal asymmetries.
  - Background asymmetries again within 1σ of zero with $\sigma \approx 0.01$.
- A_N obtained by scaling background subtracted ε by one over the luminosity weighted polarization.
- Systematics include
  - Uncertainty on the signal fraction
  - Uncertainty on the background asymmetry estimate
  - ϕ-dependent single beam backgrounds.

Transverse Spin Asymmetry A_N Preliminary Results





- Results consistent with zero for both $x_F < 0$ and $x_F > 0$
- Sensitivity not great enough to discern shape of p_T dependence
- Results lie in unmeasured region of (x_F, p_T) phase space
- Would like to include theory curves for comparison before publication

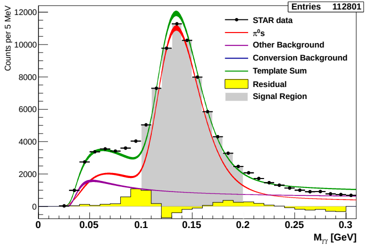
Conclusions and Outlook

- Results represent measurements in previously unmeasured kinematic regions
  - First $pp \to \pi^0 + X$ cross section within this η range
  - A_{LL} reaches lower Bjorken-x_2 than published measurements
  - A_N covers unmeasured (x_F, p_T) region
- Publication of these results is currently under review within the collaboration.
- These results demonstrate reconstruction with the EEMC is in a mature state.
- 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 η's
- These results open the door for many STAR EEMC results to come.

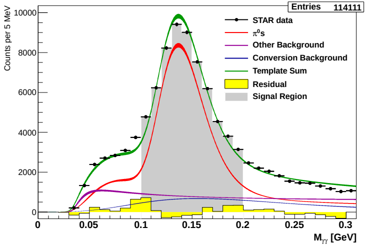
Backup Slides

Additional Template Fit Results

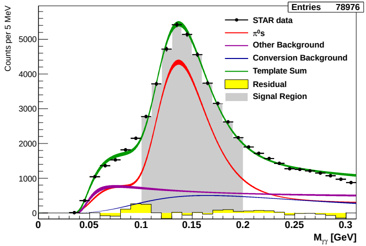
$5\ [\mathrm{GeV}] < p_T < 6\ [\mathrm{GeV}]$



$6\ [\mathrm{GeV}] < p_T < 7\ [\mathrm{GeV}]$



$7\ [\mathrm{GeV}] < p_T < 8\ [\mathrm{GeV}]$



$8\ [\mathrm{GeV}] < p_T < 9\ [\mathrm{GeV}]$