Neutral Pion Cross Section and Spin Asymmetries at $0.8 < \eta < 2.0$ and $\sqrt{s} = 200$ GeV at STAR

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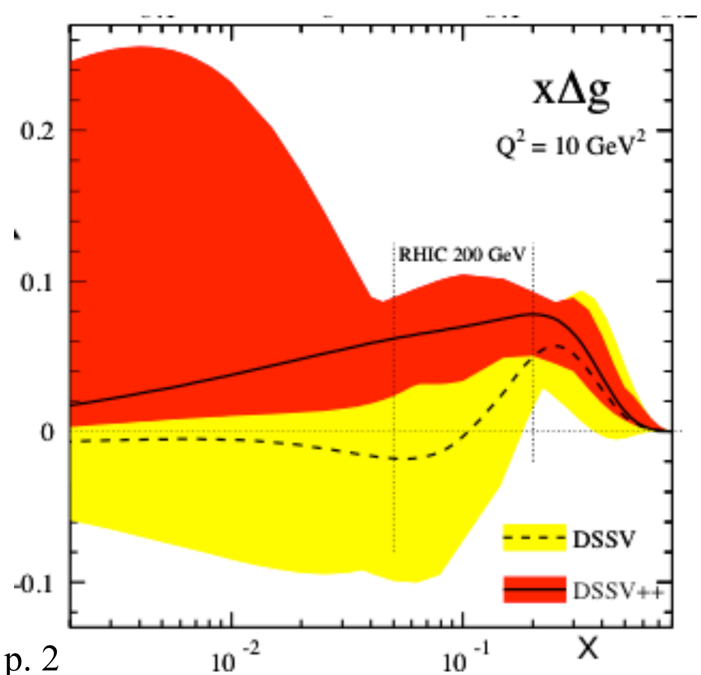
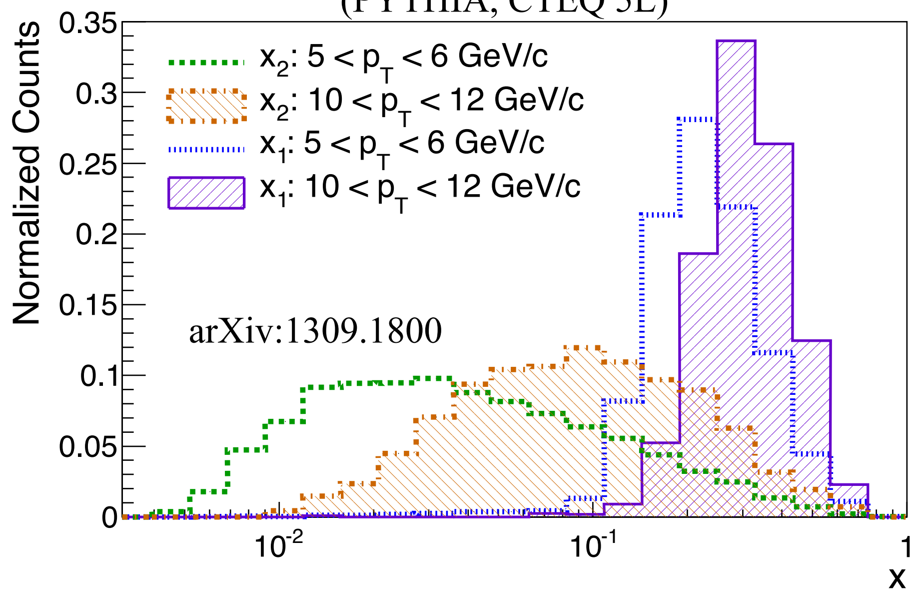
Motivation: Probe Spin Dynamics in Less-Constrained Kinematic Regions

- Gluon helicity distribution is one contributor to the total proton spin
- $\Delta g(x)$, for $0.05 < x < 0.2$, constrained to be above zero by recent RHIC measurements
  - But relatively poorly constrained at $x < 0.05$
- How to move to lower x?
  - Measure inclusive π^0 A_{LL} farther forward, e.g. for $1 < \eta < 2$ in the STAR endcap electromagnetic calorimeter (EEMC)
  - Main subprocess is qg scatering, with the gluon usually at small x

DSSV++ arXiv:1304.0079

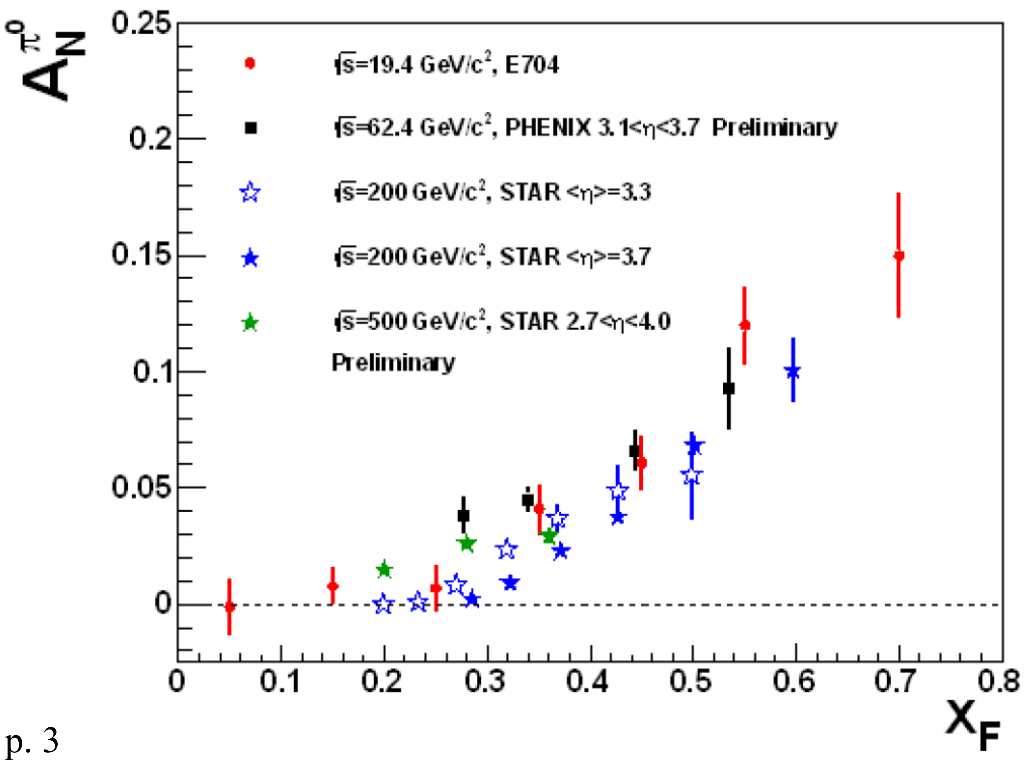


STAR π^0's at low and high p_T, for sqrt(s) 200 GeV (PYTHIA, CTEQ 5L)

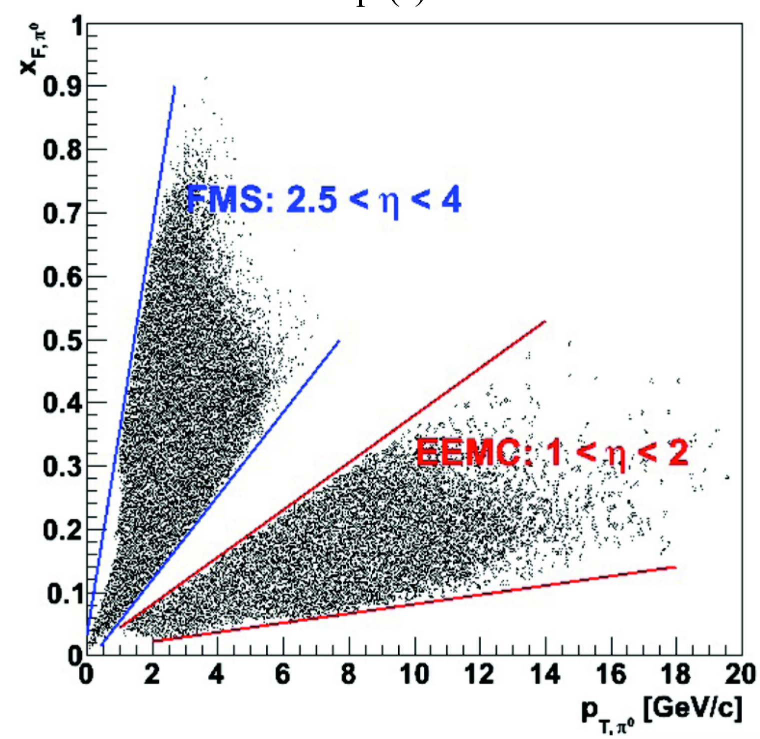


Less-Constrained Kinematic Regions for A_N

- Transverse spin asymmetry, A_N, known to be large at forward η for π^0's
- Known to be small at central η in π^0's and jets
- With the EEMC we can measure A_N in a less-constrained x_F – p_T range
  - Probably small, but may be able to test for p_T dependence
- Plan:
  - Measure π^0 cross section, A_{LL}, and A_N

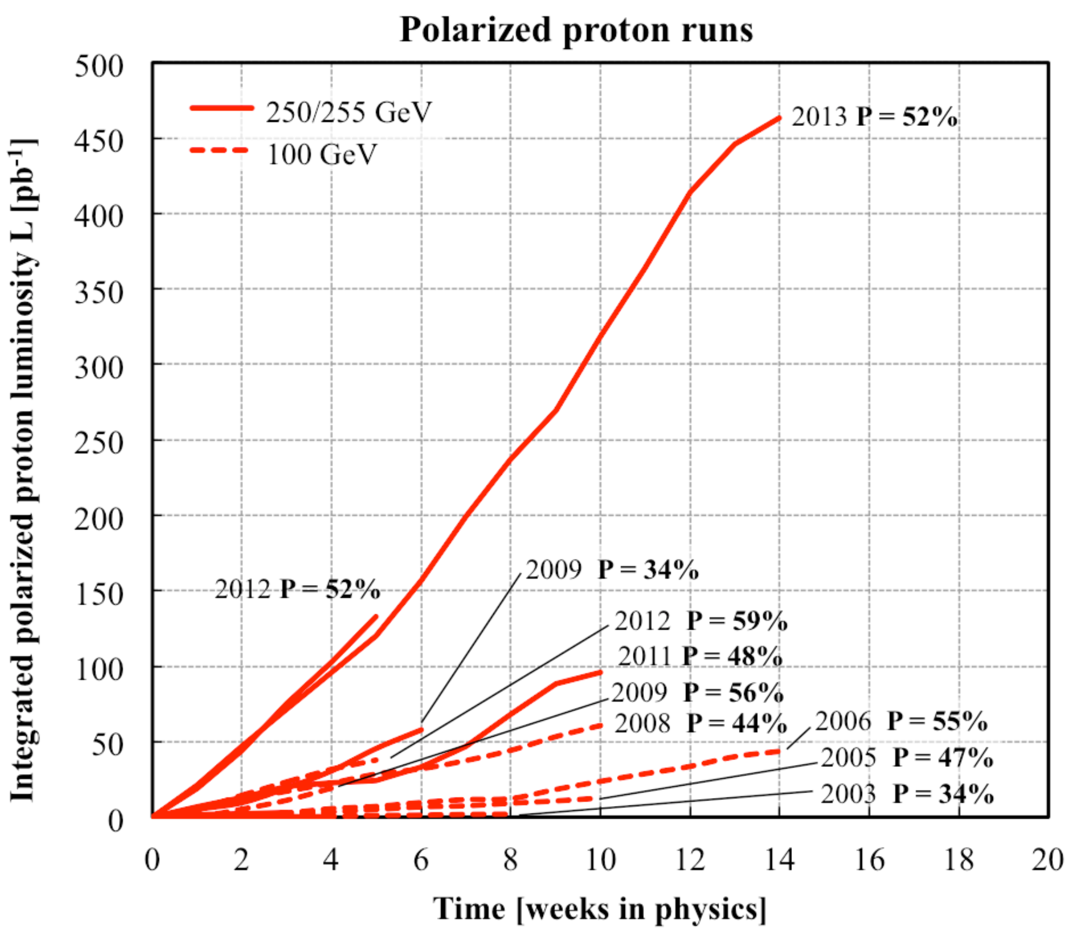


STAR at sqrt(s) 200 GeV

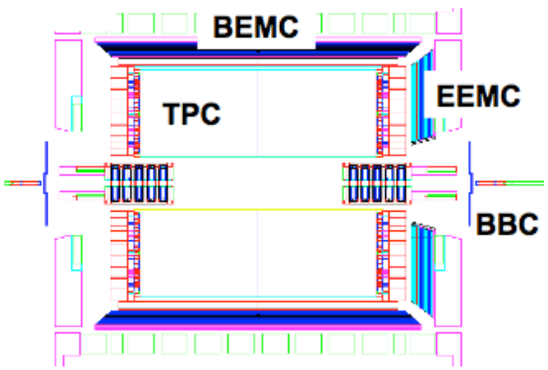


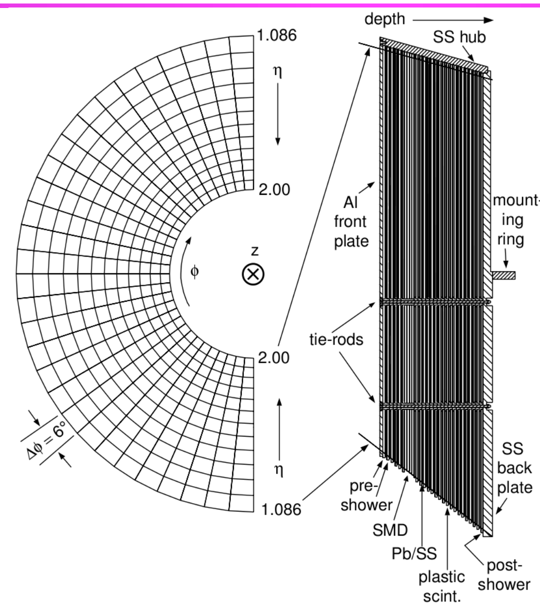
Datasets from RHIC at STAR

- 2006 dataset at STAR
  - 8.0 pb^{-1} of good quality data analyzed for cross section
  - 4.8 pb^{-1} for A_{LL}
  - 2.8 pb^{-1} for A_N
- Future years datasets for EEMC waiting to be analyzed:
- 2009: 25 pb^{-1} delivered at 200 GeV, longitudinal polarization
- 500 GeV longitudinally polarized data in 2011 and 2012
- 500 GeV transverse in 2011, 200 GeV in 2012

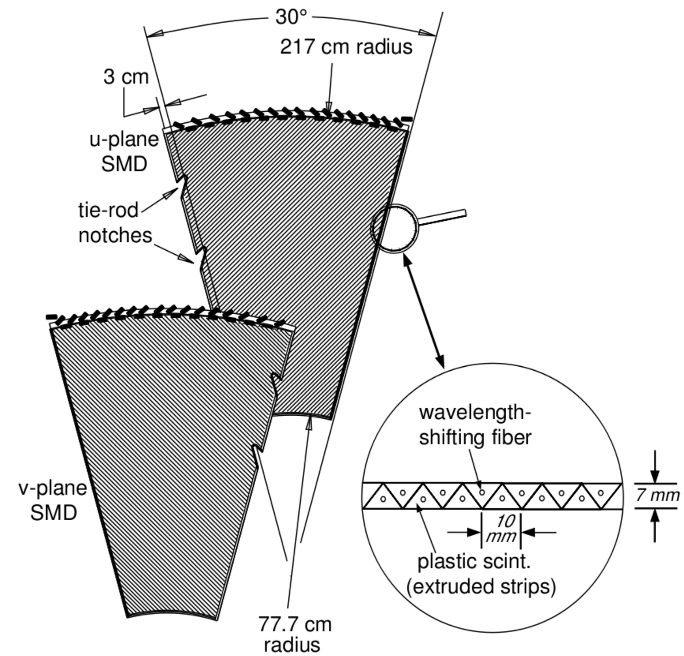


STAR's Endcap Electromagnetic Calorimeter





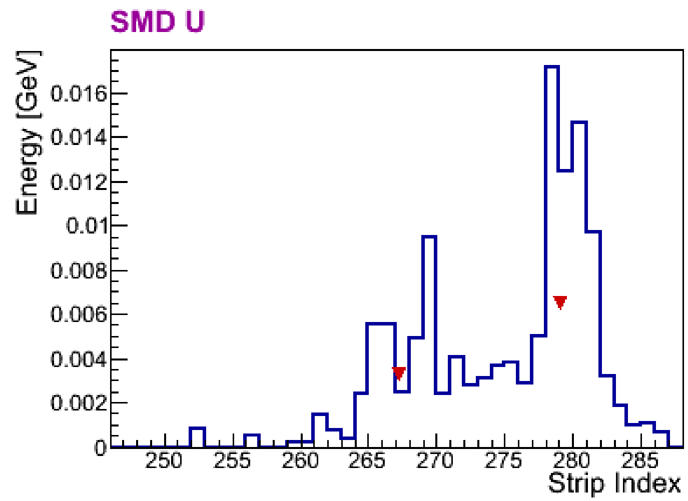
- Scintillating strip SMD
  - ϕ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

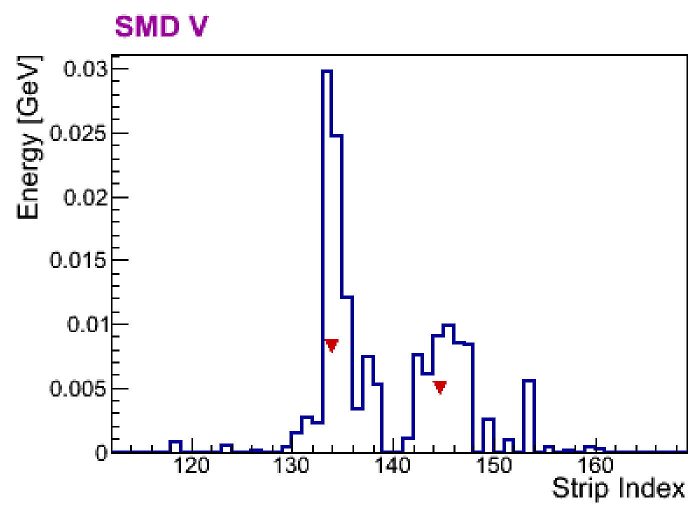


- Nucl. Instrum. Meth. **A** 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers $1.09 < \eta < 2.00$ over full 2π azimuth
  - 720 optically isolated projective towers (~22 X_0)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- Photon trigger places thresholds on maximum tower energy and the 3x3 patch of surrounding towers

Particle Reconstruction in the EEMC

- EM Particle Reconstruction Procedure
  - Identify clusters in the u and v strips
  - Determine which u and v clusters to associate with incident particles
  - Compute energy of incident particles (e.g. photons) from the towers
  - Compute momentum from the vertex and SMD cluster positions
- SMD response (right) in π^0 candidate event from data
  - Blue histograms show energy response per strip
  - Red triangles represent clusters drawn at mean strip position, and 10% of the cluster energy
- SMD clusters are found by
  - Smoothing the histogram using the method of J. Tukey
  - Identifying clusters as a strip above an energy threshold, with +-3 adjacent strips with monotonically decreasing energy
  - Setting cluster position to energy-weighted mean position of strips
- EM particle candidates built from pairs of u-v clusters
  - Clusters matched by energy of u and v strips
  - Required to have associated tower energy above threshold
  - Often have e.g. two photons from one π^0 deposited in one tower
- Reconstruction difficulties include
  - Upstream passive material: π^0 opening angle on the same order as photon conversions
  - Single particles sometimes look like two particles, and vice versa





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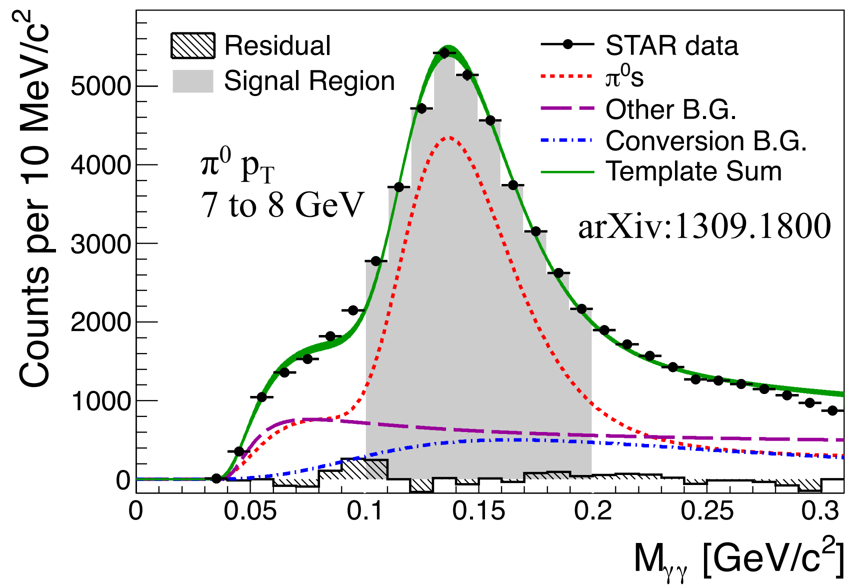
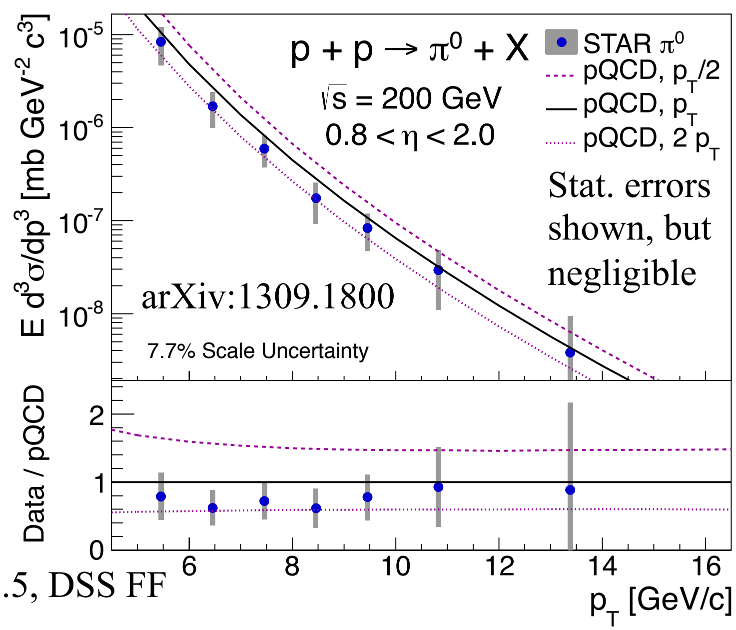
π^0 Background and Cross-Section Computation

- Inclusive π^0 mass distribution fit to templates, in bins of π^0 p_T
  - Signal
  - Conversion BG (π^0 candidate is from gamma → e+ e-)
  - All other BG (extra or missing photons, π^0 candidate is gamma and e-, etc.)
  - Shapes from MC, relative fraction (and thus signal fraction) extracted from fit to data
- Lowest analyzed bin is 5-6 GeV π^0 p_T
  - Data-MC agreement unsatisfactory below this
  - Large amount of passive material, not well modeled
- Unfolded cross section calculated with a "smearing matrix"
  - Dominant systematic is EEMC energy scale
  - Consistent with NLO pQCD (Stratman numbers)
    - B. Jaeger et al., Phys. Rev. D 67, 054005 (2003) CTEQ 6.5, DSS FF

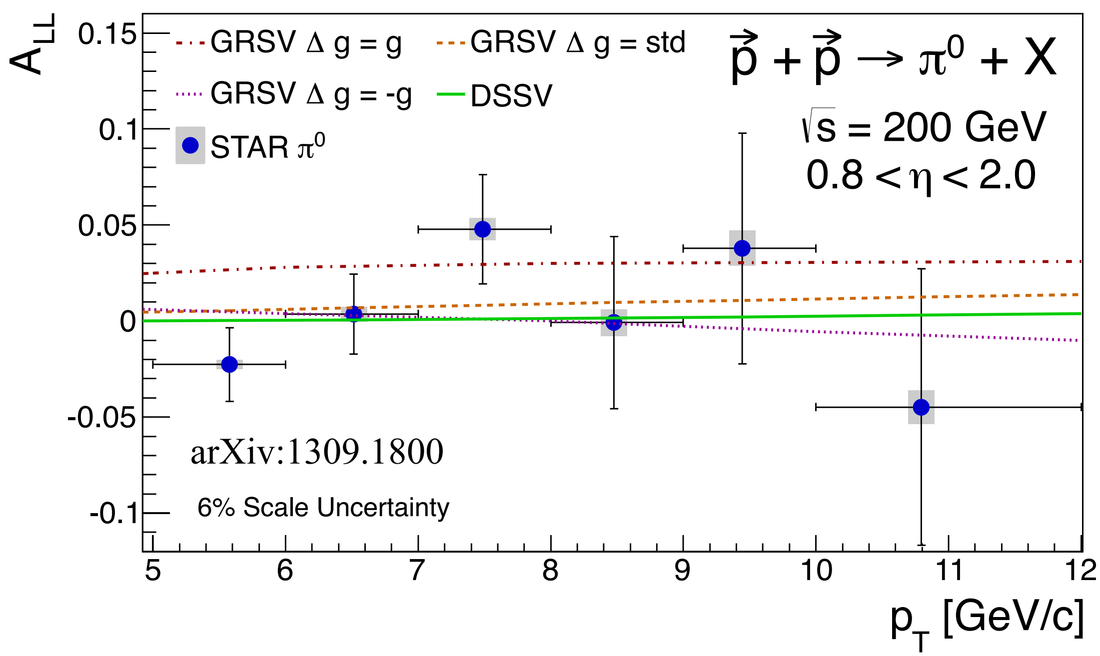




A_{LL} in π^0 + X at STAR for $0.8 < \eta < 2.0$

Result shown for the first time!

- Raw longitudinal asymmetry corrected for
  - Luminosity asymmetries (small)
  - Beam polarizations
  - Background asymmetries
    - Estimated from mass sidebands, and consistent with zero (with uncertainty ~0.01)
- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
- Integrated across p_T probably constrains GRSV Δg-max?
- **arXiv:1309.1800, submitted to Phys. Rev. D**



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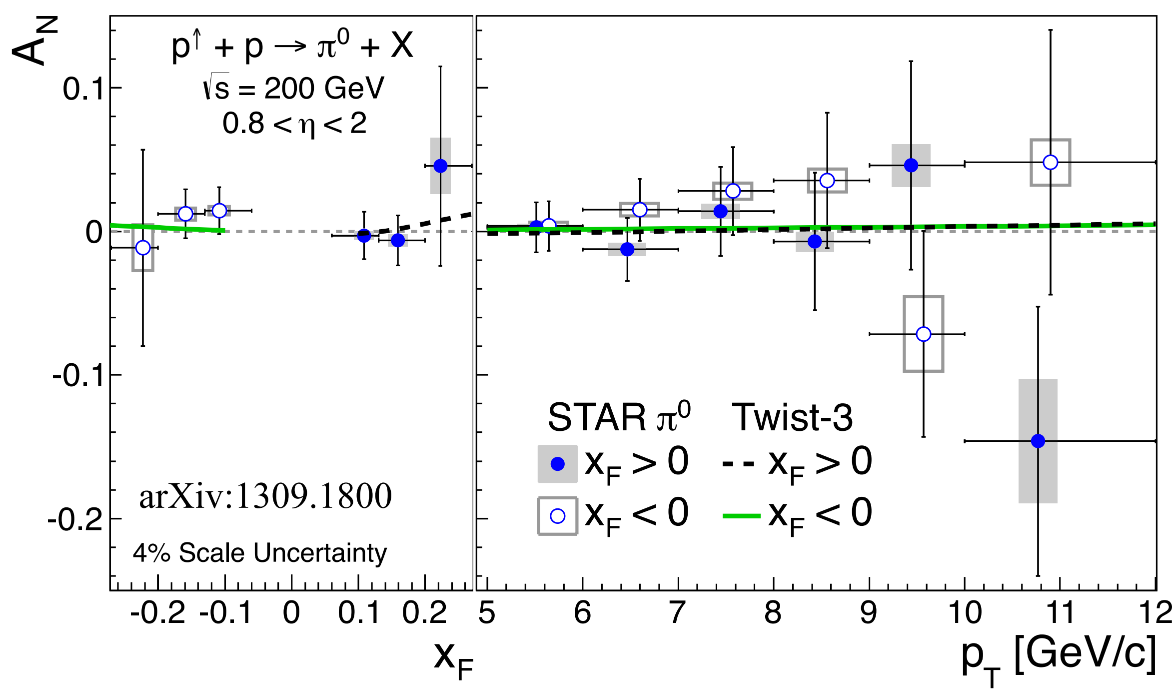
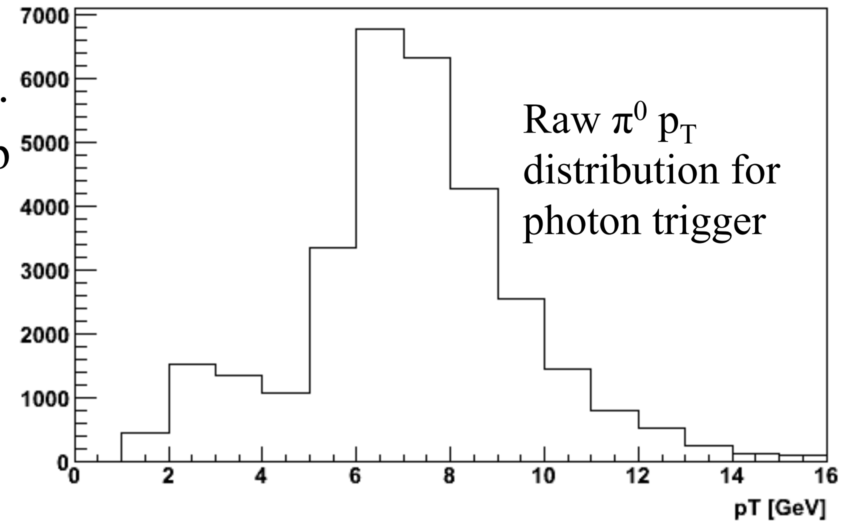
A_N in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$

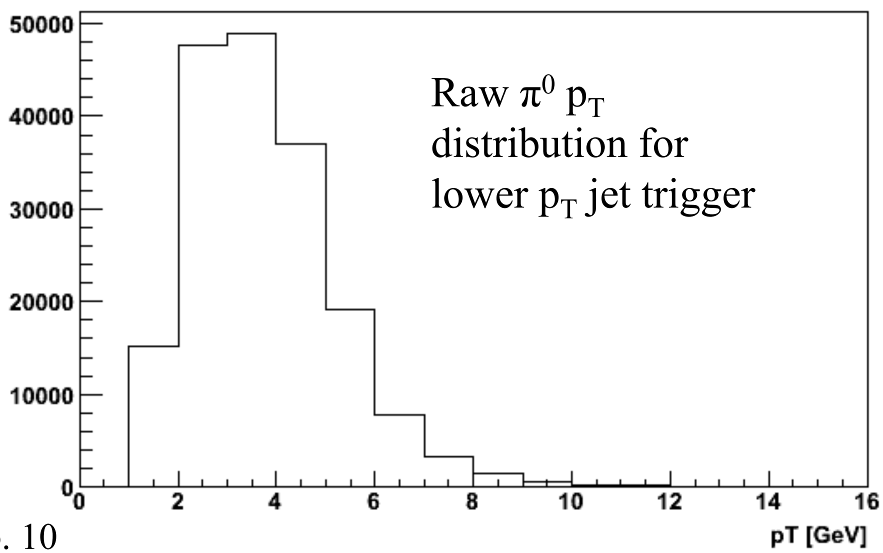
- Raw transverse asymmetry corrected for
  - Beam polarizations
  - Background asymmetries
    - Estimated from mass sidebands, and consistent with zero (with uncertainty ~0.01)
- Plotted in bins of π^0 p_T (integrated over $0.06 < x_F < 0.27$), and in bins of x_F
- Statistical error (bars) dominate
- Systematic error (boxes)
  - Signal fraction uncertainties from template fits
  - Uncertainty on background asymmetry
  - Possible single-beam backgrounds
- Twist-3 prediction
  - K. Kanazawa and Y. Koike,
  - Phys. Rev. D 83, 114024 (2011)

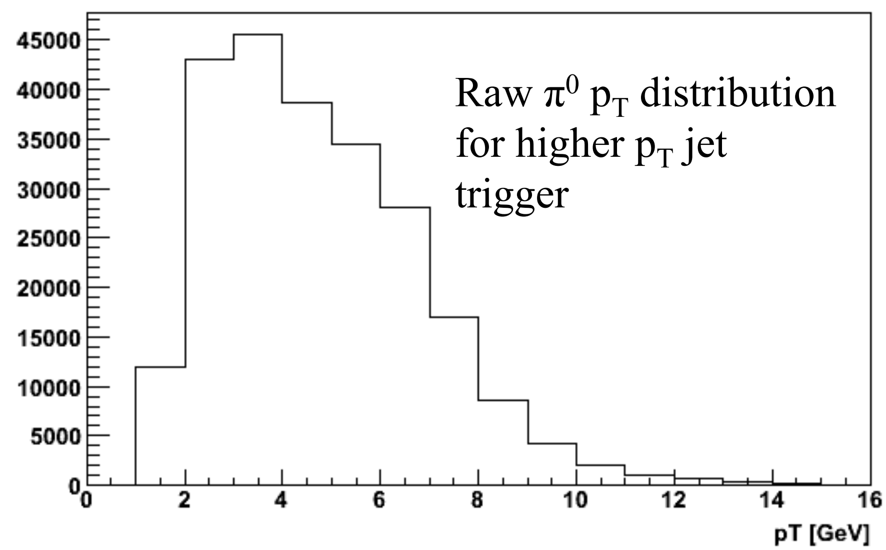


Prospects with 2009 Data for A_{LL}

- 2009 dataset offers a number of advantages
  - 3.5 times the 2006 lum. for 200 GeV, long. pol.
  - Reduced passive material in front of the endcap calorimeter
  - Although the photon triggers have a higher threshold
- Lower and higher p_T jet triggers offer new possibilities
  - Lower threshold integrated over bigger patch of towers

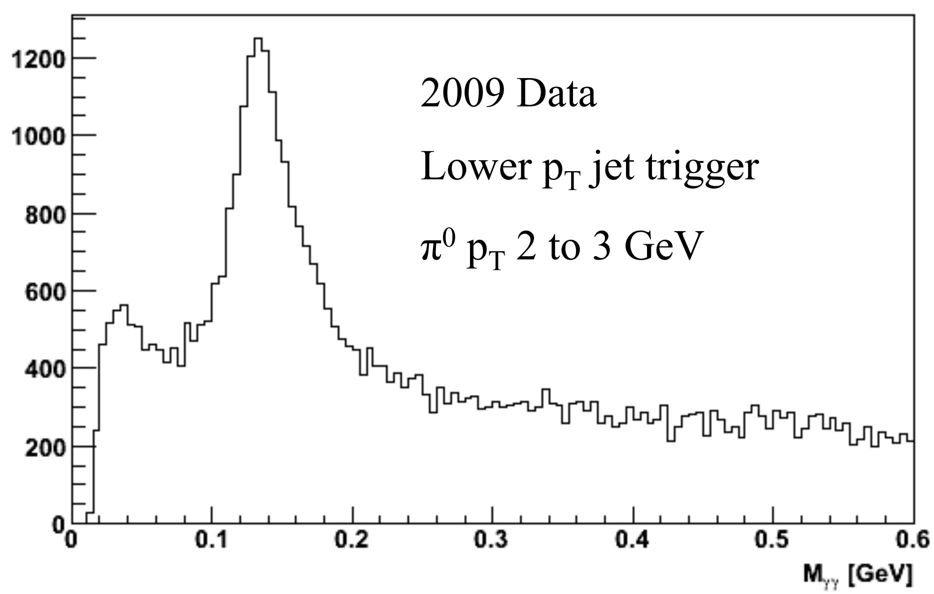






Prospects with 2009 Data, cont.

- Today showing a glimpse at only a tiny fraction of the 2009 datasets
- Larger jet trigger patch allows events with more jet background, softer π^0
- Background somewhat higher than for photon triggers
  - But can probe to considerably lower π^0 pT
  - Very reasonable π^0 peak
  - Possibility to extend reach to lower x?
- Work remains on MC validation, understanding of π^0's in "jettier" environment, etc.



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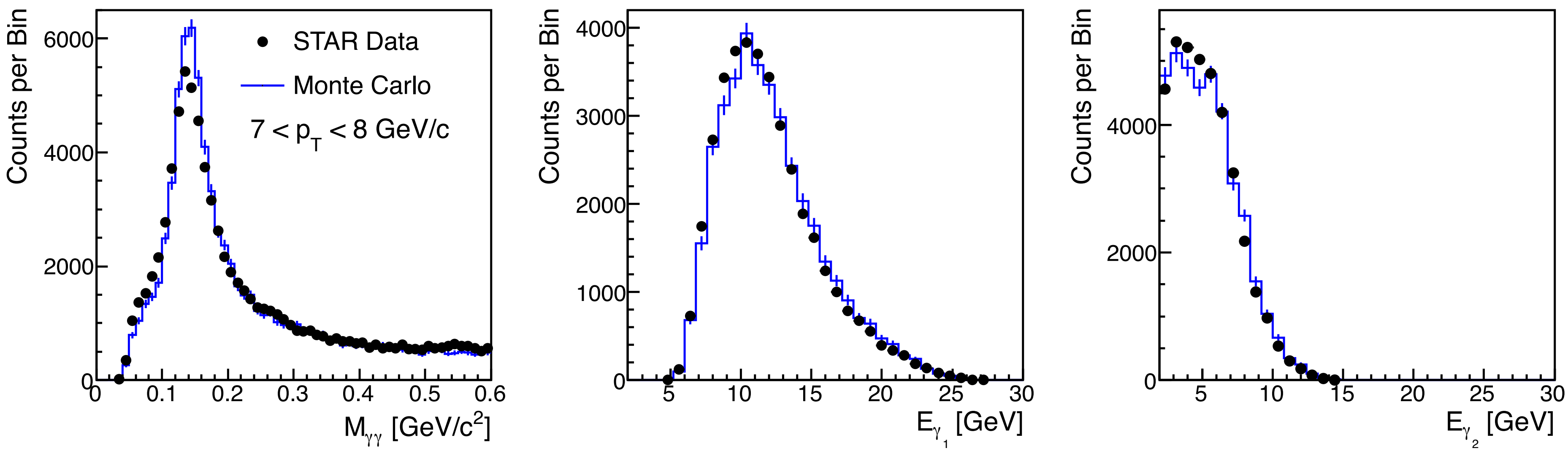
Conclusions and Outlook

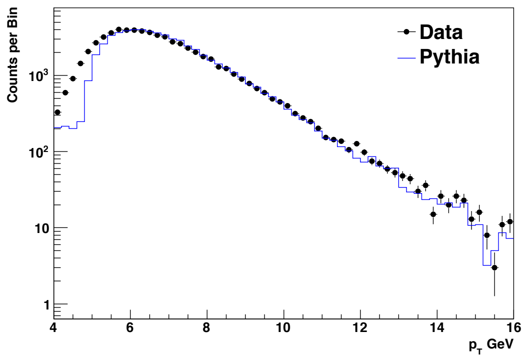
- **Successful analysis of inclusive π^0's in 2006 data**
  - Cross section, longitudinal and transverse asymmetries at 200 GeV
  - **arXiv:1309.1800, submitted to Phys. Rev. D**
  - A long time in preparation, good to wrap it up! And open door for future EEMC measurements
- **Prospects for higher luminosity datasets in the future**
  - **A_{LL} and A_N are statistically limited measurements**, at present
  - Continue to explore less-constrained kinematic regions
  - Complementary to other probes
  - Non-zero A_{LL} as for jets? Non-zero A_N as for forward π^0's?
- **2009 200 GeV longitudinal data in hand**
  - 3.5 times the integrated luminosity of 2006
  - Less passive material in front of the endcap calorimeter (EEMC)
  - Access to lower p_T π^0's on jet triggers looks appealing
  - Large enough dataset for a direct photon measurement?
- 2011 and 2012 datasets will allow 500 GeV measurements, and a return to transverse measurements

Backup Plots/Slides

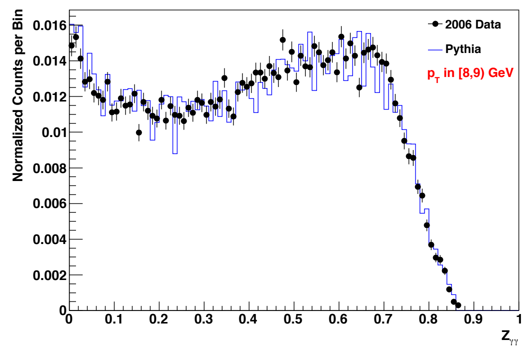

Counts per Bin
6000
4000
2000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
M_γγ [GeV/c^2]
STAR Data
Monte Carlo
7 < p_T < 8 GeV/c
Counts per Bin
4000
3000
2000
1000
0
5
10
15
20
25
30
E_γ1 [GeV]
Counts per Bin
4000
2000
0
5
10
15
20
25
30
E_γ2 [GeV]

Data/Monte Carlo Comparison

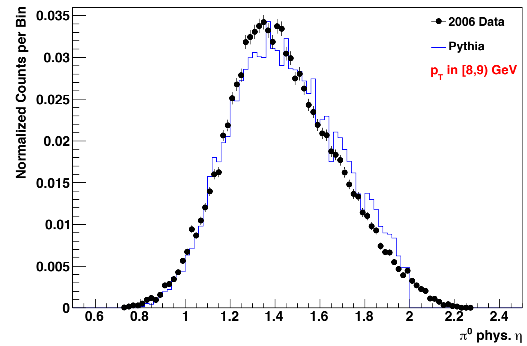
π^0 p_T



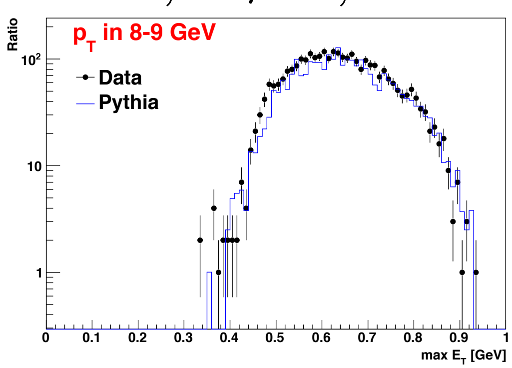
π^0 $Z_{\gamma\gamma}$



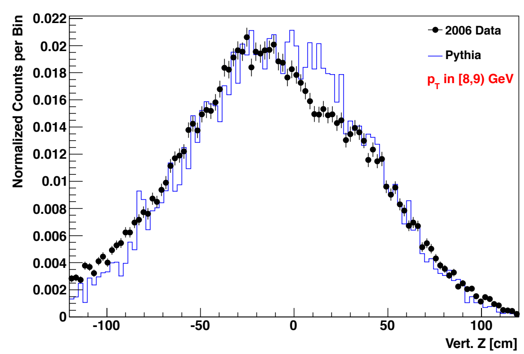
π^0 Physical η



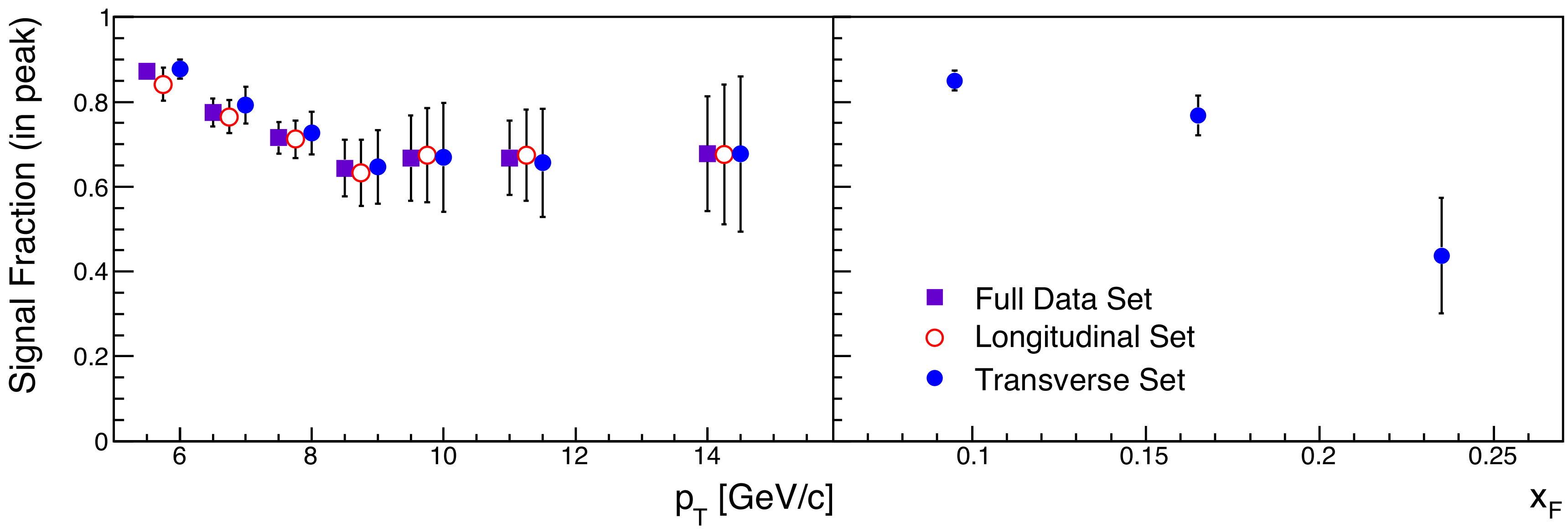
$E_{T,max}/E_{T,3x3}$

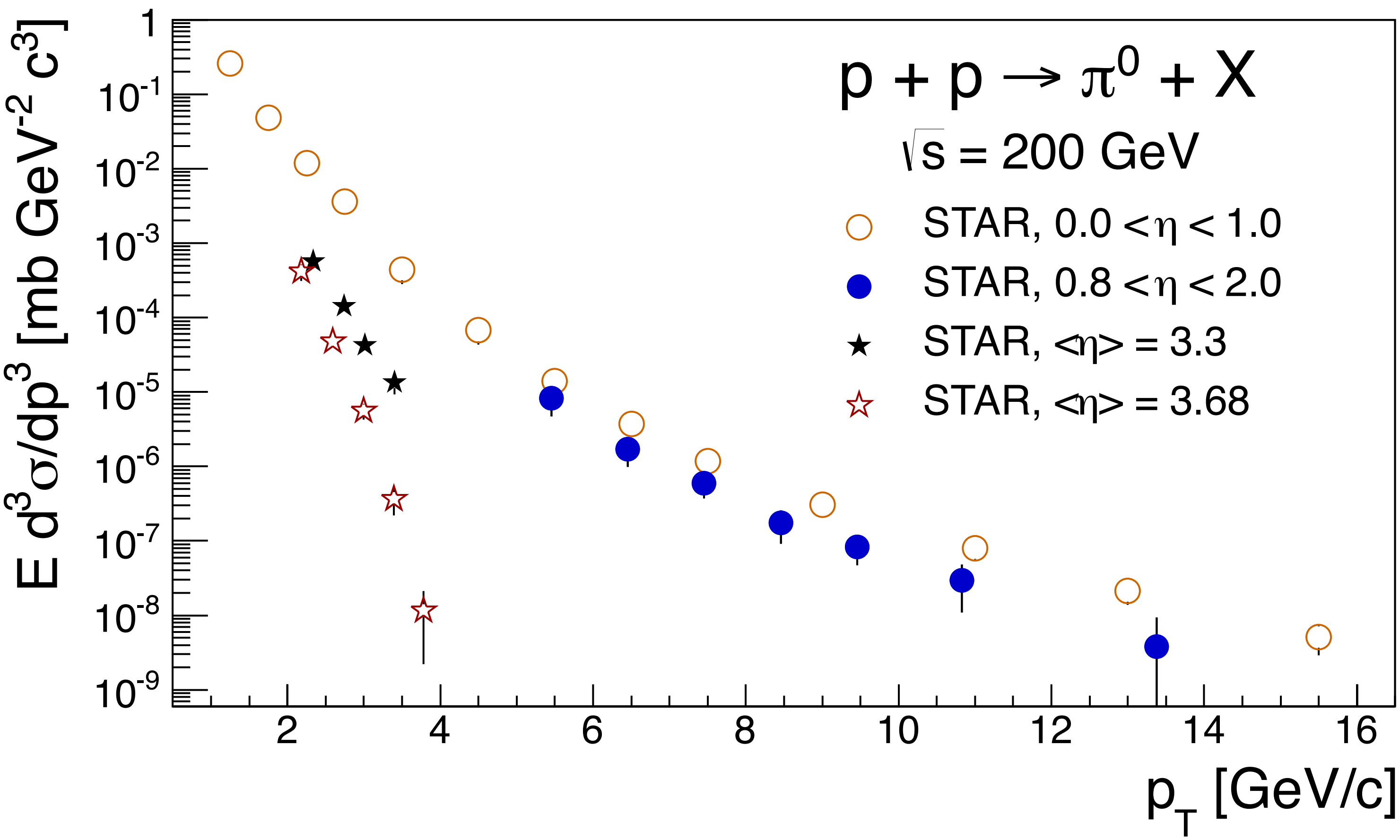


Vertex Z

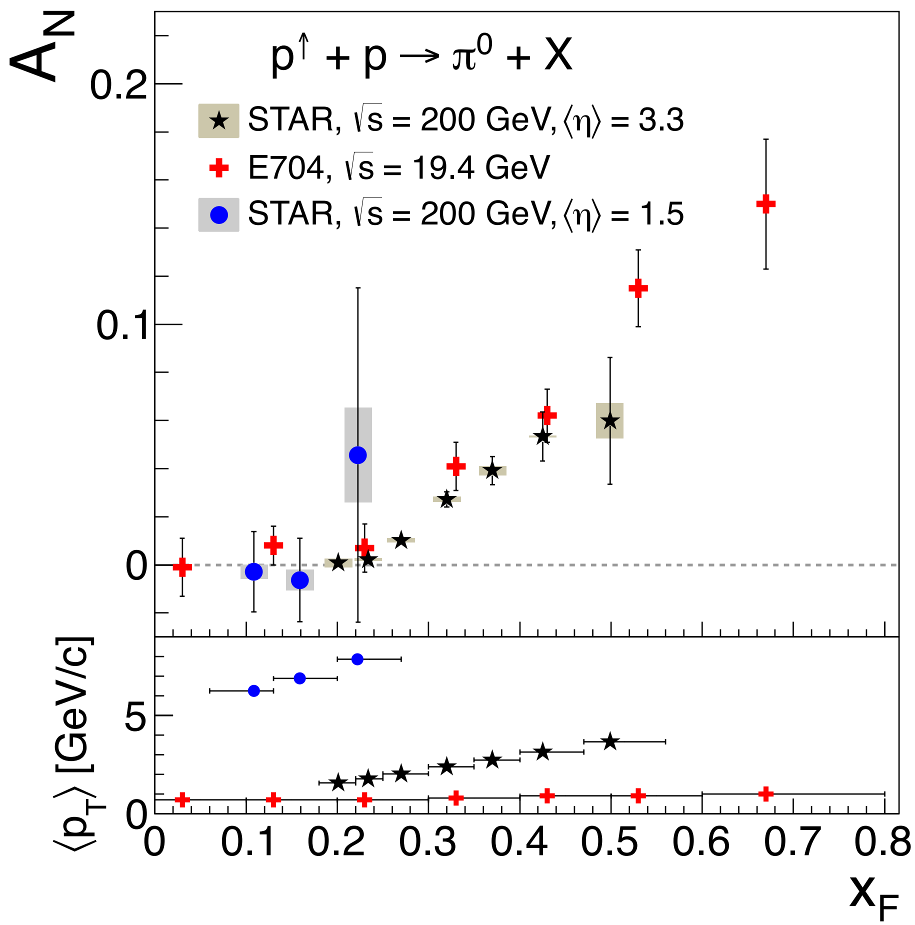


- Plots shown for π^0 p_T in 8-9 GeV
- Pythia tune 329, "Pro-pT0"
- Agreement generally good for π^0 $p_T > 6$ GeV
- $5 < p_T < 6$ GeV usable, but has higher systematic uncertainty
- Sampled lumi. of 8 pb^{-1}


Signal Fraction (in peak)
1
0.8
0.6
0.4
0.2
0
6
8
10
12
14
p_T [GeV/c]
0.1
0.15
0.2
0.25
x_F
Full Data Set
Longitudinal Set
Transverse Set



p + p → π0 + X
√s = 200 GeV
STAR, 0.0 < η < 1.0
STAR, 0.8 < η < 2.0
STAR, <η> = 3.3
STAR, <η> = 3.68
E d3σ/dp3 [mb GeV-2 c3]
pT [GeV/c]
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
2
4
6
8
10
12
14
16


$p^{\uparrow} + p \rightarrow \pi^0 + X$
STAR, $\sqrt{s}$ = 200 GeV, $\langle\eta\rangle$ = 3.3
E704, $\sqrt{s}$ = 19.4 GeV
STAR, $\sqrt{s}$ = 200 GeV, $\langle\eta\rangle$ = 1.5
A_N
$\langle p_T \rangle$ [GeV/c]
x_F

Computing the Cross Section

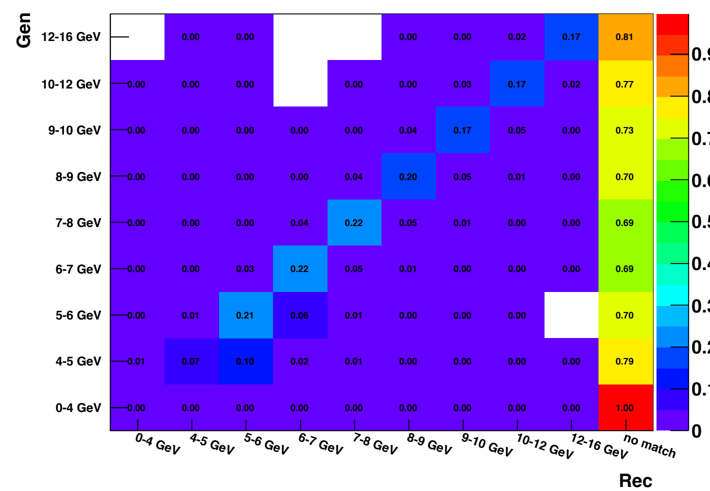
- The unfolded number of π^0s per p_T bin is computed as

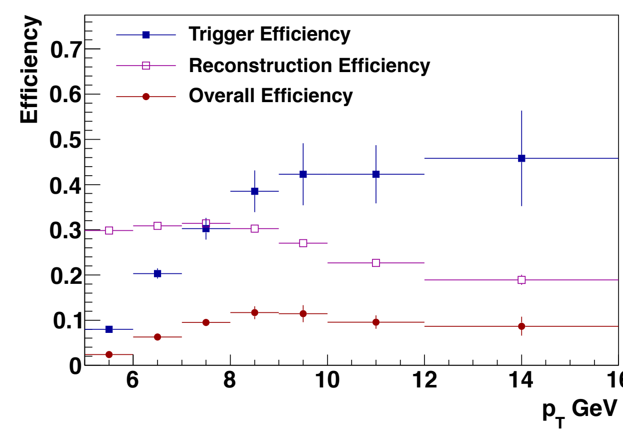
$$N_i^{(\pi^0)} = \sum_j S_{i,j}^{-1}\, f_j\, s_j\, N_j^{(\mathrm{raw})}$$

  - 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

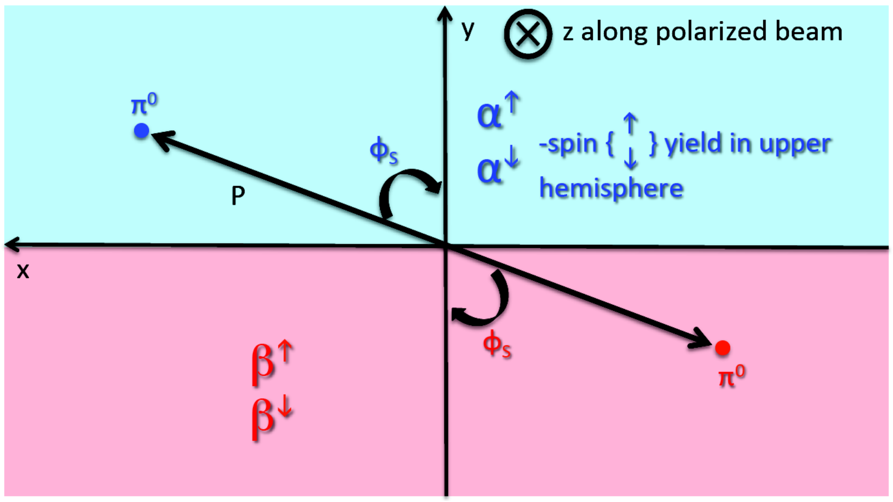
$$E\frac{d^3\sigma}{d\boldsymbol{p}^3} = \frac{1}{2\pi}\,\frac{1}{\Delta\eta}\,\frac{1}{\Delta p_T}\,\frac{1}{\langle p_T\rangle}\,\frac{1}{\epsilon}\,\frac{1}{\mathrm{B.R.}}\,\frac{N^{(\pi^0)}}{\mathcal{L}}$$

- 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)





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.