

Double-Spin Asymmetry in Neutral Pion Production at Intermediate Pseudorapidity in Longitudinally Polarized $p + p$ Collisions in the STAR Detector at RHIC



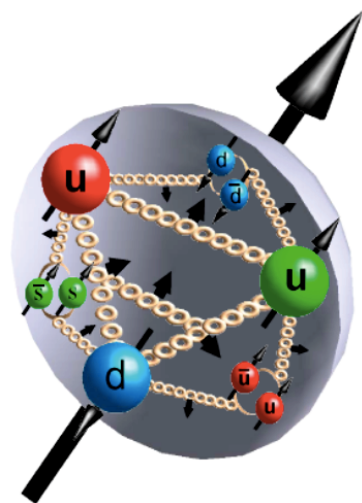
Adam Gibson
Valparaiso University

For the STAR Collaboration
DNP 2016
October 14, 2016



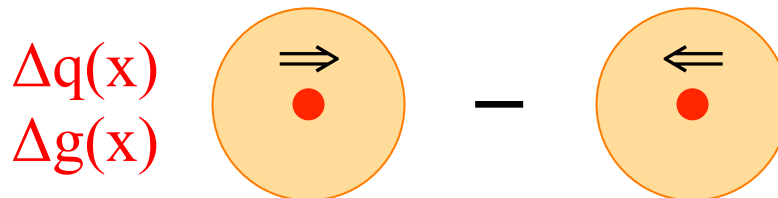


Contributions to the Proton's Spin



Consider proton moving right

Proton spin \Rightarrow



Longitudinal Polarization

Polarized DIS: ~ 0.3
Puzzling for ~ 25 years

Relatively poorly constrained
But S_g coming into focus!

Proton spin sum rule: $\frac{1}{2}\hbar = \frac{1}{2} \sum_q S_q^z + S_g^z + \sum_q L_q^z + L_g^z$

Proton spin \uparrow

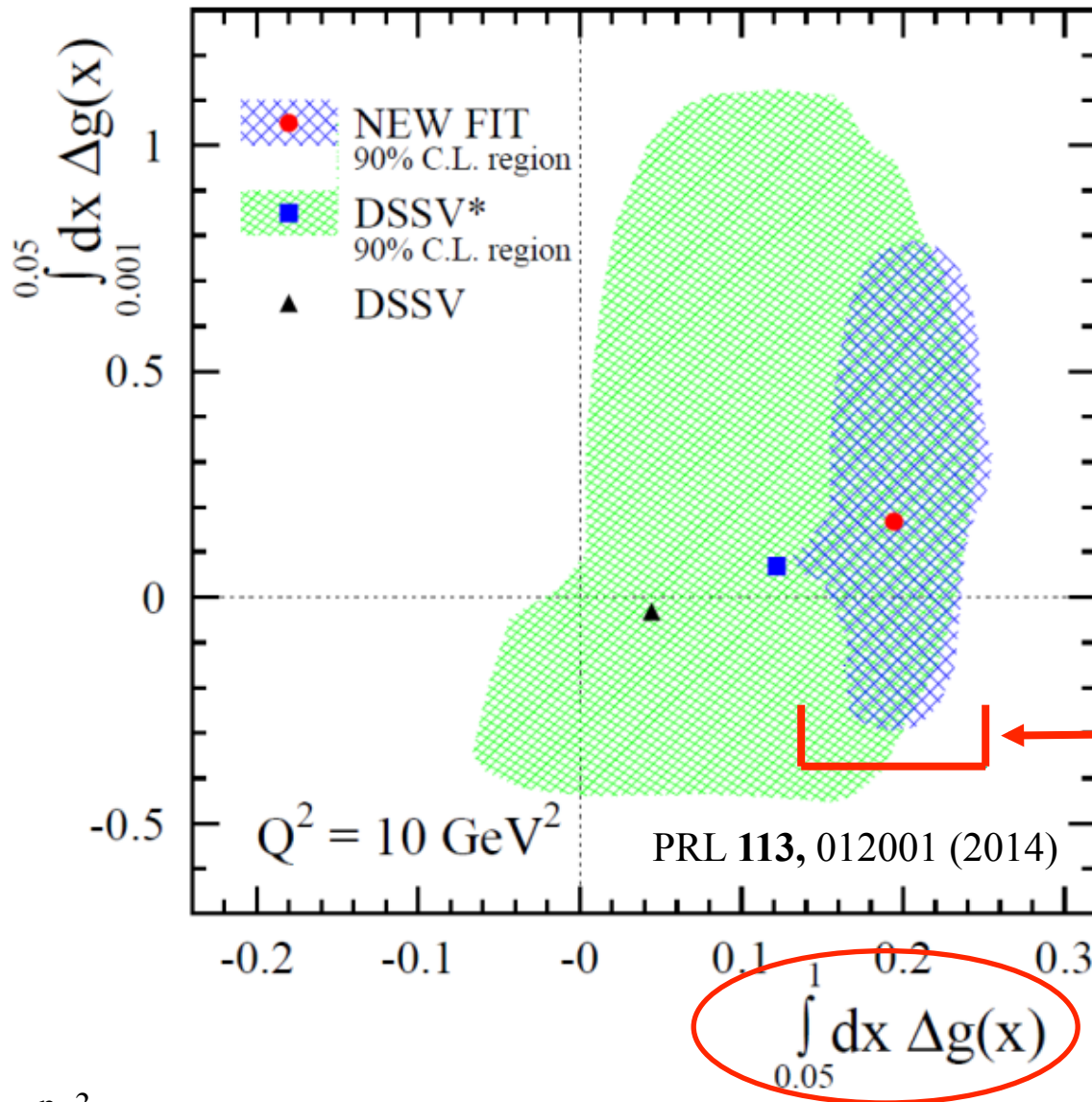


Transverse Polarization

Transversity



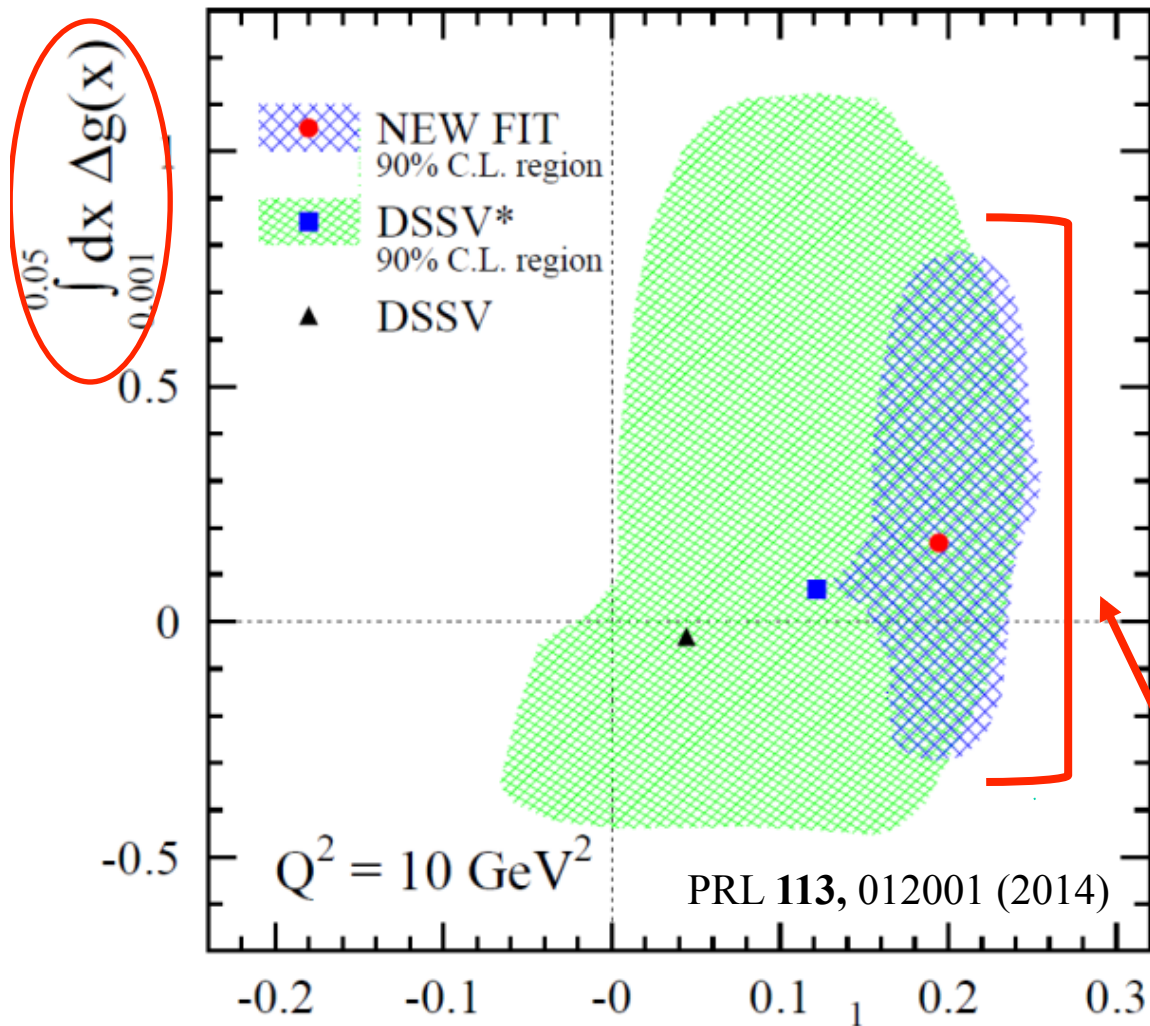
New DSSV Fit – G Comes into Focus



- With input from PHENIX π^0 's and STAR 2009 jets
- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- **First firm evidence of non-zero gluon polarization!**



New DSSV Fit – Low x Remains Blurry



- With input from PHENIX π^0 's and STAR 2009 jets
- Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable

[See also new NNPDF fit Nucl. Phys. B887 (2014) 276-308]

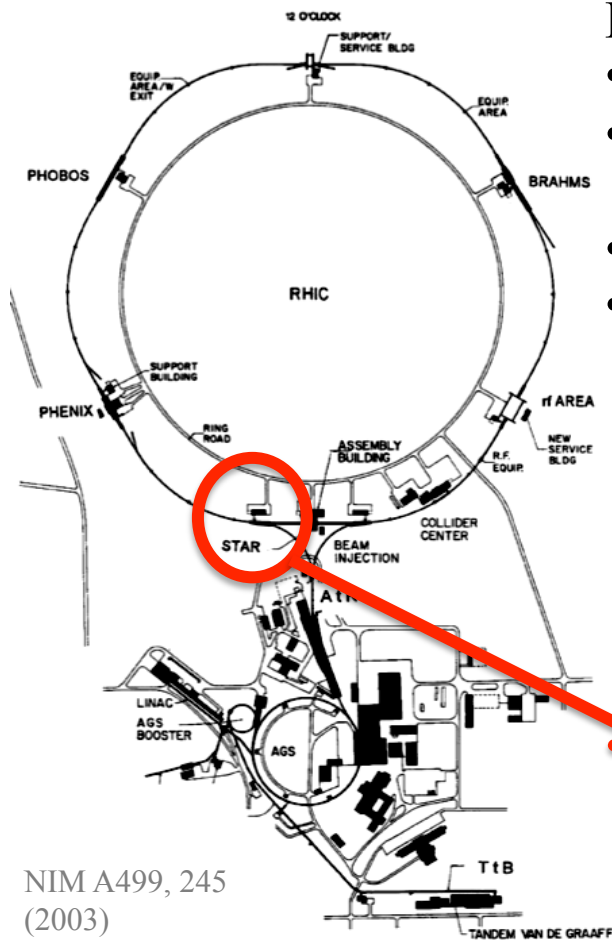


Solenoidal Tracker at RHIC

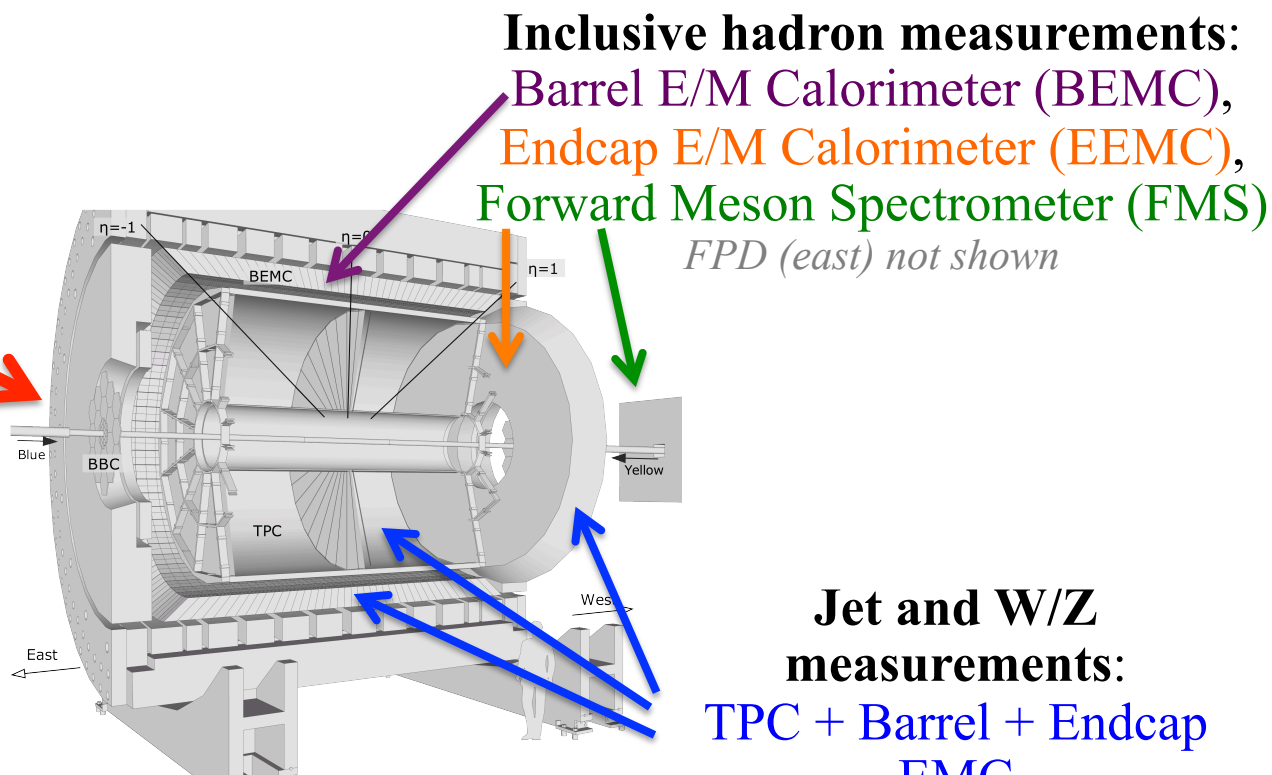


RHIC as Spin Collider

- “Siberian Snakes” → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation *independent of experiment*
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill



NIM A499, 245
(2003)



Inclusive hadron measurements:
 Barrel E/M Calorimeter (BEMC),
 Endcap E/M Calorimeter (EEMC),
 Forward Meson Spectrometer (FMS)
FPD (east) not shown

Jet and W/Z measurements:
 TPC + Barrel + Endcap
 EMC



Solenoidal Tracker at RHIC



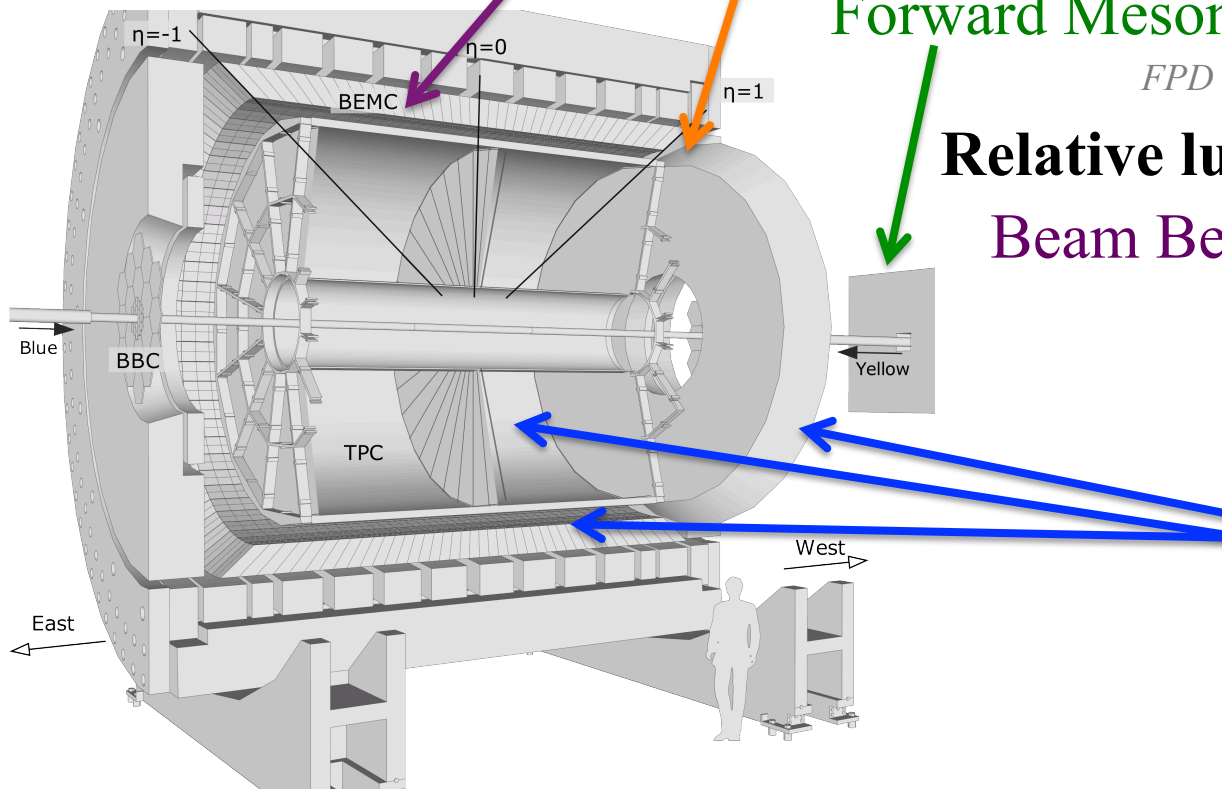
Inclusive hadron (e.g. π^0) measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and

Forward Meson Spectrometer (FMS)

FPD (east) not shown

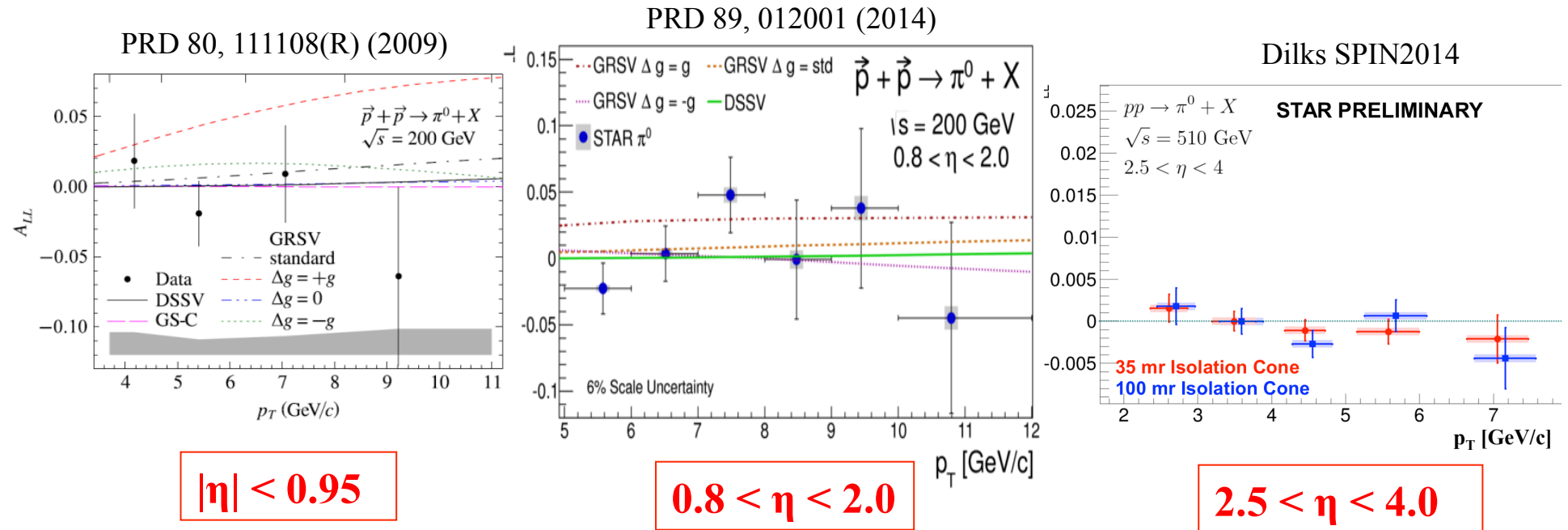
Relative luminosity measurements:
Beam Beam Counters (BBC) etc.

Jet and W/Z
measurements:
TPC +
Barrel + Endcap EMC





Probing Low x Gluons With $\pi^0 A_{LL}$



$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

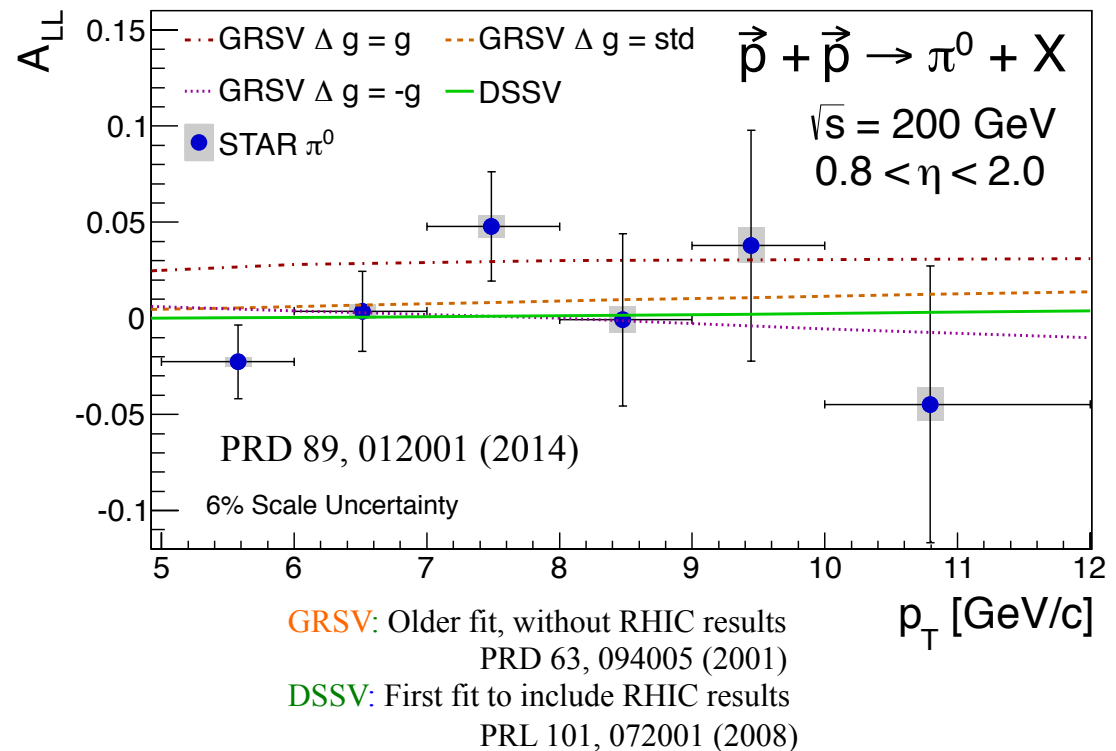
- STAR has measured $\pi^0 A_{LL}$ in three different pseudorapidity ranges
 - Different kinematics, π^0 fragmentation, different systematics
- qq scattering dominates at high η with high x quarks and low x gluons
- **No large asymmetries seen**



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

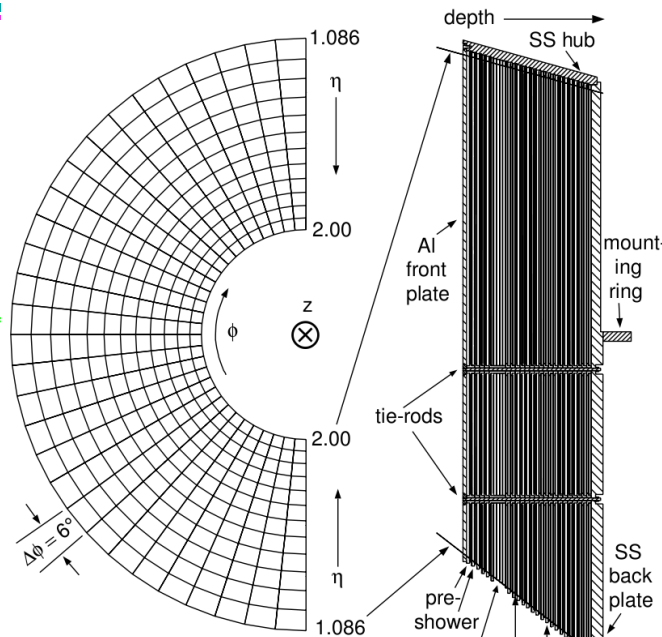
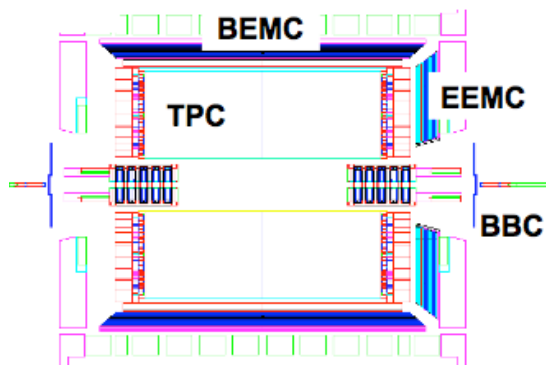


- 2006 Dataset in the Endcap Electromagnetic Calorimeter (EEMC)
 - **η region unique at RHIC**
- Push to reasonably low x by going (relatively) forward
- 4.8 pb^{-1} for A_{LL} after prescales
 - $\sim 56\%$ polarization
- Statistical error (bars) dominate
- Systematic error (boxes)
 - Signal fraction uncertainties from template fits
 - Uncertainty on background asymmetry
- Cross section and transverse asymmetry also measured



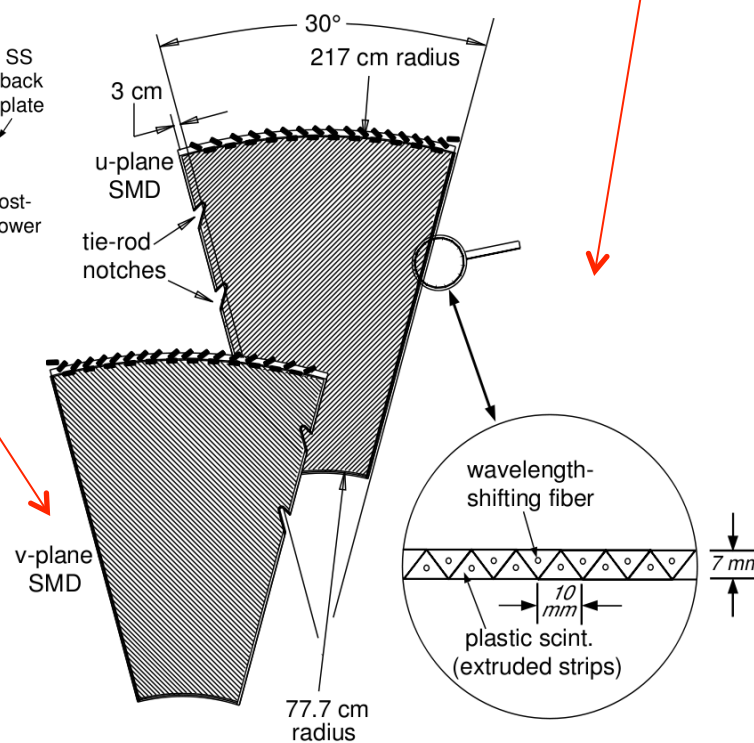


STAR's Endcap Electromagnetic Calorimeter



- 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 ($\sim 22 X_0$)
 - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- High Tower, Jet Patch, and Photon (high tower + 3x3 tower patch triggers)





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 particles
- Incident particle (e.g. **photon**) energy computed from towers
- Momentum from the vertex and SMD cluster positions

- SMD response (right) in π^0 candidate event from data

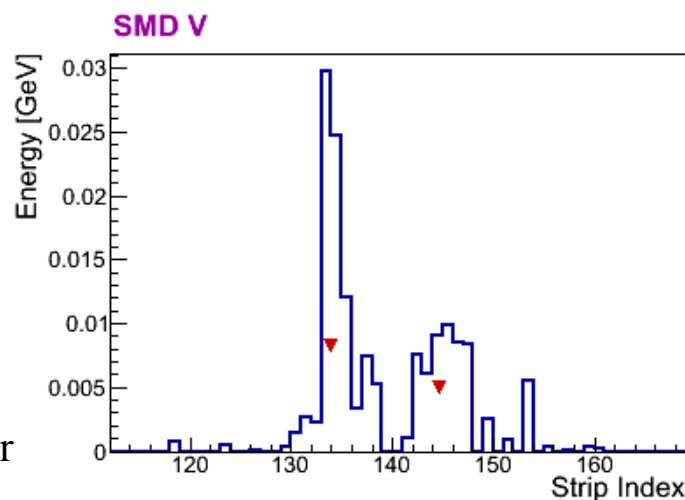
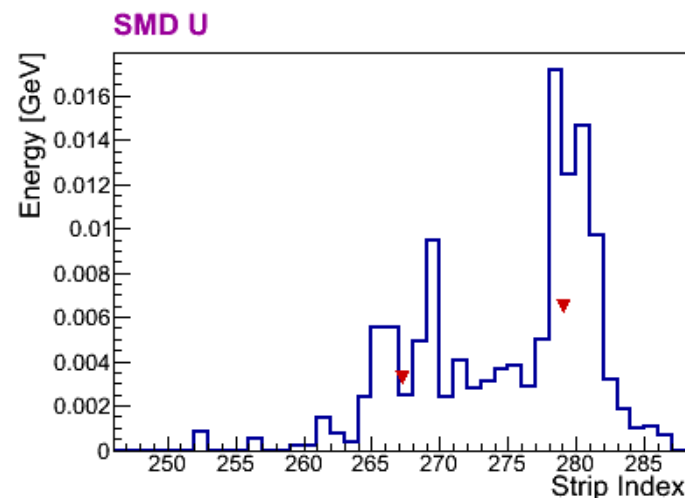
- Blue histograms show energy response per strip
- 7-strip clusters formed from smoothed strip energy distributions
- Red triangles represent clusters drawn at mean strip position, and 10% of the cluster energy

- EM particle candidates built from paired u+v clusters

- Clusters matched by energy of u and v strips
- Required to have associated tower energy above threshold

- 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

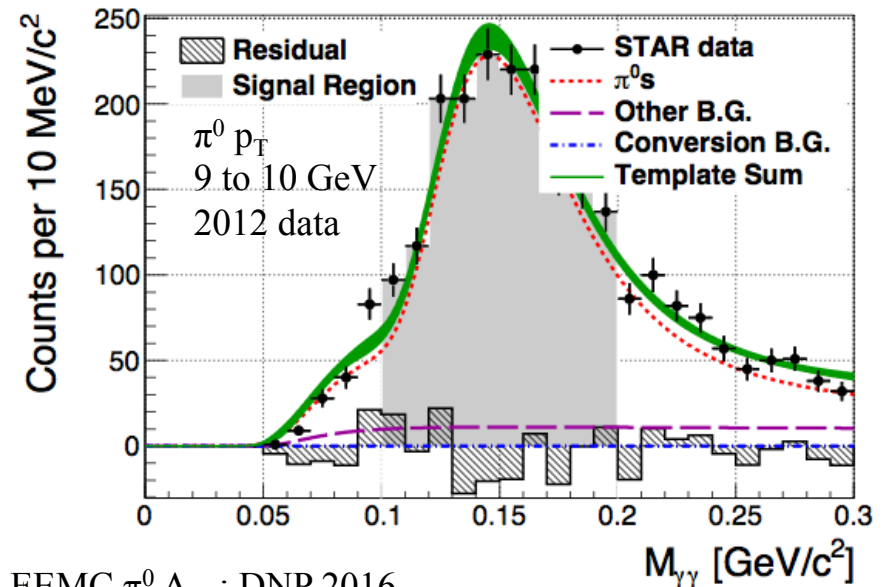
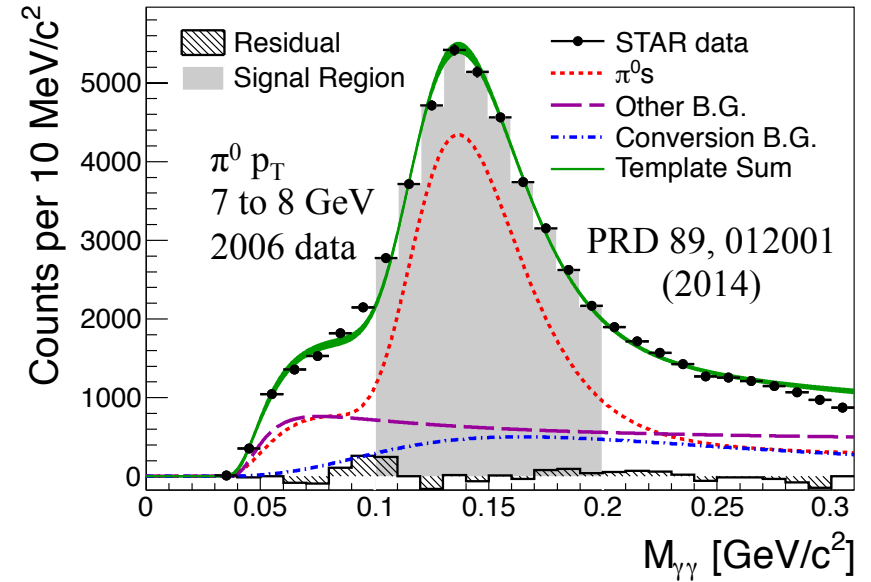




π^0 Signal and Background Computation



- Inclusive π^0 mass distribution fit to templates, in bins of $\pi^0 p_T$
 - Signal
 - Conversion BG (π^0 candidate is from gamma $\rightarrow e^+ e^-$)
 - 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
- 2012 dataset being analyzed now
 - x10 statistics; $\sim 80 \text{ pb}^{-1}$, $\sim 50\%$ polarization
 - 510 GeV CoM energy w/ similar trigger, reconstruction thresholds allows access to **lower x gluons**
 - $\sim 1\%$ of data is shown here, on HT trigger
 - For now with 2006 MC templates



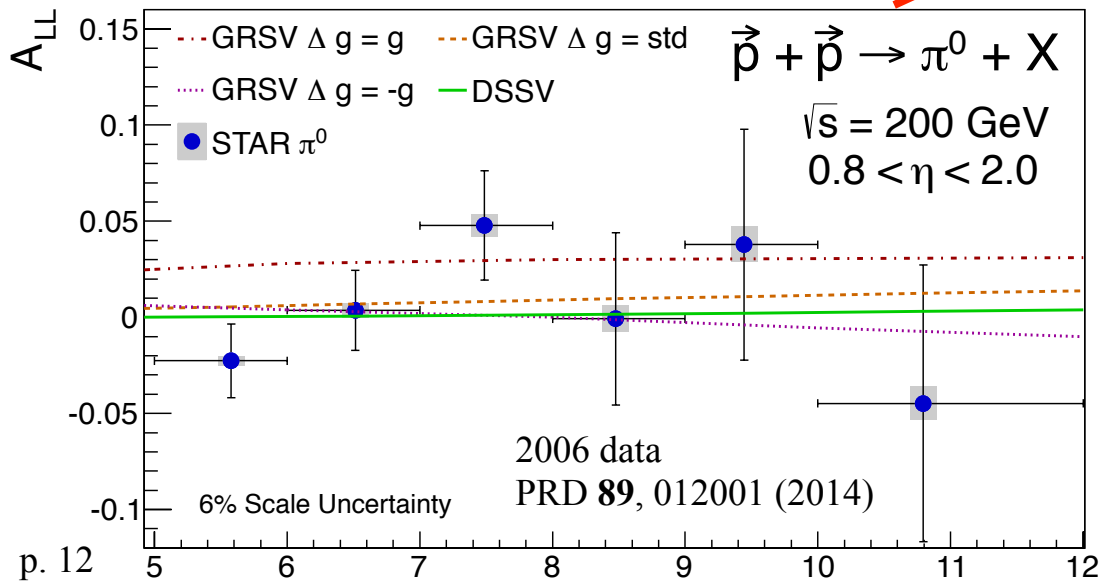
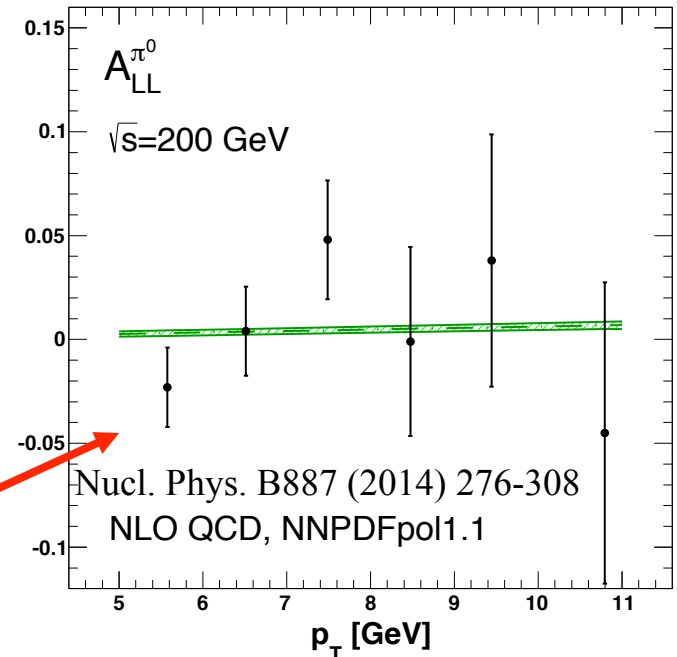


Updated Prediction for π^0 A_{LL}



- NNPDFpol1.1 includes jet results from STAR and PHENIX, including 2009 STAR inclusive jets
- Greater precision needed to constrain the fit

STAR data with NNPDF predictions

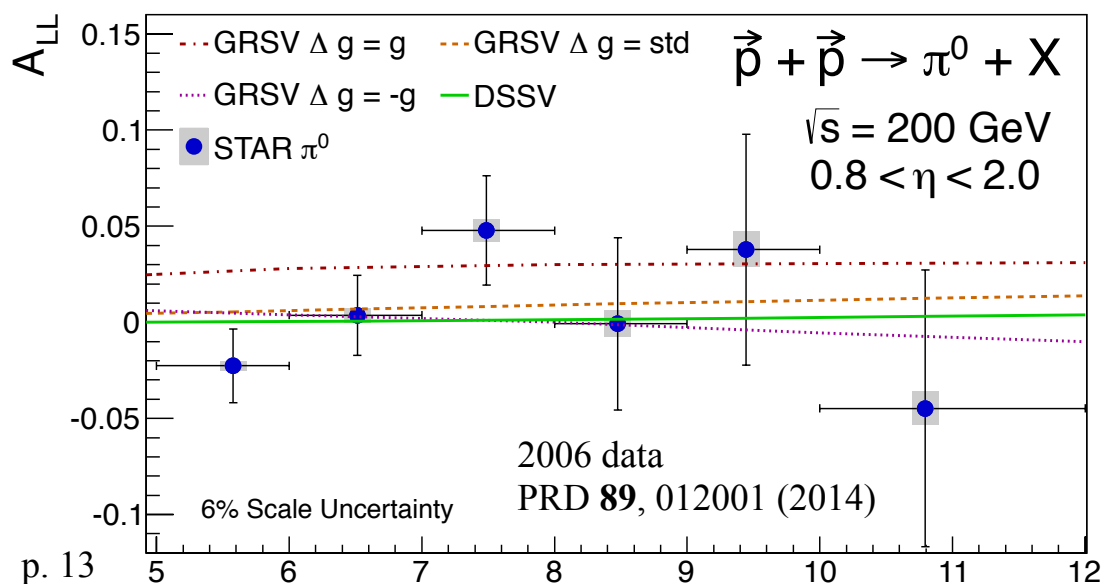
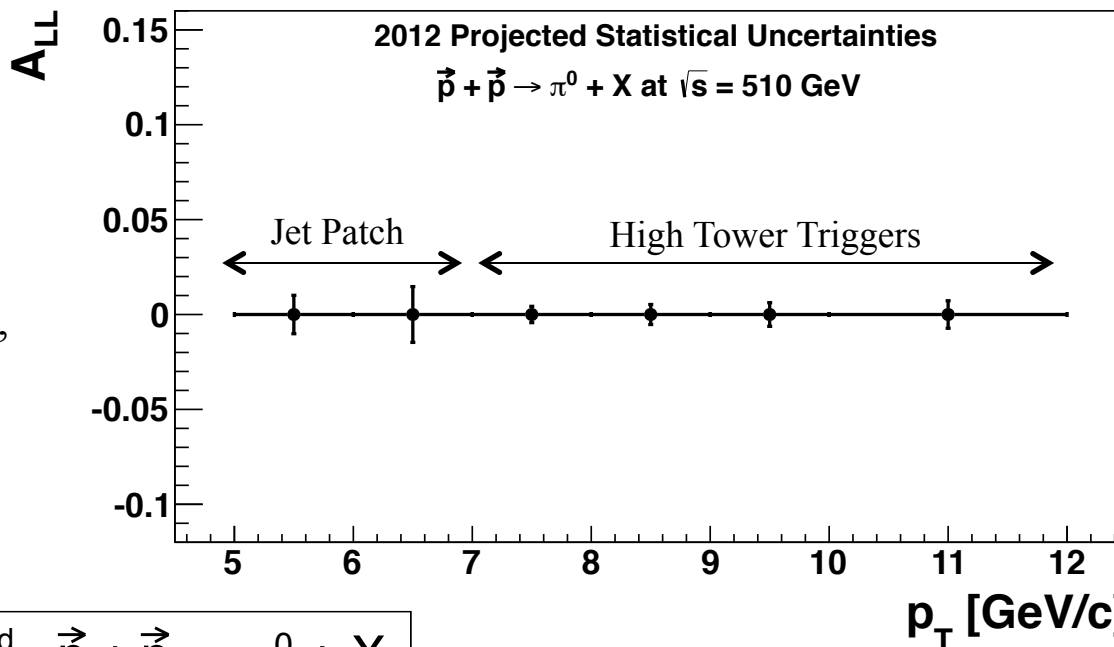




π^0 A_{LL} Prospects in 2012 Dataset



- Statistical projection from simplified, data-only fit
 - HT trigger above 7 GeV
 - JetPatch trigger 5-7 GeV
 - Large improvement in stat. uncertainty projected, as shown



- Reasonable quality π^0 's as low as 5 GeV π^0 p_T on HT triggers, as low as 2 GeV on jet triggers



Gluon Polarization and Endcap π^0 's at STAR



- After 25 years, **evidence of non-zero gluon polarization** in the proton
- Pushing to **lower x gluons**
 - With forward detectors, $\sqrt{s} = 510$ GeV, large datasets
- Work underway with **2012 dataset** at $\sqrt{s} = 510$ GeV
 - **x10 statistics** compared to 2006 measurement: push to **lower x**
 - **EEMC calibration updated**; MC update and full dataset integration in progress
 - Final trigger strategy under discussion
- Return to 200 GeV CoM and/or transverse asymmetries in endcap π^0 's possible
- Very large 2013 longitudinal dataset also available
- **Stay tuned!**

- **CEU Poster session this afternoon 2-4 PM**
- **Stability of the Gains of the STAR Endcap Calorimeter; Chamindu Amarasinghe**
- **Measurement of the Longitudinal Double-spin Asymmetry for Neutral Pion Production in Polarized Proton Collisions at $\sqrt{s} = 510$ GeV; Tae gyun Kim**



Backup

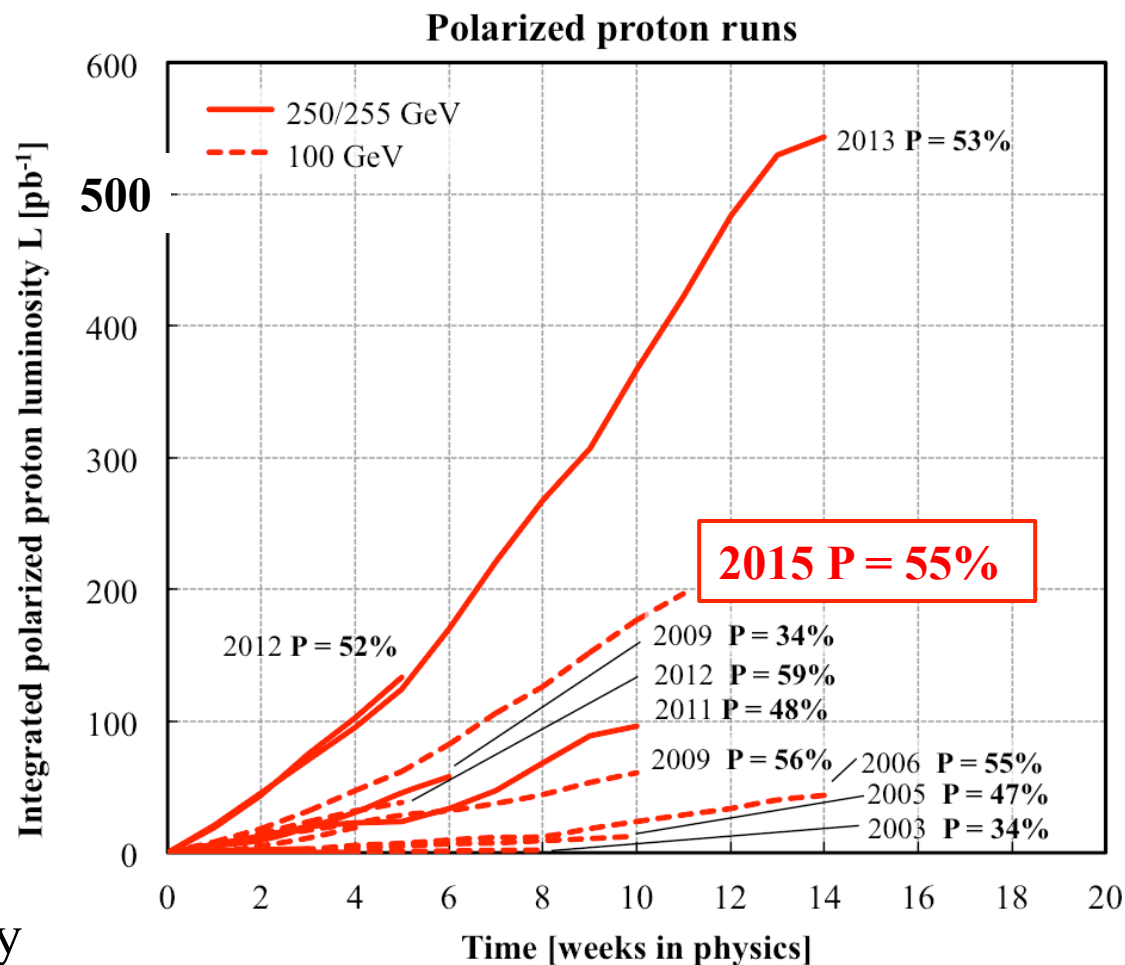




Datasets from RHIC at STAR

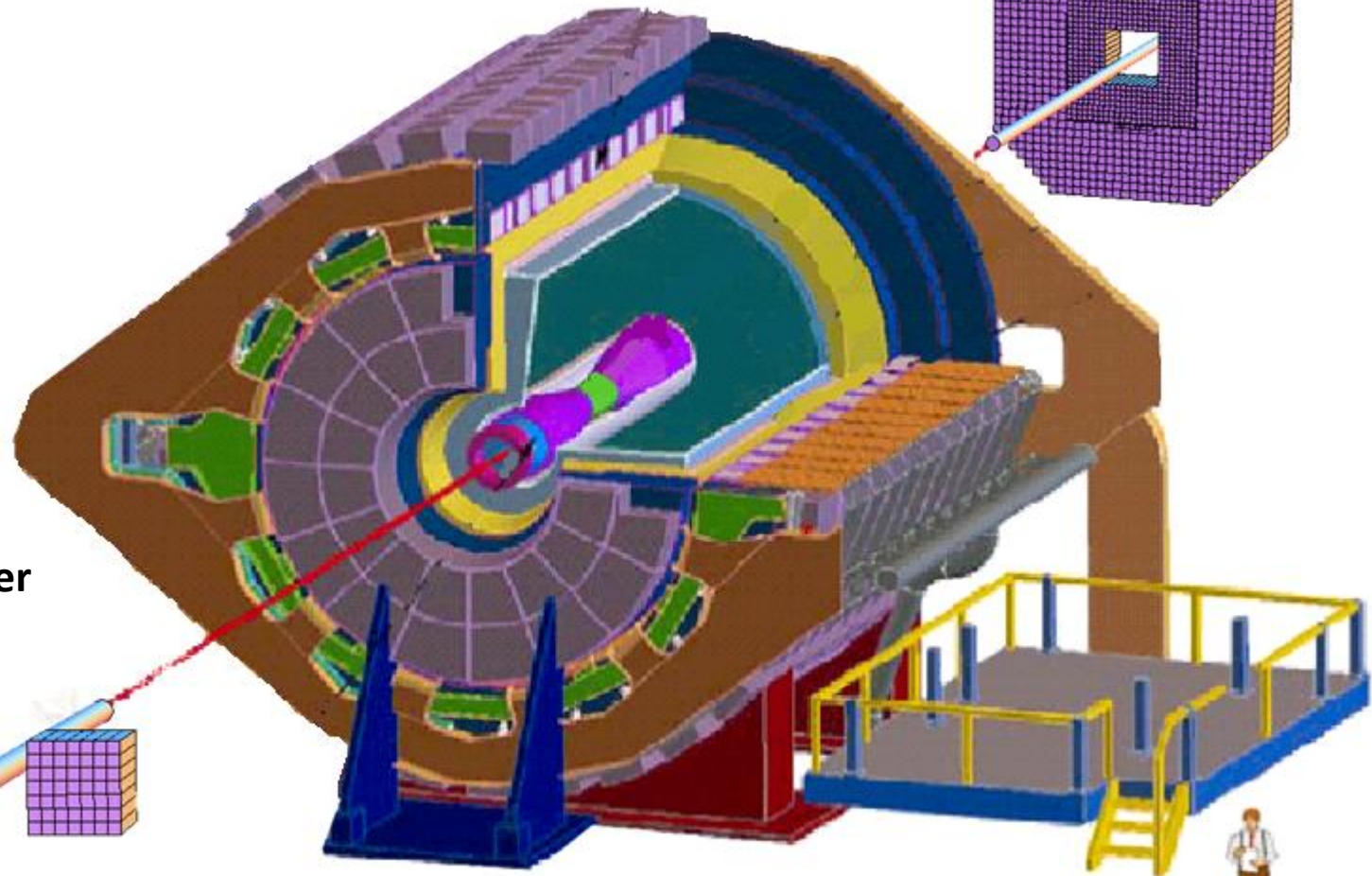
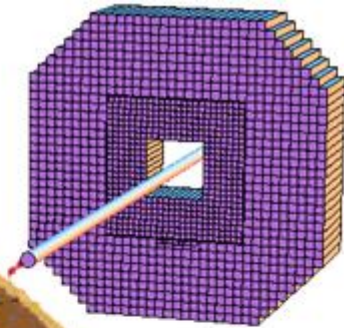


- Many published results from 2006, 2009 datasets
 - And W's more recently
- Preliminary results and work in progress from, especially
 - 2011 500 GeV trans.
 - 2012 200 GeV trans.
 - *Large* 510 GeV long. datasets in 2012 and 2013
- 2015 brought increased statistics at 200 GeV, and opened the era of high-energy spin in p+A collisions

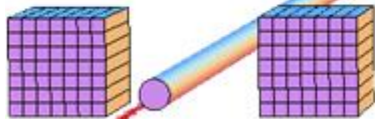


FMS

Pb Glass EM Calorimeter
pseudo-rapidity $2.7 < \eta < 4.0$
Small cells: 3.81x3.81 cm
Outer cells: 5.81 x 5.81 cm



FPD EM Calorimeter
Small cells only
Two 7x7 arrays



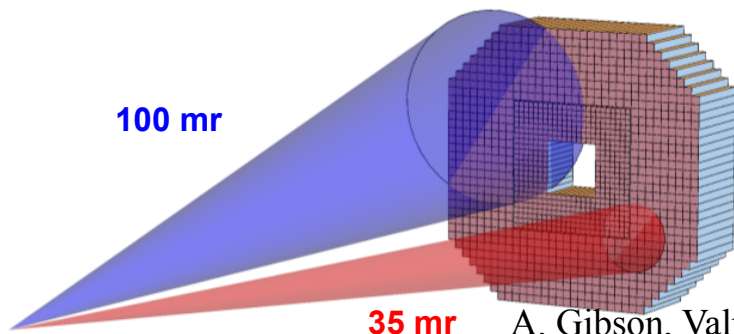
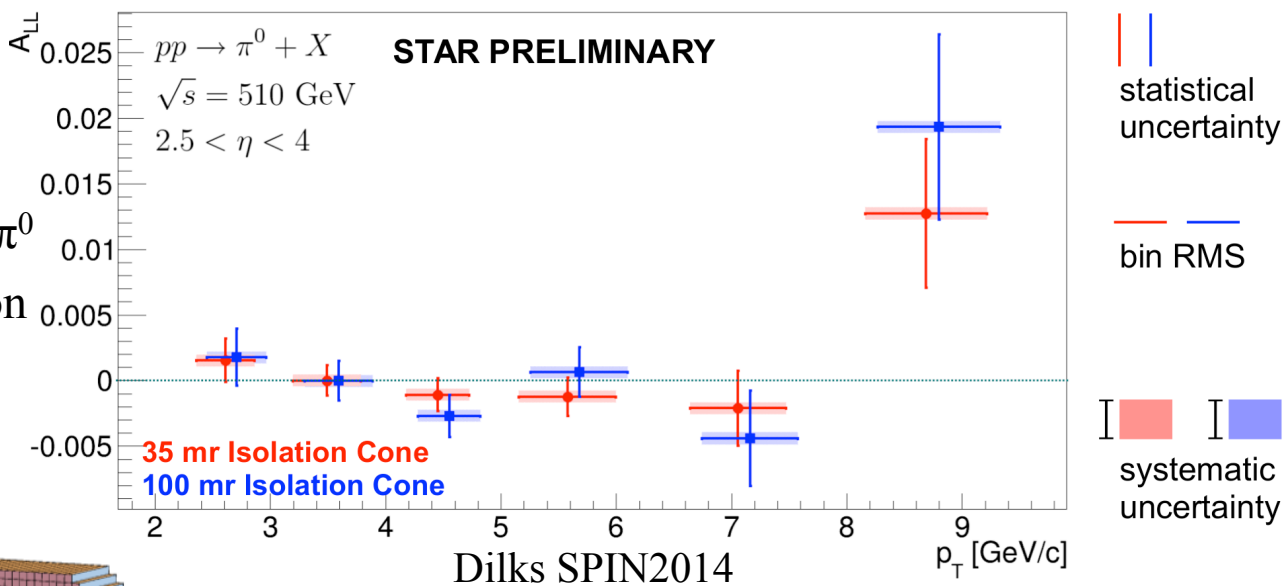


$\pi^0 A_{LL}$ Prospects in Forward Calorimeters



- Pushing even further forward, with the FMS
- Preliminary with large 2012 and 2013 datasets at 510 GeV
 - After prescales, effectively 46 pb⁻¹ in 2012, $p_T > 2.5$ GeV
 - And 8 pb⁻¹ in 2013, $p_T > 2.0$ GeV
 - An older preliminary result also exists, with the FPD (Wissink SPIN2008)

- Require isolation cone around π^0 's
 - Motivated by A_N increase for isolated π^0
 - Now exploring isolation dependence

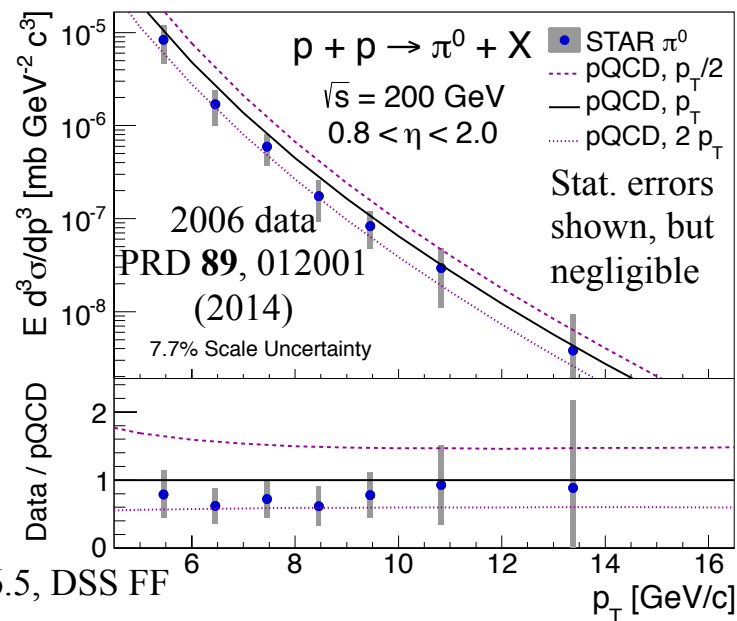
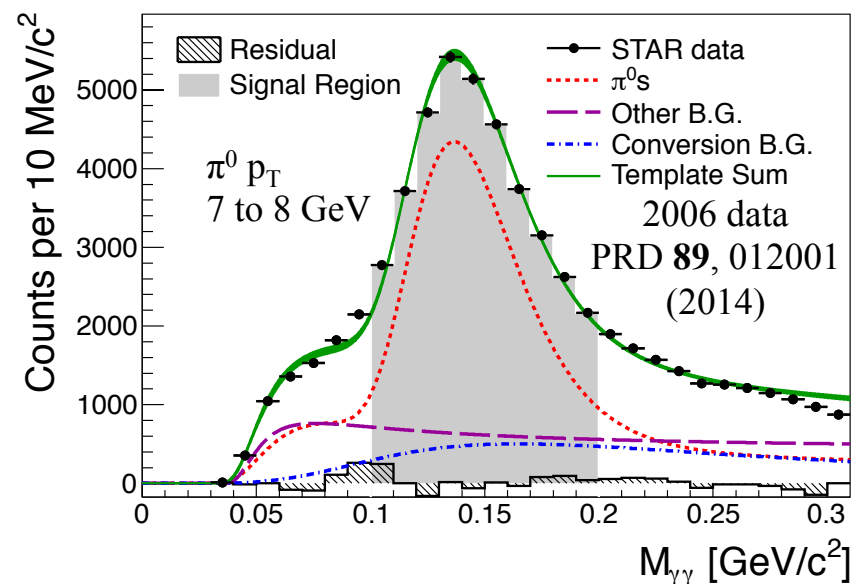




π^0 Background and Cross-Section Computation



- Inclusive π^0 mass distribution fit to templates, in bins of $\pi^0 p_T$
 - Signal
 - Conversion BG (π^0 candidate is from gamma $\rightarrow e^+ e^-$)
 - 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 $\pi^0 p_T$
 - 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)

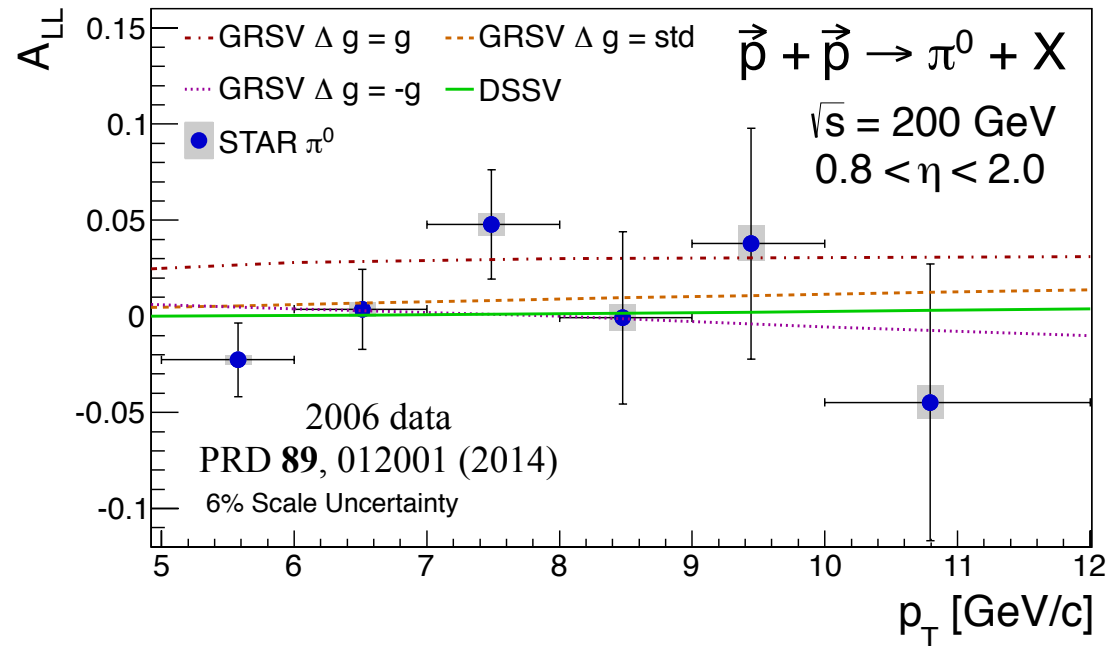




A_{LL} in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$



- 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?

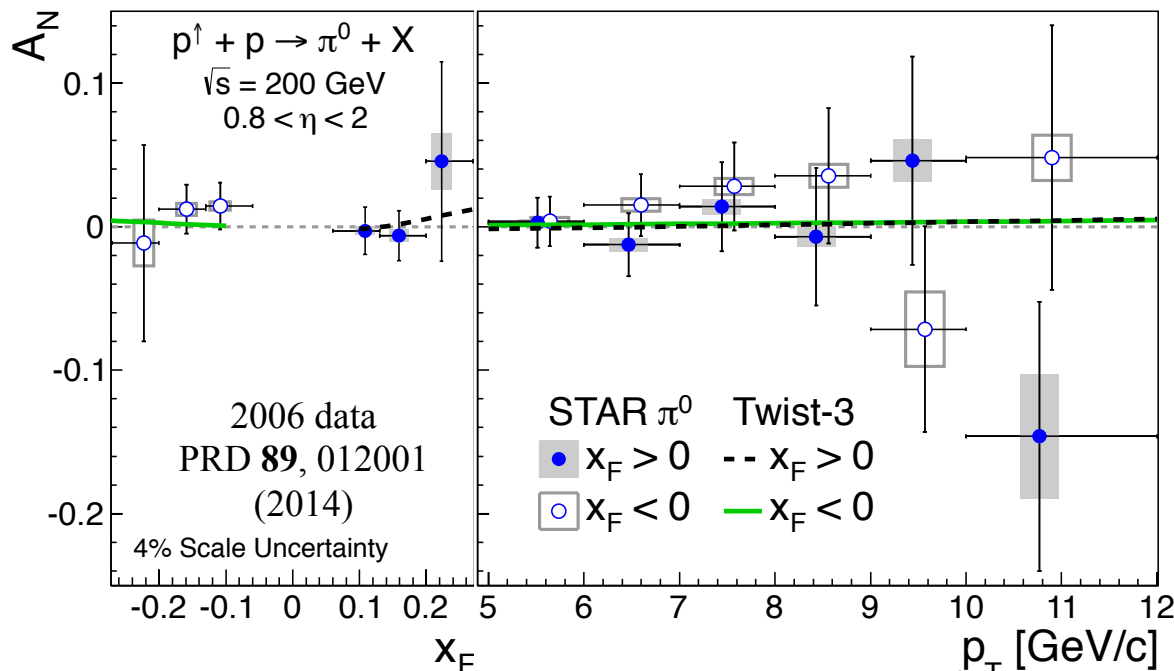




A_N in $\pi^0 + X$ at STAR for $0.8 < \eta < 2.0$



- 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 $\pi^0 p_T$ (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)





- Consider more detailed ALL formula, polarization, etc.

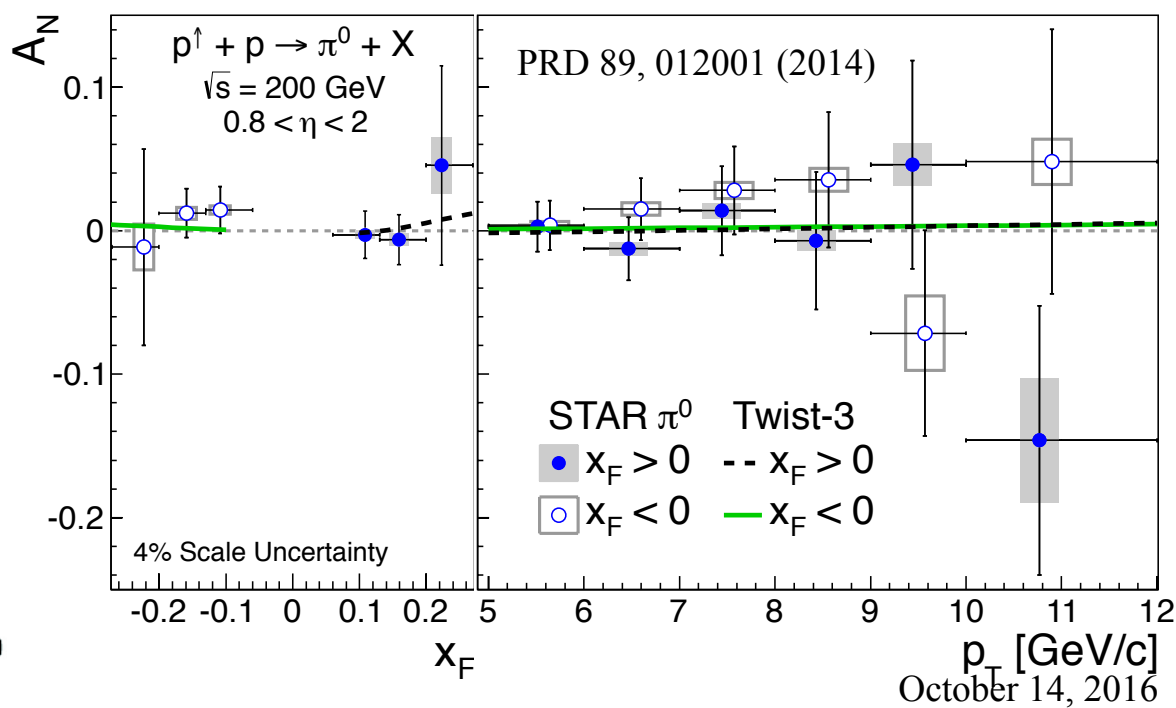
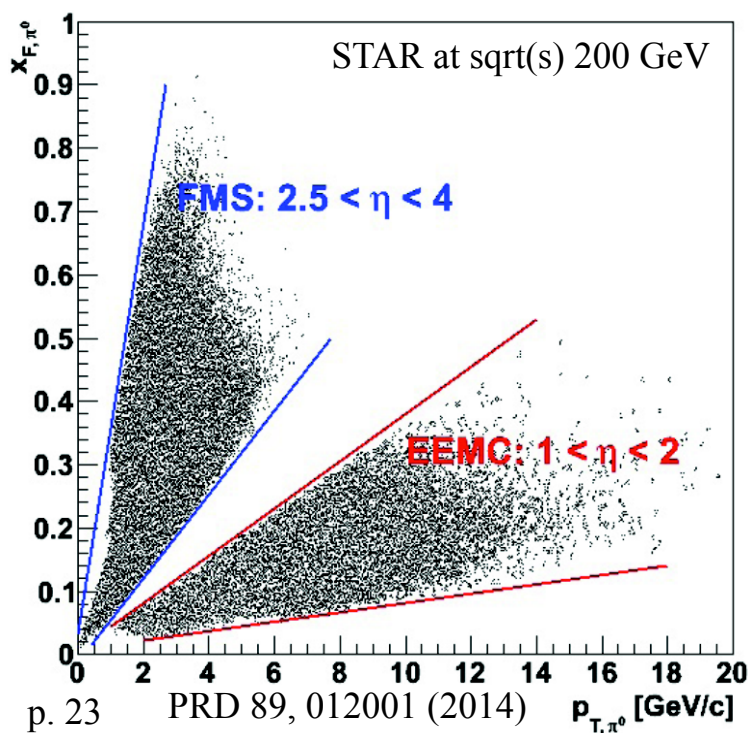
$$\frac{N_{sym} - N_{antisym}}{N_{sym} + N_{antisym}} - \frac{L_{sym} - L_{antisym}}{L_{sym} + L_{antisym}}$$



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



- Transverse asymmetries for the EEMC mid-rapidity 2006 dataset
- 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) dominates over systematic error (boxes)
- Twist-3 prediction
 - K. Kanazawa and Y. Koike,
 - Phys. Rev. D 83, 114024 (2011)





STAR Puzzle of Large Transverse Spin Asymmetries, A_N



- Anomalously large A_N observed for nearly 40 years
 - In naïve, co-linear, leading-order/leading-twist QCD expect very small A_N , especially at high energy

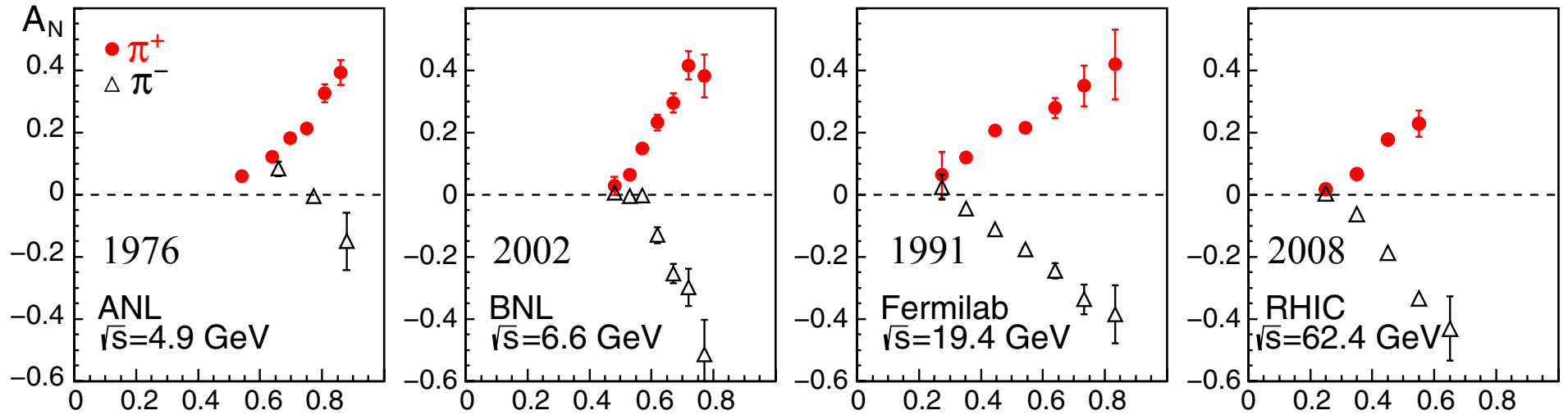
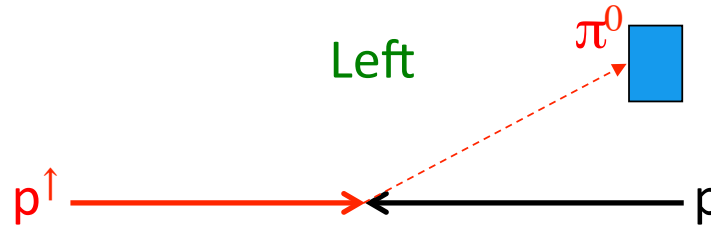


Figure Aidala *et al.* Rev. Mod. Phys., Vol. 85, No. 2

$$x_F = \frac{p_{z,\pi}}{p_{z,\max}} = \frac{p_{z,\pi}}{\sqrt{s}/2}$$

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

$d\sigma^{\uparrow(\downarrow)}$ – cross section for leftward scattering when beam polarization is spin-up(down)



Positive A_N – more π^0 to **left** of (up) polarized beam

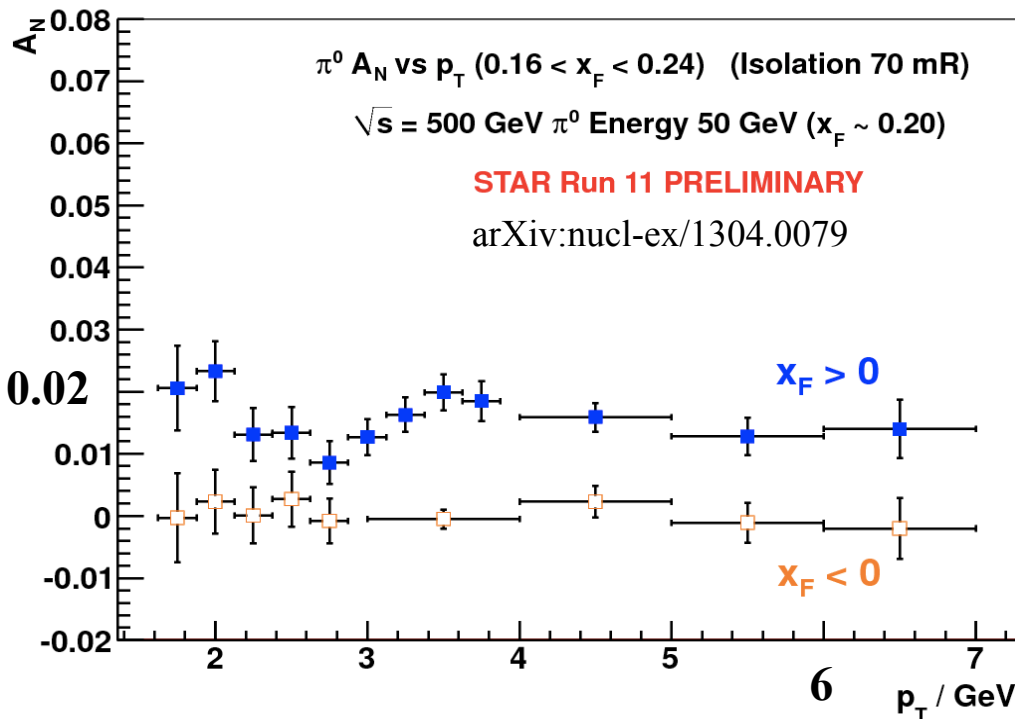
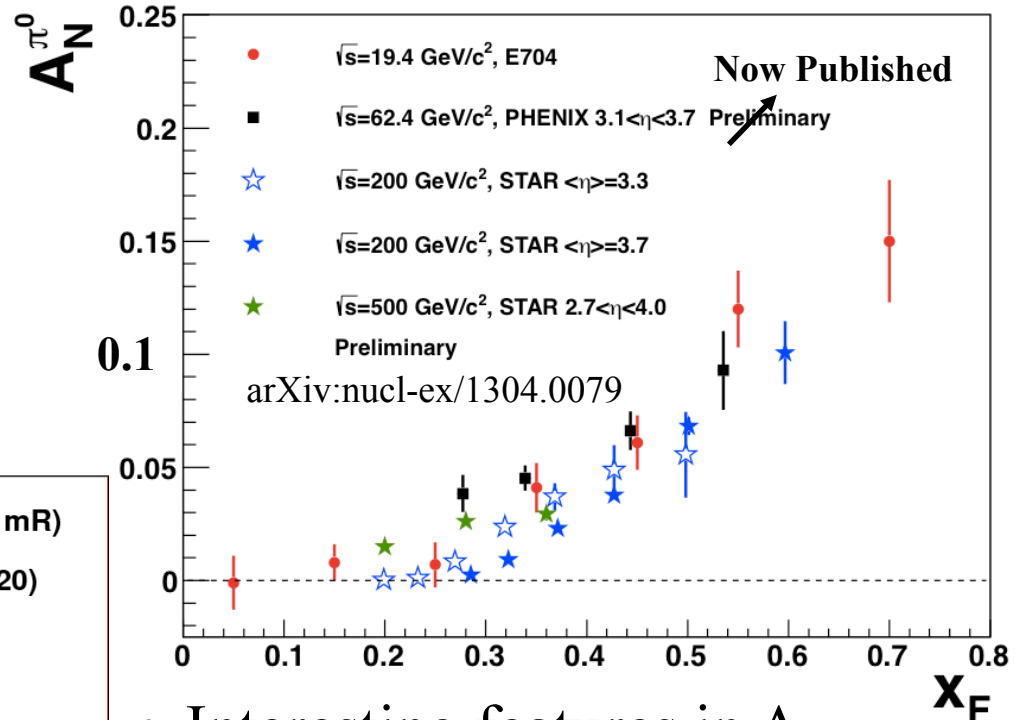
For a 2π detector, A_N manifests as an azimuthal (ϕ) asymmetry



Puzzle of Large Transverse Spin Asymmetries, A_N



- Persists at STAR/RHIC
 - At forward pseudorapidity
 - At high x_F



- Interesting features in A_N
 - Persists to surprisingly large p_T
 - Larger in η 's than π^0 's?
 - In relatively isolated π^0 's, not in jets
 - Smaller when there's central activity
 - Diffractive physics?

–New Roman Pots in 2015

Relativistic Heavy Ion Collider as a Spin Collider

Concert of Facilities

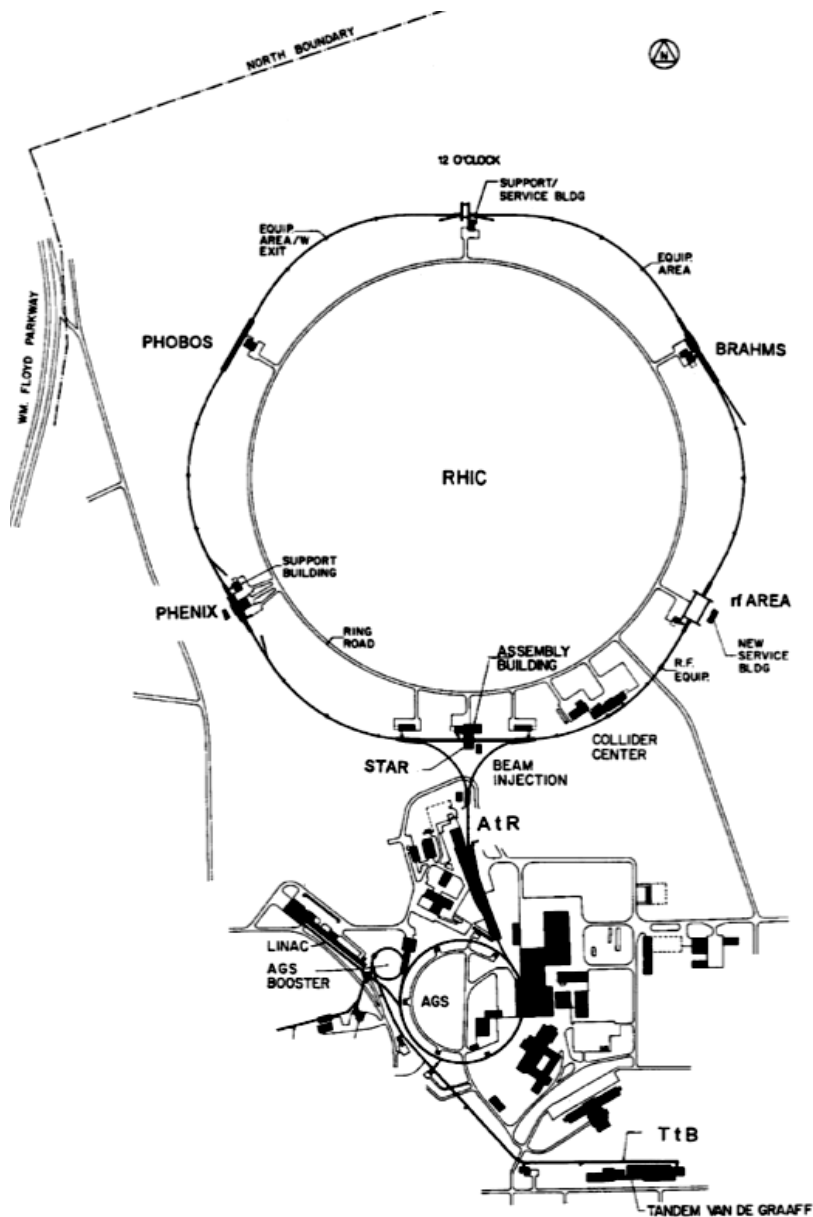
- OPPIIS → LINAC → AGS → RHIC

Polarized-proton Collider

- Mitigate effects of depolarization resonances with “Siberian Snakes”
- Polarization measured with CNI polarimeter
- Spin rotators provide choice of spin orientation *independent of experiment*

RHIC Beam Characteristics

- Clockwise beam: “blue”; counter-clockwise beam: “yellow”
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill



Solenoidal Tracker at RHIC

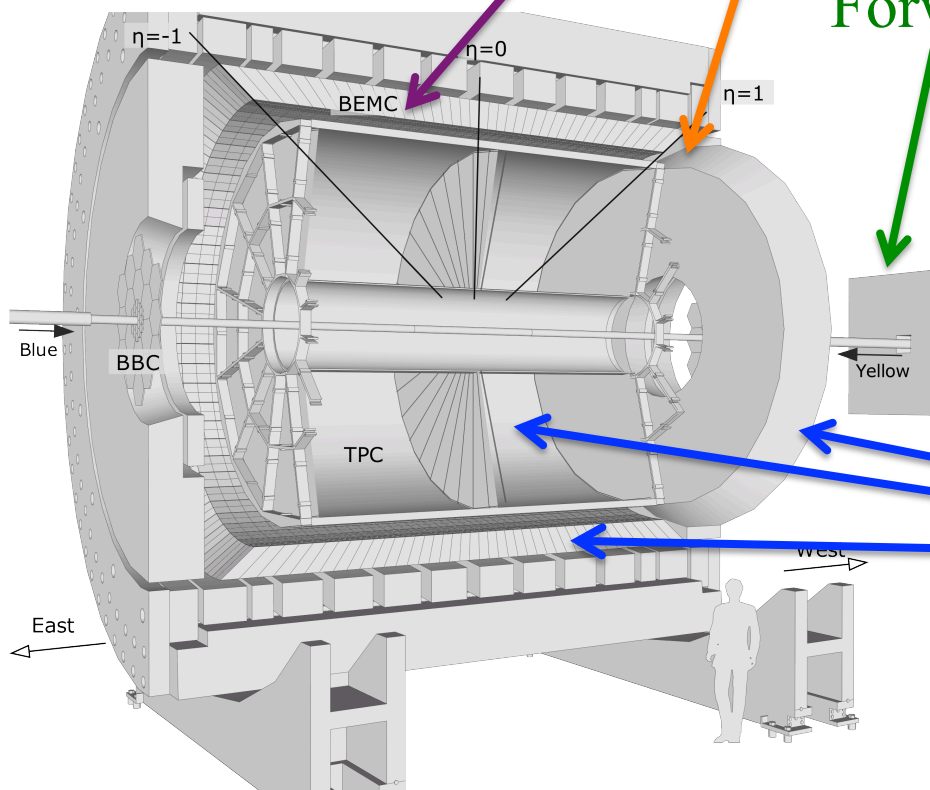
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**Jet and W/Z
measurements:**

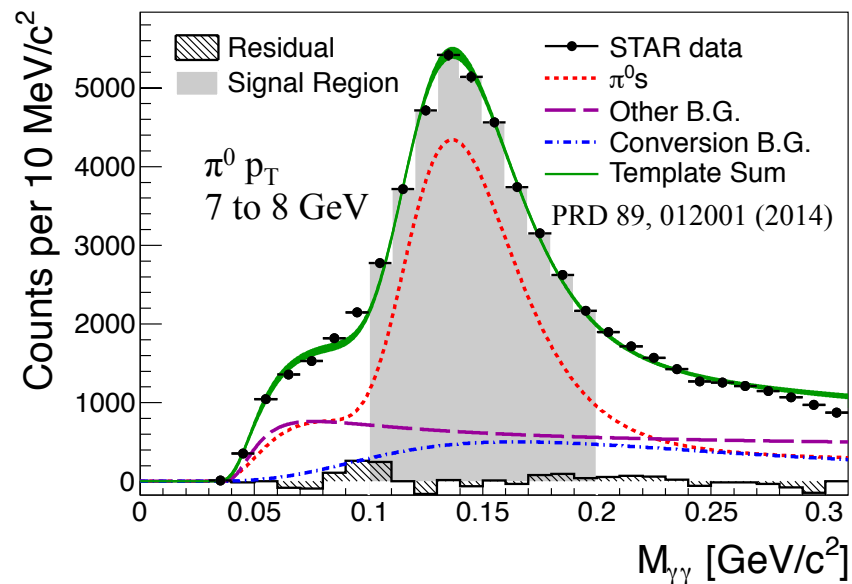
**TPC + Barrel + Endcap
EMC**



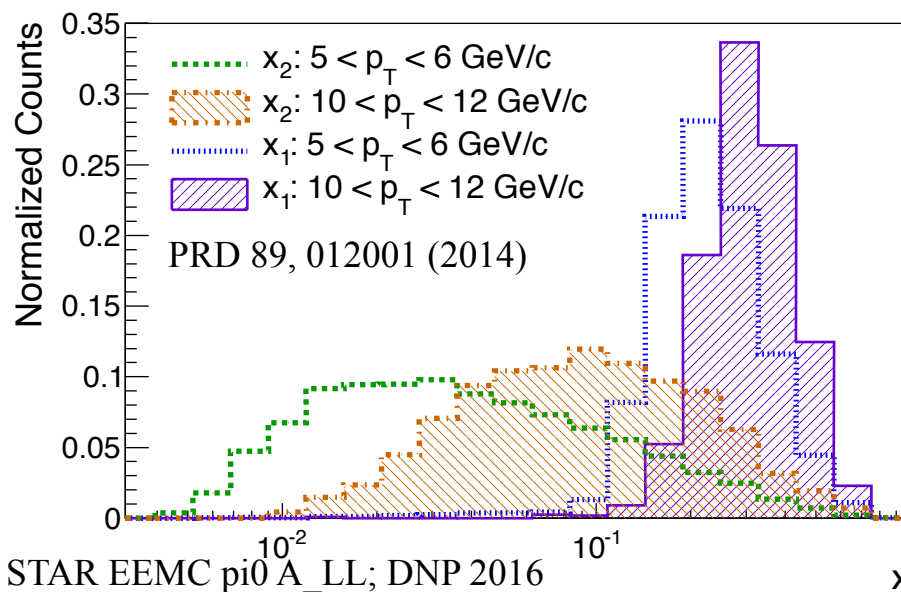
π^0 Background and Cross-Section Computation $0.8 < \eta < 2.0$ with 2006 Dataset



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

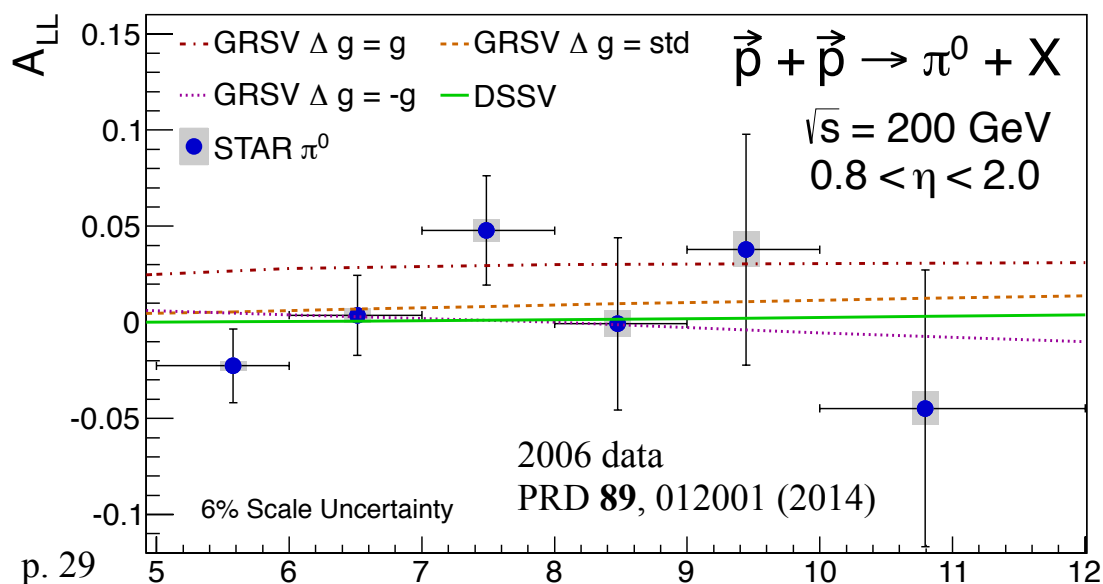
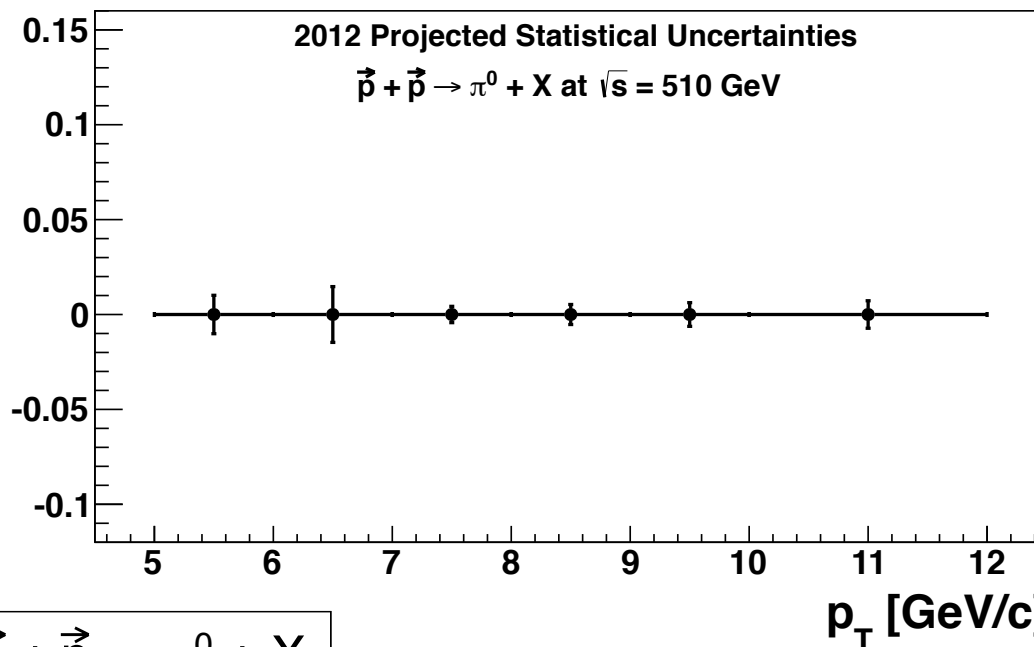




π^0 A_{LL} Prospects in 2012 Dataset



- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
 - Large improvement in stat. uncertainty projected, as shown



- Higher CoM energy
 - 200 \rightarrow 510 GeV
 - Pushes to lower x gluon

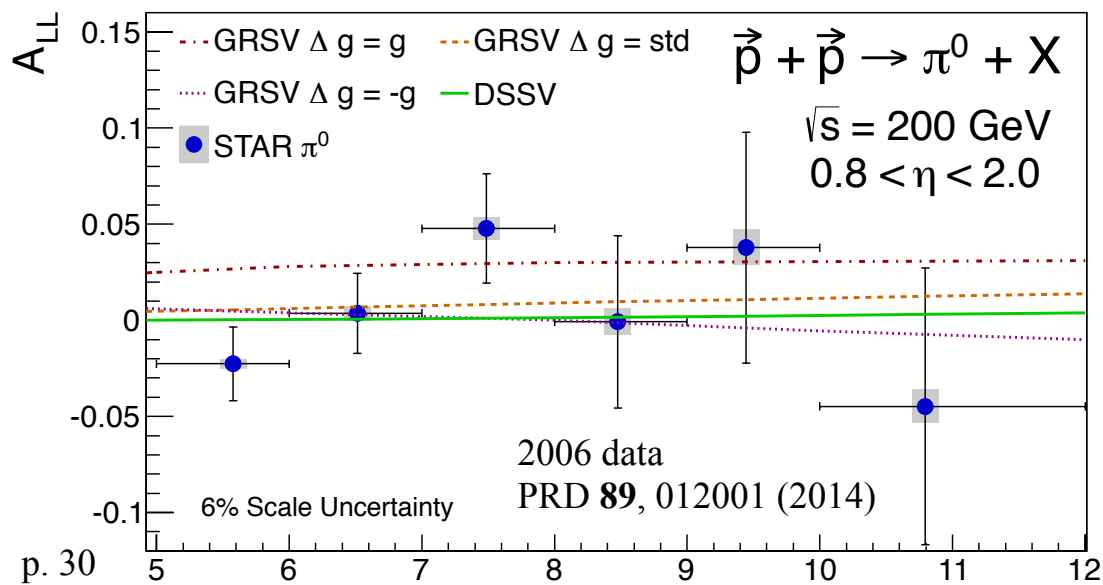
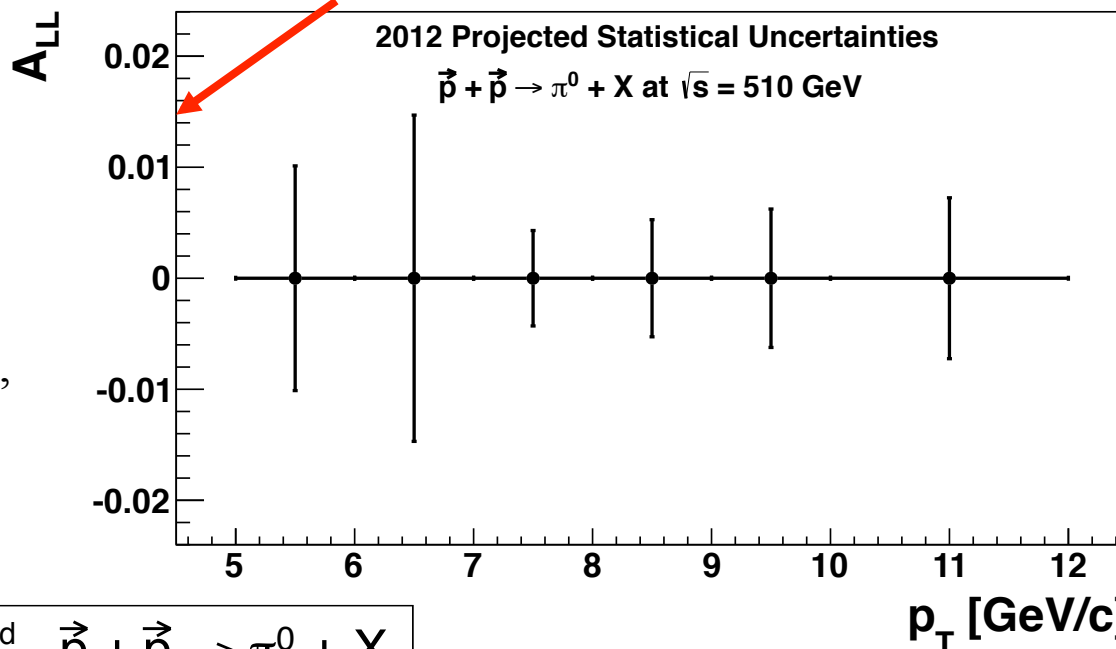


π^0 A_{LL} Prospects in 2012 Dataset



- Work underway at STAR with 2012 dataset (x10 the 2006 luminosity) at intermediate (endcap) pseudorapidity
 - Large improvement in stat. uncertainty projected, as shown

Greatly magnified!



- Higher CoM energy
 - 200 \rightarrow 510 GeV
 - Pushes to lower x gluon



Year	\sqrt{s} (GeV)	Recorded Luminosity for longitudinally / transverse polarized $p+p$ STAR	Recorded Luminosity for longitudinally / transverse polarized $p+p$ PHENIX	$\langle P \rangle$ in %
2006	62.4	-- pb ⁻¹ / 0.2 pb ⁻¹	0.08 pb ⁻¹ / 0.02 pb ⁻¹	48
	200	6.8 pb ⁻¹ / 8.5 pb ⁻¹	7.5 pb ⁻¹ / 2.7 pb ⁻¹	57
2008	200	-- pb ⁻¹ / 7.8 pb ⁻¹	-- pb ⁻¹ / 5.2 pb ⁻¹	45
2009	200	25 pb ⁻¹ / -- pb ⁻¹	16 pb ⁻¹ / -- pb ⁻¹	55
	500	10 pb ⁻¹ / -- pb ⁻¹	14 pb ⁻¹ / -- pb ⁻¹	39
2011	500	12 pb ⁻¹ / 25 pb ⁻¹	18 pb ⁻¹ / -- pb ⁻¹	48
2012	200	-- pb ⁻¹ / 22 pb ⁻¹	-- pb ⁻¹ / 9.7 pb ⁻¹	61/56
	510	82 pb ⁻¹ / -- pb ⁻¹	32 pb ⁻¹ / -- pb ⁻¹	50/53
2013	510	300 pb ⁻¹ / -- pb ⁻¹	155 pb ⁻¹ / -- pb ⁻¹	51/52
2015	200	52 pb ⁻¹ / 52 pb ⁻¹	-- pb ⁻¹ / 60 pb ⁻¹	53/57

Table 1-3: Recorded luminosities for collisions of longitudinally and transverse polarized proton beams at the indicated center-of-mass energies for past RHIC runs since 2006. The PHENIX numbers are for $|vtx| < 30$ cm. The average beam polarization as measured by the Hydrogen-jet polarimeter, if two polarization numbers are given if the average polarization for the two beams was different