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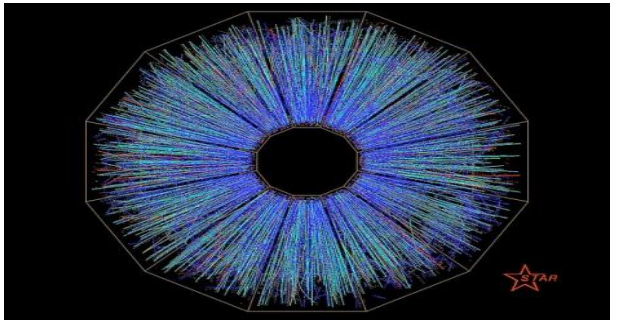


Gluon Polarization in Longitudinally Polarized pp Collisions at STAR

Zilong Chang

For STAR Collaboration

TEXAS A&M UNIVERSITY

Outline

- Introduction
- Inclusive jet measurements
- π^0 measurements
- Di-jet measurements
- Conclusion

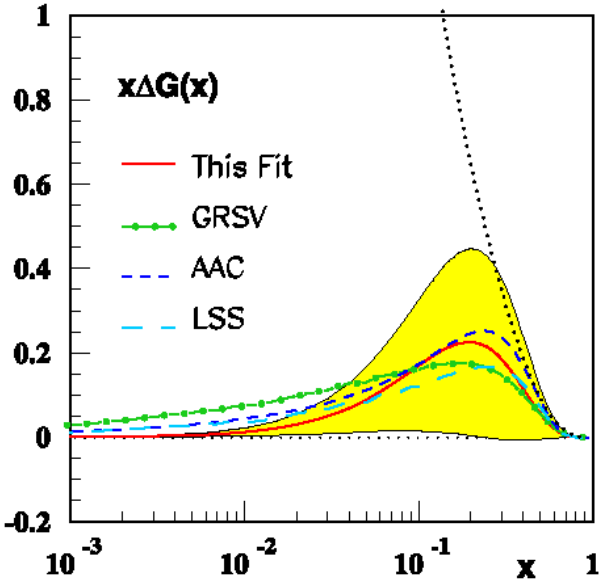
How Gluons Contribute to Proton Spin

Proton Spin:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

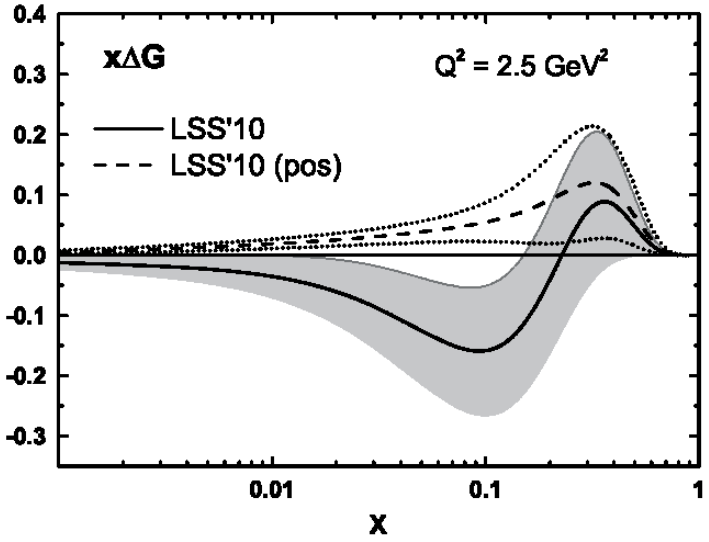
- $\Delta\Sigma$: ~0.3 measured by DIS
- ΔG: poorly determined by DIS and SIDIS
- L_q, L_g: undetermined yet.

➢ **Blümlein & Böttcher, NPB 841, 205 (2010) with fit to DIS data only**



- $\Delta G = 0.46 \pm 0.43$

➢ **Leader et al, PRD 82, 114018 (2010) with fit to DIS and SIDIS data**



- LSS'10p: $\Delta G = 0.32 \pm 0.19$
- LSS'10: $\Delta G = -0.34 \pm 0.46$

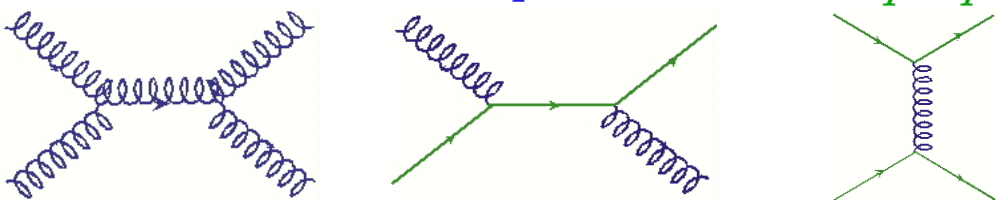
Exploring Gluon Contribution at RHIC

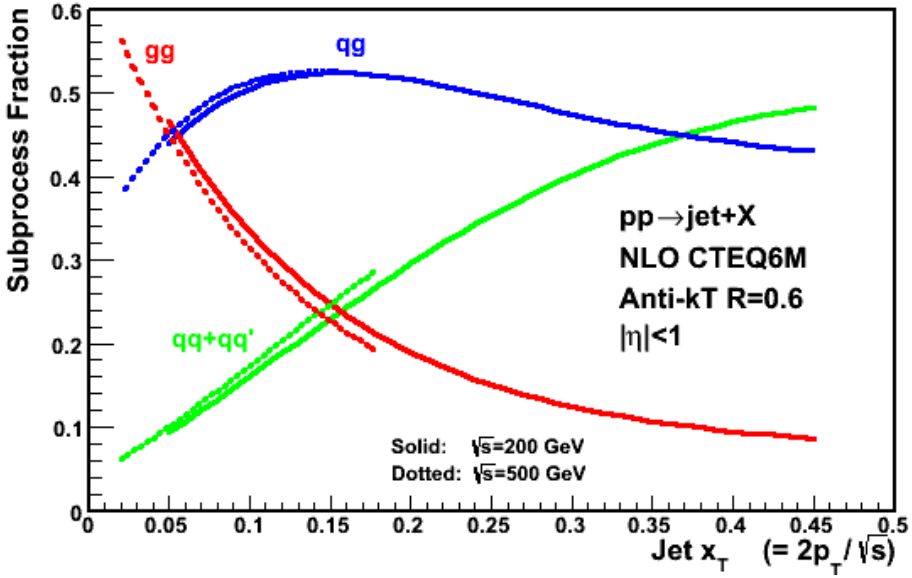
Double spin asymmetry A_{LL}:

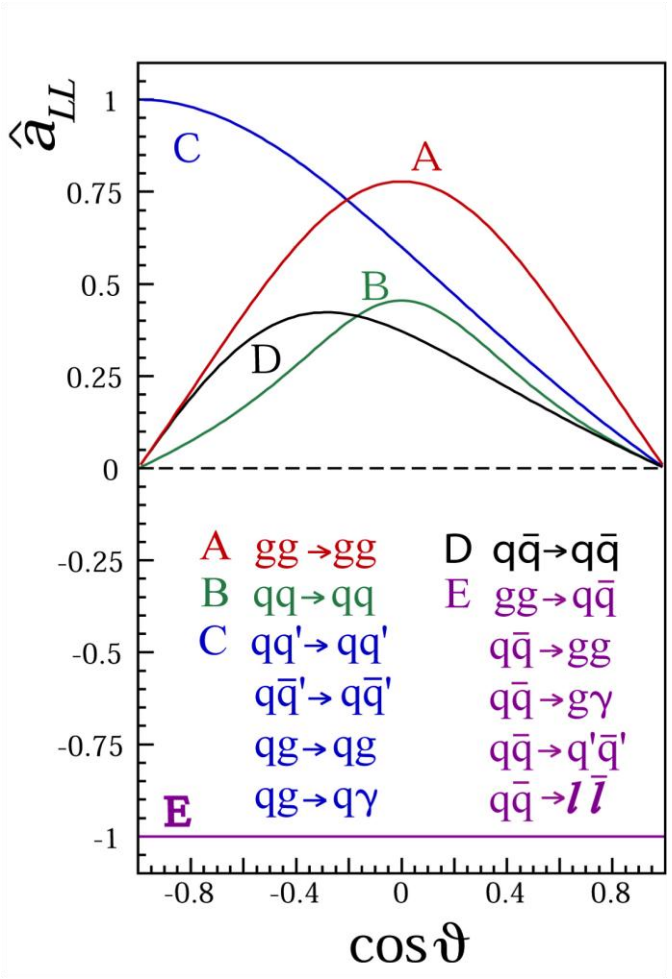
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

Δf: polarized parton distribution function

$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$



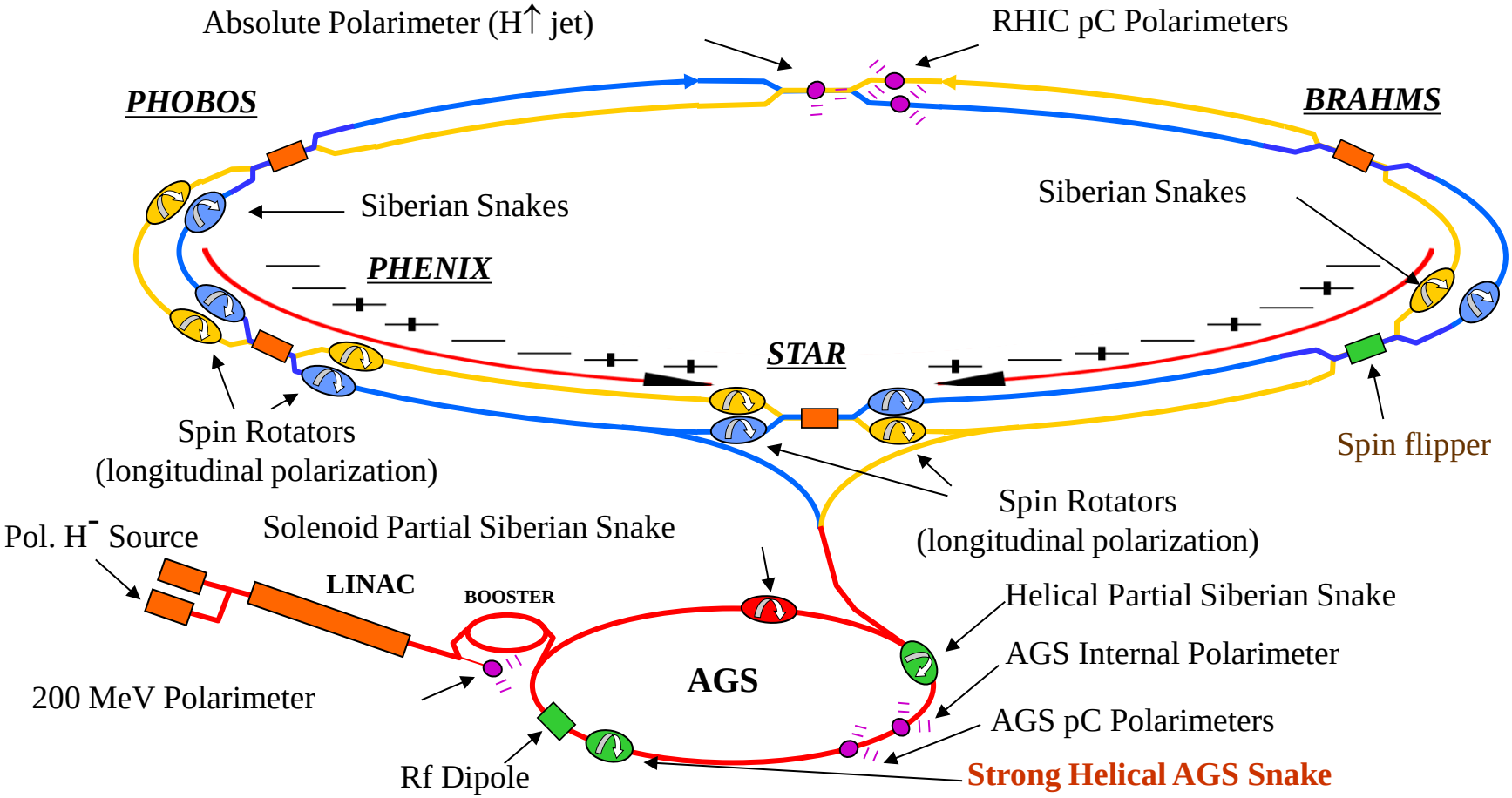




For most RHIC kinematics, gg and qg dominate, making A_{LL} for jets and π^0 sensitive to gluon polarization

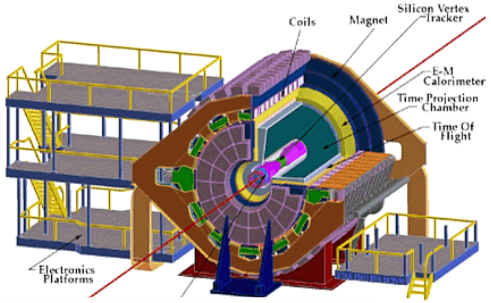
Mukherjee and Vogelsang, PRD.86.094009

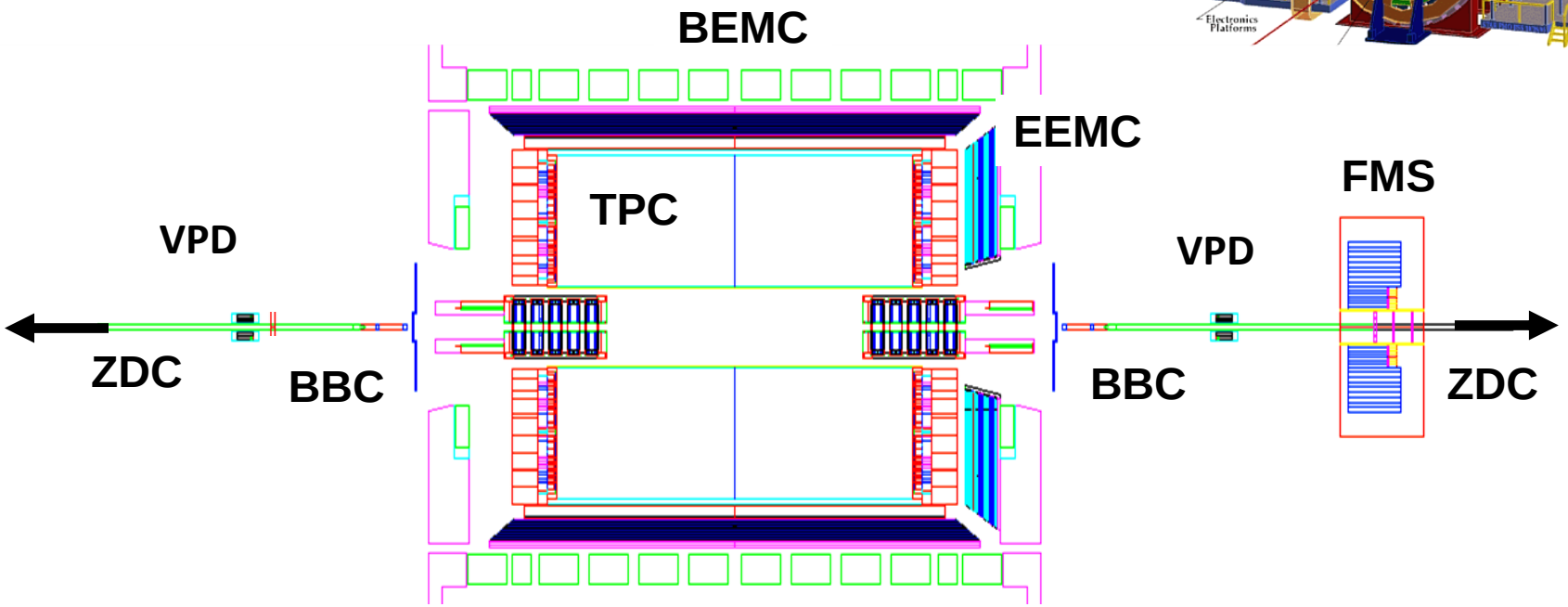
RHIC Facilities



- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

STAR Detectors





- High precision tracking with **T**ime **P**rojection **C**hamber
- High energy resolution with **B**arrel **E**lectro-**M**agnetic **C**alorimeter, **E**ndcap **E**lectro-**M**agnetic **C**alorimeter and **F**orward **M**eson **S**pectrometer
- Additional detectors (**B**eam-**B**eam **C**ounter, **V**ertex **P**osition **D**etector, and **Z**ero **D**egree **C**alorimeter) for relative luminosity and local polarimetry

STAR Experiment Unique Access to Gluon Polarization

Longitudinally polarized pp collisions at 200 GeV and 510 GeV allow both cross section and double spin asymmetry A_{LL} measurements on:

- **Inclusive Jet**

  x down to ~ 0.05 for jets in the mid-rapidity at 200 GeV

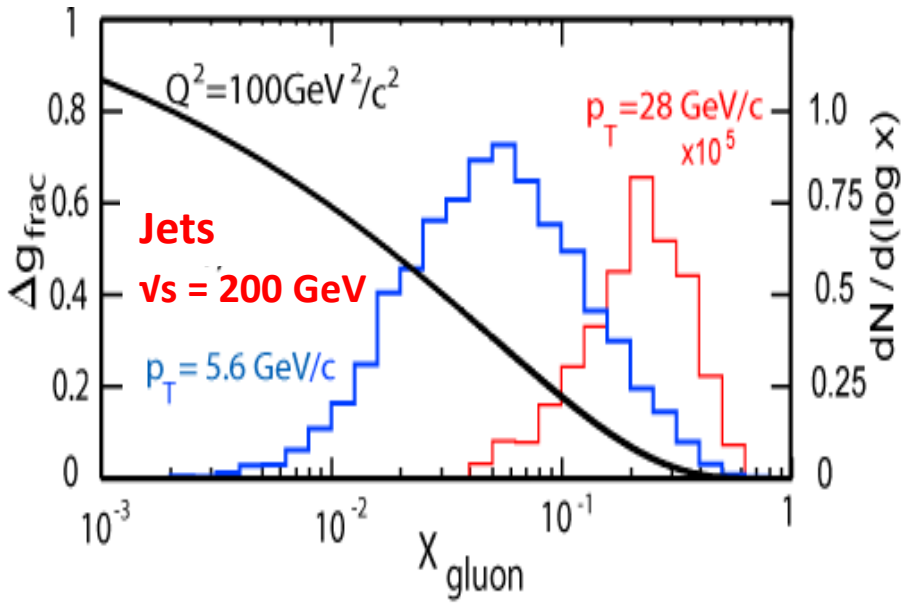
- **Inclusive π^0**

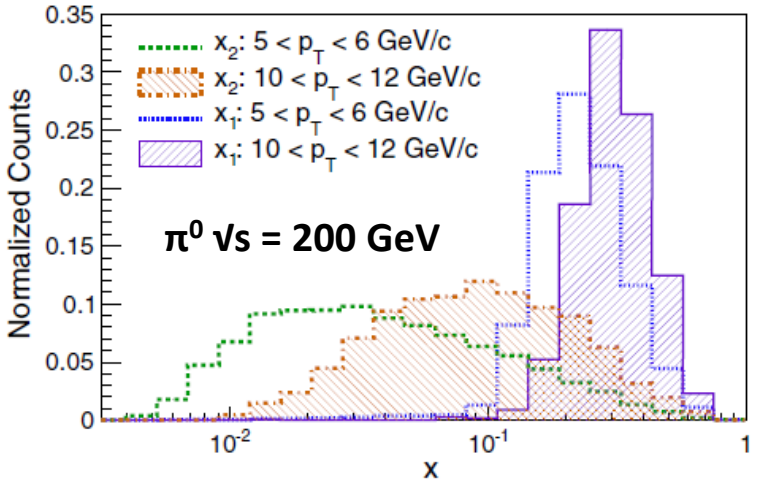
  x down to ~ 0.02 for forward π^0 $0.8 < |\eta| < 2.0$ at 200 GeV

- **Di-jet**

  Correlation unfolds x_1, x_2 at the leading order

Complementary to each other to achieve large x_g coverage of gluon polarization





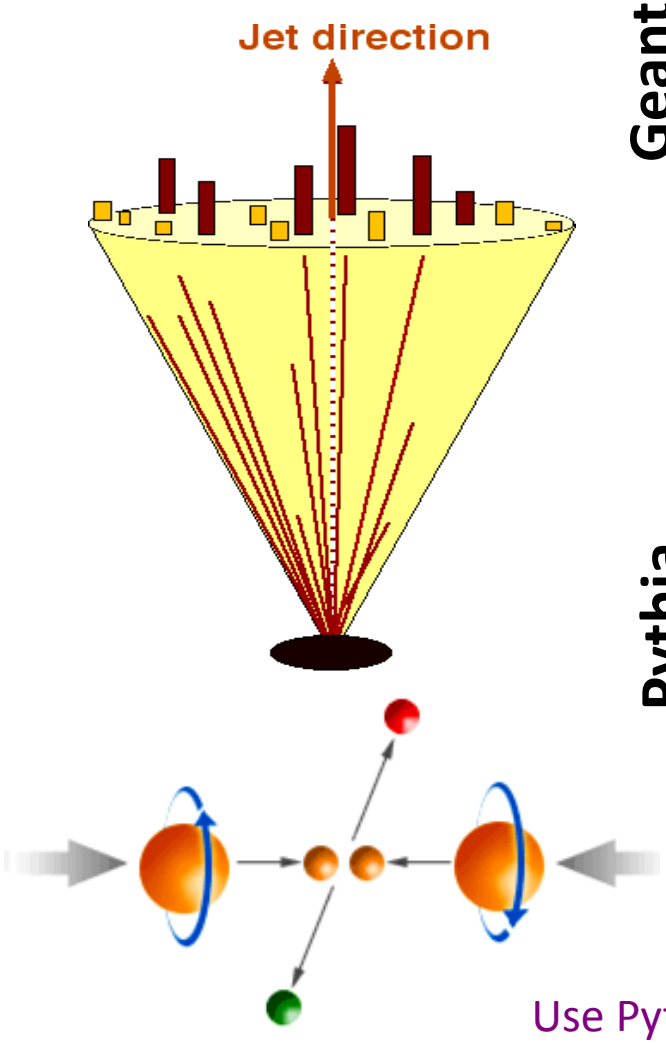
- **Inclusive jet measurements**
- π^0 measurements
- Di-jet measurements

Jet Reconstruction at STAR

Detector

Particle

Parton



Geant

Pythia

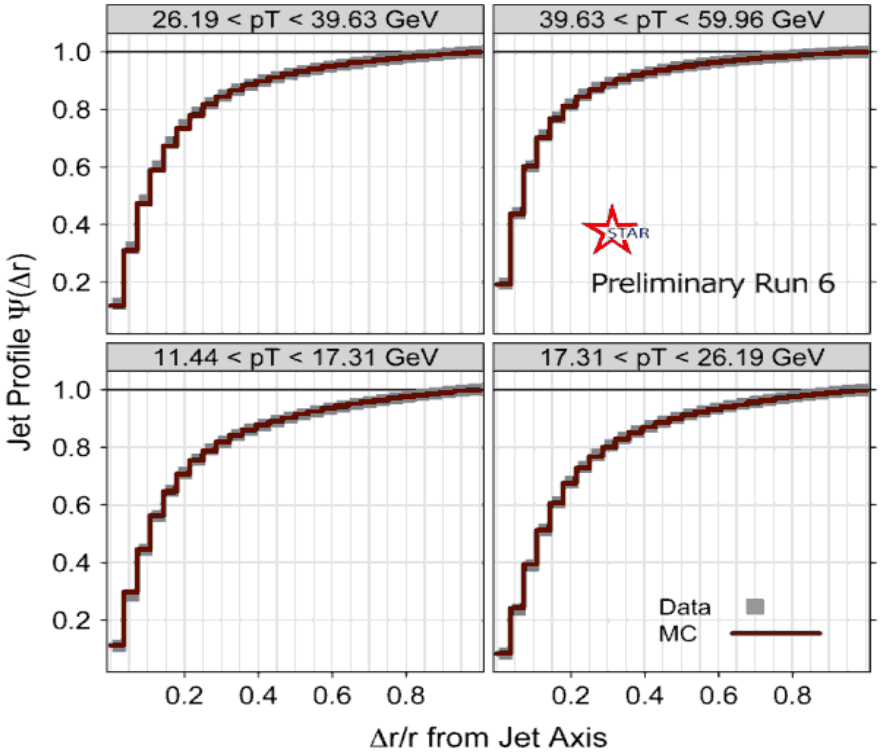
- For 2006 200 GeV data:
  Mid-point cone algorithm
  Adapted from Tevatron II – hep-ex/0005012
  a. Seed energy = 0.5 GeV
  b. Cone radius R = 0.7 in η-ϕ space
  c. Split/merge fraction f = 0.5

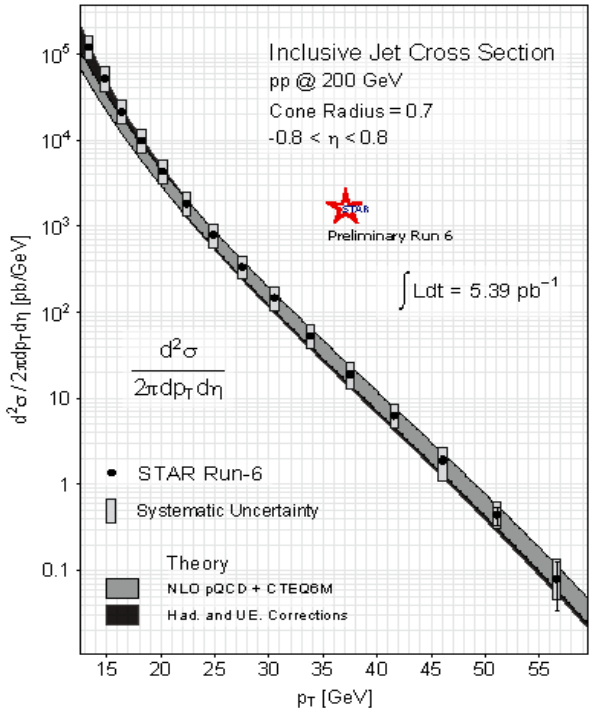
- For 2009 200 GeV data
  Anti-k_T algorithm
  Cacciari, Salam, and Soyez, JHEP 0804, 063
  - Cone radius **R = 0.6**

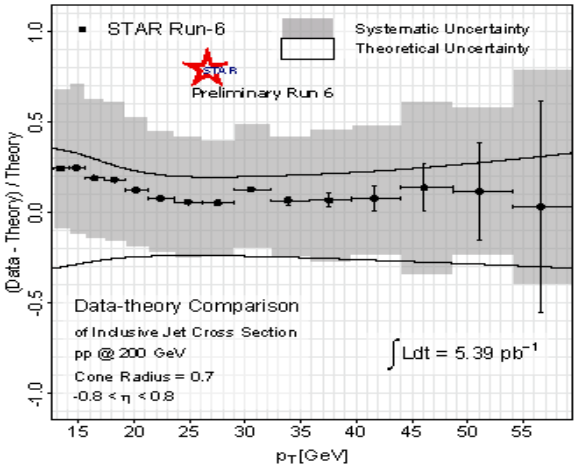
- For 2012 510 GeV data
  Anti-k_T algorithm
  - Cone radius **R = 0.5**

Use Pythia + Geant to quantify detector response
Sjostrand, Mrenna, and Skands, JHEP 05, 026

Inclusive Jet Cross Section from 2006 Data



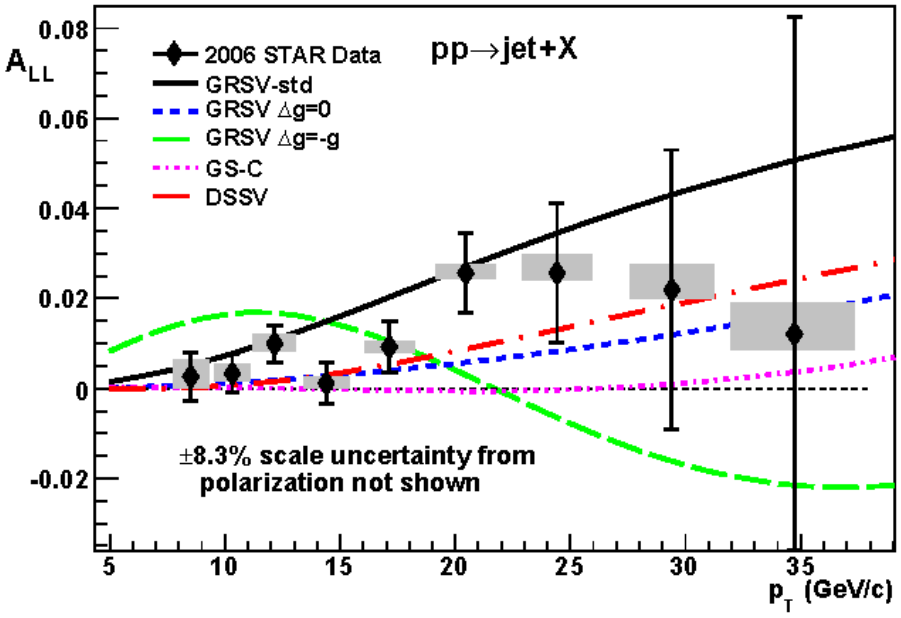


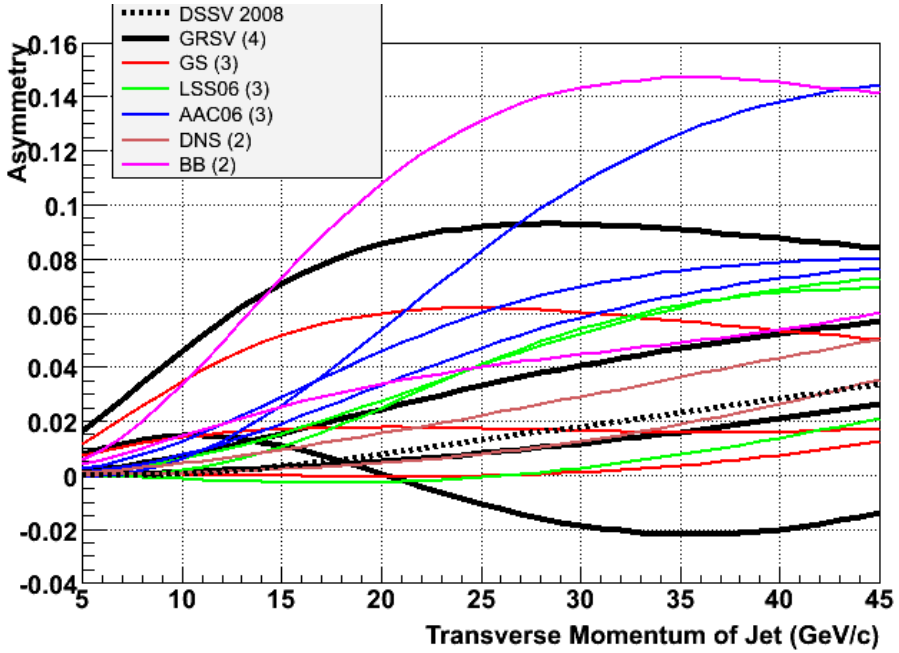


- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
- Jet production is well understood at RHIC energies

Inclusive Jet A_{LL} from 2006 Data

- **PRD 86, 032006**

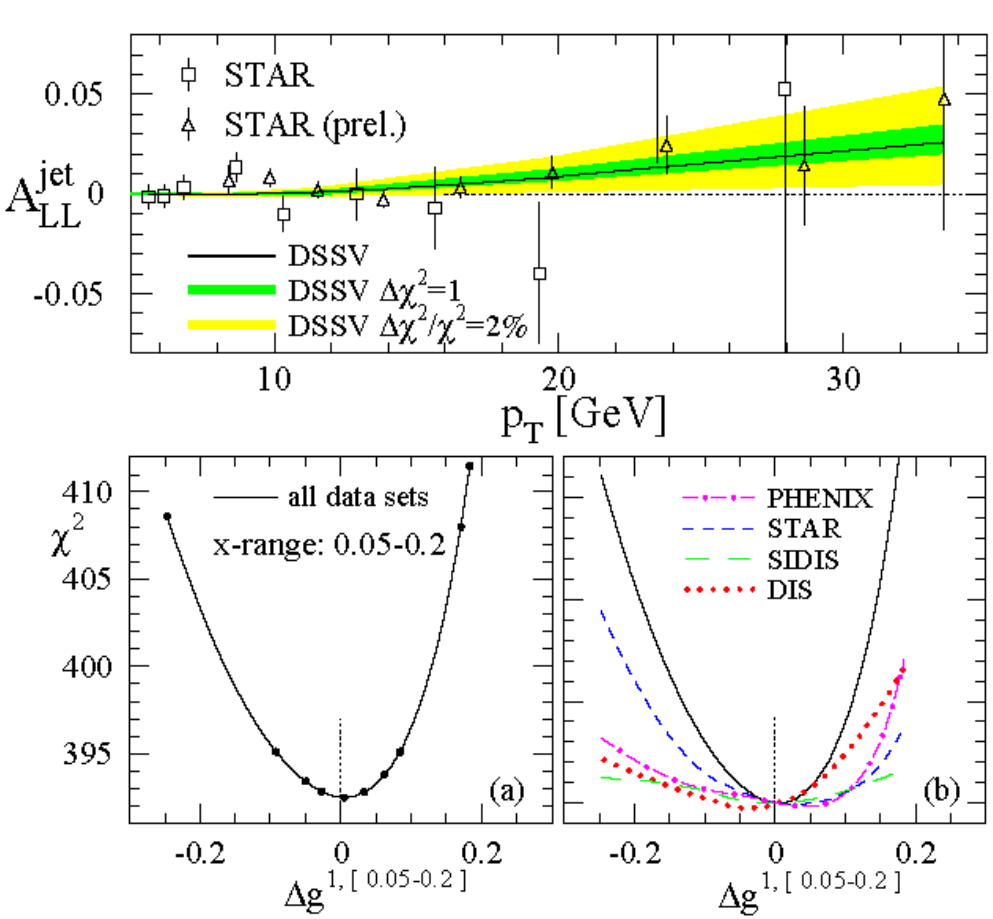


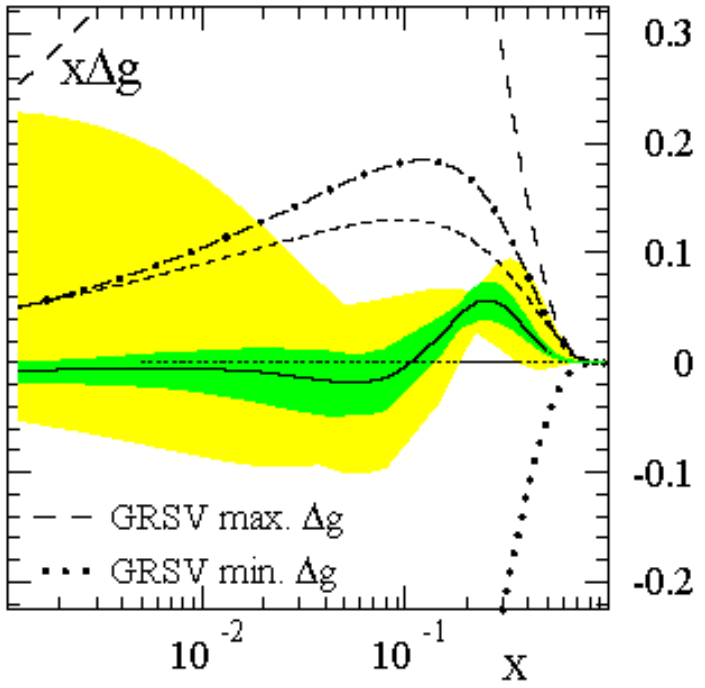


- STAR inclusive jet A_{LL} from 2006 excluded those scenarios that had a large gluon polarization within the accessible x region

DSSV – First Global Analysis with Polarized Jets

- **de Florian et al., PRL 101, 072001**





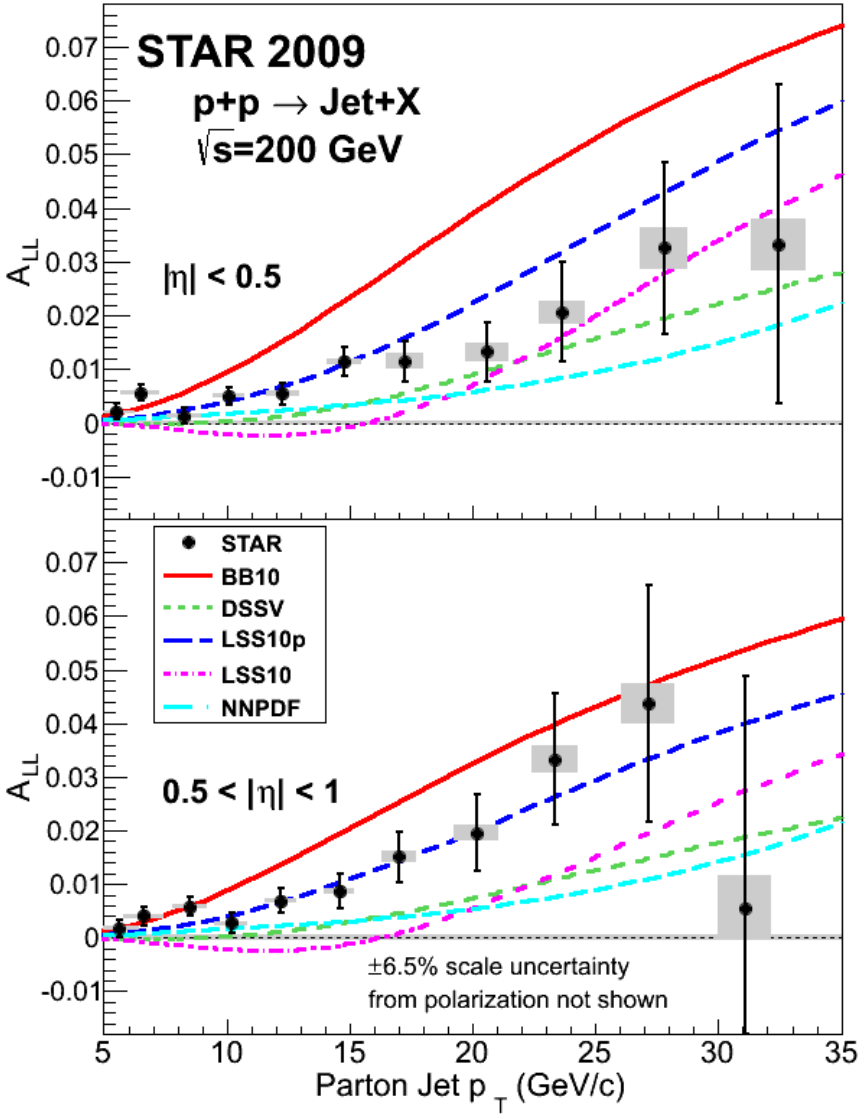
- The first global NLO analysis to include inclusive DIS, SIDIS, and **RHIC pp data** on an equal footing
- Found relatively **small gluon polarization** within the region 0.05 < x < 0.2 that was sampled by the 2006 data

Improvements for 2009

- **2009 jet patch trigger upgrades**
  - Overlapping jet patches and lower E_T threshold improve efficiency and reduce trigger bias
    - Net increase of 37% in jet acceptance
  - Remove beam-beam counter trigger requirement
    - Trigger more efficiently at high jet p_T
    - Measure non-collision background
- **Increased trigger rate and reduced thresholds enabled by DAQ1000**
- **Sampled ~ 4 times the figure-of-merit relative to 2006**
- **Nearly 20-fold increase in event statistics**
- **Improvements in jet reconstruction**
  - Subtract 100% of track momentum from struck tower energy (2009) instead of MIP (2006)
  - Overall jet energy resolution improved from 23% to 18%
  - Switch from mid-point cone to anti-k_T

Inclusive Jet A_{LL} from 2009 Data

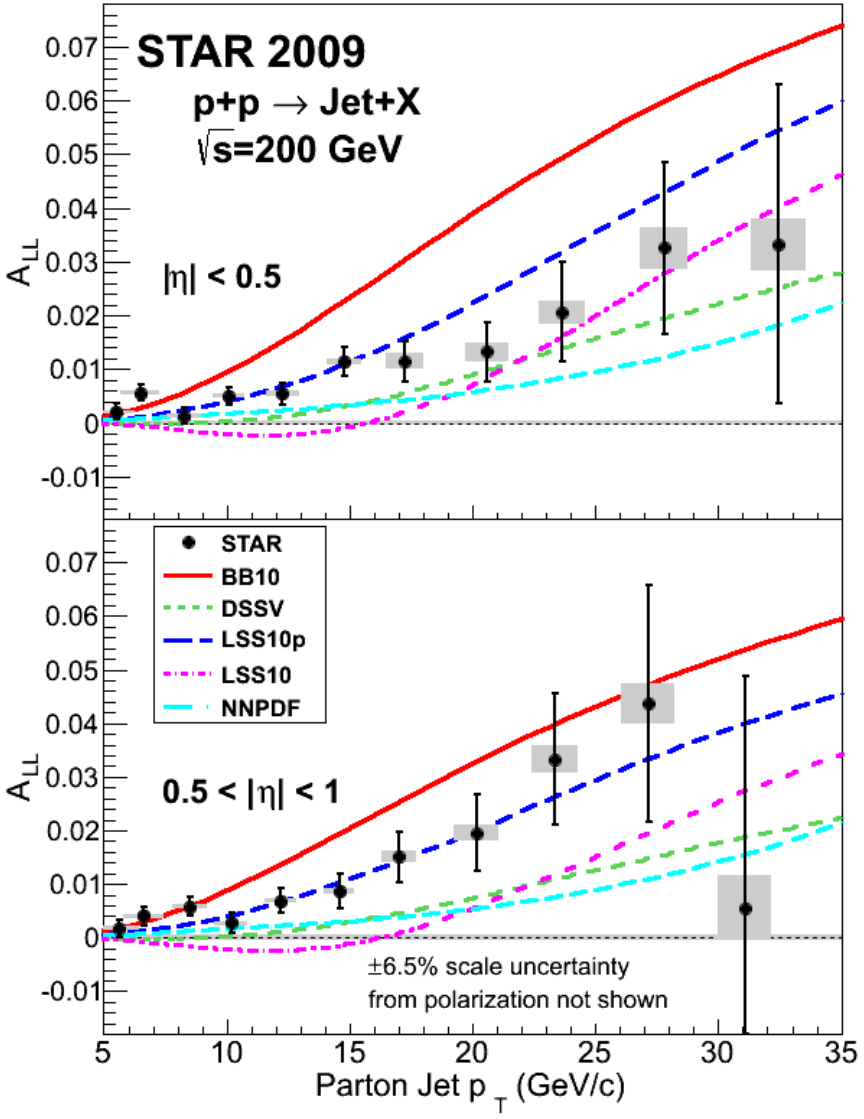
- **arXiv:1405.5134**

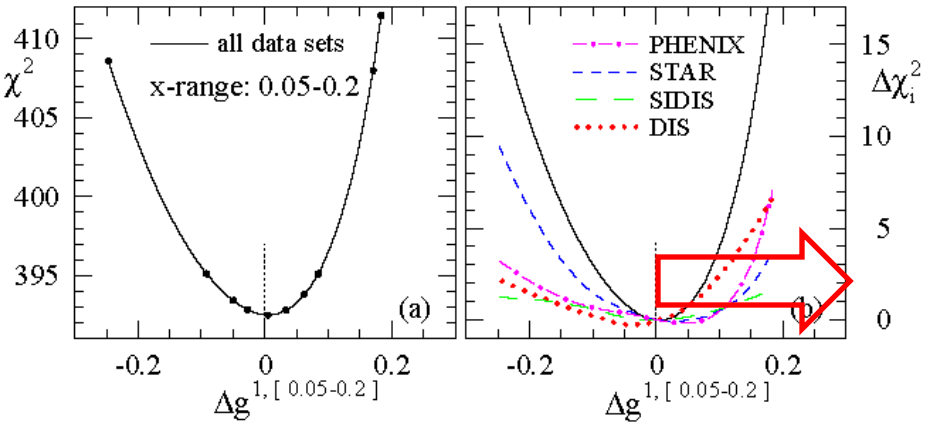


- 2009 STAR inclusive jet A_{LL} measurements are a factor of 3 (high-p_T) to >4 (low-p_T) more precise than 2006
- A_{LL} falls in the middle among several recent polarized PDF fit predictions

Inclusive Jet A_{LL} from 2009 Data

- **arXiv:1405.5134**

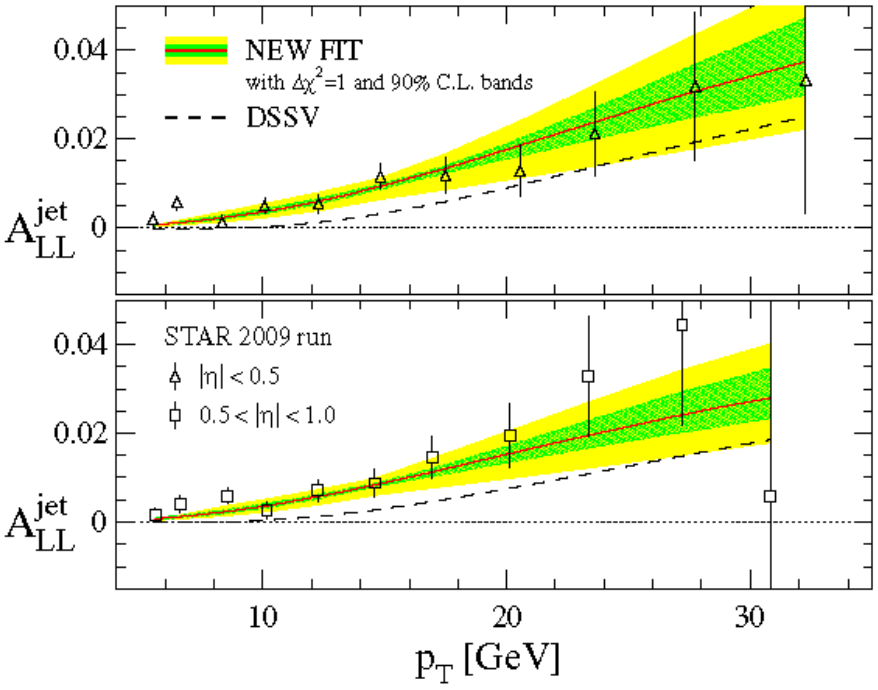




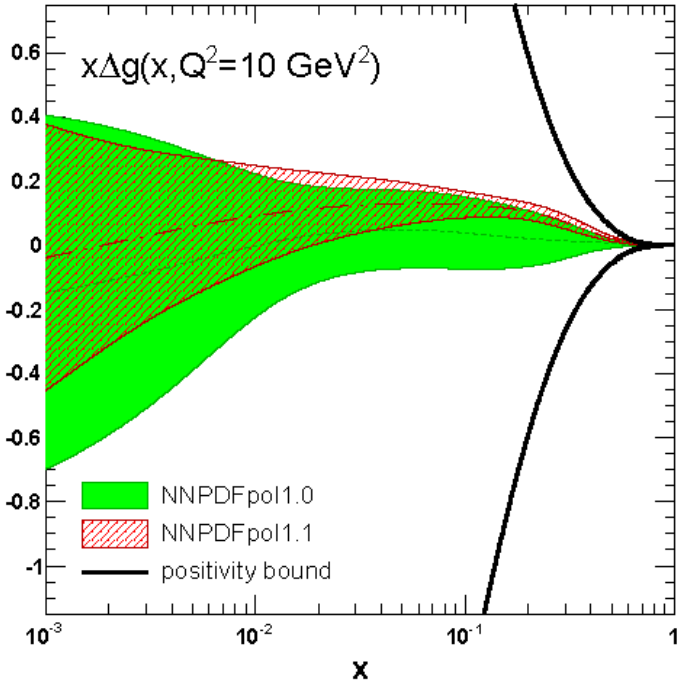
- A_{LL} is somewhat larger than predictions from the **2008 DSSV** fit
  - Points toward positive Δg in the accessible x region

Two New Polarized Distribution Fits

- **DSSV, PRL 113, 012001**



- **NNPDF, NPB 887.276**

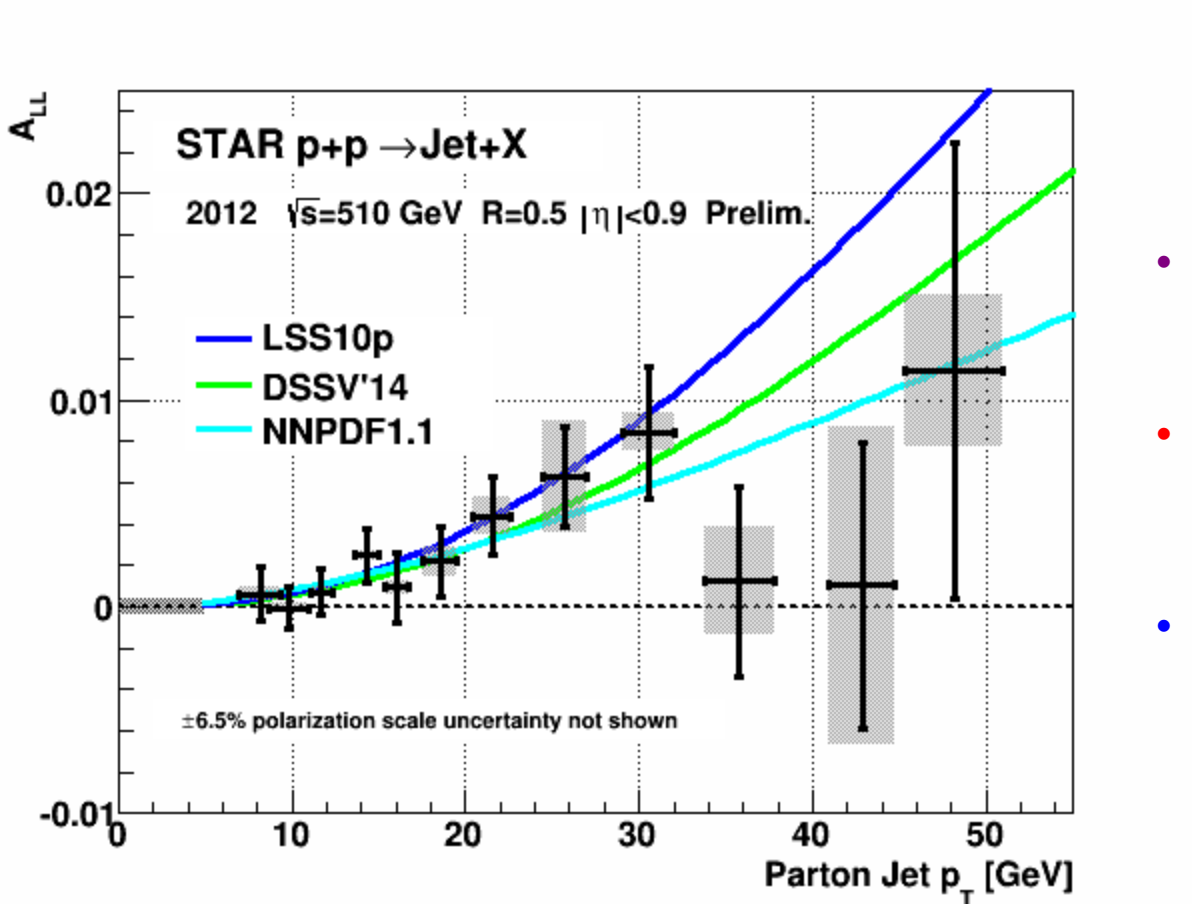


- Both DSSV and NNPDF have released new polarized PDF fits
- Both find 2009 STAR jet A_{LL} results provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region x > 0.05
  - DSSV: $0.19^{+0.06}_{-0.05}$ at 90% C.L. for x > 0.05
  - NNPDF: 0.23 ± 0.07 for 0.05 < x < 0.5

2012 pp 510 GeV Run

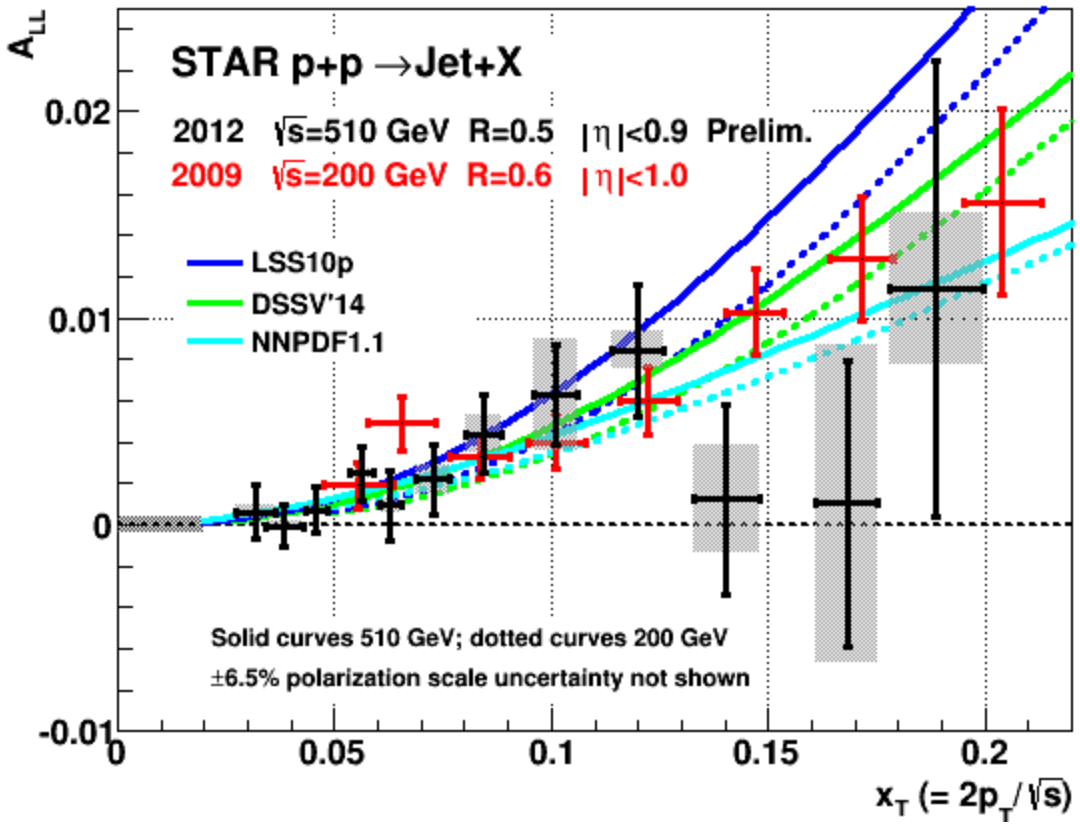
- **510 GeV longitudinally polarized pp collisions**
  - average polarization 53%
  - analysis of data of integrated luminosity 50 pb^{-1}
- **510 GeV provides sensitivity to smaller x_g**
- **Same jet reconstruction method except using smaller cone radius R = 0.5**
  - Reduced pile-up effects
  - Better matching probability from detector jet to parton jet
- **$|\eta| < 0.9$**
  - Narrower vertex distribution in 2012
- **Non-collision background and transverse residual double spin asymmetry found to make negligible contributions**

2012 Inclusive Jet A_{LL}



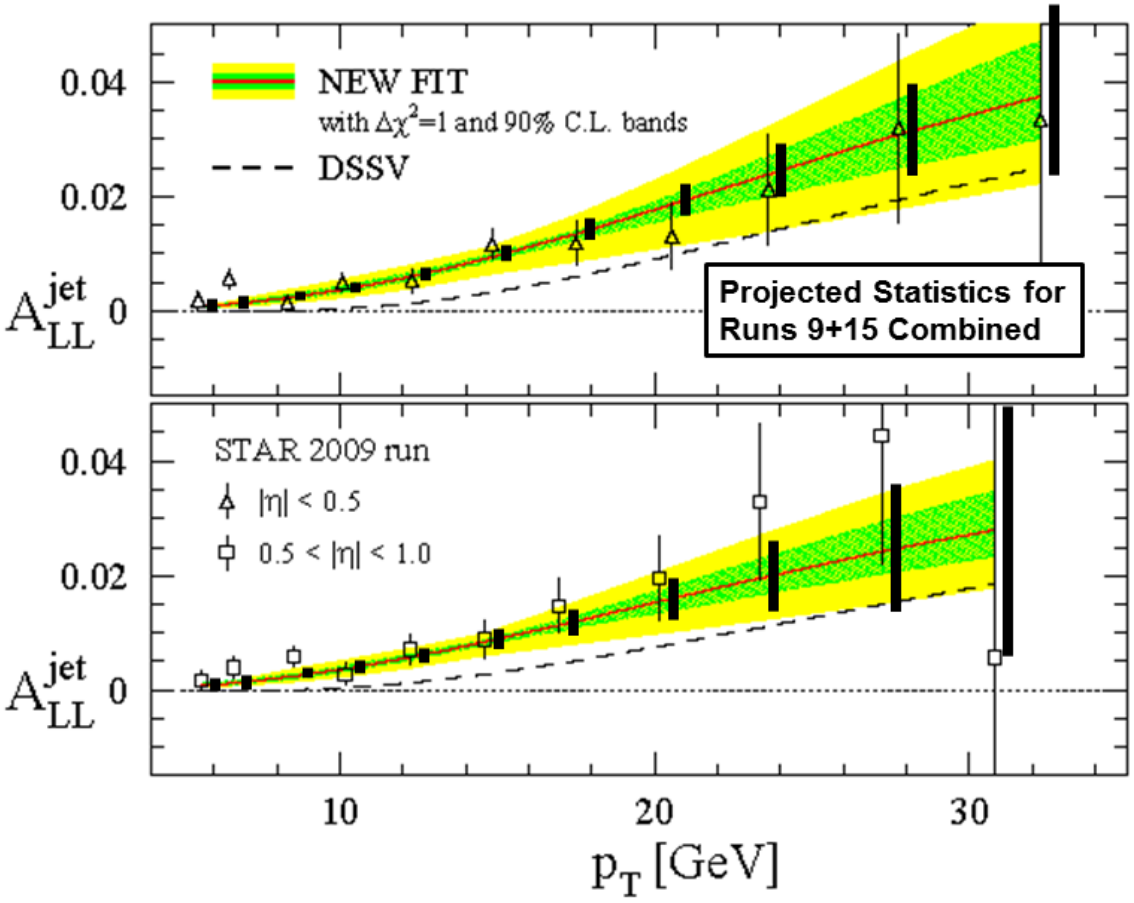
- Trigger and reconstruction bias dominates the systematic uncertainties
- Relative luminosity systematic uncertainty is 4×10^{-4}
- **Results agree well with latest NLO predictions**

2012 Inclusive Jet A_{LL} with 2009 Data



- Higher collision energy extends x_T to lower region
- 510 GeV results agree well with 200 GeV data in the overlapping region

Increased Precision at 200 GeV Coming Soon



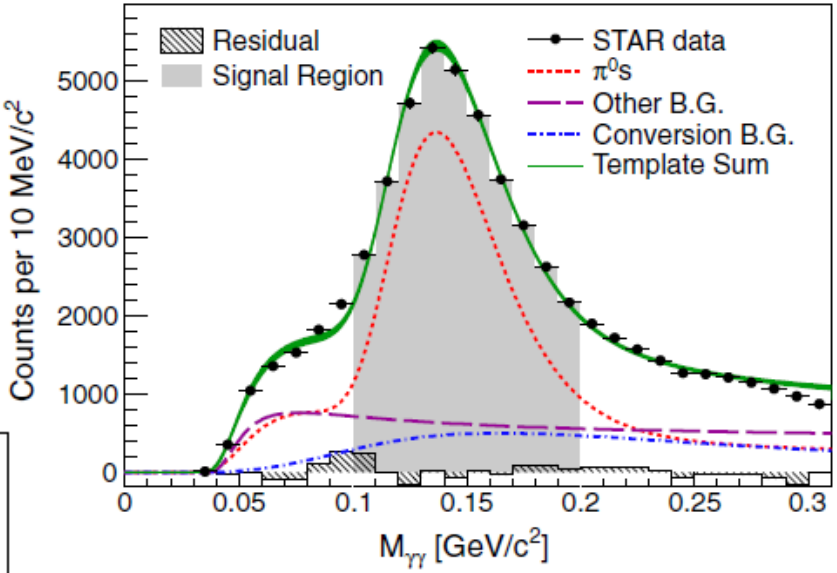
- **STAR also anticipates significant future reductions in the uncertainties for 200 GeV collisions relative to the 2009 results**
  - Hope to record **triple** the existing 200 GeV data during **the 2015 RHIC run**

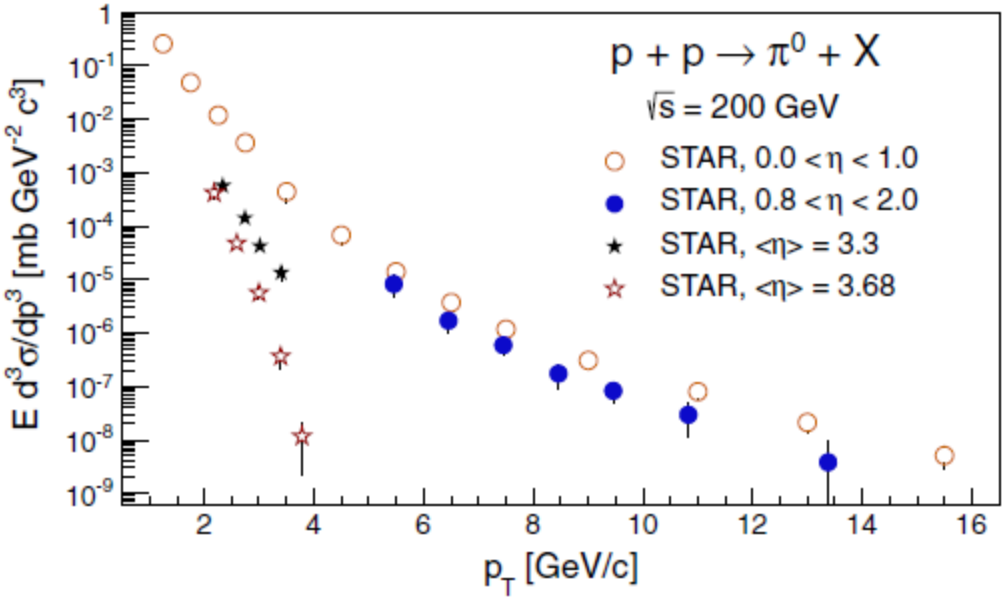
- Inclusive jet measurements
- **π^0 measurements**
- Di-jet measurements

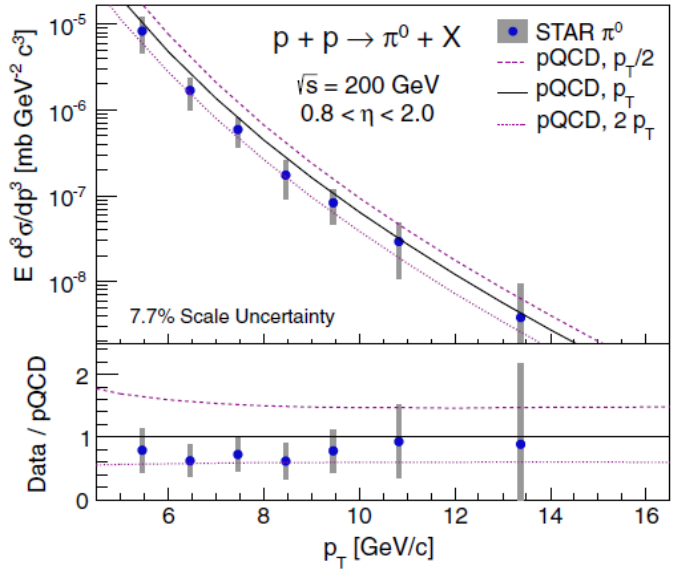
π^0 Measurements at STAR

- **PRD.89.012001**

- Studied π^0 production at **0.8 < η < 2** in 200 GeV pp collisions from 2006 data
- Measure **γ** from π^0 decay in electromagnetic calorimeter



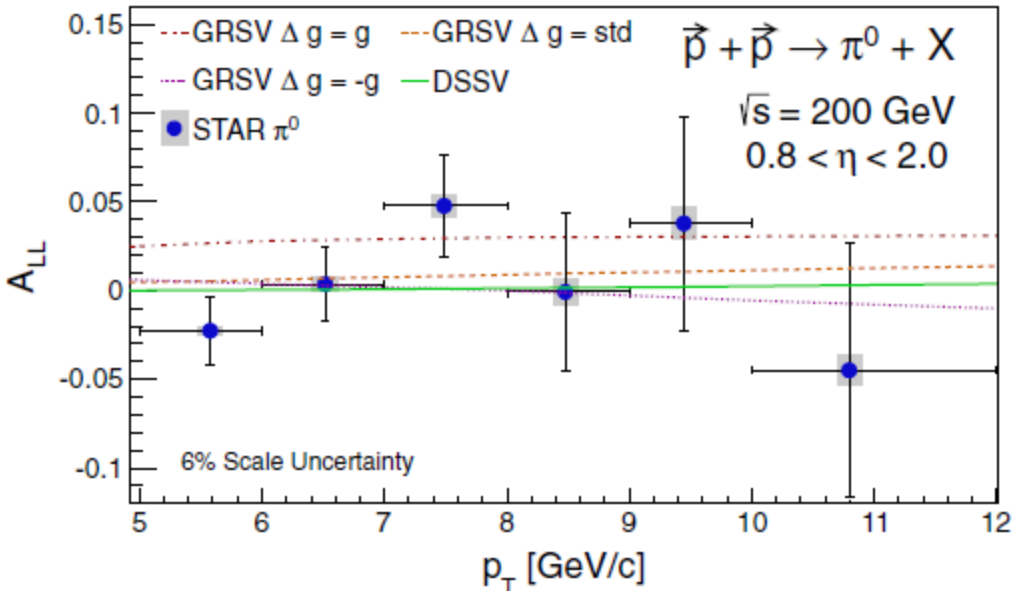




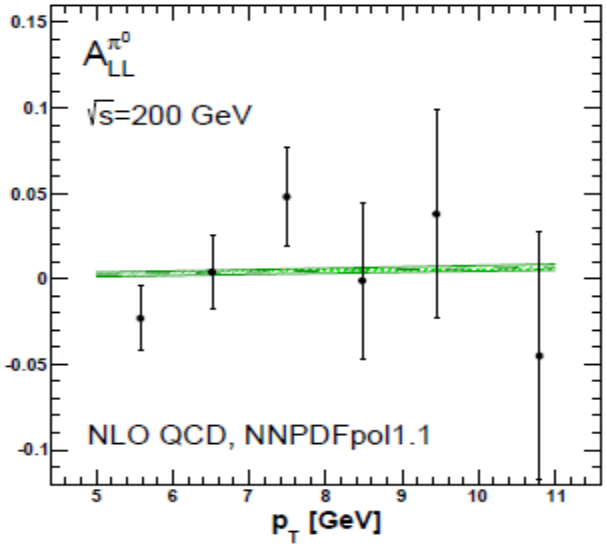
- STAR has measured the inclusive π^0 cross section over a wide pseudo-rapidity range

Inclusive π^0 Double Spin Asymmetry A_{LL}

- **PRD.89.012001**



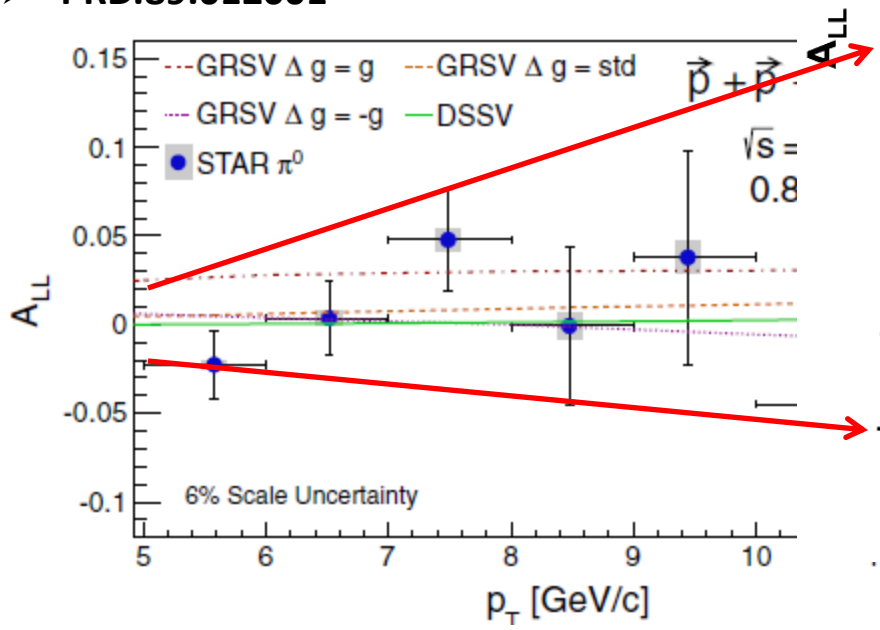
- **NPB 887.276: NNPDFpol1.1 prediction with STAR 200 GeV data (0.8 < η < 2.0)**

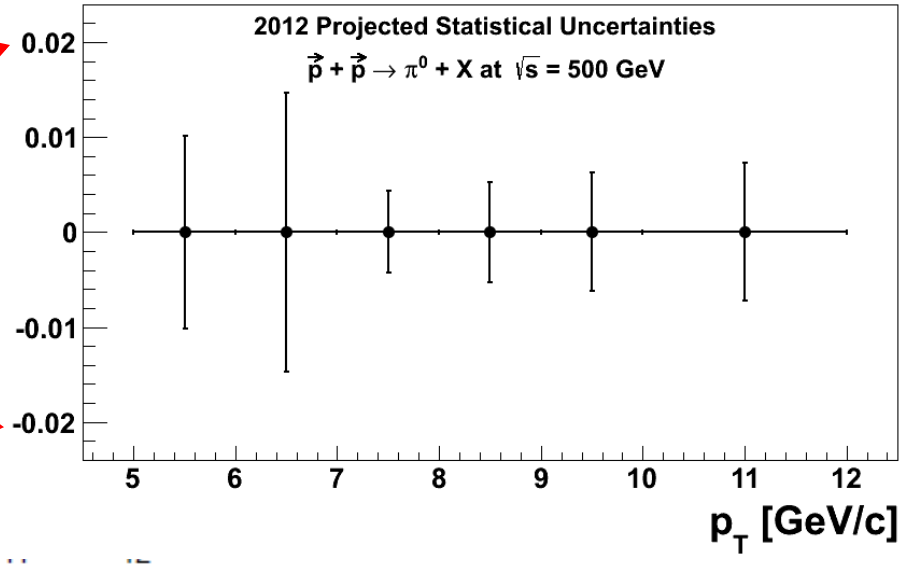


- Needs greater precision to constrain NLO fit

Inclusive π^0 Double Spin Asymmetry A_{LL}

- **PRD.89.012001**





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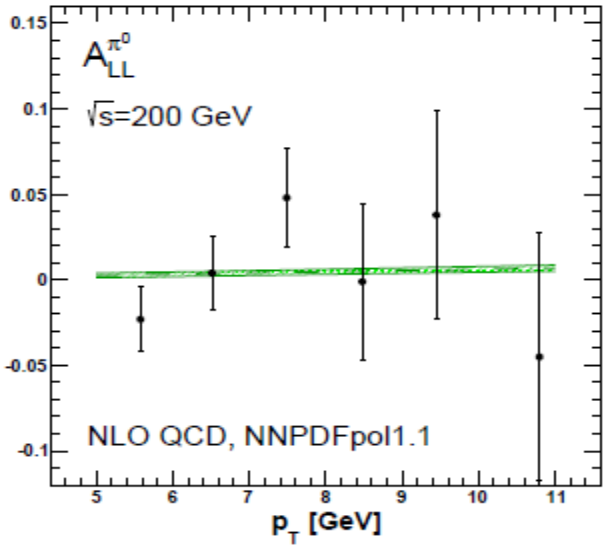
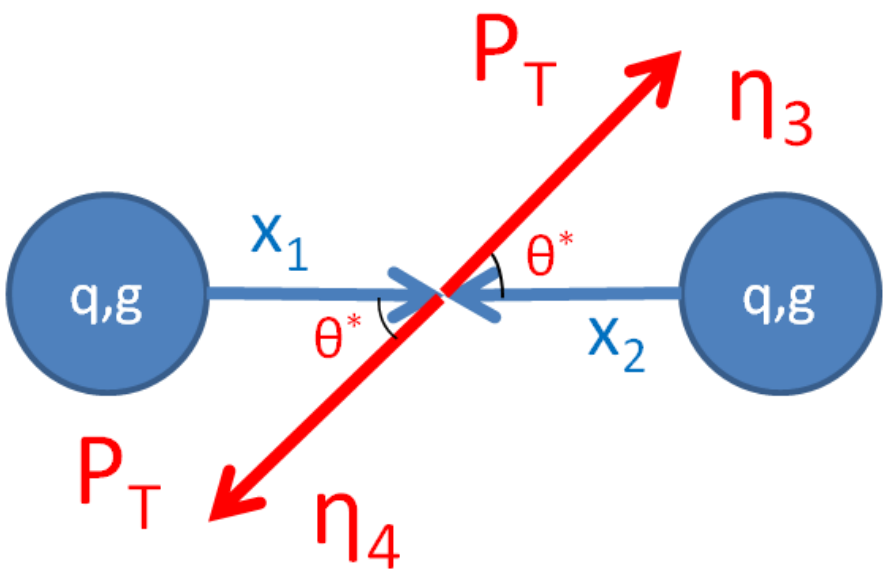


- Will achieve much greater precision with 510 GeV data that are currently being analyzed
  - Higher √*s* also pushes the sensitivity to lower x_g
- **For new results at even further forward rapidity, see the talk by Chris Dilks**

- Inclusive jet measurements
- π^0 measurements
- **Di-jet measurements**

Di-jet Measurements at STAR



$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}\right)$$

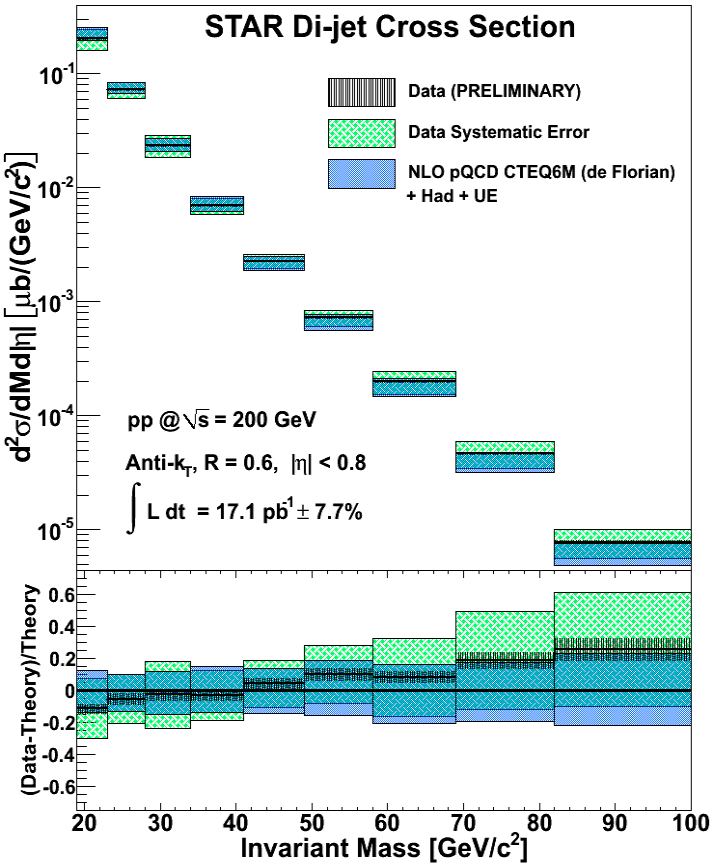
$$M = \sqrt{x_1 x_2 s}$$

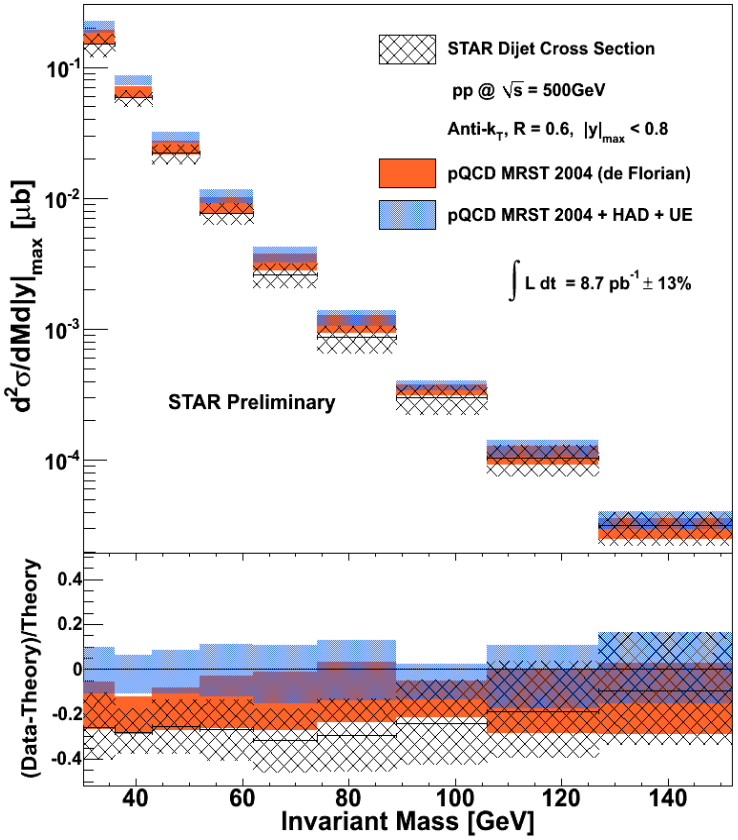
$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$

- Di-jets permit event-by-event calculations of x_1 and x_2 at leading order
- Use the same technique to reconstruct di-jets as the inclusive jets

Di-jet Cross Section at 200 GeV and 500 GeV

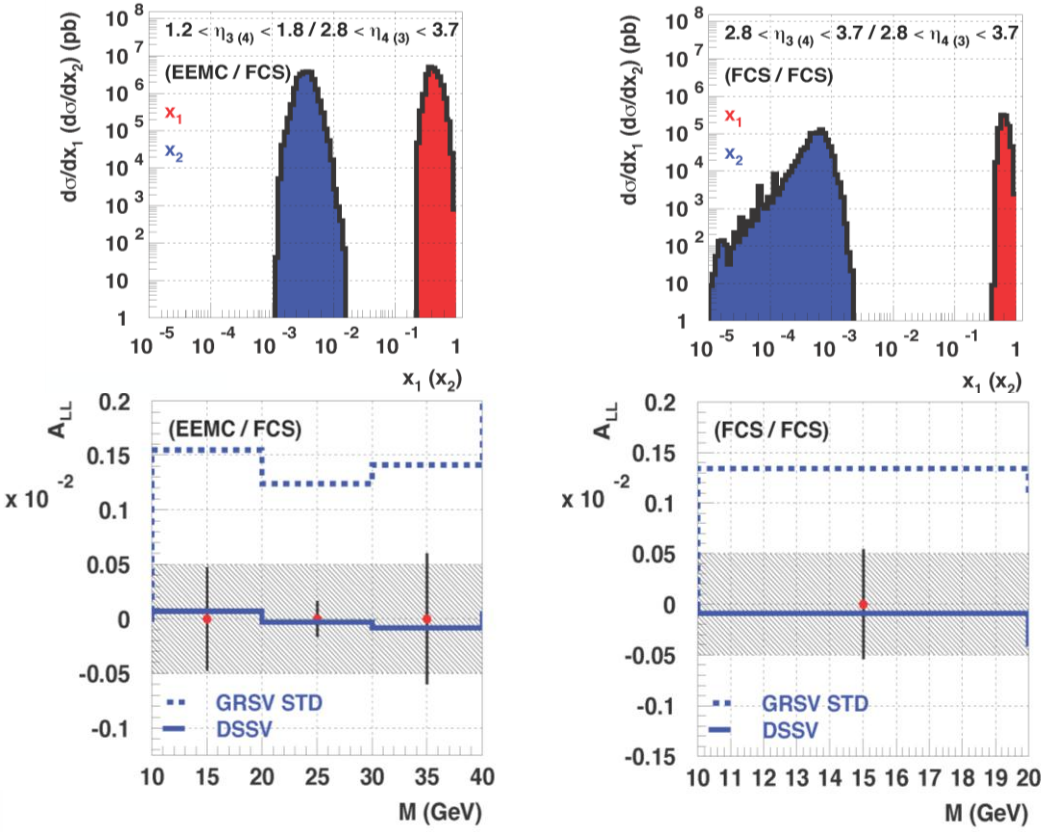




- Di-jet cross section is well-described by NLO pQCD with corrections for hadronization and underlying event
- Will have A_{LL} for 2009 di-jets at 200 GeV soon
- Also analyzing A_{LL} for di-jets at 510 GeV using data from 2012 and 2013

Di-jets in Further Future

- STAR is planning to install **a Forward Calorimeter System** (FCS) in ~2020
- This will enable di-jet measurements with one or both jets in the **forward** region **($2.8 < \eta < 3.7$)**
- FCS will provide information about gluon polarization at
  - **a)** **$x \sim 5 \times 10^{-3}$** with **FCS-EEMC** di-jets
  - **b)** **$x \leq 10^{-3}$** with **FCS-FCS** di-jets



- √s = 500 GeV
- Cone Algorithm, R = 0.7
- $E_{T,3} > 5$ GeV, $E_{T,4} > 8$GeV

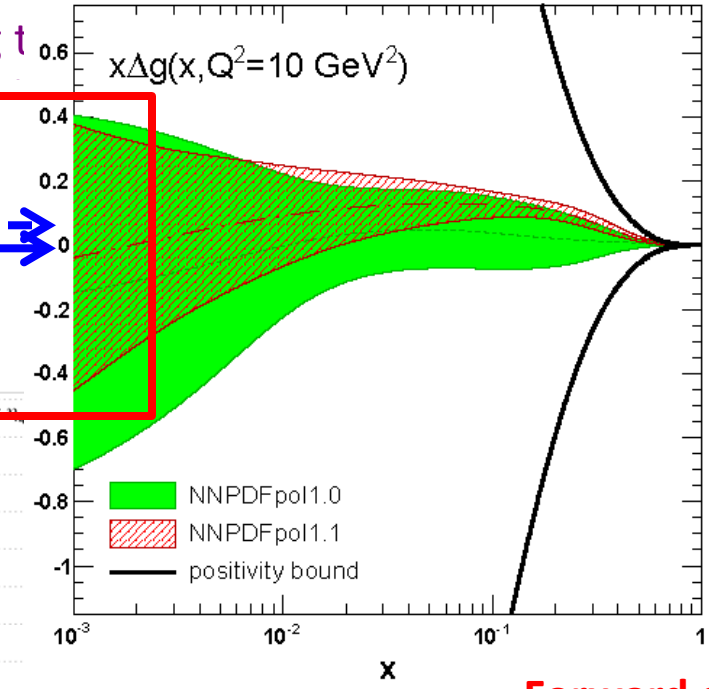
- Assumed integrated luminosity: 1000 pb^{-1}
- Assumed polarization: 60%

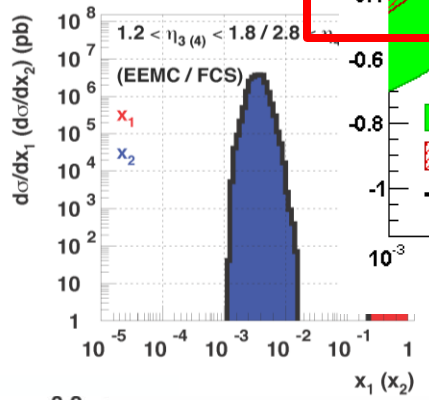
Di-jets in Further Future

- STAR is planning t…em (FCS) in ~2020
  …n jets in the forward region

GRSV ~ 0.05

DSSV ~ −0.01

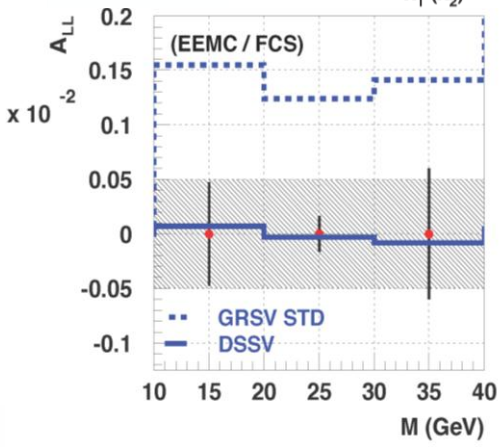


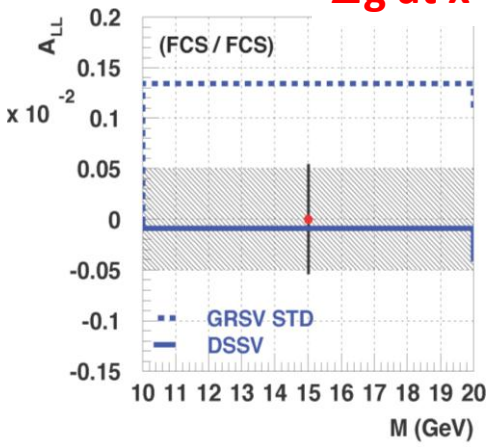


at

- √s = 500 GeV
- Cone Algorithm, R = 0.7
- $E_{T,3} > 5$ GeV, $E_{T,4} > 8$GeV

Forward di-jets will further constrain Δg at x ~ 10^{-3}





- Assumed integrated luminosity: 1000 pb^{-1}
- Assumed polarization: 60%

Conclusion

- STAR **inclusive jet, π^0, and di-jet A_{LL}** measurements are **unique** to explore gluon contribution to proton spin
- STAR 2009 inclusive jet A_{LL} results provide the first experimental evidence for **positive gluon polarization** in the RHIC range
- STAR 2012 510 GeV inclusive jet A_{LL} results extend measurements at **lower x_g** and **agree well** with STAR 2009 200 GeV data in the overlapping x_T range

- More results coming up in the near future
  - **First measurements:**
    - Di-jet A_{LL} at 200 GeV (2009)
    - Di-jet A_{LL} at 510 GeV (2012 and 2013)
    - Inclusive π^0 A_{LL} at 510 GeV (2012)
  - **Improved precision for:**
    - Inclusive jet A_{LL} at 200 GeV (2015)
- In the further future, STAR will use **forward di-jets** to explore gluon polarization at very **low x_g (~10^{-3})**