

# 20th Particles & Nuclei International Conference

25-29 August 2014  
Hamburg, Germany



## Exploring Gluon and Antiquark Polarization in the Proton with **STAR**

**Carl Gagliardi**

Texas A&M University

for the

 **STAR Collaboration**

### Outline

- Introduction
- Jets and gluon polarization
- W's and antiquark polarization

# Partonic origin of the proton spin?

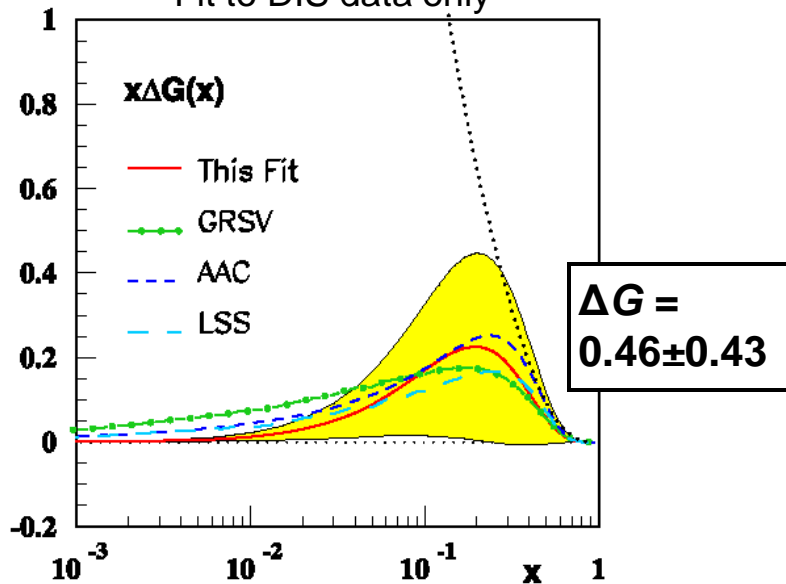
$$S_z = \frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + \langle L_z \rangle$$

Polarized DIS:  $\sim 0.3$

Poorly constrained by DIS

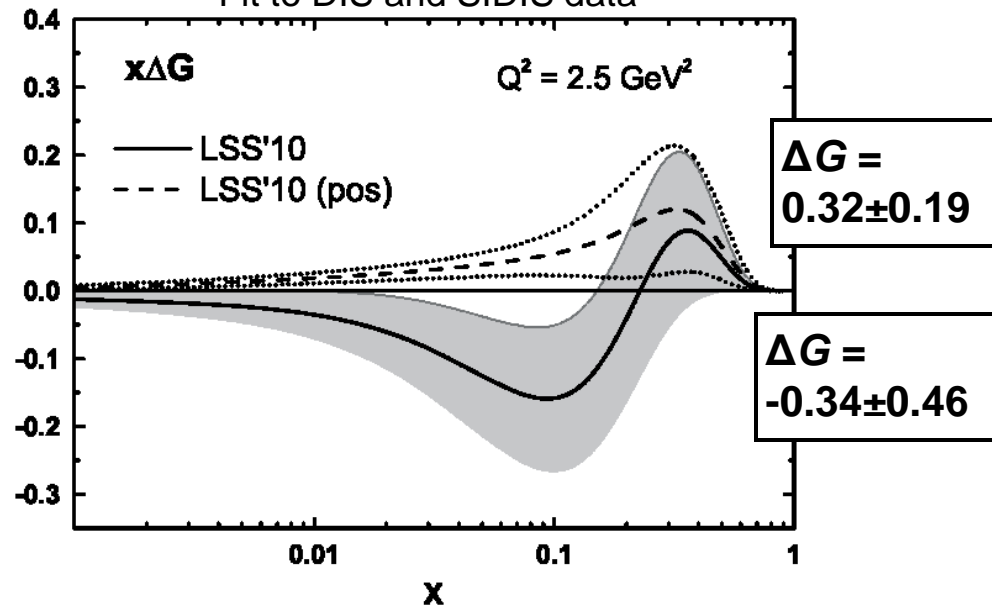
Blümlein & Böttcher, NPB 841, 205 (2010)

Fit to DIS data only



Leader et al, PRD 82, 114018 (2010)

Fit to DIS and SIDIS data

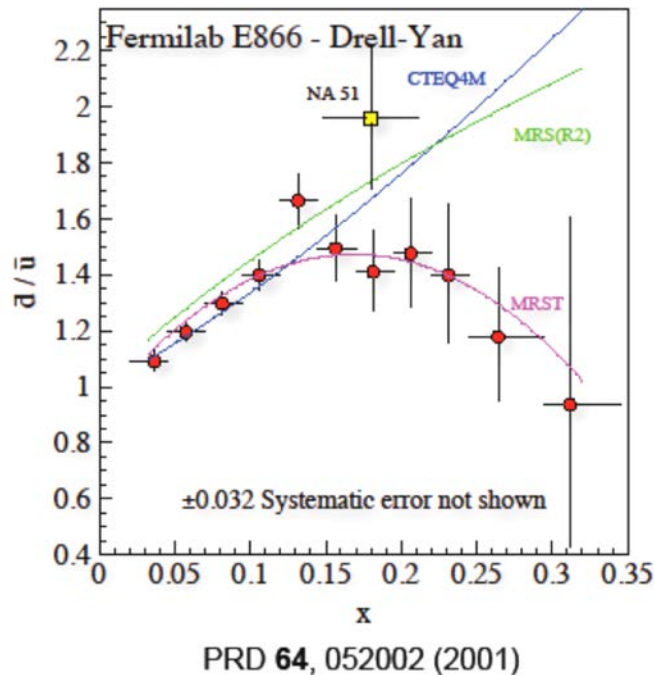


- Measuring the **gluon polarization distribution** is a **primary goal of the RHIC spin program**

# Why is $\Delta\Sigma$ so small?

$$\Delta\Sigma = \int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}) dx$$

- Polarized inclusive DIS data measure  $\Delta u + \Delta\bar{u}$  and  $\Delta d + \Delta\bar{d}$
- Polarized semi-inclusive DIS data provide flavor separation, but uncertainties remain large

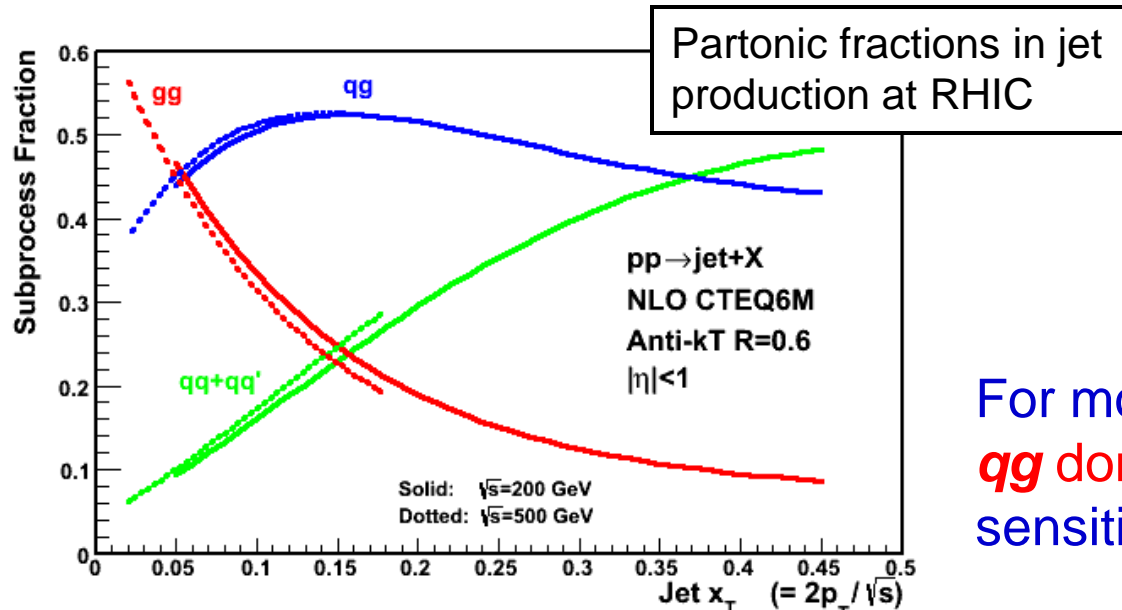
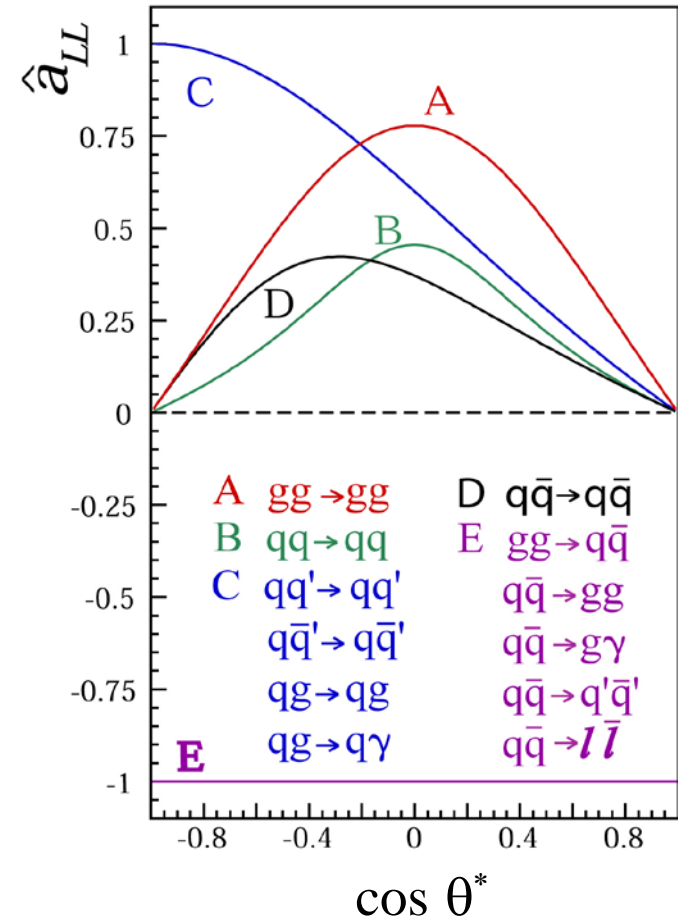
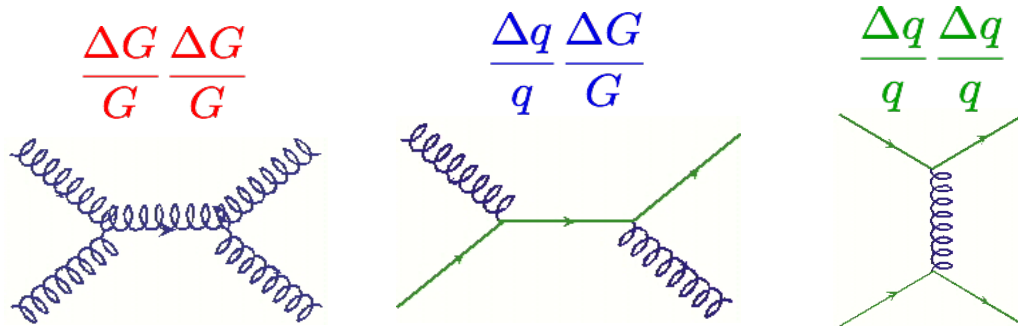


- FNAL E866 found surprising structure in the unpolarized antiquark distributions
- **Might the polarized antiquark distributions also contain surprises?**
- Measuring the **antiquark polarization distributions** is another primary goal of the RHIC spin program

# Exploring gluon polarization at RHIC

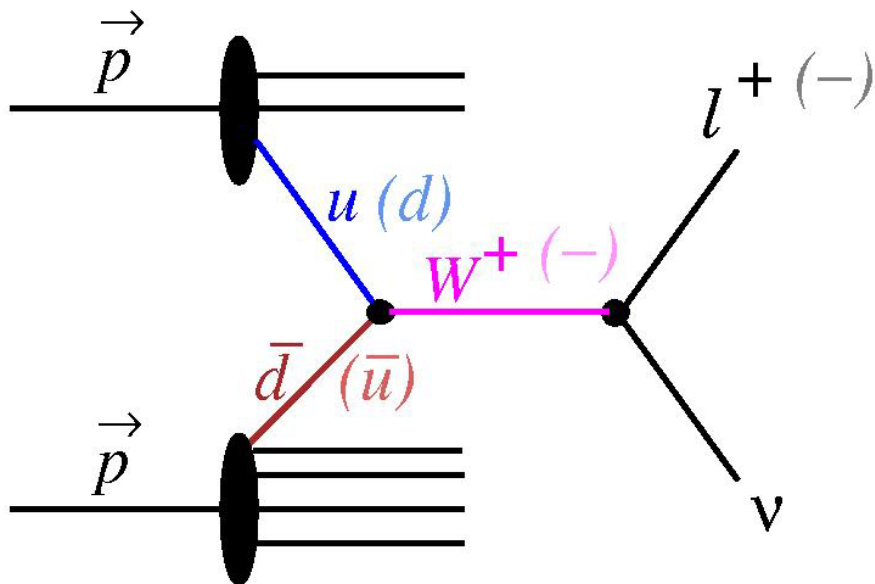
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

$\Delta f$ : polarized parton distribution functions



For most RHIC kinematics, **gg** and **qg** dominate, making  $A_{LL}$  for jets sensitive to gluon polarization.

# Exploring antiquark polarization at RHIC



$$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$$

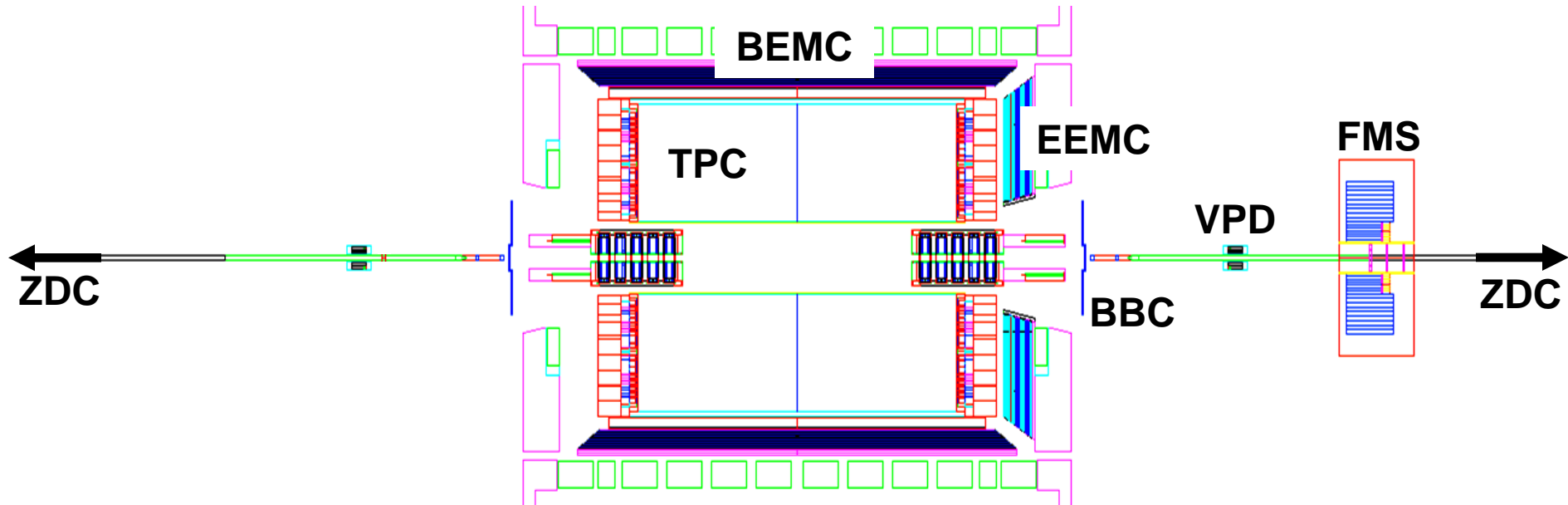
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

- $W$ 's only couple to left-handed quarks and right-handed antiquarks
  - Perfect spin separation!
- Detect  $W$ 's through  $e^-$  and  $e^+$  decay channels

The **parity-violating single-spin asymmetry,  $A_L$** , for  $W$  production provides **direct information about antiquark polarization**

$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2) \quad A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$

# STAR detector side view

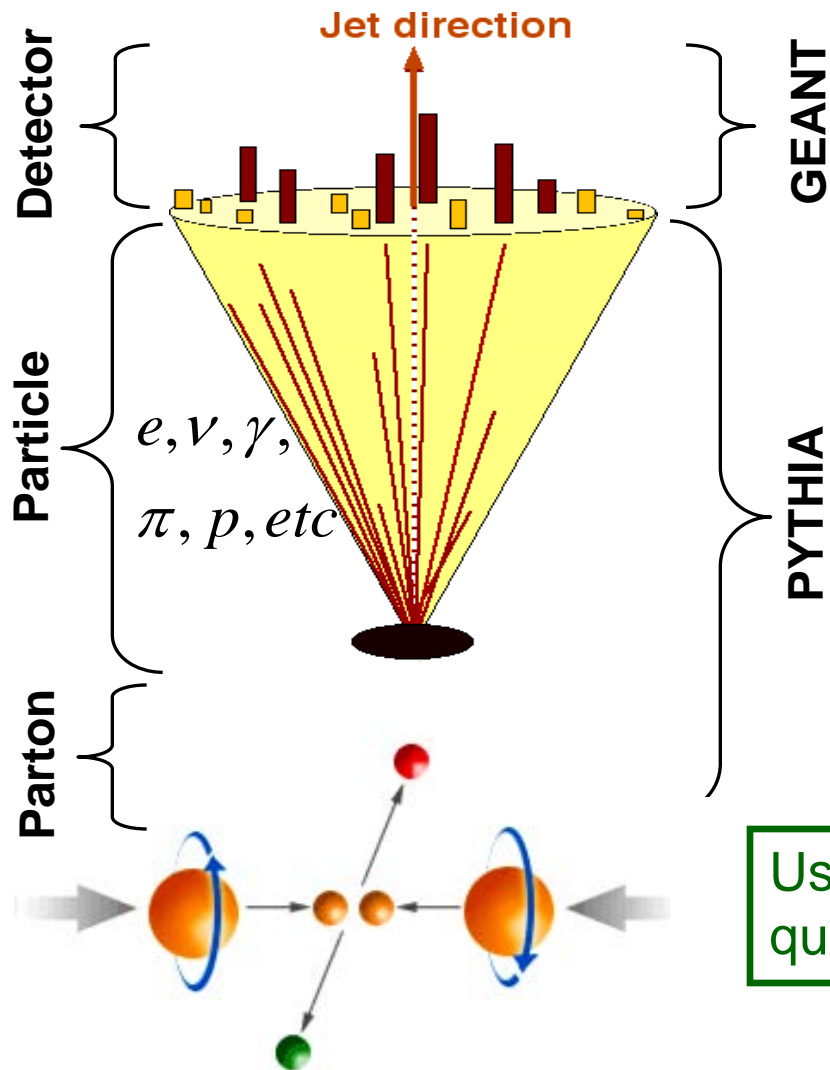


- High precision tracking with the TPC
- Electromagnetic calorimetry with the BEMC and EEMC (and FMS)
- Additional detectors (BBC, VPD, ZDC) for relative luminosity and local polarimetry

# Jet reconstruction in *STAR*

Data jets

MC jets



For 2006 data

**Midpoint cone algorithm**

Adapted from Tevatron II - hep-ex/0005012

- Seed energy = 0.5 GeV
- Cone radius  $R = 0.7$  in  $\eta$ - $\phi$  space
- Split/merge fraction  $f = 0.5$

For 2009 data and beyond

**Anti- $k_T$  algorithm**

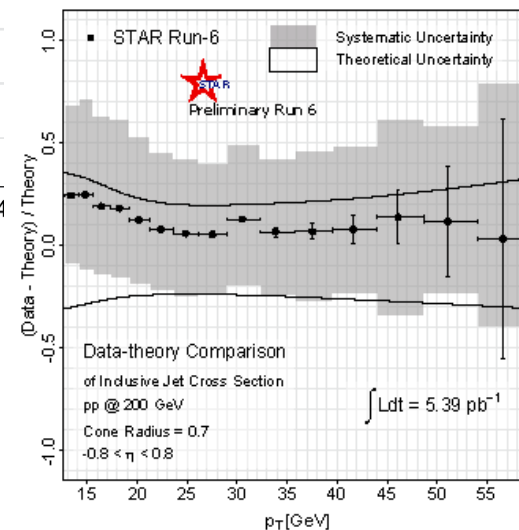
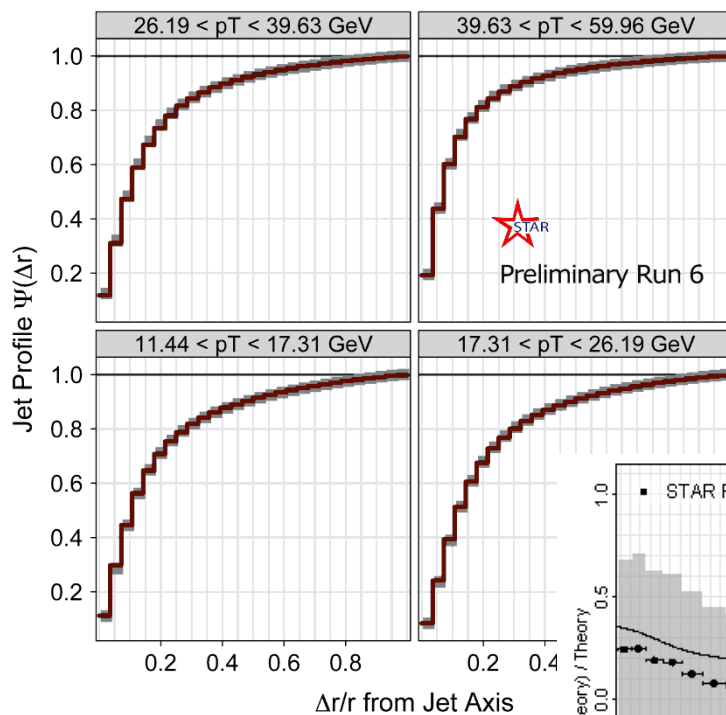
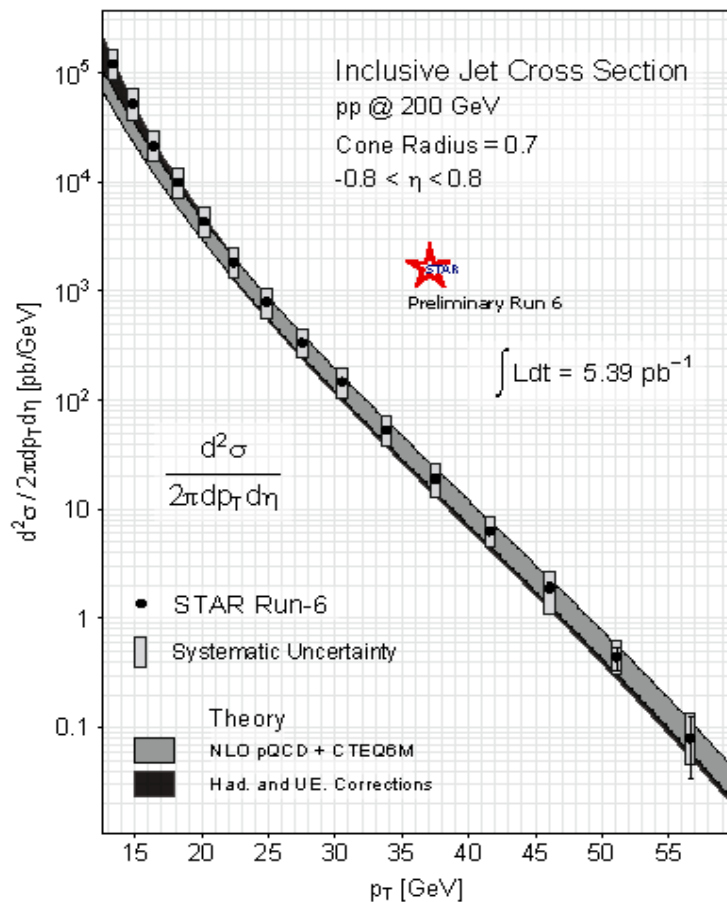
Cacciari, Salam, and Soyez, JHEP 0804, 063

- $R = 0.6$

Use **PYTHIA + GEANT** to quantify detector response

Sjostrand, Mrenna, and Skands, JHEP 05, 026

# Jet cross section from 2006 data



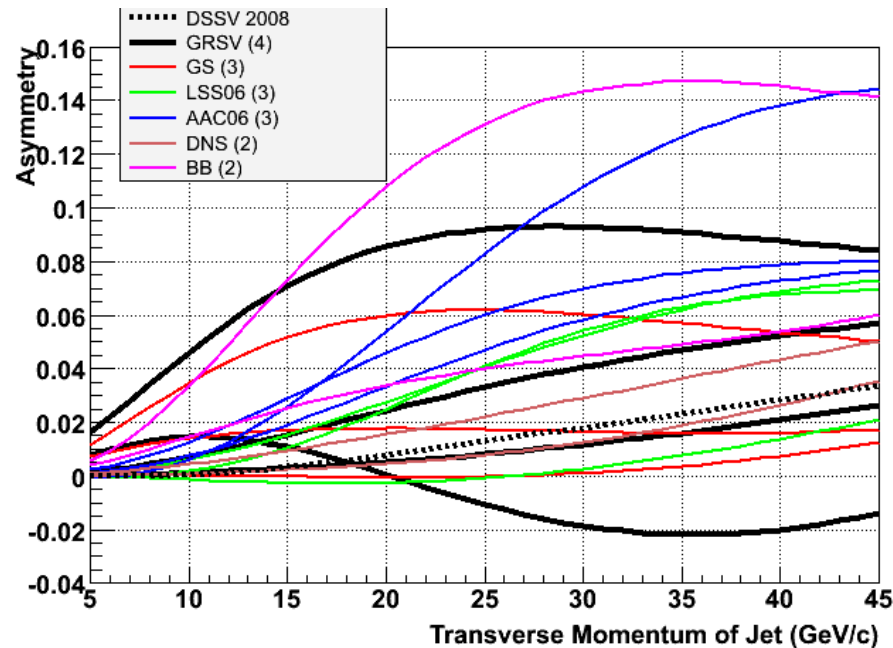
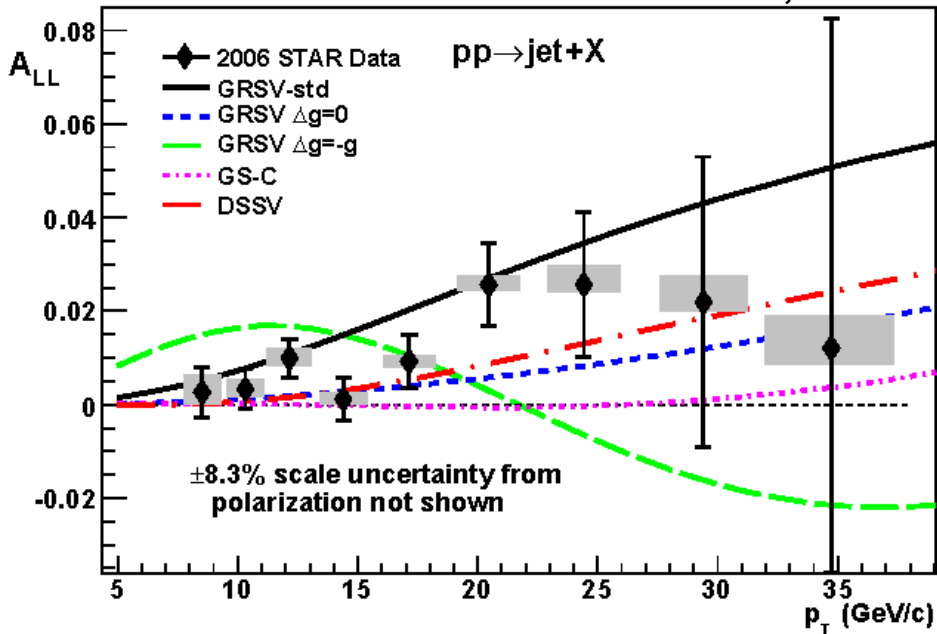
- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
- Jet production is **well understood** at RHIC energies



# STAR inclusive jet $A_{LL}$ from 2006 data



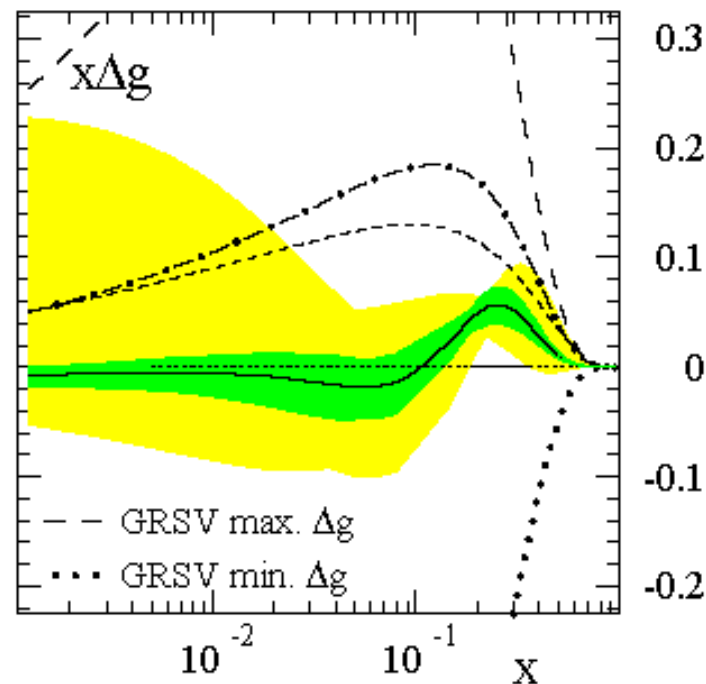
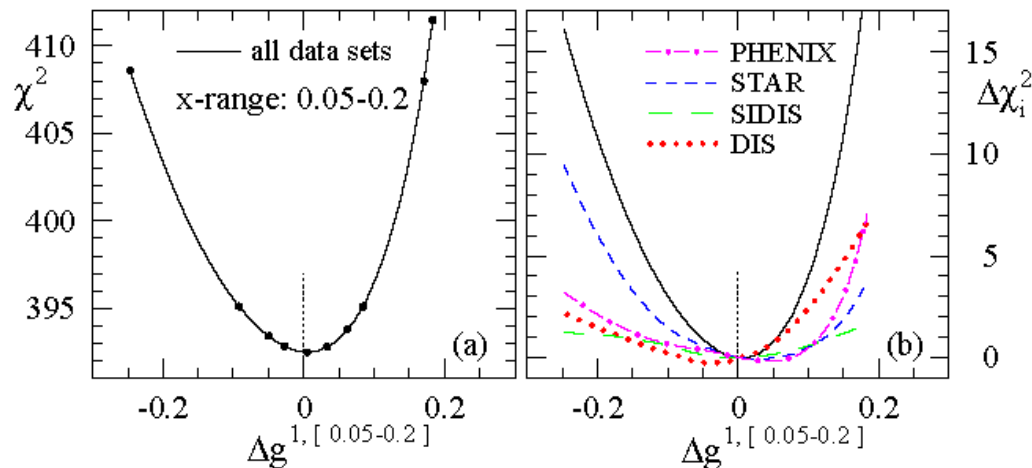
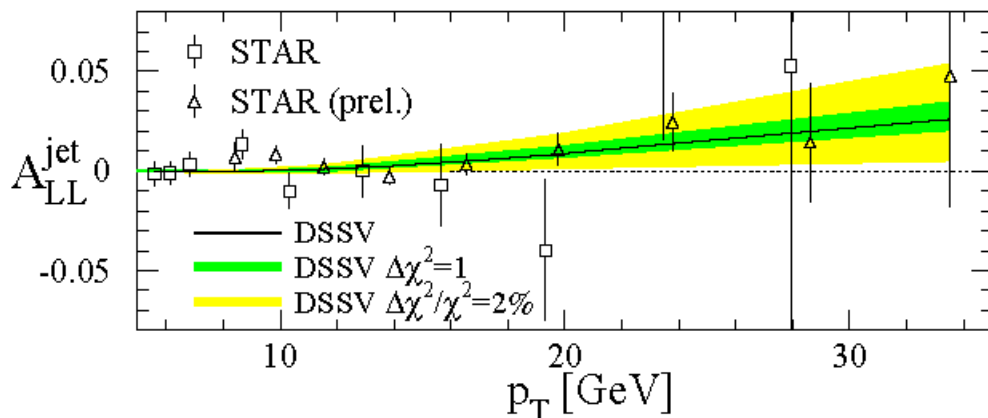
PRD 86, 032006



- **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



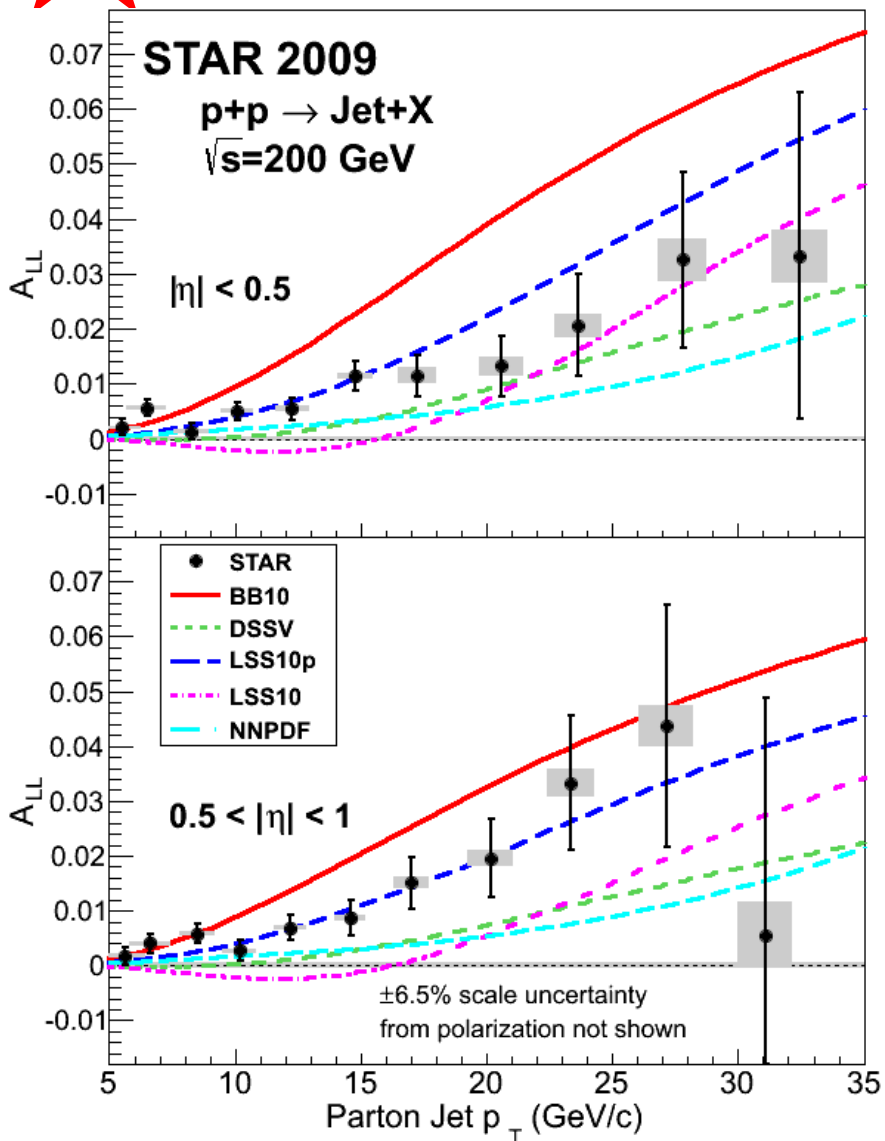
- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing
- Found relatively small gluon polarization within the region  $0.05 < x < 0.2$  that was sampled by the 2006 data

# 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  $\sim 4$  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- $k_T$

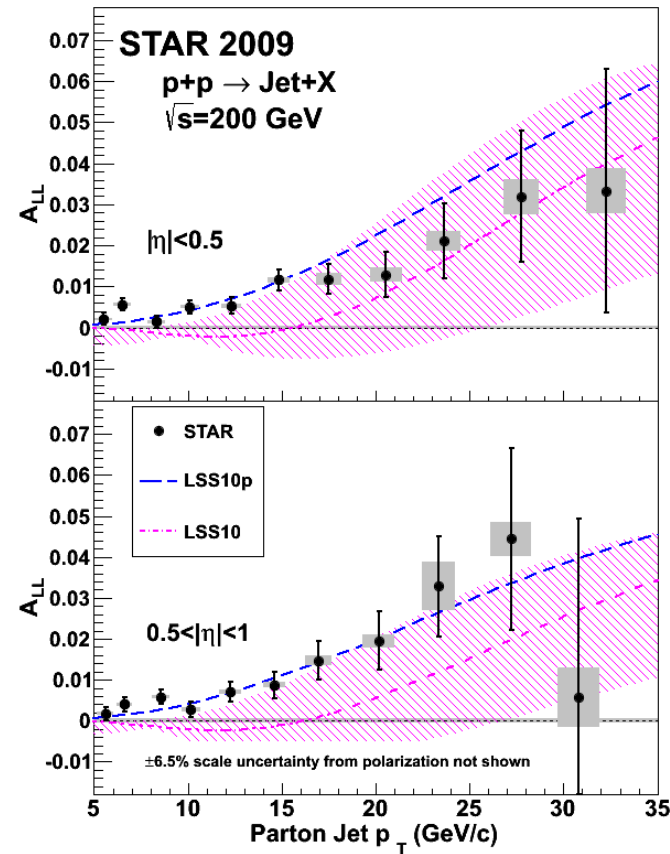
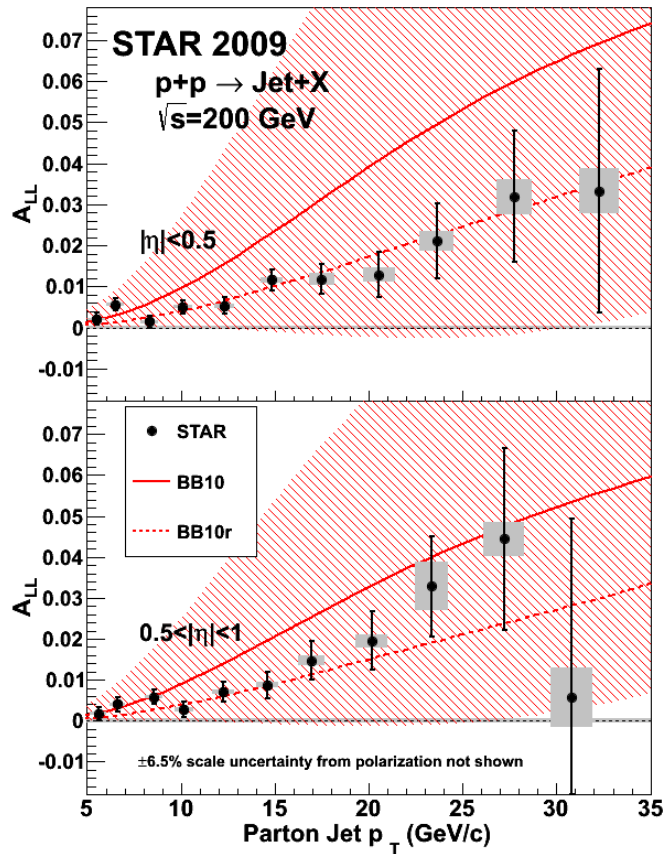
# STAR inclusive jet $A_{LL}$ from 2009 data

**STAR** arXiv:1405.5134



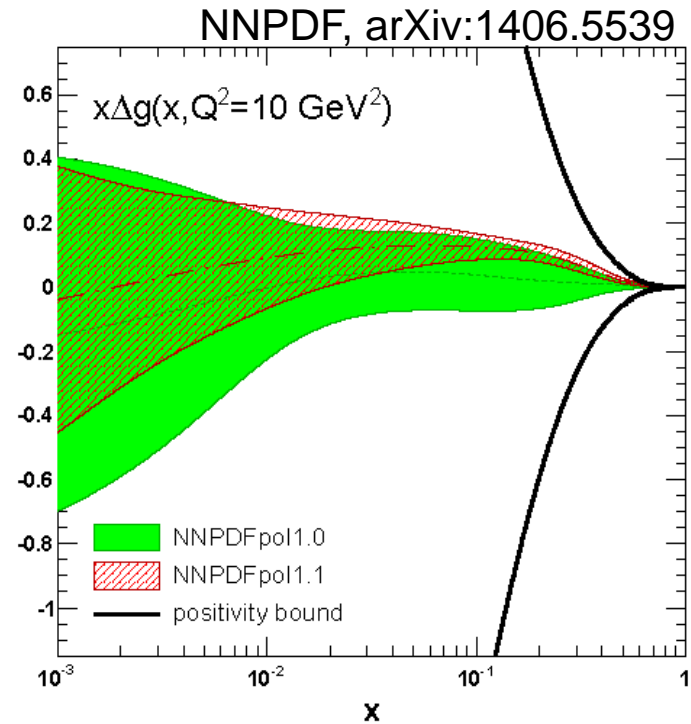
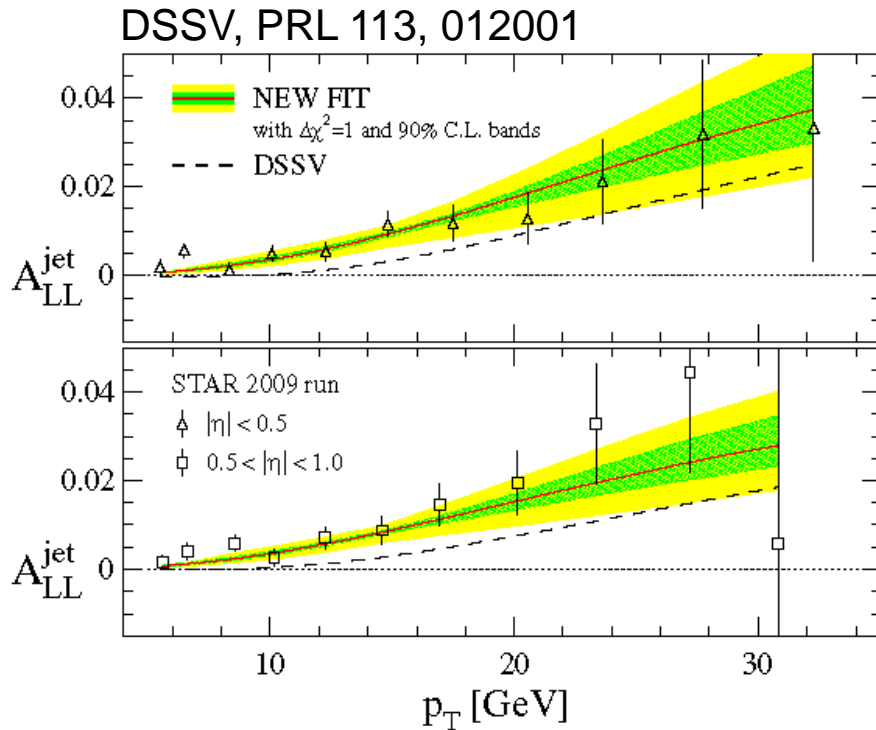
- 2009 **STAR** inclusive jet  $A_{LL}$  measurements are a factor of 3 (high- $p_T$ ) to  $>4$  (low- $p_T$ ) more precise than 2006
- $A_{LL}$  falls in the middle among several recent polarized PDF fit predictions
- $A_{LL}$  is somewhat larger than predictions from the 2008 DSSV fit
  - Points toward **positive  $\Delta g$**  in the accessible  $x$  region

# BB and LSS model uncertainties



- Results are well within the quoted BB10 uncertainties
  - Can **reduce inclusive jet  $\chi^2$  from 89 to 18** while increasing the DIS data  $\chi^2$  by less than 0.03% (0.36 in 1537, “BB10r”)
- Results fall outside the quoted LSS10 uncertainties for  $p_T < \sim 12 \text{ GeV/c}$ 
  - Very strong preference for LSS10p ( $\chi^2=22.5$ ) over LSS10 ( $\chi^2=57$ )

# Two new polarized distribution fits

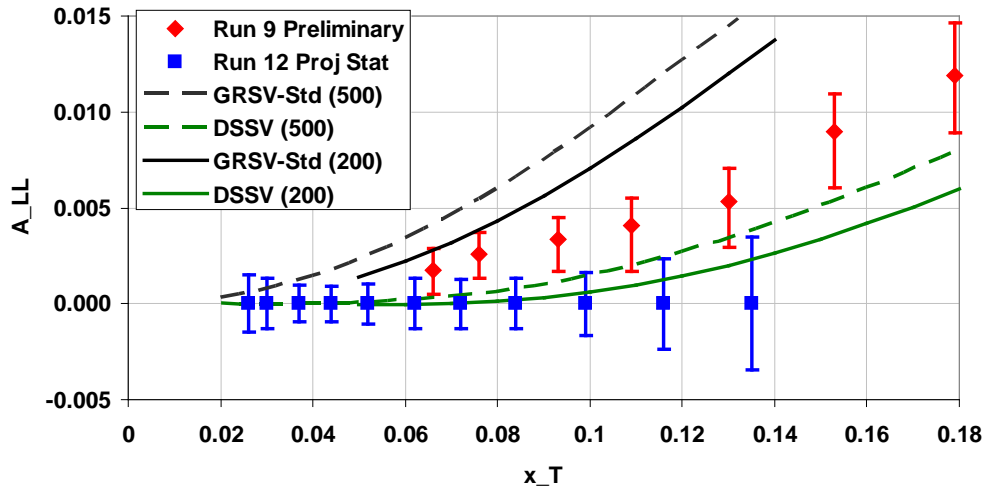


- Both DSSV and NNPDF have released new polarized PDF fits
- Both find **2009 STAR jet  $A_{LL}$  results provide significantly tighter constraints on gluon polarization** than previous measurements
- Both find **evidence for positive gluon polarization** in the region  $x > 0.05$ 
  - **DSSV:  $0.20^{+0.06}_{-0.07}$  at 90% c.l. for  $0.05 < x$**
  - **NNPDF:  $0.23 \pm 0.07$  for  $0.05 < x < 0.5$**

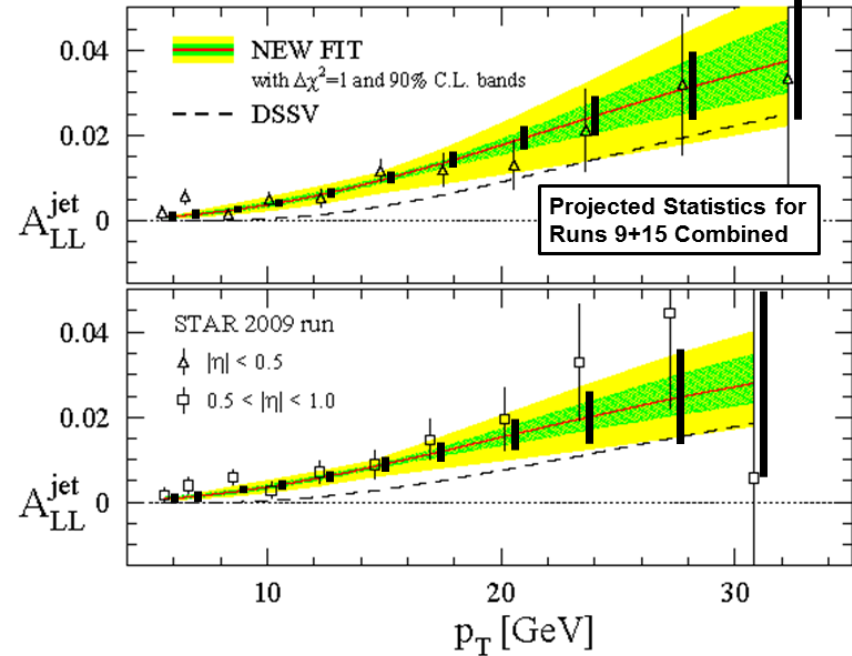
# Higher precision coming soon



510 GeV  
2012 Projection

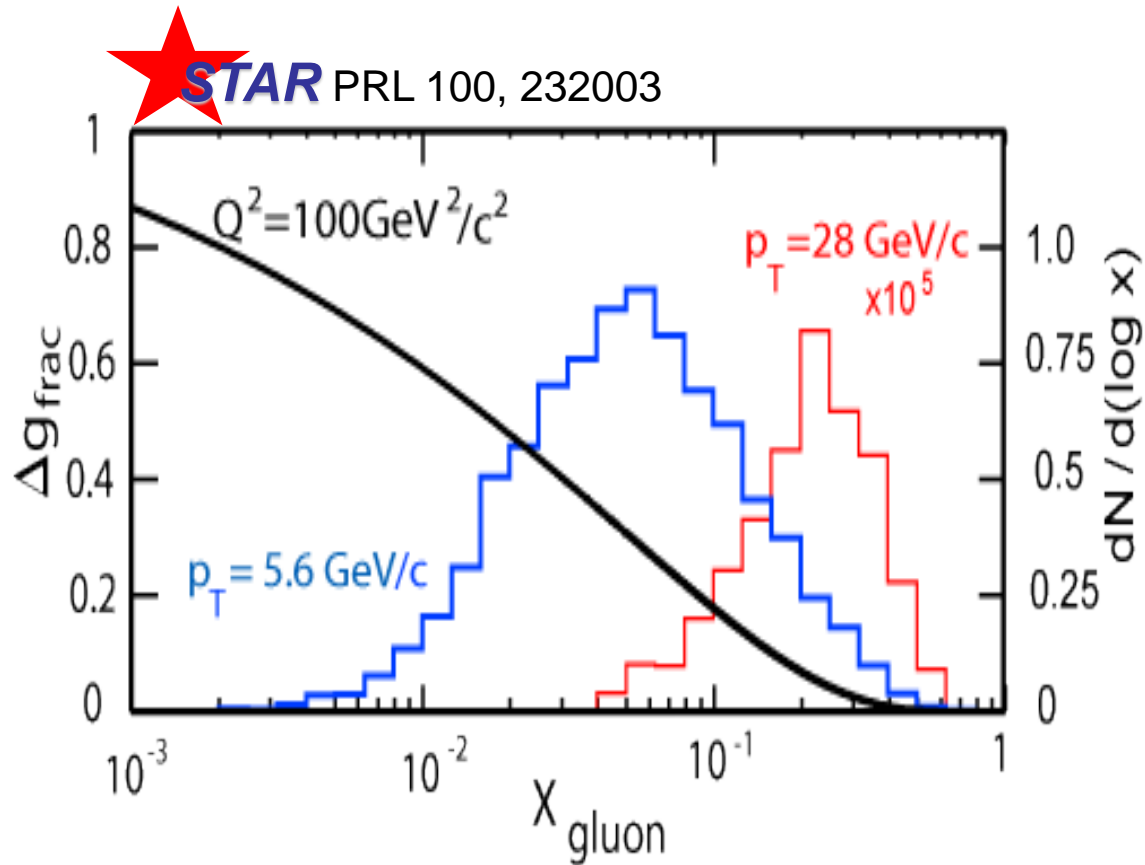


200 GeV  
2009+15 Projection



- During 2012 **STAR** measured inclusive jet  $A_{LL}$  in **510 GeV collisions**
  - Higher beam energy provides sensitivity to smaller  $x_g$
- **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

# Beyond inclusive $A_{LL}$ measurements



- Inclusive  $A_{LL}$  measurements at fixed  $p_T$  average over a **broad x range**.
- Can hide considerable structure if  $\Delta g(x)$  has a node
- **Correlation measurements can constrain the shape of  $\Delta g(x)$**



# 2009 di-jet cross section in 200 GeV pp



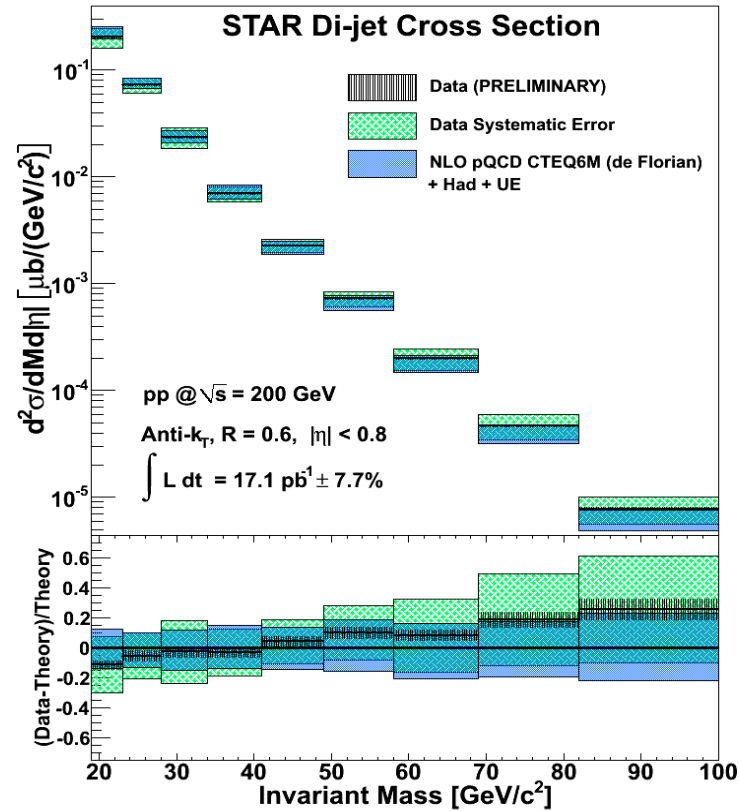
$$x_1 = \frac{1}{\sqrt{s}} (p_{T,3} e^{\eta_3} + p_{T,4} e^{\eta_4})$$

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

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

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

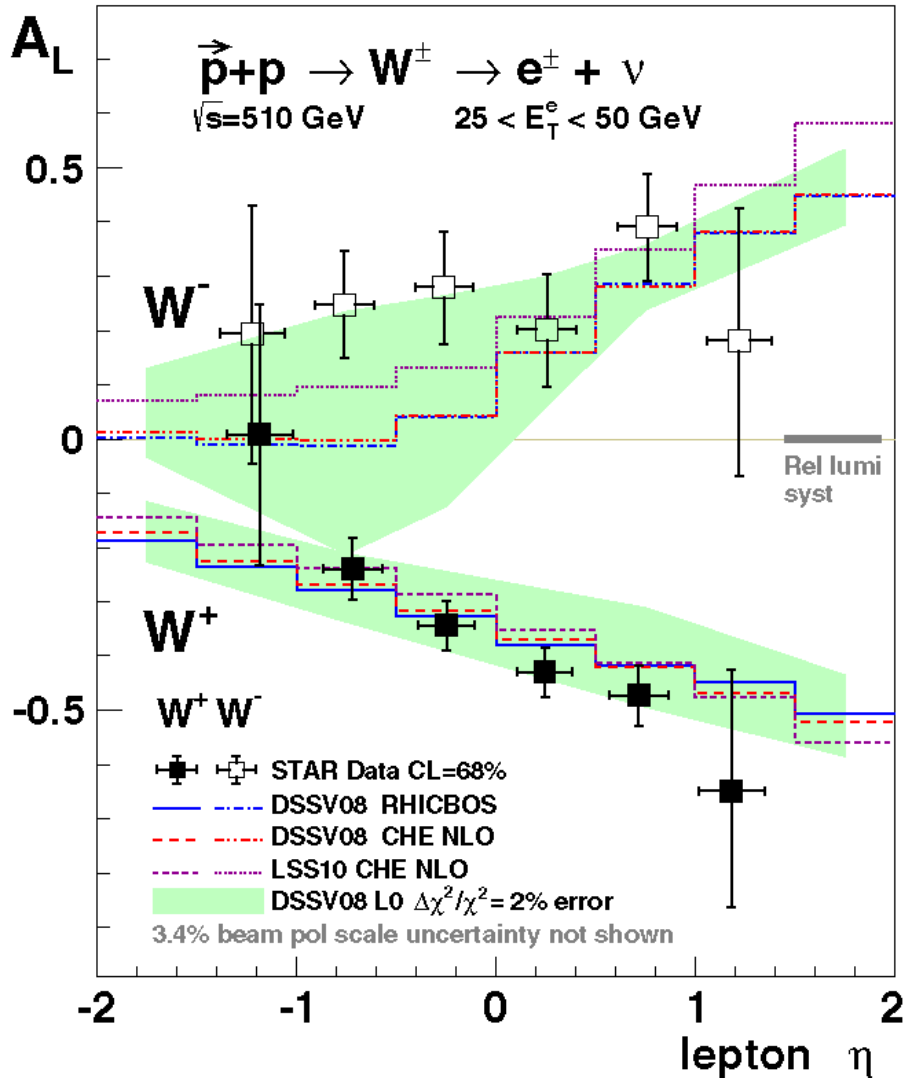
$$|\cos\theta^*| = \tanh \frac{|\eta_3 - \eta_4|}{2}$$



- Di-jets permit event-by-event calculations of  $x_1$  and  $x_2$  at LO
- 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 2013

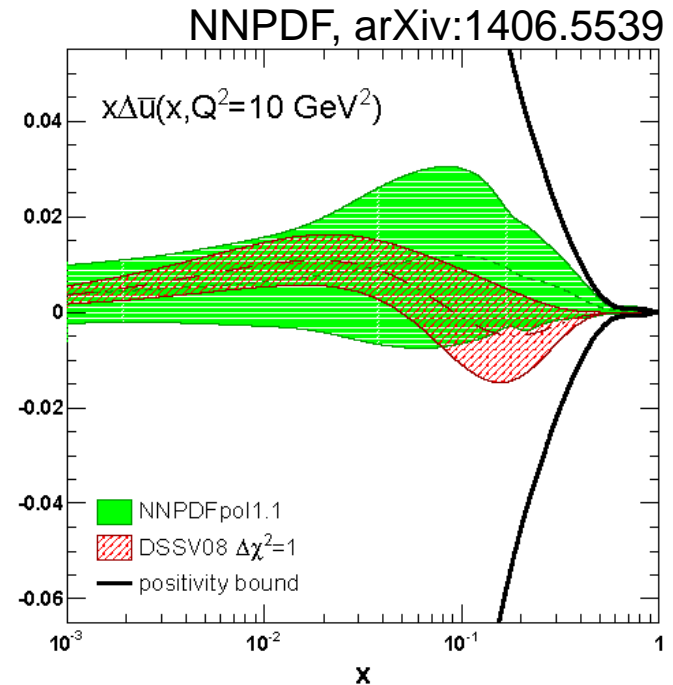
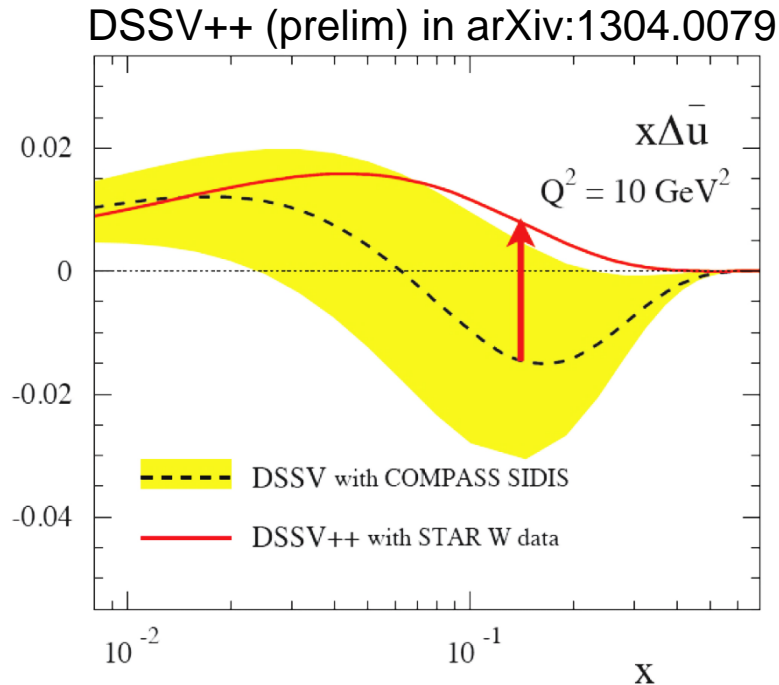
# STAR $W A_L$ from 2011+2012 data

 STAR PRL 113, 072301



- $A_L$  for  $W^+$  is consistent with theoretical predictions constrained by polarized SIDIS data
- $A_L$  for  $W^-$  is larger than the predictions for  $\eta_e < 0$ 
  - This region is particularly sensitive to  $\Delta\bar{u}$
- Preference for a **positive  $\Delta\bar{u}$**  in the range  **$0.05 < x < 0.2$**

# STAR $W A_L$ in recent polarized PDF fits

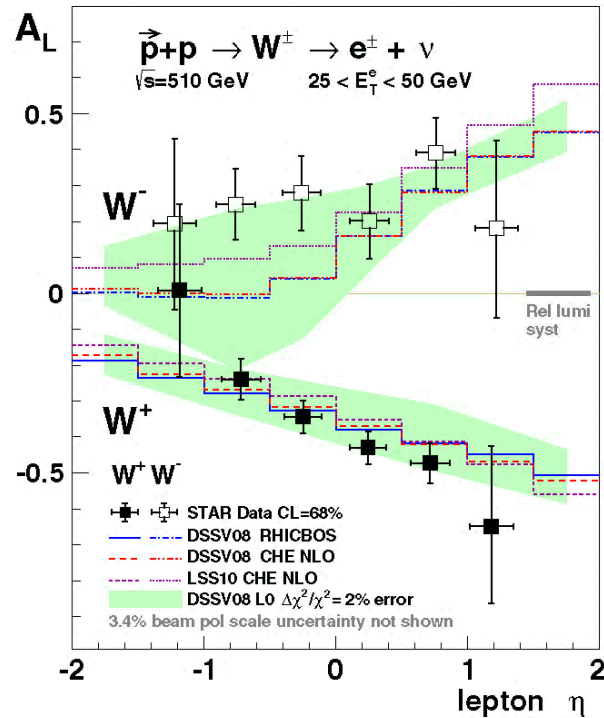


- DSSV++ is a preliminary fit that included a preliminary version of the STAR 2012  $W A_L$  results
- NNPDFpol1.1 uses the STAR  $W$  asymmetries ( $A_L$  and  $A_{LL}$ ) to constrain the antiquark polarizations
- Both find **indication of a positive  $\Delta\bar{u}$**  in the vicinity of  $x \sim 0.15$

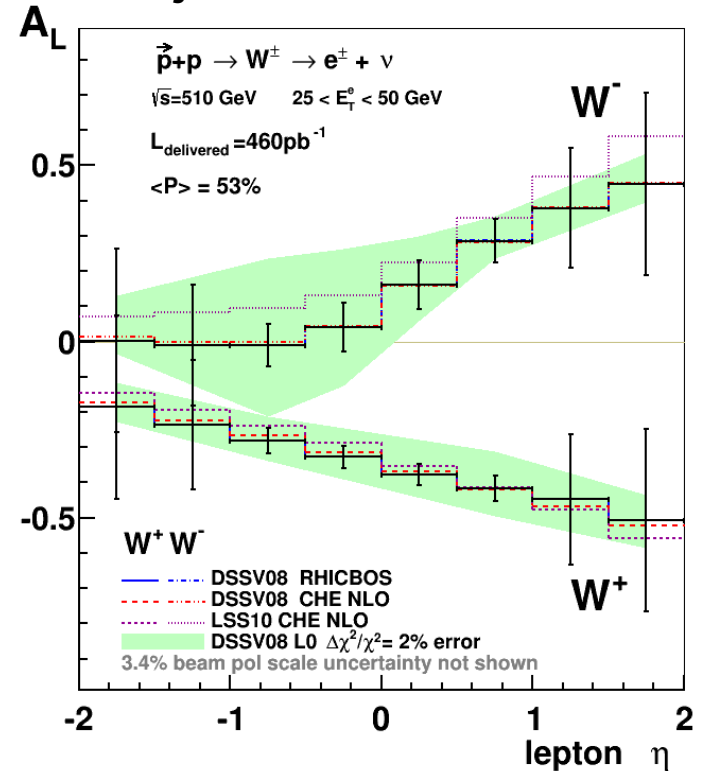
# Anticipated precision in the near future



2011+12 Achieved

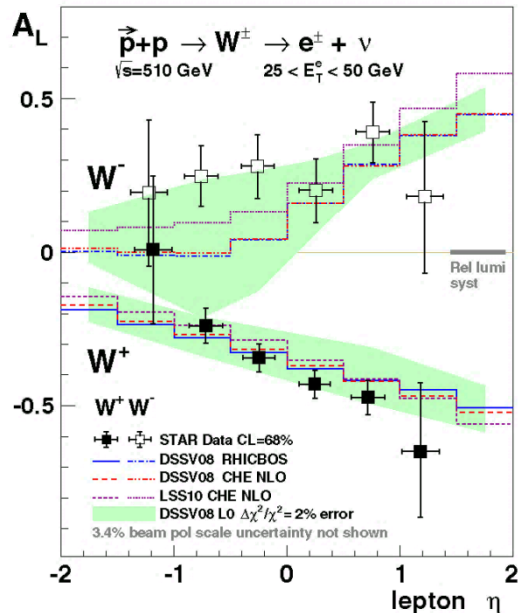
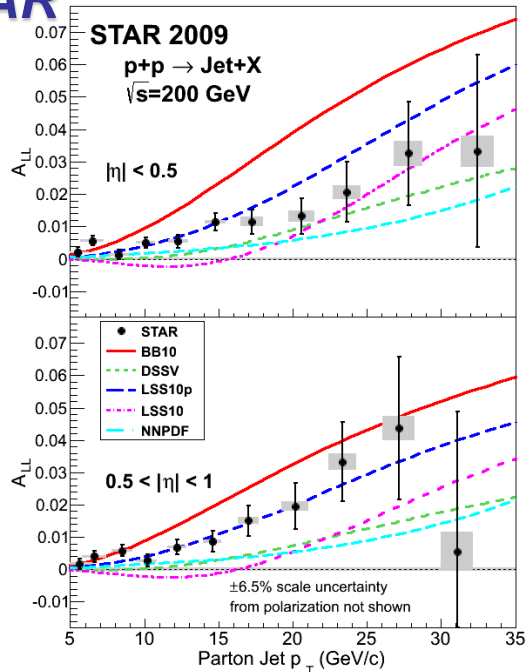


Projected 2013 Statistics



- STAR recorded ~4 times as much W asymmetry data during the 2013 RHIC run than were included in the recent analysis
- Will also extended kinematic coverage to larger  $|\eta|$  with the FGT
- Look for new  $A_L$  results soon

# Conclusions



- **STAR 2009 inclusive jet  $A_{LL}$  results provide the first experimental evidence for positive gluon polarization in the RHIC range**
- **STAR 2011+12 W  $A_L$  results provide new constraints on antiquark polarizations, including a preference for a positive  $\Delta\bar{u}$**
- **Look for several more results in the near future**
  - **First measurements:**
    - Di-jet  $A_{LL}$  at 200 and 510 GeV (2009&13 data)
    - Inclusive jet  $A_{LL}$  at 510 GeV (2012 data)
  - **Improved precision for:**
    - W  $A_L$  (2013 data)
    - Inclusive jet  $A_{LL}$  at 200 GeV (2015 data)
- **Stay tuned!**