Longitudinal double-spin asymmetries for inclusive jets produced in √s = 200 GeV proton-proton collisions at STAR
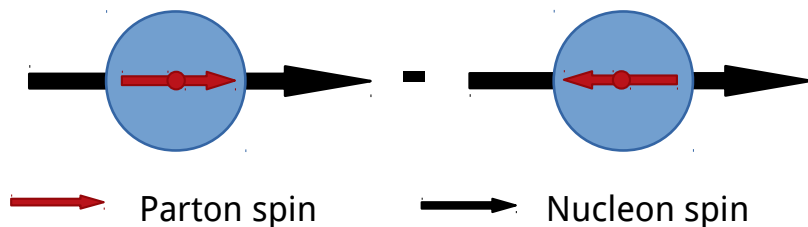
GLUON HELICITY DISTRIBUTION

STAR Spin Program:

Delineate the spin structure of the proton in terms of quarks and gluons, and study the role of spin in QCD

How do gluons contribute to the proton spin?

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

→ Parton spin   → Nucleon spin

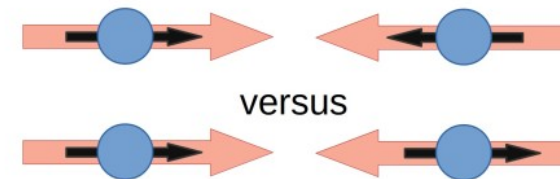Gluon helicity distribution $\Delta g(x, Q^2)$

Difference between the gluon parton distribution function for gluon and proton helicities aligned and anti-aligned

x - fraction of the proton momentum carried by the gluon
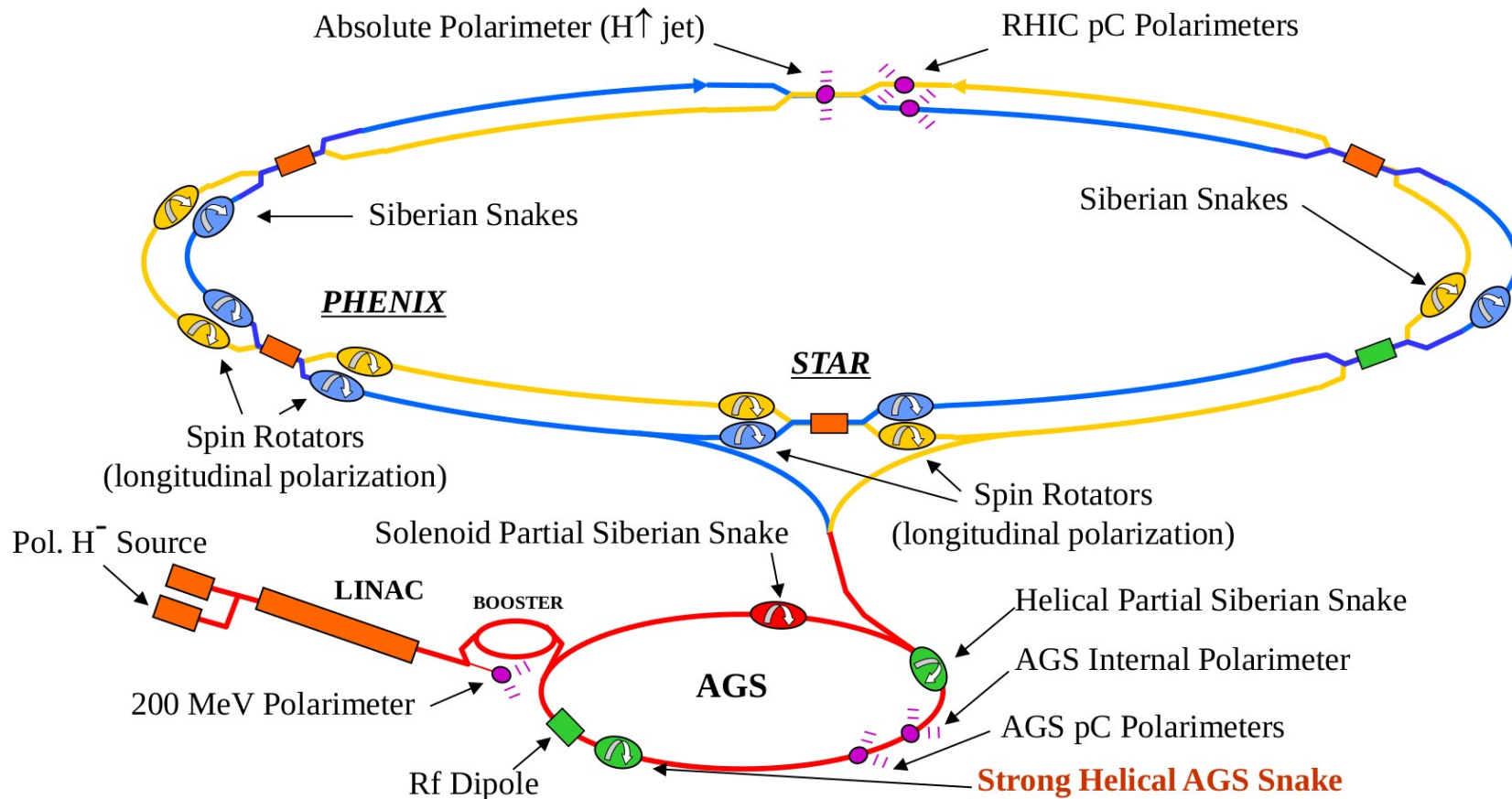Q^2 - momentum transfer scale

Double polarization

$$\vec{p} + \vec{p} \rightarrow \text{jet/dijet/hadrons} + X$$

versus

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

RHIC – POLARIZED PROTON COLLIDER

- The only polarized high-energy proton-proton collider
- Transverse and longitudinal polarization
- Polarized protons $\sqrt{s}$ = 62, 200, 500 GeV
- Alternating spin configurations bunch by bunch and fill by fill

Hard scattering processes with control of systematic effects

POLARIZED PP DATASETS AT RHIC

Year and √s	STAR L [pb^{-1}]
Longitudinal runs	
√s = 200 GeV	
2009	25
2015	52
√s = 500/510 GeV	
2009	10
2011	12
2012	82
2013	300
Transverse runs	
√s = 200 GeV	
2012	22
2015	52
√s = 500/510 GeV	
2011	25
2017	320
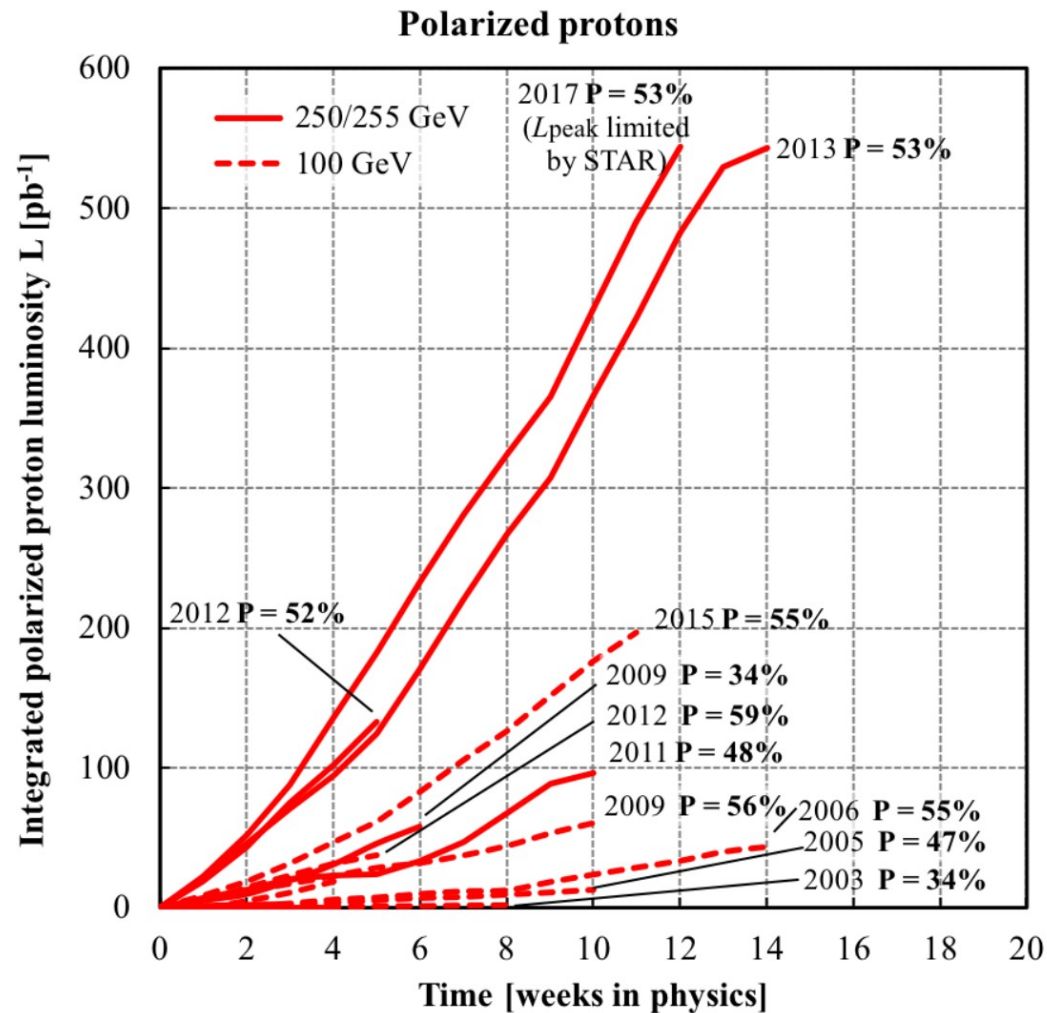
The STAR Beam Use Request for Runs 19 and 20, STAR Collaboration

Run overview of the Relativistic Heavy Ion Collider
https://www.rhichome.bnl.gov/RHIC/Runs/

SOLENOIDAL TRACKER AT RHIC

Electromagnetic Calorimeter
- $\Delta\varphi = 2\pi$, $-1 < \eta < 2$
- Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

Time Projection Chamber
- $\Delta\varphi = 2\pi$, $|\eta| < 1$, 0.5 T
- PID, tracking, vertex reconstruction

Time of Flight Barrel
- $\Delta\varphi = 2\pi$, $|\eta| < 1$
- PID

Forward Meson Spectrometer
- $\Delta\varphi = 2\pi$, $2.6 < \eta < 4$
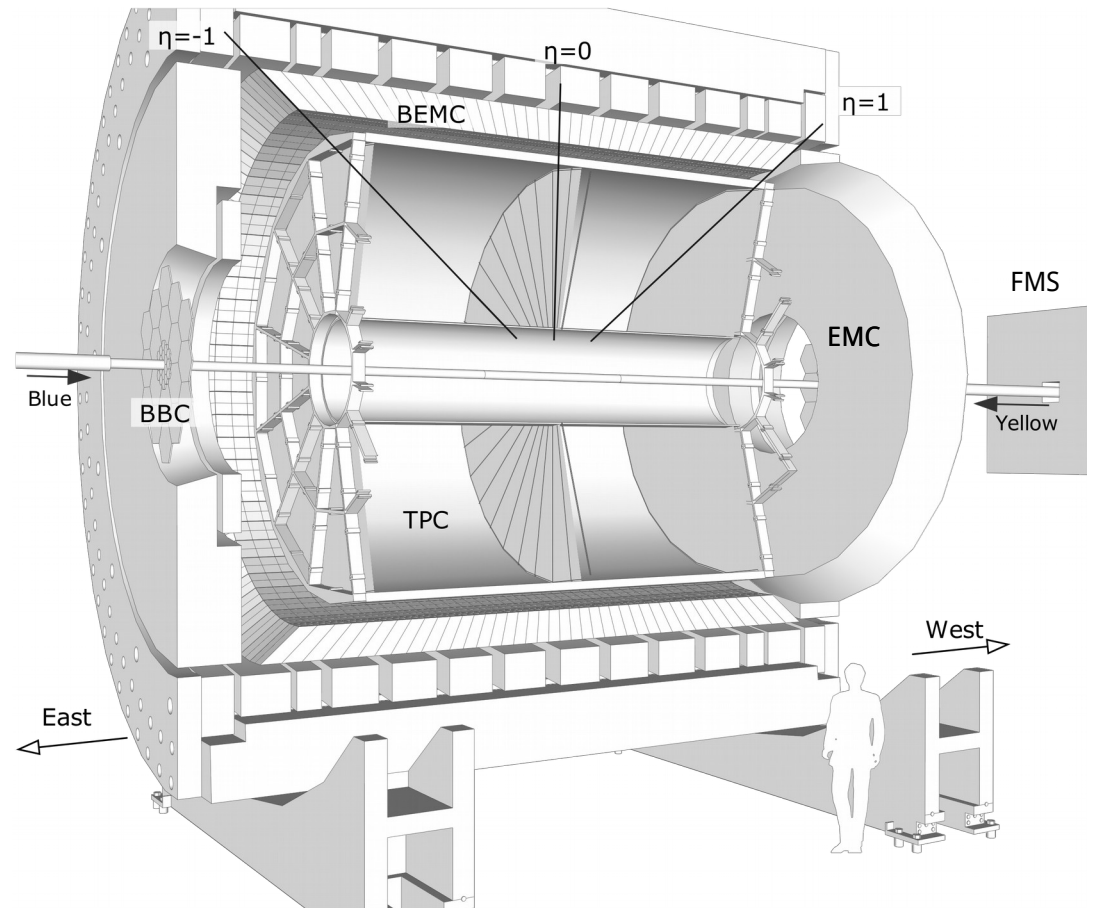- Energy measurement, trigger

Beam-Beam Counter
Vertex Position Detector
- Relative luminosity and MB trigger

Zero Degree Calorimeter
- Relative luminosity and local polarimetry
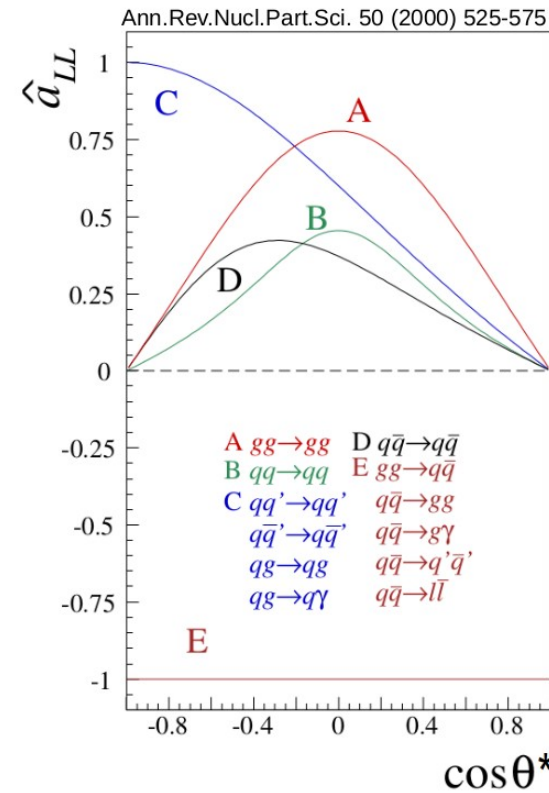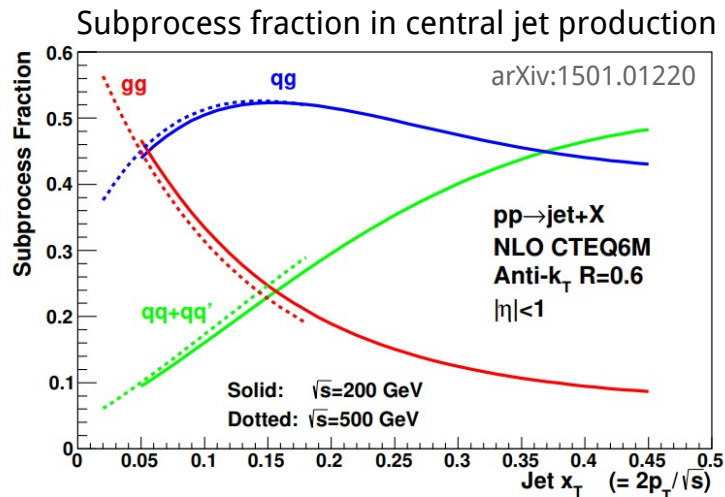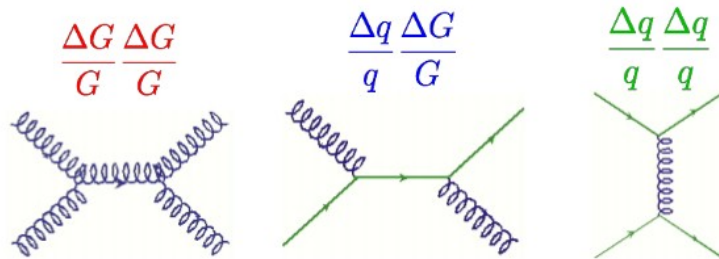
Roman Pots

Characteristics
- Large acceptance (PID and calorimetry)
- Good for jets and correlations

HOW TO ACCESS ΔG?

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a}_{LL}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

LO for illustration

Which processes dominate at RHIC?

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

Subprocess fraction in central jet production

arXiv:1501.01220

pp→jet+X
NLO CTEQ6M
Anti-k_T R=0.6
|η|<1

Solid: √s=200 GeV
Dotted: √s=500 GeV

Sensitive to qg and gg – Access to **ΔG/G**

What are a_{LL} for these processes?

Ann.Rev.Nucl.Part.Sci. 50 (2000) 525-575

A $gg \rightarrow gg$ D $q\bar{q} \rightarrow q\bar{q}$
B $qq \rightarrow qq$ E $gg \rightarrow q\bar{q}$
C $qq' \rightarrow qq'$ $q\bar{q} \rightarrow gg$
$q\bar{q}' \rightarrow q\bar{q}'$ $q\bar{q} \rightarrow g\gamma$
$qg \rightarrow qg$ $q\bar{q} \rightarrow q'\bar{q}'$
$qg \rightarrow q\gamma$ $q\bar{q} \rightarrow l\bar{l}$

STATUS OF ΔG

Precision A_{LL}
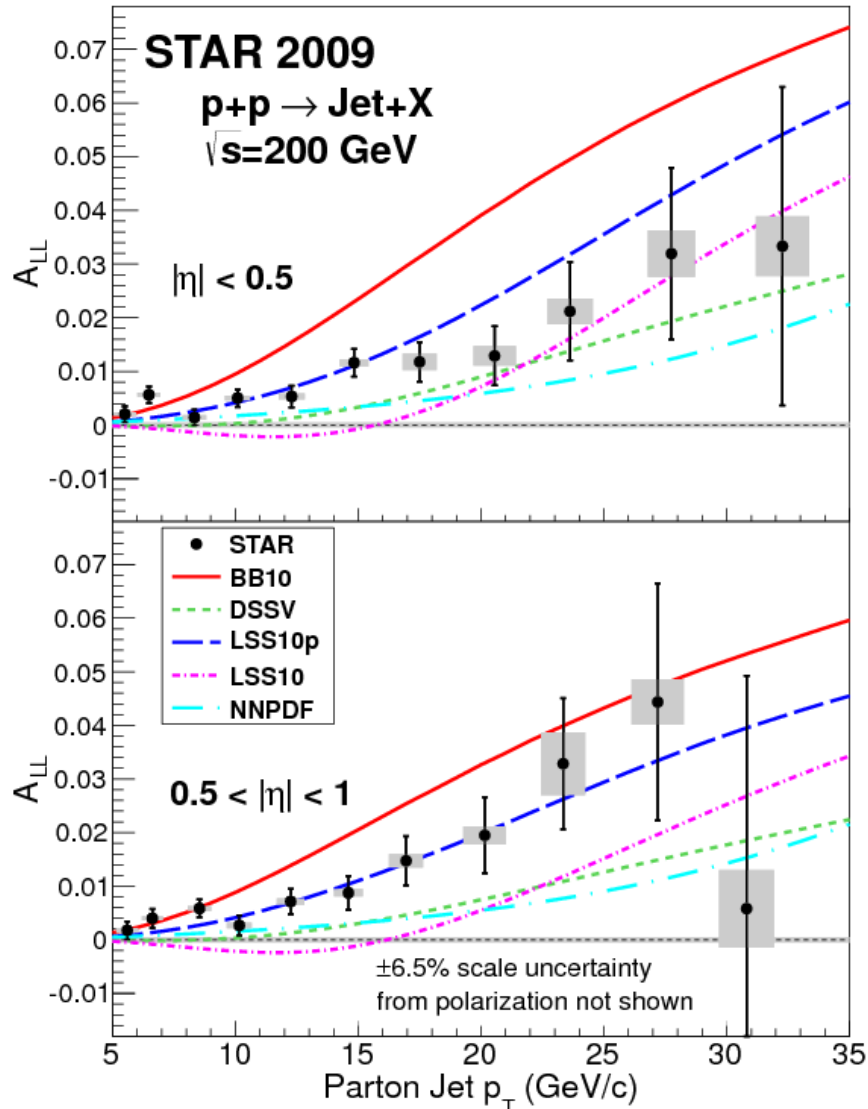
1. A_{LL} positive for large p_T - **positive gluon polarization**

2. Included in DSSV and the NNPDF **PDF fits** (NLO)
   - These data drive the constraints on ΔG in both fits
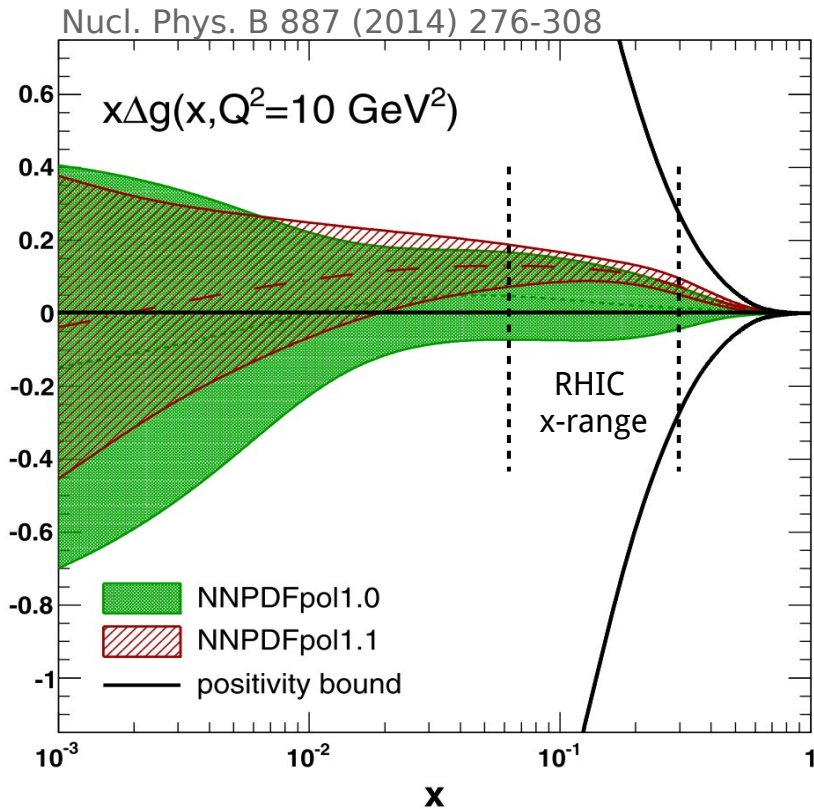   - Initial sensitivity to different x_g from different rapidity bins

Evidence for **positive gluon polarization** in the x range $0.05 < x < 0.2$ and at $Q^2 = 10$ GeV^2

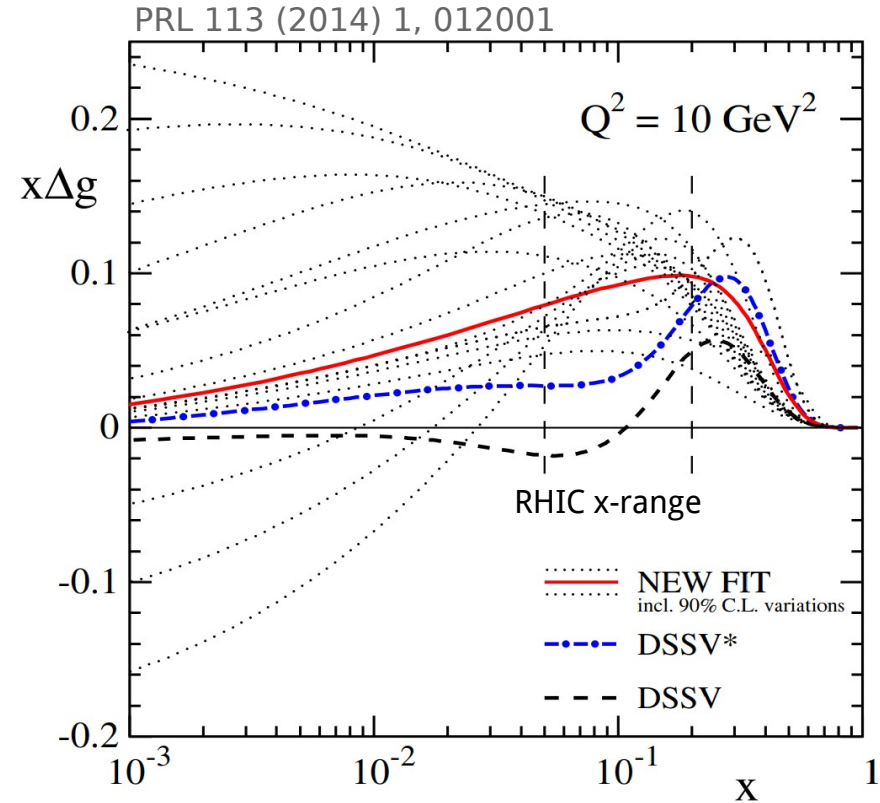Run 2009 - 25 pb^{-1}
Further precision: Run 2015 – 50 pb^{-1}

STATUS OF ΔG

Impact of A_{LL} from 2009 data on ΔG

Nucl. Phys. B 887 (2014) 276-308

PRL 113 (2014) 1, 012001

NNPDFpol1.0 – do not include STAR 2009 data
NNPDFpol1.1 – include STAR 2009 data
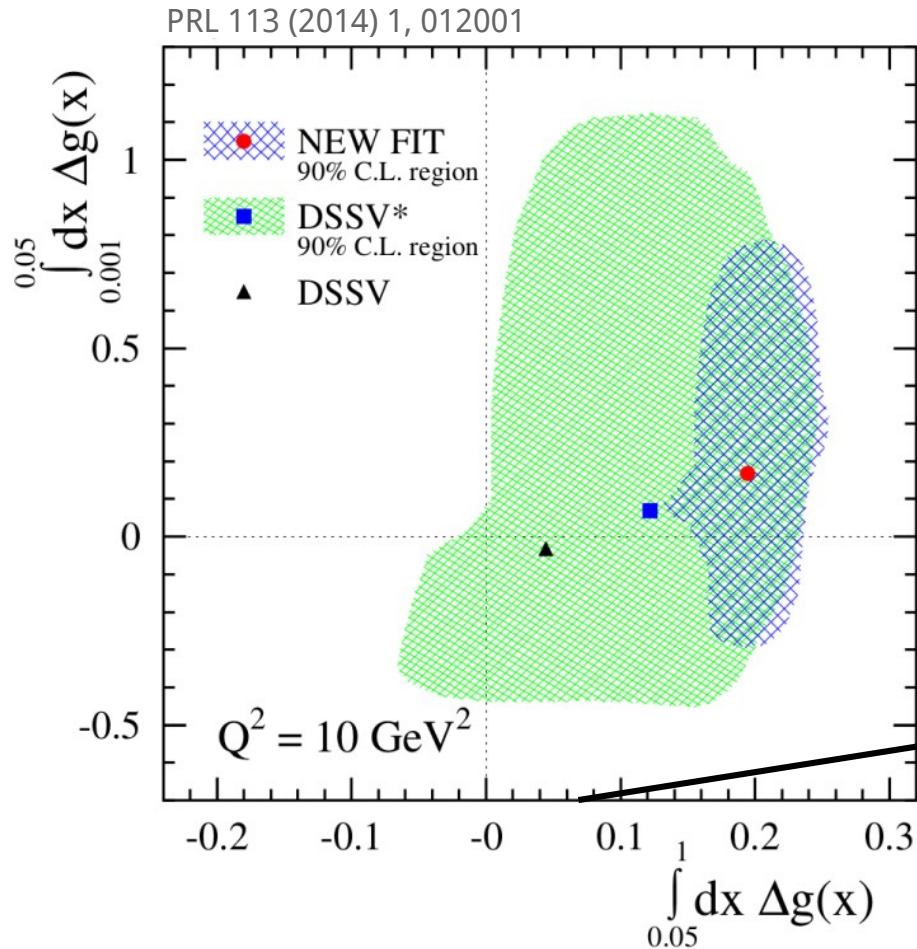
$$0.23 \pm 0.07, \quad 0.05 < x < 0.5$$

DSSV – DIS, SIDIS, BNL-RHIC, preliminary 2005 and 2006 STAR data
DSSV* – the final STAR jet results from 2005 and 2006
DSSV New fit – STAR 2009 data included

$$0.20^{+0.06}_{-0.05}, \quad \text{at } 90\% \text{ C.L. }, x > 0.05$$

STATUS OF ΔG

What's next?

PRL 113 (2014) 1, 012001

Low-x range

Extend sensitivity to smaller x_g:
- forward rapidity

$$x_g \propto \exp(-\eta)$$

- √s = 510 GeV data

$$x_g \propto 1/\sqrt{(s)}$$

High-x range

Further precision from:

- Jet and neutral pion probes
- Complementary probes (di-jets)

Near-term improvements from STAR for $x > 10^{-2}$
Deep insight from future measurements at EIC at lower x
- Scaling violation in inclusive DIS: $g_1(x, Q^2)$

INCLUSIVE JET A_{LL}

2015 dataset: 2x larger Figure-Of-Merit (FoM = $L P^4$) than for 2009 data

Asymmetry calculation

$$A_{LL} = \frac{1}{P_B P_Y} \frac{(N_{++} + N_{--}) - R_3 (N_{+-} + N_{-+})}{(N_{++} + N_{--}) + R_3 (N_{+-} + N_{-+})}$$

$N_{+/-}$ - number of produced jets N for four different beam helicity configurations

P – polarization (Y – yellow, B – blue beam) P_B = 0.523 ± 0.016, P_Y = 0.565 ± 0.017

R_3 – relative luminosity calculated using hit information from the Vertex Position Detector (VPD)

$$R_3 = \frac{L_{++} + L_{--}}{L_{+-} + L_{-+}} \quad \xrightarrow{\substack{\text{Acceptance and efficiency} \\ \text{canceled}}} \quad R_3 = \frac{N^{++} + N^{--}}{N^{+-} + N^{-+}}$$

- R_3 varies from 0.96 to 1.04 depending on the fill with the uncertainty of $\Delta R_3 \sim 4.5 \times 10^{-4}$
- Uncertainty similar to 2009 data
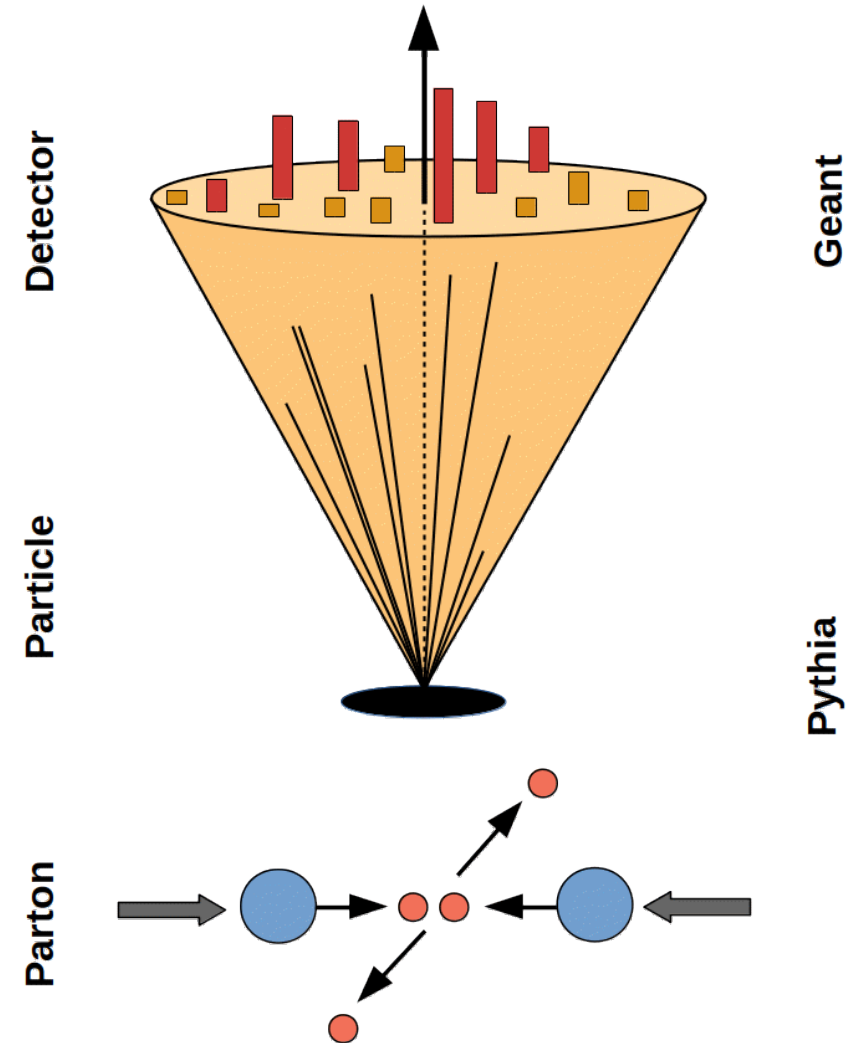
INCLUSIVE JET A$_{LL}$

Jets reconstruction
- Jets reconstructed with anti-kT algorithm with R = 0.6
- Triggers based on patches in EM calorimeter

Simulations: Perugia 2012 with a tuned $p_{T,0}$ scale parameter to reduce multiple parton interaction contribution

Embedding: With the zero bias data from the same data collection period
- Jets reconstructed at detector, particle and parton level

- Jets **corrected back to parton** level
  Detector jet p_T – parton jet p_T correction values:
  between -0.2 – 0.9 GeV/c depending on the jet p_T bin

- **Trigger bias and reconstruction efficiency** estimated using replicas from polarized NNPDF1.1 PDF set
  Corrections up to about 10% depending on the jet p_T bin

INCLUSIVE JET A$_{LL}$

Improved methods compared to 2009 results follow the approach from the 510 GeV 2012 data analysis STAR, PRD 100 (2019), 052005

- Jet-by-jet underlying event correction using off-axis cone method ALICE, PRD 91 (2015), 112012

Cone (minus)

Jet
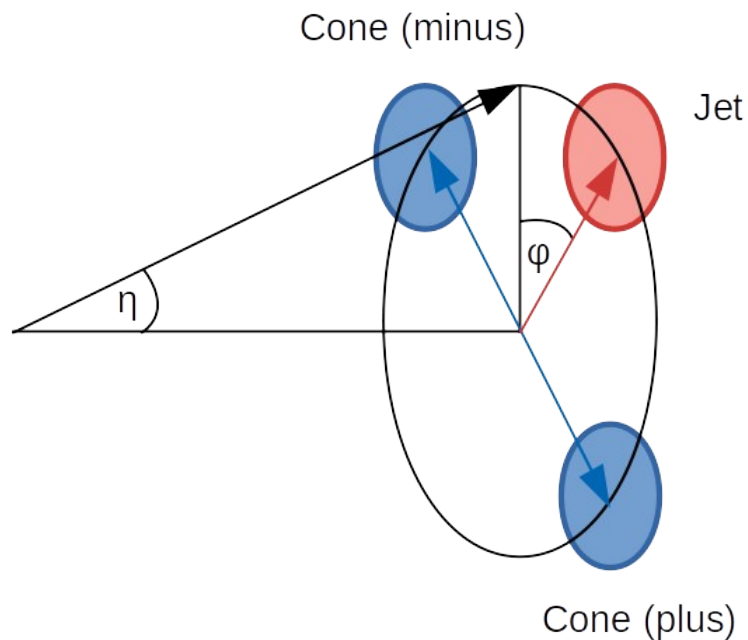
Off-axis cones at ± π/2 away in φ and at the same η

$$dp_T = \frac{1}{2}(\sigma_{\text{plus}} + \sigma_{\text{minus}}) \times A_{\text{jet}}$$

σ - energy density, A – jet area

Example UE correction values:
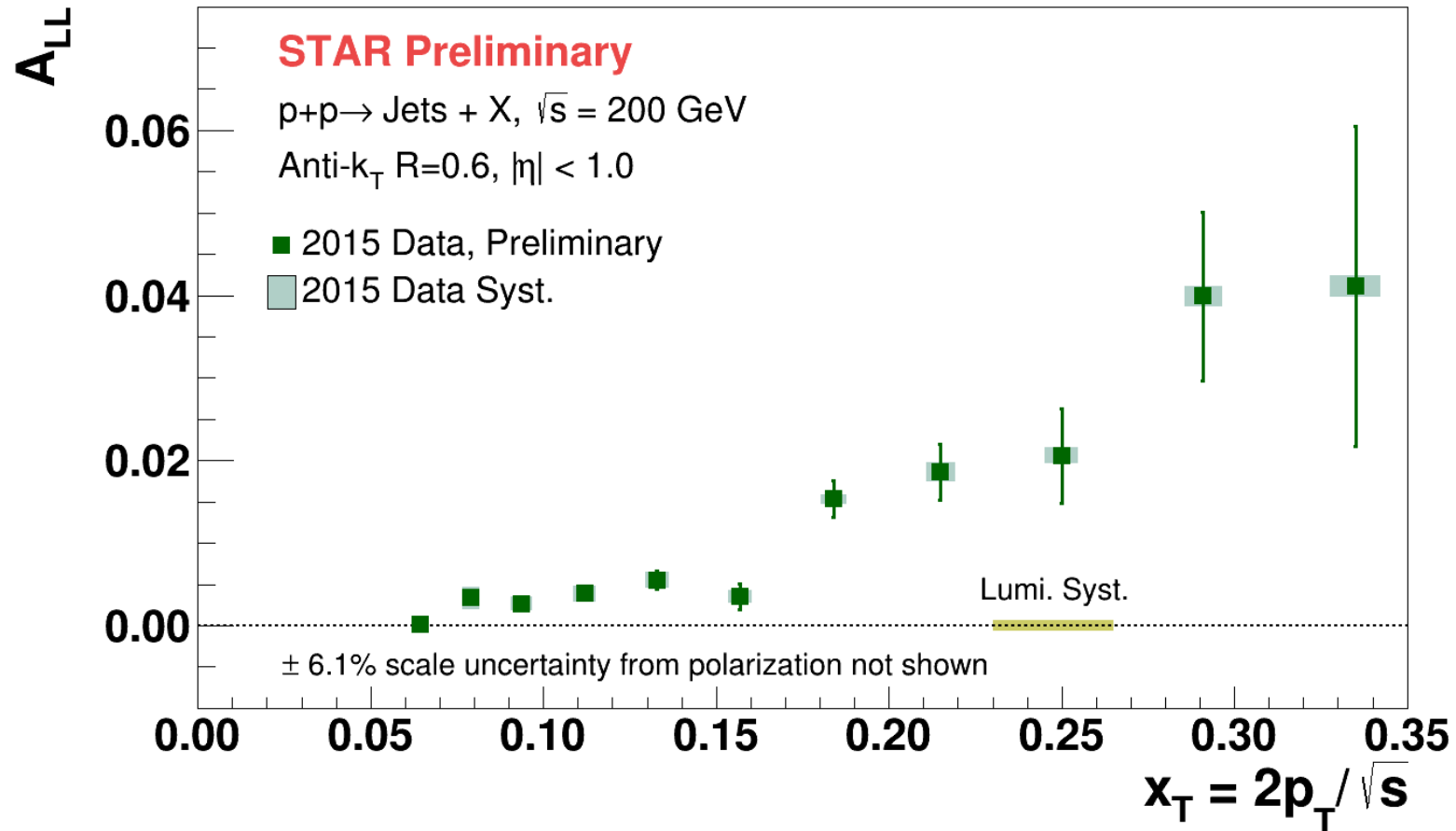p_T = 6 – 7.1 GeV/c: avarage UE dp_T ~ 1 GeV/c
p_T = 26.8 – 31.6 GeV/c: avarage UE dp_T ~ 0.7 GeV/c

Cone (plus)

Main improvements in **systematics** with respect to the 2009 result came from:
- Application of the UE correction
- Smaller residual transverse polarization
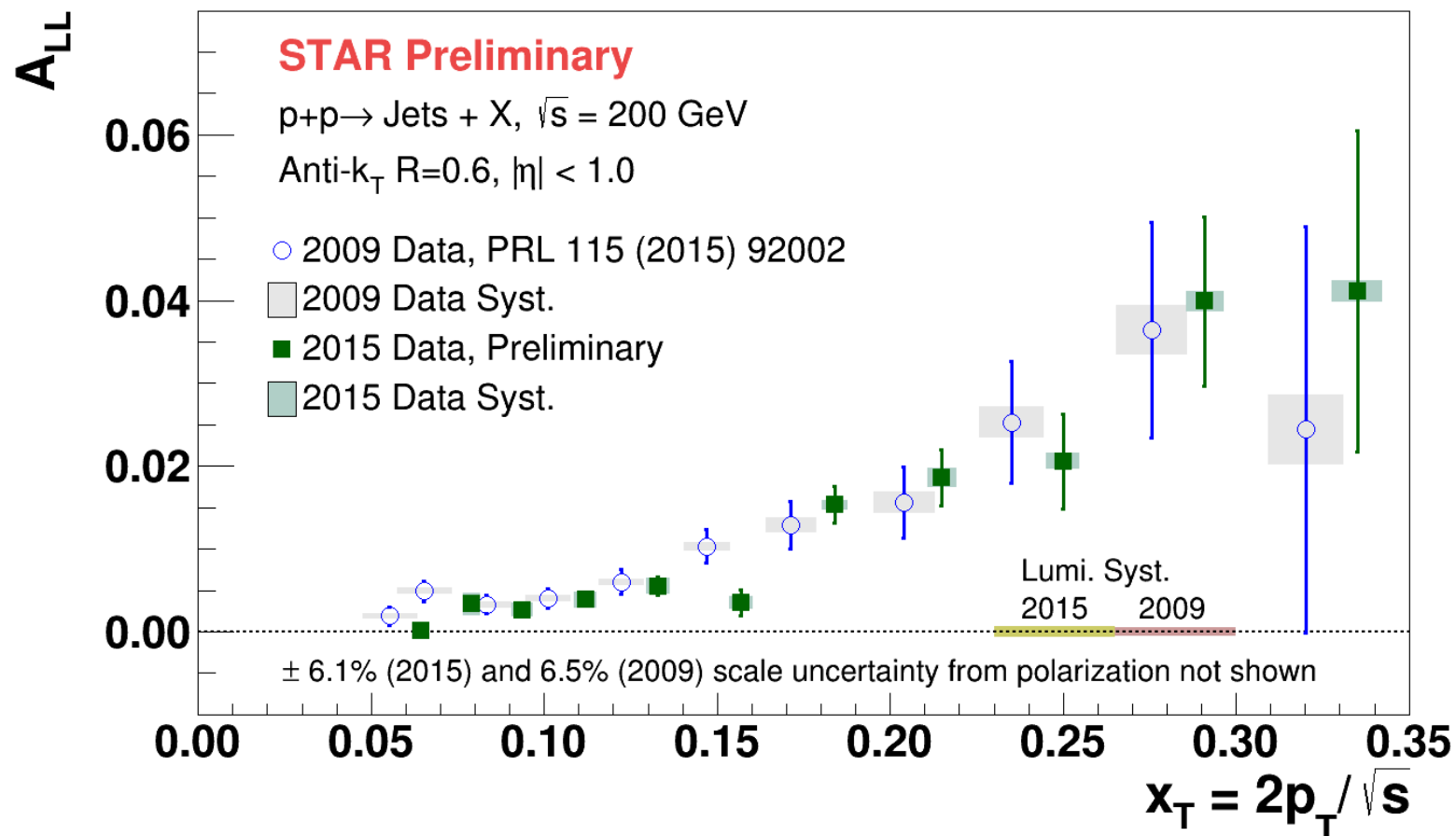- Reduced trigger bias and reconstruction uncertainty

INCLUSIVE JET A$_{LL}$

New preliminary result on A$_{LL}$ of inclusive jet production from 2015 data
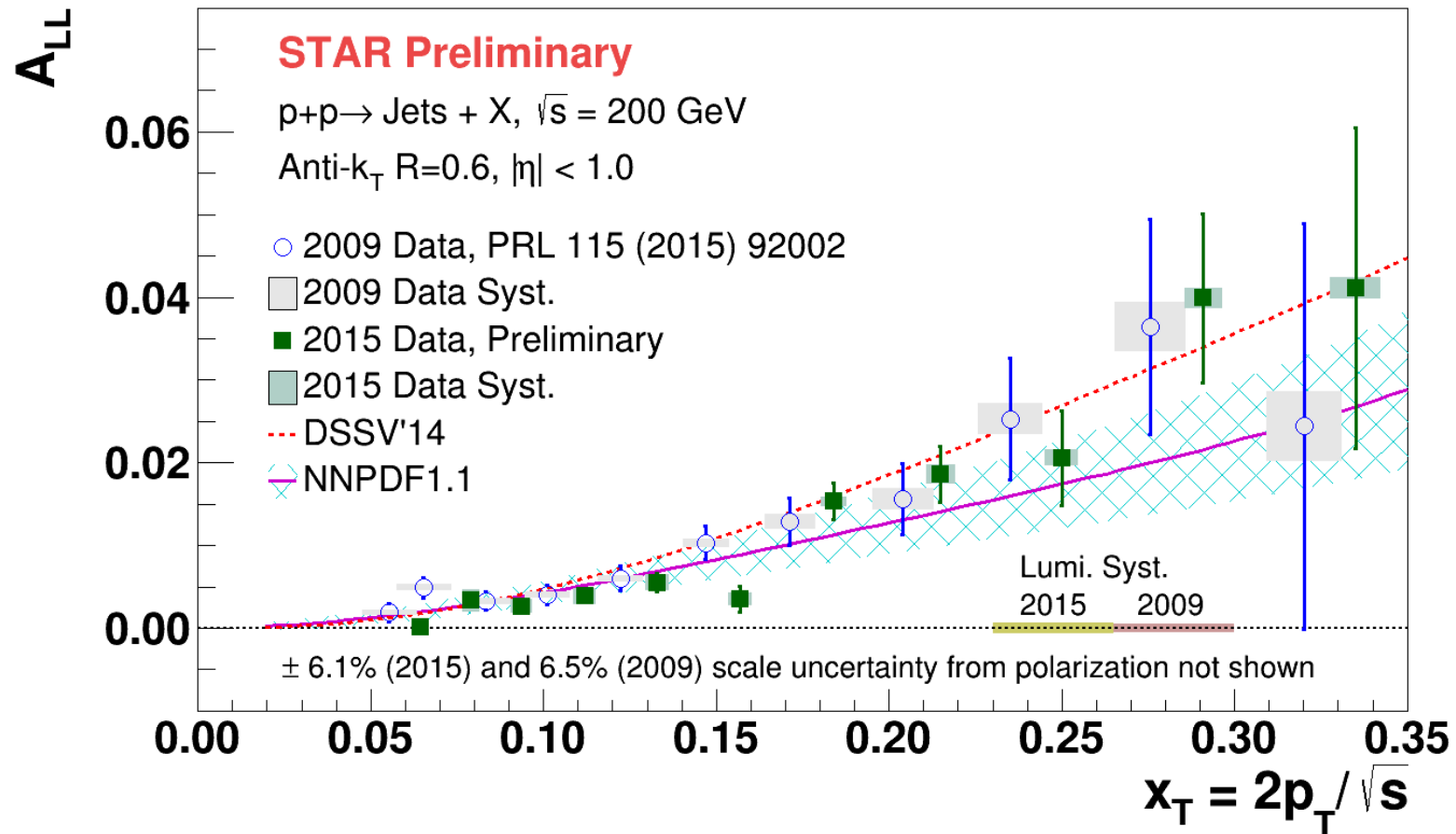
INCLUSIVE JET A$_{LL}$

New preliminary result on A$_{LL}$ of inclusive jet production from 2015 data

- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit (LP^4) with improved systematics

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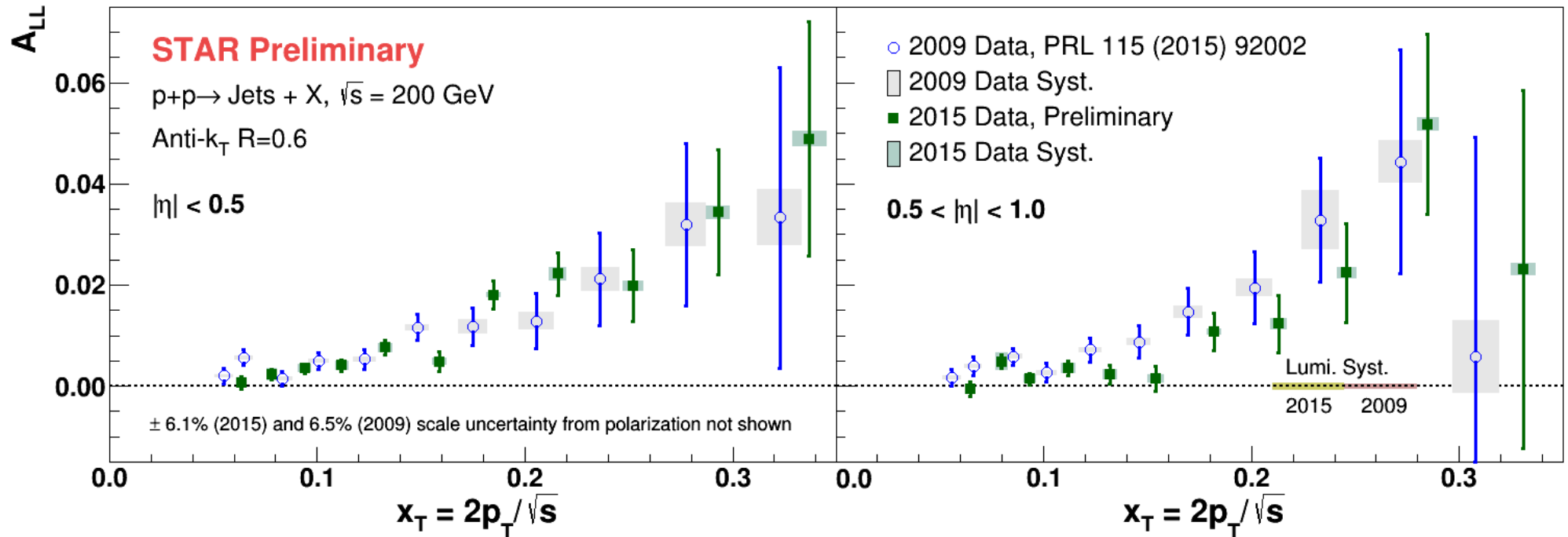
- Different eta ranges probe different gluon momentum fractions x $\quad x \approx x_T e^{-\eta}$
  - For x$_T$ = 0.1, x ~ 0.1 (η = 0), x ~ 0.06 (η = 0.5), x ~ 0.038 (η = 1)

- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
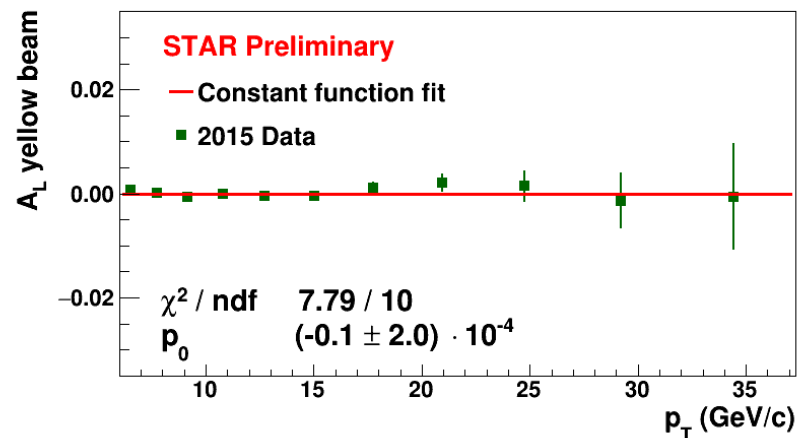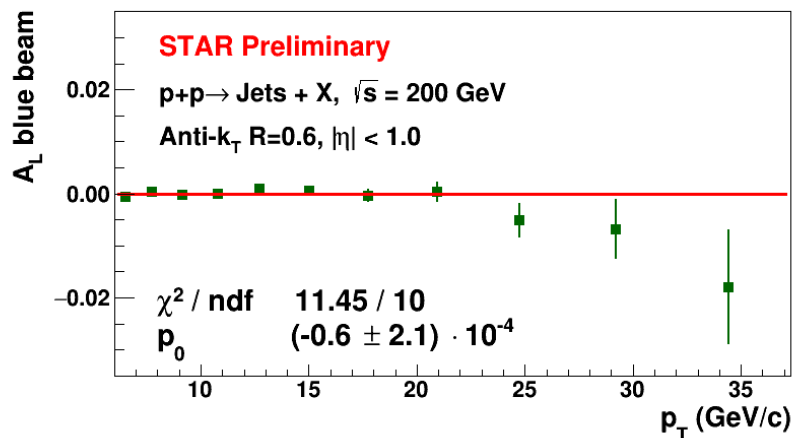- Twice larger figure-of-merit (LP^4) with improved systematics

CROSS-CHECK ASYMMETRIES
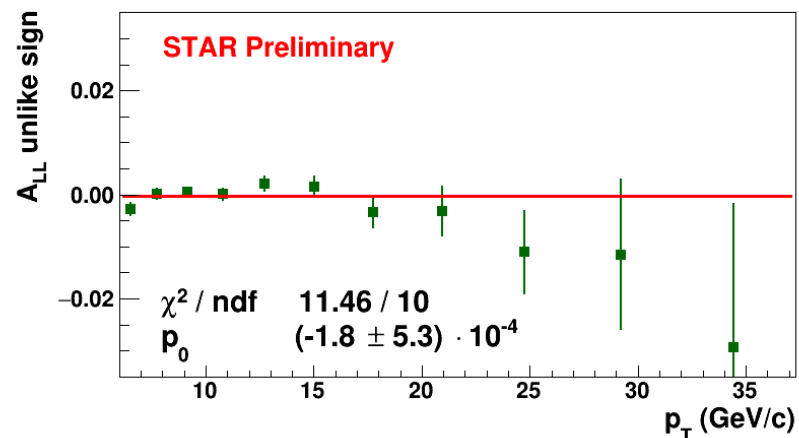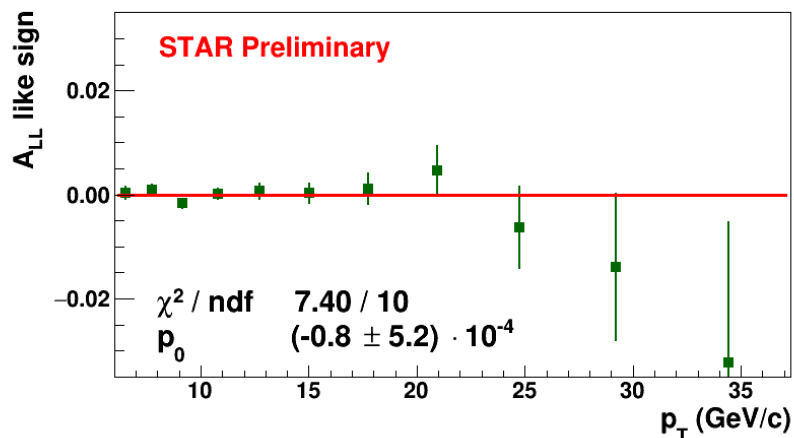
Single spin asymmetries as well as like-sign and unlike-sign double spin asymmetries determined to **cross-check** for missed systematic effects
- All asymmetries well consistent with zero within uncertainties

SUMMARY AND OUTLOOK

1. Insight into **gluon polarization ΔG(x)** at STAR
   - Possible through longitudinal double spin asymmetries of inclusive jets and di-jets

2. 2009 data at $\sqrt{s}$ = 200 GeV PRL 115 (2015) 9, 092002 included in global perturbative QCD analysis provided **evidence for positive gluon polarization** for x > 0.05

3. New impactful preliminary results on inclusive jet A_{LL} from 2015 dataset at 200 GeV

   - Significantly improved systematics and twice larger FoM
   - Work to finalize data near-complete
   - Analysis of di-jets A_{LL} from 2015 dataset in progress (N. Lukow, Temple)
   - Publication in preparation