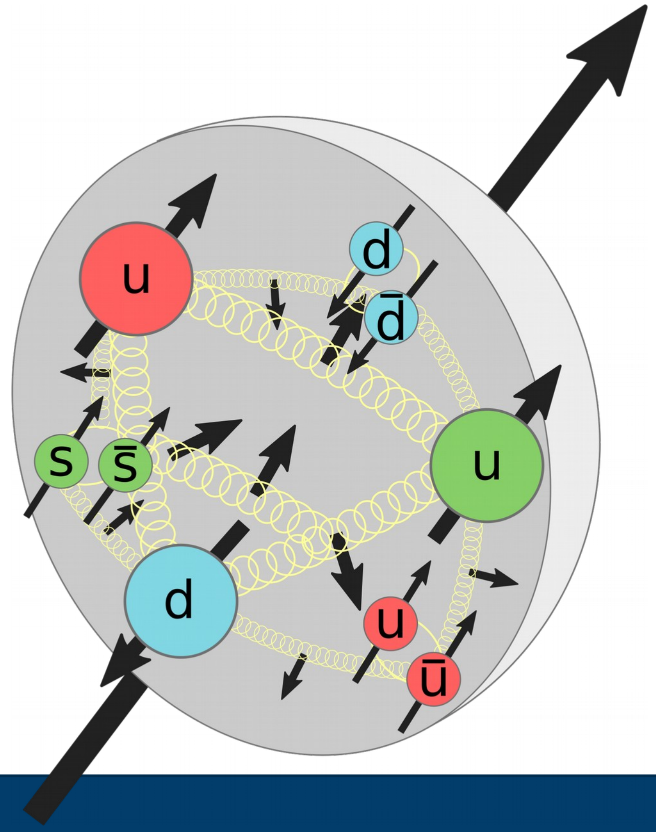
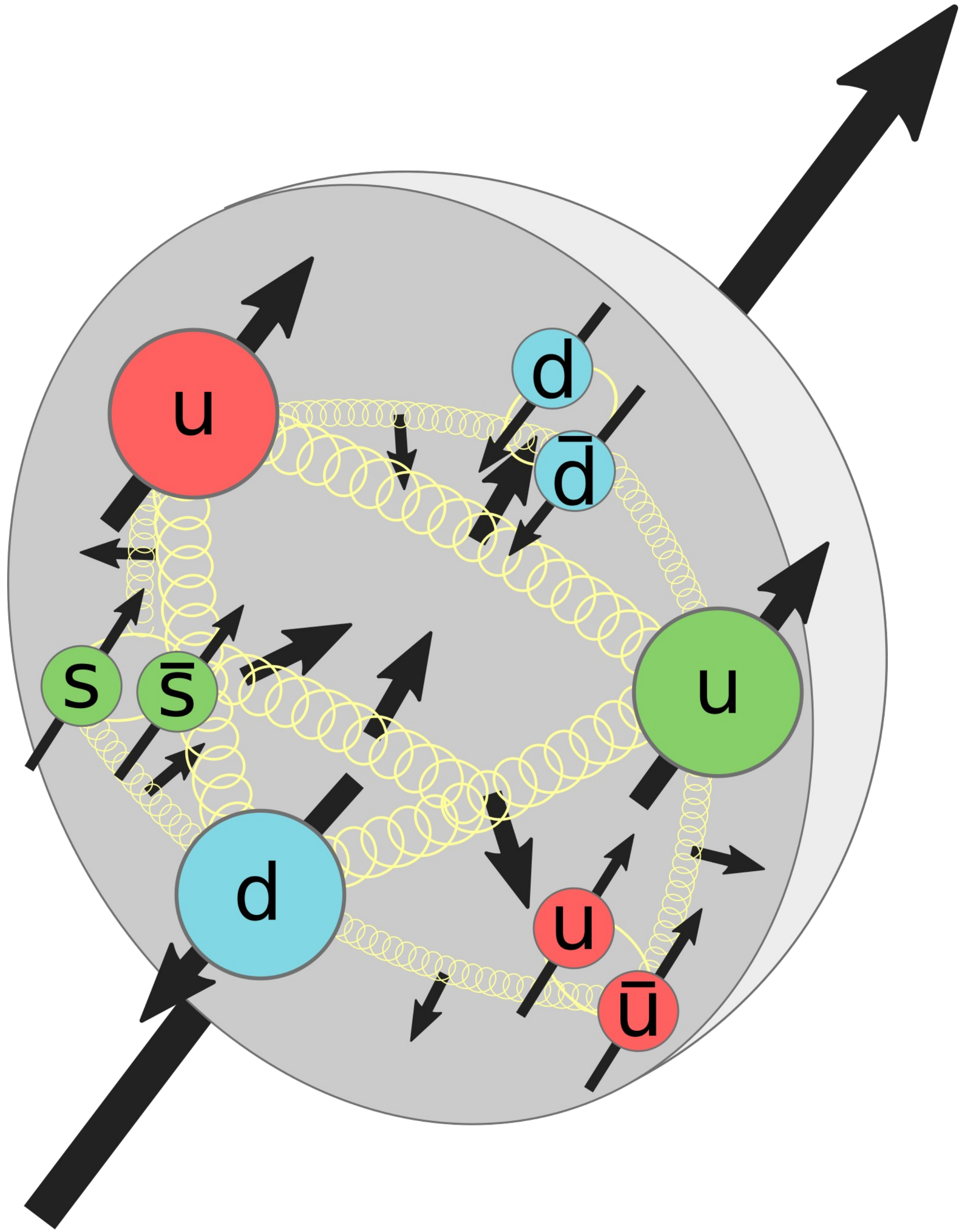


Studying the gluon helicity distribution with jets with the STAR experiment

LBNL NUCLEAR SCIENCE DIVISION MEETING | 23 FEBRUARY 2021 | MARIA ŻUREK



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GLUON HELICITY DISTRIBUTION

STAR spin program goal:

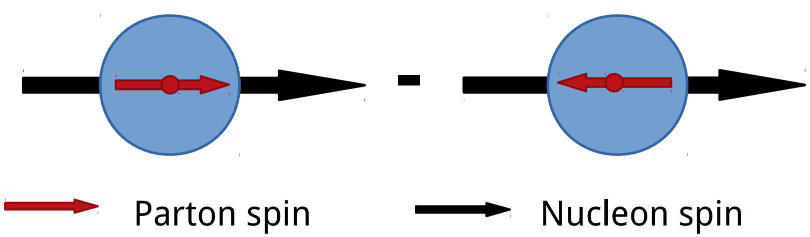
- Delineate the **spin structure of the proton** in terms of quarks and gluons and study the role of spin in QCD

Tool:

- **Strong interactions** in polarized proton-proton collisions (complementary with DIS measurements)

How do gluons contribute to the proton spin?

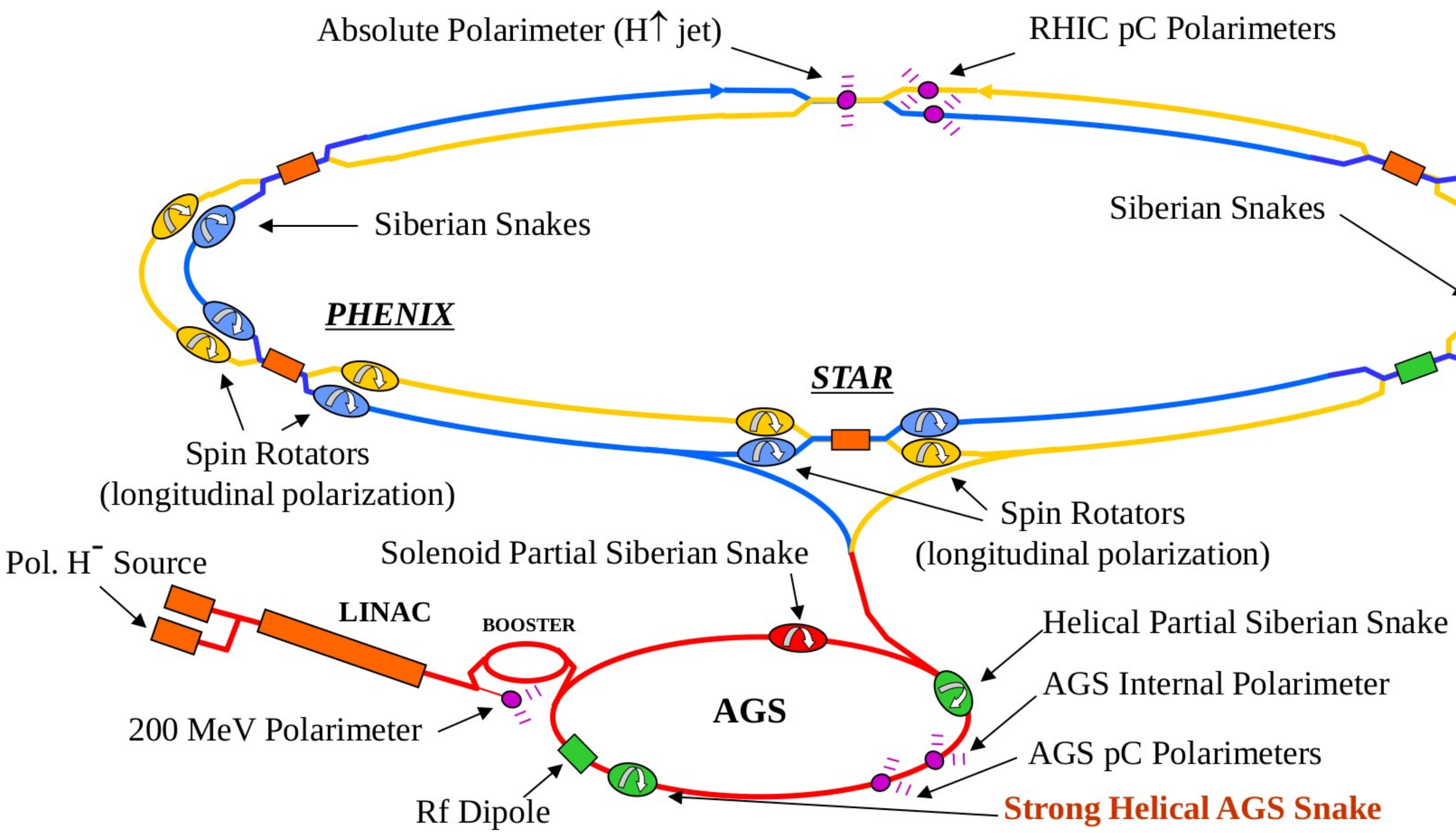
$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$



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

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

RHIC – POLARIZED PROTON COLLIDER

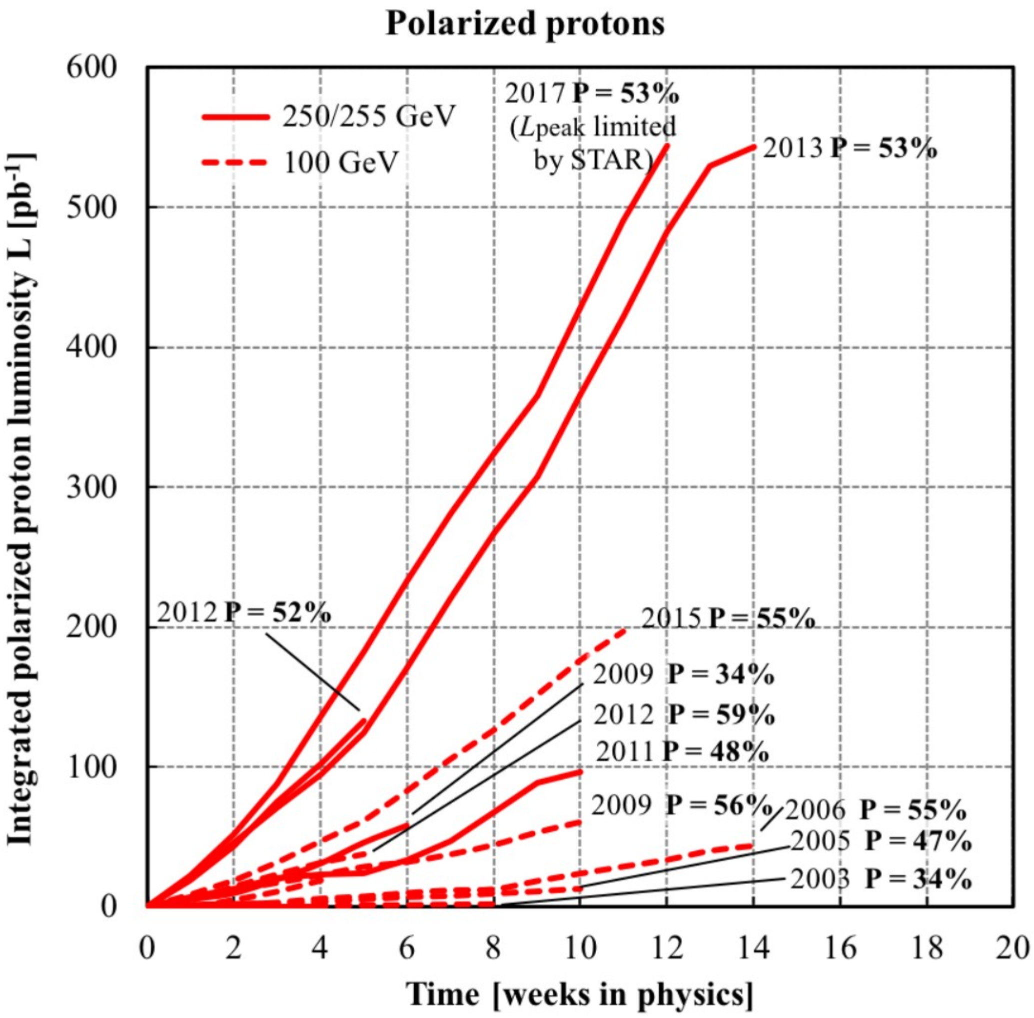


- The only polarized high-energy proton-proton collider
- Transverse and longitudinal polarization
- Polarized protons $\sqrt{s}$ = 62, 200, 500 GeV
- Alternating spin configurations bunch by bunch and fill by fill

Hard scattering processes with control of systematic effects

LONGITUDINALLY POLARIZED DATASETS

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



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

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

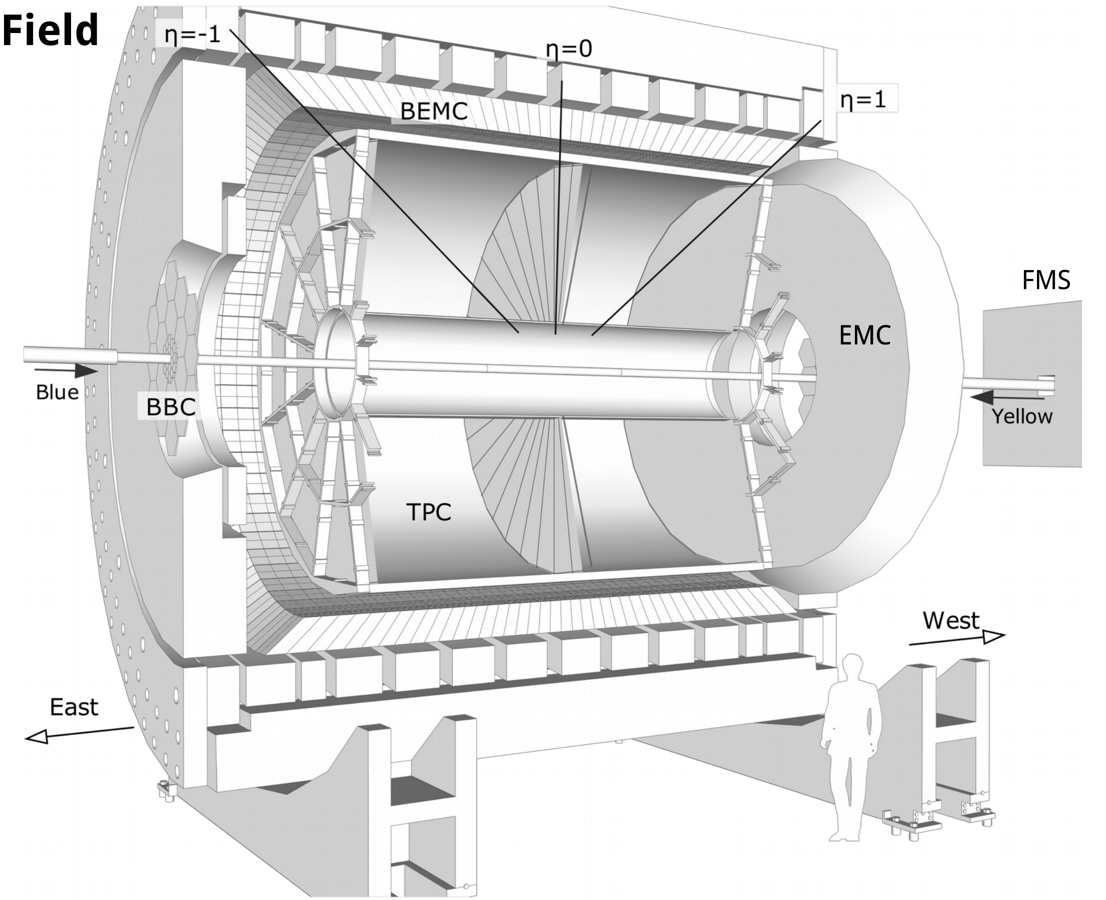
2. Electromagnetic Calorimeter
$\Delta\varphi = 2\pi$, $-1 < \eta < 2$
Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

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

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

5. Vertex Position Detector
Zero Degree Calorimeter
Beam-Beam Counter
- Relative luminosity and Minimum Bias trigger

Roman Pots



Characteristics
- Large acceptance (tracking and calorimetry)
- **Good detector for jets**
- Upgrades: iTPC, EPD, ETOF, Fwd Upgrade

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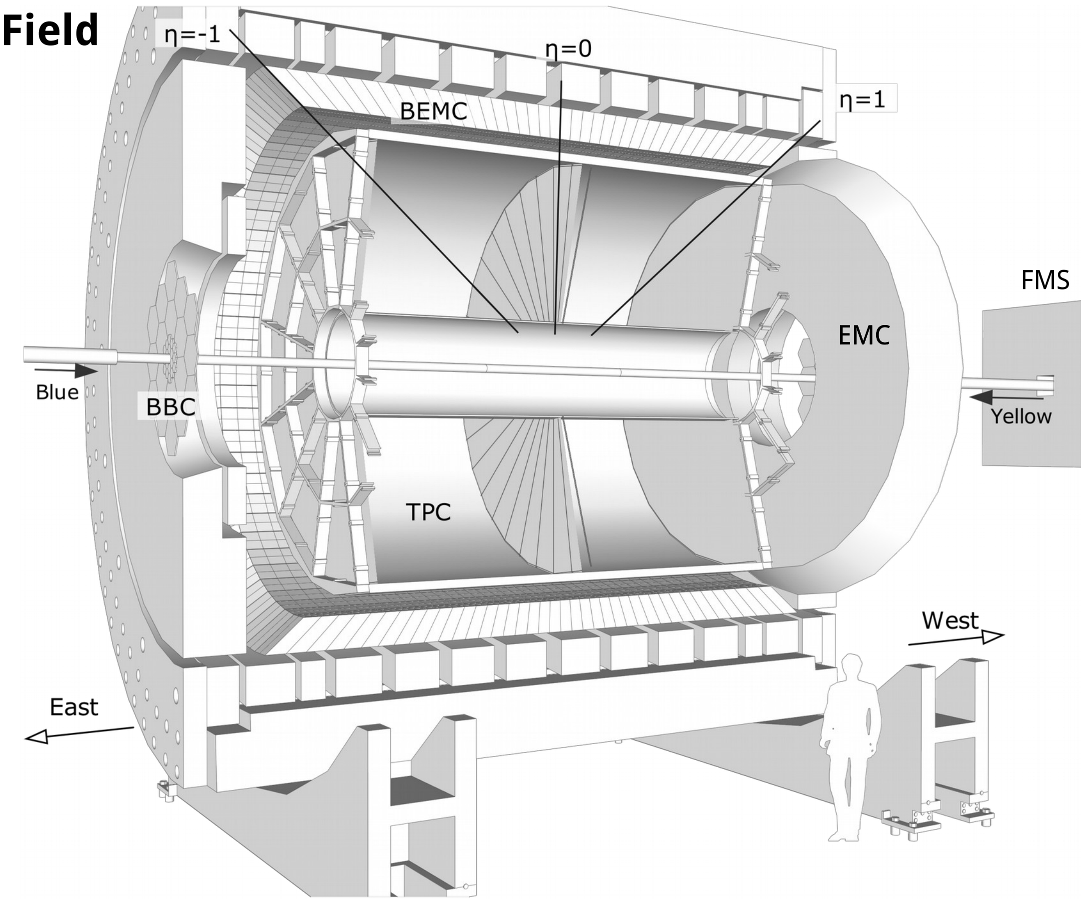
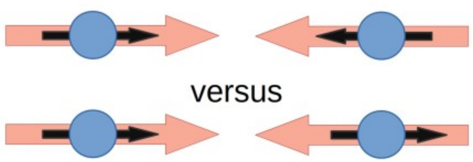


Characteristics
- Large acceptance (tracking and calorimetry)
- **Good detector for jets**
- Upgrades: iTPC, EPD, ETOF, Fwd Upgrade

HOW TO ACCESS ΔG?

At pp collider: leading order access to gluons → **ΔG/G**

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

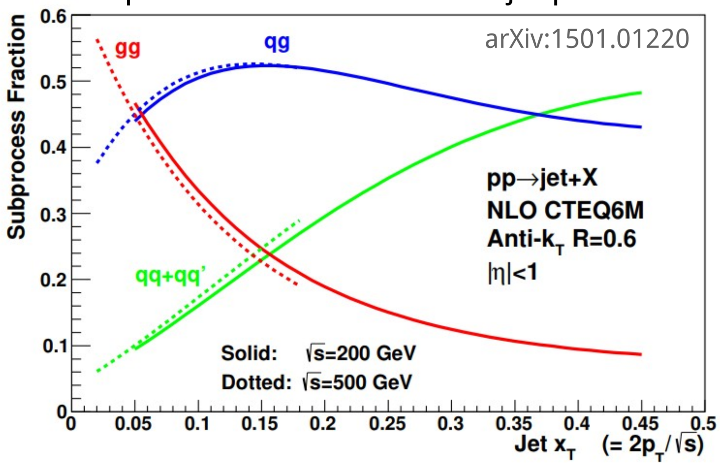


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a\hat{_{LL}}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

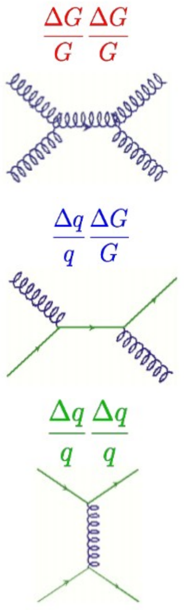
LO for illustration

Which processes dominate at RHIC?

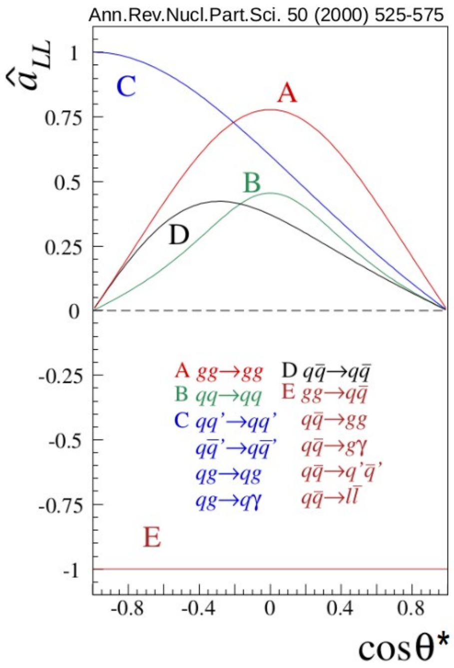
Subprocess fraction in central jet production



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



What are a_{LL} for these processes?

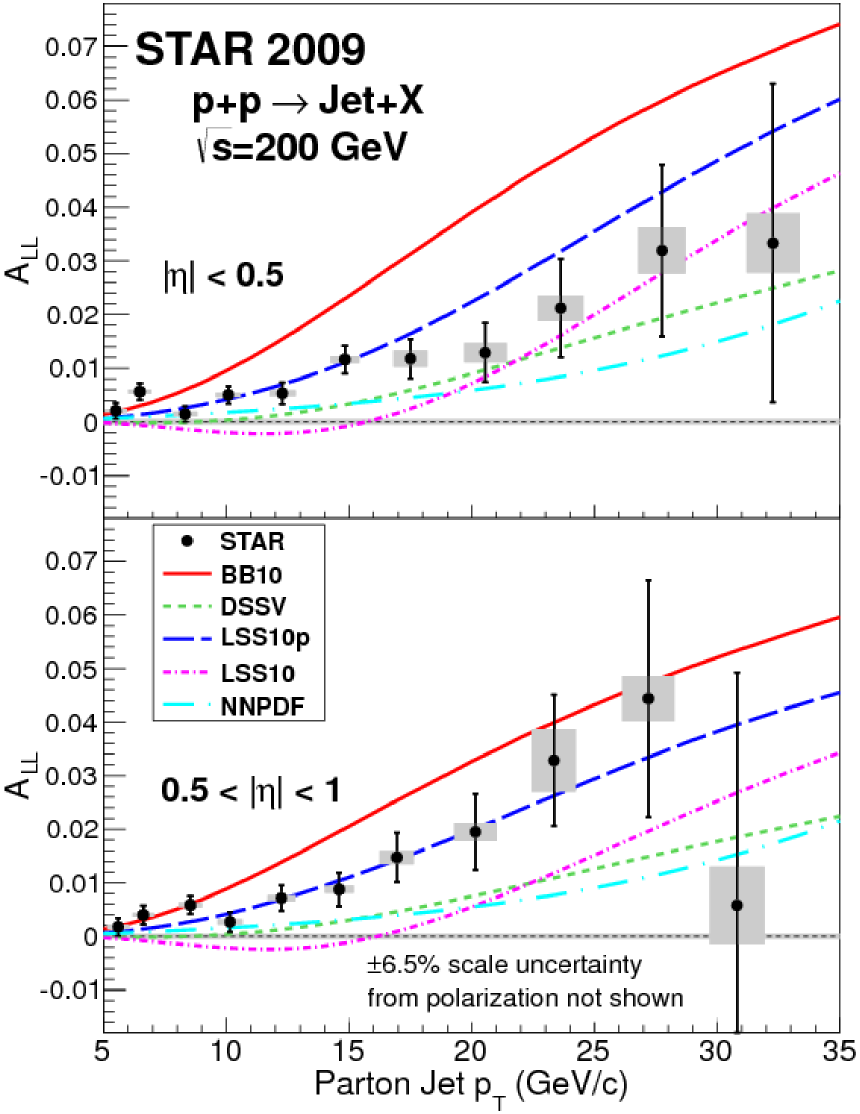


- Cross-section measurement to support the NLO pQCD interpretation of asymmetries

STATUS OF ΔG

Precision A_{LL}

PRL 115 (2015) 9, 092002



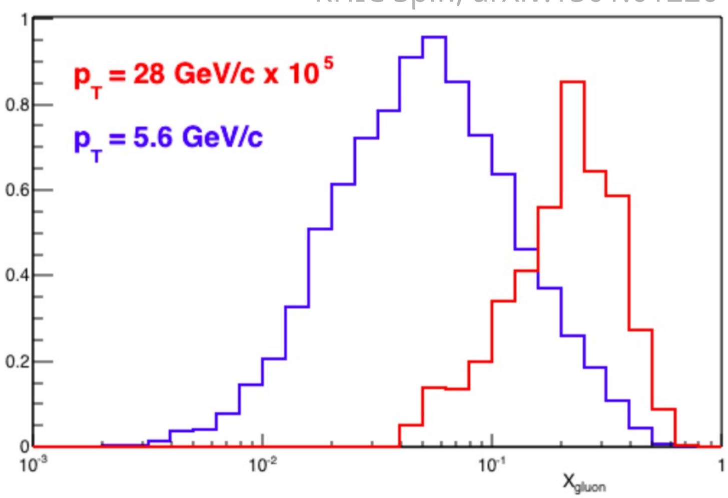
1. A_{LL} positive for large p_T - **positive gluon polarization**

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

RHIC Spin, arXiv:1501.01220

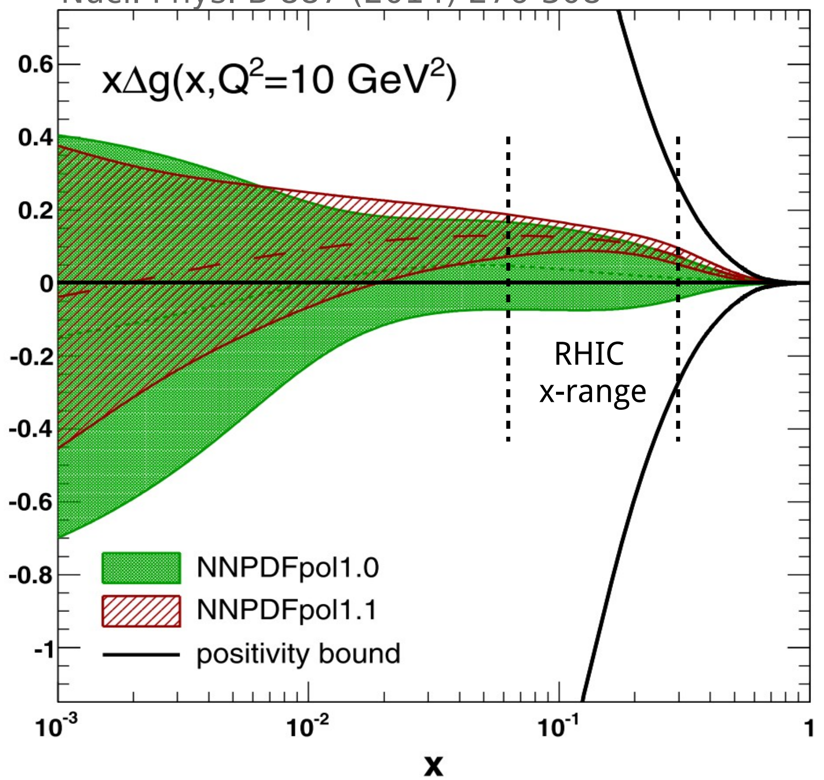


Relative contributions of gluons with a given x probed in different jet p_T regions

STATUS OF ΔG

Impact of A_{LL} from 2009 data on ΔG

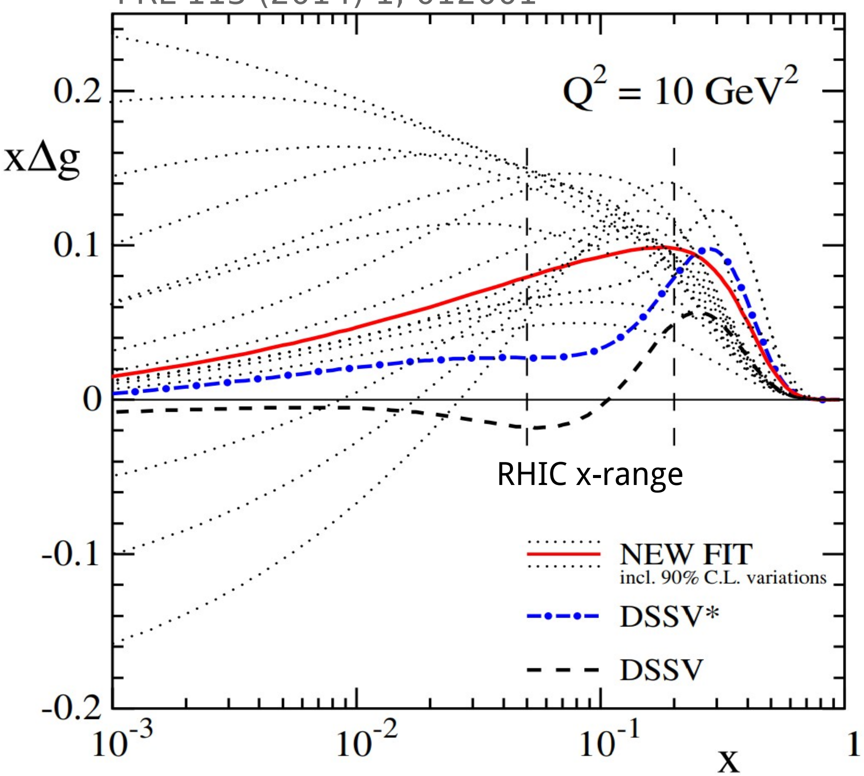
Nucl. Phys. B 887 (2014) 276-308



NNPDFpol1.0 – do not include STAR 2009 data
NNPDFpol1.1 – include STAR 2009 data

$$0.23 \pm 0.07, \quad 0.05 < x < 0.5$$

PRL 113 (2014) 1, 012001



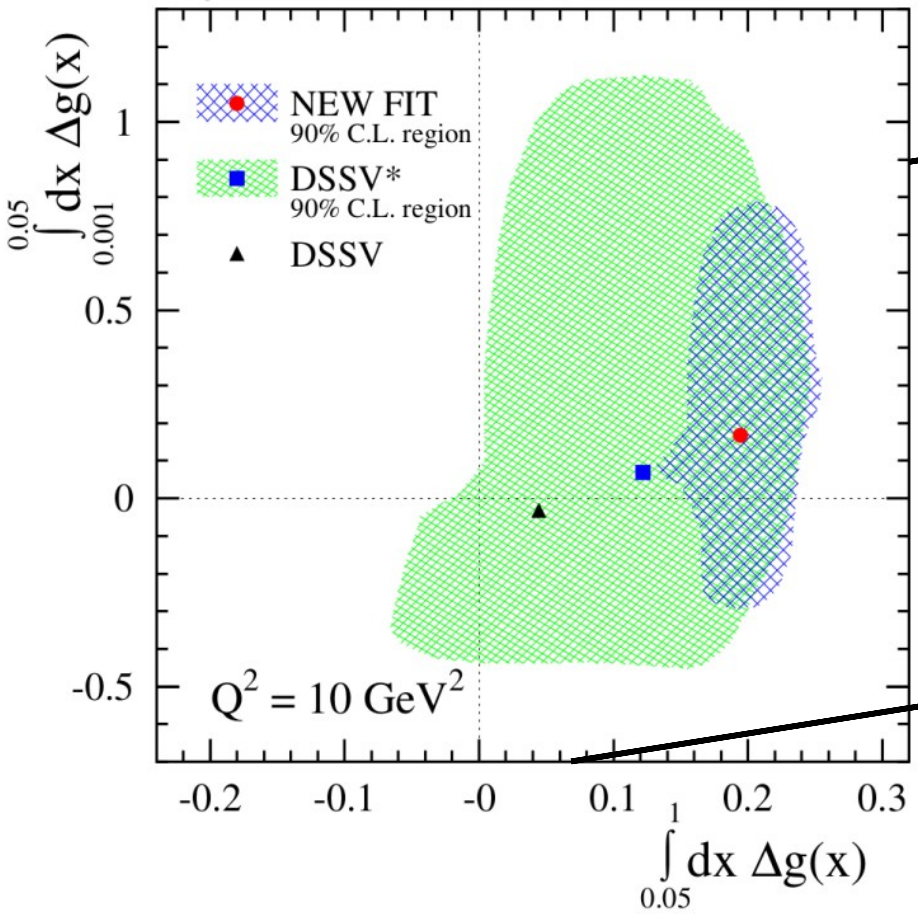
DSSV – DIS, SIDIS, BNL-RHIC, preliminary 2005 and 2006 STAR data
DSSV* – the final STAR jet results from 2005 and 2006
DSSV New fit – STAR 2009 data included

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

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:

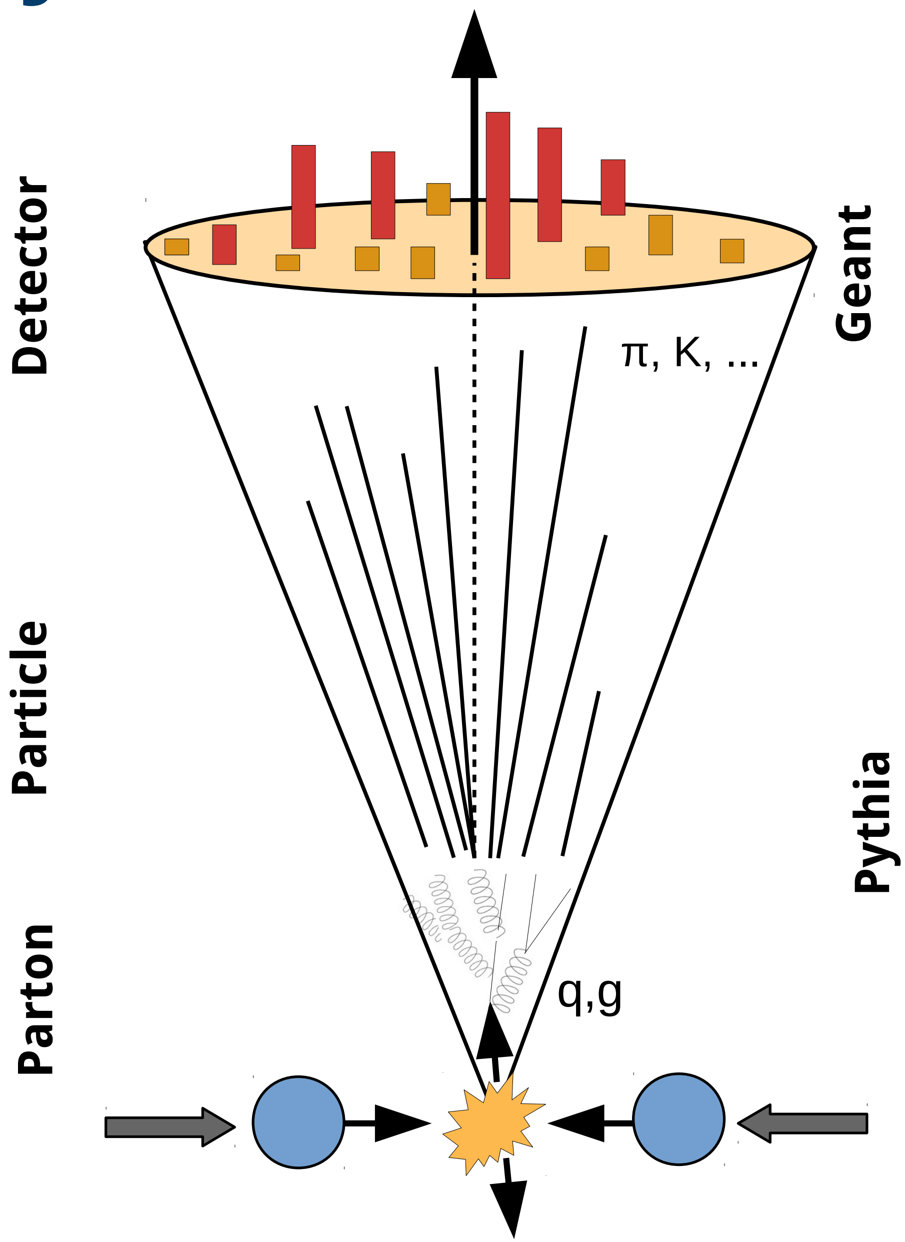
- Jet and neutral pion probes
- Complementary probes (di-jets)

Near-term improvements from STAR for $x > 10^{-2}$

Deep insight from future measurements at EIC at lower x

- Scaling violation in inclusive DIS: $g_1(x, Q^2)$

JET RECONSTRUCTION



Anti-kT algorithm via FastJet

Cacciari, Salam, Soyez, Eur. Phys. J. C 72, 1896 (2012)
Cacciari, Salam, Soyez, JHEP 04, 063 (2008)

PYTHIA + GEANT + Zero-bias events for embedding

Jets reconstructed at **three levels**:

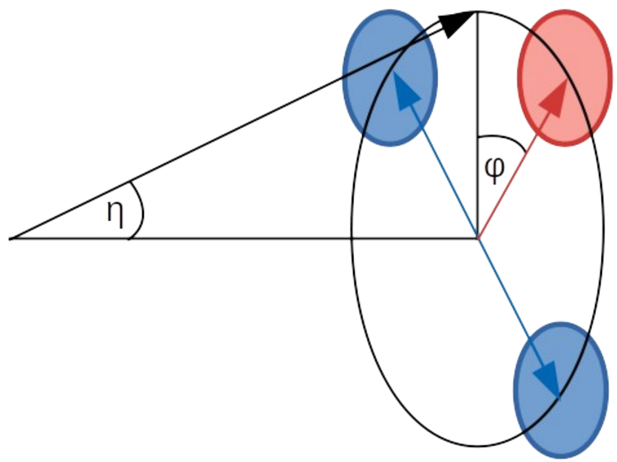
- **Detector level:** detector response to stable particles (takes into consideration finite detector acceptance, efficiency and resolution effects)
- **Particle level:** complete set of stable color-neutral particles produced in the event
- **Parton level:** hard-scattered partons from Pythia event
  - Initial-state and final-state radiation associated with the process included
  - No partons from beam remnants and multiple parton interactions

JET RECONSTRUCTION

Underlying event correction

Improved method compared to 2009 results used 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



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 for 2015 data:
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

Jets **corrected back to parton** level

- Detector jet p_T – parton jet p_T correction values:
- (for 2015 data) 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

DOUBLE-SPIN ASYMMETRY

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), e. g. for 2015 data: $P_B = 0.523 \pm 0.016$, $P_Y = 0.565 \pm 0.017$
CNI Polarimetry Group, https://wiki.bnl.gov/rhicspin/Results
R_3 – relative luminosity calculated using hit information from the Vertex Position Detector (VPD)

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

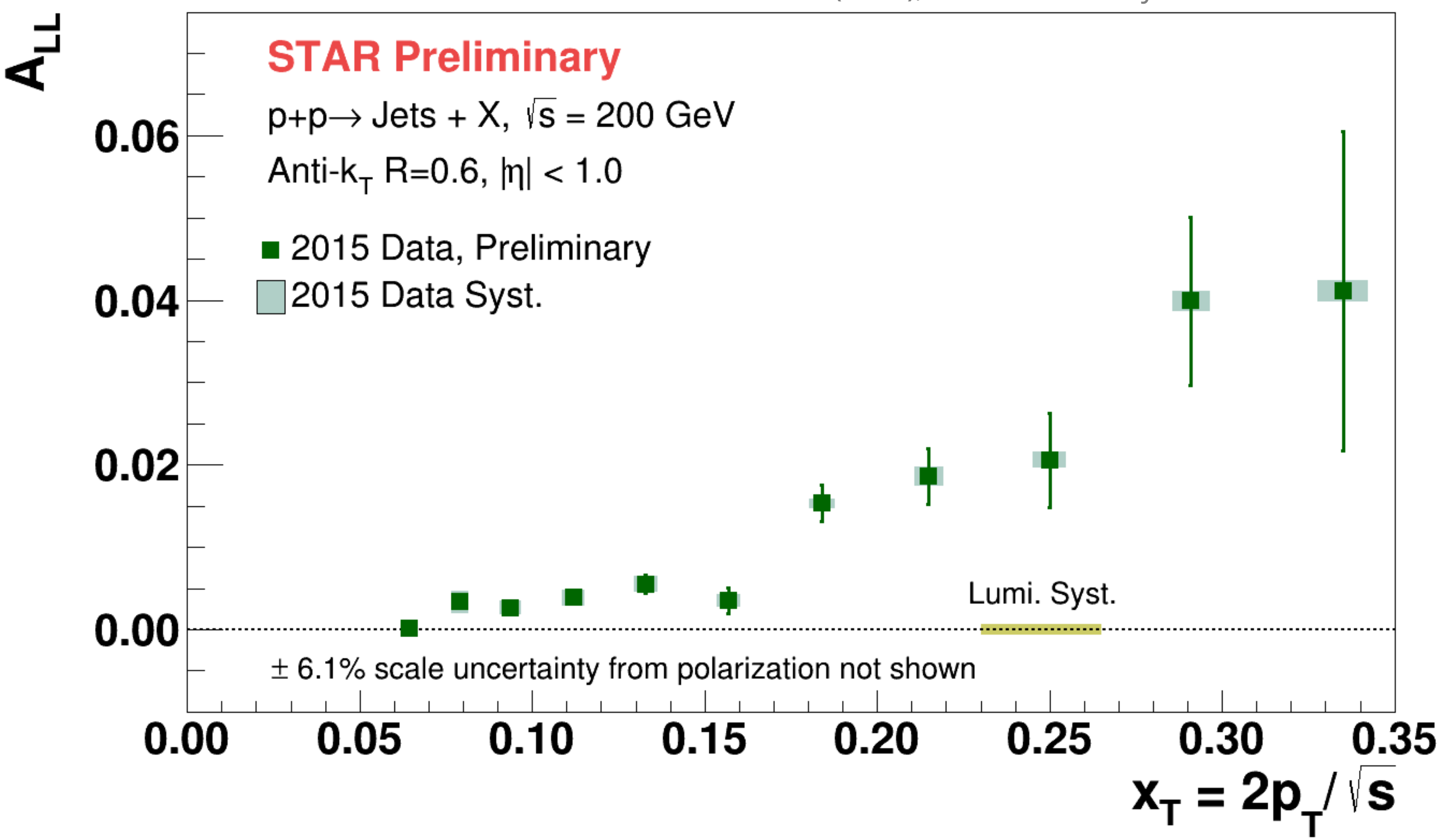
- For 2015 data R_3 varies from 0.96 to 1.04 depending on the fill with the uncertainty of $\Delta R_3 \sim 4.5 \times 10^{-4}$ (Uncertainty similar to 2009 data)

INCLUSIVE JET A_{LL}

The most precise 200 GeV dataset likely to **conclude the 200 GeV longitudinal program with jets.**

- Preliminary result on jet and dijet A_{LL} from STAR from 2015 data.

MŻ et. al (STAR), BNL Nuclear Physics Seminar 2020



- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit ($\mathcal{L}P^4$) with improved systematics
- Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits

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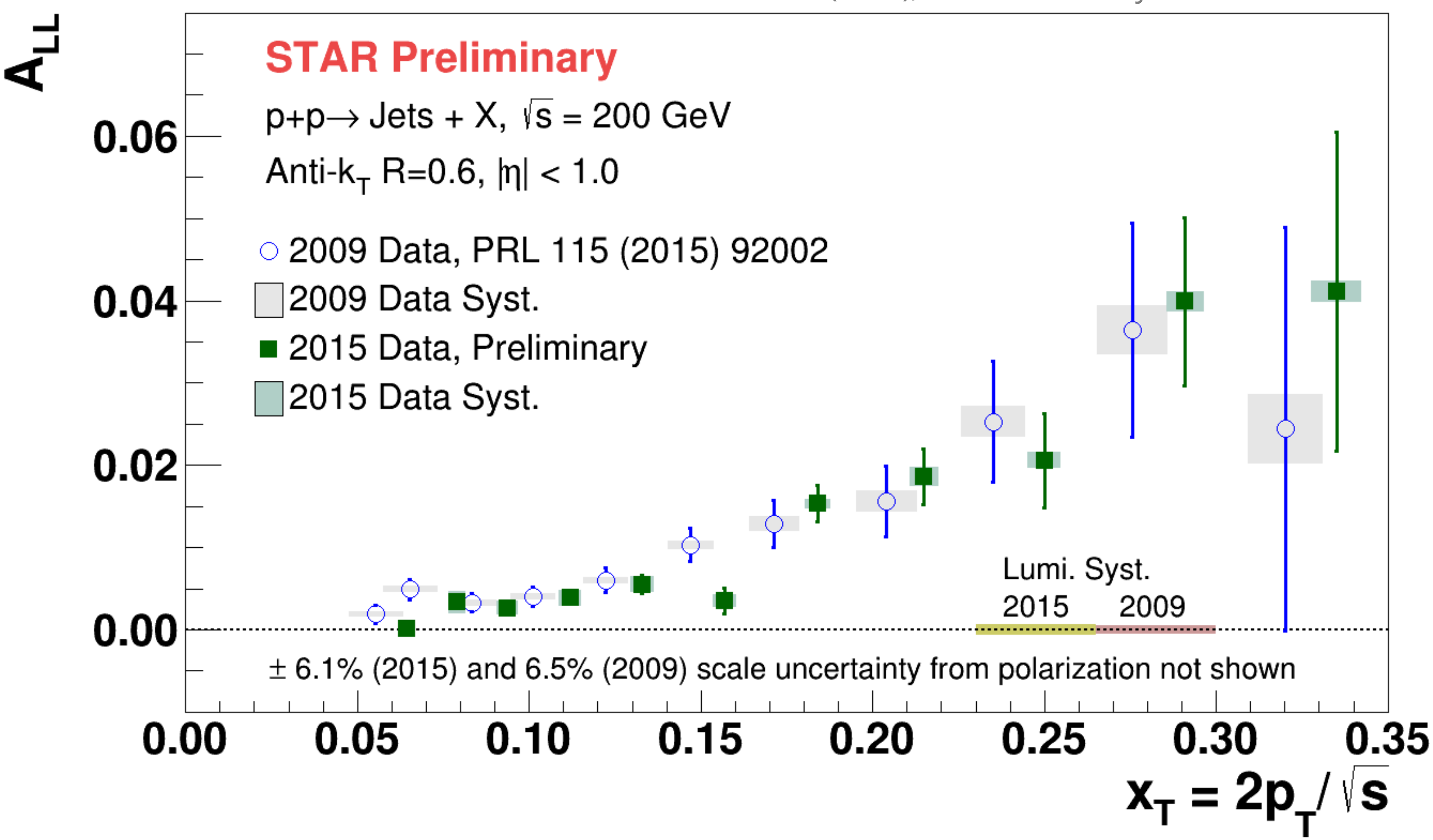

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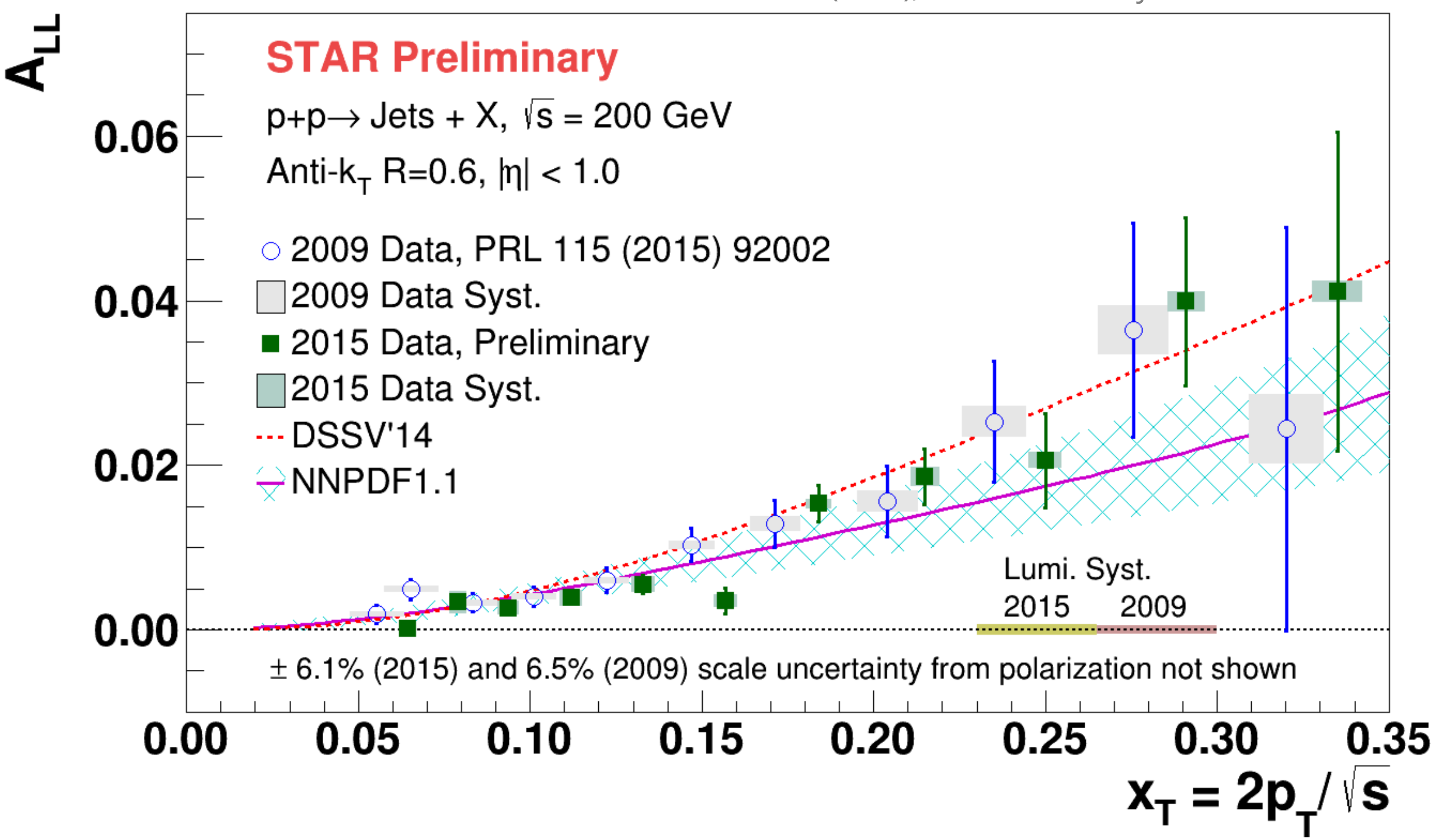
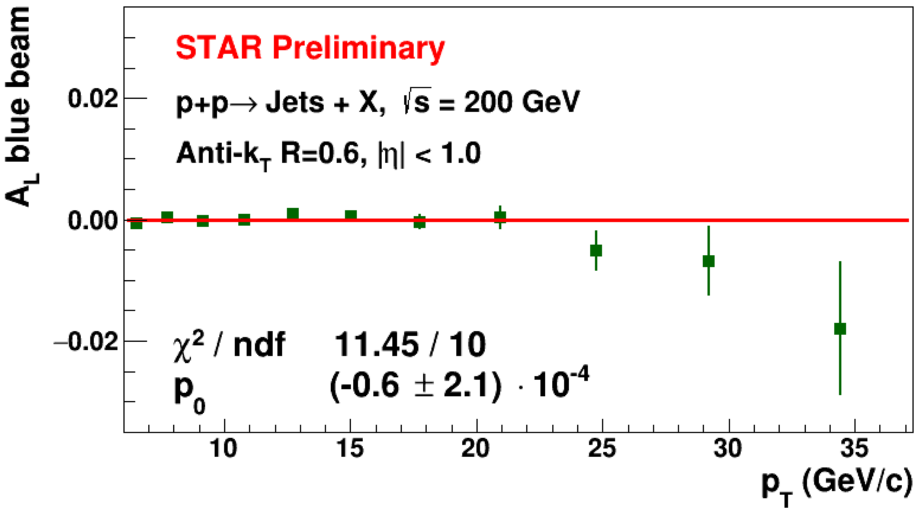
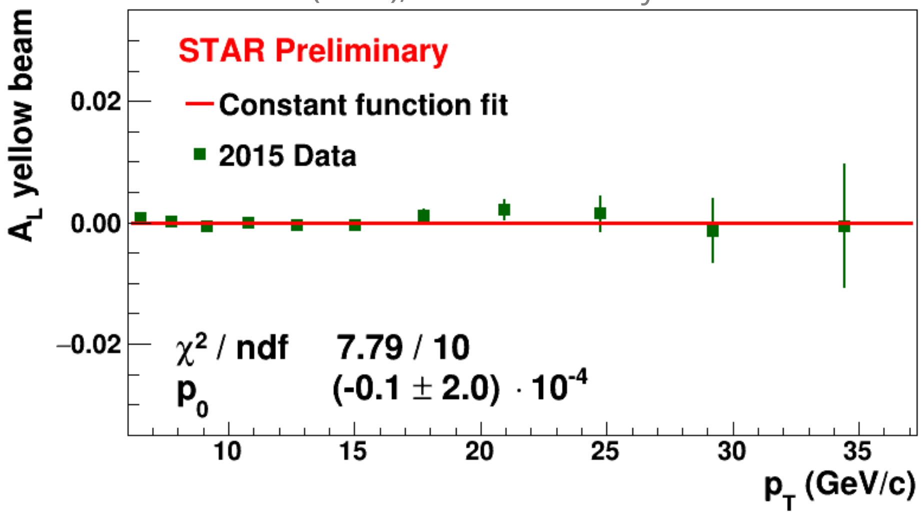


- Consistent with 2009 data, which provided first evidence for positive ΔG for x > 0.05
- Twice larger figure-of-merit (LP^4) with improved systematics
- Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits

SINGLE-SPIN ASYMMETRIES

MŻ et. al (STAR), BNL Nuclear Physics Seminar 2020





Parity violating single-spin asymmetries are **expected to be negligibly small** at 200 GeV

$$A_L \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Substantial **unaccounted systematic effects** would easily dominate these A_L

Observed asymmetries **vanish to within their statistical uncertainties**

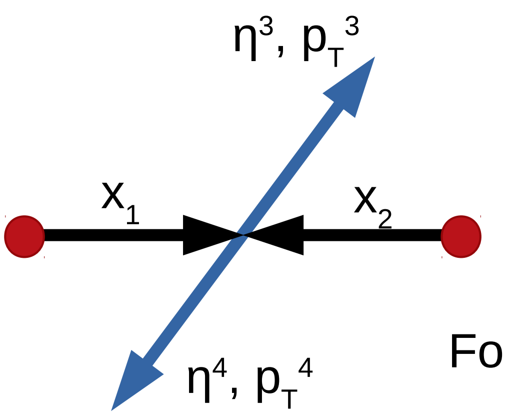
- Consistent well with the expectation

DIJET MEASUREMENTS

- Di-jets give stricter constraints to underlying **partonic kinematics**
- May place better constraints on **functional form of Δg(x)**

$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \qquad M = \sqrt{x_1 x_2 s} \qquad |\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right| \qquad \text{(LO)}$$

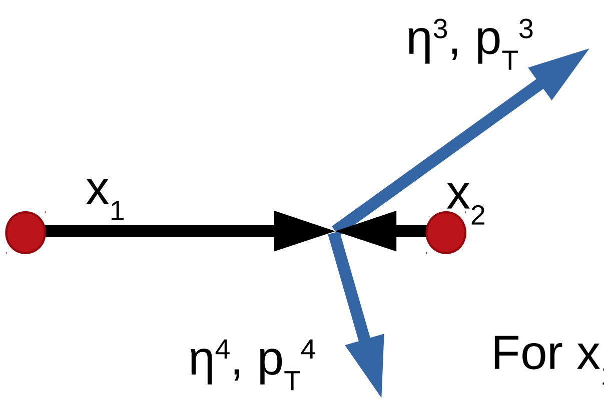
“Unlike sign topology”



For $x_1 = x_2$

Symmetric collisions

“Same sign topology”



For $x_1 > x_2$

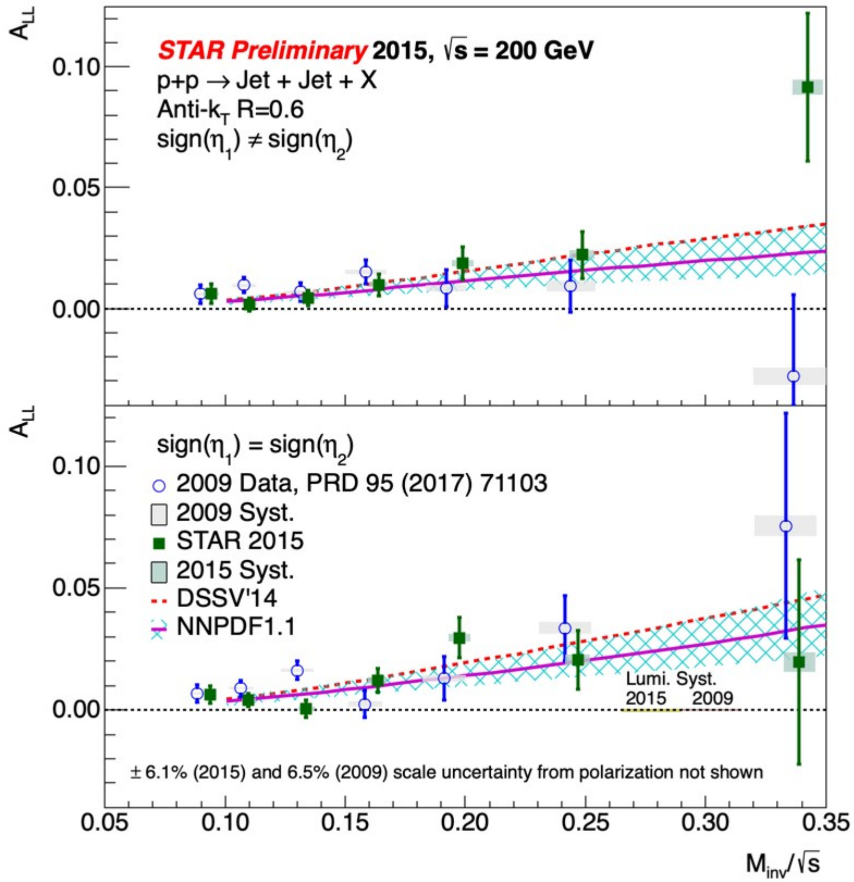
Asymmetric collisions

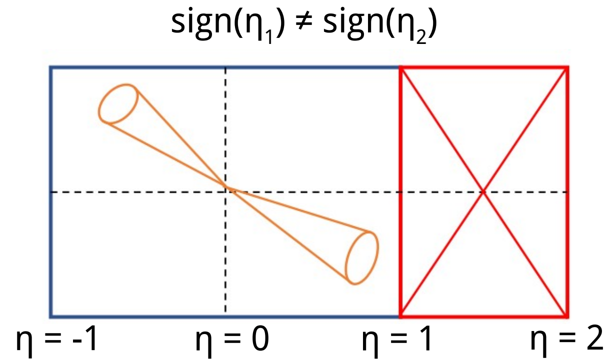
Forward jets probe lower values of x_g
For large asymmetry, likely: 2 – gluon, 1 – quark

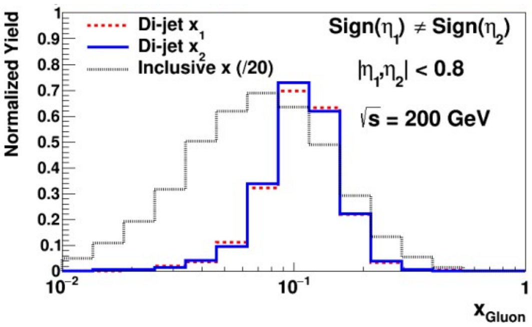
DIJETS AT 200 GEV

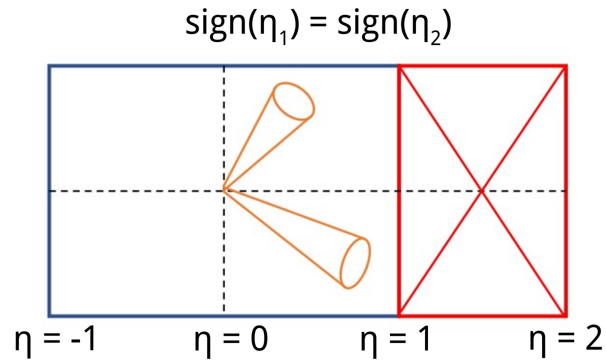
Towards higher precision at x > 0.05

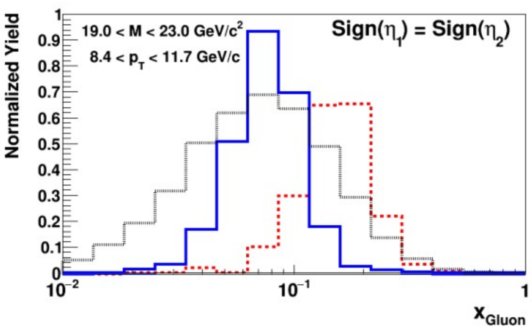
N. Lukow et. al (STAR), RAUM 2020









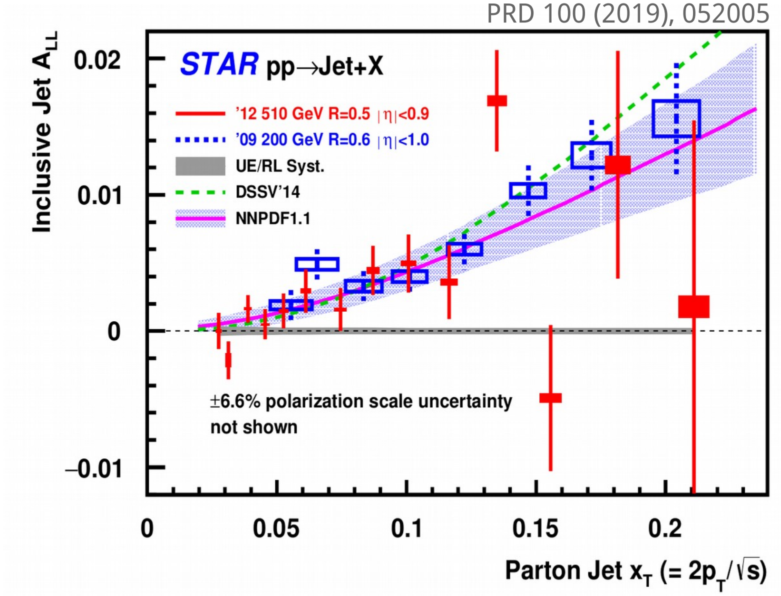


- More-forward production - **lower x down to 0.01,** x_2 – likely gluon, x_1 – likely quark
- **Narrow ranges** of initial state partonic momentum tested

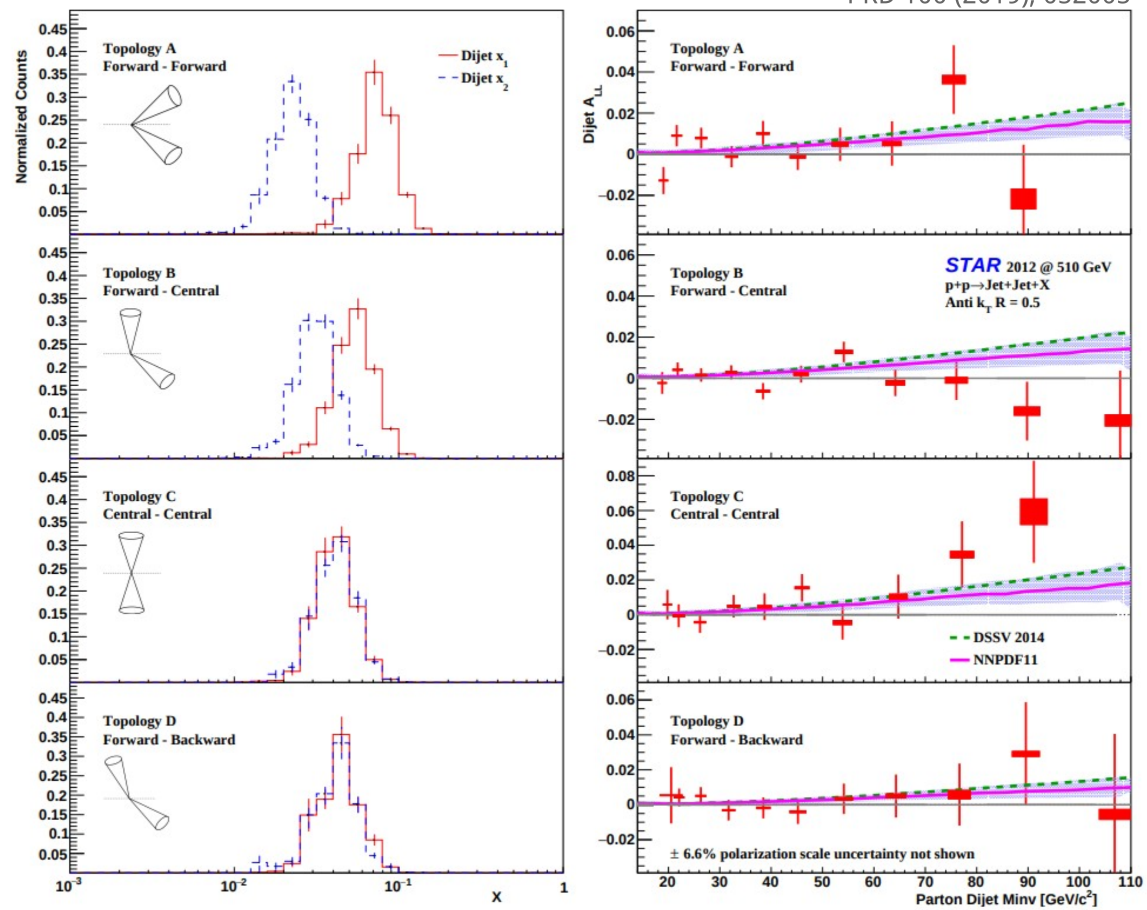
JETS AT 510 GEV

Towards smaller x and complementary probes

PRD 100 (2019), 052005



PRD 100 (2019), 052005



- **Higher √s pushes sensitivity to lower x = 0.02**
- Consistent results from both energies

Further precision: Run 2013 √s = 510 GeV – x 3.2 statistics

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 results on inclusive jets and dijets A_{LL} from 2015 dataset at 200 GeV
   - The most precise 200 GeV dataset likely to **conclude the 200 GeV longitudinal program with jets**
   - Among the most impactful results on **ΔG(x)** available before the Electron-Ion Collider will come online

4. Gluon polarization at **lower x** < 0.05
   - Improvements from STAR at 510 GeV and more forward rapidity (up to x = 10^{-2})
   - Deep insight from future measurements at EIC

BACKUP

MOTIVATION

Spin - unique probe to unravel the internal structure and QCD dynamics of nucleon

Partonic structure of hadronic matter

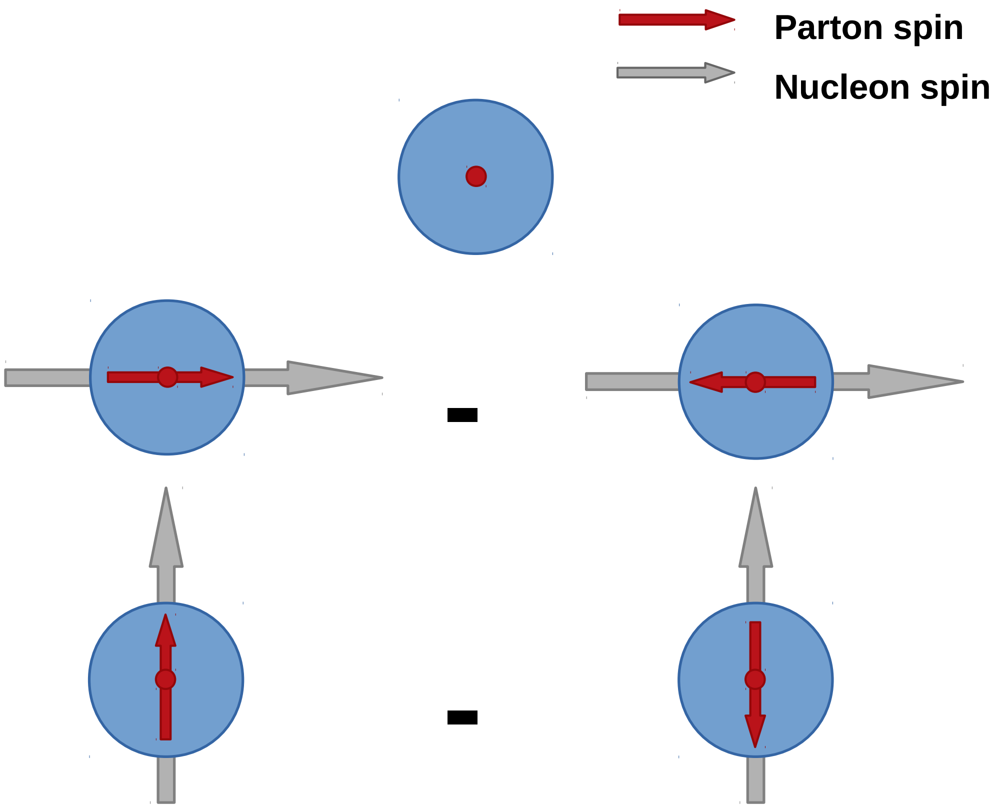
Parton distribution functions (PDFs):

- **Unpolarized: f(x)**
  Probability density for finding parton with momentum fraction x in the proton

- **Helicity: Δf(x)**
  Net density of partons with spin aligned with the longitudinally polarized nucleon

- **Transversity: δf(x)**
  Net density of partons with spin aligned with the transversely polarized nucleon

Transverse-momentum dependent PDFs

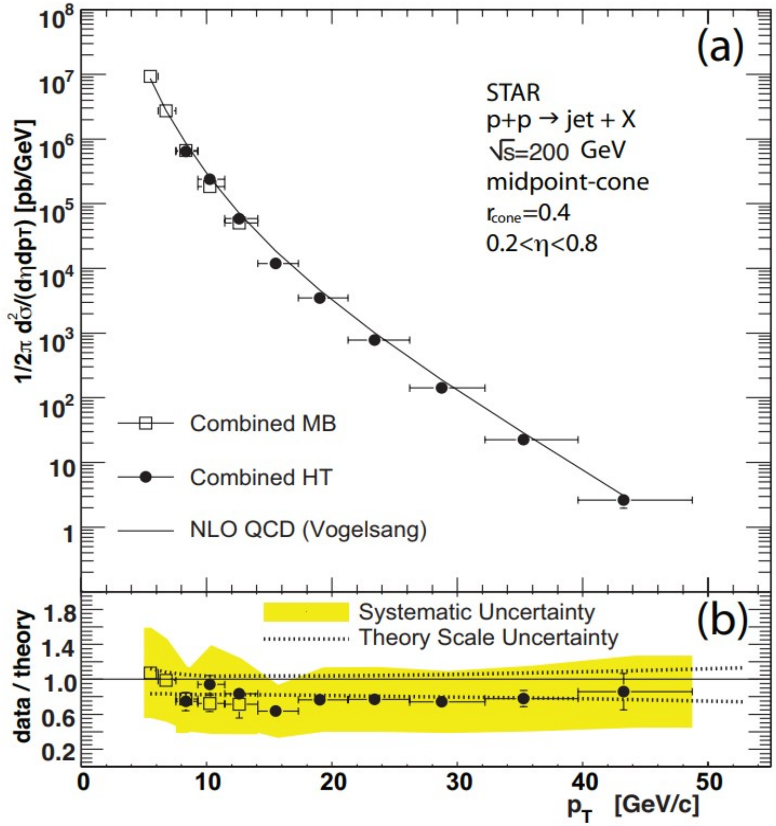


How do spin phenomena in QCD arise at the quark and gluon level?

JET CROSS-SECTIONS

Inclusive jet cross section

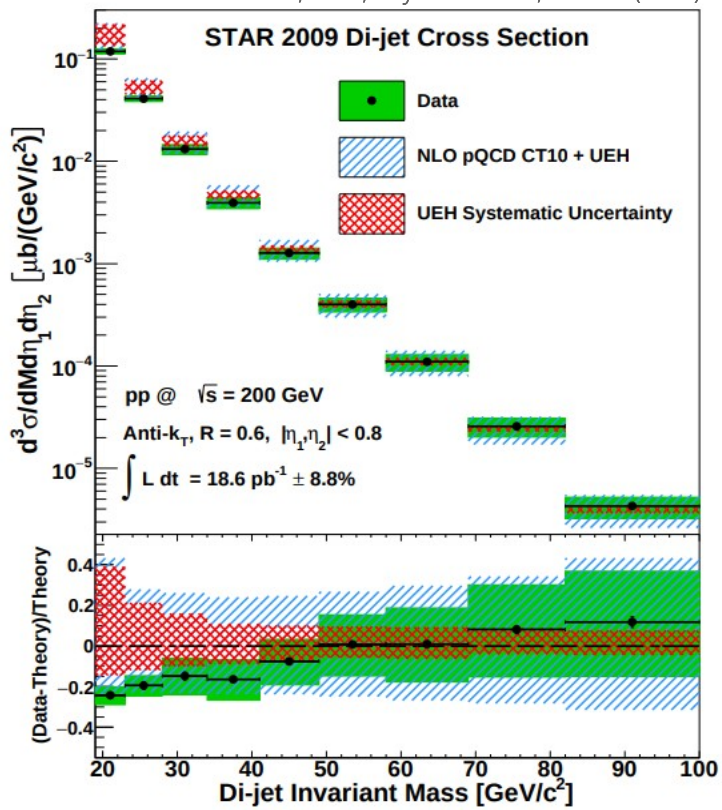
Data: Phys. Rev. Lett. 97 (2006) 252001
Theory: B. Jager et al., Phys. Rev. D 70, 034010 (2004)



- Midpoint cone algorithm
- No UE correction
- Bin-by-bin detector level corrections
- New measurement with improved analysis from STAR in progres

Dijet cross section

Data: Phys. Rev. D 95 (2017) 71103
Theory: D. de Florian, et al., Nucl. Phys. B 539, 455 (1999)
H. L. Lai, et al., Phys. Rev. D 82, 074024 (2010)



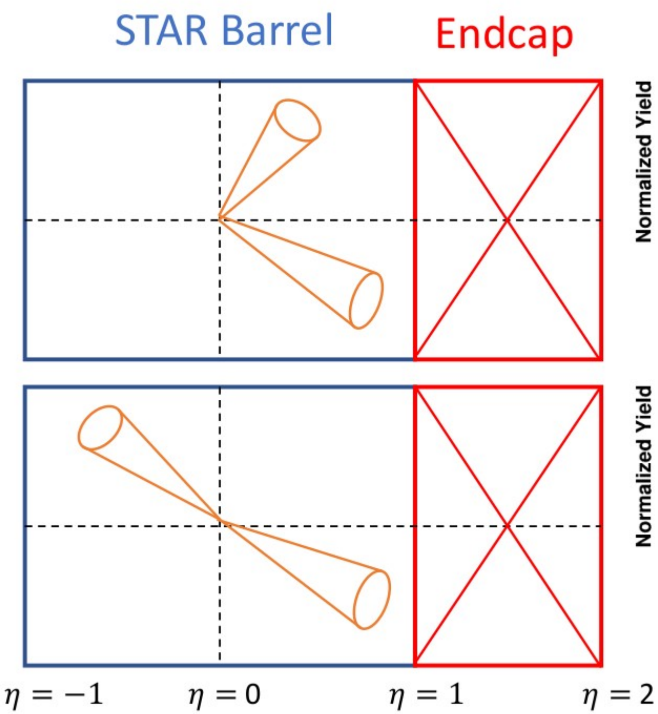
- Anti-k_T algorithm
- MC-driven UE correction
- Detector effects unfolded

Cross-section measurement support the **NLO pQCD** interpretation of asymmetries

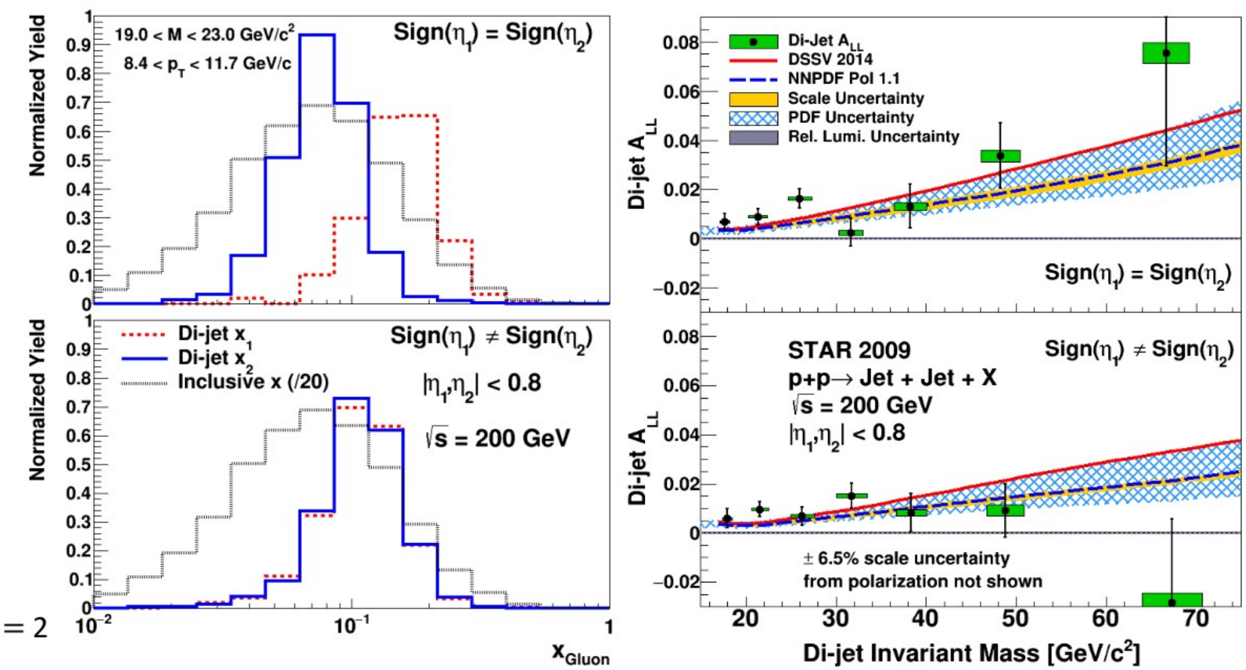
DI-JETS MEASUREMENT

Towards smaller x_g and complementary probes

- Di-jets give stricter constraints to underlying **partonic kinematics**
- May place better constraints on **functional form of Δg(x)**
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected x



Phys. Rev. D 95, 071103 (2017)

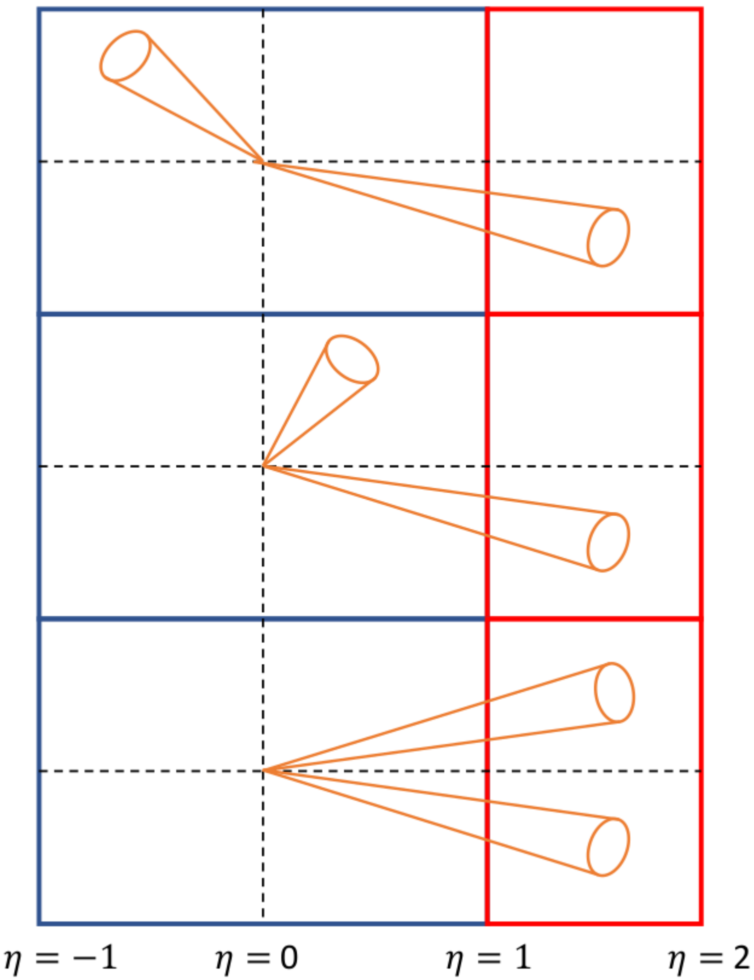


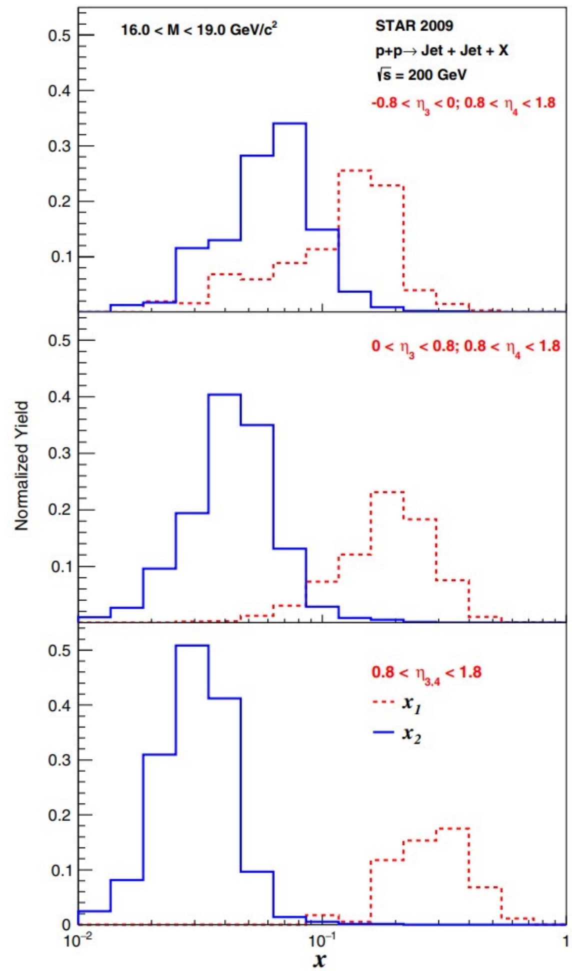
2015 data at 200 GeV (2x statistics)

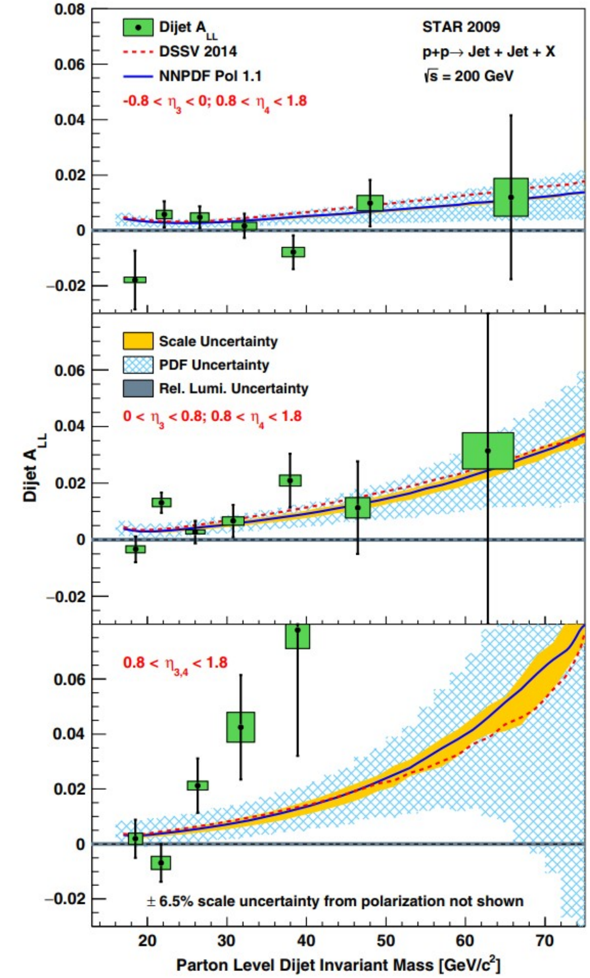
DI-JET MEASUREMENT

Towards smaller x_g and complementary probes

PRD 98 (2018), 032011





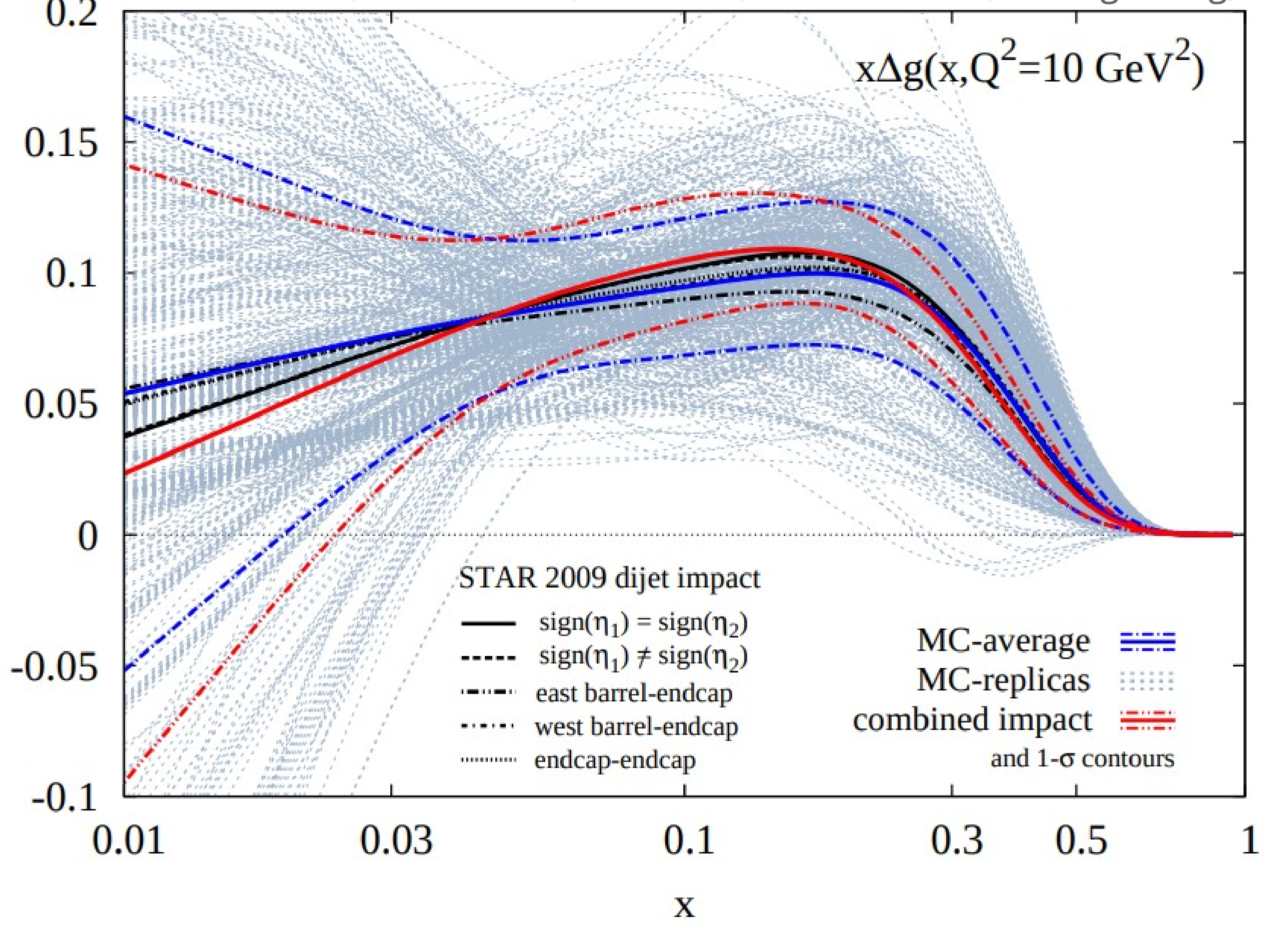


- Central di-jet measurement Run 2009 √s = 200 GeV (25 pb⁻¹): PRD 95 (2017), 071103
- Central di-jet measurement Run 2012 √s = 510 GeV (82 pb⁻¹): PRD 100 (2019), 052005
- Further precision: Run 2015 √s = 200 GeV – x 2 statistics, Run 2013 √s = 510 GeV – x 3.2 statistics

DIJET MEASUREMENT

Impact on $\Delta g(x)$

arXiv 1902.10548
D. de Florian, G. A. Lucero, R. Sassot, M. Stratmann, W. Vogelsang,

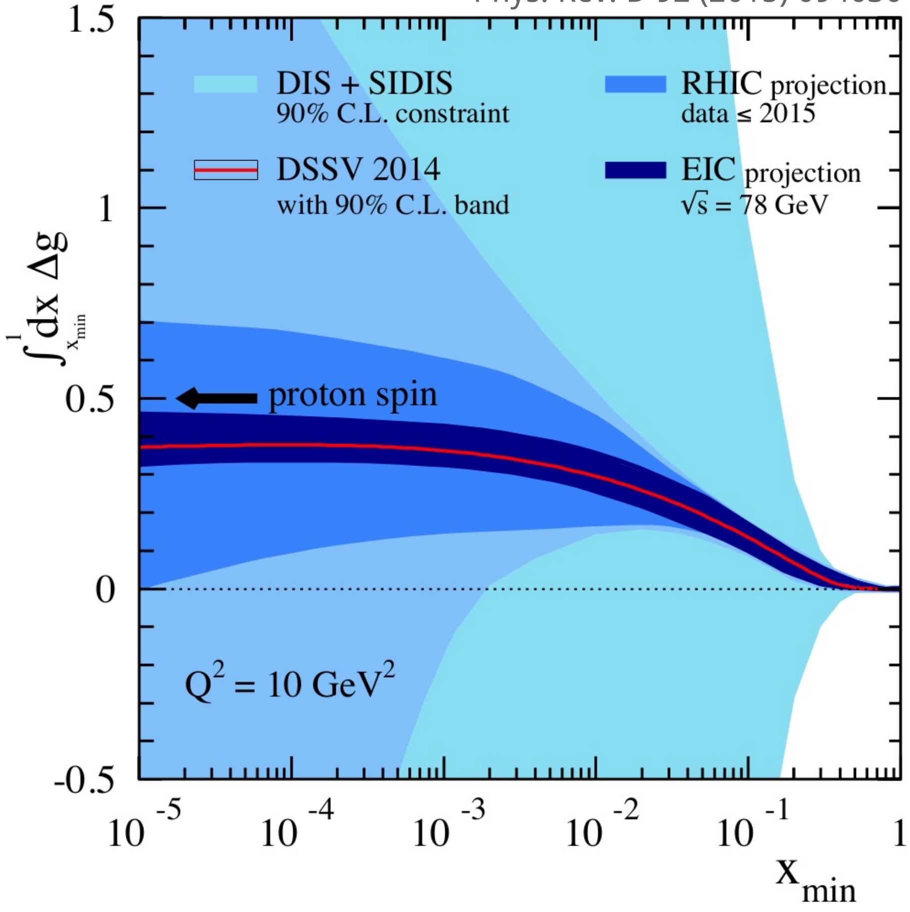


- Influence of central and forward di-jets from 2009 data (25 pb^{-1}) $\sqrt{s}$ = 200 GeV on DSSV calculations

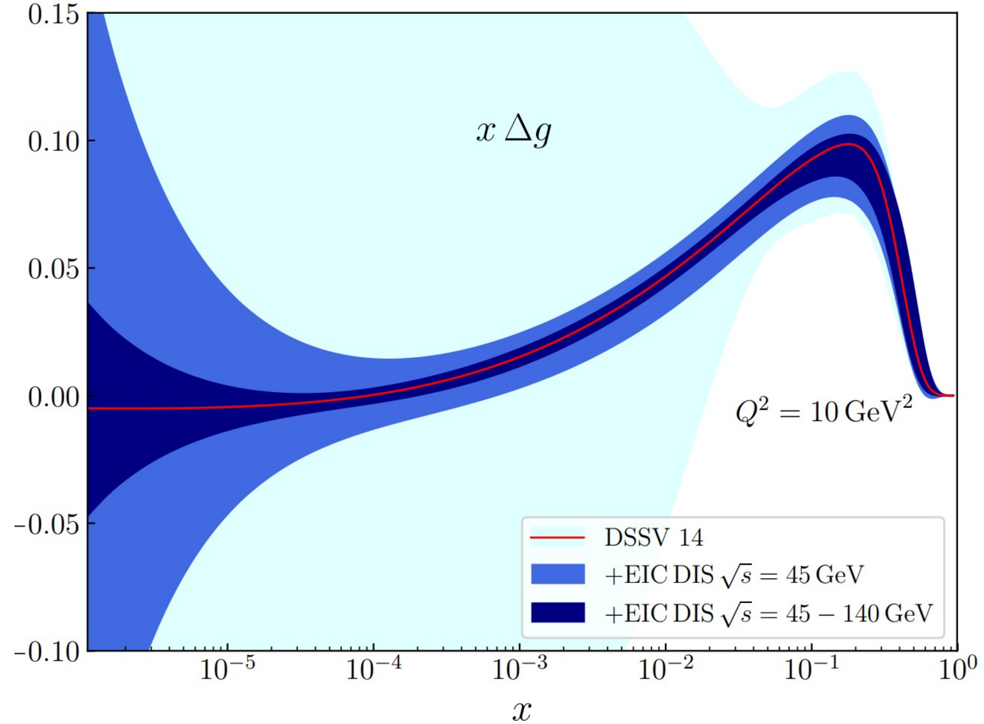
GLUON HELICITY

Deep insight with EIC from longitudinally polarized data: Scaling violation in inclusive DIS: $g_1(x, Q^2)$

Phys. Rev. D 92 (2015) 094030



ArXiv:2007.08300



Updated estimations with updated kinematics and improved uncertainty estimates

- √s = 45 GeV and 140 GeV

Predictions for: Luminosity: 10 fb $^{-1}$,
Polarization: 70%, Efficiency: 50%