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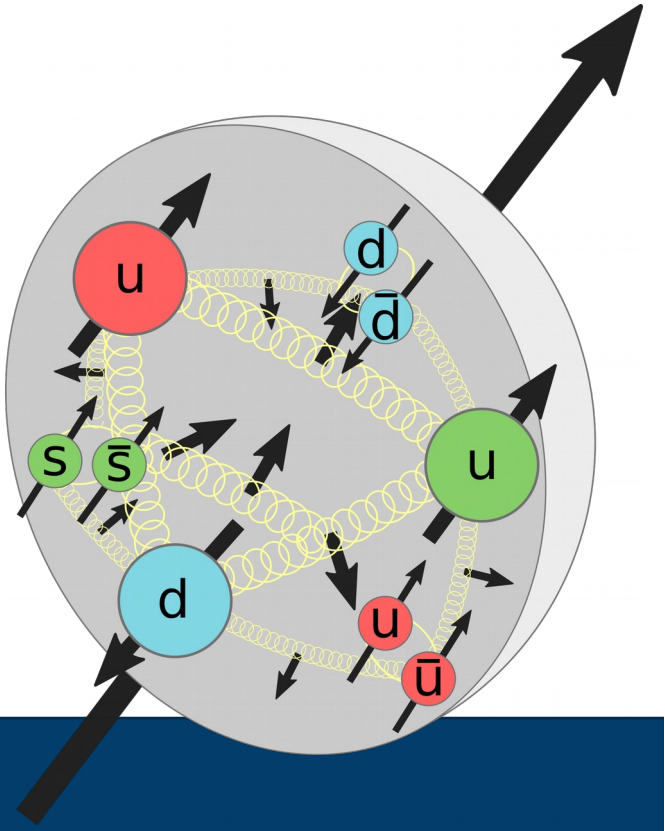


Longitudinal double-spin asymmetries of inclusive jet and di-jet production at STAR

Maria Żurek for the STAR Collaboration
Lawrence Berkeley National Laboratory | Argonne National Laboratory

XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
Stony Brook University, April 12-16, 2021

GLUON HELICITY DISTRIBUTION

STAR spin program goal:

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

Tool:

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

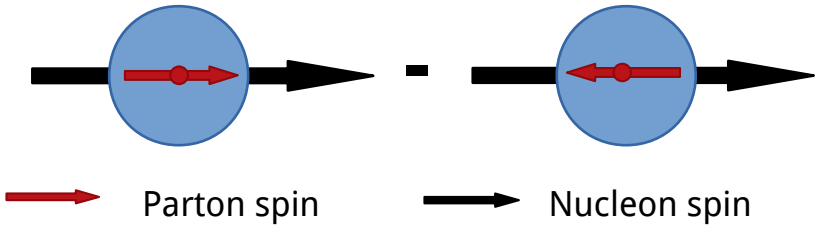
How do gluon spins contribute to the proton spin?

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

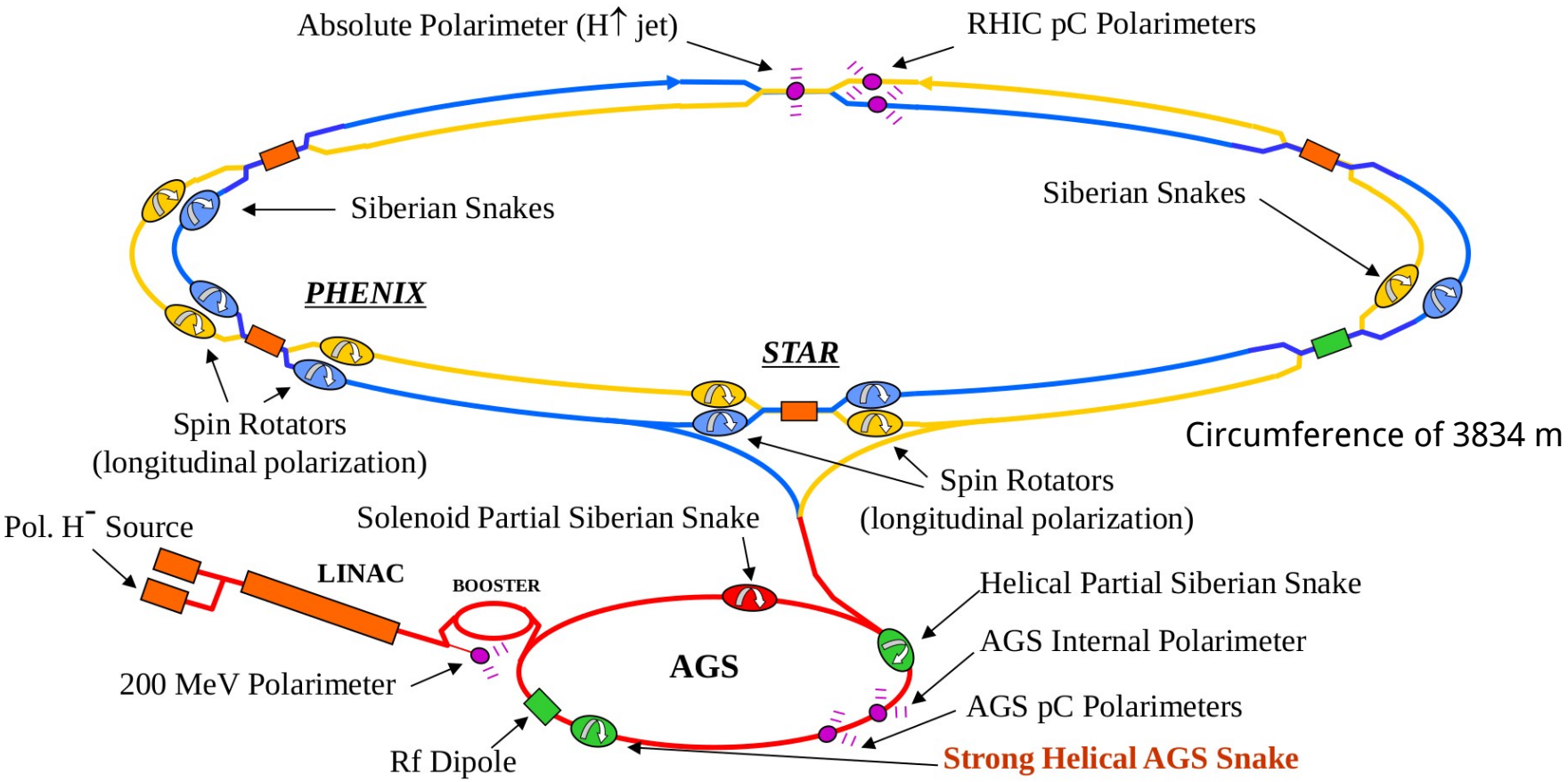
Gluon helicity distribution $\Delta g(x, Q^2)$

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

$$\Delta G = \int_0^1 \Delta g(x, Q^2)\,\mathrm{d}x$$



RHIC – POLARIZED PROTON COLLIDER

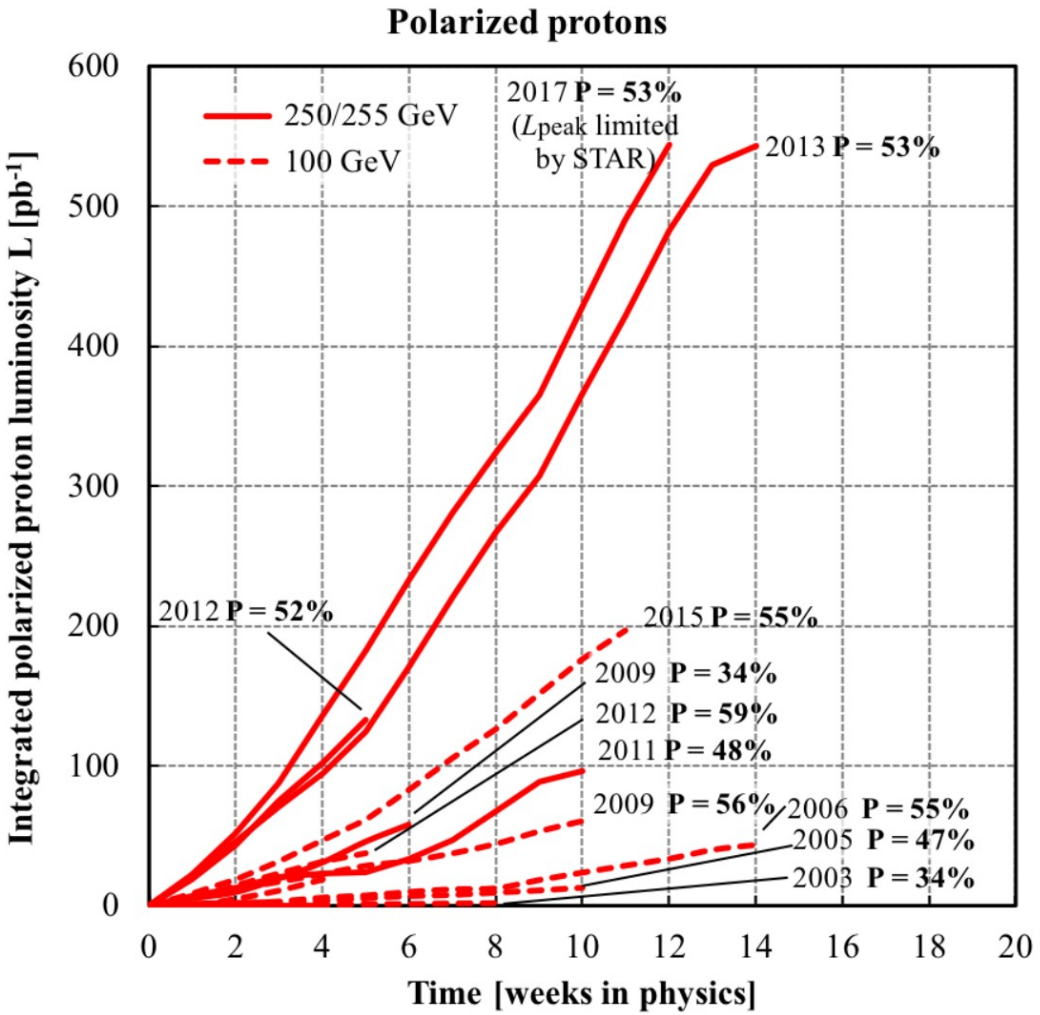


- The only polarized high-energy proton-proton collider
- Polarization: transverse and longitudinal
- Center-of-mass energy for pp collisions: √s = 62, 200, 500/510 GeV
- Alternating spin configurations bunch by bunch (spacing ~100 ns) and fill by fill (typical duration ~8 hrs)

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 RHIC 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

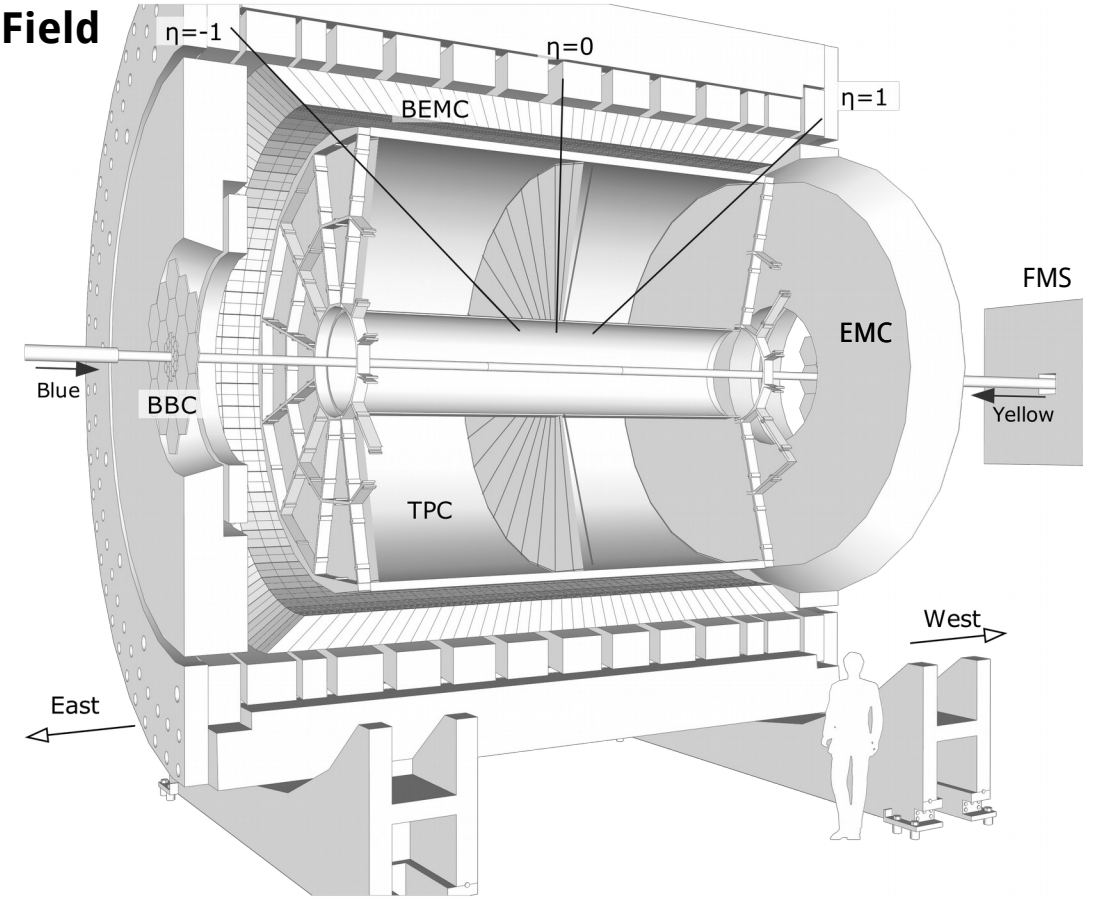
2. Electromagnetic Calorimeter
$\Delta\varphi = 2\pi$, $-1 < \eta < 2$
Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

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

6. Roman Pots
- Measurement of forward protons



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

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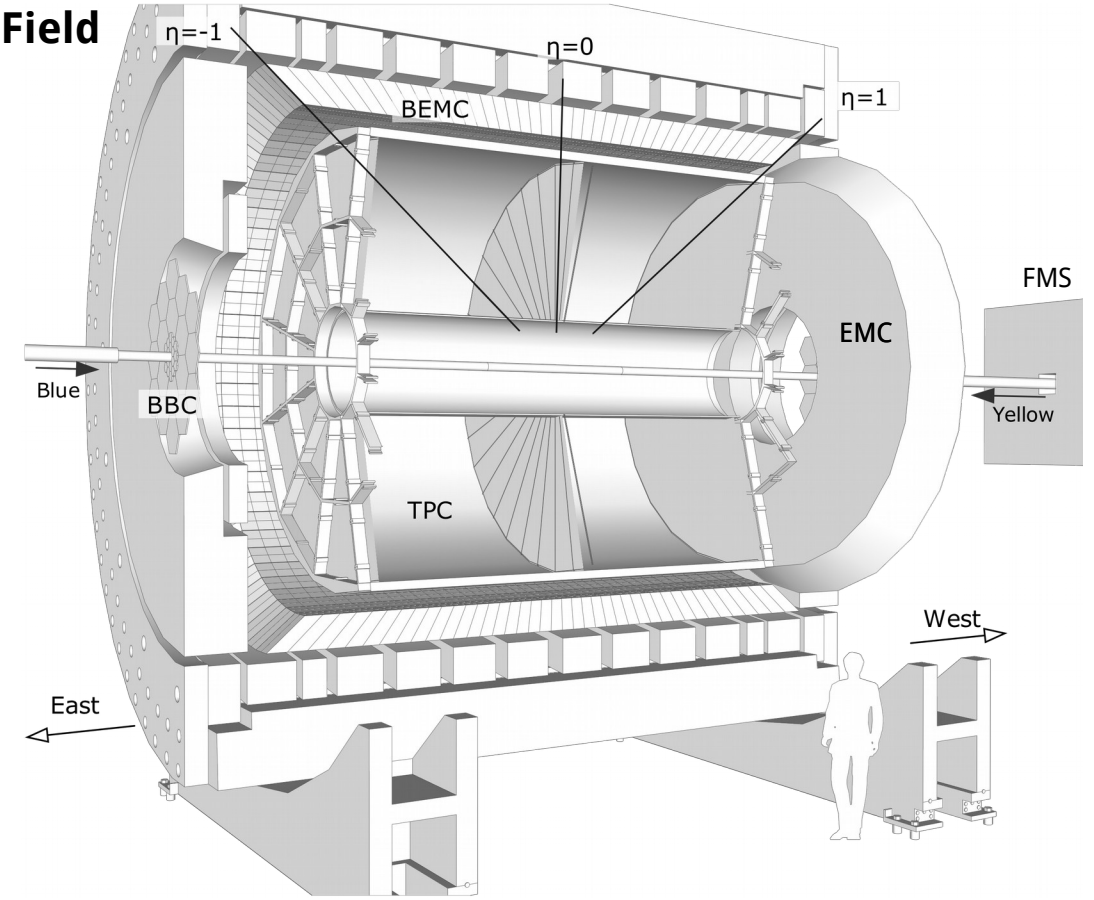

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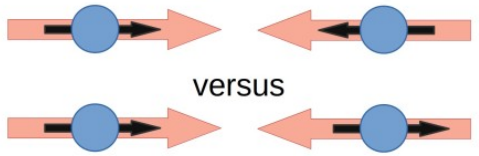
HOW TO ACCESS ΔG?

At pp collider: access to gluons at leading order → $\frac{\Delta G}{G}$

LO for illustration

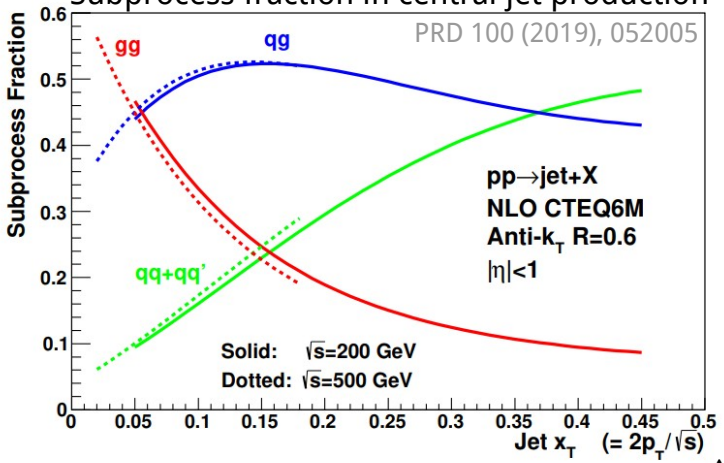
$$\vec{p}+\vec{p} \rightarrow \text{jet/dijet} + X$$



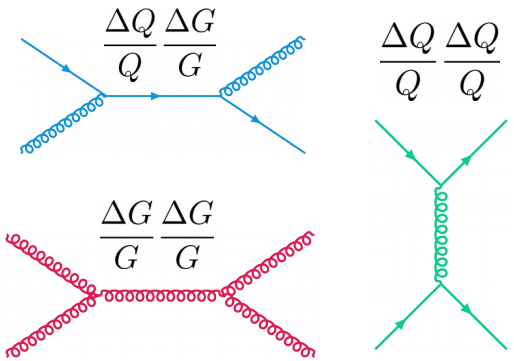
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

Which processes dominate at RHIC?

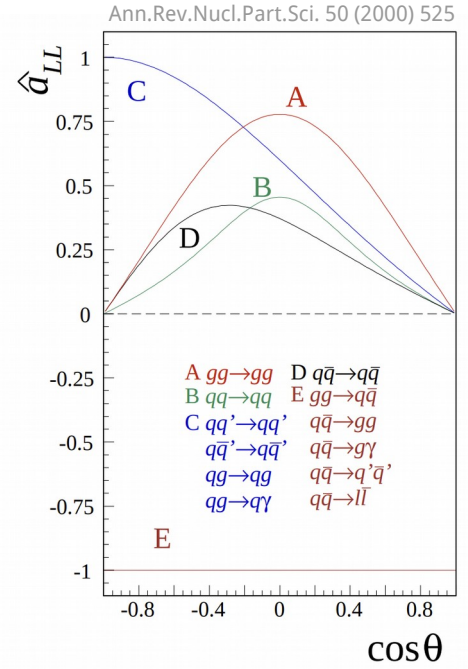
Subprocess fraction in central jet production



Sensitivity to qg and gg – Access to $\frac{\Delta G}{G}$



What are a_{LL} for these processes?



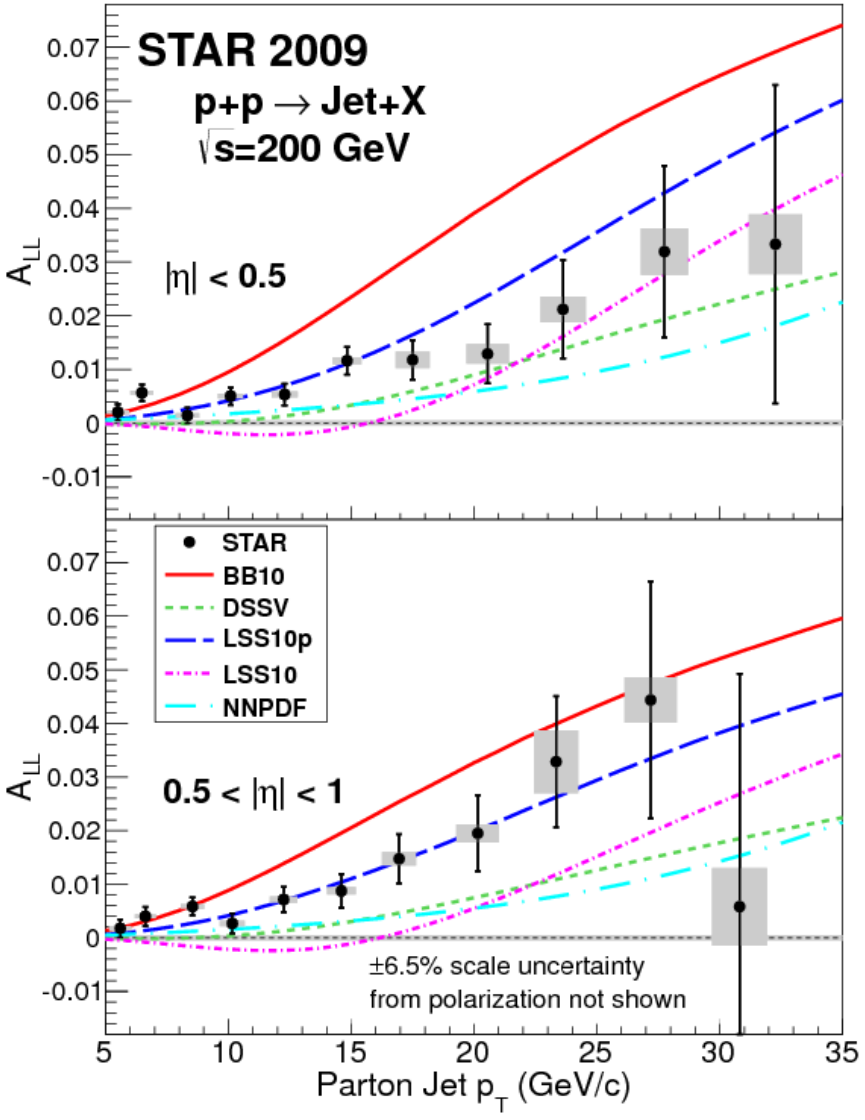
Cross-section measurements to support the NLO pQCD interpretation of asymmetries

→ See talk by D. Kalinkin (STAR), 04/15/2021, 08:18

STATUS OF ΔG

Precision A_{LL} from STAR 2009 data

STAR, PRL 115 (2015) 9, 092002

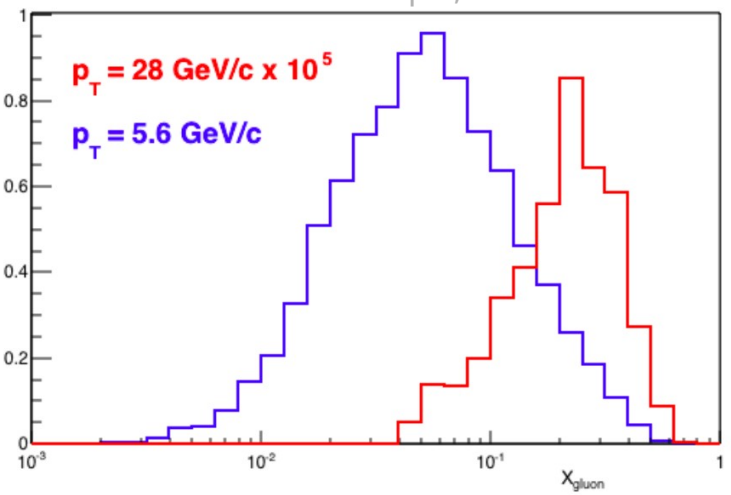


1. A_{LL} positive for large p_T - **positive gluon polarization**

2. Included in DSSV and the NNPDF **PDF fits** (NLO)
   - These data drive the constraints on ΔG in both fits
   - Sensitivity to different x 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

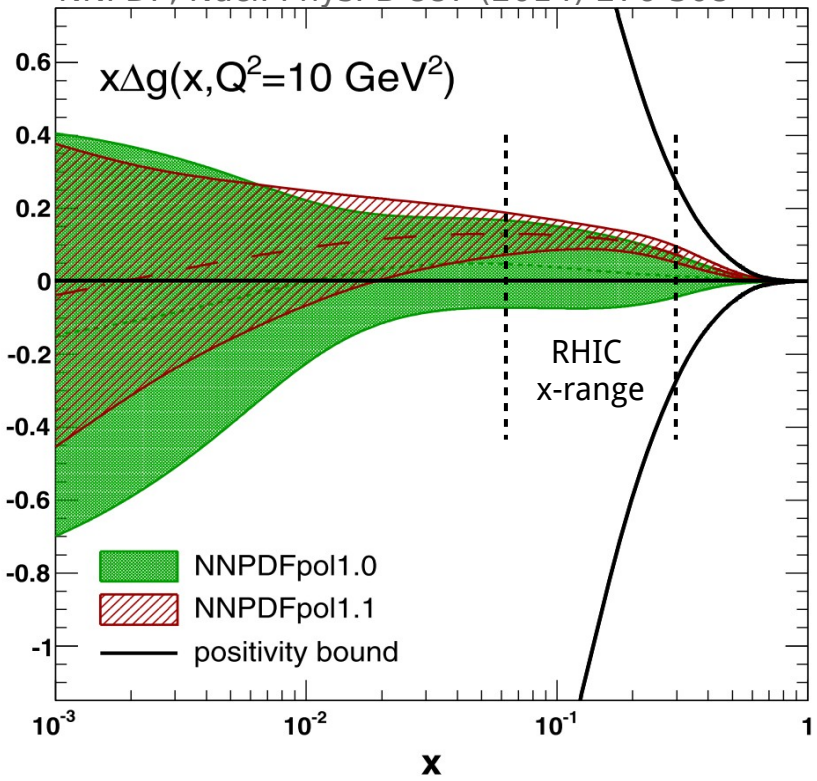


Relative contributions of gluons with a given x probed in different jet p_T regions

STATUS OF ΔG

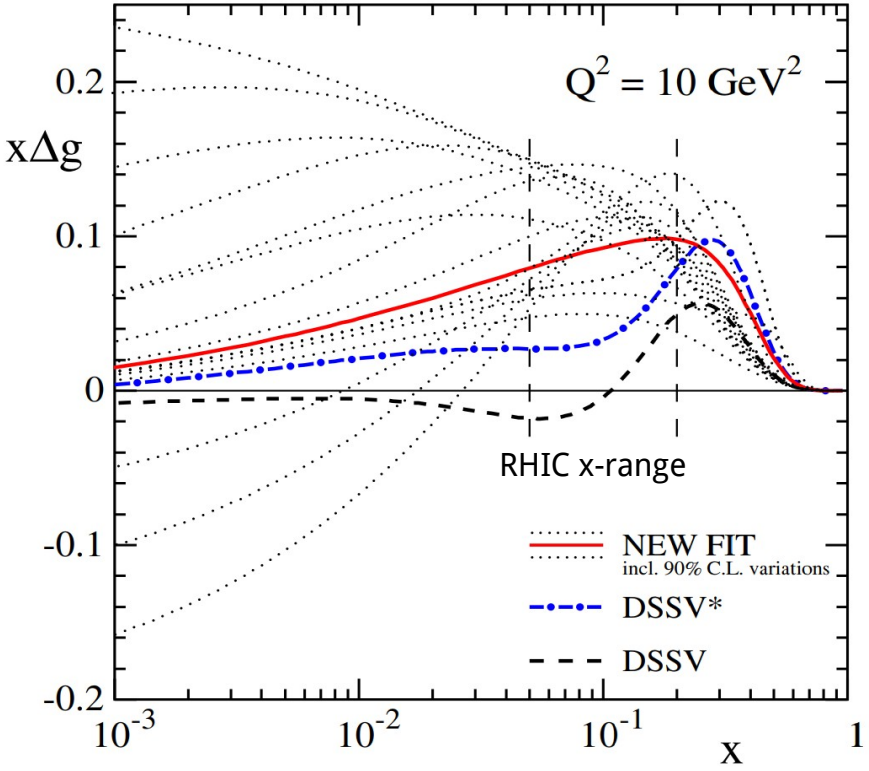
Impact of A_{LL} from 2009 data on ΔG

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



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

DSSV, PRL 113 (2014) 1, 012001



DSSV – (SI)DIS, BNL-RHIC, prelim. 2005 and 2006 STAR
DSSV* – the final STAR jet results from 2005 and 2006
DSSV New fit – STAR 2009 data included

$$\int_{0.05}^{0.5} \Delta g(x,Q^2)dx = \mathbf{0.23 \pm 0.07}$$

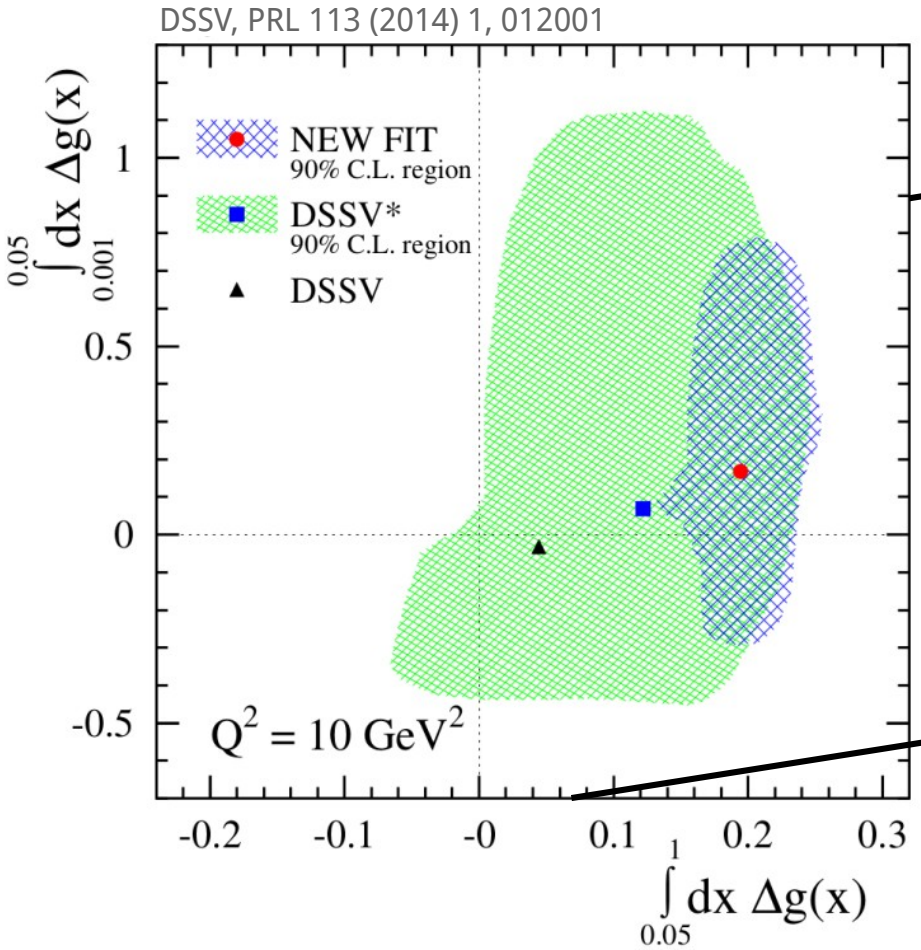
at $Q^2 = 10\,\mathrm{GeV}^2$

$$\int_{0.05}^{1} \Delta g(x,Q^2)dx = \mathbf{0.20^{+0.06}_{-0.07}}$$

at 90% C.L., $Q^2 = 10\,\mathrm{GeV}^2$

STATUS OF ΔG

What's next?



Low-x range

Extend sensitivity to smaller x:

- forward rapidity

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

- √s = 510 GeV data

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

High-x range

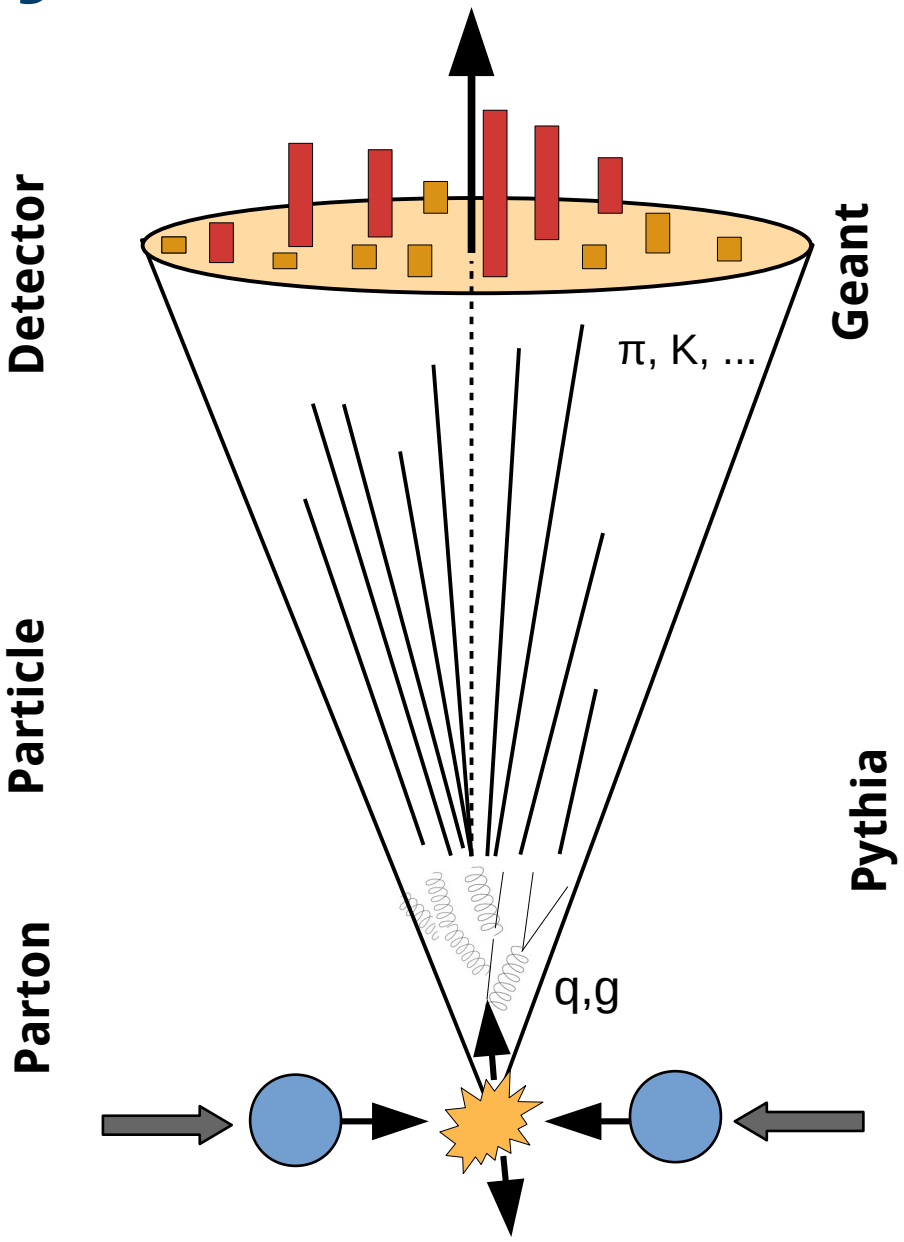
Further precision from:

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

Near-term improvements from STAR for x down to 0.02
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, particle and parton

Underlying event correction

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

  Example UE correction values for 2015 data:
  p_T = 6 – 7.1 GeV/c: avarage UE dp_T ~ 0.77 GeV/c
  p_T = 26.8 – 31.6 GeV/c: avarage UE dp_T ~ 0.6 GeV/c

Jets **corrected back to parton** level

Trigger bias and reconstruction efficiency

- Estimated using replicas from polarized NNPDF1.1 PDF set

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)

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

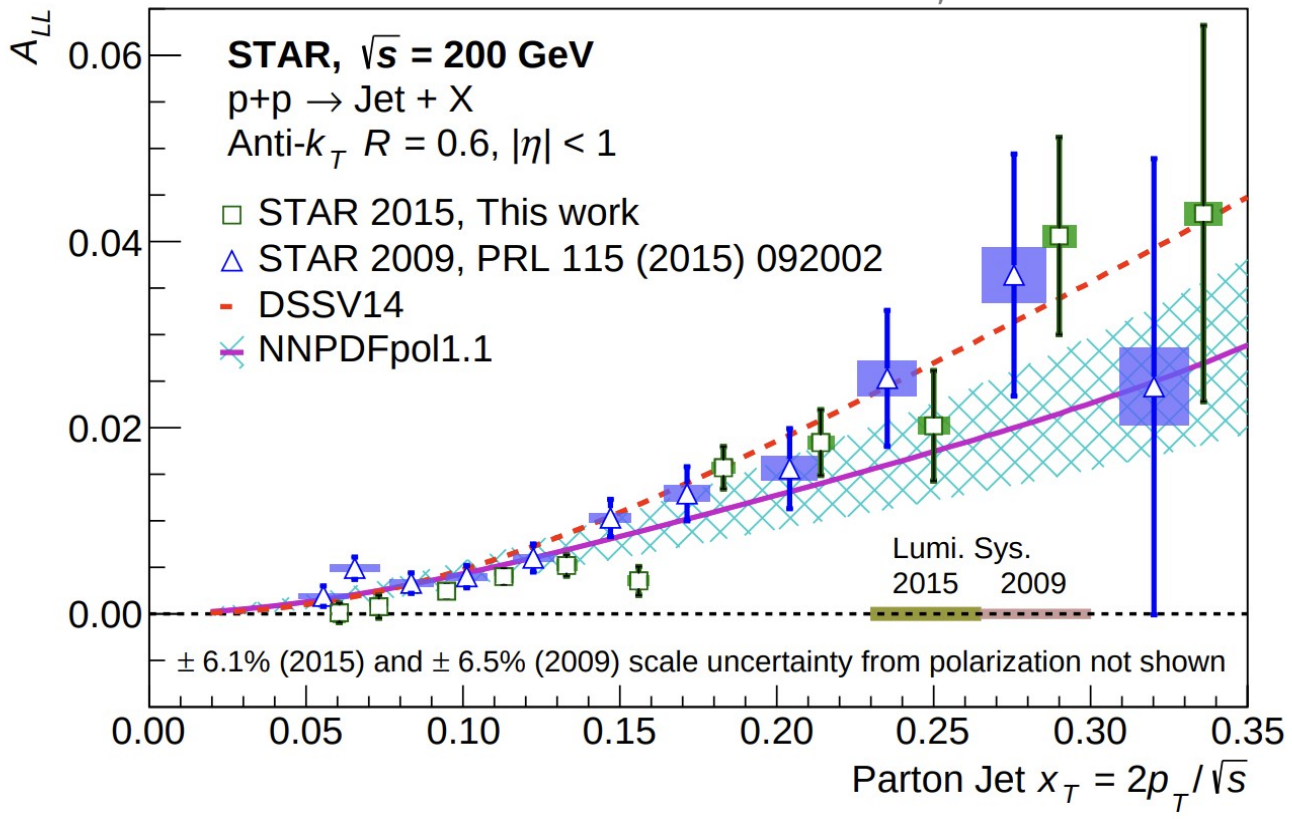
- For 2015 data R_3 varies from 0.96 to 1.04 depending on the fill with the uncertainty of $\Delta R_3 \sim 4.5 \times 10^{-4}$ (Uncertainty similar to 2009 data)

INCLUSIVE JET A_{LL}

Largest 200 GeV dataset likely to **conclude the 200 GeV longitudinal program with jets**

- Jet and dijet A_{LL} from STAR from **2015 data**

STAR, arXiv:2103.05571



- **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
- Parity violating single-spin asymmetries consistent with zero

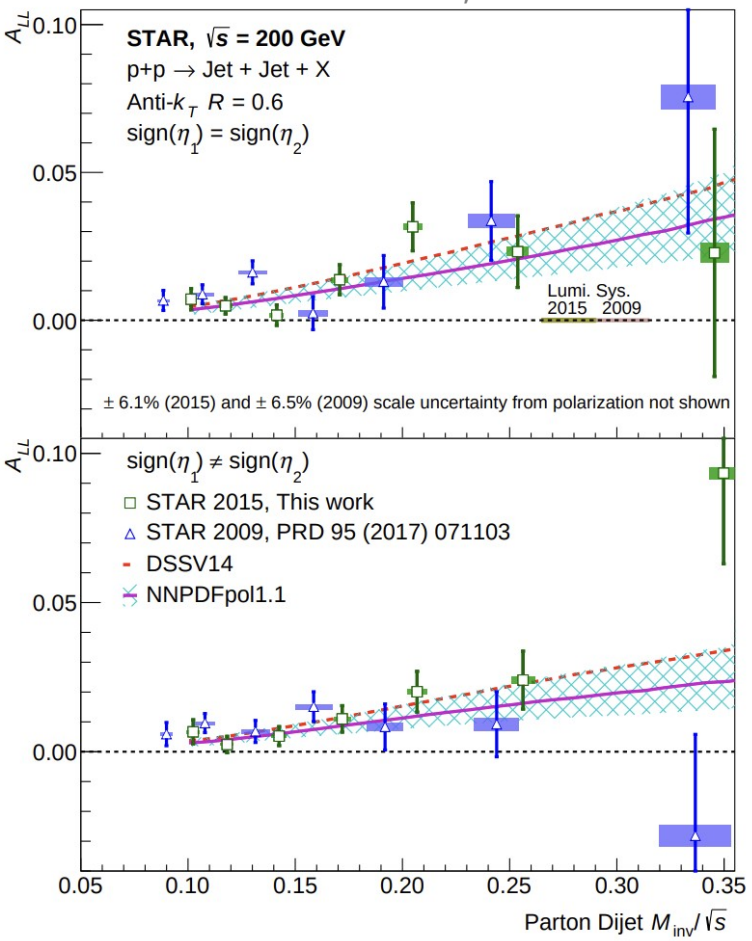
Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits

DI-JET A_{LL}

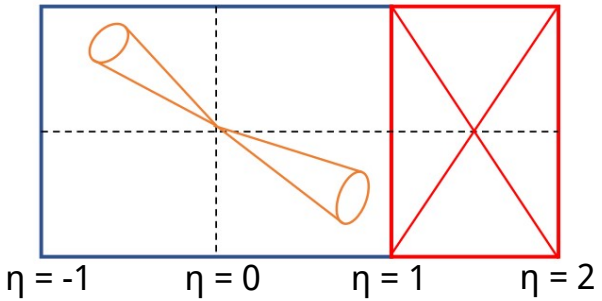
Di-jets give stricter constraints to underlying **partonic kinematics**

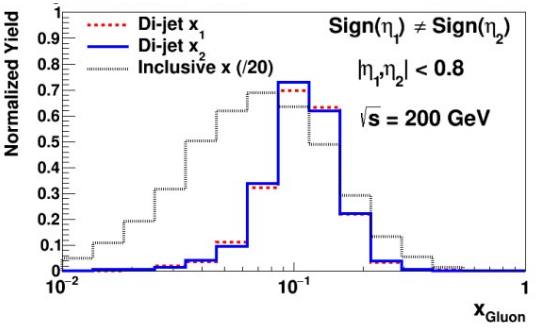
- May place better constraints on **x-dependence of Δg(x,Q²)**
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected x

STAR, arXiv:2103.05571

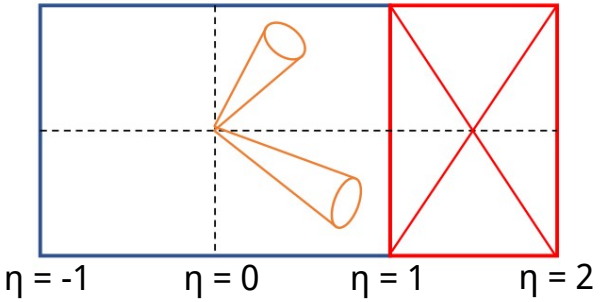


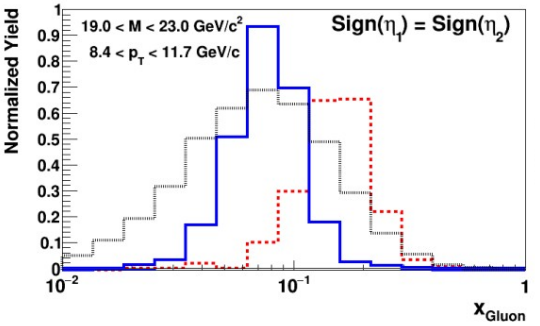
sign(η_1) ≠ sign(η_2)





sign(η_1) = sign(η_2)

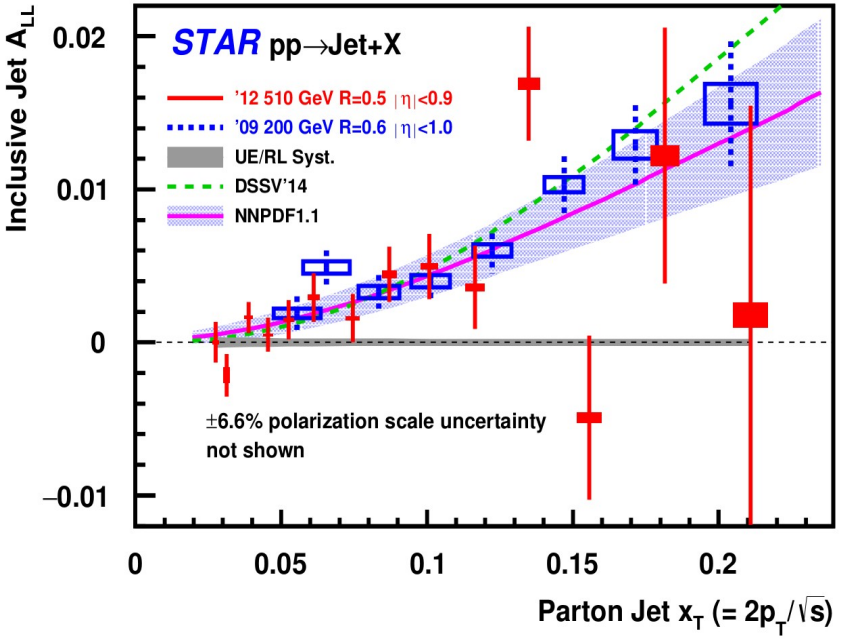




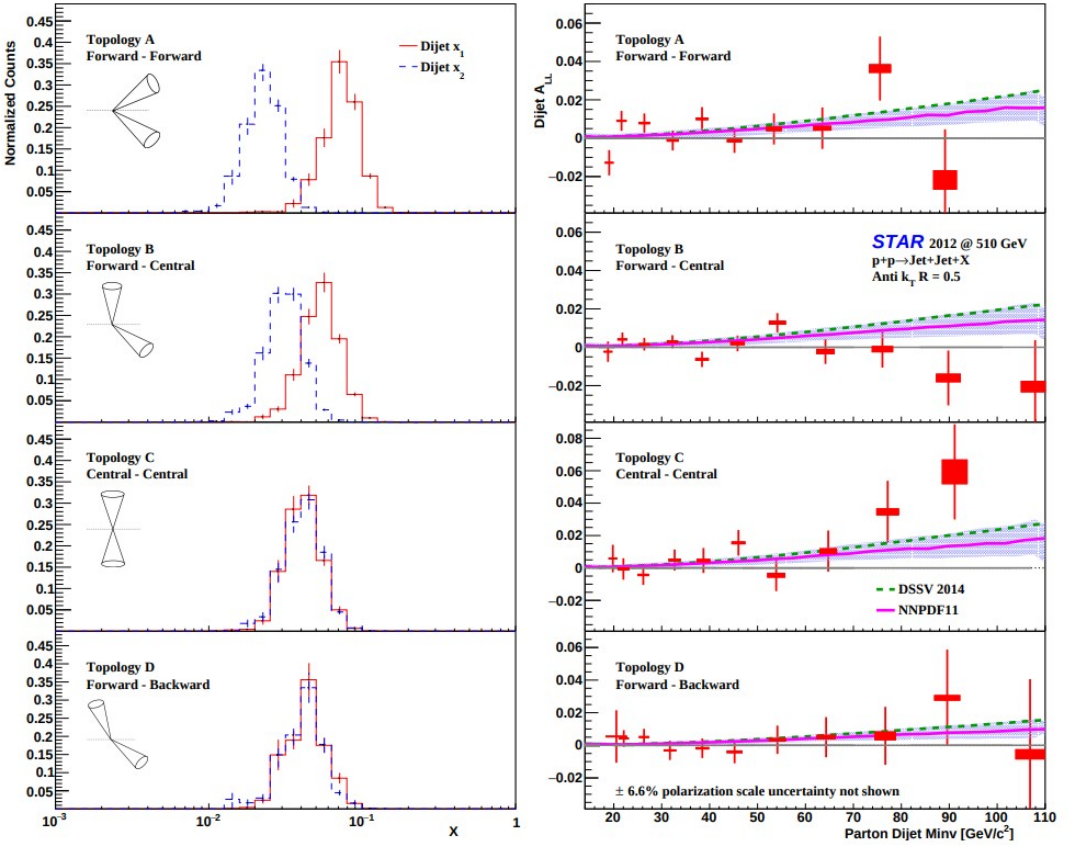
JETS AND DI-JETS AT 510 GEV

Towards smaller x

STAR, PRD 100 (2019), 052005



STAR, PRD 100 (2019), 052005



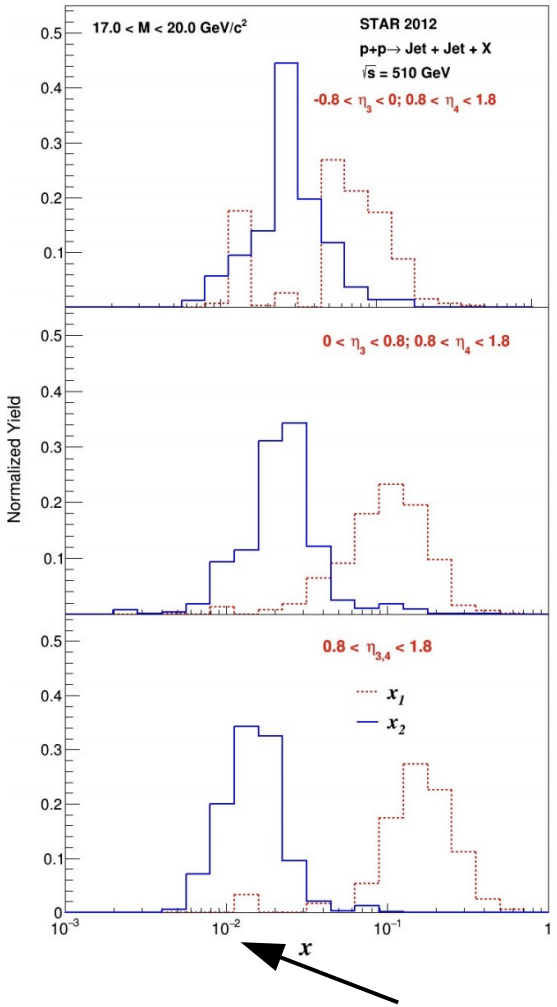
- **Higher √s pushes sensitivity to lower x (down to 0.02)**
- Consistent results from both energies

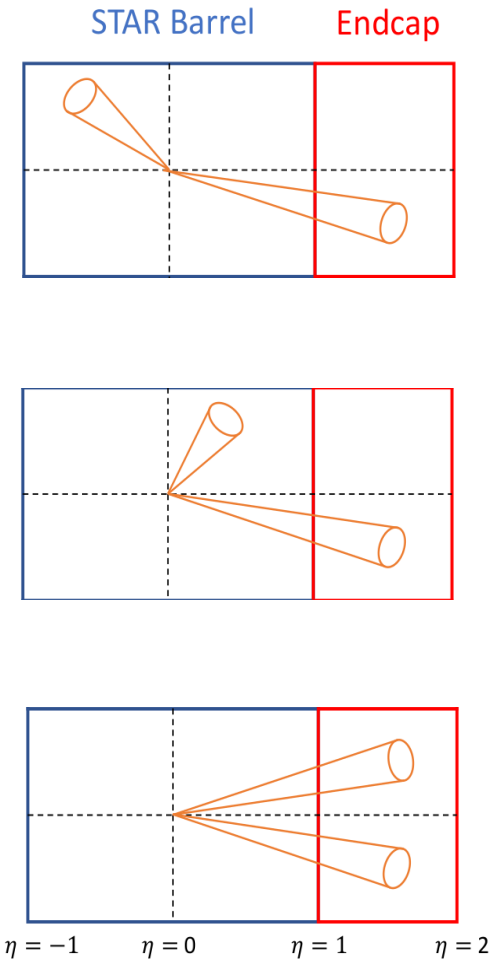
First measurement of jet and di-jet A_{LL} at 510 GeV with 2012 data

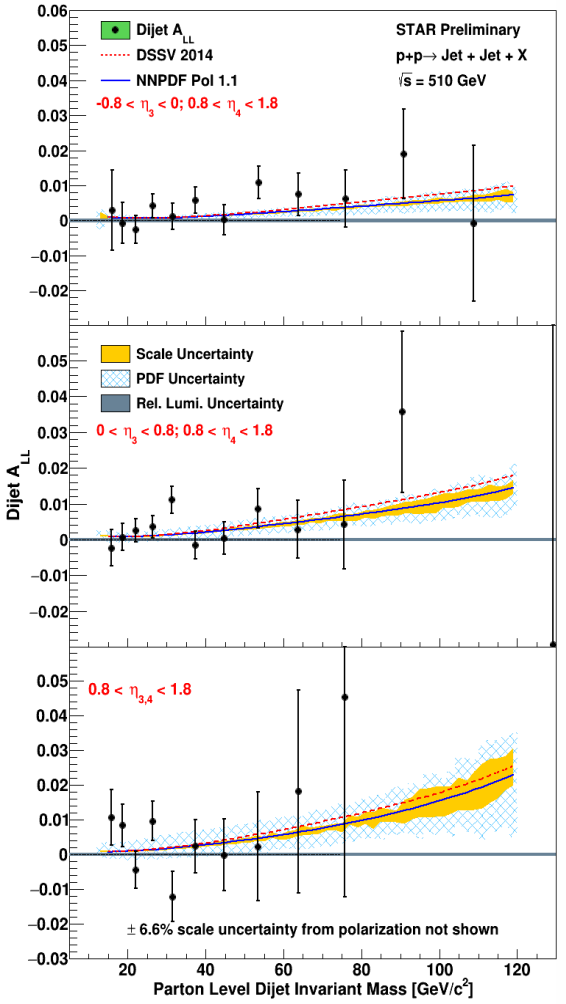
Further precision: Run 2013 data at √s = 510 GeV – x 3.7 statistics

JETS AND DI-JETS AT 510 GEV

Towards smaller x







More forward η pushes sensitivity to even lower x (down to 0.01)

Further precision: Run 2013 data at √s = 510 GeV – x 3.7 statistics

SUMMARY AND OUTLOOK

1. Insight into **gluon polarization $\Delta g(x,Q^2)$** at STAR
   - 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 with twice larger figure-of-merit than that from 2009 and with improved systematics
   - Likely to **conclude the 200 GeV longitudinal program with jets**
   - Among the most impactful results on $\Delta g(x,Q^2)$ available before the Electron-Ion Collider comes online

4. Gluon polarization at **smaller x** ($x < 0.05$)
   - Improvements from STAR at 510 GeV and more forward rapidity
   - Deep insight from future measurements at EIC