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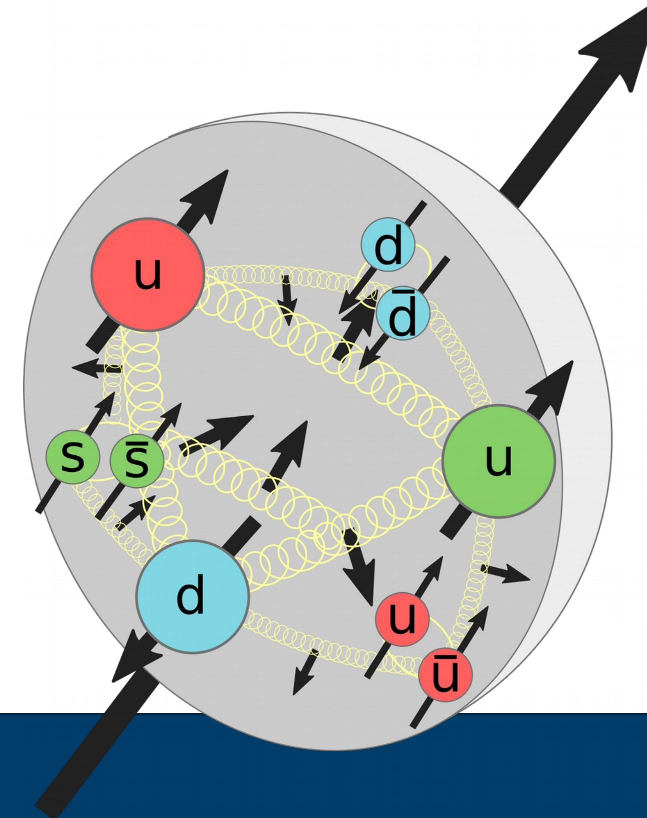


Longitudinal double-spin asymmetries of inclusive jet and di-jet production at STAR

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)

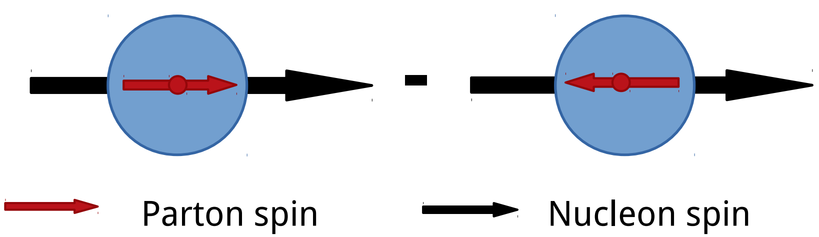
How do gluon spins contribute to the proton spin?

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

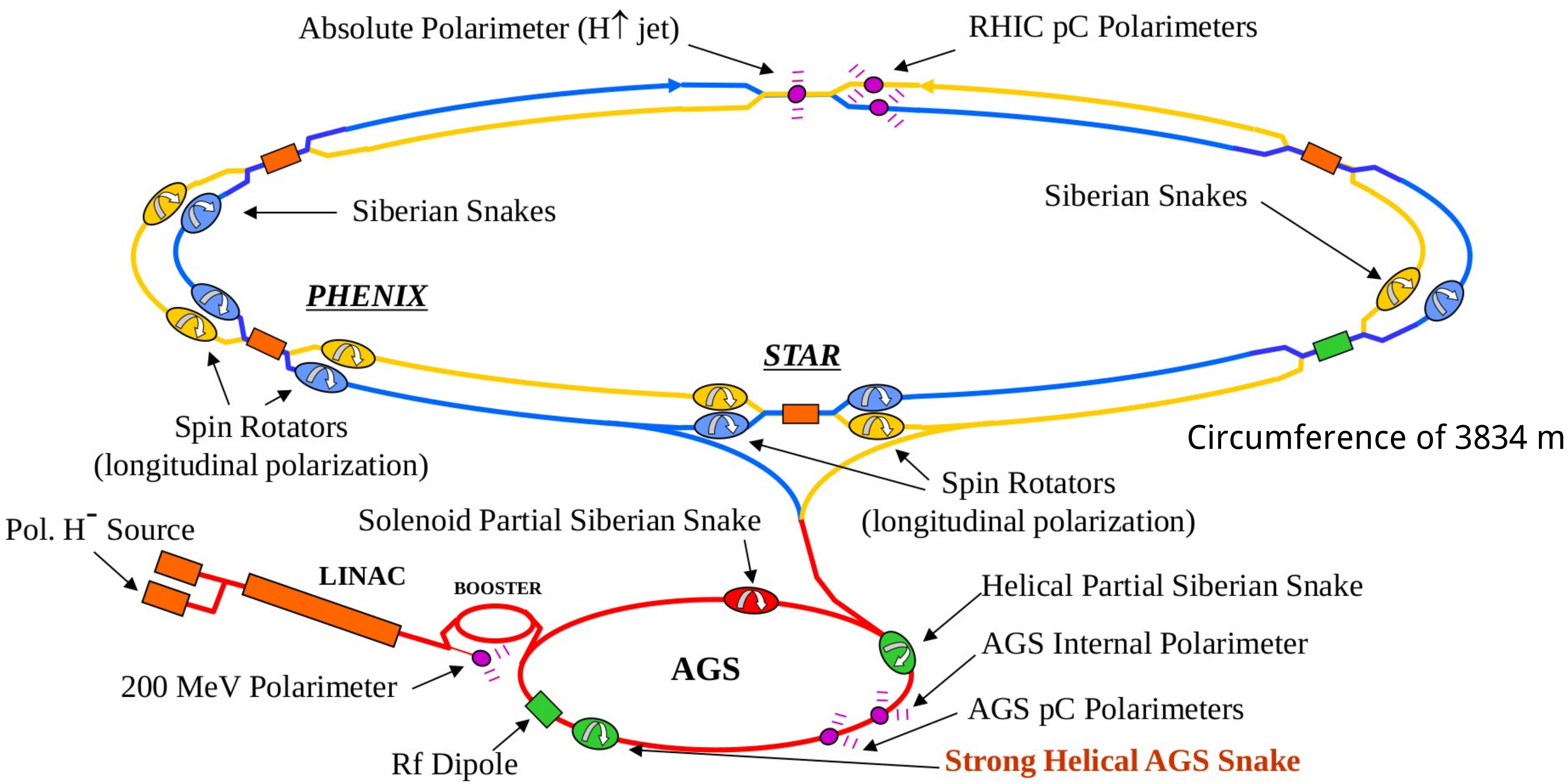
Gluon helicity distribution $\Delta g(x, Q^2)$

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

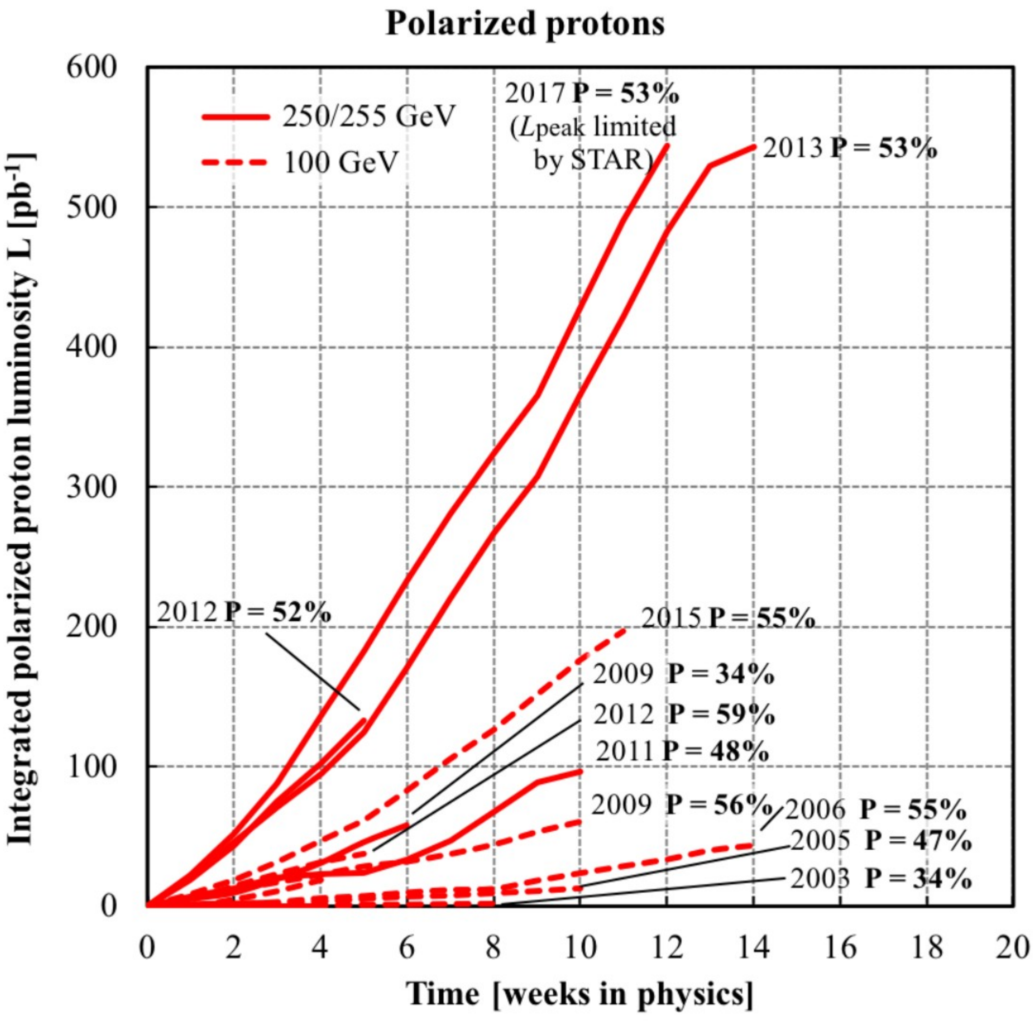


- The only polarized high-energy proton-proton collider
- Polarization: transverse and longitudinal
- Center-of-mass energy for pp collisions: $\sqrt{s}$ = 62, 200, 500/510 GeV
- Alternating spin configurations bunch by bunch (spacing ~100 ns) and fill by fill (typical duration ~8 hrs)

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

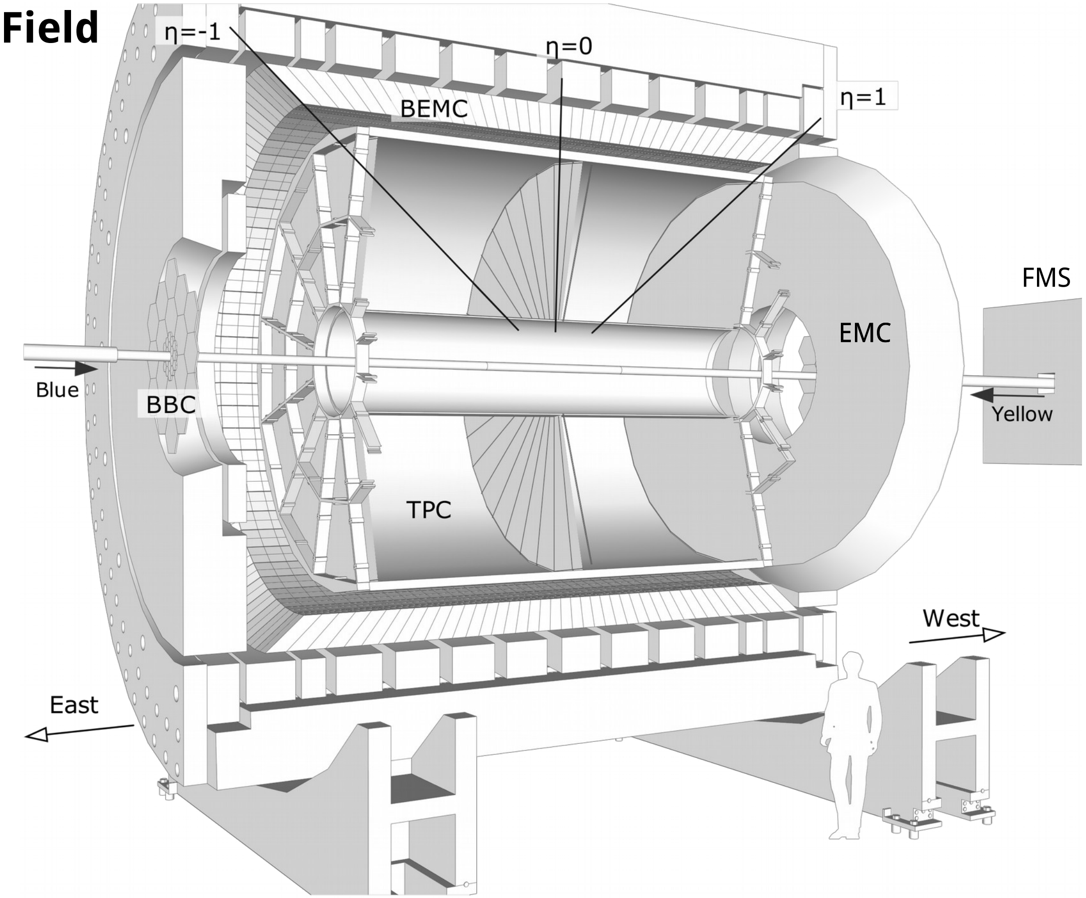
2. Electromagnetic Calorimeter
$\Delta\varphi = 2\pi$, $-1 < \eta < 2$
Barrel ($|\eta| < 1$) and Endcap ($1 < \eta < 2$)
- Energy measurement, trigger

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)

SOLENOIDAL TRACKER AT RHIC

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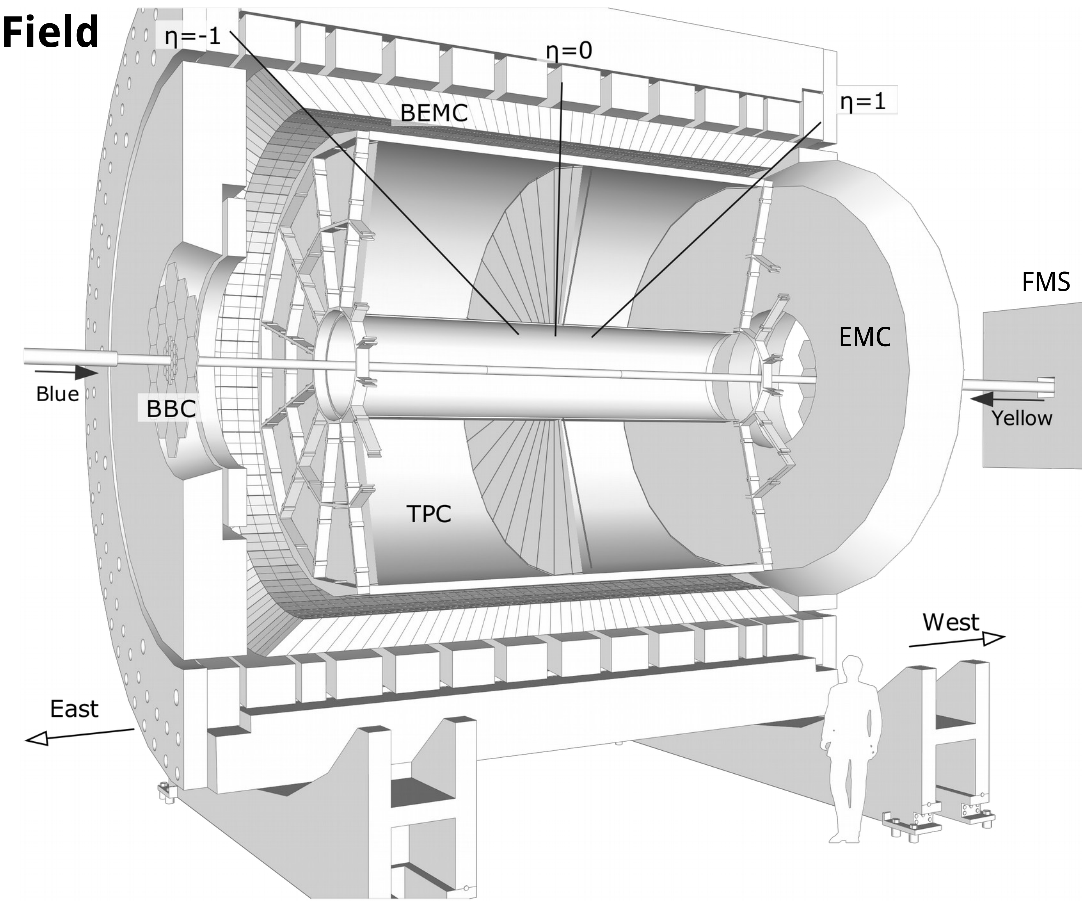


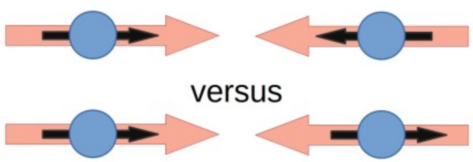
Characteristics
- Large acceptance (tracking and calorimetry)
- **Good detector for jets**
- Upgrades: iTPC, EPD, ETOF, Fwd Upgrade (ongoing)

HOW TO ACCESS ΔG?

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

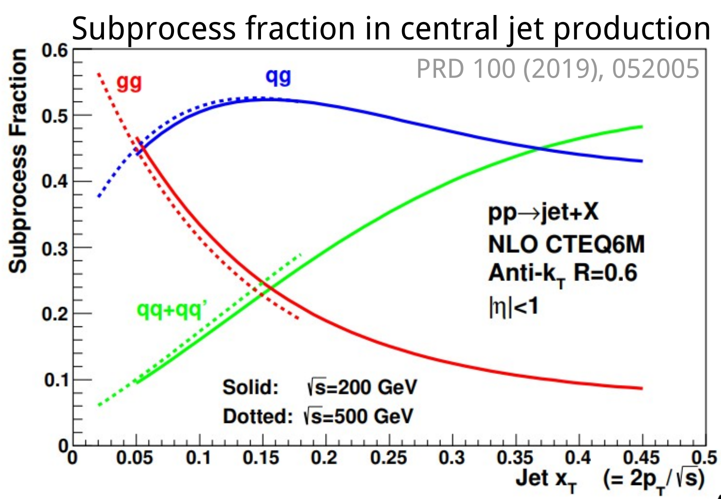
LO for illustration

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



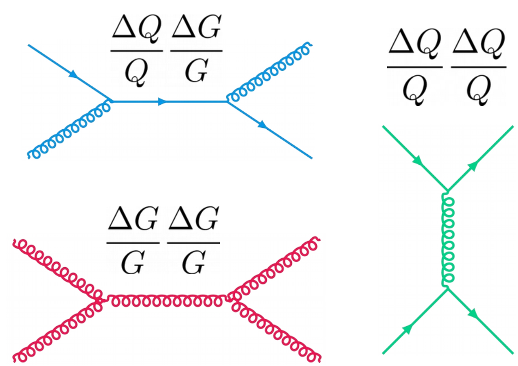
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a_{LL}}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}$$

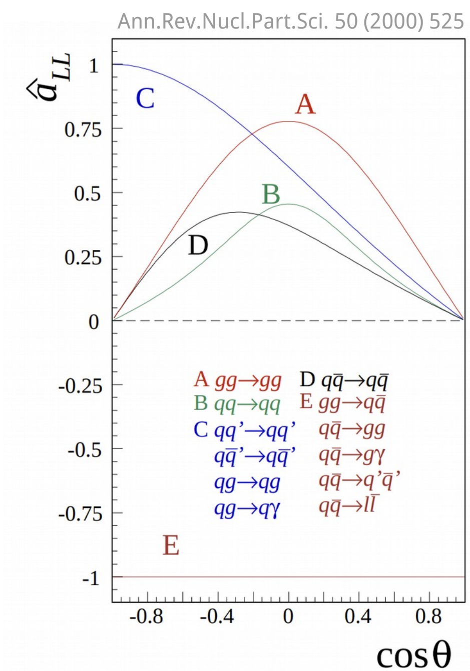
Which processes dominate at RHIC?



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

What are a_{LL} for these processes?





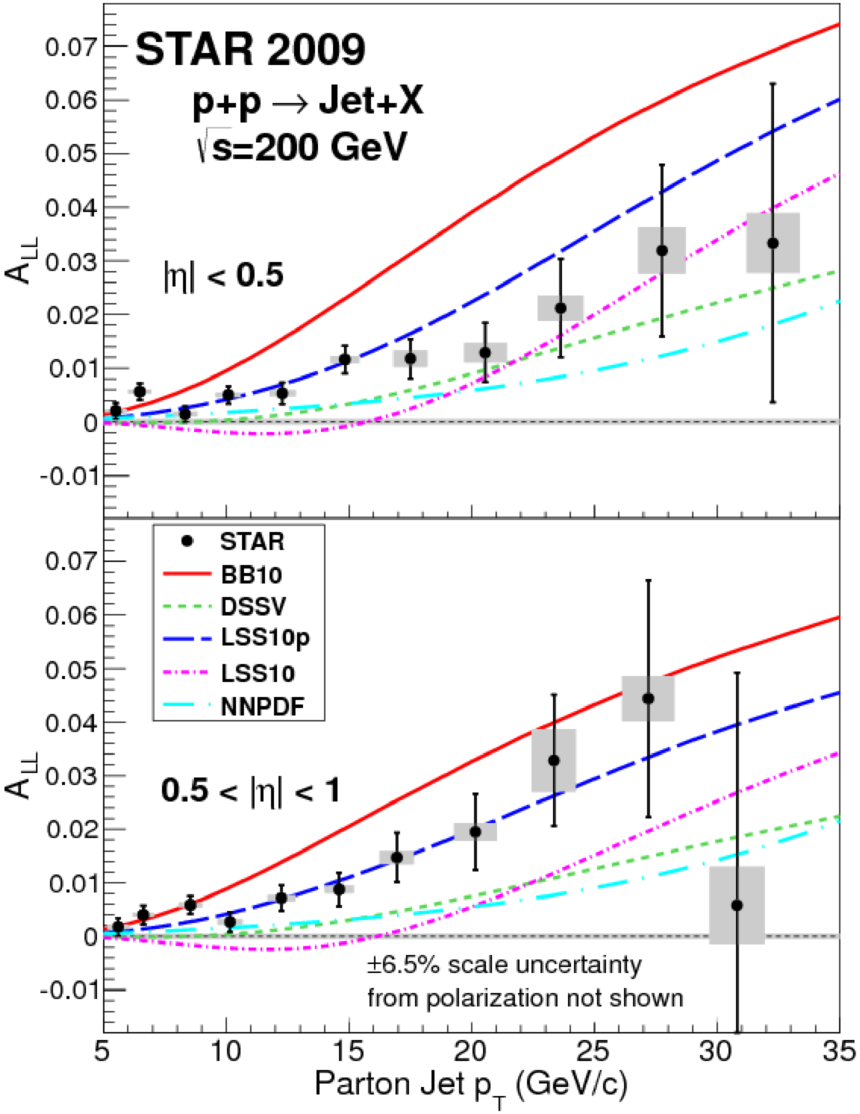
Cross-section measurements to support the NLO pQCD interpretation of asymmetries

→ 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



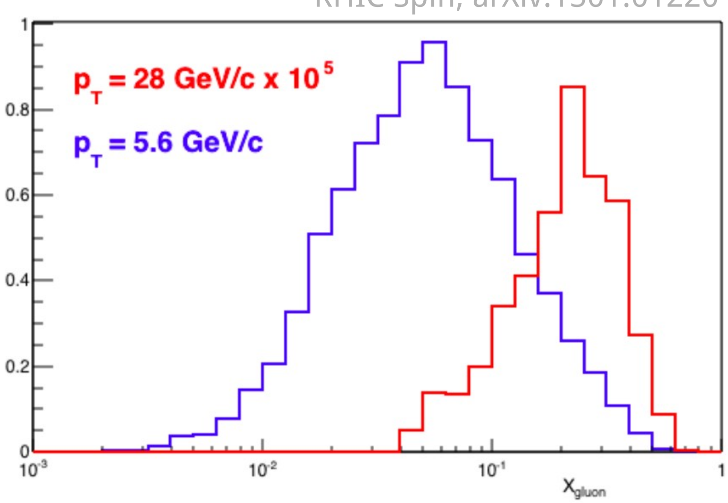
1. A_{LL} positive for large p_T - **positive gluon polarization**

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

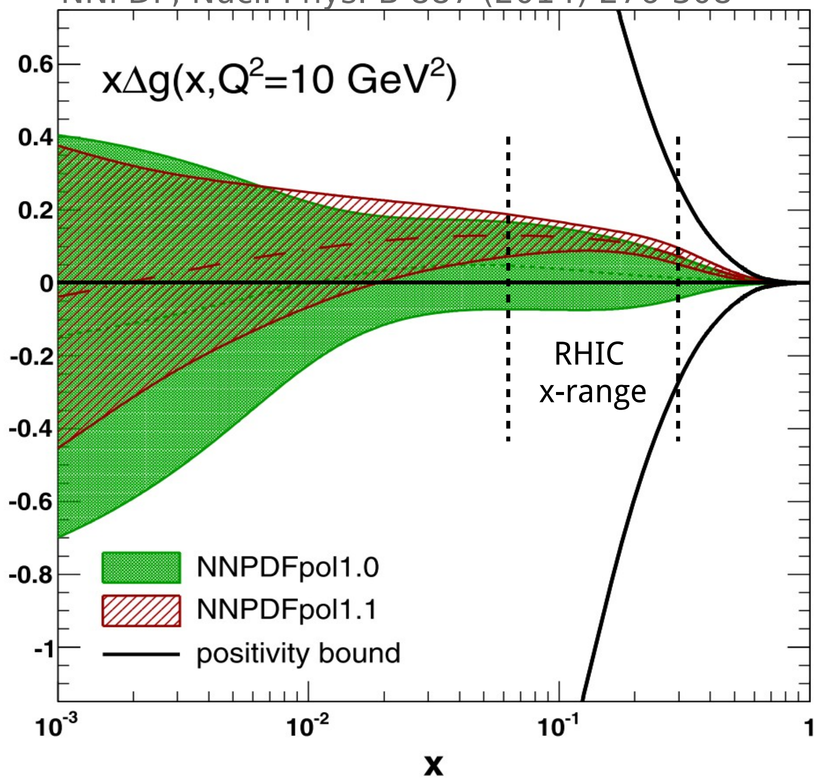


Relative contributions of gluons with a given x probed in different jet p_T regions

STATUS OF ΔG

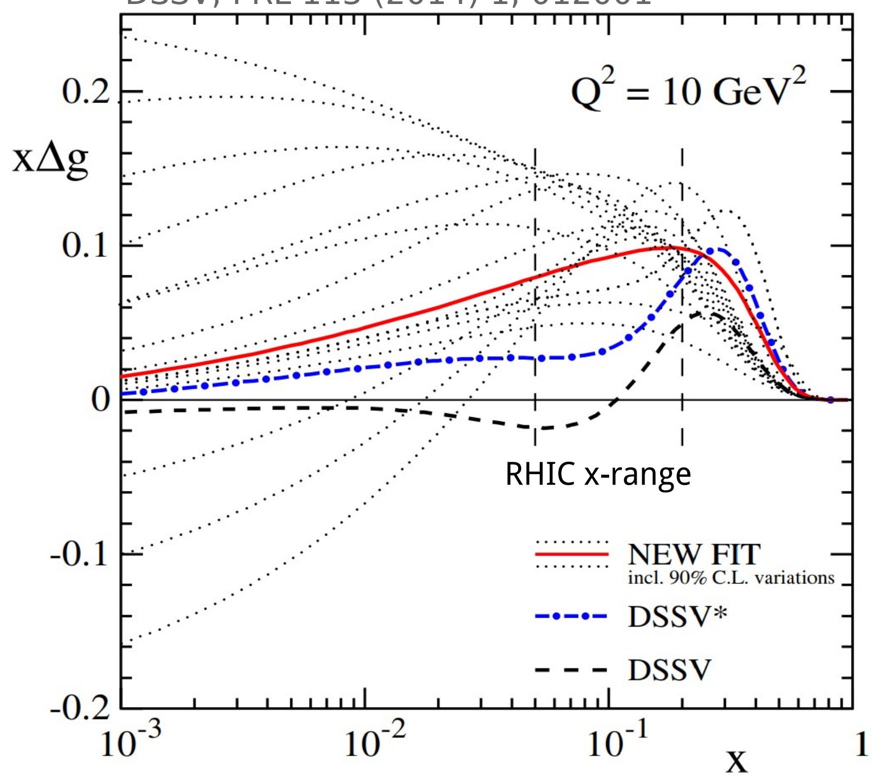
Impact of A_{LL} from 2009 data on ΔG

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

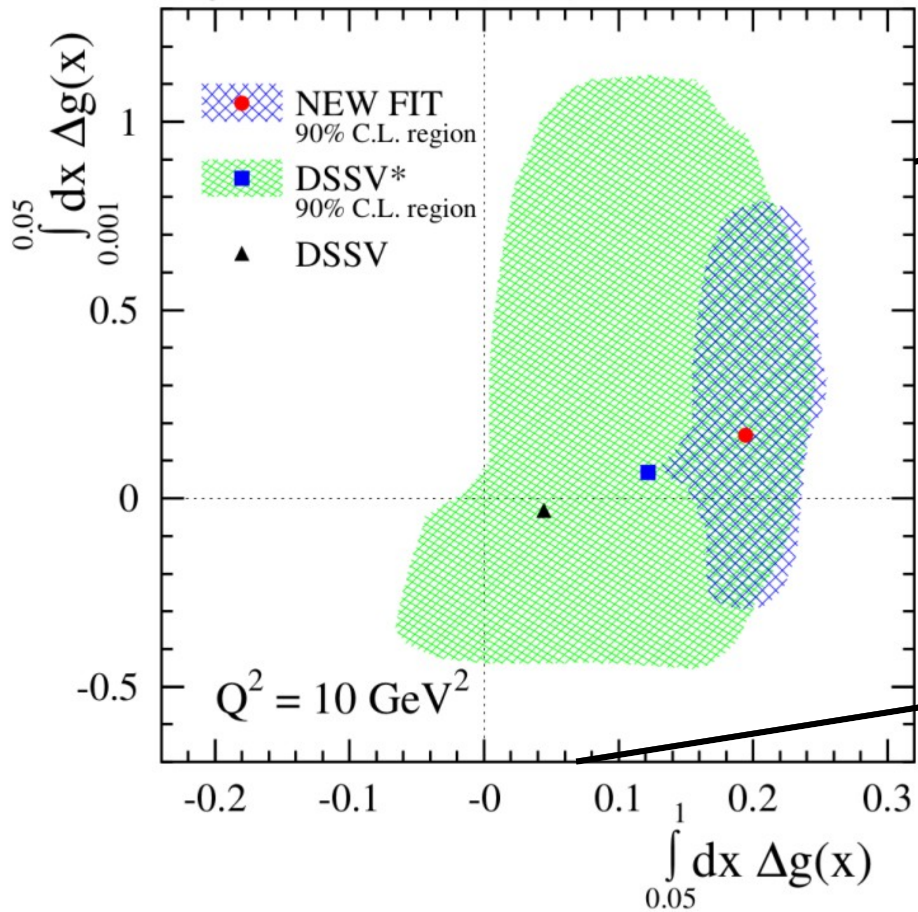
$$\int_{0.05}^{1} \Delta g(x, Q^2) dx = \mathbf{0.20^{+0.06}_{-0.07}}$$

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

STATUS OF ΔG

What's next?

DSSV, PRL 113 (2014) 1, 012001



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

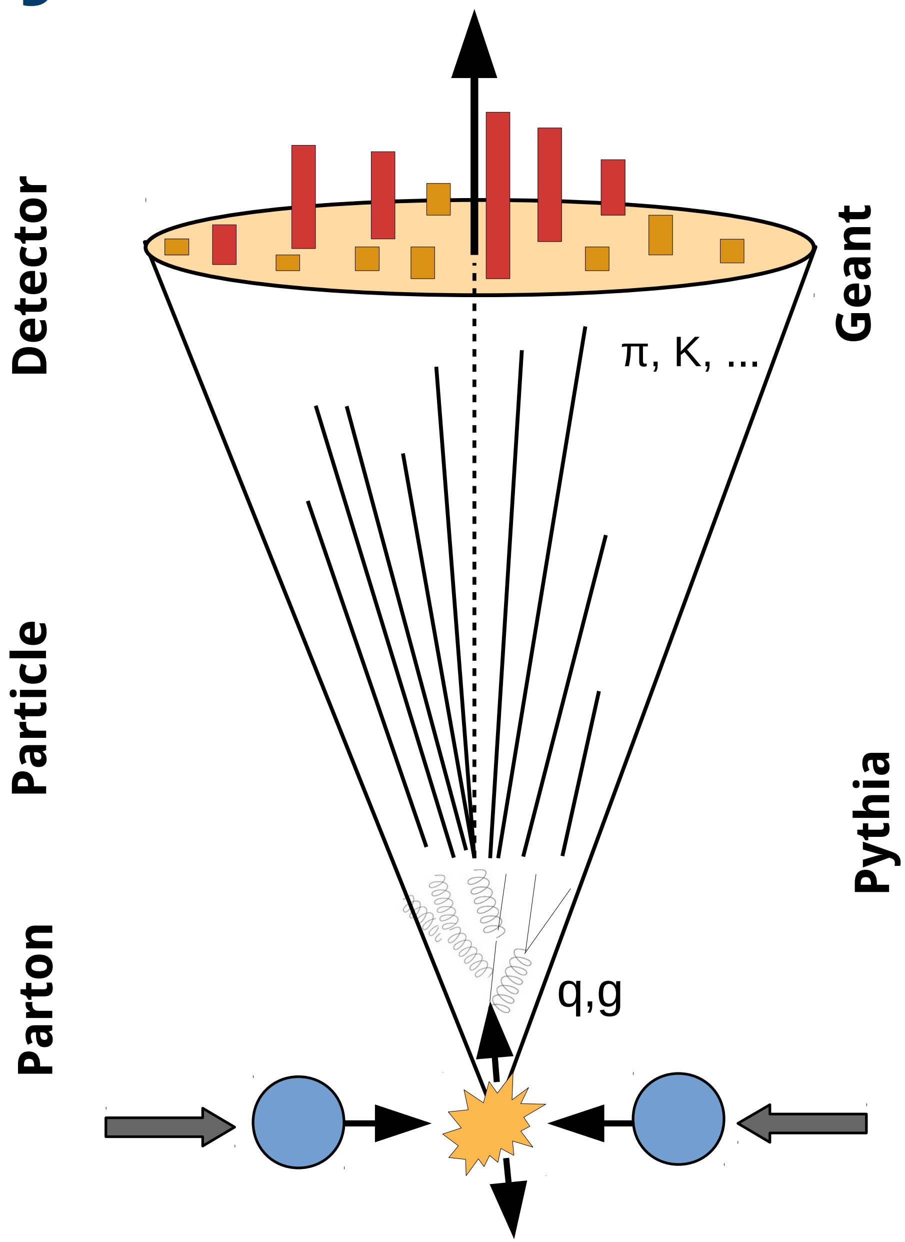
Further precision from:

- 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 ~ 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

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)

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

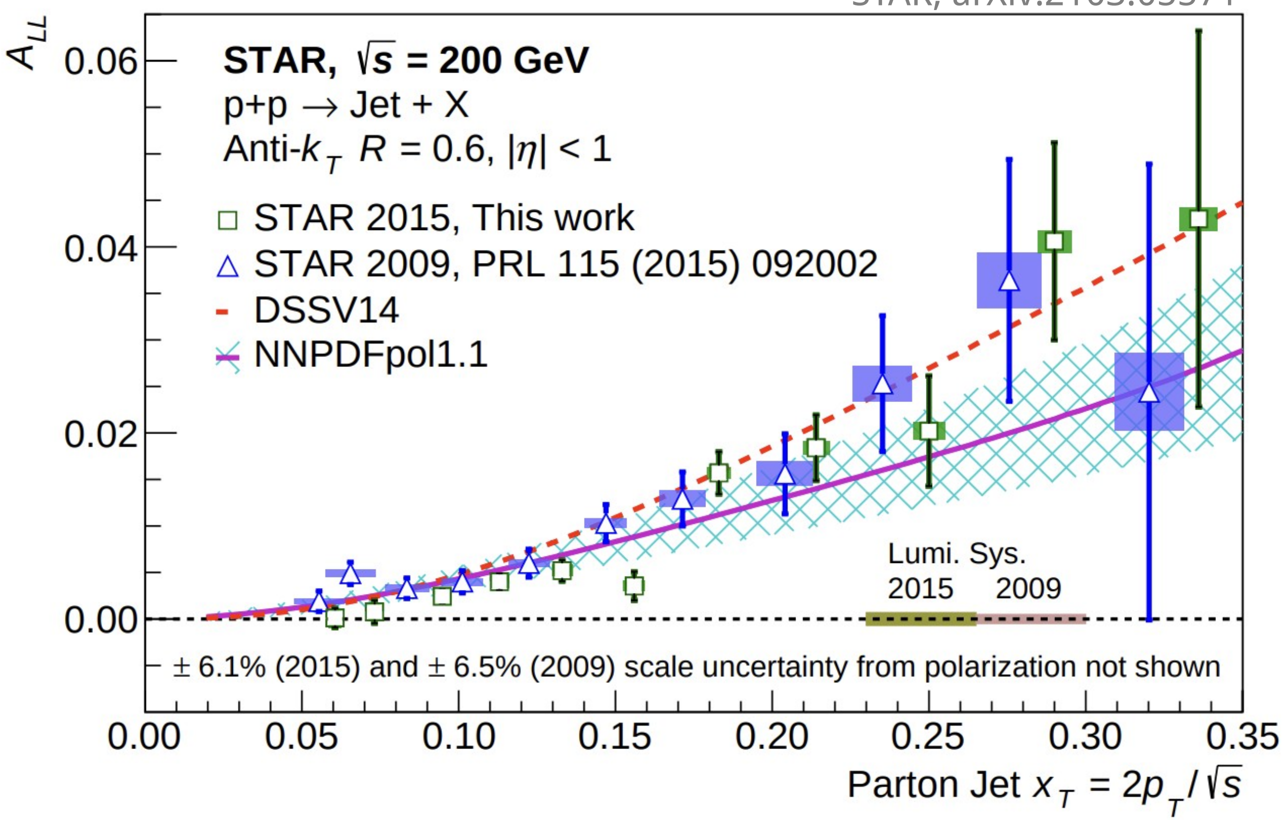
- For 2015 data R_3 varies from 0.96 to 1.04 depending on the fill with the uncertainty of $\Delta R_3 \sim 4.5 \times 10^{-4}$ (Uncertainty similar to 2009 data)

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 ($\mathcal{L}P^4$) with improved systematics
- Parity violating single-spin asymmetries consistent with zero

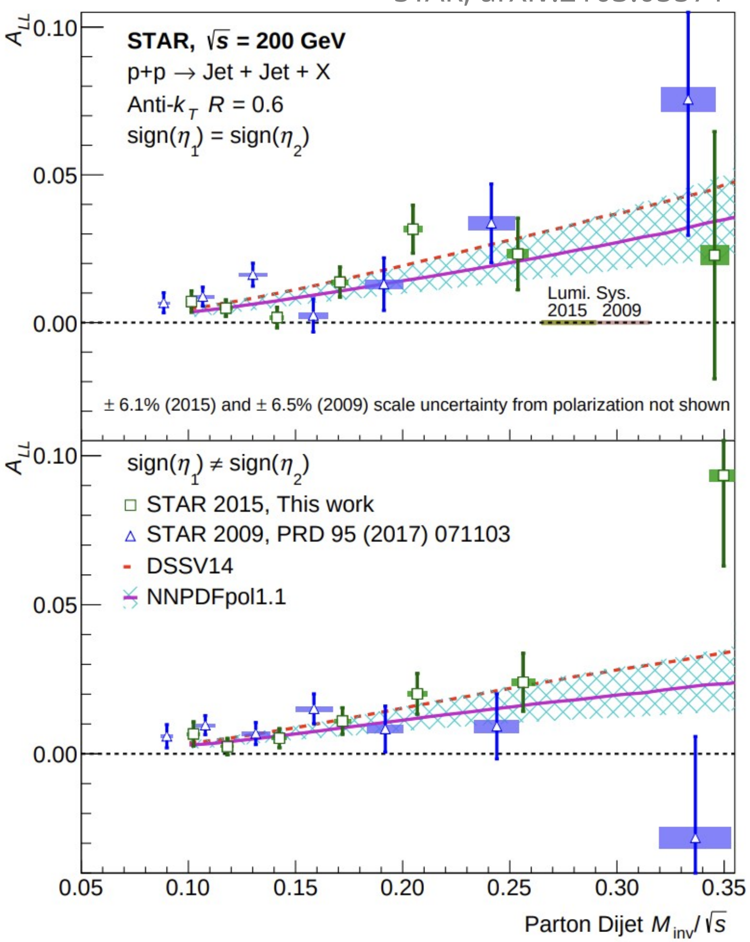
Will significantly reduce uncertainty on gluon polarization for x > 0.05 once included in global fits

DI-JET A_{LL}

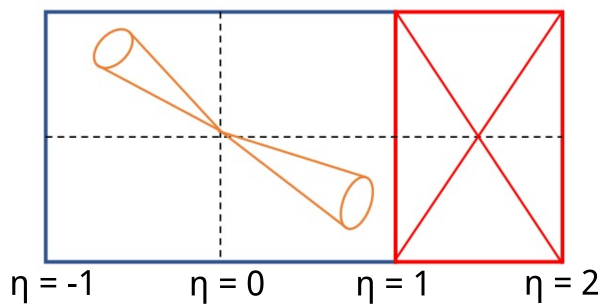
Di-jets give stricter constraints to underlying **partonic kinematics**

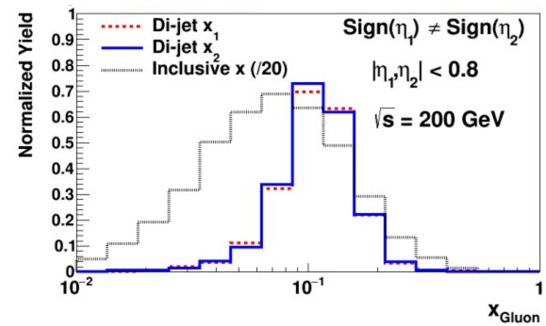
- May place better constraints on **x-dependence of $\Delta g(x,Q^2)$**
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected x

STAR, arXiv:2103.05571

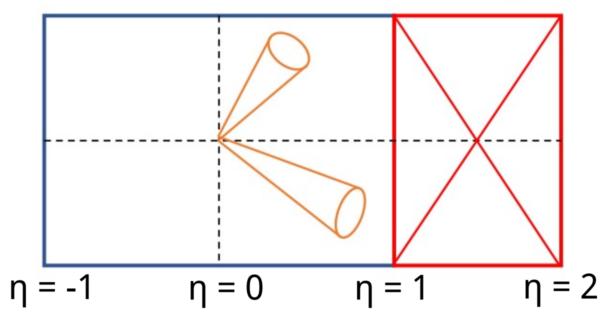


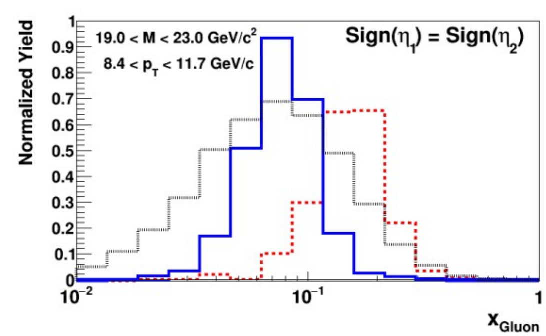
sign(η_1) ≠ sign(η_2)





sign(η_1) = sign(η_2)

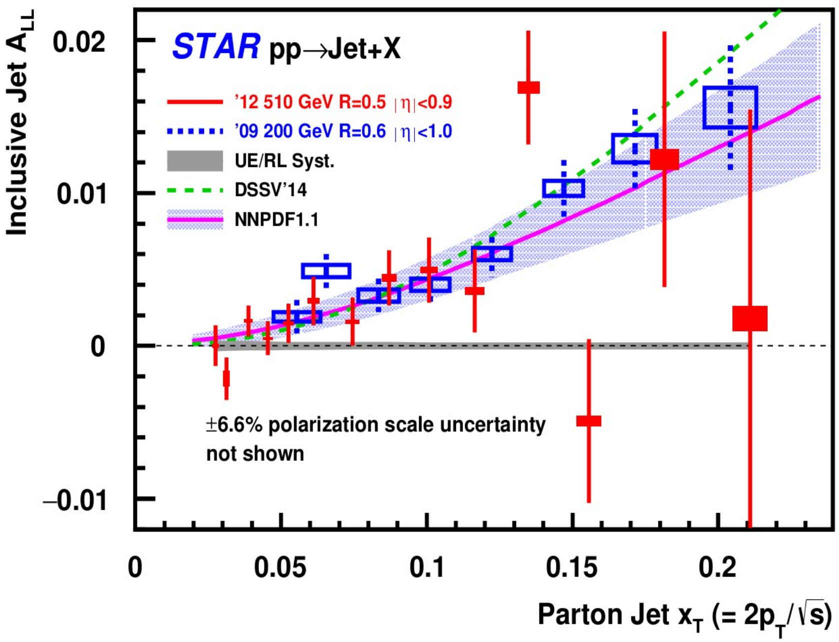




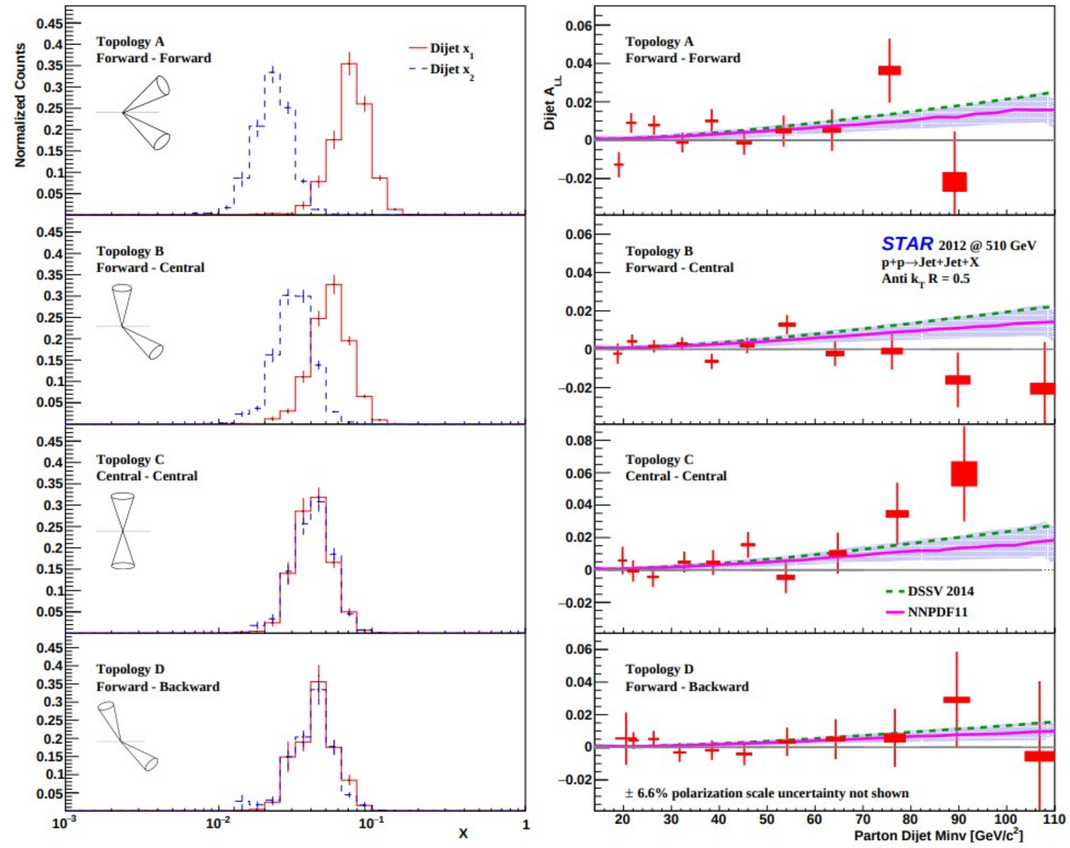
JETS AND DI-JETS AT 510 GEV

Towards smaller x

STAR, PRD 100 (2019), 052005



STAR, PRD 100 (2019), 052005



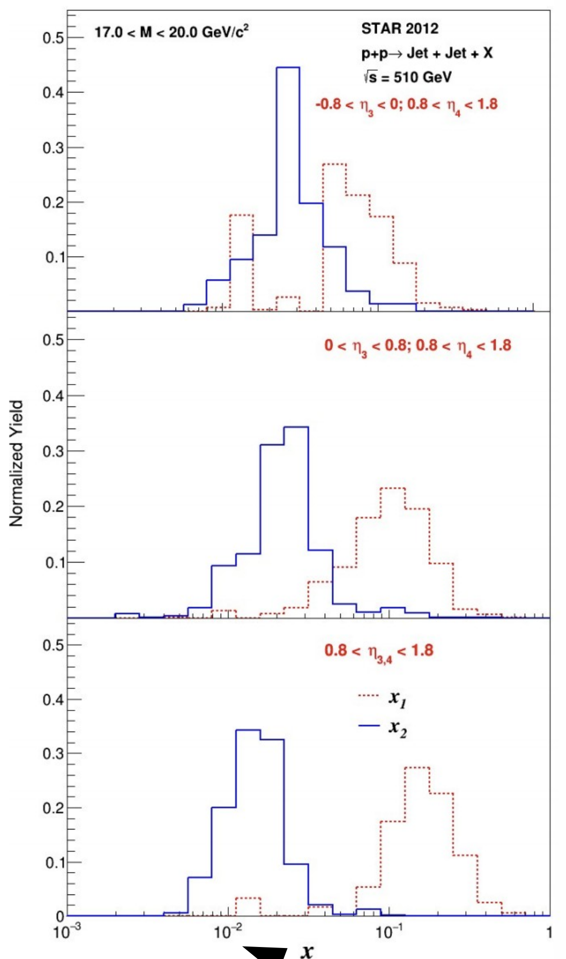
- **Higher √s pushes sensitivity to lower x (down to 0.02)**
- Consistent results from both energies

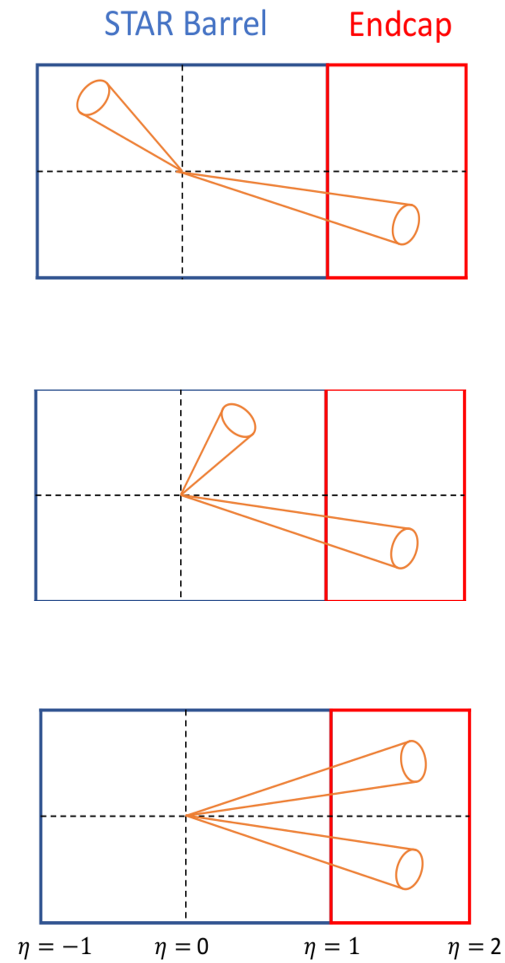
First measurement of jet and di-jet A_{LL} at 510 GeV with 2012 data

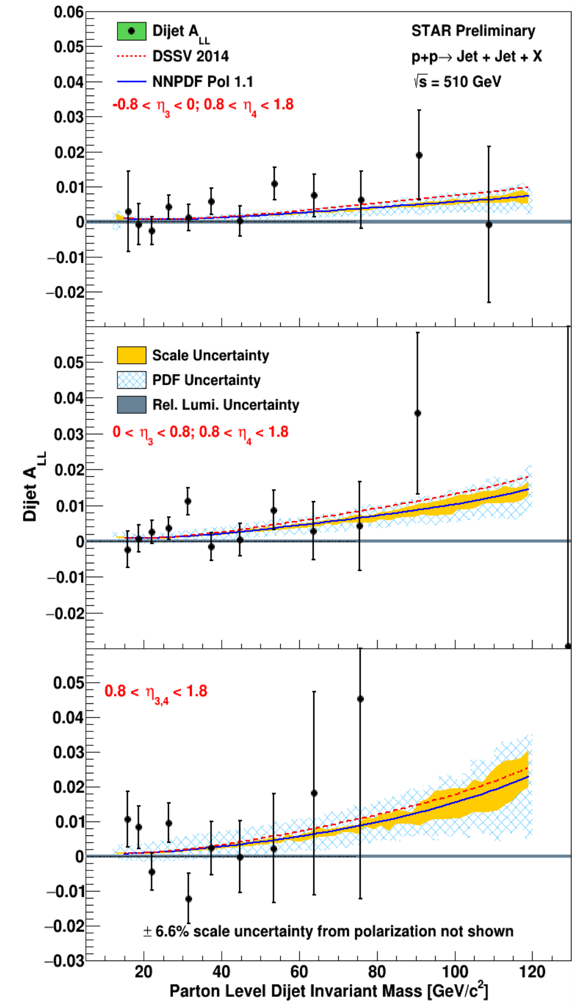
Further precision: Run 2013 data at √s = 510 GeV – x 3.7 statistics

JETS AND DI-JETS AT 510 GEV

Towards smaller x







More forward η pushes sensitivity to even lower x (down to 0.005)

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

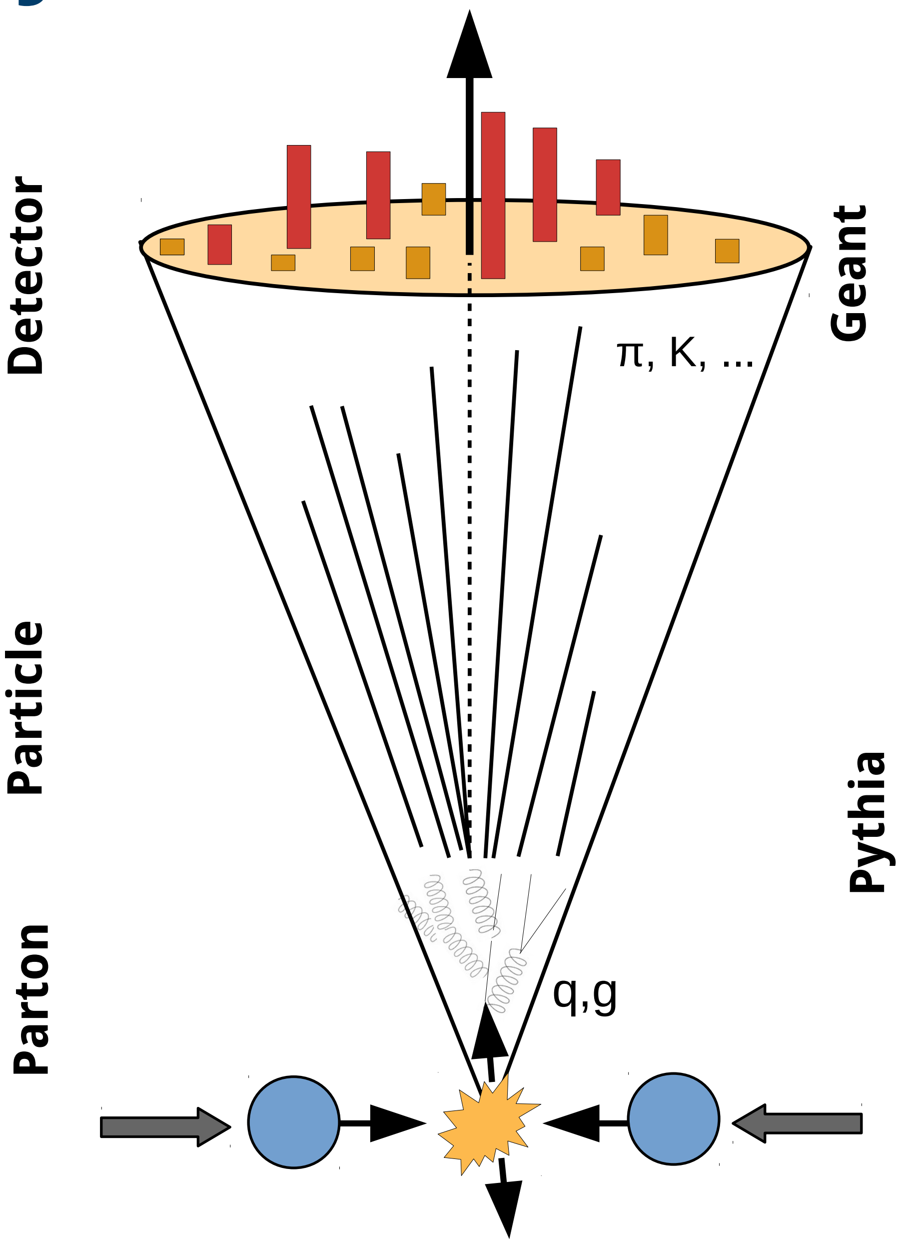
2. 2009 data at $\sqrt{s}$ = 200 GeV PRL 115 (2015) 9, 092002 included in global perturbative QCD analysis provided **evidence for positive gluon polarization** for $x > 0.05$

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

BACKUP

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**:

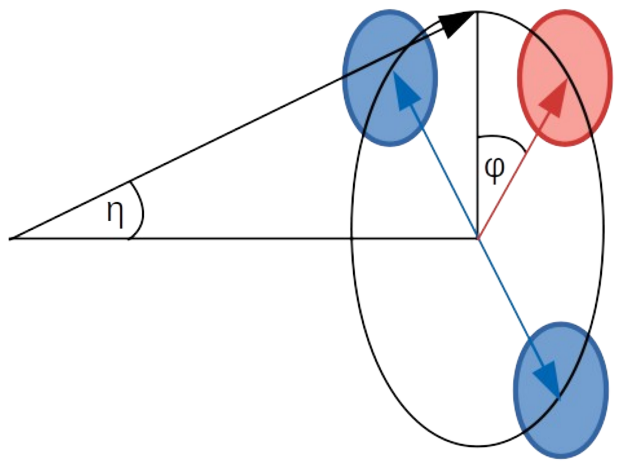
- **Detector level:** detector response to stable particles (takes into consideration finite detector acceptance, efficiency and resolution effects)
- **Particle level:** complete set of stable color-neutral particles produced in the event
- **Parton level:** hard-scattered partons from Pythia event
  - 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

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

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

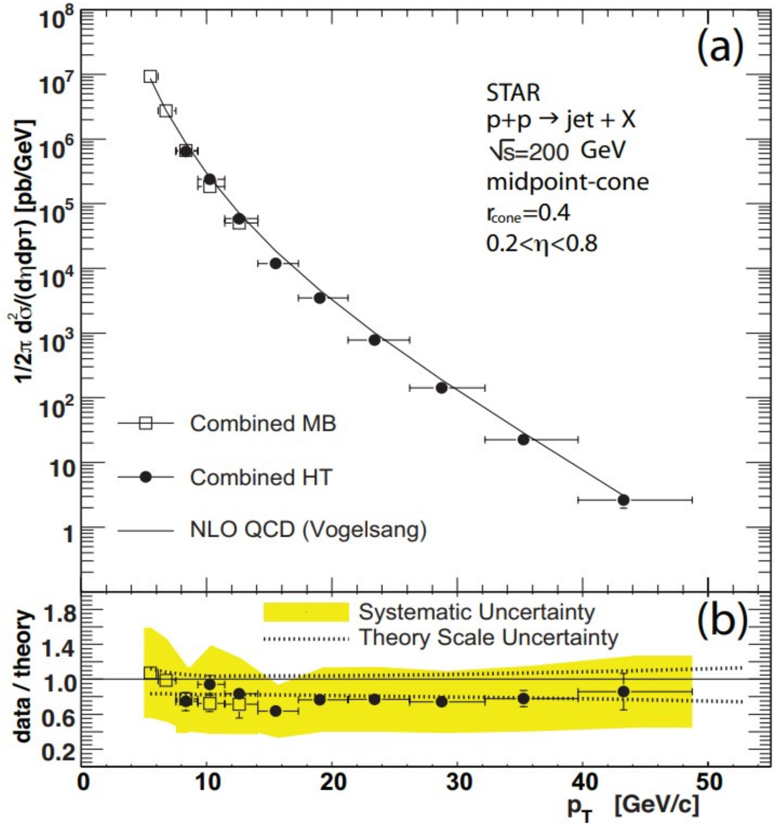
Trigger bias and reconstruction efficiency

- Estimated using replicas from polarized NNPDF1.1 PDF set
- Corrections up to about 10% depending on the jet p_T bin

JET CROSS-SECTIONS

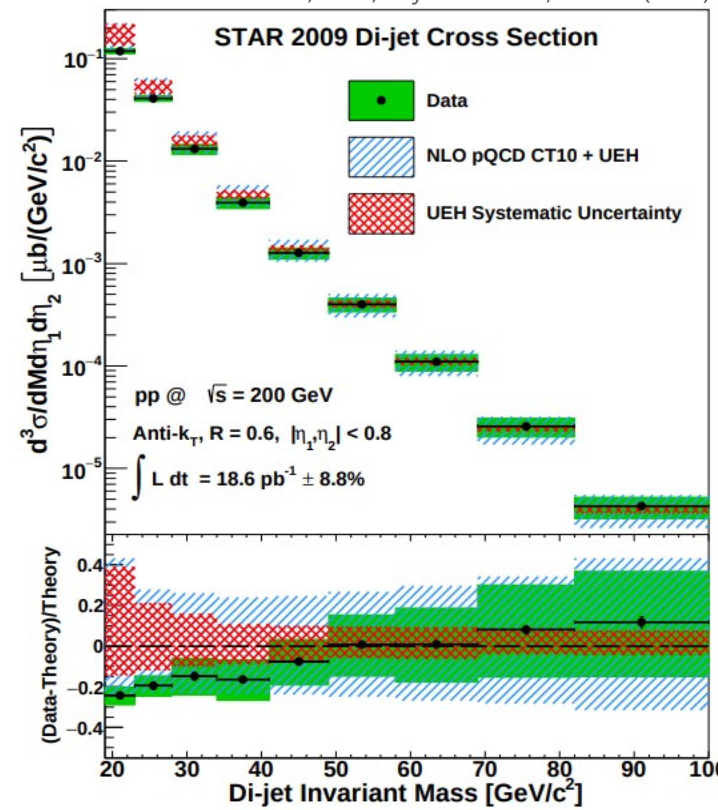
Inclusive jet cross section

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



Dijet cross section

Data: STAR, 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)



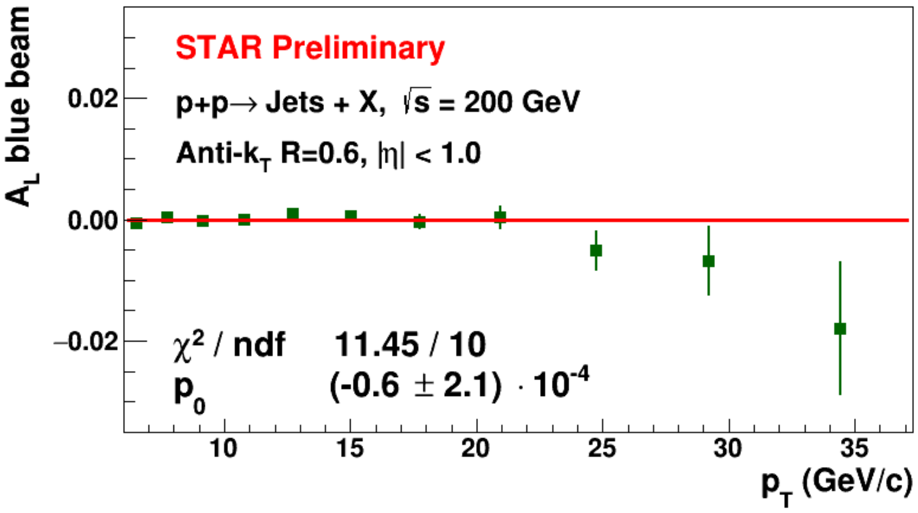
- Midpoint cone algorithm
- No UE correction
- Bin-by-bin detector level corrections
- New measurement with improved analysis from STAR in progres

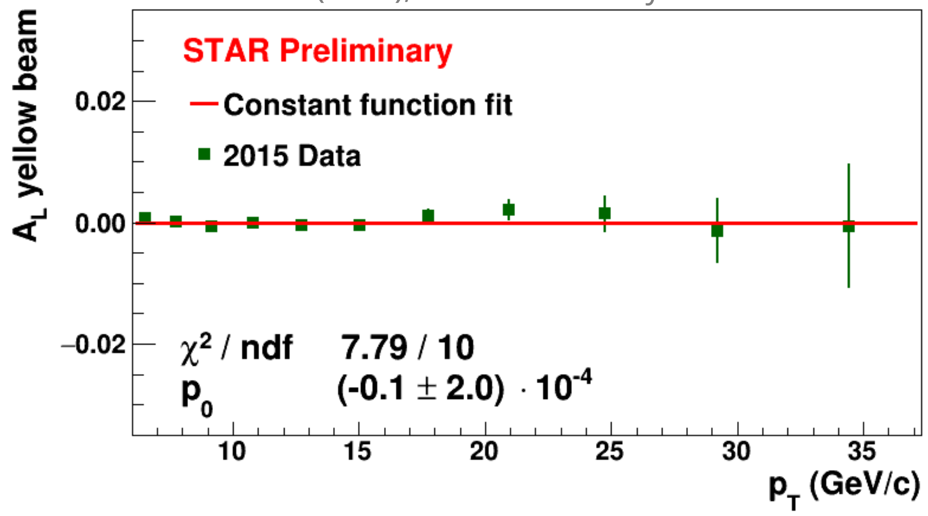
- Anti-k_T algorithm
- MC-driven UE correction
- Detector effects unfolded

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

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 within their statistical uncertainties**

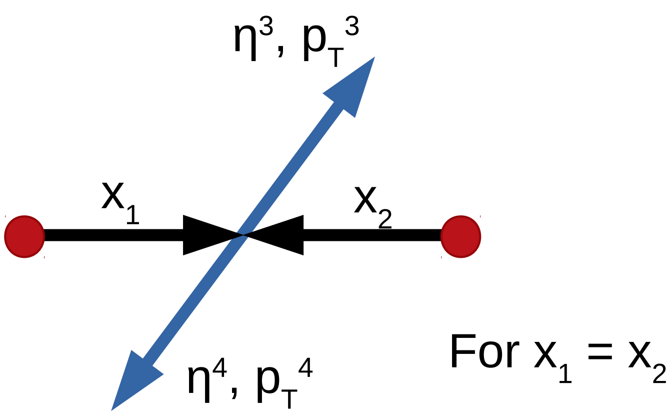
- Consistent well with the expectation

DI-JET MEASUREMENTS

- Di-jets give stricter constraints to underlying **partonic kinematics**
- May place better constraints **x-dependence of $\Delta g(x,Q^2)$**

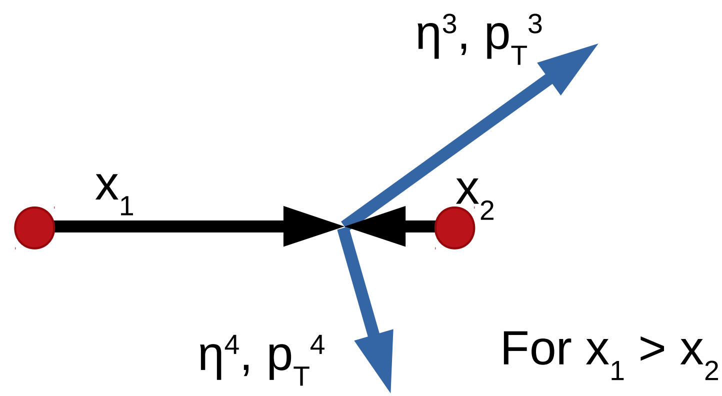
$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \qquad M = \sqrt{x_1 x_2 s} \qquad |\cos\theta^*| = \tanh\left|\frac{\eta_3 - \eta_4}{2}\right| \qquad \text{(LO)}$$

"Unlike sign topology"



Symmetric collisions

"Same sign topology"



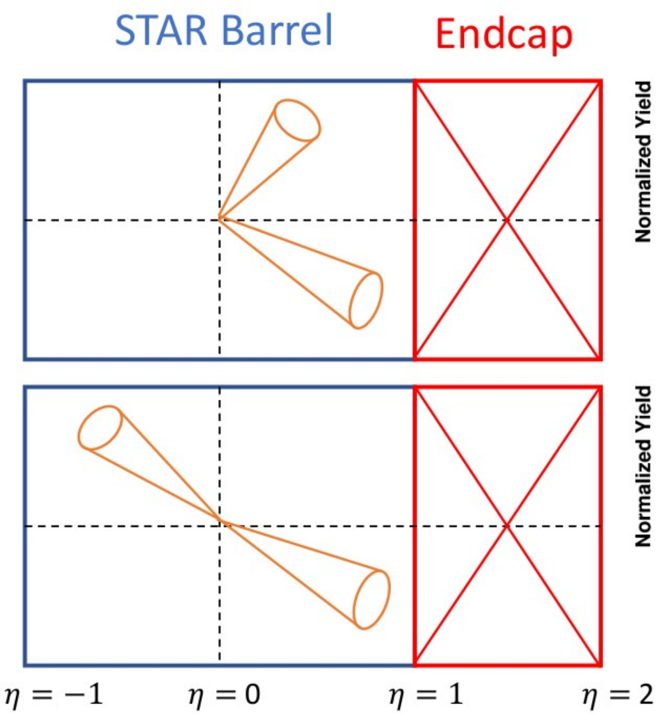
Asymmetric collisions

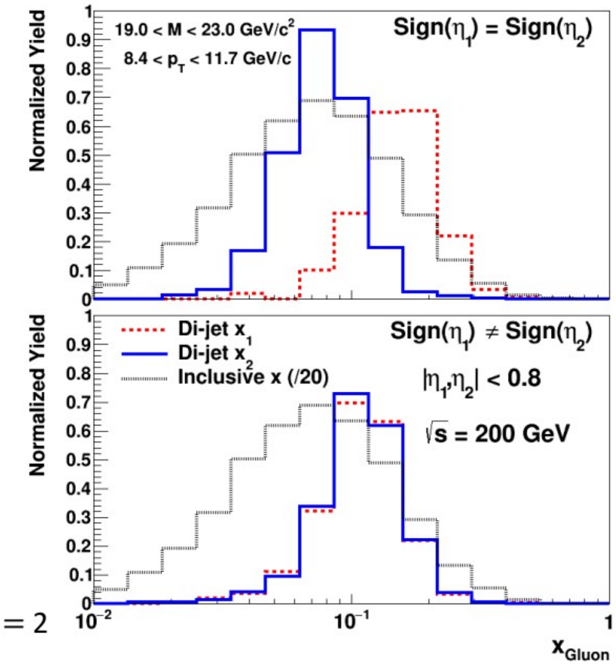
Forward jets probe lower values of x_g
For large asymmetry, likely: 2 – gluon, 1 – quark

DI-JET MEASUREMENTS

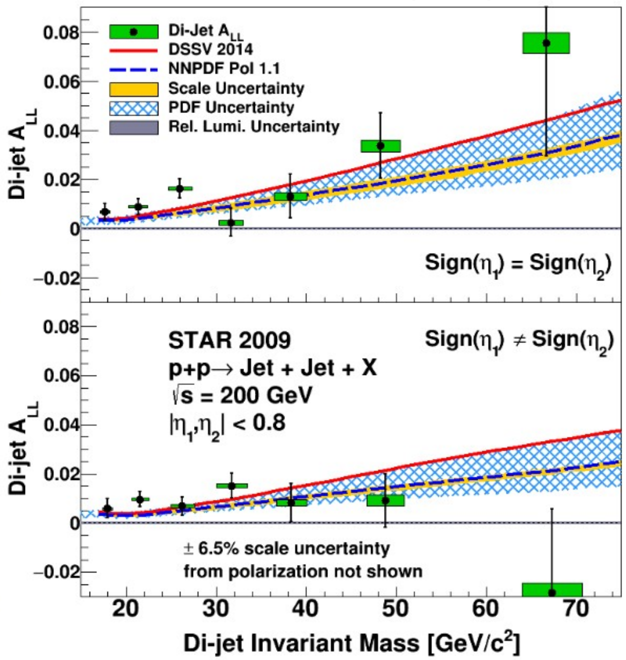
- Di-jets give stricter constraints to underlying **partonic kinematics**
- Much narrower ranges of initial state partonic momentum tested
- Different di-jet topologies enhances sensitivity of the data to selected x

Midrapidity di-jet measurement with 2009 data





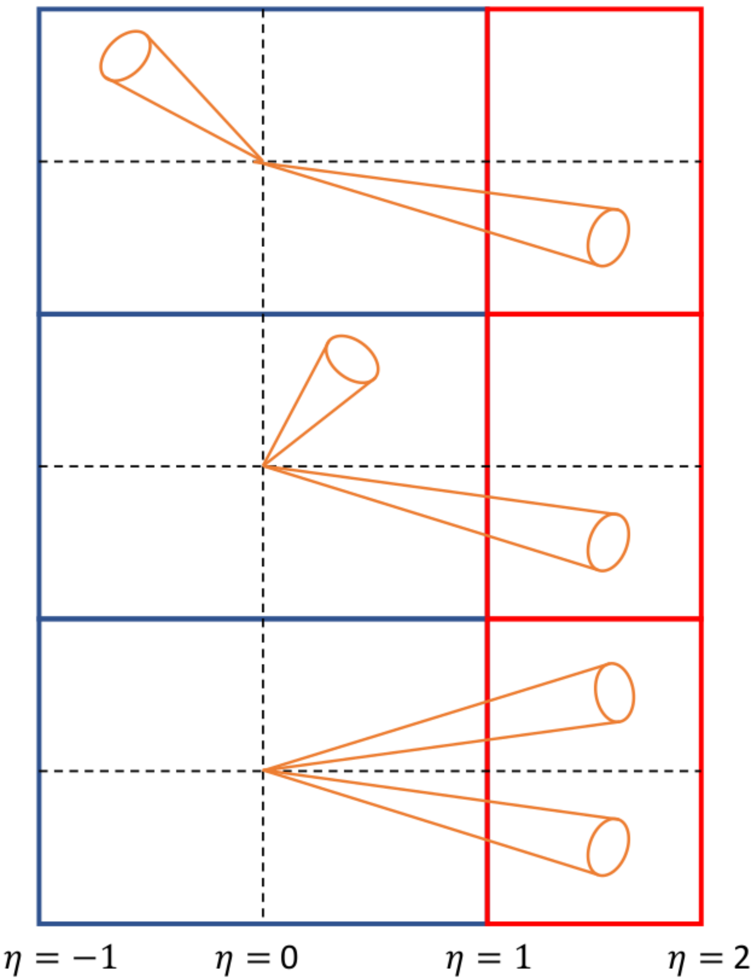
STAR, PRD 95 (2017), 071103

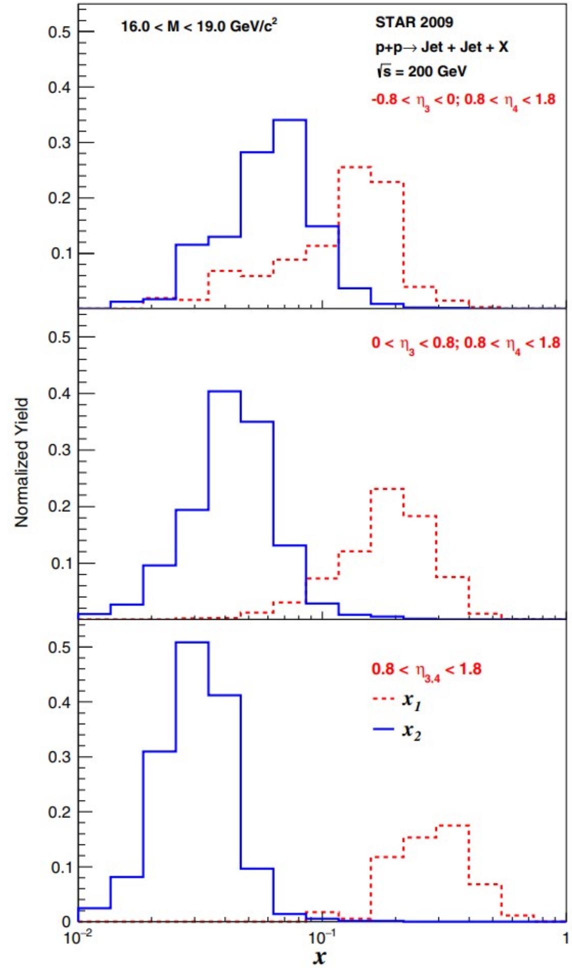


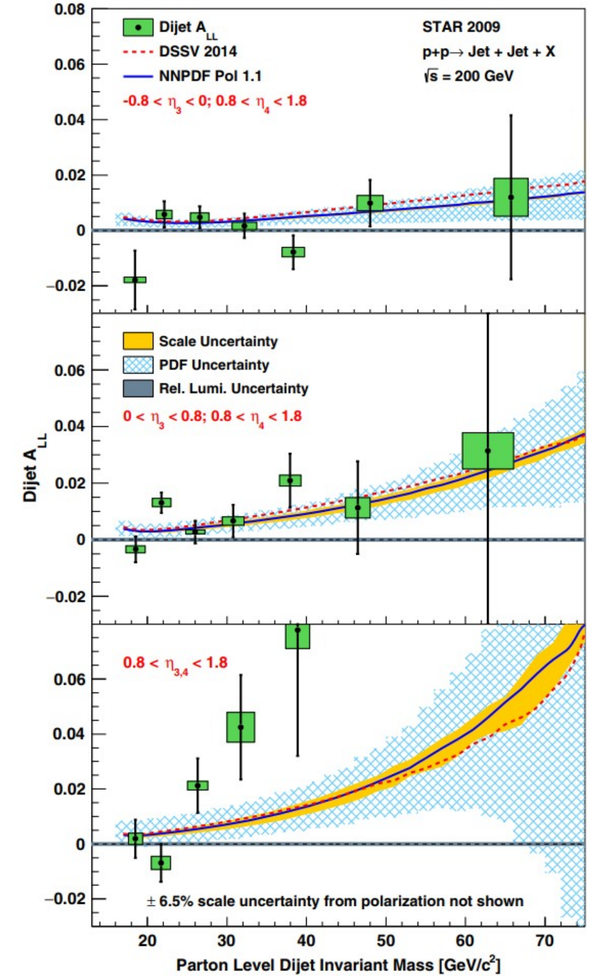
DI-JET MEASUREMENTS

Di-jet measurement with Endcap EMC based on 2009 data

STAR, PRD 98 (2018), 032011





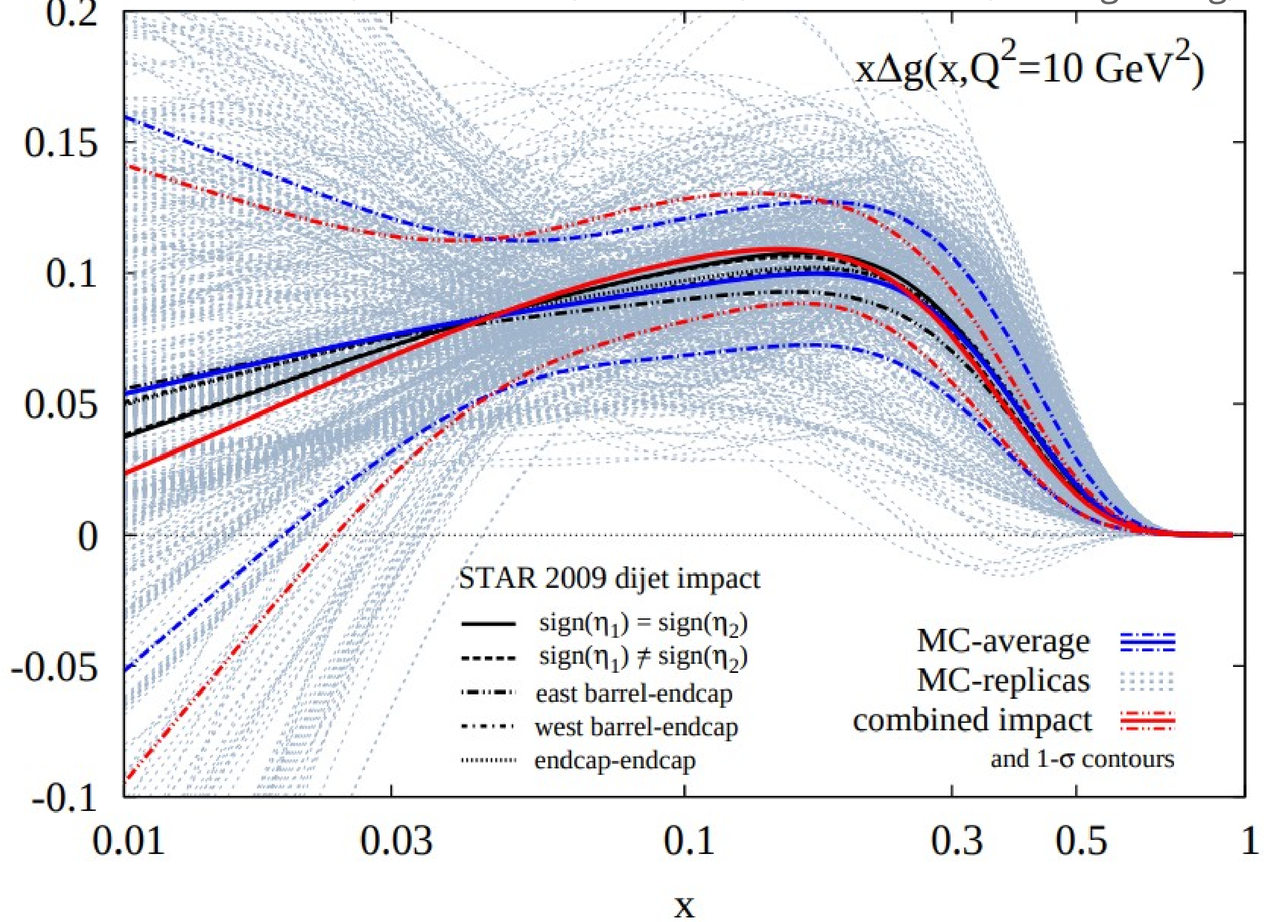


- Central di-jet measurement Run 2009 √s = 200 GeV (25 pb^{-1}): PRD 95 (2017), 071103
- Intermediate-rapidity di-jet measurement Run 2009 √s = 200 GeV (25 pb^{-1}): STAR, PRD 98 (2018), 032011
- Central di-jet measurement Run 2012 √s = 510 GeV (82 pb^{-1}): PRD 100 (2019), 052005
- Further precision: Run 2015 √s = 200 GeV – x 2 statistics, Run 2013 √s = 510 GeV – x 3.2 statistics

DI-JET MEASUREMENTS

Impact on $\Delta g(x,Q^2)$

Phys. Rev. D 100, 114027 (2019)
D. de Florian, G. A. Lucero, R. Sassot, M. Stratmann, W. Vogelsang,

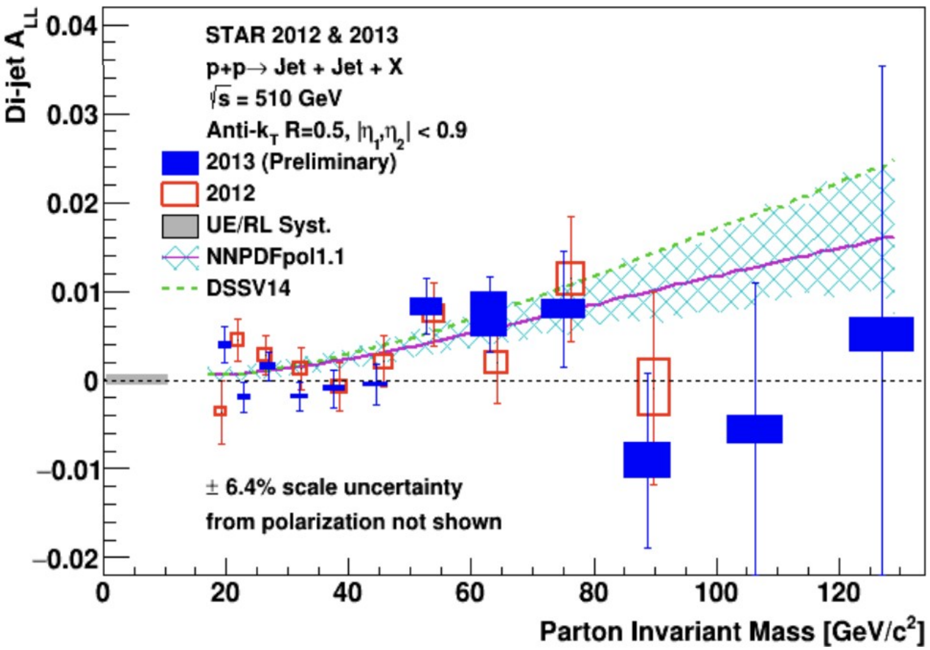


- Influence of central and forward di-jets from 2009 data (25 pb^{-1}) $\sqrt{s}$ = 200 GeV on DSSV evaluations

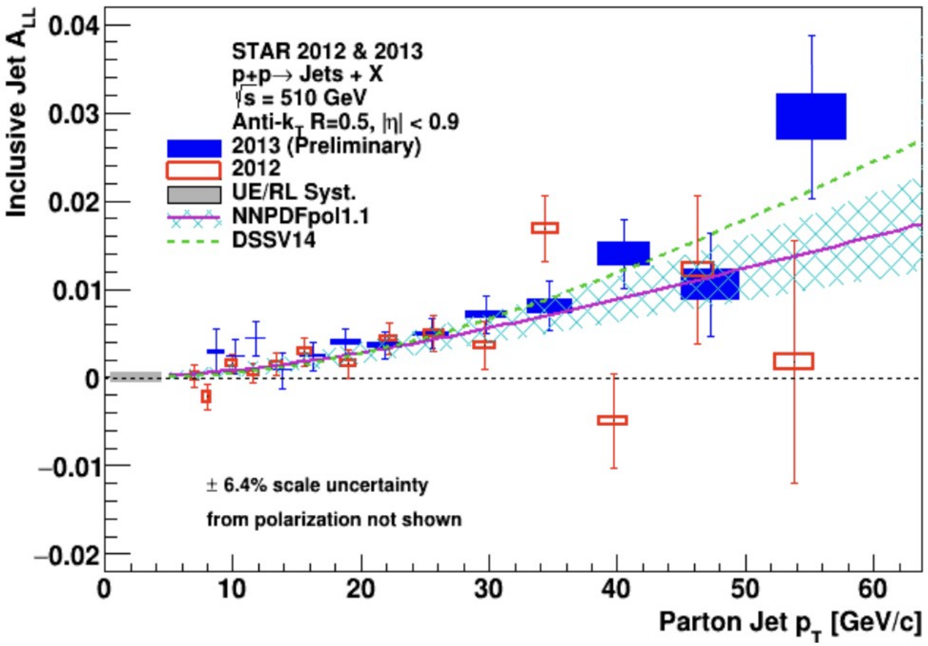
JETS AT 510 GEV

Towards smaller x

D. Olvitt et al. (STAR), RAUM 2017



A. Quintero et al. (STAR), RAUM 2017



- Further precision: Run 2013 √s = 510 GeV – x 3.2 statistics
- Preliminary results for midrapidity based on ~60% statistics