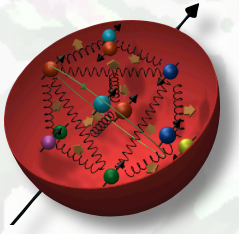
Exploring the gluon polarization using inclusive jet and dijet production in polarized proton-proton collisions at $\sqrt{s} = 510\,\mathrm{GeV}$ at RHIC

Bernd Surrow

TEMPLE UNIVERSITY

(On behalf of the STAR Collaboration)



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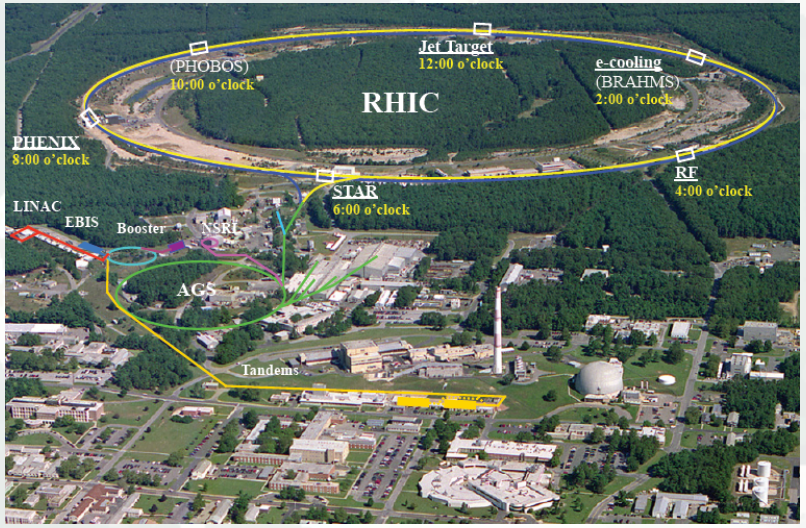
DOE NP contract: DE-SC0013405

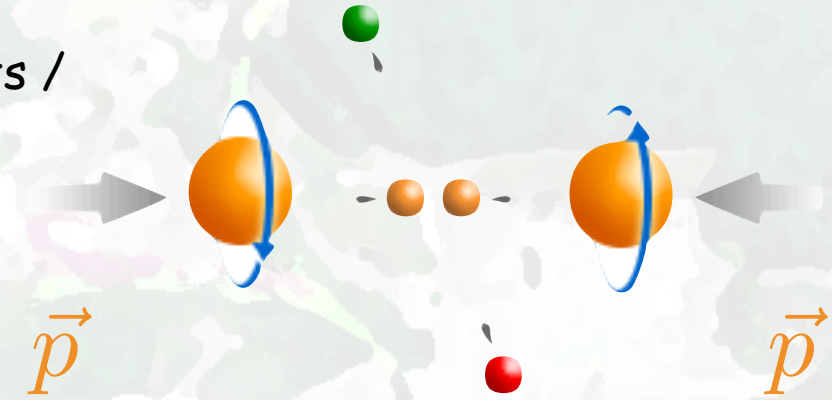
Outline



- Results: Run 13 Inclusive Jet and Di-Jet production in comparison to prior results
  - Cross-section measurements
  - Asymmetry measurements

- Experimental aspects: Asymmetry measurements / RHIC / STAR

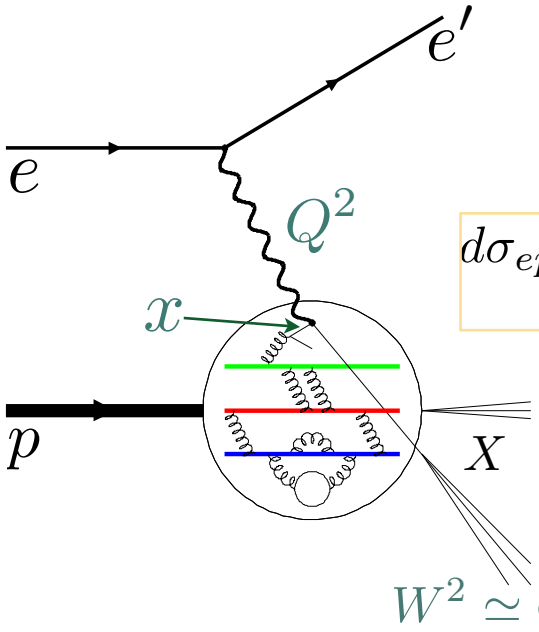
- Theoretical foundation



- Summary and Outlook

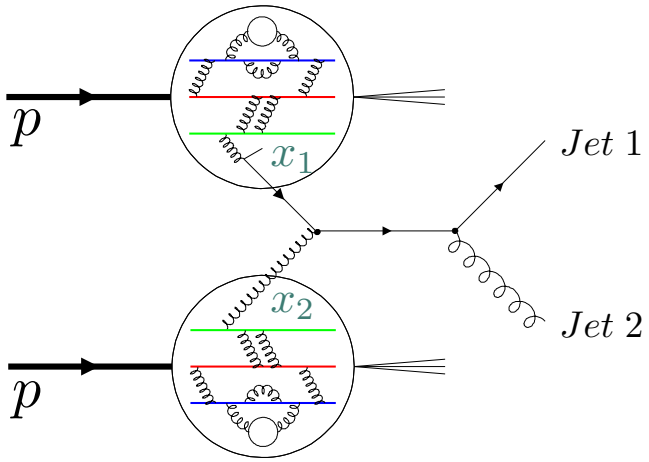
Theoretical foundation - Probing PDFs

- Probing gluons in ep vs. pp scattering



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

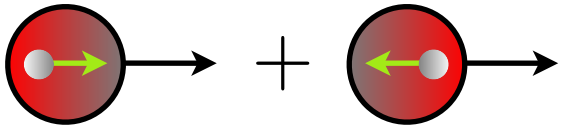
Universality



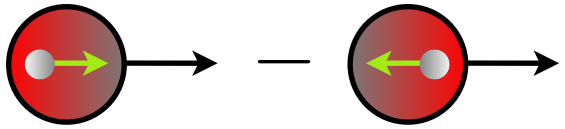
$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$ Factorization

Momentum contribution

$$f(x) = f^+(x) + f^-(x)$$



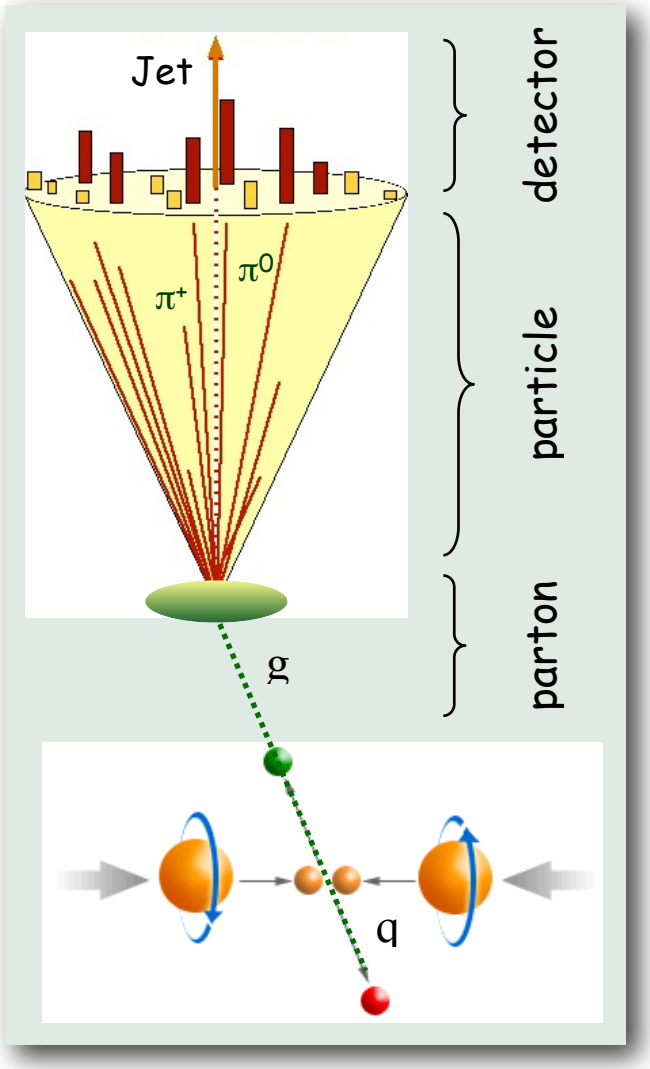
$$\Delta f(x) = f^+(x) - f^-(x)$$

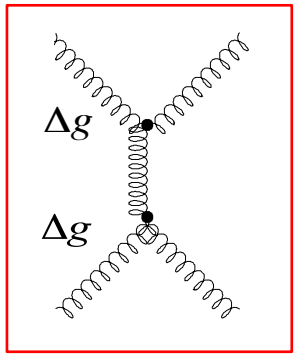


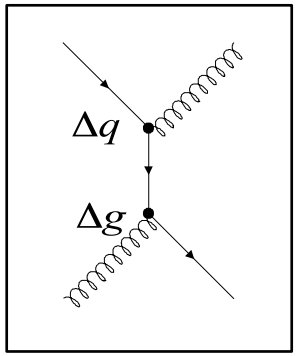
Spin contribution

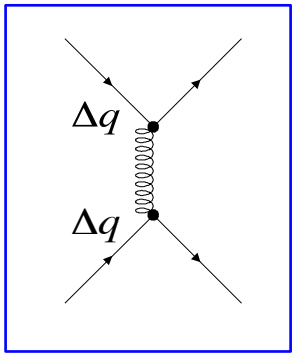
Theoretical foundation - QCD processes in pp

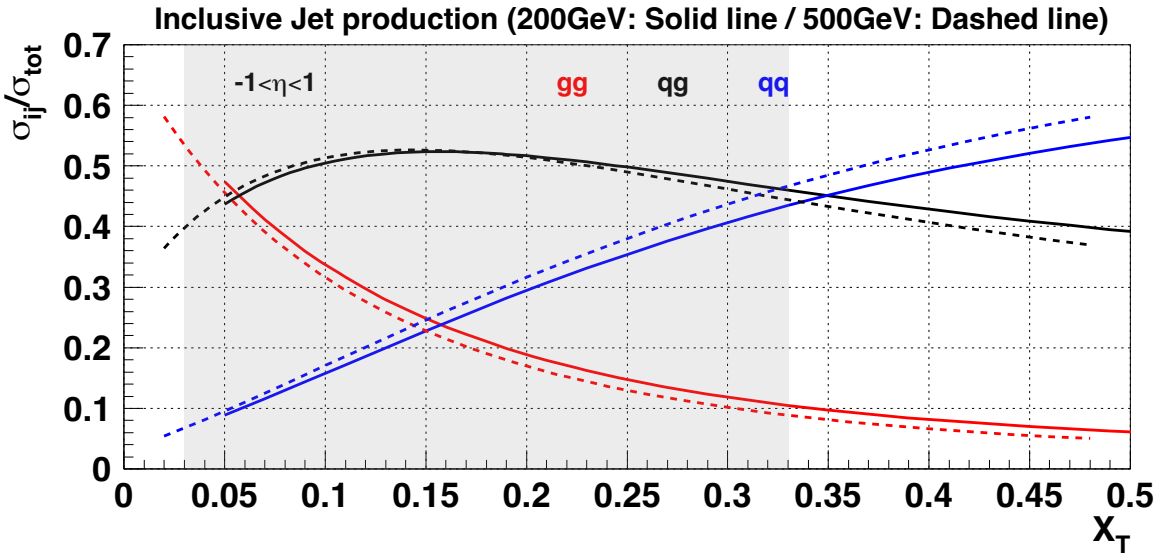
- Process contribution for jet-type measurements











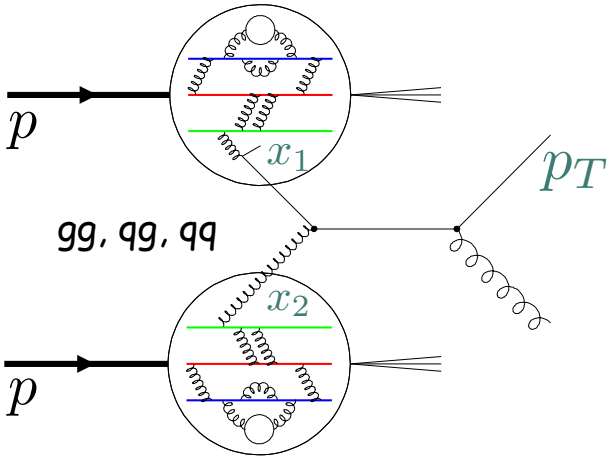
$$x_T = \frac{2p_T}{\sqrt{s}} \quad \text{(x value at } \eta = 0\text{)}$$

Theoretical foundation - pp Di-Jet measurements

Correlation Measurements: Di-Jet production

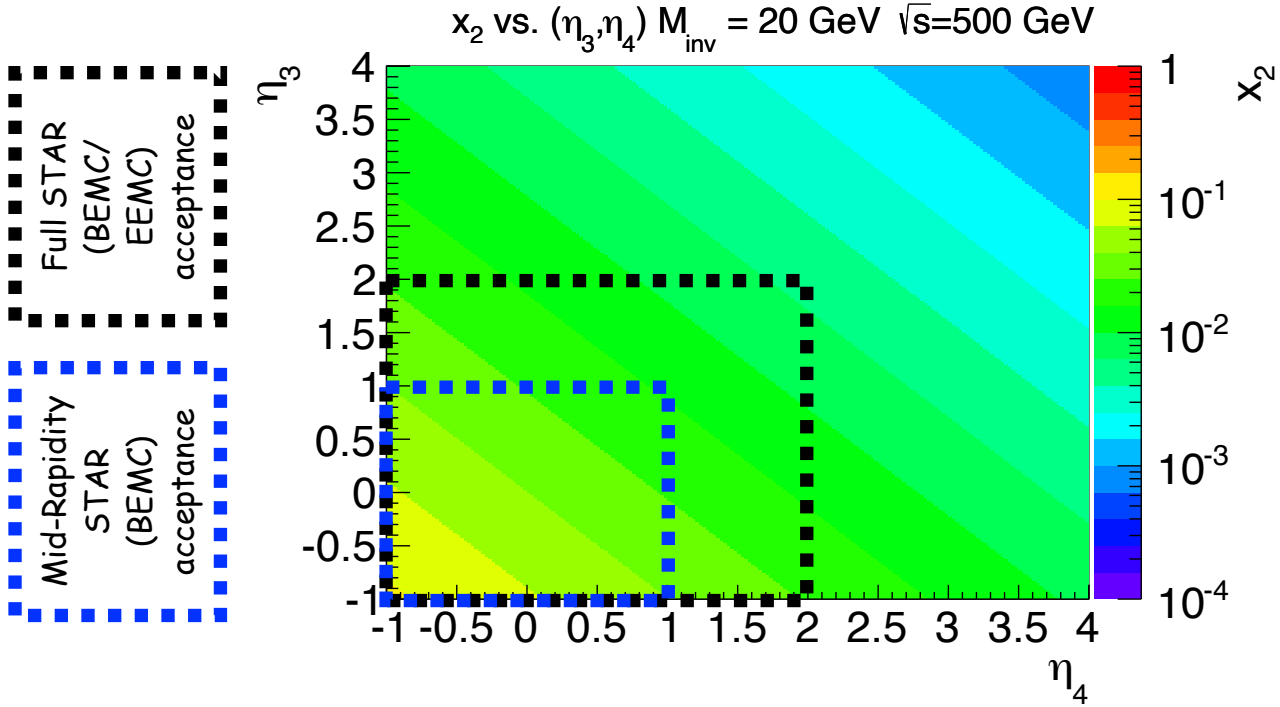
- Correlation measurements provide access to LO partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right)$$



Di-Jet production

- Bjorken x-coverage:

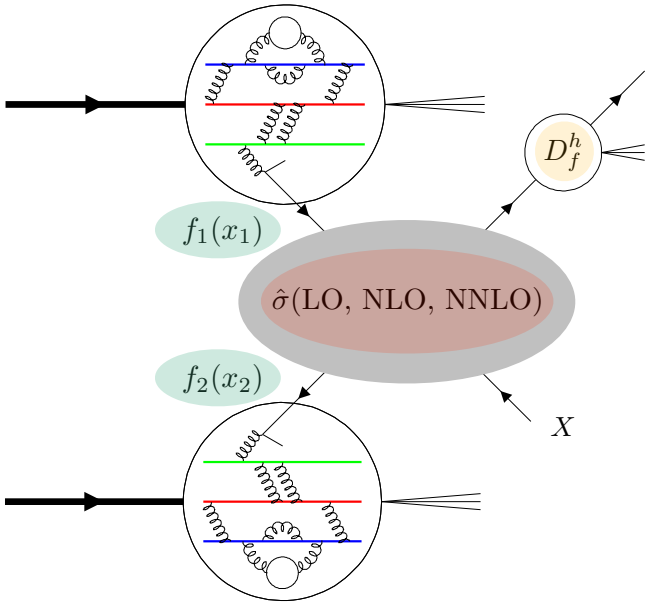


$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

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

Theoretical foundation - PDF access

- Probing helicity distribution functions
  - Observable: Longitudinal double-spin asymmetry A_{LL} ➜ Probe gluon helicity distribution function $\Delta g(x, Q^2)$ through Inclusive Jet/ Di-Jet production in global analysis!



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

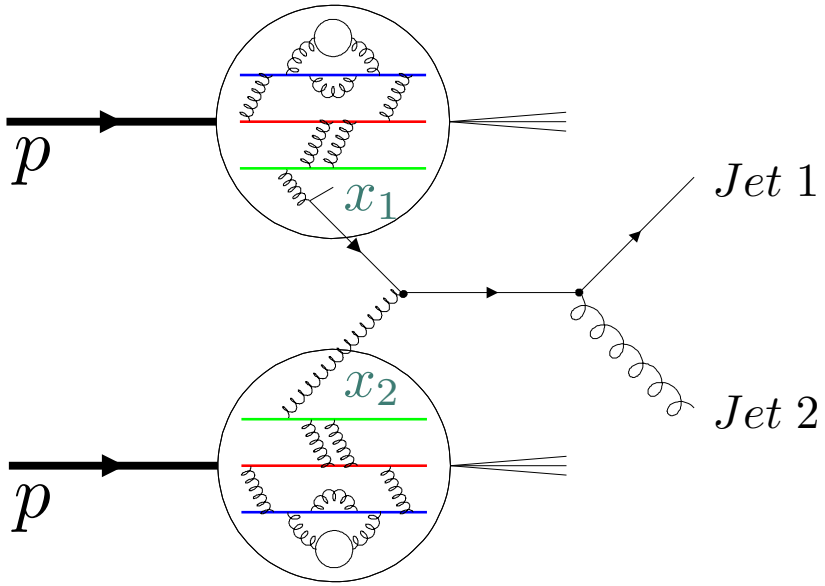
Colliding beam helicities!

$$= \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

Δf_1 Δf_2 $a_{LL} = \frac{\Delta\sigma_h}{\sigma_h}$ } Input

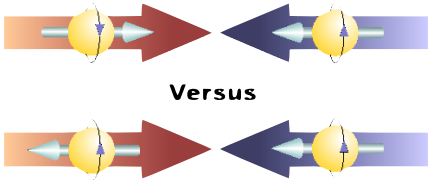
Experimental aspects - Asymmetry measurement

- Asymmetry measurement



$$A_{LL} = \frac{\sum_{\text{runs}} P_Y P_B \left(N^{++} - r N^{+-}\right)}{\sum_{\text{runs}} P_Y^2 P_B^2 \left(N^{++} + r N^{+-}\right)}$$

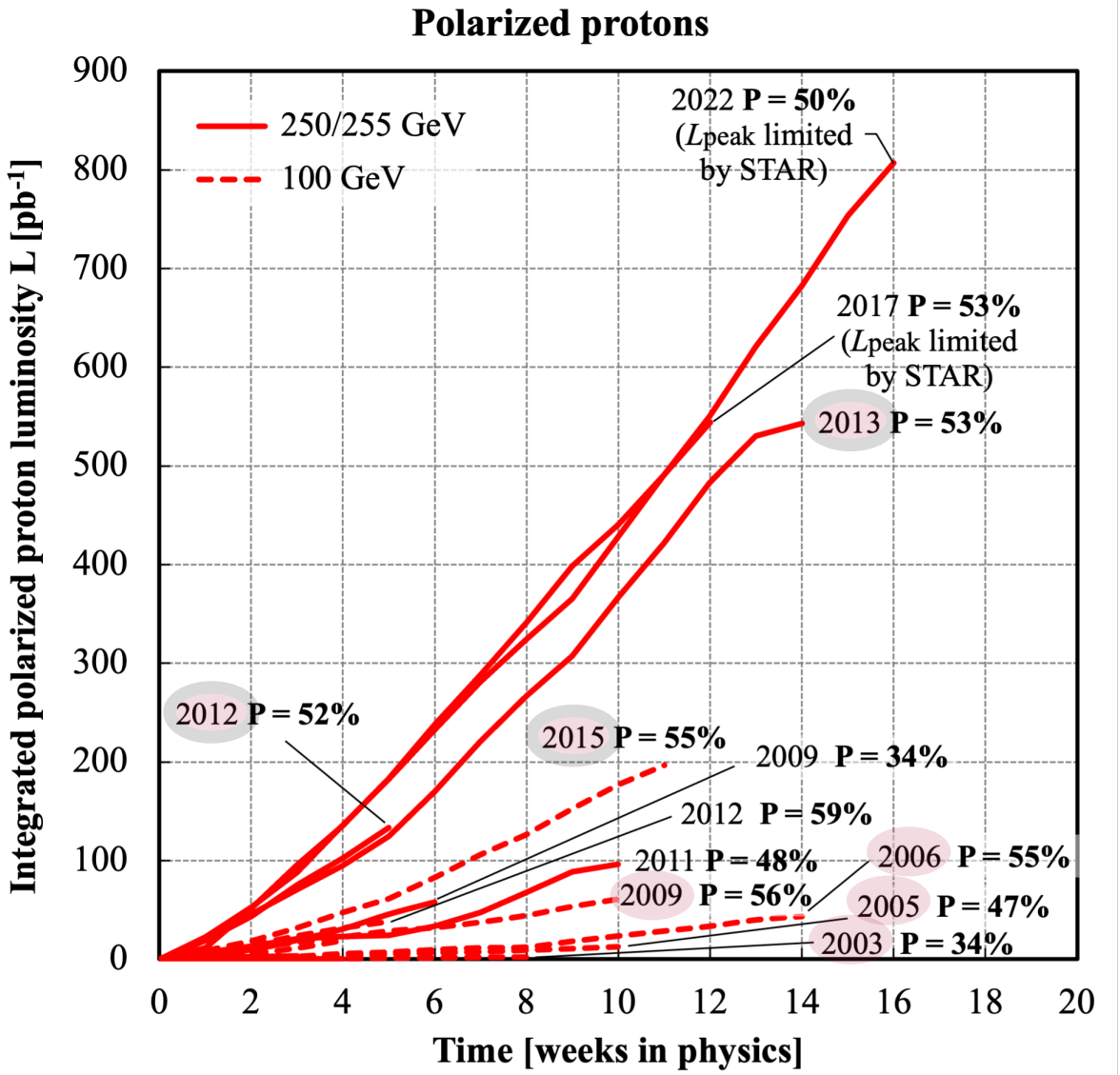
$$\frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$



- Require concurrent measurements:
  - Longitudinal beam polarization $P_{Y(B)}$ at STAR IR
  - Direction of polarization vector
  - Relative luminosity r of bunch crossings with different spin directions
  - Spin-dependent yields N^{ij} of process of interest

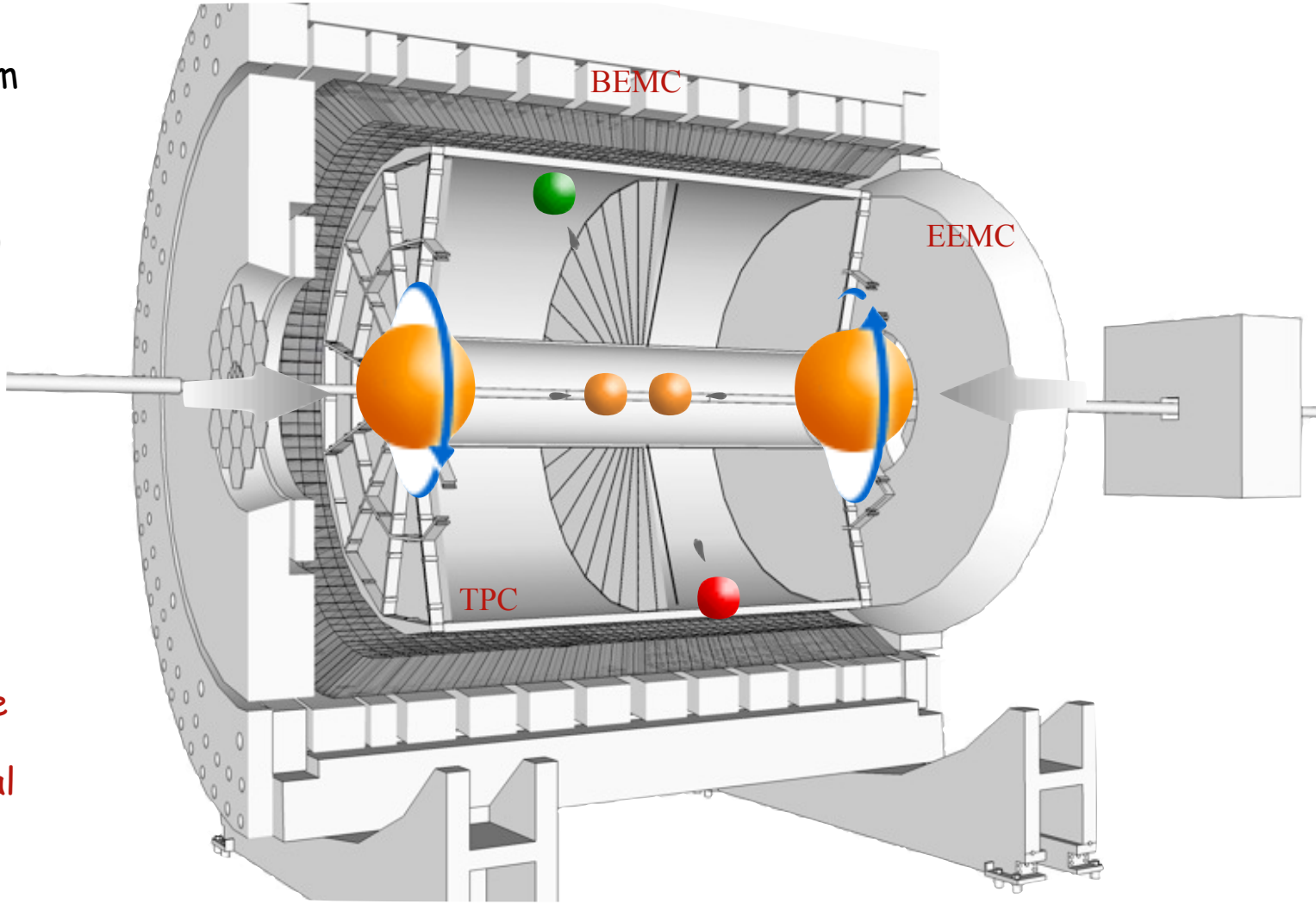
Experimental aspects - RHIC

- Polarized p+p collisions
  - Production runs at √s=200 / 500 / 510GeV (long. polarization) in 2003/2004, 2005, 2006, 2009, 2012, 2013 and 2015: Inclusive Jet and Di-Jet production (Gluon related studies!)
  - Detailed Jet results will be shown from Run 13 (510GeV) in comparison to Run 12 (510GeV) and Run 15 (200GeV)



Experimental aspects - STAR

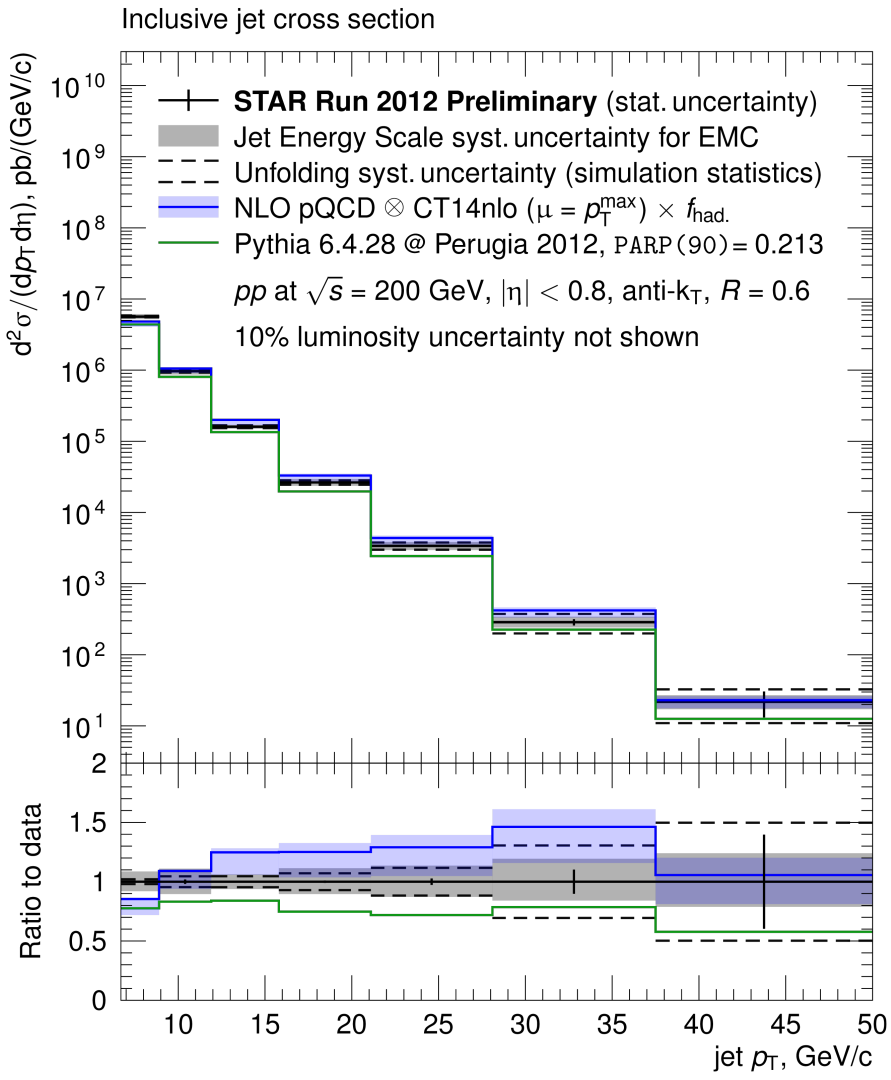
- Overview
  - Calorimetry system with 2π coverage:
    BEMC ($|\eta| < 1.0$)
    and EEMC
    ($1.1 < \eta < 2.0$)
  - TPC: Tracking and particle ID
  - VPD/ZDC: Relative luminosity and local polarimetry

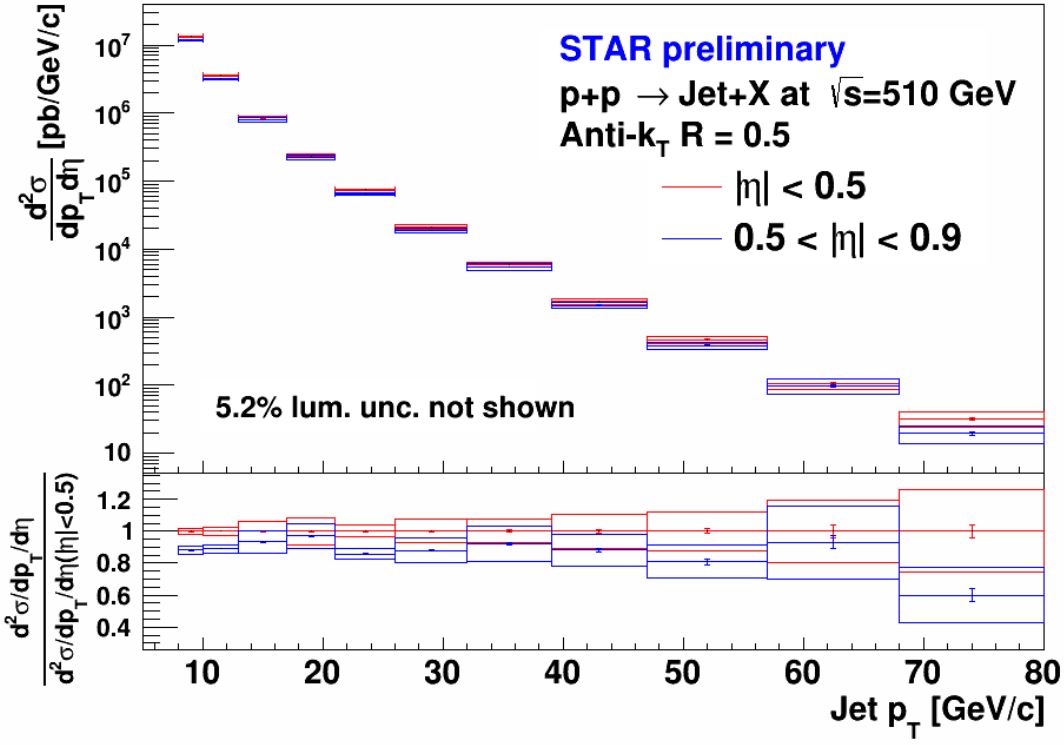


$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

STAR Results: Inclusive Jet Cross-section

Mid-rapidity Inclusive Jet cross-sections at 200GeV / 510GeV



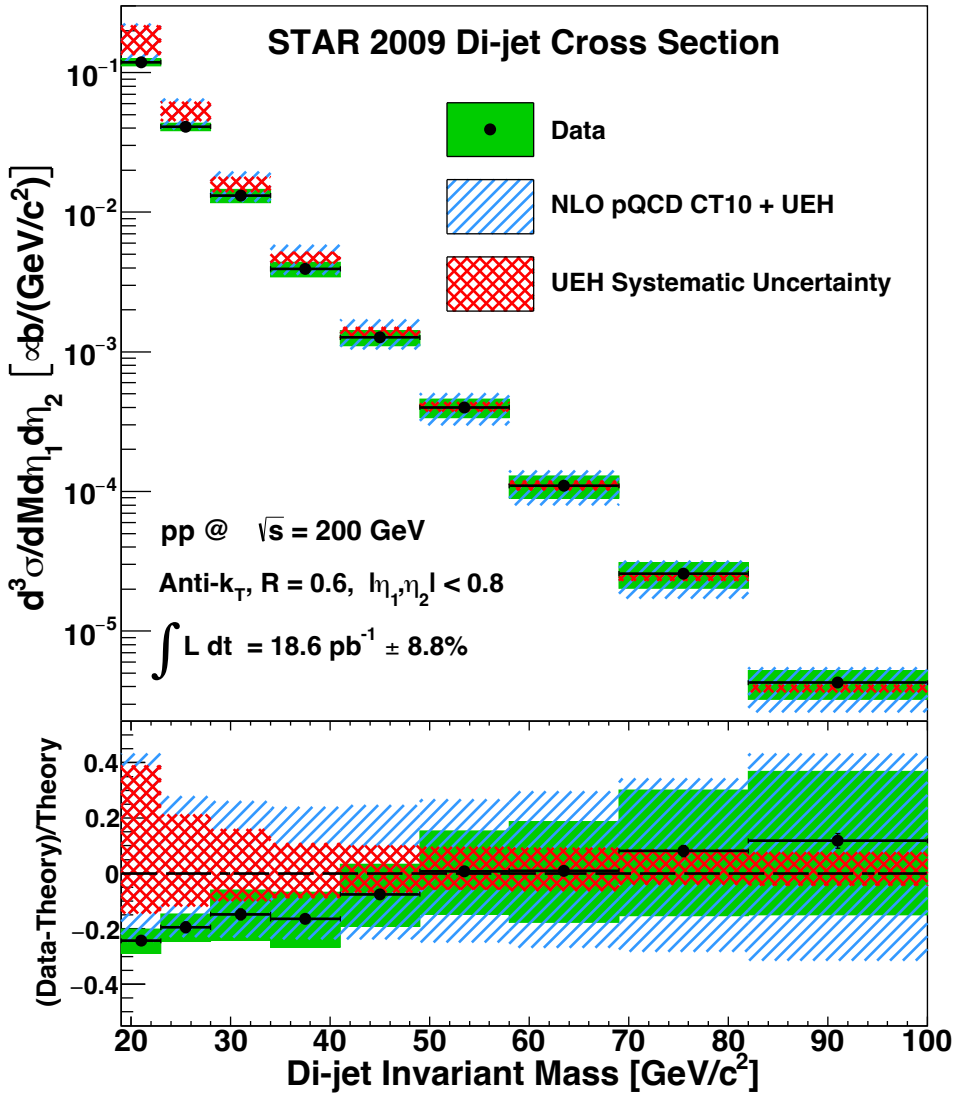


- Double-differential cross-section in jet p_T for $|\eta| < 0.8$ at $\sqrt{s} = 200\,\text{GeV}$ and for $|\eta| < 0.5$ and $0.5 < \eta < 0.9$ at $\sqrt{s} = 510\,\text{GeV}$
- Sys. uncertainties: EMC response to photon/electrons & hadrons (Dom. contr.) / TPC track mom. resolution / TPC tracking efficiency / Unfolding bias - Luminosity scale (Not shown)

STAR Results: Di-Jet Cross-section

- Mid-rapidity Di-Jet cross-section
  - Differential cross-section in di-jet invariant mass for $|\eta_1, \eta_2| < 0.8$ at $\sqrt{s} = 200\,\mathrm{GeV}$
  - Sys. uncertainties: EMC tower energy scale / TPC tracking efficiency / Track p_T resolution / Unfolding bias - Luminosity scale (Not shown)
  - Theory comparison: Cross-section corrected for underlying event and hadronization (UEH) effects / Theory uncertainty

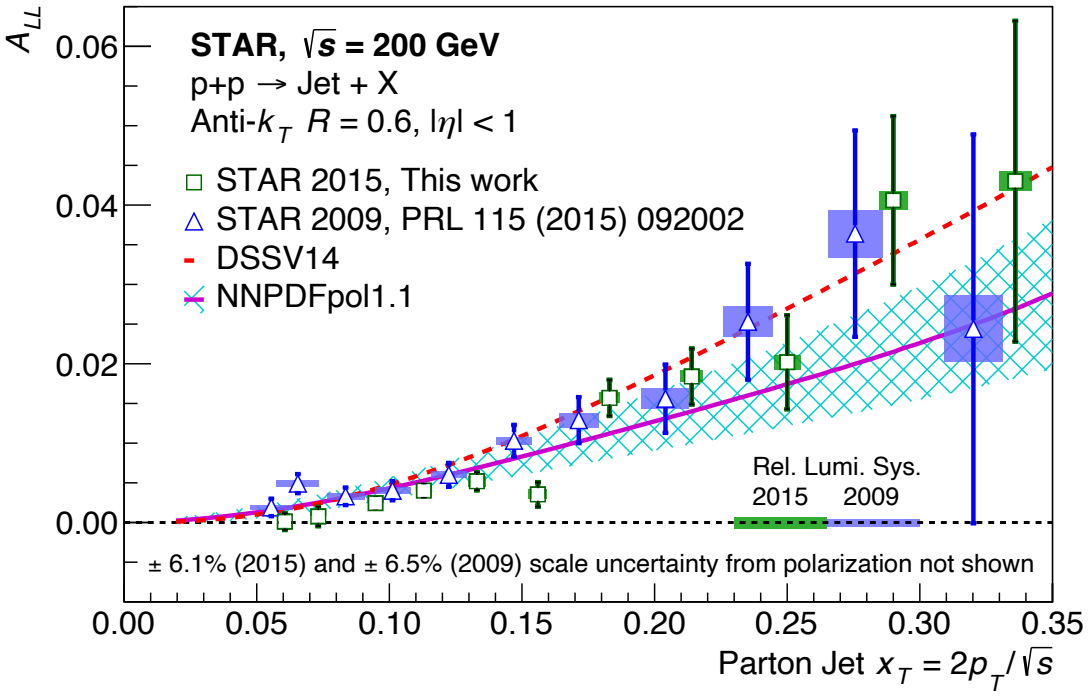
J. Adamczyk *et al.* (STAR Collaboration), *Phys. Rev.* **D 95** (2017) 7, 071103.

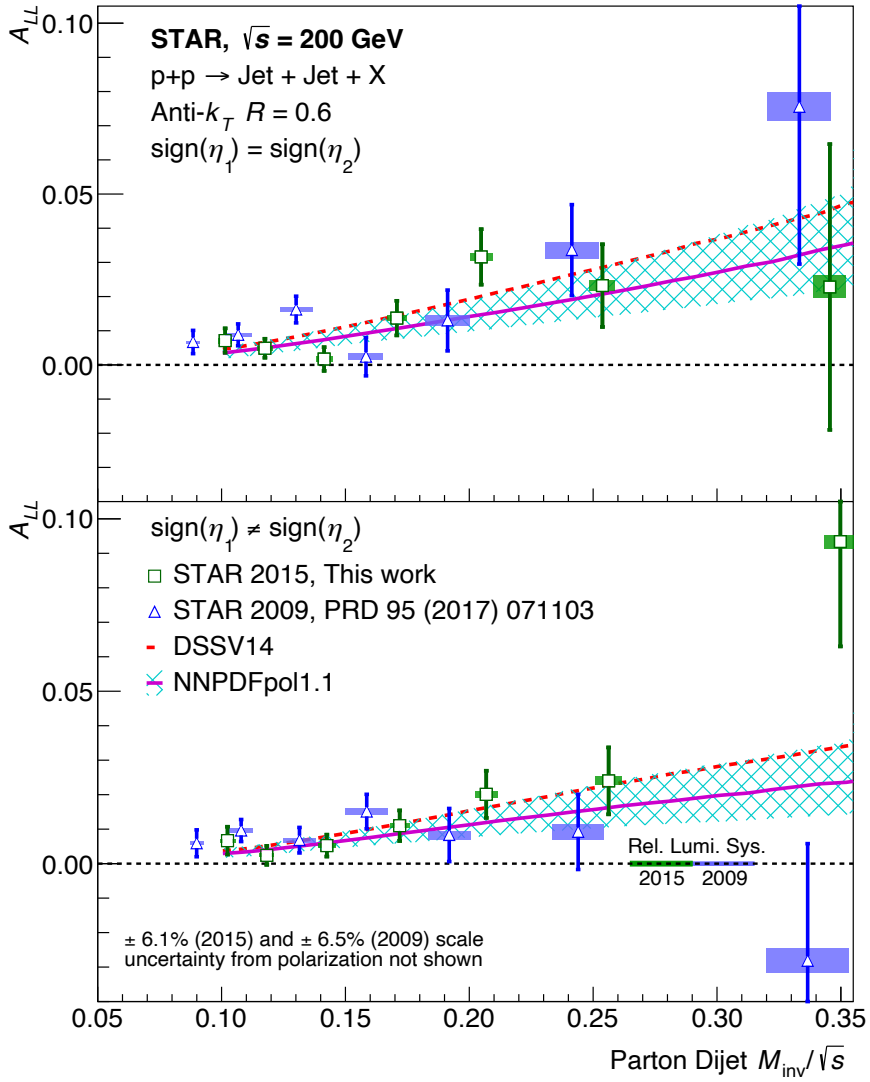


STAR Results: Run 15 Jet results at 200 GeV

Mid-rapidity Incl. Jet and Di-Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 103** (2021) 9, L091103.



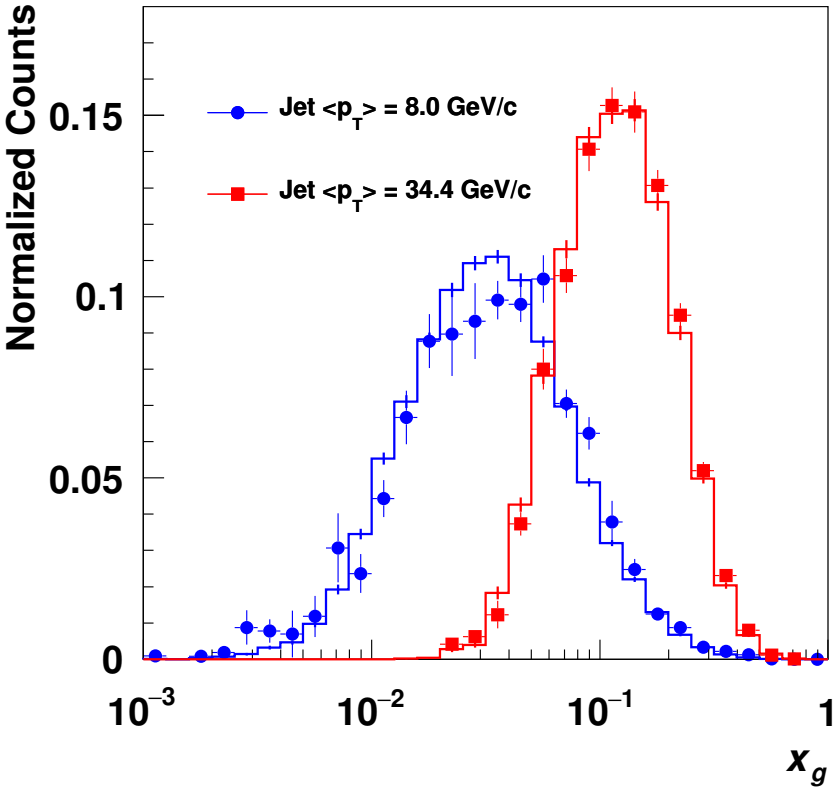


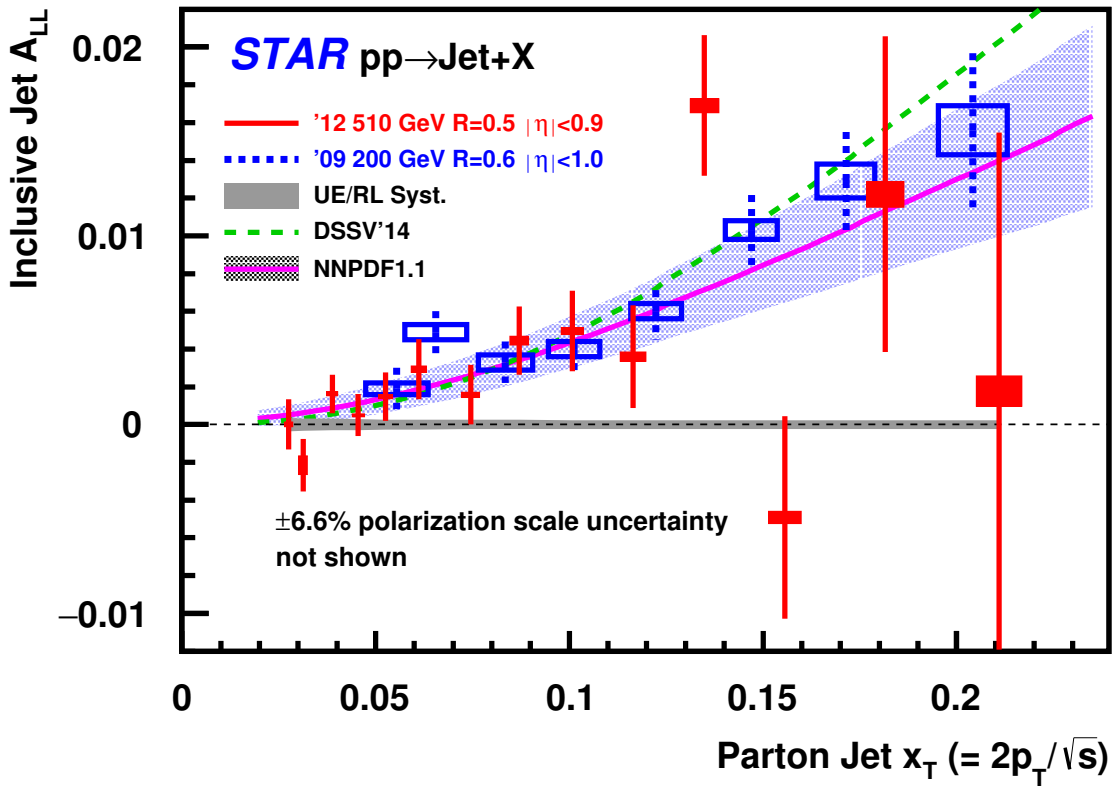
- A_{LL} inclusive and di-jet measurements for Run 15 in good agreement with Run 9 measurements - Further evidence for positive $\Delta g(x, Q^2)$ for $x > 0.05$!
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

STAR Results: Run 12 Inclusive Jet results at 510 GeV

Mid-rapidity Inclusive Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 100** (2019) 5, 052005.





- A_{LL} inclusive jets vs. x_T for Run 12 510GeV in good agreement with Run 9 200GeV measurements - Probing $\Delta g(x, Q^2)$ at smaller x ($x \approx 0.015$)!
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

STAR Results: Run 12 Di-Jet results at 510GeV

Mid-rapidity Di-Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 100** (2019) 5, 052005.

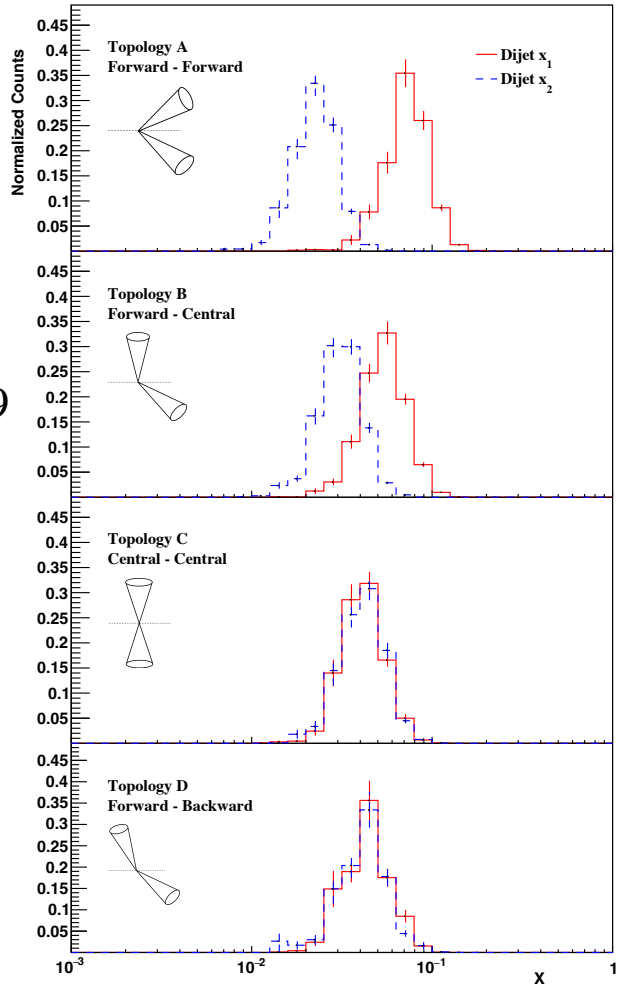
- 4 Topological configurations probing different kinematic regions in x:
  - A: Forward-Forward

    $0.3 < |\eta_{3,4}| < 0.9;\ \eta_3 \cdot \eta_4 > 0$
  - B: Forward-Central

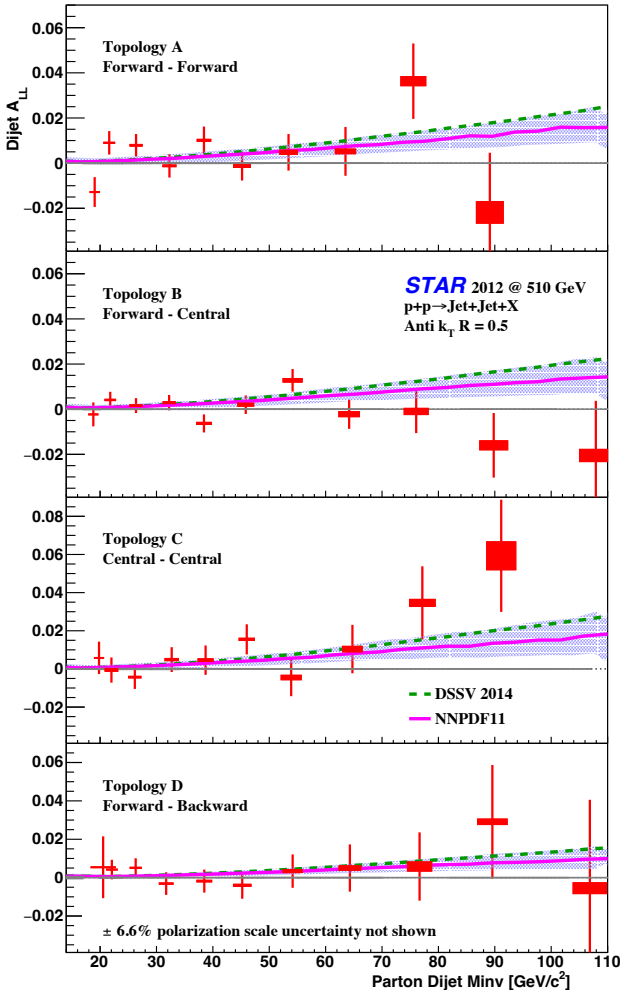
    $|\eta_{3,4}| < 0.3;\ 0.3 < |\eta_{3,4}| < 0.9$
  - C: Central-Central

    $|\eta_{3,4}| < 0.3$
  - D: Forward-Backward

    $0.3 < |\eta_{3,4}| < 0.9;\ \eta_3 \cdot \eta_4 < 0$
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set



$M_{inv} = 17 - 20\ \mathrm{GeV/c^2}$



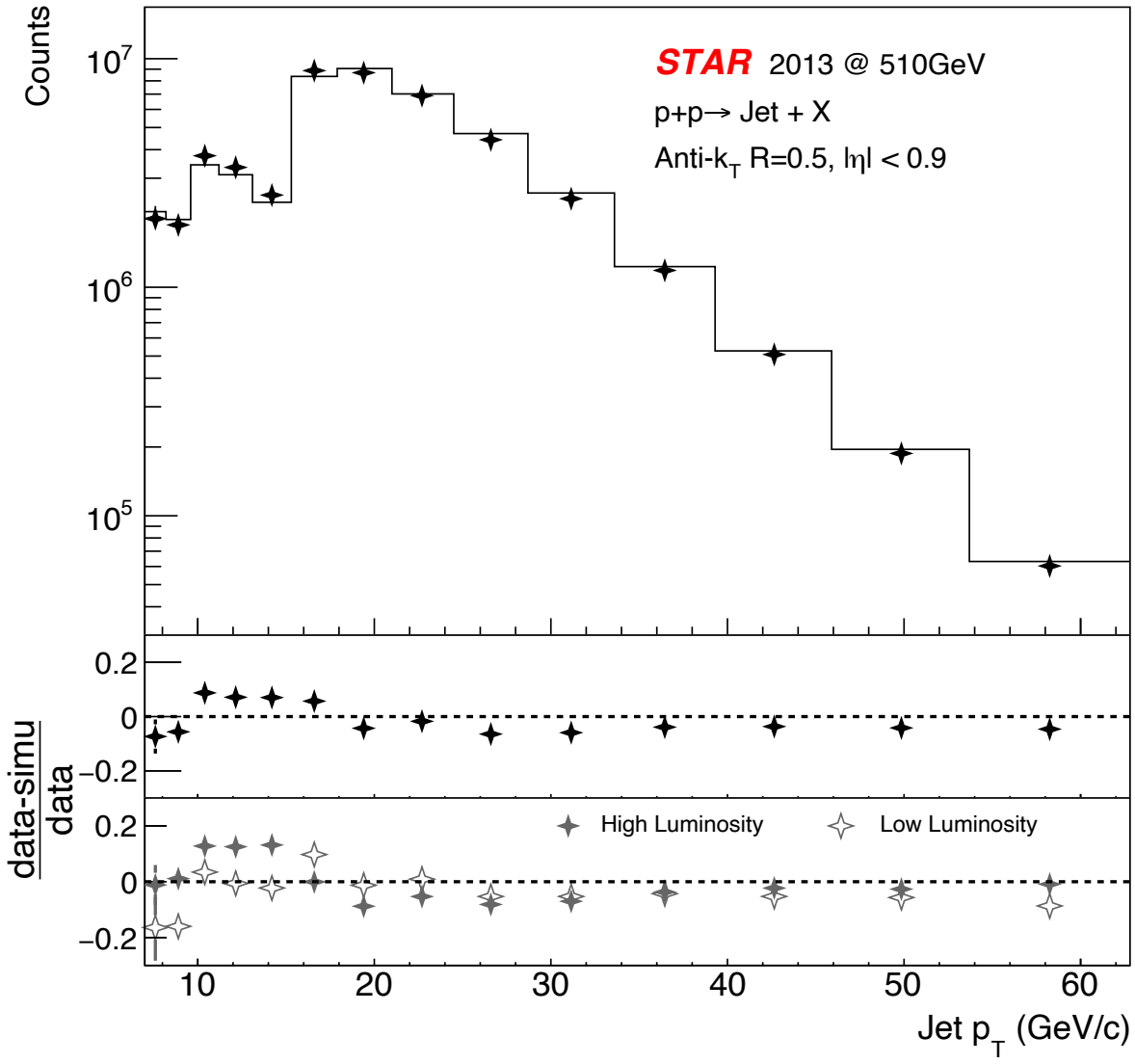
STAR Results: Run 13 data set / Selection cuts

- Overview of data size / beam conditions / selection cuts for Run 13 data
  - Data size: ~250 pb^{-1} X 3 times as large compared to Run 12 data sample
  - Beam polarization: Average beam polarization P_B = 56% and P_Y = 54%
  - Selection cuts:
    - Trigger: Jet Patch ($\Delta\eta \times \Delta\phi = 1 \times 1$) (JP0 / JP1 / JP2) / Di-Jet trigger JP0dijet & JP1dijet
    - Jet reconstruction: Anti-k_T and FastJet package (R=0.5) - TPC: $p_T > 0.2\,\mathrm{GeV/c}$ EMC : $E_T > 0.2\,\mathrm{GeV/c}$
    - DCA (Distance of Closest Approach) to vertex: < 2cm for $p_T < 0.5\,\mathrm{GeV/c}$ and < 1cm for $p_T > 1.5\,\mathrm{GeV/c}$ and linearly interpolated in-between
    - R_{EM} (Fraction of jet energy detected in calorimeter): $R_{EM} < 0.95$
    - Inclusive Jet sample: Only JP0, JP1, and JP2 triggers
    - Di-Jet sample: Two largest p_T jets and $|\Delta\eta| < 1.6$ $\Delta\phi > 120°$ asymmetric p_T cuts of 5.0 / 7.0GeV/c
  - Systematics:
    - Jet Energy Scale systematics: TPC tracking efficiency and resolution effects
    - Jet Energy Scale systematics: Electromagnetic response
    - Jet Energy Scale systematics: Difference between data and simulation for underlying-event correction
    - Jet Energy Scale systematics: Differences between nominal PYTHIA tunes and other tunes
    - Trigger and reconstruction bias effects
    - Total A_{LL} systematic uncertainty: Quadrature sum of trigger and reconstruction bias, underlying event correction, plus relative luminosity uncertainty of $4.7 \cdot 10^{-4}$

STAR Results: Run 13 Data/MC comp. Incl. Jets / Syst.

- Data/MC comparison Incl. Jets
  - Comparison between data (points) and embedded simulation for inclusive jet events as a function of p_T at detector level
  - Middle: Ratio of relative differences between all data runs and simulation
  - Botton: Ratio of relative differences between data and simulation separated into high and low luminosity runs
  - Statistical uncertainties are smaller than most of the points!

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

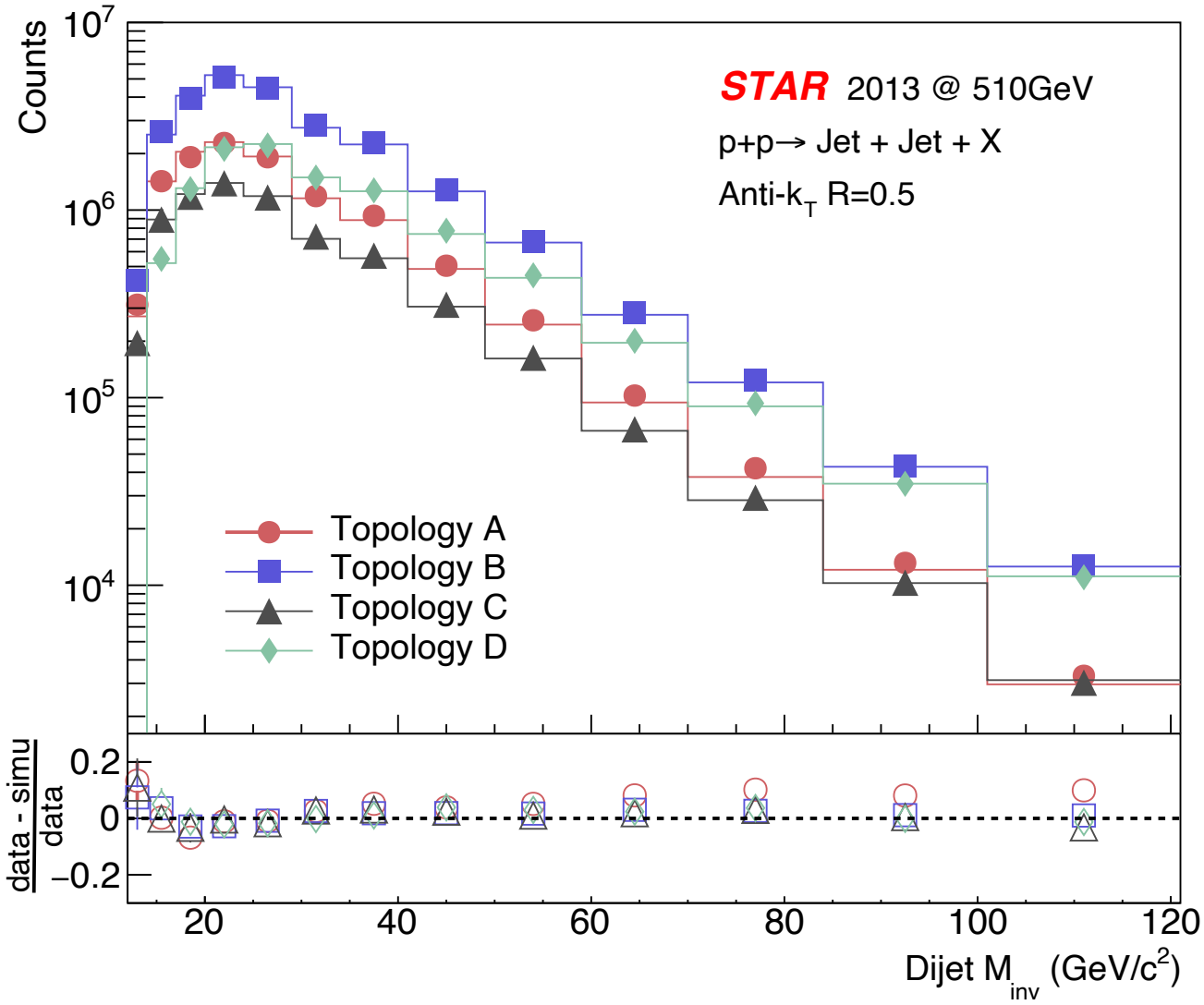


STAR Results: Run 13 Data/MC comp. Di-Jets / Syst.

Data/MC comparison Di-Jets

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

- Comparison between data (points) and embedded simulation for di-jet as a function of the di-jet invariant mass for 4 topological configurations (A-D)
- Botton: Ratio of relative differences between data and simulation
- Statistical uncertainties are smaller than most of the points!

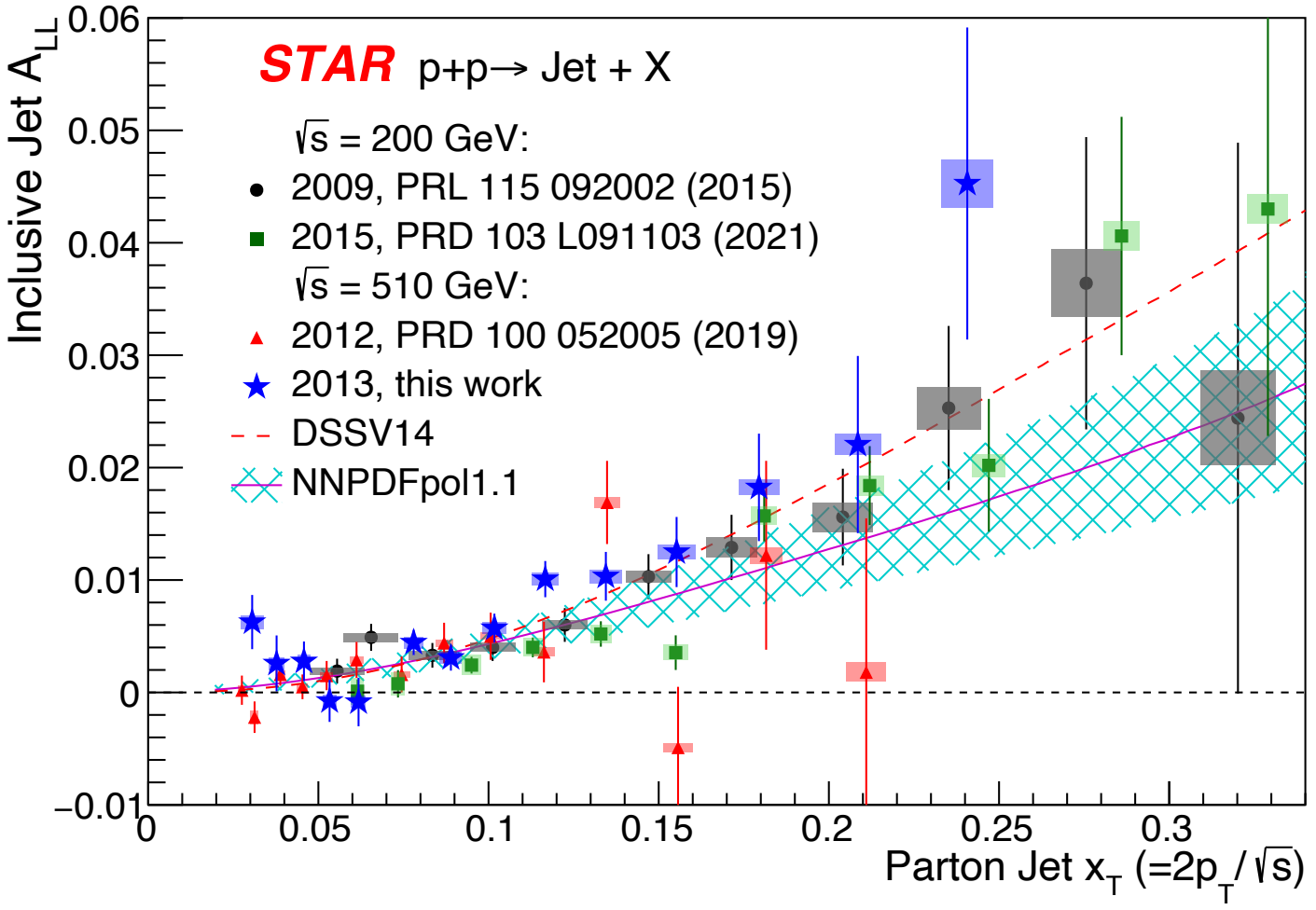


STAR Results: Run 13 Inclusive Jet results at 510 GeV

- Mid-rapidity Incl. Jet A_{LL}

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.

- Inclusive Jet A_{LL} versus x_T in comparison to 200 GeV (Run 9 / Run 15) results and 510 GeV results (Run 12) -
- Good agreement between Run 13 and previous measurements
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set

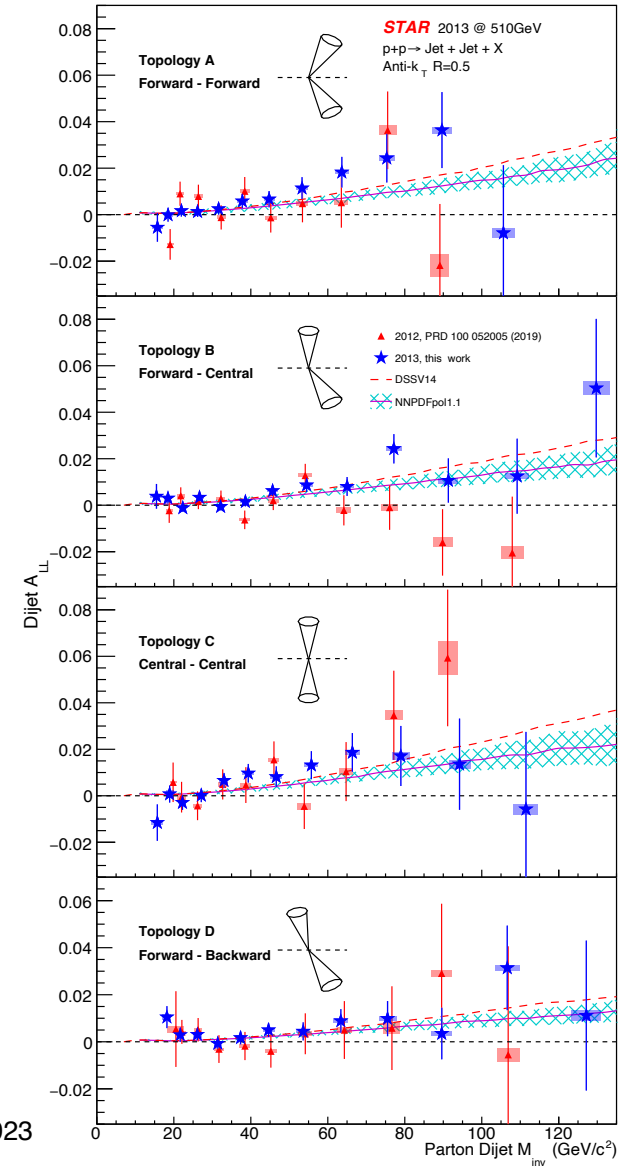


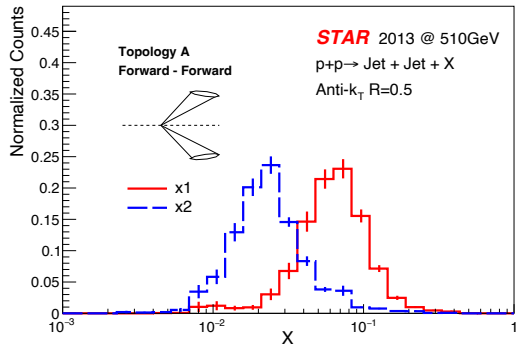
STAR Results: Run 13 Di-Jet results at 510GeV

Mid-rapidity Di-Jet A_{LL}

- Good agreement between Run 13 and Run 12 measurements
- Good agreement with NLO calculations based on DSSV14 and NNPDFpol1.1 PDF set
- Higher precision measurement will provide valuable input constraining $\Delta g(x, Q^2)$ at small x $(x \approx 0.015)$!

J. Adam *et al.* (STAR Collaboration), *Phys. Rev.* **D 105** (2022) 9, 092011.





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- C: Central-Central.

  $|\eta_{3,4}| < 0.3$

- D: Forward-Backward

  $0.3 < |\eta_{3,4}| < 0.9;\ \eta_3 \cdot \eta_4 < 0$

Summary / Outlook

- Gluon polarization program at RHIC
  - The RHIC Spin program was an enormous success resting on the synergy of accelerator physics, experimental measurements, and fundamental theory calculations to deepen understanding of the proton spin structure and dynamics
  - After about 20 years, the longitudinally polarized p+p program concluded with the last measurement at 200 GeV in Run 15 and at 510 GeV in Run 13
  - The RHIC Spin gluon polarization provided evidence that $\Delta g(x, Q^2)$ is positive for $x > 0.05$ with further improvements in kinematic coverage and precision after the inclusion of various measurements by several global analysis groups
- Future
  - The last RHIC Spin program is scheduled for Run 24 at 200 GeV of transversely polarized p+p collisions
  - The future is bright with the advent of the EIC program at BNL. The conclusion of the RHIC operation is scheduled for June 2025!

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