Jet Measurements in Longitudinally Polarized proton-proton Collisions at STAR

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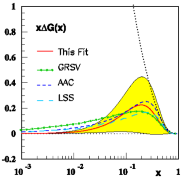
The Proton Spin

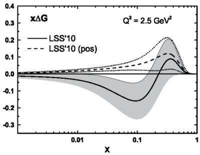
Proton spin sum rule:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \tag{1}$$

- $\Delta\Sigma$: ~ 0.3 measured by DIS.
- ΔG: poorly constrained by DIS and SIDIS.
- L_g, L_q: undertermined yet.



With fit to DIS data only, $\Delta G = 0.46 \pm 0.43$, Blümlein, Böttcher, NPB 841, 205 (2010).

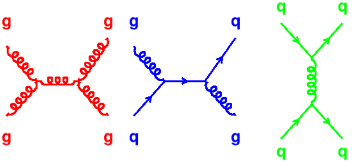


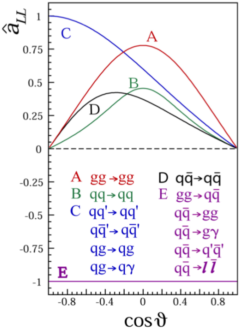
With fit to DIS and SIDIS data, $\Delta G = 0.32 \pm 0.19$ for pos, $\Delta G = -0.34 \pm 0.46$, Leader et al, PRD 82, 114018 (2010).

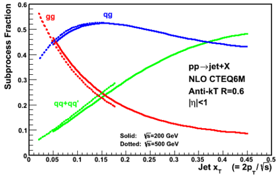
Exploring Gluon Contribution at RHIC

Longitudinal double-spin asymmetry A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \sim \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a_{LL}} \qquad (2)$$



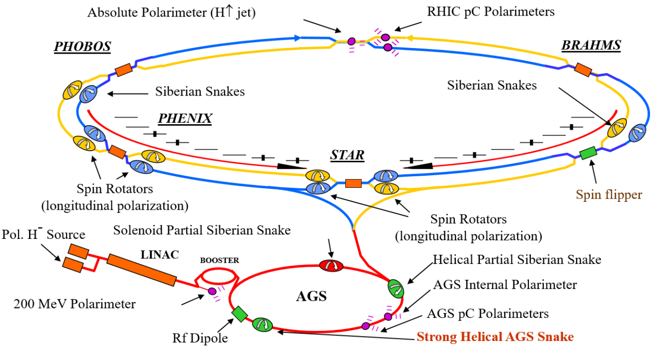




For most RHIC kinematics, *gg* and *qg* dominate jet production, making A_{LL} for jets sensitive to gluon polarization.

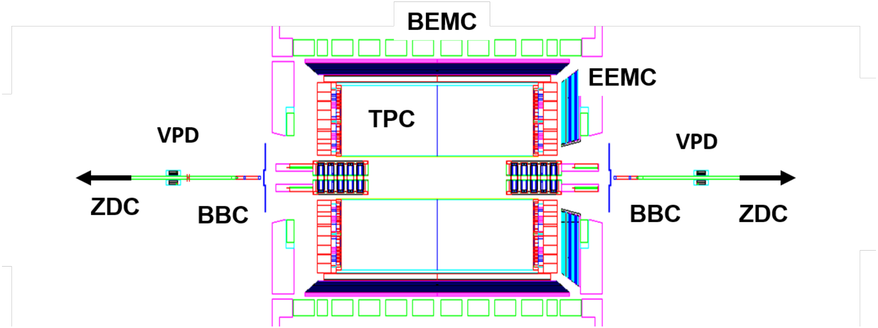
Mukherjee and Volgelsang, PRD.86.094009

RHIC Facilities



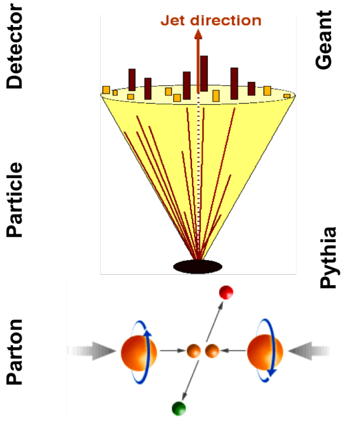
- Spin varies from RF bunches to RF bunches (9.4 MHz).
- Spin pattern changes from fill to fill.
- Spin rotators provide choice of spin orientation.
- Billions of spin reversals during a fill with little depolarization.

STAR Detectors



- High precision tracking with Time Projection Chamber.
- High energy resolution with Barrel Electro-Magnetic Calorimeter, and Endcap Electro-Magnetic Calorimeter.
- Global detectors: Beam-Beam Counter, Vertex Position Detector, and Zero-Degree Calorimeter for relative luminosity determination.

Jet Reconstruction at STAR



- 2006 200 GeV data: Mid-point cone algorithm with $E_{seed} = 0.5 GeV$, $R_{cone} = 0.7$ and $f_{split/merge} = 0.5$. (Adapted from Tevatron 2 - hep-ex/0005012).
- 2009 200 GeV data: Anti-k_T algorithm with jet parameter $R = 0.6$ (Cacciari, Salam, and Soyez, JHEP 0804, 063).
- 2012/2013 510 GeV data: Anti-k_T algorithm with jet parameter $R = 0.5$.
- In addition, use PYTHIA + GEANT + Zero-bias Events as embedding sample to study systematic uncertainties, which enables to study jets at parton, particle and detector levels.

Inclusive Jets Measurements at STAR

STAR has measured a series of inclusive jet and di-jet cross-sections and longitudinal double-spin asymmetry A_{LL}s at $\sqrt{s} = 200$ and 510 GeV.

- Inclusive jet:
  $x_g \sim 0.05$ at $\sqrt{s} = 200$ GeV
  $x_g \sim 0.02$ at $\sqrt{s} = 510$ GeV
- Di-jets:
  two jet correlation unfolds x_1 and x_2 at the leading order.

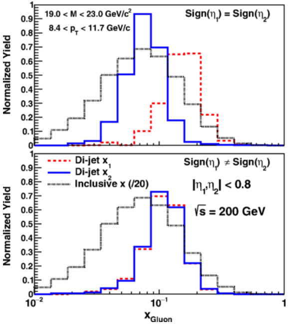
$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4}) \quad (3)$$

$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}) \quad (4)$$

$$M = \sqrt{x_1 x_2 s} \quad (5)$$

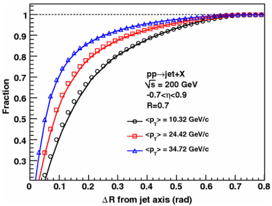
$$y = \frac{1}{2} ln \frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2} \quad (6)$$

$$|cos\theta^*| = tanh \frac{|\eta_3 - \eta_4|}{2} \quad (7)$$



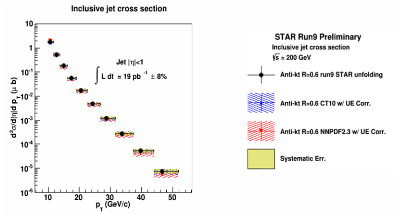
Gluon x_g sampled by inclusive and di-jets at $\sqrt{s} = 200$ GeV (PRD 95, 071103(R)).

Inclusive Jet Cross-section Measurements



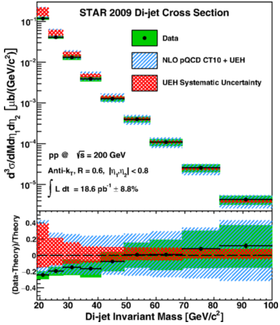
Jet profile from STAR 2006 $\sqrt{s} =$ 200 GeV data (PRD, 86, 032006).

- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction.
- Jet production is well understood at RHIC energies

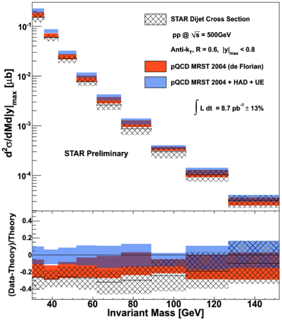


Preliminary inclusive jet cross-sections from STAR 2009 $\sqrt{s} = 200$ GeV data.

Di-jet cross-section Measurements



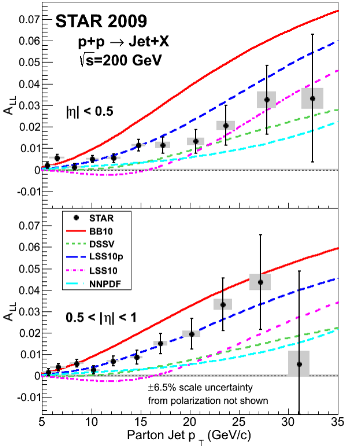
Di-jet cross-sections from STAR 2009 $\sqrt{s} = 200$ GeV data (PRD 95, 071103(R)).



Preliminary di-jet cross-sections from STAR 2009 $\sqrt{s} = 500$ GeV data.

- Di-jet cross-section is well described by the NLO pQCD calculations after hadronization and underlying event corrections.

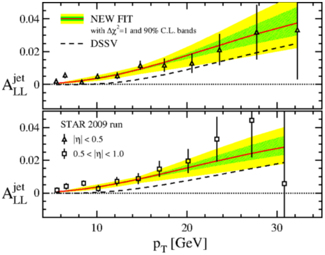
Inclusive jet double-spin asymmetry A_{LL} Measurements



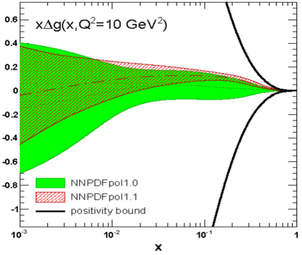
Inclusive jet A_{LL} from STAR 2009 $\sqrt{s} = 200$ GeV data (PRL 115, 092002).

- The 2009 STAR inclusive jet A_{LL} is 3 times at high jet p_T and 4 times at low jet p_T more precise than the previous measurements from the 2006 data.
- A_{LL} falls in the middle among several recent polarized PDF fit predictions.
- A_{LL} is larger than the 2008 DSSV fit, which will push the old fit towards positive Δg in the accessible x region.

Impacts of STAR 2009 Inclusive Jet A_{LL}



DSSV new fit with STAR 2009 inclusive jet A_{LL} data (PRL 113, 012001).

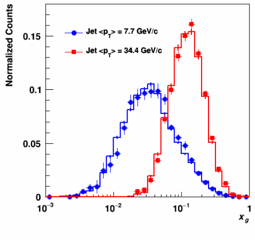


$x\Delta g$ from NNPDF with STAR 2009 inclusive jet A_{LL} data (NPB 887.276).

- Both groups find STAR 2009 inclusive jet A_{LL} provide significantly tighter constraints on gluon polarization than previous measurements.
- DSSV: $\Delta G = 0.19^{+0.06}_{-0.05}$ for $x > 0.05$ at 90% C.L.
- NNPDF: $\Delta G = 0.23 \pm 0.07$ for $0.05 < x < 0.5$.

Analysis of STAR 2012/2013 510 GeV Inclusive Jet A_{LL}

- Higher $\sqrt{s} = 510$ GeV provides sensitivity to small x_g.
- Smaller jet parameter $R = 0.5$ for anti-k_T algorithm reduces pile-up effects and is less sensitive to background.
- Comparing with various detectors, relative luminosity is estimated more precisely than previous measurements.
- Choose Perugia 2012 Tune with a smaller $p_{T,0}$ scale parameter (P_{90}) to reduce multiple parton interaction contribution in order to improve matching between PYTHIA simulation and previous STAR measurements.



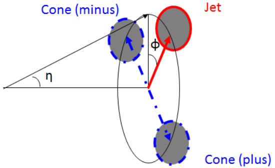
Gluon x sampled by two jet p_T ranges with mean $p_T = 7.7$ and 34.4 GeV at $\sqrt{s} = 510$ GeV.

$$\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2} \quad (8)$$

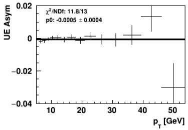
$$p_{T,0} = p_{T,ref} \times \left(\frac{\sqrt{s}}{\sqrt{s_{ref}}}\right)^{P_{90}} \quad (9)$$

Underlying Event Correction

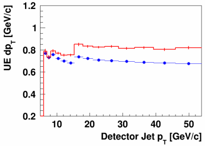
- Two off-axis cones are used to estimate underlying event for a given jet (ALICE, PRD 91, 112012).
- Underlying event contribution to jet A_{LL} in the data is estimated by measuring the underlying event correction asymmetry for beams colliding with different spin configurations. This uncertainty is comparable to the relative luminosity uncertainty.
- Systematic uncertainty due to underlying event correction is applied.
- Sample η dependence of the underlying event and can be also applied to the pA collisions.



Two off-axis cones centered at $\pm\frac{\pi}{2}$ away in ϕ and the same η relative to a given jet.

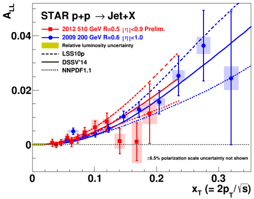


Underlying event dp_T asymmetries for different colliding beam helicity patterns.

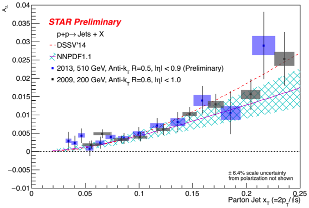


Underlying event dp_T vs. jet p_T from embedding (red) and data (blue), difference used as a systematics as underlying event correction.

STAR 510 GeV Inclusive Jet A_{LL} Measurements



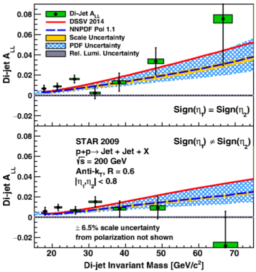
Preliminary STAR 2012 $\sqrt{s} = 510$ GeV inclusive jet A_{LL} results compared with the STAR 2009 data.



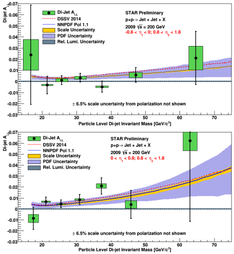
Preliminary STAR 2013 $\sqrt{s} = 510$ GeV inclusive jet A_{LL} results compared with the STAR 2009 data.

- Underlying event consideration is not applied to the 2012 preliminary results. However it is applied to the 2013 preliminary results. In addition new techniques to estimate other systematic uncertainties that weren't available in the 2012 preliminary results are applied.
- Both preliminary results agree well with STAR 2009 data in the overlapping x_T region.
- Both preliminary results agree well with recent polarized PDF predictions.

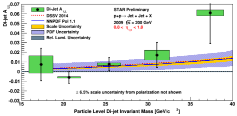
STAR 200 GeV Di-jet A_{LL} Measurements



STAR 2009 $\sqrt{s} = 200$ GeV di-jet A_{LL}measured with jets at $|\eta| < 0.8$ (PRD 95, 071103(R)).

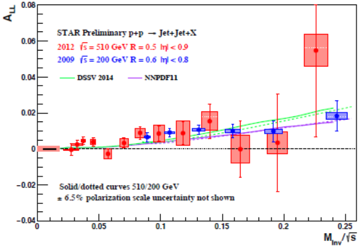


Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet A_{LL} with one jet at $|\eta| < 0.8$ and the other at $0.8 < \eta < 1.8$.

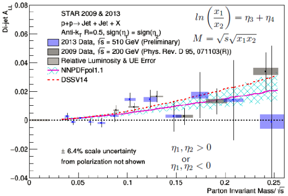


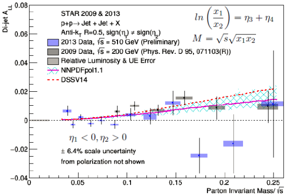
Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet A_{LL}measured with jets at $0.8 < \eta < 1.8$.

STAR 510 GeV Di-jet A_{LL} Measurements



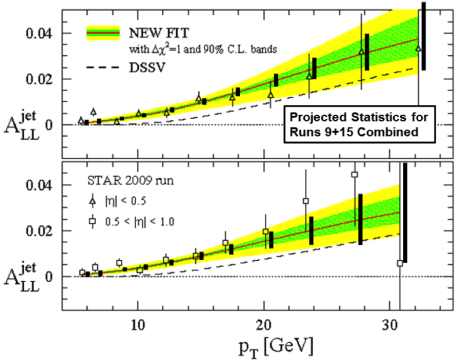
Preliminary STAR 2012 $\sqrt{s} = 510$ GeV di-jet A_{LL}measured with jets at $|\eta| < 0.9$ compared with STAR 2009 data.





Preliminary STAR 2013 $\sqrt{s} = 510$ GeV di-jet A_{LL} compared with STAR 2009 data.

Increased Precision for 200 GeV Inclusive Jet A_{LL}

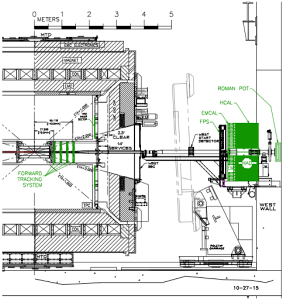


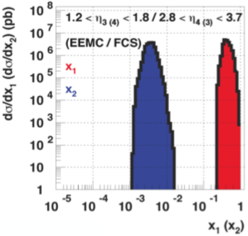
- STAR anticipates significant reduction in the uncertainties for the 200 GeV inclusive jet A_{LL} relative to the 2009 results. The data collected during the 2015 RHIC run is THREE times larger than the existing 200 GeV data.

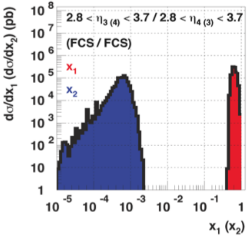
STAR Forward Upgrade

- STAR is planning to install a Forward Calorimeter System (FCS) and a forwarding tracking system in 2020s. The FCS will consist of an electromagnetic calorimeter and a hadron calorimeter.
- Di-jet measurements with one or both jets in the forward region ($2.8 < \eta < 3.7$) will be one of the highlights of this upgrade.
- FCS will provide gluon polarization at very low x
  $x \sim 5 \times 10^{-3}$ with FCS-EEMC di-jets

  $x \leq 10^{-3}$ with FCS-FCS di-jets







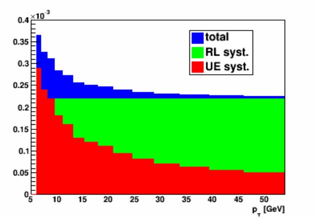
Conclusion

- STAR inclusive jet and di-jet cross-section measurements provide valuable information to constrain unpolarized gluon distribution in the proton. The results are consistent with NLO pQCD calculations.
- STAR inclusive jet and di-jet double-spin asymmetry measurements are unique to explore gluon polarization to the proton spin.
  1. STAR 2009 200 GeV inclusive jet A_{LL} results provided the first experimental evidence for positive gluon polarization in the RHIC range.
  2. STAR 2012/2013 510 GeV inclusive jet A_{LL} measurements will extend gluon polarization at lower x and agree well with the 2009 200 GeV results in the overlapping x_T region.
  3. STAR di-jet A_{LL} measurements at both 200 and 510 GeV support the positive gluon polarization over the RHIC range and further constrain the shape of polarized gluon distribution.
- The STAR forward upgrade will provide new opportunities to probe low $x \sim 10^{-3}$ gluon polarization where the current polarized PDF studies show large uncertainties.
- Finalized results and other results will be coming very soon, including 2012 510 GeV inclusive jet and di-jet A_{LL}, 2009 200 GeV forward di-jet A_{LL}, and 2012 510 GeV inclusive jet cross-sections.

Backup

$$A_{LL}^{dp_T} = \frac{1}{P_A P_B} \frac{(< dp_T >^{++} + < dp_T >^{--}) - (< dp_T >^{+-} + < dp_T >^{-+})}{(< dp_T >^{++} + < dp_T >^{--}) + (< dp_T >^{+-} + < dp_T >^{-+})} \quad (10)$$

$$\delta A_{LL} = \frac{\int_{p_{T,min} - <dp_T> \times A_{LL}^{dp_T}}^{p_{T,max} - <dp_T> \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T - \int_{p_{T,min} + <dp_T> \times A_{LL}^{dp_T}}^{p_{T,max} + <dp_T> \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T}{\int_{p_{T,min} - <dp_T> \times A_{LL}^{dp_T}}^{p_{T,max} - <dp_T> \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T + \int_{p_{T,min} + <dp_T> \times A_{LL}^{dp_T}}^{p_{T,max} + <dp_T> \times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T} \quad (11)$$



Underlying event systematic uncertainty on inclusive jet A_{LL} for 2012 510 GeV data compared with systematic uncertainty due to relative luminosity.