Inclusive Jet Measurements in Longitudinally Polarized proton-proton Collisions at STAR

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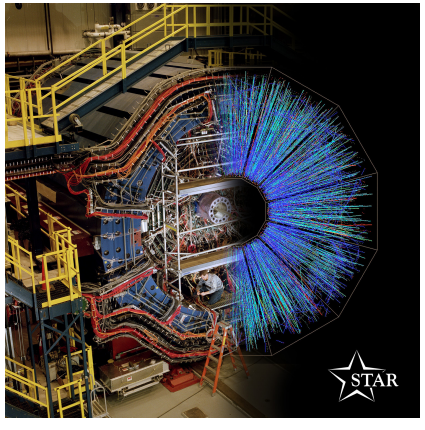
April 18, 2018

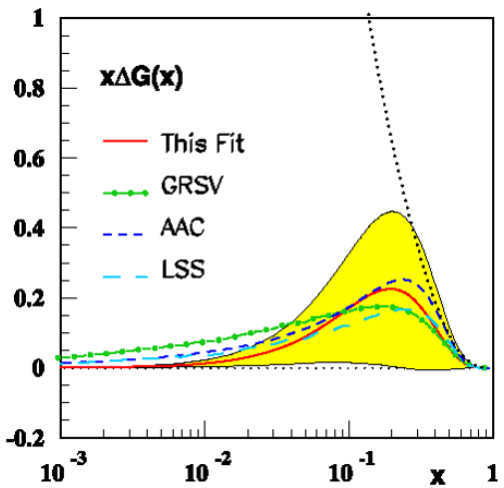


The Proton Spin

Proton spin sum rule:

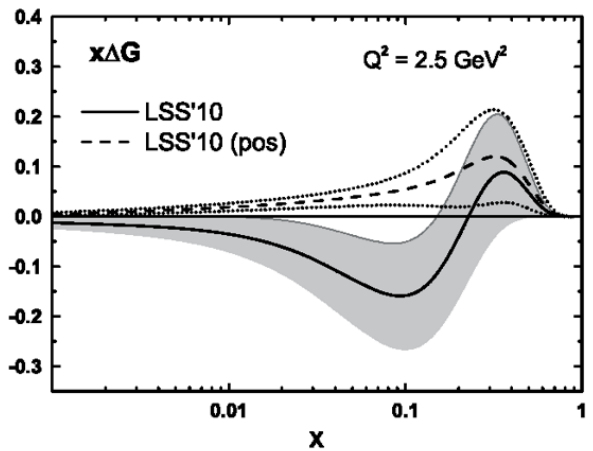
$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g} \tag{1}$$

- $\Delta\Sigma$: ~ 0.3 measured by DIS.
- ΔG: poorly constrained by DIS and SIDIS.
- $L_{q,g}$: undetermined 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,

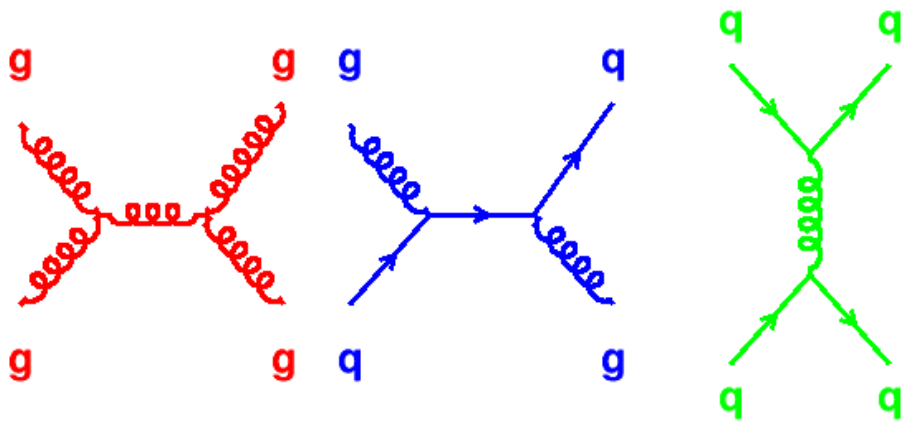
$\Delta G = 0.32 \pm 0.19$ for pos,

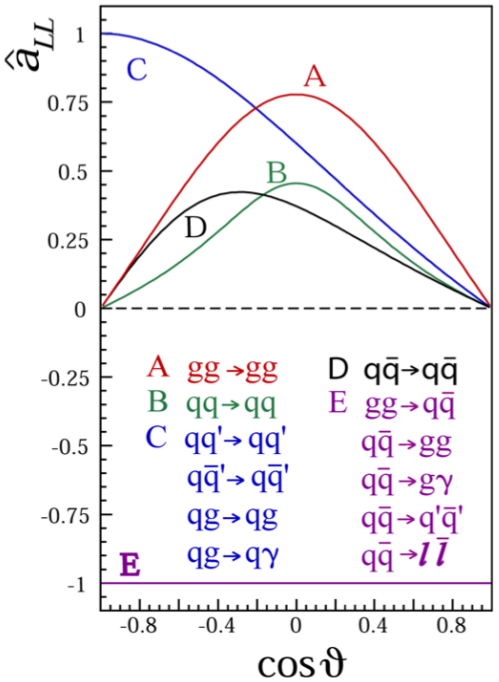
$\Delta G = -0.34 \pm 0.46$, Leader et al, PRD 82, 114018 (2010)

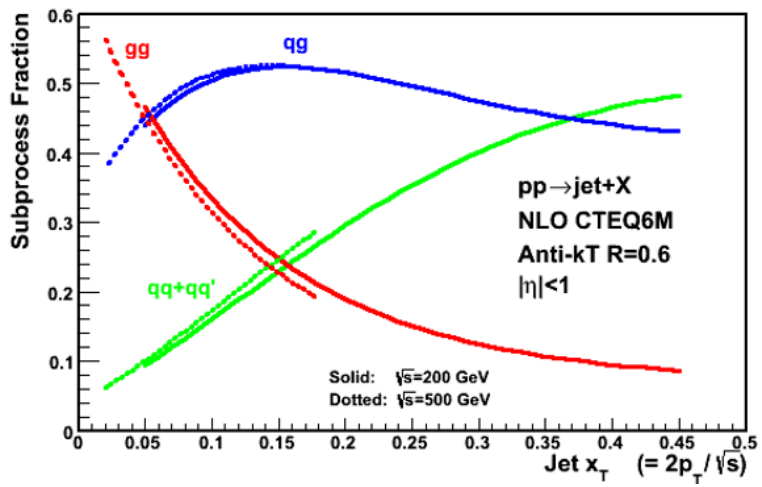
Exploring Gluon Polarization at RHIC

In longitudinally polarized pp collisions, define longitudinal double-spin asymmetry A_{LL} as,

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



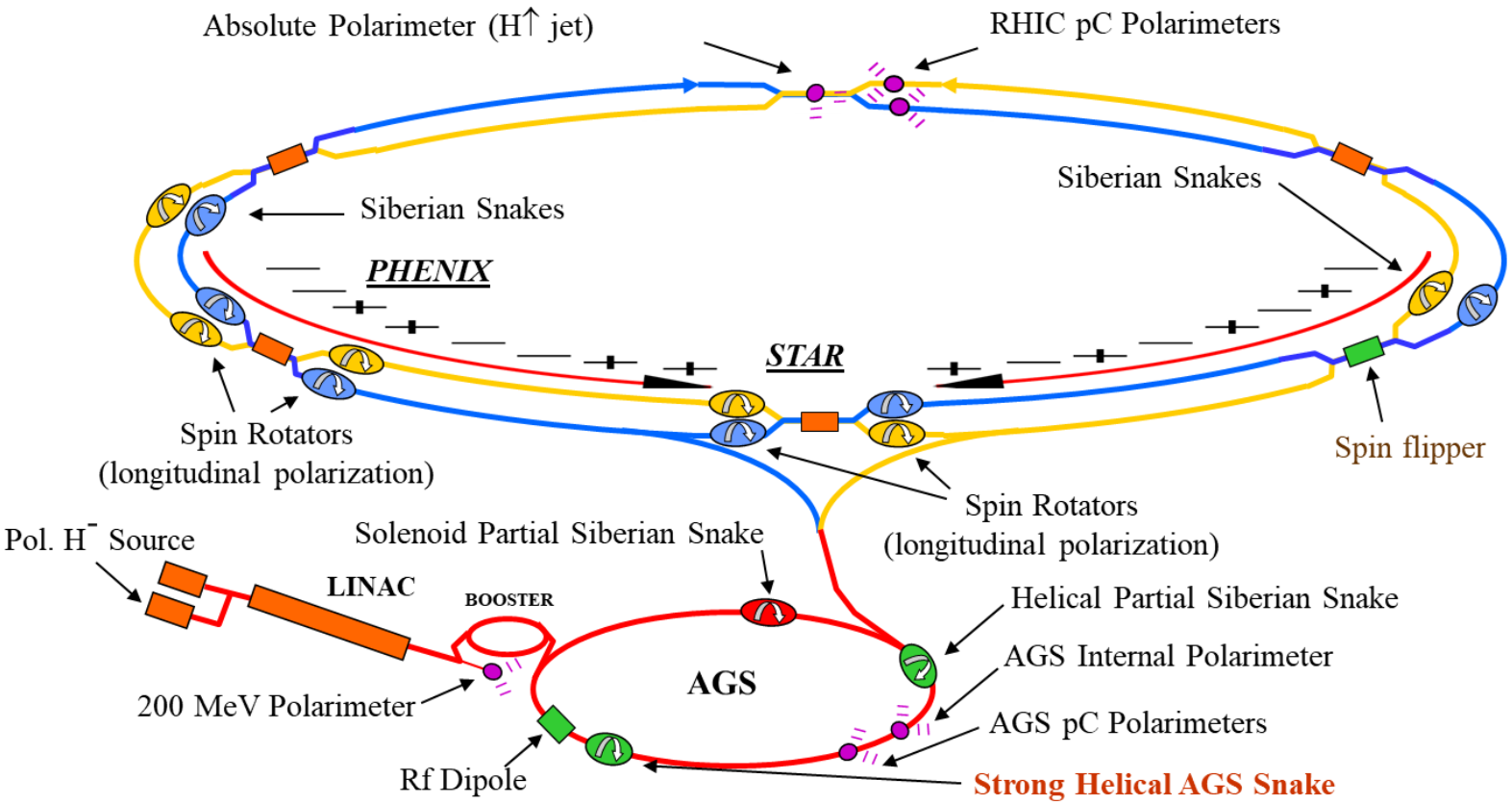




Mukherjee and Volgelsang, PRD.86.094009

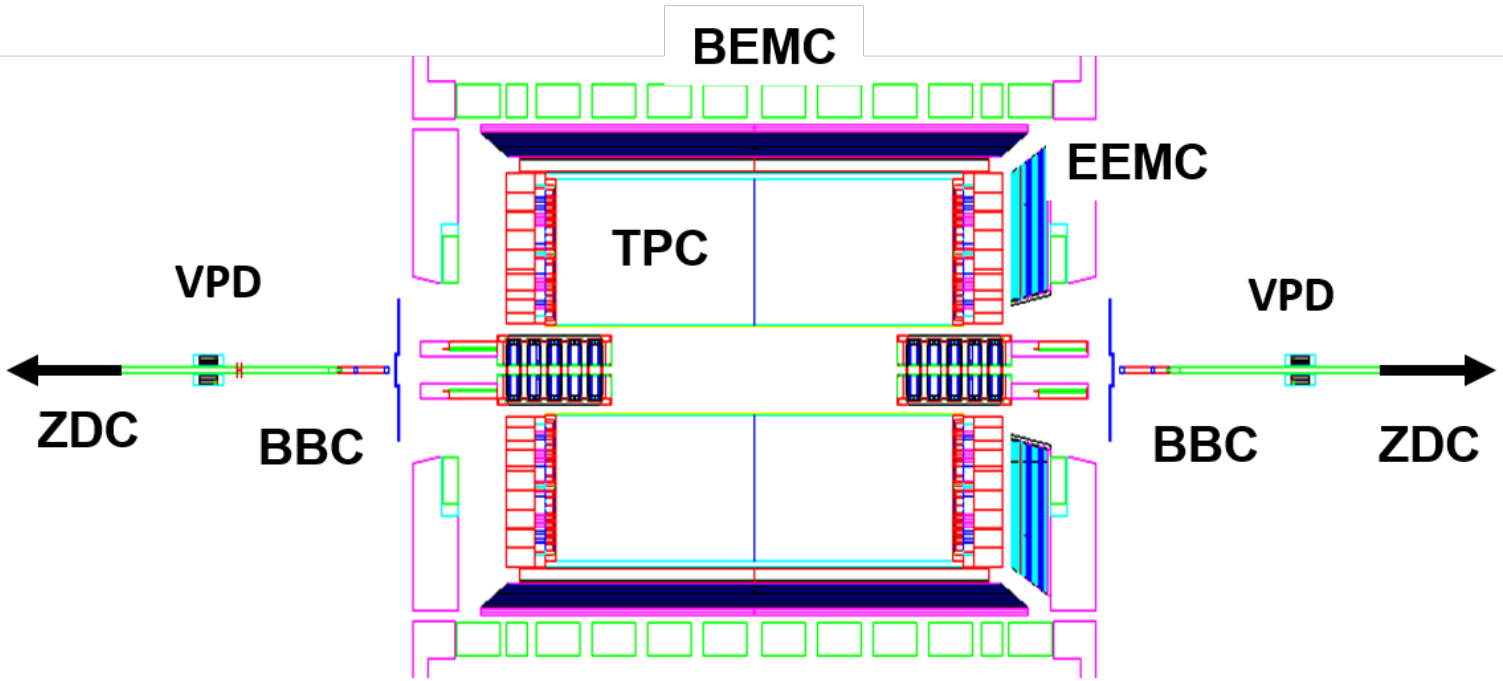
gg and qg dominate jet production, making A_{LL} for jets sensitive to gluon polarization.

RHIC Facilities



- Polarization orientation varies from RF bunches to RF bunches (9.4 MHz).
- Spin rotators provide choice of polarization orientation (longitudinal or transverse).

STAR Detectors



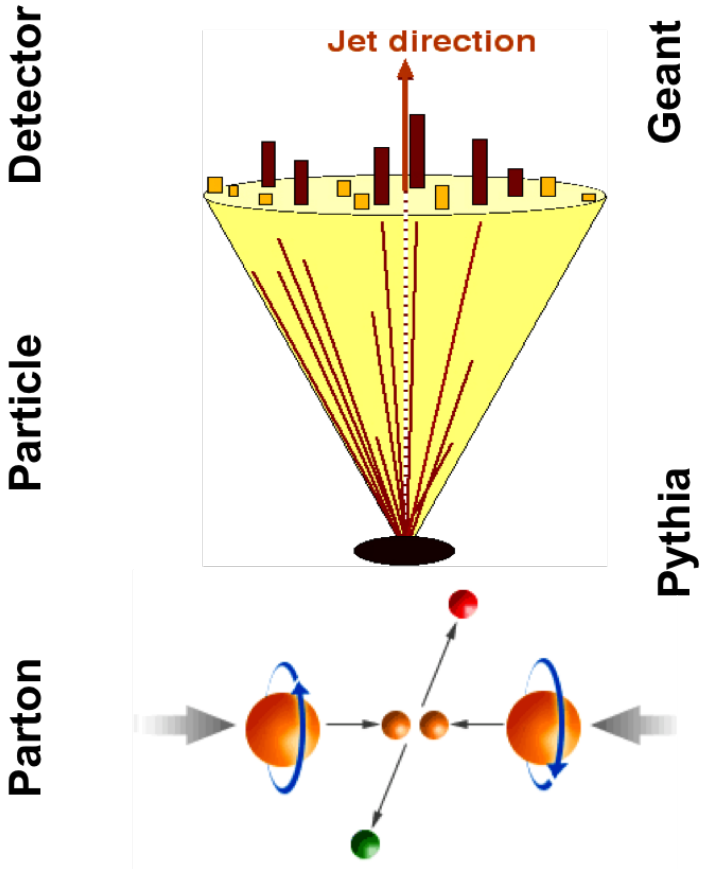
- Jet reconstruction:
  - High precision tracking with Time Projection Chamber ($|\eta| < 1.3$).
  - High energy resolution with Barrel and Endcap Electro-Magnetic Calorimeter (-1.0 $< \eta <$ 2.0).
- Global detectors for relative luminosity monitoring: Beam-Beam Counter, Vertex Position Detector, and Zero-Degree Calorimeter($|\eta| > 3.4$).

Data from Longitudinally Polarized pp Collisions at STAR

STAR longitudinally polarized pp data since 2006:

Year	$\sqrt{s}$ [GeV]	Lum. [pb^{-1}]	Pol. [%]	Jet Rec.
2006	200	45	55	Midpoint cone, $R = 0.7$
2009	200	54	56	Anti-k_T, $R = 0.6$
2009	500	53	35	Anti-k_T, $R = 0.6$
2012	510	144	52	Anti-k_T, $R = 0.5$
2013	510	500	52	Anti-k_T, $R = 0.5$
2015	200	120	57	In process

Jet Reconstruction at STAR



- PYTHIA + GEANT + Zero-bias events as embedding sample.
- Allow to correct from detector jets to particle and parton jets.
- Determine systematic uncertainties.

Inclusive and Di-Jets Measurements at STAR

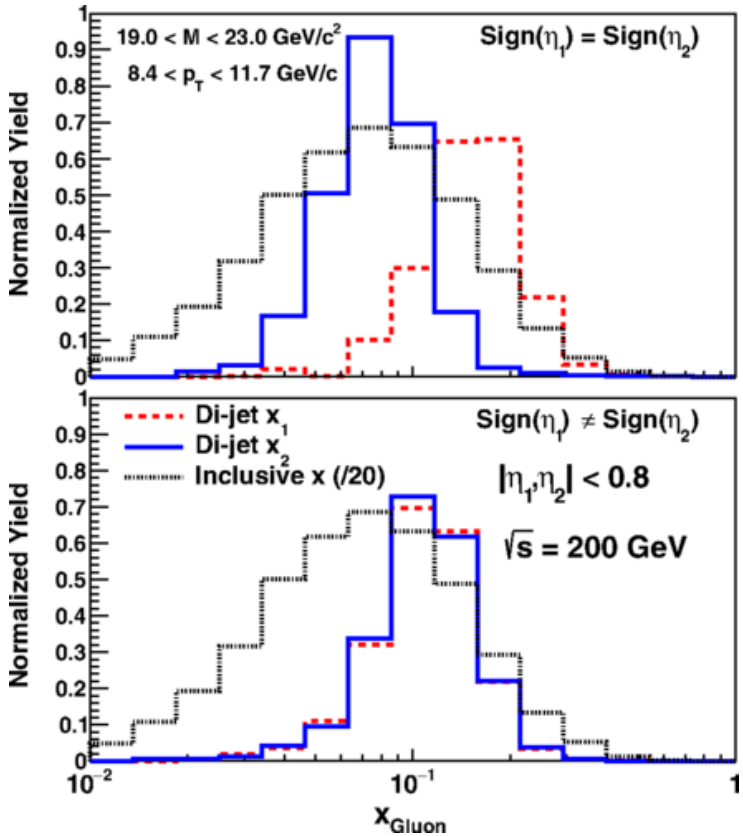
STAR has measured a series of inclusive jet and di-jet cross-sections and longitudinal double-spin asymmetry A_{LL}s at $\sqrt{s} = 200$ GeV.

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

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

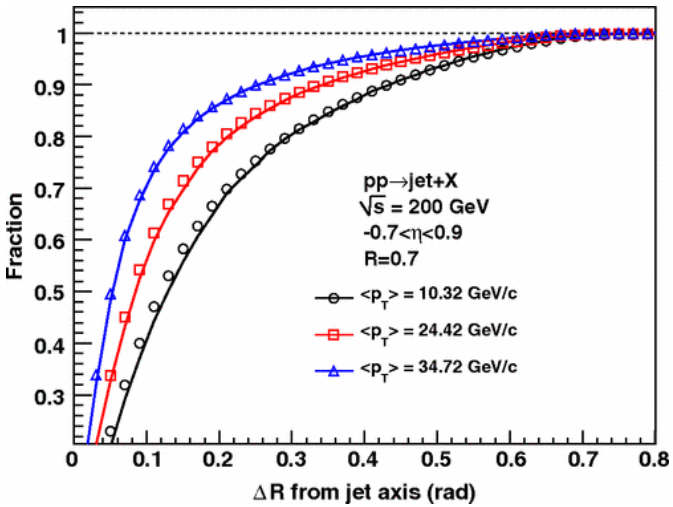
$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4}) \quad (4)$$

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

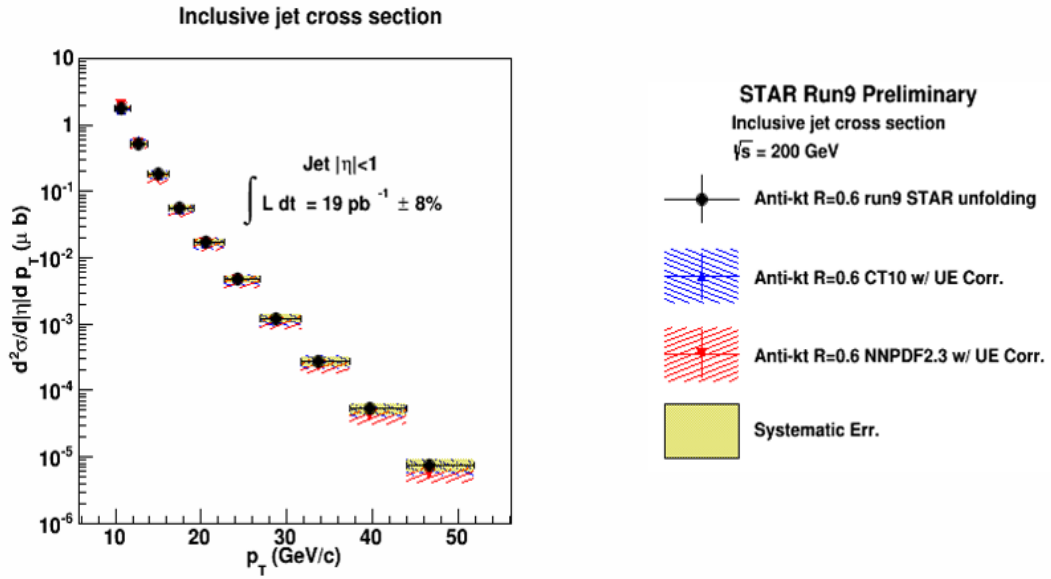


Gluon x_g sampled by inclusive and di-jets at $\sqrt{s} = 200$ GeV (PRD 95, 071103(R)).

Inclusive Jet Cross-section Measurements



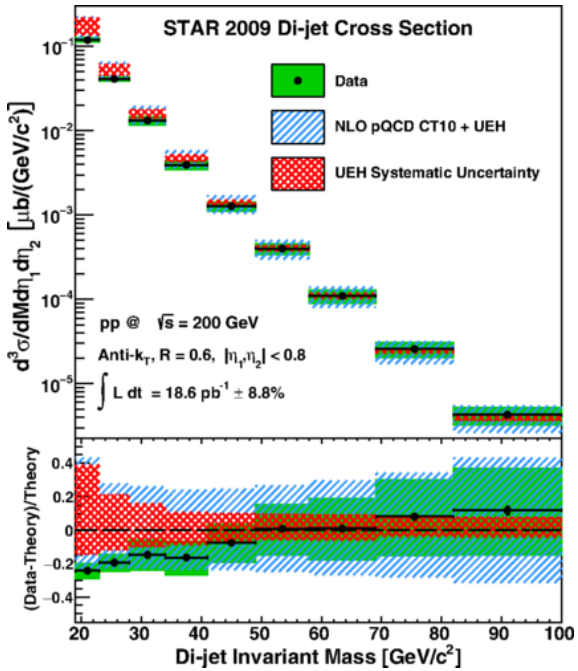
Jet profile, fraction of the total jet transverse energy within a cone of radius ΔR centered on the reconstructed thrust axis, from STAR 2006 $\sqrt{s} = 200$ GeV data (PRD, 86, 032006).



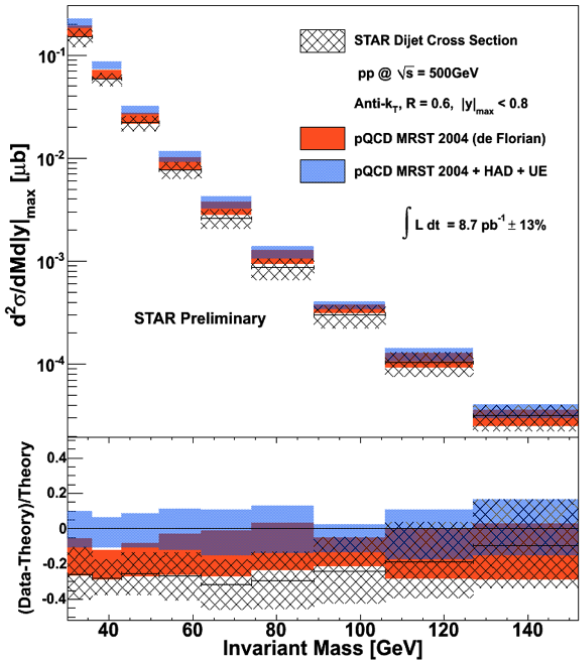
Preliminary inclusive jet cross-sections from STAR 2009 $\sqrt{s} = 200$ GeV data.

- 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

Di-jet Cross-section Measurements



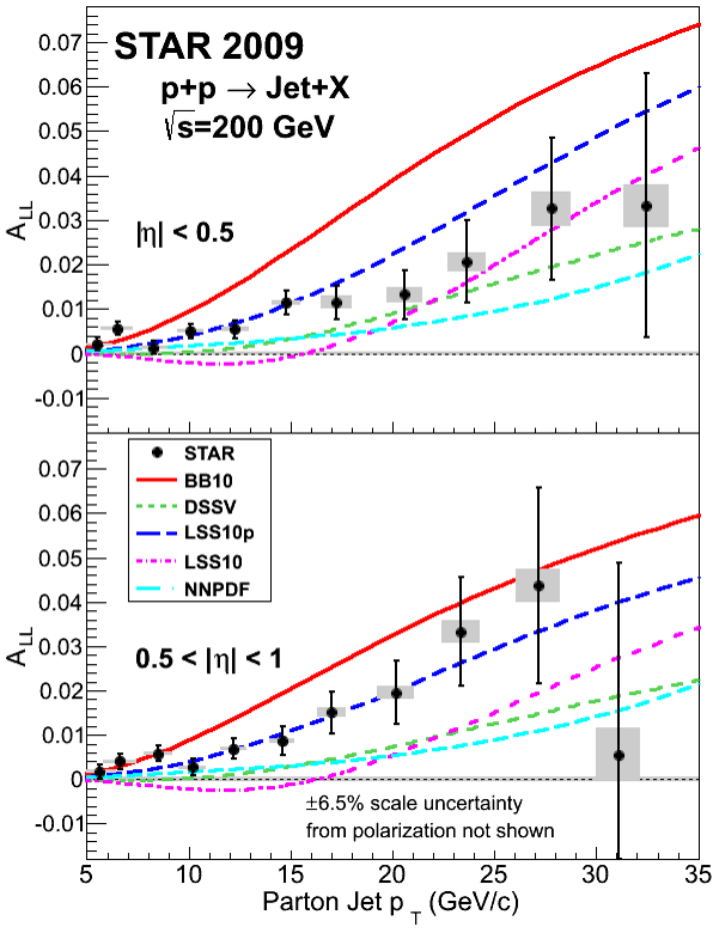
Di-jet cross-sections from STAR 2009 $\sqrt{s} = 200$ GeV data (PRD 95, 071103(R)).



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.

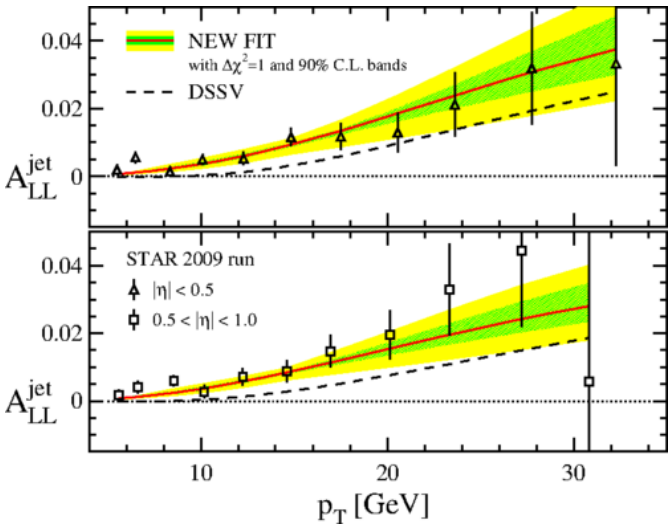
Inclusive Jet Double-spin Asymmetry A_{LL} Measurements



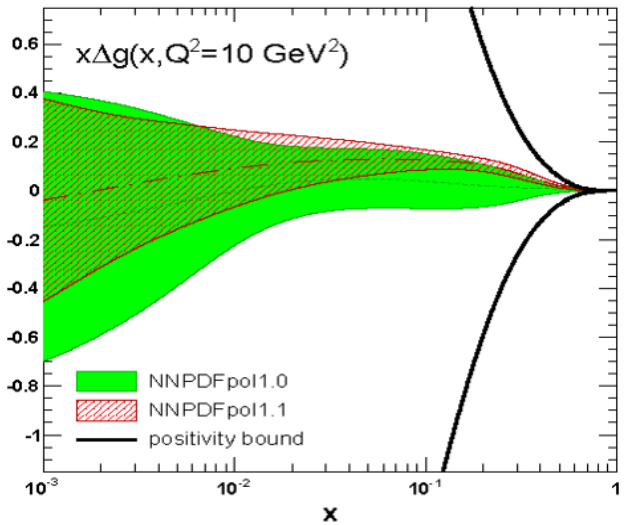
Inclusive jet A_{LL} from STAR 2009 $\sqrt{s} = 200$ GeV data (PRL 115, 092002).

- This measurement is more precise than the previous measurement from the 2006 data, (3 times at high jet p_T and 4 times at low jet p_T).
- A_{LL} falls in the middle among several polarized PDF fit predictions.
- A_{LL} is larger than the 2008 DSSV fit, and would push the 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).

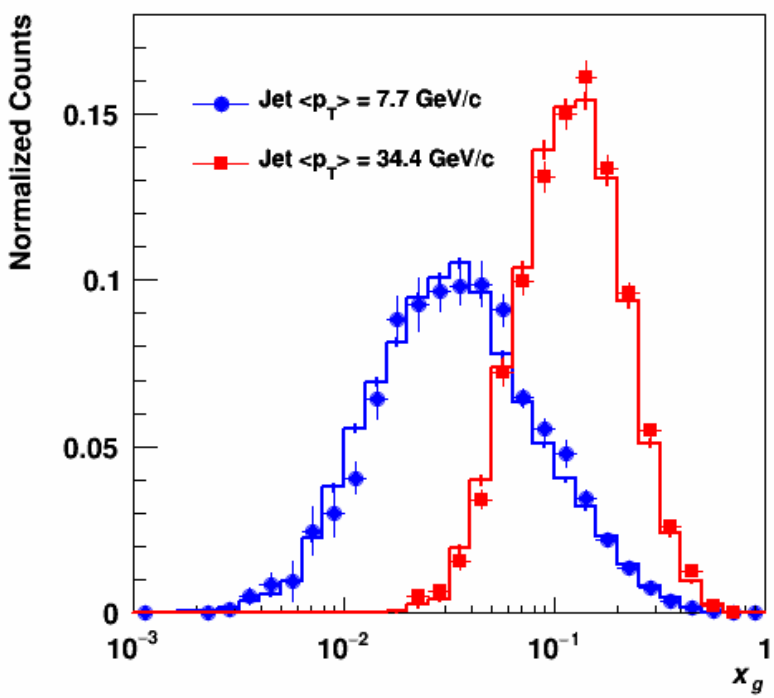


$x\Delta g$ from NNPDF with STAR 2009 inclusive jet A_{LL} data (NPB 887.276).

- Both groups find the 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 smaller x_g. x_g sampled by two jet p_T bins with mean $p_T = 7.7$ and 34.4 GeV/c:



- Smaller $R = 0.5$ for anti-k_T algorithm reduces pile-up effects and is less sensitive to background.
- By comparing with various detectors, relative luminosity is estimated more precisely than previous measurements $\sim 10^{-4}$.
- Using replicas from the polarized NNPDF PDF set to estimate trigger bias and reconstruction uncertainties

Data Simulation Comparison for 510 GeV Jet Spectrum

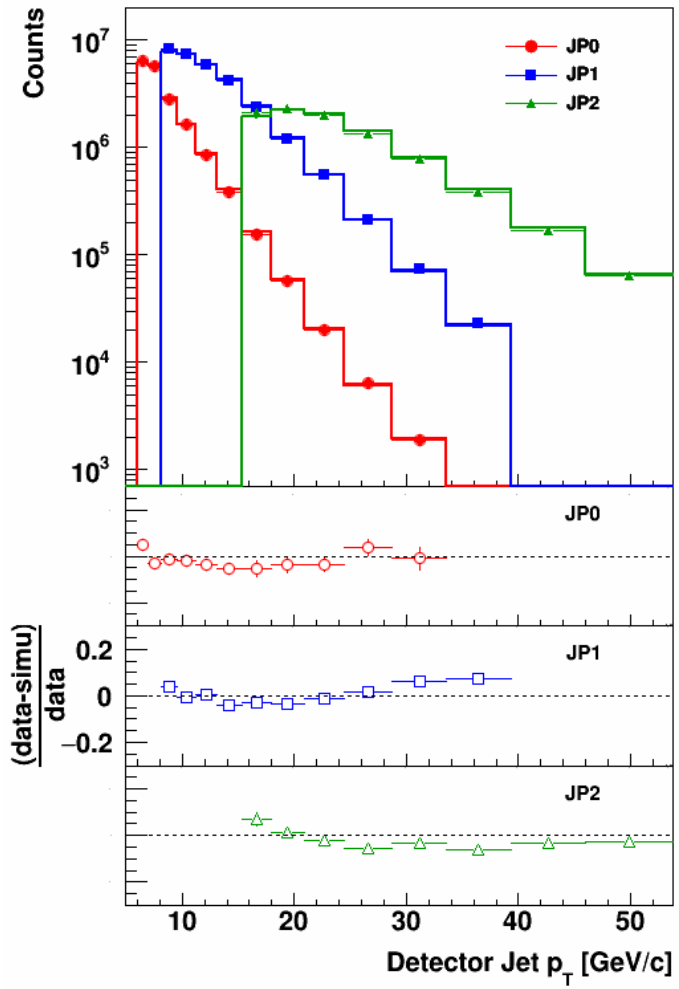
- Choose default Perugia 2012 tune with a smaller $p_{T,0}$ scale parameter (P_{90} from 0.24 to 0.213)

$$\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2} \quad (6)$$

$$p_{T,0} = p_{T,ref} \times \left(\frac{\sqrt{s}}{\sqrt{s_{ref}}}\right)^{P_{90}} \quad (7)$$

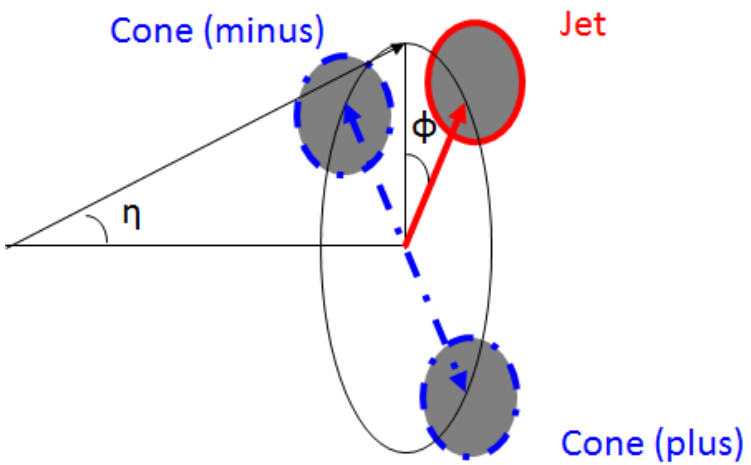
- Reduce multiple parton interaction contribution
- Lead to better matching between PYTHIA simulation and previous STAR charged $\pi^{\pm}$ spectrum measurements (PLB 637, 161,2006 and PRL 108, 072302, 2012).

Jet spectrum comparison for jet patch triggers, JP0, JP1 and JP2. Markers: data and lines: simulation



Underlying Event Correction

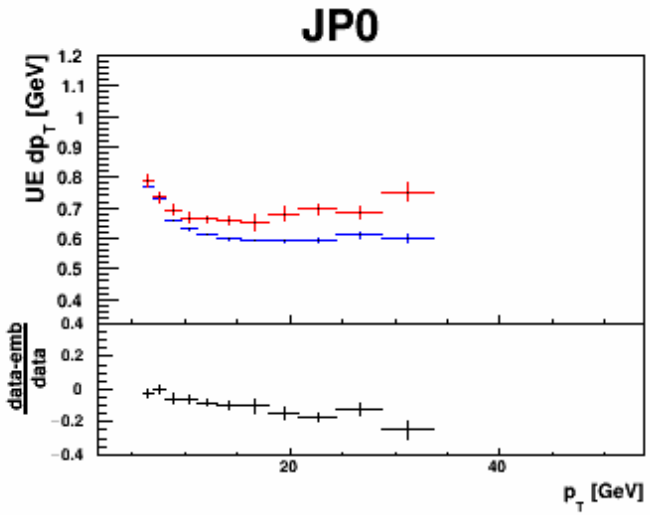
- Two off-axis cones are used to estimate underlying event for a given jet (ALICE, PRD 91, 112012).

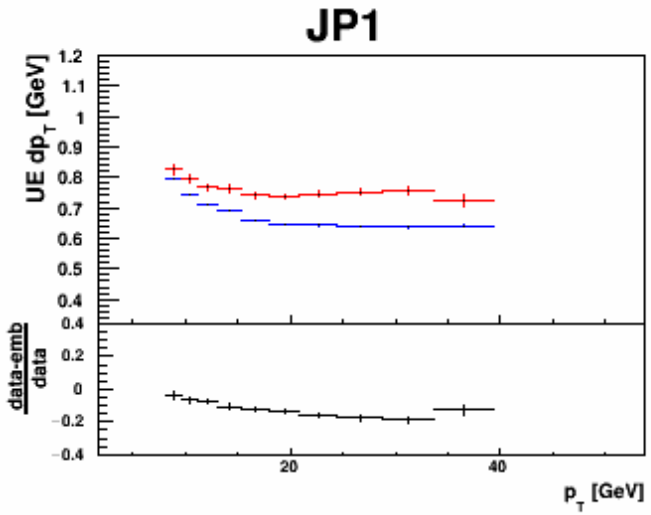


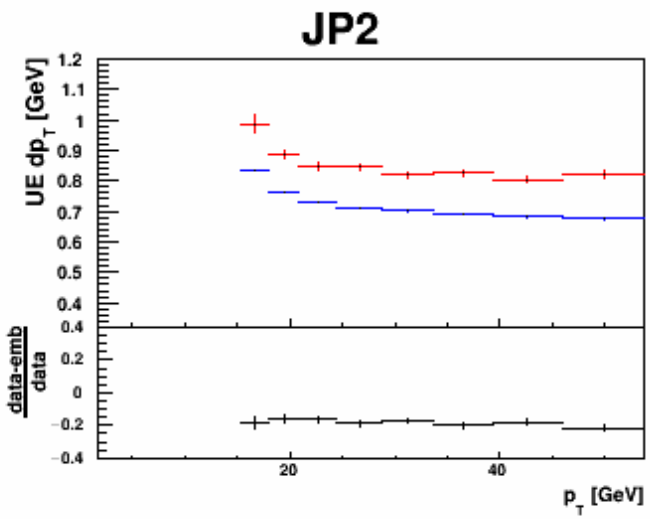
Two off-axis cones centered at $\pm\frac{\pi}{2}$ away in ϕ and the same η relative to a given jet.

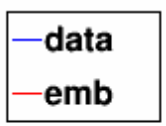
- The underlying event correction: $dp_T = \frac{1}{2}(\rho_{plus} + \rho_{minus}) \times A_{jet}$
- Sample η dependence of the underlying event.
- Other applications: jet analysis in pA collisions.

Underlying Event Correction from Data and Simulation







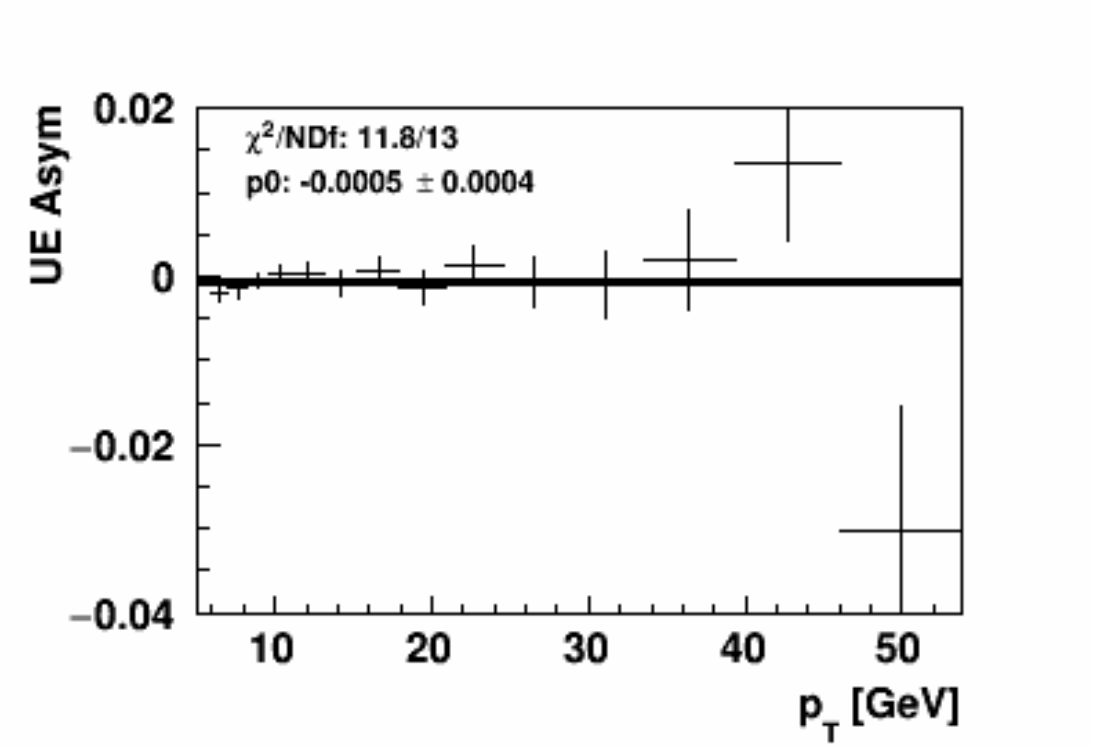


- Underlying event dp_T vs. jet p_T for three jet patch triggers JP0, JP1 and JP2. The difference in dp_T between data and simulation used as a systematics as underlying event correction on jet p_T.

Effects of Underlying Event Correction on Jet A_{LL}

- Define underlying event correction dp_T asymmetry:

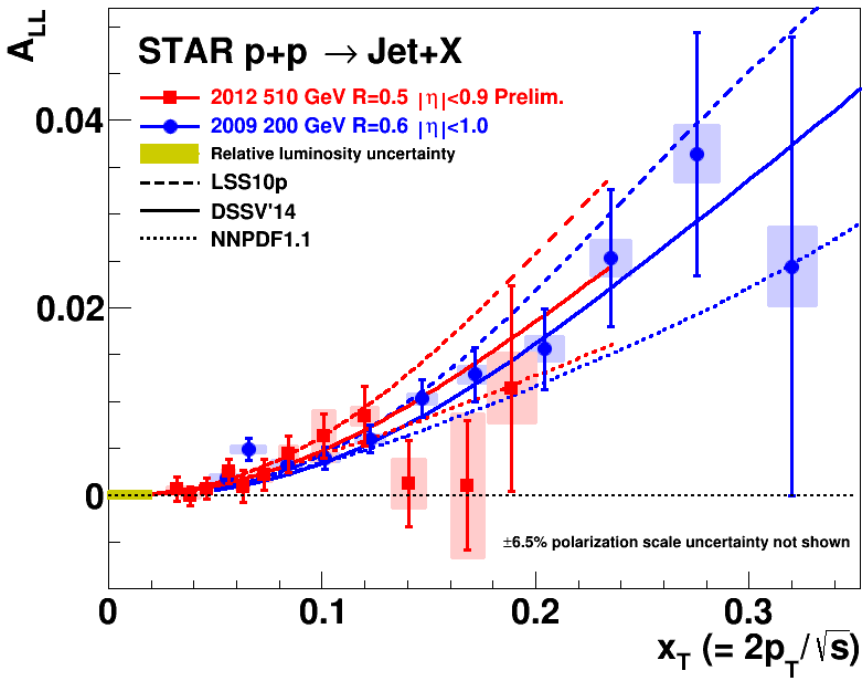
$$A_{LL}^{dpT} = \frac{1}{P_A P_B} \frac{(< dp_T >^{++} + < dp_T >^{--}) - (< dp_T >^{+-} + < dp_T >^{-+})}{(< dp_T >^{++} + < dp_T >^{--}) + (< dp_T >^{+-} + < dp_T >^{-+})} \quad (8)$$

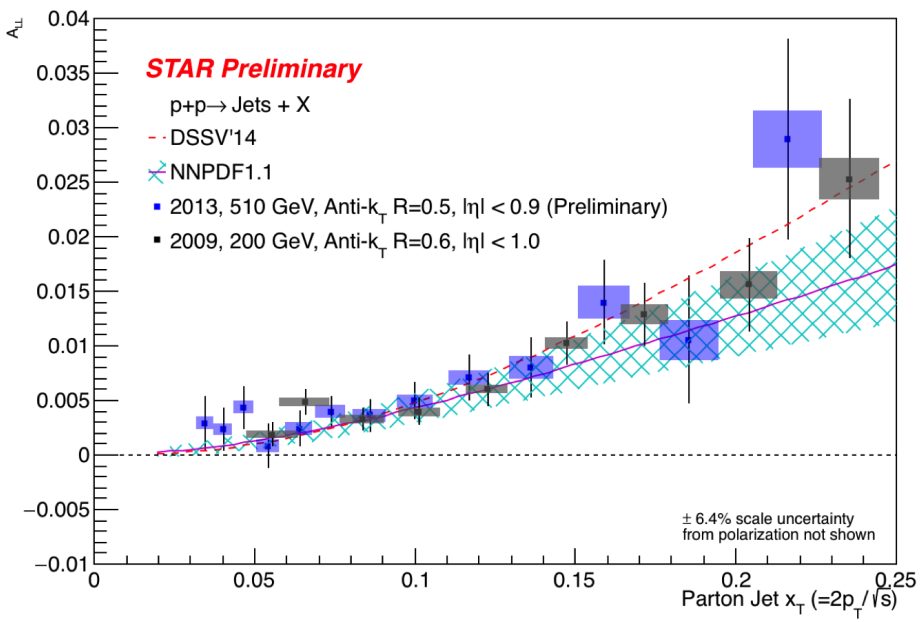


Underlying event correction dp_T asymmetries. **Little asymmetries for the underlying event correction**.

- Underlying event contribution to jet A_{LL} is estimated $\sim 10^{-4}$, assigned as an uncertainty. More detail in backup slides.

STAR 510 GeV Inclusive Jet A_{LL} Measurements

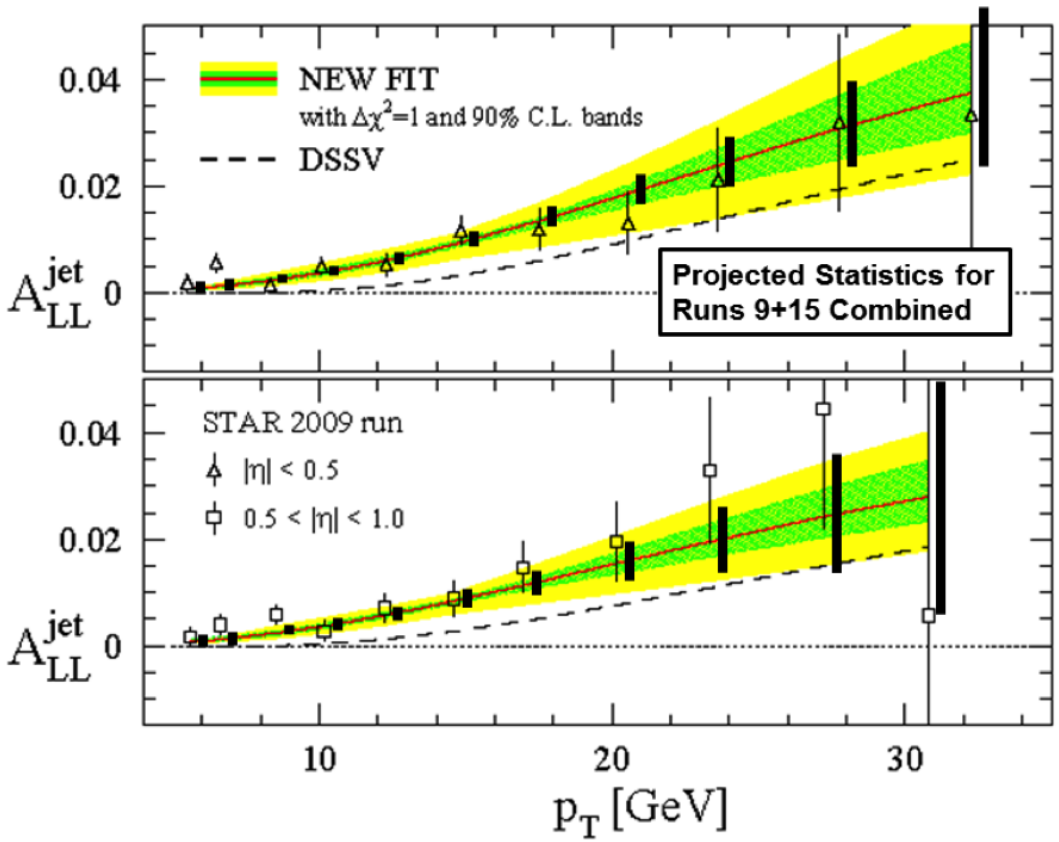




Preliminary STAR 2012 and 2013 $\sqrt{s} = 510$ GeV inclusive jet A_{LL} results compared with the STAR 200 GeV data from 2009. Both preliminary results agree well with:

- The STAR 200 GeV data in the overlapping x_T region.
- Recent polarized PDF predictions.
- Final 2012 results will have much smaller systematic uncertainties.

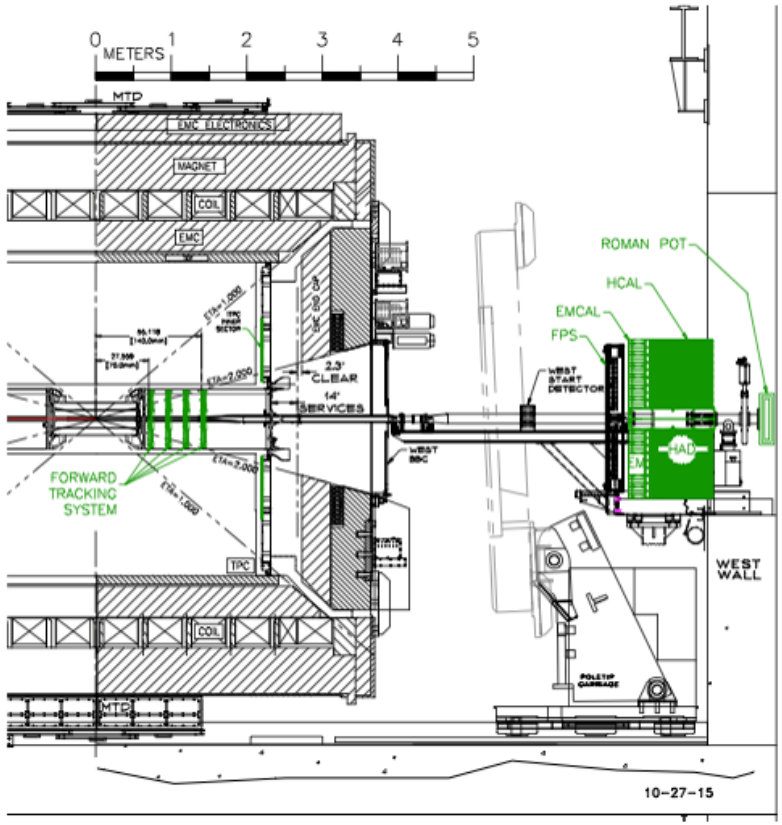
Increased Precision for 200 GeV Inclusive Jet A_{LL}

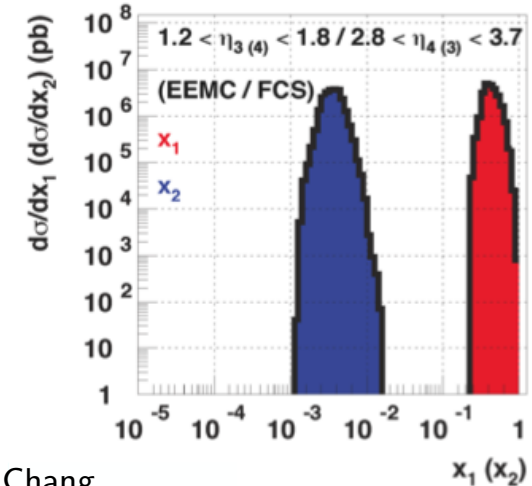


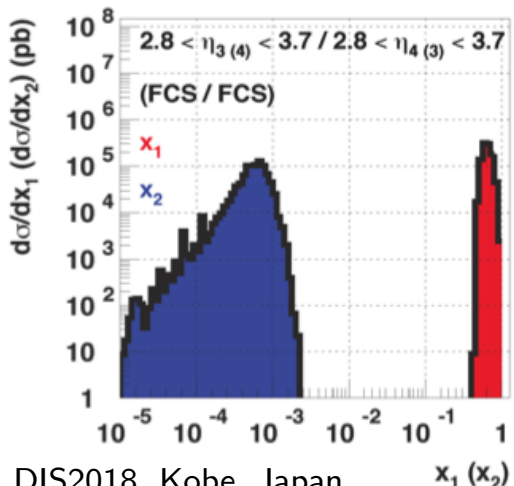
- The combined 2015 data with the existing STAR 200 GeV data will significantly reduce the uncertainties for the 200 GeV inclusive jet A_{LL}, by a factor of **two** relative to the 2009 results.

STAR Forward Upgrade

- STAR is proposing to install a Forward Calorimeter System (FCS), including an electromagnetic calorimeter and a hadron calorimeter, and a Forwarding Tracking System (FTS) in 2020s.
- 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







See Elke's talk:

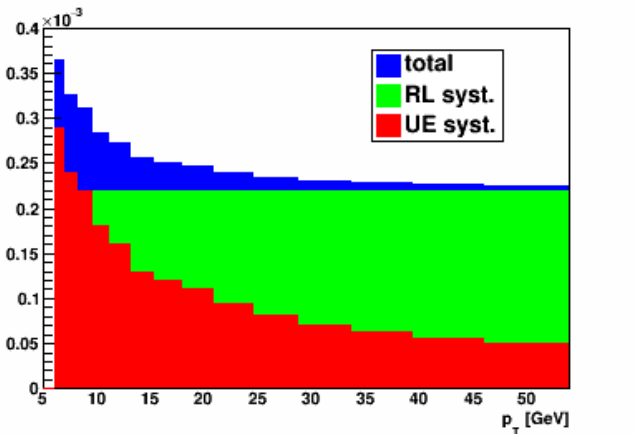
The STAR Cold QCD Physics Program after 2020.

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 in the proton.
  1. The 200 GeV results provided the first experimental evidence for positive gluon polarization over RHIC kinematic range.
  2. The 510 GeV results extend gluon polarization measurement at lower x.
- Publication preparation:
  1. 510 GeV inclusive jet and di-jet A_{LL},
  2. 200 GeV forward di-jet A_{LL},
  3. 510 GeV inclusive jet cross-sections.
- 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.

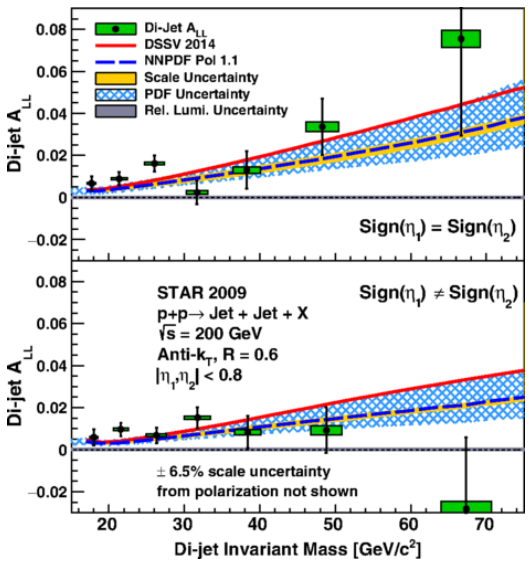
Backup:

$$\delta A_{LL} = \frac{\int_{p_{T,min}-<dp_T>\times A_{LL}^{dp_T}}^{p_{T,max}-<dp_T>\times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T - \int_{p_{T,min}+<dp_T>\times A_{LL}^{dp_T}}^{p_{T,max}+<dp_T>\times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T}{\int_{p_{T,min}-<dp_T>\times A_{LL}^{dp_T}}^{p_{T,max}-<dp_T>\times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T + \int_{p_{T,min}+<dp_T>\times A_{LL}^{dp_T}}^{p_{T,max}+<dp_T>\times A_{LL}^{dp_T}} \frac{d\sigma}{dp_T} dp_T} \quad (9)$$

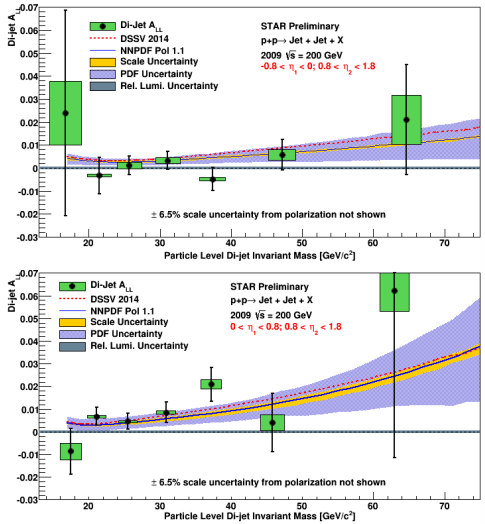


Underlying event systematic uncertainty on inclusive jet A_{LL} for 2012 510 GeV data compared with systematic uncertainty due to relative luminosity.

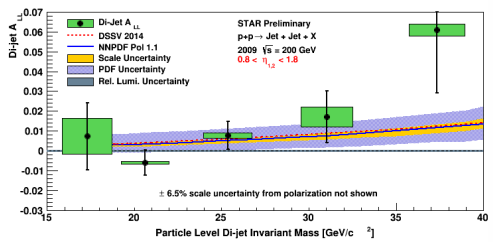
Backup: STAR 200 GeV Di-jet A_{LL} Measurements



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

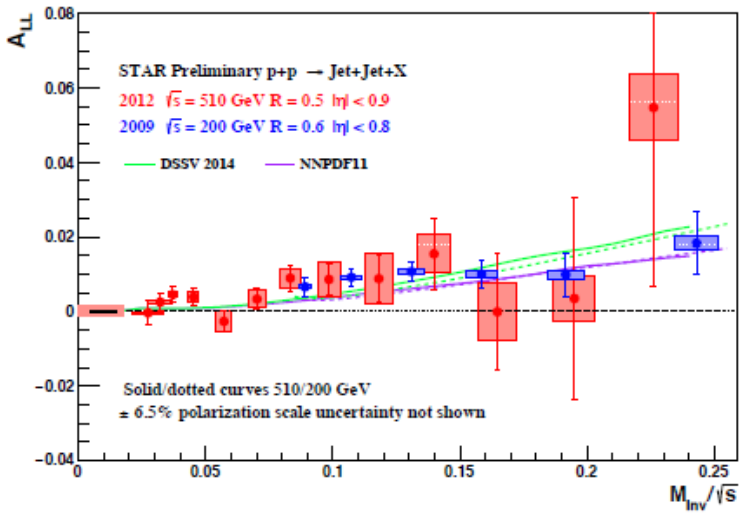


Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet A_{LL} with one jet at $|\eta| < 0.8$ and the other at $0.8 < \eta < 1.8$.

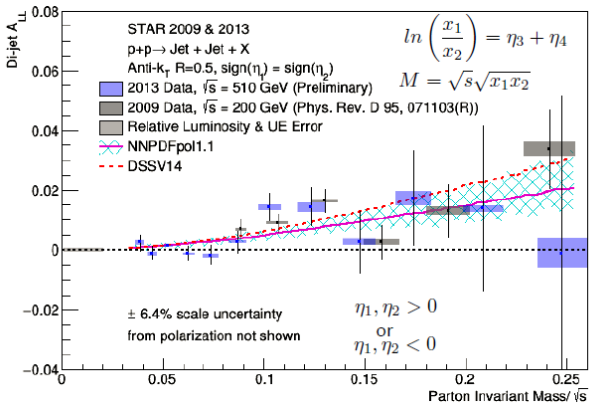


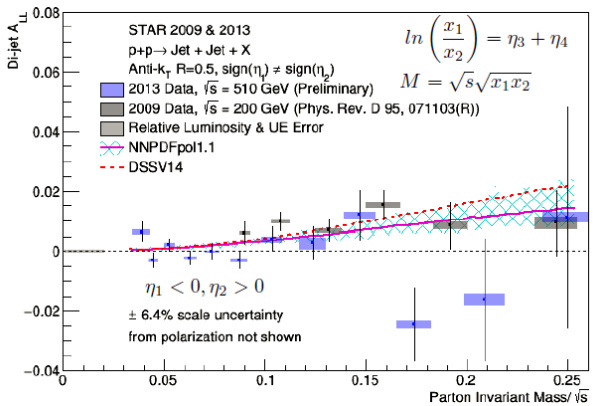
Preliminary STAR 2009 $\sqrt{s} = 200$ GeV di-jet A_{LL} measured with jets at $0.8 < \eta < 1.8$.

Backup: STAR 510 GeV Di-jet A_{LL} Measurements



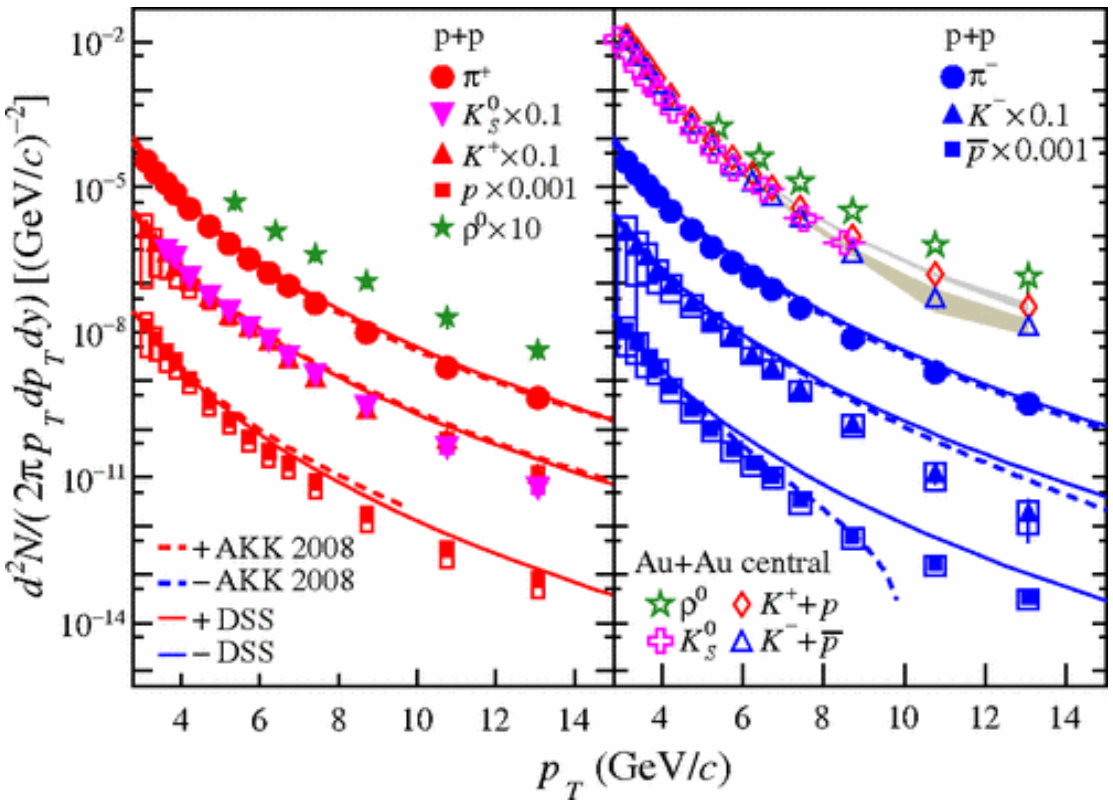
Preliminary STAR 2012 $\sqrt{s} = 510$ GeV di-jet A_{LL} measured with jets at $|\eta| < 0.9$ compared with STAR 2009 data.





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

Backup: STAR Charged $\pi^{\pm}$ Spectrum



STAR charged $\pi^{\pm}$ yields. PRL 108, 072302, 2012