Precision Measurement of the Longitudinal Double-spin Asymmetry for Dijet Production at Intermediate Pseudorapidity in Polarized proton+proton Collisions at $\sqrt{s} = 200$ GeV

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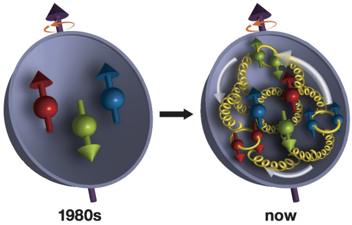
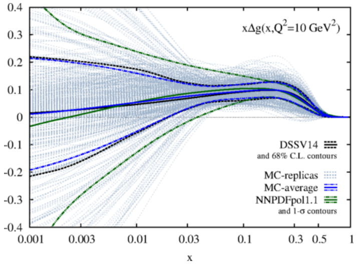
Supported in part by:

The evolving story of the proton spin

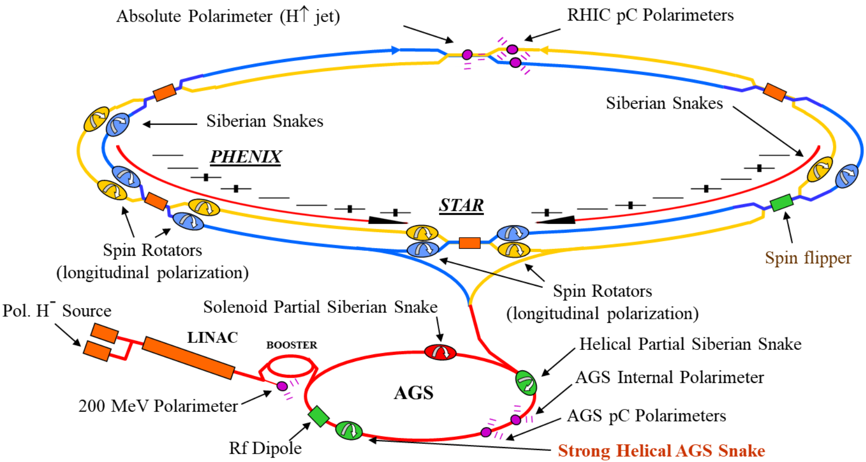
- The naive three valence quark picture evolves into a highly complex system of quarks, anti-quarks and gluons
- The proton spin puzzle: $\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$
  Jaffe and Manohar, Nucl.Phys.B,337, 509
- Precise DIS measurements have shown that quarks contribute around 30%: $\Delta\Sigma(\mathrm{Q}^2 = 3(\mathrm{GeV/c})^2) = 0.32 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}} \pm 0.05_{\mathrm{evol}}$, (COMPASS, PLB769,34)



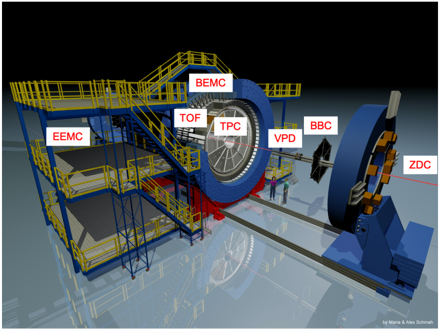


- However DIS can only constrain ΔG through scaling violations, with limited (x, Q^2) coverage at existing facilities
- Hadronic collisions such as *pp* allow direct access to ΔG through hard scatterings
- The global fit with *pp* data, DSSV'14, shows that gluons could contribute more than 50%: $\int_{0.01}^{1} dx\Delta g(x, Q^2 = 10\ \mathrm{GeV}^2) = 0.30 \pm 0.11$, (Daniel de Florian, *et al.*, PRD100,114027)
- $\langle L_z^{q,g} \rangle$: not constrained yet

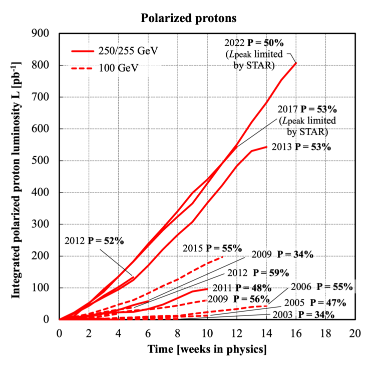
RHIC, the world's only polarized hadron collider



- 2.4 mile in circumference, two lane "racetrack"
- Spin rotators provide the choice of polarization orientations, longitudinal or transverse
- Beam polarization is between 50 to 65%



- Full 2π coverage in azimuthal
- Tracking with TPC: $|\eta| < 1.3$
- EM energy and triggering with:
  - BEMC: $-1.0 < \eta < 1.0$
  - EEMC: $1.0 < \eta < 2.0$
- Spin-sorted relative luminosity monitoring detectors: VPD, BBC and ZDC



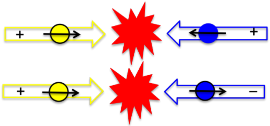
- Final longitudinally polarized datasets

Year	$\sqrt{s}$ (GeV)	Sampled L (pb^{-1})	Polarization (%)
2012	510	82	53%
2013	510	300	55%
2015	200	52	58%

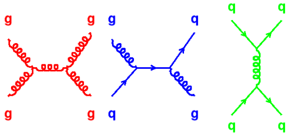
Longitudinal double-spin asymmetry for jets

- In longitudinally polarized pp collisions, define:

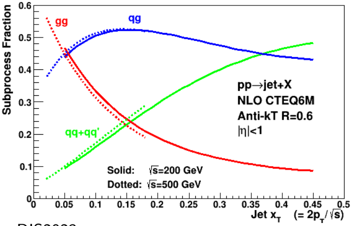
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes \hat{a}_{LL}$$



- Leading order hard QCD processes: qg, qq and gg

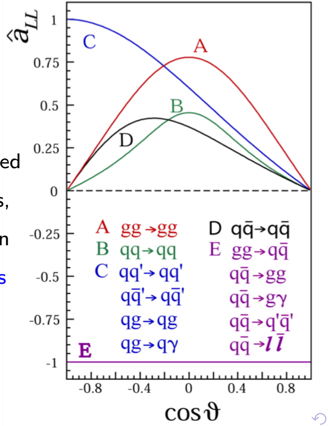


A. Mukherjee *et al.*, PRD86,094009



At RHIC energies, jet production is dominated by gluon contributions, and large $\hat{a}_{LL}$ for gluon processes $\rightarrow$ jet A_{LL} is sensitive to ΔG

J. Babcock *et al.*, PRD19,1483



Dijet measurements

- Inclusive jets:

$$x \approx \frac{2p_T}{\sqrt{s}} e^{\pm\eta}$$

- Dijets:

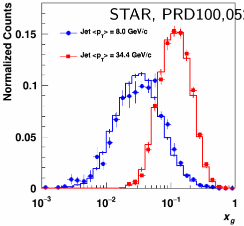
$$x_1 = \frac{1}{\sqrt{s}}(p_{T,3}e^{\eta_3} + p_{T,4}e^{\eta_4})$$

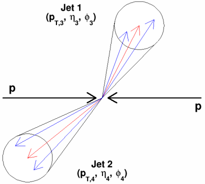
$$x_2 = \frac{1}{\sqrt{s}}(p_{T,3}e^{-\eta_3} + p_{T,4}e^{-\eta_4})$$

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

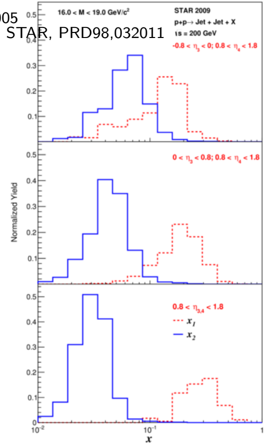
$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$

x_g sampled by inclusive jets at $\sqrt{s} = 510$ GeV





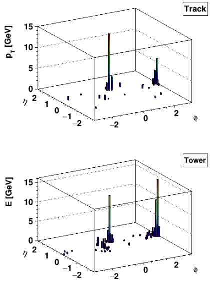
x_1 and x_2 sampled by dijets

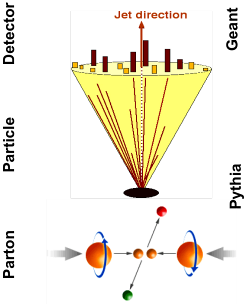


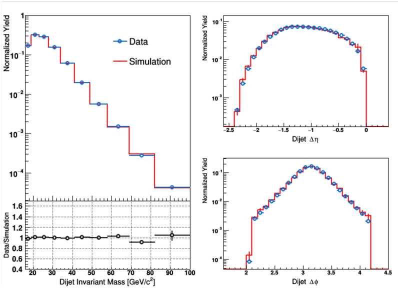
- Dijet rapidity topologies allow to sample x_1 and x_2 simultaneously in different ranges, as well as $\cos\theta^*$ on which the $\hat{a}_{LL}$ depends
- To sample low x gluons, either increase $\sqrt{s}$ or increase η
- This analysis focuses on the dijet production with one jet located at $0.8 < \eta < 1.8$, the endcap dijet, which samples x_g as low as ~ 0.02 at $\sqrt{s} = 200$ GeV

Jet studies at STAR

- Inputs to jet finder: charged TPC tracks, and EM towers
- Anti-k_T algorithm with $R = 0.6$ for 200 GeV and $R = 0.5$ for 510 GeV, less sensitive to underlying events and soft backgrounds





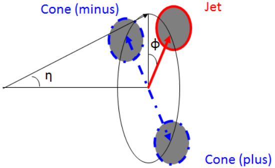


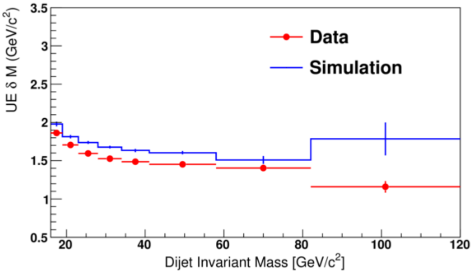
- PYTHIA 6 tuned to RHIC data based on the default Perugia 2012 tune: reduced $P_{90} = 0.213$ from 0.24 $\sigma \sim \frac{1}{(p_T^2 + p_{T,0}^2)^2}$, where $p_{T,0} = (2.65 \text{ GeV}) \times (\frac{\sqrt{s}}{7000 \text{ GeV}})^{P_{90}}$ (STAR, PRD100,052005)
- Jet reconstructions from partons, particles, and simulated detector response
- Simulated jet quantities match data very well

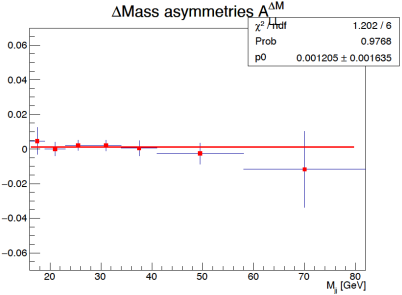
Underlying event correction

STAR, PRD100,052005

- Two off-axis cones centered at $\pm\frac{\pi}{2}$ away in ϕ and the same η relative to the signal jet are used to estimate underlying event contribution for that jet (ALICE, PRD91,112012)
  1. Correct the measured jet momentum
  2. Estimate its contribution to jet A_{LL}



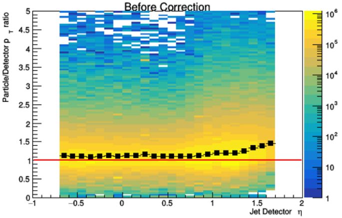


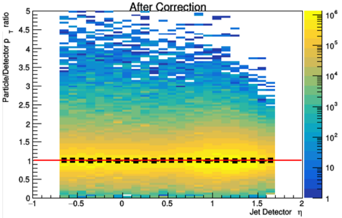


- Underlying event correction $\delta M < 2\ \mathrm{GeV}/c^2$
- Contribution to jet A_{LL} at the level of 10^{-3}

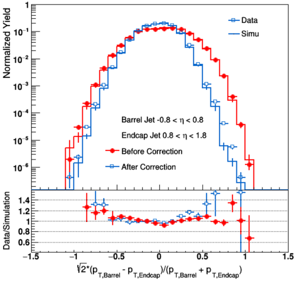
Low tracking efficiency in the endcap region

- TPC covers up to $\eta \sim 1.3$, and the tracking efficiency decreases rapidly as η increases
- Significant loss of charged particles in the endcap region
- Multilayer perceptron, a supervised machine-learning regression provided by the ROOT TMVA library, corrects the measured jet p_T to its corresponding particle jet p_T
- Input jet quantities: p_T, detector η relative to the detector center, and neutral energy fraction





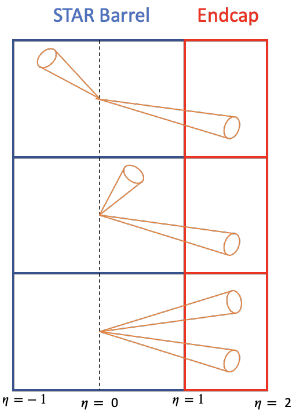
- p_T imbalance for dijets with one jet in the barrel and the other in the endcap

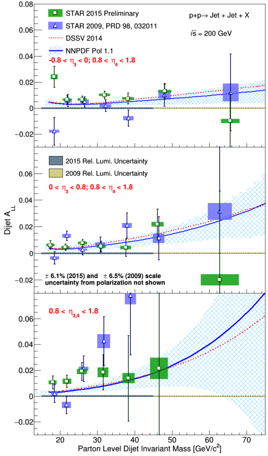


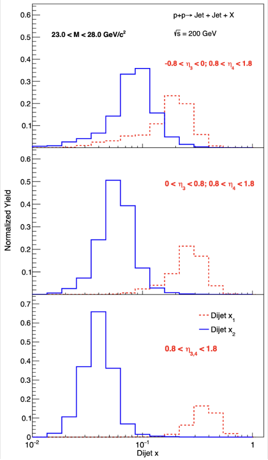
This machine learning technique works well!

Endcap dijet A_{LL} at $\sqrt{s} = 200$ GeV

- Two barrel-endcap (East-endcap and West-endcap) and endcap-endcap topologies



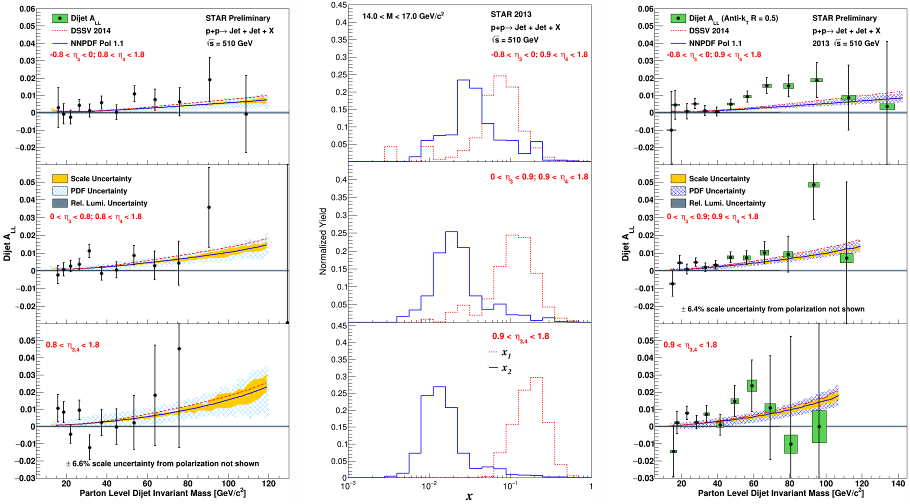




- The statistical uncertainty is smaller by almost a factor of 2 compared to the 2009 data
- Our data agree with both DSSV'14 and NNPDF pol 1.1 predictions, except for the endcap-endcap topology at low invariant mass
- More asymmetric x_1 and x_2 as both jets are in the endcap region

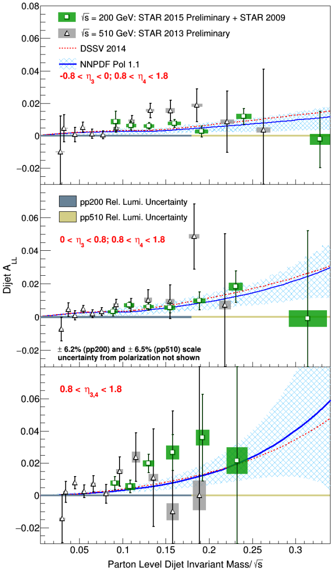
Endcap dijet A_{LL} at $\sqrt{s} = 510$ GeV

- Endcap dijet A_{LL} at $\sqrt{s} = 510$ GeV from the 2012 and 2013 data



- The highest $\sqrt{s}$ and the largest η, permitting to reach the smallest $x_g \sim 0.01$ at STAR

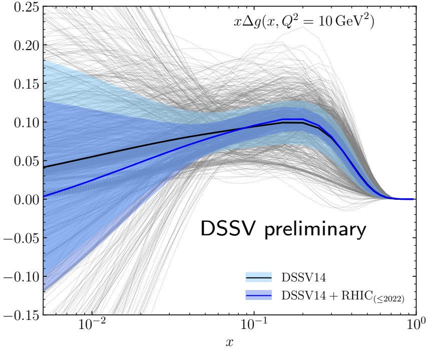
Final endcap dijet A_{LL}s

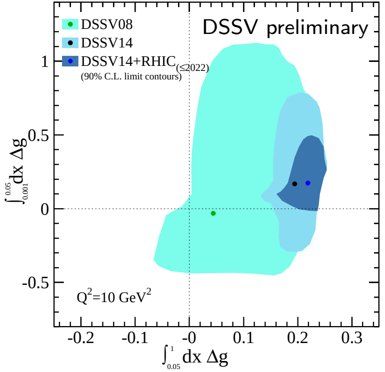


- A_{LL}s at $\sqrt{s} = 200$ and 510 GeV agree with each other as a function of $x_T = \frac{M}{\sqrt{s}}$
- No clear preference of a polarized PDF global fit for the DSSV'14 and NNPDF pol 1.1 fits
- Together with inclusive jet and dijet A_{LL} in mid-rapidity $|\eta| < 1$, (please refer B. Surrow's talk in the same session) they will conclude the analysis of jet A_{LL} at STAR
- Final publications for both results are in progress
- Gluon polarizations will be revisited in the future EIC

ΔG from the DSSV group

- $x\Delta g(x)$ vs. x and $\int dx\Delta g$ from the DSSV group





- The group included RHIC data released as of 2022, i.e., STAR inclusive jet and dijet A_{LL} and PHENIX pion A_{LL}
- With RHIC data, significant improvements on ΔG compared to 2008 results: $\int_{0.05}^{1} dx\Delta g = 0.22 \pm 0.03$, at $x > 0.05$ and $Q^2 = 10\ \mathrm{GeV}^2$, almost 8σ away from zero
- The white paper of the RHIC cold QCD program: EC, Aschenauer *et al.*, arXiv:2302.00605 [nucl-ex]

Conclusions

- At $\sqrt{s} = 200$ and 510 GeV and with the jet kinematic coverage up to η of 1.8, the endcap dijet A_{LL} not only constrains the functional form of $\Delta g(x)$ but also reaches the lowest possible $x_g \sim 0.01$
- STAR has demonstrated non-zero gluon polarizations in the proton from a series of precise measurements of inclusive jet and dijet A_{LL}
- As indicated by recent global fits, especially the DSSV group, gluons contribute about 40% of the total proton spin, when $x > 0.5$ and $Q^2 = 10\ \mathrm{GeV}^2$
- With the completion of the longitudinal polarized data taking, two remaining endcap jet A_{LL} analyses from STAR are being prepared for final publications
- In addition, through $W^{\pm}$ longitudinal single-spin asymmetry A_L, STAR has showed

  $\Delta\bar{u} > \Delta\bar{d}$ STAR, PRD,99,051102