# Longitudinal Double-spin Asymmetry for Inclusive Jet and Dijet Production in pp Collisions at $\sqrt{s} = 510$ GeV

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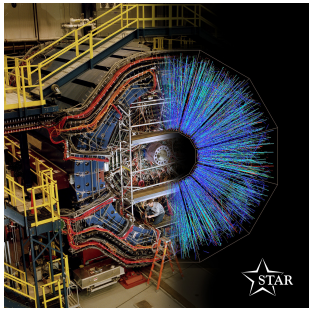
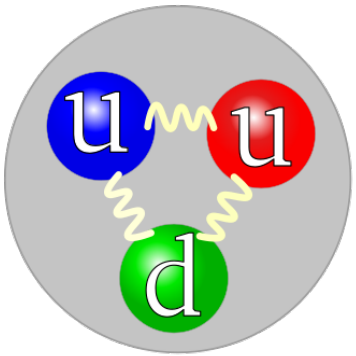
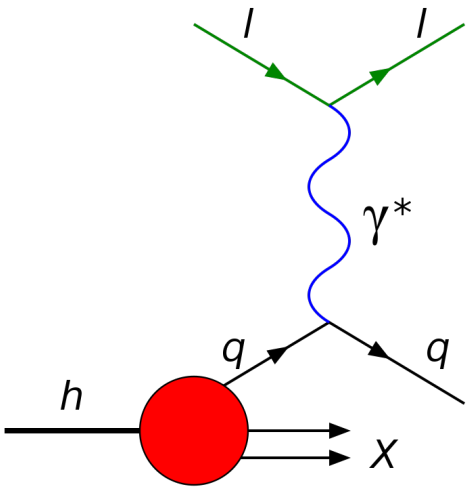


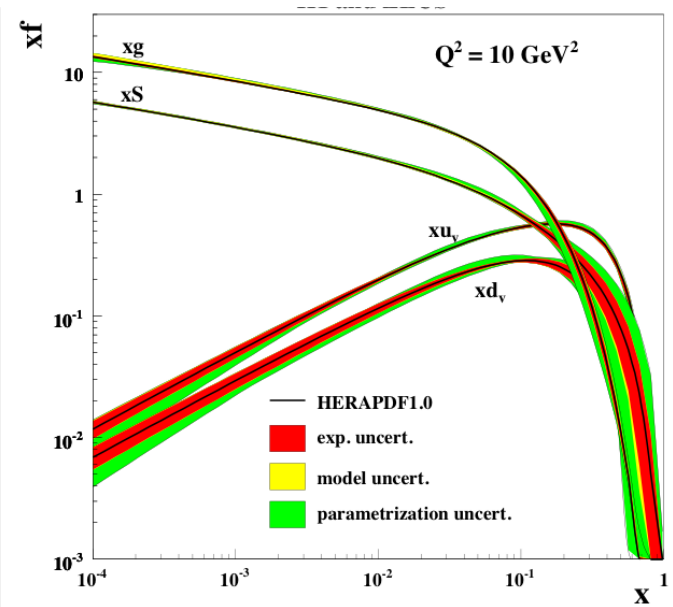
# The Proton Structure

- **Simple quark model**: $u$, $u$, $d$ quarks
- Binding force: **strong force**
- Mediator: **gluons**
- Lepton-hadron deep inelastic scattering (DIS) experiments to study the internal structure




- **Proton parton model**: there are lots of quarks and gluons inside the proton
- **Parton distribution functions**: $f(x, Q^2)$, the probability distribution function depends on the momentum transfer $\mathbf{Q^2}$ of the probe and the momentum fraction **x** carried by the parton

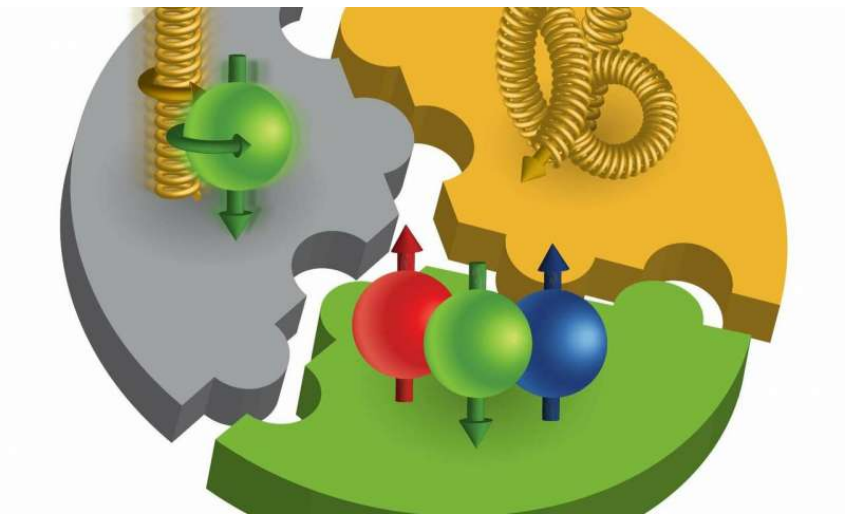



- **Gluons dominate at low $x$**

# The Proton Spin

**Contributions to the proton spin**:

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



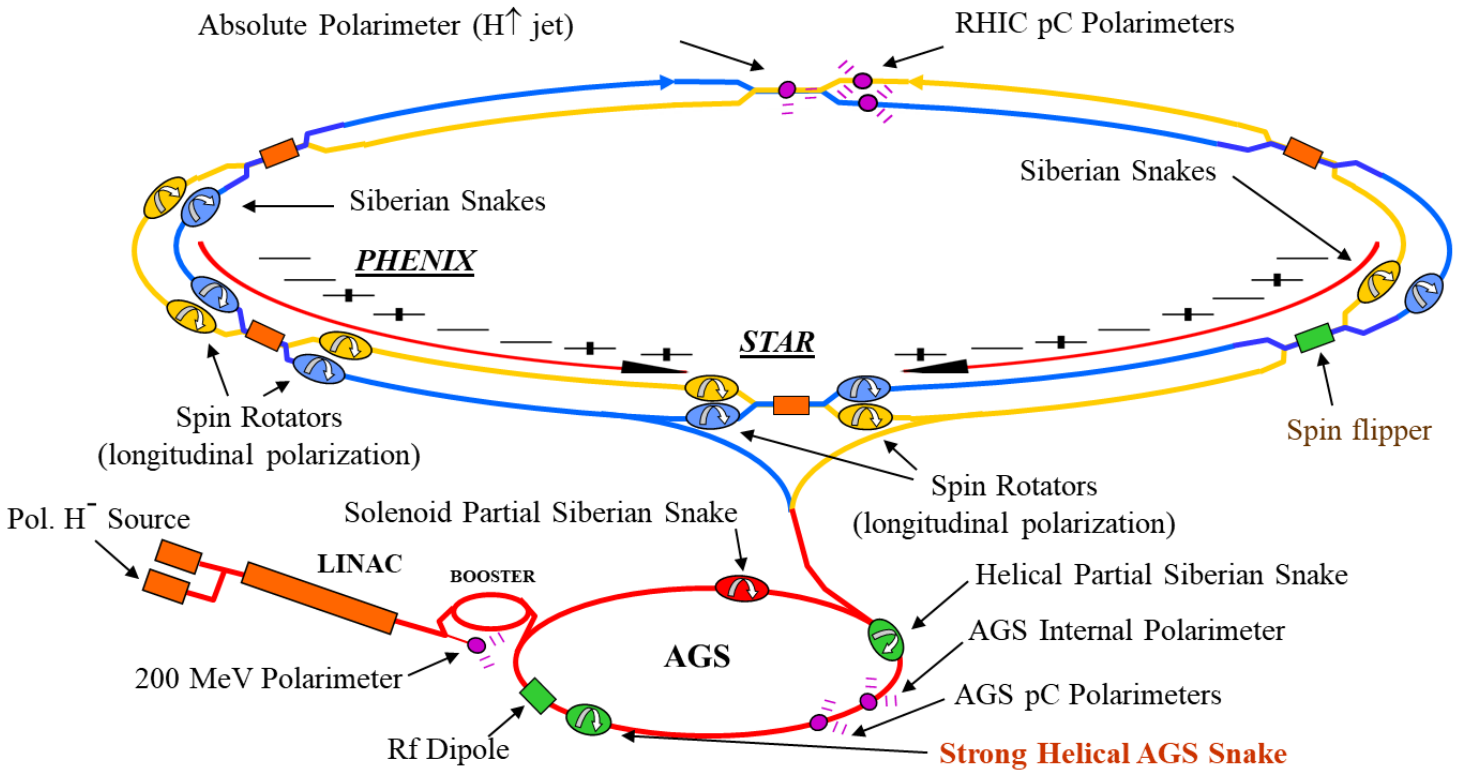
- Quark contribution $\Delta\Sigma$: approximately 30% from polarized DIS experiments
- Gluon contributions $\Delta G$: **poorly** constrained from polarized DIS experiments
- $L_{q,g}$: not constrained yet, can be achieved in the future Electron Ion Collider

## Polarized hadron-hadron scattering:

High center of mass energy $\rightarrow$ asymptotic freedom at short distances $\rightarrow$ parton-parton scattering

Direct access of polarized gluons

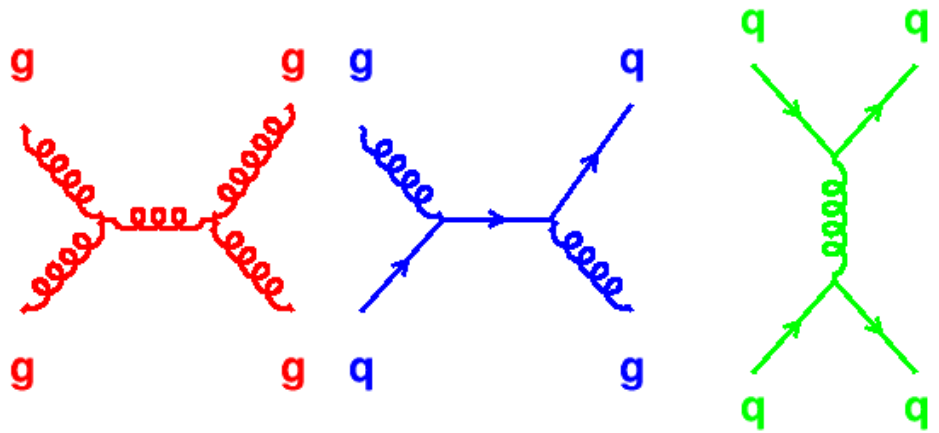
# Relativistic Heavy Ion Collider (RHIC)




- The world's only polarized hadron collider
- Polarized $pp$ beams at $\sqrt{s} = 200$ and 510 GeV
- Beam polarization measurements at 12 o'clock of the ring, $\sim$ 55% to 65%
- Experiment halls where beams collide: STAR detector at 6 o'clock

# Direct Access to Gluons at RHIC

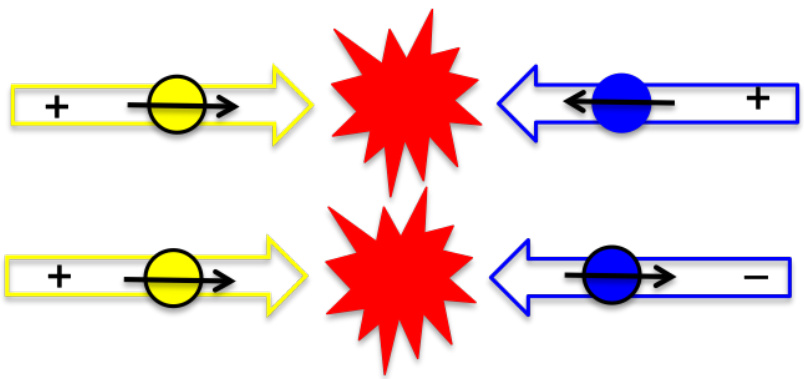
- Three partonic scattering processes in the *pp* collisions are *gg*, *qg*, and *qq*




- The scattered partons can produce a cluster of collimated particles, called a **jet**
- **At RHIC, *gg* and *qg* processes dominate jet production**

# Jet Asymmetry Measurements at RHIC

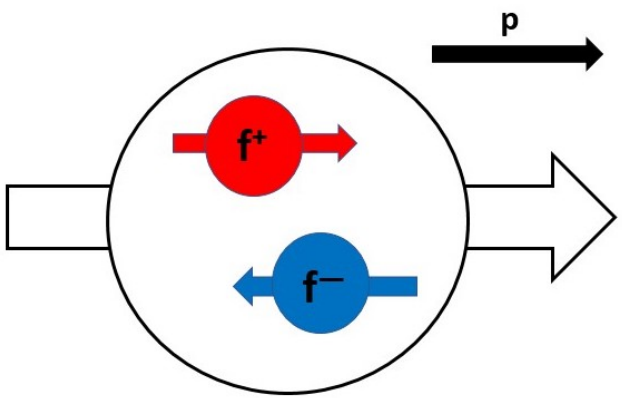
- Parton helicity: the polarization orientation of the parton is **parallel** $(+)$ or **anti-parallel** $(-)$ to its momentum direction
- Scattering combinations: $++$ and $+-$




- The partonic longitudinal double-spin asymmetry, $\hat{a}_{LL}$, responsible for the **difference in jet yields** from parton scattering processes with $++$ and $+-$:

$$\hat{a}_{LL} = \frac{\hat{\sigma}^{++} - \hat{\sigma}^{+-}}{\hat{\sigma}^{++} + \hat{\sigma}^{+-}}$$

- The **polarized** parton distribution function, $\Delta f = f^{+} - f^{-}$

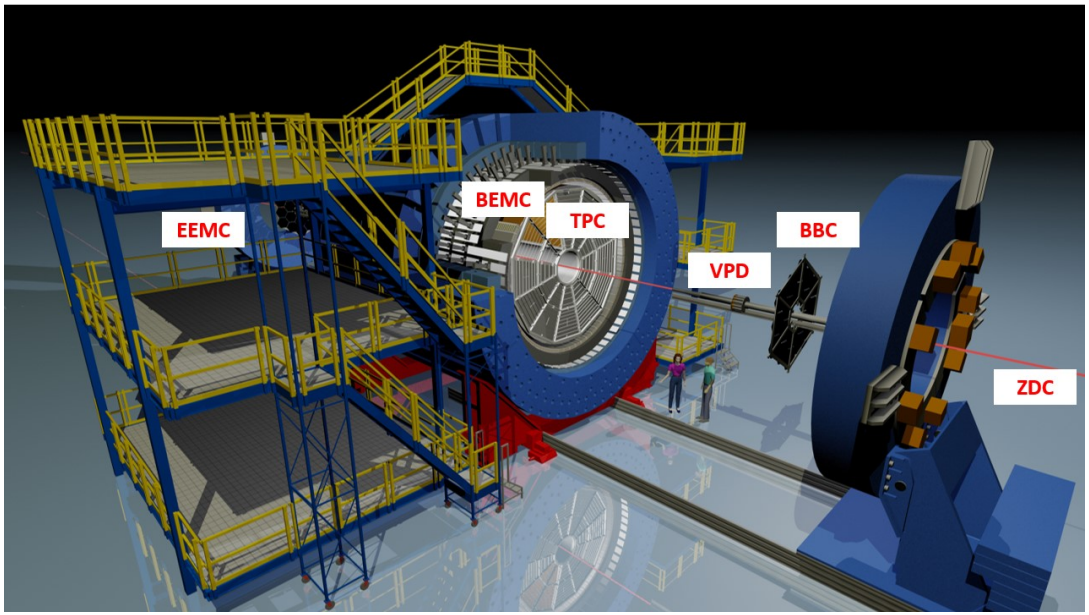



- The jet longitudinal double-spin asymmetry, $A_{LL}$ in **pp** collisions is

$$A_{LL} \sim \sum_{a,b} \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

- $gg$ and $qg$ have large $\hat{a}_{LL} \rightarrow$ **making jet $A_{LL}$ sensitive to gluon polarization**

# STAR Detectors




| $\eta$ | $\theta$ |
|---|---|
| $-1.3$ | $149.5°$ |
| $-1.0$ | $139.6°$ |
| 0 | $90°$ |
| 1.0 | $40.4°$ |
| 1.3 | $30.5°$ |
| 2.0 | $15.4°$ |

- Symmetric in full azimuth, $0 < \phi < 2\pi$
- Tracking charged particles with Time Projection Chamber: $|\eta = -ln(tan(\frac{\theta}{2}))| < 1.3$
- Electro-Magnetic (EM) energy and triggering with:

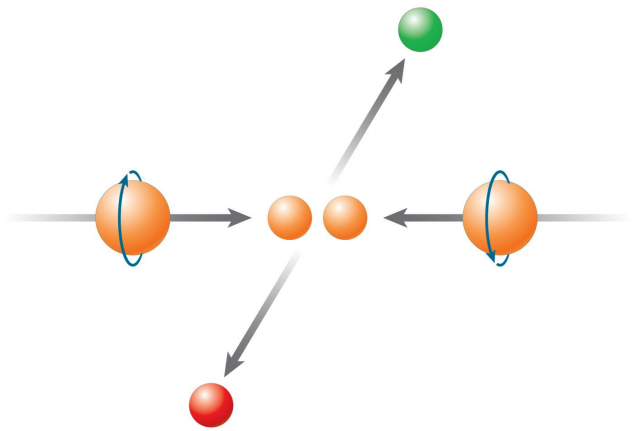
  Barrel EM Calorimeter: $|\eta| < 1.0$, Endcap EM Calorimeter: $1.0 < \eta < 2.0$
- Luminosity monitoring detectors with respect to the collision helicity combinations:

  Vertex Position Detector, Beam Beam Counter, and Zero Degree Calorimeter

# Jet $A_{LL}$ Measurements at STAR

- Relativity: the invariant mass of a particle, $M$ can be calculated from its momentum $\vec{p} = (p_x, p_y, p_z)$ and energy $E$, $M^2c^4 = E^2 - p^2c^2$
- In high energy physics, $c = 1$, $\vec{p} = (p_T, \eta, \phi)$, where $p_T$ is the transverse momentum
- Jet transverse momentum: $p_{T,jet} = \sum_i p_{T,i}$, where $i$ runs over all the particles inside the jet
- Jet energy $E_{jet} = \sum_i E_i$
- Dijet invariant mass $M_{inv}$: $M_{inv}^2 = (E_{1,jet} + E_{2,jet})^2 - (\vec{p}_{1,jet} + \vec{p}_{2,jet})^2$

- Longitudinally polarized $pp$ collisions: $++$ and $+-$

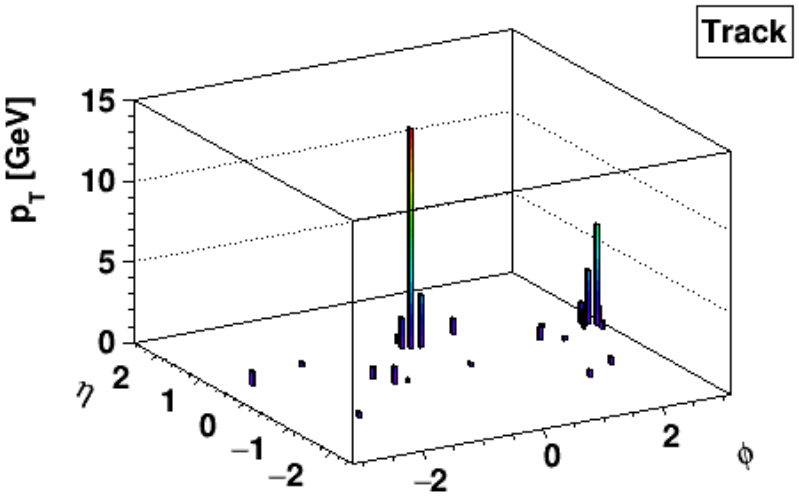


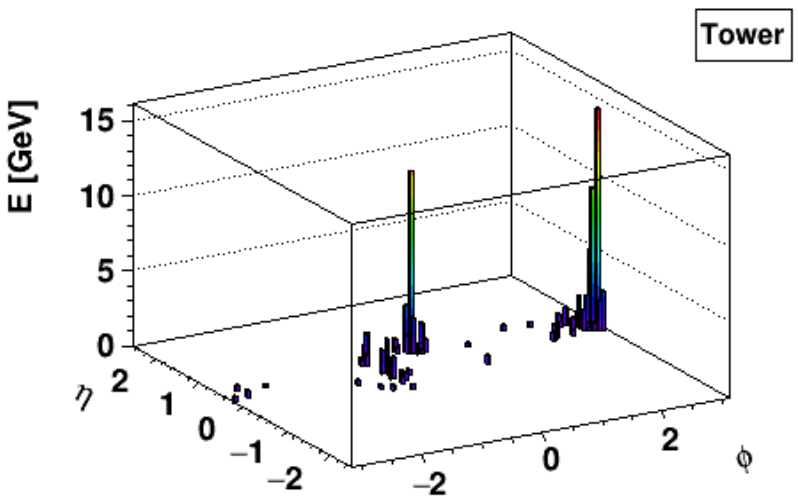
- **Count** the number of jets, $N^{++}$ and $N^{+-}$ for a given jet $p_T$ or a dijet $M_{inv}$
- Beam polarizations: $P_{B(Y)}$ and relative luminosity: $R = \frac{L^{++}}{L^{+-}}$

$$A_{LL}(p_T/M_{inv}) = \frac{1}{P_B P_Y} \frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}$$

# STAR Inclusive Jet and Dijet Measurements

- Inputs: charged tracks + EM towers

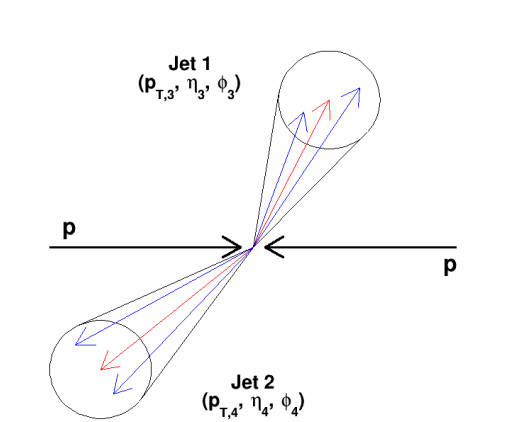



- Inclusive jet: $p + p \rightarrow Jet + X$
- Sampled parton kinematics:

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

- Dijet: $p + p \rightarrow Jet + Jet + X$



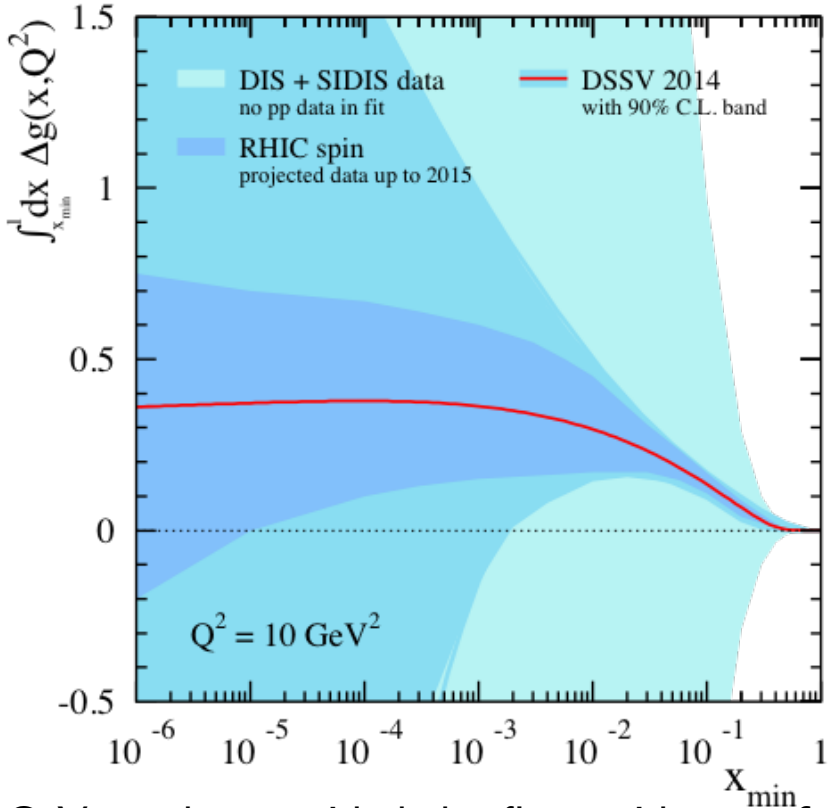

- Opening angle $\Delta\phi = \phi_3 - \phi_4 > \frac{2\pi}{3}$, remove hard gluon emissions
- Sampled parton kinematics:

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

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

# Gluon Polarization with STAR 200 GeV Jet $A_{LL}$ Results

- STAR has published a series of inclusive jet and dijet $A_{LL}$ at $\sqrt{s} = 200$ GeV
- $\int_{x_{min}}^{1} dx \Delta g(x, Q^2)$ vs. $x_{min}$, at $Q^2 = 10\ \mathrm{GeV}^2$




- The STAR 200 GeV results provided the first evidence of **positive gluon polarization**
- Recent DSSV study shows: $\int_{0.01}^{1} \Delta g(x, Q^2 = 10 GeV^2) = 0.296 \pm 0.108$

de Florian et al., arXiv:1902.10548 [hep-ph]

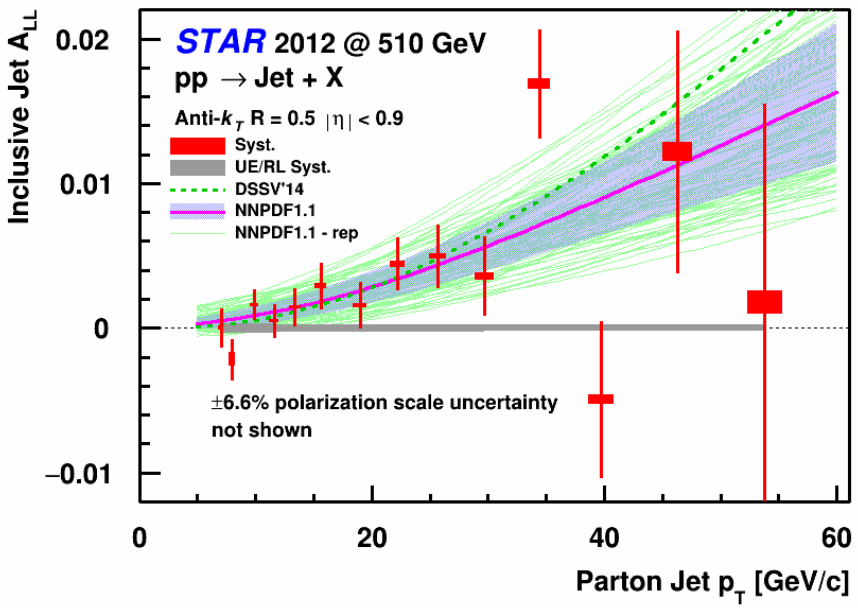
Uncertainty on $x\Delta g$ still large at $x < 0.01$, higher $\sqrt{s}$?

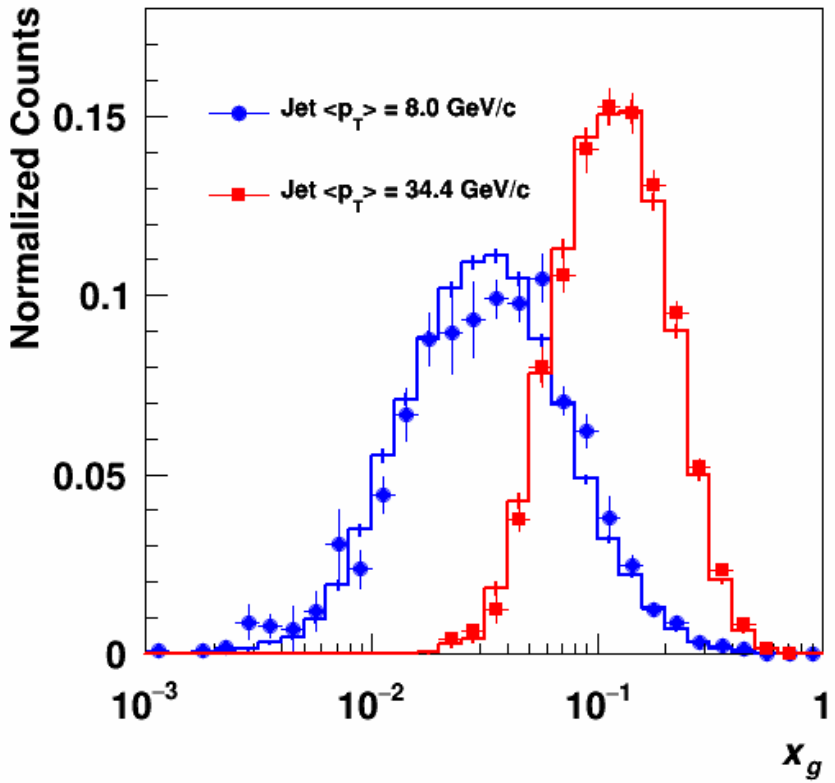
# Longitudinal double-spin asymmetry for inclusive jet and dijet production in pp collisions at $\sqrt{s} = 510$ GeV

## STAR, Phys. Rev. D 100, 052005 (2019)

# STAR 510 GeV Inclusive Jet $A_{LL}$ Results

- Inclusive jet $A_{LL}$ vs. parton jet $p_T$ at $\sqrt{s} = 510$ GeV, STAR, Phys. Rev. D 100, 052005 (2019)



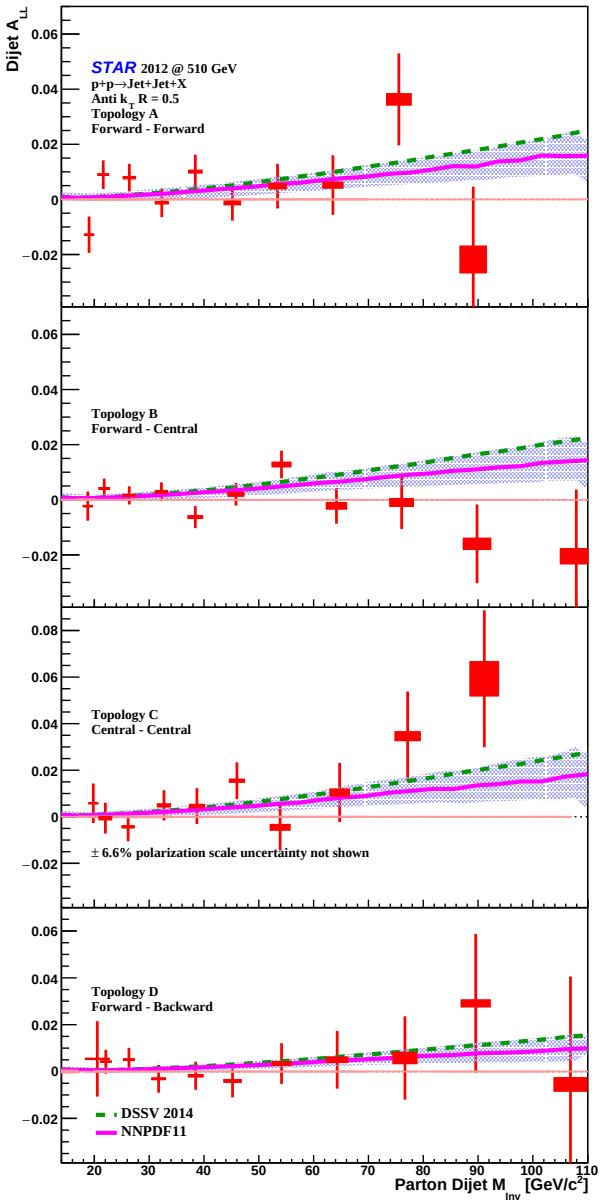

- Much reduced systematic uncertainty than the previous measurements at $\sqrt{s} = 200$ GeV
- Agree well with recent polarized PDF predictions, which are consistent with 200 GeV findings and imply positive $\Delta G$

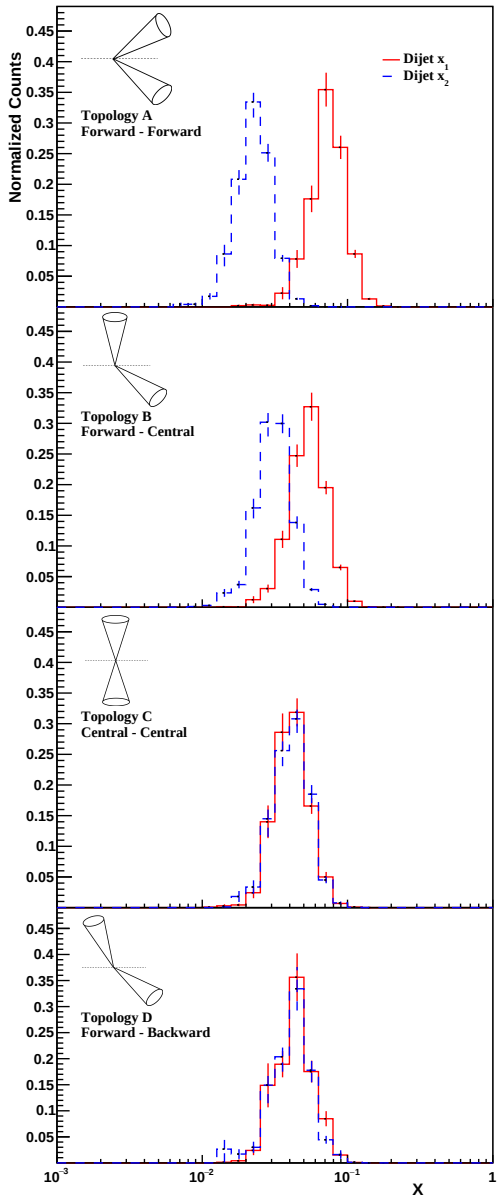
- Sampled gluon $x_g$ distributions for two jet $p_T$ bins, with $< p_T >= 8.0$ and 34.4 GeV/c
- The smaller the jet $p_T$, the lower the sampled $x_g$
- Access $\mathbf{x_g}$ as low as $\mathbf{0.015}$

# STAR 510 GeV Dijet $A_{LL}$ Results

- Dijet $A_{LL}$ vs. dijet $M_{inv}$ at $\sqrt{s} = 510$ GeV, STAR, Phys. Rev. D 100, 052005 (2019)

- Dijet $A_{LL}$ results are divided into **four $\eta$ topology bins**
- $x1$ and $x2$ distributions sampled by dijet $M_{inv}$ bin, $17 < M_{inv} < 20$ GeV/$c^2$
- Dijets sample **much narrower** $x$ distribution than the inclusive jets do
- Simultaneously sampling $x_1$ and $x_2$ permits dijet results to constrain the **shape of** $\Delta g$ as a function of $x$



# Conclusion

- STAR inclusive jet and dijet double-spin asymmetry measurements are unique to explore gluon polarization in the proton
  1. Inclusive jets constrain the magnitude of the gluon polarization
  2. Dijets constrain the shape of $\Delta g(x)$
- The 200 GeV results provided the first evidence of the positive gluon polarization
- **The first measured 510 GeV results extend the constraint of the gluon polarization down to $x \sim 0.015$, STAR, Phys. Rev. D 100, 052005 (2019)**