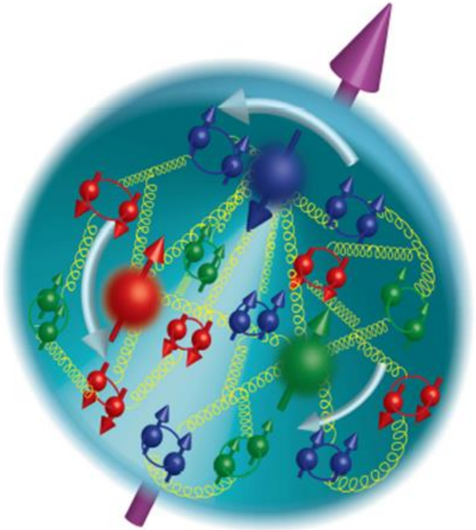
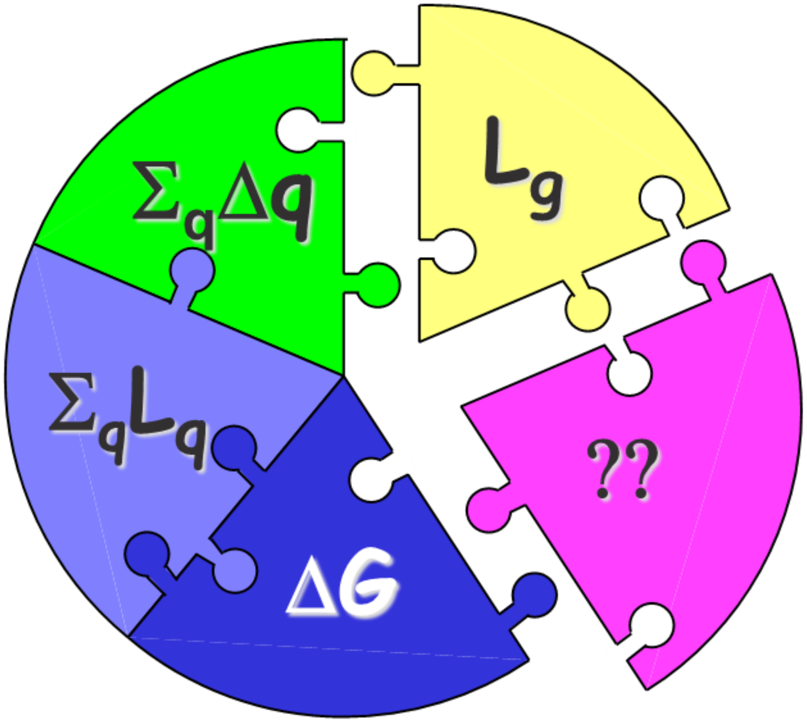
How to Unravel the Nucleon Helicity Structure at an EIC

Brian Page
Brookhaven National Laboratory

Spin 2016 - UIUC



Piecing Together the Proton Spin



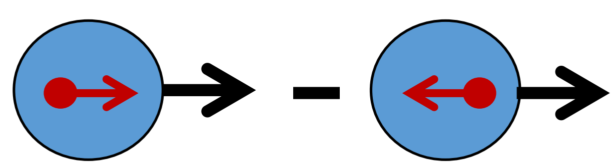
$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

- Simple picture of proton composed of three valence quarks superseded by complex interaction of quarks, antiquarks, and gluons
- The proton's spin must arise from combination of intrinsic and orbital angular momenta of these components
- This talk will deal only with the intrinsic contributions, ΔG and ΔΣ

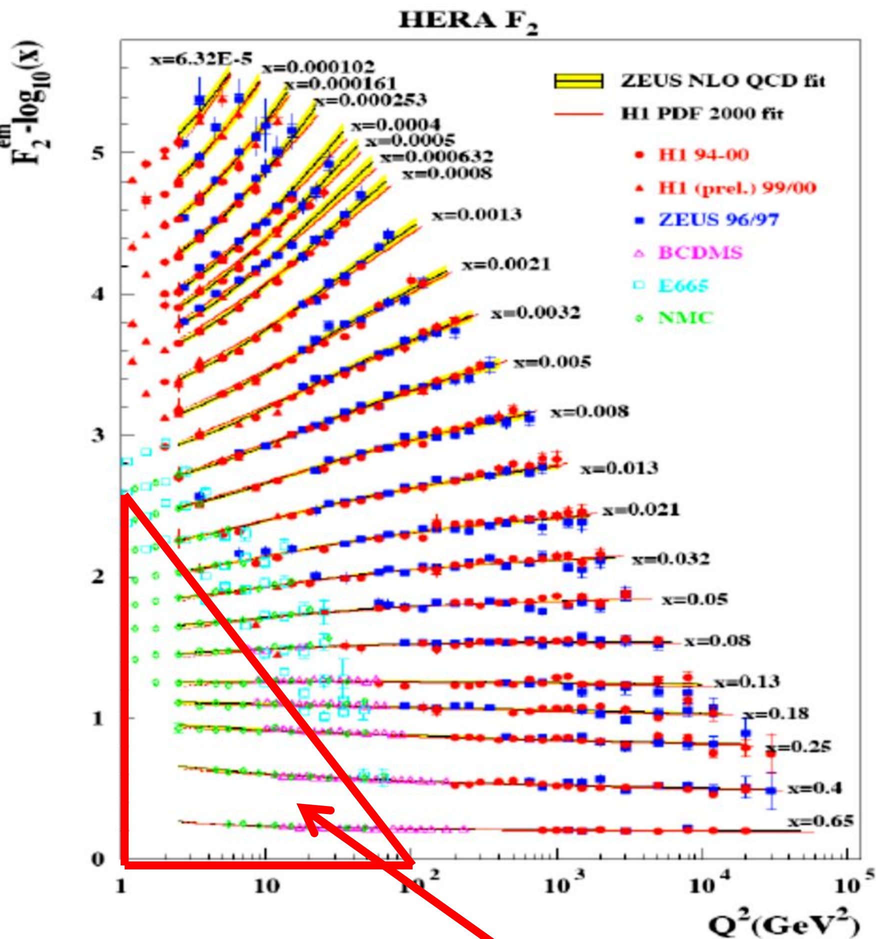
$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \cdots)dx$$

$$\Delta G = \int \Delta g(x)\, dx$$

Helicity Distributions: Δq, Δg



Intrinsic Gluon Contribution: ΔG

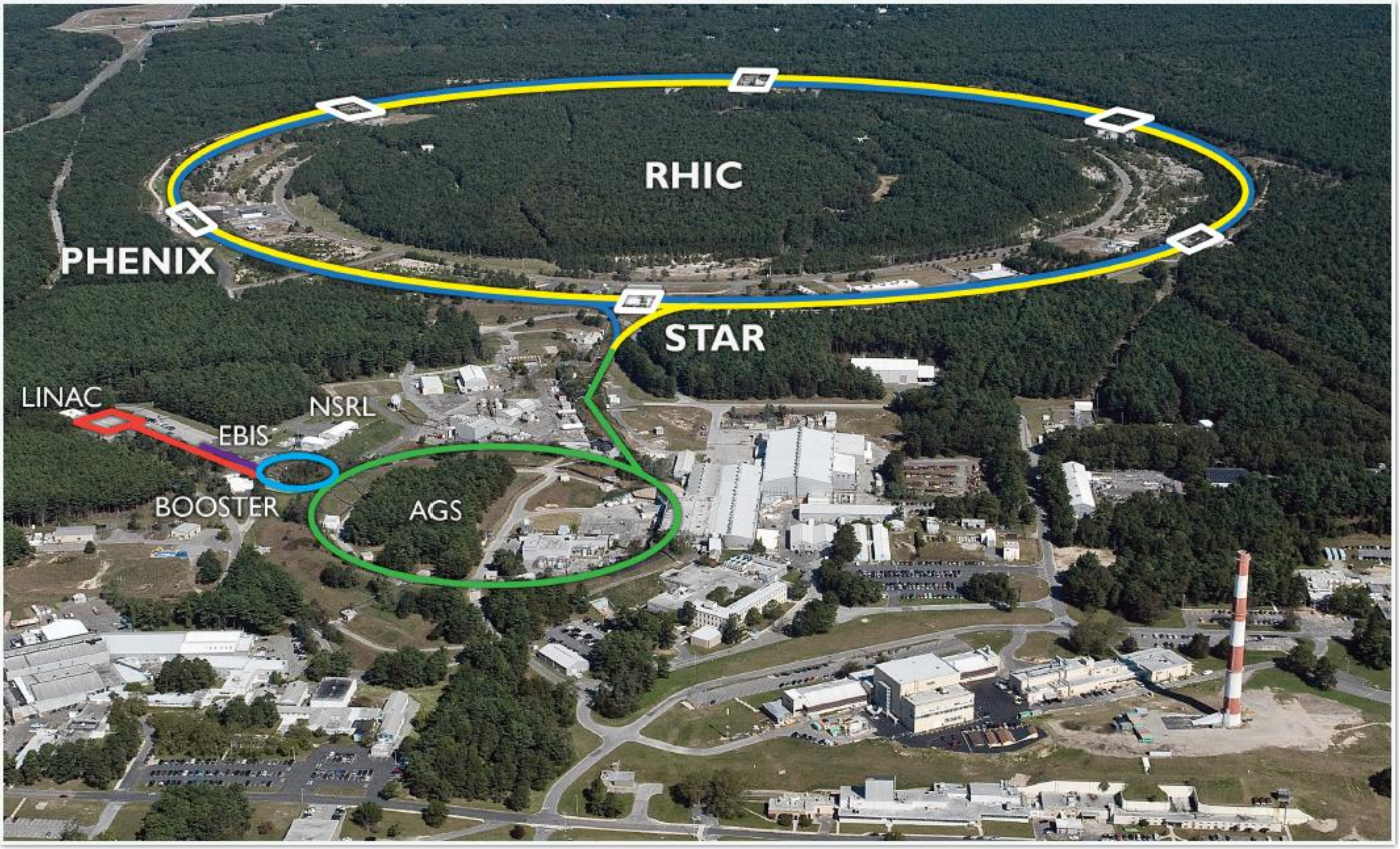


$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

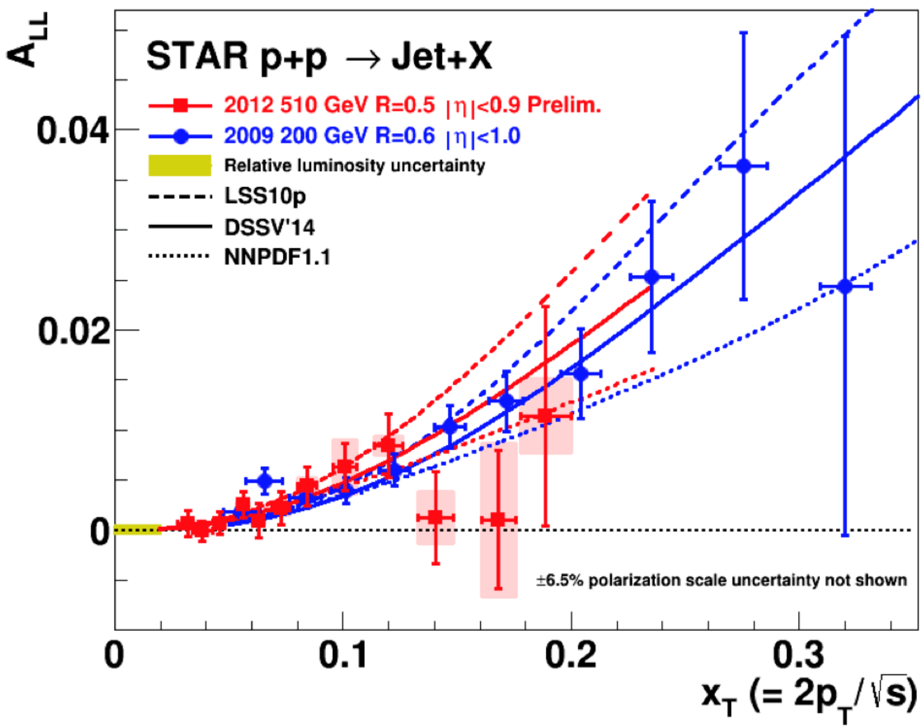
- Current fits to polarized DIS data give $\Delta\Sigma = 0.366^{+0.042}_{-0.062}$ for $10^{-3} < x < 1$
- Scaling violations of structure functions in polarized DIS gives information on gluon polarization but limited kinematic coverage leaves ΔG poorly constrained
- Want leading order access to gluons – polarized pp collisions at RHIC

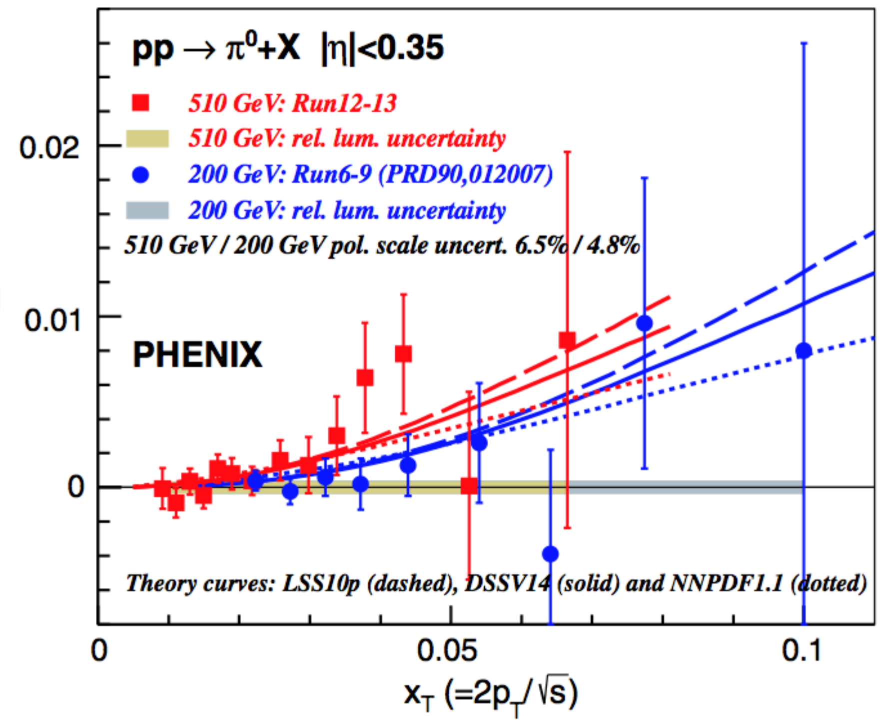
Kinematic reach of polarized DIS measurements

RHIC: First Polarized pp Collider



Accessing ΔG at RHIC: A_{LL}

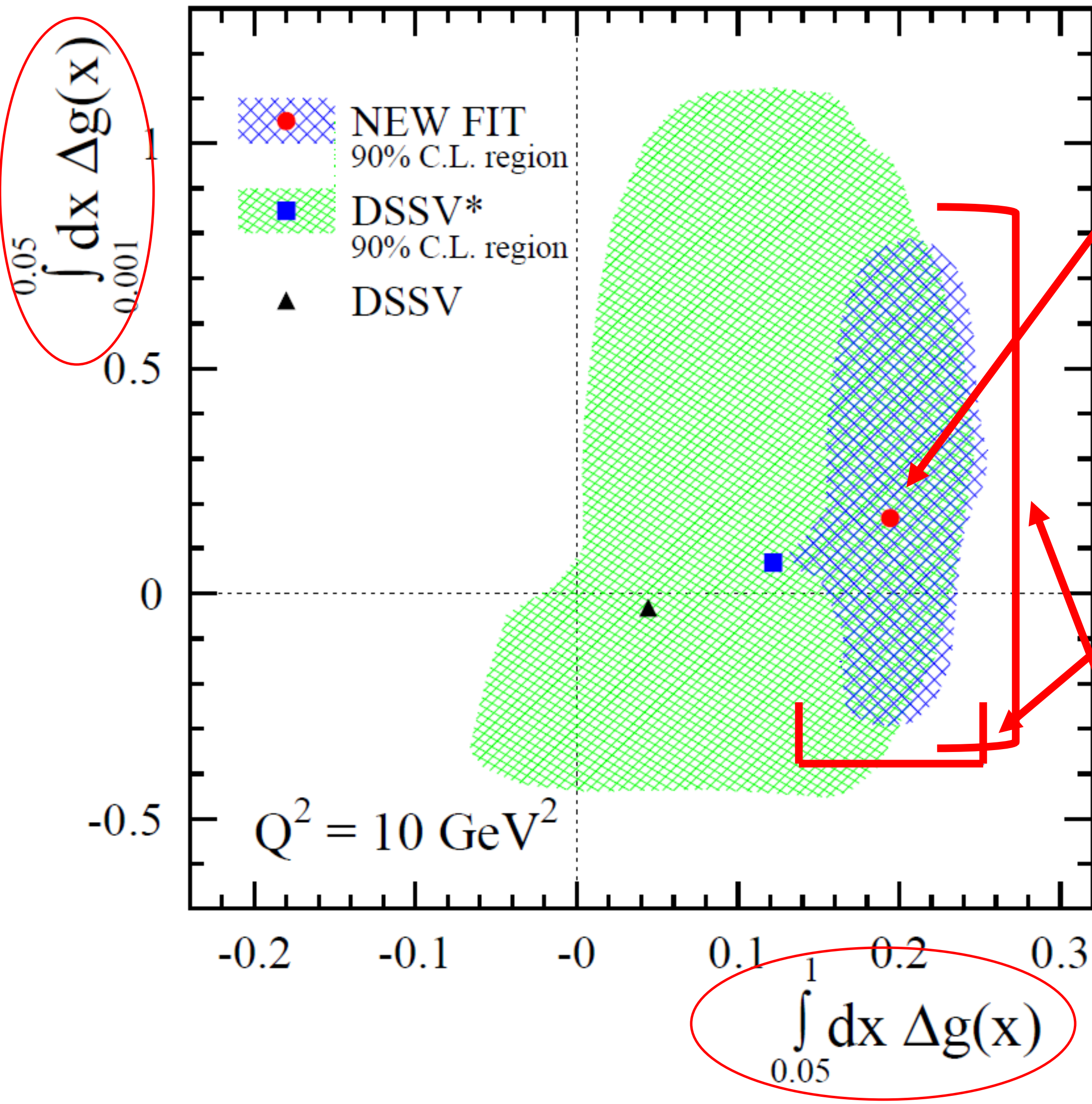




- In polarized pp collisions, access ΔG via the longitudinal double helicity asymmetry A_{LL} which is sensitive to the polarized gluon distribution at leading order

- STAR and PHENIX measure A_{LL} using inclusive jet and π^0 final states, respectively

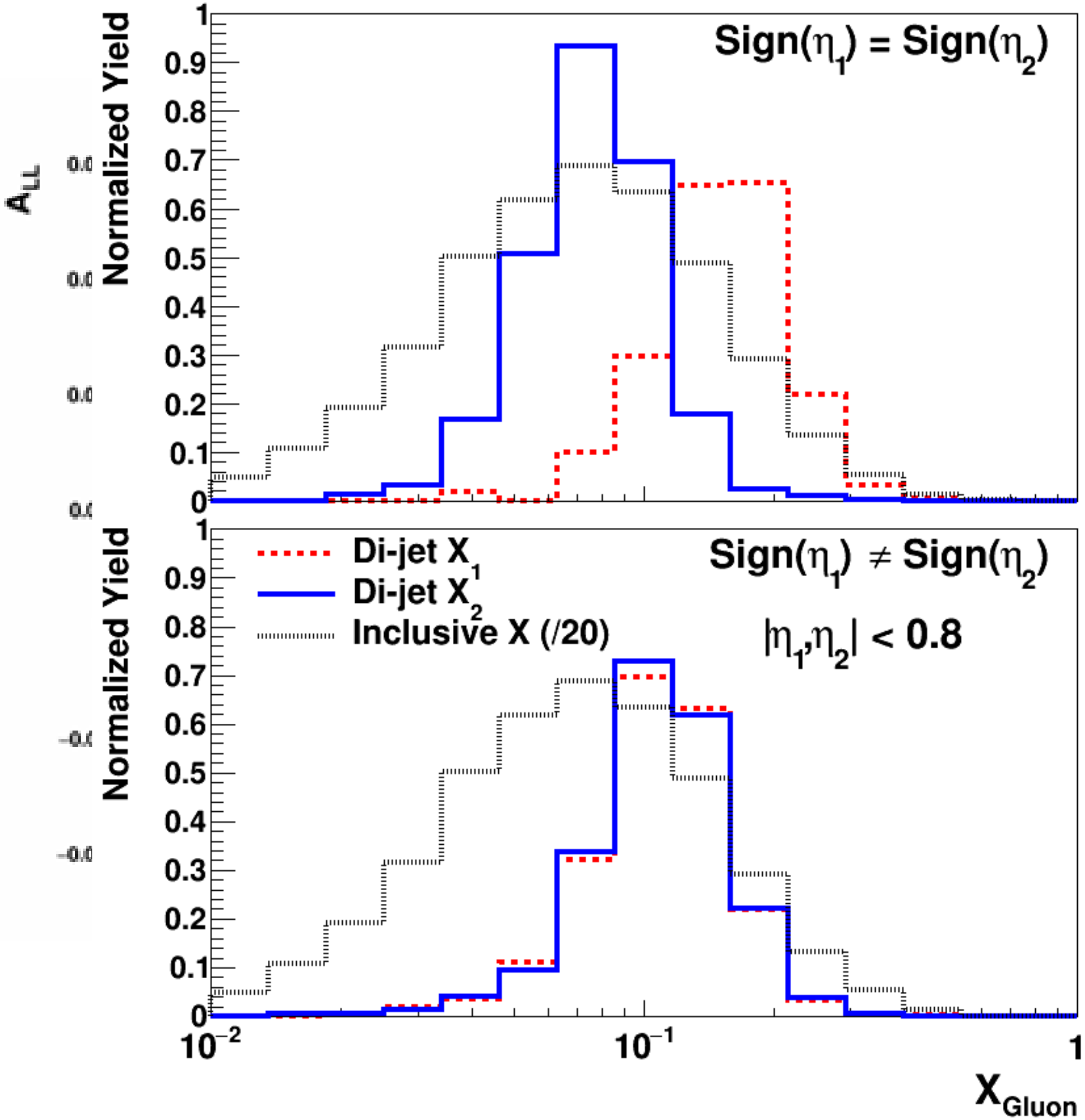
New DSSV Results



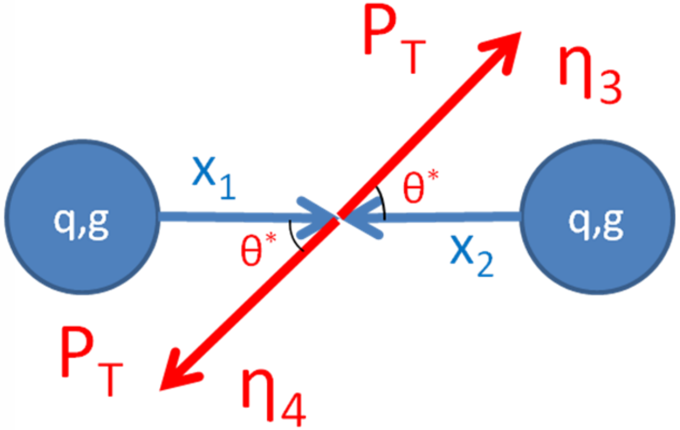
Phys. Rev. Lett. 113, 012001 (2014)

- Integral of Δg(x) in range 0.05 < x < 1.0 increases from roughly 0.05 to $0.20^{+0.06}_{-0.07}$. First indication of non-zero gluon polarization!
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable (only √s = 200 GeV RHIC data)

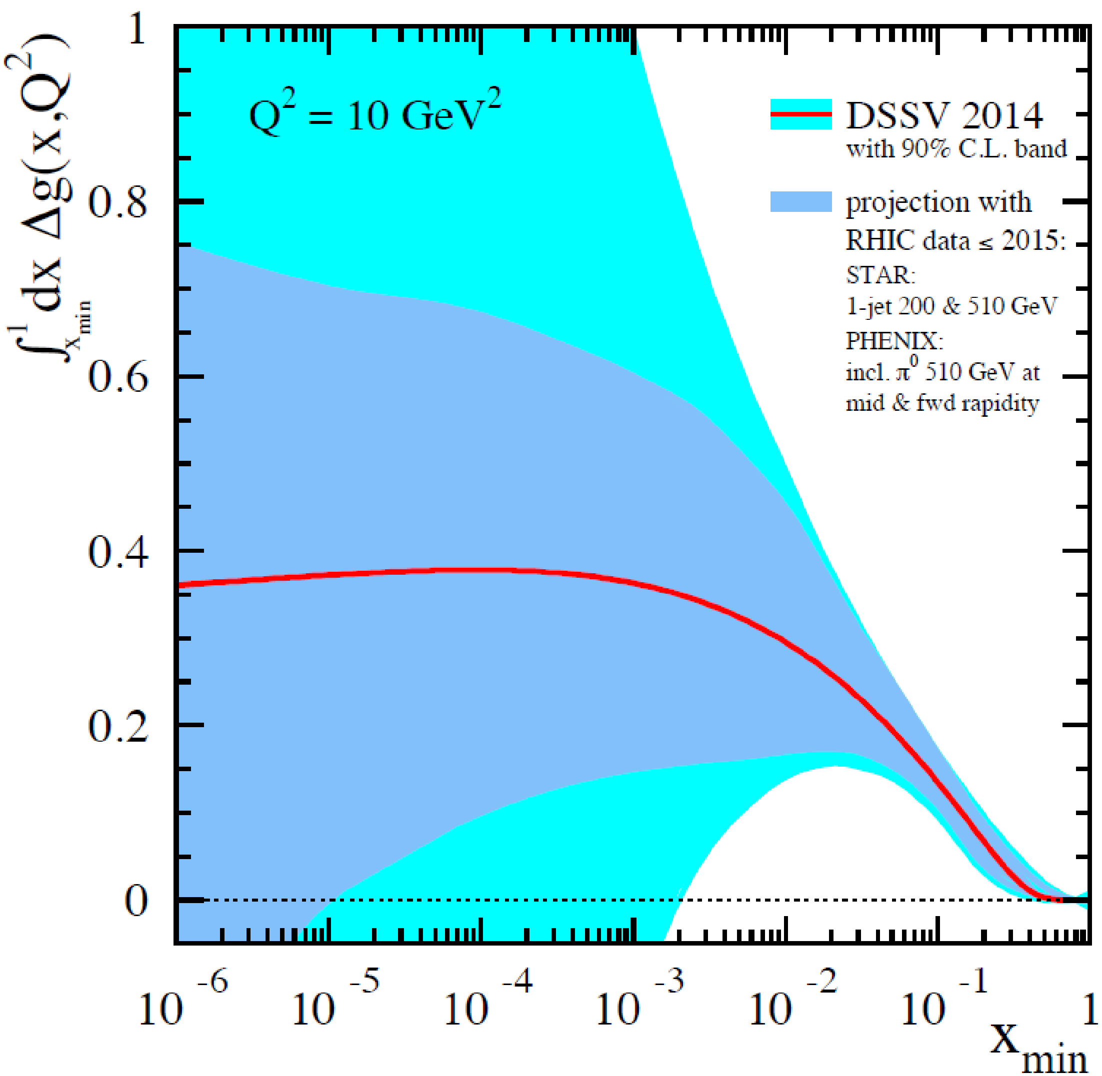
Di-jet A_{LL}



- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics

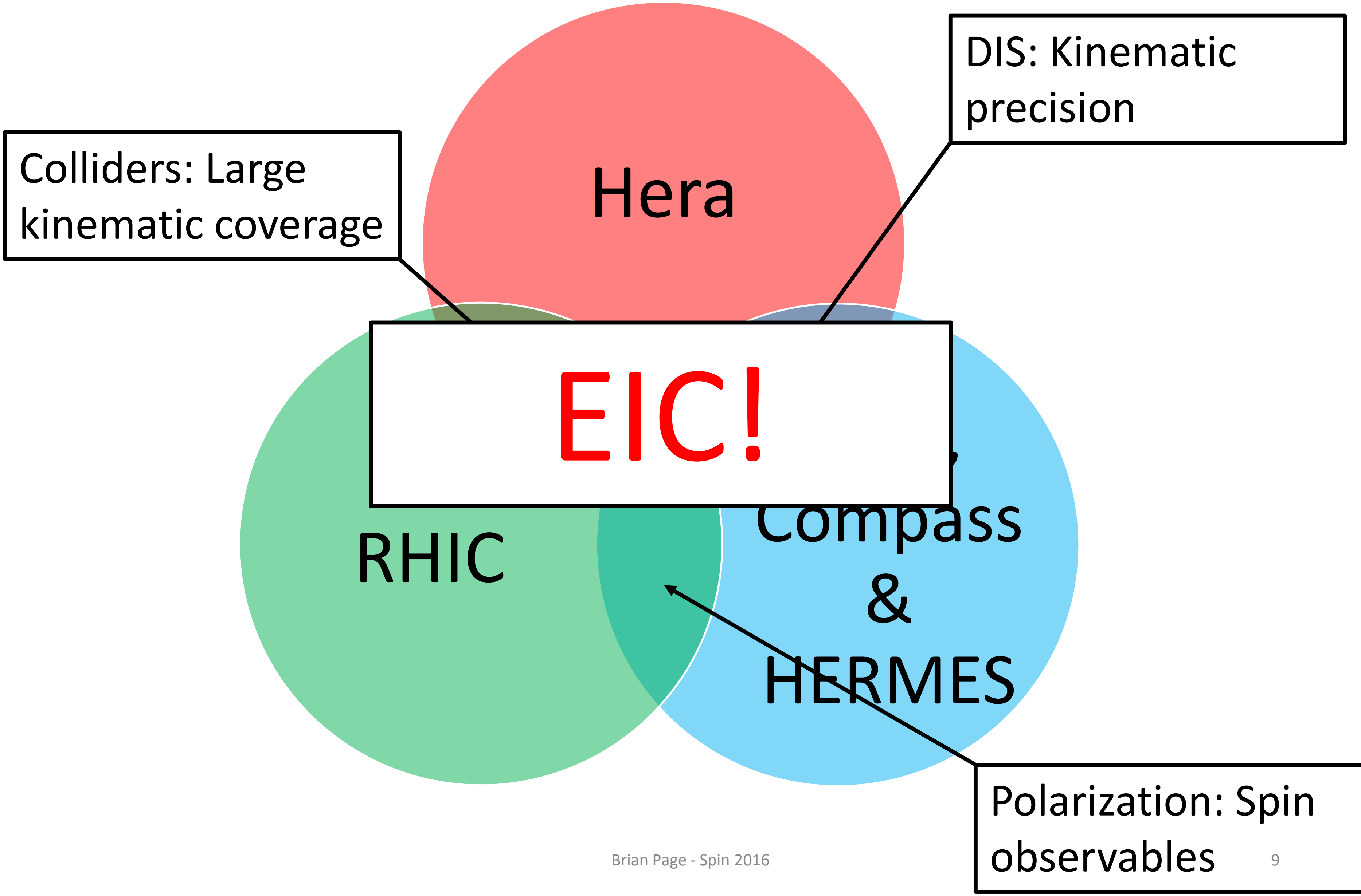


Where to from Here?

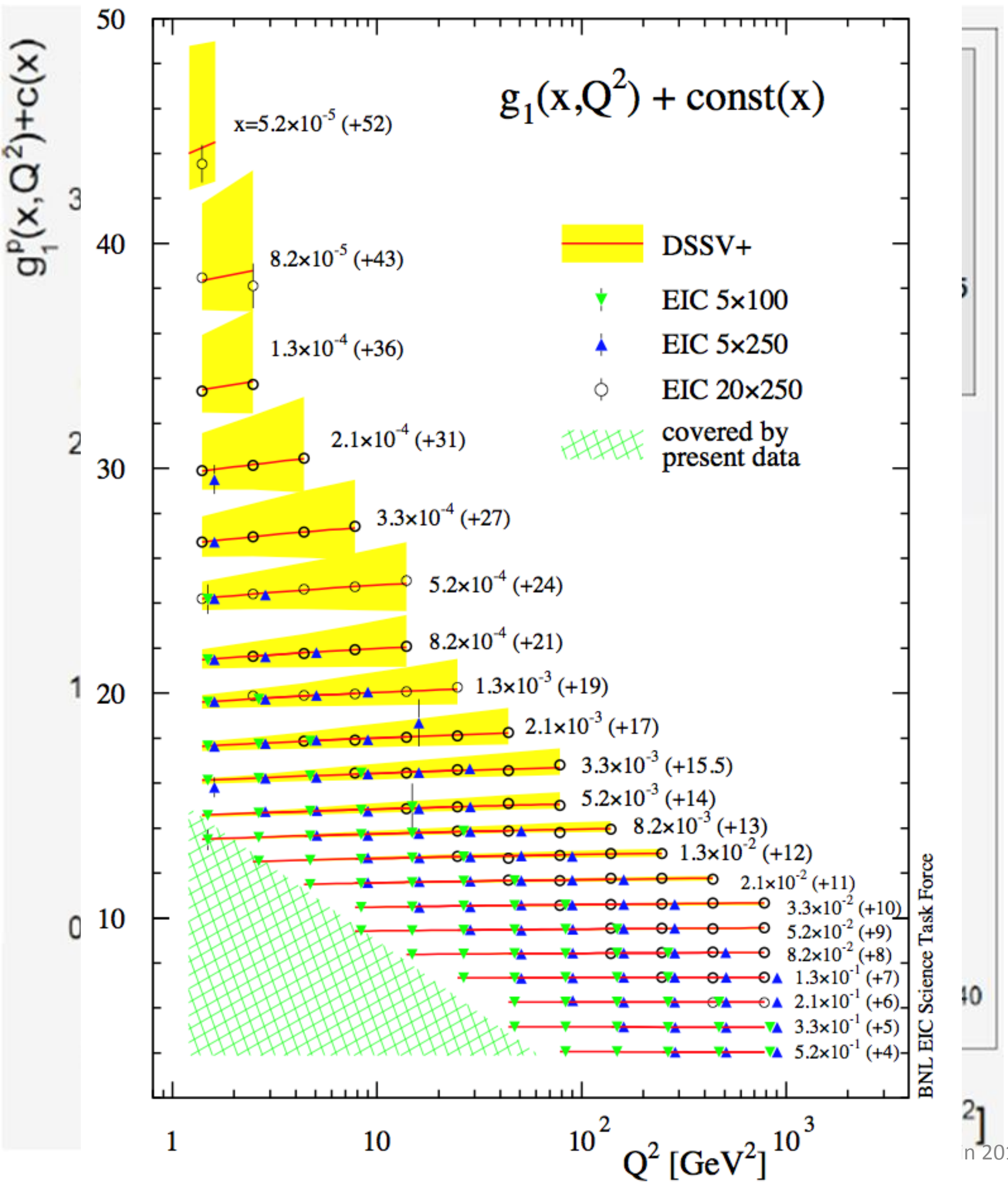


- Inclusive jet and π^0 data from RHIC have placed meaningful constraints on ΔG for 0.05 < x < 0.2
- Future results at √s = 500 GeV and forward rapidity will extend constraints to somewhat lower x and di-jet measurements will provide better constraints on the shape of ΔG
- Despite this, RHIC data will not be able to completely constrain the full integral of ΔG
- What is needed to pin down the gluon contribution to the proton spin?

EIC: Polarized ep Collider



EIC: Accessing ΔG Via g_1



arXiv:1206.6014

- Several observables are sensitive to ΔG in DIS but golden measurement at an EIC would be scaling violation of $g_1(x,Q^2)$

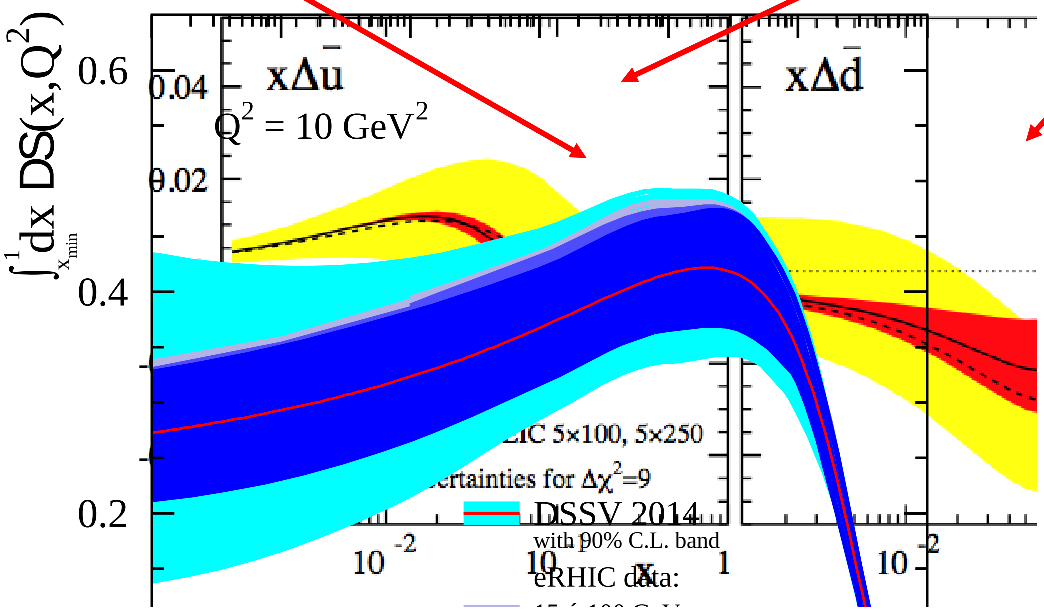
$$\frac{dg_1(x,Q^2)}{dln(Q^2)} \approx -\Delta g(x,Q^2)$$

- Current DIS constraints on ΔG hampered by limited x & Q^2 coverage

- EIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!

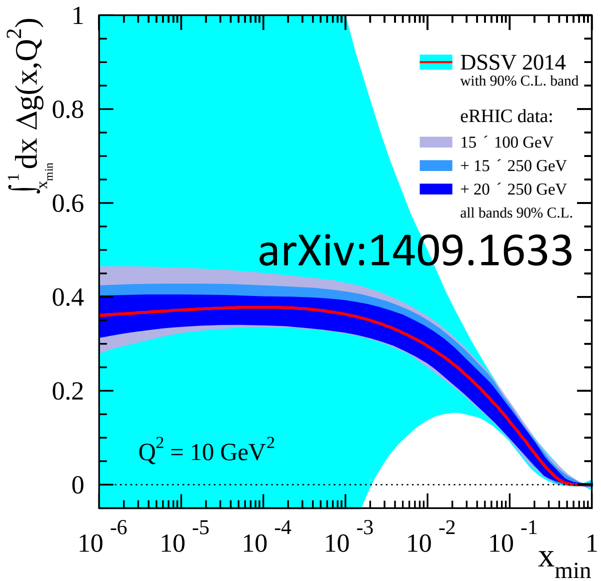
EIC: Impact on Quark Polarizations

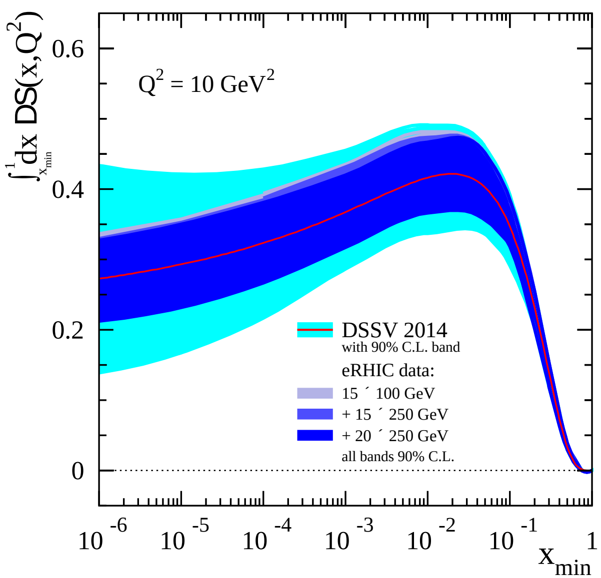
$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \cdots)dx$$

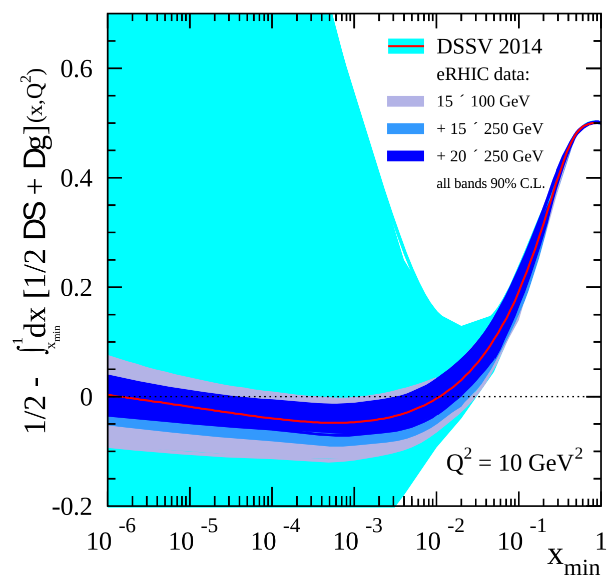


- g_1 is sensitive to the sum of all quark and anti-quark polarized PDFs meaning an EIC will place strong constraints on ΔΣ
- An EIC will also be able to constrain the individual quark and anti-quark polarized PDFs via semi-inclusive DIS (SIDIS) measurements
- The polarized anti-quark distributions
- Individual quark and anti-quark distributions can also be measured at an EIC via charged current DIS which access different combinations of PDFs
- The above plots show the expected reduction in uncertainty for the polarized anti-quark distributions from EIC SIDIS data

EIC: Solving the Spin Puzzle







1/2 - Gluon - Quarks = orbital angular momentum

- Above plot shows the running integral of $\Delta g(x,Q^2)$ from x_{min} to 1 as a function of x_{min}
- Large reduction in uncertainty on ΔG from EIC can be seen

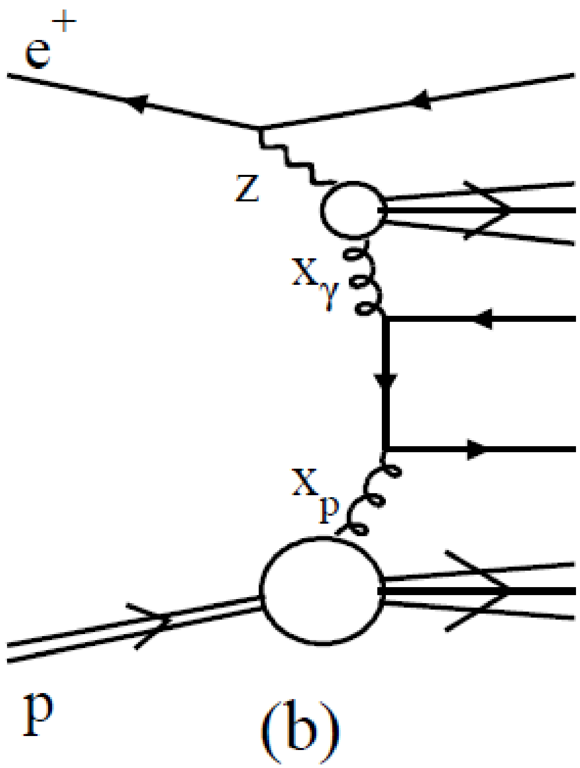
- EIC will also reduce the uncertainty on the quark contribution to the proton spin
- No assumptions about hyperon beta decay in EIC uncertainty

Constraints on gluon and quark contributions will provide information on the orbital angular momentum component of proton spin

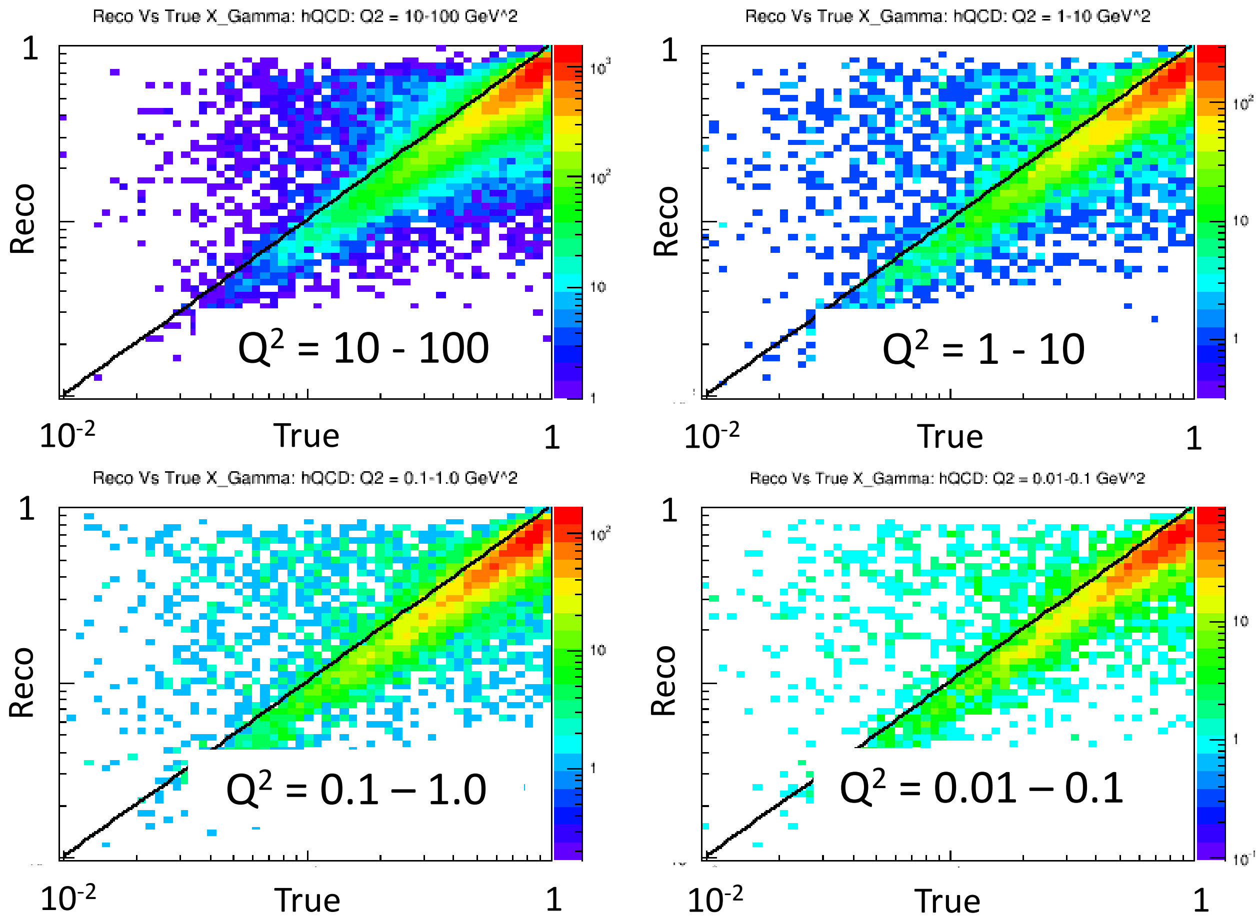
Gluon Polarization with Di-jets

- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process

Resolved



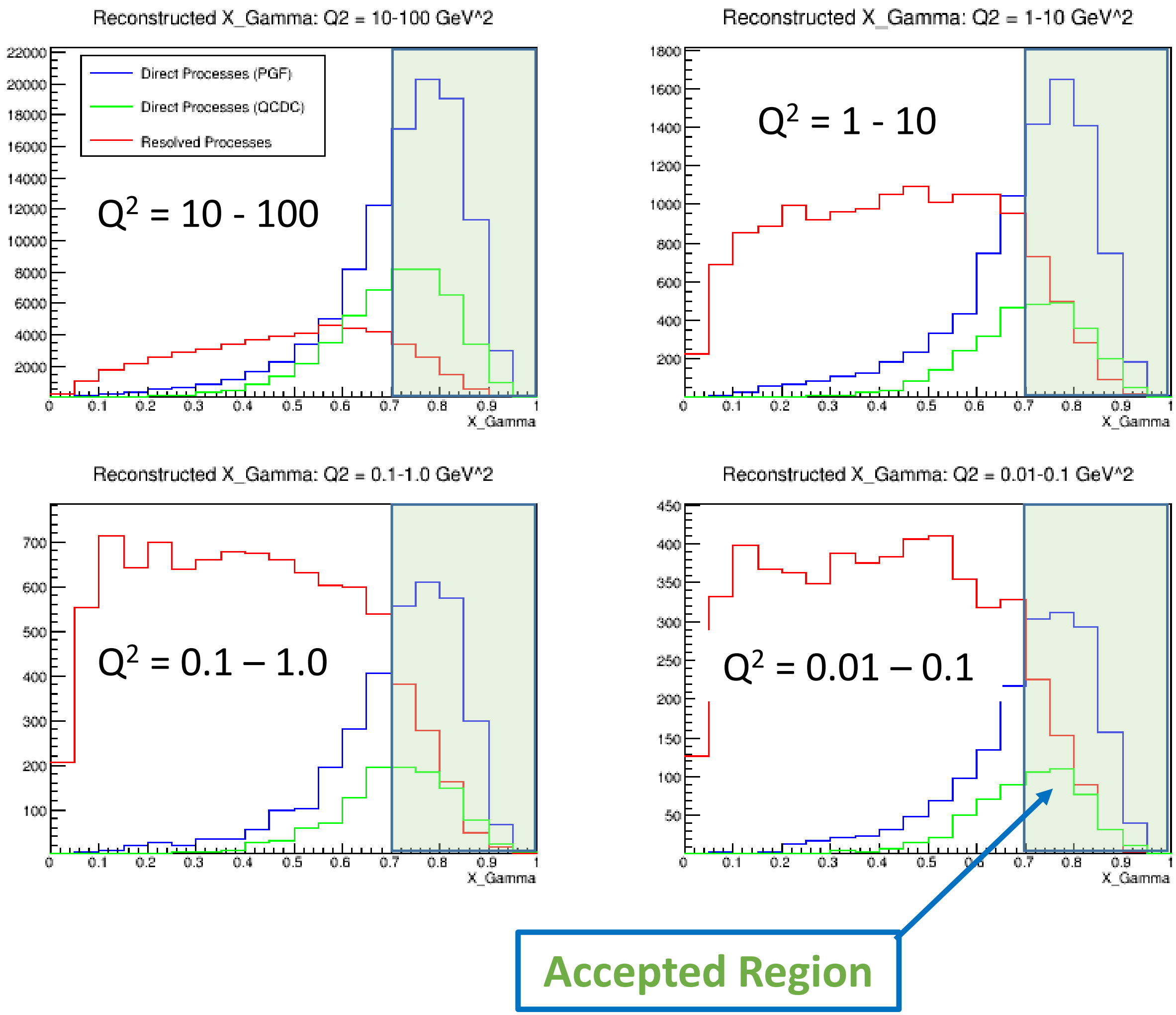
X_γ: Reconstructed Vs True



- Will use virtual photon momentum fraction to discriminate between resolved and direct processes
- See good agreement between reconstructed and true X_γ for all Q^2 ranges
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV

$$X_\gamma = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$

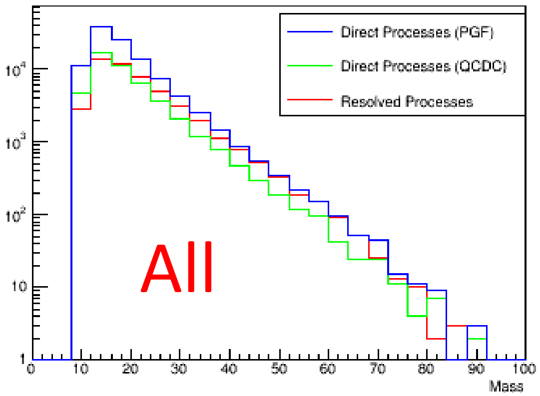
Direct Vs Resolved Processes



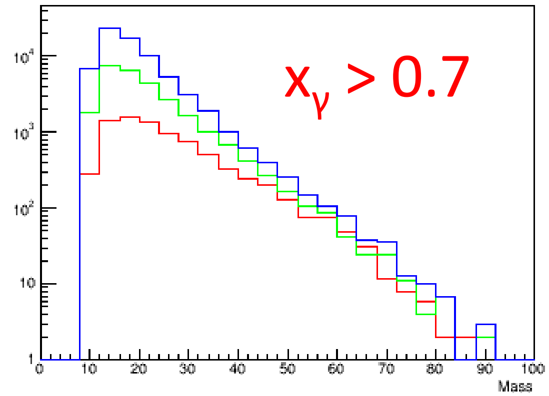
- Plot reconstructed X_γ for direct and resolved processes
- Direct processes should concentrate toward 1 while resolved processes are at lower values
- Direct processes dominate at higher Q^2 while resolved are more prevalent at low Q^2
- Cut of $X_\gamma > 0.7$ enhances the direct fraction at all Q^2

Di-jet Invariant Mass

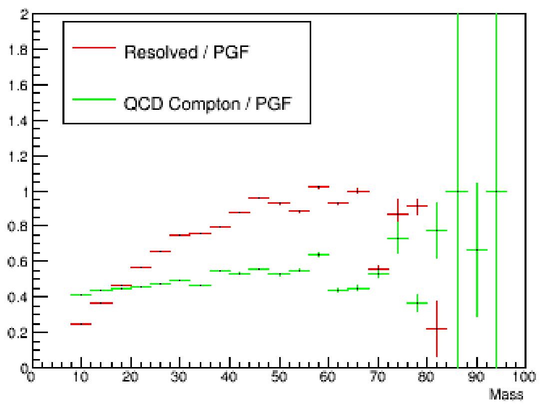
Di-jet Mass: Q^2 = 10-100



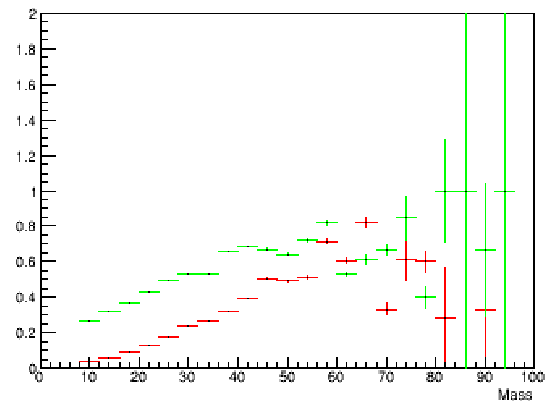
Di-jet Mass: Q^2 = 10-100



Subprocess Ratio Vs Mass: Q2 = 10-100



Subprocess Ratio Vs Mass (X_Gamma > 0.7): Q2 = 10-100



- See that the cut on X_γ significantly reduces the resolved contribution while maintaining the direct events
- Separation between resolved and direct is most prominent at high Q^2 and low di-jet invariant mass

Proton Partonic Kinematics

$$X_P = x_B\left(1 + \frac{M^2}{Q^2}\right)$$

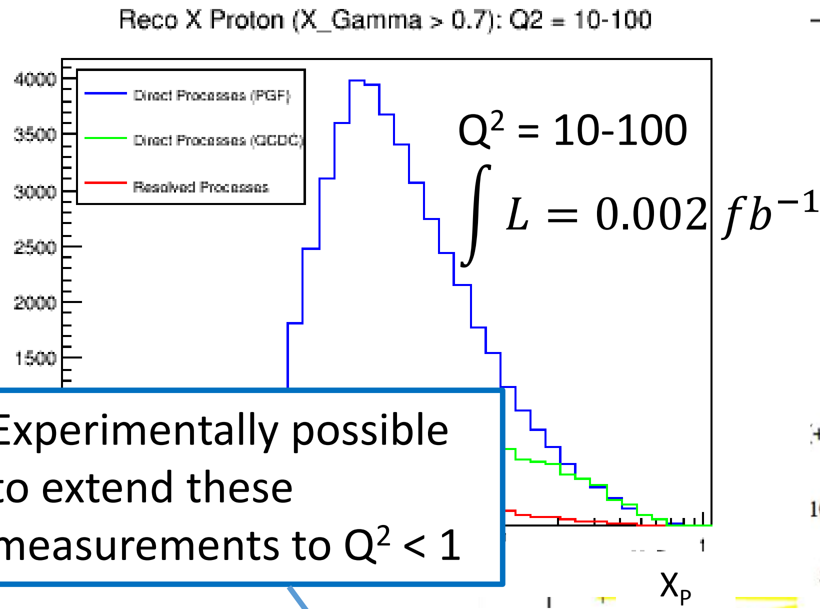
$$Q^2 = syx_B$$

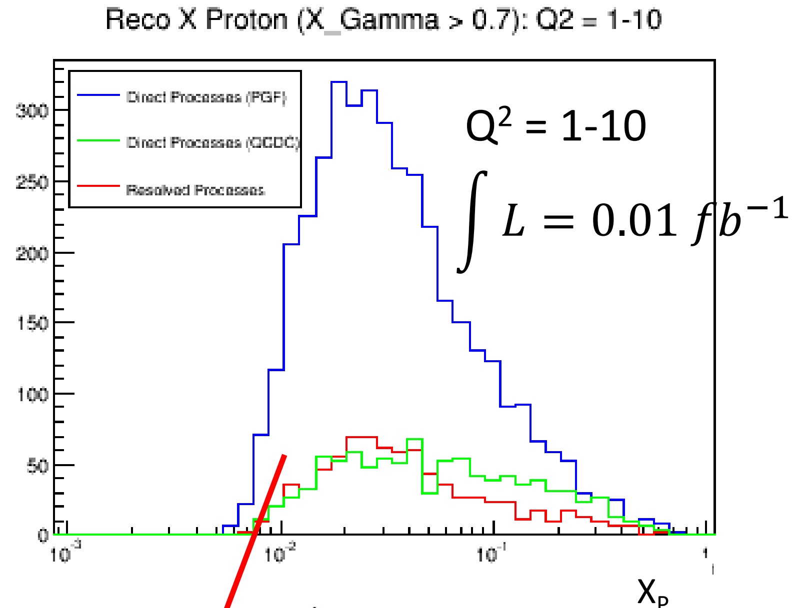
$$X_P = x_B + \frac{M^2}{sy}$$

$$\approx \frac{100}{(20000\ x\ 0.95)} \approx 0.005$$

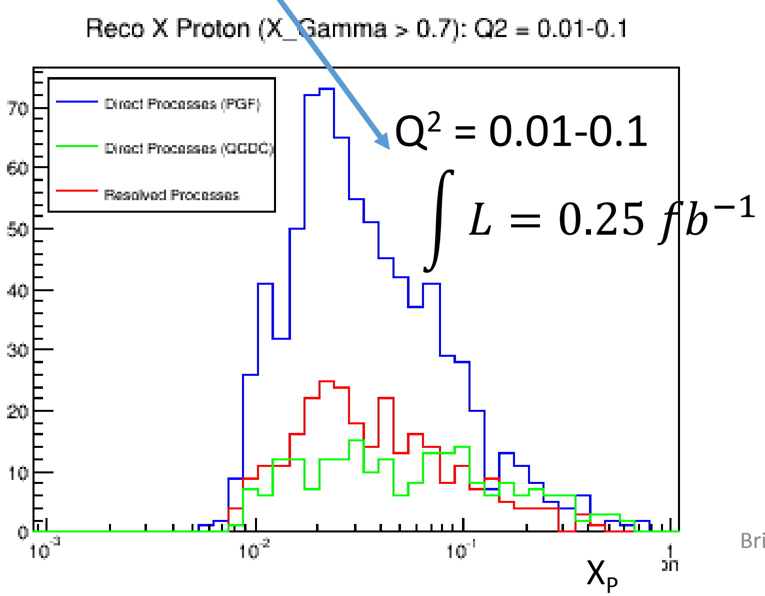
- To measure ΔG, need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed

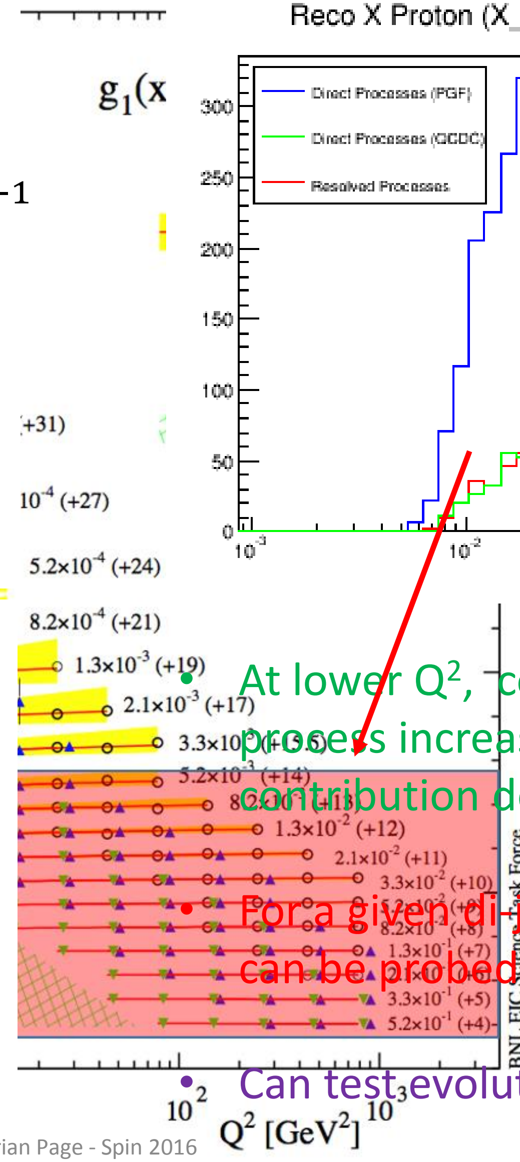
X_P For Different Q^2





Experimentally possible to extend these measurements to $Q^2 < 1$





- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases
- For a given di-jet mass range, same X_P can be probed over large range of Q^2
- Can test evolution of ΔG

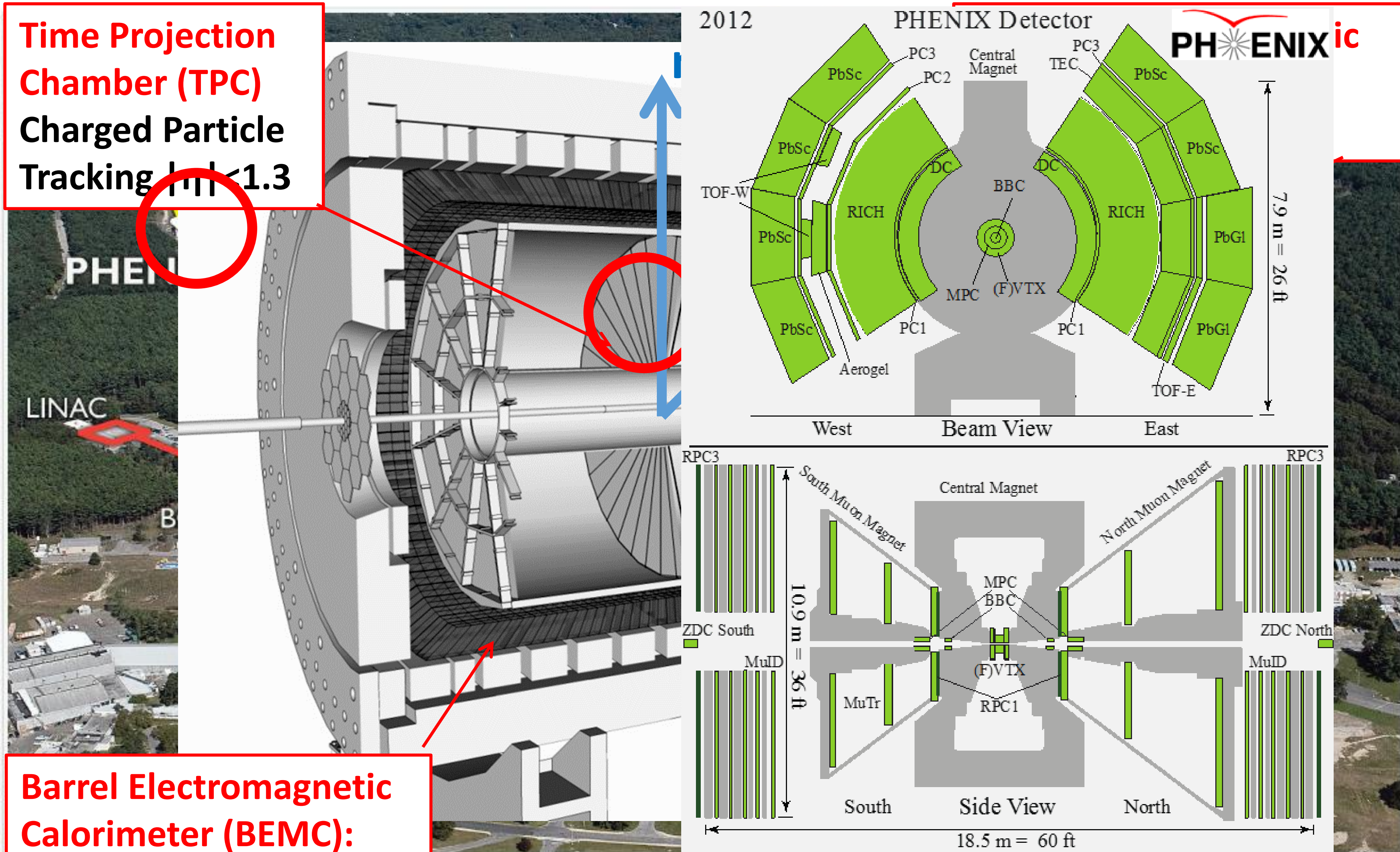
Summary

- Early fixed target data showed that the proton's spin cannot be carried by quark helicity alone but could not constrain the gluon contribution
- Jet and Pion asymmetries from polarized pp collisions at RHIC have placed strong constraints on ΔG for Bjorken-x > 0.05, but will not have the kinematic reach to fully determine the gluon contribution to the proton spin
- A high energy/luminosity polarized ep collider will have the kinematic reach and precision to pin down the gluon polarization via scaling violations of the g_1 structure function
- An EIC will also constrain both the total quark helicity contribution $\Delta\Sigma$ and the individual polarized quark and anti-quark PDFs
- NLO access to ΔG will be possible via the photon-gluon fusion process and will provide a systematic check on the g_1 results while allowing the study of the evolution of ΔG over a wide Q^2 range

Backup

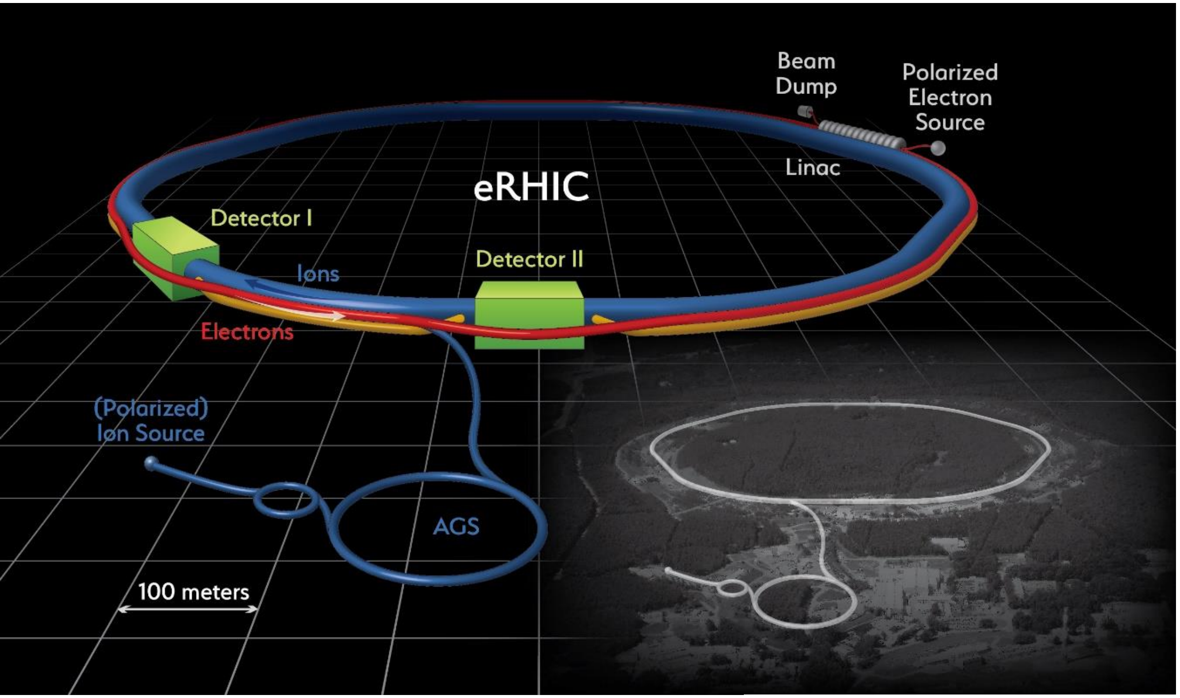
RHIC: First Polarized pp Collider

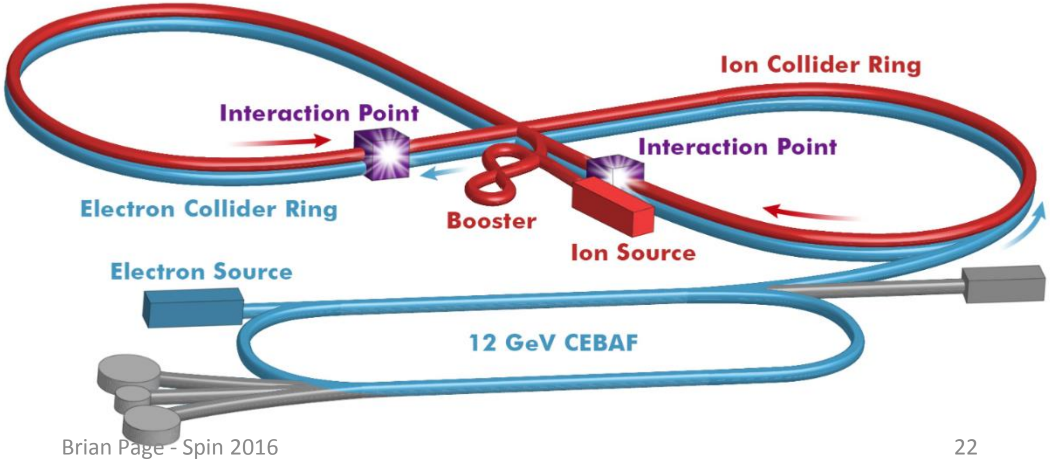
Time Projection Chamber (TPC)
Charged Particle Tracking |η|<1.3



Barrel Electromagnetic Calorimeter (BEMC):
|η|<1

EIC: eRHIC or JLEIC

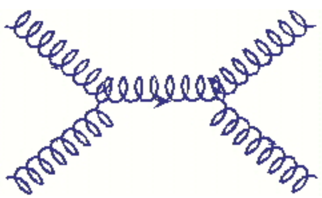




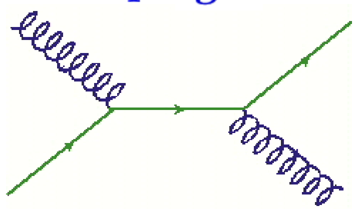
Accessing ΔG at RHIC: A_{LL}

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes D_{f_c}^{h}}$$

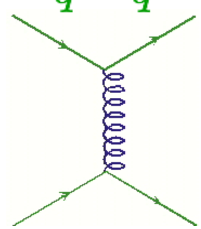
$\frac{\Delta g}{g} \frac{\Delta g}{g}$



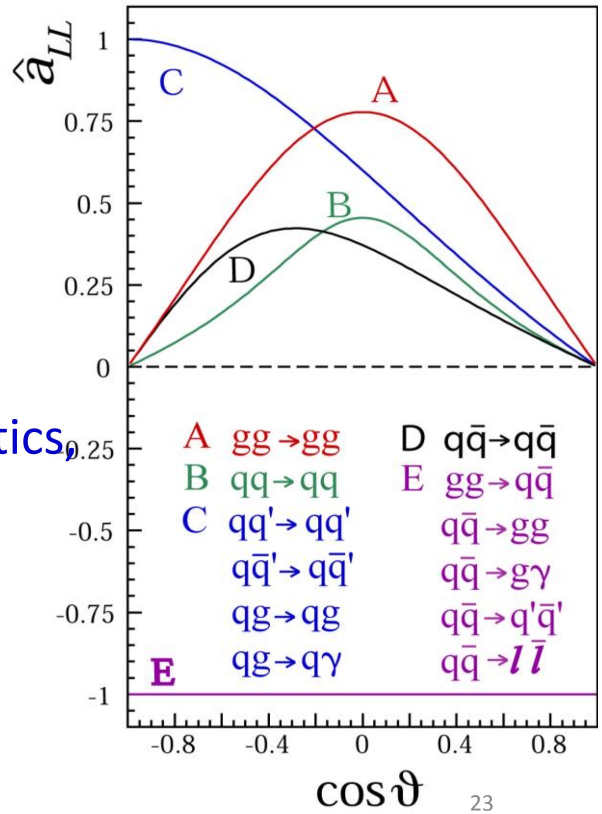
$\frac{\Delta q}{q} \frac{\Delta g}{g}$



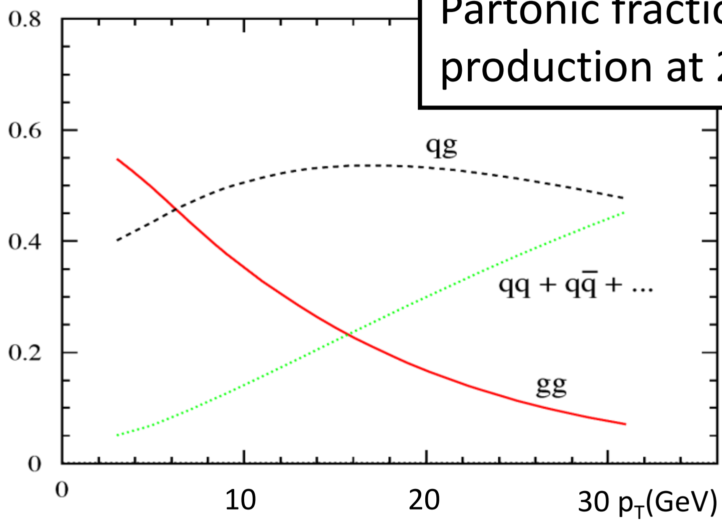
$\frac{\Delta q}{q} \frac{\Delta q}{q}$



Parton Level Asymmetry

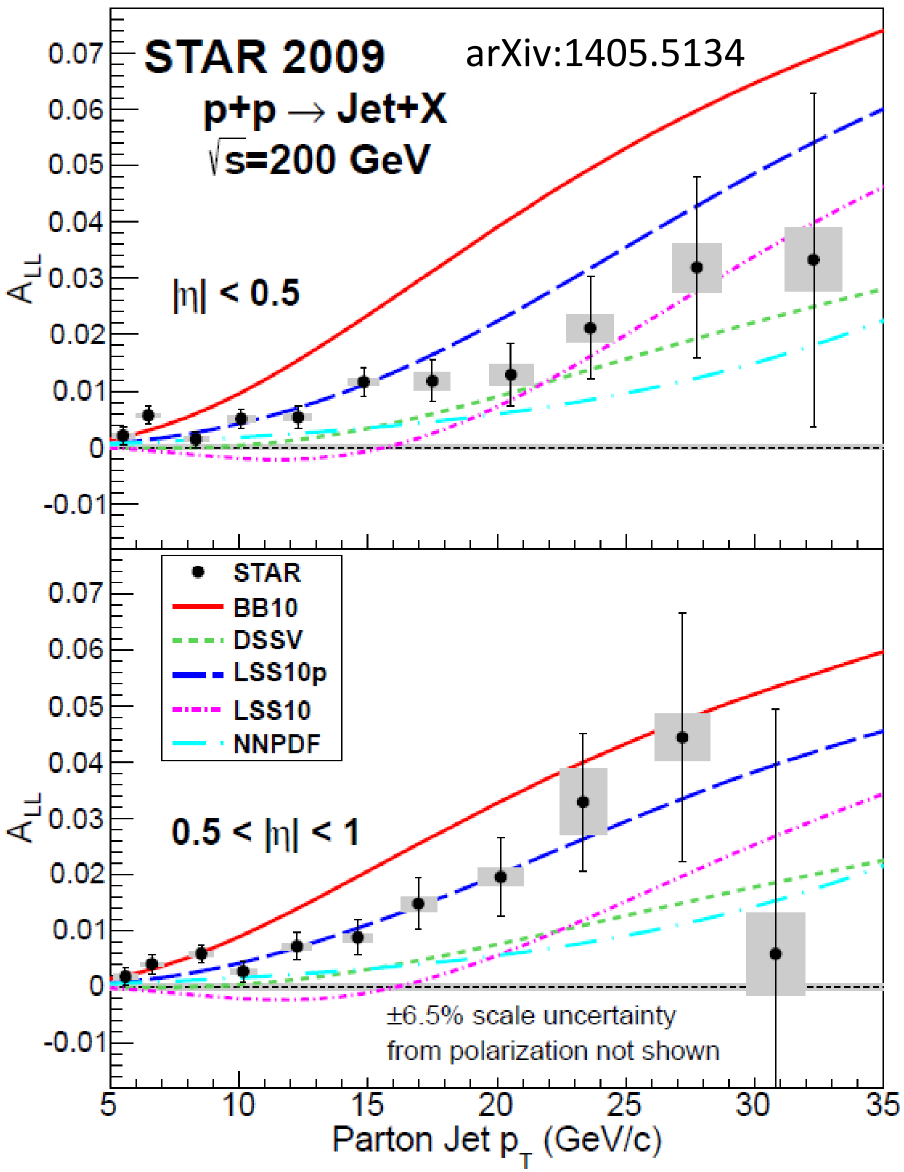


Partonic fractions in jet production at 200 GeV



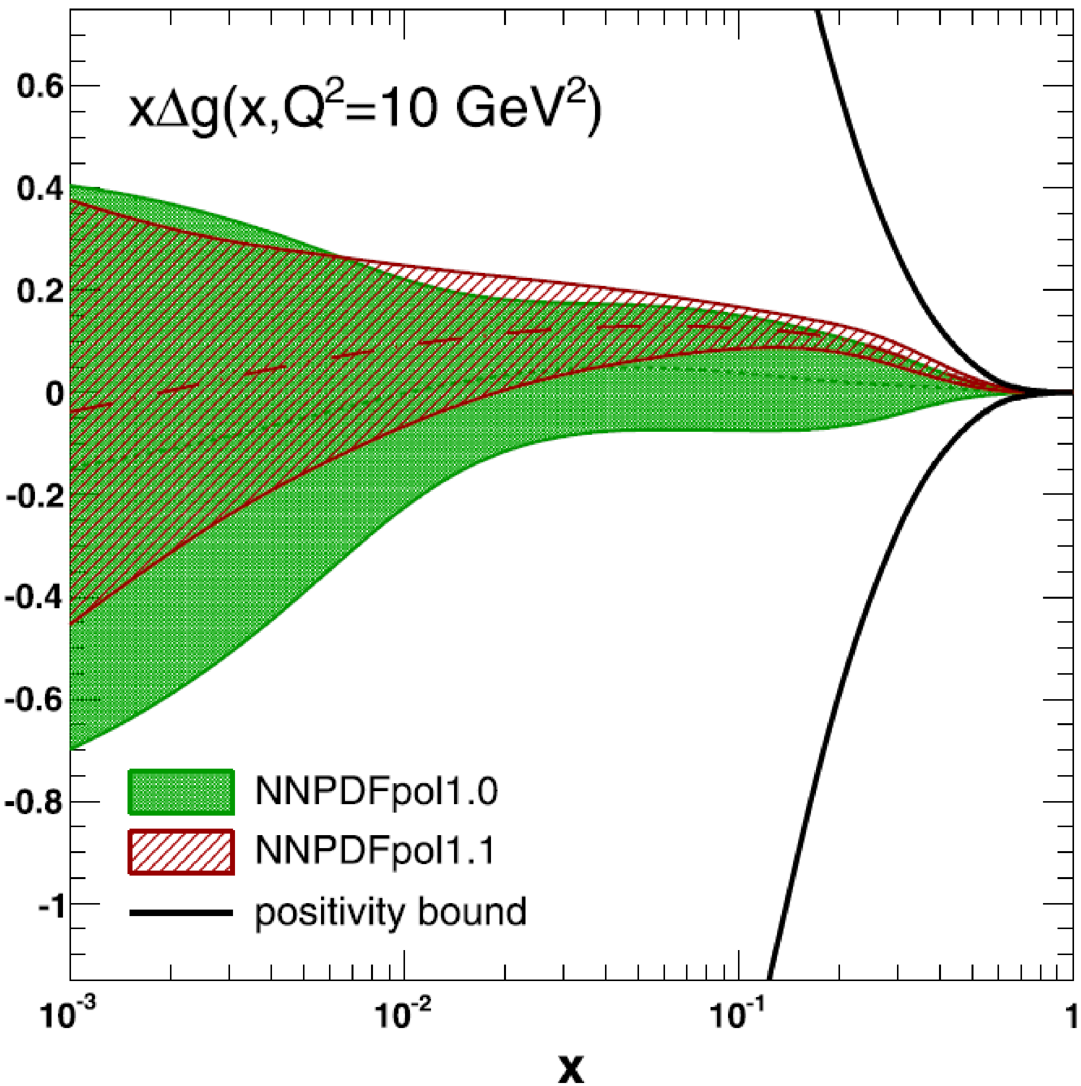
For most RHIC kinematics, **gg** and **qg** dominate, making A_{LL} for jets and hadrons sensitive to **gluon polarization.**

STAR 2009 Inclusive Jet A_{LL}



- 2009 results have factor of 3 to 4 better statistical precision than 2006 results
- Result divided into two pseudorapidity ranges which emphasize different partonic kinematics
- Result lies consistently above the 2008 DSSV fit and is consistent with the LSS10p fit

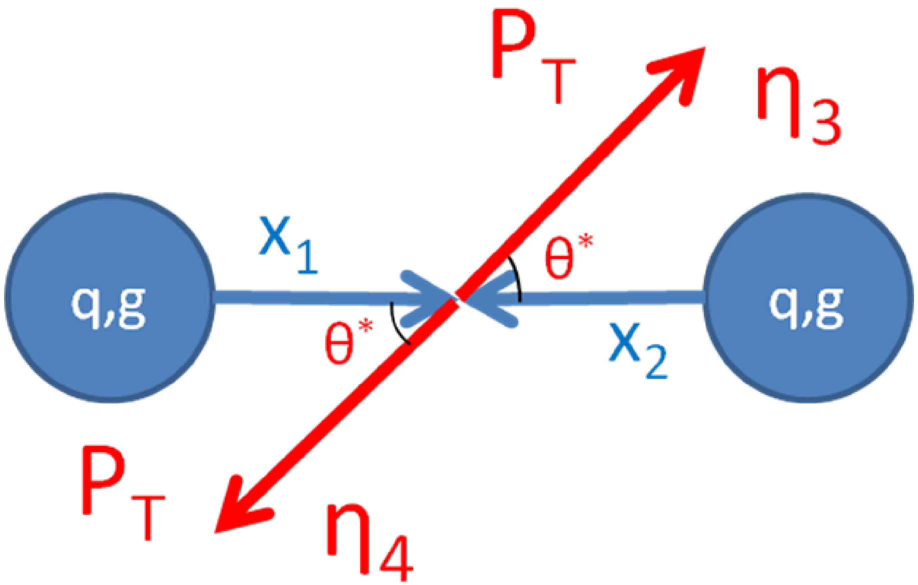
New NNPDF Results



Nucl. Phys. B 887, 276 (2014)

- Original NNPDF $\Delta g(x,Q^2)$ extraction (DIS data only) in green and new extraction including RHIC data in red
- Integral of $\Delta g(x,Q^2)$ for $0.05 < x < 0.2$ increases from 0.05 ± 0.15 to 0.17 ± 0.06
- Integral of $\Delta g(x,Q^2)$ for $x > 0.05$ is 0.23 ± 0.06 and is in agreement with new DSSV result of $0.20^{+0.06}_{-0.07}$ over the same x range

Beyond Inclusive: Di-jet Measurements



$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

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

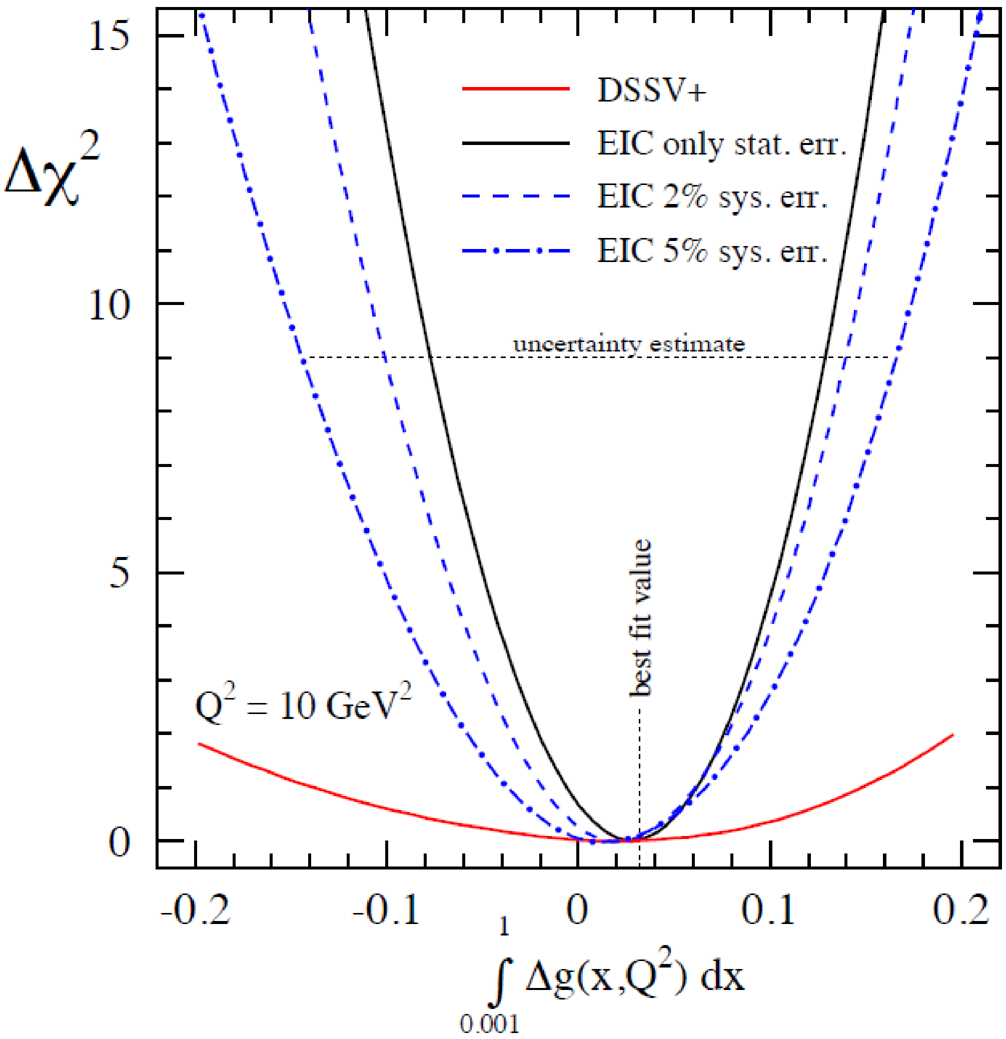
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

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

- Coincidence measurements capture more information about the partonic hard-scattering and provide a more direct link to the initial kinematics than inclusive probes

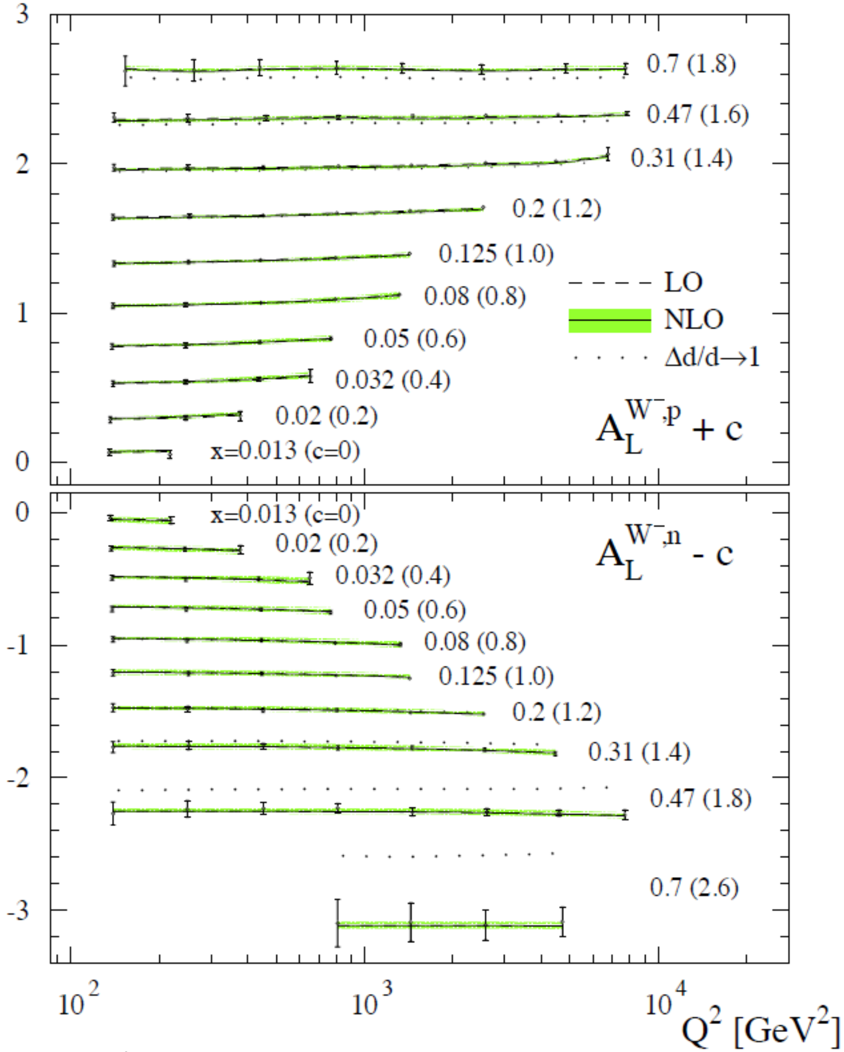
- Leading order expressions show how different jet configurations are sensitive to different kinematic values

Importance of Systematic Control

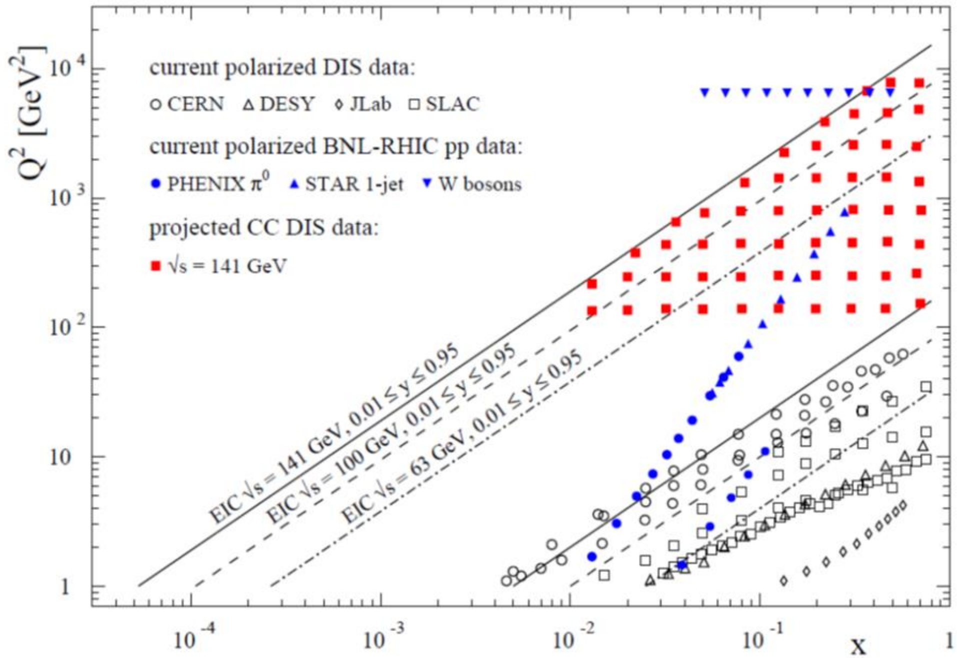


- The excellent statistical precision achievable with an EIC means control of systematics will be critical
- Above plot shows how the constraint on ΔG is affected by systematic uncertainty

EIC: Probing the Sea

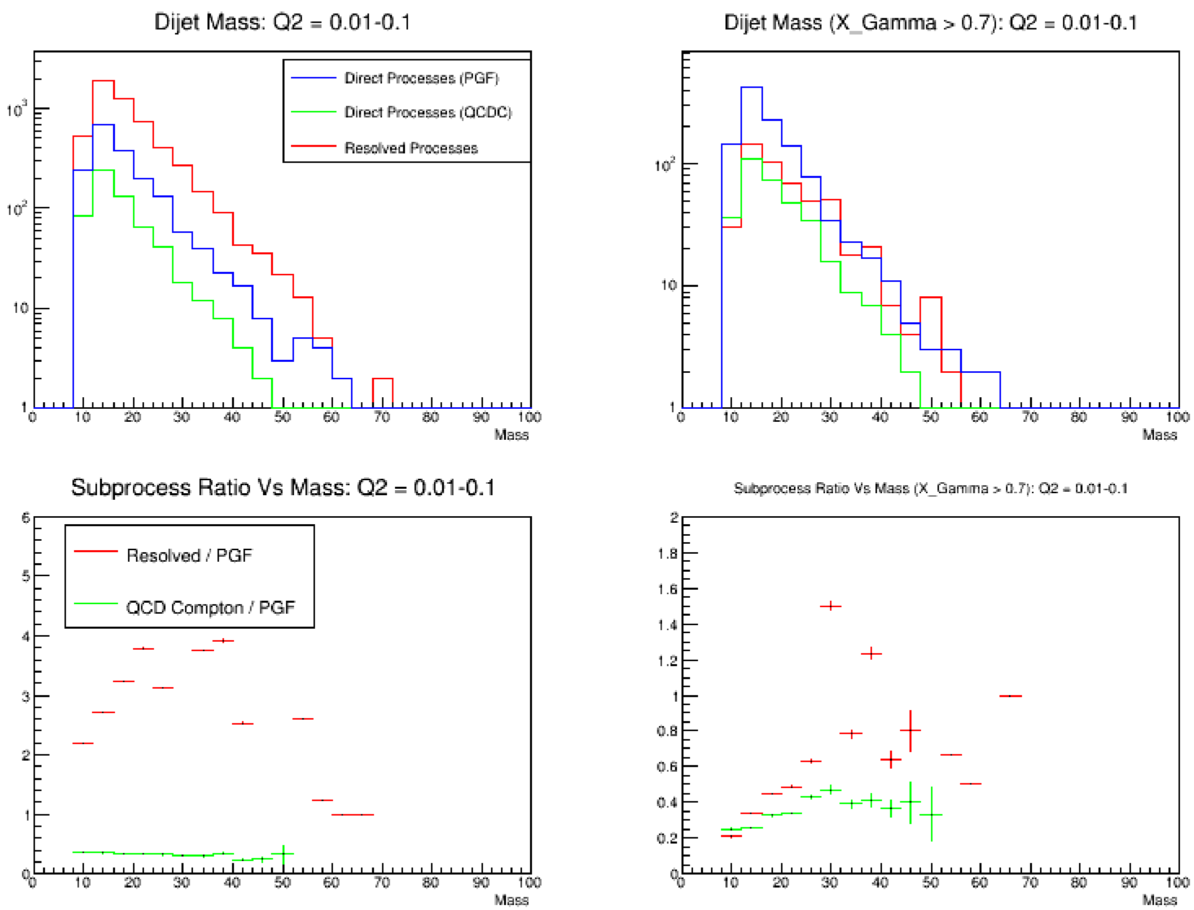


arXiv:1409.1633



- DIS largely 1-photon exchange, but can also proceed via charged current (CC) interaction mediated by W boson
- CC interactions in polarized DIS give access to quark / antiquark helicity distributions as well as unique structure functions
- Because W is virtual, can access lower values of Q^2 to overlap with and provide cross check to SIDIS measurements

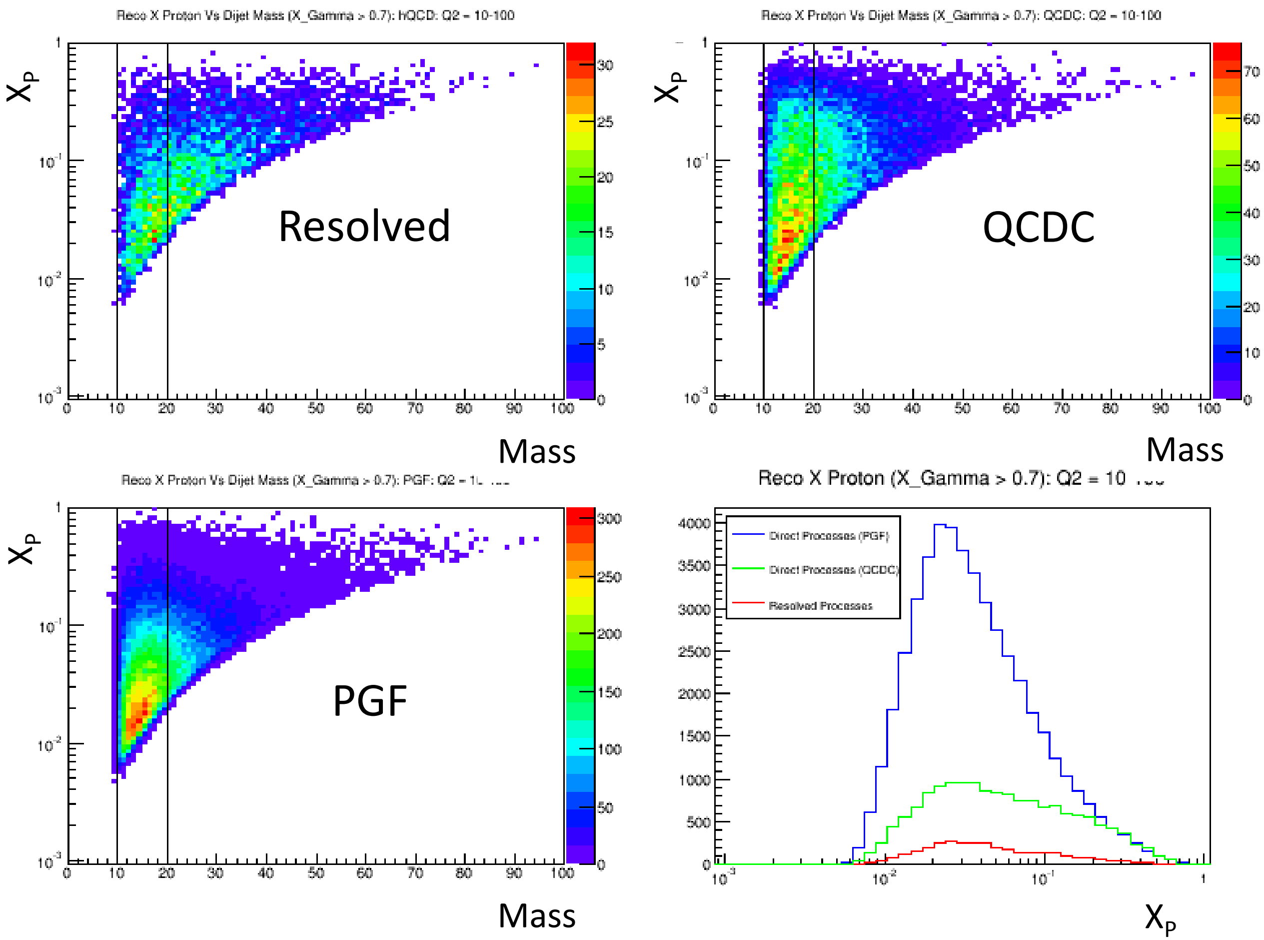
Di-jet Invariant Mass



- See that the cut on X_γ significantly reduces the resolved contribution while maintaining the direct events
- Separation between resolved and direct is most prominent at high Q^2 and low di-jet invariant mass

X_P Vs Mass

$Q^2 = 10 – 100\ GeV/c^2$



- As shown on the previous slide, accessible X_P range is determined largely by beam energy
- Different di-jet mass ranges select different process fractions with lower masses containing less resolved contribution
- Selection of high mass events also cut out low X_P contribution