Exploring the Proton Spin with Di-jets at a Future EIC

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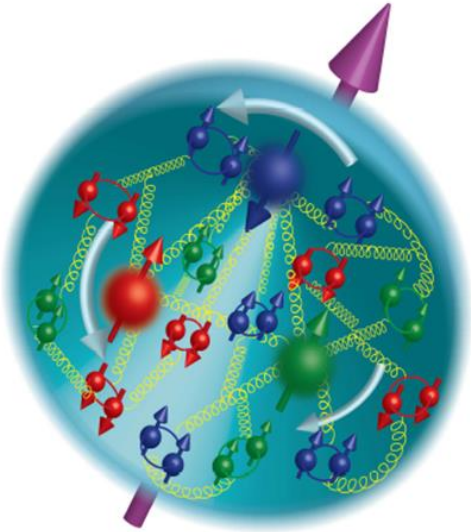
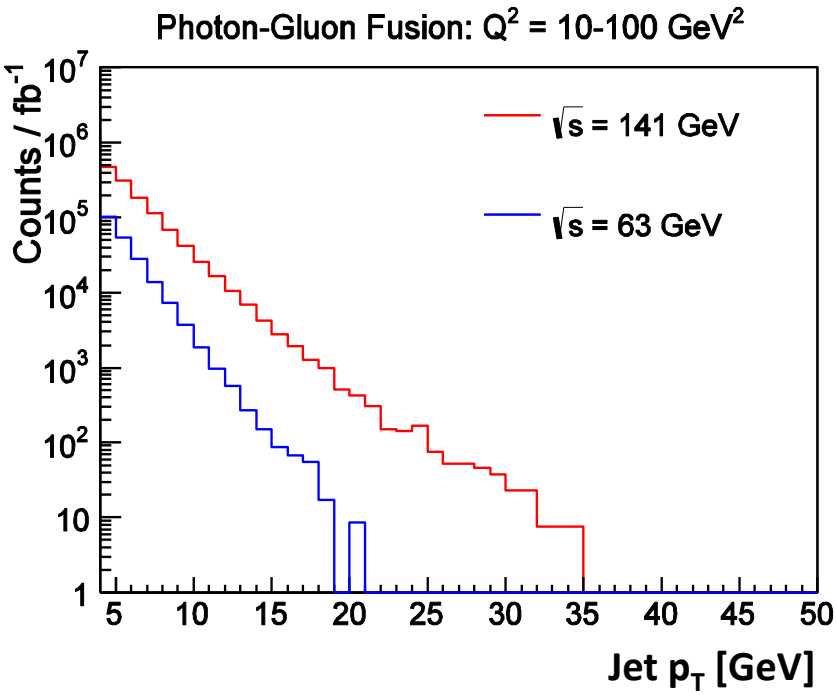
DIS 2017 - Birmingham



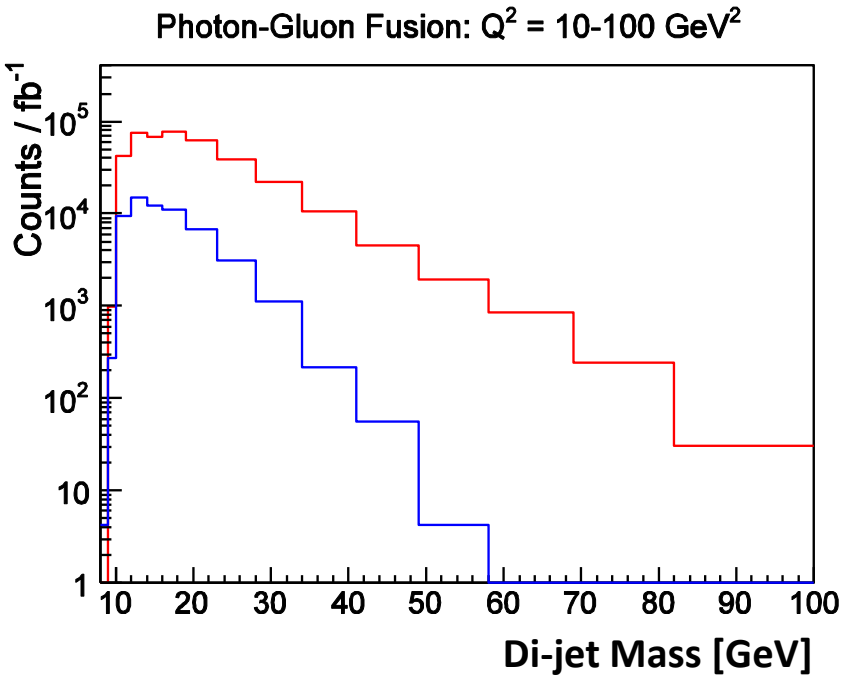
Simulation Details / Particle Cuts

- Electron – Proton events generated using PYTHIA
- Cut on inelasticity: $0.01 \leq y \leq 0.95$
- Jet Algorithm: Anti_k_T ($R = 1.0$)
- Jets found in Breit frame
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered electron

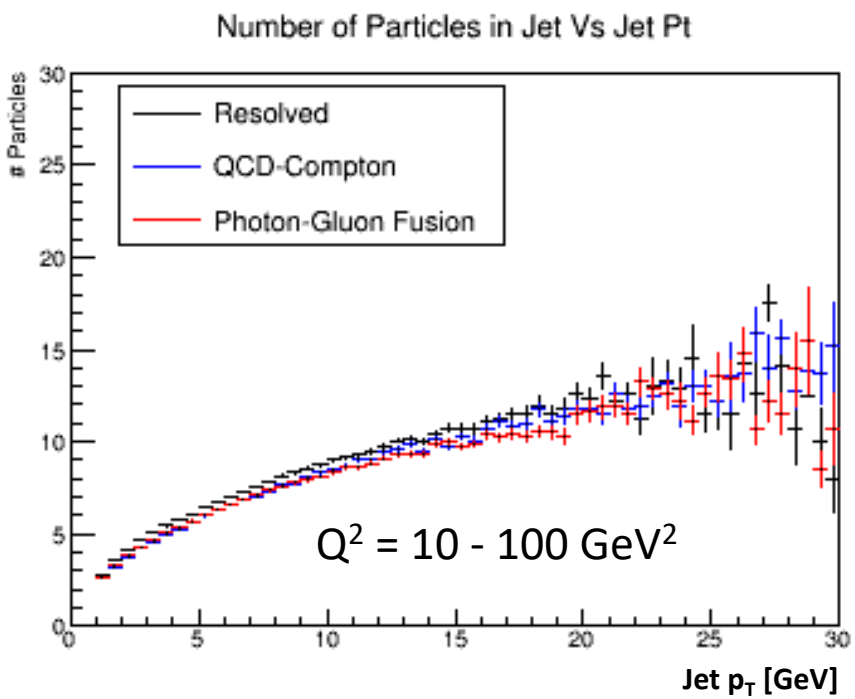
Jets at an EIC: Points to Remember



- Lower center of mass energies will lead to lower jet / di-jet yields and more limited p_T / mass reach
- Will need largest available energies and high luminosity to accumulate reasonable statistics at high p_T / mass – use √s = 141 GeV for all that follows



Jets at an EIC: Points to Remember



- Jets contain relatively few particles overall
- Events are quite clean with little underlying event activity
- Typical particle p_T is small -> precision tracking important for reducing jet energy scale uncertainties

- Lower center of mass energies will lead to lower jet / di-jet yields and more limited p_T / mass reach
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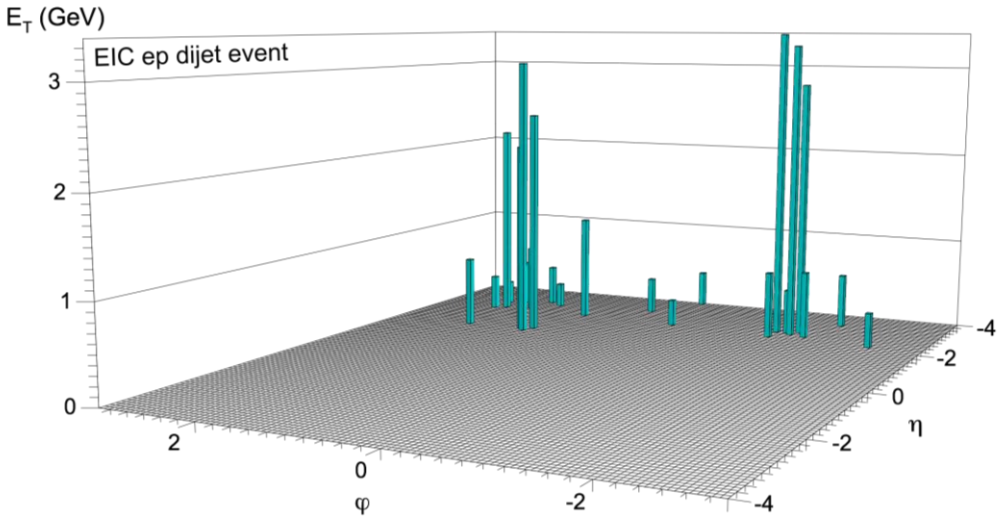


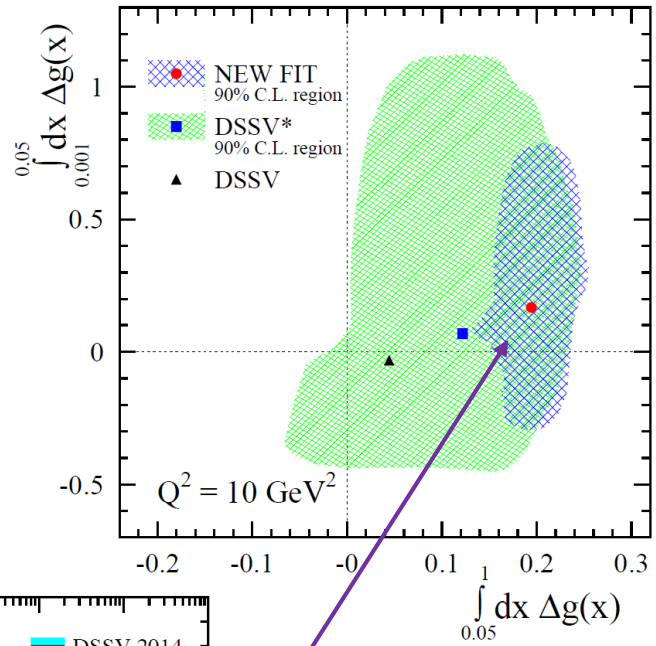
Jet / Di-jet Applications

- Electron – Nucleus Collisions
  - Nuclear PDFs
  - Medium Modification / Energy Loss
  - Hadronization and Confinement

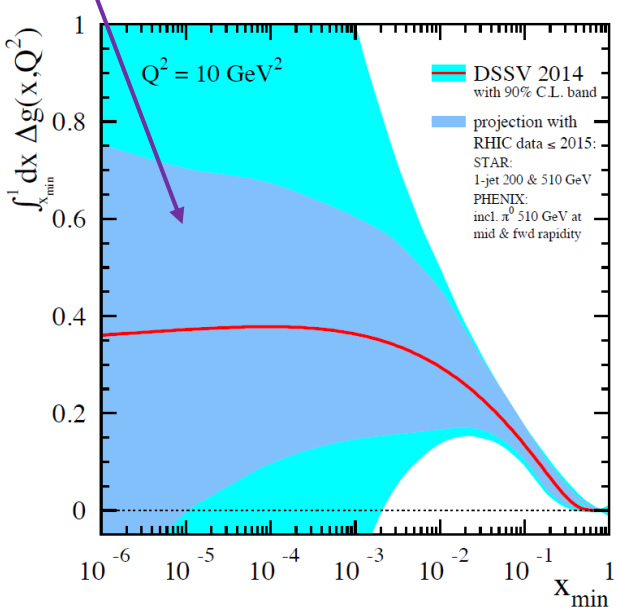
- Electron – Proton Collisions
  - High – x Proton PDFs
  - Proton Orbital Angular Momentum / Gluon Wigner Distribution at Low x (Diffractive Di-jets)
  - Saturation (Diffractive Di-jets)
  - (Un)polarized Photon PDFs
  - PGF Tagging for Proton ΔG

Need for ΔG

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



Uncertainties on low-x region will still be sizable with RHIC data



Global analyses with RHIC data through 2009 find a ΔG value of about 0.2 for x > 0.05 with small uncertainties

- Current fits to polarized DIS data give $\Delta\Sigma = 0.366^{+0.042}_{-0.062}$ for $10^{-3} < x < 1$
- This leaves over half of the proton spin budget unaccounted for – is any spin carried by the gluons?
- Polarized p+p collision data from RHIC have placed strong constraints on ΔG for x > 0.05 and given evidence of non-zero gluon contribution, but large uncertainties at low x will remain
- Need high precision and wide kinematic reach to solve spin puzzle

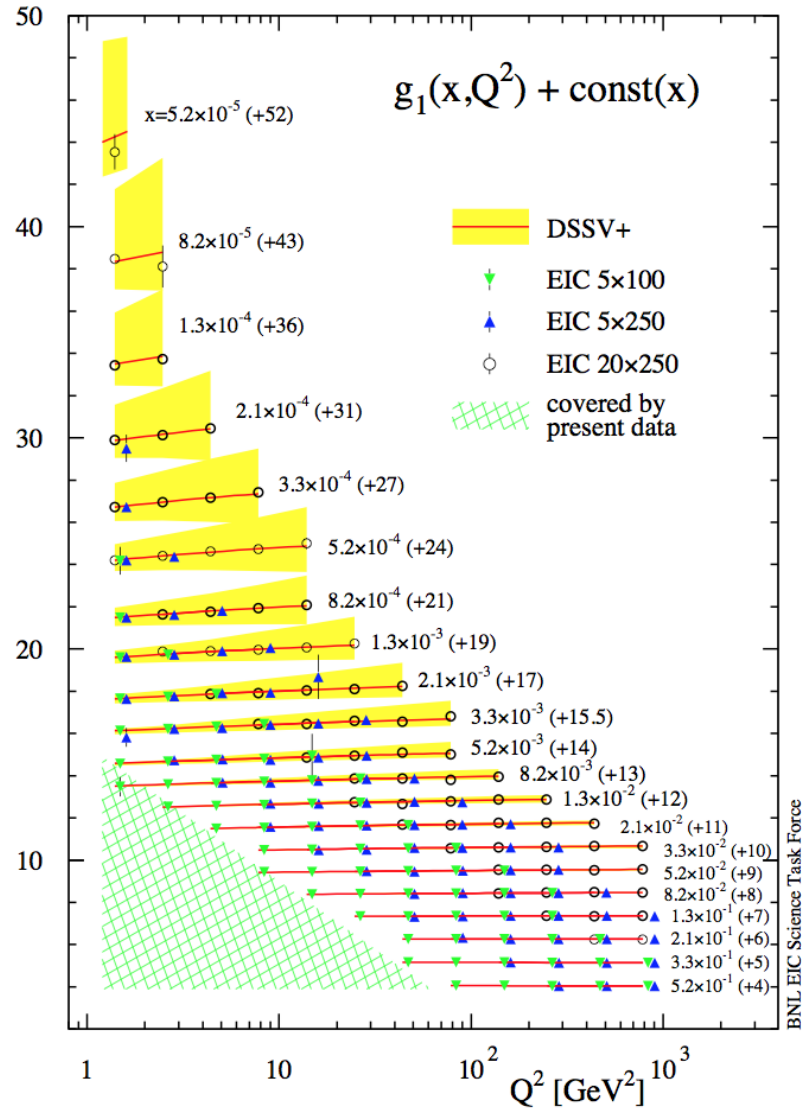
Accessing ΔG in DIS

- 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

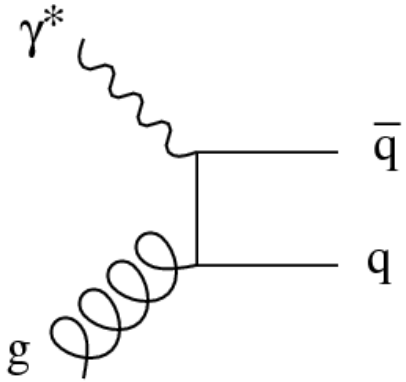
- EIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!



arXiv:1206.6014

Gluon Polarization with Di-jets

Photon-Gluon Fusion



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

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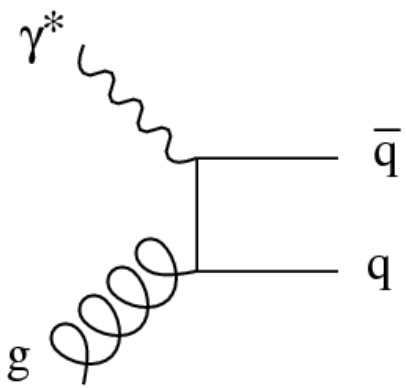
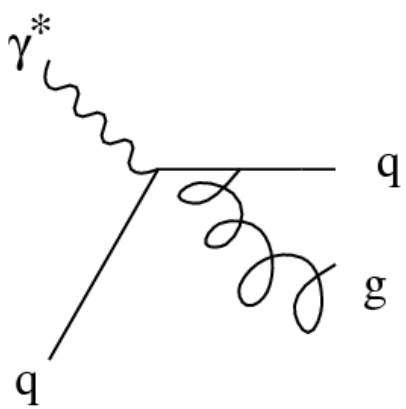


QCD – Compton



- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order

Gluon Polarization with Di-jets

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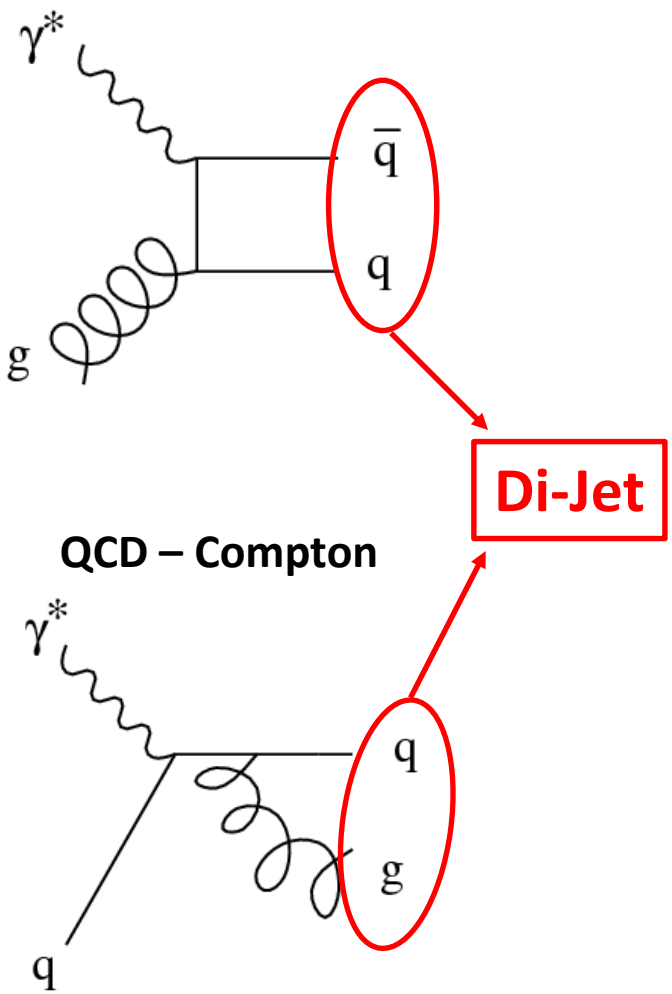
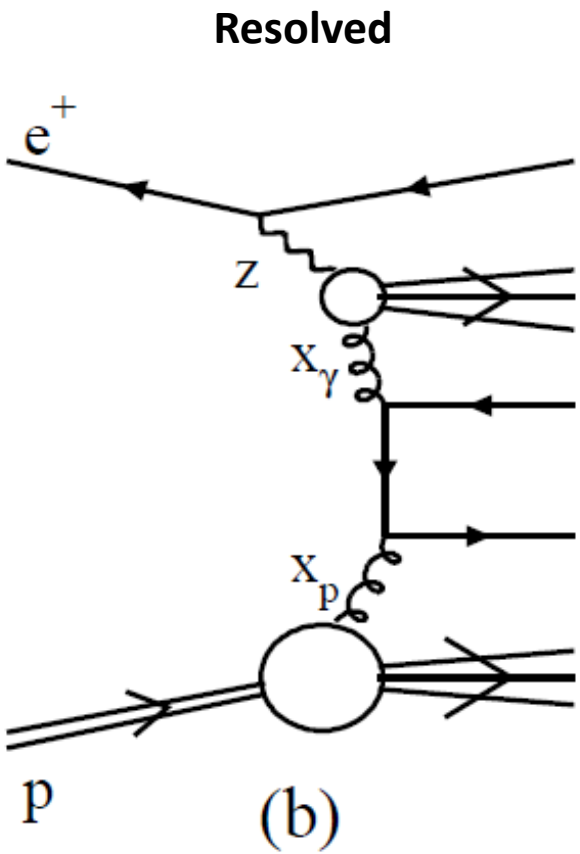


QCD – Compton

- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet

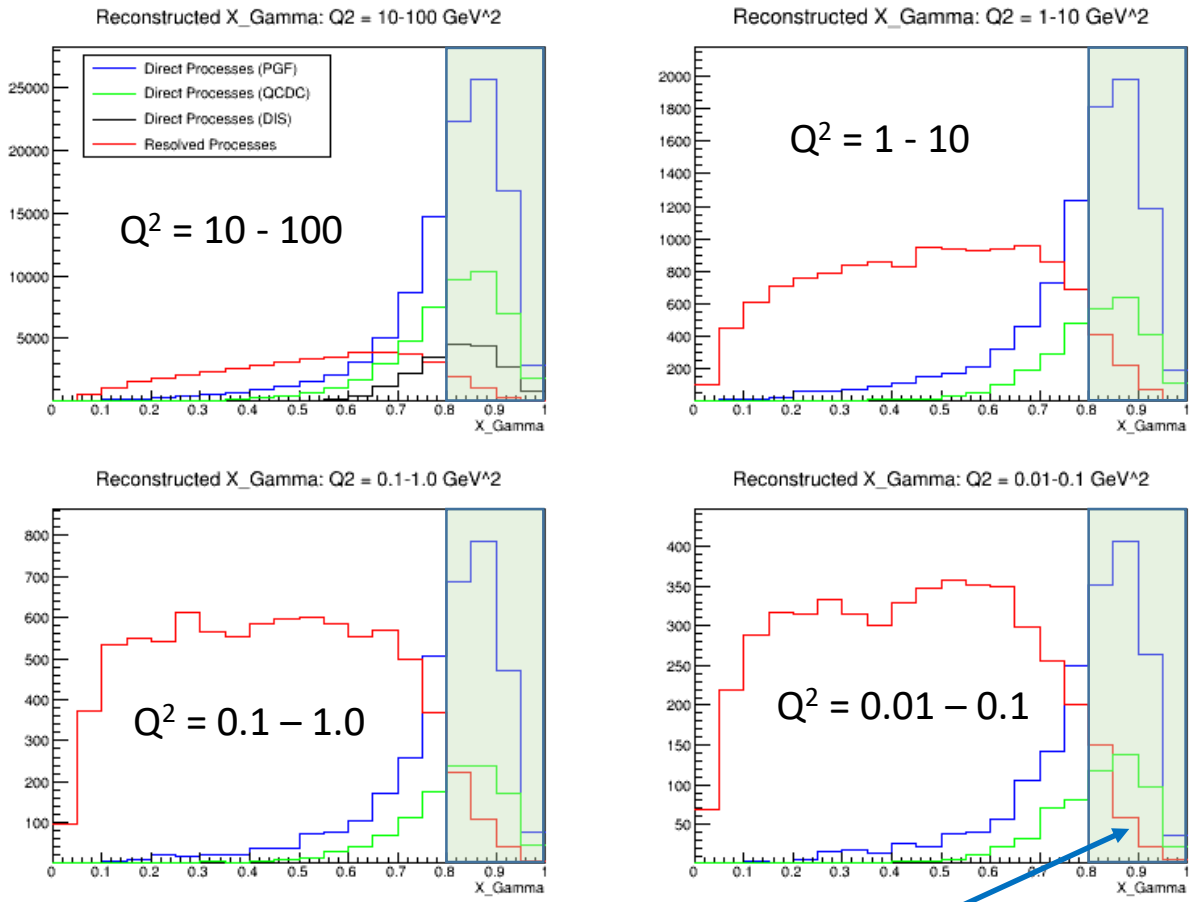
Gluon Polarization with Di-jets



- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet
- At lower Q2, resolved processes in which the photon assumes a hadronic structure begin to dominate
- Asymmetry is a convolution of polarized PDF from the proton and polarized photon structure – which is completely unconstrained
- Would like to suppress the resolved component

Direct Vs Resolved Processes

$$X_\gamma = \frac{1}{2E_e y}\left(m_{T1}e^{-y_1} + m_{T2}e^{-y_2}\right)$$

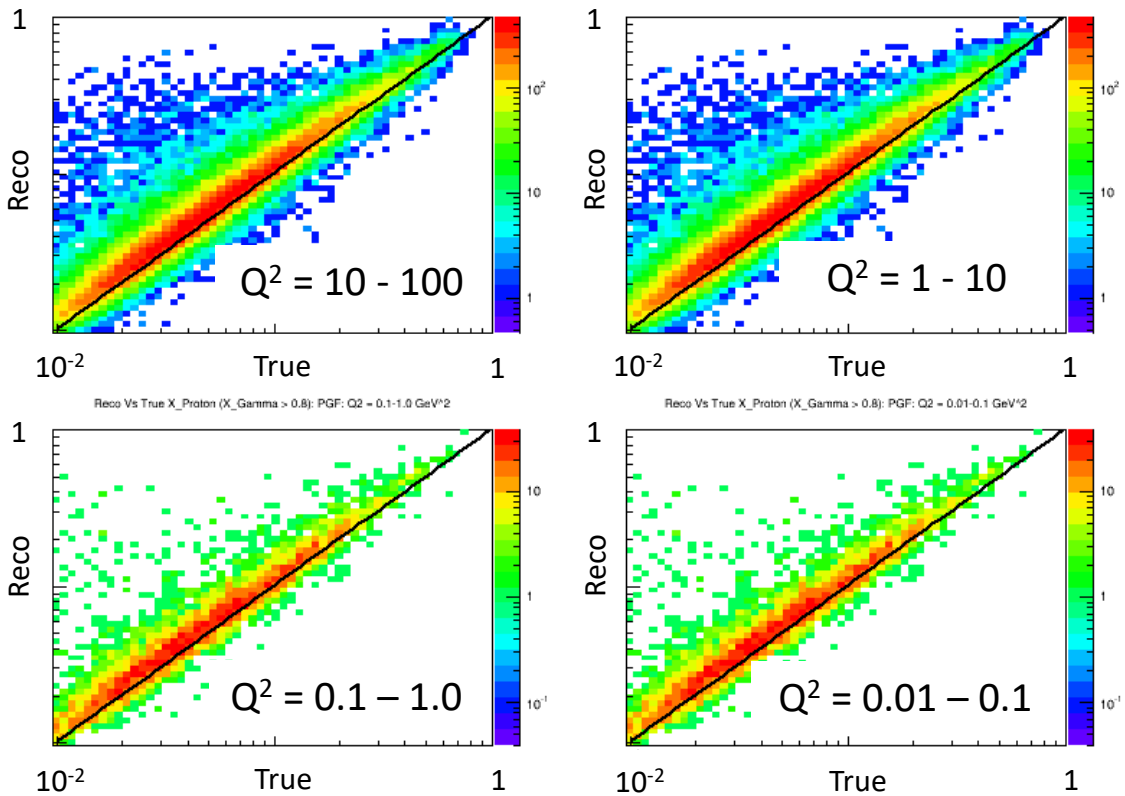


Accepted Region

- 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 $X_\gamma > 0.8$ enhances the direct fraction at all Q^2

Proton Partonic Kinematics

Parton Momentum Fraction: Photon Gluon Fusion



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

$$X_P = \frac{1}{2E_P}\left(m_{T1}e^{y_1} + m_{T2}e^{y_2}\right)$$

Proton Partonic Kinematics

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

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- X_P is related to Bjorken-x and Q^2 at leading order

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- X_P is related to Bjorken-x and Q^2 at leading order
- Q^2 and Bjorken-x are also related via the collision energy and inelasticity

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- Accessible X_P range basically determined by beam energies

Proton Partonic Kinematics

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

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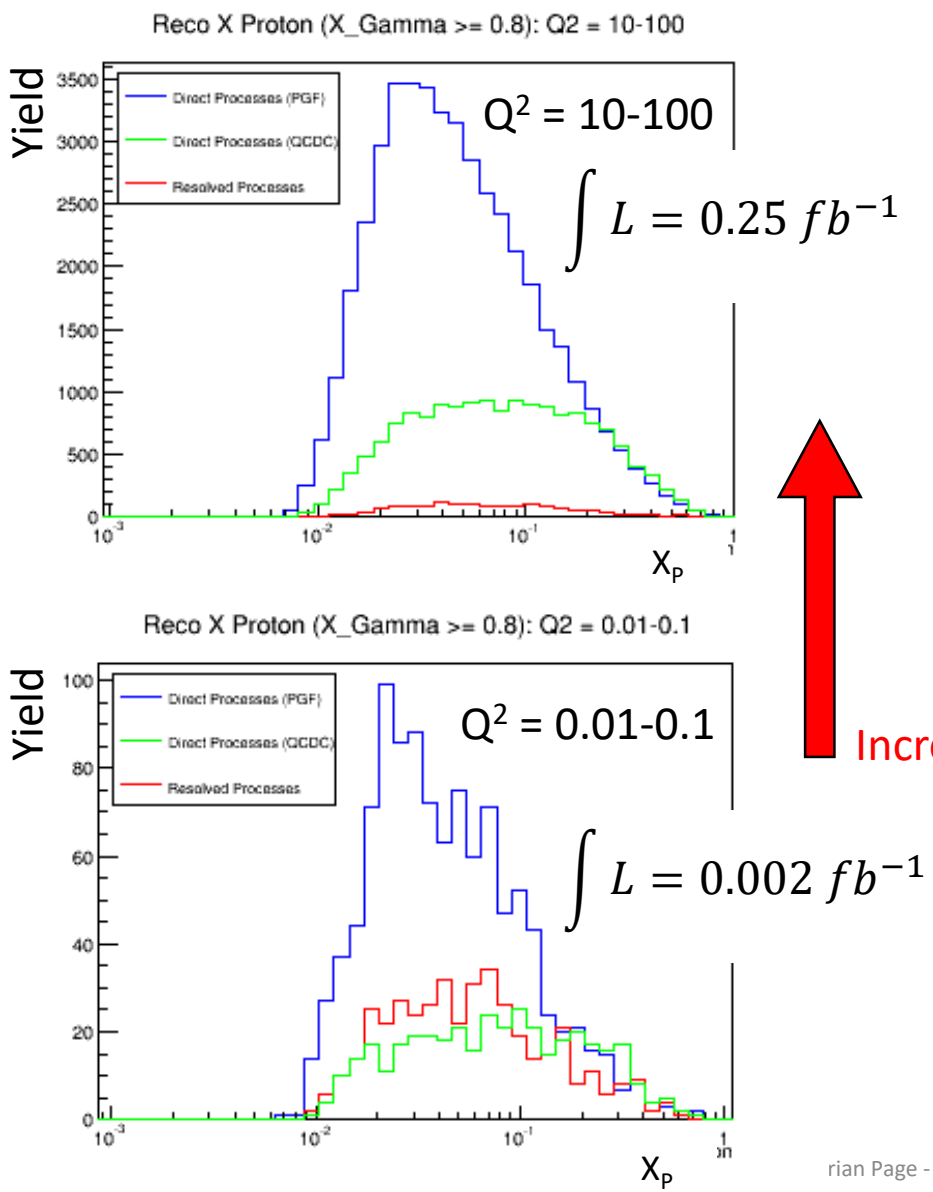
$$\boxed{\approx \frac{100}{(20000\ x\ 0.95)} \approx 0.005}$$

- To measure ΔG, need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed
- X_P is related to Bjorken-x and Q^2 at leading order
- Q^2 and Bjorken-x are also related via the collision energy and inelasticity
- Accessible X_P range basically determined by beam energies
- Lowest X_P we can probe is about 0.005

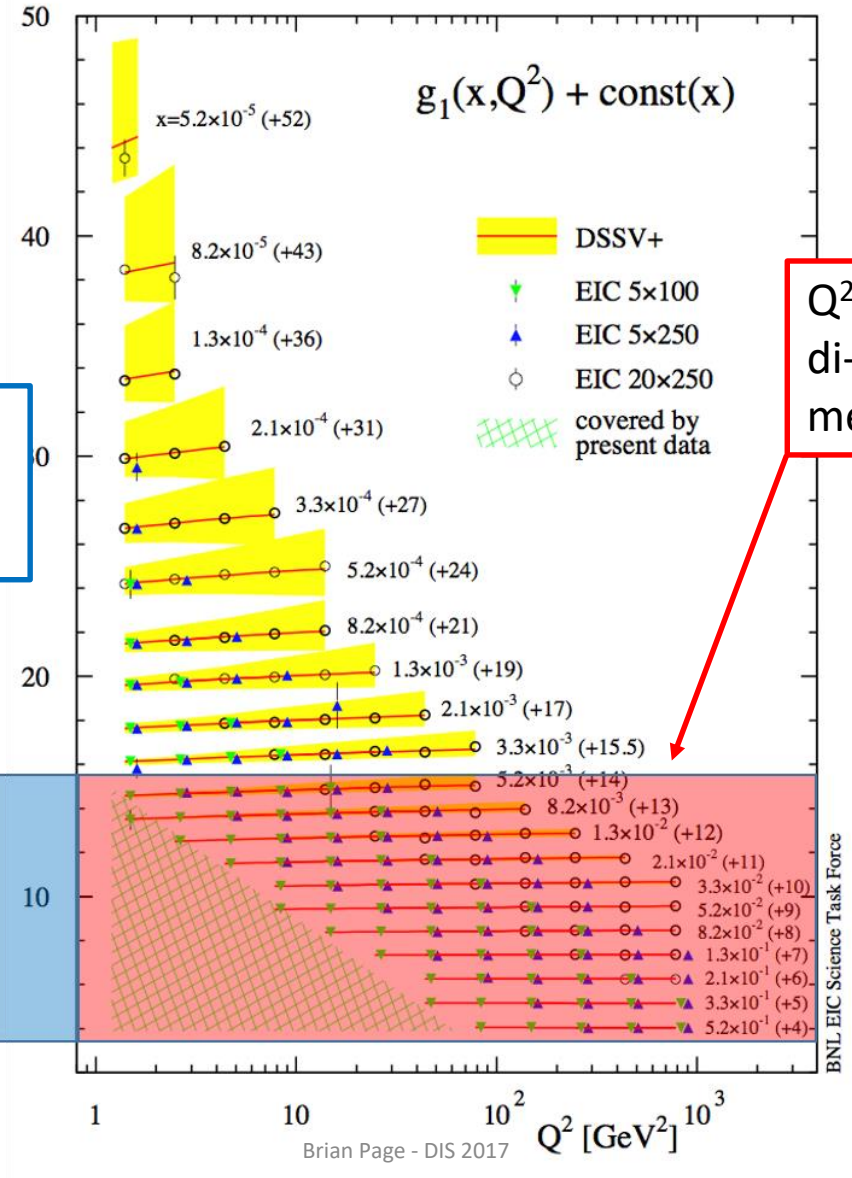
X_P For Different Q^2



Increasing Q^2

- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases
- For a given di-jet mass range (10 – 20 GeV in this case), same X_P can be reconstructed event-by-event and probed over large range of Q^2
- This will allow for robust tests of the evolution of ΔG

Complementary Coverage

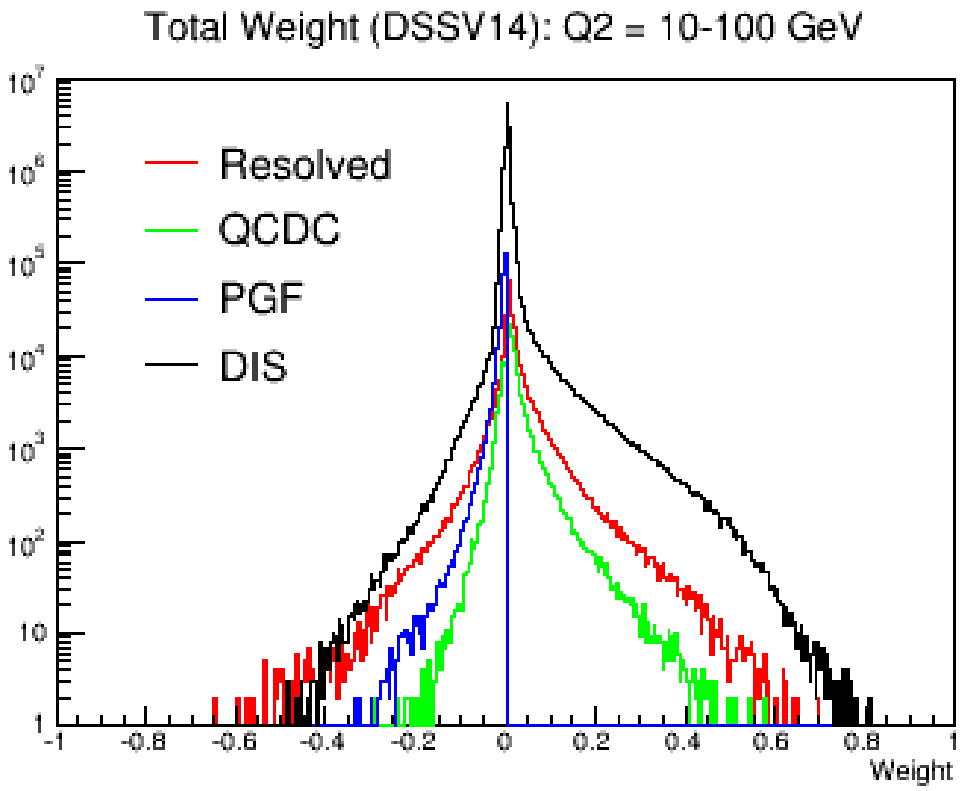


Experimentally possible to extend these measurements to $Q^2 < 1$

Q^2 and x range covered by di-jet asymmetry measurements

Weighting PYTHIA

$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$



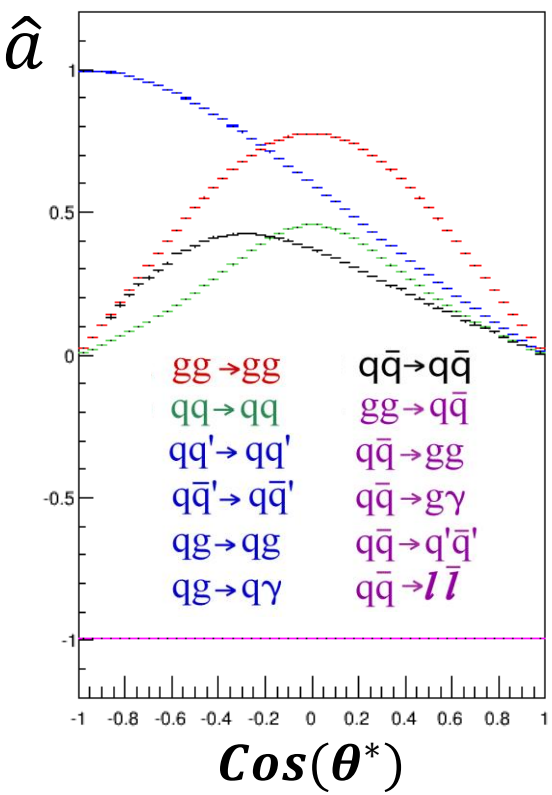
- PYTHIA does not include parton polarization effects, but an asymmetry can be formed by assigning each event a weight depending on the hard-scattering asymmetry and (un)polarized photon and proton PDFs
- Expected asymmetry is then the average over weights
- Weights are sharply spiked near zero -> expect small asymmetries

Weighting PYTHIA

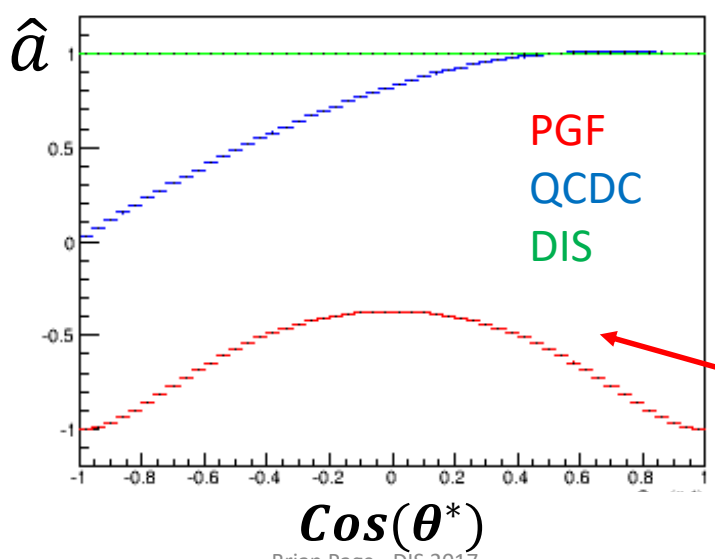
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^{N}(x_b,\mu^2)}{f_b^{N}(x_b,\mu^2)}$$

$$\hat{a}(\hat{s},\hat{t},\mu^2) = \Delta\hat{\sigma}/(2\hat{\sigma})$$

Resolved



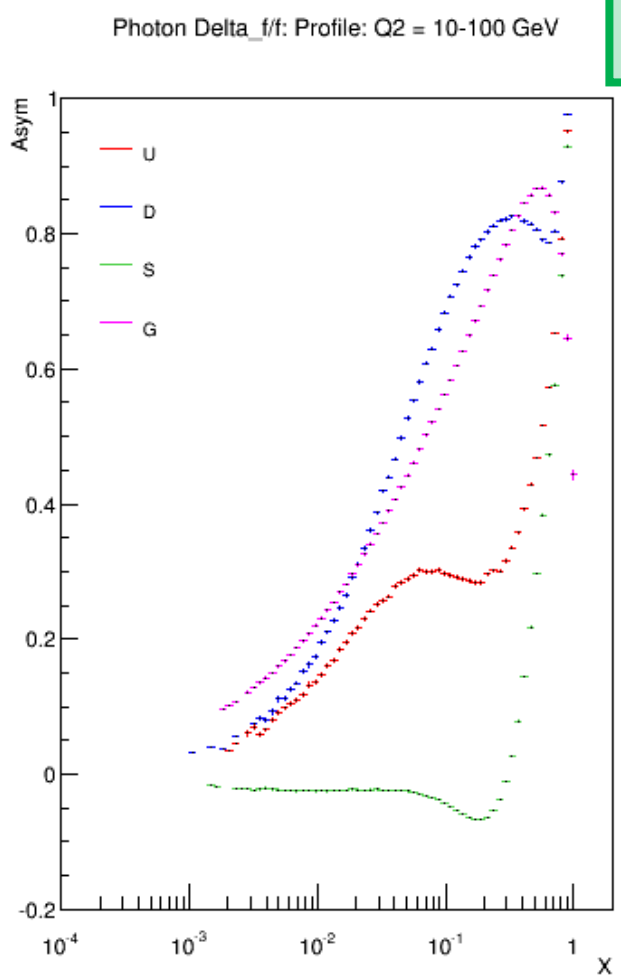
Direct



- Process-dependent hard scattering asymmetry is a function of Mandelstam variables (Cos(θ*))
- The direct process distributions will be smeared by the additional depolarization term
- Note that the asymmetry for PGF is negative

Weighting PYTHIA

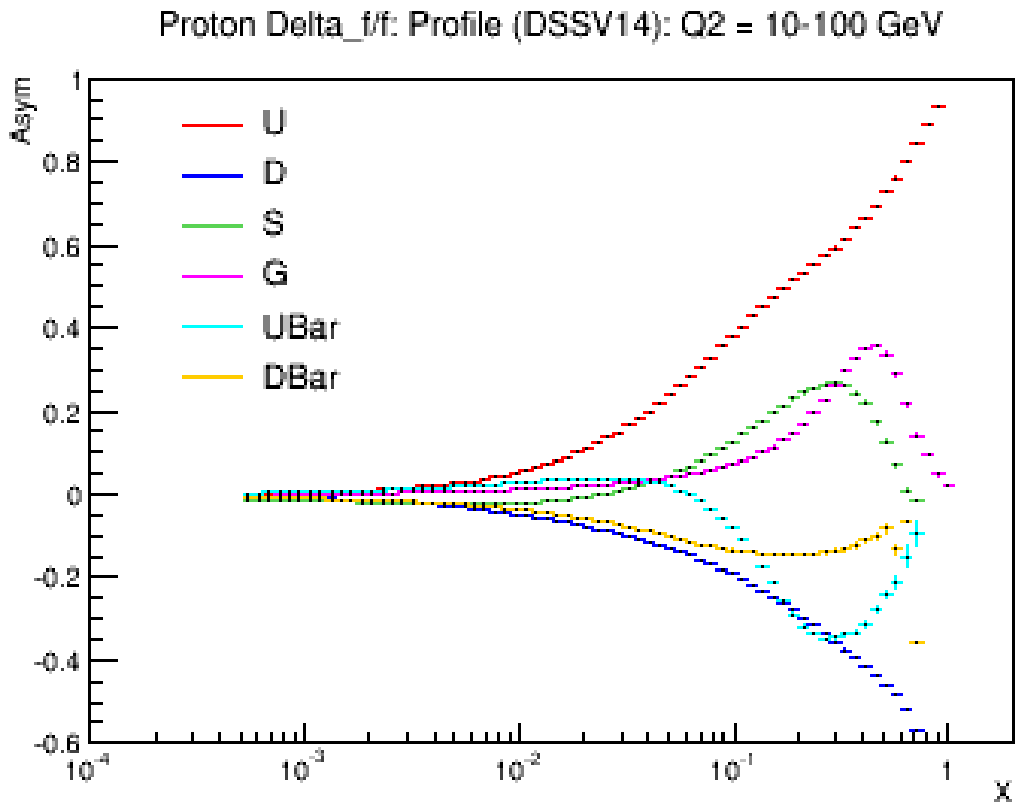
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \boxed{\frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)}} \bullet \frac{\Delta f_b^{N}(x_b,\mu^2)}{f_b^{N}(x_b,\mu^2)}$$



- Second term is the ratio of the polarized to unpolarized photon PDFs
- Use maximal scheme for polarized and GRV-G for unpolarized
- For direct processes such as Photon-Gluon Fusion, this term is identically unity

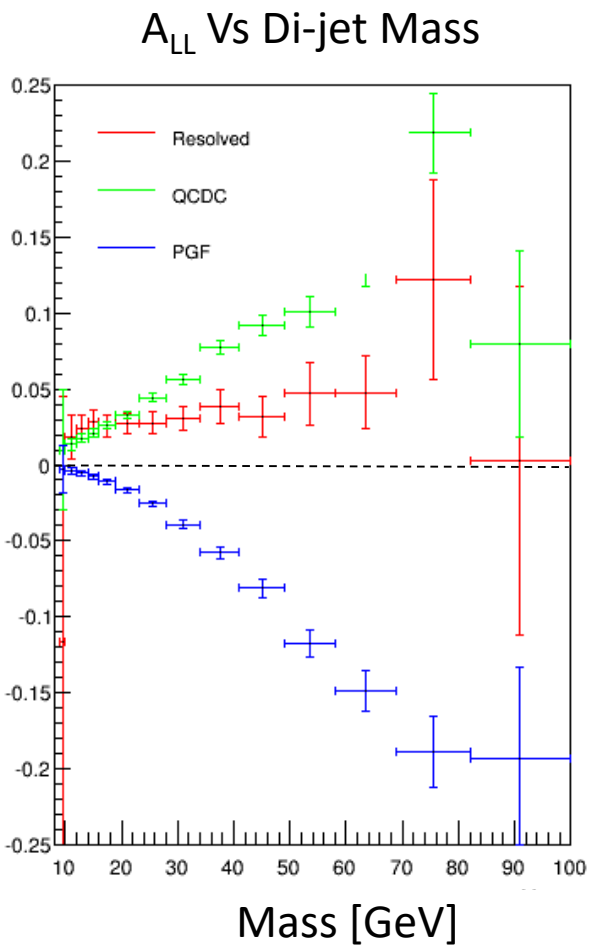
Weighting PYTHIA

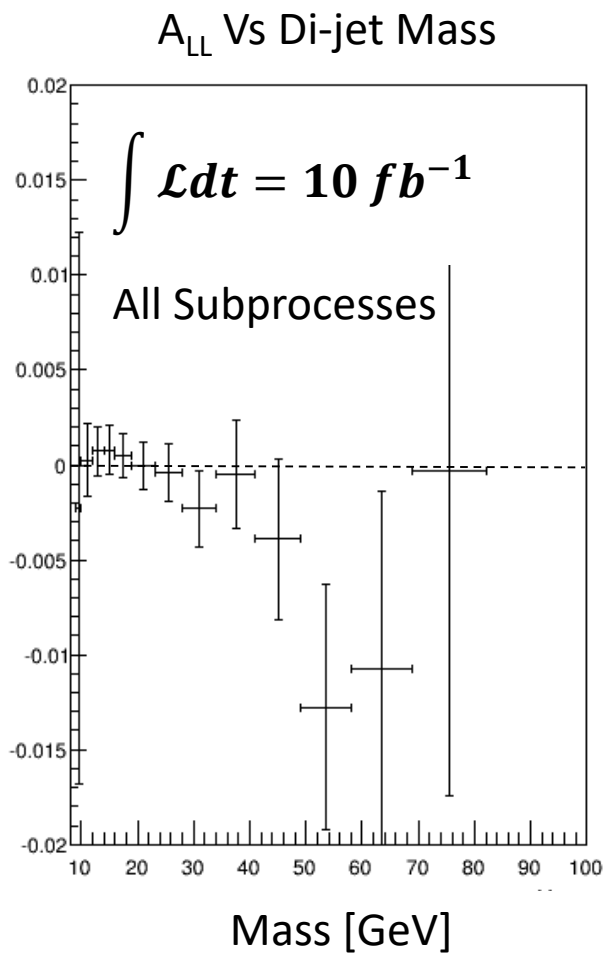
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \boxed{\frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}}$$



- Last term is the ratio of the polarized to unpolarized proton PDFs
- Use DSSV14 for polarized and CTEQ5M for unpolarized

A_{LL} Vs Di-jet Mass



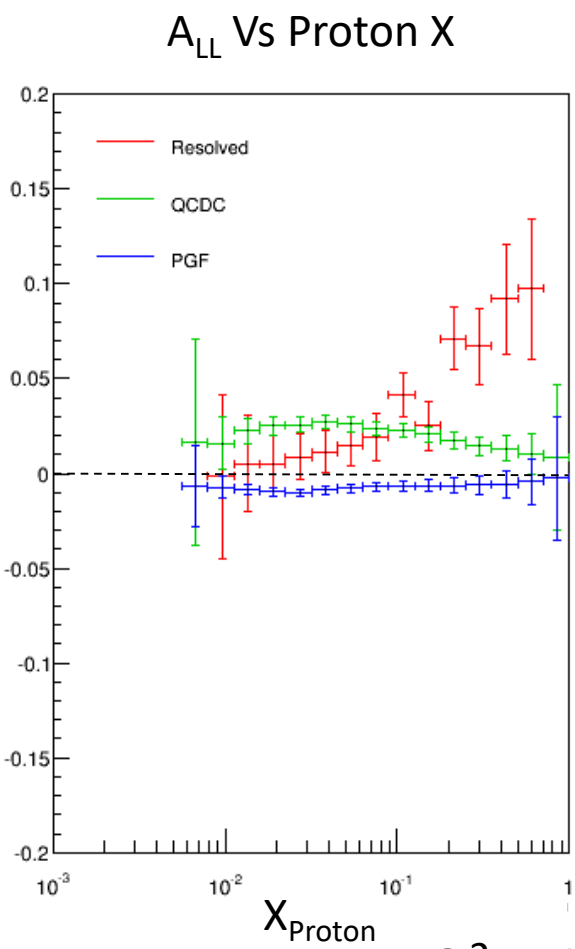


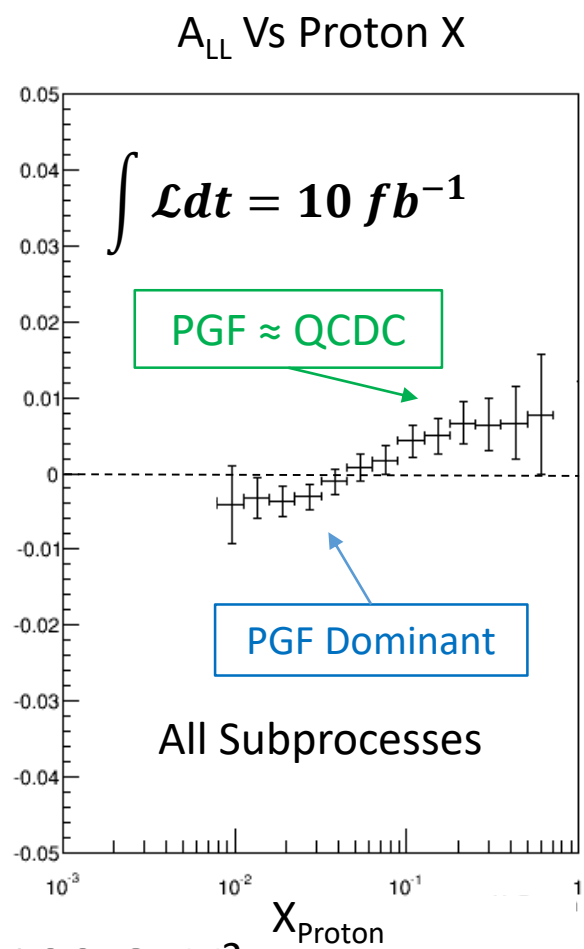
$Q^2 = 10 - 100\ GeV^2$

$$\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}$$

- Plot the expected A_{LL} as a function of di-jet invariant mass for each sub-process separately as well as the combined sample
- PGF asymmetry is nearly canceled out by QCDC asymmetry with opposite sign – would like to reduce QCDC contribution
- Need high integrated luminosity and high energy to probe the high-mass region where asymmetries can be sizable
- Control of systematics will be essential

A_{LL} Vs X_{Proton}





$Q^2 = 10 - 100\ GeV^2$

$$\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}$$

- Asymmetry is plotted as a function of the momentum fraction of the parton from the proton
- Asymmetry shown for di-jet invariant masses between 10 and 20 GeV/c^2
- Error bars are statistical and scaled to the given integrated luminosity
- Different mass ranges will emphasize different momentum fraction ranges and subprocess mixes

Summary

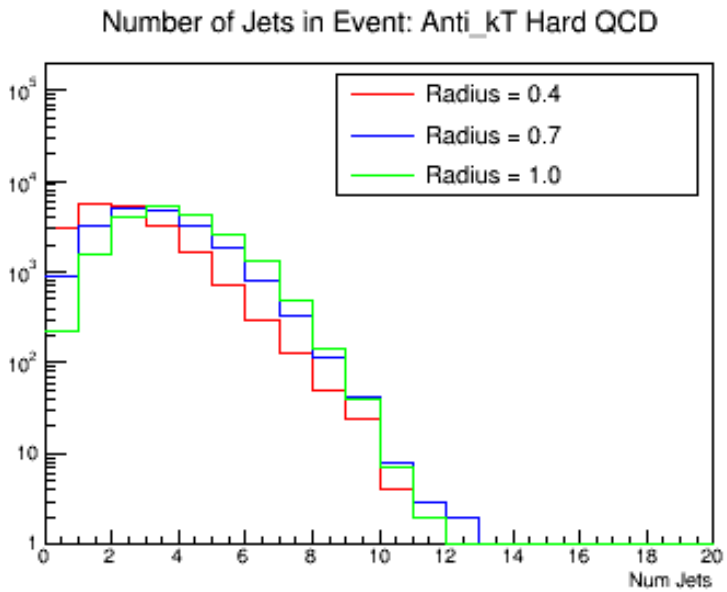
- Jets at an EIC will contain relatively few total particles and those particles will have low transverse momenta, making tracking essential for reducing jet energy scale uncertainties
- Di-jet measurements can be used to tag photon-gluon fusion events to access ΔG and investigate its evolution
- Combination of QCD-Compton and PGF subprocess asymmetries lead to small overall asymmetries
- Need large integrated luminosity and center-of-mass energy to explore asymmetries at high di-jet mass and good control on systematic effects

Backup

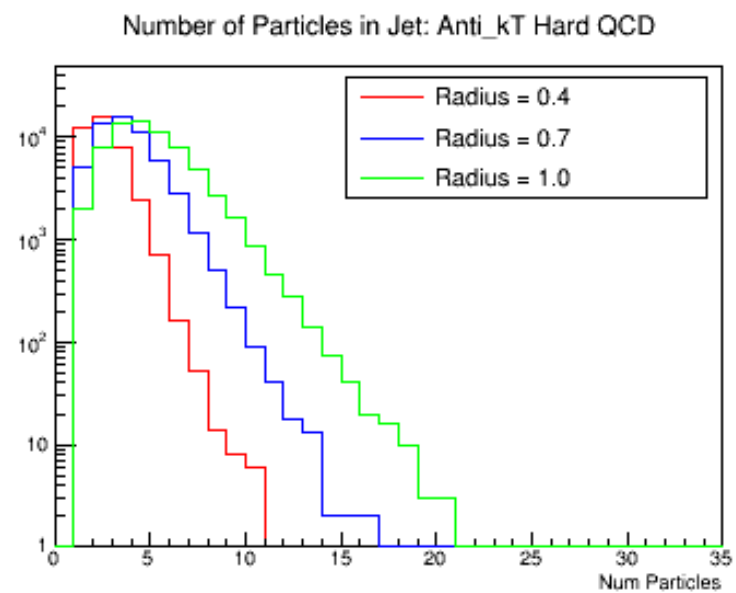
Jet Basics: Frames

- Can define several useful frames:
  - Lab: Detector-based frame
  - Hadron-Boson: Beam hadron is at rest, z-direction chosen along virtual photon momentum vector
  - Breit: Virtual photon moves in -z direction and boost such that it has zero energy. Separation into target and remnant regions
  - Center of Mass: Virtual photon and struck parton have equal and opposite momenta. Can define Feynman-x

Jet Basics: Radius



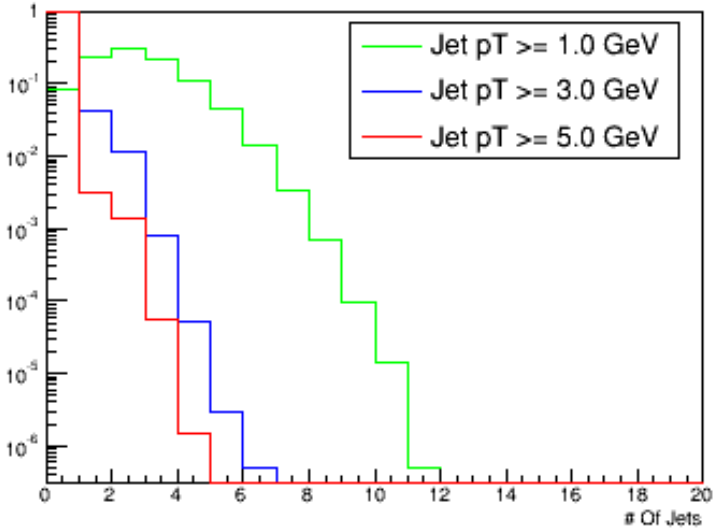
- For anti-k_T algorithm the radius parameter determines the distance at which particles can be grouped together
- Sets the effective size of the jet



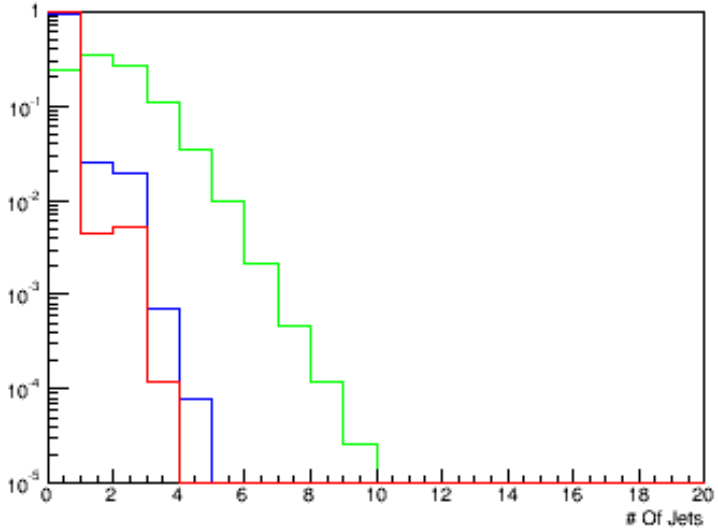
- Parameters: Min p_T = 1.0 GeV, Resolved processes
- Larger radii result in more found jets as well as more particles in jet

Jet Multiplicity: $Q^2 = 0.01 – 0.1\ GeV^2$

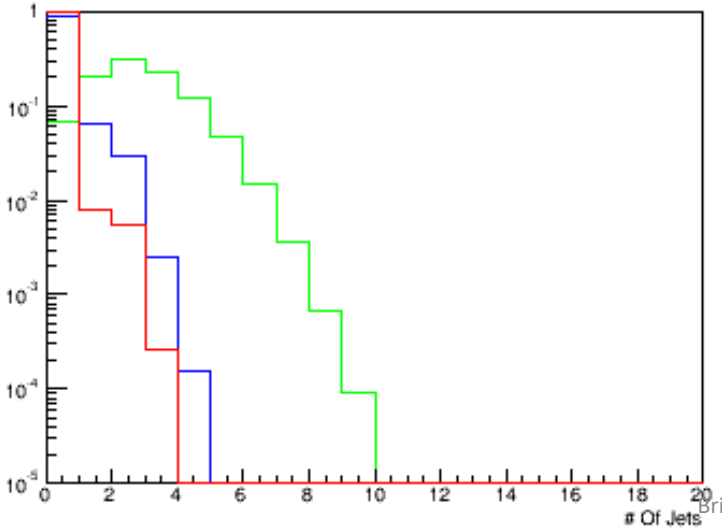
Jets: Resolved Processes



Jets: QCDC



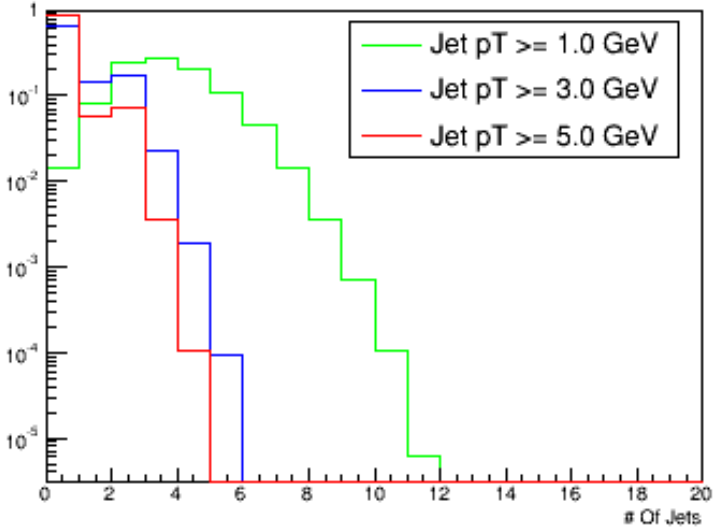
Jets: PGF



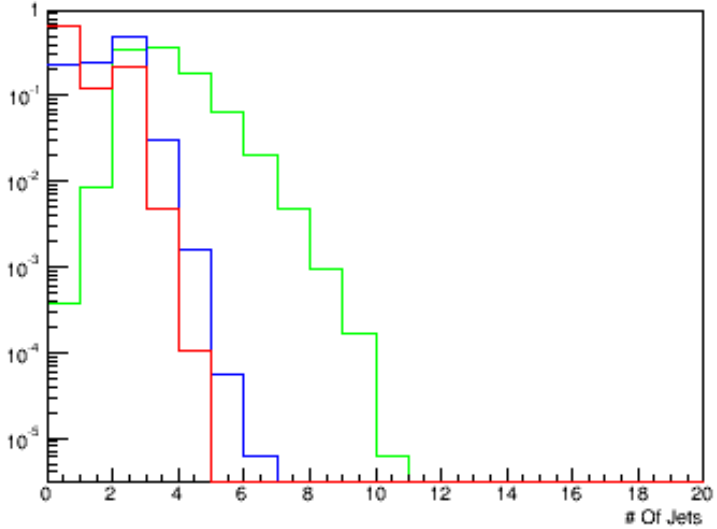
- Percentage of events with a certain number of found jets for different minimum allowed jet p_Ts
- See a decrease in number of jets with increasing minimum jet p_T
- Jet p_T of 1 GeV may not be well described theoretically
- Each curve normalized to unity

Jet Multiplicity: $Q^2 = 10 – 100\ GeV^2$

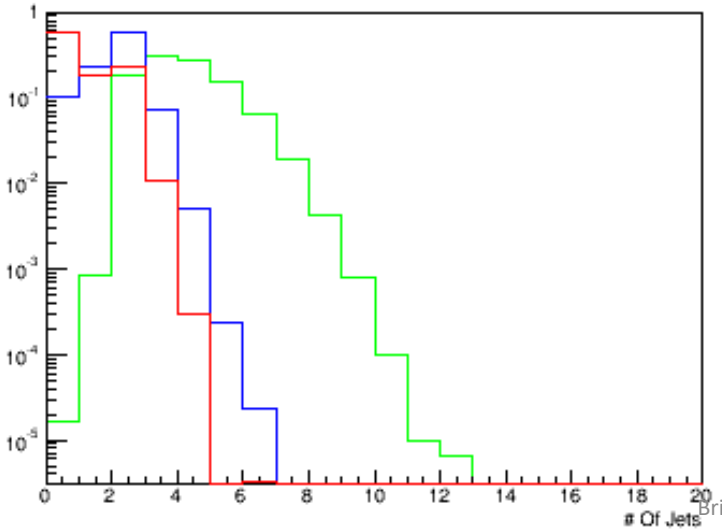
Jets: Resolved Processes



Jets: QCDC



Jets: PGF



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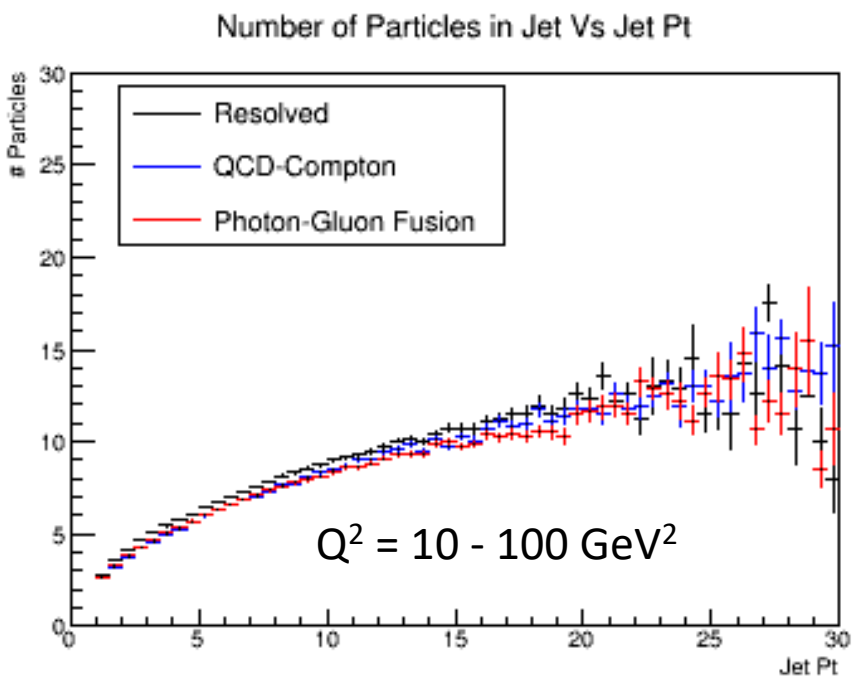
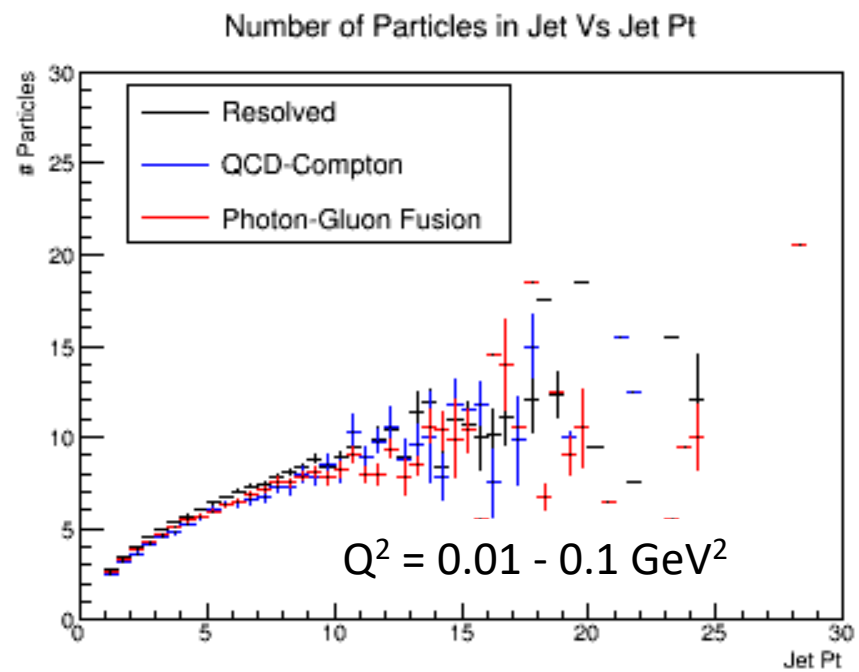
Jet Particle Multiplicity

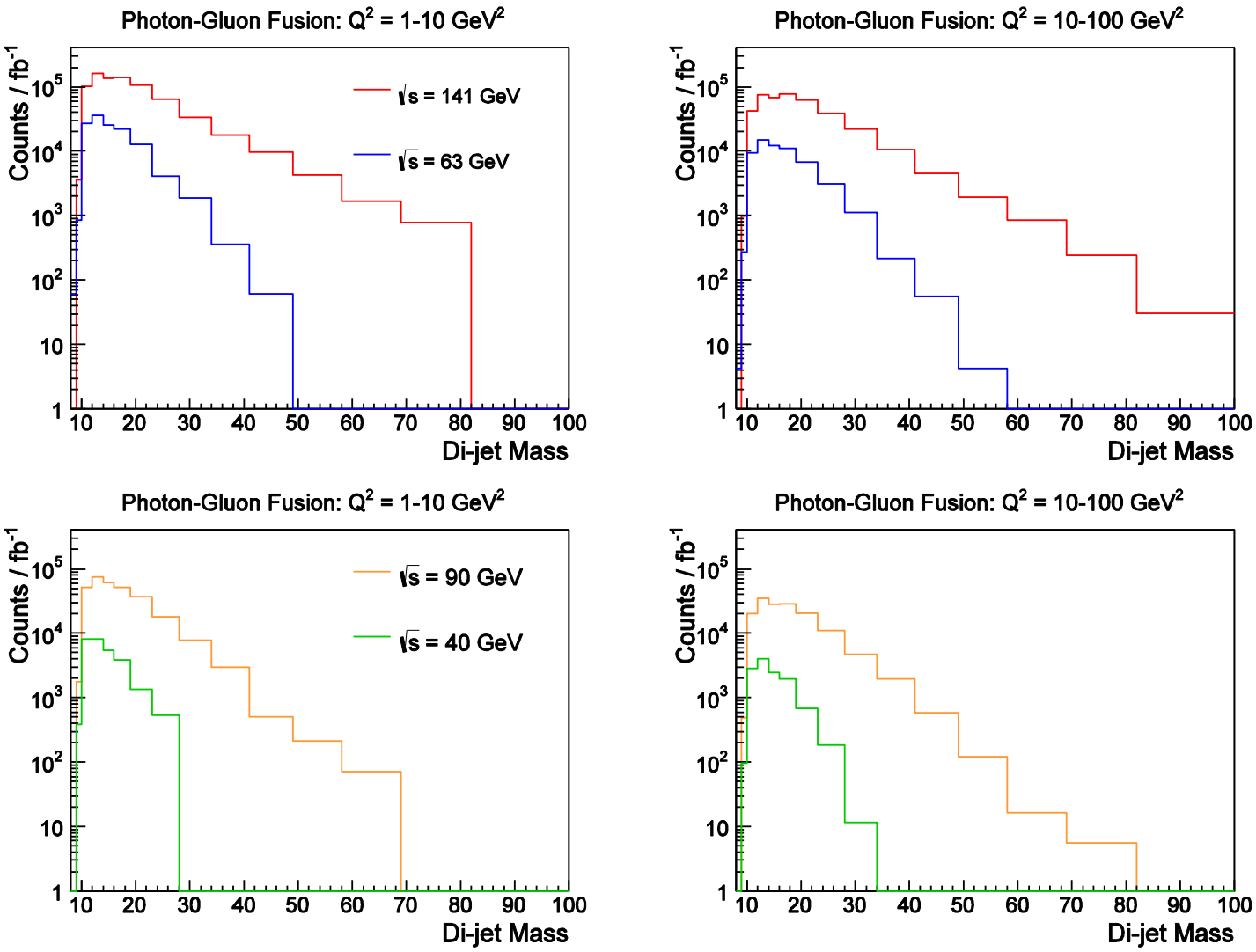


- Look at the average number of particles in jet as a function of jet p_T
- All stable particles (charged and neutral) are counted

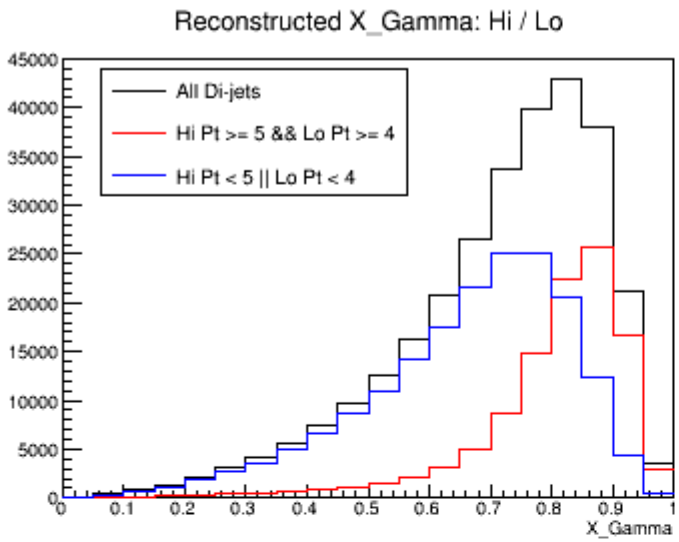


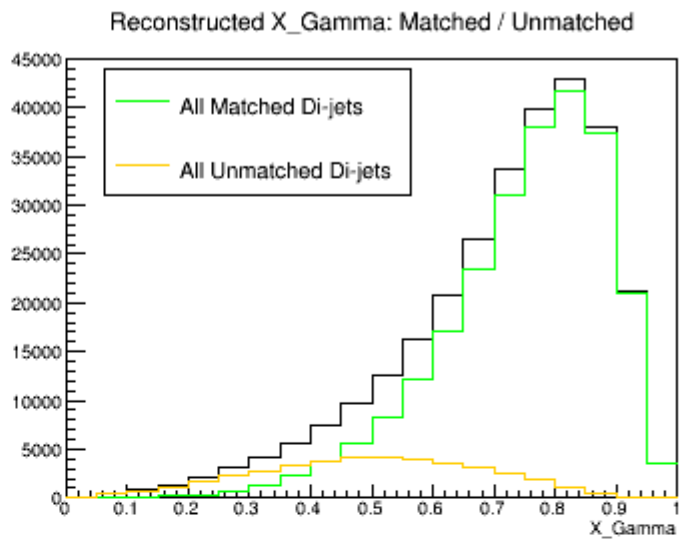
- No dependence on Q2 or subprocess
- How few particles can be in jet before it doesn't make sense to call the object a jet?

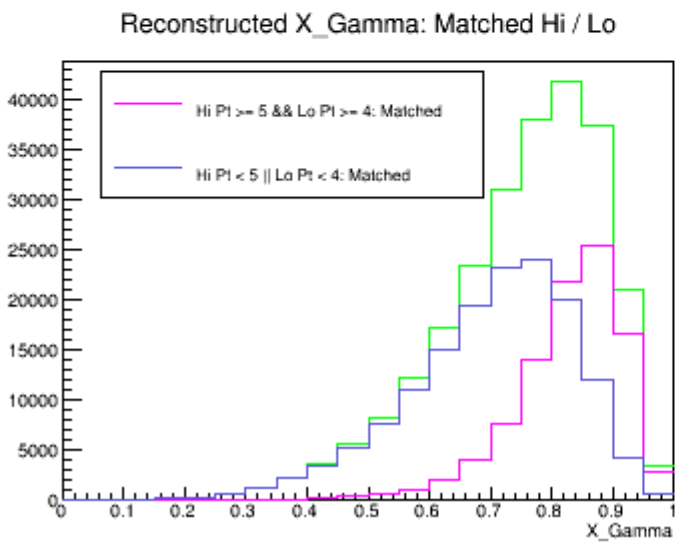
Di-jet Yields



X_γ Reproduction: $Q^2 = 10 – 100\ GeV^2$





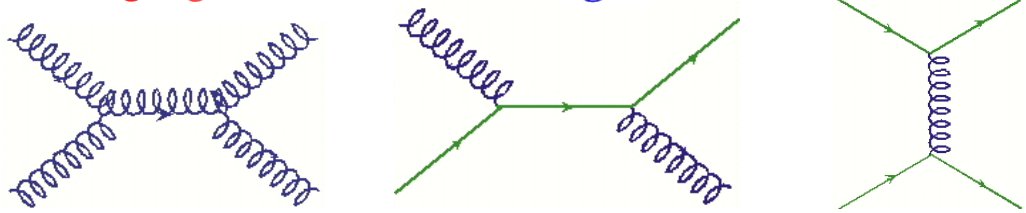


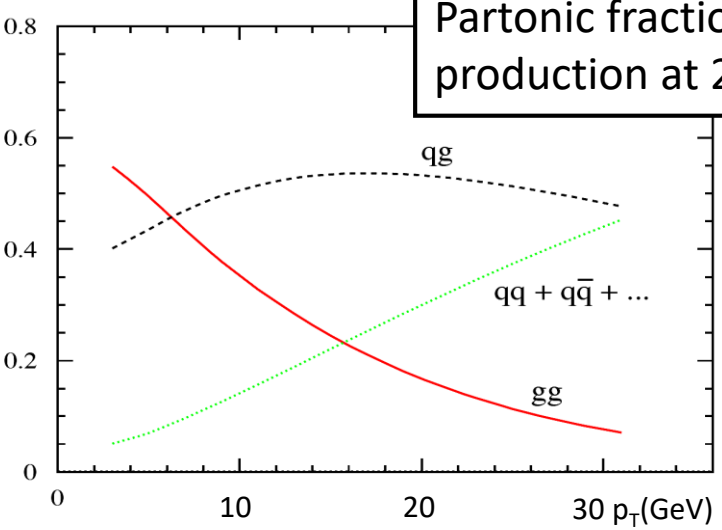
- How does the reproduction of X_γ depend on jet p_T?
- As expected unmatched events do not reproduce X_γ well
- See that high p_T range is more peaked toward 1 even for matched events

Accessing ΔG at RHIC: A_{LL}

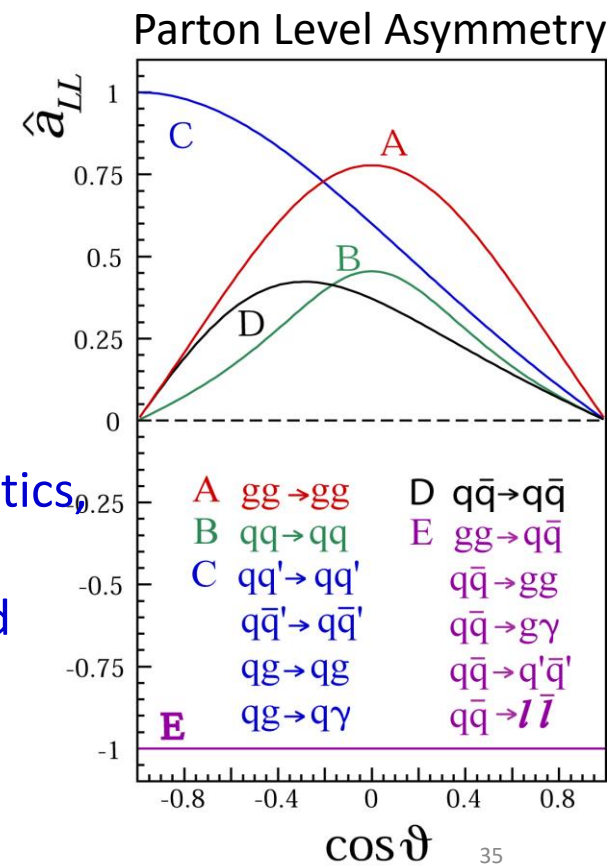
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes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

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

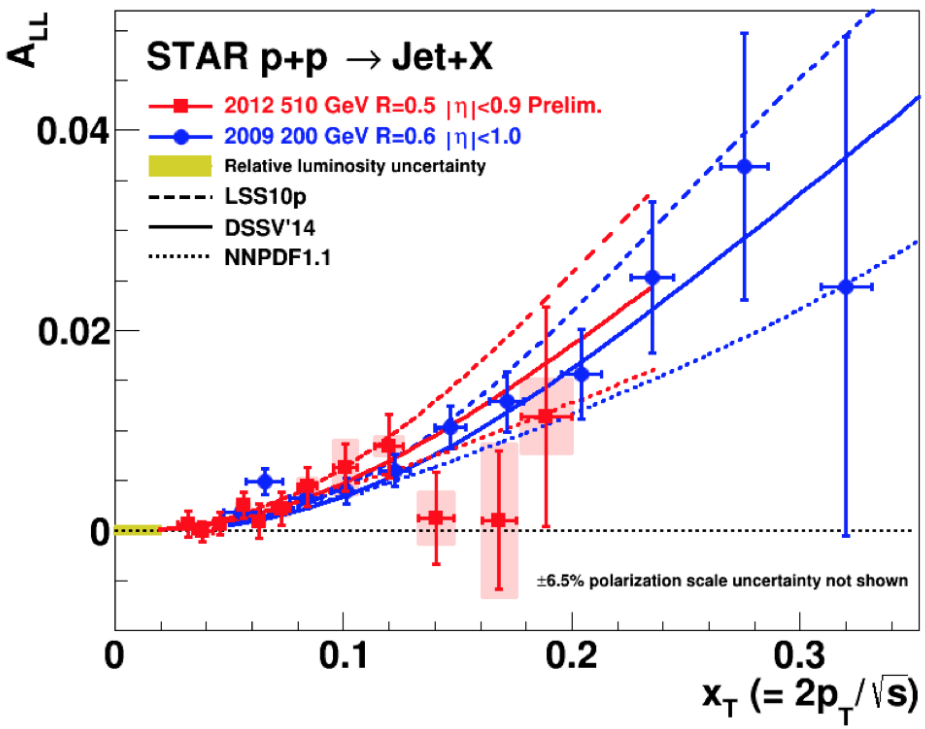


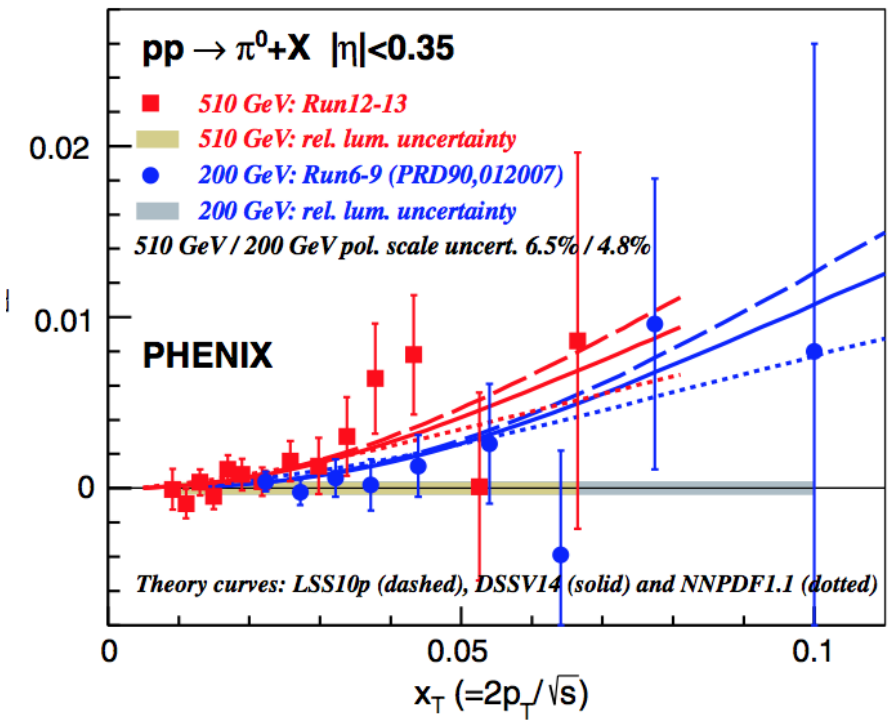


For most RHIC kinematics, **gg** and **qg** dominate, making A_{LL} for jets and hadrons sensitive to **gluon polarization**.



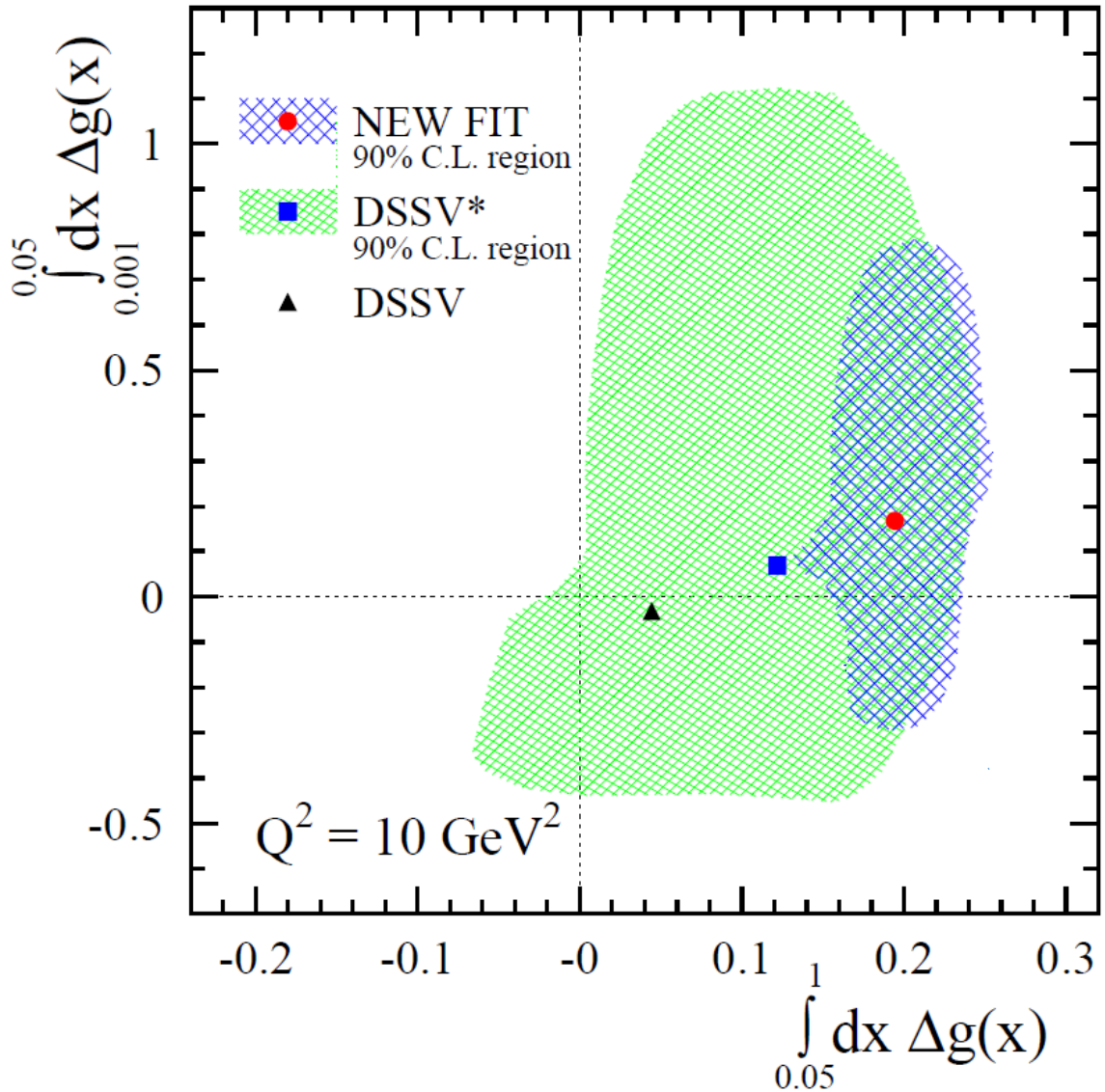
Accessing ΔG at RHIC: A_{LL}





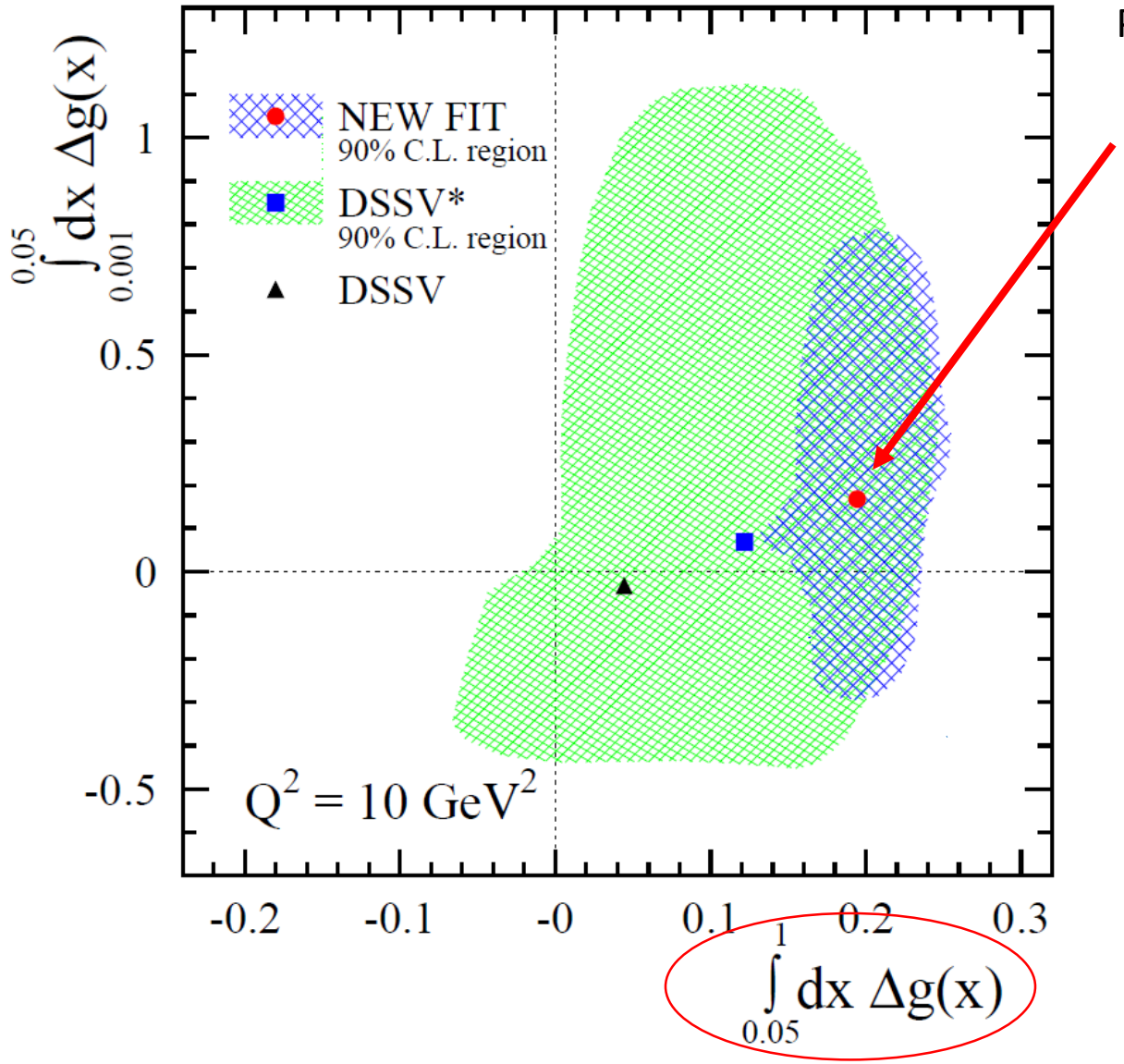
- In polarized pp collisions, access ΔG via the longitudinal double helicity asymmetry A_{LL} which is sensitive to the polarized gluon distribution at leading order
- STAR and PHENIX measure A_{LL} using inclusive jet and π^0 final states, respectively

New DSSV Results



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

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!

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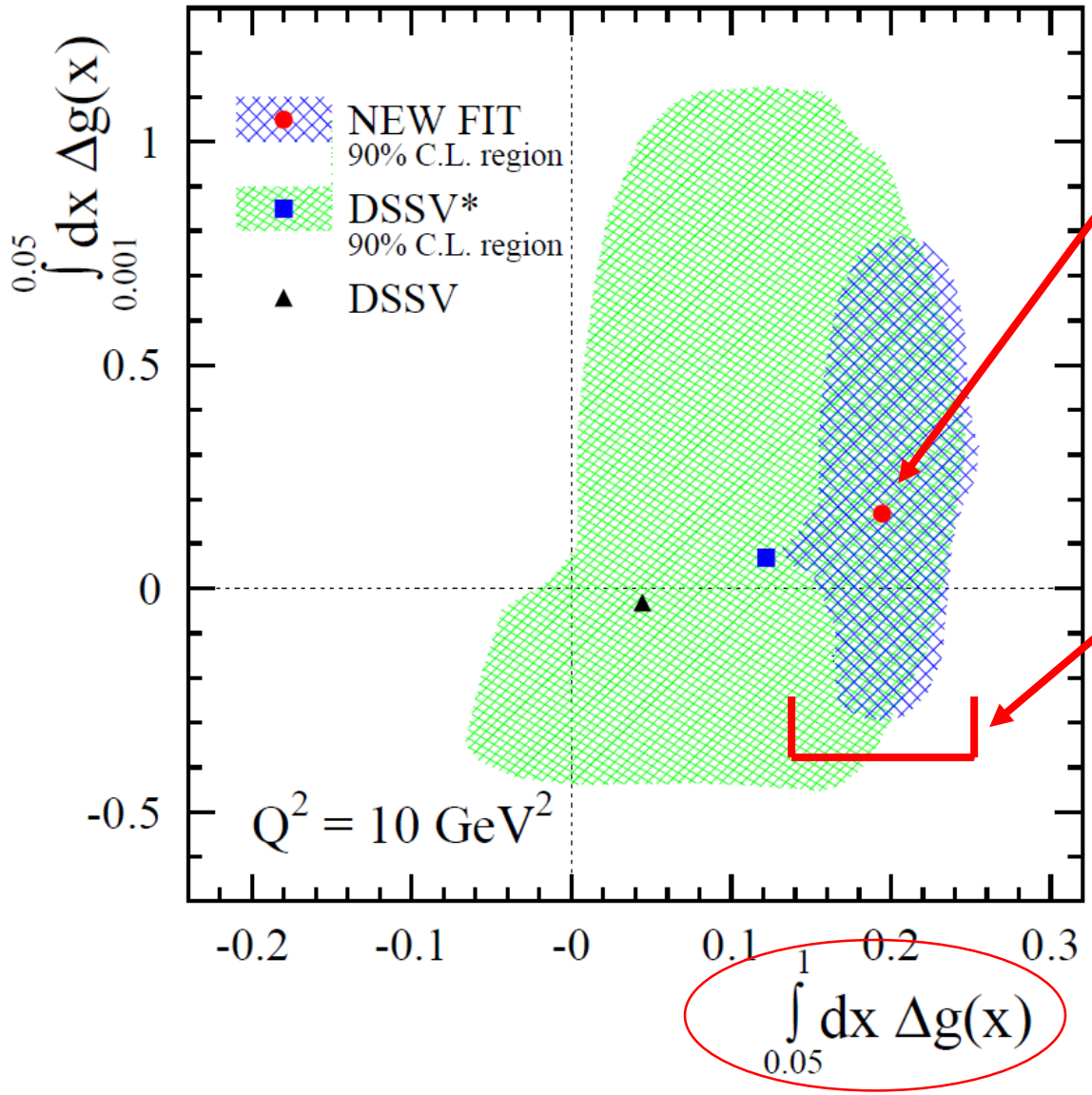

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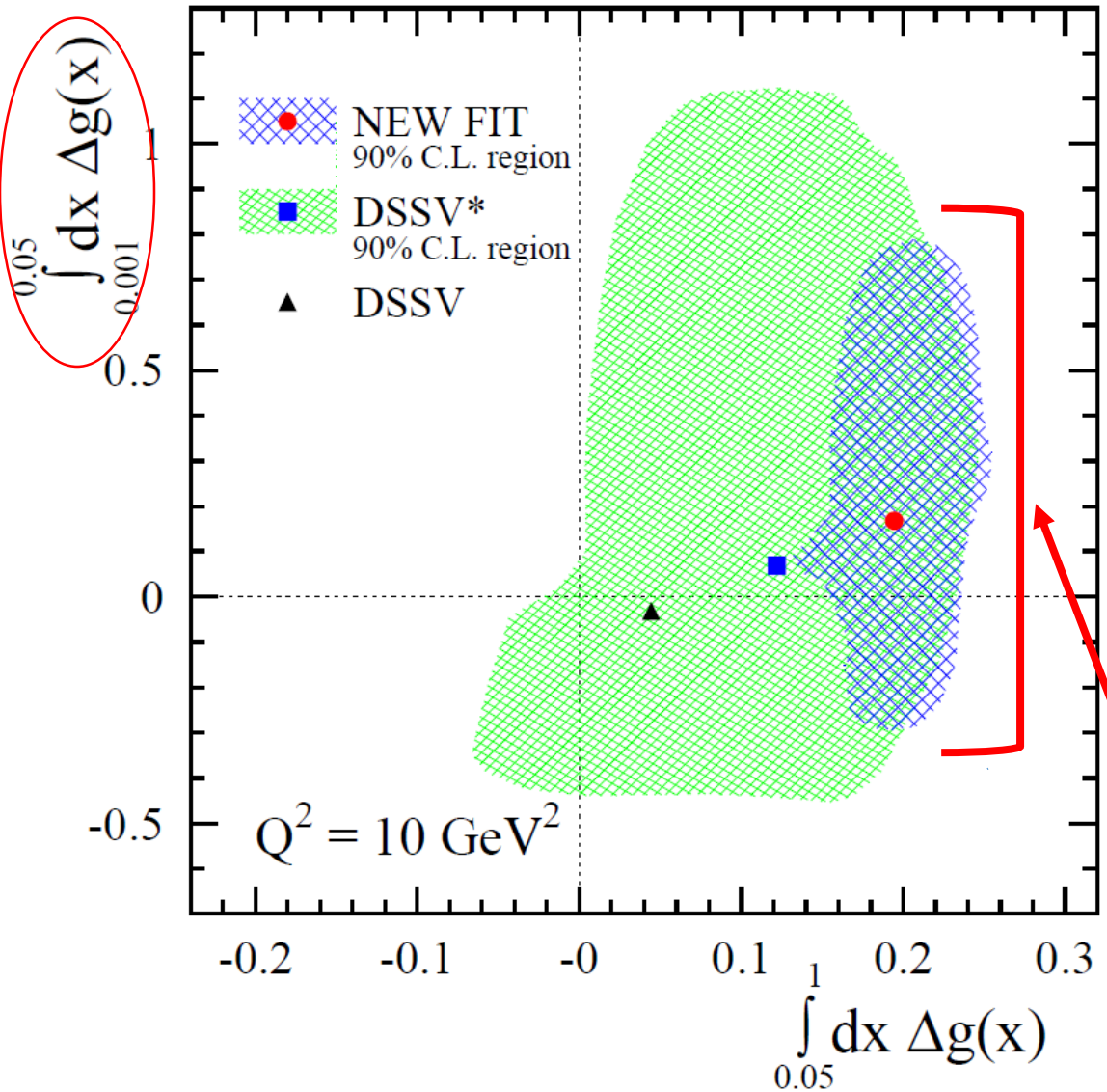

Phys. Rev. Lett. 113, 012001 (2014)

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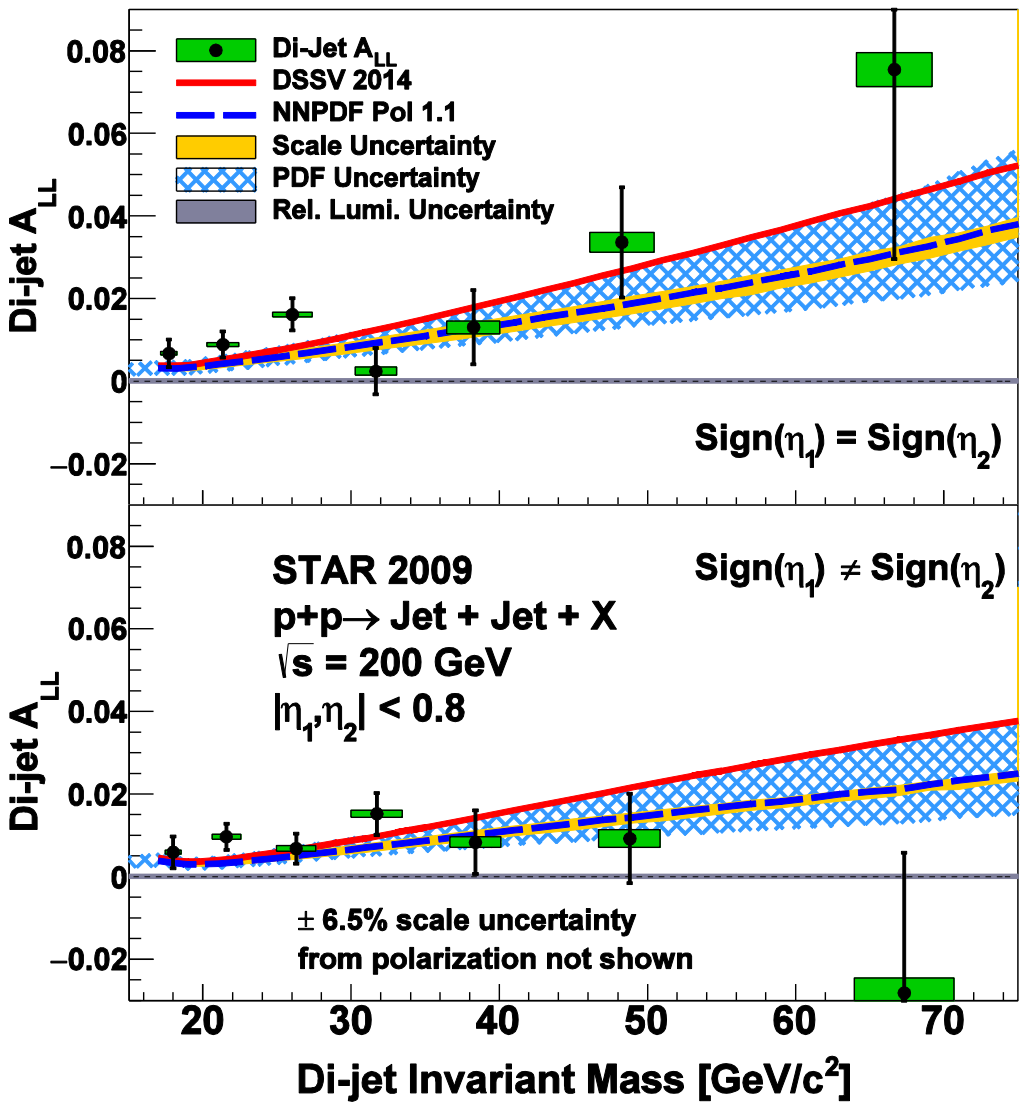
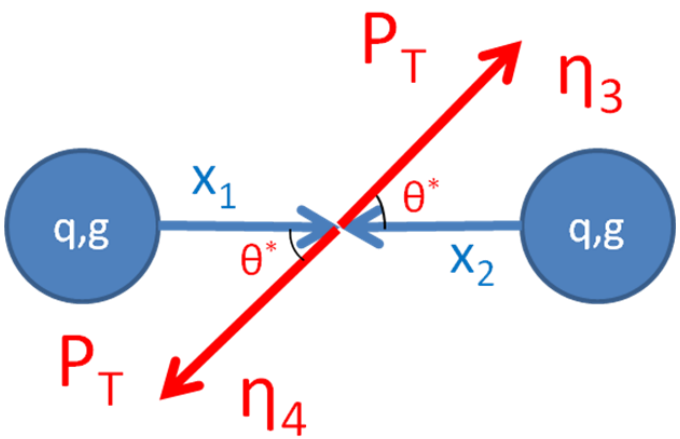
- Uncertainty shrinks substantially from DSSV* to new DSSV fit
- Uncertainty on integral over low x region is still sizable (only √s = 200 GeV RHIC data)

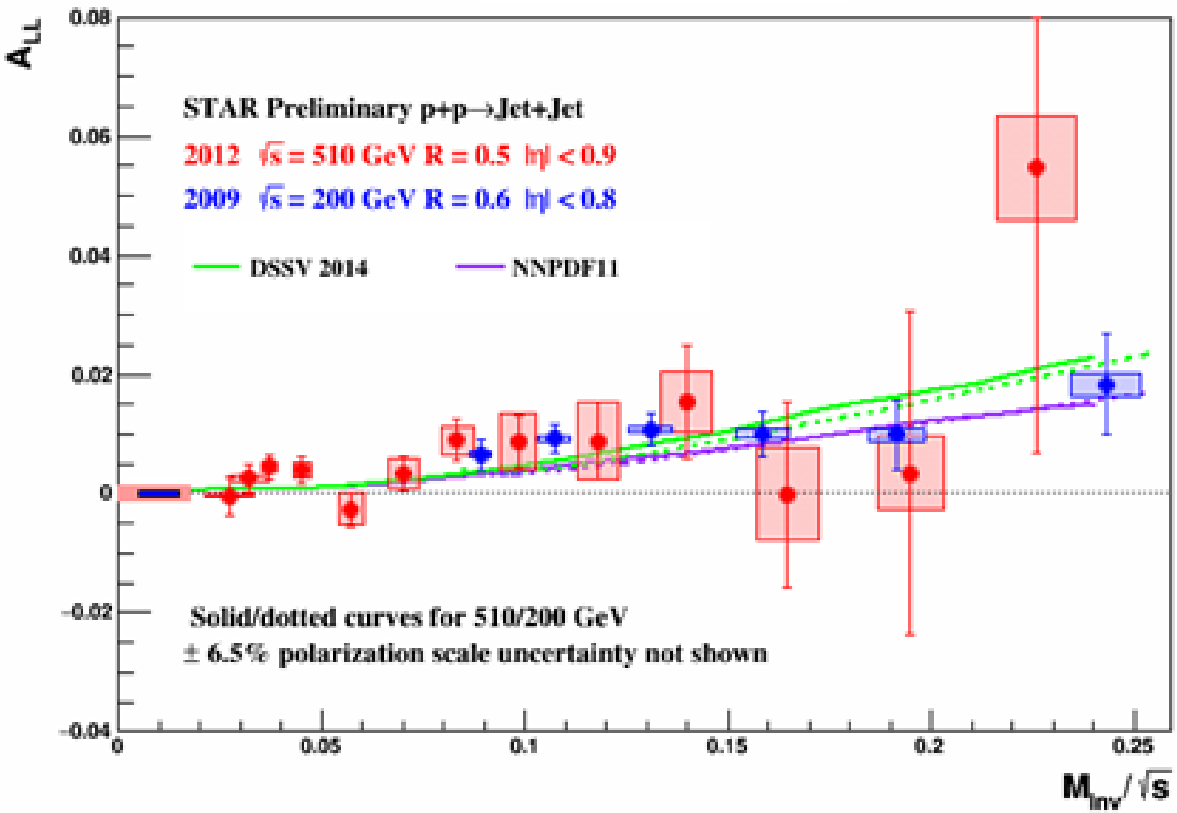
Di-jet A_{LL} (pp)



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

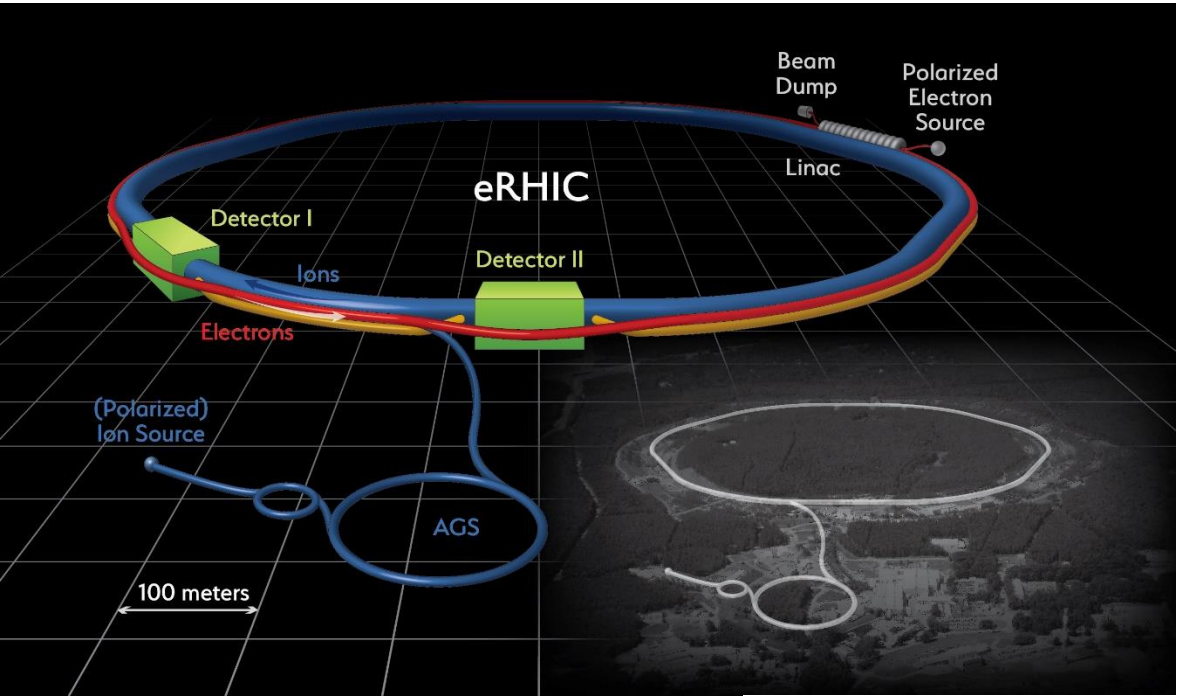


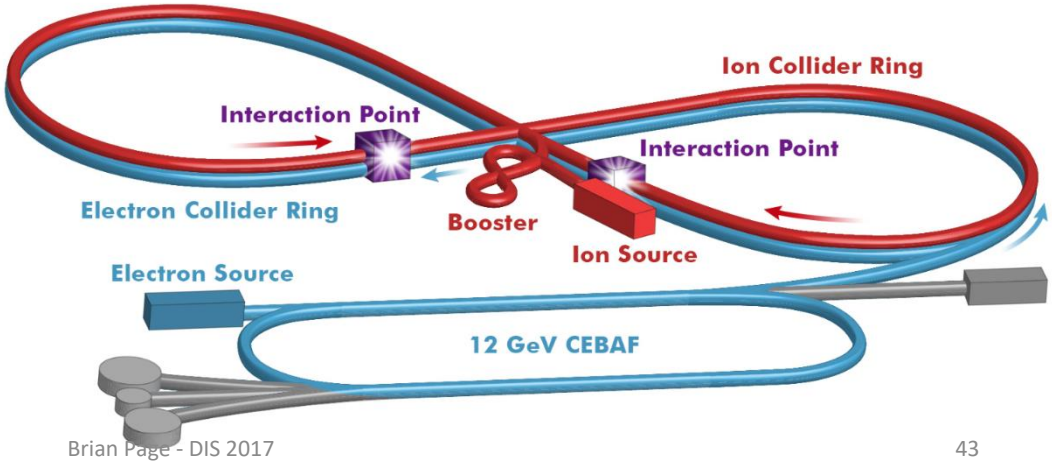
Di-jet A_{LL} (pp)



- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics
- Di-jet A_{LL} plotted vs $M_{inv}/\sqrt{s}$ (~$\sqrt{x_1 x_2}$ at L.O.) for data taken at $\sqrt{s}$ = 200 and 510 GeV
- 510 GeV data extend to lower $M_{inv}/\sqrt{s}$ (lower x) where ΔG not as well constrained while 200 GeV data give better precision at mid to high $M_{inv}/\sqrt{s}$

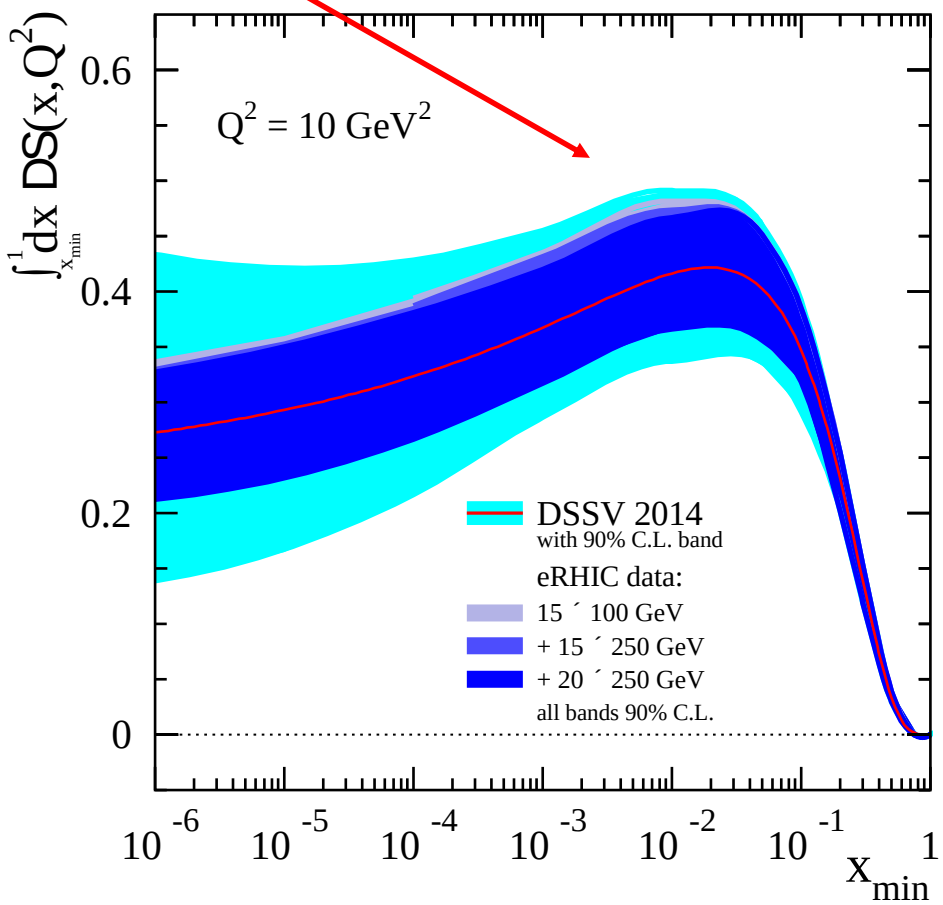
EIC: eRHIC or JLEIC





EIC: Impact on Quark Polarizations

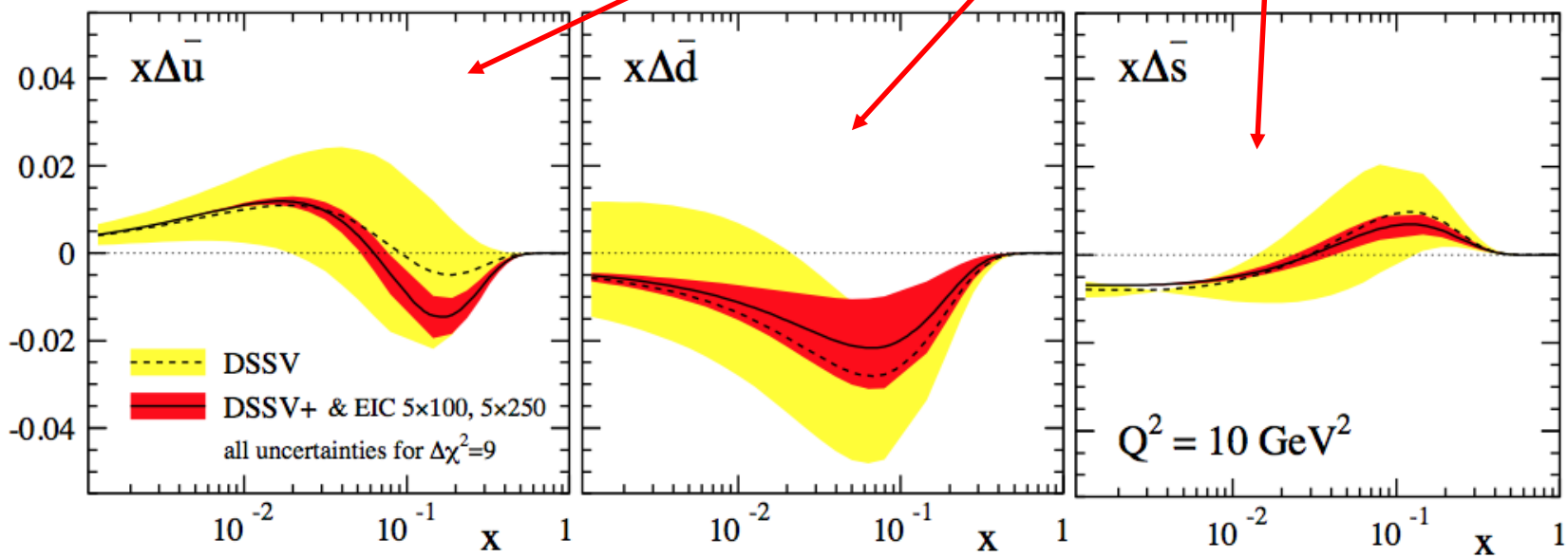
$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s} + \cdots)dx$$



- g_1 is sensitive to the sum of all quark and anti-quark polarized PDFs meaning an EIC will place strong constraints on $\Delta\Sigma$
- 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 are of particular interest as they provide information on non-perturbative aspects of proton structure

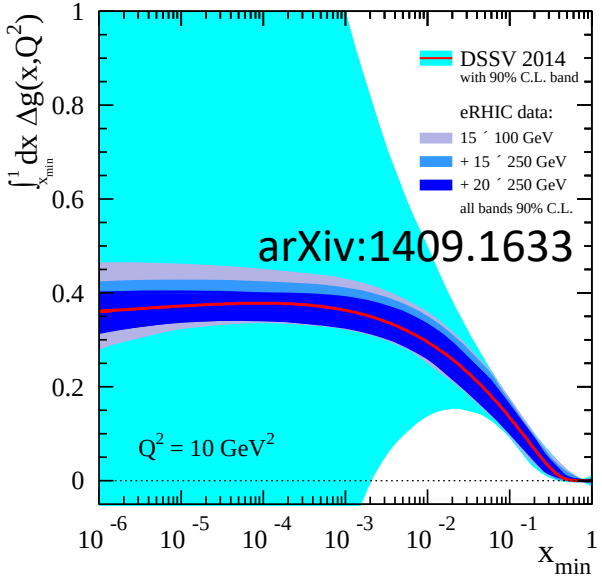
EIC: Impact on Quark Polarizations

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



- The above plots show the expected reduction in uncertainty for the polarized anti-quark distributions from EIC SIDIS data
- Individual quark and anti-quark distributions can also be measured at an EIC via charged current DIS which access different combinations of PDFs

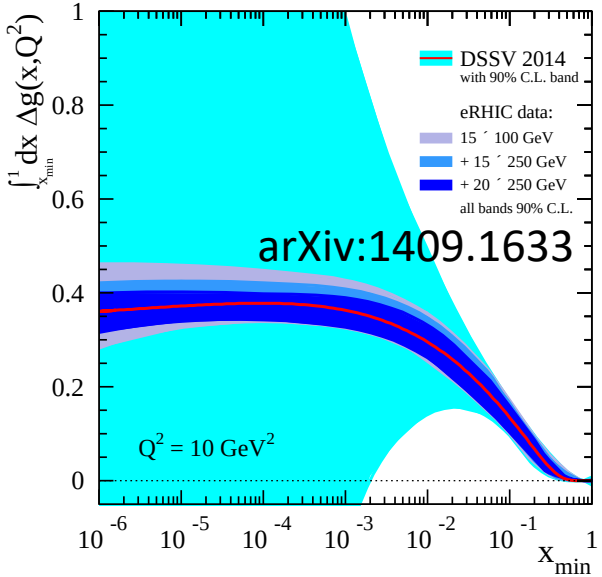
EIC: Solving the Spin Puzzle

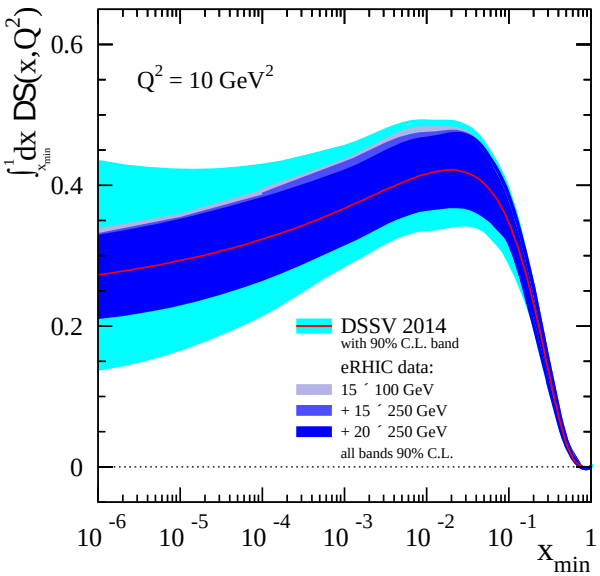


Gluon

- 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: Solving the Spin Puzzle





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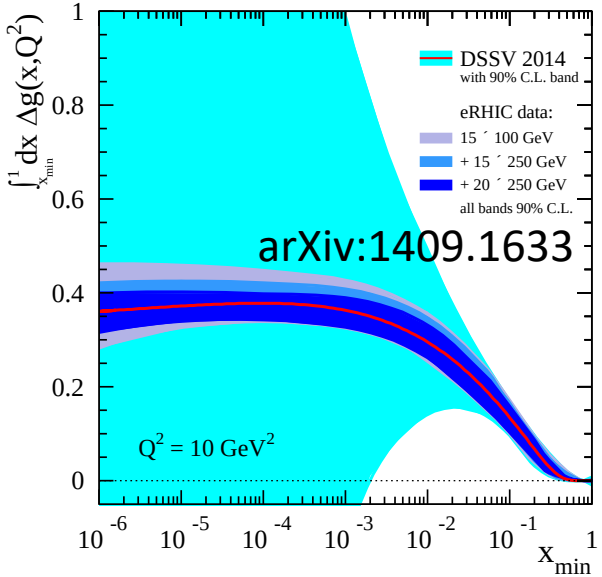
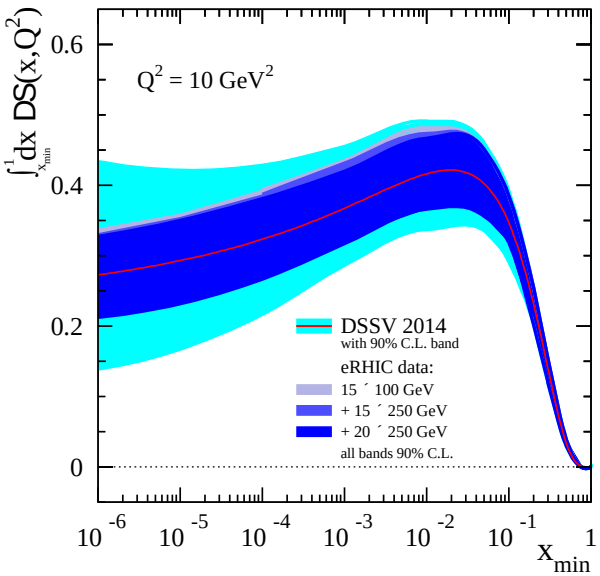
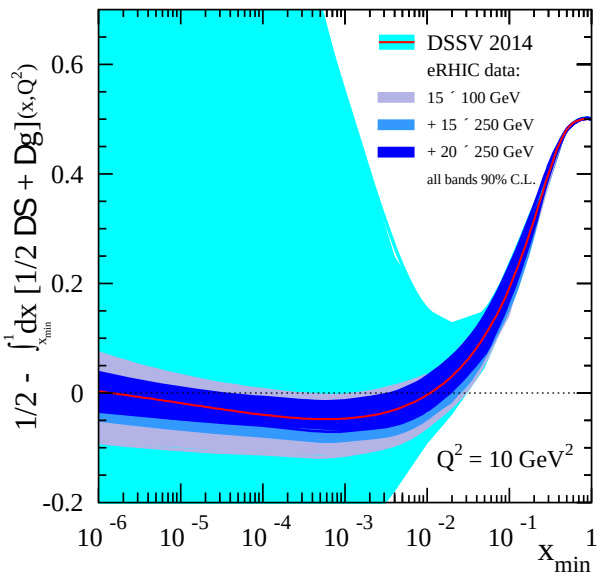
Quarks

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

EIC: Solving the Spin Puzzle







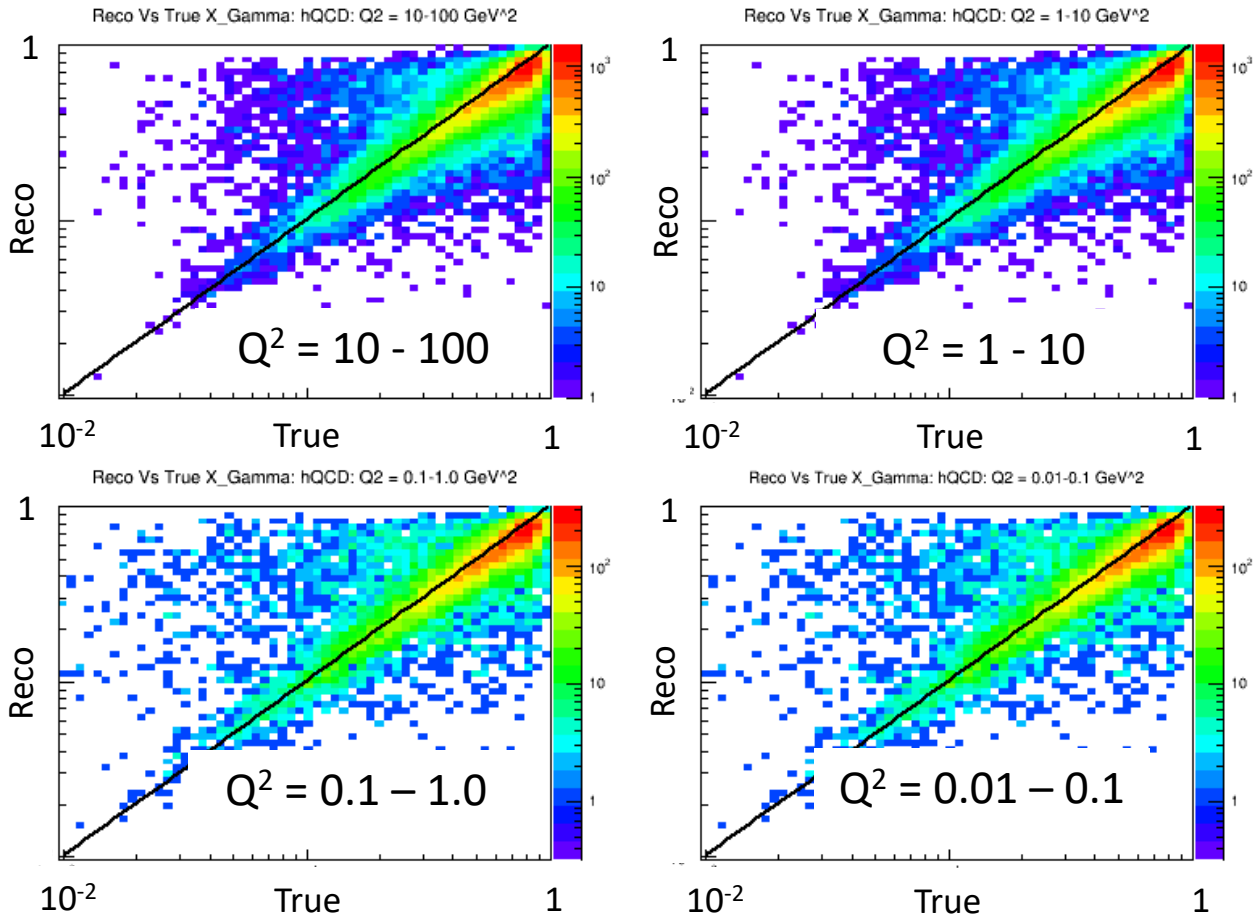
1/2 - Gluon - Quarks = orbital angular momentum

- 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

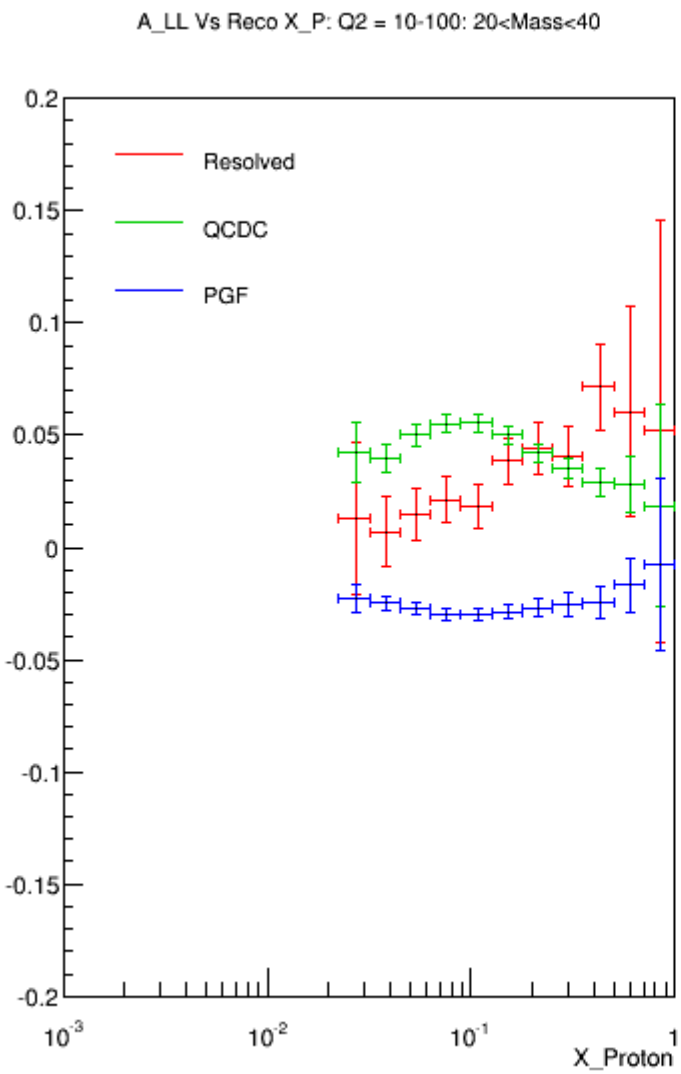
X_γ: Reconstructed Vs True

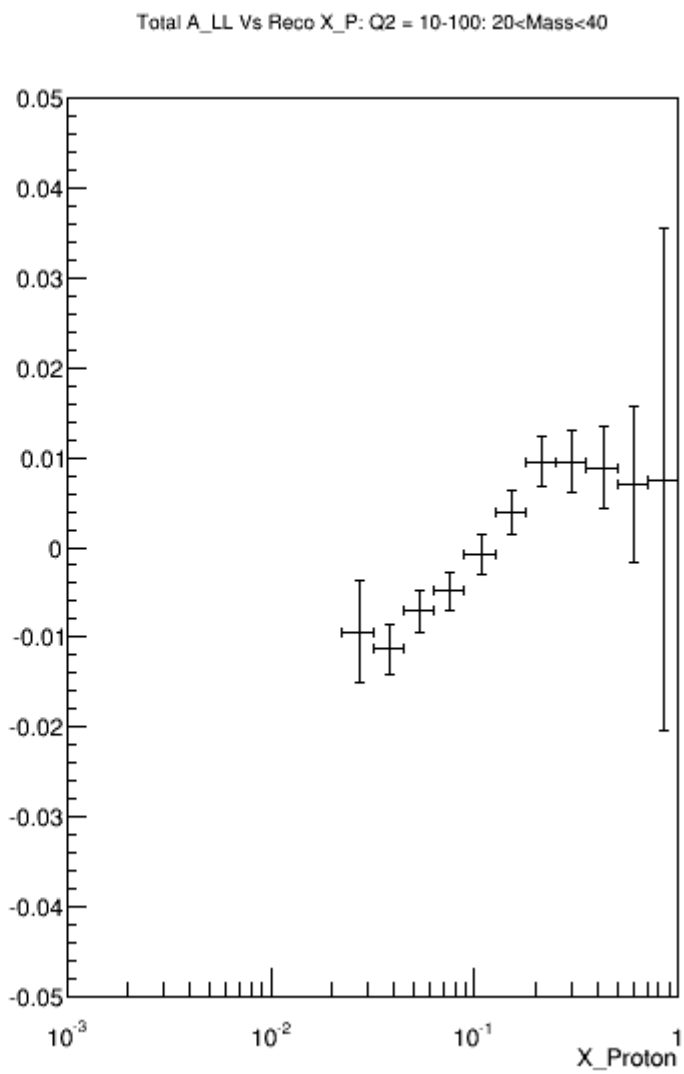


- Will use virtual photon momentum fraction to discriminate between resolved and direct processes
- See good agreement between reconstructed and true X_γ for all Q^2 ranges
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV

$$X_\gamma = \frac{1}{2E_e y}\left(m_{T1}e^{-y_1} + m_{T2}e^{-y_2}\right)$$

Asymmetry


A_LL Vs Reco X_P: Q2 = 10-100: 20<Mass<40
Resolved
QCDC
PGF
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^{-3}
10^{-2}
10^{-1}
1
X_Proton


Total A_LL Vs Reco X_P: Q2 = 10-100: 20<Mass<40
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
10^{-3}
10^{-2}
10^{-1}
1
X_Proton