# Probe gluon Sivers function with charged dijets

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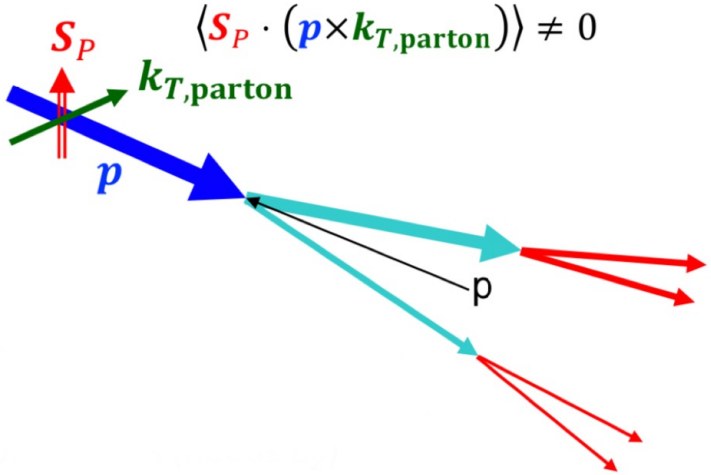
# Motivation

- **Gluon Sivers function:** correlation between gluon's transverse momentum with the proton spin




*… $k_T$ distribution of the partons could have an azimuthal asymmetry, when the hadron was transversely polarized.*

D. Sivers, Phys. Rev. D41 (1990) 83

# How to access GSF?

- **Photon-gluon fusion**
  - Main bkg: $\gamma^*$+q

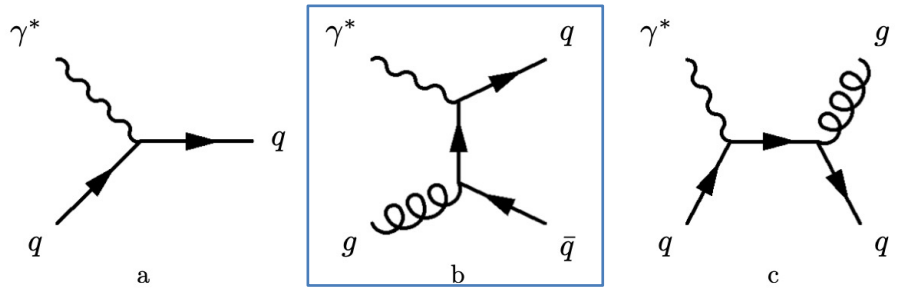



**Figure 1:** Feynman diagrams for hard subprocesses: a) $\mathcal{O}(\alpha_s^0)$ DIS, b) $\mathcal{O}(\alpha_s^1)$ Photon-Gluon Fusion, and c) $\mathcal{O}(\alpha_s^1)$ QCD Compton scattering.

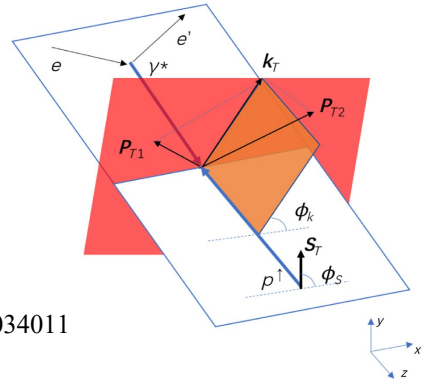
HERMES, JHEP 08 (2010) 130

- **Final states:** dijets, di-hadrons, D mesons, etc

L. Zheng, et. al., PRD 98 (2018) 034011

# Observable

- Azimuthal correlation between gluon $k_T$ and proton spin in γ*+p center-of-mass frame

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$$A_{UT}\sin(\varphi_k - \varphi_S)$$
$$\varphi_k - \varphi_S = \varphi_{kS}$$

- Use di-jet $\overrightarrow{k_T} = \vec{p}_{T,jet1} + \vec{p}_{T,jet2}$ to approximate gluon $k_T$

# Previous work: gluon Sivers

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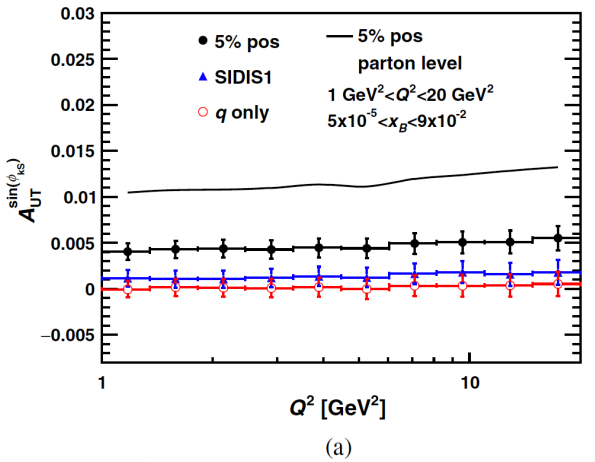
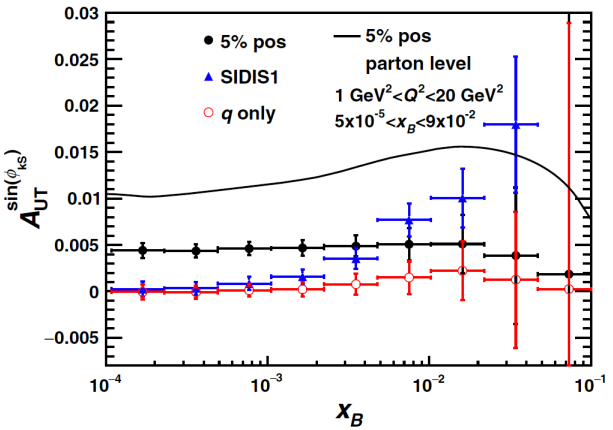
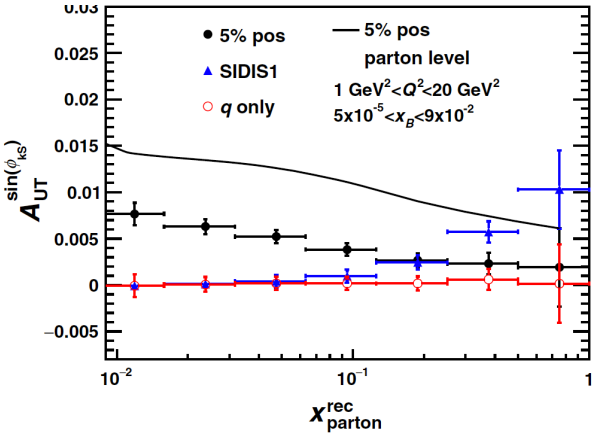



(a)

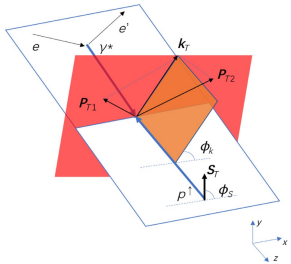



(b)




(c)

FIG. 13. SSA modulation dependent on $Q^2$ (a), $x_B$ (b) and $x_{\text{parton}}^{\text{rec}}$ (c) for the dijet channel with the following kinematic cuts: trigger jet $p_T^{\text{jet1}} > 4.5$ GeV and associated jet $p_T^{\text{jet2}} > 4$ GeV, $0.01 < y < 0.95$ and 1 GeV$^2$ $< Q^2 <$ 20 GeV$^2$ at the electron-proton beam energy 20 GeV $\times$ 250 GeV with an integrated luminosity $\mathcal{L}_{\text{int}} = 10$ fb$^{-1}$.




$$A_{UT}\sin(\varphi_k - \varphi_S)$$
$$\varphi_k - \varphi_S = \varphi_{kS}$$

# Simulation details

- PYTHIA6.428
  - pythia-eic within eic-shell
    - https://gitlab.com/eic/mceg/PYTHIA-RAD-CORR
  - Tuned to HERA data
  - PYTHIA8 could not simulate photon-gluon fusion

- Collision: ep, 18x275, $Q^2 > 1$ GeV$^2$

- Processes: $\gamma^* + g \rightarrow q + \bar{q}$, $\gamma^* + q \rightarrow g + q$ ($\sigma_{\text{total}}$ = 6.2e-5 mb)
  - Based on RUN_CARD
  - Statistics: ~400k events, L = 6.4e-3 fb$^{-1}$
  - ISR turned off
    - Avoid ambiguity with virtual photon interacting with the gluon radiated by a quark.

# Procedure

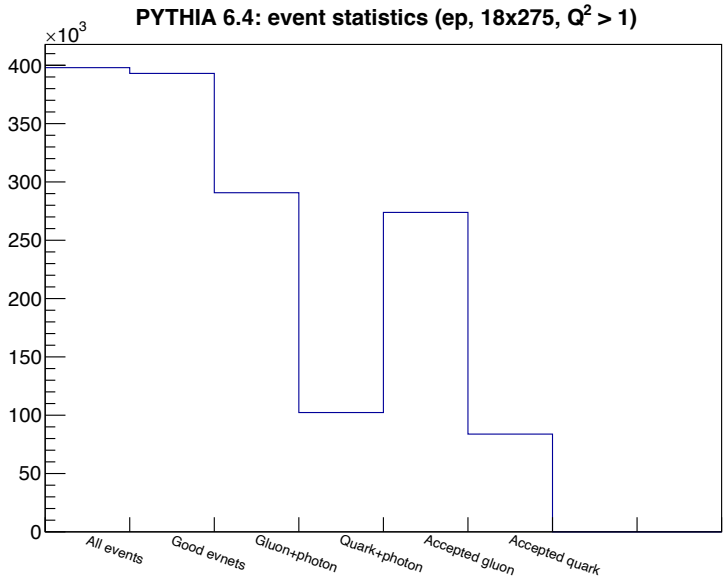
- MC level
  - Event selection: $0.01 < y < 0.95$
  - Identify the parton that interacts with the virtual photon
  - Extract parton $k_T$ in $\gamma^*$+p CoM frame, and calculate its angular difference ($\phi_{kS}^{gluon}$) to the transverse spin
    - Transverse spin is assumed to align along y-coordinate
  - For $\gamma^*$+g, apply a weight by hand to simulate asymmetry
    - Weight = $1 + A_{UT}*\sin(\phi_{kS}^{gluon})$, $A_{UT} = 0.015$
  - For $\gamma^*$+q, do not apply any weights

# Procedure

- Reconstruction level
  - Use official jet collection: charged, anti-$k_T$, R = 1.0
  - Apply kinematic cuts: $|\eta_{jet}^{lab}| < 2.5$
  - In $\gamma^*$+p CoM frame
    - Find leading and sub-leading jets
    - Accept events if $p_{T,lead}^{jet,ch} > 3.5$ GeV/c, $p_{T,sublead}^{jet,ch} > 3$ GeV/c
    - Extract di-jet pair $k_T$, and calculate its angular separation ($\phi_{kS}^{dijet}$) to transverse spin (*y* coordinate)
  - Apply weights = $1 + A_{UT}*\sin(\phi_{kS}^{gluon})$ for $\gamma^*$+g events only

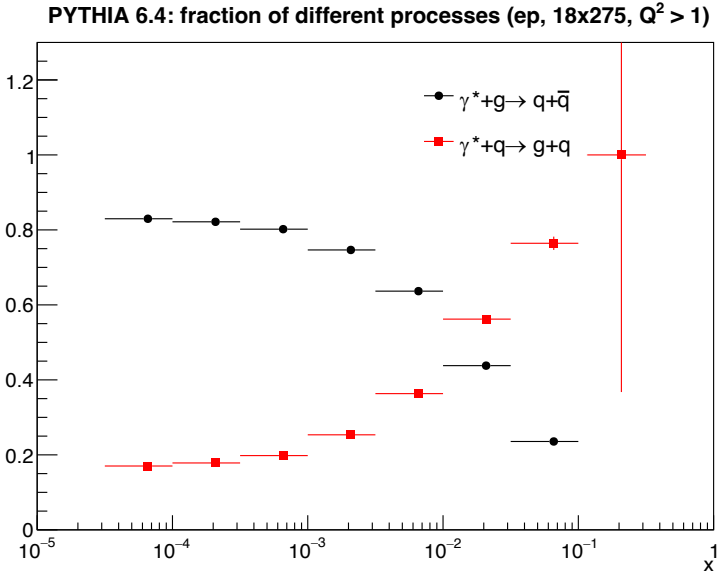
- To extract $A_{UT}$, fit $\phi_{kS}$ distribution with "[0]*(1+[1]*sin(x))" in *x* and $Q^2$ bins

# Event statistics




- Good events
  - $Q^2 > 1$
  - $0.01 < y < 0.95$

# Fraction of quark vs. gluon channels

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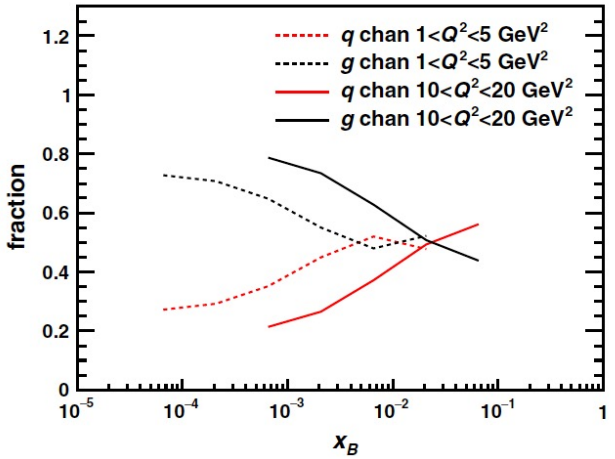
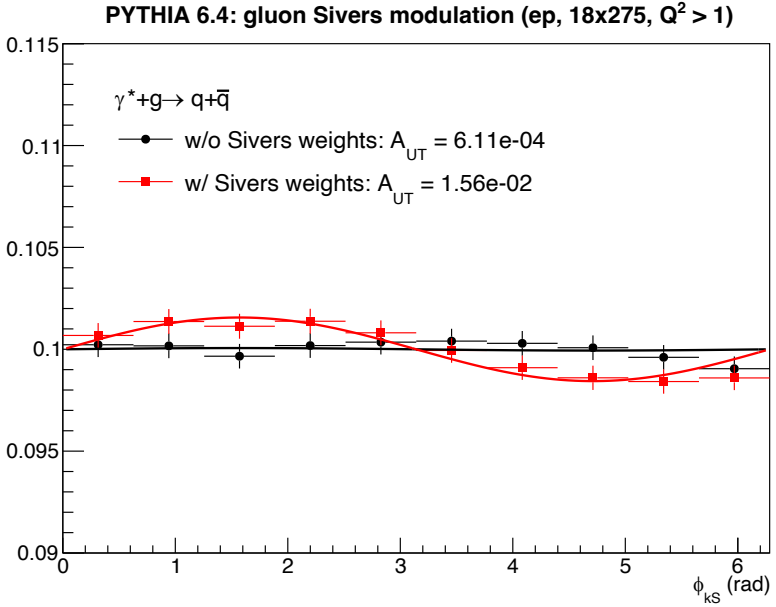


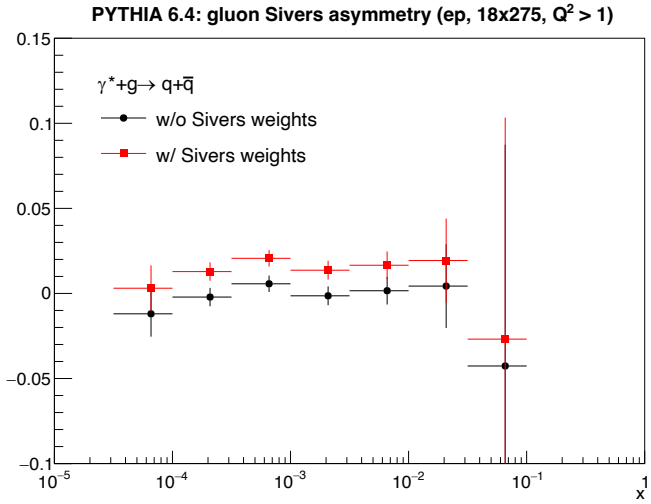

FIG. 12. Underlying subprocess fraction initiated by quarks (red curves) or gluons (black curves) for dijet production. The solid and dotted curves represent the $Q^2$ bins of $10 < Q^2 < 20$ GeV$^2$ and $1 < Q^2 < 5$ GeV$^2$, respectively.

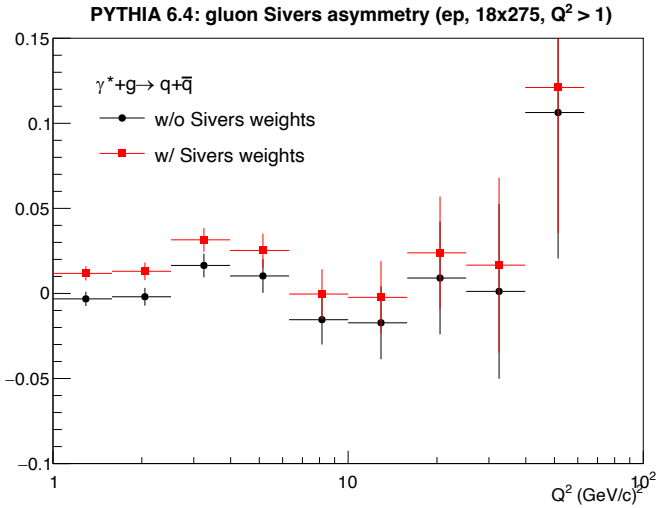
# Sanity check




- For default simulation, extracted $A_{UT} \sim 0$
- For weighted simulation, extracted $A_{UT}$ agrees with the input value of 0.015

# Sivers effect for gluons

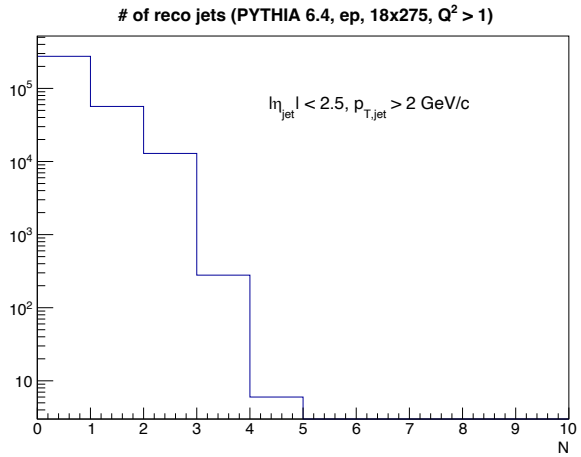


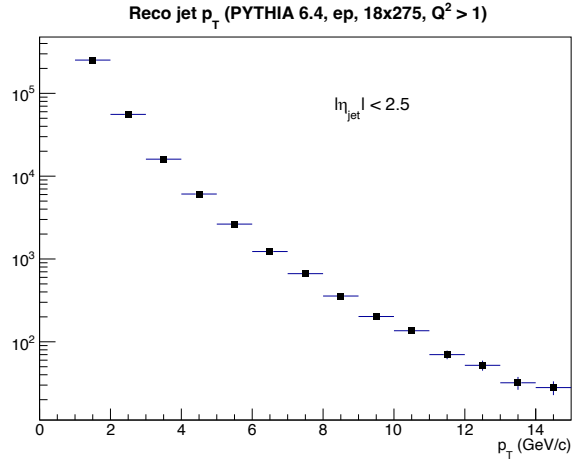




- $\gamma^*$+g events only
- Errors are from fit function
- Confirms that the weighting procedure works as expected

# Jet reconstruction

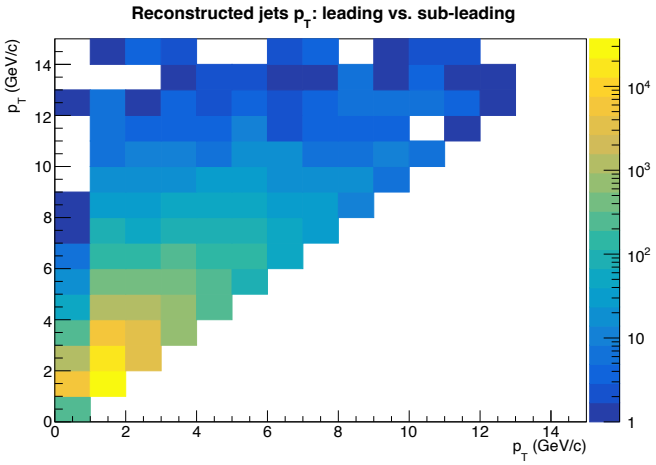
- Official “ReconstructedChargedJets” branch
  - Anti-$k_T$, $R = 1.0$
  - Charged track only
  - $|\eta_{jet}^{lab}| < 2.5$

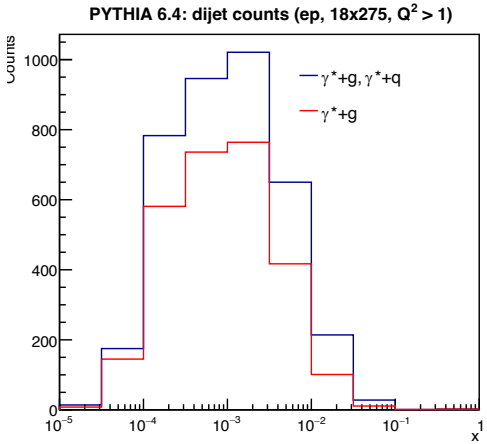


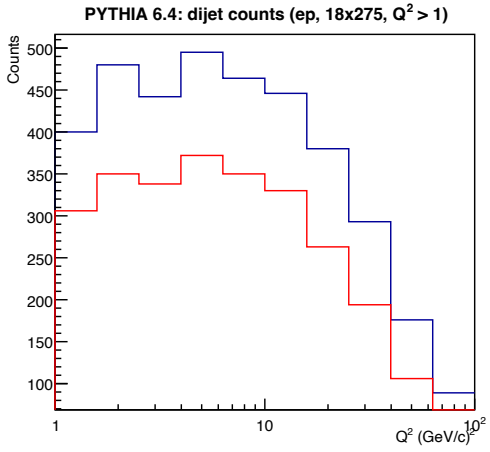



# Dijet selection

- Boost to γ*+p center-of-mass frame
- $p_{T,jet}^{lead} > 3.5$ GeV/c, $p_{T,jet}^{sub} > 3$ GeV/c

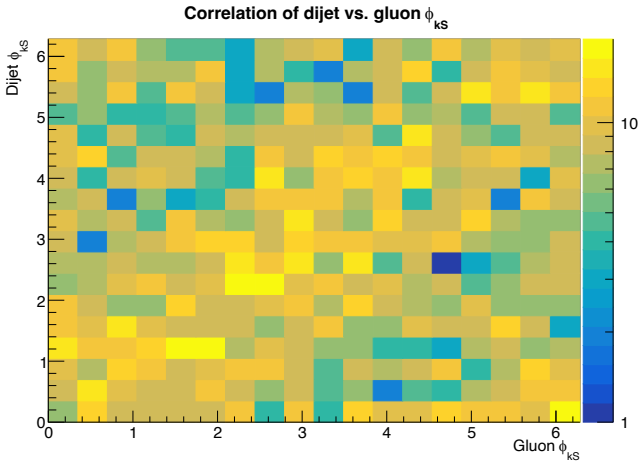


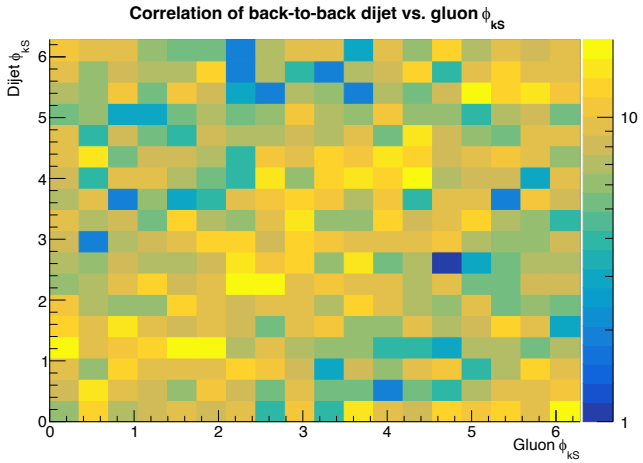



# Sivers angle: gluon vs. dijet

All dijet pairs



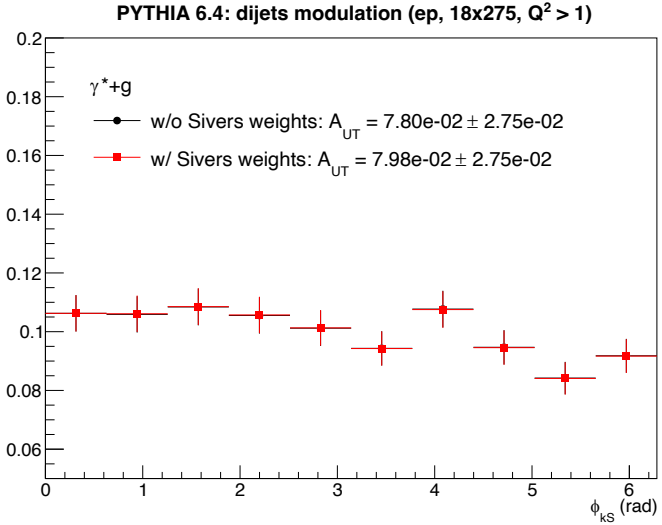

Back-to-back dijet pairs



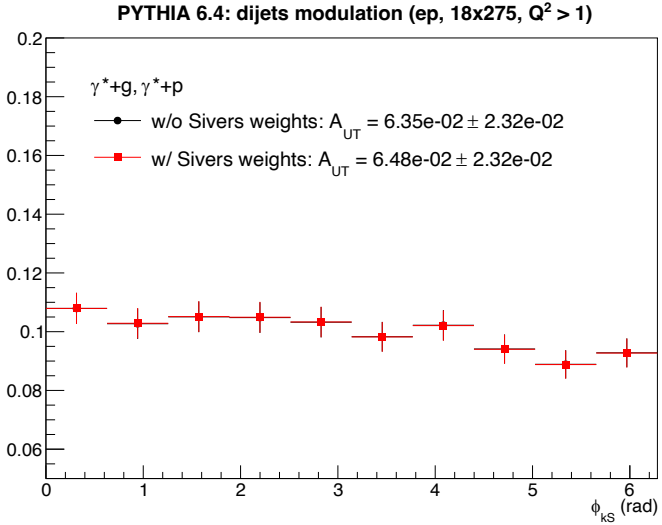

- Weak correlation for charged di-jet pairs with gluon

# $\phi_{kS}^{dijet}$ distributions for dijets

$\gamma^*$+g

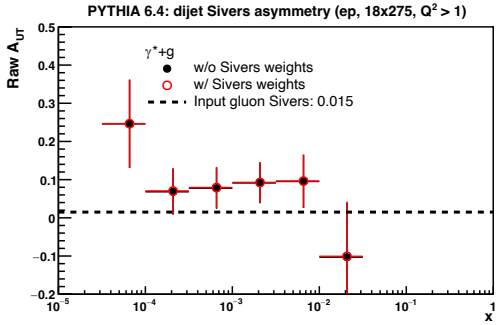


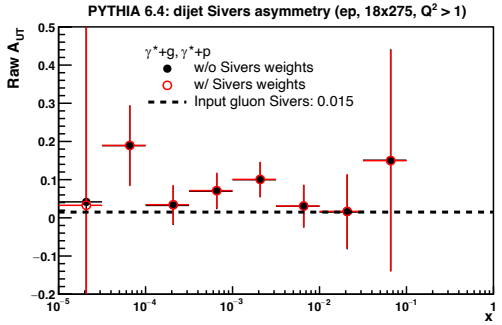

$\gamma^*$+g, $\gamma^*$+q

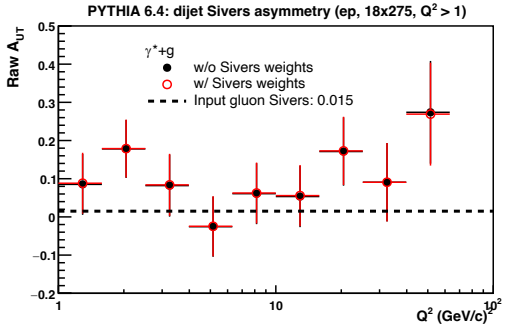


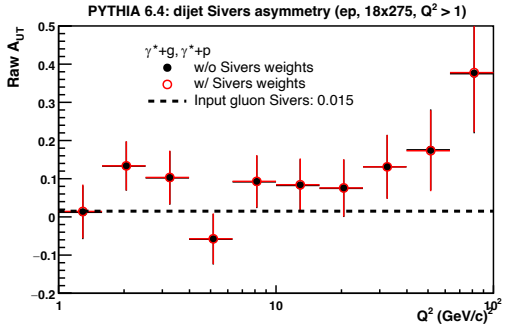

- Without including Sivers asymmetry, the extracted $A_{UT}$ is about $3\sigma$ away from 0. Biases in the measurement?
- Nevertheless, differences in extracted $A_{UT}$ with and without including Sivers asymmetry are consistent with the input value of 0.015

# Sivers asymmetry for dijets



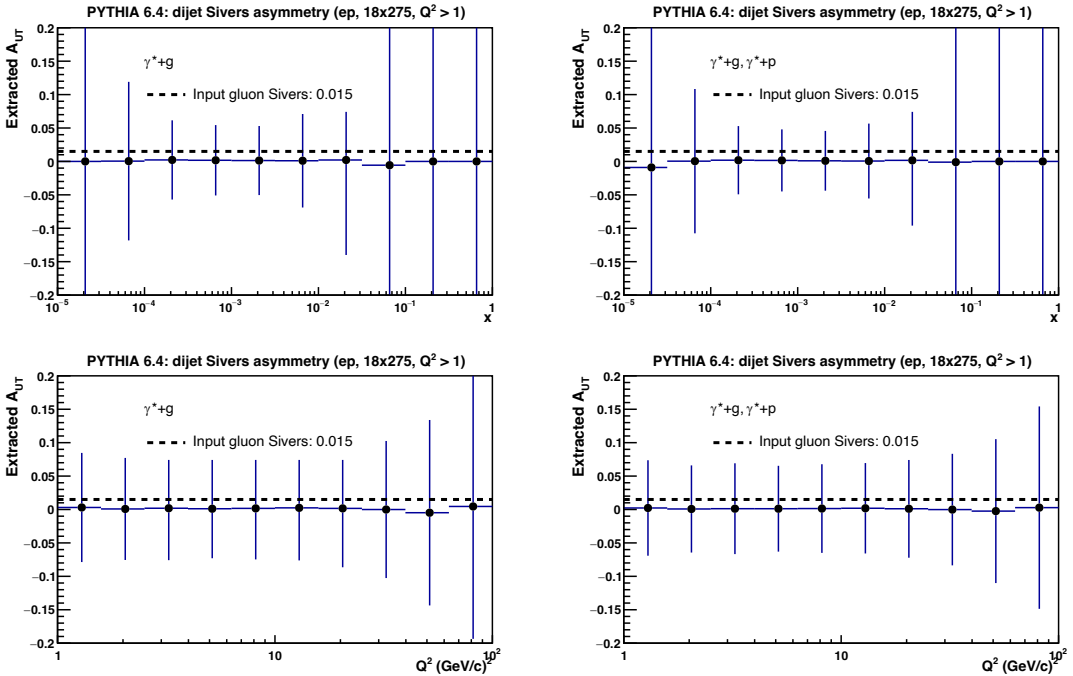




- Errors on $A_{UT}$ are from fit functions.

# Sivers asymmetry for dijets




- Take the difference in extracted $A_{UT}$ between with and without applying Sivers asymmetry for $\gamma^*$+g events
- Errors are calculated as:

In order to estimate the statistical uncertainty of the SSA in our simulation, we use $\delta A = \sqrt{\frac{1}{P^2 N} - \frac{A^2}{N}}$ from Ref. [44], where $N$ represents the count of selected pairs in a certain kinematic bin, and $P$ indicates the polarization of the proton beam. In this work, we assume a polarization $P = 70\%$ for

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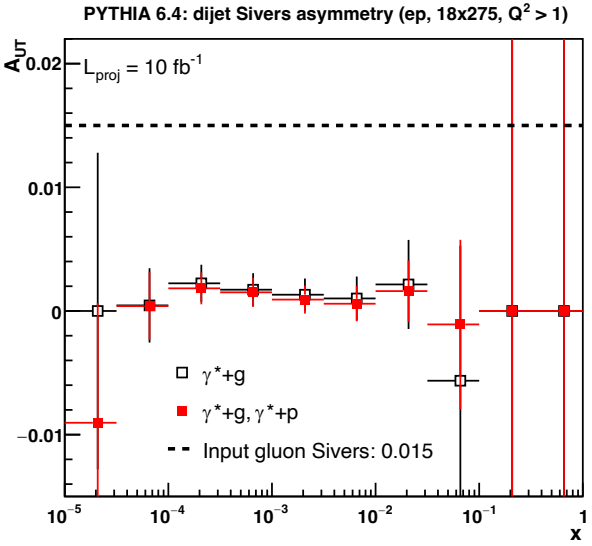
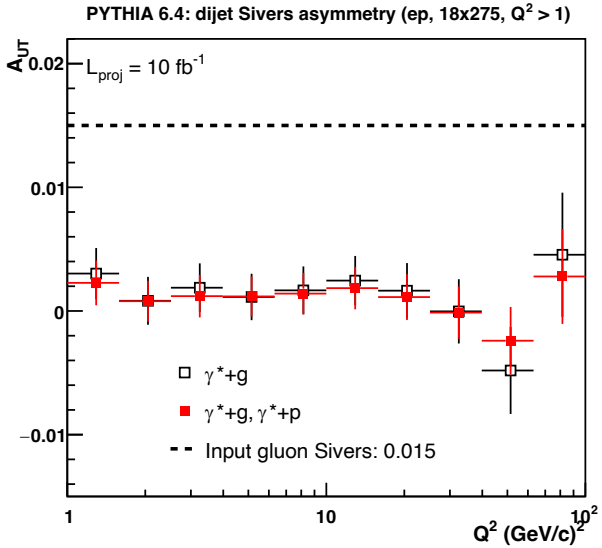
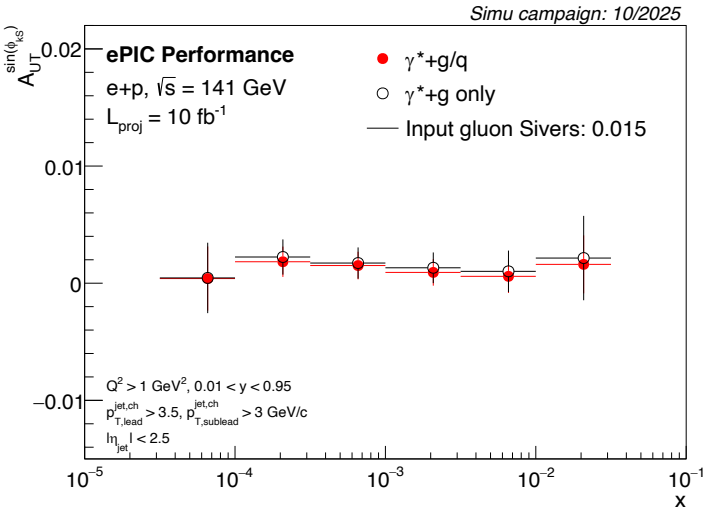
# Projected precision for dijets

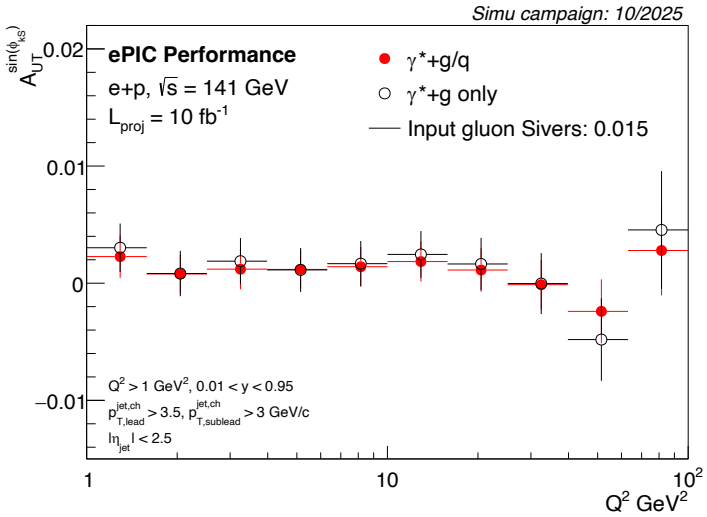



- Scale error bars in previous slide to the projected luminosity of 10 $fb^{-1}$
- About a factor 10 reduction in measured dijet asymmetry compared to input gluon Sivers asymmetry

# Candidate pTDR plots



# Summary

- Dataset: ~400k PYTHIA 6 events
  - ep, 18x275, $Q^2 > 1$ GeV$^2$
  - Include: $\gamma^* + g \rightarrow q + \bar{q}, \gamma^* + q \rightarrow g + q$

- Utilizing charged dijets, measured $A_{UT}$ is about a factor of 10 smaller than input gluon Sivers asymmetry

- Is this good enough for pTDR or we should wait to use full jets?