Jet Physics at an EIC

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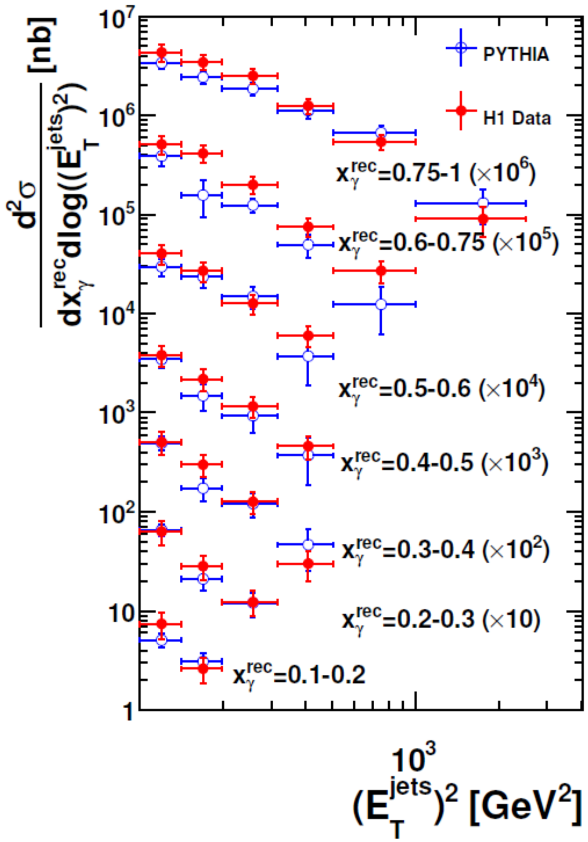
Outline

- Jets as parton surrogates
  - Accessing the (Un)polarized photon structure with dijets
  - Accessing ΔG with dijets
- Preliminary look at jet substructure at an EIC

Simulation Details / Particle Cuts

- Electron – Proton events generated at √s = 141 GeV using PYTHIA (Full energy eRHIC design 20x250 GeV electron x proton)
- 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



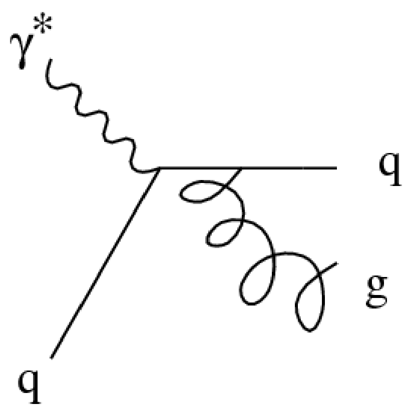
PRD 96, 074035 (2017)

Jets as Parton Surrogates

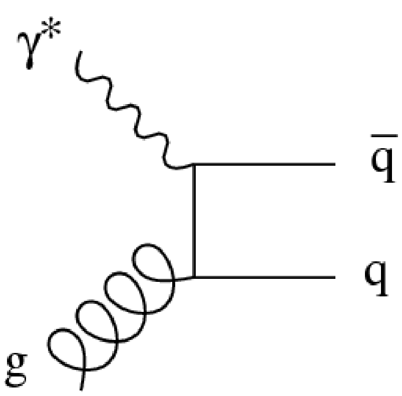
- Jets should approximate the energy and momentum of the partons from which they arise allowing the reconstruction of event kinematics such as x_γ (photon momentum fraction) and x_P (parton momentum fraction) among many other applications

- x_γ will allow tagging of direct vs resolved subprocesses which will be important for studies of photon structure (Phys. Rev. D 96, 074035) as well as alternative methods for accessing ΔG

Direct (Dominant for $Q^2 > 0$)

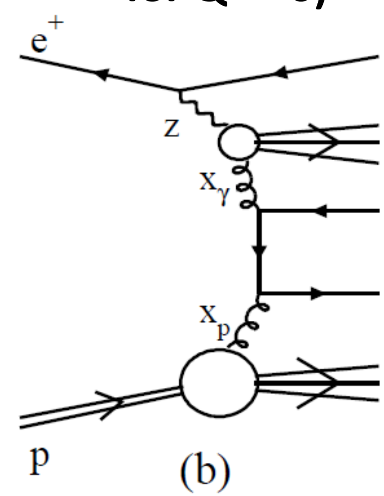


QCD – Compton

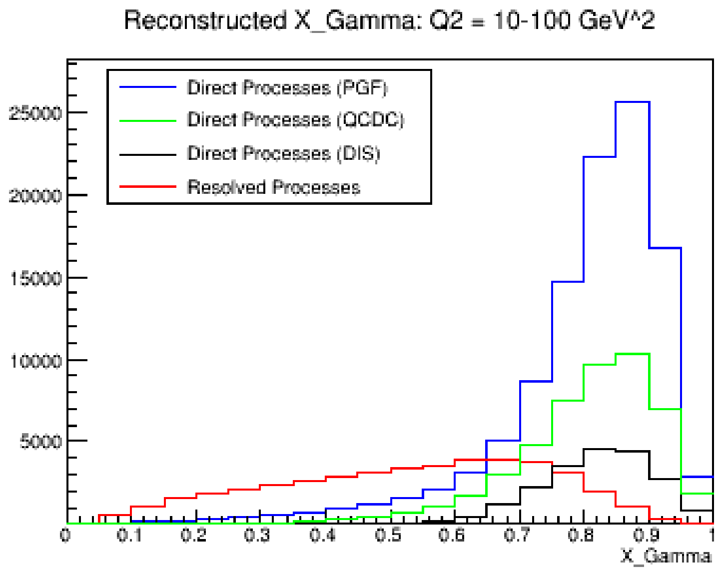


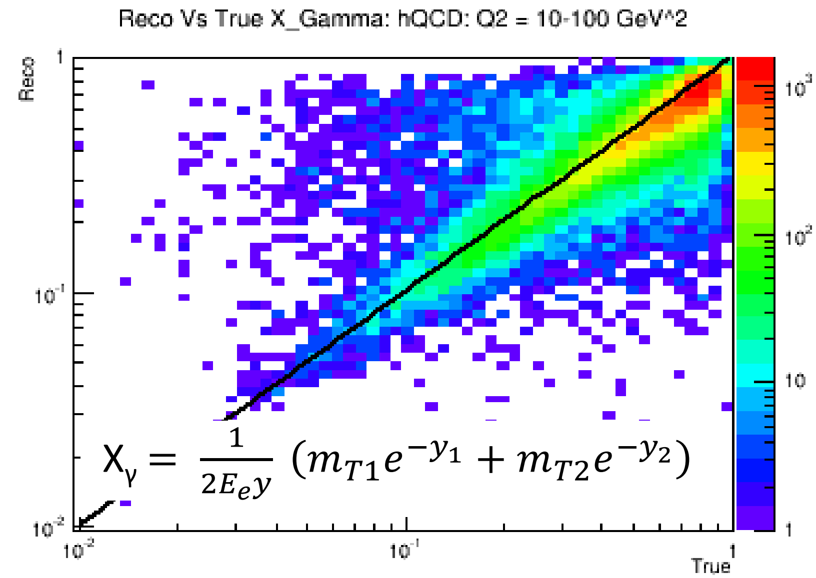
Photon-Gluon Fusion

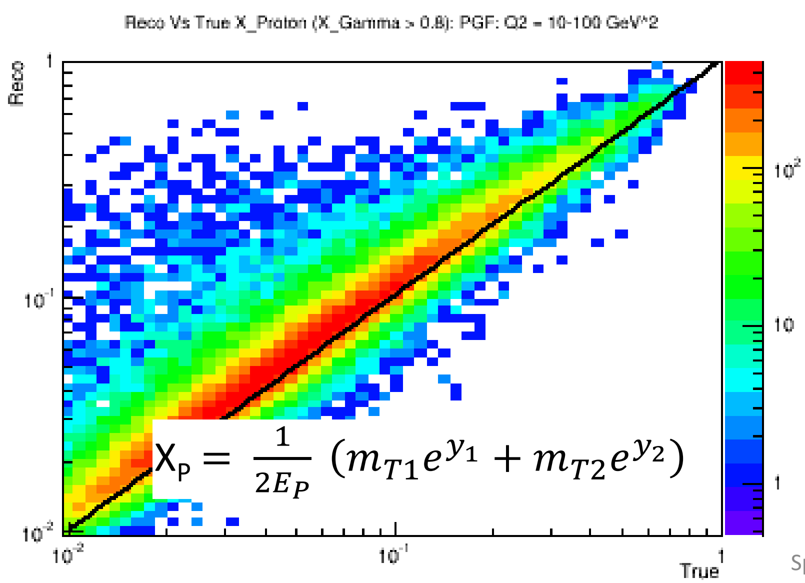
Resolved (Dominant for $Q^2 < 0$)



Subprocess Tagging and Kinematics

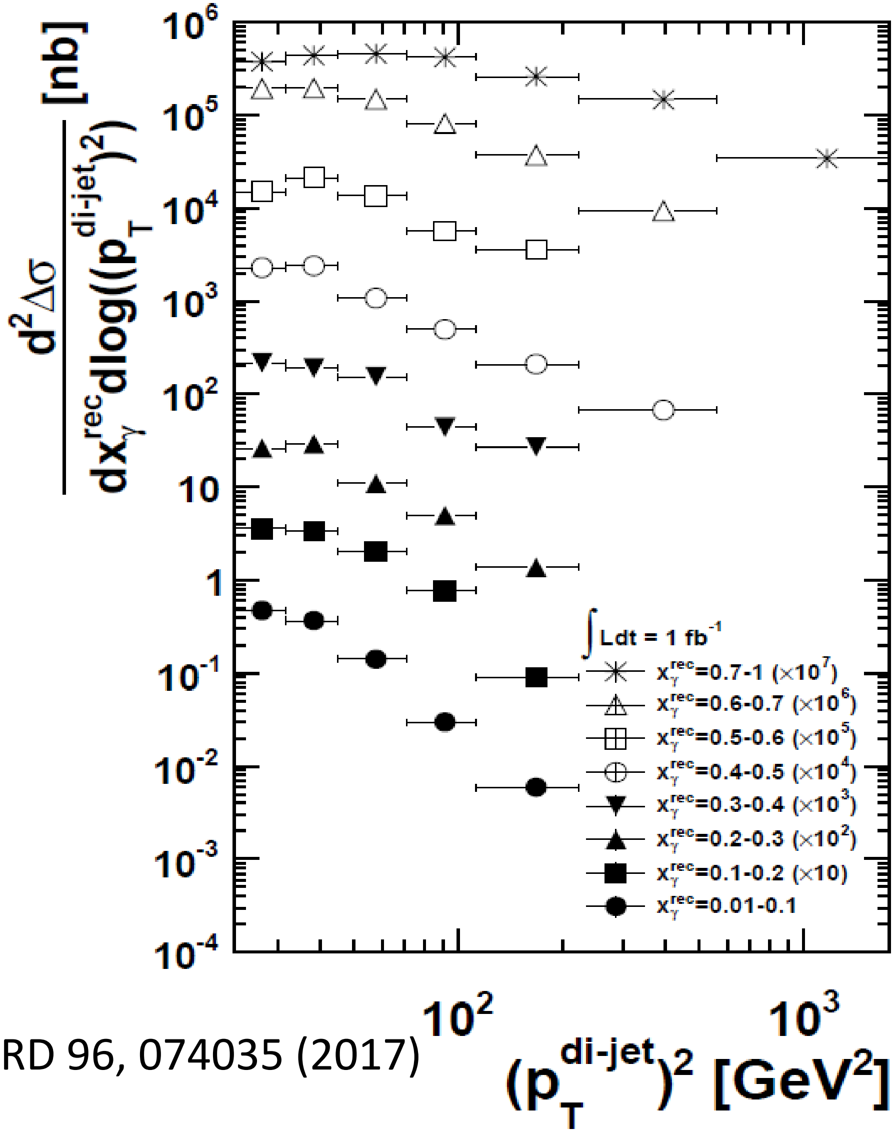




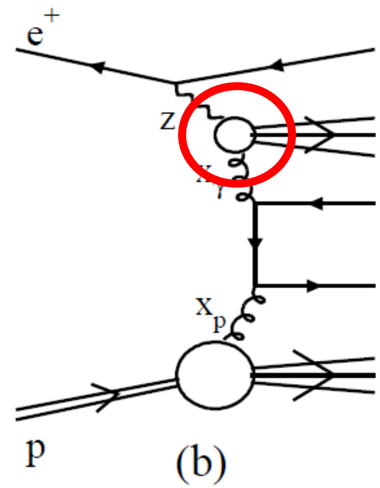


- Use dijet energy and momentum to reconstruct x_γ and x_P
- Cutting on x_γ can enhance or reduce resolved contribution (which becomes more prominent at low Q^2) depending on the analysis needs
- Both x_γ and x_P accurately reconstructed

Example: Photon Structure



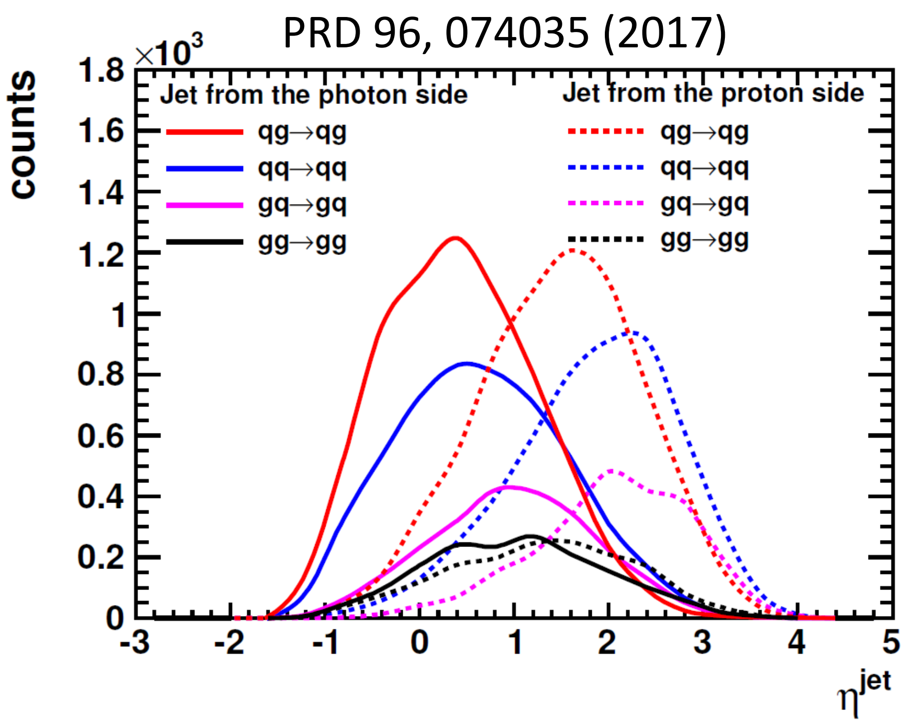
PRD 96, 074035 (2017)



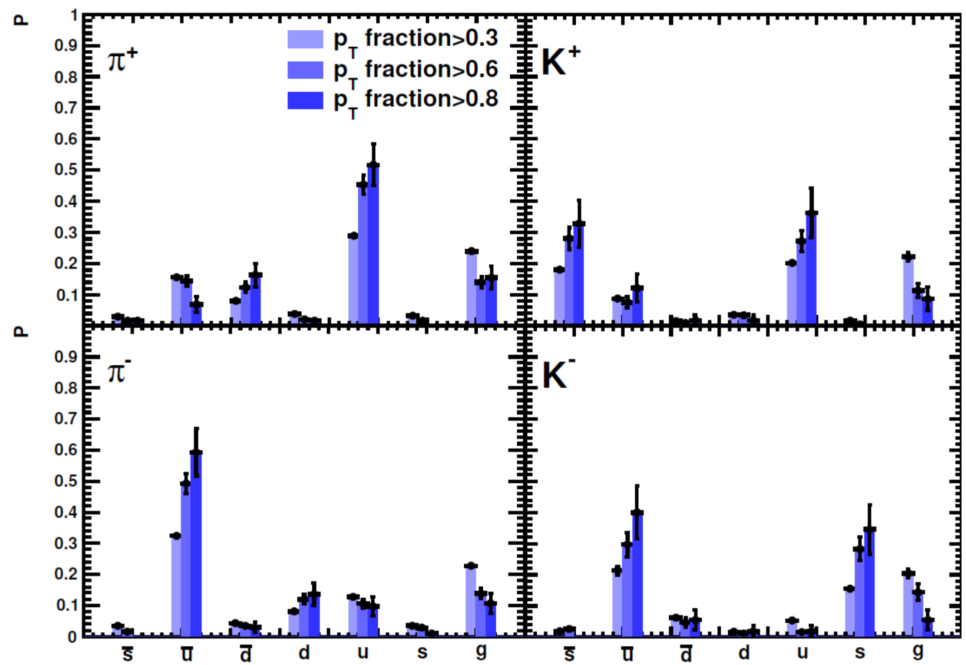
Study the polarized and unpolarized hadronic structure of the photon

- In QCD, the photon can be considered a superposition of a bare photon state and a hadronic state
- Want to characterize the polarized and unpolarized structure of this hadronic state (photon PDFs)
- EIC cross section data will allow very precise extractions of these PDFs and give access to the polarized structure for the first time

Flavor Tagging



- Would also like to look more differentially and constrain photon PDFs for different parton flavors
- See that the jet associated with the photon preferentially goes to lower pseudorapidities



- Can tag the highest p_T hadron inside the jet associated with the photon to enhance certain flavors
- See π^+ and π^- enhance u and u-bar fractions while kaons enhance u/u-bar and s/s-bar
- Take advantage of the excellent PID capabilities of the planned EIC detectors

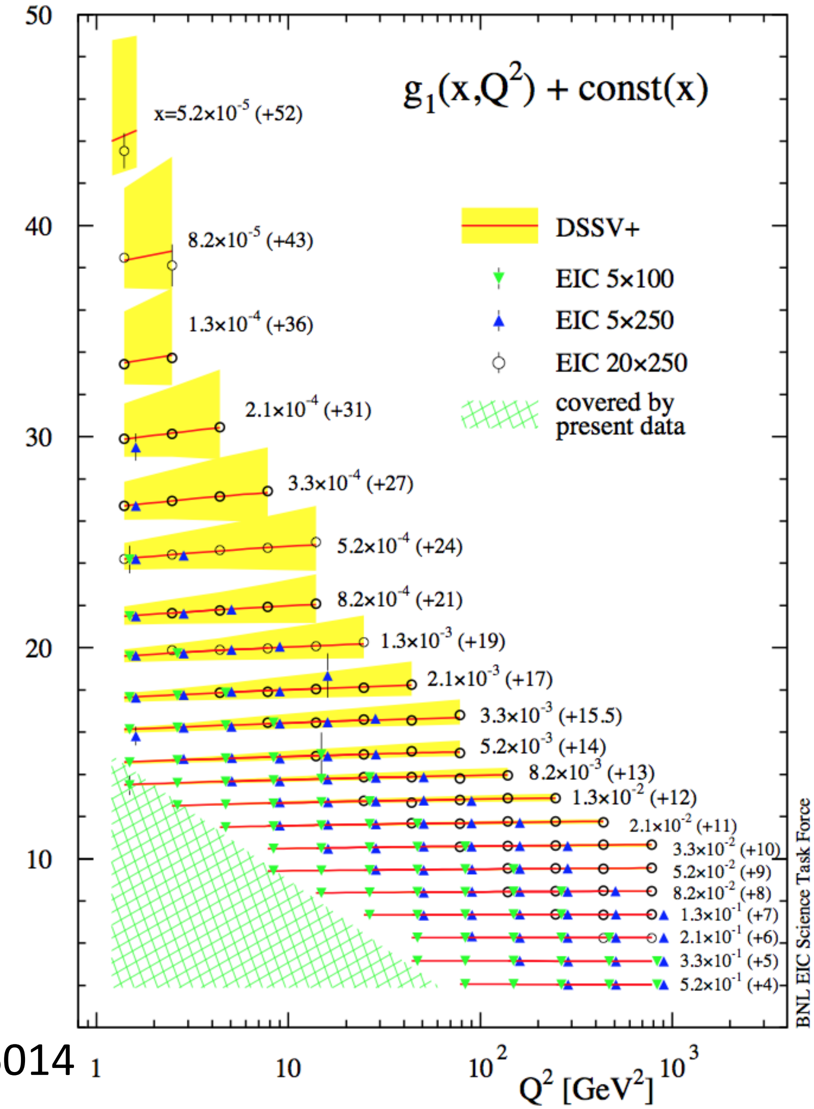
Example: Accessing ΔG with Dijets

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

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

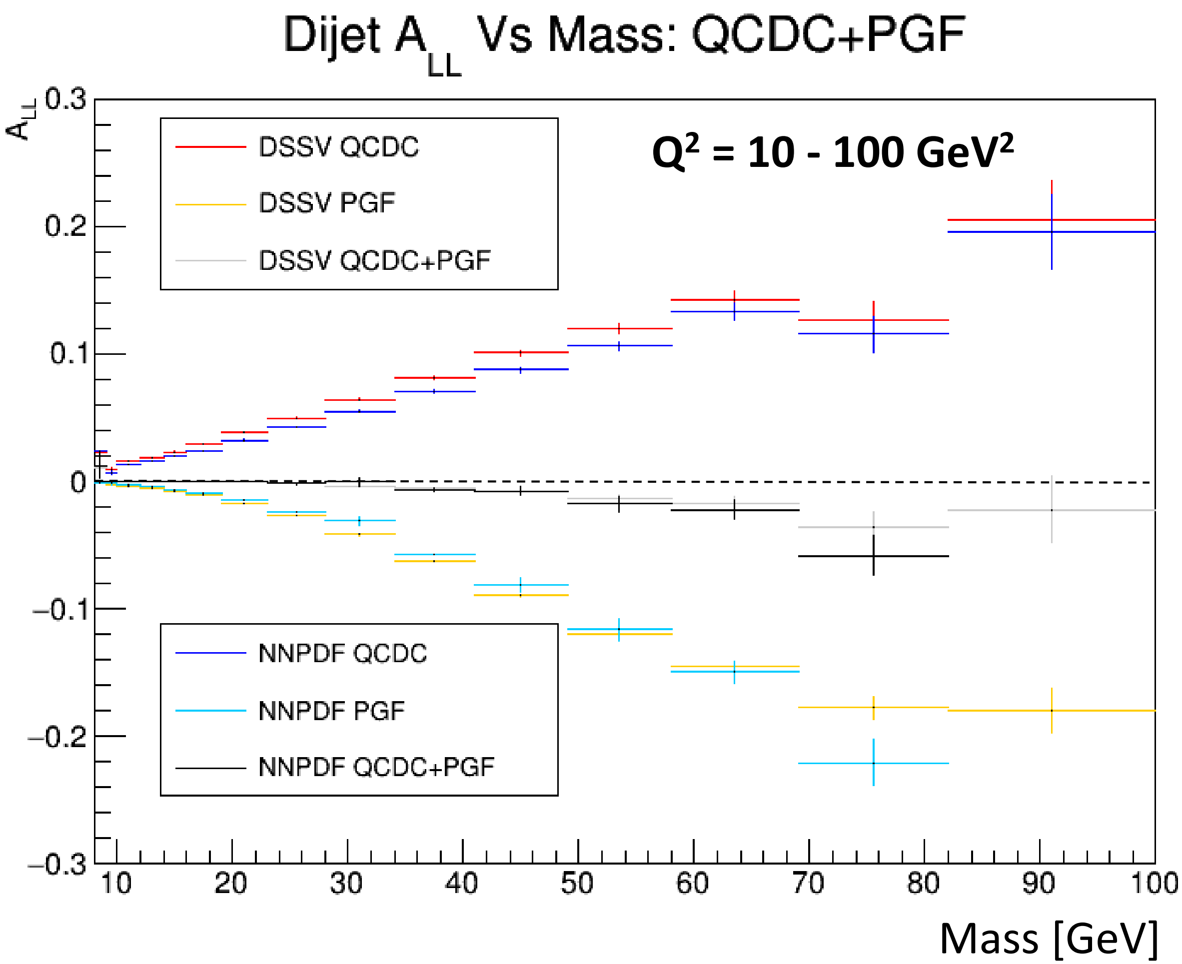
- Can also get access to ΔG by using dijets to tag the photon-gluon fusion process, providing a cross-check and allowing studies of the evolution of ΔG with respect to Q^2

- Reconstruction of x_γ will facilitate rejection of resolved events x_P will help isolate PGF from the quark-induced QCD-Compton process



arXiv:1206.6014

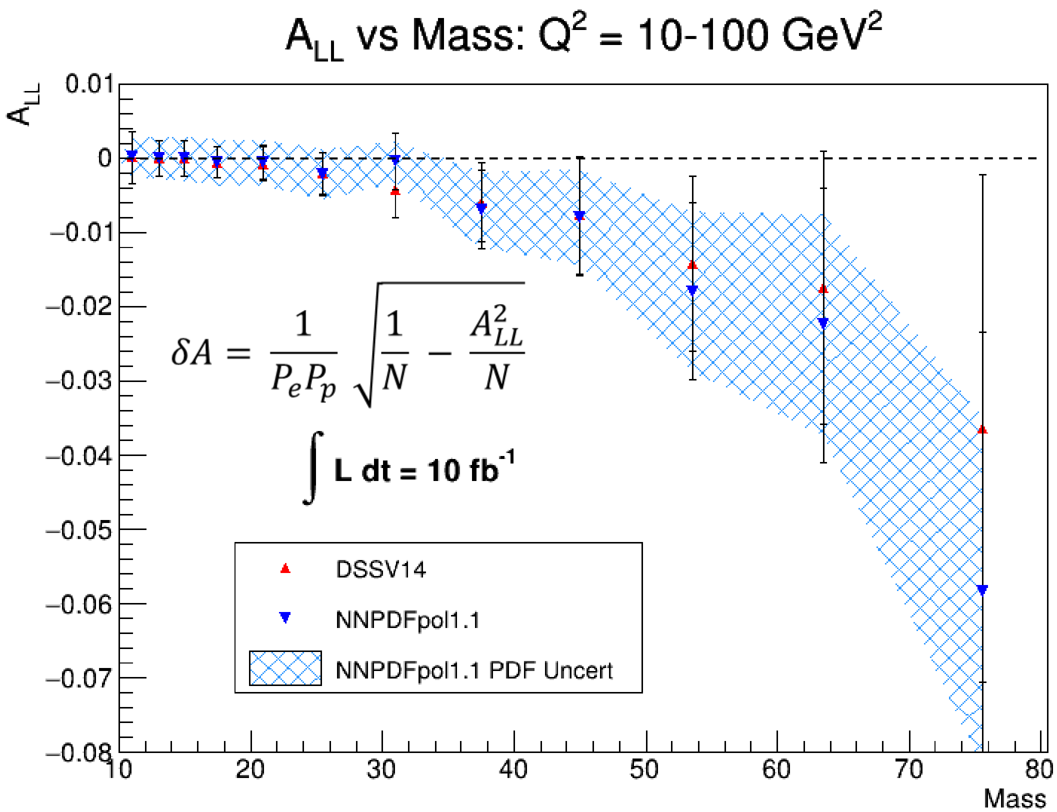
A_{LL} Vs Di-jet Mass

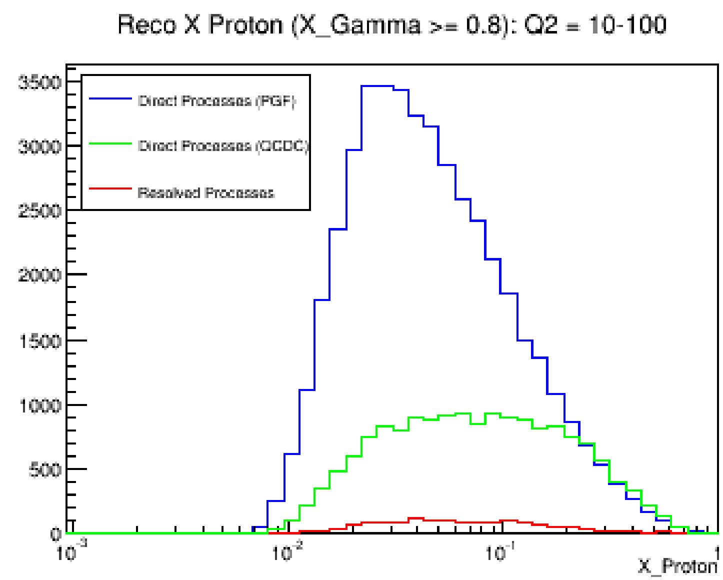


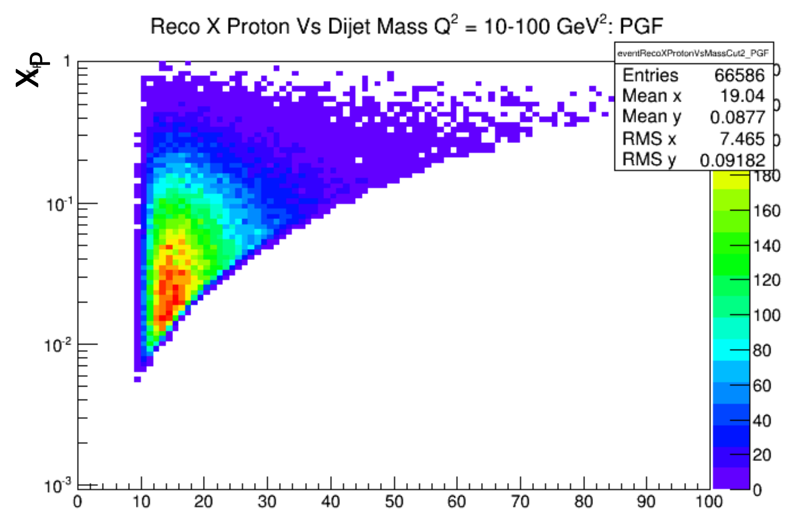
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$

- Weight simulated events by product of the partonic asymmetry and the ratios of the polarized over unpolarized photon and proton PDFs to obtain realistic estimate of A_{LL}
- 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

A_{LL} Vs Di-jet Mass: x_P Cuts



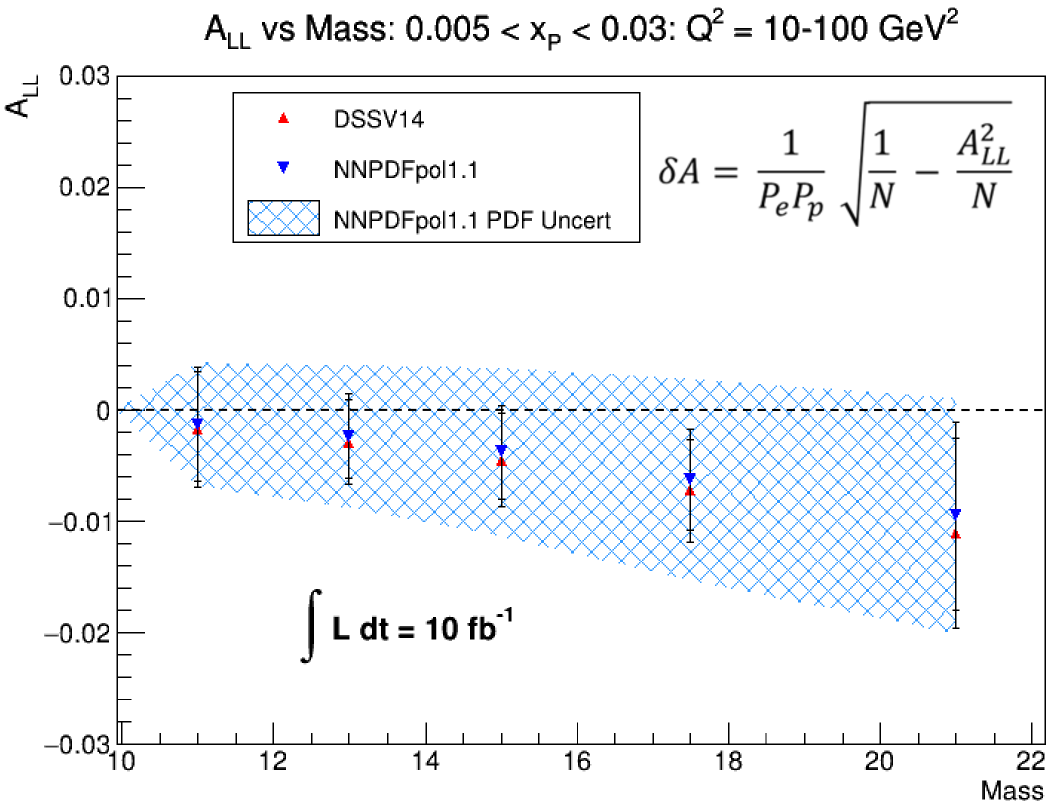


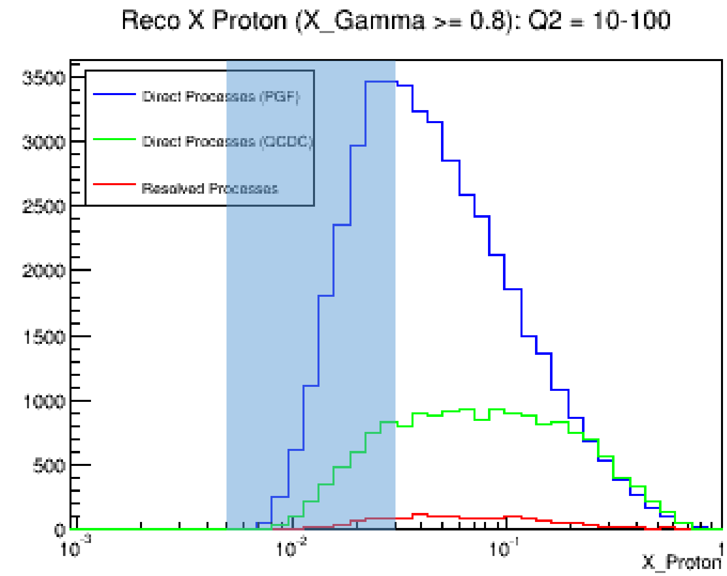


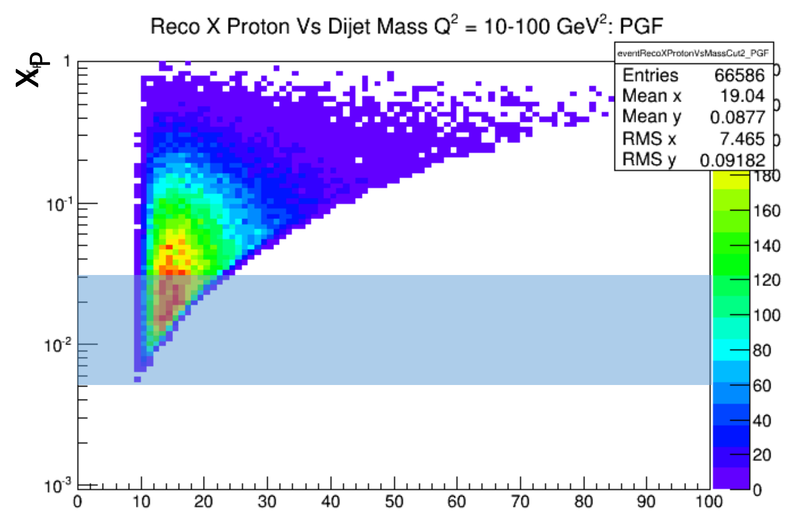
Dijet Mass

- QCDC and PGF asymmetries largely cancel out making overall asymmetry small
- Want to enhance PGF subprocess w.r.t. QCDC
- PGF events peaked to lower x_P values

A_{LL} Vs Di-jet Mass: x_P Cuts



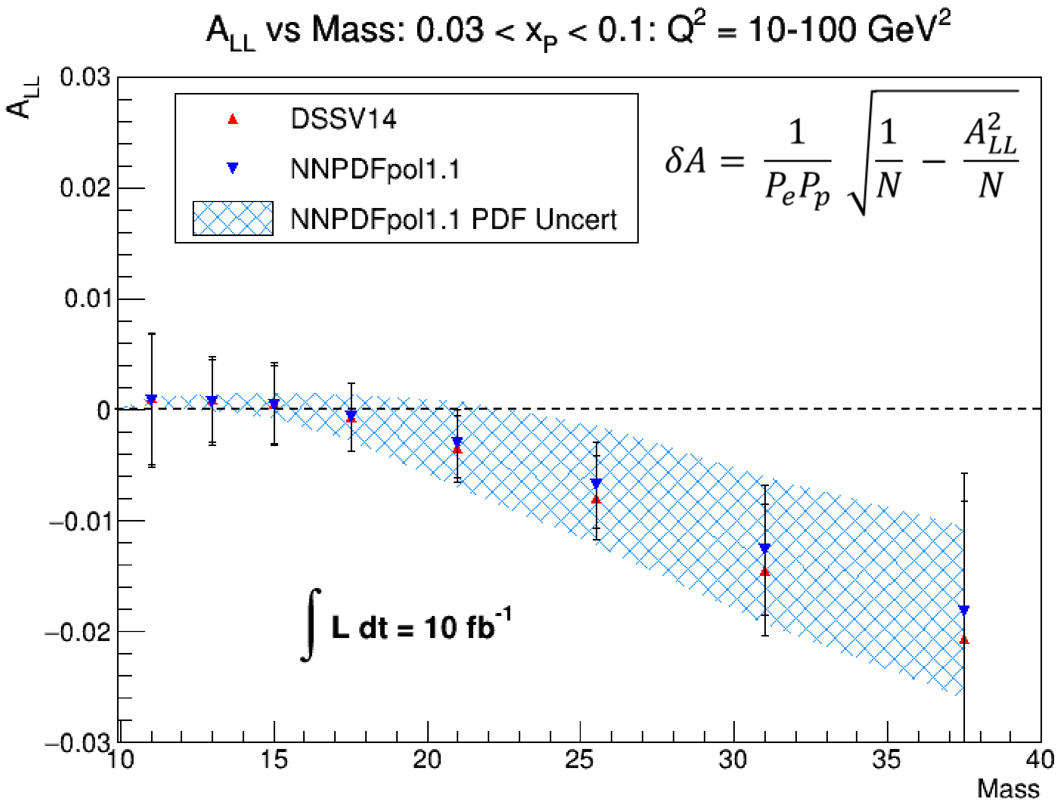


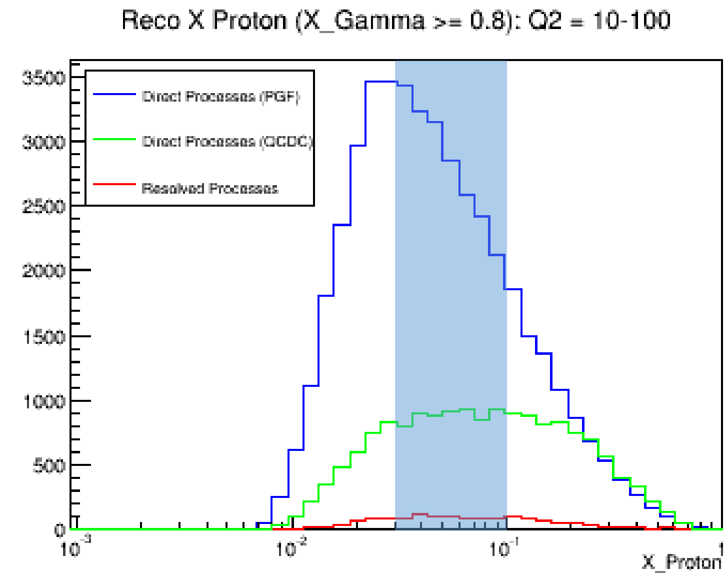


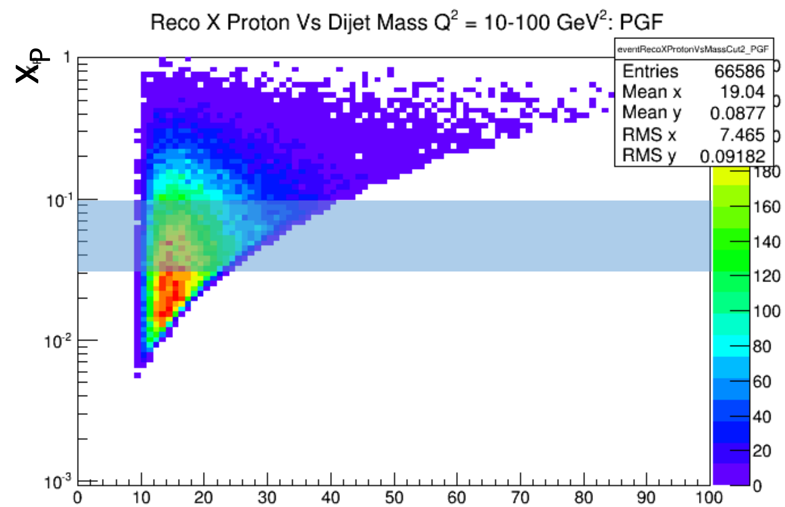
Dijet Mass

- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range

A_{LL} Vs Di-jet Mass: x_P Cuts



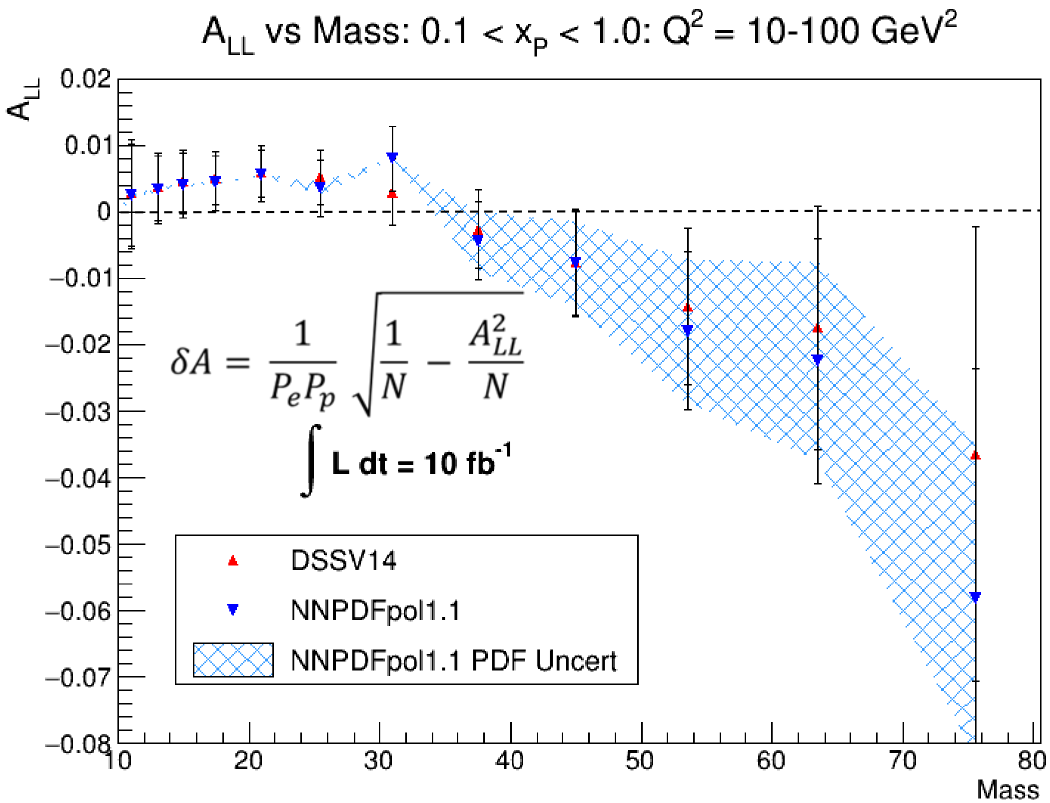


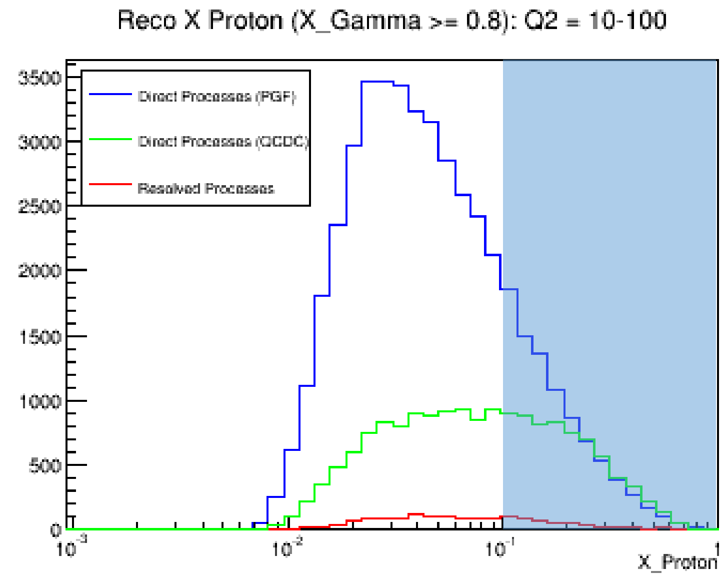


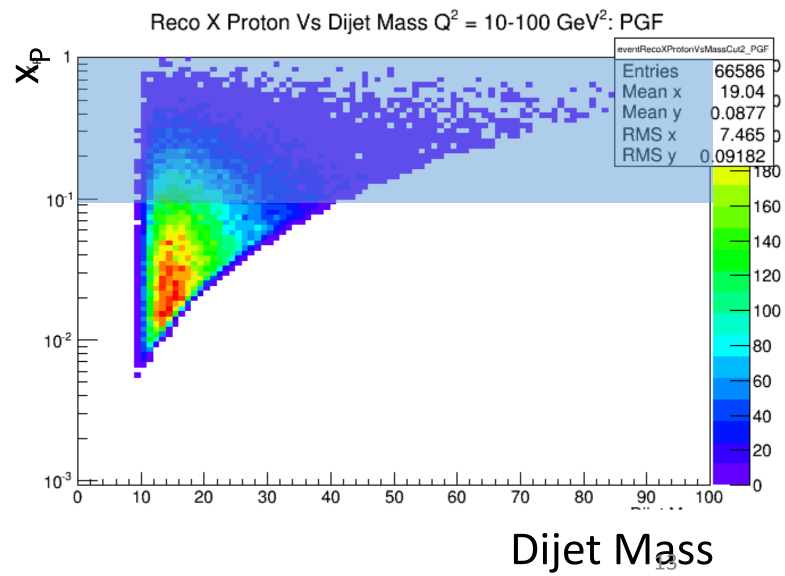
Dijet Mass

- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range
- Intermediate x_P values get more QCDC contribution

A_{LL} Vs Di-jet Mass: x_P Cuts







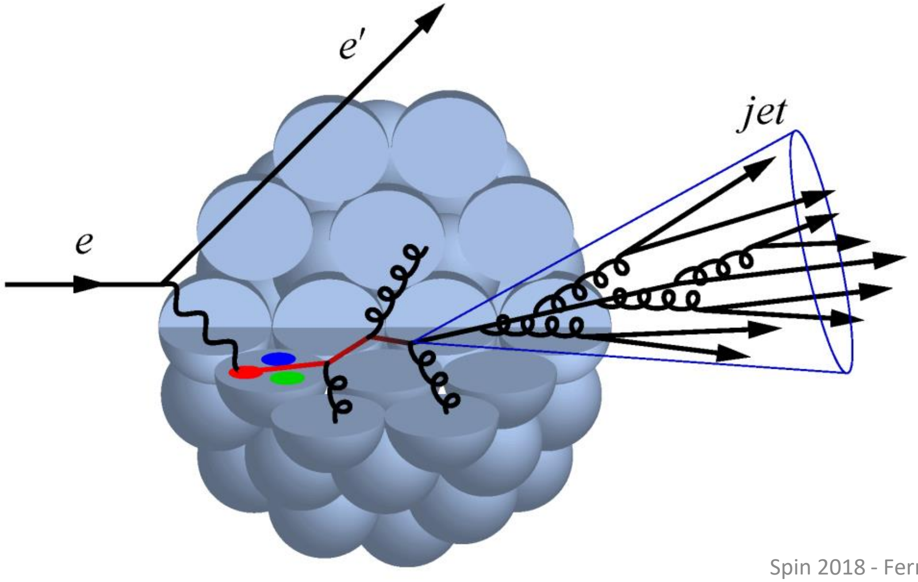
- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range
- Intermediate x_P values get more QCDC contribution
- Largest x_P values have roughly equal amounts of PGF and QCDC

Jet Substructure: Angularity

- One goal of the EIC will be the exploration of cold nuclear matter, as well as the hadronization process, via electron-nucleus collisions

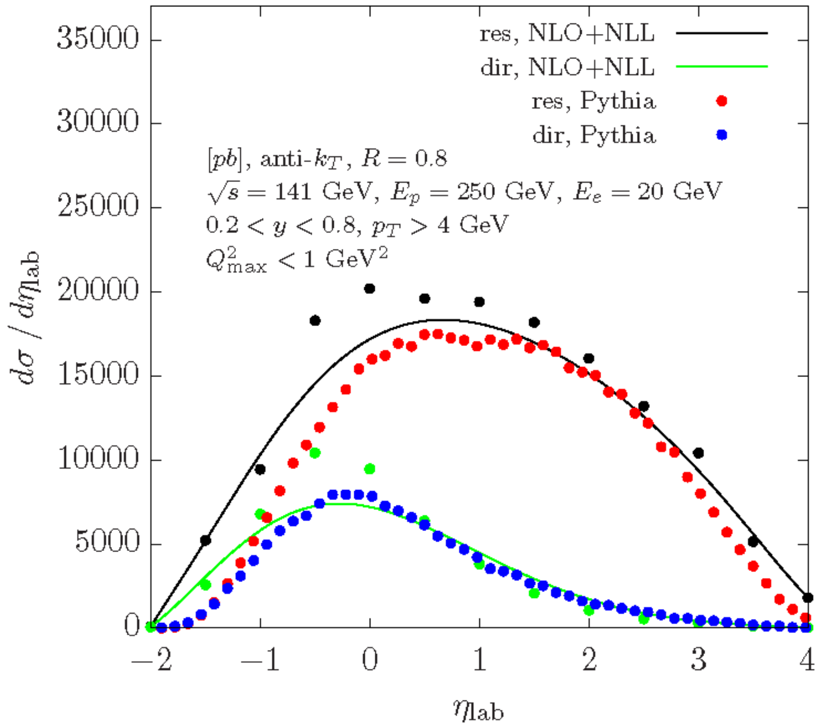
- Substructure observables quantify how energy is distributed within the jet – modification of substructure in eA may be sensitive to details of hadronization in nuclear matter and possibly to certain properties of the matter

- First step: explore behavior of substructure observables at EIC energies – focus on angularity



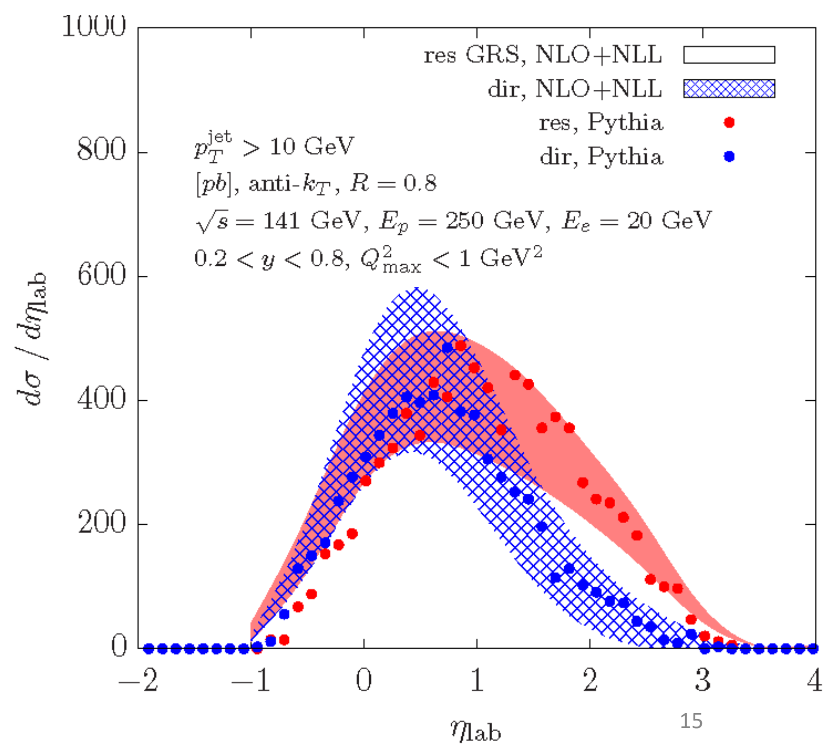
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \, (\Delta \mathcal{R}_{iJ})^{2-a}$$

Photoproduction Cross Section

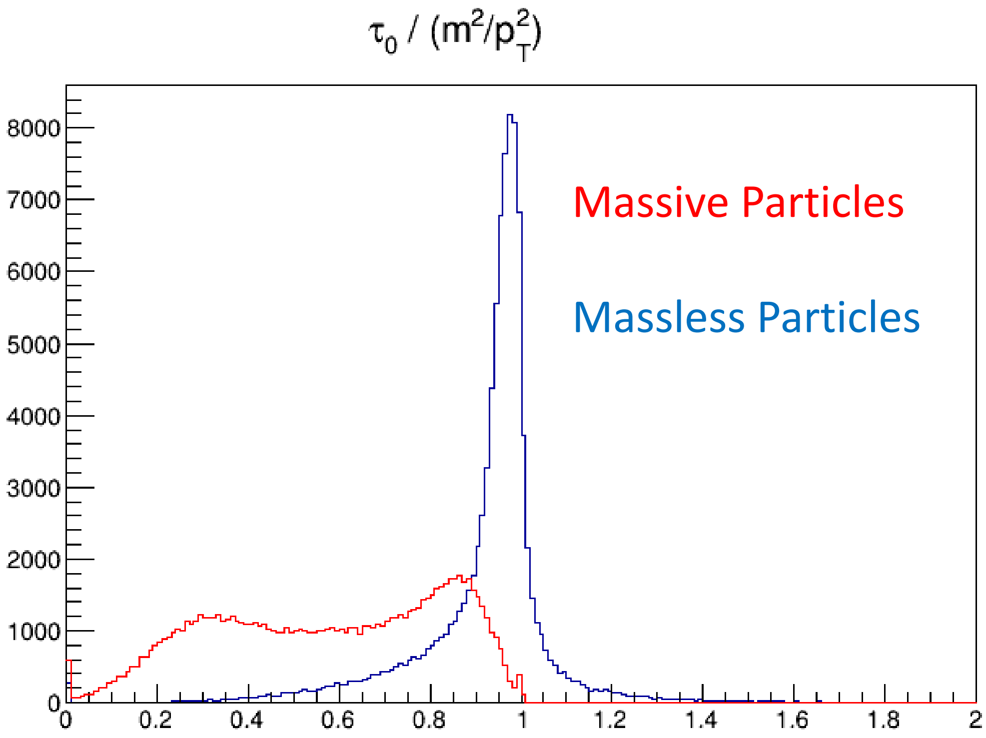


- Carry out angularity studies in photoproduction region ($10^{-5} < Q^2 < 1$)
- Resolved and direct cross sections from PYTHIA in good agreement with theoretical expectations (F. Ringer, K. Lee)

- Jet Radius = 0.8
- 0.2 < inelasticity < 0.8
- Lab Frame
- Cross sections shown for jet $p_T > 4$ and jet $p_T > 10$ GeV

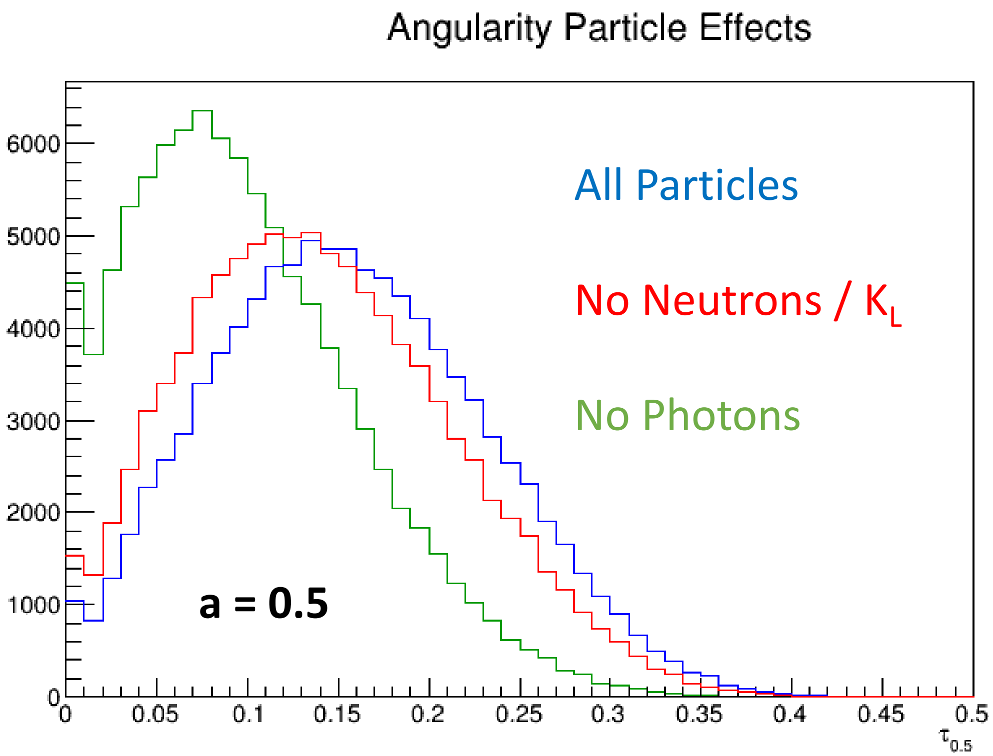


Relationship to Jet Mass



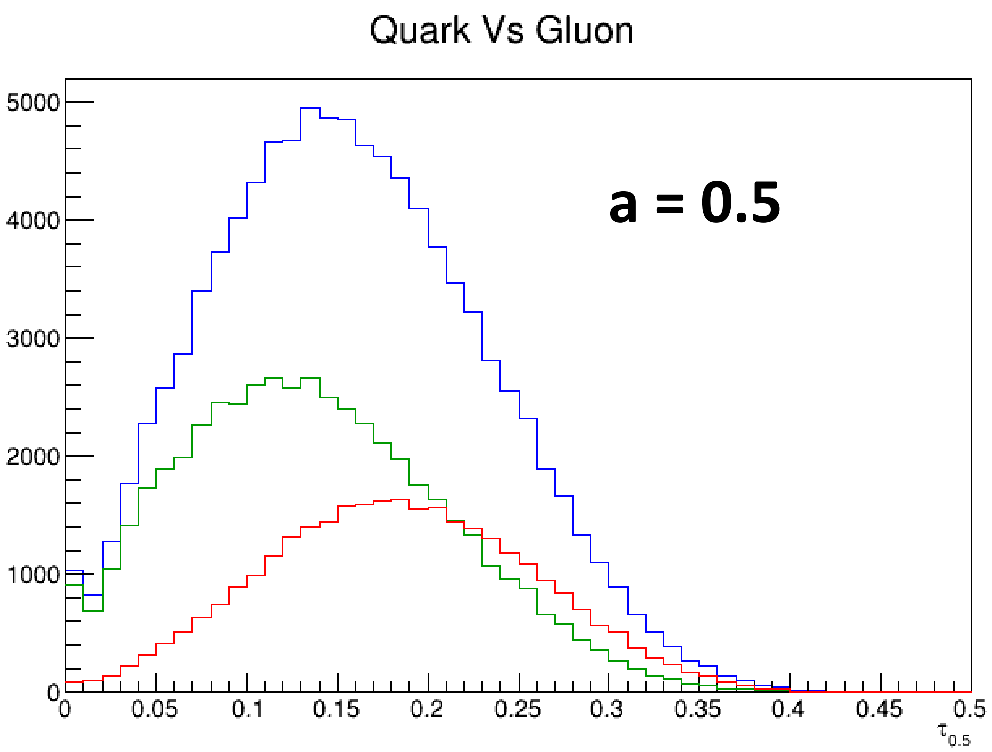
- Angularity with a = 0 is equal to the square of jet mass divided by the square of jet p_T (plus higher order terms)
- We find the validity of this relationship depends strongly on how the jet mass is constructed
- Adding full particle 4-vectors leads to discrepancy while good agreement seen for 'massless' particles
- Jet p_Ts are small at an EIC, individual particle masses can by a non-negligible contribution
- Look at relationship for high p_T jets

Detector Considerations



- In simulation, we can measure all particles exactly – what happens if some classes of particles are not measured or not measured well?
- Construct angularity excluding neutral hadrons (neutrons & K_L) and photons from pion decay
- Not measuring neutral hadrons results in a shift and slight shape change to angularity distribution
- Neglecting photons will significantly change distribution – electromagnetic calorimeter with good pointing resolution will be important

Quark / Gluon Discrimination



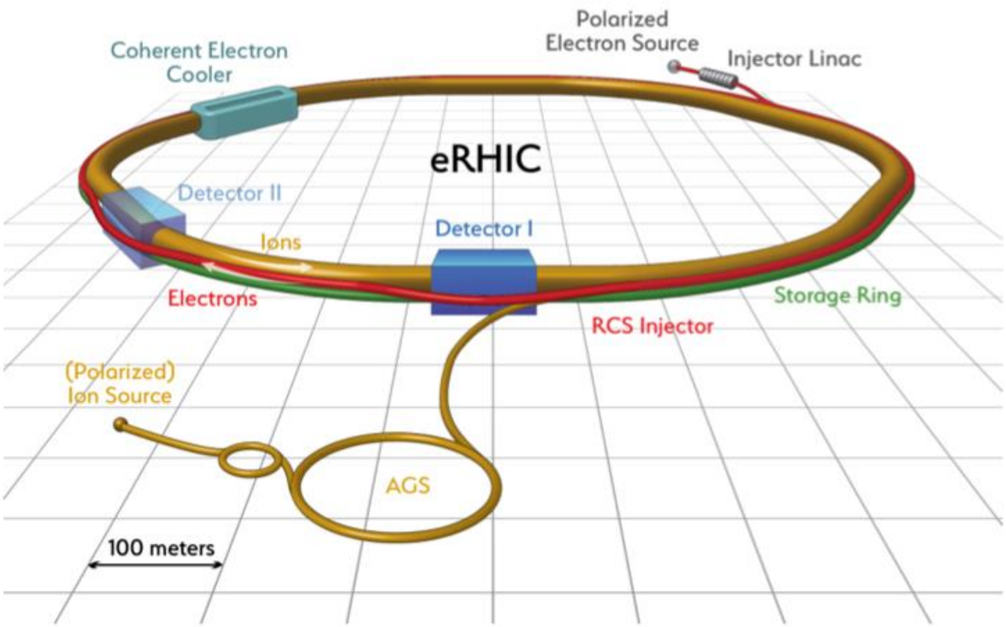
- Quarks and gluons are expected to shower in different ways with jets arising from gluons being ‘fatter’ than those from Quarks
- Can angularity differentiate between quark and gluon jets?
- See decent differentiation between light quarks and gluons for a = 0.5
- Next: explore correlations with other discriminating variables

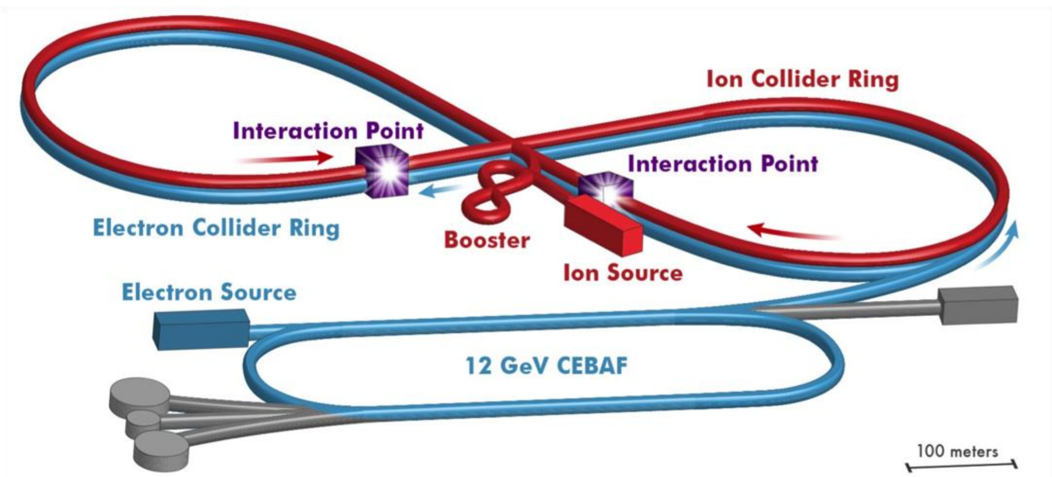
Summary

- Dijets can be used to reconstruct partonic kinematics for the purpose of separating different subprocesses
- Isolating (or enhancing) the resolved or photon-gluon fusion subprocesses allow study of photon structure and gluon polarization, respectively
- Further applications of dijets include studies of the gluon Sivers function (Phys. Rev. D 98, 034011 2018, arXiv:1805.05290) and the WW distribution of linearly polarized gluons (arXiv:1809.02615)
- Several aspects of an angularity measurement at an EIC were discussed including the affect of particle masses and the need for good EM calorimetry
- Angularity shows some ability to differentiate between quark and gluon jets

Backup

Potential EIC Realizations

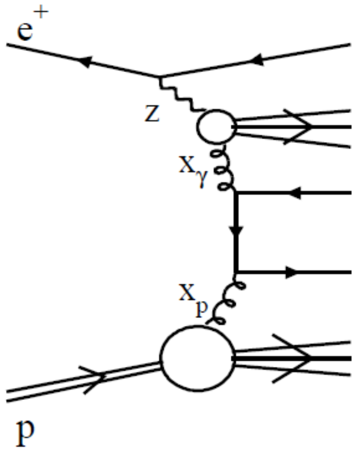




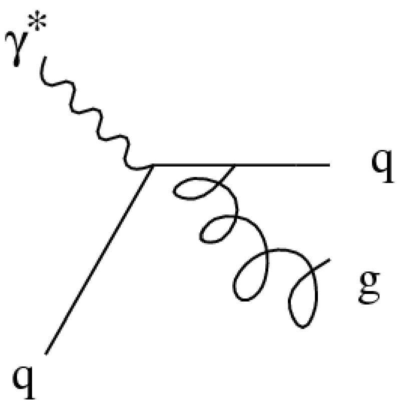
- Two designs are in active development:
  - eRHIC (BNL)
  - JLEIC (JLab)
- eRHIC utilizes the existing RHIC hadron facility and adds an electron ring and injector
- JLEIC utilizes CEBAF as an electron accelerator and adds a hadron source / booster and collider rings
- Broad tradeoff: eRHIC will start with lower luminosities but have larger center of mass energies while JLEIC will prioritize luminosity but with smaller collision energies

Relevant Subprocesses

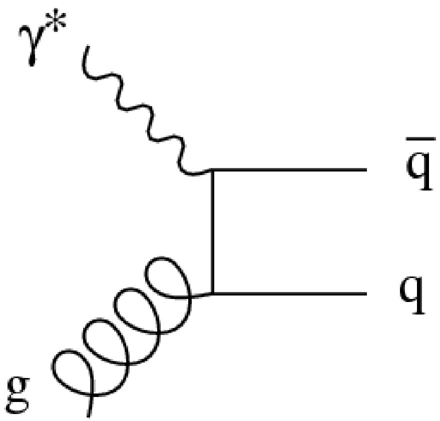
Resolved



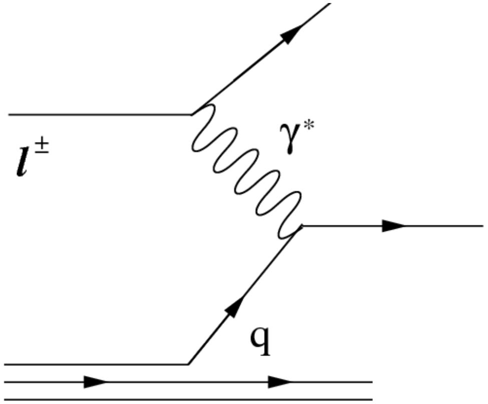
QCD-Compton (QCDC)



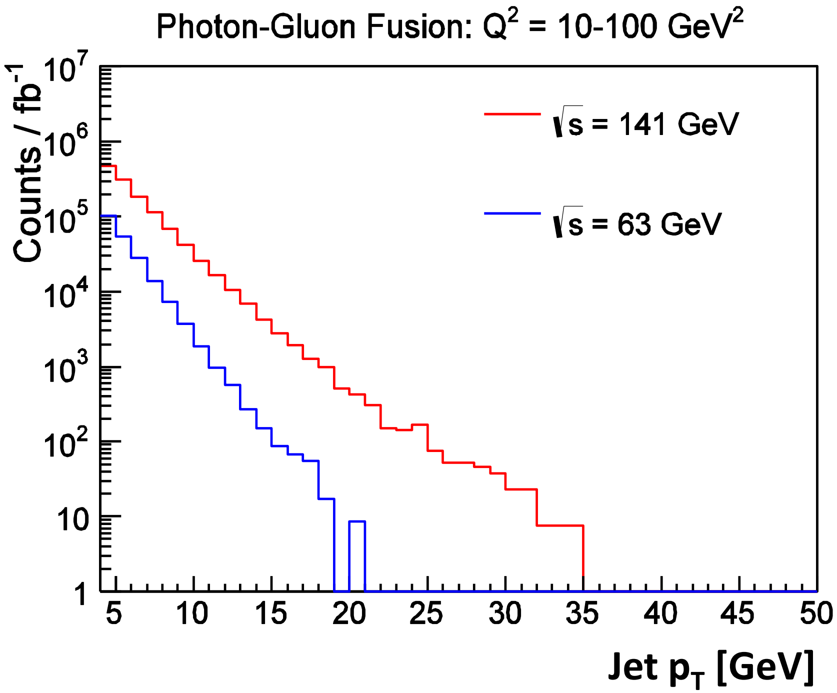
Photon-Gluon Fusion (PGF)



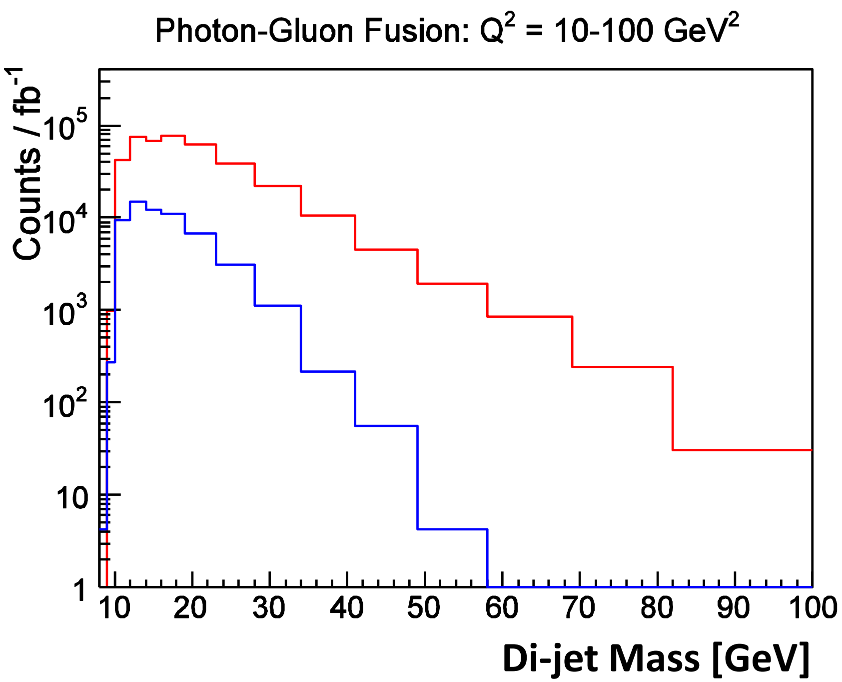
DIS



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 $\sqrt{s}$ = 141 GeV for all that follows



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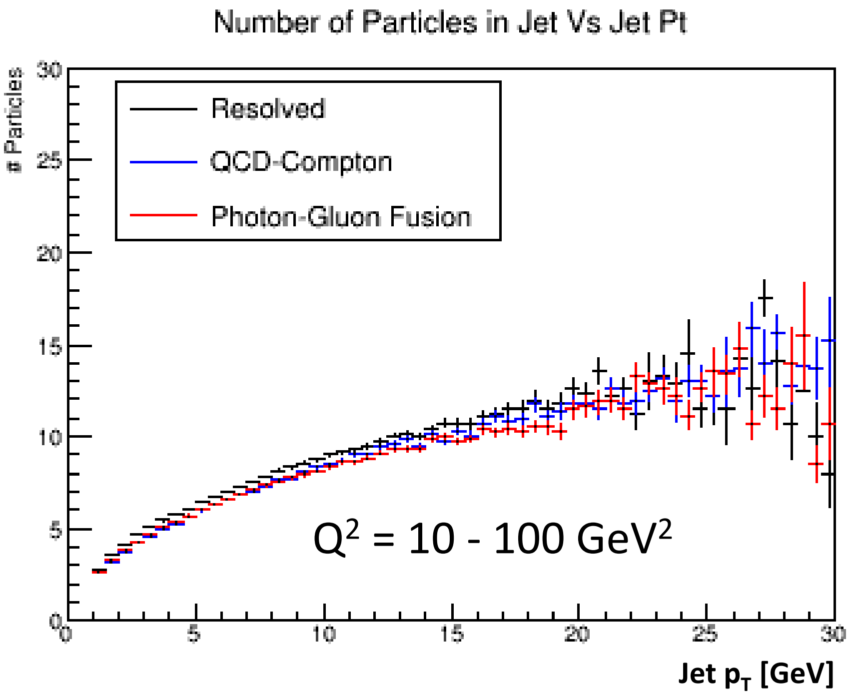

- Jets contain relatively few particles overall
- Events should be relatively clean with moderate underlying event
- Typical particle p_T is small -> precision tracking important for reducing jet energy scale uncertainties

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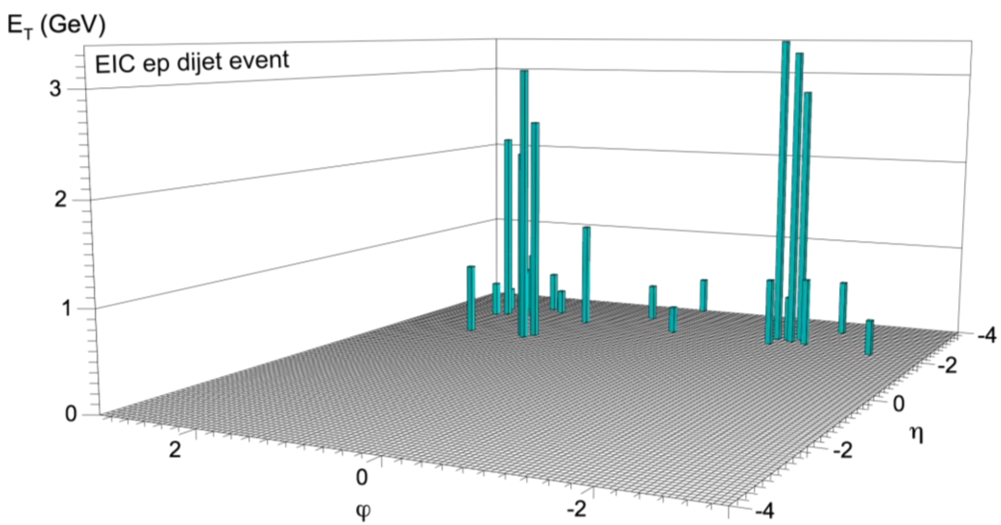
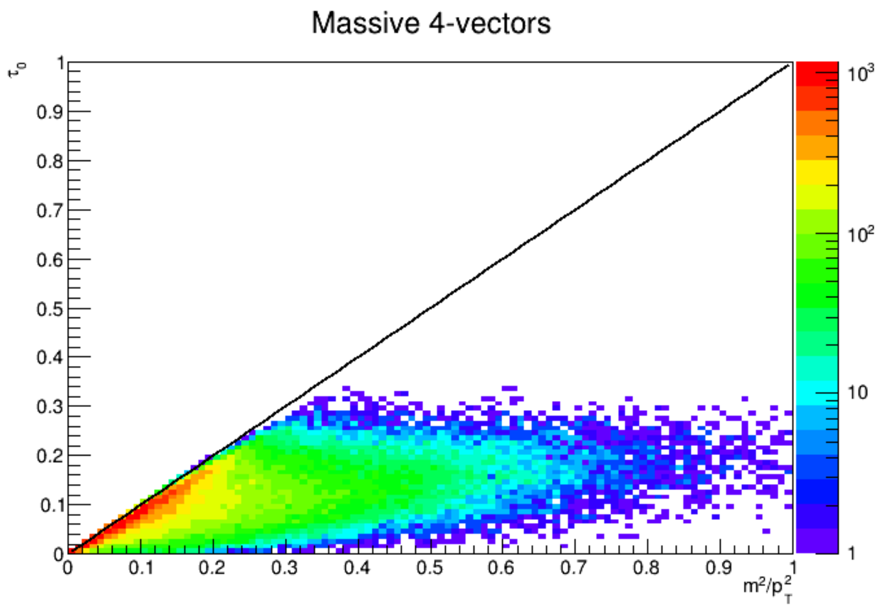
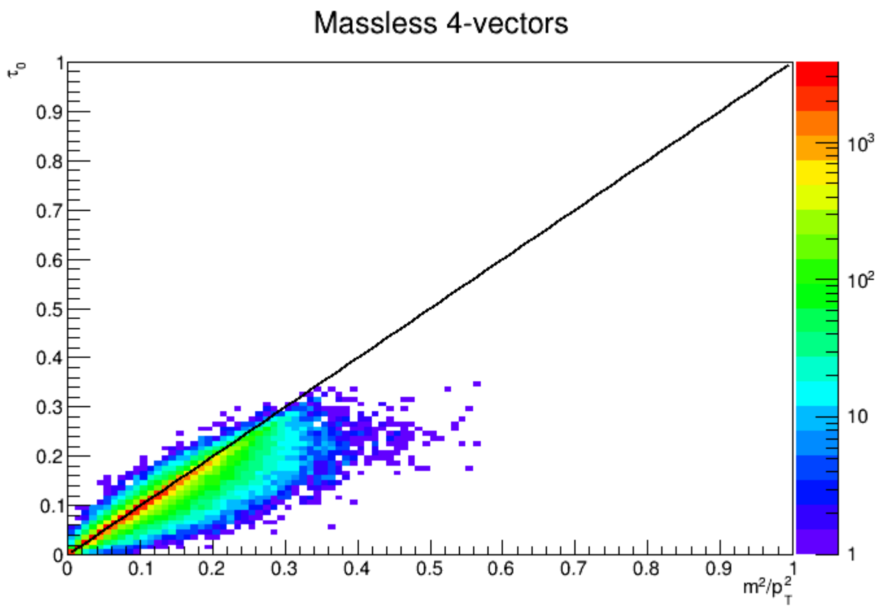
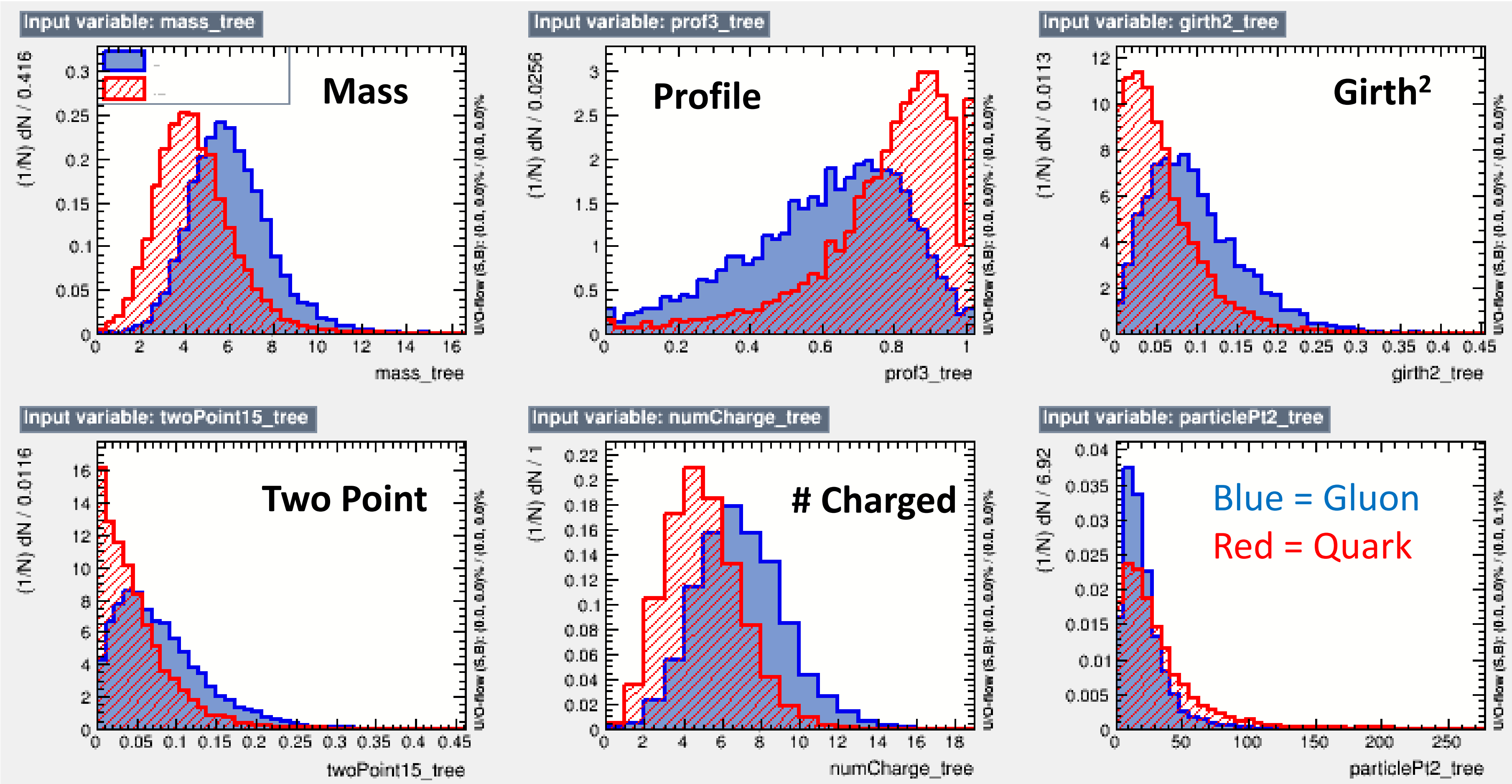


Relationship to Jet Mass





Input Variables



$$\text{Girth}^2 = \sum_i \frac{p_{Ti}}{p_{Tjet}} |r_i|^2$$

$$2\text{ Point} = \frac{1}{{p_{Tjet}}^2} \sum_{i \neq j} p_{Ti} * p_{Tj} * |r_{ij}|^\beta$$