Jets at an EIC: An Experimental Perspective

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Santa Fe Jets and Heavy Flavor Workshop

Outline

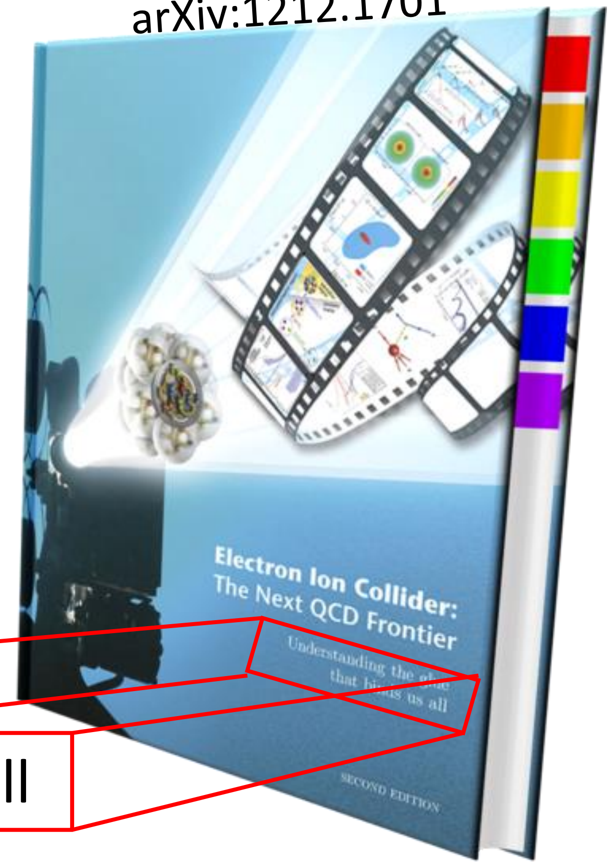
- Brief Introduction to the Electron Ion Collider (EIC)
- Underlying Event Characteristics
- Accessing Photon Structure and Gluon Spin with Dijets
- Quark – Gluon Discrimination
- Detector Smearing

EIC Goals in a Nutshell

Gain a Better Understanding of QCD via Precision Measurements of the Bound States of the Theory

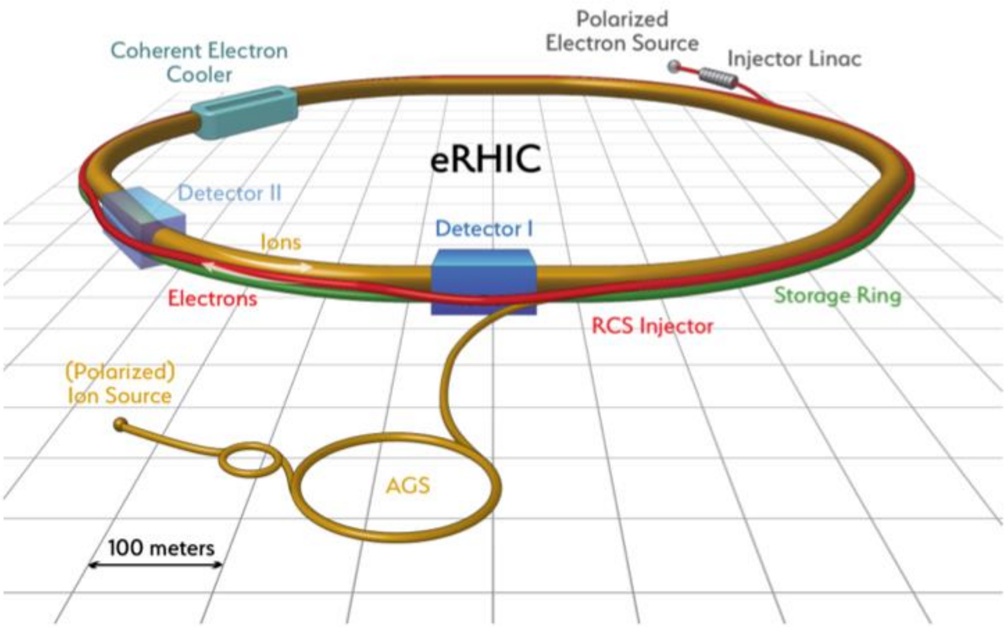
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

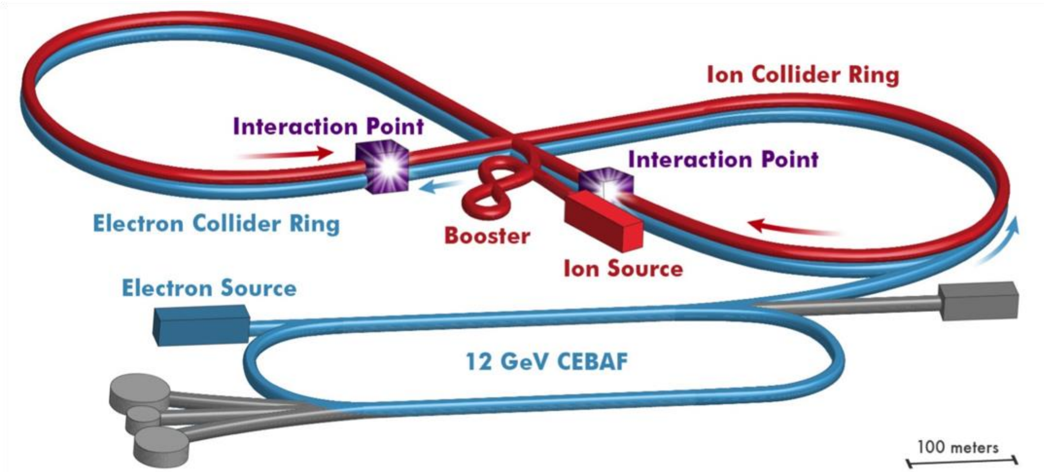
arXiv:1212.1701



Understanding the glue that binds us all

Potential EIC Realizations

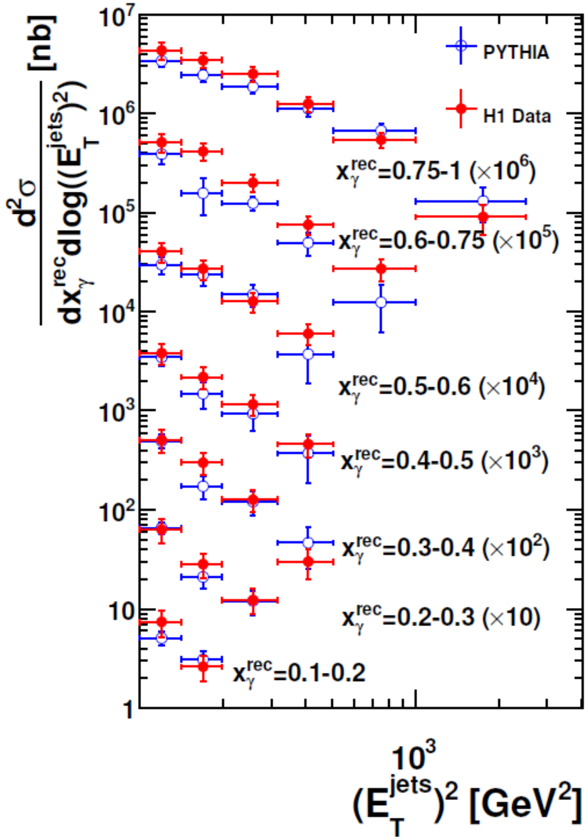




- Two designs are in active development:
  - eRHIC (BNL)
  - JLEIC (JLab)
- eRHIC utilizes the existing RHIC hadron facility and adds an electron ring and injector
- JLEIC utilizes CEBAF as an electron accelerator and adds a hadron source / booster and collider rings
- Broad tradeoff: eRHIC will start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

Simulation Details / Particle Cuts

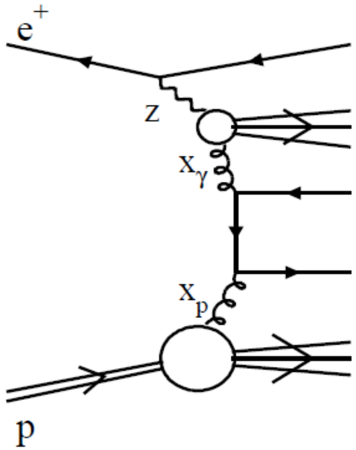
- Electron – Proton events generated at √s = 141 GeV using PYTHIA (Full energy eRHIC design 20x250 GeV electron x proton)
- Cut on inelasticity: $0.01 \leq y \leq 0.95$
- Jet Algorithm: Anti_k_T (R = 1.0)
- Jets found in Breit frame
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered electron



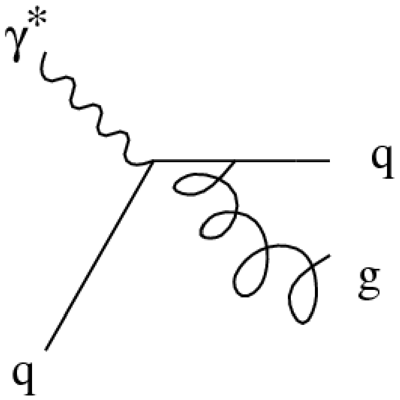
PRD 96, 074035 (2017)

Relevant Subprocesses

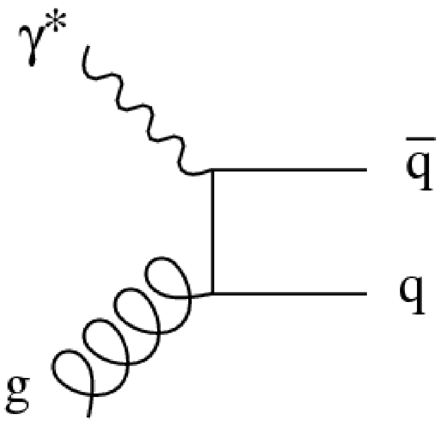
Resolved



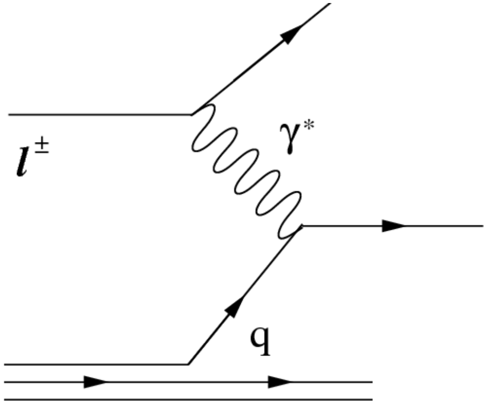
QCD-Compton (QCDC)



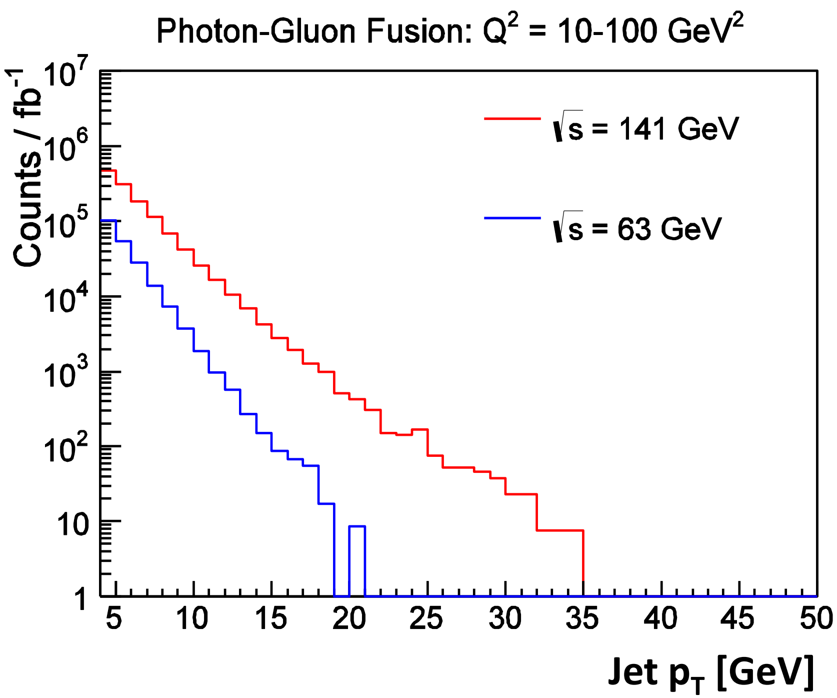
Photon-Gluon Fusion (PGF)



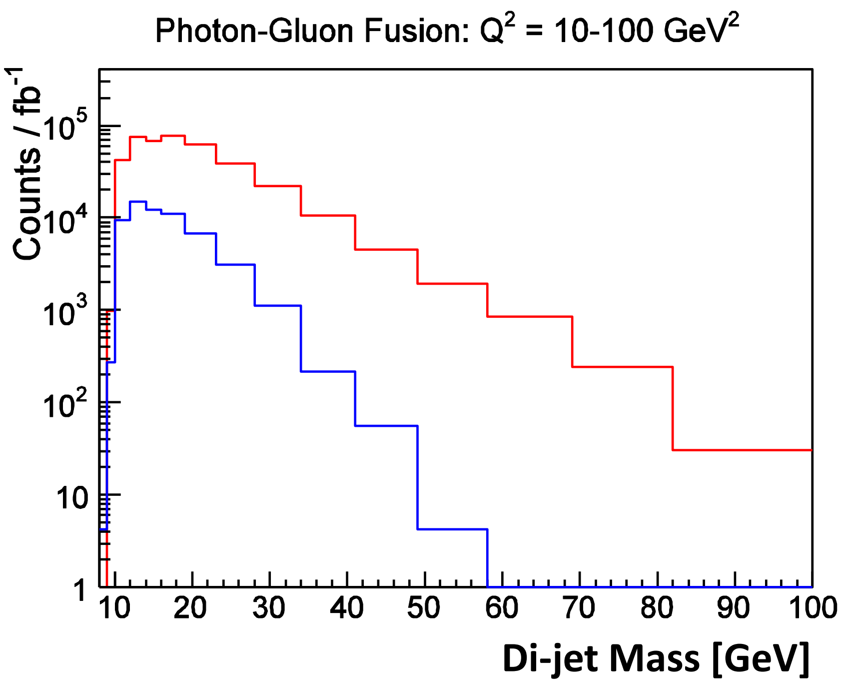
DIS



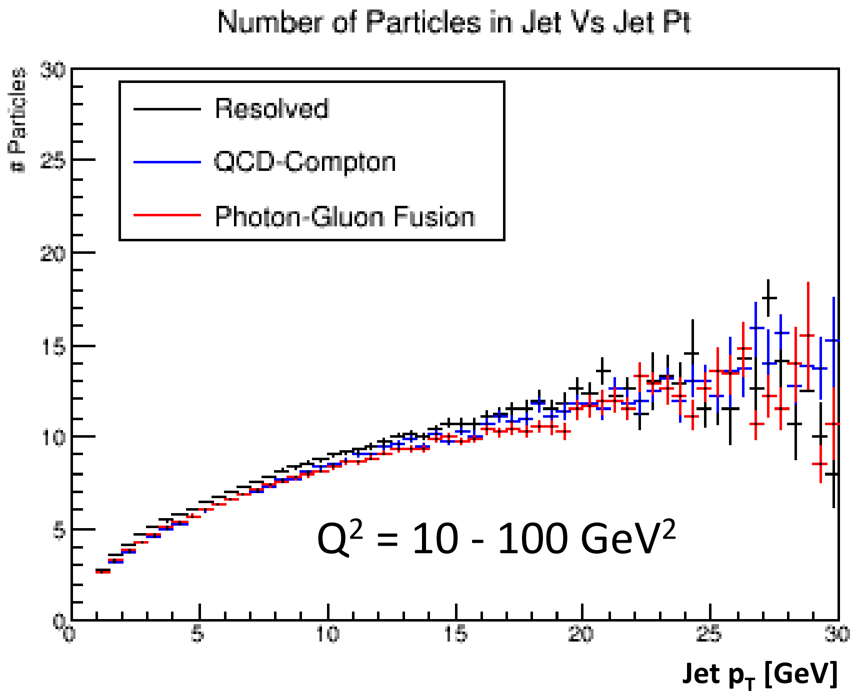
Jets at an EIC: Points to Remember



- 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

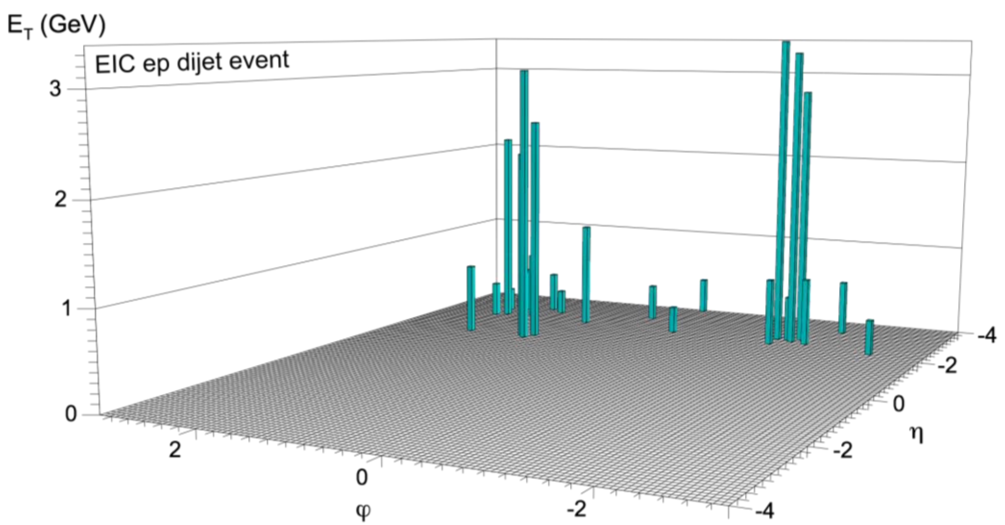


Jets at an EIC: Points to Remember



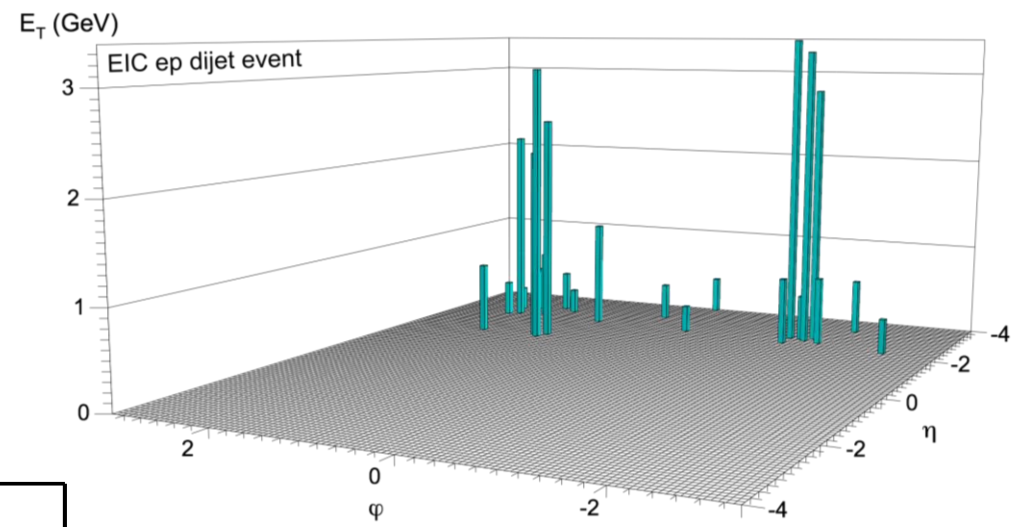
- Jets contain relatively few particles overall
- Events should be relatively clean with moderate underlying event
- Typical particle p_T is small -> precision tracking important for reducing jet energy scale uncertainties

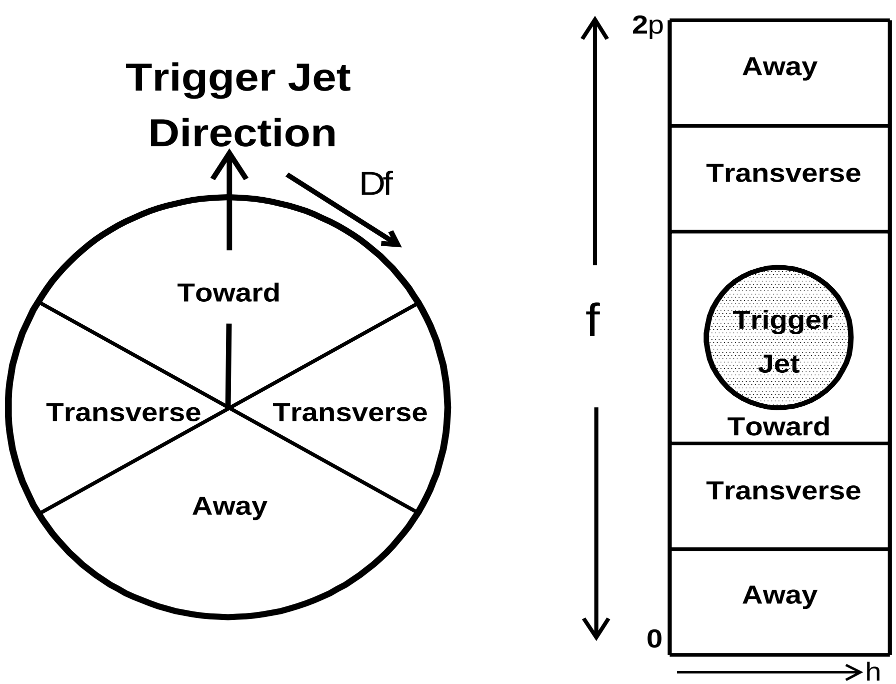
- Lower center of mass energies will lead to lower jet / di-jet yields and more limited p_T / mass reach
- Will need largest available energies and high luminosity to accumulate reasonable statistics at high p_T / mass – use √s = 141 GeV for all that follows



Underlying Event Study

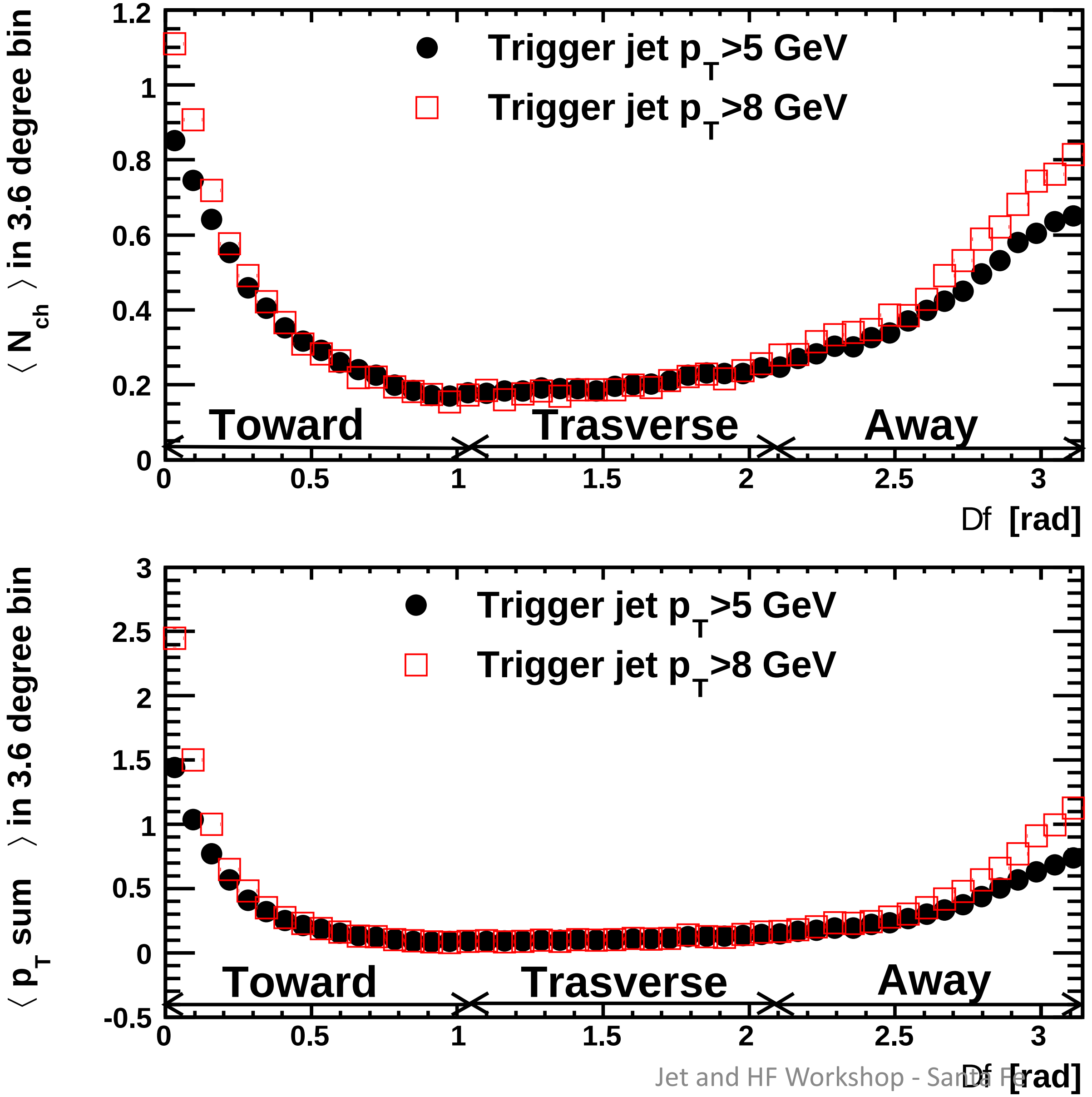
- ep events are expected to be relatively clean, with moderate underlying event activity
- Want to systematically quantify the amount of underlying event present in a typical event





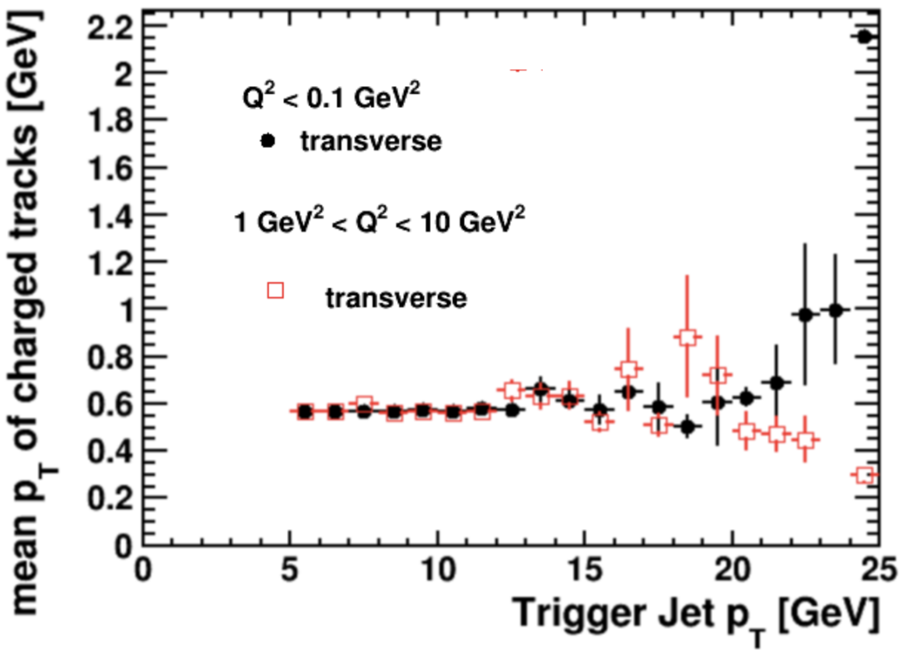
- Divide event into regions based on position of a trigger jet
- Transverse regions sensitive to underlying event contribution
- For this study: Dijet events from Resolved, QCDC, and PGF subprocesses; $Q^2 < 1$ GeV^2; $p_{T1} > 5$, $p_{T2} > 4.5$ GeV/c

Underlying Event Characteristics



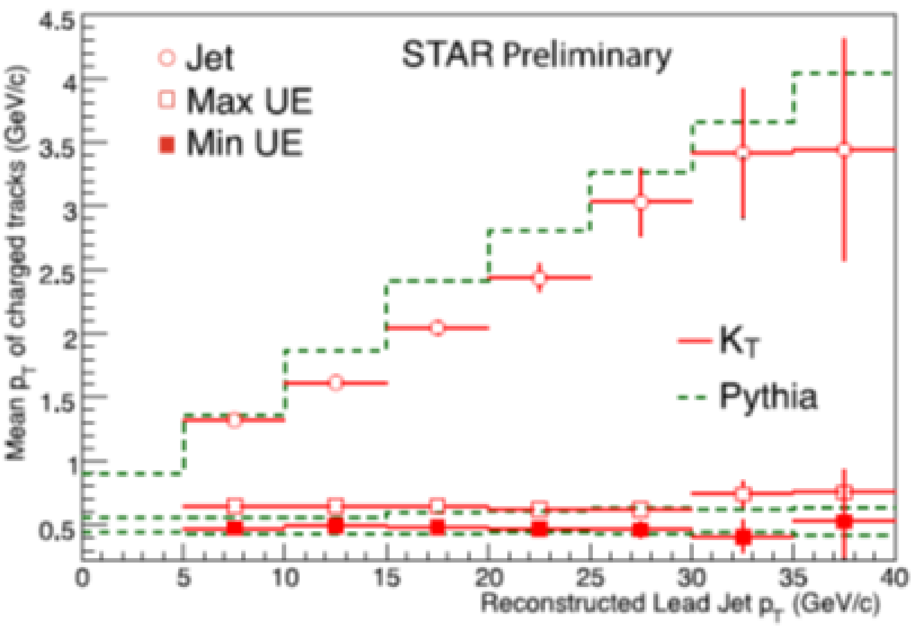
- Plot average number of charged particles per event as a function of azimuthal angle from trigger jet
- Also plot the average summed particle p_T
- See little dependence on trigger jet p_T
- The number of charged particles and p_T sum in transverse region is small

Comparison with STAR



- Plot the average p_T for charged tracks as a function of trigger jet p_T
- See that these quantities are independent of the trigger jet p_T in transverse region as well as Q^2

arXiv:1107.4891



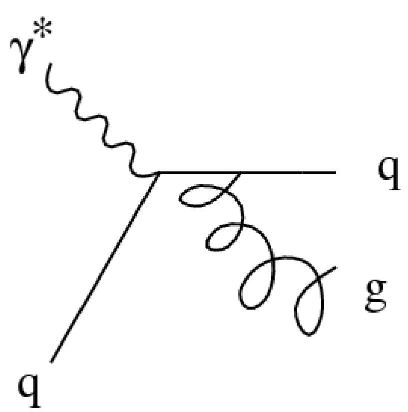
- See similar behavior in 200 GeV pp events at STAR
- Can we use STAR data to study certain EIC jet observables?

Jets as Parton Surrogates

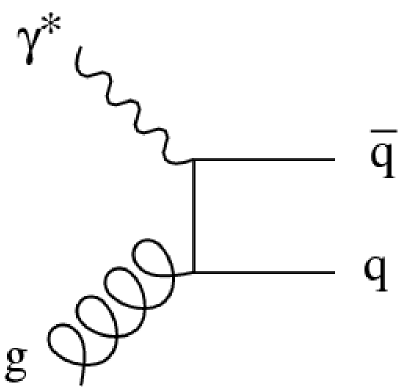
- Jets should approximate the energy and momentum of the partons from which they arise allowing the reconstruction of event kinematics such as x_γ (photon momentum fraction) and x_P (parton momentum fraction) among many other applications

- 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

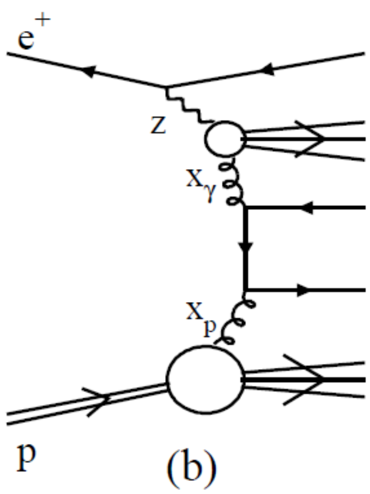


QCD – Compton

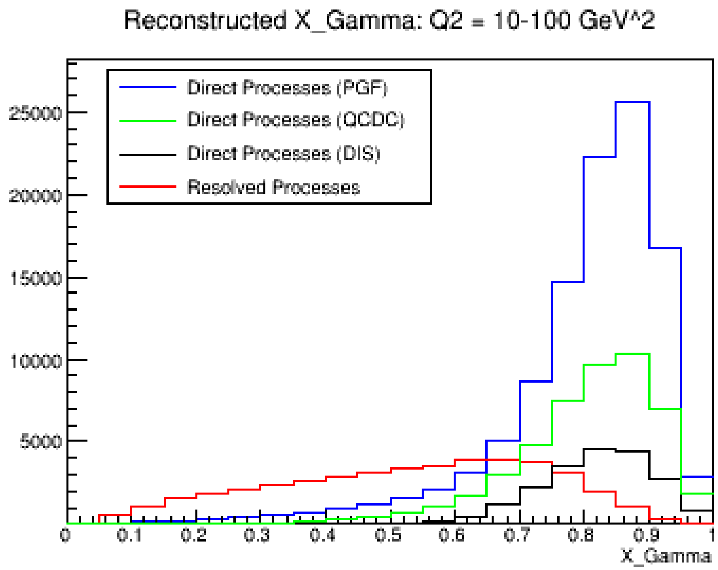


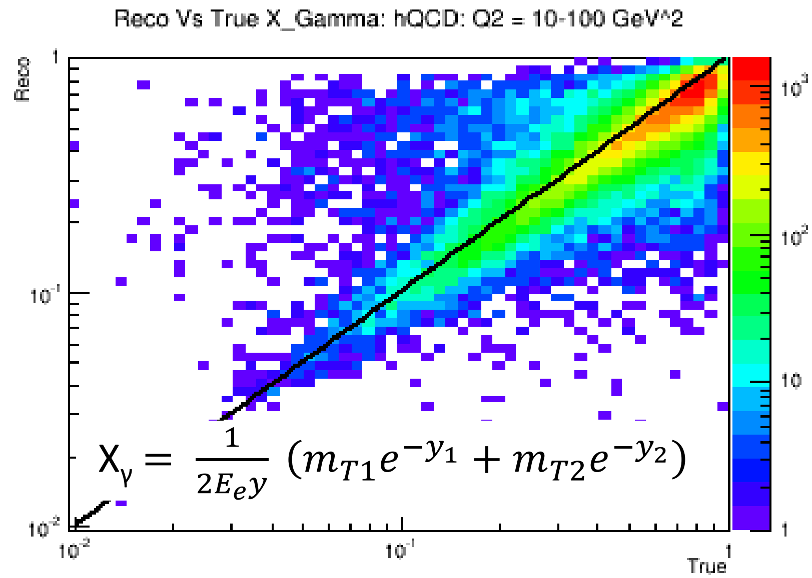
Photon-Gluon Fusion

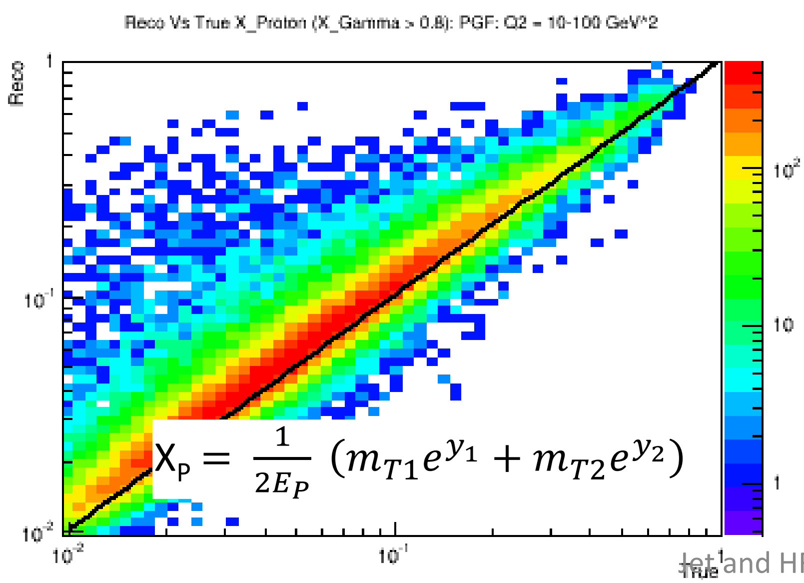
Resolved



Subprocess Tagging and Kinematics

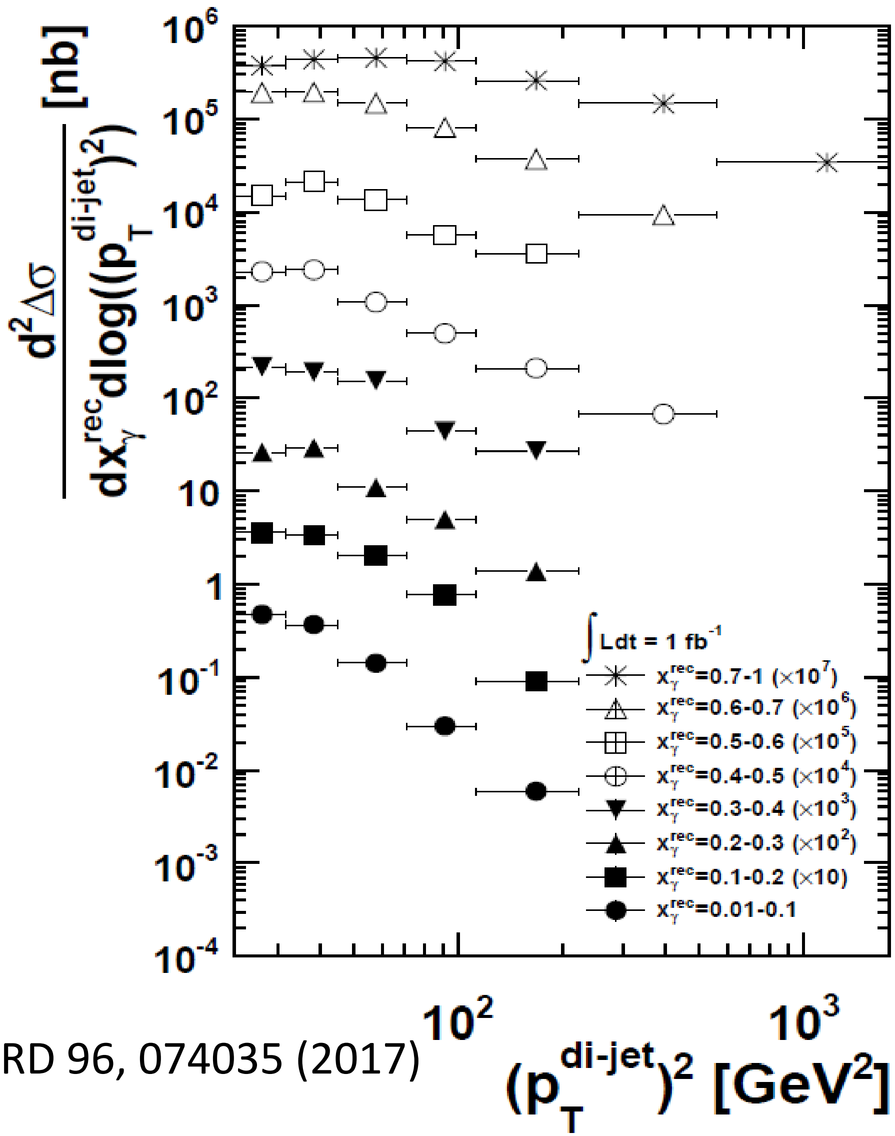






- Use dijet energy and momentum to reconstruct x_γ and x_P
- Cutting on x_γ can enhance or reduce resolved contribution (which becomes more prominent at low Q^2) depending on the analysis needs
- Both x_γ and x_P accurately reconstructed

Example: Photon Structure



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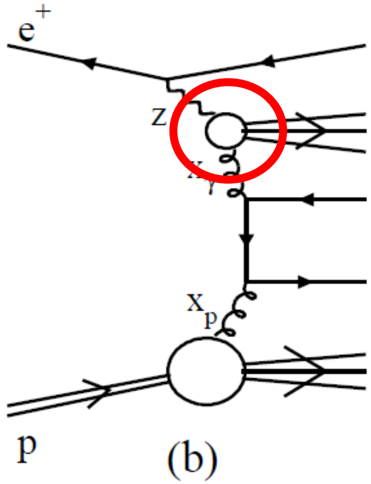

Study the polarized and unpolarized hadronic structure of the photon

- 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

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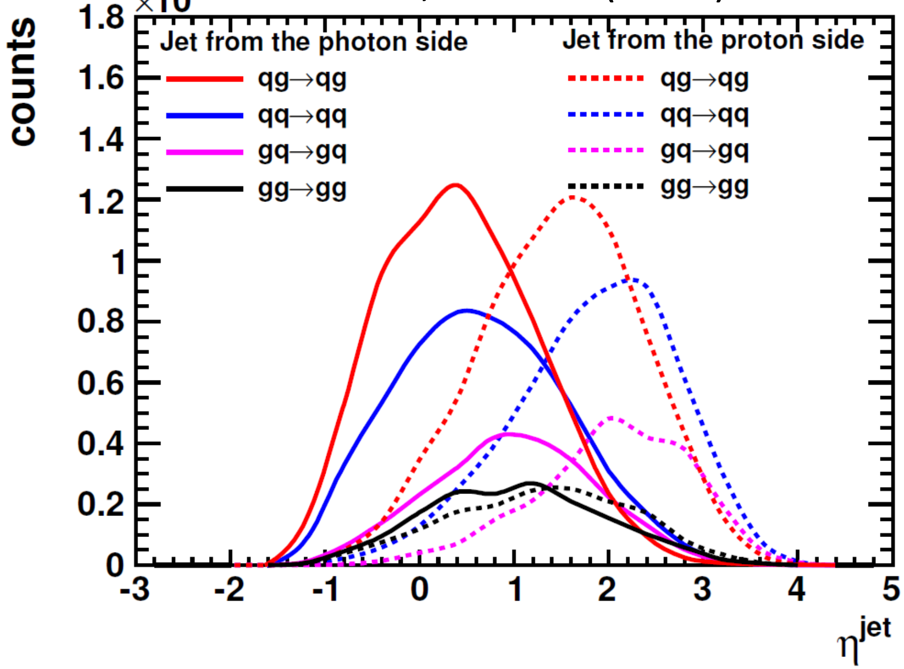
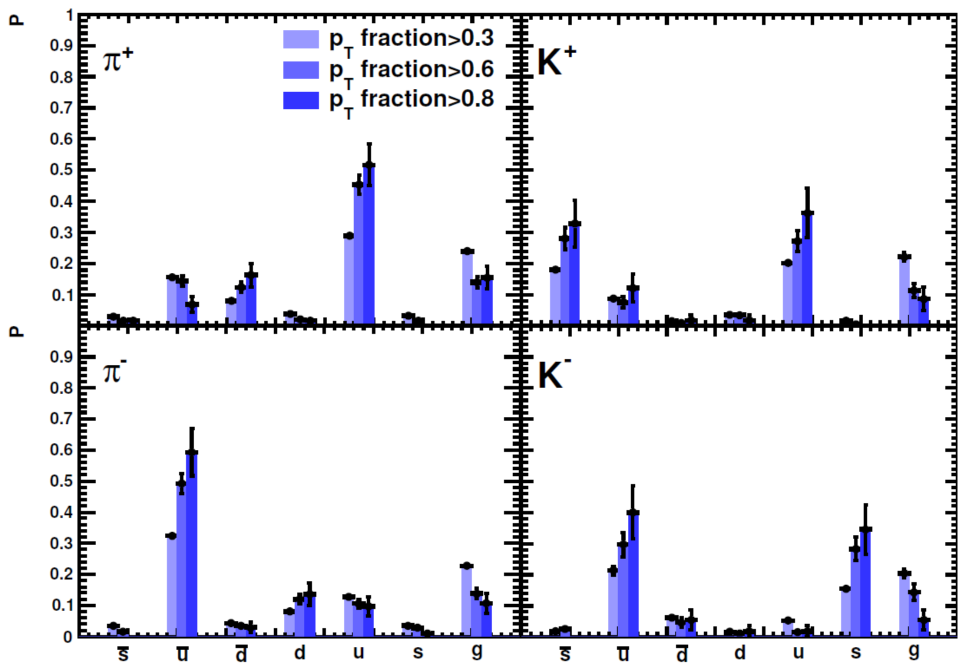


- Would also like to look more differentially and constrain photon PDFs for different parton flavors
- See that the jet associated with the photon preferentially goes to lower pseudorapidities



- 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

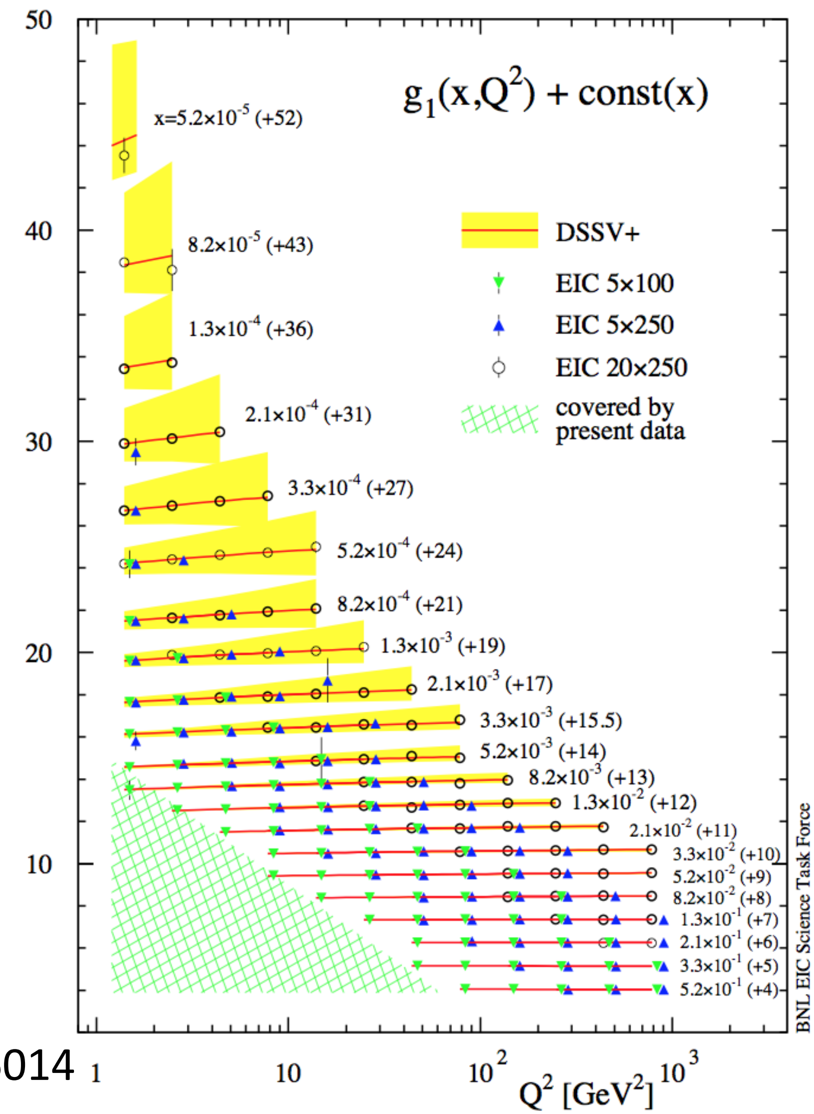
Example: Accessing ΔG with Dijets

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

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

- 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

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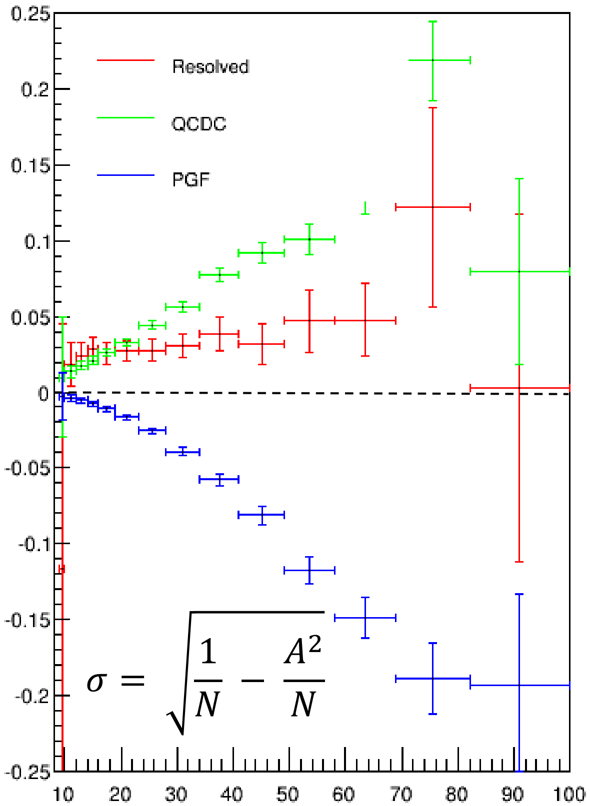
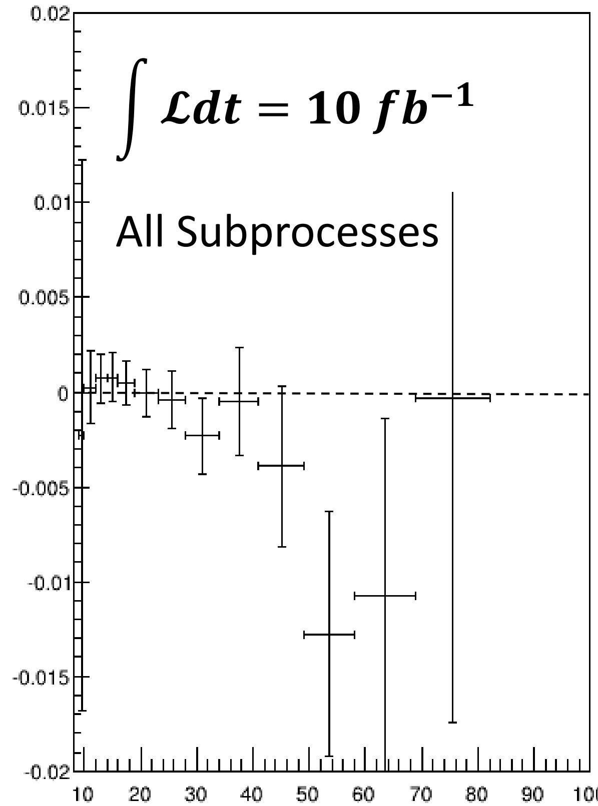


Mass [GeV]

Q^2 = 10 - 100 GeV^2

A_{LL} Vs Di-jet Mass

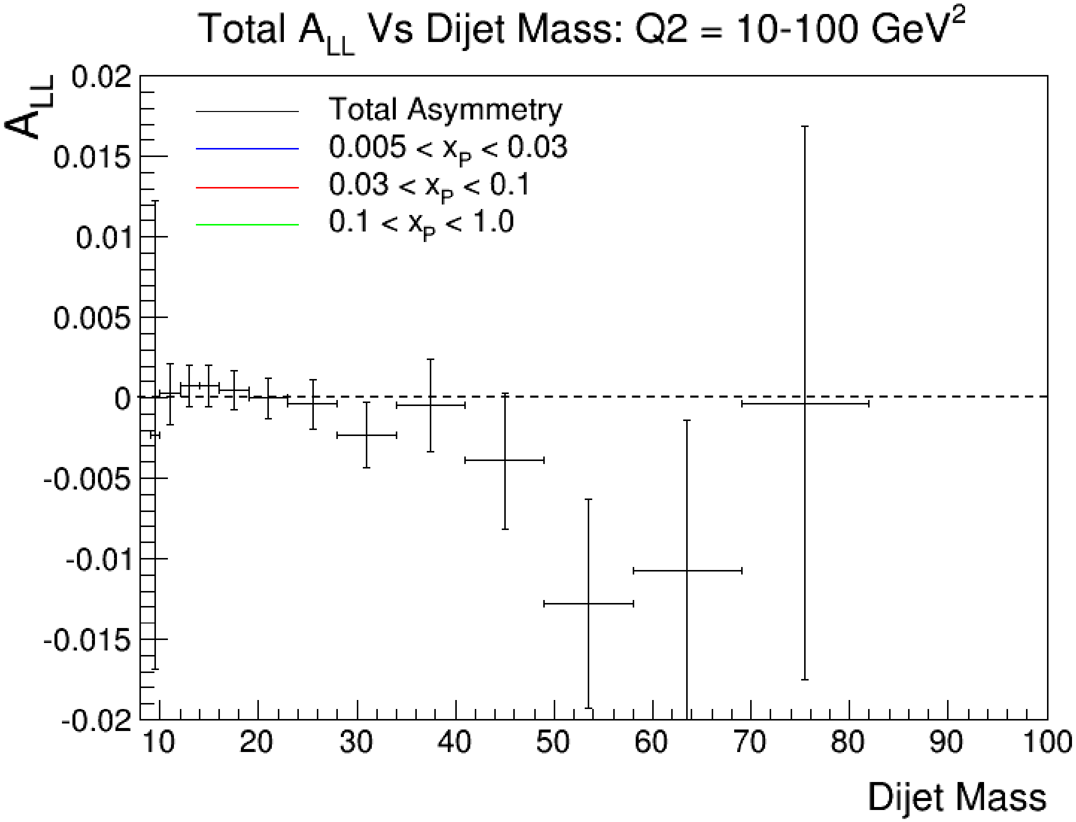


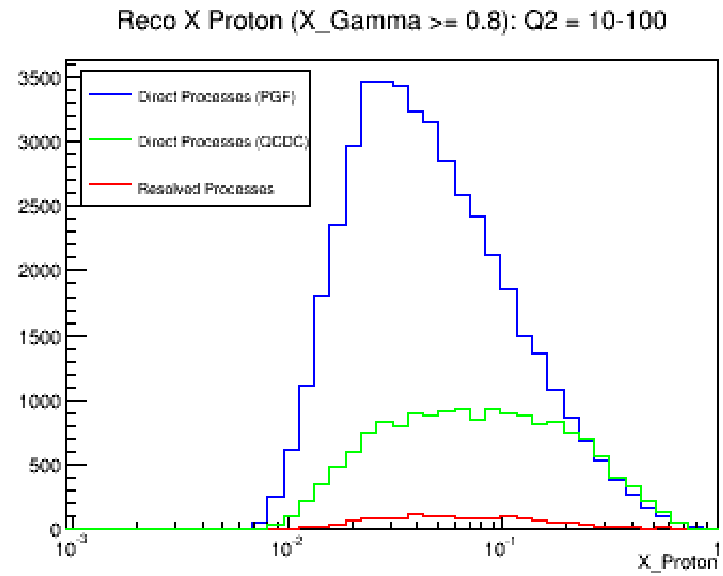
Mass [GeV]

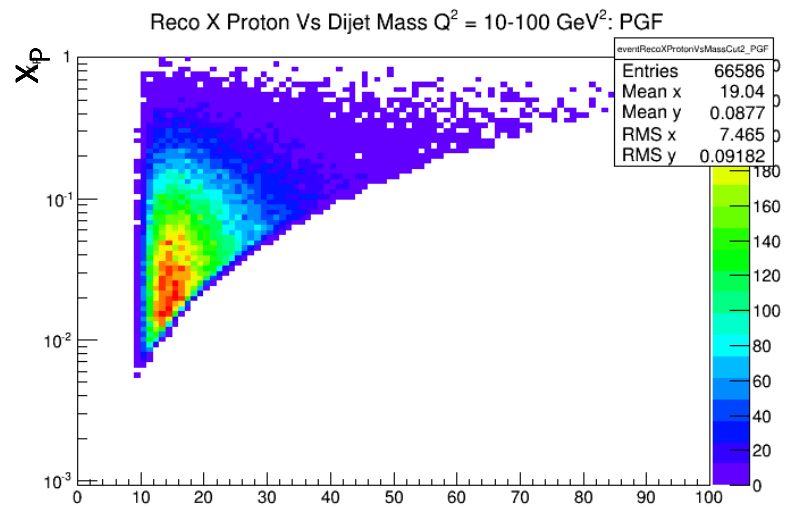
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$

- 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

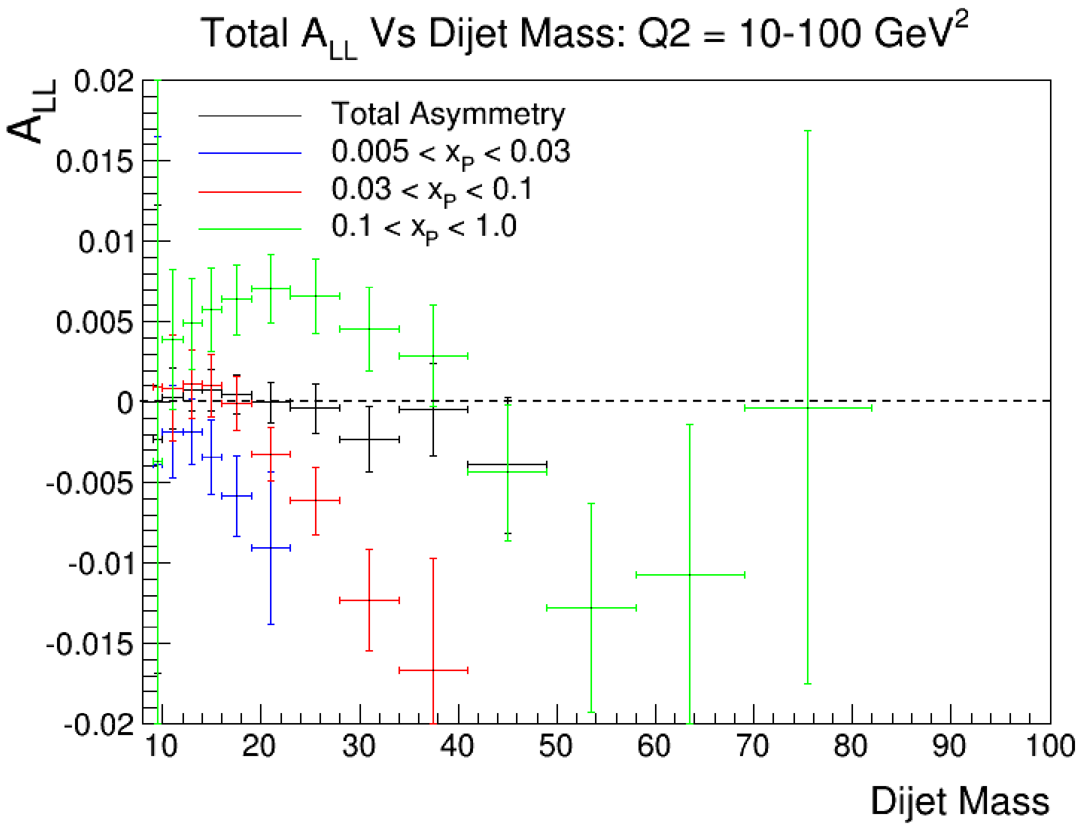


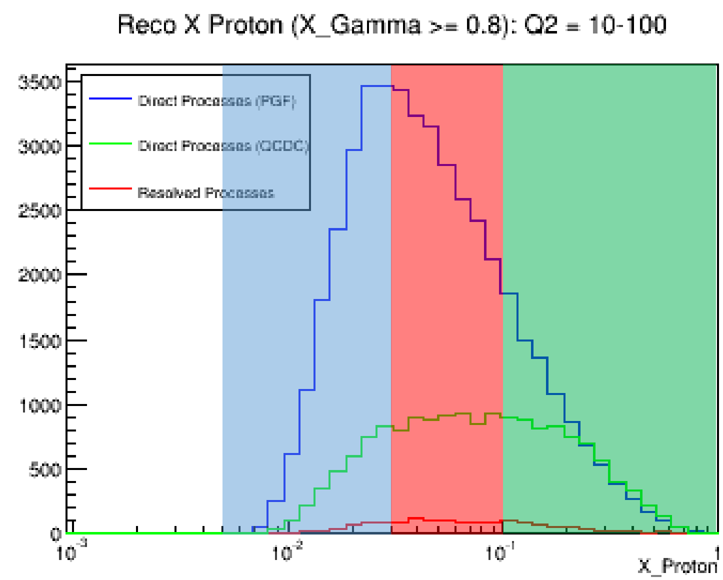


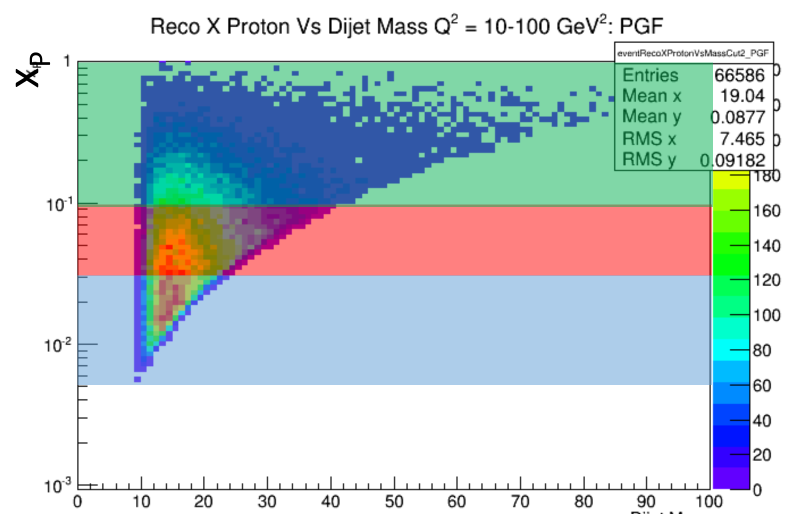


- QCDC and PGF asymmetries largely cancel out making overall asymmetry small
- Want to enhance PGF subprocess w.r.t. QCDC
- PGF events peaked to lower x_P values

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







- 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

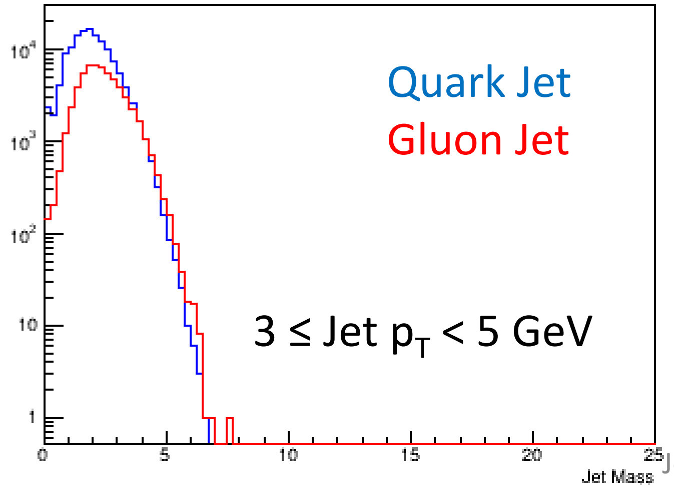
Quark – Gluon Discrimination

- Can we use the distribution of energy within a jet to determine if that jet arose from a quark or a gluon? Possibility to tag QCD-Compton process via detection of a gluon

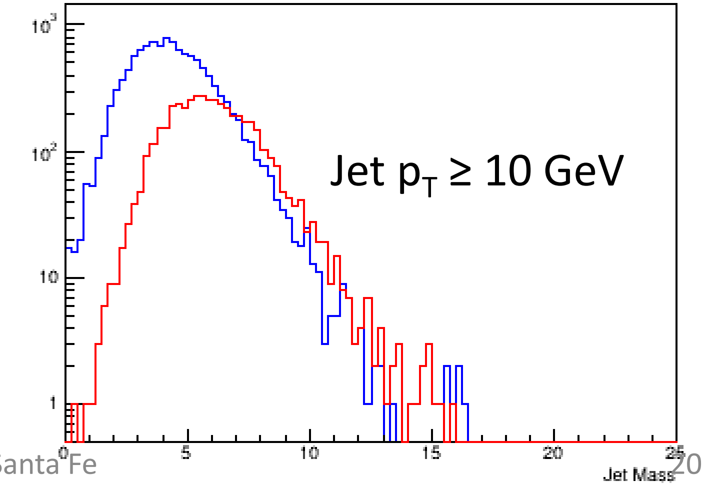
- This is a preliminary look at jet substructure at eRHIC; eventually want to explore the utility of substructure for studying how partons loose energy and hadronize in the cold nuclear medium

- For this study, look at jets with $p_T \geq 10$ GeV as this is where separation between quark and gluon jets is seen. Only consider light quarks: u, d, and s

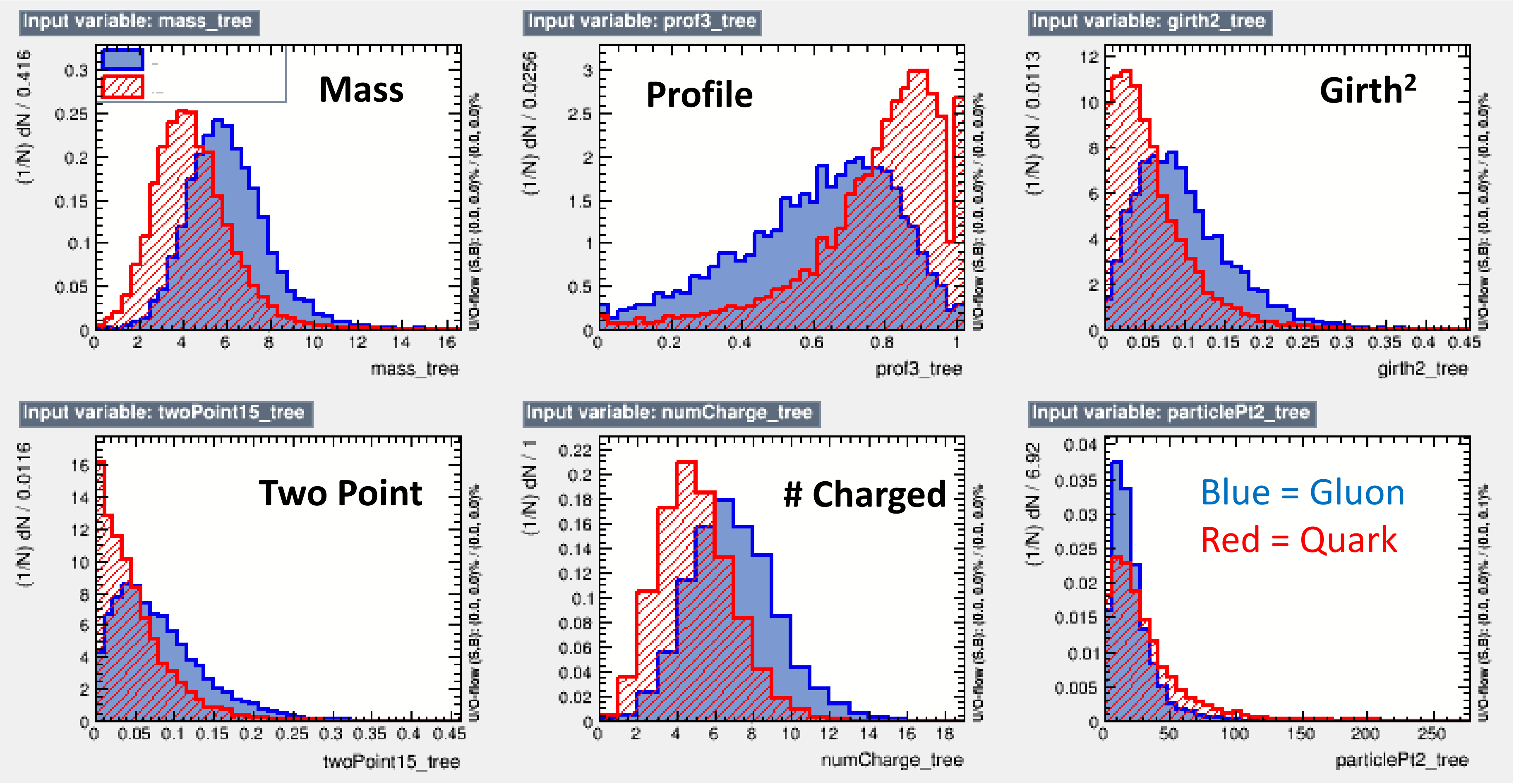
Jet Mass: Low Jet p_T



Jet Mass: High Jet p_T



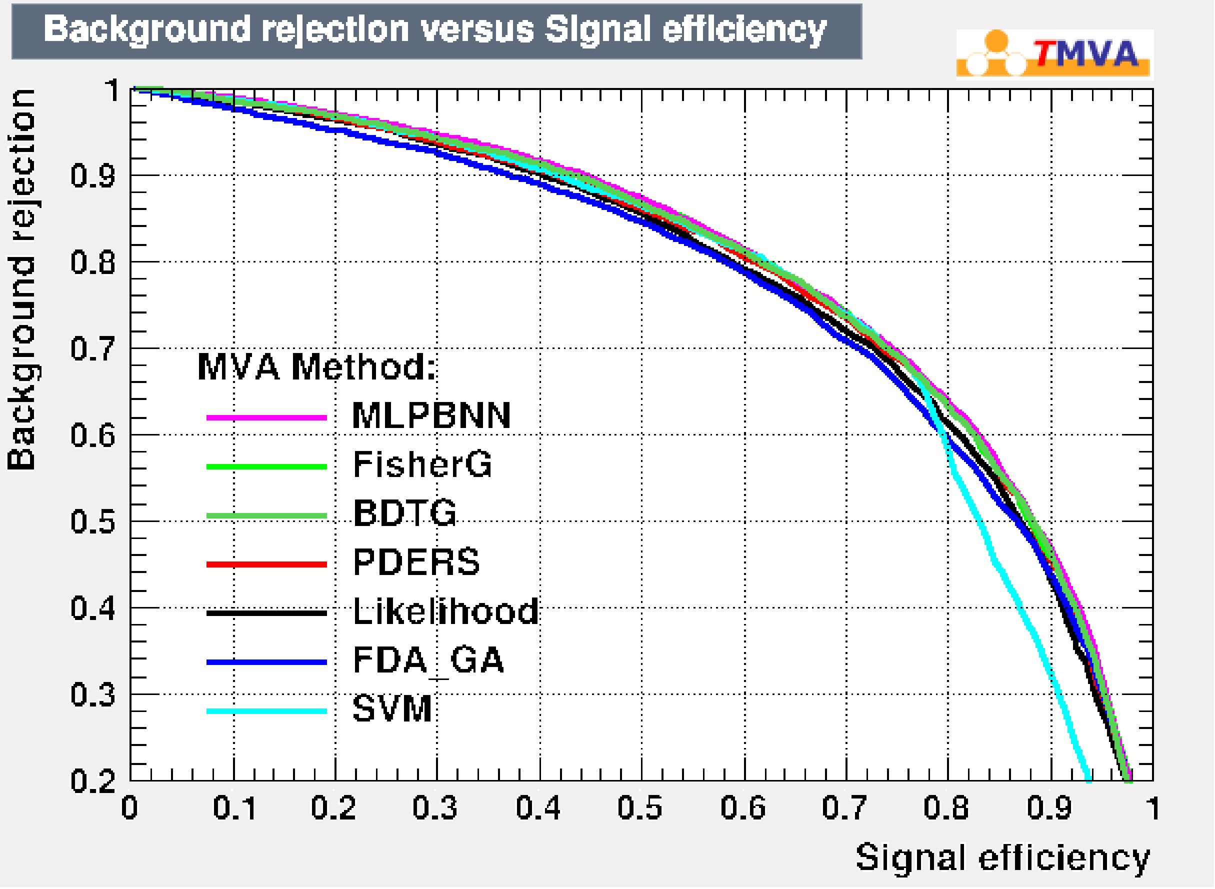
Input Variables



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

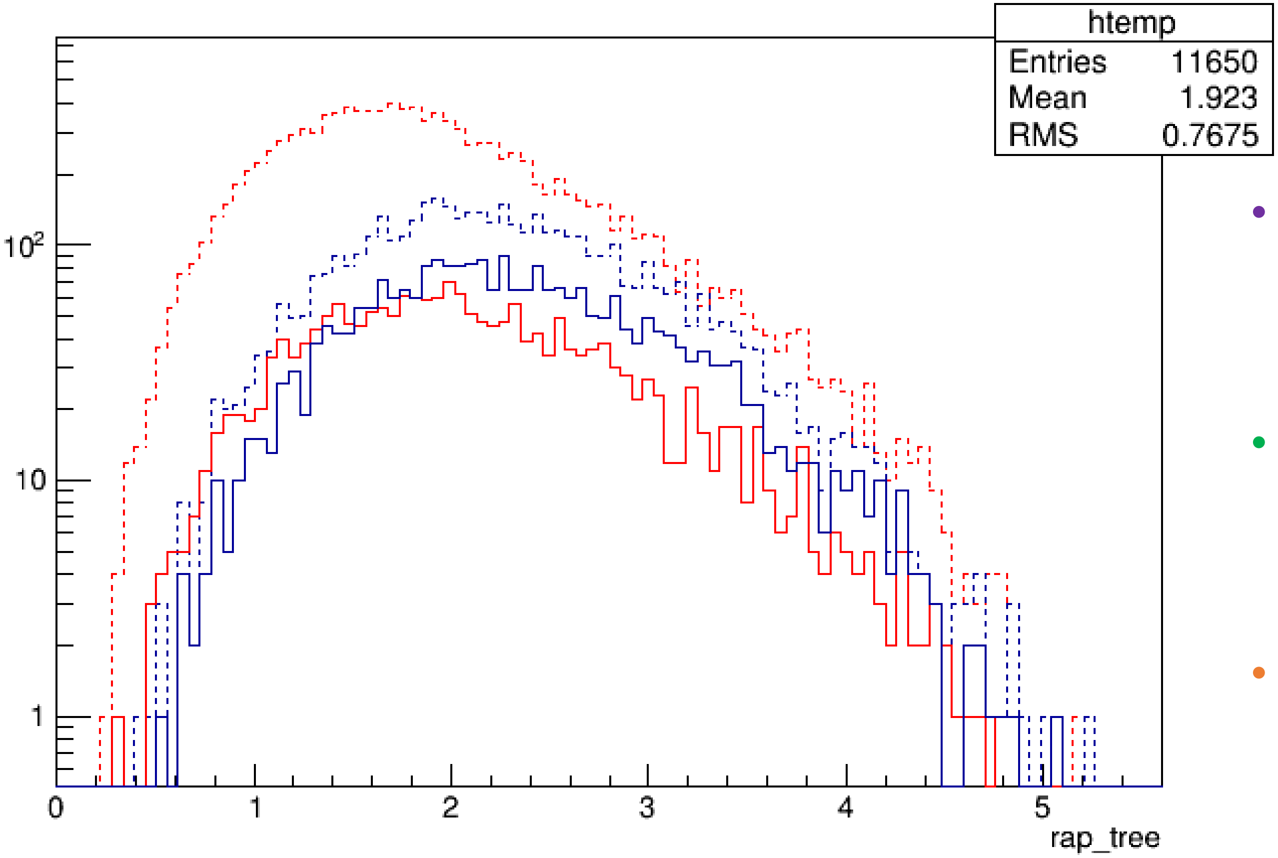
$$2\ \text{Point} = \frac{1}{{p_{Tjet}}^2} \sum_{i \neq j} p_{Ti} * p_{Tj} * |r_{ij}|^{\beta}$$

Discrimination Performance



- Characterize a number of multivariate methods by percentage of background (quarks) rejected vs signal (gluons) retained
- All methods performed roughly the same
- For the following, use MLPBNN which is a neural network implementation

Jet Rapidity Spectra



- After cut is applied, can plot quark and gluon jets vs any relevant variable
- Here we see that gluons dominate at higher rapidity
- Look at jets with rapidity > 1.8 to further enhance gluon fraction

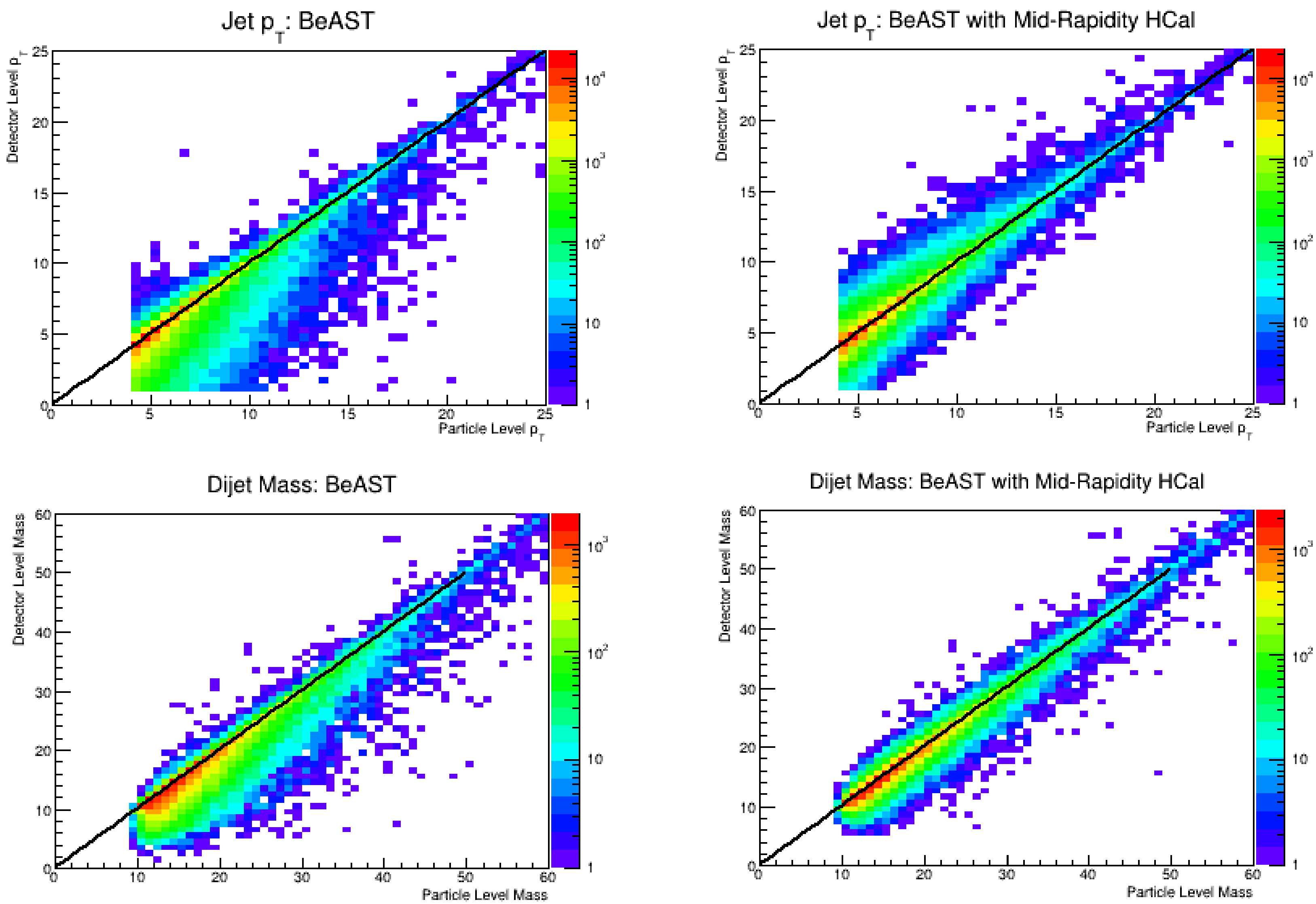
Dotted Red = All Quarks (11650)
Dotted Blue = All Gluons (4511)
Solid Red = Quarks After Cut (1964)
Solid Blue = Gluons After Cut (2568)

G/Q Before Cut = 0.39
G/Q After Cut = 1.31
G/(G+Q) Before = 28%
G/(G+Q) After = 57%

Simulating Detector Response

- Need to study the effect that detector smearing will have on jet observables and kinematic quantities reconstructed from jets
- Do this via a fast smearing program based on the BeAST detector design
- Electromagnetic calorimeter coverage spans range of +/- 4.5 in pseudorapidity with resolution between 7 and 15%/√E
  - EM clusters assumed to be massless
- Tracking coverage spans range of +/- 3.5 in pseudorapidity
  - Tracks assumed to have pion mass
  - Tracking inefficiencies of 5 and 10% also considered
- Hadronic calorimetry in forward / backward region ($1 < |eta| < 4.5$) with resolution of $1.5\% \oplus 50\%/\sqrt{E}$
  - Optional mid-rapidity calorimeter with $7\% \oplus 85\%/\sqrt{E}$ also considered

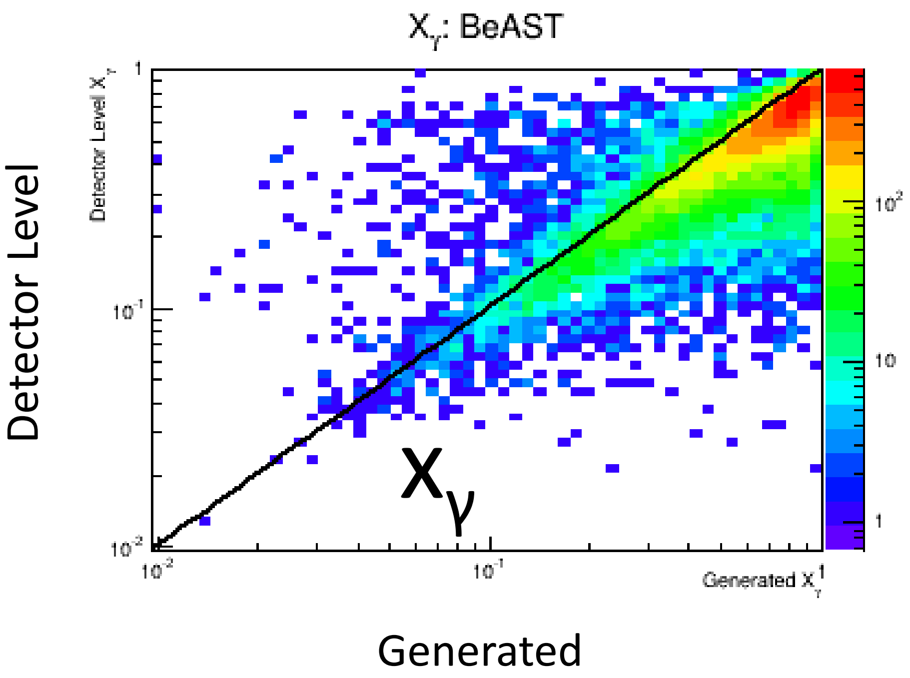
Particle – Detector Comparison



Detector Level

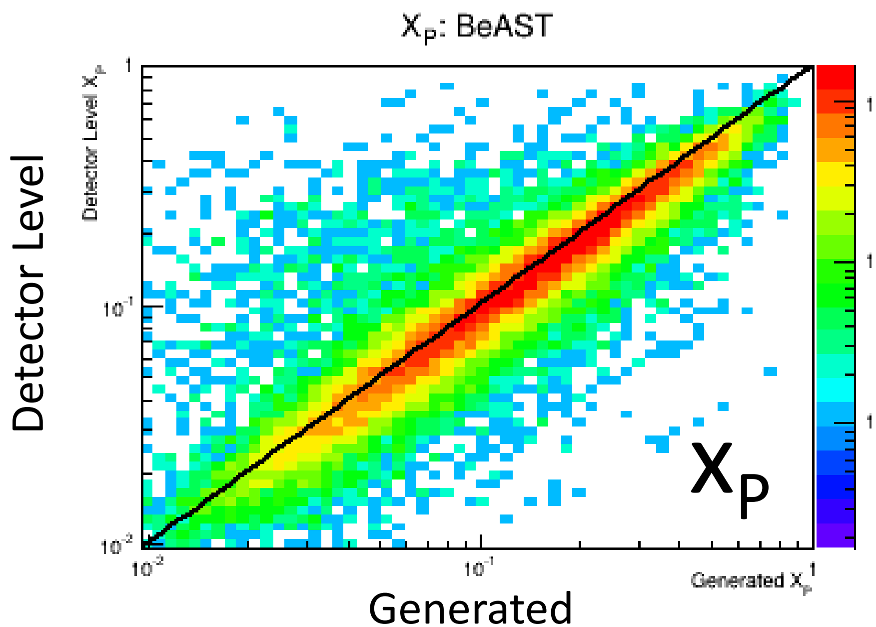
Particle Level

Particle – Detector Comparison



- Have seen that the individual jet quantities are well reproduced after smearing
- What about quantities derived from jet properties such as x_γ and x_P?

- Both x_γ and x_P show good agreement between the generated and smeared values
- Level of smearing is similar to that seen between particle level and generated values

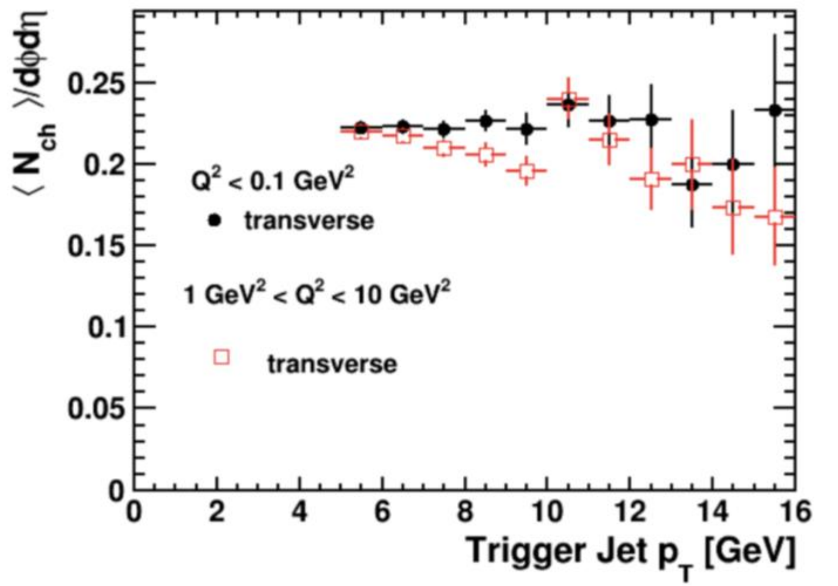


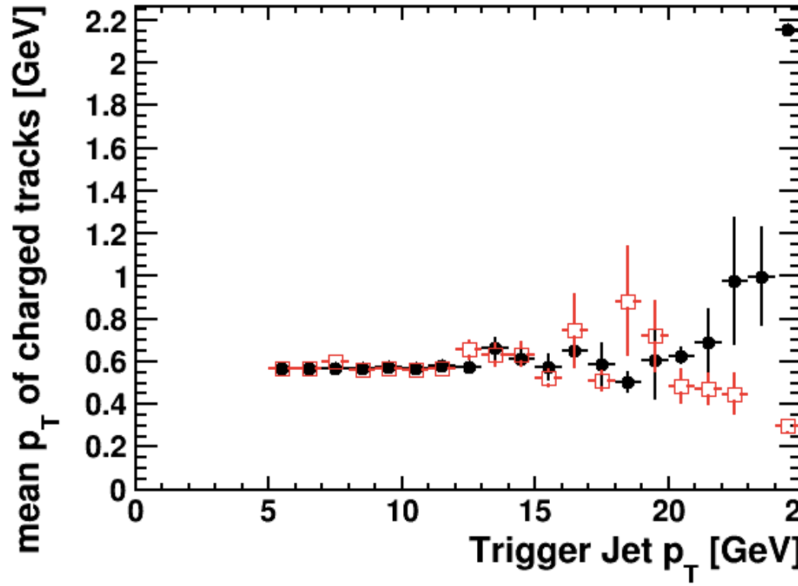
Summary

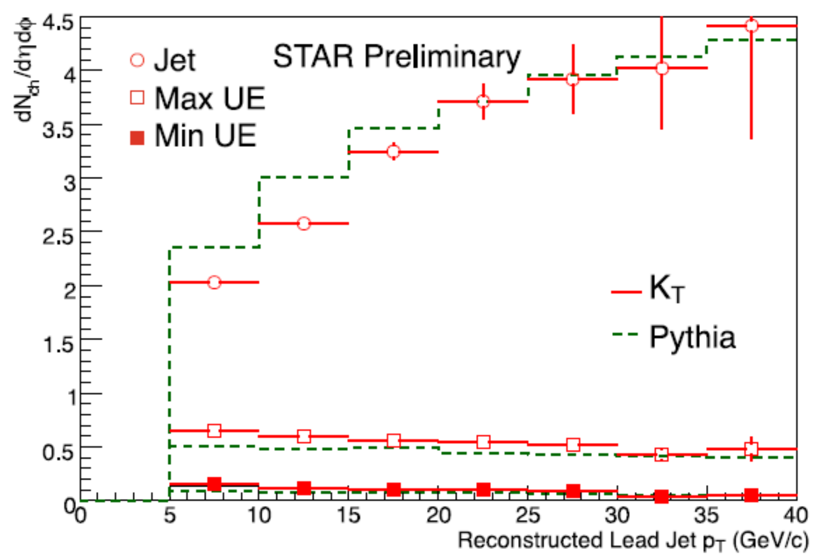
- Characterization of the underlying event was made and the contribution was found to be rather small
- Methods for studying photon structure and gluon polarization using dijets were detailed
- Studies of jet substructure are beginning and a preliminary look at their utility for discriminating between quark and gluon initiated jets has been done
- Impacts of detector effects on jet observables are being investigated using a fast smearing package and BeAST detector parameters

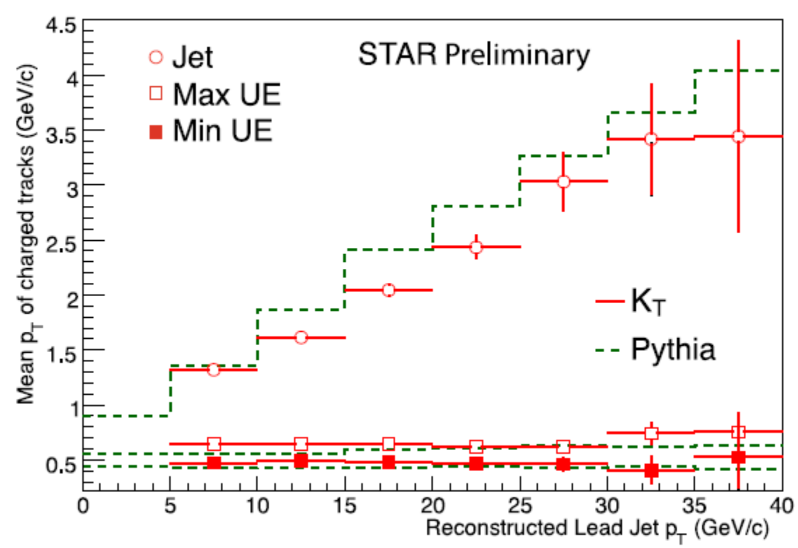
Backup

Comparison with STAR

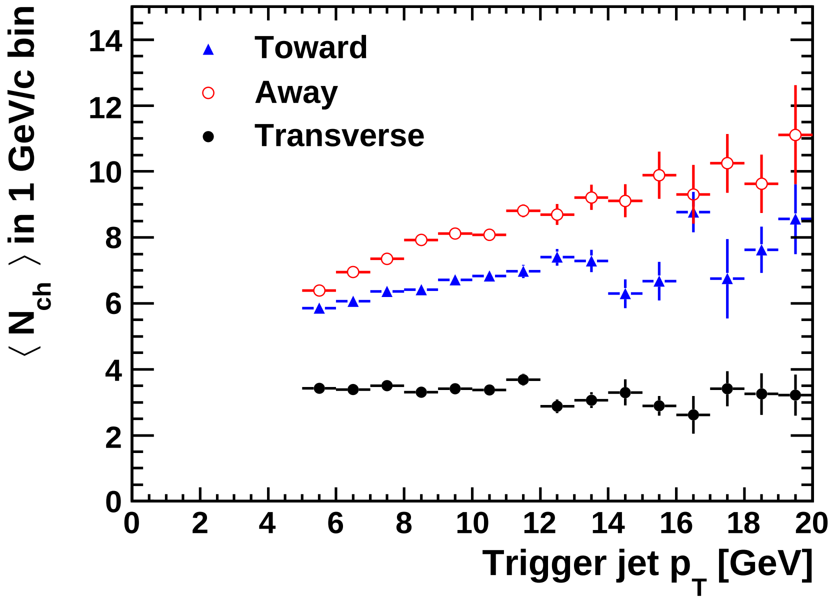






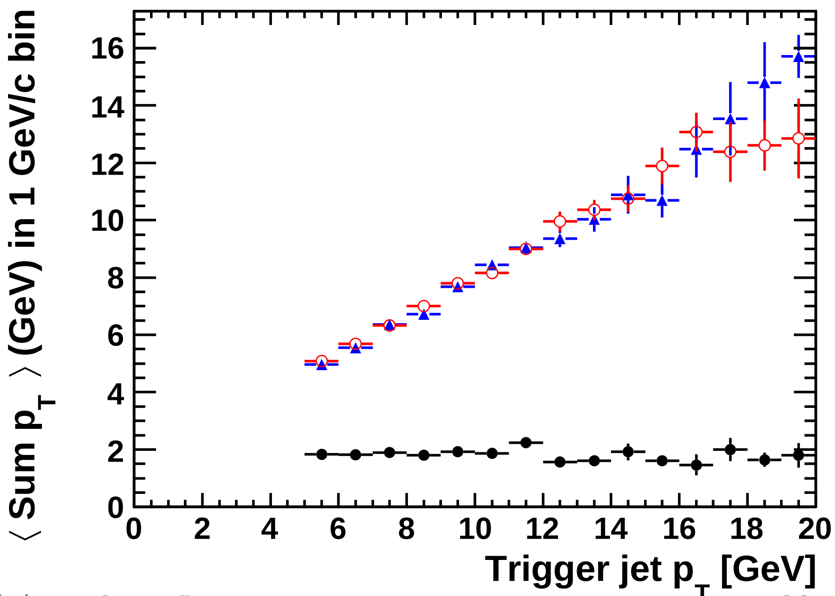


Underlying Event Characteristics

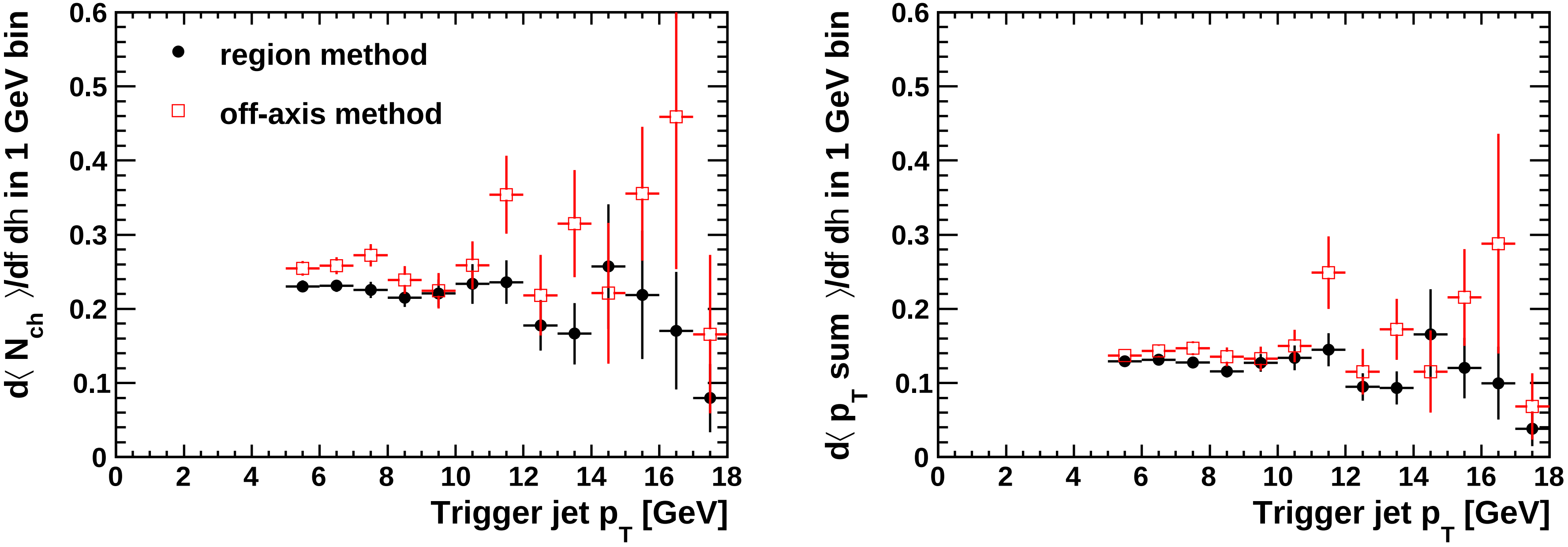


- Plot the average number of charged particles and average summed p_T for the three regions as a function of trigger jet p_T
- See that these quantities are independent of the trigger jet pT in transverse region

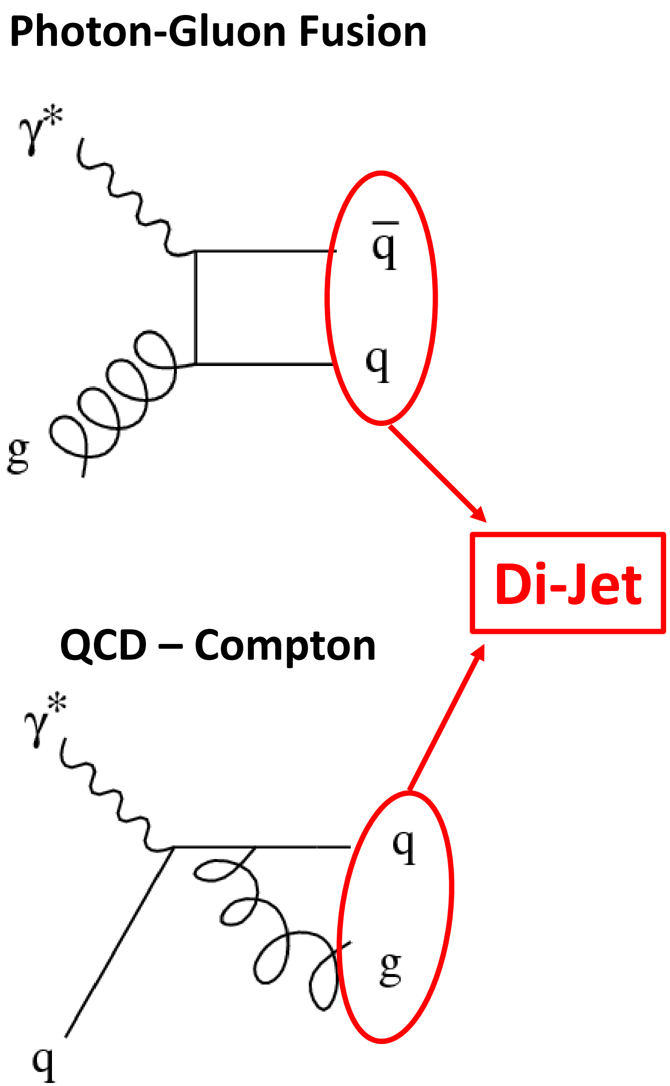
- Underlying event activity similar to that seen in pp collisions at STAR at √s = 200 GeV



UE Method Comparison



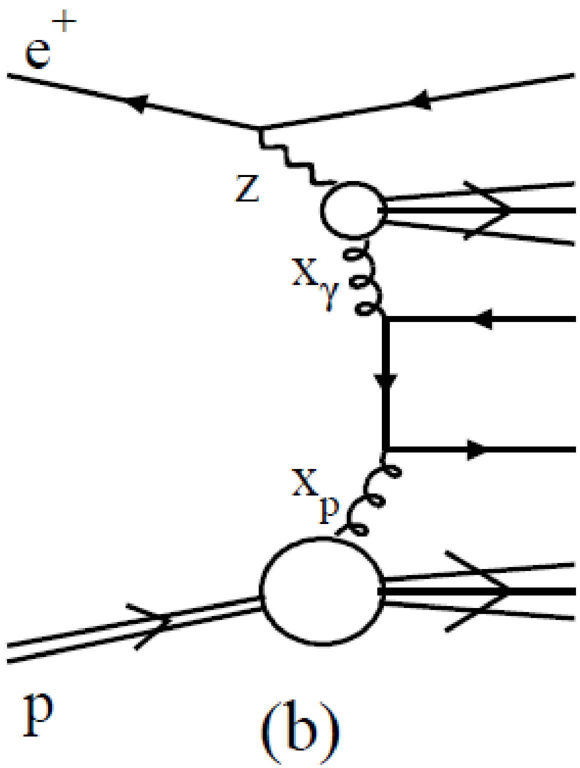
Gluon Polarization with Di-jets



- 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

Gluon Polarization with Di-jets

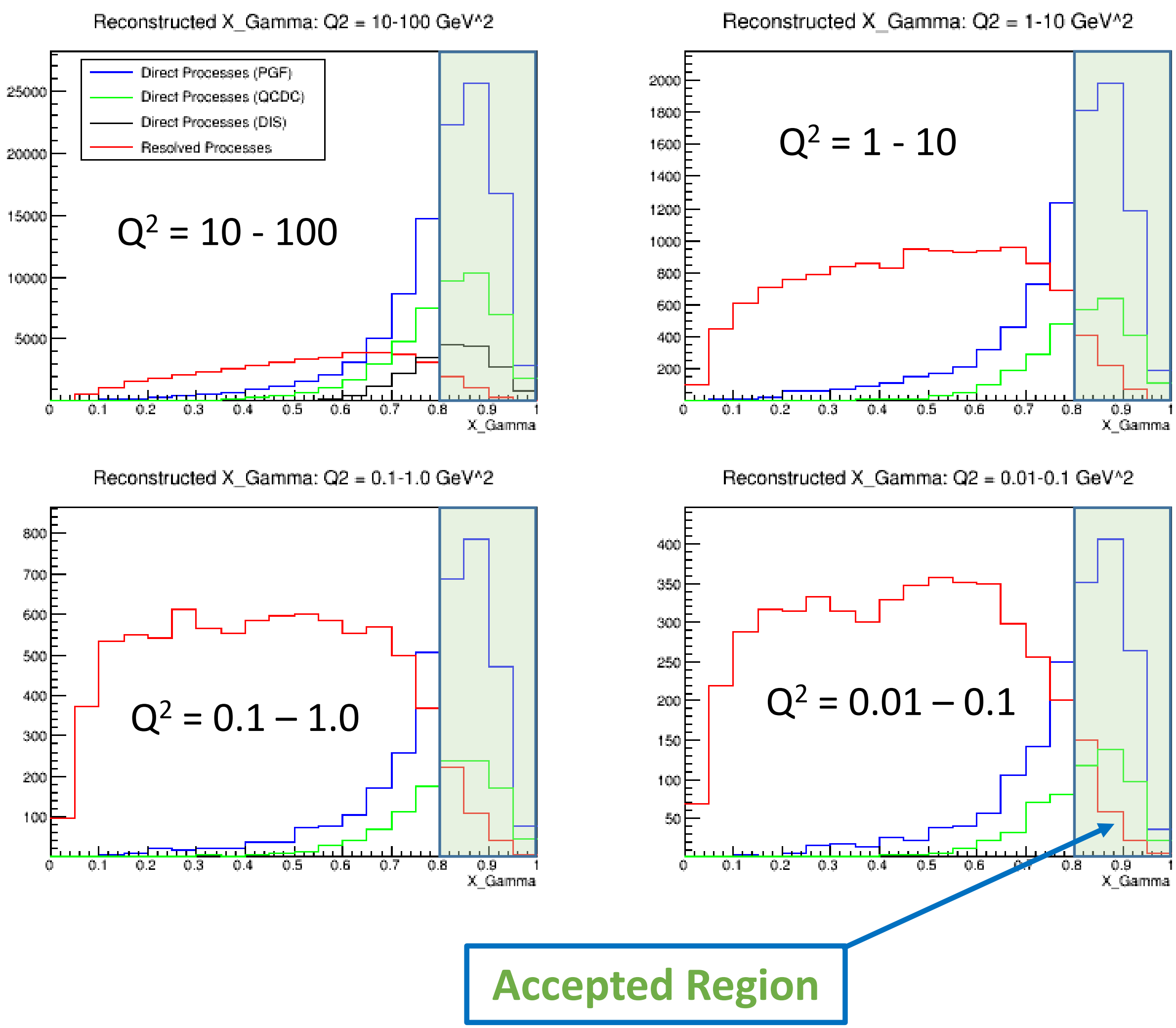
Resolved



- 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

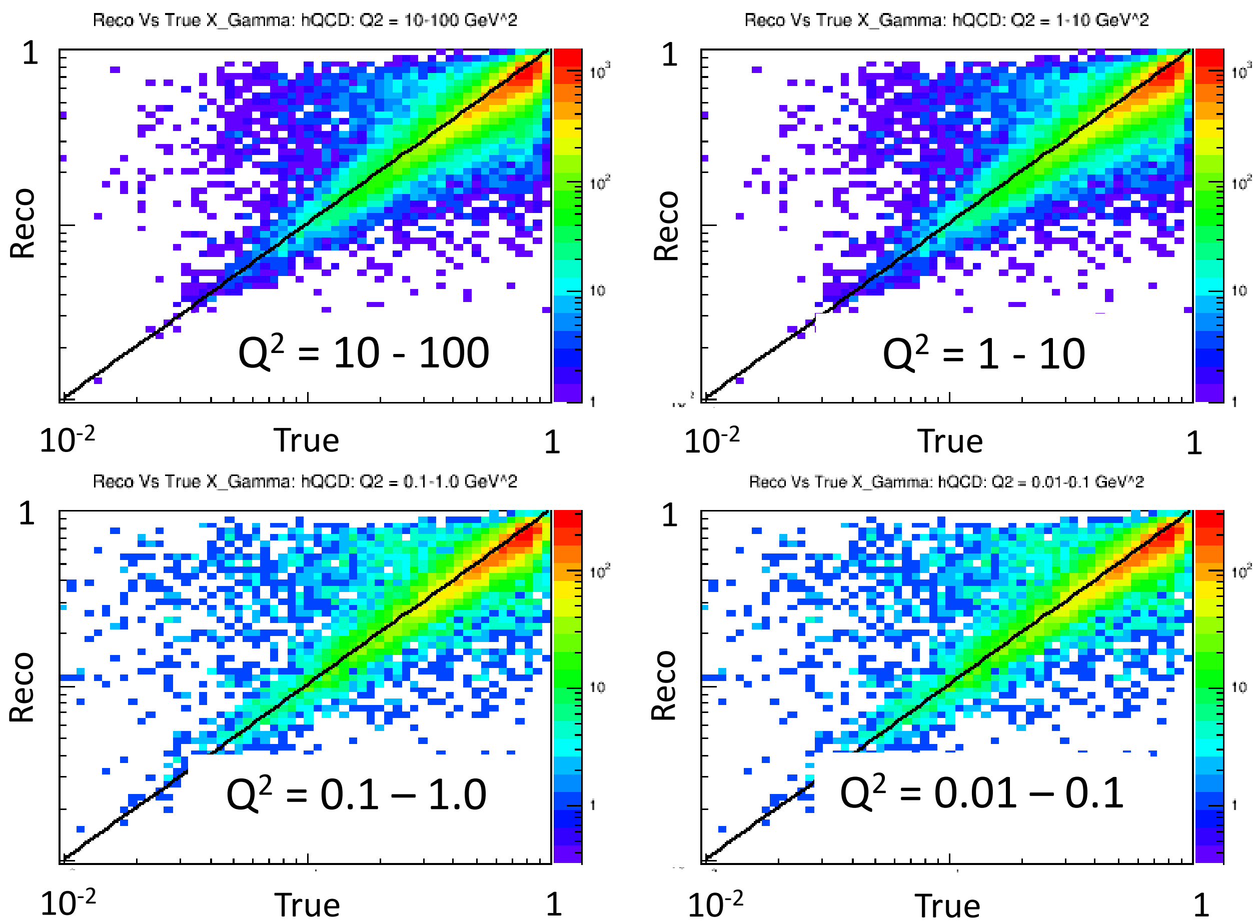
Direct Vs Resolved Processes

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



- 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

X_γ: Reconstructed Vs True

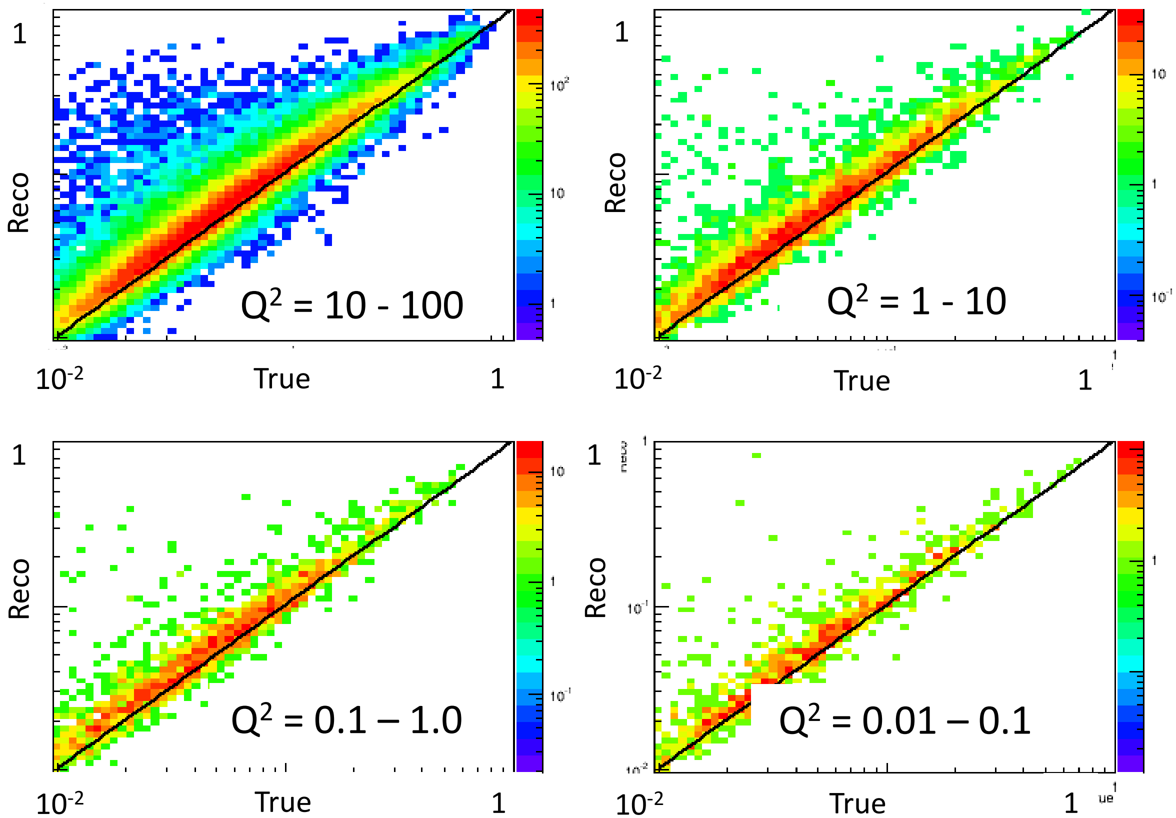


- Will use virtual photon momentum fraction to discriminate between resolved and direct processes
- See good agreement between reconstructed and true X_γ for all Q^2 ranges
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV

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

Proton Partonic Kinematics

Parton Momentum Fraction: Photon Gluon Fusion



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

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

Proton Partonic Kinematics

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

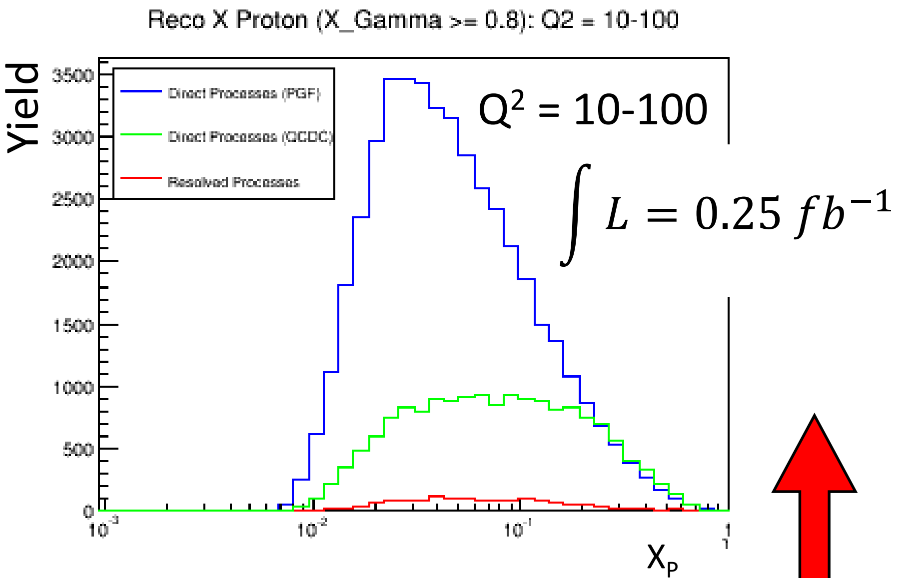
$$Q^2 = syx_B$$

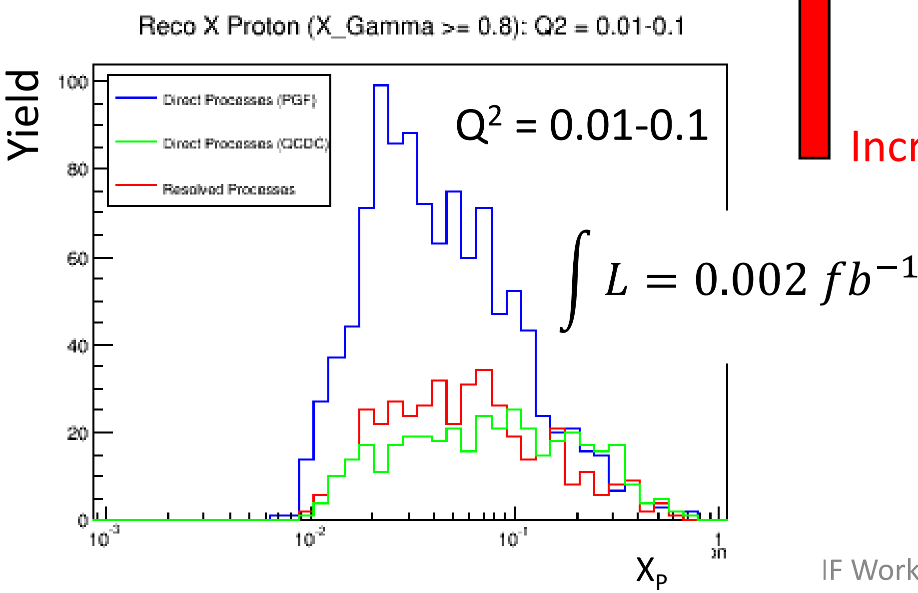
$$X_P = x_B + \frac{M^2}{sy}$$

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

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



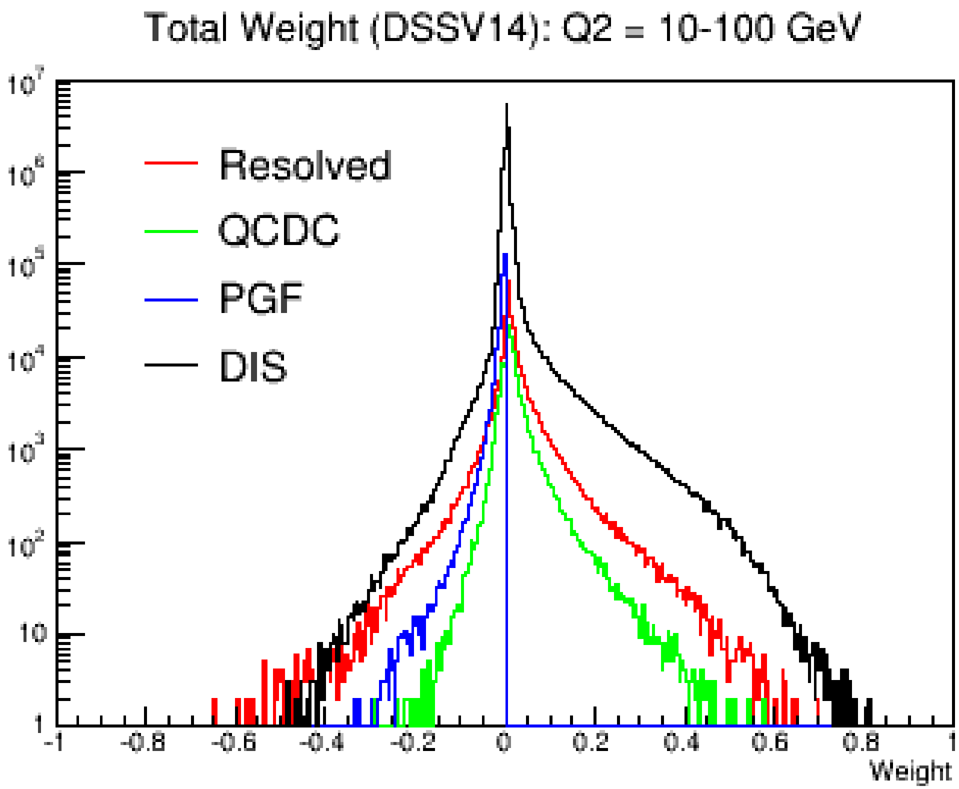


Increasing Q^2

- 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

Weighting PYTHIA

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

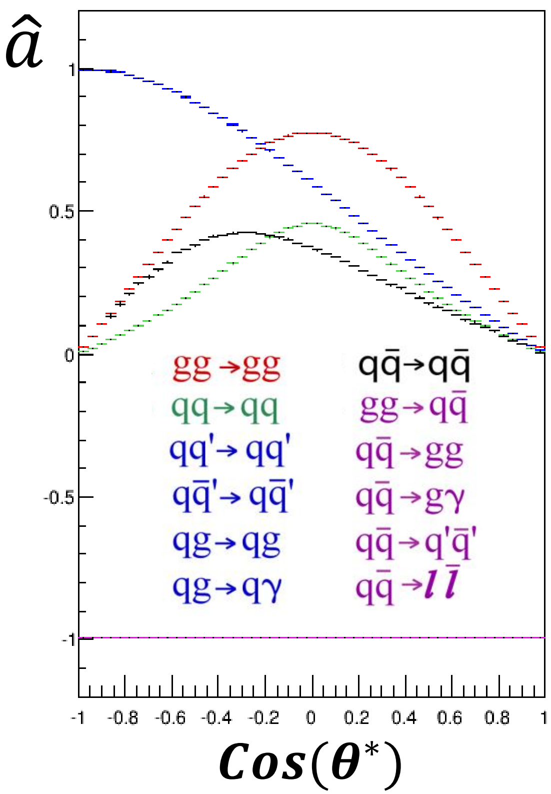


- PYTHIA does not include parton polarization effects, but an asymmetry can be formed by assigning each event a weight depending on the hard-scattering asymmetry and (un)polarized photon and proton PDFs
- Expected asymmetry is then the average over weights
- Weights are sharply spiked near zero -> expect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

Weighting PYTHIA

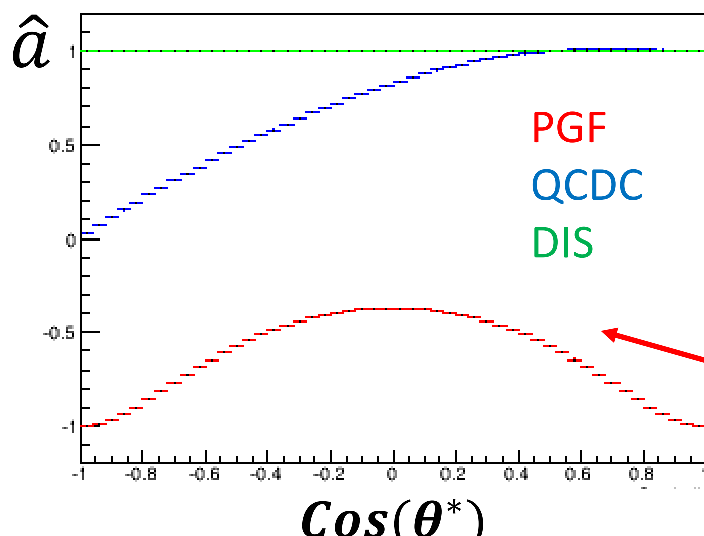
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$

Resolved



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

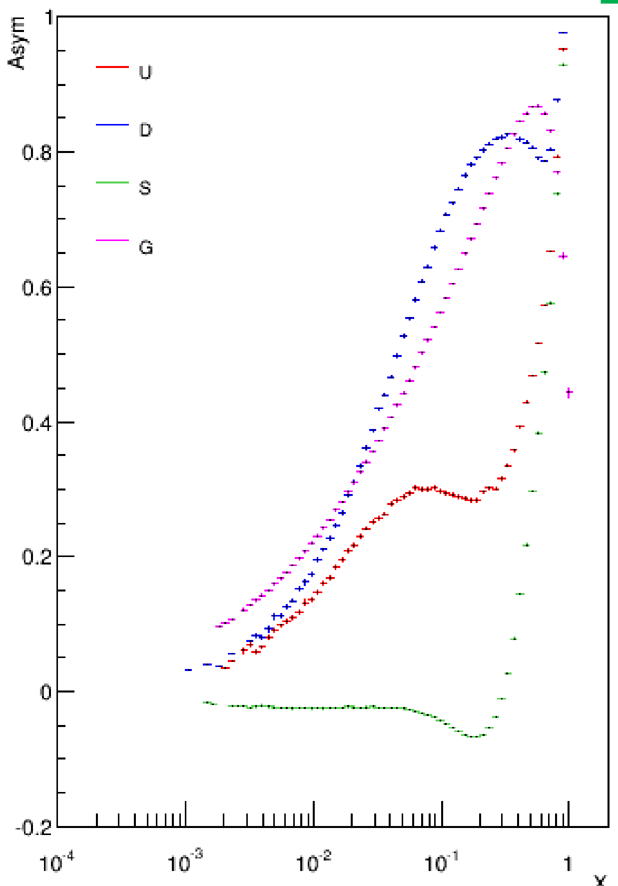
Direct



- 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

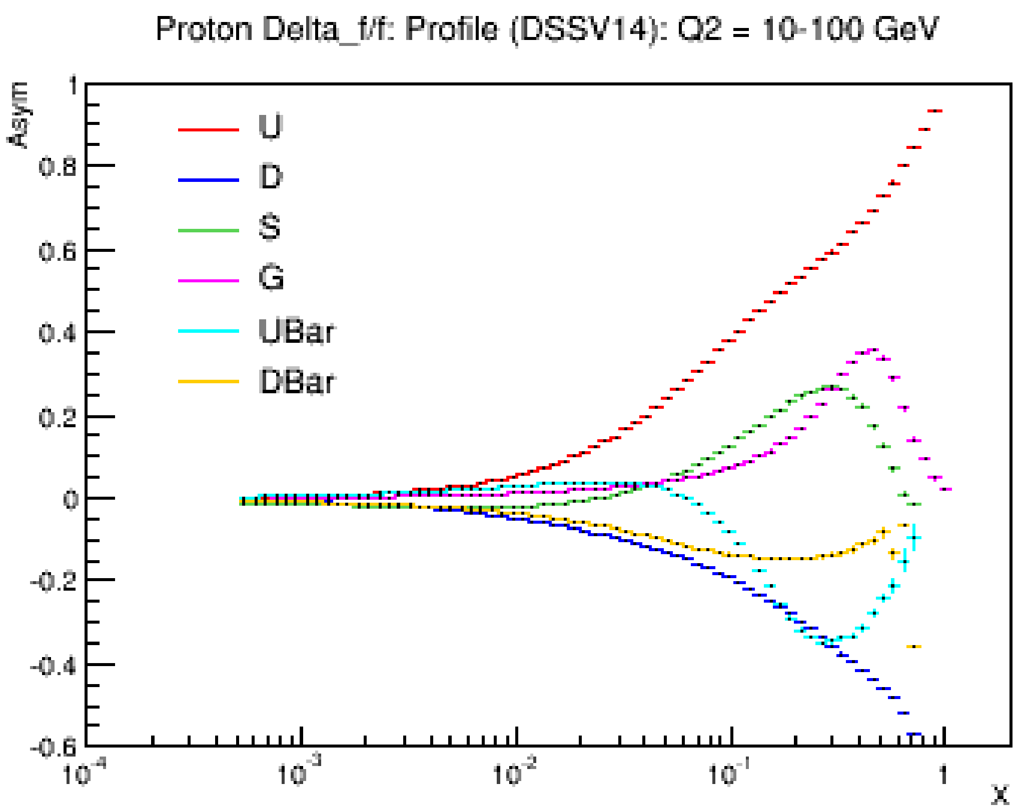
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$



- 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

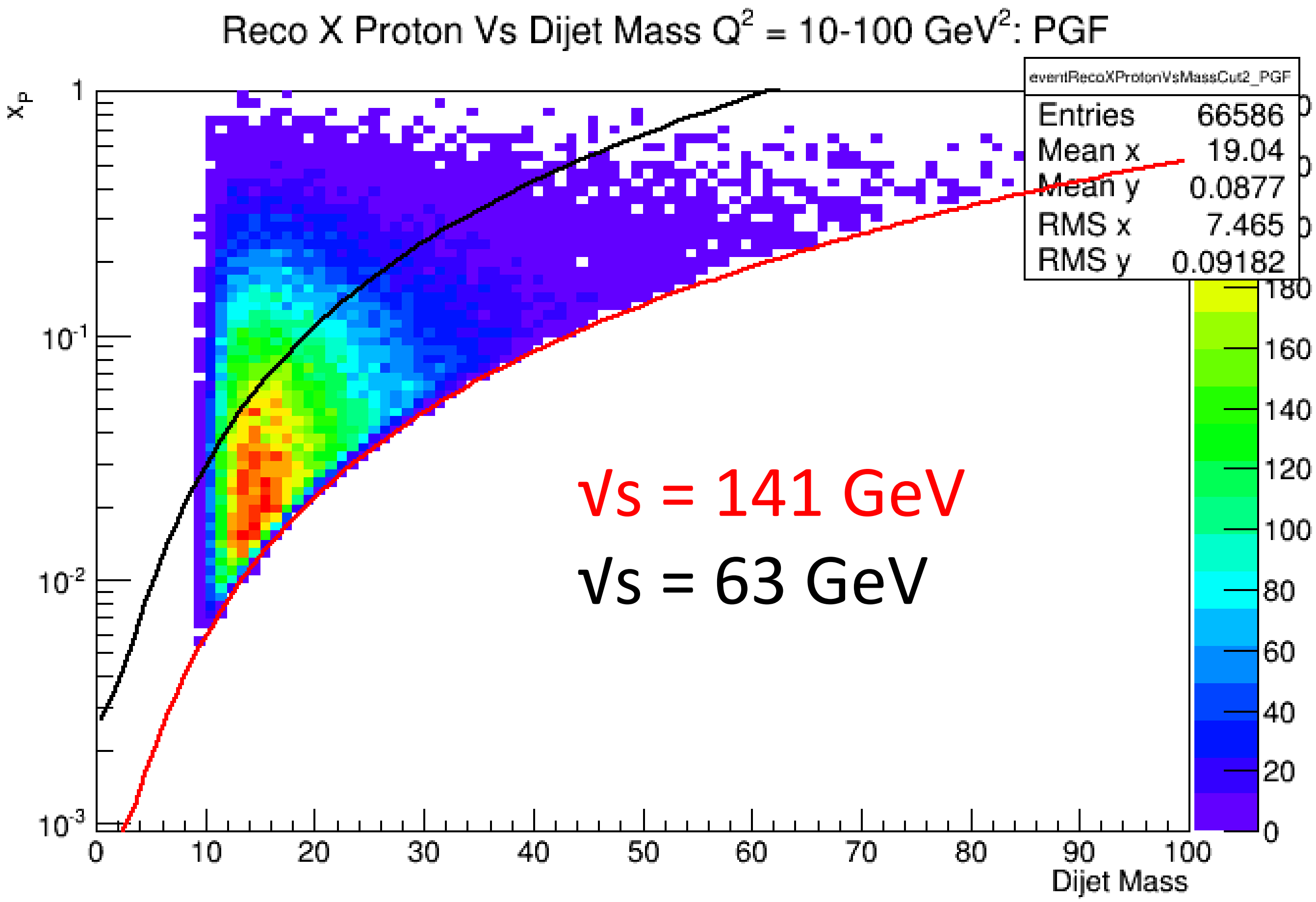
Weighting PYTHIA

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



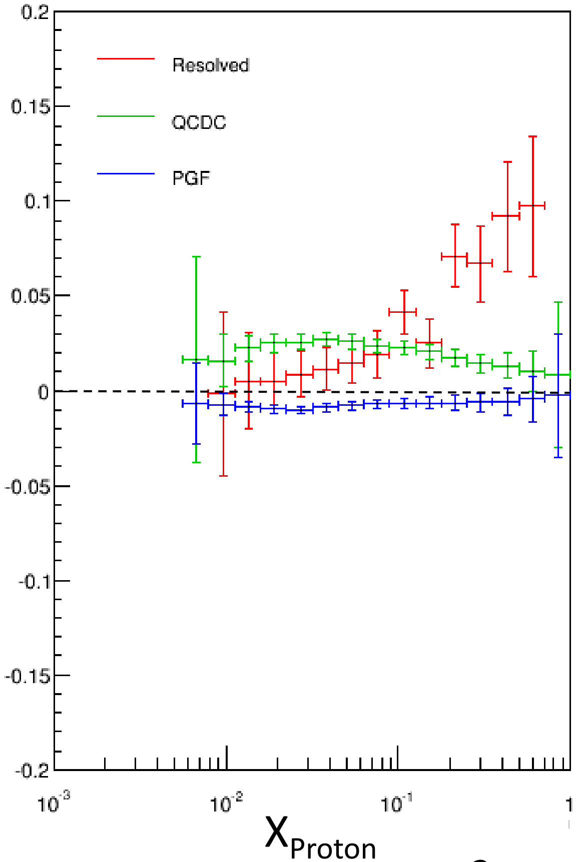
- Last term is the ratio of the polarized to unpolarized proton PDFs
- Use DSSV14 for polarized and CTEQ5M for unpolarized

Dijet Phase Space

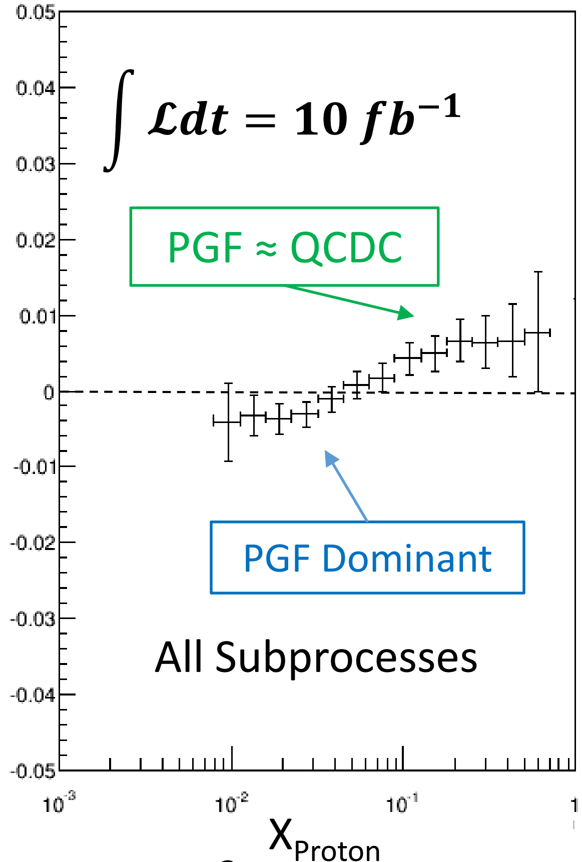


A_{LL} Vs X_{Proton}

A_{LL} Vs Proton X



A_{LL} Vs Proton X

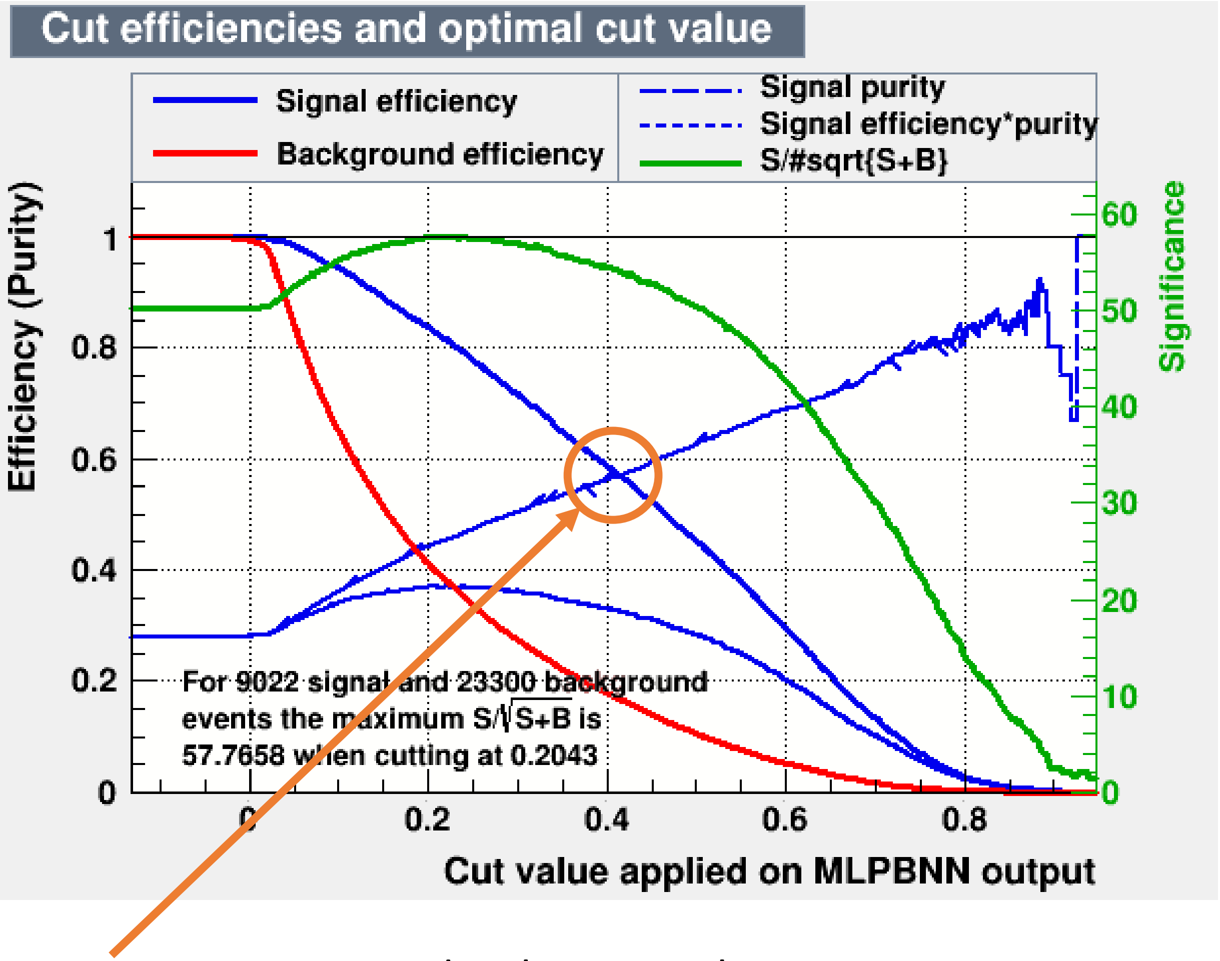


$Q^2 = 10 - 100\ GeV^2$

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

- 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

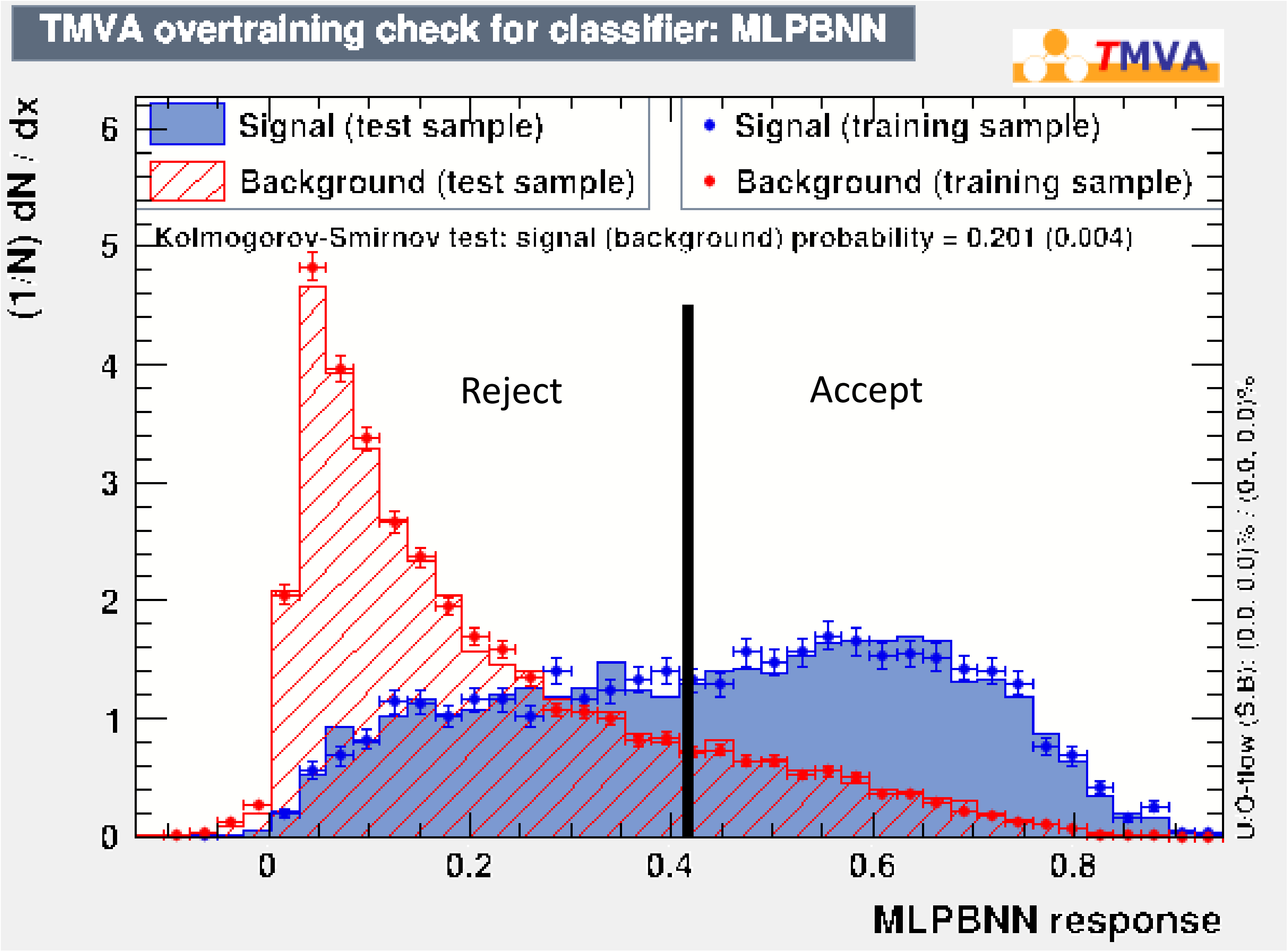
Cut Optimization



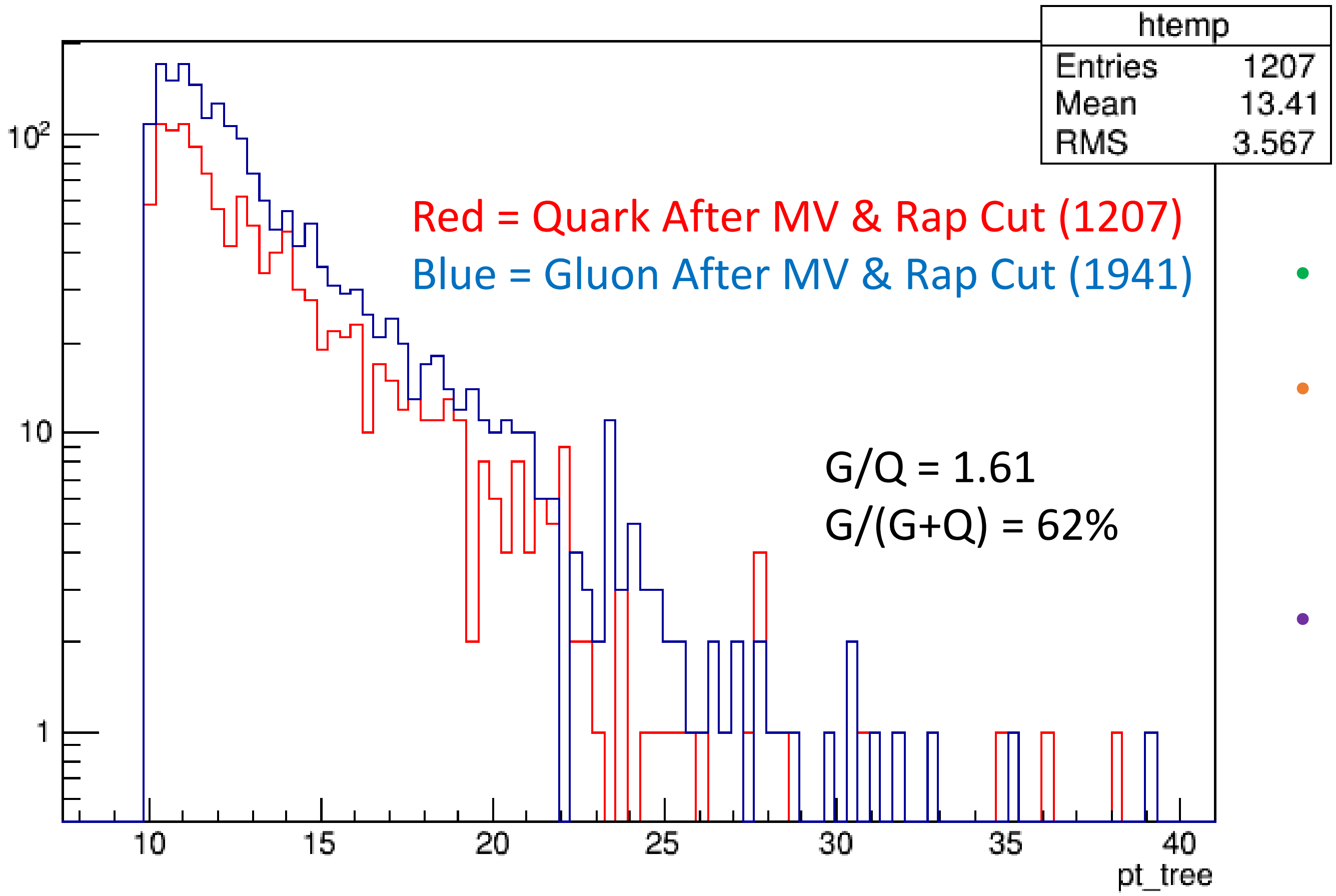
- TMVA evaluates all input and maps them to a single variable with more signal-like events having a higher value
- Plot signal & background efficiency, signal purity, significance, etc as a function of this cut value
- This plot shows where to place cut in order to maximize purity, efficiency, or whatever an analysis requires

- For current study, place cut where signal purity = signal efficiency

MLPBNN Response

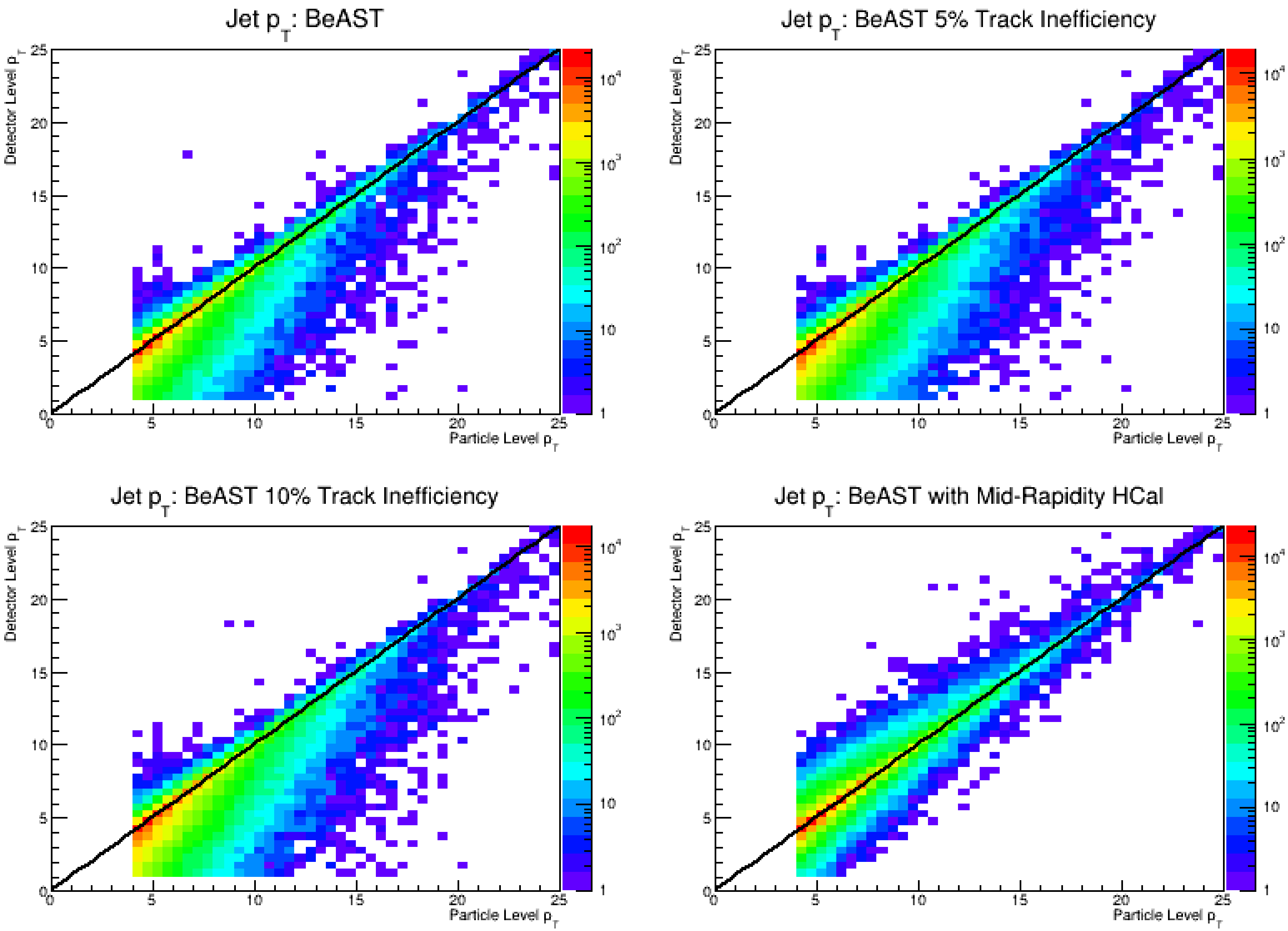


Jet p_T Spectra With Rapidity Cut

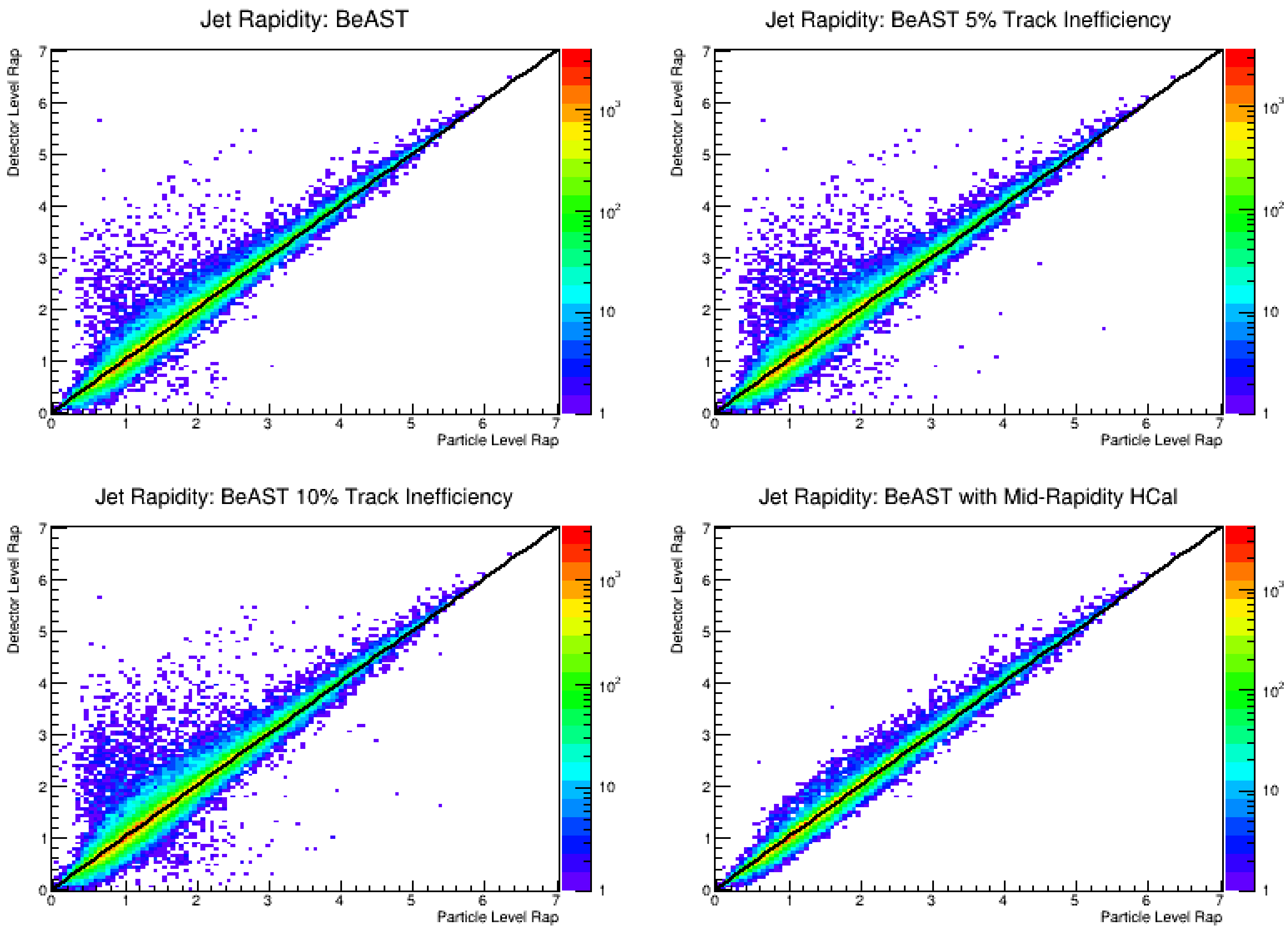


- Plot jet p_T after all cuts
- See reasonable enhancement of gluon jets over p_T range
- Should be able to get relatively pure quark sample and enhanced gluon sample for applications which require identification

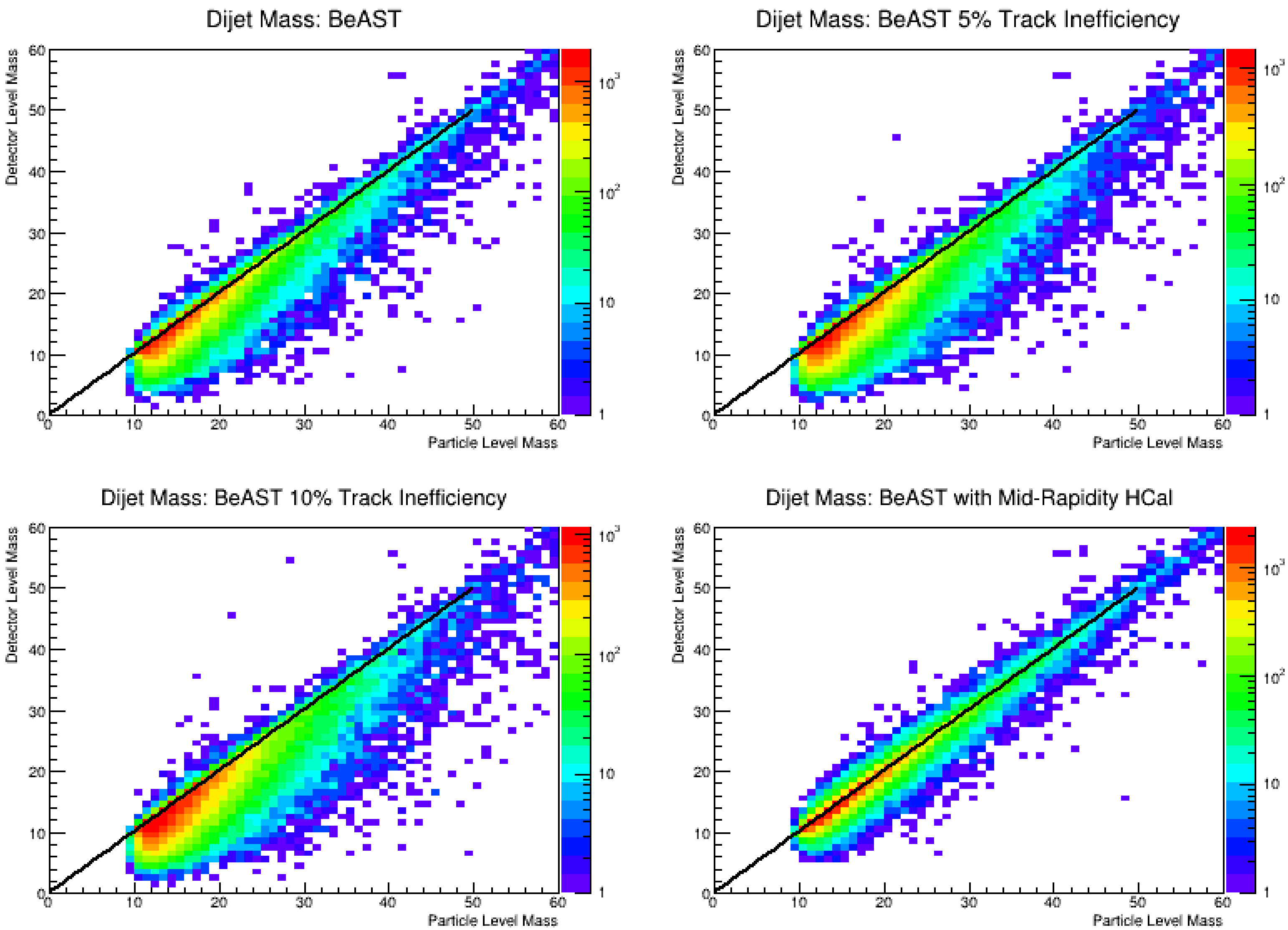
Particle – Detector Jet pT



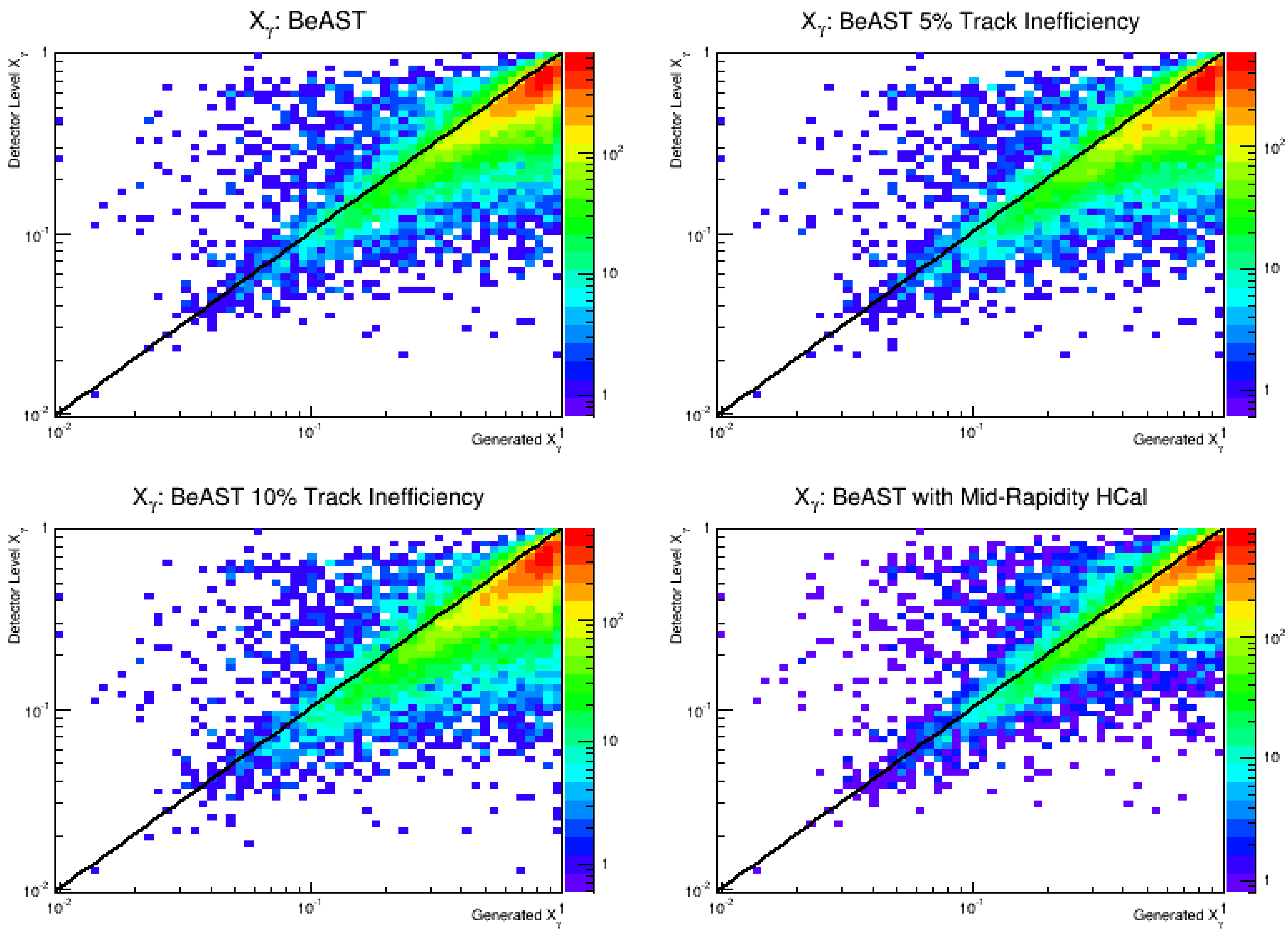
Particle – Detector Jet Rapidity



Particle – Detector Dijet Mass



Particle – Detector X_Gamma



Particle – Detector X_Proton