Jets at an EIC:
A Window on the Partons

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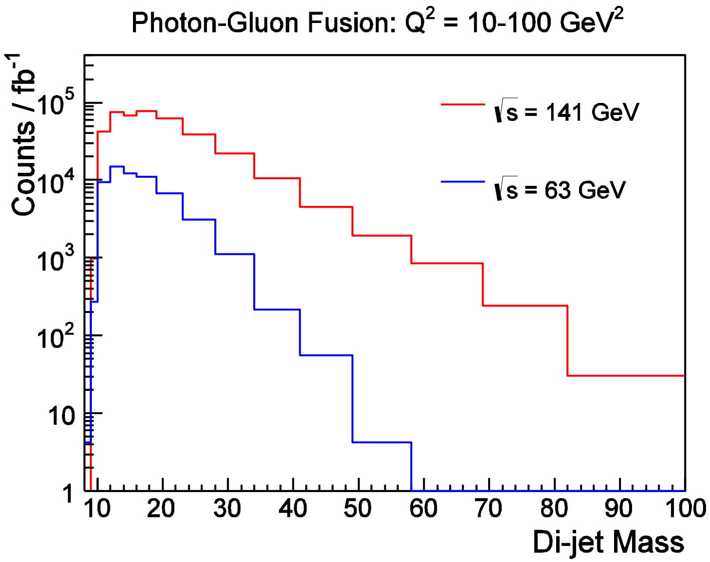
EIC Users Meeting – Trieste

Outline

- Underlying Event Characteristics
- Accessing Gluon Spin with Dijets
- Detector Smearing

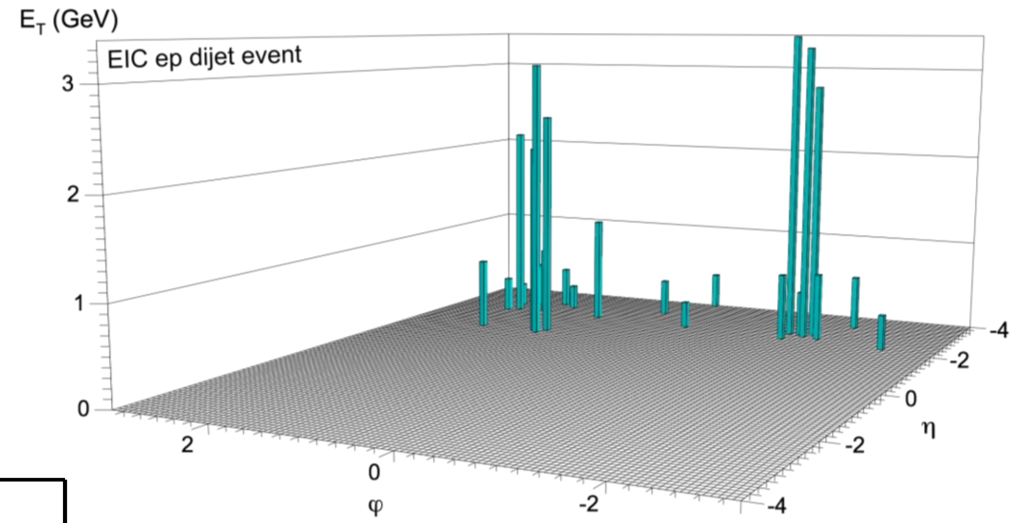
Simulation Details / Particle Cuts

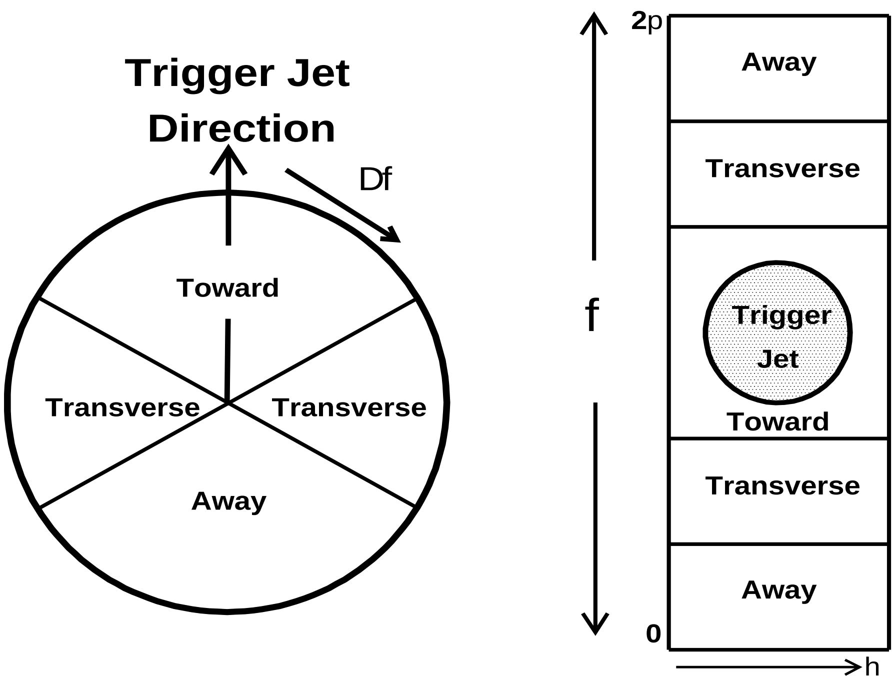
- Electron – Proton events generated at √s = 141 GeV using PYTHIA
- Cut on inelasticity: $0.01 \leq y \leq 0.95$
- Jet Algorithm: Anti_k_T (R = 1.0)
- Jets found in Breit frame
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered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



Underlying Event Study

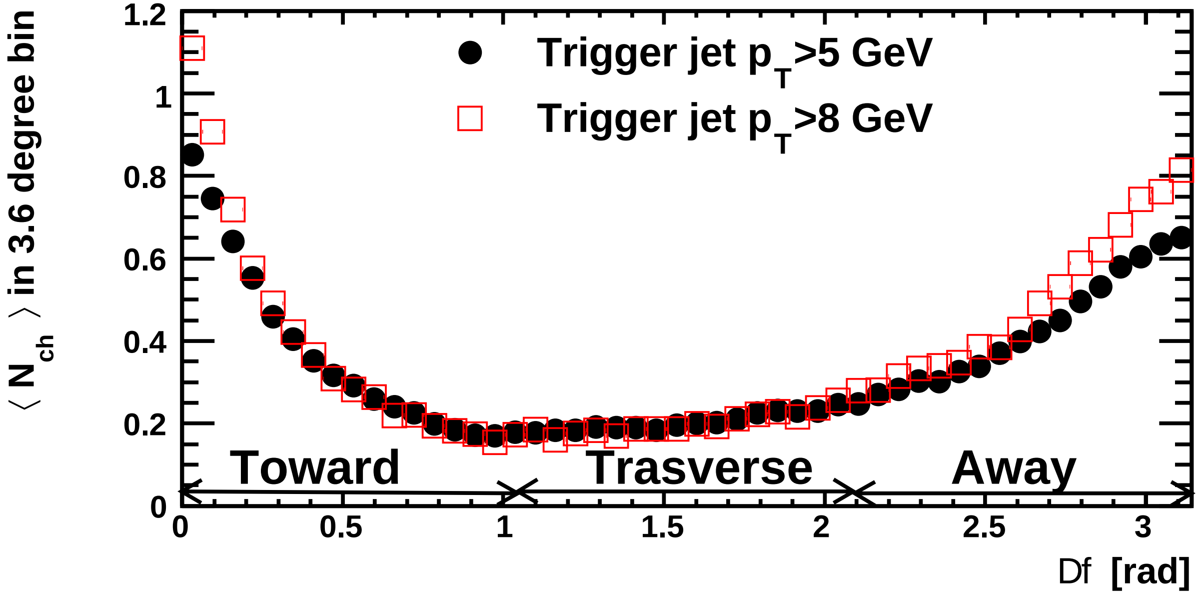
- ep events are expected to be very clean with little underlying event
- Want to systematically quantify the amount of underlying event present in a typical event

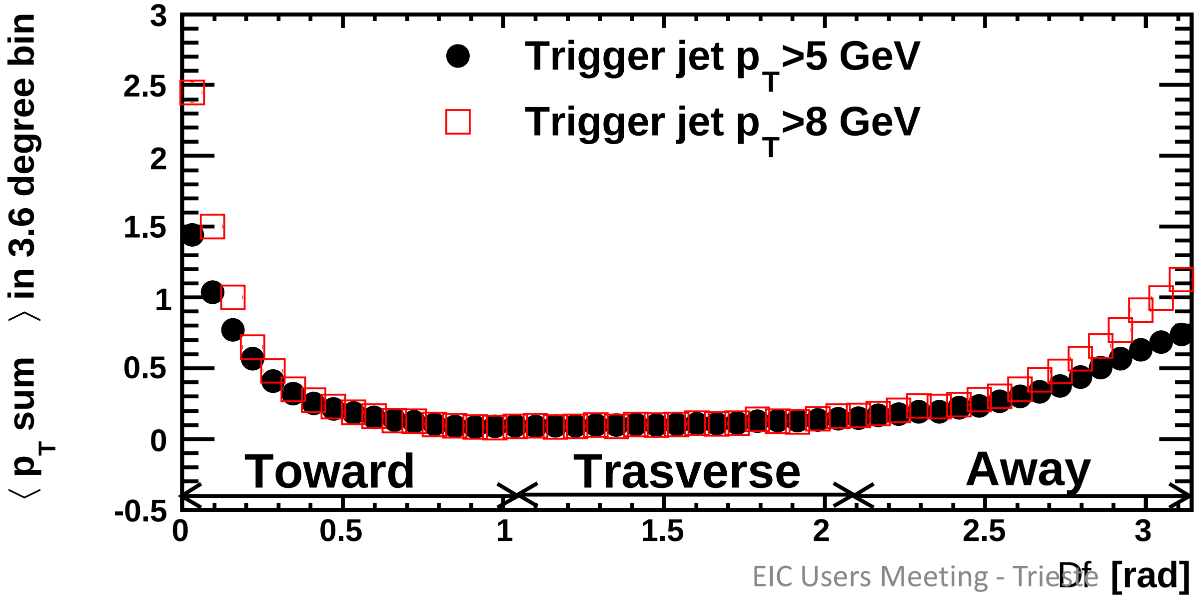




- Divide event into regions based on position of a trigger jet
- Transverse regions sensitive to underlying event contribution
- For this study: Dijet events from Resolved, QCDC, and PGF subprocesses; $Q^2 < 1$ GeV^2; $p_{T1} > 5$, $p_{T2} > 4.5$ GeV/c

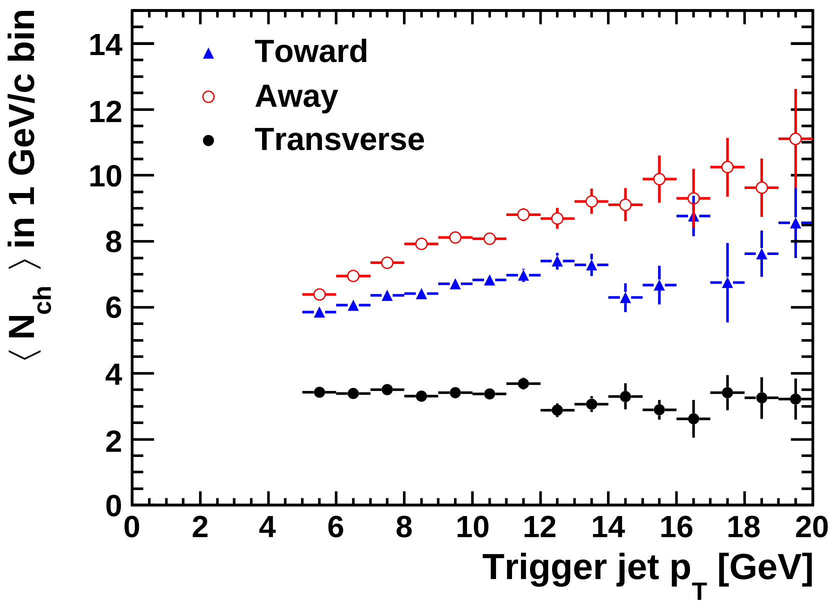
Underlying Event Characteristics



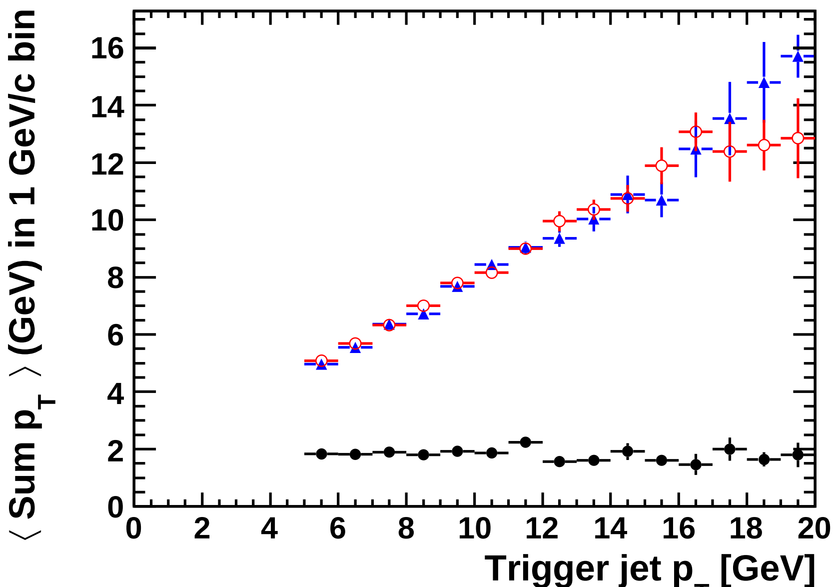


- Plot average number of charged particles per event as a function of azimuthal angle from trigger jet
- Also plot the average summed particle p_T
- See little dependence on trigger jet p_T
- The number of charged particles and p_T sum in transverse region is small

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 for Resolved, QCDC, and PGF event classes similar to that seen in pp collisions at STAR at √s = 200 GeV
- Studies with $Q^2 > 1$ GeV^2 forthcoming

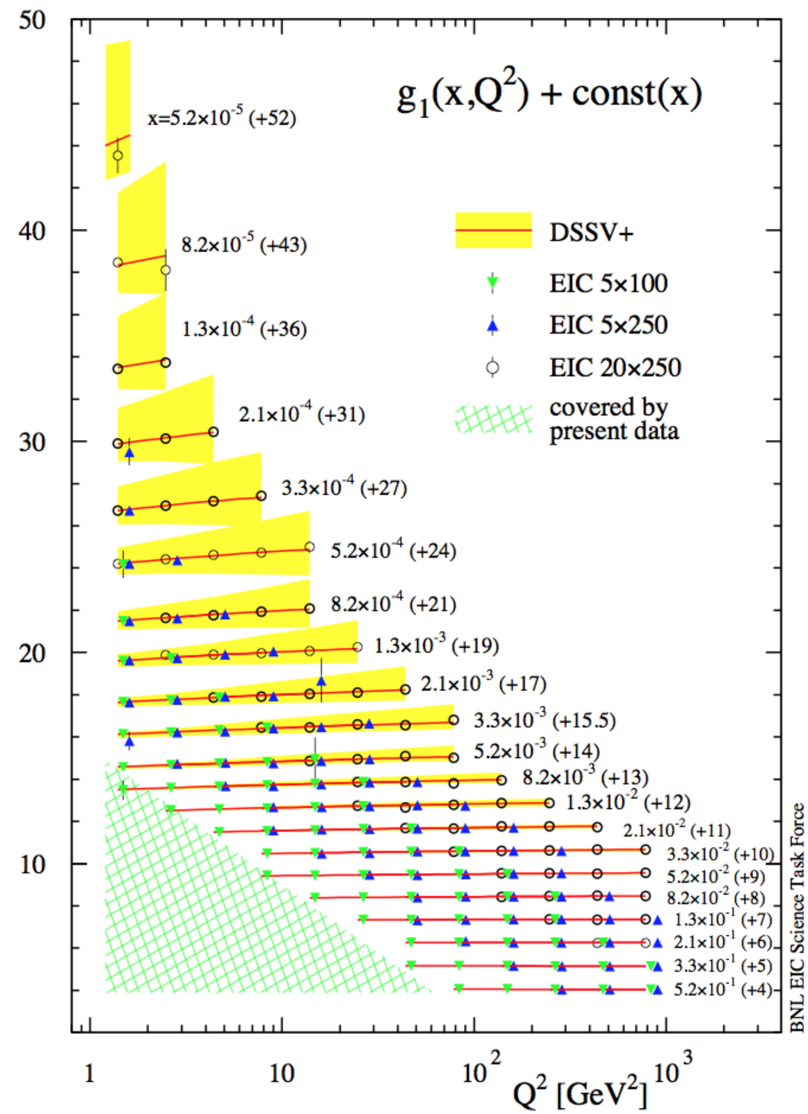
Accessing ΔG in DIS

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

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

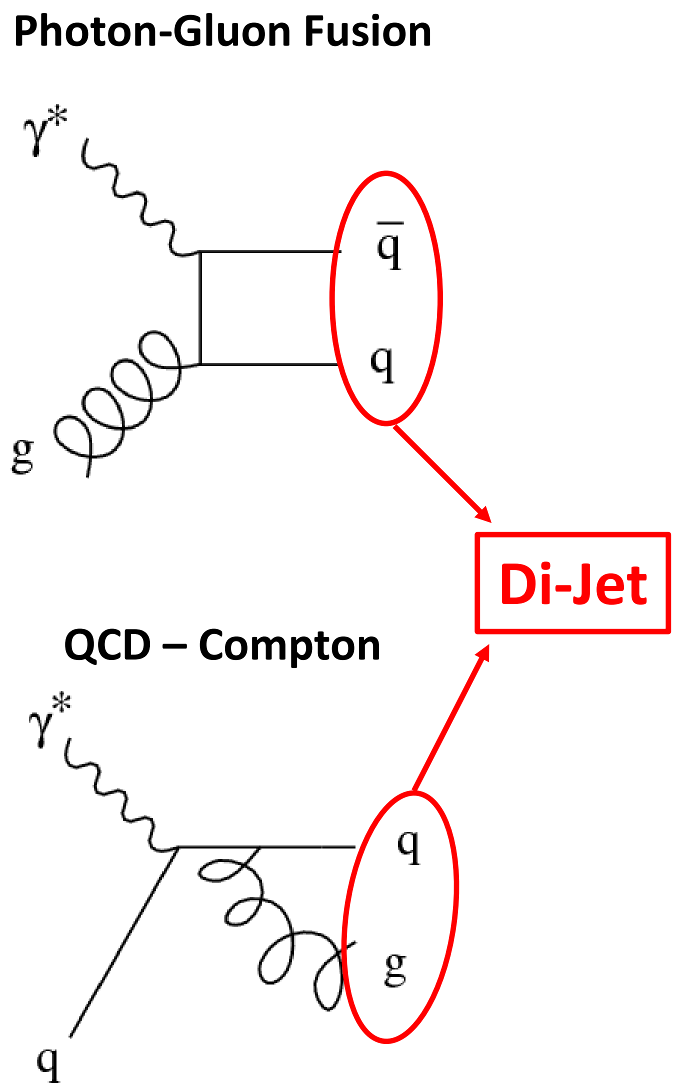
- Current DIS constraints on ΔG hampered by limited x & Q^2 coverage

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



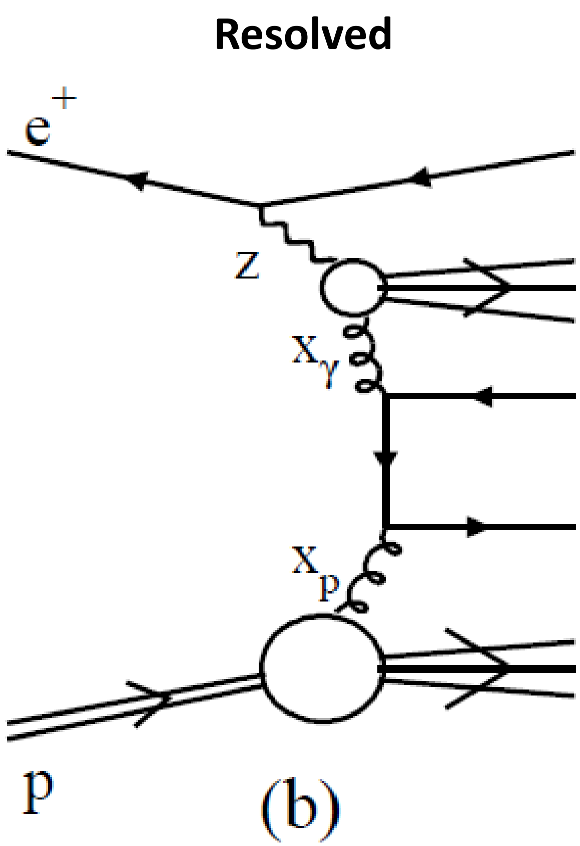
arXiv:1206.6014

Gluon Polarization with Di-jets



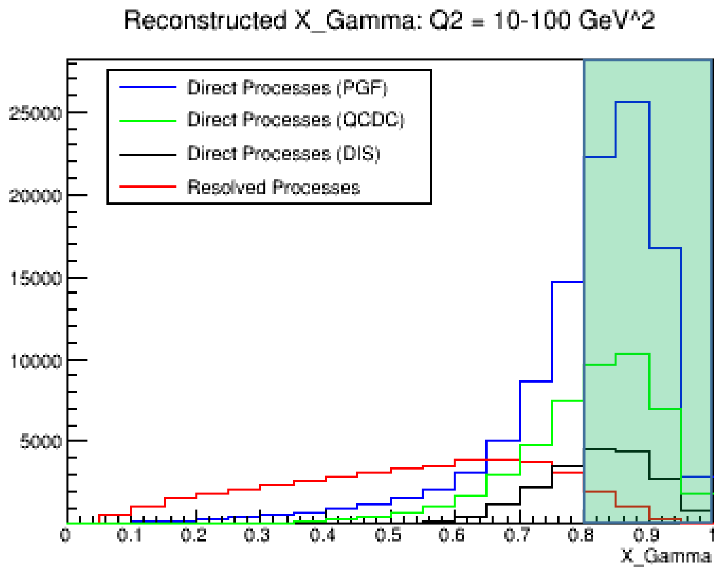
- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet

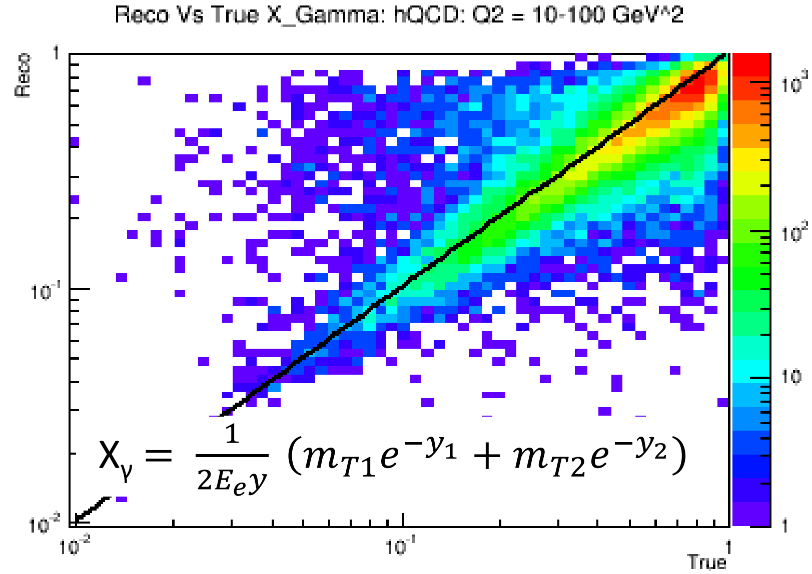
Gluon Polarization with Di-jets

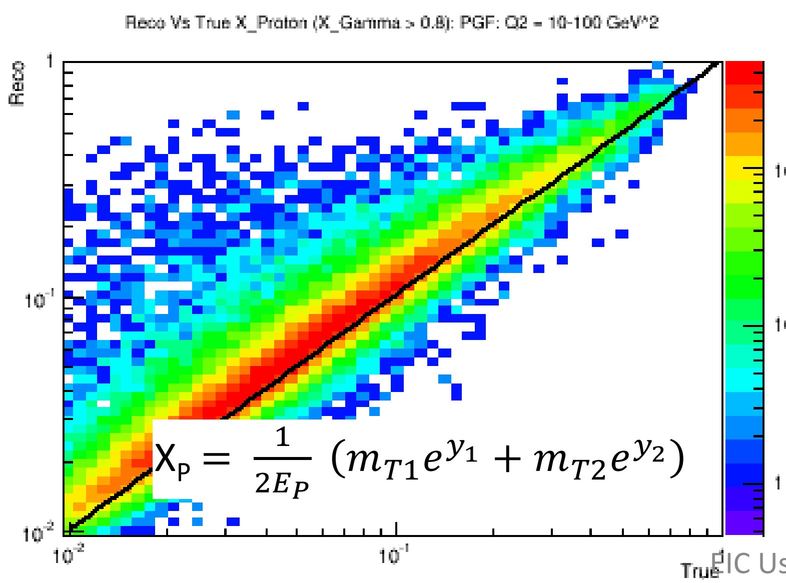


- Gluons can be also be probed in DIS via the higher-order photon gluon fusion process
- Also have the QCD – Compton process which probes quarks at the same order
- Both processes produce 2 angularly separated hard partons -> Di-jet
- At lower Q2, resolved processes in which the photon assumes a hadronic 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

Gluon Polarization with Di-jets



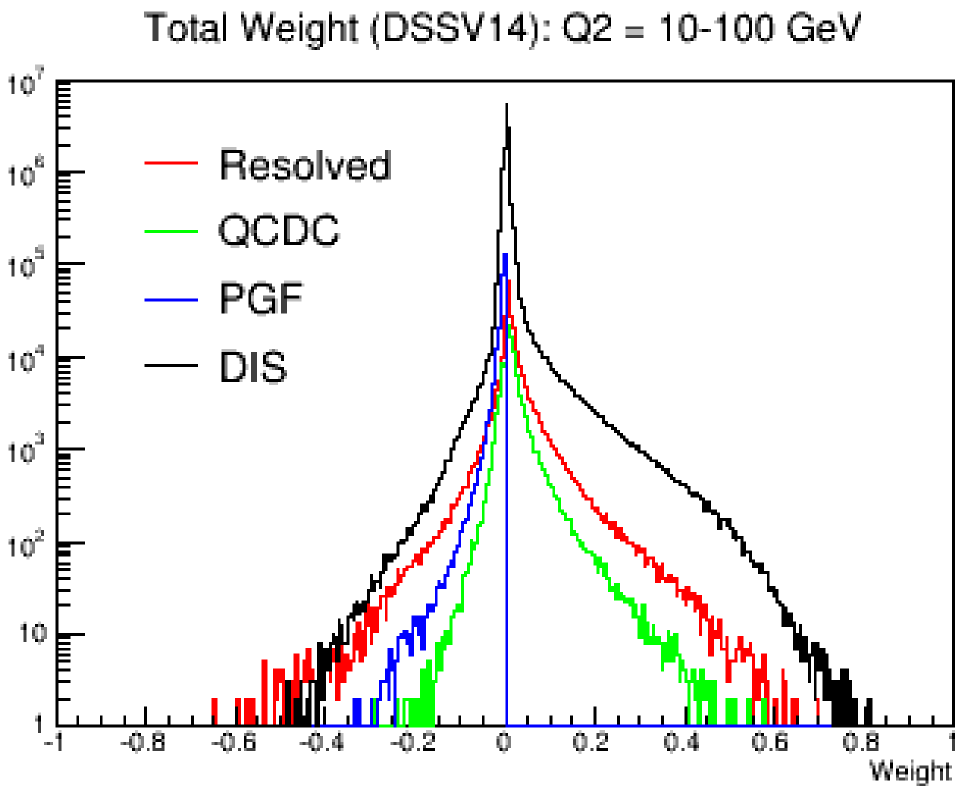




- Reconstruct virtual photon momentum fraction x_γ; direct processes concentrate toward 1 with resolved processes at lower values
- Cut of $x_\gamma > 0.8$ enhances the direct fraction
- Can also reconstruct momentum fraction of parton from the proton, x_P
- Both x_γ and x_P accurately reconstructed

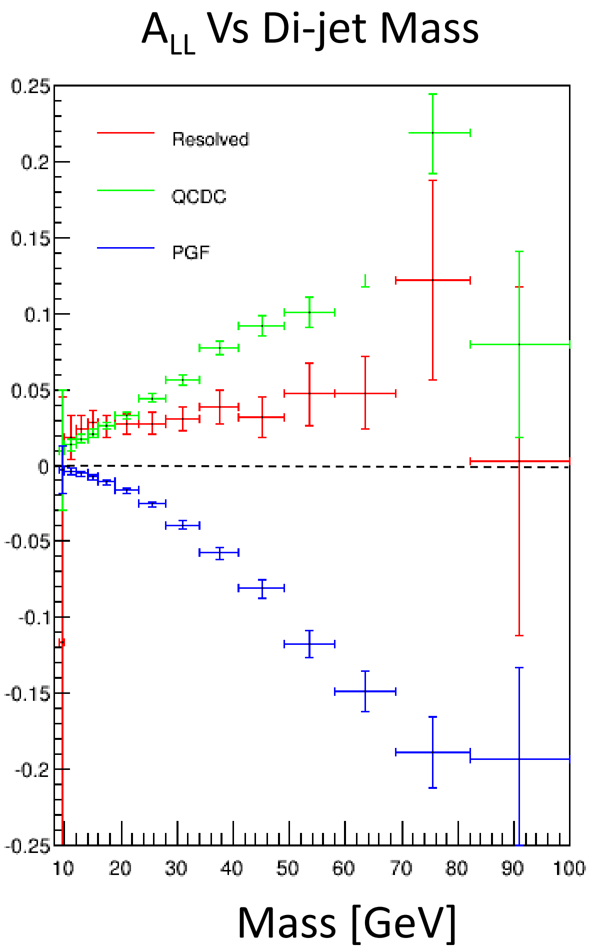
Weighting PYTHIA

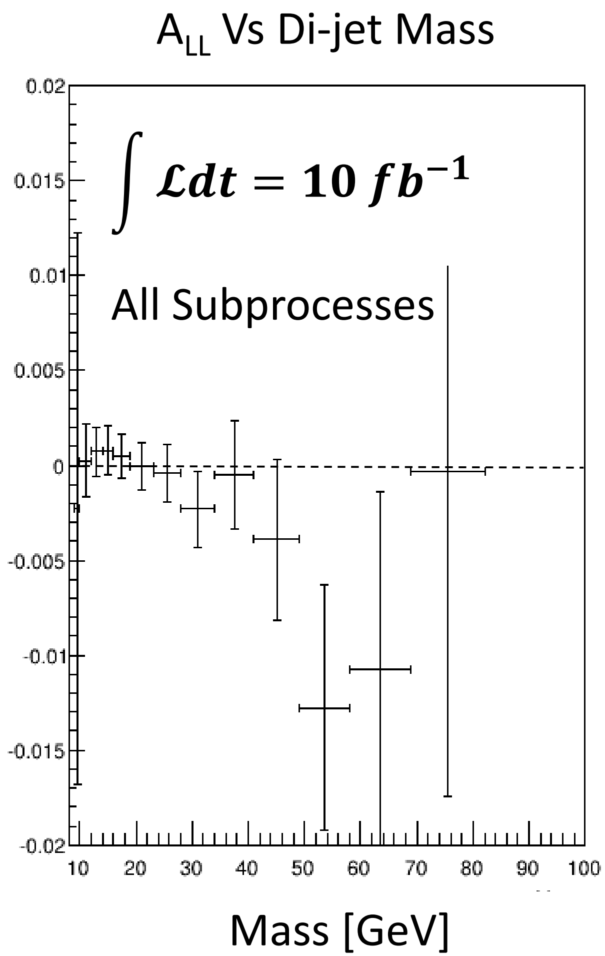
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^{N}(x_b,\mu^2)}{f_b^{N}(x_b,\mu^2)}$$



- 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

A_{LL} Vs Di-jet Mass



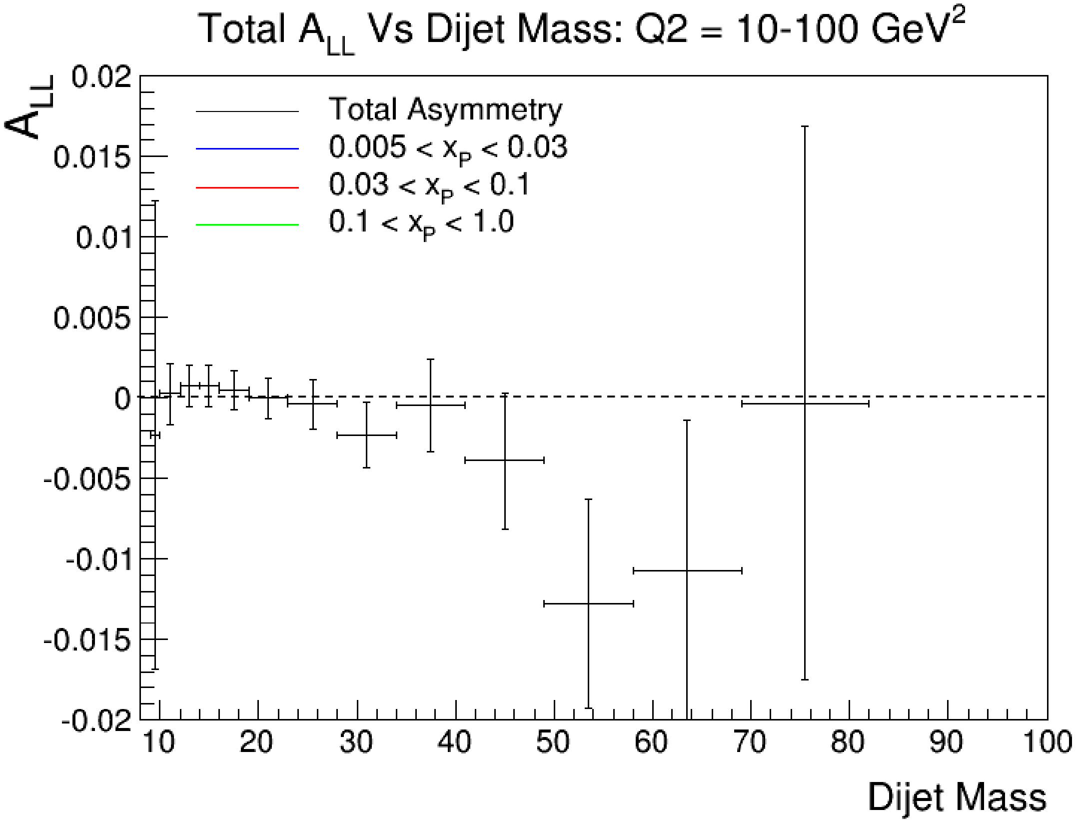


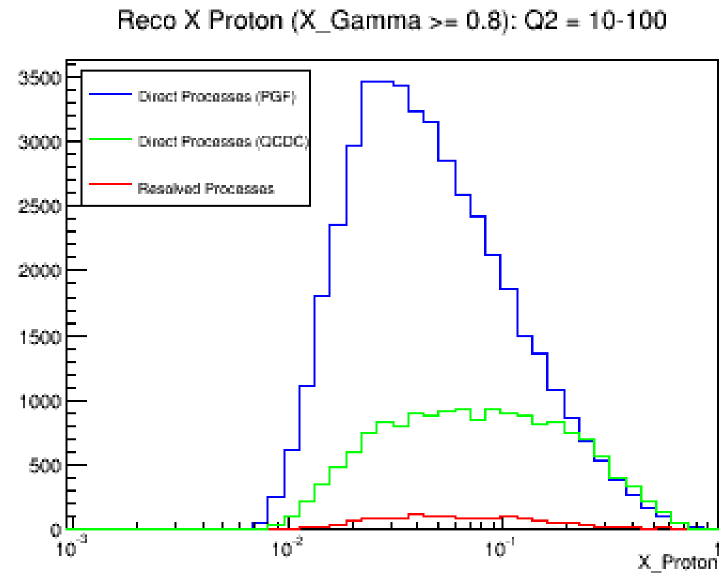
$Q^2 = 10 - 100\ \mathrm{GeV}^2$

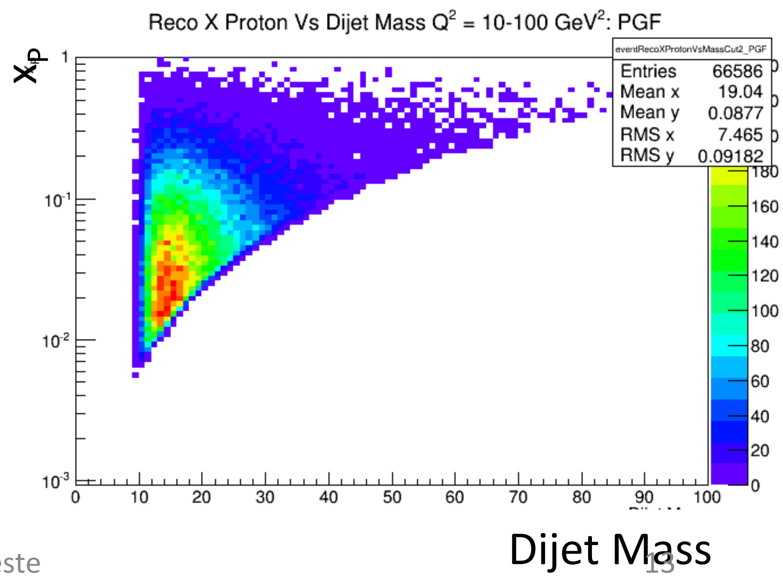
$$\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}$$

- 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 Di-jet Mass: x_P Cuts

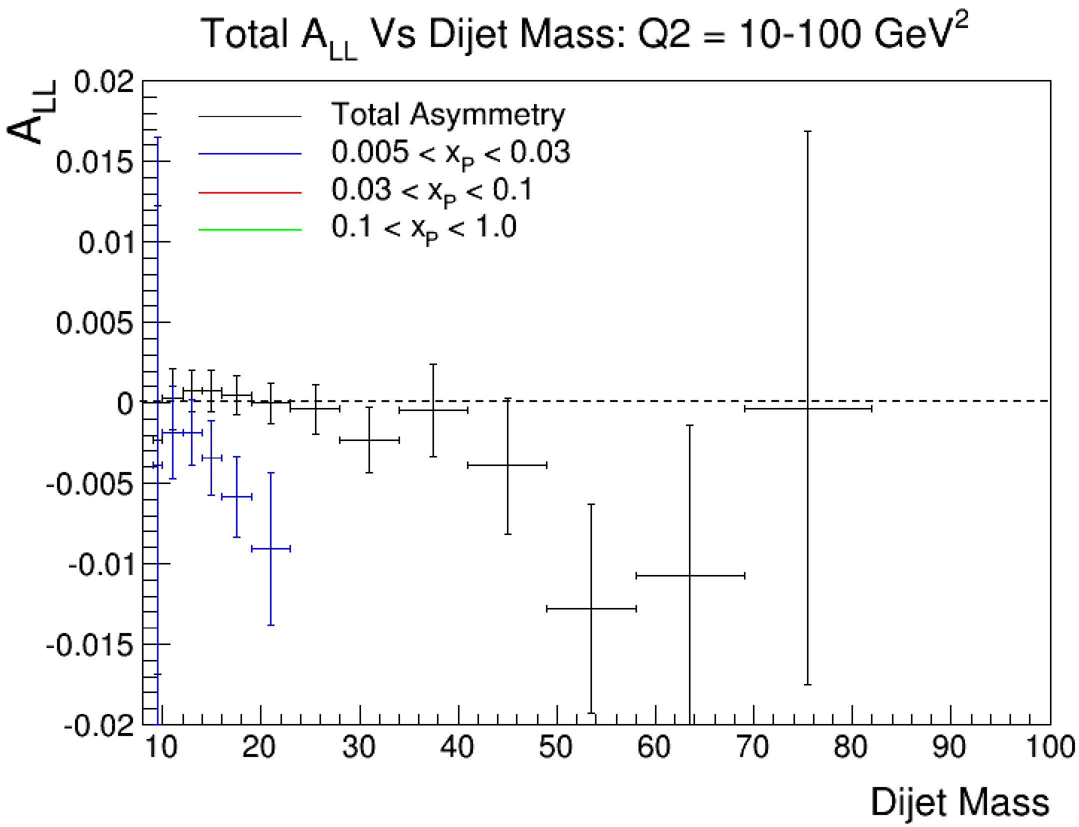


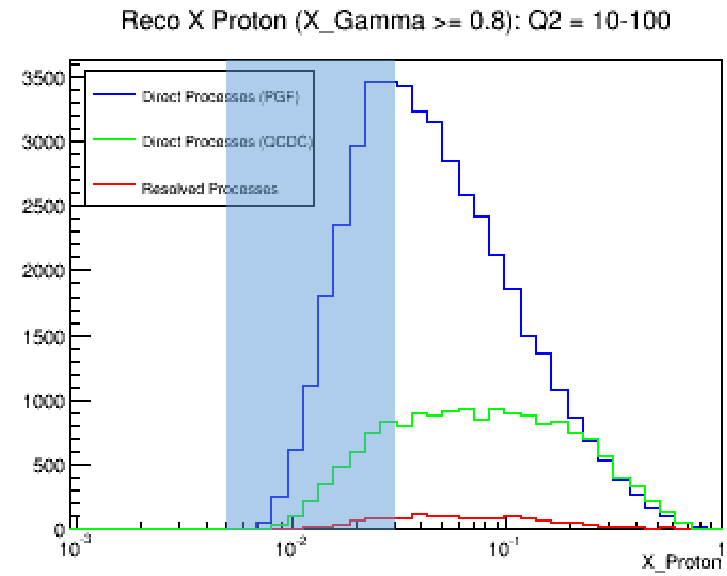


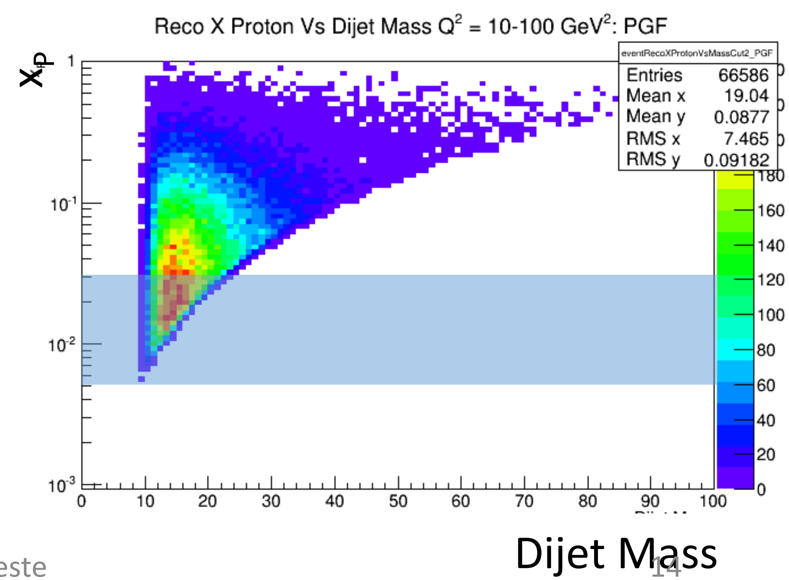


- QCDC and PGF asymmetries largely cancel out making overall asymmetry small
- Want to enhance PGF subprocess w.r.t. QCDC
- PGF events peaked to lower x_P values

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

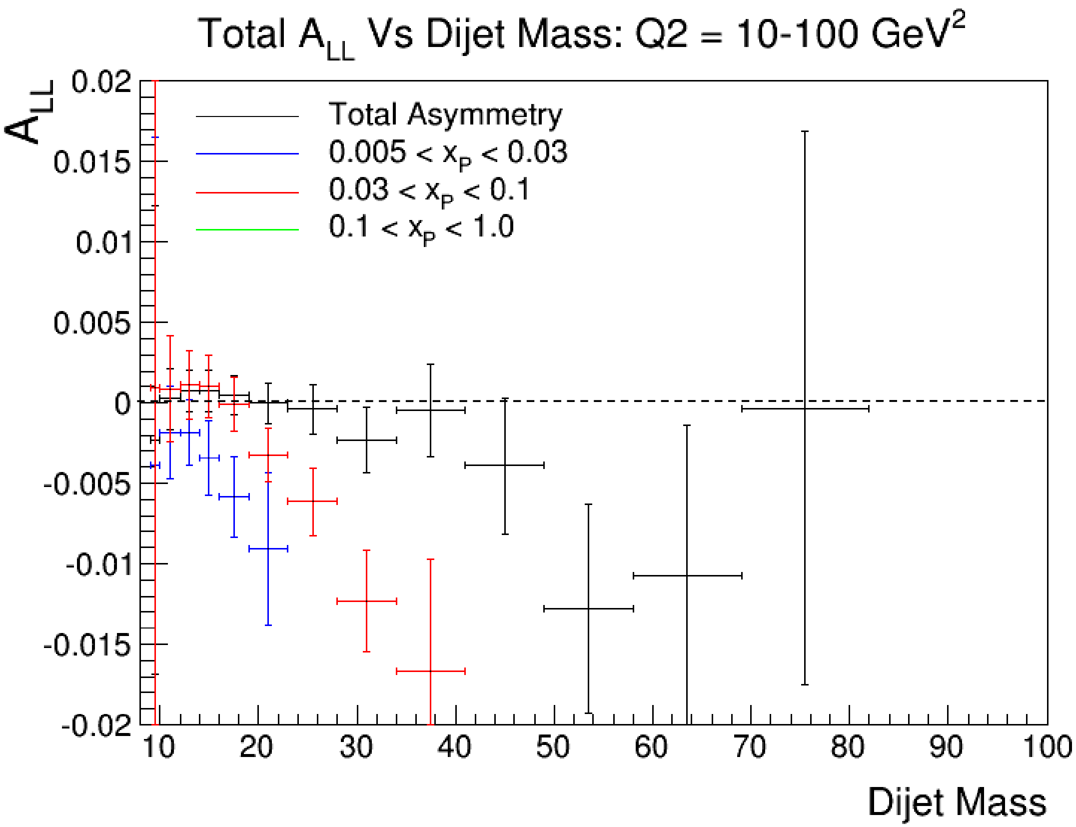


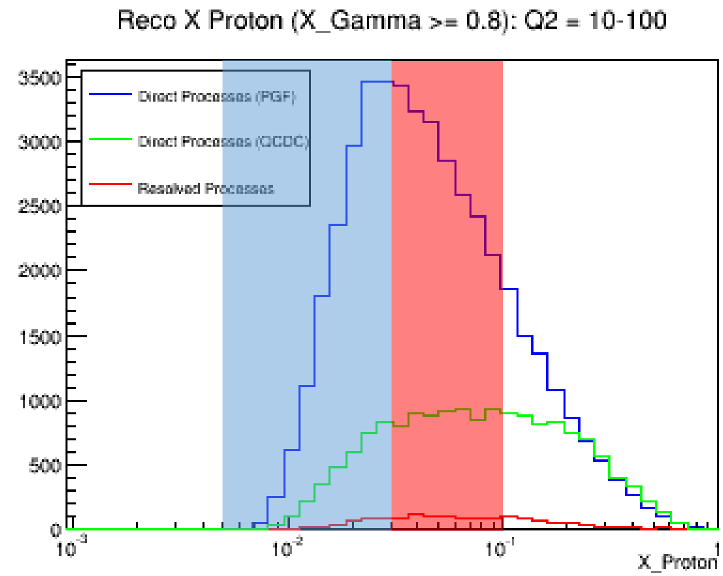


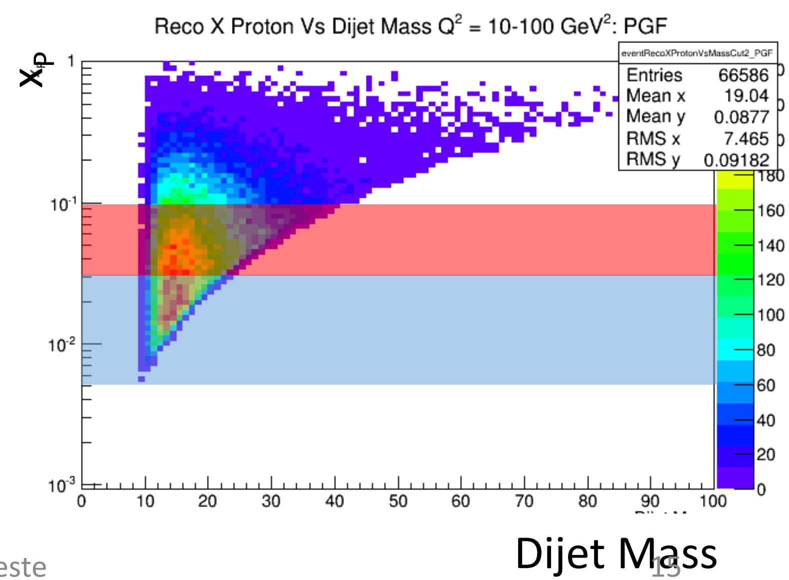


- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range

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







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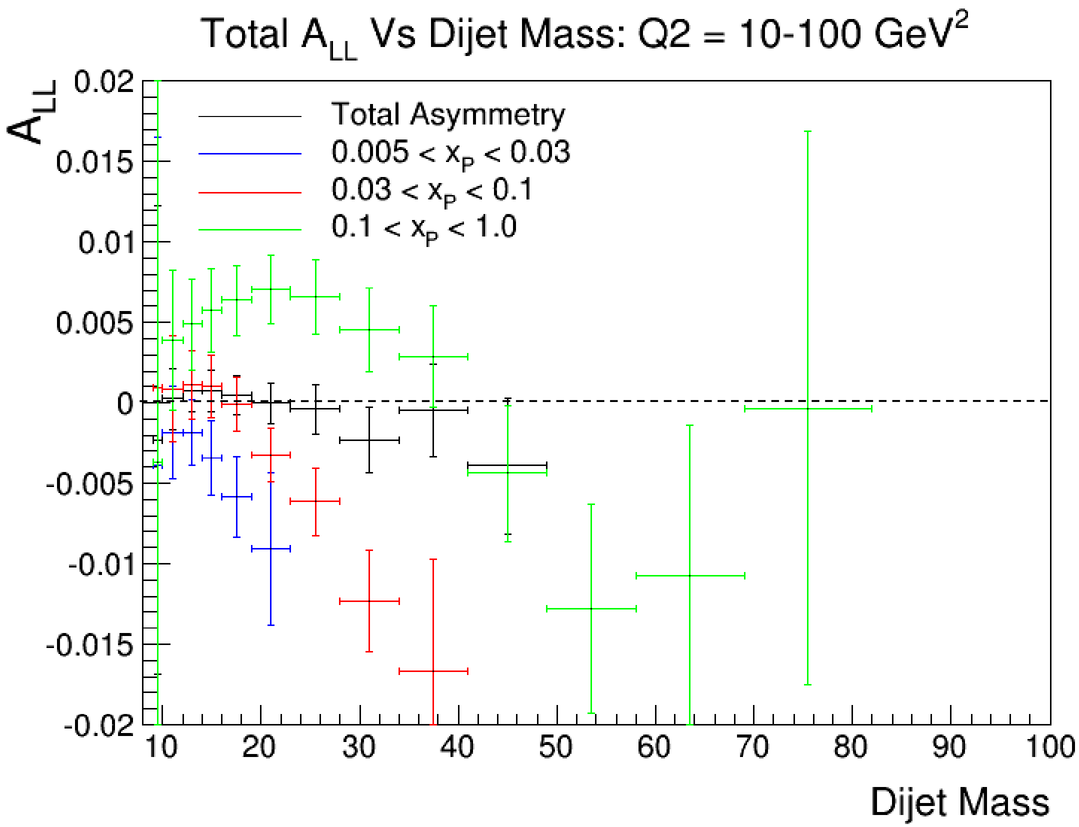
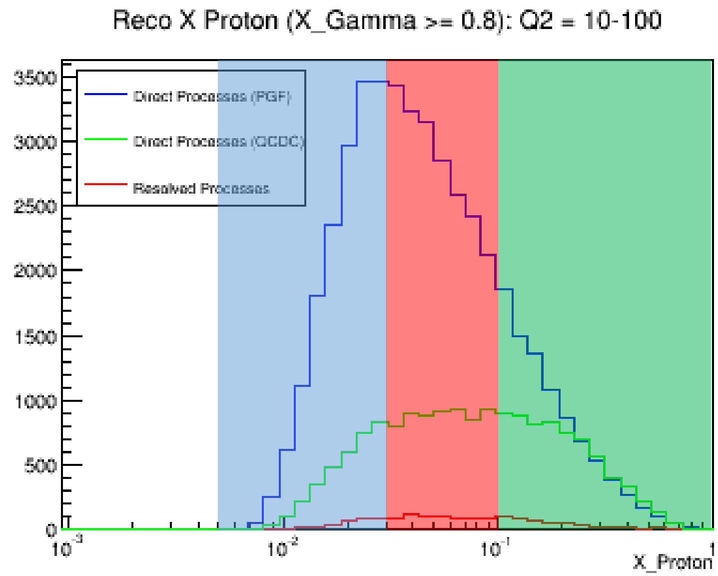
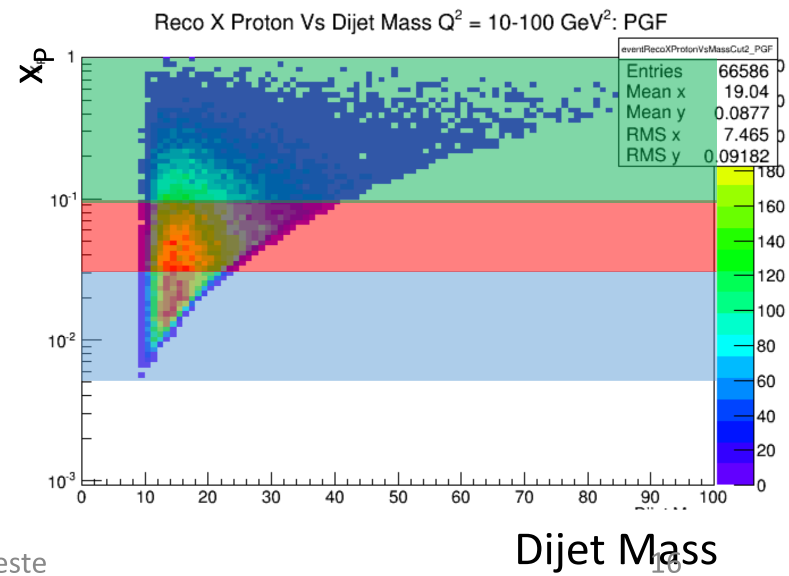
- Intermediate x_P values get more QCDC contribution

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





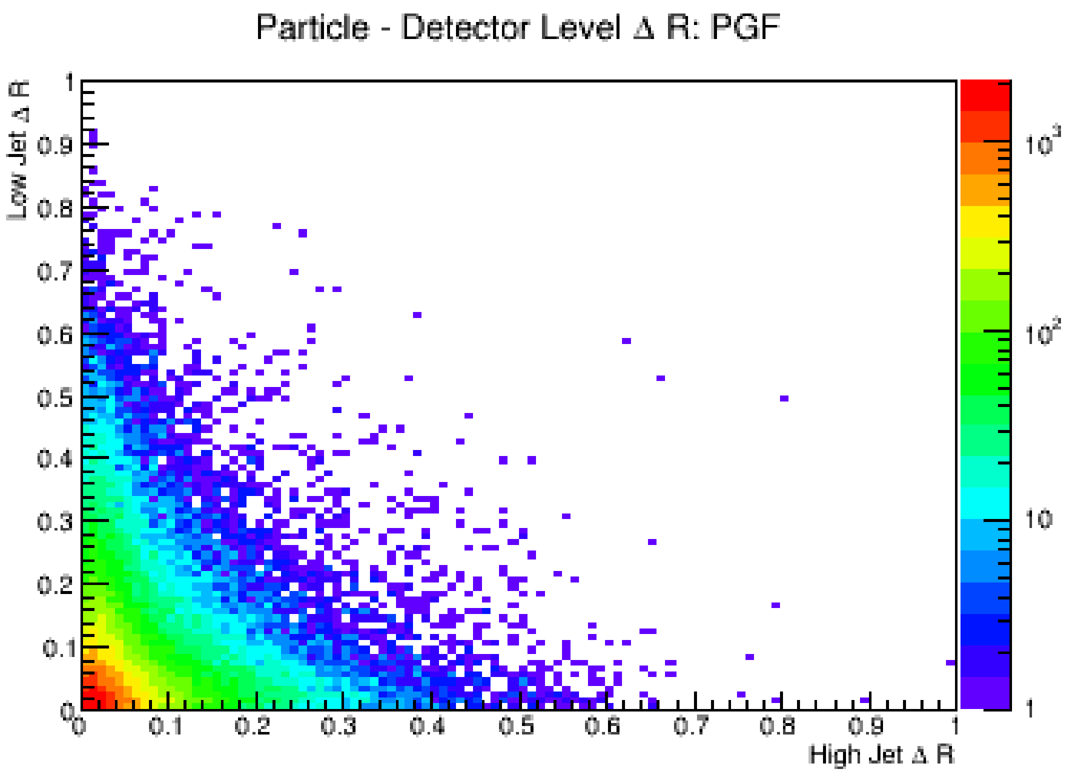


- Selecting events with $0.005 < x_P < 0.03$ enhances PGF asymmetry but restricts mass range
- Intermediate x_P values get more QCDC contribution
- Largest x_P values have roughly equal amounts of PGF and QCDC

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 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
- Hadronic calorimetry in forward region between 1 and 4 in pseudorapidity with resolution of 50%/√E
  - Neutral Hadrons (Neutrons & K_Ls) at mid-rapidity are not included in jet finding

Particle – Detector ΔR

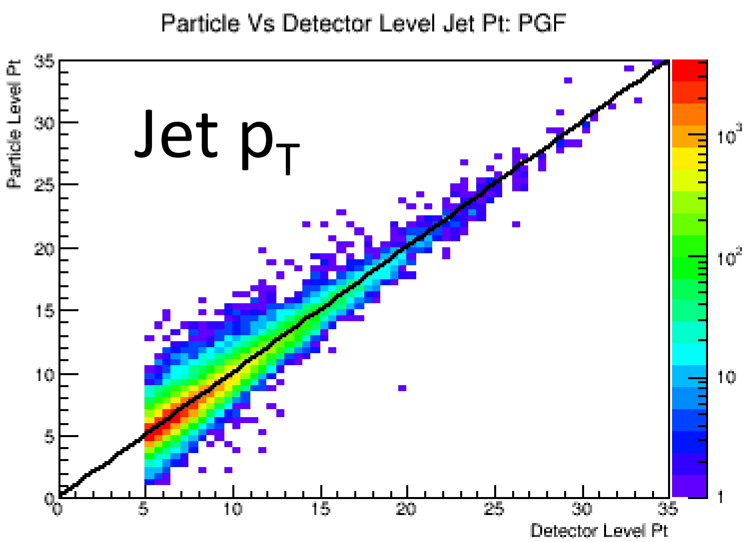


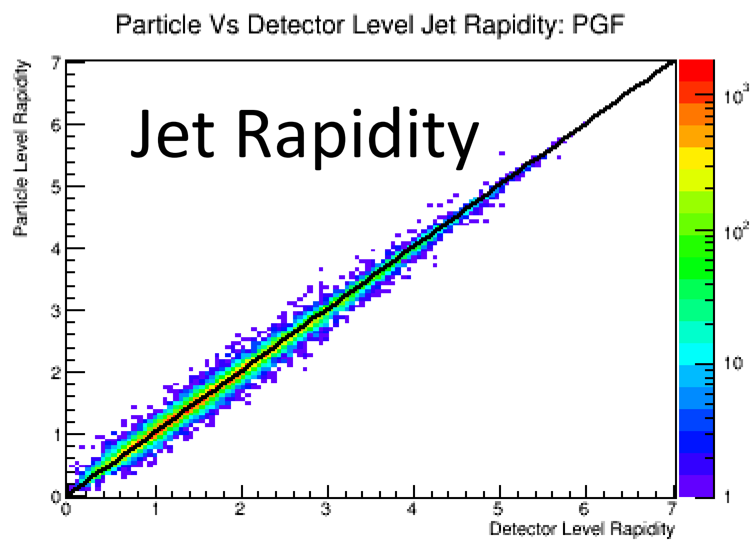
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

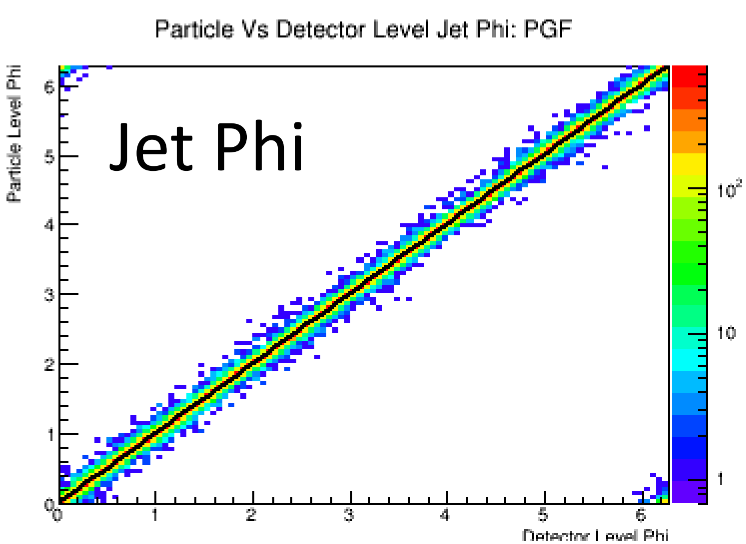
- For each smeared jet, find the particle level jet such that ΔR is smallest
- Plot ΔR for the low detector p_T jet vs that for the high p_T jet
- Most ΔR values are less than 0.1 meaning jet thrust axis is not altered very much by detector smearing

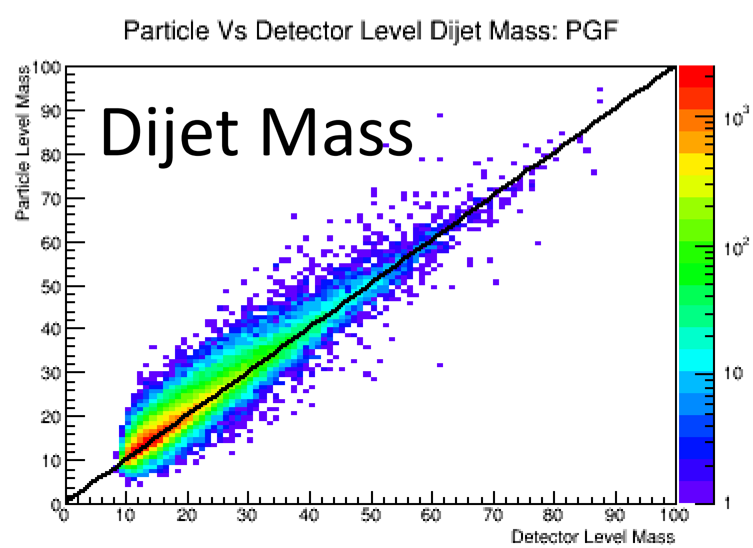
Particle – Detector Comparison

Particle Level



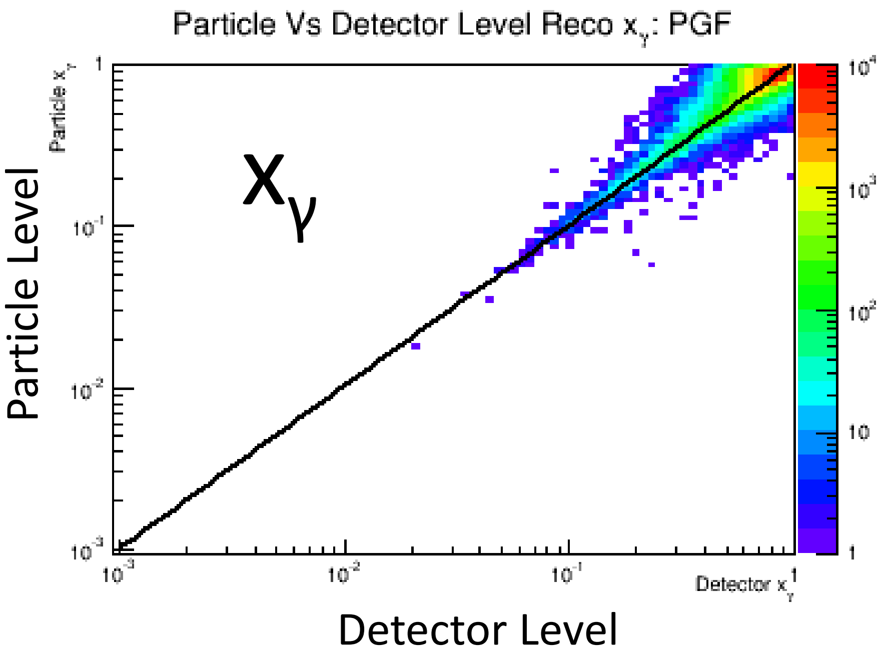






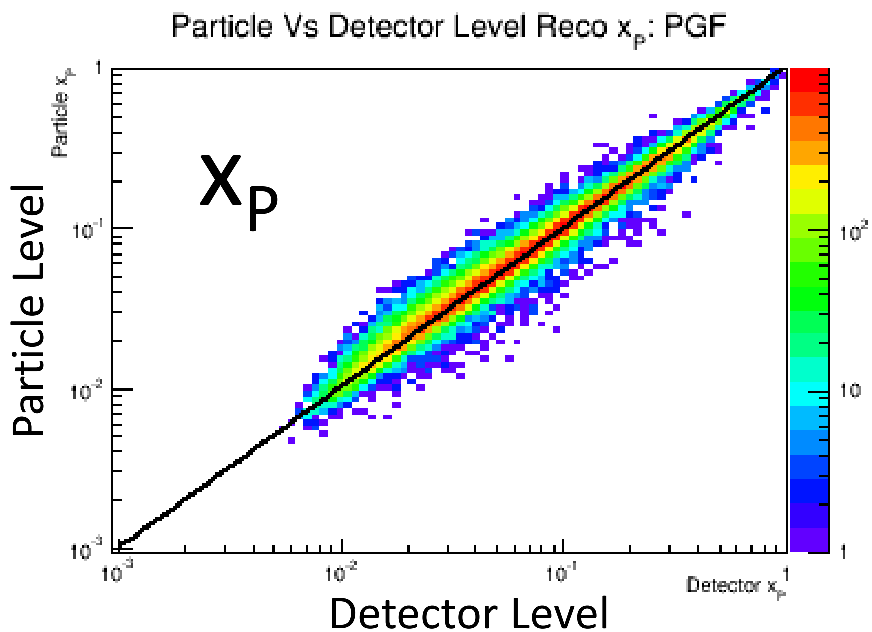
Detector Level

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 particle level and smeared values
- Level of smearing is similar to that seen between particle level and generated values

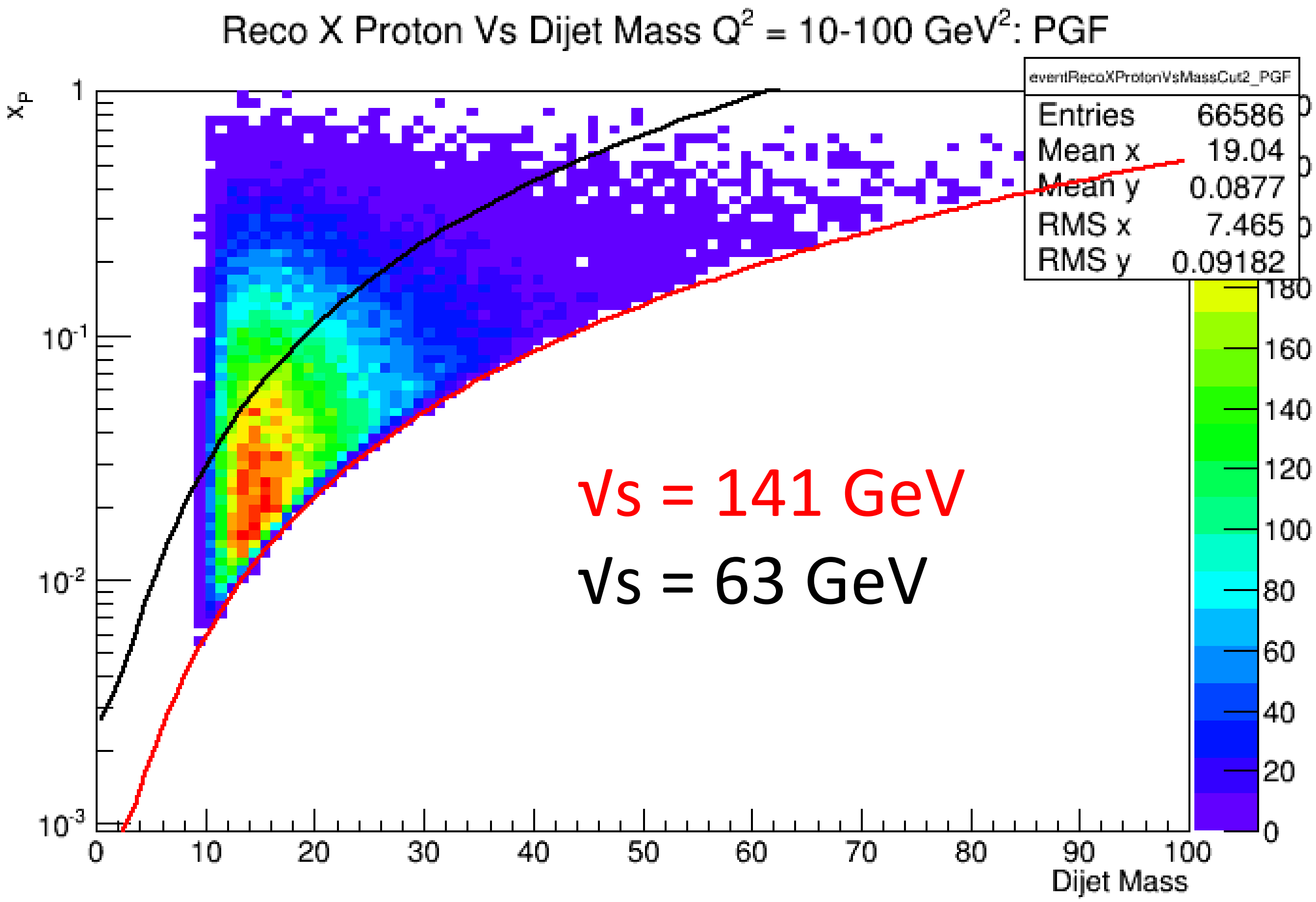


Summary

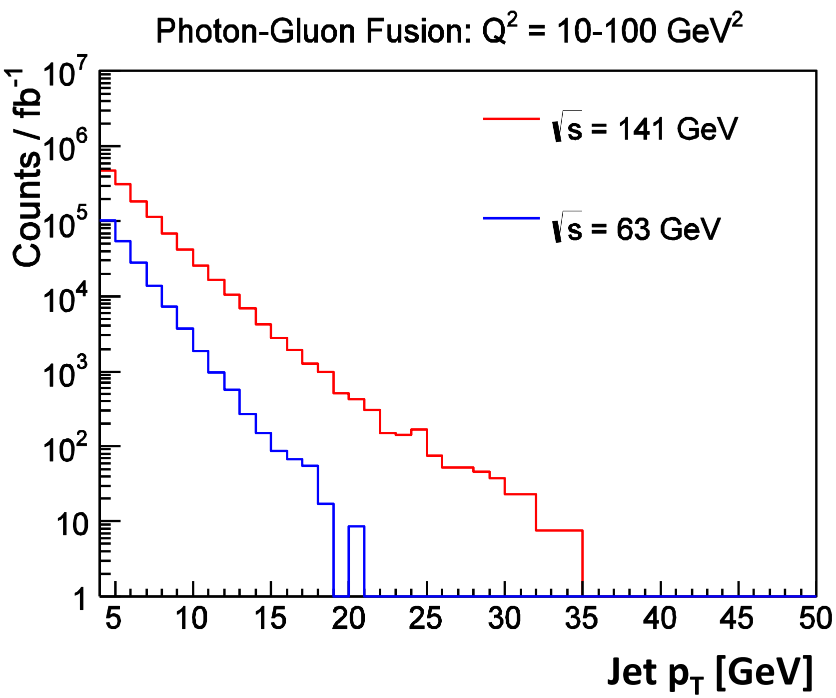
- Characterization of the underlying event was made and the contribution was found to be rather small
- A method for accessing the gluon polarization using dijets to tag photon-gluon fusion events was presented and expected asymmetries given various cuts were found
- Impacts of detector effects on jet observables are being investigated using a fast smearing package and BeAST detector parameters
- Bonus: Studies on the possibility of discriminating between quark and gluon initiated jets can be found in the backup
- See Also: the paper by Xiaoxuan Chu et al on the use of dijets to tag resolved process events for studies of the photon structure (arXiv:1705.08831)

Backup

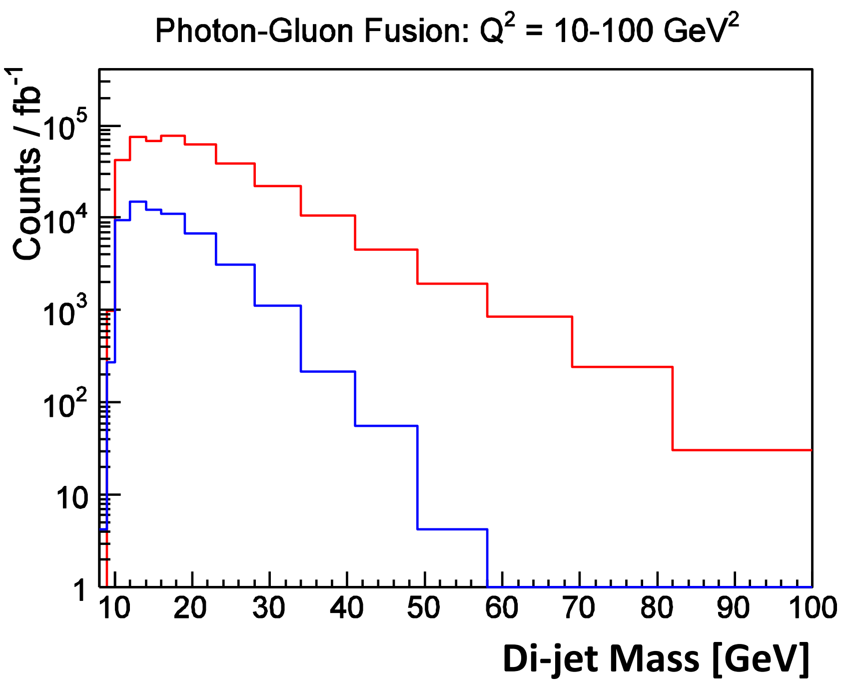
Dijet Phase Space



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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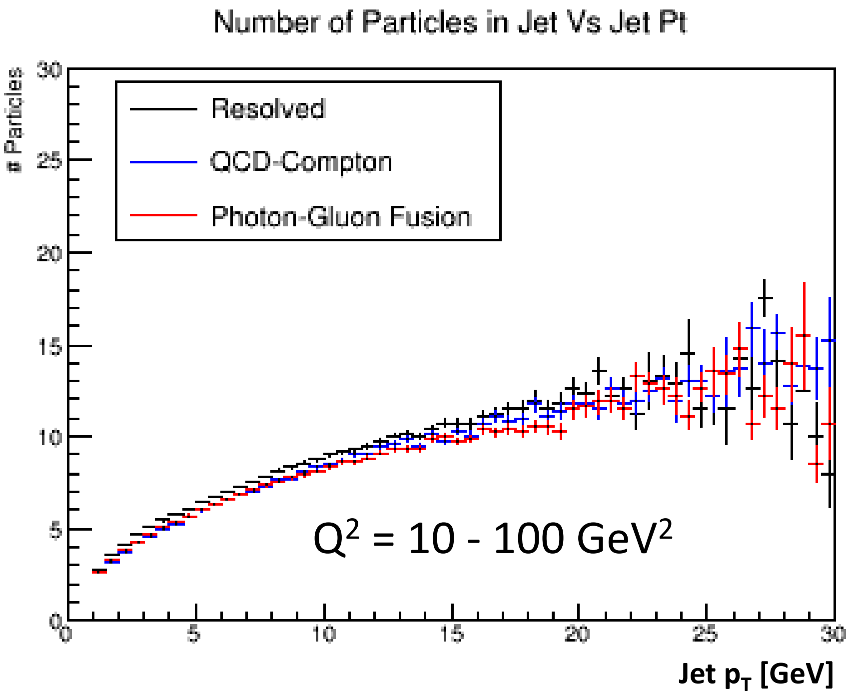

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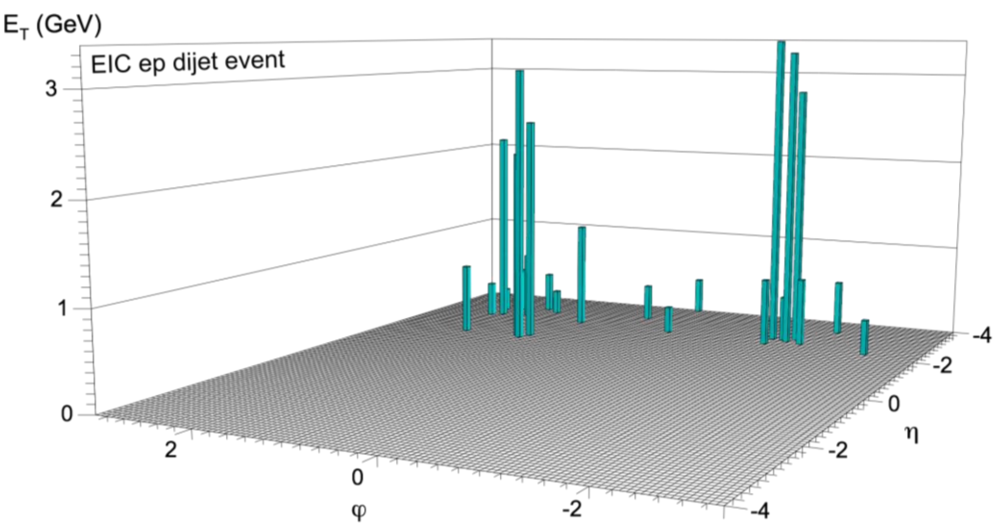
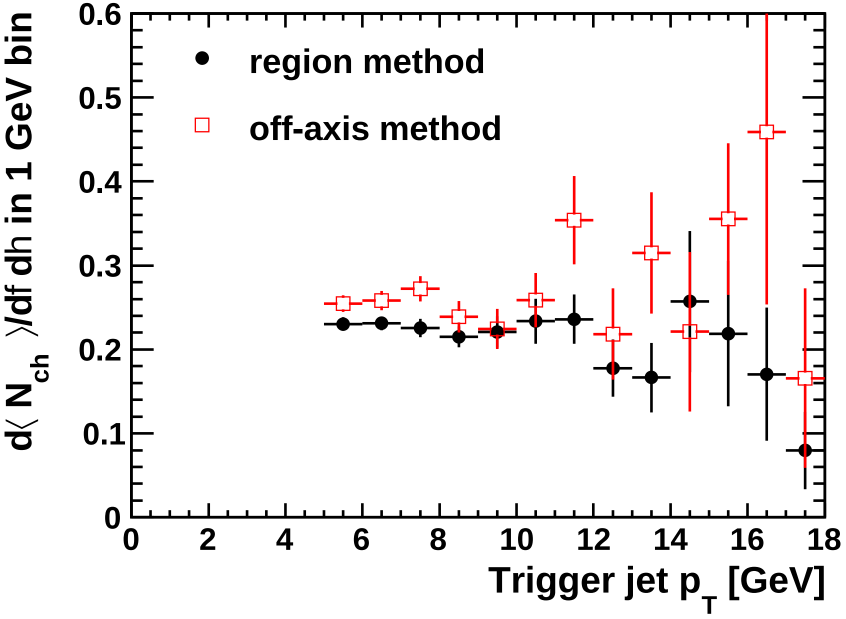
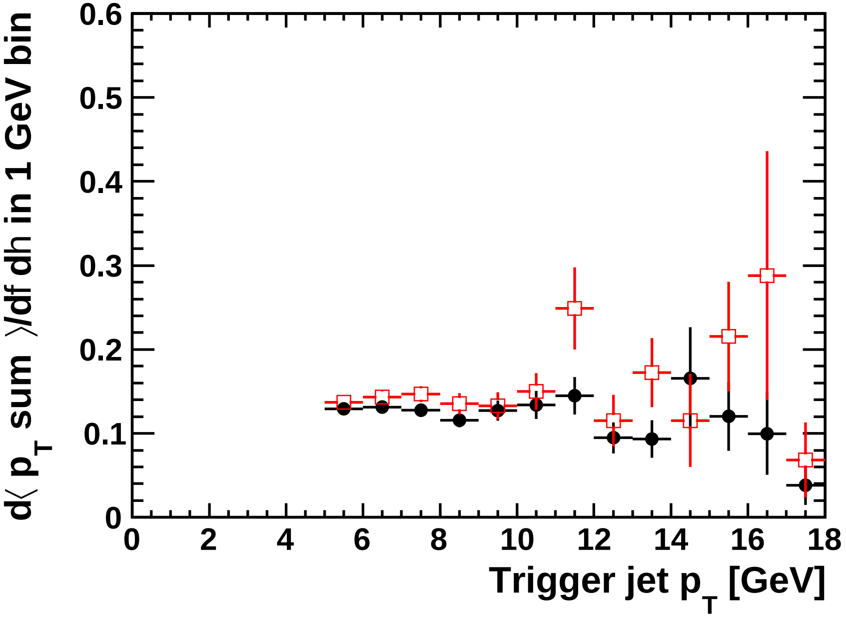


- Jets contain relatively few particles overall
- Events are quite clean with little underlying event activity
- Typical particle p_T is small -> precision tracking important for reducing jet energy scale uncertainties

UE Method Comparison

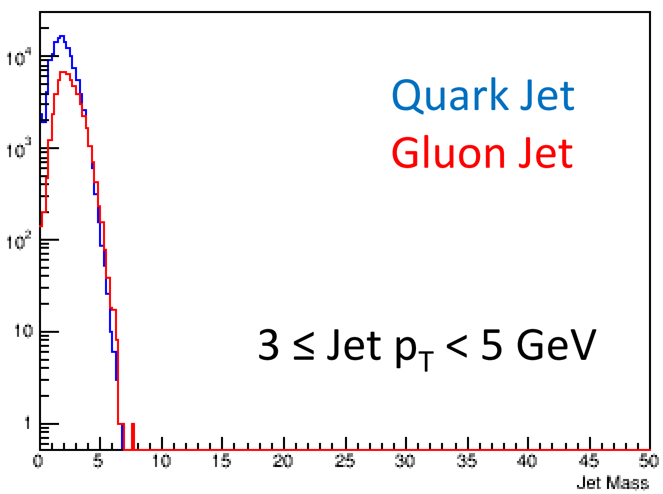




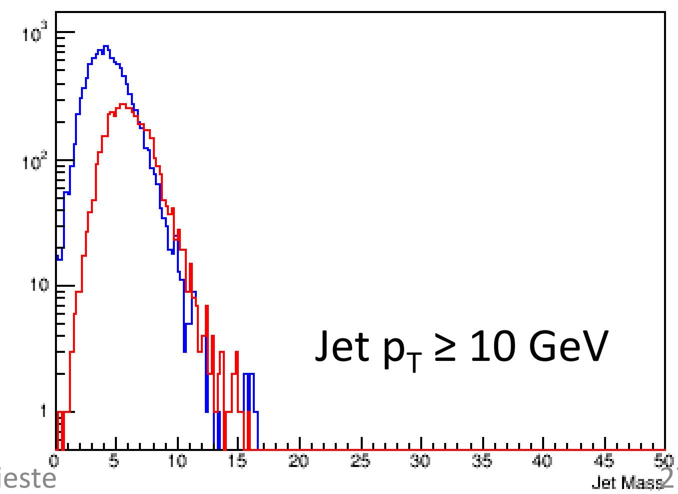
Quark – Gluon Discrimination

- Can we discriminate between jets arising from quarks and those arising from gluons?
- For this study, only consider light quarks: u, d, and s. Assume that heavy quark tagging will employ different methods
- Jets (part of a di-jet) are found in the Breit frame from events with Q^2 = 10 – 100 GeV^2 and resolved, QCDC, and PGF subprocess
- Look only at jets with $p_T \geq 10$ GeV as the separation between quark and gluon jets is more pronounced

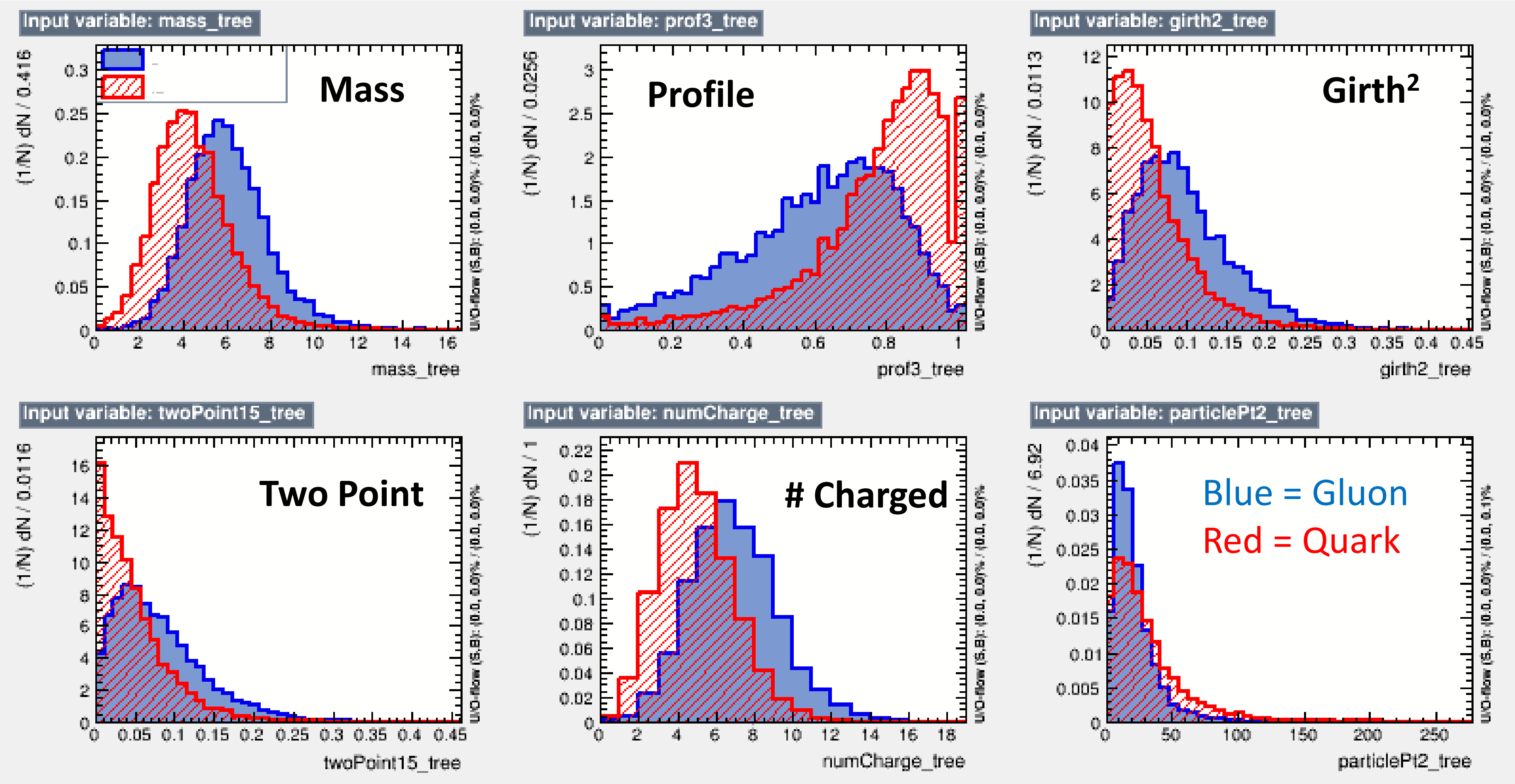
Jet Mass: Low Jet p_T



Jet Mass: High Jet p_T



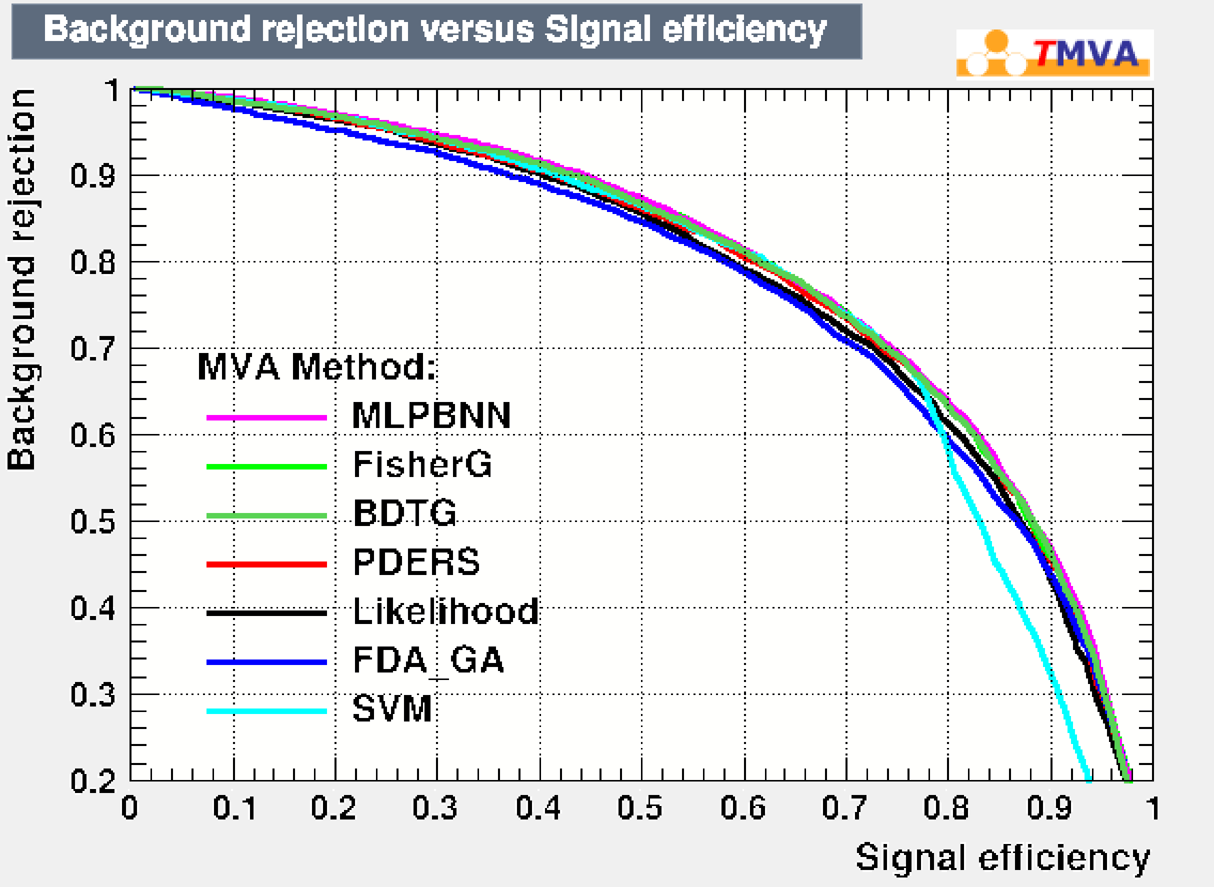
Input Variables



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

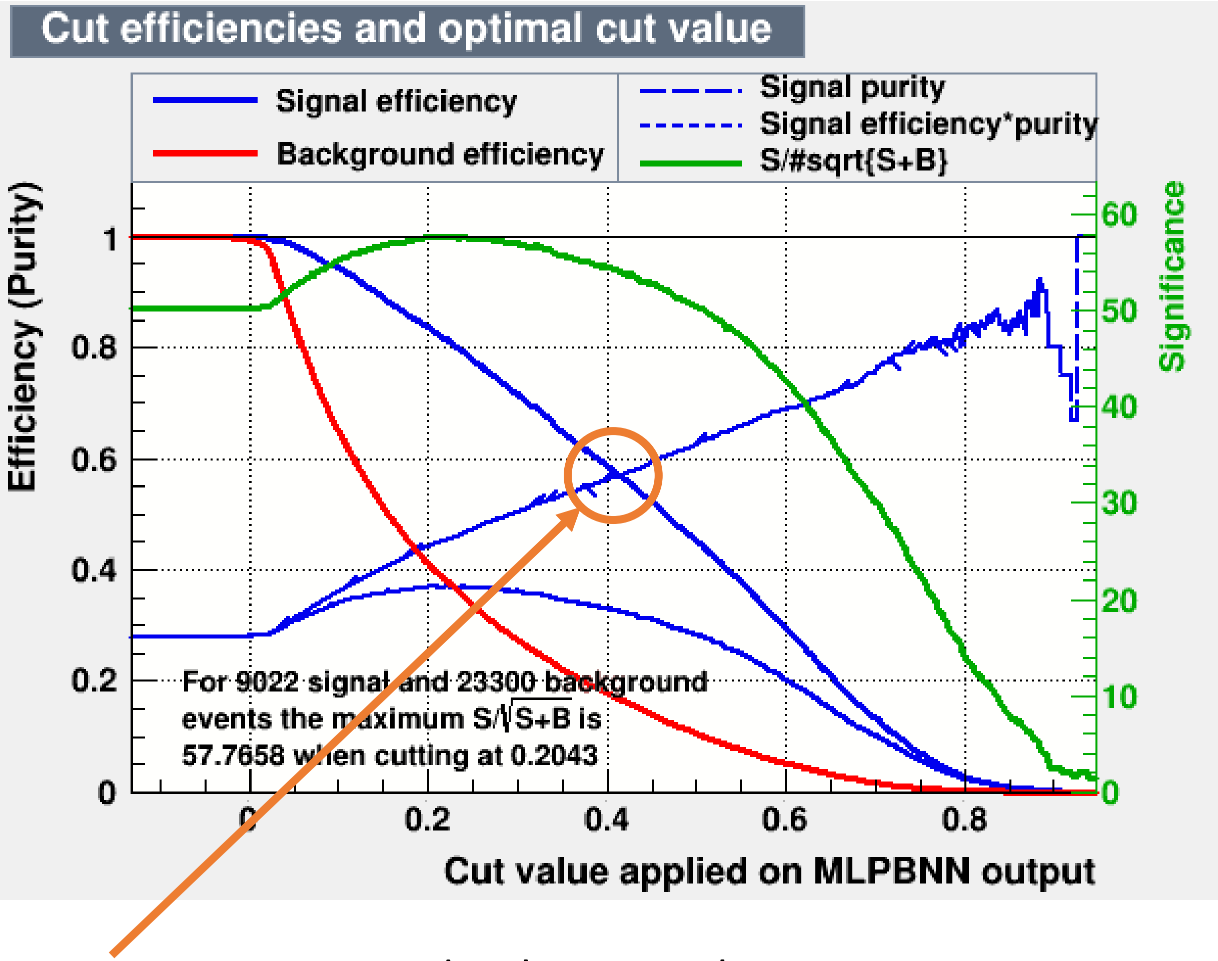
$$2\ \text{Point} = \frac{1}{p_{Tjet}^{\ 2}} \sum_{i \neq j} p_{Ti} * p_{Tj} * |r_{ij}|^{\beta}$$

Method Comparison



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

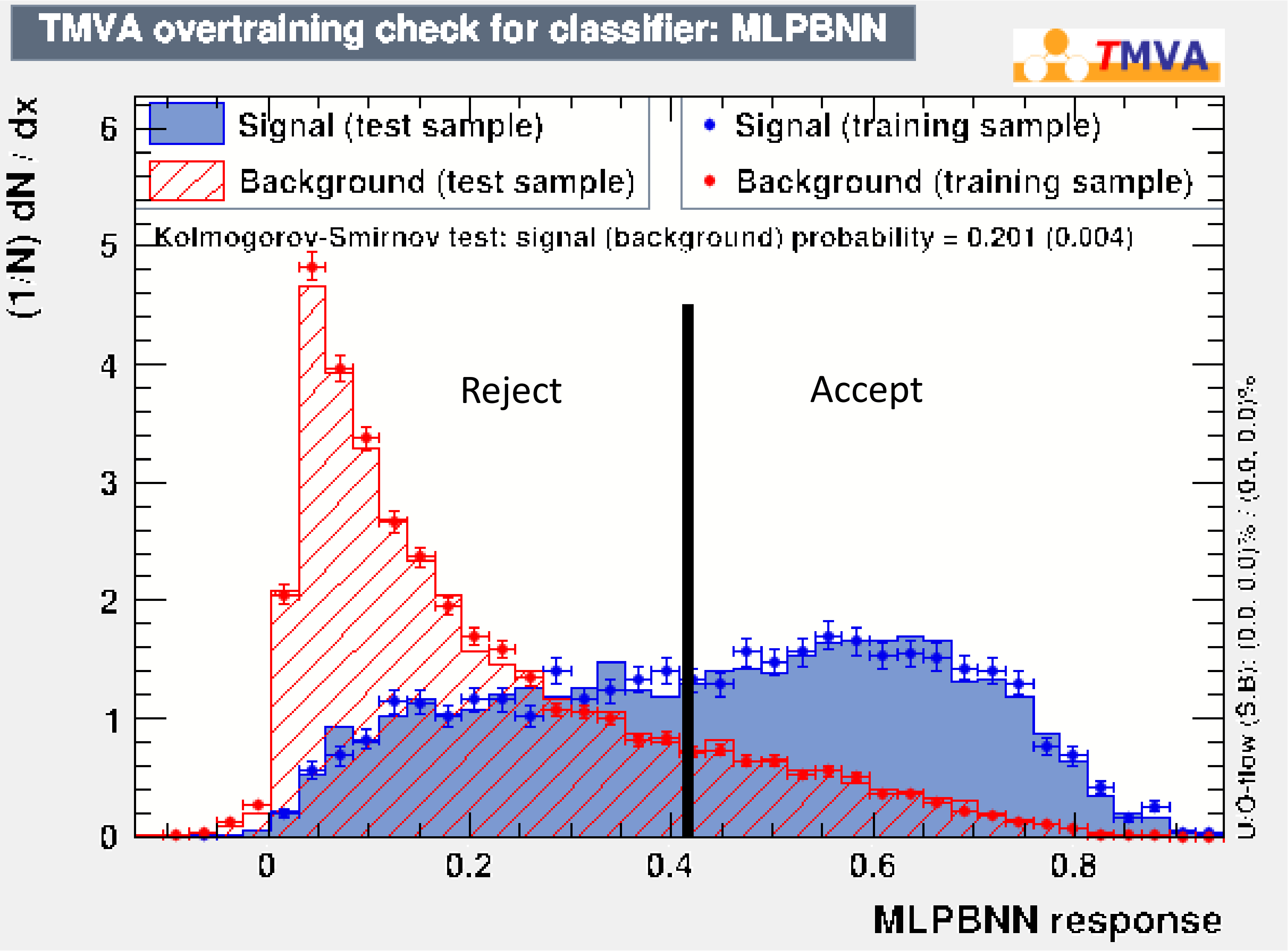
Cut Optimization



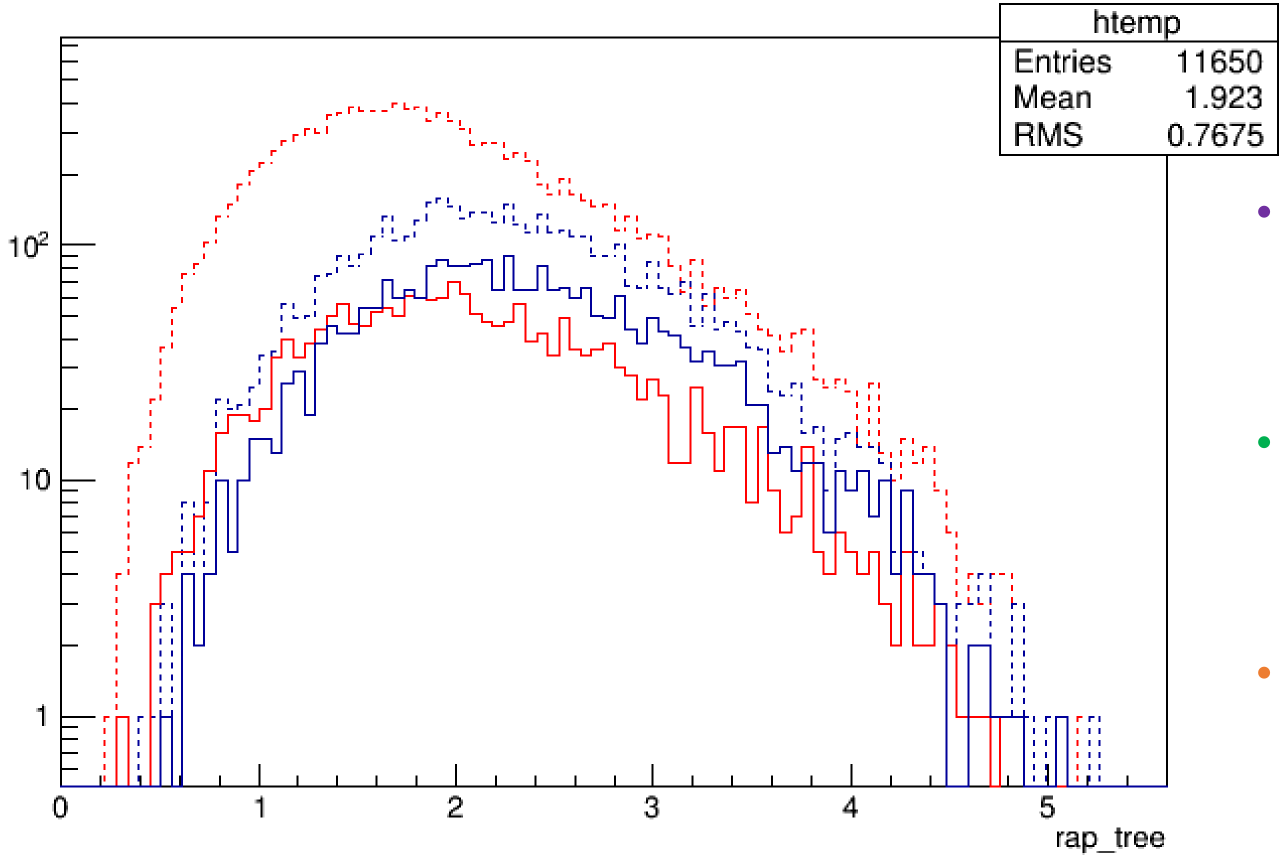
- TMVA evaluates all input and maps them to a single variable with more signal-like events having a higher value
- Plot signal & background efficiency, signal purity, significance, etc as a function of this cut value
- This plot shows where to place cut in order to maximize purity, efficiency, or whatever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

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

MLPBNN Response



Jet Rapidity Spectra

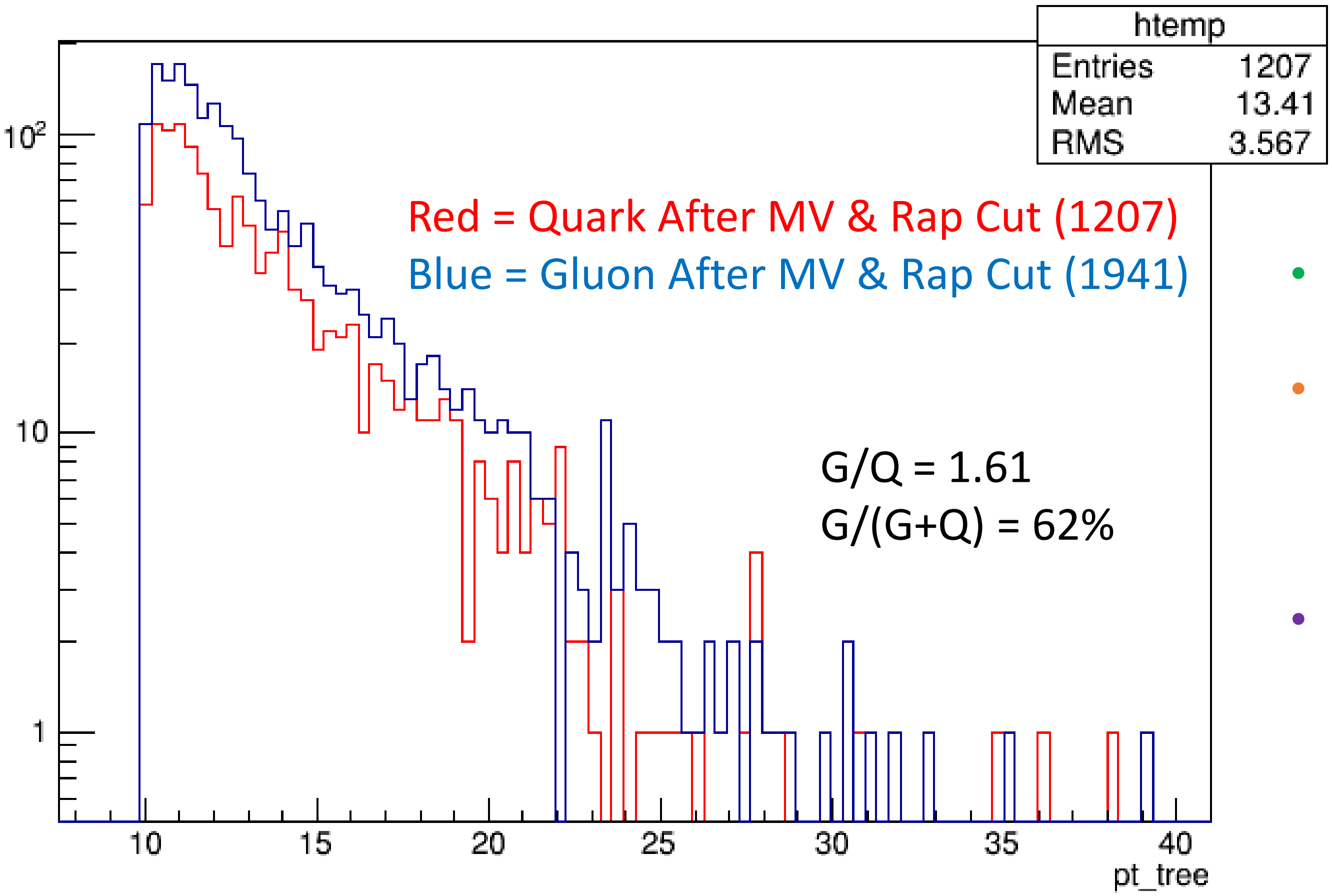


- After cut is applied, can plot quark and gluon jets vs any relevant variable
- Here we see that gluons dominate at higher rapidity
- Look at jets with rapidity > 1.8 to further enhance gluon fraction

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%

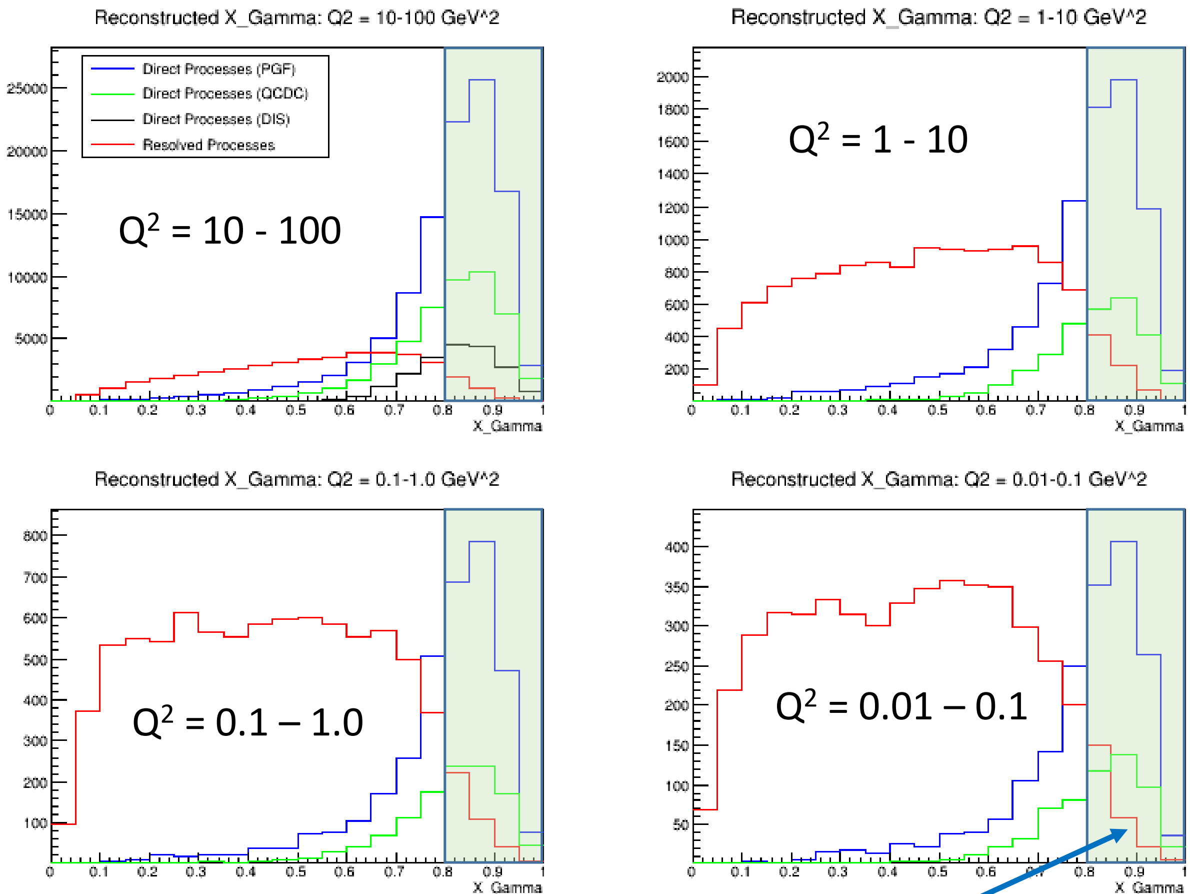
Jet p_T Spectra With Rapidity Cut



- 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

Direct Vs Resolved Processes

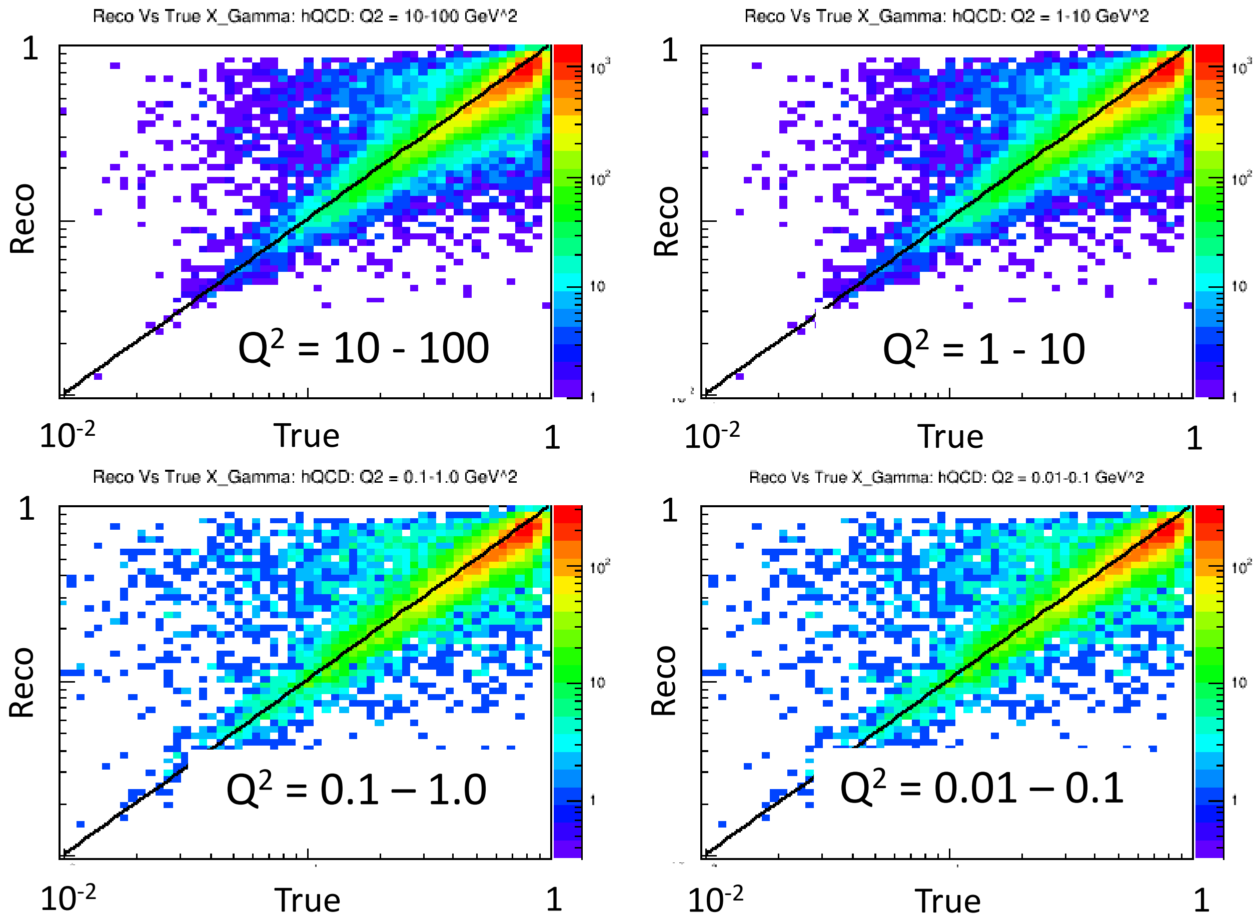
$$X_\gamma = \frac{1}{2E_e y}\left(m_{T1}e^{-y_1} + m_{T2}e^{-y_2}\right)$$



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

X_γ: Reconstructed Vs True

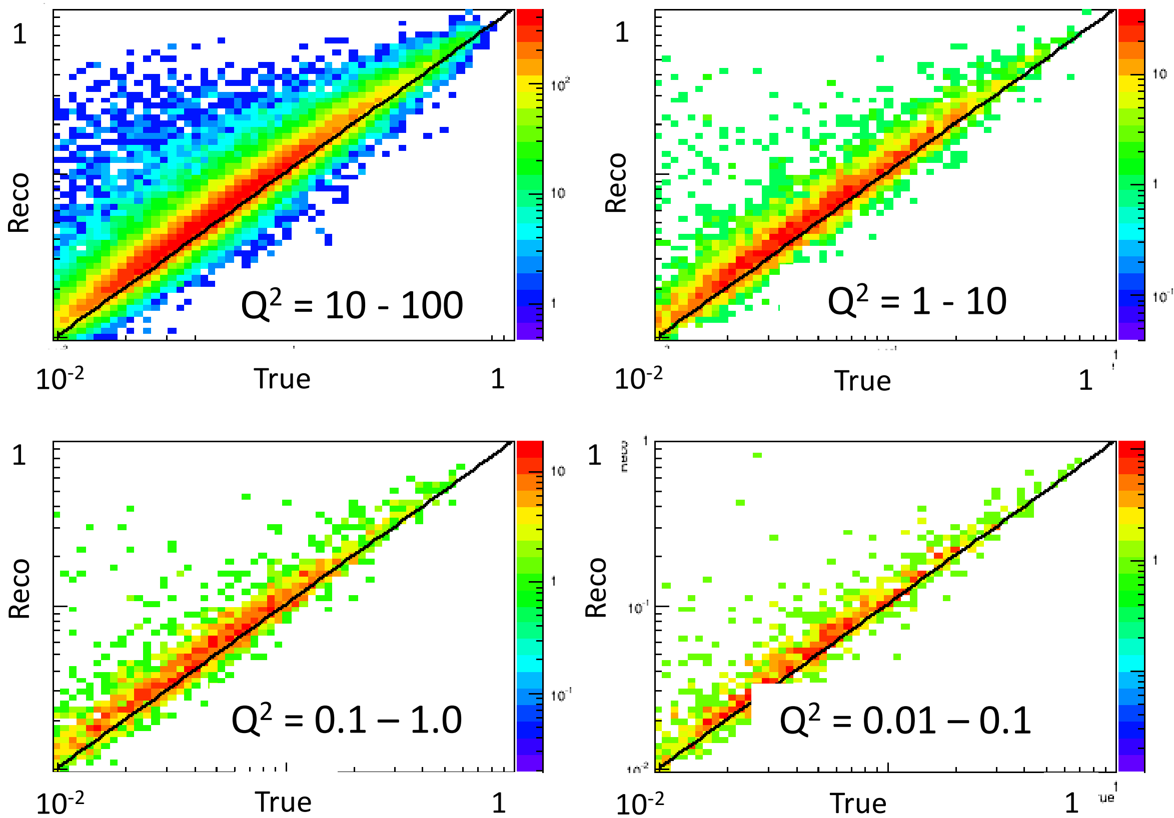


- Will use virtual photon momentum fraction to discriminate between resolved and direct processes
- See good agreement between reconstructed and true X_γ for all Q^2 ranges
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV

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

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

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

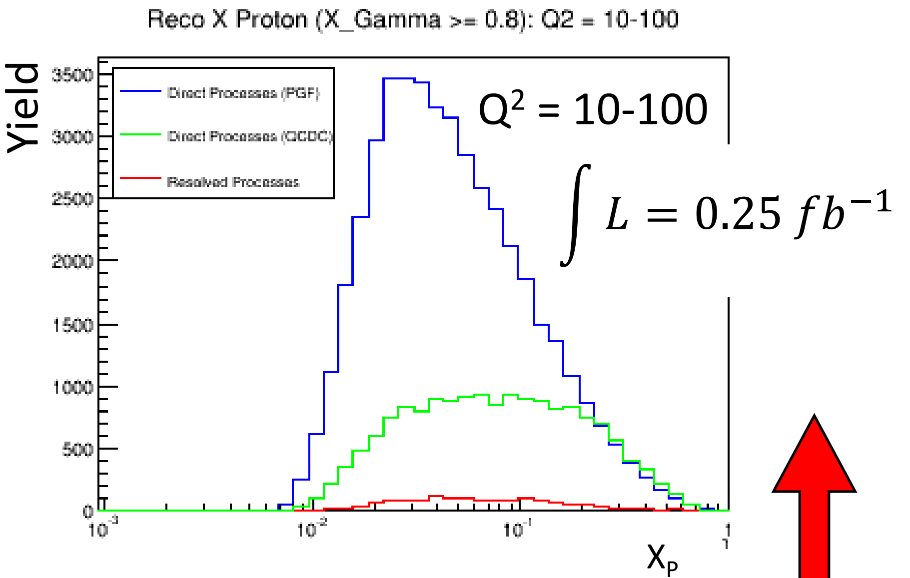
$$Q^2 = syx_B$$

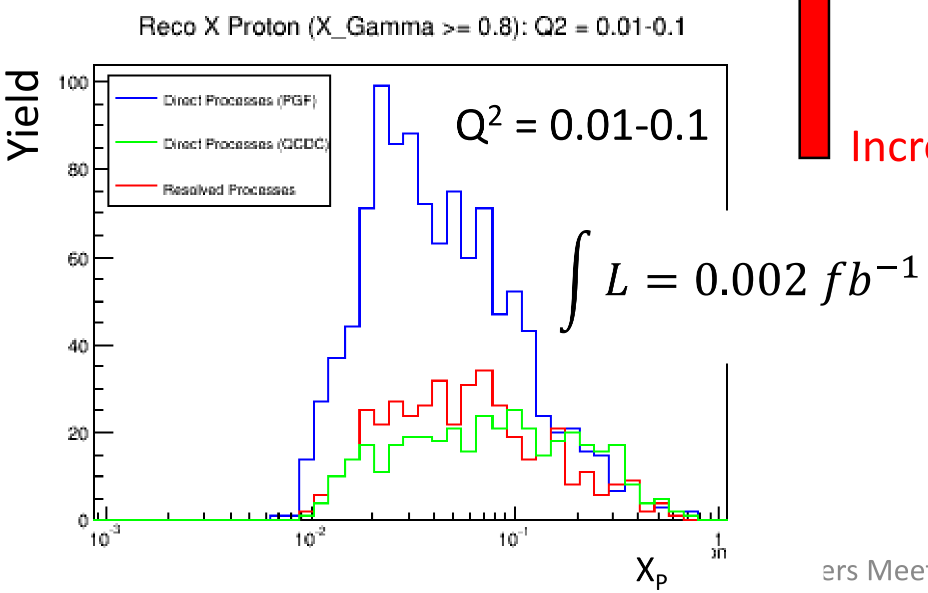
$$X_P = x_B + \frac{M^2}{sy}$$

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

- 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

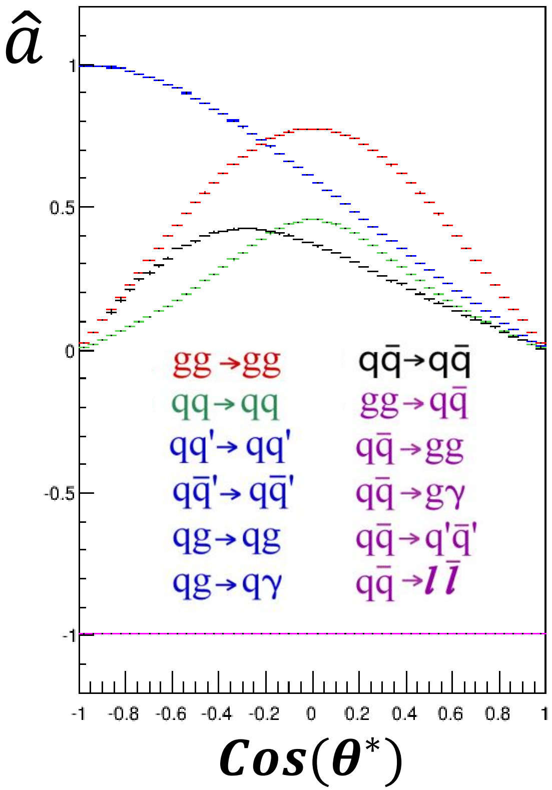
- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases
- For a given di-jet mass range (10 – 20 GeV in this case), same X_P can be reconstructed event-by-event and probed over large range of Q^2
- This will allow for robust tests of the evolution of ΔG

Weighting PYTHIA

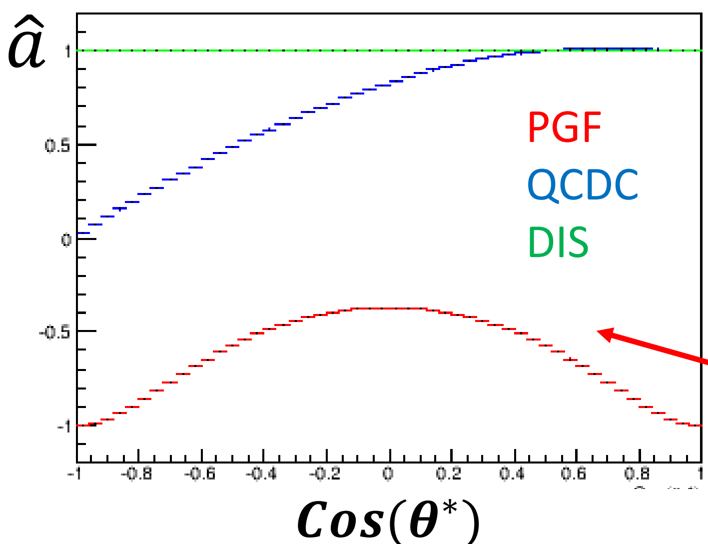
$$w = \boxed{\hat{a}(\hat{s},\hat{t},\mu^2,Q^2)} \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \frac{\Delta f_b^{N}(x_b,\mu^2)}{f_b^{N}(x_b,\mu^2)}$$

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

Resolved



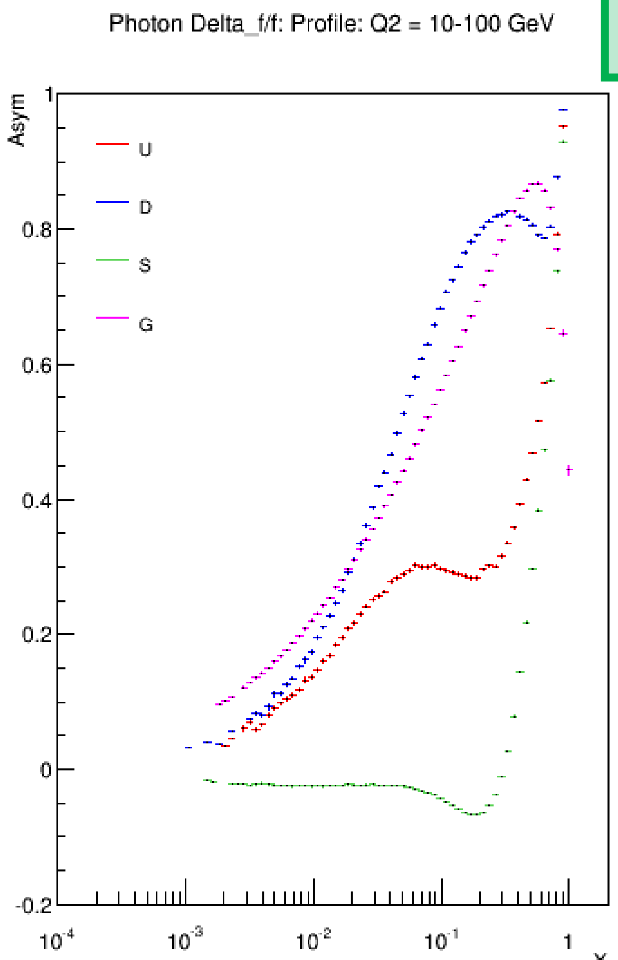
Direct



- 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

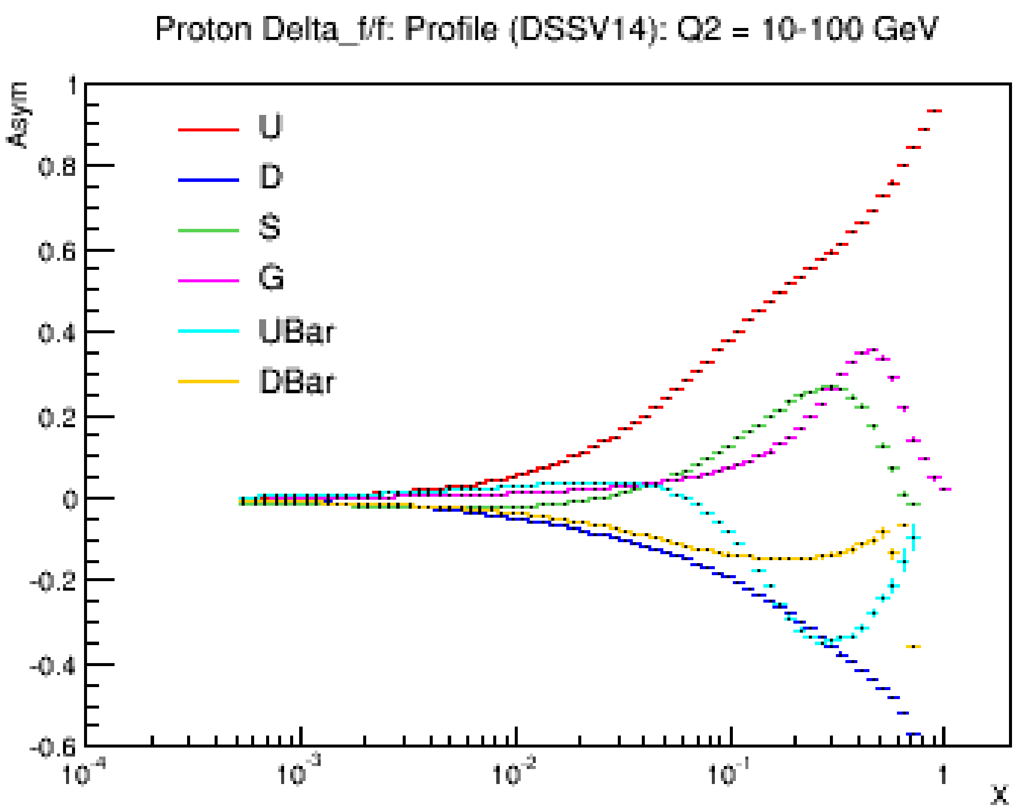
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \boxed{\frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)}} \bullet \frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}$$



- 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

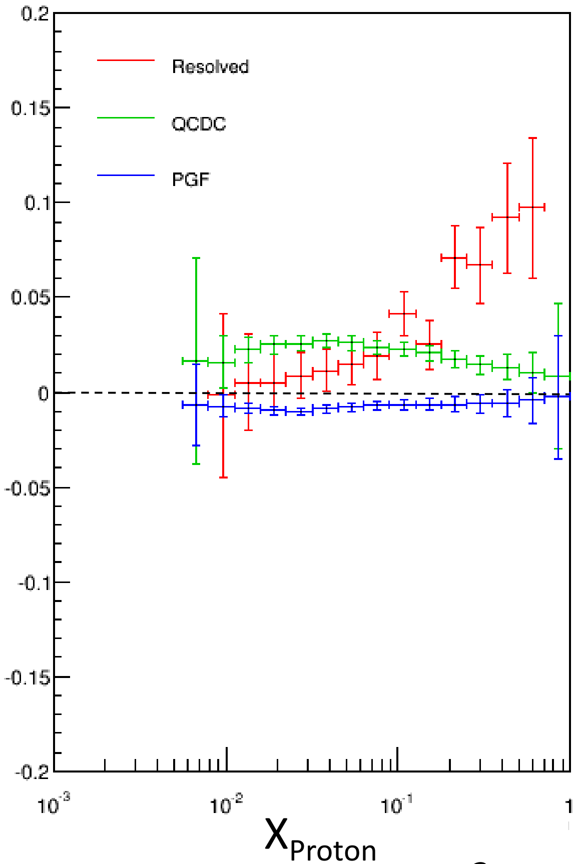
$$w = \hat{a}(\hat{s},\hat{t},\mu^2,Q^2) \bullet \frac{\Delta f_a^{\gamma^*}(x_a,\mu^2)}{f_a^{\gamma^*}(x_a,\mu^2)} \bullet \boxed{\frac{\Delta f_b^N(x_b,\mu^2)}{f_b^N(x_b,\mu^2)}}$$



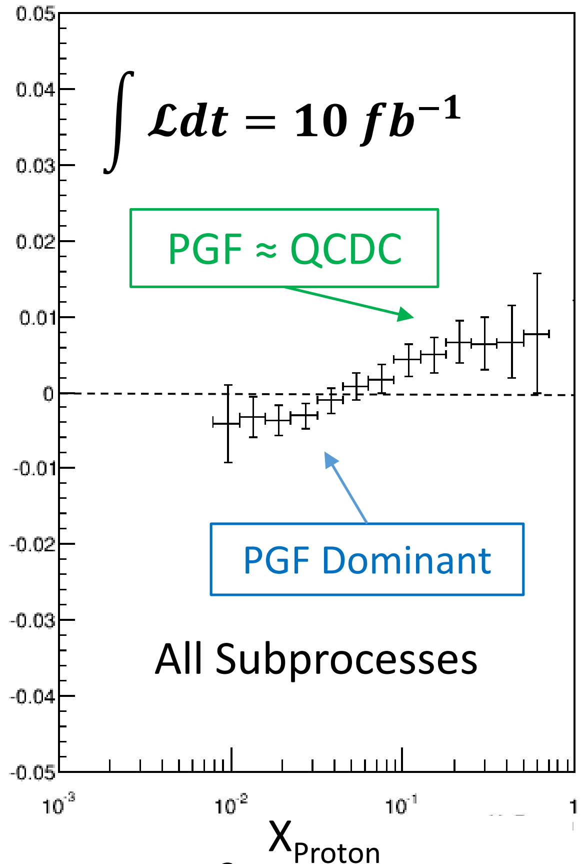
- Last term is the ratio of the polarized to unpolarized proton PDFs
- Use DSSV14 for polarized and CTEQ5M for unpolarized

A_{LL} Vs X_{Proton}

A_{LL} Vs Proton X



A_{LL} Vs Proton X

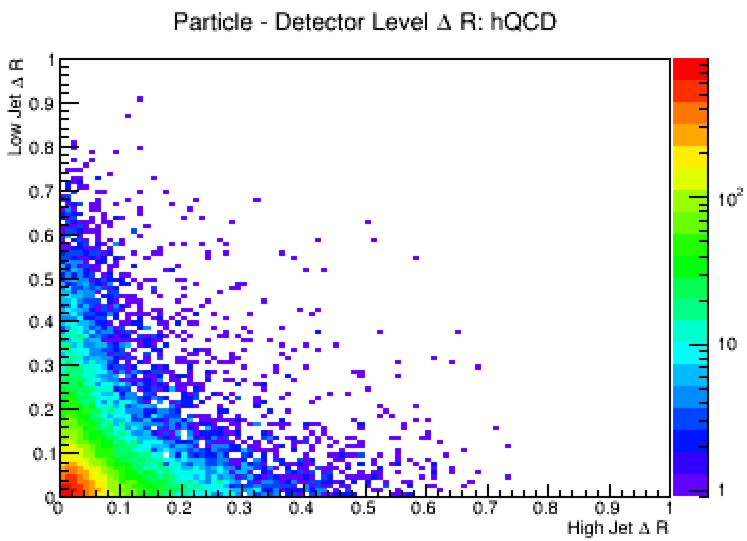


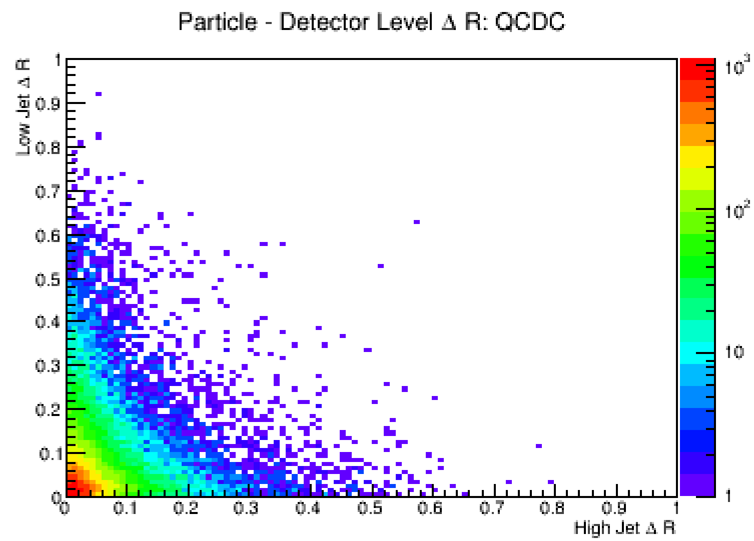
Q^2 = 10 - 100 GeV^2

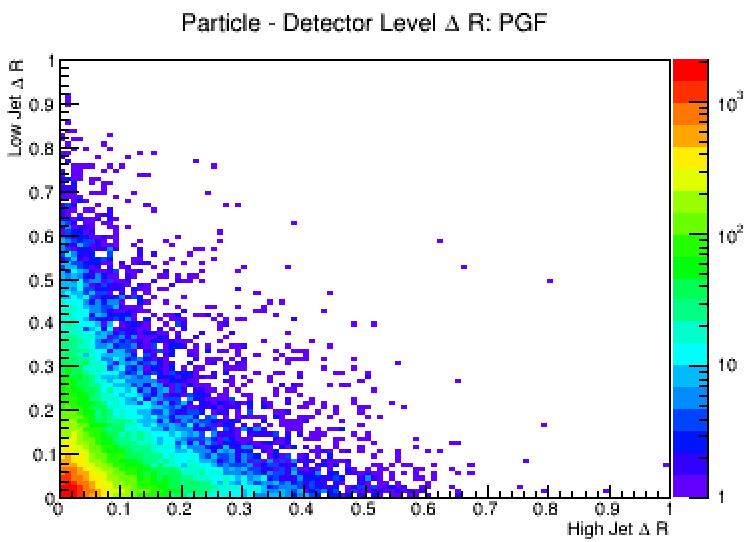
$$\sigma = \sqrt{\frac{1}{N} - \frac{A^2}{N}}$$

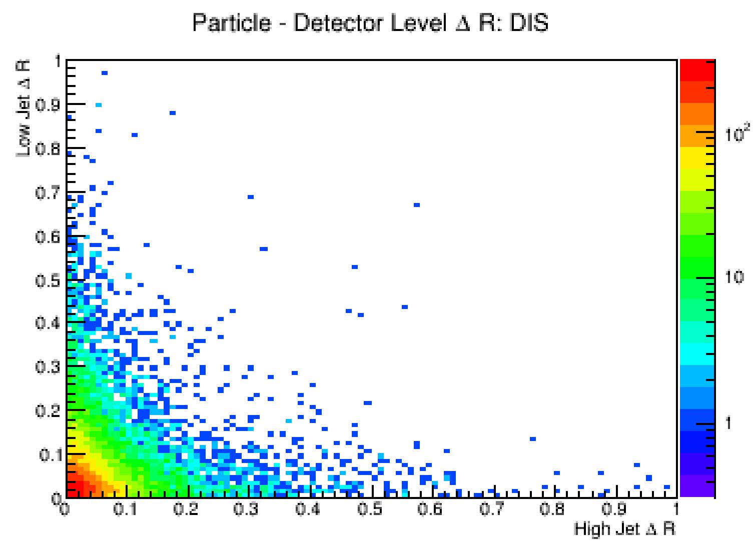
- Asymmetry is plotted as a function of the momentum fraction of the parton from the proton
- Asymmetry shown for di-jet invariant masses between 10 and 20 GeV/c^2
- Error bars are statistical and scaled to the given integrated luminosity
- Different mass ranges will emphasize different momentum fraction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

Particle – Detector ΔR

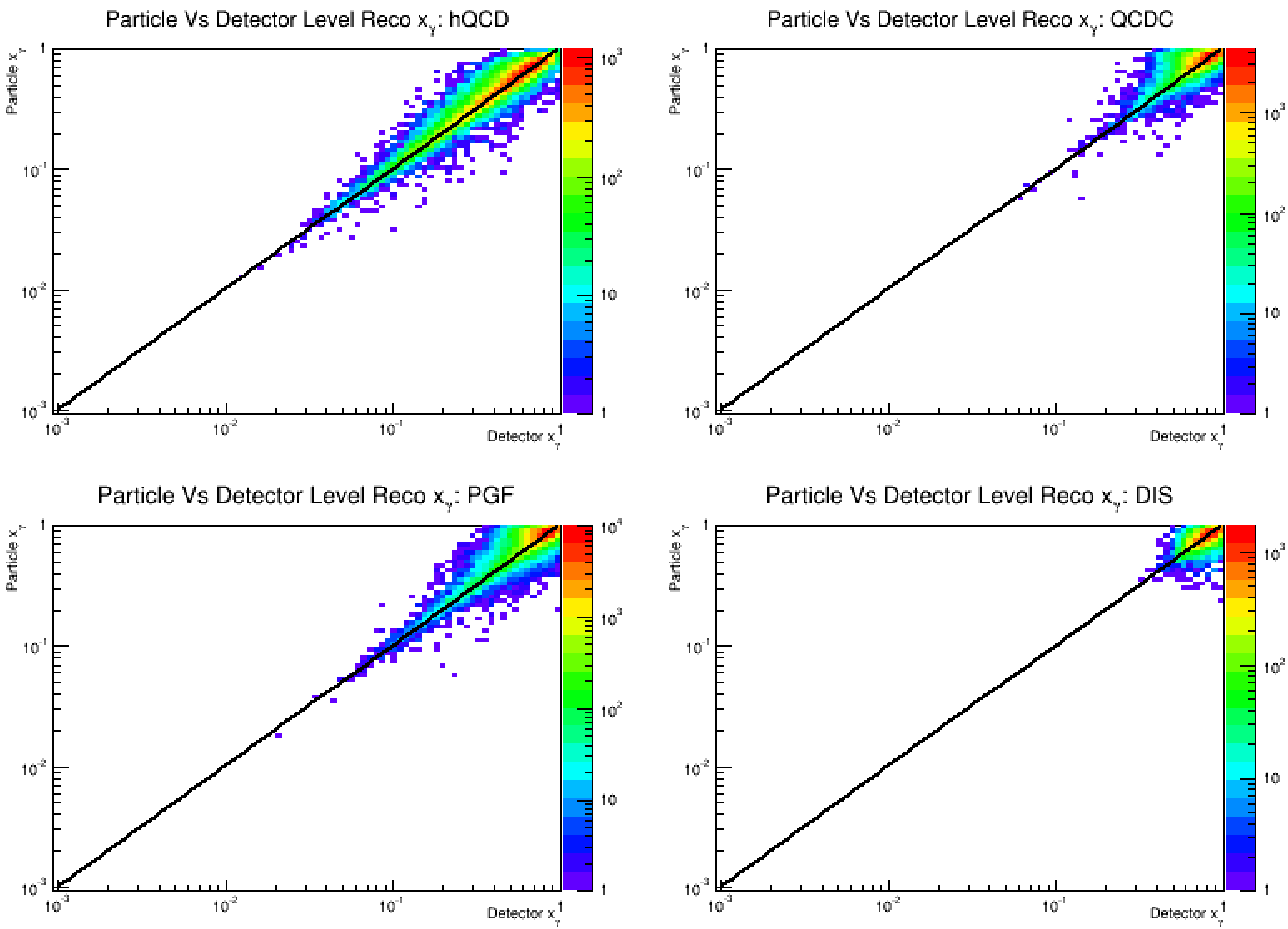








Particle – Detector Comparison



Particle – Detector Comparison