Jet Physics at an EIC

Brian Page

EIC User Meeting: ANL

July 2016

Outline

- Particle Content of Jets
  - Is a Mid-Rapidity Hadron Calorimeter Necessary?
- Quark Jet Vs Gluon Jet Discrimination
- Accessing Gluon Polarization with Di-jets
- Diffractive Di-jets
- Summary

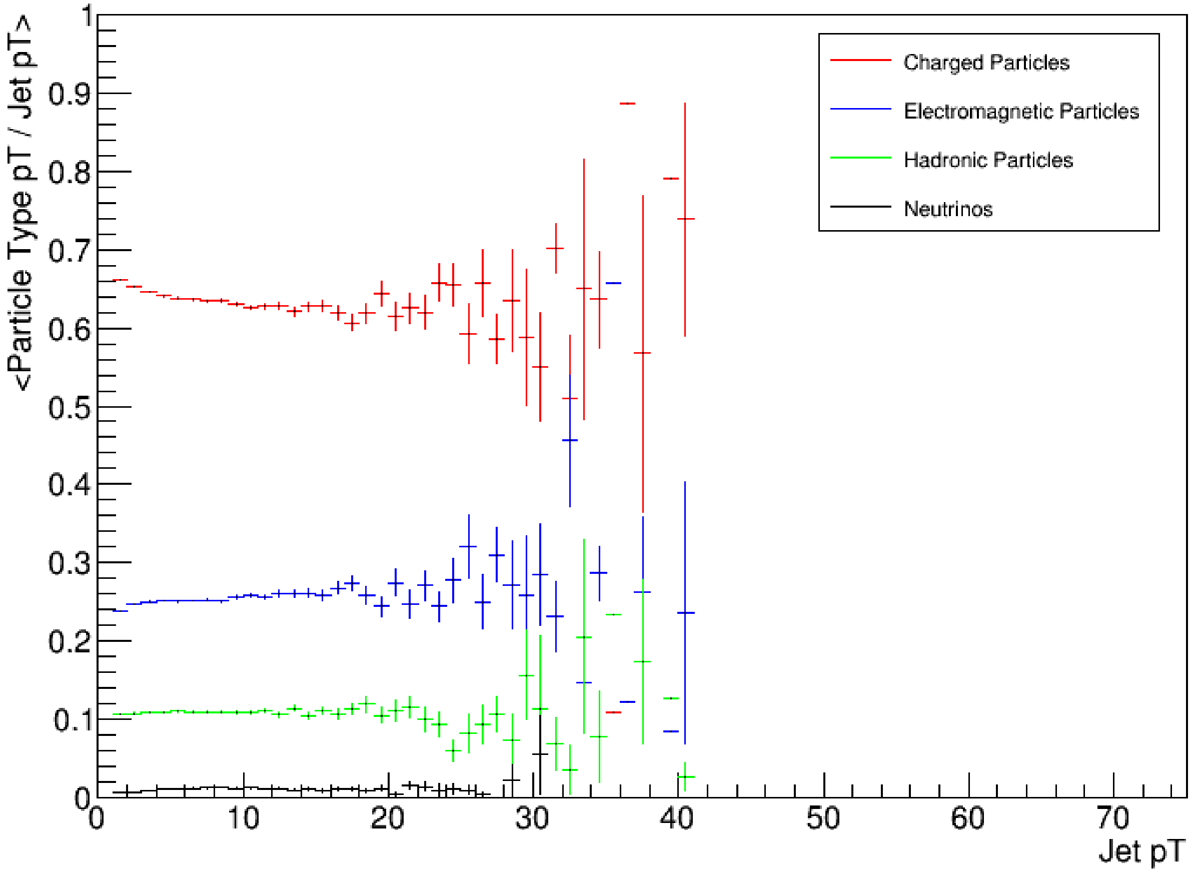
Do We Need a Hadron Calorimeter?

- Group particles by how they interact with detector elements and look at average fraction of jet pT carried by each particle type and average number of each particle type in jets to determine if barrel hadronic calorimeter is necessary

- Only look at jets in the mid-rapidity region, between -1 <= eta_lab <= 1, Q^2 = 10 – 100 GeV^2

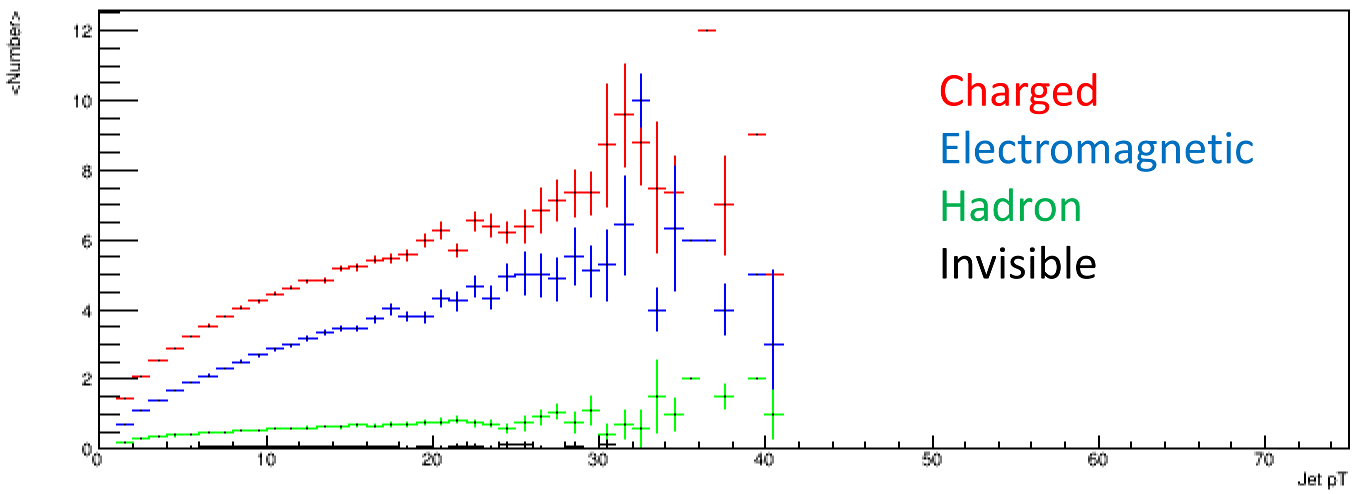
- Particle groupings are:
  - Charged = muons, pions, kons, rhos, protons
  - Electromagnetic = photons, pi0, electrons
  - Hadrons = neutrons, K0_Long
  - Invisible = neutrinos

Particle p_T Fractions Vs Jet p_T



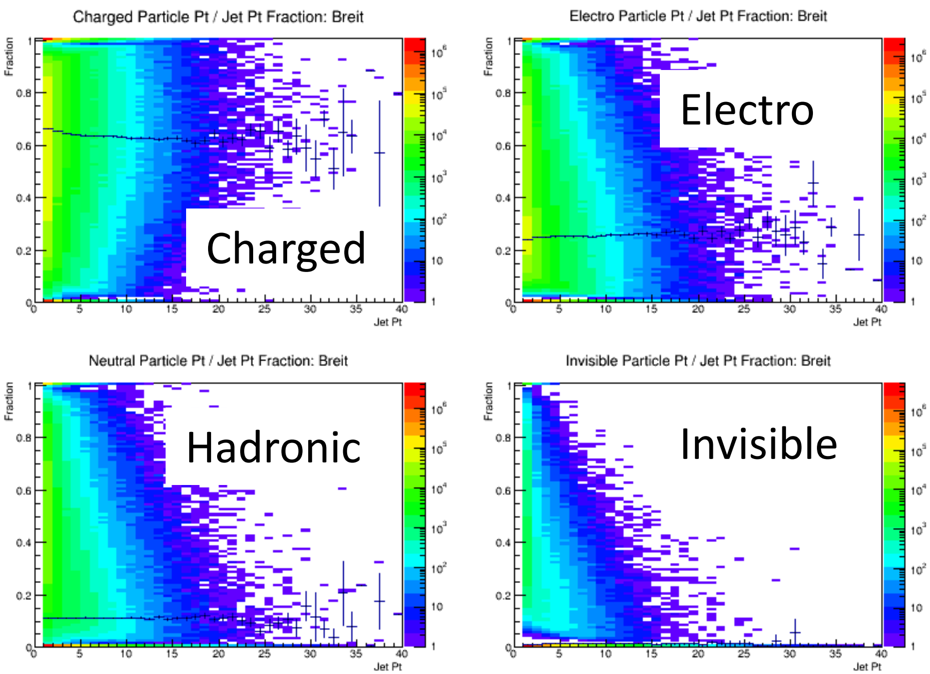
- Take vector sum of particles of given type and find total transverse momentum
- Plot average p_T of each particle class vs total jet p_T
- See that charged particles dominate while neutral hadrons contribute roughly 10%

Particle Number Vs Jet p_T

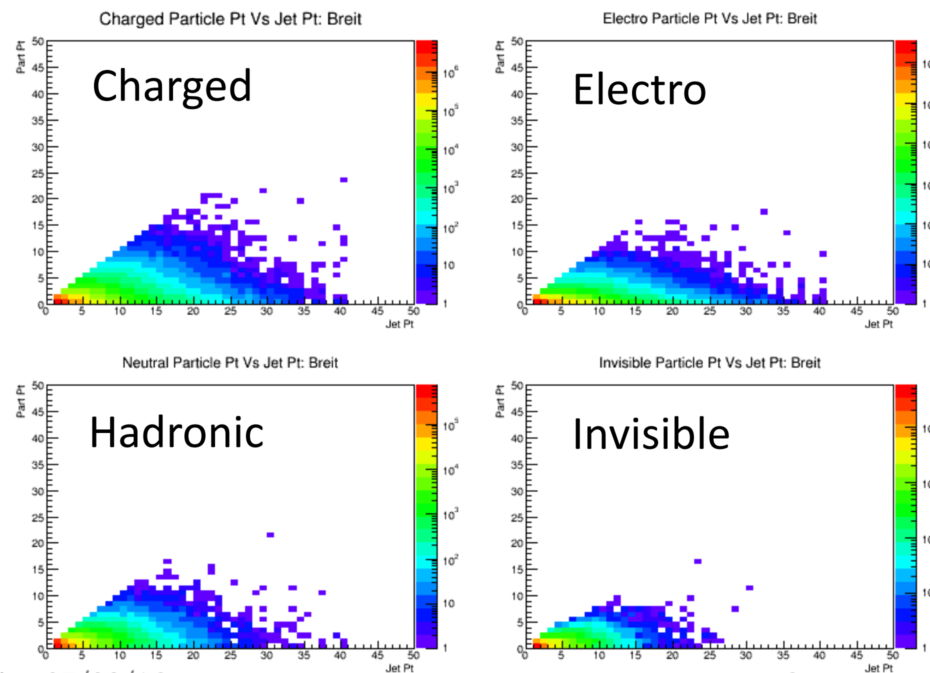


- Find average number of each particle type in a jet
- Similar story as with p_T fractions: jets are dominated by charged hadrons and electromagnetically interacting particles

Particle – Jet 2D Correlations



- Plots to the left show particle class p_T over total jet p_T vs jet p_T – scatter plot of second to previous slide
- See that for charged particle, there is large locus at a fraction of 1 while for hadronic, the majority of events are at 0
- Fraction of jets with majority hadronic content is small

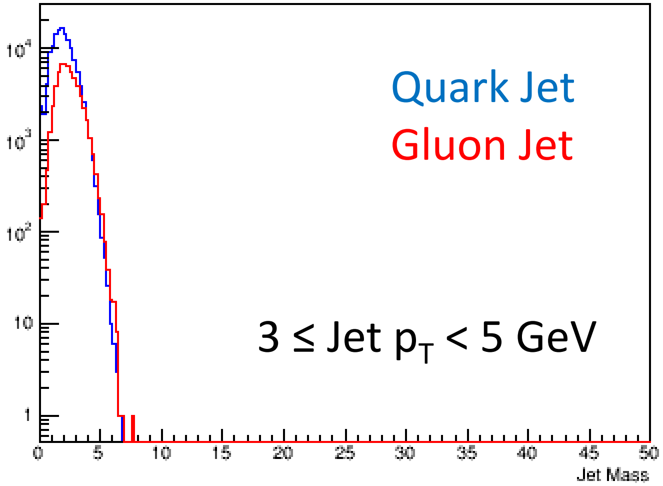


- Plots to the right show individual particle p_T vs the p_T of the jet they are a part of
- See that high p_T jets are not dominated by single high p_T particle, but are more often composed of multiple lower p_T particles
- Jet measurements do not appear to drive the need for a hadron calorimeter

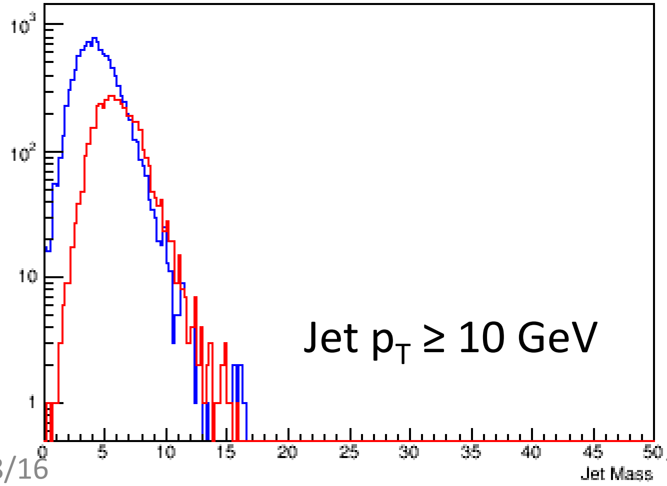
Quark – Gluon Discrimination

- 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

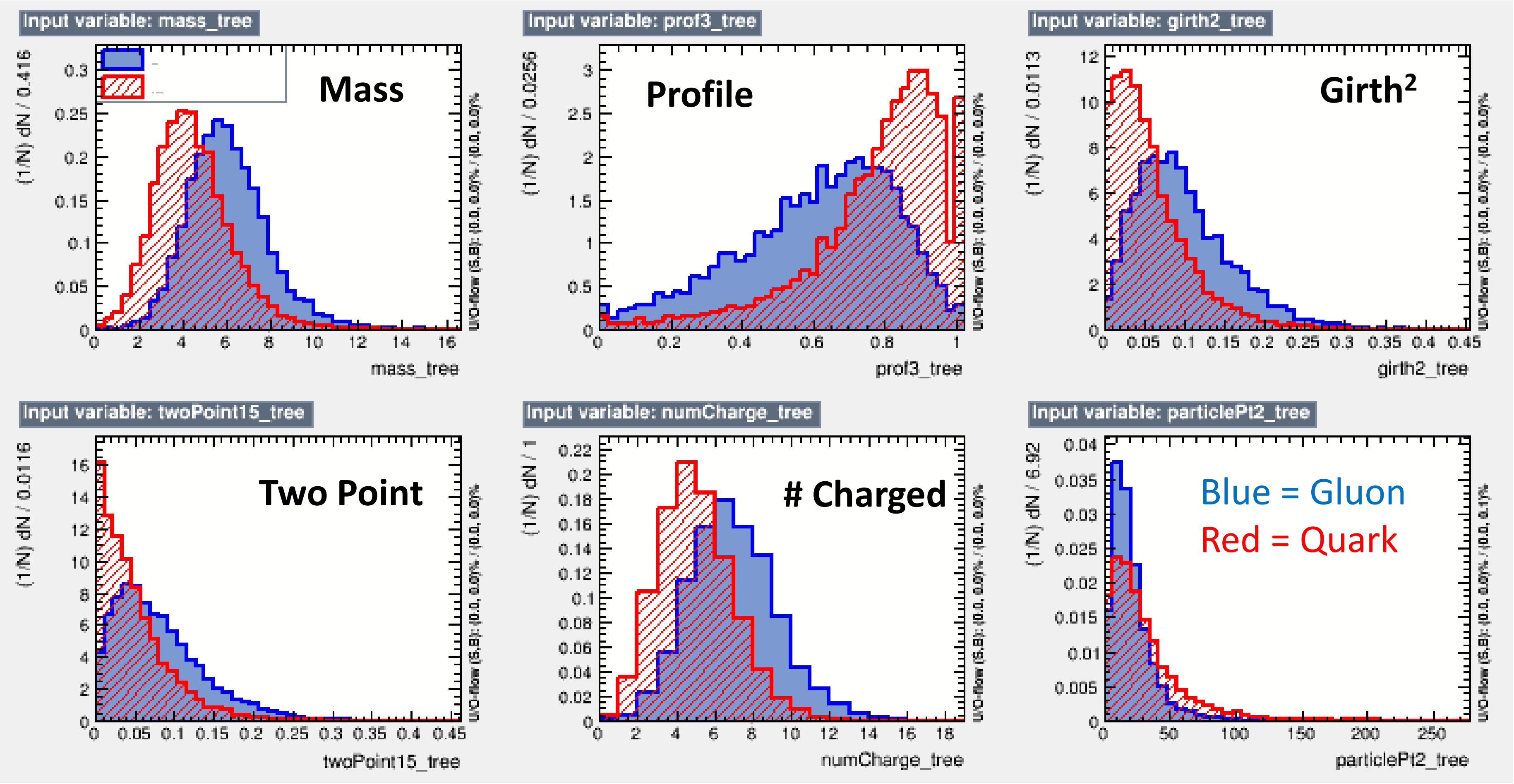
Jet Mass: Low Jet p_T



Jet Mass: High Jet p_T



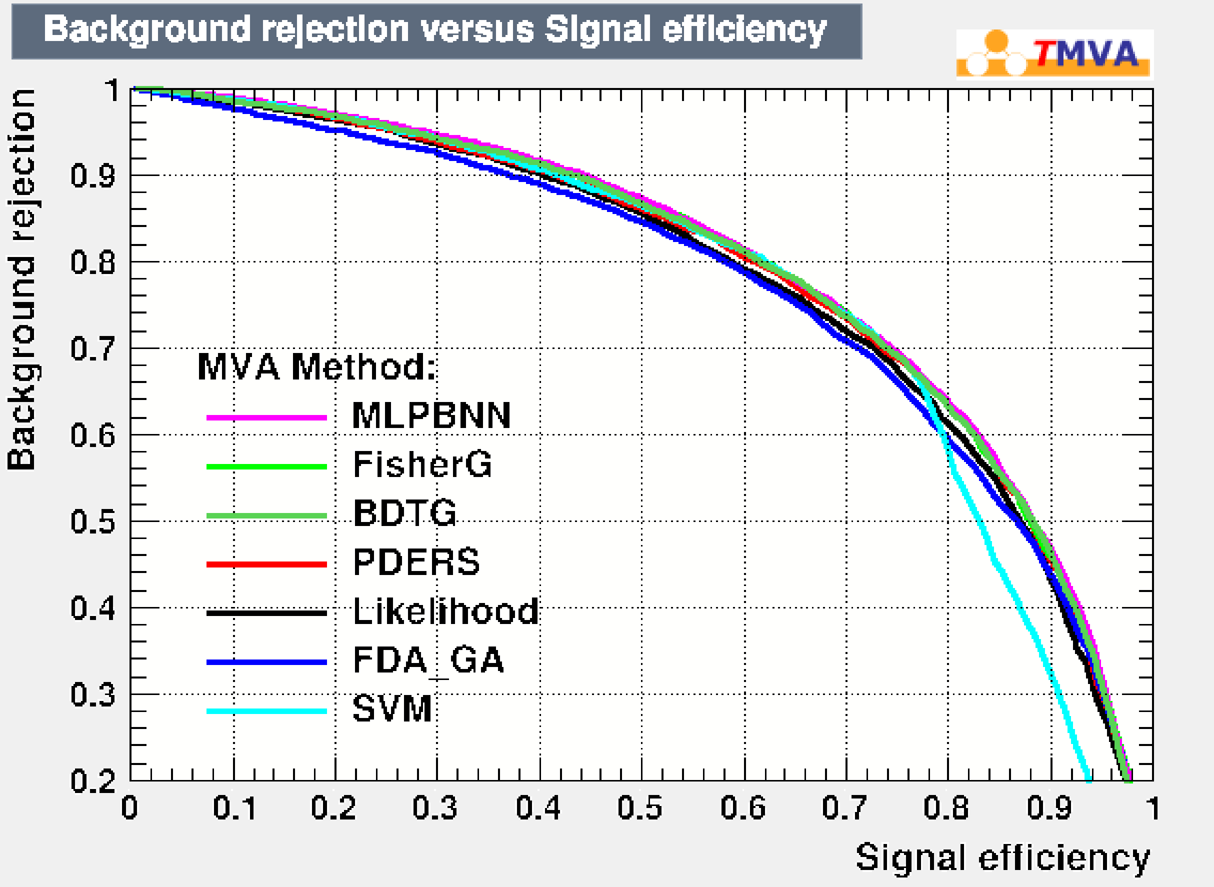
Input Variables



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

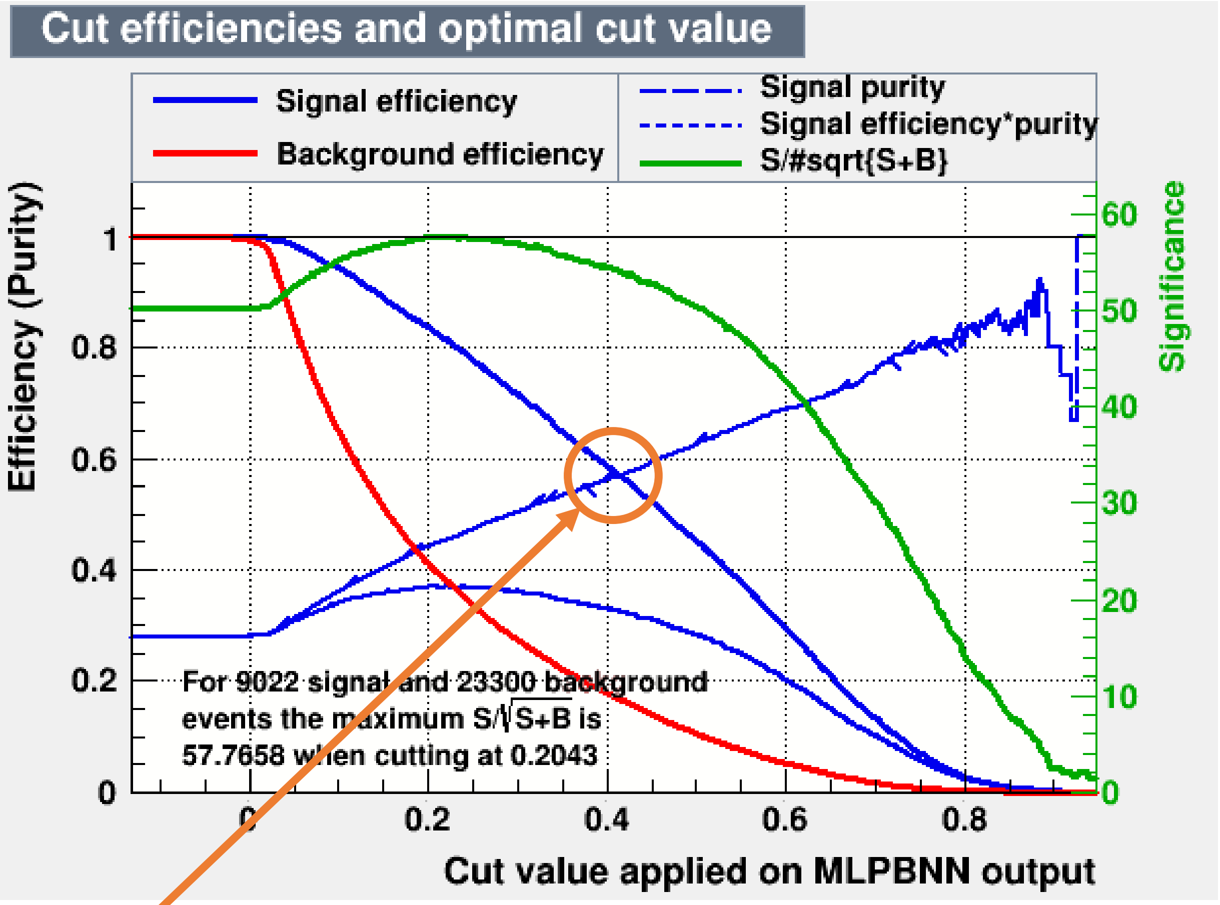
$$2\ \text{Point} = \frac{1}{{p_{Tjet}}^2} \sum_{i \neq j} p_{Ti} * p_{Tj} * |r_{ij}|^{\beta}$$

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

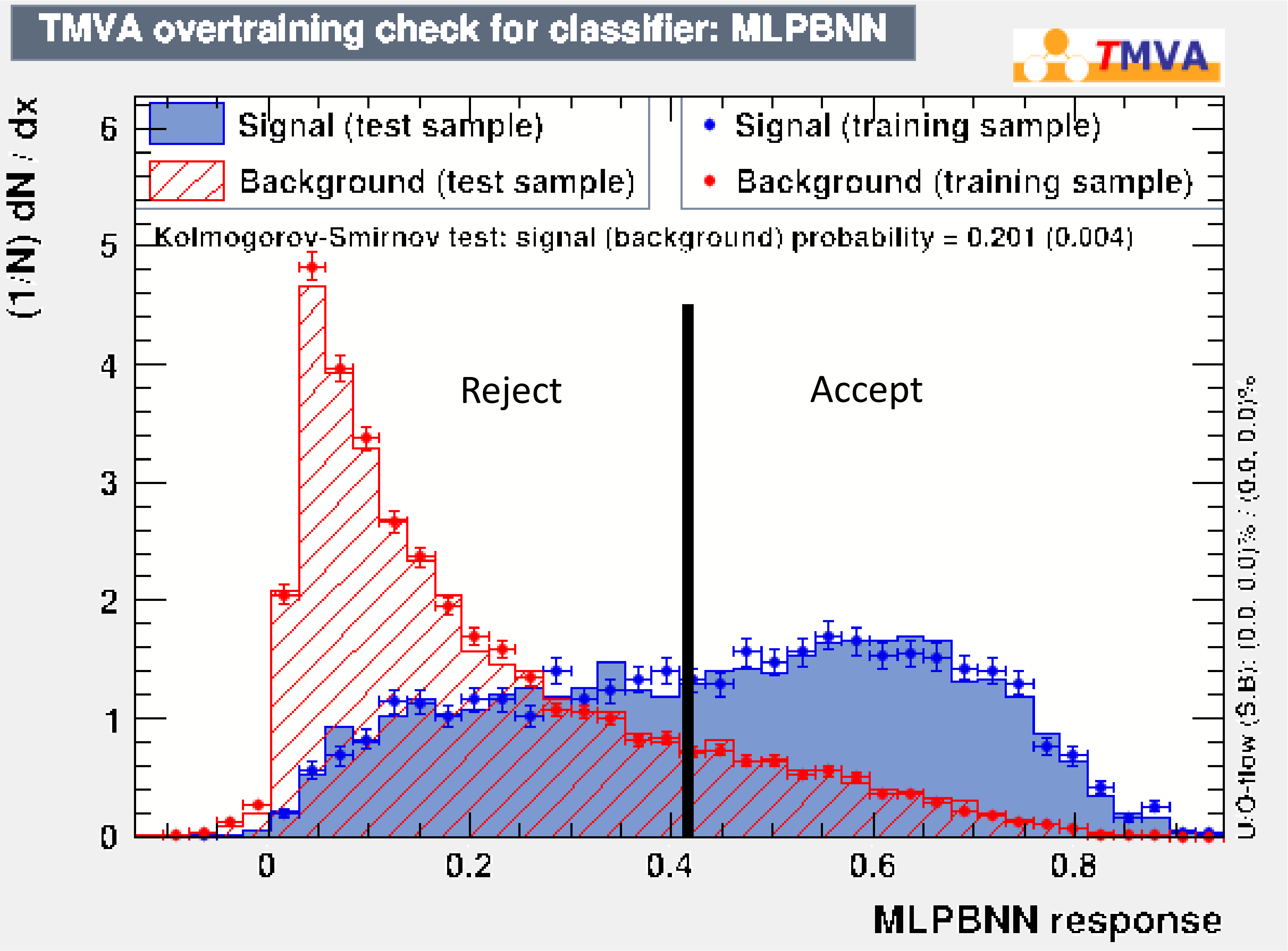
Cut Optimization



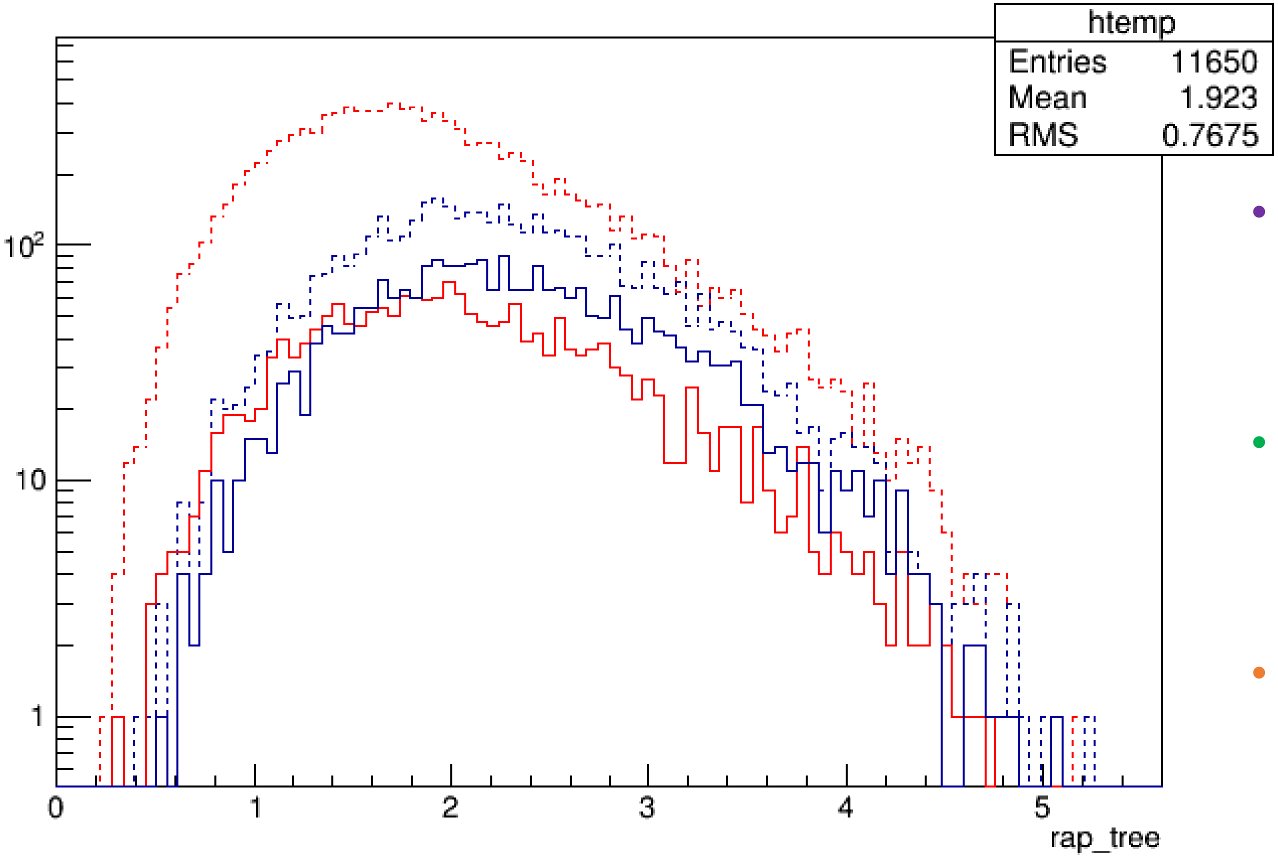
- TMVA evaluates all input and maps them to a single variable with more signal-like events having a higher value
- Plot signal & background efficiency, signal purity, significance, etc as a function of this cut value
- This plot shows where to place cut in order to maximize purity, efficiency, or whatever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

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

MLPBNN Response



Jet Rapidity Spectra

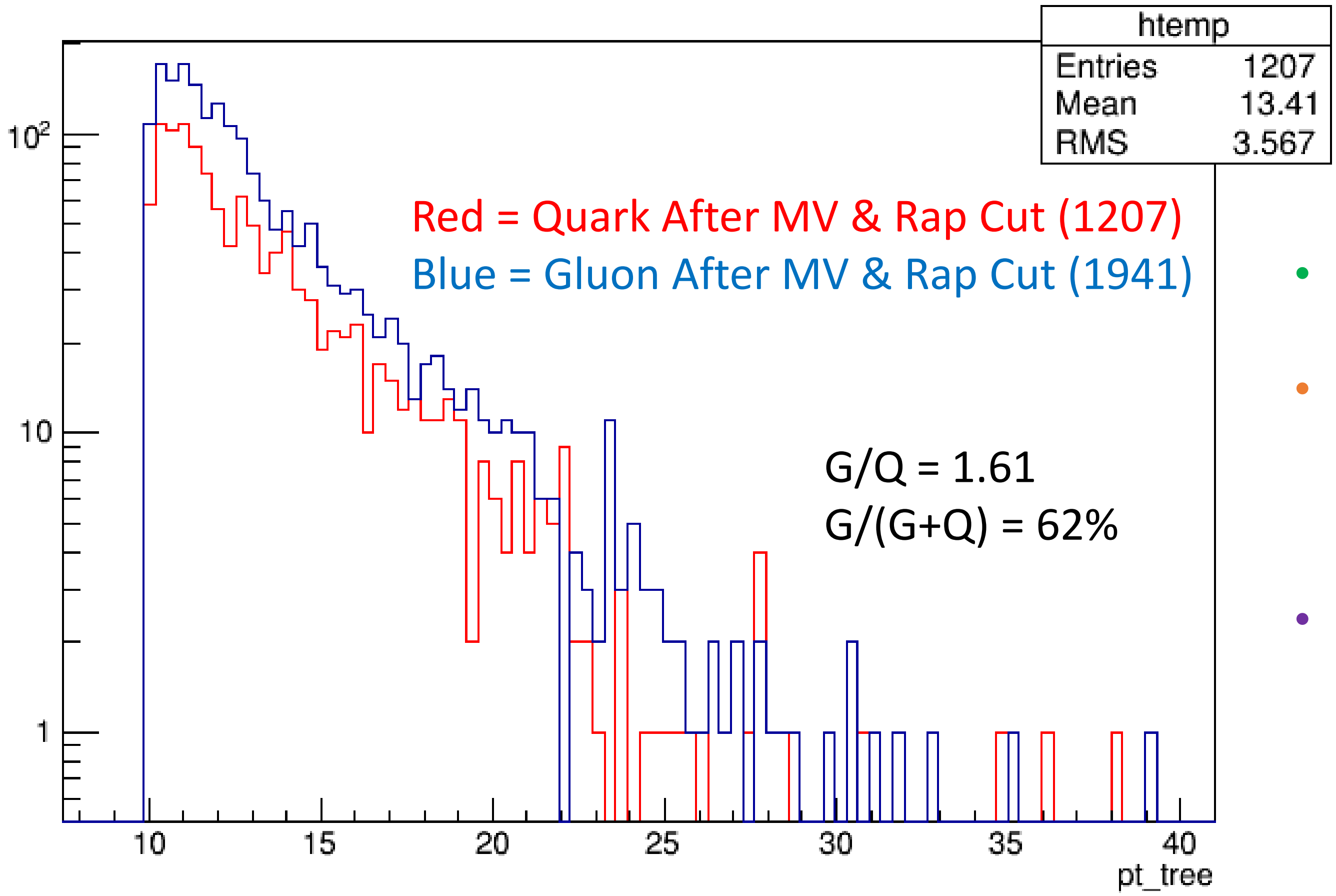


- After cut is applied, can plot quark and gluon jets vs any relevant variable
- Here we see that gluons dominate at higher rapidity
- Look at jets with rapidity > 1.8 to further enhance gluon fraction

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

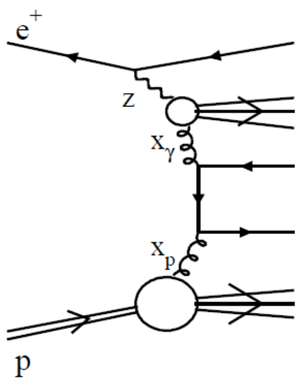
Gluon Polarization with Di-jets

- Measurements of scaling violations of the g_1 structure function will be the primary method of accessing gluon polarization at an EIC, however alternate measurements will be important for cross checks and differing systematic effects

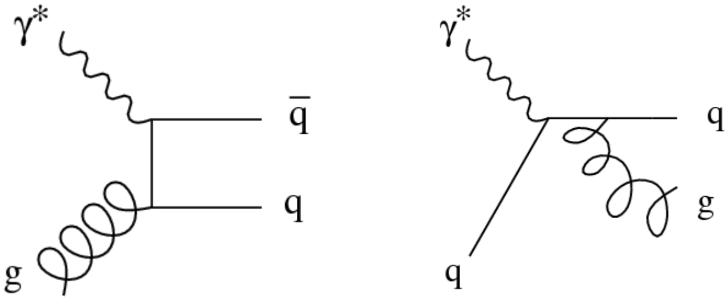
- Can access gluon polarization by measuring di-jet production arising from direct processes in which the virtual photon is point-like (see Xiaoxuan Chu's talk on using resolved processes to measure polarized photon structure functions)

- Hope is that di-jet mass provides perturbative scale to extend gluon polarization measurements to $Q^2 < 1$ GeV^2

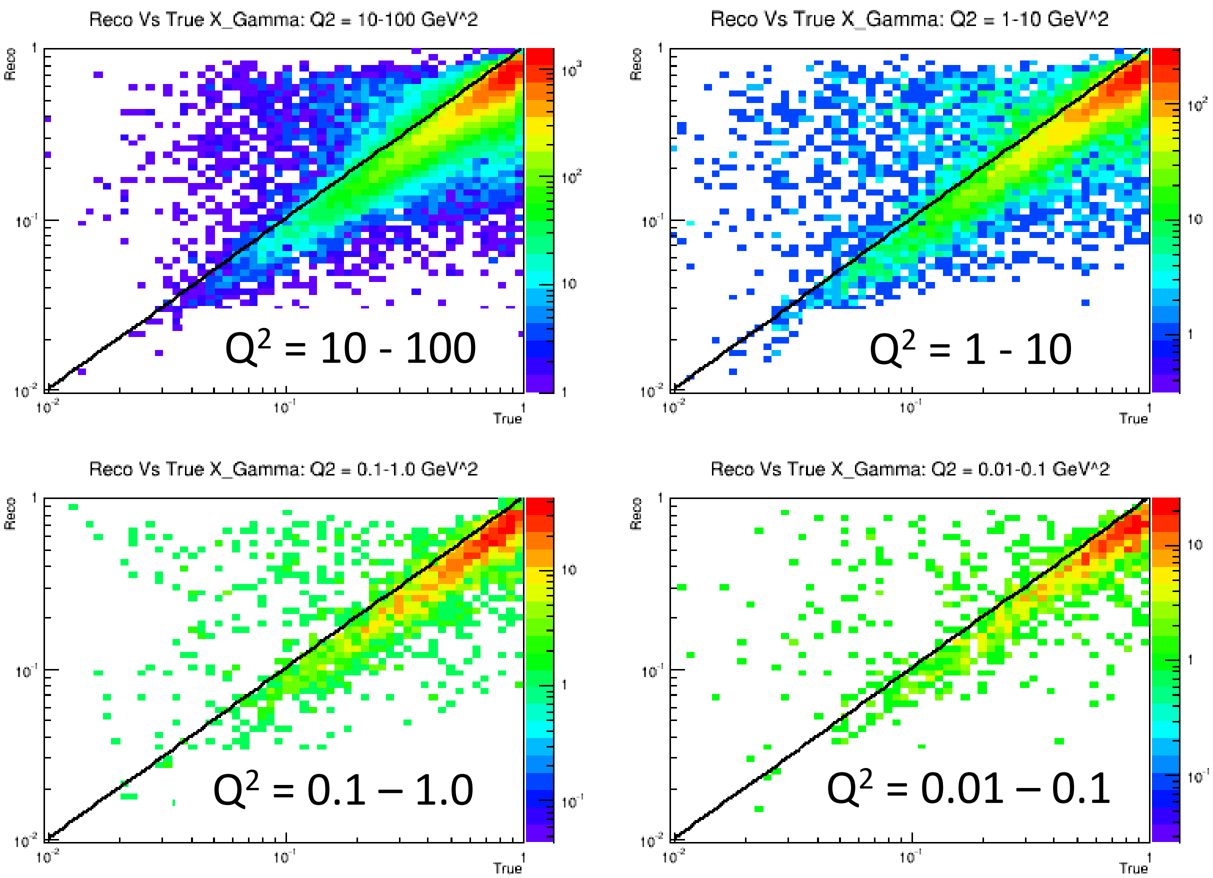
Resolved



Photon-Gluon Fusion & QCD-Compton



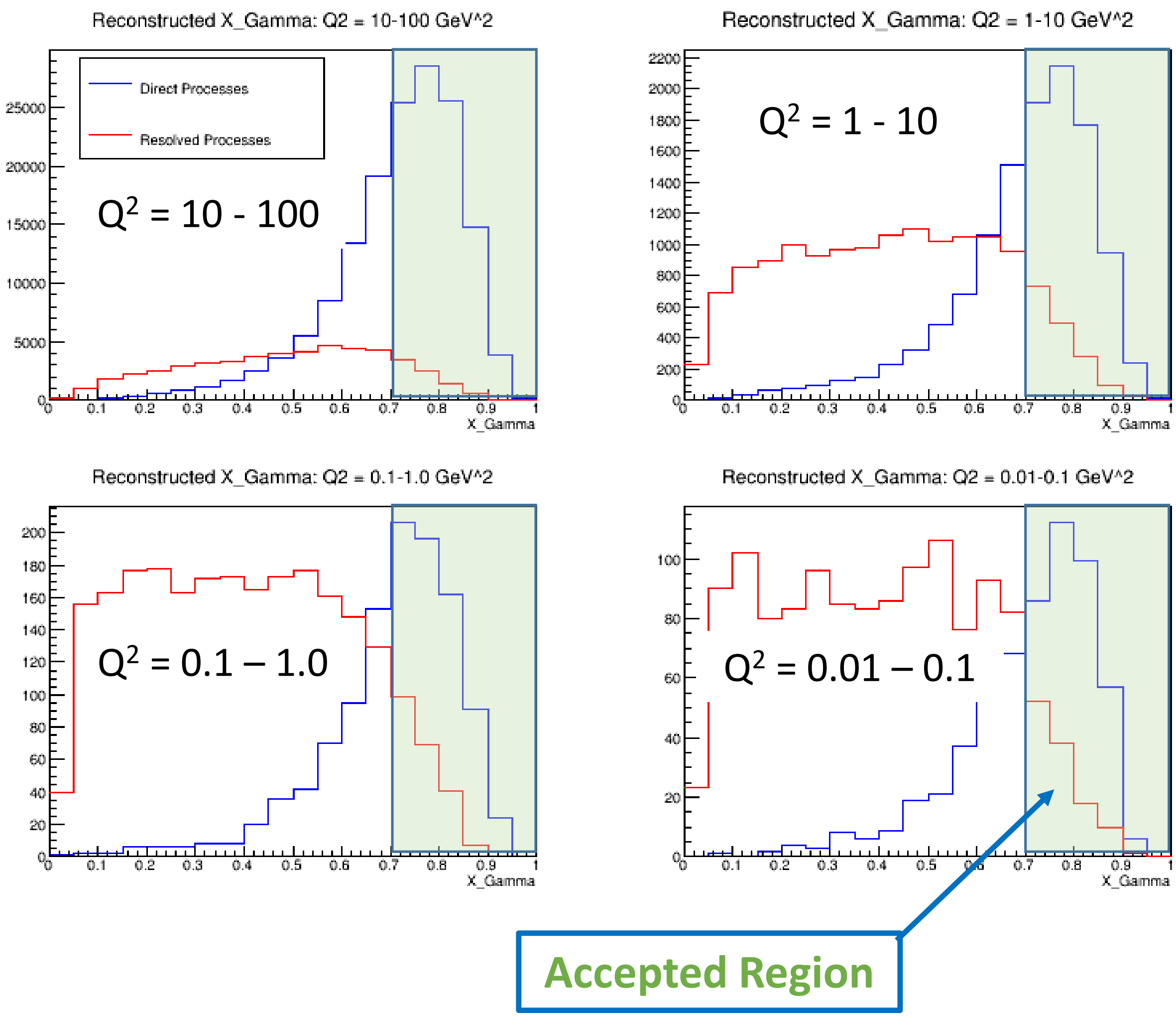
X_γ: Reconstructed Vs True



- 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

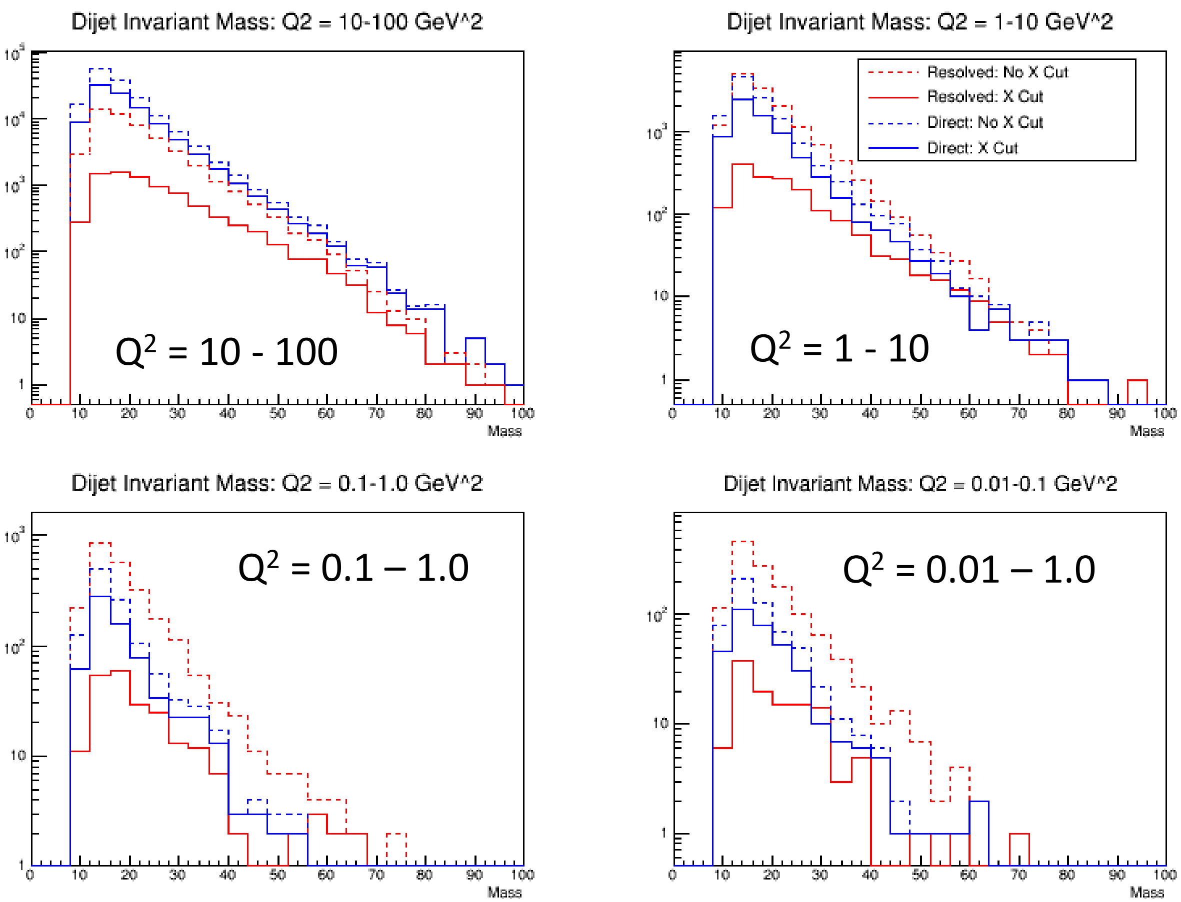
$$X_\gamma = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$

Direct Vs Resolved Processes



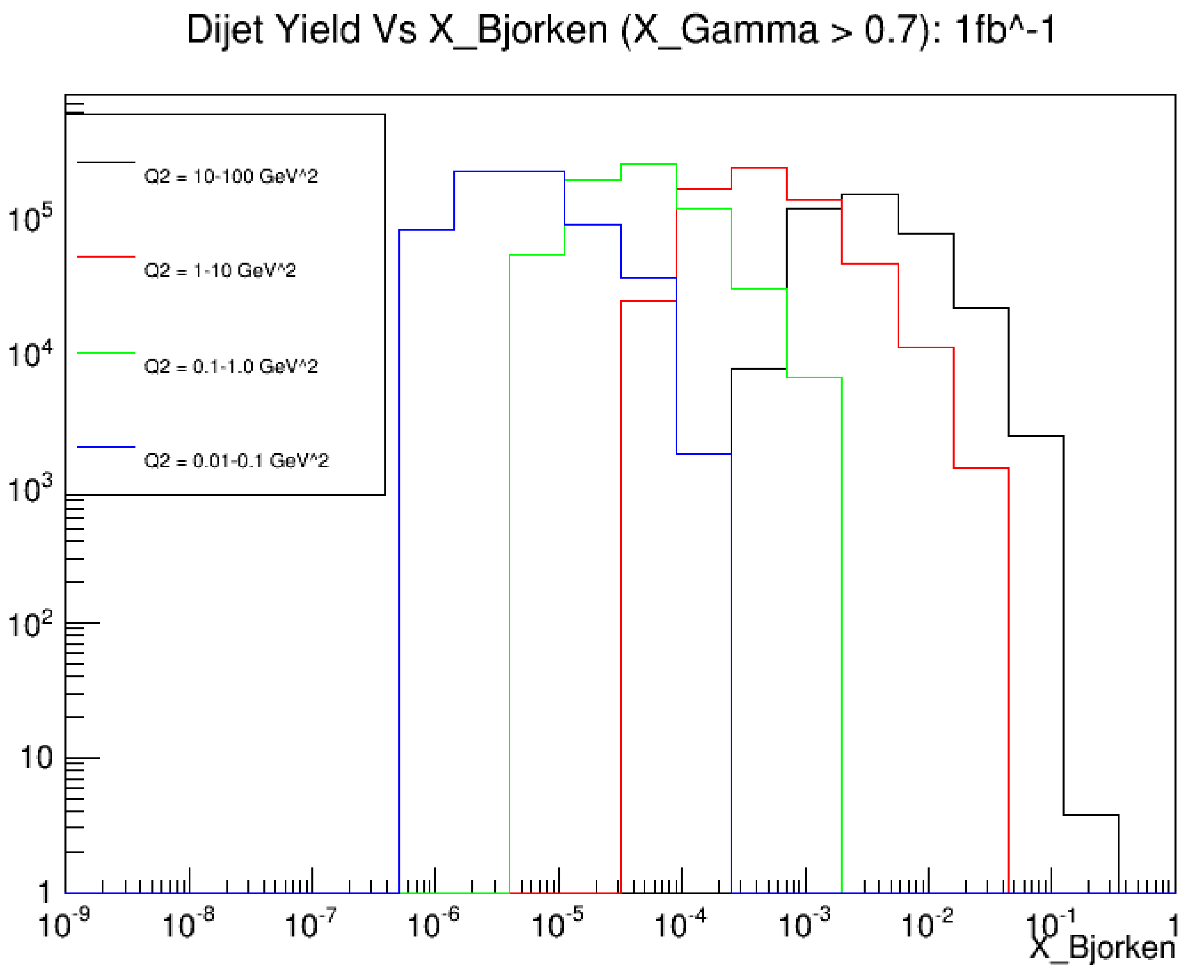
- Plot reconstructed X_γ for direct and resolved processes
- Direct processes should concentrate toward 1 while resolved processes are at lower values
- Direct processes dominate at higher Q^2 while resolved are more prevalent at low Q^2
- Cut of $X_\gamma > 0.7$ enhances the direct fraction at all Q^2

Di-jet Invariant Mass



- See that the cut on X_γ significantly reduces the resolved contribution while maintaining the direct events
- Separation between resolved and direct is most prominent at high Q^2 and low di-jet invariant mass
- Further suppression of resolved events may be possible by looking at lab-frame rapidity correlations

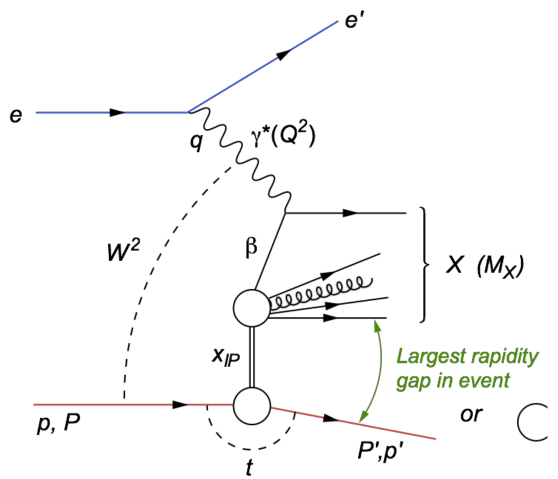
Di-jet Yield in X and Q^2: $1fb^{-1}$



- Yield of di-jet events which pass X_γ cuts vs x_B for the four Q^2 bins simulated
- Yield has been scaled to an integrated luminosity of $1fb^{-1}$
- See multiple decades of Q^2 coverage for several x_B bins
- Different x_B ranges can be accessed at a given Q^2 by varying the collision energy
- Study is in early stage but outlook is positive – can isolate direct contribution even at low Q^2

Diffractive Di-jet Studies

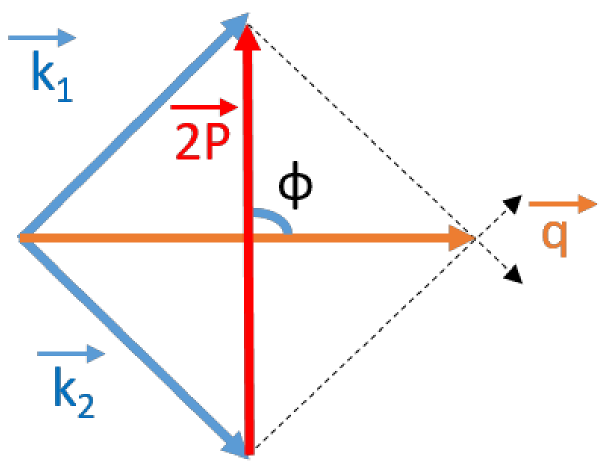
Diffractive



- There have been several recent papers looking at angular correlations between jets in diffractive di-jet events: see for example Phys. Lett. B758 P373 and PRL 116, 202301

- Would like to explore basics of diffractive di-jet production at an EIC – rates, t-dependence, masses, etc

- Will simulate hard diffractive events using RAPGAP – beginning to integrate generator into existing eRHIC simulation framework



$$\overrightarrow{2P} = \vec{k}_1 - \vec{k}_2$$

$$\vec{q} = \vec{k}_1 + \vec{k}_2$$

Summary

- Jet particle content and p_T budget dominated by charged particles with ~10% contribution from neutral hadrons – mid-rapidity hadron calorimeter likely not necessary
- See reasonable ability to isolate quark or gluon initiated jets, especially at high jet p_T
- Preliminary work has begun on investigating the use of di-jets as a probe of the gluon polarization
- Work is beginning on investigating diffractive di-jets using the RAPGAP Monte Carlo

Backup

Subprocess Codes

11: $f_i\ f_j \rightarrow f_i\ f_j$
12: $f_i\ f_i\_bar \rightarrow f_k\ f_k\_bar$
13: $f_i\ f_i\_bar \rightarrow g\ g$
28: $f_i\ g \rightarrow f_i\ g$
53: $g\ g \rightarrow f_k\ f_k\_bar$
68: $g\ g \rightarrow g\ g$

Resolved

91: Elastic
92: Single Diffraction (xB)
93: Single Diffraction (Ax)
94: Double Diffraction
95: Low-p_T Production

Elastic / Soft

131: $f_i\ \gamma_T^* \rightarrow f_i\ g$
132: $f_i\ \gamma_L^* \rightarrow f_i\ g$
135: $g\ \gamma_T^* \rightarrow f_i\ f_i\_bar$
136: $g\ \gamma_L^* \rightarrow f_i\ f_i\_bar$

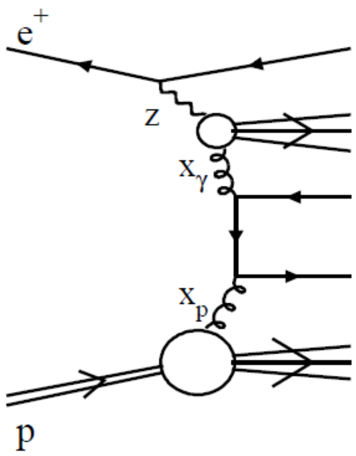
PGF / QCDC

99: $\gamma^* q \rightarrow q$

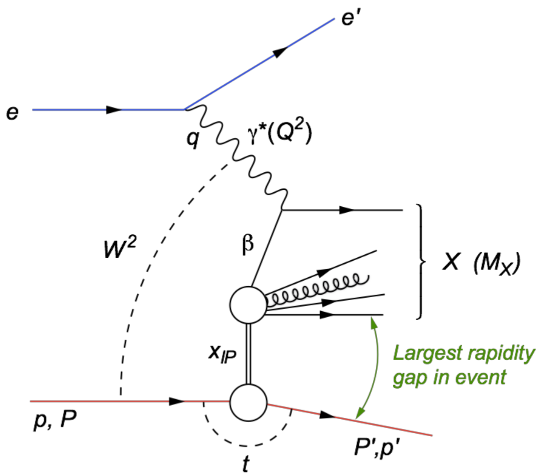
DIS

Subprocess Codes

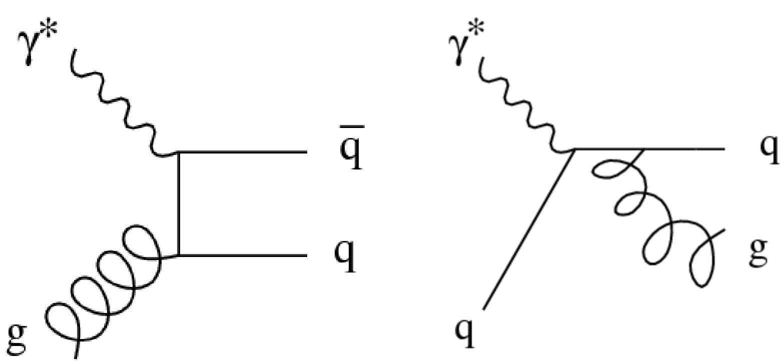
Resolved



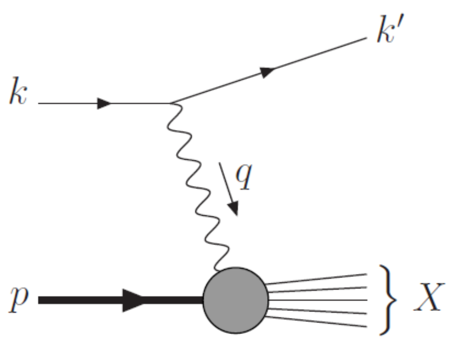
Diffractive



Photon-Gluon Fusion & QCD-Compton



DIS

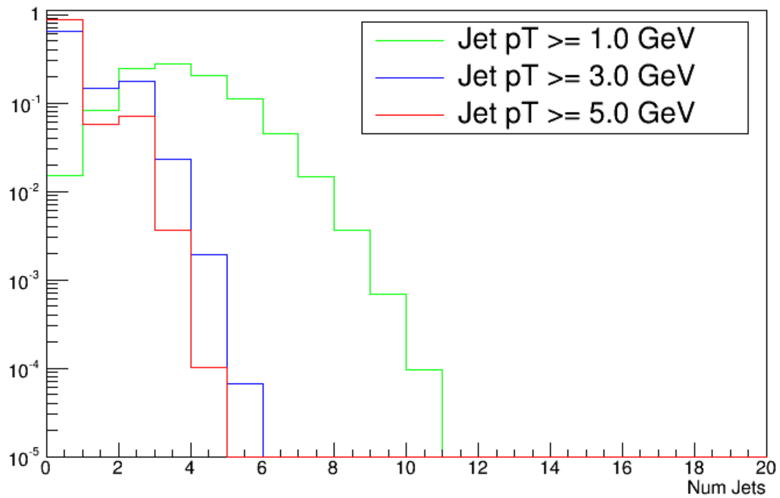


Jet Basics: Frames

- Can define several useful frames:
  - Lab
  - 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

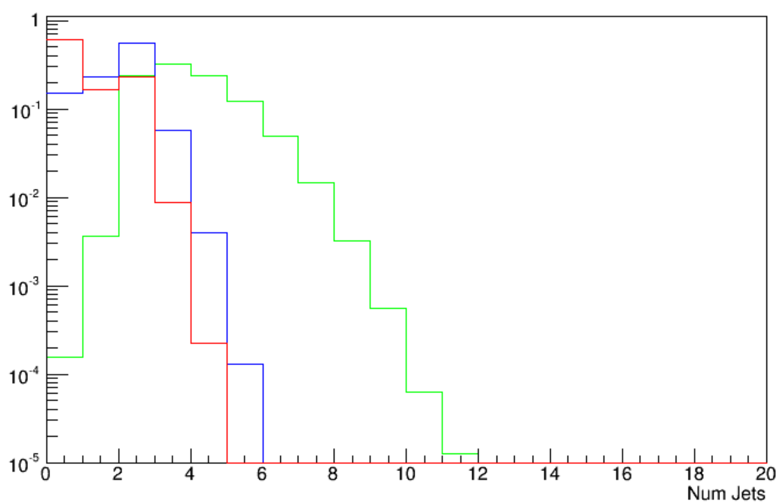
Jet Multiplicity: $Q^2 = 10 - 100\ GeV^2$

Jets: Resolved Processes

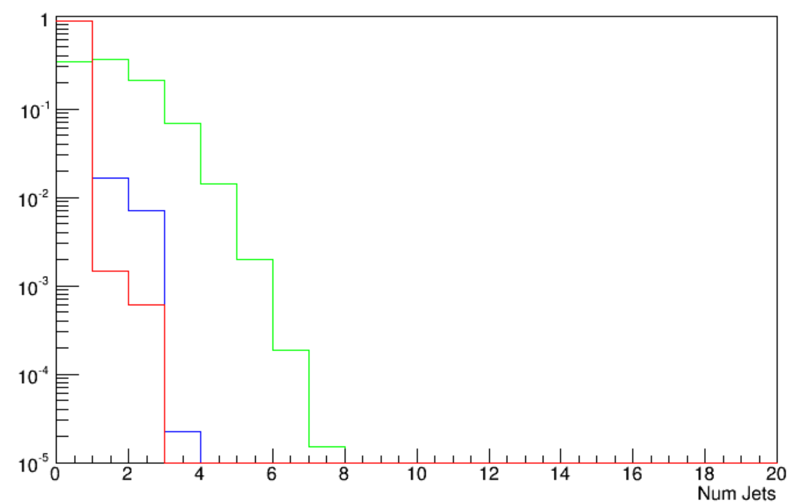


- Percentage of events with a certain number of found jets for different minimum allowed jet p_Ts
- See a decrease in number of jets with increasing minimum jet p_T
- Jet p_T of 1 GeV may not be well described theoretically
- Each curve normalized to unity

Jets: PGF / QCDC

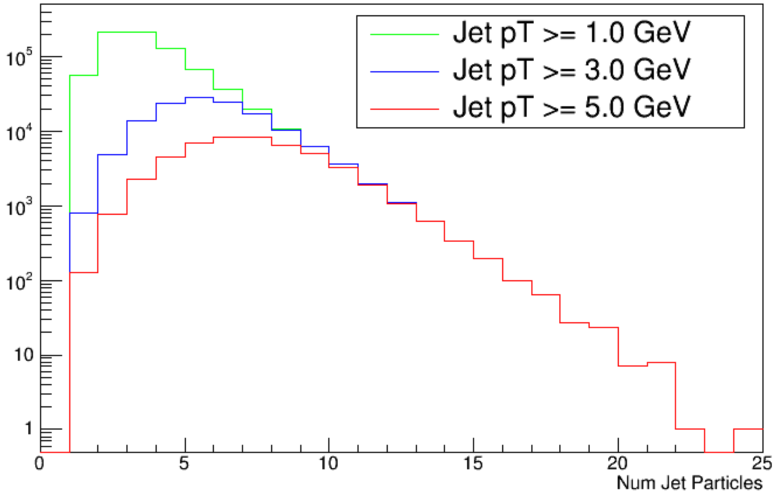


Jets: L.O. DIS



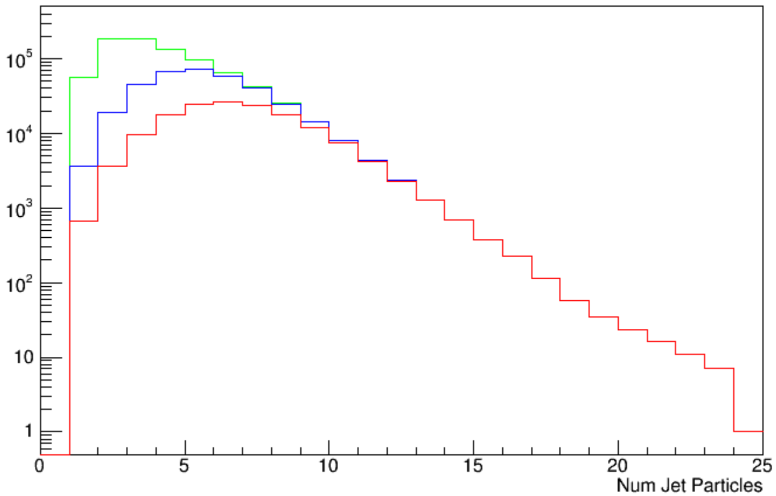
Jet Particle Mult: Q^2 = 10 – 100 GeV^2

Jet Particles: Resolved Processes

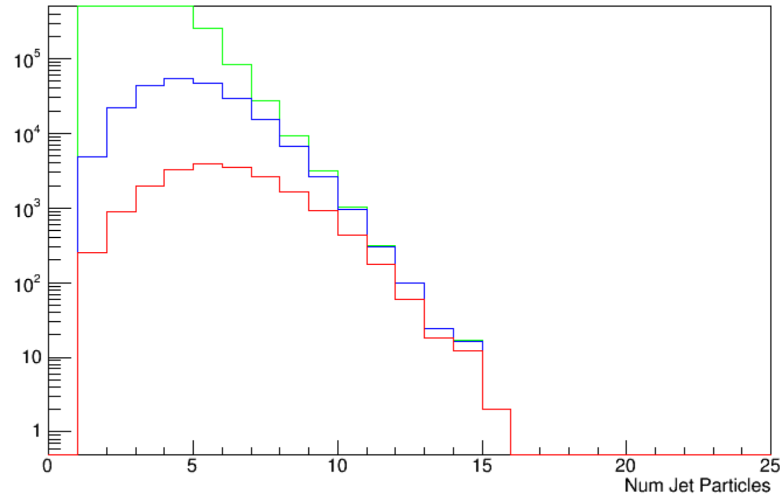


- Number of particles in a jet for 3 minimum jet p_T values
- Increase in minimum jet p_T leads to increase in average number of particles in jet
- Higher p_T jets -> more "jet like" than "single particle like"

Jet Particles: PGF / QCDC

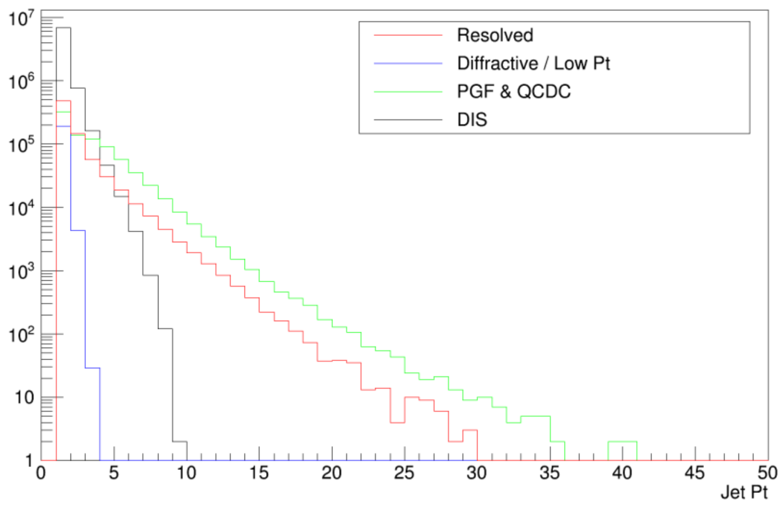


Jet Particles: L.O. DIS



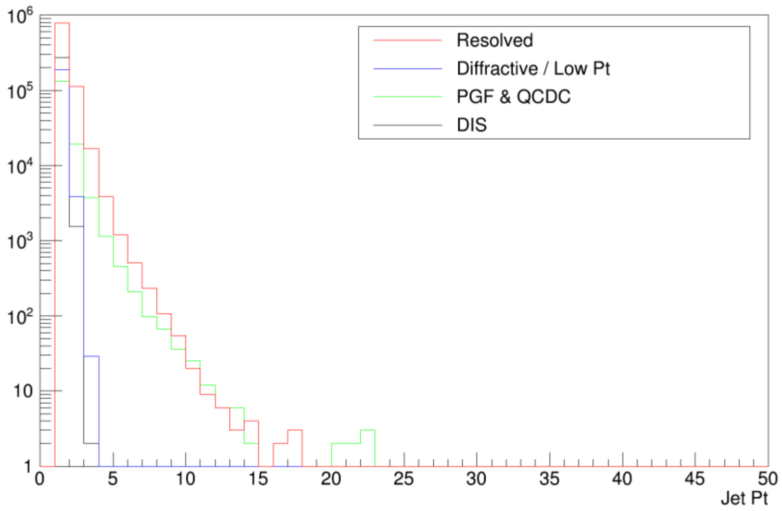
Jet p_T: Process and Q^2 Dependence

Inclusive Jet p_T: Q^2 = 10-100 GeV^2



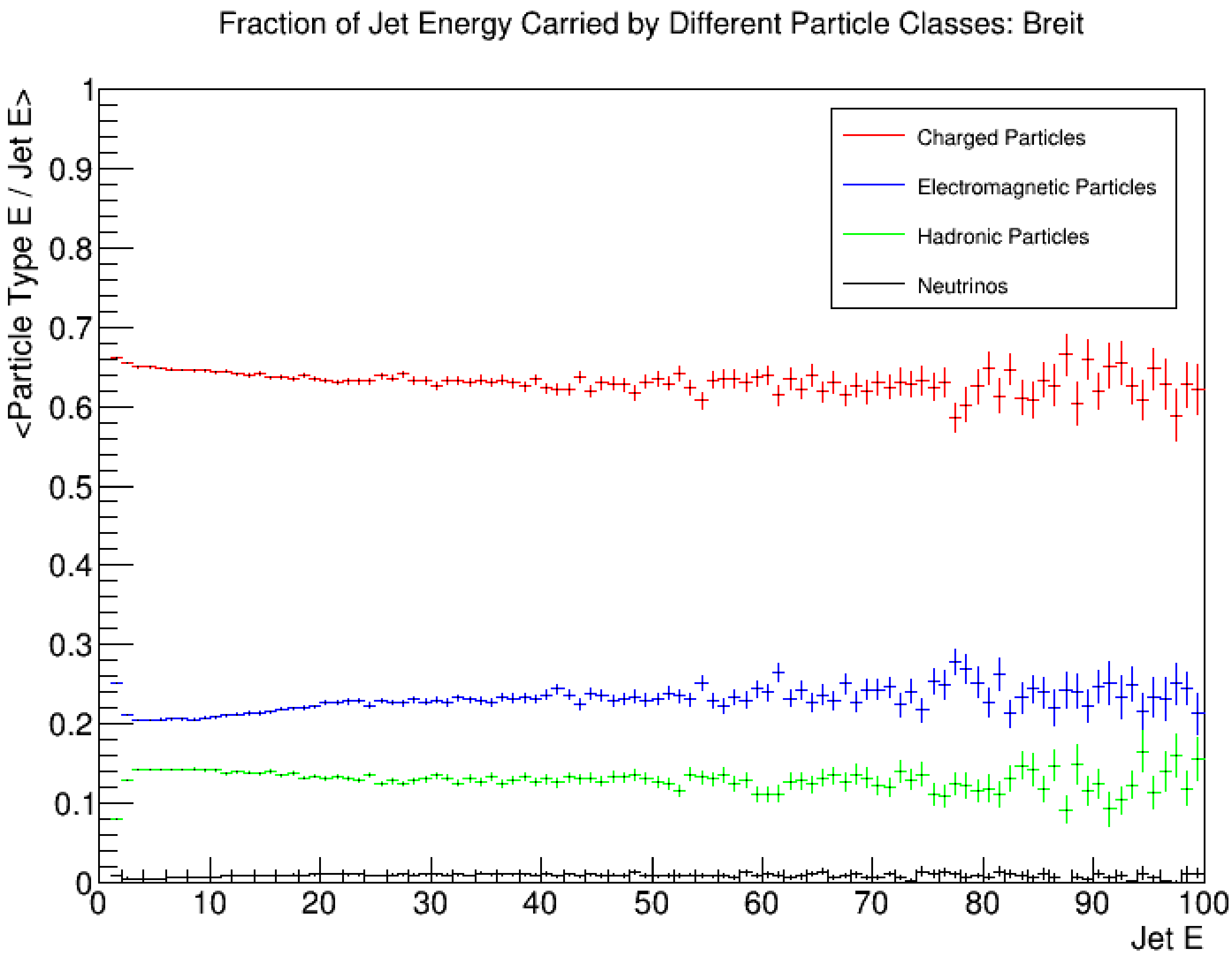
- Jet p_T spectra for different sub-processes and Q^2 ranges
- Jets found in Breit frame

Inclusive Jet p_T: Q^2 = 10^{-5}-10^{-4} GeV^2

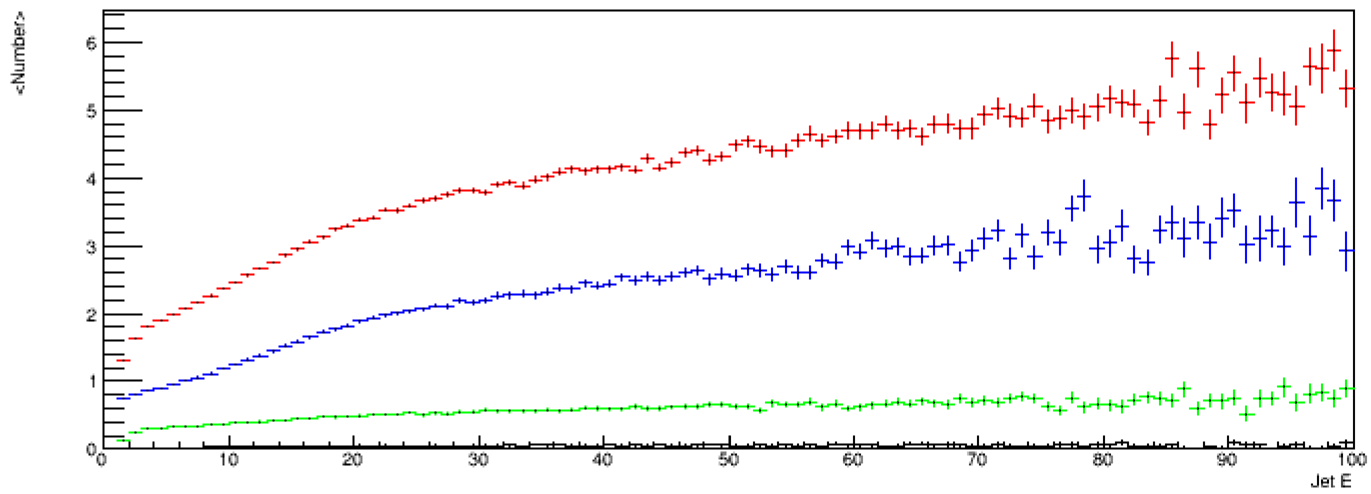


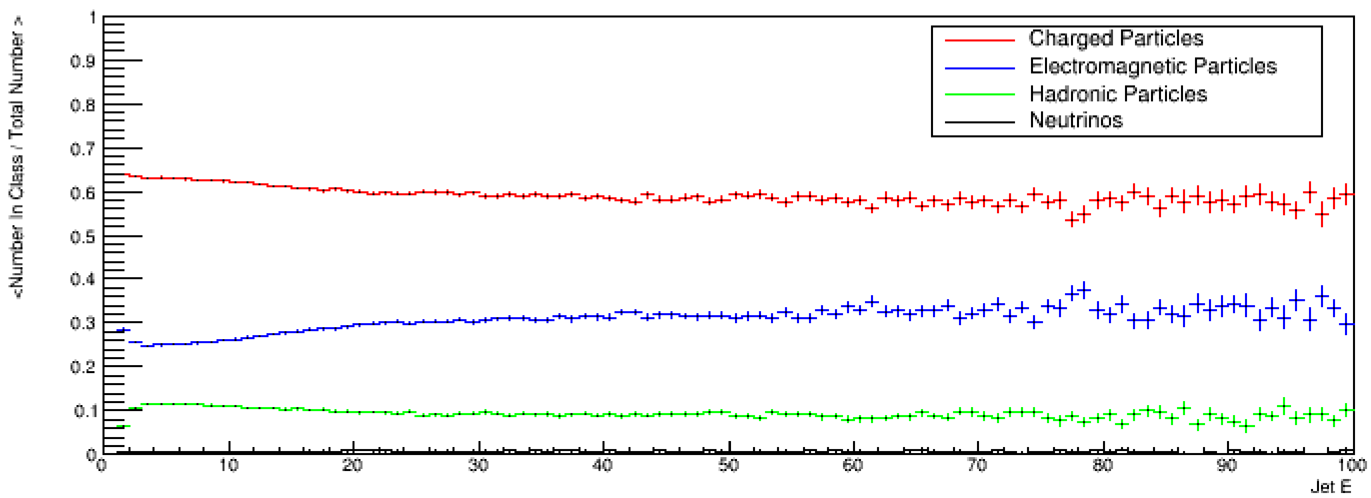
- Larger Q^2 leads to larger jet p_T for all sub-processes
- Corresponds to behavior seen in particle multiplicities

Particle Energy Fractions: Breit Frame

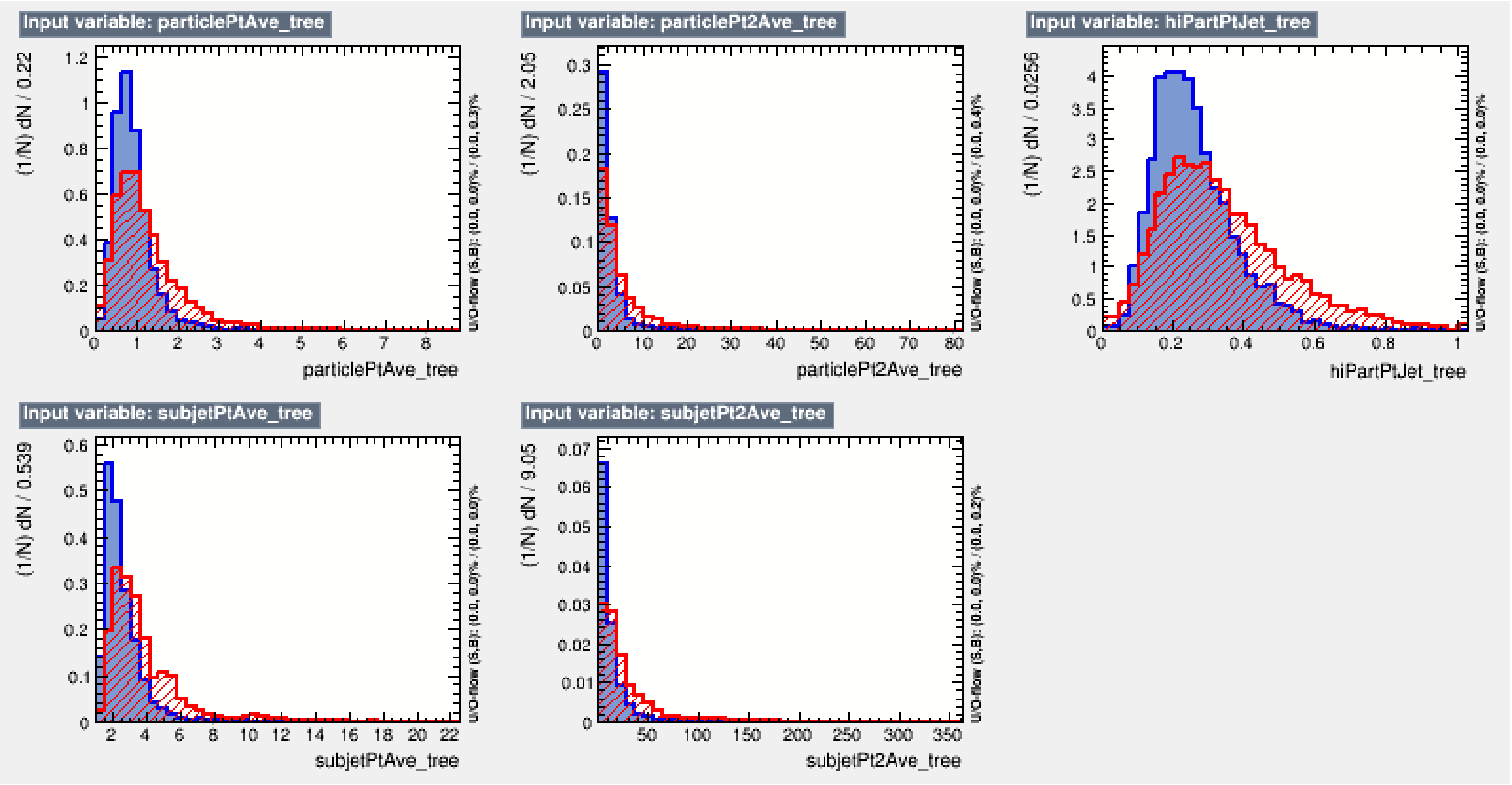


Particle Number Vs E: Breit Frame





Remaining Input Variables



Jet p_T Spectra