Jets and Jet Substructure at an EIC

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Jet Substructure: Angularity

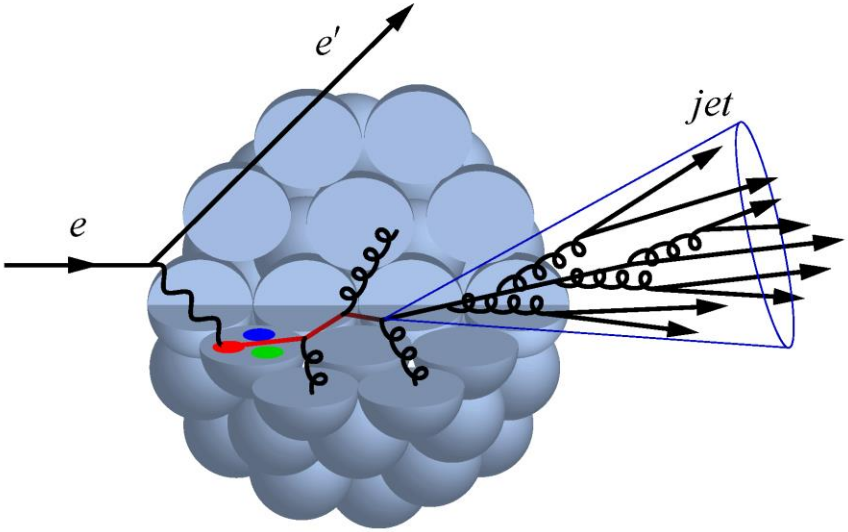
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

- Jet substructure observables track how energy is distributed within the jet – this talk will focus on Angularity

- Substructure studies may be useful at an EIC for better understanding the hadronization process and for characterizing the properties of cold nuclear matter – look at modification of energy distribution between ep and eA

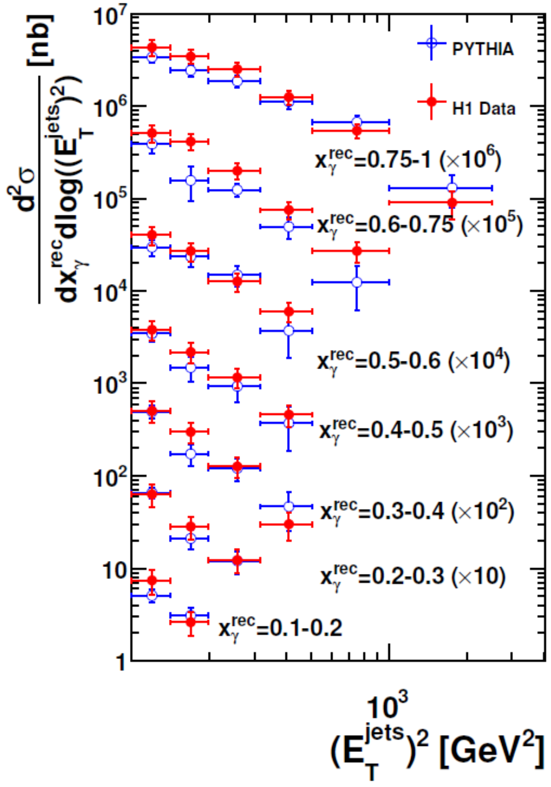
- Also pure theoretical interest in better understanding the factorization needed to describe the radiation patterns within the jet

- This work: characterize the behavior of jets and angularity observables at EIC energies



Simulation Details / Particle Cuts

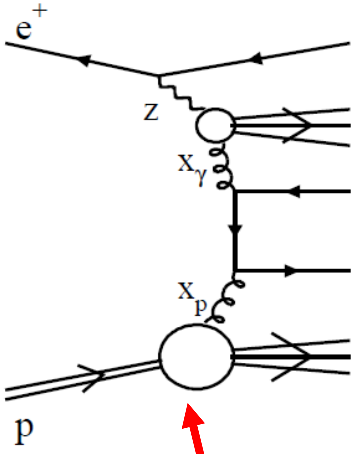
- Electron – Proton events generated at √s = 141 GeV using PYTHIA (Full energy eRHIC design 20x250 GeV electron x proton)
- Cut on inelasticity: $0.2 \leq y \leq 0.8$
- Jet Algorithm: Anti_k_T (R = 0.8, 0.4)
- Jets found in Lab frame
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ (or 500) MeV
  - $\eta \leq 4.0$
  - Parent cannot originate from scattered electron



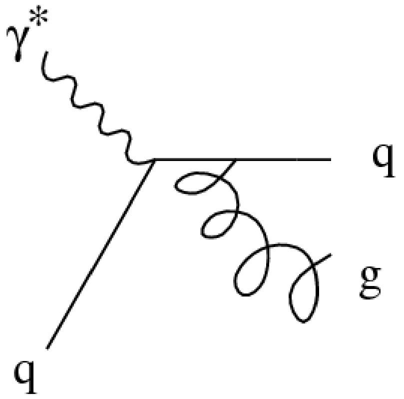
PRD 96, 074035 (2017)

Relevant Subprocesses

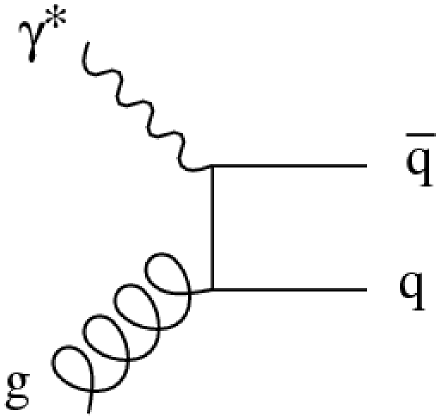
Resolved



QCD-Compton (QCDC)



Photon-Gluon Fusion (PGF)

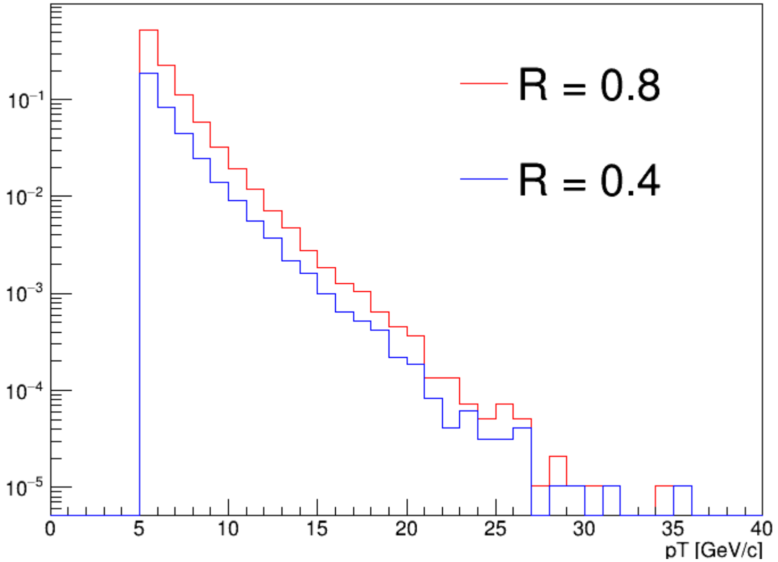


Resolved

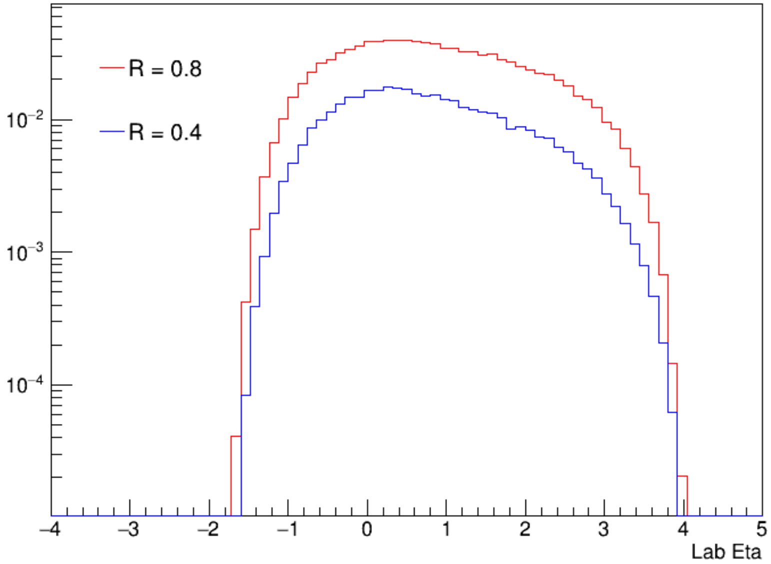
Direct

Jet Properties

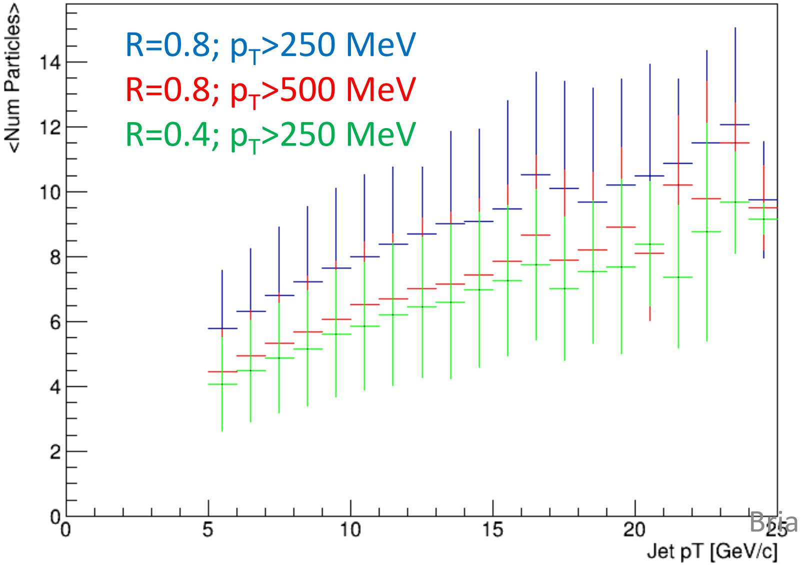
Jet Transverse Momentum



Jet Pseudorapidity (Lab Frame)

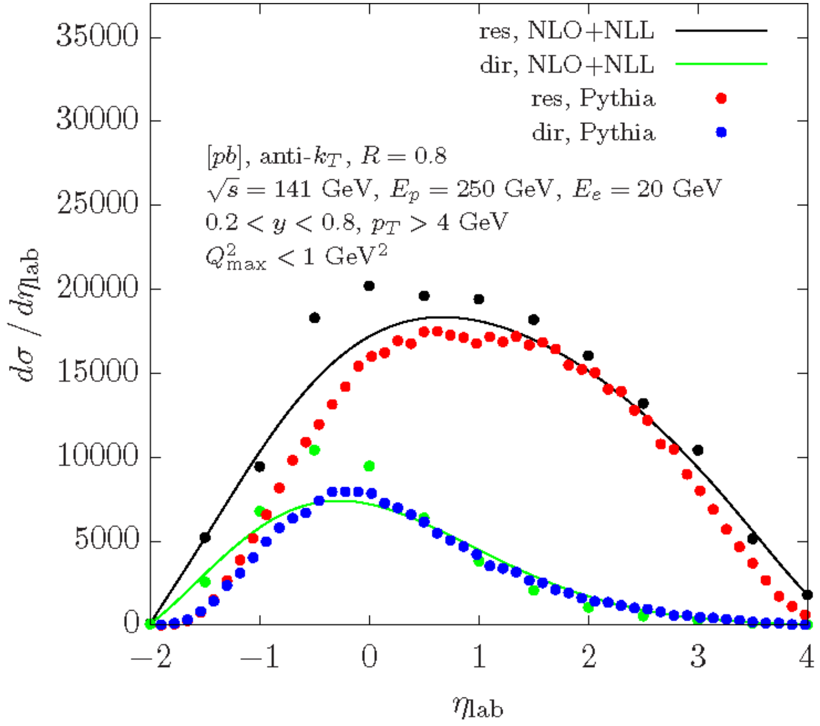


<# Particles> Vs Jet p_T

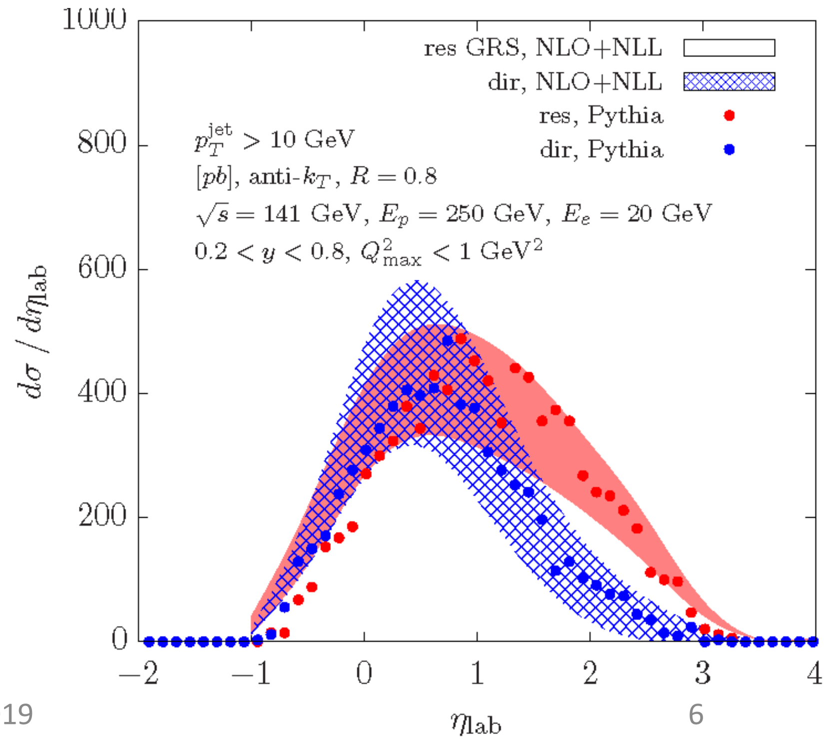


- In photoproduction region jet yield is dominated by resolved processes and spectrum is soft – 95% of jets have $p_T < 10$ GeV
- Jet yield peaks at mid-rapidity but still substantial number of counts forward
- Jets contain few total particles on average and increasing min particle p_T to 500 MeV reduces particle content of R=0.8 jets to roughly that of R=0.4 jets

Photoproduction Cross Section



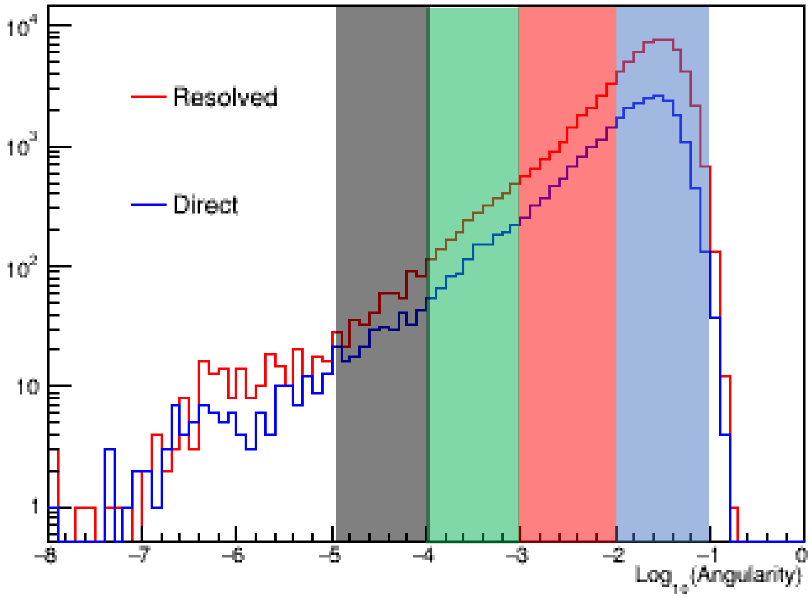
- Carry out angularity studies in photoproduction region ($10^{-5} < Q^2 < 1$)
- Resolved and direct cross sections from PYTHIA in good agreement with theoretical expectations (F. Ringer, K. Lee)



- 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

Angularity Overview

Angularity: R = 0.8; a = -2.0

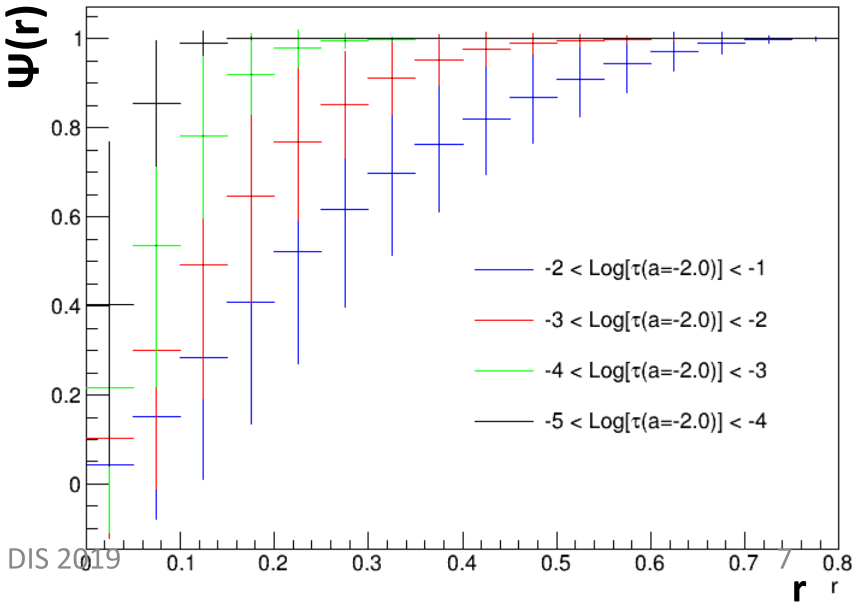


- Log of the angularity spectrum with ‘a’ = -2.0 is shown above for resolved and direct jets with R = 0.8
- The jet profiles of the jets in the 4 colored regions are shown to the right
- Jet Profile is the fraction of p_T contained in a radius ‘r’ from the center of the jet
- For a given ‘R’ and ‘a’, jets with lower angularity are more collimated

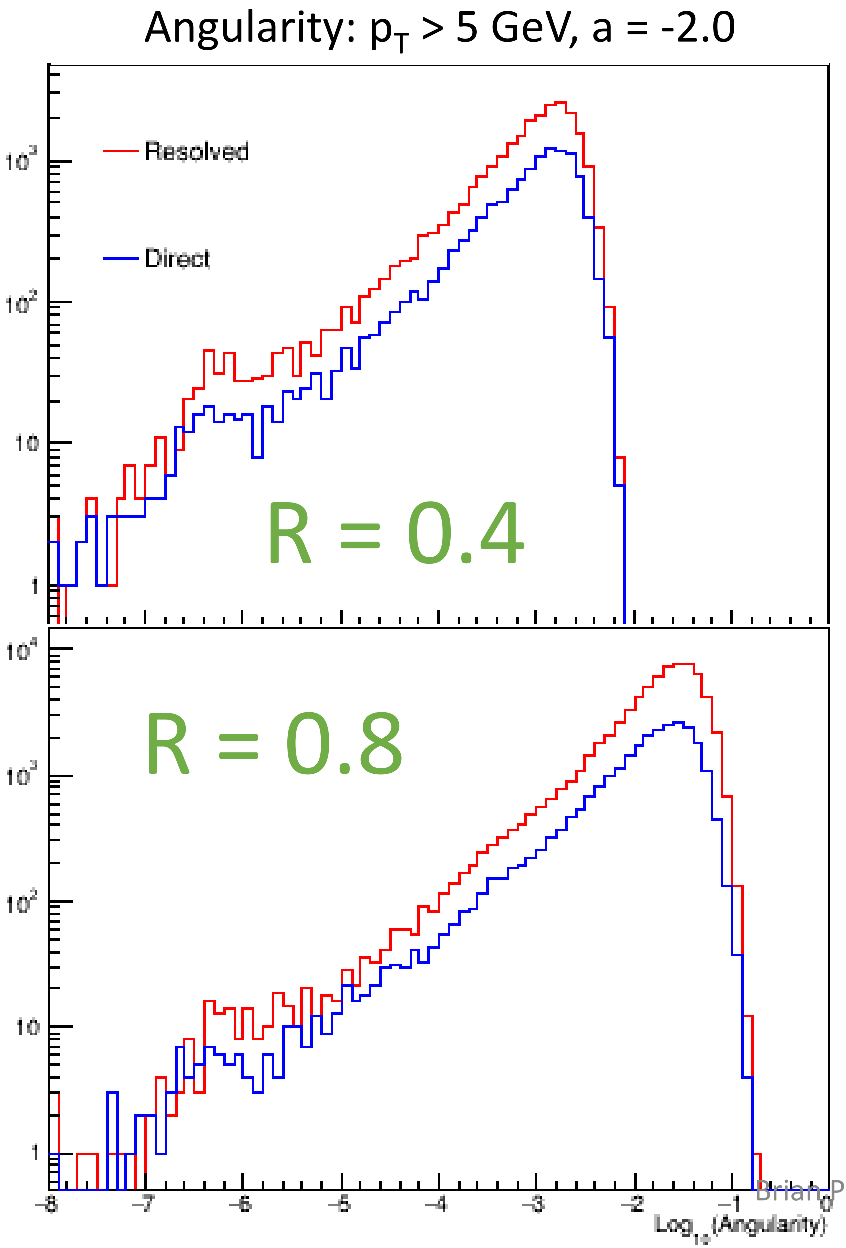
$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ} \right)^{2-a}$$

- Angularity sums over each p_T of the particles in the jet weighted by the distance of the particle from the jet thrust axis
- The ‘a’ parameter controls how heavily the distance is weighted

Jet Profile



Angularity Overview: R Dependence



$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

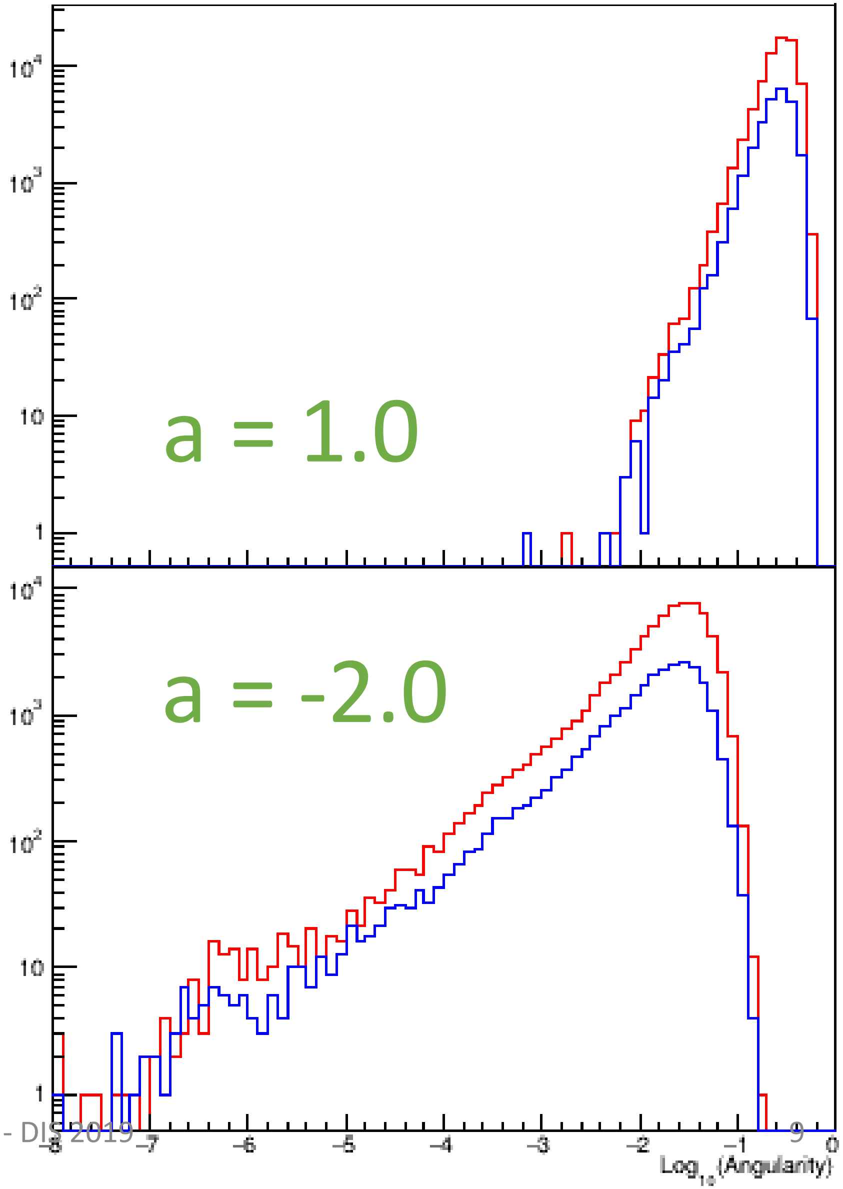
- For a given ‘a’, we see that smaller jet radii will have smaller angularity values
- Jets with larger radii will have particles with larger ΔR values which increase the value of τ

Angularity Overview: ‘a’ Dependence

$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

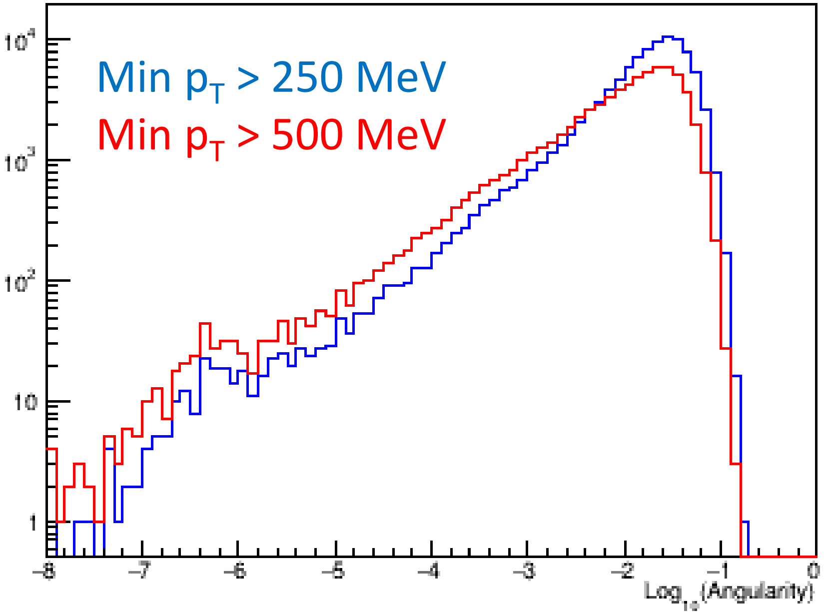
- Also, for a given jet radius, smaller ‘a’ values will push the peak of the angularity distribution lower and stretch out the spectrum

Angularity: $p_T > 5$ GeV, R = 0.8



Detector Considerations

Angularity: R = 0.8, ‘a’ = -2.0



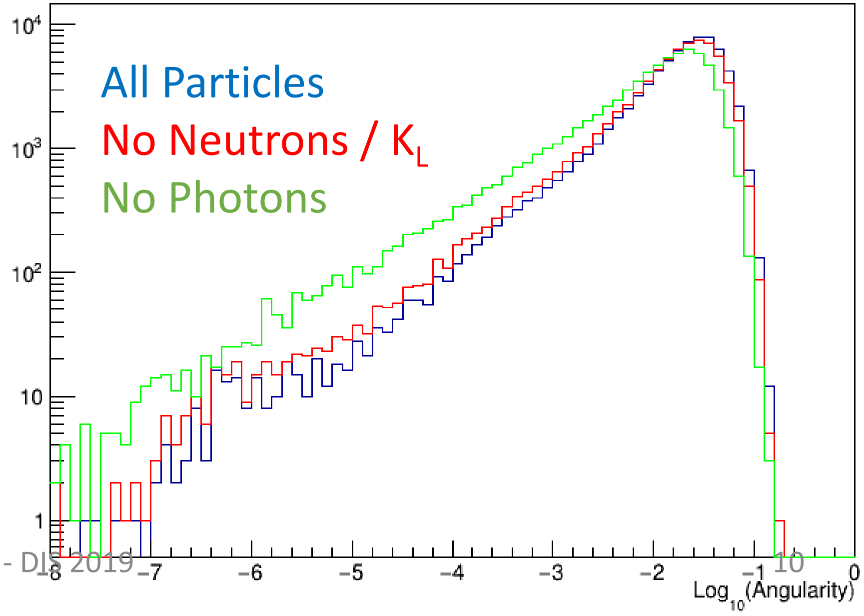
- In simulation, we can measure all particles exactly – what happens if some classes of particles are not measured or not measured well?

- Construct angularity excluding neutral hadrons (neutrons & K_L) and photons from pion decay

- There is a lower limit to the p_T of particles included in the jet clustering due to (for example) magnetic field acceptance or calorimeter noise

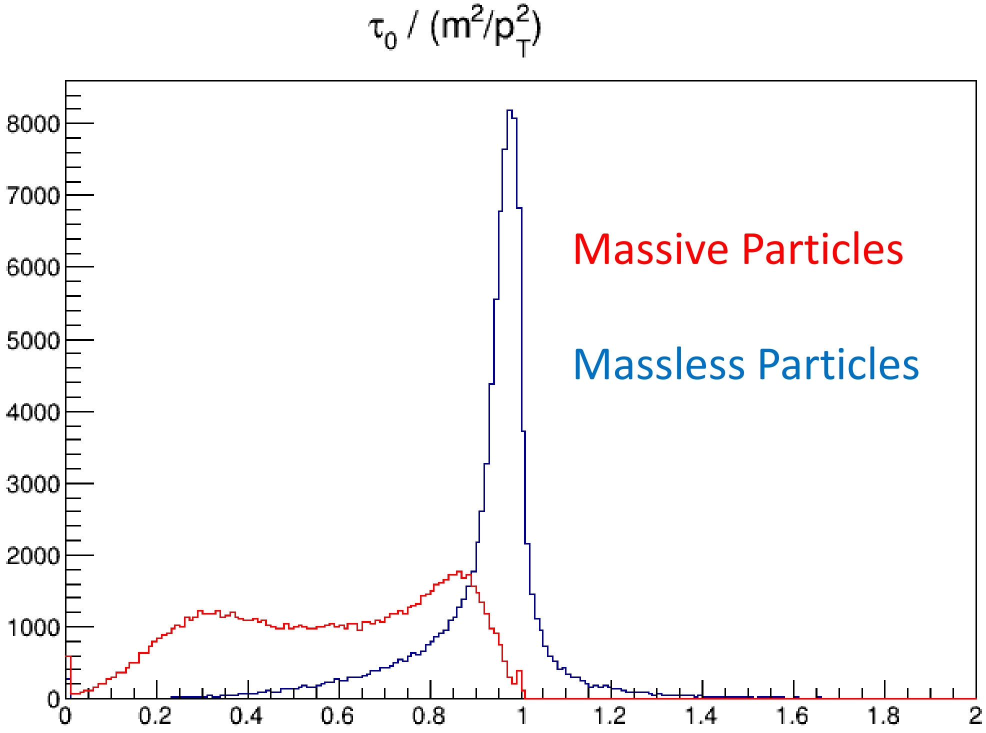
- The effect of placing a higher minimum p_T cut (500 MeV) is shown to the left – the jets become slightly more collimated

Angularity: R = 0.8, ‘a’ = -2.0



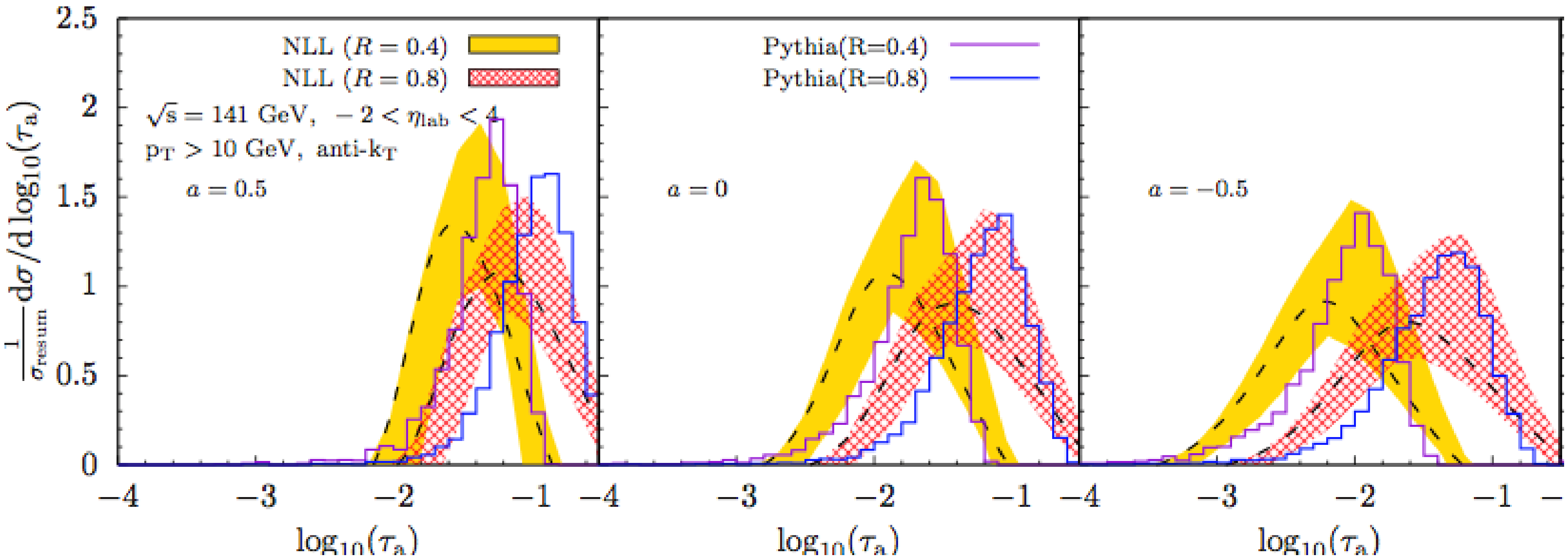
Relationship to Jet Mass

$$\tau_0 = \frac{m_J^2}{p_T^2} + \mathcal{O}(\tau_0^2)$$



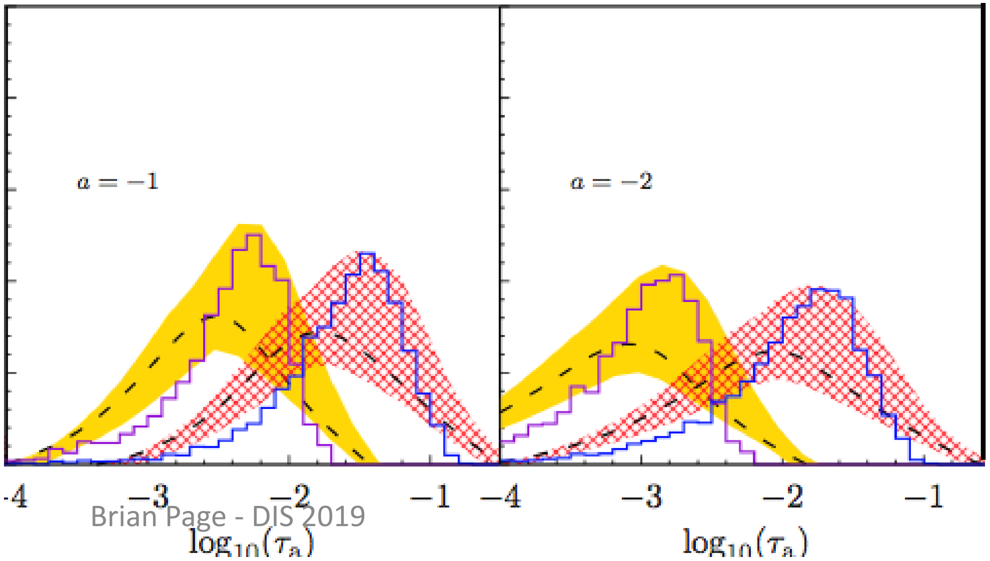
- Angularity with a = 0 is equal to the square of jet mass divided by the square of jet p_T (plus higher order terms)
- We find the validity of this relationship depends strongly on how the jet mass is constructed
- Adding full particle 4-vectors leads to discrepancy while good agreement seen for ‘massless’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

Angularity: Theory Vs PYTHIA



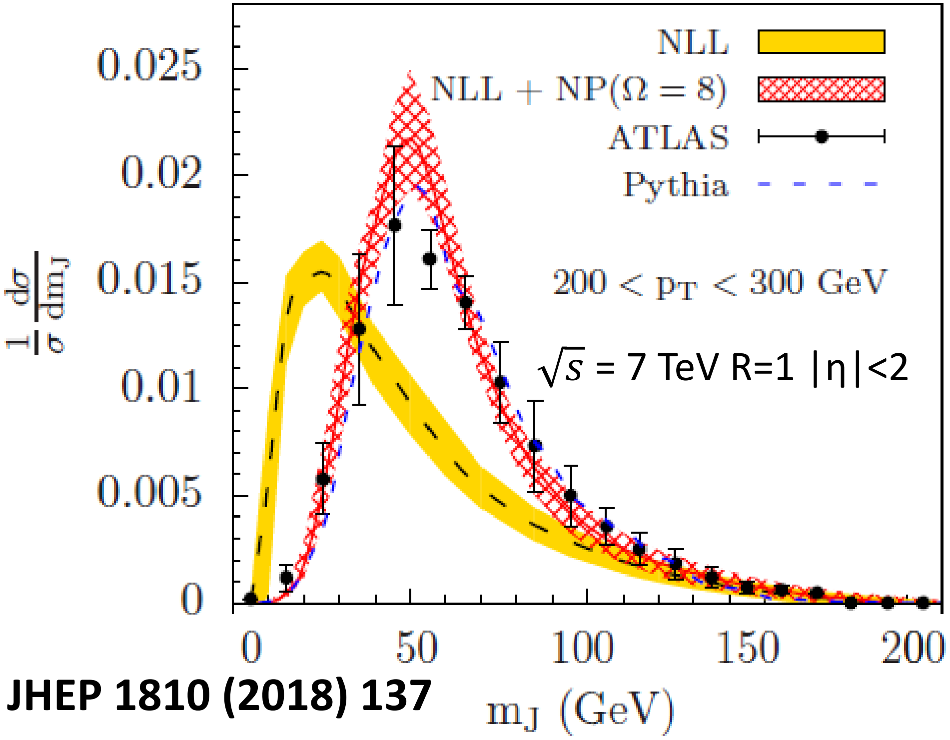
- Dotted curve represents NLO+NLL theory result using natural scale choice

- Bands represent envelope when varying scales by factors of 2



With F. Ringer & K. Lee

Non-Perturbative Effects



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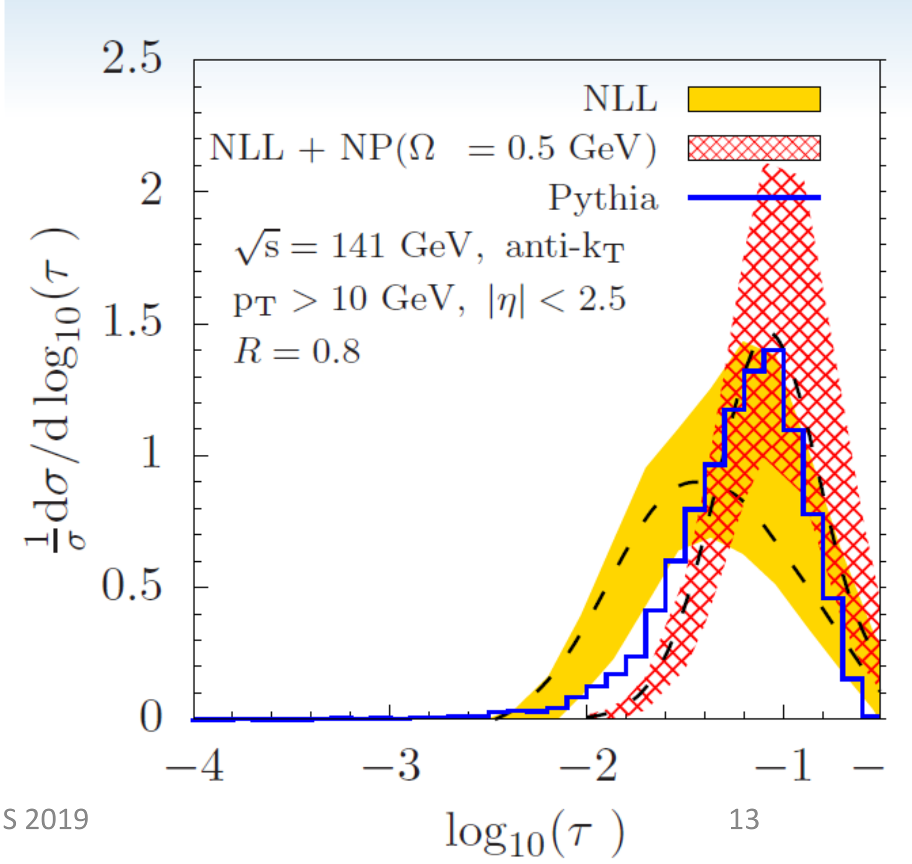
- Non-perturbative effects are modeled using a single parameter shape function which is convoluted with the perturbative cross section

$$F_\kappa(k) = \frac{4k}{\Omega_\kappa^2} exp\left(-\frac{2k}{\Omega_\kappa}\right)$$



- Non-perturbative effects (MPI and pileup) are large at the LHC but the correction shifts the perturbative results to match the data

- At the EIC, the perturbative results already agree quite well and only a small correction factor is needed to make the agreement better

With F. Ringer & K. Lee

Power Corrections

$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

$$\tau_a^{e^+e^-} = \frac{1}{2E_J} \sum_{i \in J} \left|p_T^{iJ}\right| exp\left(-|\eta_{iJ}|(1-a)\right)$$

$$\tau_a = \left(\frac{2E_J}{p_T}\right)^{2-a} \tau_a^{e^+e^-} + \mathcal{O}(\tau_a^2)$$

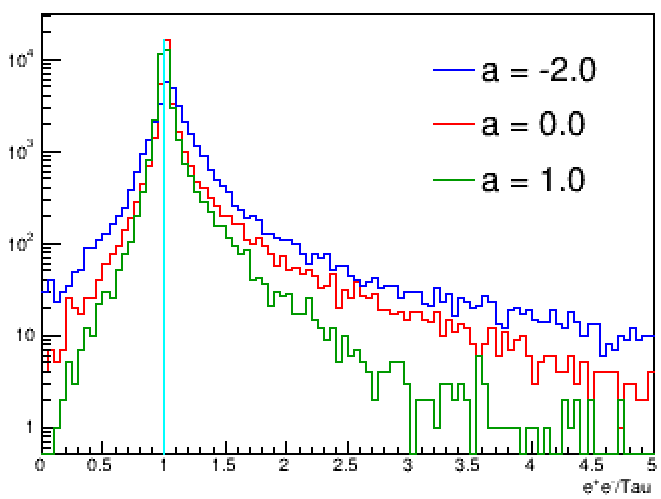
- In addition to the definition given before, can define angularity in terms of particle p_T and eta with respect to the jet thrust axis – call this τ^e+e-
- The original angularity is equal to τ^e+e- times a prefactor plus power corrections
- Can explore the behavior of these corrections by taking a ratio of τ^e+e- to the original definition
- Significance of power corrections can be controlled by varying R, jet p_T, and 'a'

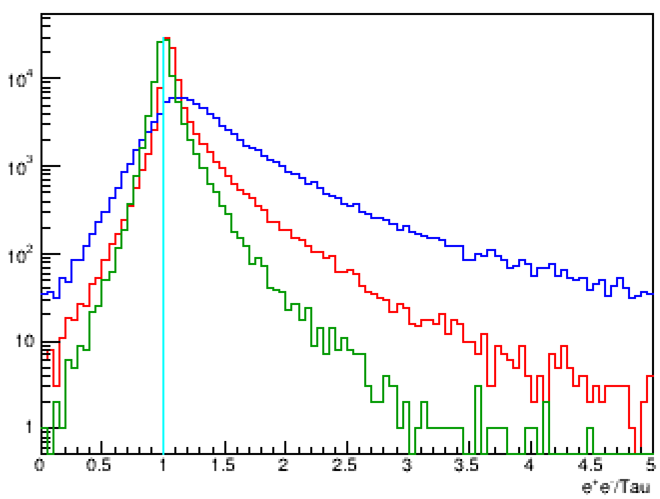
Power Corrections: Compare ‘a’

R = 0.4

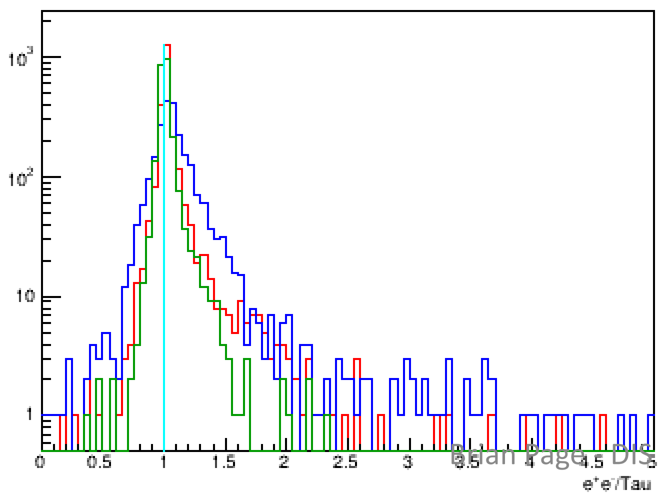
R = 0.8

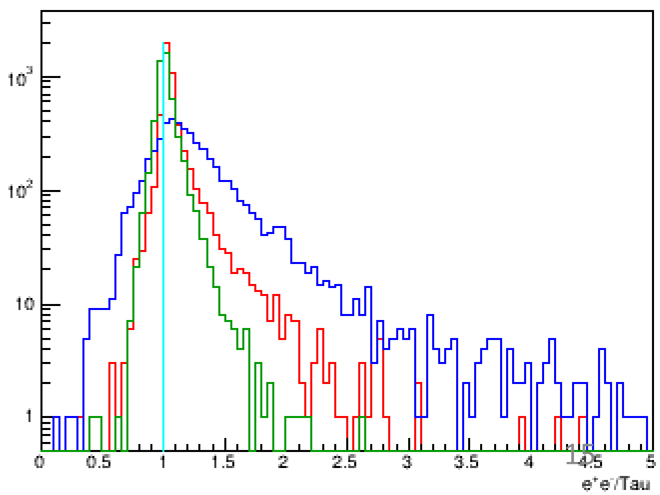
$p_T > 5.0$


Angularity e$^+$e$^-$ Over Tau (Massless Particles): R=0.4 pT>5.0


Angularity e$^+$e$^-$ Over Tau (Massless Particles): R=0.8 pT>5.0

$p_T > 10.0$


Angularity e$^+$e$^-$ Over Tau (Massless Particles): R=0.4 pT>10.0


Angularity e$^+$e$^-$ Over Tau (Massless Particles): R=0.8 pT>10.0

Power Corrections: Compare ‘a’

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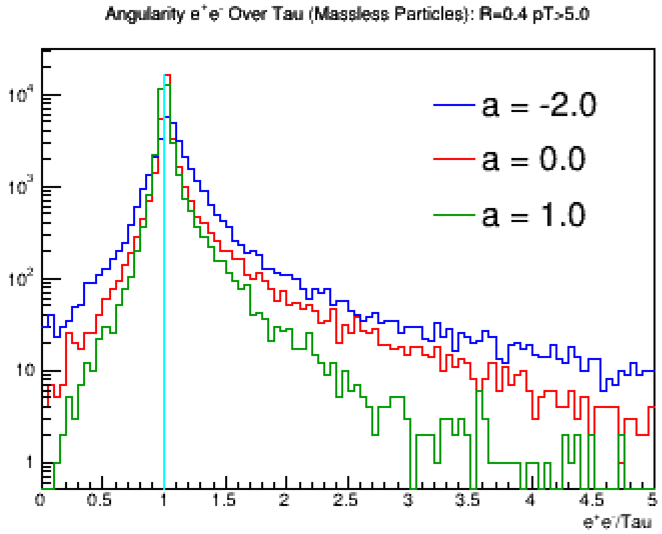
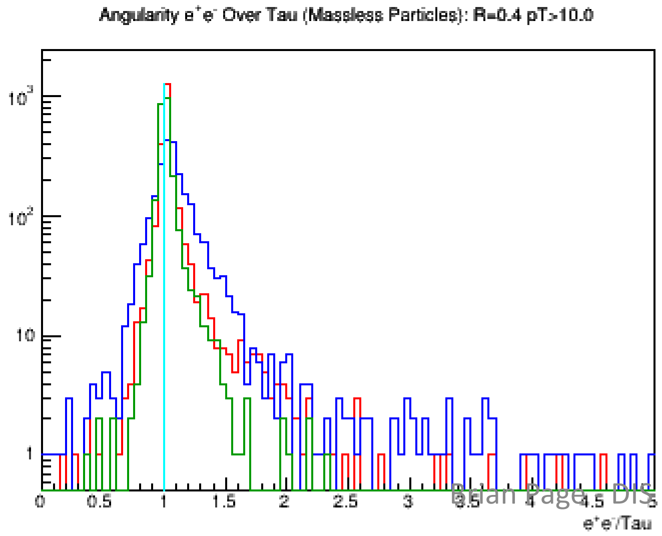


Angularity e^+e^- Over Tau (Massless Particles): R=0.4 pT>5.0

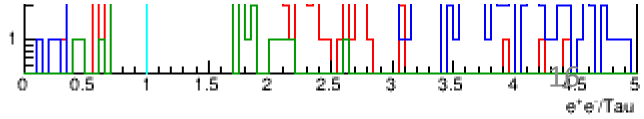
Angularity e^+e^- Over Tau (Massless Particles): R=0.8 pT>5.0

- For a given radius and transverse momentum, power corrections become more prominent as ‘a’ decreases
- Smaller ‘a’s place more weight on the angular distribution of energy
- For smallest ‘a’ and largest radii, increasing p_T reduces higher order corrections modestly
- Using a smaller radius reduces higher order terms noticeably for the smallest ‘a’ values where these terms are largest

$p_T > 10.0$



Angularity e^+e^- Over Tau (Massless Particles): R=0.4 pT>10.0



Summary

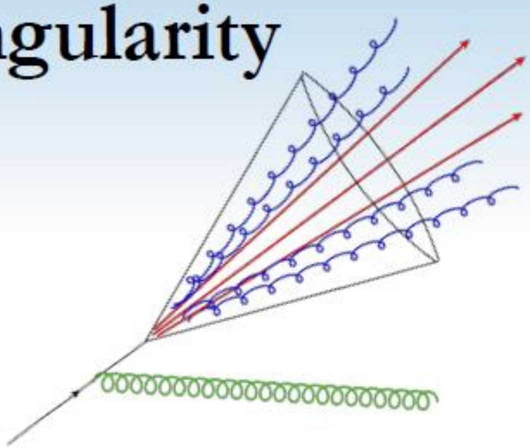
- Jet substructure measurements may be interesting at an EIC for several reasons including the characterization of cold nuclear matter and better theoretical understanding of jet physics

- The angularity substructure observable was studied with Monte Carlo in the photoproduction region for kinematics relevant to an EIC and several experimental concerns were discussed

- Angularity values from Monte Carlo were compared with NLO+NLL predictions and were found to agree well, while small perturbative corrections were seen to improve agreement

- A method for systematically studying the role of power corrections by comparing different angularity definitions was also presented

Factorization for jet angularity

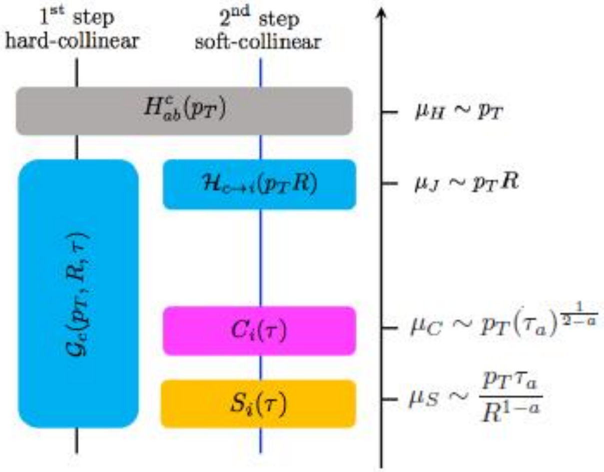


- Replace $J_c(z, p_T R, \mu) \to \mathcal{G}_c(z, p_T R, \tau_a, \mu)$
- When $\tau_a \ll R^2$, Refactorize $\mathcal{G}_c$ as

Power corrections

$$\mathcal{G}_c(z, p_T R, \tau_a, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu) \times \int d\tau_a^{C_i} d\tau_a^{S_i} \delta(\tau_a - \tau_a^{C_i} - \tau_a^{S_i}) C_i(\tau_a^{C_i}, p_T \tau_a^{\frac{1}{2-a}}, \mu) S_i(\tau_a^{S_i}, \frac{p_T \tau_a}{R^{1-a}}, \mu) \boxed{+\mathcal{O}\left(\frac{m^2}{p_T^2 R^2}\right)}$$

- Each pieces describe physics at different scales.
- Resums $(\alpha_s \ln R)^n$ and $(\alpha_s \ln^2 \frac{R}{\tau_a^{1/(2-a)}})^n$



Slide from Kyle Lee, INT 2018

Kang, KL, Ringer `18

Non-perturbative Model

- As τ gets smaller, $\mu_S \sim \frac{p_T \tau}{R}$ (smallest scale) can approach a non-perturbative scale.

  We shift our perturbative results by convolving with non-perturbative shape function to smear

$$\frac{d\sigma}{d\eta dp_T d\tau} = \int dk F_\kappa(k) \frac{d\sigma^{\text{pert}}}{d\eta dp_T d\tau}\left(\tau - \frac{R}{p_T}k\right)$$

- Single parameter NP soft function :

$$F_\kappa(k) = \left(\frac{4k}{\Omega_\kappa^2}\right)\exp\left(-\frac{2k}{\Omega_\kappa}\right)$$

Stewart, Tackmann, Waalewijn `15

- Both hadronization and MPI effects in jet mass is well-represented by just shifting first-moments.
- The parameter Ω_κ is related to shift in the distribution:

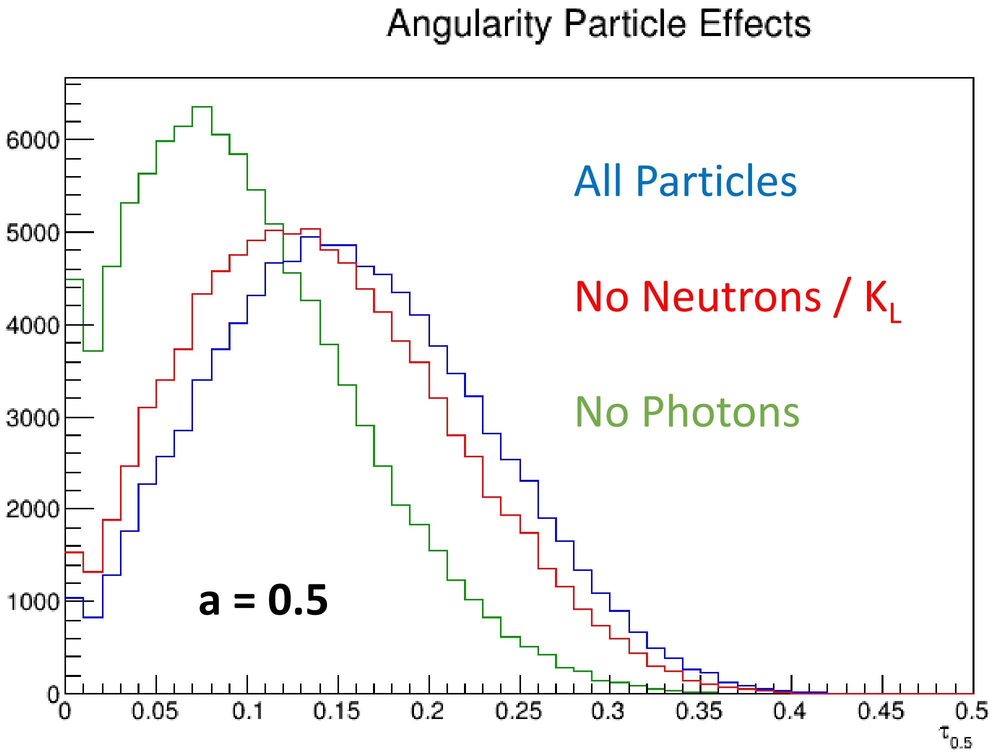
$$\tau = \tau_{\text{pert}} + \tau_{\text{NP}} = \tau_{\text{pert}} + \frac{R\Omega_\kappa}{p_T} = \tau_{\text{pert}} + \frac{R\left(\Lambda_{\text{hadro.}} + \Lambda_{\text{MPI}}\right)}{p_T}$$

$\Omega_\kappa \sim \Lambda_{had} \sim 1\,\text{GeV}$ corresponds to non-perturbative effects coming primarily from the hadronization alone.

Slide from Kyle Lee, INT 2018

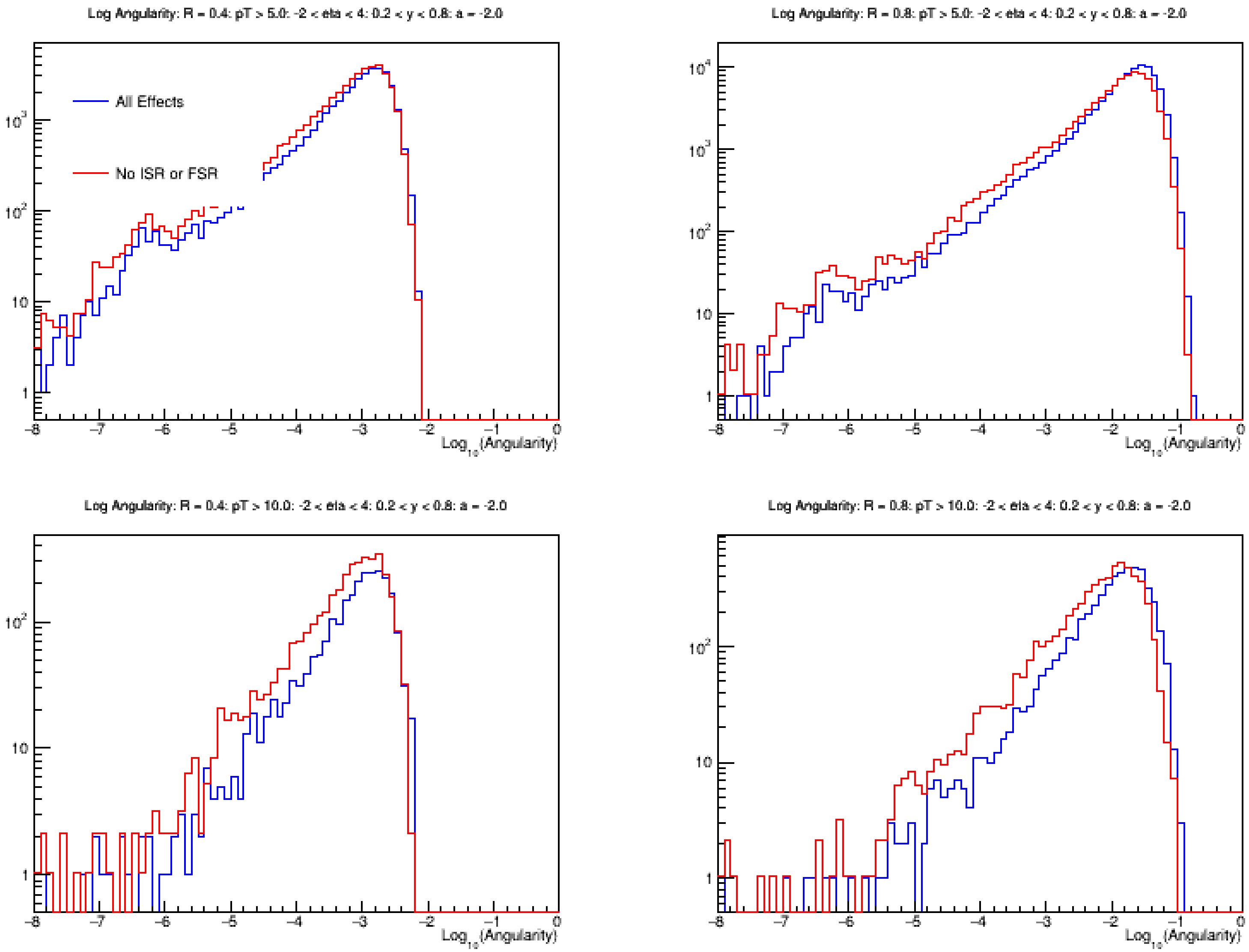
Detector Considerations

Angularity Particle Effects



- 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

ISR / FSR Contribution



Log Angularity: R = 0.4: pT > 5.0: -2 < eta < 4: 0.2 < y < 0.8: a = -2.0

Log Angularity: R = 0.8: pT > 5.0: -2 < eta < 4: 0.2 < y < 0.8: a = -2.0

Log Angularity: R = 0.4: pT > 10.0: -2 < eta < 4: 0.2 < y < 0.8: a = -2.0

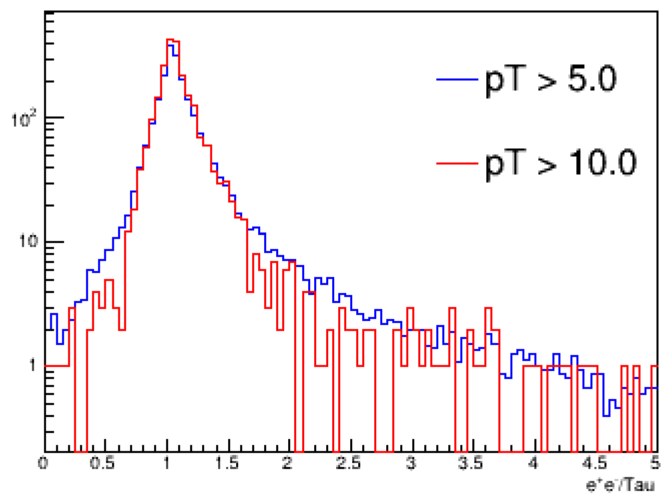
Log Angularity: R = 0.8: pT > 10.0: -2 < eta < 4: 0.2 < y < 0.8: a = -2.0

Power Corrections: Compare p_T

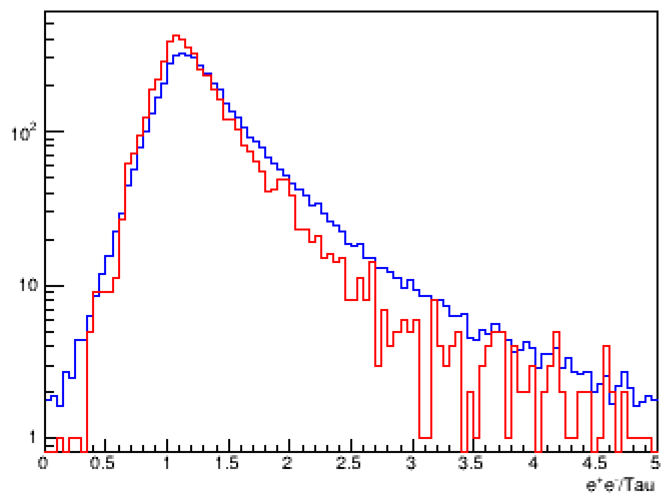
R = 0.4 **R = 0.8**

a = -2.0

e⁺e⁻/Tau pT Comparison: R=0.4, a=-2.0

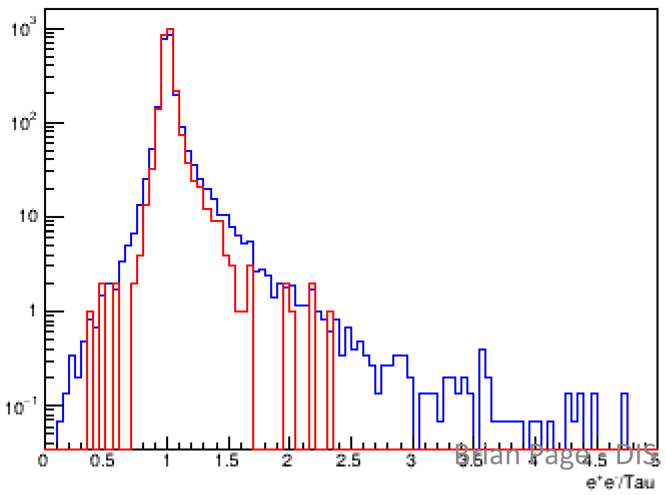


e⁺e⁻/Tau pT Comparison: R=0.8, a=-2.0

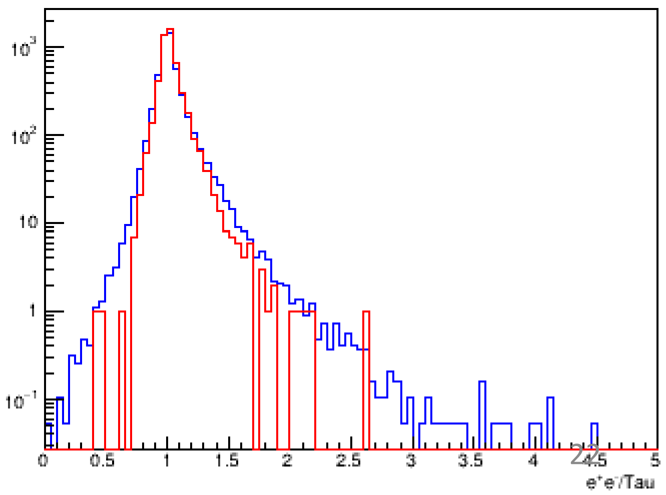


a = 1.0

e⁺e⁻/Tau pT Comparison: R=0.4, a=1.0



e⁺e⁻/Tau pT Comparison: R=0.8, a=1.0

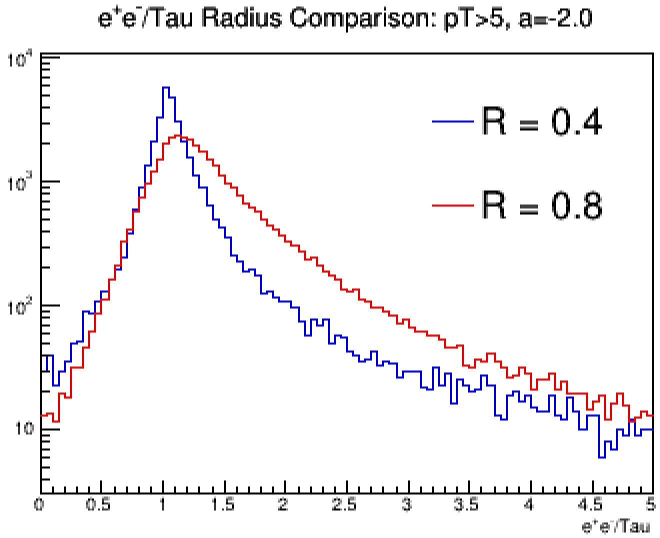


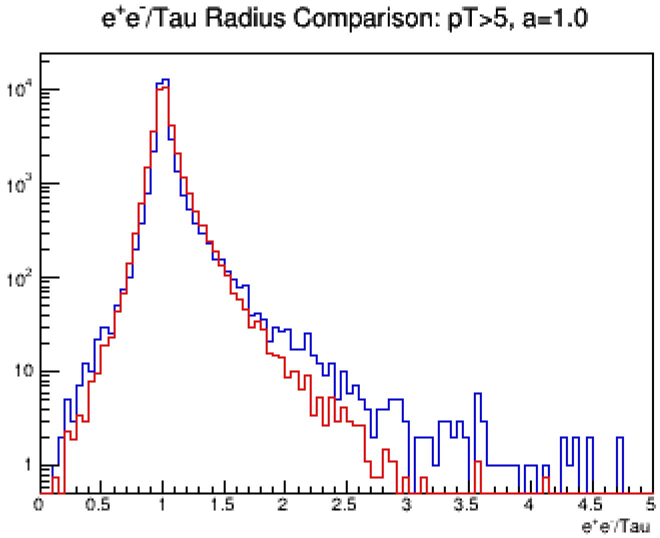
Power Corrections: Compare R

a = -2.0

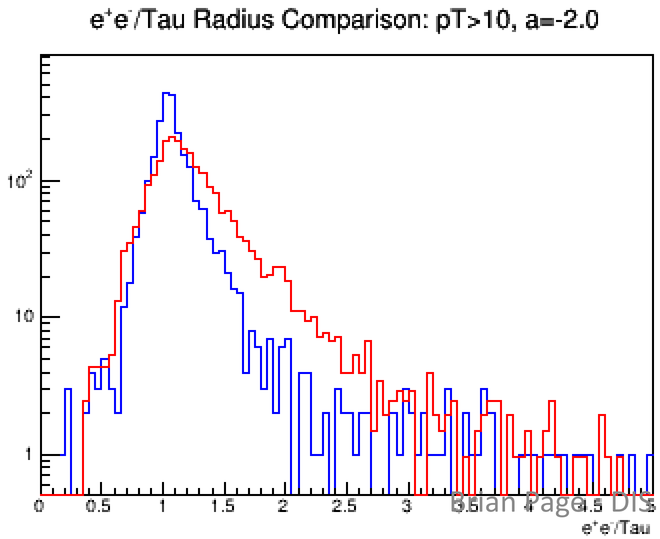
a = 1.0

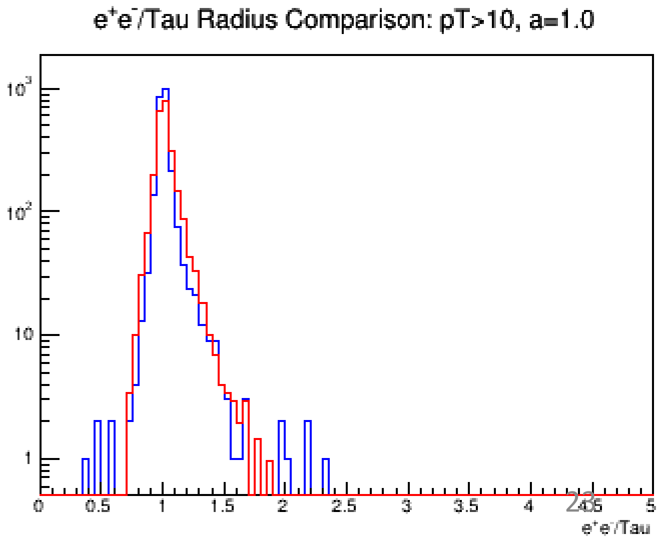
p_T > 5.0





p_T > 10.0





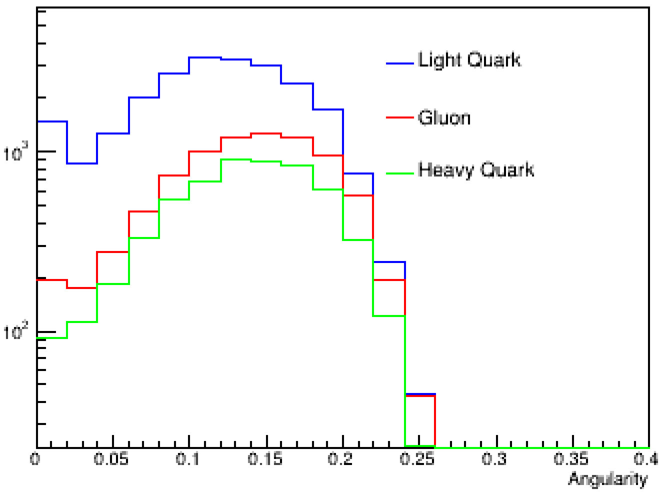
Quark Vs Gluon ‘a’ = 1.0

R = 0.4

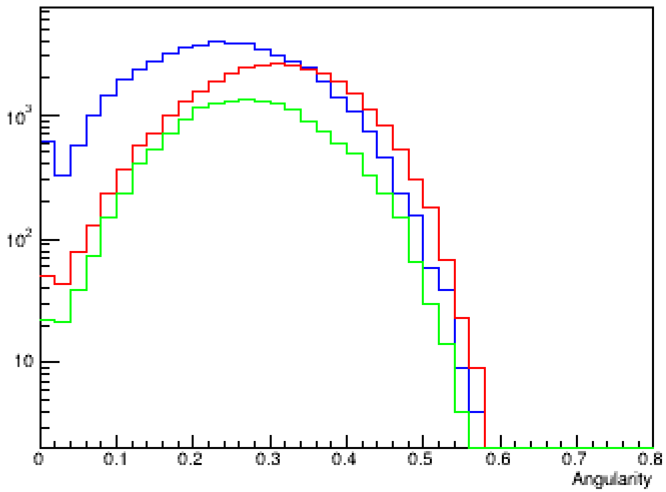
R = 0.8

$p_T > 5.0$

Angularity: R = 0.4: pT > 5.0: a = 1.0

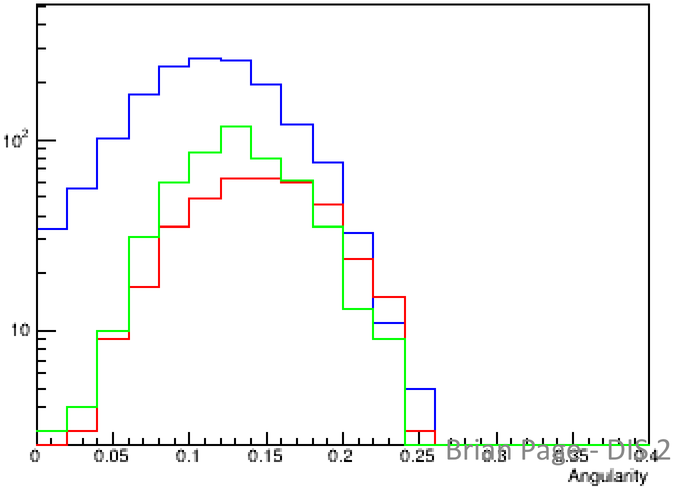


Angularity: R = 0.8: pT > 5.0: a = 1.0

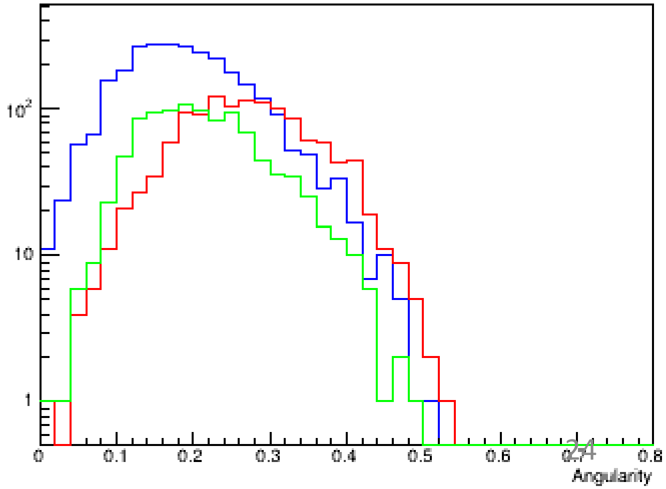


$p_T > 10.0$

Angularity: R = 0.4: pT > 10.0: a = 1.0



Angularity: R = 0.8: pT > 10.0: a = 1.0

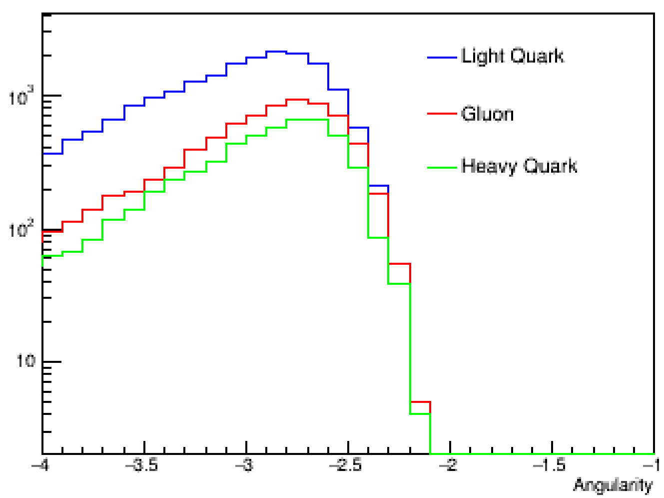


Quark Vs Gluon ‘a’ = -2.0

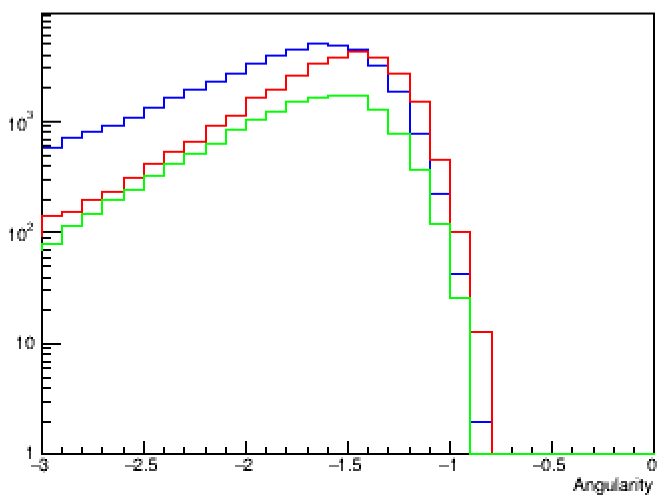
R = 0.4

R = 0.8

p_T > 5.0

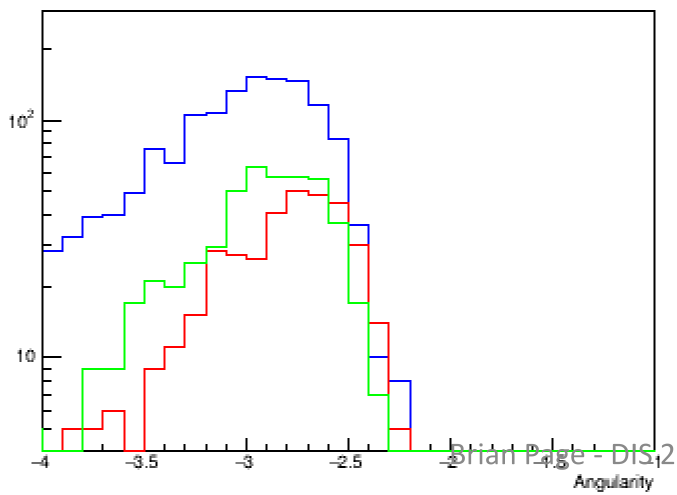


Log Angularity: R = 0.4: pT > 5.0: a = -2.0

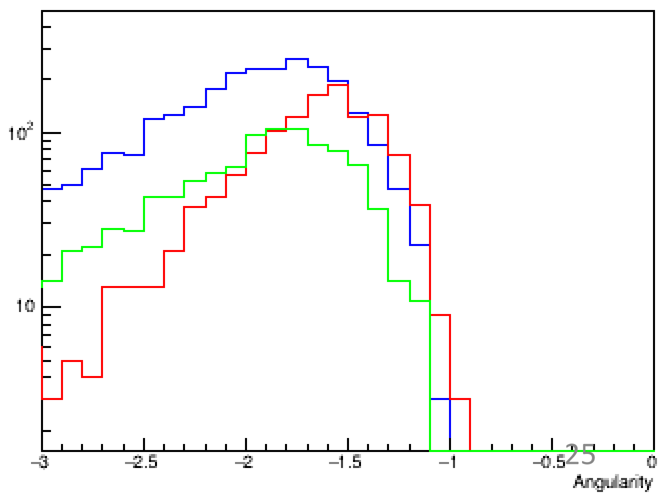


Log Angularity: R = 0.8: pT > 5.0: a = -2.0

p_T > 10.0



Log Angularity: R = 0.4: pT > 10.0: a = -2.0



Log Angularity: R = 0.8: pT > 10.0: a = -2.0

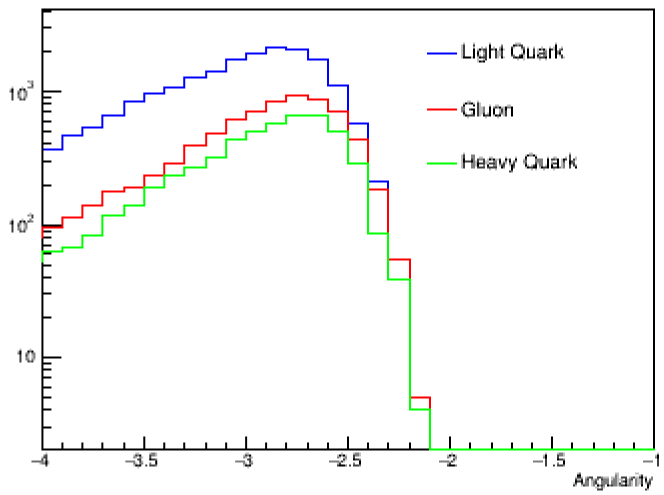
Quark Vs Gluon ‘a’ = -2.0

R = 0.4

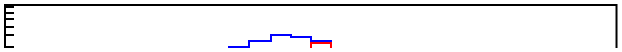
R = 0.8

p_T > 5.0

Log Angularity: R = 0.4: pT > 5.0: a = -2.0



Log Angularity: R = 0.8: pT > 5.0: a = -2.0



- See decent separation between light quark and gluon jets for R = 0.8 and full range of ‘a’ values
- Poor separation at R = 0.4 may be due to selection bias – Smaller radius will select those gluon jets which happen to have a narrower fragmentation and thus look more like quark jets
- Nevertheless, may want to use larger radii when looking at medium effects, especially as eA collisions should have less underlying event contaminating the jet

p_T > 10.0

Log Angularity: R = 0.4: pT > 10.0: a = -2.0