Jets in eA as a Probe of Hadronization and Energy Loss in the Cold Nuclear Medium

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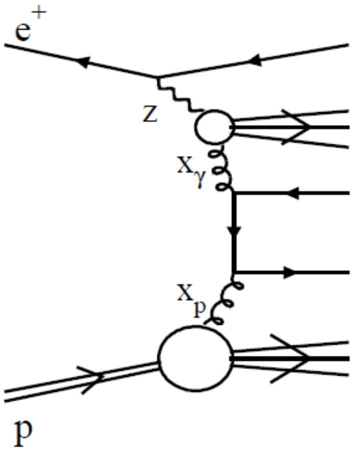
Outline

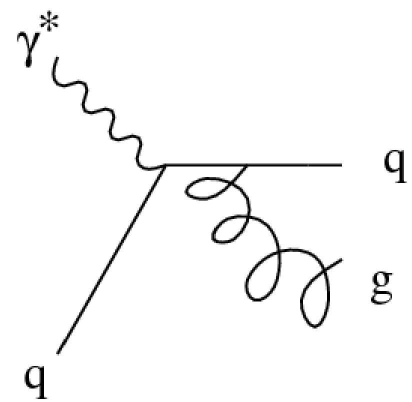
- General Jet Properties
- Underlying Event Study
- Substructure Investigation
  - Theory / Simulation Comparisons
  - Power Corrections
  - Quark / Gluon Discrimination

Relevant Subprocesses

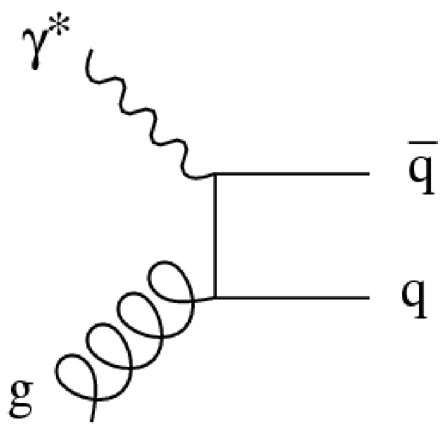
Resolved



QCD-Compton (QCDC)



Photon-Gluon Fusion (PGF)



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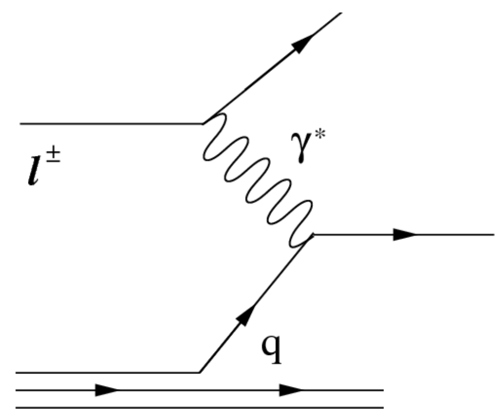
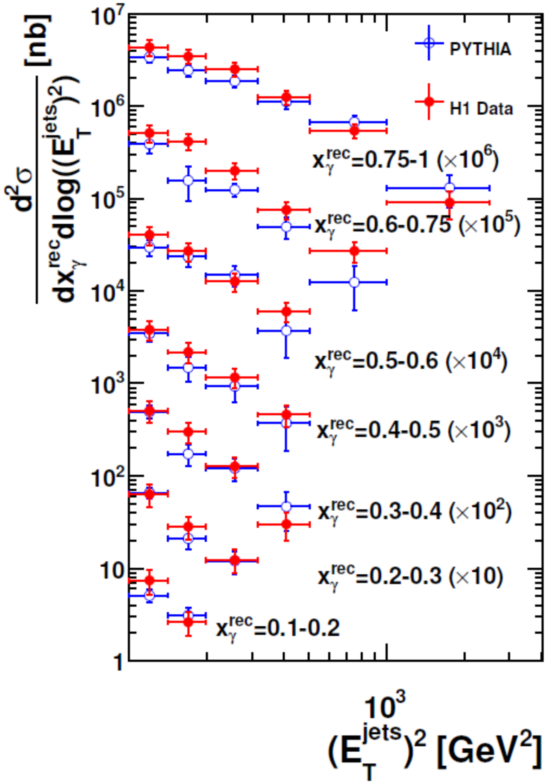


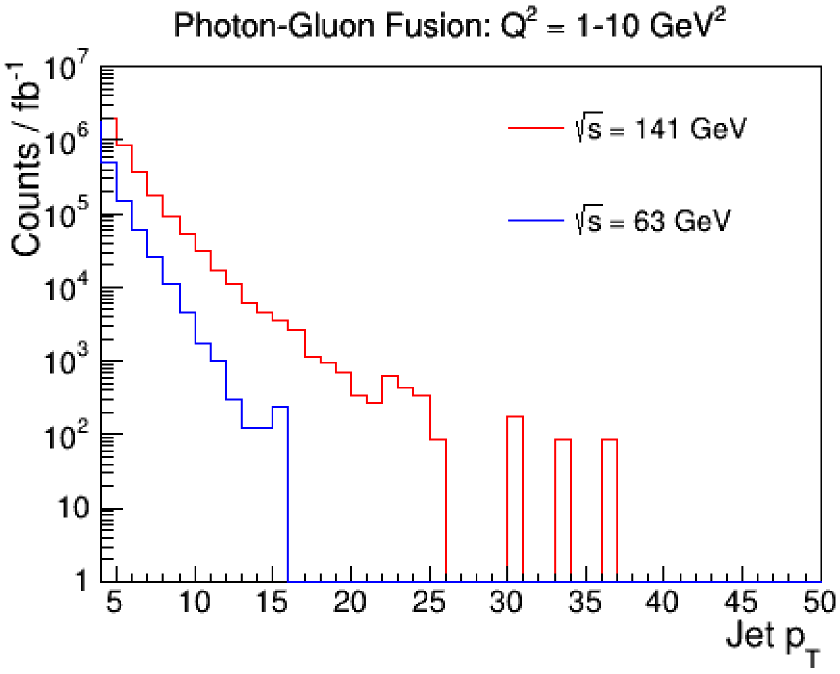
Simulation Details / Particle Cuts

- 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, 0.8, 0.4)
- Jets found in Breit or Lab frame
- Particles used in jet finding:
  - Stable
  - $p_T \geq 250$ MeV
  - $\eta \leq 4.5$
  - Parent cannot originate from scattered electron



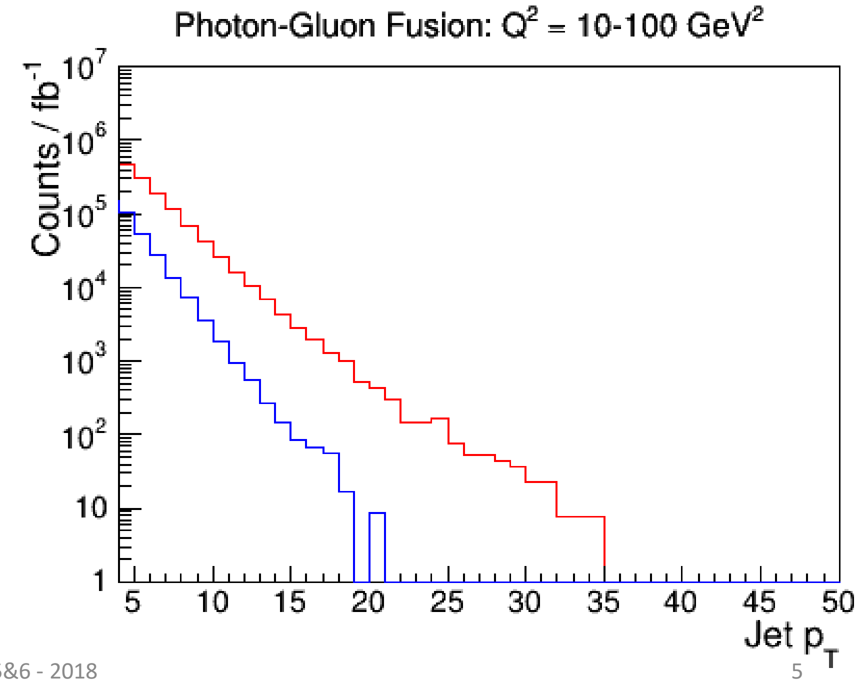
PRD 96, 074035 (2017)

Jet p_T: How Low is Too Low?

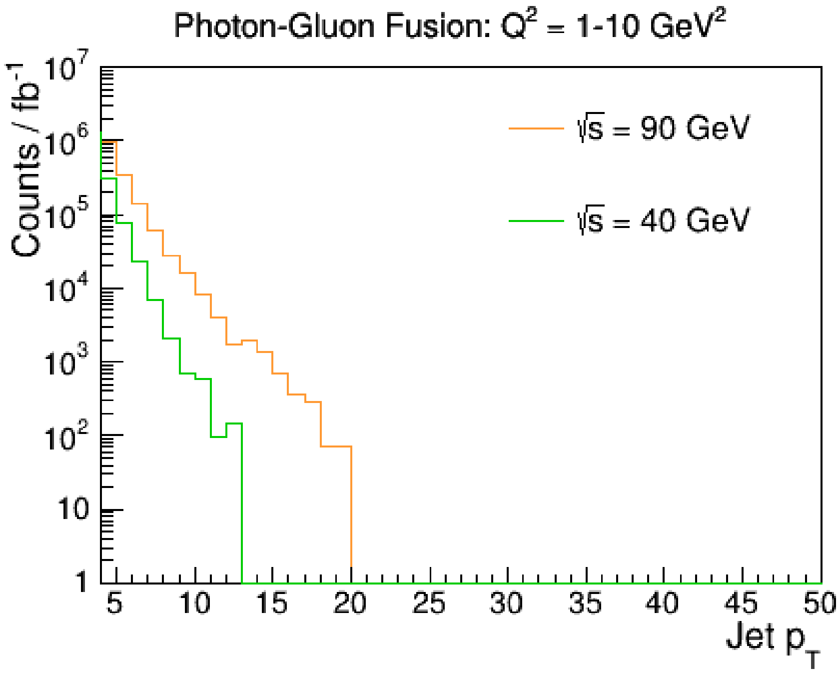


- Photon-gluon fusion jet p_T spectrum shown for two center of mass energies and two Q^2 ranges
- √s = 141 -> 20x250
- √s = 63 -> 10x100

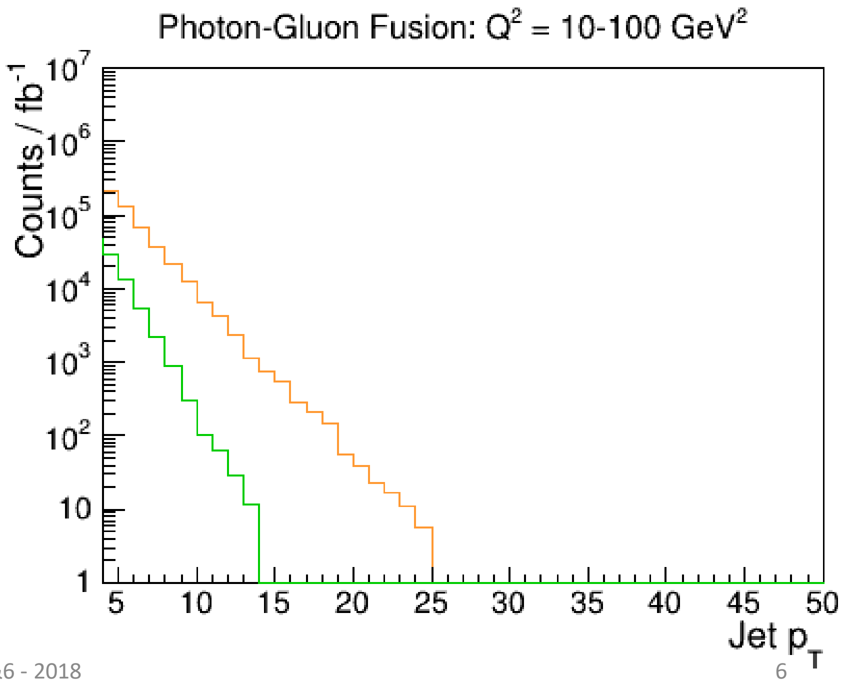
- In principle, can cluster particles and find 'jets' with very small p_T
- Where does theory break down?
- Would like to go as low as possible to get statistics



Jet p_T: How Low is Too Low?



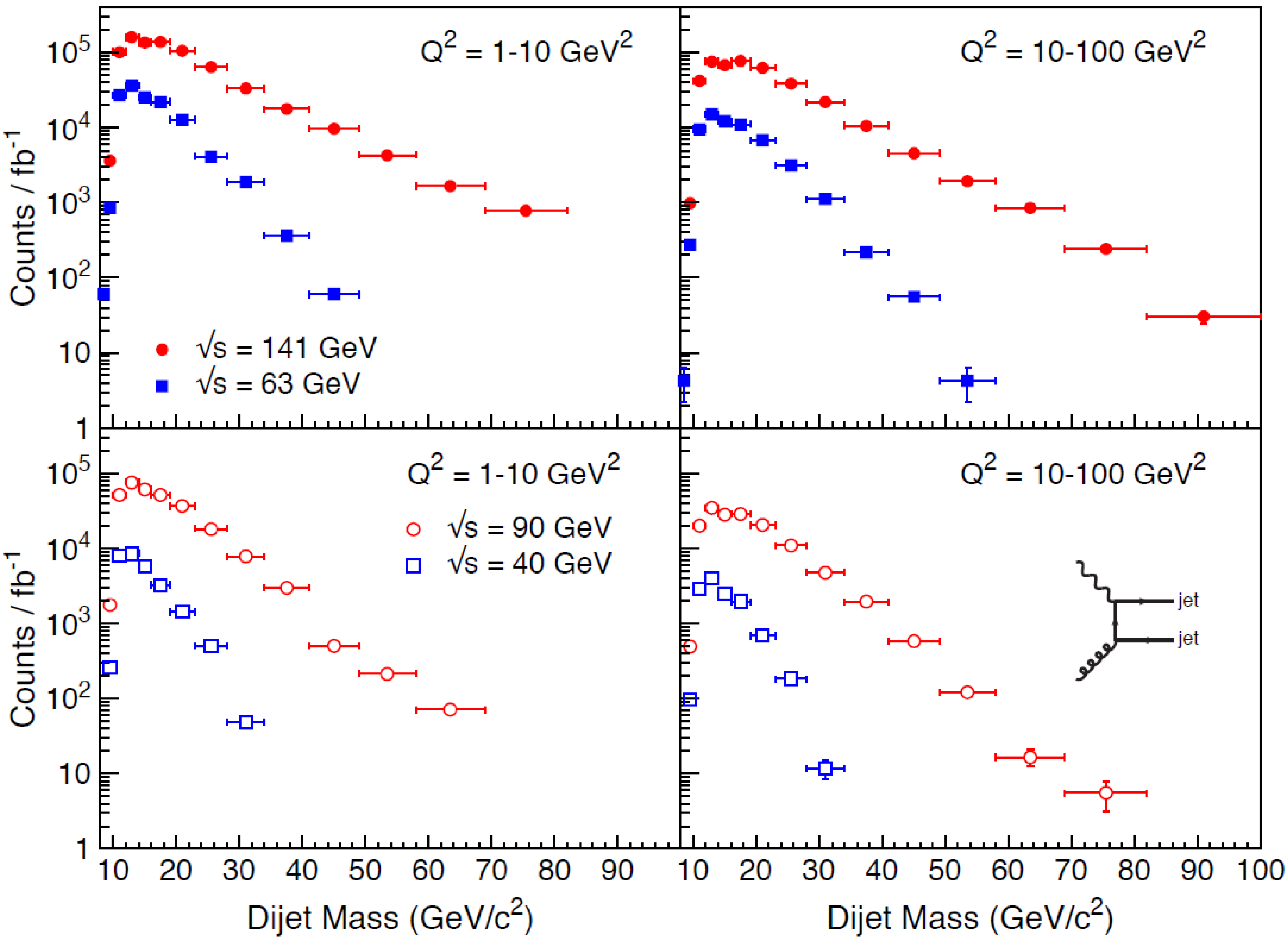
- √s = 90 -> 20x100
- √s = 40 -> 10x40



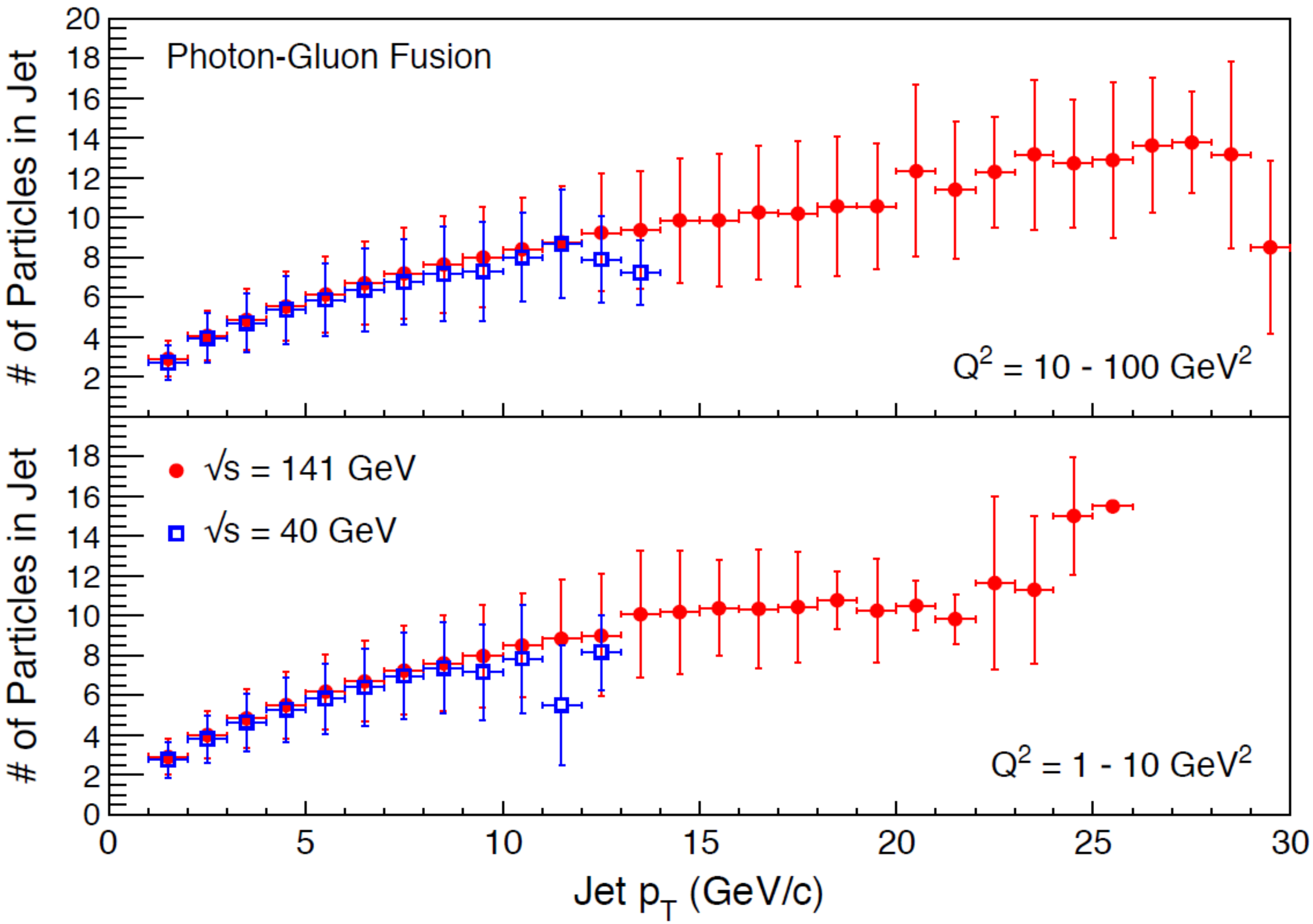
- The lower energies that come with running heavy ions will make jet measurements challenging from a statistics and kinematic reach standpoint

- Being able to push to lower p_T will be even more essential than for ep

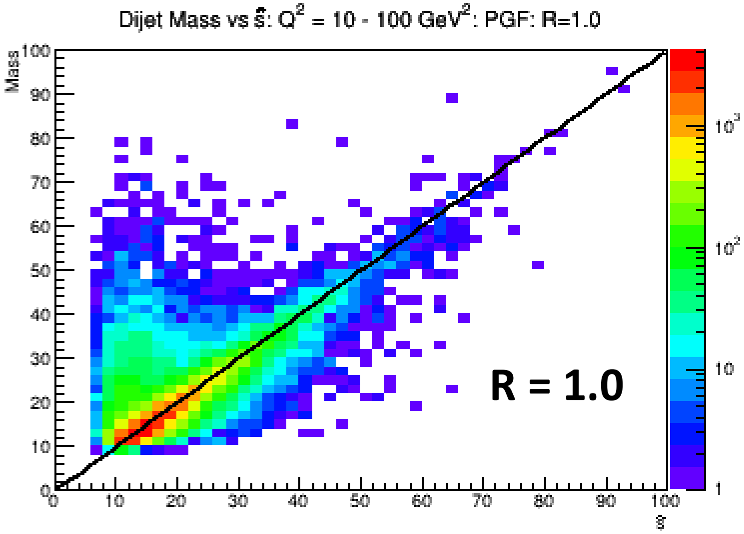
Dijet Mass Spectra

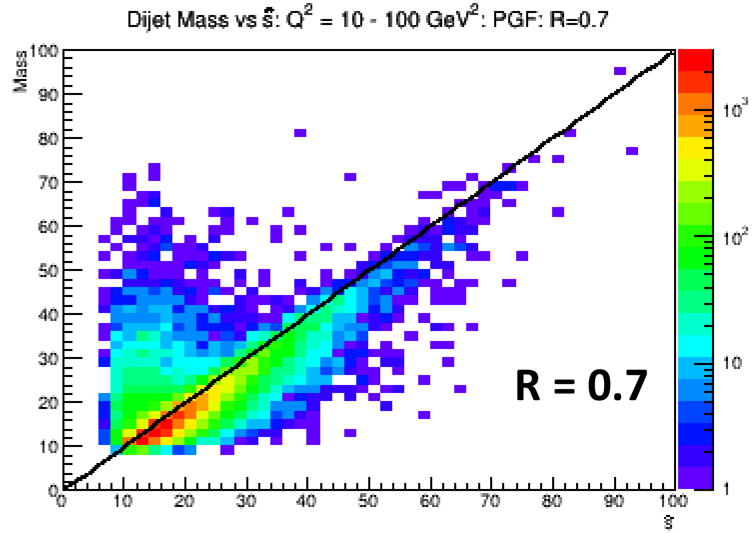


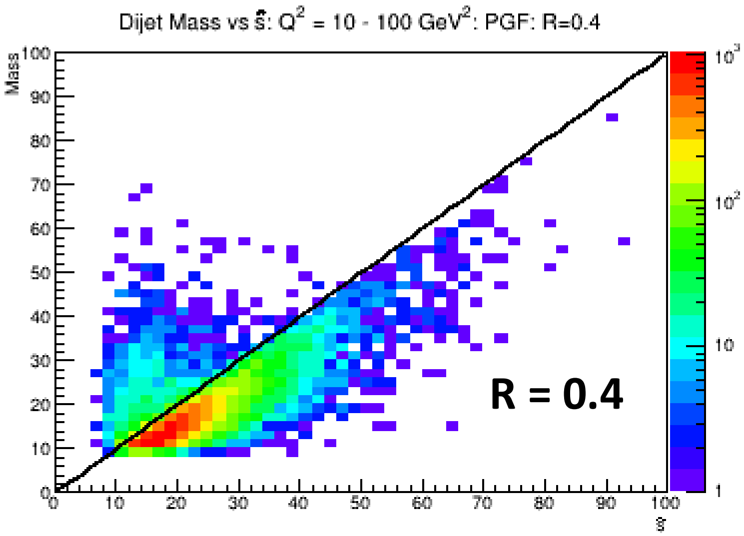
Jet Particle Content



Jet Radius Considerations



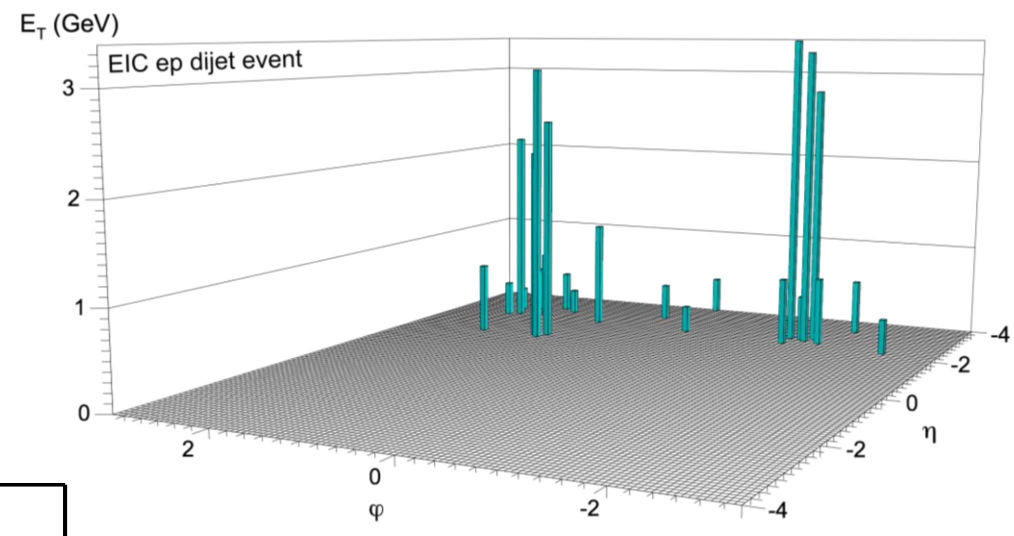


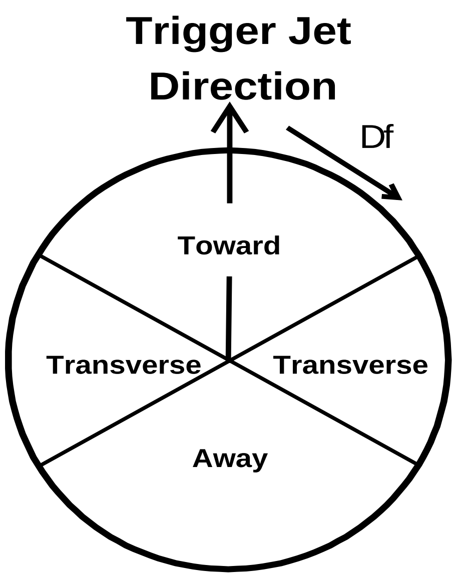


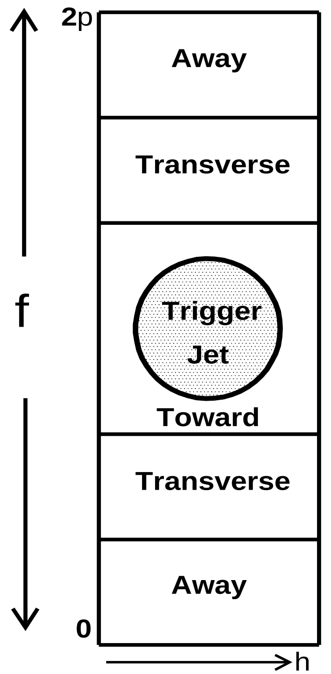
- What size radius is optimal?
- Dijet mass reproduces partonic s-hat better with larger radius
- Other analyses may benefit from smaller radii

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

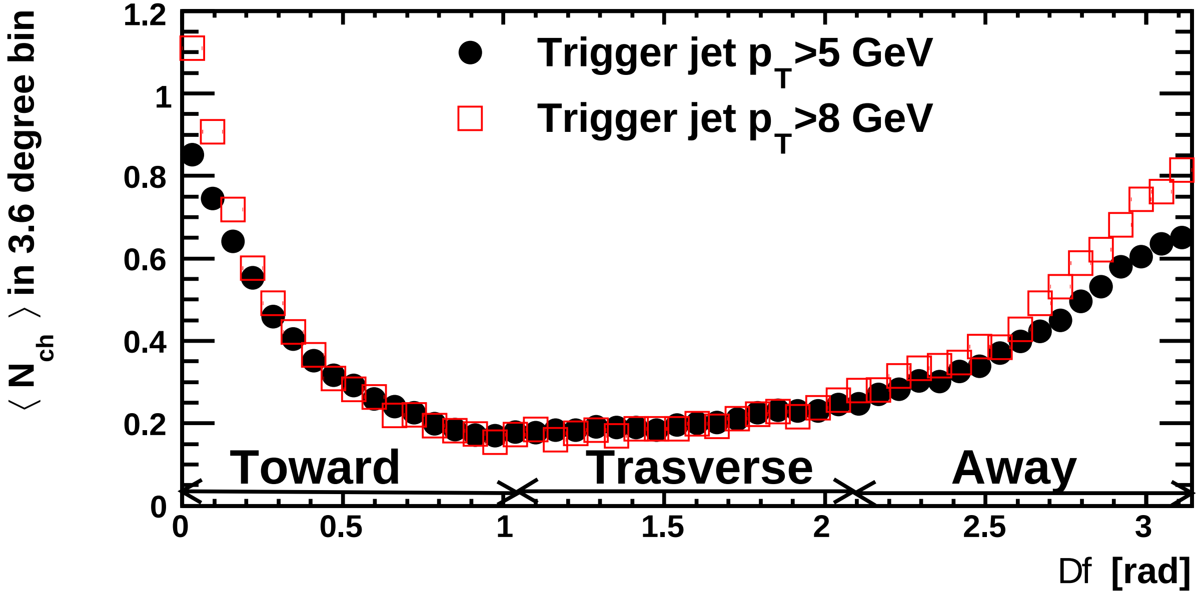


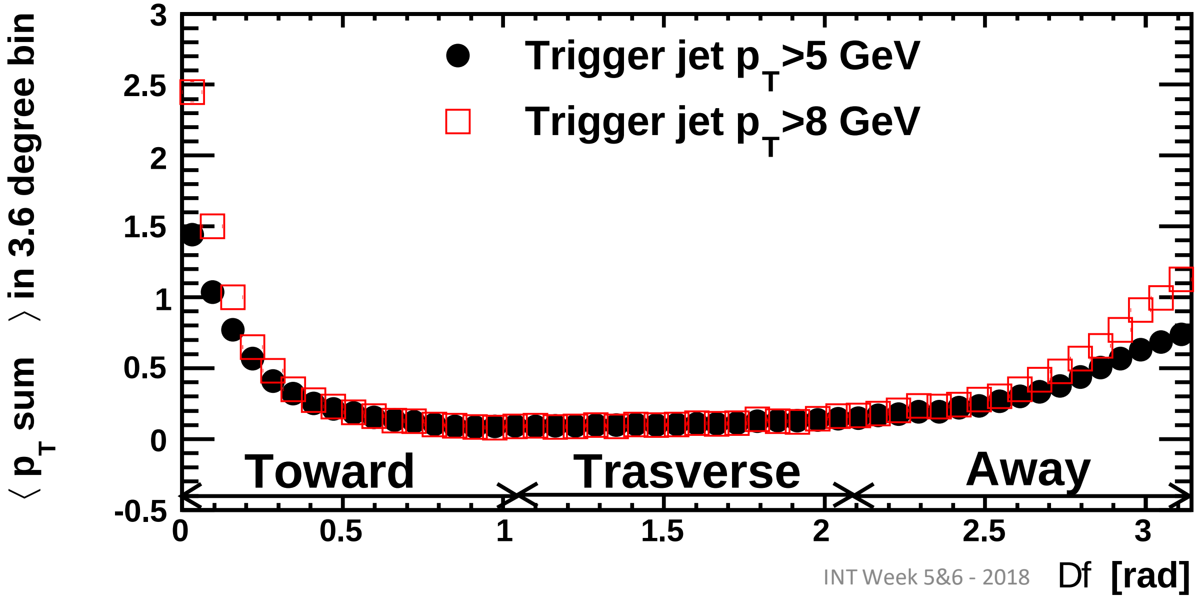




- Divide event into regions based on position of a trigger jet
- Transverse regions sensitive to underlying event contribution
- For this study: Dijet events from Resolved, QCDC, and PGF subprocesses; $Q^2 < 1$ GeV^2; $p_{T1} > 5$, $p_{T2} > 4.5$ GeV/c

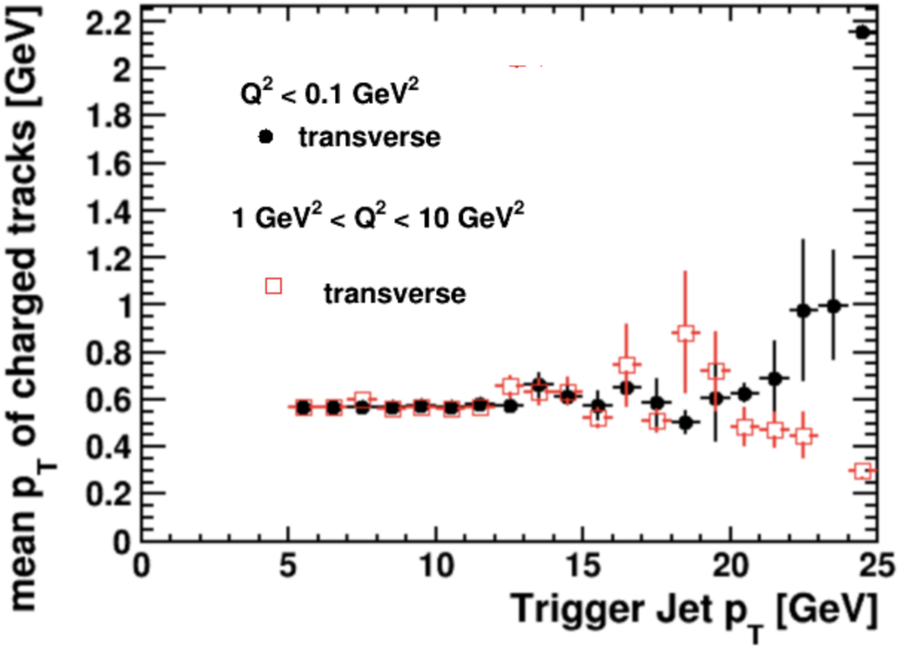
Underlying Event Characteristics





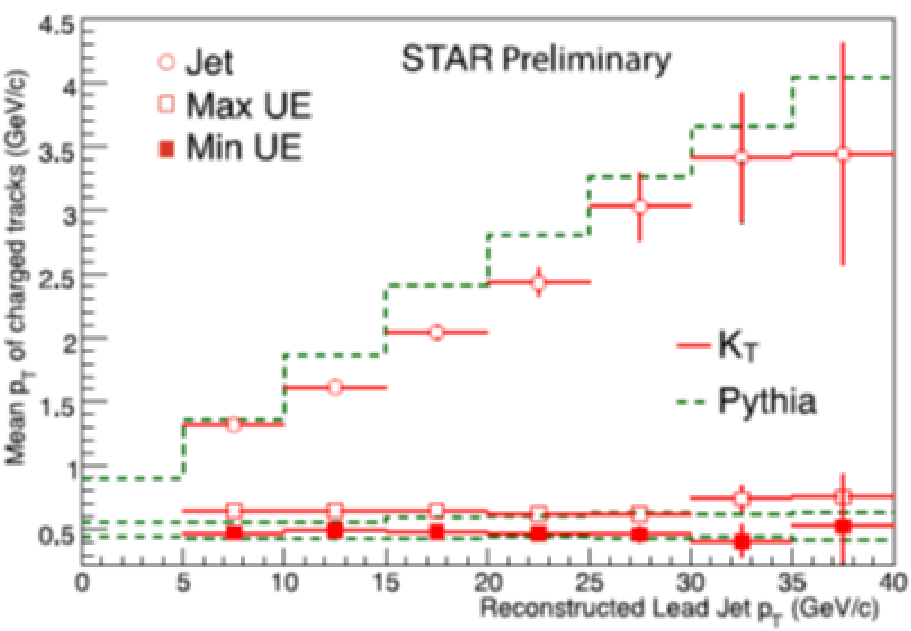
- Plot average number of charged particles per event as a function of azimuthal angle from trigger jet
- Also plot the average summed particle p_T
- See little dependence on trigger jet p_T
- The number of charged particles and p_T sum in transverse region is small

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



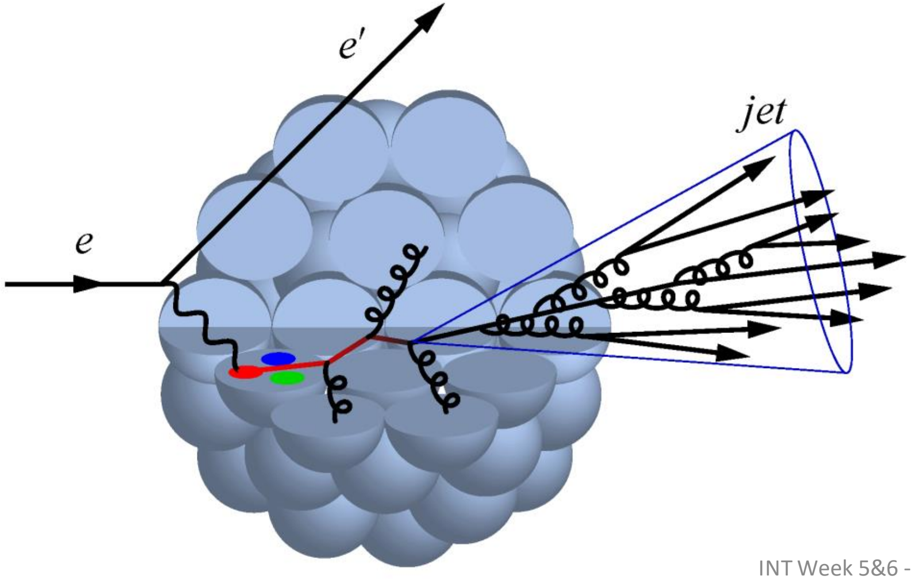
- See similar behavior in 200 GeV pp events at STAR
- Can we use STAR data to study certain EIC jet observables?

Jet Substructure: Angularity

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

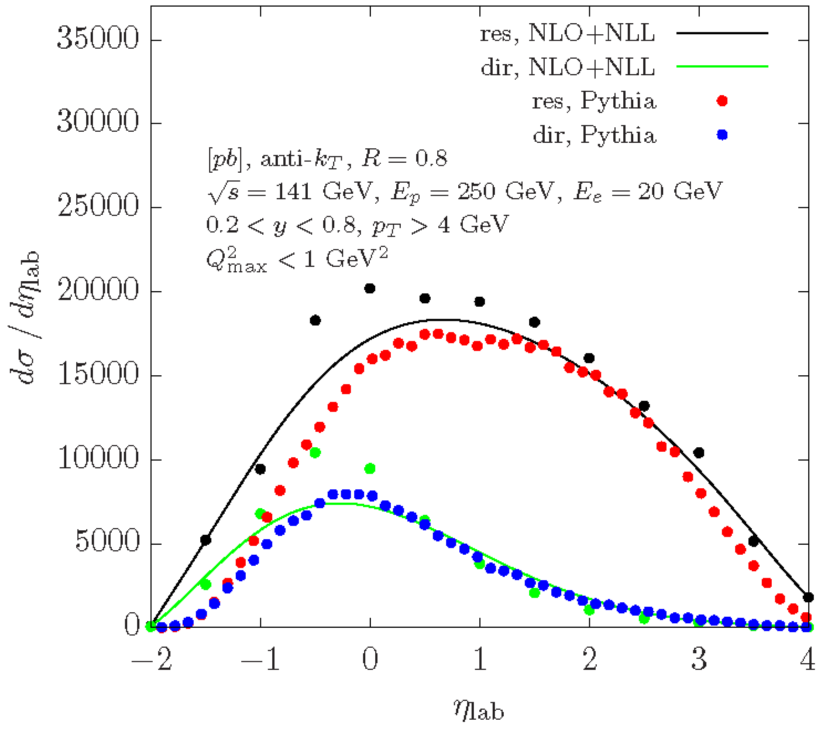
- Substructure observables quantify how energy is distributed within the jet – modification of substructure in eA may be sensitive to details of hadronization in nuclear matter and possibly to certain properties of the matter

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

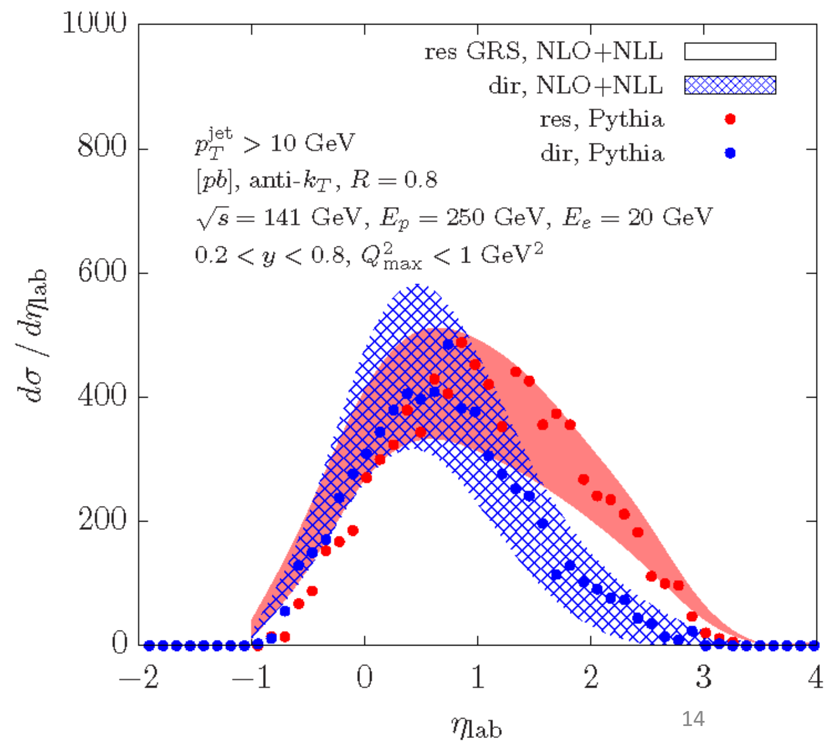


$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta \mathcal{R}_{iJ}\right)^{2-a}$$

Photoproduction Cross Section

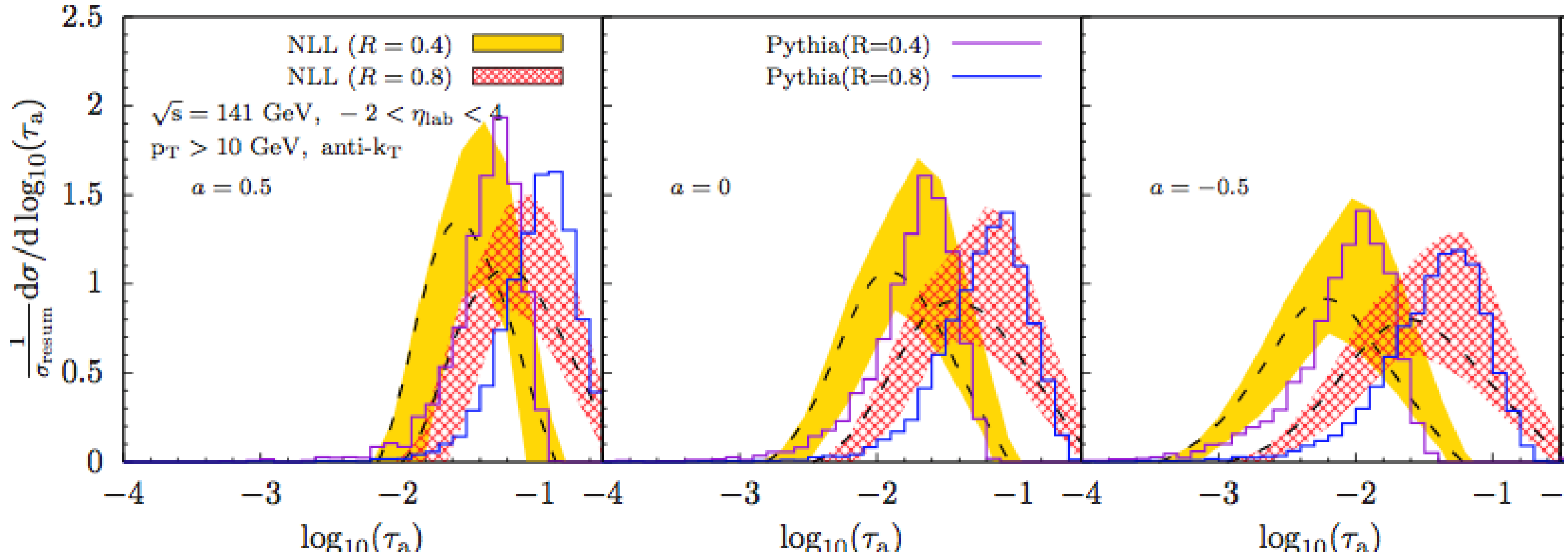


- Carry out angularity studies in photoproduction region ($10^{-5} < Q^2 < 1$)
- Resolved and direct cross sections from PYTHIA in good agreement with theoretical expectations (F. Ringer, K. Lee)



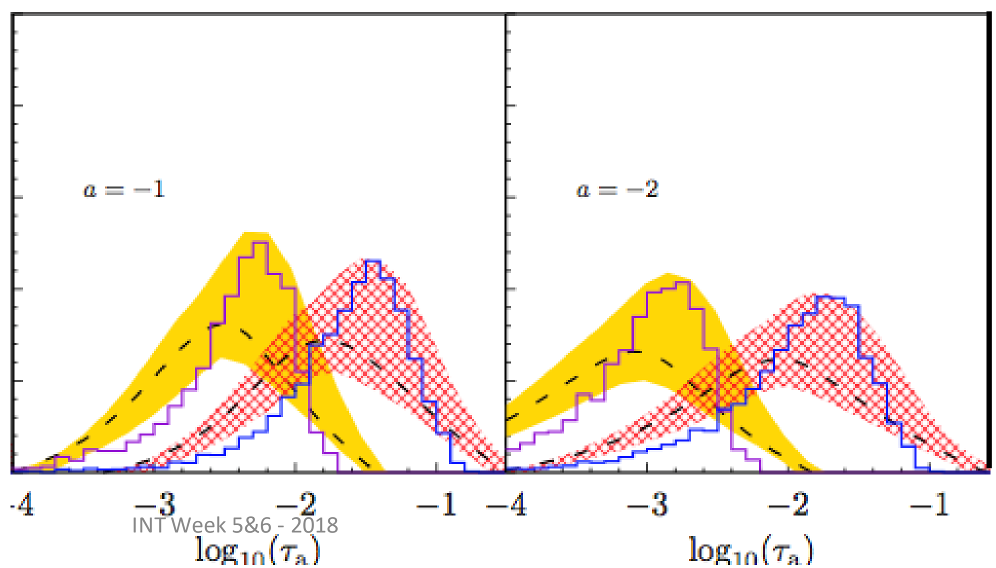
- Jet Radius = 0.8
- 0.2 < inelasticity < 0.8
- Lab Frame
- Cross sections shown for jet $p_T > 4$ and jet $p_T > 10$ GeV

Angularity: Theory Vs PYTHIA



- Dotted curve represents theory result using natural scale choice

- Bands represent envelope when varying scales by factors of 2

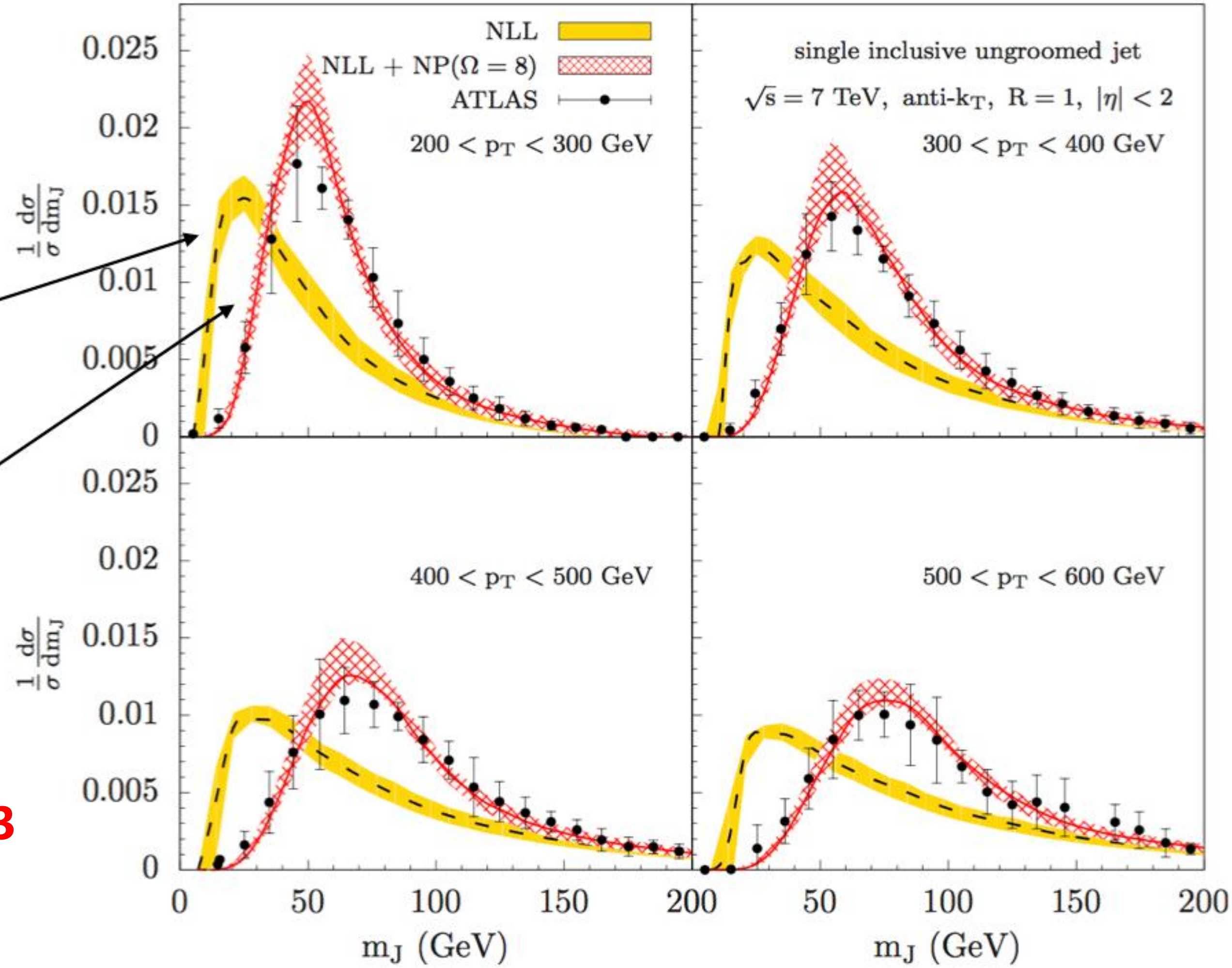


Non-Perturbative Effects

$pp \to (\text{jet}\, m_J^2)X$

Perturbative result

Including $d\sigma^{\text{pert}} \otimes F$
NP shape function



See F. Ringer's Talk from Week 3

$$F_i(k) = \frac{4k}{\Omega^2}\exp(-2k/\Omega)$$

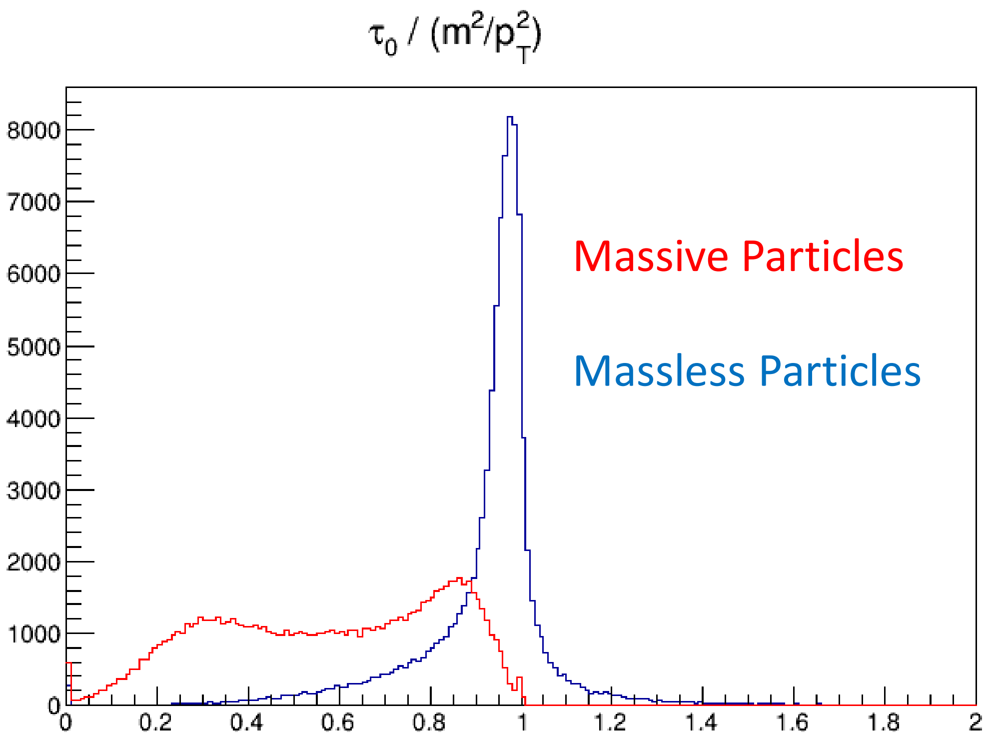
Stewart, Tackmann, Waalewijn `15

ATLAS, JHEP 05 (2012) 128

Kang, Lee, FR `18,
Kang, Lee, Liu, FR `18

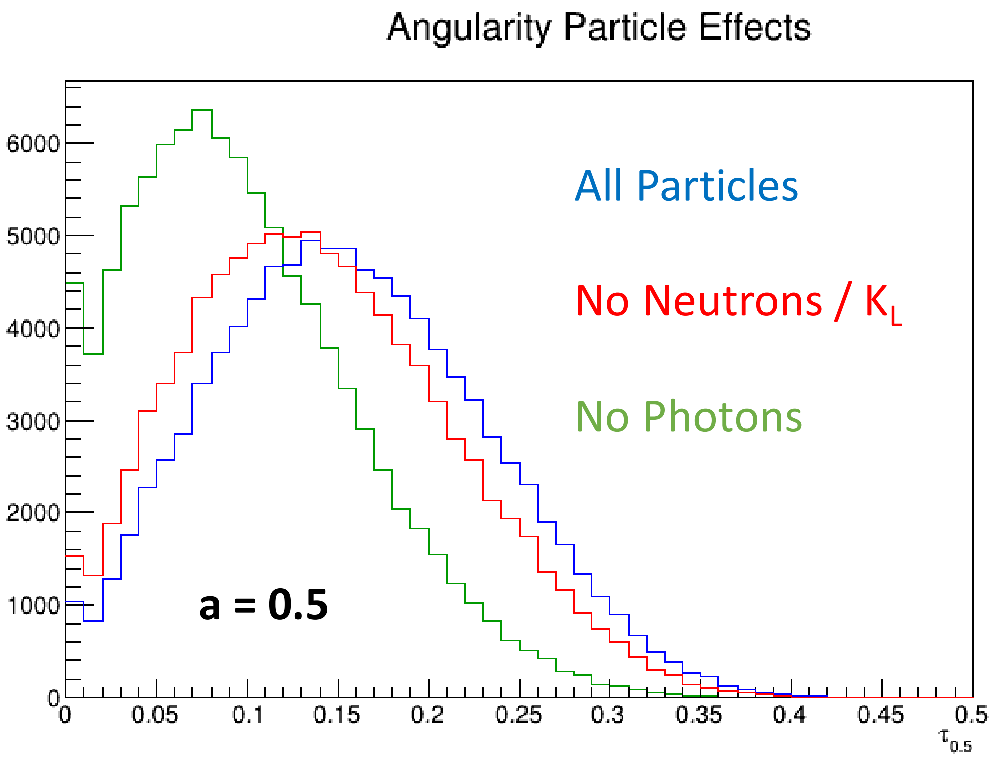
Relationship to Jet Mass

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



- 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
- Look at relationship for high p_T jets

Detector Considerations



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

Power Corrections

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

$$\tau_a^{e^+e^-} = \frac{1}{2E_J}\sum_{i\in J} |\vec{p}_T^{\,iJ}|\exp(-|\eta_{iJ}|(1-a))$$

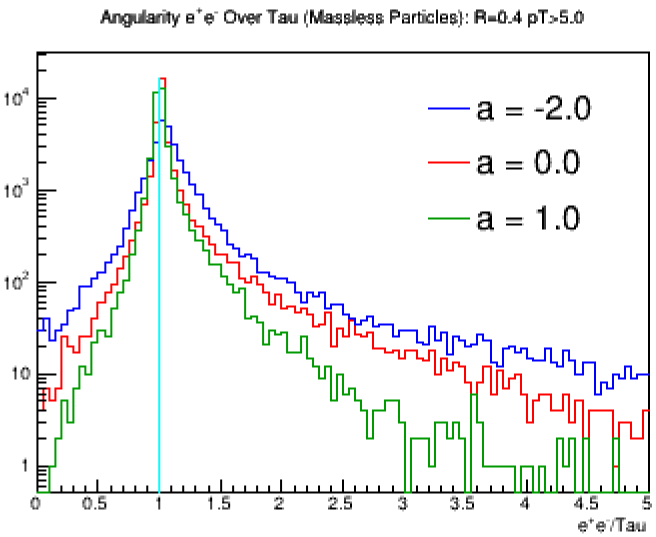
$$\tau_a = \left(\frac{2E_J}{p_T}\right)^{2-a}\tau_a^{e^+e^-} + \mathcal{O}(\tau_a^2)$$

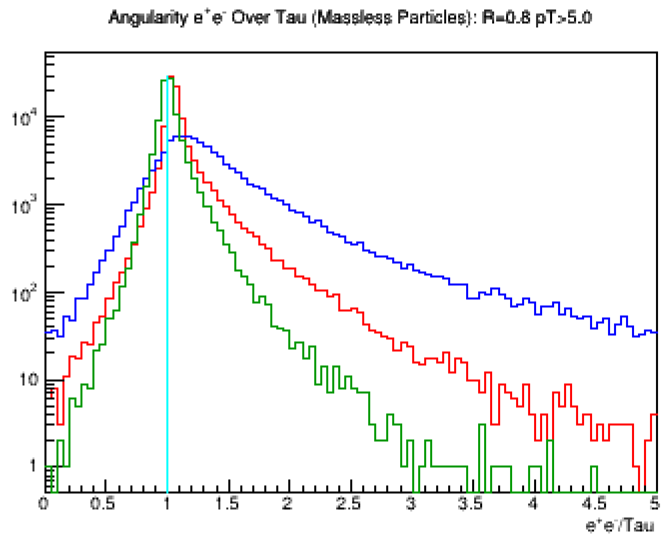
- In addition to that given above, can define angularity in terms of particle p_T and eta with respect to the jet thrust axis – call this tau^e+e-
- The original angularity is equal to tau^e+e- times a prefactor plus power corrections
- Can explore the behavior of these higher order terms by taking a ratio of tau^e+e- to the original definition

Power Corrections: Compare ‘a’

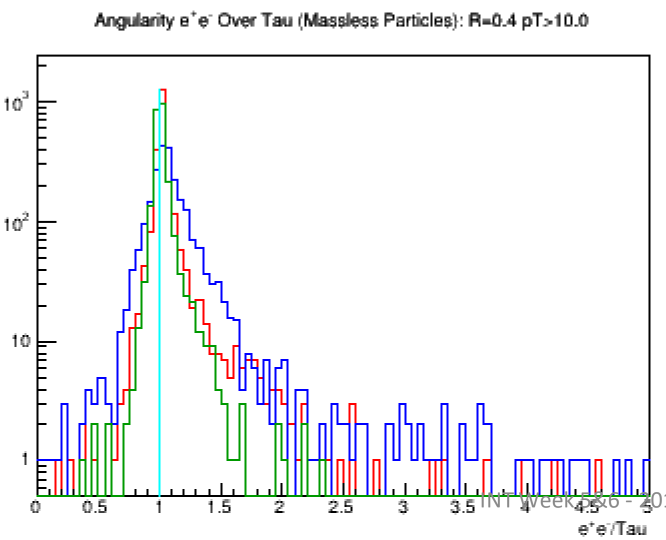
R = 0.4 | **R = 0.8**

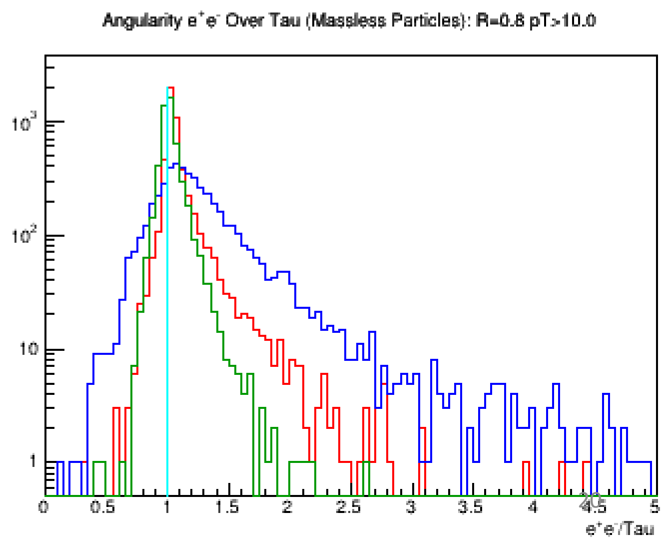
$p_T > 5.0$





$p_T > 10.0$

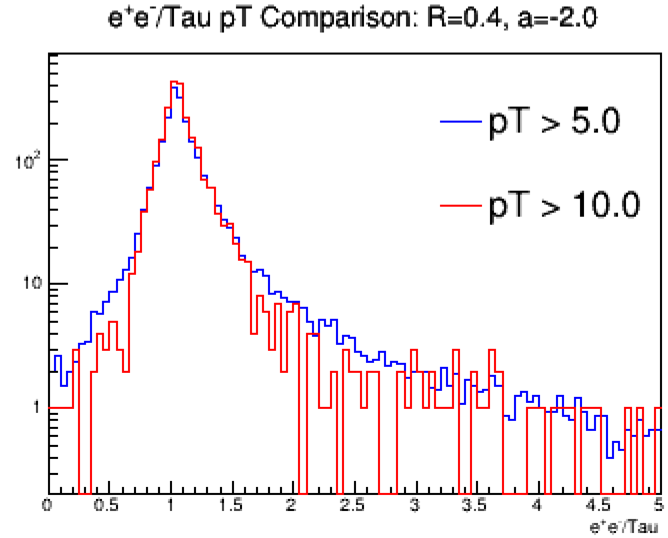


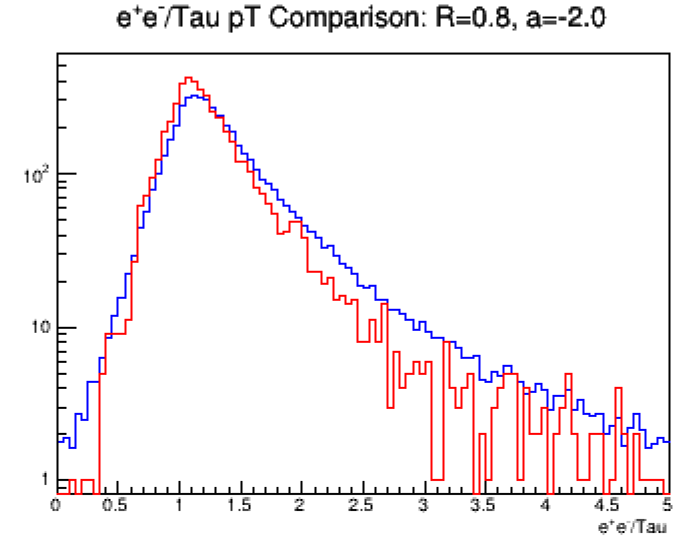


Power Corrections: Compare p_T

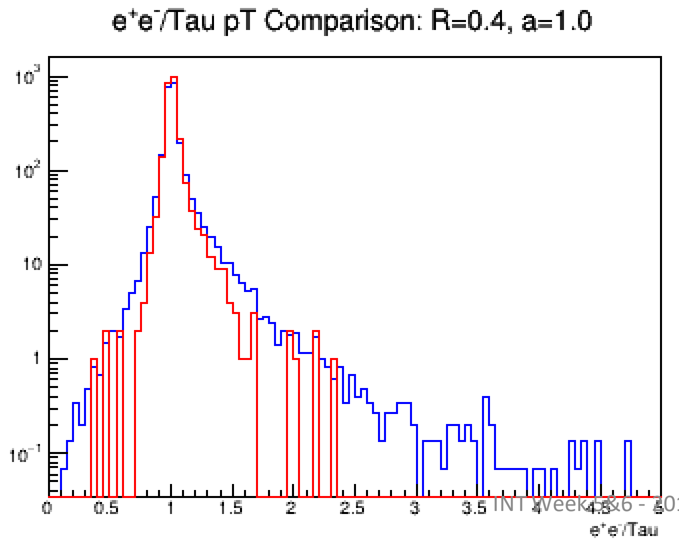
R = 0.4 | **R = 0.8**

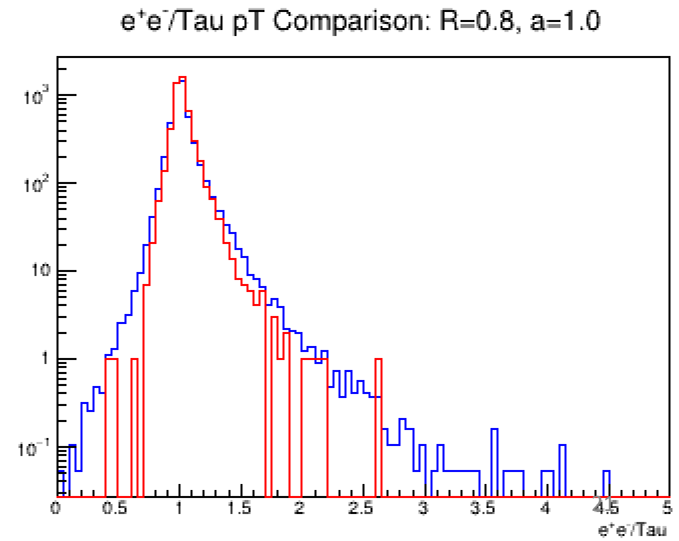
a = -2.0





a = 1.0

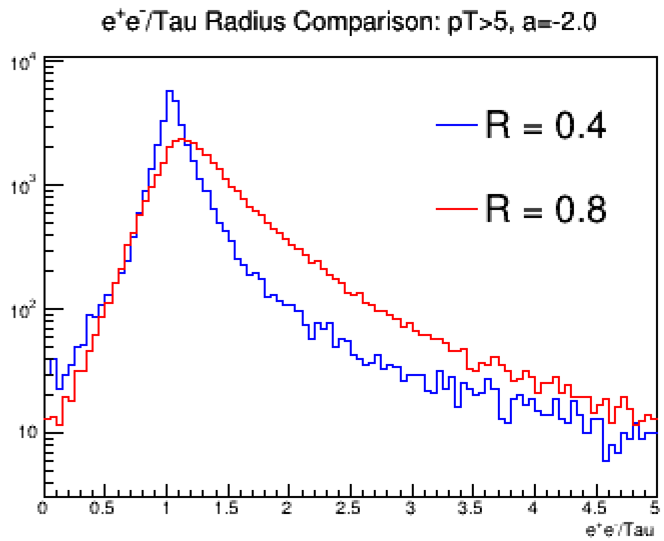


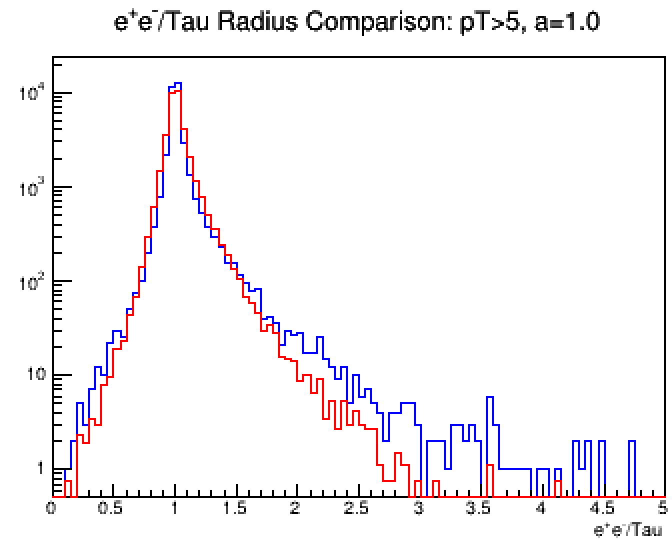


Power Corrections: Compare R

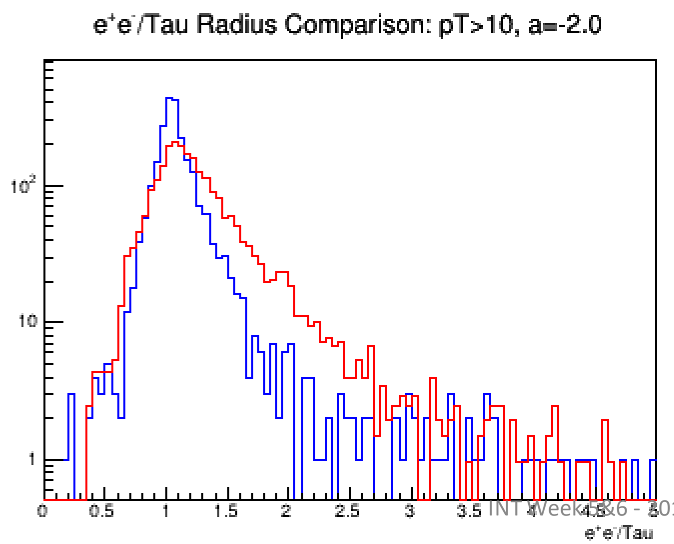
a = -2.0 | **a = 1.0**

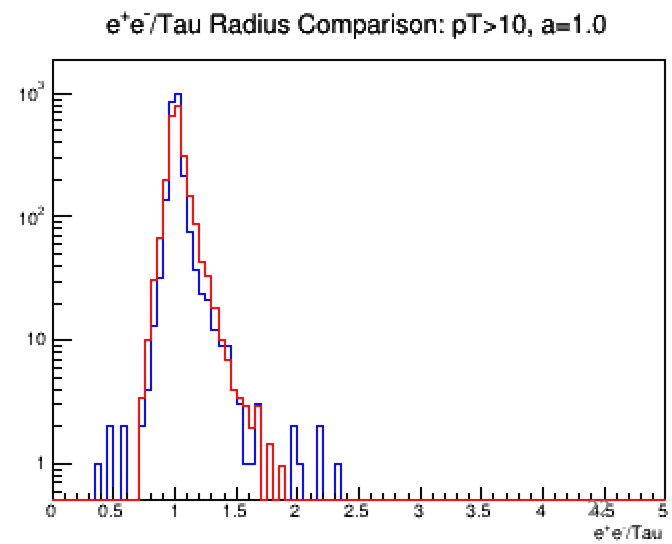
$p_T > 5.0$





$p_T > 10.0$





Power Corrections: Compare R

a = -2.0 | **a = 1.0**

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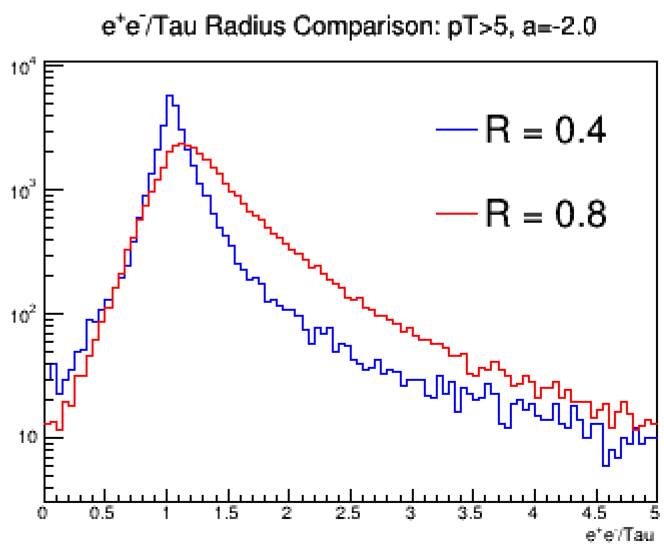
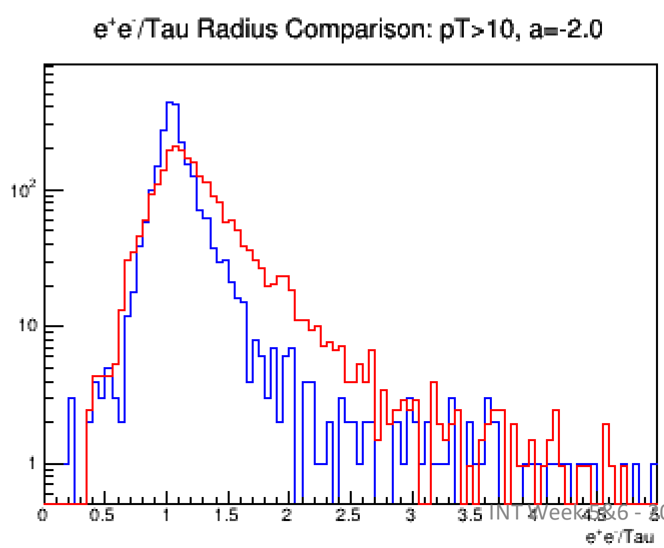
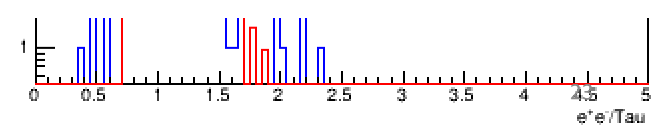


e+e-/Tau Radius Comparison: pT>5, a=1.0

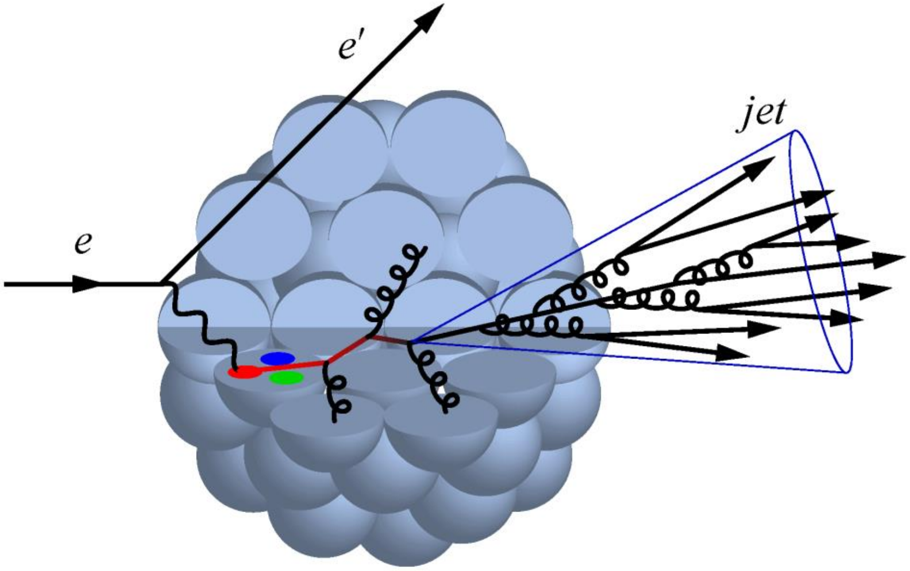
- For a given radius and transverse momentum, higher order corrections become more prominent as ‘a’ decreases
- Smaller ‘a’ place more weight on energy far from the thrust axis
- For smallest ‘a’ and largest radii, increasing p_T reduces higher order corrections modestly
- Using a smaller radius reduces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

$p_T > 10.0$





Quark / Gluon Discrimination

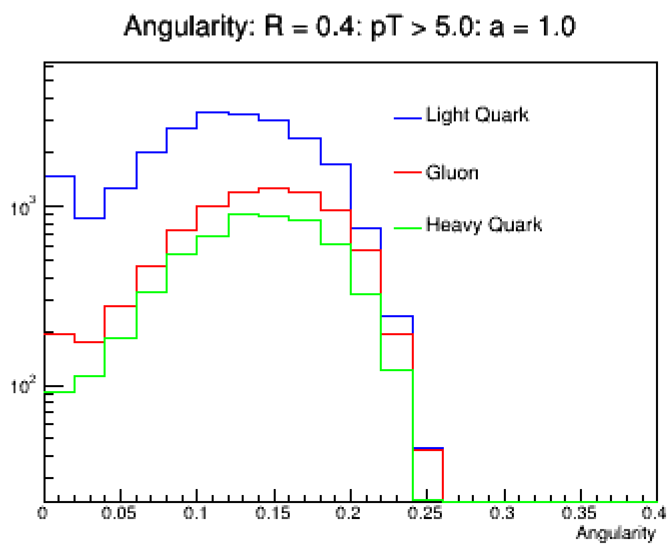


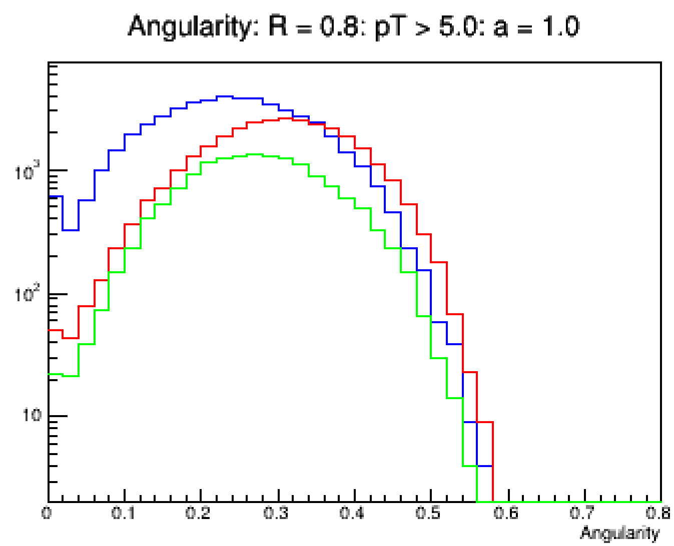
- Ultimately want to see if angularities could be useful in exploring properties of cold nuclear matter
- Simulate the formation of jets in a medium and then vary parameters of interest and see how the energy distribution within a jet changes using angularity
- Not there yet
- Look at quark vs gluon jet discrimination to get a feeling for how sensitive angularities are to different energy distributions within a jet (gluon jets should be 'fatter' on average)

Quark Vs Gluon ‘a’ = 1.0

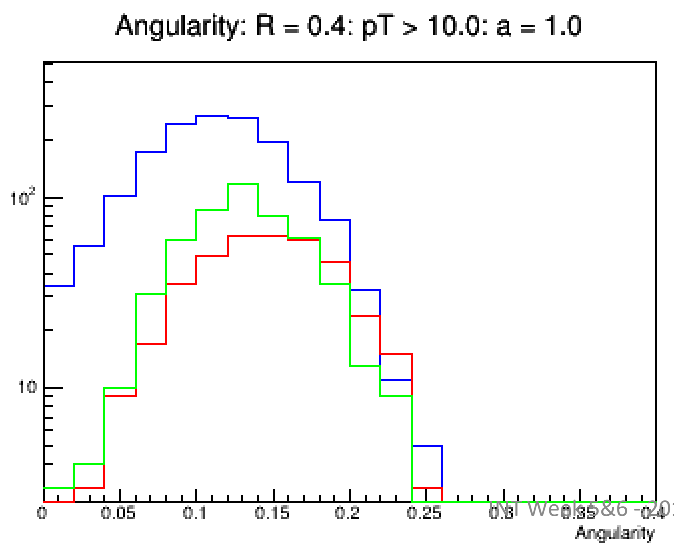
R = 0.4 | **R = 0.8**

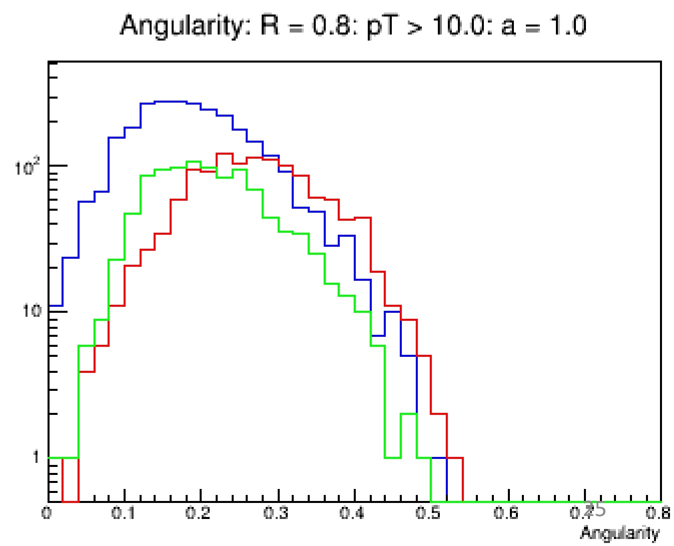
p_T > 5.0





p_T > 10.0

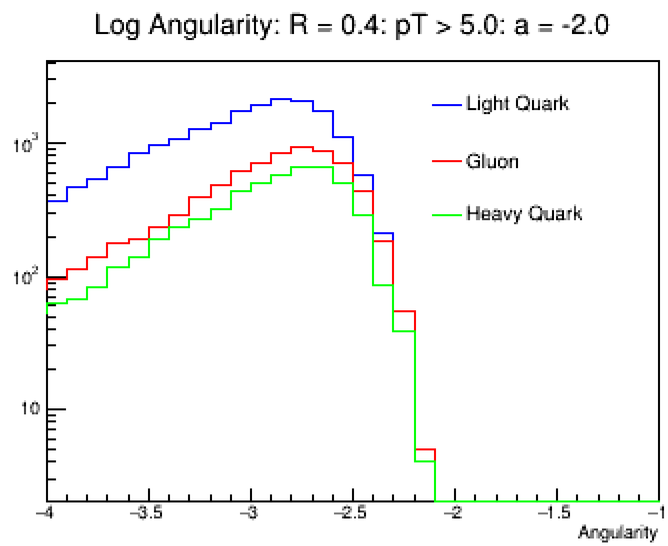


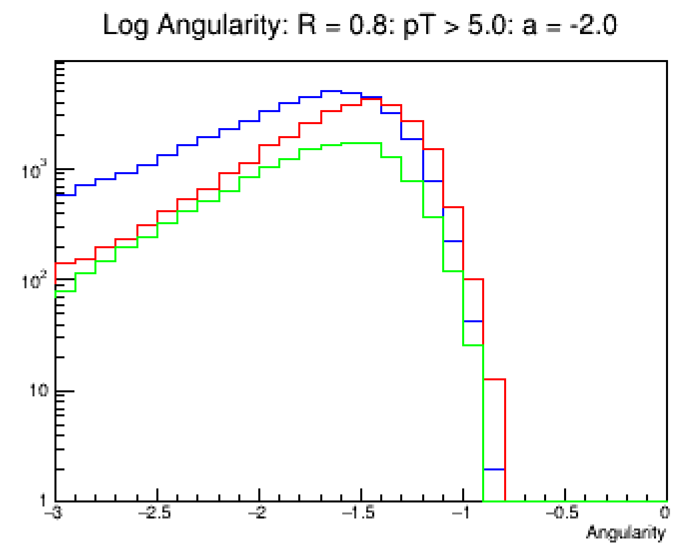


Quark Vs Gluon ‘a’ = -2.0

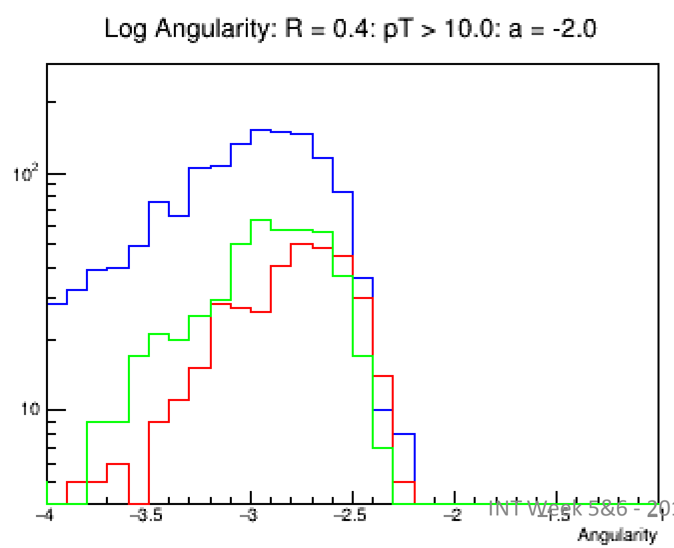
R = 0.4 **R = 0.8**

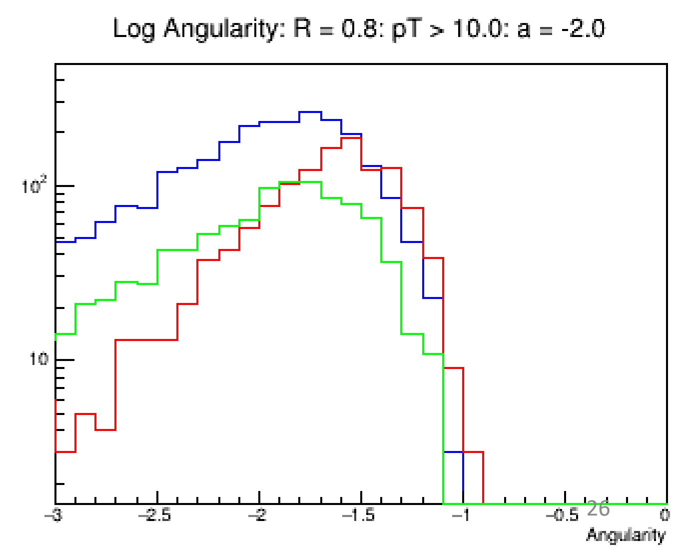
$p_T > 5.0$





$p_T > 10.0$



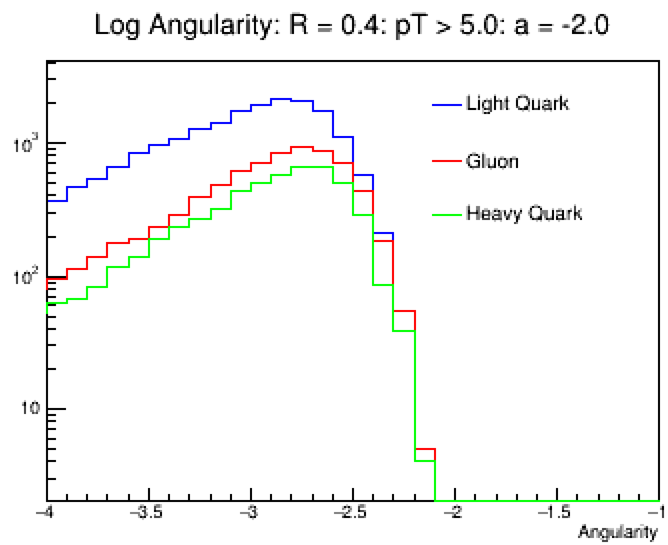


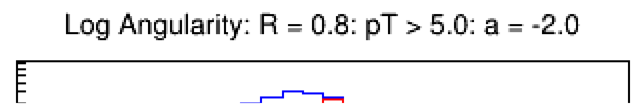
Quark Vs Gluon ‘a’ = -2.0

R = 0.4

R = 0.8

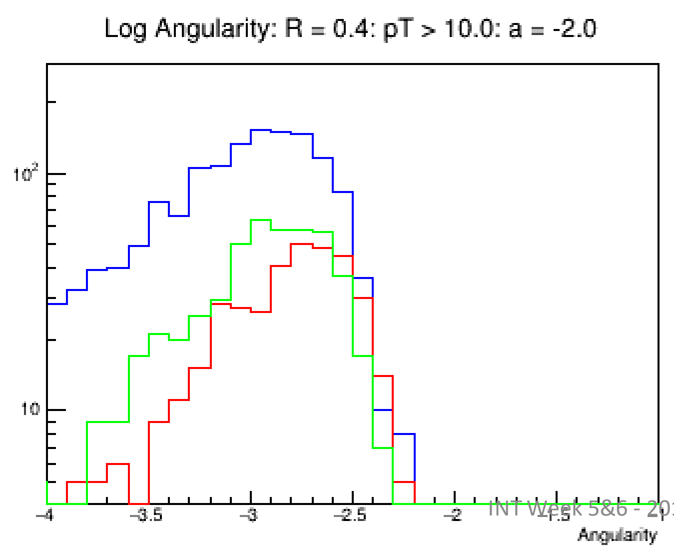
p_T > 5.0

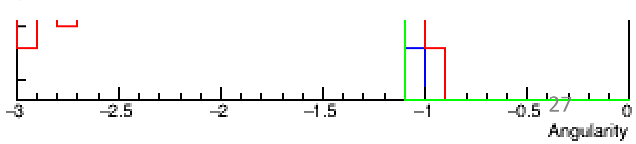




- See decent separation between light quark and gluon jets for R = 0.8 and full range of ‘a’ values
- Poor separation at R = 0.4 may be due to selection bias – Smaller radius will select those gluon jets which happen to have a narrower fragmentation and thus look more like quark jets
- Nevertheless, 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





Conclusions

- General jet properties were presented and it is seen that high energies will be important for gathering statistics and extending kinematic reach
- Angularities were investigated in Monte Carlo and found to be in good agreement with theory
- Method for exploring the impact of higher order corrections was presented
- Angularity observable shows sensitivity to energy distribution in jet arising from different fragmentation of quarks vs gluons
- Next steps:
  - Simulate at expected eA energies
  - Implement realistic nuclear matter effects
  - Possibly look at grooming
  - Look into different recombination schemes (winner-take-all) which are not sensitive to soft recoils

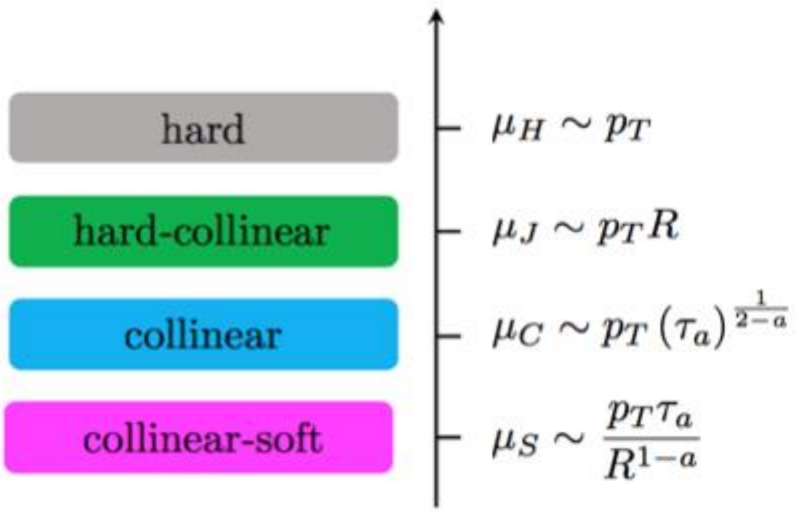
Backup

Relevant Scales

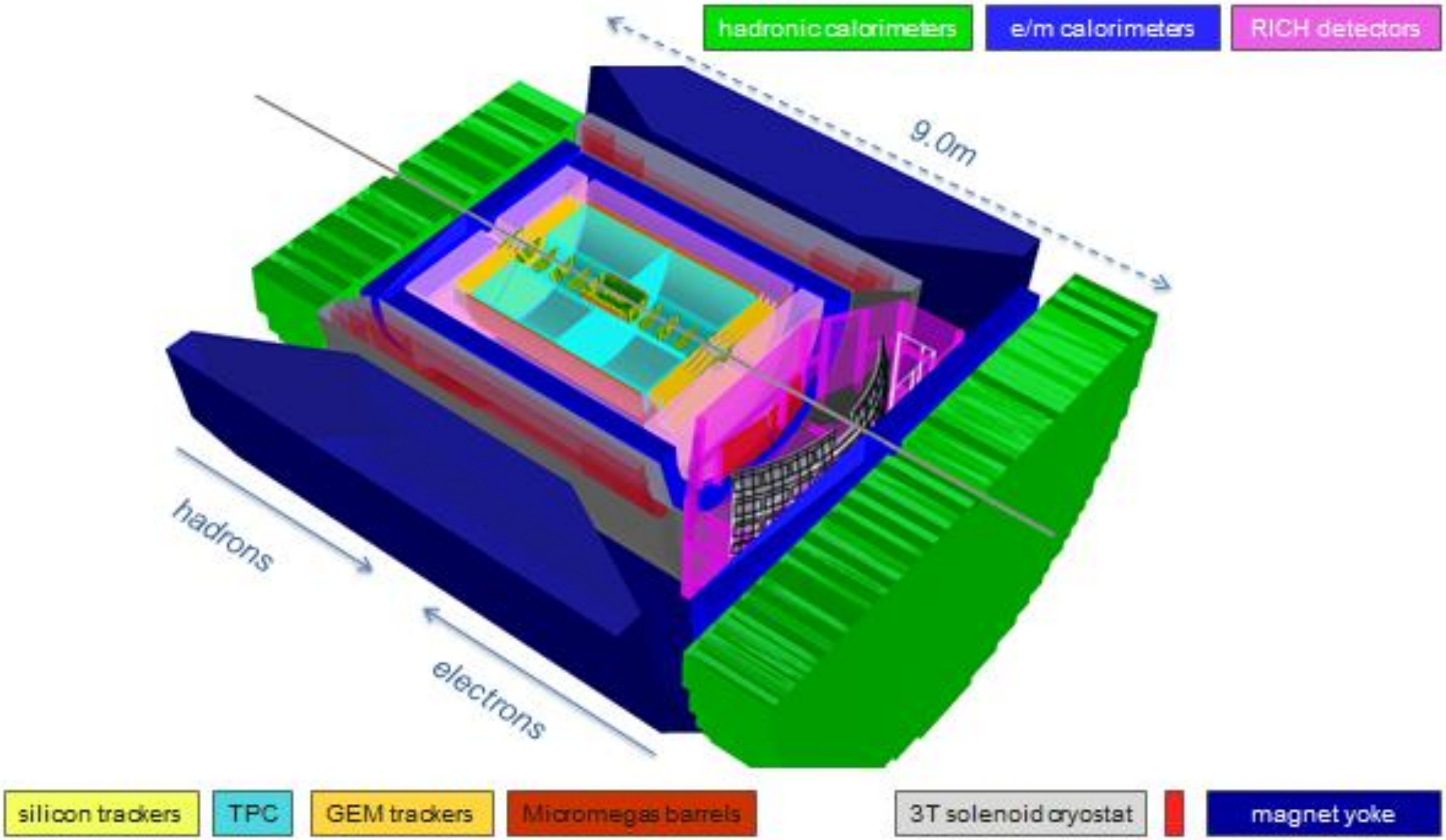
$$\frac{d\sigma}{d\eta dp_T d\tau} = \sum_{abc} f_a(x_a, \mu) \otimes f_b(x_b, \mu) \otimes H^c_{ab}(x_a, x_b, \eta, p_T/z, \mu) \otimes \mathcal{G}_c(z, p_T, R, \tau, \mu)$$

$$\mathcal{G}_c(z, p_T, R, \tau, \mu) = \sum_i \mathcal{H}_{c\to i}(z, p_T R, \mu)\, {\color{blue} C_i(\tau, p_T, \mu)} \otimes {\color{red} S_i(\tau, p_T, R, \mu)}$$

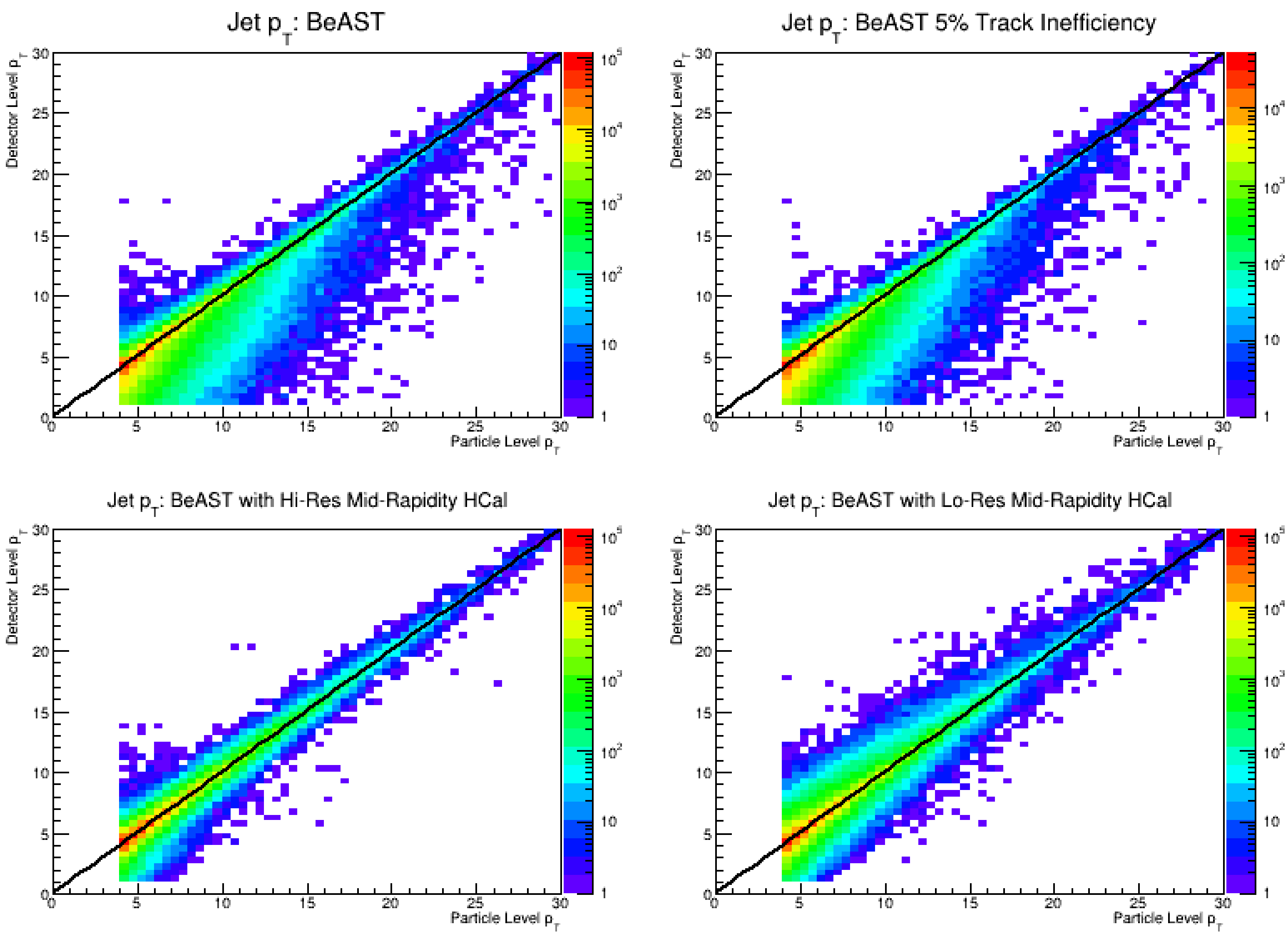
See F. Ringer's Talk from Week 3



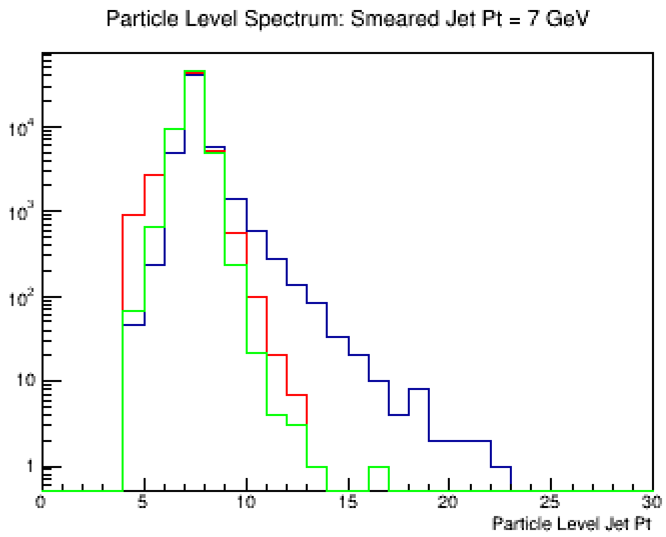
Detector Overview (BNL)

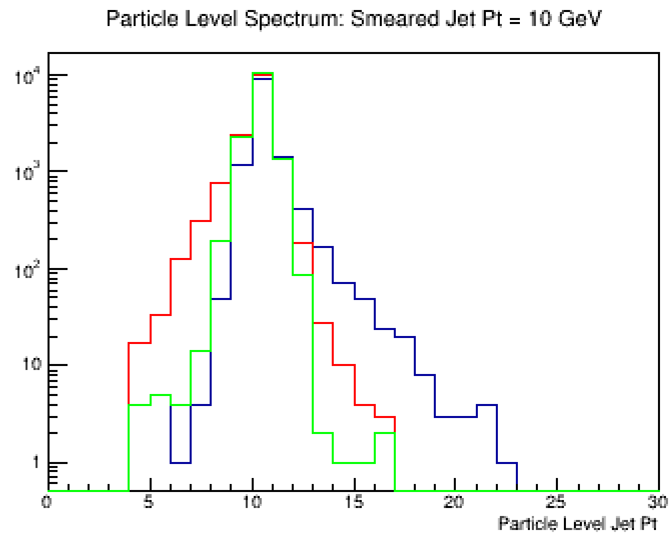


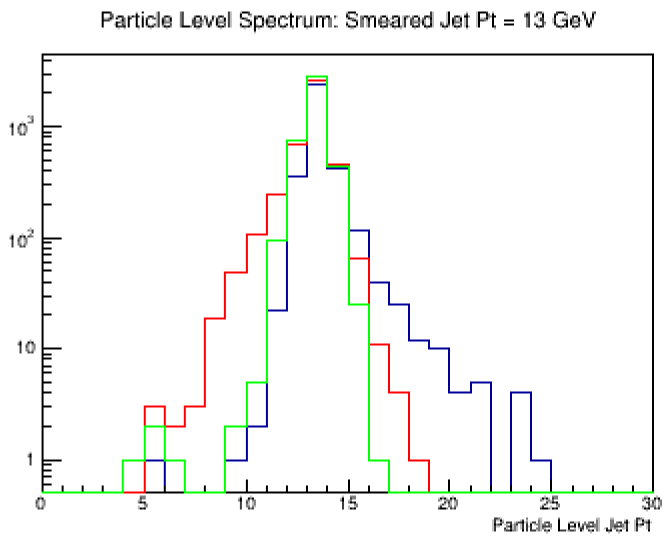
Jet p_T Reconstruction: HCal Options



Comparing Resolutions

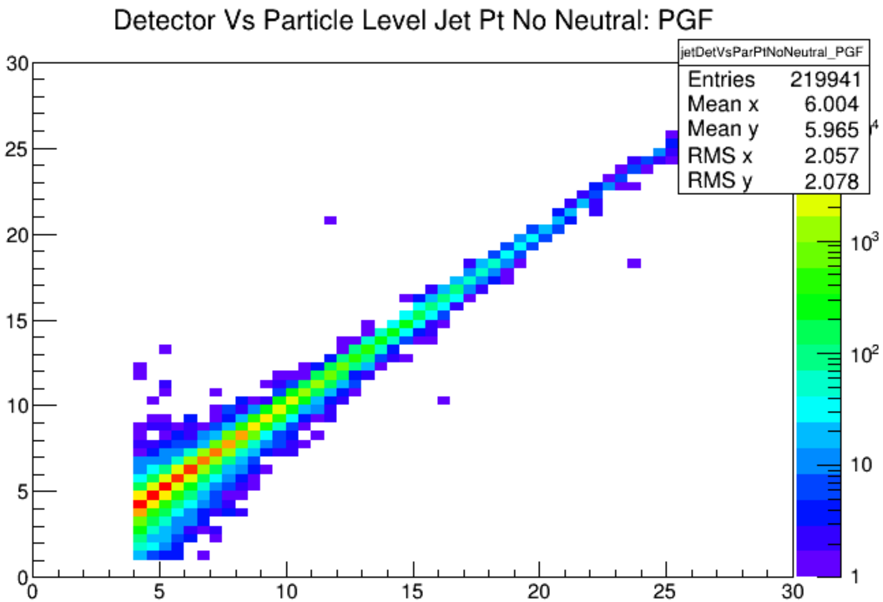


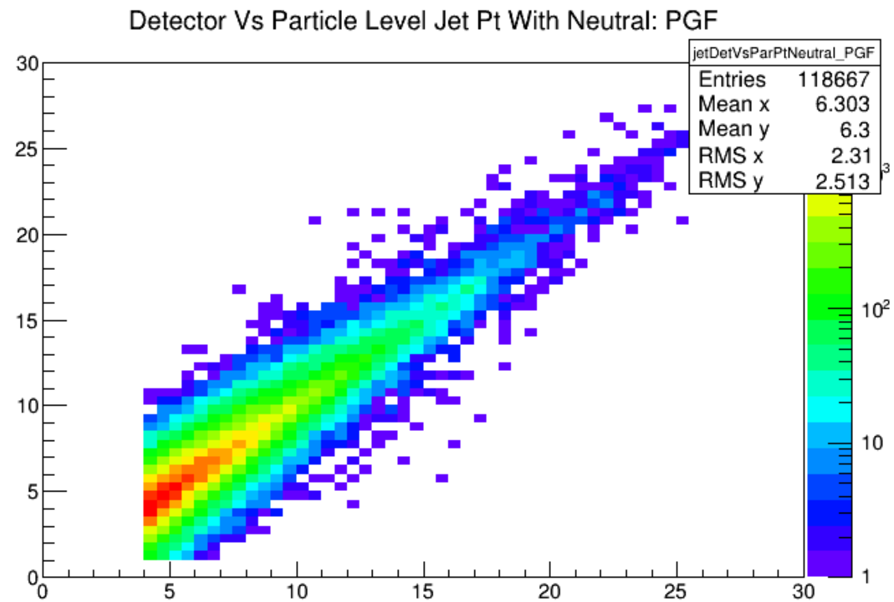




- Show particle level jet p_T spectrum for 3 specific reconstructed jet p_T values
- No mid-rapidity HCal
- Lo Res mid-rapidity HCal
- Hi Res mid-rapidity HCal

Neutral Hadron Veto





- Can use lo res HCal to select jets which contain a neutral hadron
- This subsample can be unfolded while leaving the larger jet sample which do not contain a neutral hadron alone