An Experimentalist View of Jet Structure Studies

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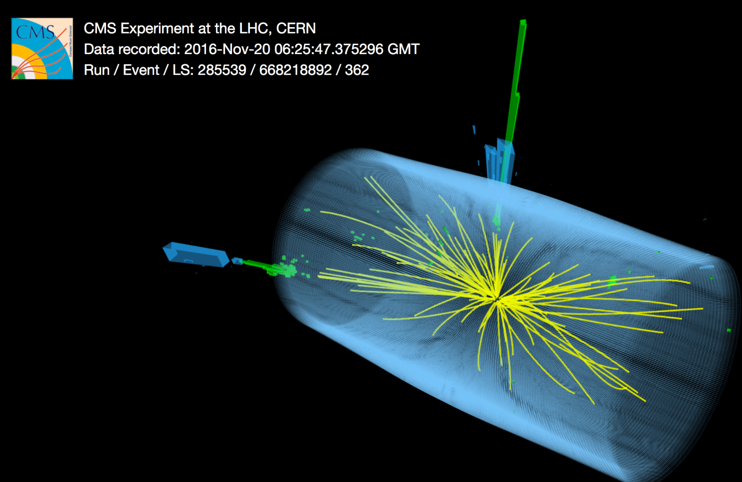
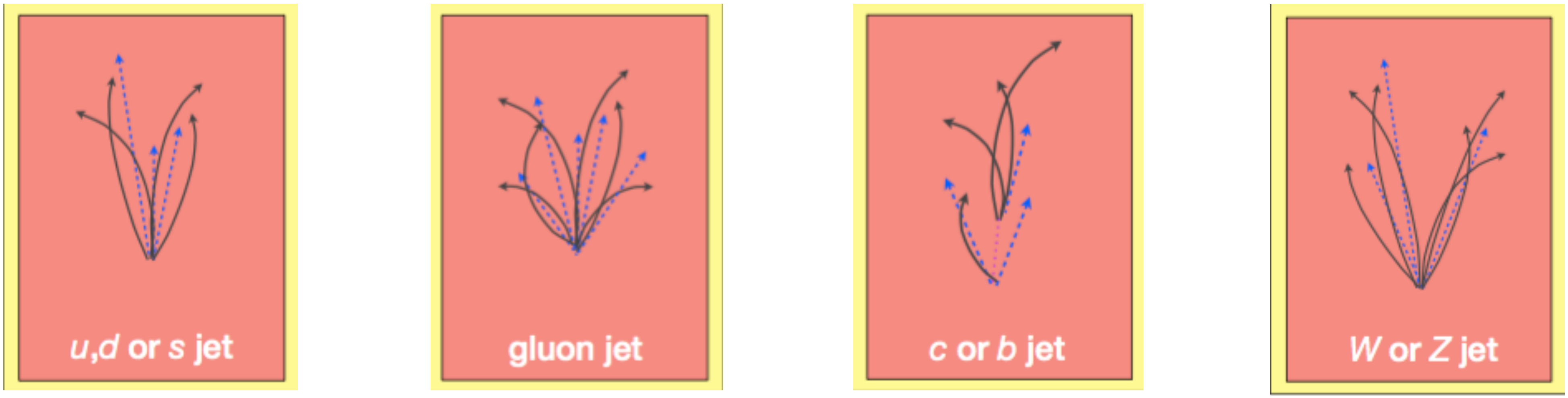
Rutgers University



Jet Substructure Observables:

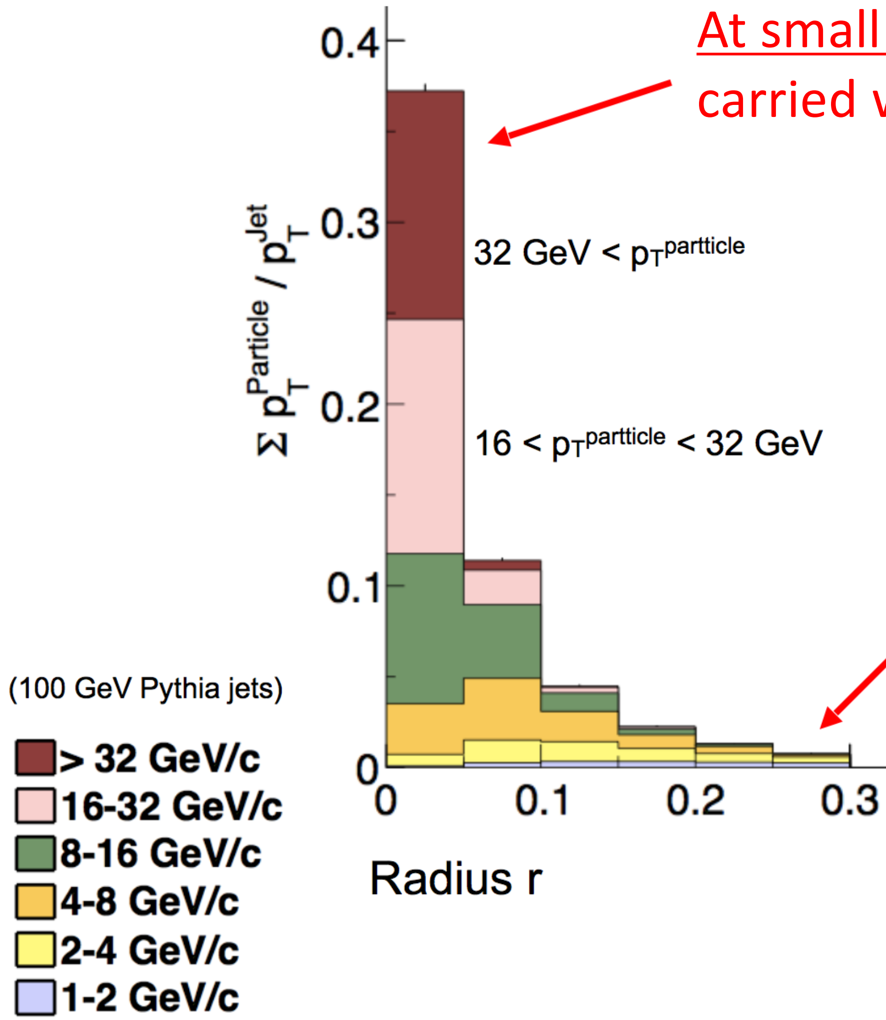
Jets are quenched! How? Need to explore jet inner-workings.



Jets can be a valuable tool!
How to extract properties of QGP the most effective way?
To what extent can the identities of underlying partons be deduced from properties of the jets they produce?

Jet Morphology: Angular and Momentum Structures

A Pythia Jet

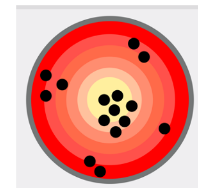


At small angles: Most of the p_T and carried with high p_T constituents

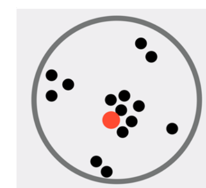
At large angles: Small fraction of p_T and carried with softer constituents

Jet Shapes and Geometric Moments

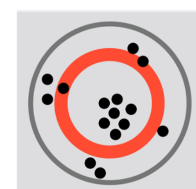
- Jet Mass $$M = \sqrt{E^2 - p_\mathrm{T}^2 - p_\mathrm{z}^2},$$ Measures how spread out the constituents of the jet are.
- *Momentum*
- *dispersion pTD:* $$p_T^D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$ *Measures 2nd moment of the constituent p_T distribution in the jet and is connected to how hard or soft the jet fragmentation is*
- *Radial moment*
- *– girth (g):* $$g = \sum_i \frac{p_{T,i}}{p_{T,jet}} |\Delta R_i|$$ *Measures 1st radial moment or angularity and is sensitive to collimation / broadening of a jet*



- *LeSub:* $$LeSub = p_{T,track}^{lead} - p_{T,track}^{sublead}$$
- *Fragmentation*
- *function (FF):* $$FF(z) = \frac{1}{N_{jet}} \frac{dN}{dz}$$

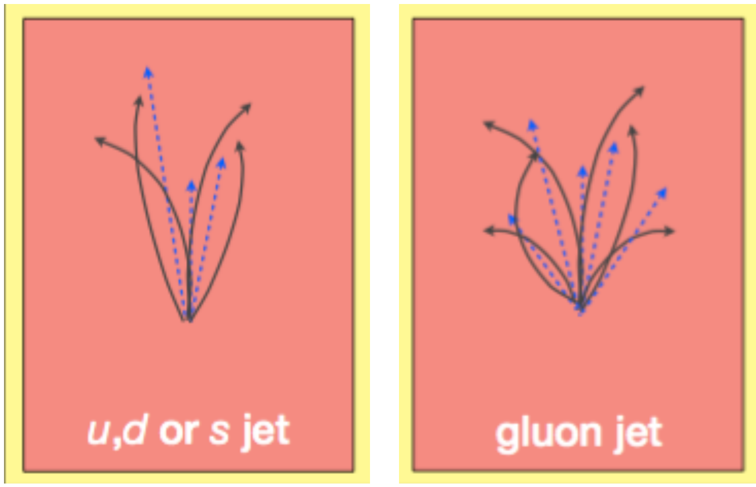


- *Differential*
- *jet shape:* $$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_\mathrm{jets}} \Sigma_\mathrm{jets} \frac{\Sigma_{\mathrm{tracks} \in (r_a, r_b)} p_\mathrm{T}^\mathrm{trk}}{p_\mathrm{T}^\mathrm{jets}}$$



Not an inclusive list but examples of jet substructure measurements that are currently being used as tools to disentangle different kinds of jets and study the effects of QGP.

An example in pp: Quark-gluon discrimination



Compared to gluon jets,
quark jets in vacuum have:

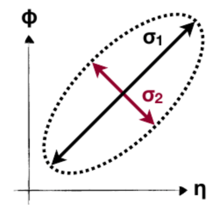
1. Fewer constituents
2. Narrower shape
3. Harder fragmentation function

and less symmetric energy sharing among constituents

http://cds.cern.ch/record/1599732/files/JME-13-002-pas.pdf

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

1. Multiplicity: Total, Charged, Neutral → Particle-Flow in CMS
2. Width Variables



obtained by diagonalizing

$$\frac{1}{\sum_i p_{\mathrm{T},i}^2}\sum_i p_{\mathrm{T},i}^2 \begin{pmatrix} (\Delta\phi_i)^2 & (\Delta\phi_i\Delta\eta_i) \\ (\Delta\eta_i\Delta\phi_i) & (\Delta\eta_i)^2 \end{pmatrix}$$

$$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$$

3. Energy Sharing Variables: Pull, R, $p_T D$

$$|\vec{t}| = \left| \frac{\sum_i p_{\mathrm{T},i}^2 \, |r_i| \, \vec{r_i}}{\sum_i p_{\mathrm{T},i}^2} \right| \qquad \vec{r_i} = (\Delta\eta_i, \Delta\phi_i)$$

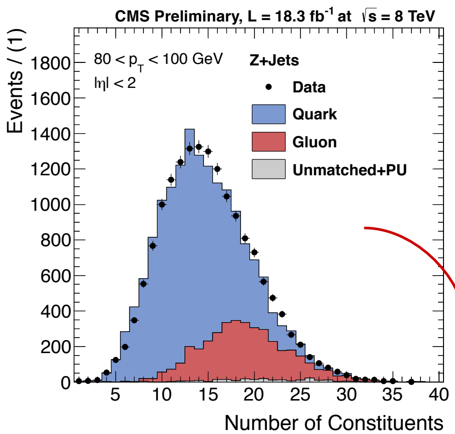
$$R = \frac{\max(p_{\mathrm{T},i})}{\sum_i p_{\mathrm{T},i}} \qquad p_{\mathrm{T}}D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

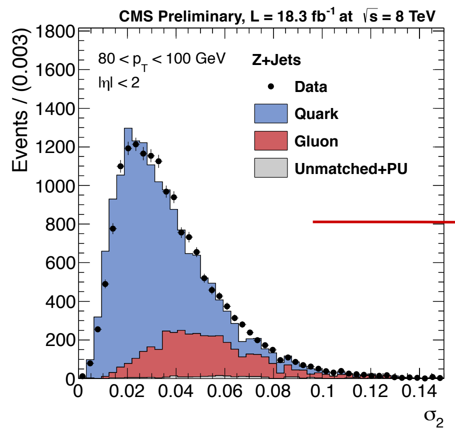
$p_T D$=1 single jet constituent

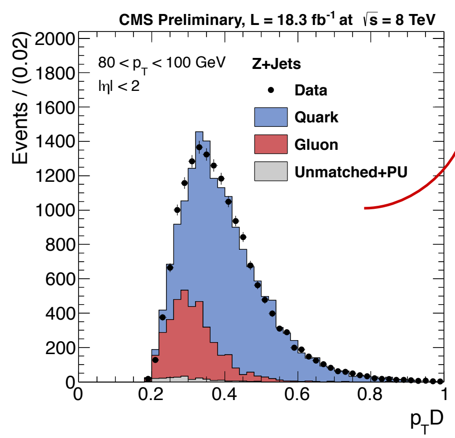
$p_T D$=0 ∞ number of jet constituents.

Quark-gluon discrimination:

quark/gluon discrimination is difficult, but not impossible

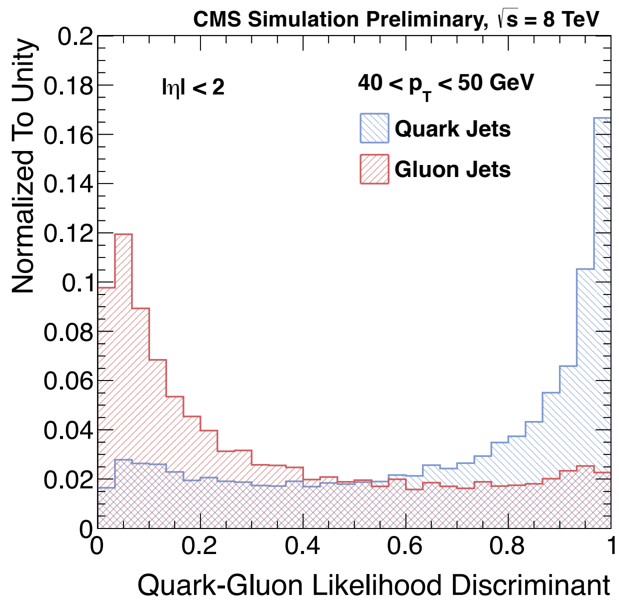


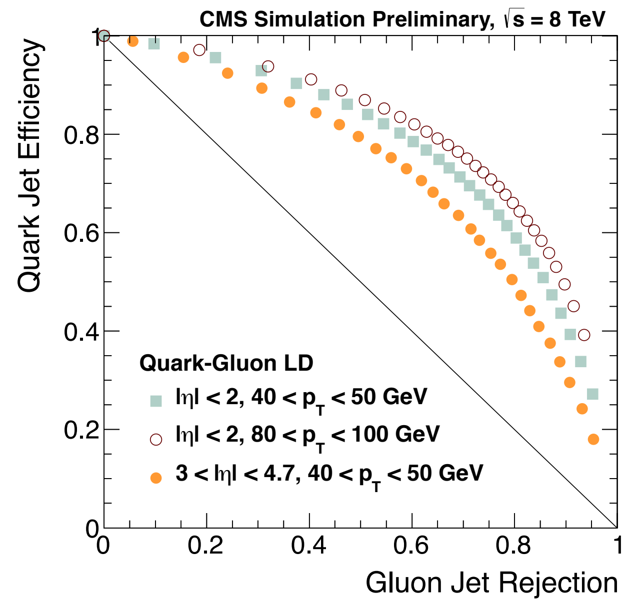




Likelihood based discriminator obtained by combining 3 variables:

- Total multiplicity
- Minor axis
- $p_T D$





Good background rejection and signal efficiency

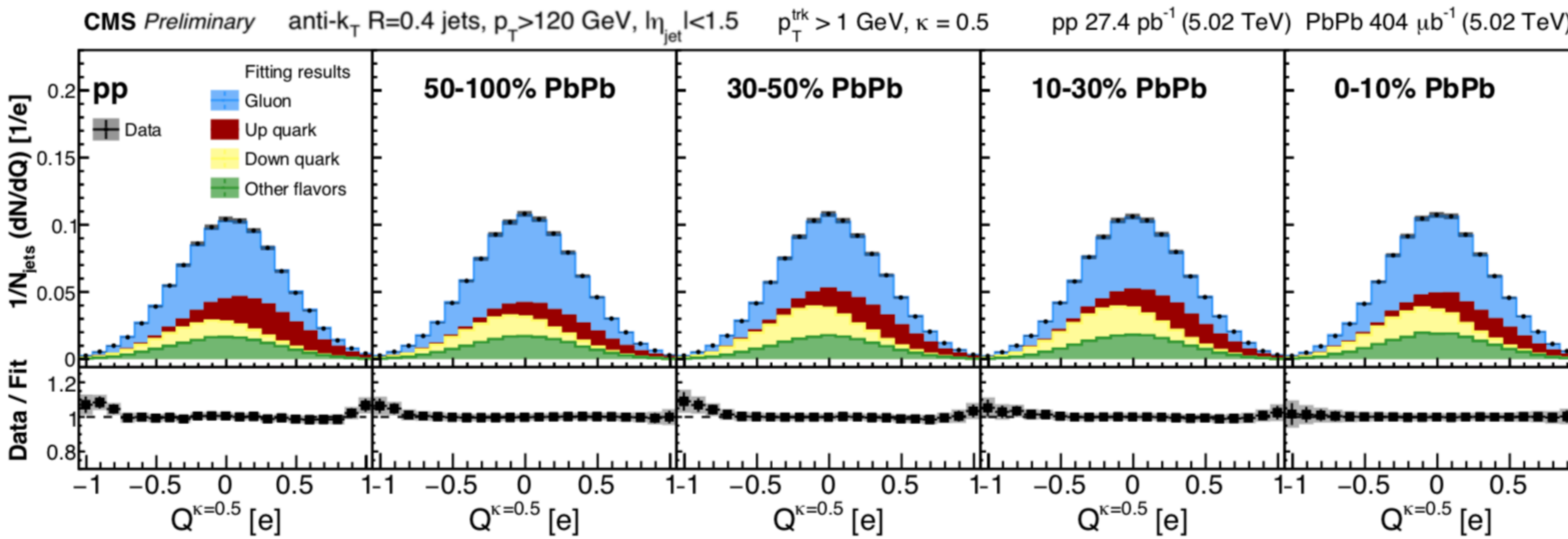
Stability vs pile-up is under investigation

Might not be directly applicable to AA but combine it with other taggers.

http://cds.cern.ch/record/1599732/files/JME-13-002-pas.pdf

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

An approach for PbPb Quark/Gluon-like Jet Fractions



$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_{i \in jet} q_i (p_{\mathrm{T}}^{i})^{\kappa}.$$

κ parameter adjusts sensitivity of jet-charge to high/low p_T tracks

κ = 0.5 → most sensitive to parton charge initiating jet! [according to theory]

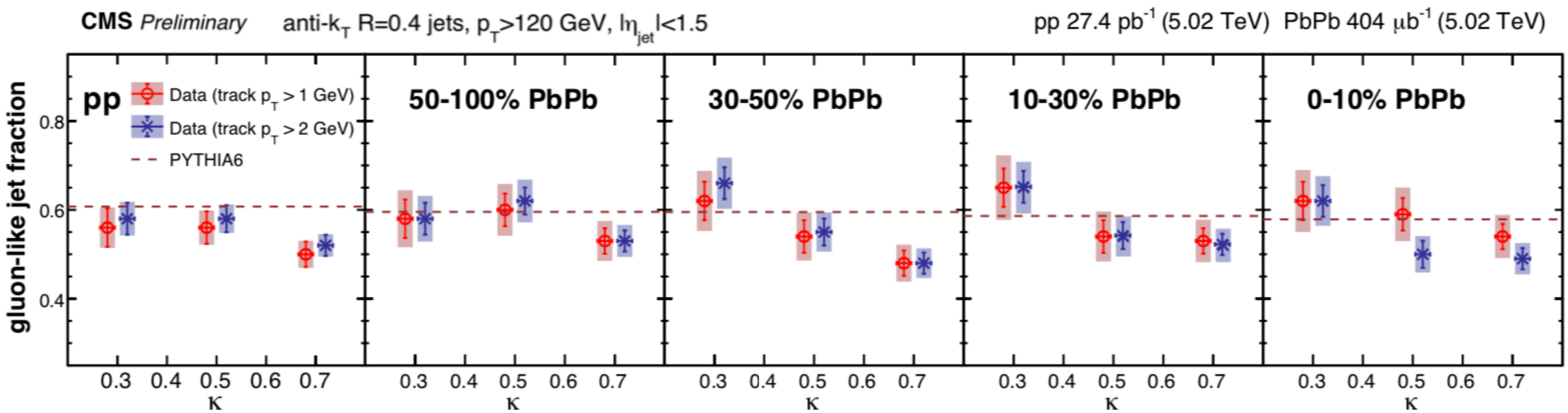
quark/gluon jet fractions extracted with template-fitting method

- Use PYTHIA and PYTHIA+HYDJET for pp/PbPb model
- Q^{κ} in data fully corrected for both background effects and tracking inefficiencies

CMS-HIN-18-018

Quark/Gluon-like Jet Fractions

CMS-HIN-18-018



$$Q^{\kappa} = \frac{1}{(p_T^{jet})^{\kappa}} \sum_{i \in jet} q_i (p_T^i)^{\kappa}.$$

κ parameter adjusts sensitivity of jet-charge to high/low p_T tracks
κ = 0.5 → most sensitive to parton charge initiating jet! [according to theory]

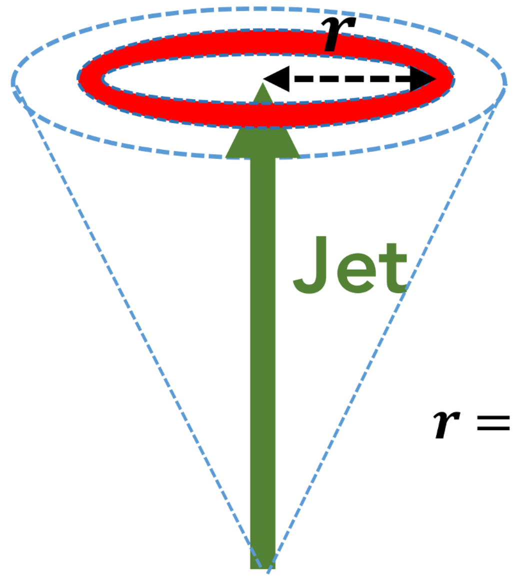
No significant modification of quark/gluon jet fraction in PbPb
Contradicts expectations of some jet quenching models
Remains to be the case for variation of track pT cuts, κ values

Differential jet shape

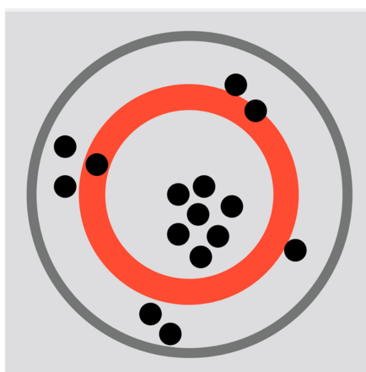
Averaged over many jets

- *Differential jet shape:*

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}\, p_{\mathrm{T}}^{\text{trk}}}{p_{\mathrm{T}}^{\text{jets}}}$$

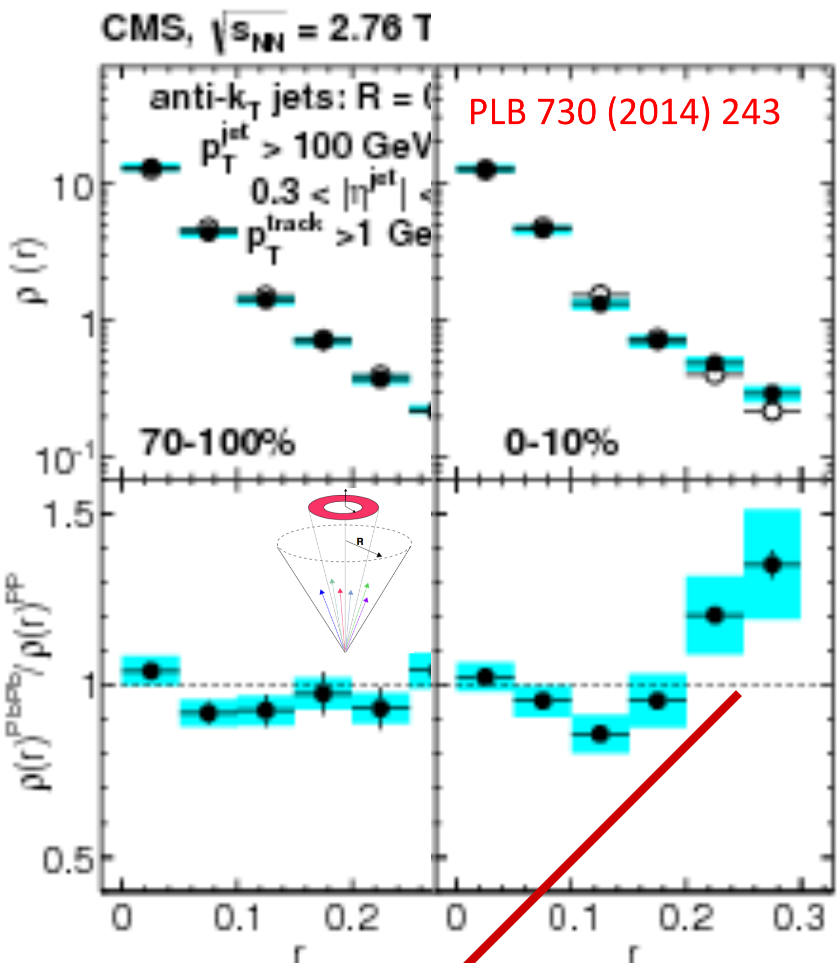


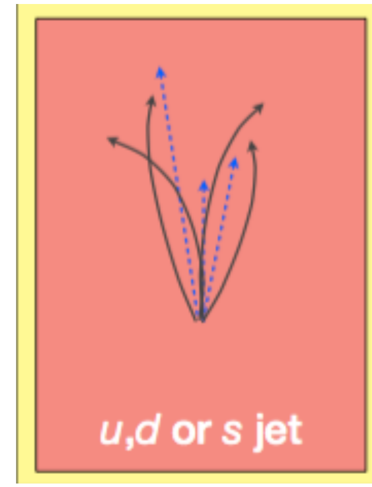
$$\boldsymbol{r} = \sqrt{(\boldsymbol{\Delta\varphi})^2 + (\boldsymbol{\Delta\eta})^2}$$



Jet shape function: provides information about the radial distribution of the momentum carried by the jet constituents (fragments)

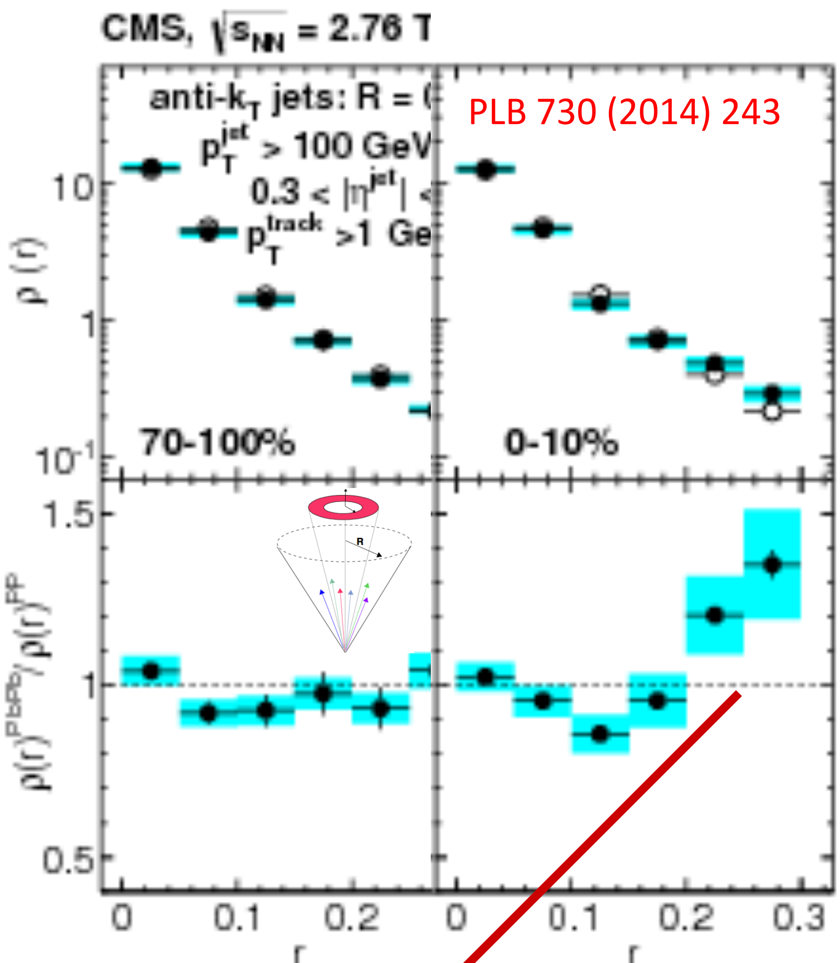
Jet Shapes @ LHC:

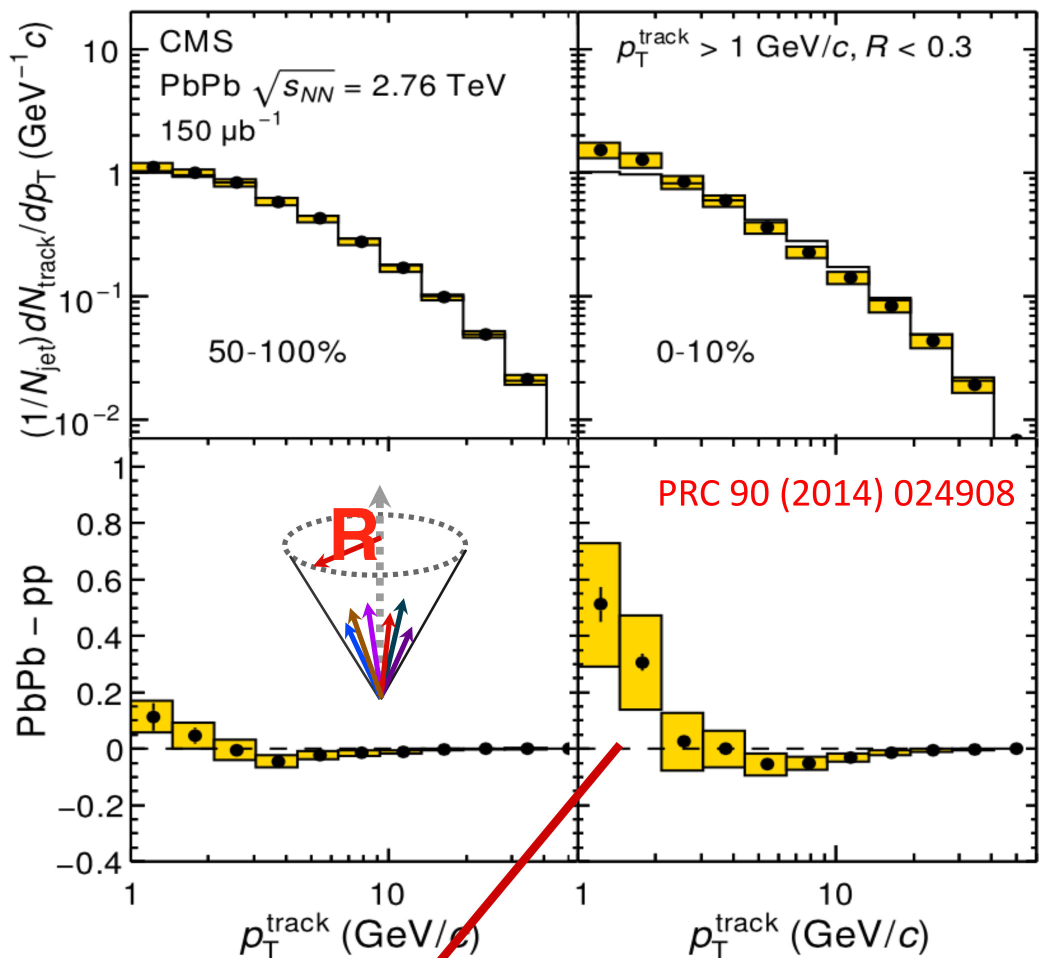




Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis

Change in Jet Morphology as seen with CMS @ LHC:

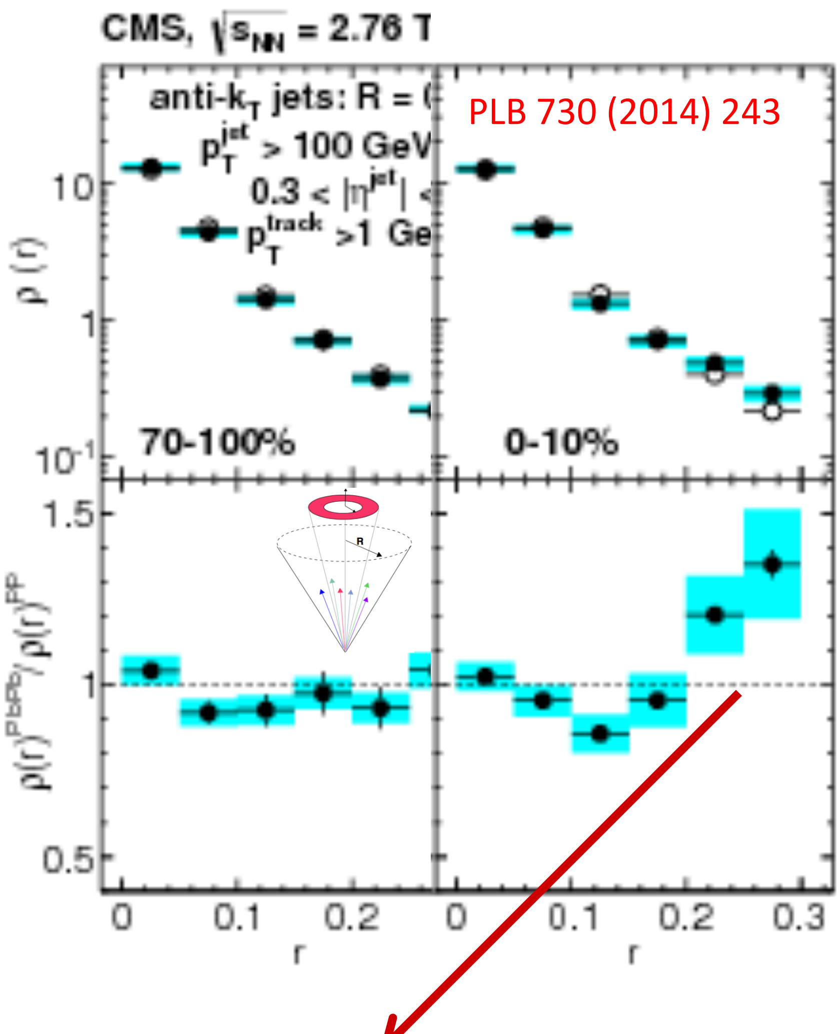


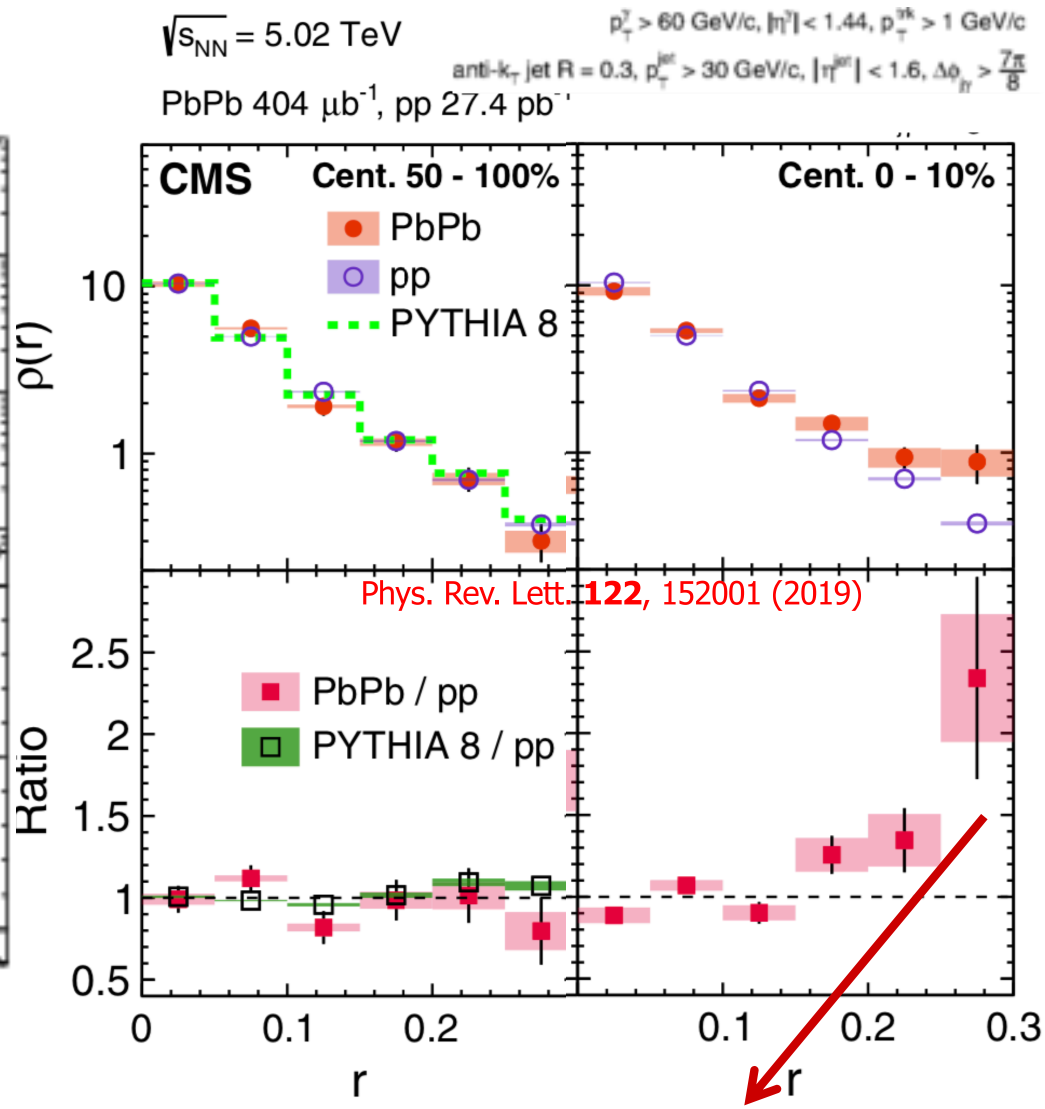


Jet Shapes: Structure of reconstructed jets modified towards an excess of particles far from the jet axis

Fragmentation Functions: Structure of reconstructed jets is modified towards an excess of particles at low p_T.

Jet Shapes @ LHC:

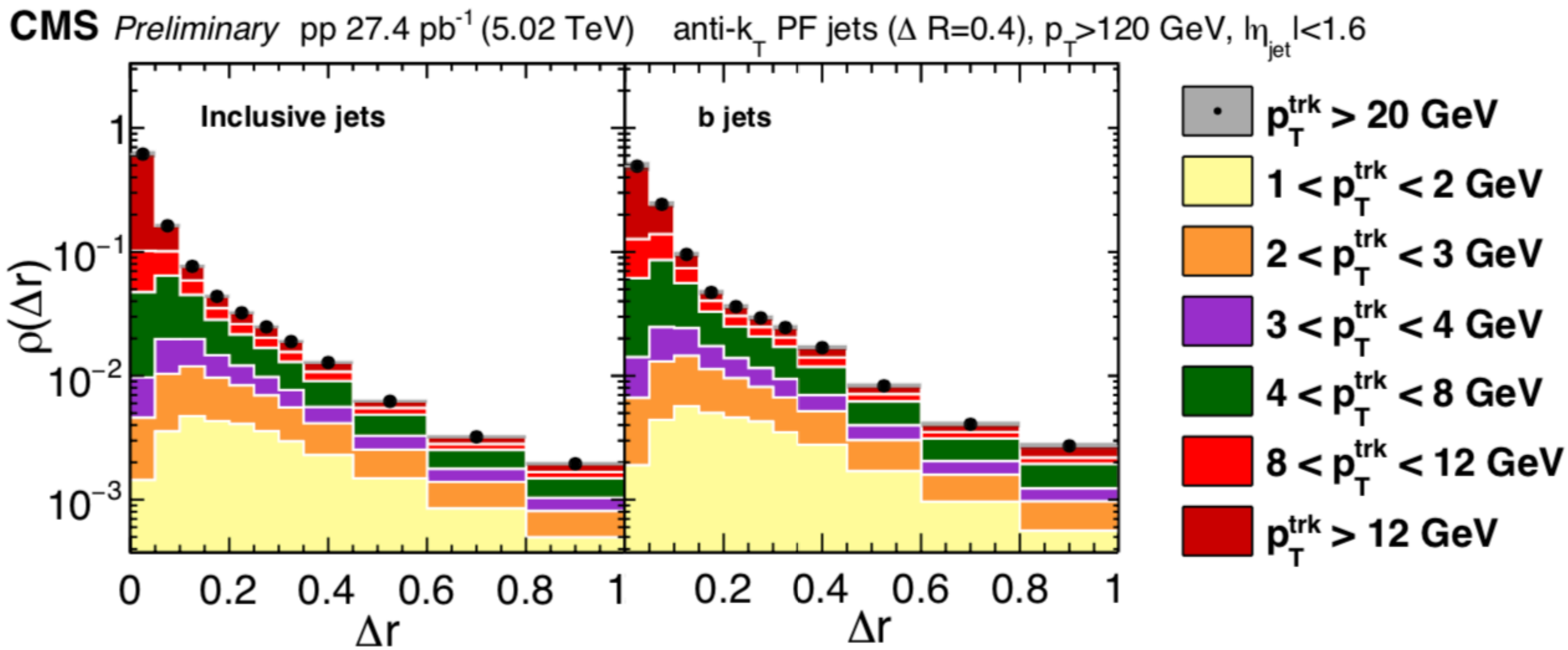


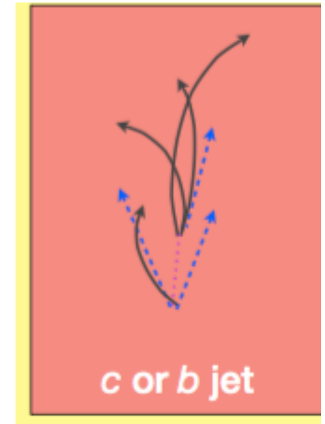


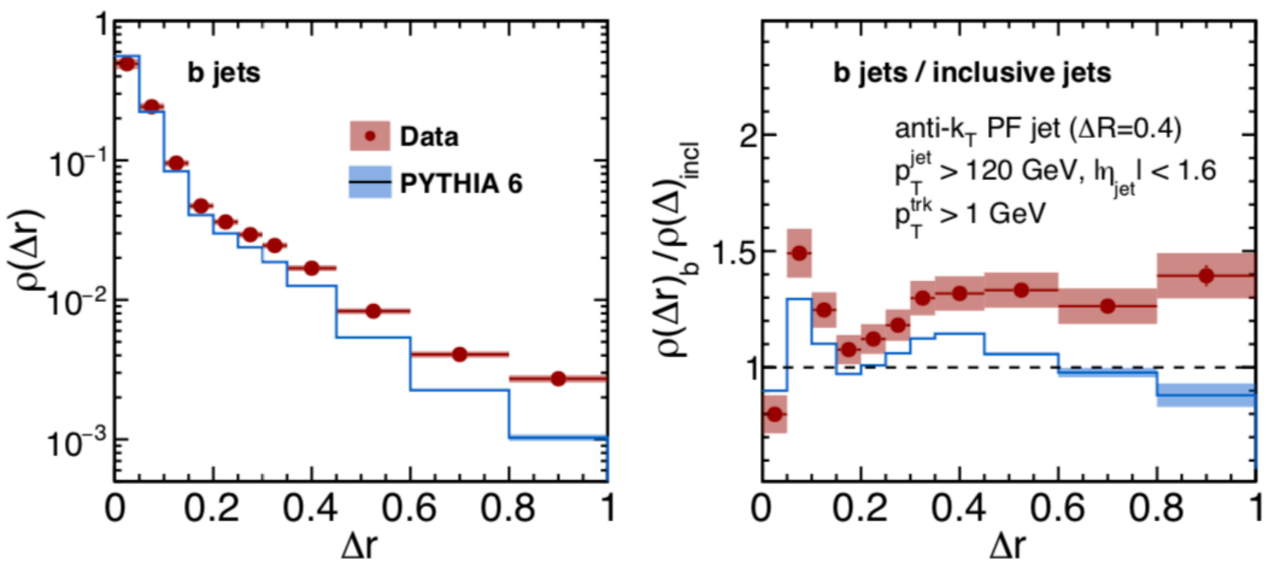
<u>Jet Shapes:</u> Structure of reconstructed jets modified towards an excess of particles far from the jet axis

<u>Jet Shapes of $\gamma + jet$:</u> Structure of reconstructed mostly quark-jets is modified towards an excess of particles from the jet axis.

Jet Shapes @ LHC:





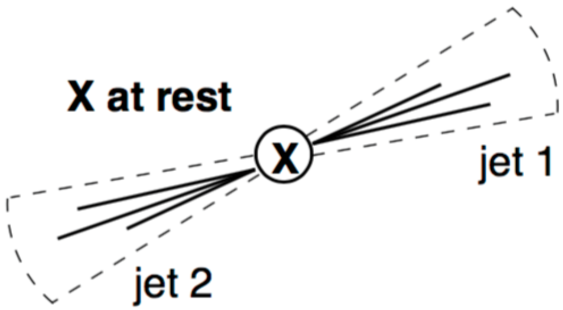


Constraints on pQCD calculations for flavor dependencies in parton

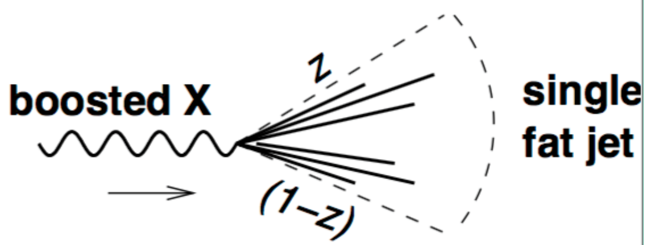
Important reference for the future studies of flavor effects for parton interactions with the quark-gluon plasma.

HIN-18-020

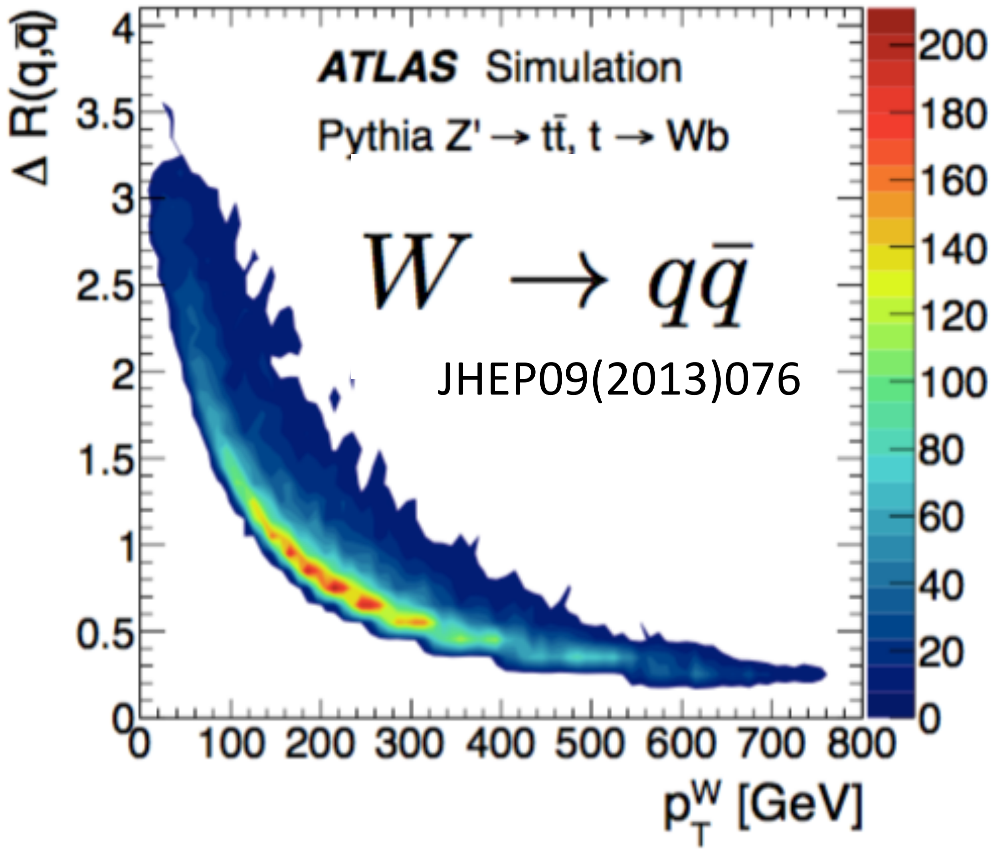
Utilize tools developed for pp - Jet Grooming:
the systematic removal of a subset of the jet constituents
→remove soft and wide-angle radiation from the jet



High-pT regime: $p_T > 2m/R$



Decay is collimated i.e., qq are in the same jet.



Utilize tools developed for pp - Jet Grooming:
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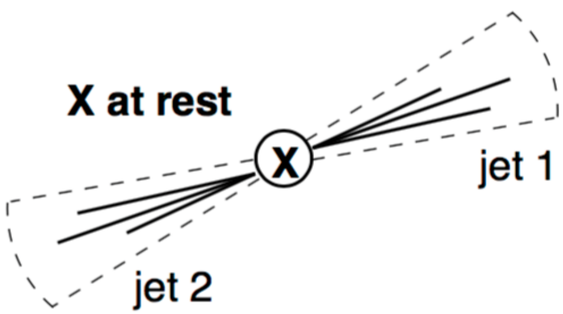
→remove soft and wide-angle radiation from the jet



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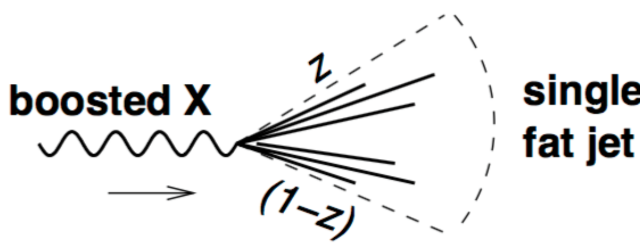

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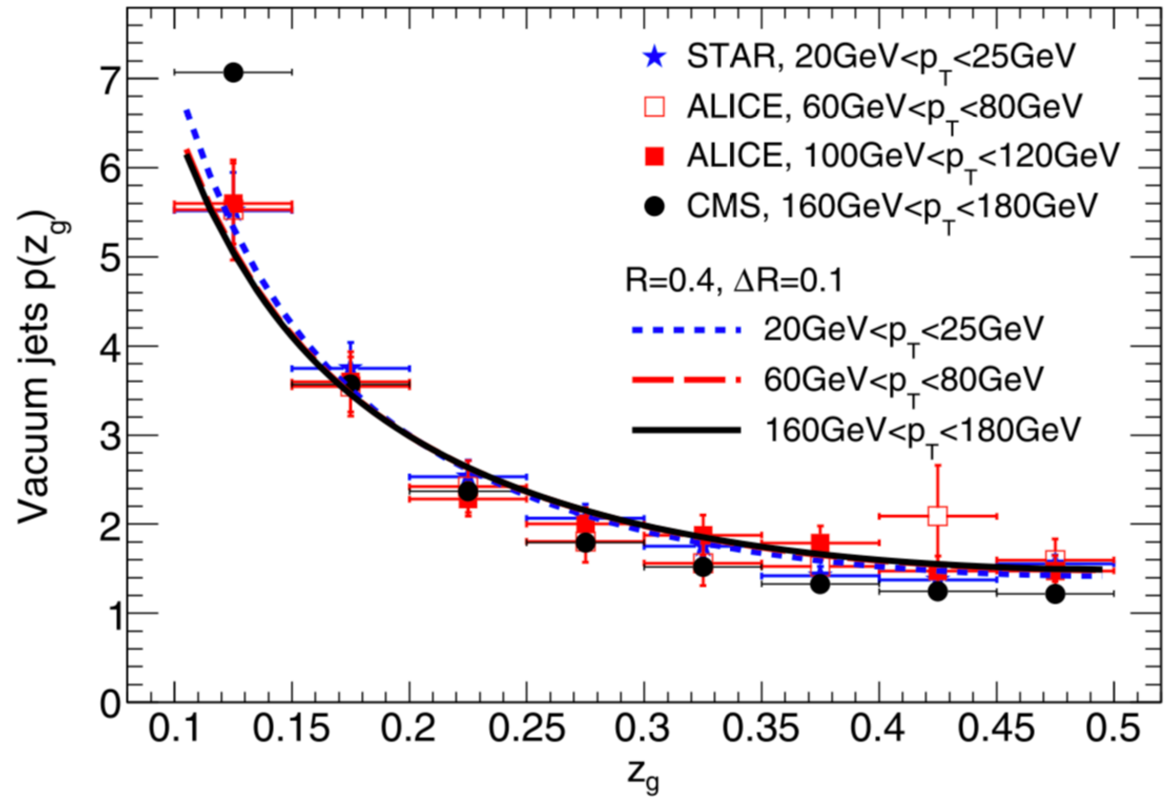
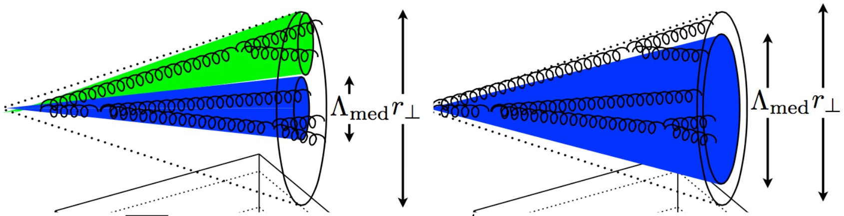


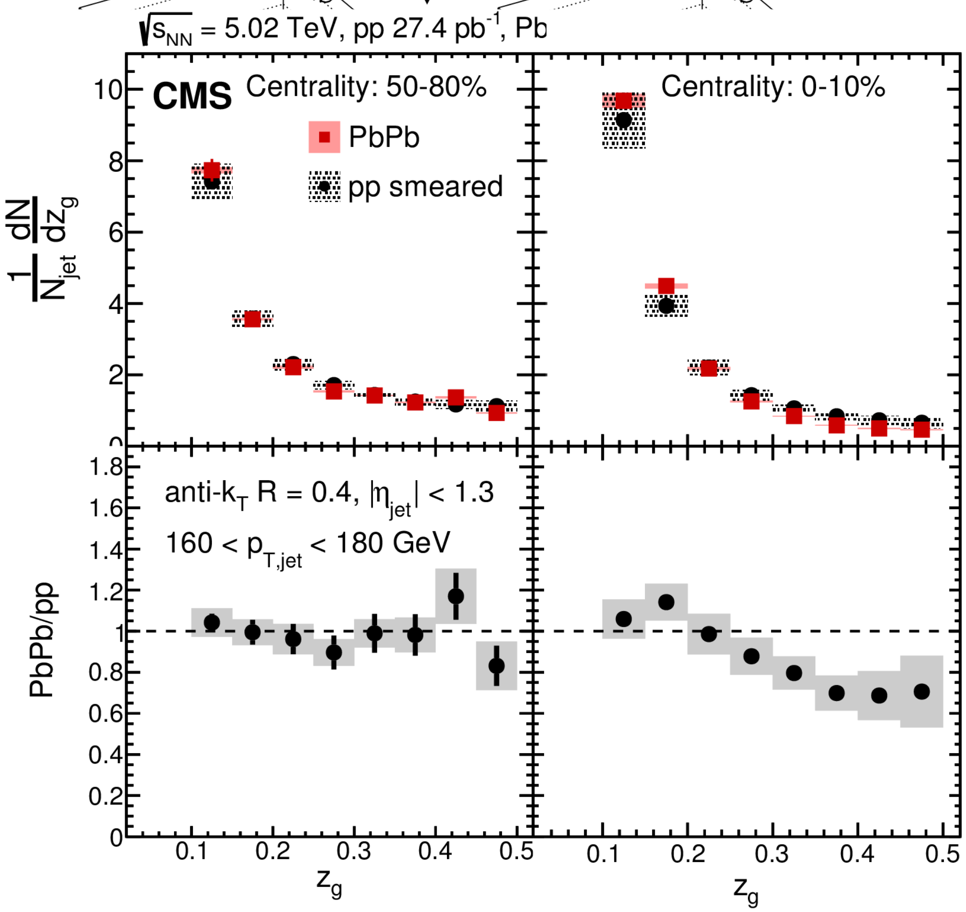
Compiled by N.-B. Chang et al. / Physics Letters B 781 (2018) 423–432

Momentum sharing between two leading subjets:

Utilizing Jet Grooming @ LHC



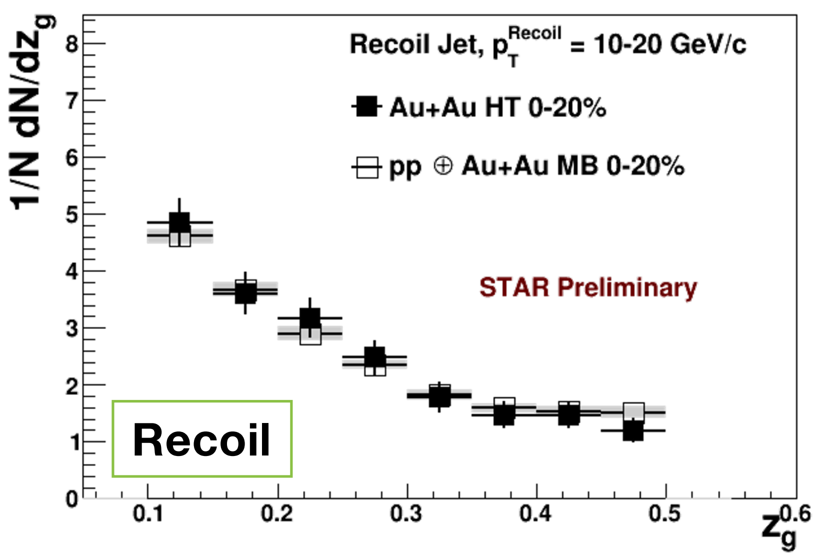
large-angle soft radiation and bkg removed by grooming!



$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

Strong modification of branch splitting!

Utilizing Jet Grooming @ RHIC



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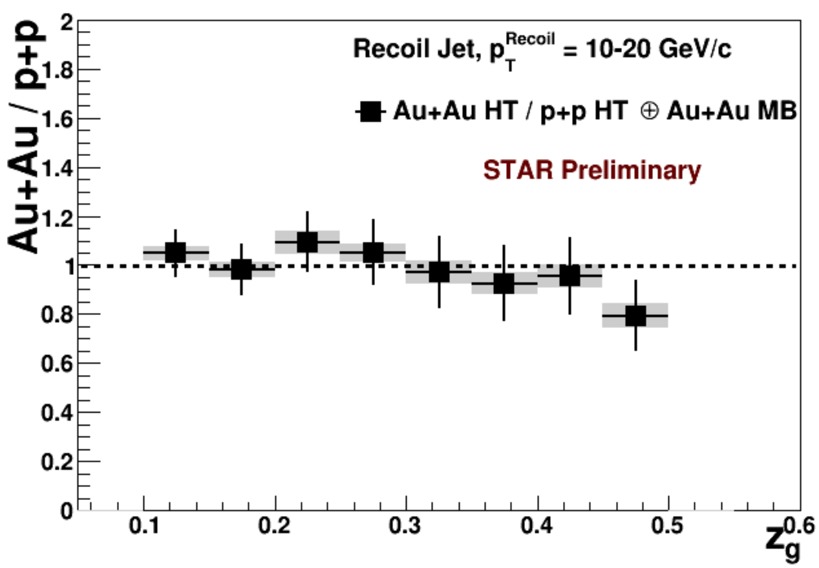
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



Contrast to LHC
→ Time of split, kinematics, dilution,

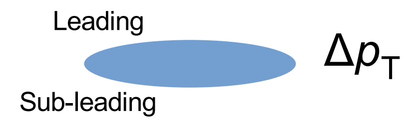
No significant splitting modification on near-or away-side at RHIC

In this talk: Jet structure observables at RHIC energies

- *LeSub:*

$$LeSub = p_{T,track}^{lead} - p_{T,track}^{sublead}$$

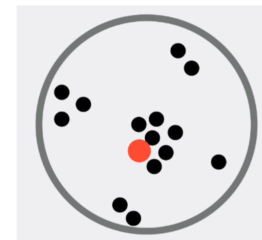
(Thomas Gosart – Rutgers) – charged jets



- *Fragmentation*
- *function (FF):*

$$FF(z) = \frac{1}{N_{jet}} \frac{dN}{dz} \qquad z = \frac{p_{||}^{track}}{p^{jet}}$$

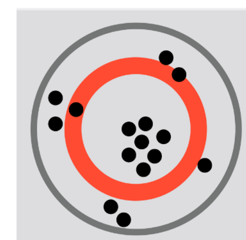
(Saehanseul Oh – LBL) – charged jets



- *Differential*
- *jet shape:*

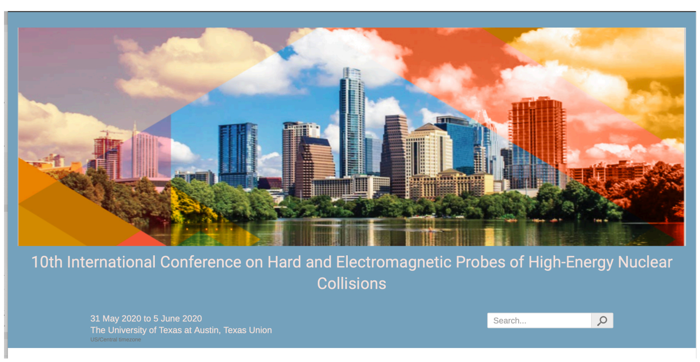
$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\mathrm{jets}}} \Sigma_{\mathrm{jets}} \frac{\Sigma_{\mathrm{tracks} \in (r_a, r_b)} p_{\mathrm{T}}^{\mathrm{trk}}}{p_{\mathrm{T}}^{\mathrm{jets}}}$$

(Joel Mazer – Rutgers) – full jets



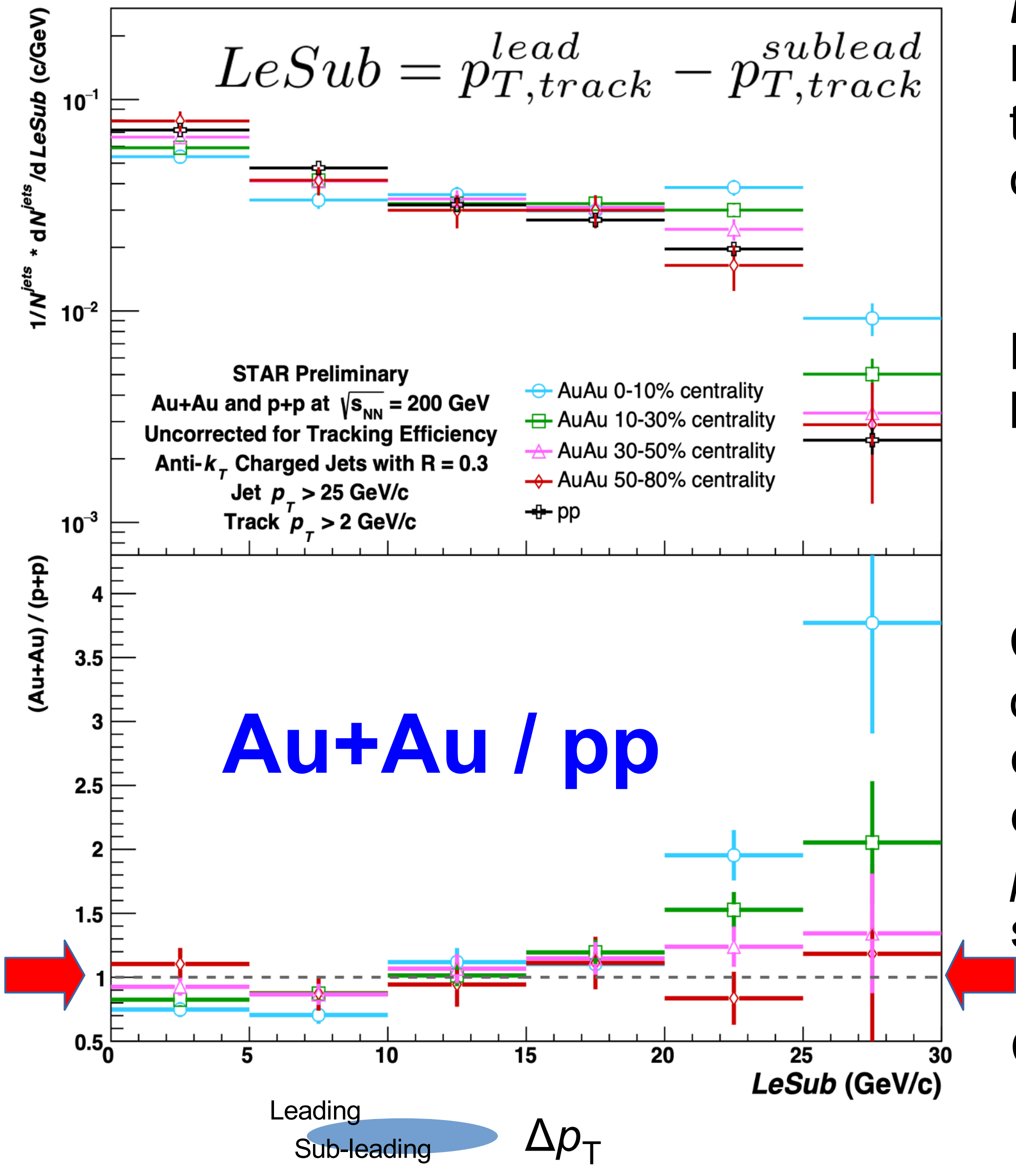
girth (g),
angurlarity

This is not a complete list of studies!



New results will be presented during Hard Probes!
(in Austin, remotely or in a postponed day!)

LeSub @ RHIC



LeSub:

Measures the differences in momentum of the two highest (leading and subleading) constituents in a jet

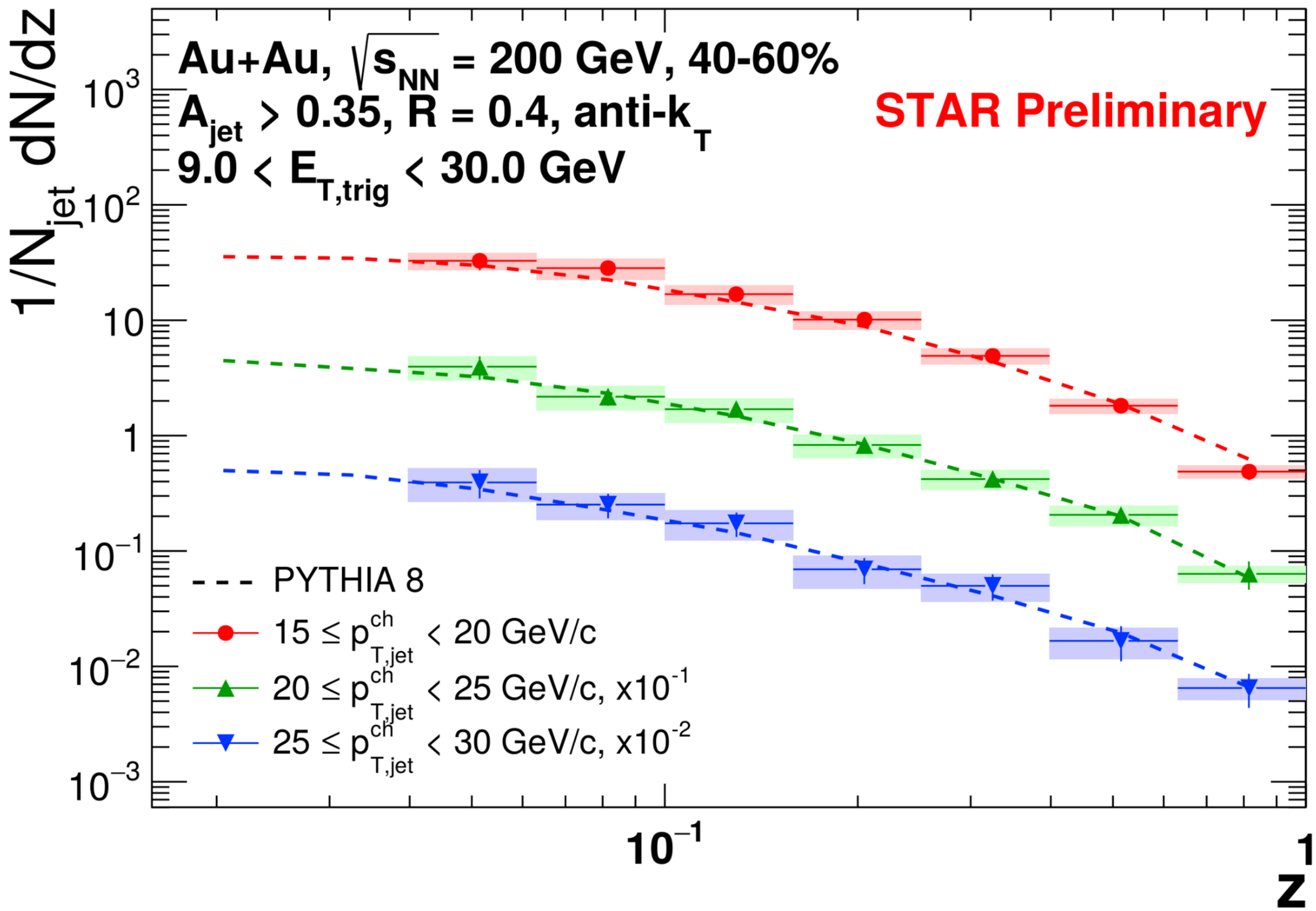
Robust against contributions of soft background particles

Comparison of pp with different Au+Au centralities suggest that the presence of a QGP in Au+Au causes a larger difference between the two highest p_T constituents of a jet (effect may be selection bias)

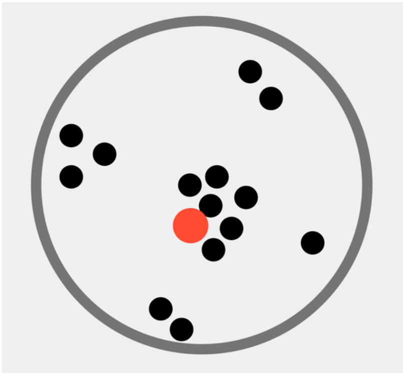
Caveat: Corrections like tracking efficiency are not complete.

Fragmentation Function @ RHIC

Fragmentation function: distribution of longitudinal momentum fraction of particle with respected to the jet

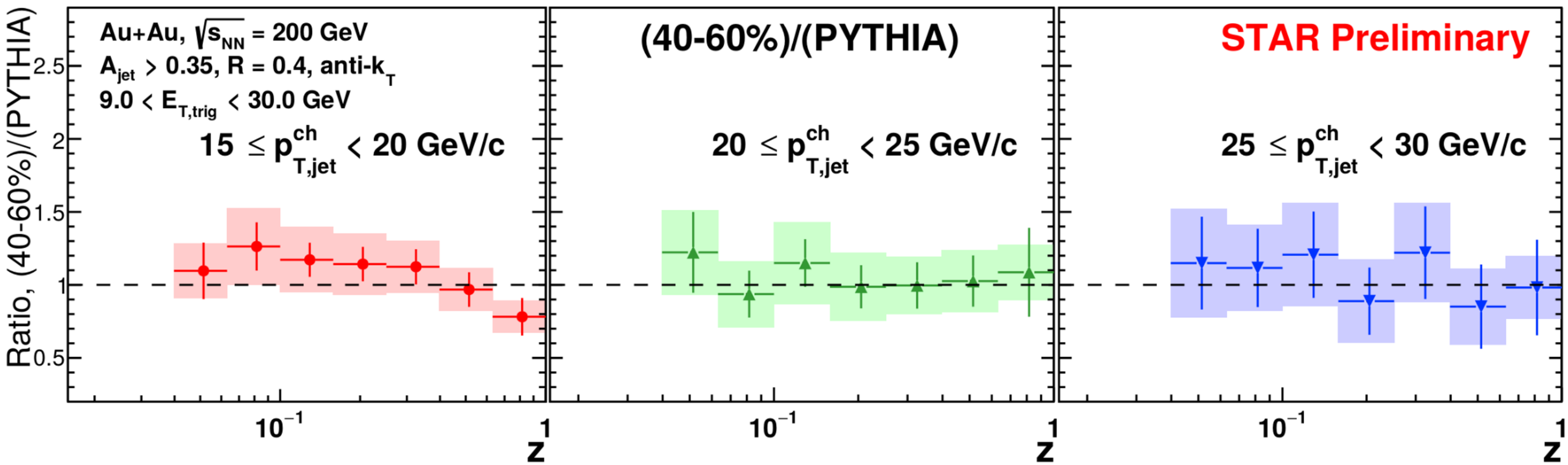


$$z = \frac{p_{||}^{track}}{p^{jet}}$$



Peripheral (40-60% central) Au+Au collisions for 3 jet p_T ranges (15-30 GeV/*c)* are compatible with corresponding PYTHIA 8 calculations of pp at 200 GeV

Fragmentation Function @ RHIC



40-60% central Au+Au / pp (PYTHIA) ratio at 200 GeV:

–Remains near 1 within uncertainties throughout the full z range and for 3 separate charged jet p_T ranges spanning **15-30 GeV/*c***

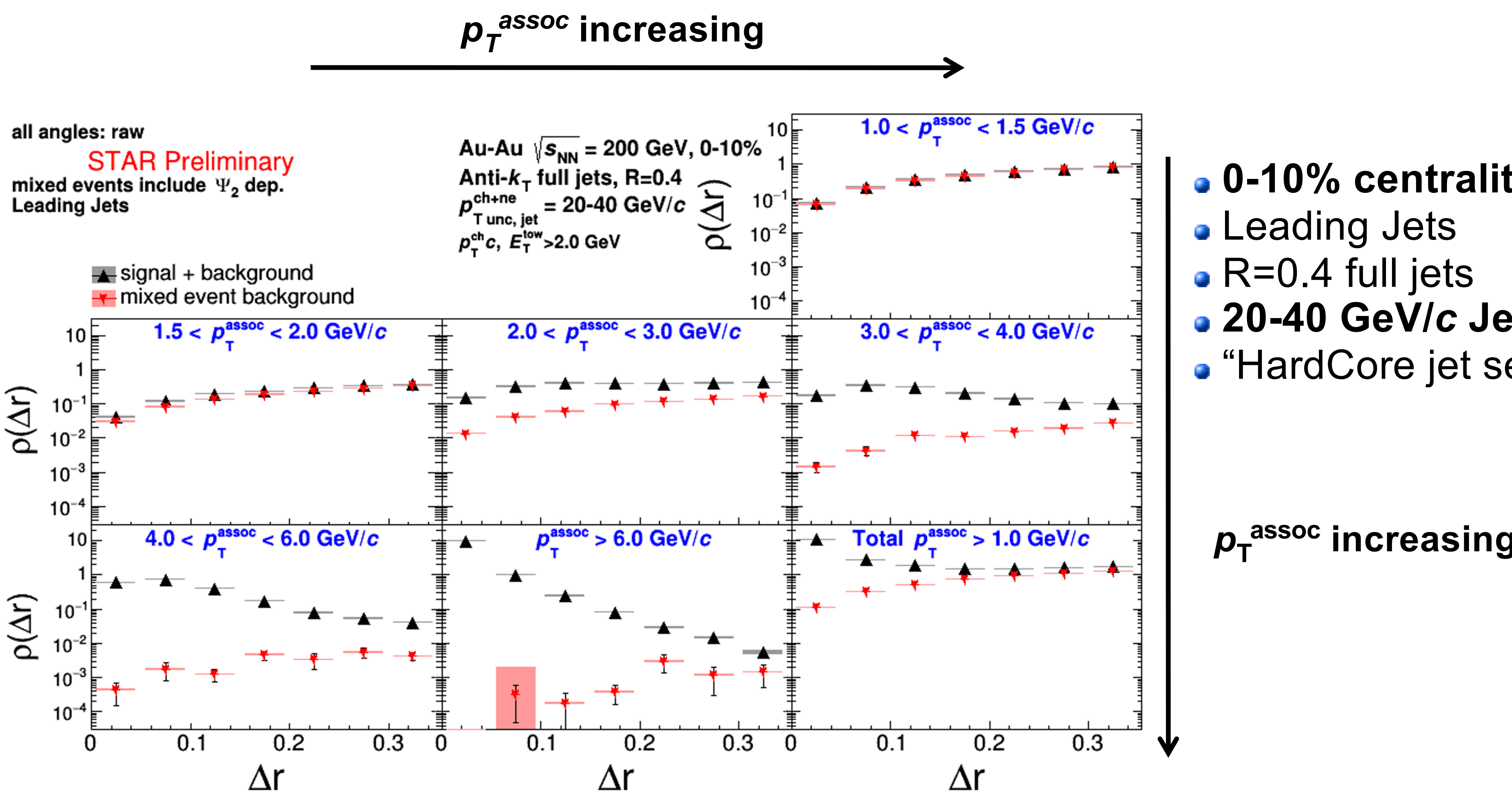
These results can potentially be connected to various physics scenarios:

–Tangential jet selection with a high-p_T trigger particle and recoil jet configuration? which causes no significant in-medium path-length of the jet

–Less jet-medium interactions in 40-60% central heavy-ion collisions at 200 GeV?

–Short path-length of jets in medium in 40-60% centrality?

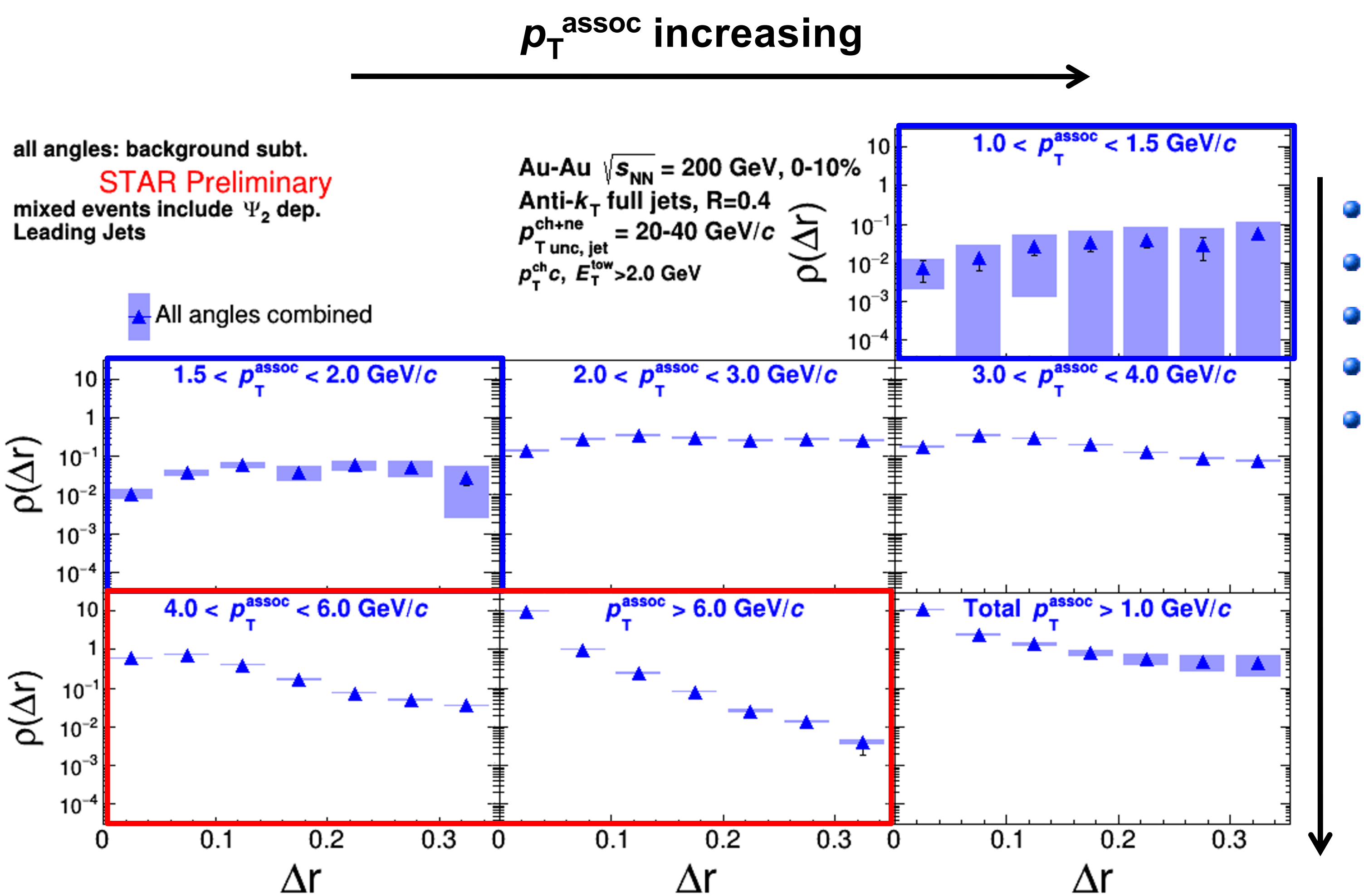
Raw differential jet shape



- **0-10% centrality**
- Leading Jets
- R=0.4 full jets
- **20-40 GeV/*c* Jets**
- "HardCore jet selection

- Sum up charged track p_T in Δr bins from the trigger jet axis
- Sum up charged track p_T in Δr bins from background jet axis in mixed events from minimum bias events of similar event class (centrality, z_{vtx}, event plane angle)

Corrected differential jet shape: central

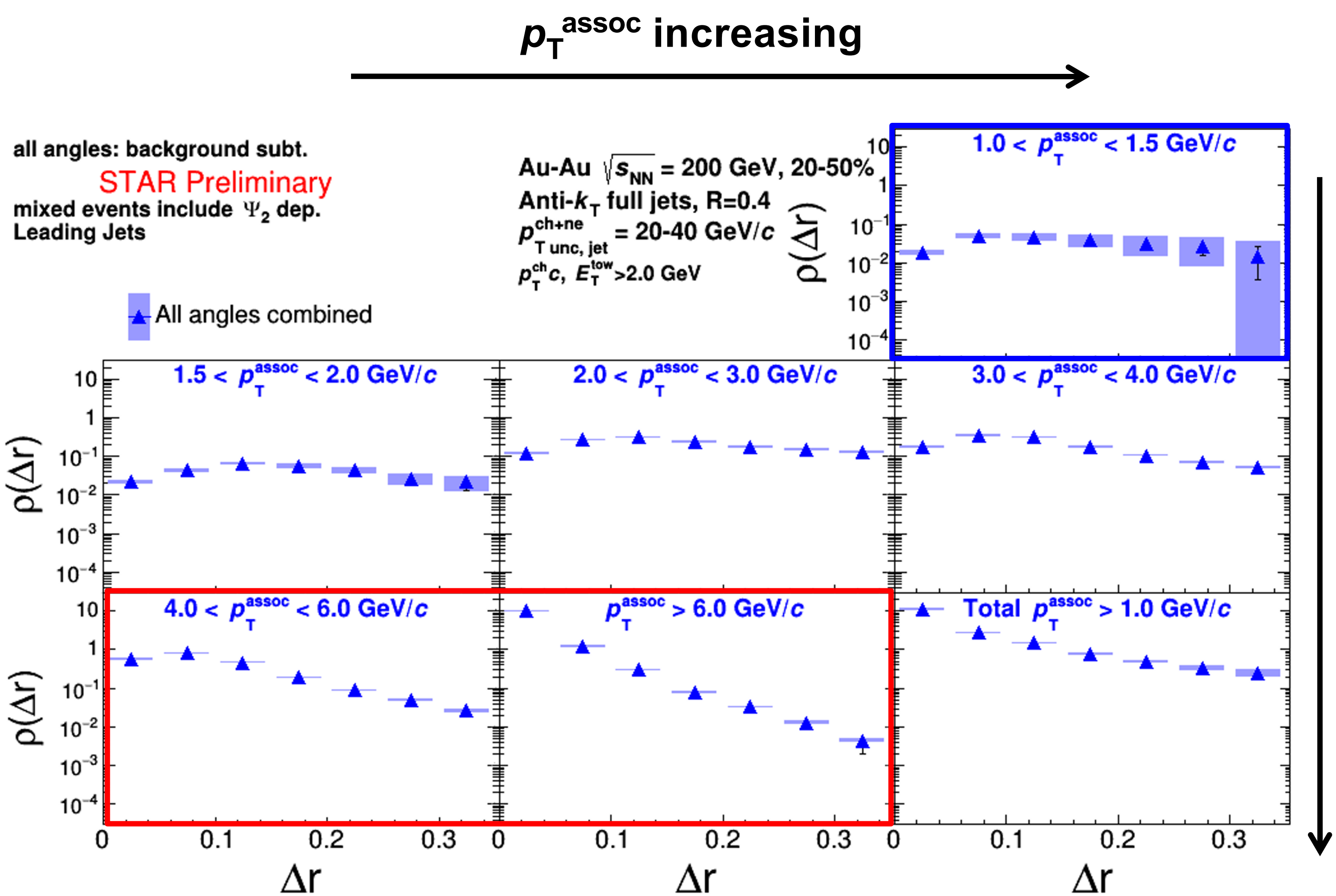


- **0-10% centrality**
- Leading Jets
- R=0.4 full jets
- **20-40 GeV/*c* Jets**
- “HardCore jet selection

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}\, p_T^{\text{trk}}}{p_T^{\text{jets}}}$$

- Low-p_T tracks dominated by background
- High-p_T tracks located near jet core compared to low-p_T, as expected

Corrected differential jet shape: mid-peripheral



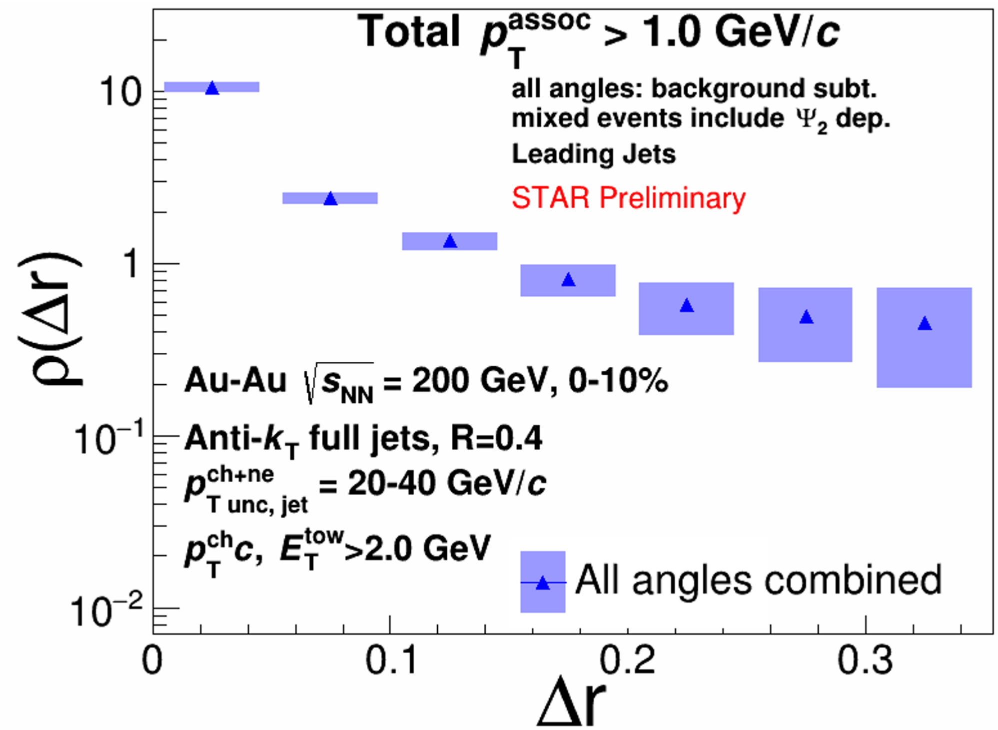
- **20-50% centrality**
- Leading Jets
- R=0.4 full jets
- **20-40 GeV/*c* Jets**
- “HardCore jet selection

$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}\,p_T^{\text{trk}}}{p_T^{\text{jets}}}$$

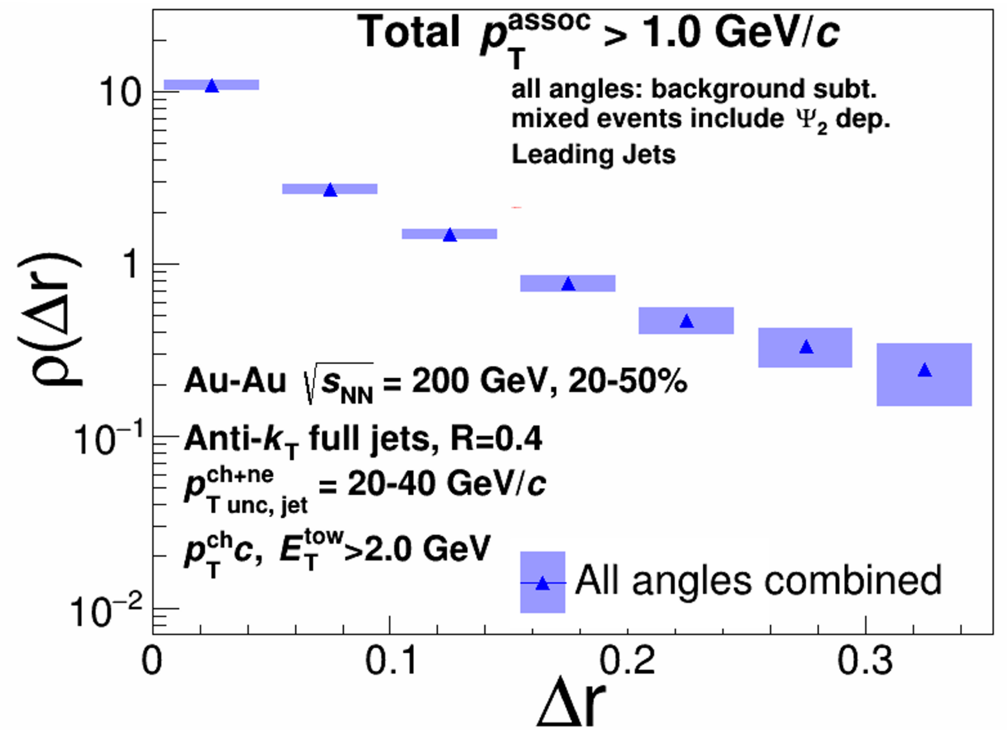
- Higher low-p_T yield near the core compared to central
- High-p_T tracks located near jet core compared to low-p_T, as expected

Total differential jet shape: 1.0+ GeV/*c* tracks

0-10% centrality



20-50% centrality



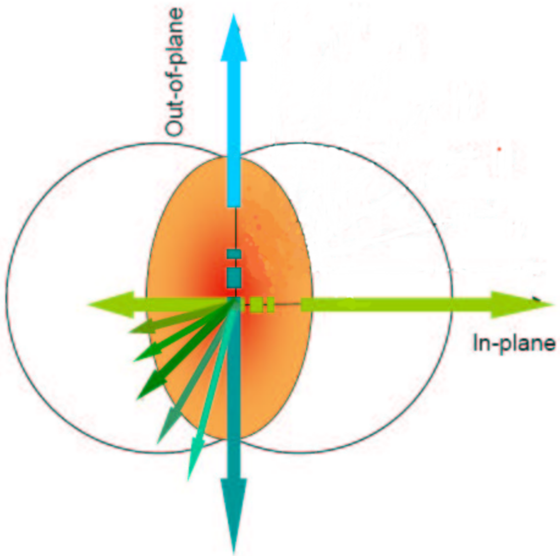
R=0.4 full jets, **20-40 GeV/*c*,** ***"HardCore jet selection"***

Jet shapes appear to be less steep at 200 GeV than at LHC energies

- Changes in kinematic range

Jet shapes relative to event plane

- Can we control *path-length* of jet quenching with centrality and *event plane angle?*
- Fix trigger jet relative to the “2nd order” event plane: $\Psi_{EP,2}$



Event plane reconstruction: similar approach to Phys. Rev. C89 (2014) 041901(R)

Event plane dependence

IN-plane: $0° < |\varphi_{jet} - \Psi_{EP,2}| < 30°$

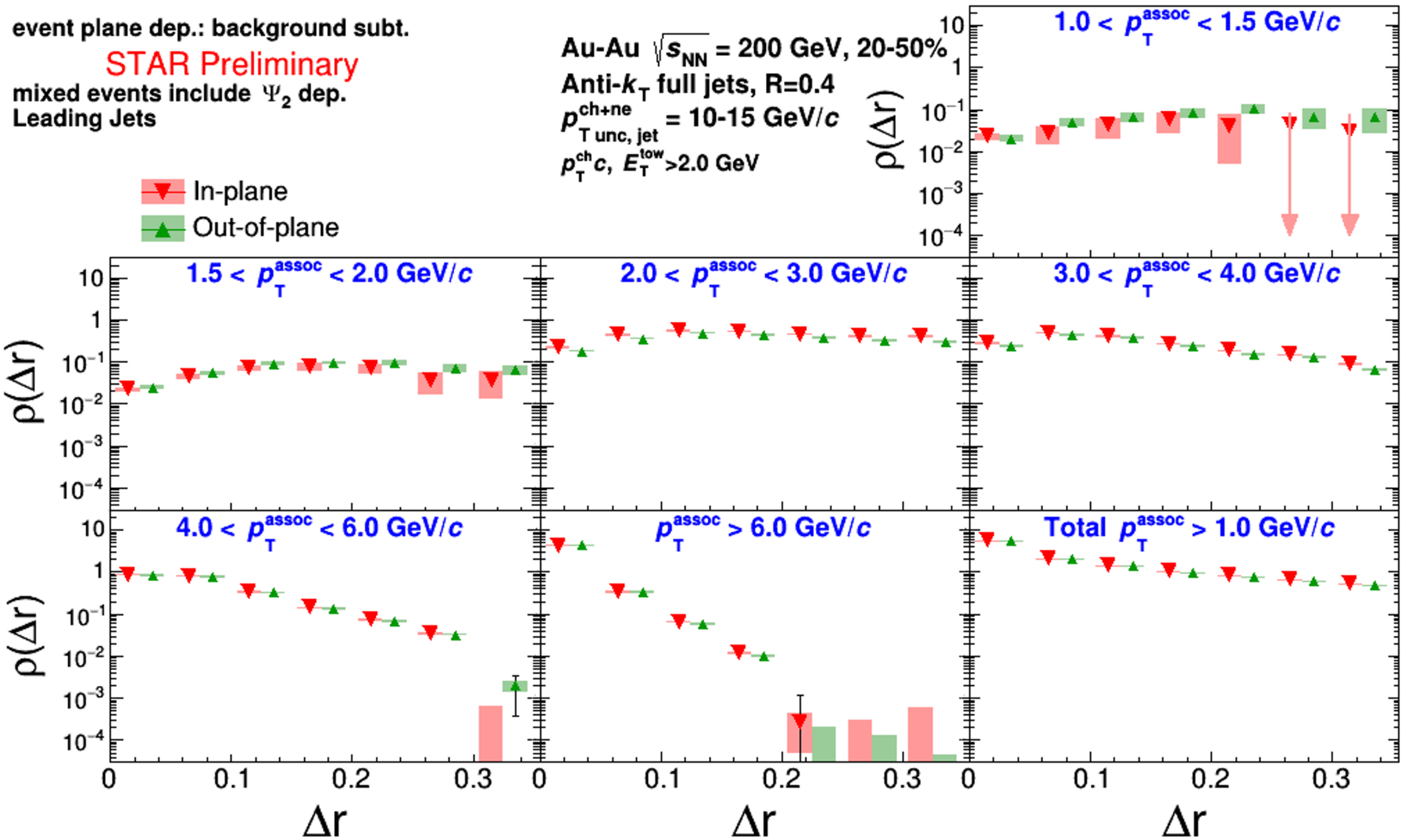
MID-plane: $30° < |\varphi_{jet} - \Psi_{EP,2}| < 60°$

OUT-of-plane: $60° < |\varphi_{jet} - \Psi_{EP,2}| < 90°$

- **Average path-length OUT > average path-length IN**
- Event plane (path-length) dependence of medium modifications?
- Are we sensitive enough?

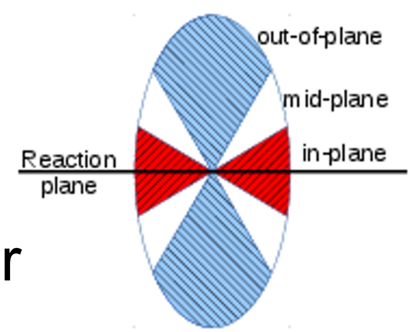
Event plane dependence

p_T^{assoc} increasing



- **20-50% centrality**
- R=0.4 full jets
- **10-15 GeV/*c* Jets**
- “HardCore jet selection”
- Background subtracted

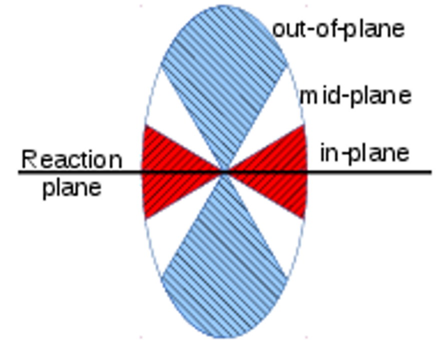
p_T^{assoc} increasing

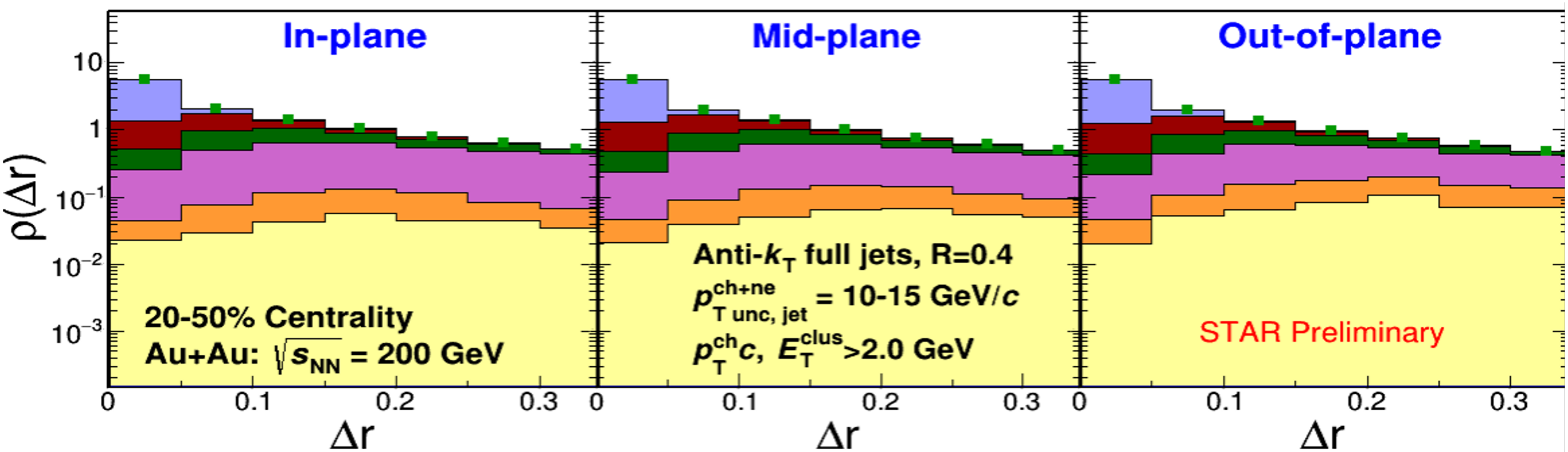


Corrected for event plane resolution
Above 2 GeV/*c*, results are consistent with each other

Event plane dependence: p_T^{jet}=10-15 GeV/*c*

- **20-50% centrality**
- **10-15 GeV/*c* R=0.4 full jets**
- Jet constituents: 2.0+ GeV/*c*
- *Mixed event background:*
- *centrality, z_{vtx}, event plane angle*

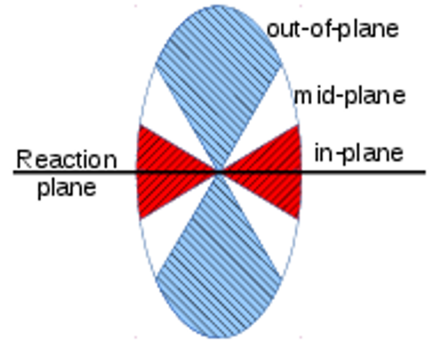


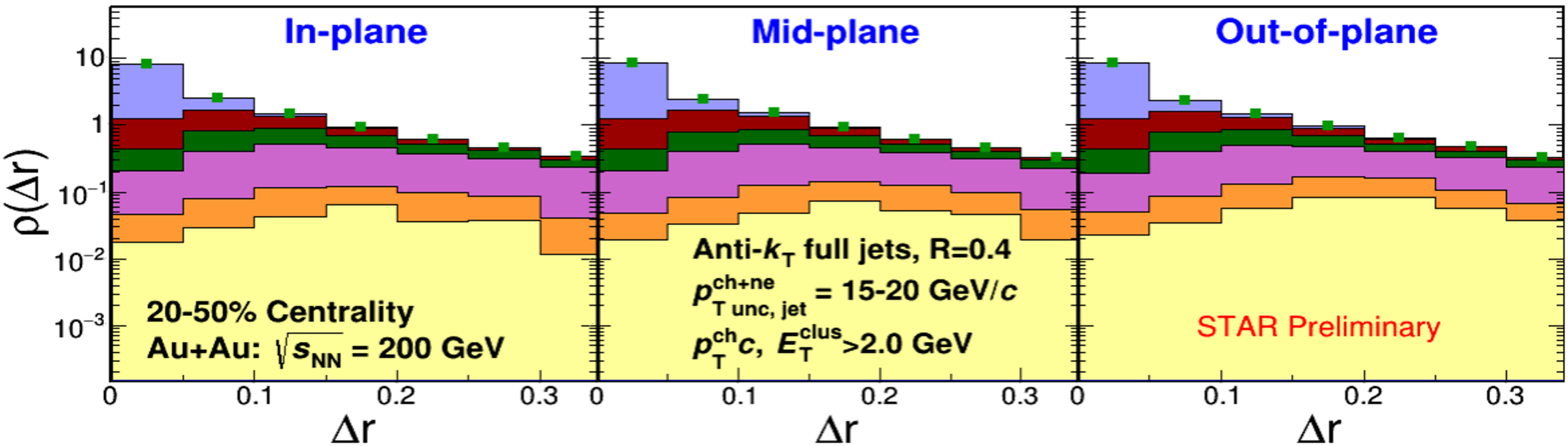


- Corrected for event plane resolution
- Hints of low-p_T tracks pushed toward farther distances in out-of-plane direction relative to in-plane direction
  - –Larger effects in the out-of-plane direction due to longer in-medium path-length?
- Above 2 GeV/*c*, results are consistent with each other

Event plane dependence: p_T^{jet}=15-20 GeV/*c*

- **20-50% centrality**
- **15-20 GeV/*c* R=0.4 full jets**
- Jet constituents: 2.0+ GeV/*c*
- *Mixed event background:*
- *centrality, z_{vtx}, event plane angle*

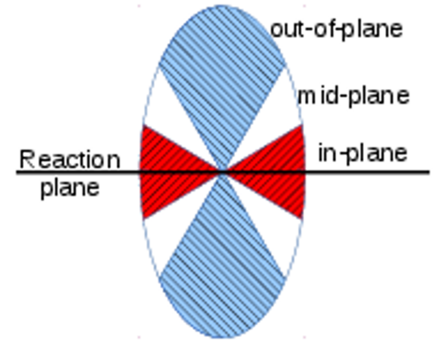


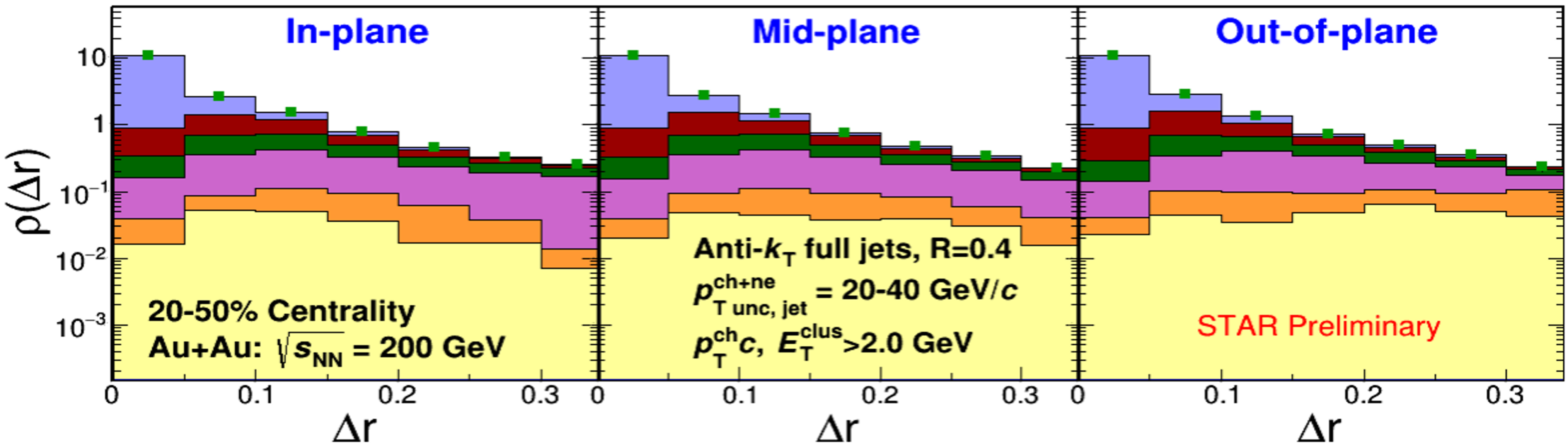


- Corrected for event plane resolution
- Hints of low-p_T tracks pushed toward farther distances in out-of-plane relative to in-plane
- Above 2 GeV/*c*, results are consistent with each other

Event plane dependence: p_T^{jet}=20-40 GeV/*c*

- **20-50% centrality**
- **20-40 GeV/*c* R=0.4 full jets**
- Jet constituents: 2.0+ GeV/*c*
- *Mixed event background:*
- *centrality, z_{vtx}, event plane angle*





- Corrected for event plane resolution
- Hint of event plane ordering at low p_T with current uncertainties

–Low-p_T tracks sensitive on path-length dependence of jet quenching?

- Higher momentum jets are more collimated: in/mid/out-of-plane

Conclusions

Jet Tomography has been explored with multiple jet substructure & constituent observables at various kinematic ranges.

But need to characterize medium parton interactions in detail!
Requires continuous interaction between Experiment & Theory