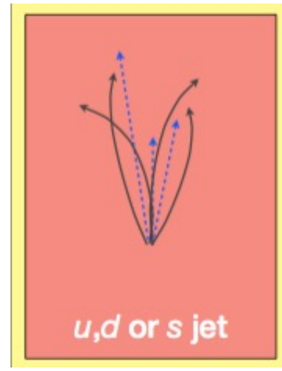
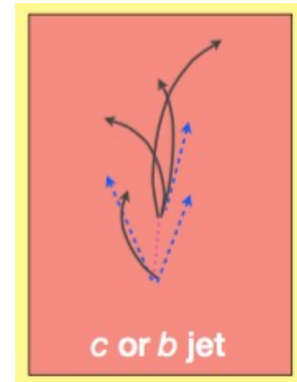
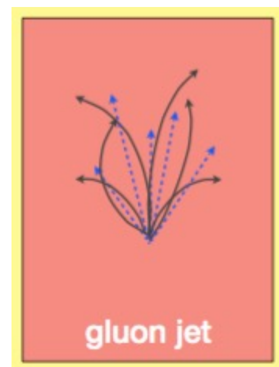
An overview of recent RHIC and LHC Jet Measurements

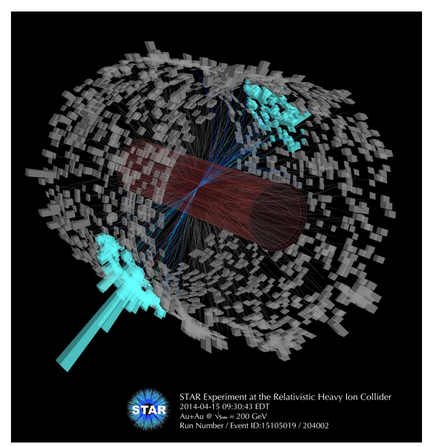
Sevil Salur

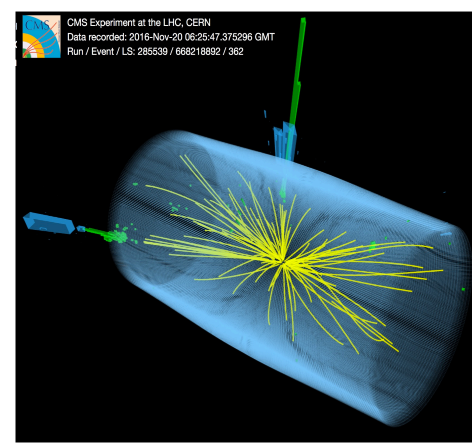
Rutgers University





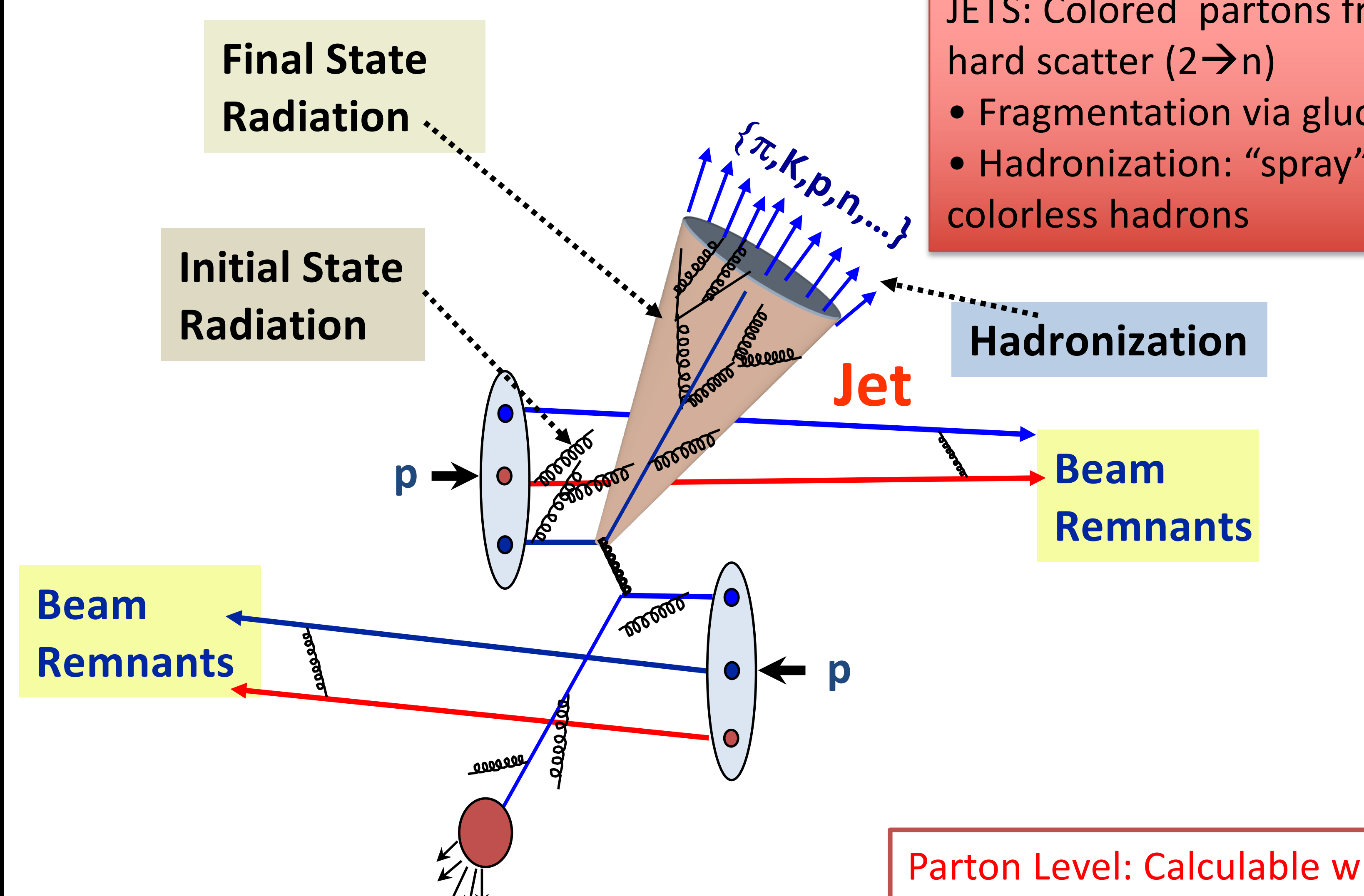






Jets: Theorist View

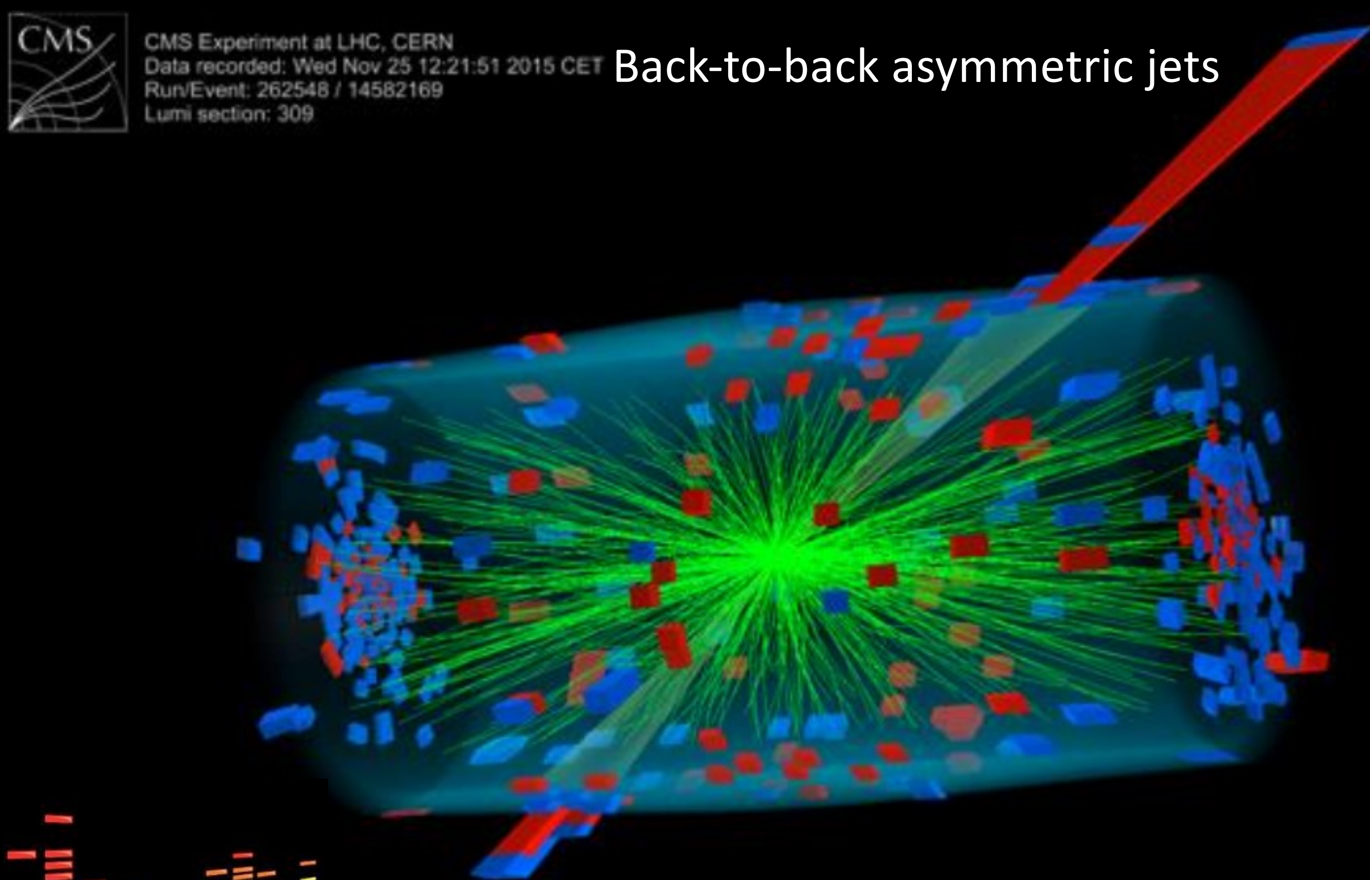
JETS: Colored partons from the hard scatter (2→n)
- Fragmentation via gluon radiation
- Hadronization: "spray" of colorless hadrons



Parton Level: Calculable with pQCD
Underlying Event: Beam remnants
→ Soft Background

S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977)
... and many more

Jets: Experimentalist View



Back-to-back asymmetric jets

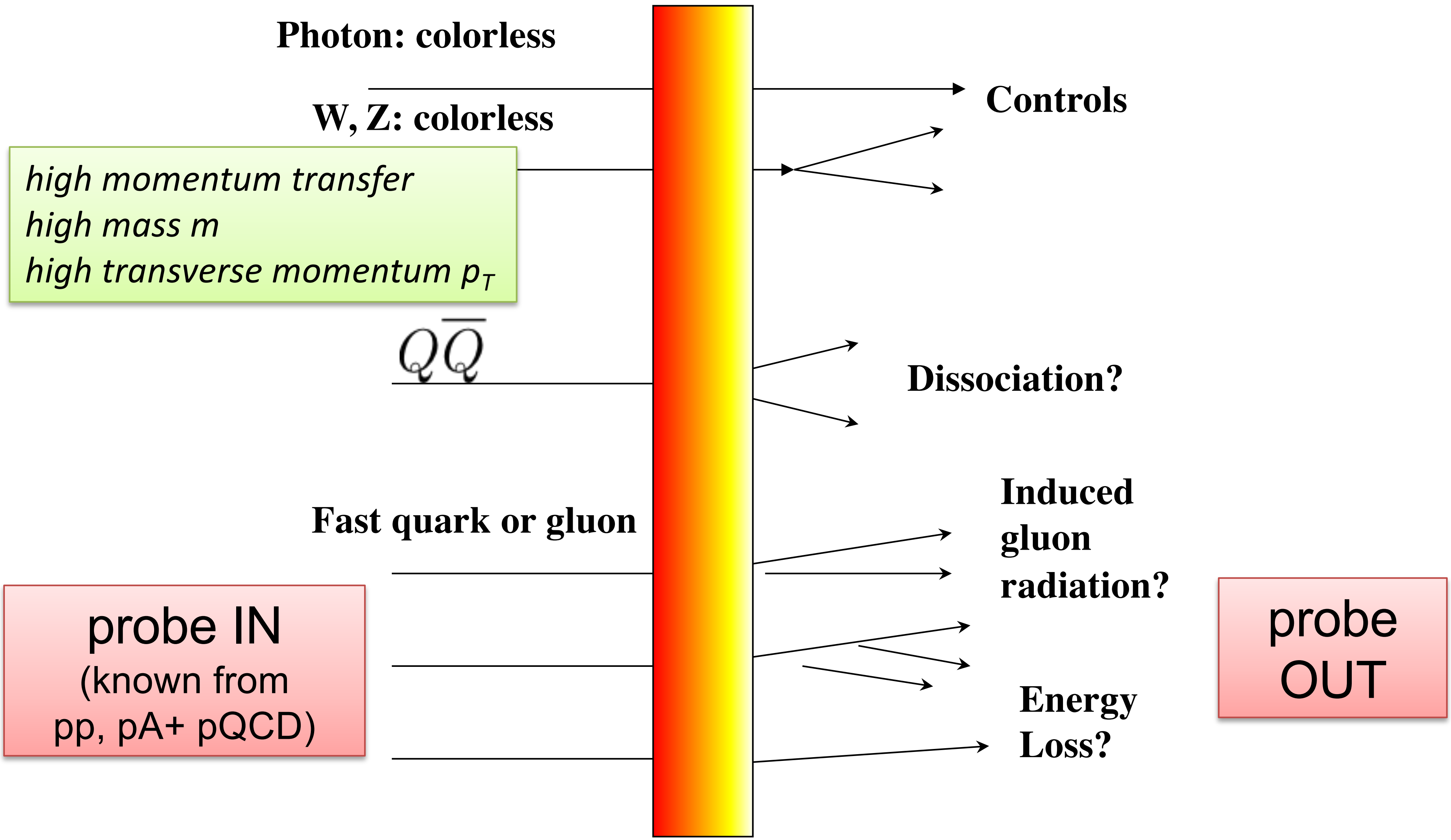
Large Fluctuating Underlying Event

Snow Mass Acord:

Experimental and theoretical definitions of jets must match!

Underlying event is the hardest to match.

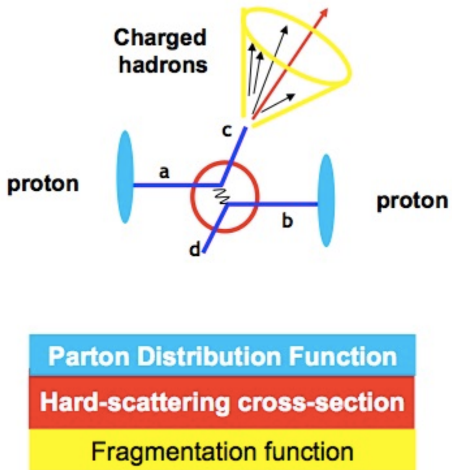
Unknown Medium

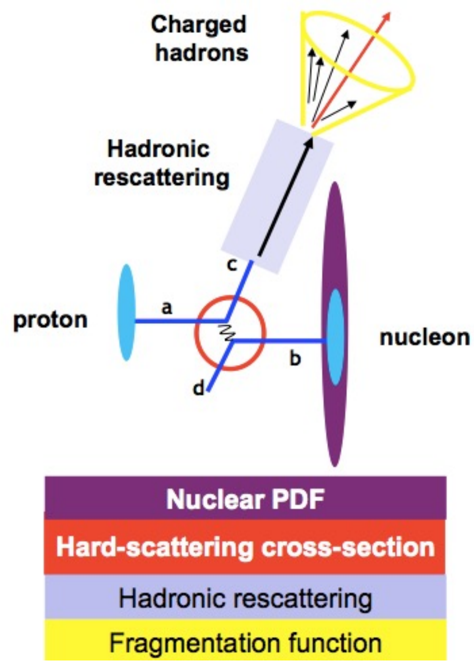


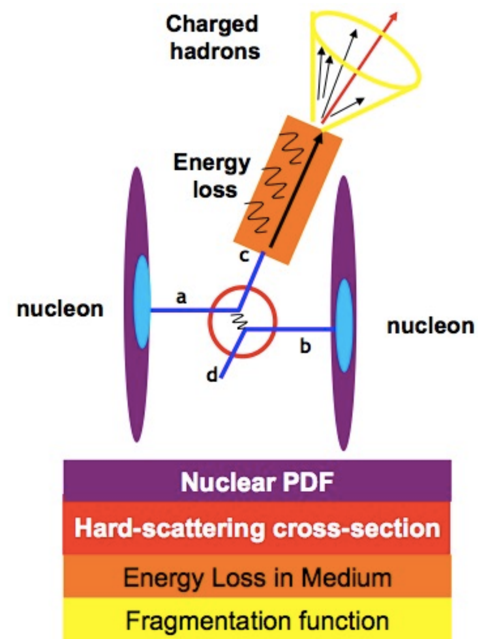
Diagnosing medium: pass a QCD-sensitive internal probe through it, then look for any modifications due to the medium.

To learn about the medium:

- Look at elementary/smaller collision systems
  - Measure an observable (e.g., in this case jet production)
- Look at Heavy Ion collisions
  - Measure the same observable as we do in elementary/smaller system
  - Compare them, is there something new?



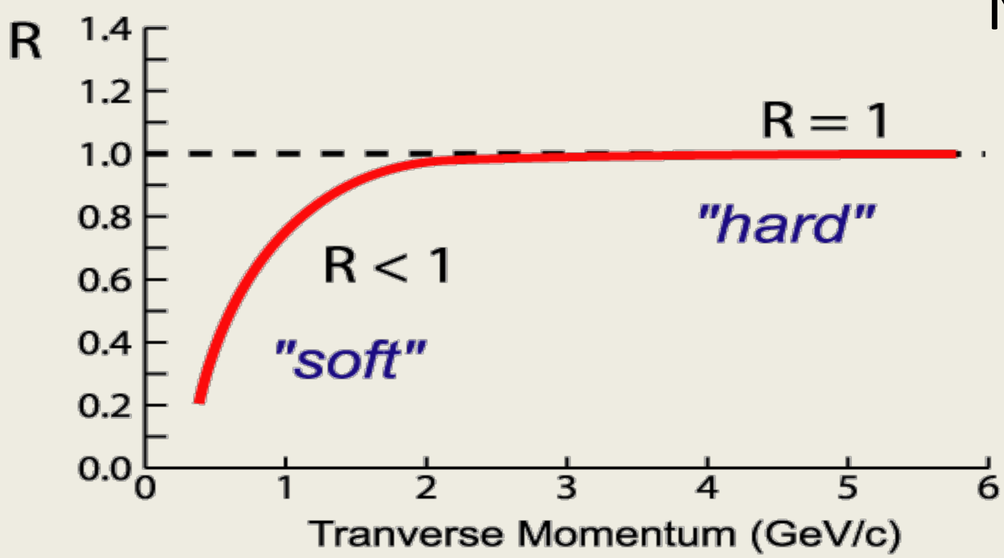




A Simple Physics Observable:

Nuclear Modification Factor:

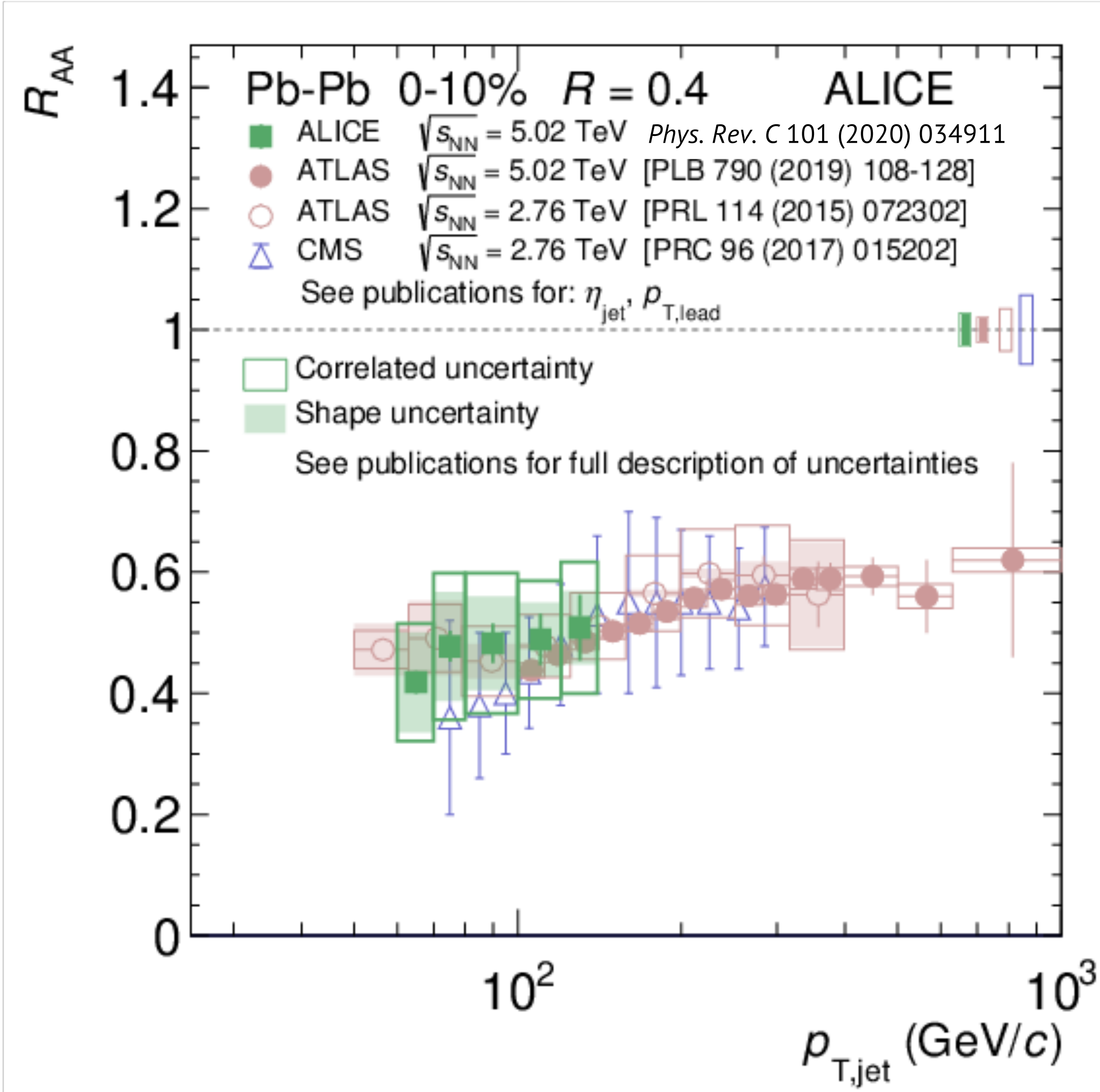
$$R_{AA} \equiv \frac{\text{Yield in A+A Events}}{N_{bin}\,(\text{Yield in p+p Events})}$$



If no "effects":
R < 1 in regime of soft physics
R = 1 at high-p_T where hard scattering dominates

When reference measurement is not available look instead to smaller systems like peripheral events and construct the Rcp.

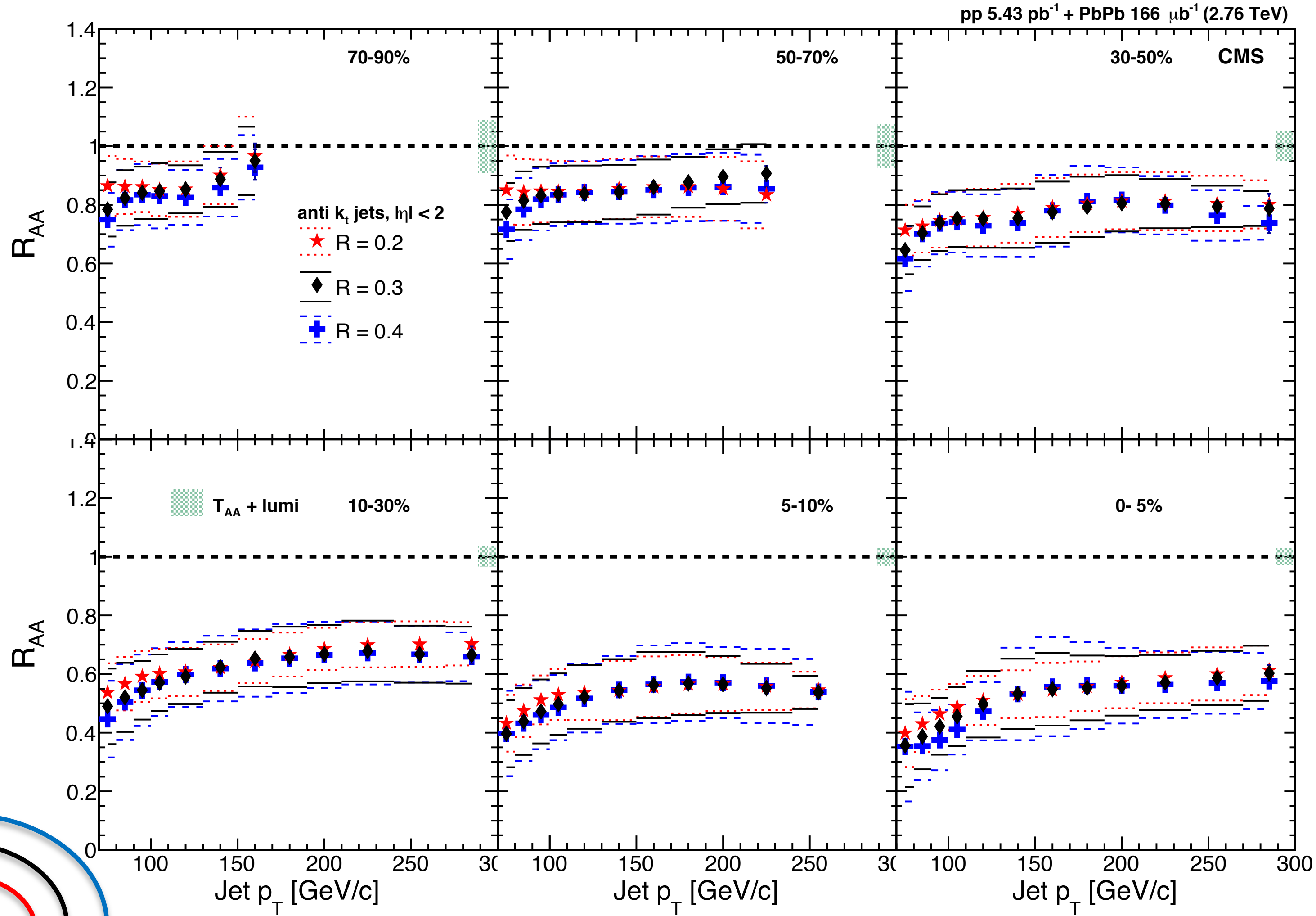
Jet R_{AA} @ LHC

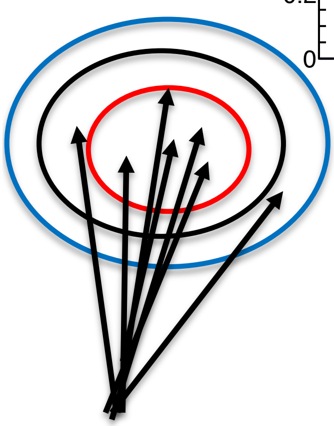


Jets appeared to be quenched in a collision energy independent way!

ALICE , Phys. Rev. C 101 (2020) 034911

Jet R_{AA} radius dependence @ LHC

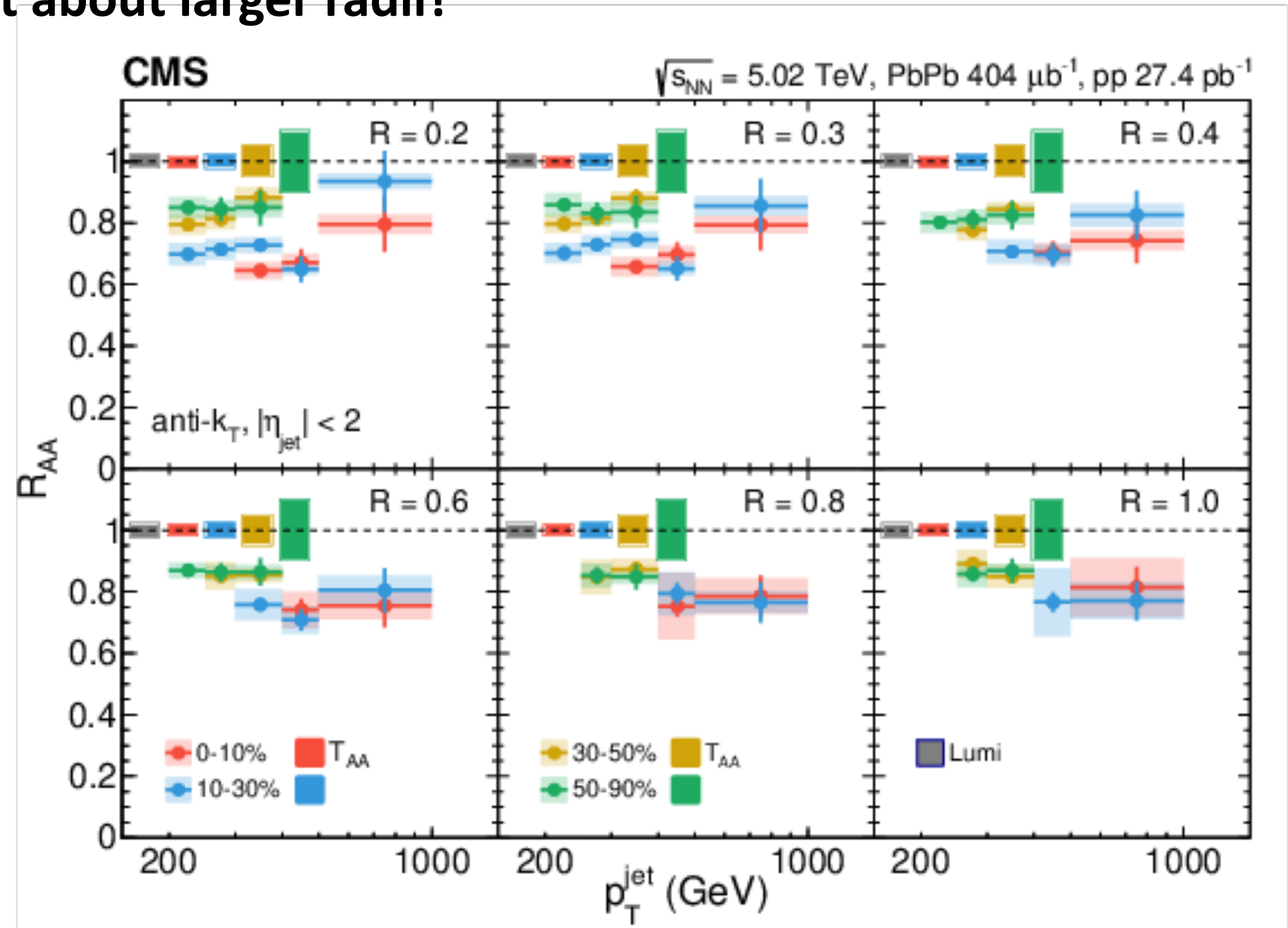




No strong dependence on jet radius!

CMS, Phys. Rev. C 96 (2017) 015202

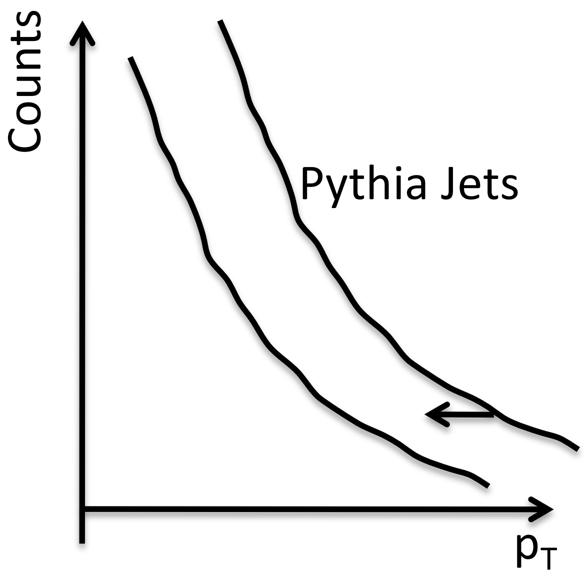
What about larger radii?

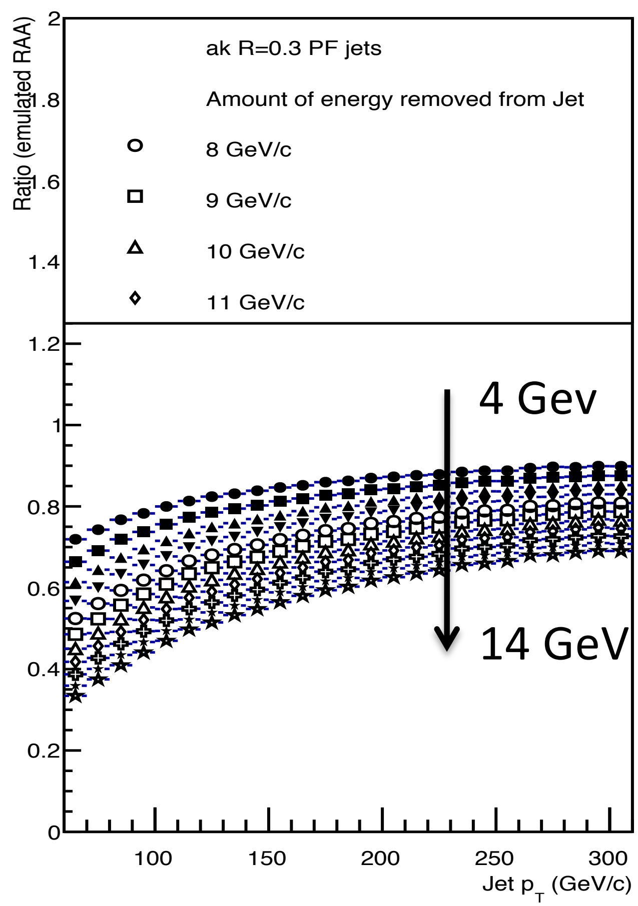


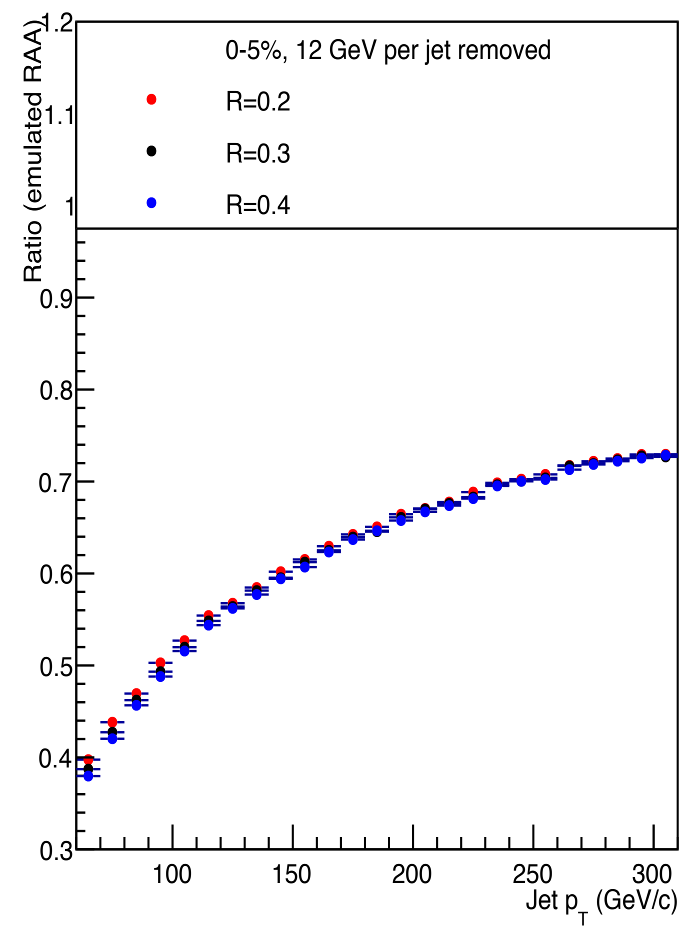
No strong dependence on jet radius persists at high pt and large R!

CMS, arXiv:2102.13080

A very naïve Toy Model







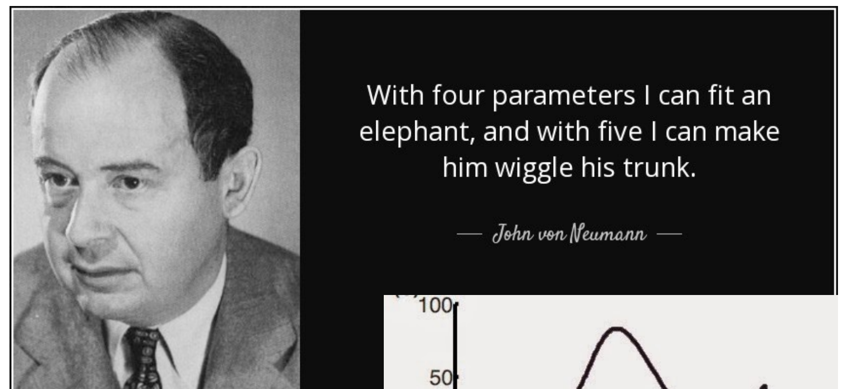
The choice of ΔE can emulate the RAA suppression.
Same shape of spectra: No R dependence: Same RAA for the same ΔE

Theoretical Challenges: Rigorous calculations of jet variables
"Model building of in-medium modifications… "

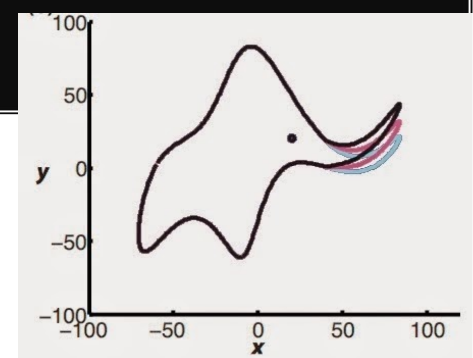
- Jewel (Jet Evolution With Energy Loss): K. Zapp et. Al. Medium recoil parton (Parton shower with microscopic description of interactions with medium – random process of scattering is used to modify the formation time of the radiated gluon.)
- Q-Pythia: N. Armesto et. Al.

MC implementation in Pythia of medium-induced gluon radiation through an additive term in the vacuum splitting functions.

- Many others …. Martini (S. Jeon), YaJEM (T. Renk)
  PYQUEN (Lokhtin, Snigriev),
  PQM (Dainese, Loizides, Paic),
  HIJING (Gyulassy, Wang)…



Analytic Calculations: Vitev et. al., Borghini et al.
SCETG: Splitting function (large angle radiation)
CCNU: recoil parton + hydro dynamical evolution

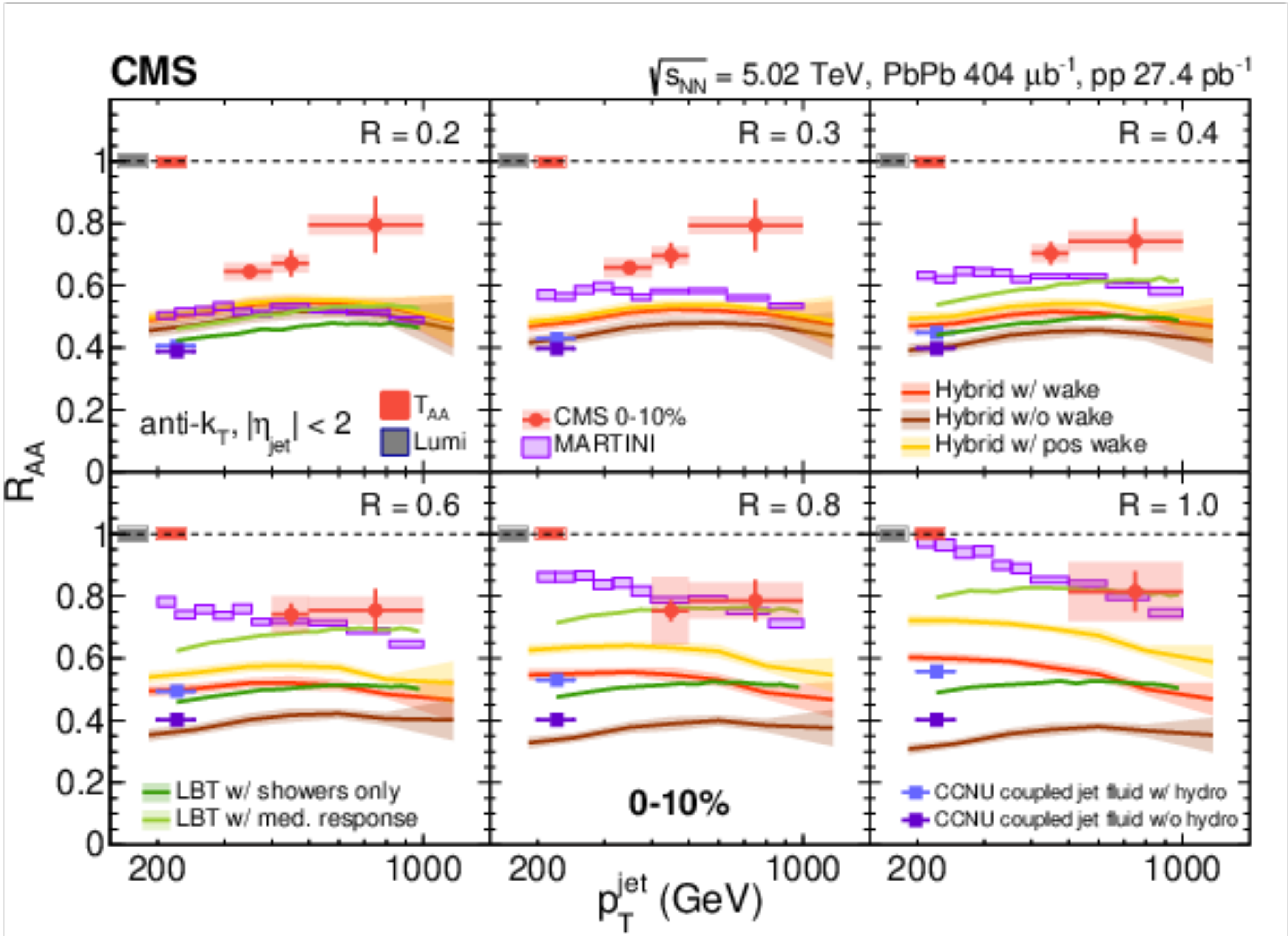


JETSCAPE

Not a complete list…

Measure various jet observables that have different sensitivities!

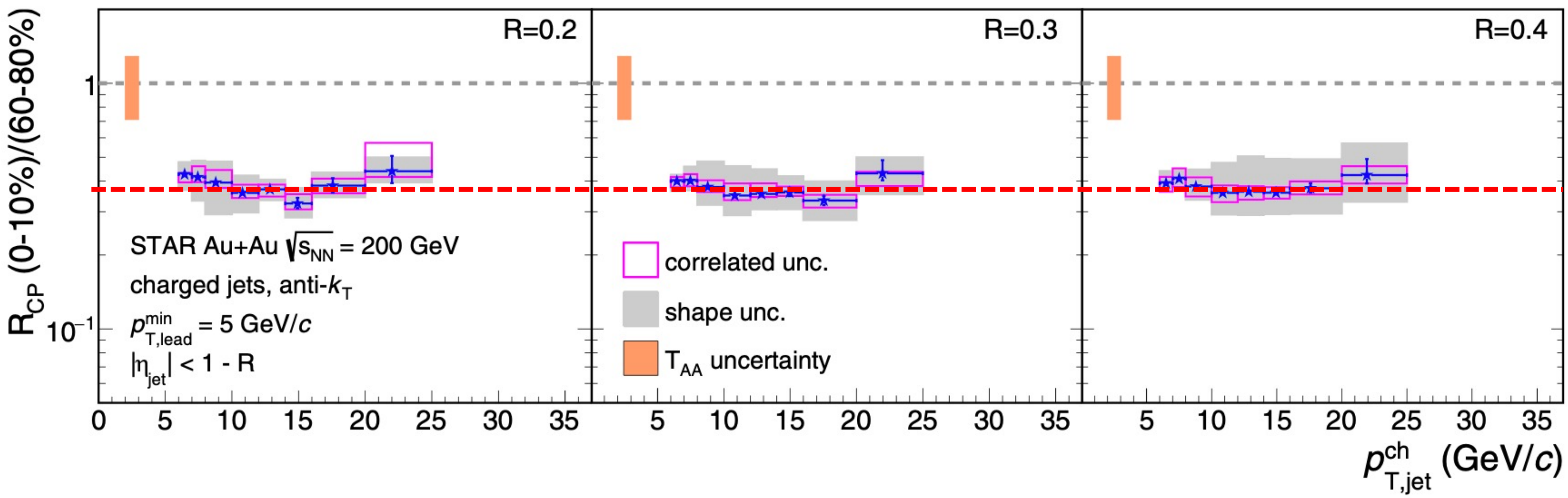
Confronting LHC large jets with realistic calculations: CMS arXiv:2102.13080



Significant tension remains in view of the large jets.

Further constraints on the underlying jet quenching mechanisms.

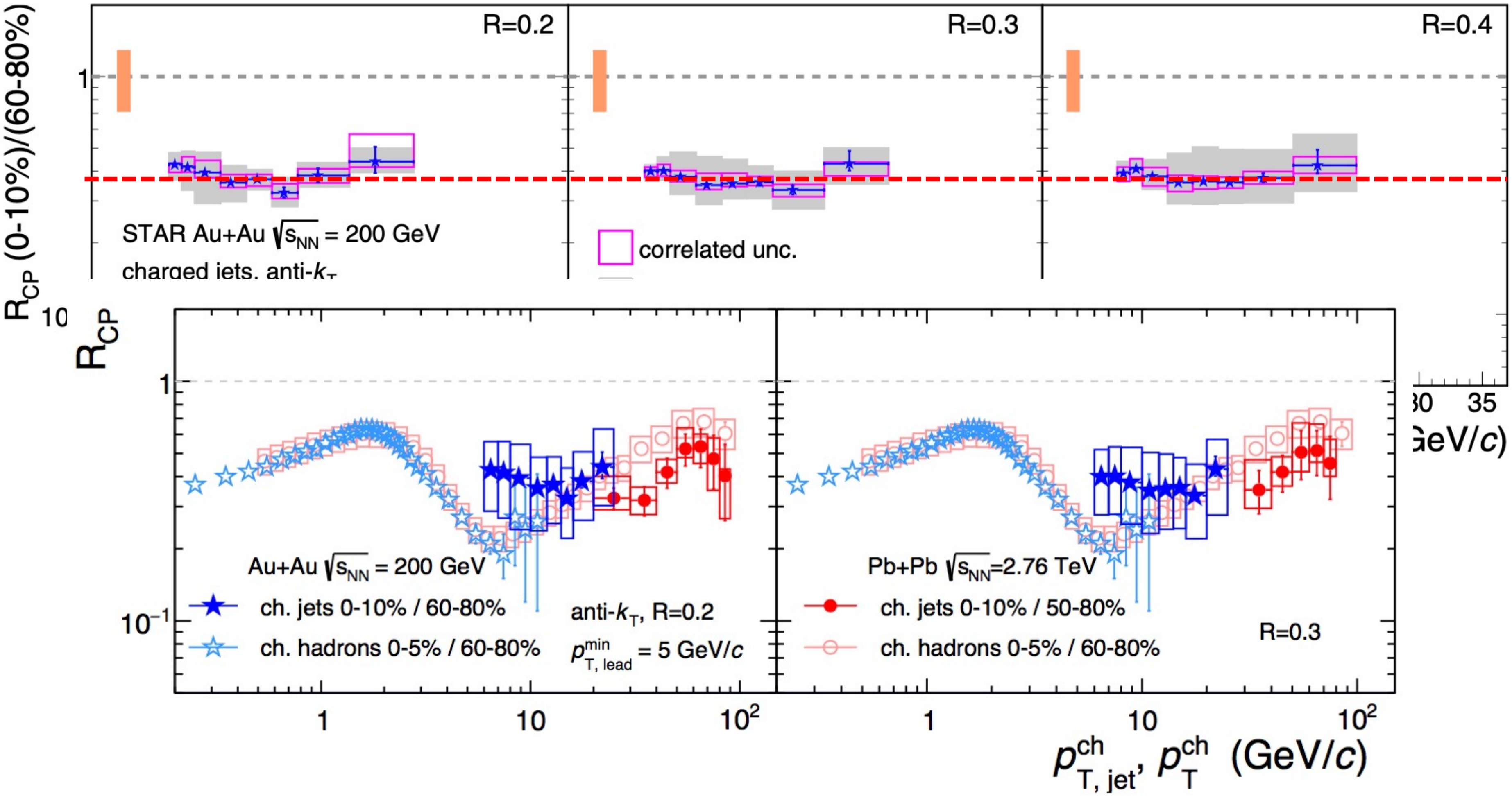
When we don't have precision pp reference:



No strong dependence on jet radius in low pt kinematic range !

STAR, Phys. Rev. C 102 (2020) 054913

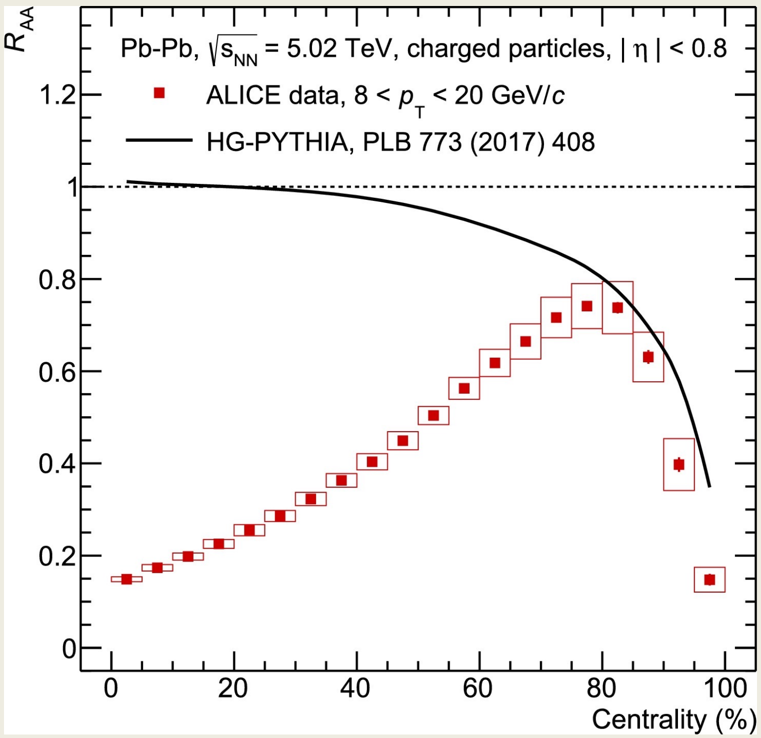
When we don't have precision pp reference:



Similar magnitude of suppression at RHIC and the LHC

STAR, Phys. Rev. C 102 (2020) 054913

A Simple Physics Observable – Nuclear Modification Factor:



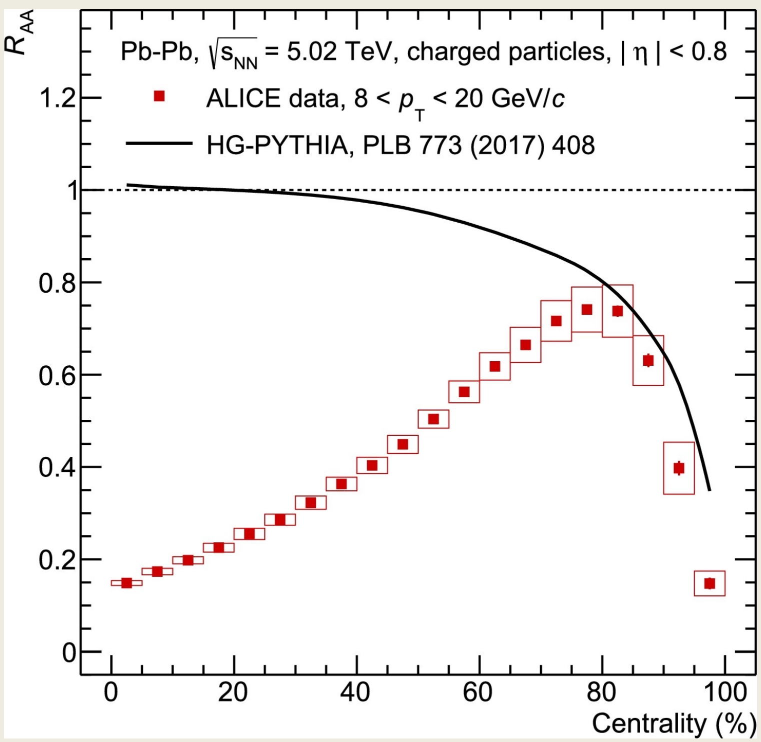
ALICE, Phys.Lett.B 793 (2019) 420-432

High p_T $h^{\pm}$ suppressed in peripheral events

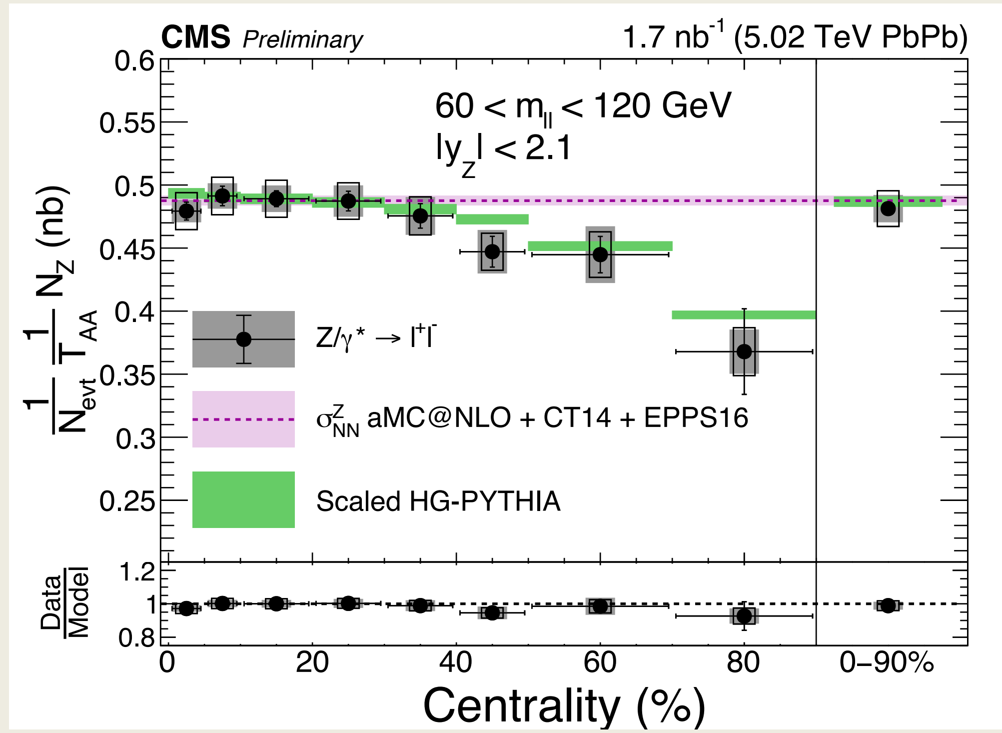
Geometric biases (on initial nn impact parameter) → Centrality selection biases.

A Simple Physics Observable – Nuclear modification Factor:

We need to be careful but there is hope!



ALICE, Phys.Lett.B 793 (2019) 420-432



CMS, arXiv:2103.14089

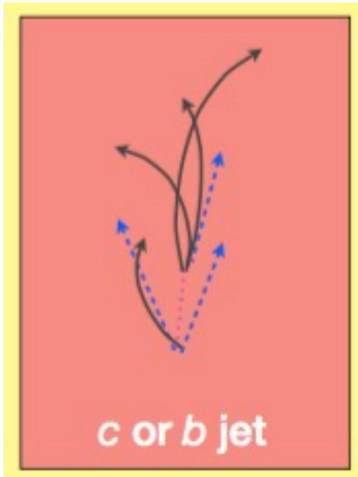
High p_T $h^{\pm}$ suppressed in peripheral events

Geometric biases (on initial nn impact parameter) → Centrality selection biases.

Peripheral Z boson yields are also suppressed

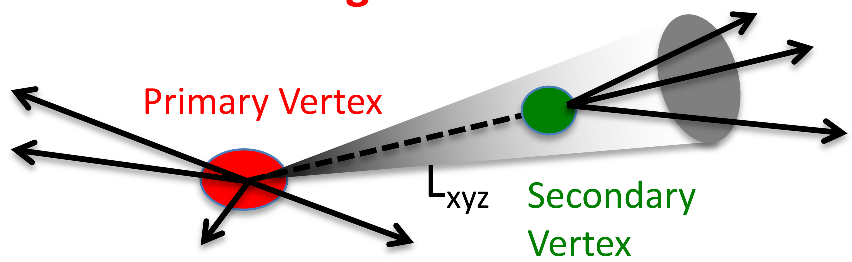
New data driven methods to study this bias!

Heavy Flavour Dependence

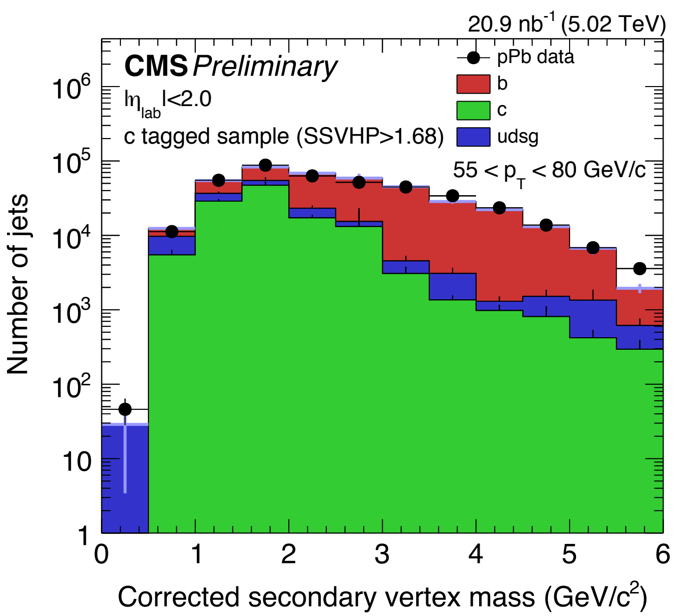


Bottom and charm tagged jets are selected on displaced vertices.

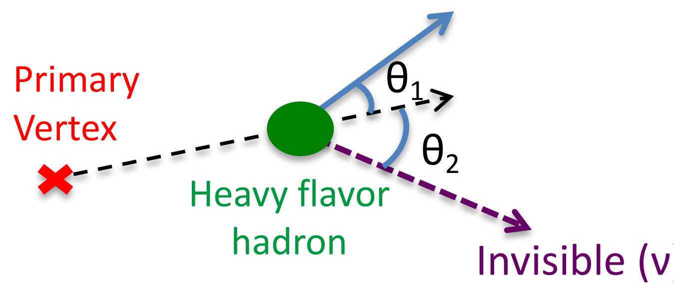
3+ Body Secondary Vertex Tagging: light vs c



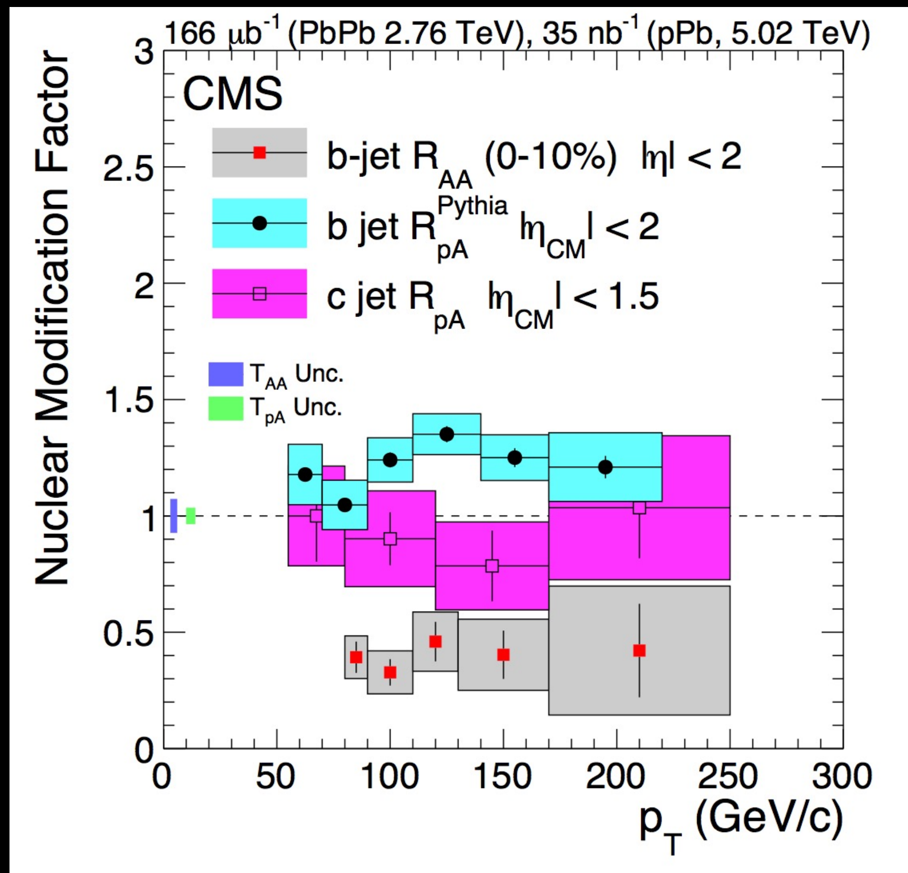
Feed into template shapes
charm jet contribution extracted



Corrected Secondary Vertex Mass: c vs b



Heavy Flavour Dependence

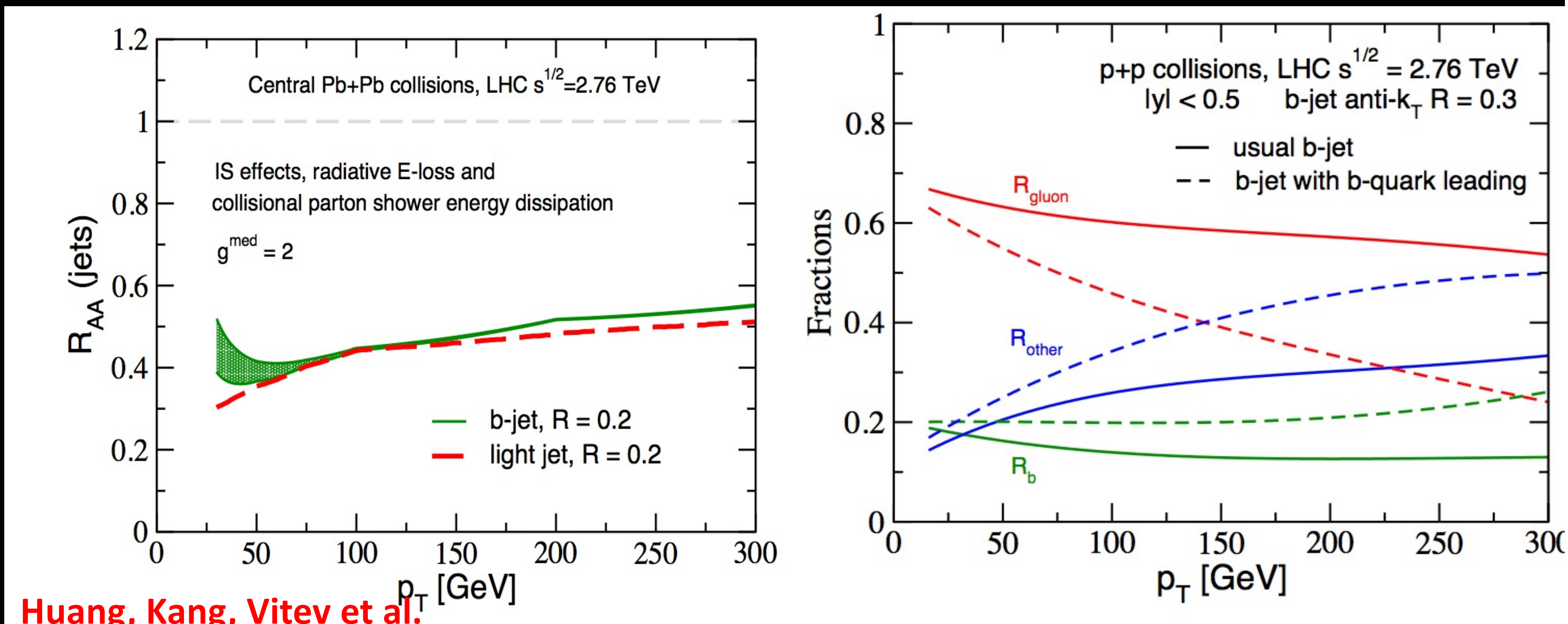


Suppression of b quarks in PbPb, while
no apparent suppression in pPb collisions

Explore with future RHIC data!

CMS, Phys. Rev. Lett. 113, no. 13, 132301 (2014)
CMS, Phys. Lett. B 754, 59 (2016)
CMS, arXiv:1612.08972 (2016)

Caveat: b/c jet might not be original!



Huang, Kang, Vitev et al.

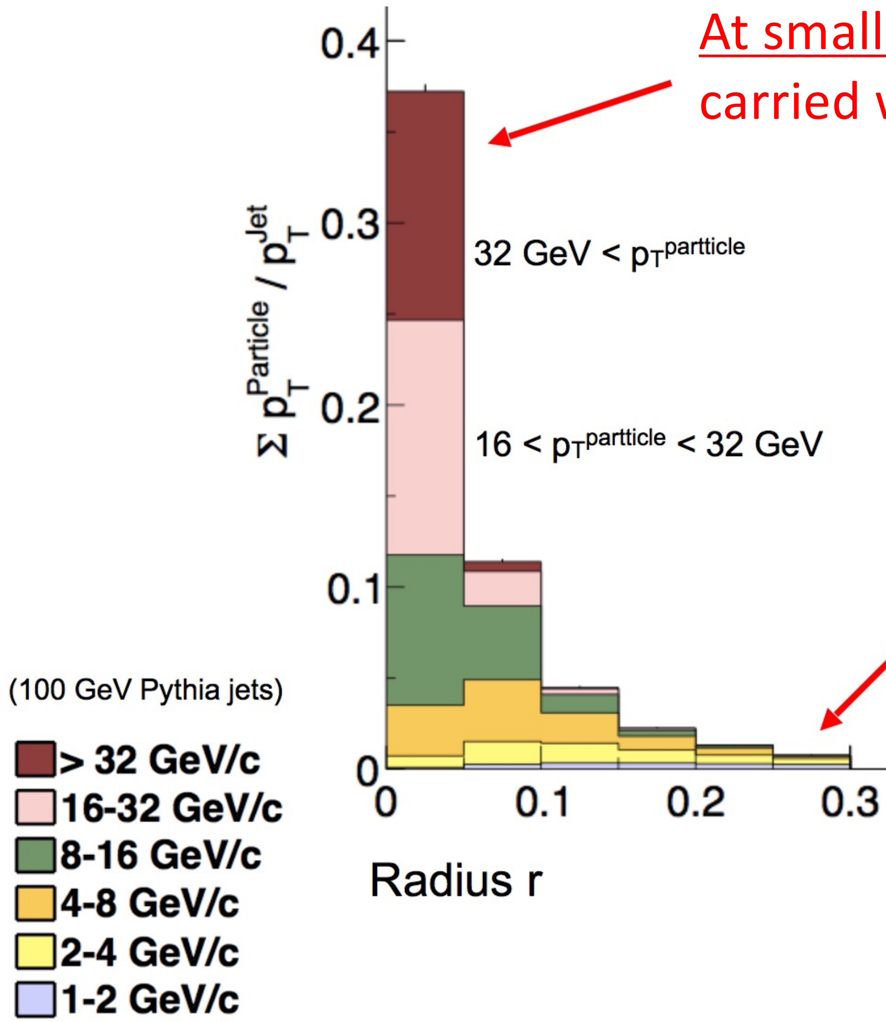
At high pt region, mass effect can be neglected

R_{gluon}:fraction of g->b
R_b :fraction of b->b
R_{other}:fraction of q->b

Explore multi tags such as c/b jet with D/B and γ.

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

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

Many Jet Shape Observables:

- 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 p_T^D:*

(Energy Sharing)

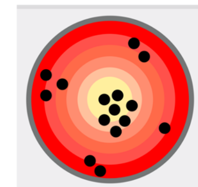
$$p_T^D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

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

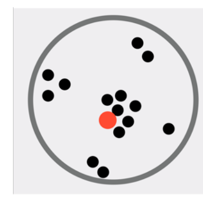


- *LeSub:*

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

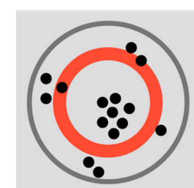
- *Fragmentation*
- *function (FF):*

$$FF(z) = \frac{1}{N_{jet}} \frac{dN}{dz}$$



- *Differential*
- *jet shape:*

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

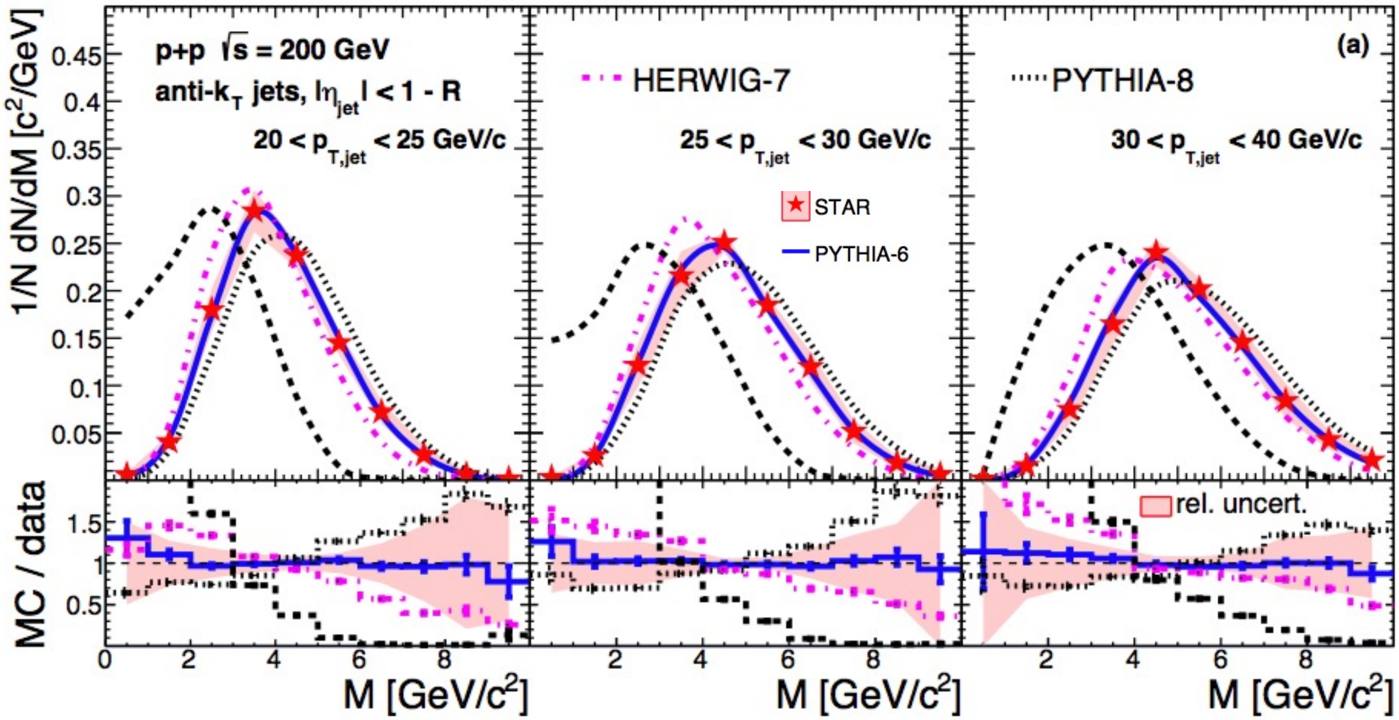


- *Jet Charge:*

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

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.

Jet Mass @ RHIC

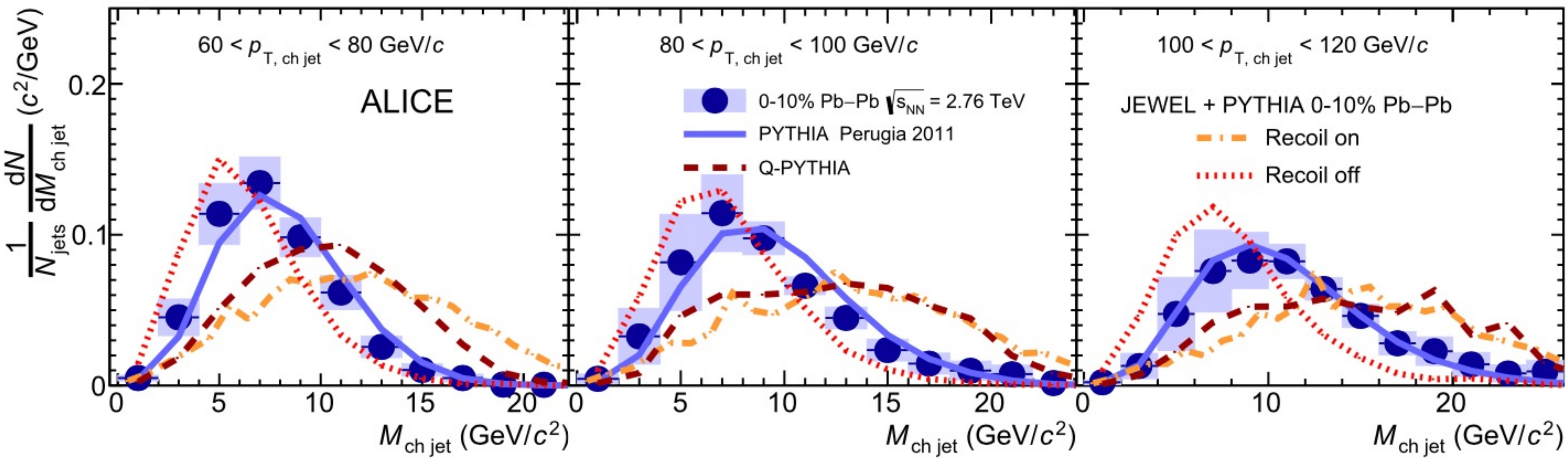


Baseline for measurements in heavy-ion collisions at RHIC

Well-described by the RHIC-tuned PYTHIA-6 Perugia 2012,
others fail providing crucial input for further RHIC tunes.

STAR, arXiv:2103.13286,

Jet Mass @ LHC

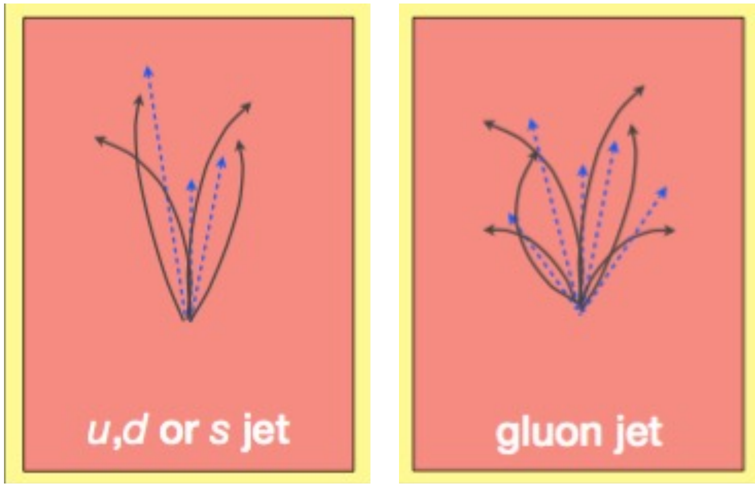


Well-described by the LHC-tuned PYTHIA-6 Perugia 2011,

Tension between data & quenching models!

Phys. Lett B Vol. 776, (2018) 249-264

An example in pp: Quark-gluon discrimination

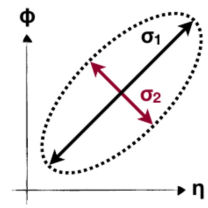


Compared to gluon jets,
quark jets in vacuum have:

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

and less symmetric energy sharing among constituents

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 Variable: $p_T D$

$$p_{\mathrm{T}} D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

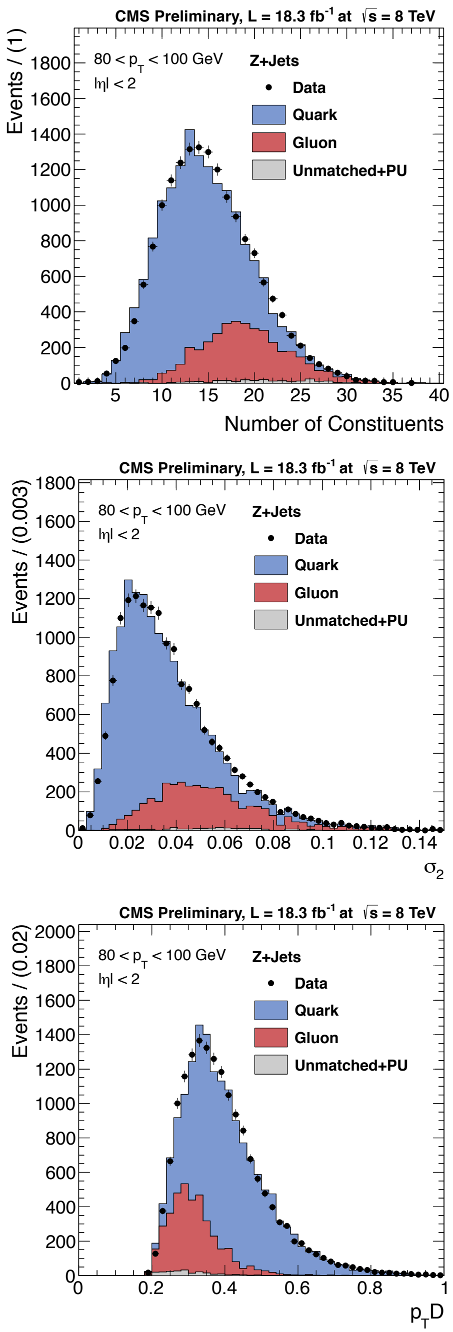
$p_T D$=1 single jet constituent

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

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

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

Quark-gluon discrimination:



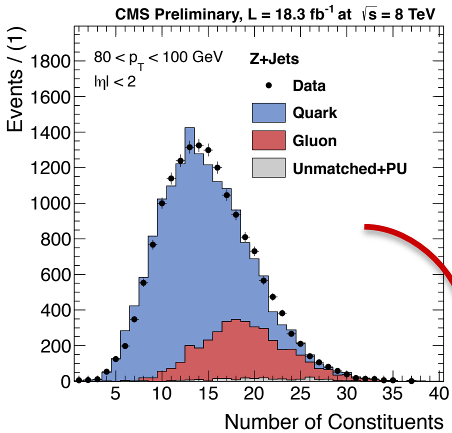
Likelihood based discriminator obtained by combining 3 variables:

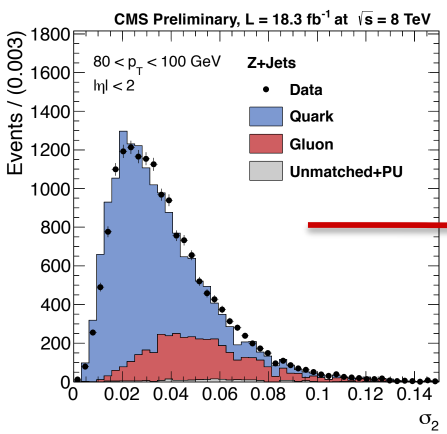
- Total multiplicity
- Minor axis
- $p_T D$

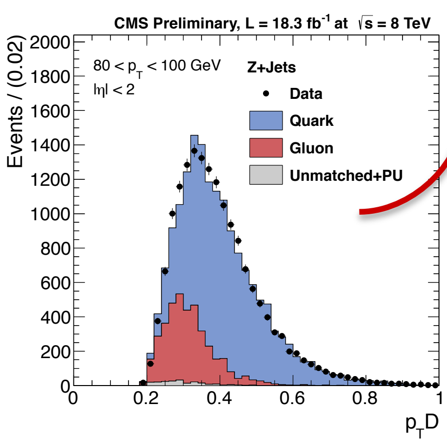
http://cds.cern.ch/record/1599732/files/JME-13-002-pas.pdf

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

Quark-gluon discrimination:





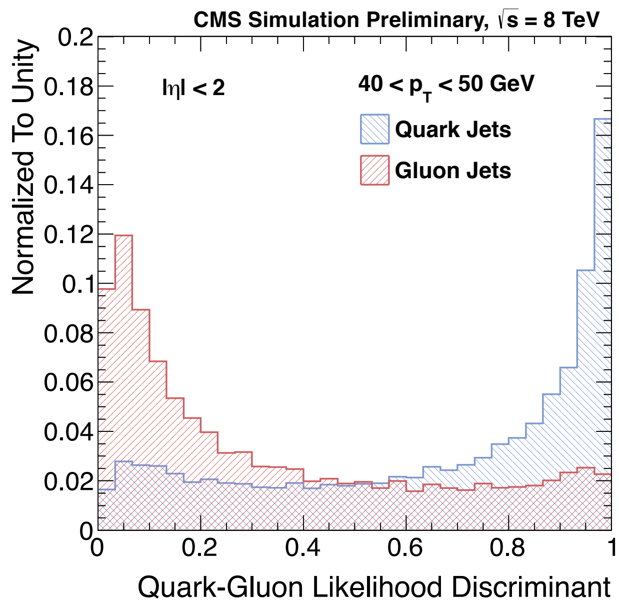


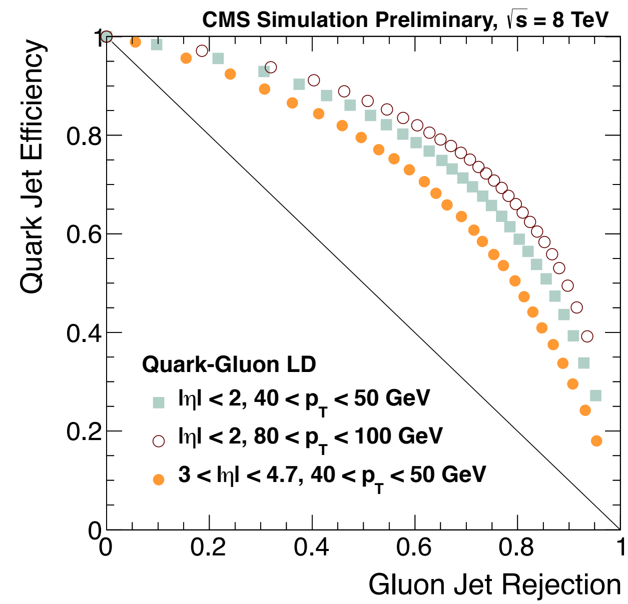
Likelihood based discriminator obtained by combining 3 variables:

- Total multiplicity
- Minor axis
- p_TD

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

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

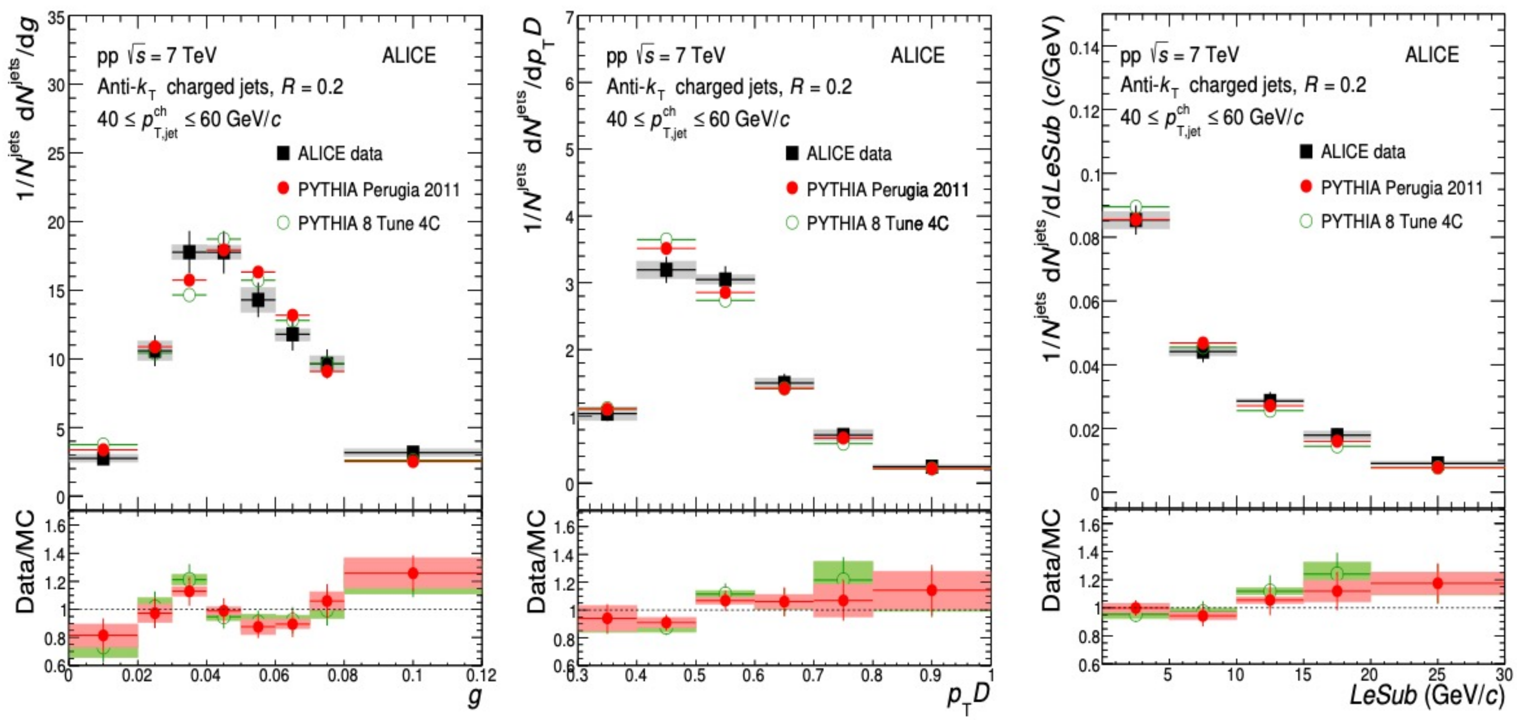




quark/gluon discrimination is difficult, but not impossible in pp

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

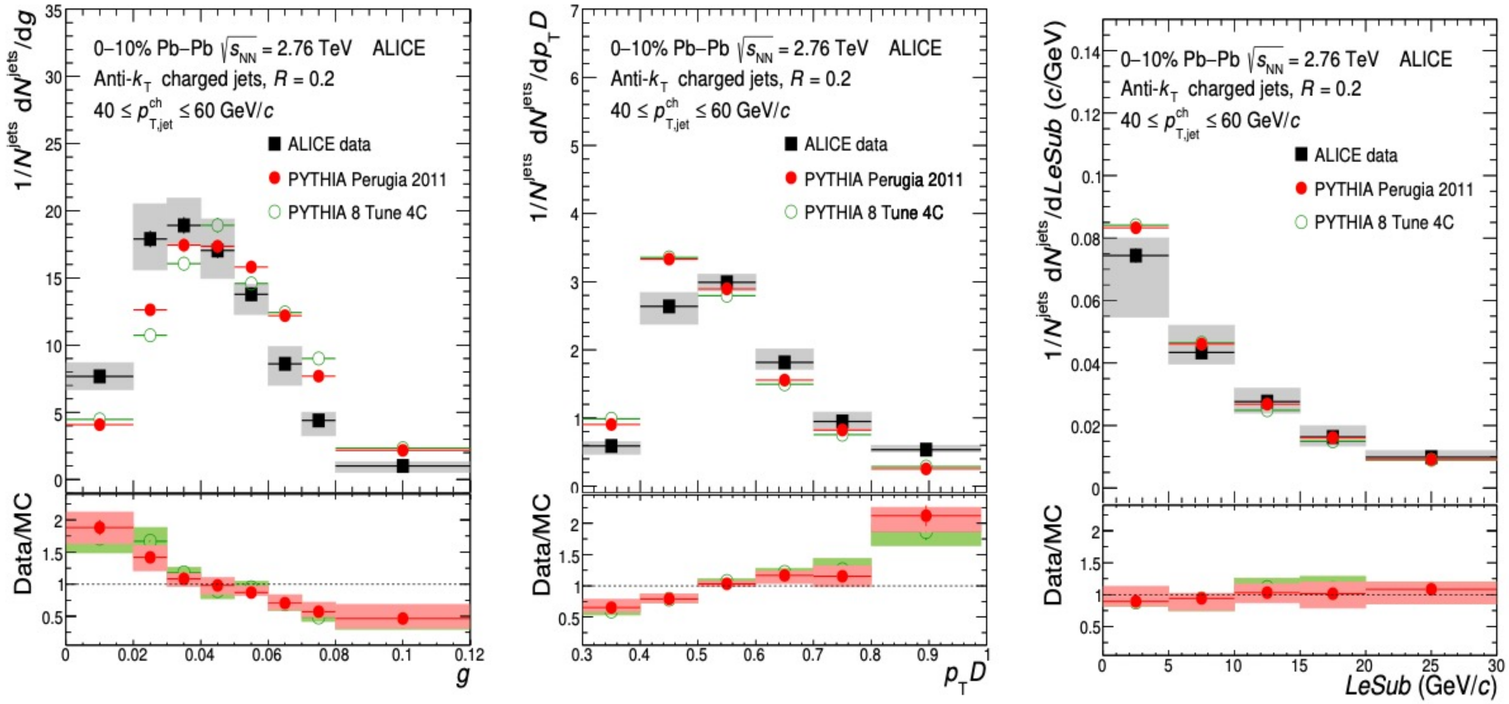
Can we learn something about Quark vs Gluon jets through observables alone?



pp distributions are well represented by Pythia!

JHEP10(2018)139

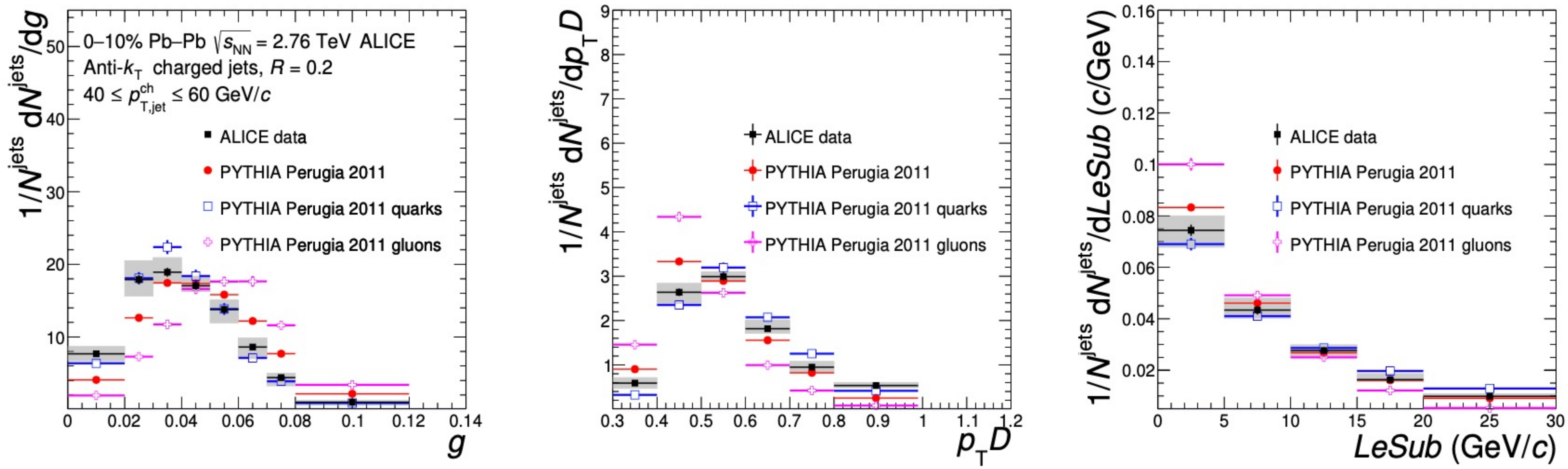
Can we learn something about Quark vs Gluon jets through observables alone?



Discrepancies between PbPb distributions and Pythia!

JHEP10(2018)139

Can we learn something about Quark vs Gluon jets through observables alone?



Fragmentation resembles that of quark jets in vacuum.
A useful bias to investigate at RHIC energies.

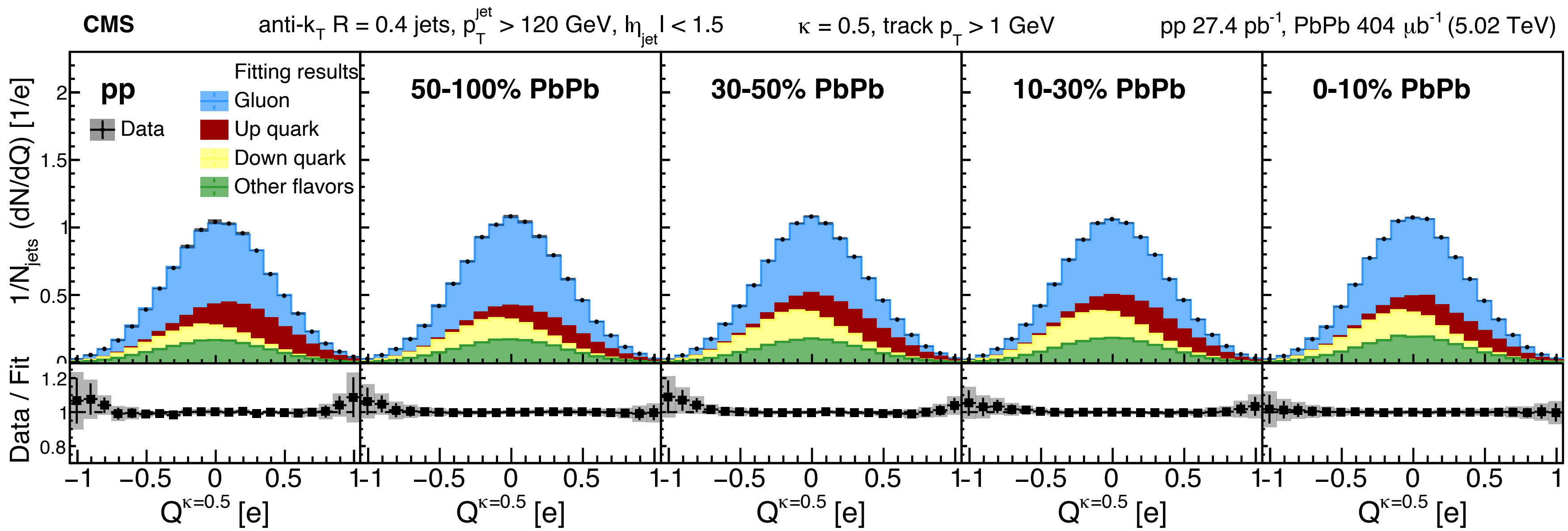
JHEP10(2018)139

Jet Charge: Another approach for Quark/Gluon-like jets

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

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

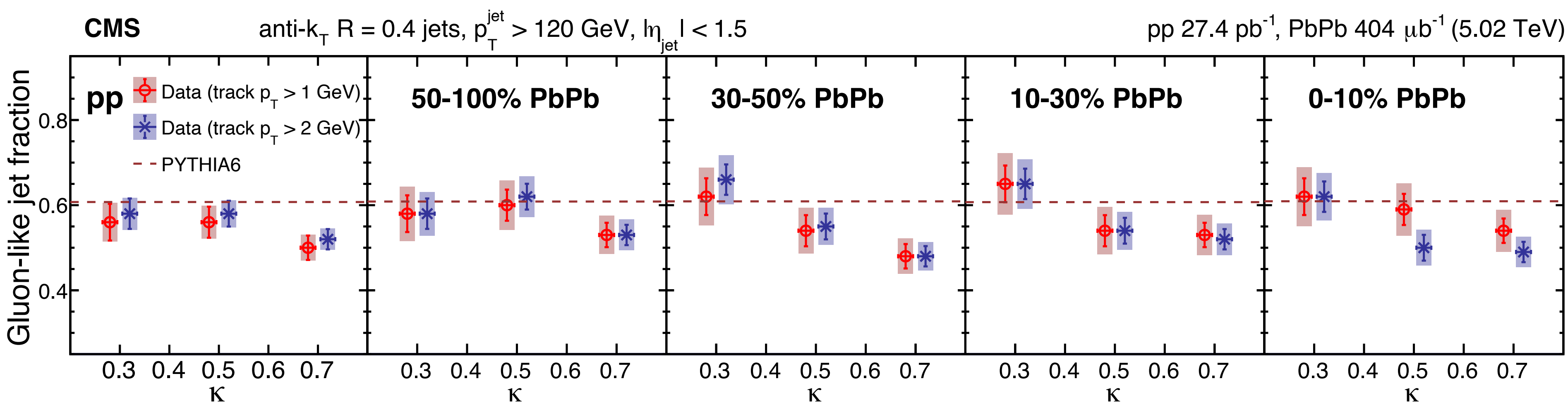
κ = 0.5 → most sensitive to parton charge initiating jet! [according to theory]



quark/gluon jet fractions extracted with template-fitting method
•Use PYTHIA and PYTHIA+HYDJET for pp/PbPb model

JHEP 07 (2020) 115

Quark/Gluon-like Jet Fractions



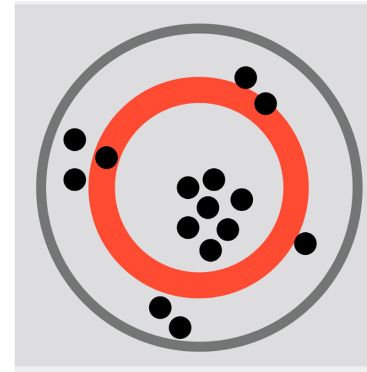
$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_{i \in jet} q_i (p_{\mathrm{T}}^{i})^{\kappa}.$$

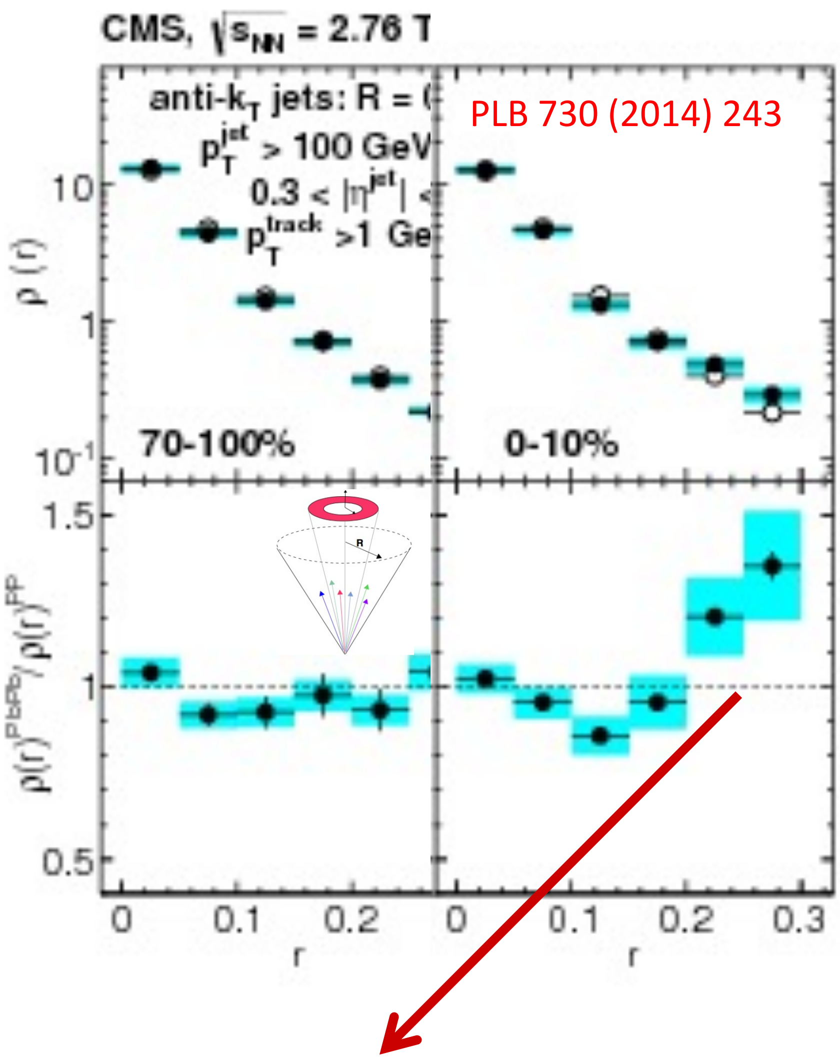
No significant modification of quark/gluon jet fraction in PbPb

Contradicts expectations of some jet quenching models

JHEP 07 (2020) 115

Jet Shapes @ LHC:



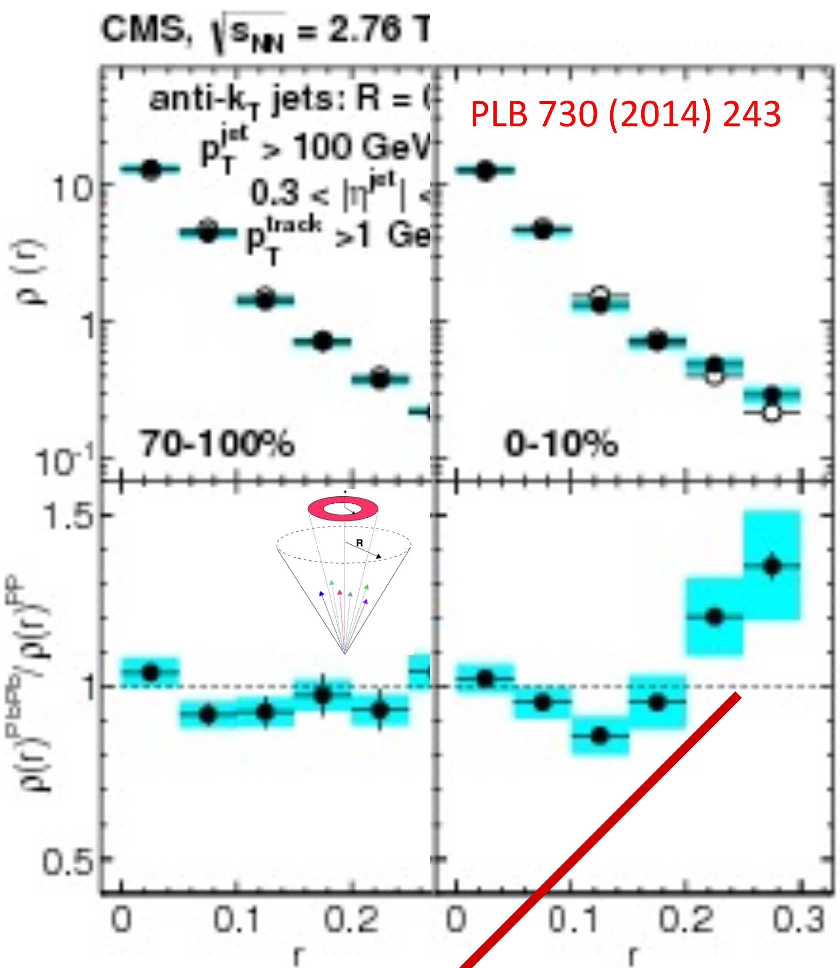


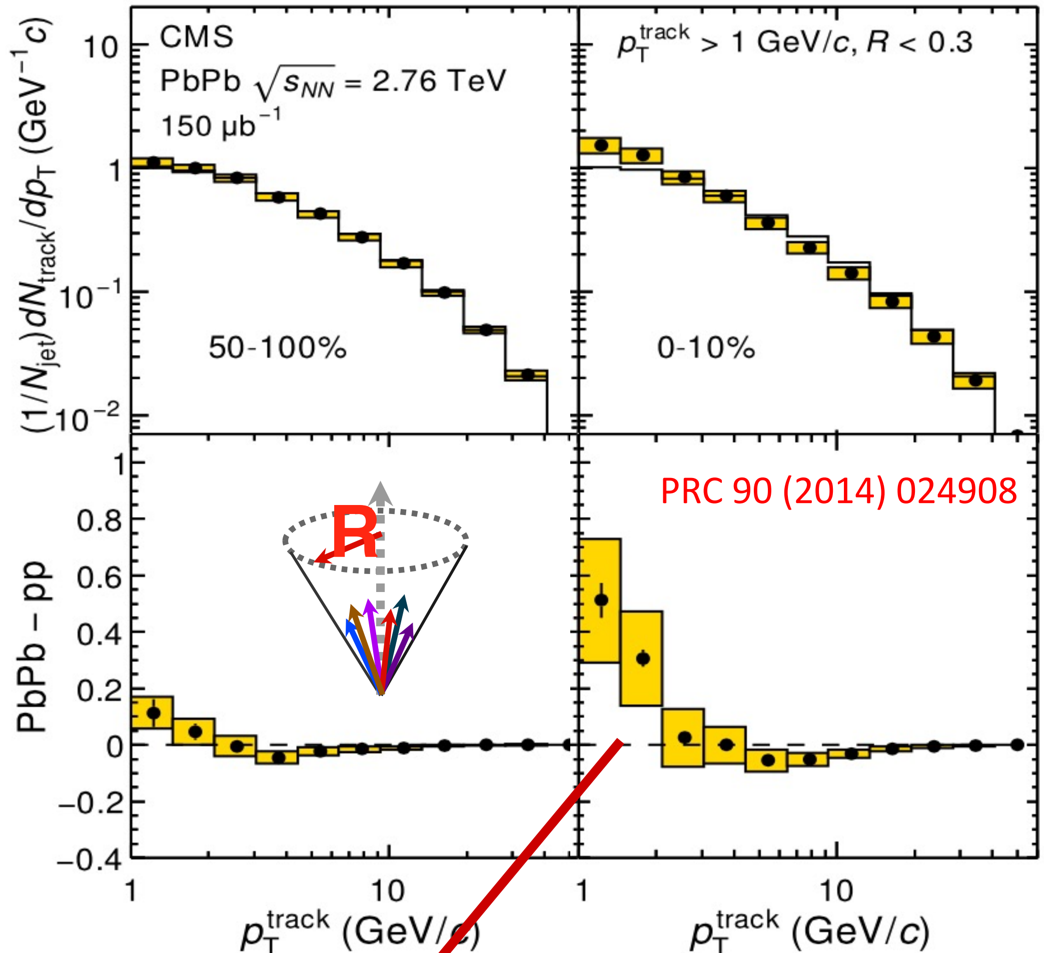
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}p_T^{\text{trk}}}{p_T^{\text{jets}}}$$

<u>Averaged over many jets</u>

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

Change in Jet Morphology as seen with CMS @ LHC:

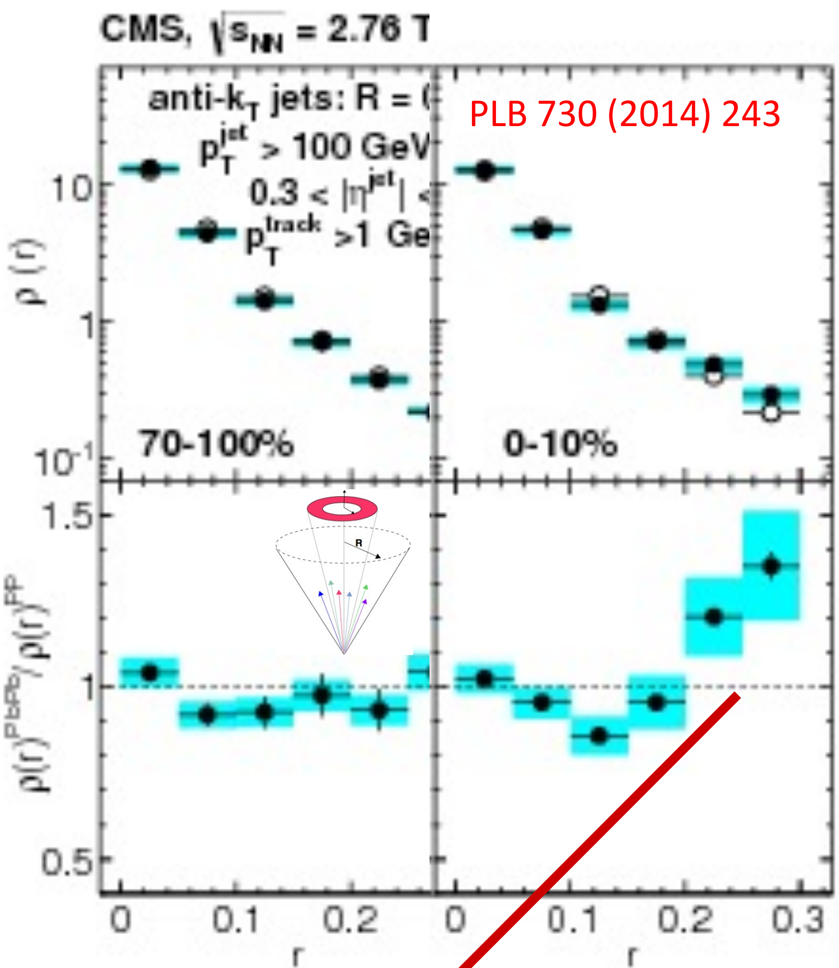


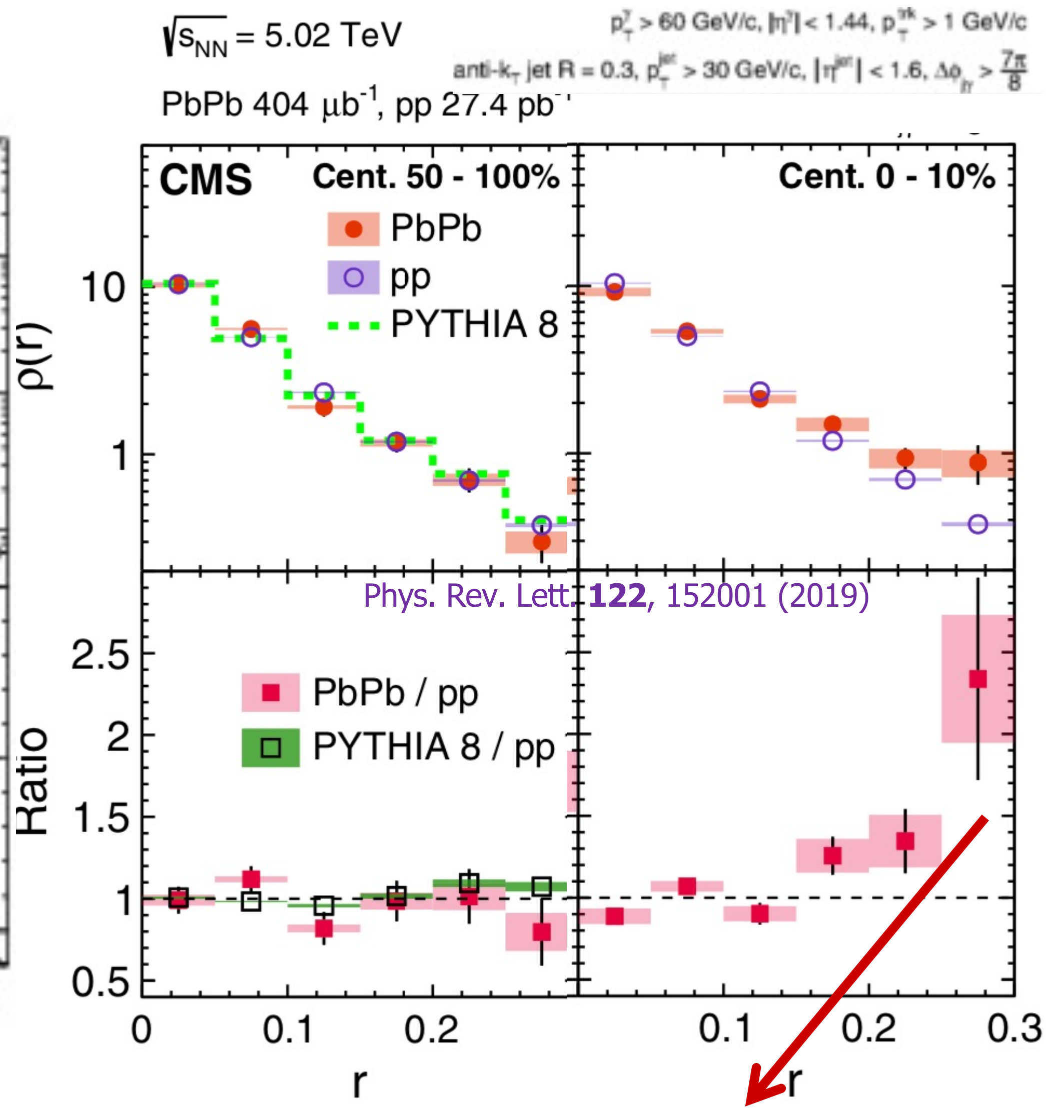


<u>Jet Shapes:</u> Structure of reconstructed jets modified towards an excess of particles far from the jet axis

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

Jet Shapes @ LHC:

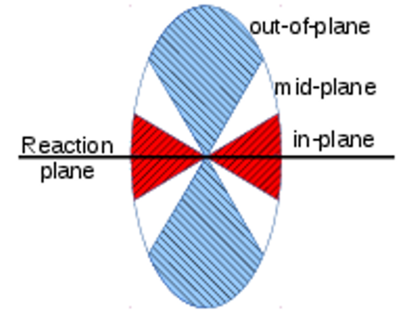




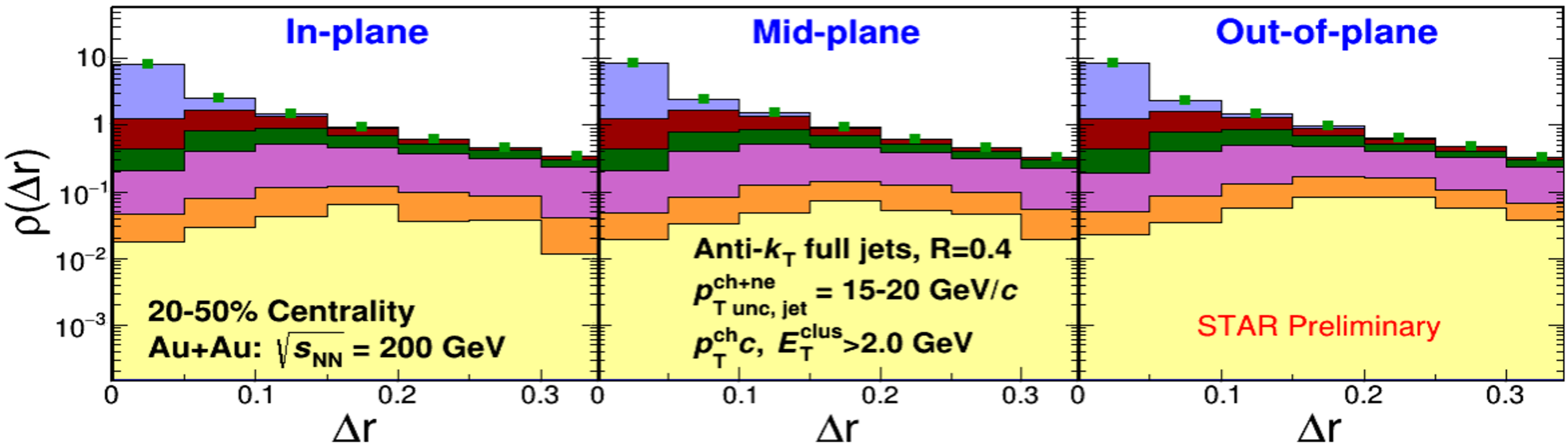
<u>Jet Shapes:</u> Structure of reconstructed jets modified towards an excess of particles far from the jet axis

<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 @ RHIC:



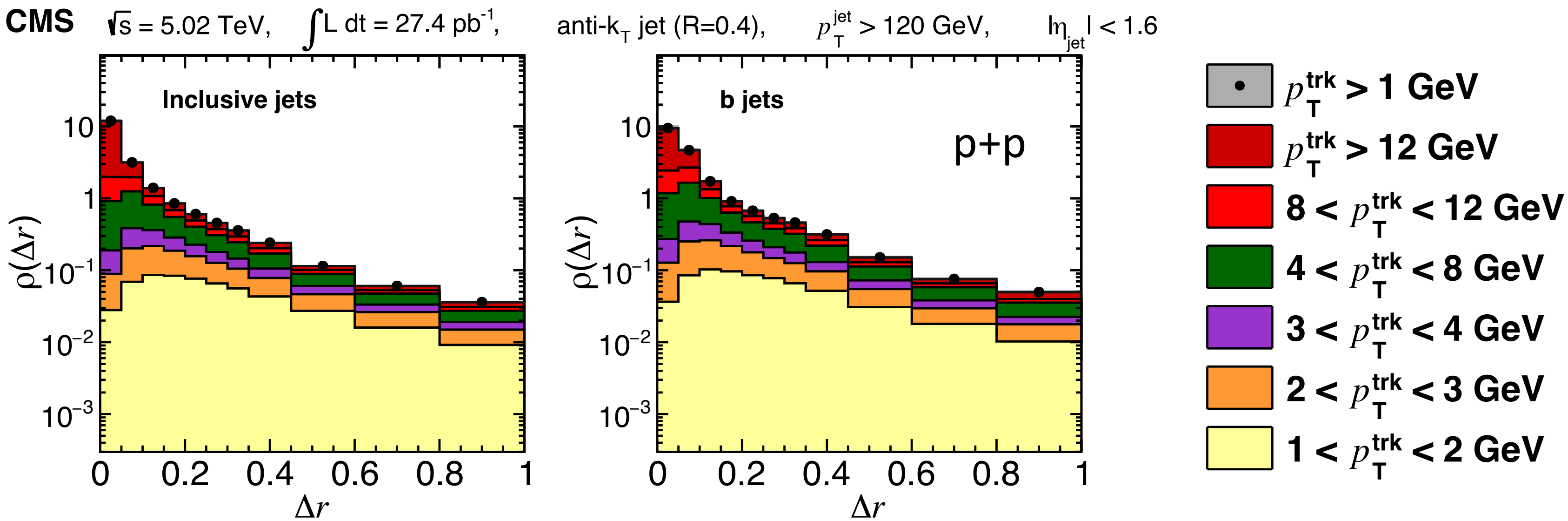
Event plane dependence is studied with low kinematic range jets.

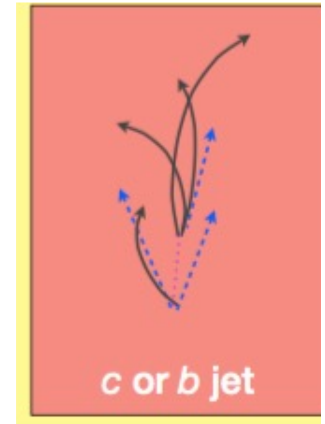


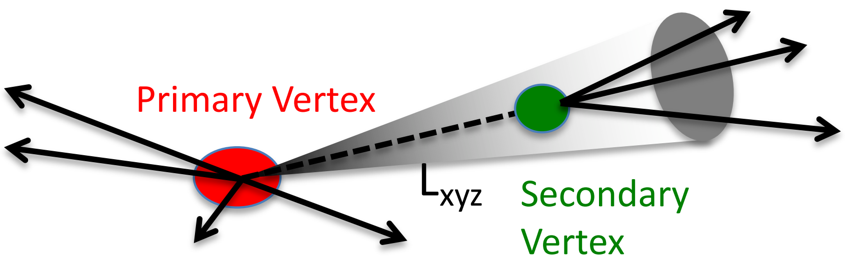
- Hints of low-p_T tracks pushed toward farther distances in out-of-plane relative to in-plane
- Above 2 GeV/c, results are consistent with each other

Less steep than @ LHC energies

Flavored Jet Shapes @ LHC:



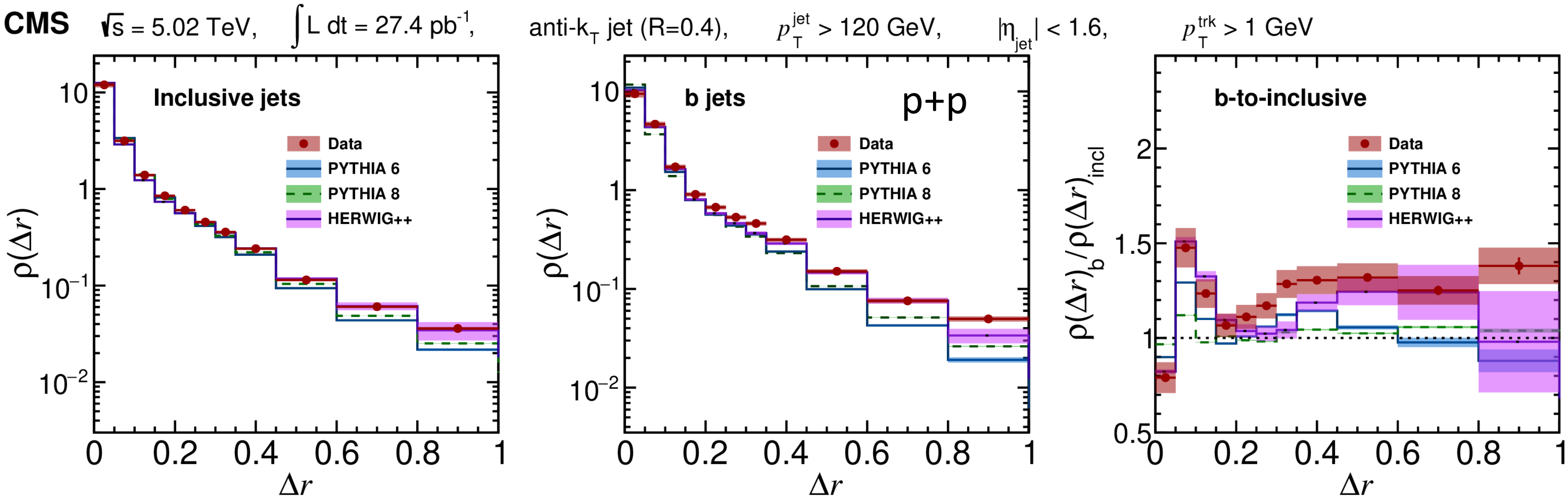




Important reference for the future studies of flavor effects for parton interactions with QGP.

JHEP 05 (2021) 054

Flavored Jet Shapes @ LHC

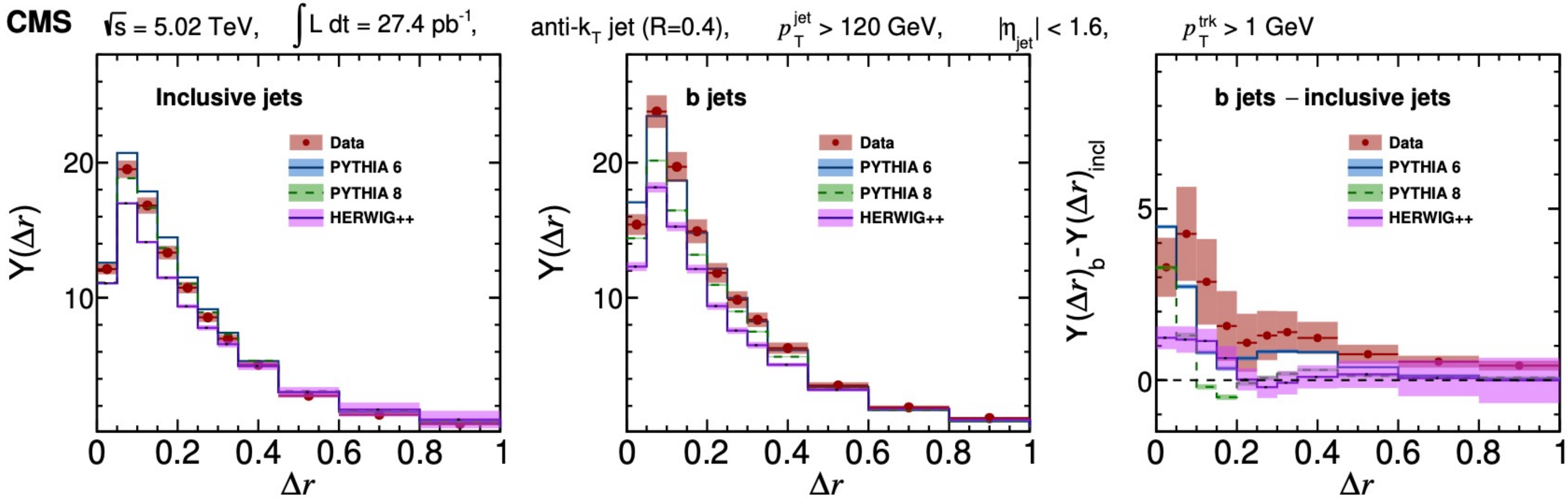


Simulations show different jet shape predictions at large angular distances, where nonperturbative contributions are likely to dominate.

JHEP 05 (2021) 054

Flavored Jet Shapes @ LHC

The radial distributions of the total charged-particle yields:

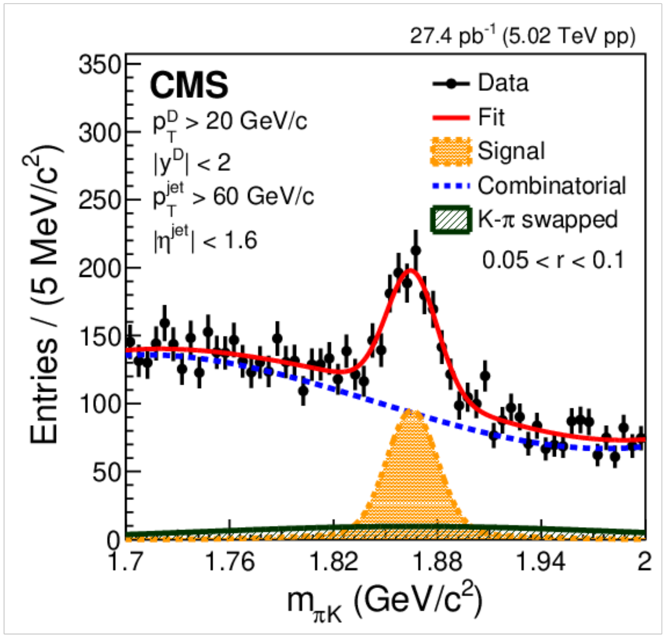


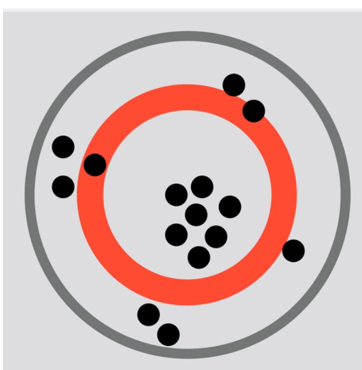
Larger radial distances are only well-estimated by HERWIG++

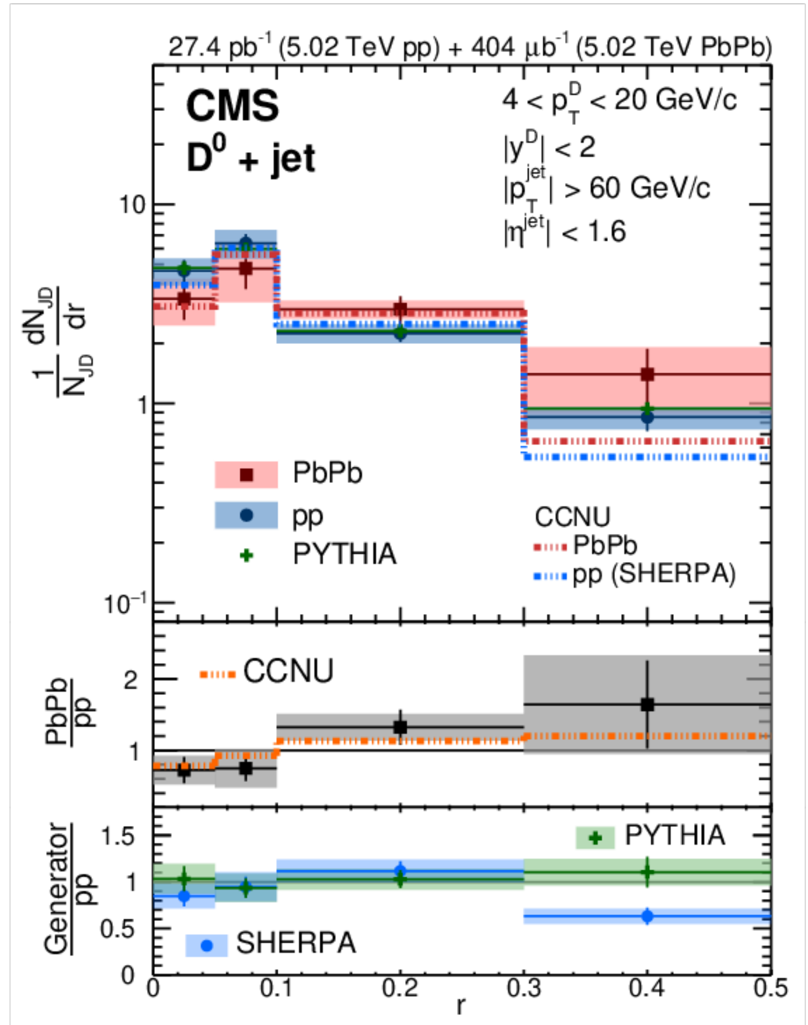
Constraints on pQCD calculations for flavor dependencies in parton

JHEP 05 (2021) 054

D^0 Radial distributions @ LHC







Phys. Rev. Lett. 125 (2020) 102001

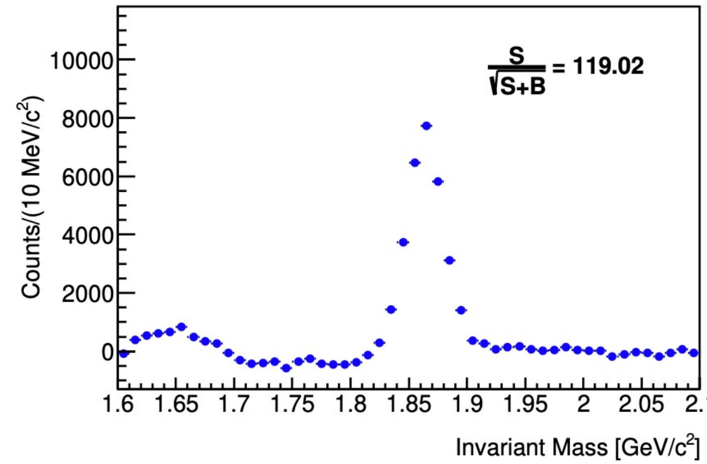
Hint of a diffusion of charm quarks in the medium created in heavy ion collision

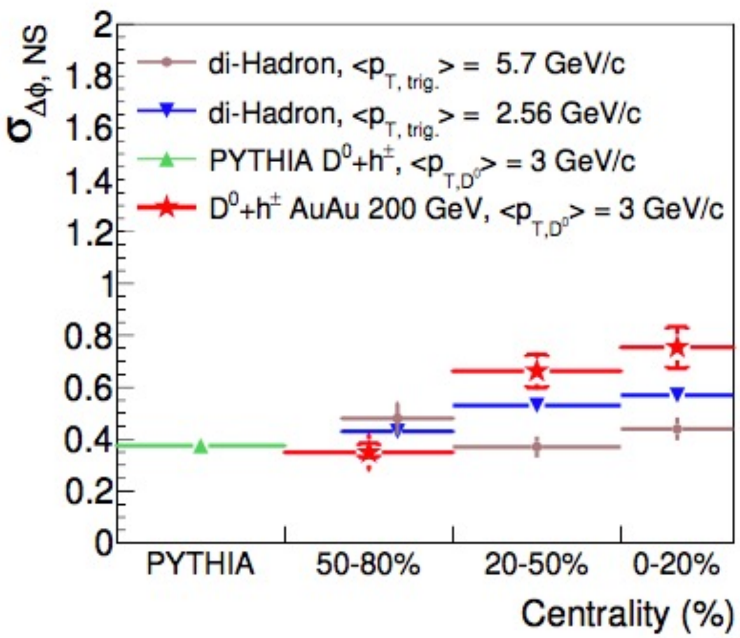
D^0 Radial distributions @ RHIC

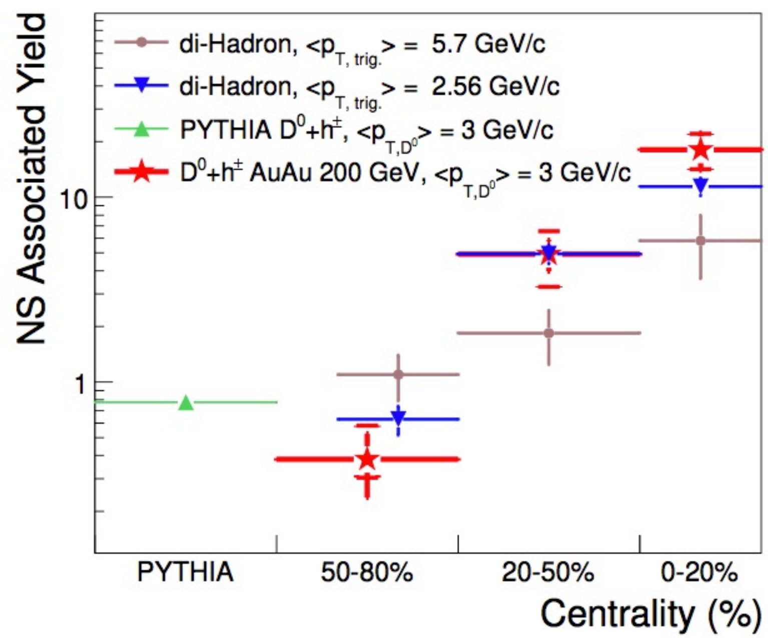
Access to lower p_T

D0 meson angular correlation as the proxy.

D^0-hadron ($D^0 \rightarrow \pi^{\pm} K^{\mp}$)







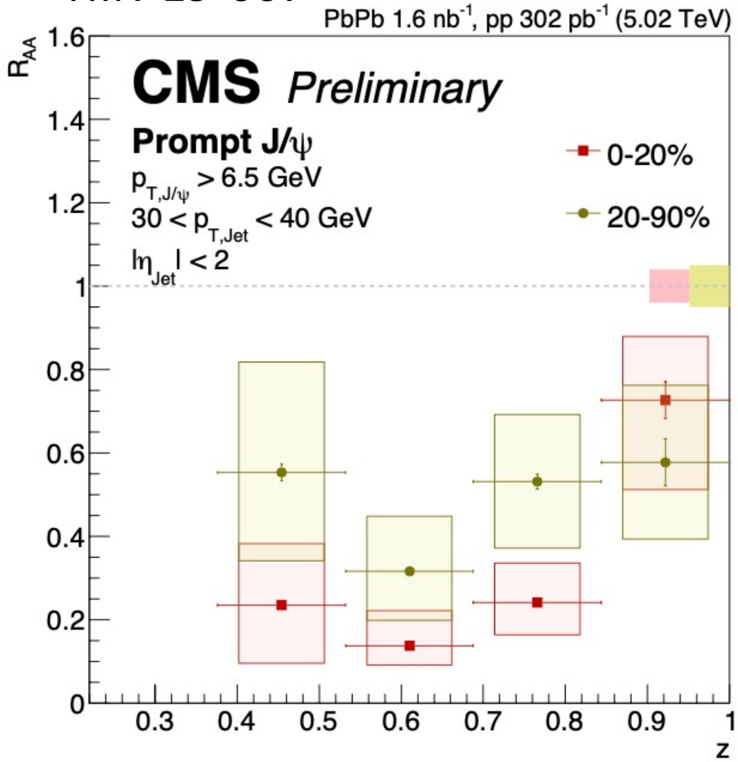
Similar width and yield to light-flavor correlations

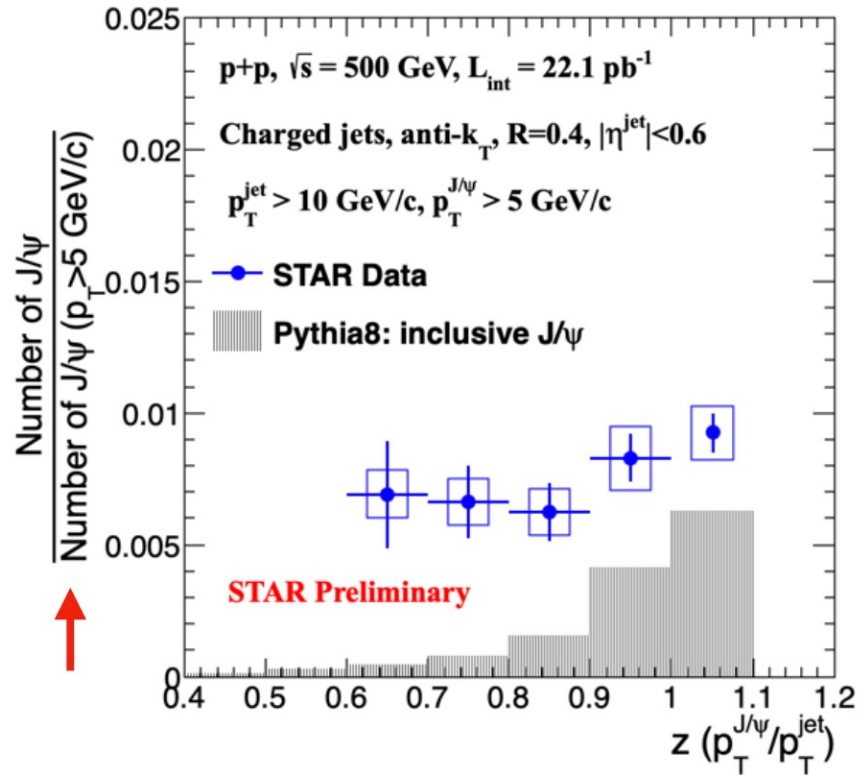
Charm-quark interaction with the medium is similar to light-flavor interaction with the medium.

STAR, Phys. Rev. C 102 (2020) 14905

J/ψ in a jet @ LHC & RHIC

HIN-19-007





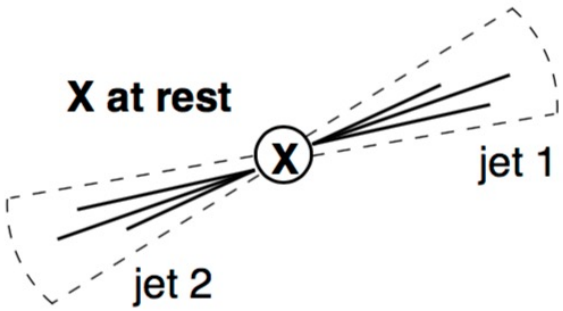
More suppression at low *z:*

J/*ψ* produced with a large degree of surrounding jet activity are more highly suppressed than those produced in isolation

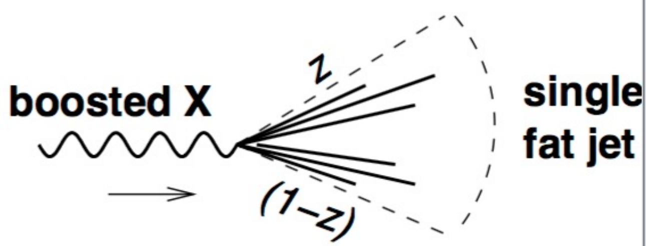
More J/*ψ* in jets in data

J/*ψ* *p*opulate lower values of *z* than predicted by PYTHIA at LHC & RHIC→ Further tunning of models/calculations.

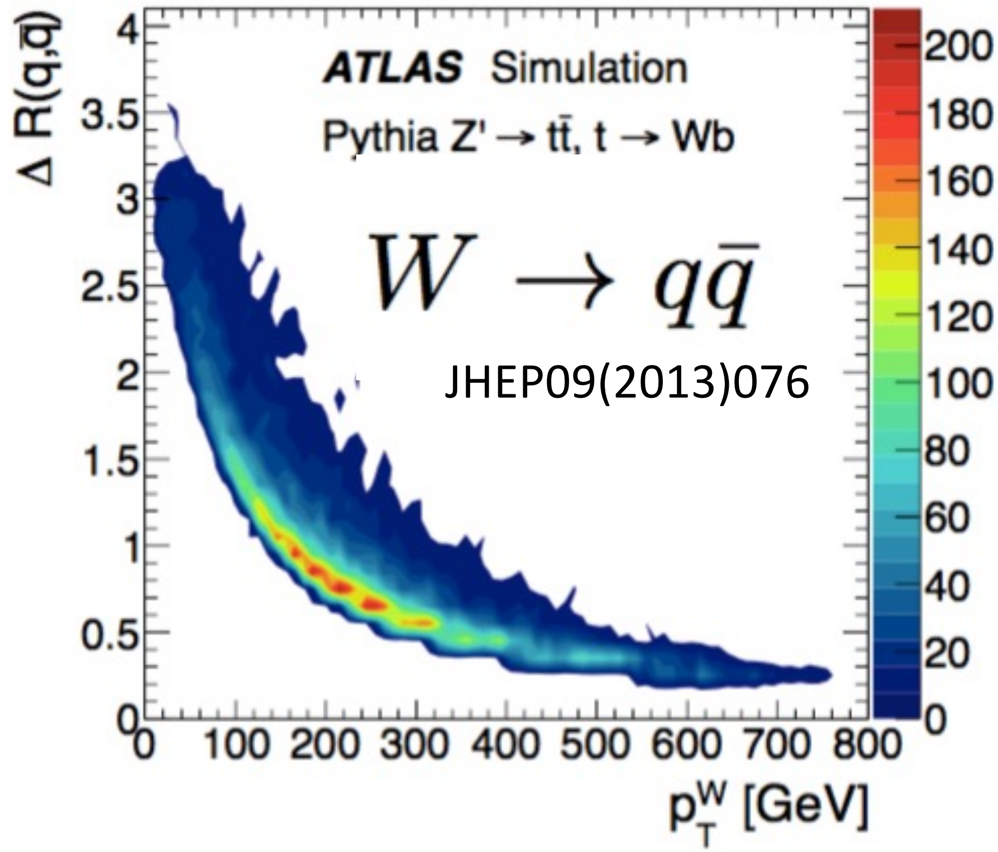
Utilize tools developed for pp - Jet Grooming: the systematic removal of a subset of the jet constituents →remove soft and wide-angle radiation from the jet



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

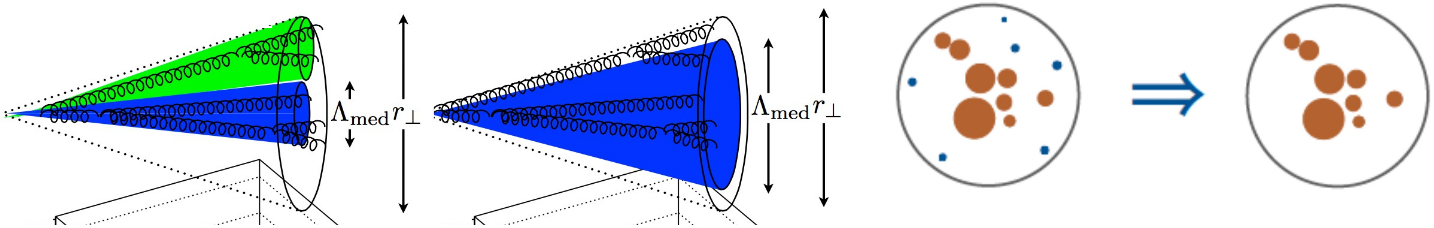


Decay is collimated i.e., qq are in the same jet.

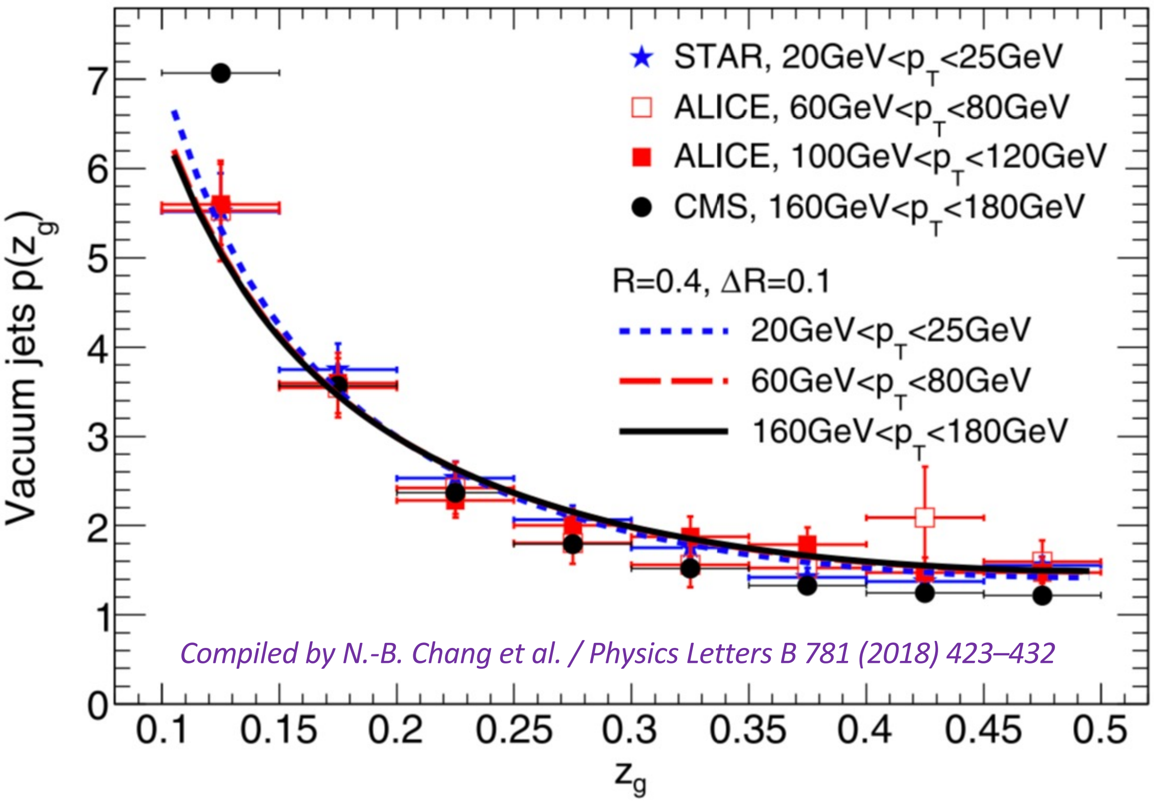


Grooming systematically removes jet constituents in order to reduce contamination from initial-state radiation (ISR), underlying event (UE), and multiple parton-parton/proton-proton collisions (MPI/pileup).

Utilizing Jet Grooming



large-angle soft radiation and bkg removed by grooming!

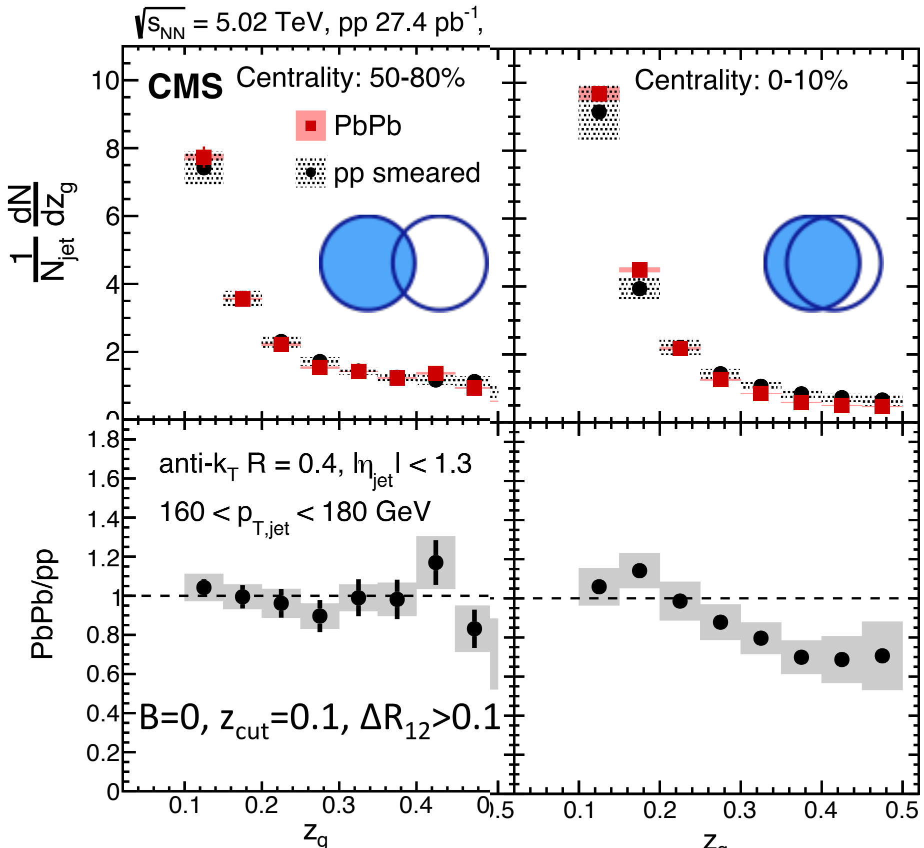


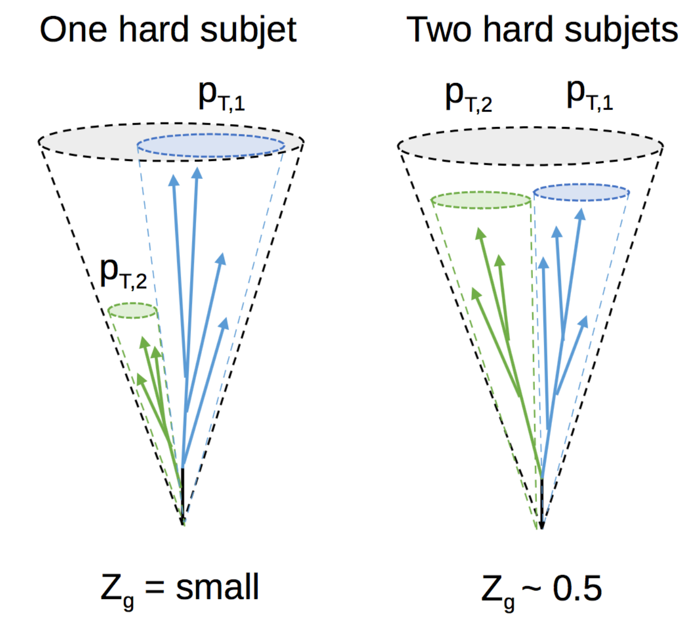
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

- Splitting functions appear to be universal.
- Calculation shows weak dependence on the jet of the vacuum jet splitting function

Utilizing Jet Grooming @ LHC

large-angle soft radiation and bkg removed by grooming!





CMS PRL 120 (2018) 142302

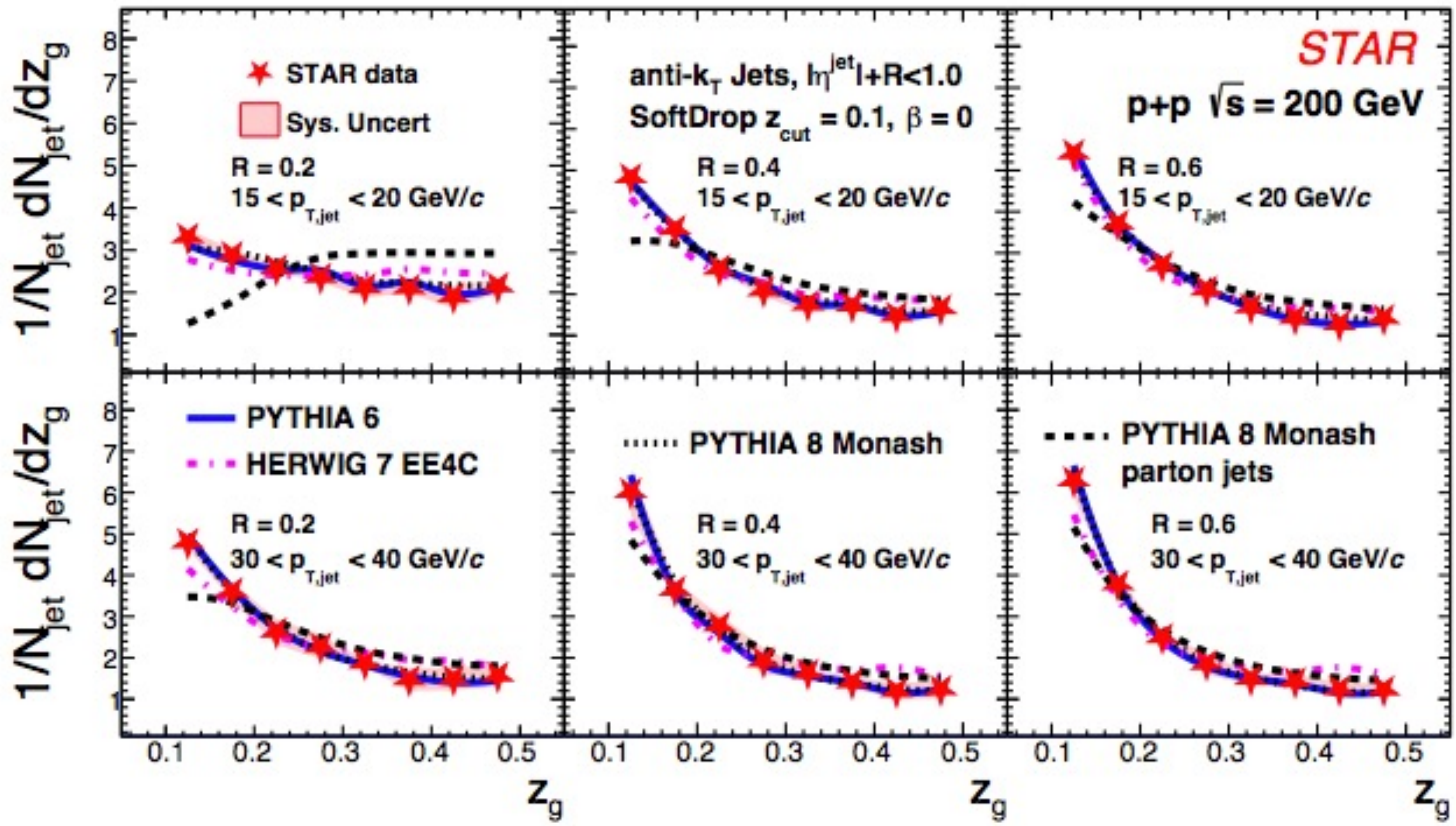
$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta},$$

Two hard subjets (large Zg) more suppressed than the ones with a single core (small Zg)
(Or small Zg is enhanced)

Momentum sharing between two leading subjets

Modification of splitting of inclusive jet measurements !

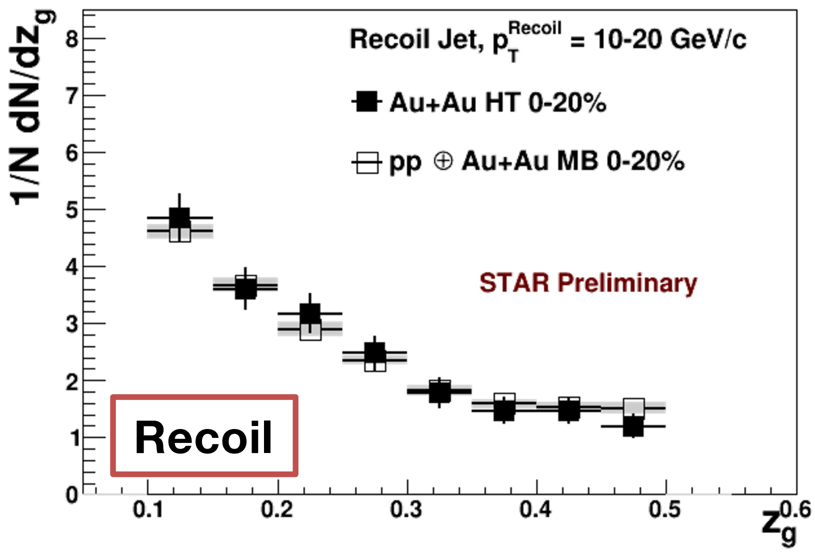
Utilizing Jet Grooming @ RHIC



Good agreement between data and RHIC-tuned PYTHIA 6

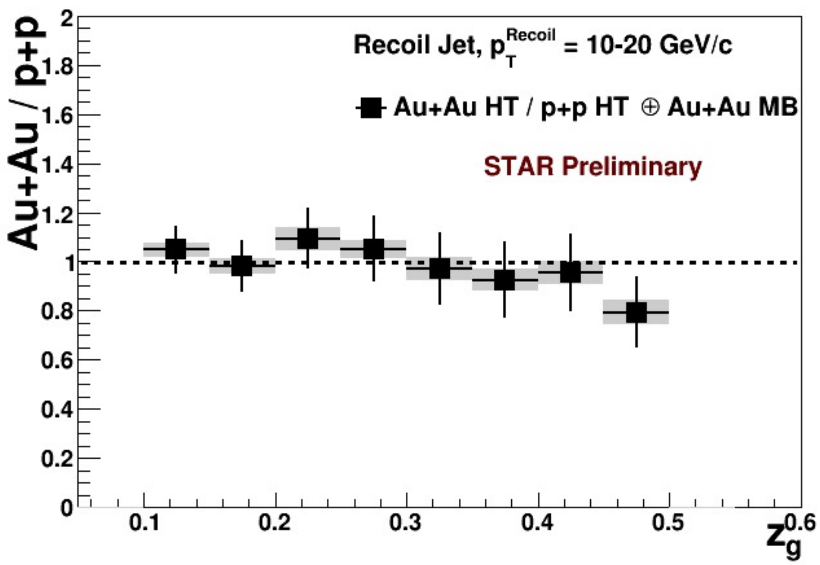
STAR Phys. Lett. B 811 (2020) 135846

Utilizing Jet Grooming @ RHIC



large-angle soft radiation and bkg removed by grooming!

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



Contrast to LHC results
→ Different population of jets, time of split, kinematics, dilution, …

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

Conclusions

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

Need to characterize medium parton interactions in detail with experiments and theory simultaneously!

Requires continuous interaction between Experiment & Theory