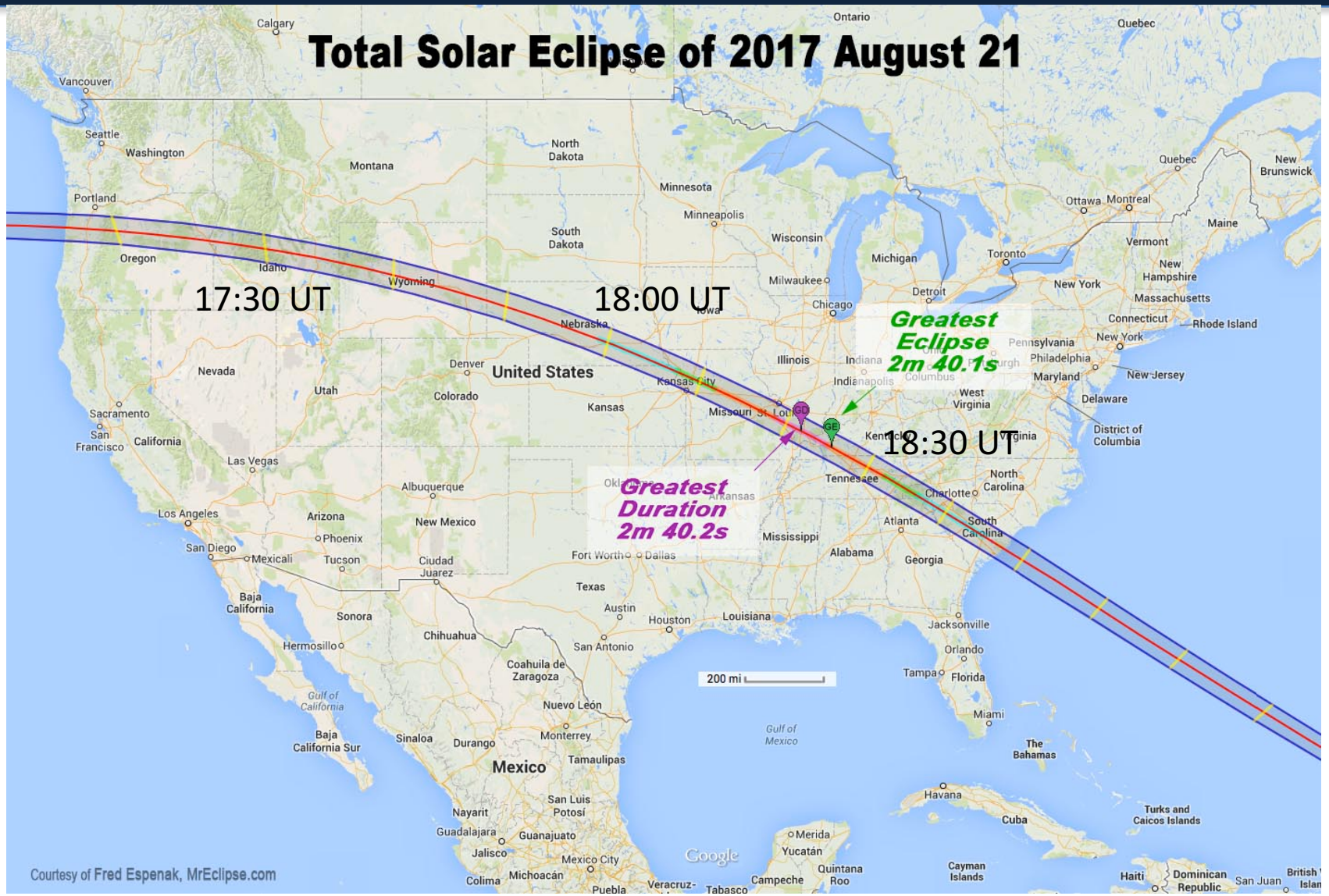
Jet Spectra and Correlations with CMS

Kurt Jung [Univ. Illinois at Chicago]

CERN HI Jet Workshop, Geneva, Switzerland

Aug. 21, 2017

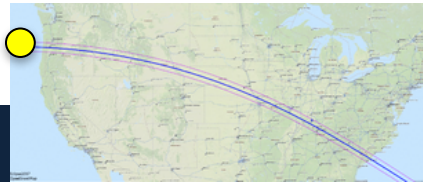
A Natural Timeline



Eclipse Predictions by Fred Espenak, NASA/GSFC Emeritus

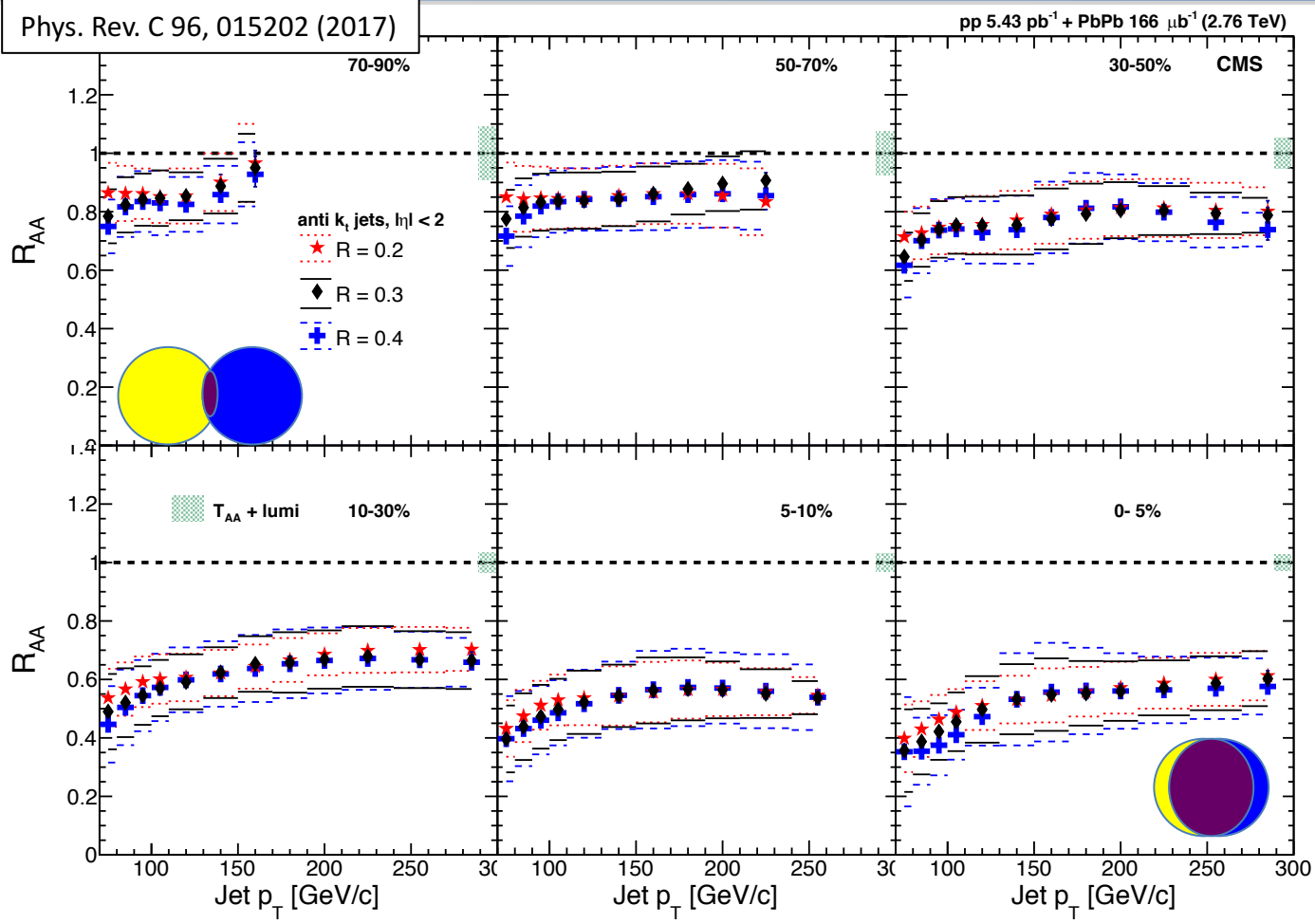
Jet Spectra

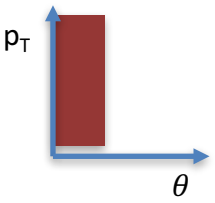
- Jet spectra measurements
  - Virtually background-free at high-p_T and semi-direct access to parton kinematics
  - Convolute a wide variety of physical processes
    - E-loss, medium response, jet shape modif., etc, etc…
  - Comparisons to other jets or pp references are always comparing apples-to-oranges
    - Mitigated somewhat recently by boson+jet studies
  - Good first look, require more detailed work to fully understand jet-medium interaction



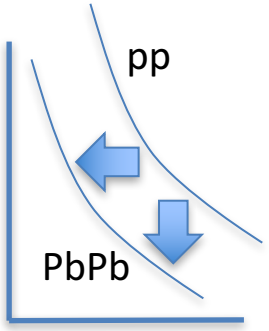
Centrality/Radial Dependence of R_{AA}

Phys. Rev. C 96, 015202 (2017)

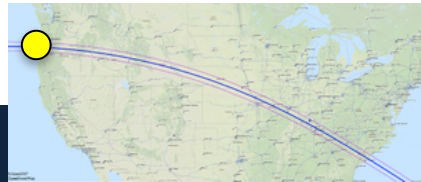




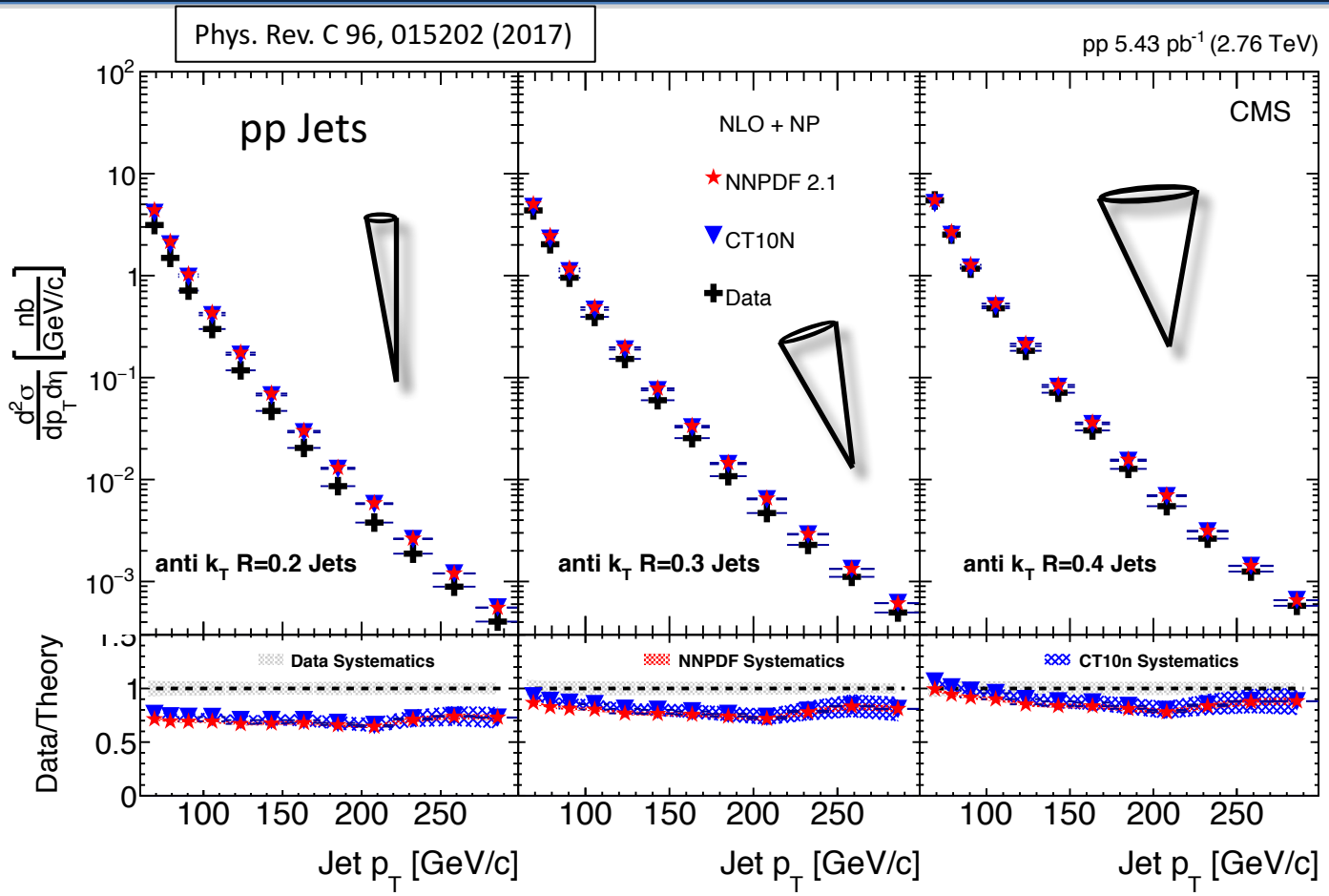
$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



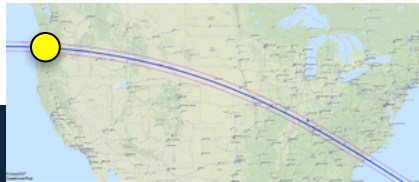
- Measurements of R_{AA} using various cone sizes show virtually identical suppression magnitude
  - All measured jet cones are still relatively "small"



Jet radius dependencies in pp

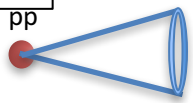


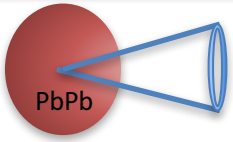
- Small-cone pp is not well constrained by NLO+NP theories
  - Cone-size dependence of simple jet cross-sections is underestimated by theory

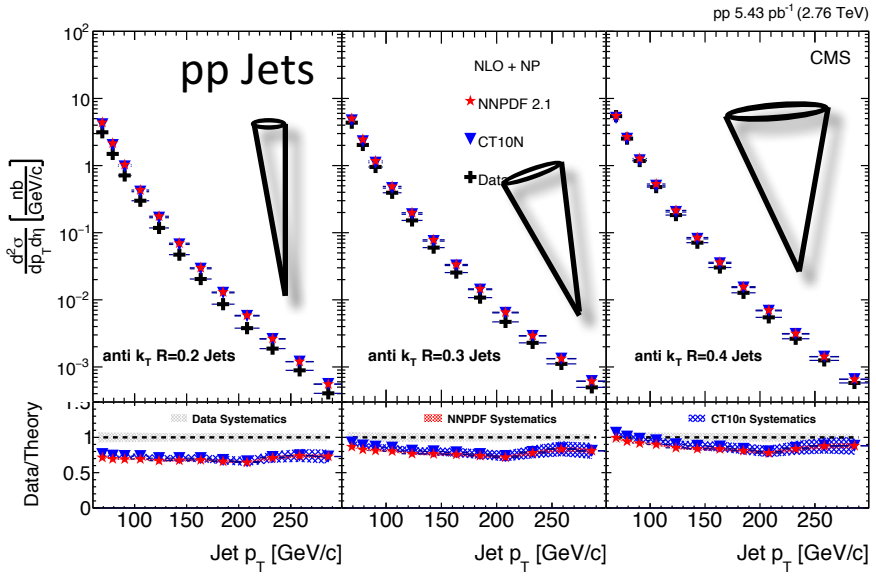


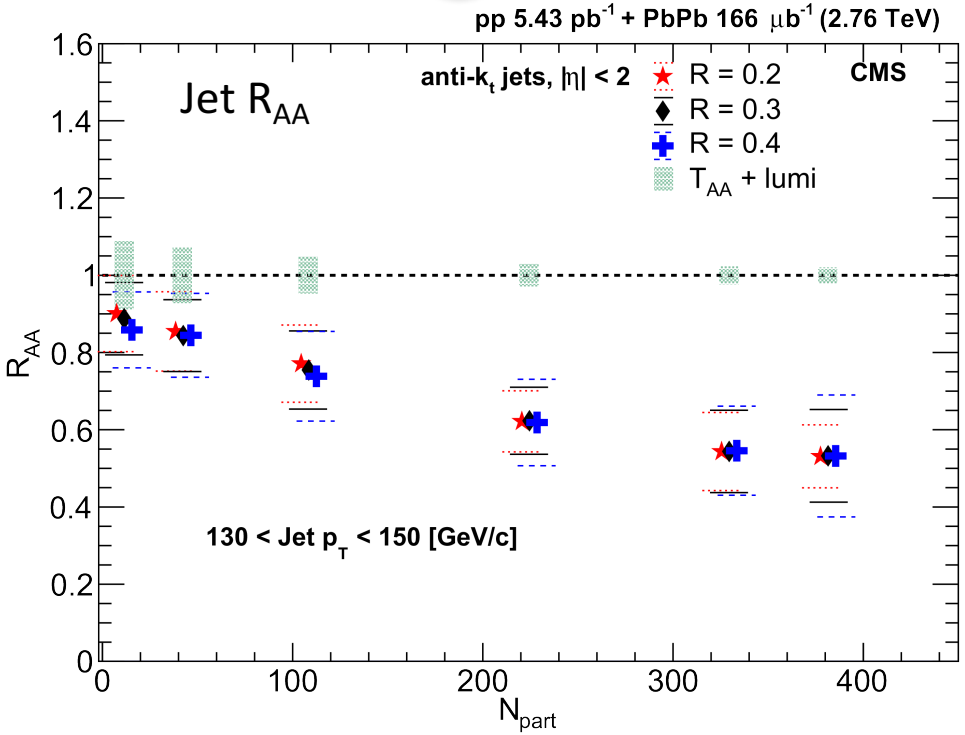
Jet radius dependence of R_{AA}

Phys. Rev. C 96, 015202 (2017)

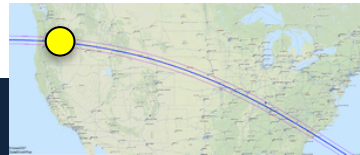






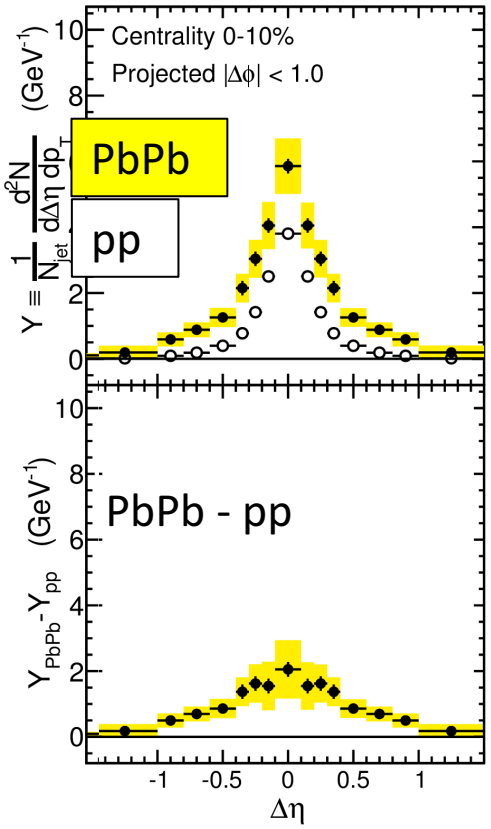


- Quenching dependence on jet radius parameter is negligible for small cones
  - Likely non-adherence to NLO+NP theory is factorized in RAA measurements

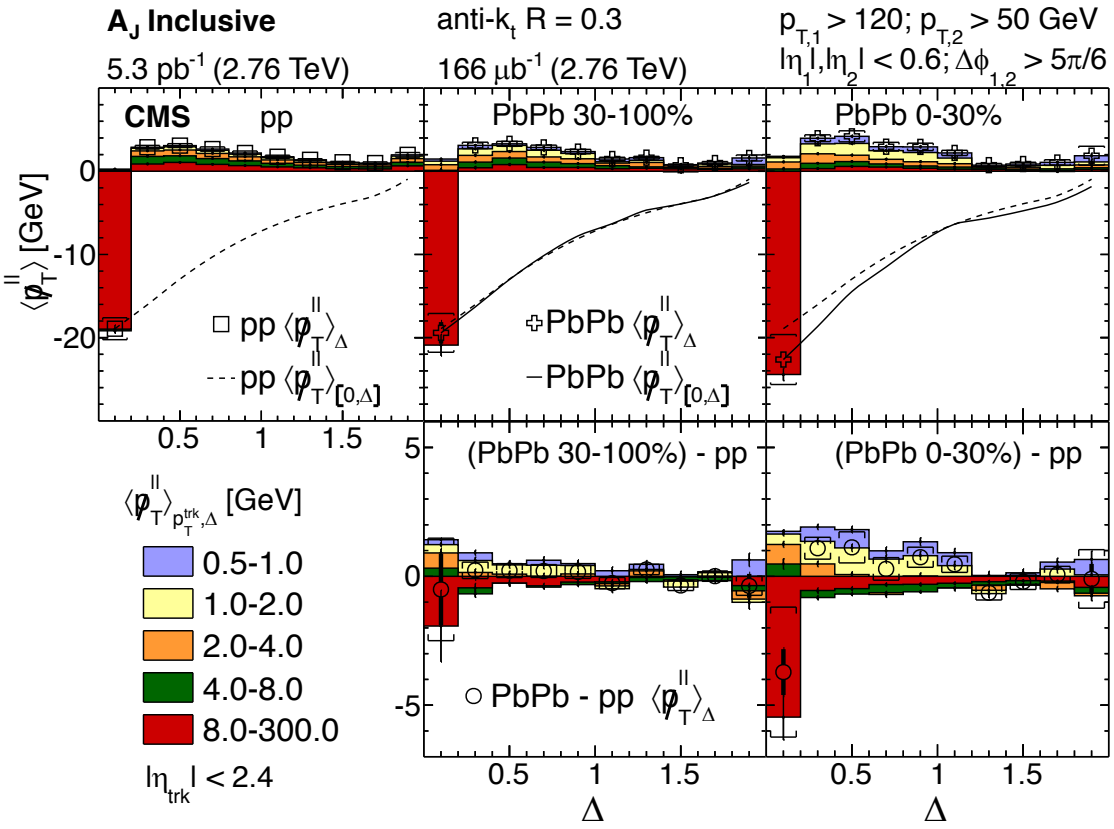


Jet radius dependence of R_{AA}

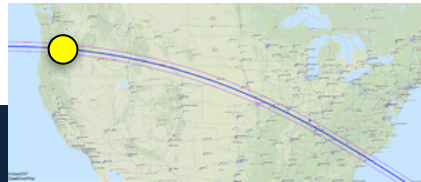
JHEP 02 (2016) 156



JHEP 01 (2016) 006

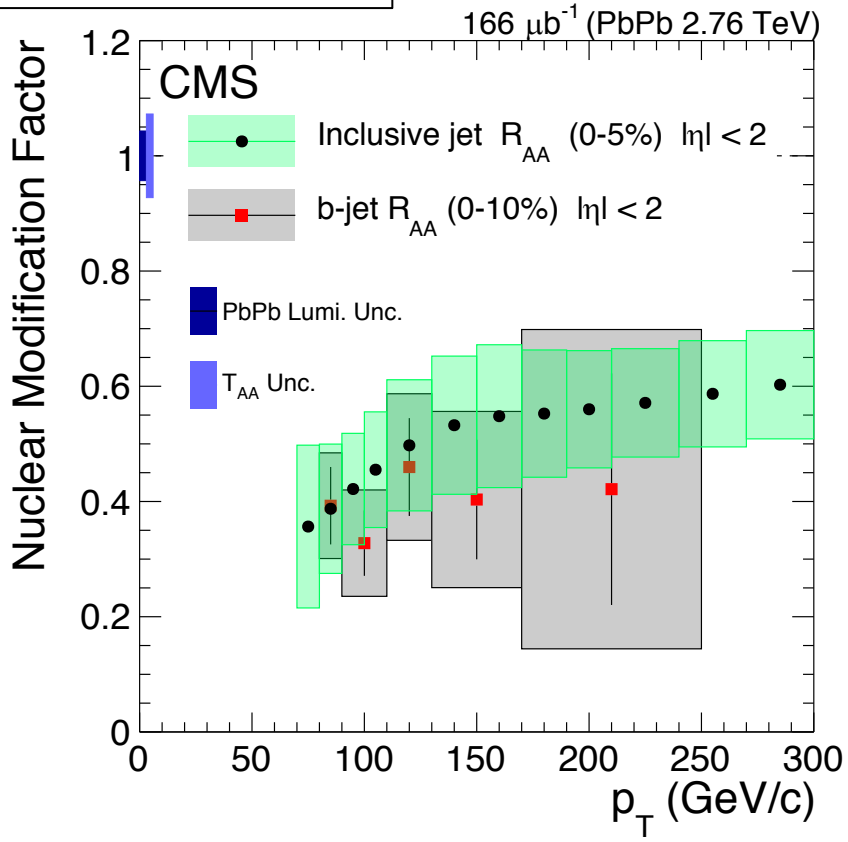


- Dependence on jet radius parameter is negligible for small cones
  - Large cone sizes ΔR>1.5 needed to fully recover jet energy (seen in jet-track correlations)

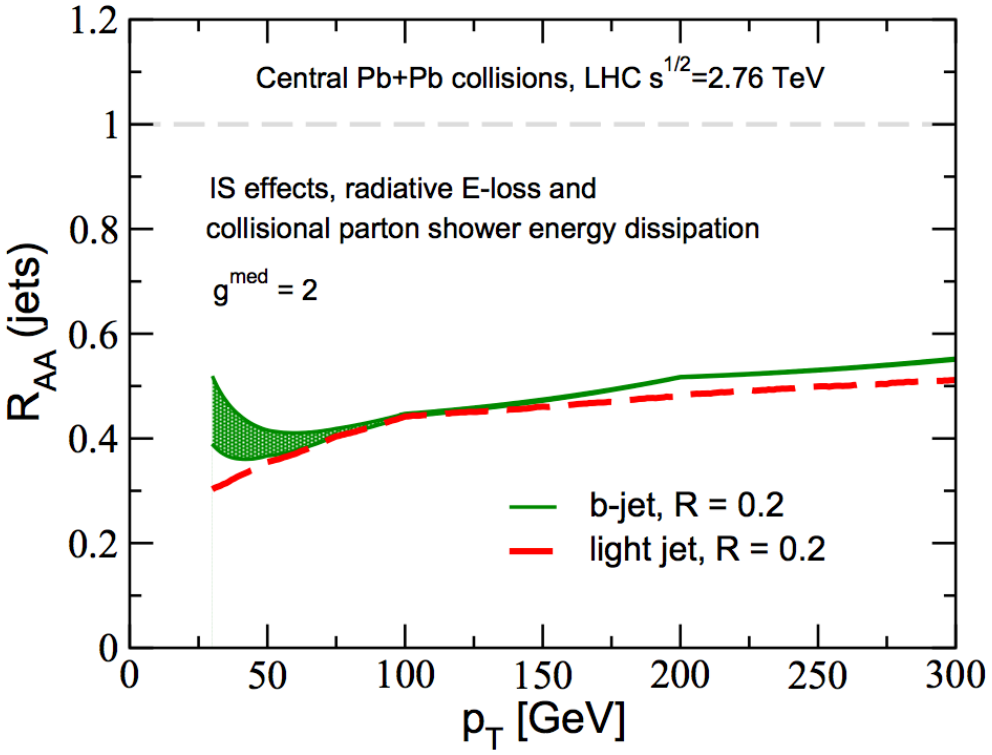


Heavy Jets behave like light jets (@ high-p_T)

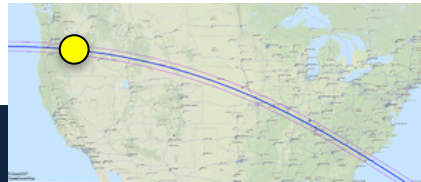
Phys. Rev. C 96, 015202
Phys. Rev. Lett. 113, 132301



PLB 726 (2013) 251-256

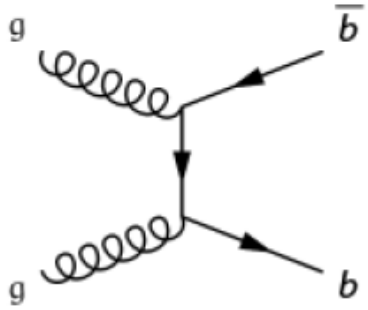


- CMS observes similar quenching magnitude (R_{AA}) between b-jets and light jets
  - Confirmed by theoretical pQCD measurements
  - Caveats involving b-jet production mechanisms here!
    - Gluon-splitting still a **dominant mechanism**

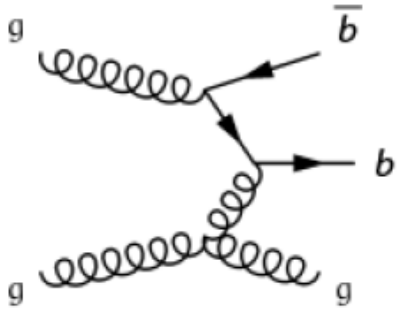


b-jet Production Mechanisms

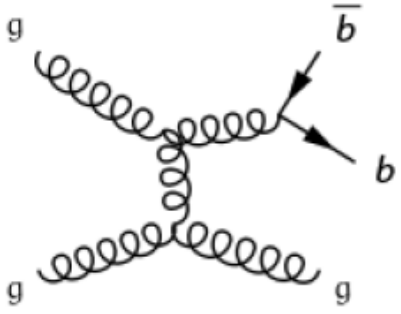
Flavor Creation ("FCR")

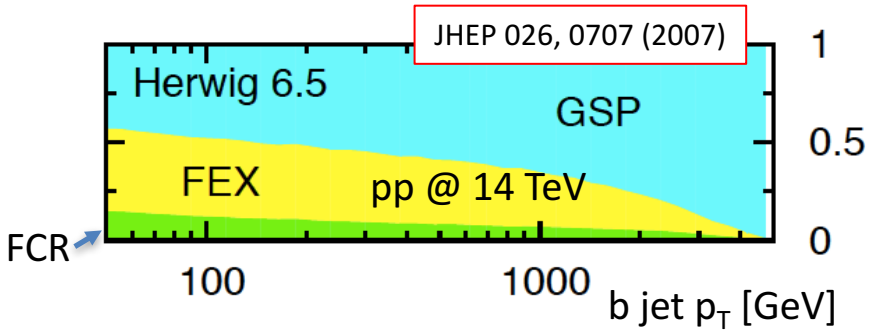


Flavor Excitation ("FEX")

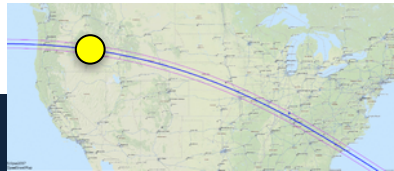


Gluon Splitting ("GSP")



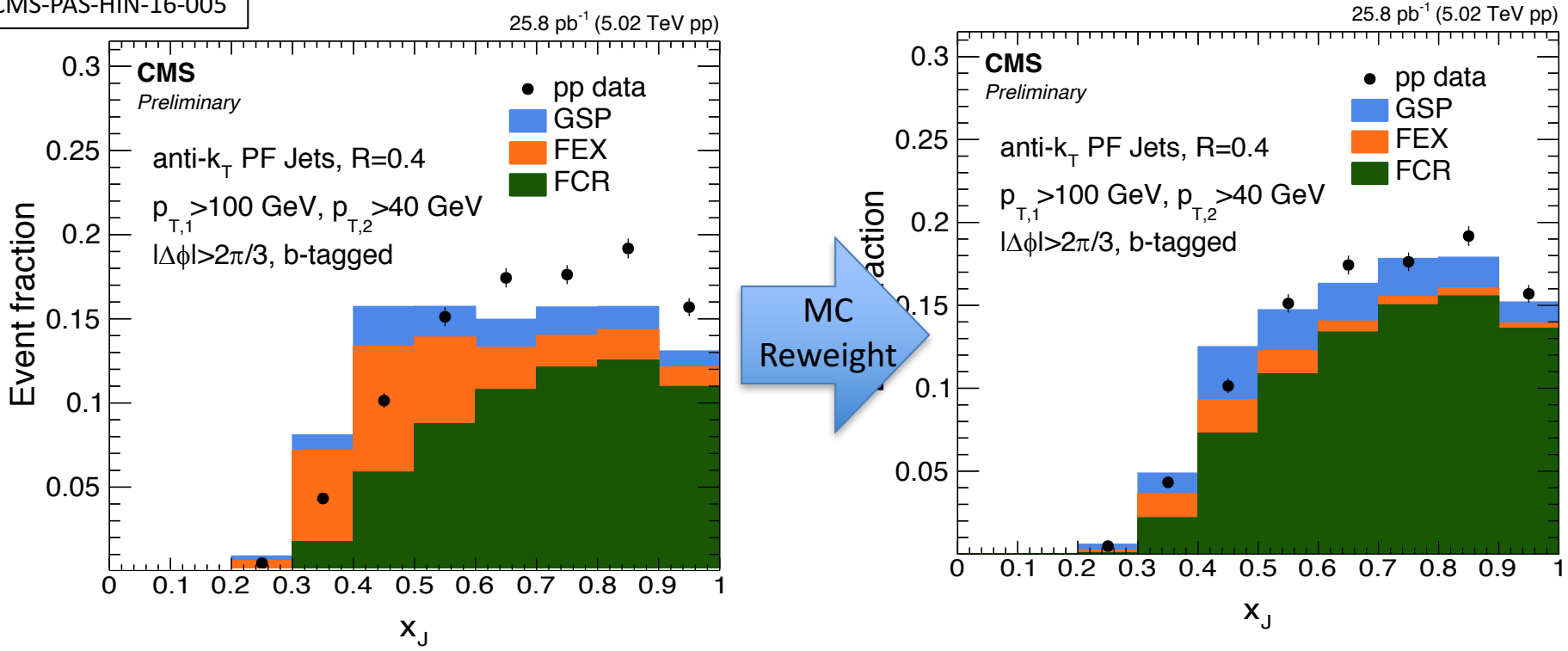


- Measurements of jet R_{AA} do not separate b-quark production mechanisms
- Herwig (NLO) predicts large contributions from all three production mechanisms in the measured p_T range
  - Gluon can split anywhere from early to late in the medium evolution -> convolutes energy loss measurements!
- b dijet measurements are essential to deconvolute leading-order energy loss from gluon splitting processes



b-jet Production Mechanisms

CMS-PAS-HIN-16-005



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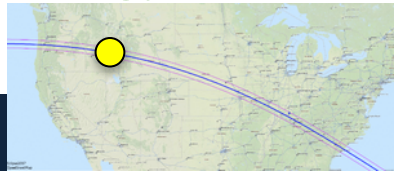
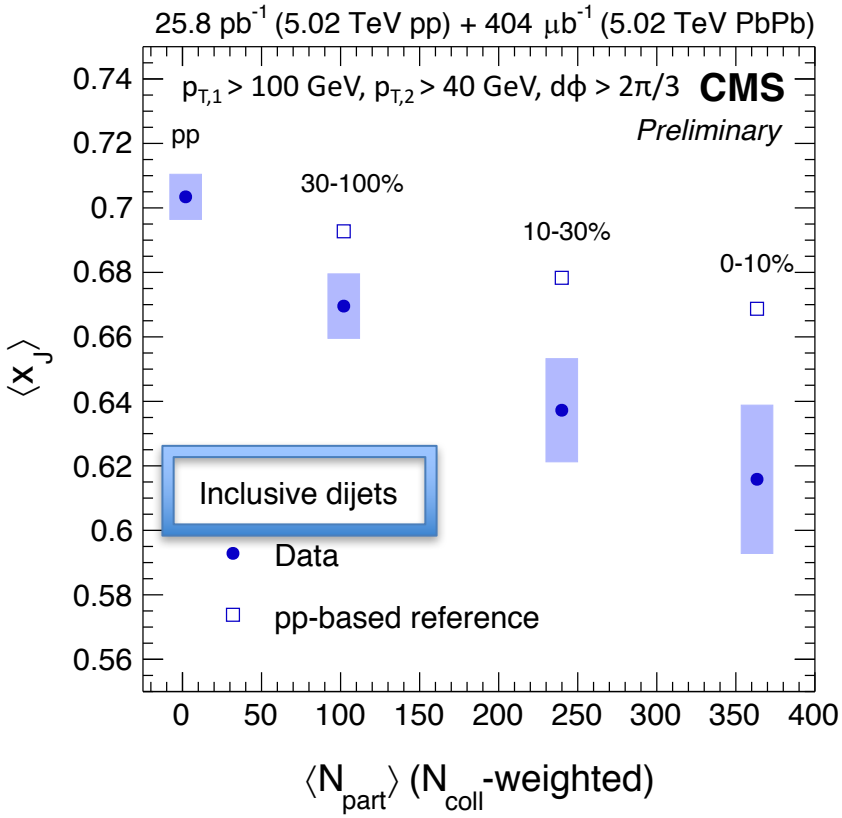
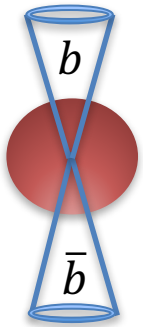


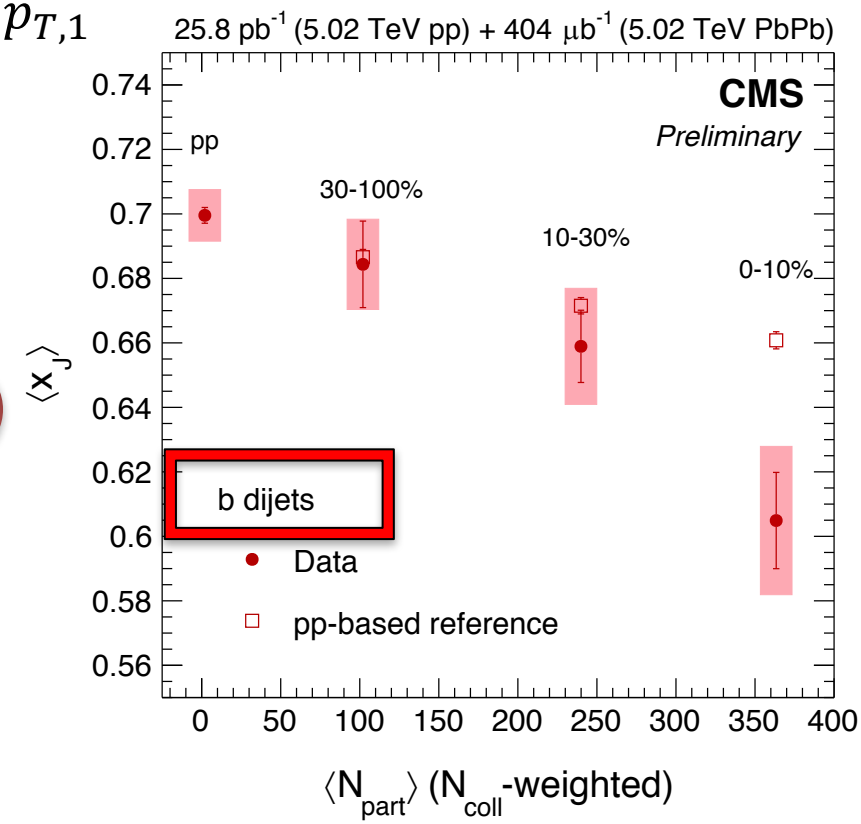
Toward more sensitive observables

CMS-PAS-HIN-16-005

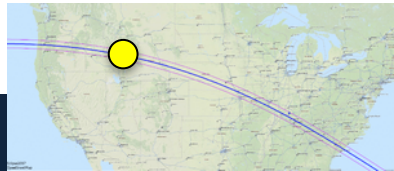
$$\langle x_J \rangle = \frac{p_{T,2}}{p_{T,1}}$$







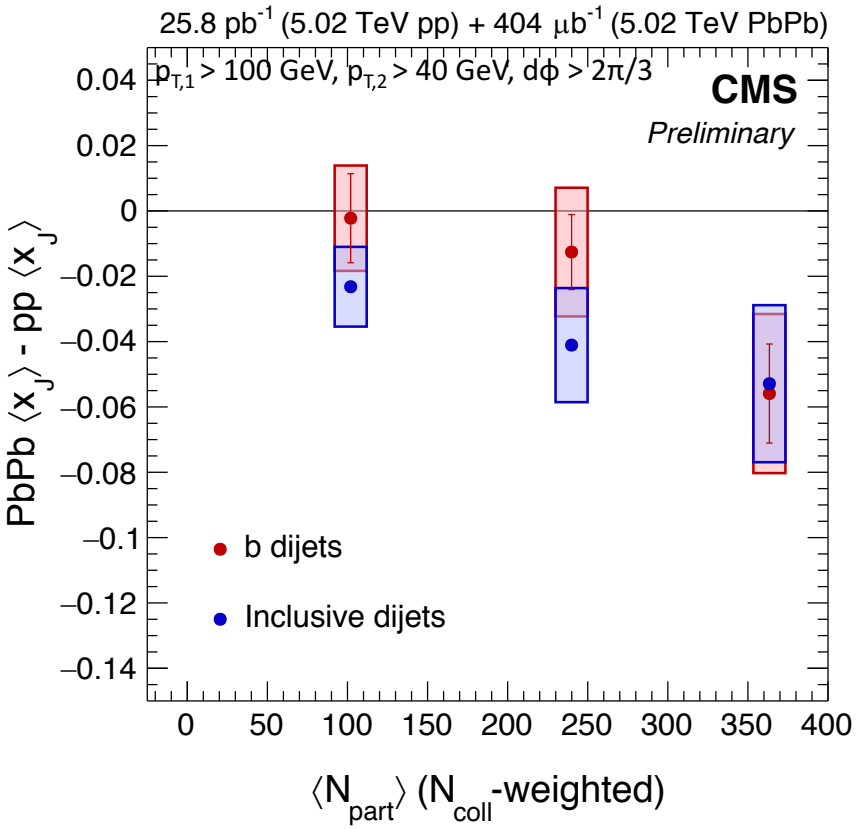
- b dijet R_{AA} removes ambiguity regarding production mechanisms
- Probes **leading-order** jet production component

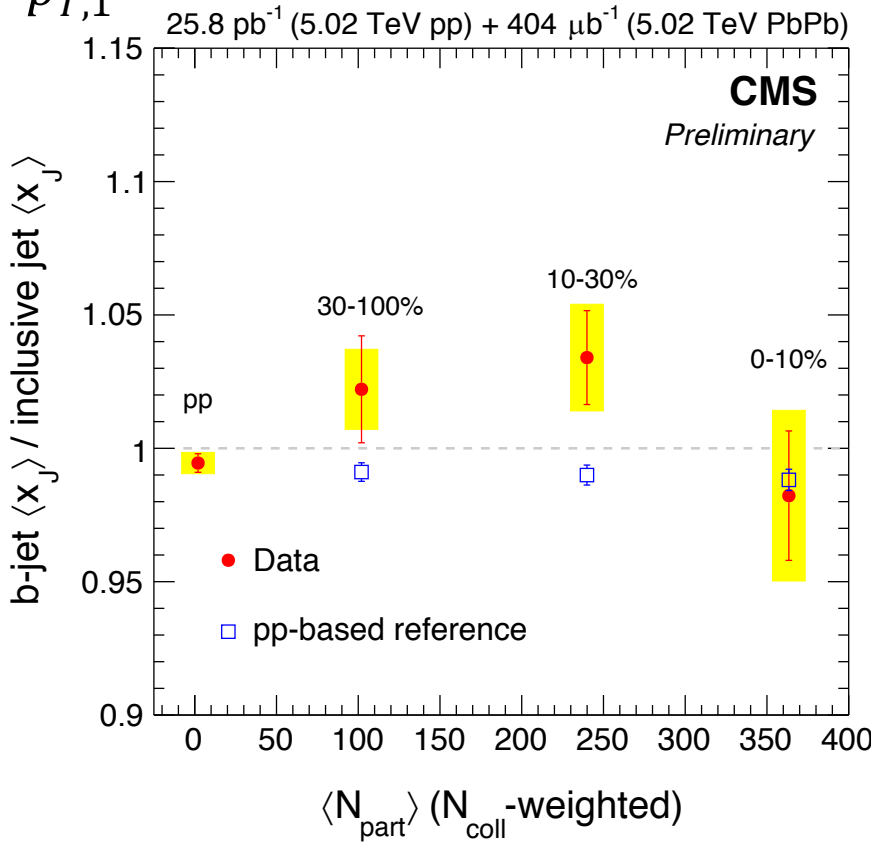


b Dijets

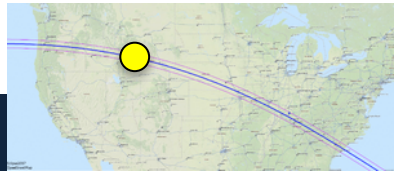
CMS-PAS-HIN-16-005

$$\langle x_J \rangle = \frac{p_{T,2}}{p_{T,1}}$$

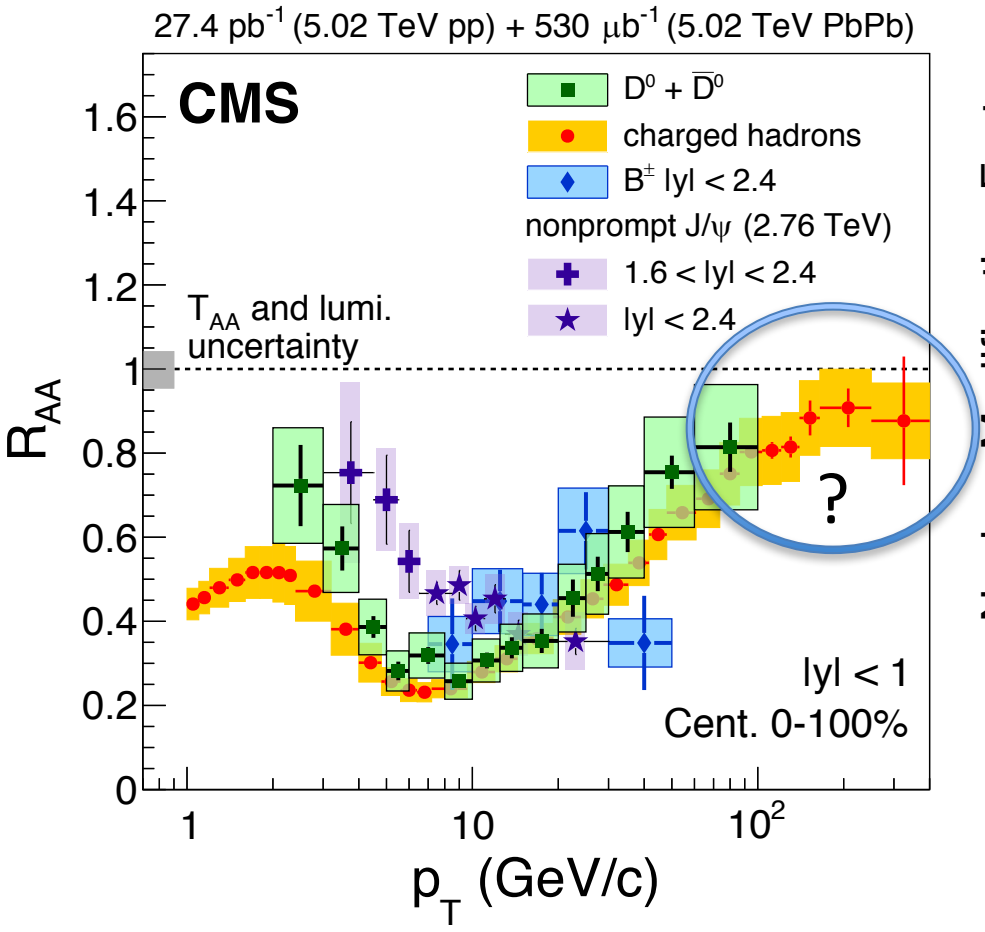


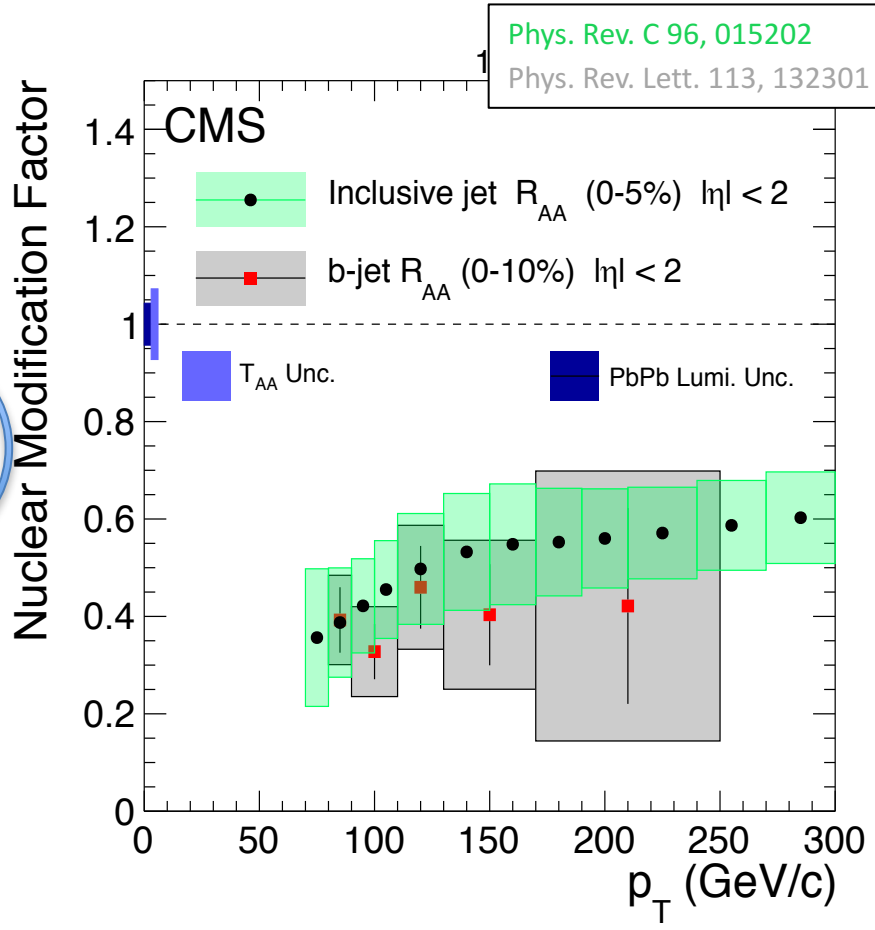


- Observe modification consistent with inclusive-jet measurements
- Directly comparing b dijet/inclusive dijet PbPb shows virtually no effect as a function of centrality



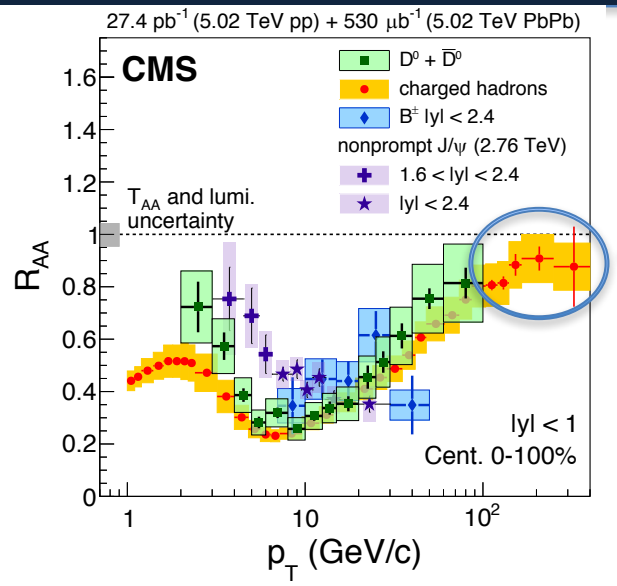
A Comparison of Jets and Mesons

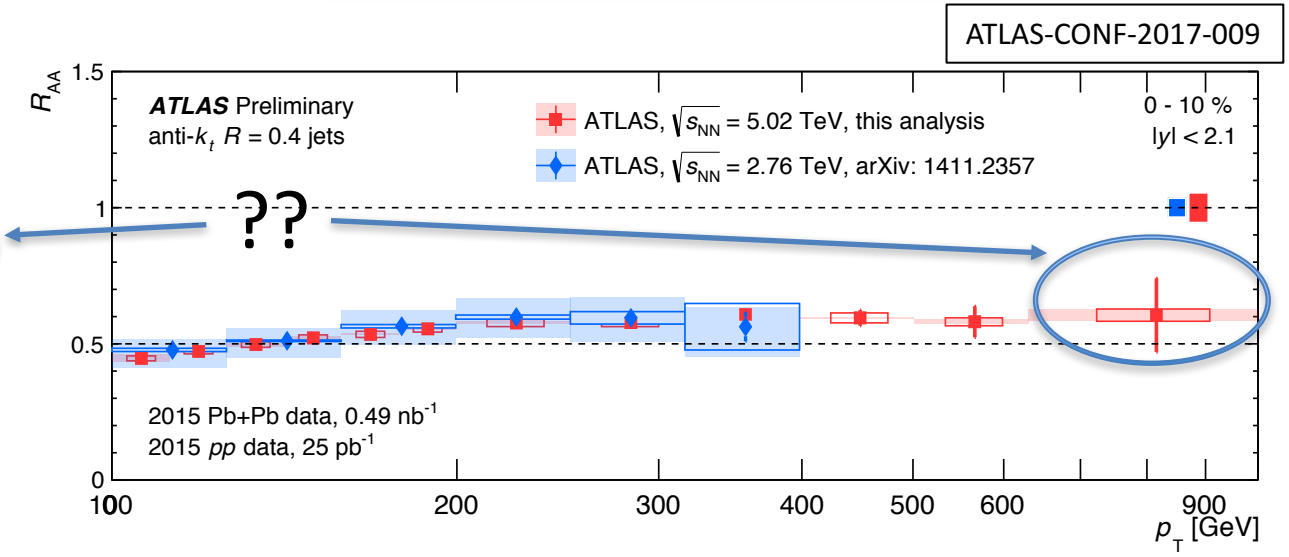




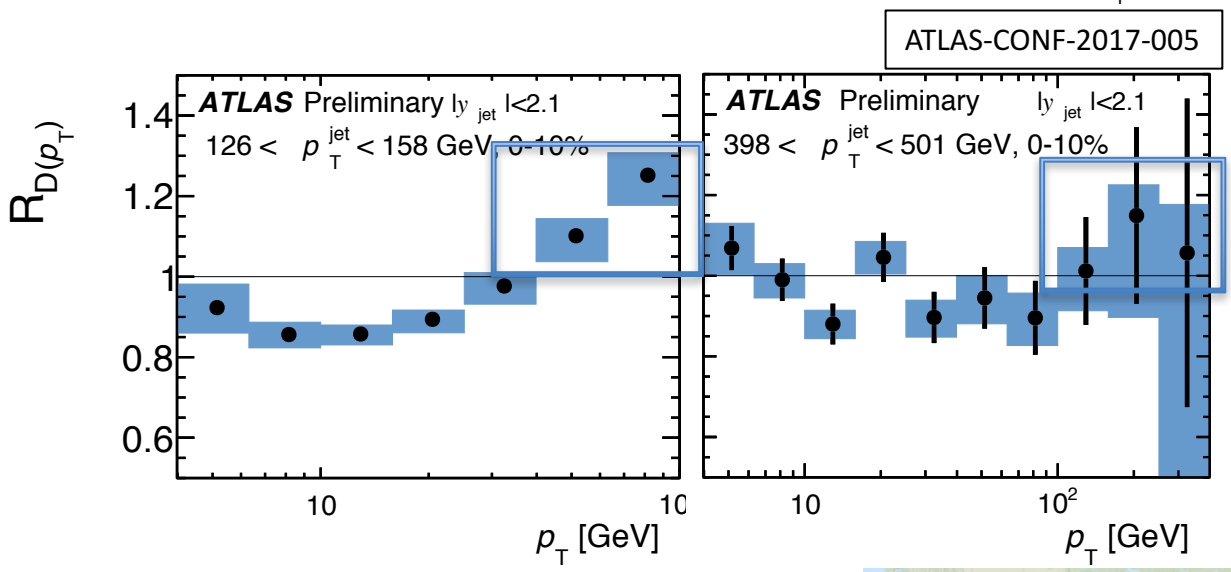
- Magnitude of R_{AA} is similar between flavored mesons and jets
  - Convoluting spectra shapes with fragmentation functions
    - Very different for heavy/light flavors

A Comparison of Jets and Mesons



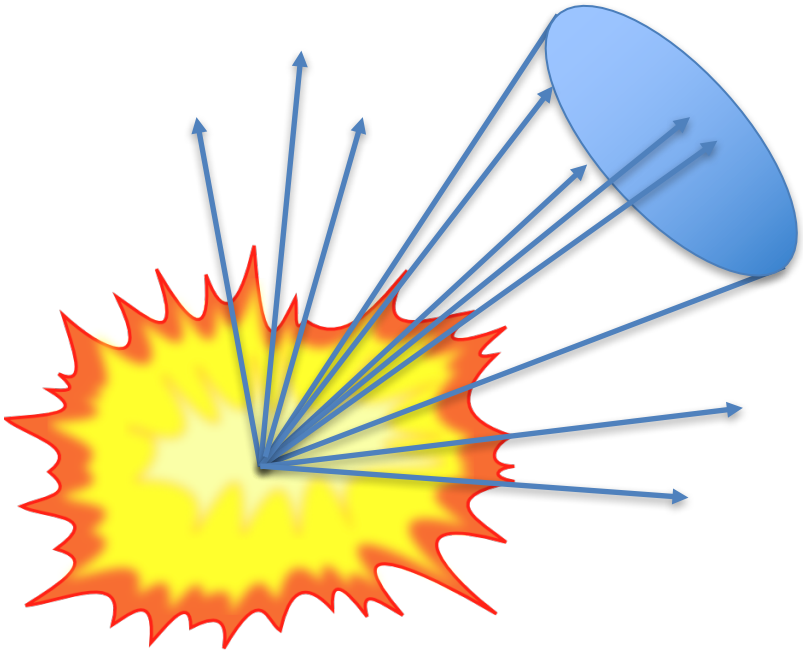


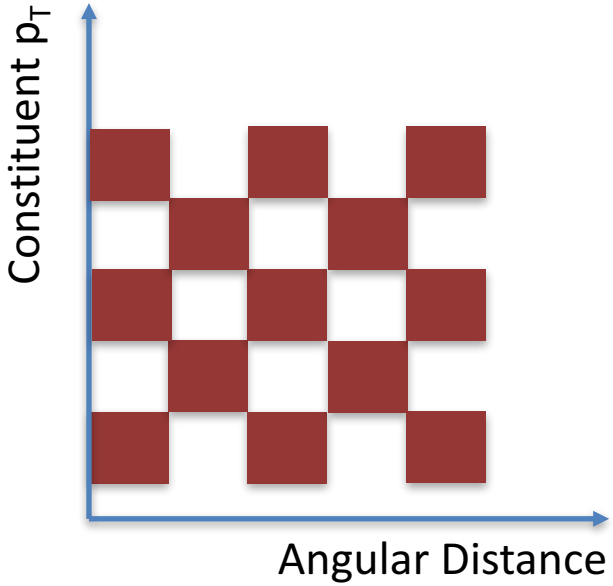
- ATLAS FF measurements directly observe high-p_T discrepancy
  - Quenching depends on FF of jet?
  - Evidence of coherent quenching behavior?
  - Spectrum-shape dependence?



Jet-Track Correlations

- Measurement correlates jets to all tracks to factorize energy loss in bins of p_T and angular distance
- Attempt to dive into substructure of jet and *quantify where the quenched energy goes*
- Uses (unquenched) pp as a reference

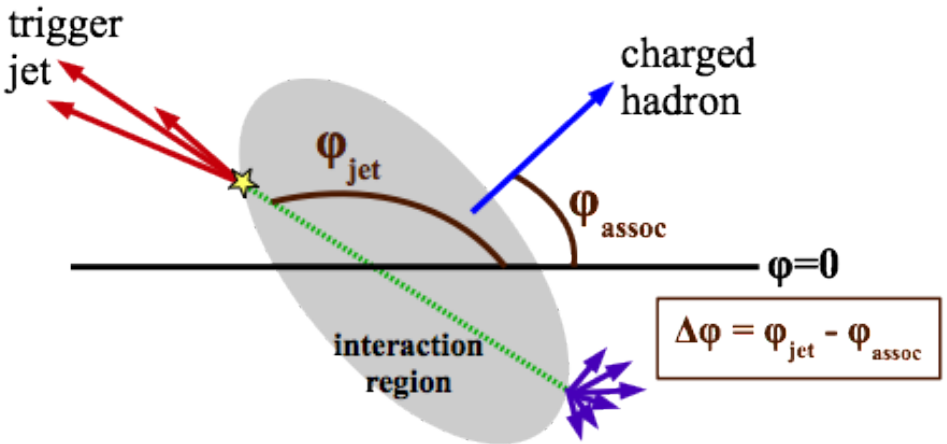


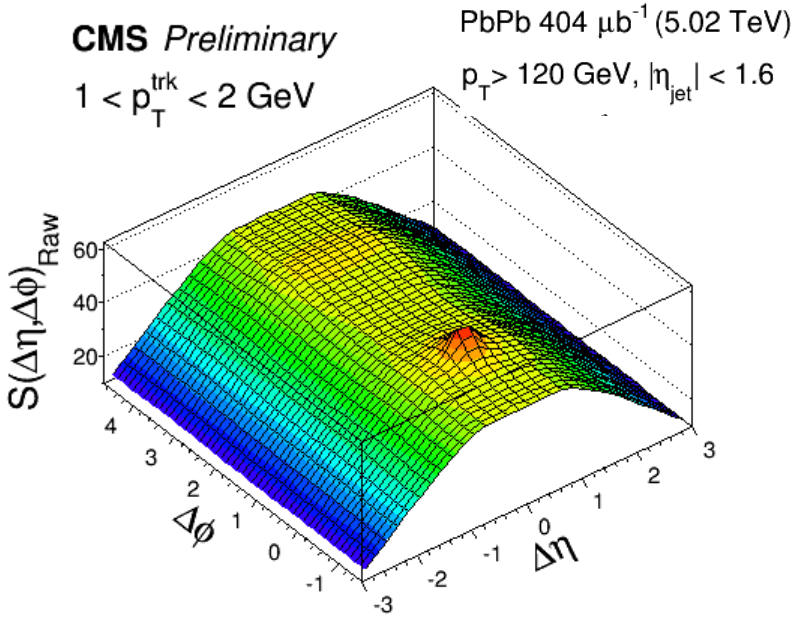


Constructing Jet-Track Correlations

Analysis procedure in PbPb and pp:

1. Construct 2D Δη—Δϕ charged particle correlations relative to jet axis
2. Pair acceptance geometric correction (using event mixing techniques)
3. Subtract long-range and uncorrelated background (using sideband in Δη)
4. Correct correlations for jet reconstruction-related biases

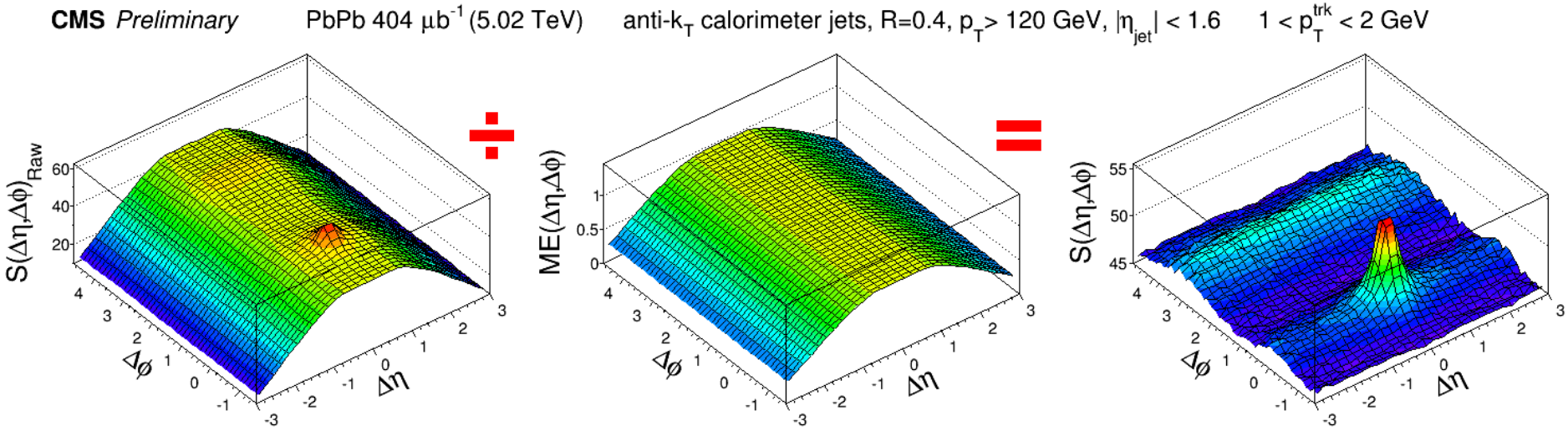




Jet-Track Pair-Acceptance Correction

- Finite jet and track acceptances result in trapezoidal geometry

- Correct for this pair acceptance effect with a mixed-event correction:
  - Jets from sample correlate with tracks from different events
  - Events used for mixing are matched on centrality and v_z

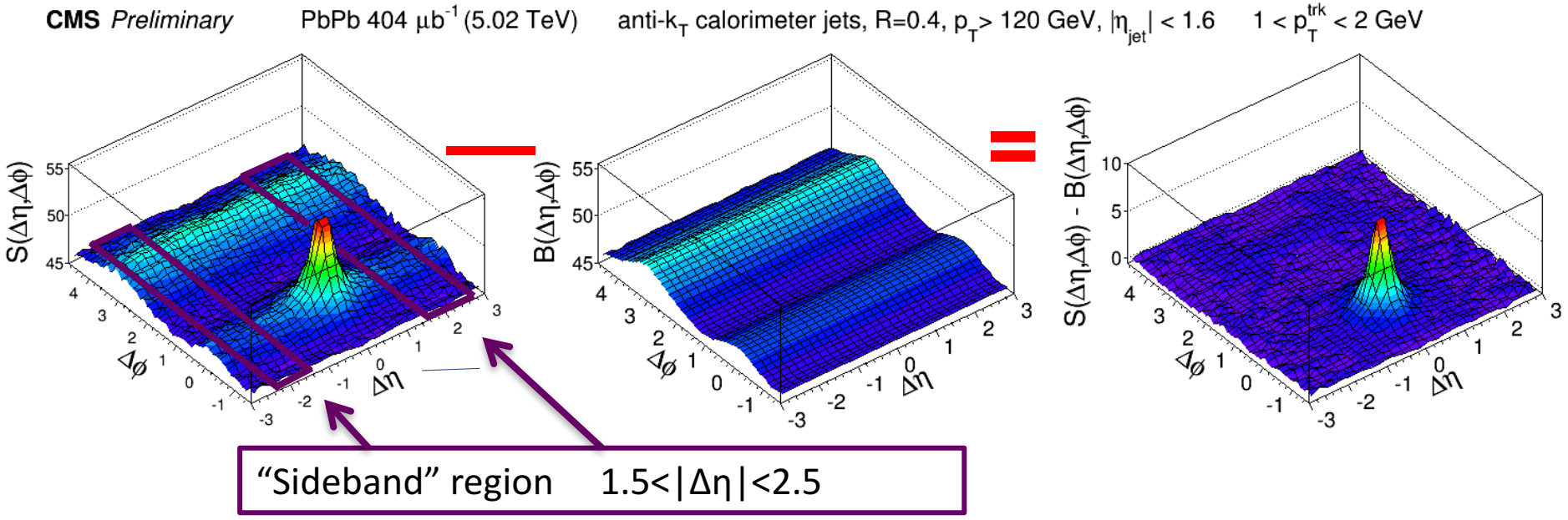


Jet-Track Background Subtraction

- Project background (measured on 1.5<|Δη|<2.5) into Δφ
- Propagate this background distribution in 2D
- Subtract from background from signal to yield isolated jet peak

Signal + Background

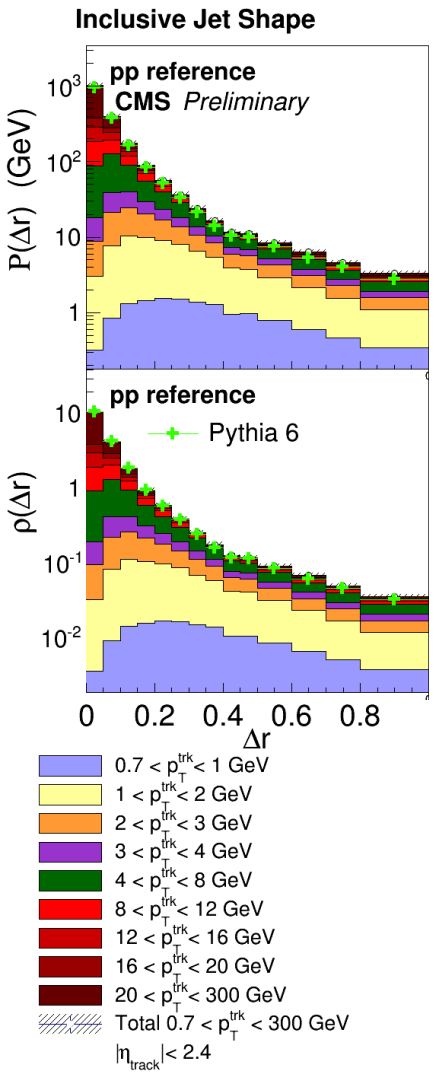
Signal Only



"Sideband" region 1.5<|Δη|<2.5

Radial p_T Profile and Jet Shape

CMS-PAS-HIN-16-020



Transverse momentum profile P(Δr)

- Weight Δη-Δϕ correlations per-track by track-p_T
- Integrate correlations in rings of $\Delta r = \sqrt{((\Delta\eta)^2+(\Delta\phi)^2)}$

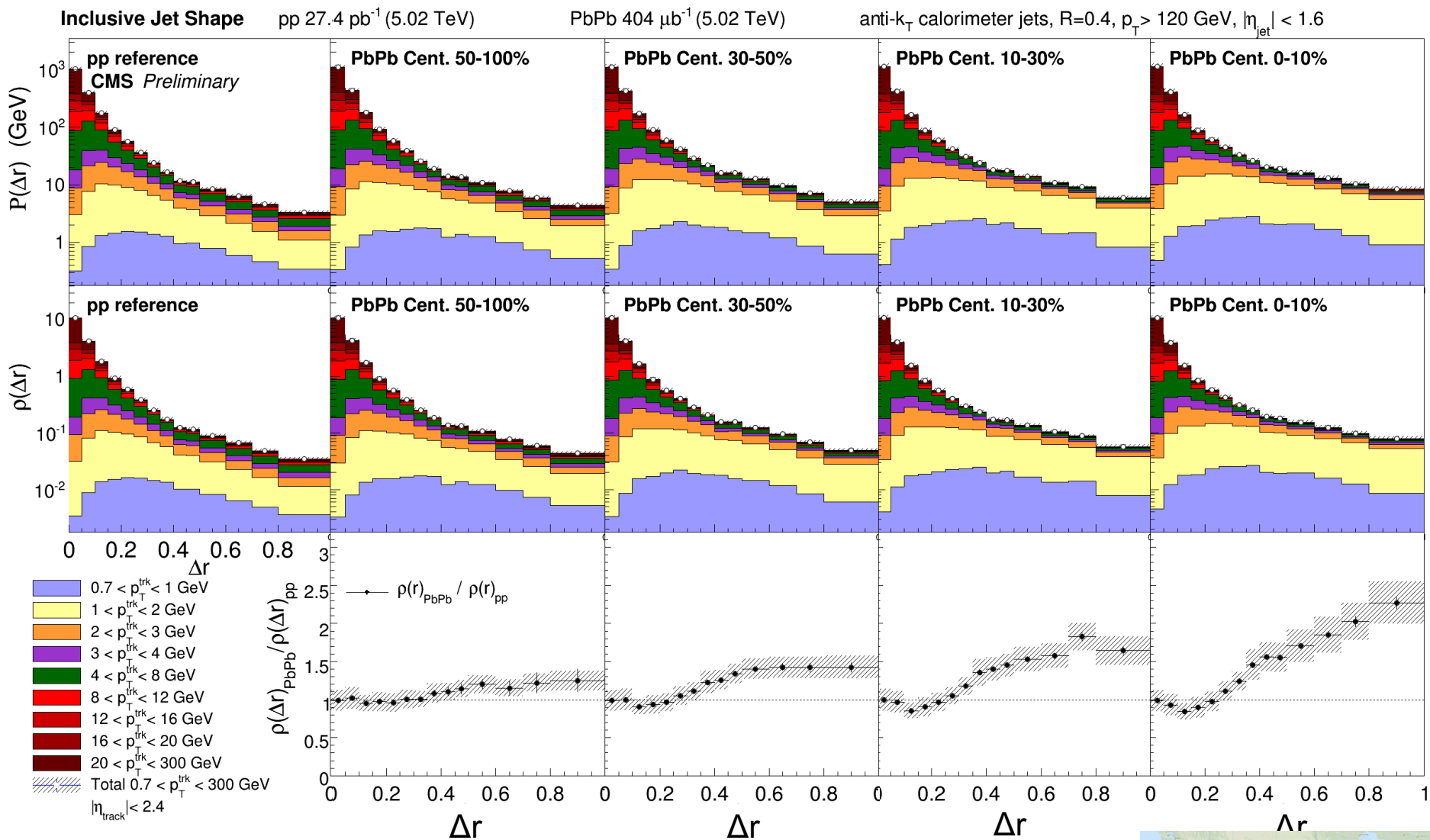
$$\mathrm{P}(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\Sigma_{\mathrm{jets}}\Sigma_{\mathrm{tracks}\in(\mathrm{r_a},\mathrm{r_b})}p_{\mathrm{T}}^{\mathrm{trk}}$$

Jet shape ρ(Δr)

- Normalize P(Δr) to unity over range $\Delta r < 1$
- Measures self-normalized p_T distribution of jet

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

Radial p_T Profile and Jet Shape



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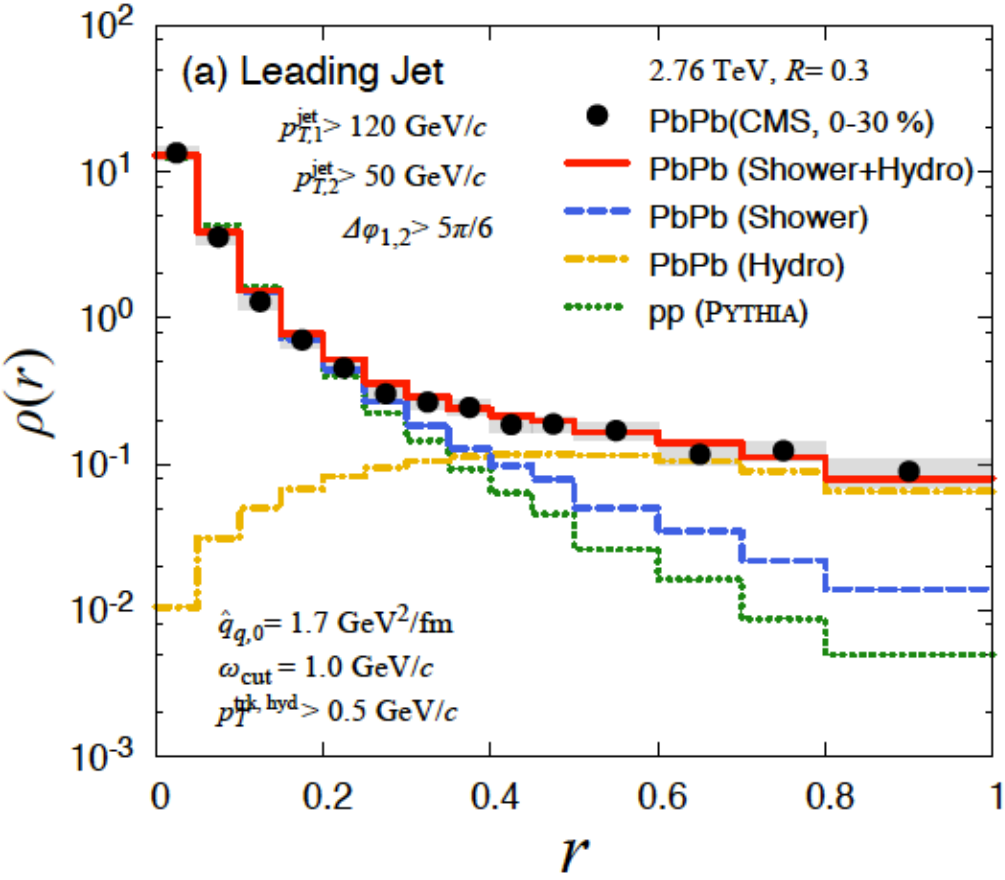
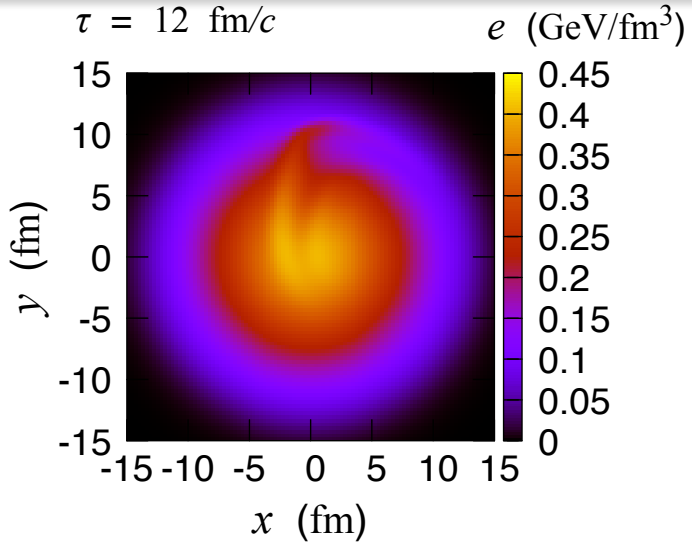
Importance of the Medium Response

Phys. Rev. C 95, 044909 (2017)



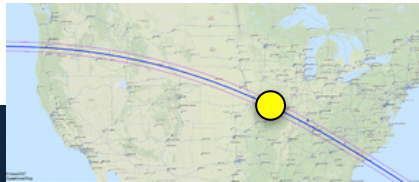


Quenched parton shower + medium excitation

Quenched parton shower

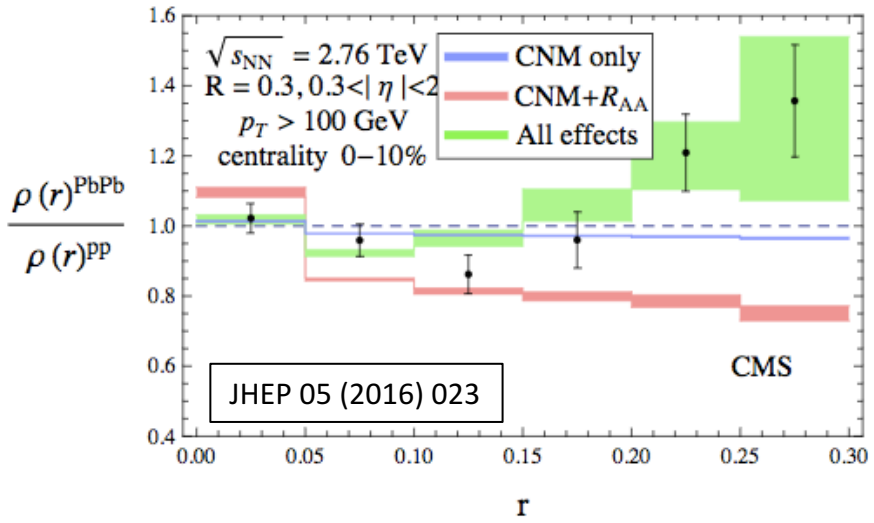
Vacuum parton shower

- Medium response is needed to explain large-angle ΔR flattening
  - QGP gets "dragged along" in shockwave behind the jet



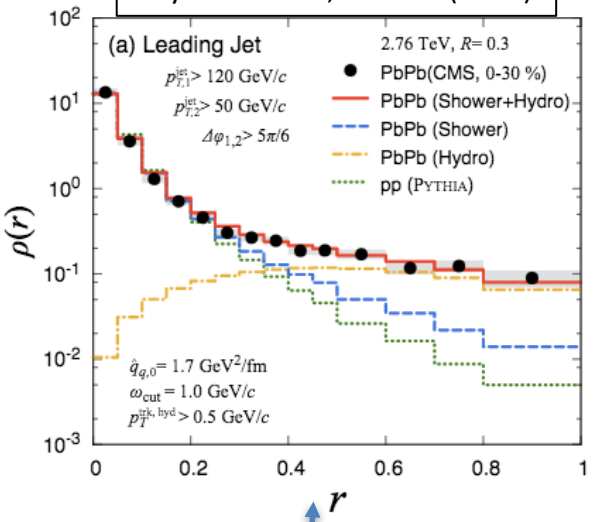
Other Jet-Track Theoretical Results

SCET$_G$ (including soft Glauber-gluon interactions in the QGP)



Shower+hydro medium response

Phys. Rev. C 95, 044909 (2017)



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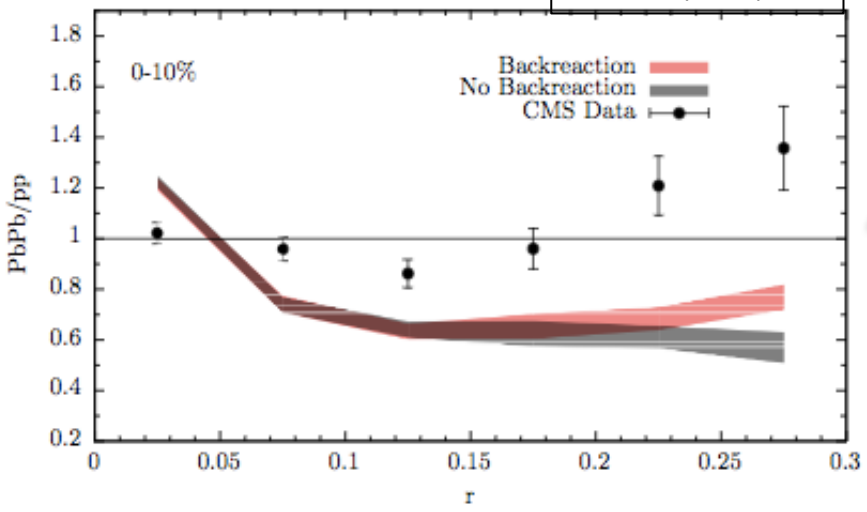
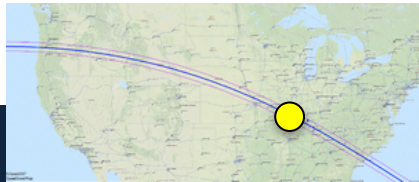


Hybrid model with backreaction ("plasma wake")

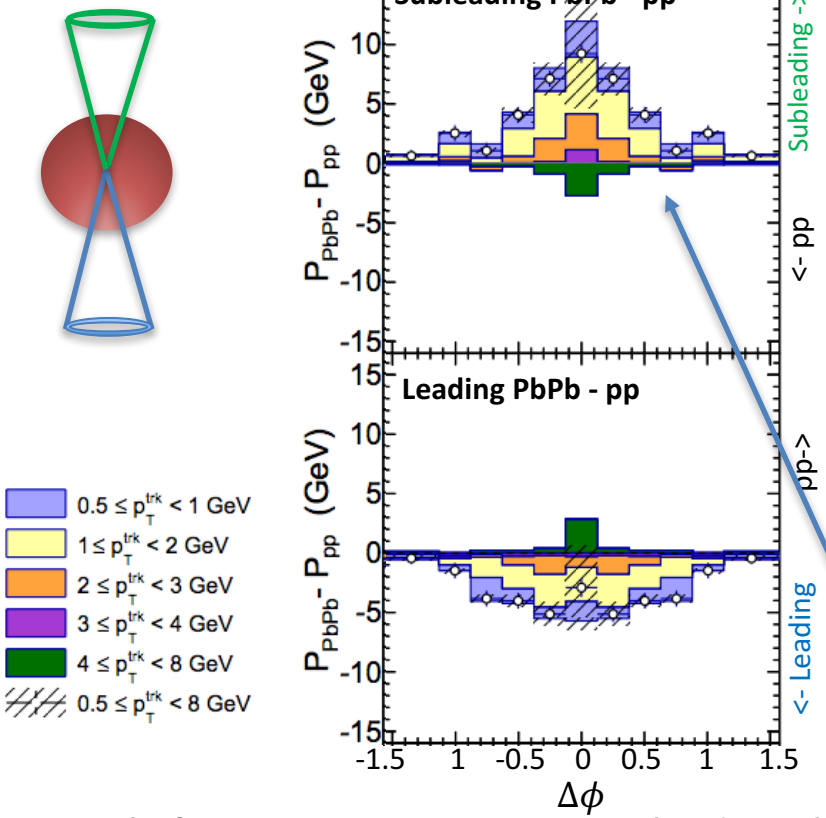
Theoretical curves model the medium response using different methods



Jet Track Correlations

JHEP 11 (2016) 055

A_J < 0.22, $p_{T,1}$ > 120 GeV, $p_{T,2}$ > 50 GeV



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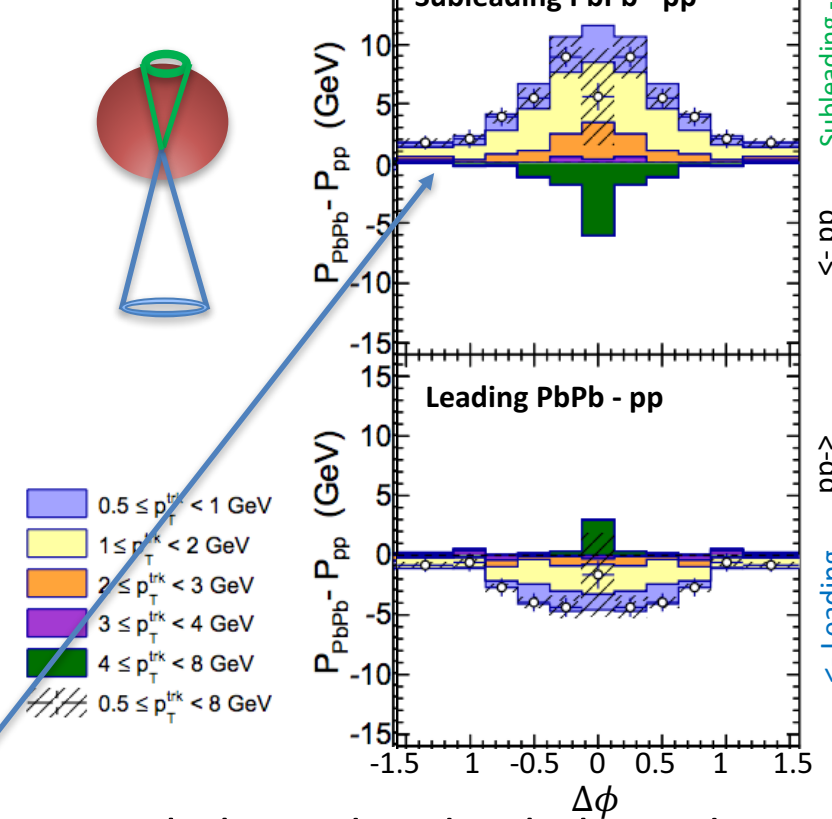
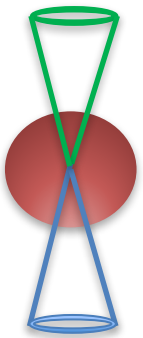


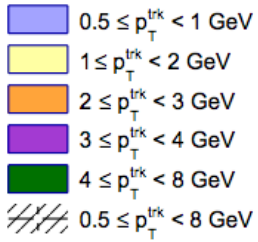
- Shift in constituent particle distribution between balanced and unbalanced jets
  - Subleading jet low-pT constituents pushed farther away for quenched jets
  - Leading jet particle distributions consistent between quenched/unquenched sample

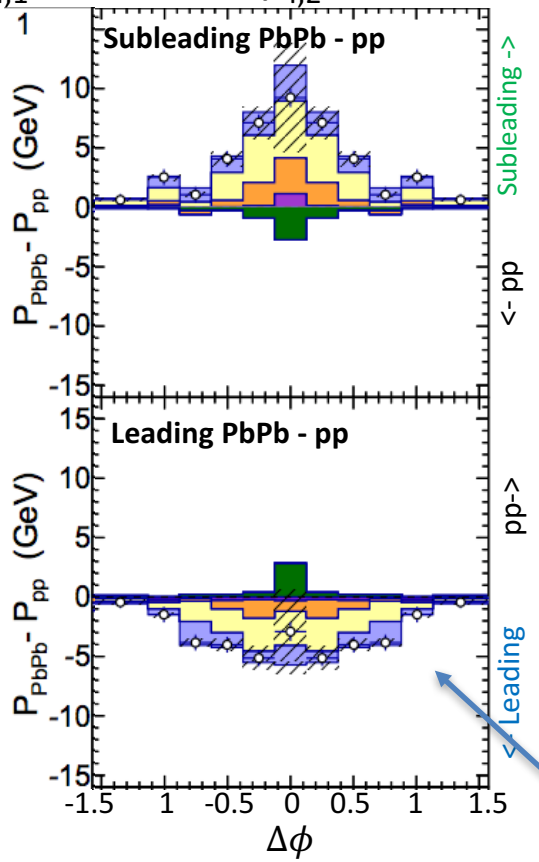
Jet Track Correlations

JHEP 11 (2016) 055

$A_J < 0.22$, $p_{T,1} > 120$ GeV, $p_{T,2} > 50$ GeV







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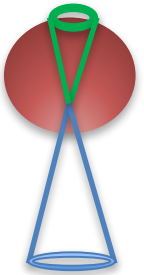
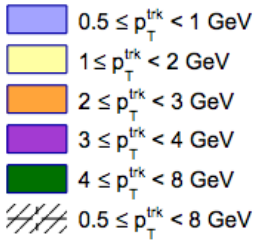
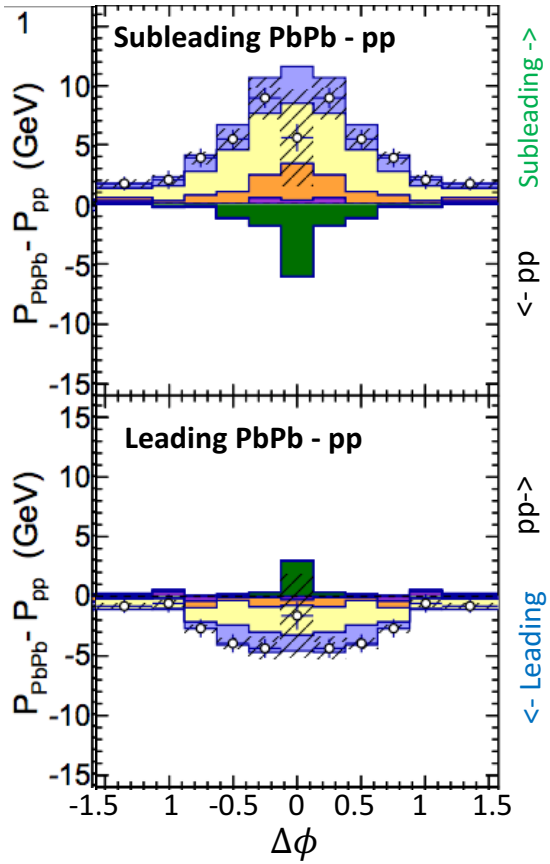
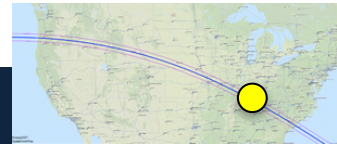






- Leading jet constituents are modified, even for **balanced** dijets (!)
  - Assumption that leading jet is unmodified may not be true at LHC energies
  - Need a ***<u>better reference</u>*** for jet suppression than another jet



Jet Track Correlations

JHEP 11 (2016) 055

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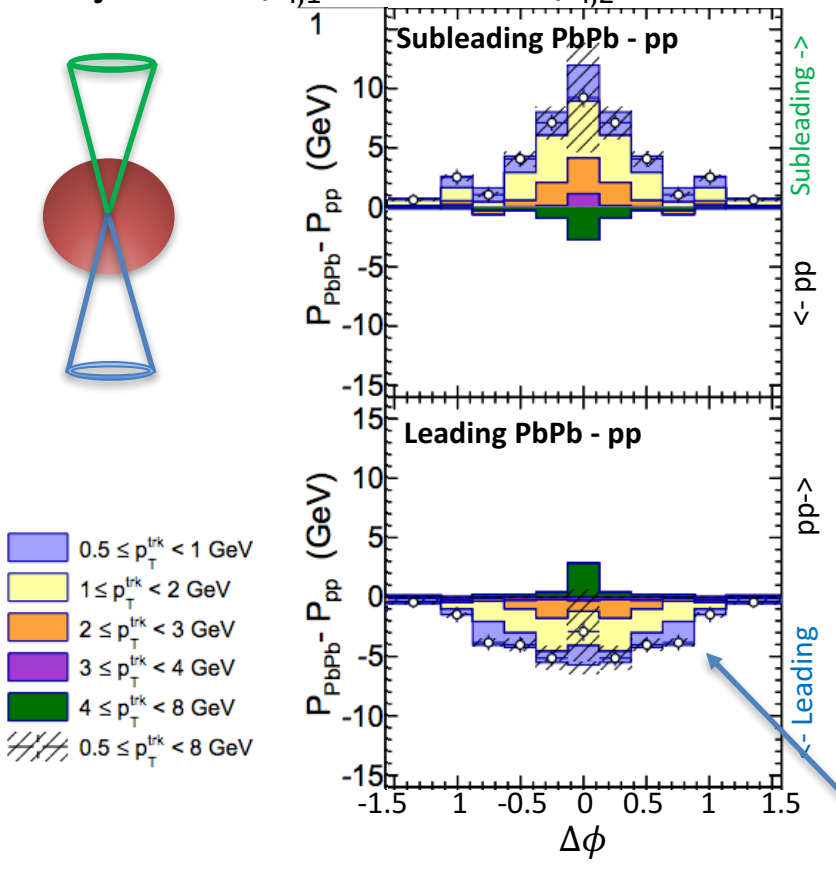
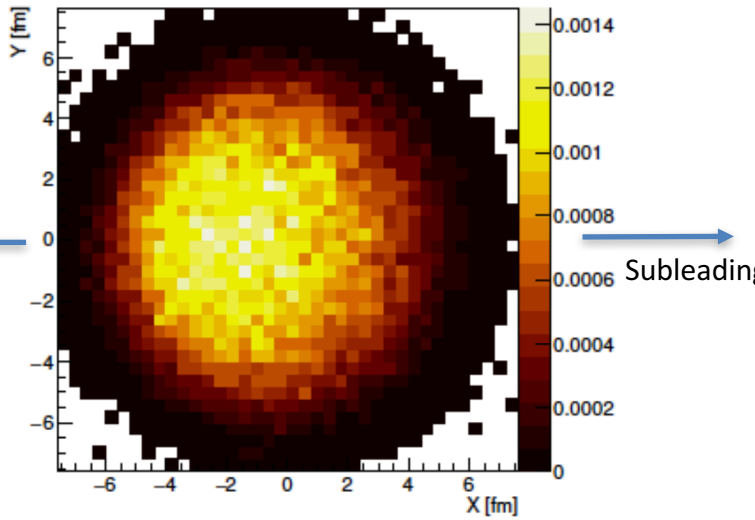


Surface Bias from asymmetric jet selection

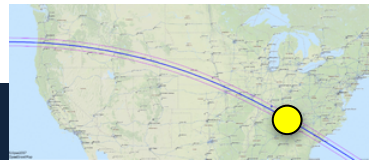
Leading jet



Subleading jet

JEWEL, K. Lapidus, HP 2016

- Leading jet constituents are modified, even for **balanced** dijets (!)
  - JEWEL predicts this phenomenon looking at dijet surface bias

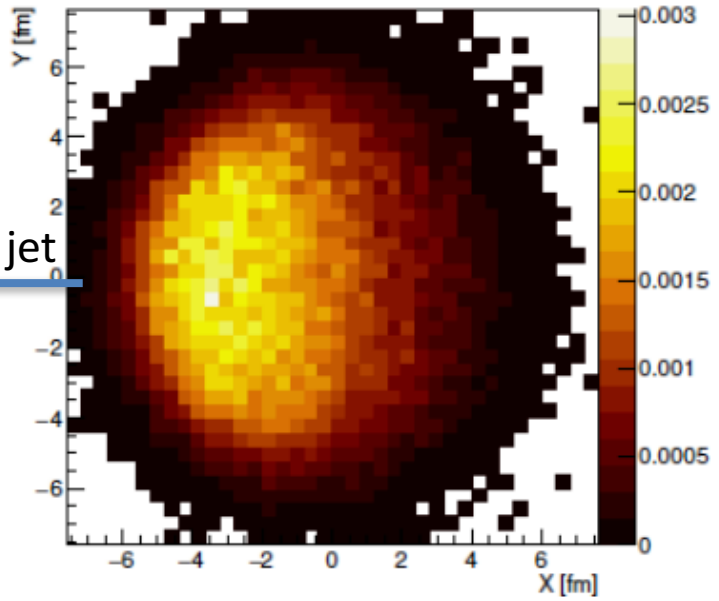


Measuring the surface bias of dijets

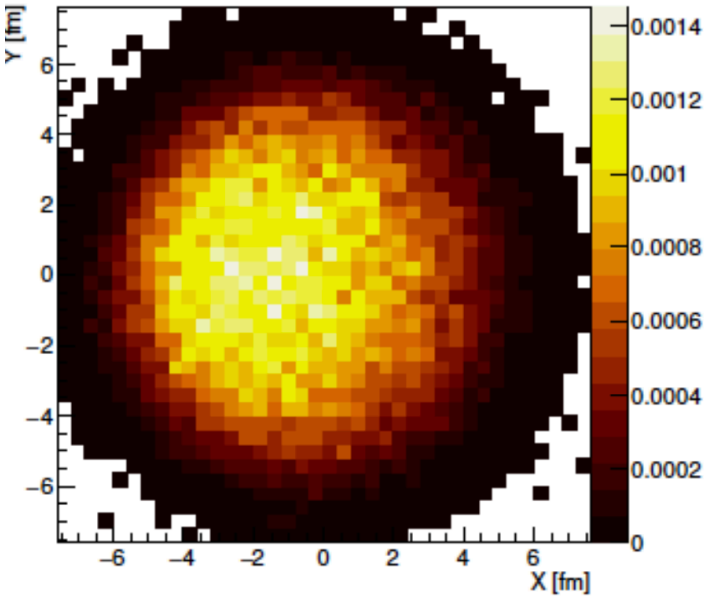
JEWEL, K. Lapidus, HP 2016

Hard-Scattering Vertex from asymmetric jet selection

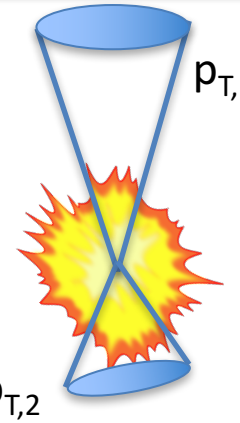
RHIC (Au+Au, 200 GeV)



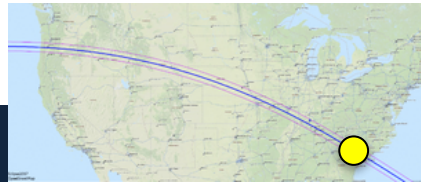
LHC (Pb+Pb, 2.76 TeV)



Leading jet



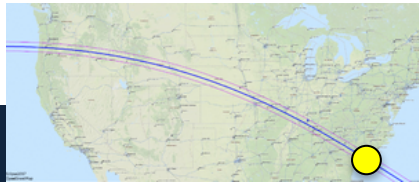
- LHC jets show smaller surface bias than RHIC jets
  - Need a true unmodified reference for jet quenching



Summary

- Jet R_{AA} measurements useful to constrain simple magnitude of quenching
  - Insensitive to small cones – energy pushed very far away from jet axis at LHC energies
  - Insensitive to details of quenching (broadening, e-loss mechanisms, q/g differences, etc)
  - High-pT flavored jets and light jets behave similarly

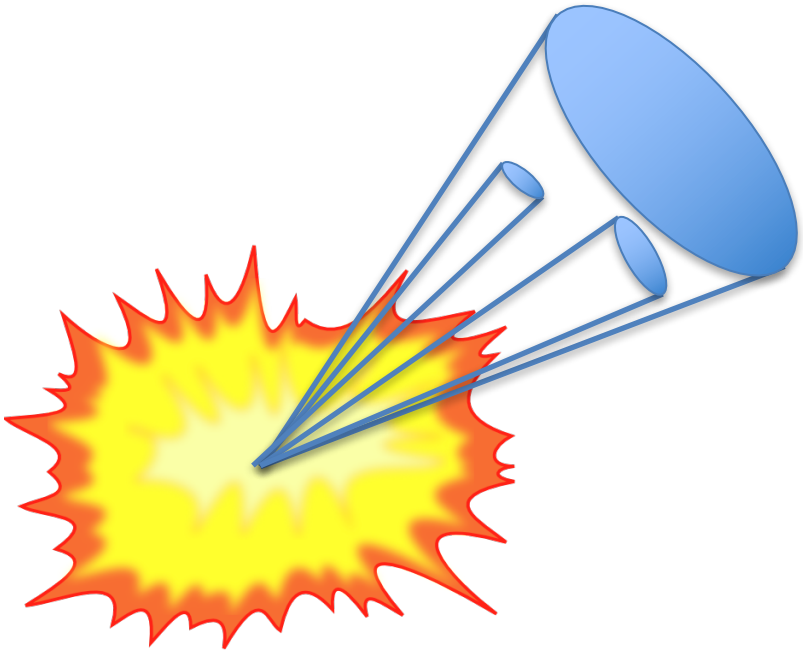
- Jet-track correlations show transfer of energy from small-angle high-p_T to large-angle low-p_T
  - Very **large enhancement in large-angle jet shapes** difficult to describe without huge **medium response**

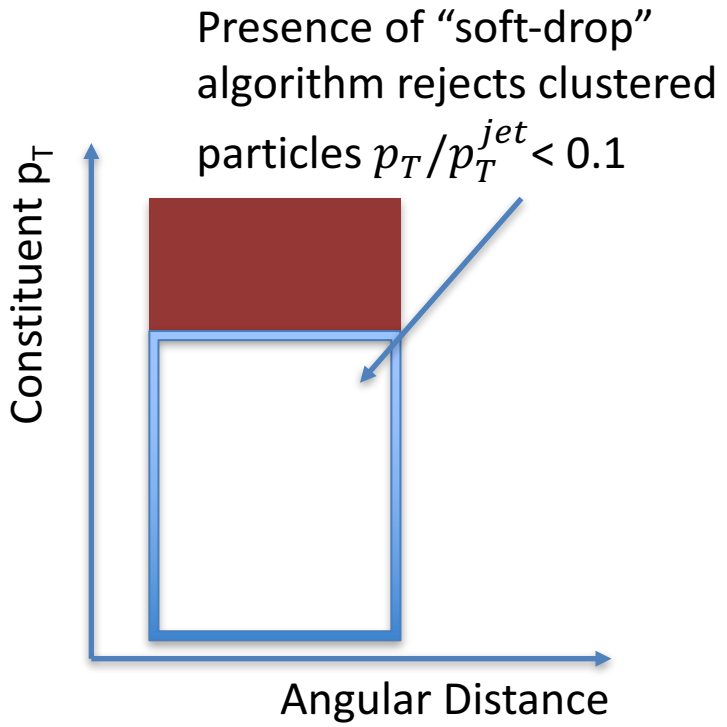


BACKUP

Jet Substructure

- After clustering with anti-k_T algorithm, recluster with a sequential clustering algorithm like C/A to obtain fragmentation hierarchy
  - Observe fragmentation-specific behavior within the jet
  - Less sensitive to hadronization than jet-track correlations

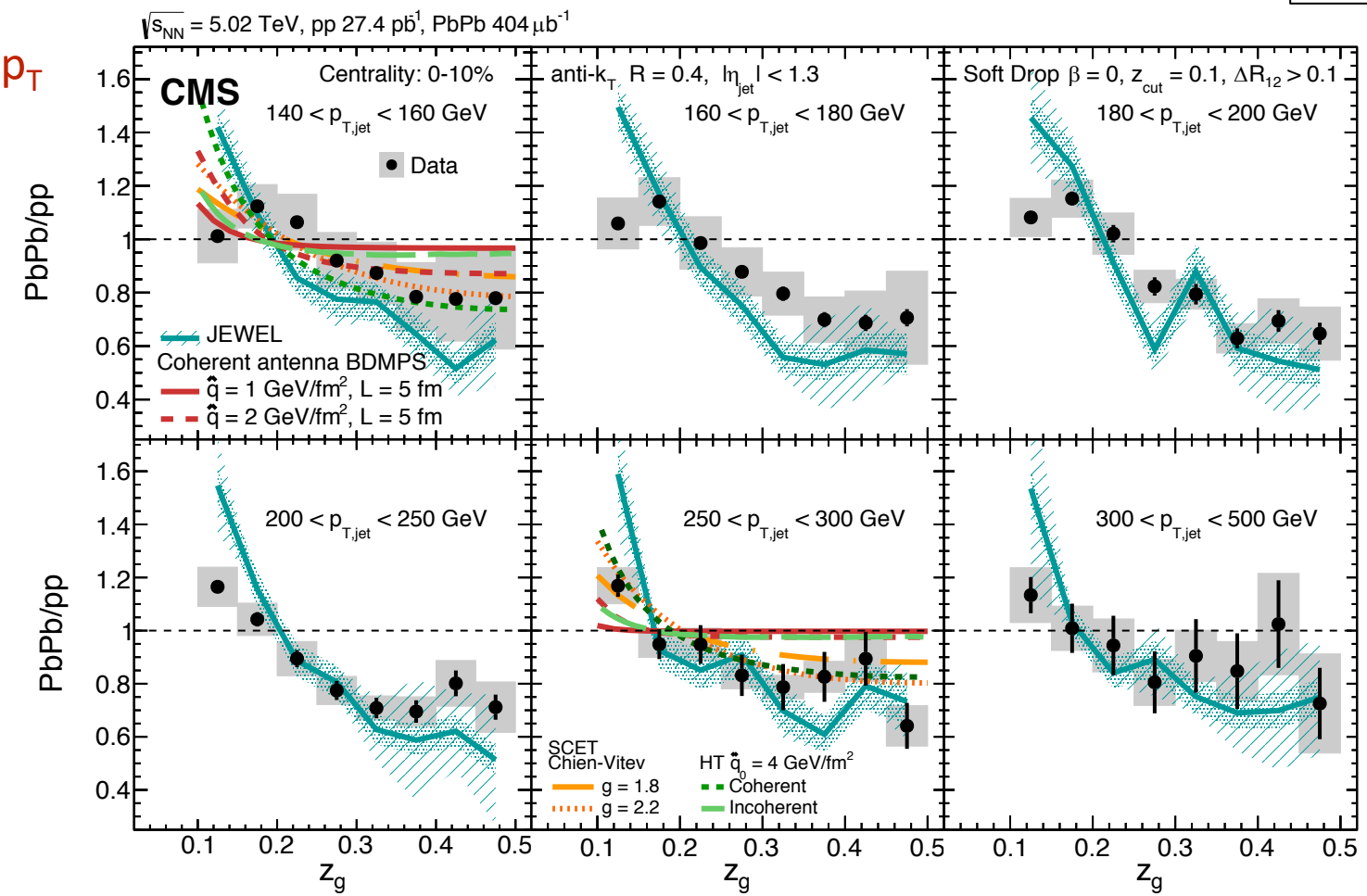




Jet p_T dependence

CMS-PAS-HIN-16-006

Low p_T

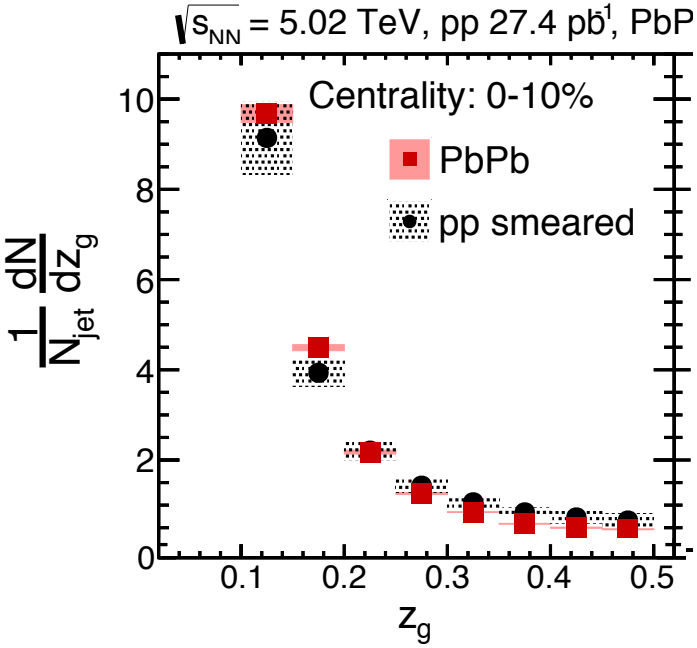


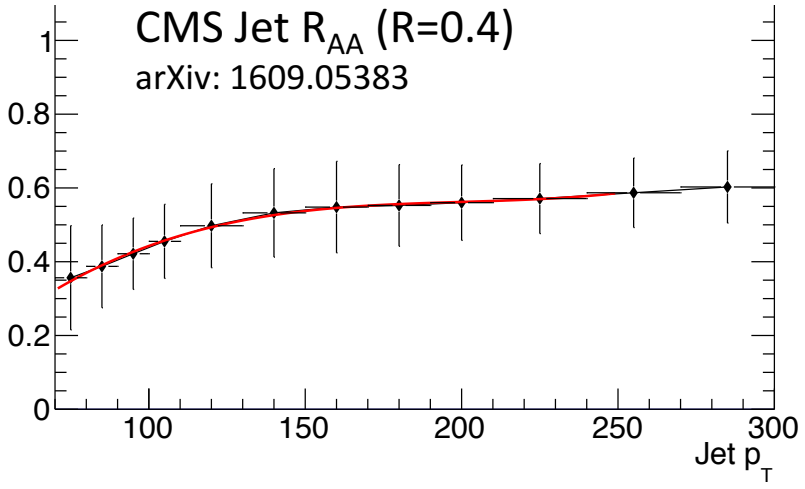
High p_T

- Clear indication of *reduced modification with increasing jet p_T*
- Distributions are self-normalized – cannot differentiate between low z_g enhancement or high z_g suppression

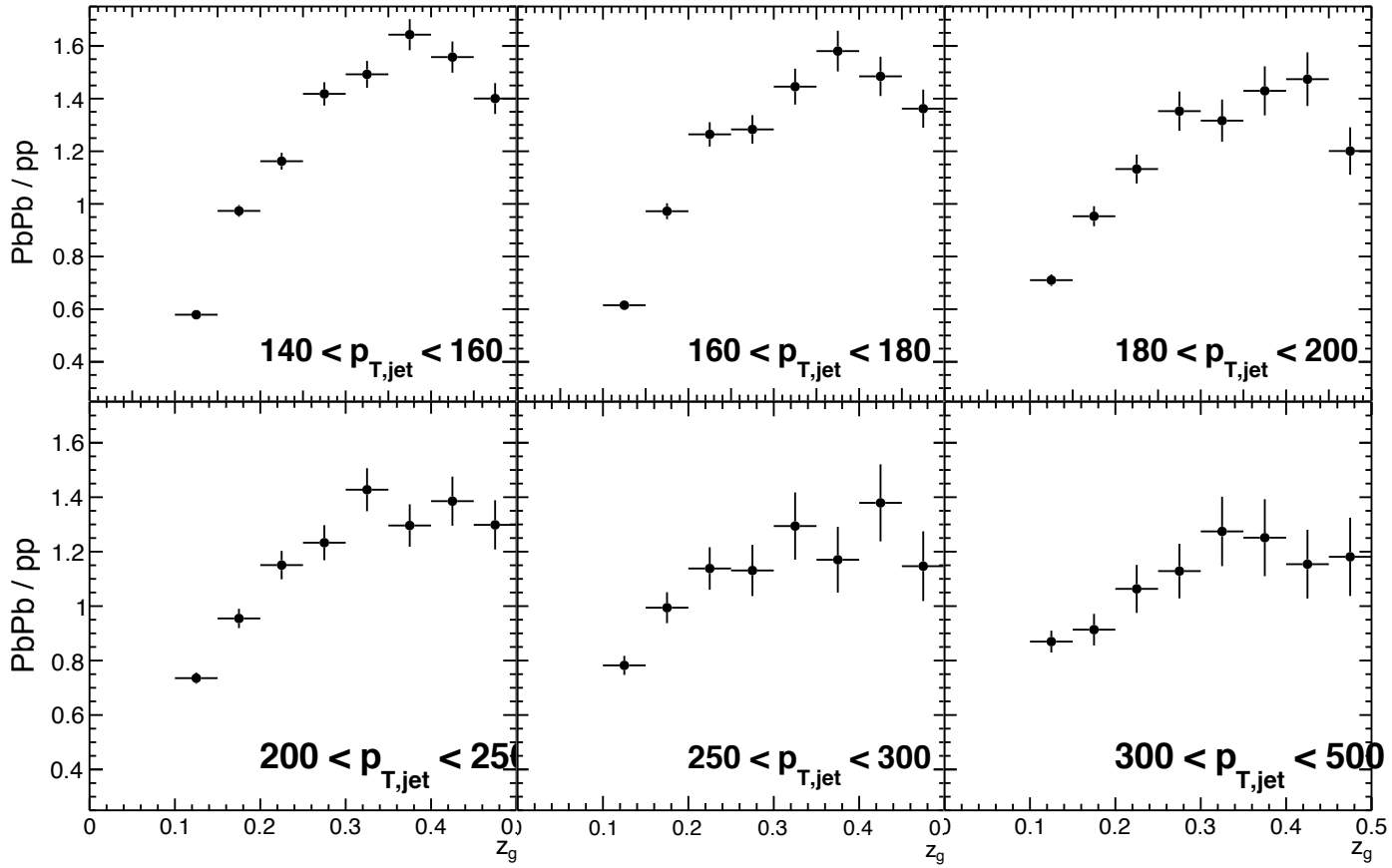
Toy MC Study

- Testing jet substructure modification assuming pure (incoherent) jet energy loss
  - Assume some distribution of subjet splitting using measurements from CMS data
  - Fix the subjet energy loss in PbPb using R_{AA}



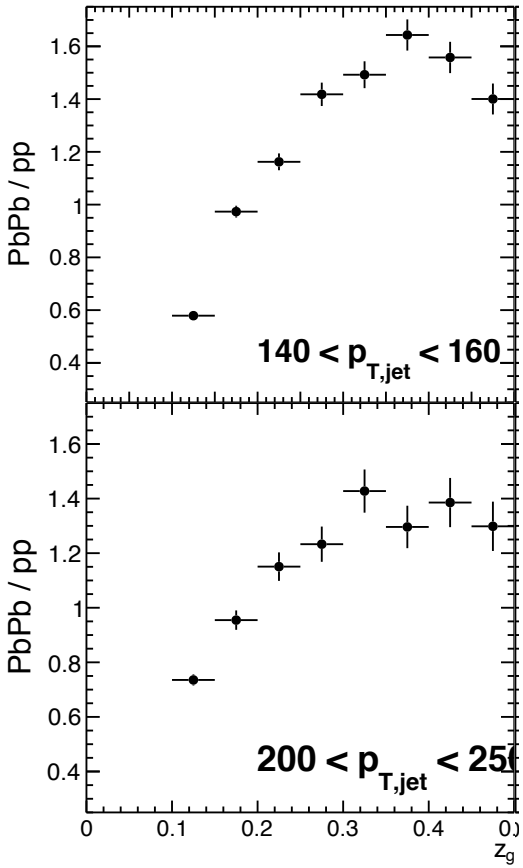


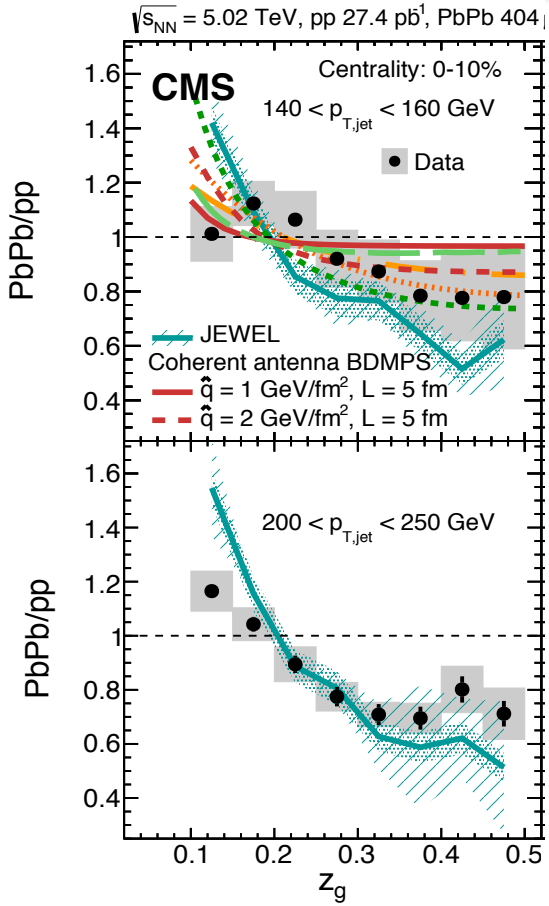
Toy MC Study



- Simple energy loss model not enough to describe z_g data
  - Even goes the complete wrong direction!
  - Caveat: "Third" subjet not used when subleading subjet is dropped

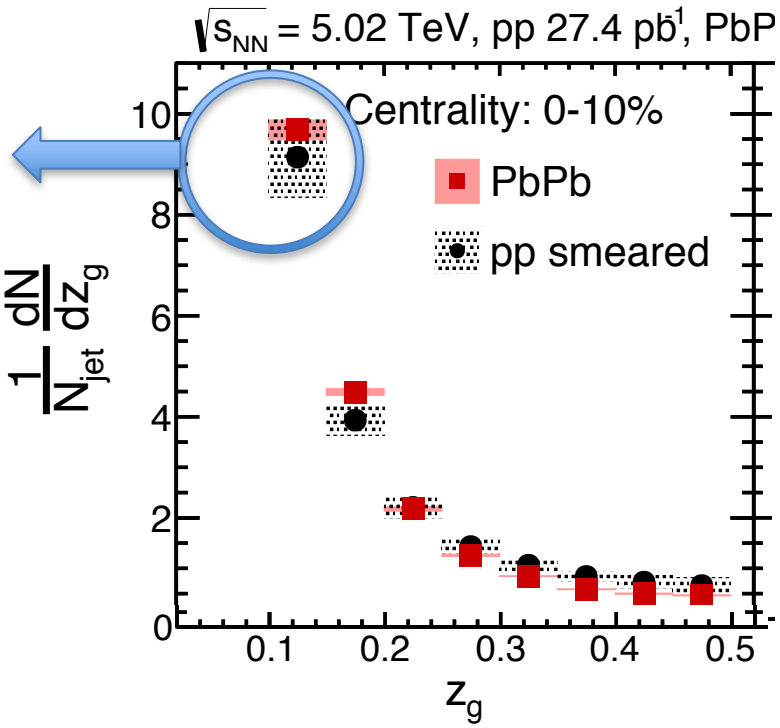
Toy MC Study

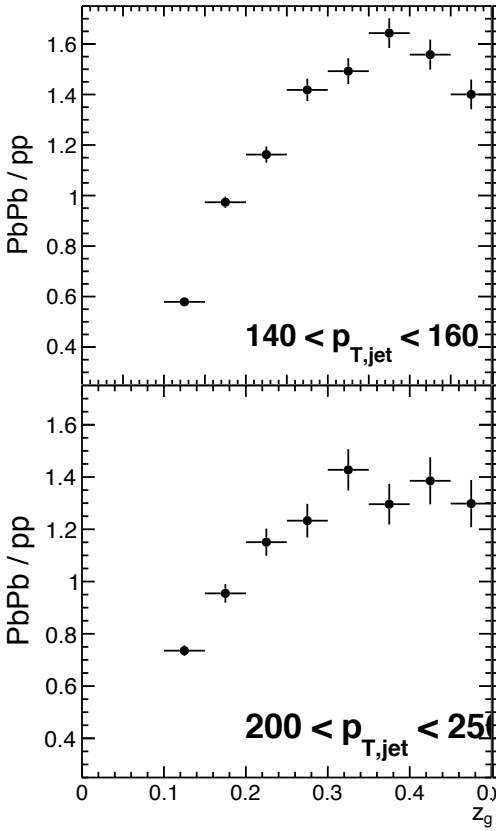




- Simple incoherent energy loss model not enough to describe z_g data
  - Even goes the complete wrong direction!
  - Caveat: “Third” subjet not used when subleading subjet is dropped

Toy MC Study





- Simple incoherent energy loss model not enough to describe z_g data
  - Due to steepness of dN/dz_g distribution, most subjets **fall below $z_g < 0.1$** threshold