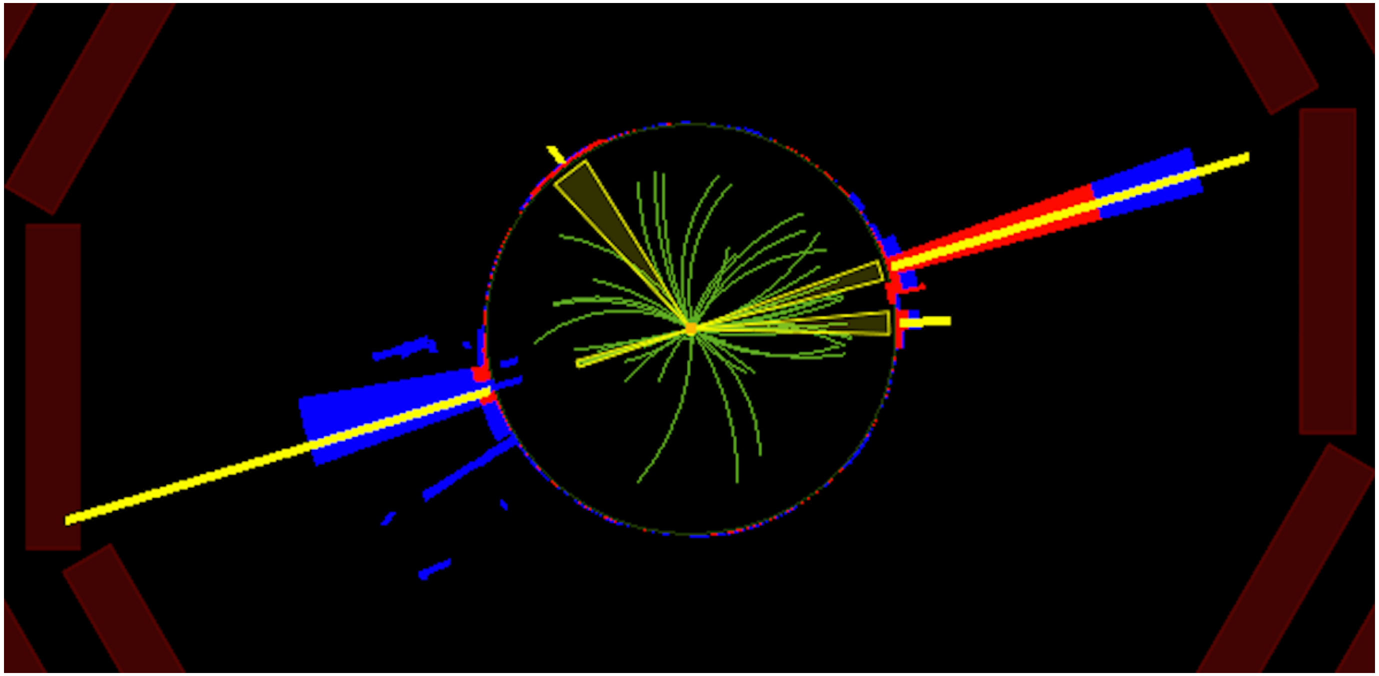
Recent Jet Measurements at the LHC



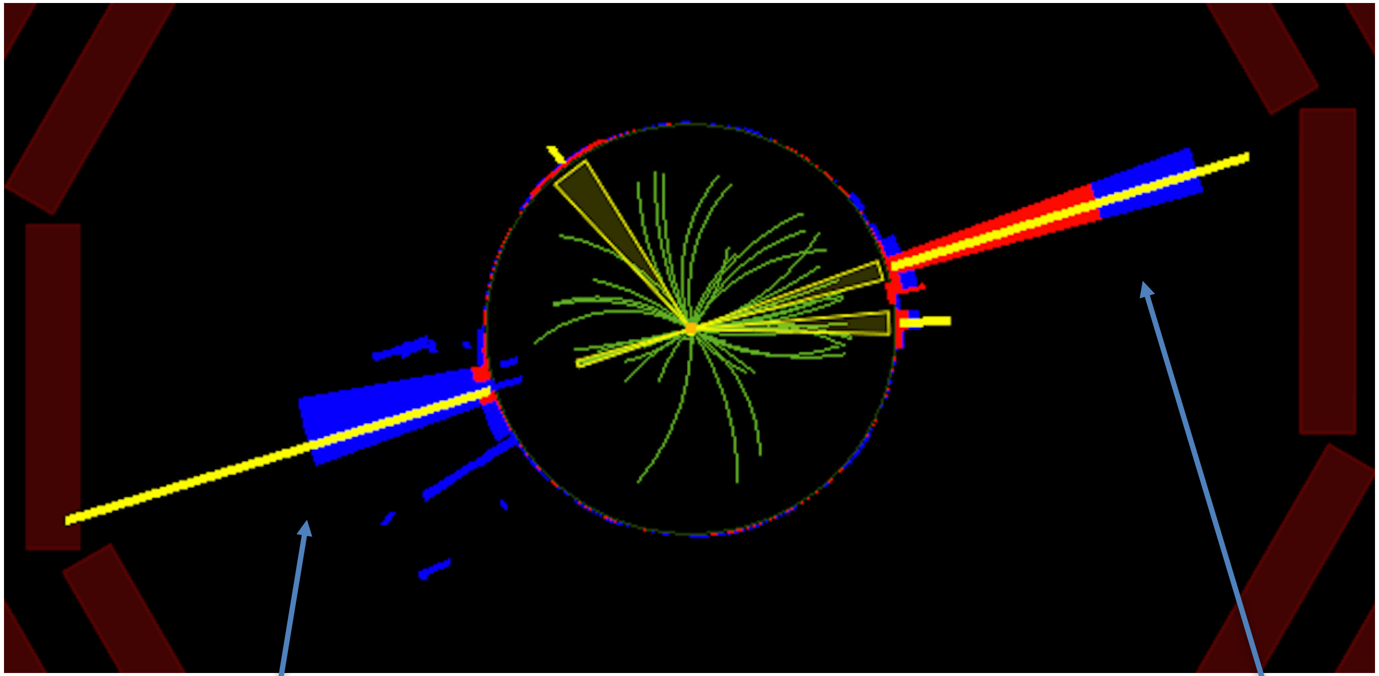
Kurt Jung, Univ. of Illinois at Chicago

INT Workshop Seminar

May 8, 2017

8 TeV p+Pb event (CMS Experiment, 20 Nov. 2016)

Dijet event produced by a ~ **1 TeV** virtual gluon



E_T = 431.6 GeV

E_T = 511.8 GeV

Probing the QGP with Jets

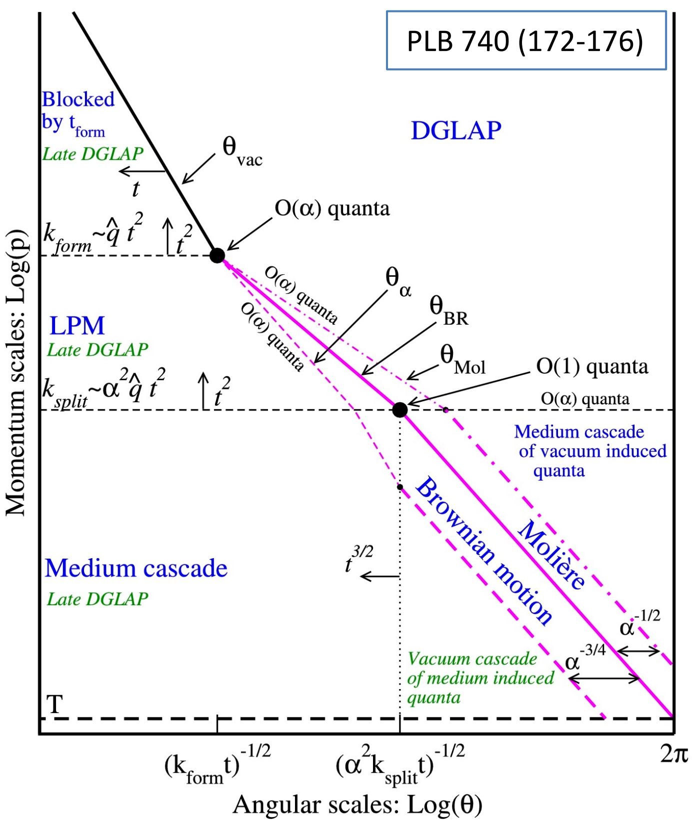
- Jets are typically background free, but probing a specific subprocess always carries caveats:

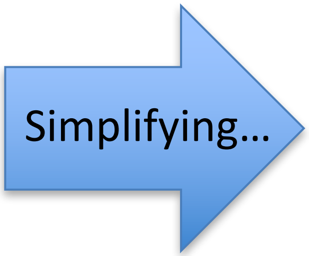
- The medium can:
  - Redistribute jet constituent particles ("jet broadening")
  - "Quench" the jet - reduce the energy of the particles that make up the jet
  - Induce gluon radiation
  - Get swept up by the jet ("medium response") and get reconstructed as part of the jet
  - …

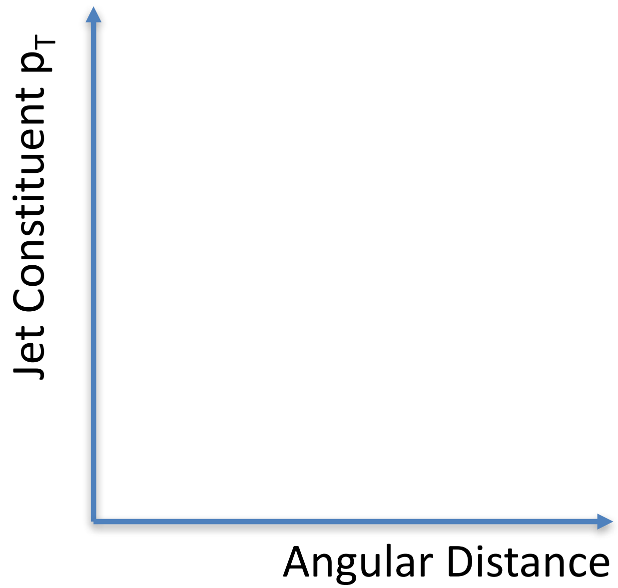
- Can we use a map to help guide where our measurements probe?
  - Many (all) measurements probe more than one effect

Global Jet "phase space"

- Many new jet observables and measurements, often with complicated caveats and techniques
- Could use a visual aid to help us disentangle the wealth of new information from LHC + RHIC jet measurements







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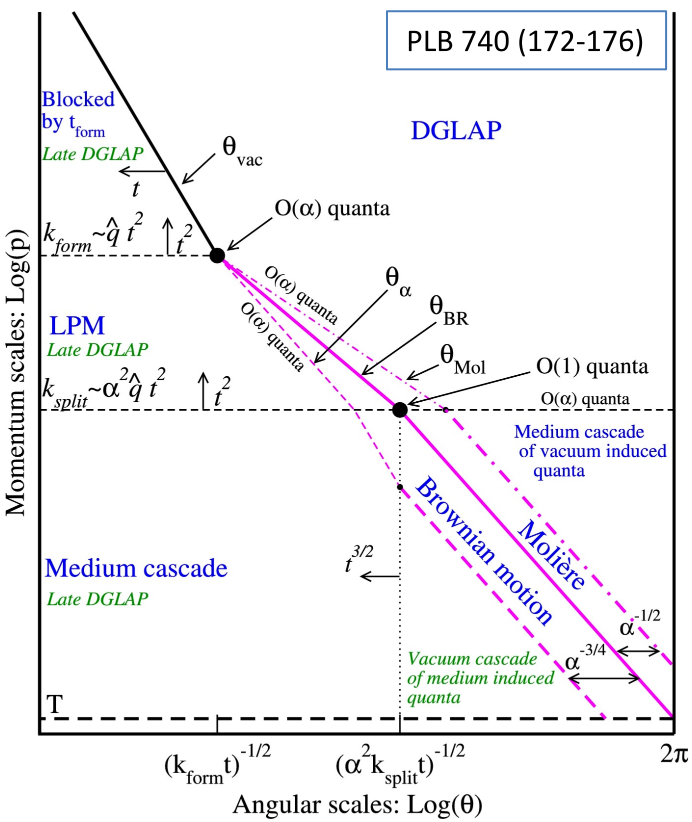
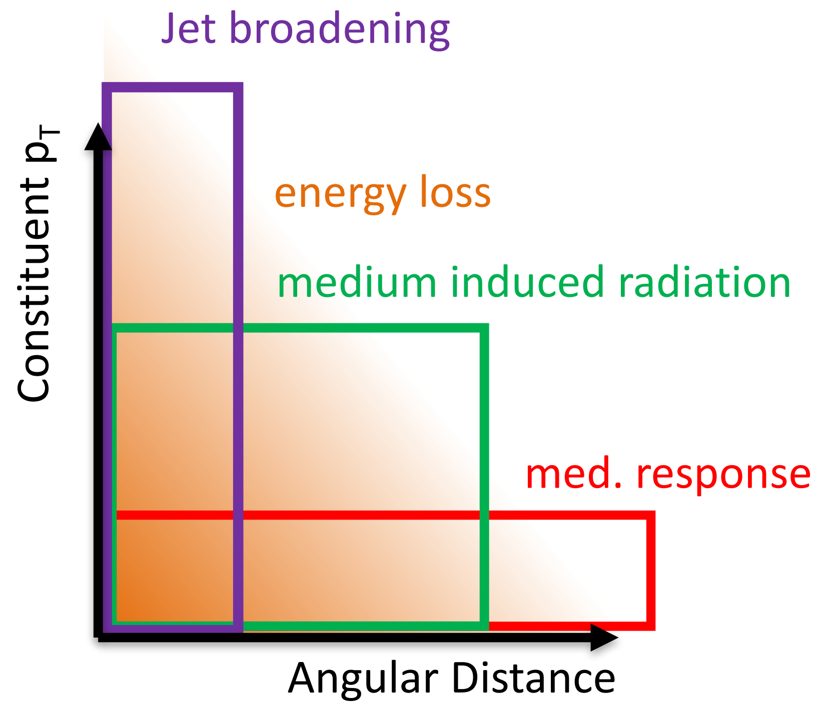
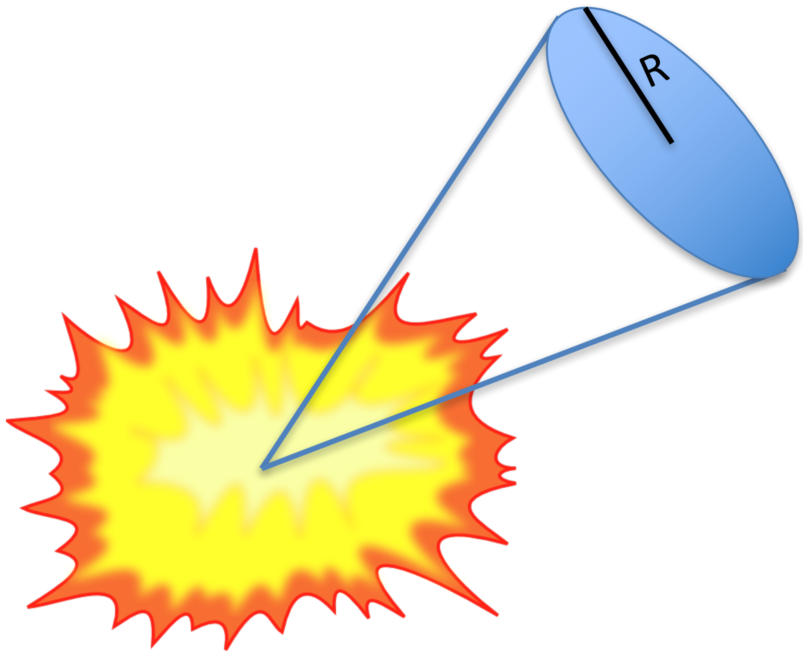
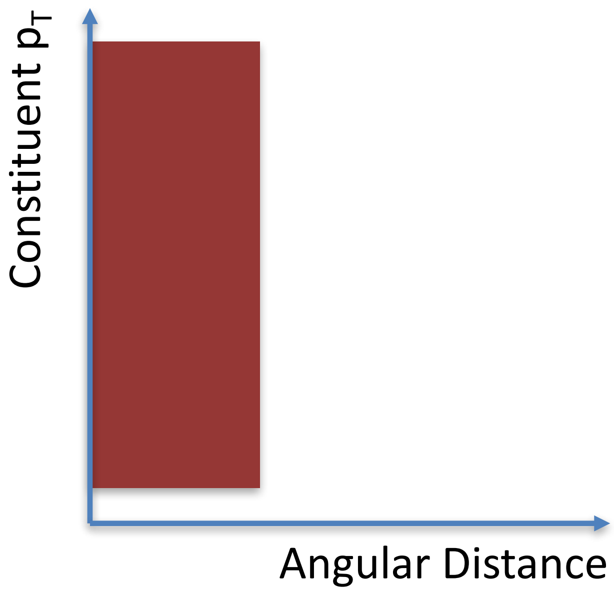




Inclusive Jet Measurements

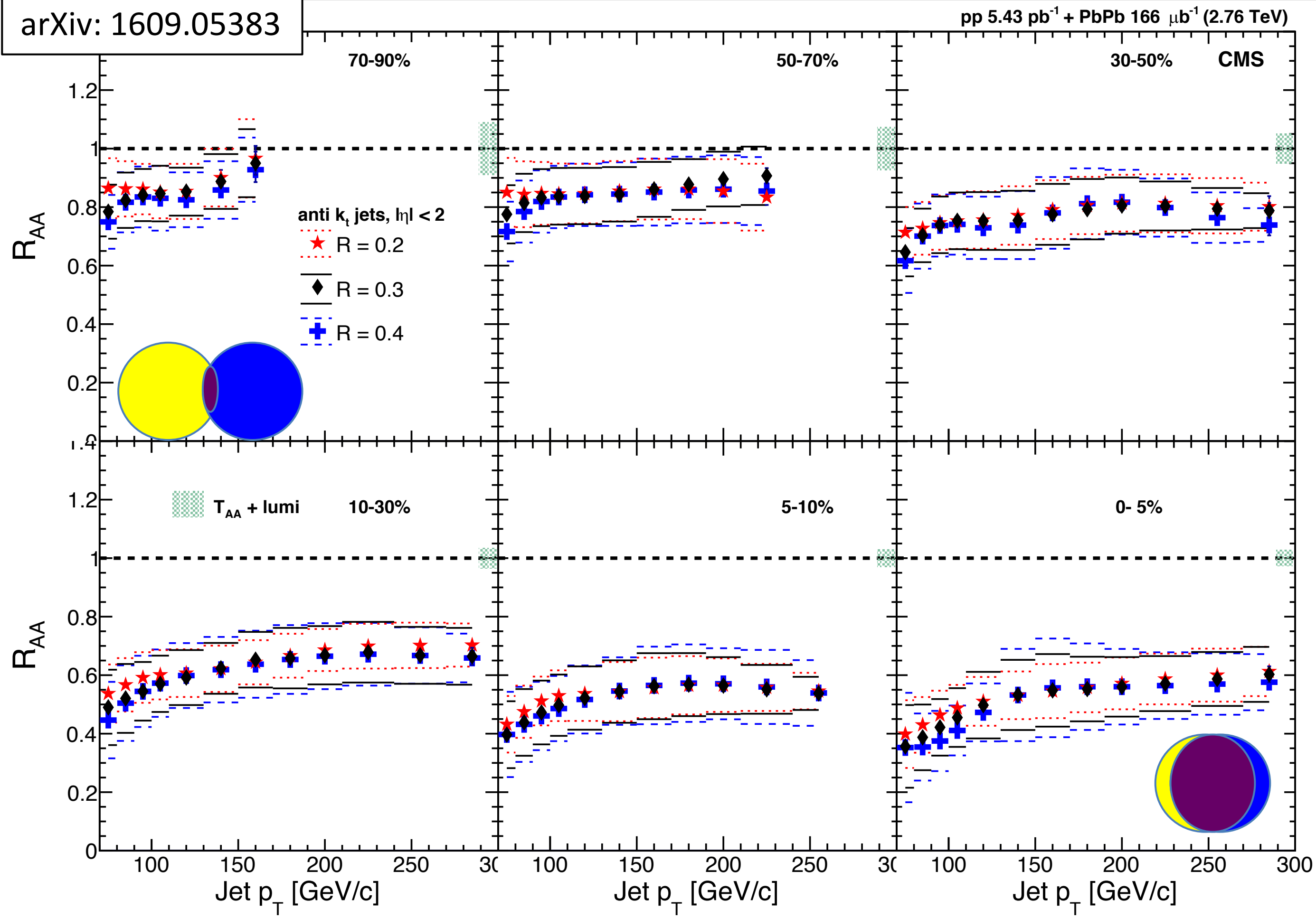
- Measurements of single-jet energy loss *relative to pp*
- Simple and well-defined; models can accurately predict energy-loss
- Convolution of all nuclear effects + QGP

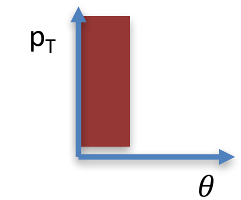




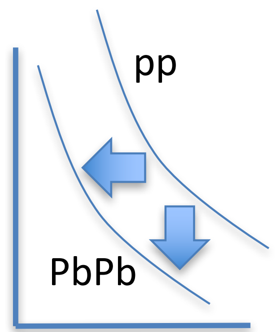
Centrality/Radial Dependence of R_{AA}

arXiv: 1609.05383





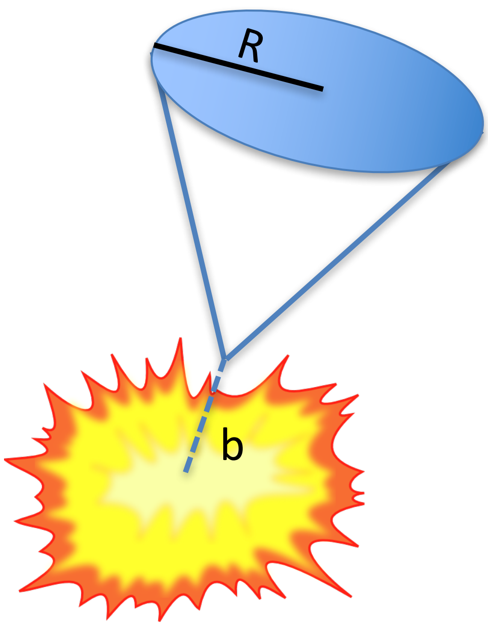
$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



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

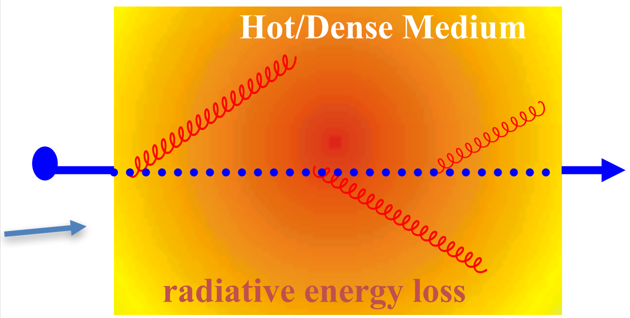
b-Jet Measurements

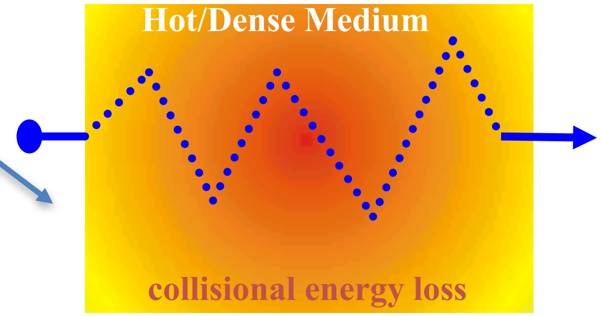
- b-Jets are identified using Secondary Vertices
  - Long lifetime of b-quark → mm or cm displacement
- Individual track displacement used as cross-check



QCD predicts modified energy loss mechanisms for heavy quarks:

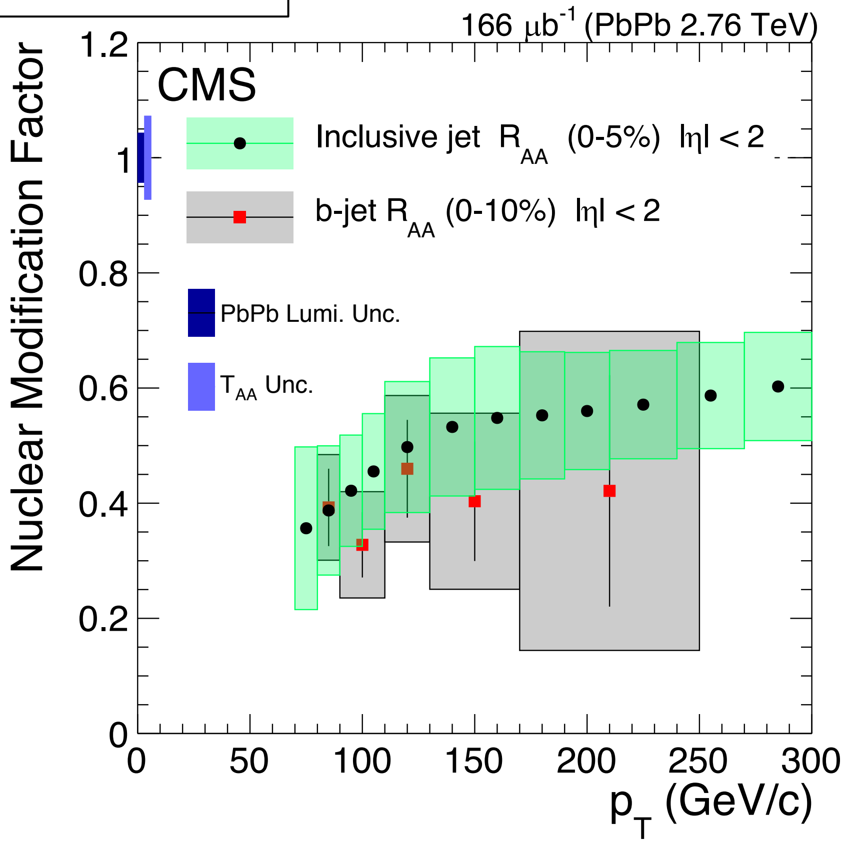
- Radiative energy loss modified by "dead-cone" effect
- Collisional energy loss modified by additional mass coupling to interactions
- …and others!

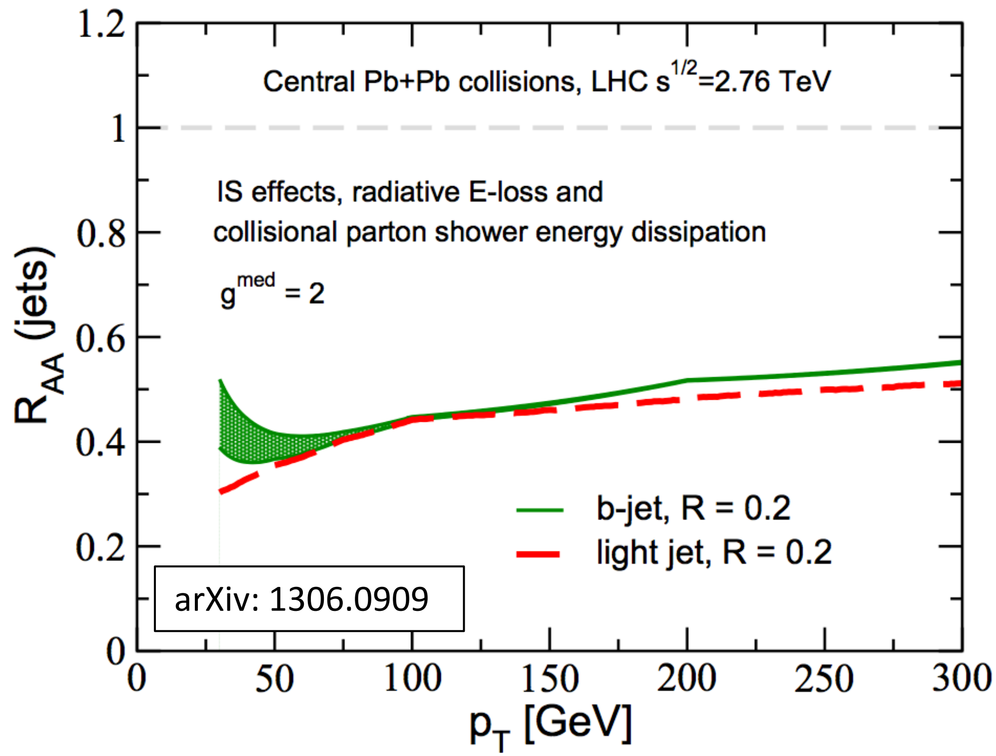




Heavy Jets behave like light jets…

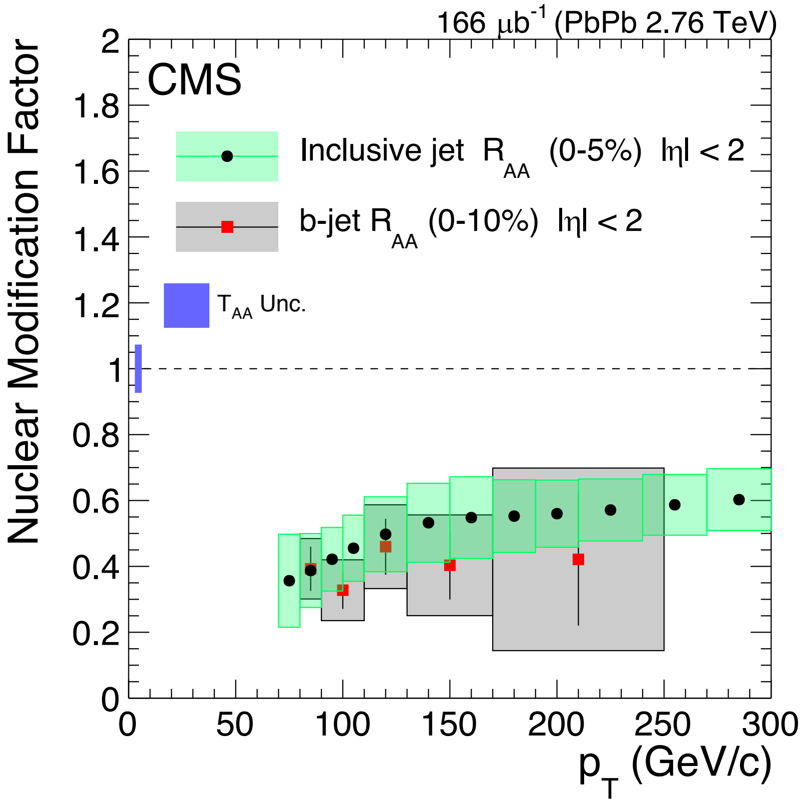
arXiv: 1609.05383
arXiv: 1312.4198

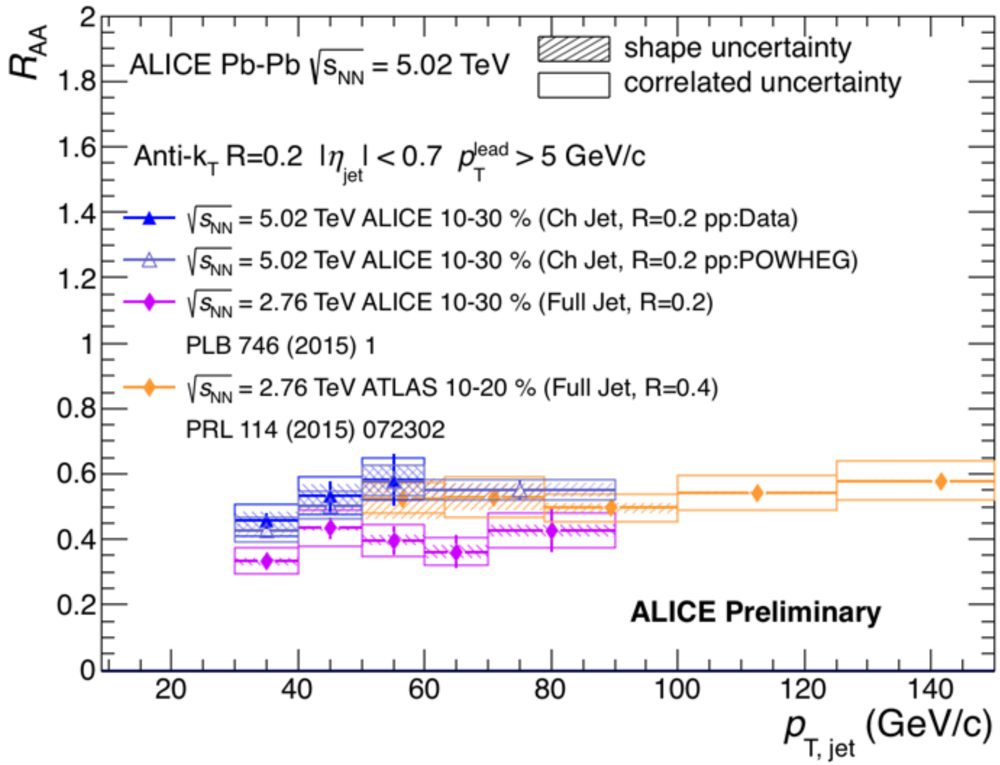




- CMS observes similar quenching magnitude (R_{AA}) between b-jets and light jets
  - Confirmed by theoretical pQCD measurements from I. Vitev, et. al.

…but so does everything!

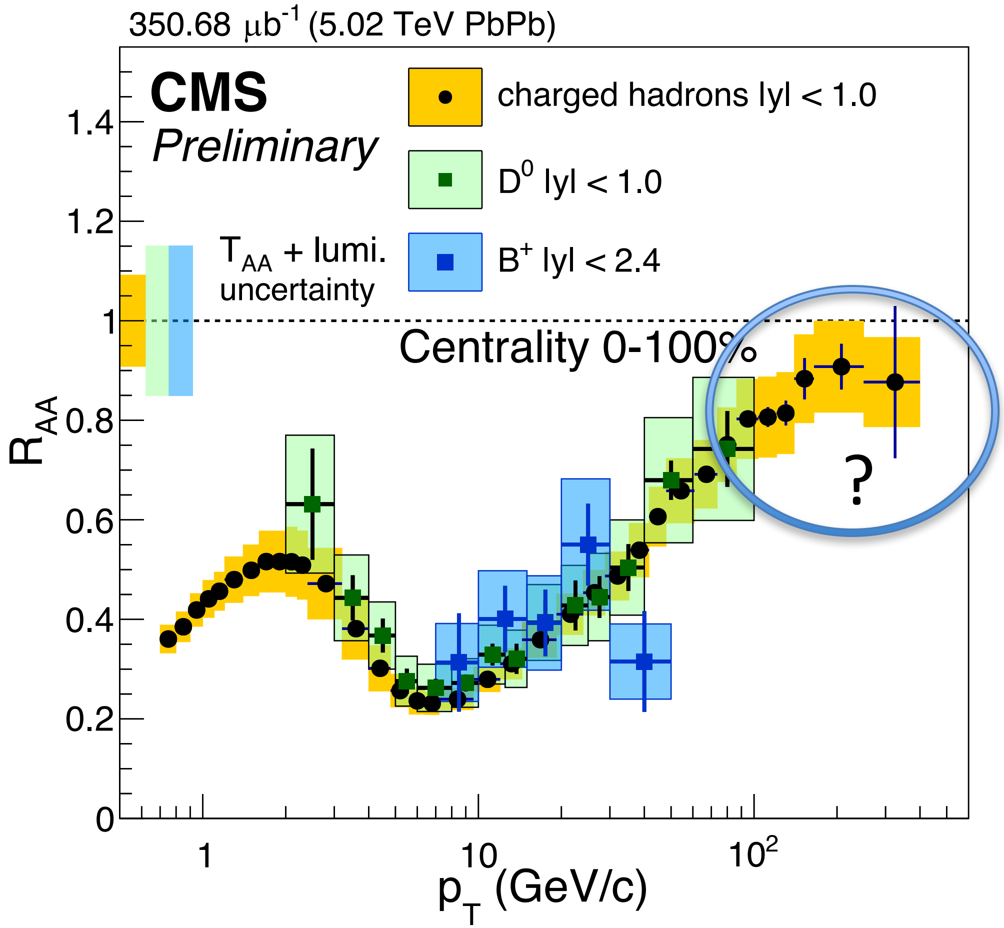


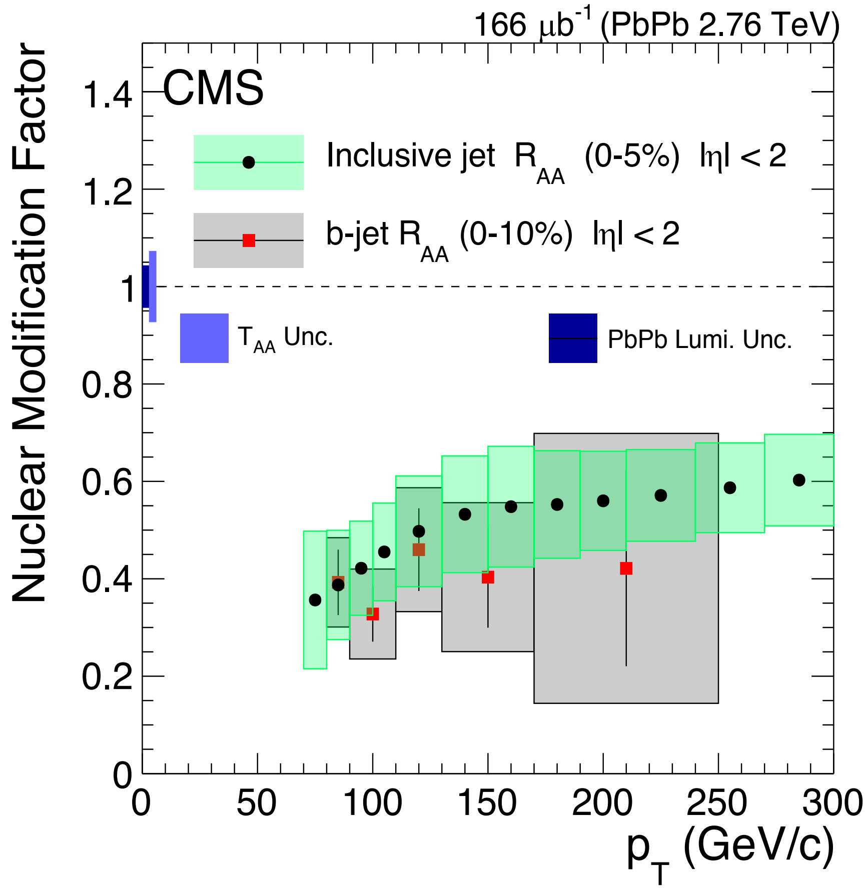


- R_{AA} proven to be relatively insensitive to many observables
  - <u>For collision energy dependence</u>: Do we just get lucky that spectrum flatness cancels out the additional energy loss?
  - <u>For flavor dependence</u>: Is the absence of a flavor dependence to R_{AA} simply an extension of this insensitivity?

arXiv: 1609.05383 arXiv: 1312.4198

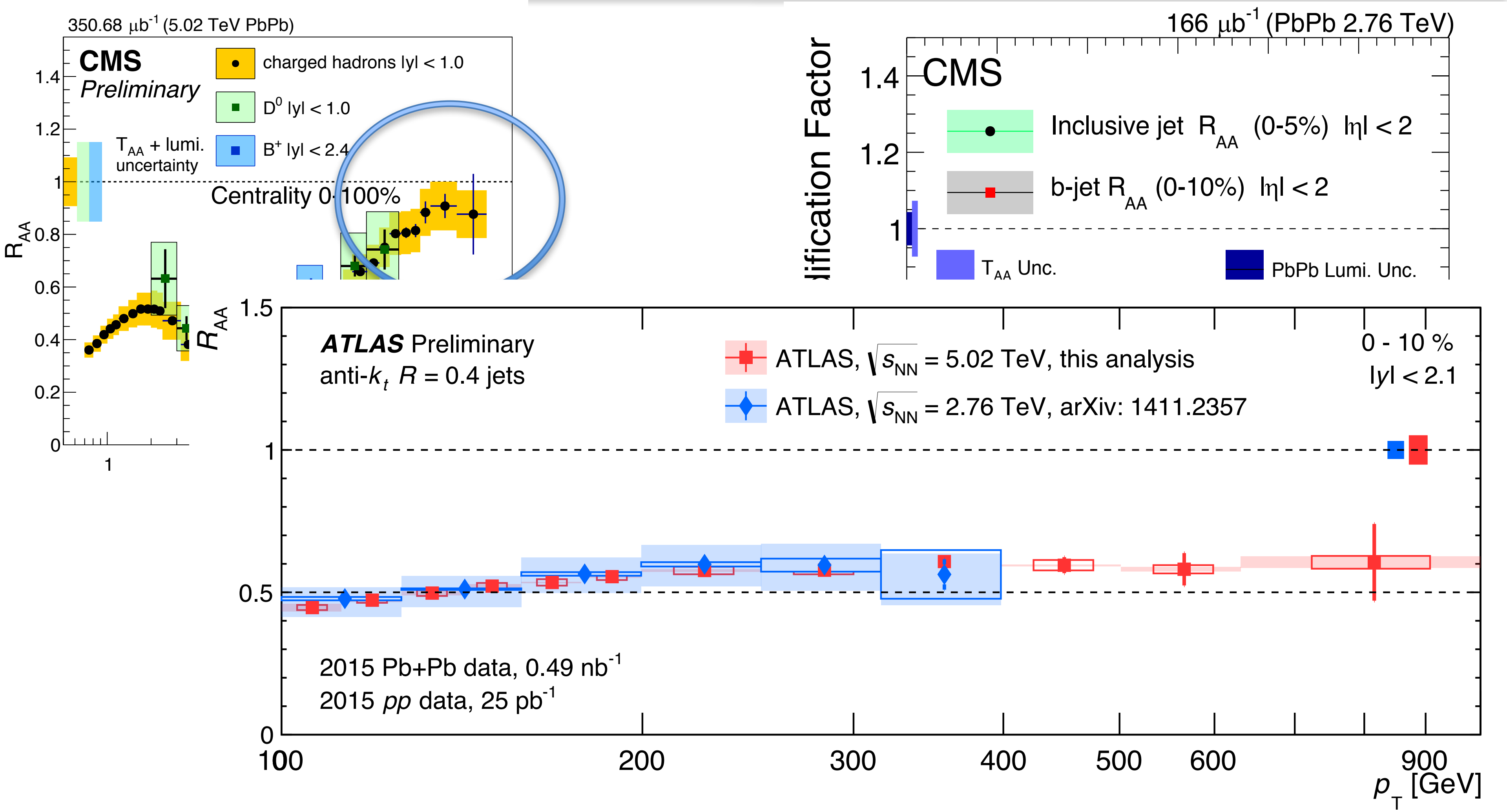
A Comparison of Jets and Mesons





- Magnitude of energy loss is similar between flavored mesons and jets
  - Maybe some interesting effects at very large particle p_T

A Comparison of Jets and Mesons



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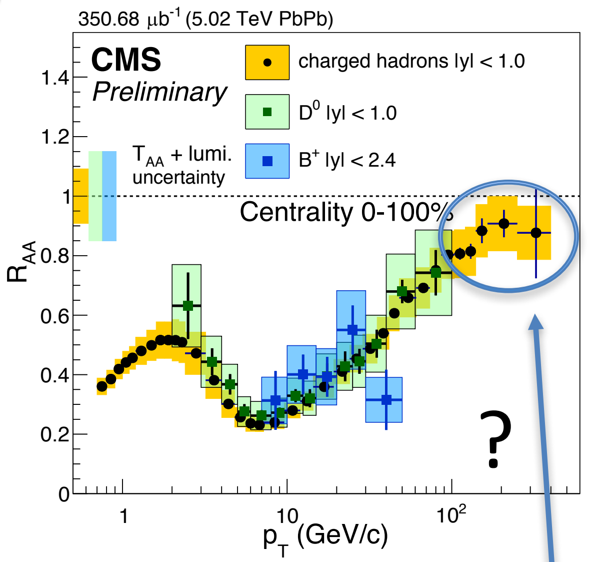
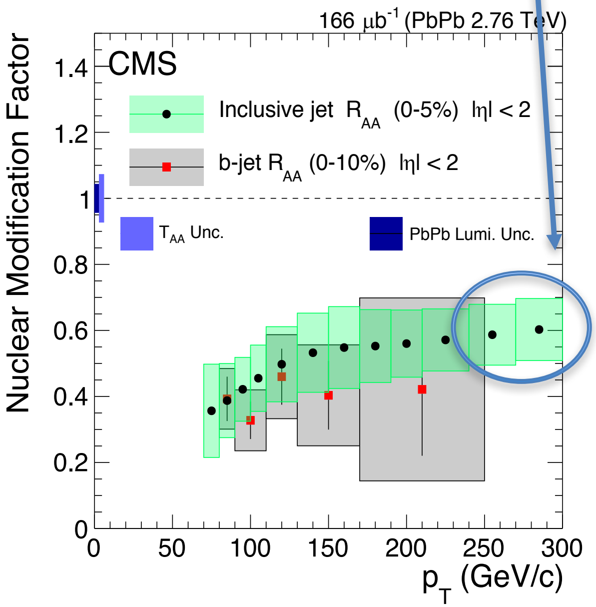
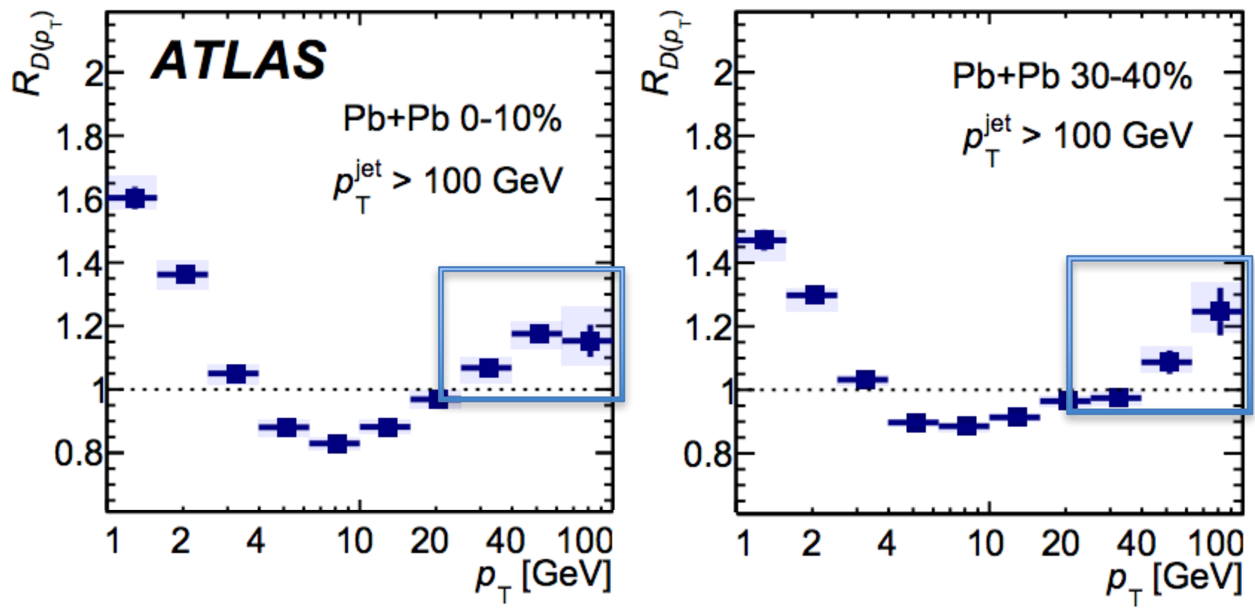




arXiv: 1702.00674

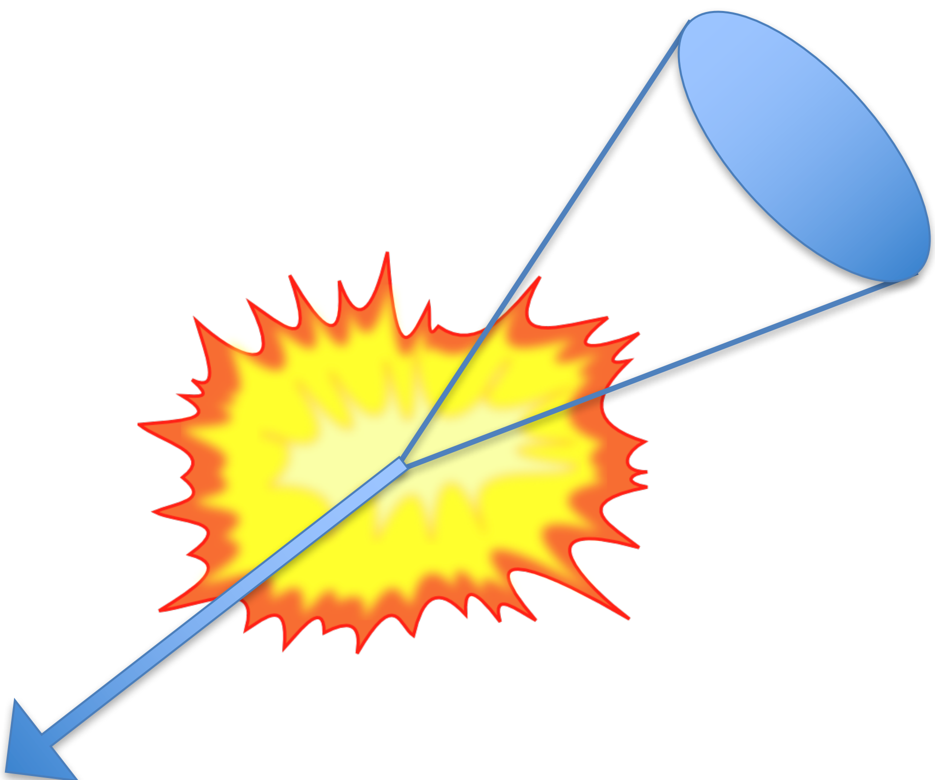
Fragmentation ratios of particles within R=0.4 jets



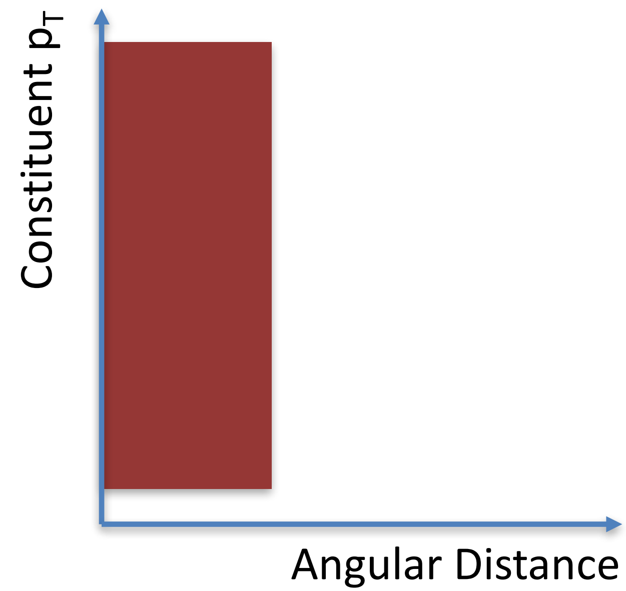
- High-p_T excess confirmed by studies of fragmentation functions
  - Possible that high-p_T jets quench more than high-p_T mesons?
  - Different scattering virtuality is likely…

Jet+X Measurements

- Fluctuations and initial state geometries can drive energy loss outside of a simple "average" suppression
- Attempt to measure energy loss via *in-situ* reference



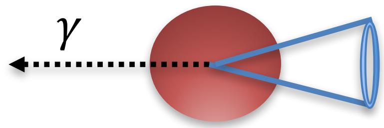
Z, γ, jet, b-jet…



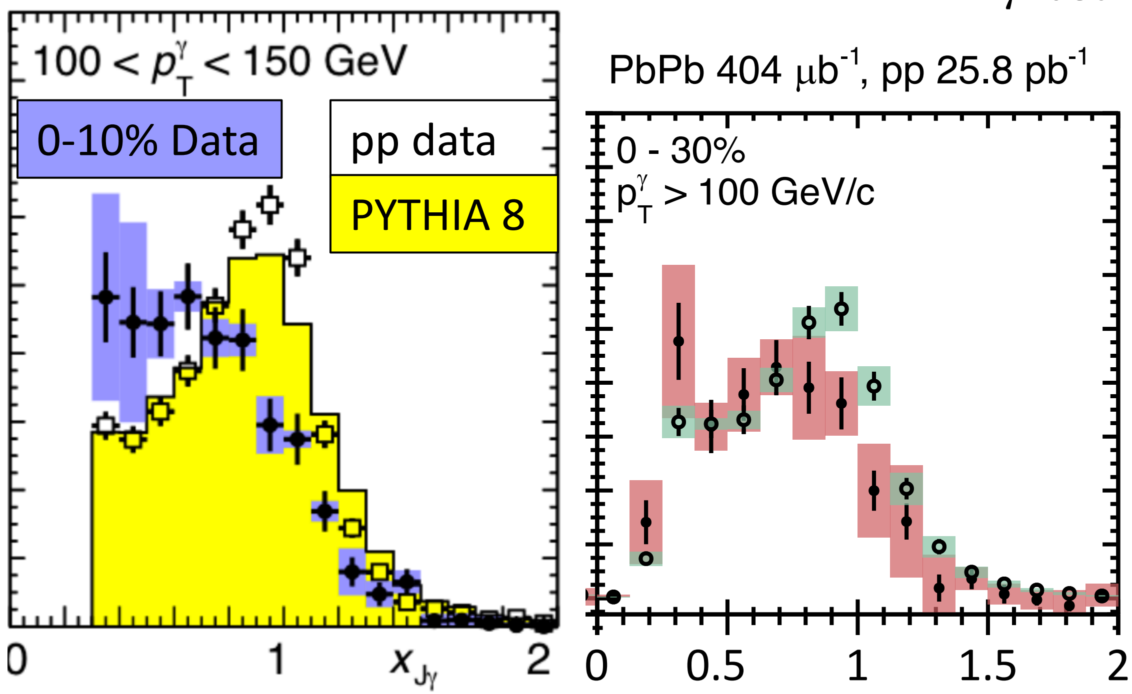
Electroweak Boson References in PbPb

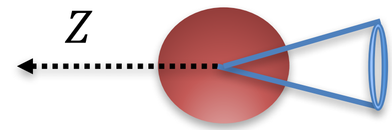
ATLAS-CONF-2016-110

CMS-PAS-HIN-16-002

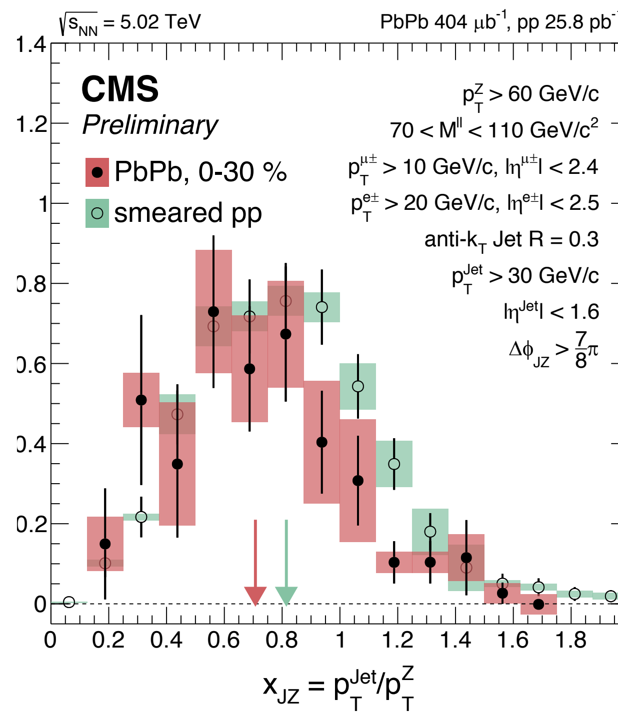


γ+Jet





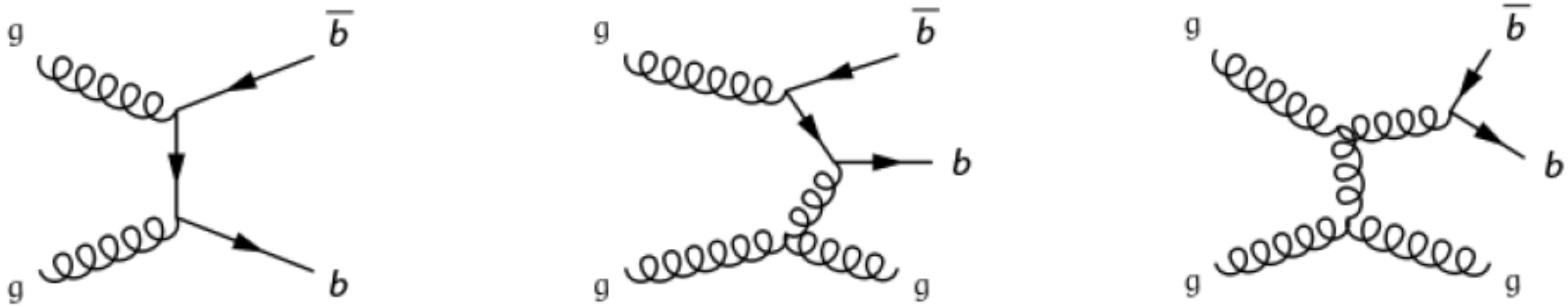
Z+Jet



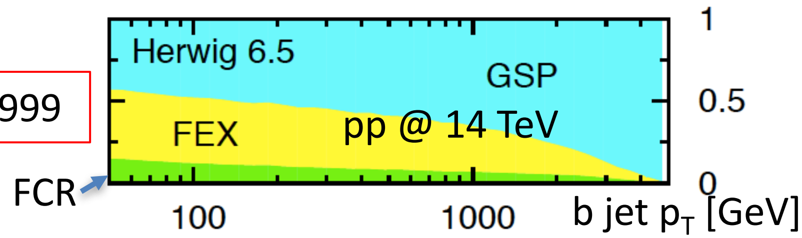
- $\langle X_{J\gamma} \rangle$ in central PbPb reduced from pp
  - Relative shift in quenched jets similar between both new electroweak references: photons and Z-Bosons

b-jet Production Mechanisms

Flavor Creation ("FCR") | Flavor Excitation ("FEX") | Gluon Splitting ("GSP")



arXiv:0704.2999



- Measurements of jet R_{AA} and jet R_{pA} do not distinguish between different 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 gluon splitting processes from leading-order processes

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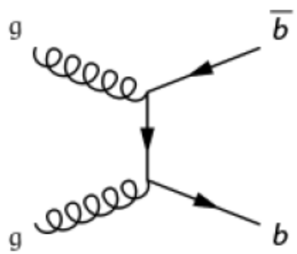
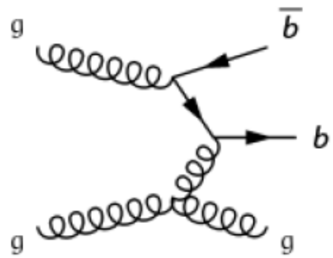
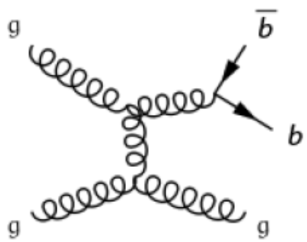
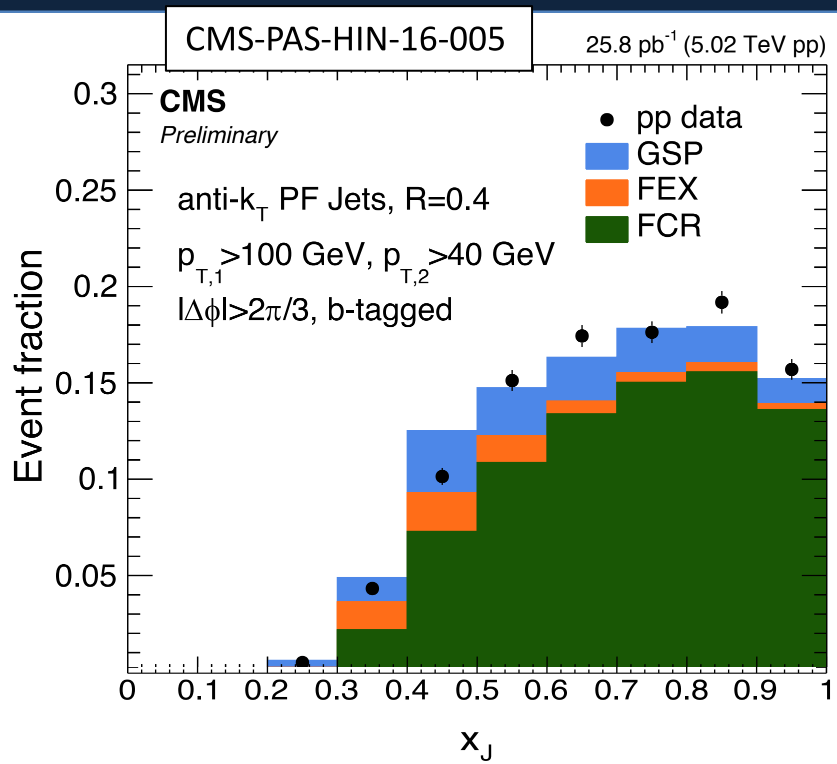


Flavor Excitation ("FEX")



Gluon Splitting ("GSP")





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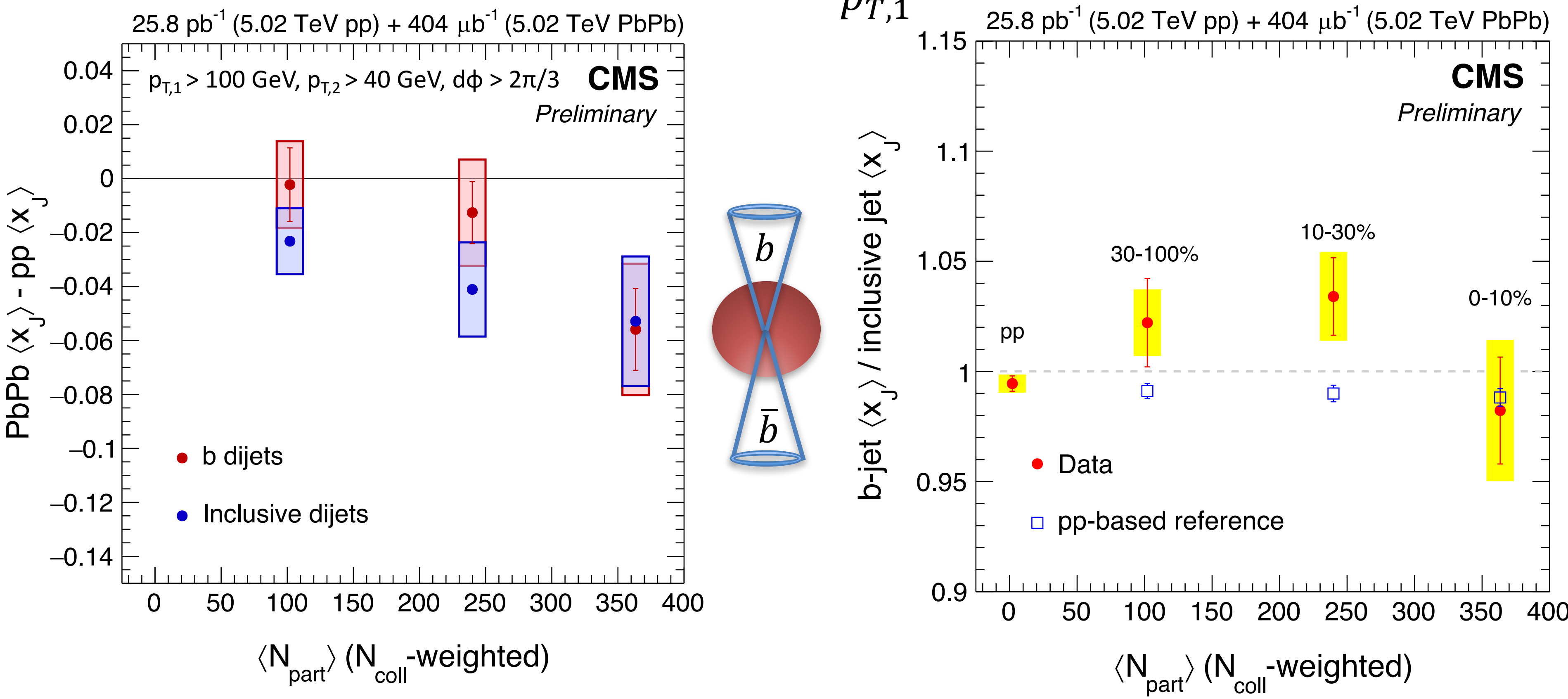
b Dijets

CMS-PAS-HIN-16-005

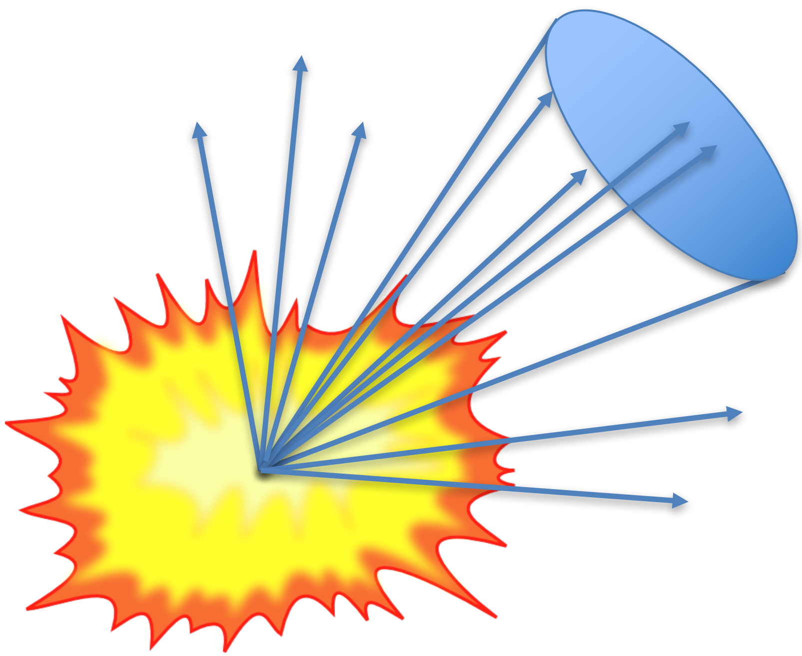
$$\langle x_J \rangle = \frac{p_{T,2}}{p_{T,1}}$$

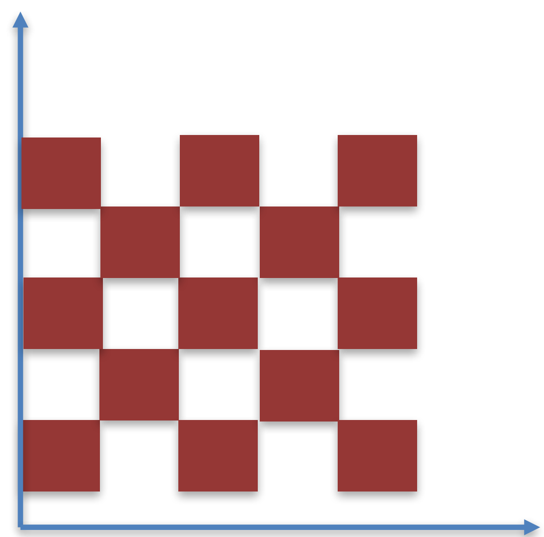


- Observe modification consistent with inclusive-jet measurements
- Directly comparing b dijet/inclusive dijet PbPb shows virtually no effect as a function of centrality

Jet-Track Correlations

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

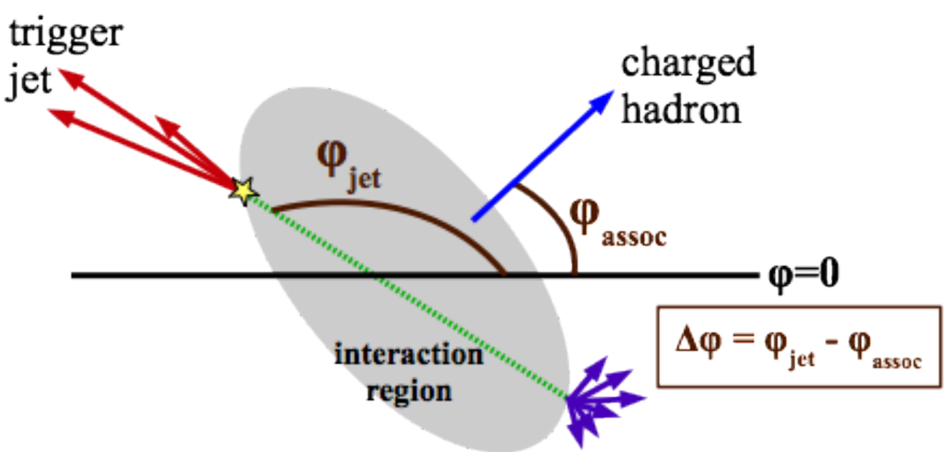


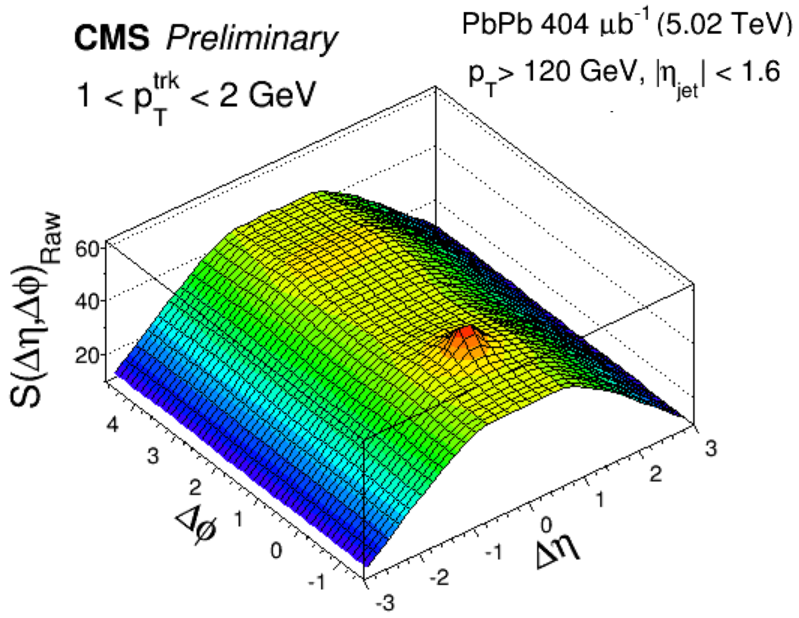


Constructing Jet-Track Correlations

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

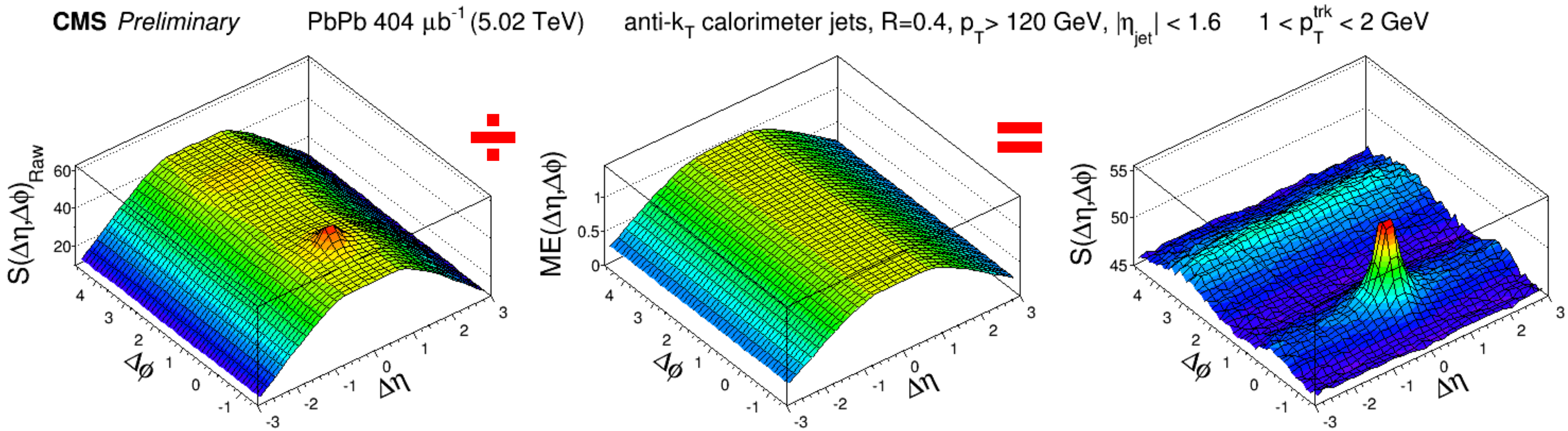




Jet-Track Pair-Acceptance Correction

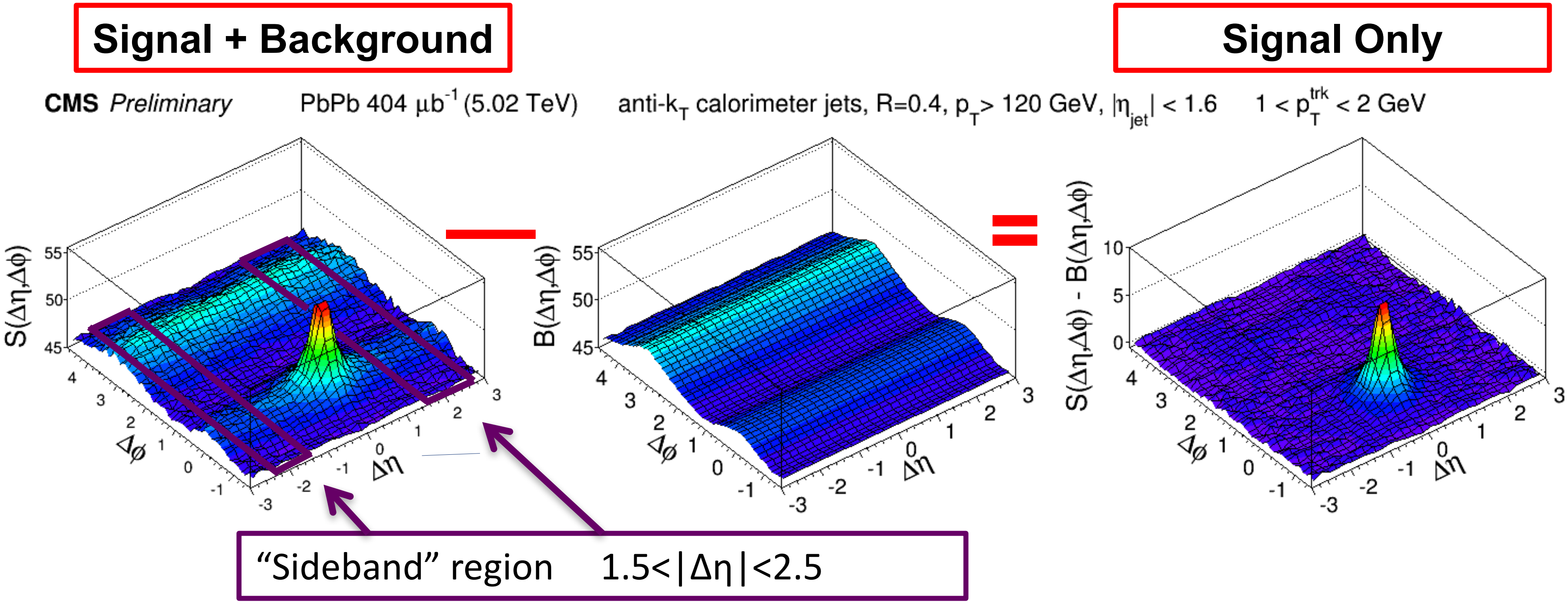
- Finite jet and track acceptances result in trapezoidal geometry

- 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



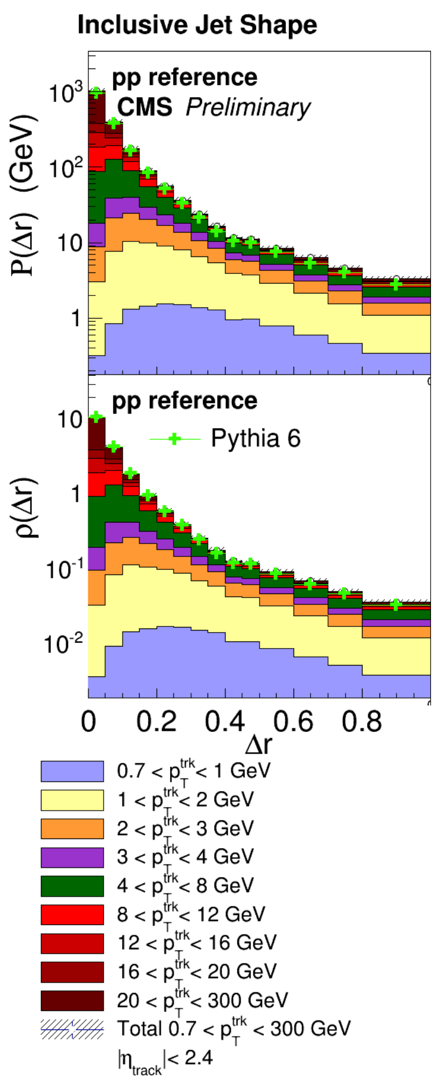
Jet-Track Background Subtraction

- 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



- Finally: apply two MC-based corrections for jet reconstruction biases

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

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

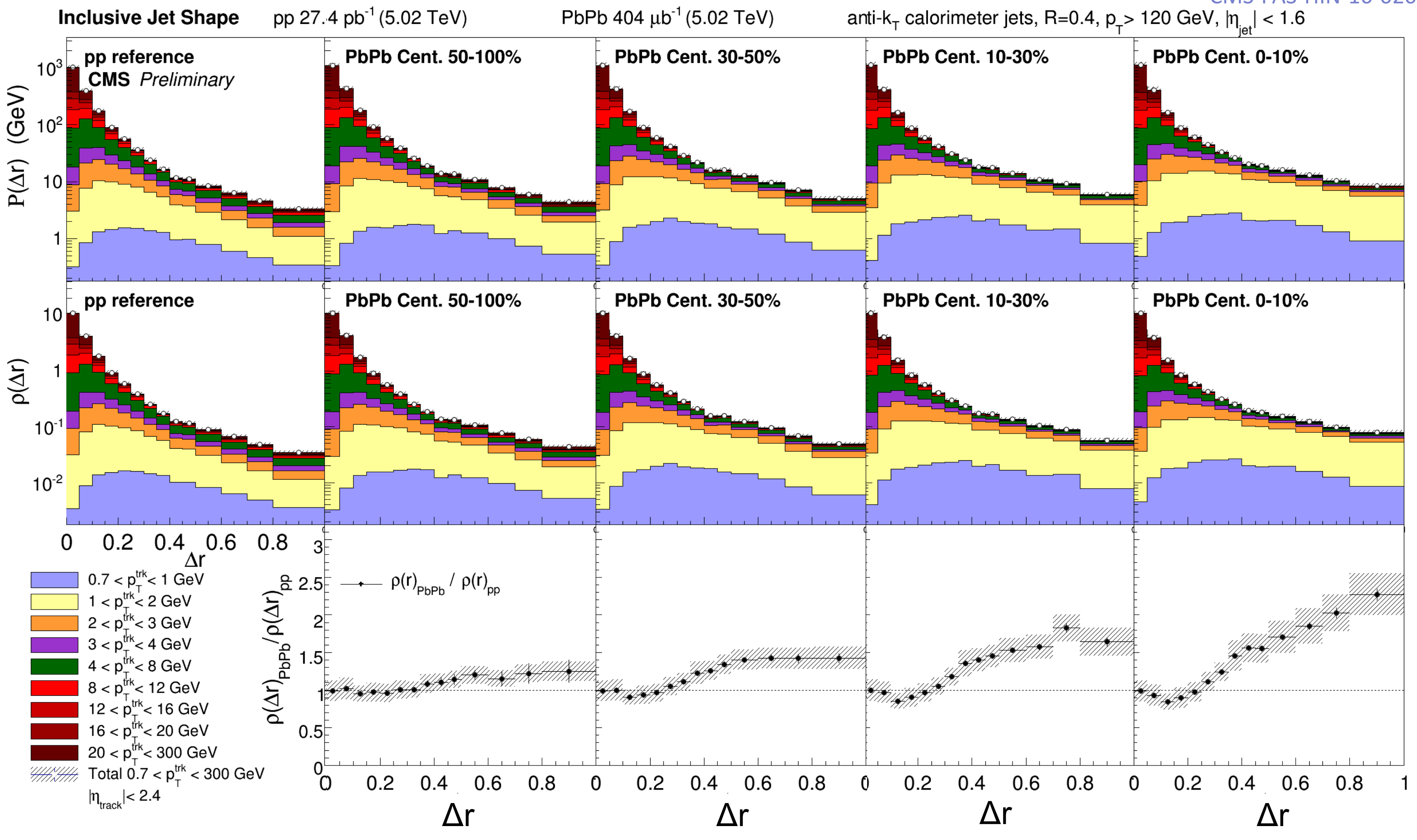
Jet shape ρ(Δr)

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

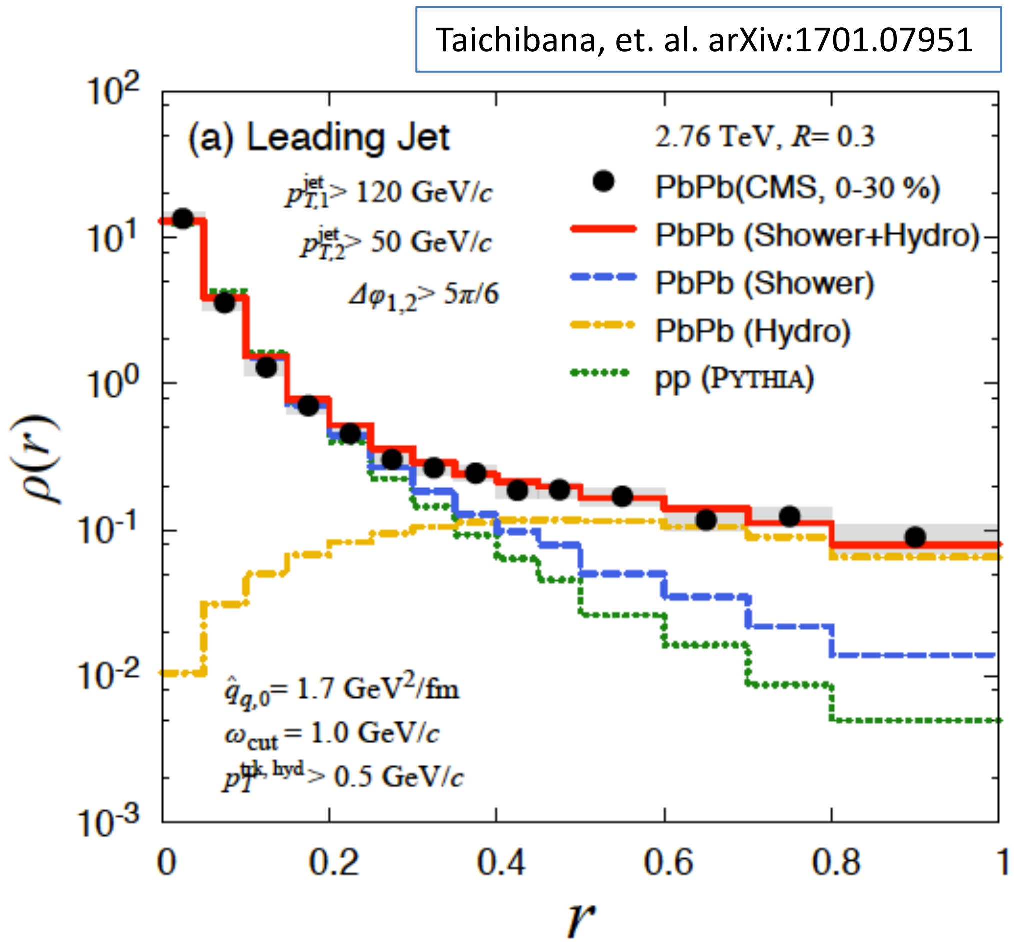
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jets}}}\Sigma_{\mathrm{jets}}\frac{\Sigma_{\mathrm{tracks}\in(\mathrm{r_a},\mathrm{r_b})}p_{\mathrm{T}}^{\mathrm{trk}}}{\Sigma_{\mathrm{tracks}}p_{\mathrm{T}}^{\mathrm{trk}}}$$

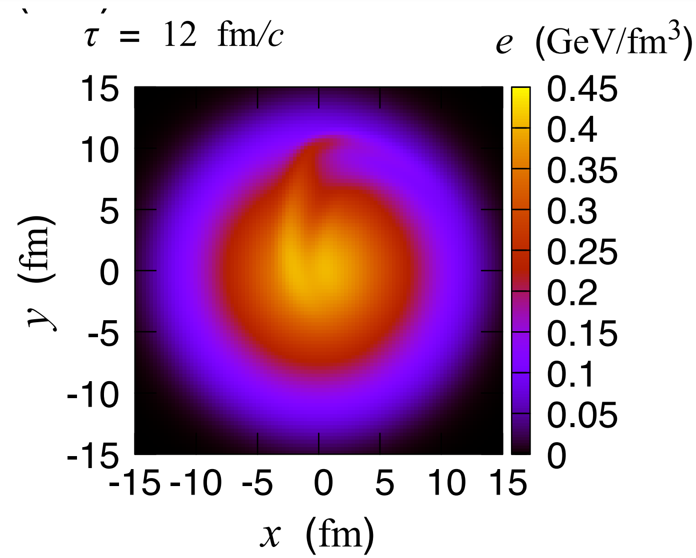
Radial p_T Profile and Jet Shape

CMS-PAS-HIN-16-020



Importance of the Medium Response





Quenched parton shower
+ medium excitation

Quenched parton shower

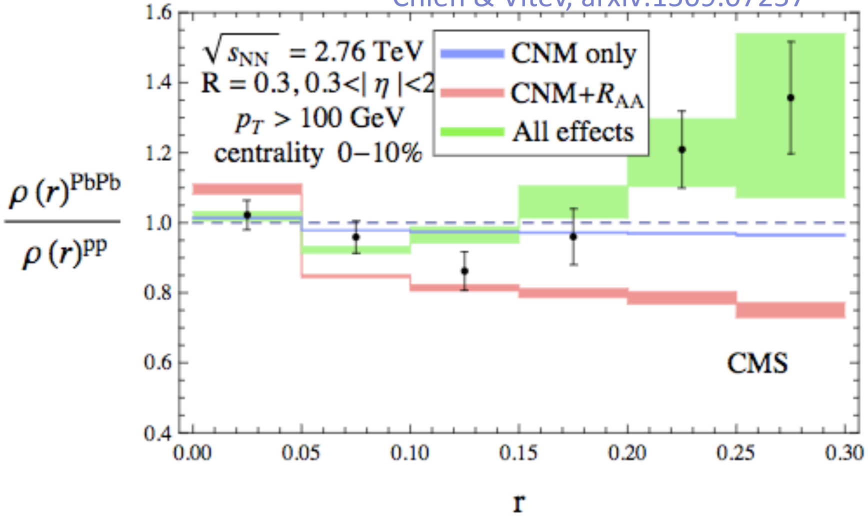
Vacuum parton shower

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

Other Jet-Track Theoretical Results

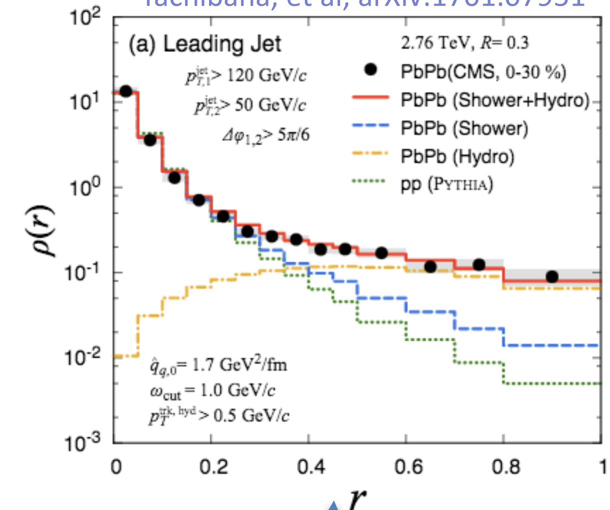
SCET$_G$ (including soft Glauber-gluon interactions in the QGP)

Chien & Vitev, arxiv:1509.07257

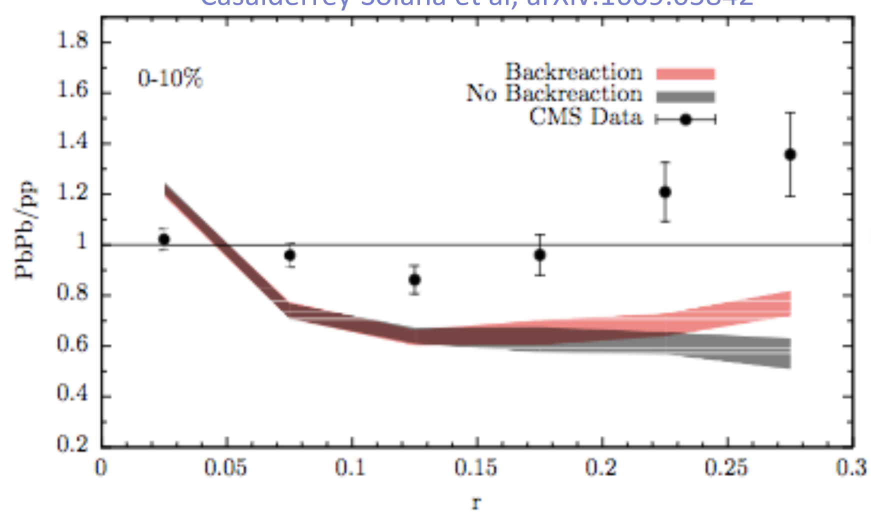


Shower+hydro medium response

Tachibana, et al, arXiv:1701.07951



Casalderrey-Solana et al, arXiv:1609.05842



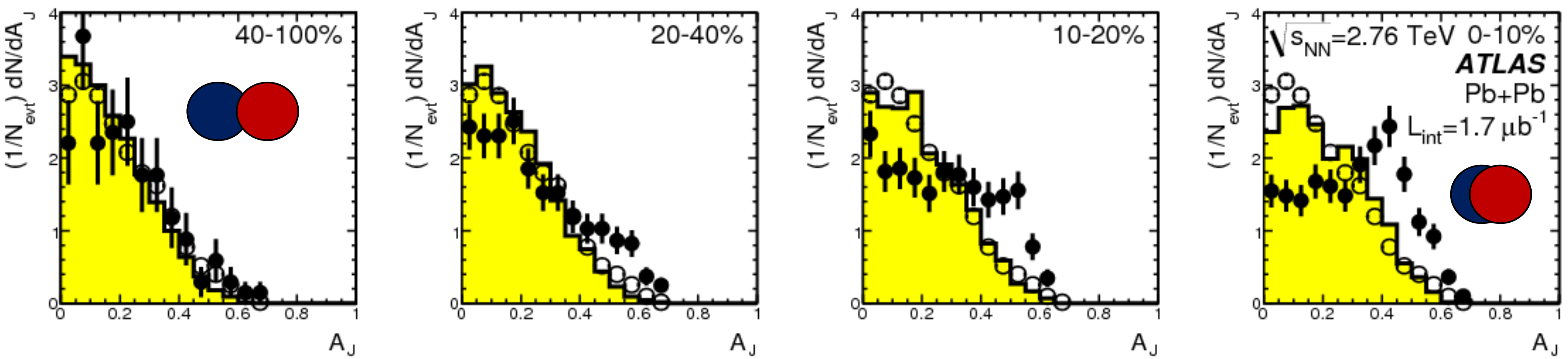
Hybrid model with backreaction (“plasma wake”)

Theoretical curves model the medium response using different methods

Extensions using back-to-back jets

arXiv: 1011.6182

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



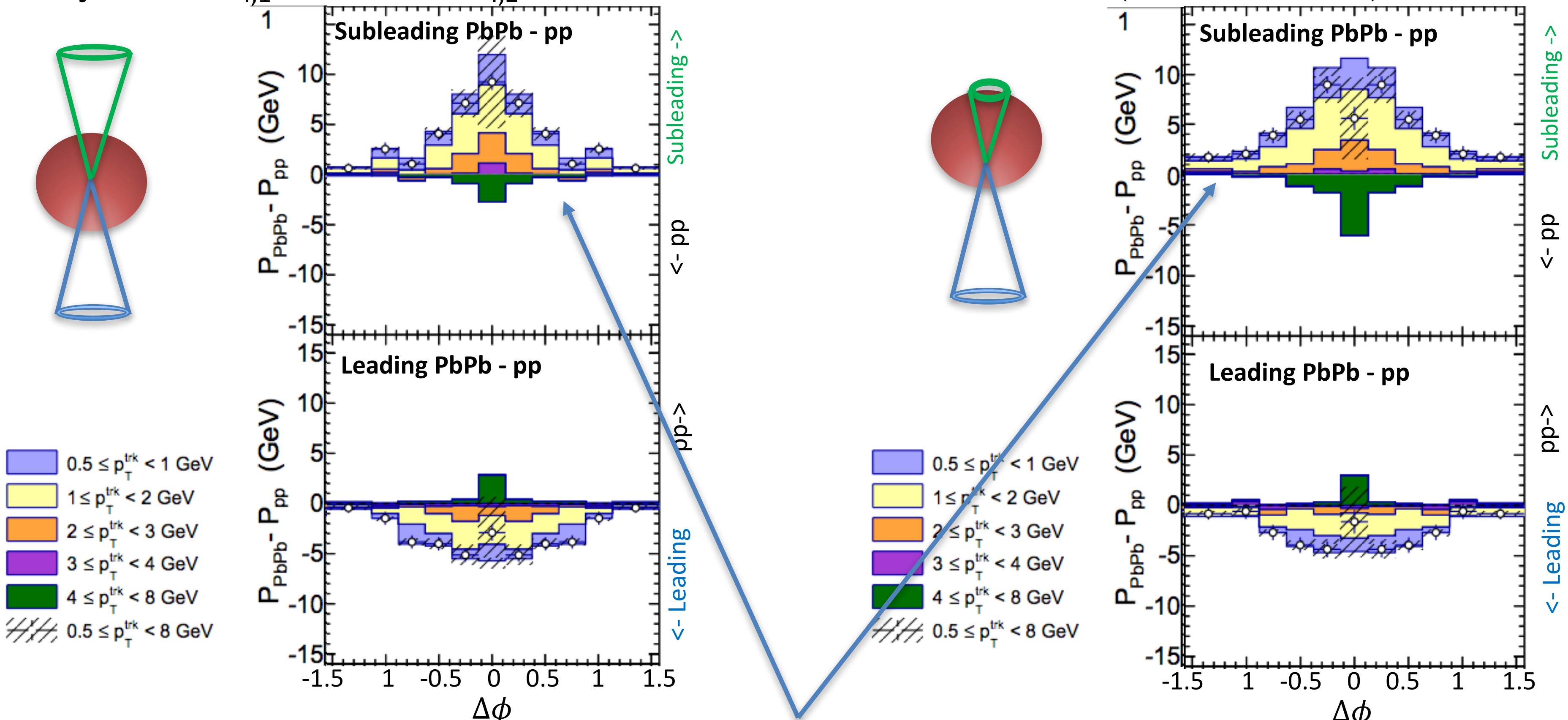
- Attempt to use a leading jet as reference and study effects on subleading jet
  - Observe larger jet asymmetry in central collisions

Jet Track Correlations

arXiv: 1609.02466

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

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

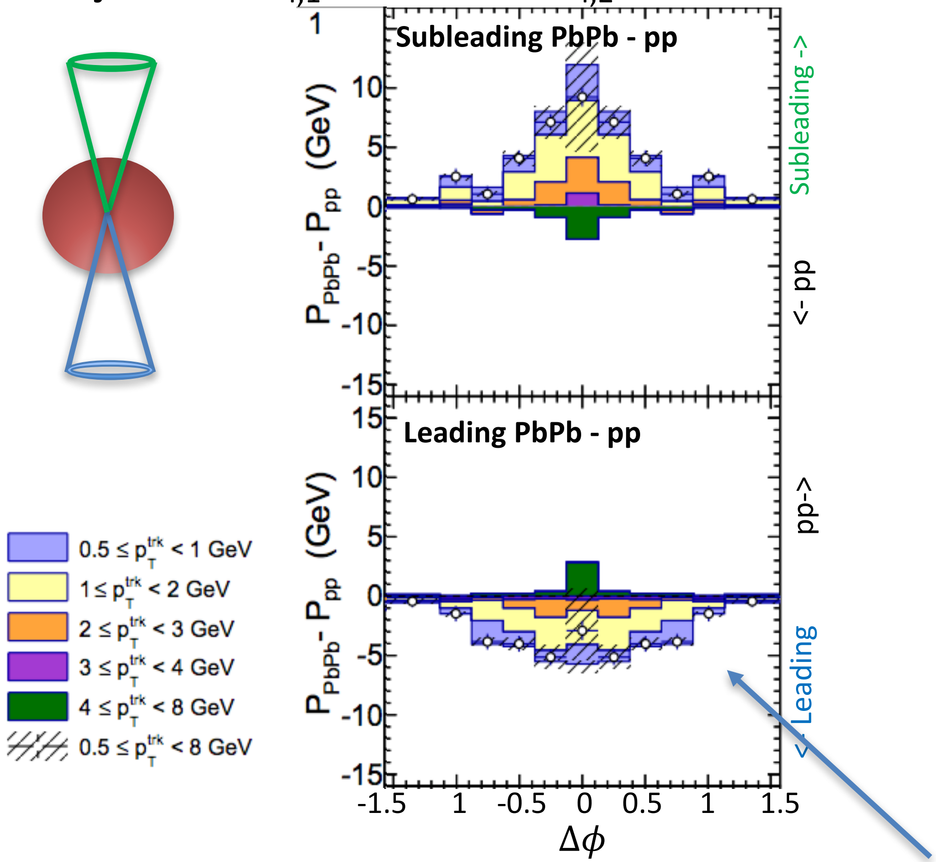


- Shift in constituent particle distribution between balanced and unbalanced jets
  - Subleading jet low-pT constituents pushed farther away for quenched jets
  - Leading jet particle distributions consistent between quenched/unquenched sample

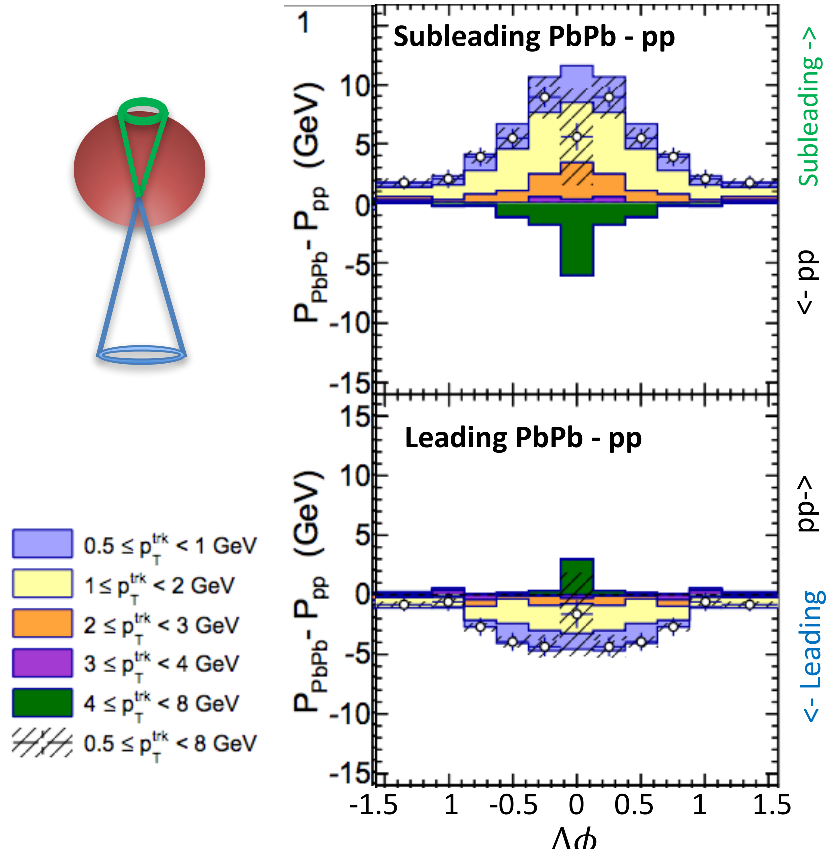
Jet Track Correlations

arXiv: 1609.02466

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



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

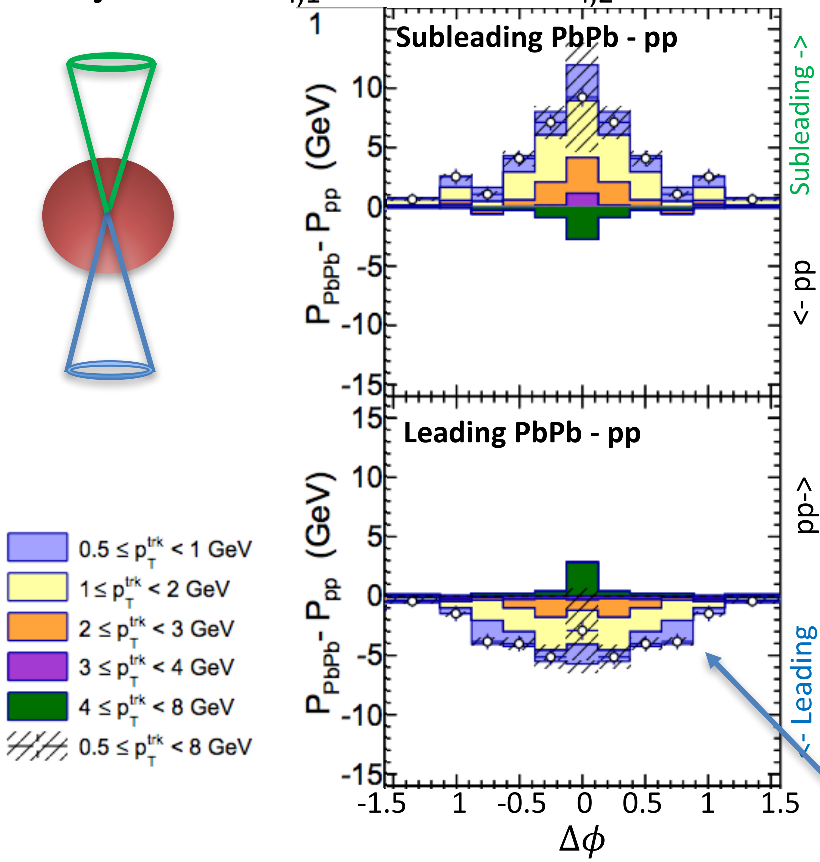


- Leading jet constituents are modified, even for **balanced** dijets (!)
  - Assumption that leading jet is unmodified may not be true at LHC energies
  - Need a ***better reference*** for jet suppression than another jet

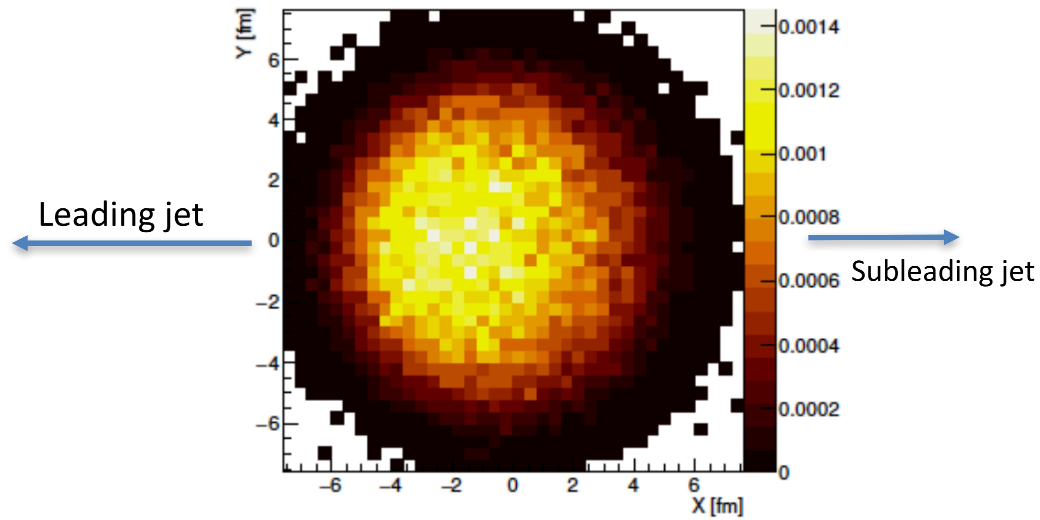
Jet Track Correlations

arXiv: 1609.02466

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



Surface Bias from asymmetric jet selection



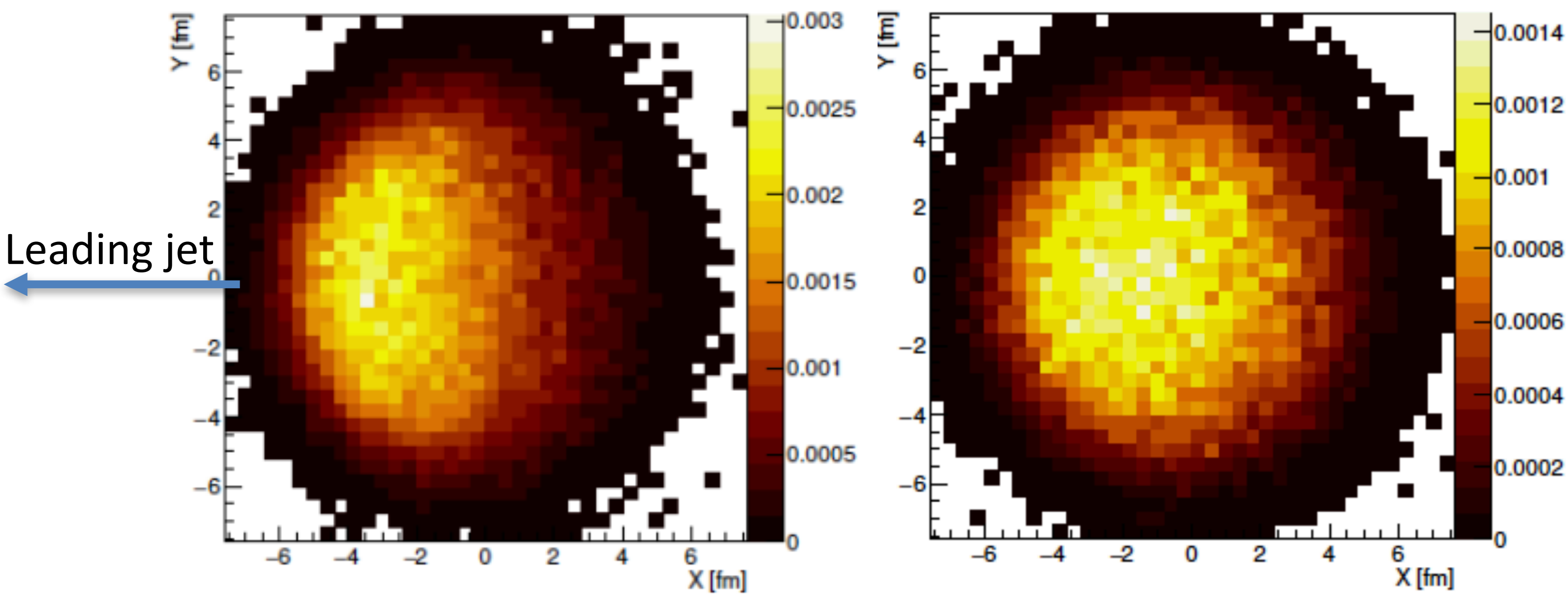
- Leading jet constituents are modified, even for **balanced** dijets (!)
  - JEWEL predicts this phenomenon looking at dijet surface bias

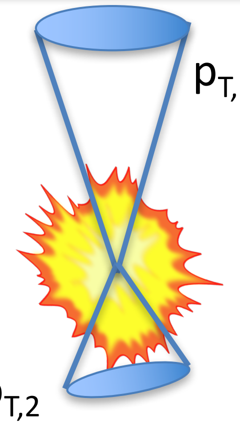
Measuring the surface bias of dijets

K. Lapidus, HP 2016

Hard-Scattering Vertex from asymmetric jet selection

RHIC (Au+Au, 200 GeV) LHC (Pb+Pb, 2.76 TeV)





- LHC jets show smaller surface bias than RHIC jets
  - Need a true unmodified reference for jet quenching
  - Use jet-track correlations binned differentially for balanced and unbalanced dijets

Summary (I) – Theoretical Needs

http://jetscape.wayne.edu/

- Need new MC generators to fully describe the collision dynamics in a coherent and systematic way
  - Avoid comparing apples to oranges by allowing consistent treatment of one aspect of the collision and varying others
  - Snap-in "modules" can work together to simulate a full collision – no need to reinvent the wheel

Summary (II) – Experimental Needs

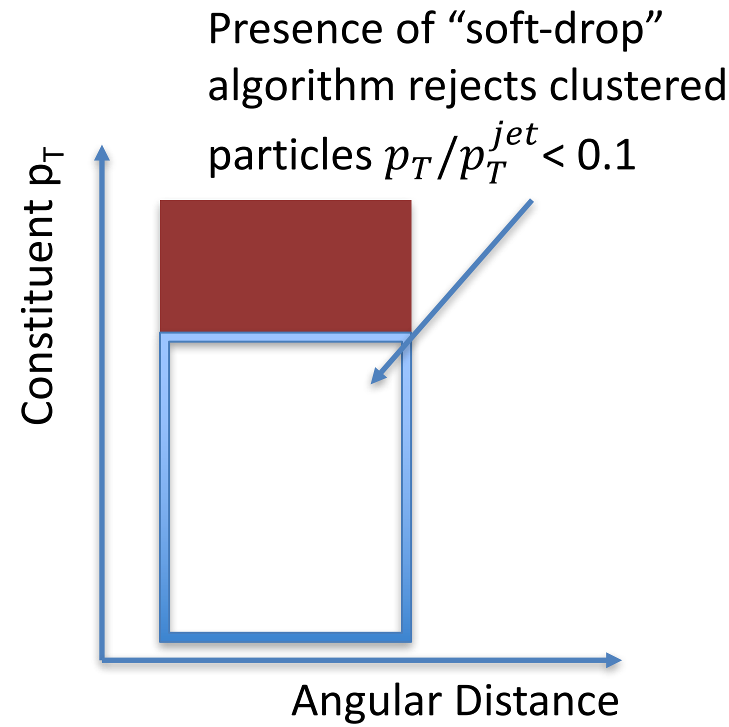
- Need to make sense of the wealth of jet physics measured at LHC (and RHIC!)
  - Should attempt to describe results as a part of a whole, draw conclusions based on entire physical picture (not just on a single measurement)

- Jet quenching clearly observed for many years
  - Jet-Track studies show clear evidence of energy transported to low-p_T at large angles
- New measurements (e.g. jet substructure) can remove some sensitivities to post-collision dynamics and start to discriminate between quark and gluon jets – more like this will be required!

BACKUP

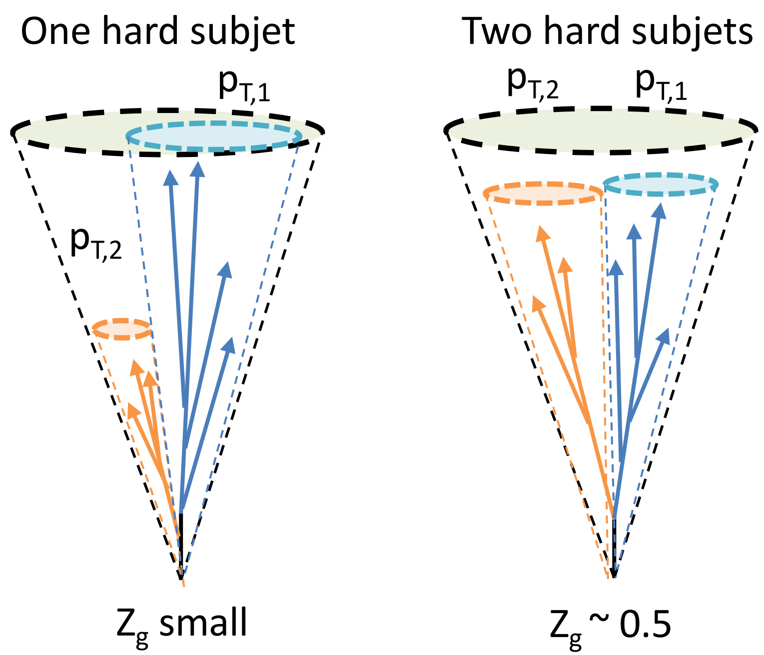
Jet Substructure

- 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

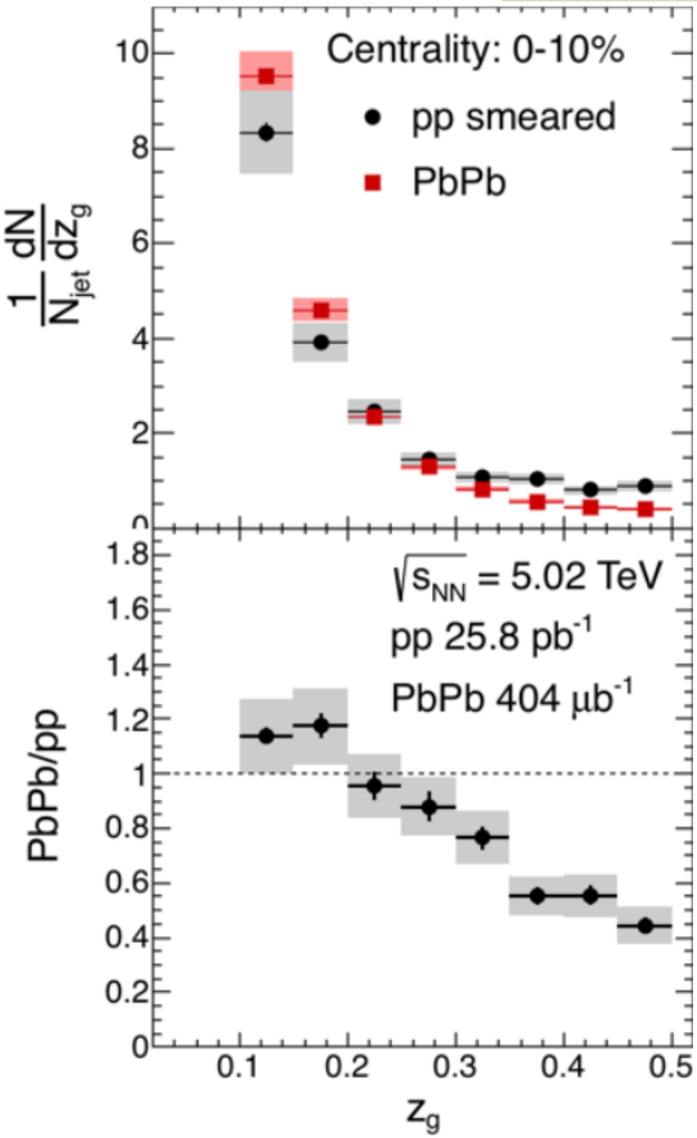


Measuring the Jet Substructure

CMS-PAS-HIN-16-006



$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

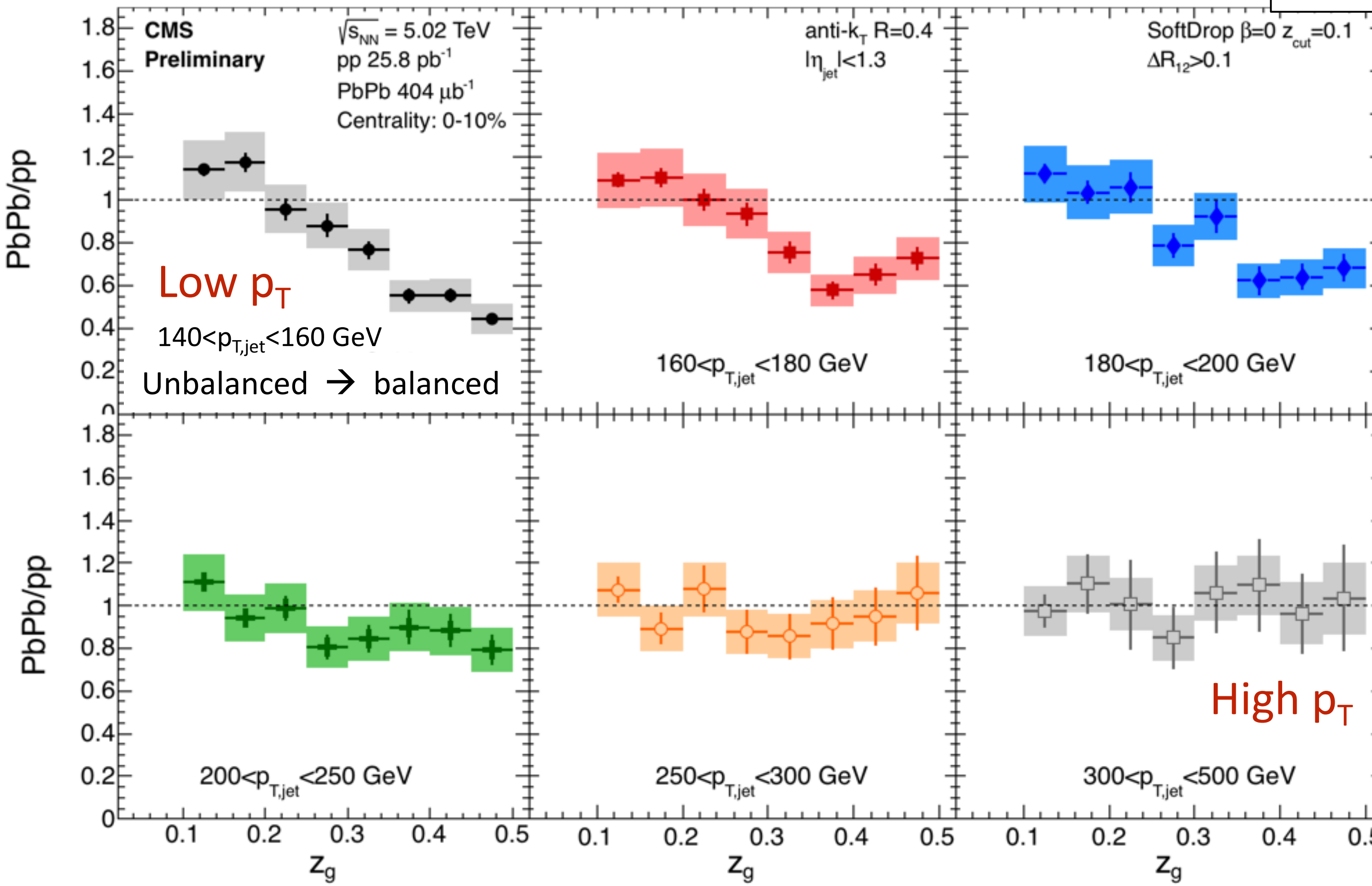


- Quark and gluon z_g distributions are very similar in pp
- Jets with two hard subjets (large z_g) **relatively** more suppressed than jets with a single core (small z_g)

QGP can "see" the parton shower!

Jet p_T dependence

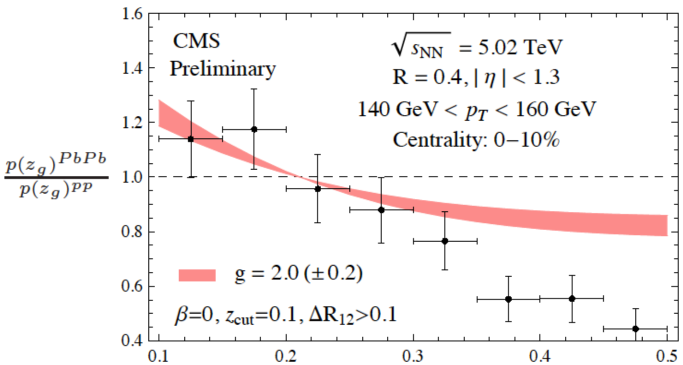
CMS-PAS-HIN-16-006



- 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

Ideas for z_g modification

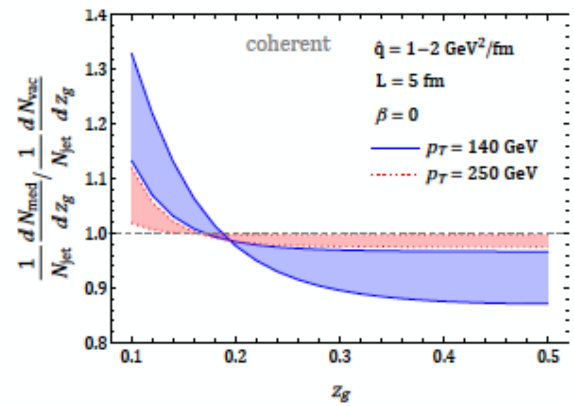
Medium modified splitting with $SCET_G$



LO diagrams dressed with vacuum like multiple emissions

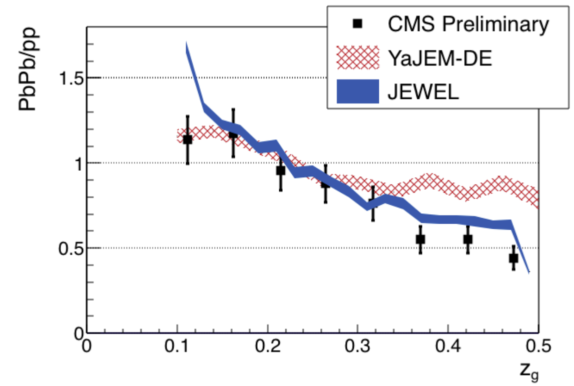
Chien and Vitev. arXiv:1608.07283

Coherent + semi-hard BDMPS radiation



Mehtar Tani and Tywoniuk arXiv:1610.08930

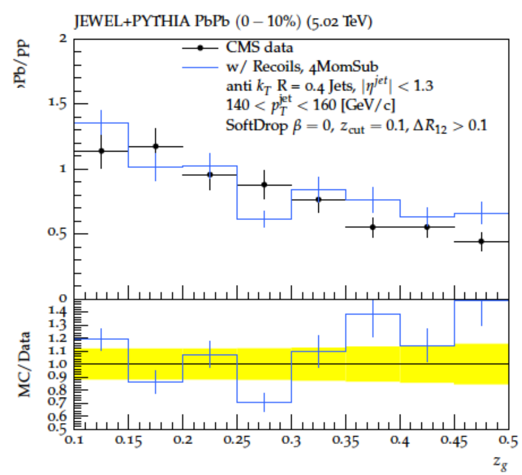
Jet quenching MCs



Kirill Lapidus, HP2016
R. Kunnawalkam Elayavalli, K. Zapp, G. Milhano

Jet-correlated medium

Promotion of splittings into sample due to medium push

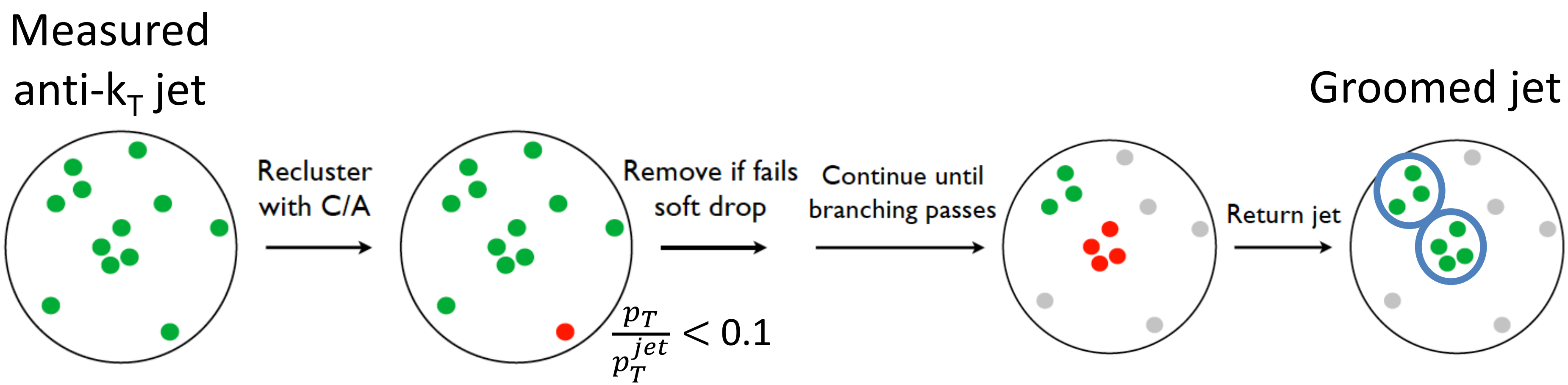


Large variety of concepts, describe general trend of data

Describing centrality and jet p_T dependence seems challenging

Jet grooming

- Jet grooming removes soft divergences and uncorrelated background
  - "Soft-drop" primarily removes late-stage soft gluon emission
- Common technique in HEP - introduced in heavy-ion collisions



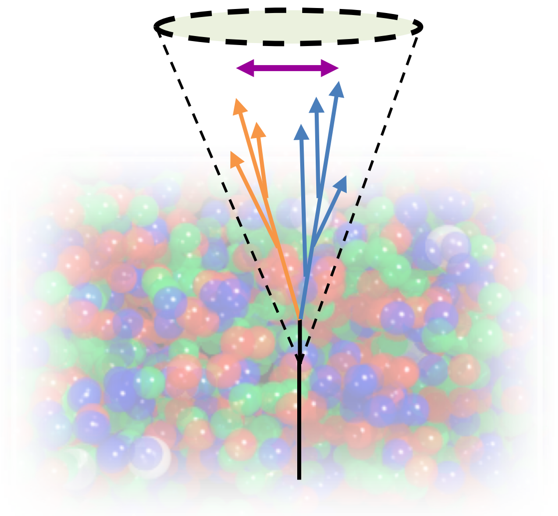
Procedure finds splitting with largest angular separation

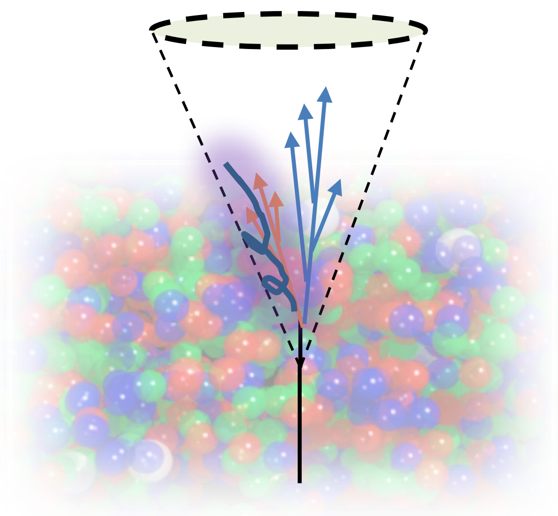
Hadronization effects are suppressed – more useful than single-particle meas.

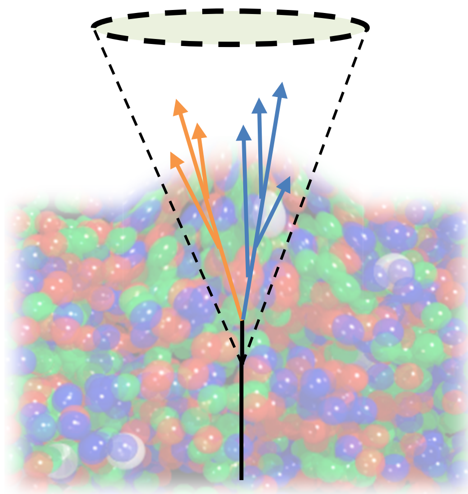
Schematic sketch from A. Larkoski
LPC Workshop Jan. 2014

Substructure Probes of the QGP

Jet suppression might depend on the shower shape in a number of different ways…







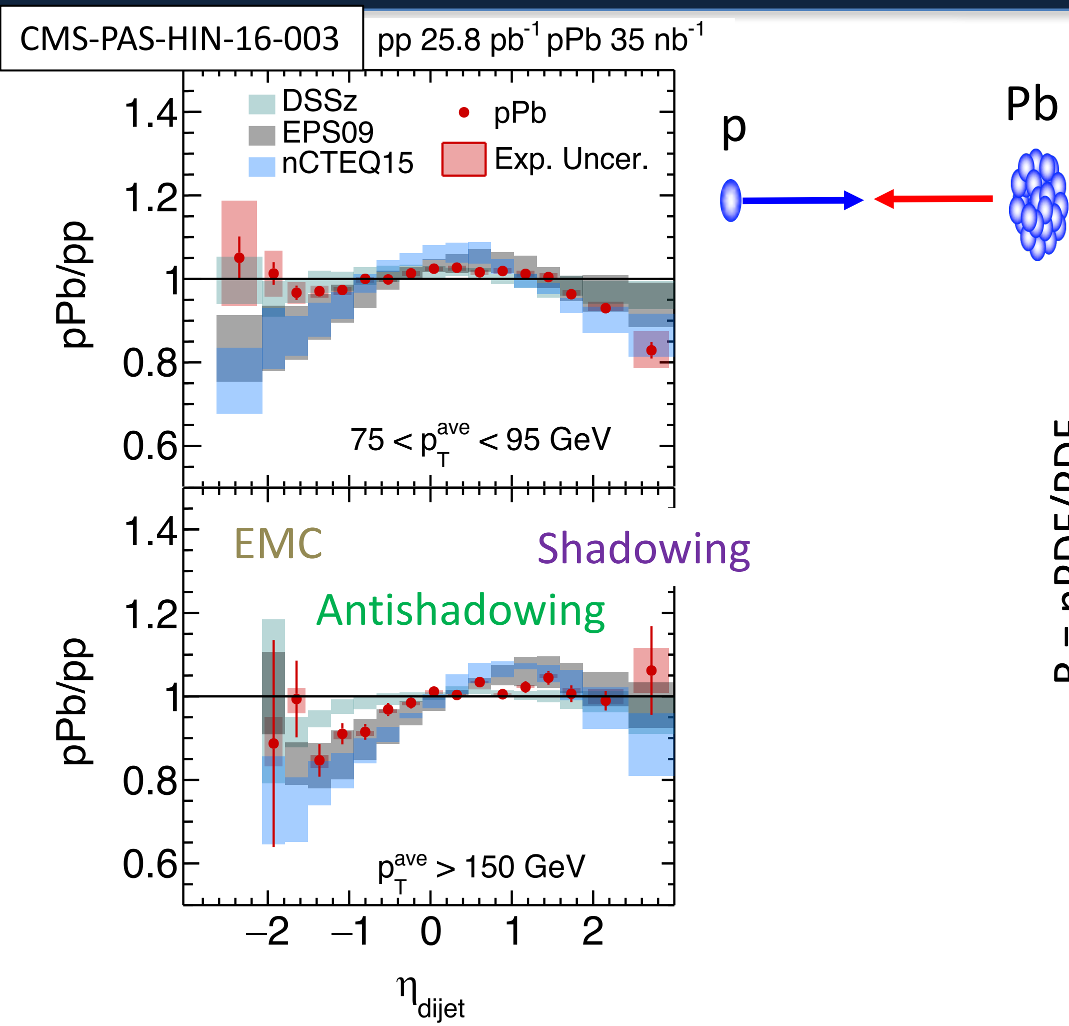
When the jet prongs are **separated enough** so that they are each seen (and quenched) by the QGP

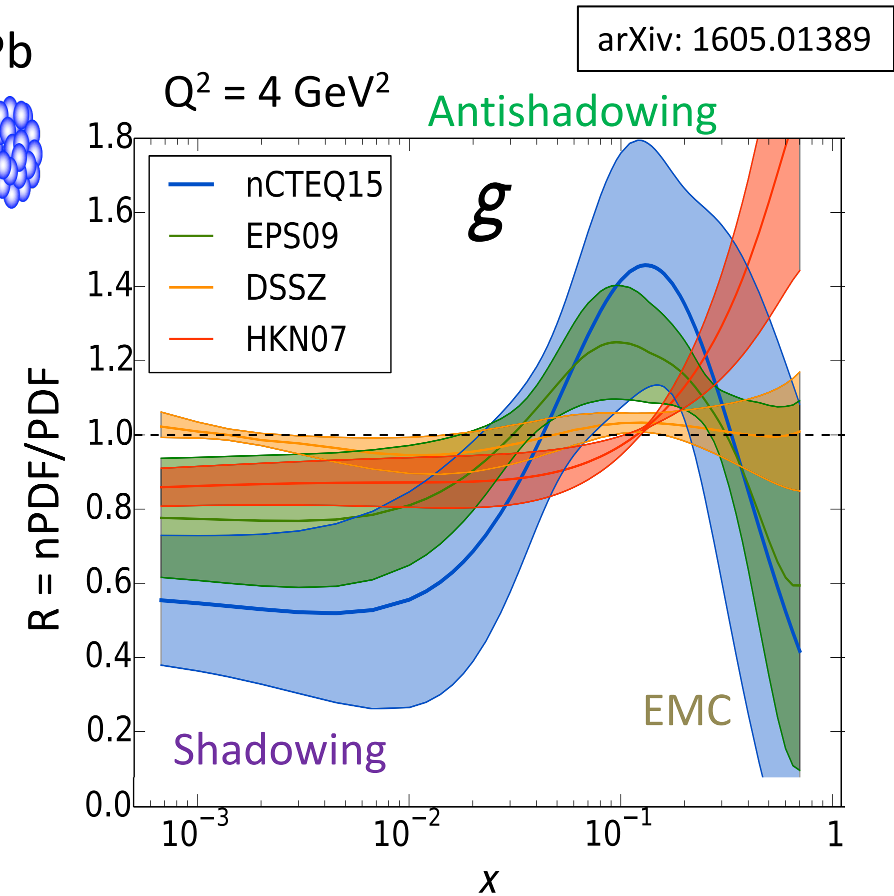
Presence of **extra emission** and/or modification of parton branching in the QGP

If there are **correlated background particles** with the shower in the QGP

(Suggested by Jet-Track studies)

Constraining nPDFs with Dijets



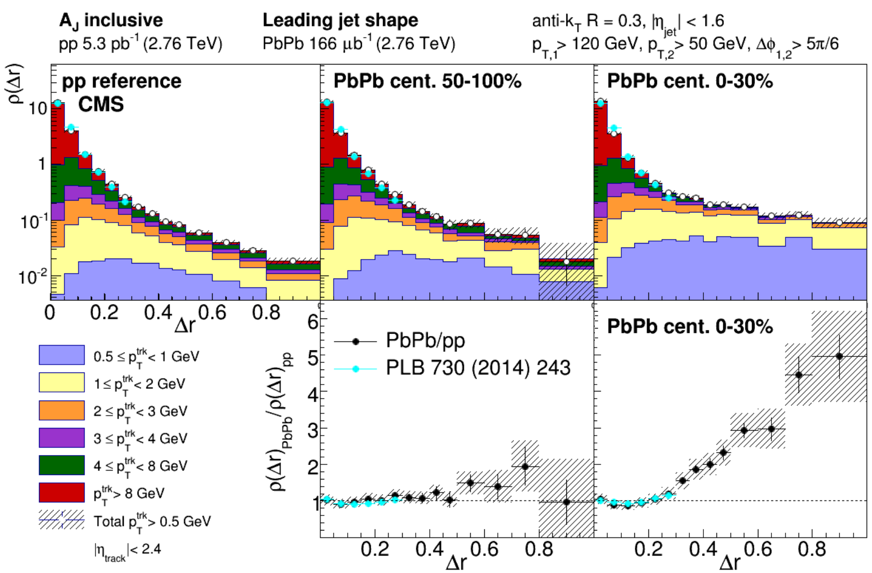


- Dijet η distributions correlate strongly with Bjorken-x
  - Measurements of inclusive-jet η_{dijet} can constrain nPDFs

Radial p_T Profile and Jet Shape

2.76 TeV Leading Jets

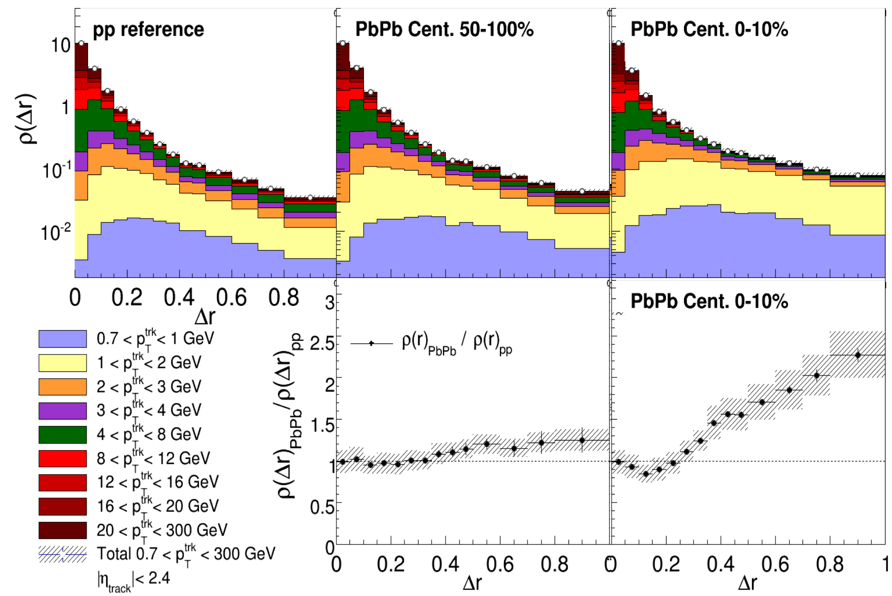
10.1007/JHEP11(2016)055



- Anti-k_t calo jets, R = 0.3
- Leading jets, p_T > 120 GeV
- PLB: Inclusive jets, p_T > 120 GeV
- Normalized over Δr < 0.3
- 0-30% centrality bin

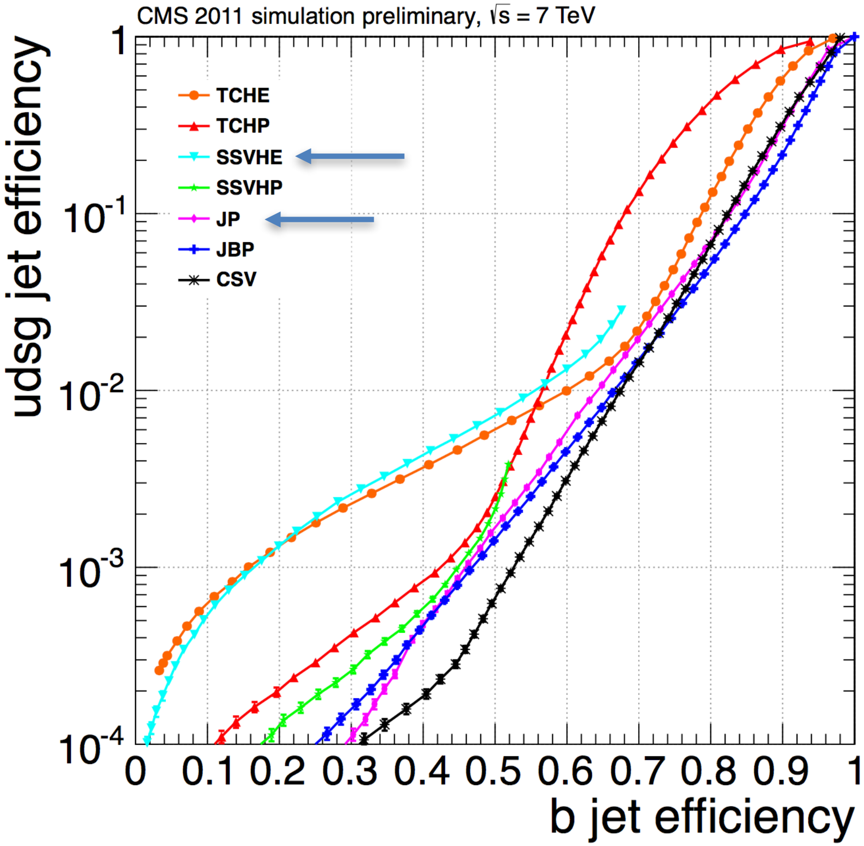
5.02 TeV Inclusive Jets

CMS-PAS-HIN-16-020



- Anti-k_t calo jets, R = 0.4
- Inclusive jets, p_T > 120 GeV
- Normalized over Δr < 1
- 0-10% centrality bin

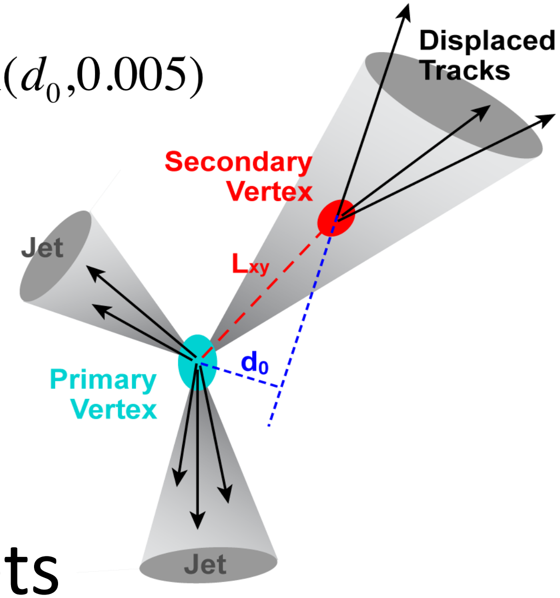
PbPb to pp modifications are similar at 5.02 and 2.76 TeV: differences in pp reference jet shape account for differences in ratio $\rho(\Delta r)_{PbPb}/\rho(\Delta r)_{pp}$



$$SSV = \ln(1 + |L_{xy}| / \sigma(L_{xy}))$$

$$JP = \Pi \cdot \sum_{nTracks=0}^{N-1} \frac{(-\ln \Pi)^i}{i!}$$

$$\Pi = \prod_{nTrack=1}^{N} \max(d_0, 0.005)$$

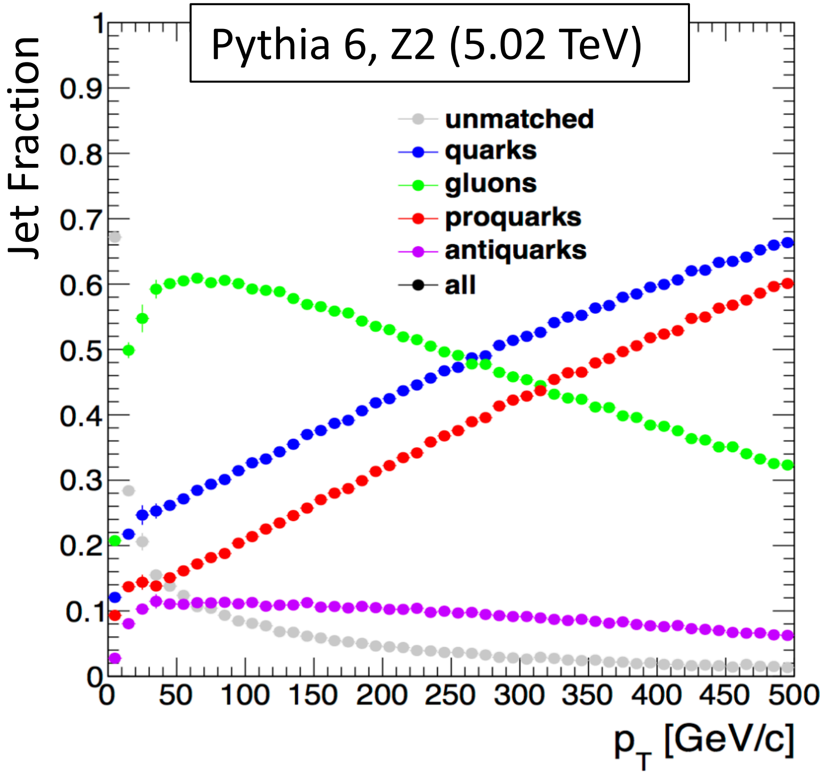


- In principle, many ways of tagging b-jets
  - We use "SSV" = Simple secondary vertex
  - "JP" = Jet Probability tagger used as cross-check (no SV)

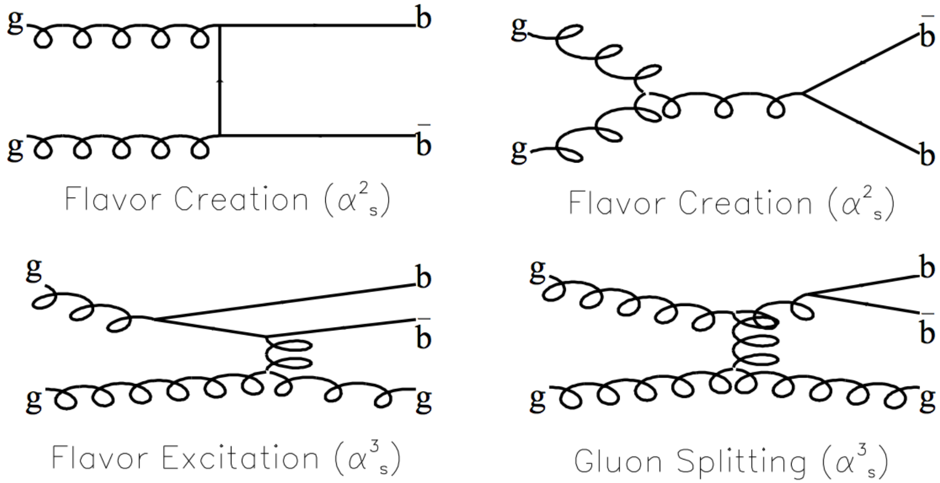
arXiv: 1211.4462

b & c-jets: A good probe of gluon nPDFs

Inclusive jet production types



B-jet production types (gg prod. only)

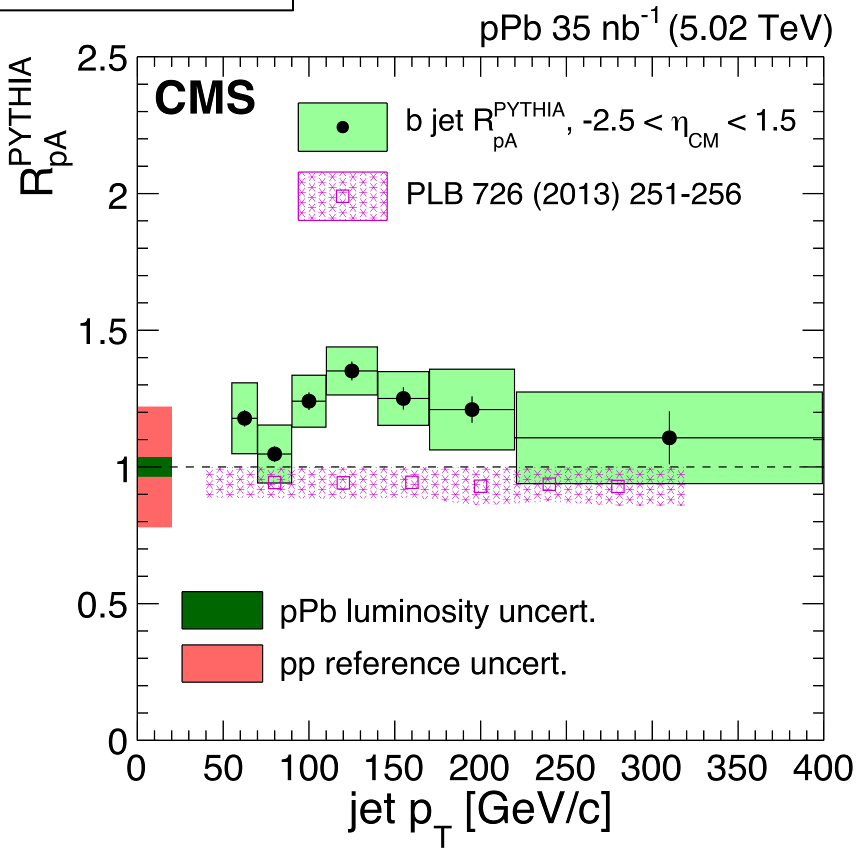


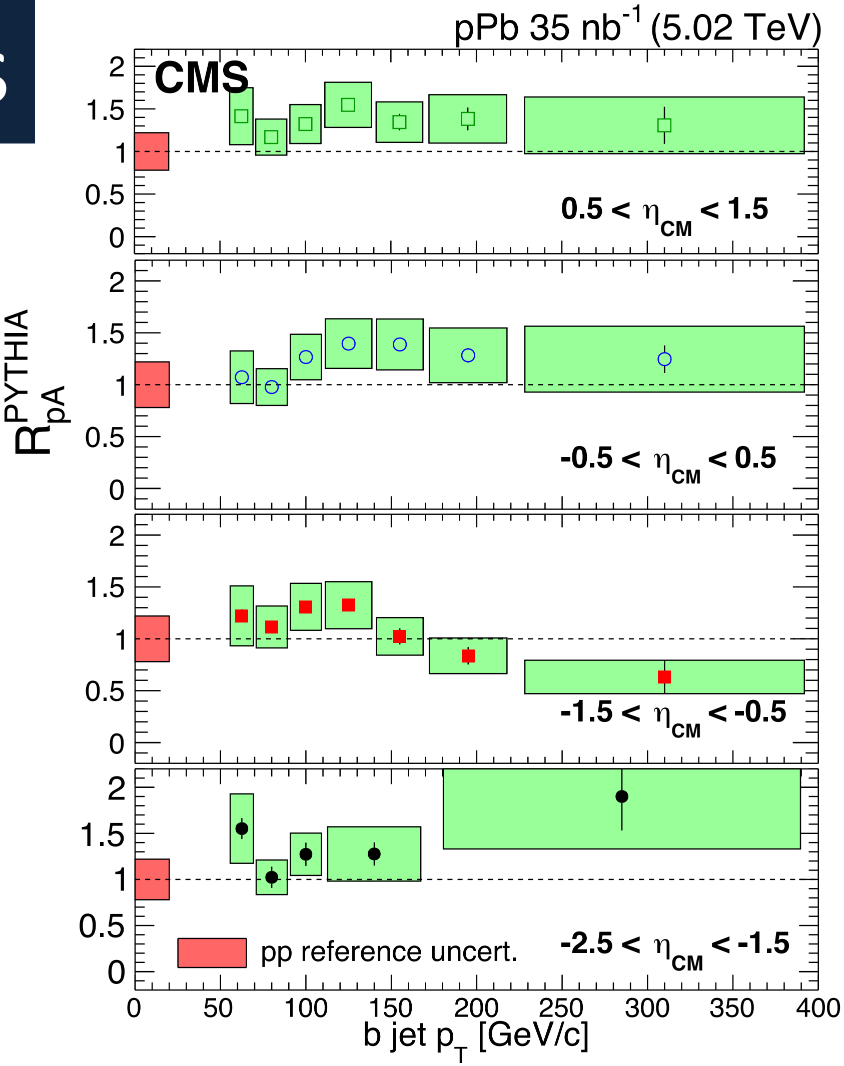
arXiv: hep-ex/0412006

– Inclusive dijet measurement convoluted by ***quark PDFs***, while b/c-jet measurements are dominated by ***gluon PDFs***

b-Jets in pPb Collisions

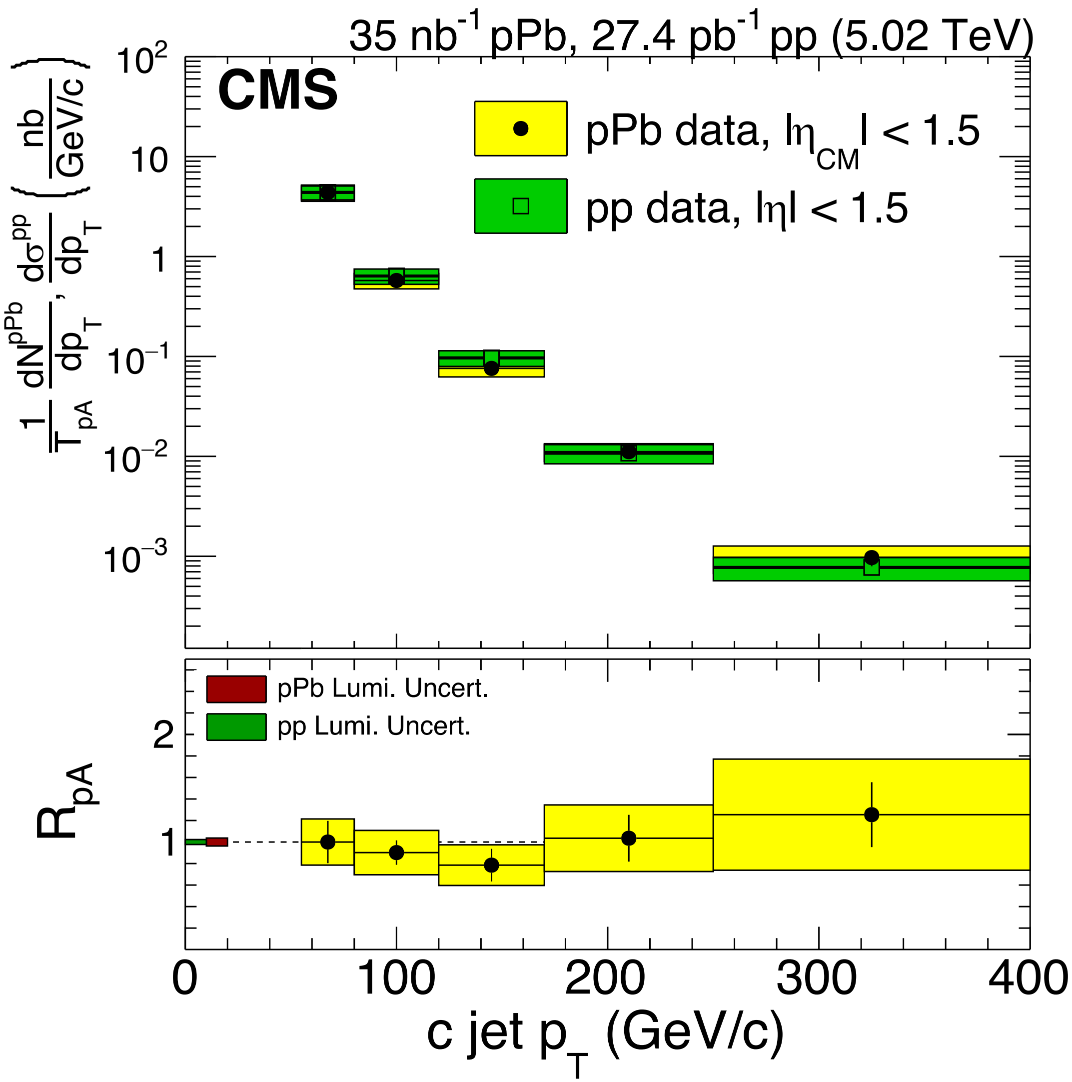
arXiv: 1510.03373





- b-Jet R_{pA}^{Pythia} finds no discrepancy from unity
- Inclusive measurements of b-jets in pPb not sensitive enough to probe gluon nPDFs – need more data!

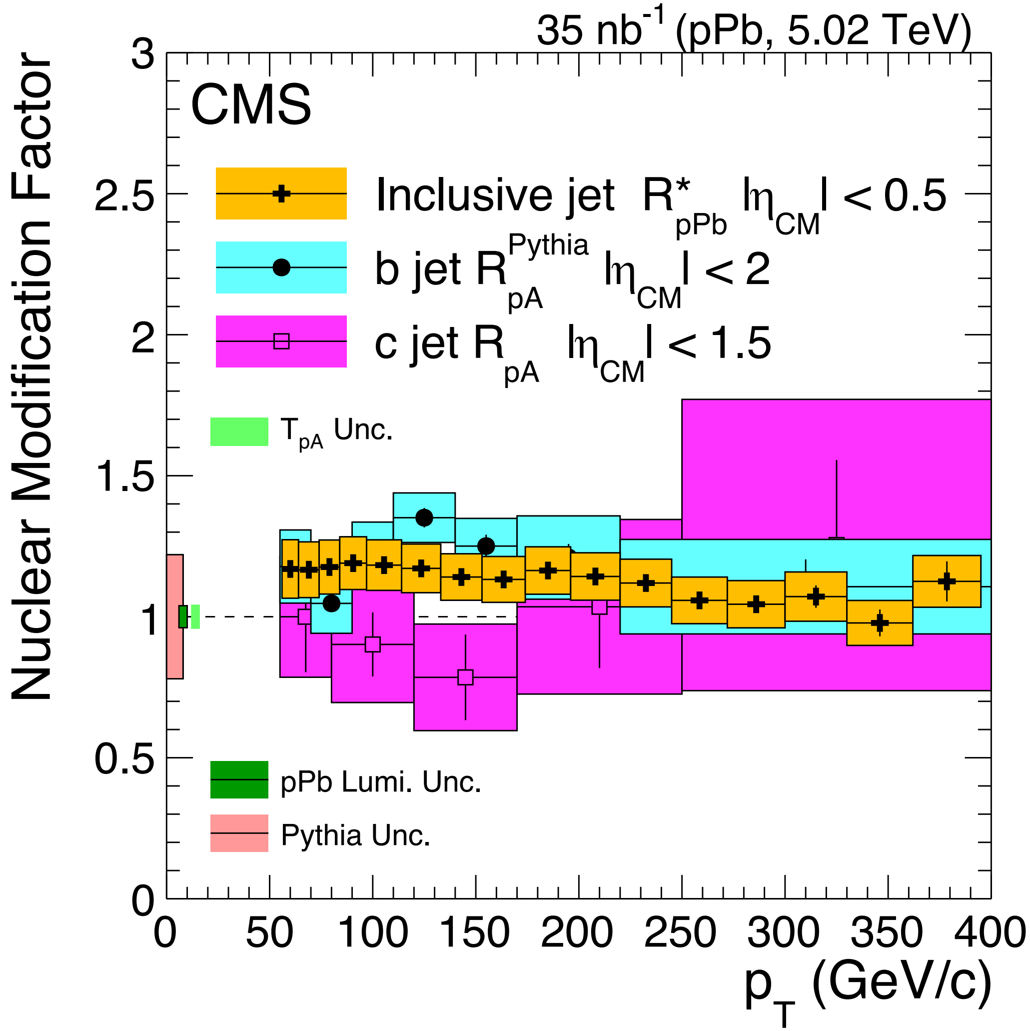
Charm-Jet Spectra



- First measurement of an inclusive charm-jet cross-section
- Observe consistency of charm-jet spectra in pPb relative to pp within uncertainties

arXiv: 1612.08972, PLB to appear

R_{pA} for heavy+light flavors



Inclusive jet: 1601.02001
b jet: 1510.03373
c jet: 1612.08972

- All jet samples are consistent with one another
- No indications of flavor-dependent nPDF effects within uncertainties