Studies of Heavy Flavored Jets using the CMS Detector

Kurt Jung (for the CMS Collaboration)
[U. of Illinois at Chicago]

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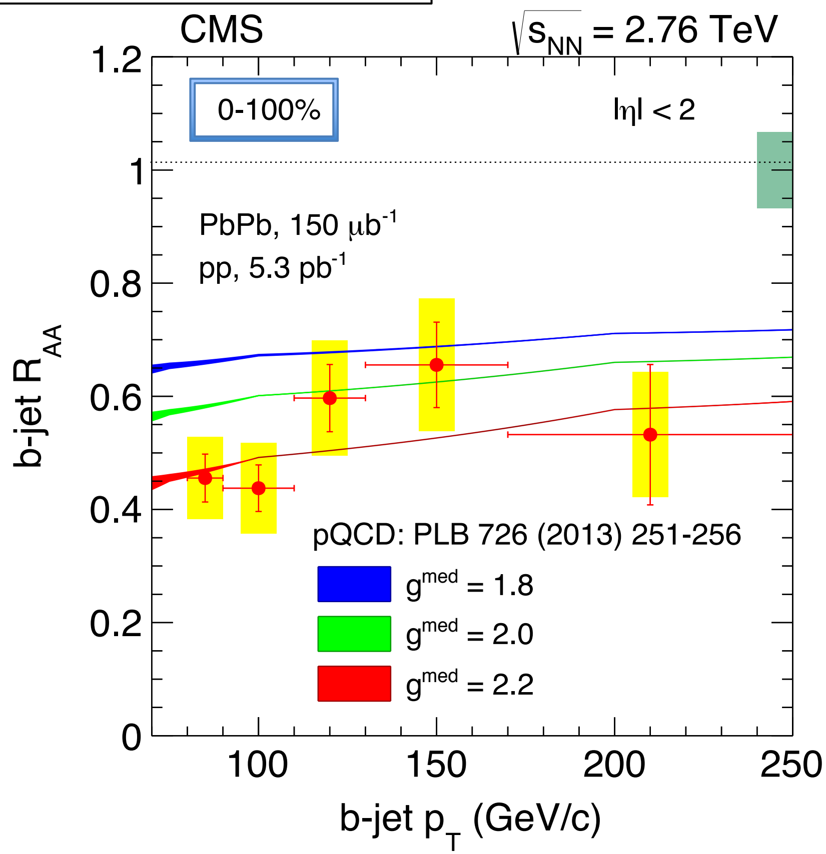
Motivation for Flavored Jets

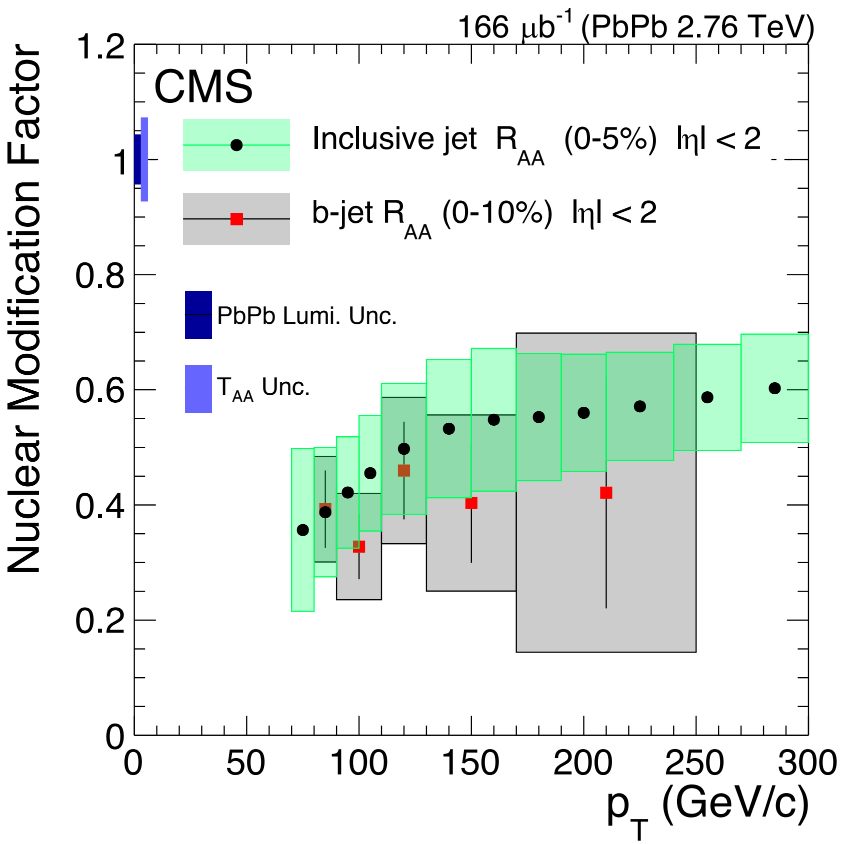
- **In Lead-Lead collisions (2012)**: Observation of flavor-dependent energy loss?
  - Differences in quark-plasma interactions based on quark mass or quark/gluon ratios?
  - Most pQCD models predict similar high-p_T jet behavior for flavored and light jets [Djordjevic (PRC 90:034910) & Vitev (PLB 726:251)]
    - Some differences in flavored jet production, e.g. q/g ratio + spectra slope

- **In Proton-Lead collisions (2014)**: Quantification of the cold nuclear matter effects for heavy-flavor objects at high-p_T
  - Allow for factorization of quenching effects in PbPb; theoretical predictions can be constrained by flavor-dependent energy-loss measurements
  - Observe flavor-dependence of CNM effects at high-p_T?
  - Observations of gluon nPDFs using jets?

Heavy Jets behave like light jets…

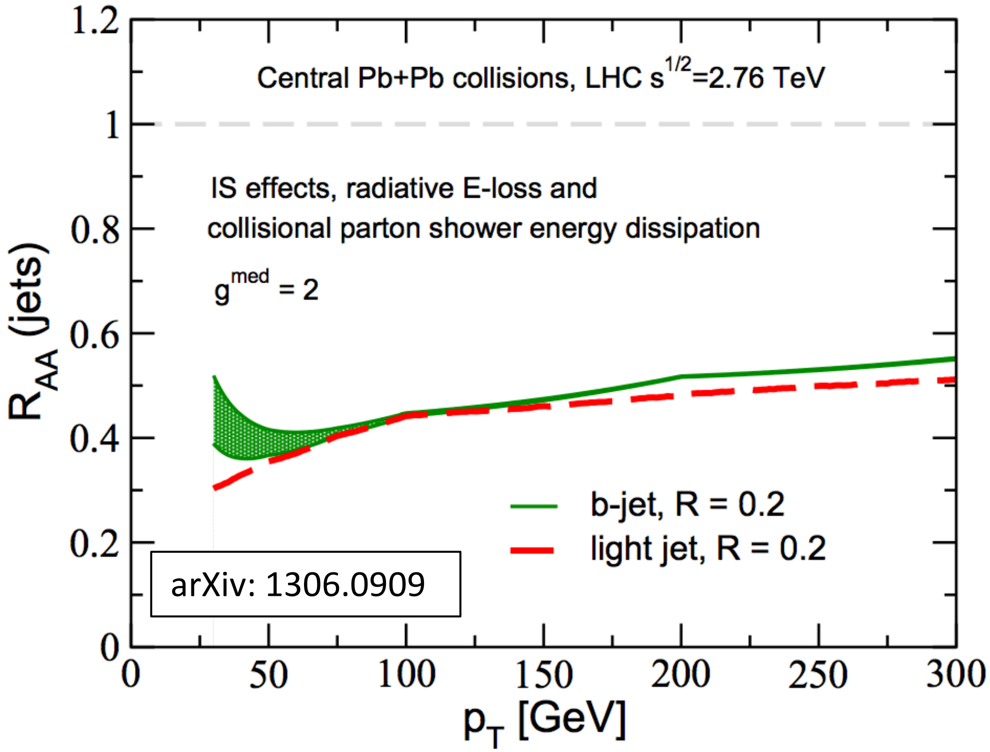
PRL 113 (2014) 132301

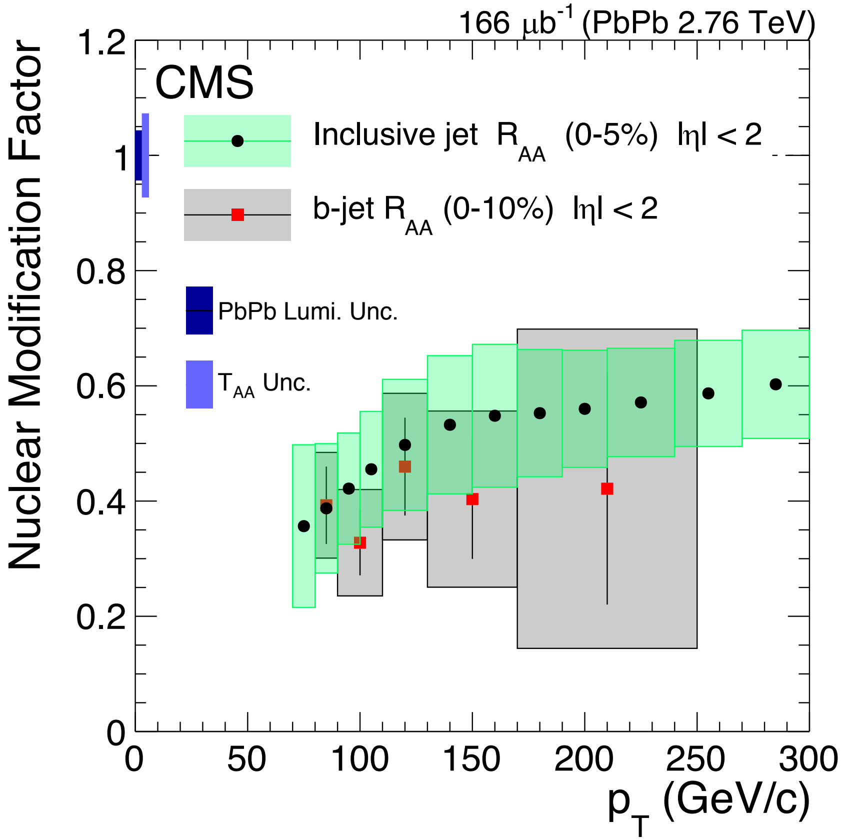




- Simple observables like R_{AA} seem to indicate similar quenching magnitude between b-jets and inclusive jets

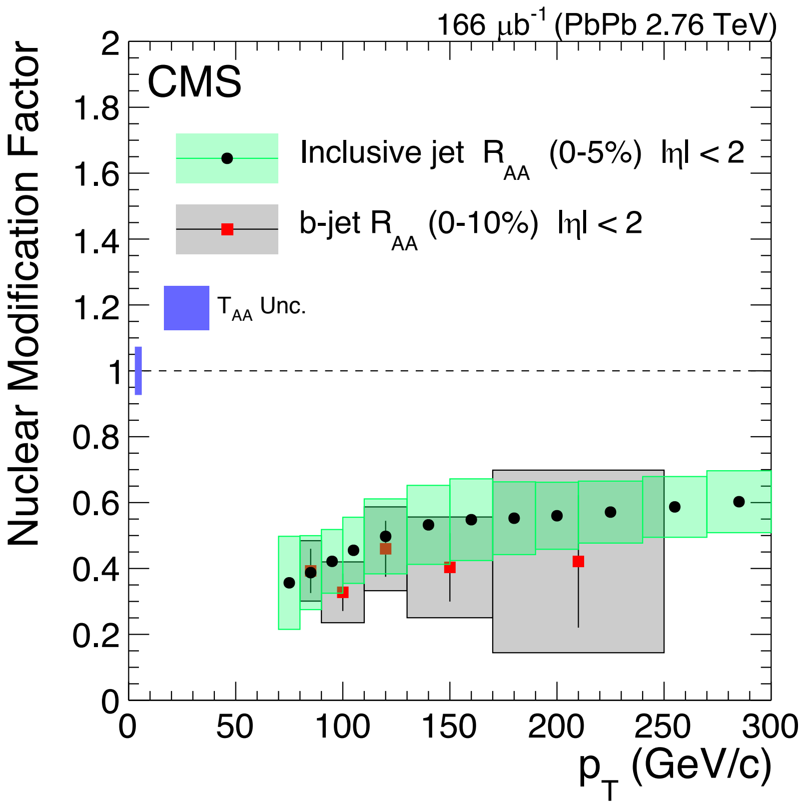
Heavy Jets behave like light jets…

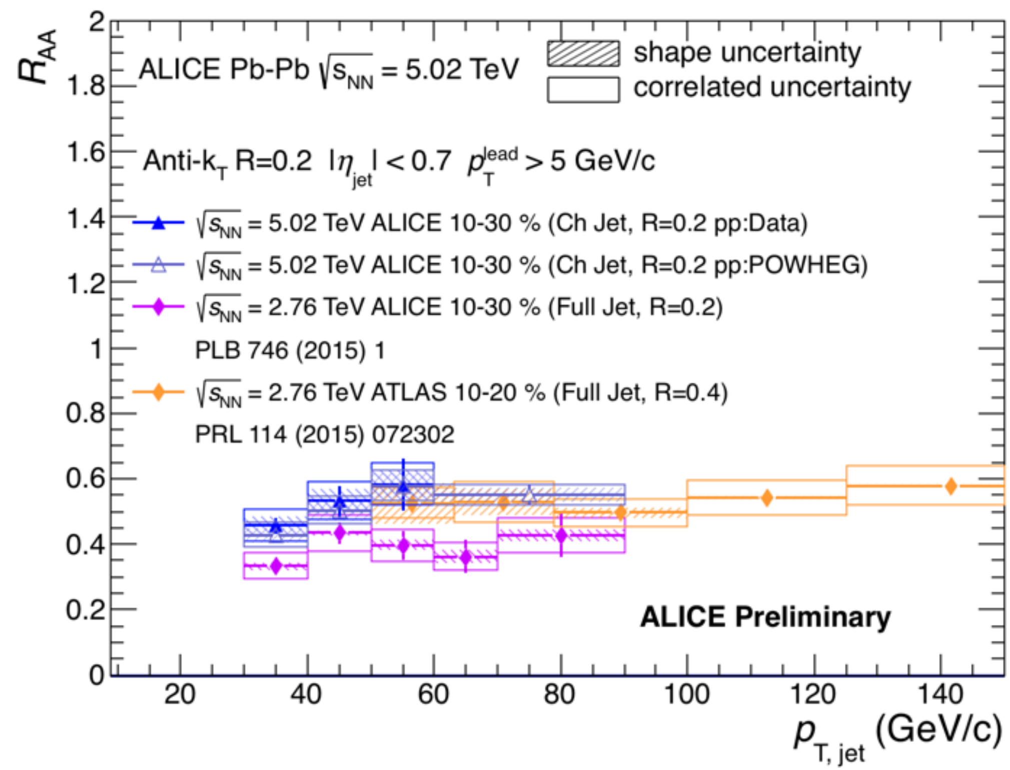




- Simple observables like R_{AA} seem to indicate similar quenching magnitude between b-jets and light jets

…but so does everything!

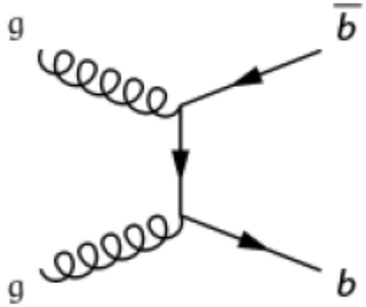




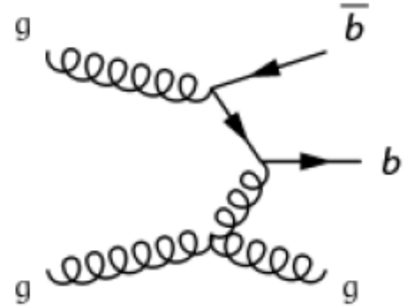
- R_{AA} proven to be relatively insensitive to many observables
  - Is absence of R_{AA} flavor dependence an extension of this insensitivity?
  - Can we use alternative tools to get around this?

b-jet Production Mechanisms

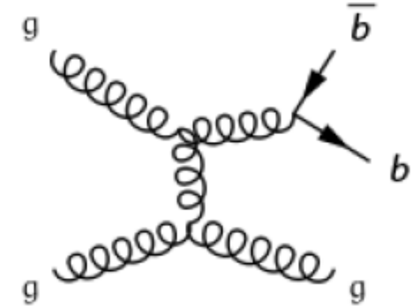
Flavor Creation ("FCR")



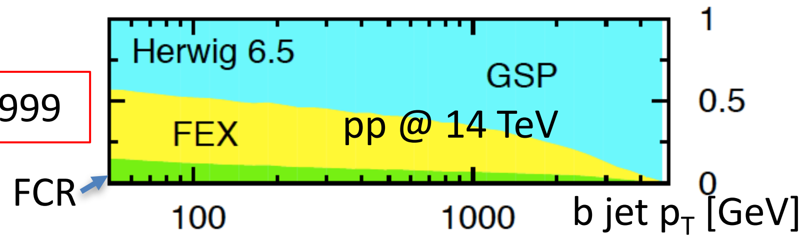
Flavor Excitation ("FEX")



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

b-jet Production Mechanisms

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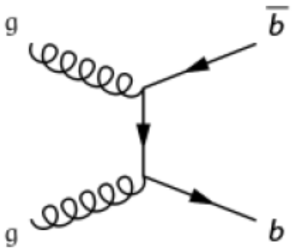

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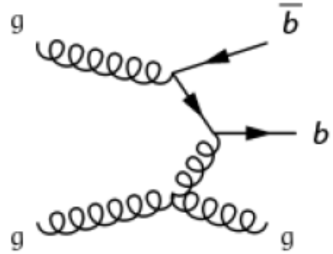

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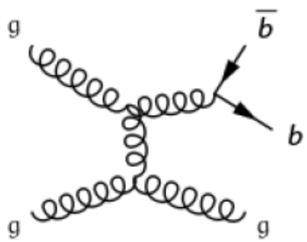

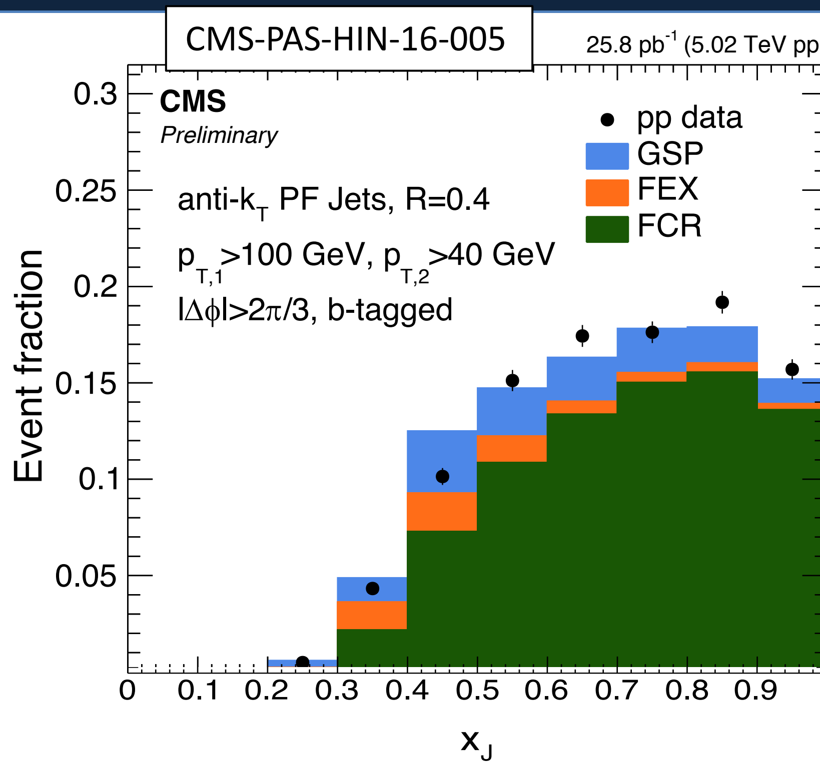

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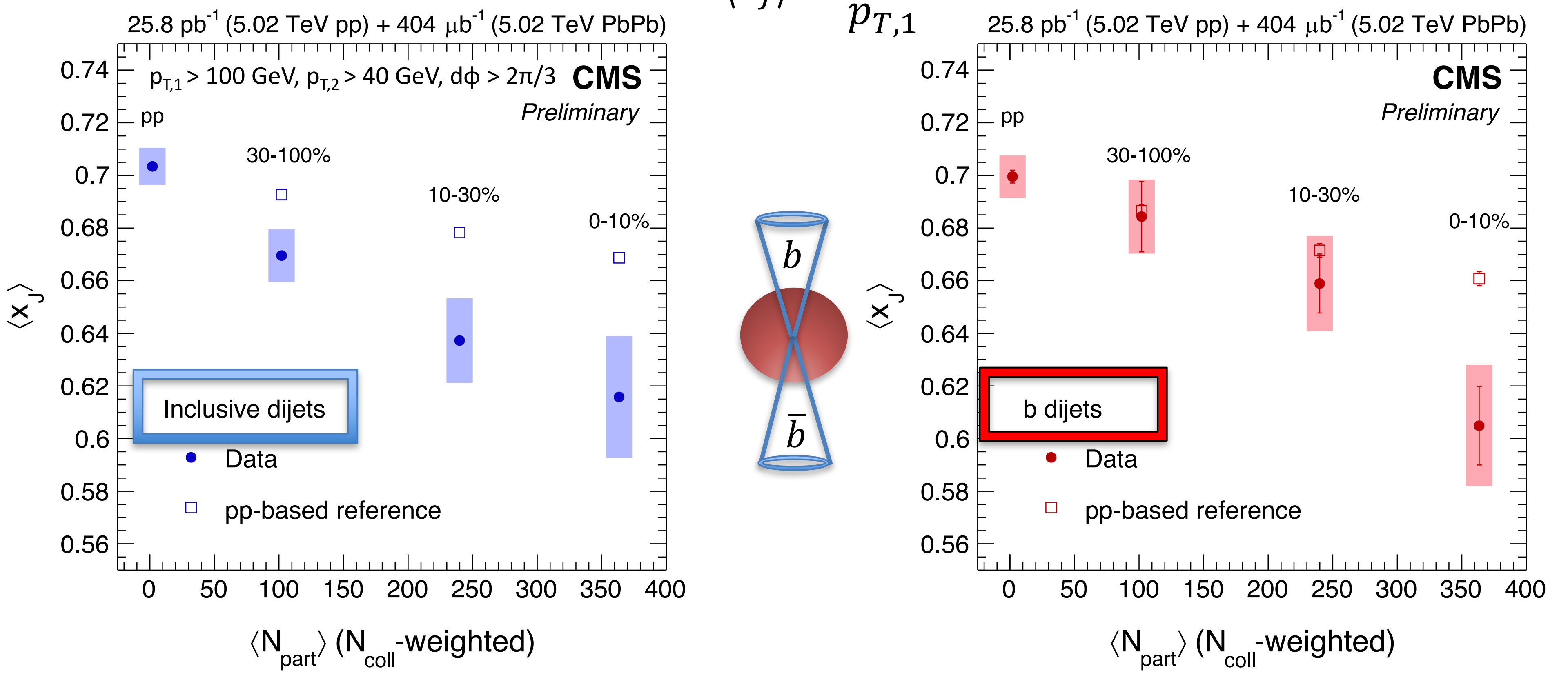
Toward more sensitive observables

CMS-PAS-HIN-16-005

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

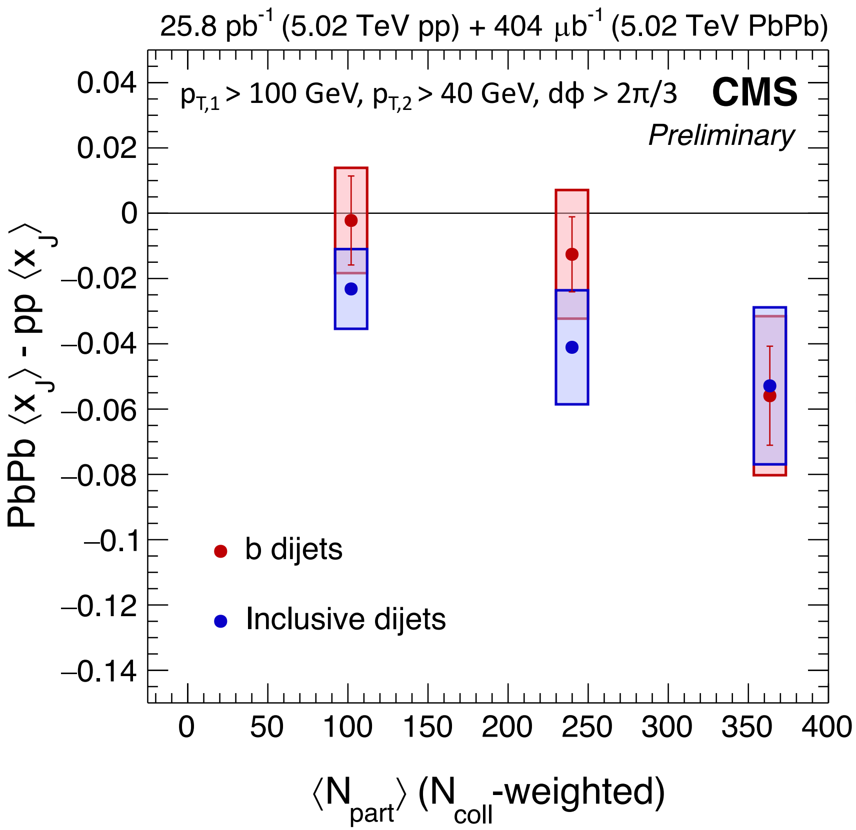


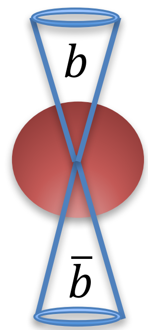
- b dijet R_{AA} removes ambiguity regarding production mechanisms
- Probes **leading-order** jet production component

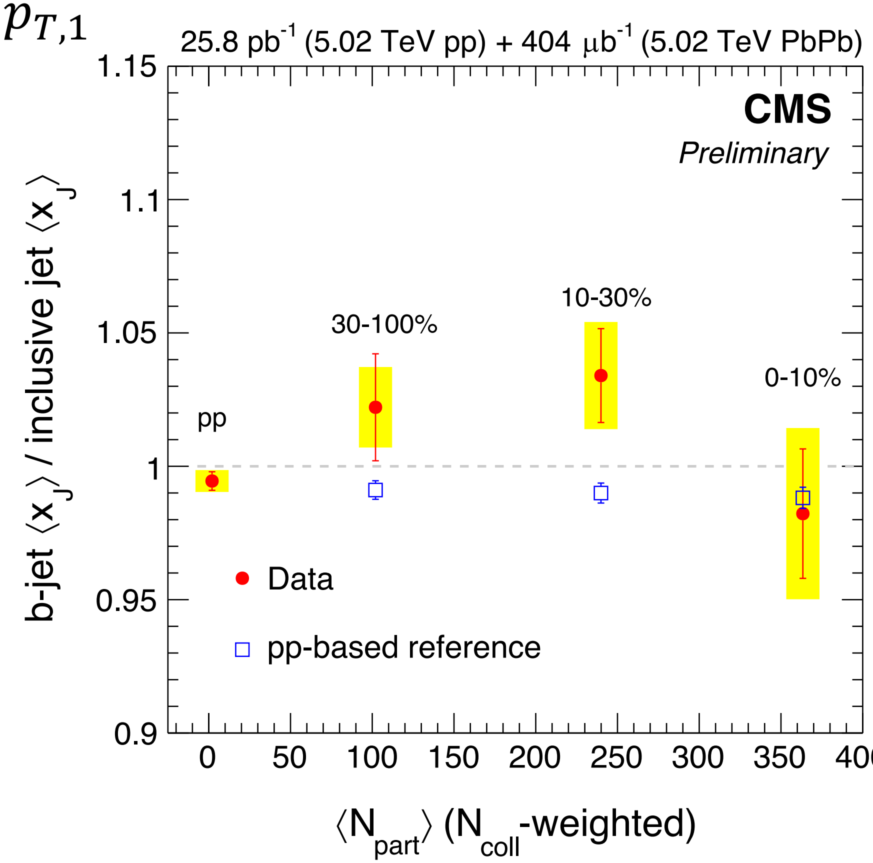
b Dijets

CMS-PAS-HIN-16-005

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

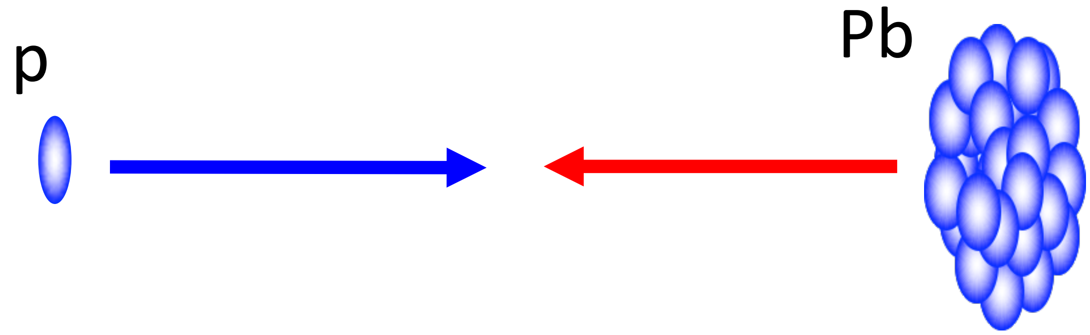






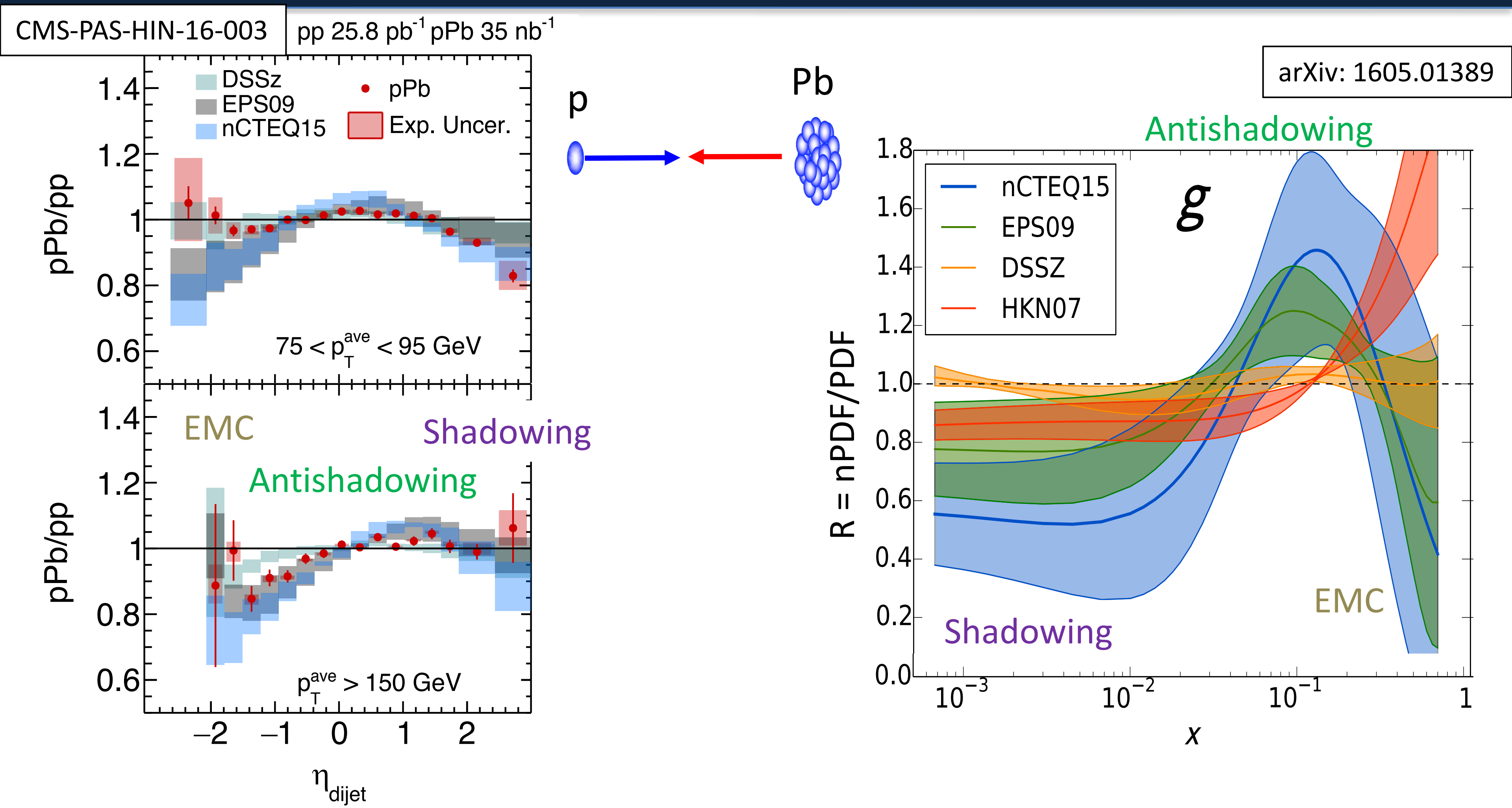
- Observe modification consistent with inclusive-jet measurements
- Directly comparing b dijet/inclusive dijet PbPb shows virtually no effect as a function of centrality

Proton-Lead Collisions



- Probe initial-state effects for flavored objects at high-p_T
  - Allow for future factorization of these effects in PbPb
  - Theoretical predictions can be further constrained by flavor-dependent energy-loss measurements
  - Do flavor dependencies of CNM effects exist at high-p_T?
- Additional possibilities to probe the nuclear PDFs
  - Strong correlation of b-jet production to gluon nPDFs

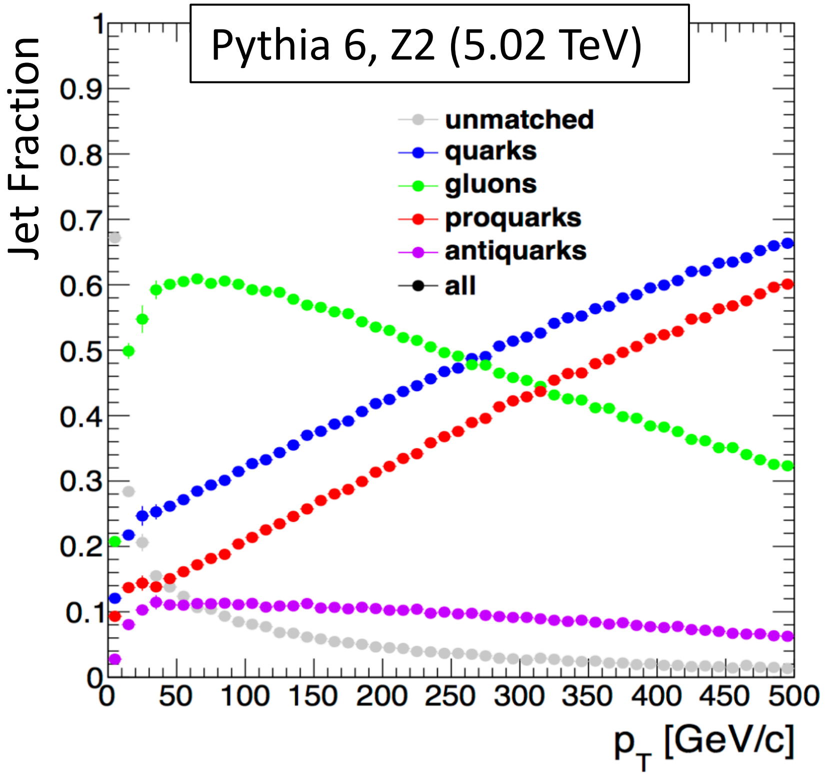
Existing nPDF probes with Dijets



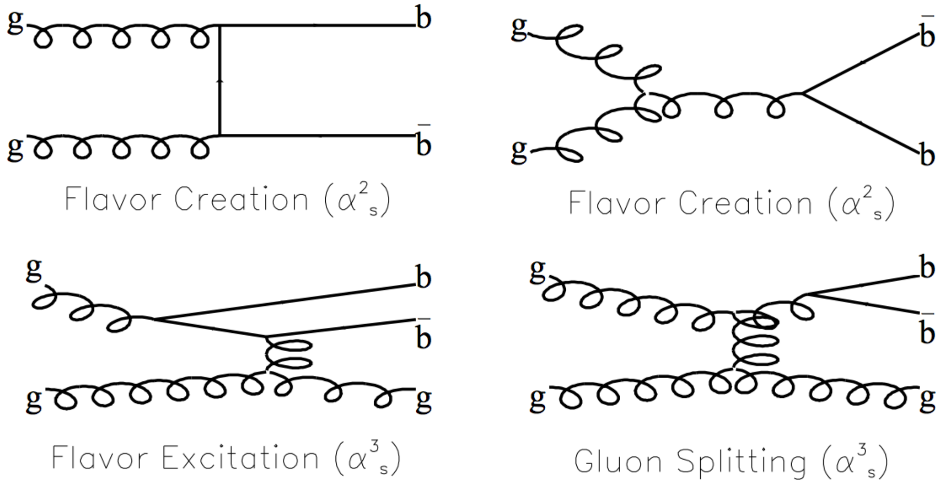
- Dijet η distributions correlate strongly with Bjorken-x
  - Measurements of inclusive-jet η_{dijet} can constrain nPDFs

b & c-jets: A good probe of <u>gluon</u> nPDFs

Inclusive jet production types



B-jet production types (gg prod. only)

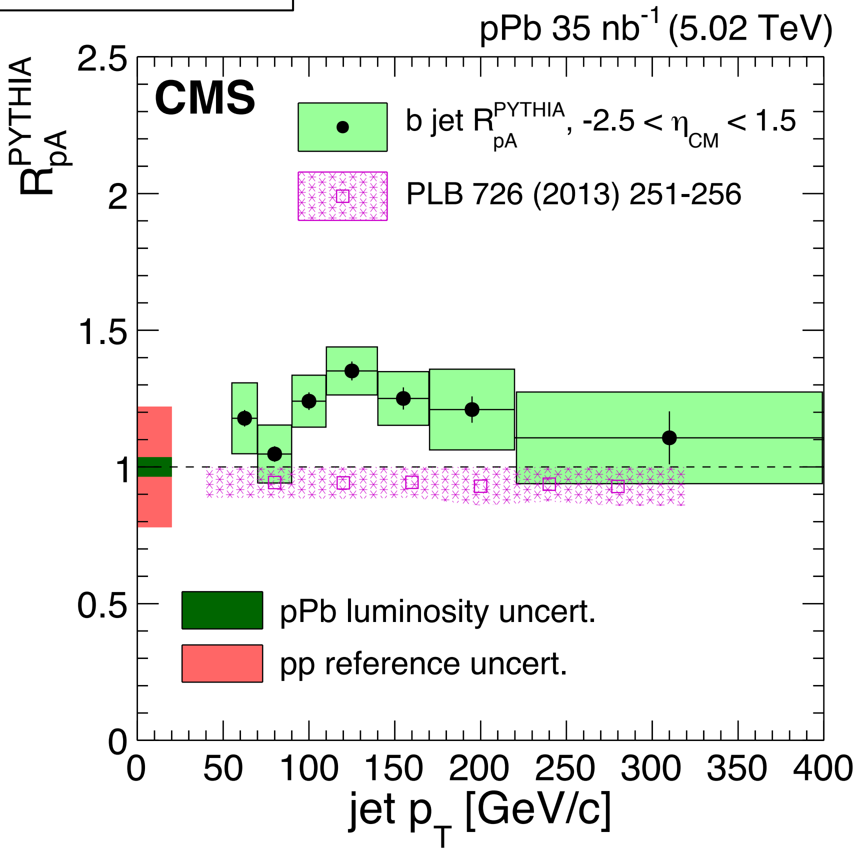


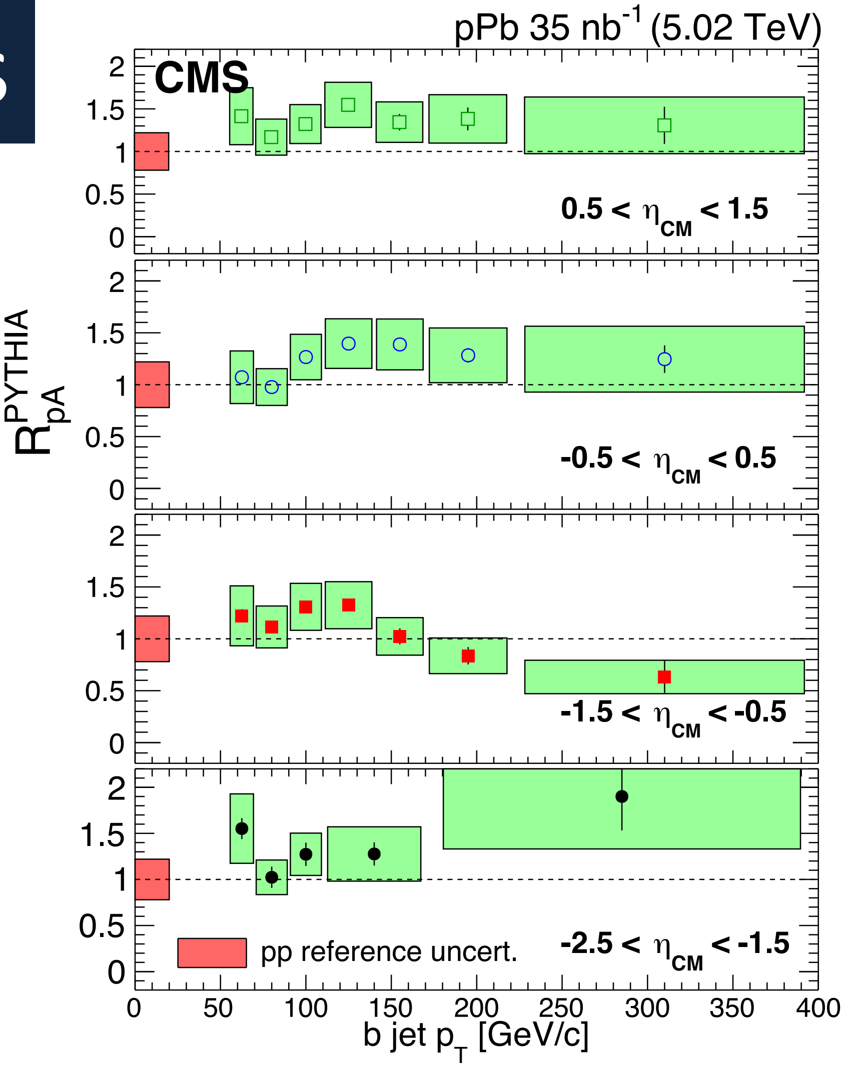
arXiv: hep-ex/0412006

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

b-Jets in pPb Collisions

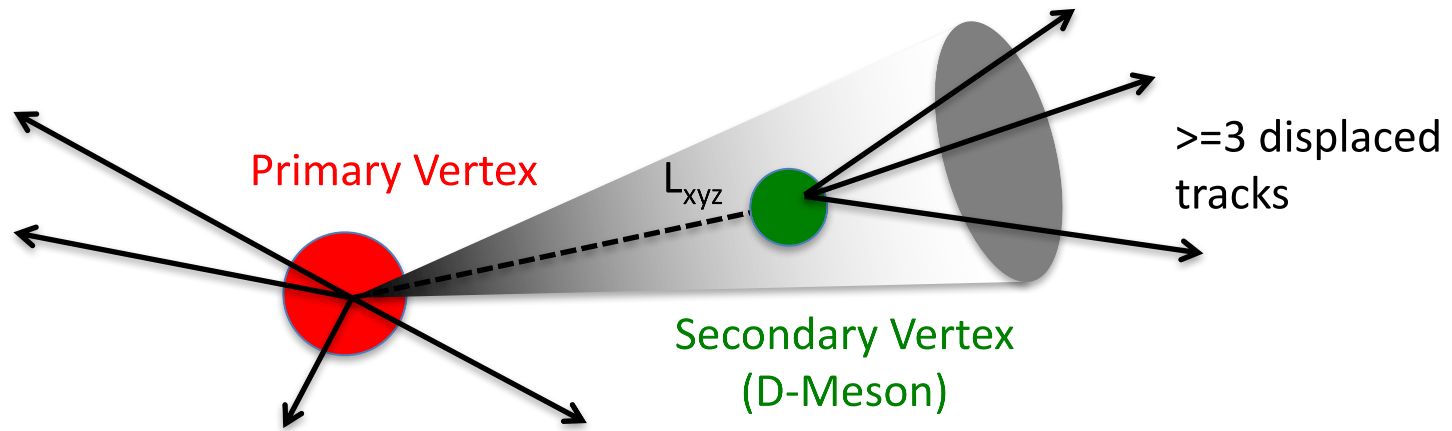
arXiv: 1510.03373





- 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!

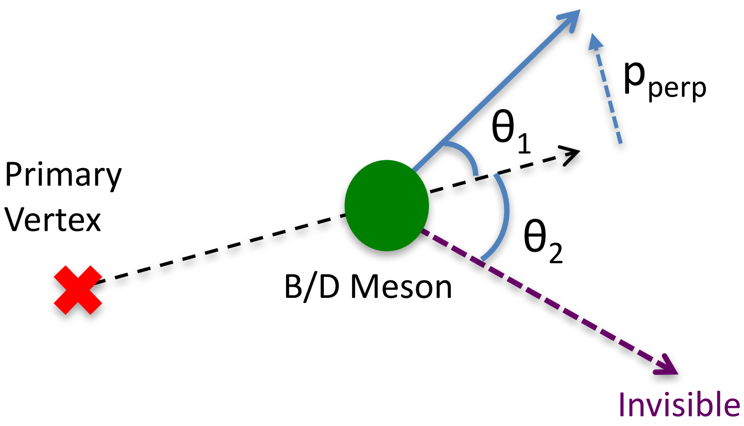
Identifying Charm Jets



- Impose tight selections on secondary vertex decay to increase c-jet tagging efficiency
  - b jets use simple 2+ track vertexing algorithm
  - Charm tagging requires 3+ track secondary vertex, (<65% of tracks shared with PV)
  - 3+ track vertices dominated by heavy flavored (b/c) jets

Corrected Secondary Vertex Mass

arXiv: 1504.07670



$$p_{1,CM} = p_{\upsilon,CM}$$

$$p_{1,lab}\sin\theta_1 = p_{\upsilon,lab}\sin\theta_2$$

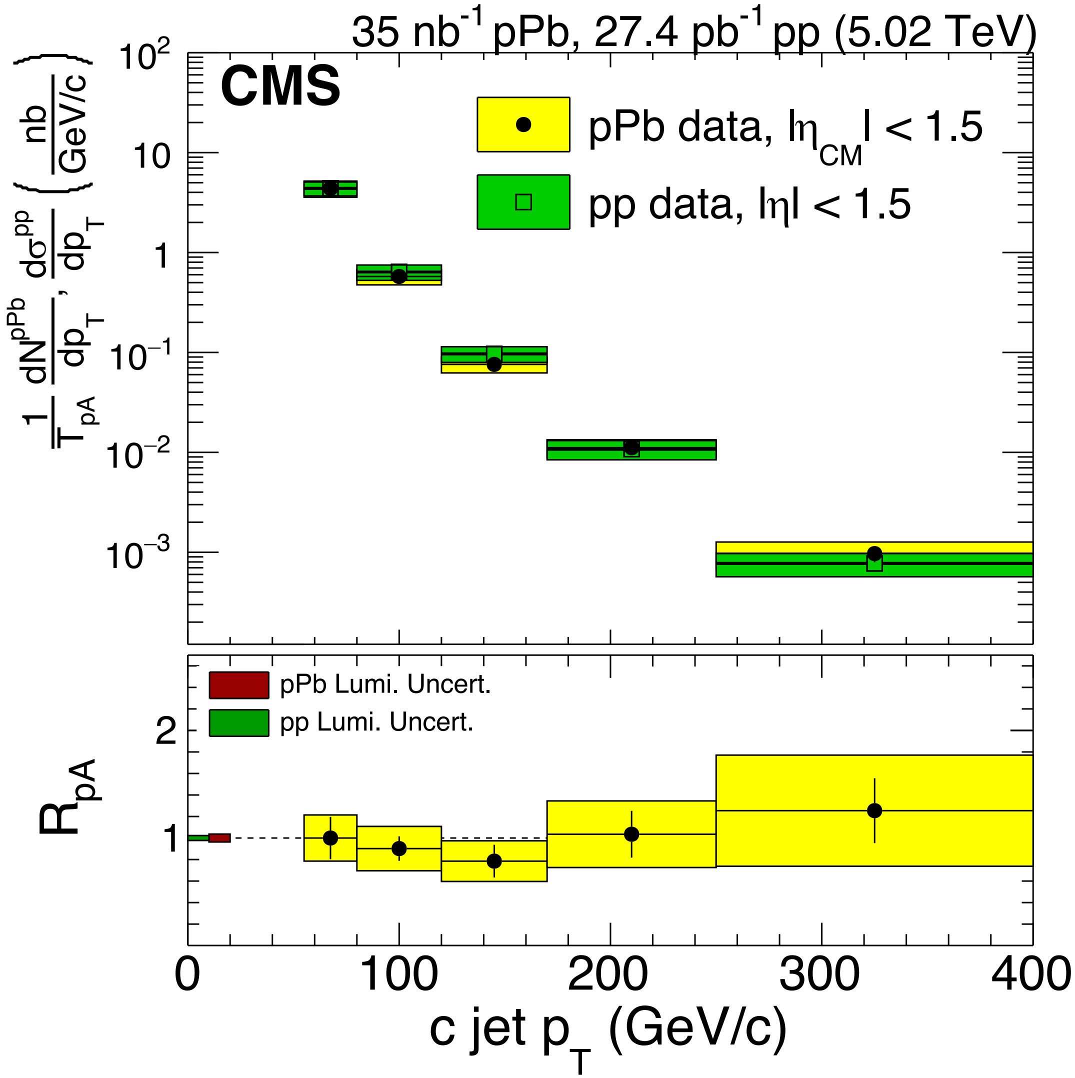
$$M_{corr} = \sqrt{M_1^2 + p_1^2} + \sqrt{M_\upsilon^2 + p_\upsilon^2}$$

= 0 (min)

$$M_{corr}(\min) = \sqrt{M_1^2 + p_1^2\sin^2\theta_1} + p_1\sin\theta_1$$

- M_{corr} = Minimum secondary vertex mass that is consistent with the vertex flight direction
- Attempts to restore p_{perp} balance from missing energy with respect to flight direction (from e.g. ν, π^0, etc.)
- B hadrons have higher p_{perp} (on average) than C hadrons
  - B's have statistically larger values of M_{corr}

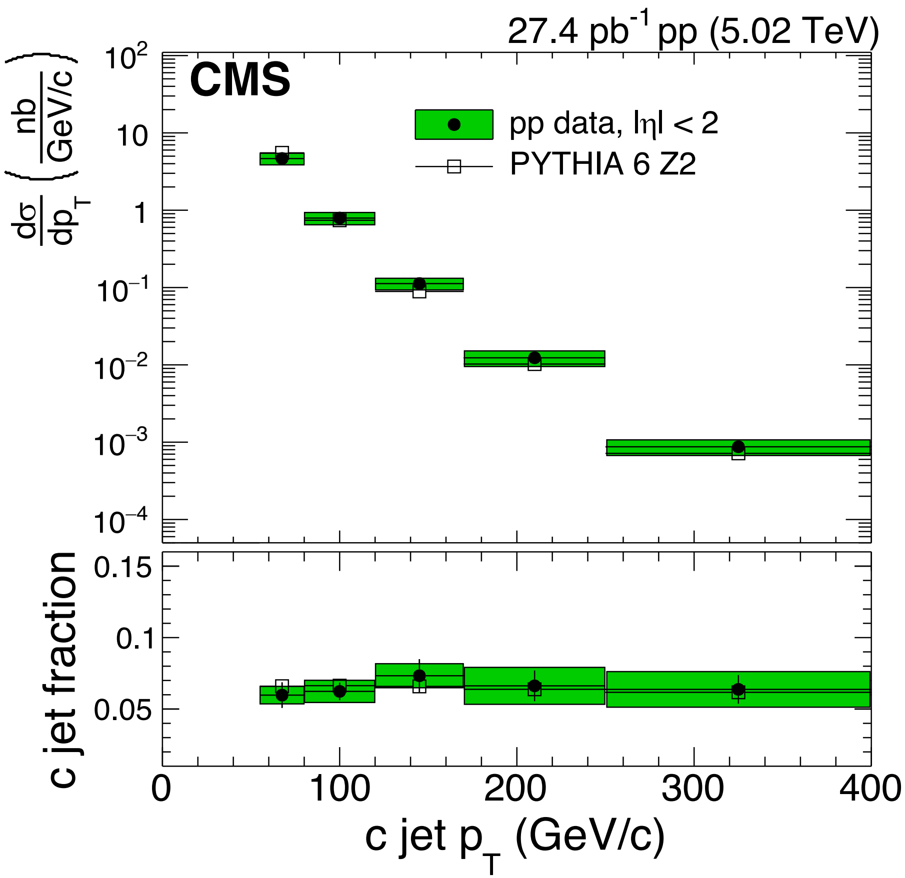
Charm-Jet Spectra

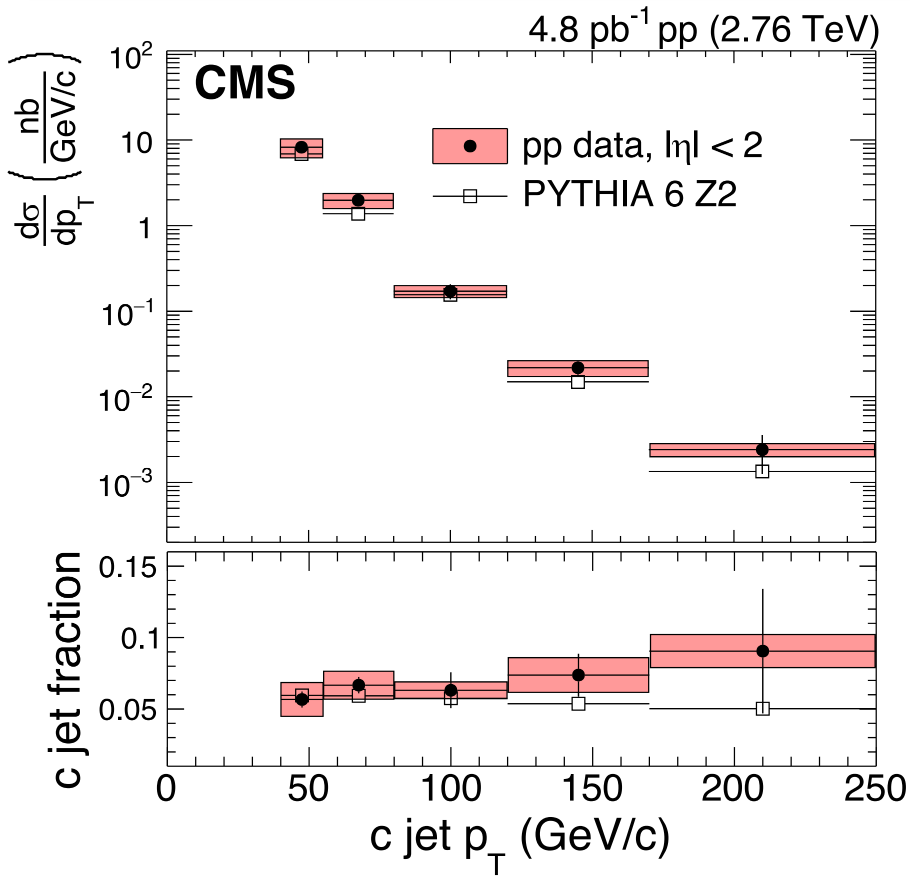


- First measurement of an inclusive charm-jet cross-section
- Observe consistency of charm-jet spectra in pPb relative to pp within uncertainties

arXiv: 1612.08972, PLB to appear

Charm-Jet Fraction

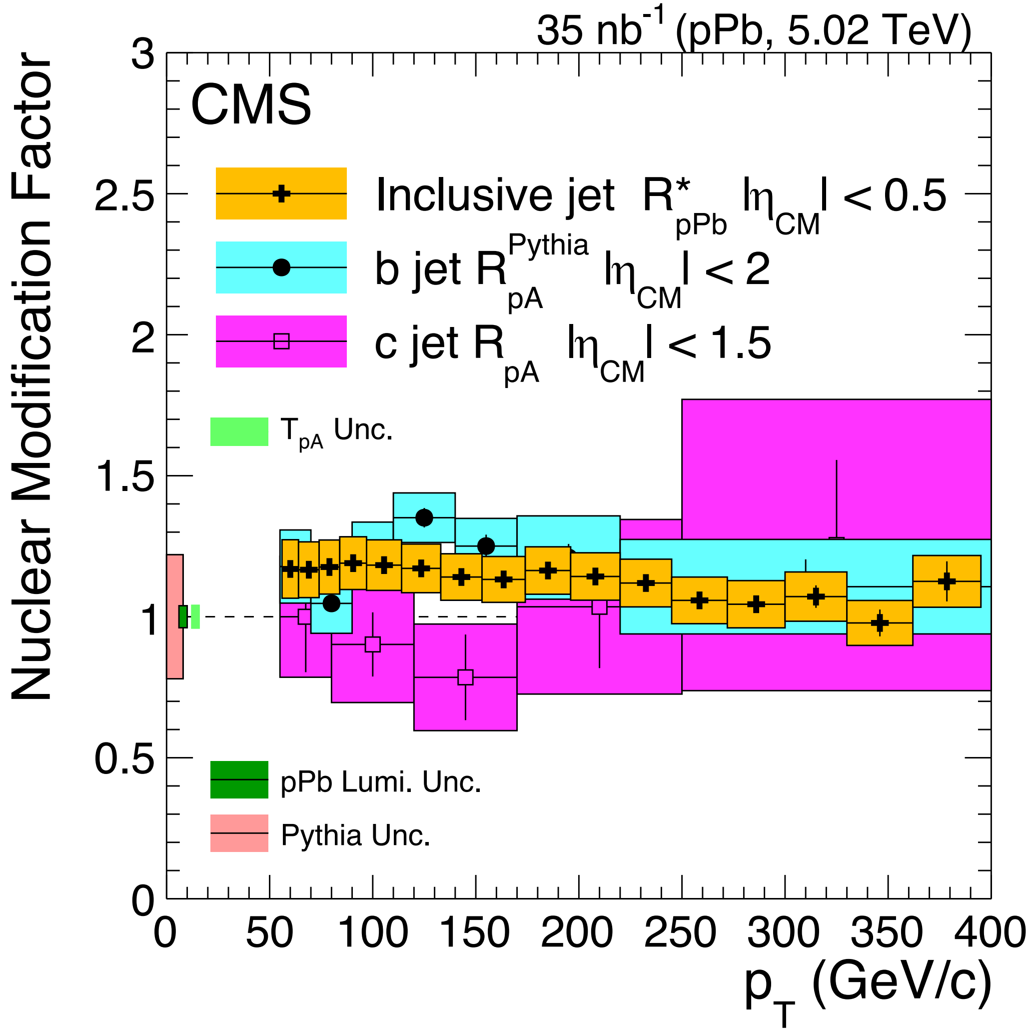




- Very minor sqrt(s) dependence on c-jet fraction
  - High-p_T excess in 2.76 TeV consistent within statistical uncertainties

arXiv: 1612.08972, PLB to appear

R_{pA} for heavy+light flavors



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

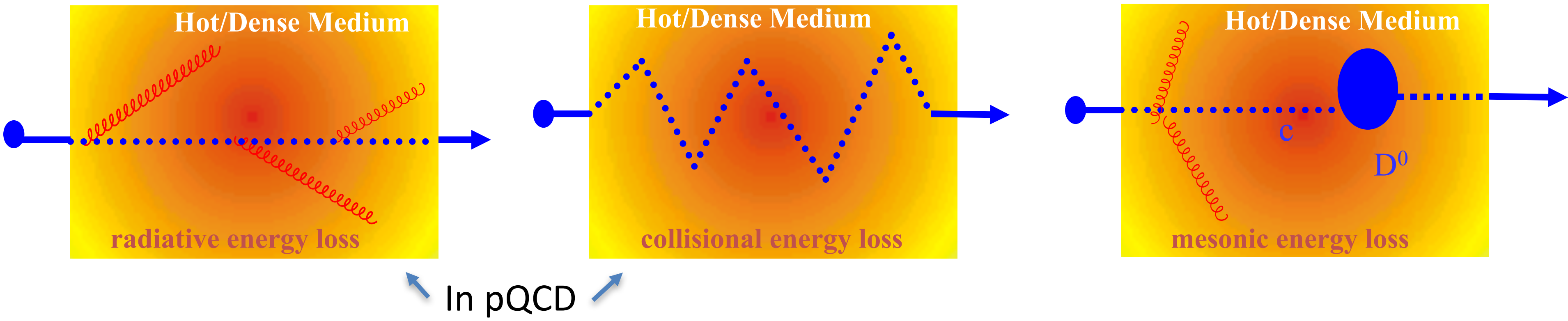
- All jet samples are consistent with one another
- No indications of flavor-dependent nPDF effects within uncertainties

Conclusions

- Dijet asymmetry similar for b-jets and inclusive jets, consistent with similar quenching magnitude
- Charm jets measured for first time in heavy-ion (pPb) collisions
  - R_{pA} values consistent with unity
- Future studies will:
  - Use b/c-tagging to look for quark/gluon jet **fragmentation** differences
  - Potential to further constrain gluon nPDFs at large x with enhanced b and c-tagging methodologies

BACKUP

Energy Loss Possibilities



- Different possibilities for in-medium energy loss mechanisms
  - Heavy quarks suffering **radiative energy loss** suppressed by dead-cone effect
  - **Collisional energy loss** affected by forced radiation from acceleration in collisions
  - **Mesonic energy loss** affected by modified meson dissociation probabilities (shorter meson formation time)
- These three energy loss mechanisms all depend on the quark masses *differently*

Calculating the b-jet Fraction

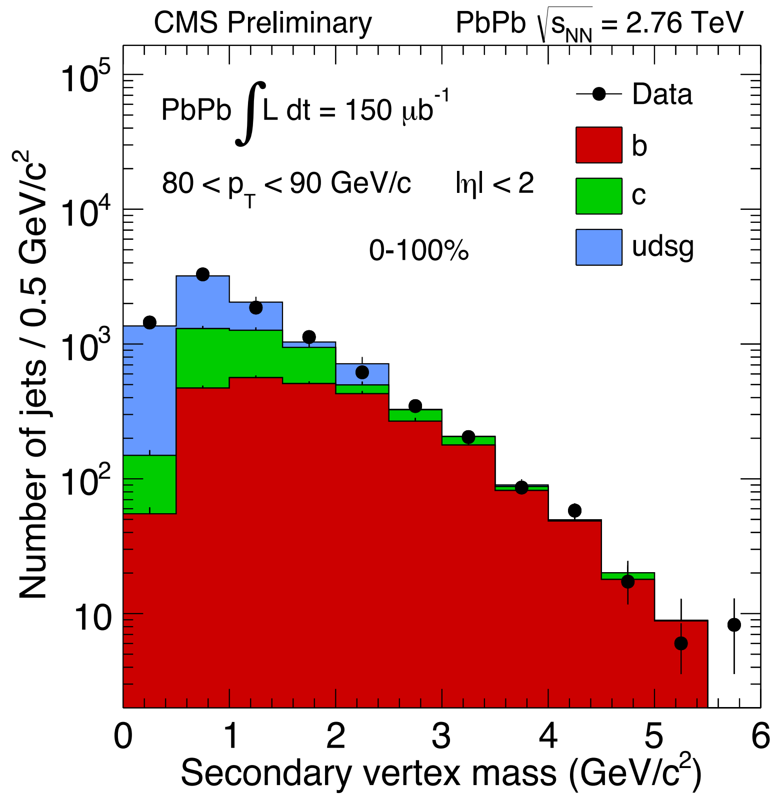
$$\varepsilon_b = \frac{C_b f_b^{btag} N_{jets}^{btag}}{f_b^{untagged} N_{jets}^{untagged}} \quad [1]$$

$$N_{jets}^{b} = N_{jets}^{total} \frac{f_b^{btag}}{\varepsilon_b} \quad [2]$$

f_b = b-tagging purity
ε_b = b-tagging efficiency
C_b = Fraction of jets with tagger information

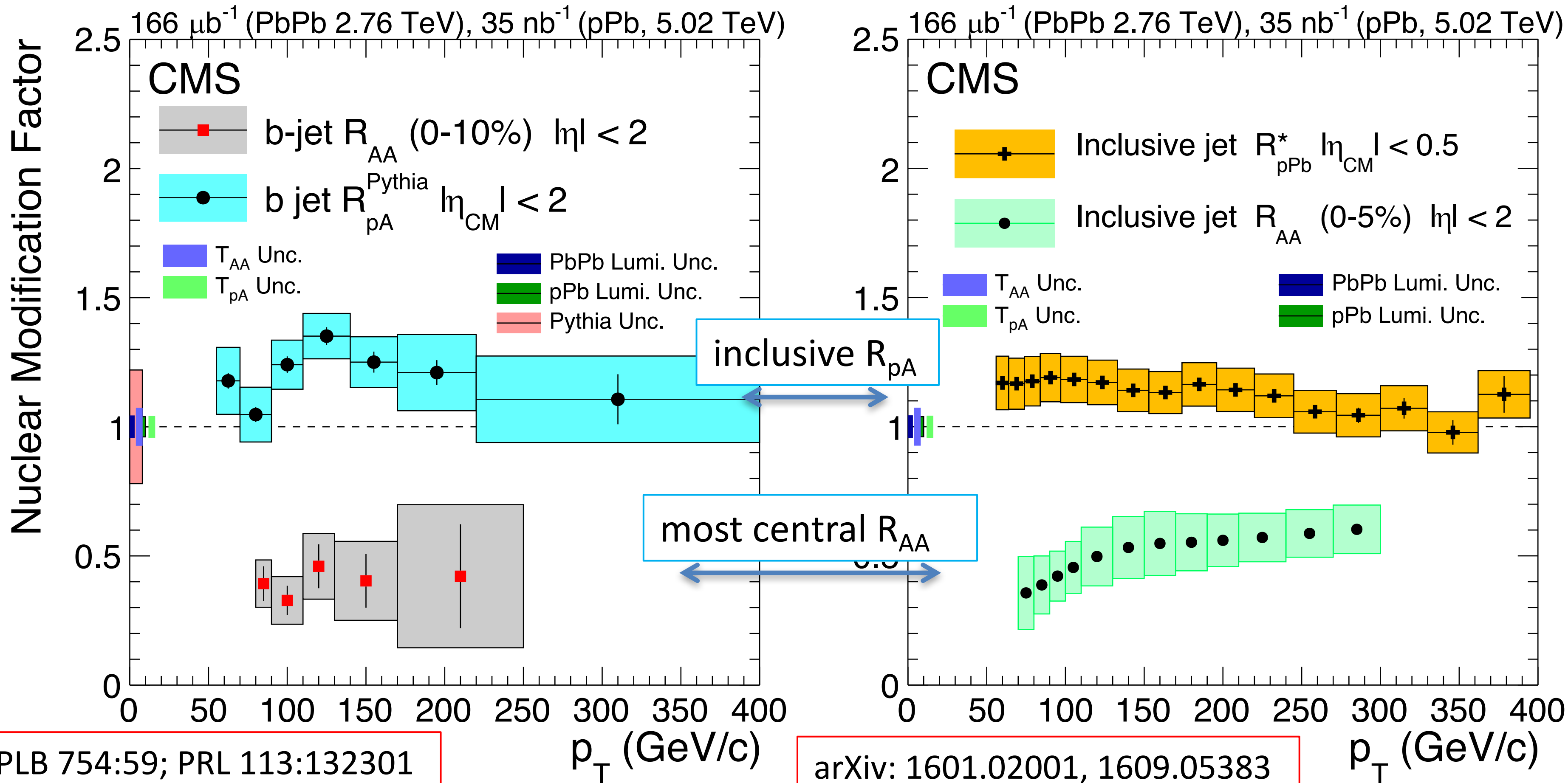
$N^{untagged}$ = All jets
$f_b^{untagged}$ = B-tagging purity of total jet sample

- Purity calculated via template fits to secondary vertex mass
- Efficiency calculated using template fittings both before and after flavor tagging [Eq. 1]
- Efficiency and purity are used to find the number of total b-jets in the sample [Eq. 2]



PRL 113:132301 (2014)

Comparison to Inclusive-Jets

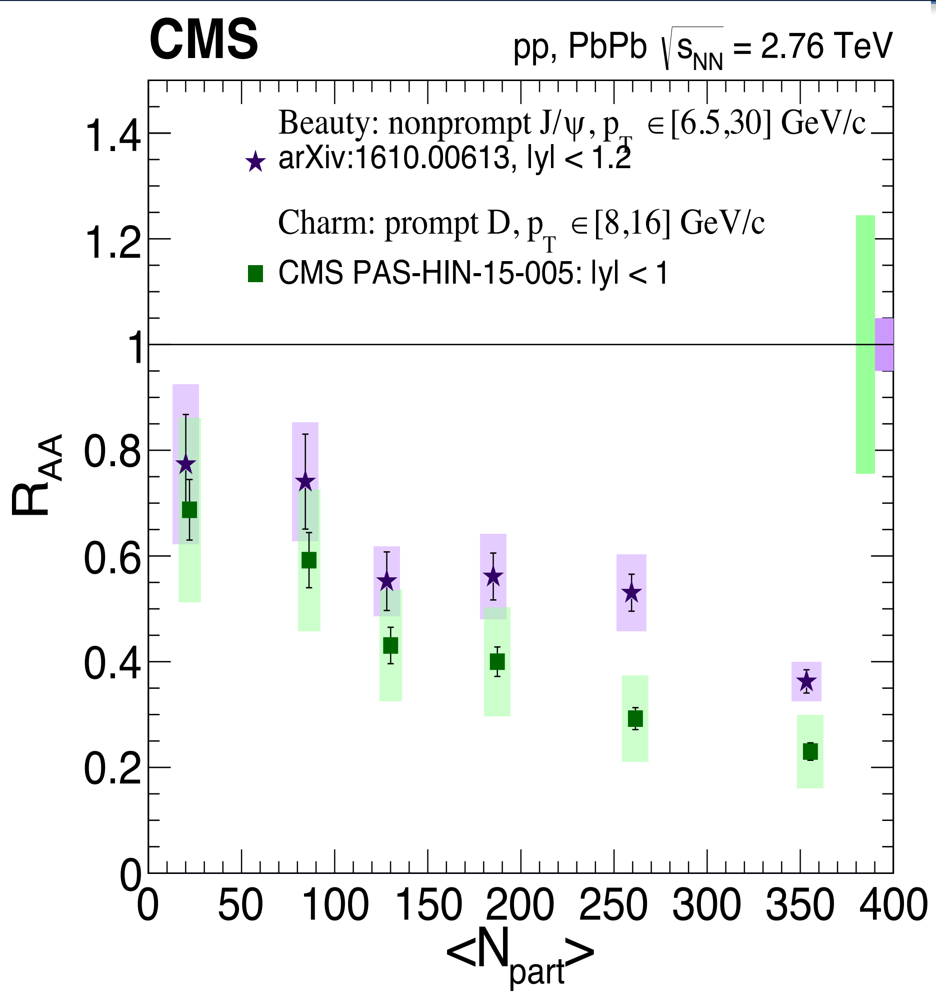


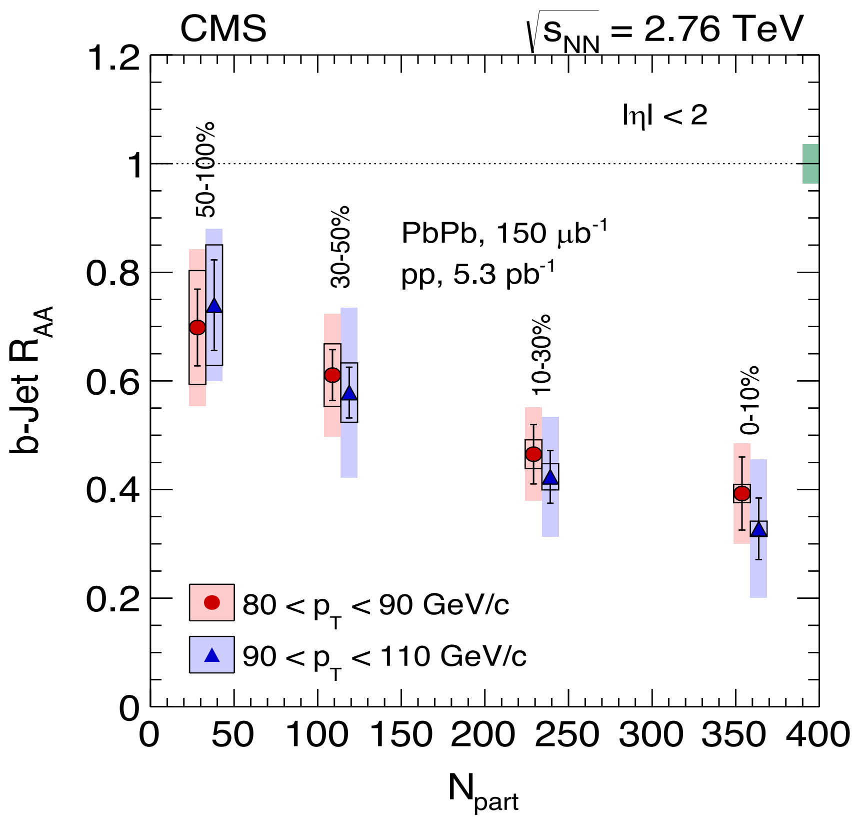
PLB 754:59; PRL 113:132301

arXiv: 1601.02001, 1609.05383

- So far, the story is the same
  - B-jets show similar trends as do light jets across collision species and collision energy

Comparison to Mesons

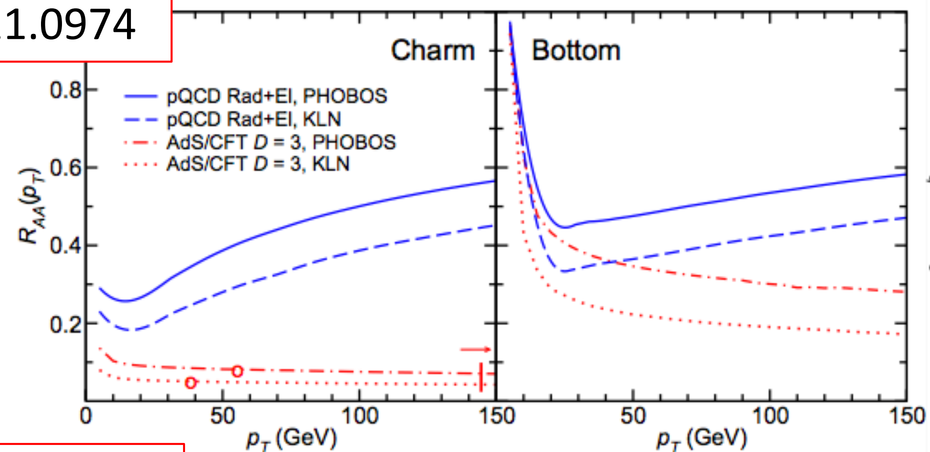


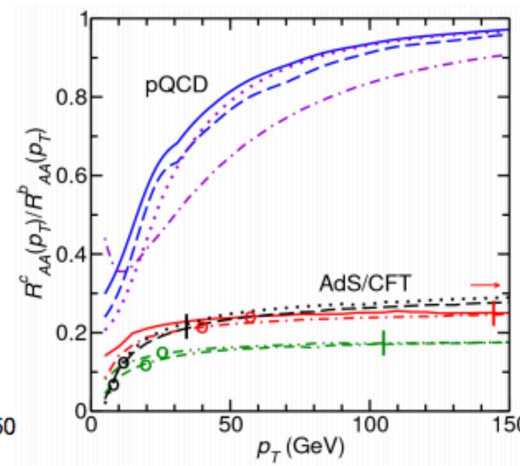


Open beauty measurements show consistent suppression vs Npart
(for mid-pT B-Mesons)

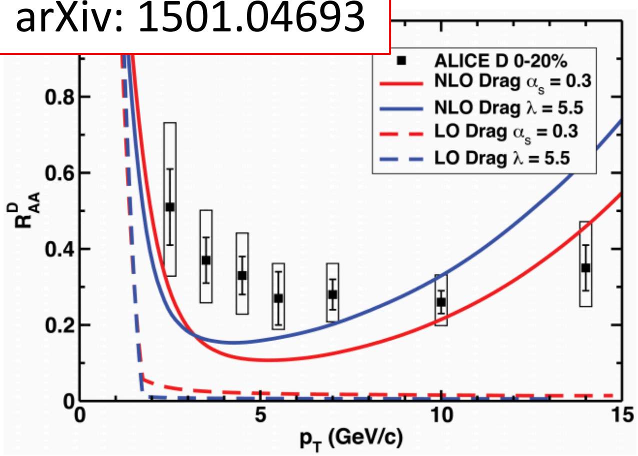
AdS/CFT Models "Need More Work"

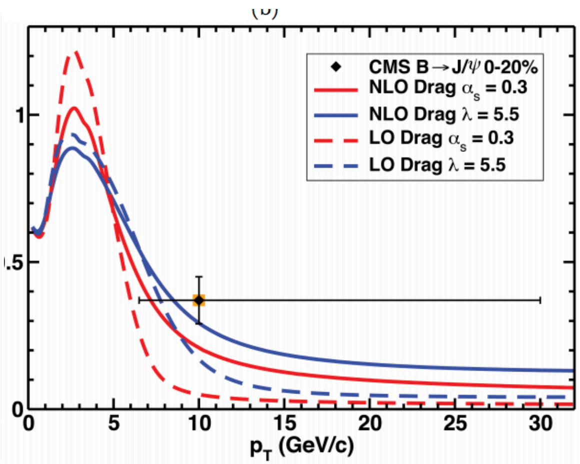
arXiv: 0711.0974

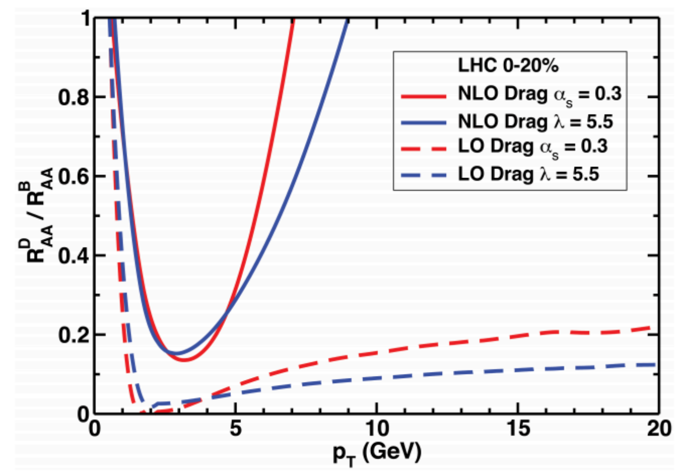




arXiv: 1501.04693

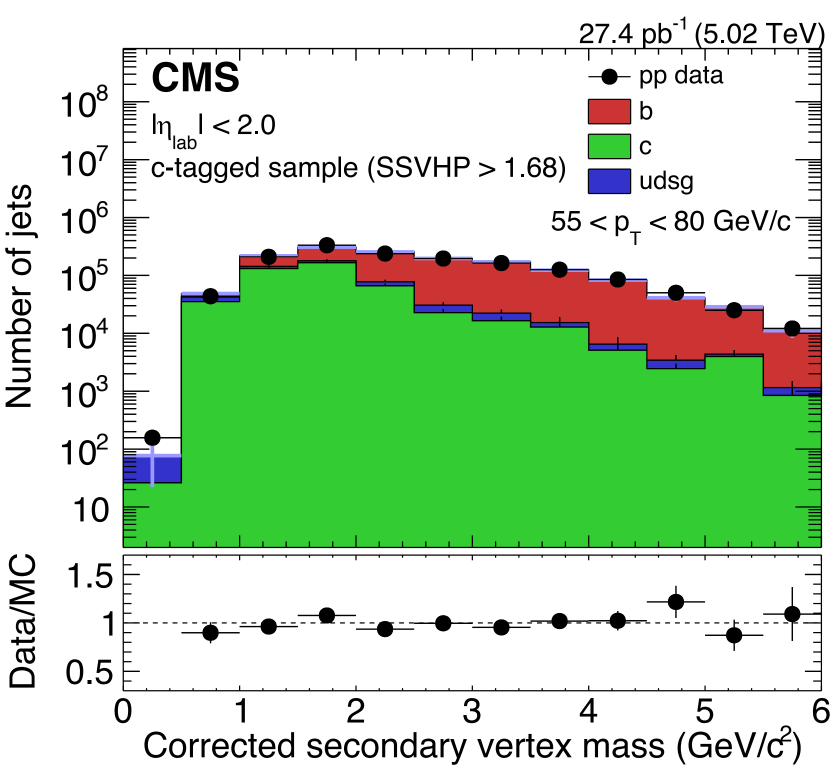


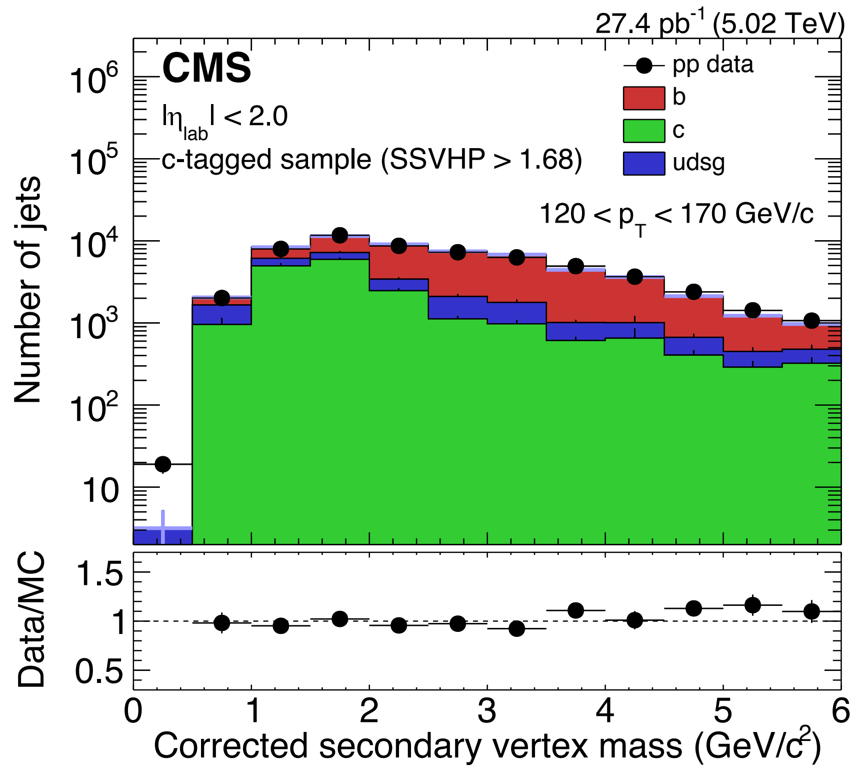




- Previous LO AdS/CFT predictions showed very different behavior for b/c jet RAA.
  - New addition of NLO effects limit applicability of these claims

Corrected Secondary Vertex Mass





- M_{corr} provides additional discrimination power between light/charm/bottom jets than does pure secondary vertex mass
- Shapes between bottom and charm different for M_{corr}