Heavy Flavored Jet Measurements using the CMS Detector

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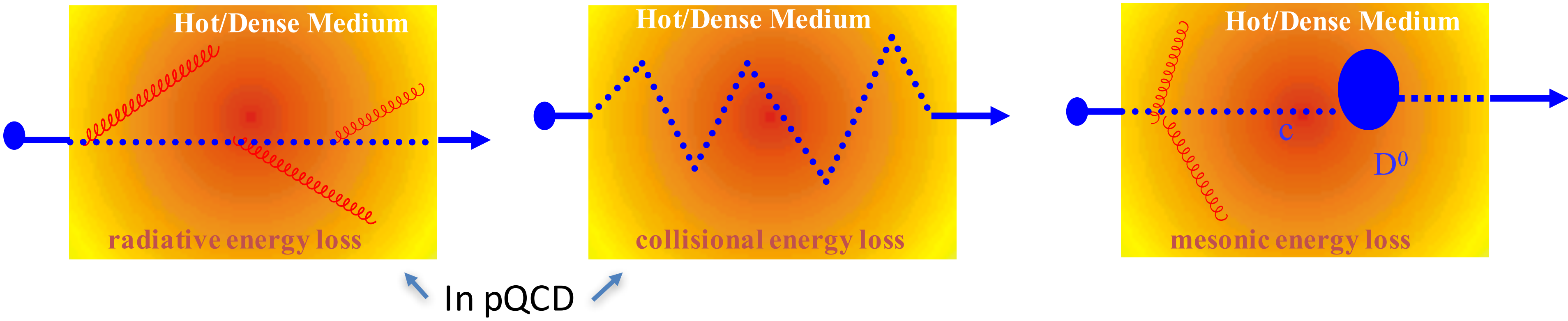
Motivation for Flavored Jets

- **In Lead-Lead collisions**: Observation of flavor-dependent energy loss?
  - Differences in quark-plasma interactions based on quark mass differences?
  - 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**: 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?

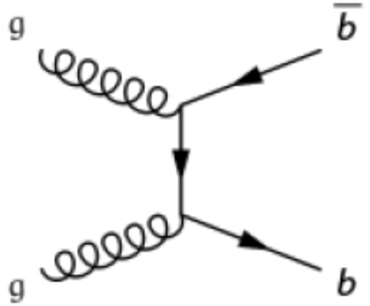
Energy Loss Possibilities



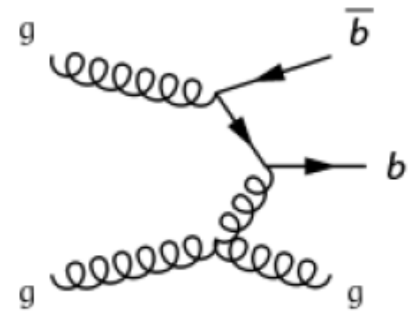
- Different possibilities for in-medium energy loss mechanisms
  - Heavy quarks suffering **radiative energy loss** suppressed by dead-cone effect
  - **Collisional energy loss** affected by forced radiation from acceleration in collisions
  - **Mesonic energy loss** affected by modified meson dissociation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

b-jet Production Mechanisms

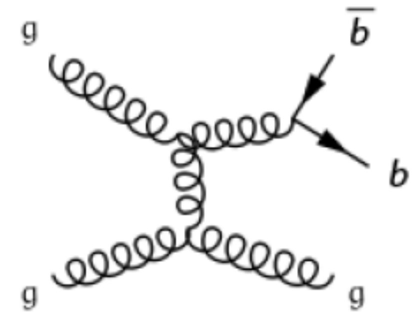
Flavor Creation (“FCR”)



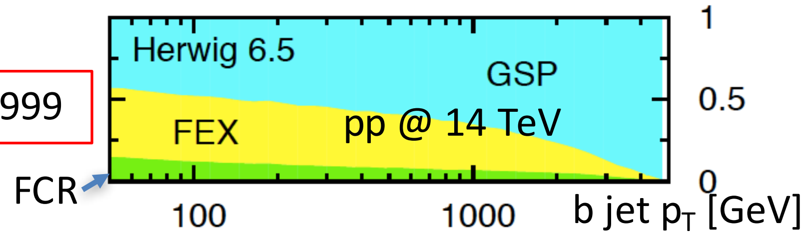
Flavor Excitation (“FEX”)



Gluon Splitting (“GSP”)

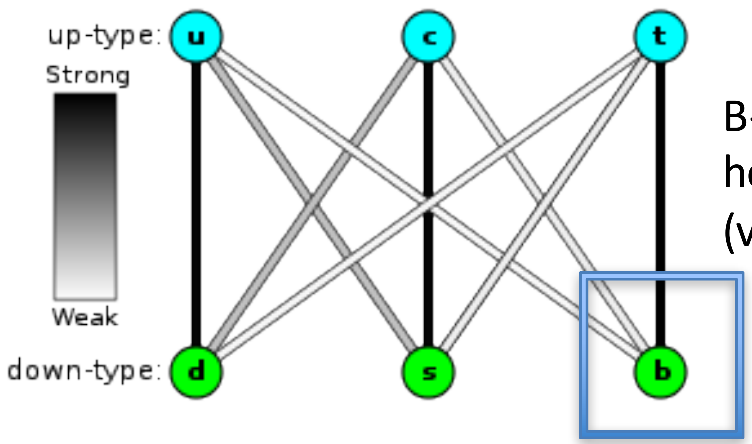


arXiv:0704.2999

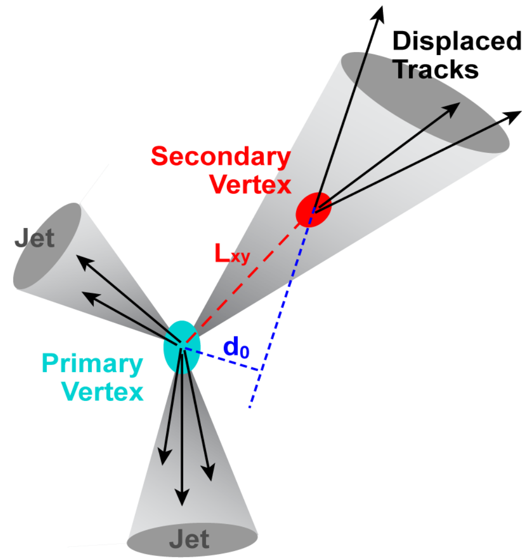


- Current flavored jet measurements do not distinguish between different production mechanisms
- Herwig (NLO) predicts large contributions from all three production mechanisms in the measured p_T range
  - Gluon can split anywhere from early to late in the collision evolution -> convolutes energy loss measurements!
- These first LHC b-jet measurement are critical starting points for the future
  - di-b-jet and b jet-hadron correlations can shed additional light

Identifying B-Jets



B-quark decays are heavily CKM-suppressed (violate CP conservation)



- Primary identification method is using a **Secondary Vertex**
  - Long lifetime of b = mm or cm vertex displacement
- Flight distance (L_{xy}) of the secondary vertex used as a discriminating variable
- Also use displacement of jet tracks (impact parameters) as a cross-check

Algorithms described in:
JINST 8 (2013) P04013

Calculating the b-jet Fraction

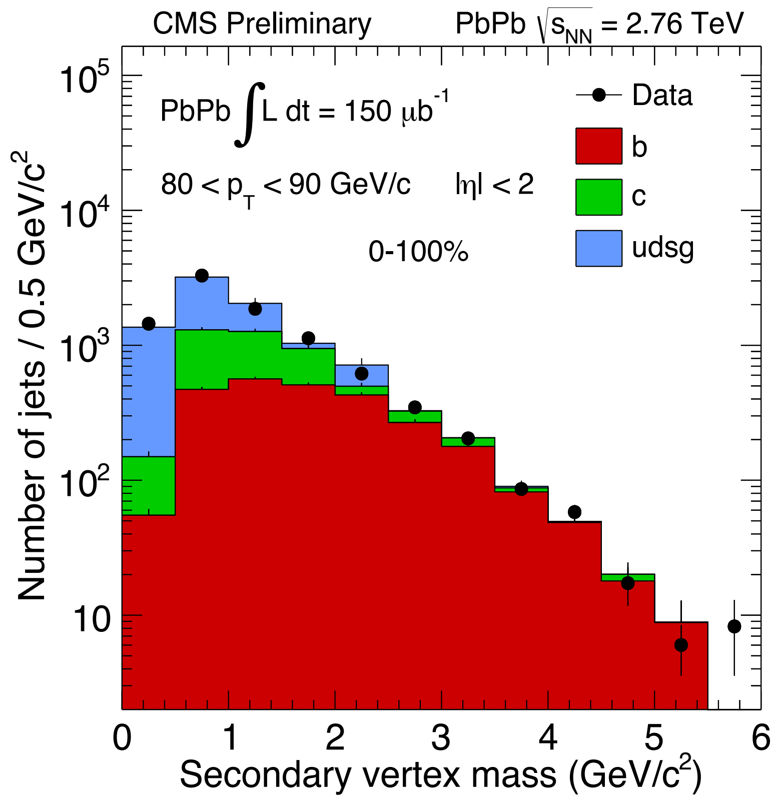
$$\varepsilon_b = \frac{C_b f_b^{btag} N_{jets}^{btag}}{f_b^{untagged} N_{jets}^{untagged}} \quad [1]$$

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

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

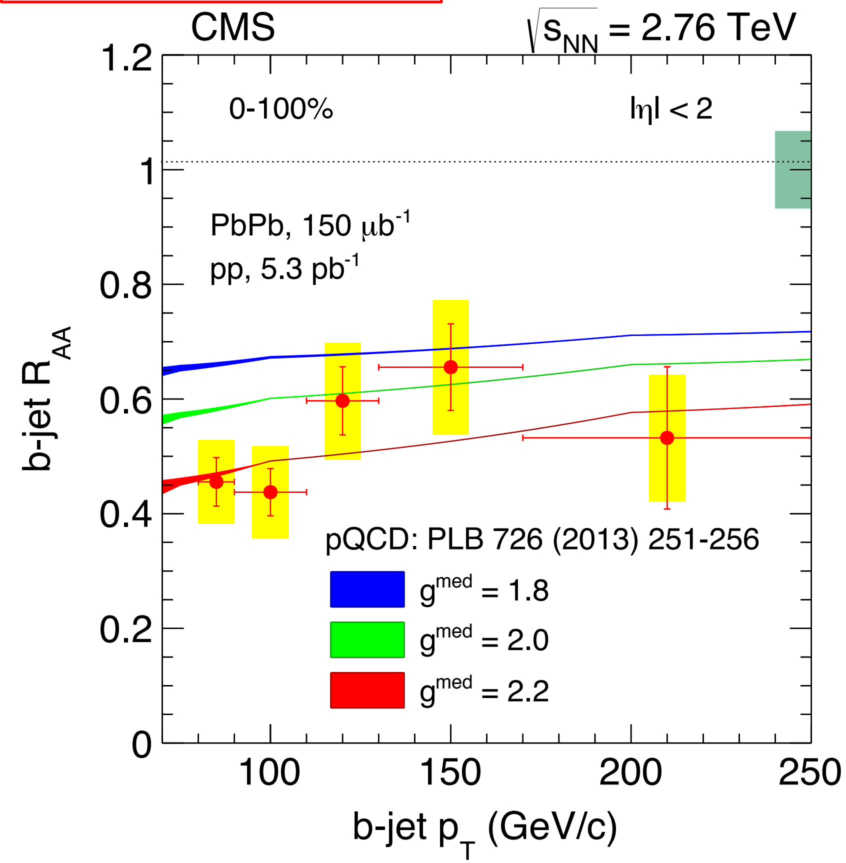
- Purity calculated via template fits to secondary vertex mass
- Efficiency calculated using template fittings both before and after flavor tagging [Eq. 1]
- Efficiency and purity are used to find the number of total b-jets in the sample [Eq. 2]

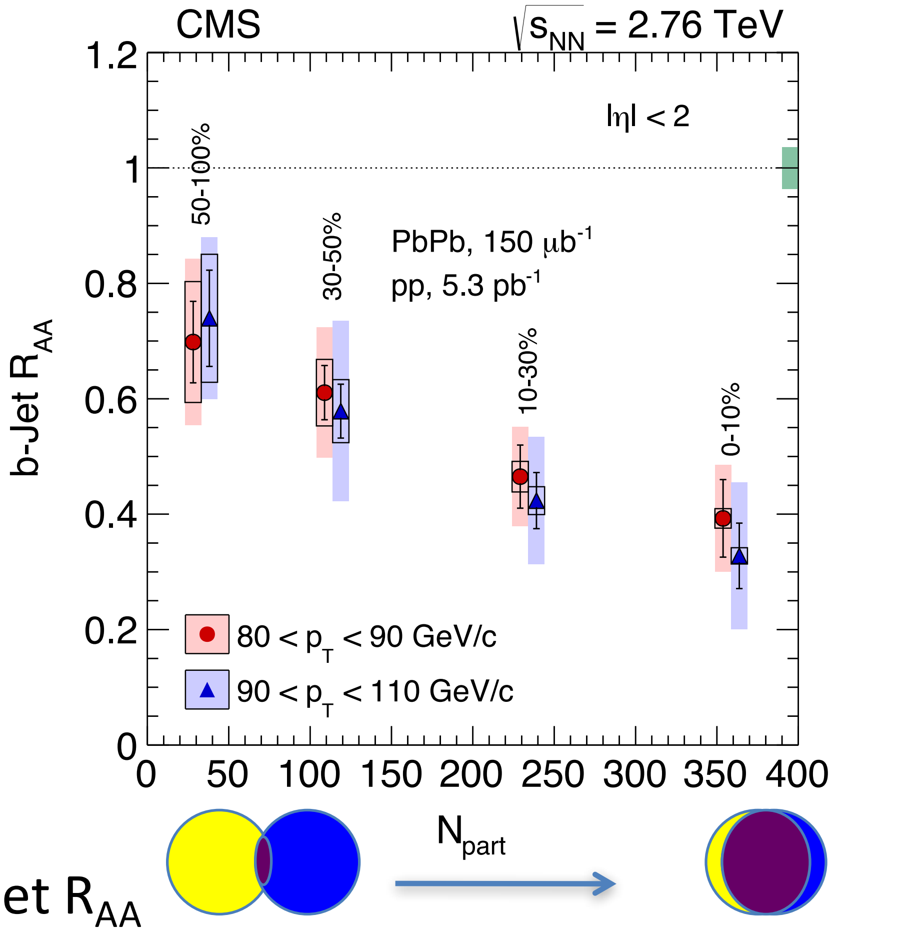


PRL 113:132301 (2014)

B-Jet R_{AA}

PRL 113 (2014) 132301



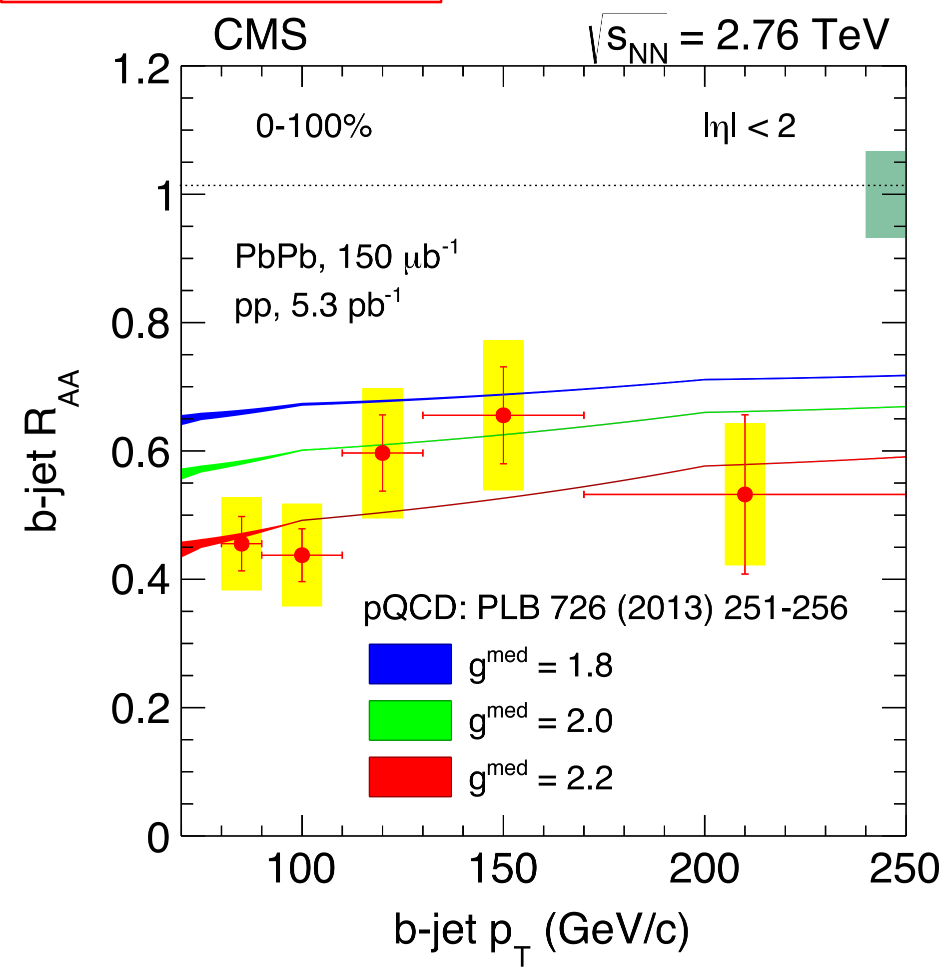


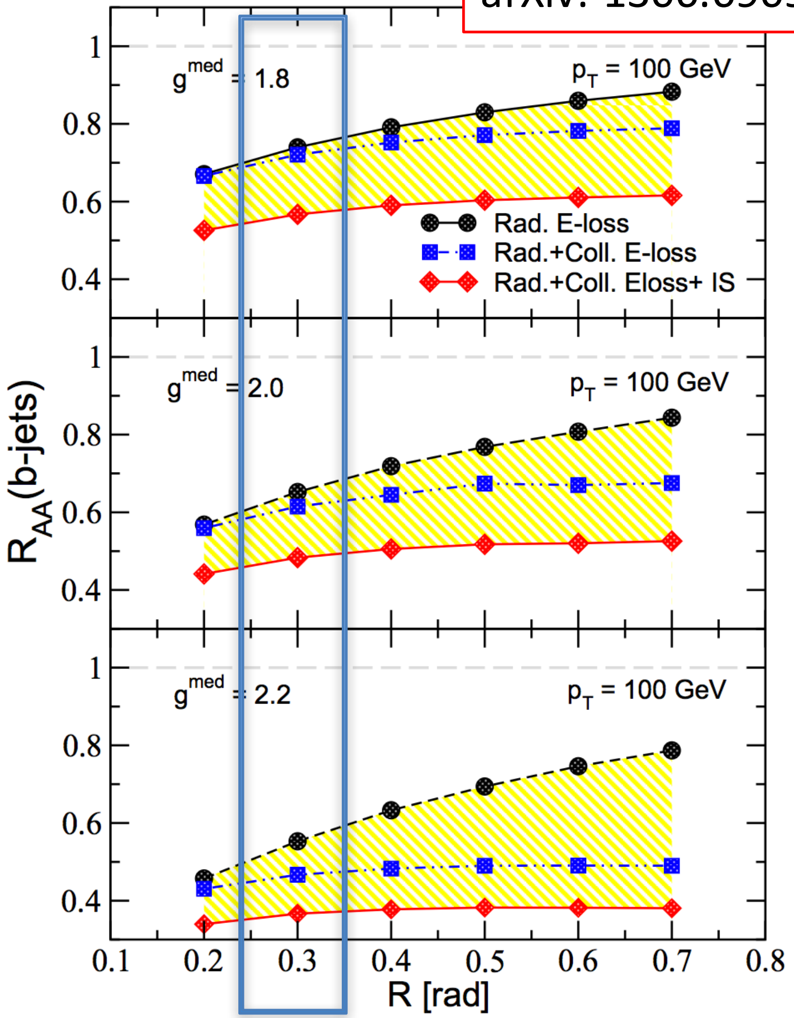
- First measurement of heavy flavor jet R_{AA}
- Clear suppression of b-jets
  - R_{AA} as a function of p_T shows significant suppression to very high p_T
  - R_{AA} shows clear trend as a function of centrality

B-Jet R_{AA}

PRL 113 (2014) 132301

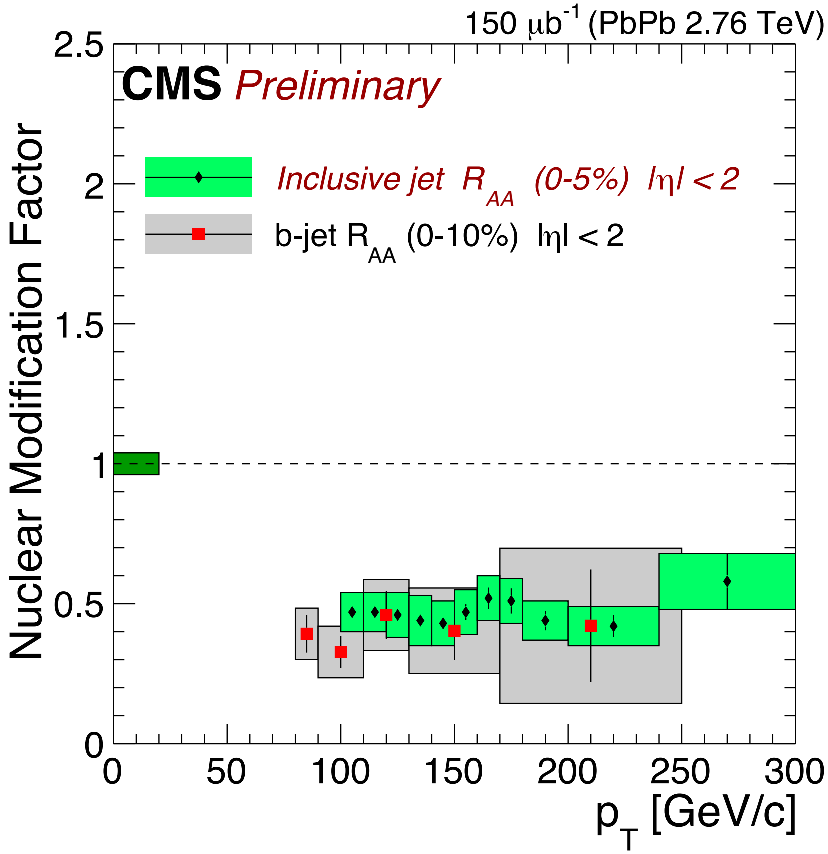
arXiv: 1306.0909





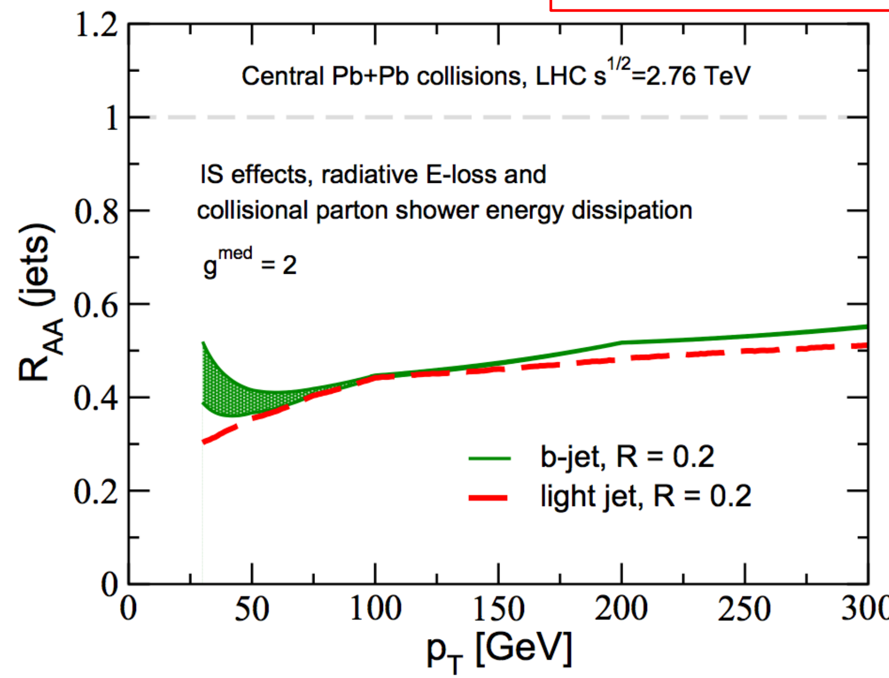
- *"Need pPb measurement* to resolve degeneracy between g^{med}=2.0 with Initial State and g^{med}=2.2 without Initial State"

Comparisons to Inclusive Jets



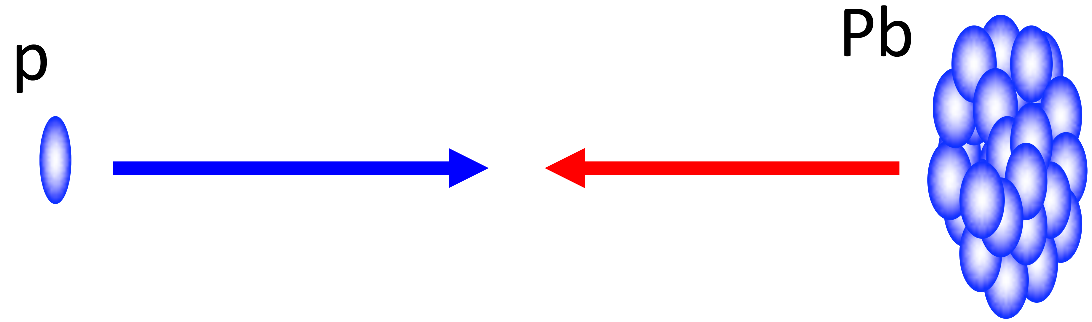
CMS PAS HIN-12-004 | PRL 113:132301 (2014)

arXiv: 1306.0909



- B-Jet suppression (0-10%) is consistent with inclusive jet (0-5%) suppression to within systematic error
- Systematics between inclusive and b-tagged jets are mostly uncorrelated

Proton-Lead Collisions

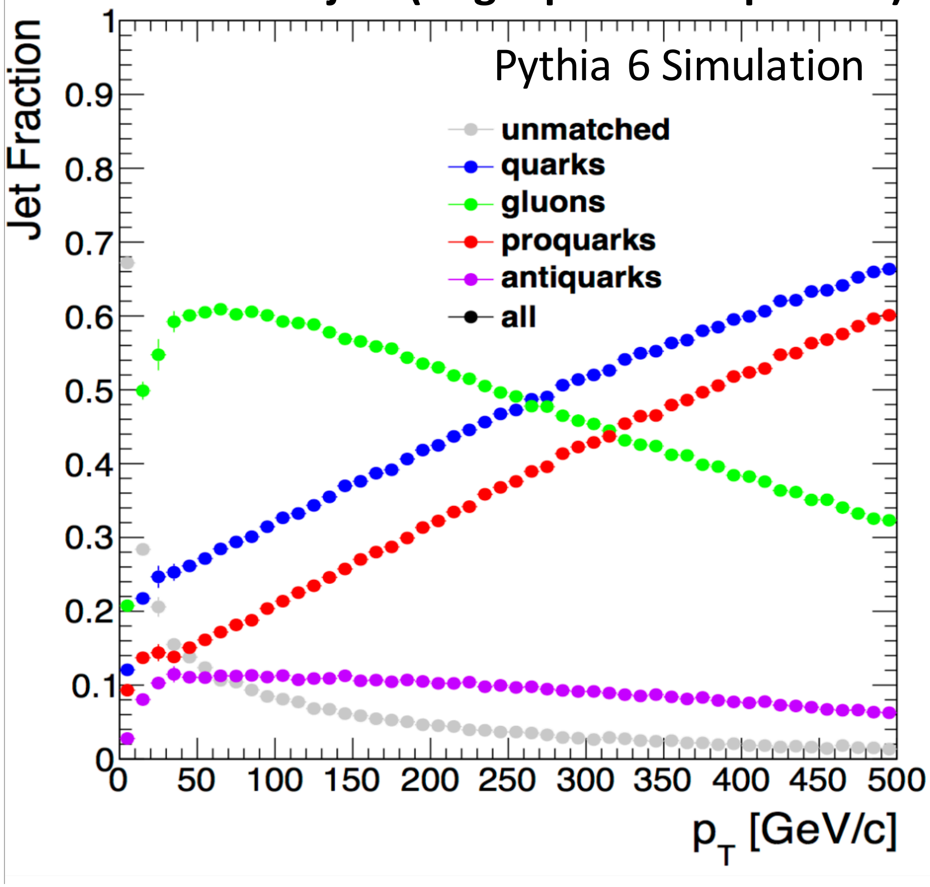


- Quantification of the initial-state effects for heavy-flavor objects at high-pT
  - Allow for future factorization of these effects in PbPb; theoretical predictions can be constrained by flavor-dependent energy-loss measurements
  - Are there flavor-dependences of CNM effects at high-pT?
- Additional possibilities to probe the nuclear PDFs
  - Strong correlation of b-jet production to gluon nPDFs

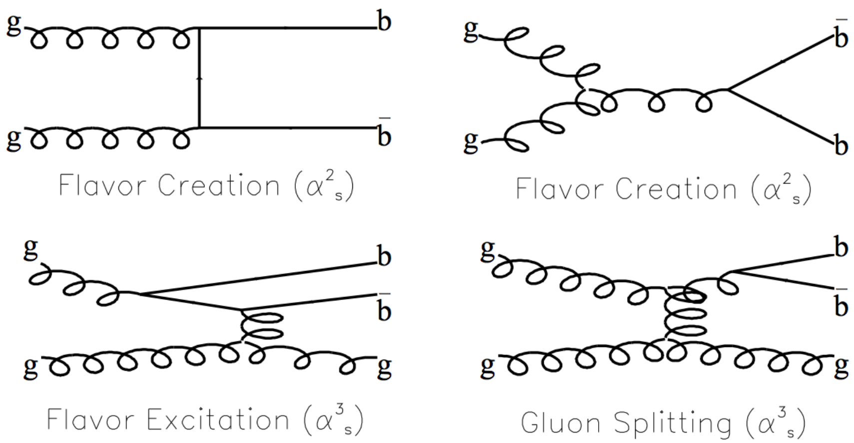
Still a good probe of **gluon** nPDFs

arXiv: hep-ex/0412006

Inclusive-jets (large quark component)

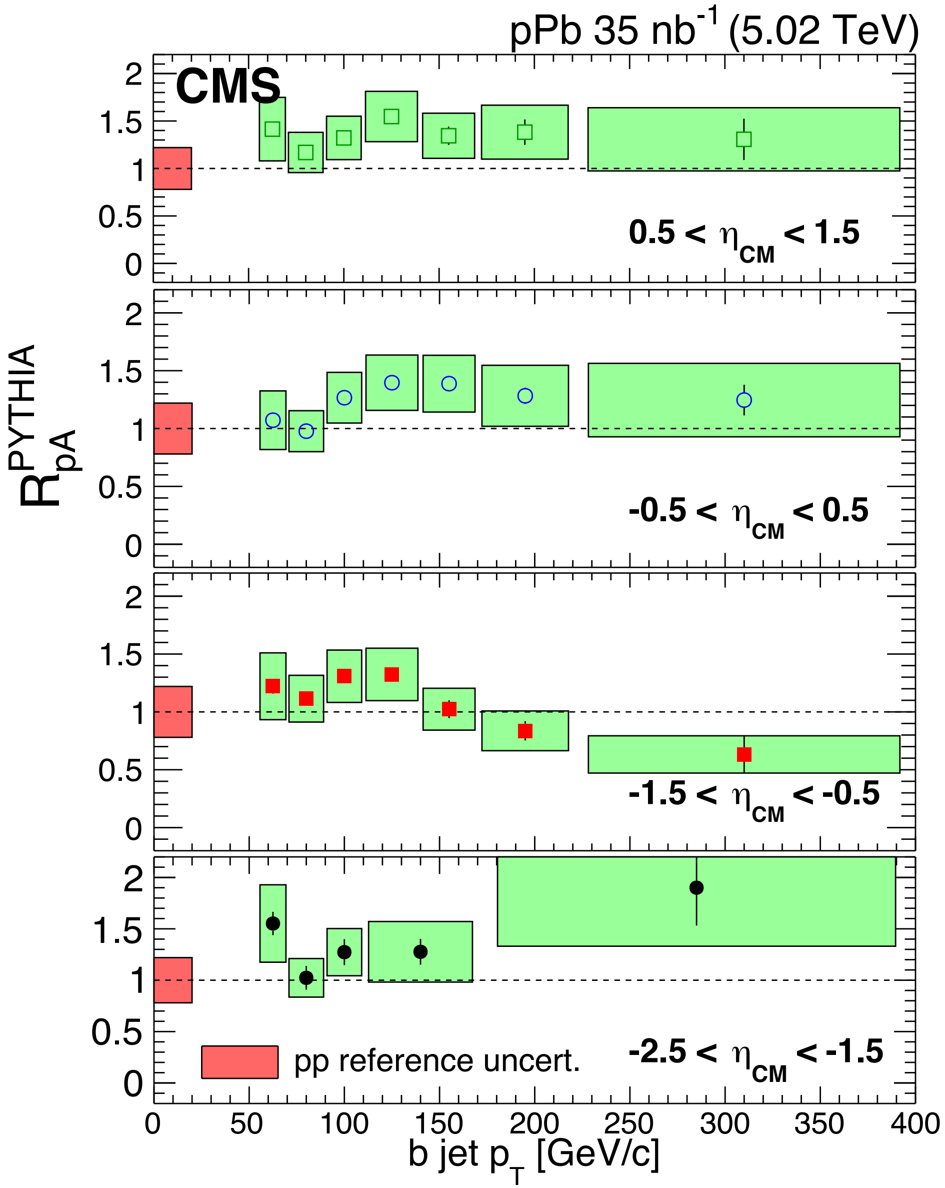


B-jet production types (gg prod. only)



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

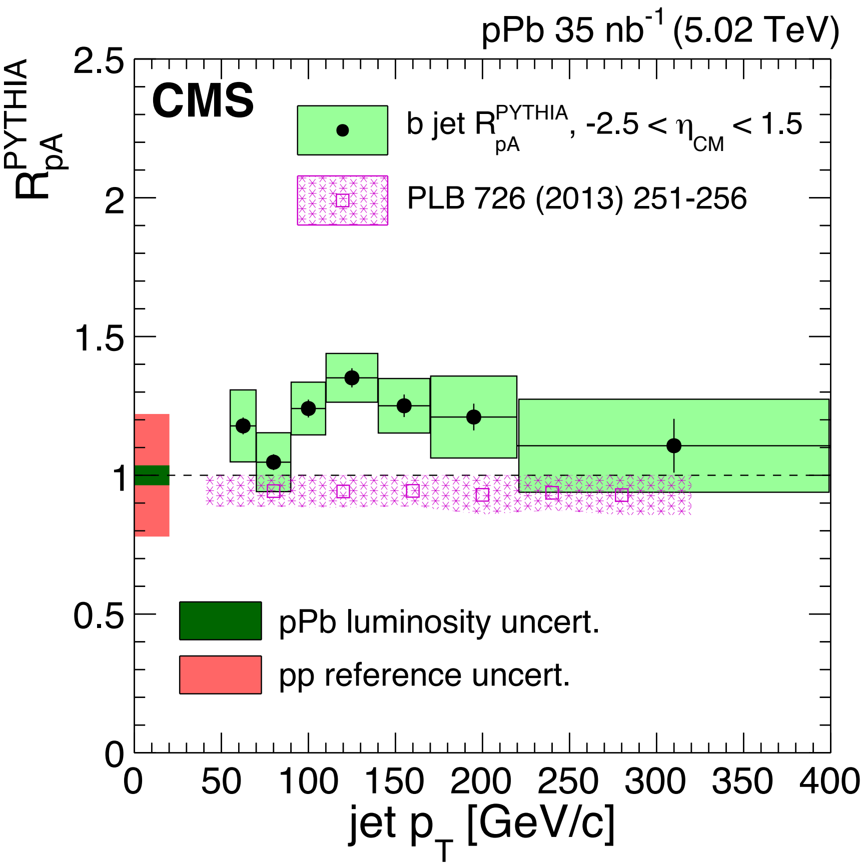
B-Jet Spectra (pPb)

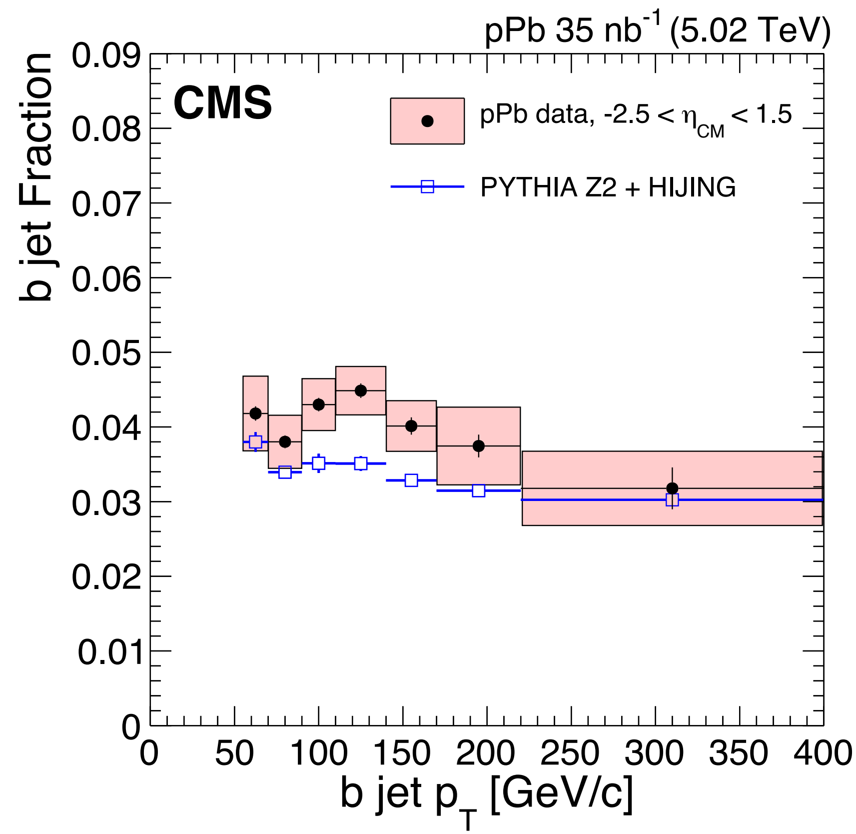


- Separation into pseudorapidity bins tests for nPDF effects
  - Bjorken-x correlates with jet rapidity
- Observe minimal effects w.r.t. η
  - No indications of nuclear-PDF effects
  - Dijet studies (future) can shed more light

PLB 754 (2016) 59

B-jet R_{pA} & fraction





- Consistent with no enhancement (< 1σ effect) for jets in pPb with respect to Pythia 6
  - Large reference uncertainty – no pp data @ 5 TeV
- B-jet fraction relatively consistent with PYTHIA 6 Z2 tune

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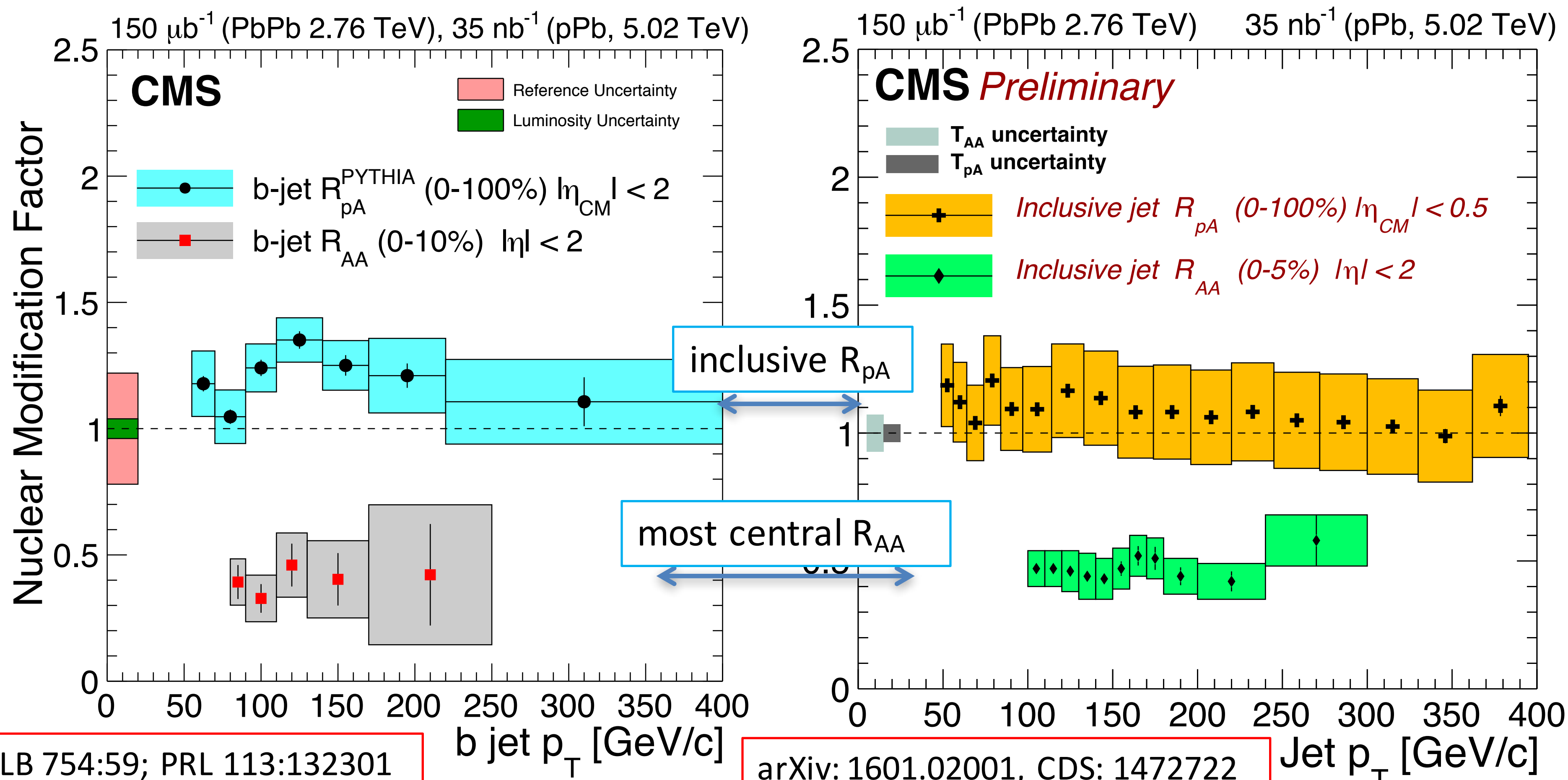
Comparison to Inclusive-Jets

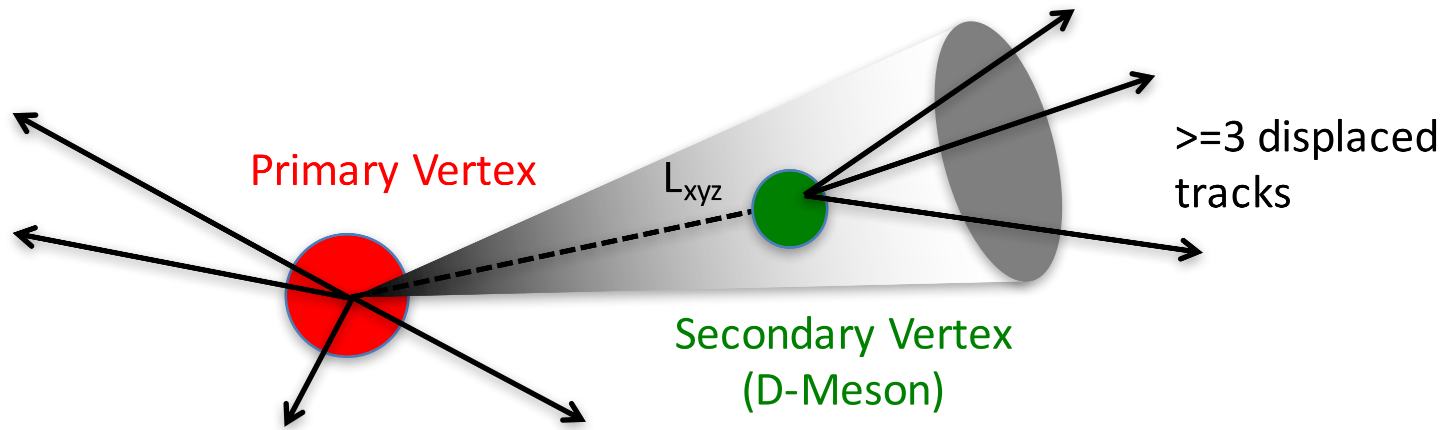


PLB 754:59; PRL 113:132301

arXiv: 1601.02001, CDS: 1472722

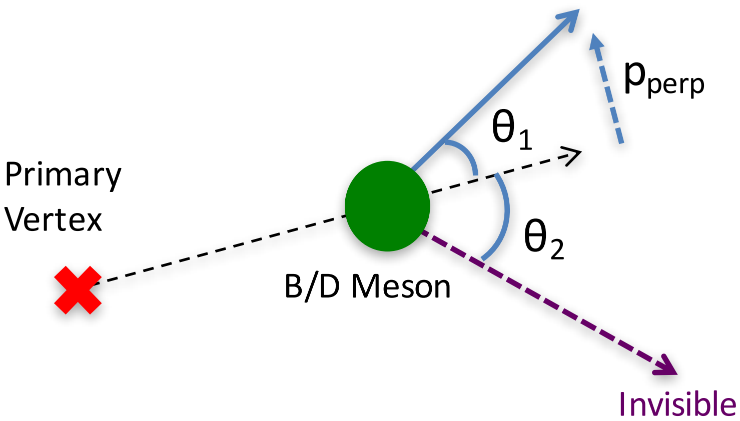
- So far, the story is the same
  - B-jets show similar trends as do light jets across collision species and collision energy

Identifying Charm Jets



- Impose tight selections on secondary vertex decay to increase c-jet tagging efficiency
  - PbPb b jets use simple 2-prong Sec. Vtx. algorithm
  - C-Tagging uses 3-prong secondary vertex, displaced from Primary Vertex (< 65% of tracks shared with PV)
  - 3-prong vertices dominated by Heavy Flavored jets

Corrected Secondary Vertex Mass



LHCb Collaboration
arXiv: 1504.07670

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

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

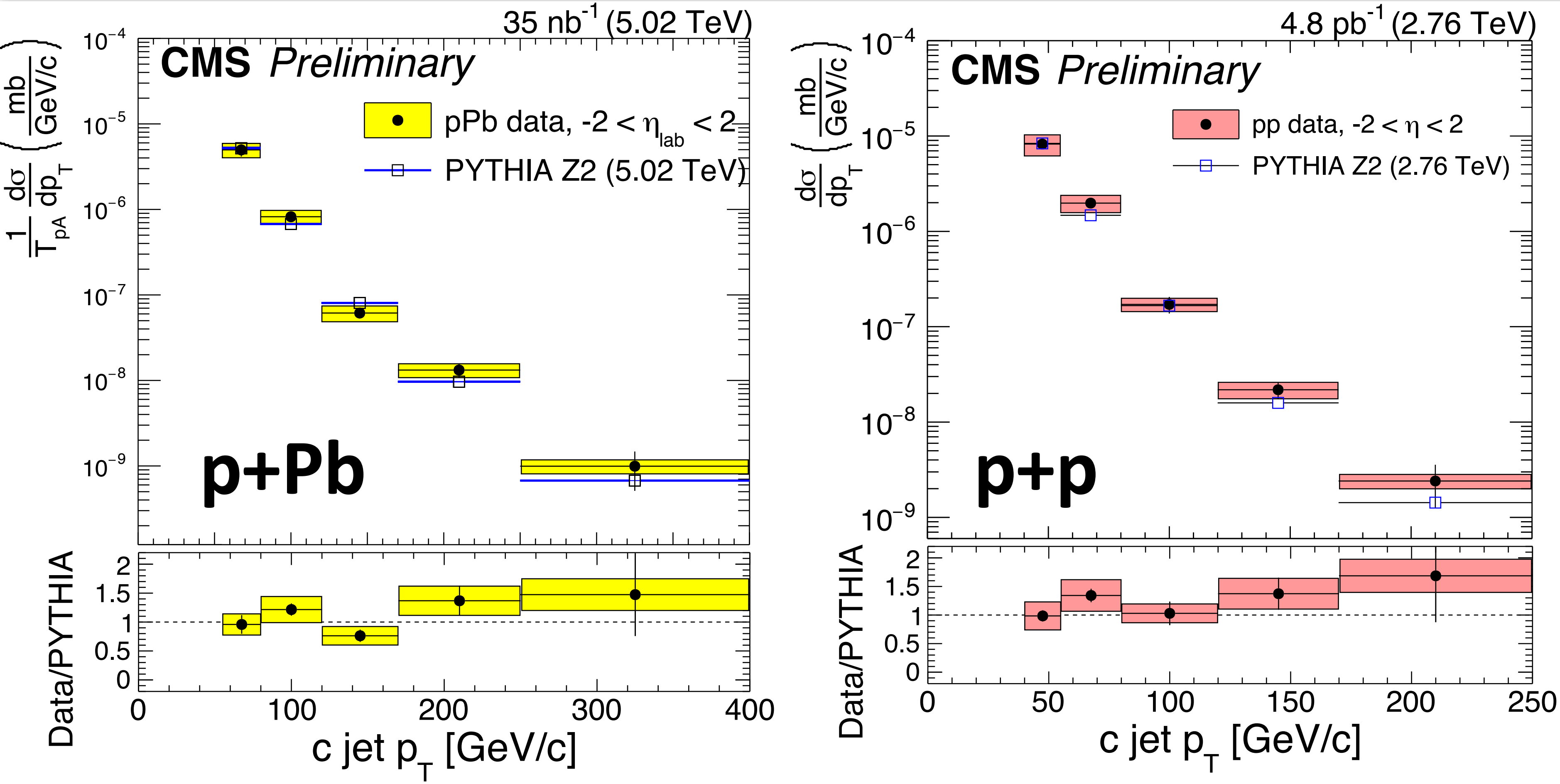
$$M_{corr} = \sqrt{M_1^2 + p_1^2} + \sqrt{M_\upsilon^2 + p_\upsilon^2}$$

= 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 consistent with vertex flight direction
- Attempts to restore p_{perp} balance w.r.t. flight direction from missing energy (e.g. ν, π^0, etc.)
- B hadrons have higher p_{perp} components (on average) than do C hadrons
  - B's have statistically larger values of M_{corr}

Charm-Jet Spectra



- First ever measurement of charm jets in a heavy-ion environment
  - One of the first ever in the high-energy field
- Find charm-jet spectra in pPb is consistent with PYTHIA prediction

CMS PAS HIN-15-012, CDS: 2055705

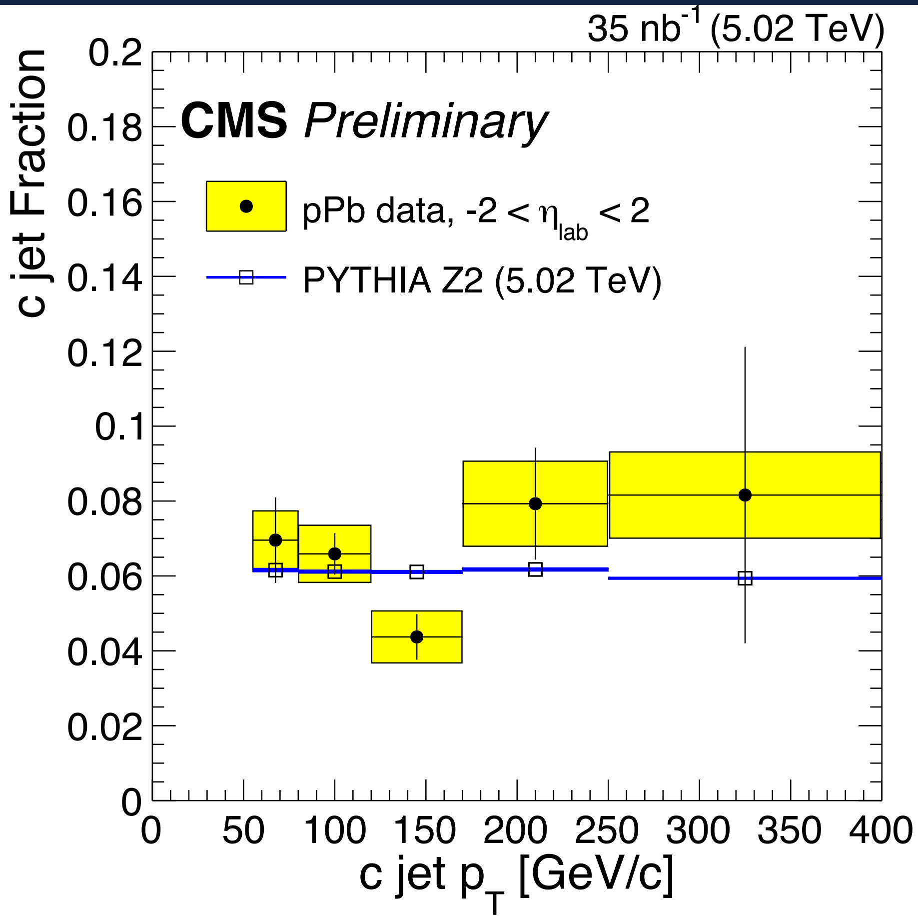
Summary

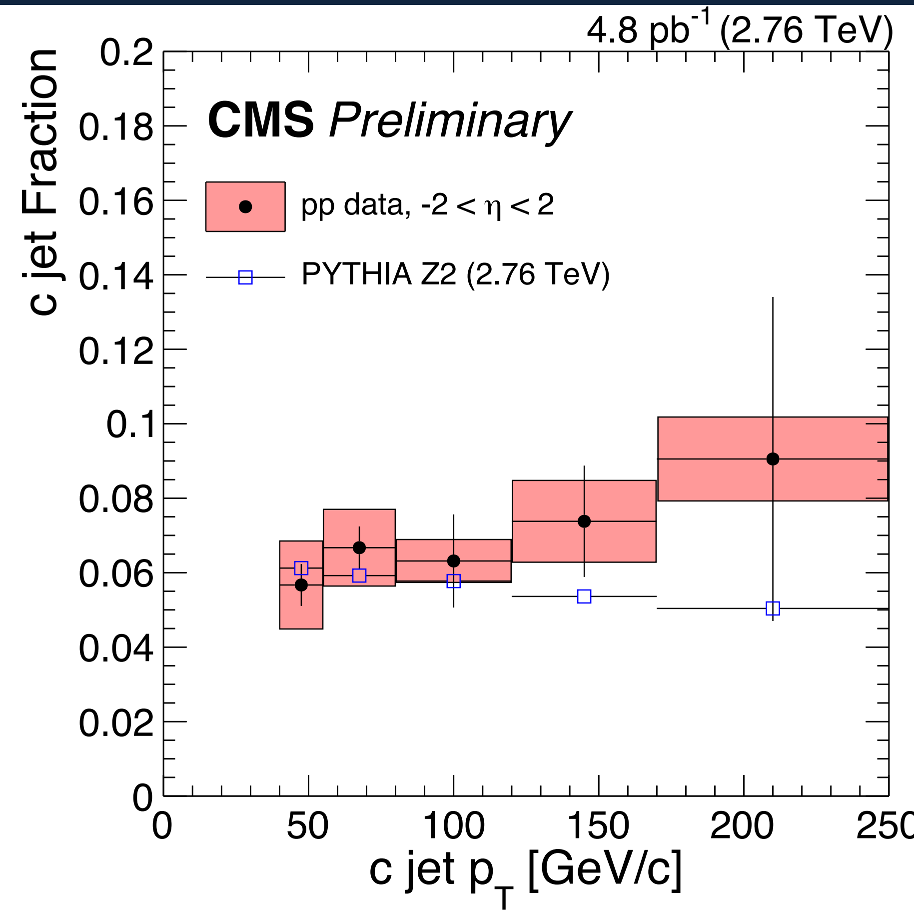
- **In Lead-Lead collisions**:
  - Flavor-dependent energy loss?
    - Not a dramatic effect
  - Differences in quark-plasma interactions based on quark mass differences?
    - Not at high-p_T - consistent with pQCD predictions

- **In Proton-Lead collisions**:
  - Observe flavor-dependence of CNM effects at high-p_T?
    - Results consistent with pQCD predictions of small CNM effects
    - Extends to both b-jets and c-jets (w.r.t. PYTHIA 6)
  - Observations of gluon nPDFs through jets?
    - Possibly with increased statistics and measurement of HF dijets

BACKUP

Charm-Jet Fraction

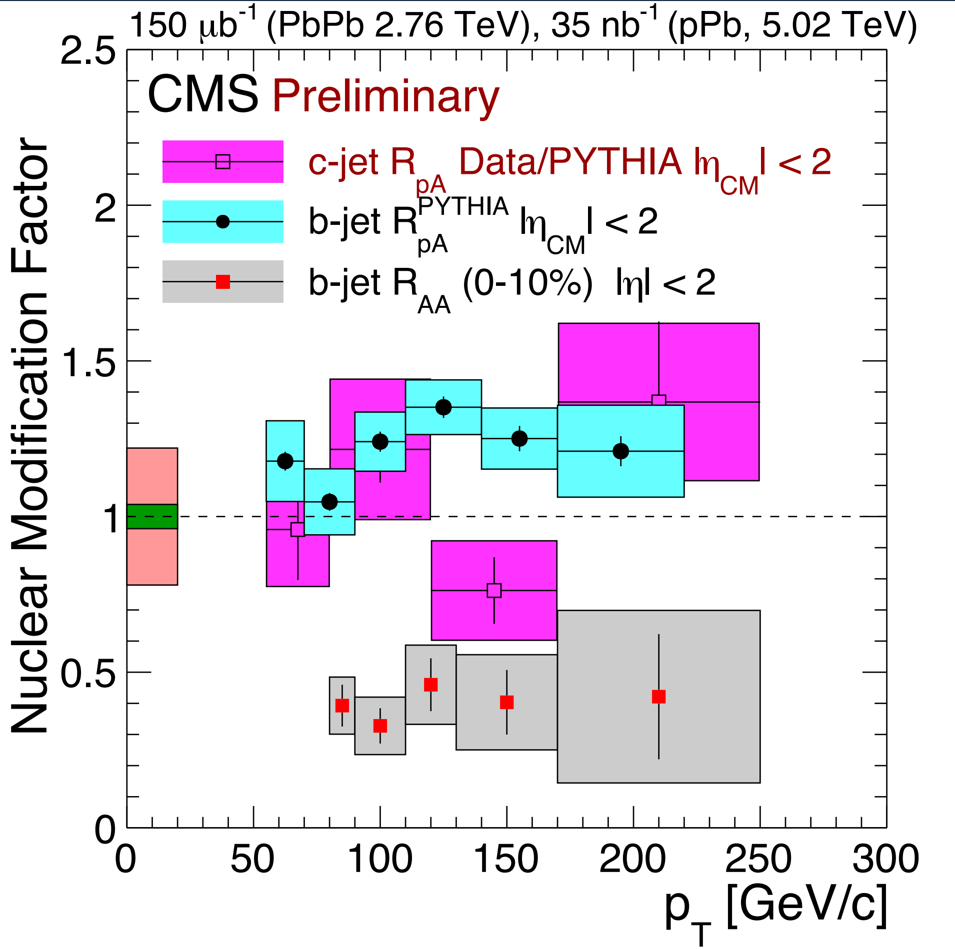




- Charm jet fraction also consistent with PYTHIA prediction
  - Somewhat surprising – PYTHIA not known for reproducing jet flavor as well as NLO generators (HERWIG, POWHEG)

CMS PAS HIN-15-012, CDS: 2055705

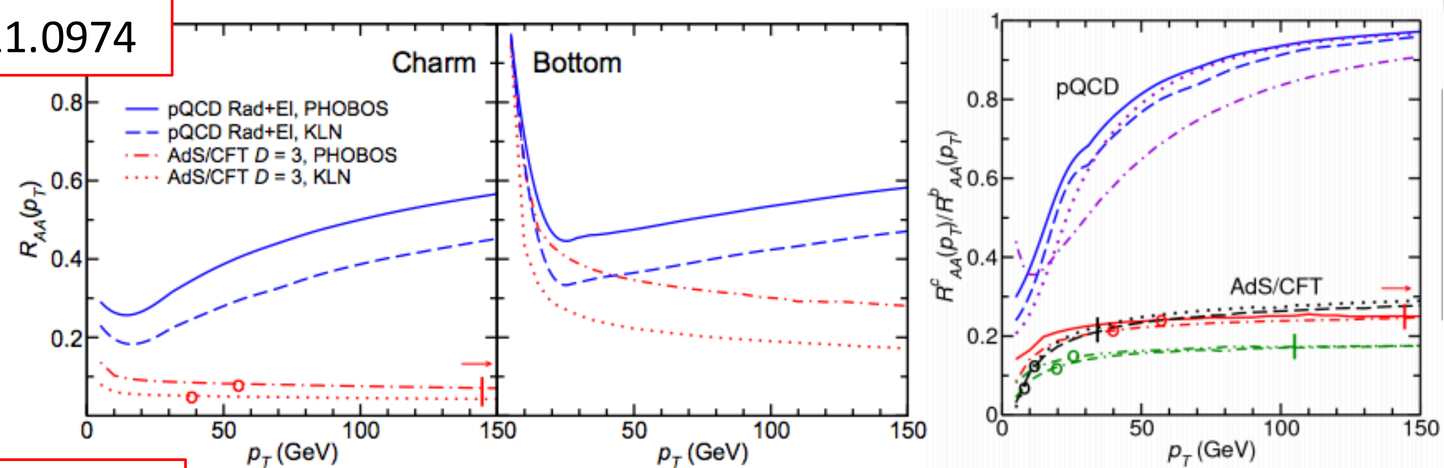
One Figure Summary



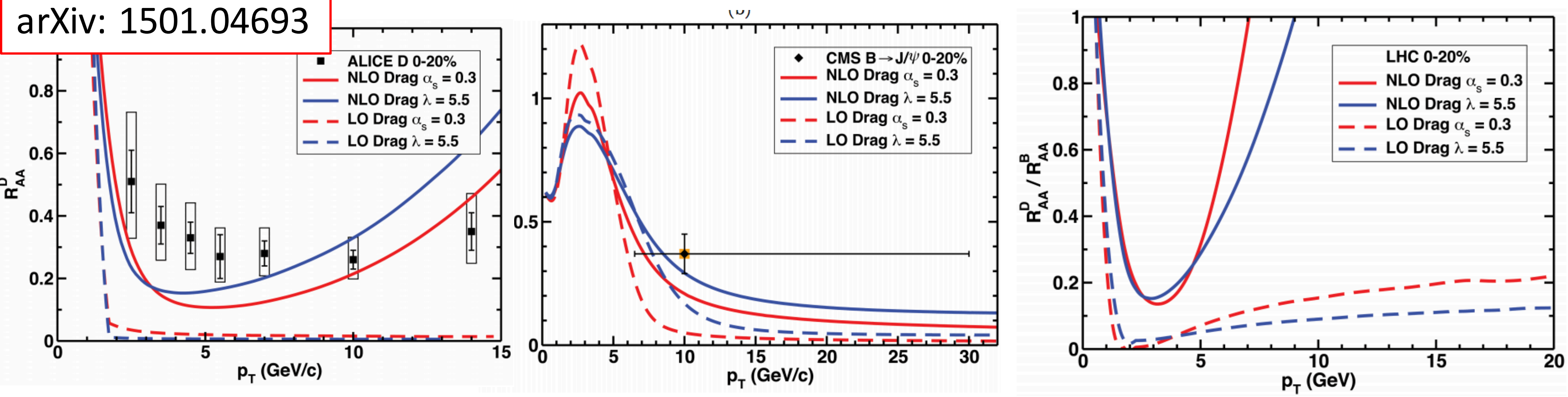
- Global perspective of heavy-ion, heavy-flavored jet modification
  - Parton mass-dependent effects are small at high-p_T
  - C-jet systematic uncertainties reduced with addition of 5 TeV pp data (soon!)

AdS/CFT Models "Need More Work"

arXiv: 0711.0974

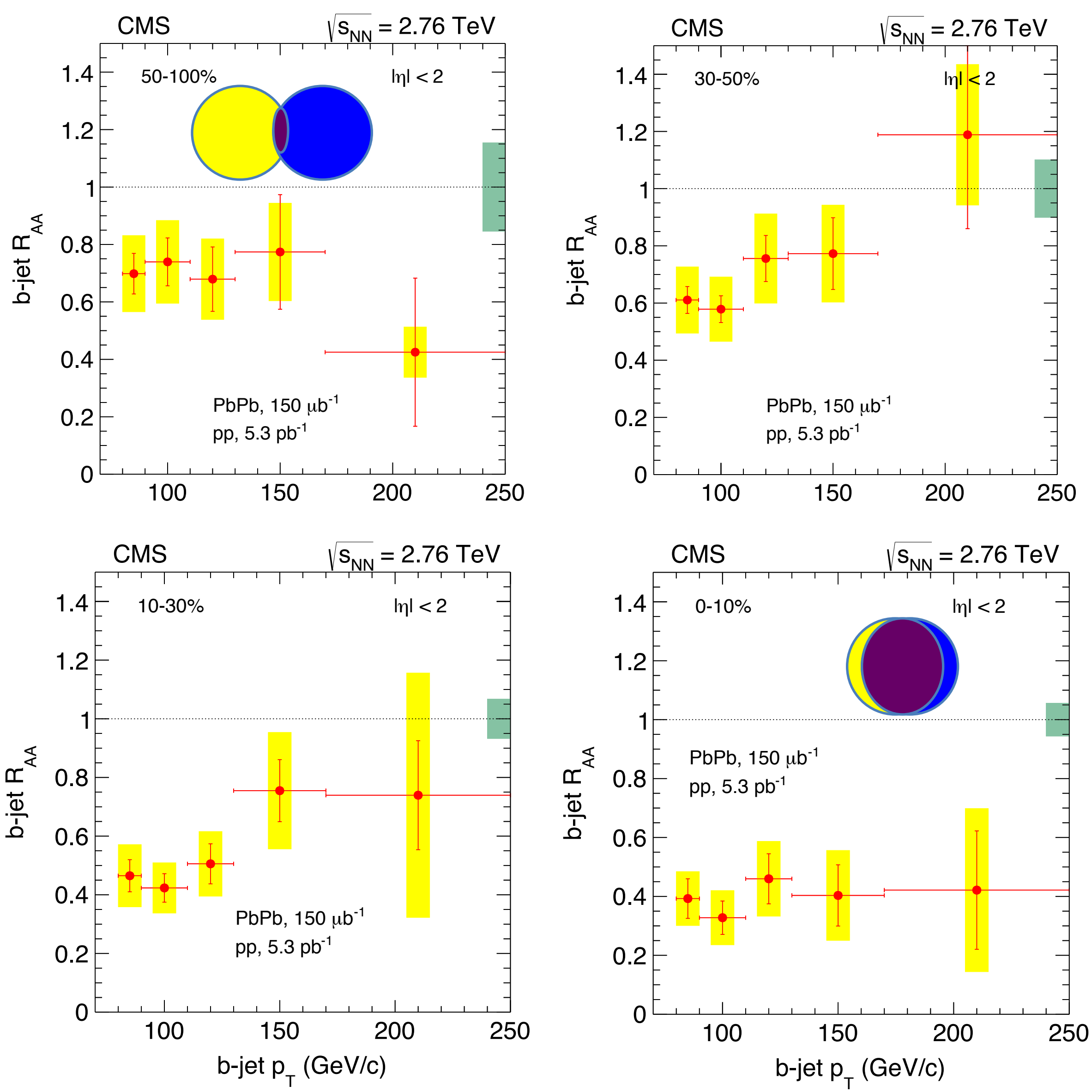


arXiv: 1501.04693



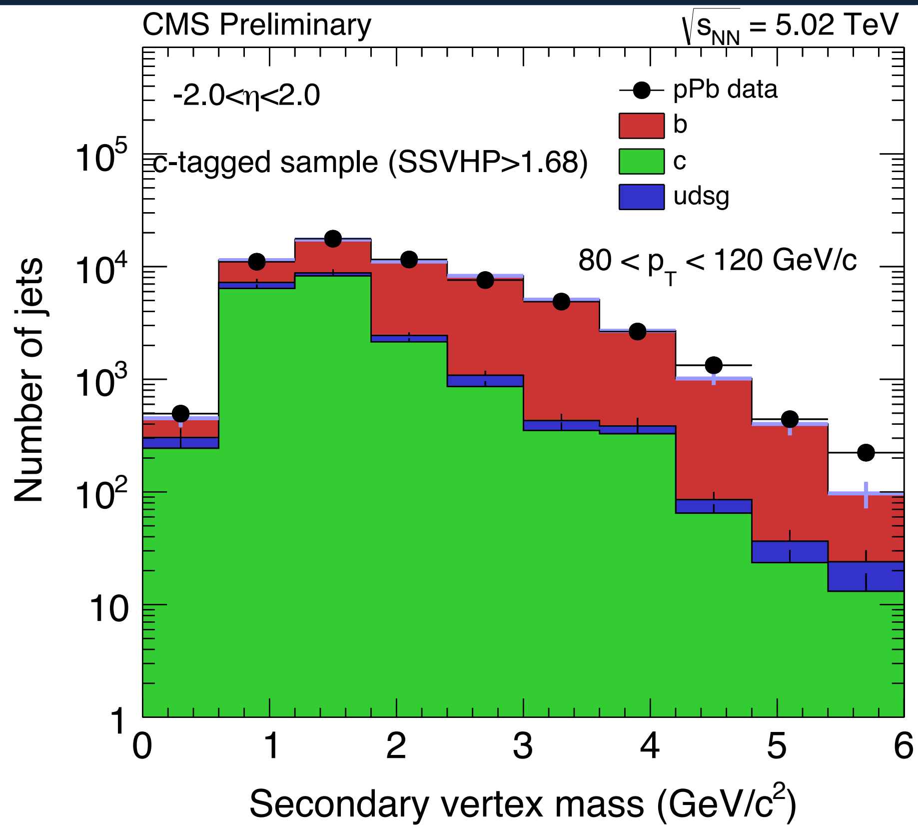
- Previous AdS/CFT predictions showed very different behavior for b/c jet RAA.
  - New addition of NLO effects limit applicability of these claims

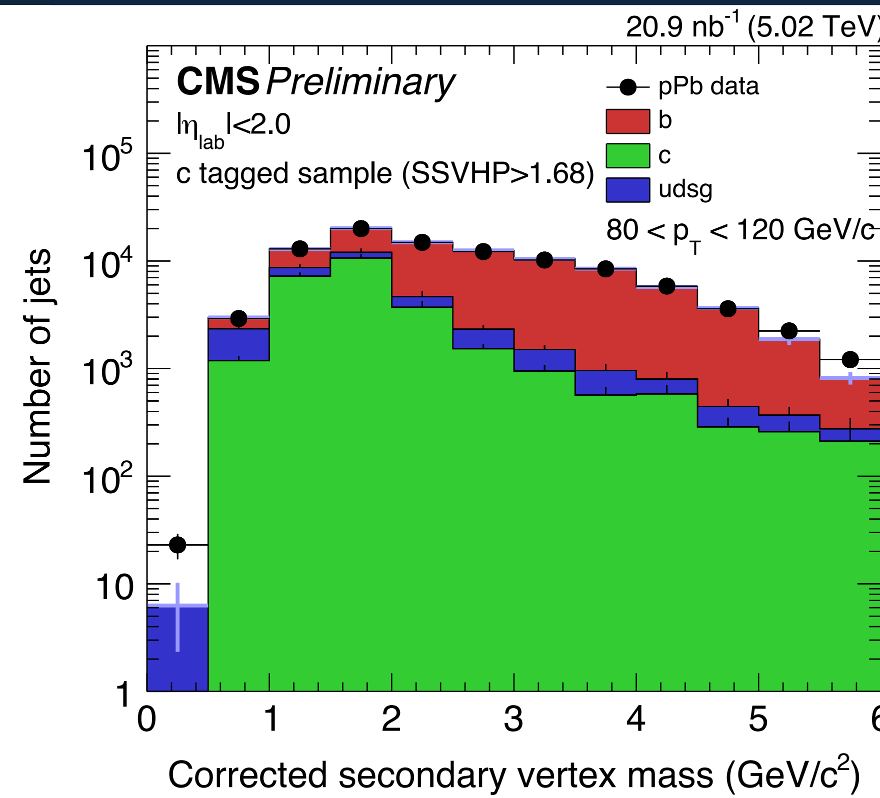
B-jet R_{AA} (centrality)



- R_{AA} is smallest for most central collisions and moves toward unity for peripheral collisions
- Most central b-jets show consistent suppression with inclusive jets (next slide)

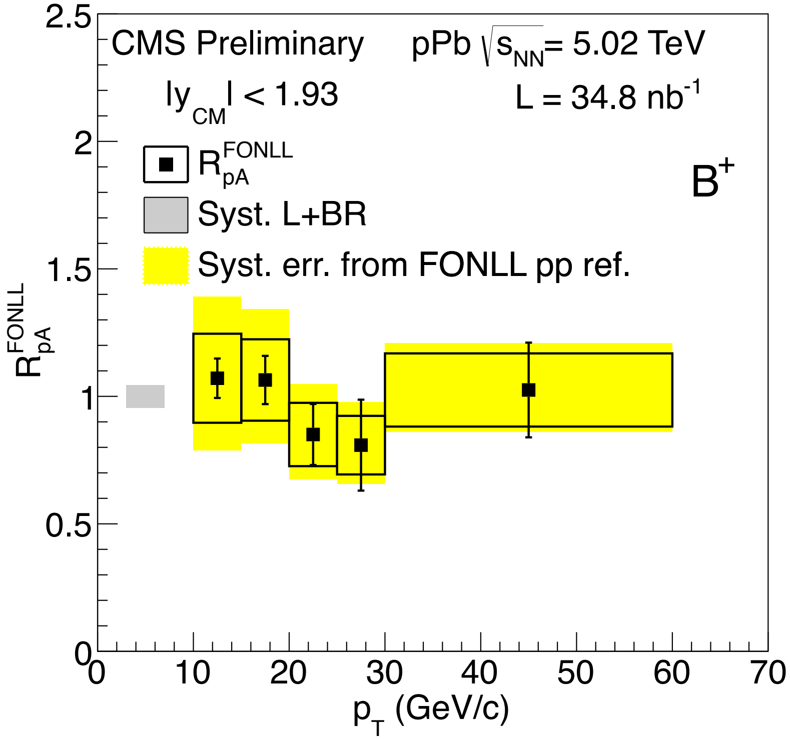
Corrected Secondary Vertex Mass



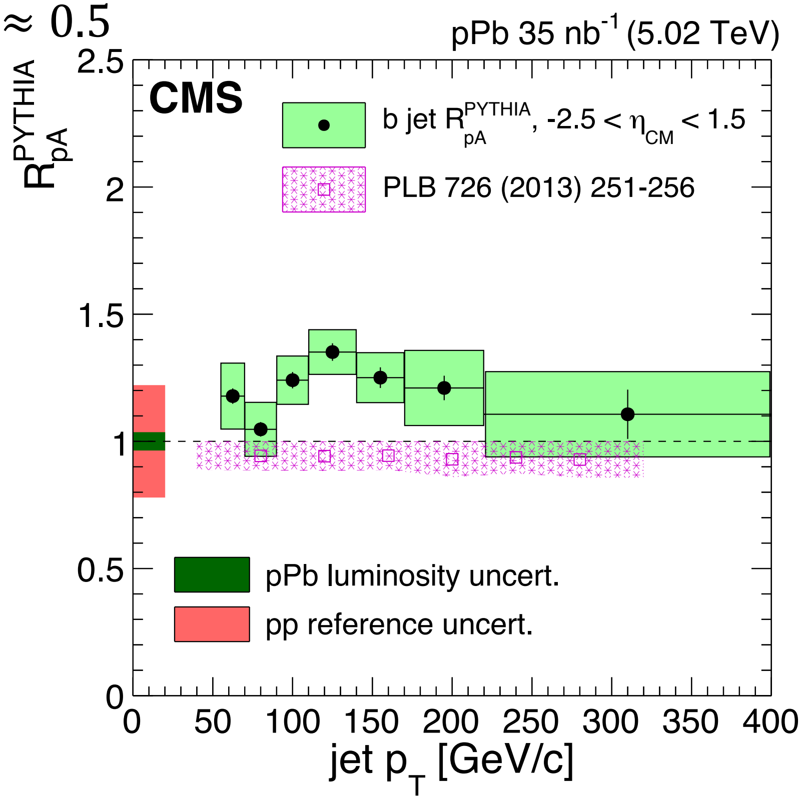


- M_{corr} provides additional discrimination power between light/charm/bottom jets than does pure secondary vertex mass
- Shapes between bottom and charm different for M_{corr}

Comparison to B-Mesons

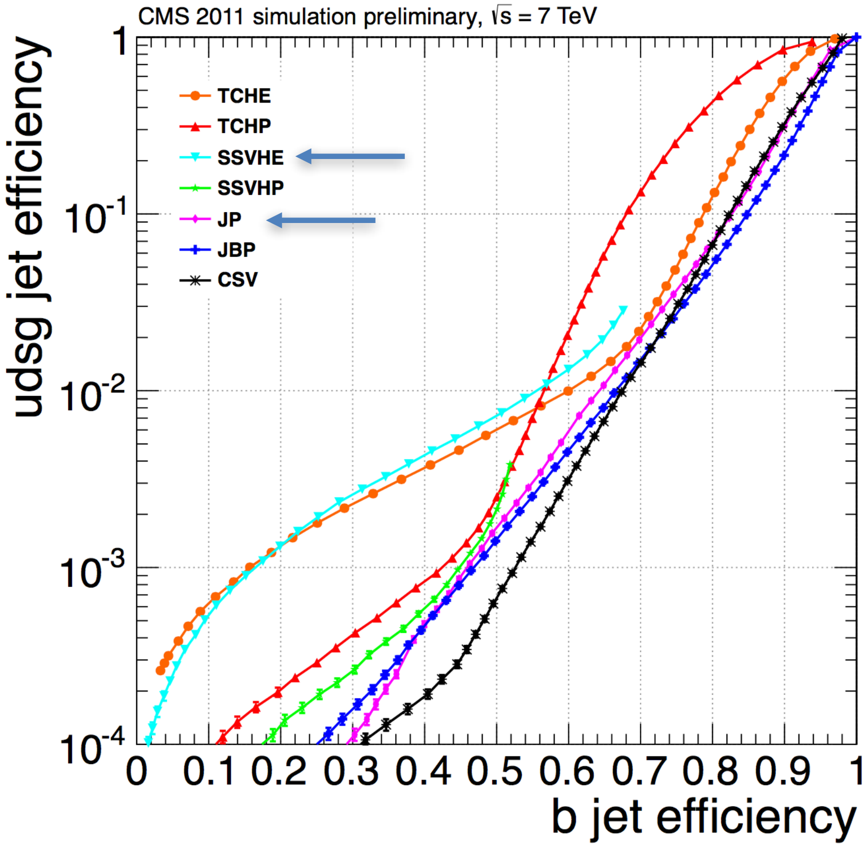


$$\frac{p_T(Meson)}{p_T(Jet)} \approx 0.5$$



- "Global" Heavy flavor results can show p_T-dependent effects
  - Somewhat obscured by fragmentation function widths
  - Extension of B-Meson result to PbPb may show mass-dependent suppression effects

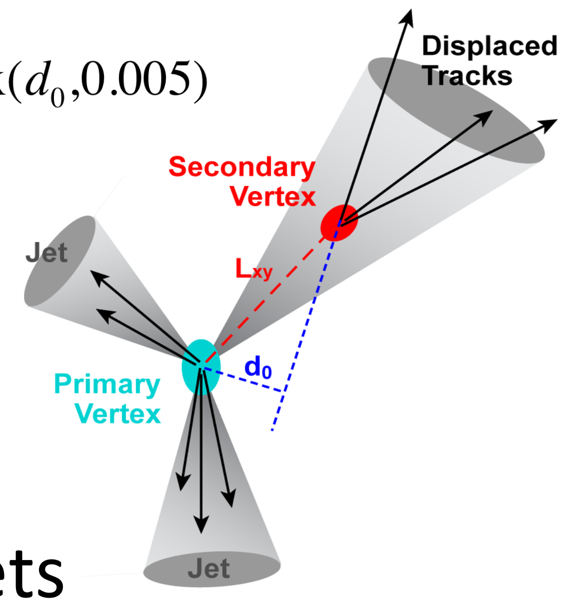
Discriminators



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

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

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



arXiv: 1211.4462

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