Heavy quark jets

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Outline

- 1 b-jet
- 2 b-jets
- Some thoughts about future directions (time permitting)

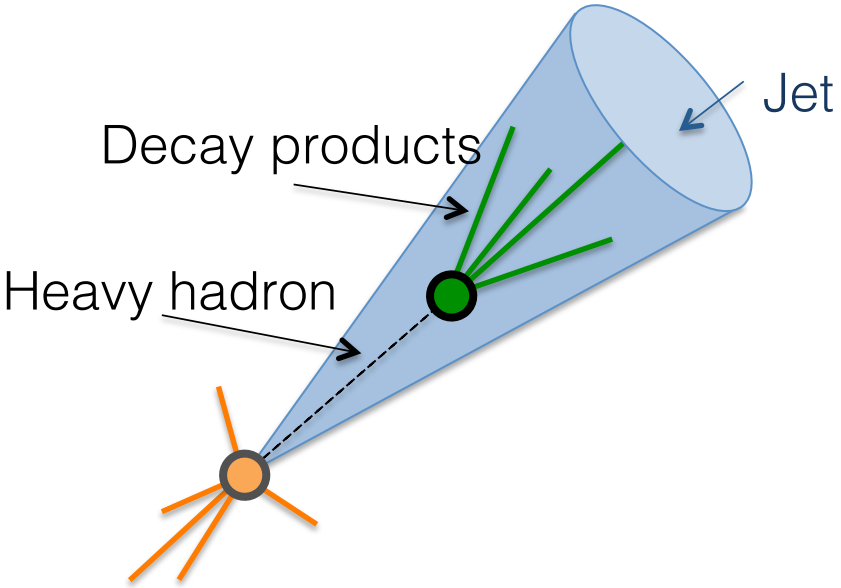
What is a heavy quark jet?

What we would like them to be:

Jets initiated by a heavy quark

What is actually measured:

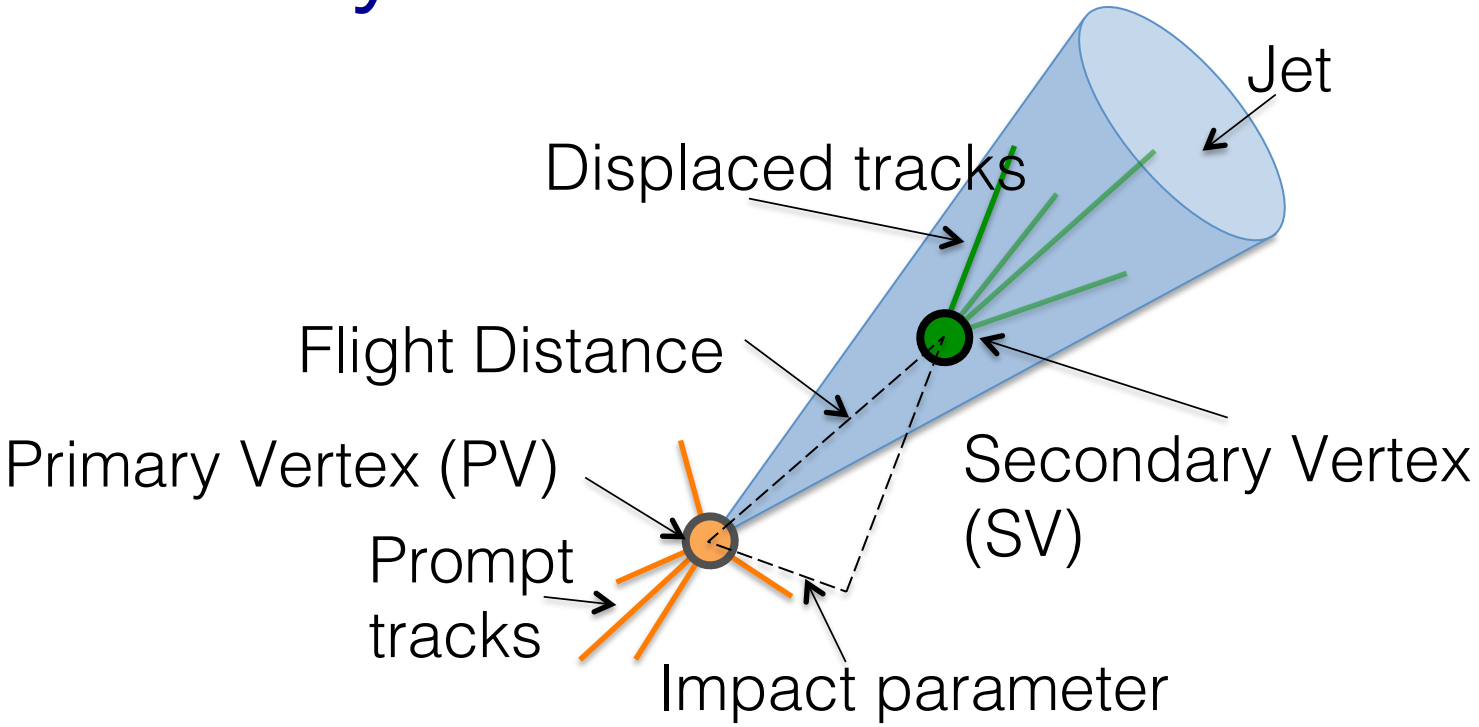
Jets containing one or more heavy hadrons



This is not an academic point.

Heavy quarks are not always produced at early times, and jets containing more than one heavy quark are not rare

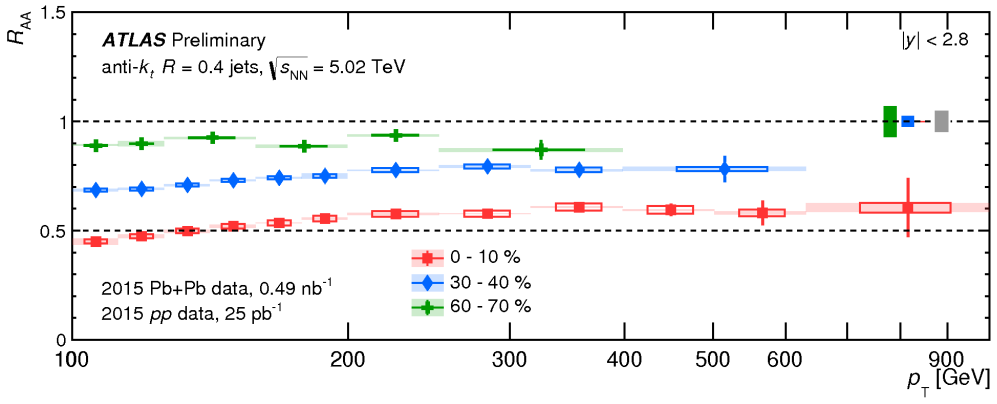
How are they measured?



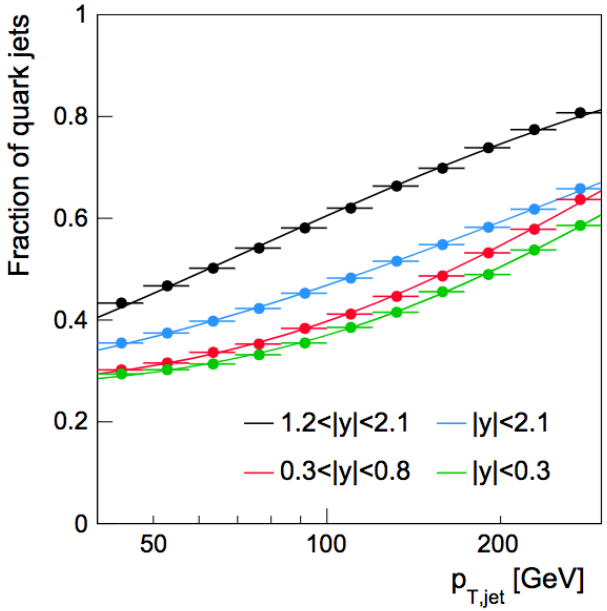
- Lifetime methods: Exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays
- Soft-lepton tagging: μ or e inside the jet

Inclusive jets

ATLAS-CONF-2017-009

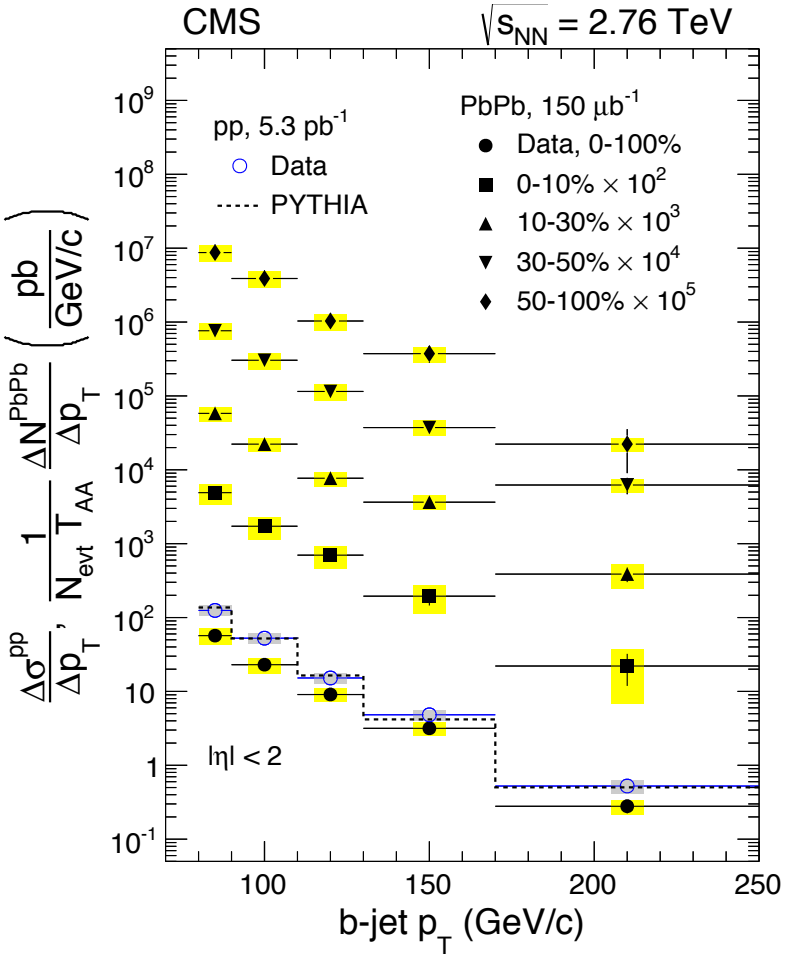


EPJC76 (2016) 50

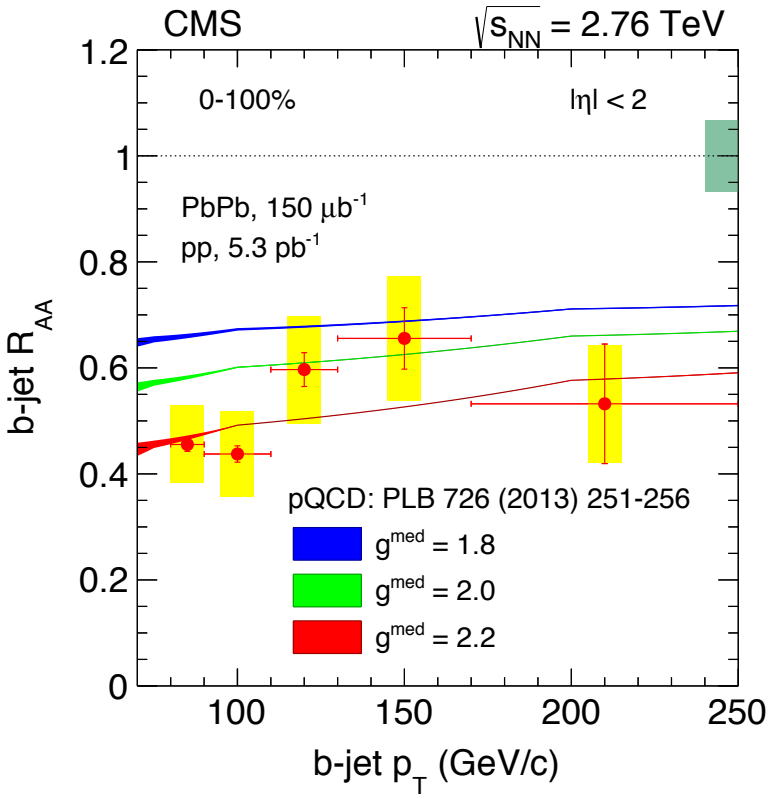


- Spectra are suppressed out to the large transverse momenta measured
- Both quark and gluon-initiated jets play a role, with a modest dependence on p_T and rapidity
- A comparison to heavy quark initiated jets is of great interest even (especially?) in the regime where mass effect are negligible
- Of course heavy quarks fragment much harder than light quarks, so no guarantee they interact with the QGP in the same way as light quarks

b-jet x-section & R_{AA}

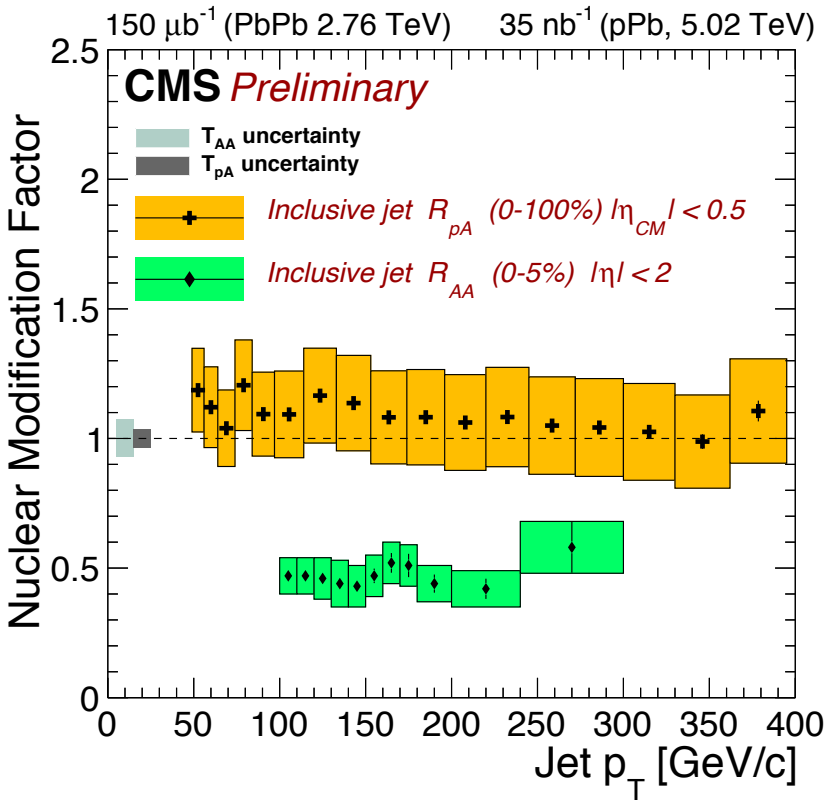


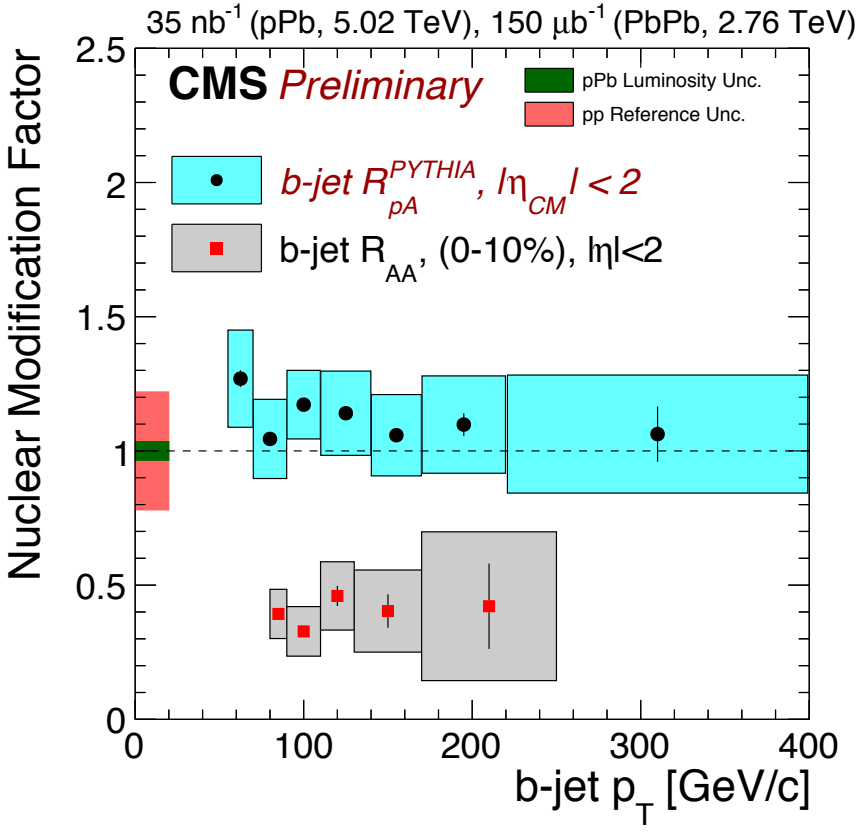
PRL 113 (2014) 132301



- Unfolded jet spectra for several centrality selections and pp
- Suppression of ~ 2x, compatible w/ pQCD model expectations

b-jet vs. inclusive jet quenching

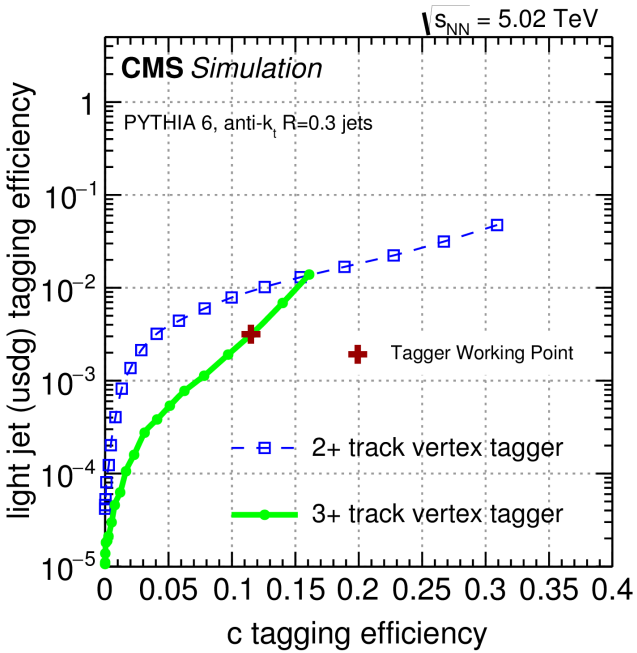




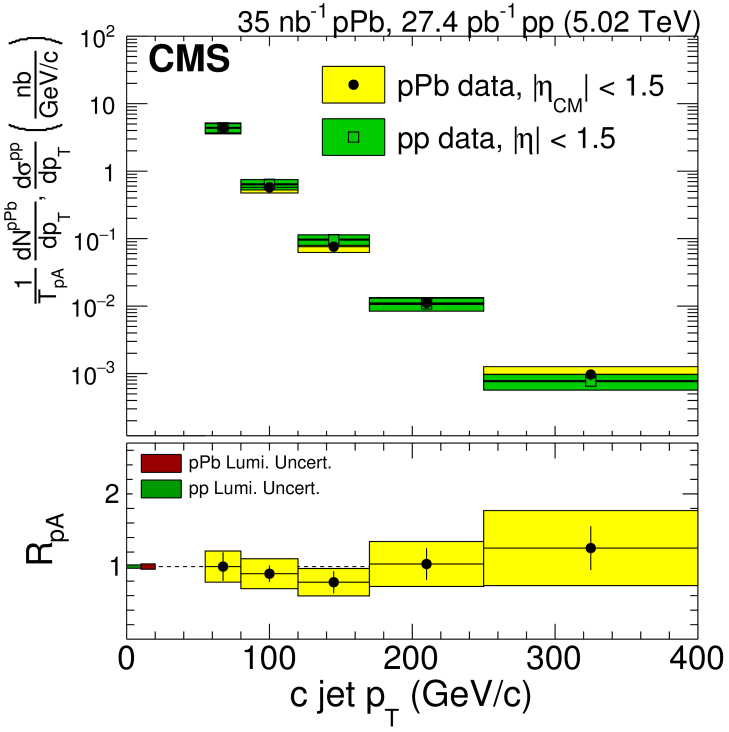
- pPb measurements consistent w/ no nuclear effect (w/ large errors)
- Similar b-jet and inclusive modification in PbPb, within still large errors

What about charm jets?

Charm jets are also measurable!
Same cut & fit analysis as for b jets



R_{pA} compatible with unity
(expect ~10% nPDF effects)



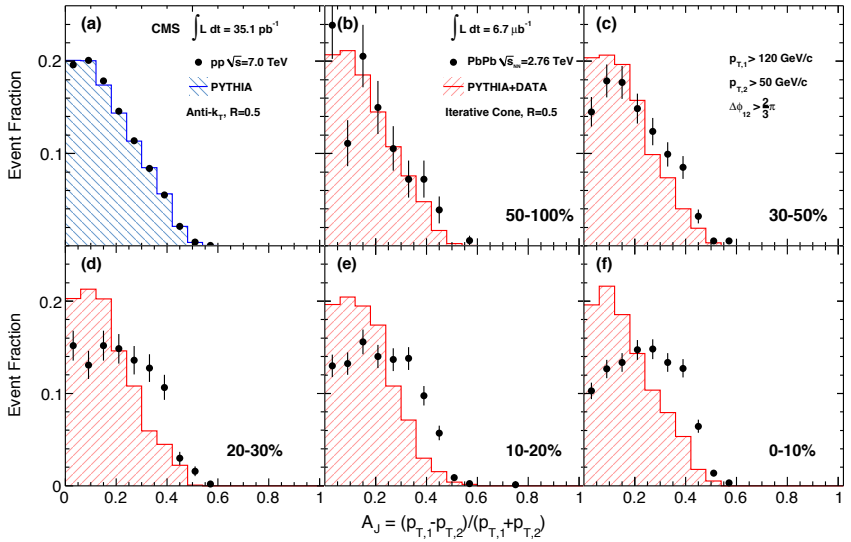
Much lower efficiency than for b jets, due to: shorter lifetime, lower multiplicity and softer fragmentation

Prospects for c-jet measurements:
O(10%) of c-hadrons fully reconstructable
→ FF & jets shapes, D+D, D+X, etc.

arXiv:1612.08972

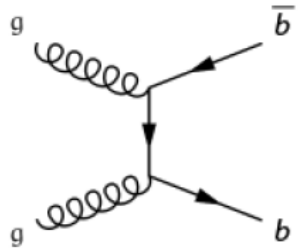
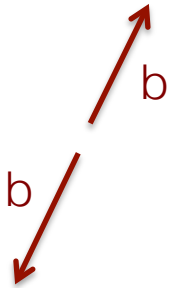
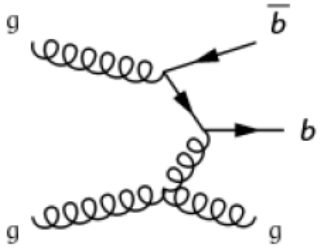
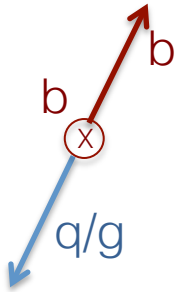
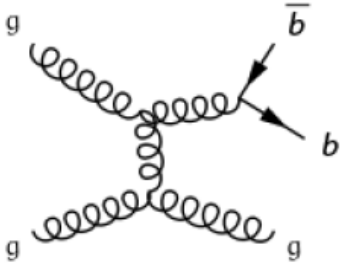
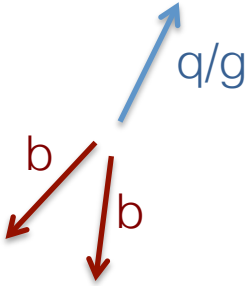
Two b's are better than one

Inclusive dijet p_T imbalance

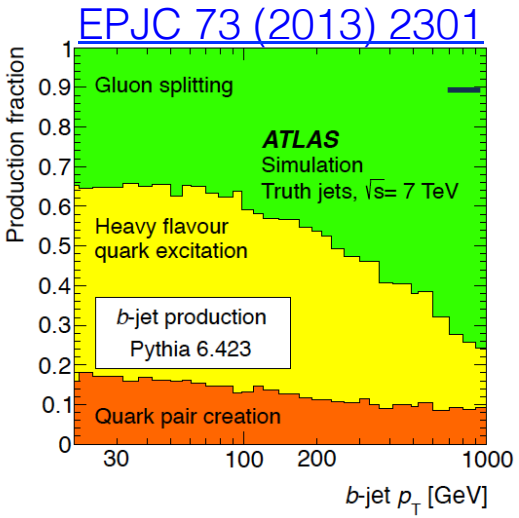


- Recoiling jets interesting in general:
  - Sensitivity to path-length & fluctuations
  - Reduced systematics compared to spectra
- For b-jets there's an additional motivation…

Heavy flavor production @ NLO

Process:	Example diagram	Typical topology
Flavor Creation (FCR)		
Flavor Excitation (FEX)		
Gluon Splitting (GSP)		

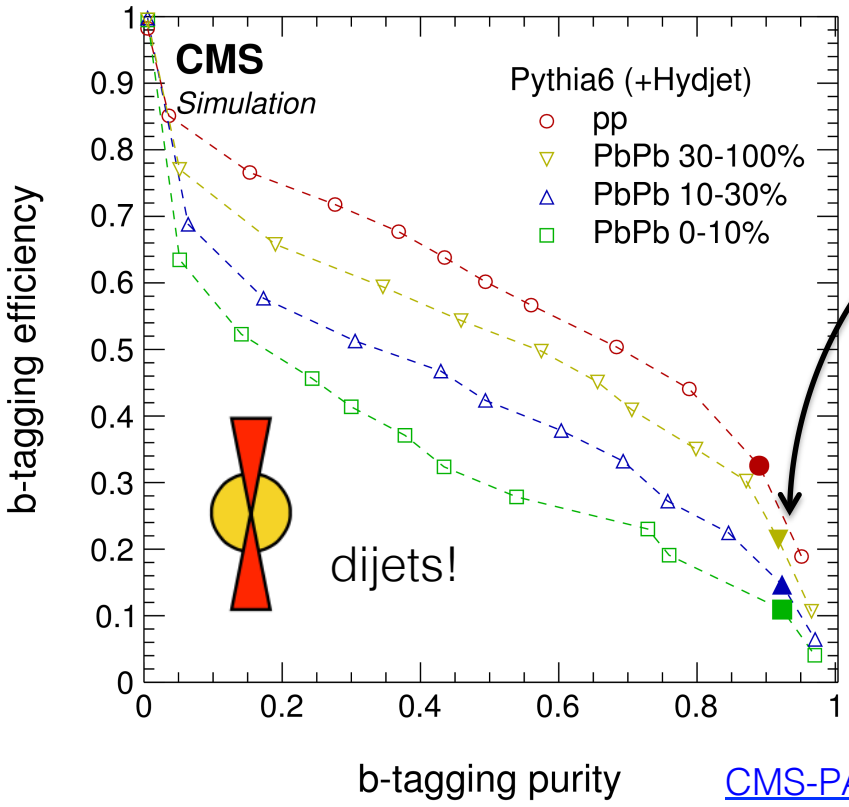
Back-to-back topology picks out b's produced in the hard scattering (g + g → b + bbar)



NLO contributions dominate inclusive x-section

Performance for b-dijets

Now using “Combined Secondary Vertex”



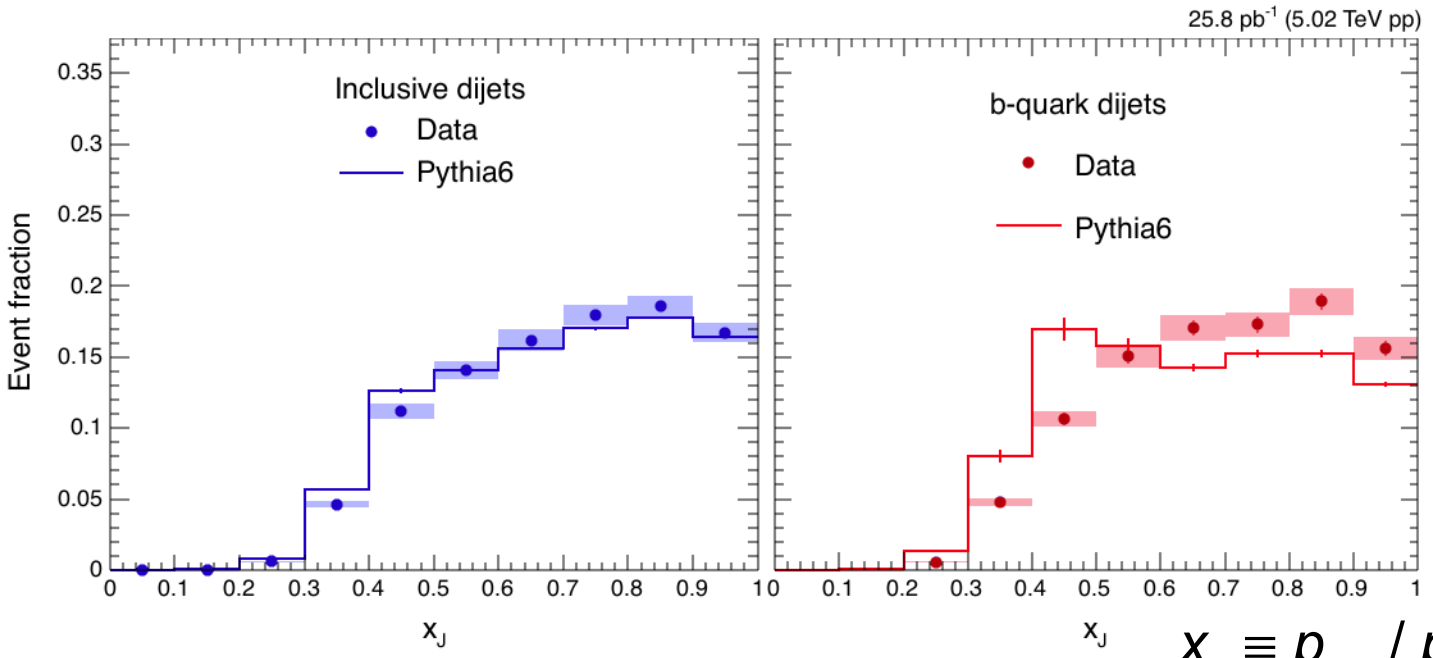
Extremely tight working point
~ 90% purity

Cost is efficiency of 10 – 30%

CMS-PAS-HIN-16-005

Centrality dependence can be mitigated by dedicated optimization of tagger for different centrality classes (left for future improvements)

(b-)dijet imbalance in pp



$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.5$

CMS-PAS-HIN-16-005

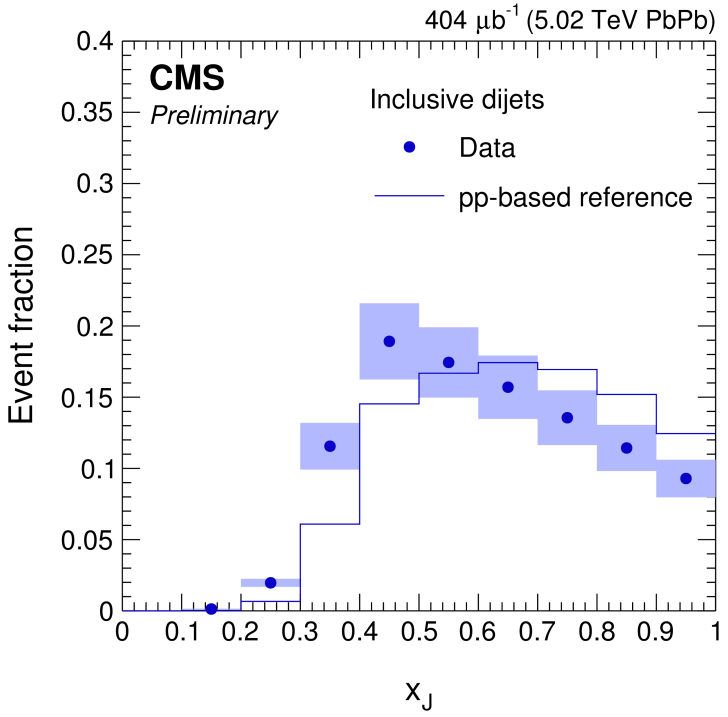
$x_J \equiv p_{T,2} / p_{T,1}$

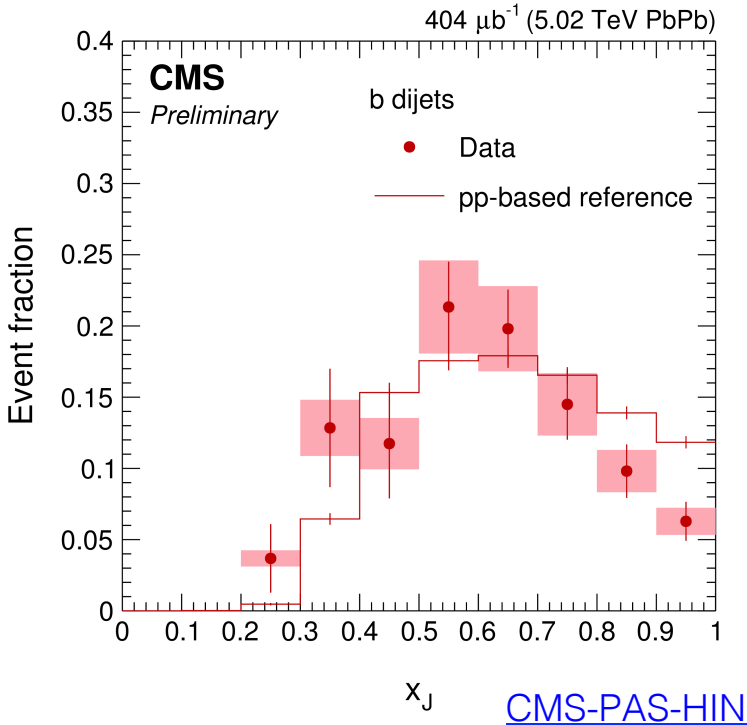
- Pythia 6 (tune Z2) ok for inclusive dijet imbalance
- Incidentally, much better than LHC Pythia 8 tunes
- Dijet imbalance is fairly similar for inclusive and b-dijets
- Pythia 6, however, predicts something else entirely …

(b)-dijet imbalance in PbPb

$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.5$

Centrality 0 – 10 %

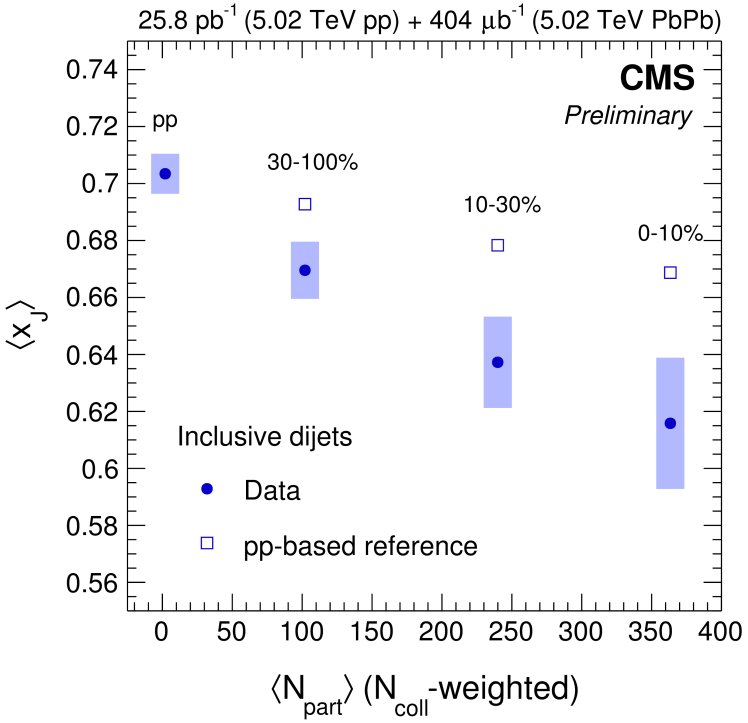


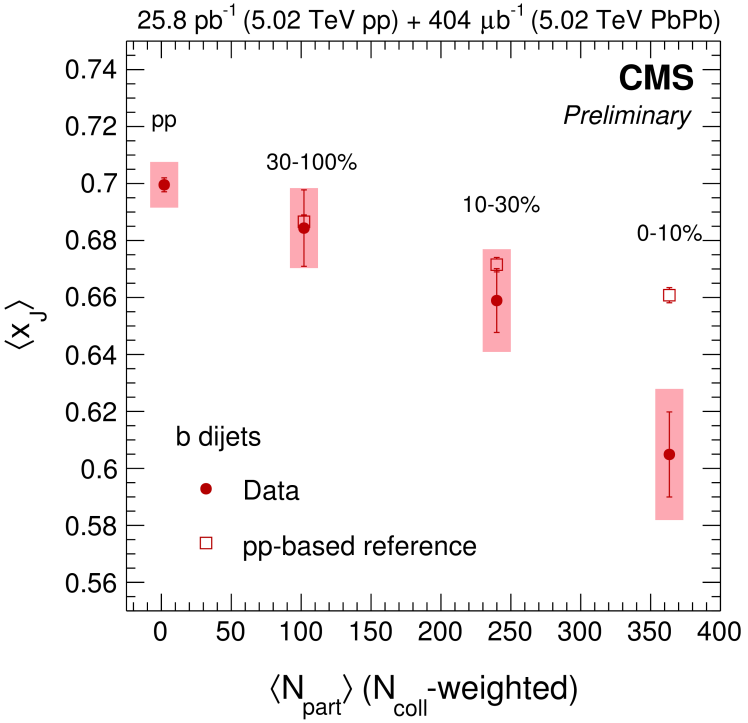


CMS-PAS-HIN-16-005

First measurement of b-bbar correlations in heavy ions!
To the extent we can say so far, b-jet imbalance looks like inclusive jet

Mean p_T imbalance





$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.5$

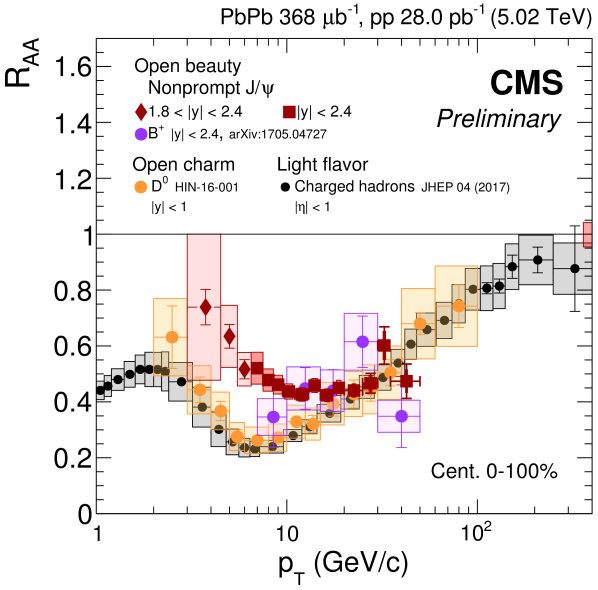
No difference between inclusive and b-dijets so far…

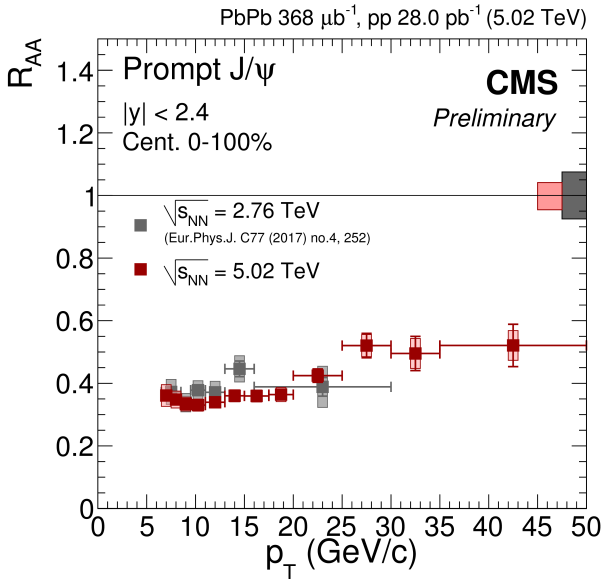
Sensitivity to could be improved by increasing leading jet p_T, where quenching is more prominent

CMS-PAS-HIN-16-005

Future directions

“Universal” e-loss?





CMS-PAS-HIN-16-025

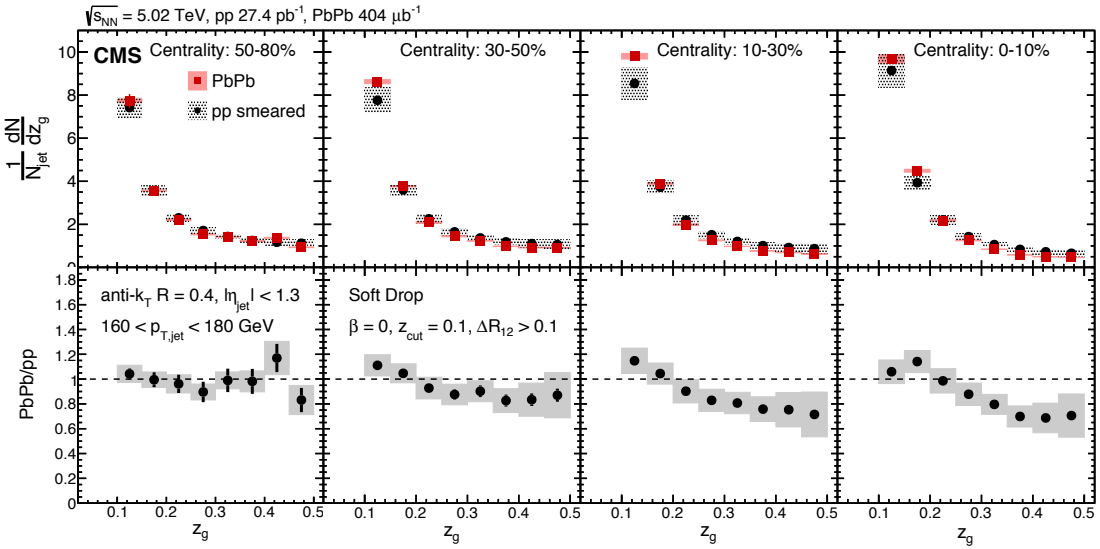
- Should not overstate the case, uncertainties are not small
- However, data are not inconsistent species independent R_{AA} at high p_T, including prompt j/psi

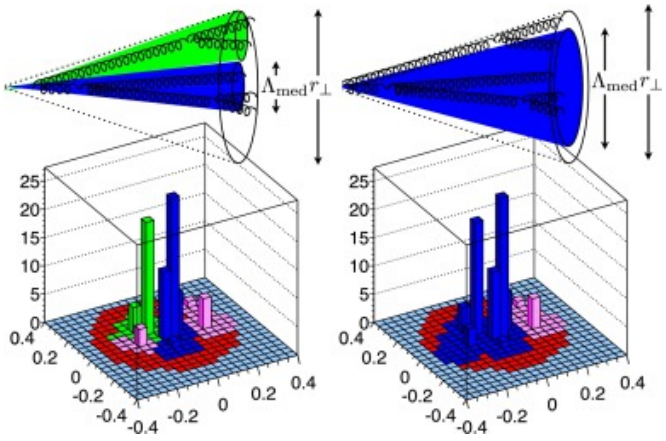
Brings to mind some fundamental questions:

- In what regime (if any) is parton energy loss relevant for quarkonia?
- How does the energy loss of a quark pair (let’s call it an “antenna”) differ from that of a single quark?

Groomed momentum fraction

arxiv:1708.09429

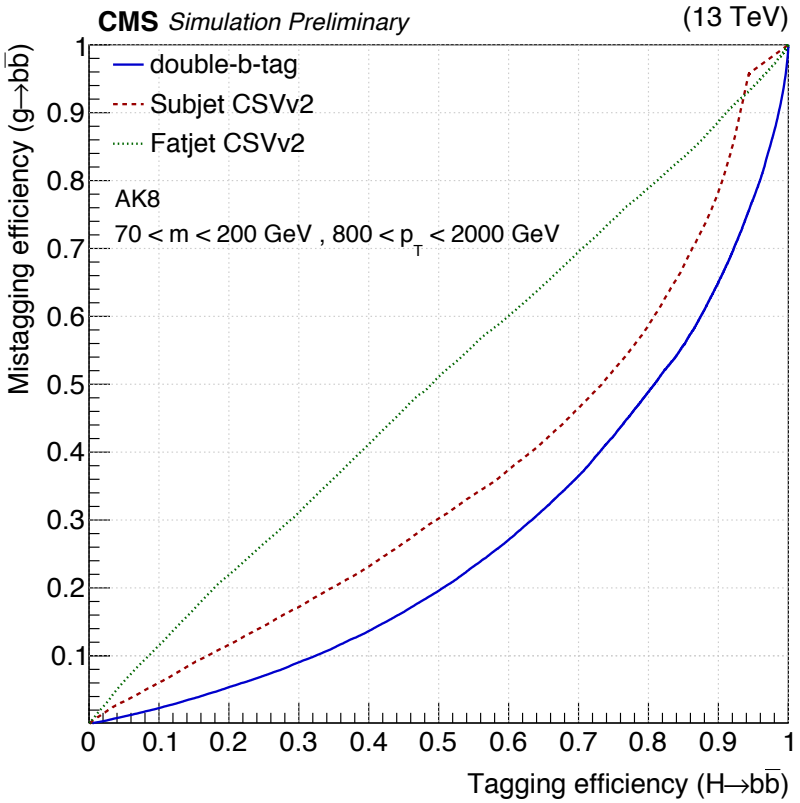


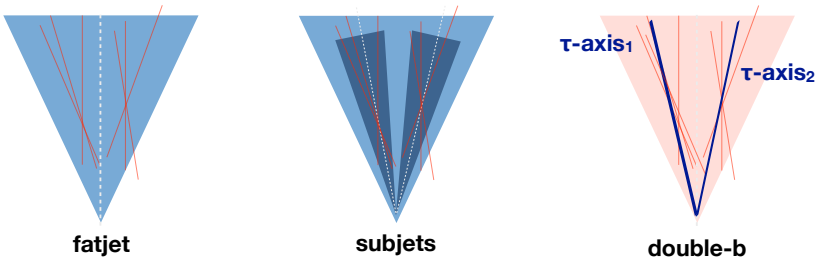


PLB 725 (2013) 357

- Momentum sharing between leading subjets
- Suffice to say, strong interest in studying to what extent medium can resolve nearby partons in the presence of coherence effects

Double b-tagging





- "Fat" jets containing two b quarks studied extensively in pp
- Their primary concern: H→ bb vs. g→ bb

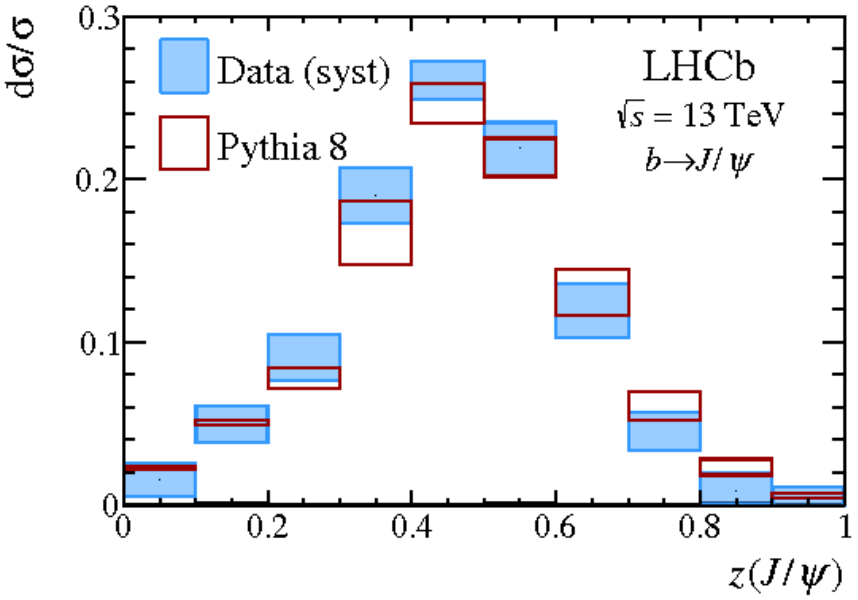
Would be very interesting to study the substructure of g→ bb jets in heavy ions

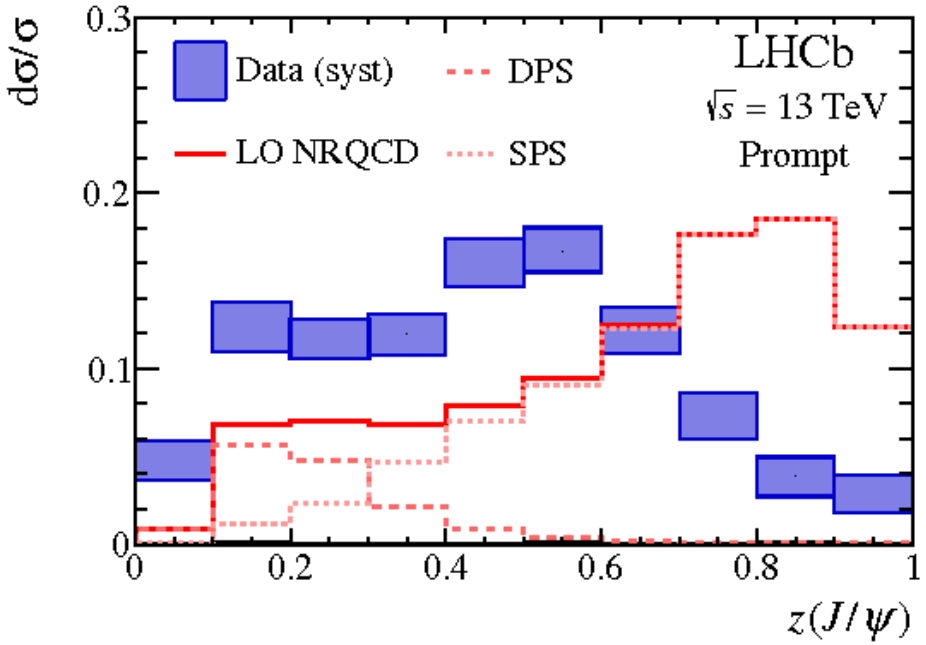
CMS-PAS-BTV-15-002

Bound states in jets

Whereas open beauty fragmentation is well-described by standard MCs….

Prompt J/ψ are much more jetty than one would expect



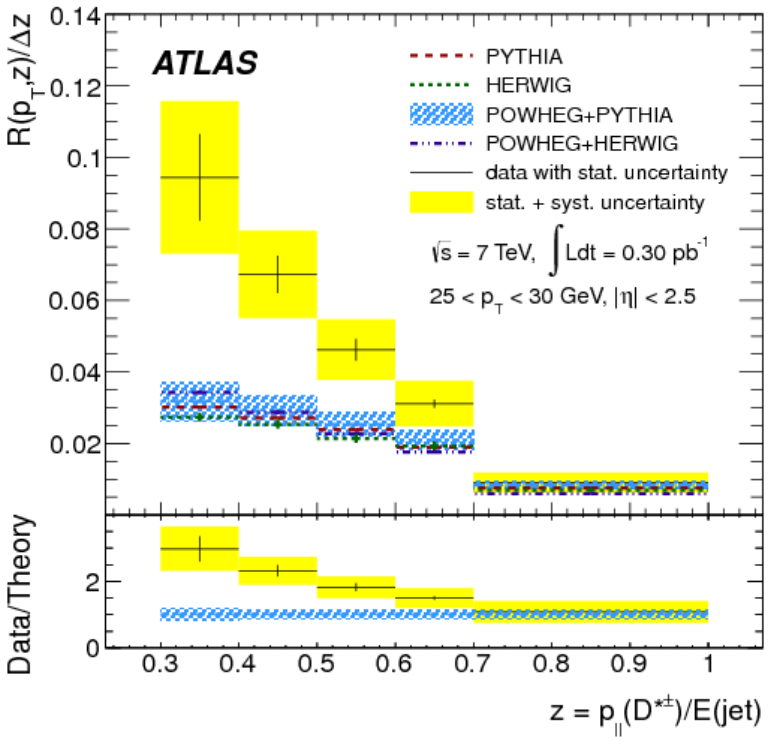


In fact, prompt J/ψ fragmentation looks rather similar to open beauty (aside from a secondary low z peak, apparently from DPS)

If J/ψ's are jetty, how do these jets quench? → would be very interesting to measure the j/ψ z distribution in heavy ions

D* in jets

- Open charm fragmentation not particularly well described by MC either, even including NLO
- Suggests late production of charm is underestimated
- Discrepancy gets smaller with increasing jet p_T

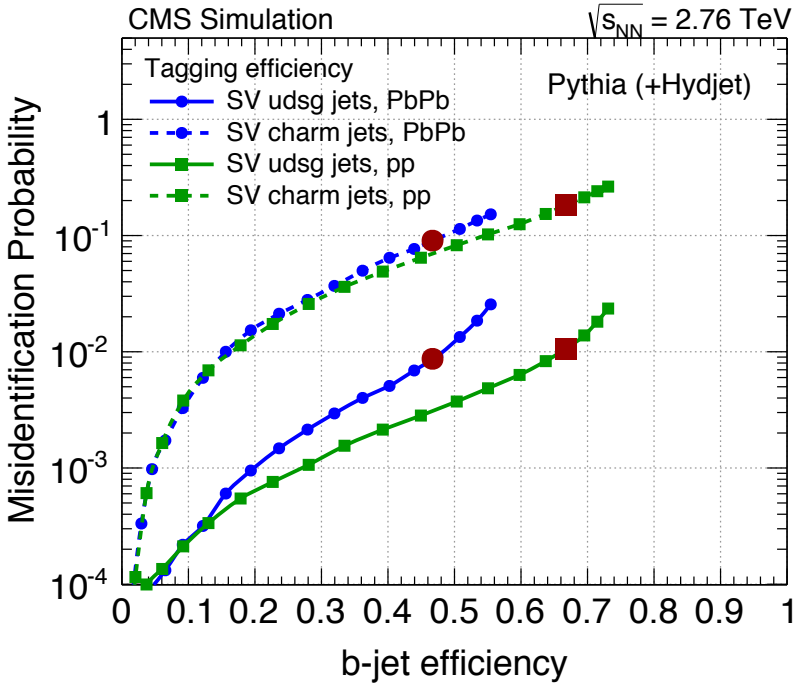


Conclusion / Outlook

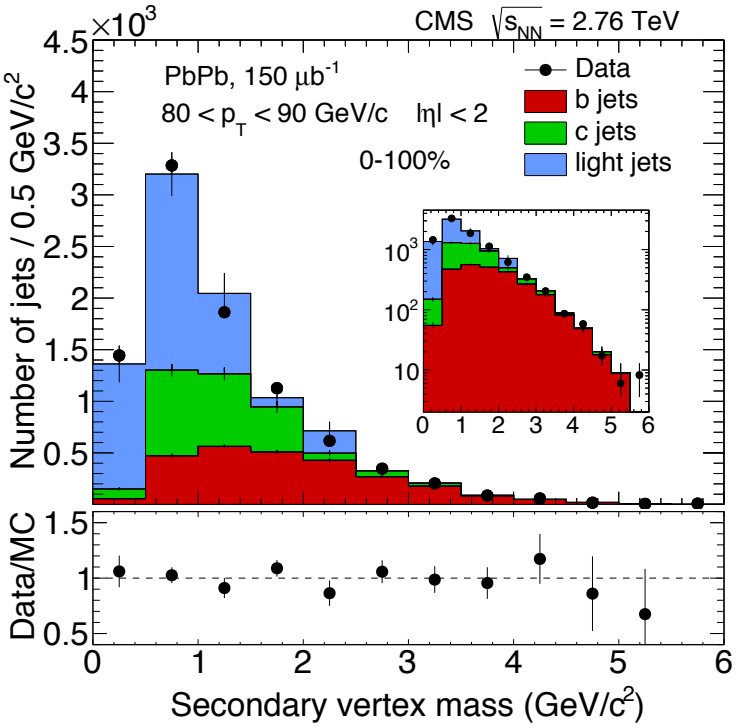
- LHC Run 1: b-jet ID was demonstrated in AA
- b-jet spectra measured in pp, pA, AA
- c-jet identification also demonstrated in pp, pA
- 1st Run 2 measurement: b-bbar dijet imbalance
- So far no difference in R_{AA} w.r.t. inclusive jets
- Plenty of prospects w/ Run 2 data and beyond

b jets in Run 1: cut & fit

Cut on flight distance significance of the secondary vertex in the jet



Fit the mass distribution of the remaining jets to extract the b signal

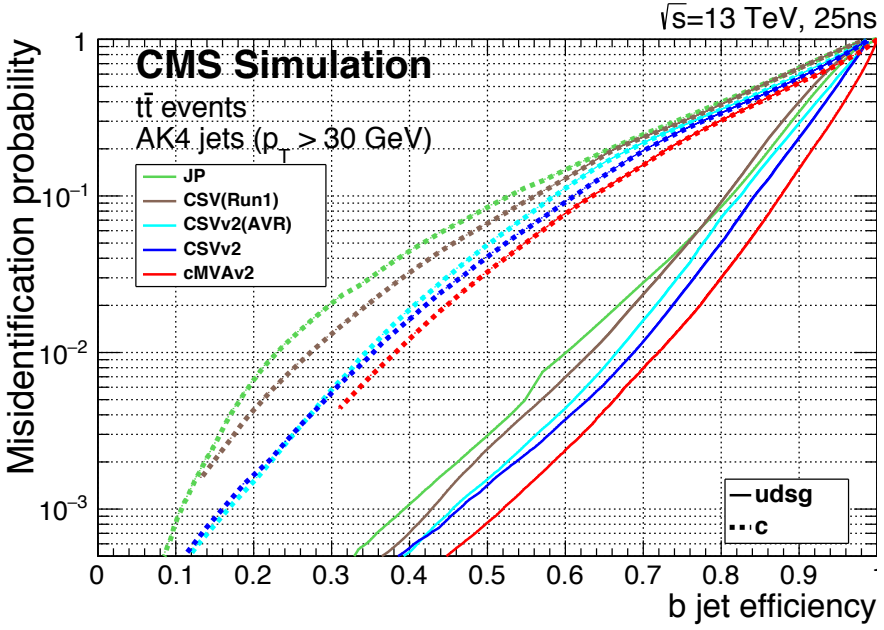


Compared to pp:
Reduced b-jet efficiency from tracking
Similar c-jet contamination
Larger light jet bknd from combinatorics

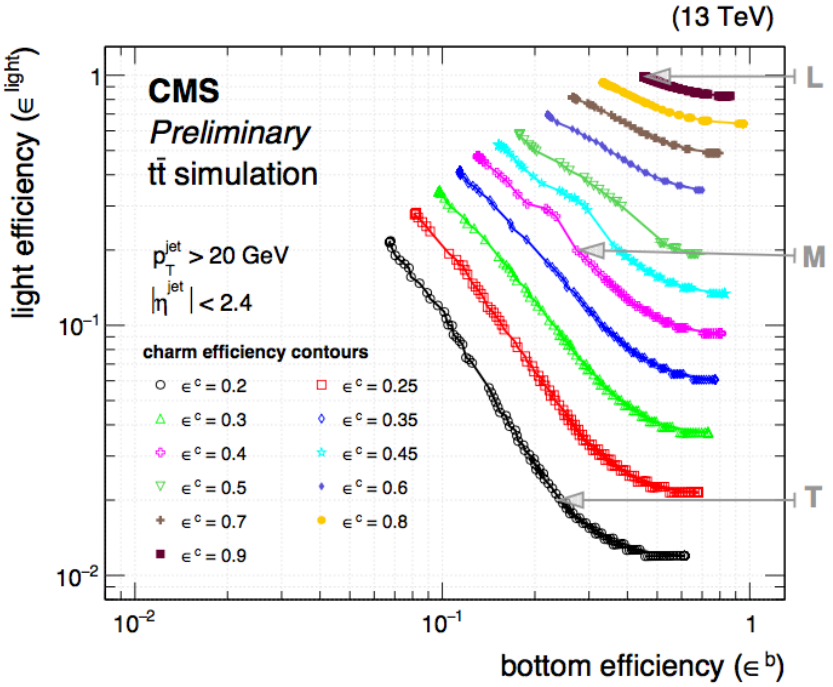
Despite larger light jet background, Quenching, etc., fit works remarkably well! [PRL 113 (2014) 132301]

Flavor tagging in Run 2

"Identification of b quark jets Run 2"
CMS-PAS-BTV-15-001



"Identification of c-quark jets"
CMS-PAS-BTV-16-001



- Moving away from the cut & fit strategy towards fancier things
- Combined secondary vertex (CSV) uses a larger number of variables, SV mass, SV p_T, # of tracks, etc. in a multivariate estimator
- Recent iterations based on Boosted Decision Trees or Deep Learning