Heavy quark jets with CMS

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Heavy quark jet results

- b-jet R_{AA}

  PRL 113 (2014) 132301
- b-dijet p_T balance in PbPb

  JHEP 1803 (2018) 181

} This talk

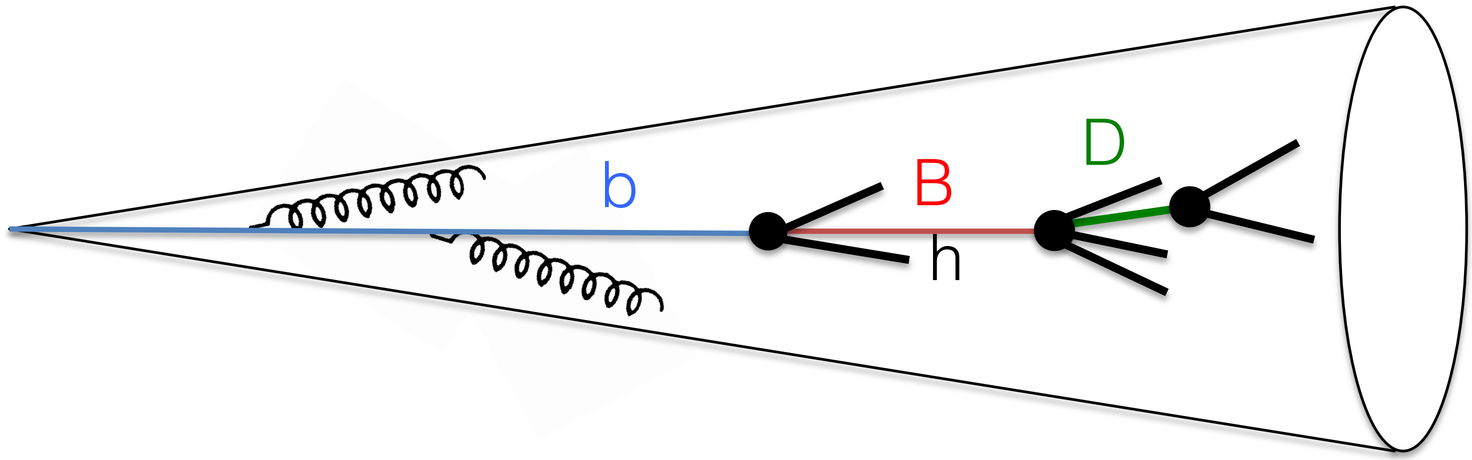
- J/ψ-jet fragmentation in pp ← Inna's talk

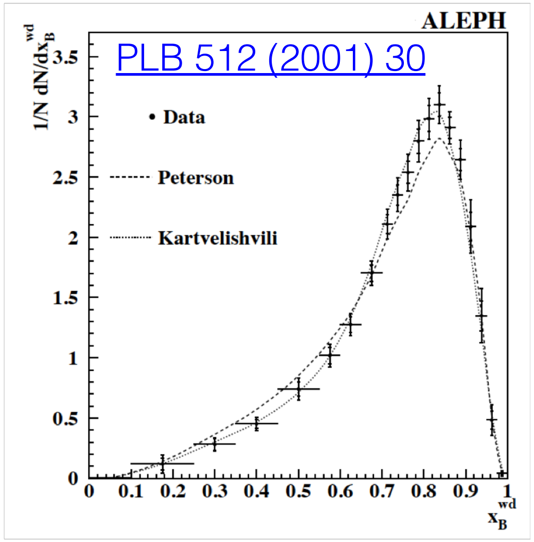
  CMS-PAS-HIN-18-012
- Will not discuss b-jet and c-jet results from pPb

  PLB 754 (2016) 59, PLB 772 (2017) 306
- Heavy flavor tagging methods in CMS for Run 2

  JINST 13 (2018) P05011

Properties of b-hadrons

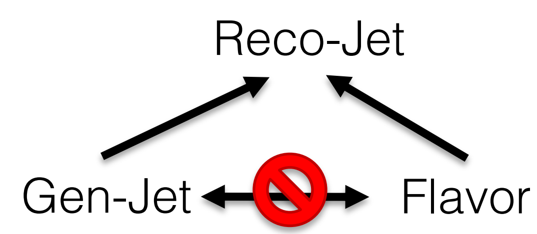




- Fragment hard, $\langle z_B \rangle \sim 0.7 - 0.8$
- B→D cascading decays are typical
- Large decay multiplicity, $\langle n_{ch} \rangle \sim 5$
- Long-lived hadrons cτ ~ 500 μm → mm – cm displacement in lab frame
- Tend to decay semi-leptonically (20% for μ and e)

Defining heavy quark jets

- HQ jet *not*, strictly speaking, initiated by a heavy quark
- Heavy hadrons are reclustered into jets as *ghosts*
- A b-jet is a jet containing one or more b-hadrons
- A c-jet is a jet containing one or more c-hadrons & not containing any b-hadrons
- MC truth association in CMS

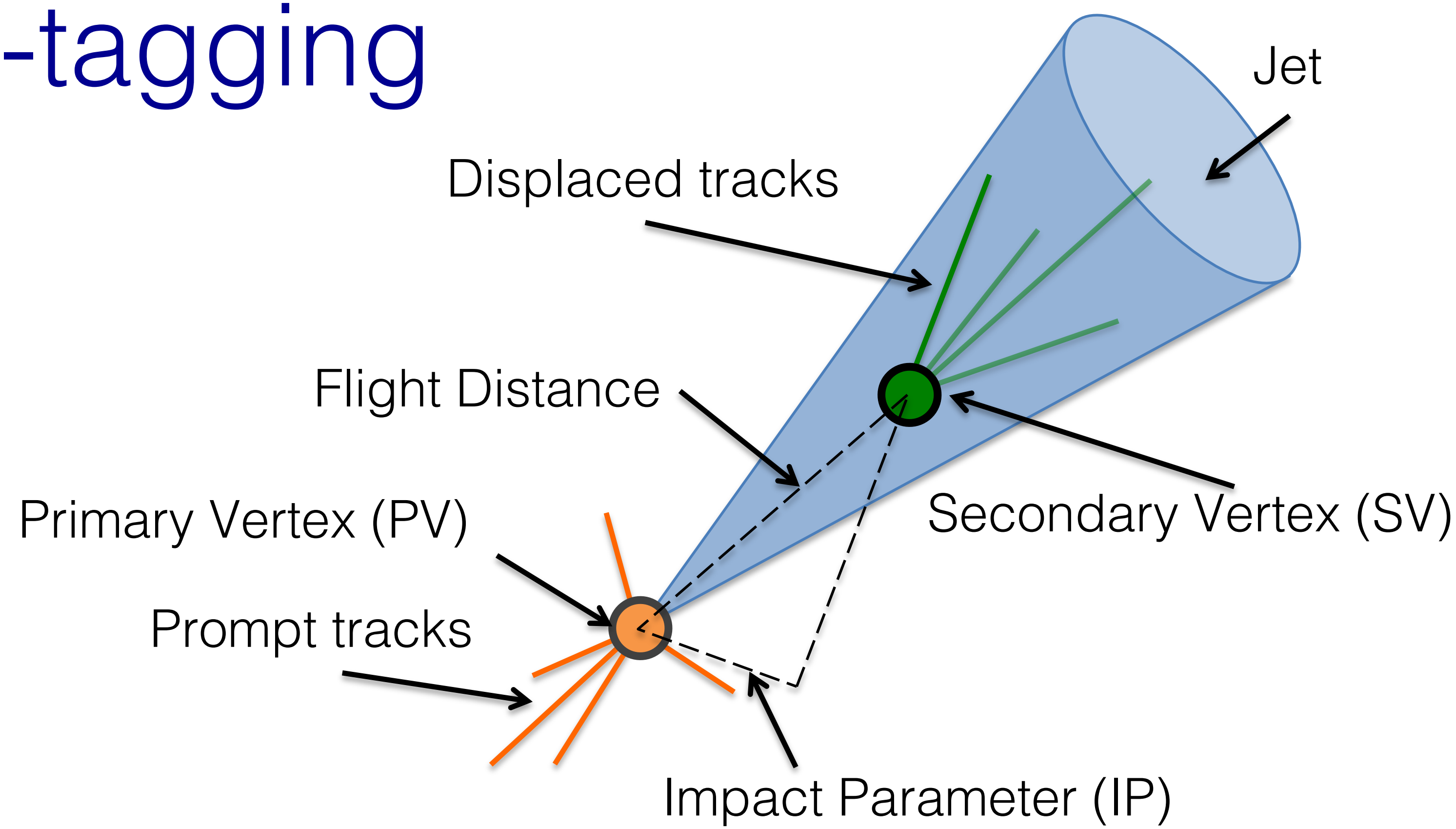


- HI MC typically overlays signal event, e.g., Pythia with PbPb UE, e.g., Hydjet

➢ Gen info only matched to signal event, HQ jets from UE are a source of “fakes”

Same approach used for PU in pp

b-tagging



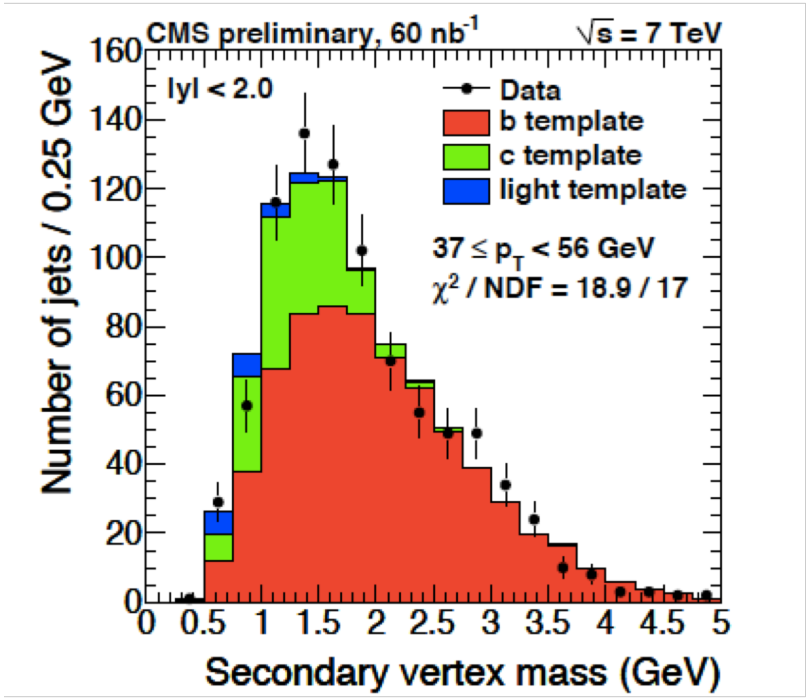
- Lifetime methods: Exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays
- Soft-lepton tagging: μ or e inside the jet
- In-situ methods for tagging efficiency and mistagging rate

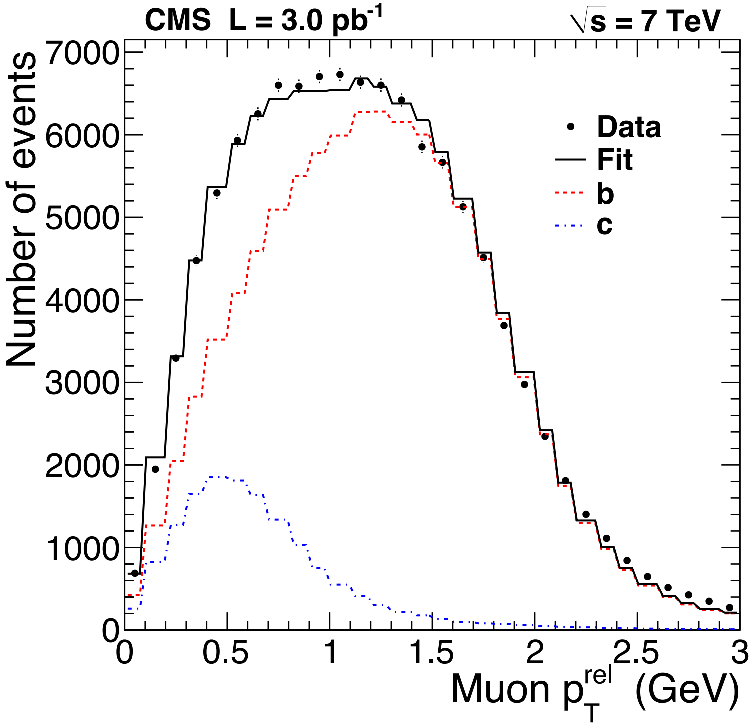
b-tagging in pp @ 7 TeV

JHEP 1204 (2012) 084

Run 1 strategy: cut & fit

1) Select reasonably large flight distance vertices (w/ ≥ 2 or ≥ 3 tracks)
2) Template fit on SV mass or lepton p_T relative to jet axis



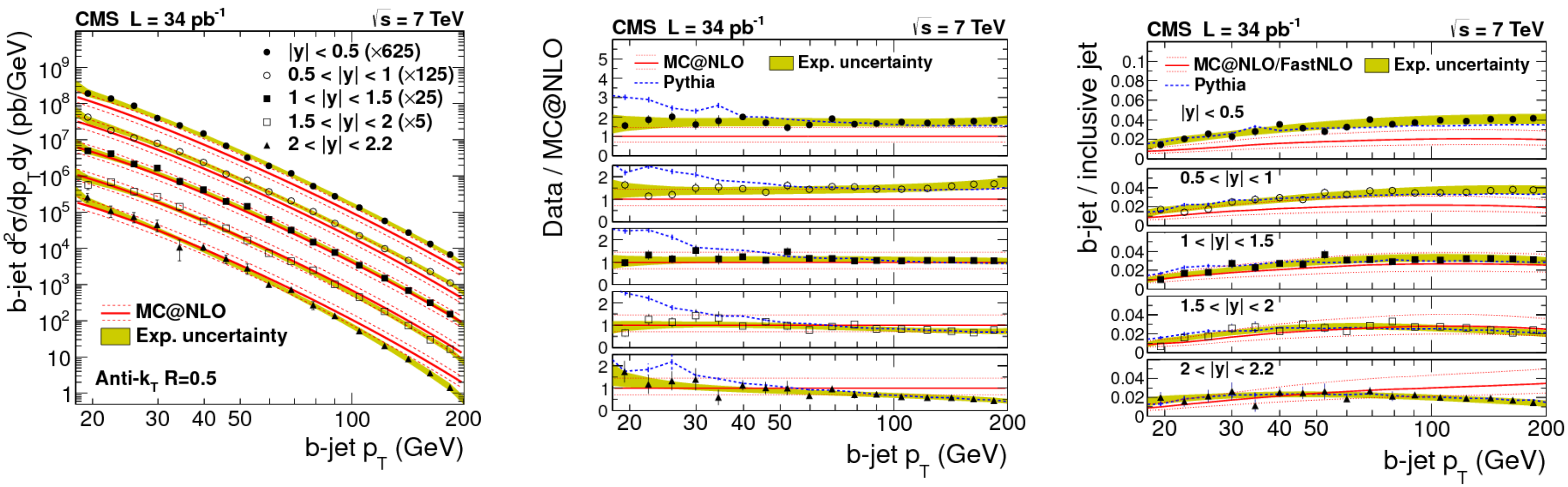


Soft muon tagging used as a cross-check

Review of Run 1 b-tagging methods in CMS: JINST 8 (2013) P04013

b-jet x-section in pp @ 7 TeV

JHEP 1204 (2012) 084

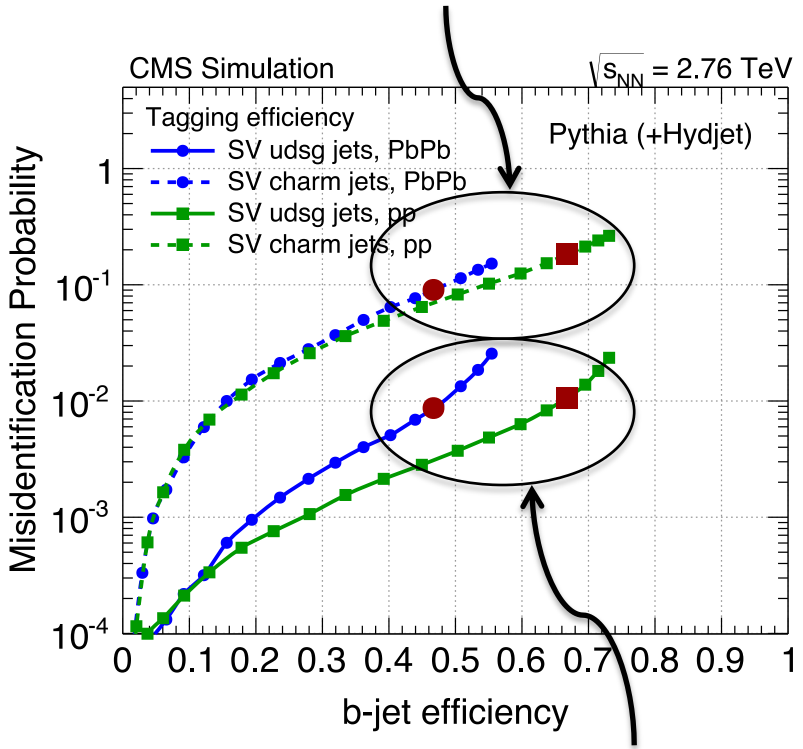


- Neither Pythia nor MC@NLO describes the cross-section well over full range
- Powheg + Pythia does a better job (see ATLAS, EPJC 71 (2011) 1846)
- Pythia alone does a good job with the b-jet fraction
- Expect Run 2 update from CMS soon

b-tagging in PbPb (Run 1)

b-tagging efficiency reduced,

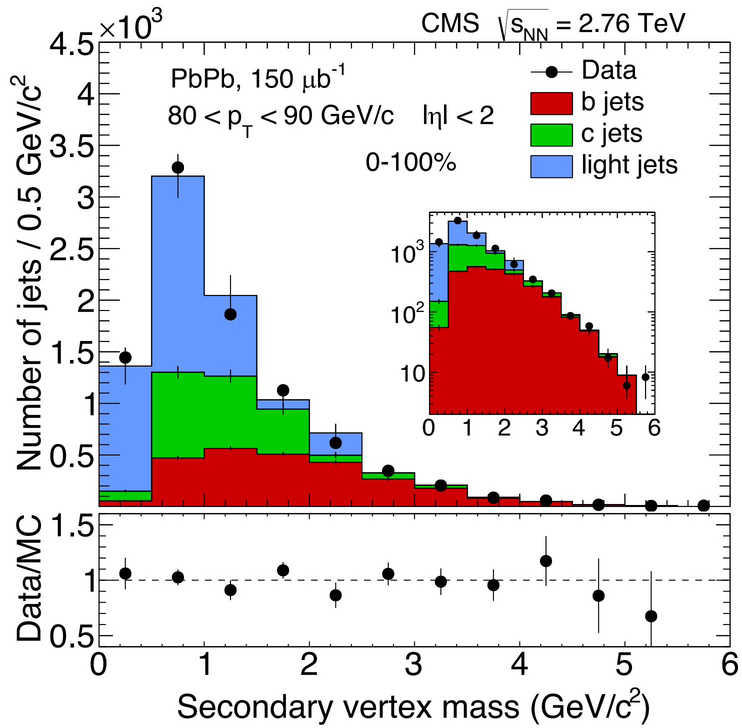
but c-jet rejection fixed (wrt pp)



Light jet mis-tagging rate in PbPb

increased due to combinatorics

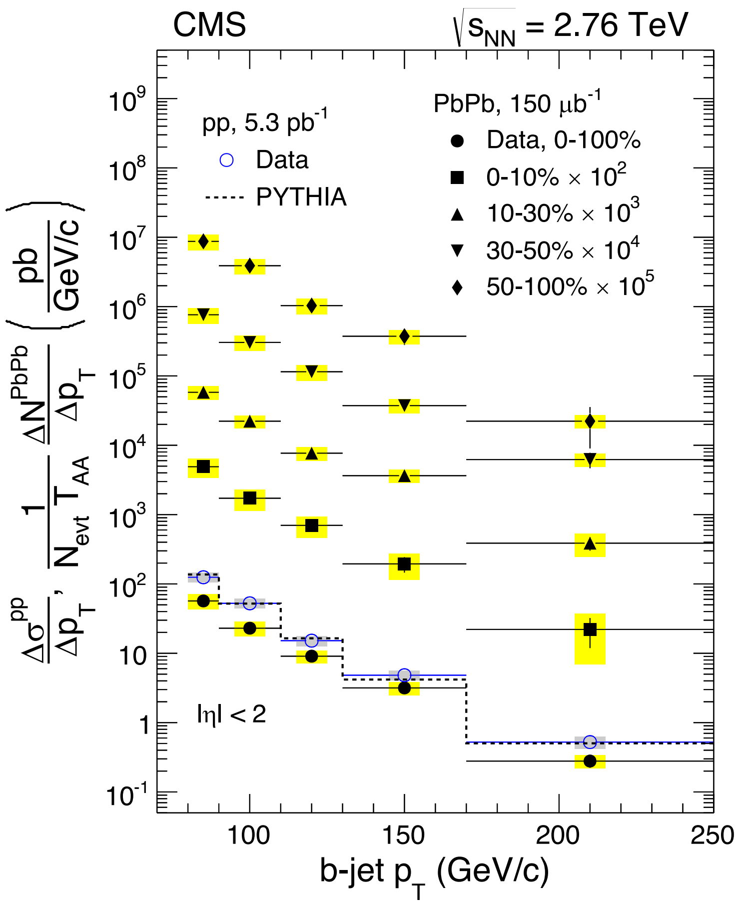
PRL 113 (2014) 132301



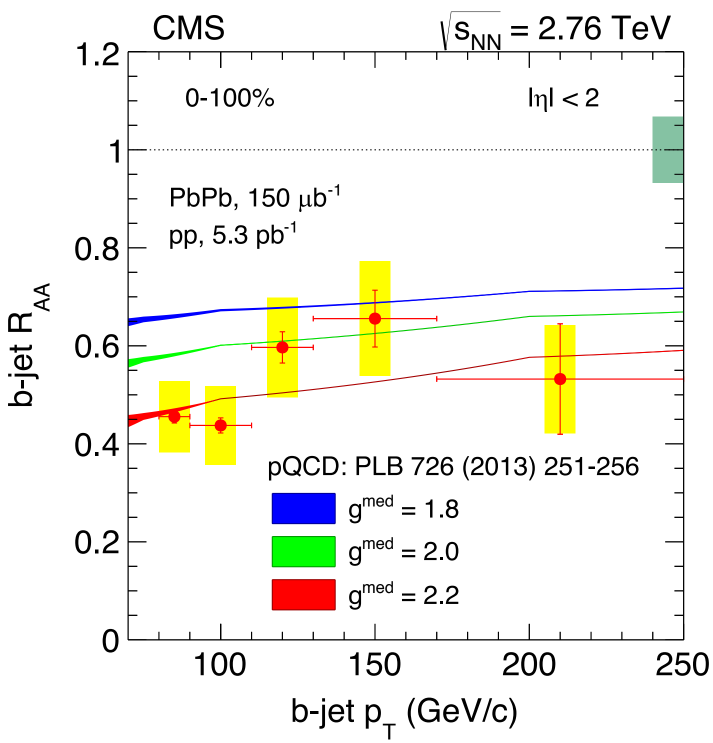
Despite larger light jet background,

fit works remarkably well!

b-jet x-section & R_{AA}



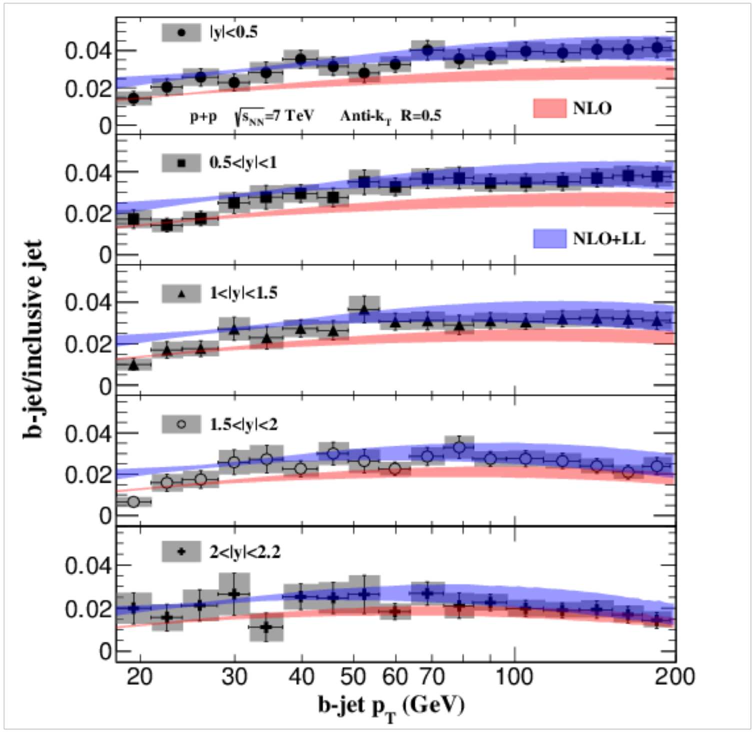
PRL 113 (2014) 132301



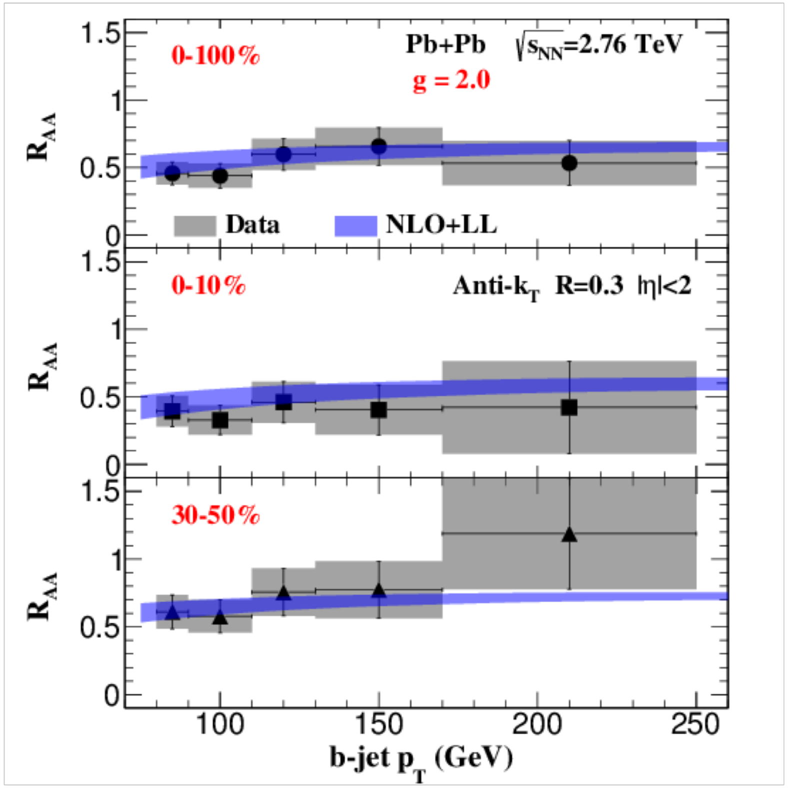
- Unfolded jet spectra for several centrality selections and pp
- Suppression consistent w/ medium-coupling from inclusive jets

State-of-the-art calculations

SCET used to perform large R resummation   Li & Vitev, arXiv:1811.07905



Improved description of b-jet fraction, compared to NLO

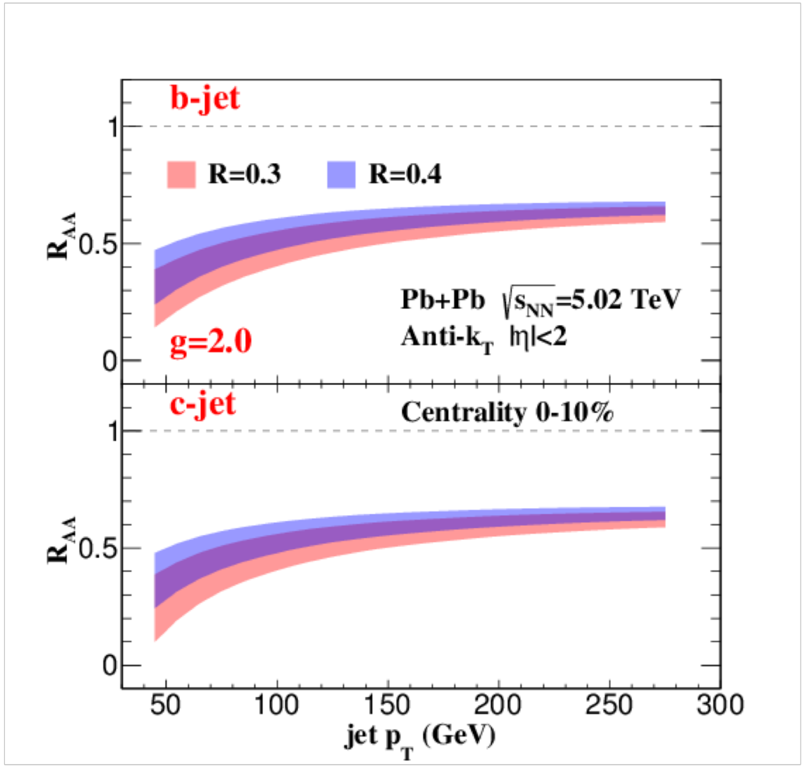


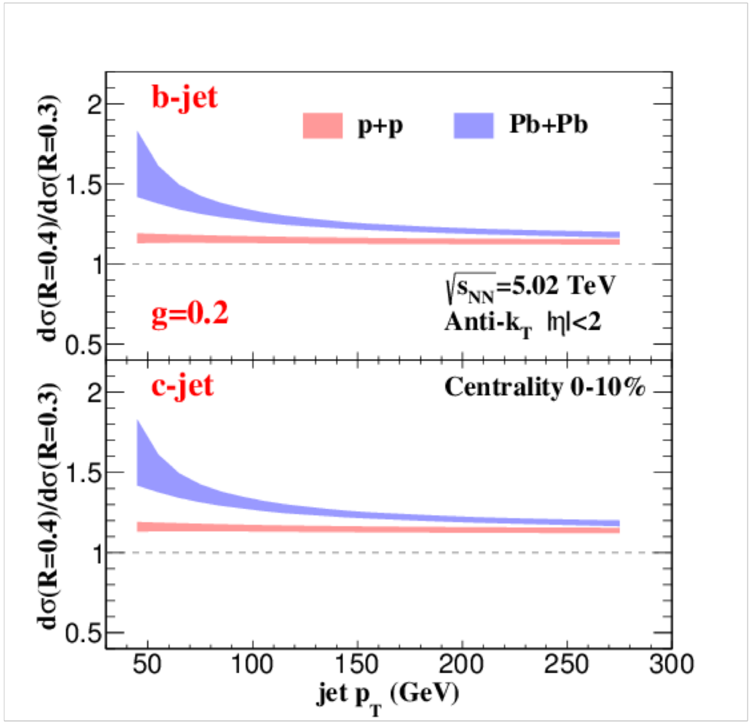
Consistent with R_{AA} data, with medium coupling parameter = 2.0

g→bb shower component:
Dai, Kim & Leibovich, JHEP 1809 (2018) 109

… and interesting predictions

Li & Vitev, arXiv:1811.07905

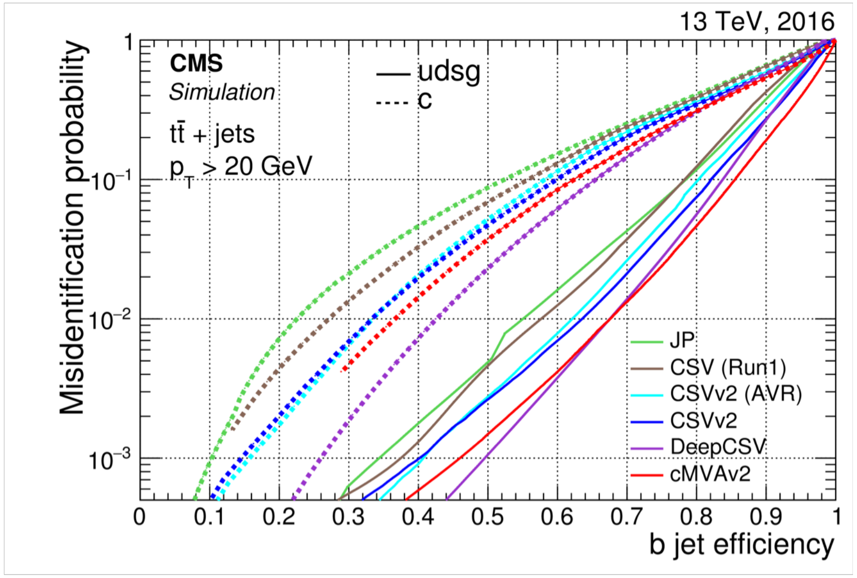




- Radiative e-loss depends on R, while collisional e-loss (and CNM) does not

  → R dependence of R_{AA} would test the relevance of these two processes
- Also an interesting discussion of CNM effects, which may be large for b-jets

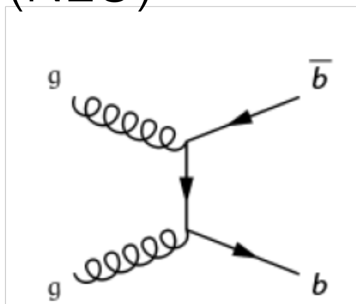
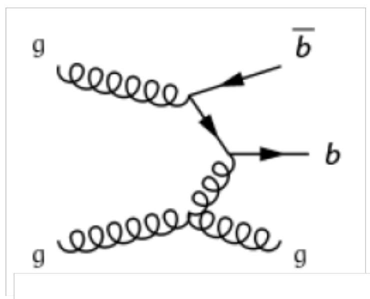
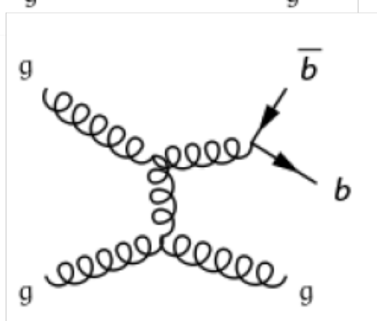
State-of-the-art flavor tagging

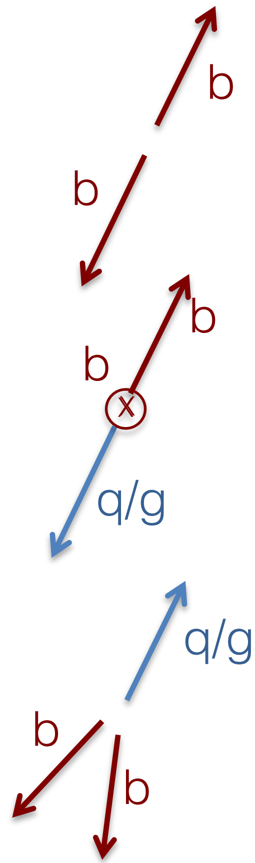


JINST 13 (2018) P05011

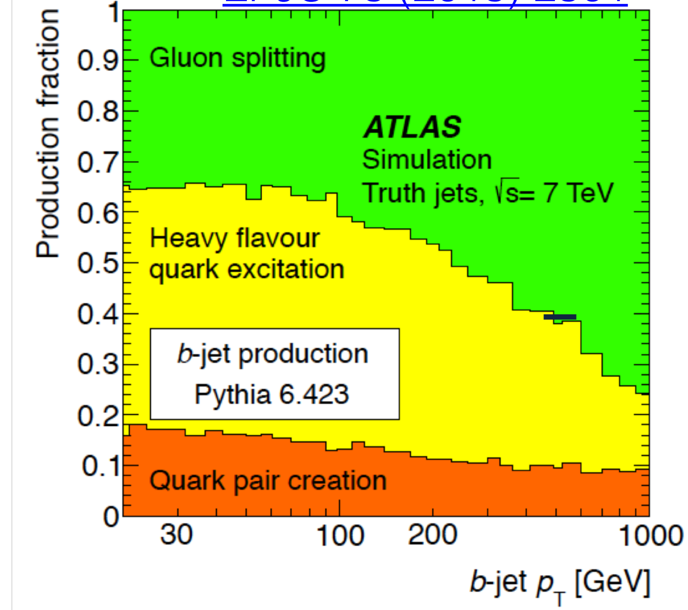
- Early Run 2 results rely on *Combined Secondary Vertex* (CSV), uses a large number of SV and IP variables in an MVA
- Recent results use a deep learning tagger, "DeepCSV"

Heavy flavor production

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

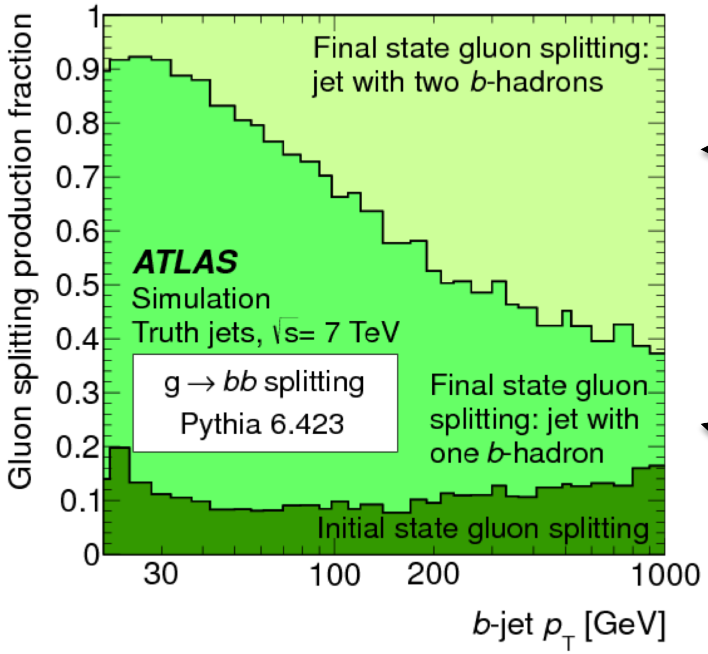


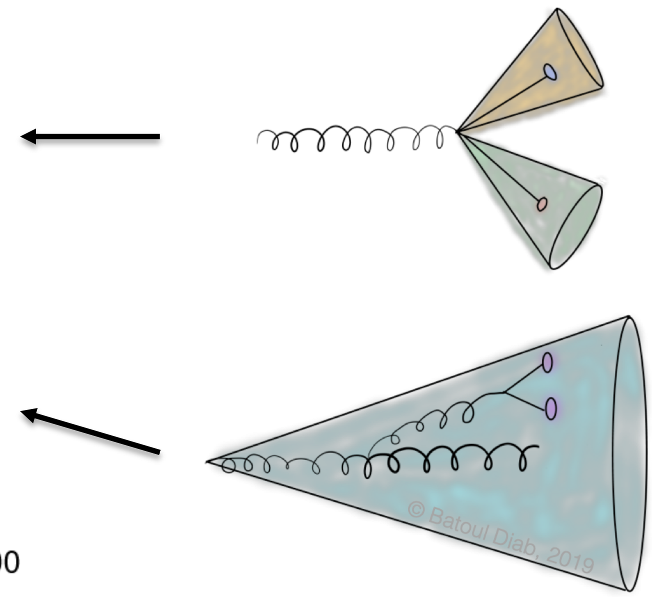
EPJC 73 (2013) 2301



Leading order type production subdominant

Gluon splitting



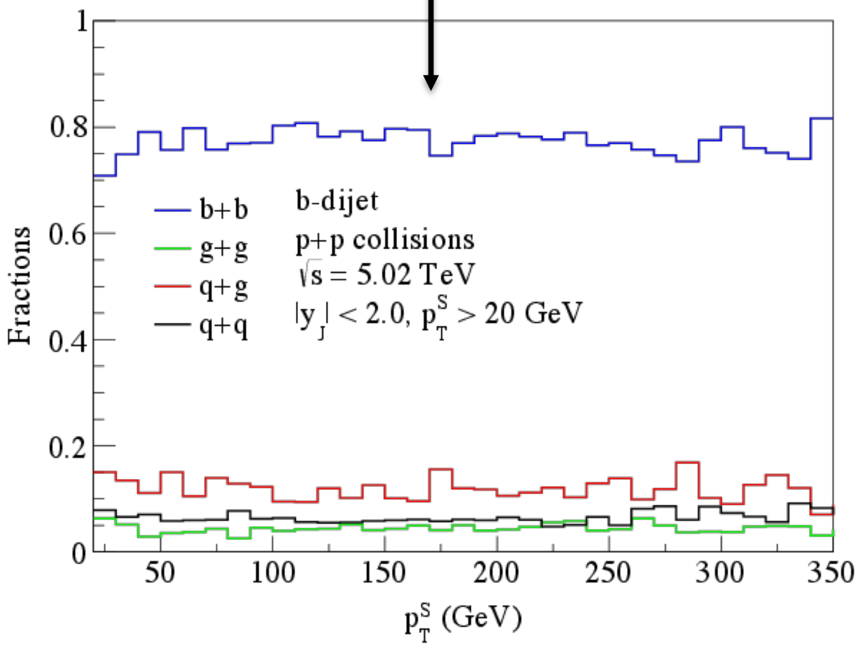


- Harder splitting tends to give distinct jets
- Softer splitting, i.e., in parton shower, tends to give a single jet

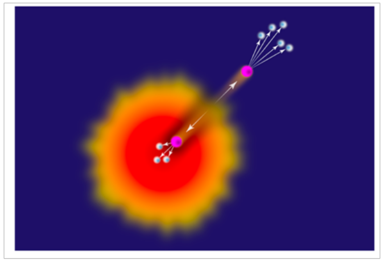
* E-loss for merged b-jets should be different from primary ones

b-bbar correlations

Recoiling b-jets feature enhanced primary b-jet production



Kang, Reitan, Vitev & Yoon, arXiv:1810.1000

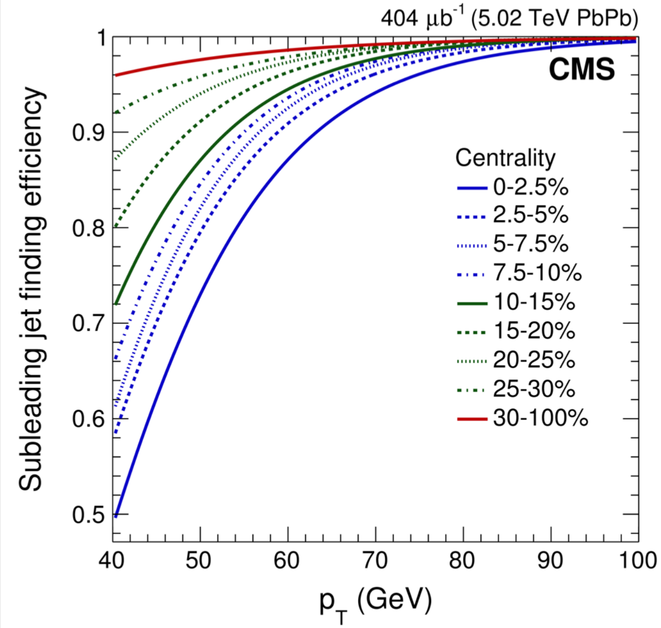


Dijet p_T balance is a natural observable for this channel

Dijet selection

- CMS dijet p_T balance analyses select leading & subleading jets (within some η window)
- Boson+jet analyses instead select all jets on the recoil side
  - Pro: Easier to deal w/ combinatorial background (via mixed events), allowing to go to lower p_T jets
  - Con: Less balanced initial state
- b-dijets use leading / subleading
  - Additional recoil jets tend to come from NLO-like processes (GSP, FEX)
  - Negligible combinatorial background for b-tagged dijets

Combinatorial jets can eclipse true partner jets



Subleading jet efficiency determined directly from the inclusive jet p_T spectrum in data

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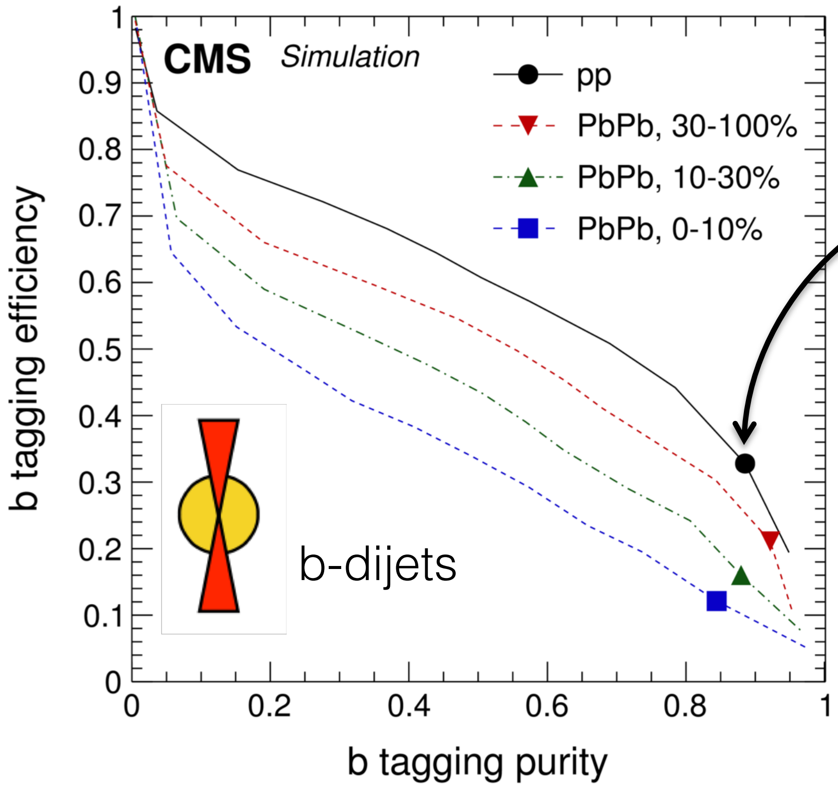
Performance for b-dijets

Using Combined Secondary Vertex



Extremely tight working point ~ 90% purity

Cost is efficiency of 10 – 30%

Remaining background is from heavy flavor (bl, cc, cb)

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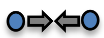
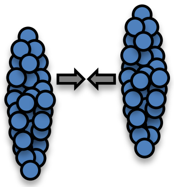
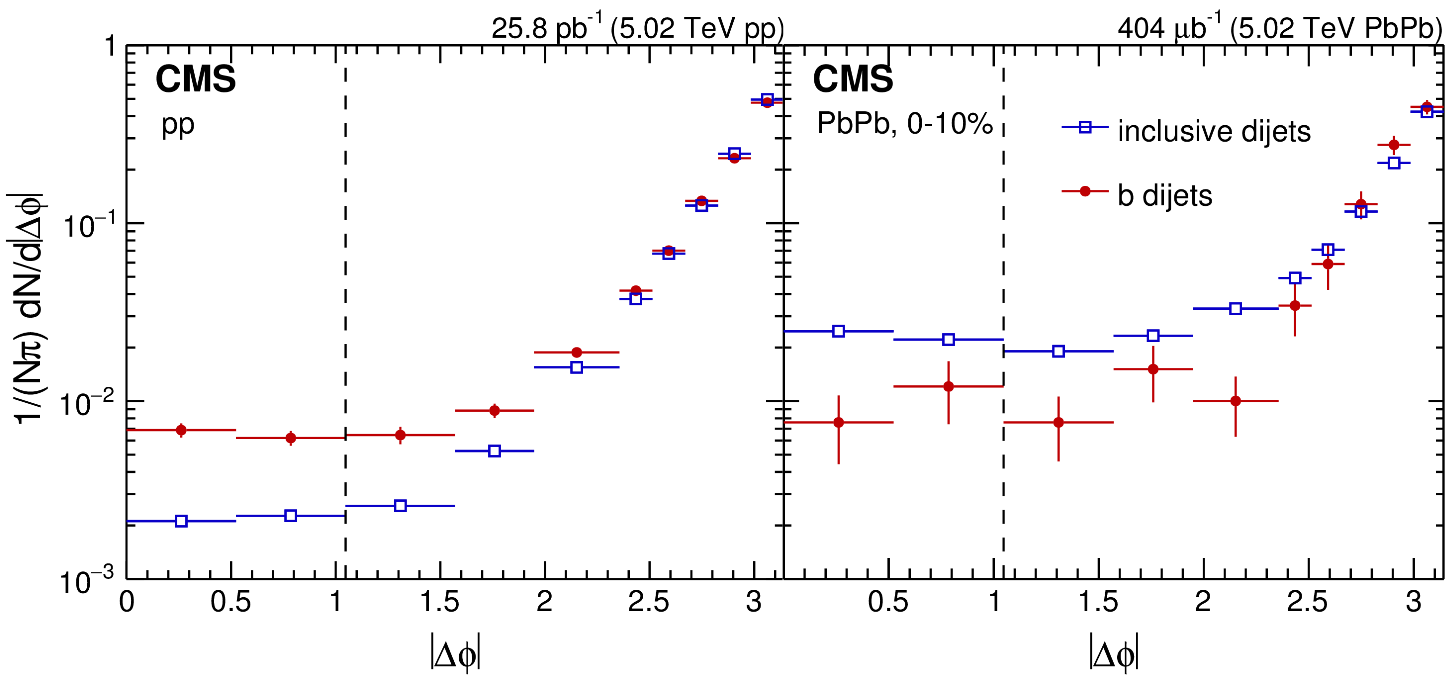
Δϕ correlations





$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$|\eta| < 1.6$



- No significant angular deflection for b-jets (as for inclusive jets)
- Nearly no combinatorial background for b-jets due to tagging

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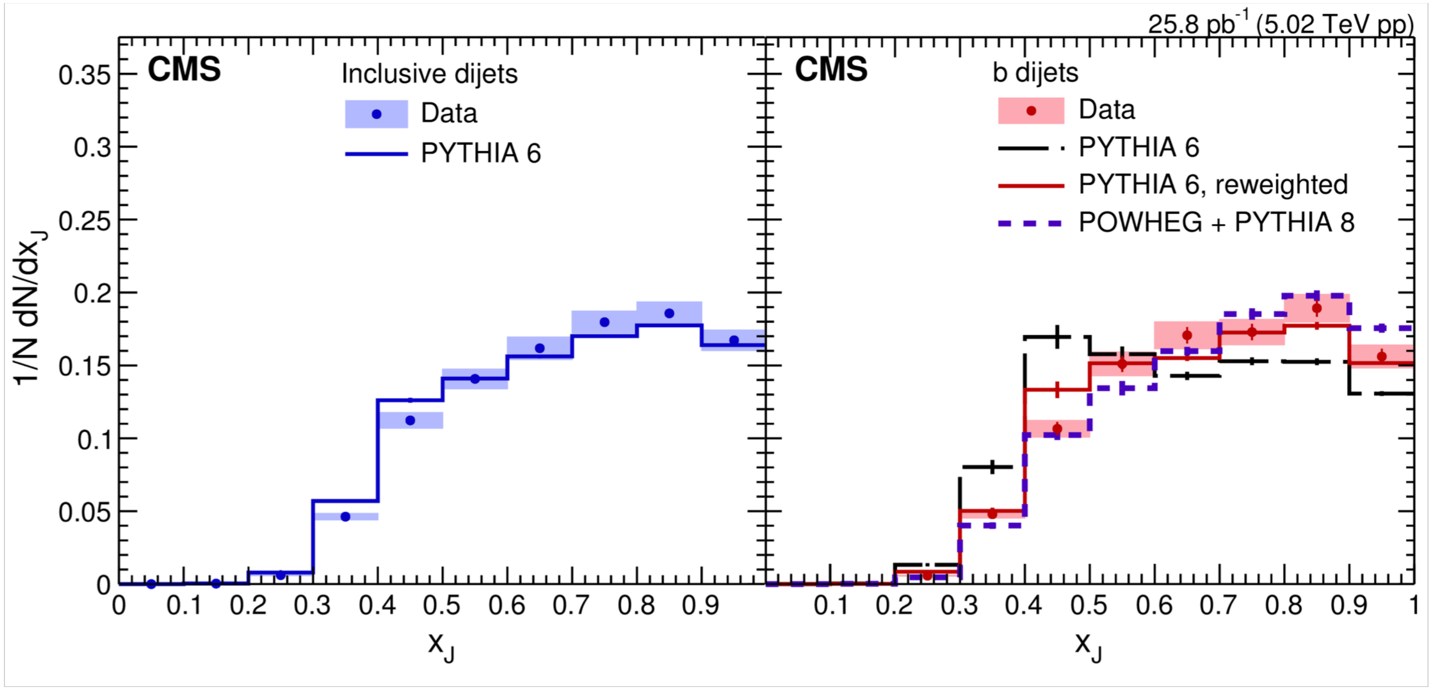
(b)-dijet p_T balance in pp



$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.6$

- Similar balance for inclusive and b-dijet data → useful for comparisons
- Pythia 6 works well for inclusive dijets (better than CMS tunes of Pythia 8)
- Pythia 6 works poorly for b-dijets, due to mismodelling of FEX process
- Use data-driven reweighting procedure to improve Pythia description
- Powheg + Pythia 8 works very well out of the box

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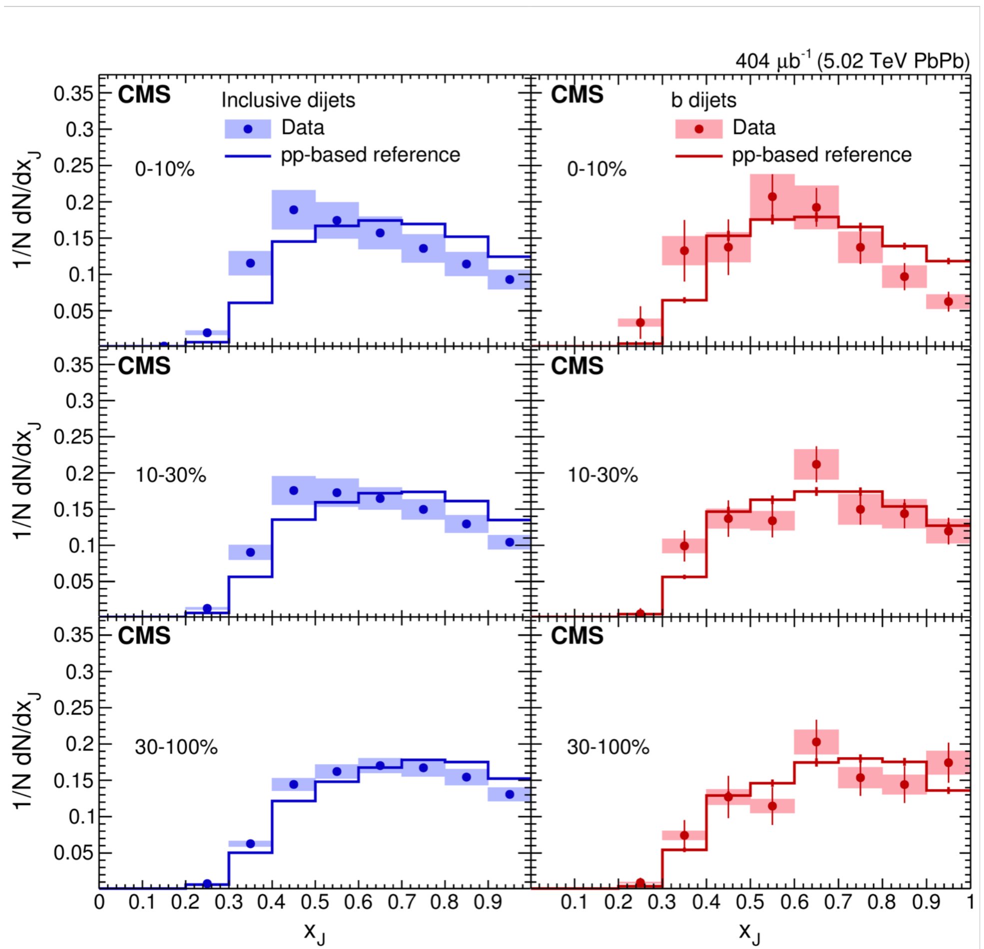
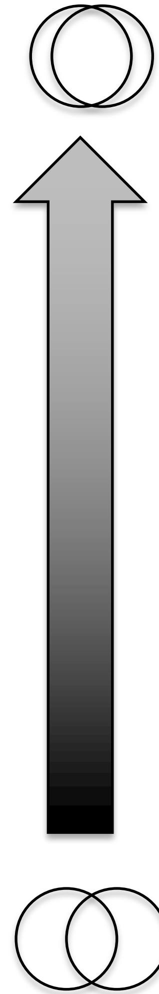
(b)-dijet p_T balance in PbPb





As for inclusive dijets, increasing imbalance w/ centrality

Reference is smeared pp data baseline

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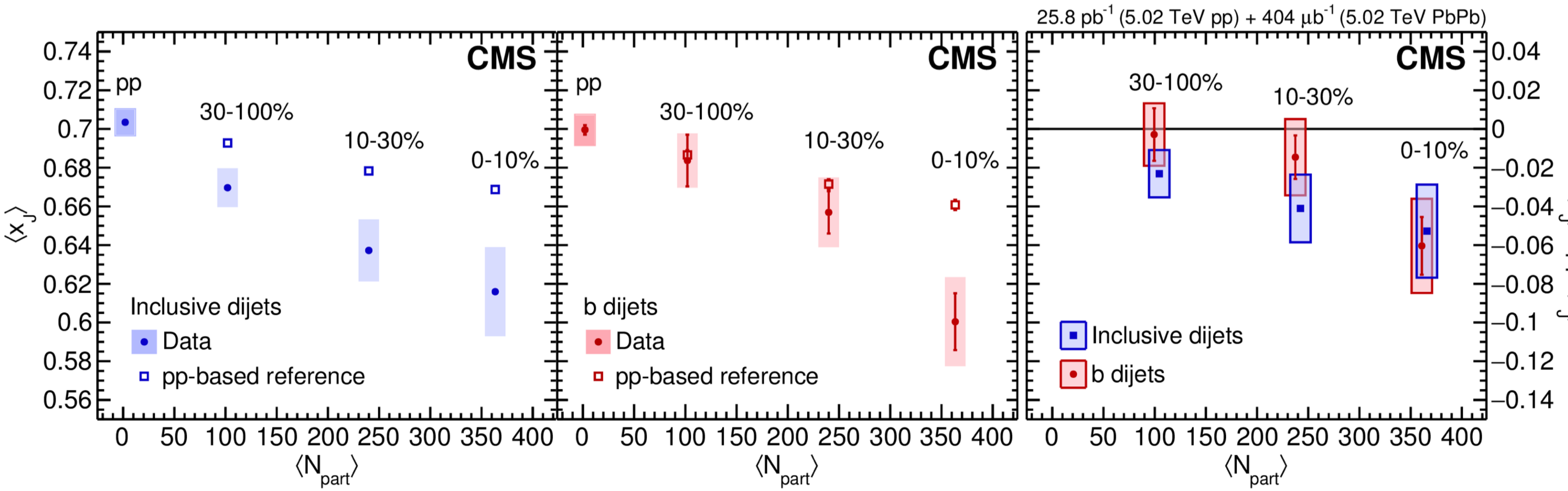
Mean p_T balance

$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.6$



Mean x_J for inclusive & b-dijet similar at level of current uncertainties

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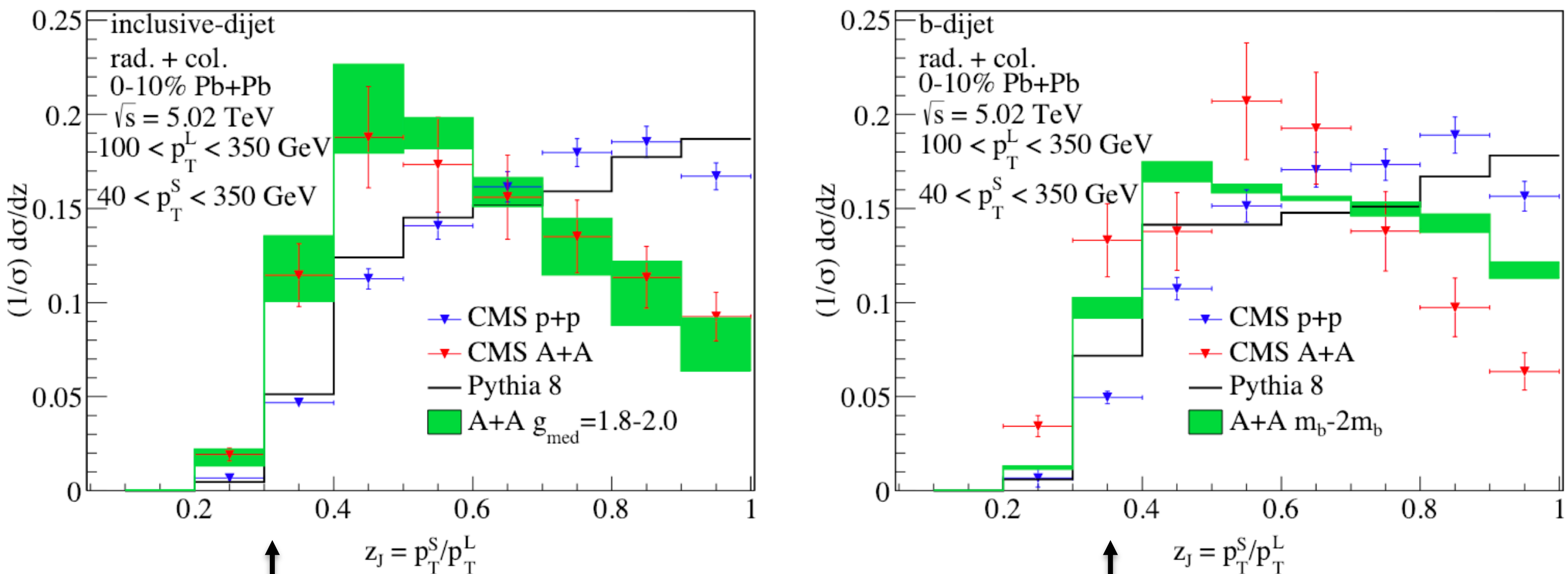
b-dijet calculations

E-loss calculations initialized w/ Pythia 8

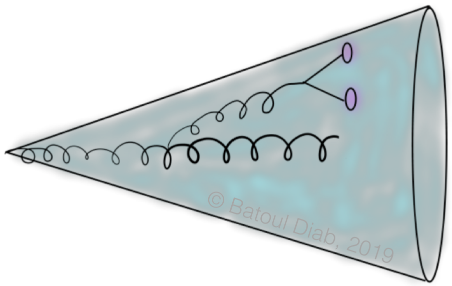
Kang, Reitan, Vitev & Yoon, arXiv:1810.1000



Good description of inclusive dijet imbalance

Reproduces our conclusion that Pythia poorly describes b-dijet pp balance

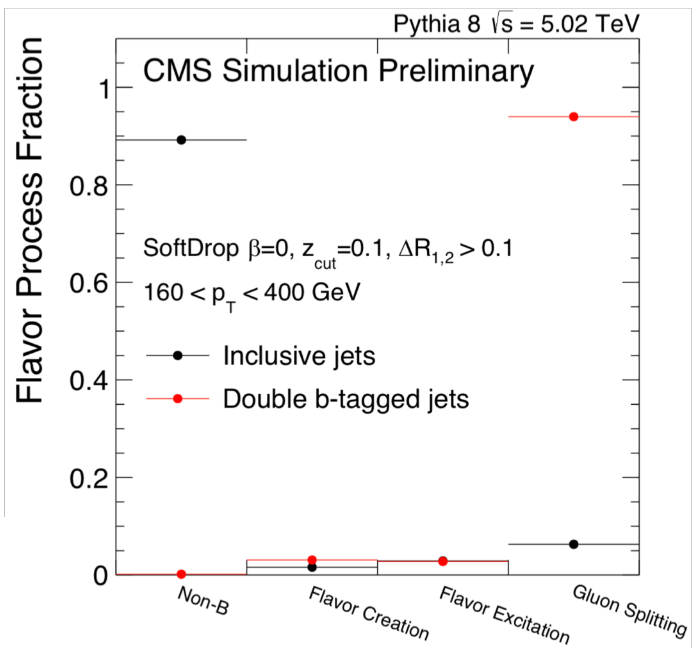
Jets with 2 heavy quarks

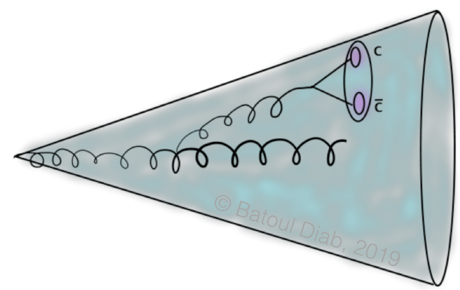


Can identify g→bb by tagging subjets

However, tagging biases distributions

(see Kurt Jung's QM17 talk)





Can also look at bound states

Subject of Inna's talk today

Conclusions & outlook

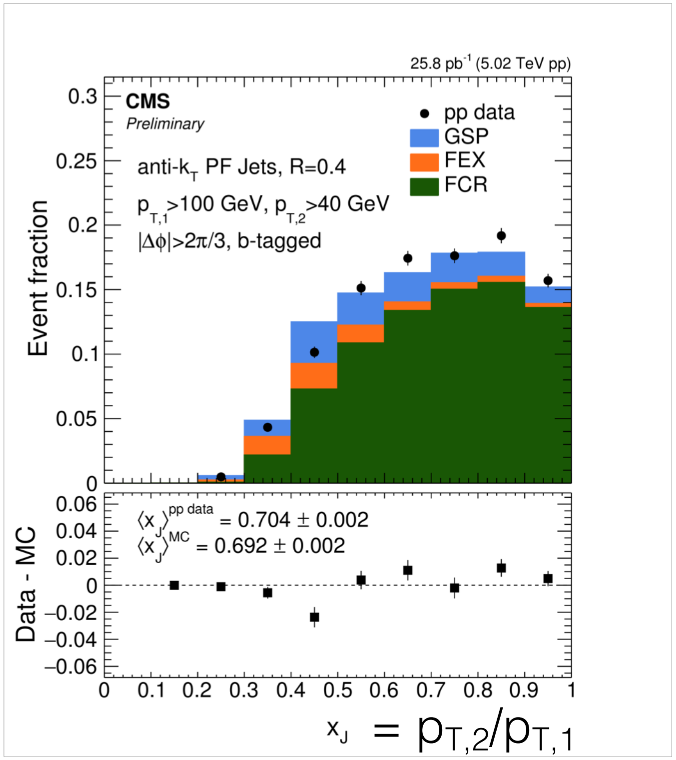
- b-jet tagging was demonstrated in heavy ions
- R_{AA} measured with Run 1 data from 2011

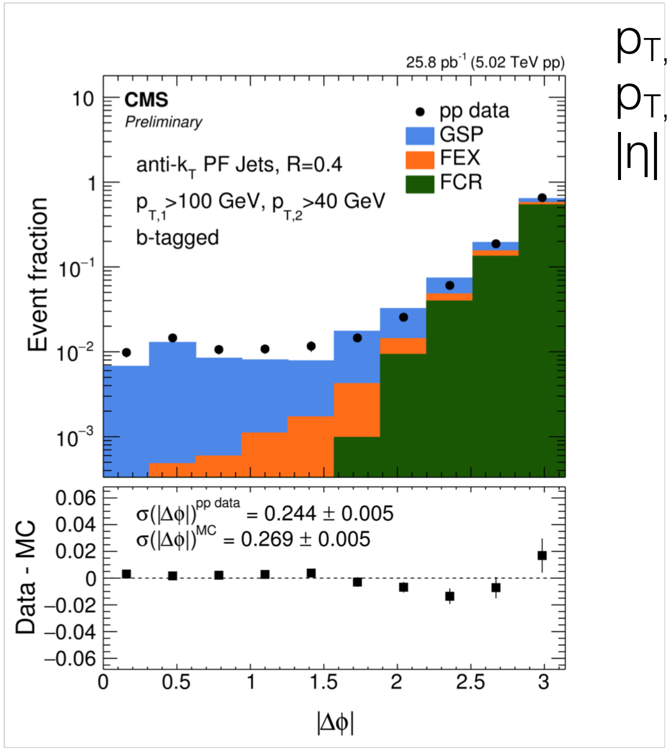
  → comparable quenching to inclusive jets
- Dijet p_T balance measured with 2015 PbPb data

  → comparable imbalance to inclusive jets
- Conclusions can be sharpened w/ reduced uncertainties
- Plan R_{AA} from 2018 PbPb data w/ updated methods

Backup

Process contribution to b-dijets





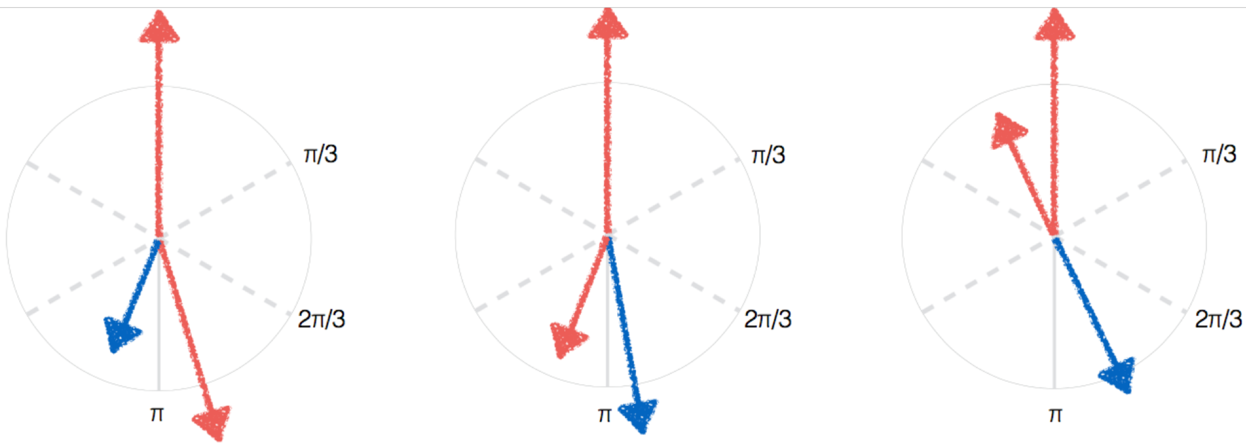
$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$|\eta| < 1.6$

- Pythia 6 gives a satisfactory description of dijet p_T and angular correlations
- After selection, flavor creation dominates (70 – 80 %)
- Pythia 8 turned out to give too imbalanced dijets overall (not just b-jets)

Flavor process reweighting

Idea: Divide 3-jet events into 3 classes, each sensitive to a different process

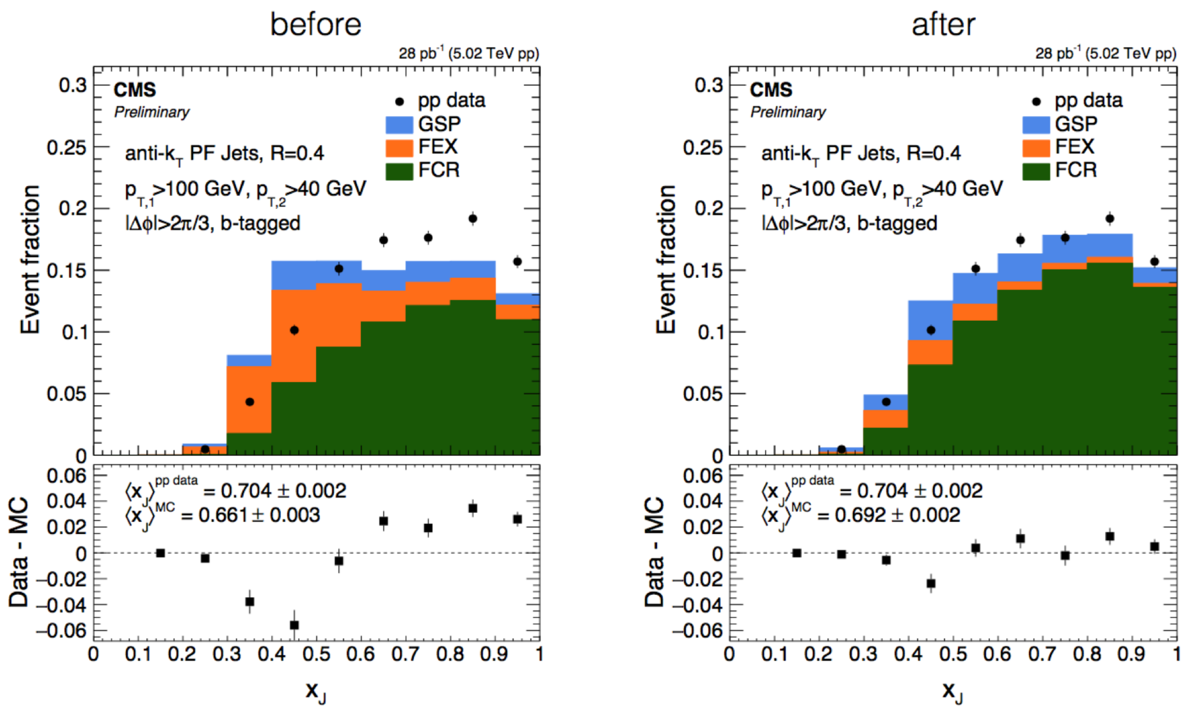
1) Two highest p_T jets are b-tagged and back-to-back ($\Delta\phi_{1,2} > 2\pi/3$)
2) 1st and 3rd highest p_T jets b-tagged and back-to-back ($\Delta\phi_{1,3} > 2\pi/3$)
3) 1st and 3rd highest p_T jets are b-tagged and nearby ($\Delta\phi_{1,3} < \pi/3$)



Category	FCR	FEX	GSP
$\|\Delta\phi_{1,2}\|>2\pi/3$	**57%**	26%	17%
$\|\Delta\phi_{1,3}\|>2\pi/3$	11%	**62%**	27%
$\|\Delta\phi_{1,3}\|<\pi/3$	0%	17%	**83%**

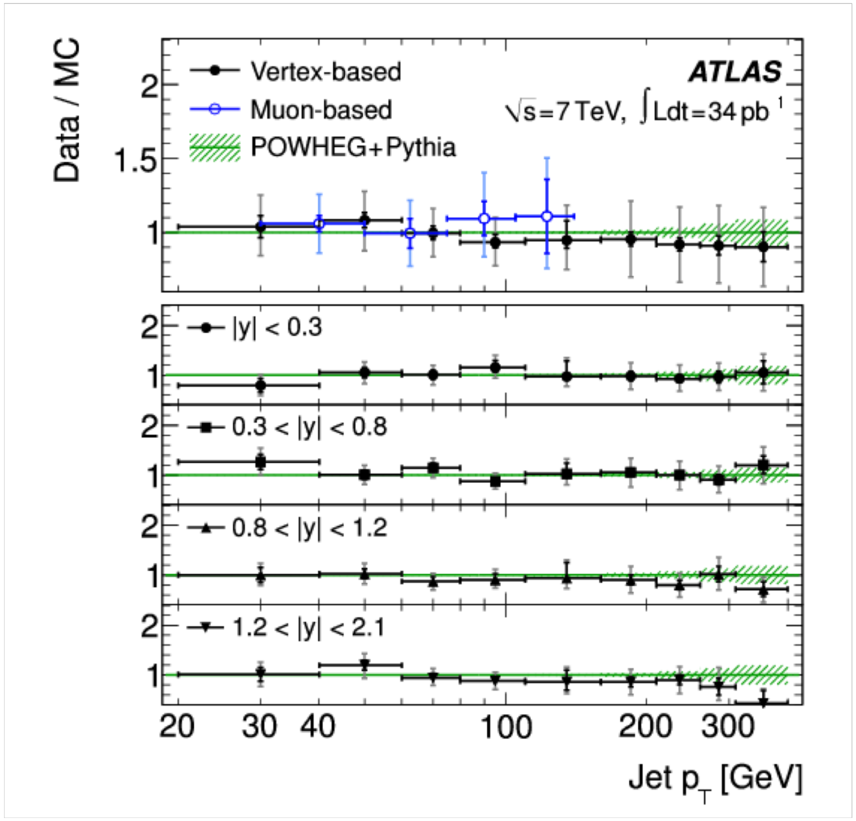
Category	MC	Data
$\|\Delta\phi_{1,2}\|>2\pi/3$	46%	56%
$\|\Delta\phi_{1,3}\|>2\pi/3$	49%	37%
$\|\Delta\phi_{1,3}\|<\pi/3$	5%	7%

Effect of reweighting

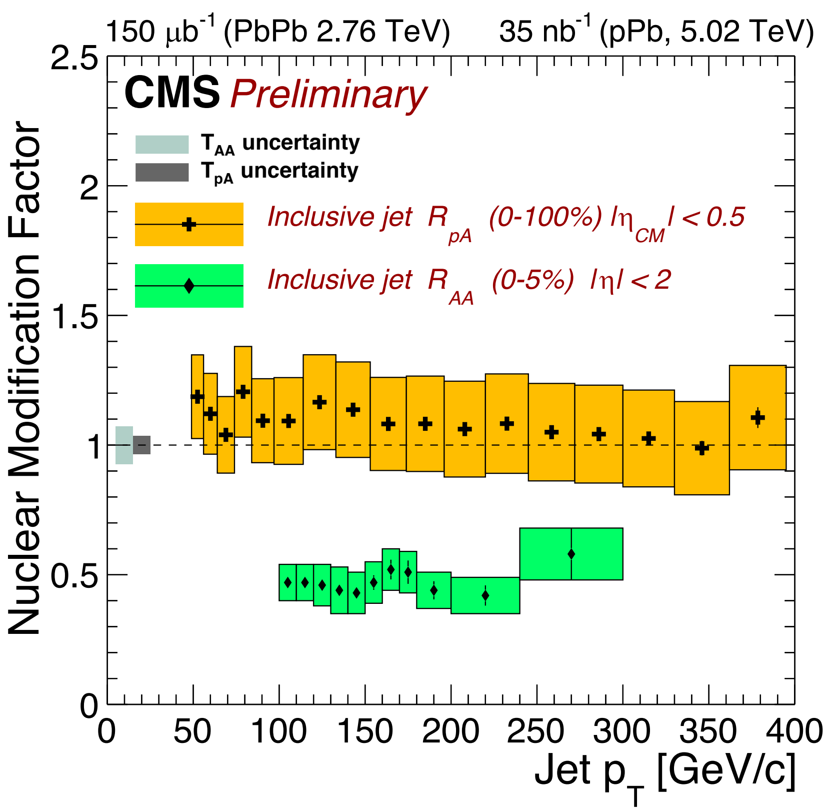


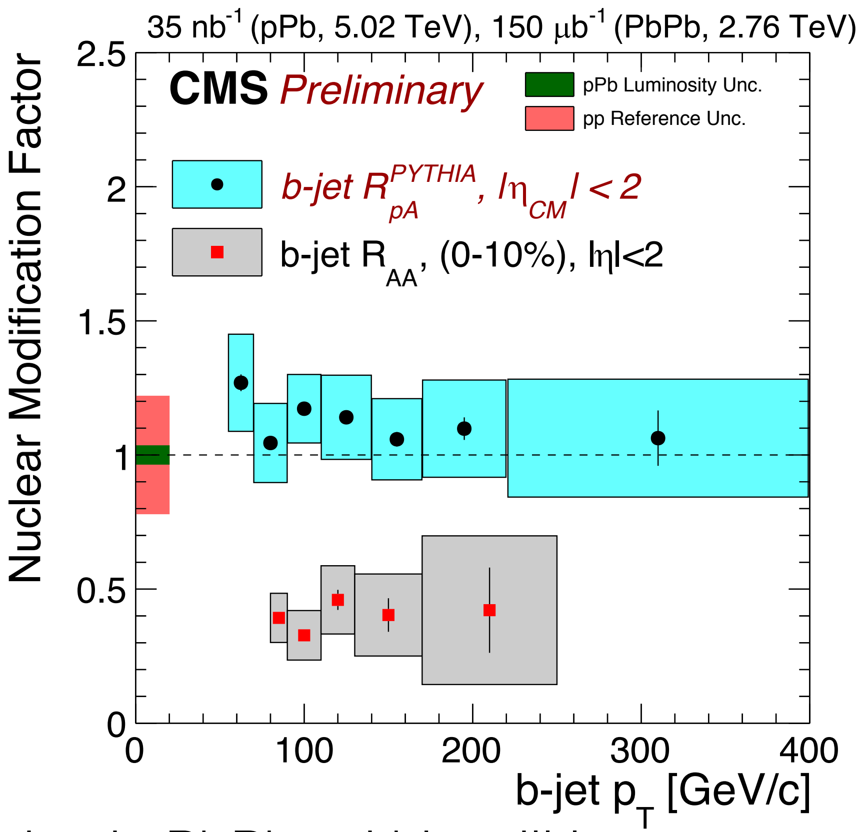
- Result: FCR fraction in analysis selection 50% → 70%
- Pythia overestimates the FEX contribution to back-to-back topologies.
- After reweighting - same data/Pythia agreement as for inclusive jets
- Similar conclusion in CDF PRD71 (2005) 092001

ATLAS b-jet x-section



b-jet vs. inclusive jet quenching

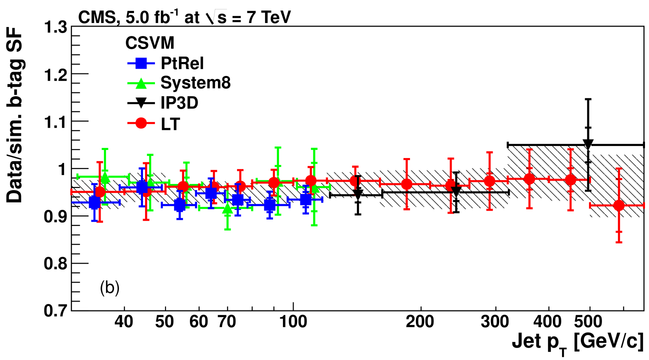


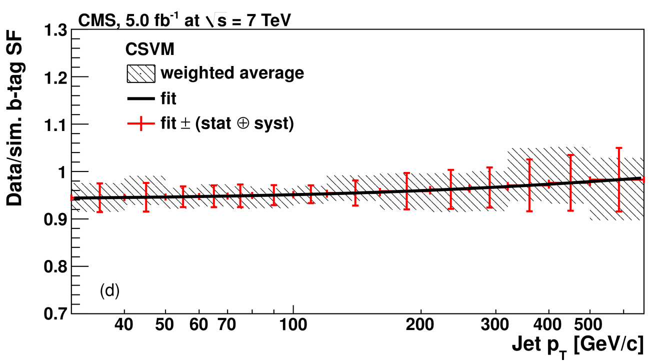


- Similar b-jet and inclusive modification in PbPb, within still large errors
  - Inclusive jets dominated by gluons
  - b jets should tag quarks, but sizable contribution from gluon splitting
- pPb measurements consistent w/ no nuclear effect (w/ large errors)

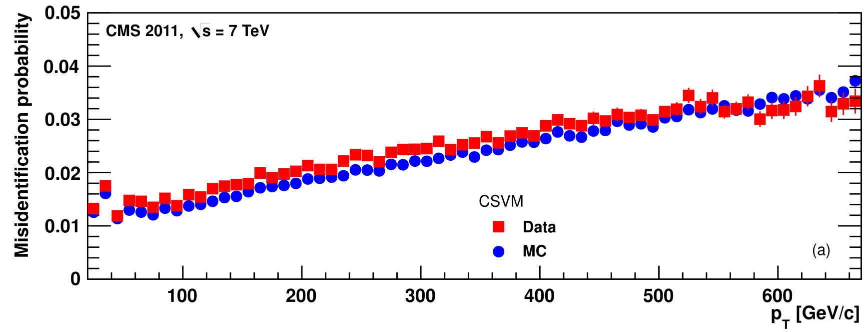
In-situ corrections (Run 1)

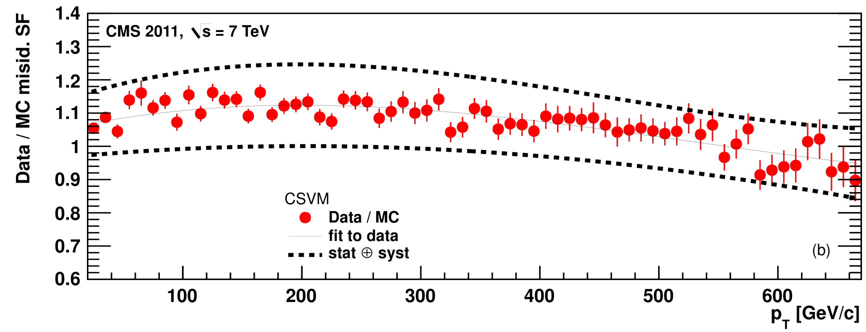
b-tagging efficiency





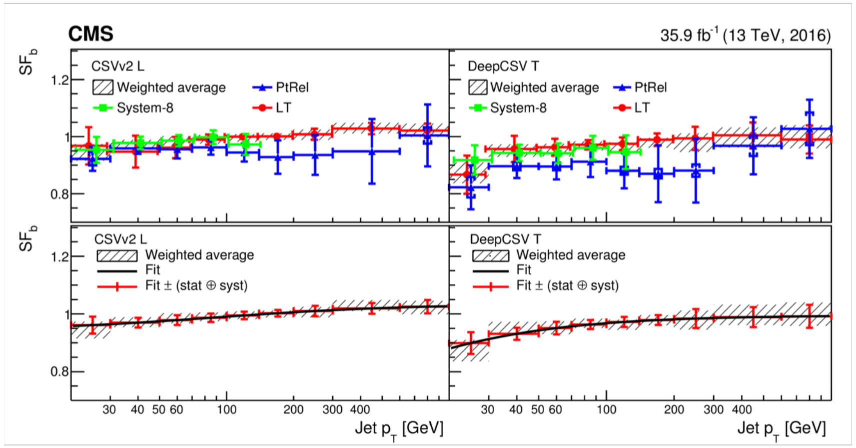
mistagging rate





In-situ corrections (Run 2)

b-tagging efficiency



mistagging rate