Heavy quark jets in heavy-ions

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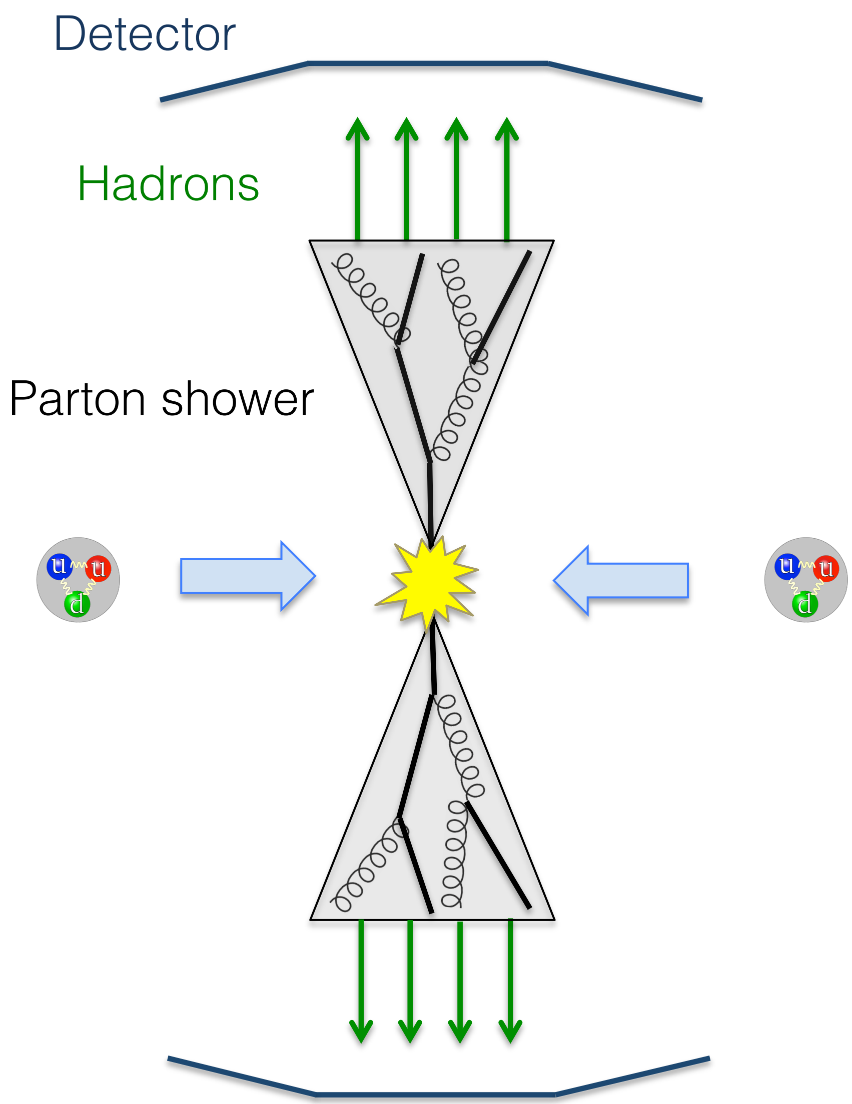
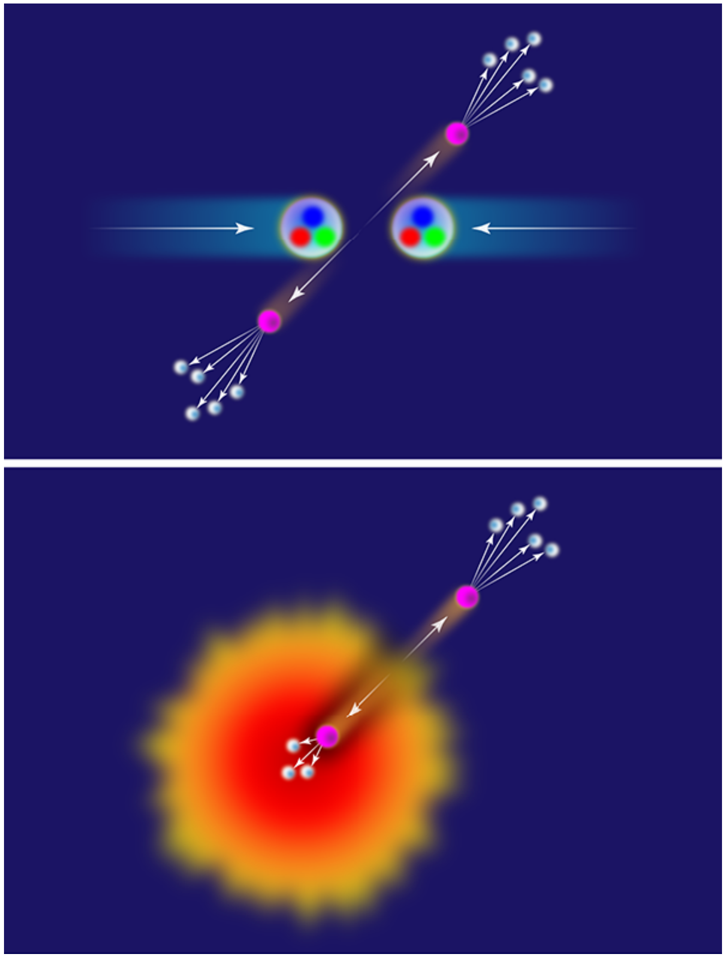
December 5th, 2016

Jets

- Collimated spray of hadrons
- Precisely calculated in pQCD
- "Reconstruct" parton kinematics via jet clustering



Jet quenching



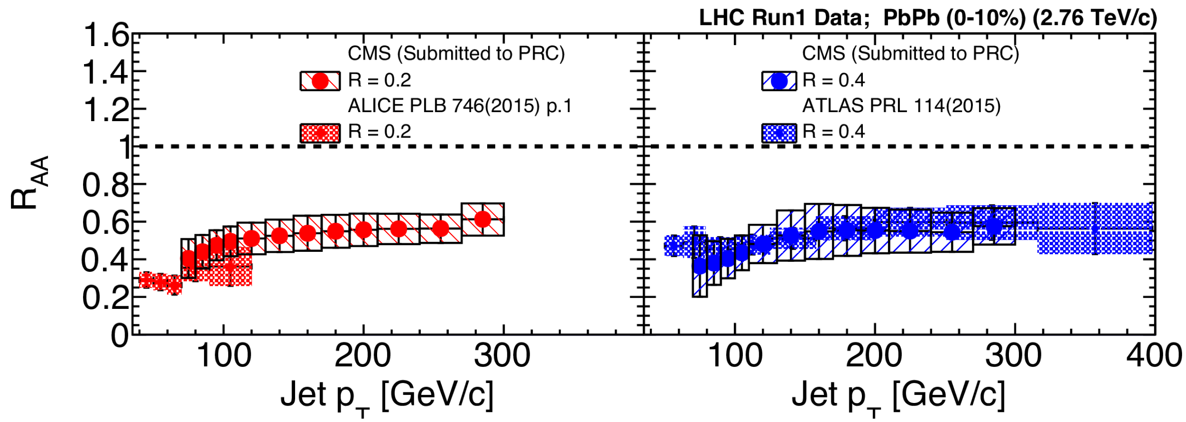
Cartoon from C.Manuel, PRL Viewpoint:
"The stopping power of hot nuclear matter"

- What happens when a hard scattering is embedded in a QGP?
- ➢ Partons lose energy
- Recoiling partons may lose energy differently
  - Path length difference
  - E-loss fluctuations

Jet quenching @ the LHC

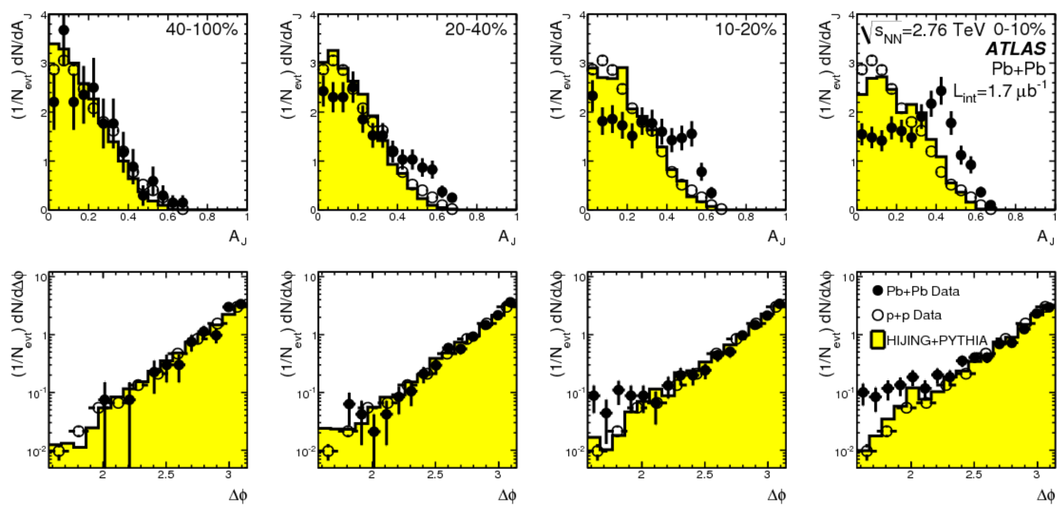
Jet R_{AA}

arXiv:1610.00613



Dijet imbalance

PRL 105 (2010) 252303

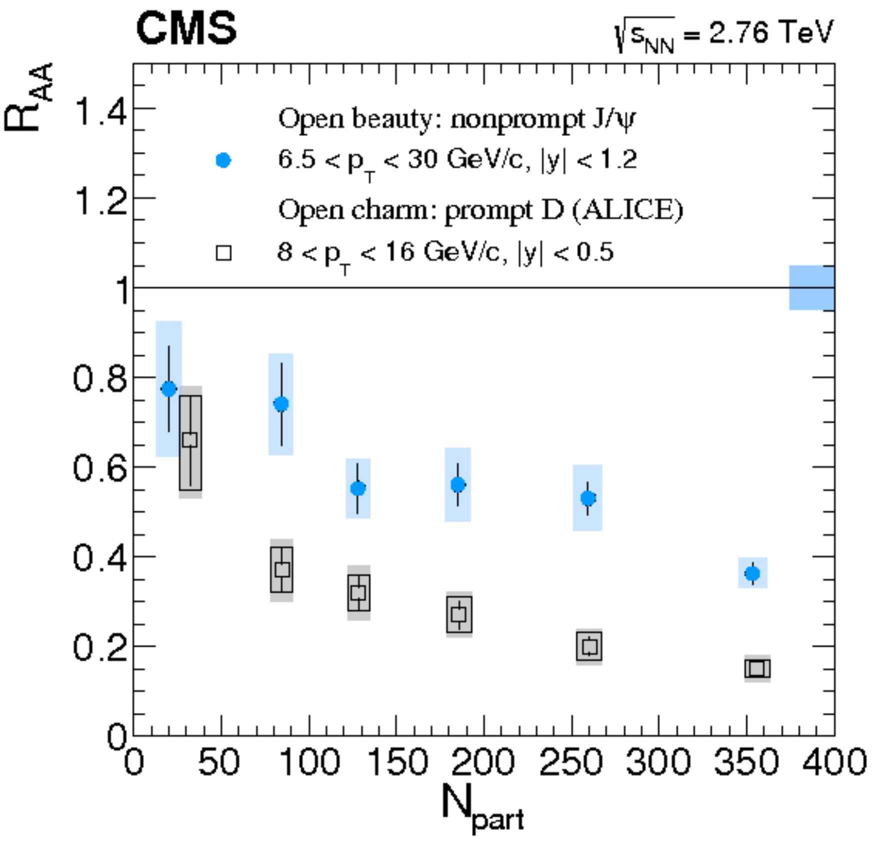


+ much more: jet fragmentation, shapes, substructure, etc.

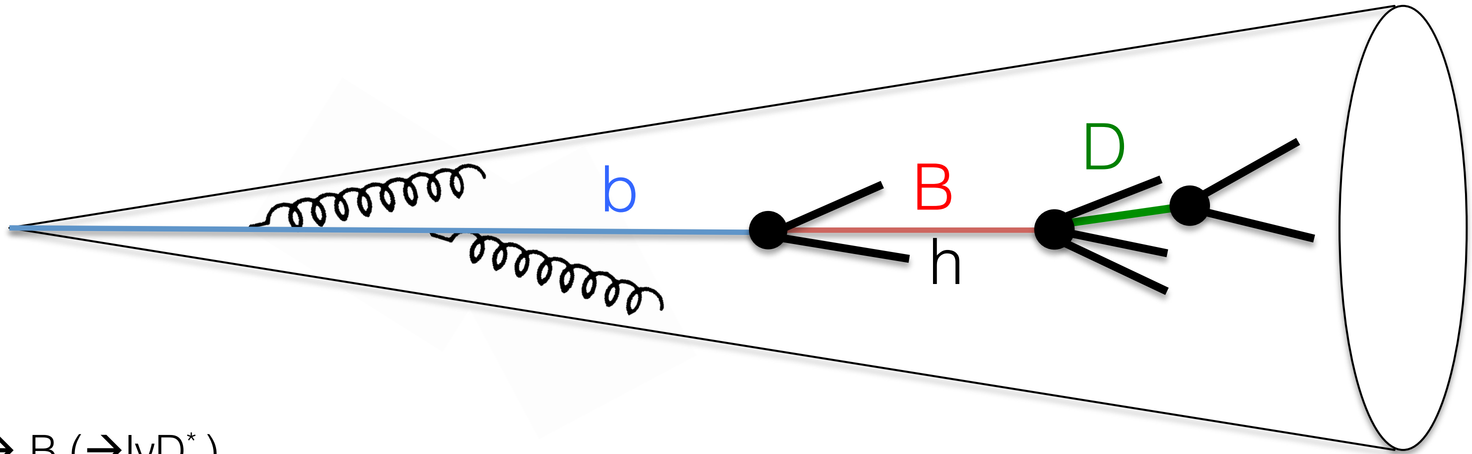
see my review talk at QM15: https://indico.cern.ch/event/355454/contributions/838380/

Heavy quark energy loss

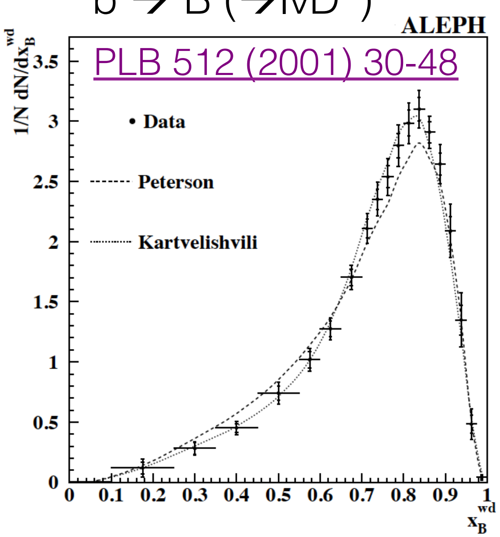
- Interest is two-fold
  1) Quark vs gluon e-loss
  2) Mass effect: radiation damping in “dead cone
- Heavy quark jets vs. hadrons
  - Higher detection efficiency
  - Typically larger energies
  - Potentially more information



Properties of b-quark jets



b → B (→lνD*)



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

$$\langle x_B^{wd} \rangle = 0.7163 \pm 0.0061\,(\mathrm{stat}) \pm 0.0056\,(\mathrm{syst})$$

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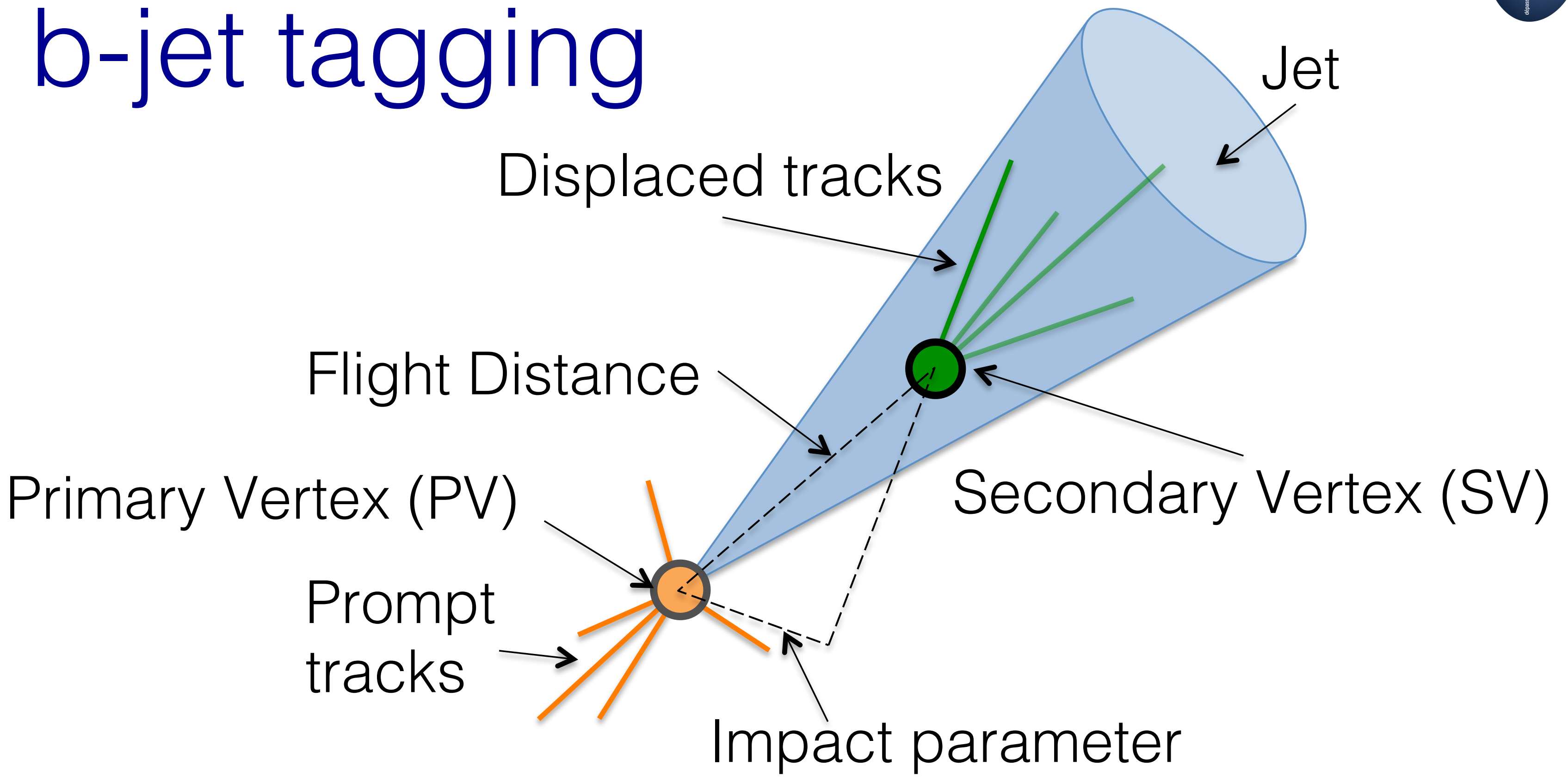
b-jet tagging



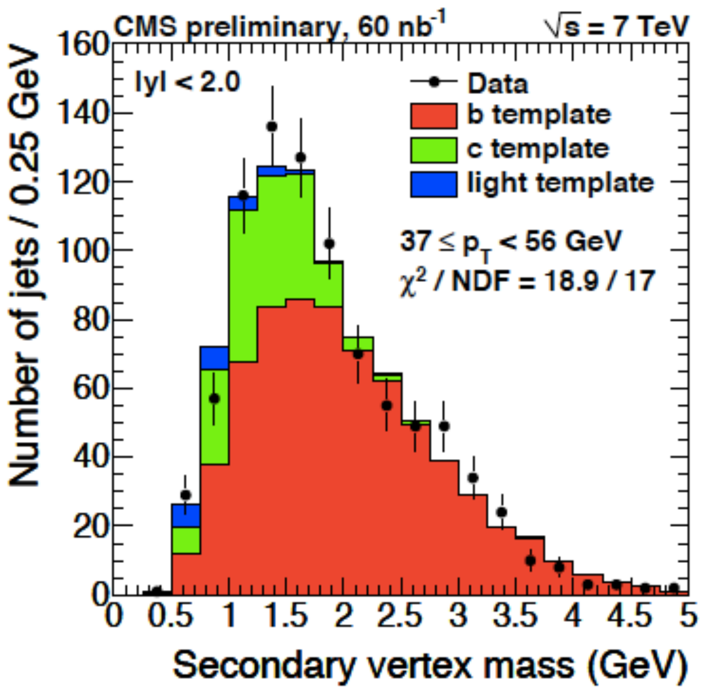
- b-jet definition: Any jet which contains a b-hadron
- Lifetime methods: Exploit displaced vertices and/or tracks, both b-hadron and subsequent c-hadron decays
- Soft-lepton tagging: μ or e inside the jet

b-tagging in pp @ 7 TeV

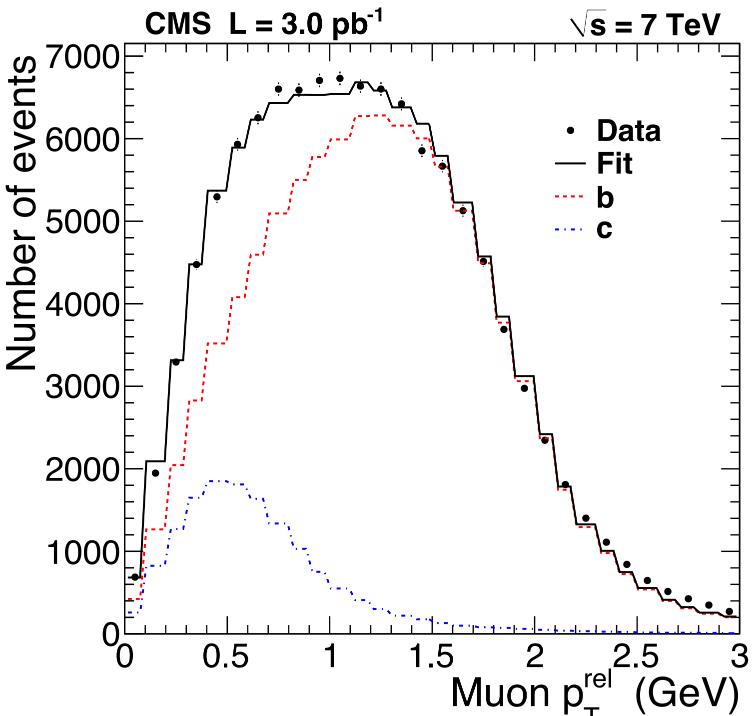
JHEP 1204 (2012) 084

General strategy:

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



"Lifetime tagging" uses SV and/or or large IP tracks

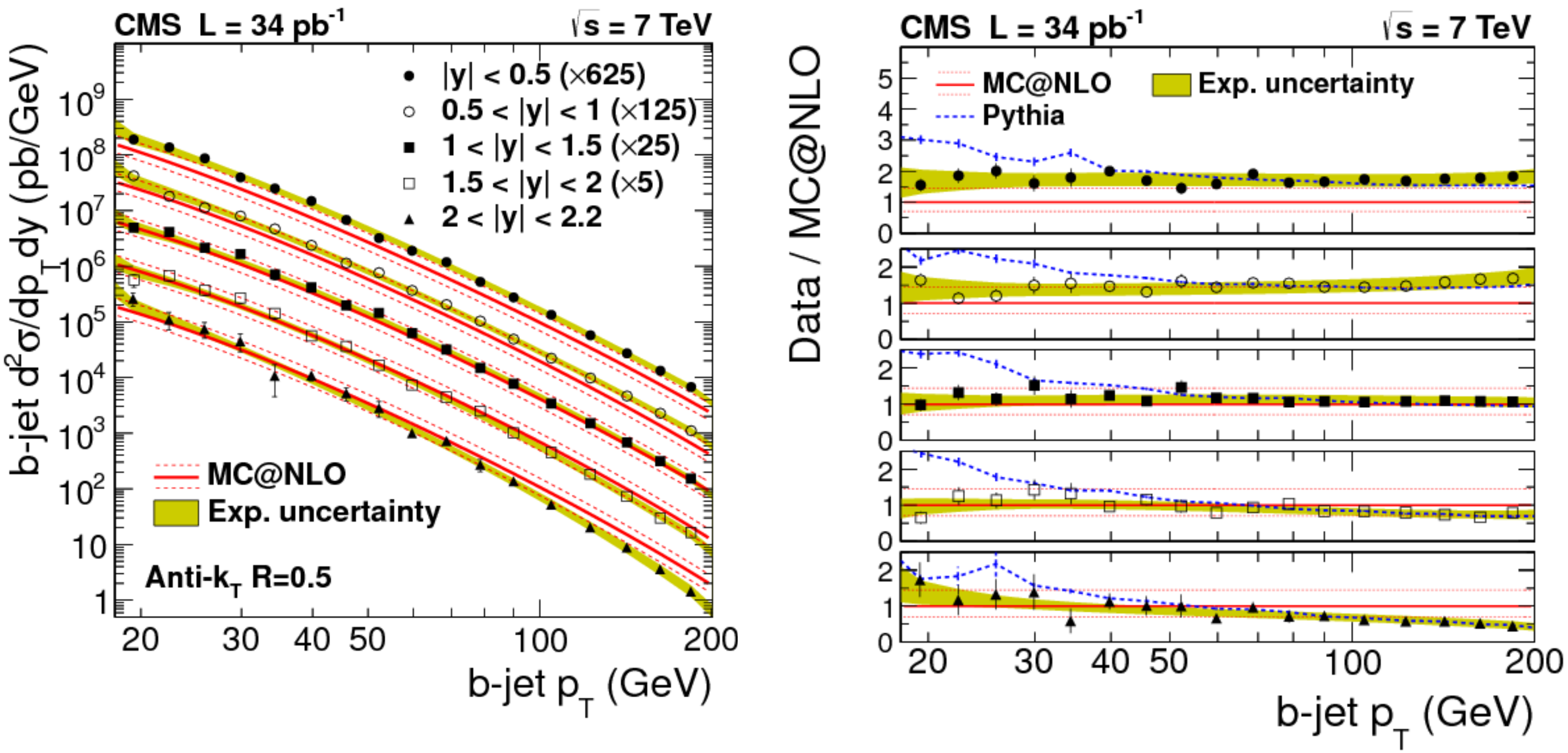


Soft lepton tagging: e's or μ's,
Usually to calibrate lifetime taggers

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

b-jet x-section in pp @ 7 TeV

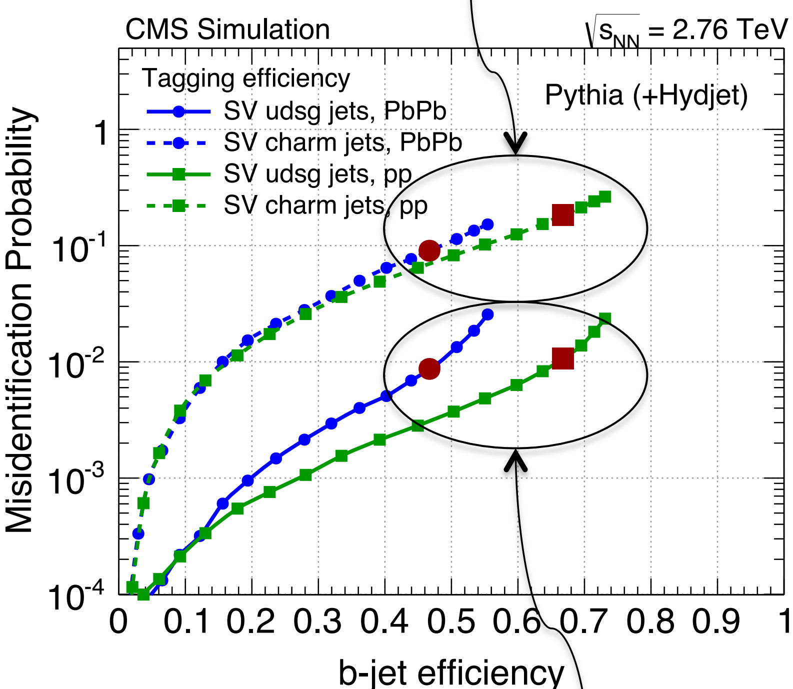
JHEP 1204 (2012) 084

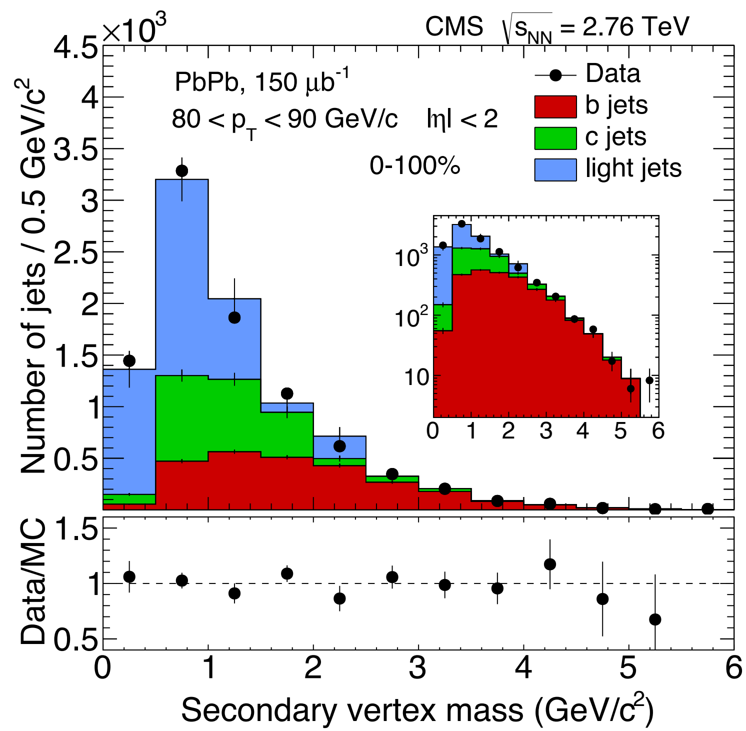


b-tagging in PbPb (Run 1)

[PRL 113 (2014) 132301](#)

b-tagging efficiency reduced, but c-jet rejection fixed (wrt pp)

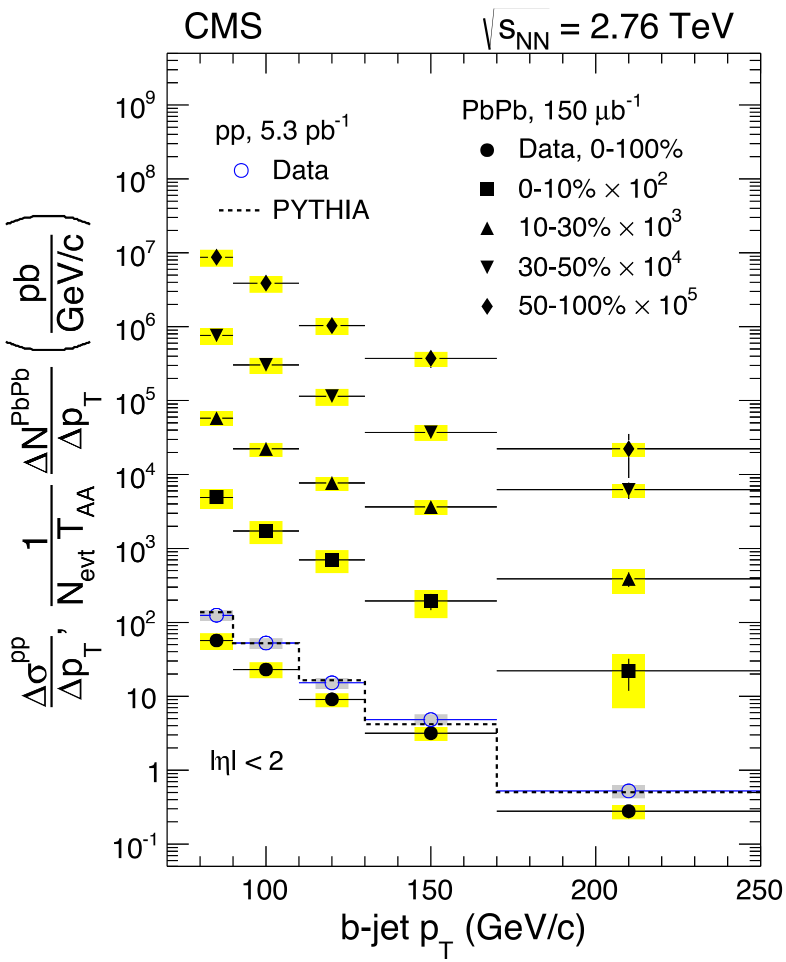




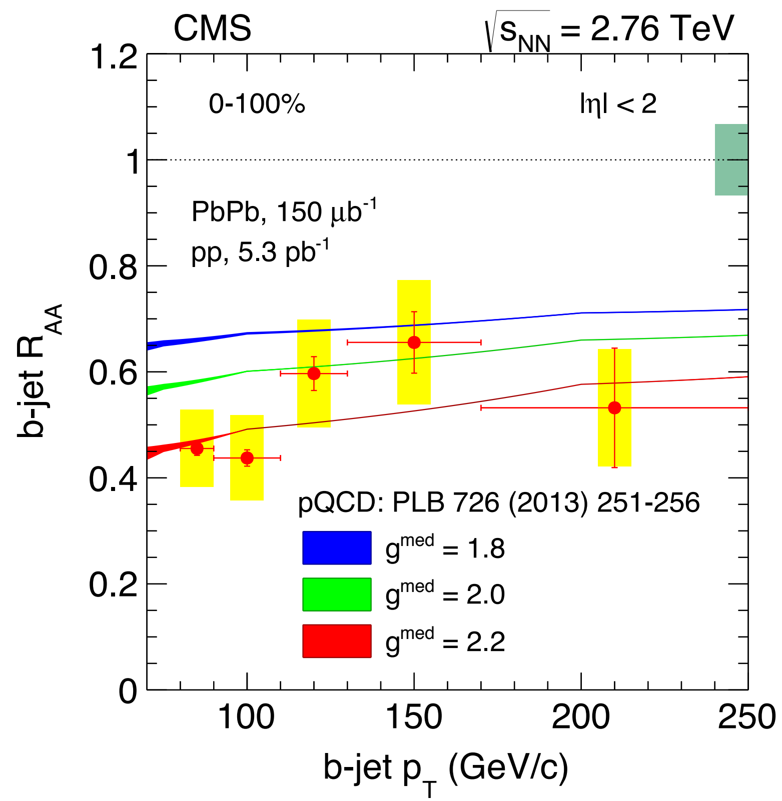
Light jet mis-tagging rate in PbPb increased due to combinatorics

Despite larger light jet background, fit works remarkably well!

b-jet x-section & R_{AA}

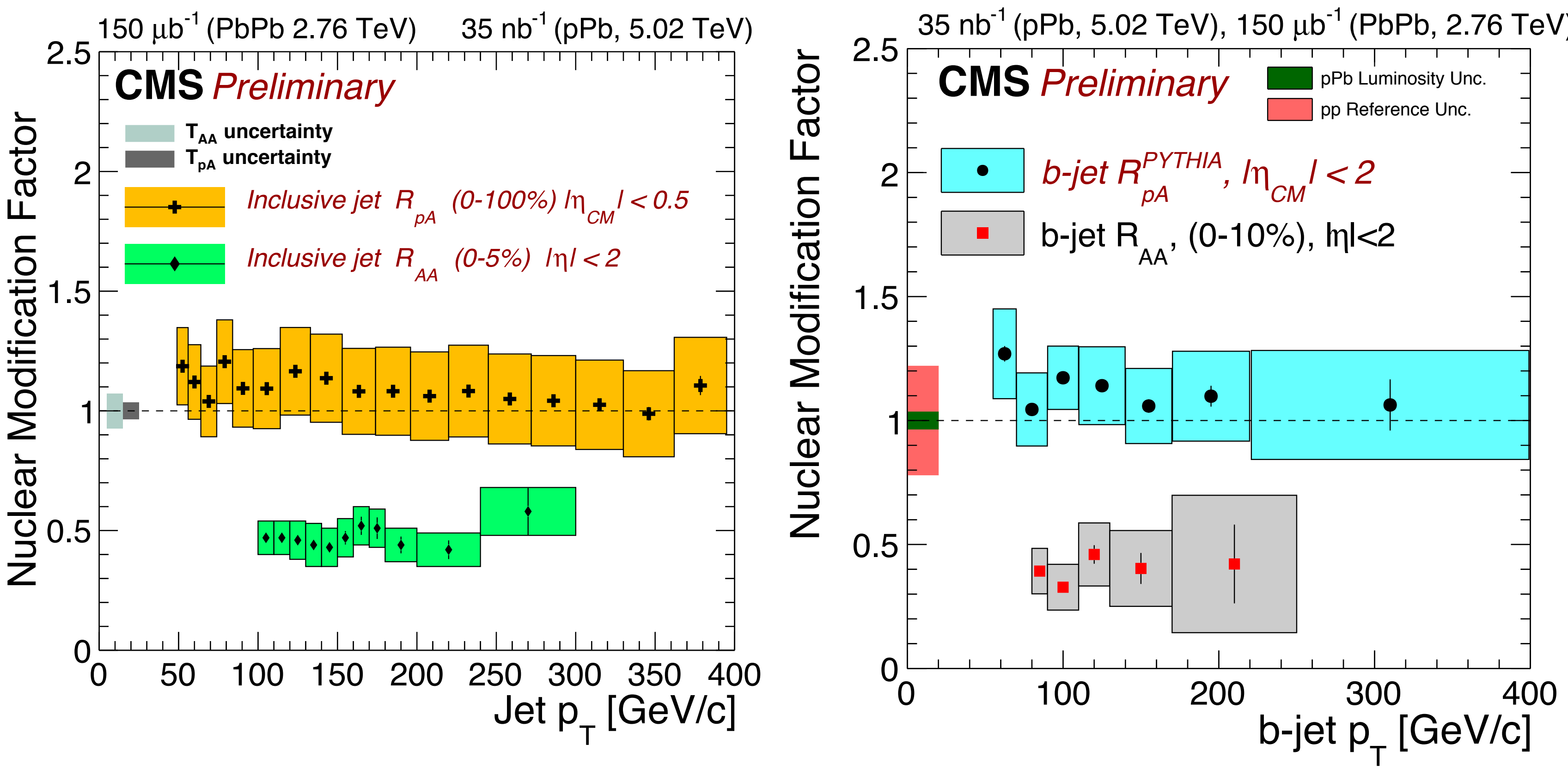


PRL 113 (2014) 132301



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

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)

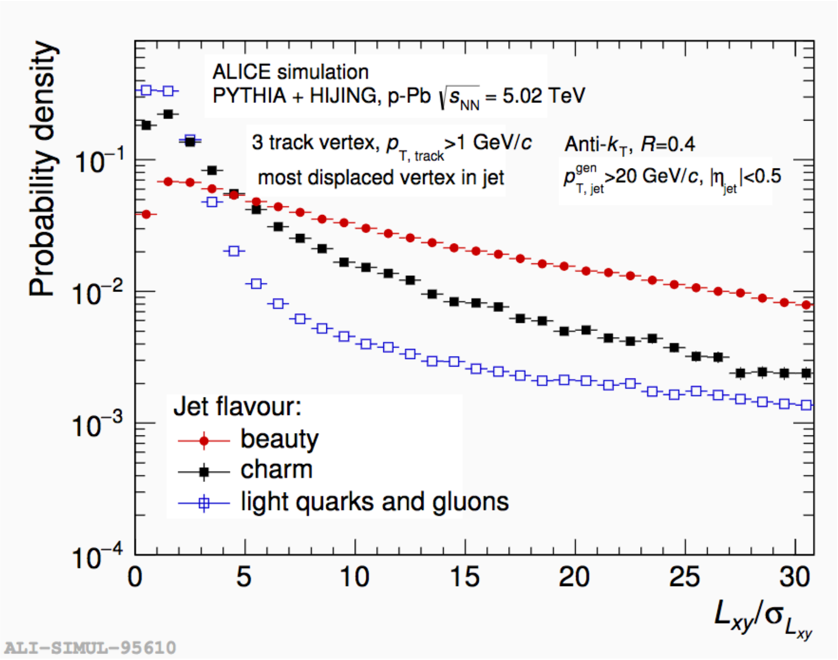
ALICE is also in the game

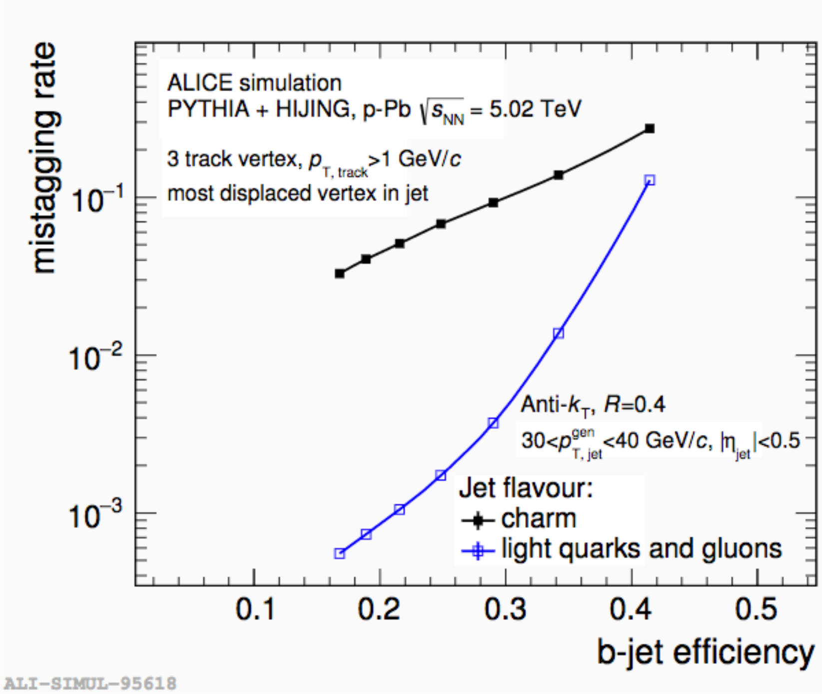
Performance of the ALICE secondary vertex b-tagging algorithm

G. Eyyubova[1,2,a] and L. Kramárik[1,b] on behalf of the ALICE collaboration

[1] *FNSPE, Czech Technical University in Prague*
[2] *SINP MSU, Russia*

arXiv:1605.00143





What about charm jets?

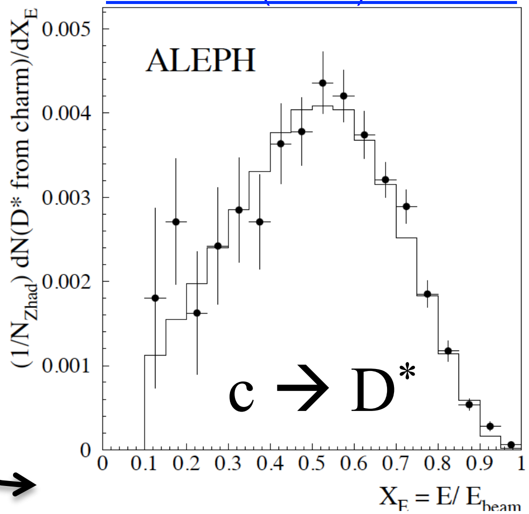
Despite somewhat larger rate (~2x), c-jets are much harder to identify

Compared to b, c-quarks:

- Fragment softer, $<z_D> \sim 0.5$
- Smaller multiplicity, $<n_{ch}> \sim 2$
- Shorter lived, cτ 100 – 300 μm

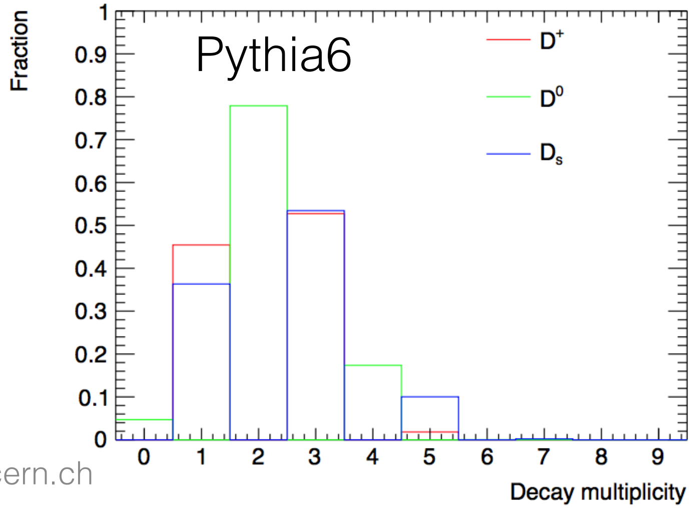
On the other hand, larger fraction of decays are fully reconstructed

EPJC 16 (2000) 597-611



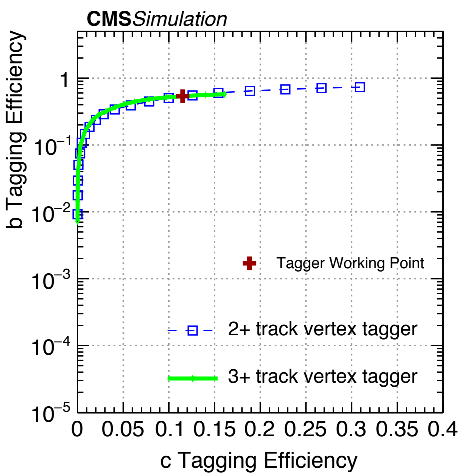
$$\langle X_E(D^*)\rangle_{c\bar{c}} = 0.4878 \pm 0.0046 \pm 0.0061$$

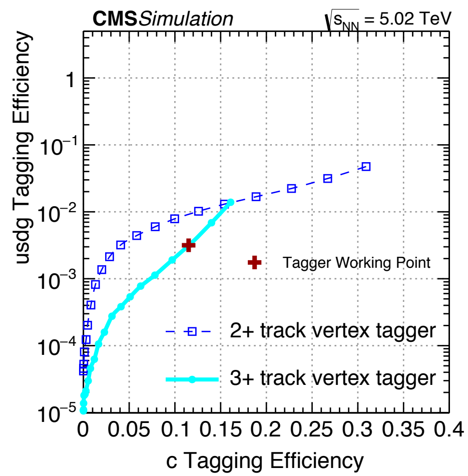
Species	PDG	PYTHIA
D^+	1.96 ± 0.08	2.13
D^0	2.25 ± 0.08	2.25
D_s^+	2.41 ± 0.38	2.46



c-jet tagging in pA

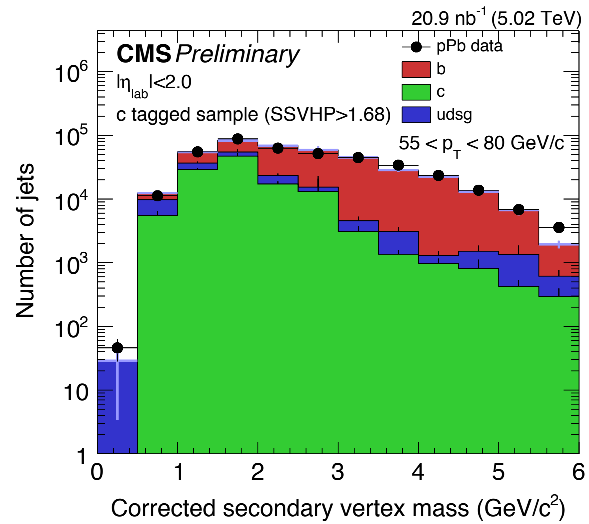
Same “cut & fit” SV method as used in PbPb

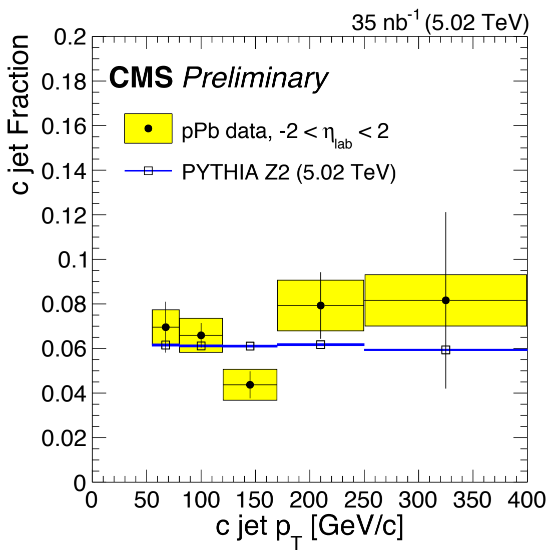




Require ≥ 3 tracks in SV to kill light jet background

Max efficiency of ~ 15%





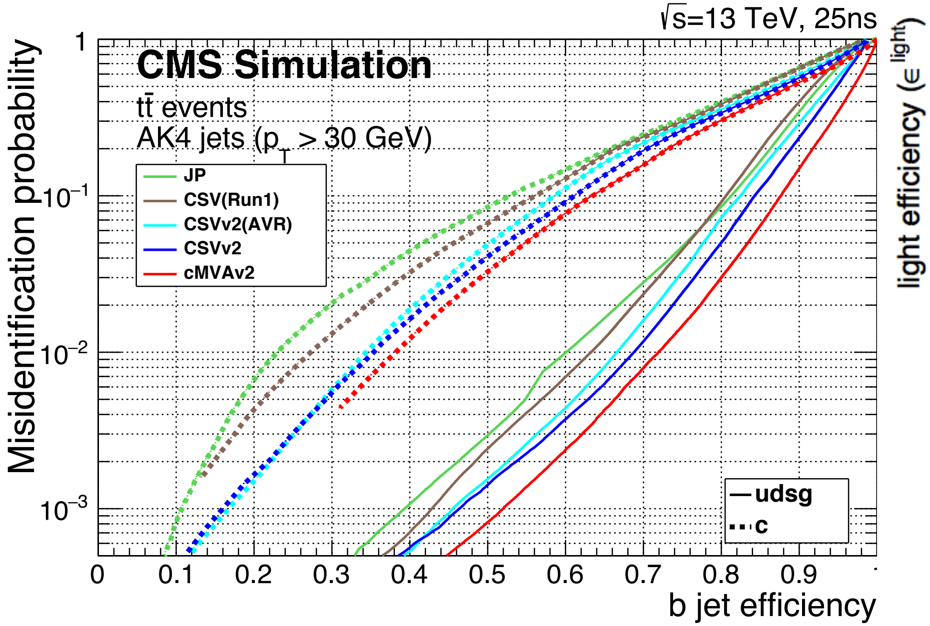
HIN-15-012

c-jet fraction pA consistent w/ Pythia

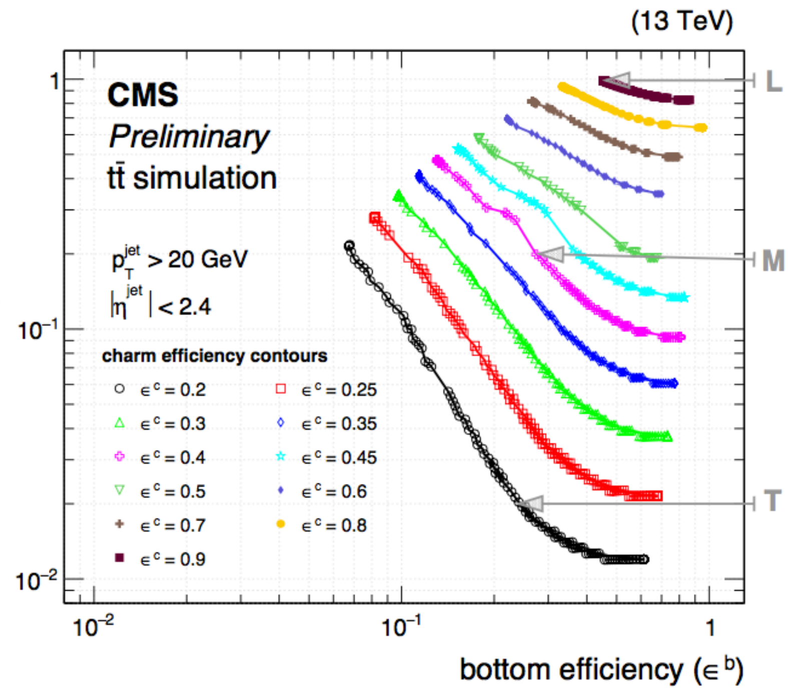
Publication coming shortly:
Reduced systematics and RpA

State of the art flavor tagging

"Identification of b quark jets Run 2"
[BTV-15-001]



"Identification of c-quark jets"
[BTV-16-001]



- Combined secondary vertex (CSV) uses a larger number of variables, SV mass, SV p_T, # of tracks, etc. in a multivariate estimator
- Most recent iterations based on Boosted Decision Trees

Heavy flavor production

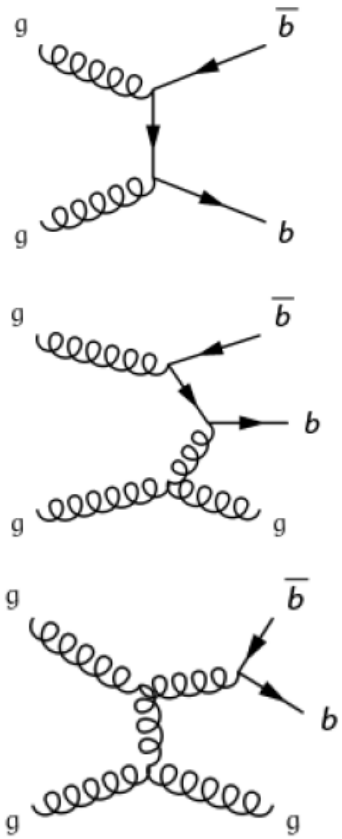
Process: | Example diagram | Typical topology

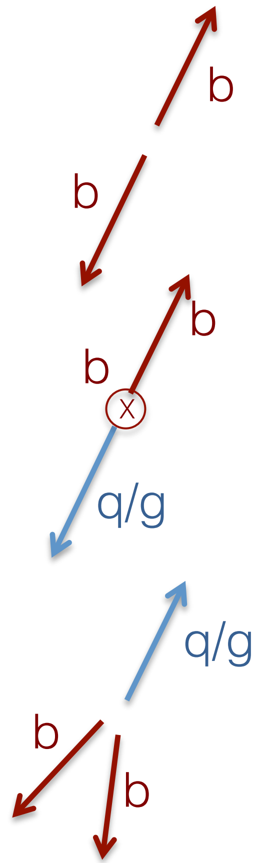
NLO contributions larger than LO b-bbar!

Flavor Creation (FCR)

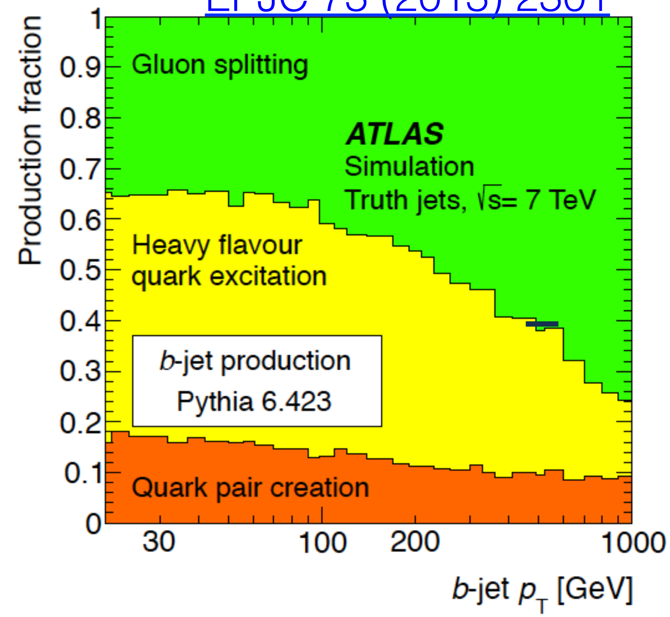
Flavor Excitation (FEX)

Gluon Splitting (GSP)





EPJC 73 (2013) 2301

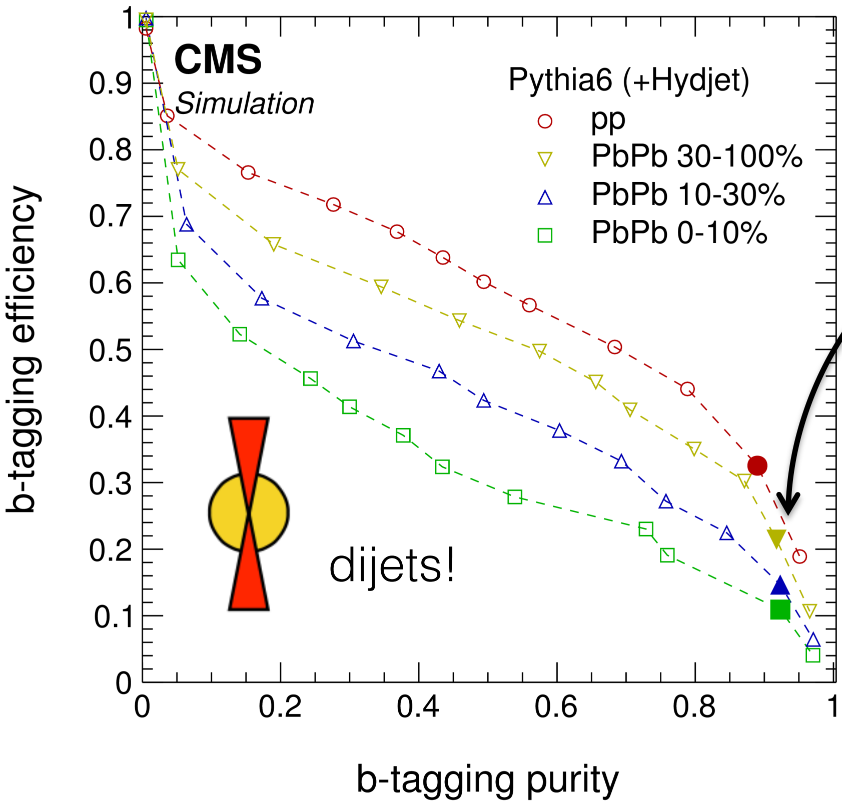


E-loss of split gluons may be different from primary b quarks!

Performance for b-dijets

Using (Run 1) Combined Secondary Vertex

HIN-16-005

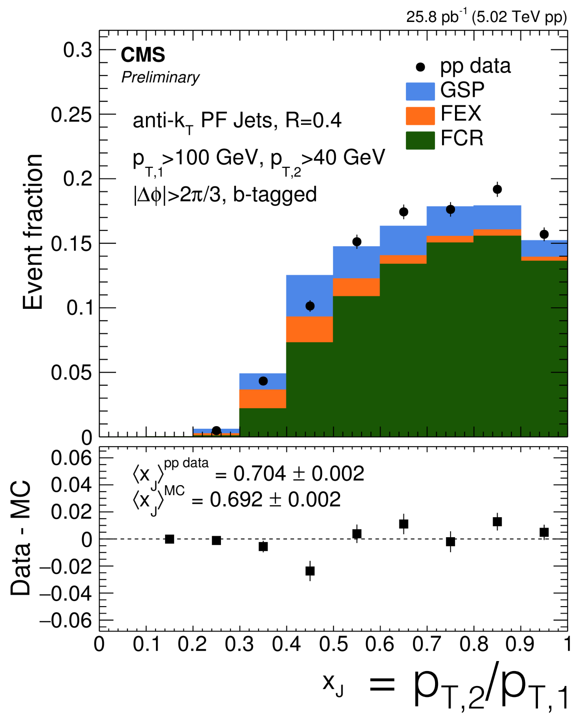


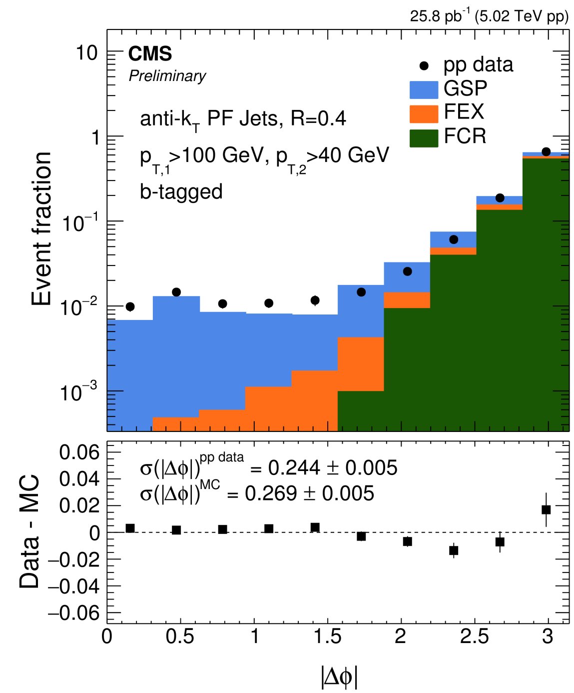
Extremely tight working point ~ 90% purity

Cost is efficiency of 10 – 30%

Centrality dependence can be mitigated by dedicated optimization of tagger for different centrality classes (ongoing…)

Process contribution to dijets





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

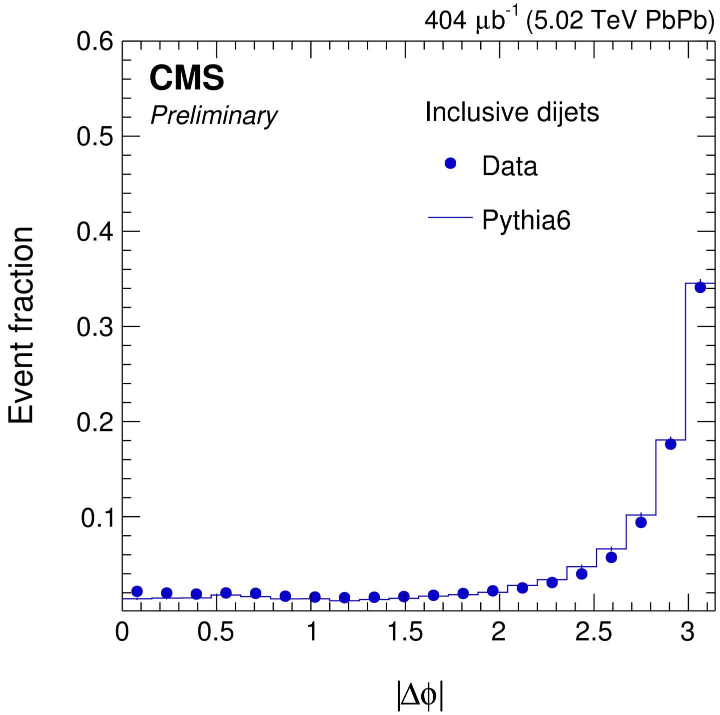
- Pythia 6 gives a satisfactory description of dijet p_T and angular correlations*
- After selection, flavor creation dominates (70 – 80 %)
- Pythia 8 turned out to give too imbalanced dijets overall (not just b-jets)
- Investigating higher order generators (MadGraph/aMC@NLO, Powheg, etc.)

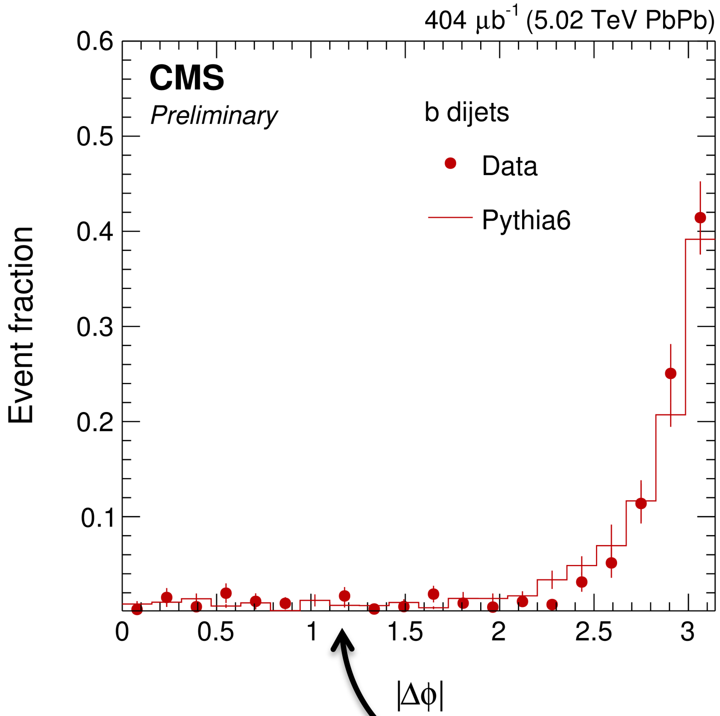
*Pythia6 did not behave like this “out of the box”. This was an interesting, but technical story, I can come to at the end it you’re interested.

$\Delta\phi$ correlations

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

Centrality 0 – 10 %



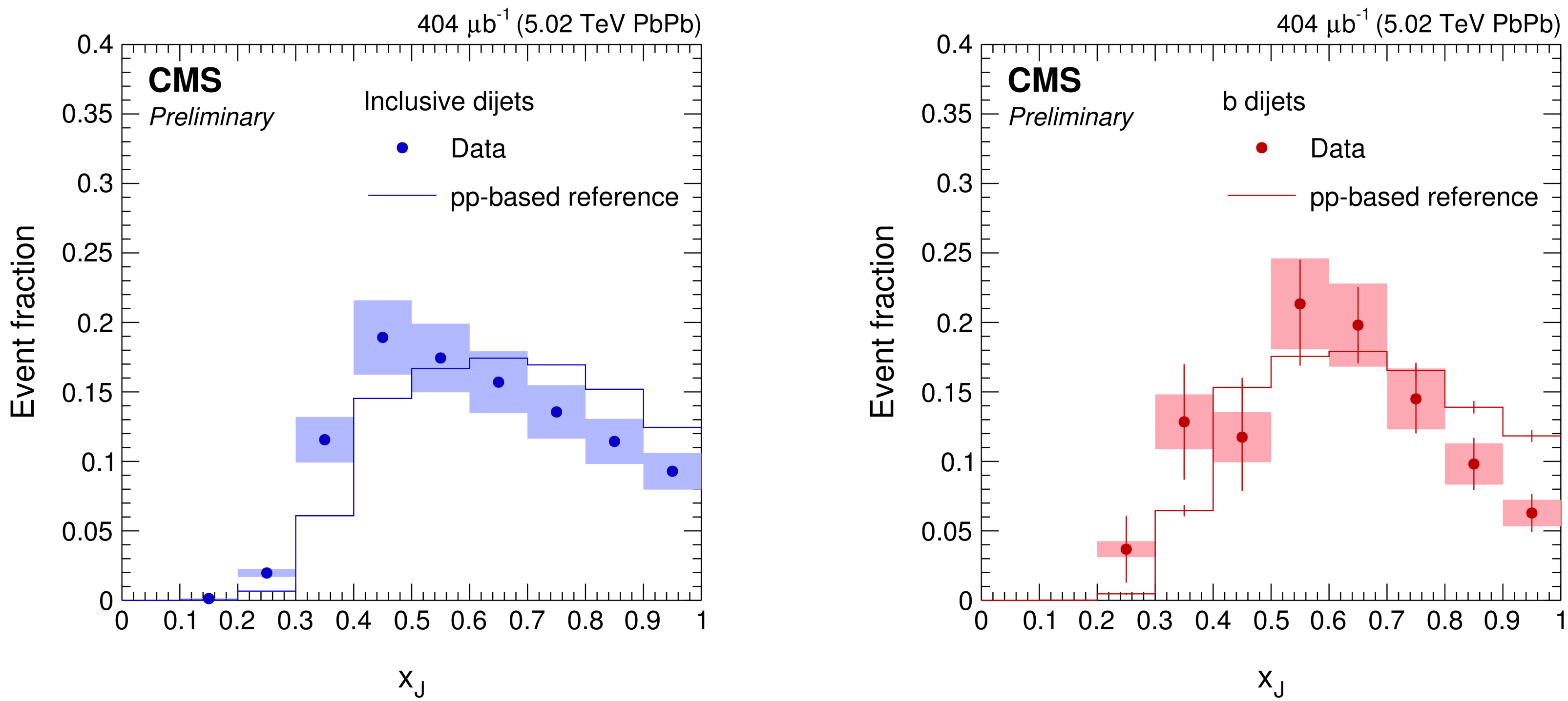


- No angular deflection for b-jets (as for inclusive jets)
- Reduced combinatorial background for b-jets from tagging

(b)-dijet imbalance

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

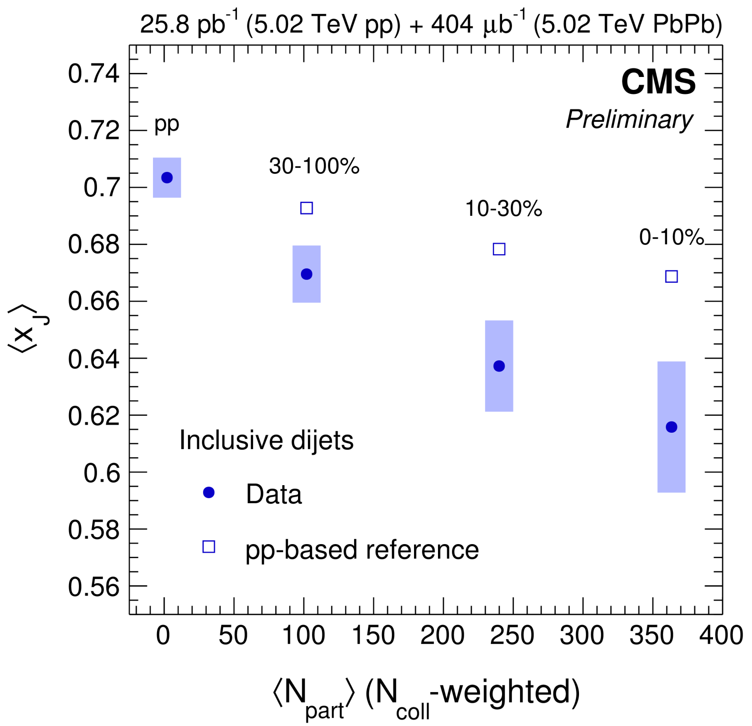
Centrality 0 – 10 %

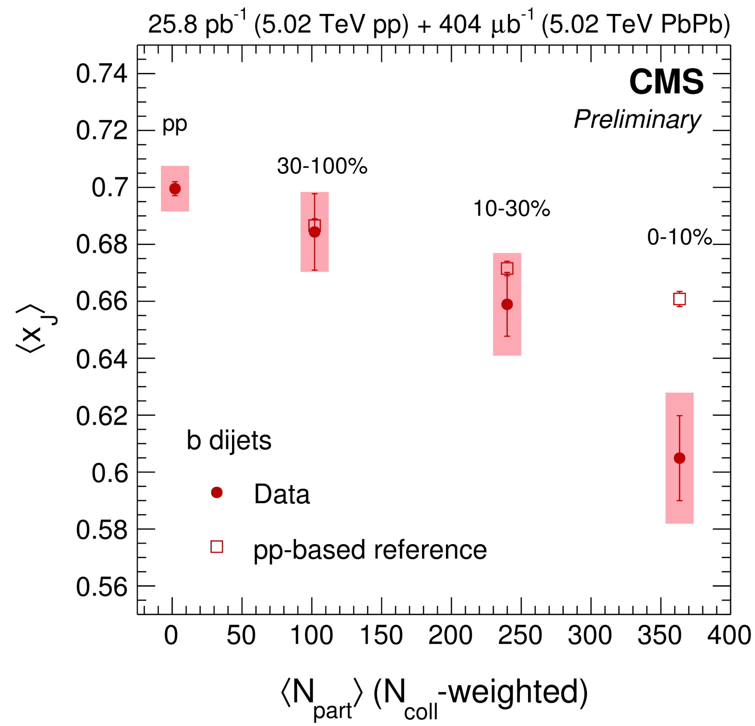


First measurement of b-bbar correlations in heavy ions!
To the extent we can say so far, b-jet imbalance looks like inclusive jet

Mean p_T imbalance

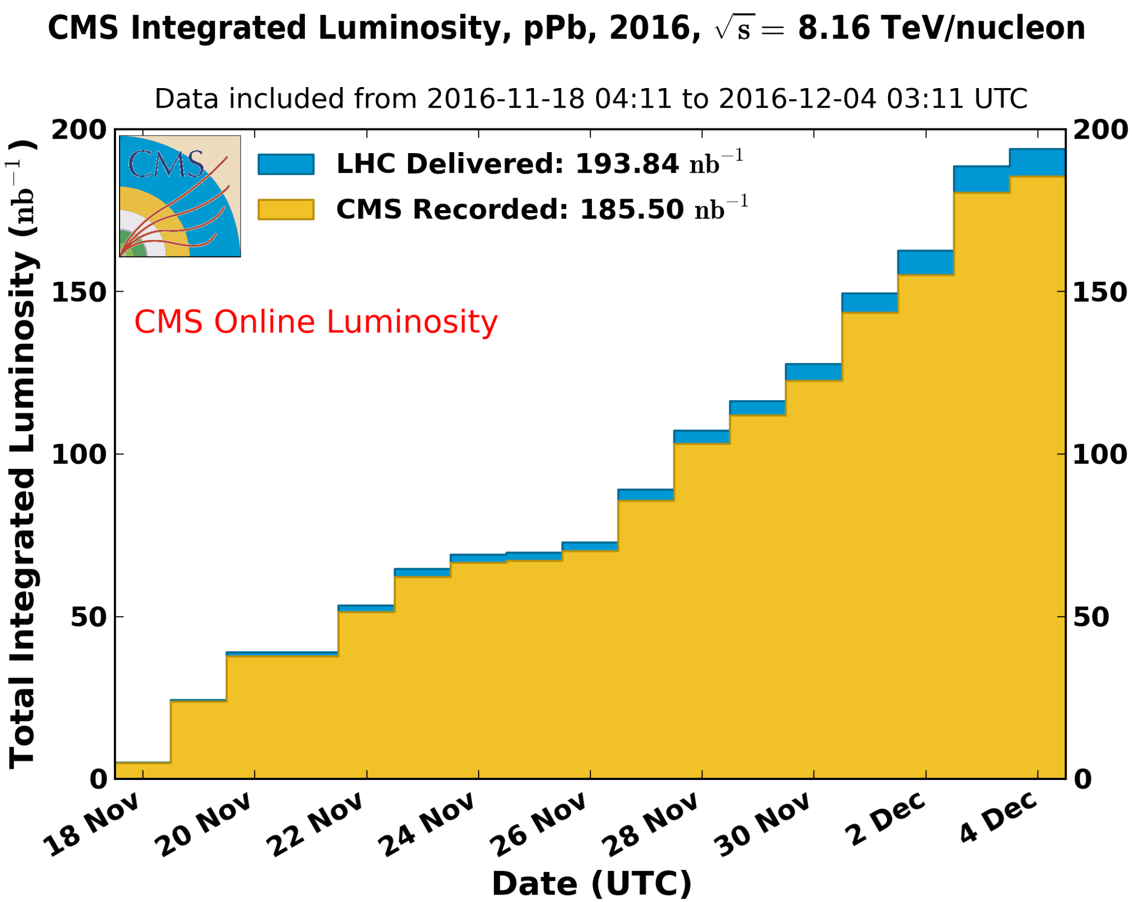
$p_{T,1} > 100$ GeV
$p_{T,2} > 40$ GeV
$\Delta\phi > 2\pi/3$
$|\eta| < 1.6$





No difference between inclusive and b-dijets so far…
We're working to beat down uncertainties

pA data @ 8 TeV

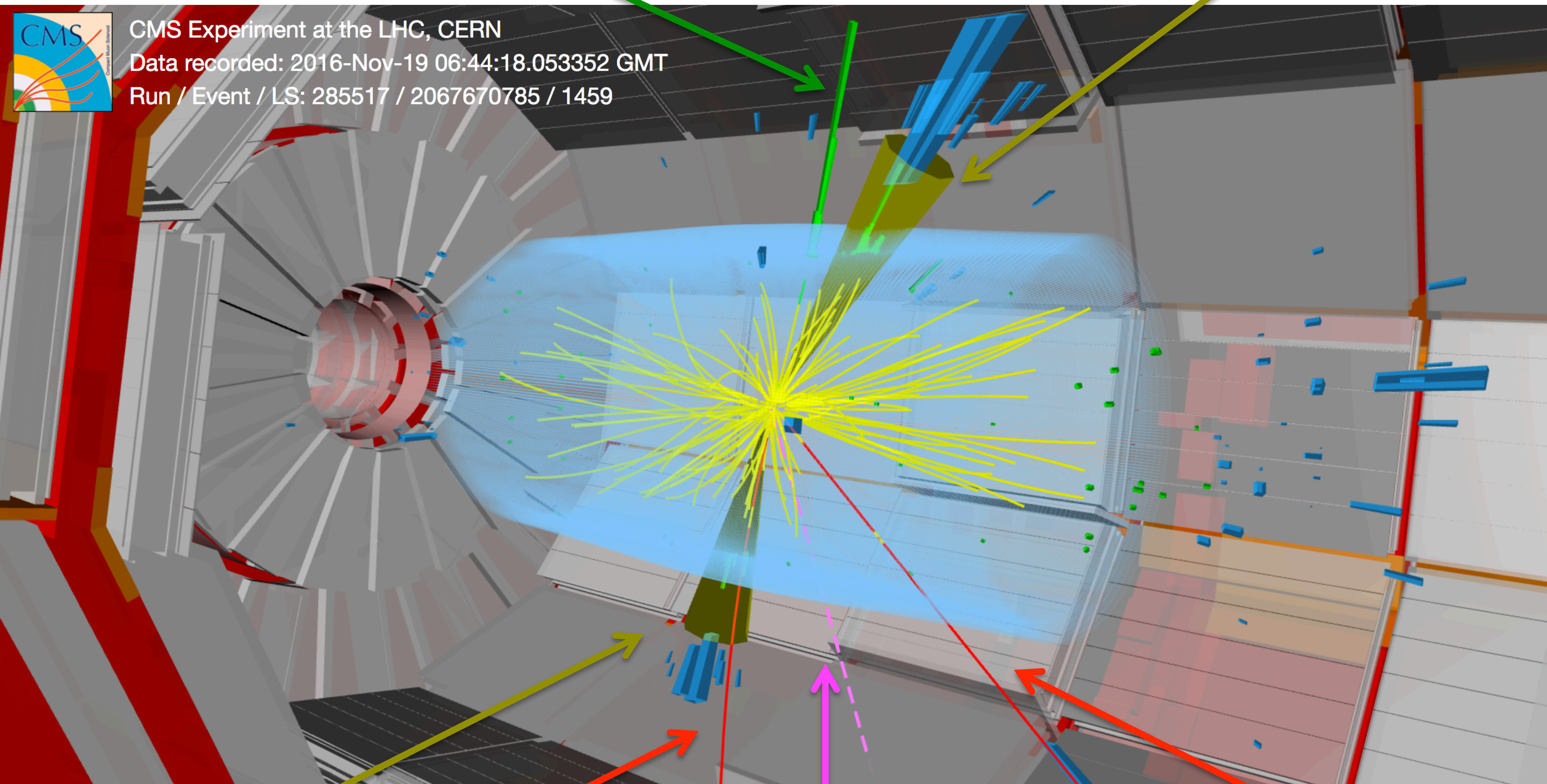


CMS recorded 185 nb^{-1}, > 5x the data sampled in 2013 @ 5 TeV!
We also collected more than 1 billion MB events at 5 TeV

t-tbar event in pPb @ 8 TeV

91 GeV isolated electron

104 GeV b-jet



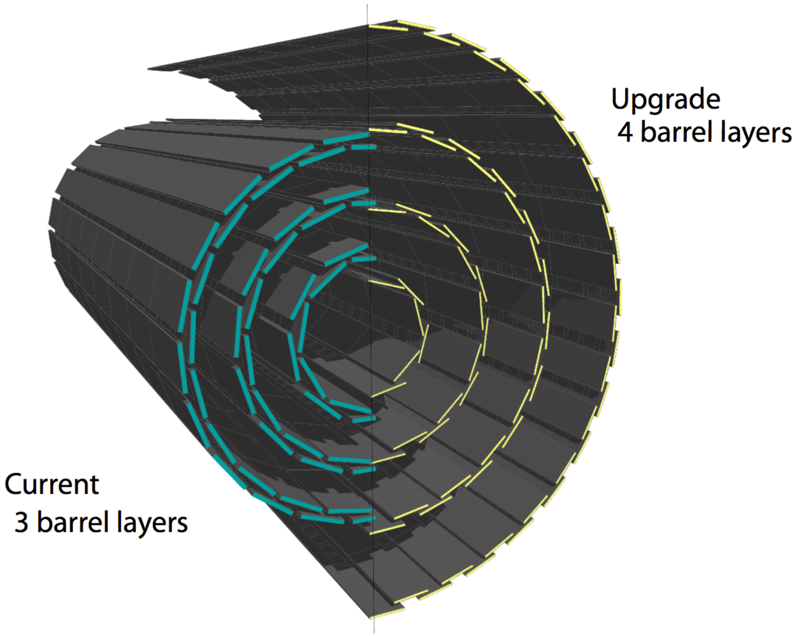
87 GeV b-jet w/ 14 GeV muon

49 GeV missing E_T

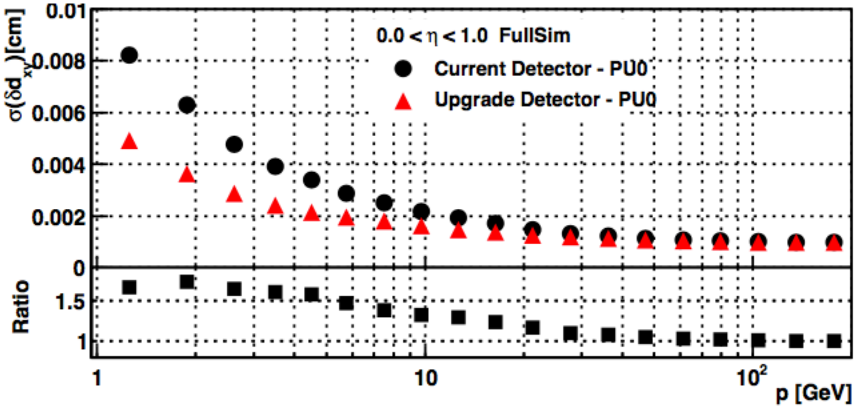
88 GeV isolated muon

4-layer pixel upgrade

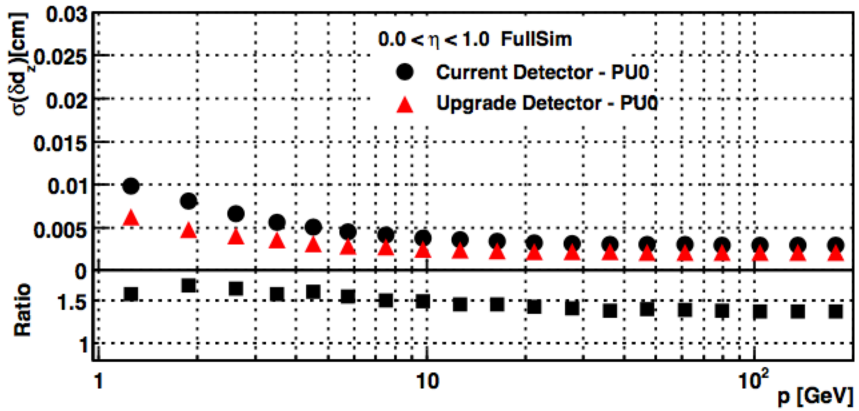
CMS pixel upgrade TDR
[CERN-LHCC-2012-016]()



Transverse impact parameter resolution



Longitudinal impact parameter resolution



Being installed as we speak!

Will be very interesting to see what improvement this gives for heavy ions

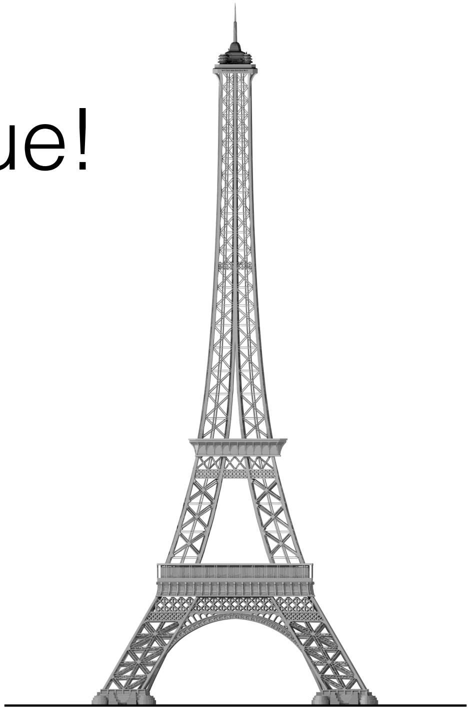
Conclusion / Outlook

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

Wanna join the fun?

Or know someone who might?

We’re hiring @ Ecole Polytechnique!



Looking for a post-doc

http://inspirehep.net/record/1498804

And a PhD student

http://llr.in2p3.fr/IMG/pdf/cms_llr_qgp.pdf

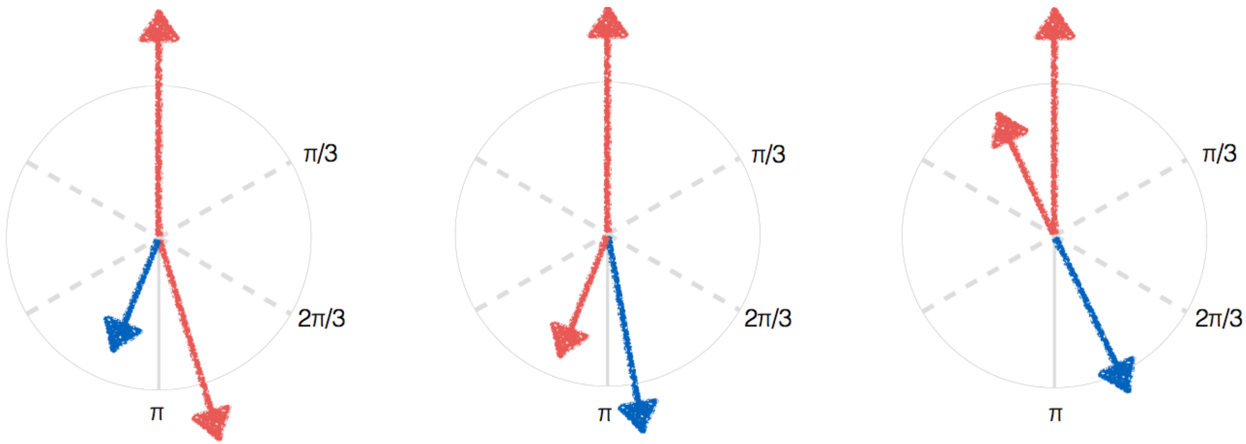
to work on heavy flavor jet measurements (and more!)

Backup

Flavor process reweighting

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

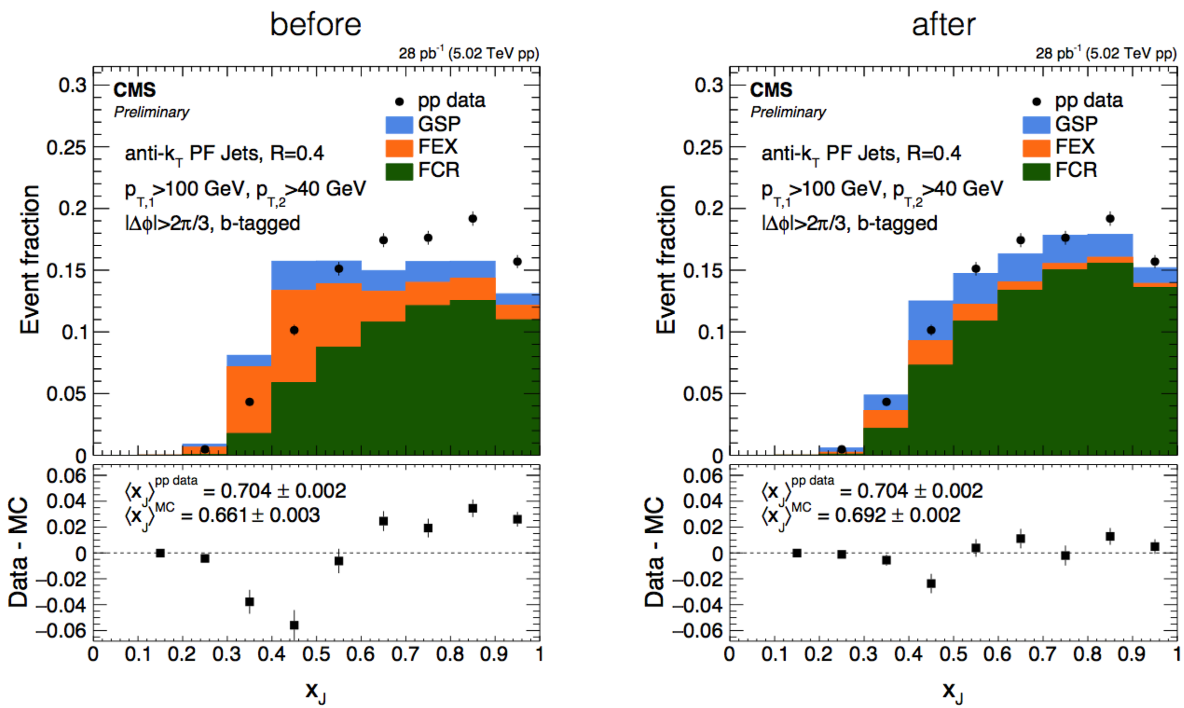
1) Two highest p_T jets are b-tagged and back-to-back ($\Delta\phi_{1,2} > 2\pi/3$)
2) 1^{st} and 3^{rd} highest p_T jets b-tagged and back-to-back ($\Delta\phi_{1,3} > 2\pi/3$)
3) 1^{st} and 3^{rd} highest p_T jets are b-tagged and nearby ($\Delta\phi_{1,3} < \pi/3$)



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%

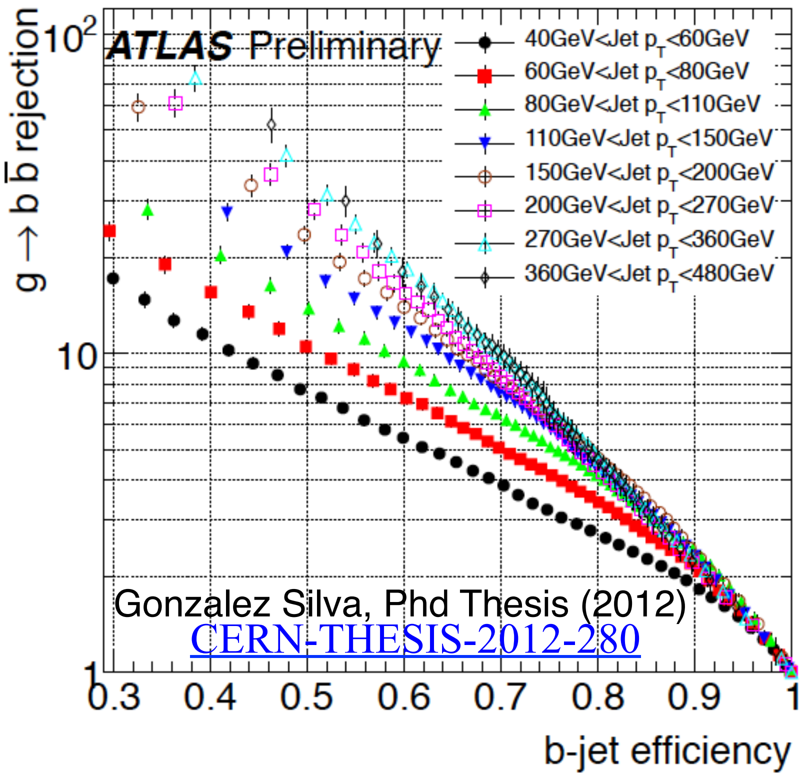
Effect of reweighting



- 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

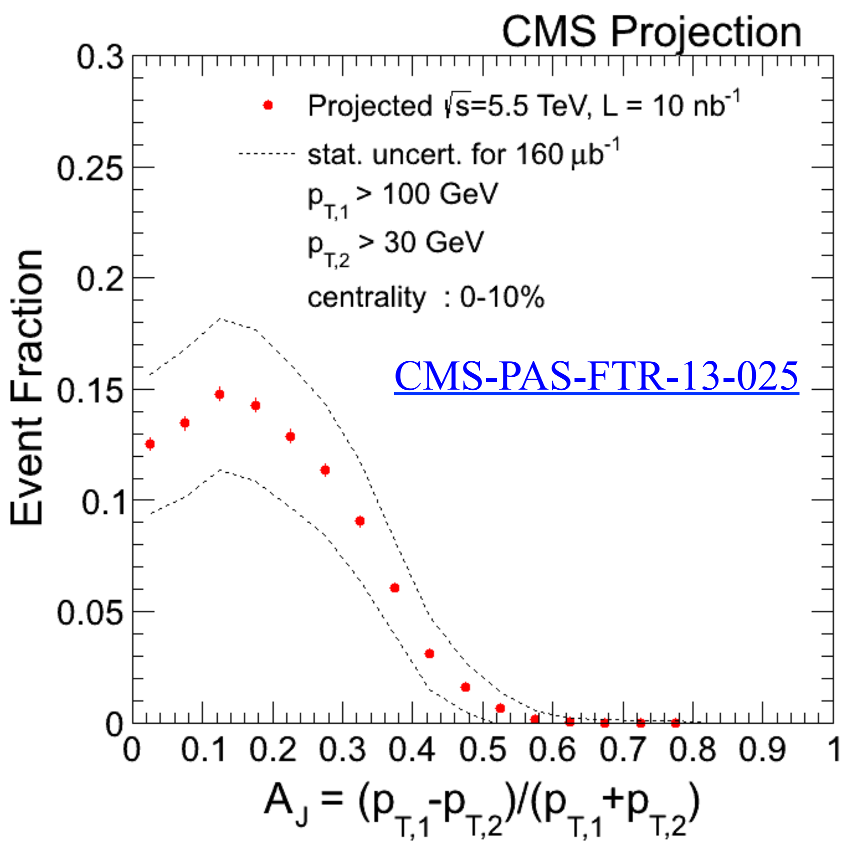
Beyond inclusive b-jet spectra

- Merged jet ID



- Identifiable w/ jet substructure methods
- Also useful for q/g separation
- Never been tried in heavy ions

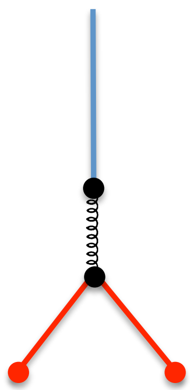
- Double b-tagged dijets



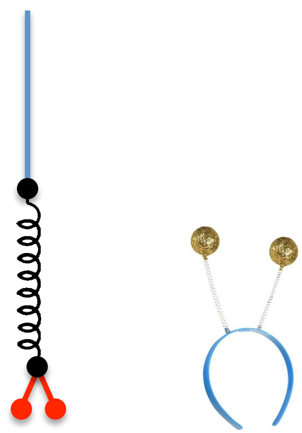
- LO-like production, i.e., reduced gluon splitting
- Small systematics, can be compared to inclusive jets w/ high precision
- High purity, but low efficiency and x-section

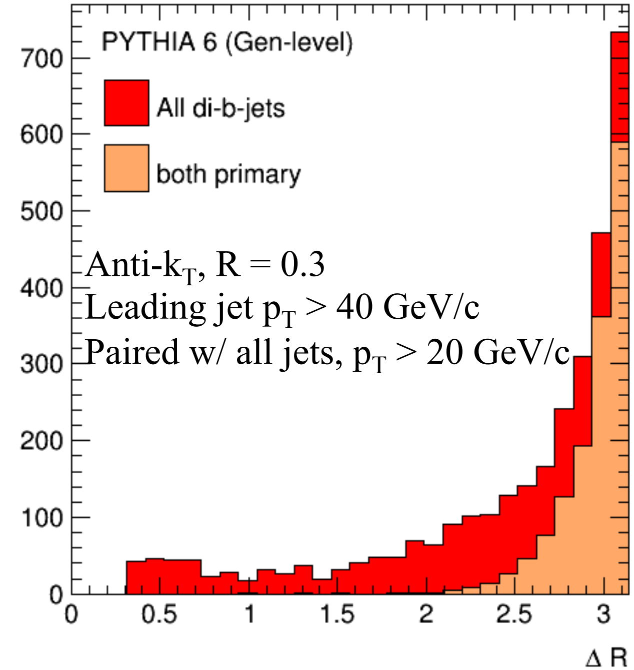
Angular dependence of gluon splitting

Hard splitting



Soft splitting



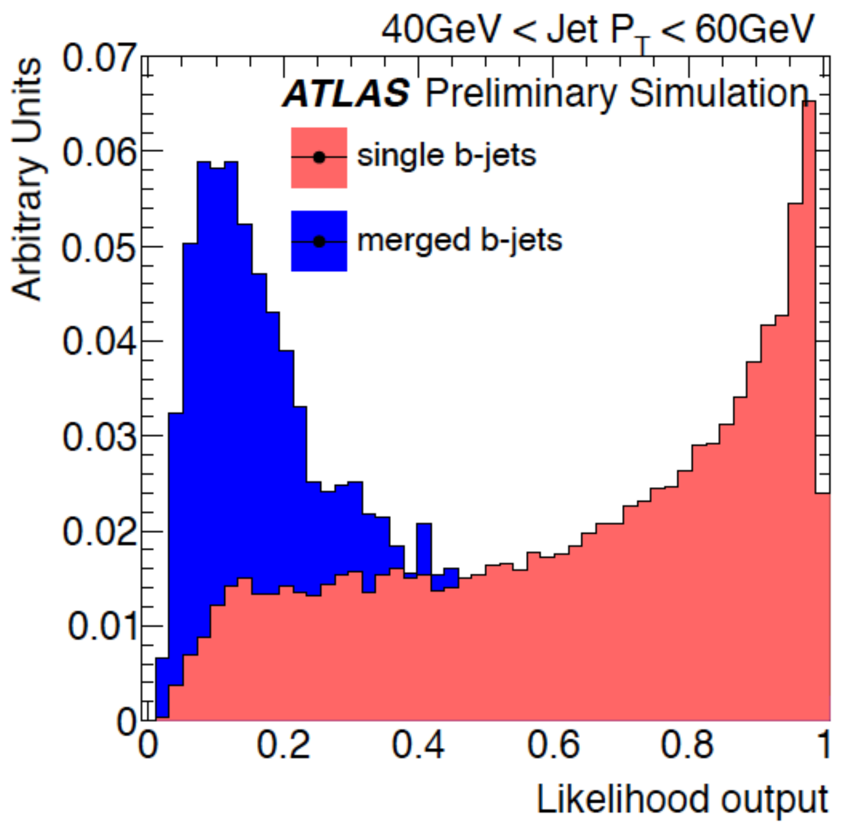


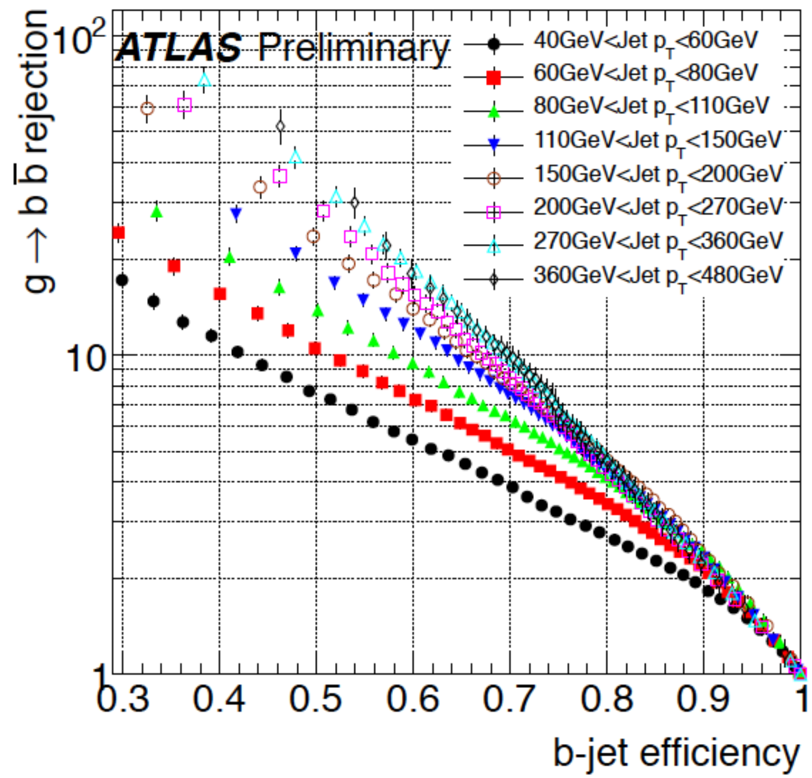
- Hard splitting
  - Tend to give 3-jet topology
  - More b-jet-like w.r.t. e-loss
- Soft splitting
  - May be clustered as a single jet
  - More gluon-like w.r.t. e-loss

- Smooth variation between topologies
- Nearby jets merged
- Some GSP back-to-back
- ⚠ Pythia poorly describes angular dependence

Tagging merged jets

Gonzalez Silva, Phd Thesis (2012)
CERN-THESIS-2012-280



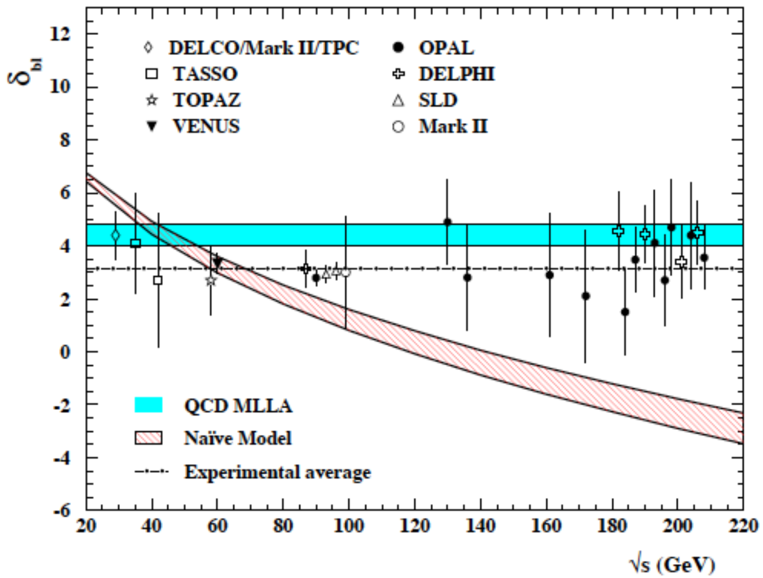


Merged jets can be tagged via their substructure
Variables used by ATLAS:

1) Jet track multiplicity
2) Jet width
3) ΔR between k_T subjets

Possible in heavy ions?
Also interesting for q/g discrimination

Dead cones



Vacuum:

Heavy quark multiplicity calculated in MLLA+LPHD

$\delta_{bl} = N_b^{ch}\text{-}N_l^{ch} = 3.12 \pm 0.14$

Dokshitzer, et al EPJC 45 (2006) 387-4001

In medium:

- Suppression of induced radiation [1]
- Finite size effects [2]
- Interference effects → radiation fills cone [3]

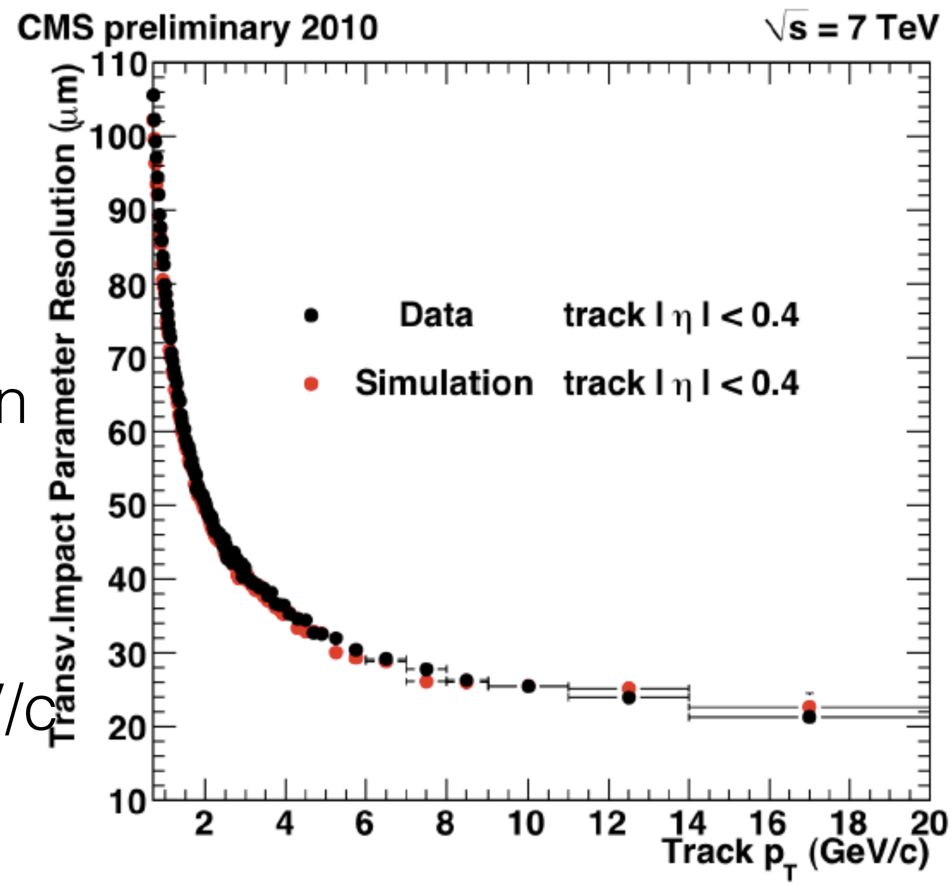
[1] Dokshitzer, Kharzeev PLB 519 (2001) 199-206
[2] Aurenche, Zakharov JETP Lett. 90 (2009) 237-243
[3] Armesto, Salgado, Wiedemann PRD 69 (2004) 114003

IP Resolution

- Pixel spatial resolution ~ 15-20 μm (rϕ and z)
- IP resolution

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

  - Constant term depends on geometry
  - Material dependent term important at low p_T
  - 100 (20) μm @ 1 (20) GeV/c
- Accurate GEANT simulation



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