

LHC



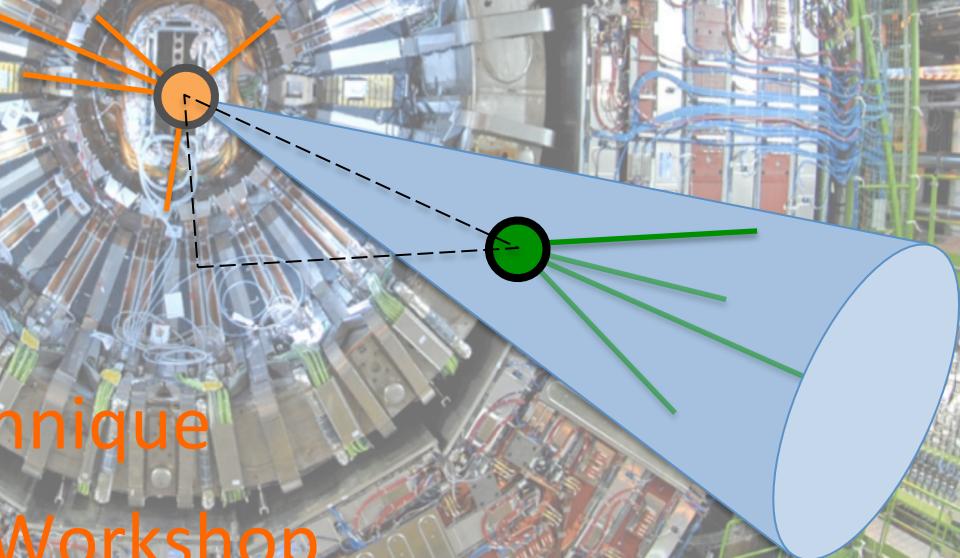
# b-Jets: Status and Perspectives

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LLR – Ecole Polytechnique

HI Jet Observables Workshop

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# Outline

- Introduction: b-tagging, why and how?
- b-Jet results from pp collisions
- First results from heavy ions
- Post LS1 perspective

# Quark Mass Effects in HI

- QCD color factors imply flavor dependence of energy loss (quark vs. gluon)
- Characteristic angle for radiative energy loss

$$\theta \simeq \frac{k_\perp}{\omega} \sim \left( \frac{\hat{q}}{\omega^3} \right)^{1/4}$$

- Radiation cannot decouple from heavy quarks in the direction of propagation → the dead cone effect

$$dP_{HQ} = dP_0 \cdot \left( 1 + \frac{\theta_0^2}{\theta^2} \right)^{-2} \quad \theta_0 \equiv \frac{M}{E}$$

“Heavy Quark Calorimetry of QCD Matter”,  
Dokshitzer and Kharzeev  
hep-ph/0106202 (2001)

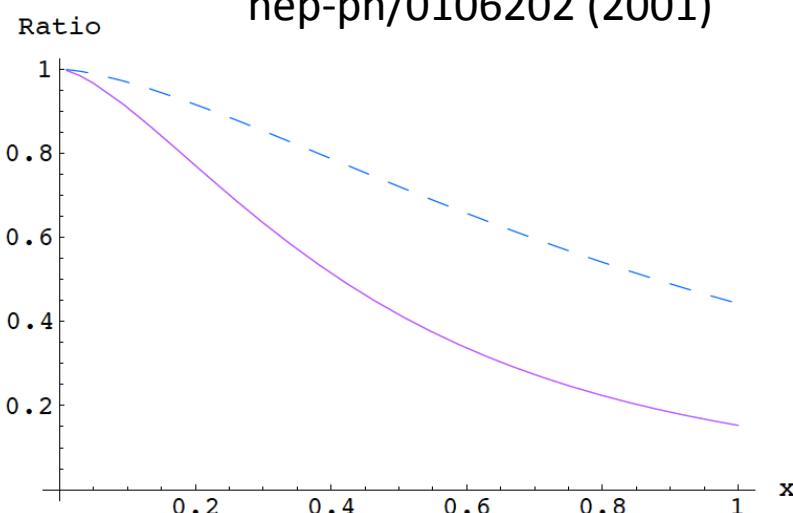
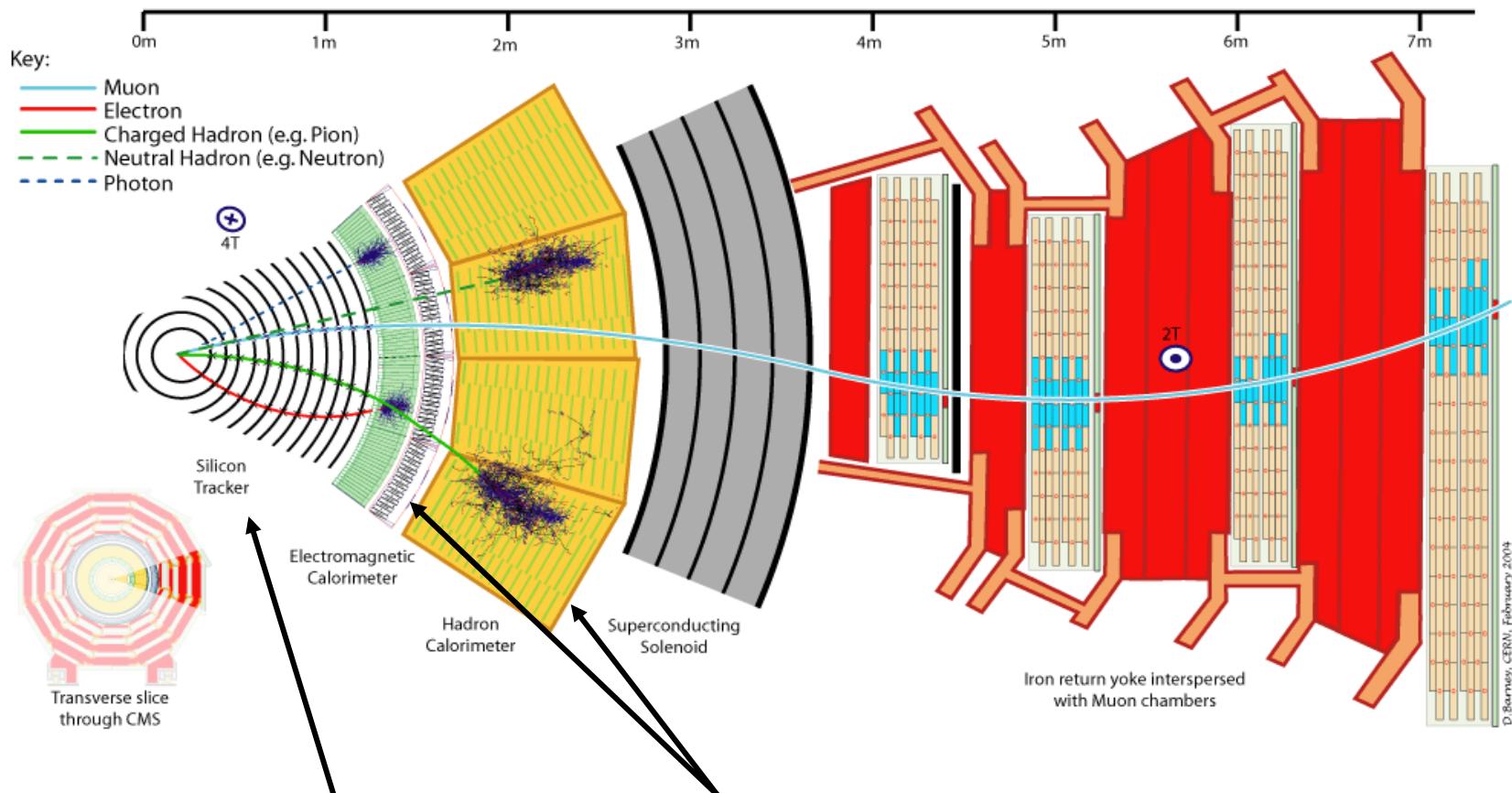


Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta  $p_\perp = 10$  GeV (solid line) and  $p_\perp = 100$  GeV (dashed);  $x = \omega/p_\perp$ .

“... the pattern of medium induced gluon radiation appears to be qualitatively different for heavy and light quarks in the kinematic regime of practical interest”

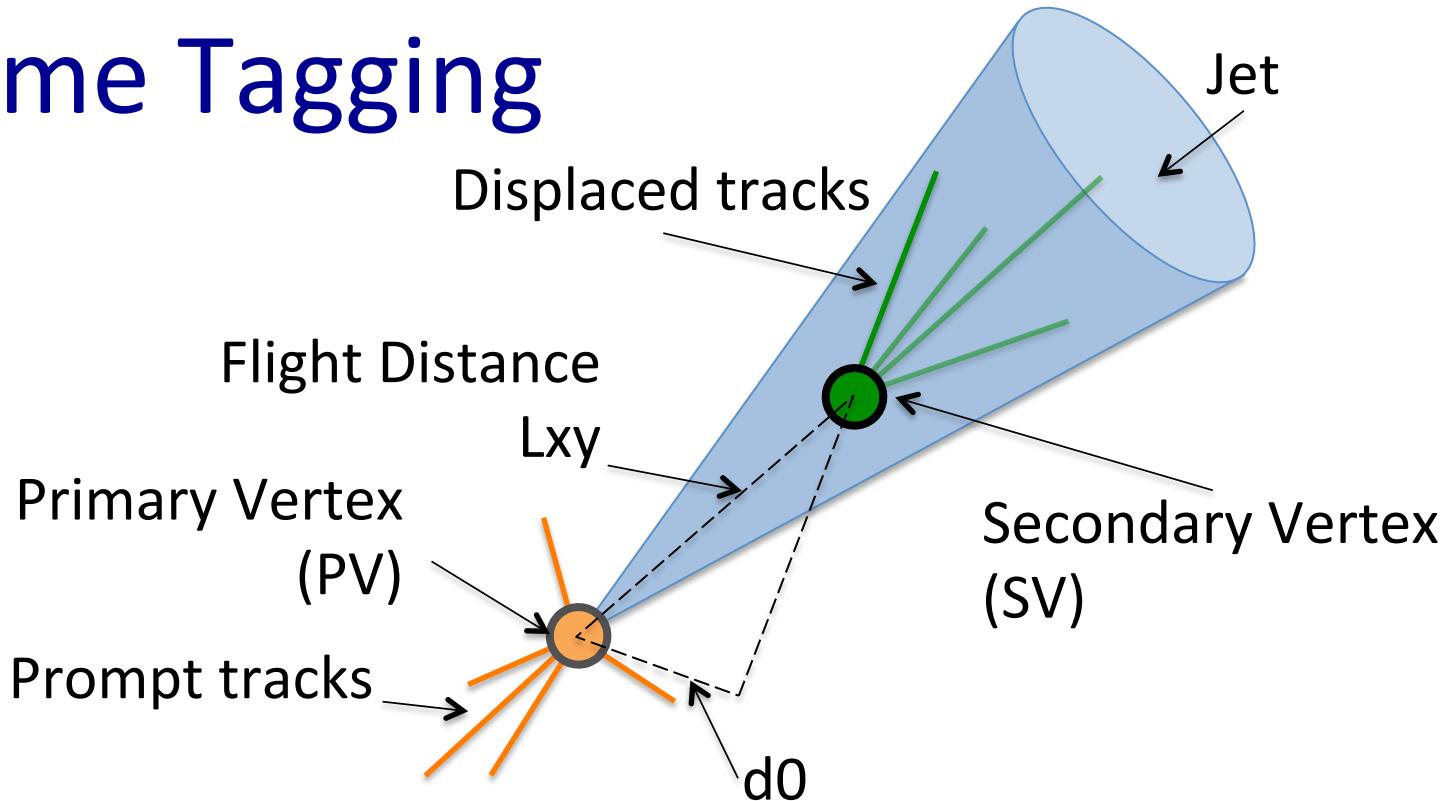
# The CMS Detector



Silicon tracker used in jet reconstruction and for secondary vertices

EM and hadronic calorimeters used for jet reconstruction

# Lifetime Tagging



- Long B-hadron lifetime ( $\sim 1.5$  ps)  $\rightarrow$  decays mm – cm from PV
- Likely subsequent charm decay w/ tertiary vertex
- *Lifetime tagging* based on
  - (Partially) reconstructed secondary vertices (SV)
  - Impact parameter (IP) of displaced tracks
- Jet measurement is identical to inclusive jets

# IP Resolution

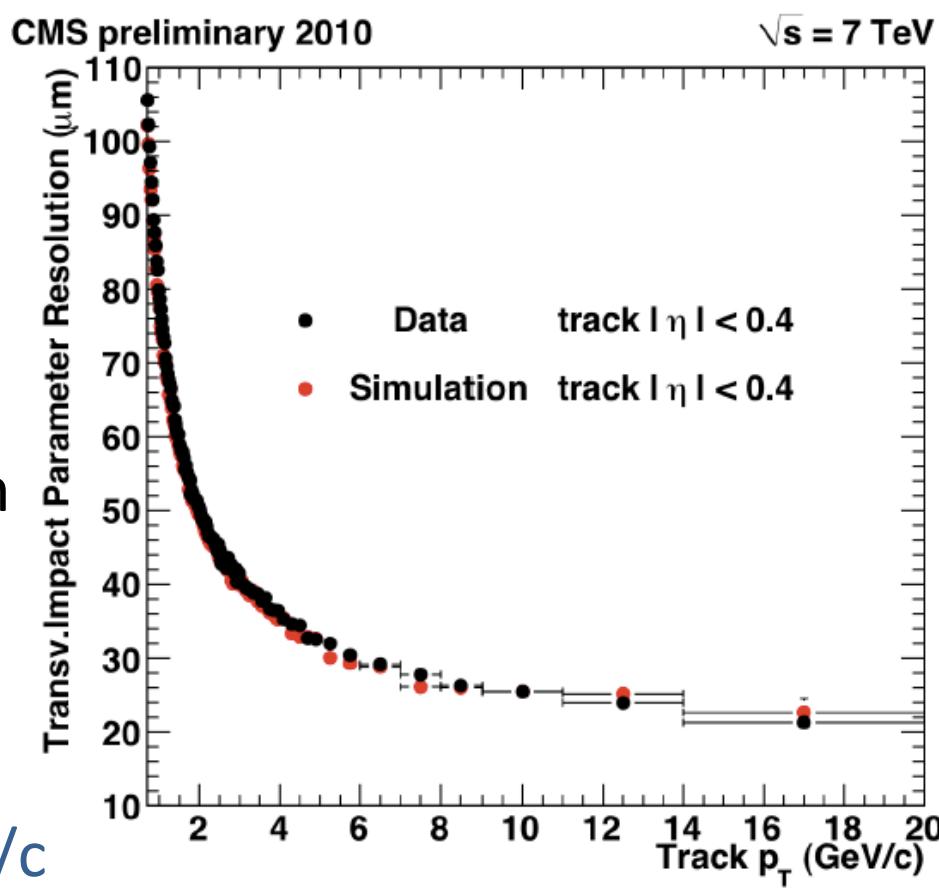
- Pixel spatial resolution

~ 15-20  $\mu\text{m}$  ( $r\phi$  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)  $\mu\text{m}$  @ 1 (20)  $\text{GeV}/c$
- Accurate GEANT simulation

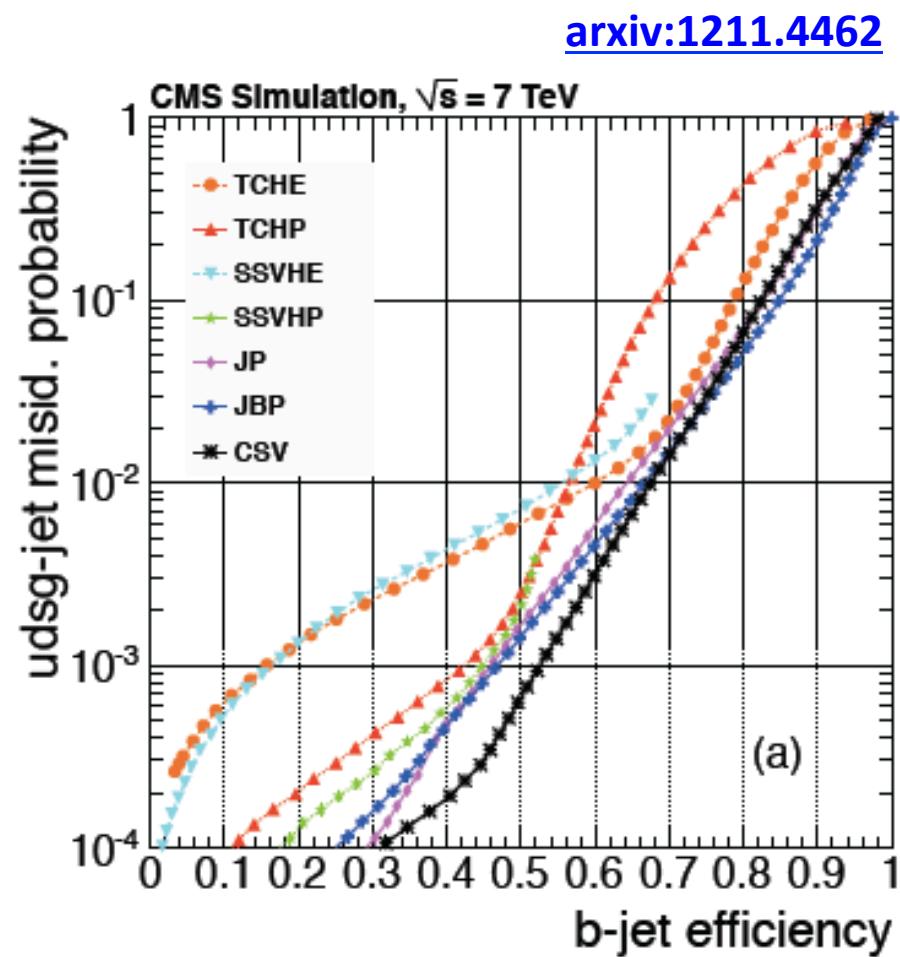


CMS-PAS-TRK-10-005

# CMS b-Jet Discriminators

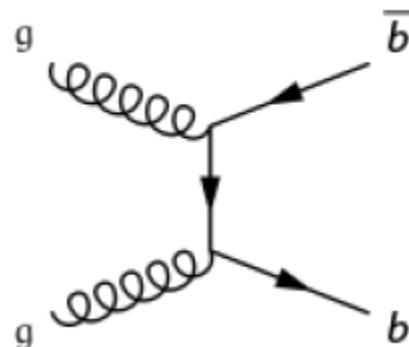
Single variable (*discriminator*), gives some b-tagging efficiency/purity, for a given working point

- IP-based taggers
    - Track counting (TC): IP significance (IP-sig) of Nth most displaced track
    - Jet Probability (JP): PV compatibility of all tracks
  - SV-based taggers
    - Simple SV (SSV): Uses flight distance significance
    - Combined SV (CSV): More variables, defaults to track IP if no reco'd SV
  - Soft lepton taggers:
    - $p_{T,\text{rel}}$  of IP-sig of muons or electrons

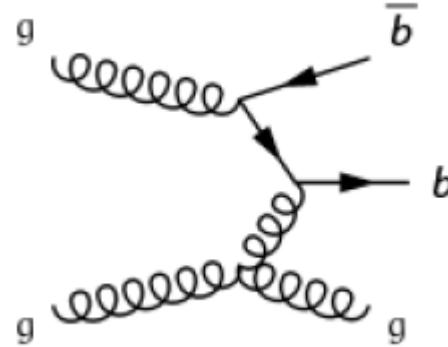


# Bottom Production

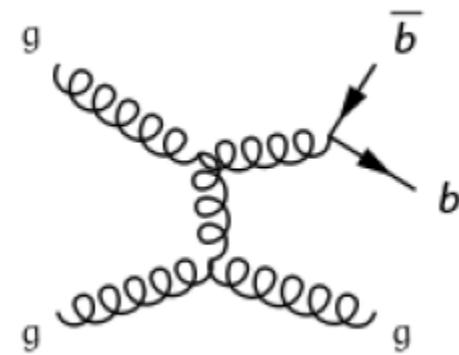
Flavor Creation (FCR)



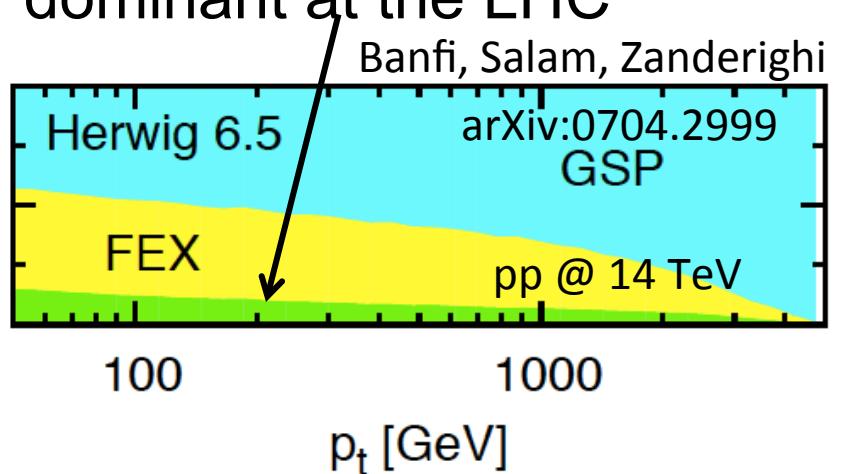
Flavor Excitation (FEX)



Gluon Splitting (GSP)



- LO  $b\bar{b}$  production (FCR) not dominant at the LHC

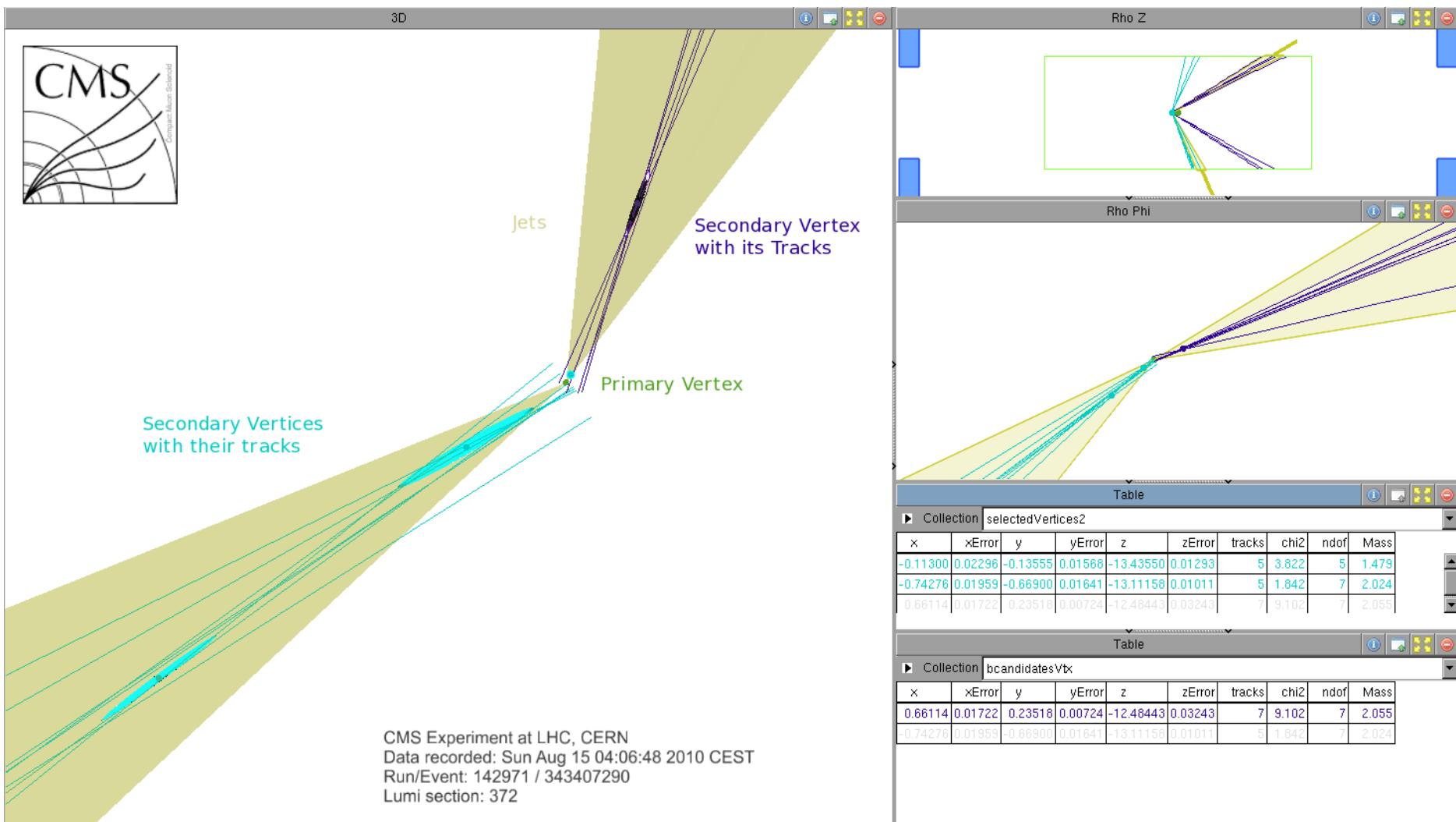


- At NLO

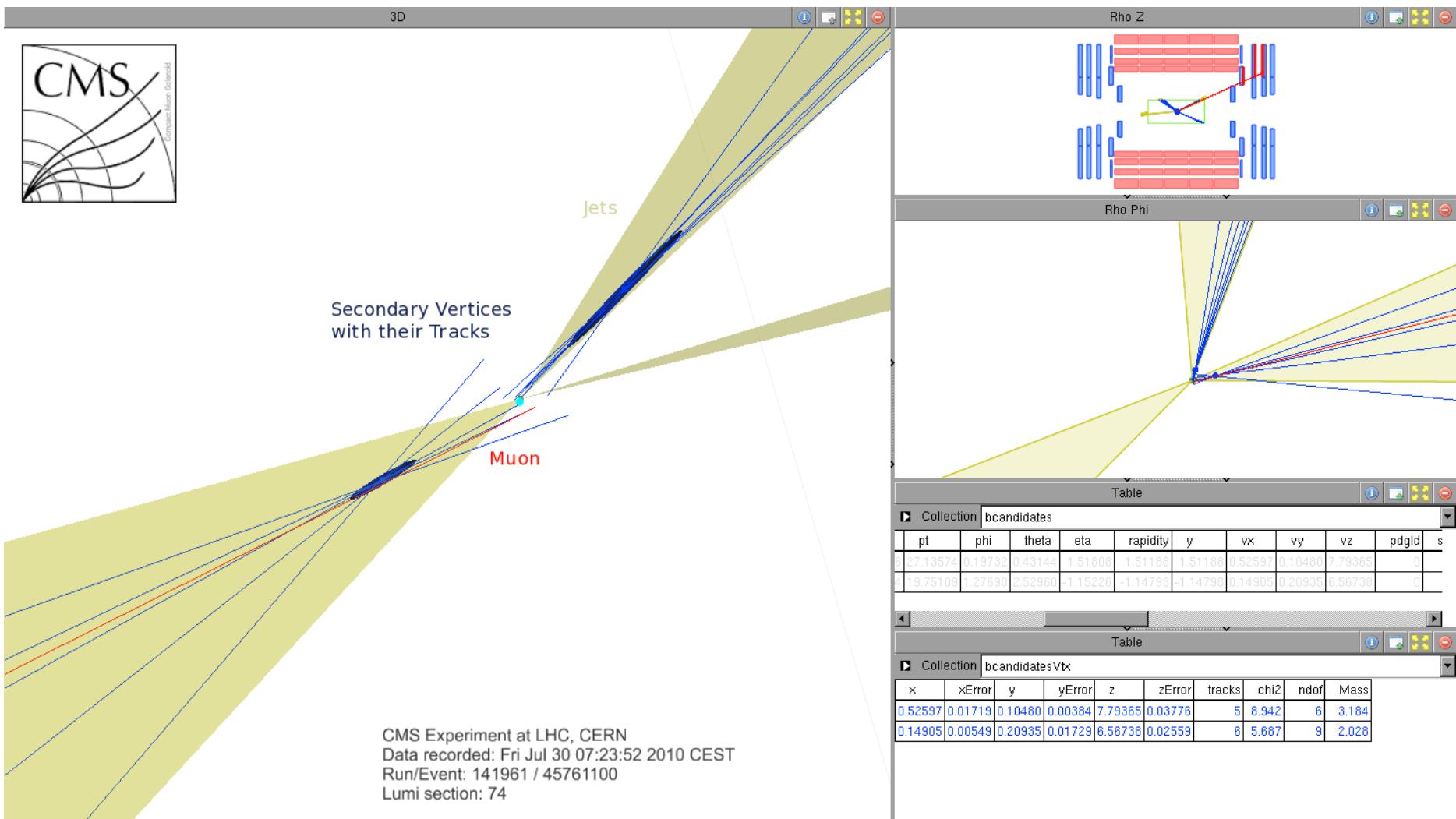
- Excitation of sea quarks  $\rightarrow b(b\bar{b}) +$  light dijet, w/  $b(b\bar{b})$  at beam rapidity
- Gluon splitting into  $b$  and  $\bar{b}$  which can be reconstructed as a single jet

Energy loss of split gluons could be quite different from primordial b-jets

# Flavor Creation Candidate (7 TeV)



# Gluon Splitting Candidate (7 TeV)

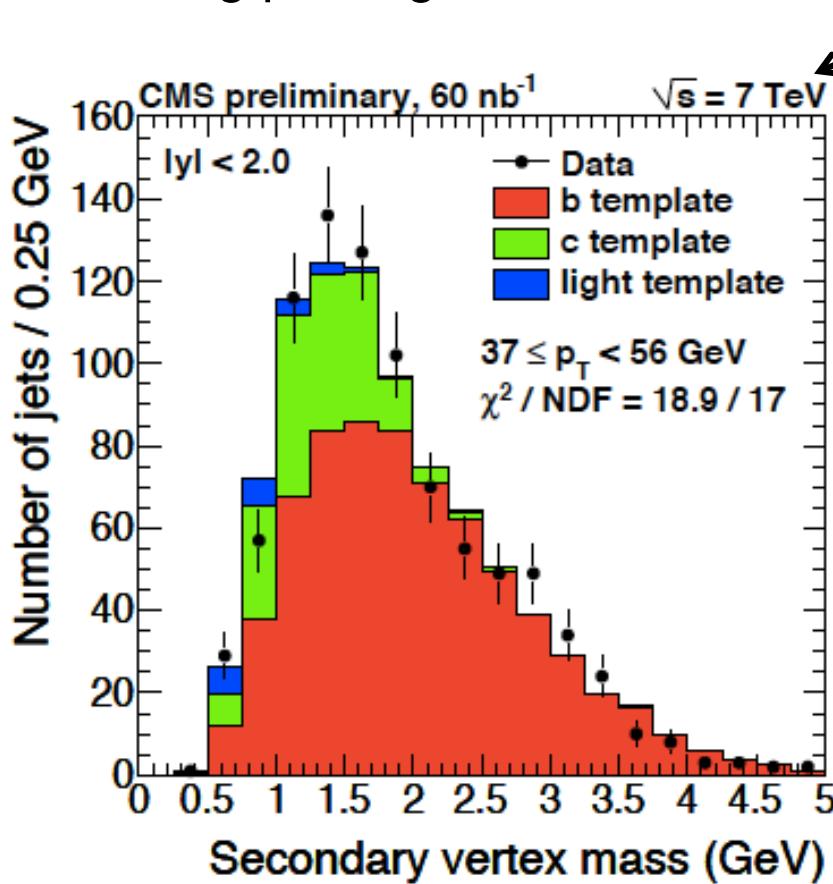


# SV Reconstruction and Selection

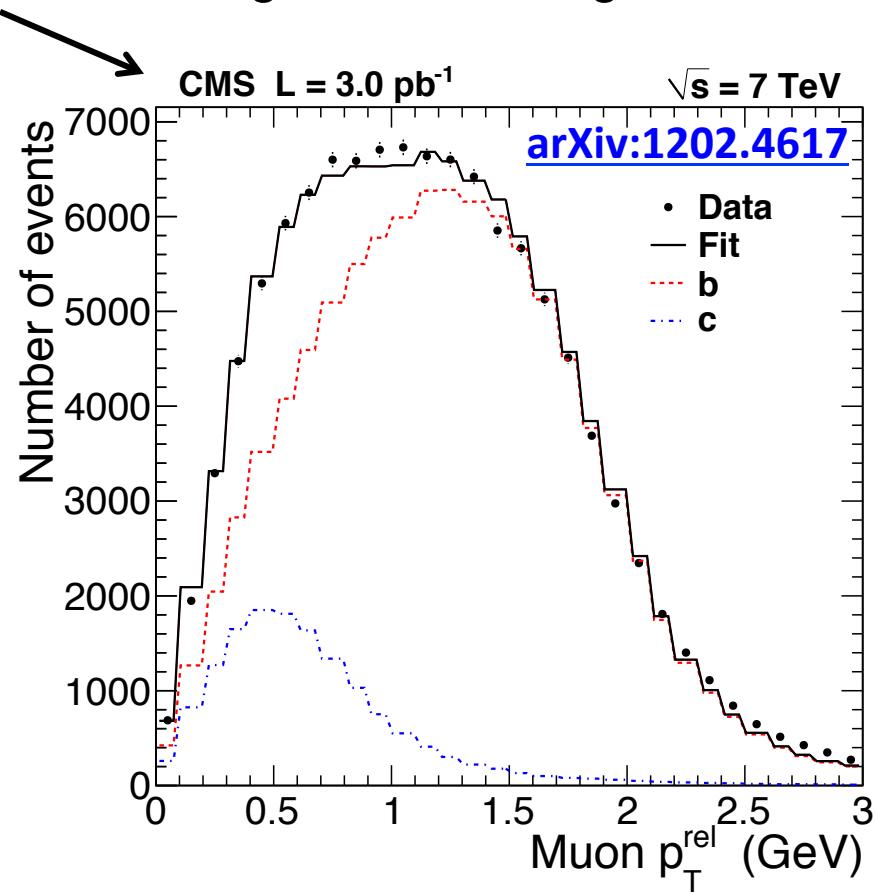
- Jet-track association
  - $R < 0.5$  w.r.t. jet axis
  - $p_T > 1 \text{ GeV}/c$
  - # of hits  $> 8$  (12) for pp (HI) collisions (+ other track quality cuts)
- *Adaptive* vertex fitter, robust against outlying tracks
- $< 35\%$  shared tracks with the primary vertex
- $> 3\sigma$  flight distance significance
- Rejection of long-lived particles and material interactions
  - $< 2.5 \text{ cm}$  radial distance from primary vertex
  - $K^0$  mass veto
  - Mass  $< 6.5 \text{ GeV}/c^2$
- *High Efficiency (Purity)* Selection  $\geq 2$  (3) tracks

# Methods Used in pp @ 7 TeV

Starting point: good SV with a selection on the flight distance significance



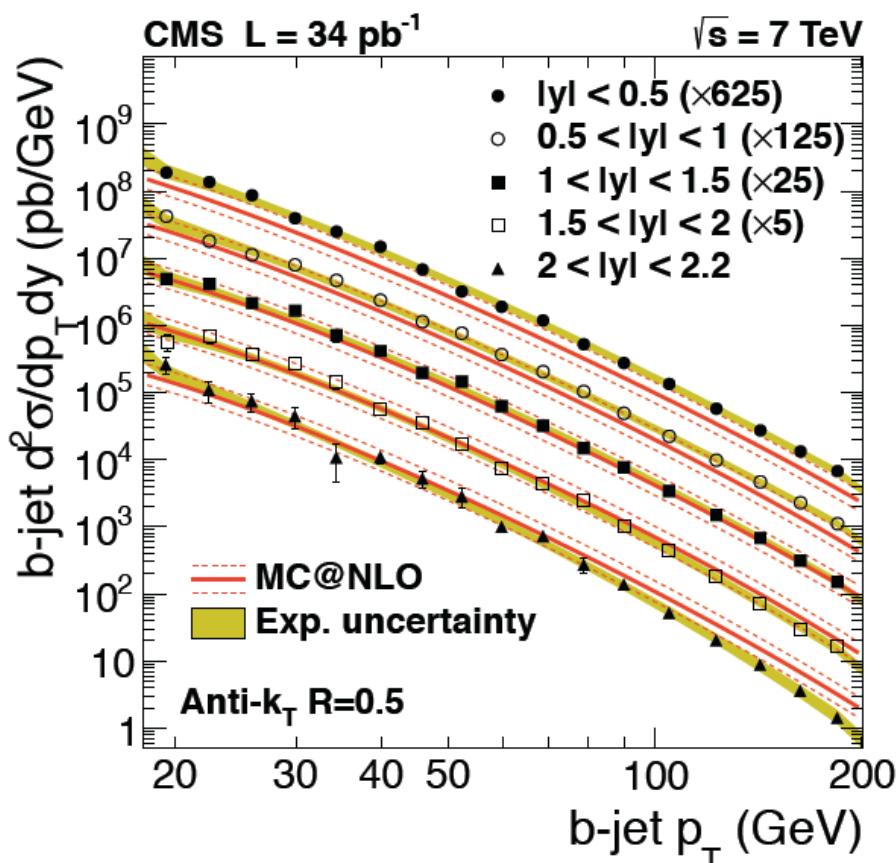
b-jet contribution determined by a template fit to the SV mass distribution



Alternate analysis uses muon-jets w/  $p_{T,\text{rel}}$  as a discriminating variable

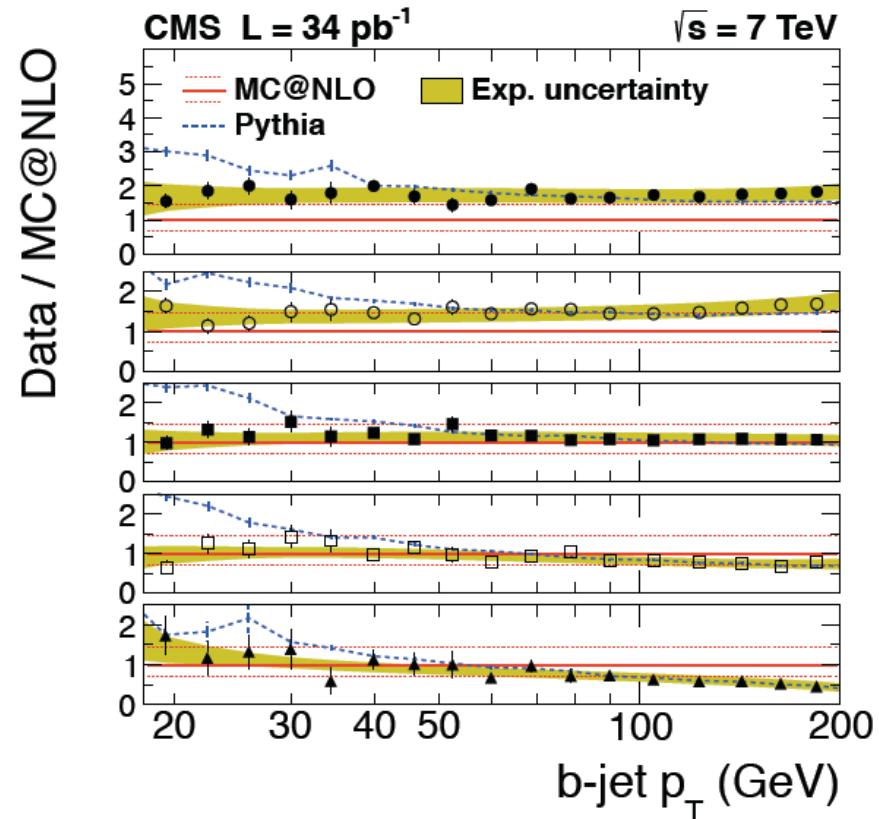
# b-Jet Cross Section

Double differential x-section



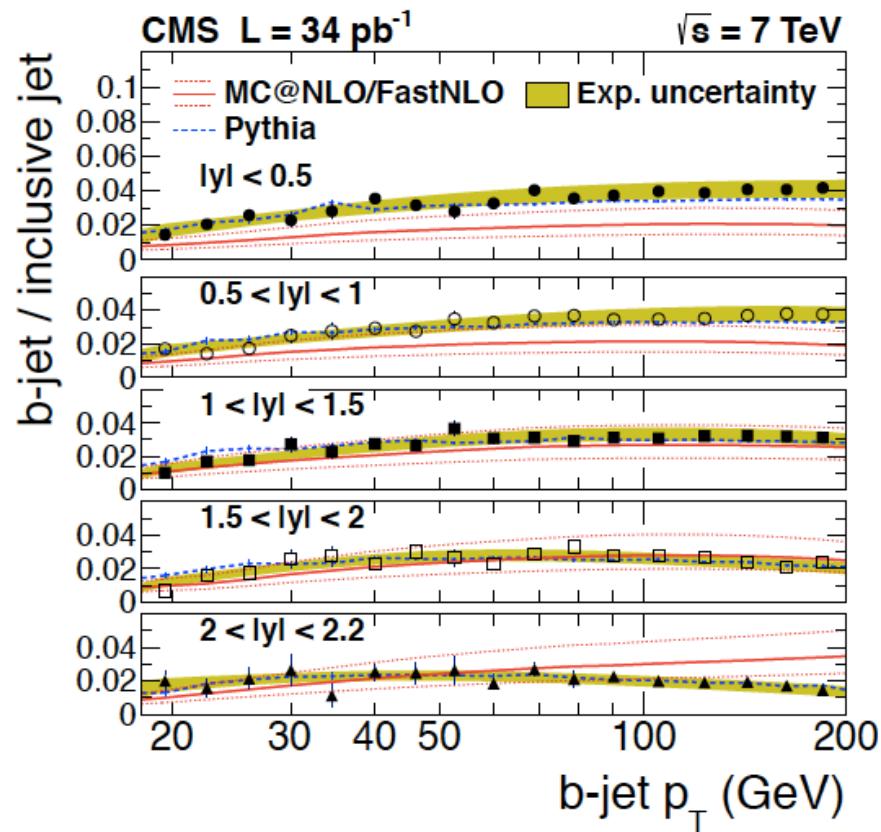
Ratio to MC@NLO

[arXiv:1202.4617](https://arxiv.org/abs/1202.4617)



- MC@NLO agreement at the edge of uncertainties
- Pythia overshoots at low  $p_T$ , agrees well at high  $p_T$

# b-Jet to Inclusive Jet Ratio

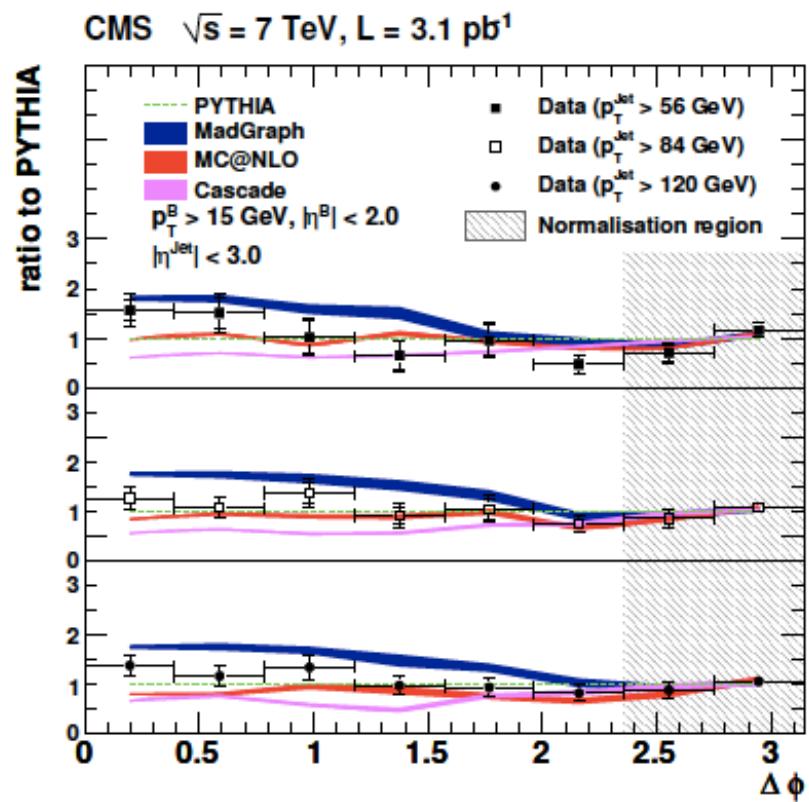
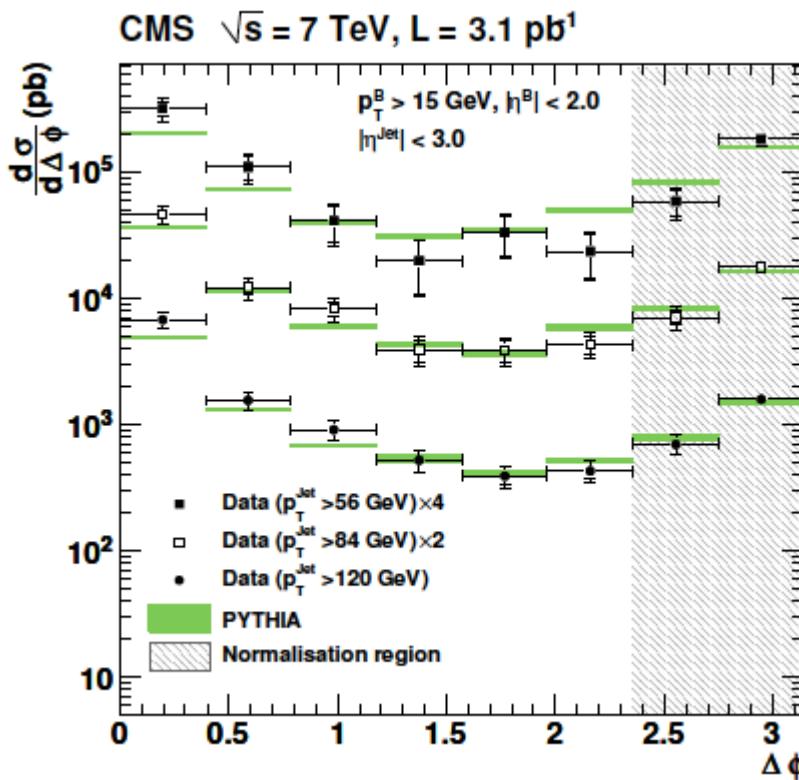


[arXiv:1202.4617](https://arxiv.org/abs/1202.4617)

Despite relatively poor description of the cross section,  
Pythia gives a good description of the b-jet / inclusive jet ratio

# B-Bbar Angular Correlations

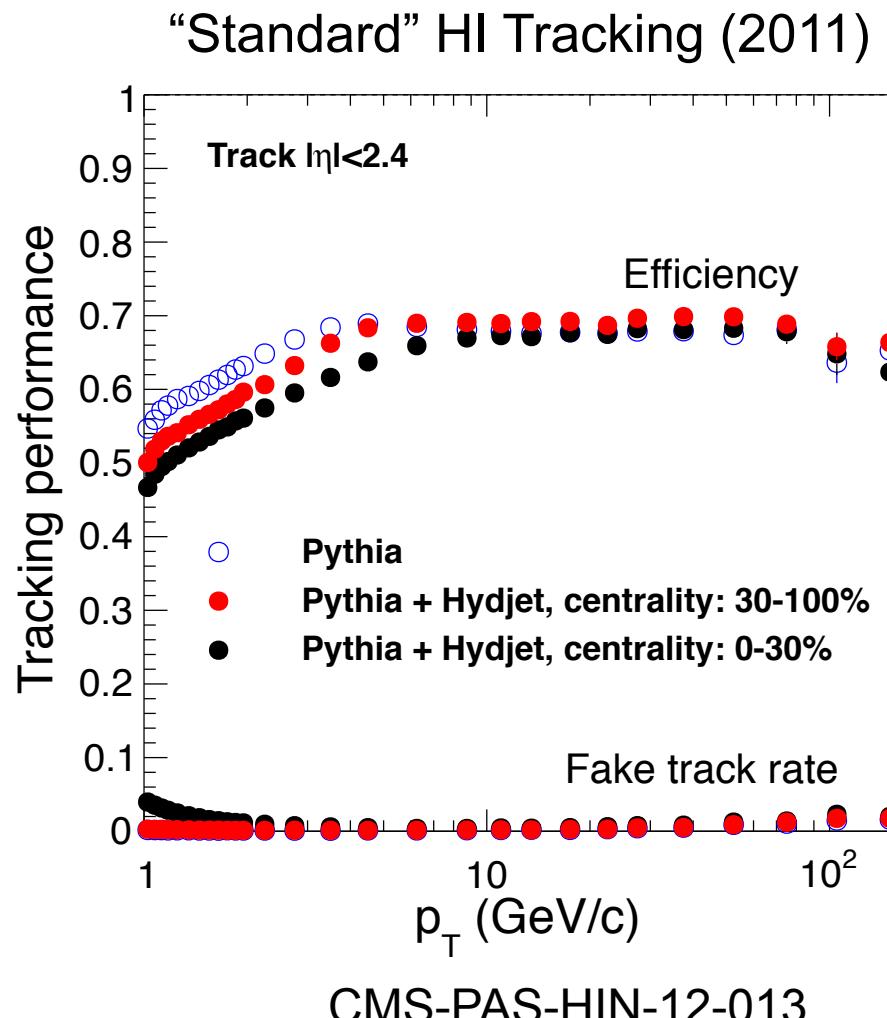
[arXiv:1102.3194](https://arxiv.org/abs/1102.3194)



- Angular correlations of double b-tagged jets are sensitive to the production mechanisms
- “Inclusive vertex finder” adept at separating nearby b vertices
- Most generators tend to under-predict the gluon splitting contribution

# Tracking in Heavy Ions

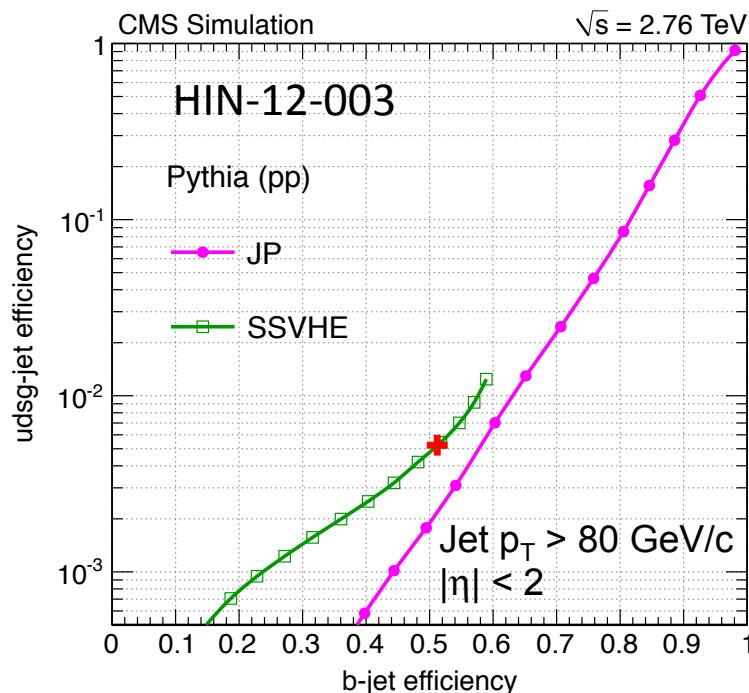
- Biggest challenge in PbPb is reconstructing displaced tracks in central events
- Standard HI track reco. and selection has a reasonable efficiency and low fake rate for primary tracks
- Reconstructing all displaced tracks is so far not possible due to huge number of hit combinations
- Solution is to run additional tracking locally inside jets to recover secondary tracks



# b-Tagging Performance

Two discriminators are used in the HI analysis:

- *Simple Secondary Vertex High Efficiency (SSVHE)*
- *Jet Probability (JP)*



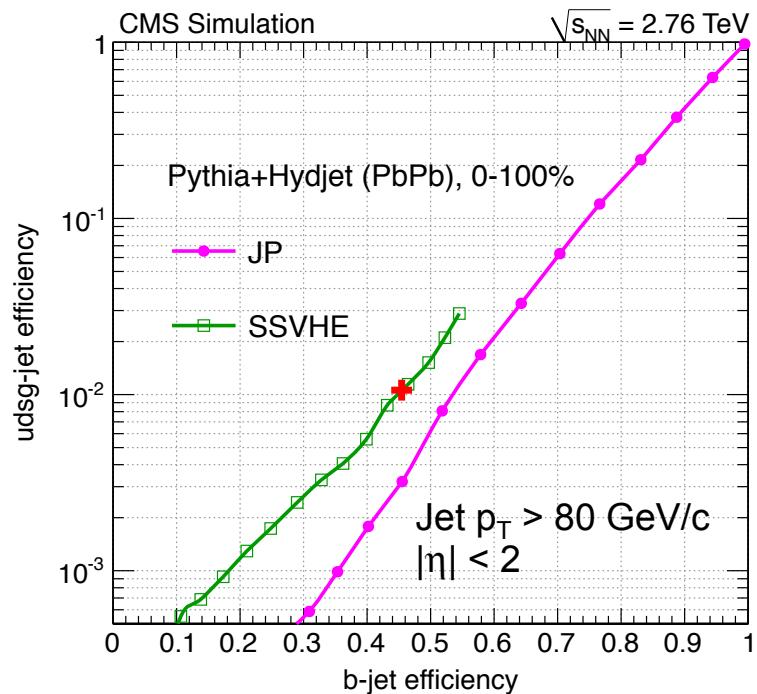
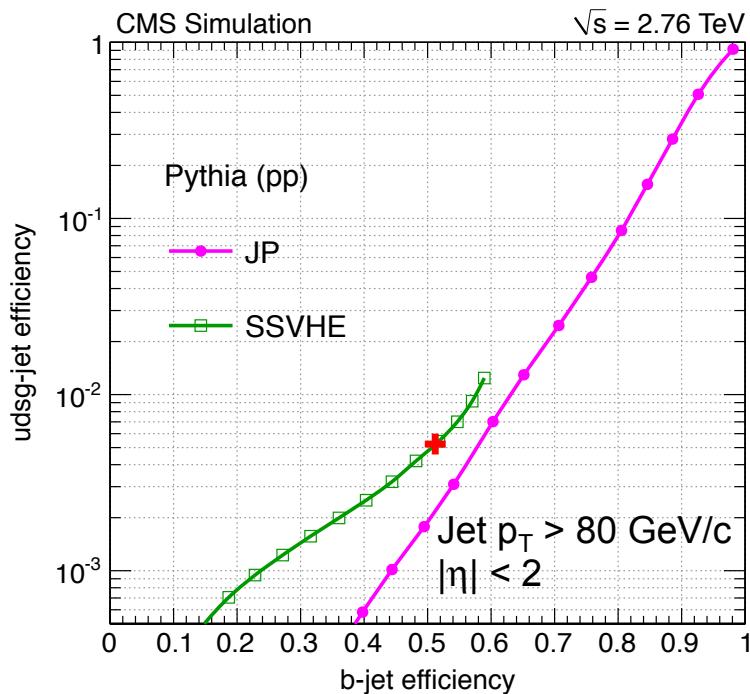
- *SSVHE*
  - Uses flight distance significance
  - Additional discrimination from SV mass
- *JP*
  - Uses all large IP tracks to estimate a likelihood of PV compatibility
  - Discriminates for  $\sim$  all b-jets
  - Independent data and MC calibrations using negative IP tracks
- SSVHE working point gives a factor of several hundred in light jet rejection for a b-jet efficiency of about 50%
- JP used to cross-check the SV tagging efficiency in a data-driven way

# Light Jet Discrimination

Jets are tagged by cutting on discriminating variables

- *Simple Secondary Vertex High Efficiency (SSVHE)*
- *Jet Probability (JP)*

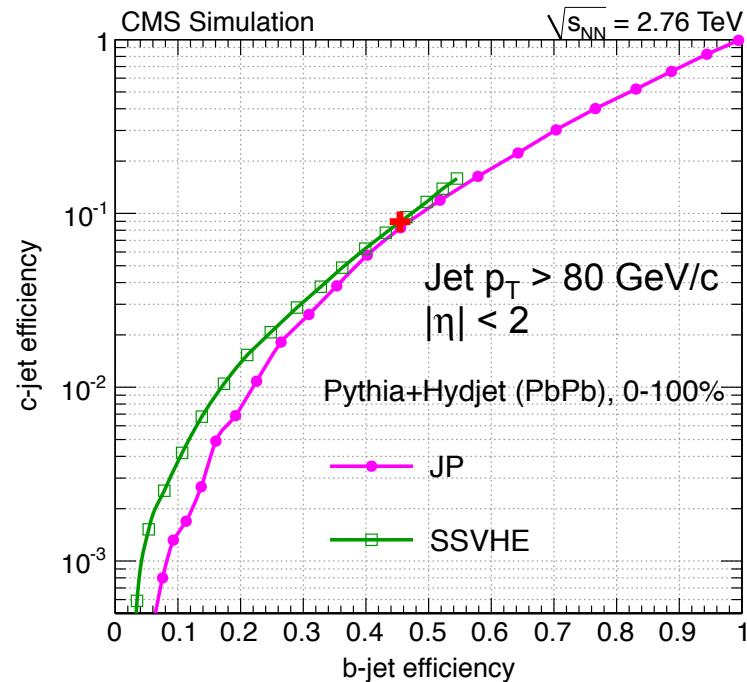
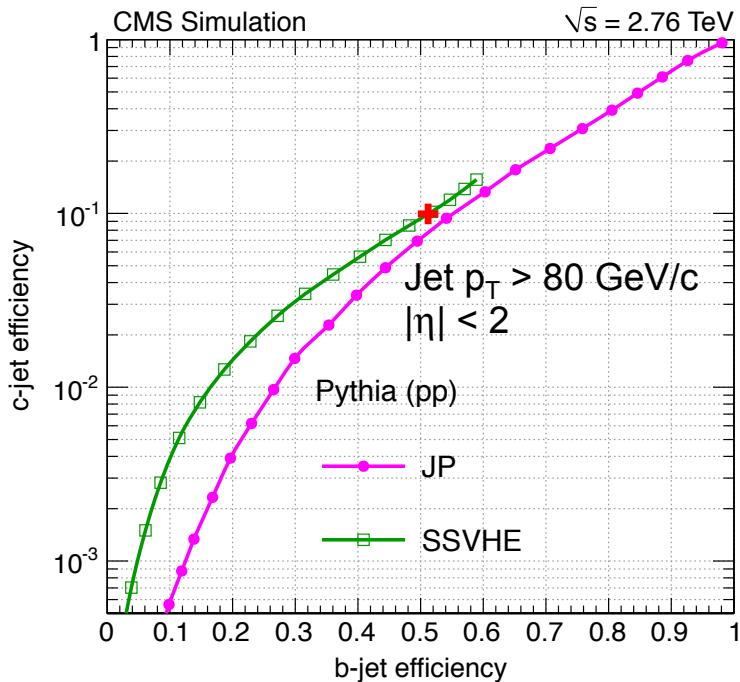
HIN-12-003



Some degradation of performance in PbPb compared to pp,  
but still a factor of  $\sim 100$  light jet rejection for  $\sim 45\%$  b-jet efficiency

# Charm Jet Discrimination

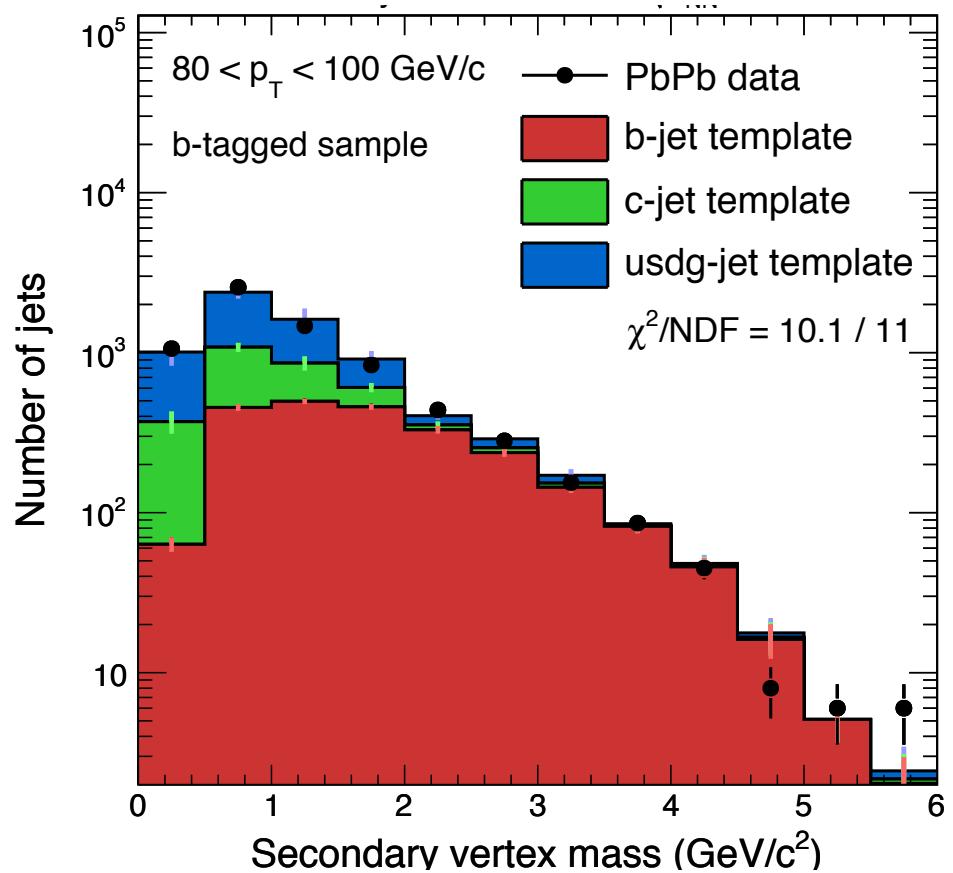
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- Charm rejection is about a factor of 10 for the same working point
- Again, some degradation of performance for PbPb w.r.t. pp

# Secondary Vertex Mass Fits

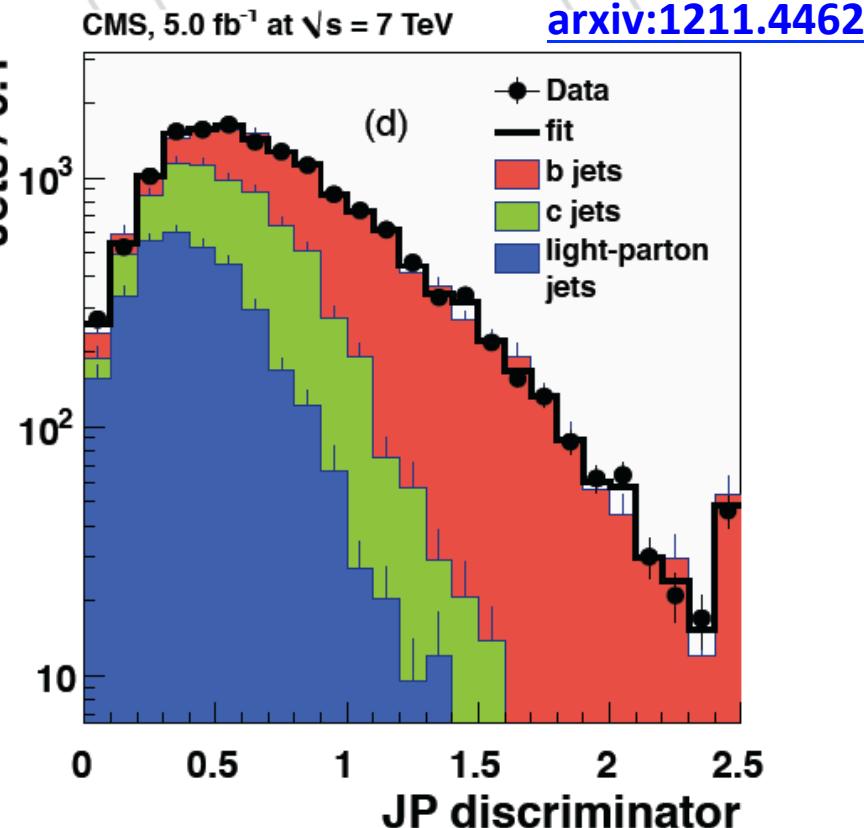
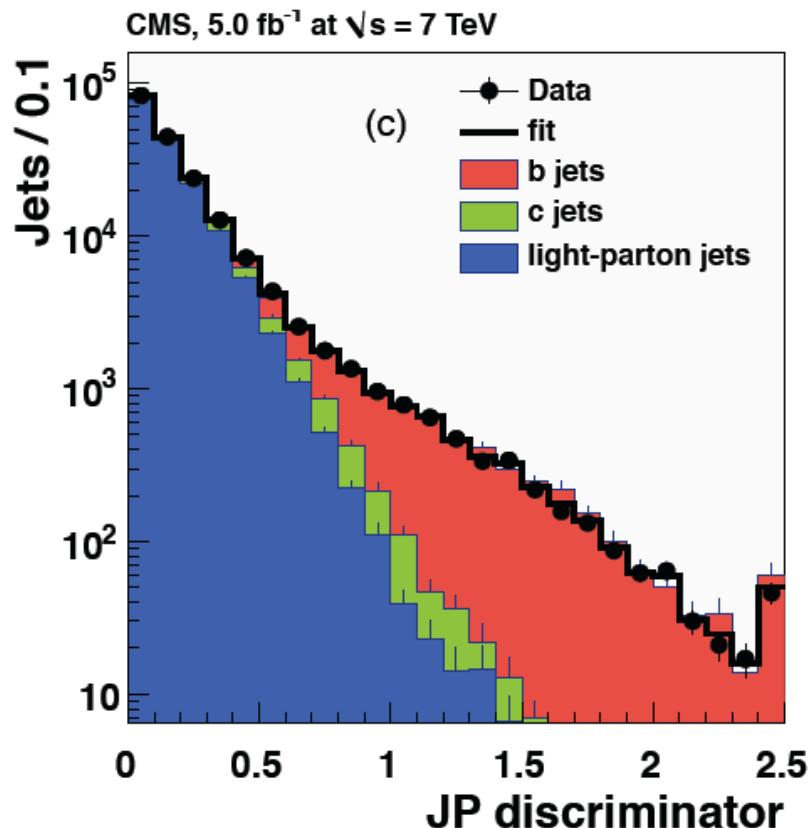
- After enriching sample in b-jets with the SSVHE tagger, the b-jet *purity* is derived from a fit to the SV mass distribution
- Shapes of b, c and light templates taken from MC, normalizations allowed to float
- Sytematics
  - Shapes of the non-b templates are cross-checked with data-driven templates
  - Charm:light normalization is fixed by MC and refit
  - Stability of fits is checked by varying SSVHE working point
  - Gluon splitting contribution is varied by 50%



HIN-12-003

# Reference Tagger Method

Idea: use a weakly correlated tagger to derive SV tagging efficiency

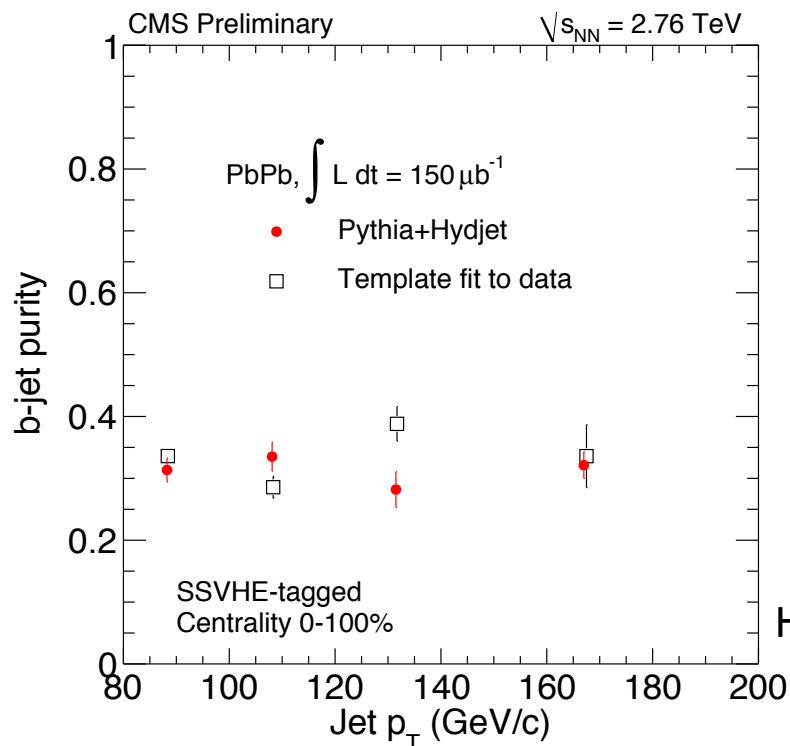


$$\varepsilon_b(\text{data}) = \frac{C_b f_b^{tag} N_{\text{data}}^{tag}}{f_b^{notag} N_{\text{data}}^{notag}}$$

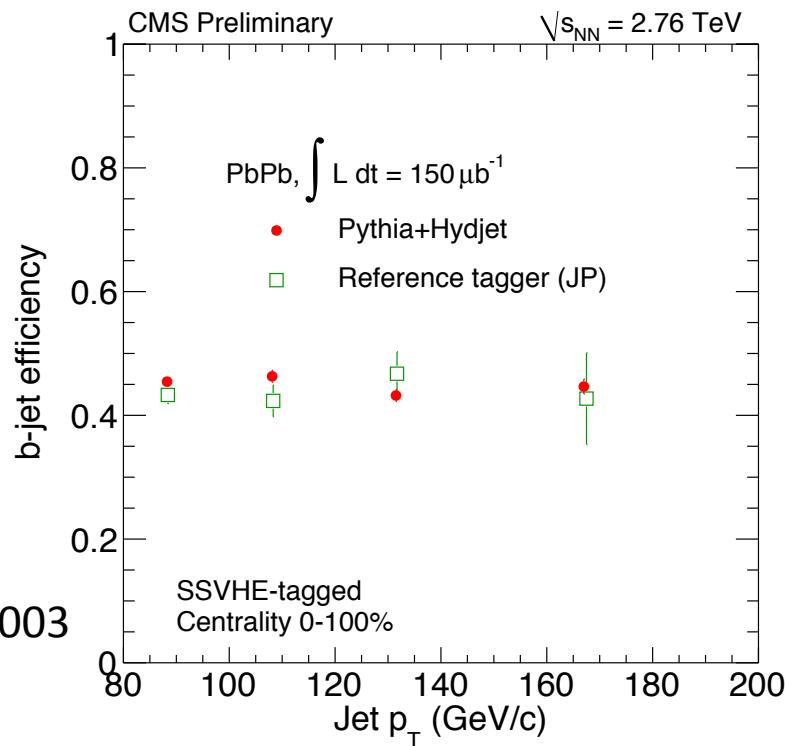
$f_b$  = purity from template fit  
 $\#$  of tagged jets in data  
 $\#$  of jets with JP information  
 $C_b$  = fraction of jets with JP information

# b-Tagging Purity and Efficiency

Purity: b-jet fraction in SV tagged sample extracted from SV mass fit



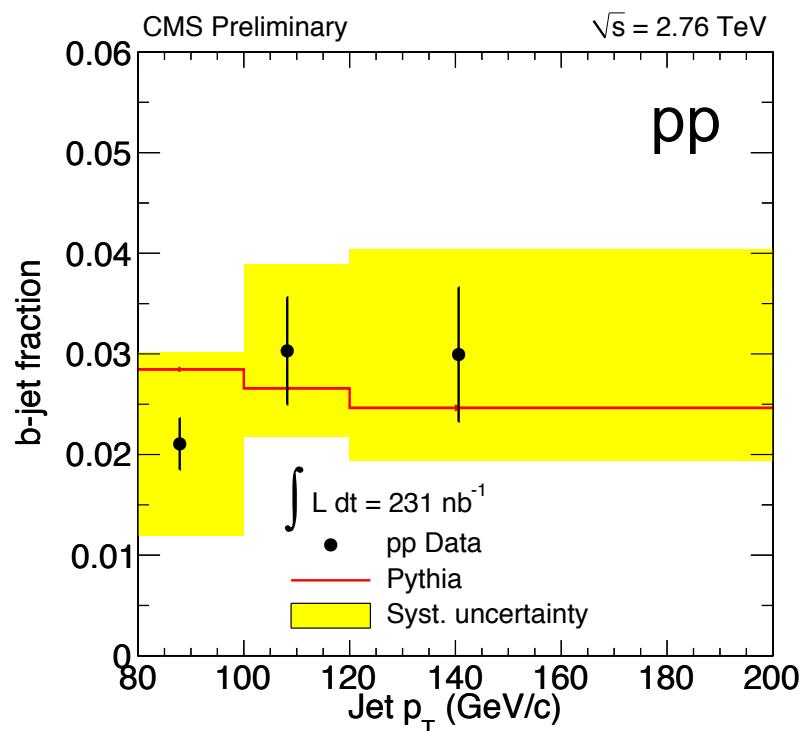
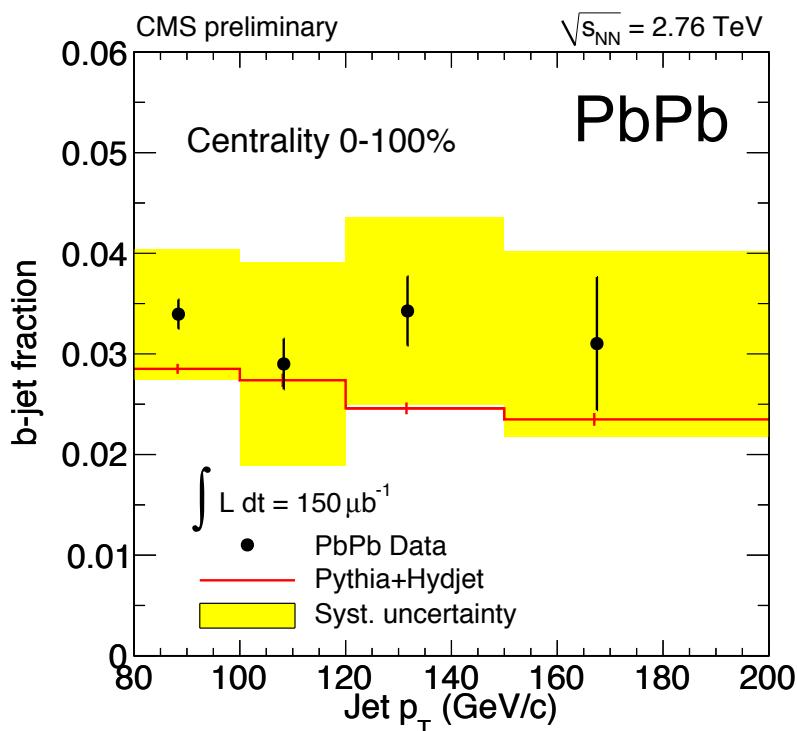
Efficiency: Fraction of b-jets which are tagged by their SV



- Efficiency is extracted from simulation and with a data-driven method using the JP tagger, i.e., w/o requiring a SV
- For both efficiency and purity, MC is fairly close to data “out of the box”

# b-Jet to Inclusive Jet Ratio

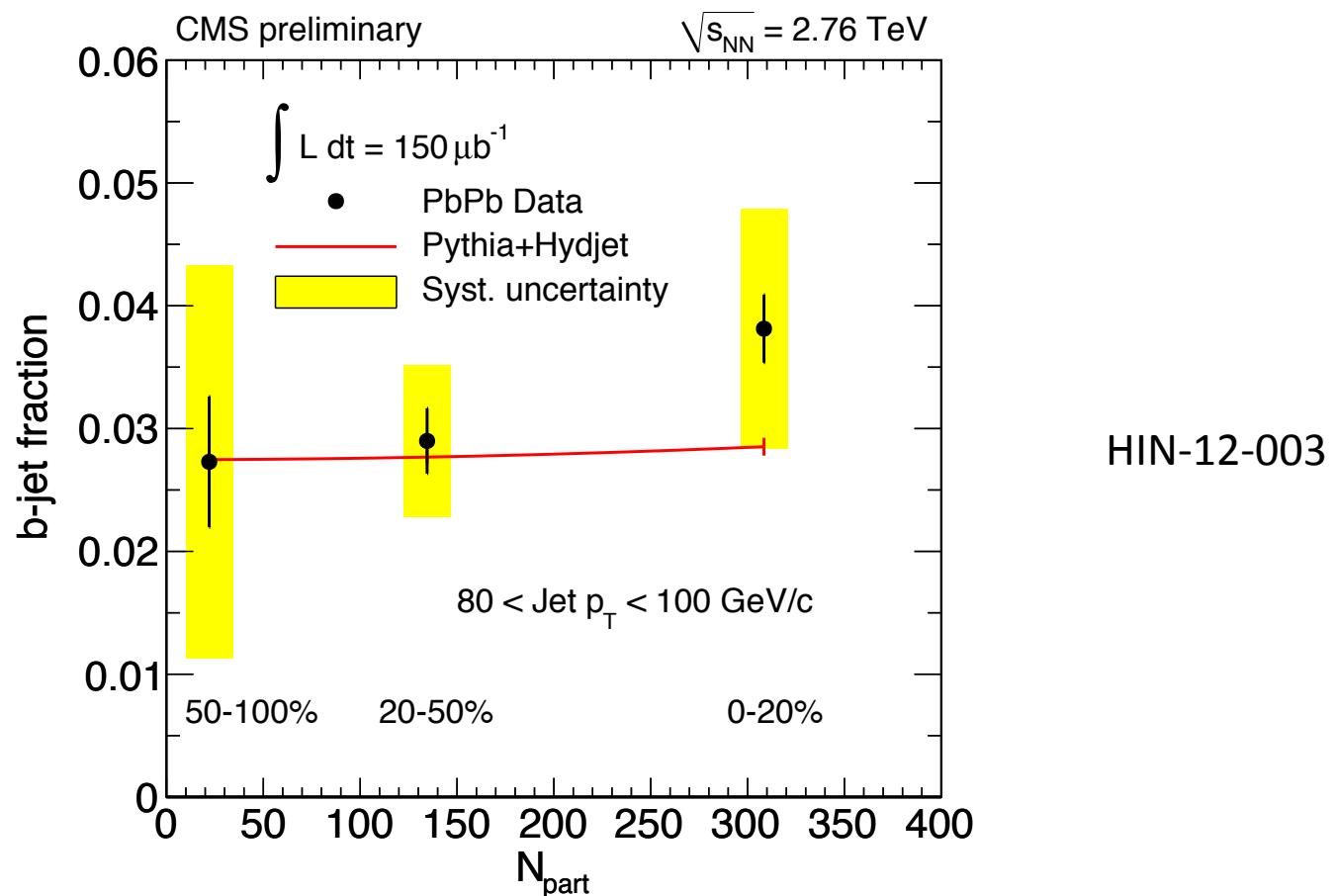
b-jet fraction = # of tagged jets \* purity / efficiency



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- b-jet fraction in PbPb larger than MC, but consistent within uncertainties
- pp data are also consistent with MC prediction

# b-Jet Fraction vs. Centrality

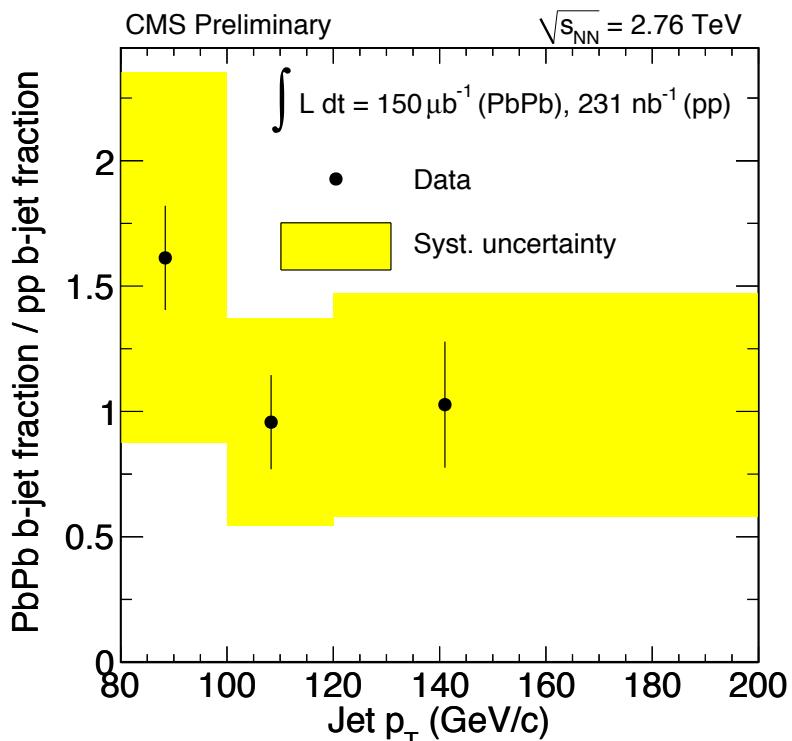


b-jet fraction does not show a strong centrality dependence

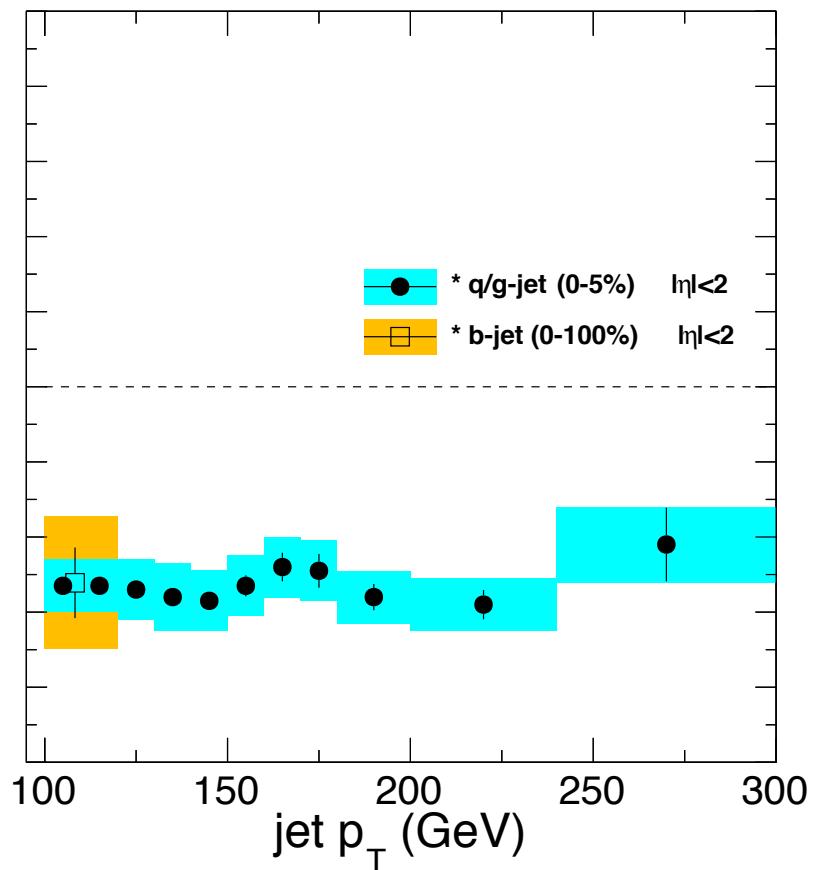
# b-Jet R<sub>AA</sub>

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b-jet fraction double ratio =  
 b-jet fraction |<sub>PbPb</sub> / b-jet fraction |<sub>pp</sub>



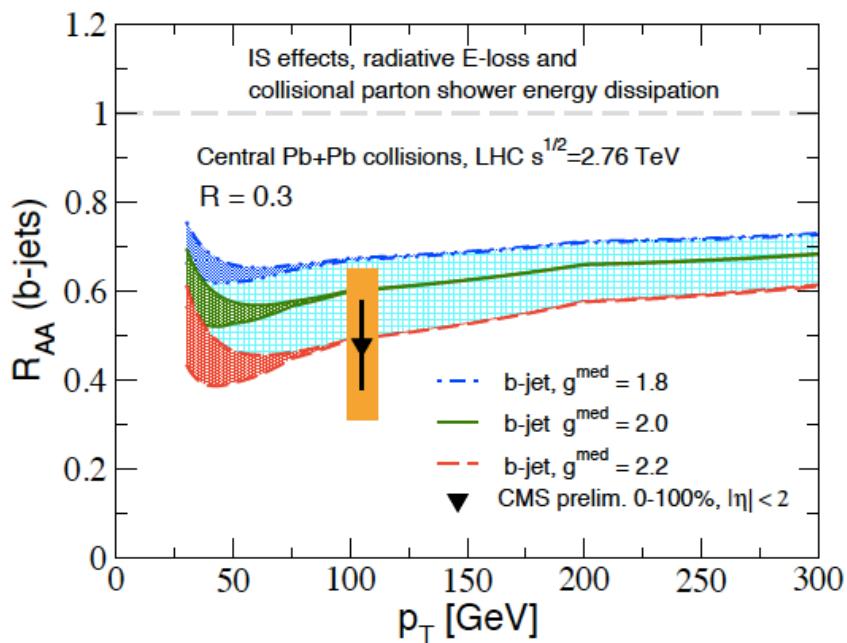
b-jet R<sub>AA</sub>  
 = inclusive jet R<sub>AA</sub> \* double ratio



Conclusion: To within errors b-jets and light jets are suppressed by the same factor

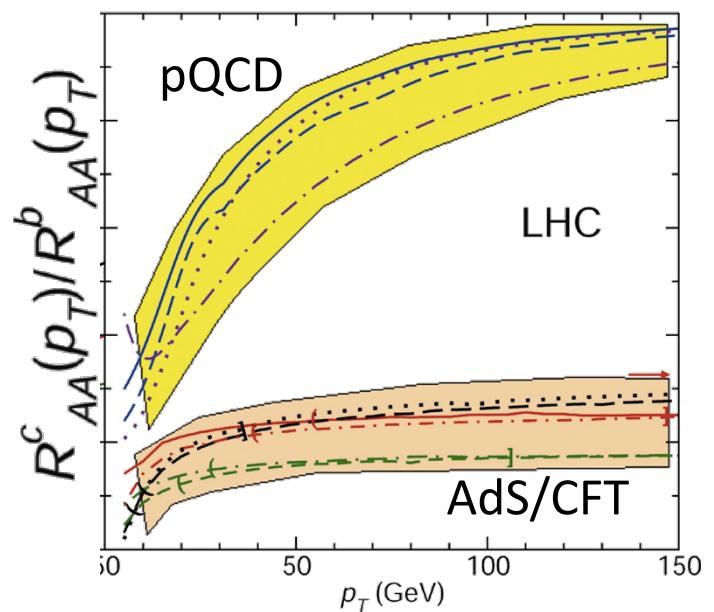
# Have we learned anything yet?

Huang, Kang and Vitev  
arXiv:1306.0909 (2013)



Models now indicate that mass effects are restricted to  $p_T < 75 \text{ GeV}/c$

Gyulassy and Howitz  
arXiv:0804.4330 (2008)



On the other hand, there were models predicting quite large effects even at large  $p_T$

# Conclusions so far

- b-jet cross section measured in 7 TeV pp collisions
  - Using secondary vertices
  - Using muon jets
- Results agree with Pythia predictions
- Fully reconstructed b-jets have been identified in heavy-ion collisions for the first time
- b-jet fraction in PbPb is consistent with Pythia and pp data @ 2.76 TeV within fairly sizeable uncertainties
- Look forward to
  - New high statistics 2013 pp data @ 2.76 TeV
  - Further analysis pushing to lower  $p_T$  jets, double b-tagged dijets, etc.

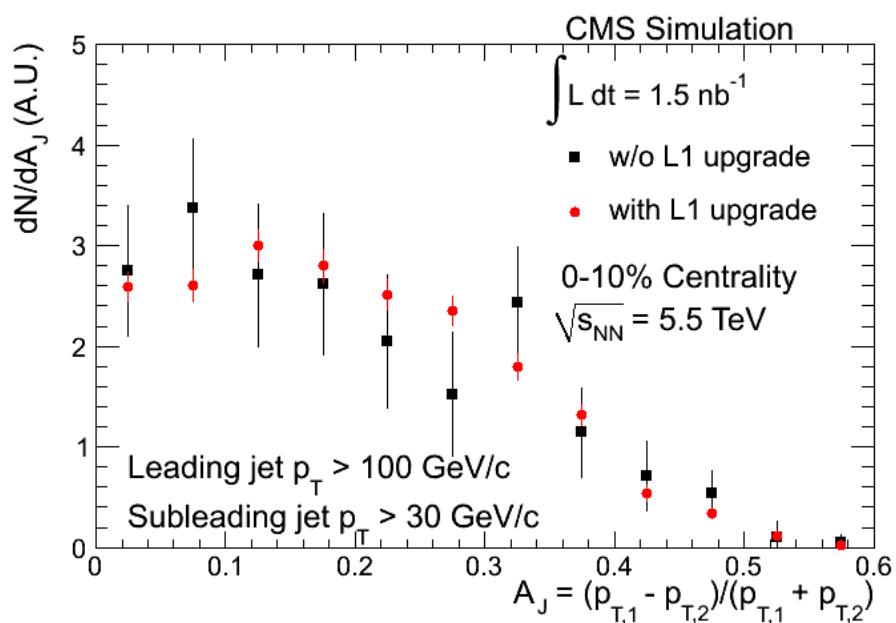
# B-Jet Statistics Today

- In 2011 we recorded  $\sim 0.5$  billion  $R=0.3$  jets at  $p_T > 80 \text{ GeV}/c$ , with no trigger prescale
- Corresponding # of b-jets is  $\sim 15k$
- Golden measurement: double b-tagged dijets
  - Removes gluon splitting component
  - Allows to obtain a high purity sample of b-jets
  - Small systematics w.r.t. inclusive jet measurement
- However:
  - Double b-tagging efficiency  $\sim 0.5^2 = 0.25$
  - LO flavor creation mode only contributes  $\sim 15\%$
- $< 1000$  tagged di-b-jets (leading jet  $p_T > 80 \text{ GeV}/c$ )

# After LS1

- Large data volumes
  - 10x integrated luminosity not unrealistic
  - 5x from  $\sqrt{s}$
- L1 jet trigger
  - Currently insufficient to read out larger rate
  - Upgraded system w/ background subtraction will make this possible
- Precision measurement will be feasible!

Projection for di-b-jet asymmetry for  $1.5 \text{ nb}^{-1}$



CMS L1 Trigger Upgrade TDR  
<https://cds.cern.ch/record/1556311?>

# Triggering on b-Jets

- Current jet-triggered data samples are  $O(100 \text{ TB})$
- 50x stats  $\rightarrow 5 \text{ PB}$  of data
- To reduce the data volume need a dedicated b-jet triggering algorithm for HI
- Already using full tracking at trigger-level
  - High multiplicity triggers
  - Muon “L3” triggers
- Displaced tracks in jets are more challenging than these use-cases
- Timing of track reconstruction may be an issue
- Looking into fast track reconstruction algorithms

# References

- Identification of b-quark jets with the CMS experiment  
**JINST 8 (2013) P04013, [arxiv:1211.4462](#)**
- Inclusive b-jet production in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$   
**JHEP 1204 (2012) 084, [arXiv:1202.4617](#)**
- Measurement of BB Angular Correlations based on Secondary Vertex Reconstruction at  $\sqrt{s} = 7 \text{ TeV}$   
**JHEP 1103 (2011) 136, [arXiv:1102.3194](#)**
- Measurement of the b-jet to inclusive jet ratio in PbPb and pp collisions at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$   
**CMS-PAS-HIN-12-003, [arxiv:1102.3194](#)**
- CMS TDR for the L1 Trigger Upgrade, **[CMS-TDR-012](#)**