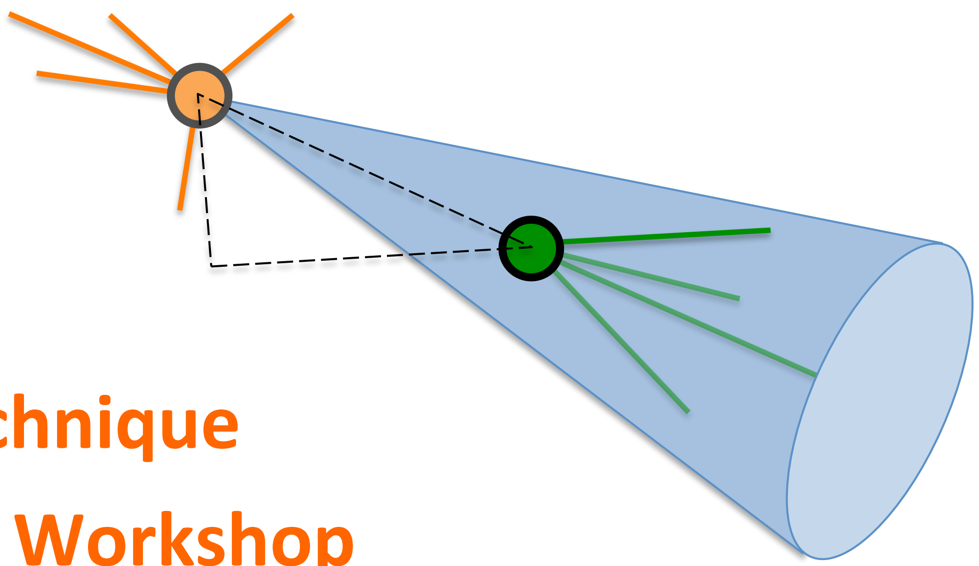
Overview of heavy quark experimental results in HI



Matt Nguyen

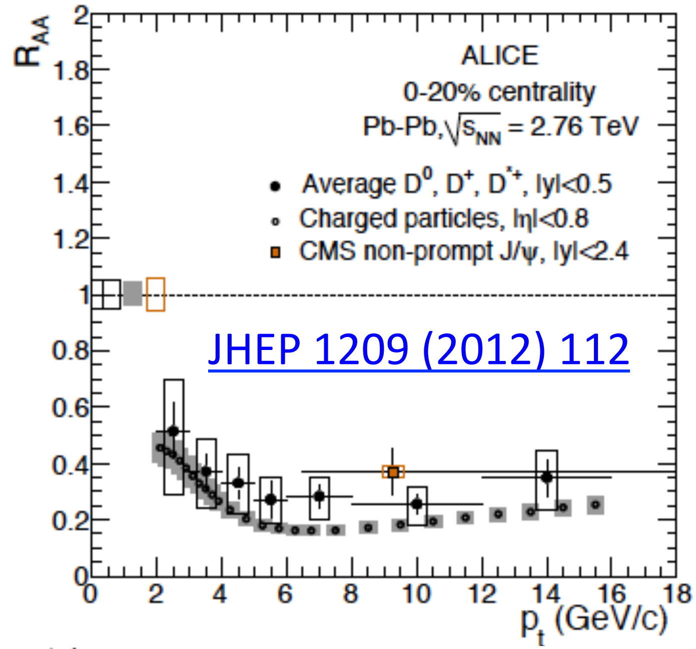
LLR – Ecole Polytechnique

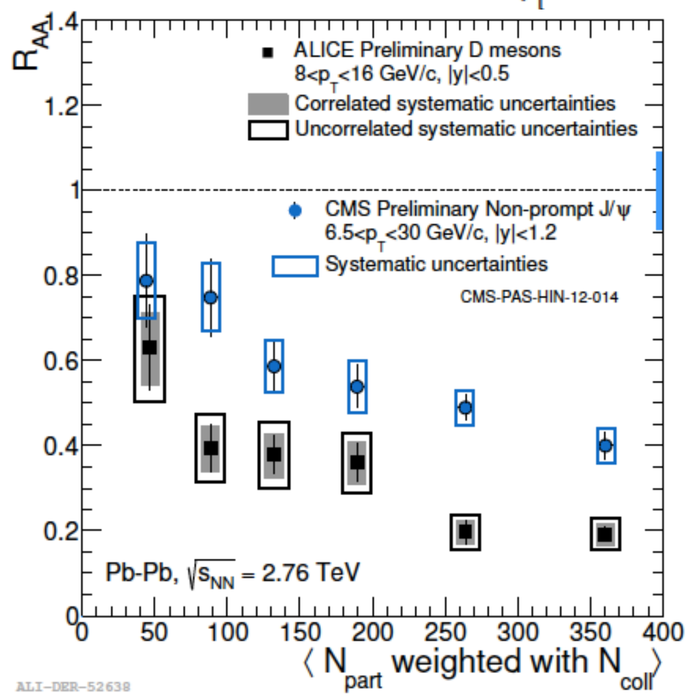
HI Jet Observables Workshop

July 10th, 2014

Heavy quark energy loss

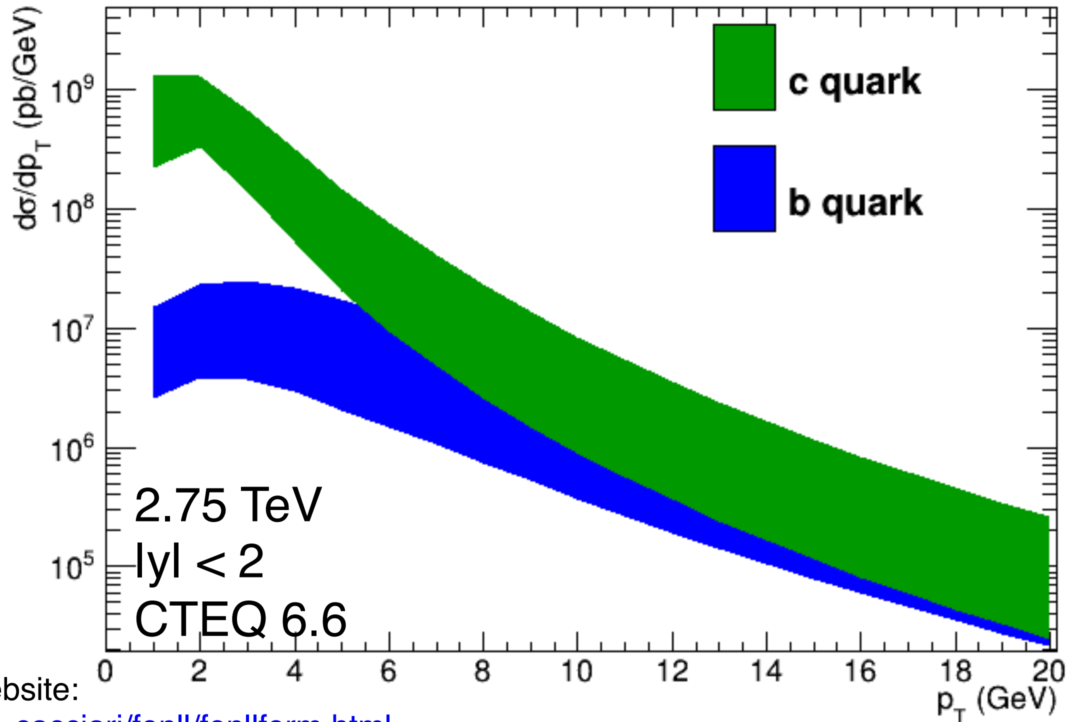
- Interest is two-fold
  - Quark vs gluon e-loss
  - Mass effects (radiation damping)
- Non-prompt J/ψ R_{AA} > D meson R_{AA} >? h R_{AA}
- What is the relationship between energy loss and R_{AA} for HF?





Spectral shape of HF production

As calculated in FONLL (= NLO + NLL)

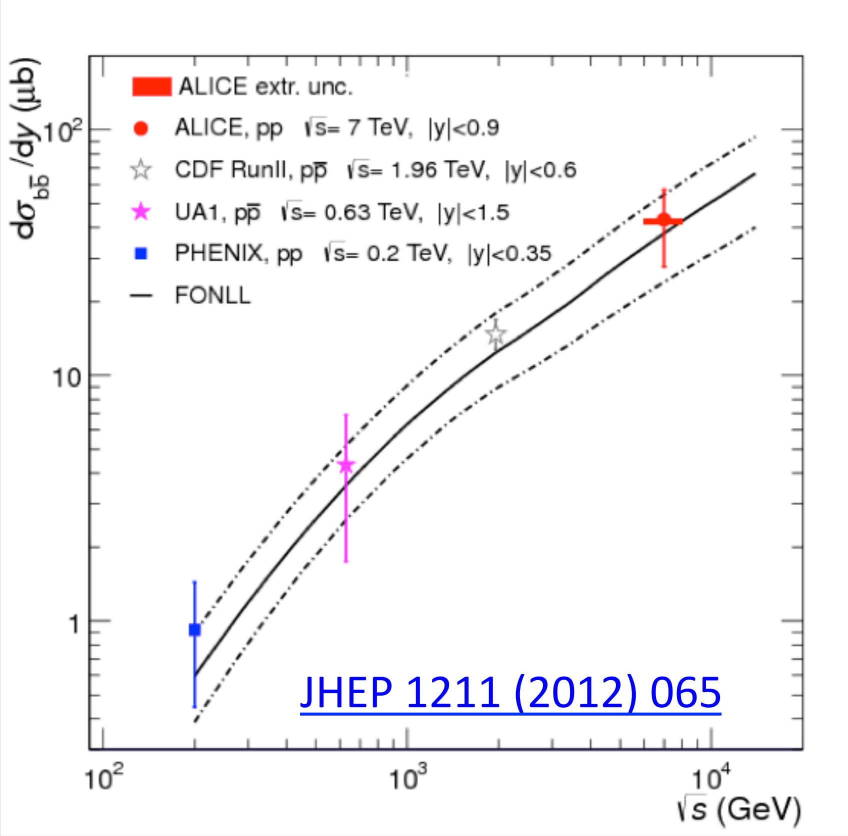


From Matteo Cacciari's website:
http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html

- Shape of spectra different at low p_T due to quark mass
- Uncertainties are non-negligible
  - Mostly due to scale (cancel in b/c ratio?)
  - Mass uncertainties important at very low p_T ($p_T <$ mass)

Data vs theory

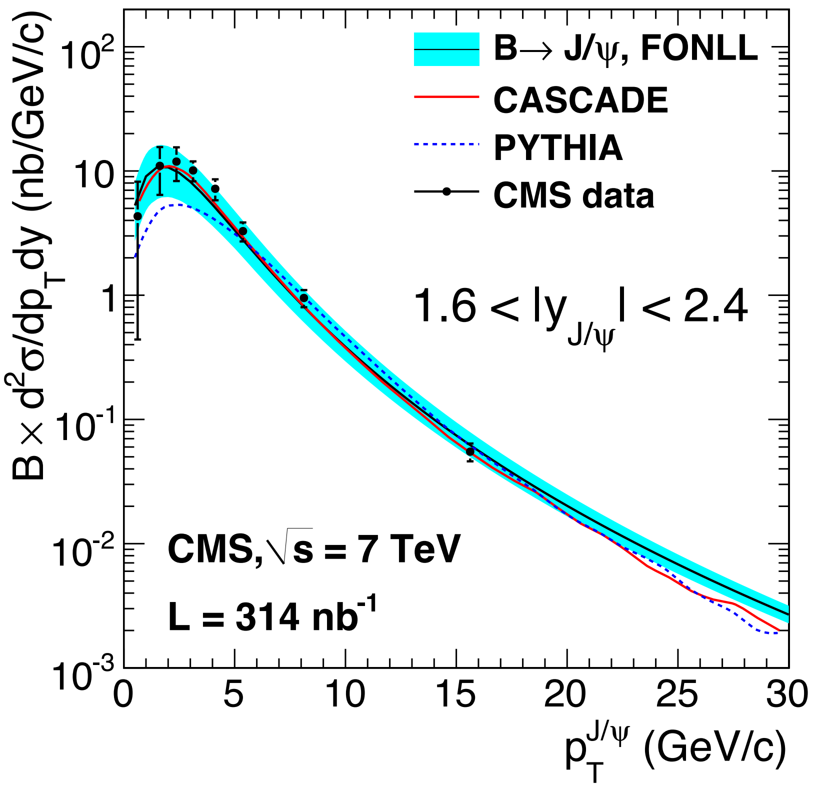
Total x-section



See also LHCb ($b \rightarrow D^0 \mu \nu X$)

PLB 694 (2010) 209-216

p_T differential

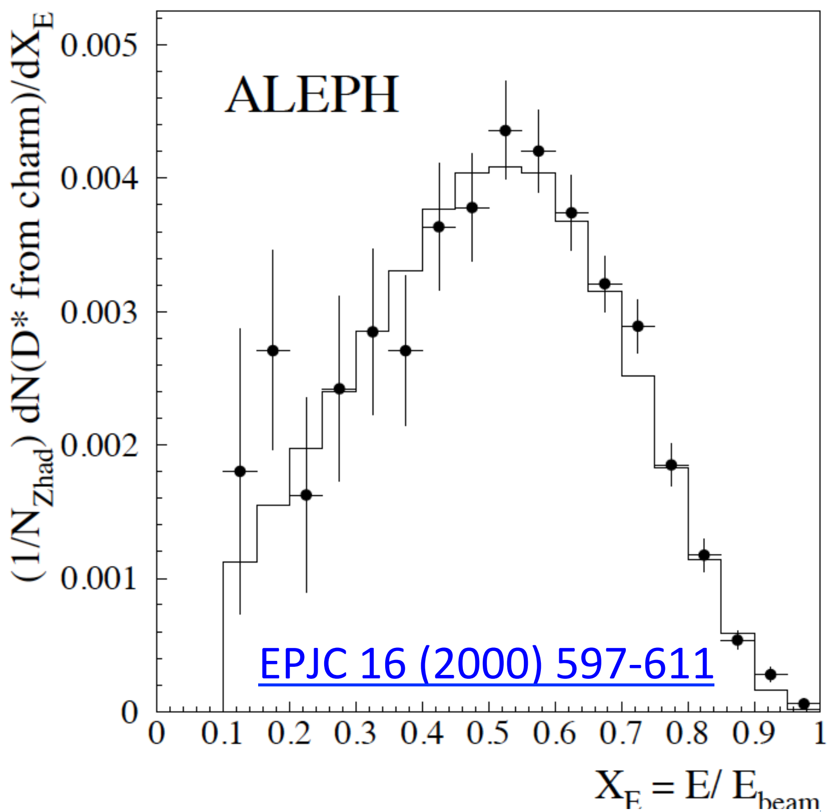


Measured by all 4 LHC collab's

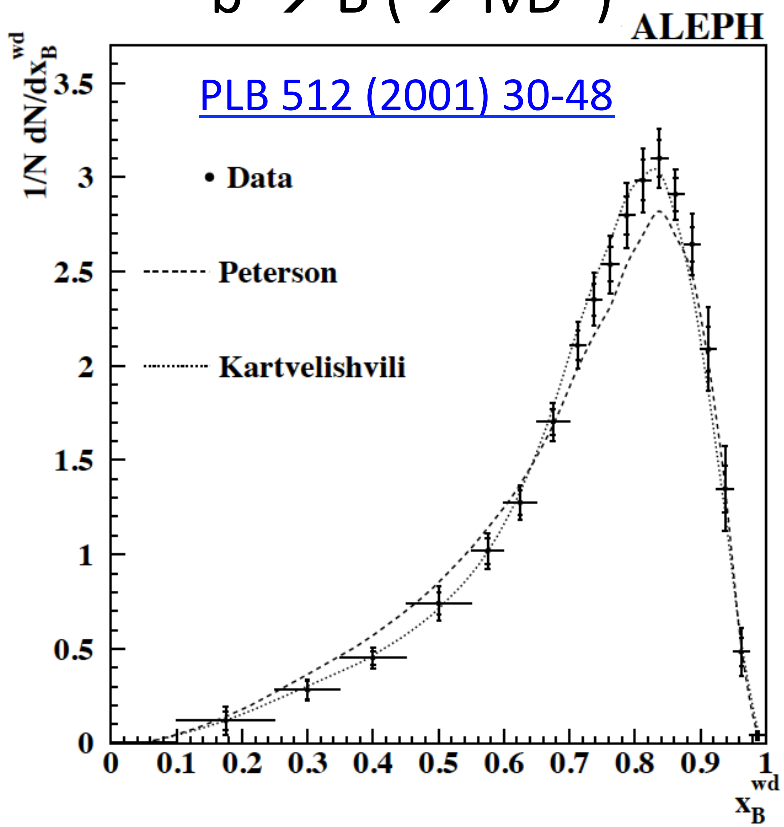
Also B^+, B^0, B_s, Λ_b, etc.

Heavy quark fragmentation

c → D*



b → B (→ lνD*)

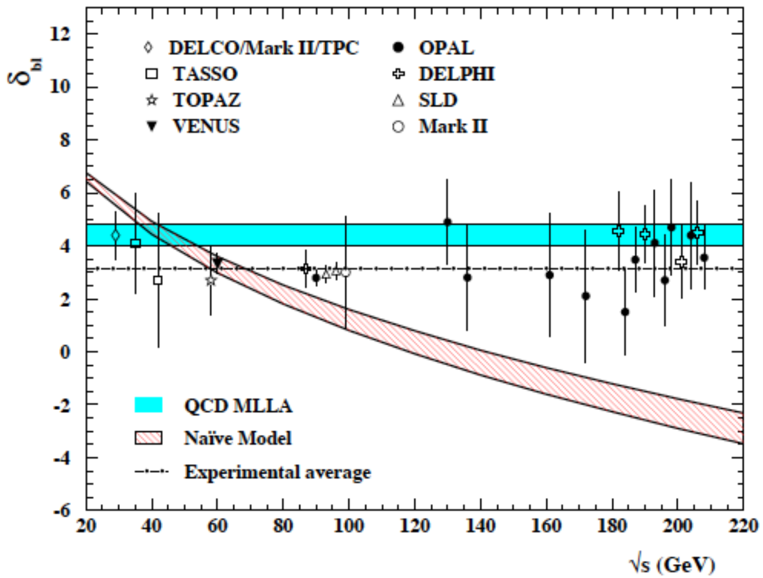


$\langle X_E(\mathrm{D}^*)\rangle_{c\bar{c}} = 0.4878 \pm 0.0046 \pm 0.0061$

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

b → B harder than c → D harder than q/g → h

Dead cones



In medium:

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

Vacuum:

Heavy quark multiplicity calculated in MLLA+LPHD

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

Dokshitzer, et al EPJC 45 (2006) 387-400l

[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

E-loss → R_{AA}

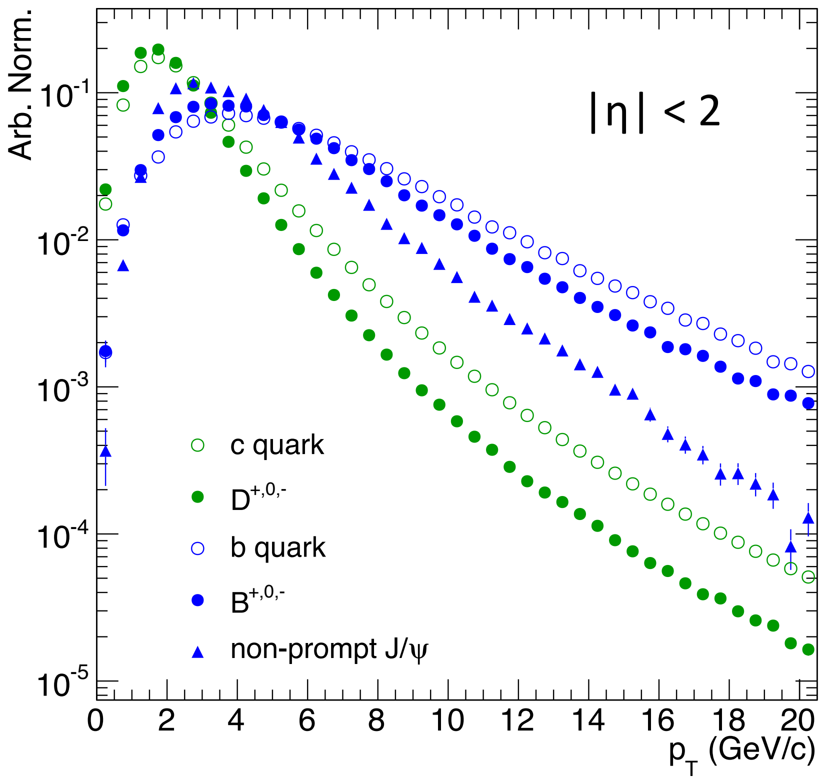
A simple exercise:

1) Run Pythia, filtering on D and B→J/ψ events ($|\eta| < 2$)
2) Reweight the parton spectra w/ FONLL
3) Take delta function energy loss of $\Delta E/E = 0.4$
4) Reweight the spectra w/ e-loss to calculate resulting R_{AA}

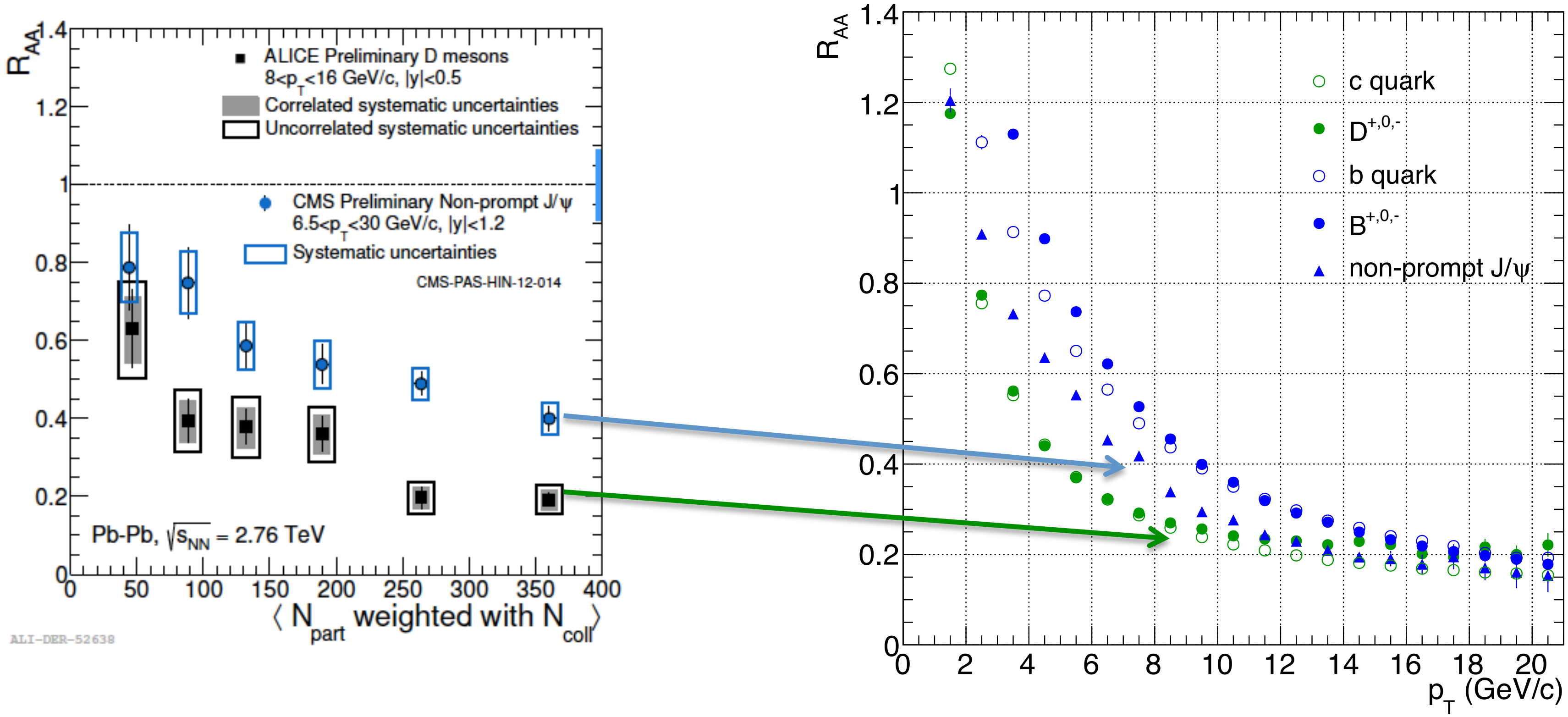
Hadronization and decay

- Fragmentation
  - Changes shape somewhat
  - Larger effect for b than c (b fragments hard)
- B→J/ψ decay a sizable effect

Pythia 6, tune Z2
Reweighted w/ FONLL



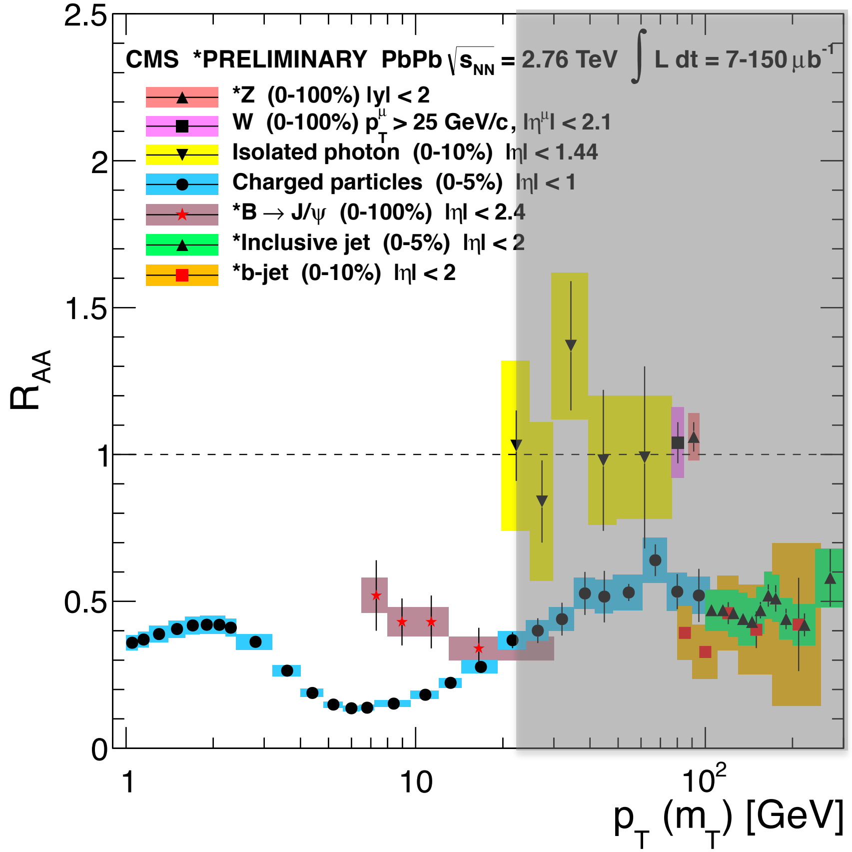
R_{AA} ordering?



- For same energy loss b and c (and B and D) have very different R_{AA}
- Fragmentation doesn't change the picture too much
- B→J/ψ decay mitigates the effect somewhat
- Simple model qualitatively replicates effect seen in the data
- Sensitivity to mass should be quantified in more realistic models

Species dependence vs p_T

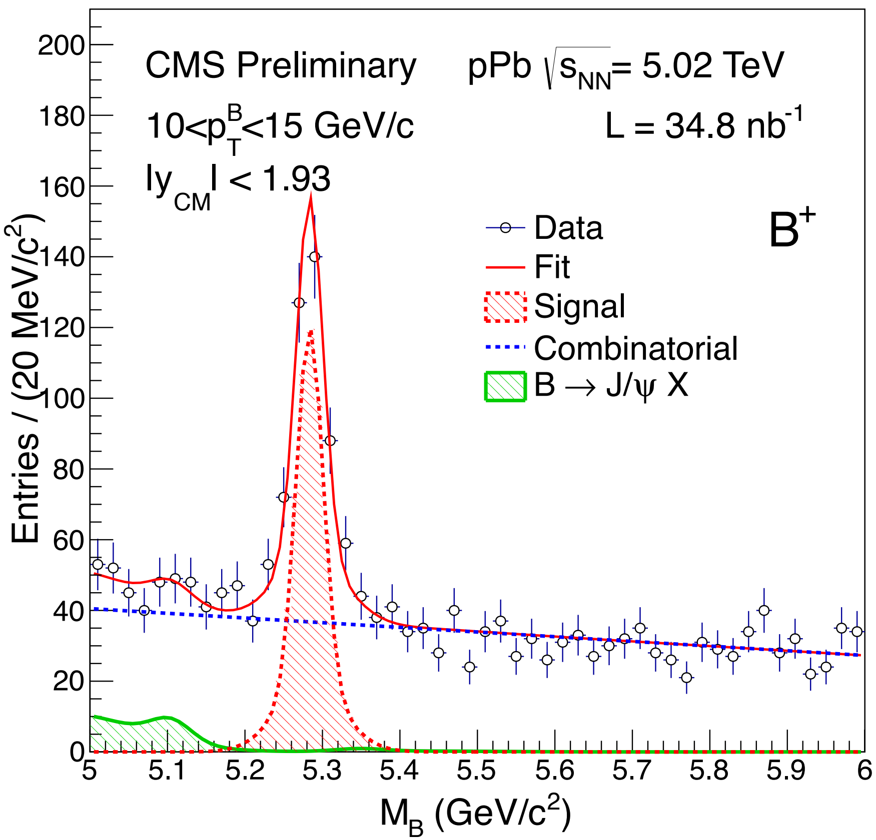
- Indication that species dependence dies out ~ where mass stops distorting the spectrum
- Could be that mass effects on e-loss die out
- Are we probing flavor dependence of e-loss, i.e., quark vs gluon?

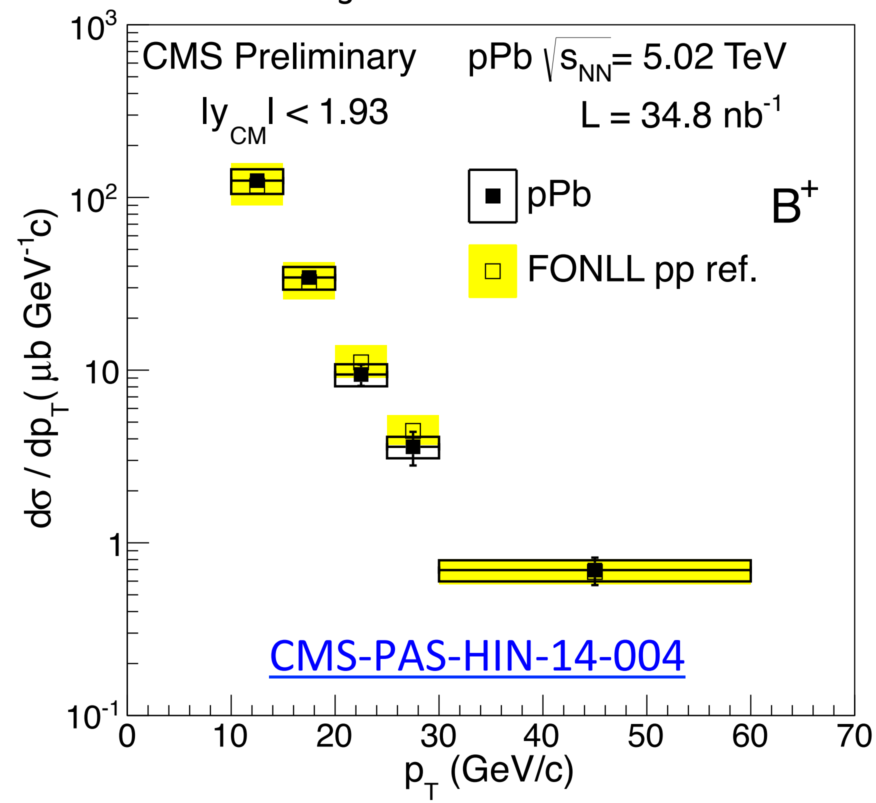


Exclusive B meson (pPb)

Also measured:
$B^0 \rightarrow J/\psi + K^*(892)$
$B_s^0 \rightarrow J/\psi + \phi$

Shown: $B^+ \rightarrow J/\psi + K^+$



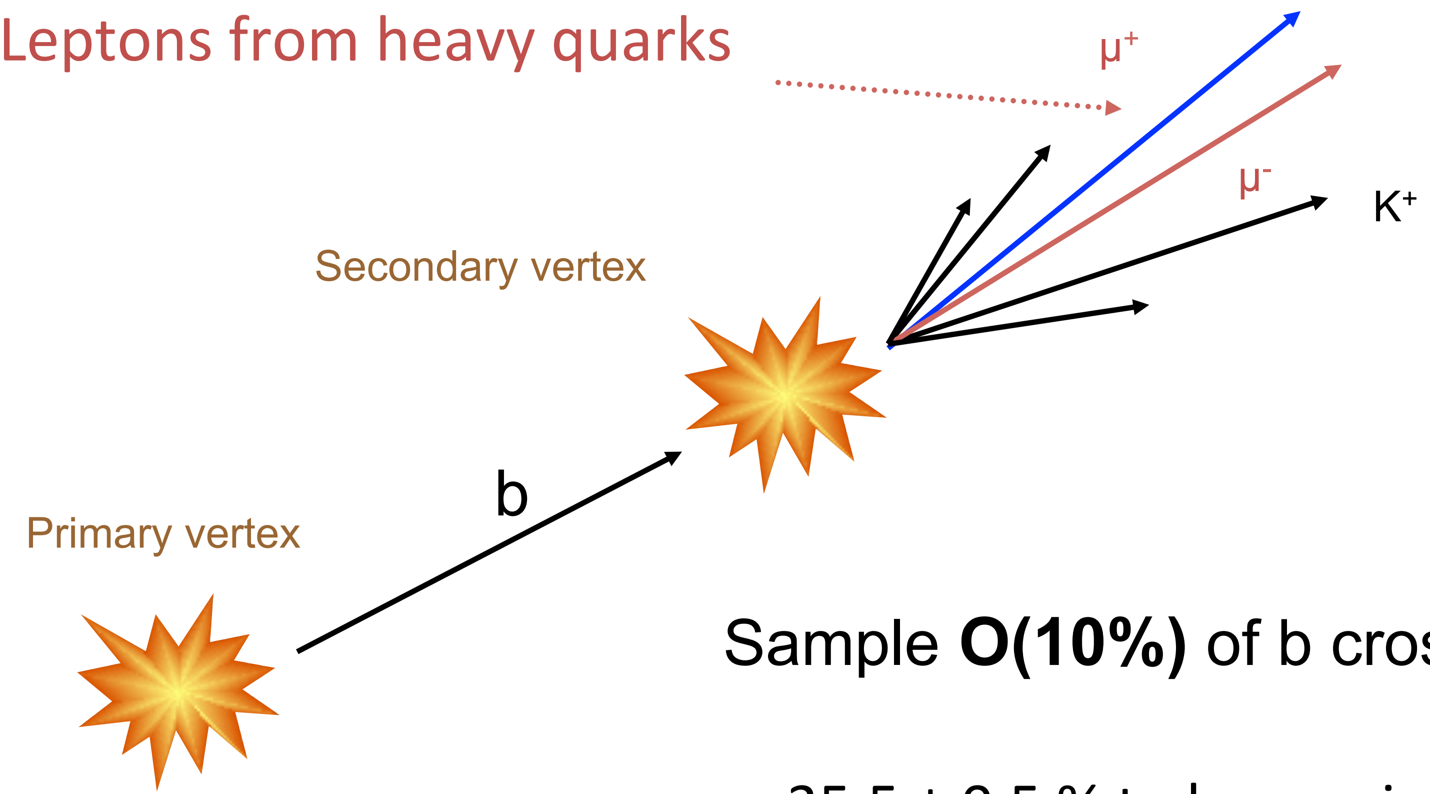


- No large nuclear modification in pPb, as expected
- What gain w/ full reconstruction, w.r.t. non-prompt J/ψ
- Measure b jet → B meson "FF" in PbPb? Also j_T

Measuring open HF

Cartoon by Yen-Jie

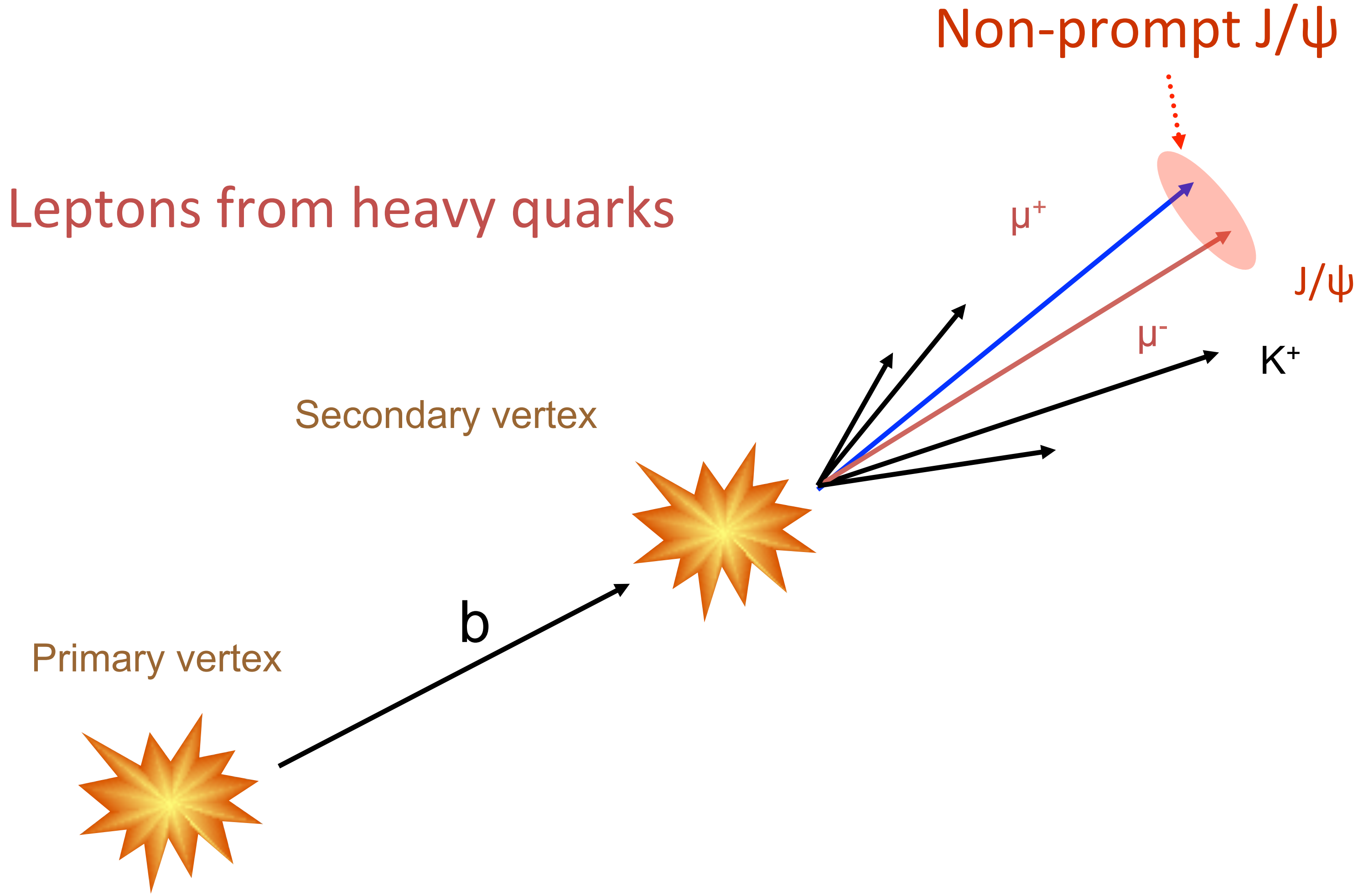
Leptons from heavy quarks



Sample **O(10%)** of b cross-section

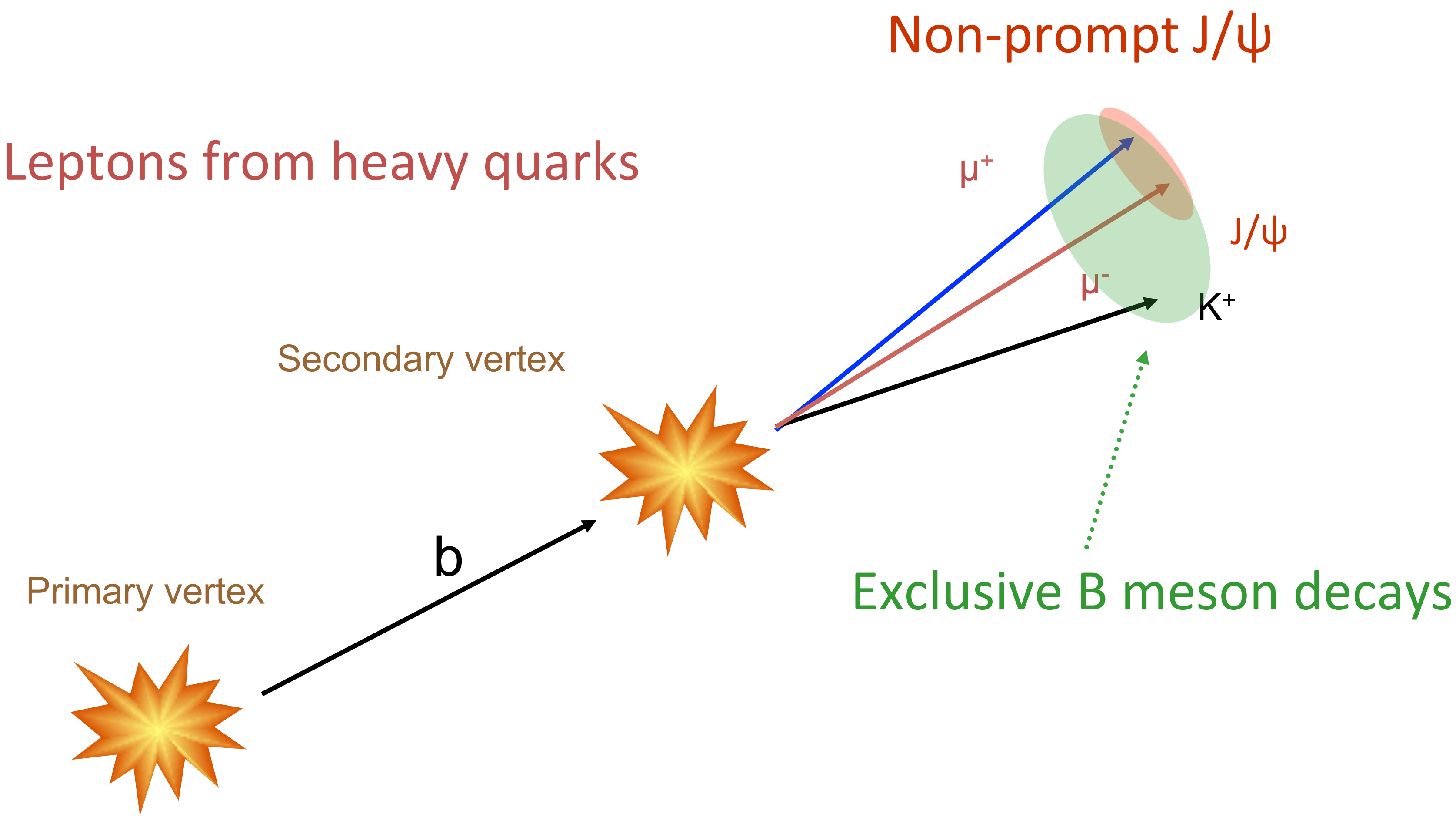
35.5 ± 0.5 % to be precise ☺

Measuring open HF



Dilepton channels sample **O(0.1%)** of b cross-section

Measuring open HF

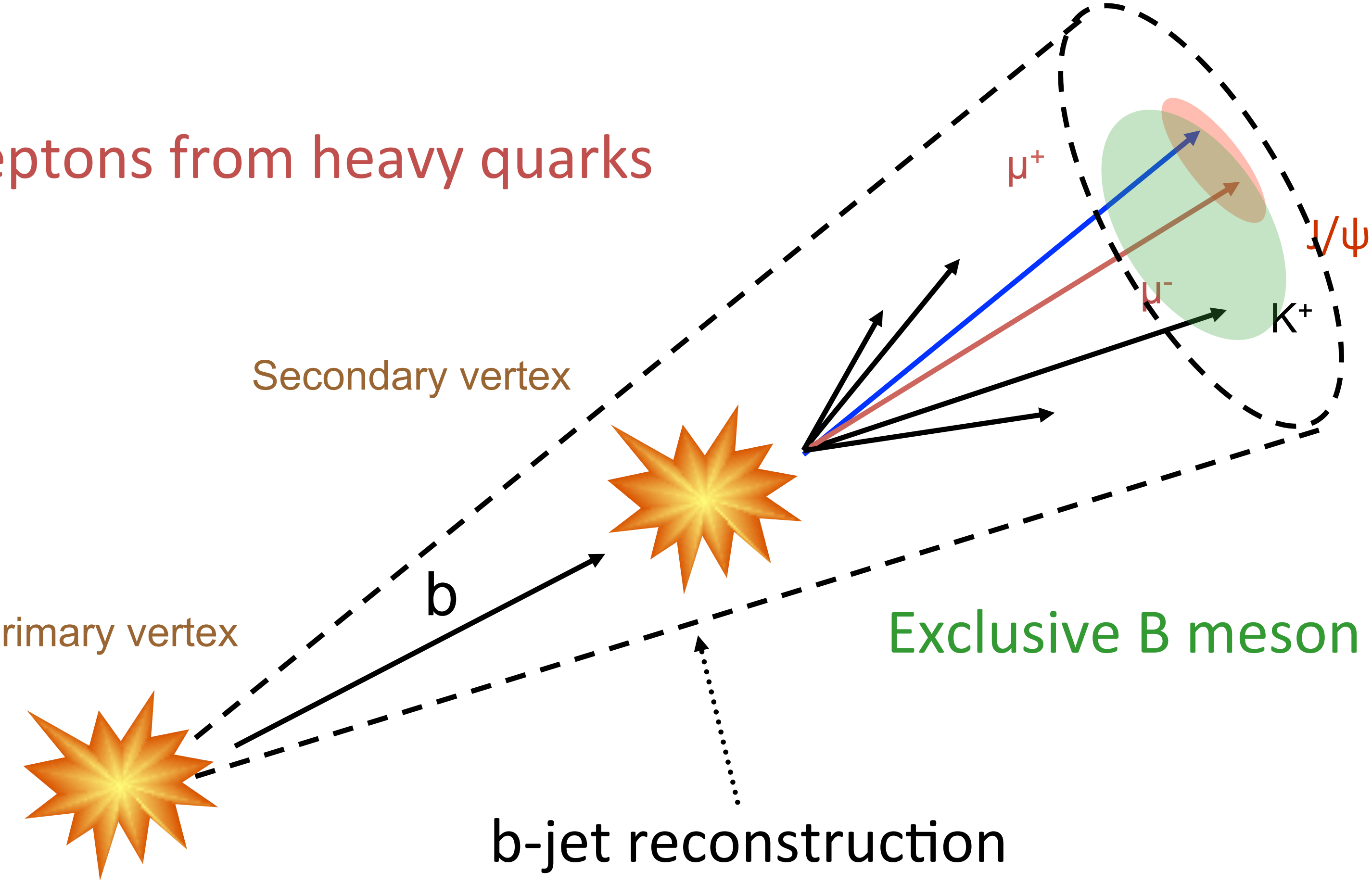


J/ψ+1(2) tracks decay channels sample **O(0.01%)** of b cross-section

Measuring open HF

Non-prompt J/ψ

Leptons from heavy quarks

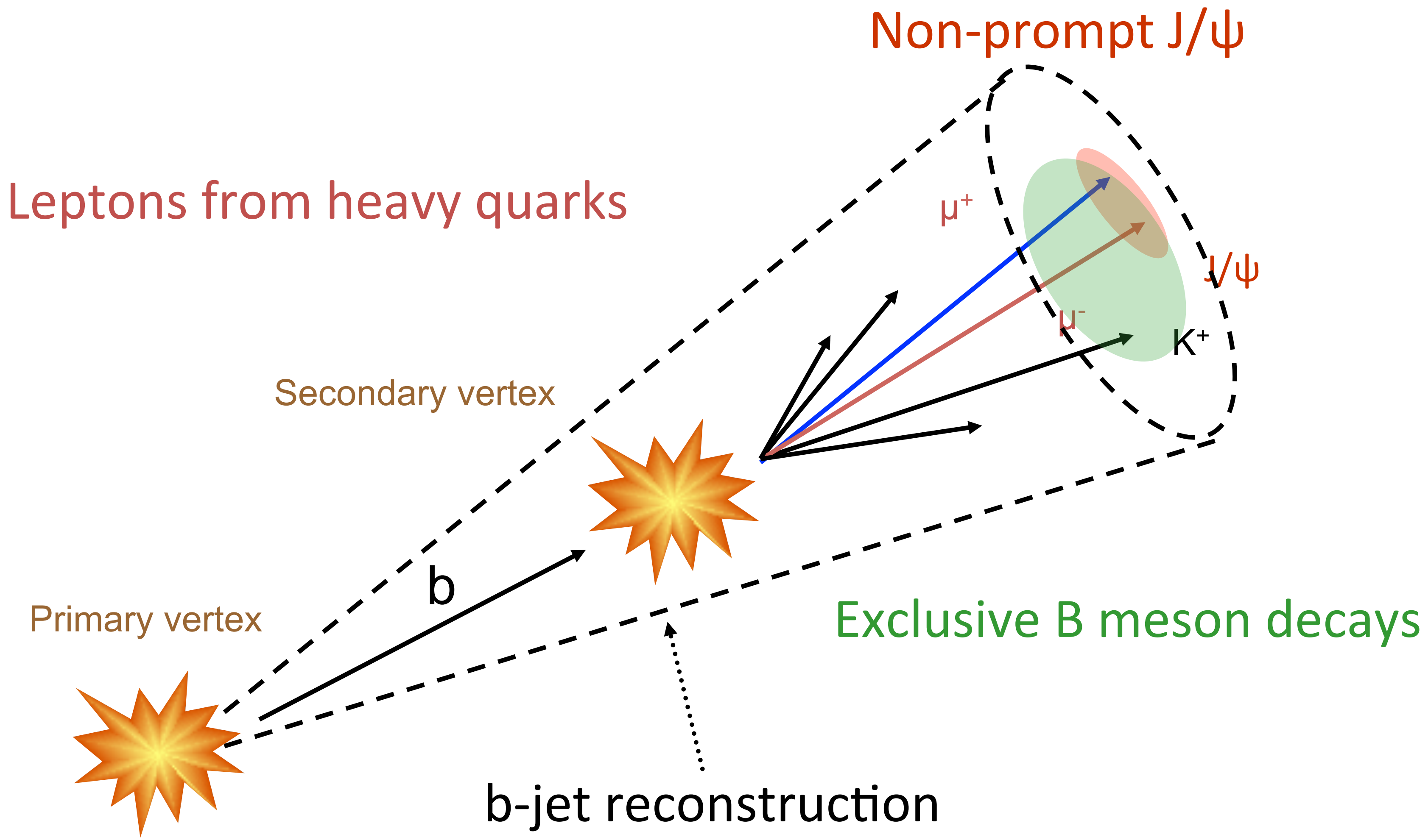


Exclusive B meson decays

b-jet reconstruction

b-tagged jet sample **O(100%)** of b cross-section and ~70-90% of the b quark energy

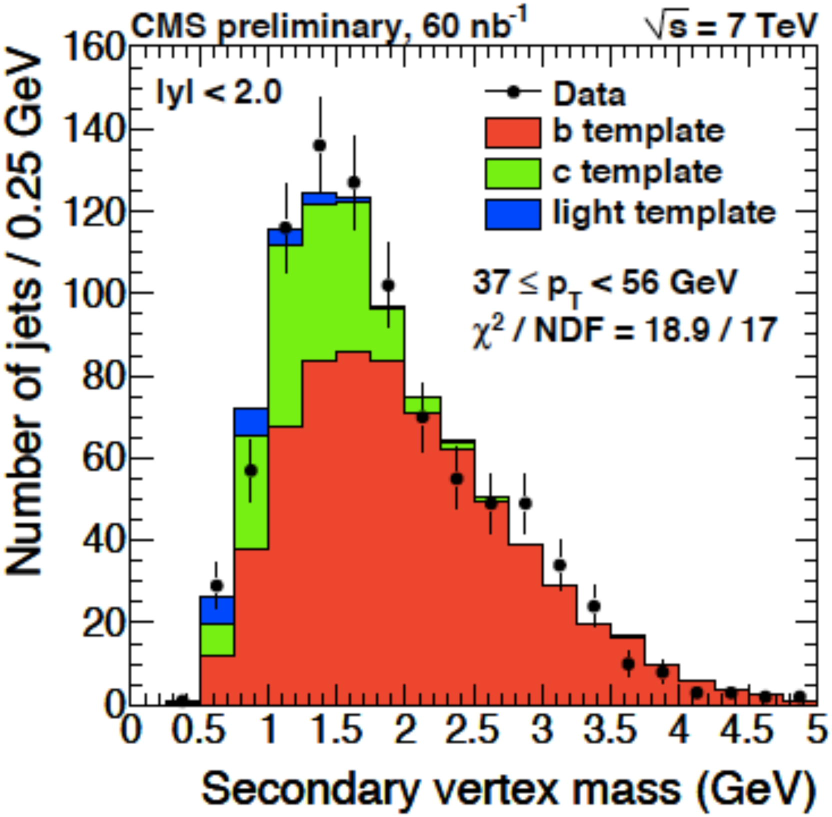
Requirements

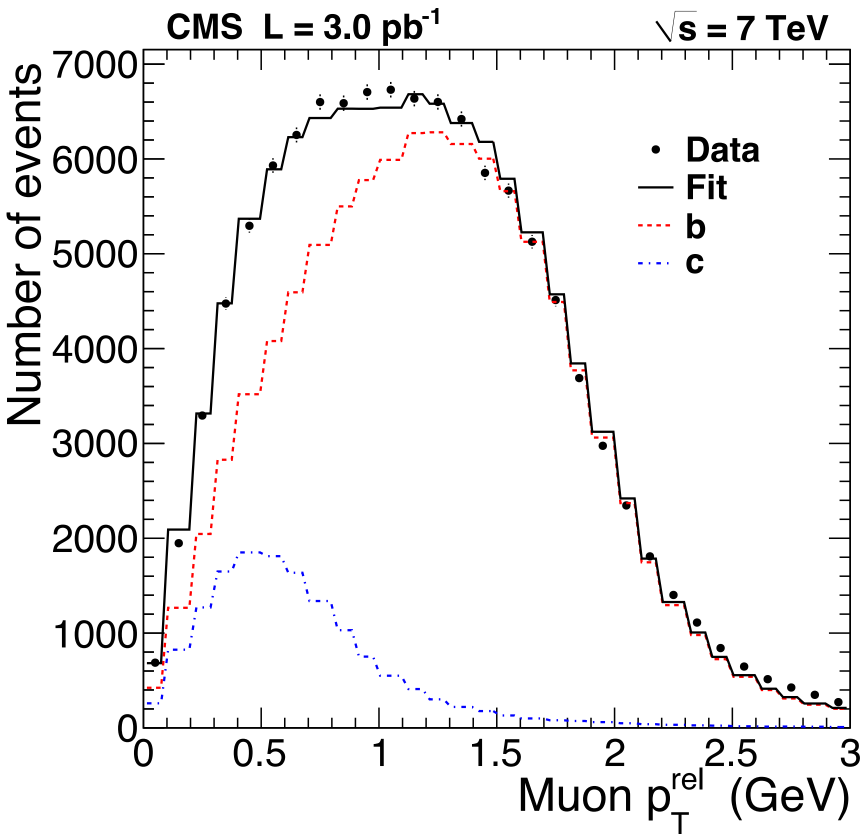


Requirements: flexible trigger system, lepton ID, secondary vertex reconstruction, jet reconstruction

b tagging in pp @ 7 TeV

JHEP 1204 (2012) 084





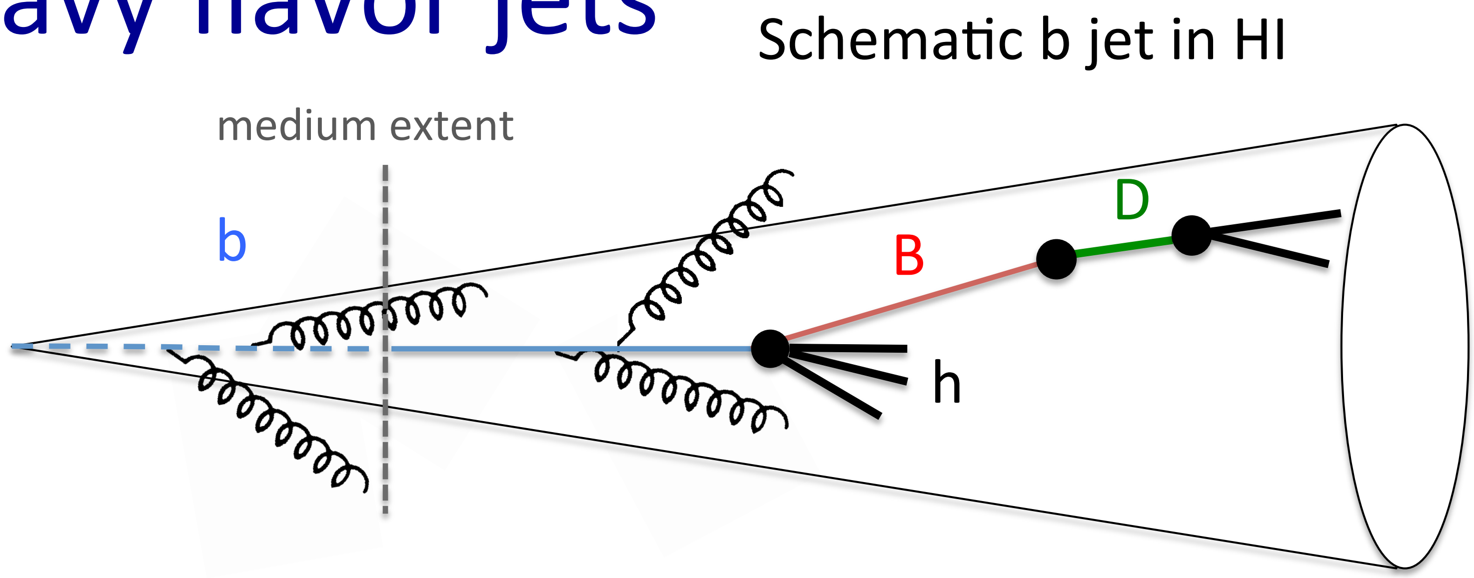
Lifetime tagging: Reco'd SVs or large impact parameter tracks

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

Discriminating variable constructed from SV, lepton properties

Review of b-tagging methodology in CMS: JINST 8 (2013) P04013

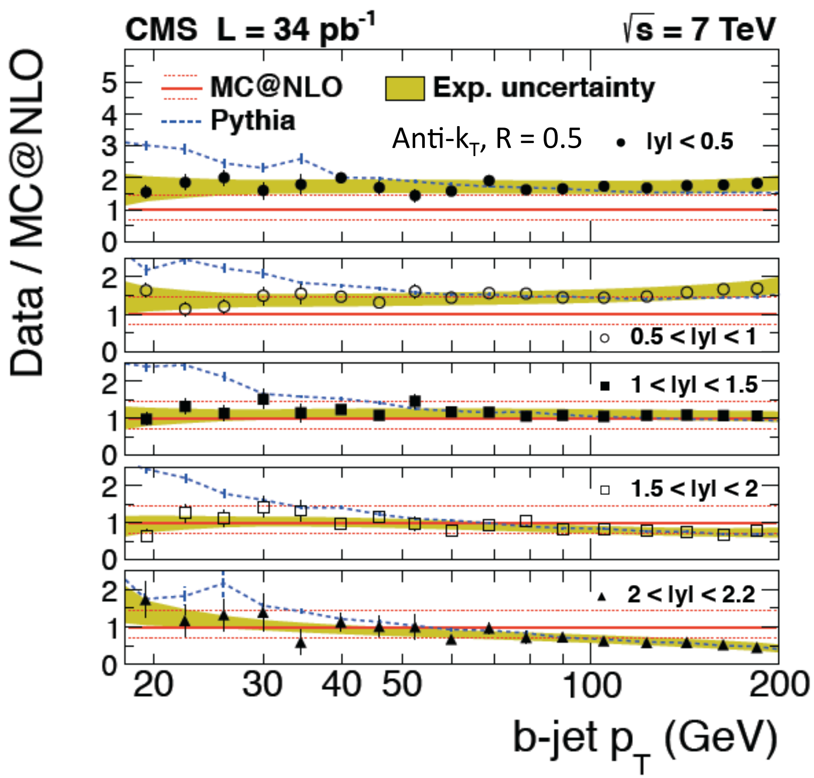
Heavy flavor jets



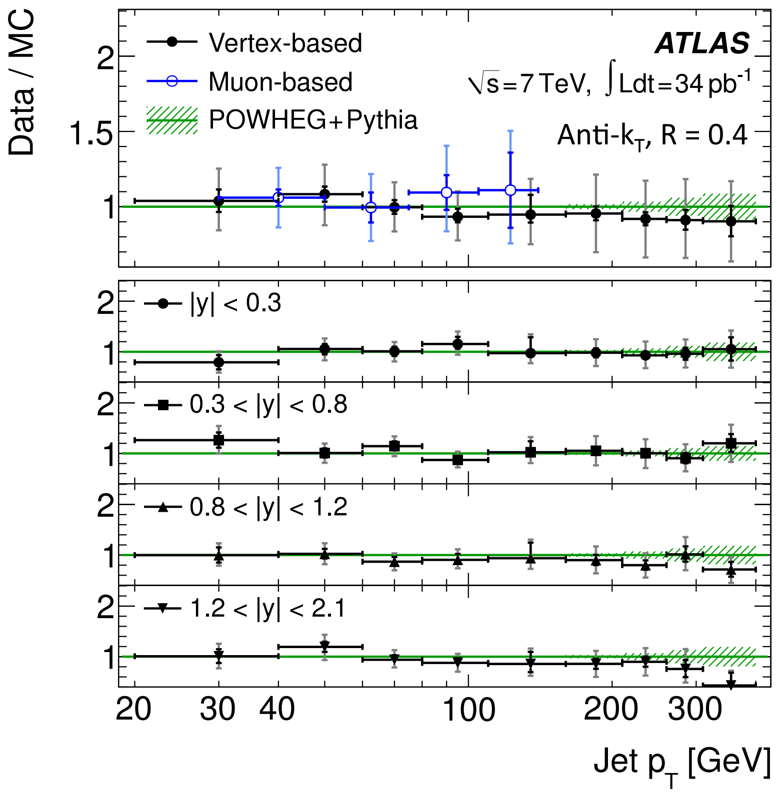
- HF jet = HF hadron + energy in cone
- HF hadrons usually not be fully reconstructed
- b quark need not be primary (as depicted), although typically assumed for e-loss calc's
- Standard flavor definition:
  - If b quark within some ΔR from jet axis, then it's a b jet
  - Same for c jets, except b quarks take priority

b-jet differential x-sections

CMS JHEP 1204 (2012) 084

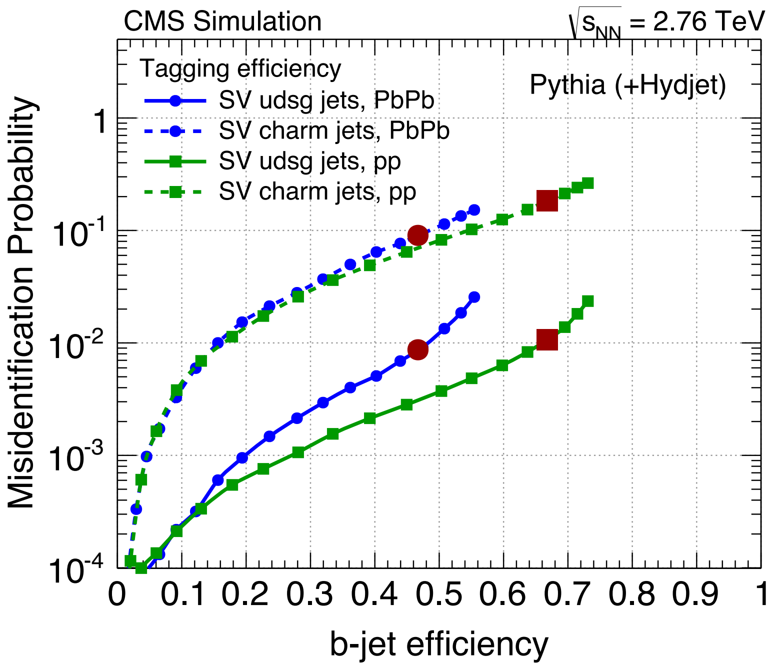


ATLAS EPJC 71 (2011) 1846



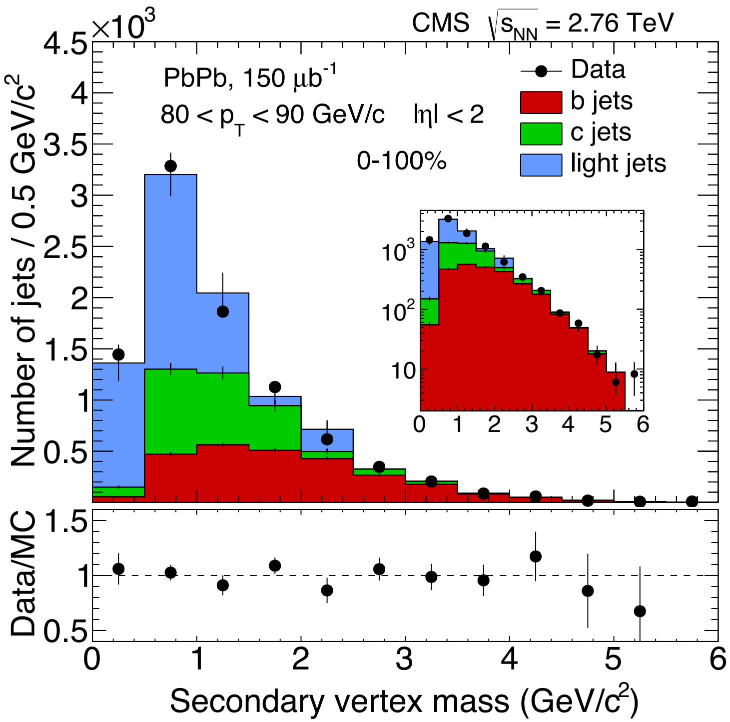
- Systematics uncertainties typically 20% or larger
- Fully exclusive final states require NLO + PS Monte Carlo generators
- Powheg + Pythia gives a better description than MC @ NLO + Herwig

b-tagging (SV) performance in PbPb



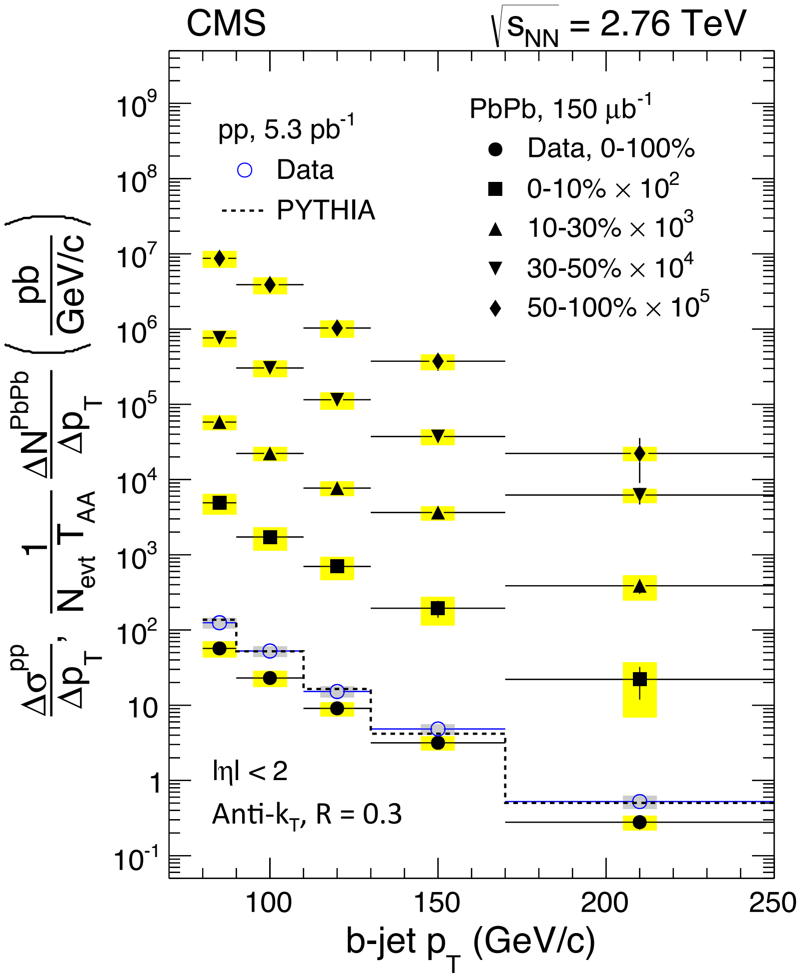
- Reduced efficiency in PbPb due to tighter track selections
- Larger light jet mis-ID in PbPb from combinatorics / UE
- Similar c-jet rejection → c-jet tagging in PbPb?

Combinatorial b jets in PbPb



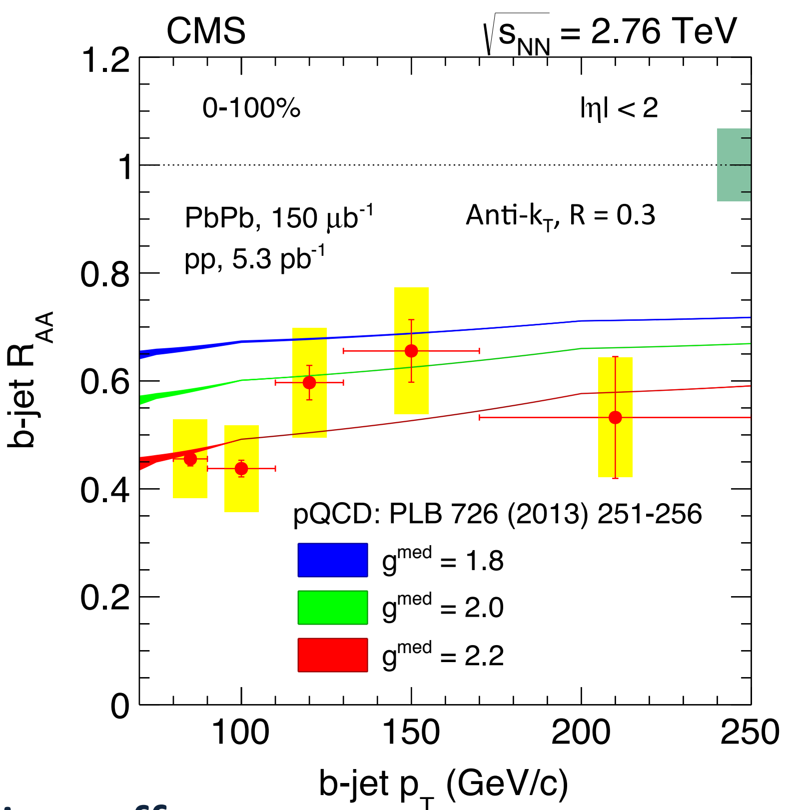
- Back of the envelope
  - bb x-section, |η|< 2 ≈ 45 μb
  - pp inelastic x-section = 55 mb
  - For n_{part} = 1000, O(1) b jet/evt
  - ~ 1% overlap prob. for ΔR < 0.3
  - Comparable to b-jet fraction!
- Real rate much smaller as UE b's are much softer
- Pythia+Hydet: 2% of tagged jets in 0-20% match to UE b
- Flavor matched to Pythia signal event only → combinatorial jets go into the light jet template (as they should)

Inclusive b jets in PbPb



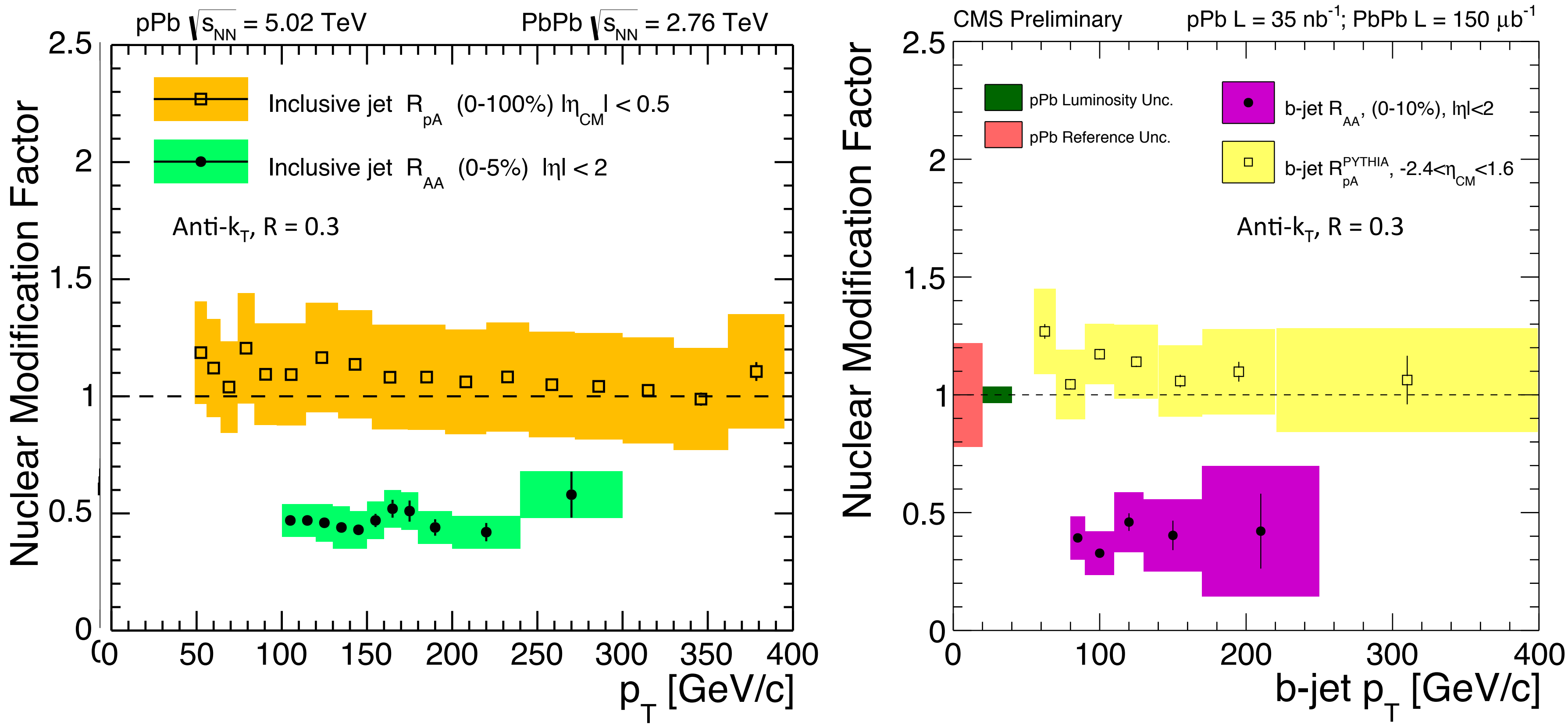
arXiv:1312.4198

New since last workshop!



- Spectra are unfolded for resolution effects
- Reference based on high statistics 2013 pp data

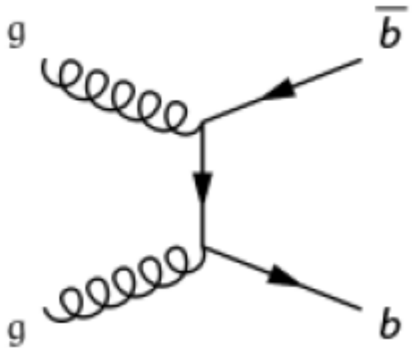
b-jet vs. inclusive jet quenching



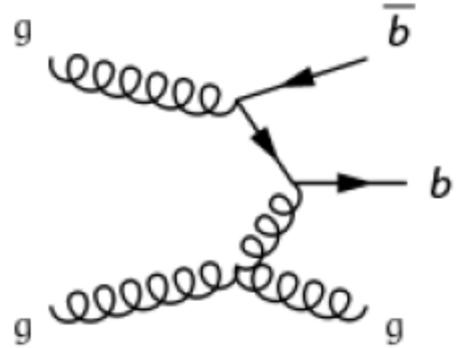
- Similar b jet and inclusive jet R_{AA}, within still large errors
- Inclusive jets dominated by gluons
- b jets contain an important contribution from gluon splitting
- Also measured b-jet RpA!

HF Production @ NLO

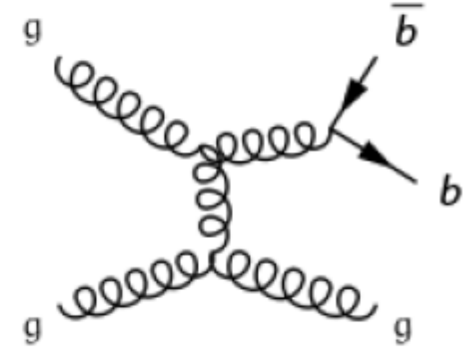
Flavor Creation (FCR)



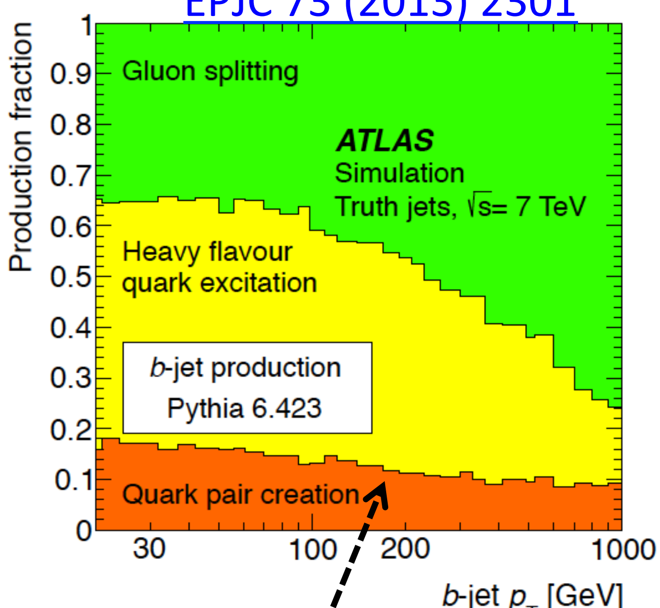
Flavor Excitation (FEX)



Gluon Splitting (GSP)



EPJC 73 (2013) 2301



LO b-$\bar{b}$ production (FCR) sub-dominant at the LHC

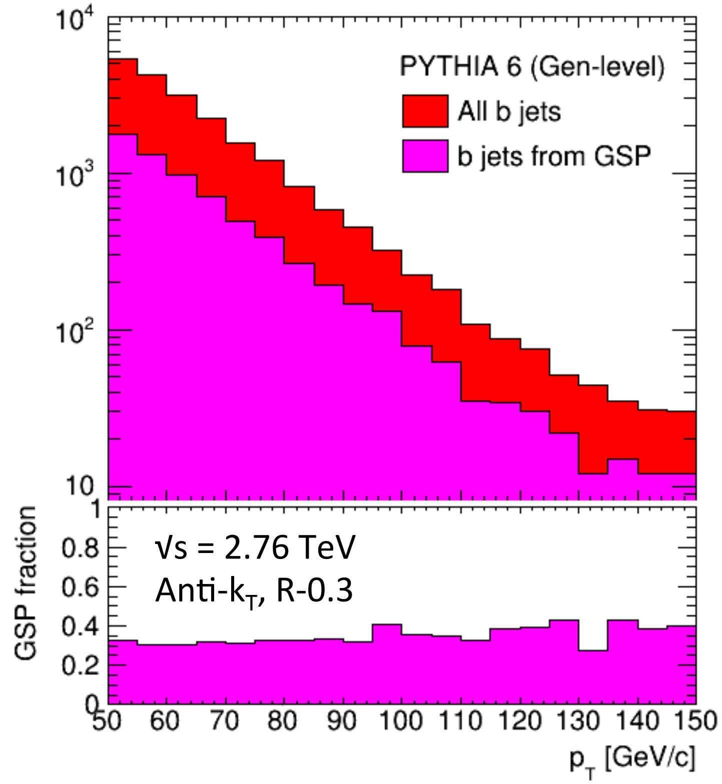
At NLO:

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

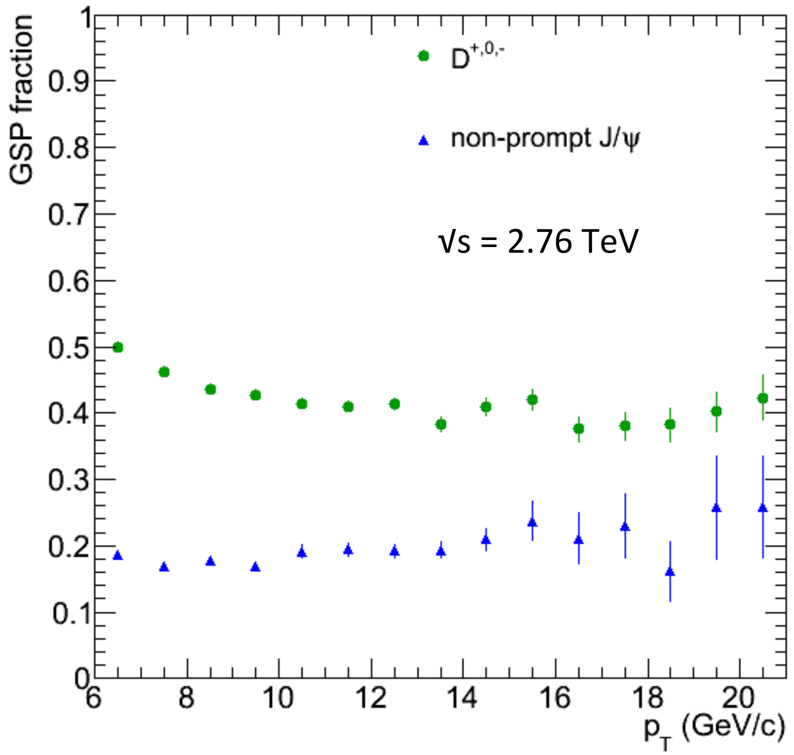
E-loss of split gluons should be different from primary b quarks

Gluon splitting contribution

b jets



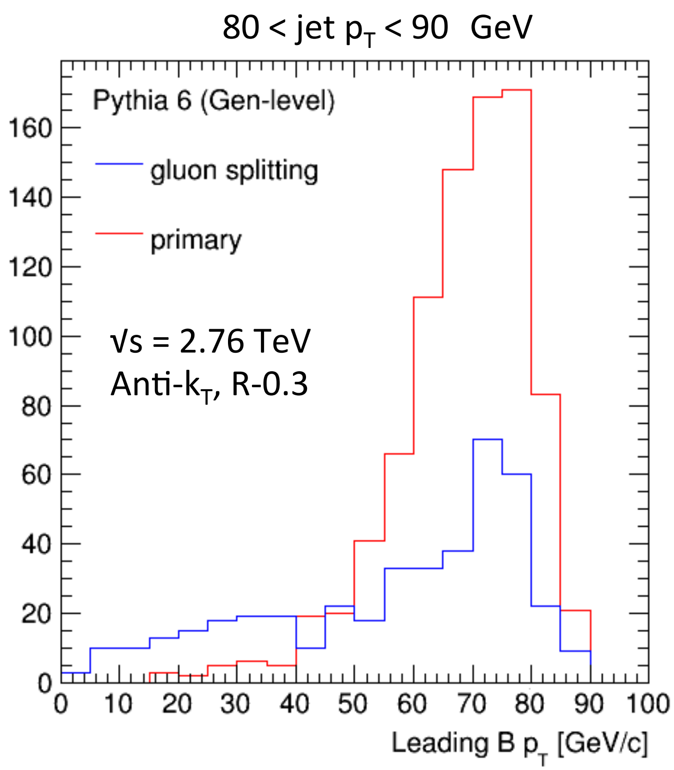
D mesons, non-prompt J/ψ

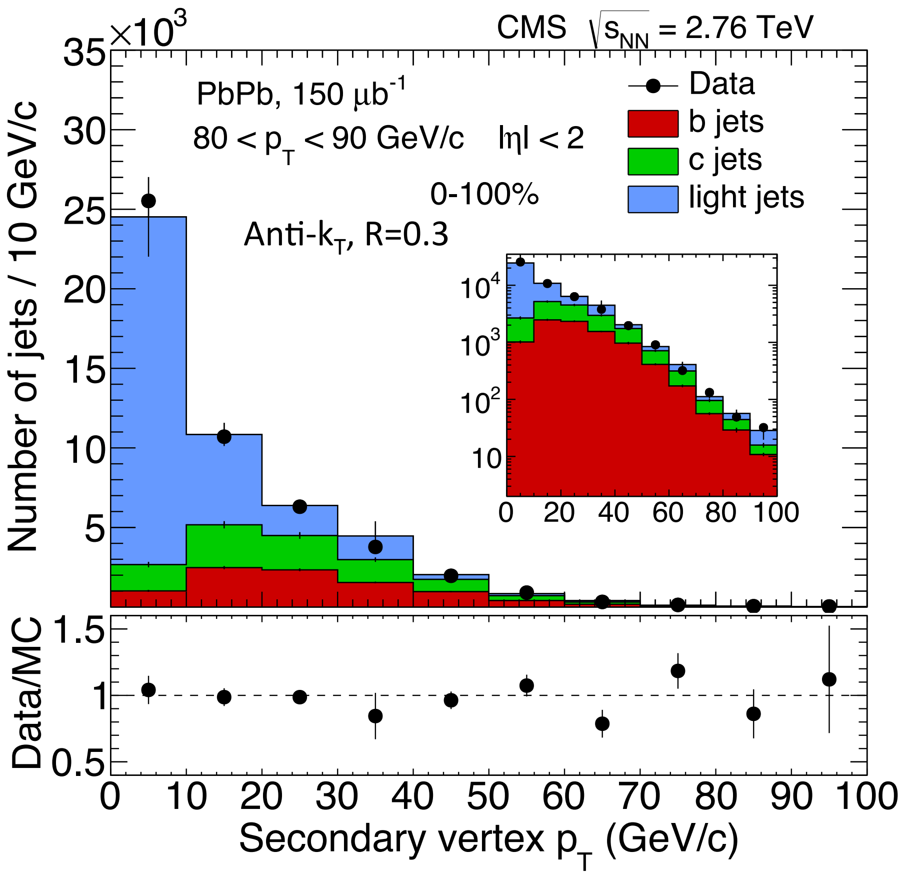


- Contribution larger for jets than for single hadrons
- However, non negligible for hadrons as well
- Even more important for charm than for bottom

p_T dependence of GSP

Cut on hard fragmenting b jets to limit GSP contamination?



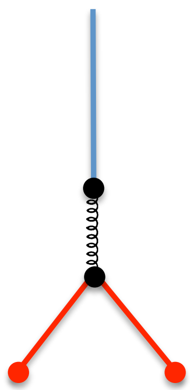


Hadron p_T does give some separation between primary and split gluon jets

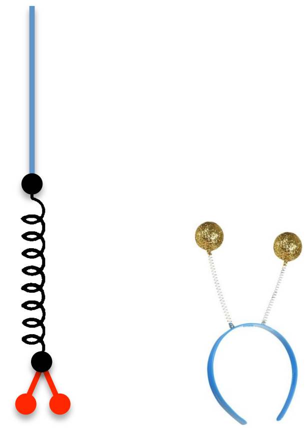
Difference washed out by partial SV reco. Note no large distortion of SV p_T spectrum

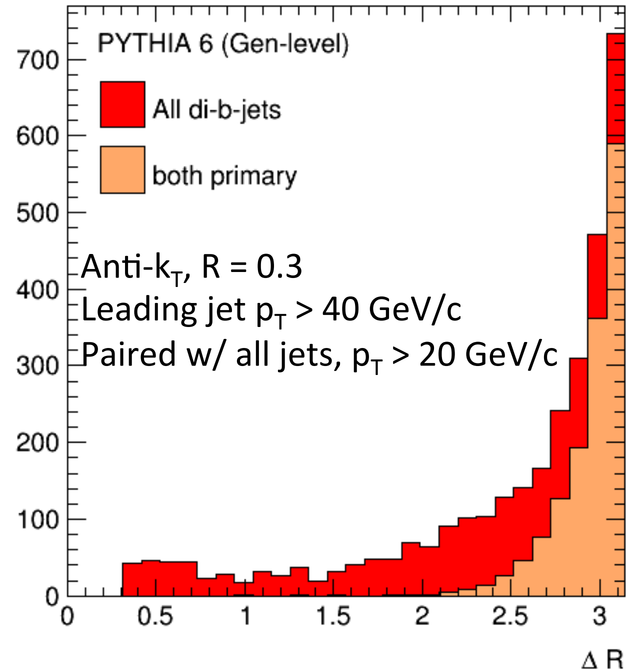
Angular dependence of gluon splitting

Hard splitting



Soft splitting





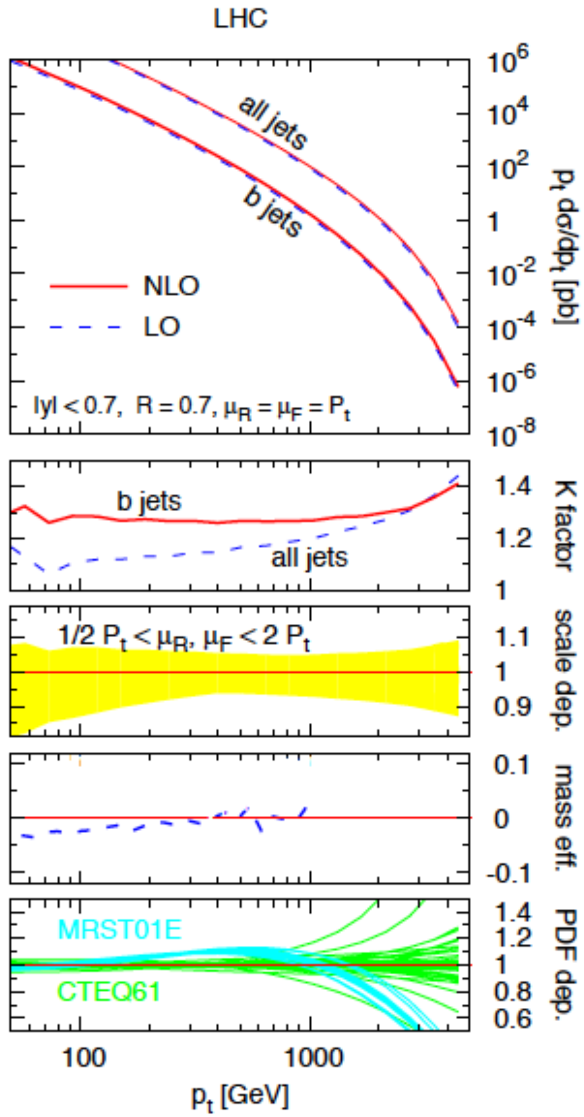
- Hard splitting
  - Tend to give 3-jet topology
  - More b-jet-like w.r.t. e-loss
- Soft splitting
  - May be clustered as a single jet
  - More gluon-like w.r.t. e-loss

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

Flavor definition

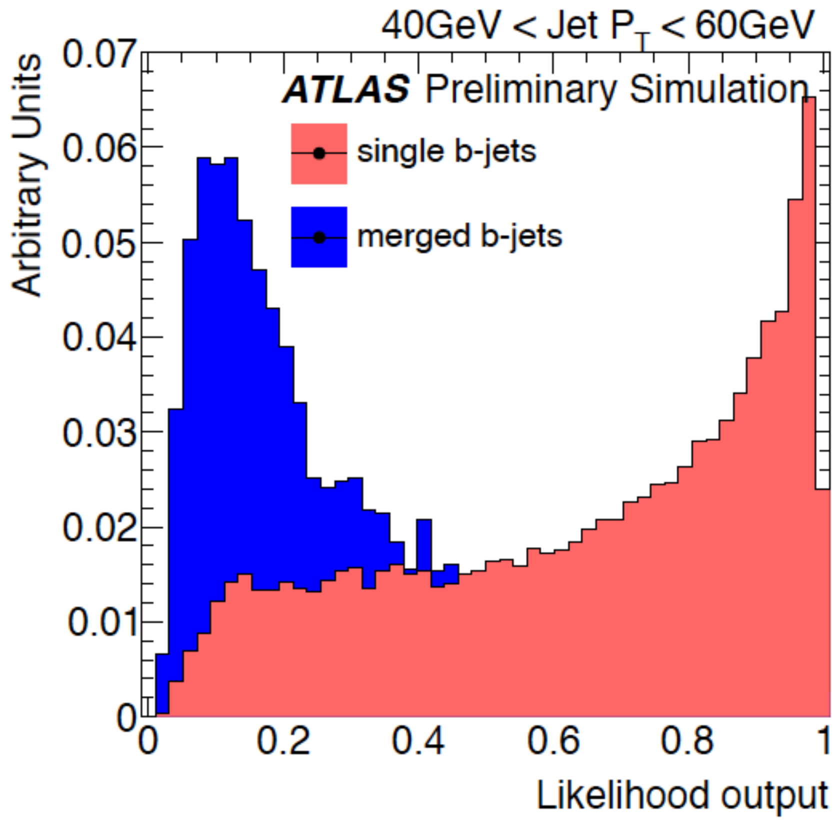
Banfi, Salam, Zanderighi
JHEP 0707 (2007) 026

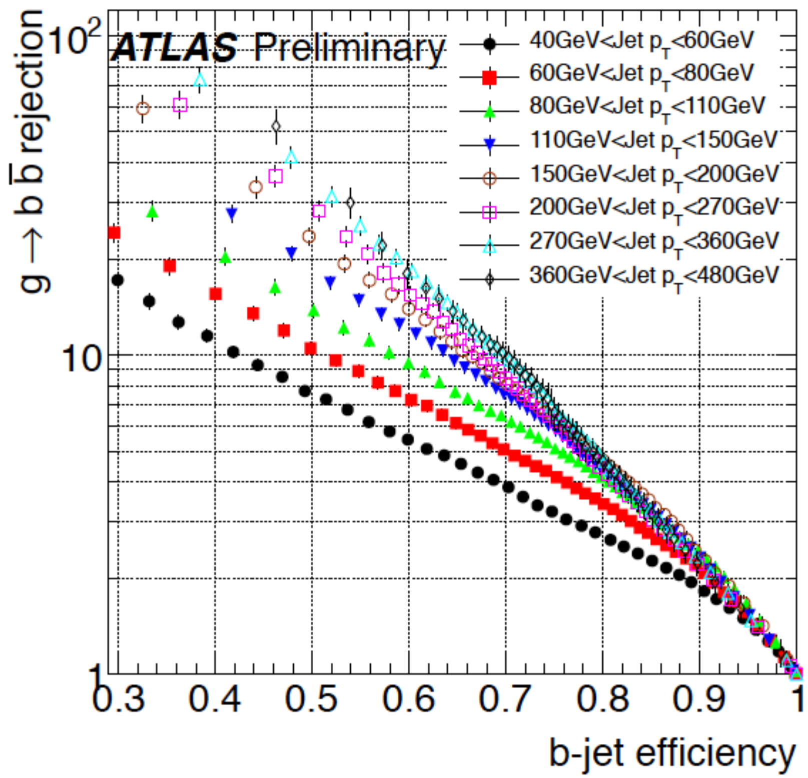
- Standard definition doesn't correspond to primary b's
- Flavor-k_T algorithm does this and is also infrared safe
- Sums heavy flavor in the jet, merged b's are gluons
- Reduces theory uncertainty
- Requires that we identify both vertices in merged jets
- Experimentally challenging
  - b→c cascade
  - Finite vertex efficiency



Tagging merged jets

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





Merged jets can be tagged via their substructure

Variables used by ATLAS:

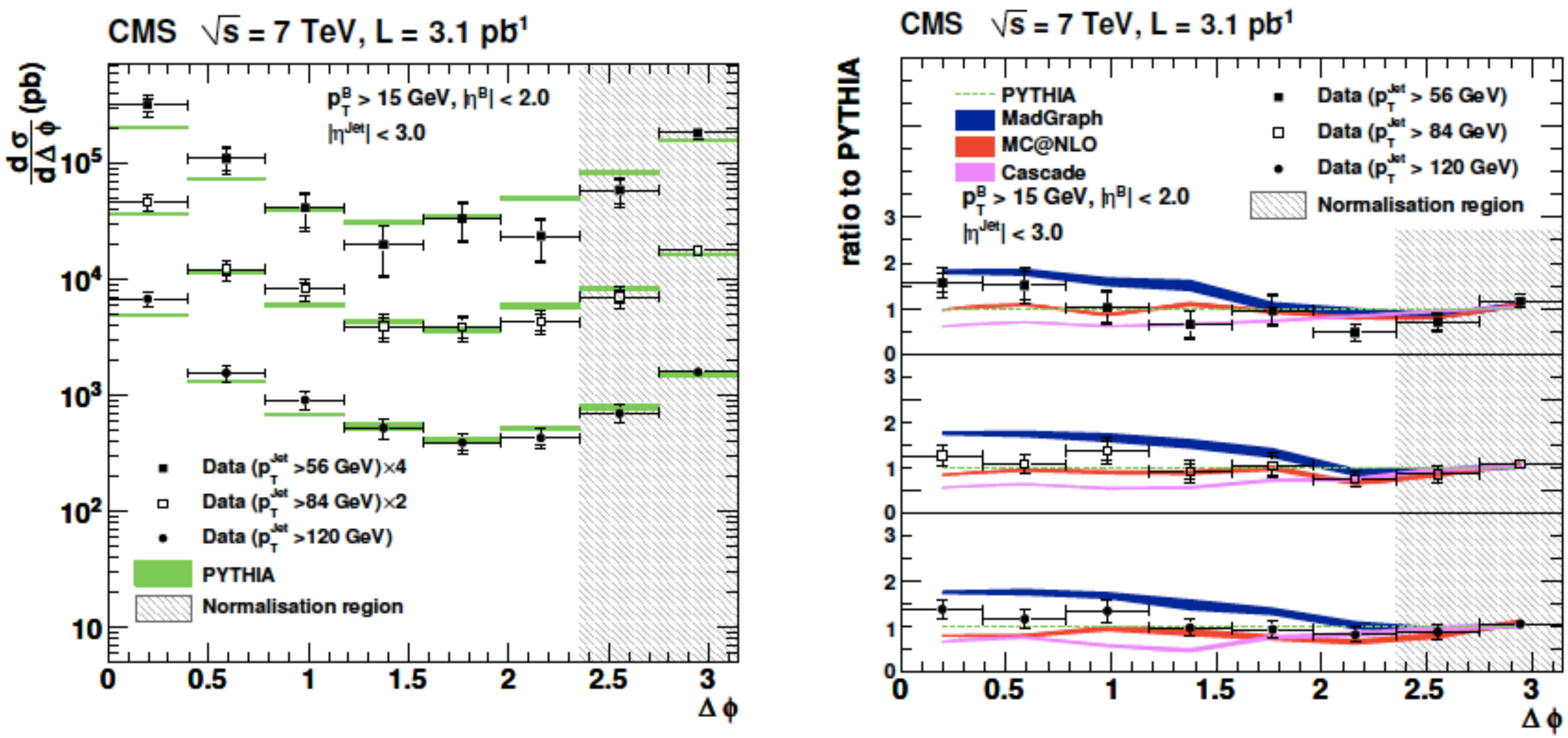
1) Jet track multiplicity
2) Jet width
3) ΔR between k_T subjets

Possible in heavy ions?

Also interesting for q/g discrimination

B-Bbar Angular Correlations

JHEP 1103 (2011) 136

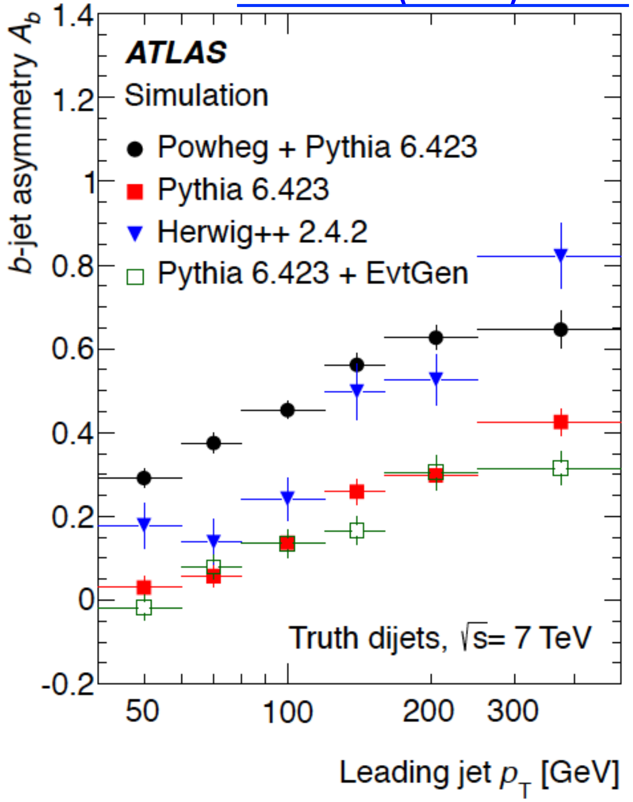


- Angular correlations of di-b-jets sensitive to GSP contribution
- "Inclusive vertex finder" adept at separating nearby b vertices
- B → D → X vertices are merged
- Most generators under predict small angle jet rate

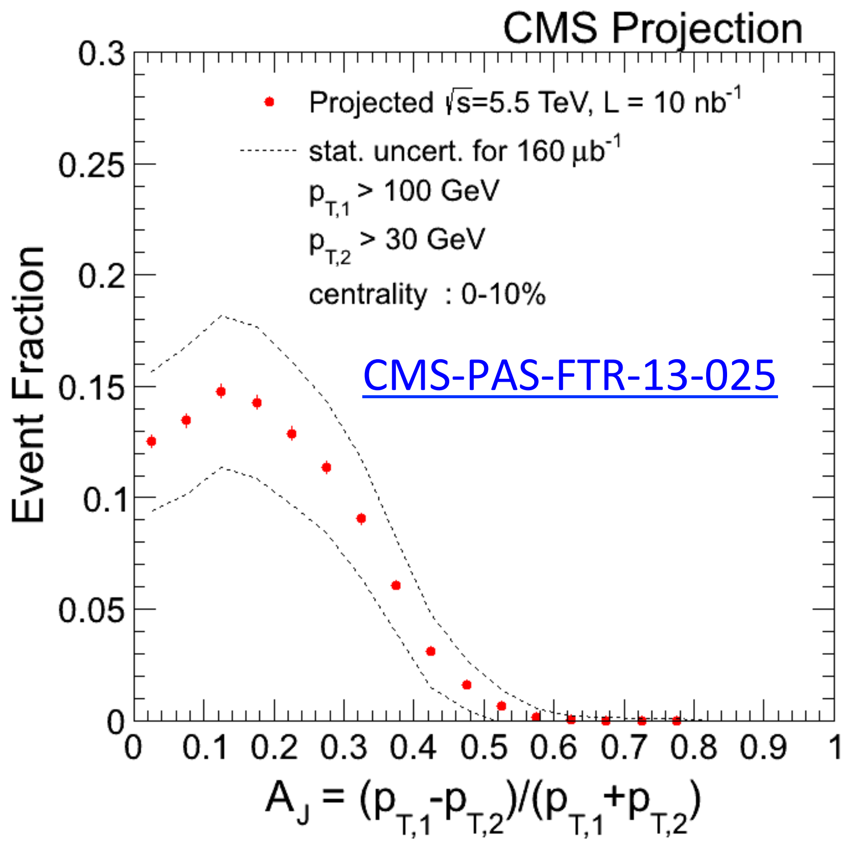
b-jet p_T asymmetry

Simulation for pp @ 7 TeV

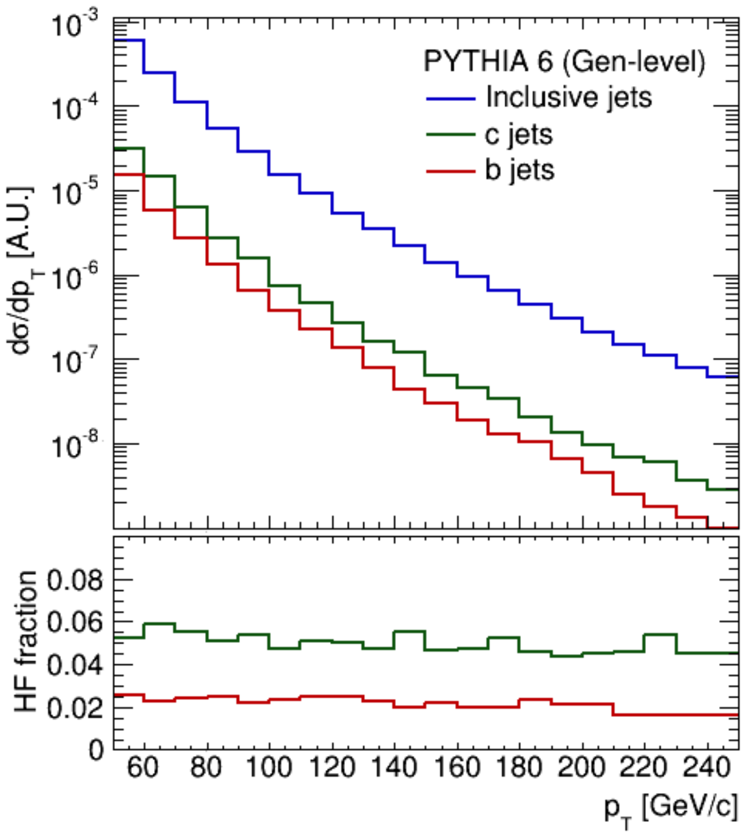
ATLAS EPJC 73 (2013) 2301

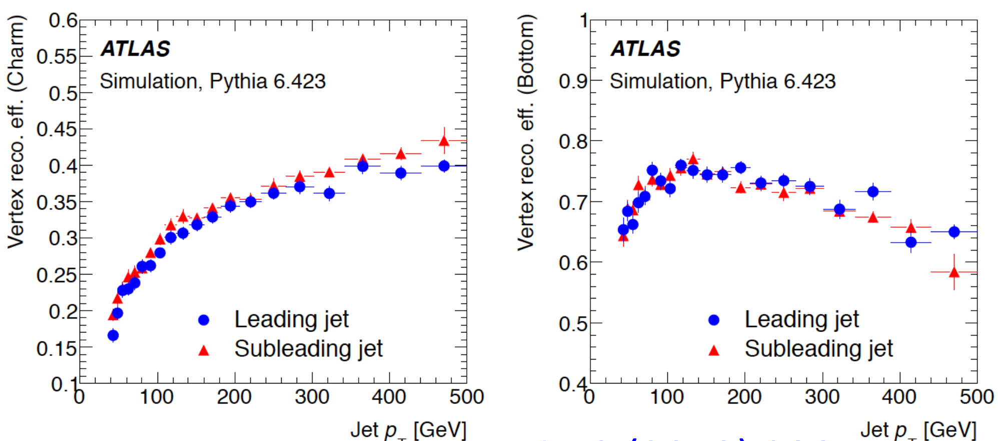


PbPb Projection for HL-LHC



- Much reduced systematics for A_J (A_b) w.r.t. inclusive jet spectra
- Dominated by primary b jets from flavor creation at large Δϕ





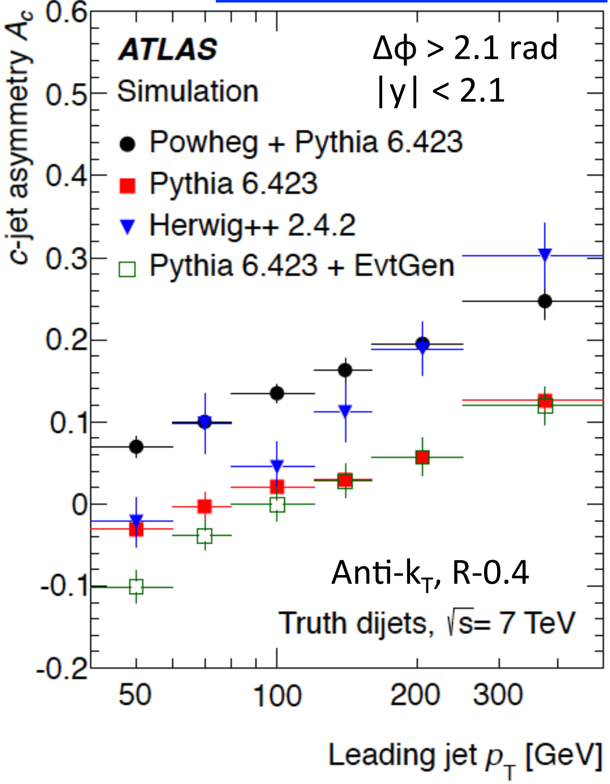
EPJC 73 (2013) 2301

Charm jets

- Rate ~ 2-2.5x b jets
- More difficult to tag
  - Shorter cτ 100-300 μm
  - Smaller multiplicity
  - Softer fragmentation
- Direct tagging?
  - Via, e.g., D+ → K π π
  - Branching ratio ~ 10%
- Combinatorial c jets?

Simulation for pp @ 7 TeV

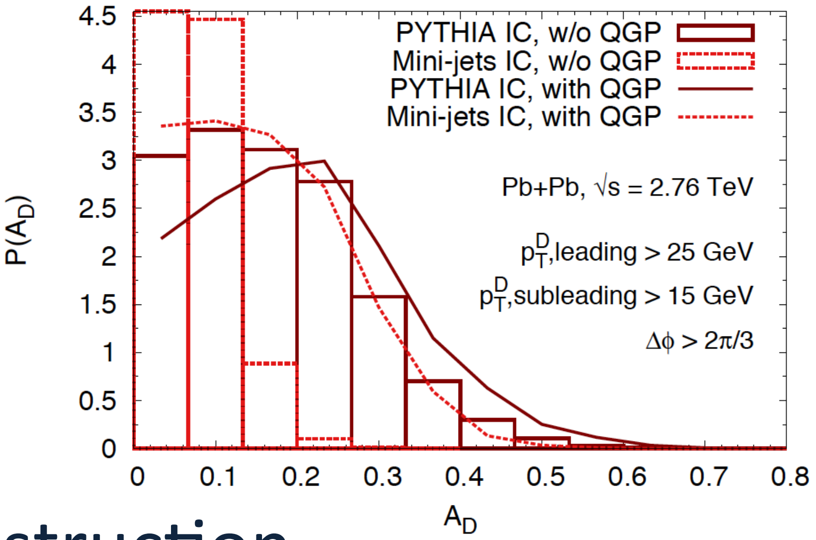
ATLAS EPJC 73 (2013) 2301



c-jet p_T asymmetry

Predications for D meson p_T asymmetries w/ BAMPS

Uphoff, et al. PRC89 (2014) 064906



- With direct D meson reconstruction
  - Expect high c-jet purity
  - Can compare meson vs jet asymmetry
- Mixed tagging also possible, e.g., D-lepton, D-SV

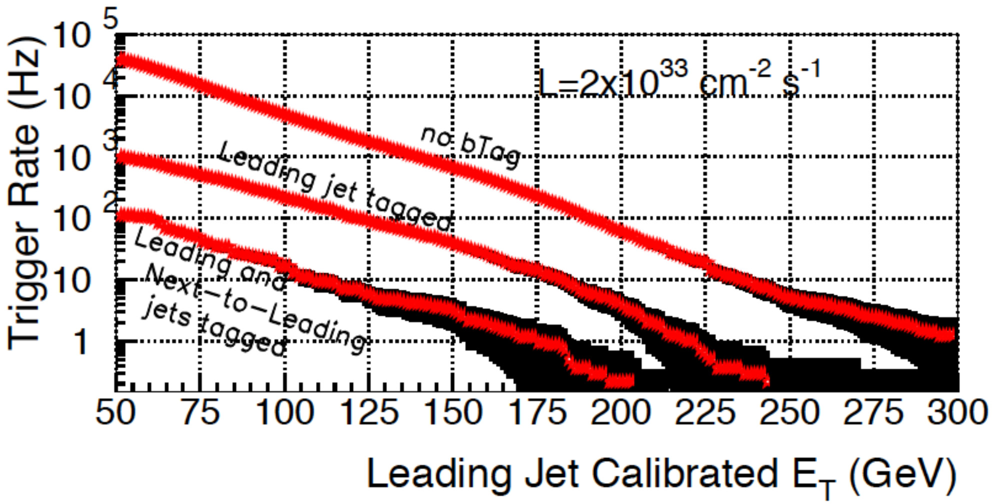
Conclusions

- HF hadron spectra have been measured in HI: non-prompt J/ψ, D and now exclusive B (pPb)
  - B mesons show a larger R_{AA} than D and h
  - Production effects play a role, not just e-loss
- First HF jet measurement in HI has been done
  - No large flavor dependence seen yet
  - GSP contamination an issue (also for HF hadrons!)
- LHC Run 2 and 3 data WILL solve open questions
  - HF jet "fragmentation functions"
  - HF hadron and jet pair asymmetries (both b and c)
  - HF jet angular correlations

Backup slides

Towards higher luminosity

- Recorded O(100 TB) of jet-triggered data in 2011 PbPb
- Expect ~10x int. lumi in Run 2
- Jet rate ~5x w/ 2x larger √s
- → 5 PB of data!



- Triggering on b jets dramatically reduces the rate and data volumes
- HI program already using full tracking at trigger-level
    - High multiplicity triggers
    - Muon "Level 3" triggers
- Displaced tracks in jets are more challenging than these use-cases, particularly in terms of timing

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

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

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

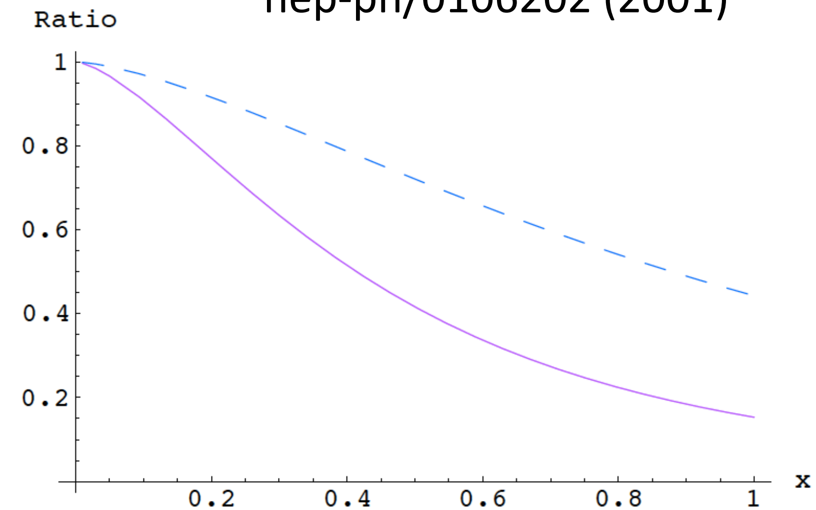
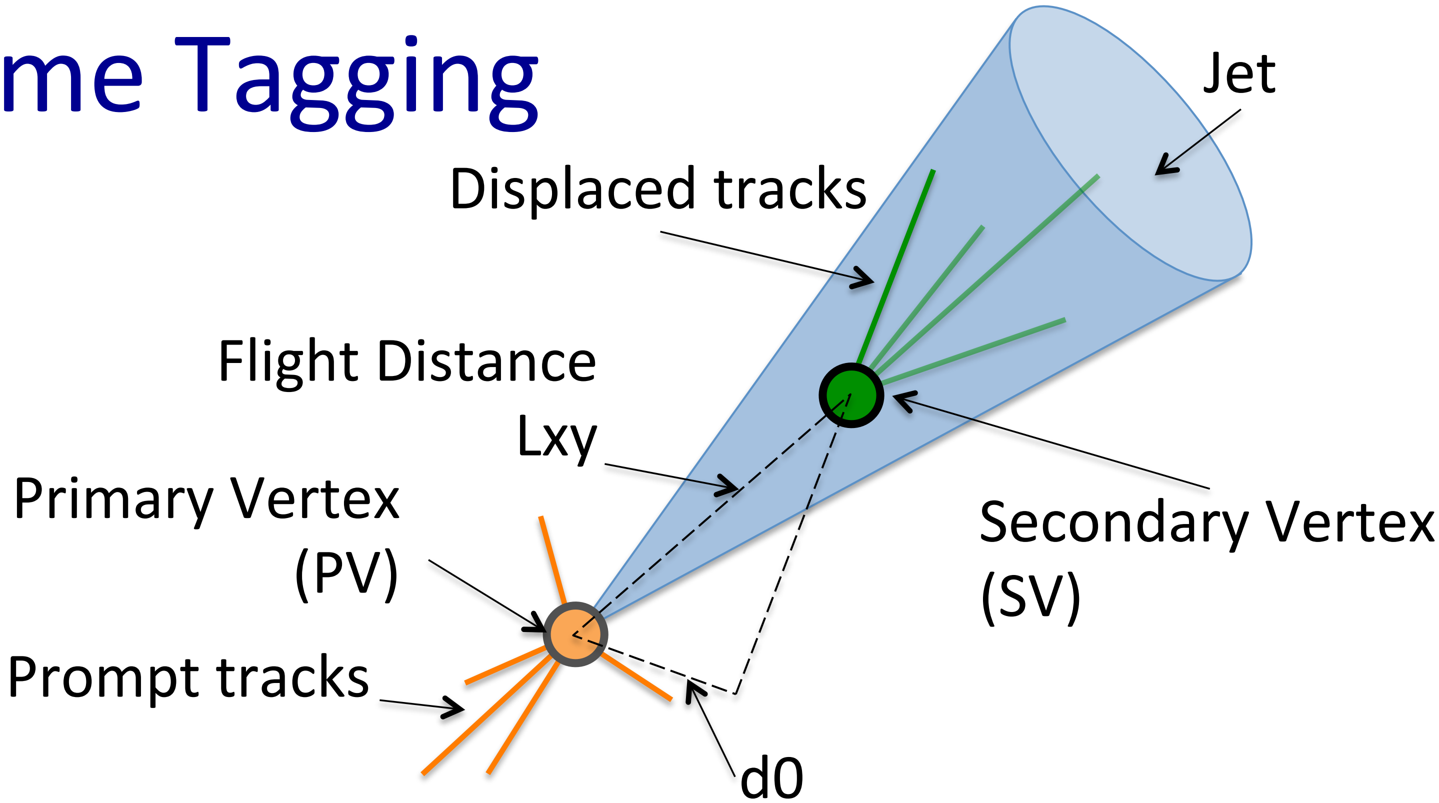


Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta $p_\perp = 10\,\mathrm{GeV}$ (solid line) and $p_\perp = 100\,\mathrm{GeV}$ (dashed); $x = \omega/p_\perp$.

"… the pattern of medium induced gluon radiation appears to *be qualitatively different for heavy and light quarks* in the kinematic regime of practical interest"

Lifetime Tagging



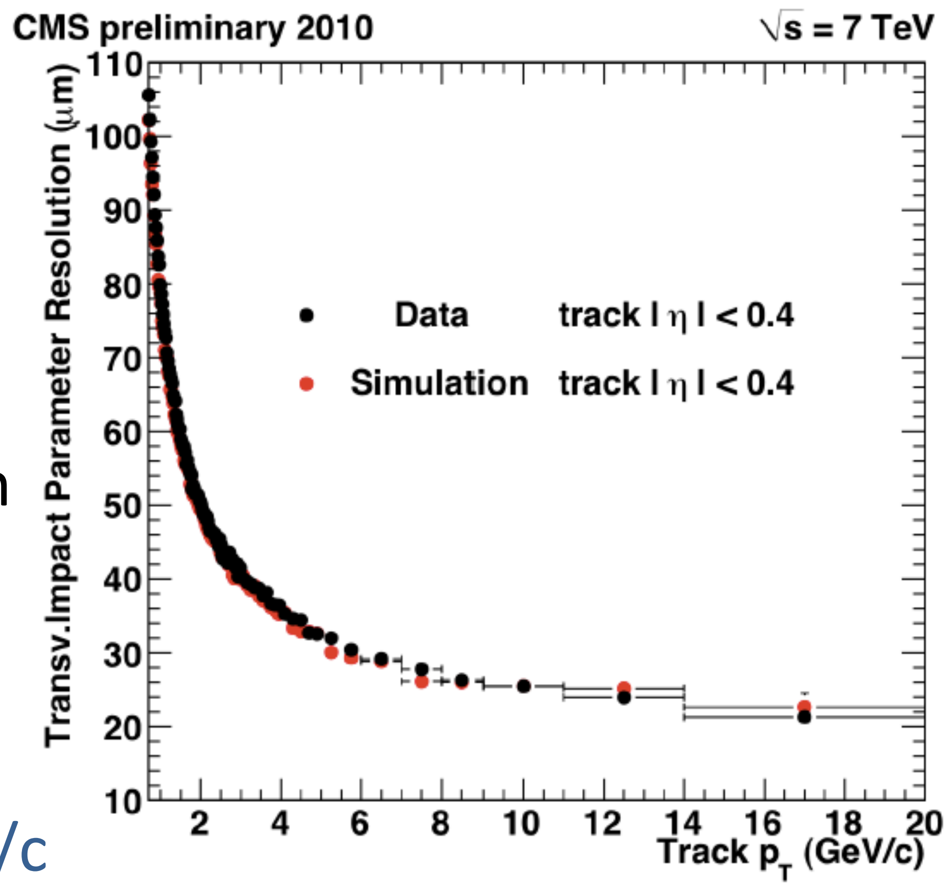
- Long B-hadron lifetime (~1.5 ps) → decays mm – cm from PV
- Likely subsequent charm decay w/ tertiary vertex
- *Lifetime tagging* based on
  - (Partially) reconstructed secondary vertices (SV)
  - Impact parameter (IP) of displaced tracks
- Jet measurement is identical to inclusive jets

IP Resolution

- Pixel spatial resolution ~ 15-20 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



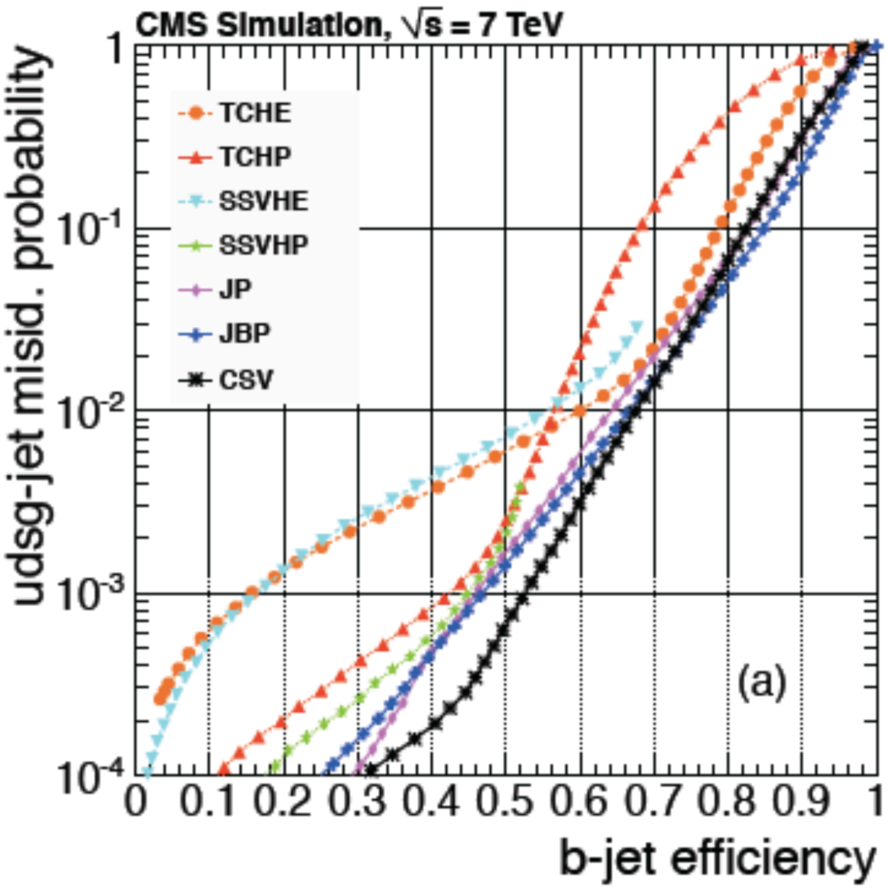
CMS-PAS-TRK-10-005

CMS b-Jet Discriminators

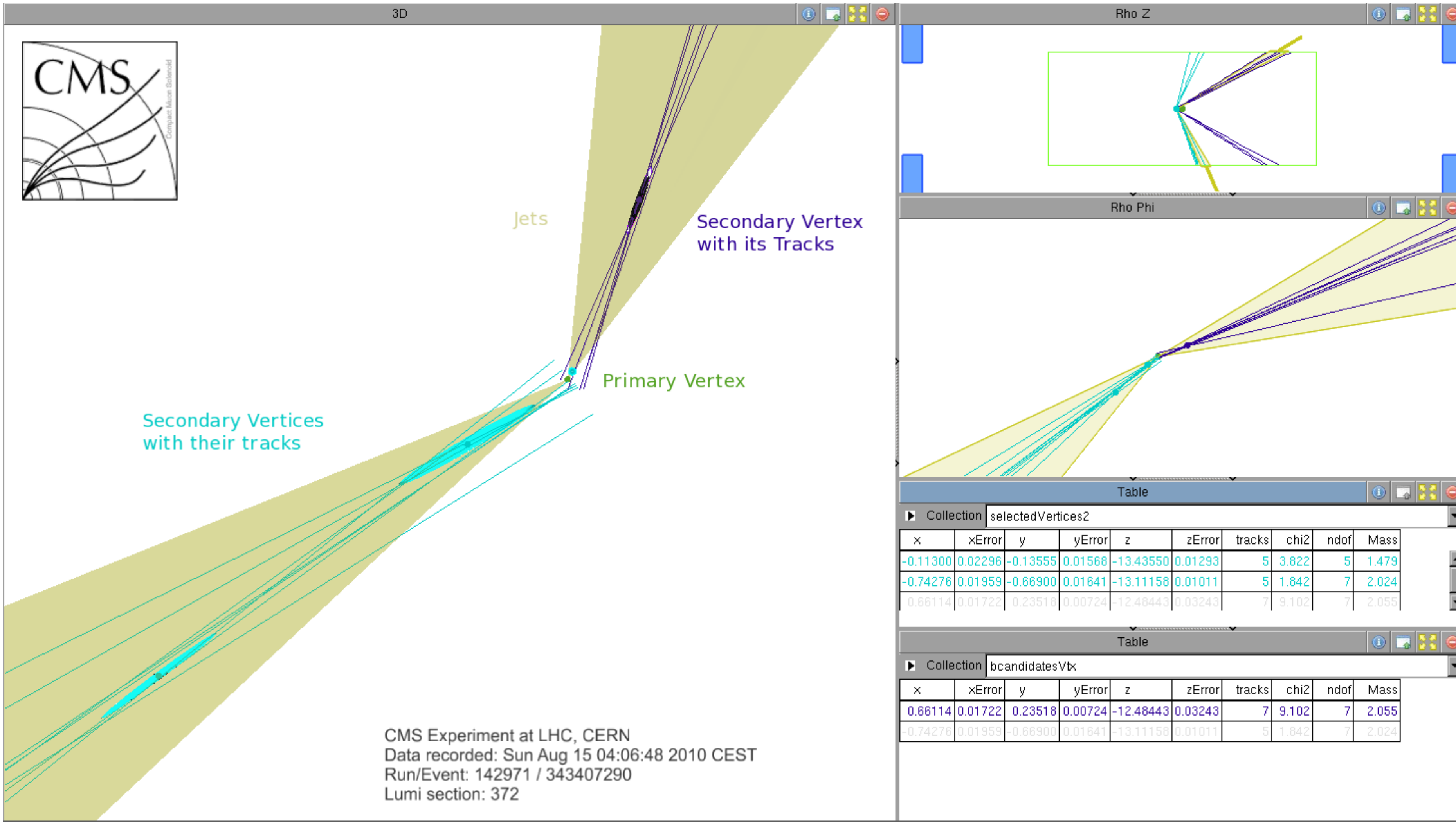
Single variable (*discriminator*), gives some b-tagging efficiency/purity, for a given working point

- 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:
  - $p_{T,rel}$ of IP-sig of muons or electrons

arxiv:1211.4462



Flavor Creation Candidate (7 TeV)



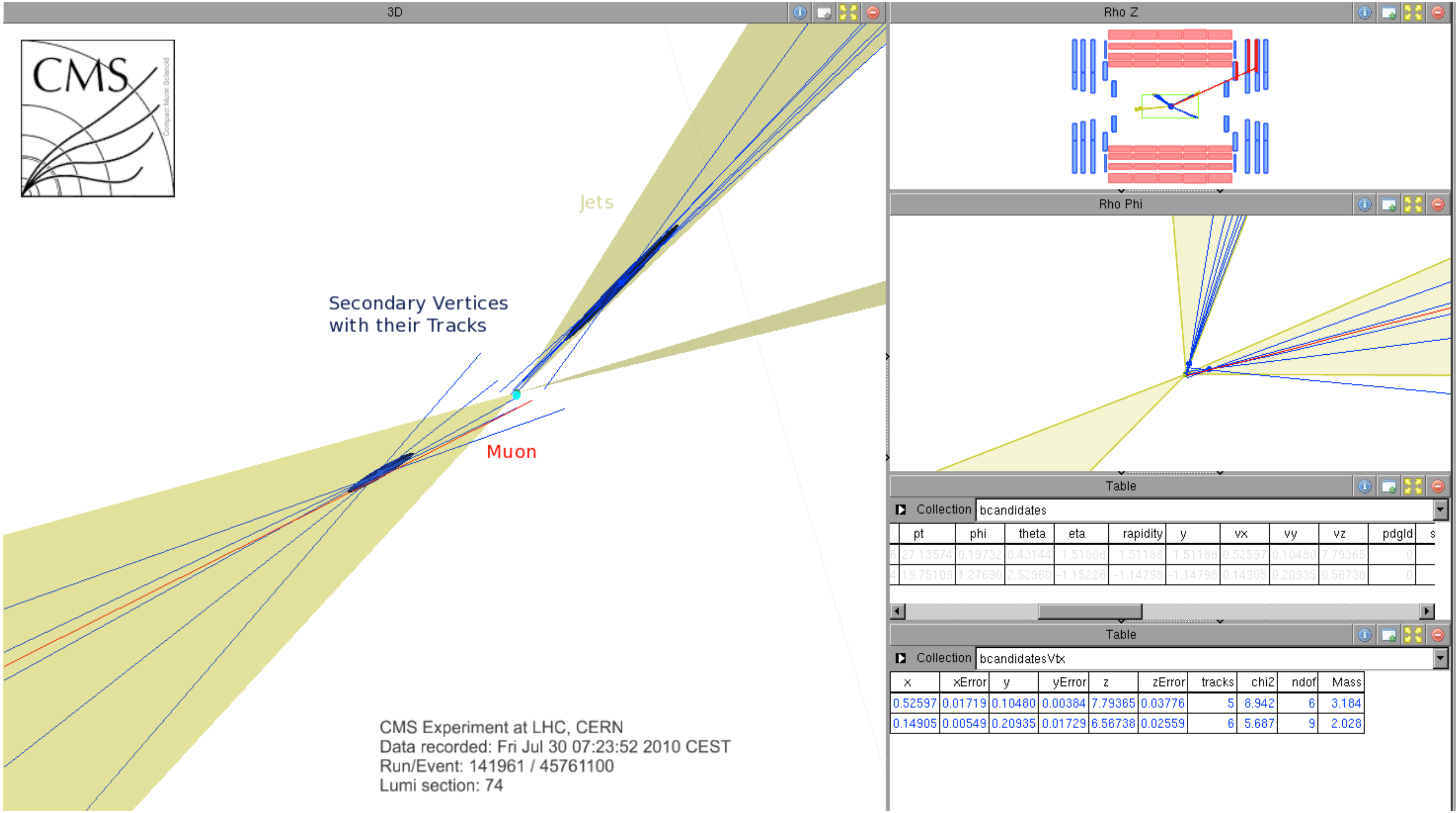
Collection: selectedVertices2

x	xError	y	yError	z	zError	tracks	chi2	ndof	Mass
-0.11300	0.02296	-0.13555	0.01568	-13.43550	0.01293	5	3.822	5	1.479
-0.74276	0.01959	-0.66900	0.01641	-13.11158	0.01011	5	1.842	7	2.024
0.66114	0.01722	0.23518	0.00724	-12.48443	0.03243	7	9.102	7	2.055

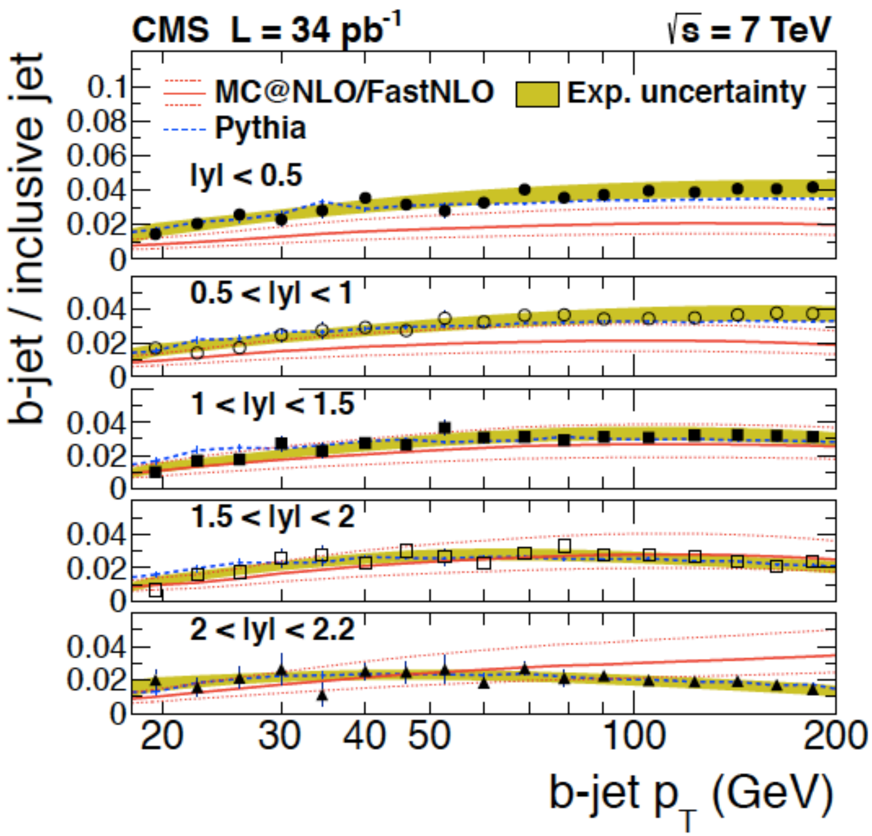
Collection: bcandidatesVtx

x	xError	y	yError	z	zError	tracks	chi2	ndof	Mass
0.66114	0.01722	0.23518	0.00724	-12.48443	0.03243	7	9.102	7	2.055
-0.74276	0.01959	-0.66900	0.01641	-13.11158	0.01011	5	1.842	7	2.024

Gluon Splitting Candidate (7 TeV)



b-Jet to Inclusive Jet Ratio



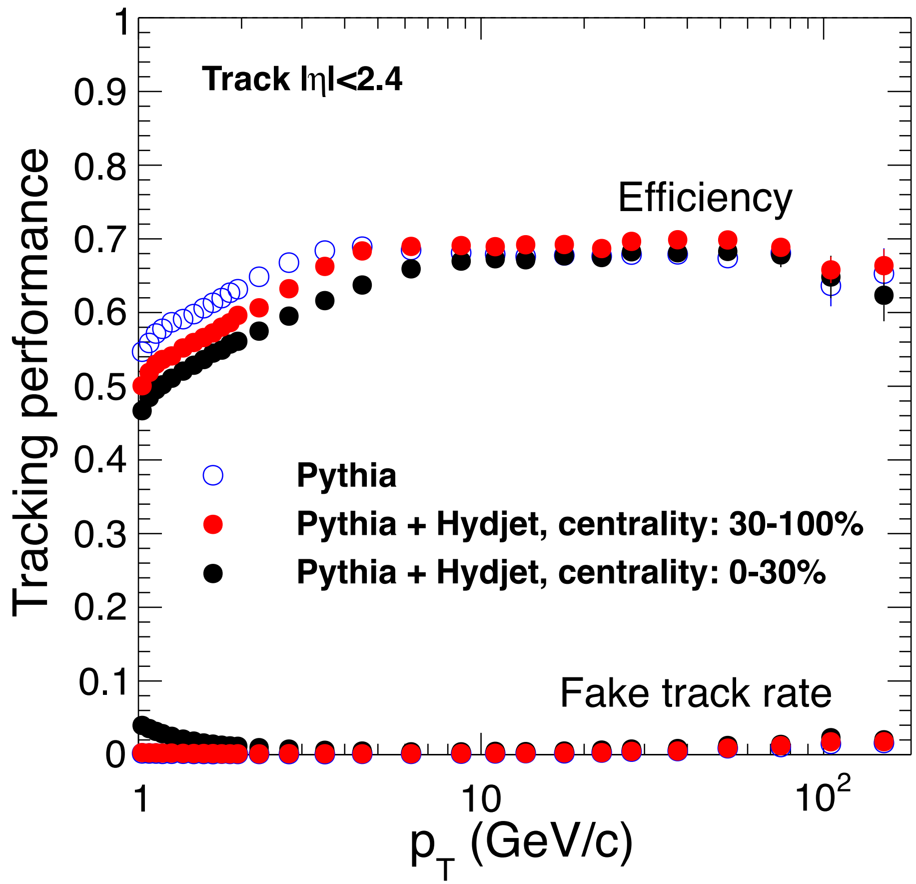
arXiv:1202.4617

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

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

“Standard” HI Tracking (2011)

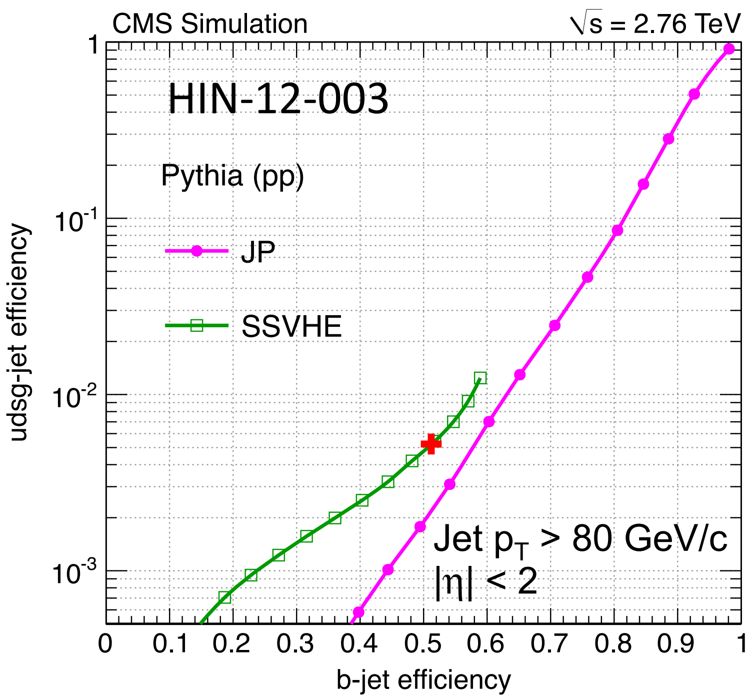


CMS-PAS-HIN-12-013

b-Tagging Performance

Two discriminators are used in the HI analysis:

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

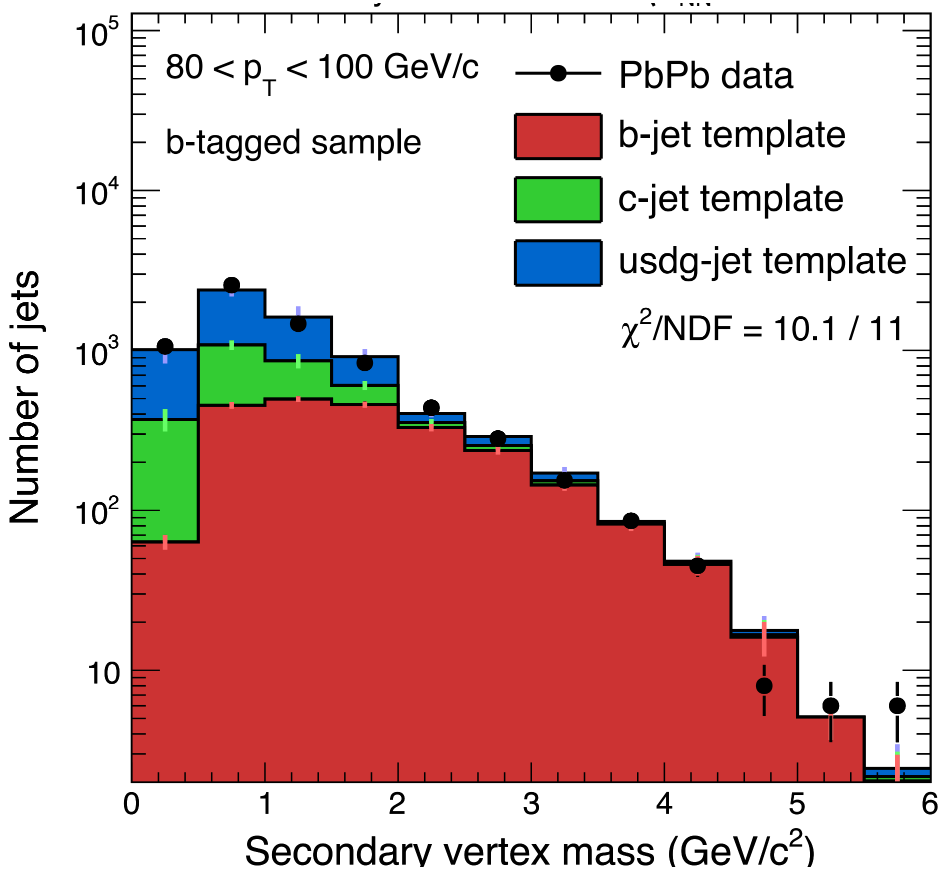


- *SSVHE*
  - Uses flight distance significance
  - Additional discrimination from SV mass
- JP
  - Uses all large IP tracks to estimate a likelihood of PV compatibility
  - Discriminates for ~ all b-jets
  - Independent data and MC calibrations using negative IP tracks

- 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

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%

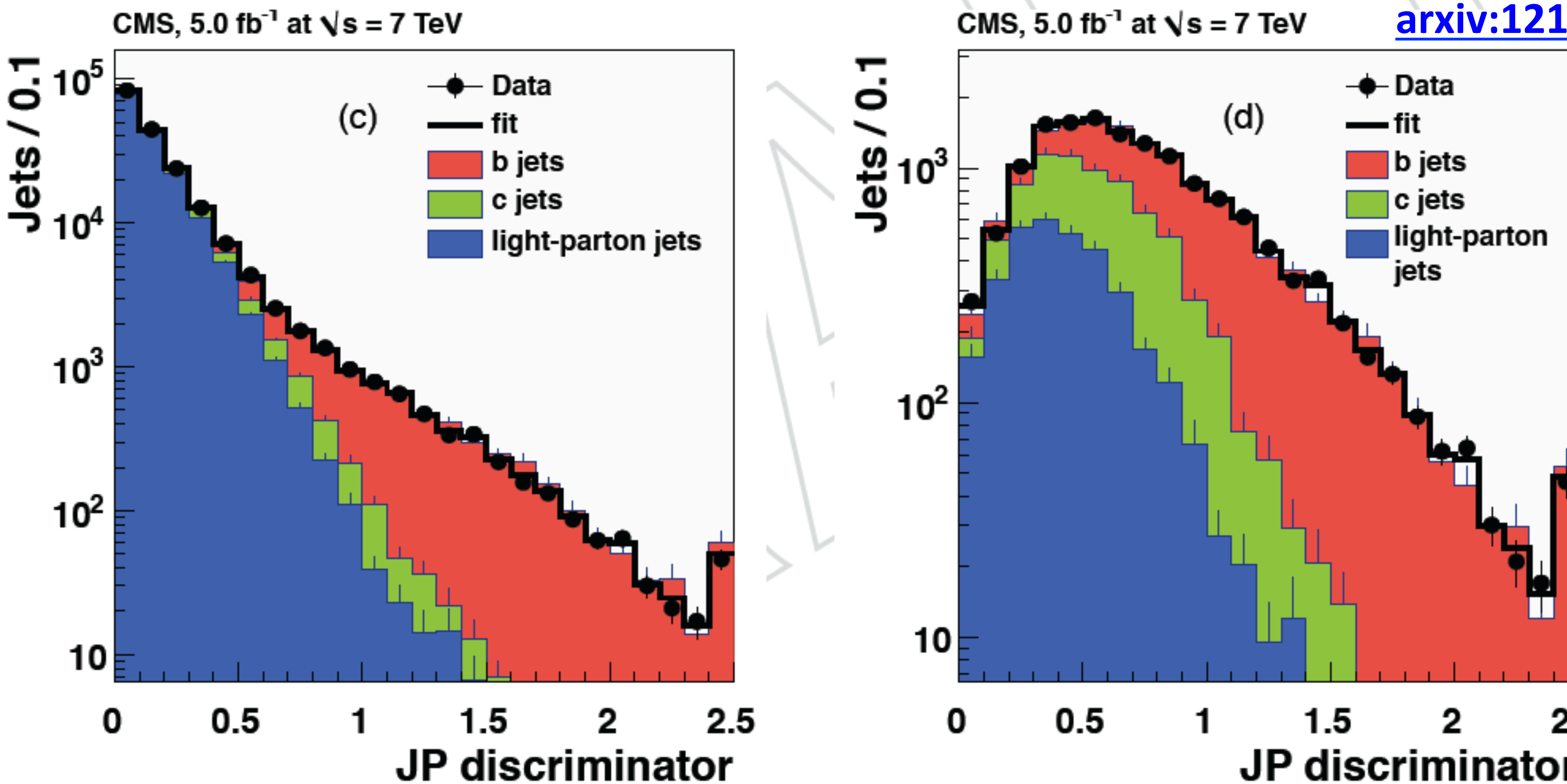


HIN-12-003

Reference Tagger Method

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

arxiv:1211.4462



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

f_b = purity from template fit

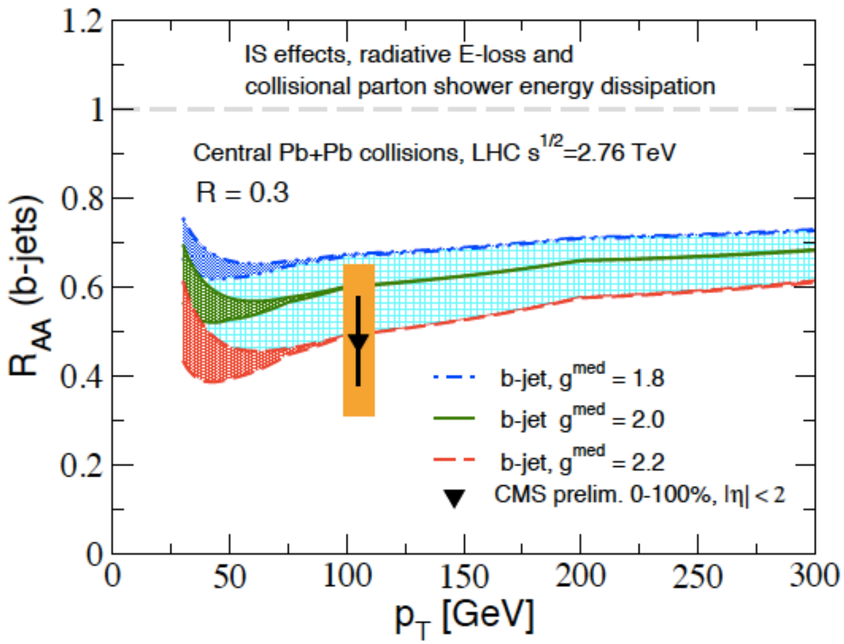
\# of tagged jets in data

\# of jets with JP information

C_b = fraction of jets with JP information

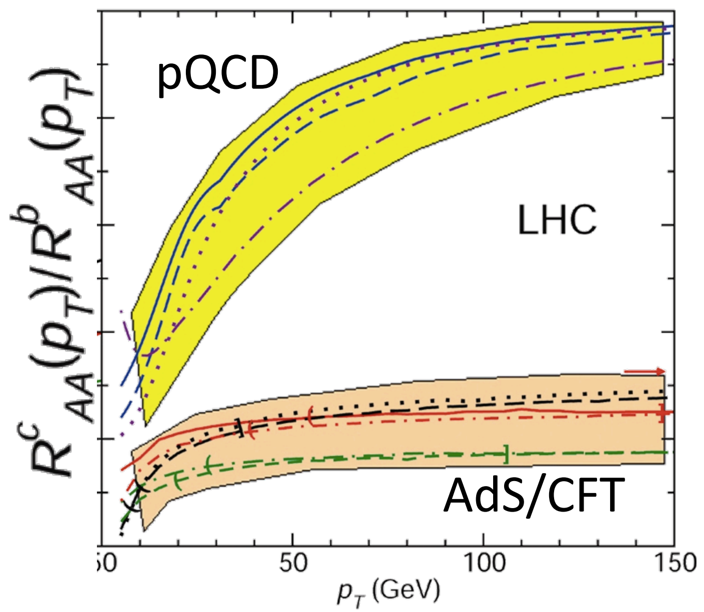
pQCD vs AdS/CFT

Huang, Kang and Vitev
arXiv:1306.0909 (2013)



Models now indicate that mass effects are restricted to p_T < 75 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

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 TeV
  JHEP 1204 (2012) 084, arXiv:1202.4617
- Measurement of BB Angular Correlations based on Secondary Vertex Reconstruction at $\sqrt{s}$ = 7 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 TeV
  CMS-PAS-HIN-12-003, arxiv:1102.3194
- CMS TDR for the L1 Trigger Upgrade, CMS-TDR-012