Open Heavy Flavor Measurements in Heavy Ion Collisions with CMS

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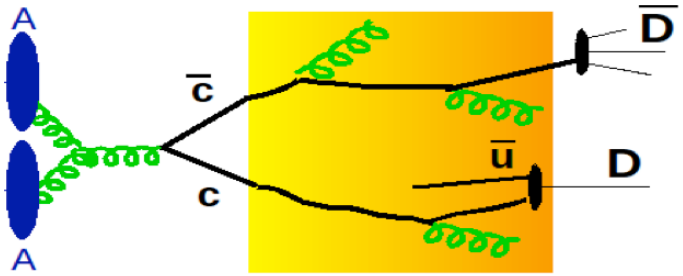
Physics Motivation

- Heavy quarks are produced primarily at the early stages of the collisions

→Experience the full evolution of the medium



- Flavor dependence energy loss
  - Heavy quarks are expected to lose less energy than light quarks and gluons in medium due to color charge and dead cone effect [1]

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

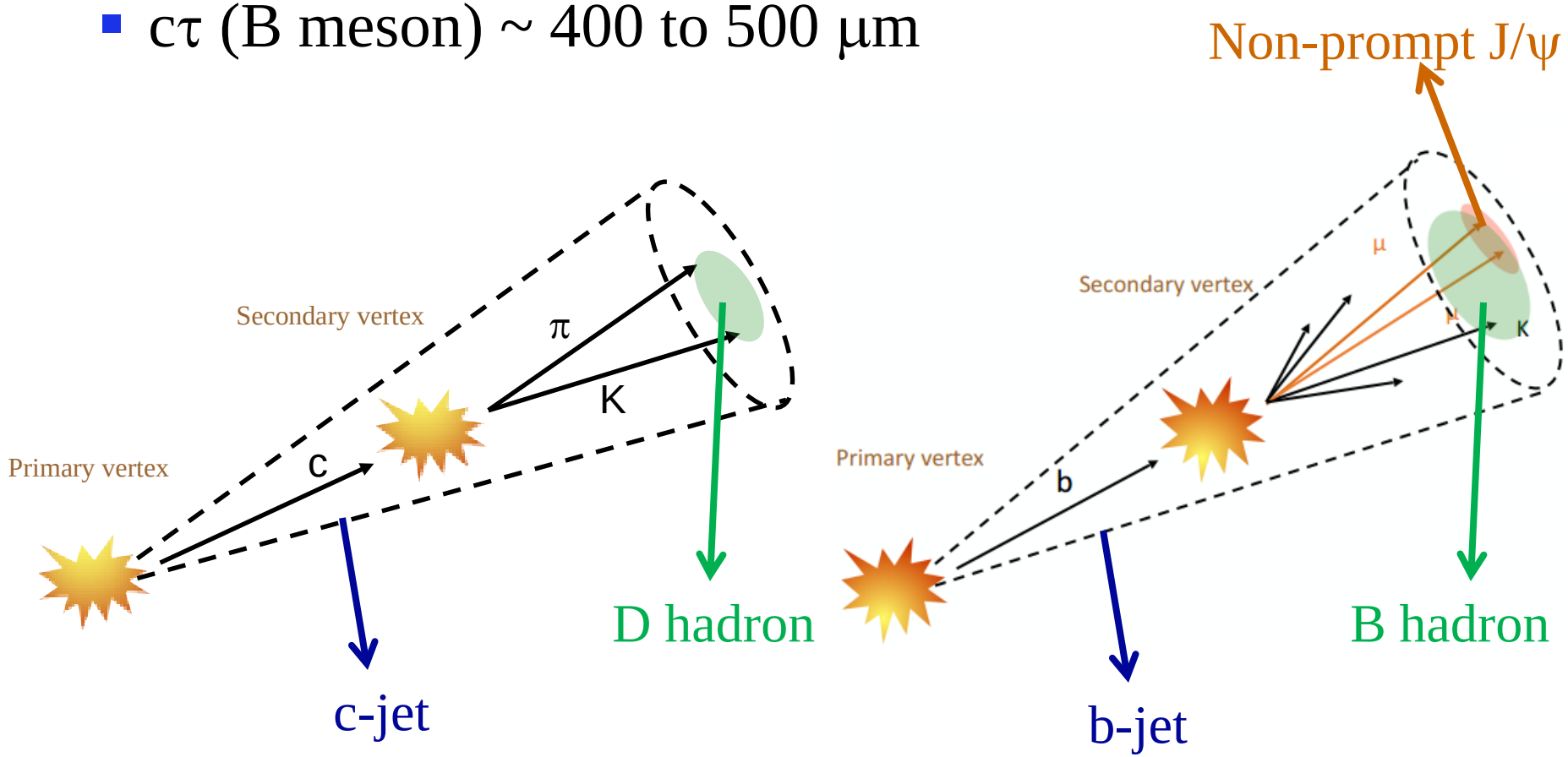
  - From light to heavy quark: ratio between radiative and collisional energy loss changes

[1] Y.L. Dokshitzer, D. E. Kharzeev, Phys. Lett. B 519 (2001) 199

- Cold nuclear matter effects through heavy flavor study in pPb

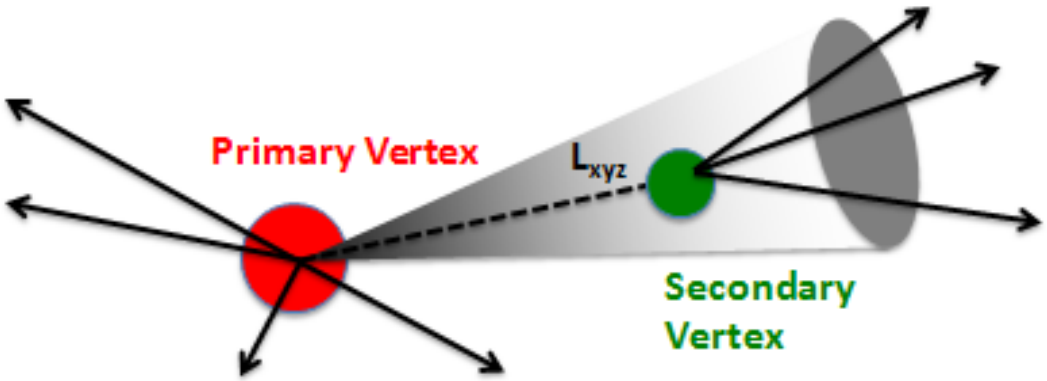
Open heavy flavor measurements with CMS

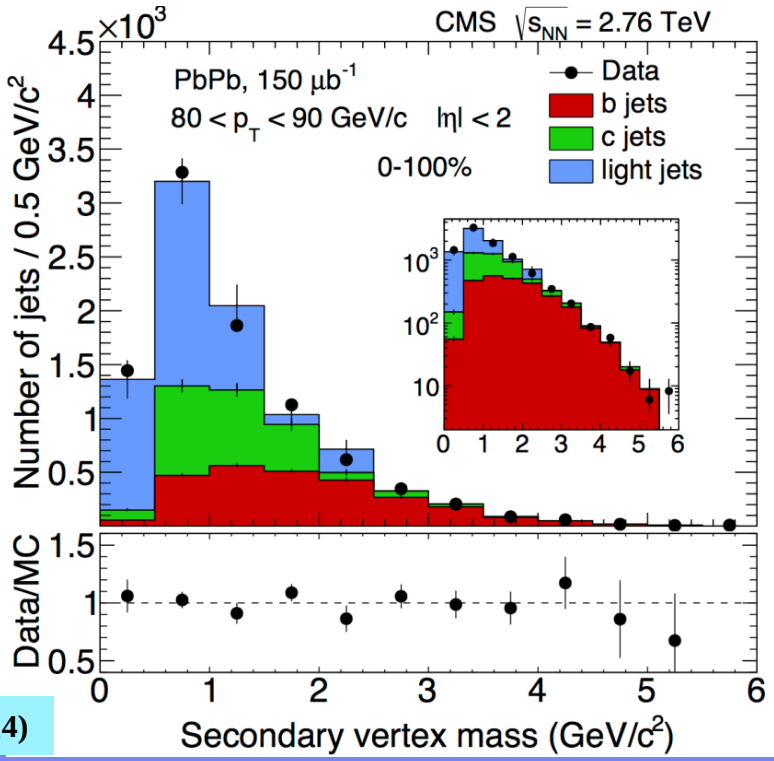
- c/b-jet, D/B hadron and non-prompt J/ψ
  - cτ (D meson) ~ 100 to 300 μm
  - cτ (B meson) ~ 400 to 500 μm



c/b-jet identification and fraction determination

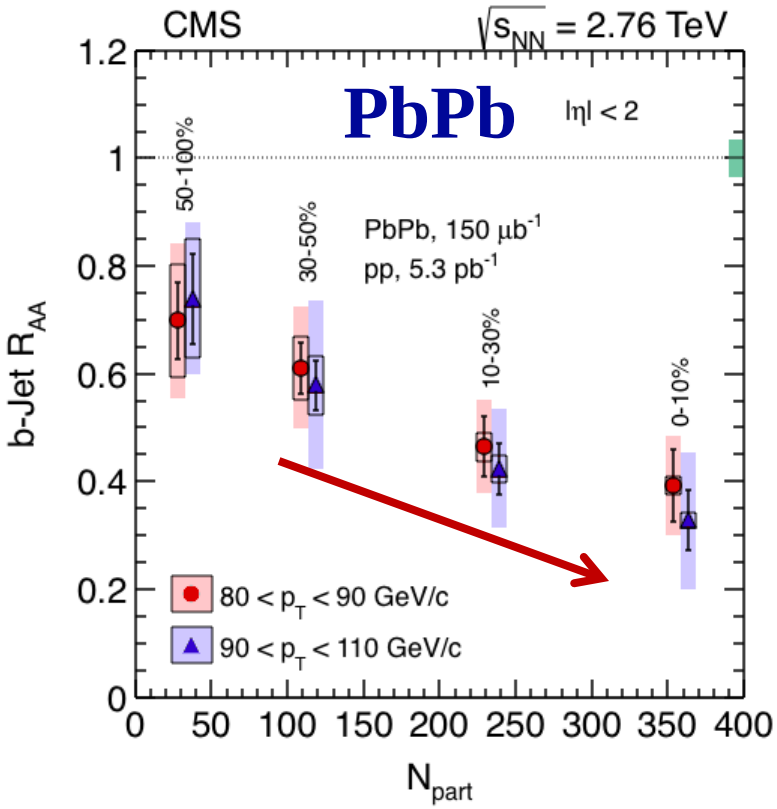
- Secondary vertices used to tag heavy flavor jet
  - **c-jet: requires secondary vertex with >= 3 tracks**
  - **b-jet: requires secondary vertex with >= 2 tracks**
- c/b-jet purity is obtained through template fit of secondary vertex mass

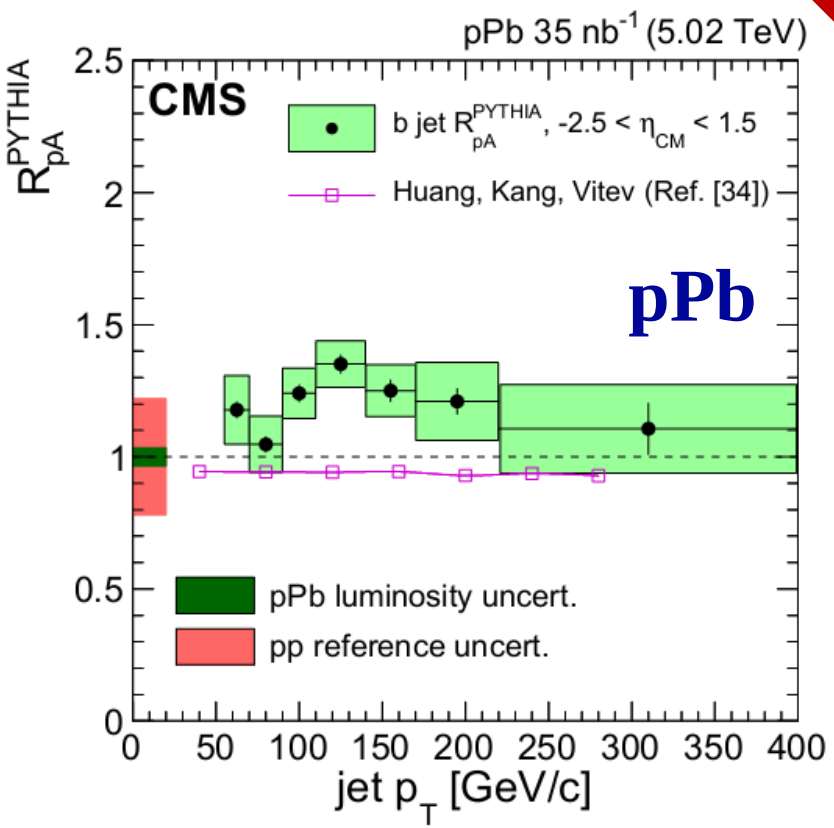




Phys. Rev. Lett. 113, 132301 (2014)

b-jet in PbPb and pPb





- **b-jet production is suppressed in PbPb. And the suppression has strong centrality dependence**

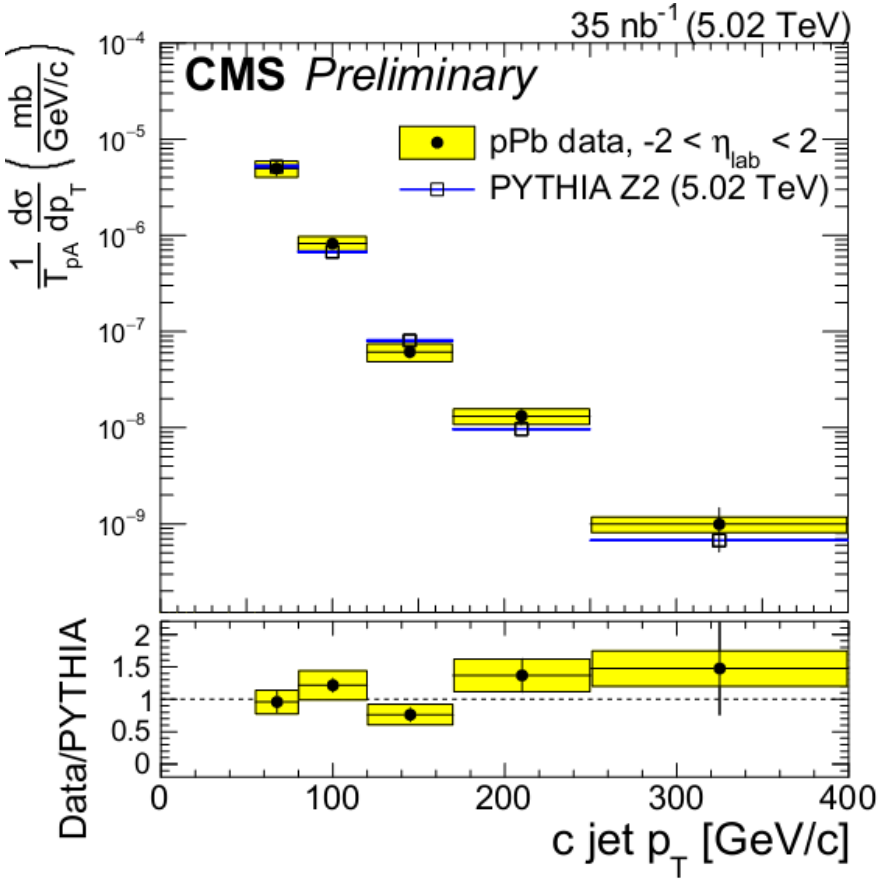
- **R_{pA} is consistent with unity within uncertainties**
  - **No significant cold nuclear matter effects. Suppression in PbPb is from hot medium effect.**

Phys. Rev. Lett. 113, 132301 (2014) | **CMS-PAS-HIN-12-004** | **Submitted to PLB**

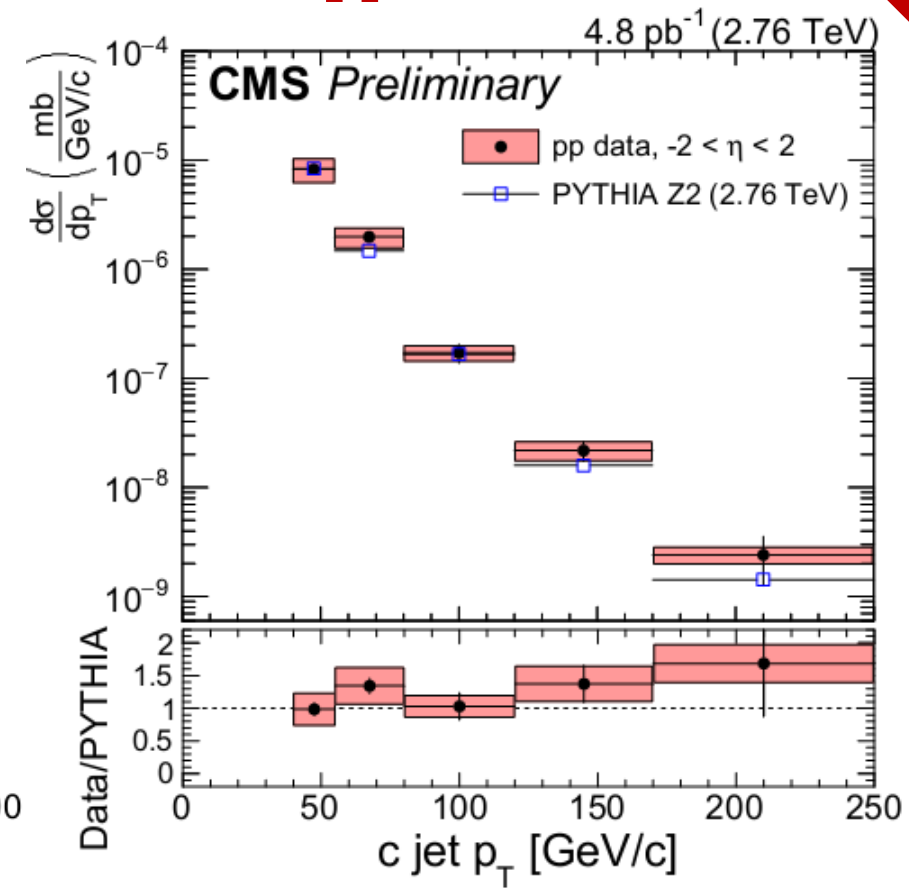
c-jet spectrum in pPb and pp

New

pPb 5.02 TeV



pp 2.76 TeV

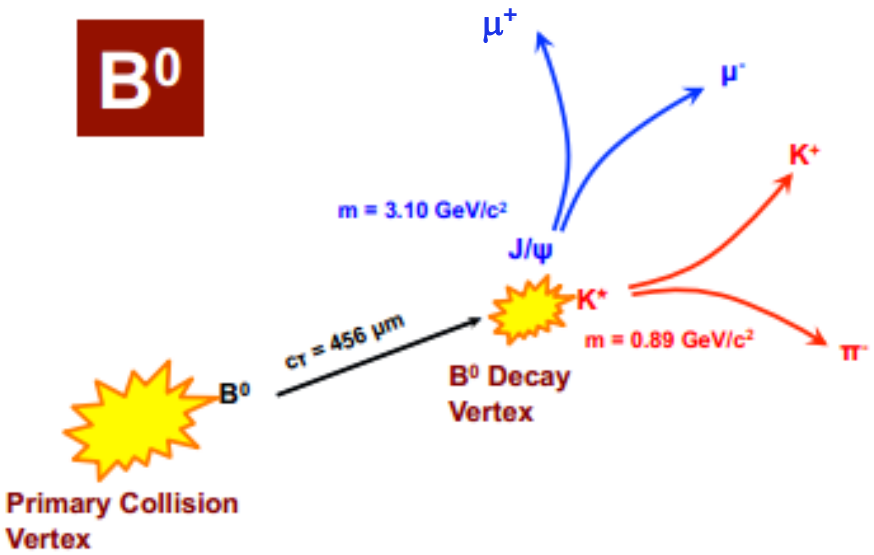


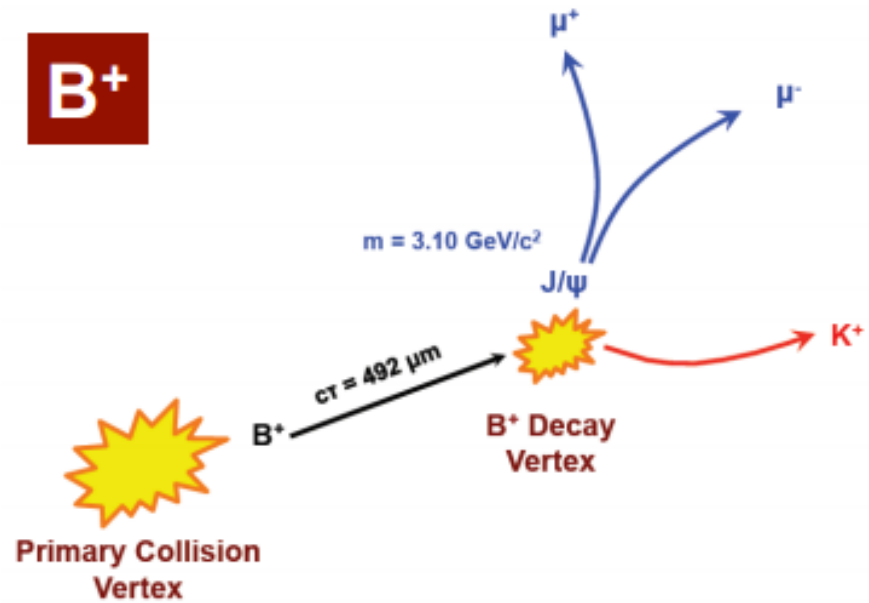
- **c-jet spectrum consistent with PYTHIA for both pPb and pp**
  - Data/Pythia: 1.00 ± 0.19 (pPb) and 1.15 ± 0.27 (pp)

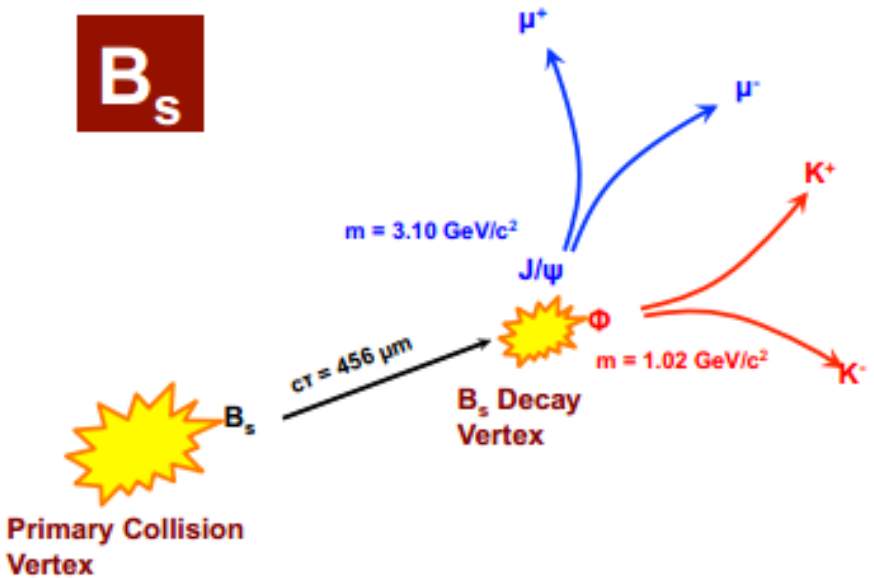
See poster by Kurt Jung

CMS PAS HIN-15-012

B meson in pPb





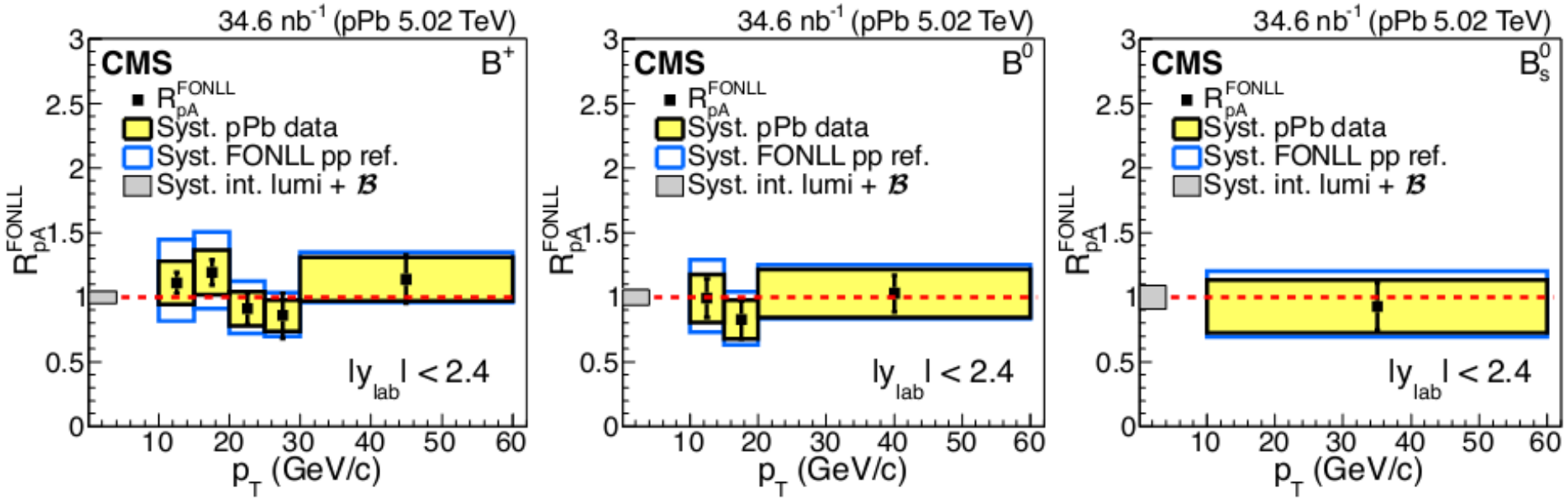


- **Fully reconstructed hadronic decays:**
  - $B^+ \rightarrow J/\psi\, K^+ \rightarrow \mu^+\mu^-\, K^+$
  - $B^0 \rightarrow J/\psi\, K^{0*} \rightarrow \mu^+\mu^-\, K^+\pi^-$
  - $B_s^0 \rightarrow J/\psi\, \varphi \rightarrow \mu^+\mu^-\, K^+K^-$

B mesons in pPb: R_{pA}^{FONLL}

Final

- FONLL prediction as pp reference (no data reference available)
- R_{pA} is consistent with unity within uncertainties
- No significant cold nuclear matter effects observed within uncertainties
- Important reference for PbPb analysis



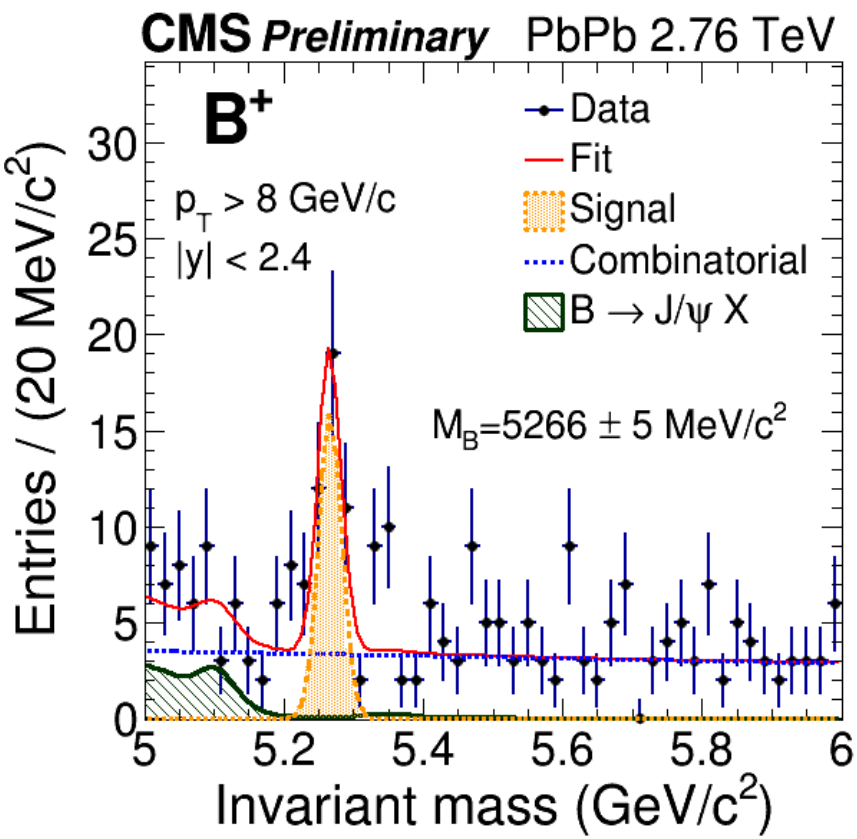
Submitted to PRL arXiv:1508.06678

B mesons in PbPb

- Capable of reconstructing B mesons in PbPb with CMS
- First fully reconstructed B meson signal in PbPb!
- 2015 Run-2: 20x more statistics (Increased luminosity and higher collision energy)
- Measurements of B^+, B^0 and B_s^0 in PbPb

See poster by Kisoo Lee

CMS detector performance plot



B^+ invariant mass spectrum in 2011 PbPb data

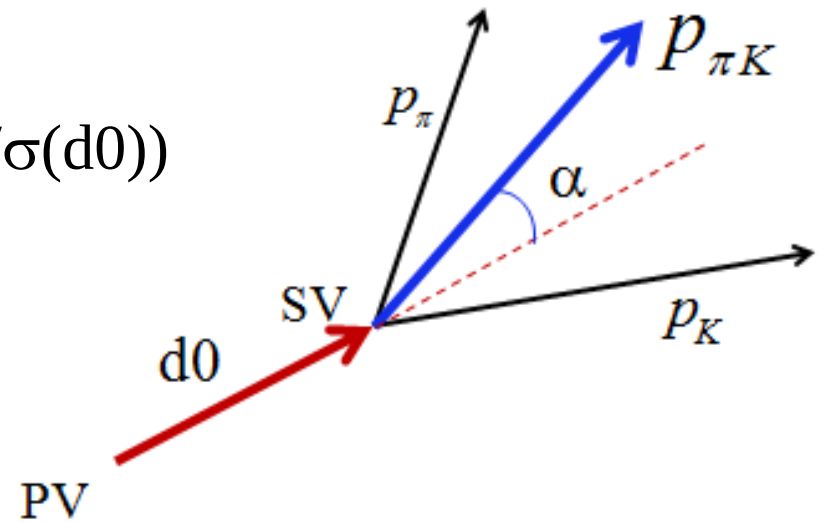
D^0 Reconstruction

New

- **$D^0 \rightarrow K\pi$, BR = 3.88±0.05%, $c\tau(D^0)$ = 122.9 μm**

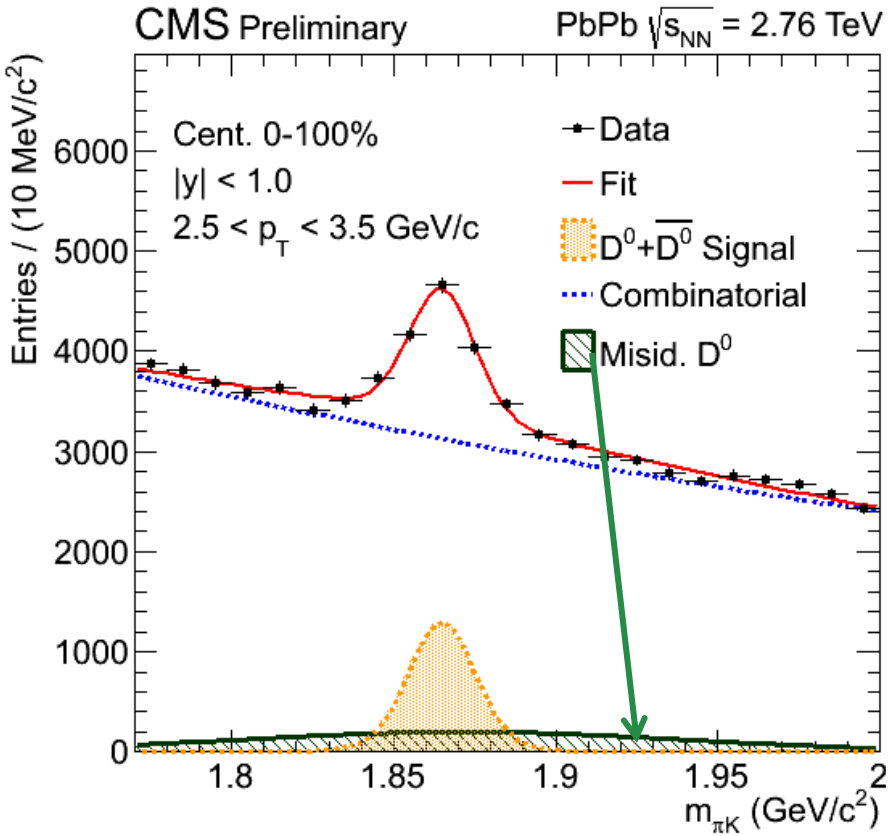
- **D^0 candidates reconstructed by combining oppositely charged tracks**
  - No PID selection applied: two mass assignments for one track pair→**Two candidates for one track pair**

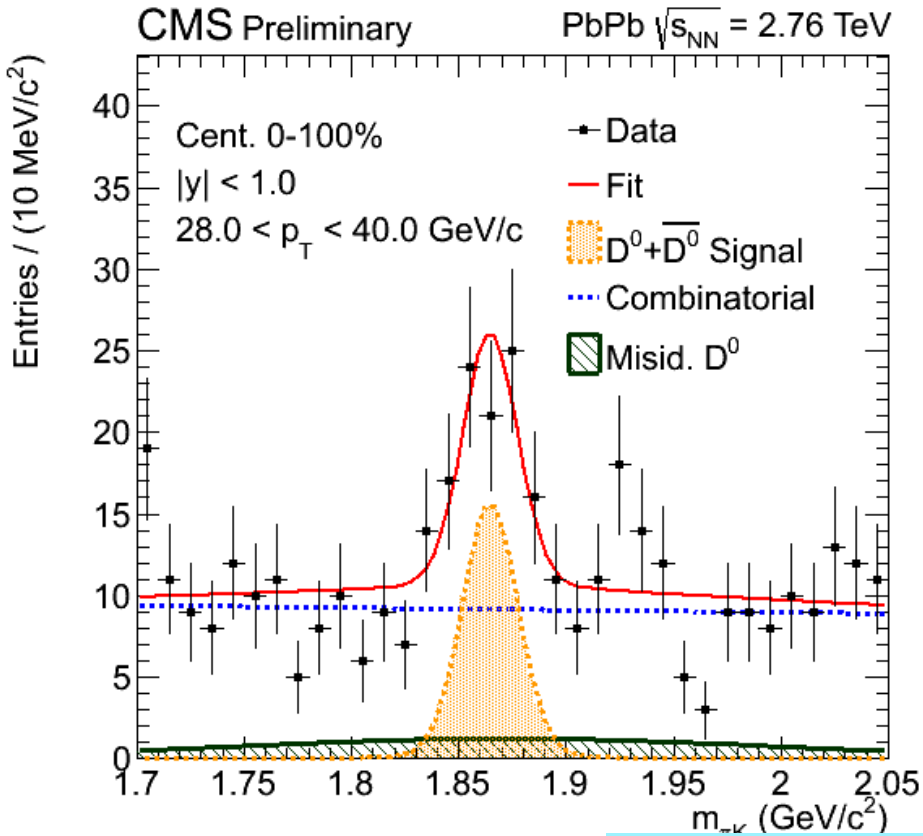
- **Topological selections:**
  - 3D decay length significance (d0/σ(d0))
  - Pointing angle α
  - Vertex χ^2 fit probability



D^0 signal extraction: $D^0 \rightarrow K\pi$

- **Data: 2011 PbPb data with minimum bias trigger ~ 30M events**
- **Clear D^0 signal in p_T range 2.5 to 40 GeV**
- Misidentification (k-π swapped) D^0 because of wrong mass assignment

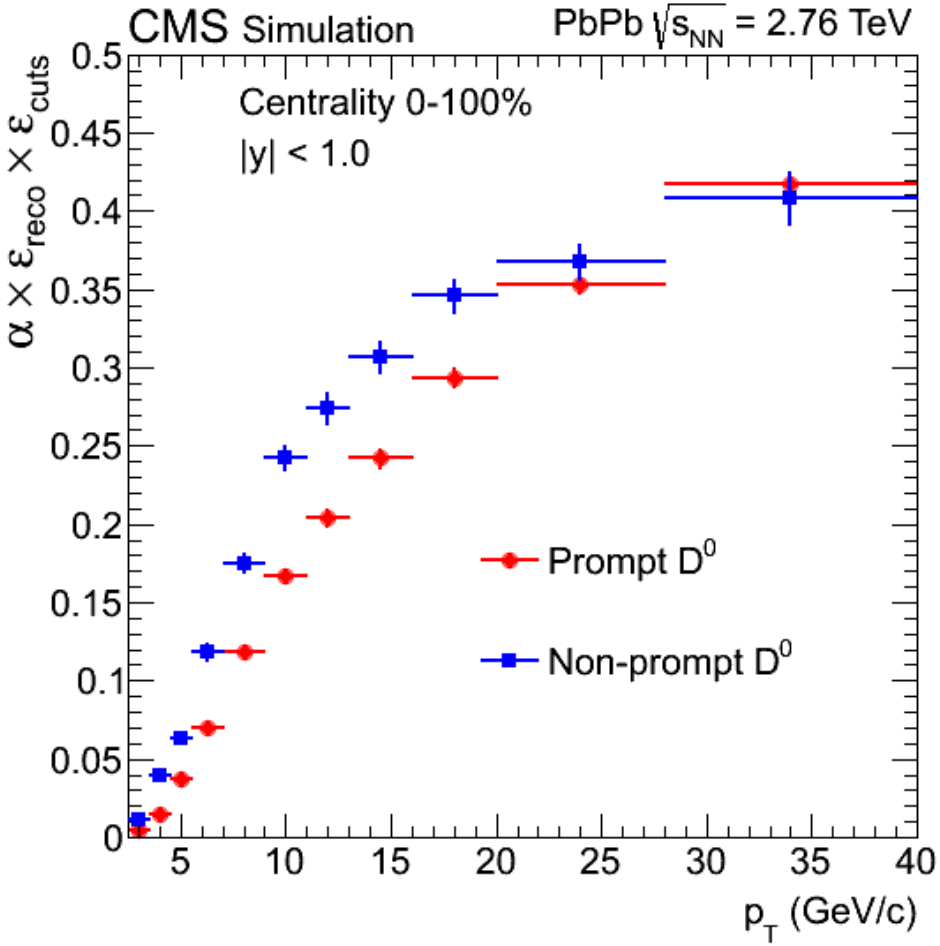




CMS PAS HIN-15-005

Acceptance and efficiency correction

$$\frac{dN_{PbPb}}{dp_T} = \frac{f_{prompt} \cdot \frac{1}{2} N_{D^0}^{raw}}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}$$



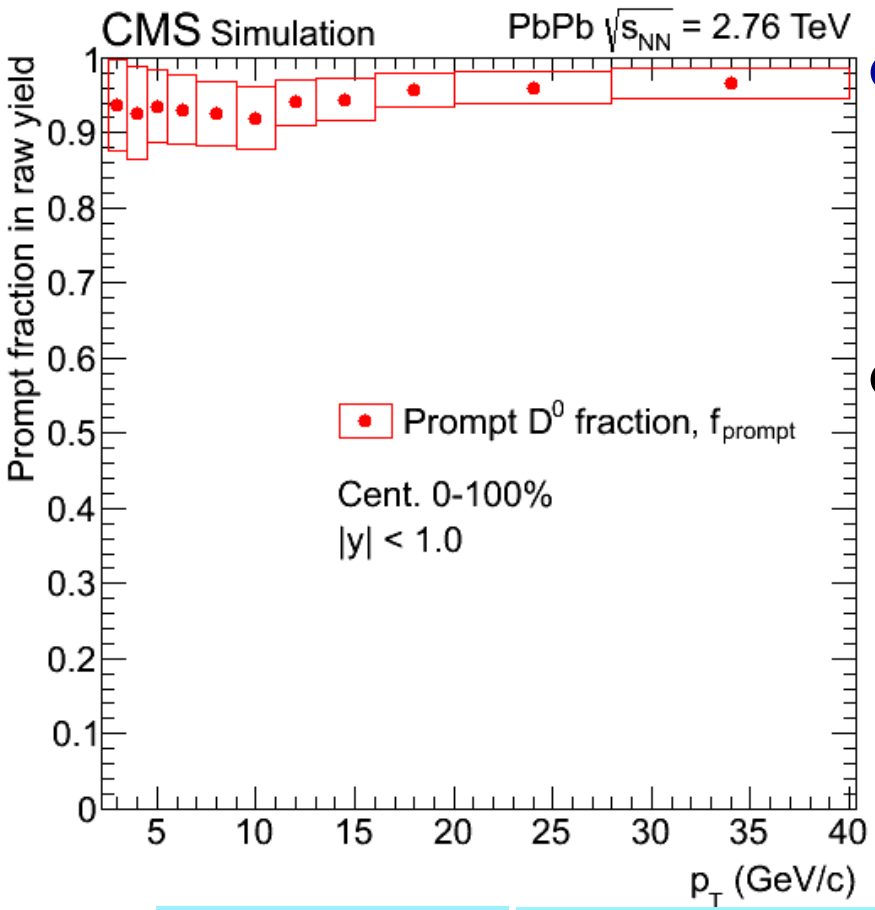
- Combined effects of tracking efficiency and cut selection efficiency

- Acceptance and efficiency of non-prompt D^0 (D^0 from B-hadron decay) will be used to estimate the the B feed-down correction factor

CMS PAS HIN-15-005

B feed-down correction

$$\frac{dN_{PbPb}}{dp_T} = \frac{f_{prompt} \cdot \frac{1}{2} N_{D^0}^{raw}}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}$$



- Non-prompt D^0 subtraction:

$$f_{prompt} = 1 - \frac{N_{Non-prompt\ D^0}^{raw}}{\frac{1}{2} N_{D^0}^{raw}}$$

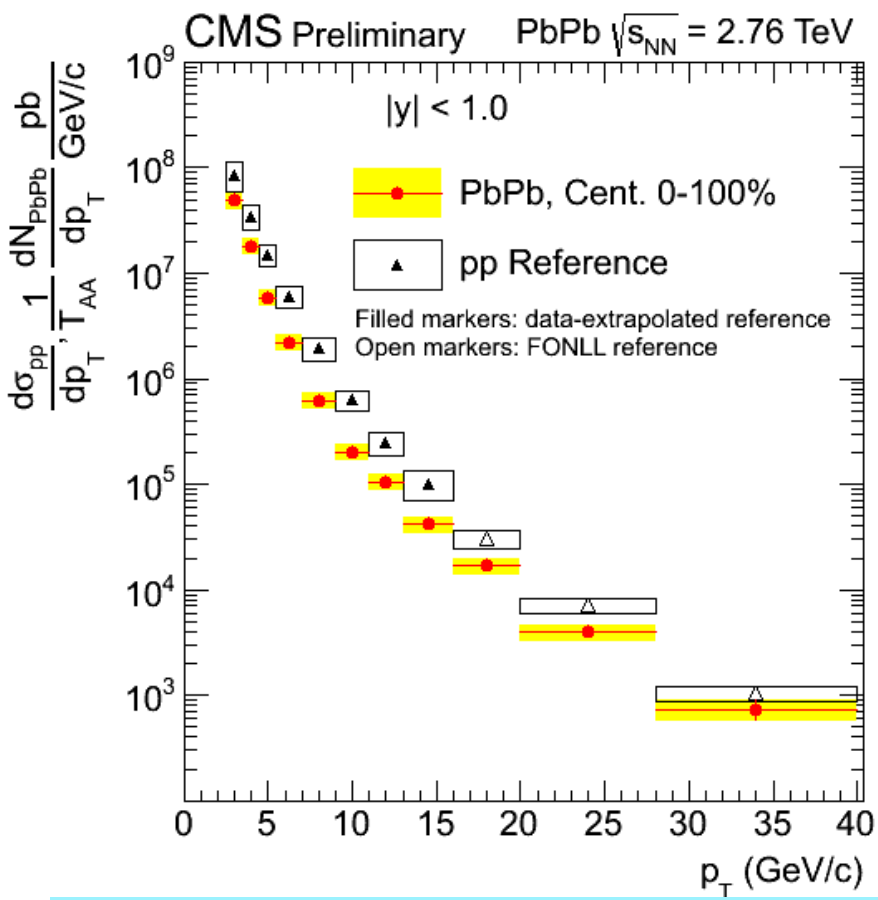
- Raw yield of non-prompt D^0
  - ➢Beauty production from FONLL [1]
  - ➢Acceptance and efficiency from Pythia embedded Hydjet
  - ➢R_{AA} of non-prompt D^0 constrained by non-prompt J/ψ and b-jet R_{AA}

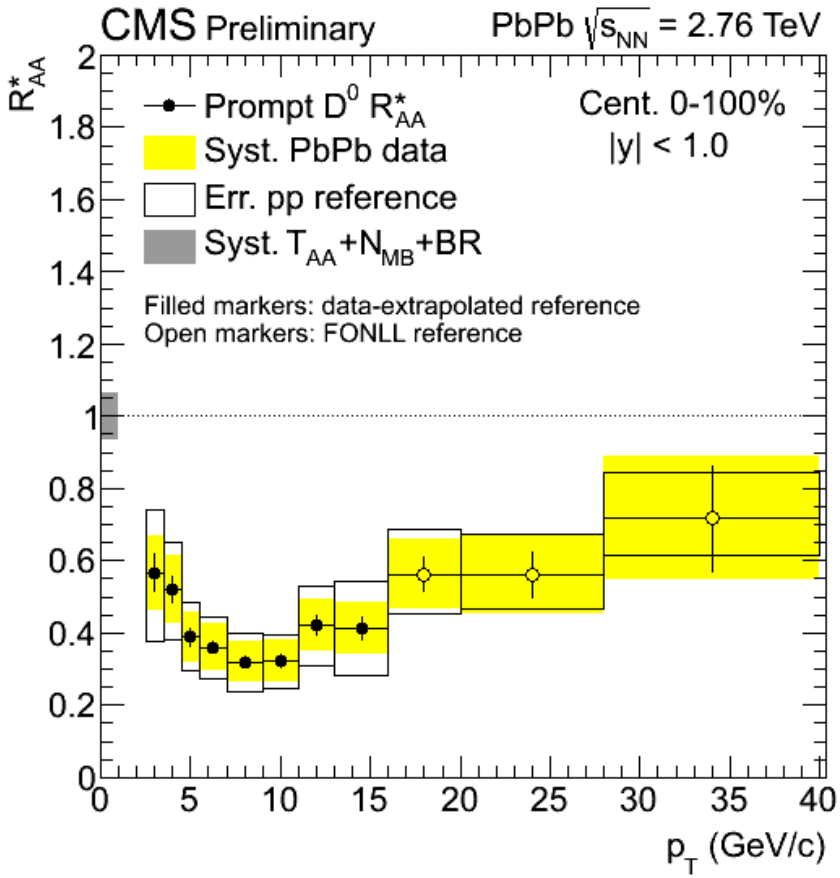
CMS PAS HIN-12-014 | Phys. Rev. Lett. 113, 132301 (2014) | [1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

Prompt D^0 spectrum and R^*_{AA} in centrality 0-100%

→pp reference:
- ➢p_T < 16 GeV, data-extrapolated, scaled from ALICE measurement [1] with FONLL [2]
- ➢p_T > 16 GeV, FONLL calculation

●**Prompt D^0 production is strongly suppressed in PbPb collisions**

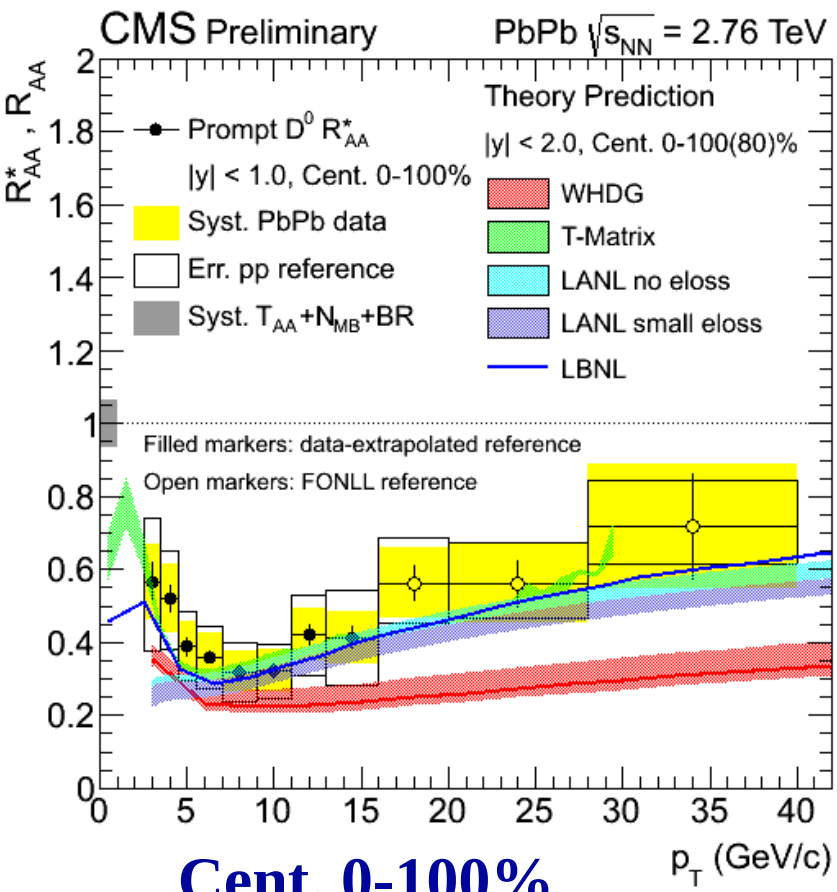




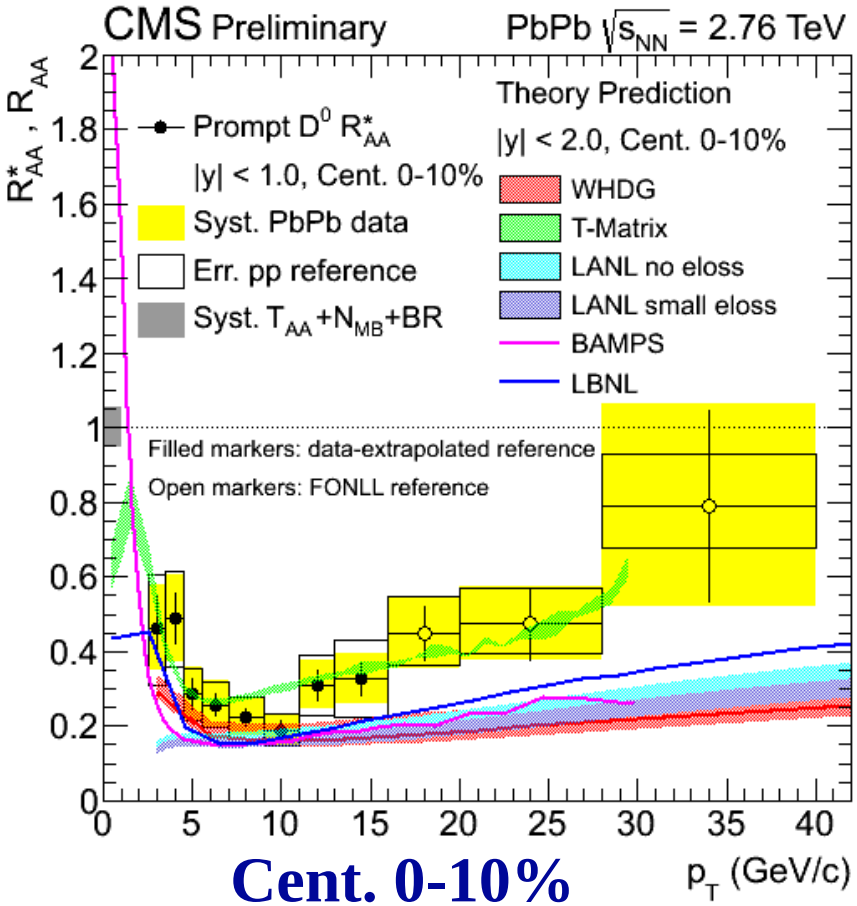
CMS PAS HIN-15-005

[1] B. I. Abelev et al. [Alice Collaboration], JHEP 01 (2012) 128
[2] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

Comparison with models



Cent. 0-100%



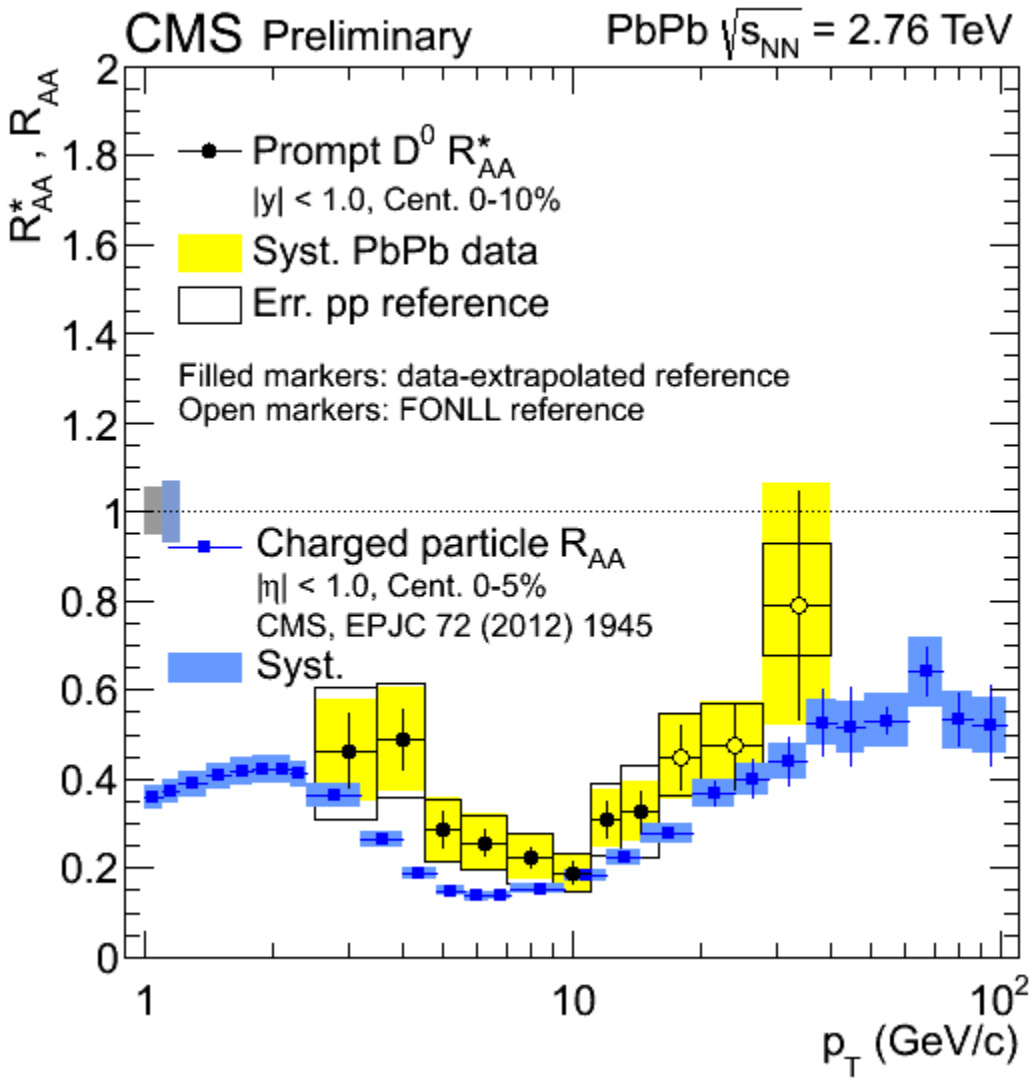
Cent. 0-10%

- **For p_T > 16 GeV, the FONLL reference should be taken into account**

WHDG: Horowitz et al., arXiv:1104.4958
T-Matrix: He, Rapp, private communication
LBNL: Cao et al., PRC 92 (2015) 2, 024907, PRC88 (2013) 4, 044907

BAMPS: Uphoff et al., arXiv:1408.2964
LANL: Vitev et al., arXiv:1507.05987, PRC 80 (2009) 054902, PRC 87 (2013) 4, 044905, PRL 114 (2015) 9, 092002

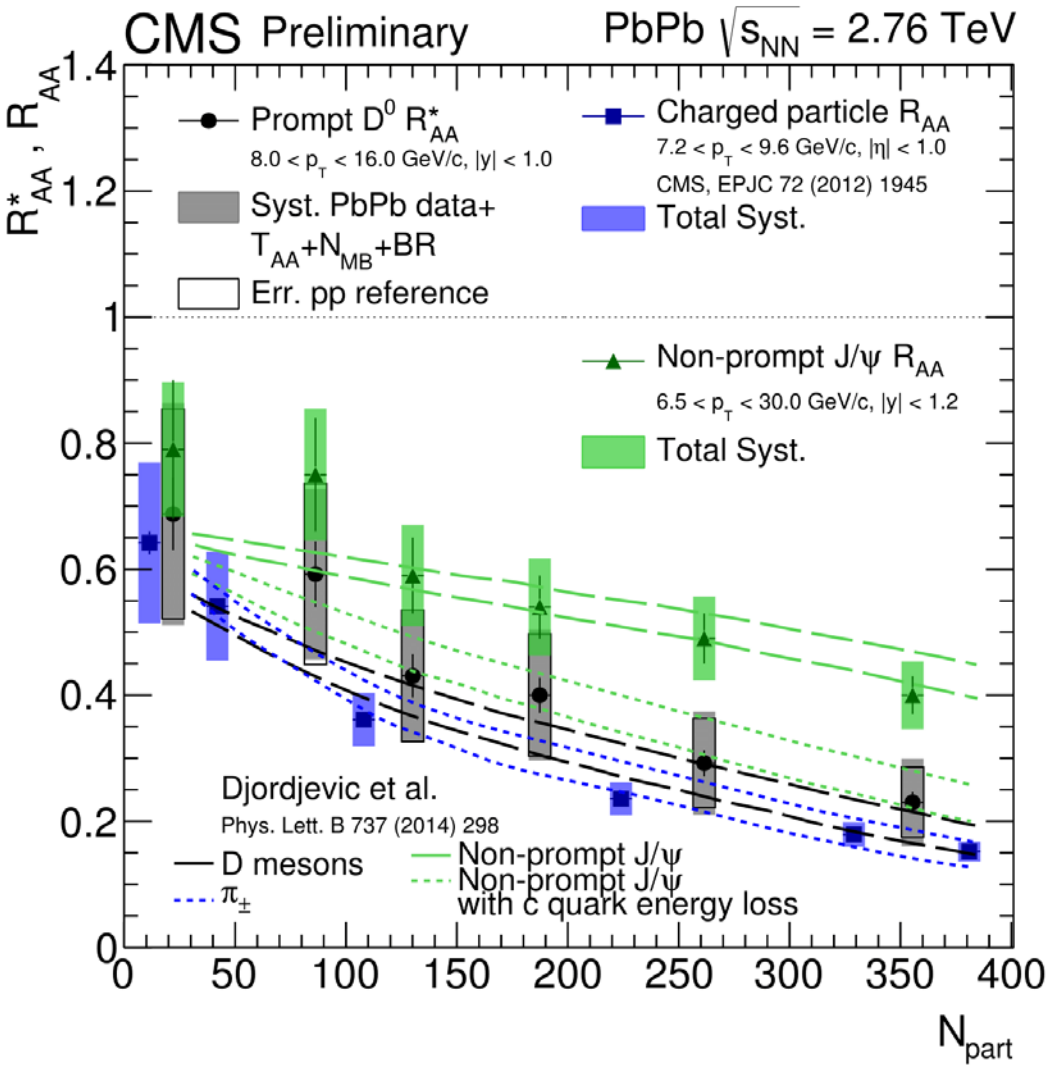
Comparison with charged particle and non-prompt J/ψ R_{AA}



EPJC 72 (2012) 1945

CMS PAS HIN-15-005

Comparison with charged particle and non-prompt J/ψ R_{AA}



Prompt D^0 R^*_{AA}
Charged particle R_{AA}
Non-prompt J/ψ R_{AA}

- **Hint of R_{AA} (non-prompt J/ψ) > R_{AA} (prompt D^0) > R_{AA} ($h^\pm$)**
- **The data measurements agree with calculations by Djordjevic et al. within uncertainties**

See poster by Yen-Jie Lee

EPJC 72 (2012) 1945 | Djordjevic et al. Phys. Lett. B 737 (2014) 298 | CMS PAS HIN-15-005 | CMS PAS HIN-12-014

Summary

- **First D meson measurement in heavy ion collisions from CMS**
  - Prompt D^0 production is strongly suppressed in PbPb collisions and the suppression is clearly centrality dependent
  - Hint of R_{AA} (non-prompt J/ψ) > R_{AA} (prompt D^0) > R_{AA} ($h^{\pm}$)

See poster by Yen-Jie Lee

- **First c-jet measurement in heavy ion collisions**
  - c jet spectrum and fraction consistent with PYTHIA in pPb

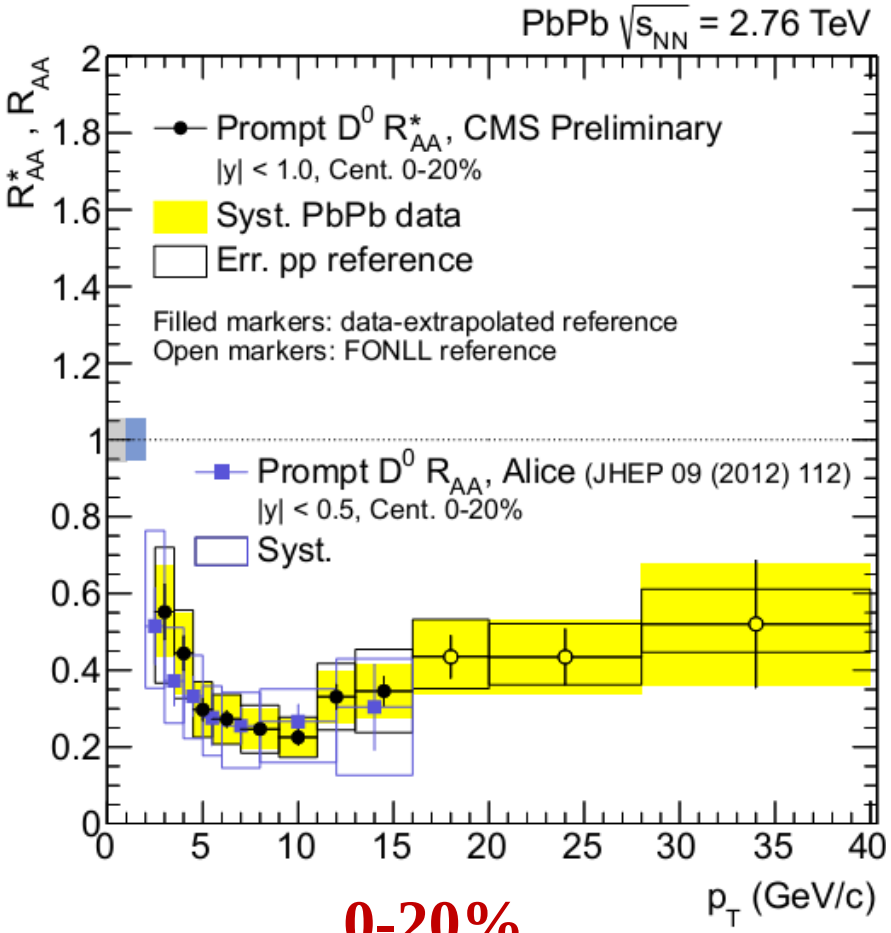
See poster by Kurt Jung

- Non-prompt J/ψ and b-jet are strongly suppressed in PbPb and the suppression is clearly centrality dependent

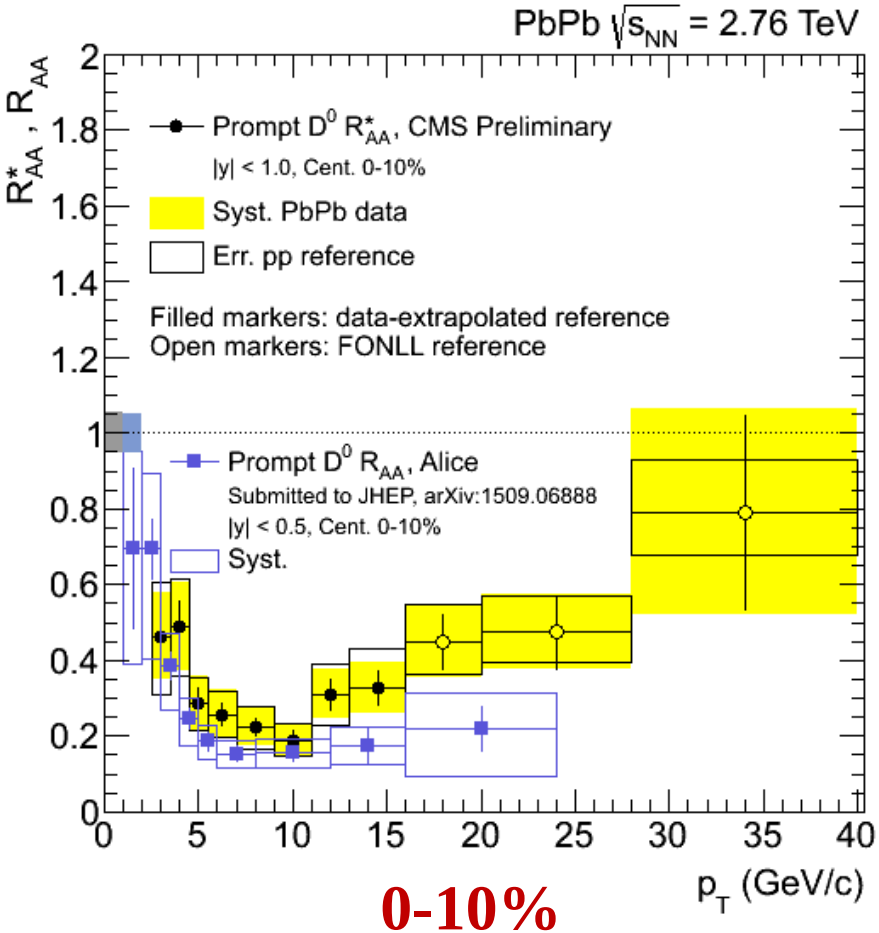
- No significant modification due to cold nuclear matter effects are observed within uncertainties through B meson, c-jet and b-jet studies in pPb

Backup

Comparison with Alice results



0-20%

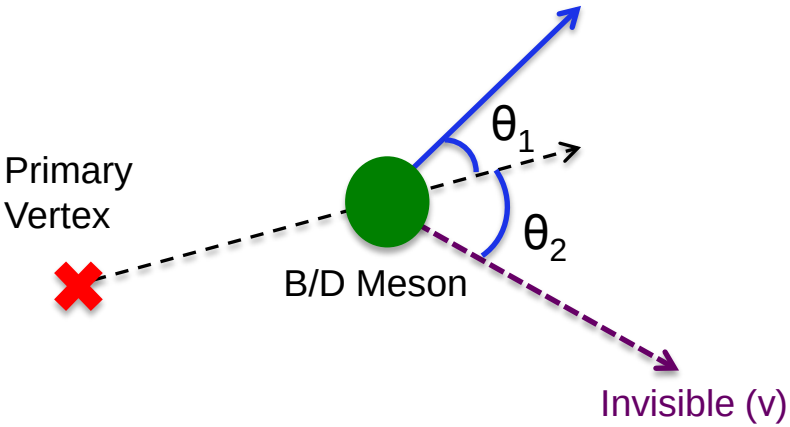


0-10%

- **For p_T > 16 GeV, differences in pp reference should be taken into account**

Corrected Secondary Vertex Mass

LHCb Collaboration
arXiv: 1504.07670



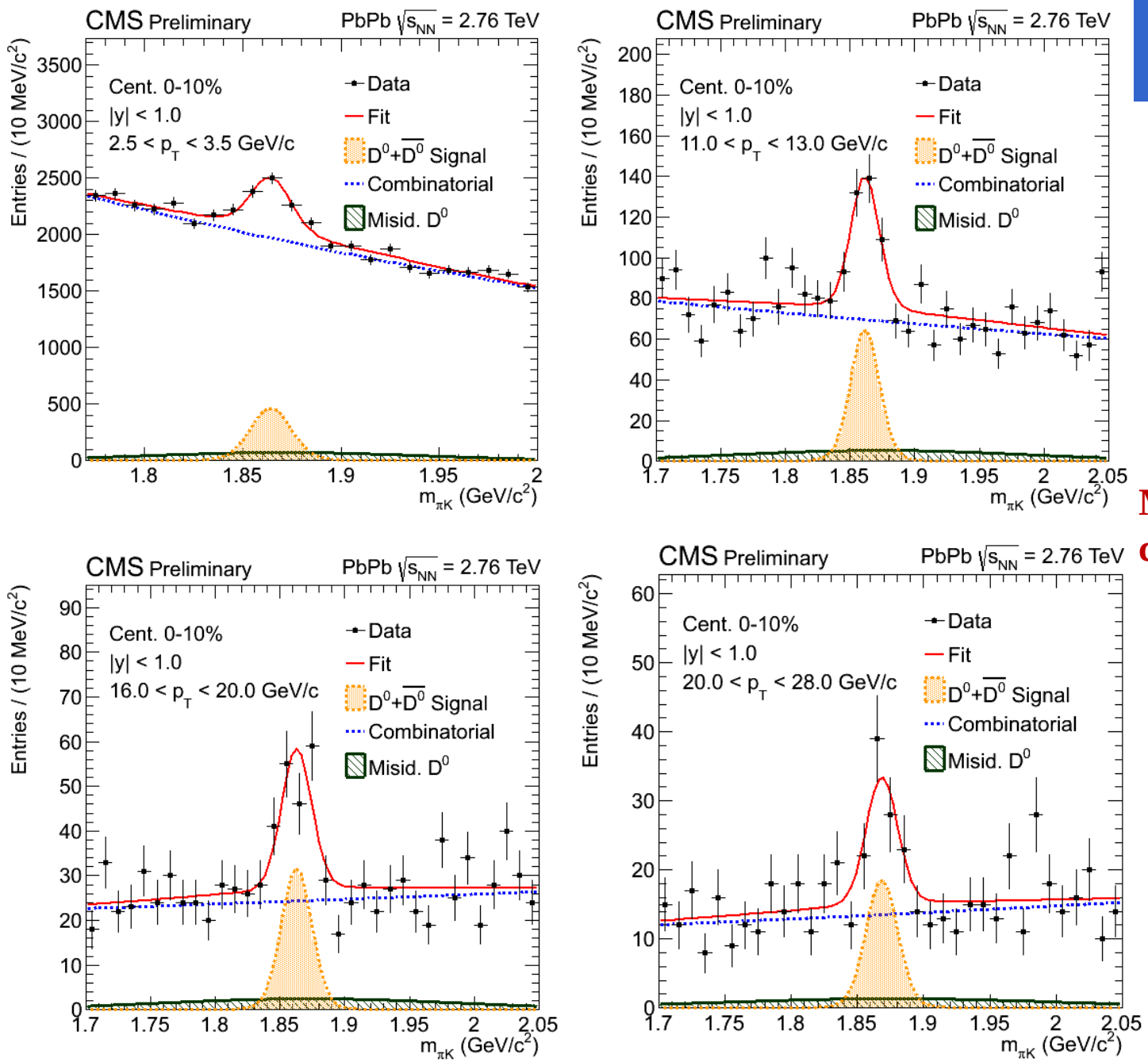
$$p_{1,CM} = p_{\upsilon,CM}$$

$$p_{1,lab}\sin\theta_1 = p_{\upsilon,lab}\sin\theta_2$$

$$M_{corr} = \sqrt{M_1^2 + p_1^2} + \sqrt{\cancelto{0}{M_\upsilon^2} + p_\upsilon^2}$$

$$\boxed{M_{corr}(\min) = \sqrt{M_1^2 + p_1^2\sin^2\theta_1} + p_1\sin\theta_1}$$

- M_{corr} = "Minimum mass of meson decay that's consistent with direction of flight
- Attempts to restore p_{perp} balance w.r.t. flight direction from missing energy (e.g. ν, π^0, etc.)
- B hadrons have higher p_{perp} components (on average) than do C hadrons
  - -> B's have statistically larger values of M_{corr}

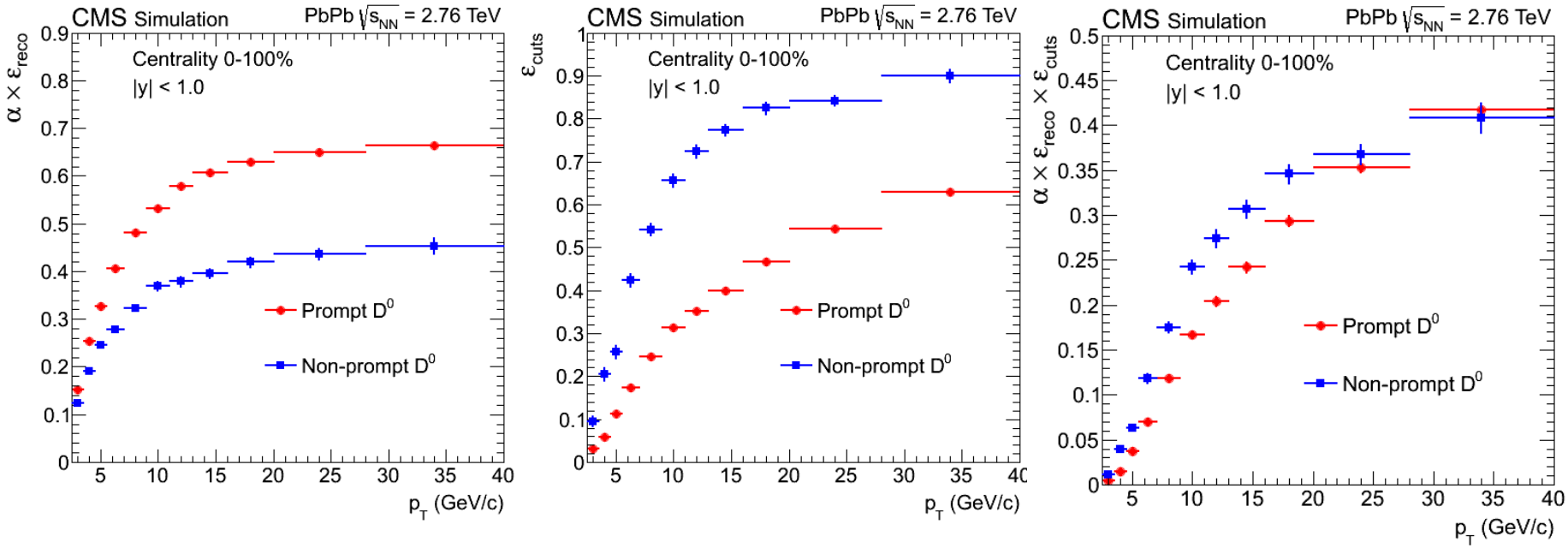


Mass spectrum fit for centrality 0-10%

p_T(GeV/c)	$d_0/\sigma(d_0)$	α (radians)	Vertex Probability
2.5-3.5	> 5.90	< 0.12	> 0.248
3.5-4.5	> 5.81	< 0.12	> 0.200
4.5-5.5	> 5.10	< 0.12	> 0.191
5.5-7.0	> 4.62	< 0.12	> 0.148
7.0-9.0	> 4.46	< 0.12	> 0.102
9.0-11.0	> 4.39	< 0.12	> 0.080
11.0-13.0	> 4.07	< 0.12	> 0.073
13.0-16.0	> 3.88	< 0.12	> 0.060
16.0-20.0	> 3.67	< 0.12	> 0.055
20.0-28.0	> 3.25	< 0.12	> 0.054
28.0-40.0	> 2.55	< 0.12	> 0.050

Table 1: Summary table of the selection criteria in different p_T intervals.

Acceptance and efficiency correction



- **$\alpha \times \varepsilon_{reco}$: prompt D0 higher than non-prompt D0 (D0 from B-hadron decay)**
  - ➢Tracks from non-prompt D^0 are more displaced from primary vertex than tracks from prompt D^0
  - ➢Hi tracking has lower efficiency on further displaced tracks

- **ε_{cuts}: non-prompt D0 higher than prompt D0**
  - ➢Non-prompt D^0 are more displaced from primary vertex than prompt D^0, thus bigger d0/error_d0

CMS PAS HIN-15-012

B feed-down correction

$$\frac{dN_{PbPb}}{dp_T} = \frac{f_{prompt} \cdot \frac{1}{2} N_{D^0}^{raw}}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}$$

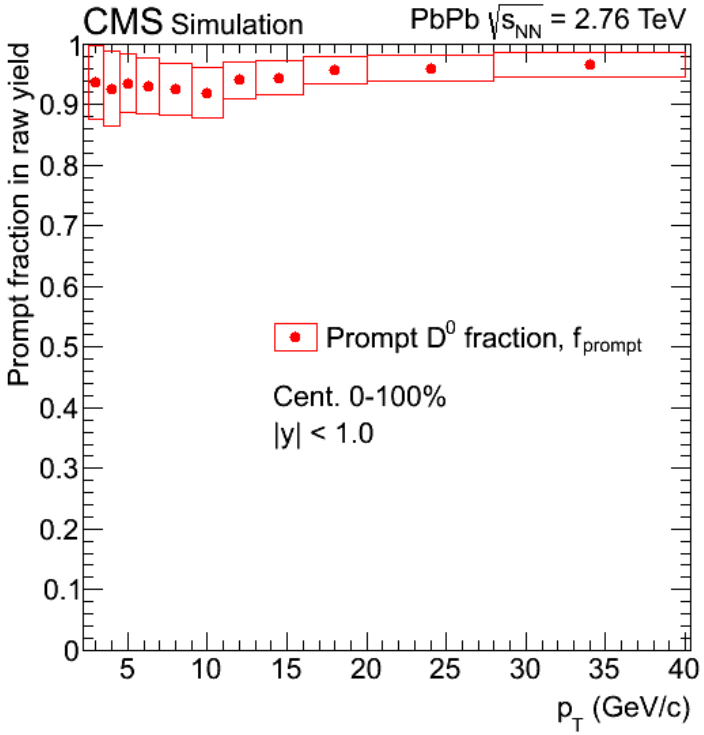
- To get prompt D0 spectrum, non-prompt D0 should be subtracted
  - ➢Rely on FONLL prediction and simulation to calculate expected raw number of non-prompt D0

$$f_{prompt} = 1 - \frac{N^{raw}_{Non-prompt\ D^0}}{\frac{1}{2} N^{raw}_{D^0}}$$

$$N^{raw}_{Non-prompt\ D^0} = T_{AA} \cdot \left(\frac{d\sigma}{dp_T}\right)^{FONLL}_{Non-prompt\ D^0} \cdot R^{Non-prompt\ D^0}_{AA} \cdot (\alpha \times \varepsilon)_{Non-prompt\ D^0} \cdot \Delta p_T \cdot Br \cdot N_{evt}$$

➢FONLL B meson spectrum
➢Pythia+EvtGen B→D⁰ decay kinematics

●Converted from non-prompt J/ψ R_{AA} and hypothesis
●Pythia+EvtGen B→J/ψ and B→D⁰ decay kinematics

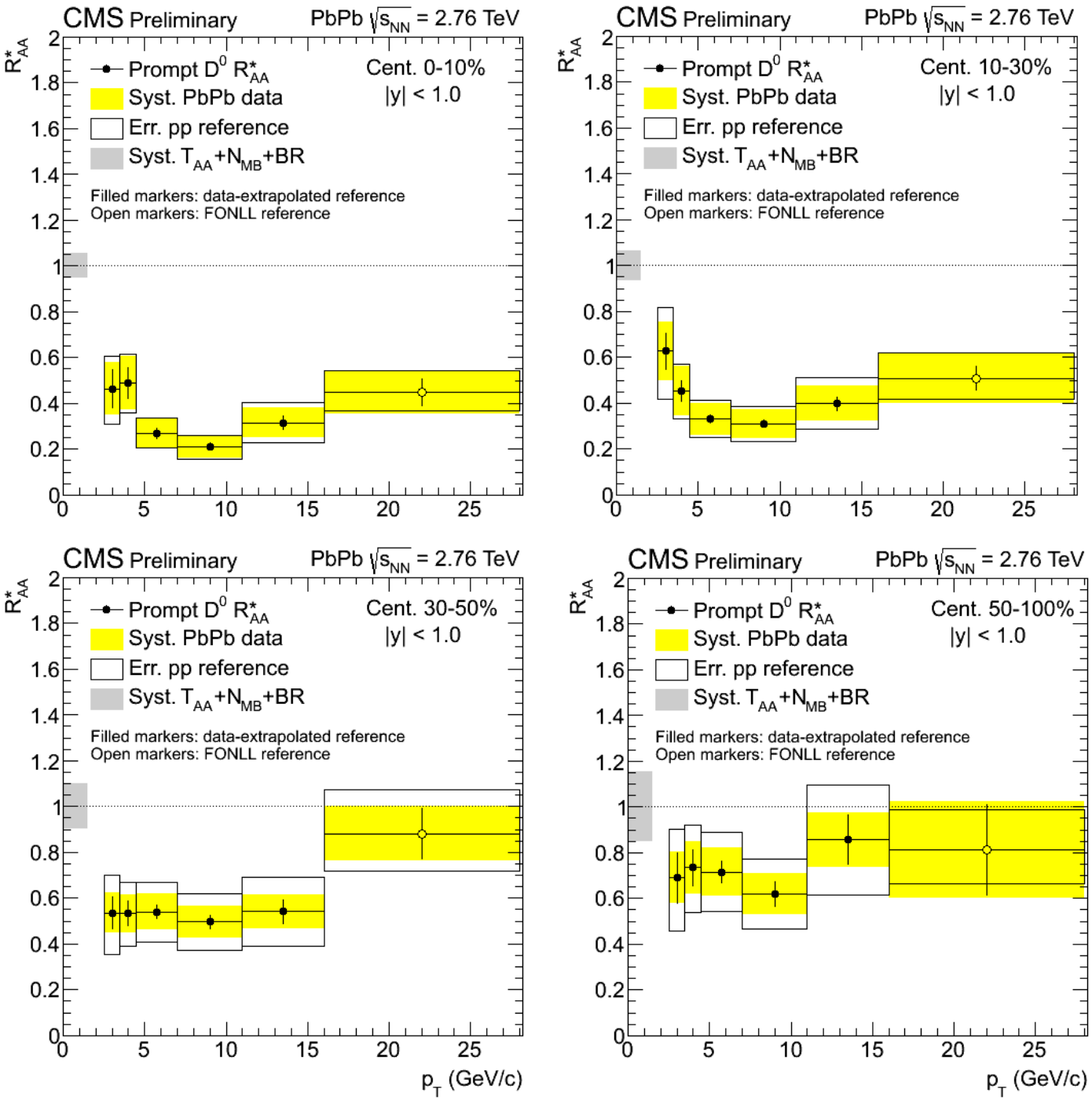


CMS PAS HIN-15-012

Non-prompt Jpsi RAA to Non-prompt D0 RAA

- Non-prompt J/psi R_{AA}
  - Intermediate pt (3 to 30 GeV) results from HIN-12-014
  - Low pt range (< 3 GeV) assumed to be 1.0±1.0 (no available measurements)
  - High pt range (> 30 GeV) assumed to be 0.5±0.5 based on b-Jet results

- Conversion from non-prompt J/psi R_{AA} to non-prompt D^0 R_{AA} relies on
  - FONLL B meson spectrum
  - Pythia+EvtGen B→Jpsi and B→D^0 decay kinematics



Strong centrality dependence