Open Heavy Flavor Meson in pp, pPb and PbPb collisions with CMS

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(For the CMS collaboration)

Santa Fe Jets and Heavy Flavor Workshop

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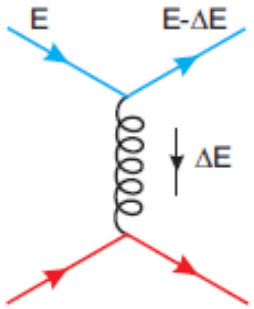
Flavor Dependence of Parton Energy Loss

- From QCD
  - Color charge:

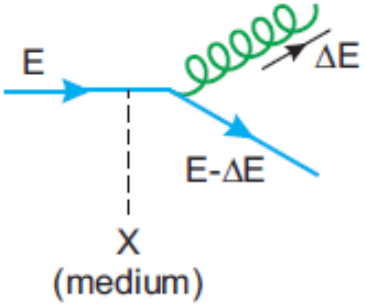
    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":
    E_{loss} in quarks > E_{loss} in heavy quarks

Heavy Quark vs. Light Quark:
Changing the ratio of collisional and radiative energy loss

Collisional energy loss



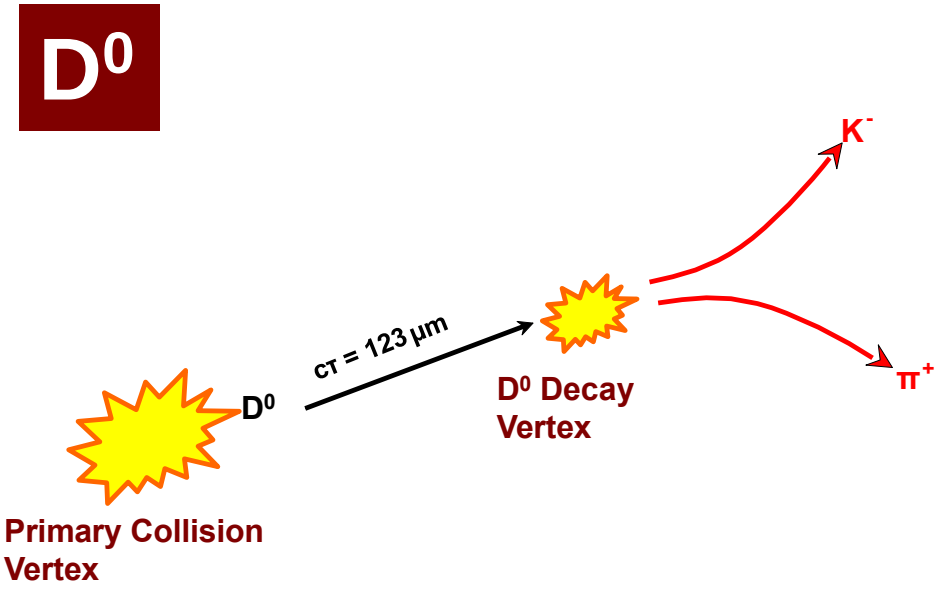
Radiative energy loss

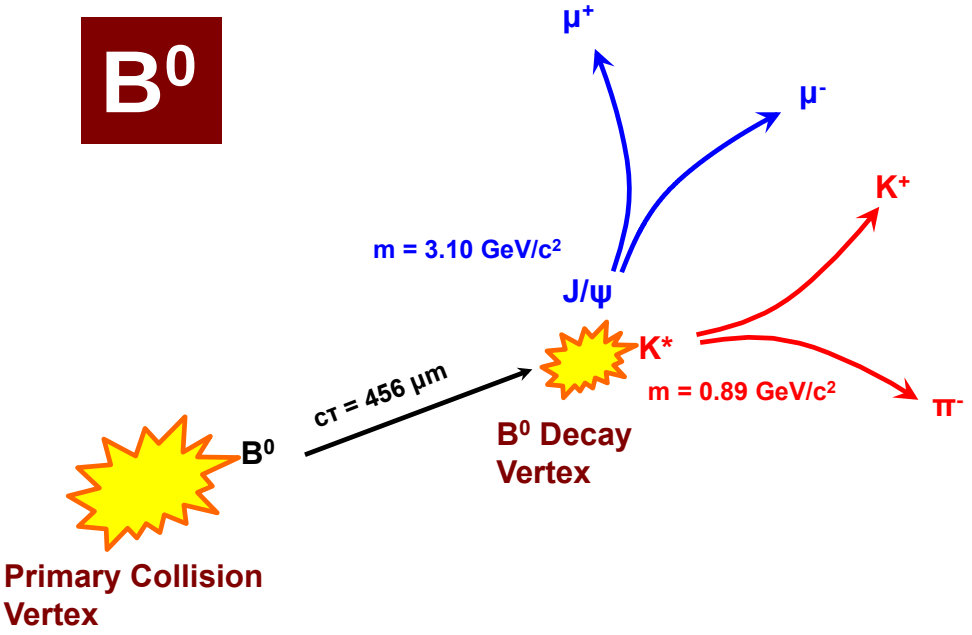


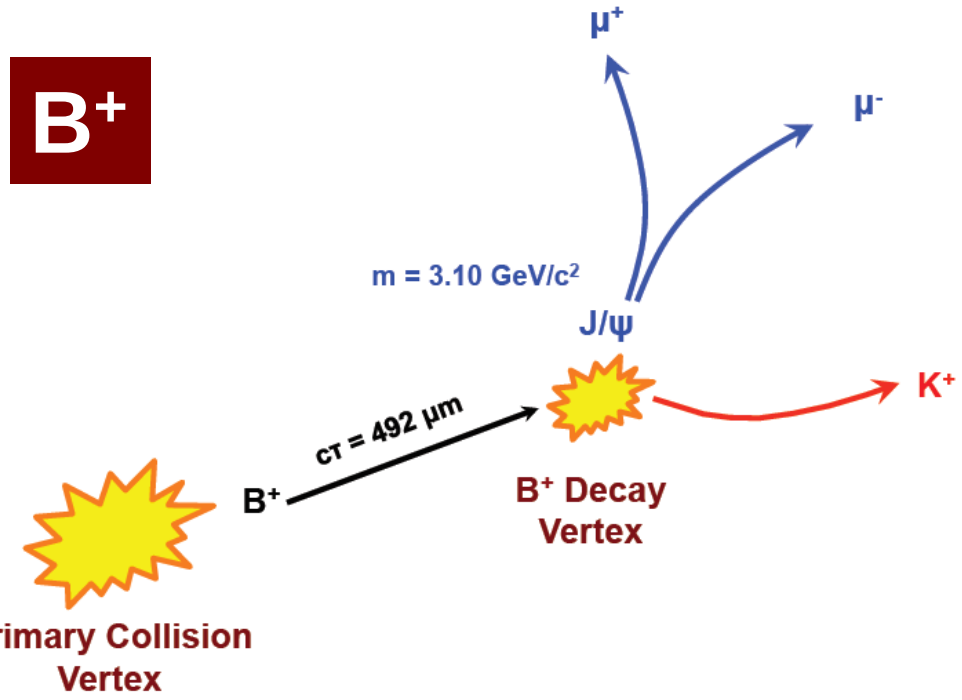
Heavy flavor hadron (and jet) analyses cover a wide kinematics range
→ Suppression of induced radiation at low p_T and the disappearance of this effect at high p_T

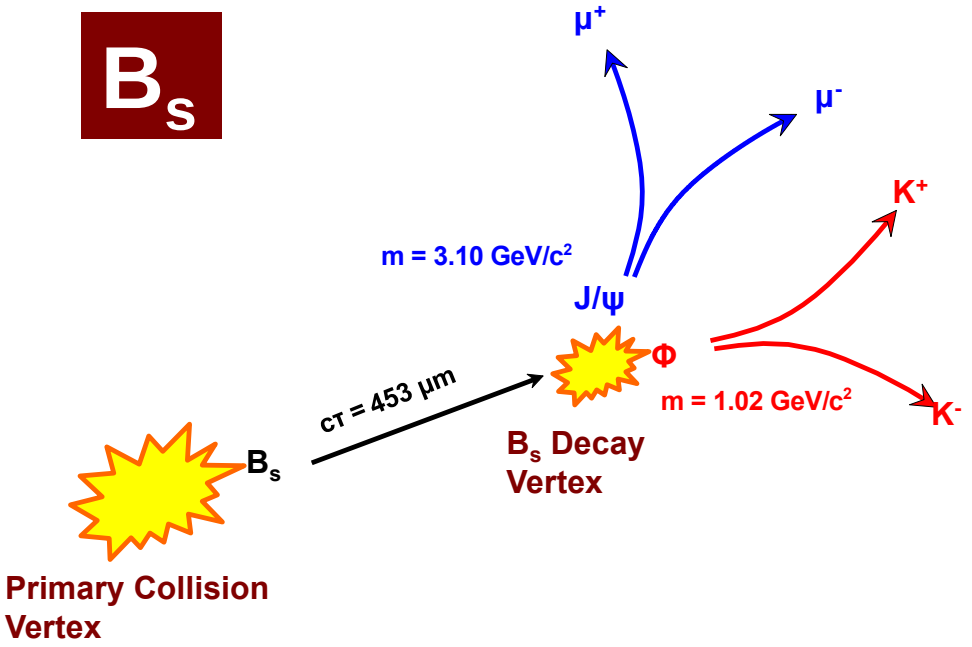
See Raghav and Gunther's talk on (HF) jet observables

D and B Meson Decay Channels



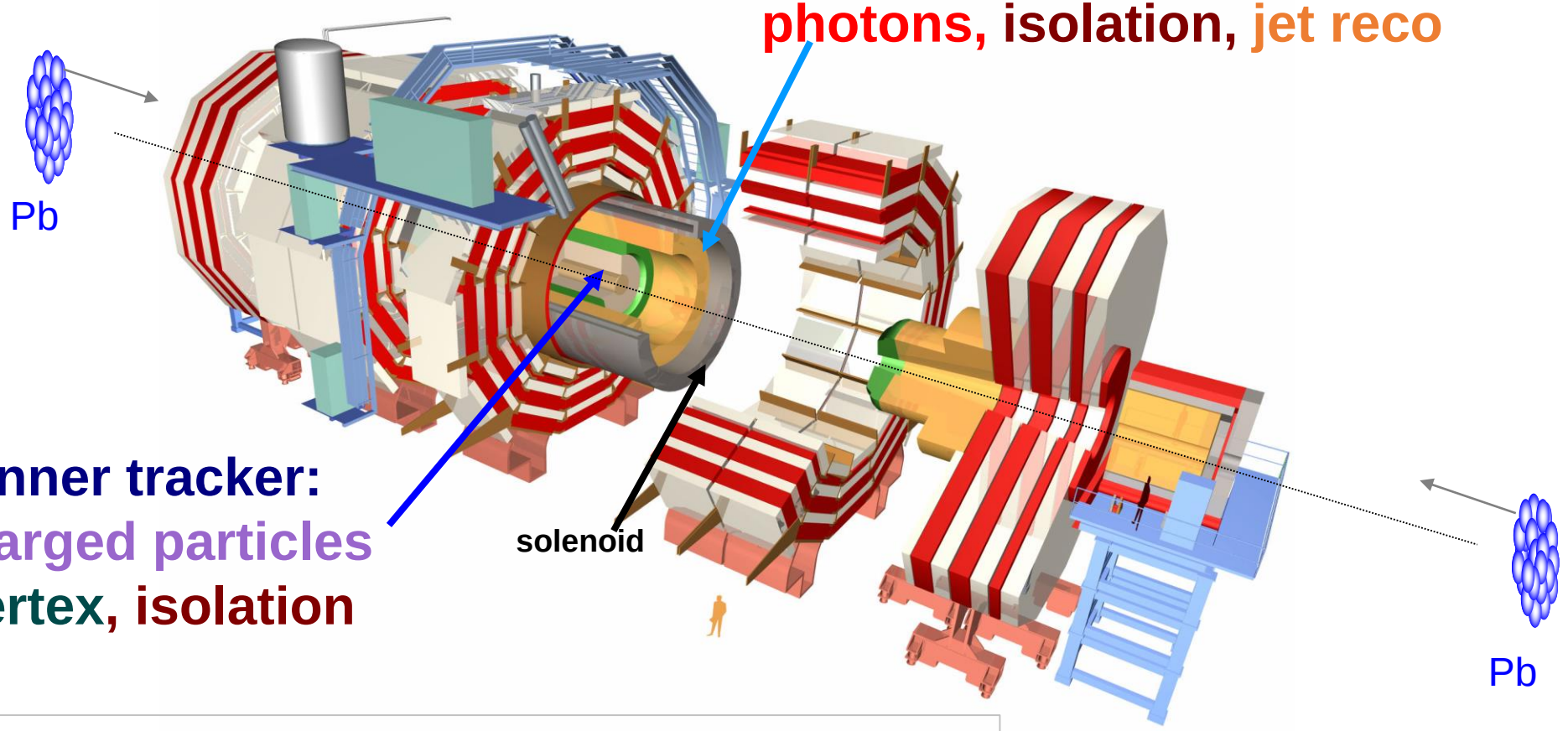




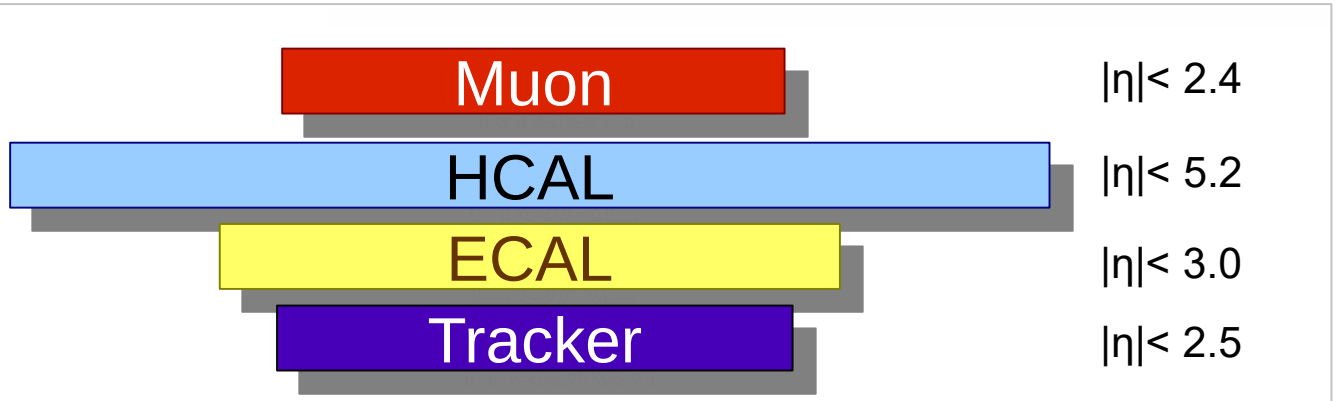


The CMS Detector

EM and Hadron calorimeters
photons, isolation, jet reco

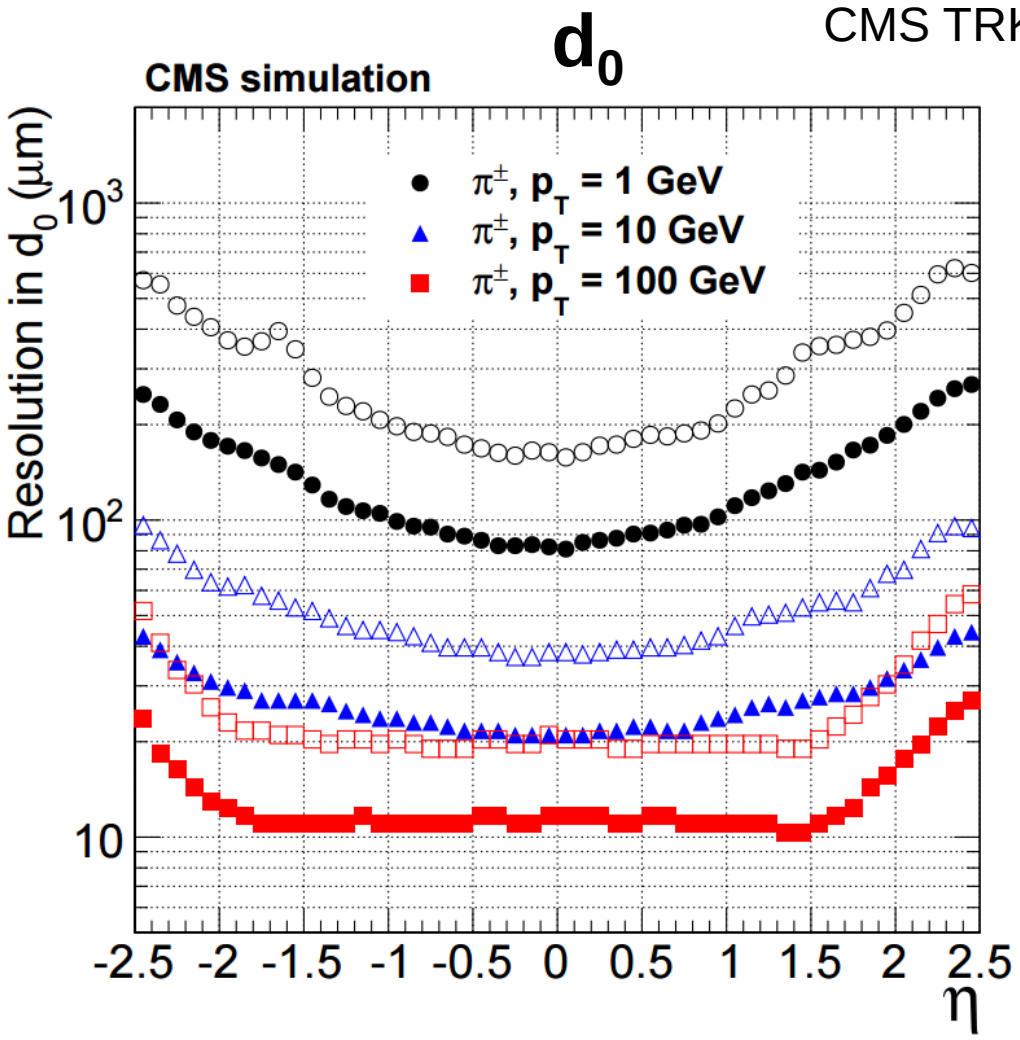


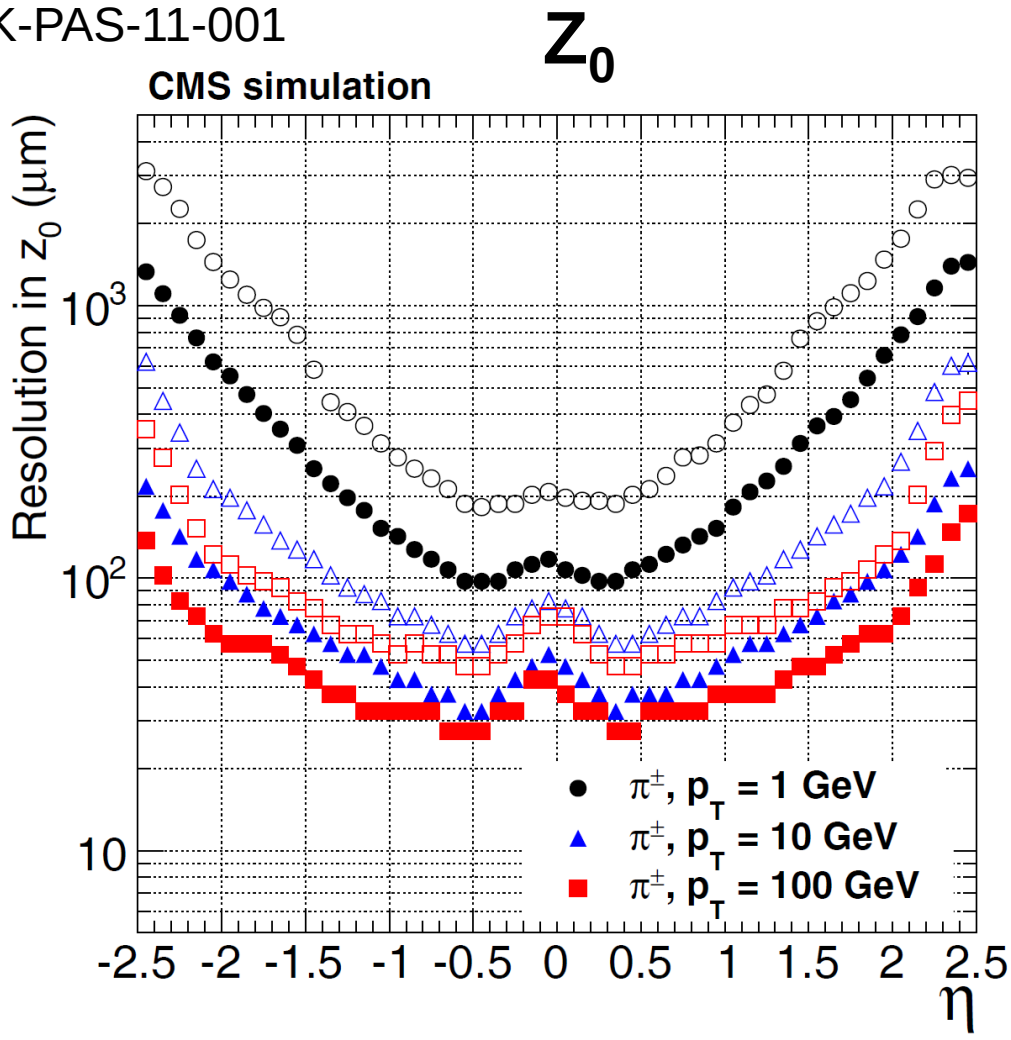
Inner tracker:
charged particles
vertex, isolation



Charged Track Impact Parameter Resolution in pp

CMS TRK-PAS-11-001

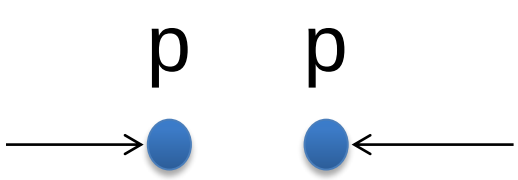


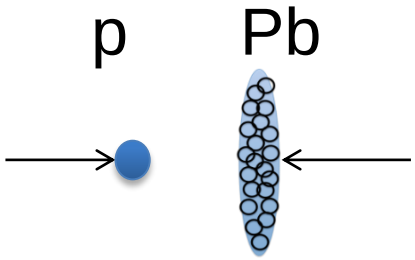


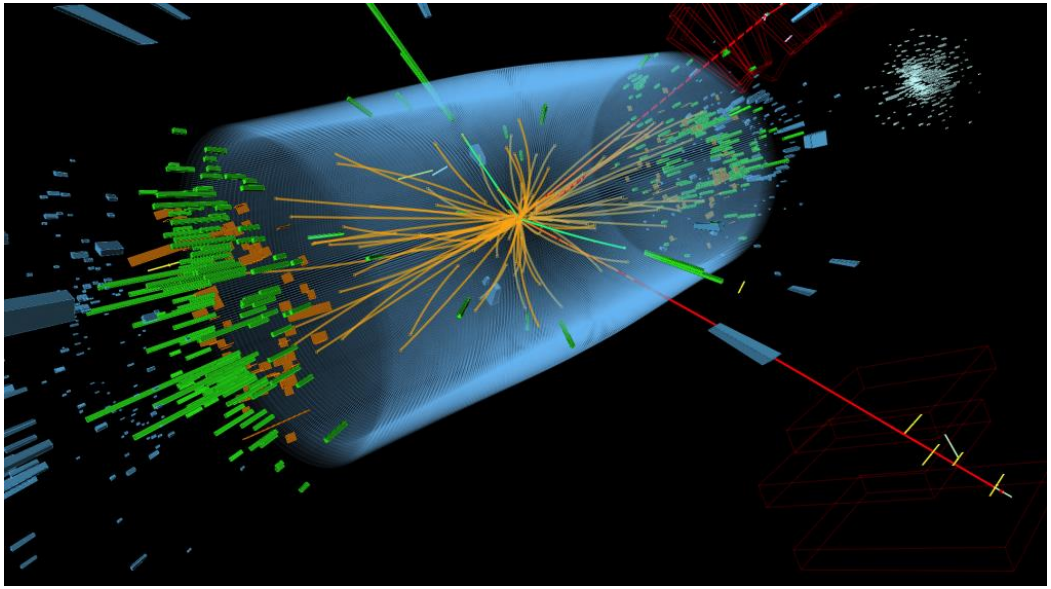
Track impact parameter resolution:

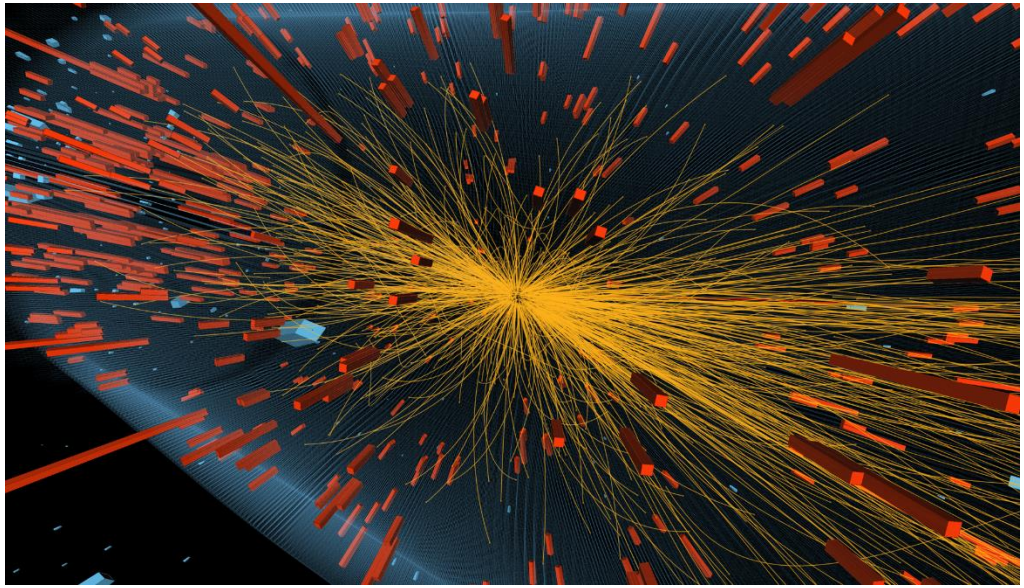
- d_0: ~80 μm @ 1 GeV/c, ~20 μm @ 10 GeV/c
- z_0: ~100 μm @ 1 GeV/c, ~40 μm @ 10 GeV/c

Results from pp and pPb

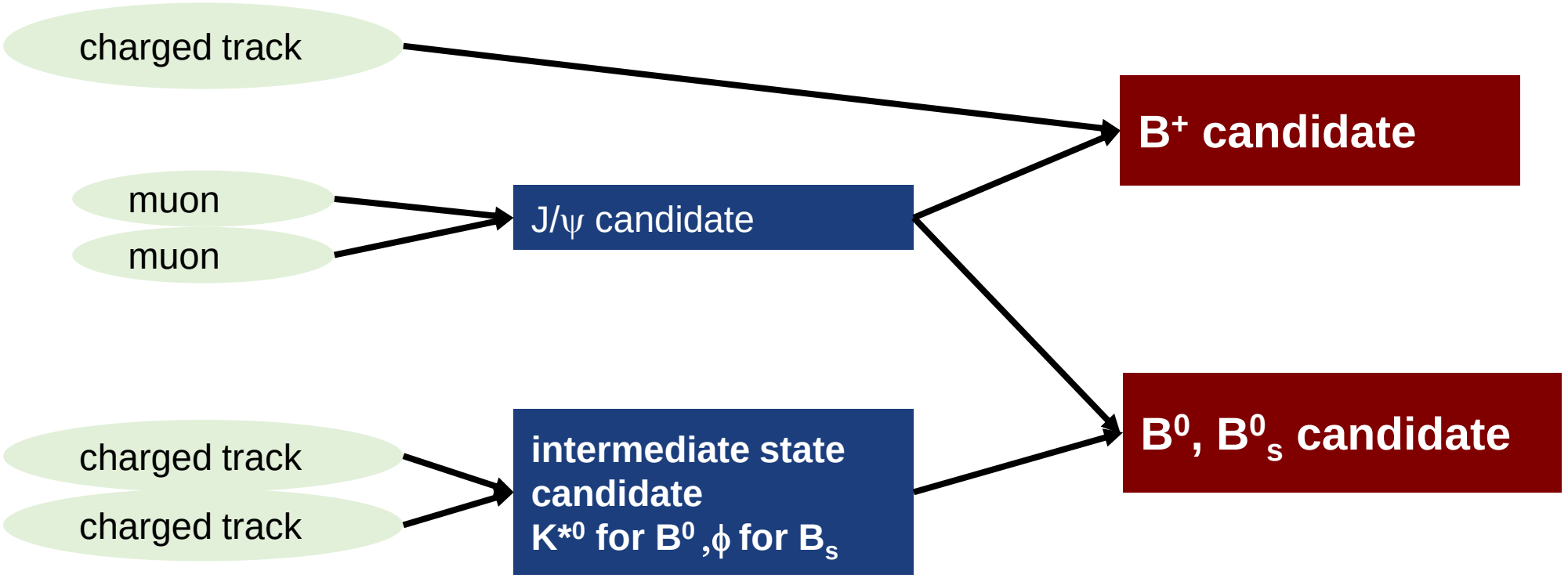








B Meson Reconstruction in CMS

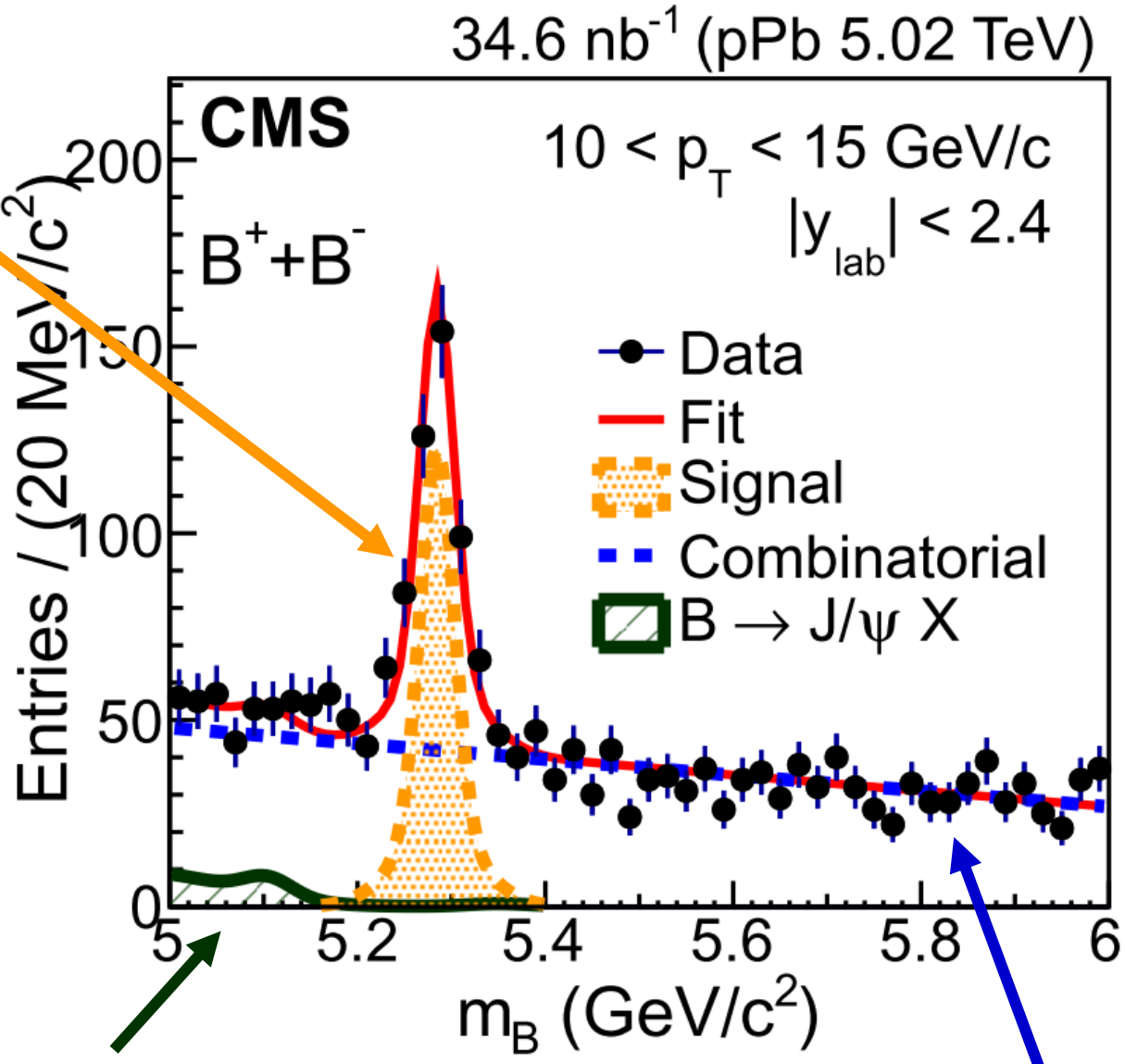


- B^+ : J/ψ + 1 track (kaon, p_T> 0.9 GeV/c)
- B^0 : J/ψ + 2 tracks (kaon + pion, p_T>0.7 GeV/c)
- B_s : J/ψ + 2 tracks (kaon + kaon, p_T>0.4 GeV/c)

- Charged tracks and muons are reconstructed within $|\eta| < 2.4$
- Trigger muon $p_T > 3$ GeV/c
- No PID: Assigned the mass of kaon or pion to charged tracks

B^+ Meson Mass Spectra in pPb

$B^+ \rightarrow J/\psi K^+$ signal



B^+

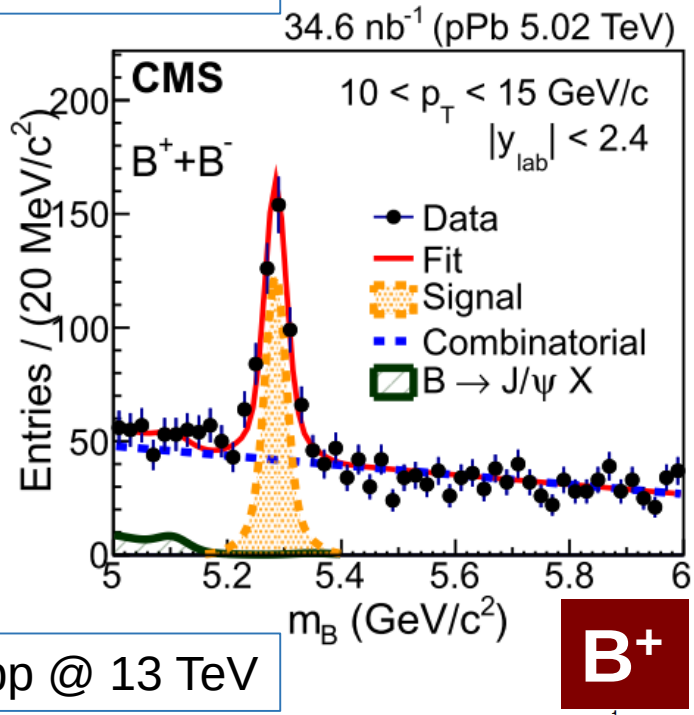
Peaking background from $B \rightarrow J/\psi X$, for instance $B \rightarrow J/\psi K\pi$

Inclusive J/ψ + Track combinatorial background

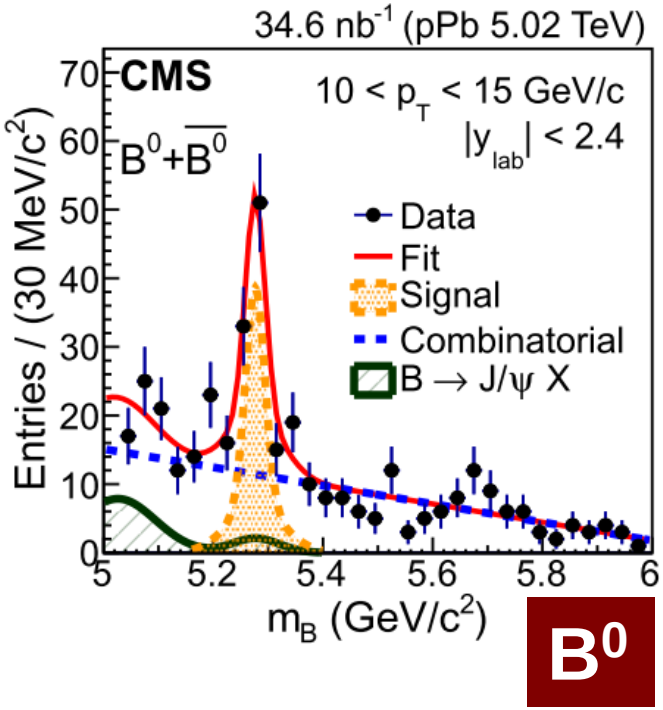
B Meson Mass Spectra in pp and pPb

pPb @ 5 TeV

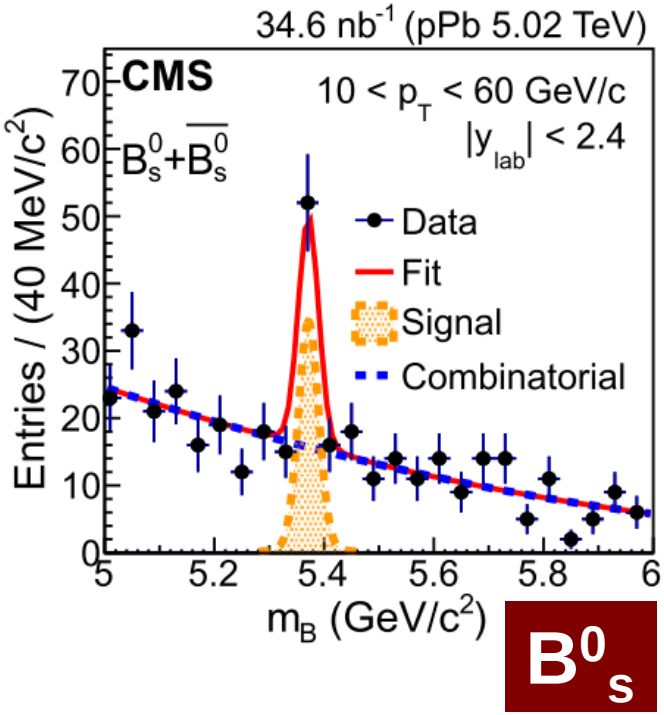
Accepted by PRL arXiv:1508.06678



B^+

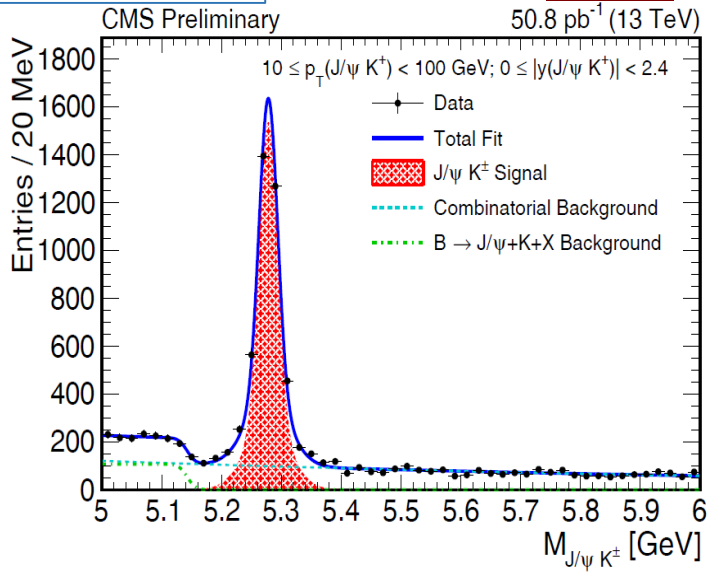


B^0



B^0_s

pp @ 13 TeV



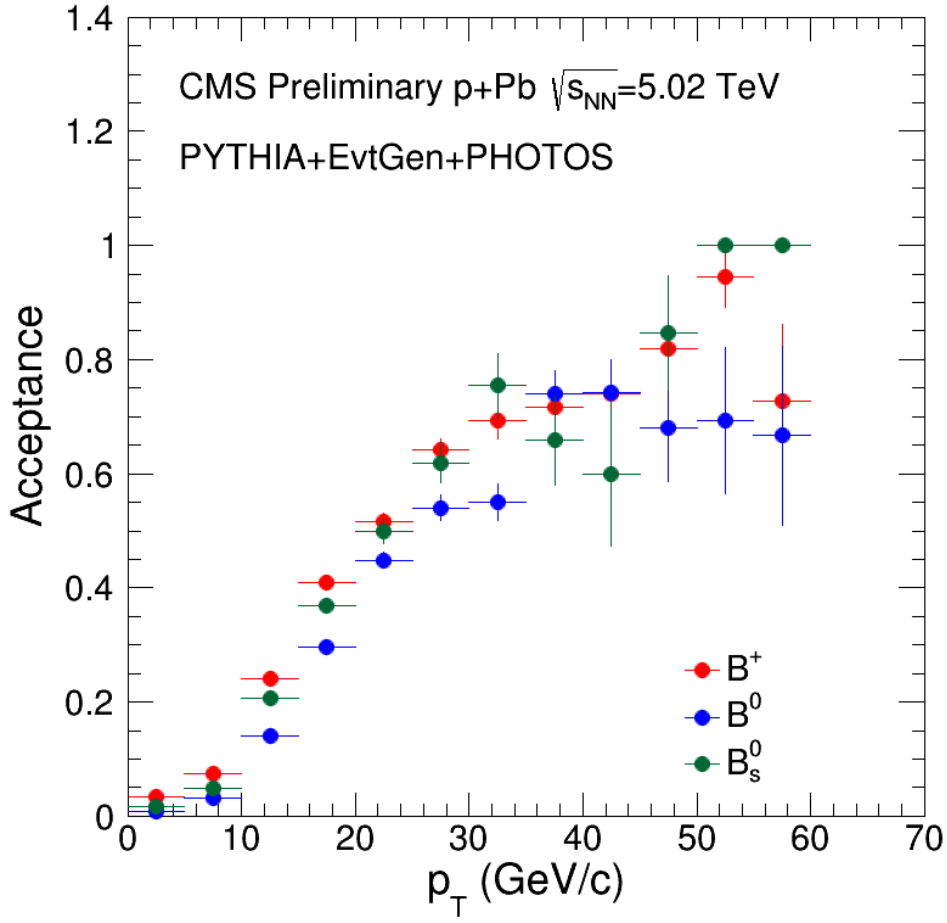
Significant B meson signal was observed in pp and pPb collisions

CMS-PAS-BPH-15-004

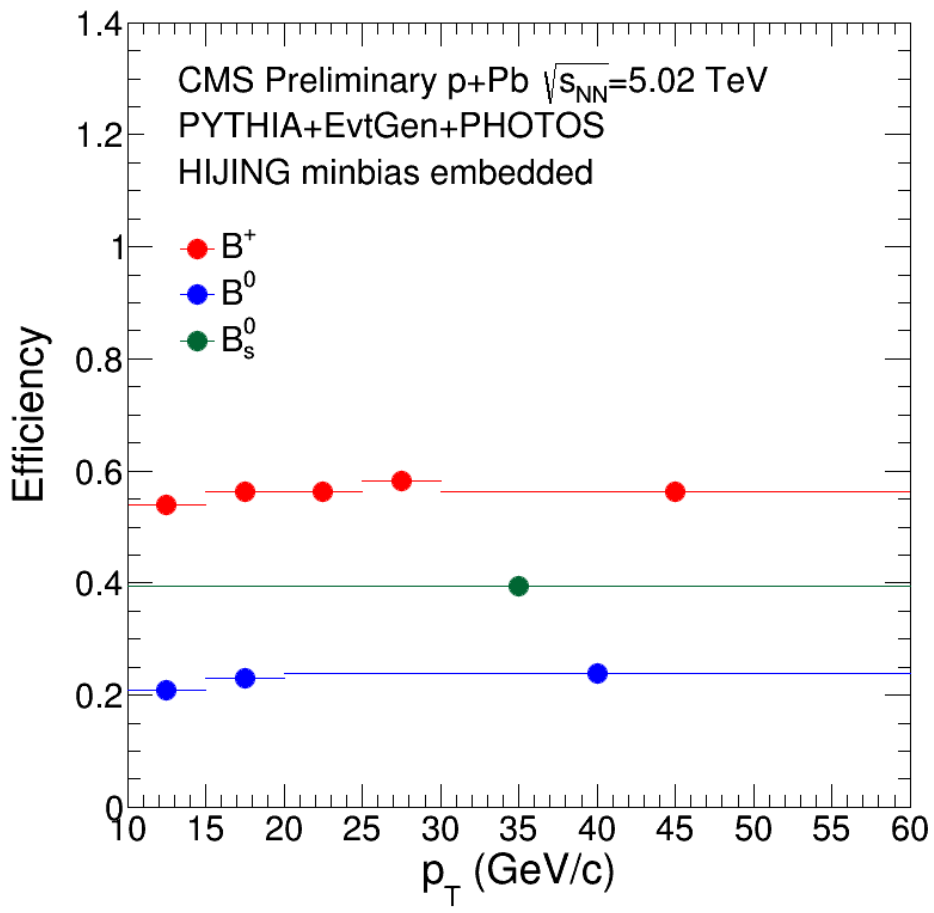
B Meson Acceptance and Efficiency

- Raw yields are corrected by acceptance and efficiency

Acceptance

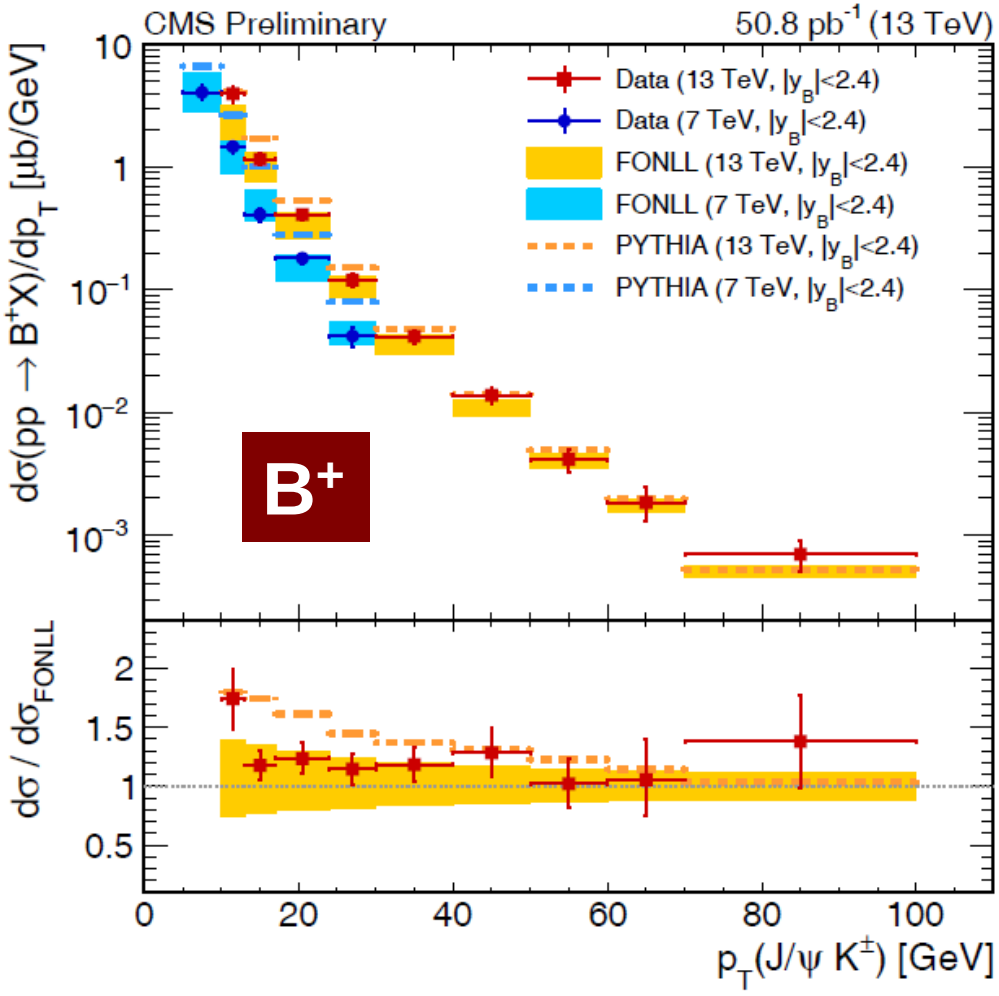


Efficiency

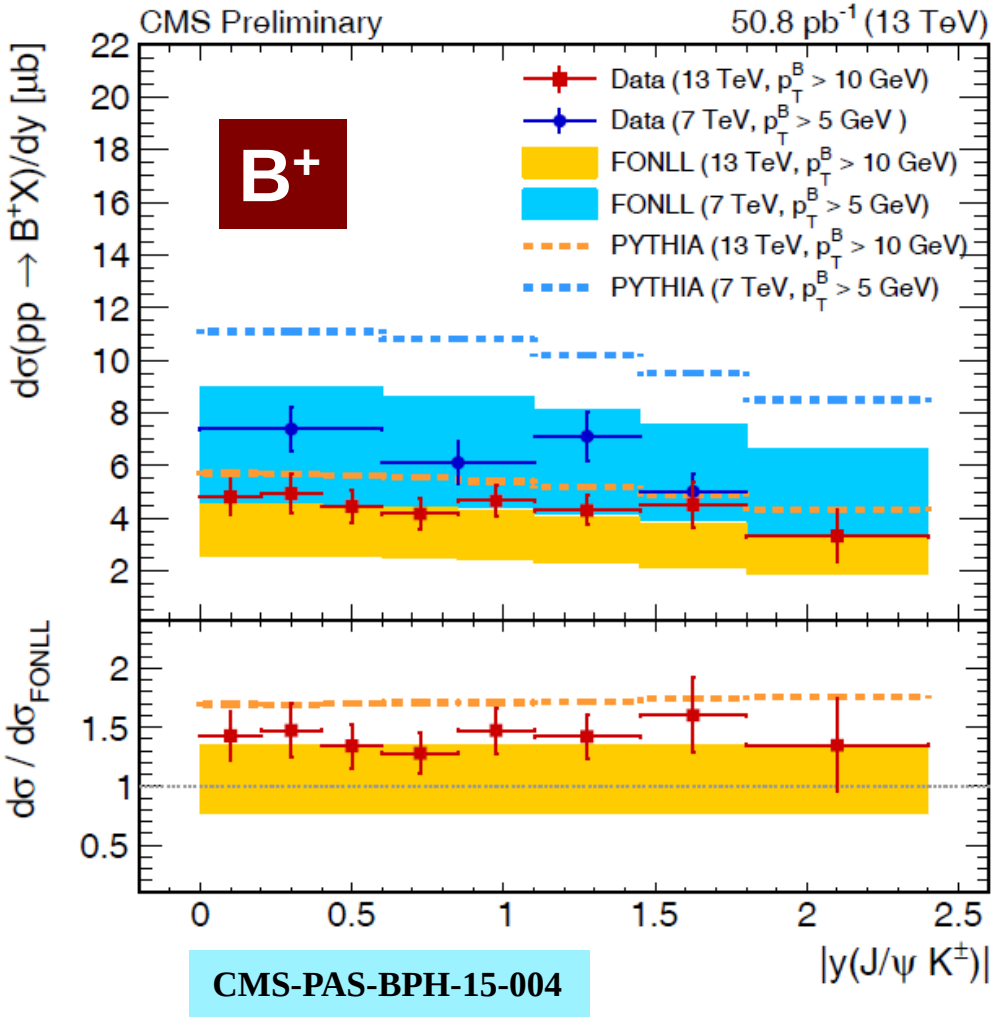


Results from pp @ 7 and 13 TeV

Transverse momentum spectra



Rapidity distribution



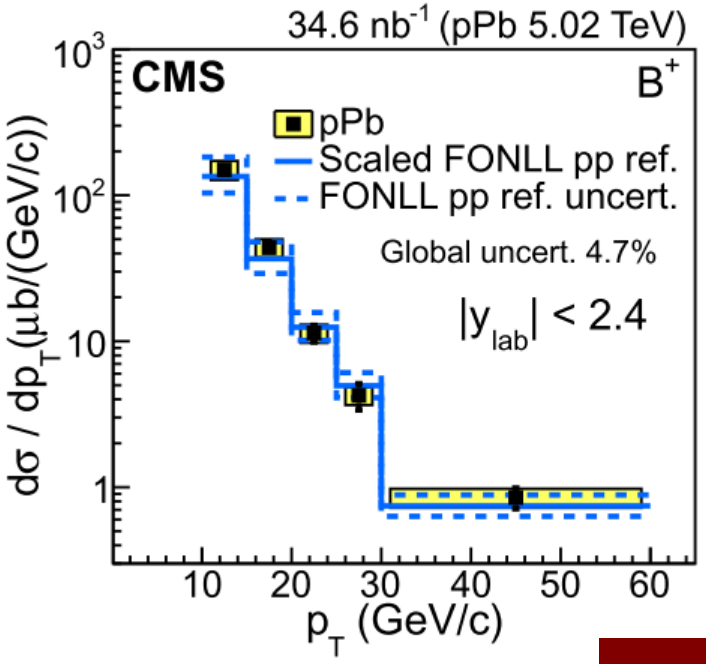
CMS-PAS-BPH-15-004

- pp at **7 TeV** and **13 TeV** are in agreement with FONLL calculation within the quoted uncertainties
- The central values of **7 TeV** data match better with FONLL center value than **13 TeV**

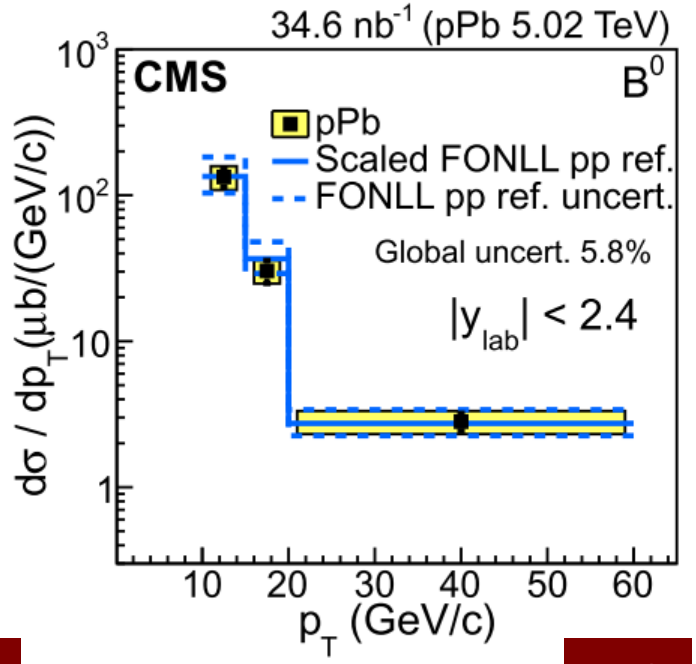
Differential Cross-section in pPb @ 5 TeV

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{B}}}{\mathrm{d}p_T}\right|_{|y_{\mathrm{CM}}|<2.4} = \frac{1}{2}\,\frac{1}{\Delta y\,\Delta p_T}\,\frac{N^{\mathrm{B}}\big|_{|y_{\mathrm{CM}}|<2.4}}{(\mathrm{Acc}\times\epsilon)\cdot\mathrm{BR}\cdot L_{\mathrm{int}}}\,.$$

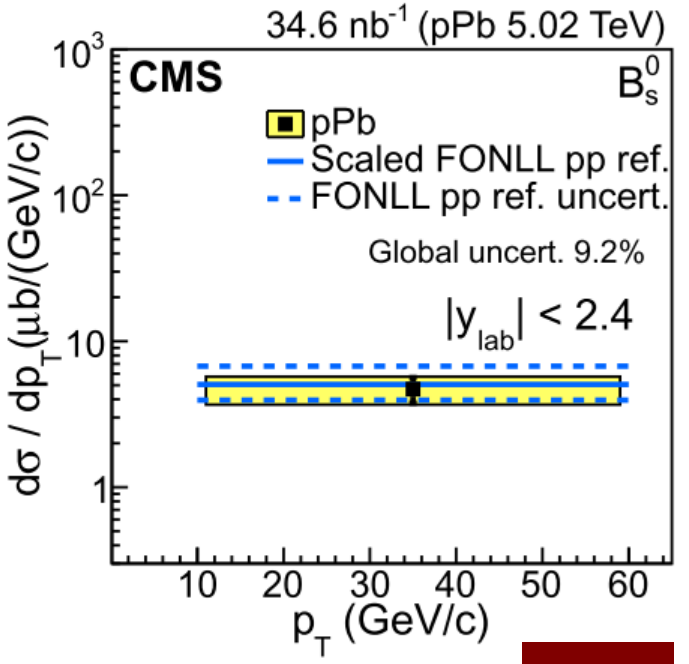
- pp reference : FONLL expectation is used
  - agreement with CDF and CMS(ATLAS) data
  - calculated in **http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html**



B+



B0

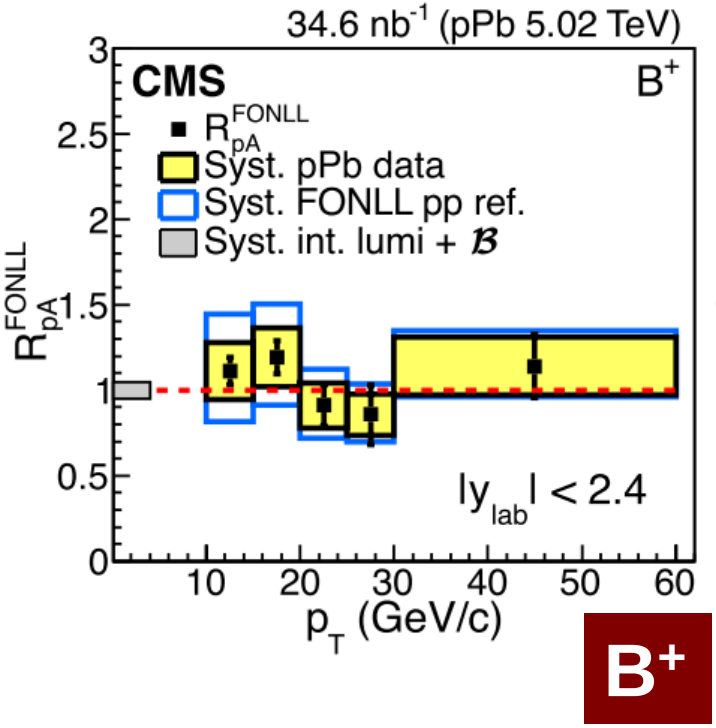


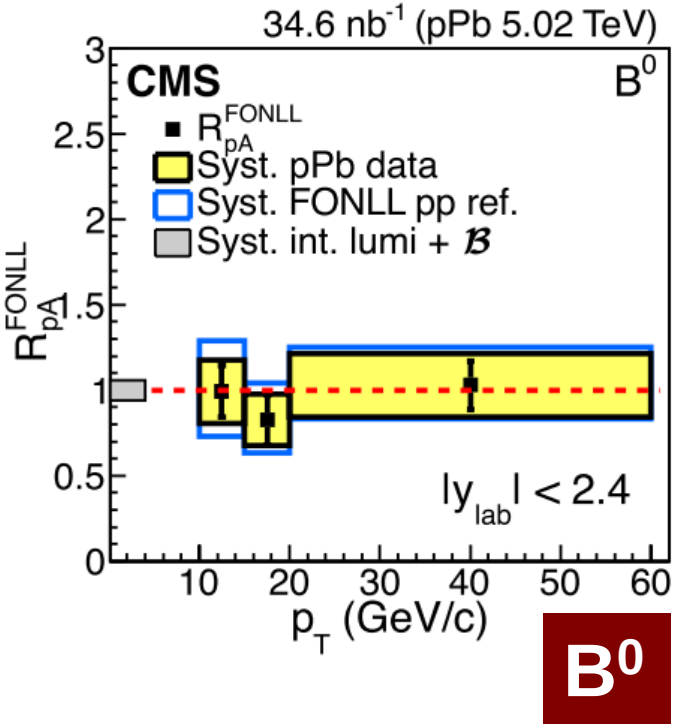
B0s

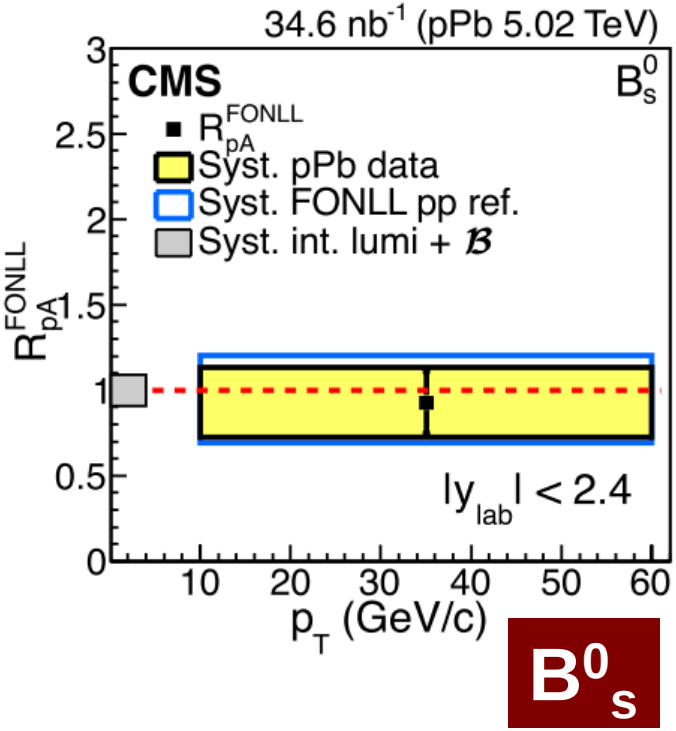
Nuclear Modification Factor : R_{pA}^{FONLL}

$$R_{pA}^{FONLL}(p_T) = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma^{FONLL}}{dp_T}\right)_{pp}}$$

Accepted by PRL arXiv:1508.06678



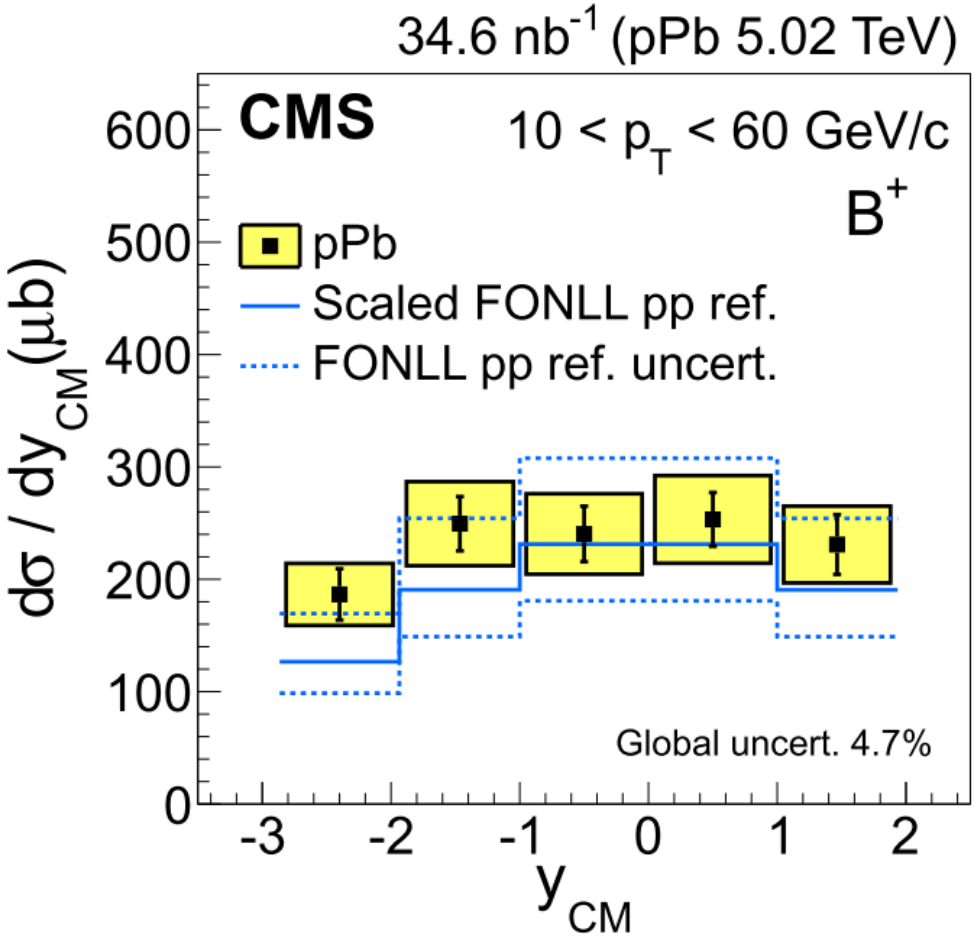


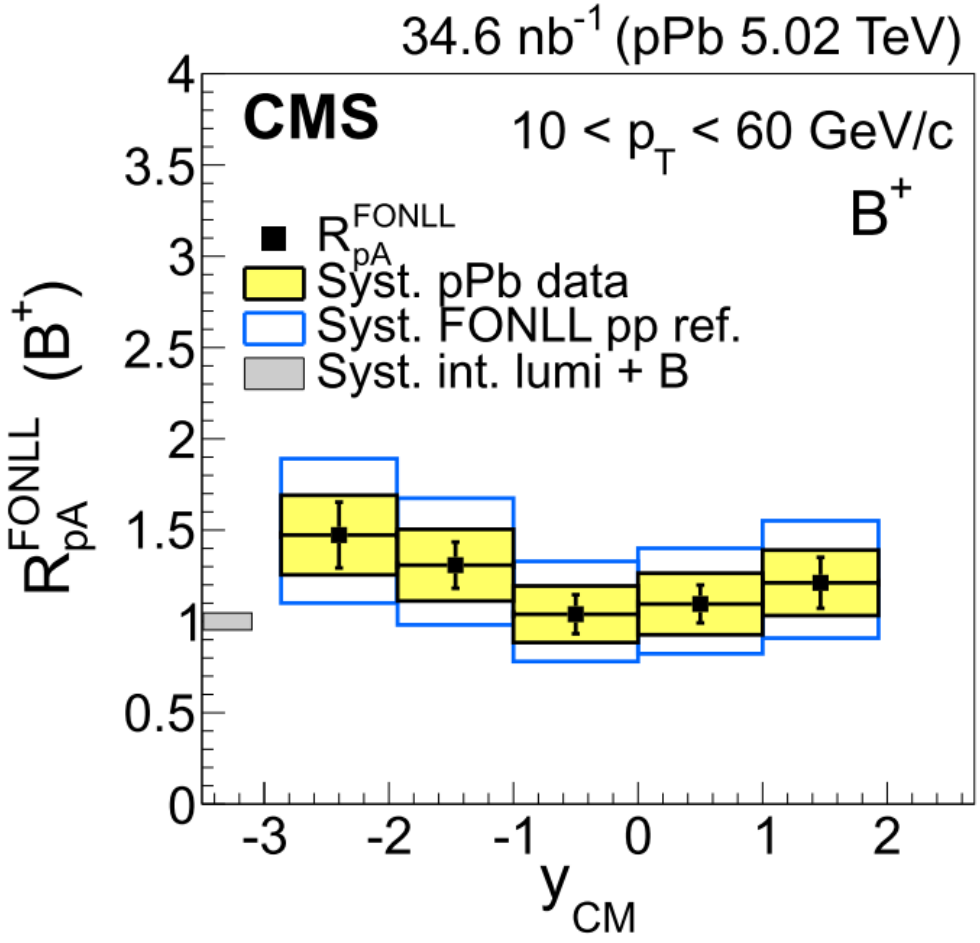


- R_{pA}^{FONLL} is compatible with unity within given uncertainties for three B mesons
- pp reference data at 5 TeV can significantly lower the systematical uncertainty

Rapidity Distribution in pPb @ 5 TeV

- Rapidity dependence of B^+ production

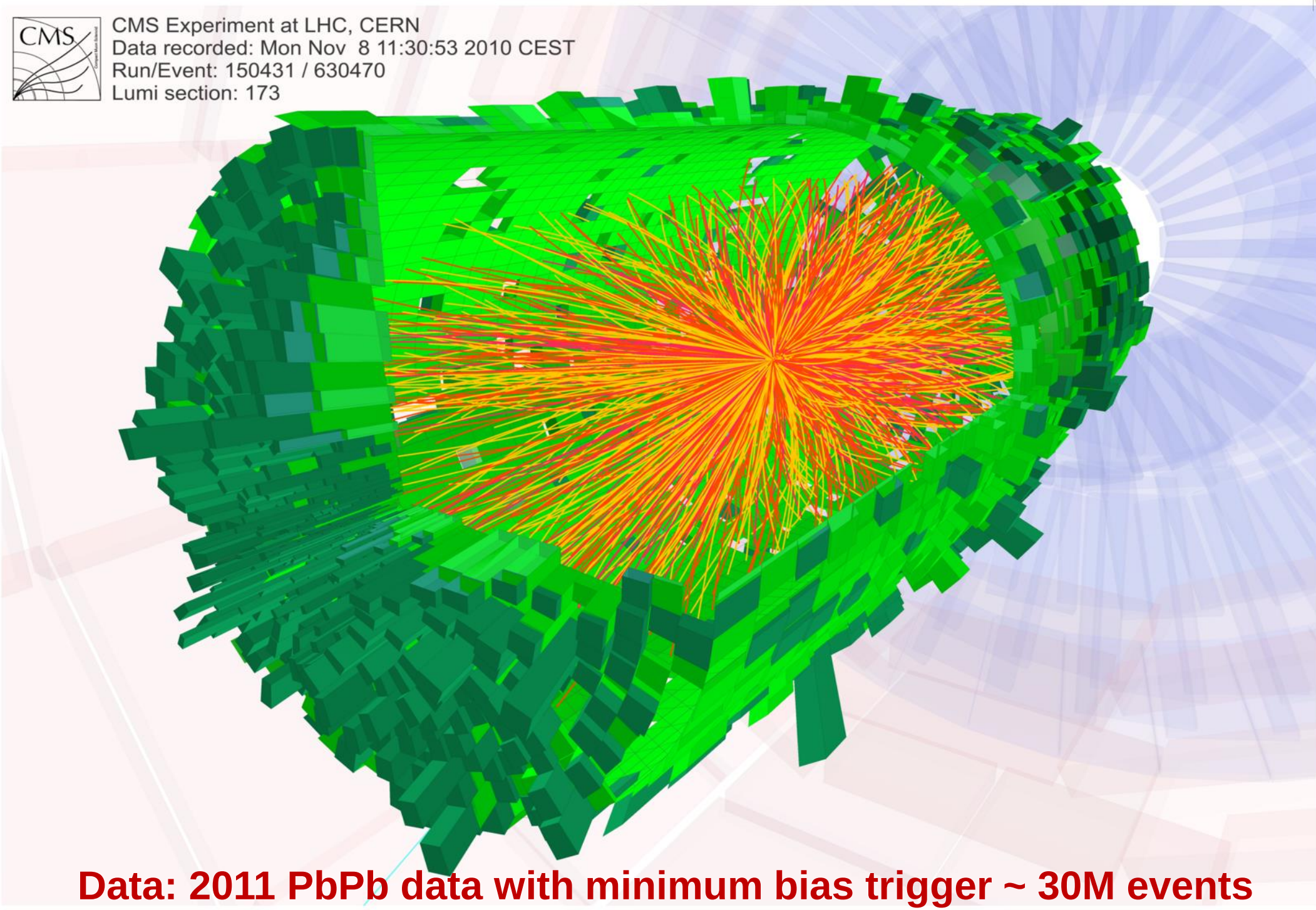




R_{pA}^{FONLL} is compatible with unity within theoretical and experimental uncertainties

Accepted by PRL arXiv:1508.06678

D^0 meson in PbPb collisions @ 2.76 TeV



Data: 2011 PbPb data with minimum bias trigger ~ 30M events

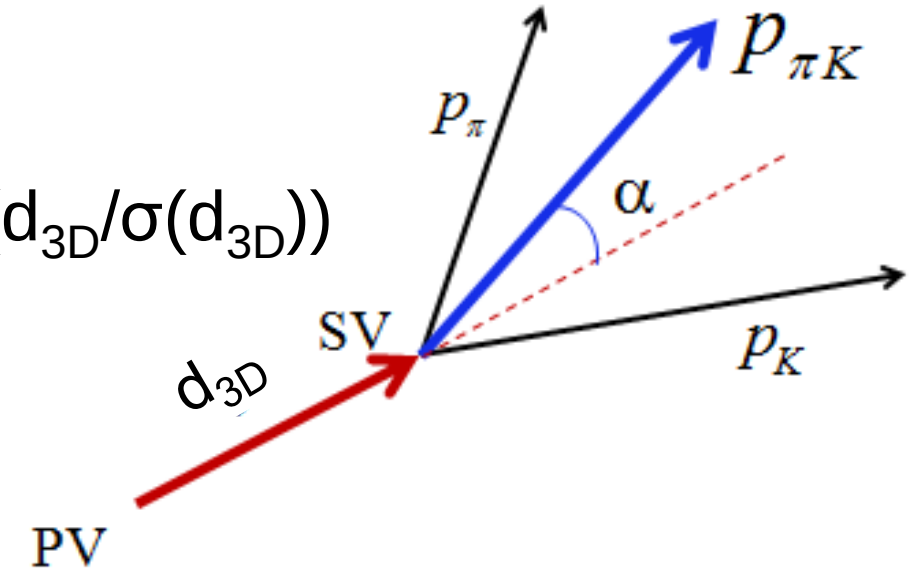
D^0 Reconstruction

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

- **D^0 candidates reconstructed by combining oppositely charged tracks**
  - Tracks with high purity selection, $|\eta|<1.1$ and $p_T > 1$ GeV/c
  - No (K-π) particle identification applied: two mass assignments for one track pair→**Two candidates for one track pair**

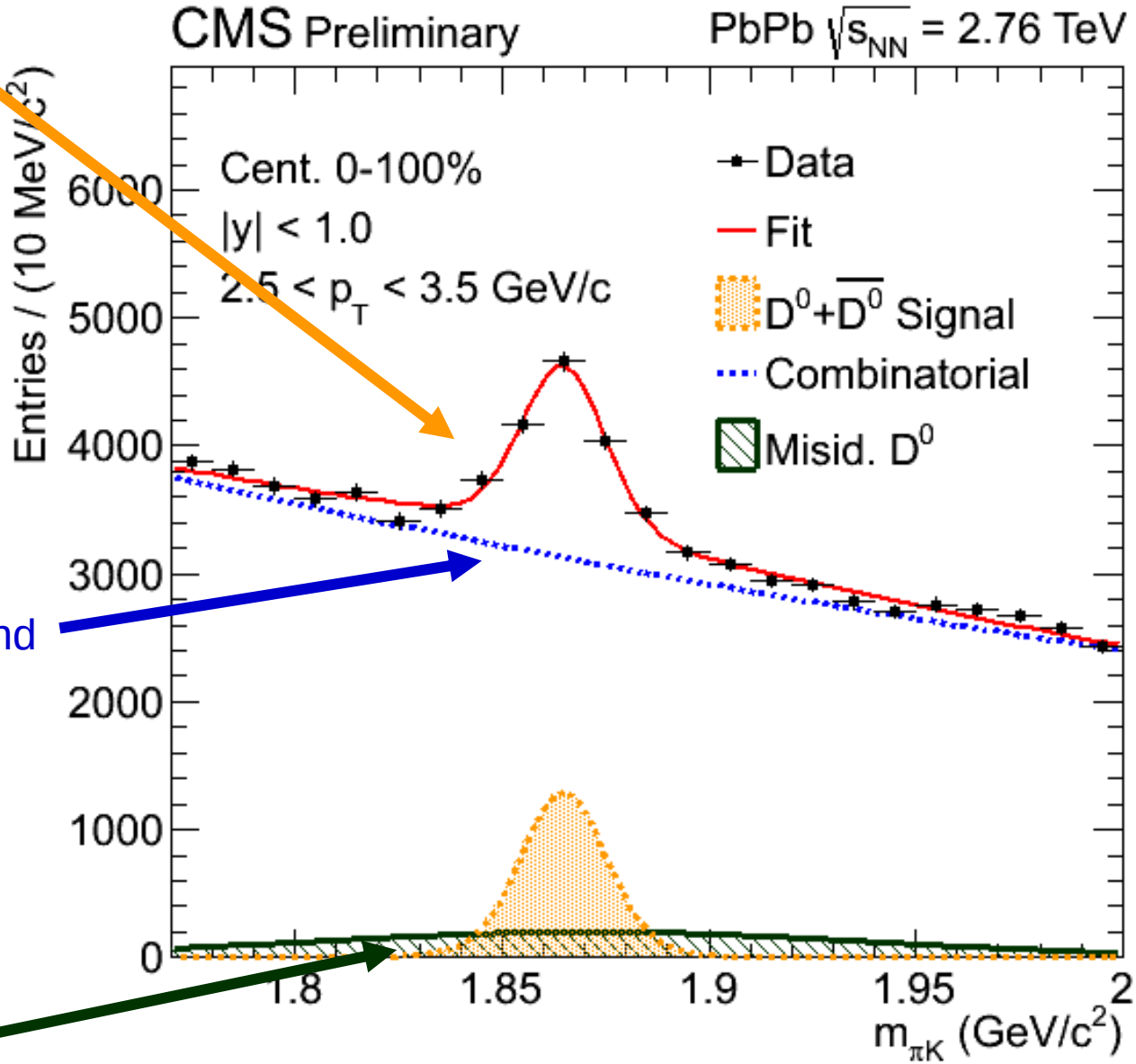
❖ **Topological selections:**

- 3D decay length significance ($d_{3D}/\sigma(d_{3D})$)
- Pointing angle α
- Vertex χ^2 fit probability



D^0 Signal Extraction: $D^0 \rightarrow K^- \pi^+$

$D^0 \rightarrow K^- \pi^+$ signal (Double Gaussian)



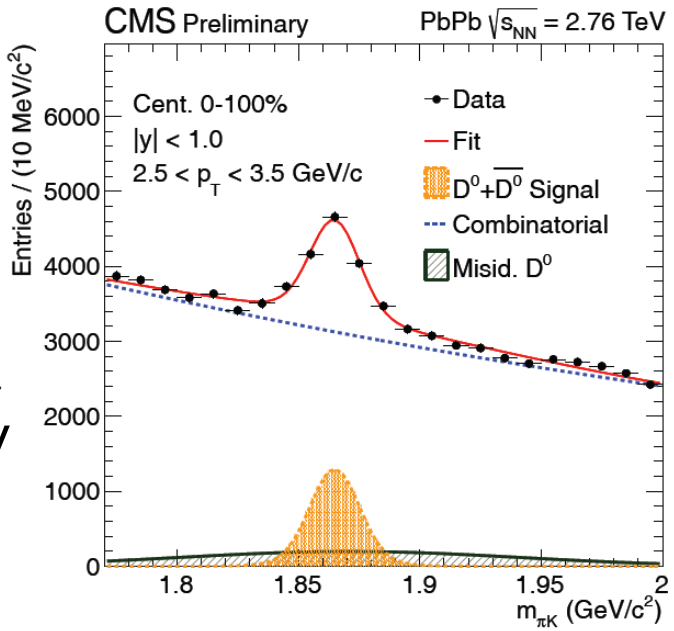
Combinatorial background (Exponential function)

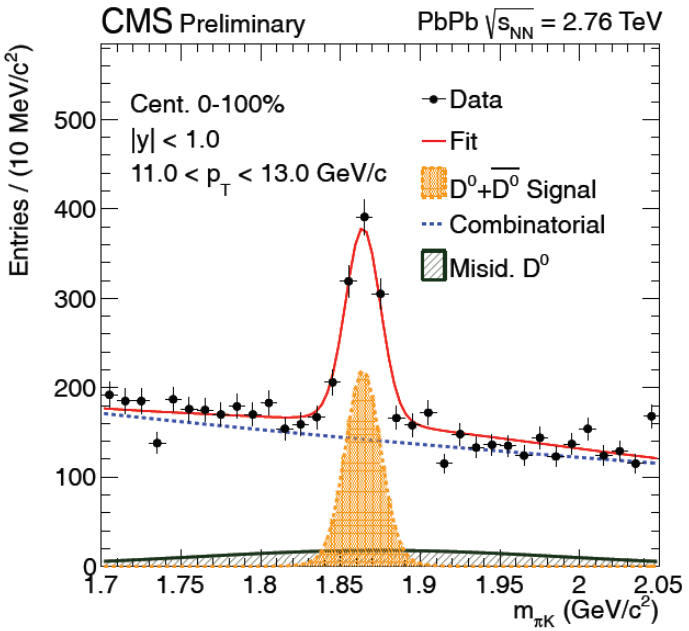
Misidentification (K-π swapped) due to wrong mass assignment (Gaussian)

CMS PAS HIN-15-005

Clear D^0 Signal in p_T Range 2.5 to 40 GeV

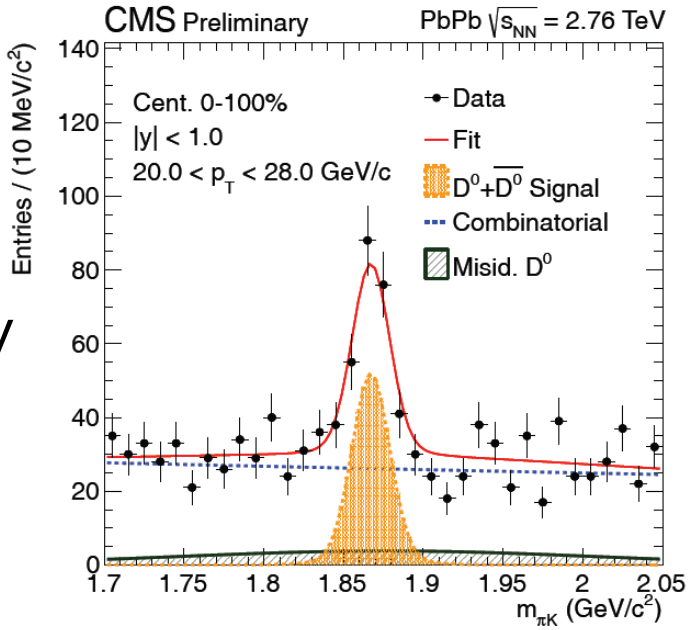
D meson p_T 2.5-3.5 GeV

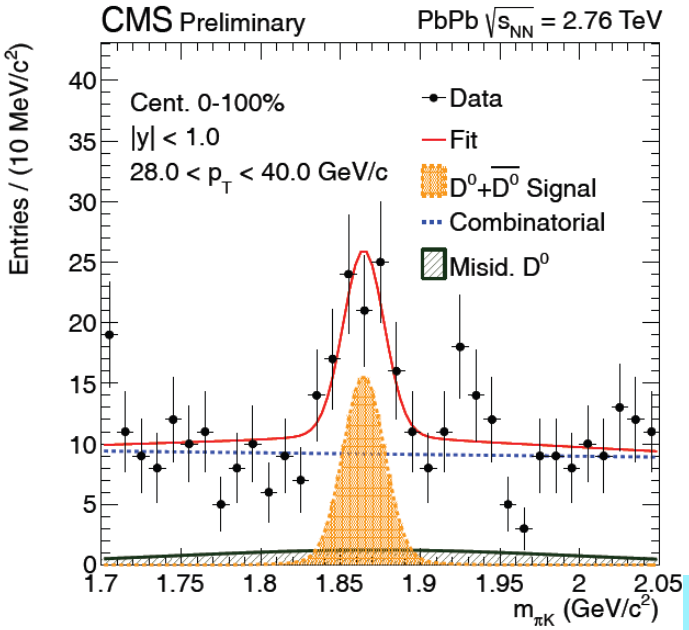




11-13 GeV

20-28 GeV





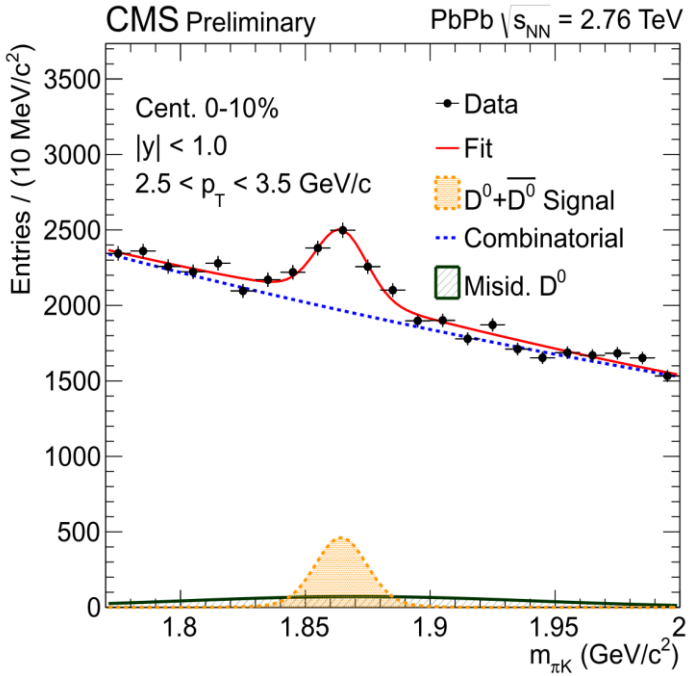
28-40 GeV

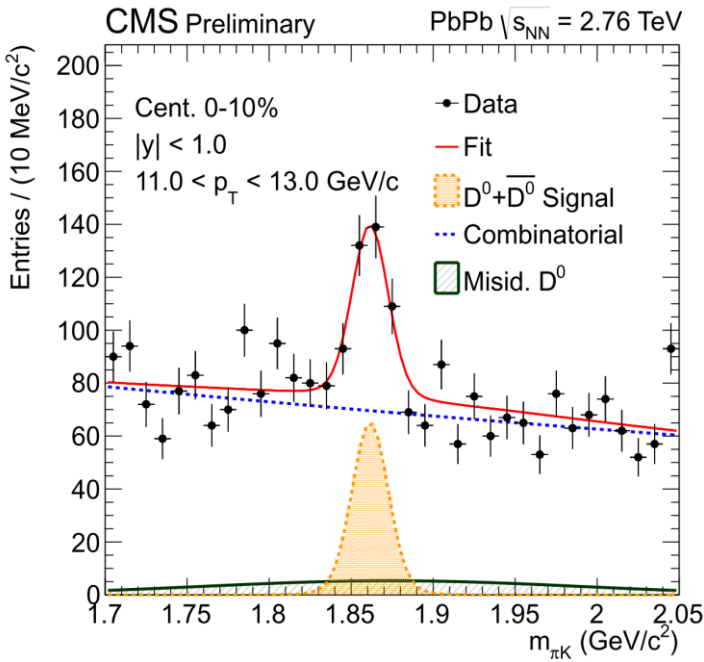
CMS PAS HIN-15-005

D^0 Signal to Background Ratio Comparison

0-10%

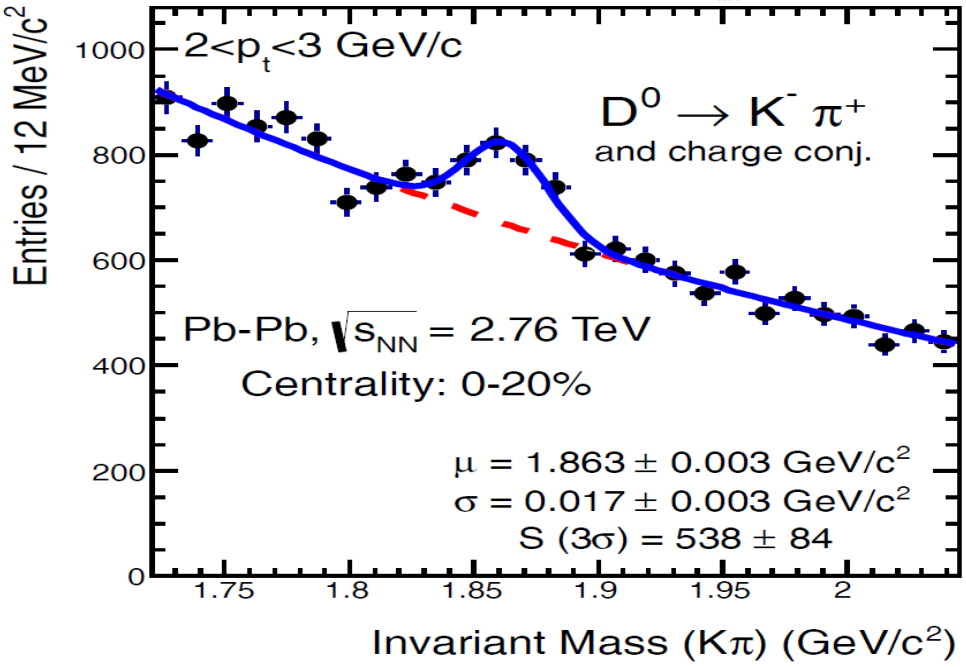
(No K-π ID)

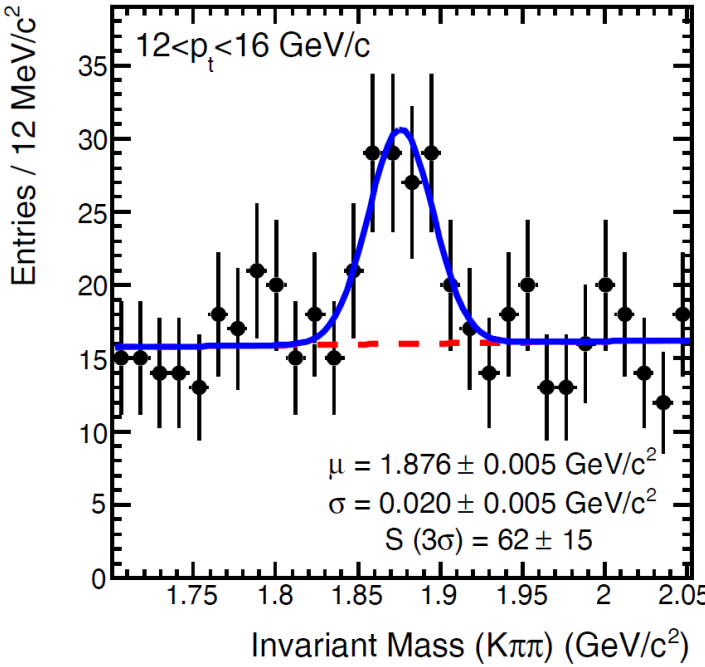




0-20%

ArXiv 1203.2160





D^0 Signal to Background Ratio Comparison

0-10%

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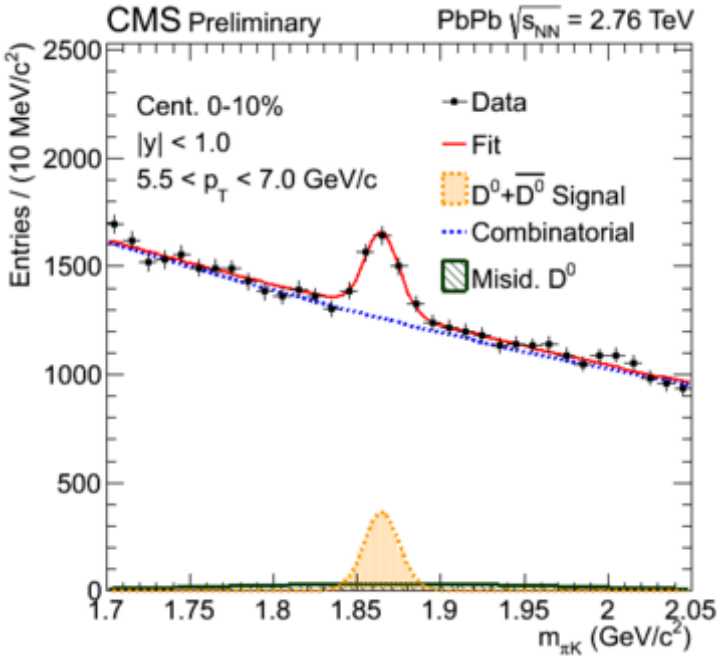
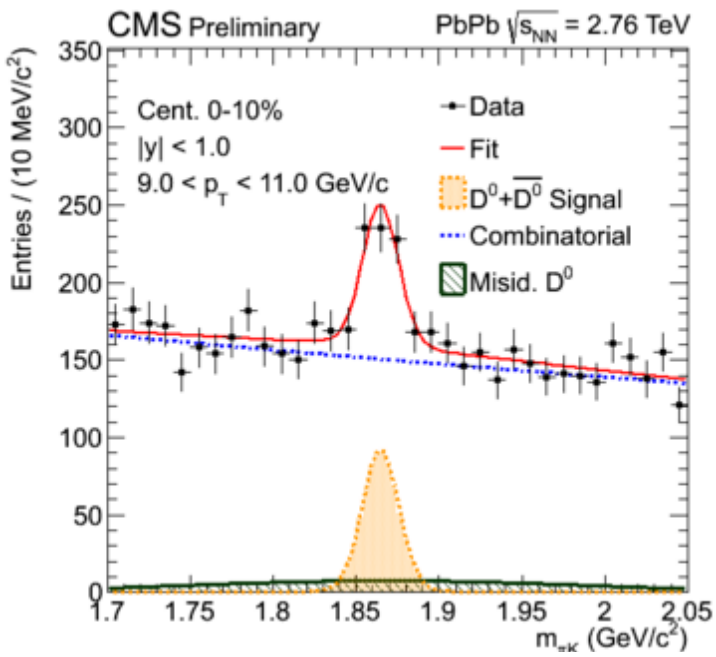
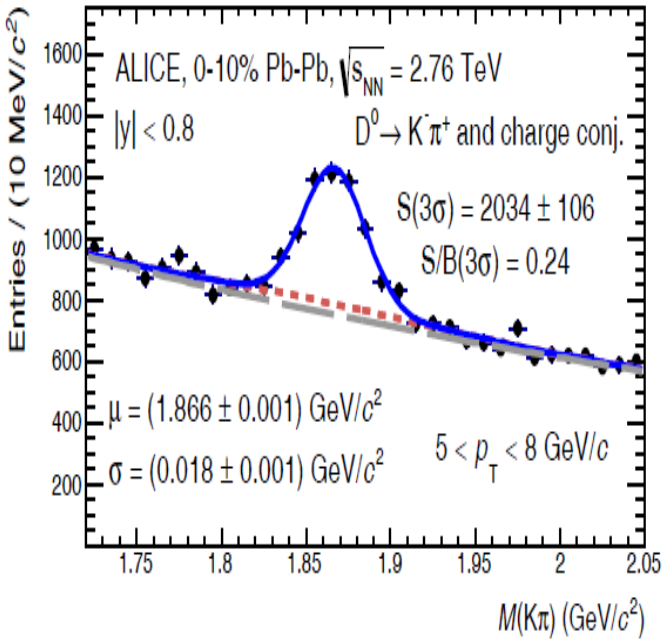
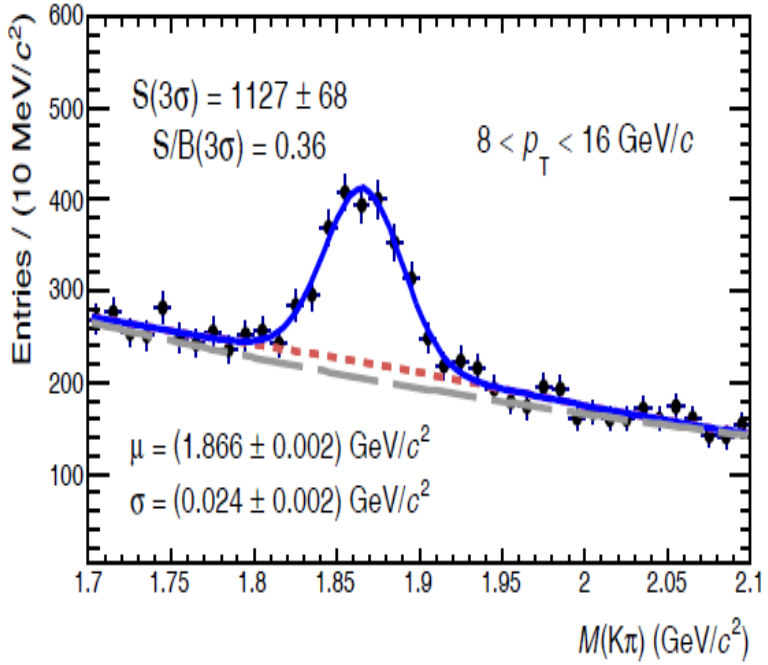




0-10%

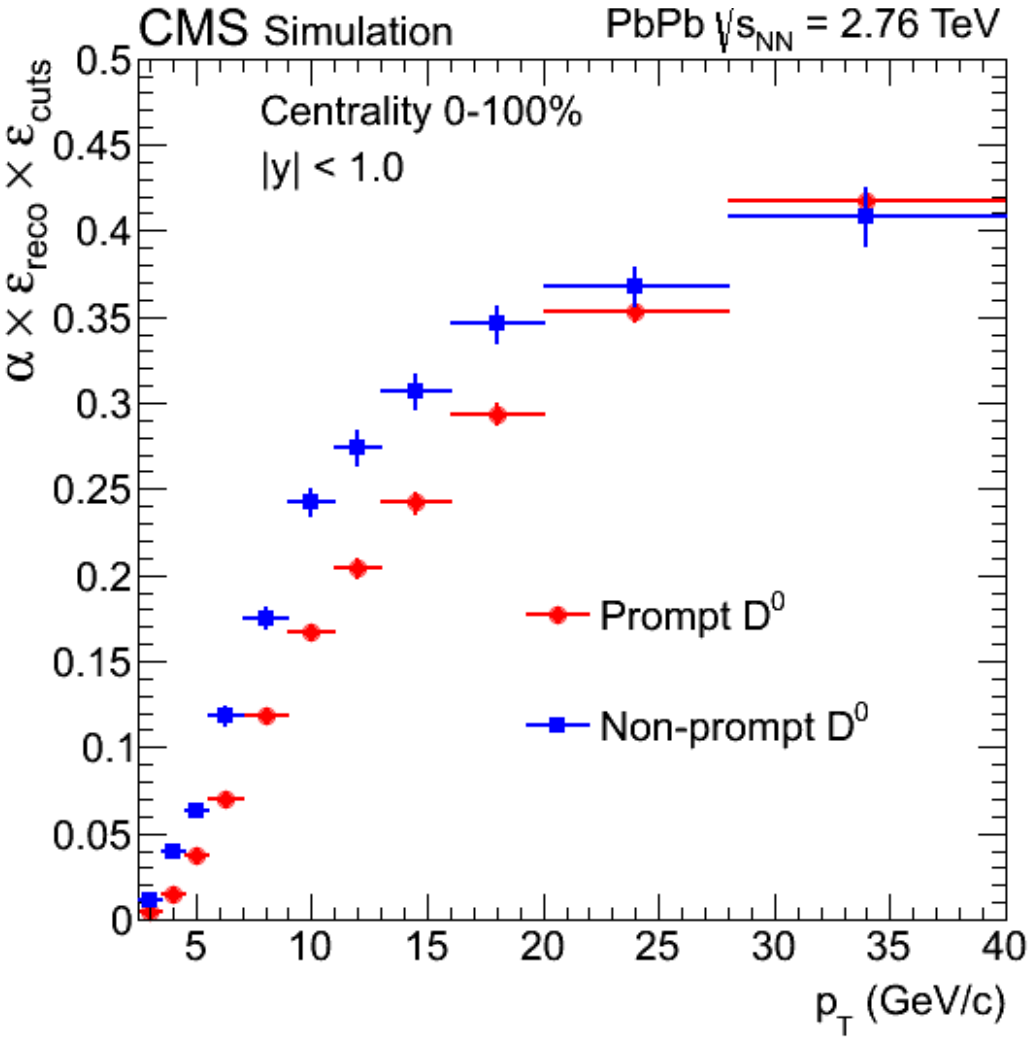
ArXiv 1506.06604





Acceptance and Efficiency Correction

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



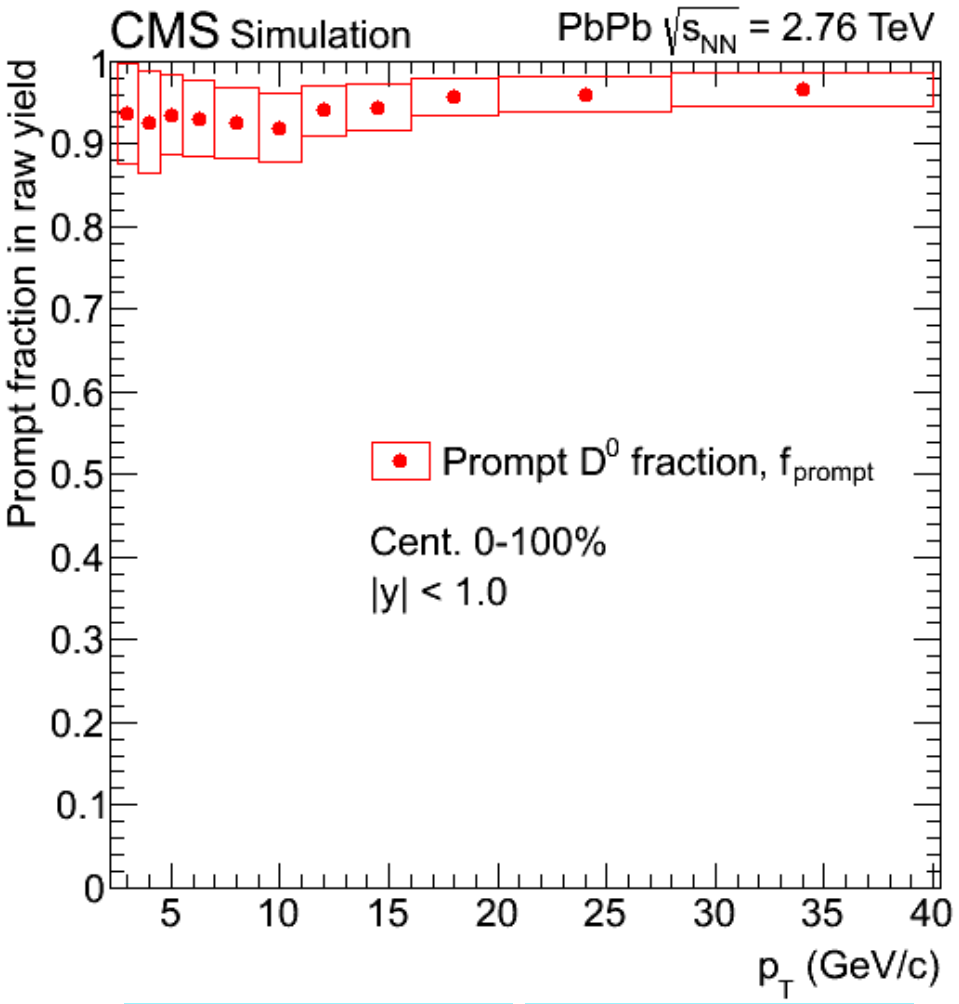
- Combined effects of tracking efficiency and D^0 meson selection efficiency

- 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→D Feed-down Correction

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



- Non-prompt D^0 subtraction:

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

- Raw yield of non-prompt D^0
  - Beauty production from FONLL [1], decay with EvtGen or PYTHIA
  - Acceptance and efficiency from PYTHIA+HYDJET
  - R_{AA} of non-prompt D^0 constrained by non-prompt J/ψ and b-jet R_{AA}

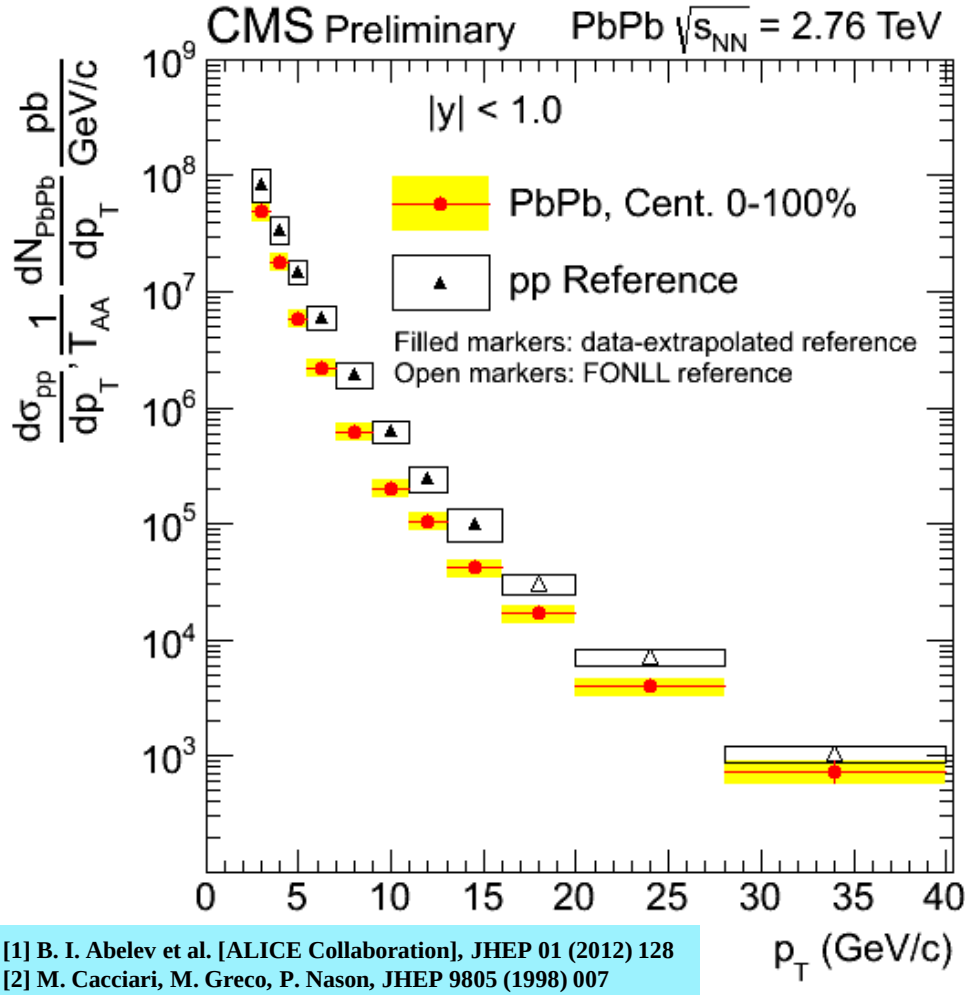
[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

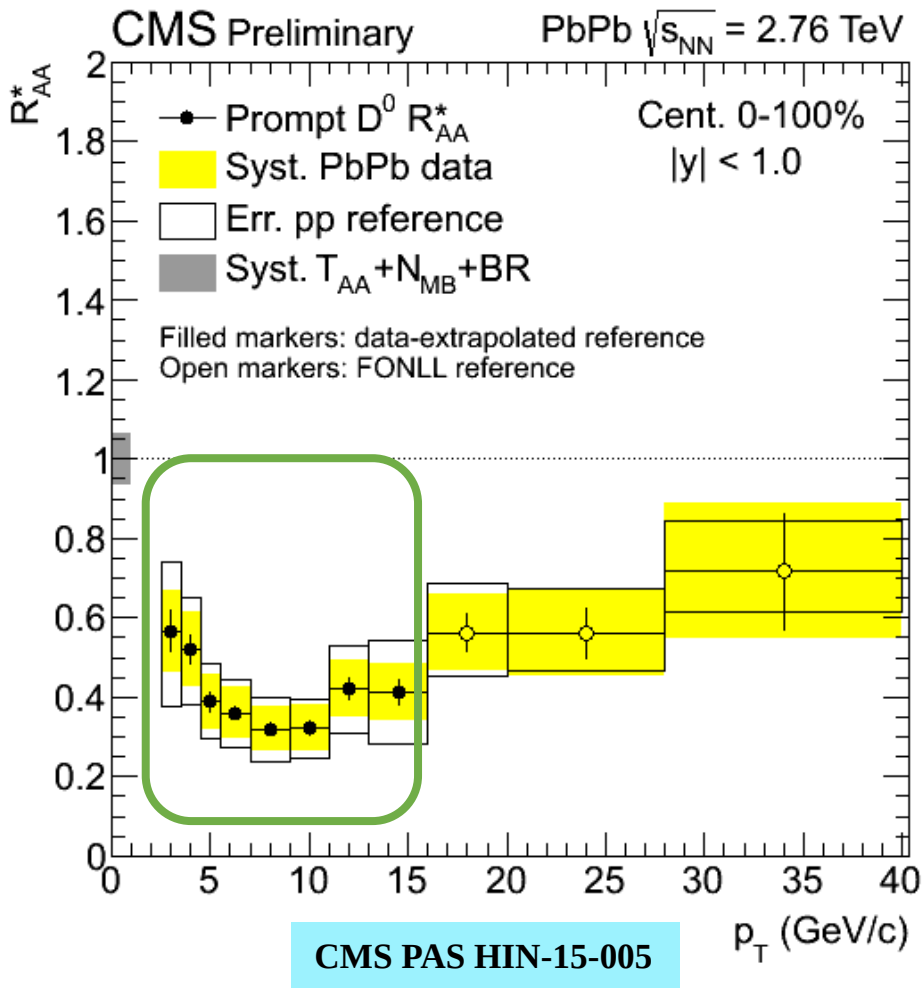
CMS PAS HIN-15-005 | CMS PAS HIN-12-014 | Phys. Rev. Lett. 113, 132301 (2014)

Prompt D^0 Spectrum and R^*_{AA} in Centrality 0-100%

pp reference:

- p_T < 16 GeV, data-extrapolated, scaled from ALICE pp @ 7 TeV [1] with FONLL [2]
- p_T > 16 GeV, FONLL calculation





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

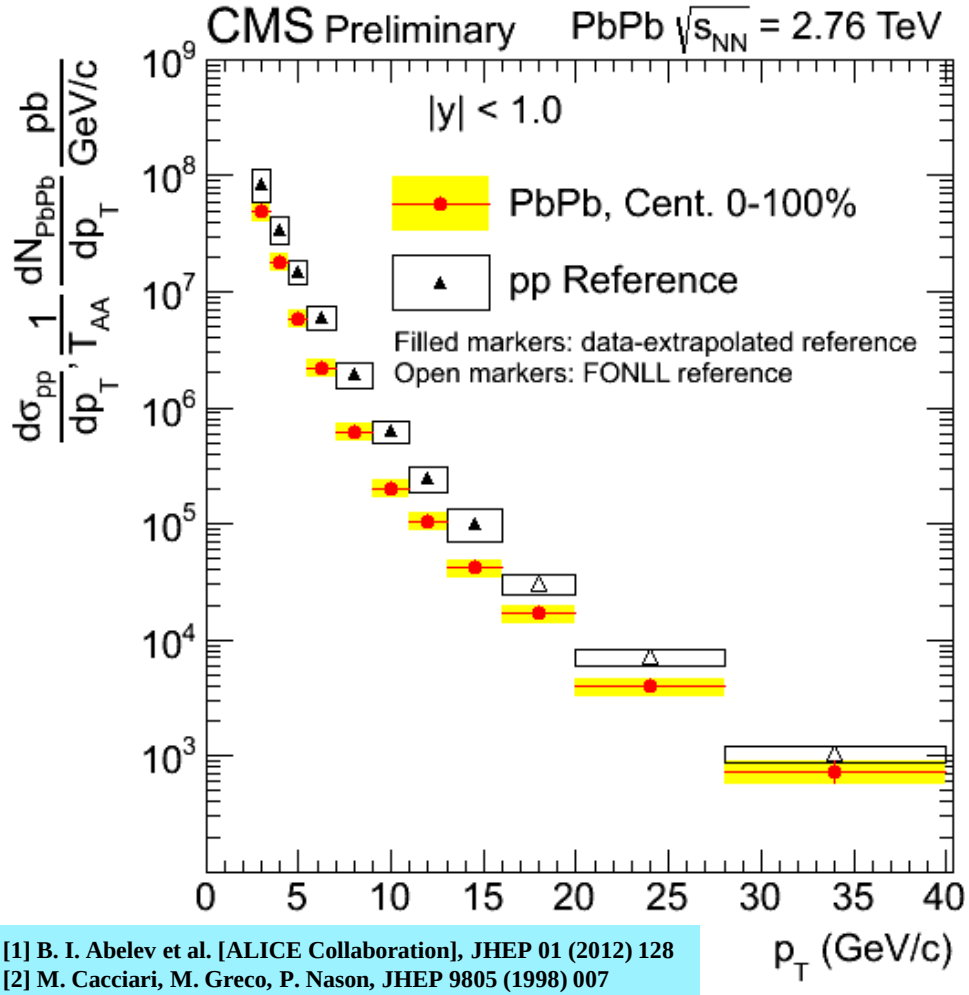
CMS PAS HIN-15-005

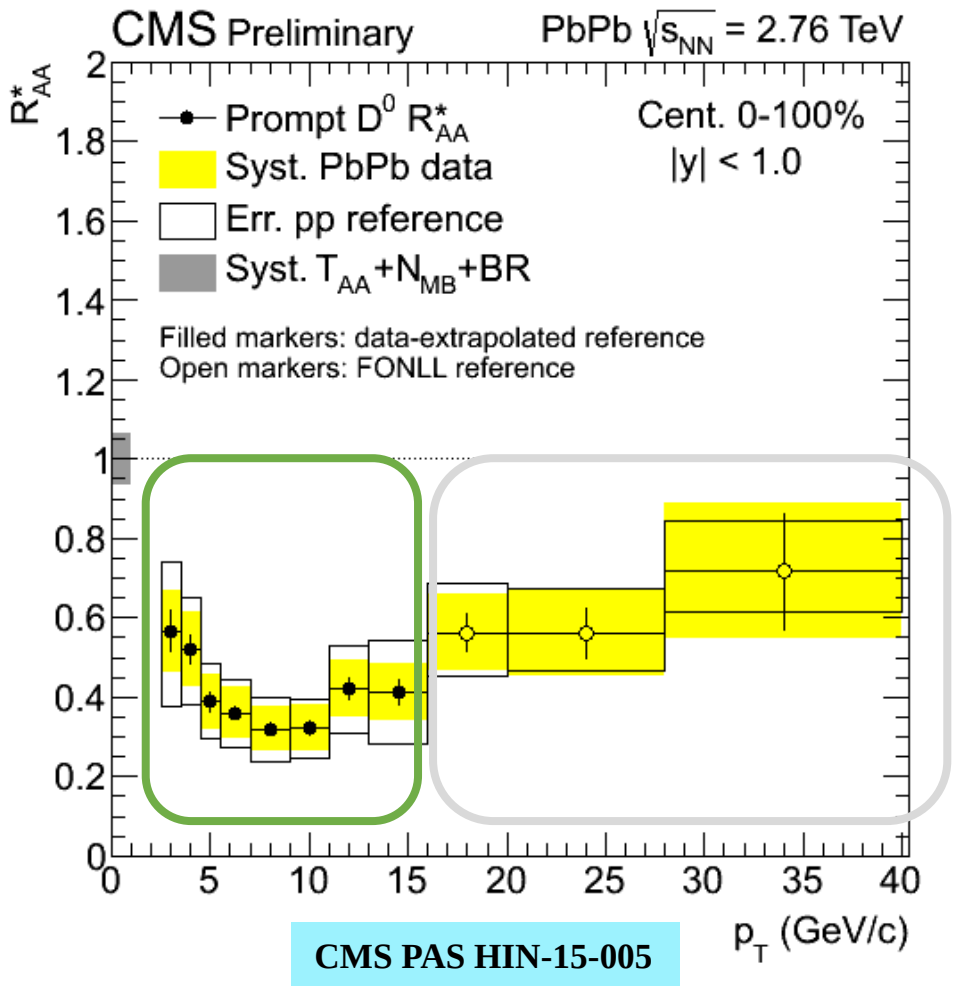
Prompt D^0 Spectrum and R^*_{AA} in Centrality 0-100%

pp reference:

- p_T < 16 GeV, data-extrapolated, scaled from ALICE pp @ 7 TeV [1] with FONLL [2]
- p_T > 16 GeV, FONLL calculation

Prompt D^0 production is strongly suppressed in PbPb collisions

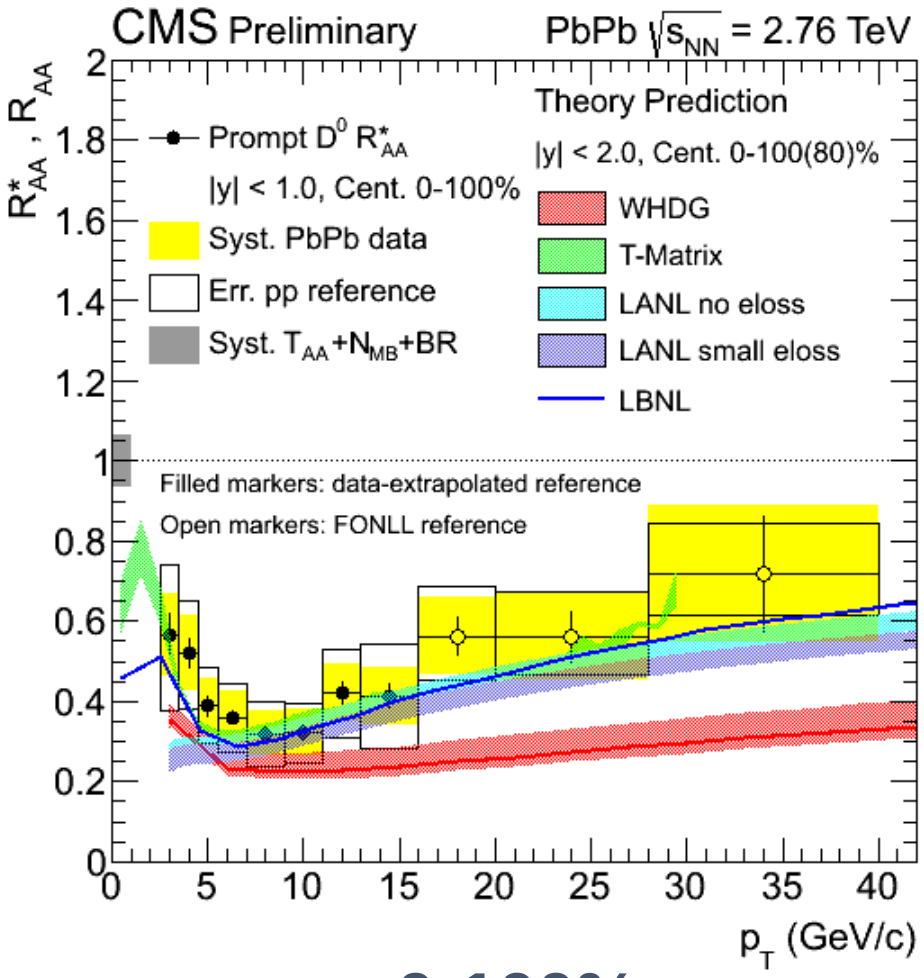




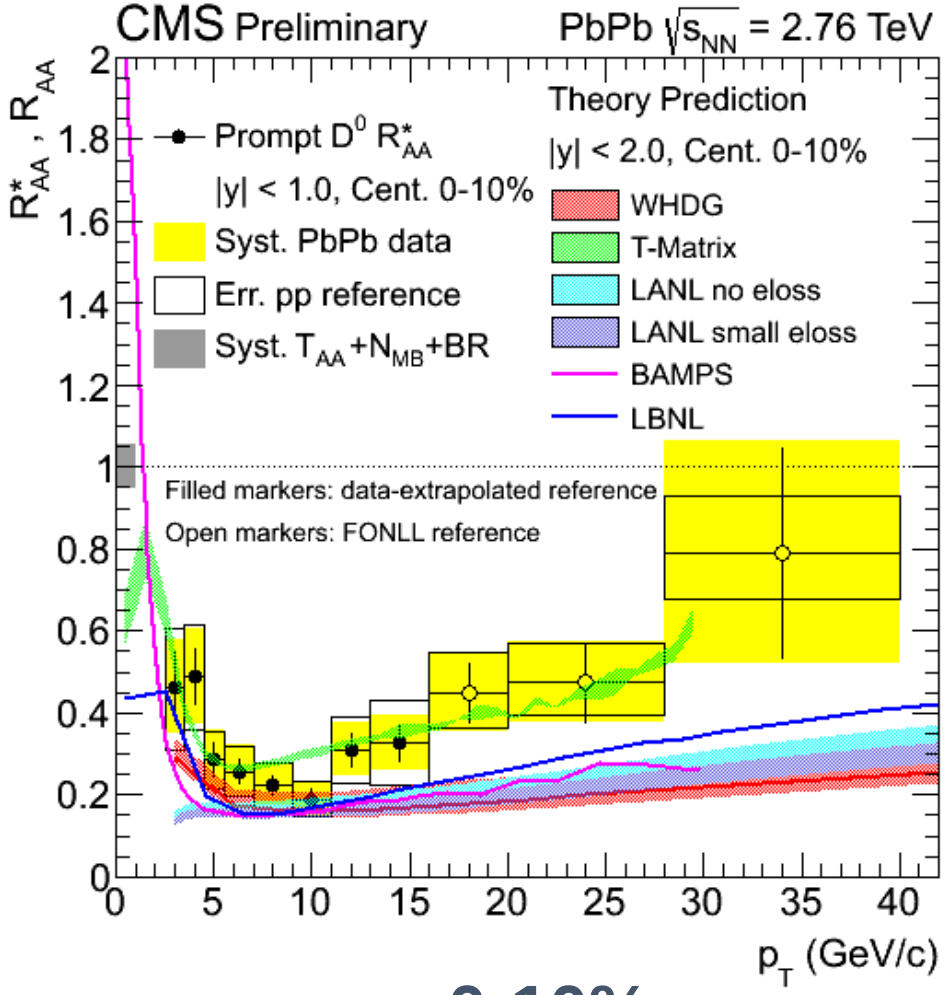
[1] B. I. Abelev et al. [ALICE Collaboration], JHEP 01 (2012) 128
[2] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

CMS PAS HIN-15-005

Comparison with Theoretical Models



0-100%

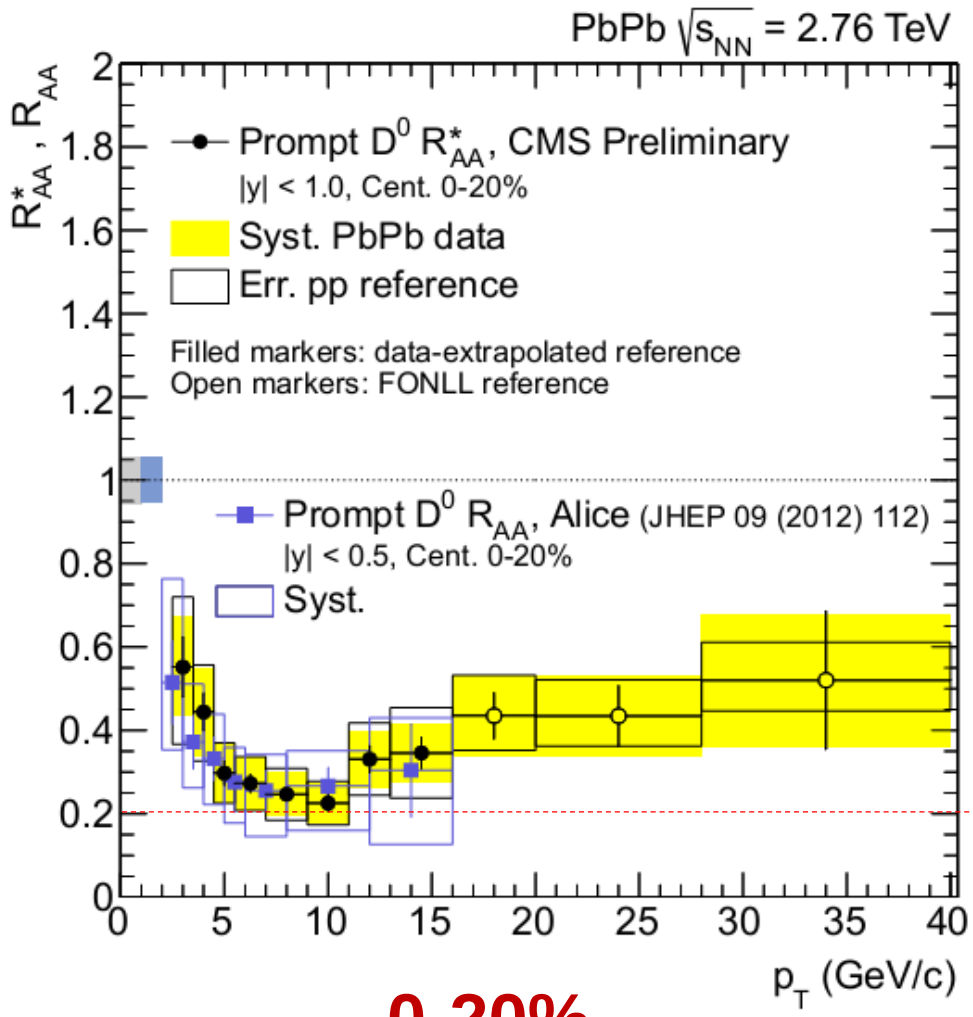


0-10%

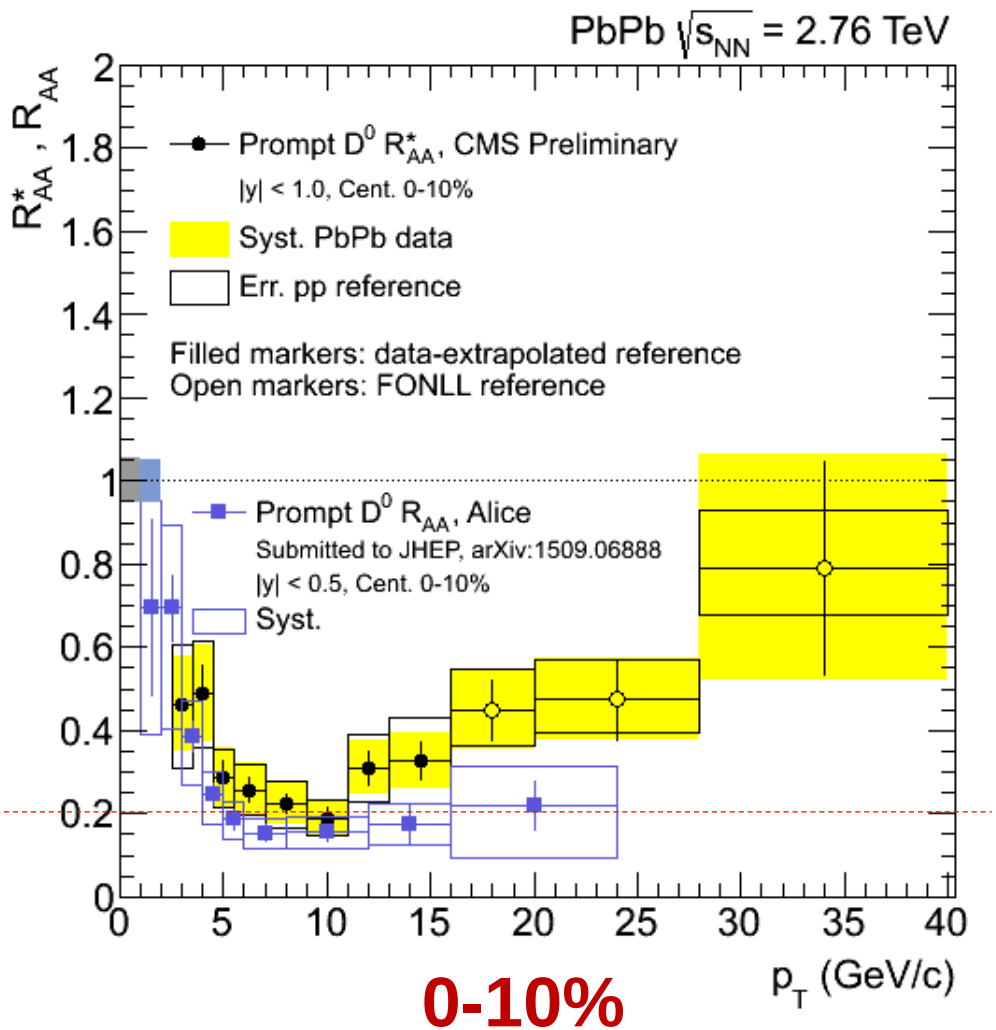
WHDG: Horowitz et al., arXiv:1104.4958
T-Matrix: He, Rapp, private communication
LBNL: Cao et al., PRC 92 (2015) 2, 024907, PRC88 (2013) 4, 044907

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

CMS vs. ALICE Results



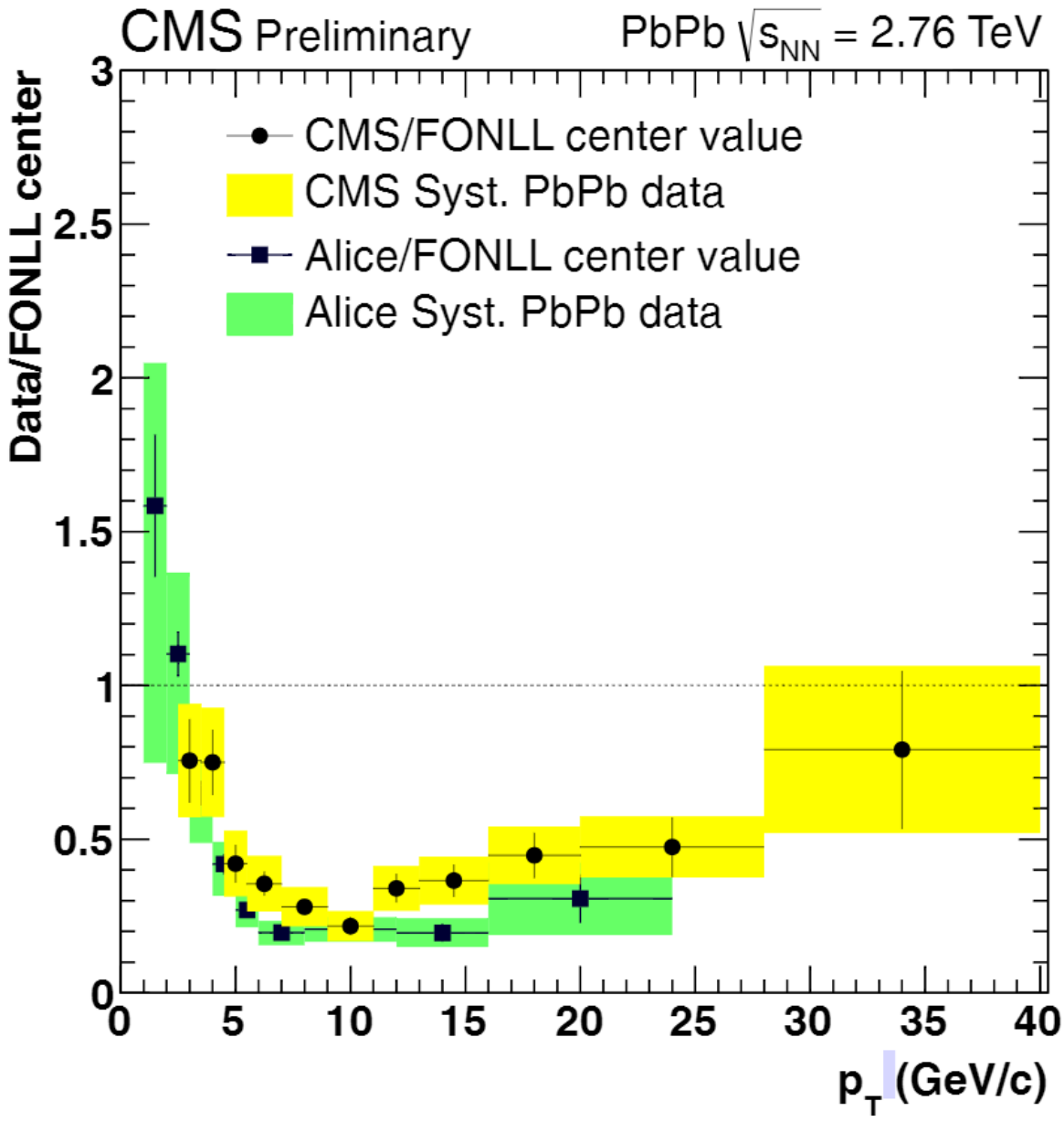
0-20%



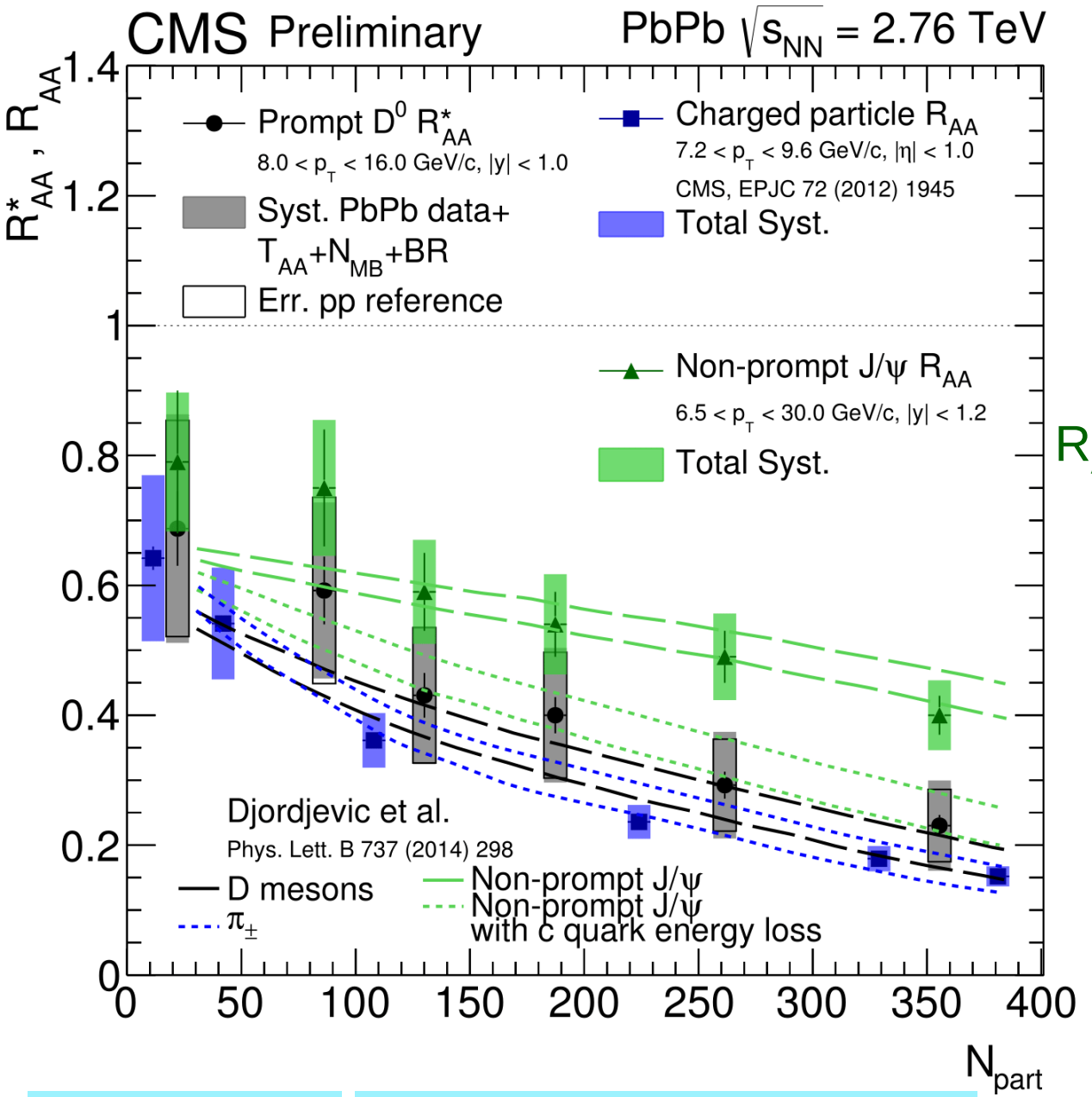
0-10%

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

CMS vs. ALICE using FONLL as Reference



Flavor Dependence of the R_{AA}



Prompt D^0 R^*_{AA}

Charged particle R_{AA}

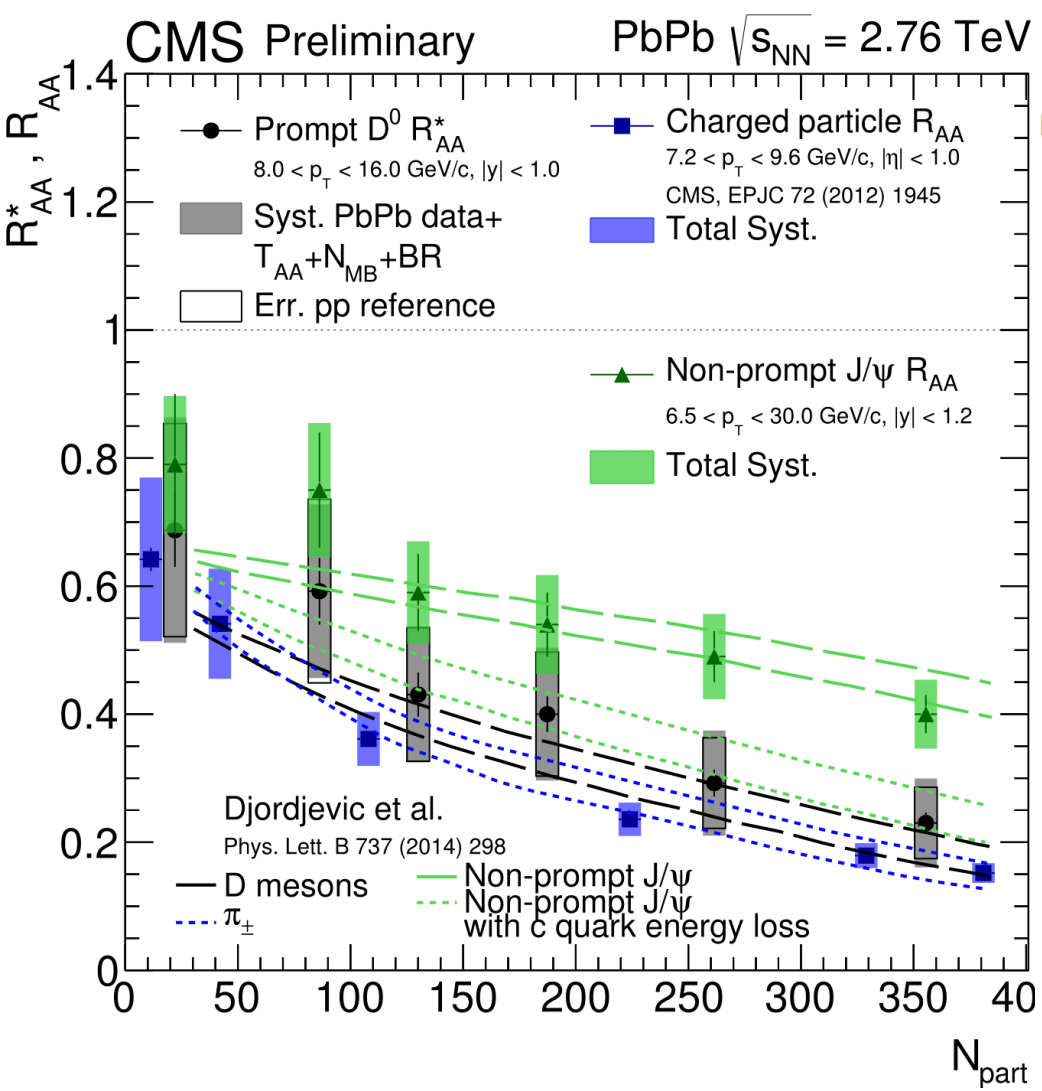
Non-prompt J/ψ R_{AA}

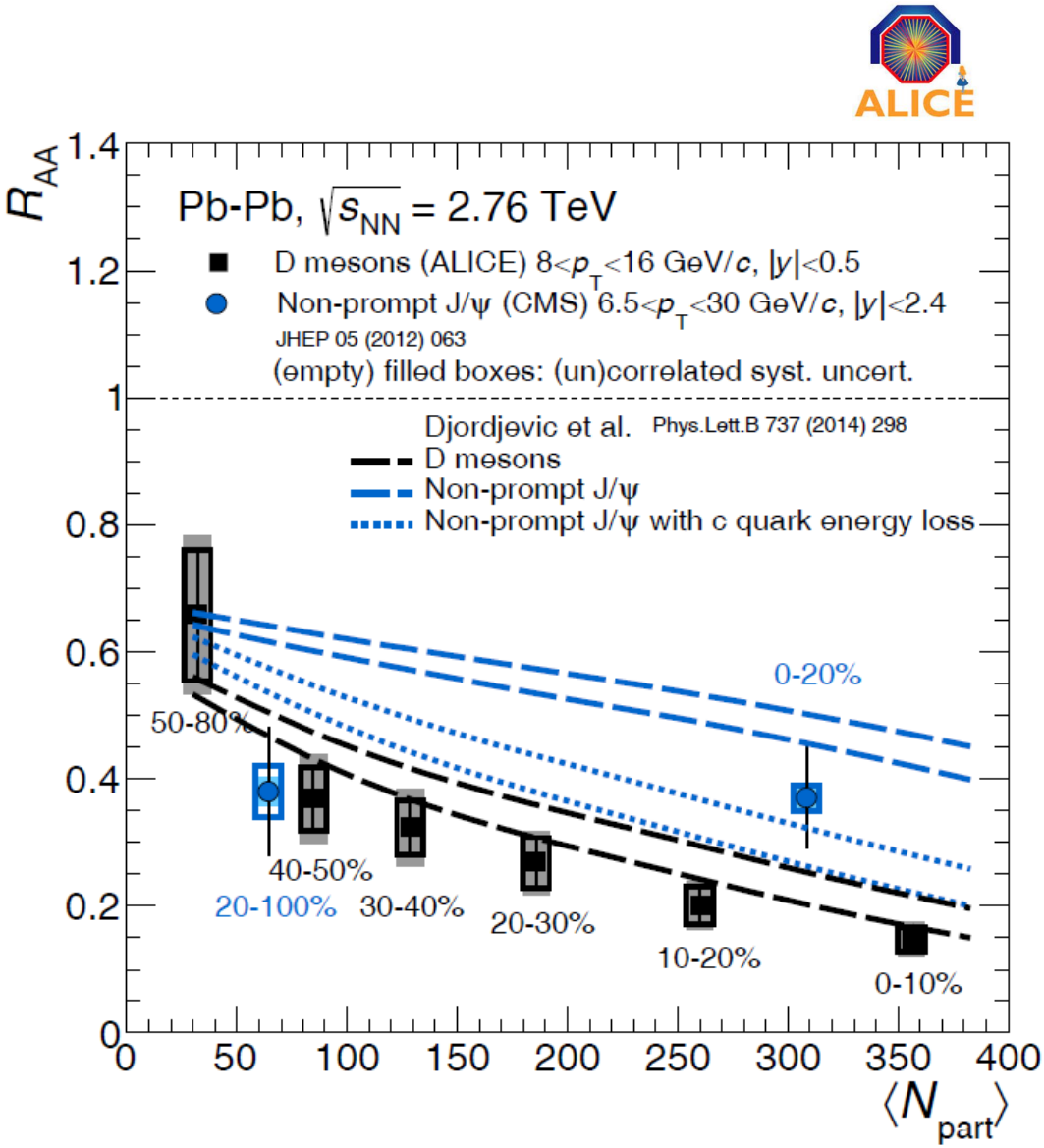
$R_{AA}^{(b\rightarrow J/\psi)} > R_{AA}^{(\text{prompt D0})} >= R_{AA}^{(h\pm)}$

The data agree with calculations by Djordjevic et al. within uncertainties

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

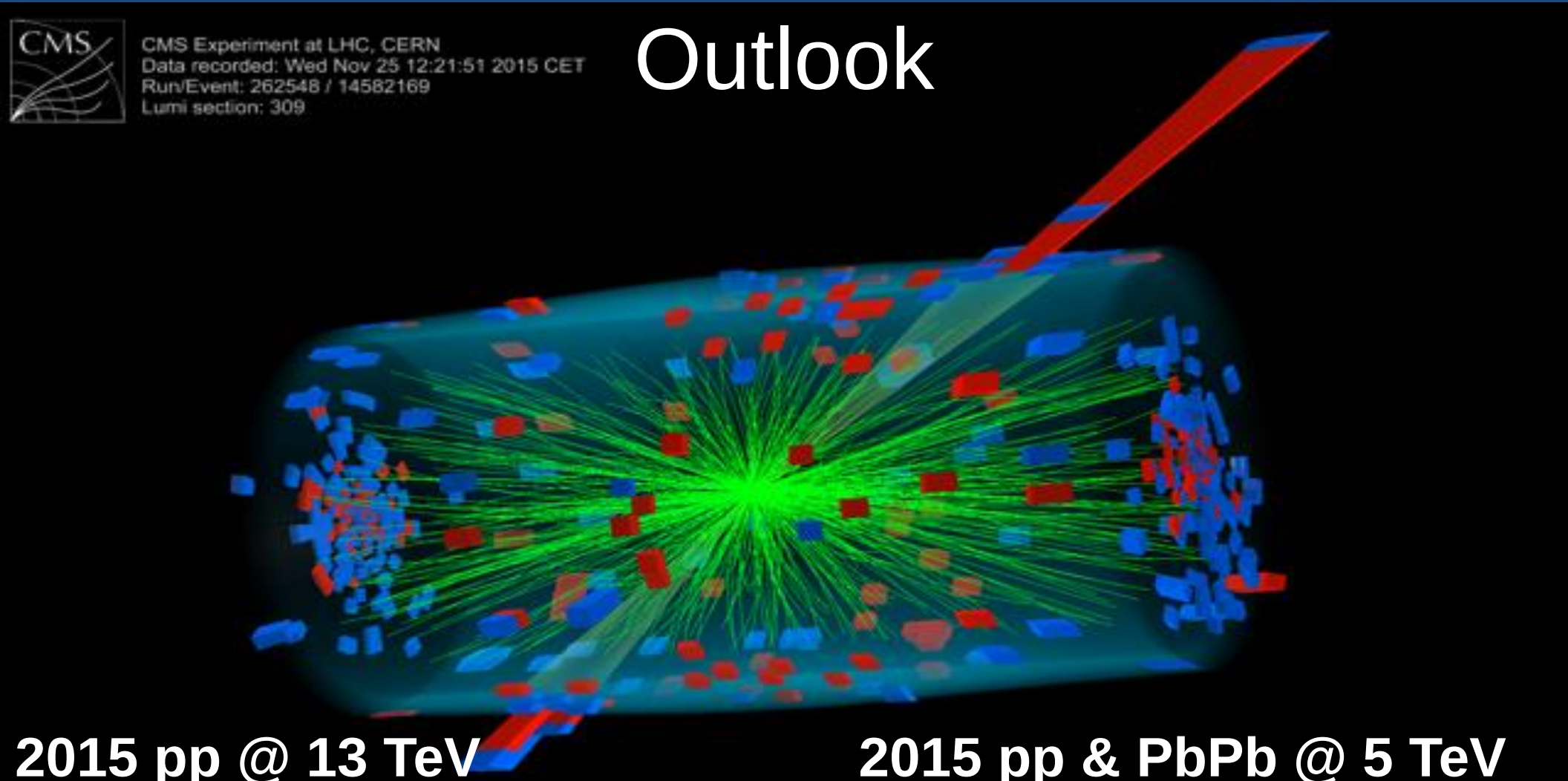
Centrality Dependence (CMS vs. ALICE)





ArXiv 1506.06604

Outlook

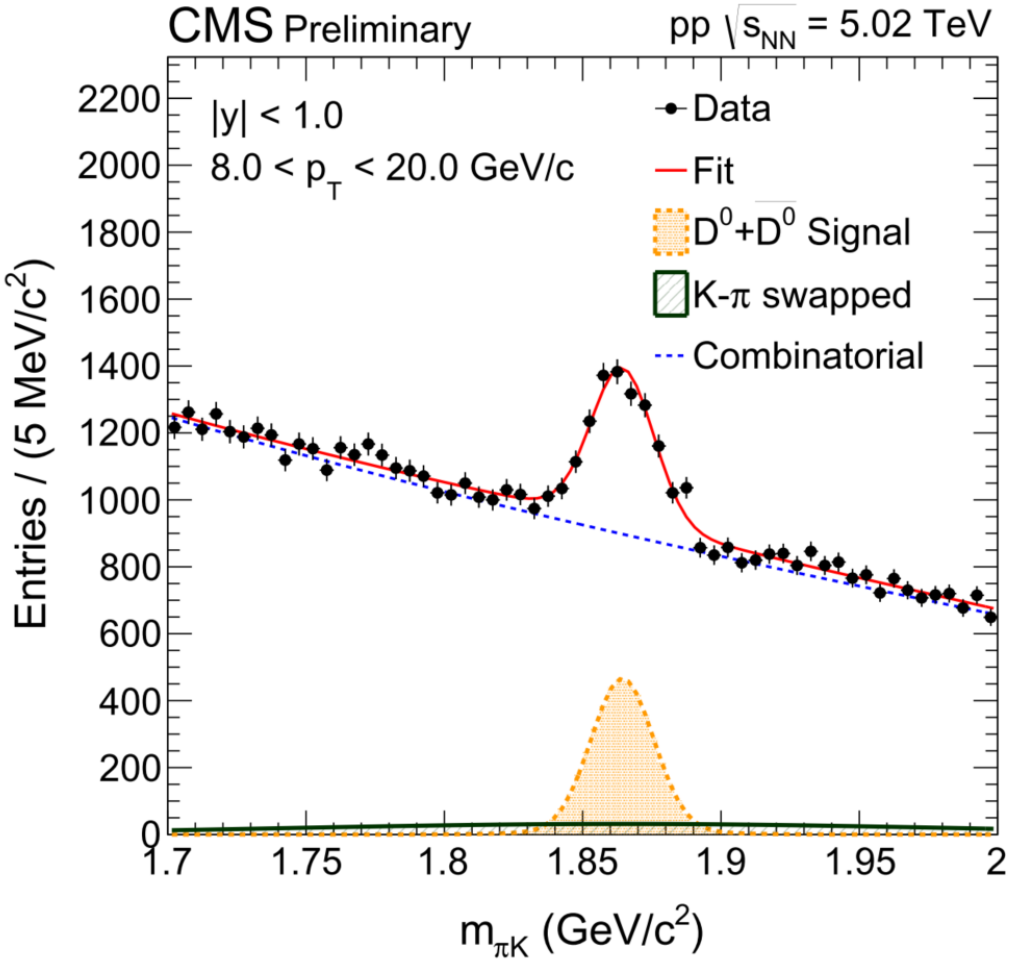


2015 pp @ 13 TeV

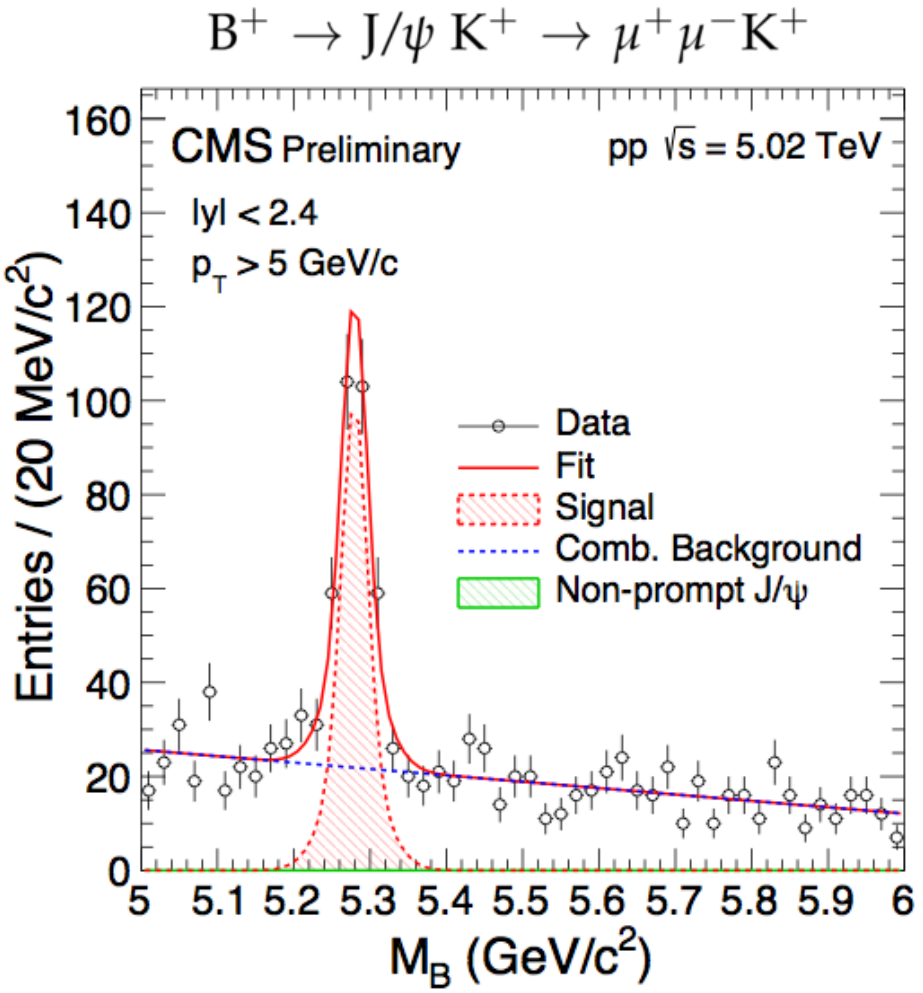
2015 pp & PbPb @ 5 TeV

D^0 and B^+ peak in **proton-proton** collisions @ 5.02 TeV

D^0 mesons from online trigger



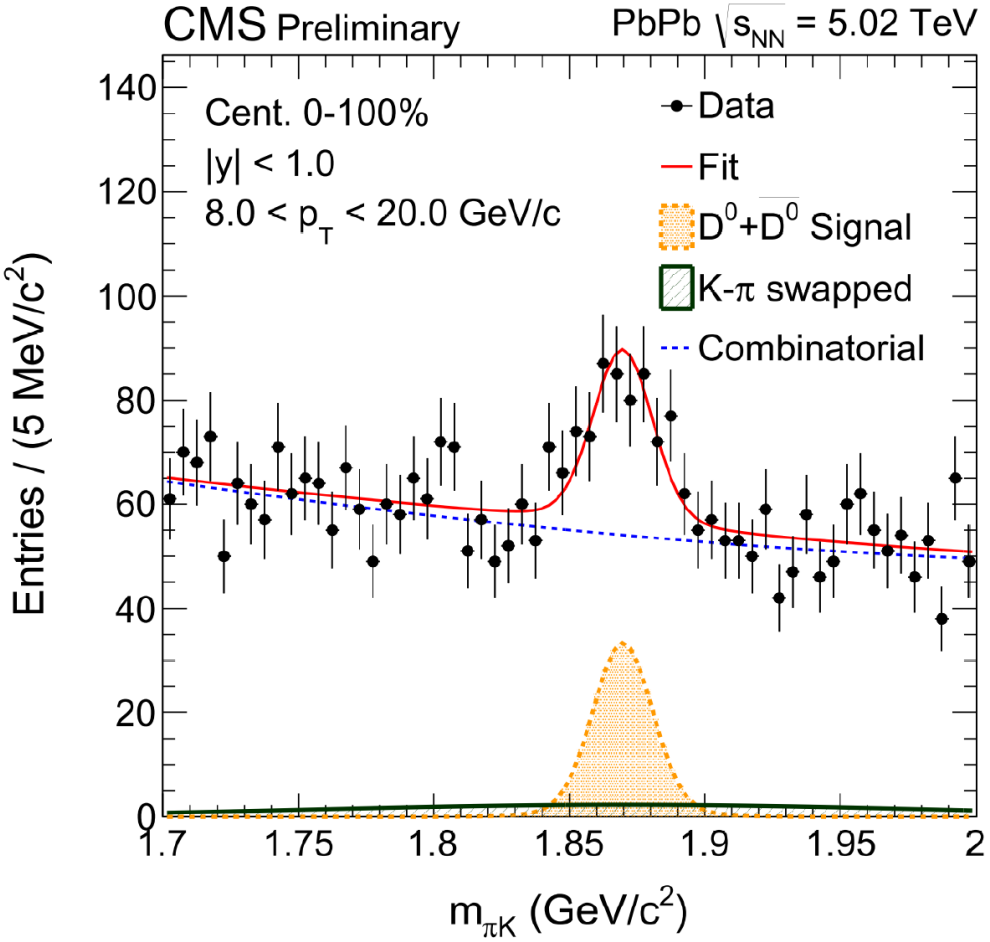
B^+ meson from dimuon triggered sample

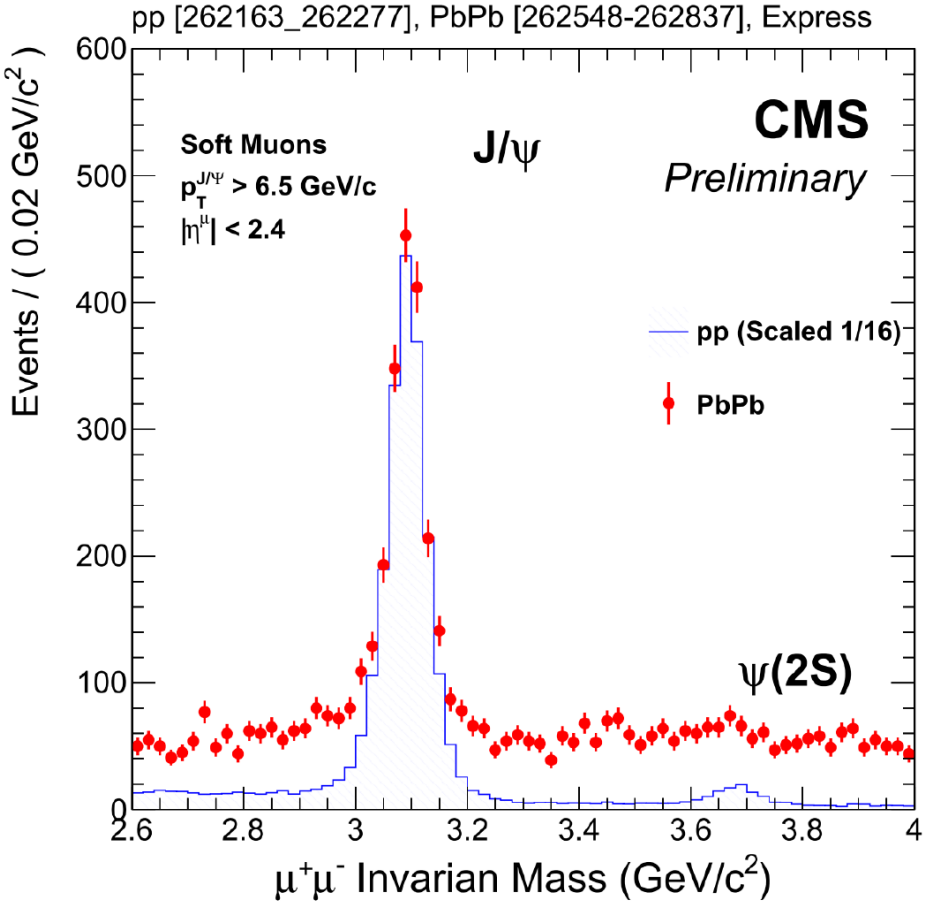


2.5 billion minimum-bias events recorded for low p_T D meson analyses (p_T<20 GeV/c). D^0 meson trigger for high p_T D^0 analyses (p_T> 8 GeV/c)

D^0 and ψ peak in **PbPb** collisions @ 5.02 TeV

D^0 mesons from online trigger





A large minimum bias sample (and centrality triggered sample) is recorded for low p_T D^0, D^+, D^* and D_s analyses

Summary

- B meson in pp (7, 13 TeV) and pPb (5.02 TeV) collisions
  - Transverse momentum and rapidity distributions of B mesons agrees with FONLL calculation within the quoted experimental uncertainties

- D^0 meson in PbPb (2.76 TeV) over a wide kinematics range
  - D^0 mesons can be reconstructed without particle identification
  - Significant suppression of D^0 in PbPb collision is observed
  - Hint of R_{AA} (non-prompt J/ψ) > R_{AA} (prompt D^0) >= R_{AA} ($h^{\pm}$)

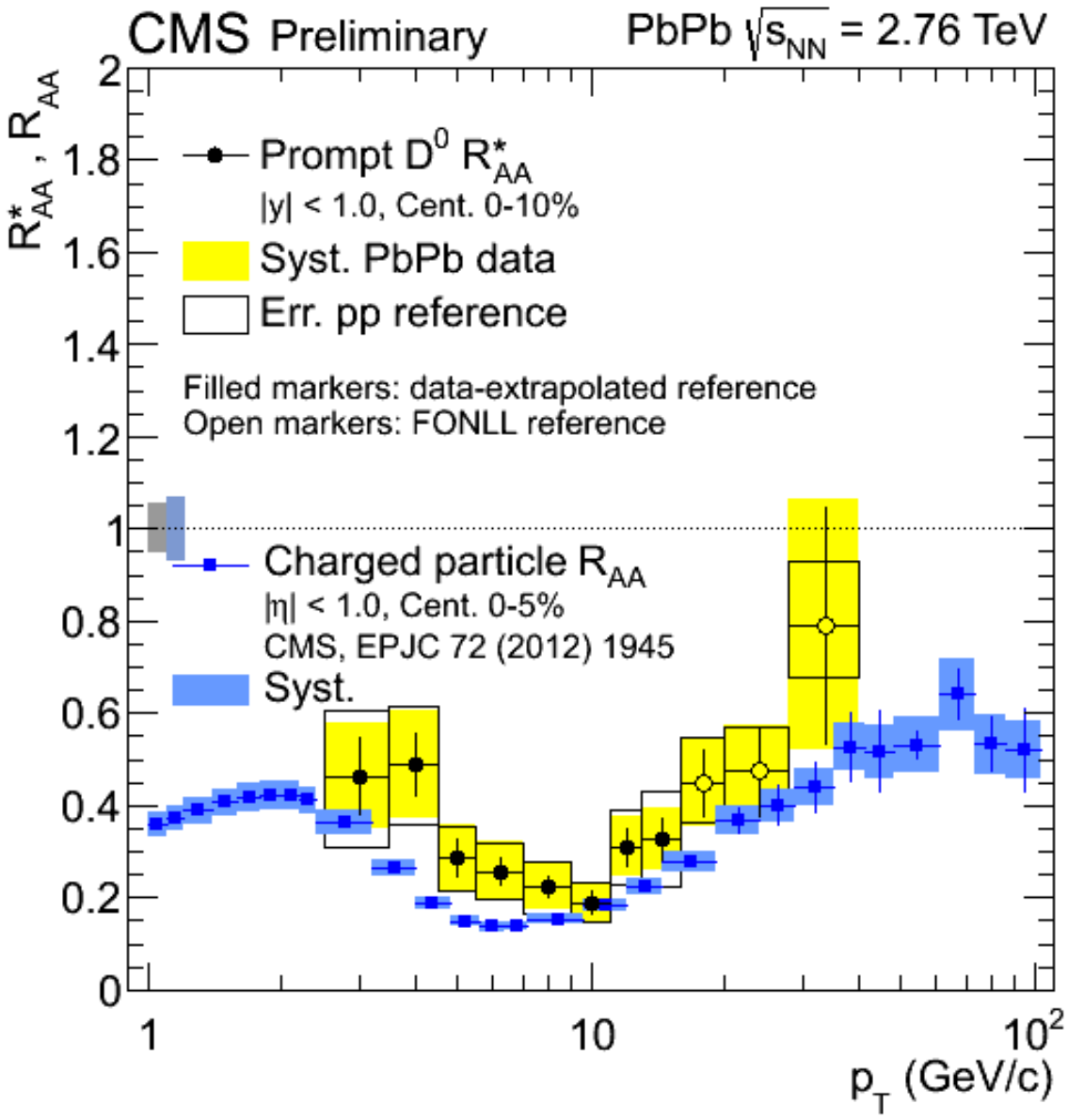
- Very successful data-taking with CMS in 2015!
  - A high statistics pp (2.5 billion events) and PbPb minimum bias sample at 5.02 TeV is collected for low p_T D^0 meson analyses
  - Online high p_T D^0 meson triggers are deployed during pp and PbPb data-taking period to record high p_T D^0 mesons
  - Online dimuon triggers are used to record high statistics J/ψ for B meson and non-prompt J/ψ analyses

- Looking forward to many exciting results from Run II

… stay tuned!

- Backup slides

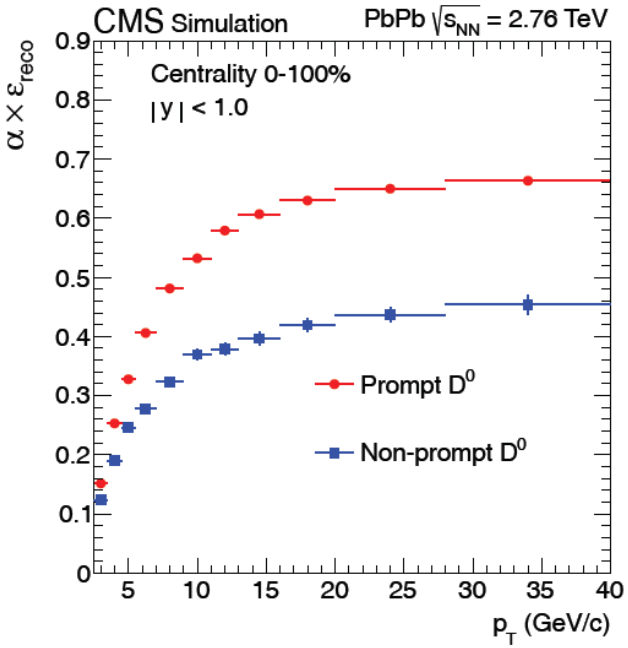
Comparison with charged particle R_{AA}



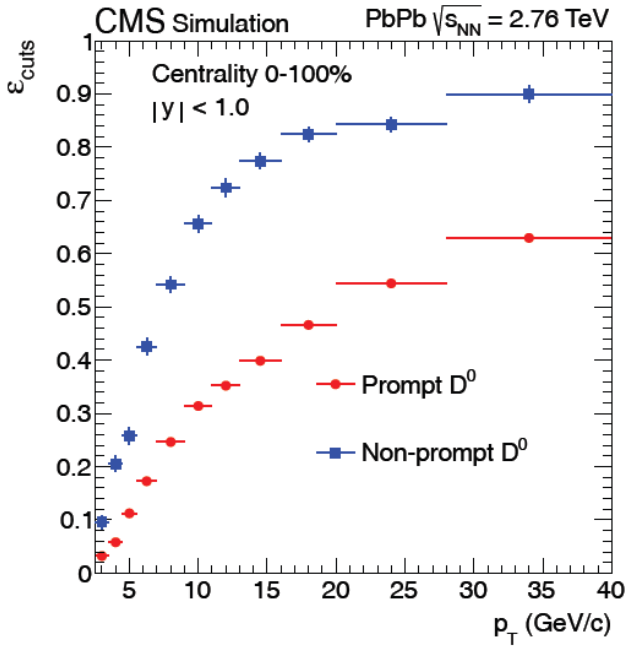
EPJC 72 (2012) 1945

CMS PAS HIN-15-005

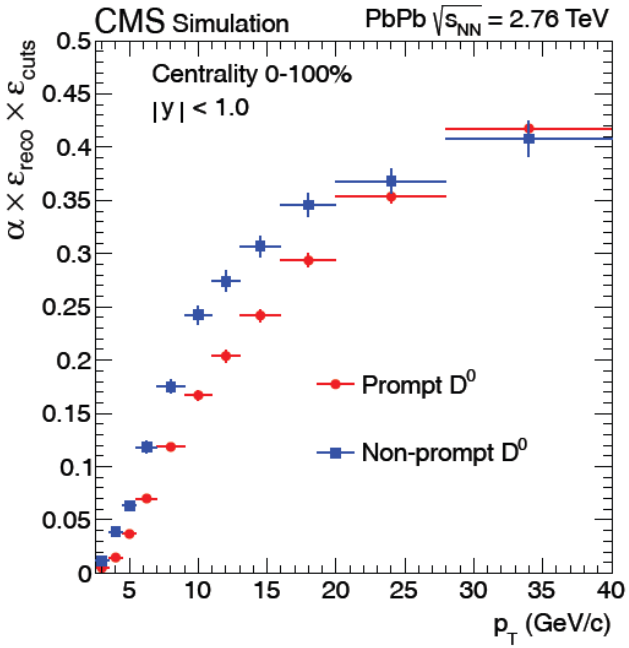
Efficiency and Acceptance Correction



Reconstruction

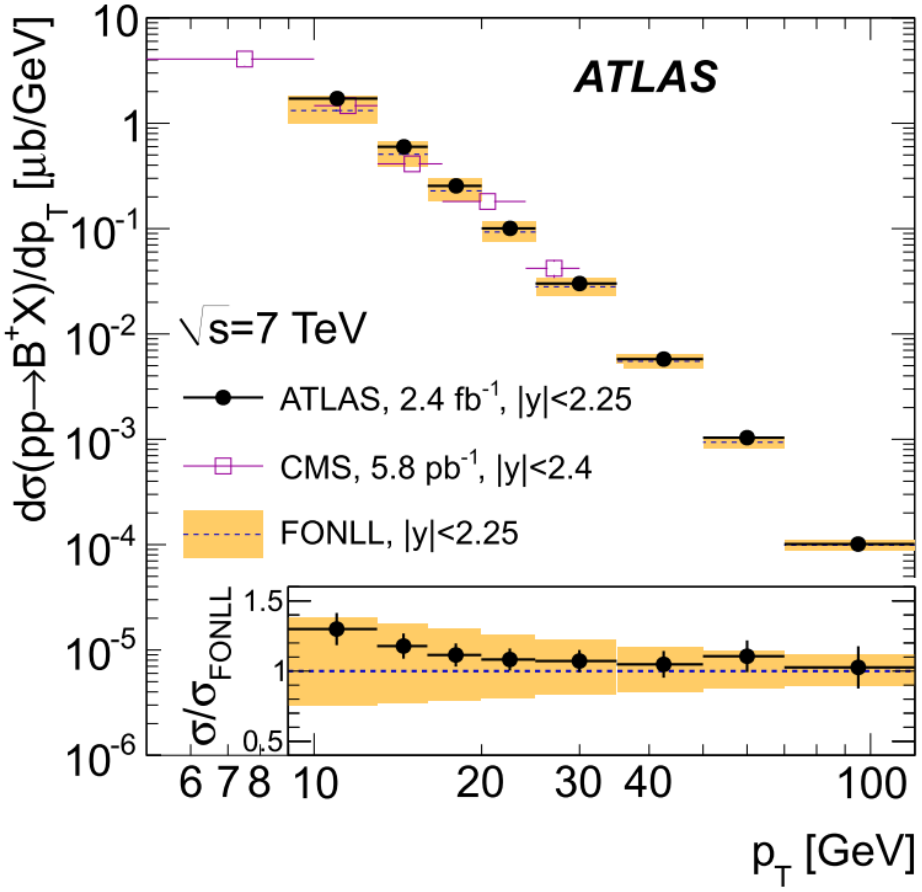


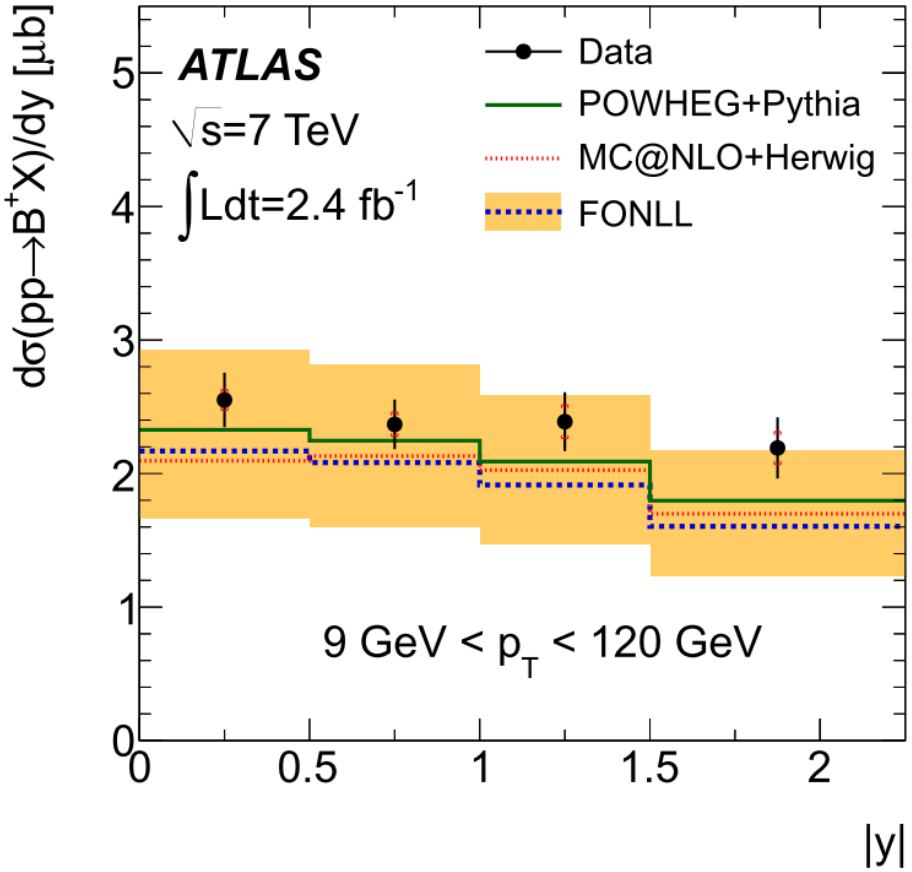
D meson selection

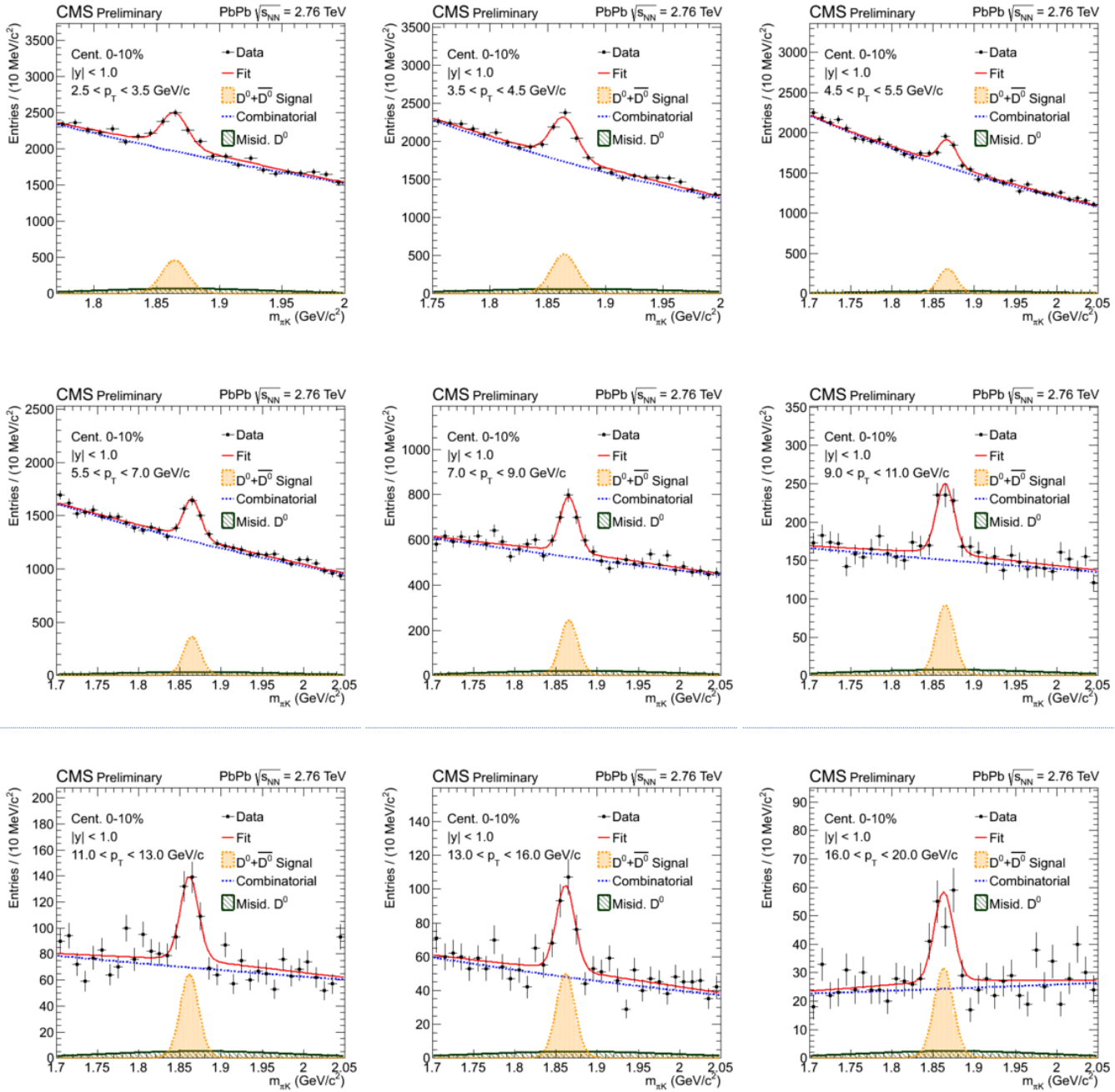


Full eff x acc

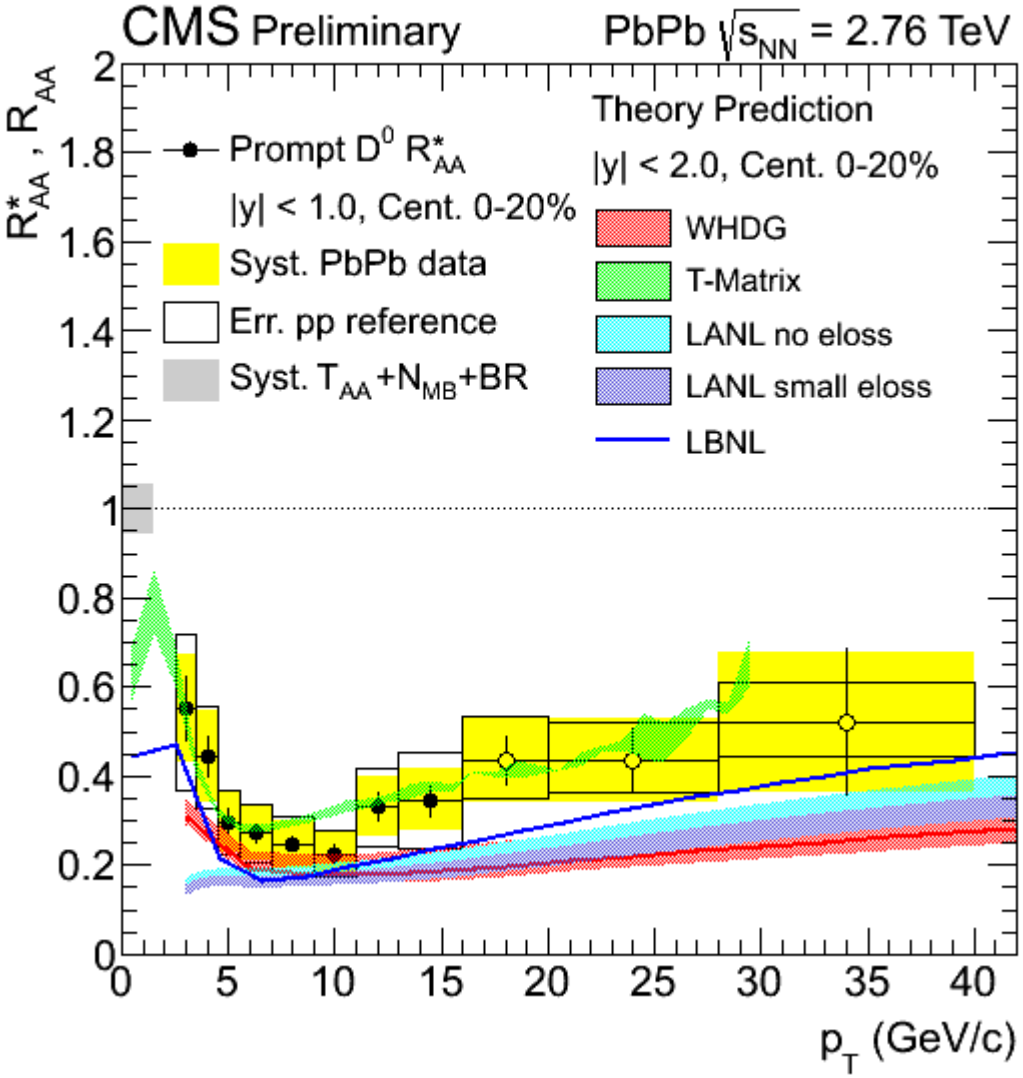
ATLAS result at 7 TeV






CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Cent. 0-10%
|y| < 1.0
2.5 < p_T < 3.5 GeV/c
3.5 < p_T < 4.5 GeV/c
4.5 < p_T < 5.5 GeV/c
5.5 < p_T < 7.0 GeV/c
7.0 < p_T < 9.0 GeV/c
9.0 < p_T < 11.0 GeV/c
11.0 < p_T < 13.0 GeV/c
13.0 < p_T < 16.0 GeV/c
16.0 < p_T < 20.0 GeV/c
Data
Fit
$D^0+\overline{D^0}$ Signal
Combinatorial
Misid. D^0
Entries / (10 MeV/c^2)
$m_{\pi K}$ (GeV/c^2)

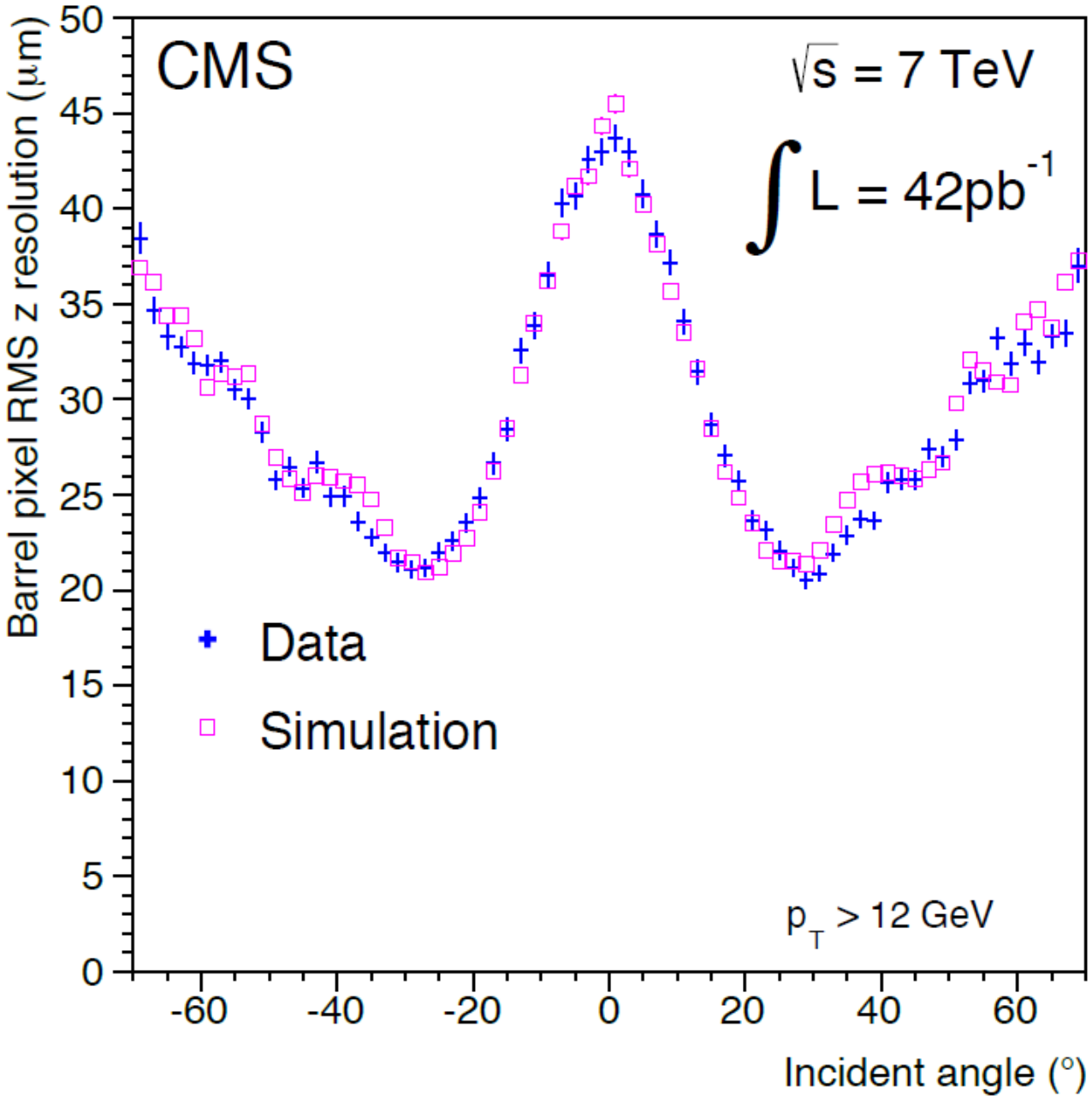
Nuclear Modification Factors:



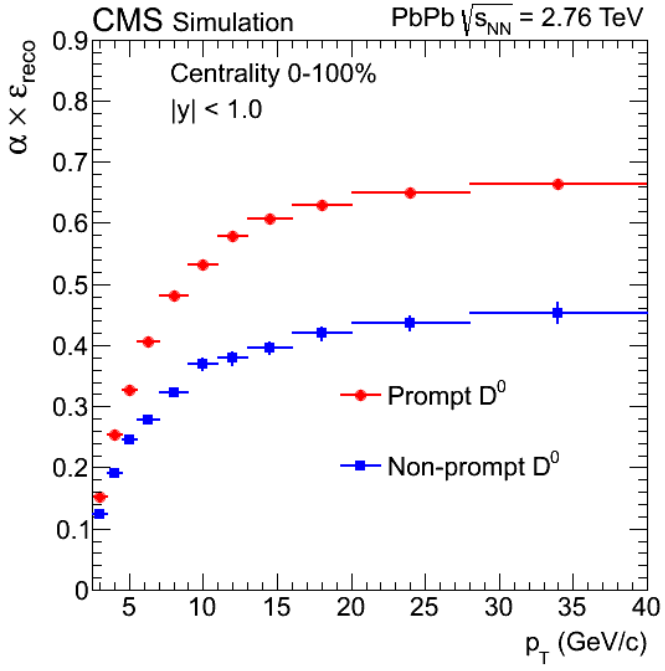
Information for pPb Analysis

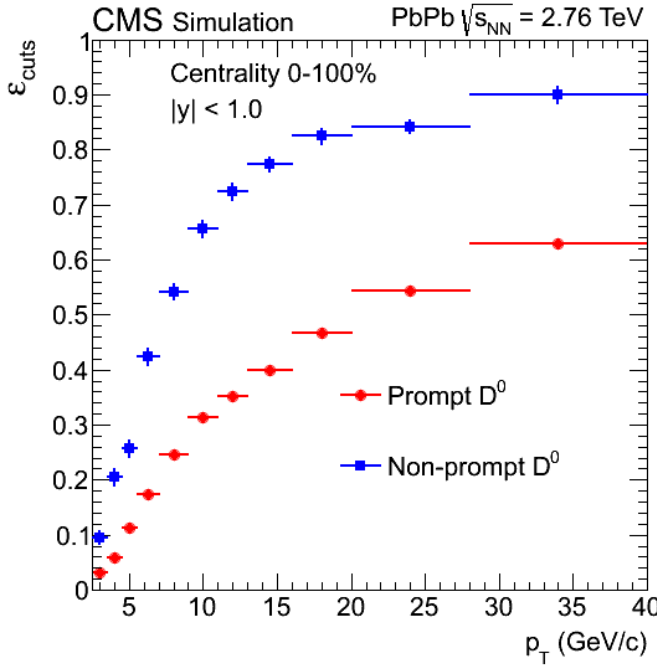
- CMS experiments of pPb collision in 2013
  - LHC delivered 4TeV (p) and 1.58 TeV/nucleon (Pb) beam
  - Integrated luminosity : 34.8 nb^{-1}
  - rapidity boosted to proton going side(forward) by 0.465 in lab frame
- Charged B, B_0, B_s trio are measured vi J/ψ decay channels
- Kinematic range covered
  - p_T : 10 – 60 GeV/c
  - rapidity : $|y_{CM}|<1.93$
- B^+ and B^- are inclusively measured and expressed as B^+ from now on

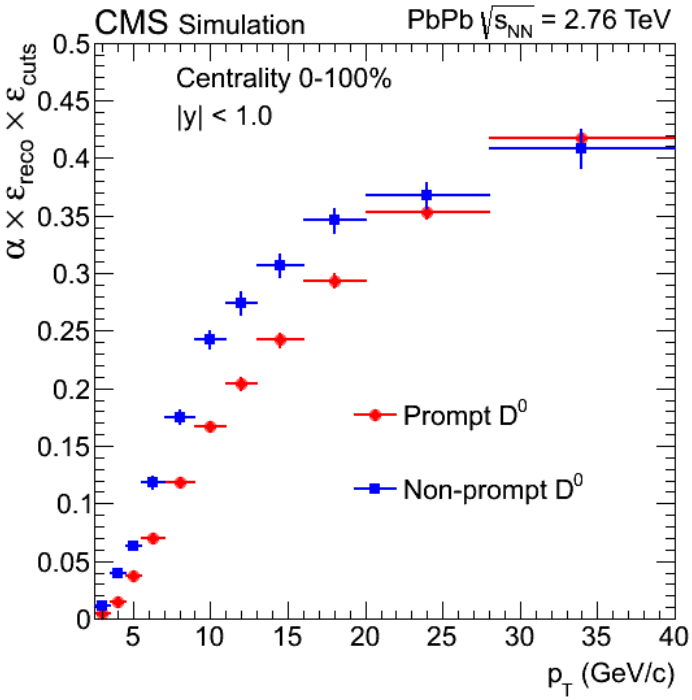
Hit Position Resolution



Acceptance and efficiency correction







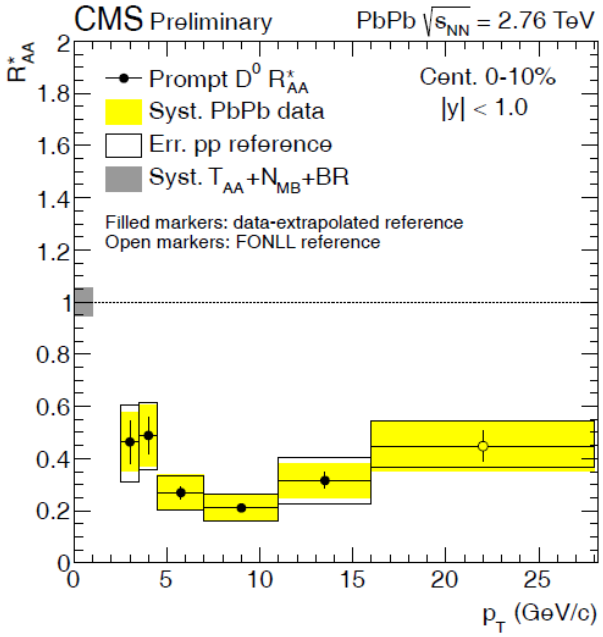
- **$a \times e_{reco}$: prompt D0 higher than non-prompt D0 (D0 from B-hadron decay)**
  - Tracks from non-prompt D^0 are more displaced from primary vertex than tracks from prompt D^0
  - Hi tracking has lower efficiency on further displaced tracks

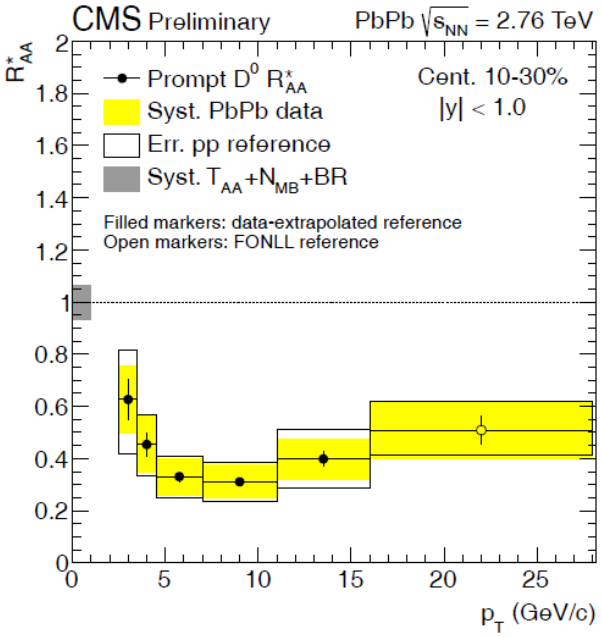
- **e_{cuts}: non-prompt D0 higher than prompt D0**
  - Non-prompt D^0 are more displaced from primary vertex than prompt D^0, thus bigger d0/error_d0

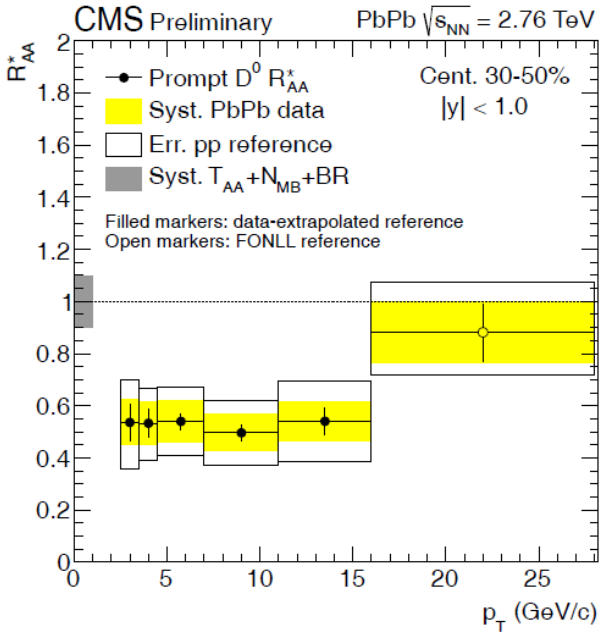
CMS PAS HIN-15-012

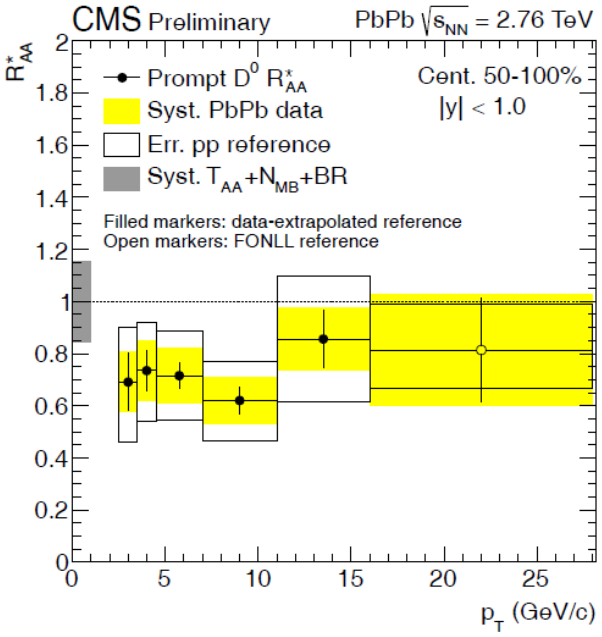
p_T(GeV/c)	$d_0/\sigma(d_0)$	α (radians)	Vertex Probability
2.5-3.5	> 5.90	< 0.12	> 0.248
3.5-4.5	> 5.81	< 0.12	> 0.200
4.5-5.5	> 5.10	< 0.12	> 0.191
5.5-7.0	> 4.62	< 0.12	> 0.148
7.0-9.0	> 4.46	< 0.12	> 0.102
9.0-11.0	> 4.39	< 0.12	> 0.080
11.0-13.0	> 4.07	< 0.12	> 0.073
13.0-16.0	> 3.88	< 0.12	> 0.060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


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 0-10%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 10-30%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 30-50%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 50-100%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)