# Heavy Flavor Jet and Meson Measurements from CMS

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*(For the CMS collaboration)*

*EMMI RRTF: Extraction of heavy-flavor transport coefficients in QCD Matter*

**GSI, Germany**

18-22 July, 2016

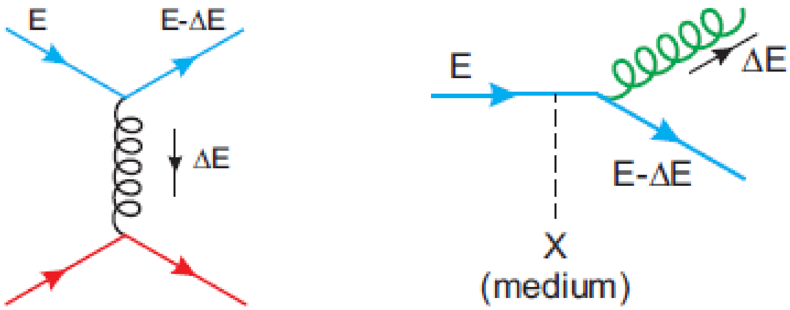
# Flavor Dependence of Parton Energy Loss

- 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

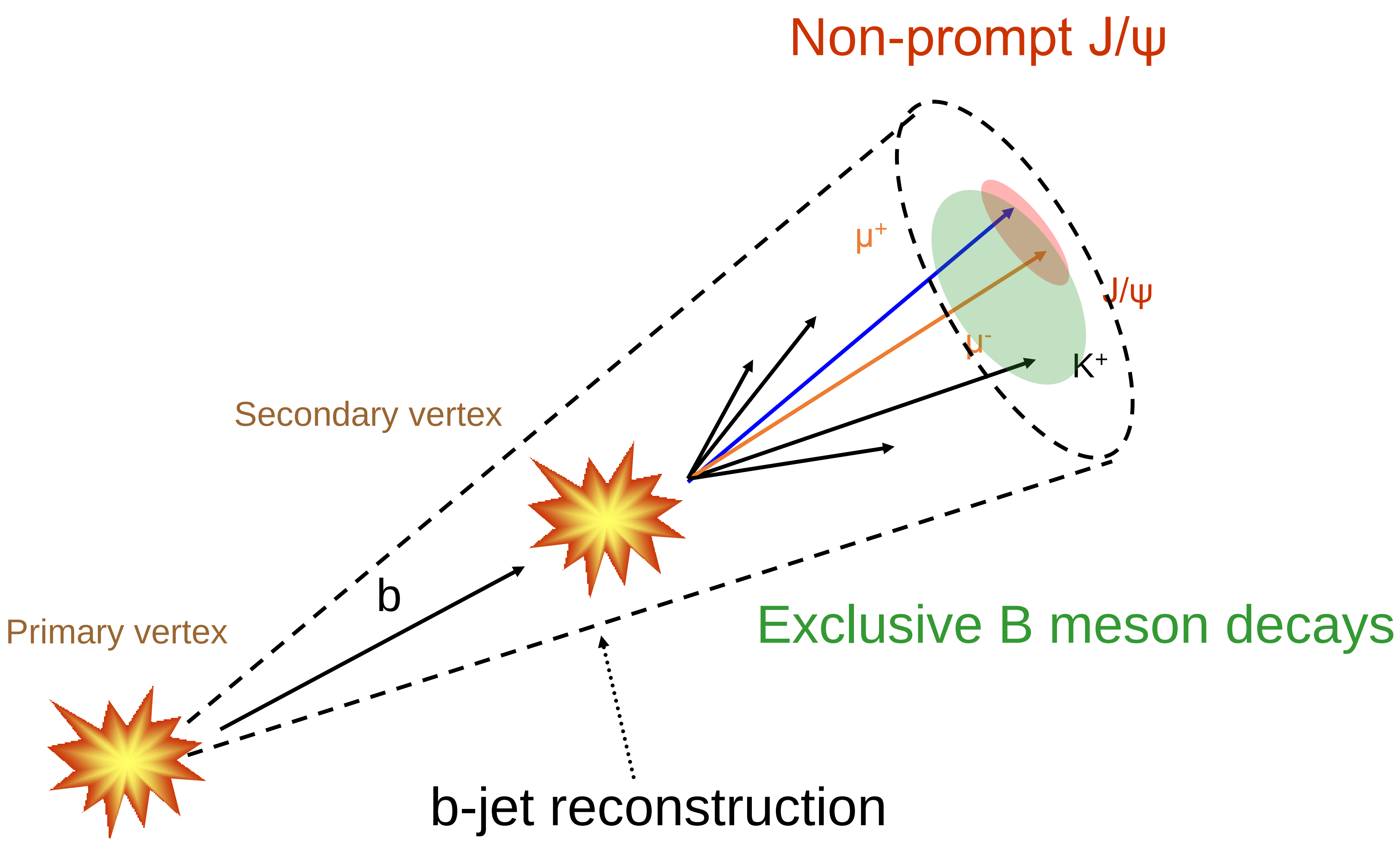
Collisional energy loss

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 $p_T$

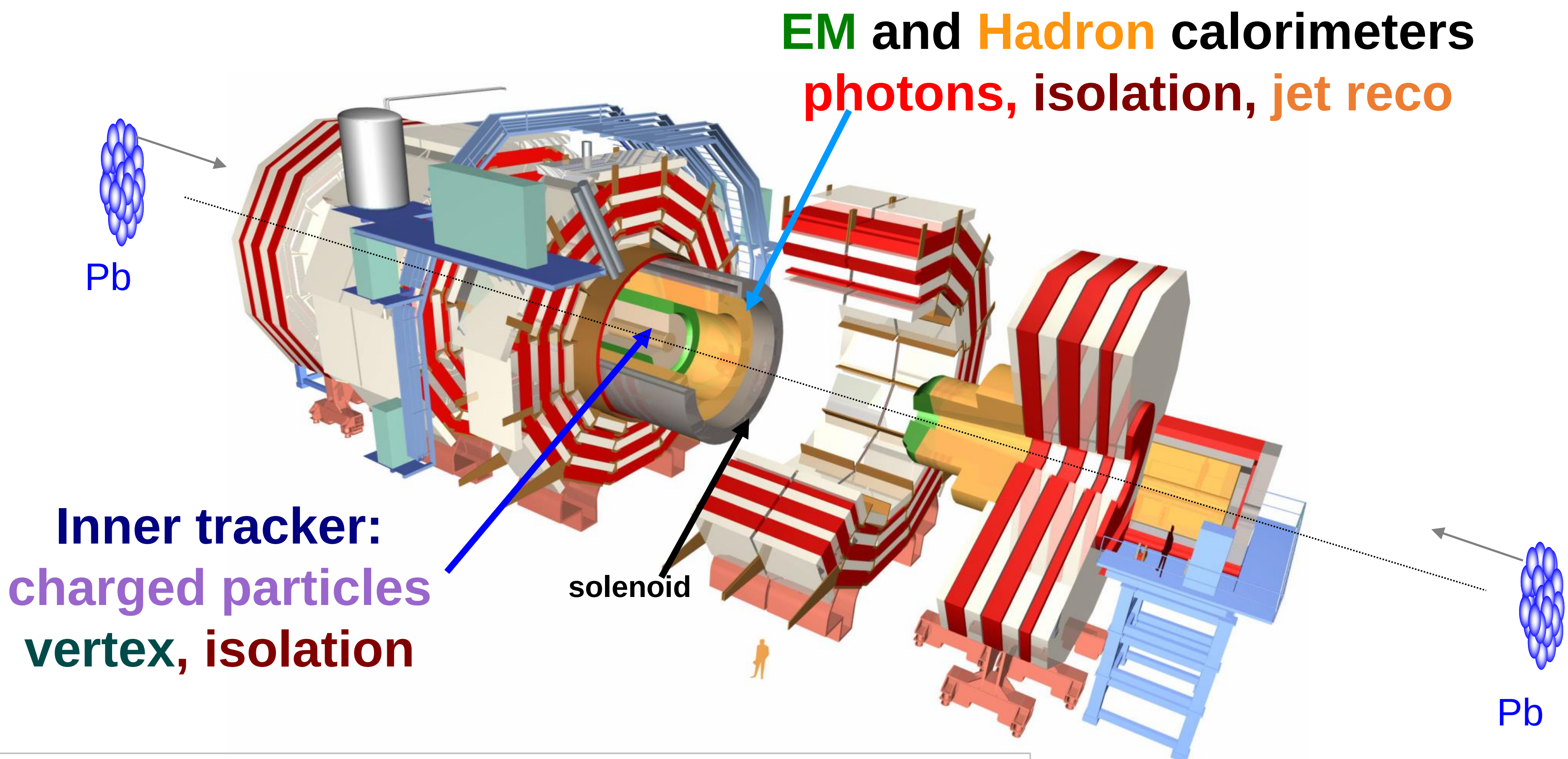
# Heavy Flavor Measurements

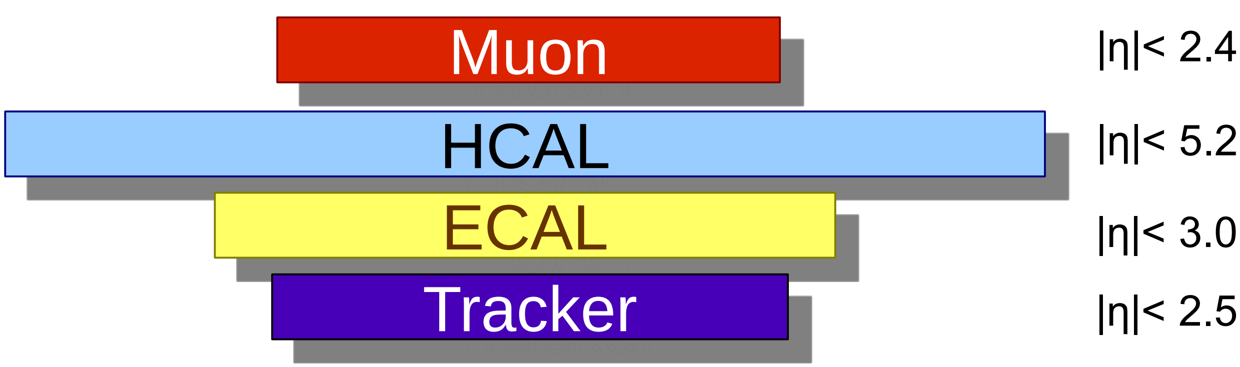



**Requirement:** flexible trigger system, muon / electron detection, secondary vertex reconstruction, jet reconstruction

# The CMS Detector

# The CMS Detector

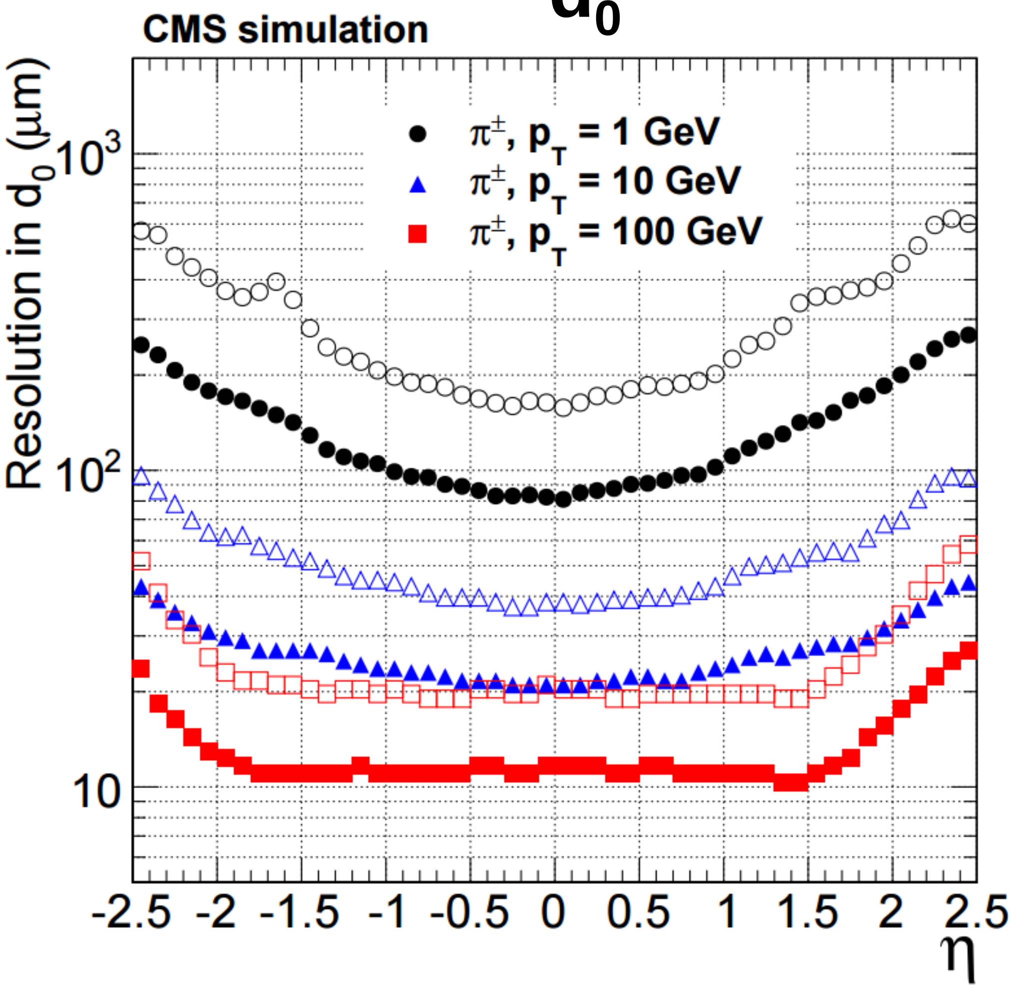


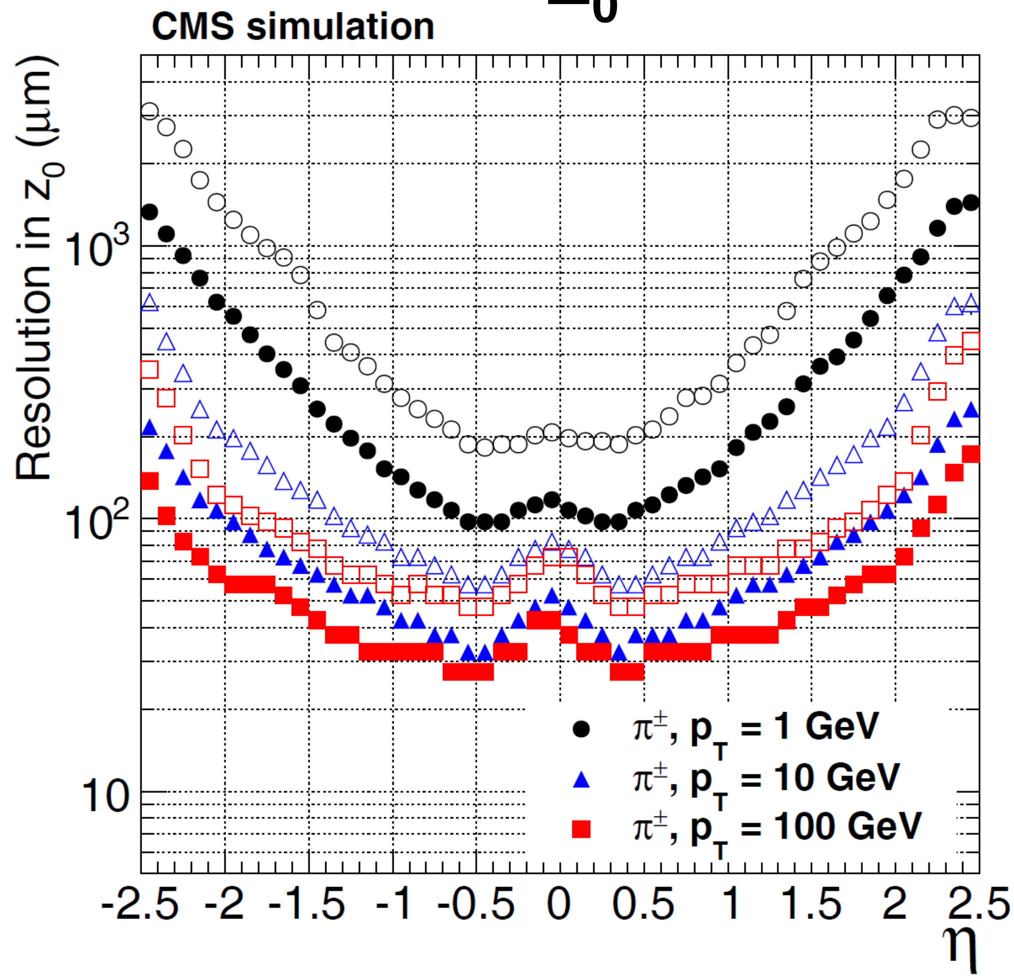
# Charged Track Impact Parameter Resolution in pp

CMS TRK-PAS-11-001

$d_0$



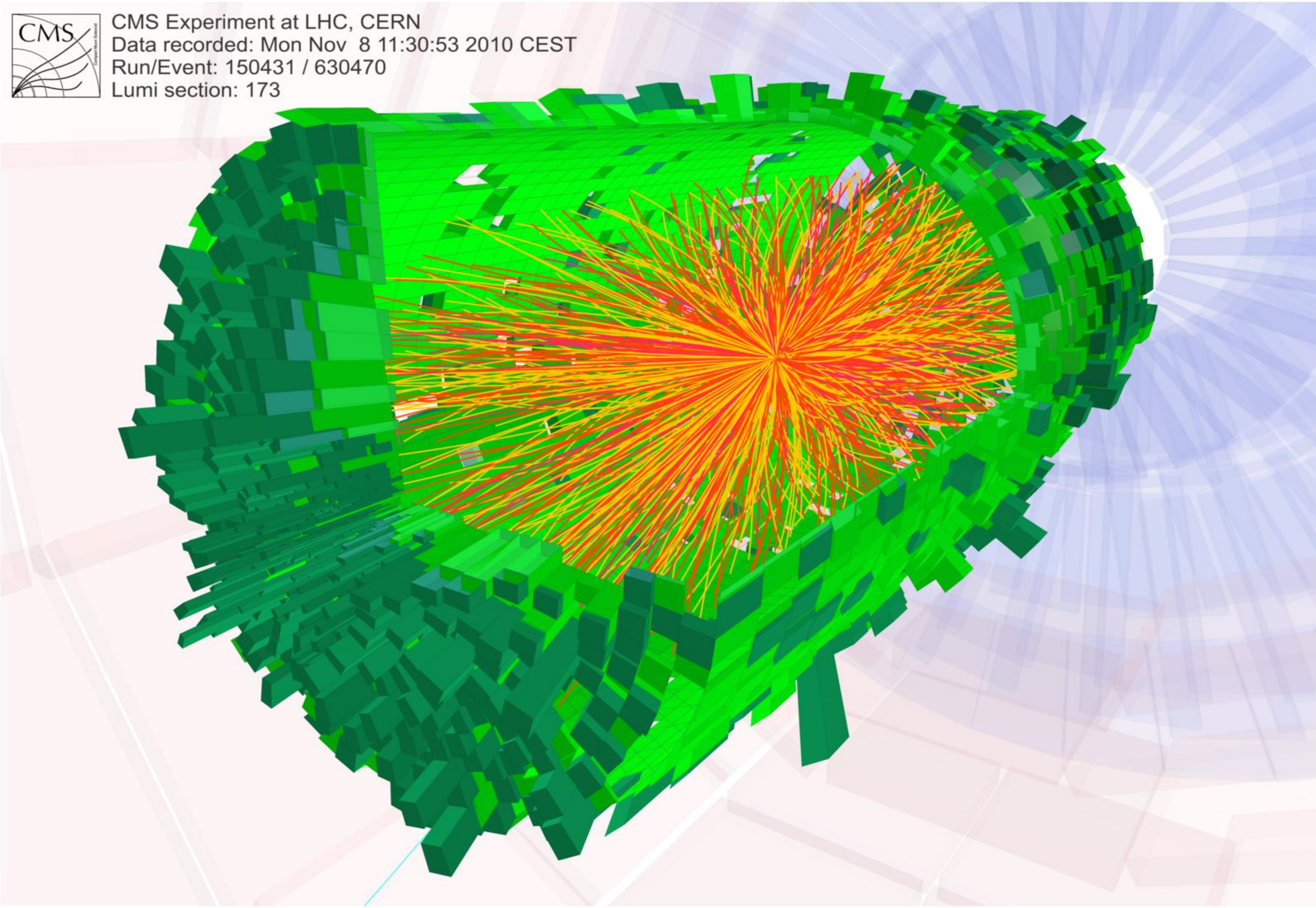

$z_0$



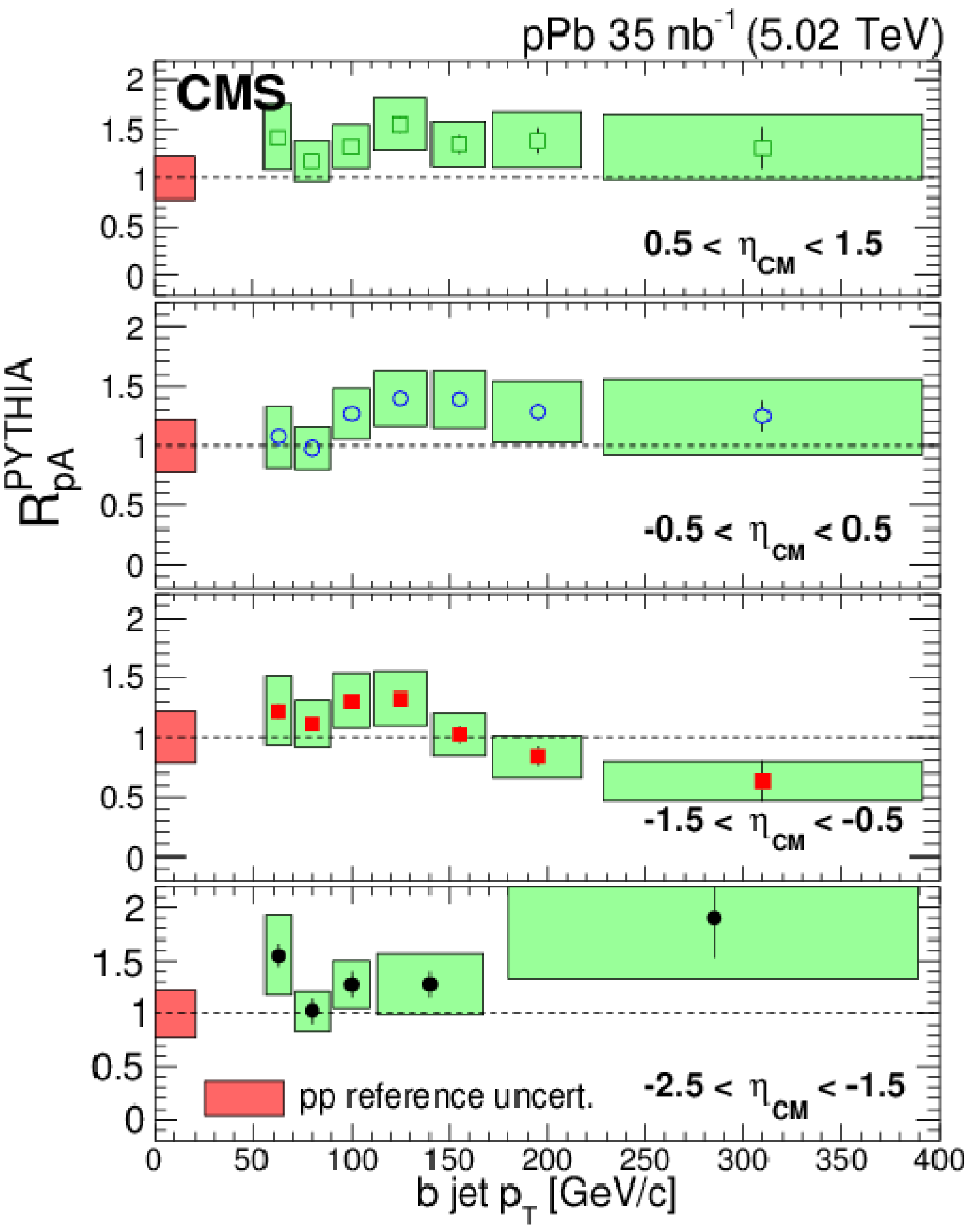

Track impact parameter resolution:

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

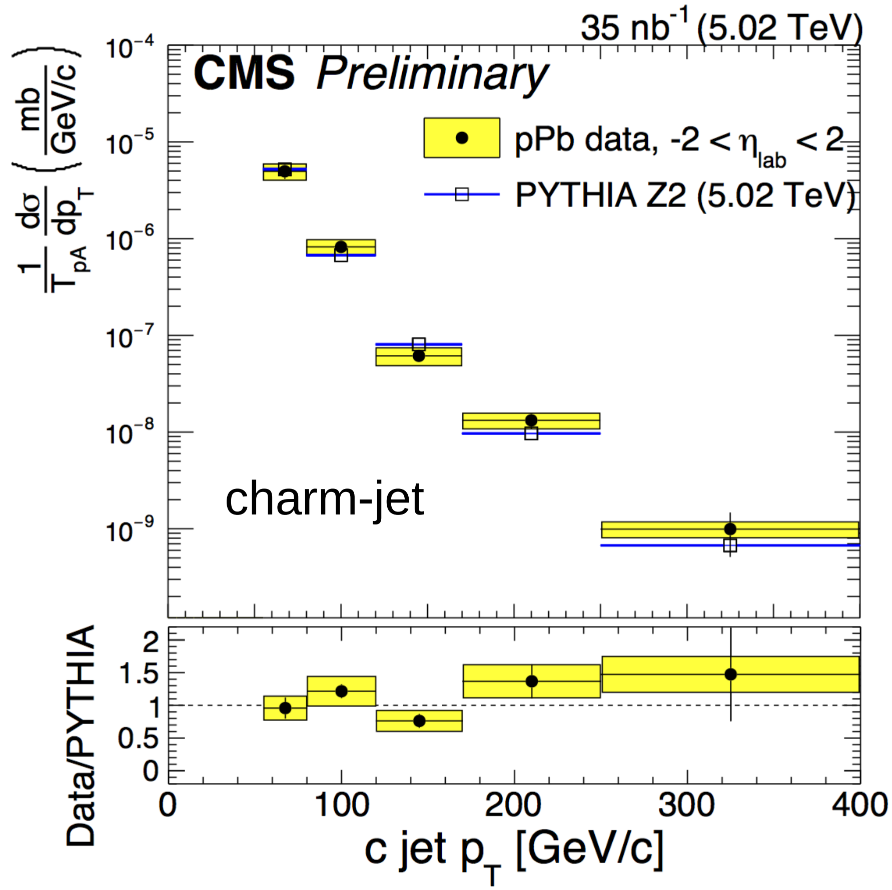
# Results from pp and Run I Heavy Ion Data



# b-Jet and c-Jet $R_{pA}$ at 5.02 TeV




PLB 754 (2016) 59



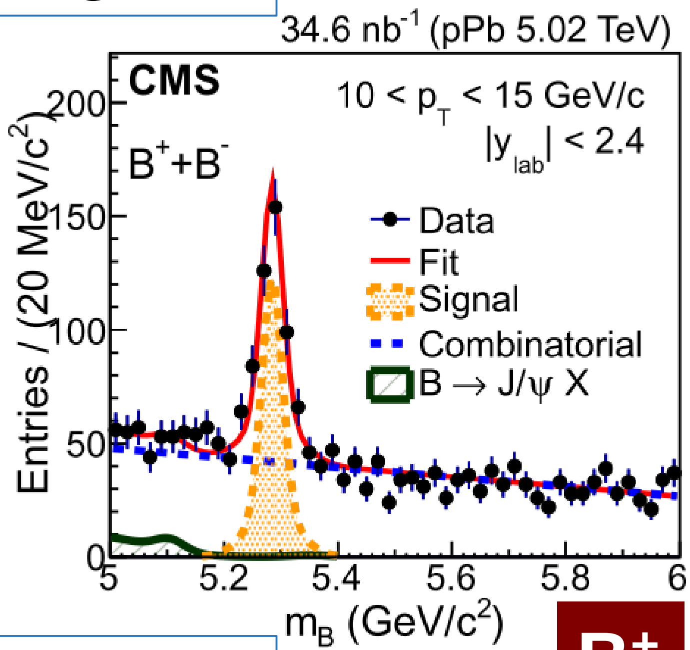

CMS PAS HIN-15-012

- First **c-jet** and b-jet results in pPb collisions.
- pp reference obtained from PYTHIA6
- Within uncertainties, no significant CNM effect at $p_T$ > 50 GeV/c

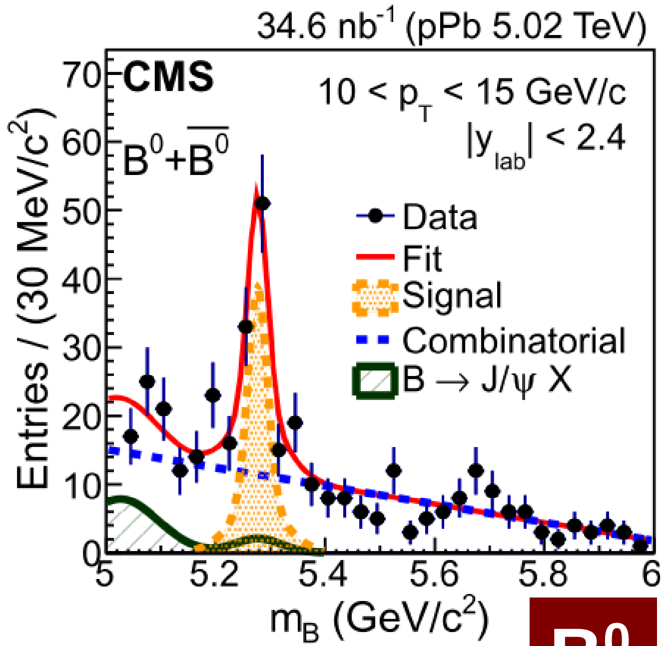
# B Meson Mass Spectra in pp and pPb

pPb @ 5 TeV

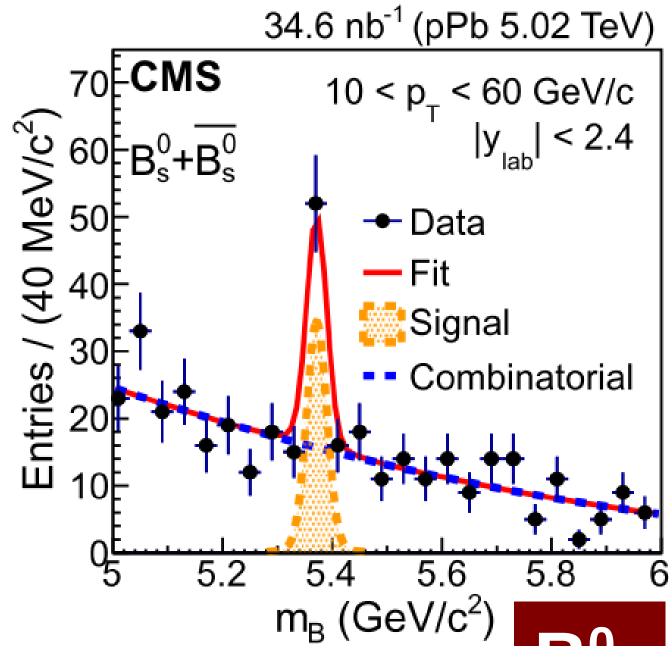
PRL 116 (2016 032301




$B^+$

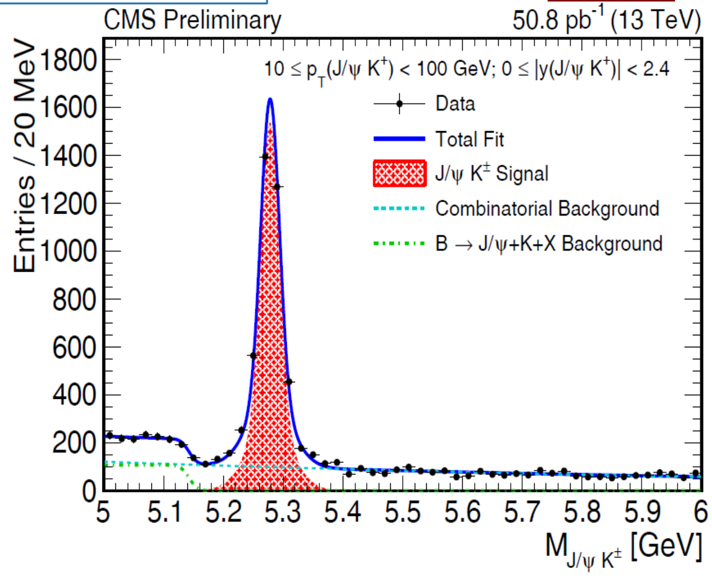



$B^0$




$B^0_s$

pp @ 13 TeV




Direct reconstruction of B mesons

$B^+ \to J/\psi K^+ \quad \to \mu^+\mu^- K^+$

$B^0 \to J/\psi K^{0*} \to \mu^+\mu^- K^+\pi^-$

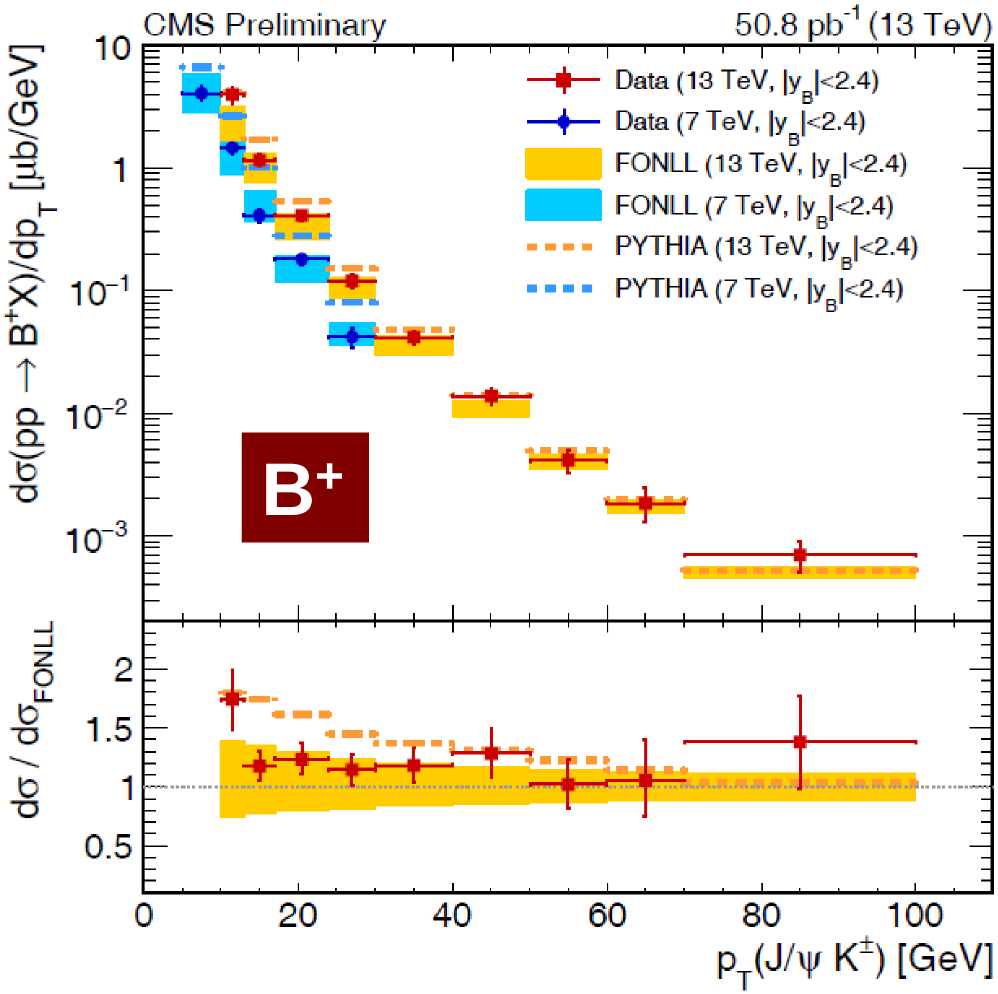
$B_s \to J/\psi \varphi \quad \to \mu^+\mu^- K^+K^-$

Significant B meson signal was observed in pp and pPb collisions

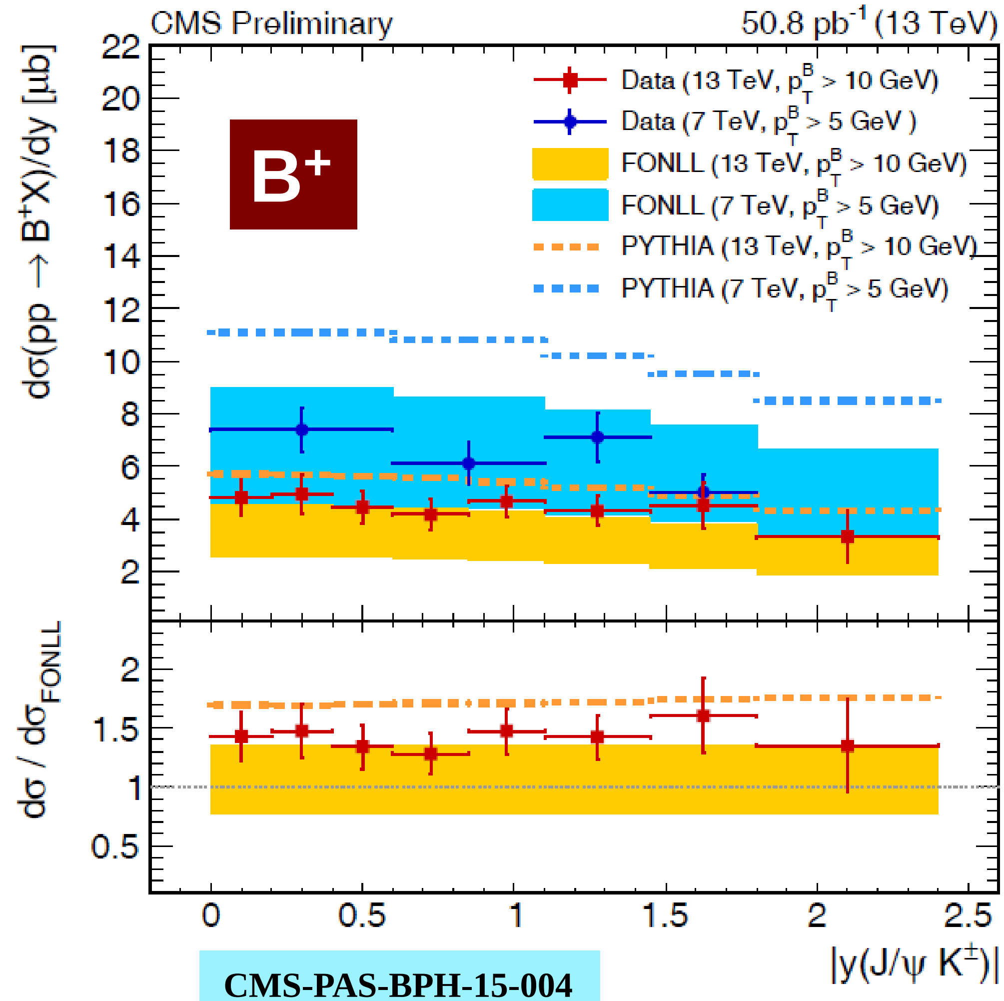
CMS-PAS-BPH-15-004

# Results from pp @ 7 and 13 TeV

Transverse momentum spectra




Rapidity distribution



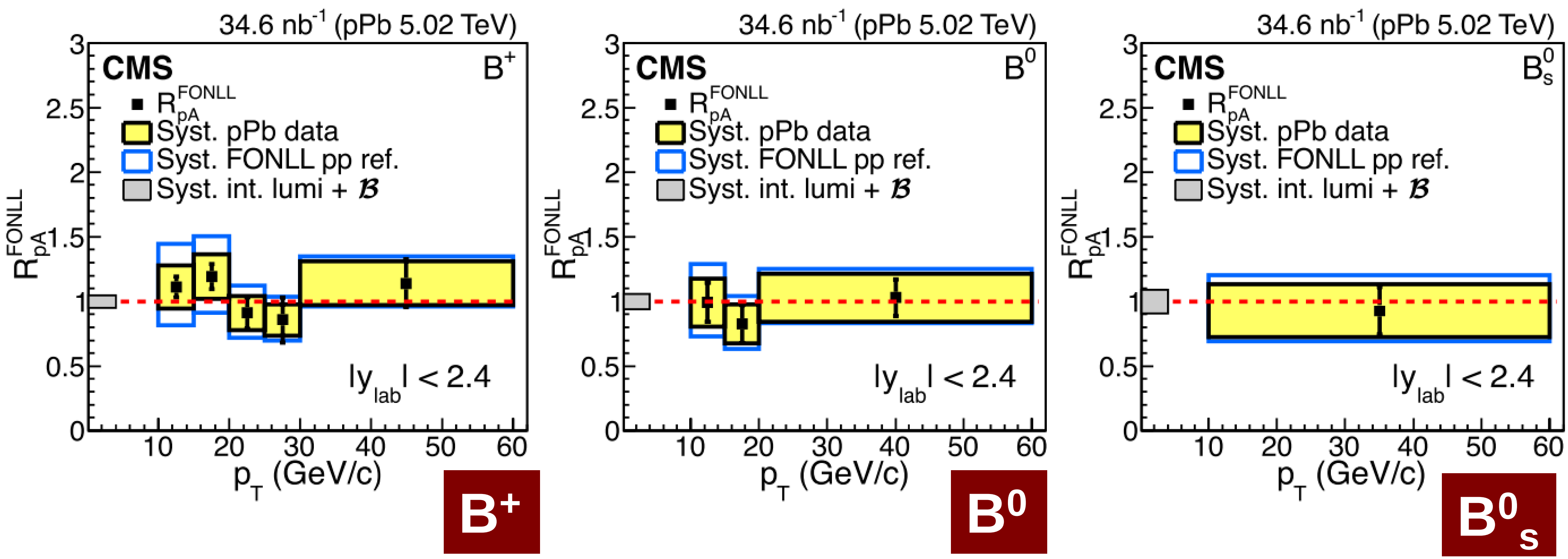

**CMS-PAS-BPH-15-004**

- pp at **7 TeV** and **13 TeV** are in agreement with FONLL within the quoted uncertainties
- The central values of **7 TeV** data match better with FONLL center value than **13 TeV**
- PYTHIA doesn't give a perfect description of the $B^+$ $p_T$ spectra

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

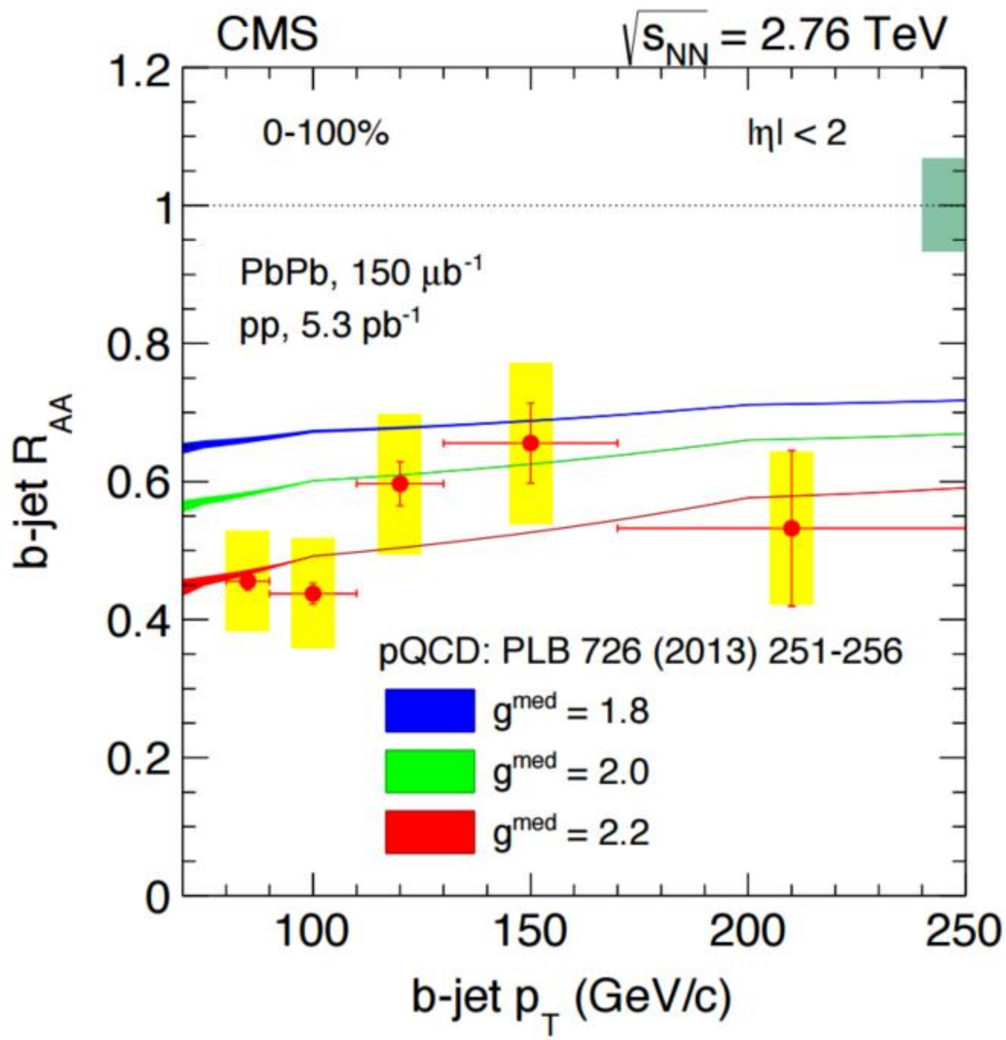
$$R_{pA}^{FONLL}(p_T) = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma^{FONLL}}{dp_T}\right)_{pp}}$$

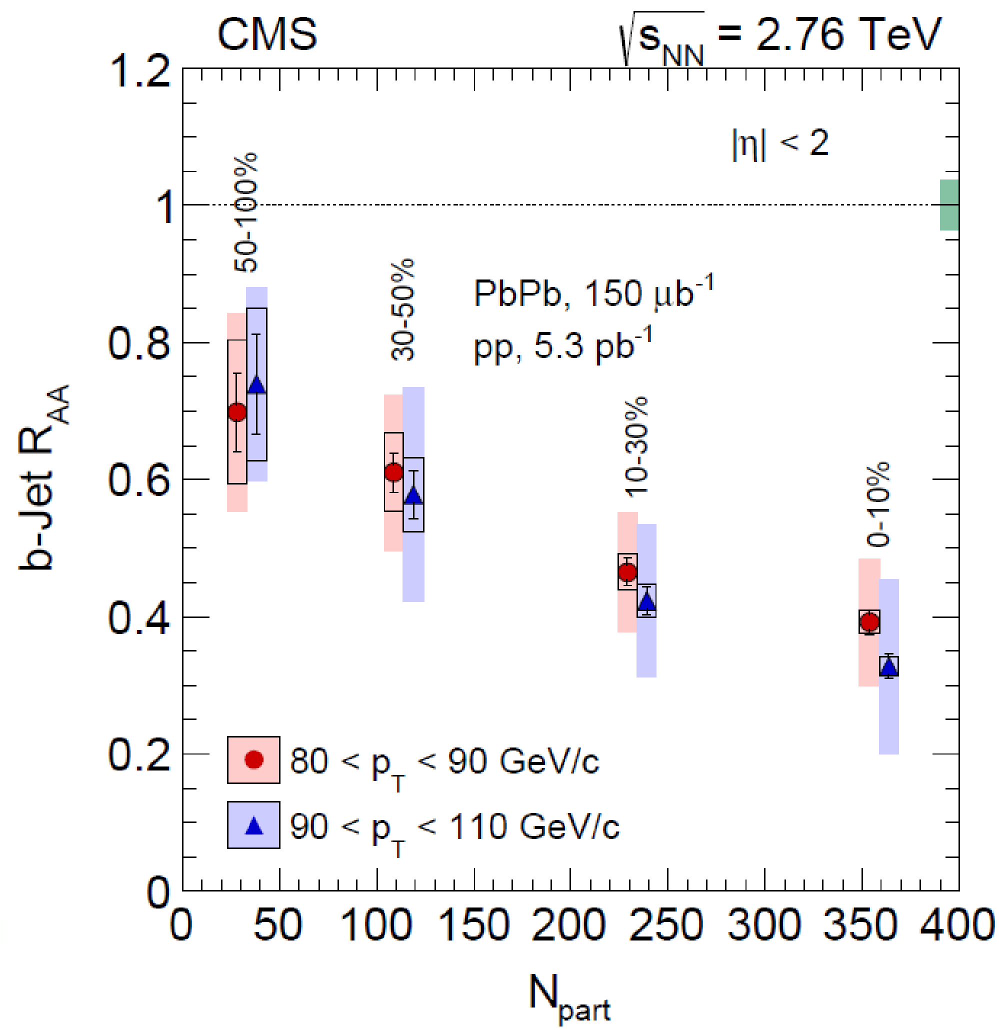
**PRL 116 (2016) 032301**
**arXiv:1508.06678**




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

# b-Jet $R_{AA}$

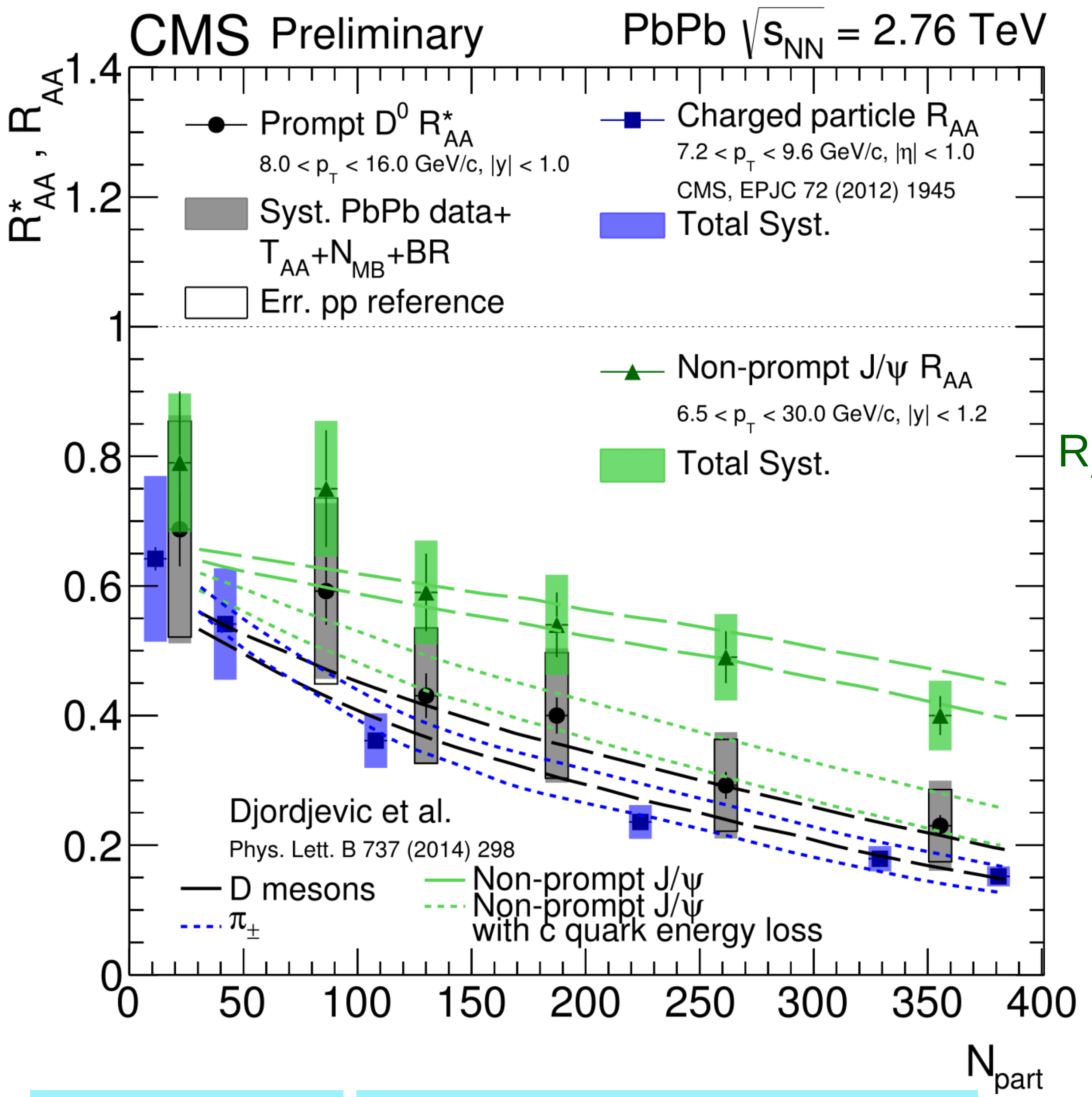



PRL 113, 132301 (2014)

- First measurement of b-jet $R_{AA}$**!!**
- **Evidence of b-jet suppression in PbPb collisions**
- Suppression favors pQCD model with stronger jet-medium coupling

# Flavor Dependence of $R_{AA}$ in PbPb at 2.76 TeV




Prompt $D^0$ $R^*_{AA}$

Charged particle $R_{AA}$

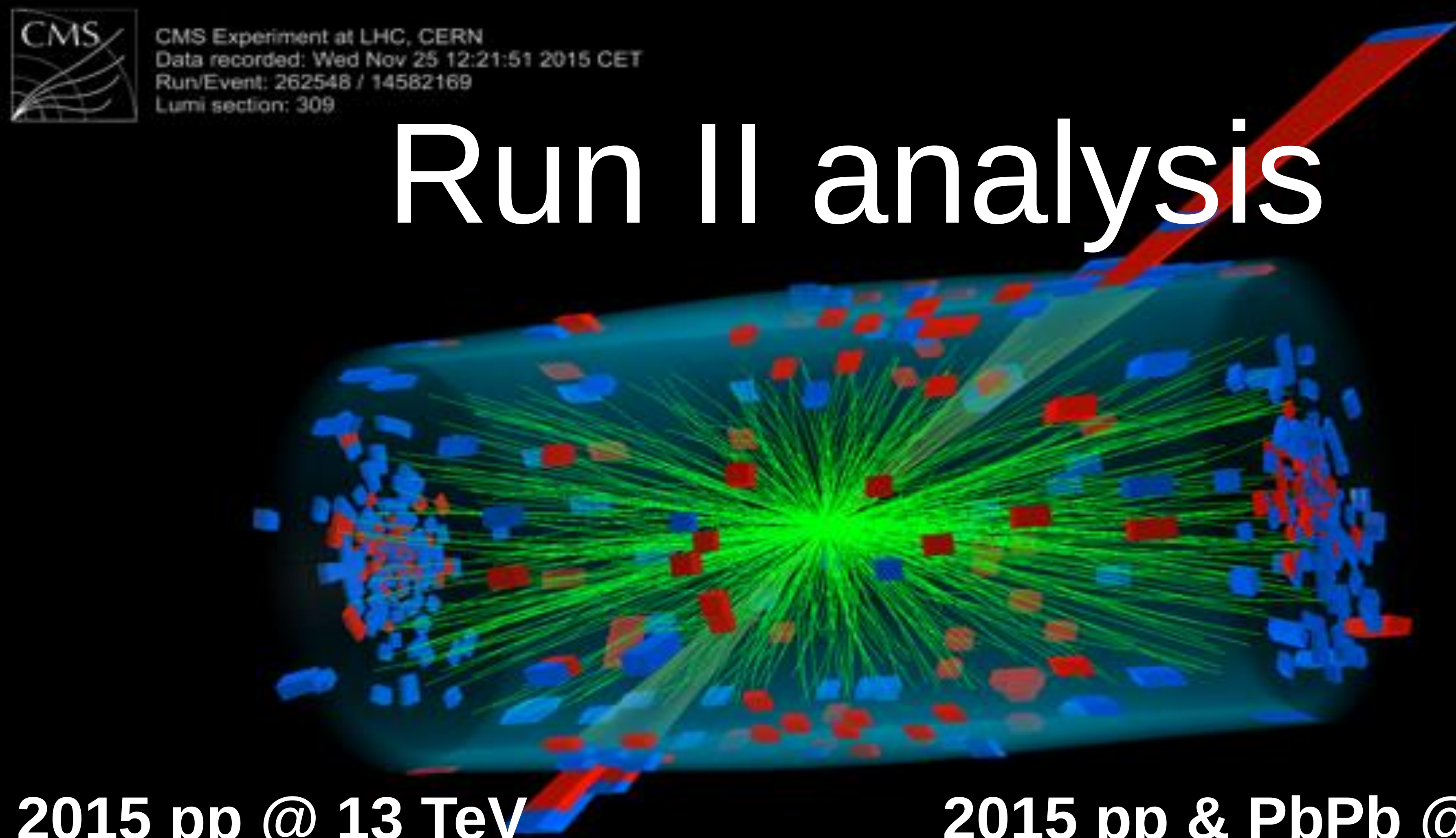
Non-prompt J/ψ $R_{AA}$

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

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**

# Run II analysis

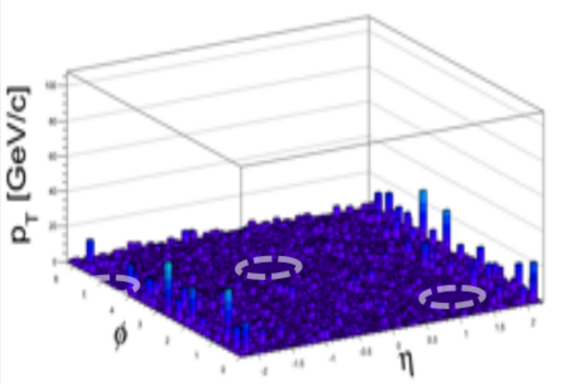



**2015 pp @ 13 TeV**

**2015 pp & PbPb @ 5 TeV**

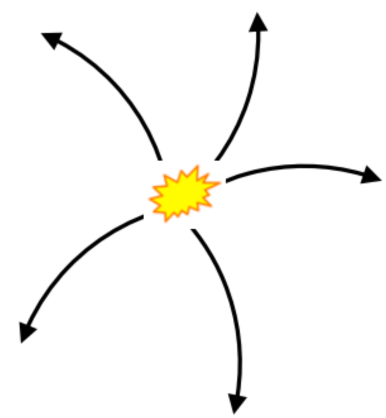
# Online $D^0$ triggers

**Hardware L1 jet triggers selection**




- Level-1 (L1) jet algorithm with online background subtraction

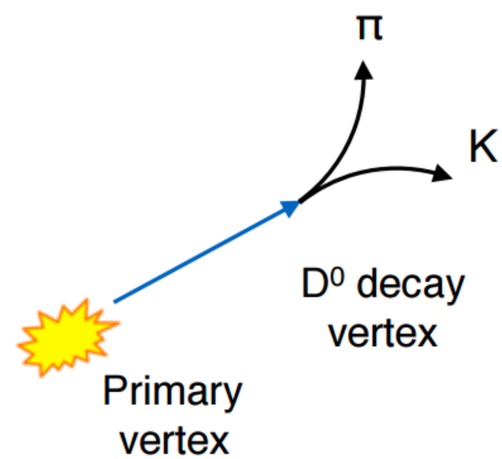
**Track selection in software triggers**



Track seed $p_T$ cut applied:

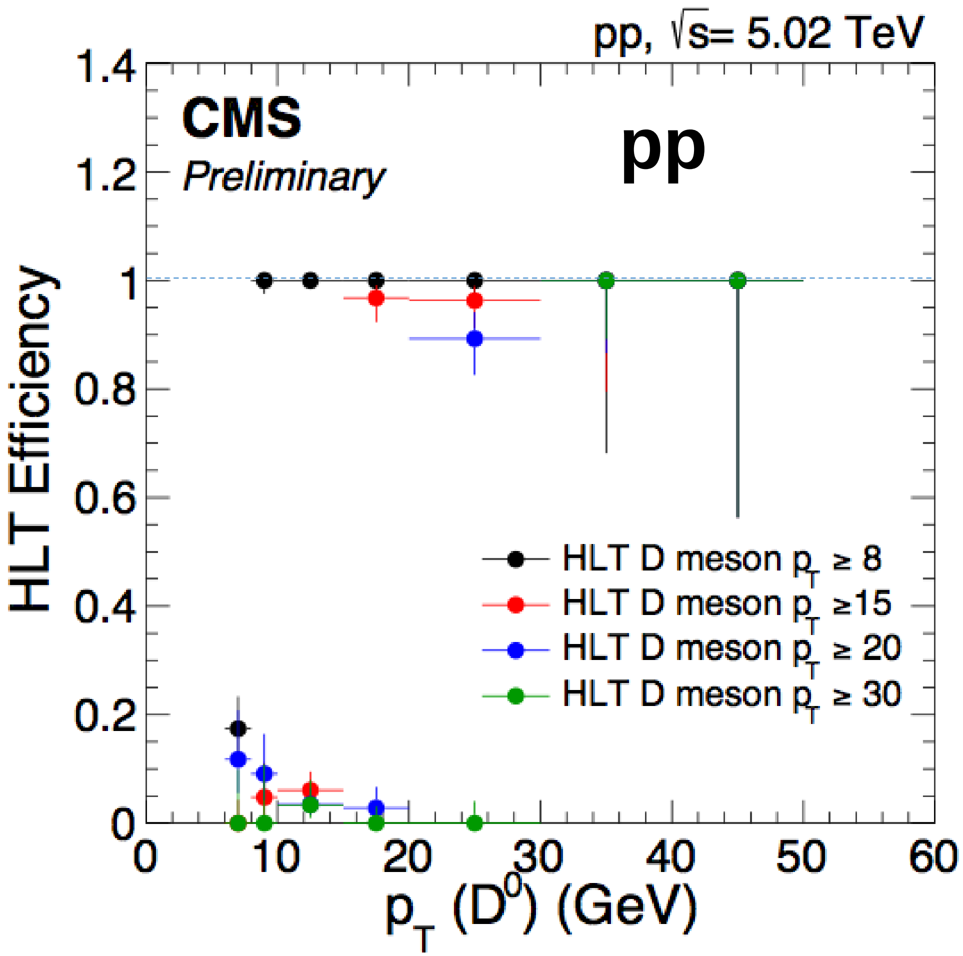
- $p_T > 2$ GeV for pp
- $p_T > 8$ GeV for PbPb

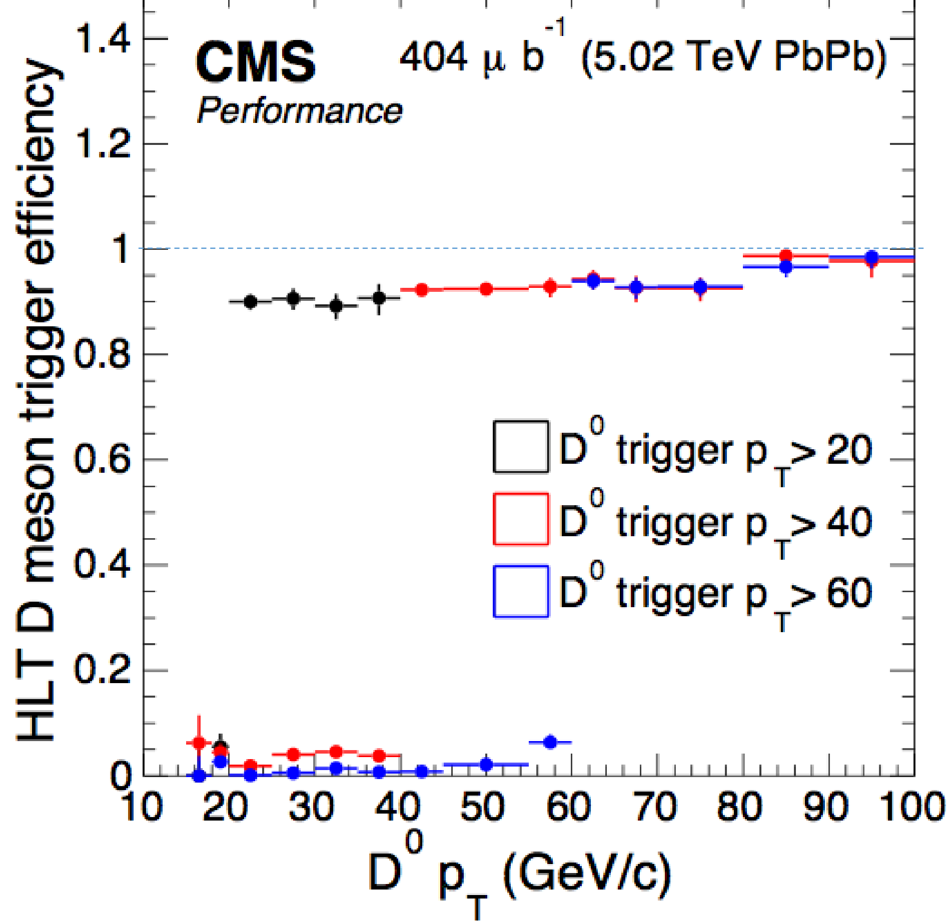
**$D^0$ selection**




- $D^0$ online reconstruction
- loose selection based on $D^0$ vertex displacement

# Performance of $D^0$ triggers




pp efficiency reaches 100% above the $D^0$ $p_T$ trigger threshold

→ PbPb trigger efficiency is better than 90%, evaluated by minimum-bias data and jet triggers

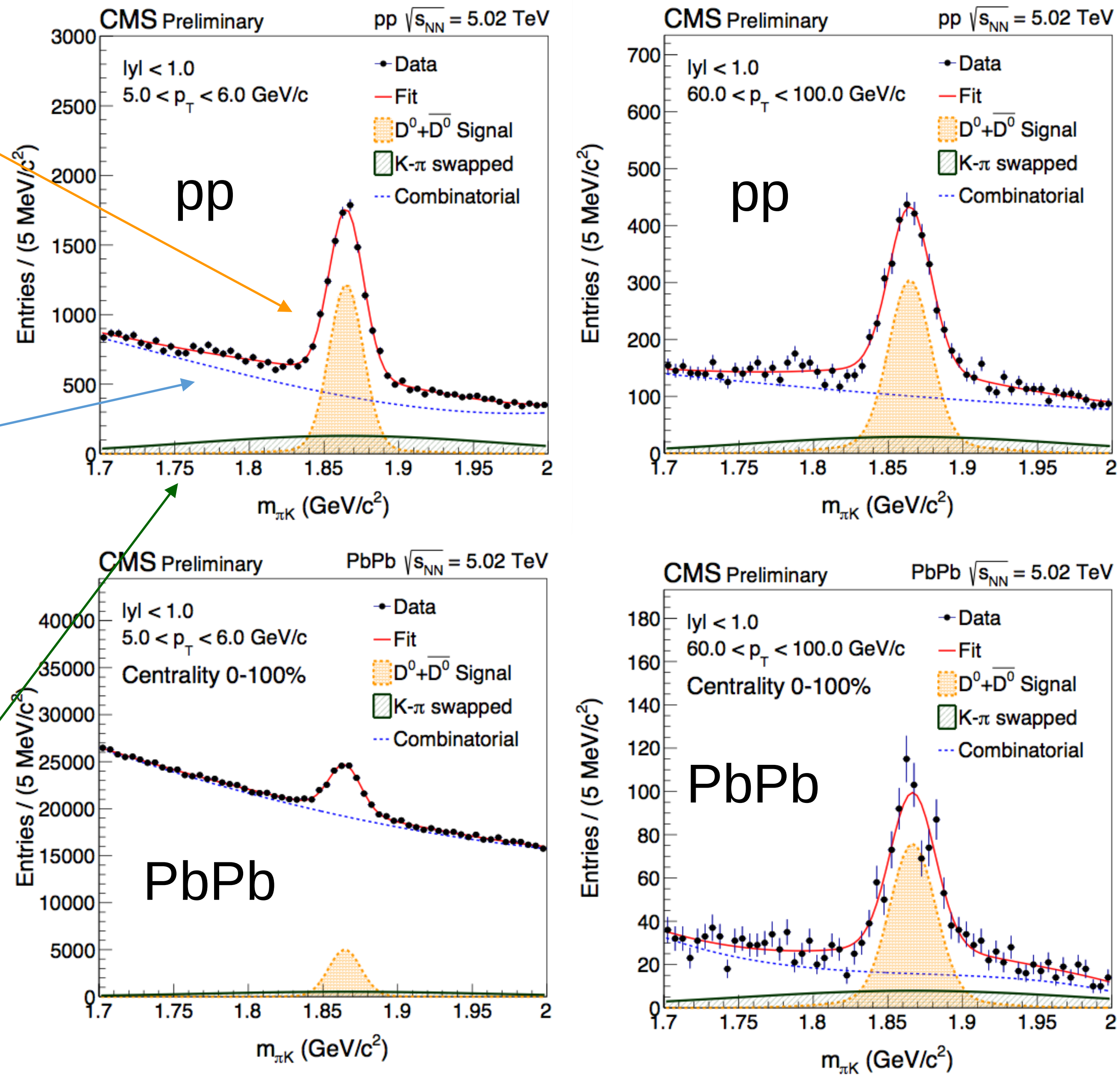
# $D^0$ mass spectra in pp and PbPb at 5.02 TeV

Double Gaussian for
**$D^0 \rightarrow K\pi$ signal**

3rd order polynomial for
**combinatorial background**

Gaussian shape for
**swapped mass hypothesis**

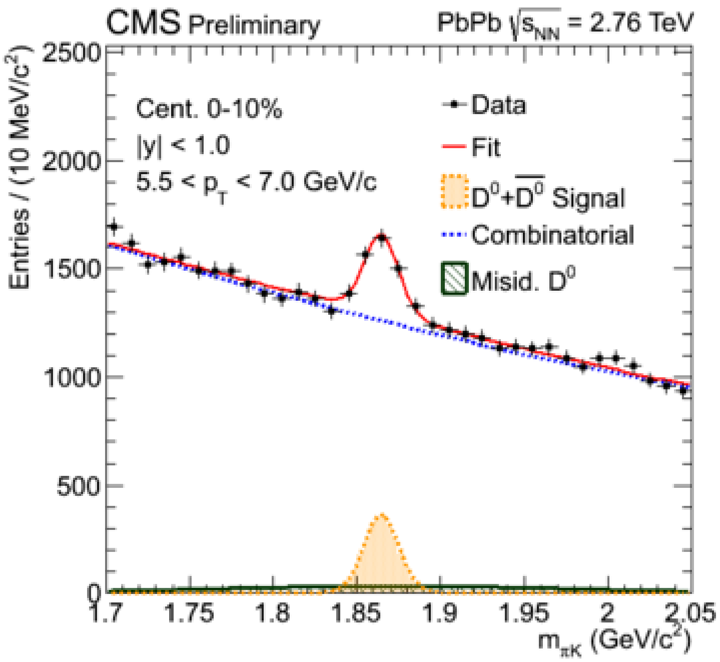
**$5 < p_T < 6$ GeV/c** **$60 < p_T < 100$ GeV/c**

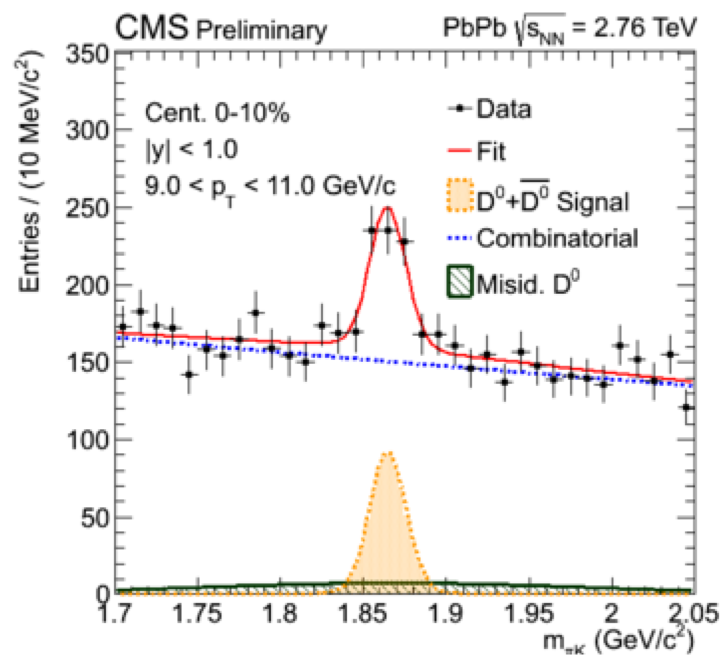


# $D^0$ Signal to Background Ratio Comparison

0-10%

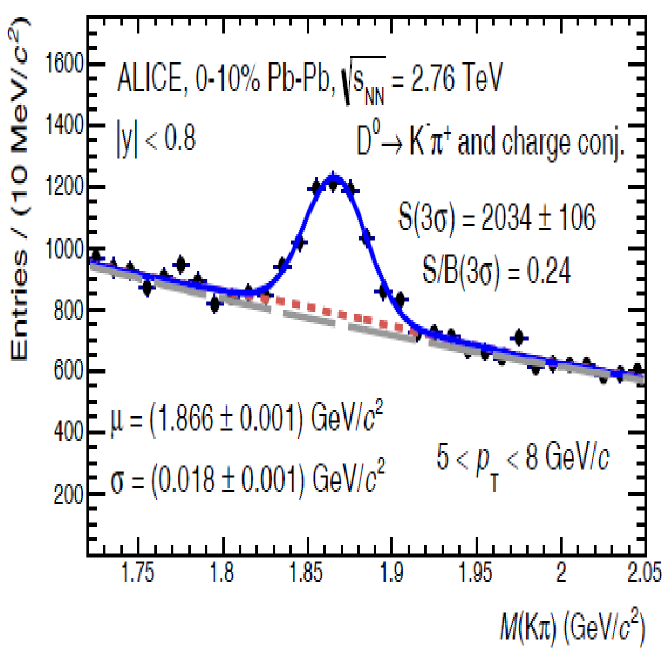
(No K-π ID)

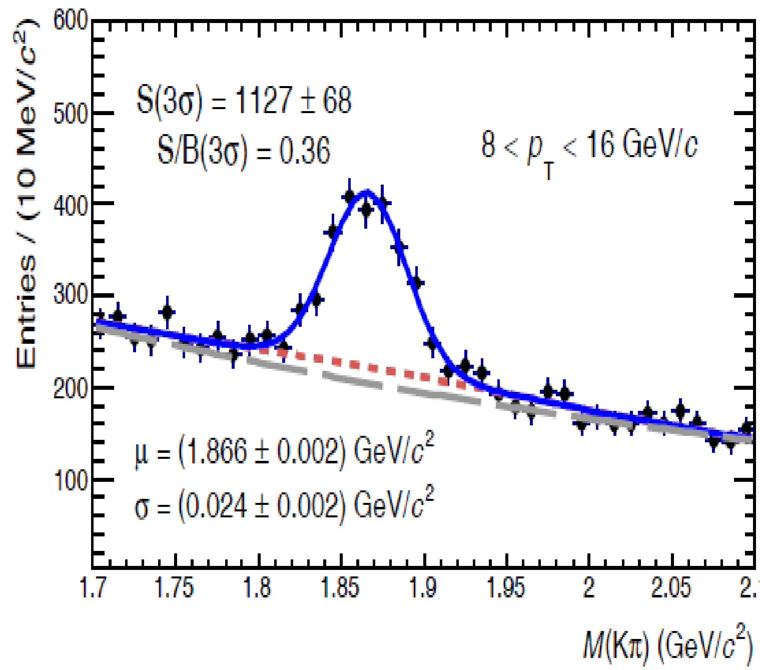



0-10%

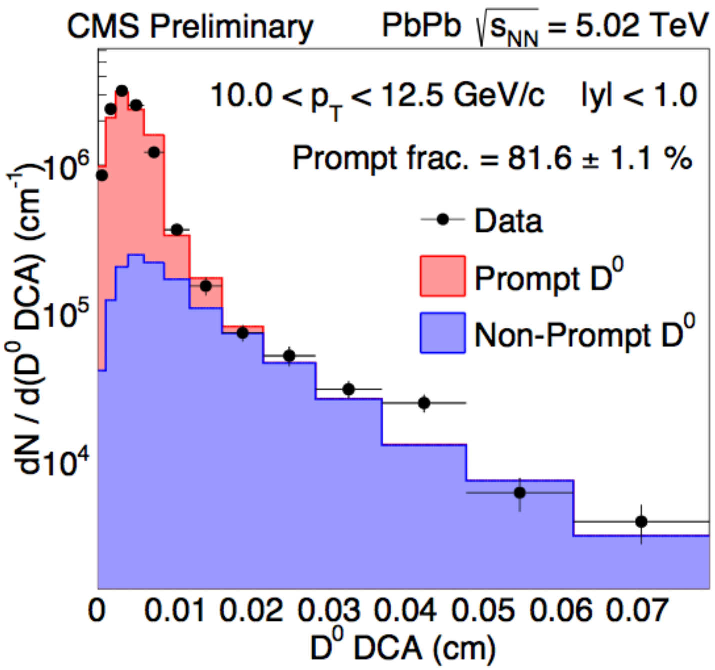
ArXiv 1506.06604



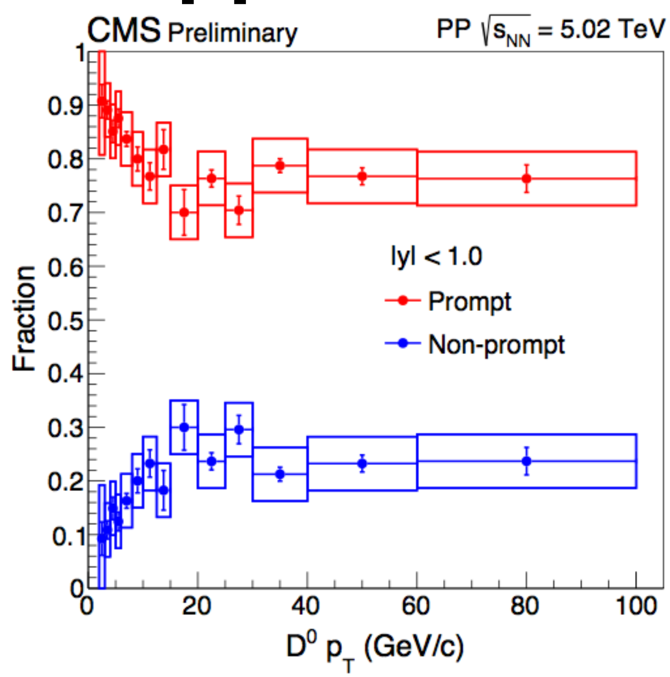



# b→D$^0$ feed-down subtraction in pp and PbPb collisions

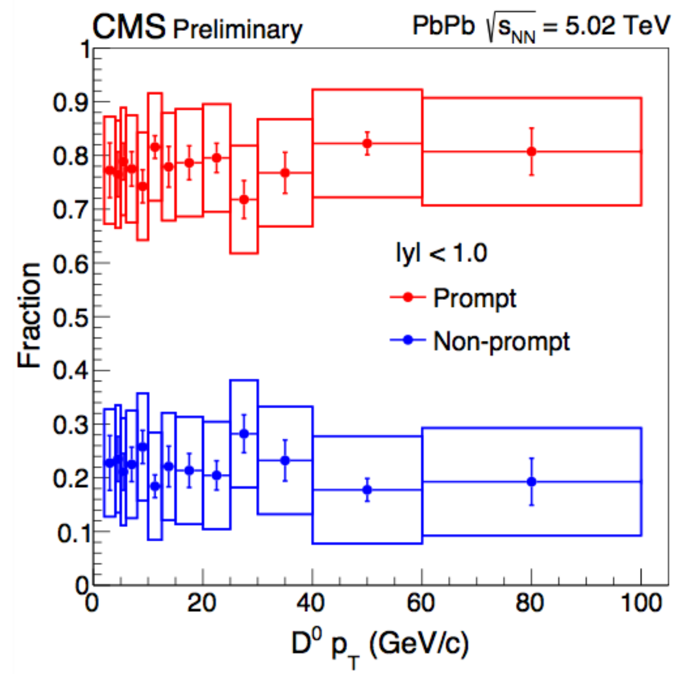
**CMS-PAS-HIN-16-001**




**pp 5.02 TeV**

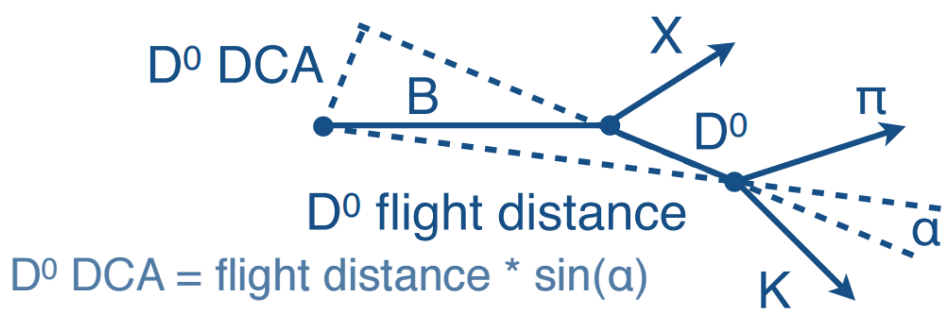



**PbPb 5.02 TeV**



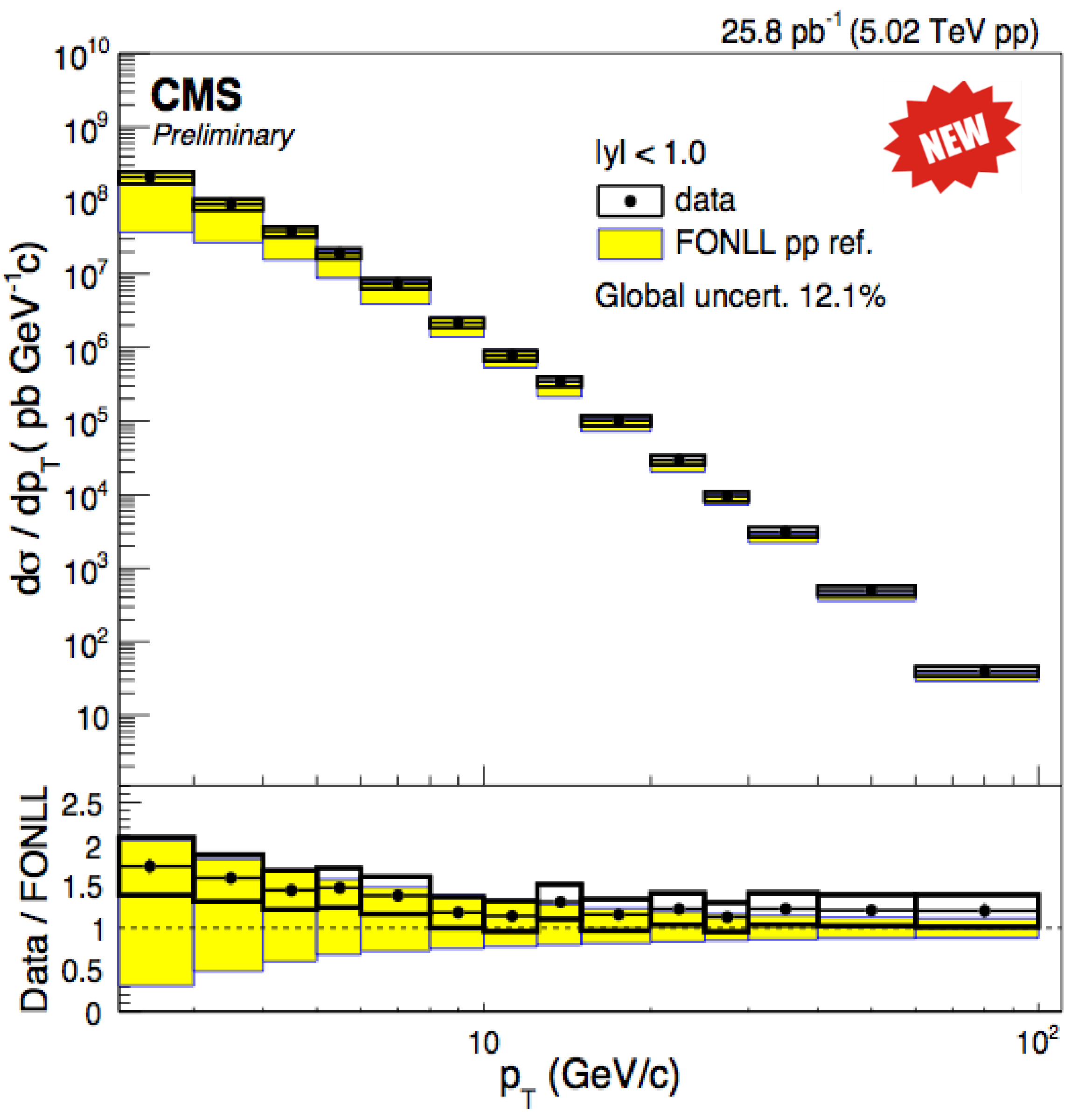

NEW

- **Data-driven extraction in heavy-ion collision with DCA**
- Prompt D$^0$ fraction extracted from ***data*** is 70-90% in pp and PbPb
- Extract non-prompt D$^0$ spectra: complementary to direct B meson reconstruction and non-prompt J/ψ analysis



# $D^0$ $p_T$-differential cross section in pp at 5.02 TeV

**CMS-PAS-HIN-16-001**



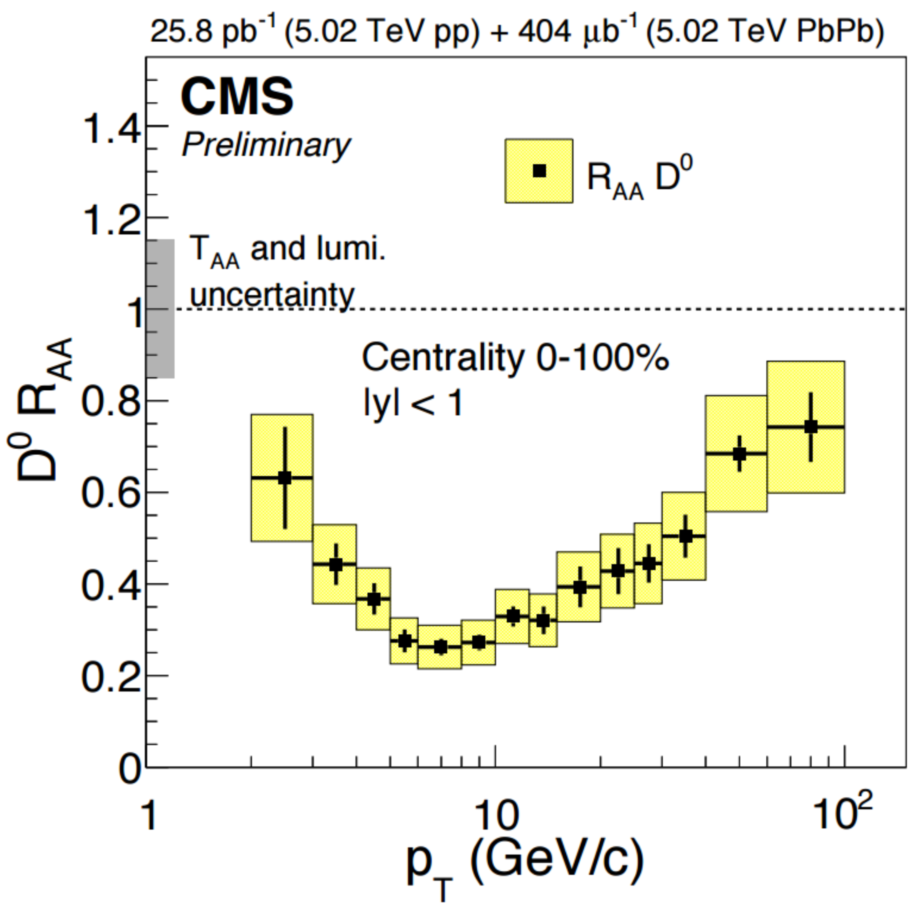

- First measurement of pp $D^0$ cross section at 5.02 TeV using 2 billion minimum bias and $D^0$ triggers
- $D^0$ $p_T$ coverage from **2** to **100** GeV/c in $|y|<1.0$
- **Results are consistent with the FONLL calculations. Similar to that was observed in $B^+$ analyses.**

# Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

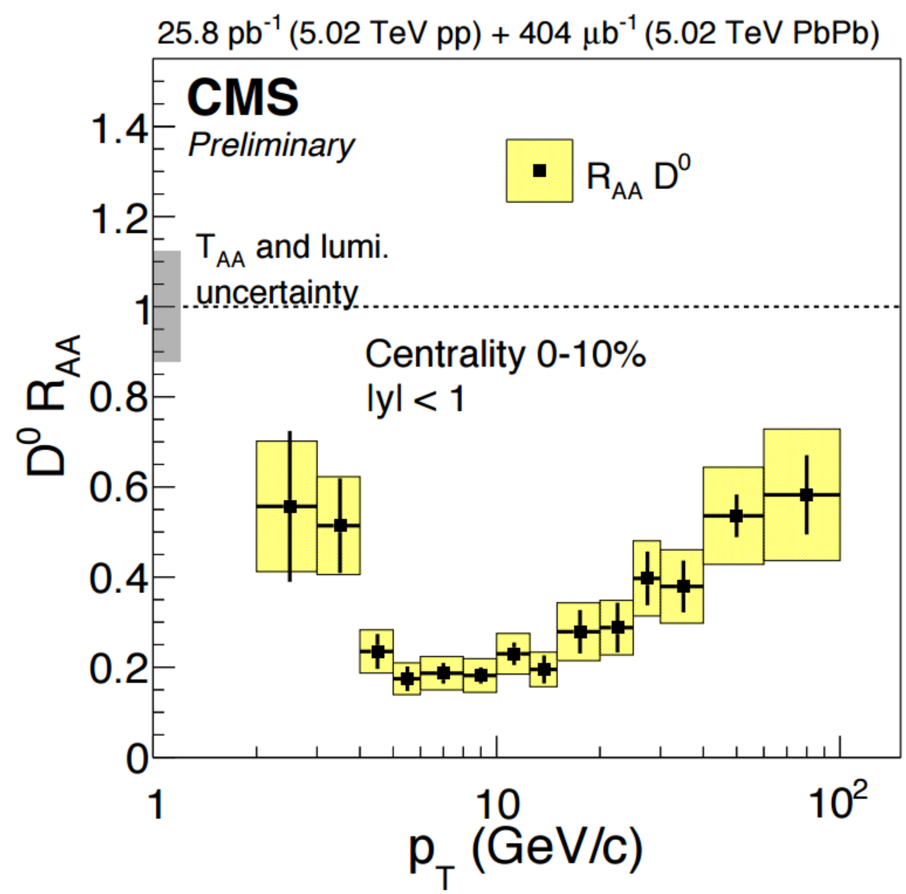
CMS-PAS-HIN-16-001

NEW

**0-100%**




**0-10% Central**



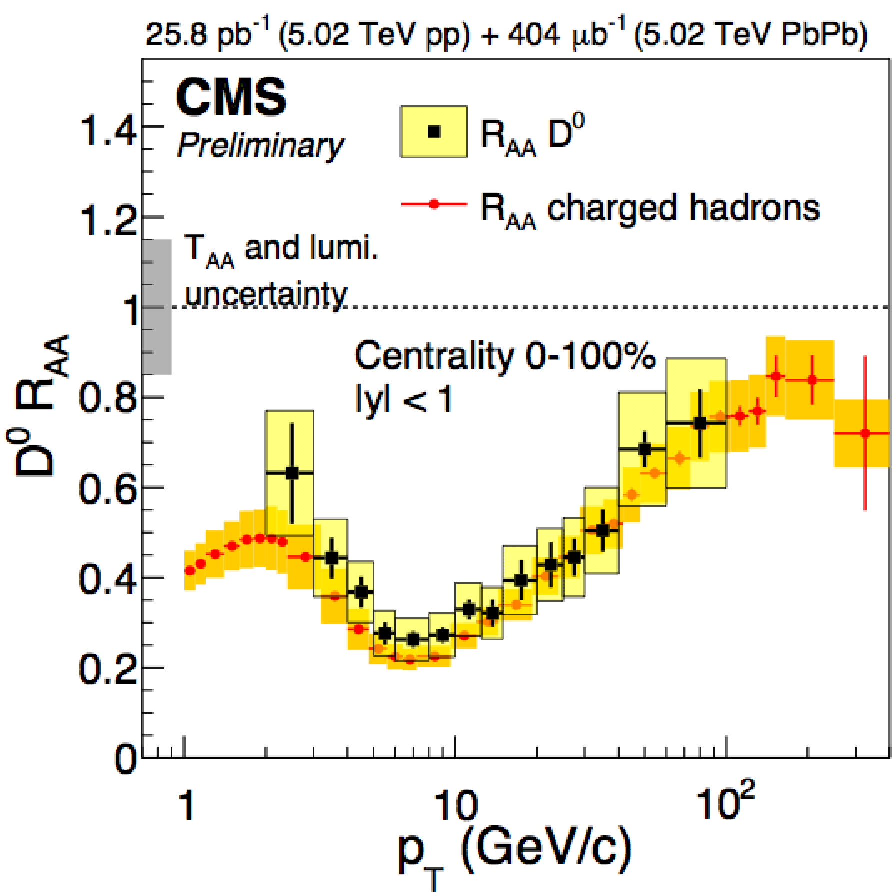

- The first $D^0$ $R_{AA}$ measurement in PbPb at 5.02 TeV!
- Mind the 12% normalization uncertainty from Lumi (will go down to a few % soon)
- $D^0$ production is strongly suppressed (by a factor of ~ 5) at ~10 GeV
- At high $p_T$ > 10 GeV: $D^0$ $R_{AA}$ **increases** as a function of $D^0$ $p_T$

# $D^0$ and charged particle $R_{AA}$ in 0-100%

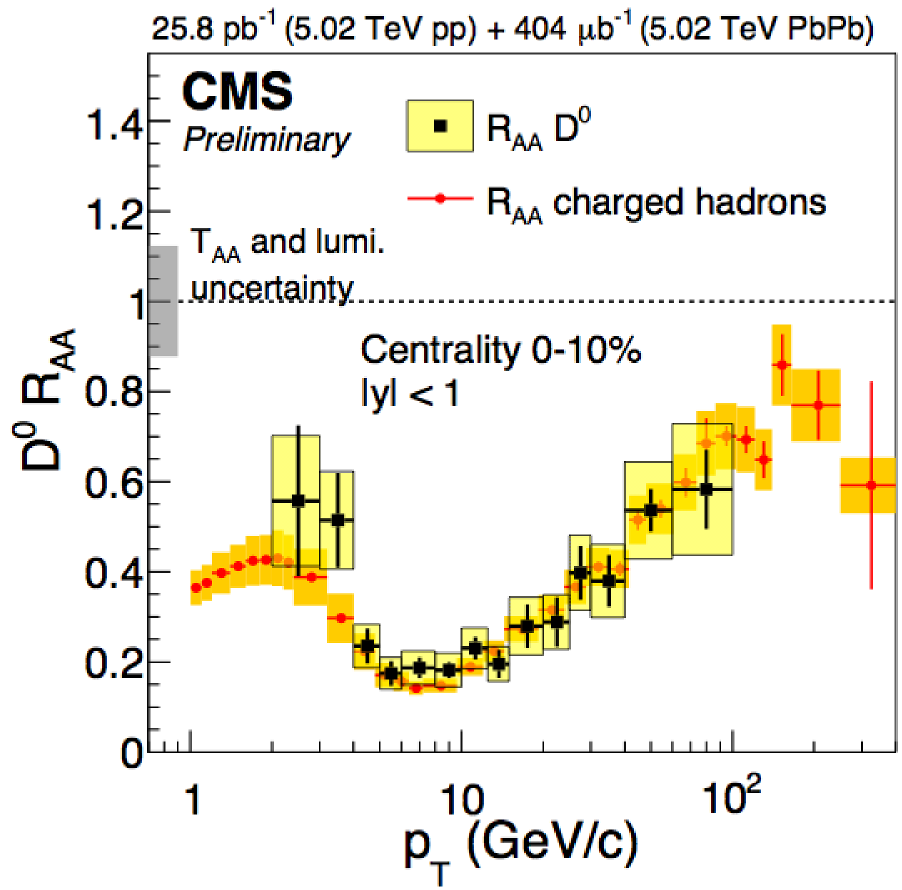
NEW

**CMS-PAS-HIN-16-001** **CMS-PAS-HIN-15-015**

**0-100%**




**0-10% Central**

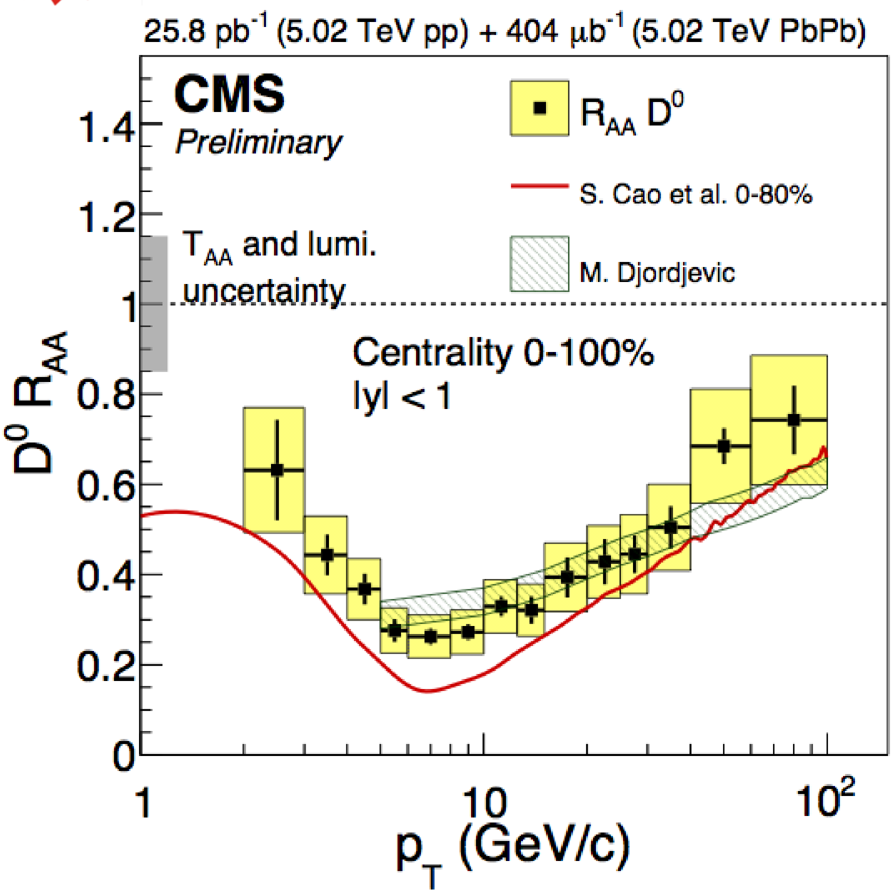



- Compared to the first measurement of charged particle $R_{AA}$ at 5.02 TeV cover a **very wide** kinematic range (up to $p_T$ ~ 300 GeV)
- Suppression patterns are **very similar** between $D^0$ and inclusive charged particles!
- Less $D^0$ suppression than inclusive hadron at low $p_T$ ?

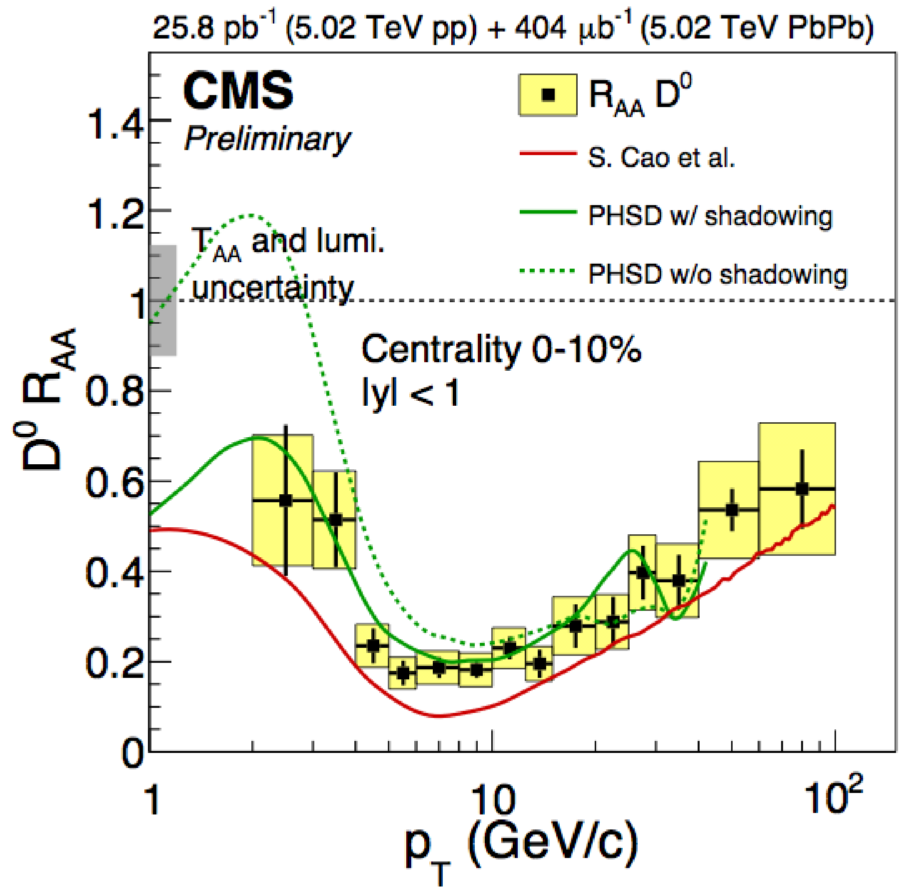
# $D^0$ $R_{AA}$ vs predictions

**CMS-PAS-HIN-16-001**

**0-100%**




**0-10% Central**




- Predictions before data capture the observed structure at low D0 $p_T$!
- PHSD: Need to include shadowing effects to describe the data at low $p_T$

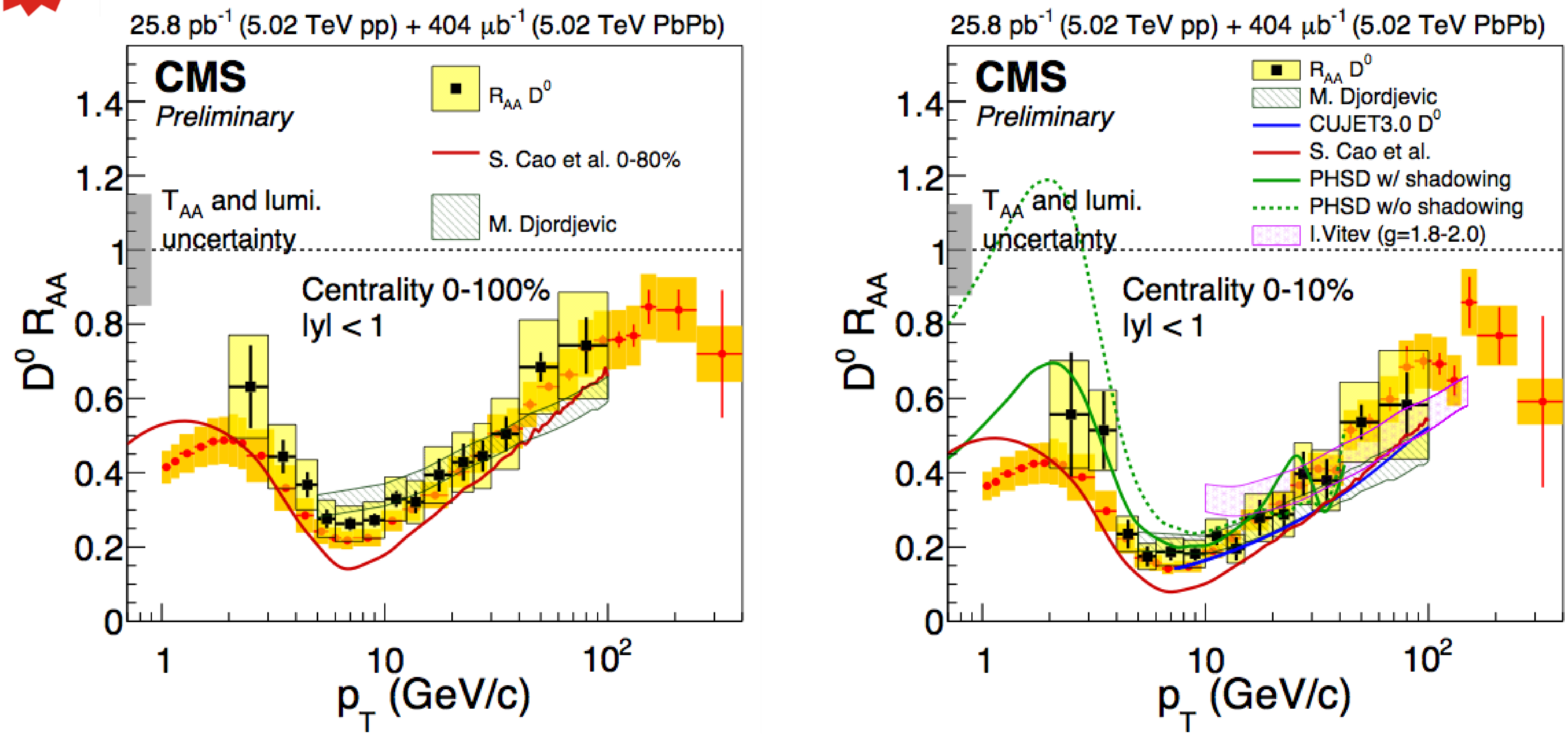
- PHSD (Parton-Hadron-String Dynamics model[2])
- S.Cao et al. ( Linearized Boltzmann transport model + hydro ) arXiv:1605.06447v1
- M. Djordjevic ( QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss ) Phys. Rev. C 92 (Aug, 2015) 024918

# $D^0$ $R_{AA}$ vs predictions

NEW

CMS-PAS-HIN-16-001 CMS-PAS-HIN-15-015

0-100% | 0-10% Central




- Predictions before data capture also the **rising trend** of the D0 $R_{AA}$

- PHSD (Parton-Hadron-String Dynamics model[2])
- S.Cao et al. ( Linearized Boltzmann transport model + hydro ) arXiv:1605.06447v1
- M. Djordjevic ( QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss ) Phys. Rev. C 92 (Aug, 2015) 024918
- CUJET3.0 (jet quenching model based on DGLV opacity expansion theory) JHEP 02 (2016) 169
- I.Vitev (Jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG)) Phys. Rev. D 93 (Apr, 2016)

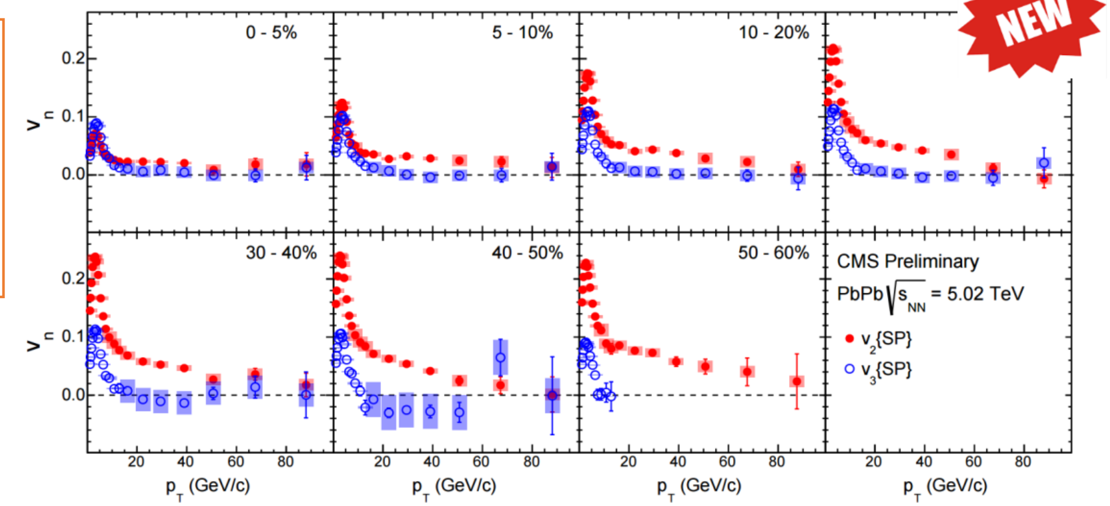
# Outlook

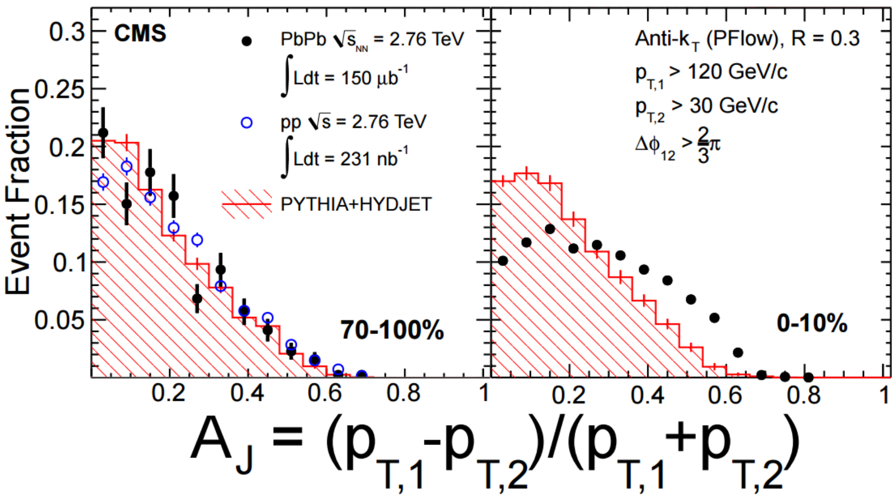
# Near Term Plan

$D^0$ meson $v_N$ measurement in PbPb at 5.02 TeV, complementary to charged particle $v_N$ measurement at

**High precision $D^0$ azimuthal anisotropy**

CMS-PAS-HIN-15-014



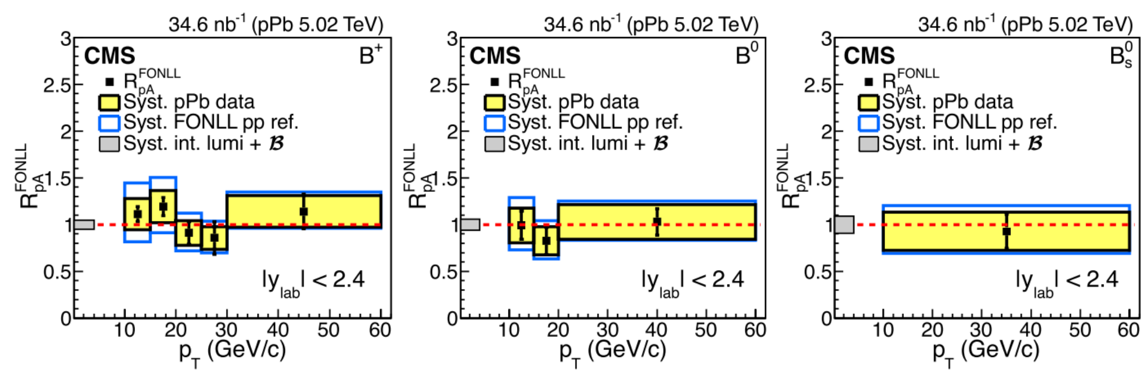




Back-to-back doubly tagged b-jets $p_T$ asymmetry in PbPb at 5.02 TeV, to be compared to inclusive dijet

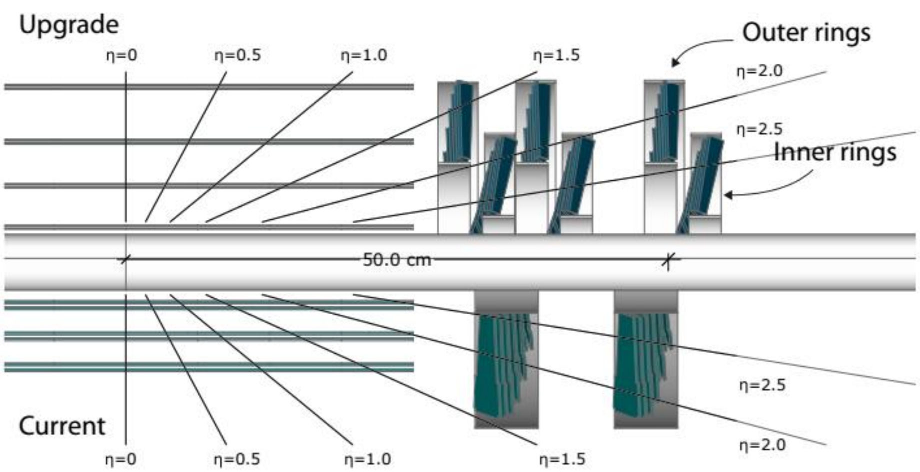
**Suppress gluon splitting contribution**

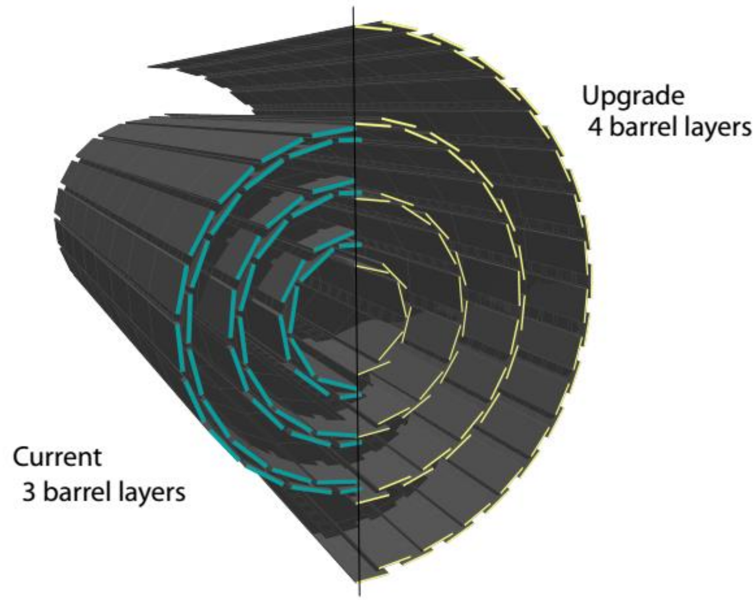
B meson $R_{AA}$ in PbPb at 5.02 TeV, to be compared to B meson $R_{pA}$, charged particle & D0 meson $R_{AA}$

Flavor dependence of jet quenching with **fully reconstructed B meson**



# Pixel Upgrade (2016 YETS)



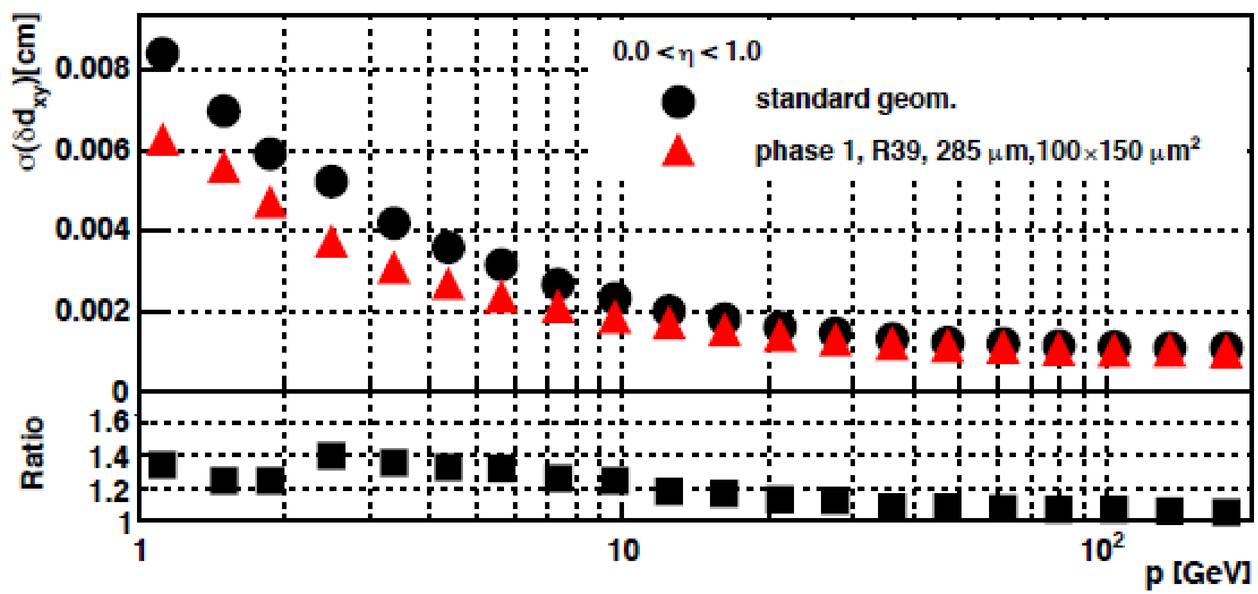




(b) Barrel

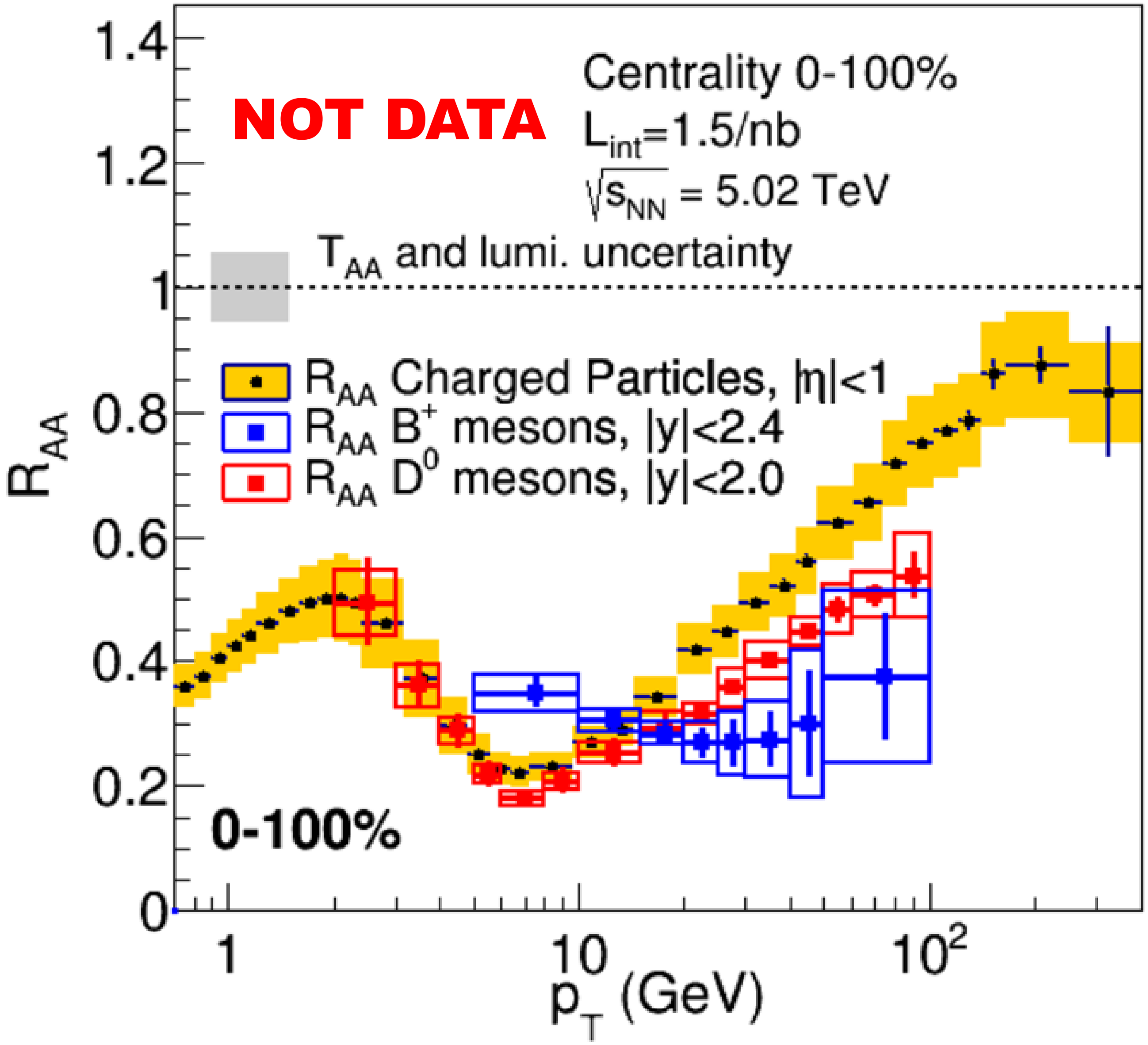
(a) Barrel and For

**~40%** better impact parameter resolution at low track $p_T$

Significant reduction of the fake track rate, and improvement of the b(c)-jet tagging and $D^0$ meson reconstruction efficiency



# Near Term Future (2018)




High precision charged particle, $D^0$ and $B^+$ $R_{AA}$ and $v_N$ data!

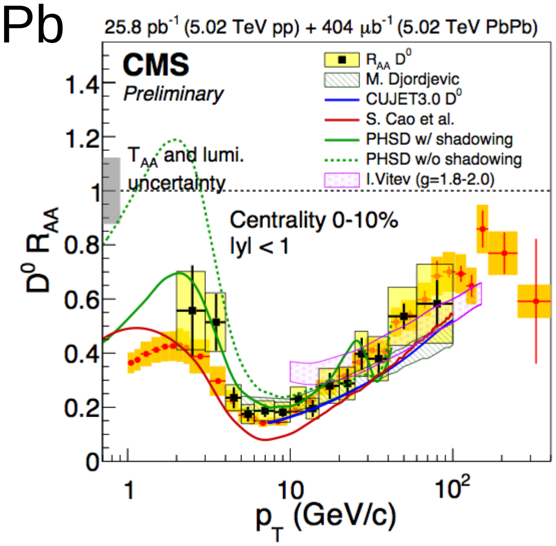
# Summary

- B and D meson in pp and pPb collisions: $p_T$ and y distributions of B and $D^0$ mesons agrees with FONLL calculation within the quoted uncertainties

- b-jet and c-jet in pPb collisions: No significant nuclear effect observed within the current uncertainties in the kinematics range studied with respect to PYTIHA

- Very successful data-taking with CMS in 2015!
  - High statistics pp (~2.5 billion events) and PbPb minimum bias sample at 5.02 TeV 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

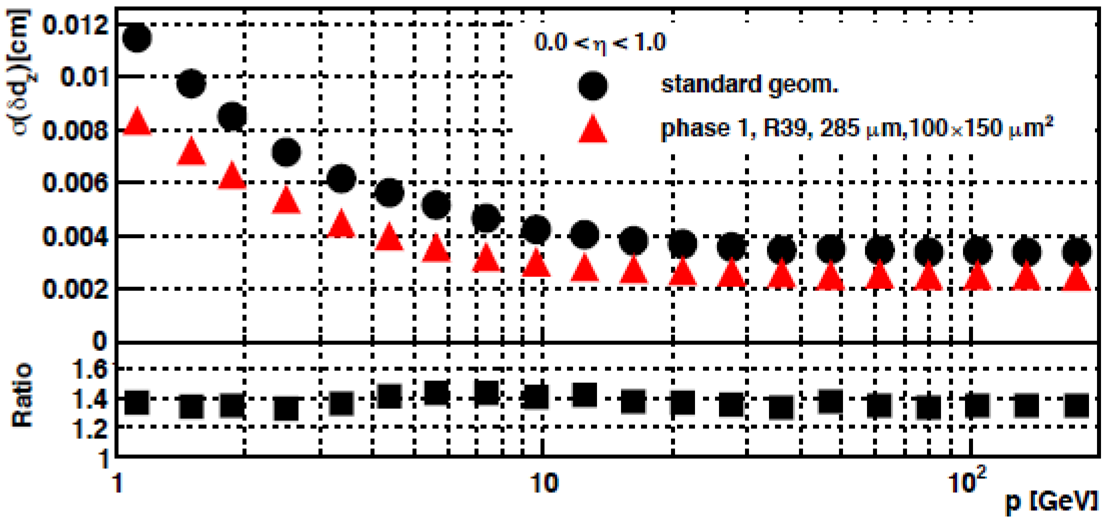
- Run II result: The first $D^0$ meson and charged particles in PbPb at 5.02 TeV
  - Use pp reference at the same collision energy
  - Prompt $D^0$ fraction from data-driven method
  - $D^0$ mesons can be reconstructed without particle identification
  - Significant suppression of $D^0$ is similar to inclusive charged particle over a wide kinematics range




- Many more exciting results from Run II data coming soon!

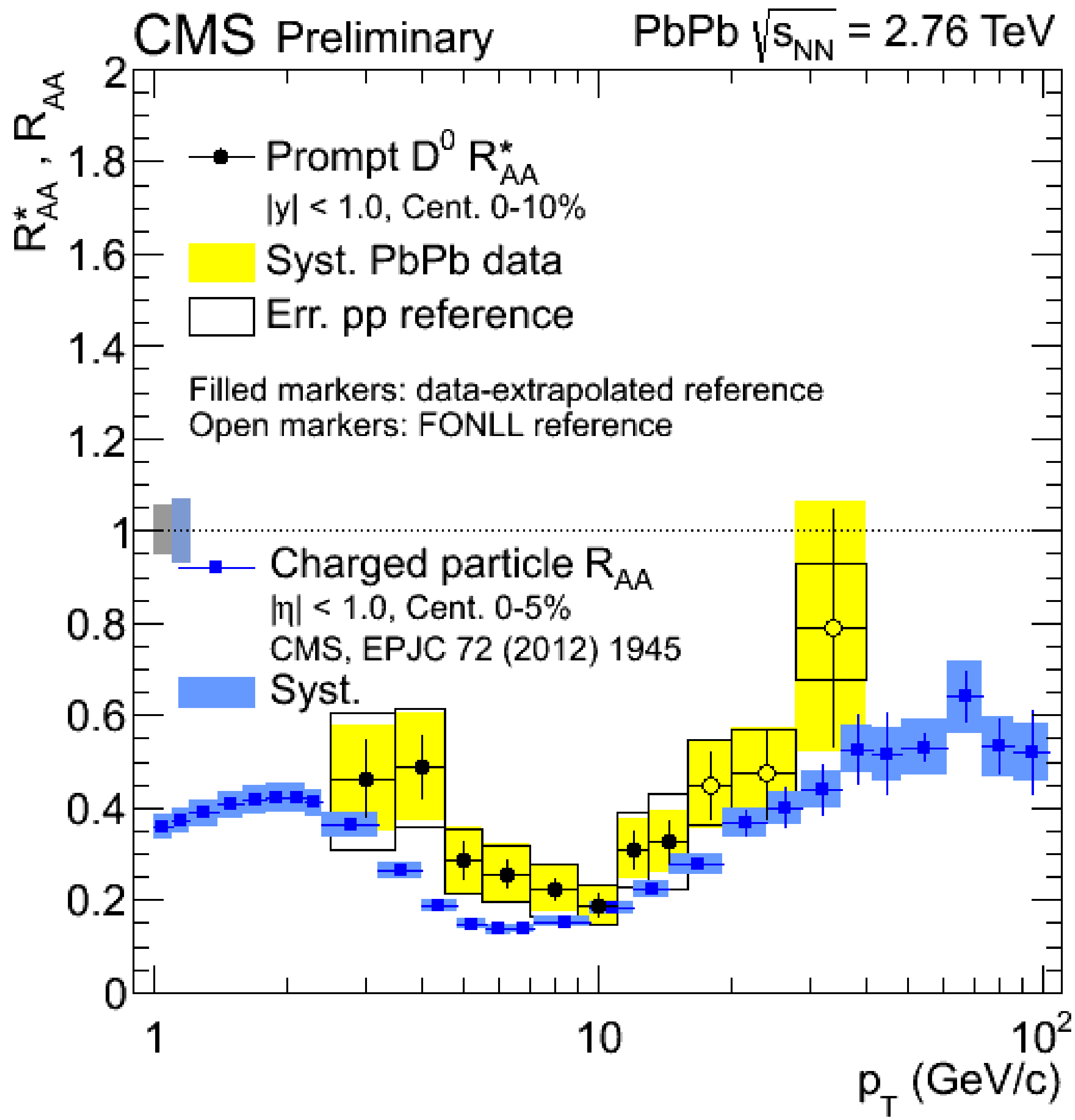
… stay tuned!

- Backup slides



σ(δd_z)[cm]
0.012
0.01
0.008
0.006
0.004
0.002
0
0.0 < η < 1.0
standard geom.
phase 1, R39, 285 μm,100×150 μm²
Ratio
1.6
1.4
1.2
1
1
10
10²
p [GeV]

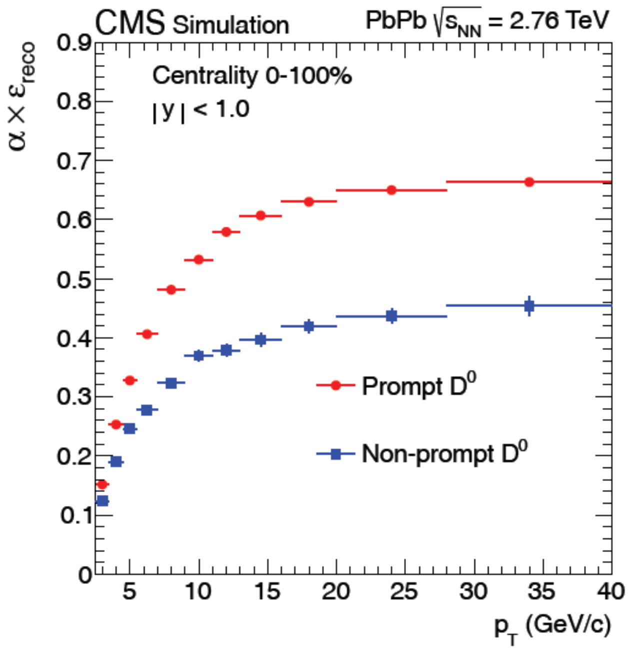
# Comparison with charged particle $R_{AA}$



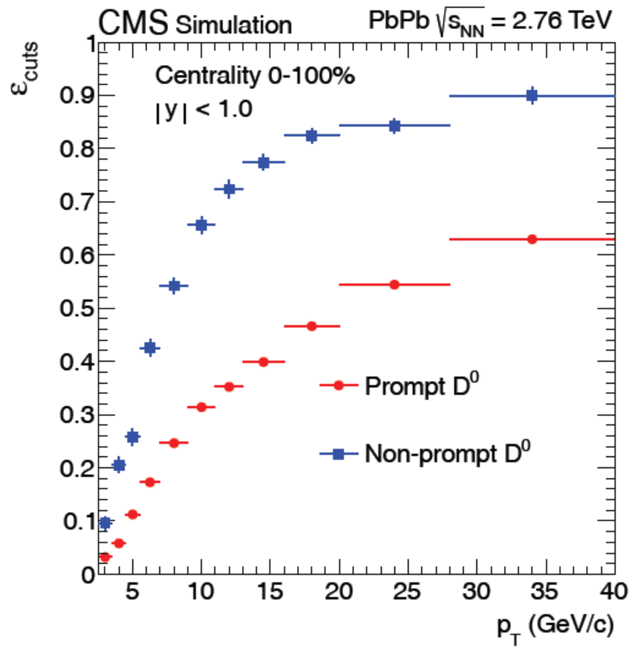

**EPJC 72 (2012) 1945**

**CMS PAS HIN-15-005**

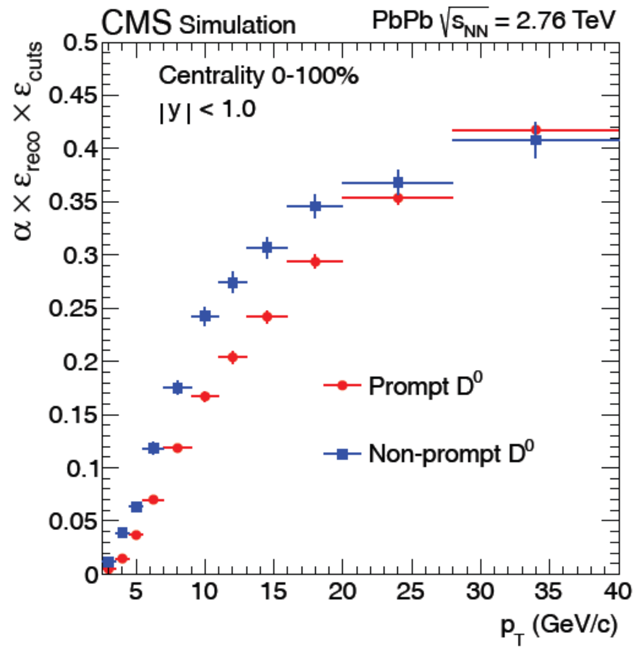
# Efficiency and Acceptance Correction




Reconstruction

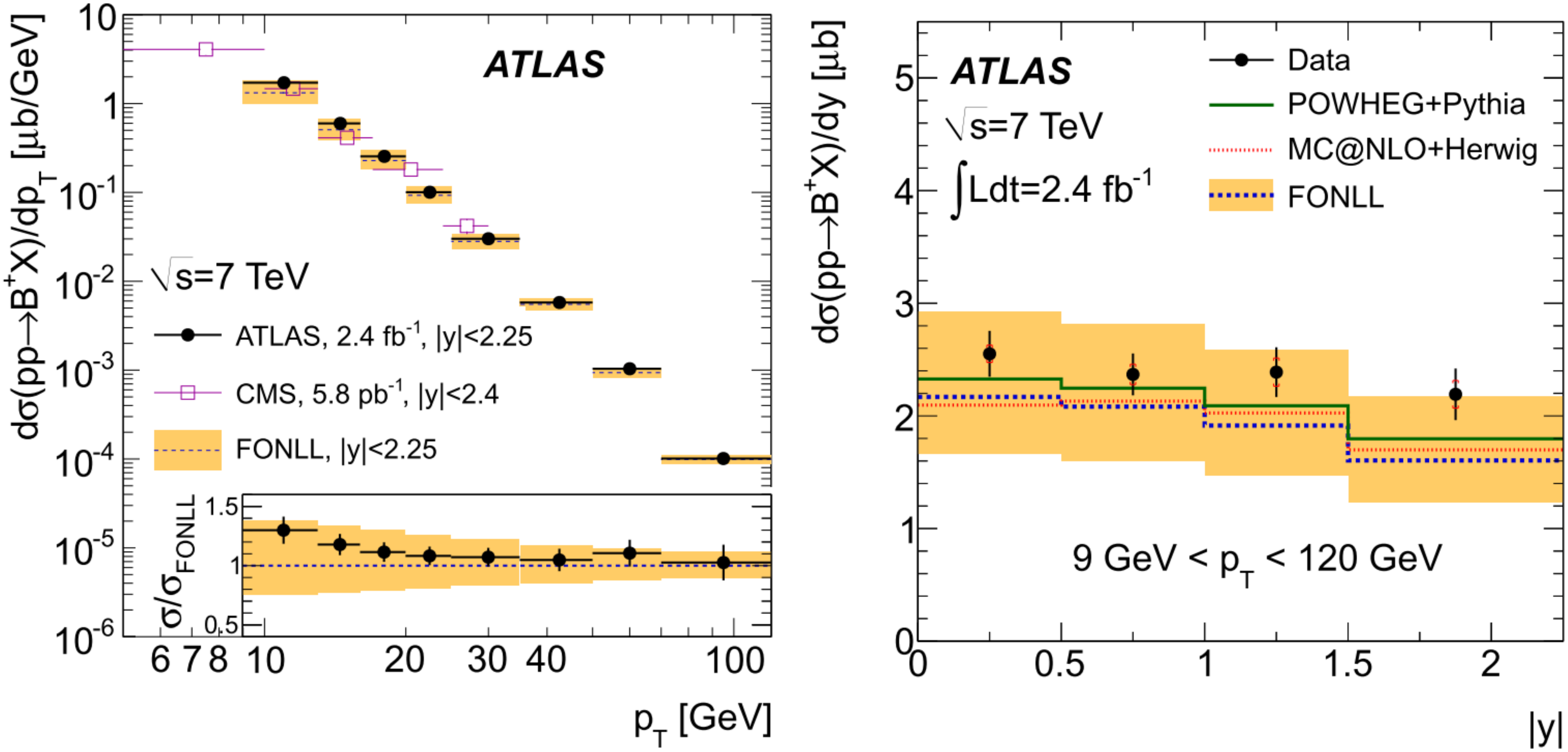


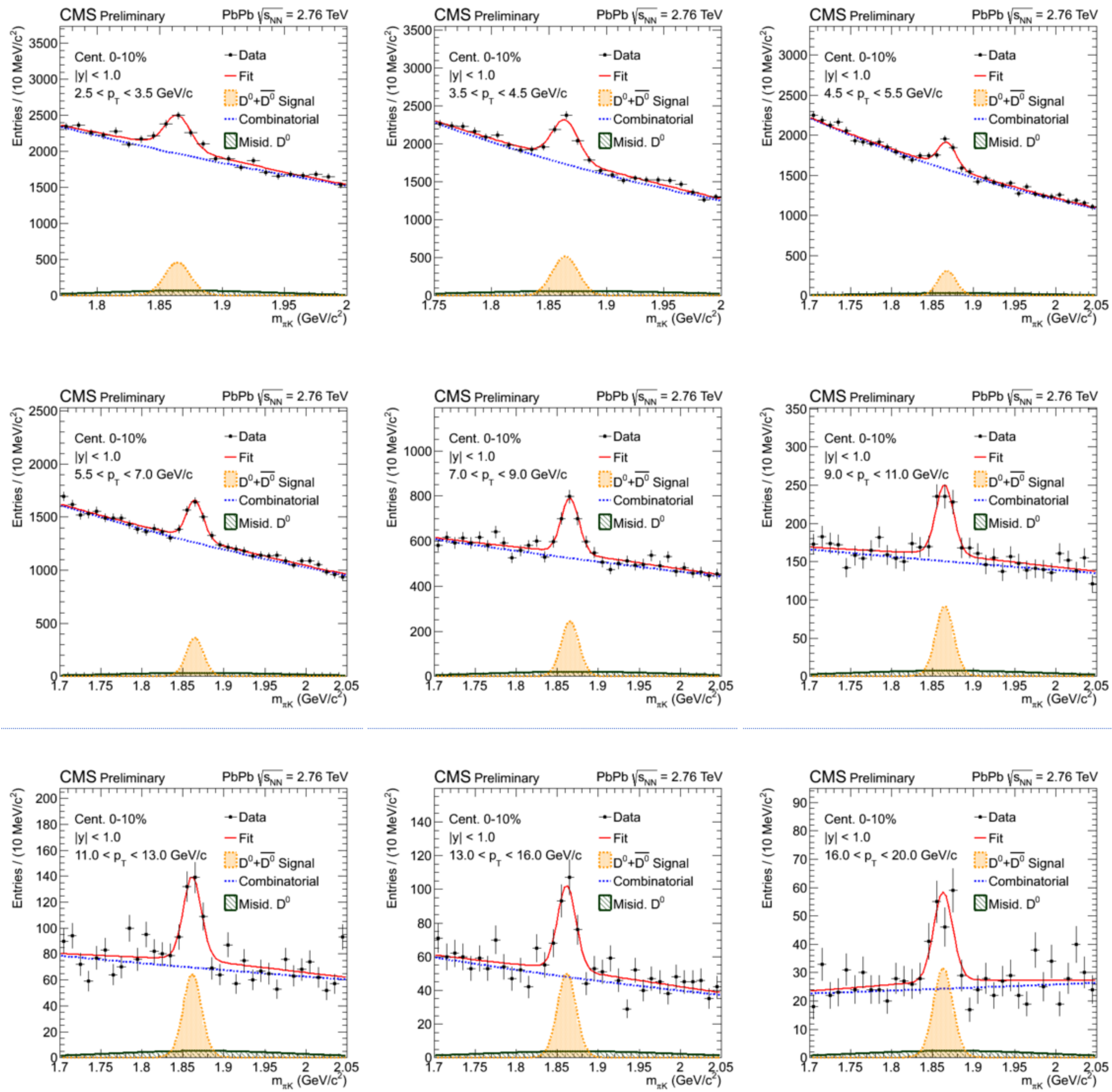

D meson selection



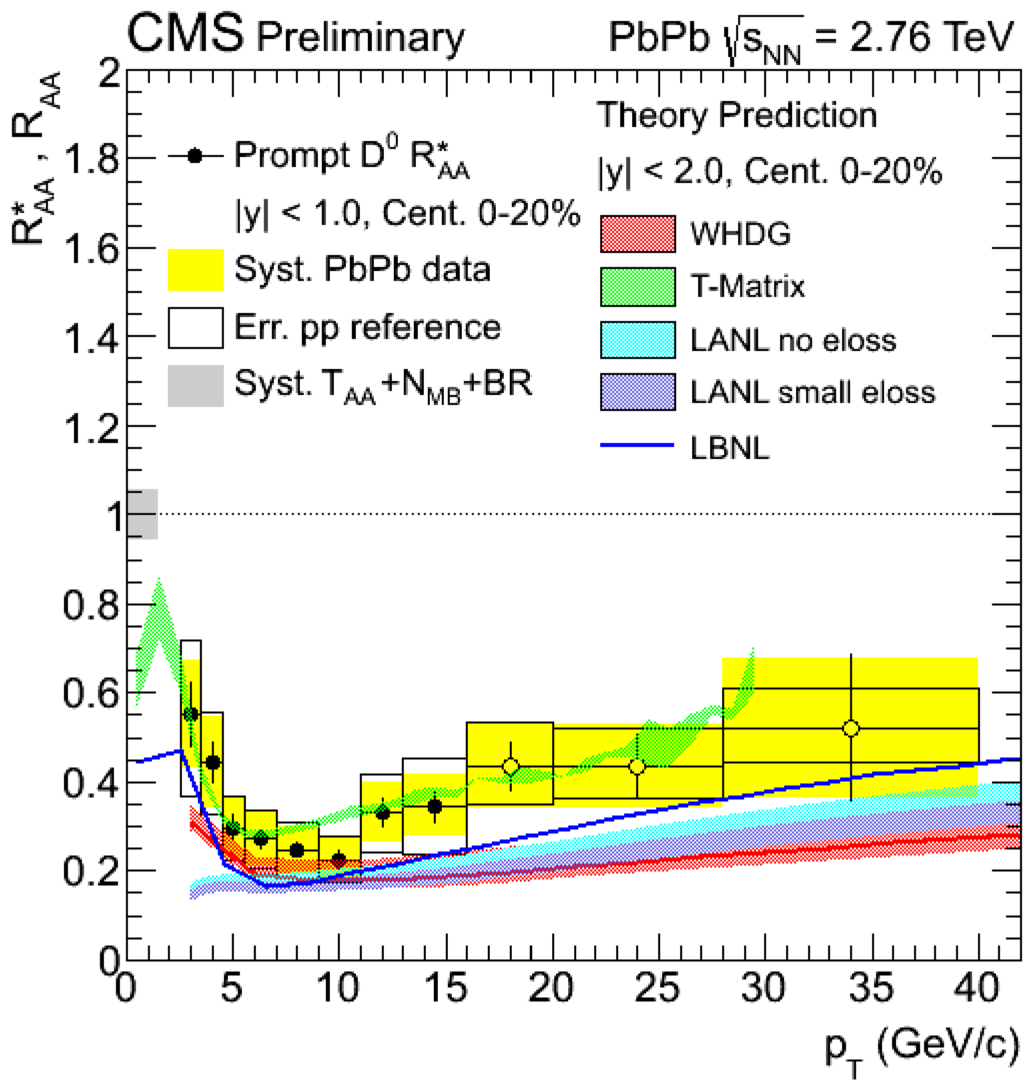

Full eff x acc

# 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/$c^2$)

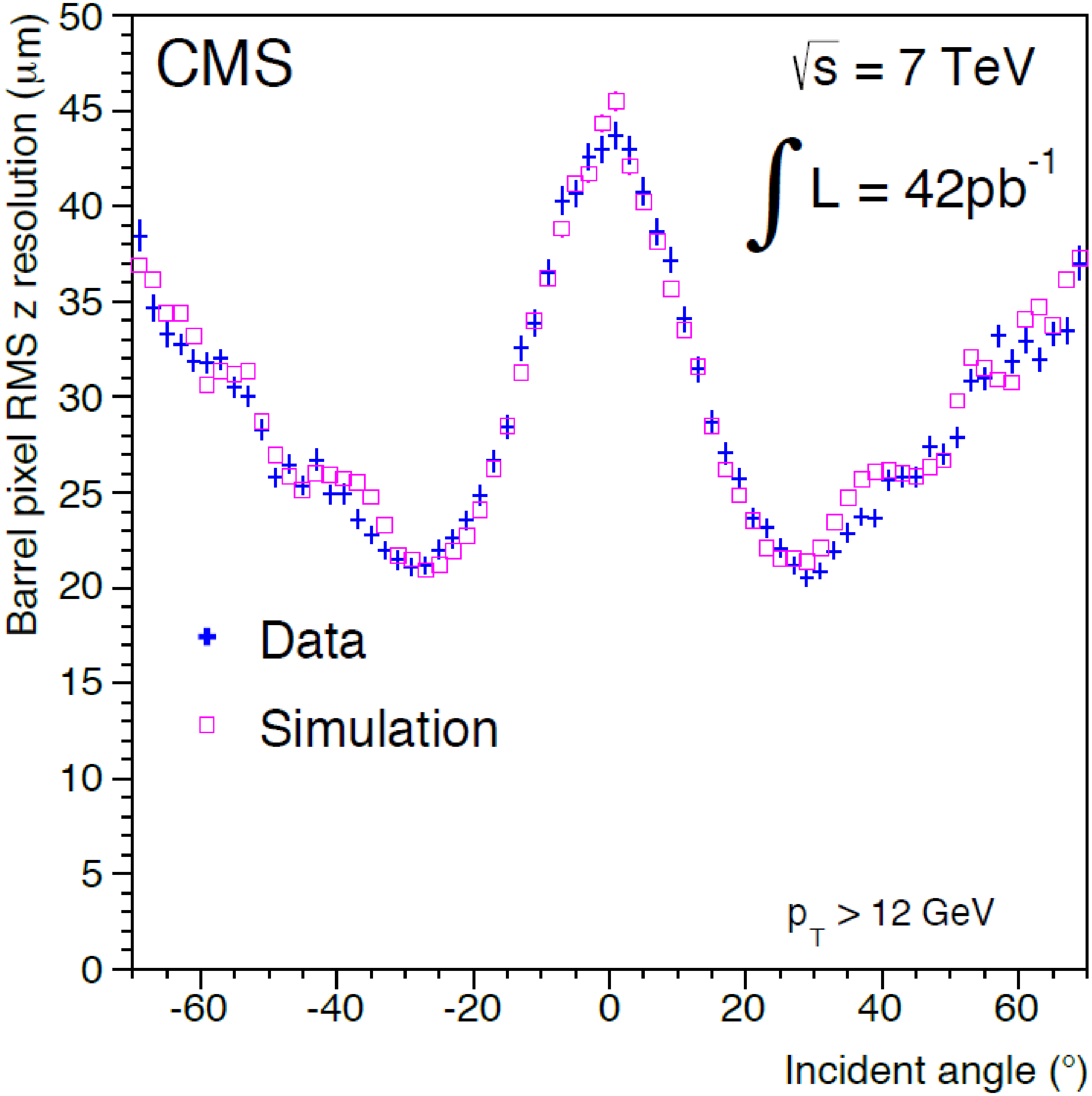
# Nuclear Modification Factors:



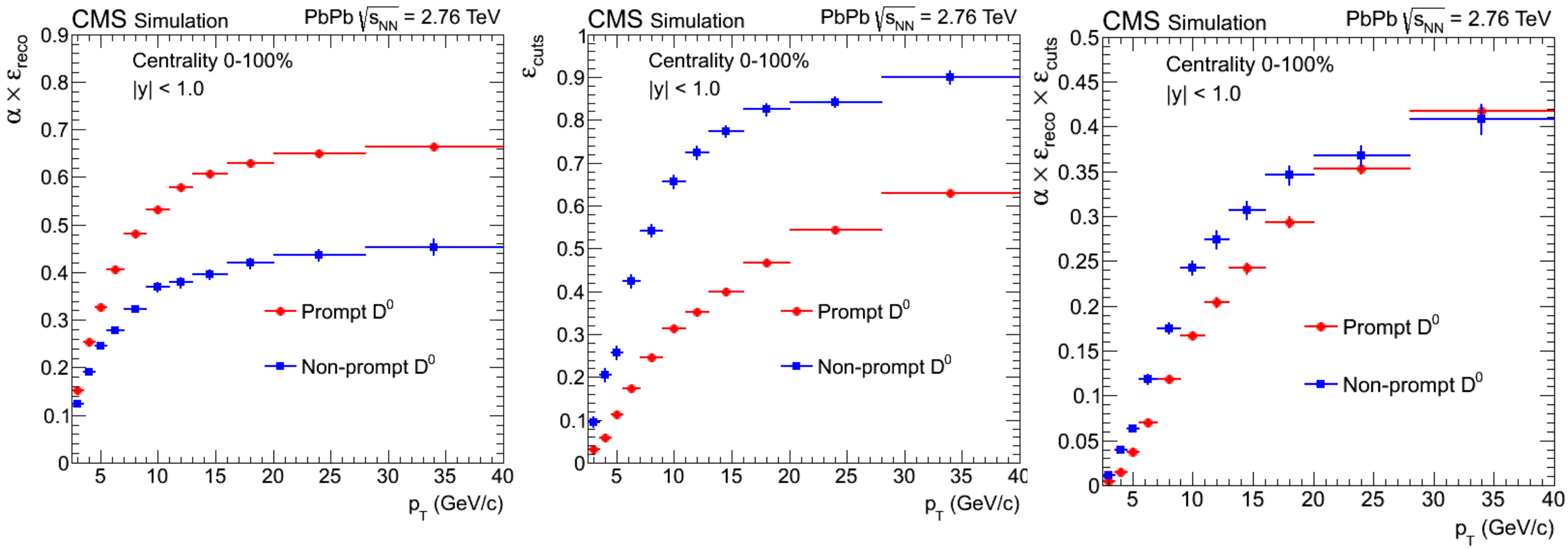
# Information for pPb Analysis

- 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 $J/\psi$ 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



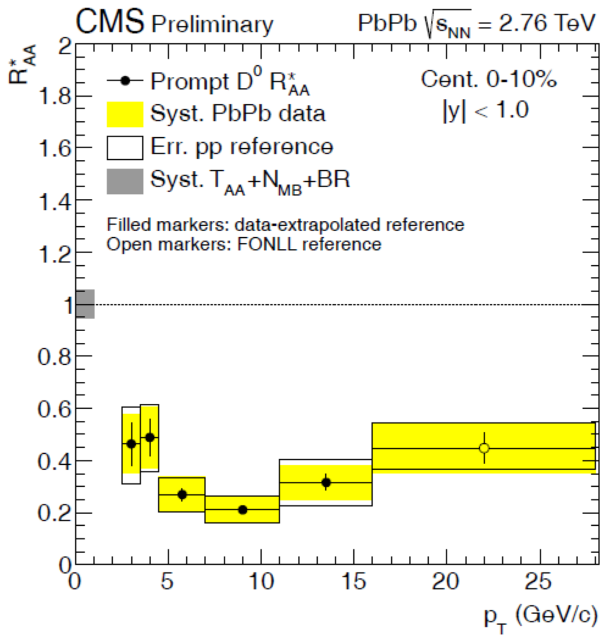

- **$a \times e_{reco}$: prompt D0 higher than non-prompt D0 (D0 from B-hadron decay)**
  - ➢ Tracks from non-prompt $D^0$ are more displaced from primary vertex than tracks from prompt $D^0$
  - ➢ Hi tracking has lower efficiency on further displaced tracks

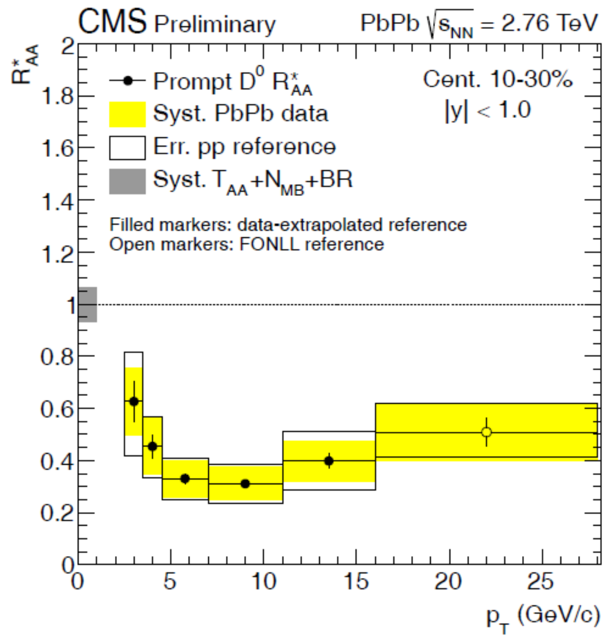
- **$e_{cuts}$: non-prompt D0 higher than prompt D0**
  - ➢ Non-prompt $D^0$ are more displaced from primary vertex than prompt $D^0$, thus bigger d0/error_d0

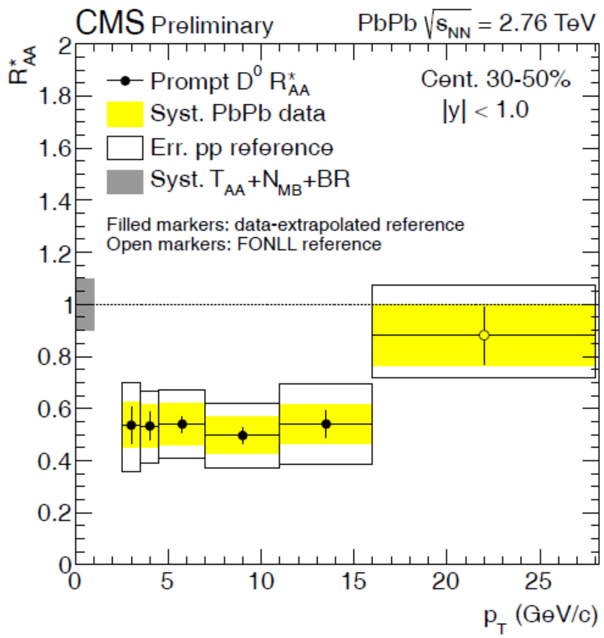
**CMS PAS HIN-15-012**

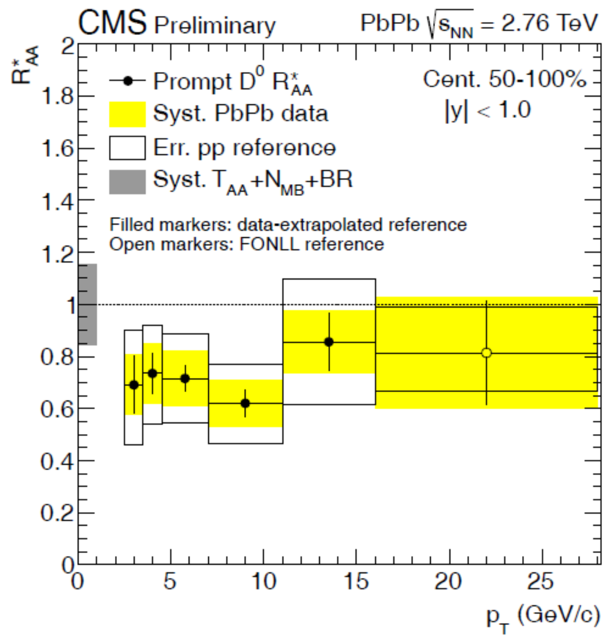
| $p_T$ ( **GeV/**$c$ ) | $d_0/\sigma(d_0)$ | $\alpha$ (radians) | **Vertex Probability** |
|---|---|---|---|
| 2.5-3.5 | $> 5.90$ | $< 0.12$ | $> 0.248$ |
| 3.5-4.5 | $> 5.81$ | $< 0.12$ | $> 0.200$ |
| 4.5-5.5 | $> 5.10$ | $< 0.12$ | $> 0.191$ |
| 5.5-7.0 | $> 4.62$ | $< 0.12$ | $> 0.148$ |
| 7.0-9.0 | $> 4.46$ | $< 0.12$ | $> 0.102$ |
| 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 √sNN = 2.76 TeV
Prompt D0 R*AA
Syst. PbPb data
Err. pp reference
Syst. TAA+NMB+BR
Cent. 0-10%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R*AA
pT (GeV/c)

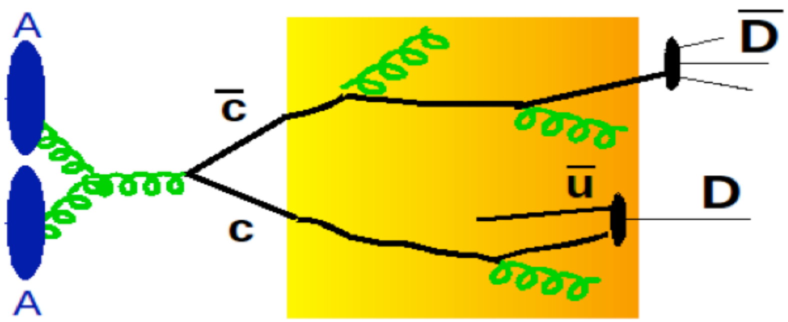

CMS Preliminary
PbPb √sNN = 2.76 TeV
Prompt D0 R*AA
Syst. PbPb data
Err. pp reference
Syst. TAA+NMB+BR
Cent. 10-30%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R*AA
pT (GeV/c)


CMS Preliminary
PbPb √sNN = 2.76 TeV
Prompt D0 R*AA
Syst. PbPb data
Err. pp reference
Syst. TAA+NMB+BR
Cent. 30-50%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R*AA
pT (GeV/c)


CMS Preliminary
PbPb √sNN = 2.76 TeV
Prompt D0 R*AA
Syst. PbPb data
Err. pp reference
Syst. TAA+NMB+BR
Cent. 50-100%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R*AA
pT (GeV/c)

# Why studying heavy flavours in HI?

Heavy quarks produced in hard scatterings (described by pQCD) at the early stages of the collisions **interact with medium and lose energy!**

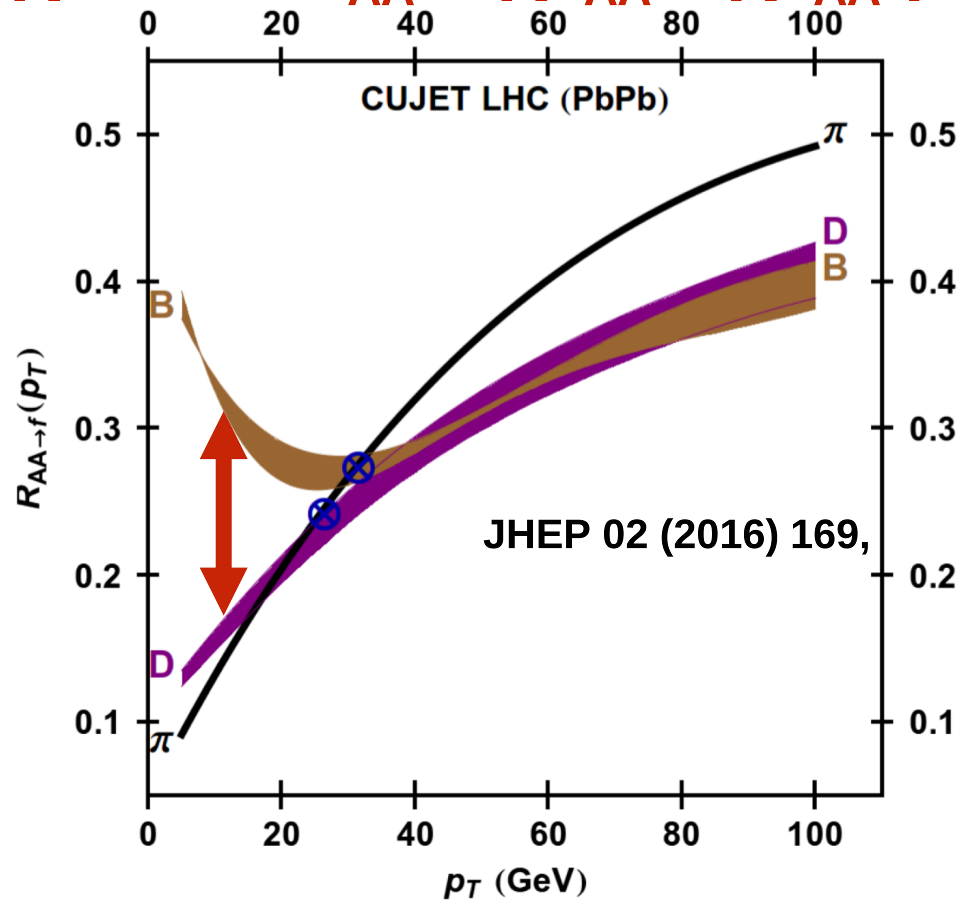



**Does energy loss depends on the flavour?**

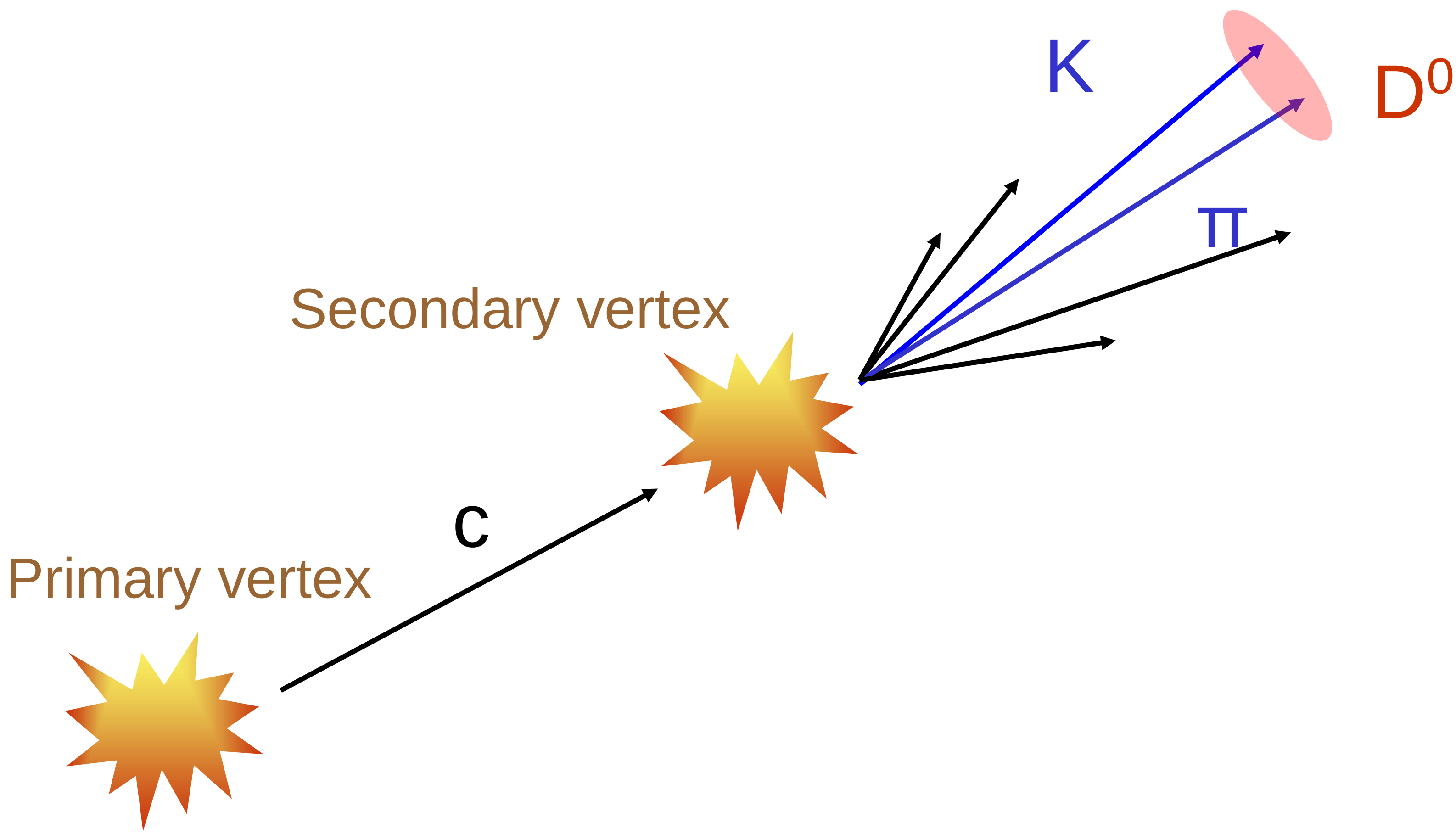
Expected $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ due to:

- Casimir factor= $\langle\Delta E\rangle \propto C_R$
- **Dead cone effect** (radiation suppressed at small angles)

$R^{light\ particle}_{AA} < R^{D}_{AA} < R^{B}_{AA}$ ?



# How to measure charm with CMS



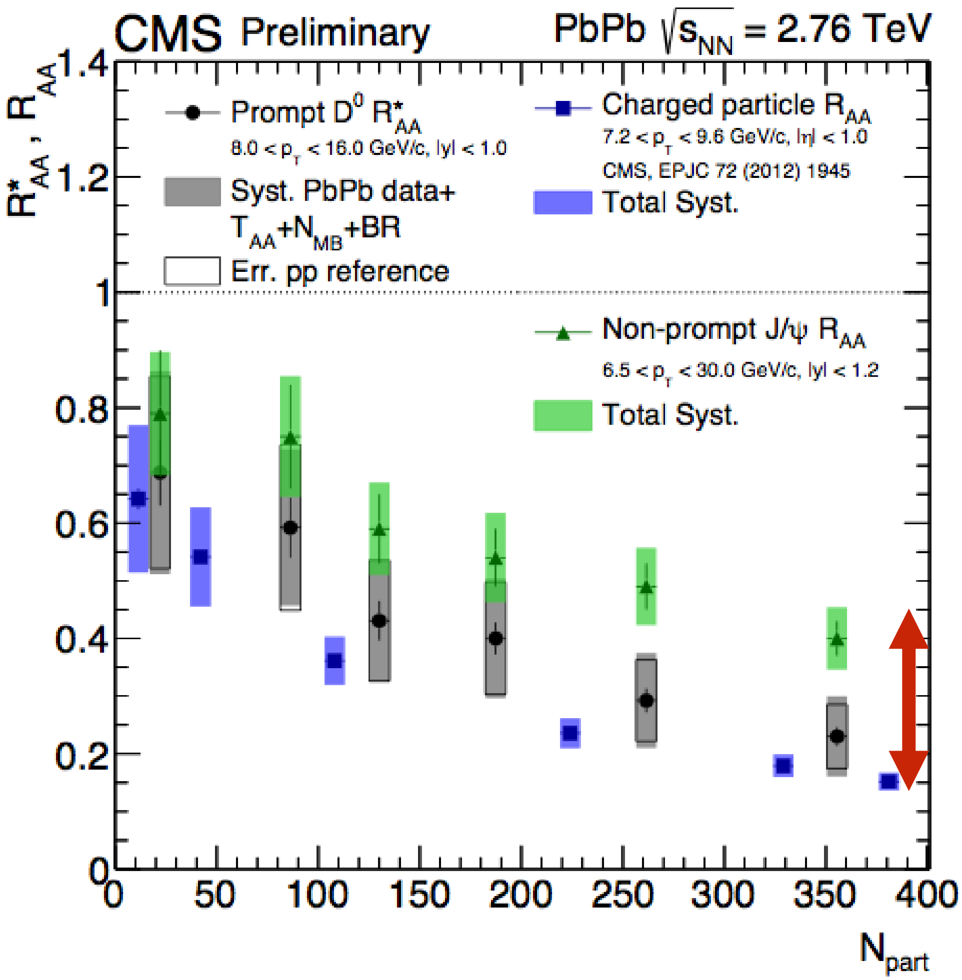

$D^0 \rightarrow K\pi$ decay channels sample **O(0.01%)** of c cross-section

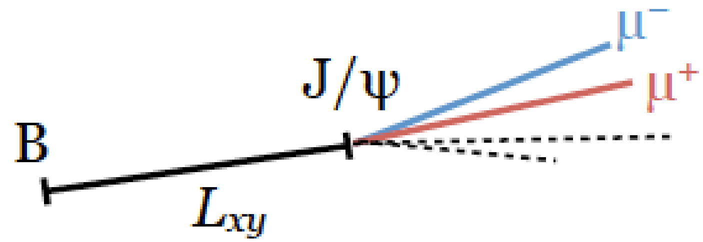
# Run I heavy flavour analysis

# non-prompt J/ψ measurements

CMS-HIN-15-005

Getting closer to the b-quark kinematics!



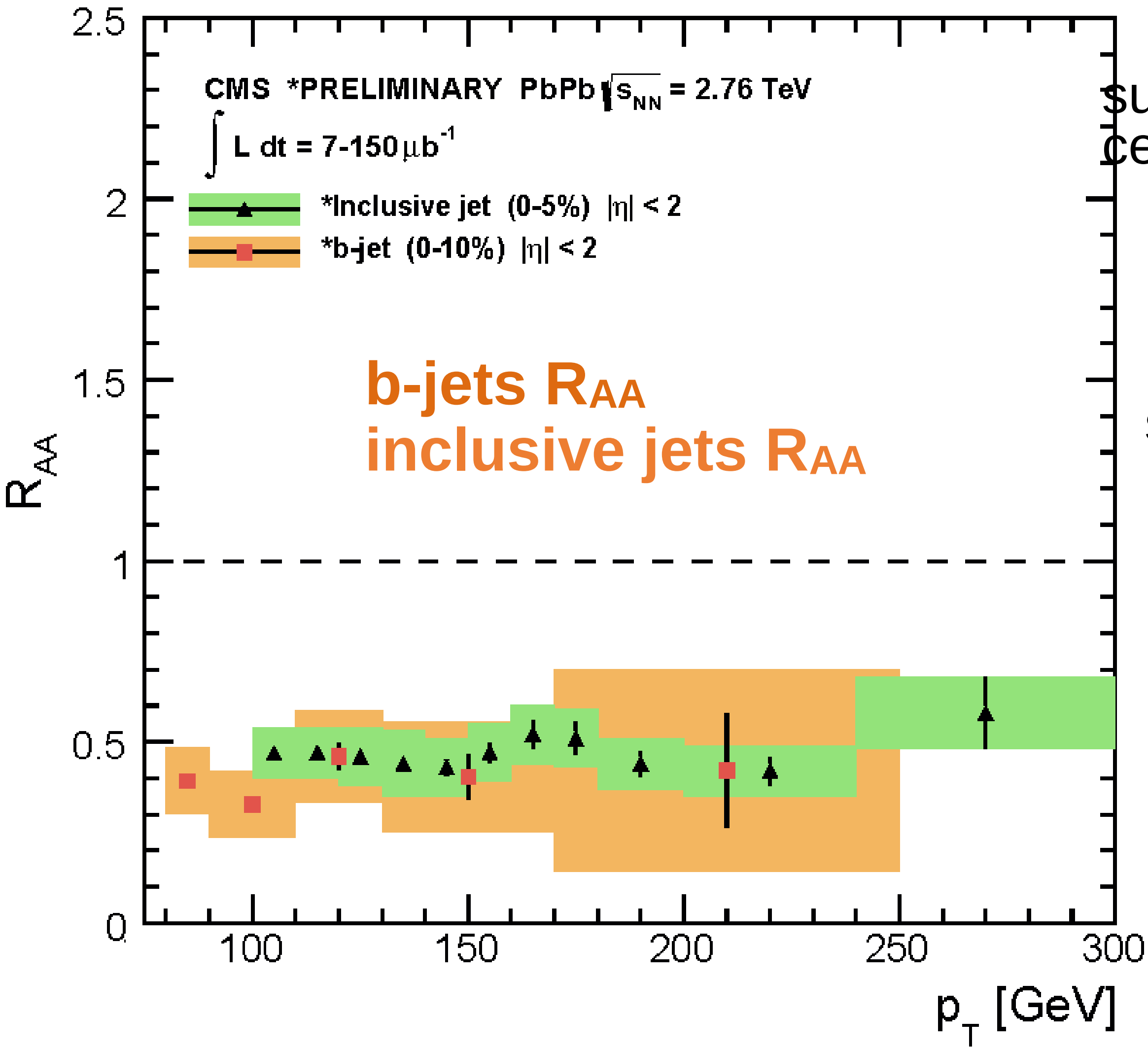




**Charged particle**
**Non prompt J/ψ**
**D mesons**

Hints of different suppression for **D mesons** and **non-prompt J/ψ** at low $p_T$!

# b-jet nuclear modification in PbPb at 2.76 TeV

b-jets tagged by selecting displaced secondary vertices (SV) in the jet cone




**b-jets $R_{AA}$** shows strong suppression (factor~3) observed in central PbPb collisions (0-5%)

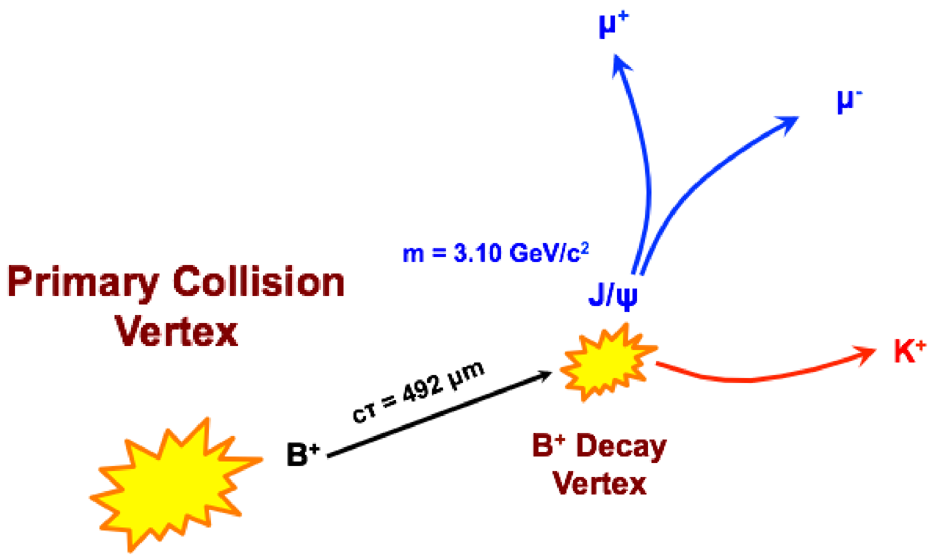
Same suppression observed for **b-jets** and **inclusive jets** in the same centrality

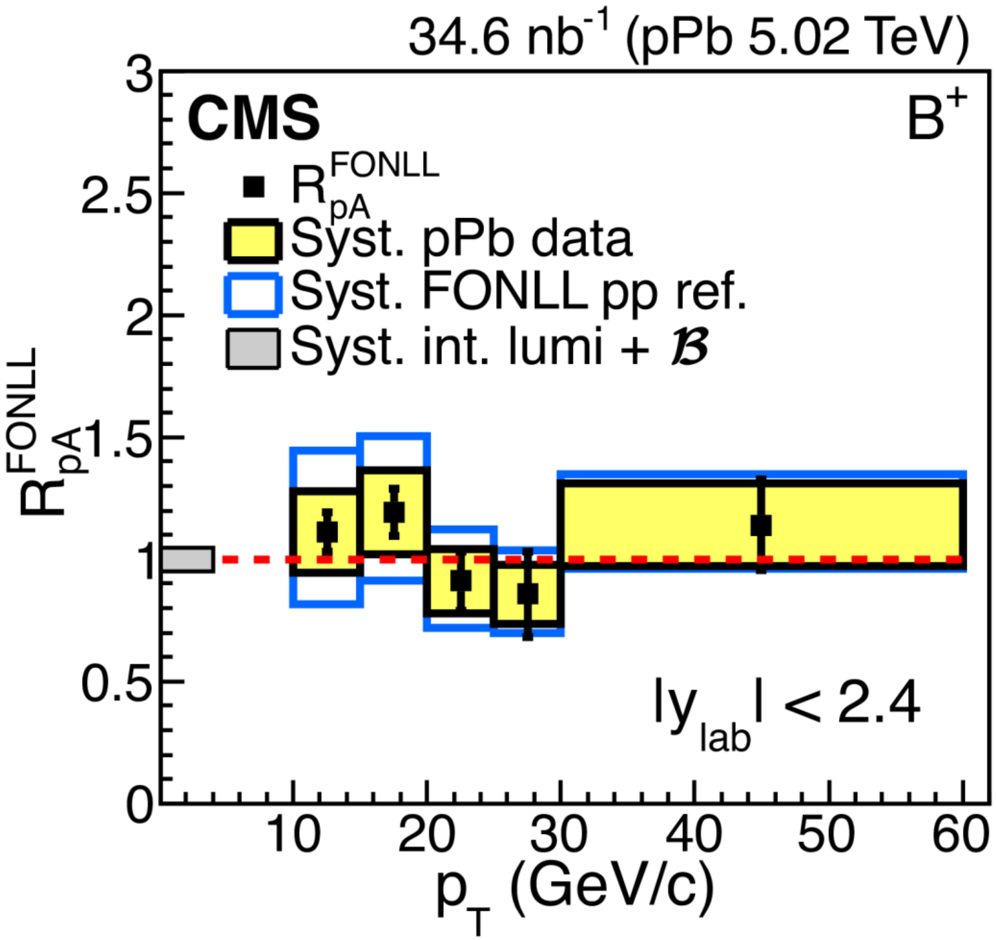
**Are we measuring the energy loss of gluons in both cases (gluon splitting)?**

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

# Exclusive B meson measurements

PRL 116 (2016) 032301




- $J/\psi \rightarrow \mu^+\mu^-$ reconstruction
- Tracks are associated to $J/\psi$ candidate to build B-meson candidates

Measured in pPb collisions only:

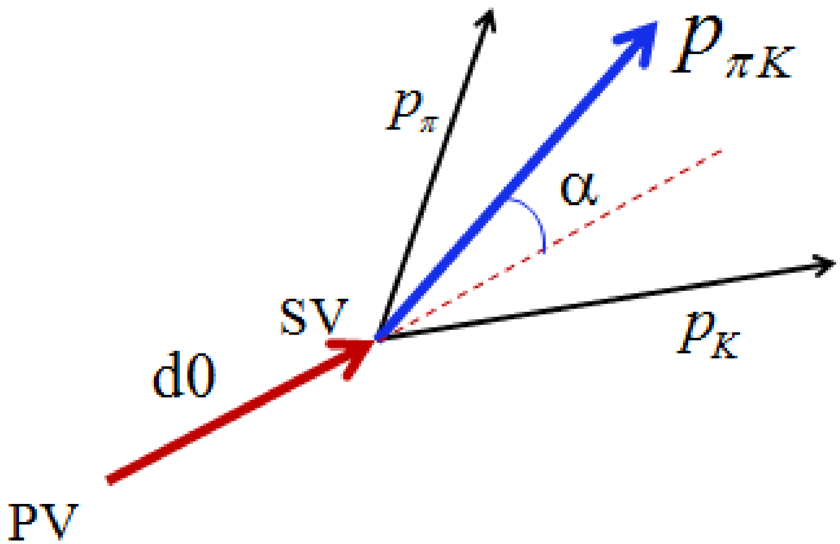
- $R^{FONLL}_{pA}$ consistent to unity

**PbPb measurement coming soon!**

# First Run II heavy flavour analysis!

**CMS-PAS-HIN-16-001**

# $D^0$ measurements in pp and PbPb collisions




**$D^0$ □ $K^- \pi^+$ in pp and PbPb collisions** (0-10% and 0-100%) at 5.02 TeV in |y|<1.0

**Analysis strategy:**

- Primary and $D^0$ vertex reconstruction
- $D^0$ candidate reconstruction
- D meson selection**:**
  - pointing angle **(α)**
  - decay length normalised to its error **($d_0$)**
  - $D^0$ vertex probability

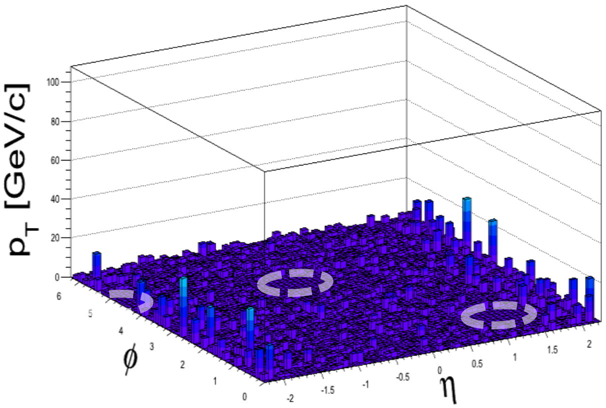
↓

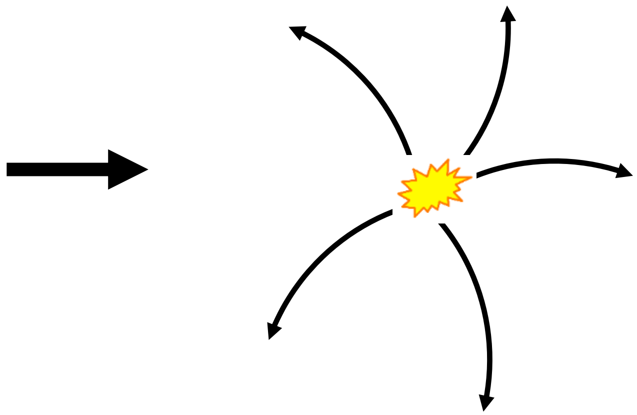
**Invariant mass analysis**

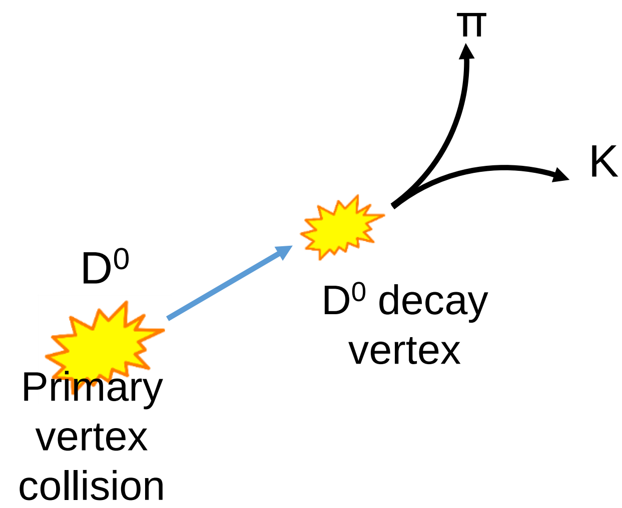
**Data samples:**

- **2 billion pp MB events** in pp and **150 million PbPb MB** for low $p_T$ analysis (<20 GeV/c)
- **Triggered sample** selected with dedicated HLT $D^0$ filters to enhance the statistics up to very high $p_T$ ($p_T$>20 GeV/c)

# $D^0$ triggers at High-Level-Trigger (HLT)






**Events firing hardware jet triggers (Level-1) are selected**

•L1 jet algorithm with online background subtraction

**Tracks are reconstructed in software trigger system (HLT) for selected events**

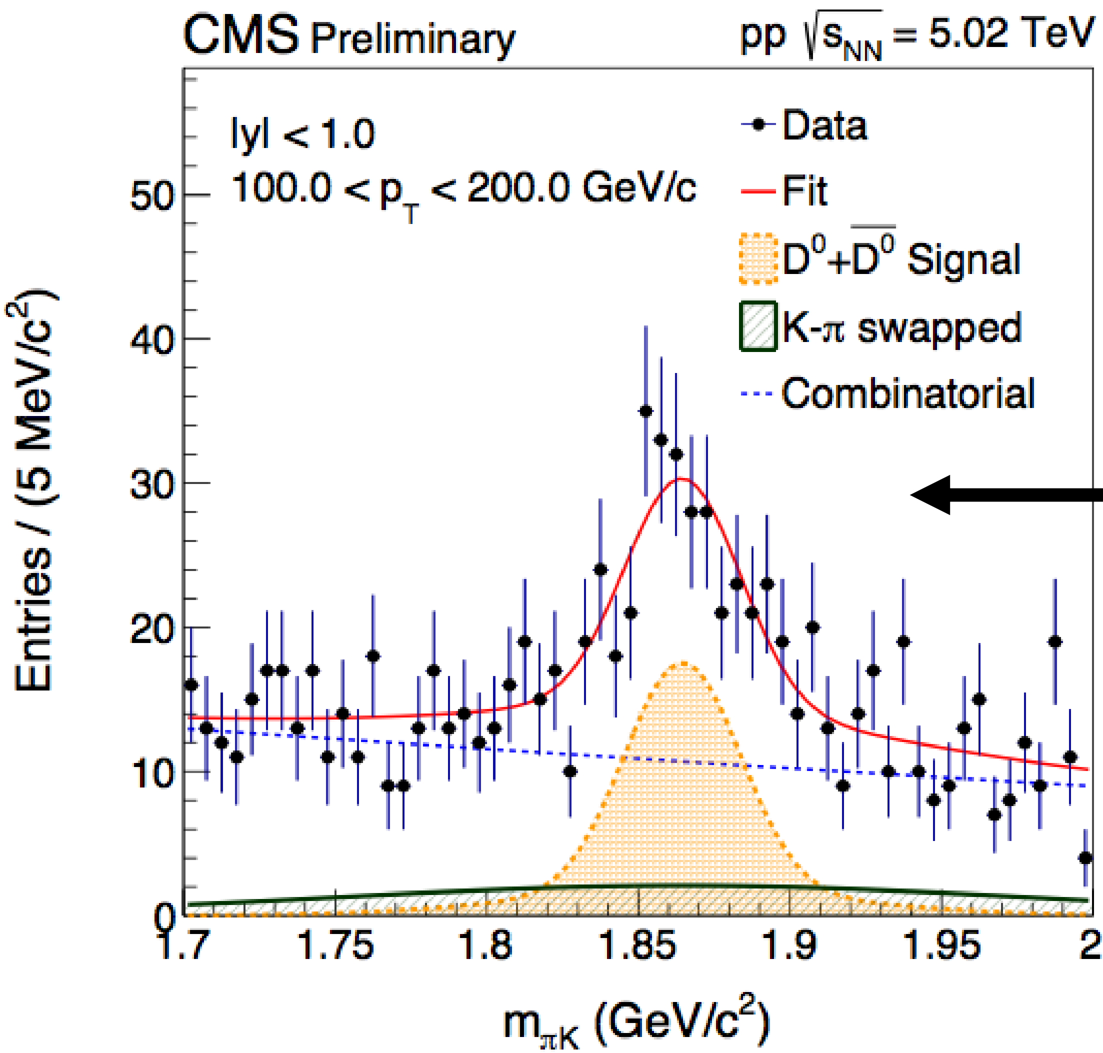
Track seed $p_T$ cut applied:
•$p_T > 2$ GeV for pp
•$p_T > 8$ GeV for PbPb

**$D^0$ meson are reconstructed**

- Online $D^0$ reconstruction
- loose selection to reduce the rates based on $D^0$ vertex displacement


50

# $D^0$ triggers at High-Level-Trigger




pp collisions at 5.02 TeV

**extending the high $p_T$ reach of $D^0$ analysis up to 200 GeV!**

# Outlook

- **More precise measurements of B production are getting urgent:**
  - with Run2 data, CMS can measure with good precision the b-production via $J/\psi \leftarrow B$, b-jets and **exclusive B measurements**
    → complete picture of the HF energy loss

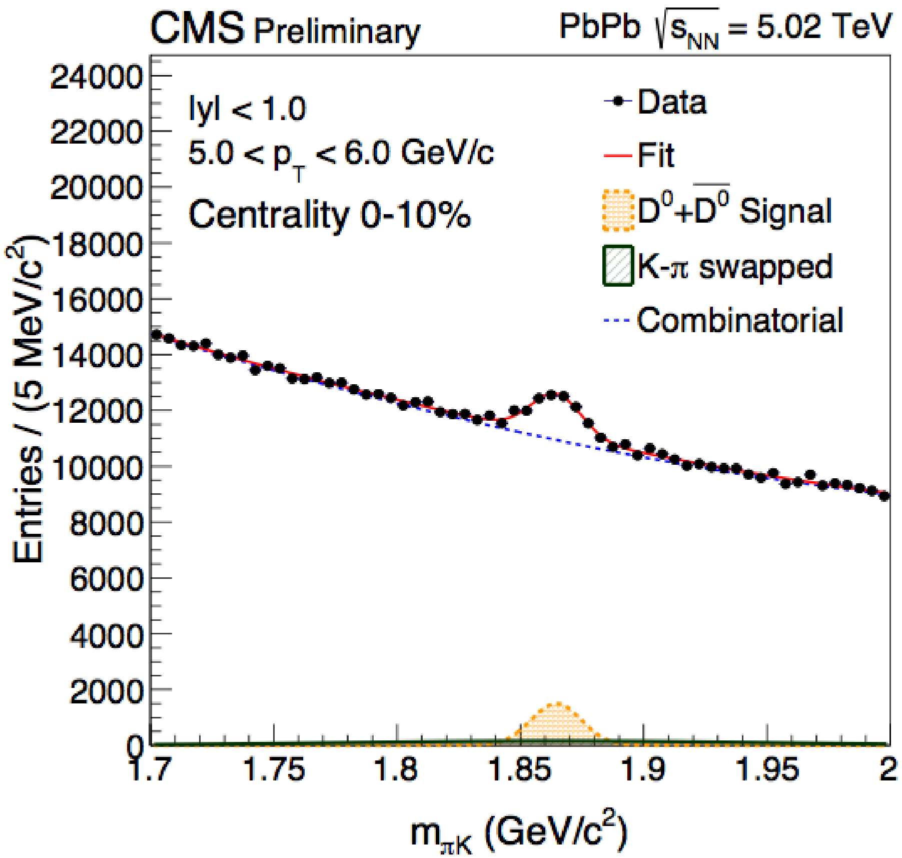
- **D-meson production at low $p_T$**
  - measure D meson production in PbPb (and pPb) down to ~1 GeV to further constrain the mechanisms of productions (e.g. recombination) and relevance of cold nuclear effects

- **D and B $v_n$ measurements**
  - fundamental to understand collective behaviour of HF quarks and to constraint theoretical calculations

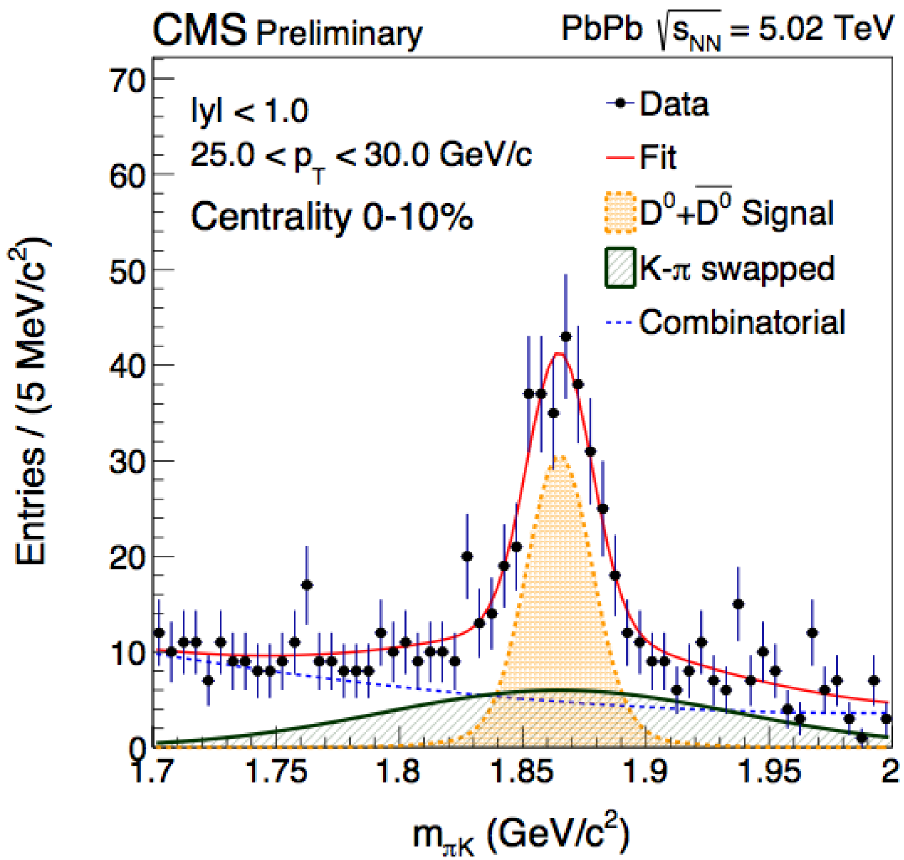
- **Gluon splitting?**
  - the relevance of soft and hard gluon splitting processes still needs to be addressed. Are we always measuring gluon energy loss?
  - More differential measurement (HF/photon, D-hadron correlations) are needed

# BACKUP

# PbPb analysis at 5.02 TeV in 0-10%

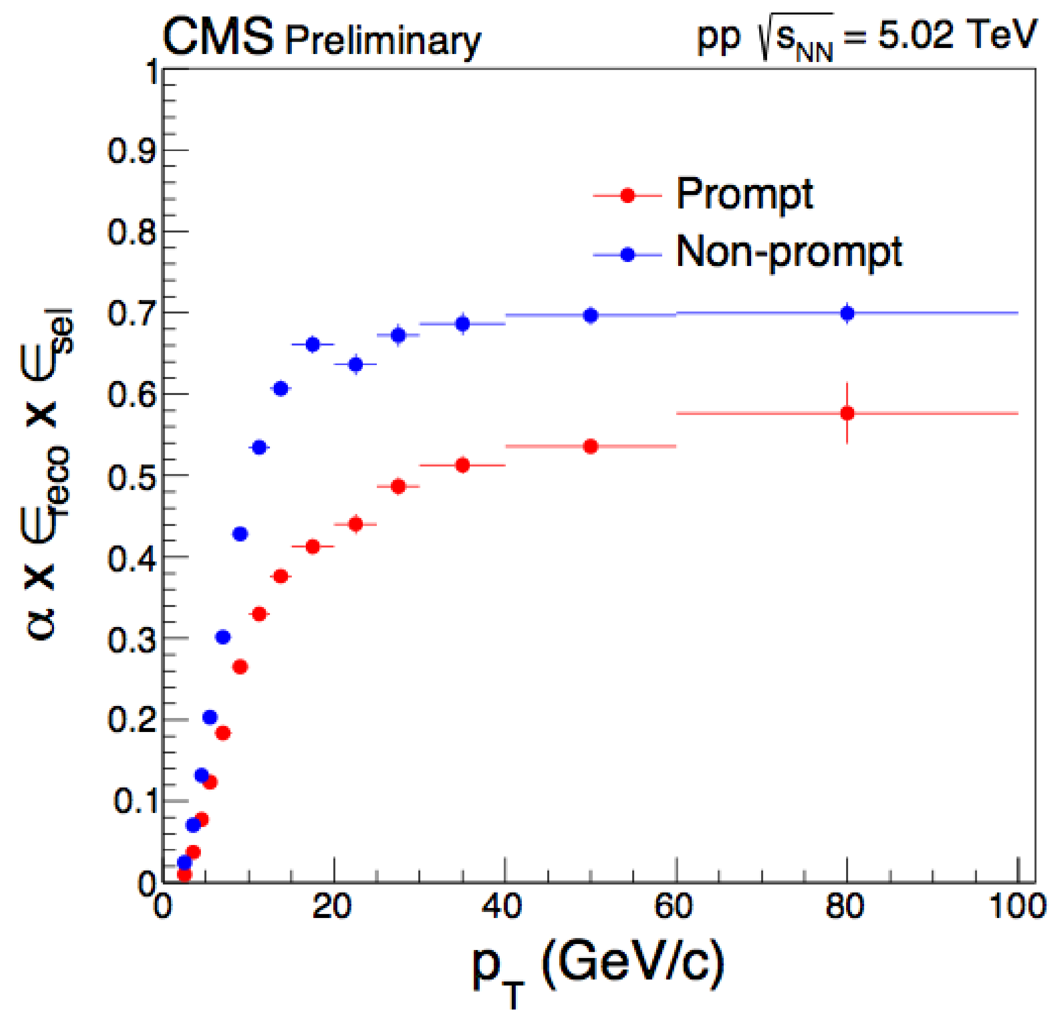



**5<$p_T$<6 GeV/c**

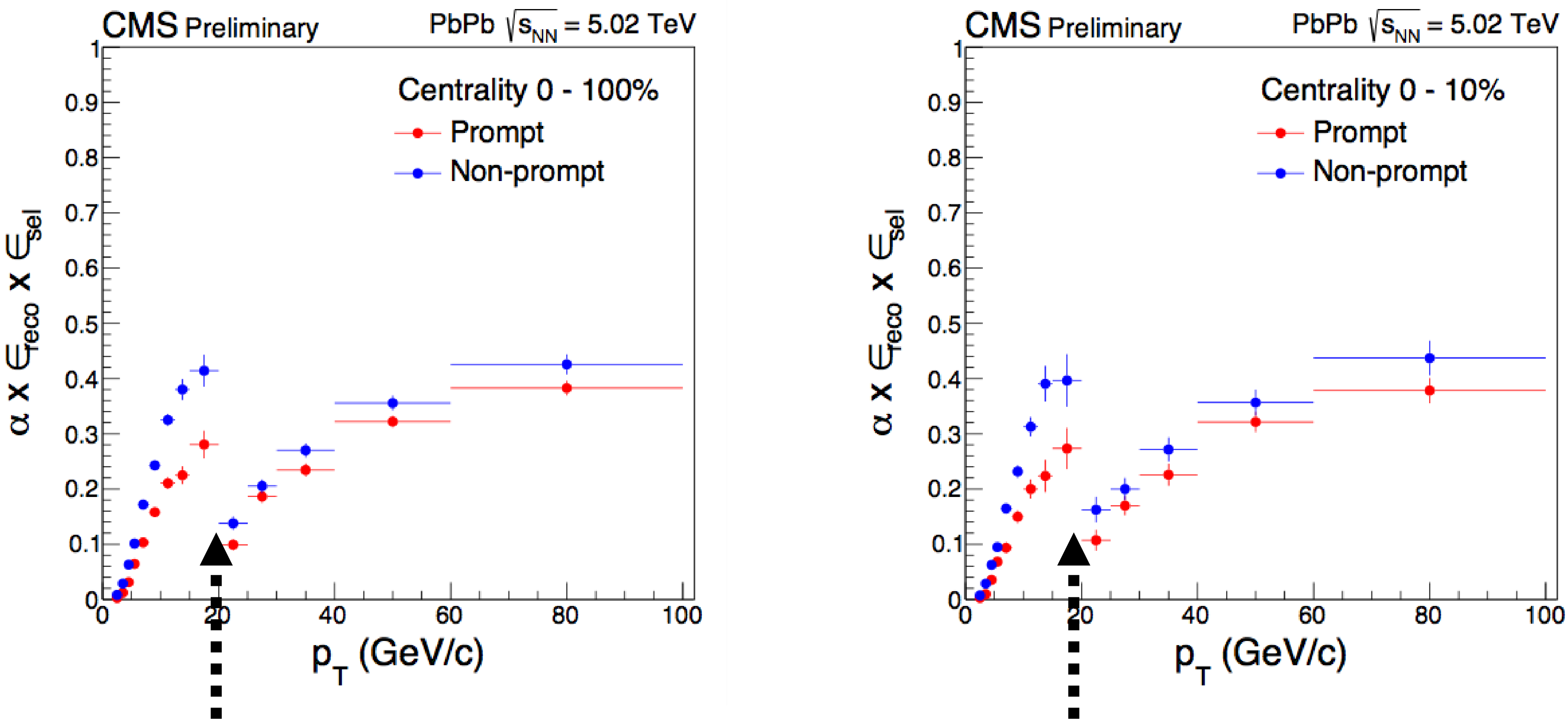



**60<$p_T$<100 GeV/c**

# Acceptance x efficiency in pp collisions

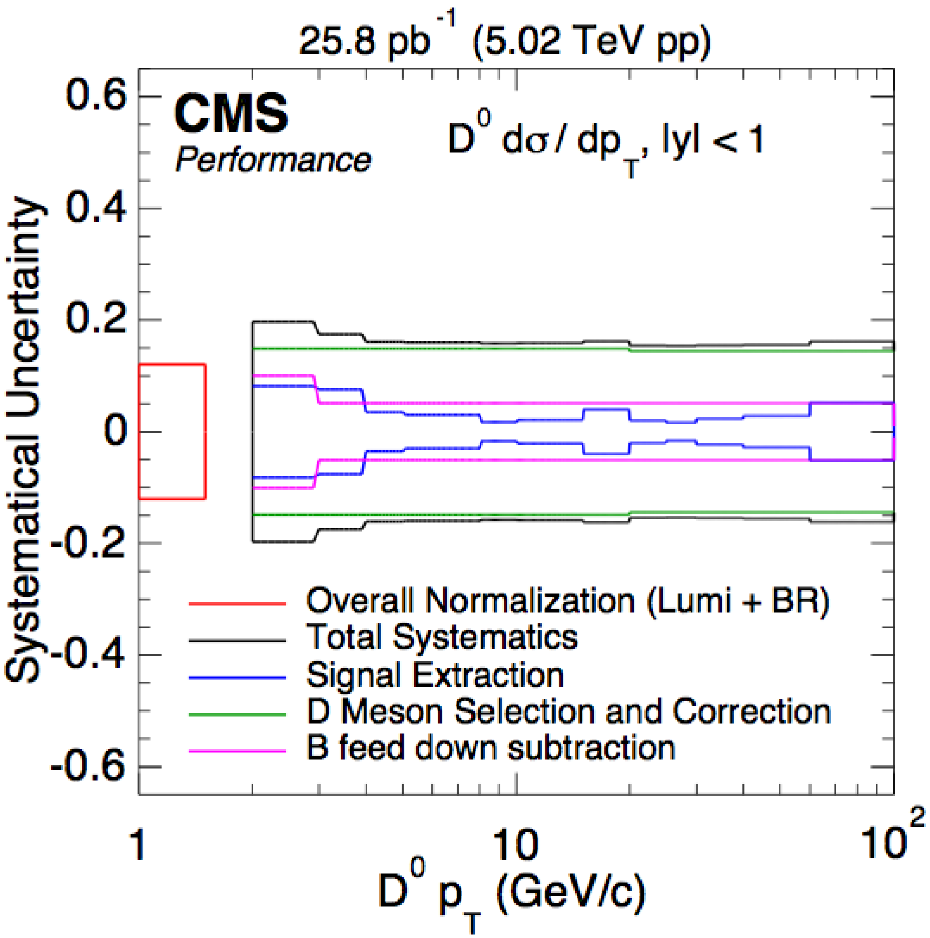


# Acceptance x efficiency in PbPb collisions

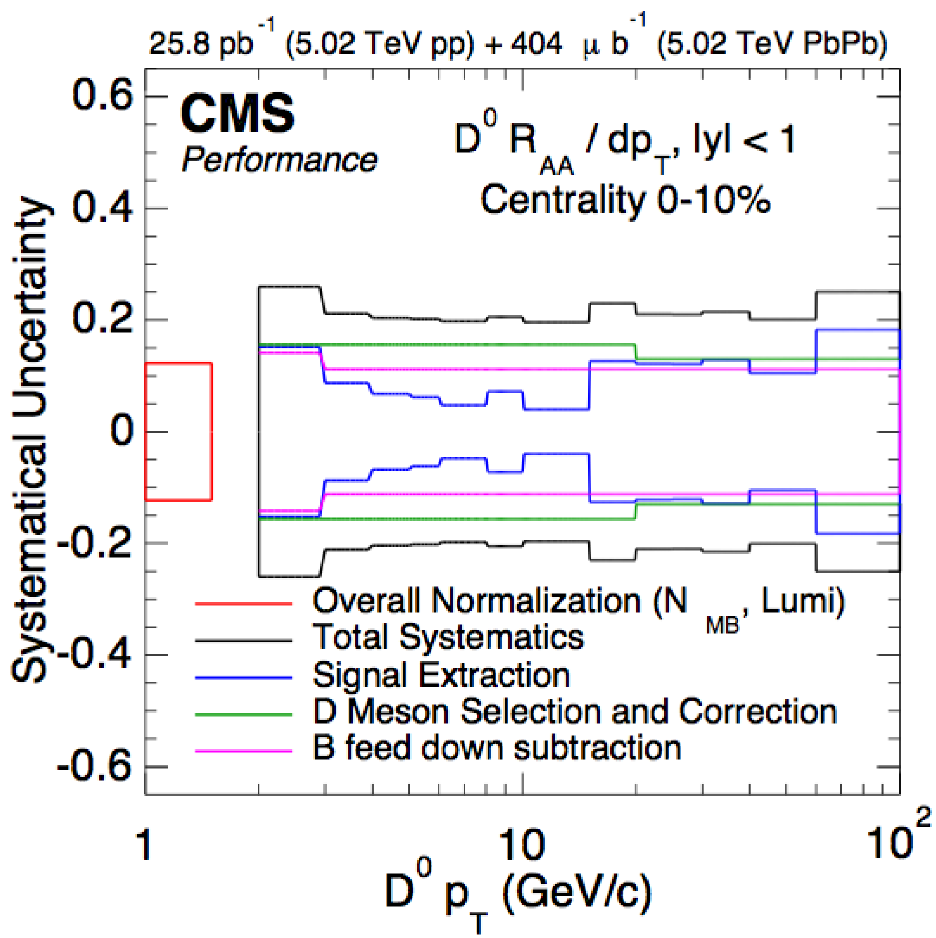



Drop in the efficiency is due to the tracking selection applied in the HLT tracking that requires a tight selection in the offline analysis

# Summary of systematic uncertainties

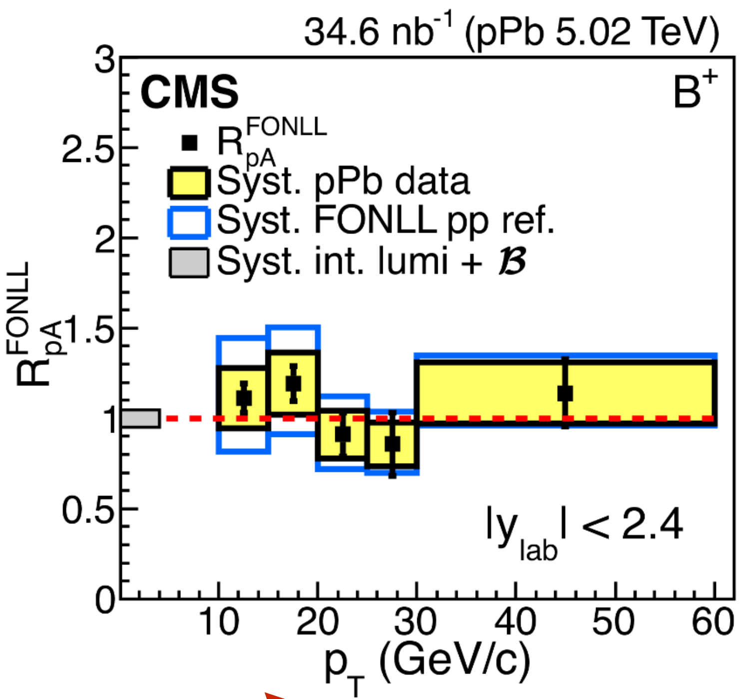


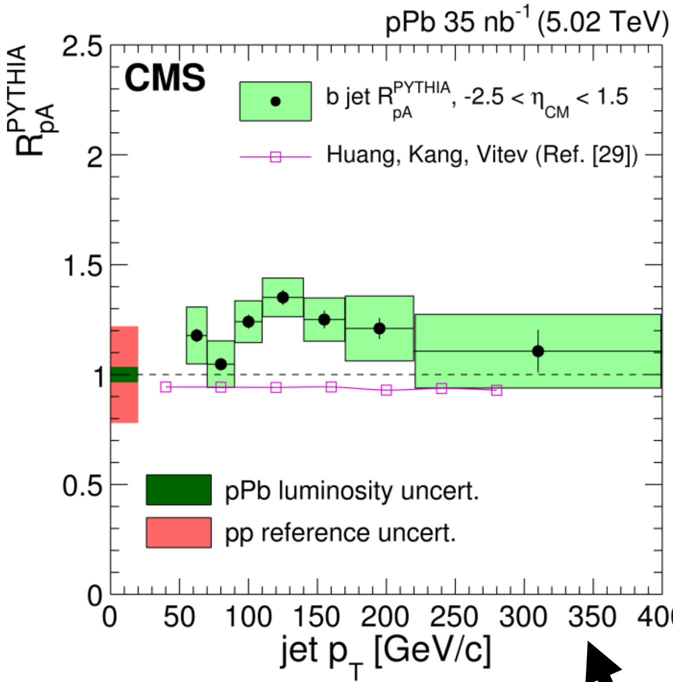

**pp 5.02 TeV**

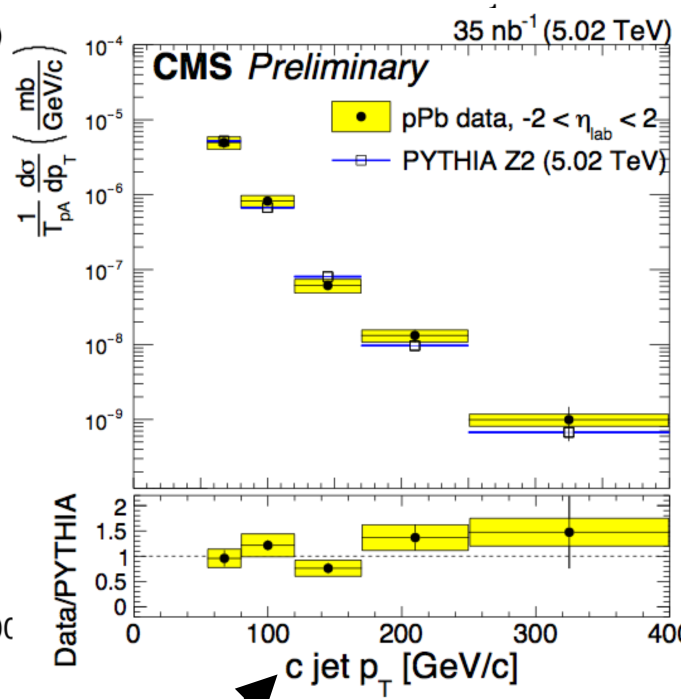



**PbPb 5.02 TeV Centrality 0-10%**

# Heavy-Flavour production in pPb



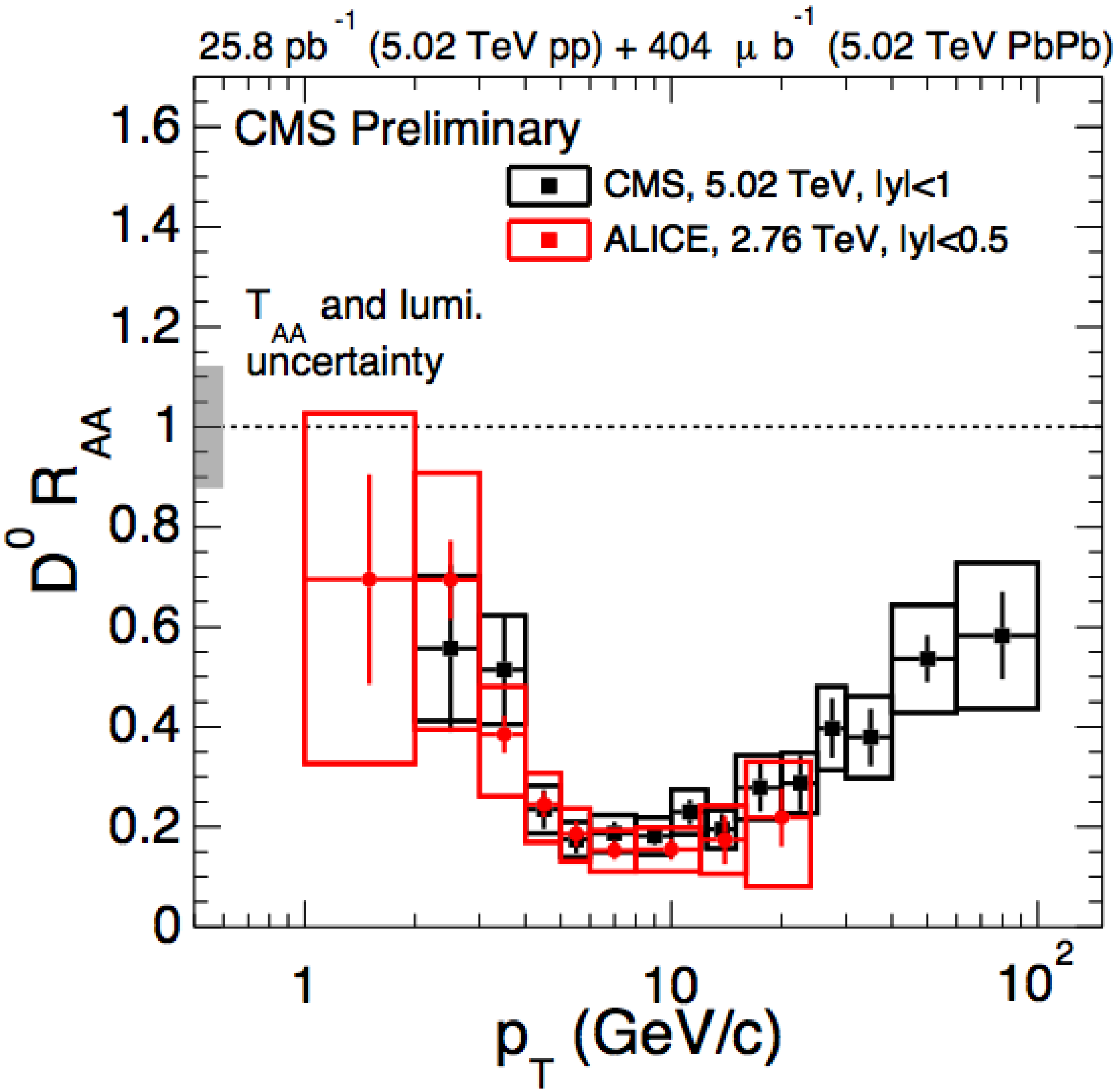

$B^+$ production in pPb
→ compatible with predictions from FONLL scaled by A=208

tagged c and b-jet production
→ compatible with predictions from PYTHIA scaled by A=208

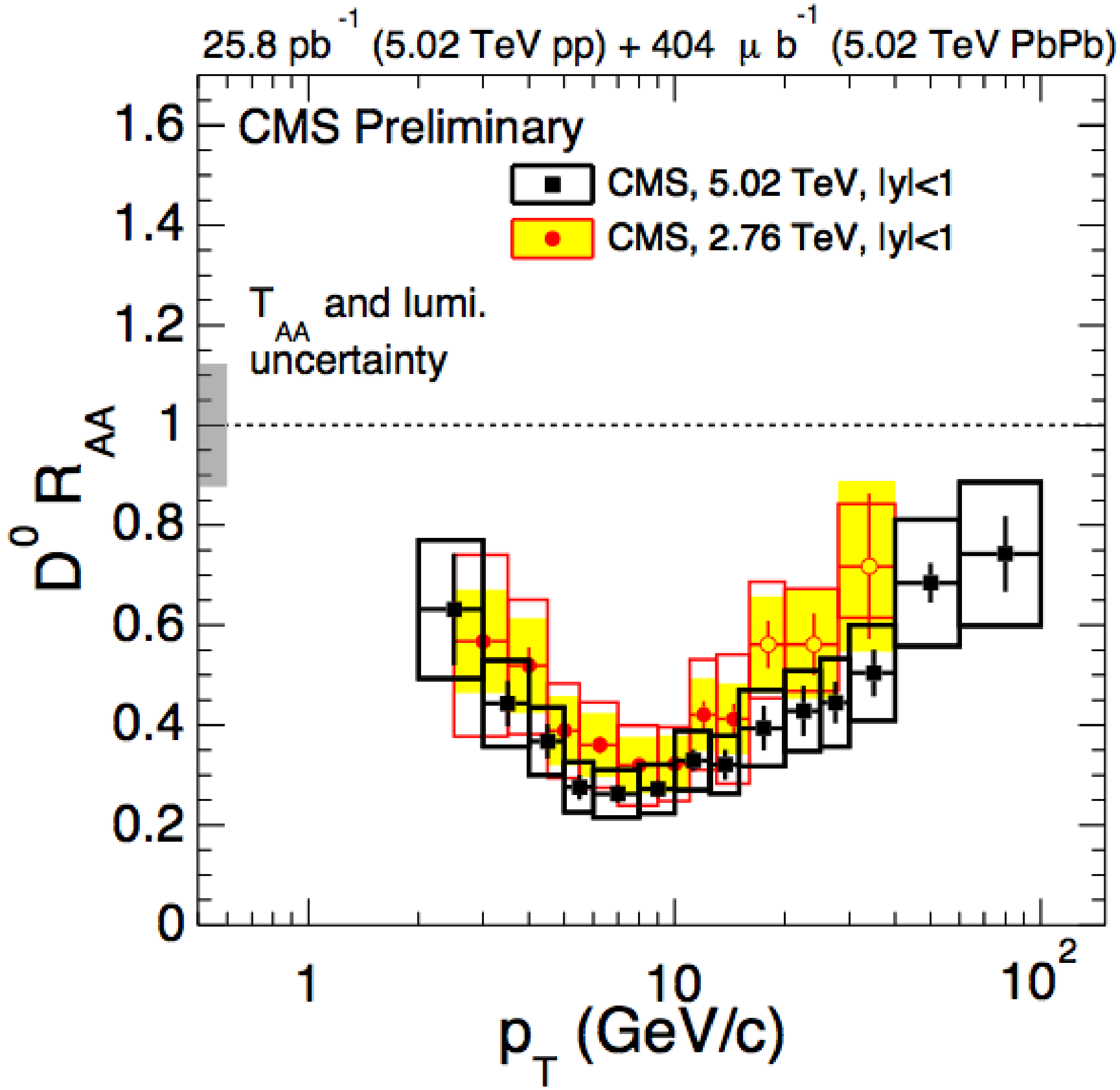
**HF pPb production not significantly modified by cold nuclear matter effects (e.g. PDF modification in nuclei)**

PRL 116 (2016) 032301, CMS-HIN-15-012 ,PLB 754 (2016) 59

# $D^0$ $R_{AA}$ comparison with ALICE



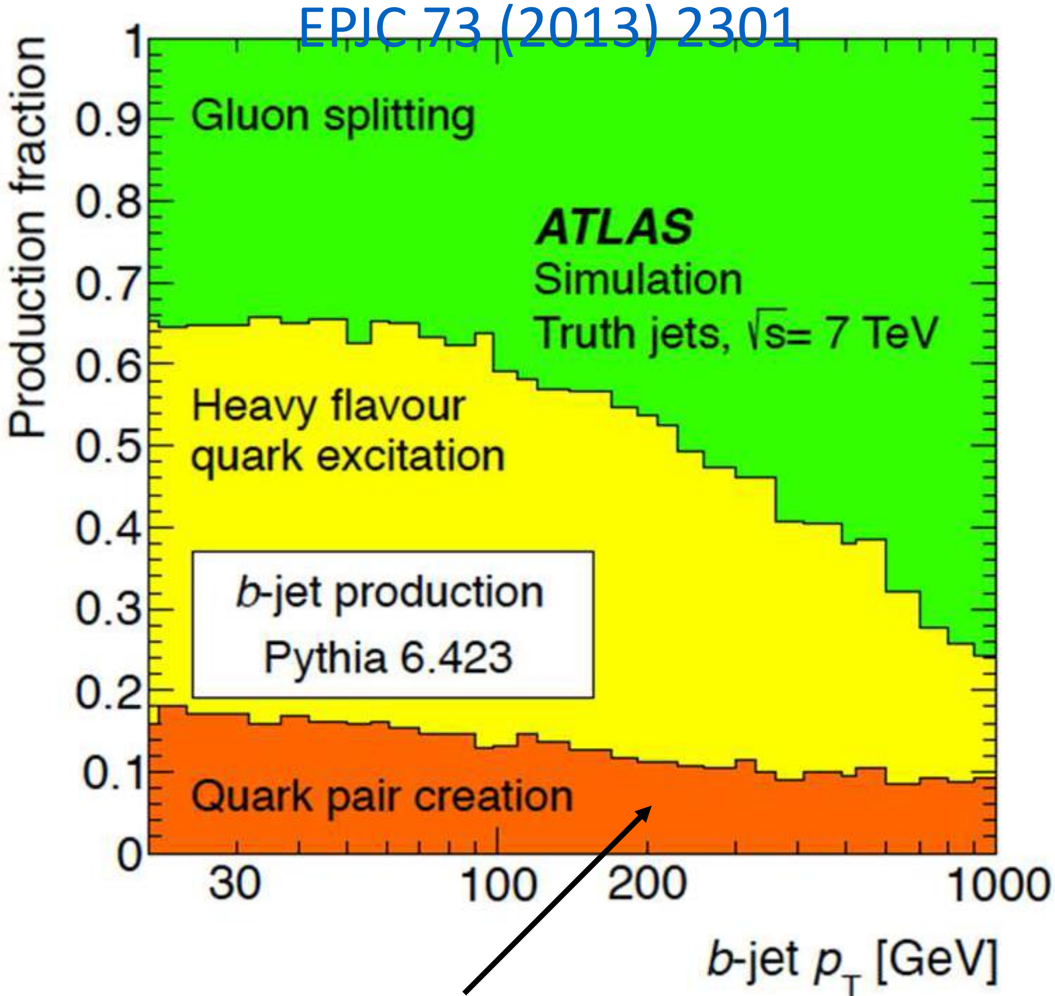
# $D^0$ $R_{AA}$ comparison with CMS 2.76 TeV




**2.76 TeV pp reference was done by extrapolating ALICE measurement via FONLL**

# HF production mechanisms in pp

EPJC 73 (2013) 2301

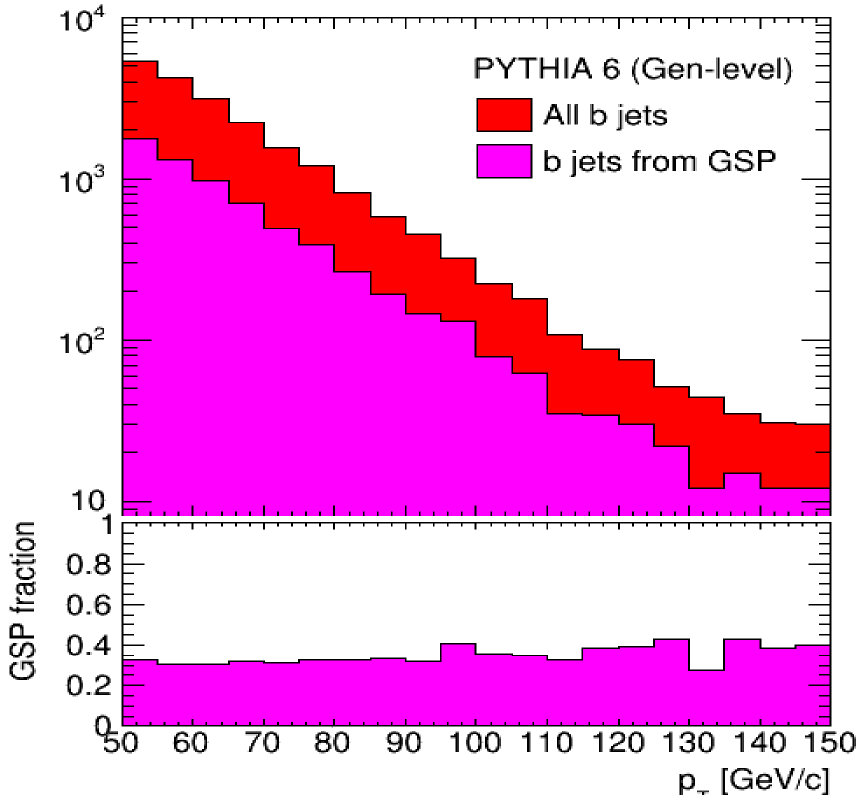


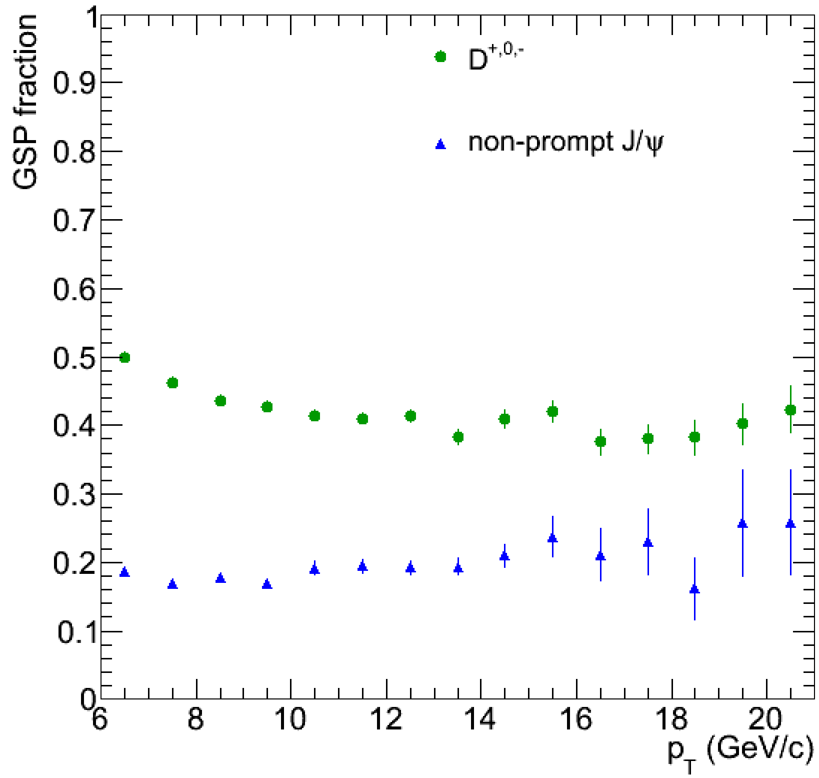

LO production mechanisms are not dominant at the LHC energies

# Gluon splitting matters!

b jets

D mesons, non-prompt J/ψ



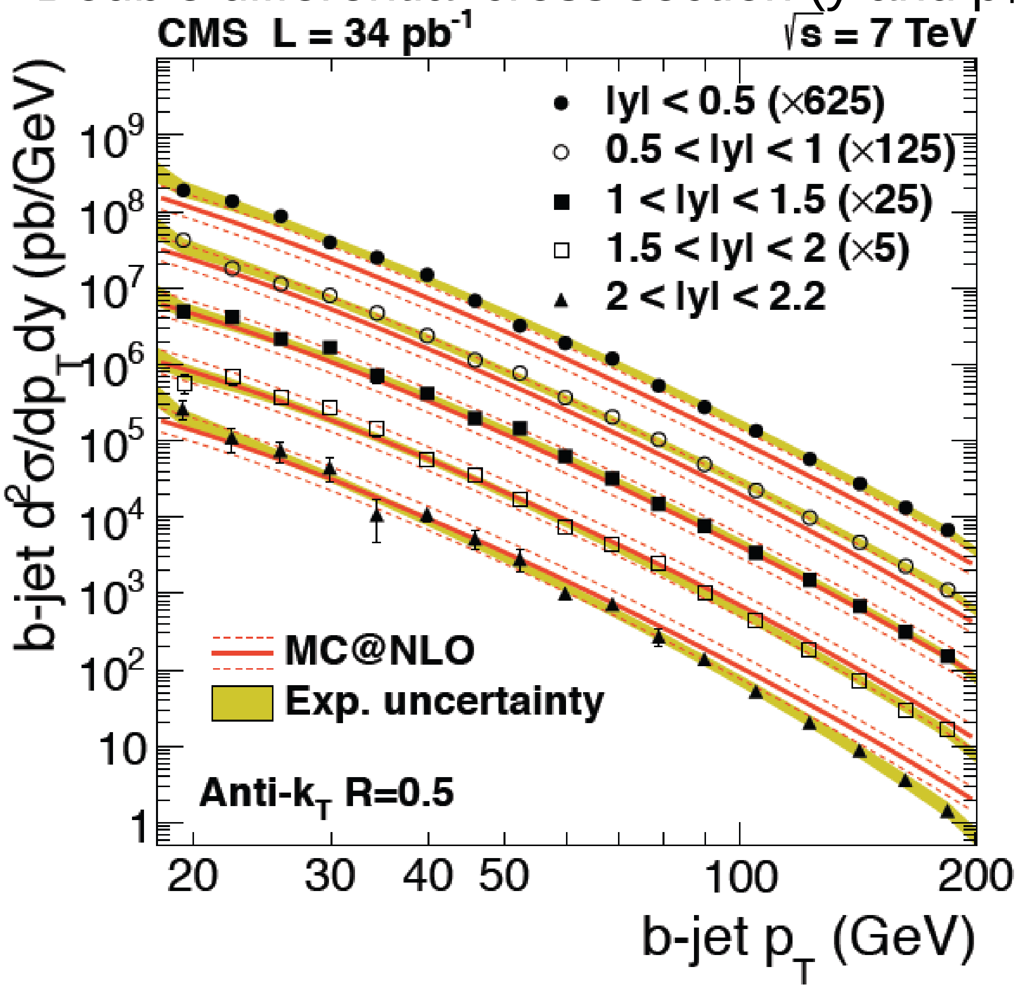



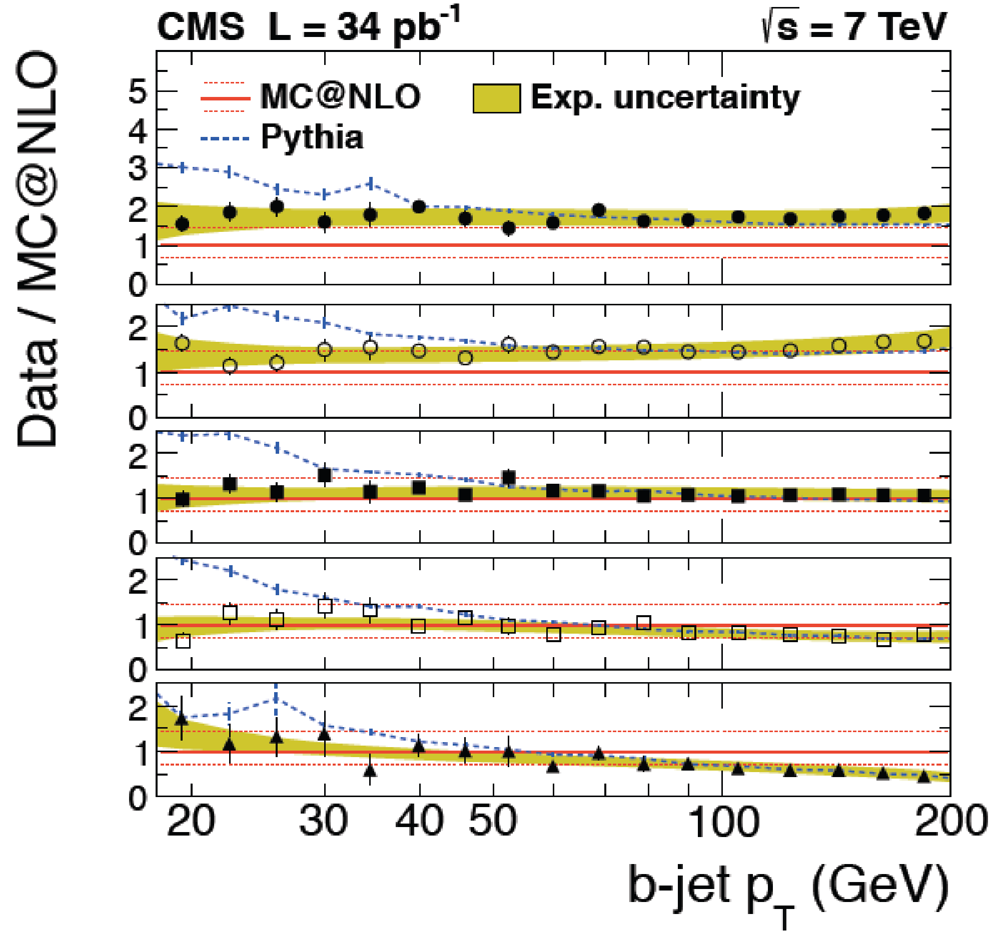

*Plots from Matthew Nguyen*

- A non negligible fraction of b-jets at the LHC come from gluon splitting
- ➓ Even more important for charm than for bottom at LHC energy!

# b-jet cross section

Double differential cross section (y and $p_T$)

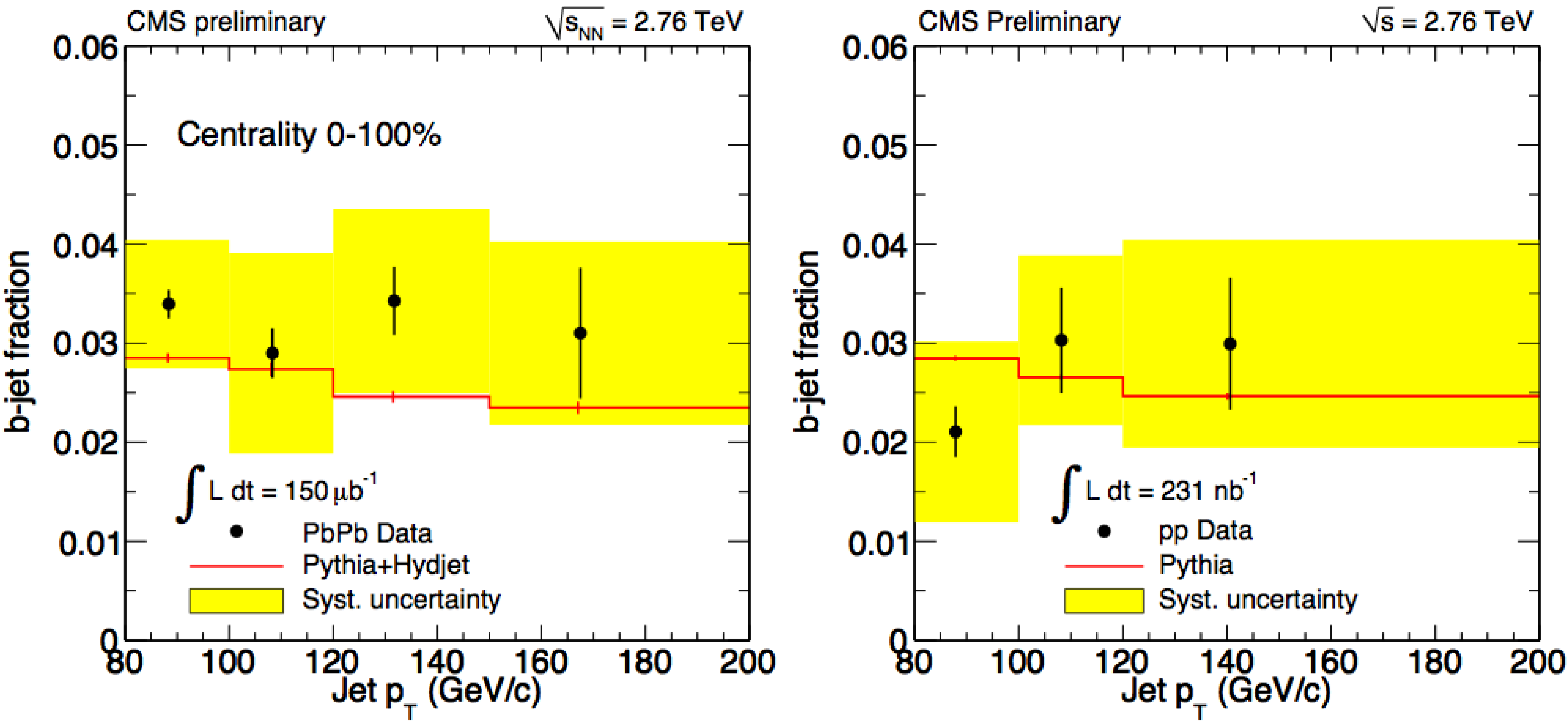



- MC@NLO agreement at the edge of uncertainties
- Pythia overshoots at low $p_T$, agrees well at high $p_T$

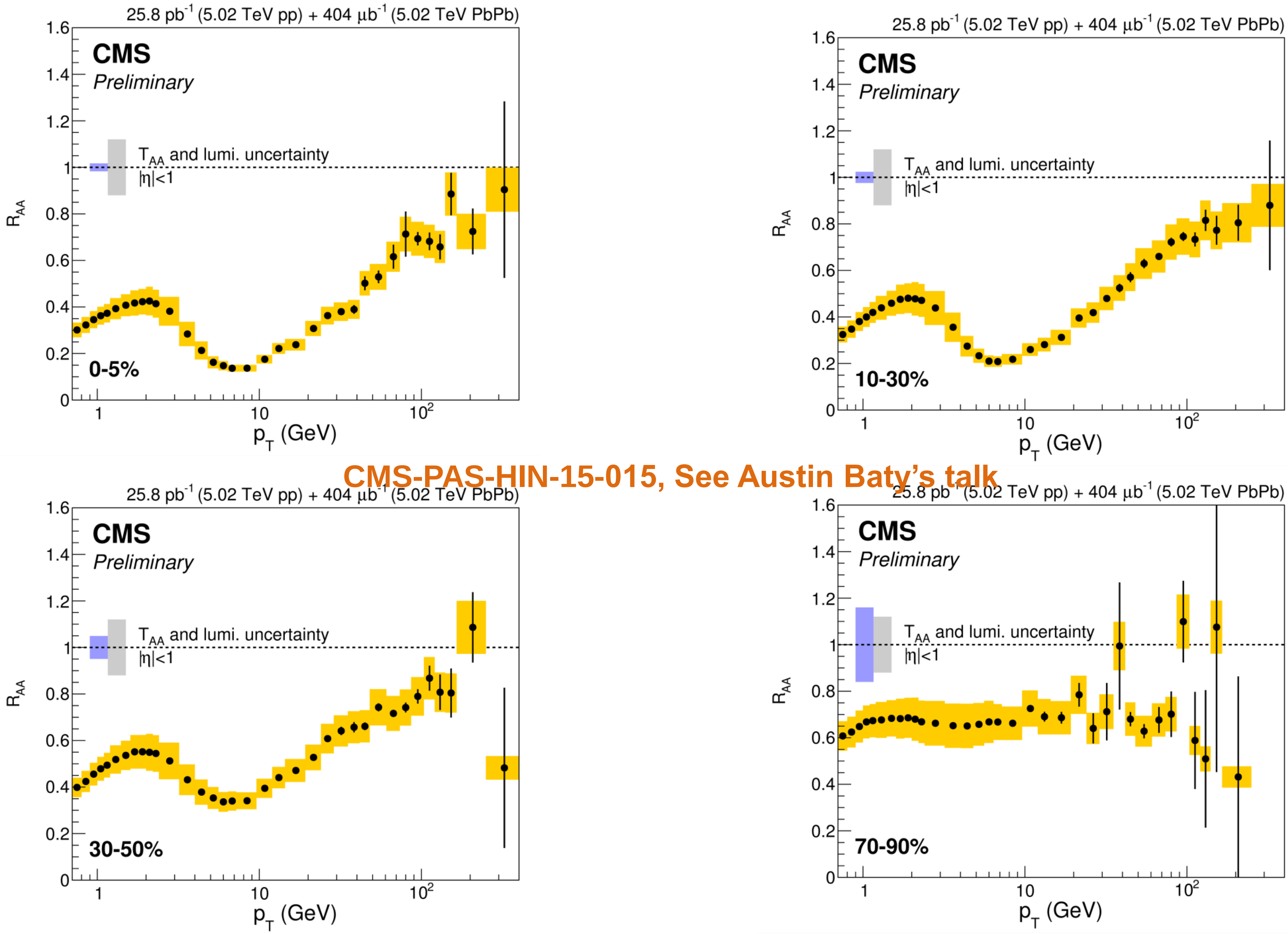
# b-jet to inclusive jet ratio

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



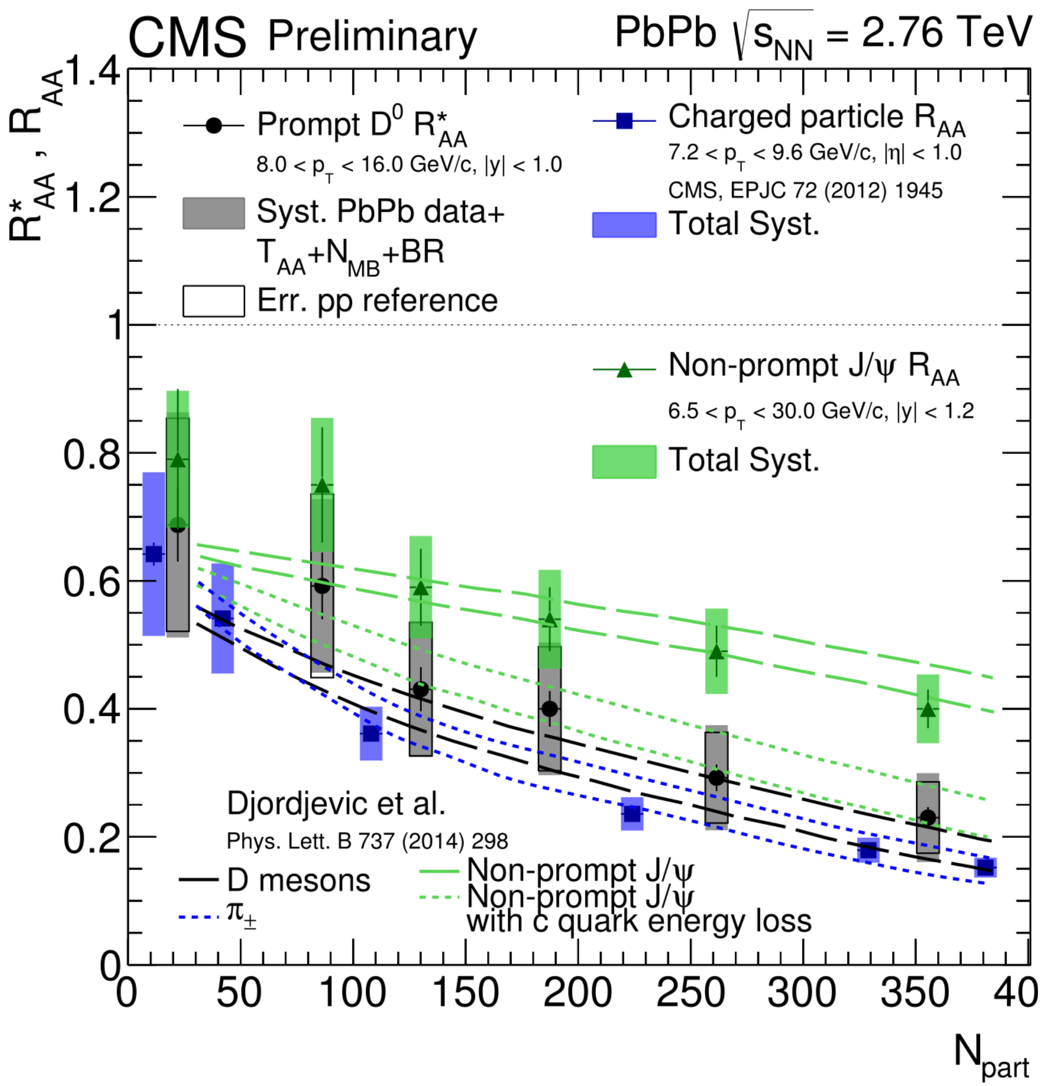

- b-jet fraction consistent within pp and PbPb within uncertainty
- Both measurements consistent with MC predictions

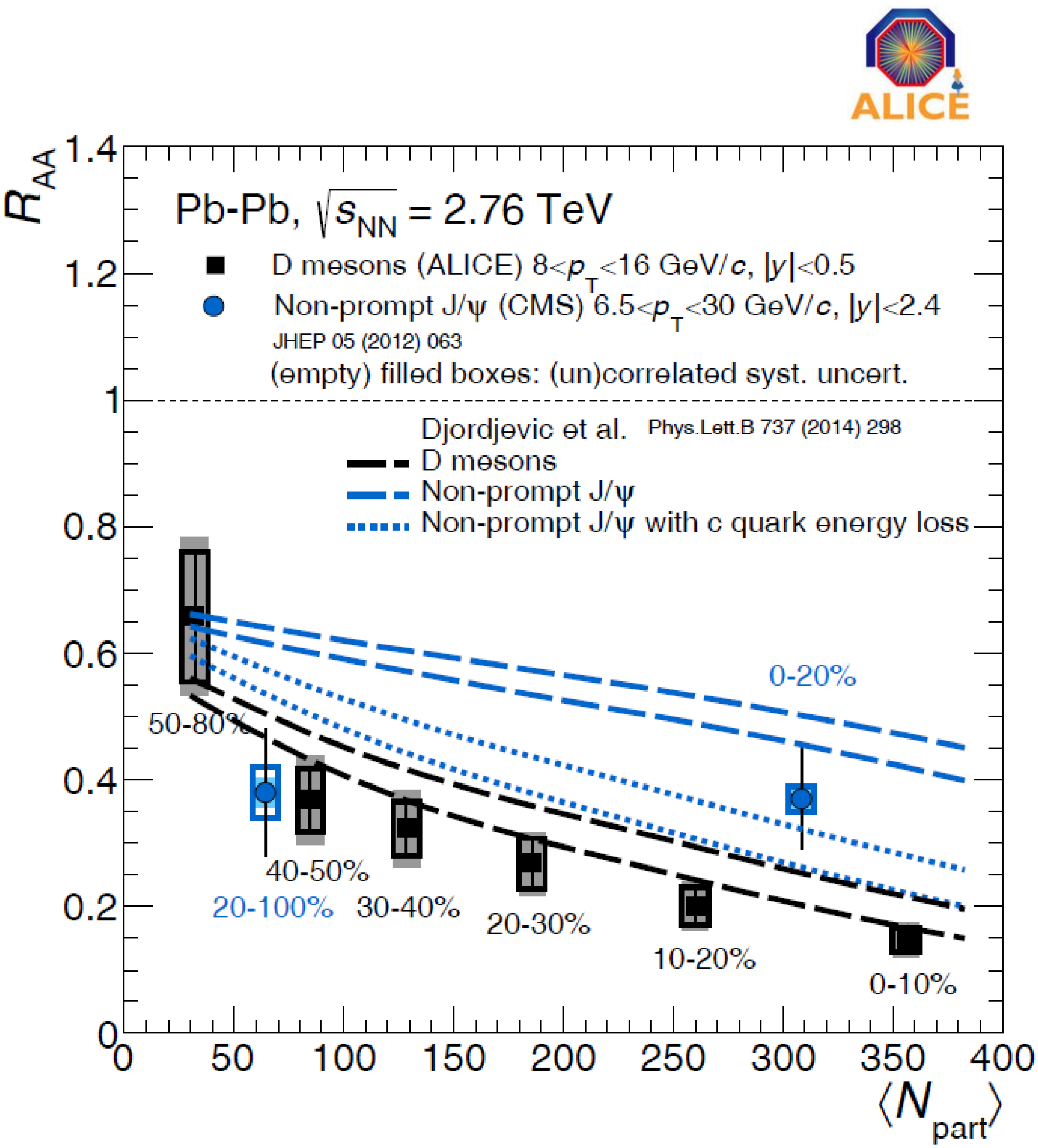
# Charged particle $R_{AA}$ at 5.02 TeV




CMS-PAS-HIN-15-015, See Austin Baty's talk

# Centrality Dependence (CMS vs. ALICE)

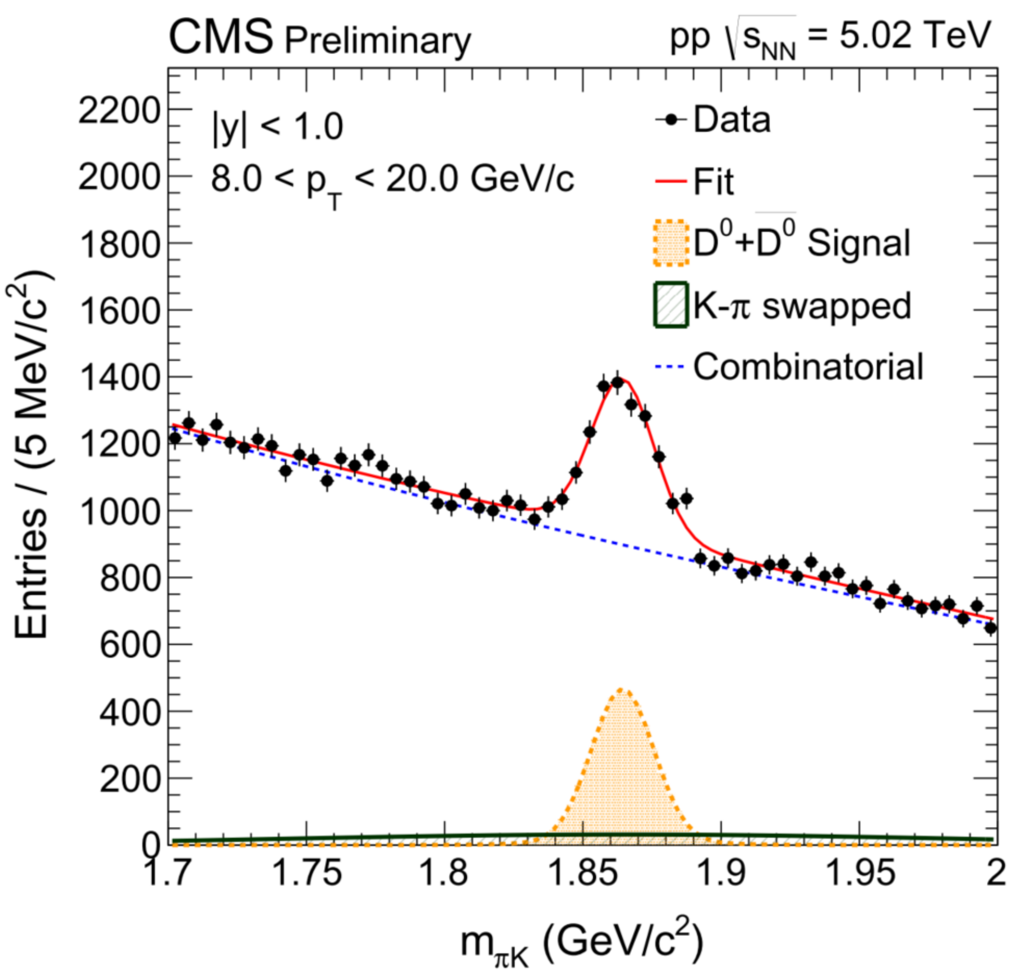


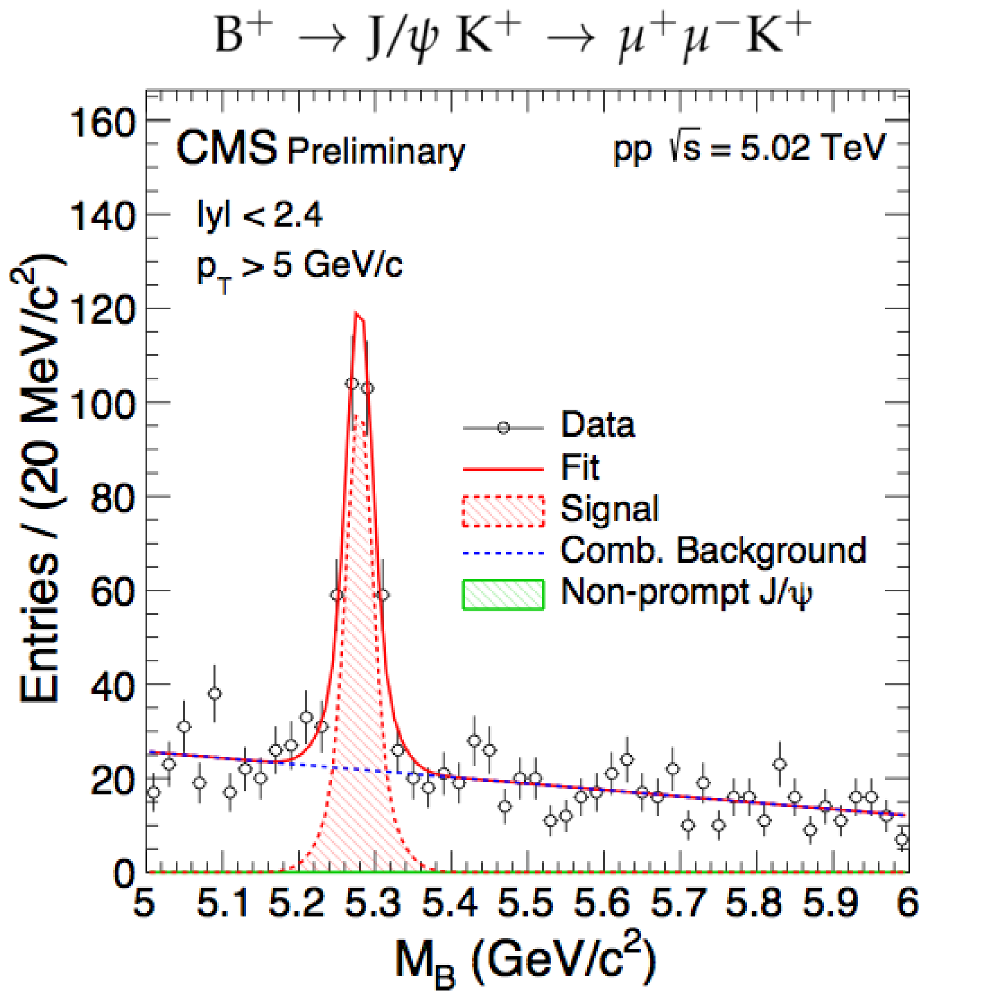

ArXiv 1506.06604

# $D^0$ 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)

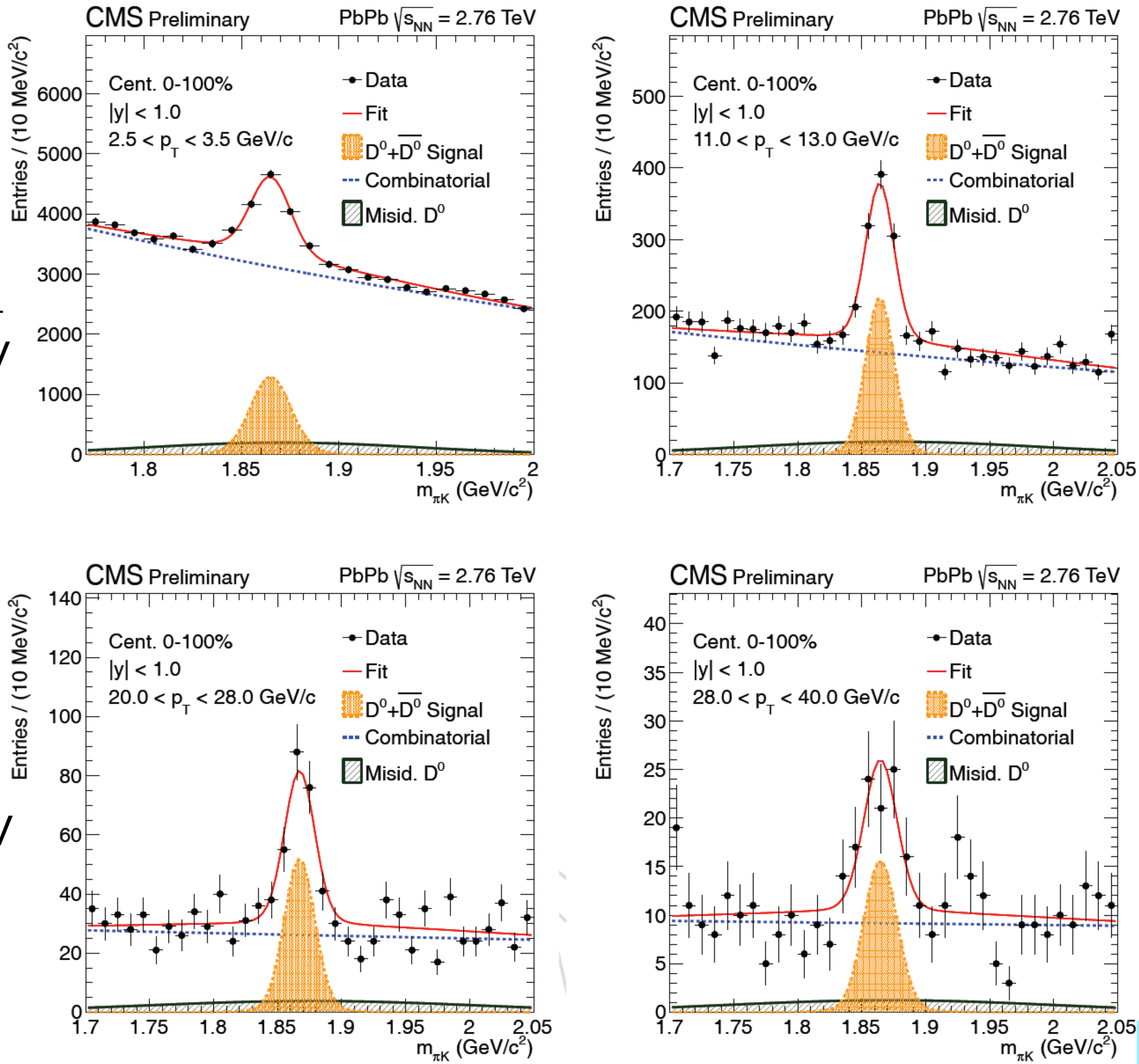
# Clear $D^0$ Signal in $p_T$ Range 2.5 to 40 GeV

D meson $p_T$
2.5-3.5 GeV

11-13 GeV

20-28 GeV

28-40 GeV

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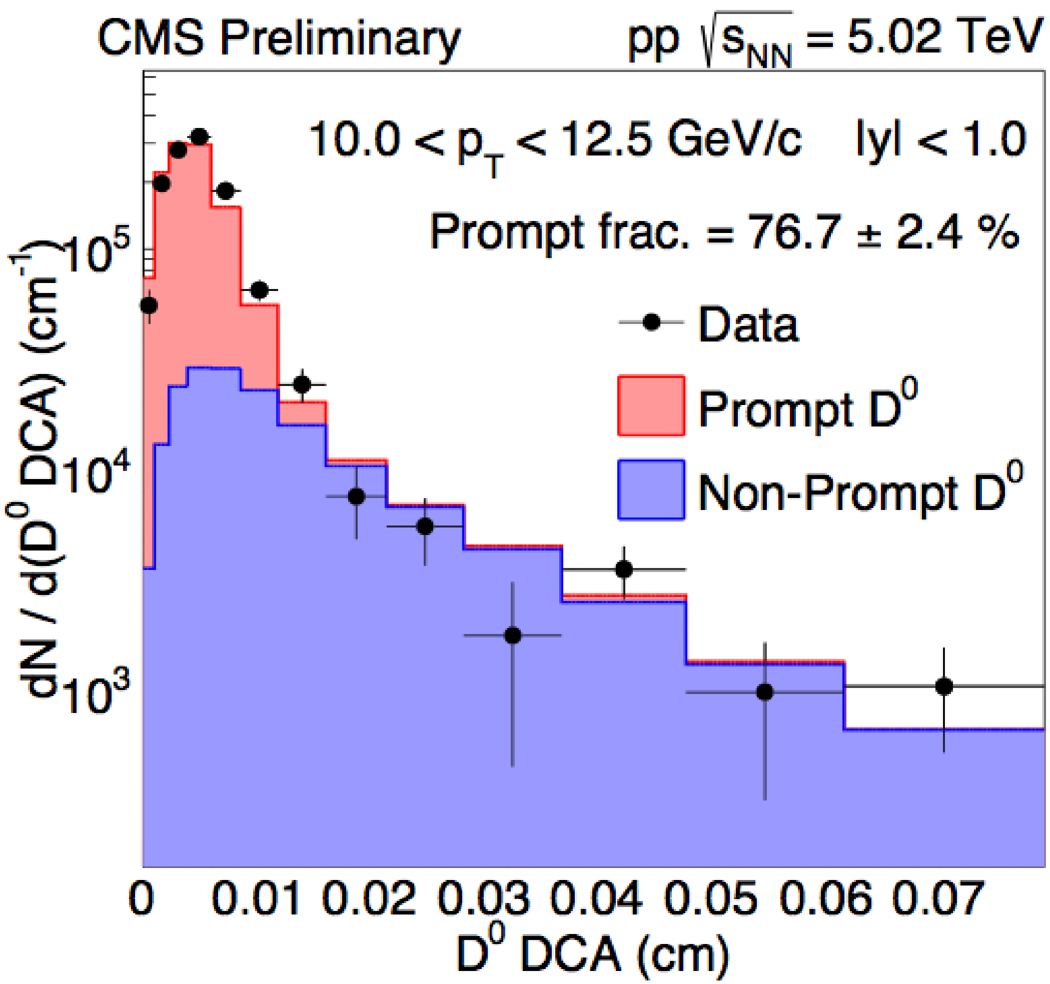
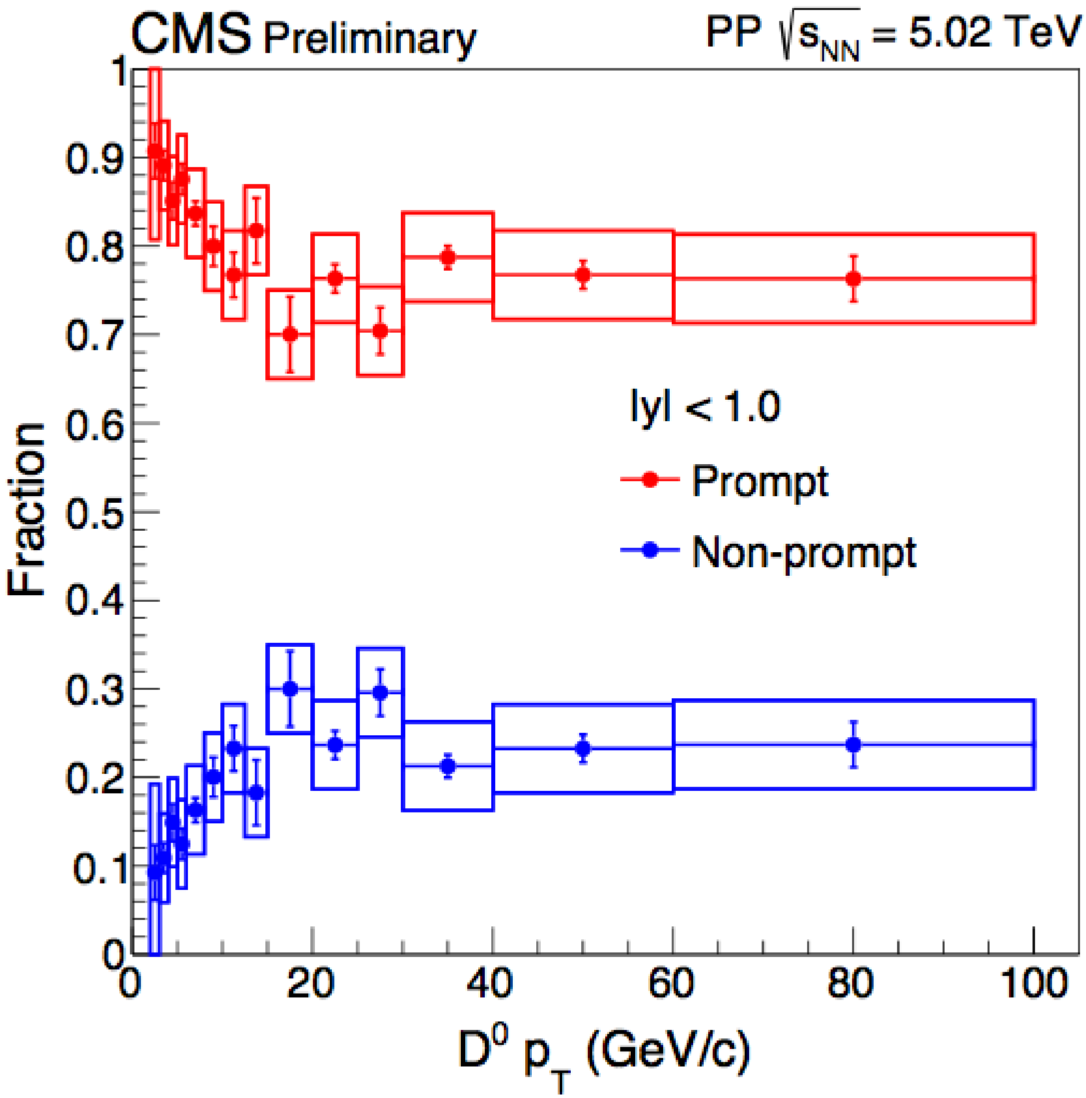
# b-feed subtraction in pp collisions

- **$f_{prompt}$** = fraction of $D^0$ mesons coming from c-quark fragmentation

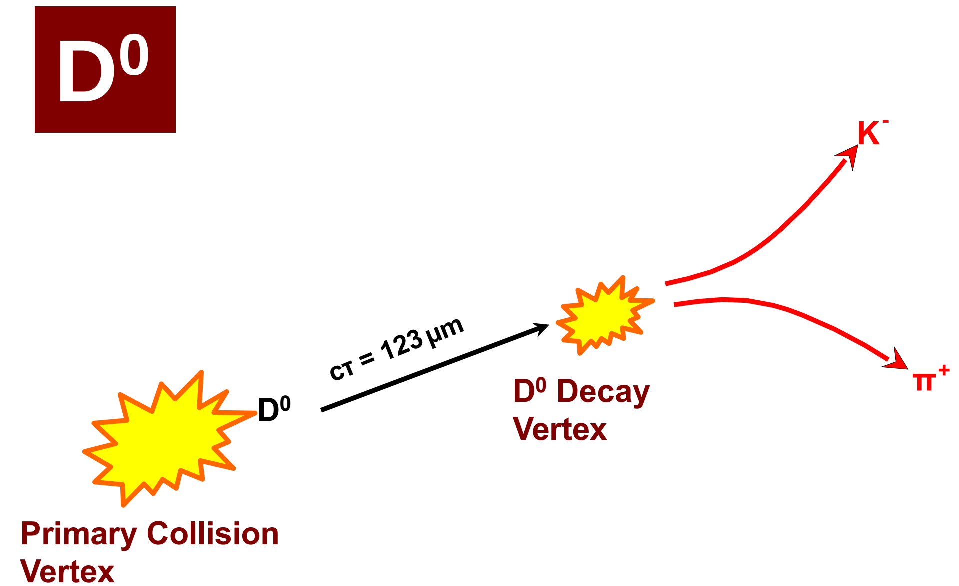
$f_{prompt}$ estimated **fully data driven** by exploiting the different shapes of distance of closest approach (DCA) distributions of prompt and non prompt $D^0$ mesons

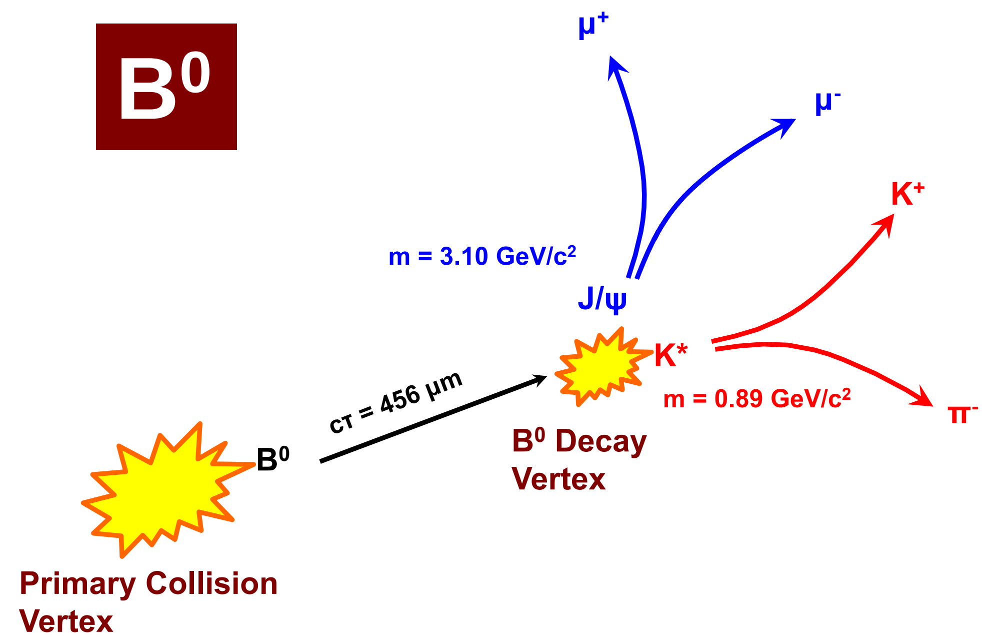


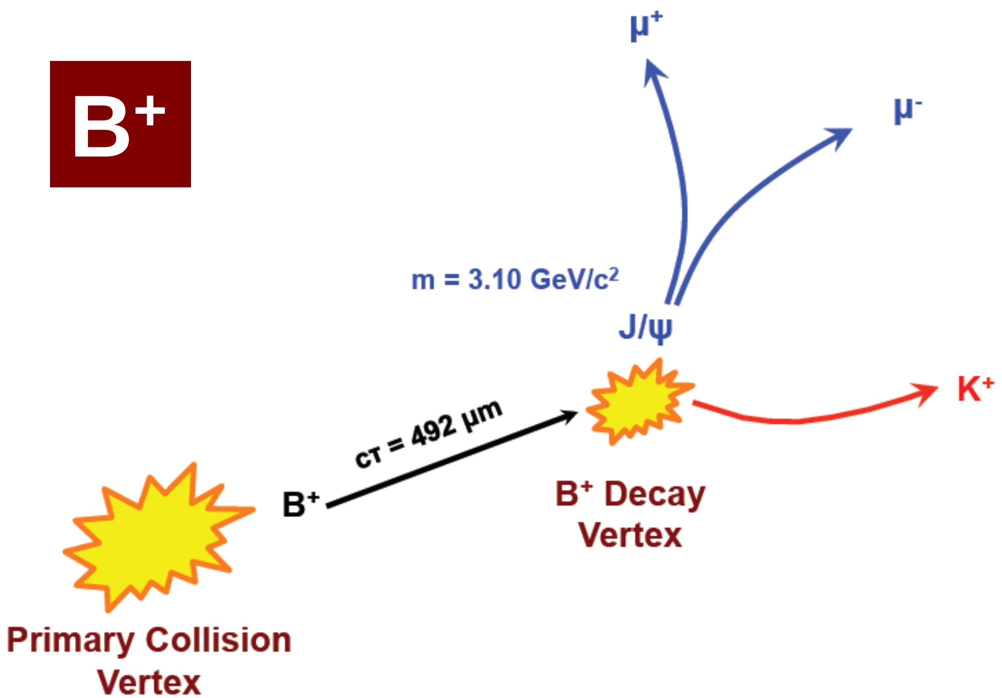
# $f_{prompt}$ fraction in pp collisions

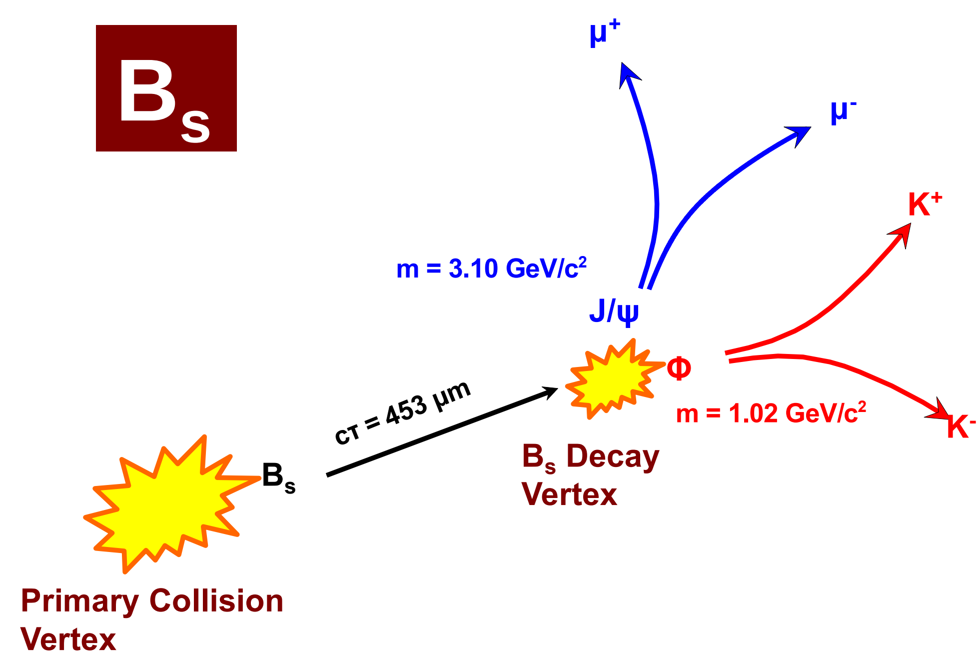


# D and B Meson Decay Channels

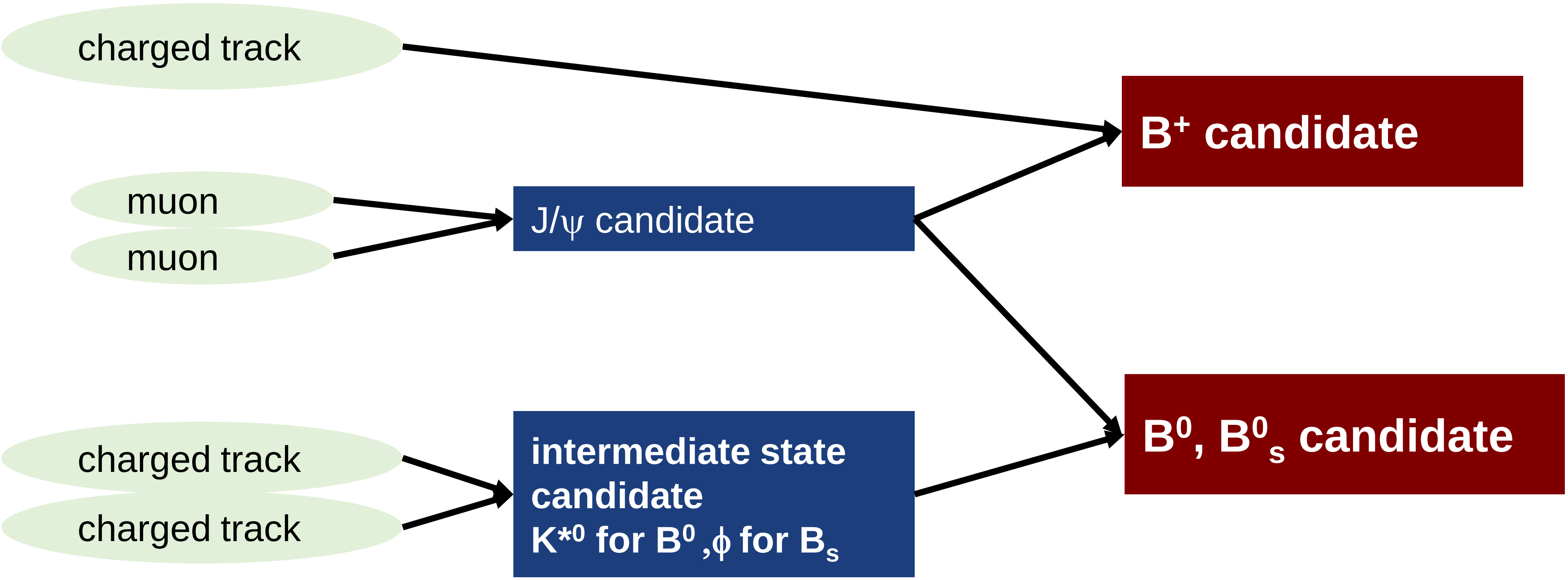


# B Meson Reconstruction in CMS



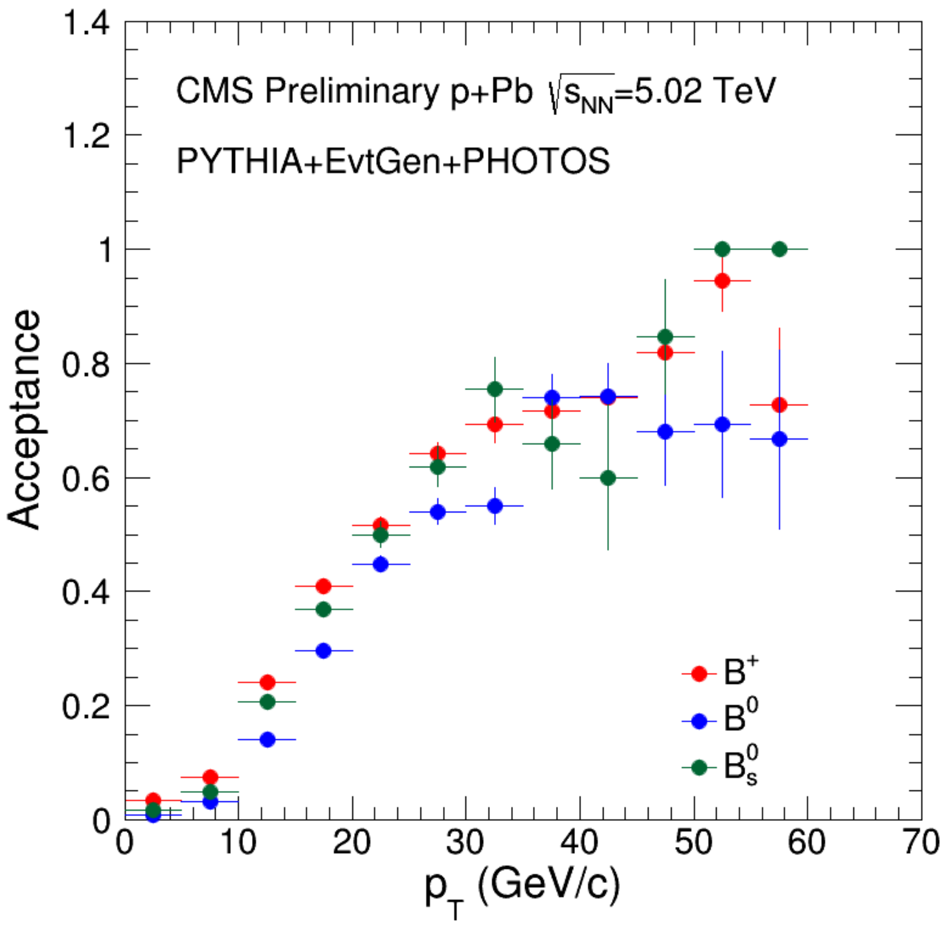

- $B^+$ : $J/\psi$ + 1 track (kaon, $p_T$> 0.9 GeV/c)
- $B^0$ : $J/\psi$ + 2 tracks (kaon + pion, $p_T$>0.7 GeV/c)
- $B_s$ : $J/\psi$ + 2 tracks (kaon + kaon, $p_T$>0.4 GeV/c)

- 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

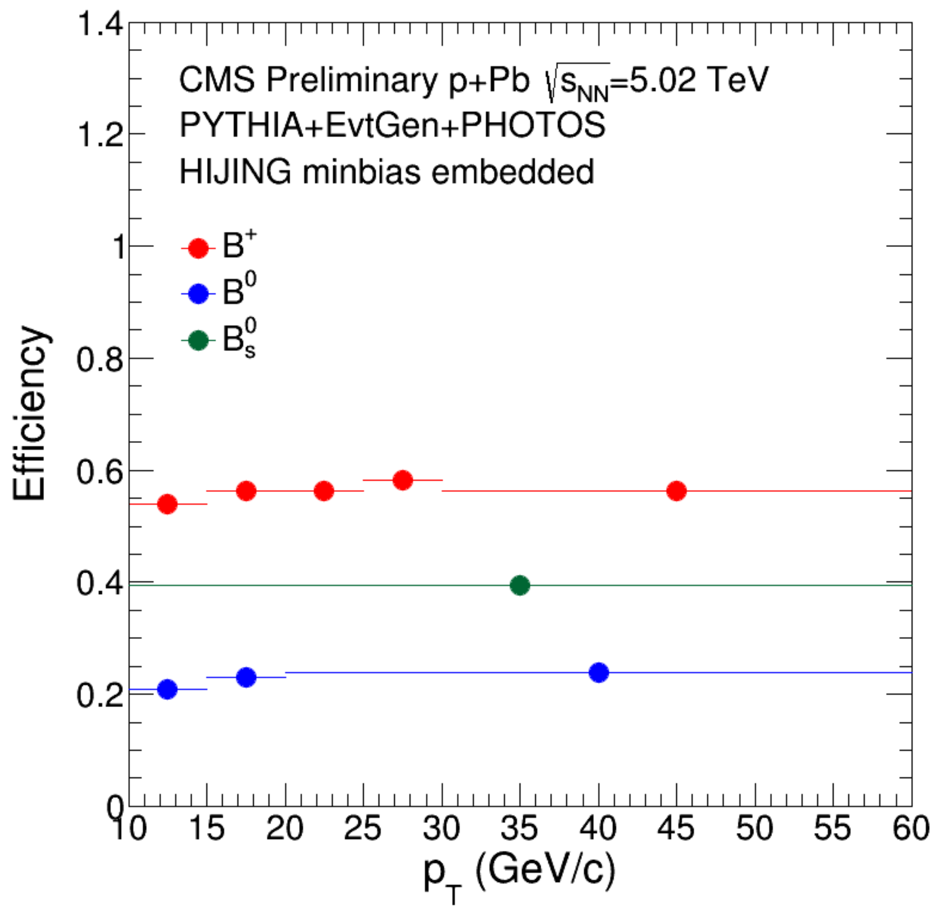
# B Meson Acceptance and Efficiency

- Raw yields are corrected by acceptance and efficiency

**Acceptance**



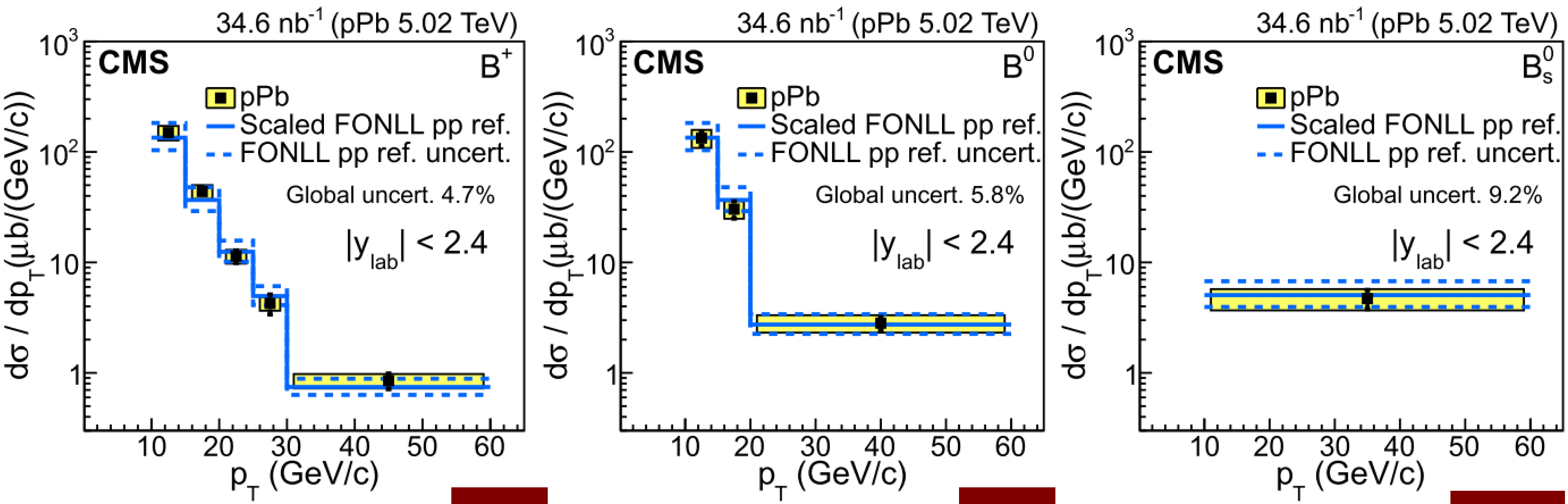

**Efficiency**



# Differential Cross-section in pPb @ 5 TeV

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

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

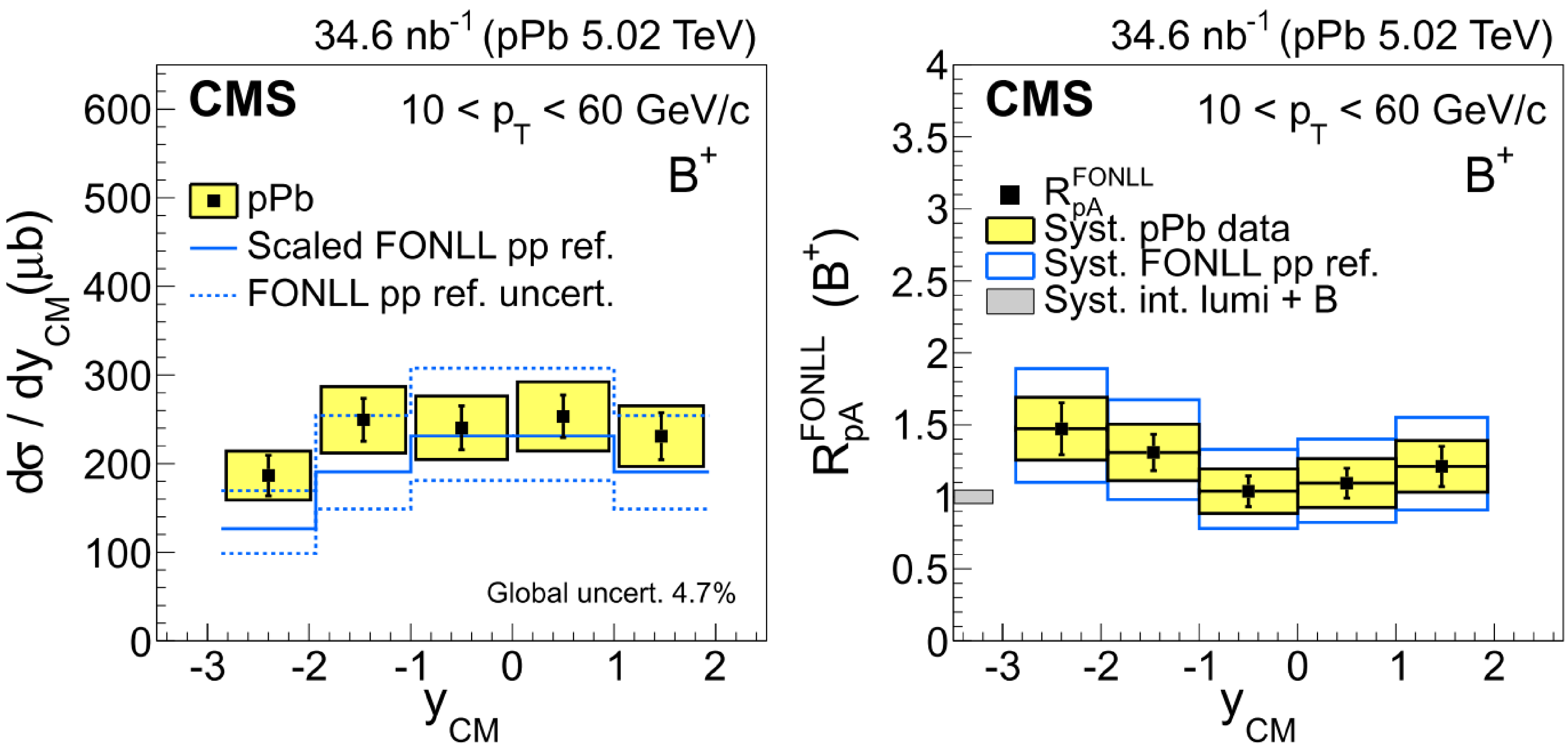



**$B^+$** **$B^0$** **$B^0_s$**

# Rapidity Distribution in pPb @ 5 TeV

- Rapidity dependence of $B^+$ production

$B^+$

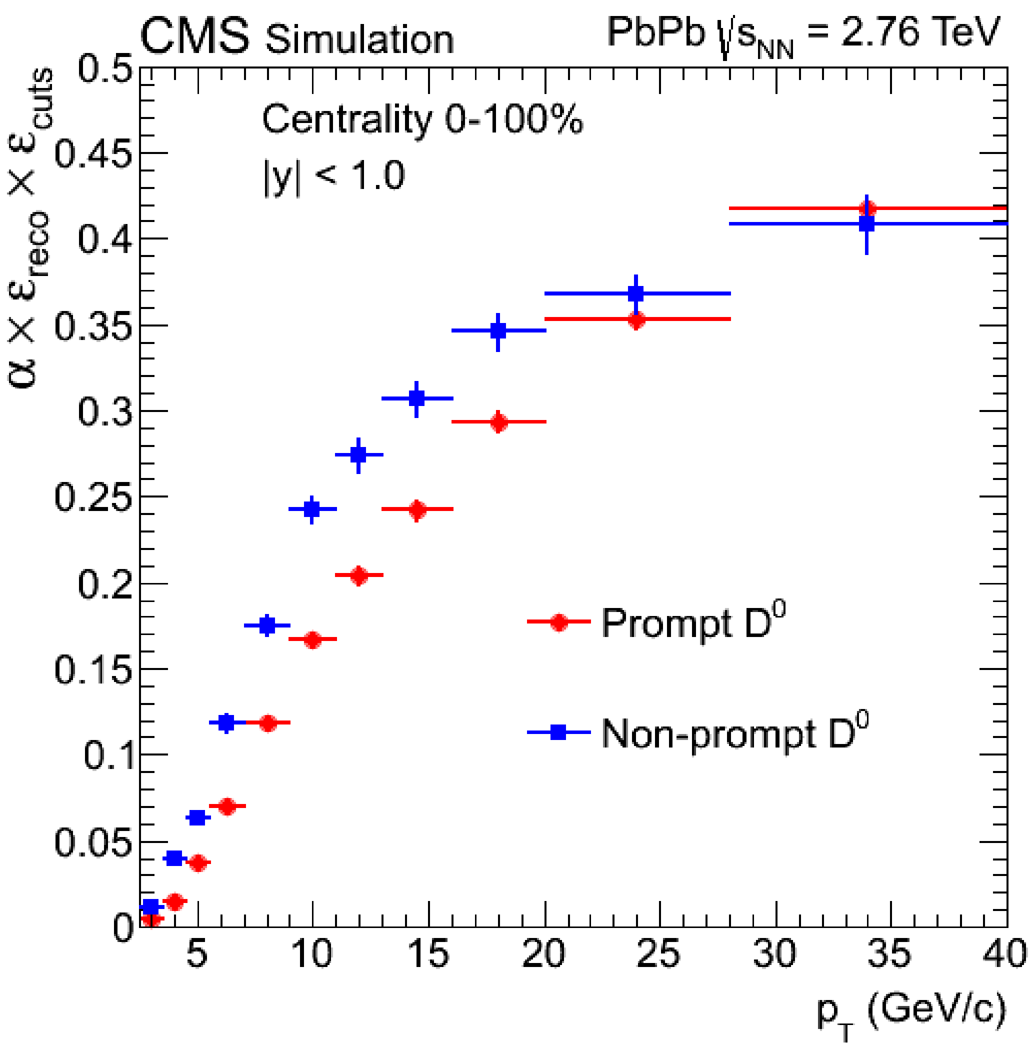



$R_{pA}^{FONLL}$ is compatible with unity within theoretical and experimental uncertainties

PRL 116 (2016) 032301
arXiv:1508.06678

# Acceptance and Efficiency Correction

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




- 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

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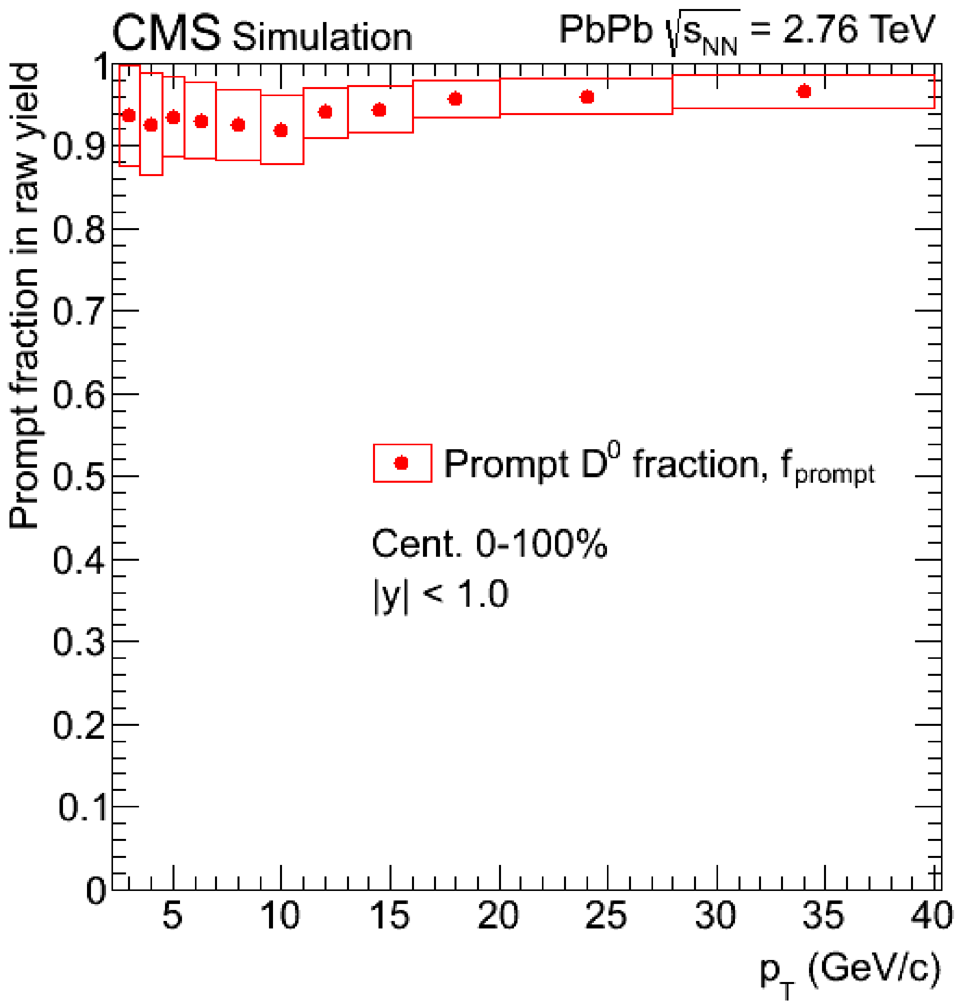
# B→D Feed-down Correction

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




- 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 $R_{AA}$

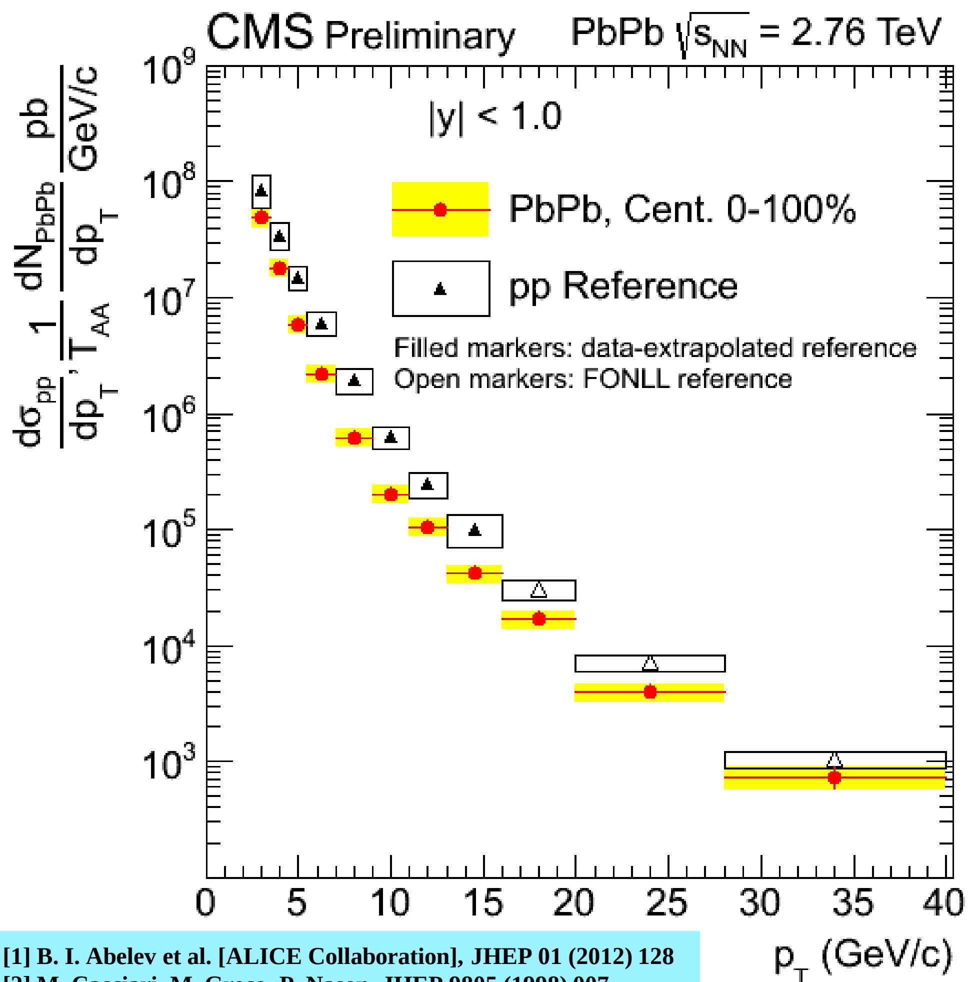
[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

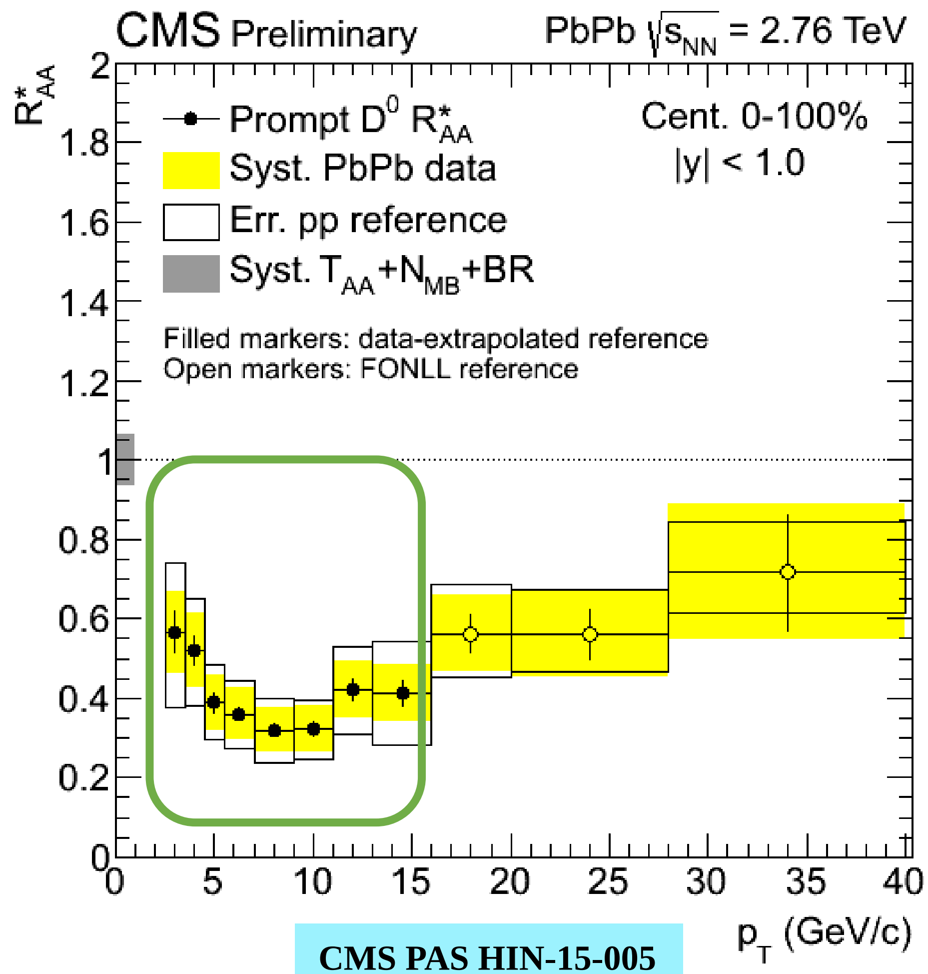
CMS PAS HIN-15-005 | CMS PAS HIN-12-014 | Phys. Rev. Lett. 113, 132301 (2014)

# 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

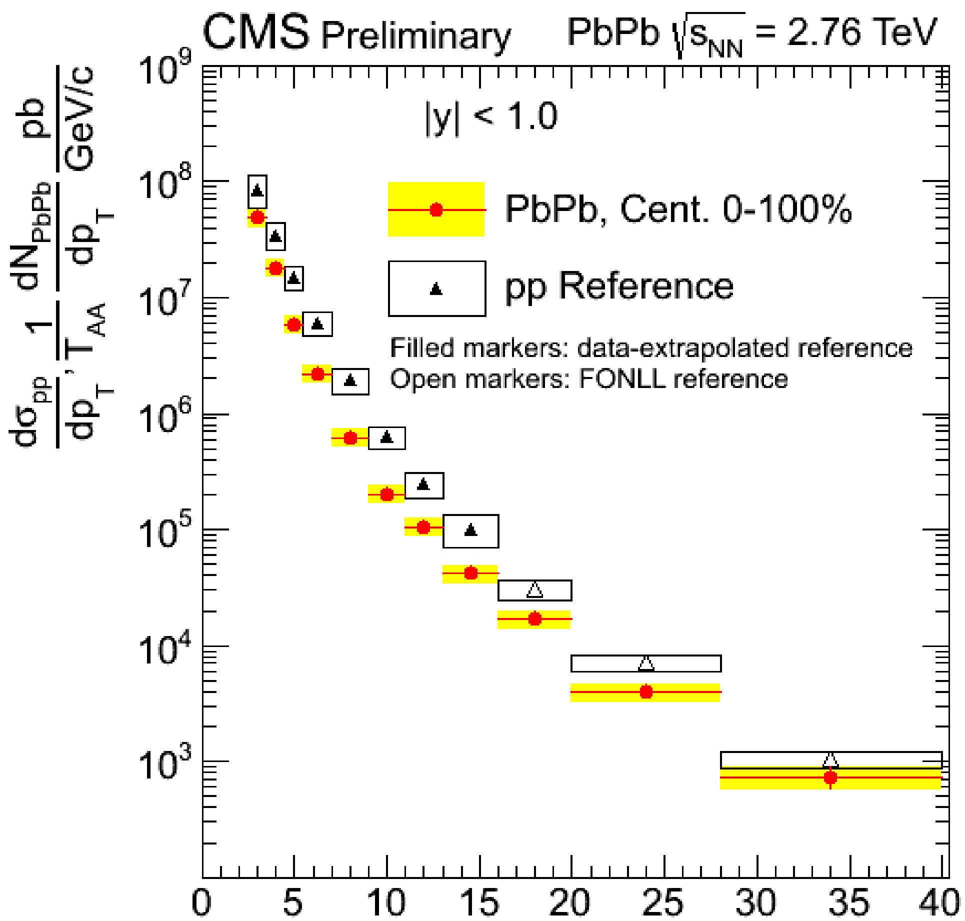

**CMS PAS HIN-15-005**

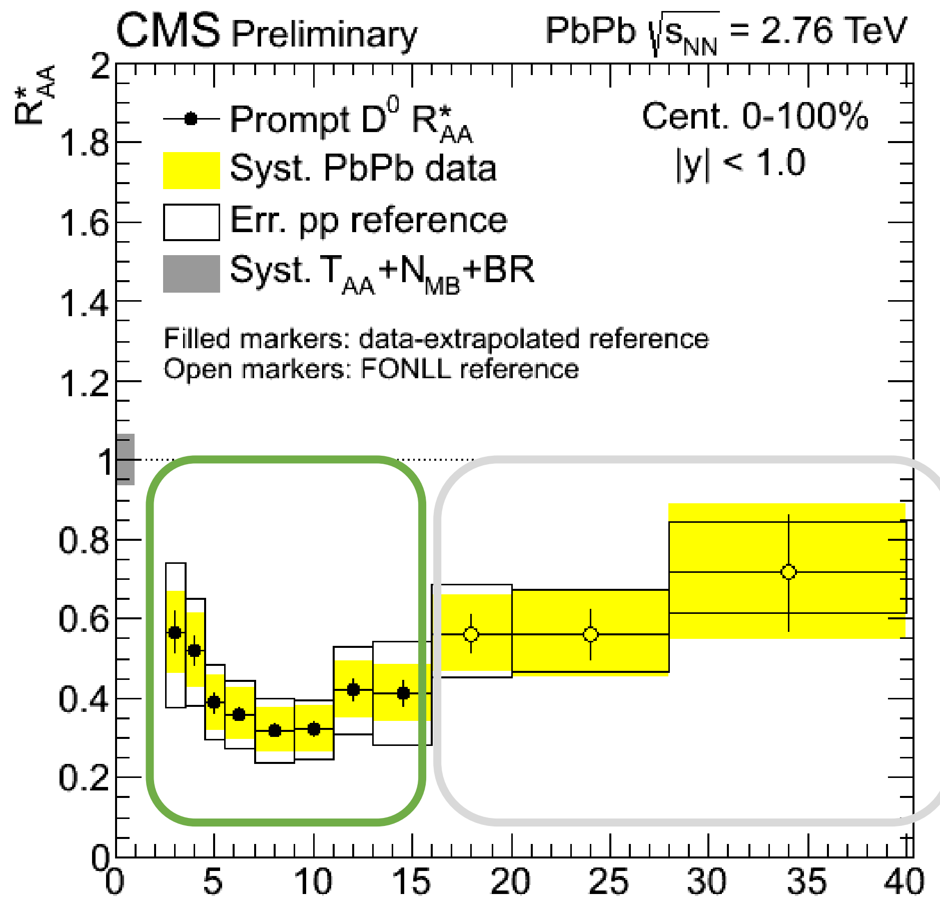
# Prompt $D^0$ Spectrum and $R^*_{AA}$ in Centrality 0-100%

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**

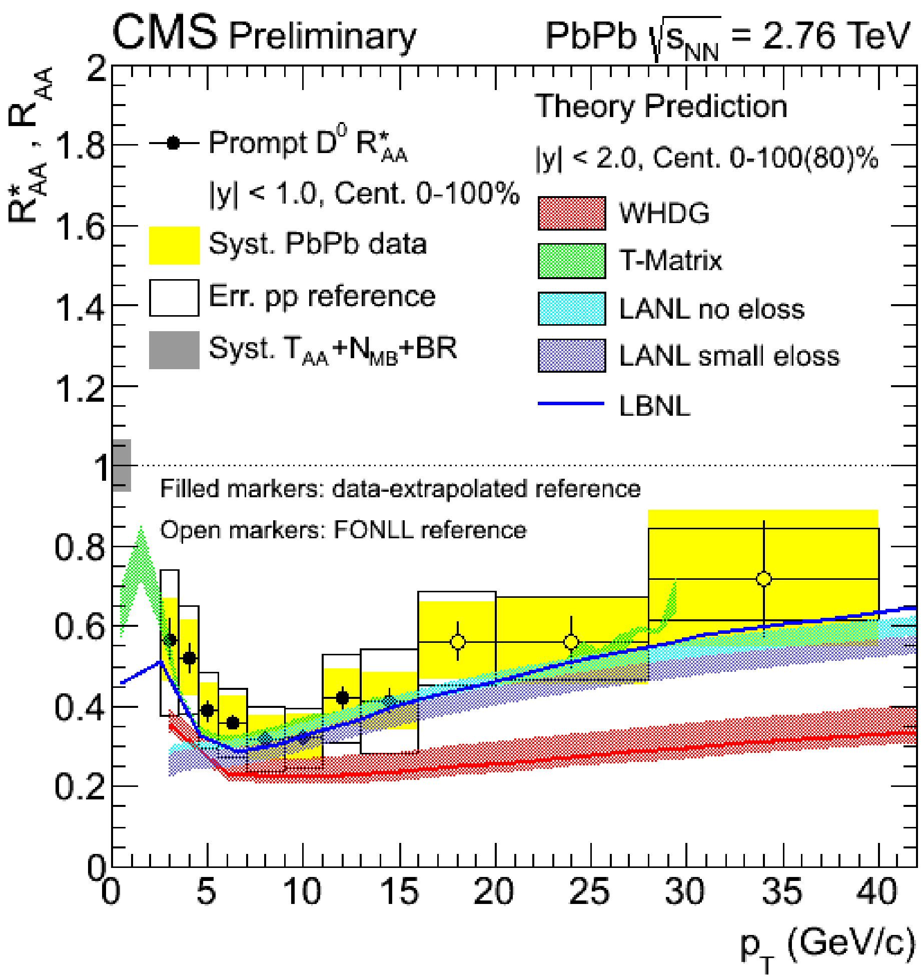


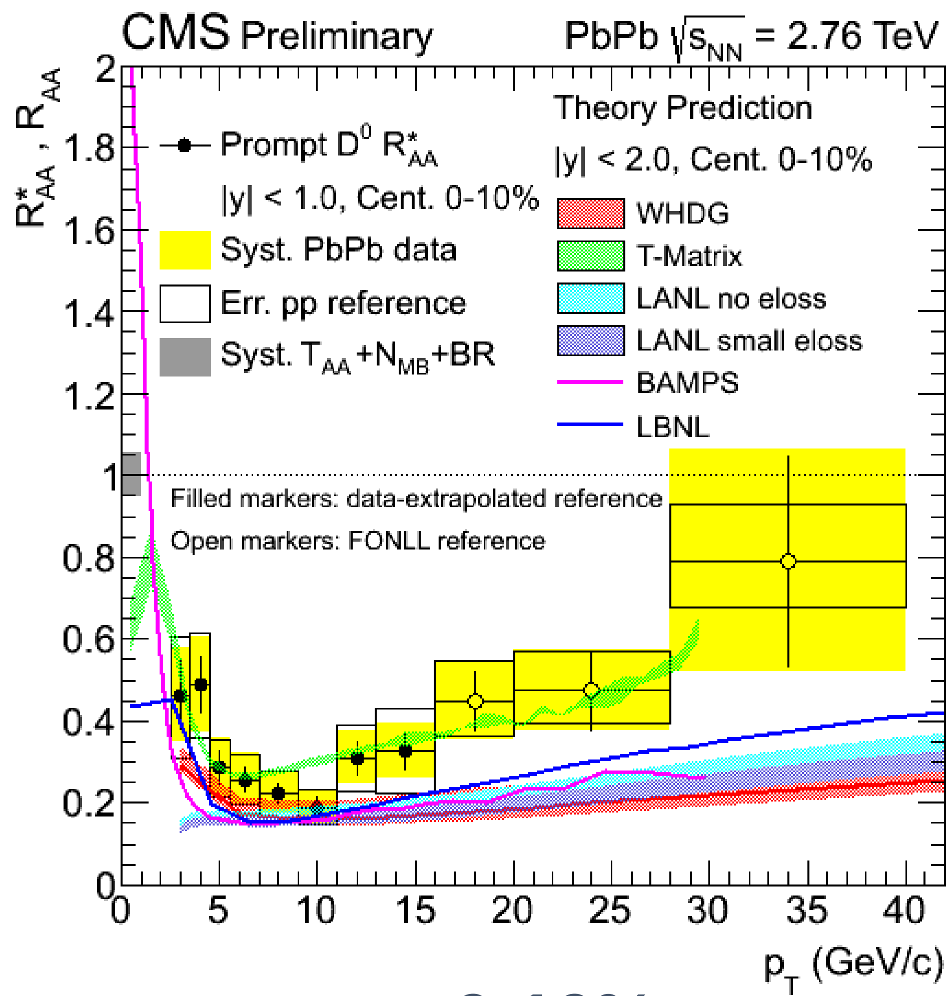

**CMS PAS HIN-15-005**

[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 Theoretical Models




**0-100%**

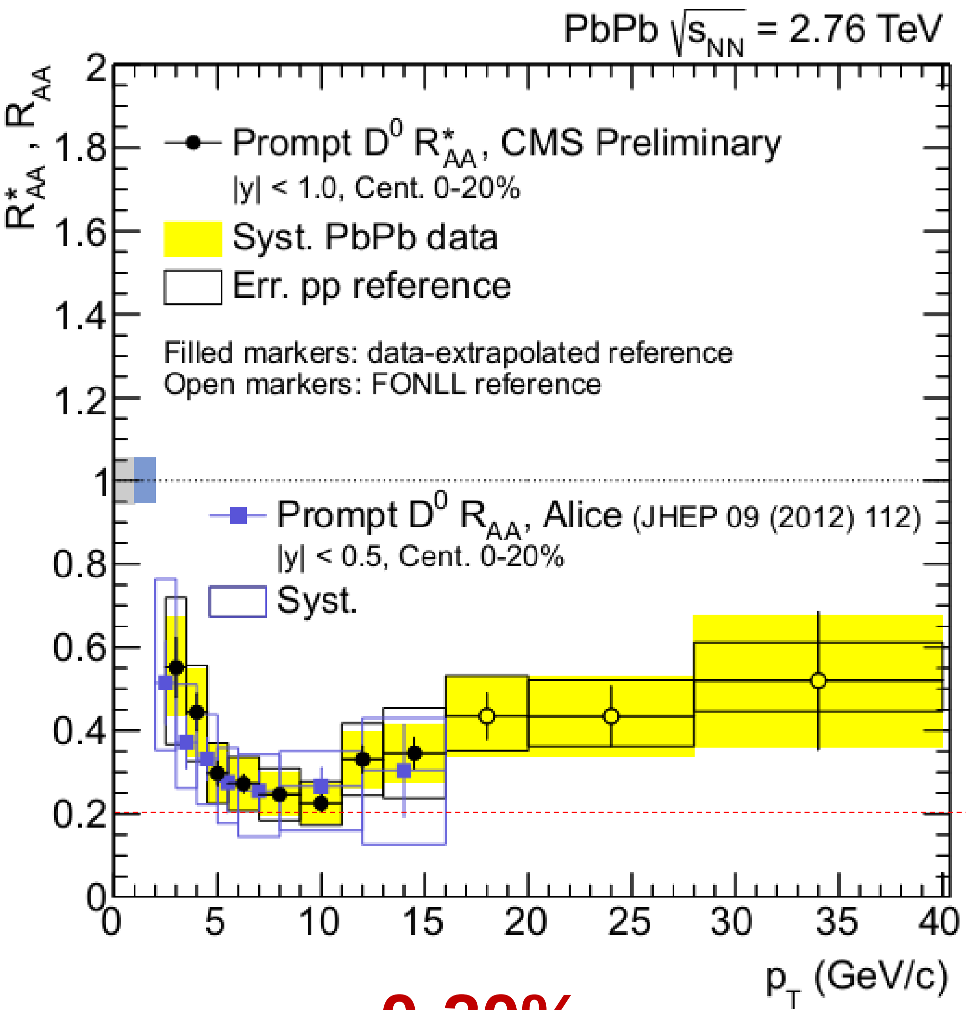


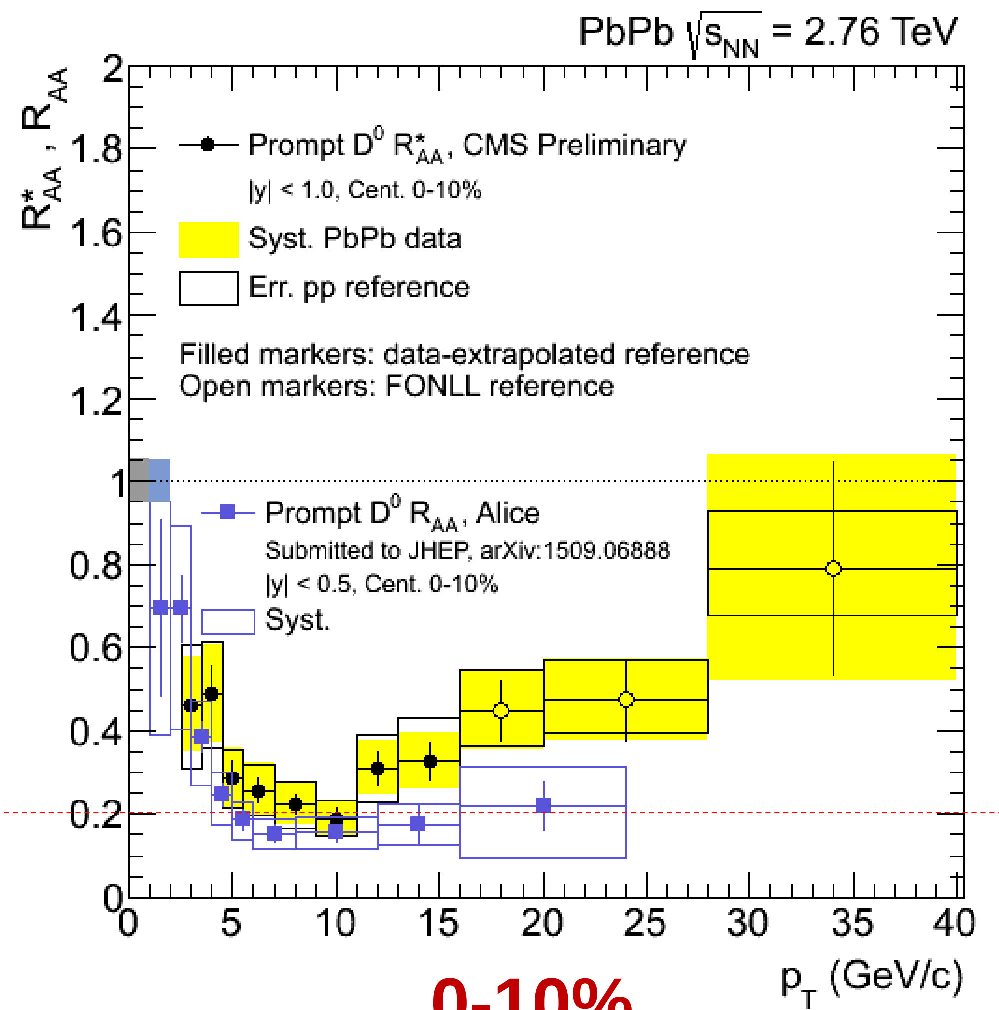

**0-10%**

**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



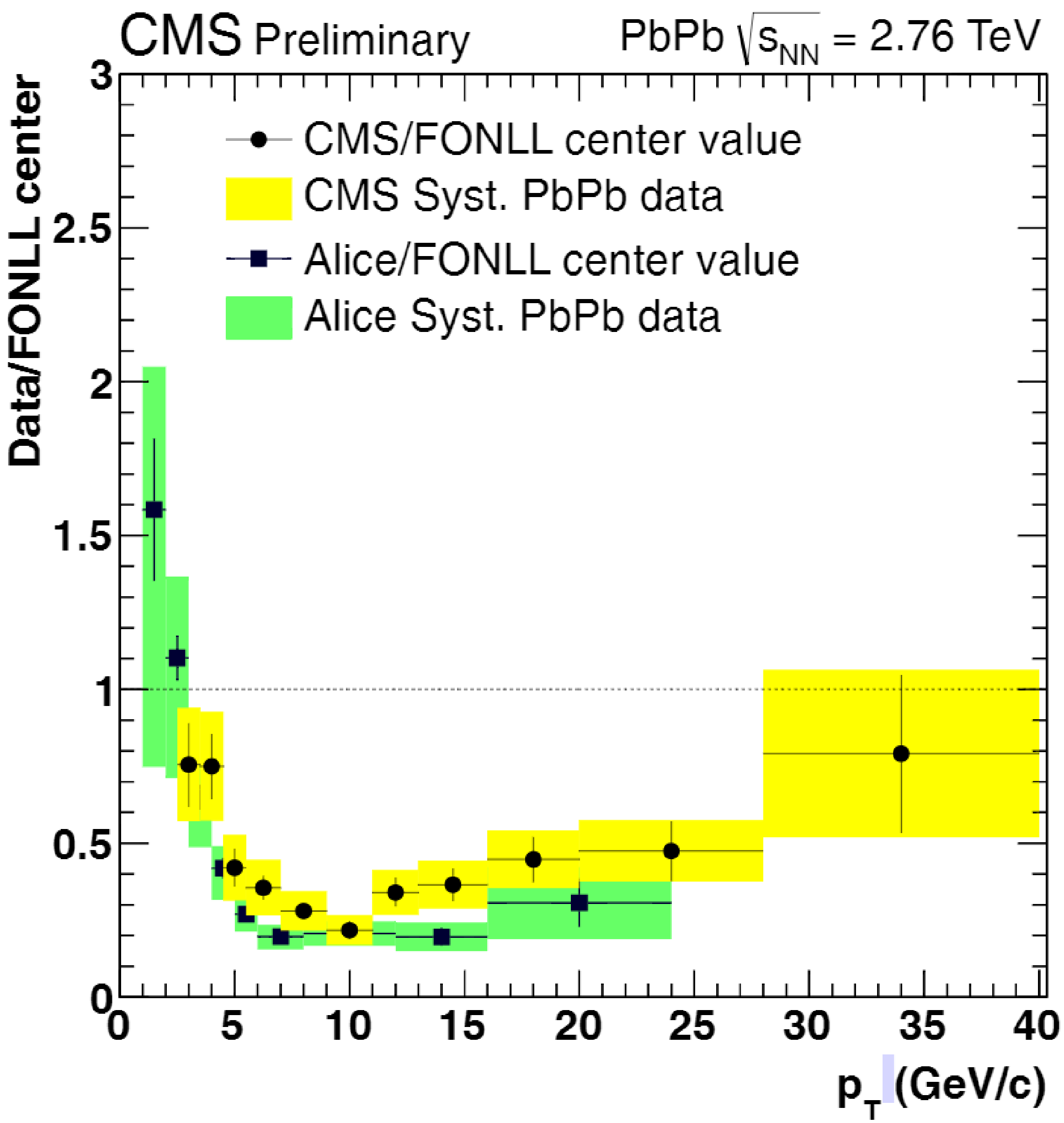




**0-20%**

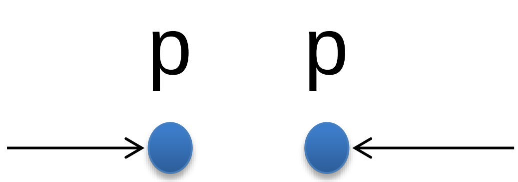
**0-10%**

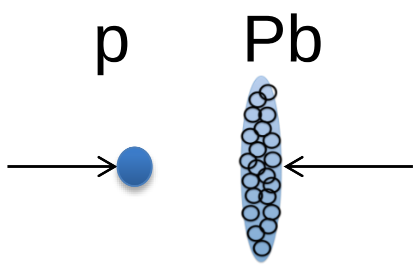
**For $p_T$ > 16 GeV, differences in pp reference should be taken into account**

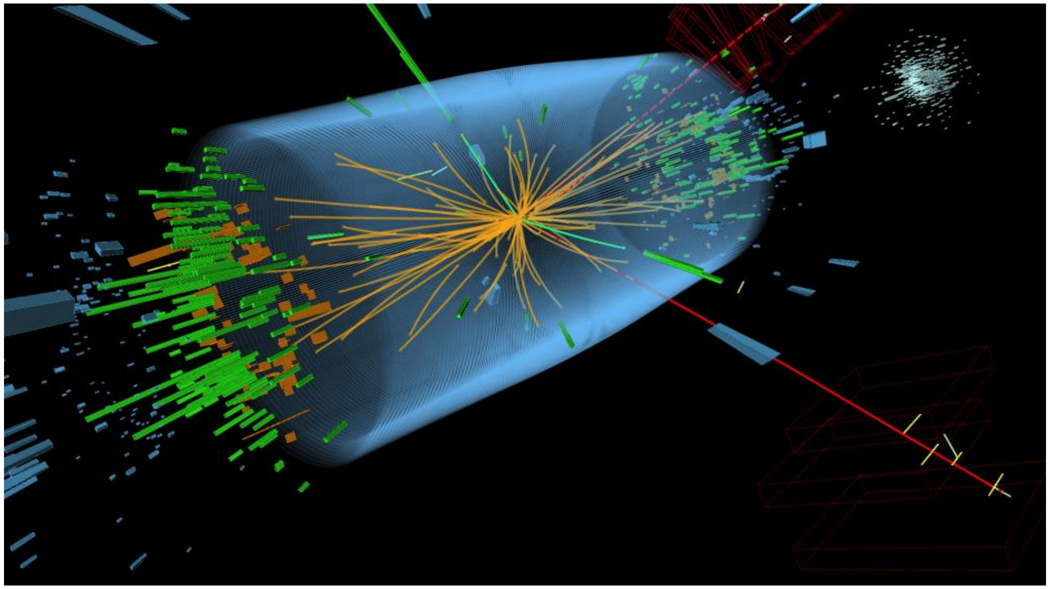
# CMS vs. ALICE using FONLL as Reference

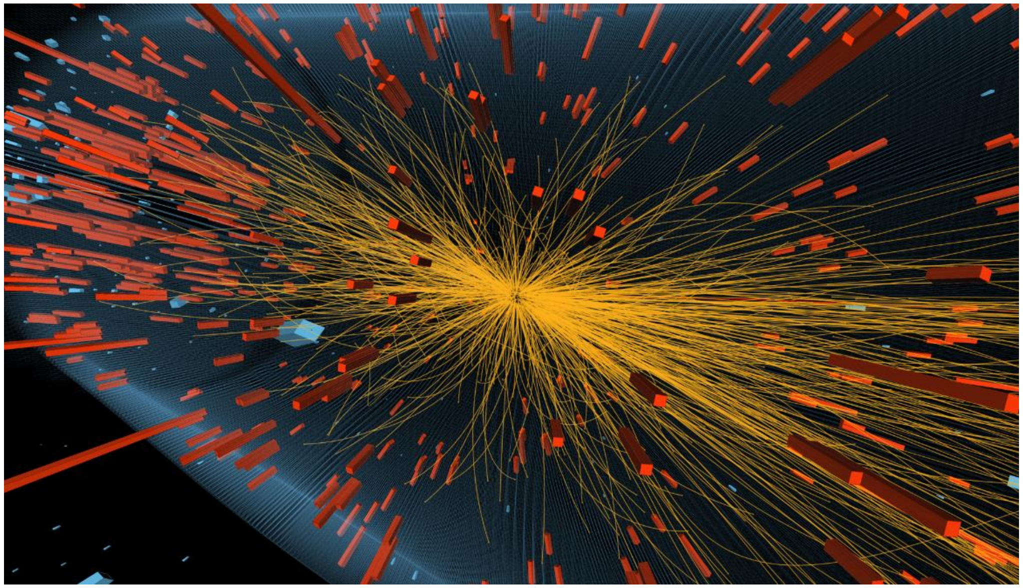


# Results from pp and pPb



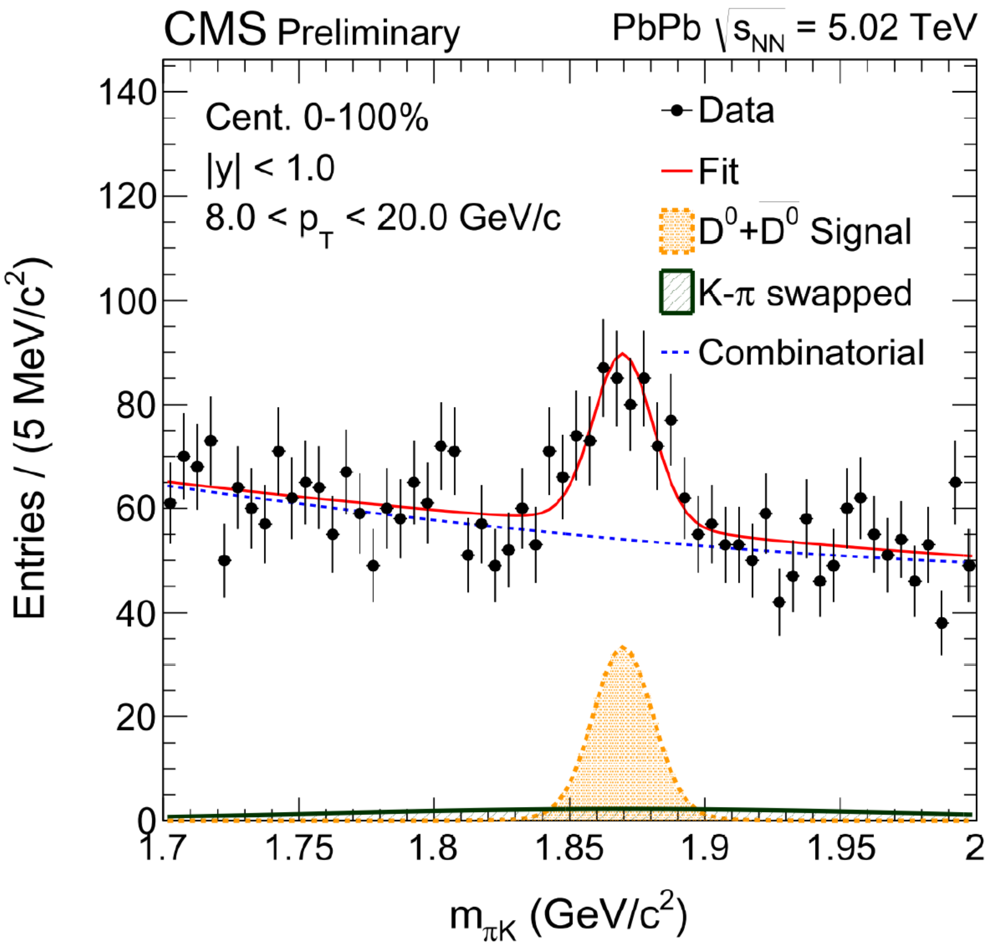



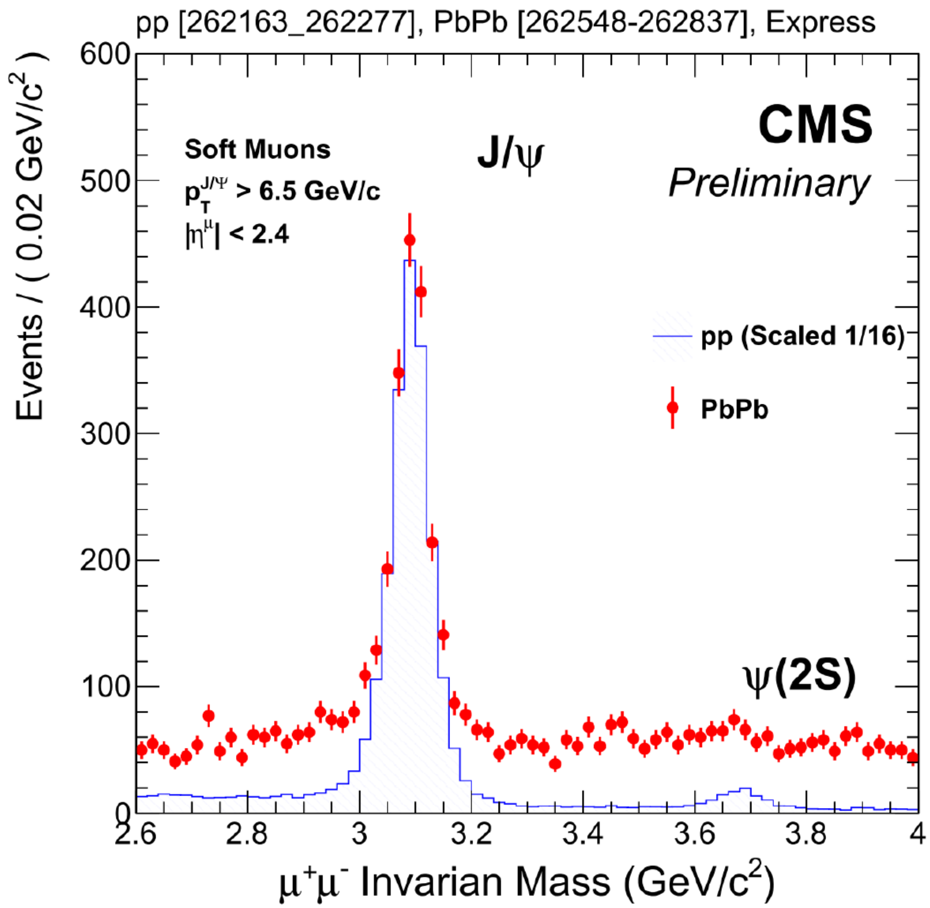





# $D^0$ and ψ peak in **PbPb** collisions @ 5.02 TeV

$D^0$ mesons from online trigger



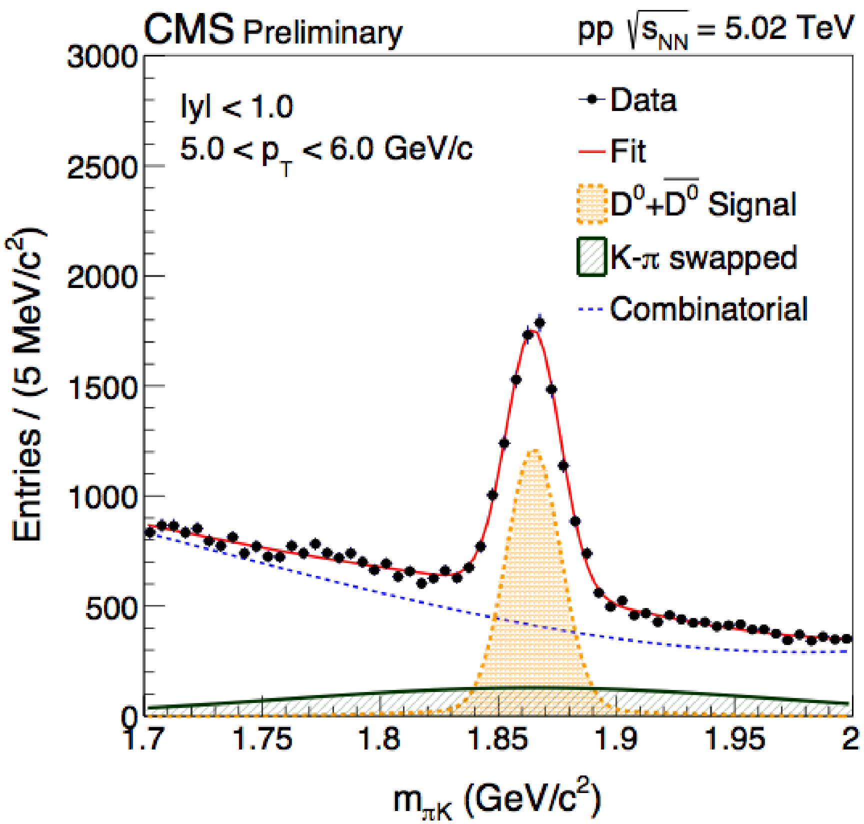




A large minimum bias sample (and centrality triggered sample) is recorded for low $p_T$ $D^0$, $D^+$, $D^*$ and $D_s$ analyses

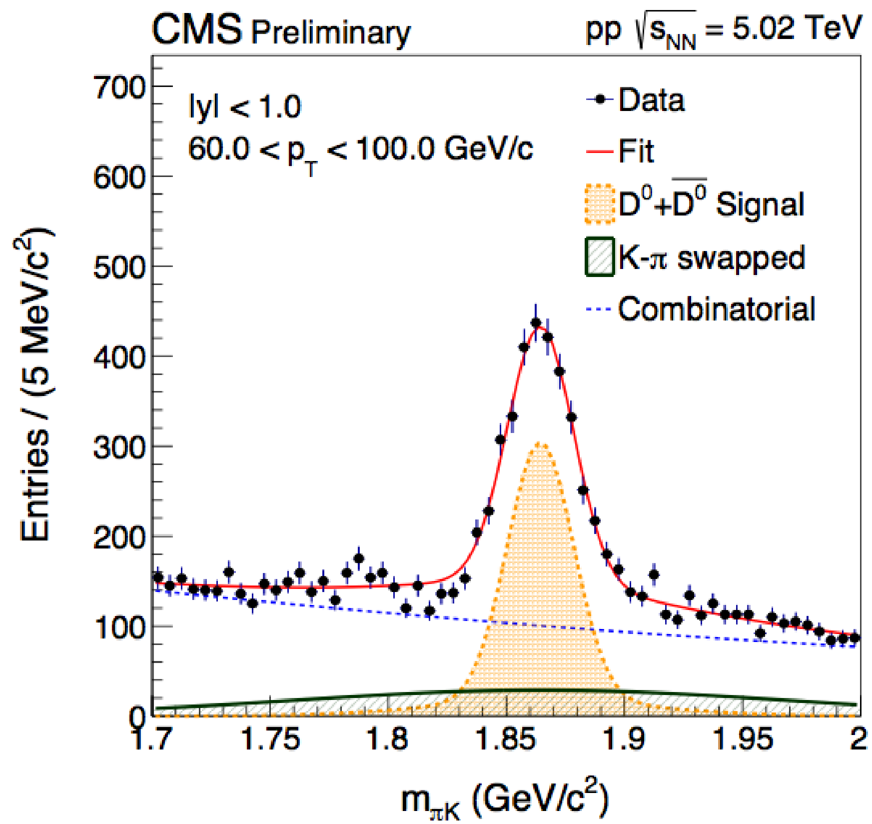
# $D^0$ spectra in pp at 5.02 TeV

- Invariant mass spectra of $D^0$ mesons in pp collisions at 5.02 TeV

**5<$p_T$<6 GeV/c**




**60<$p_T$<100 GeV/c**




Mass distributions fitted with:

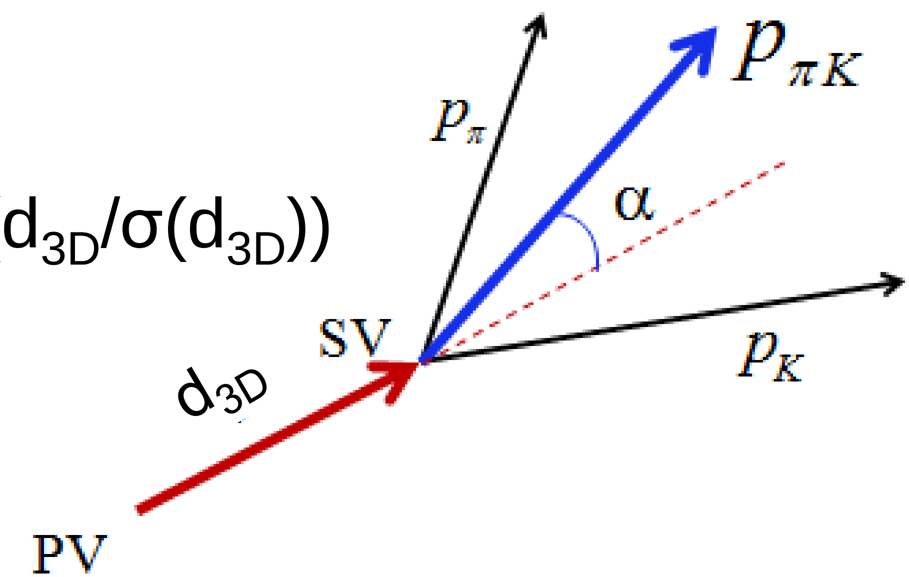
- 3rd order polynomial fit for **combinatorial background**
- Double gaussian to **model the signal**
- Gaussian shape to model **the candidates with swapped mass hypothesis**

# $D^0$ Reconstruction

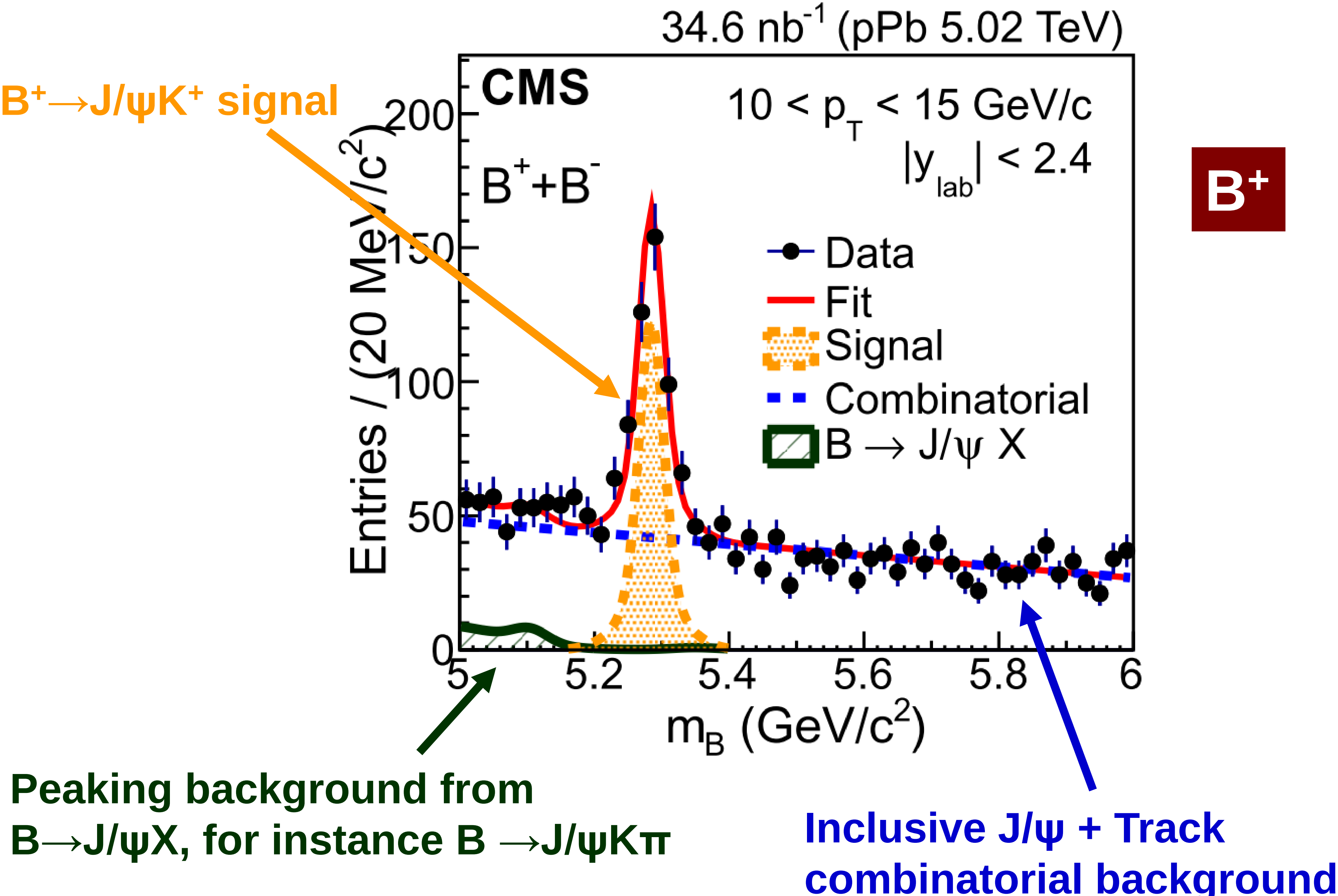
- **$D^0 \rightarrow K^- \pi^+$ , BR = 3.88 ± 0.05%, $c\tau(D^0)$ = 122.9 μm**

- **$D^0$ 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 $\chi^2$ fit probability



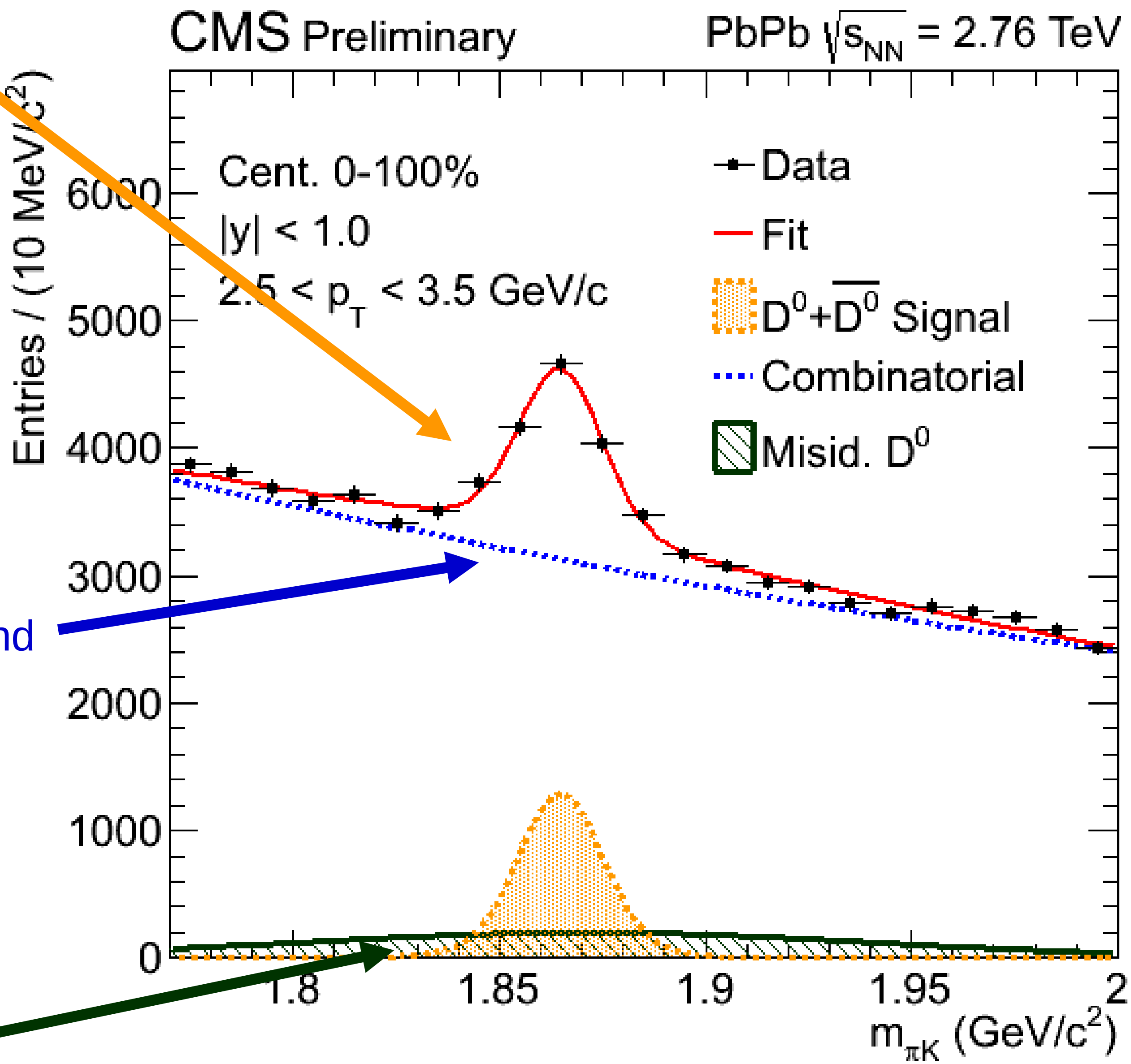
# $B^+$ Meson Mass Spectra in pPb




**B+**

# $D^0$ 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)

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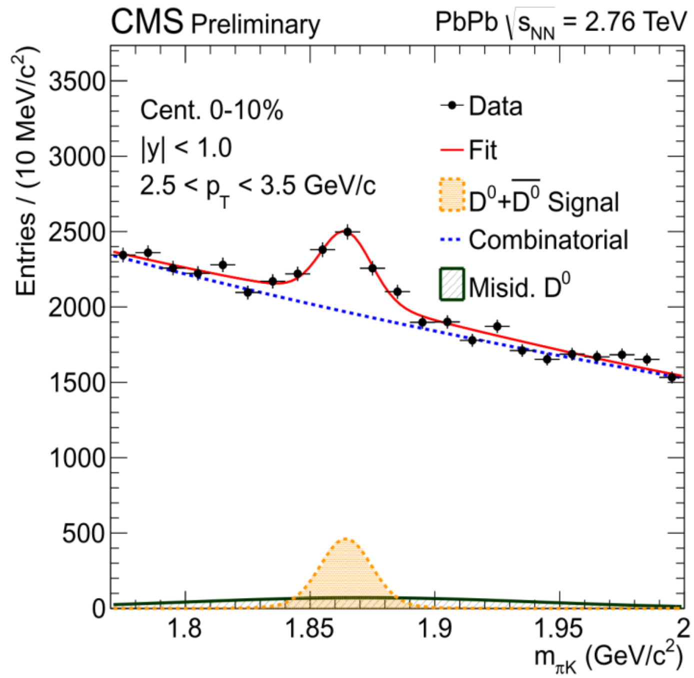
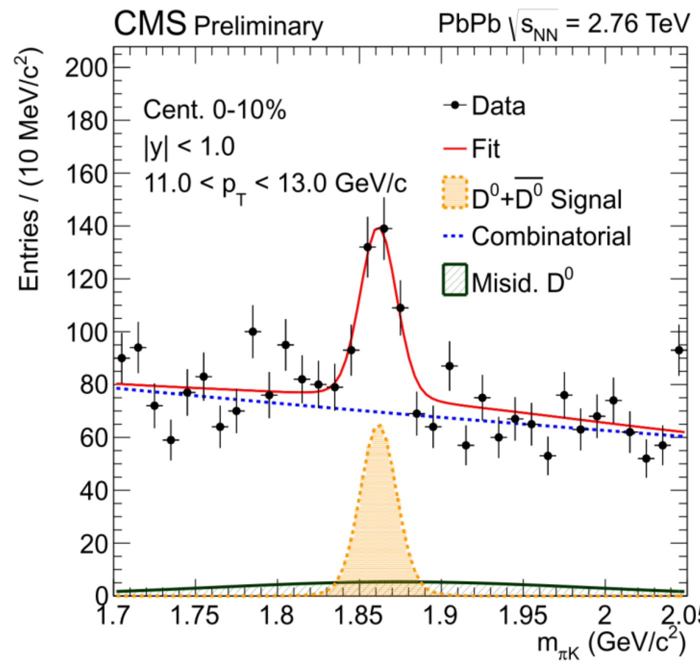
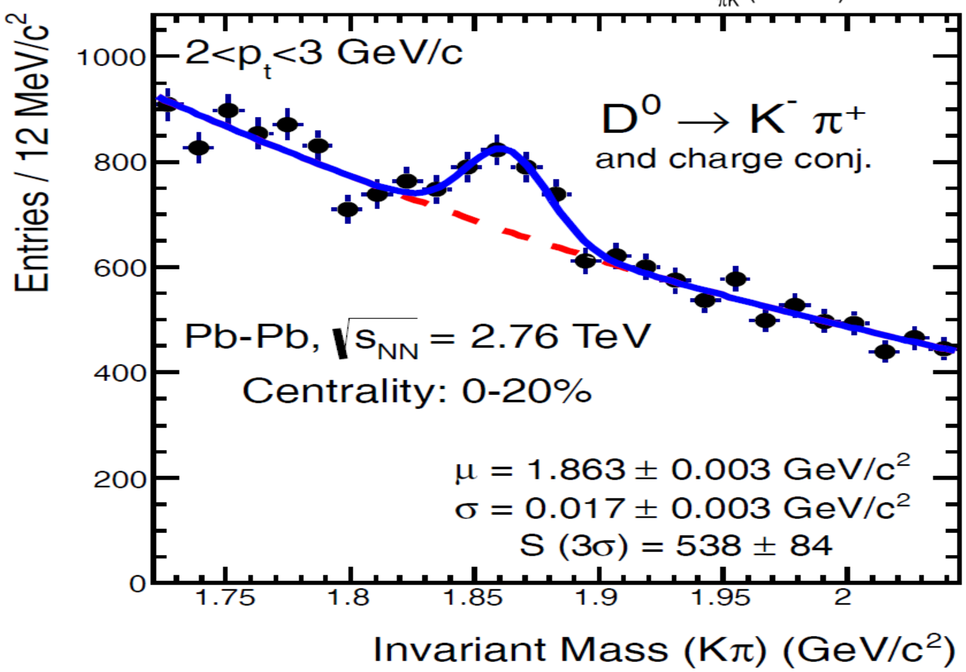
# $D^0$ Signal to Background Ratio Comparison

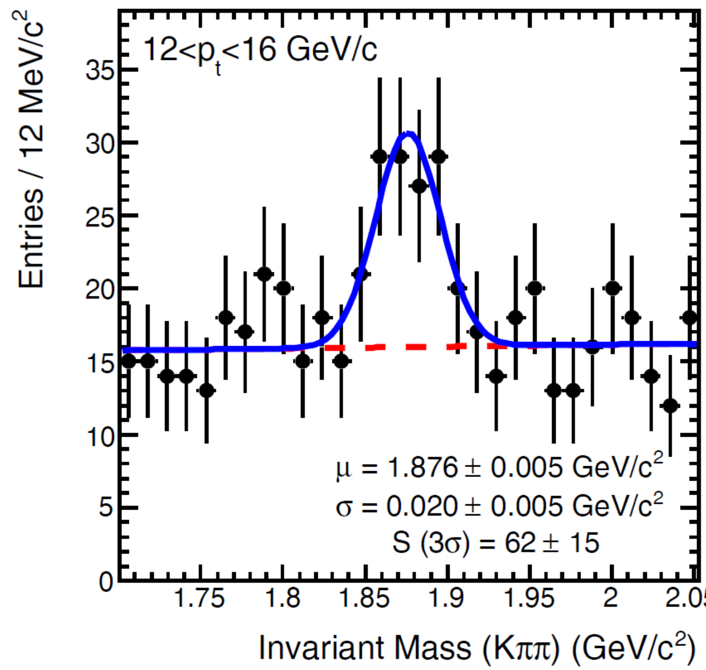



0-10%

(No K-π ID)



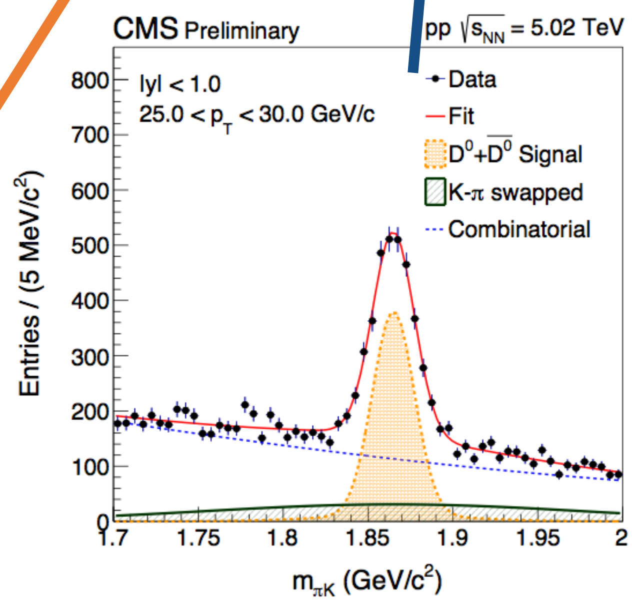

0-20%

ArXiv 1203.2160

# From raw yields to cross sections

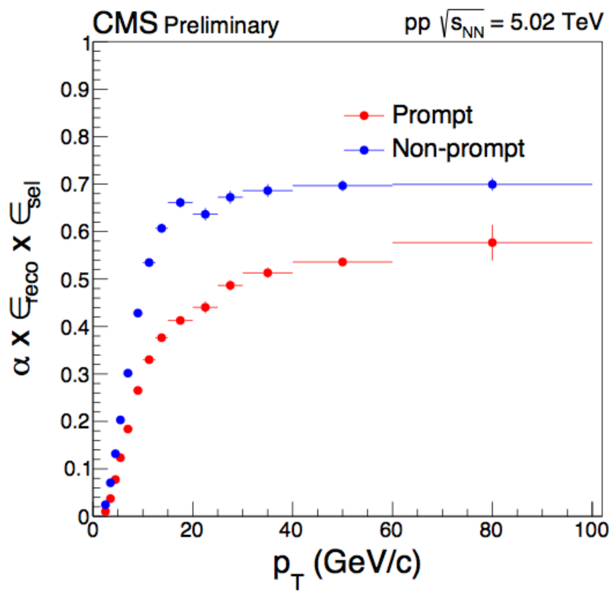
$$\left.\frac{d\sigma^{D^0}}{dp_T}\right|_{|y|<1.0} = \frac{1}{2}\frac{f_{prompt}}{\Delta p_T}\frac{\left.N^{D^0}\right|_{|y|<1.0}}{(\mathrm{Acc}\times\epsilon)_{prompt}\cdot \mathrm{BR}\cdot \alpha_{prescale}\cdot\ \epsilon_{trigger}\cdot\mathcal{L}}$$

**fraction of prompt D⁰:**
fully data driven for the first time in heavy ions




**raw yields** extracted via fits to invariant mass distributions

**For triggered data:**
- Needs to correct for trigger selection efficiency



# Systematic uncertainty summary

**•Signal extraction systematics**

- Varying signal and background fit functions

**•D meson selection:**

- Comparing data and MC data driven efficiencies of the different cut selections
- Systematic on trigger efficiency
- Tracking efficiency systematic: (evaluated data driven with 2 and 4 prongs $D^0$ decays!)

**•B-feed down uncertainty**

- Obtained by comparing $f_{prompt}$ estimation with alternative method based on decay length and with FONLL-based predictions