# $D^0$ Meson Production in Heavy Ion Collisions in CMS experiment

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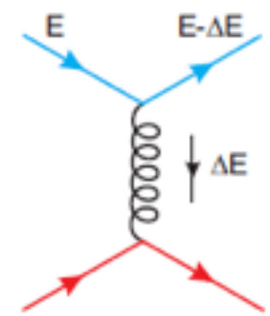
Berkeley (United States)

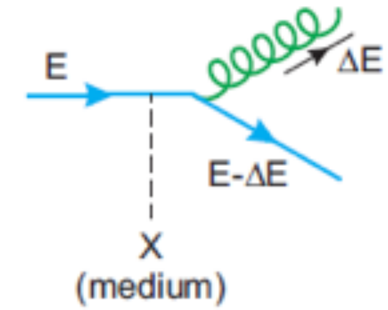
# Why studying heavy flavors in HI?

## Heavy quarks are produced via initial hard scatterings

- Carry information about the system at early stage → **Good probe of QGP**

↓ the probe heavy quarks interact with the medium



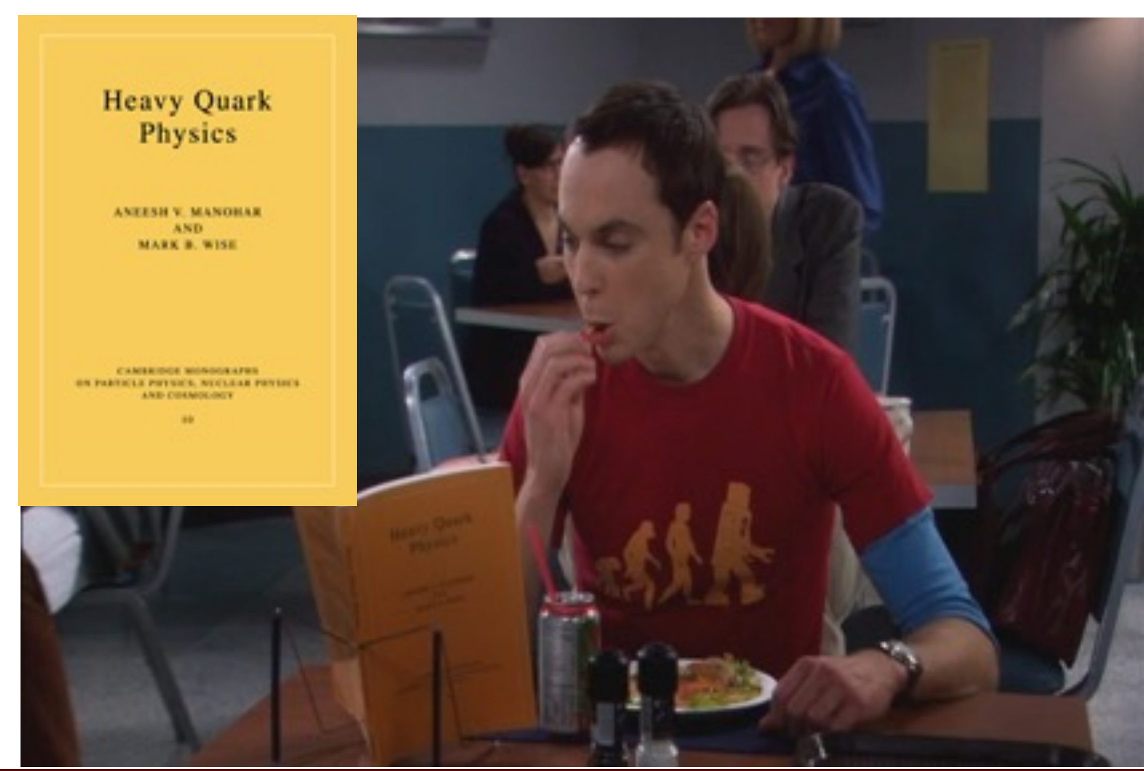




## In-medium energy loss

- Two energy loss mechanisms: **Collisional** + **Radiative**
- **Flavor-dependent**
  - Dead cone effect [1] (*Radiative energy loss is suppressed at small angels*)

$$dP = \frac{\alpha_s\, C_F}{\pi}\,\frac{d\omega}{\omega}\,\frac{k_\perp^2\, dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2}, \qquad \theta_0 \equiv \frac{M}{E}$$

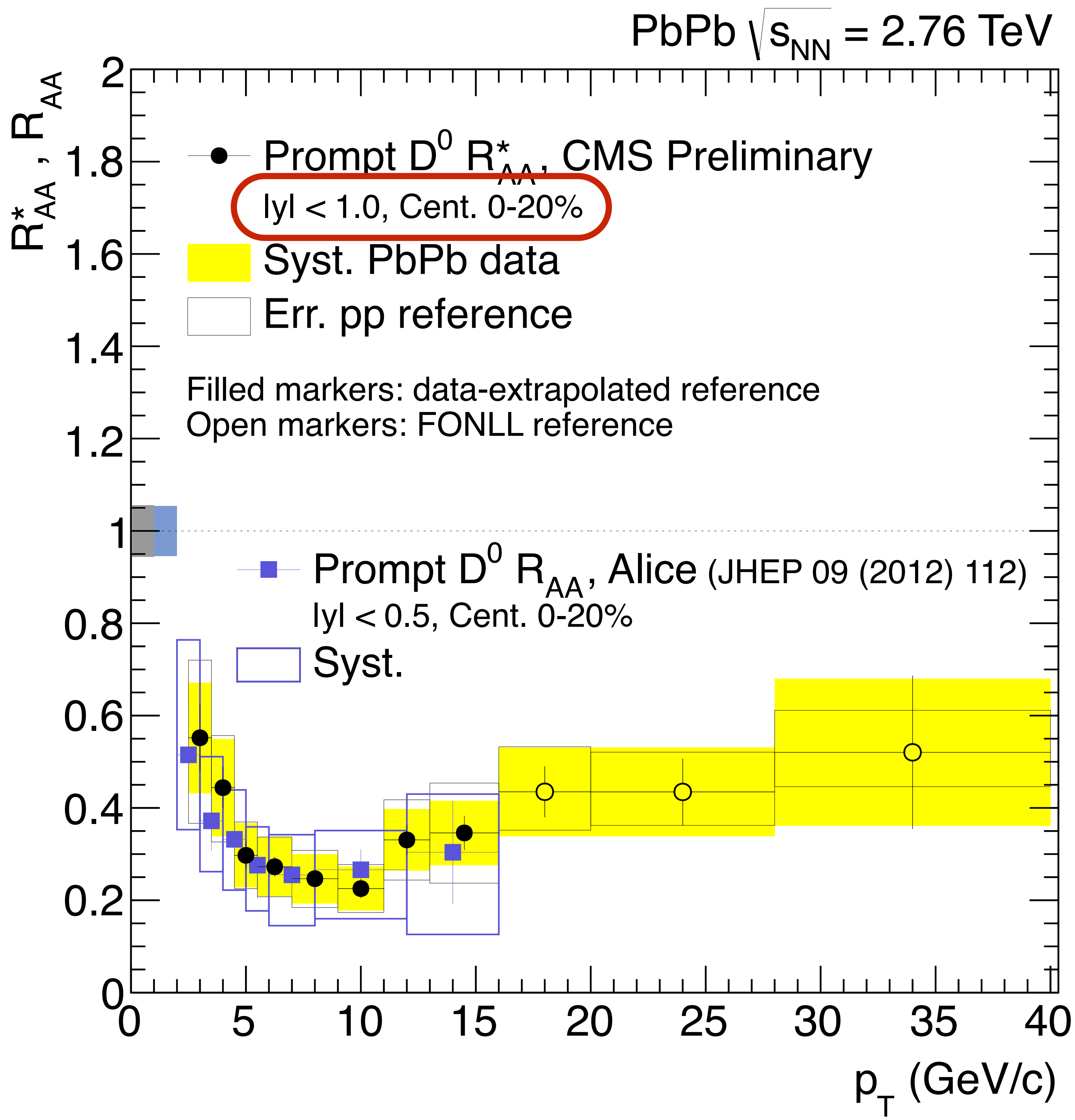
  - Expect: $\Delta E^{light} > \Delta E^{c} > \Delta E^{b}$
  - Nuclear modification factor:
  - $\mathbf{R^{light}_{AA} < R^{D}_{AA} < R^{B}_{AA}}$ **?**
  - Dead cone effect is expected to be important at low $p_T$




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

# $D^0$ measurements with CMS in Run I

## PbPb @ 2.76 TeV




- Dataset: MB events
- $p_T$: 2-40 GeV/c
- pp reference: data-extrapolated and FONLL

## Run II 5.02 TeV

- $p_T$: 2-100 GeV/c
- pp reference: direct data

Measurements reaching very high $p_T$ for the first time!

CMS-PAS-HIN-15-005

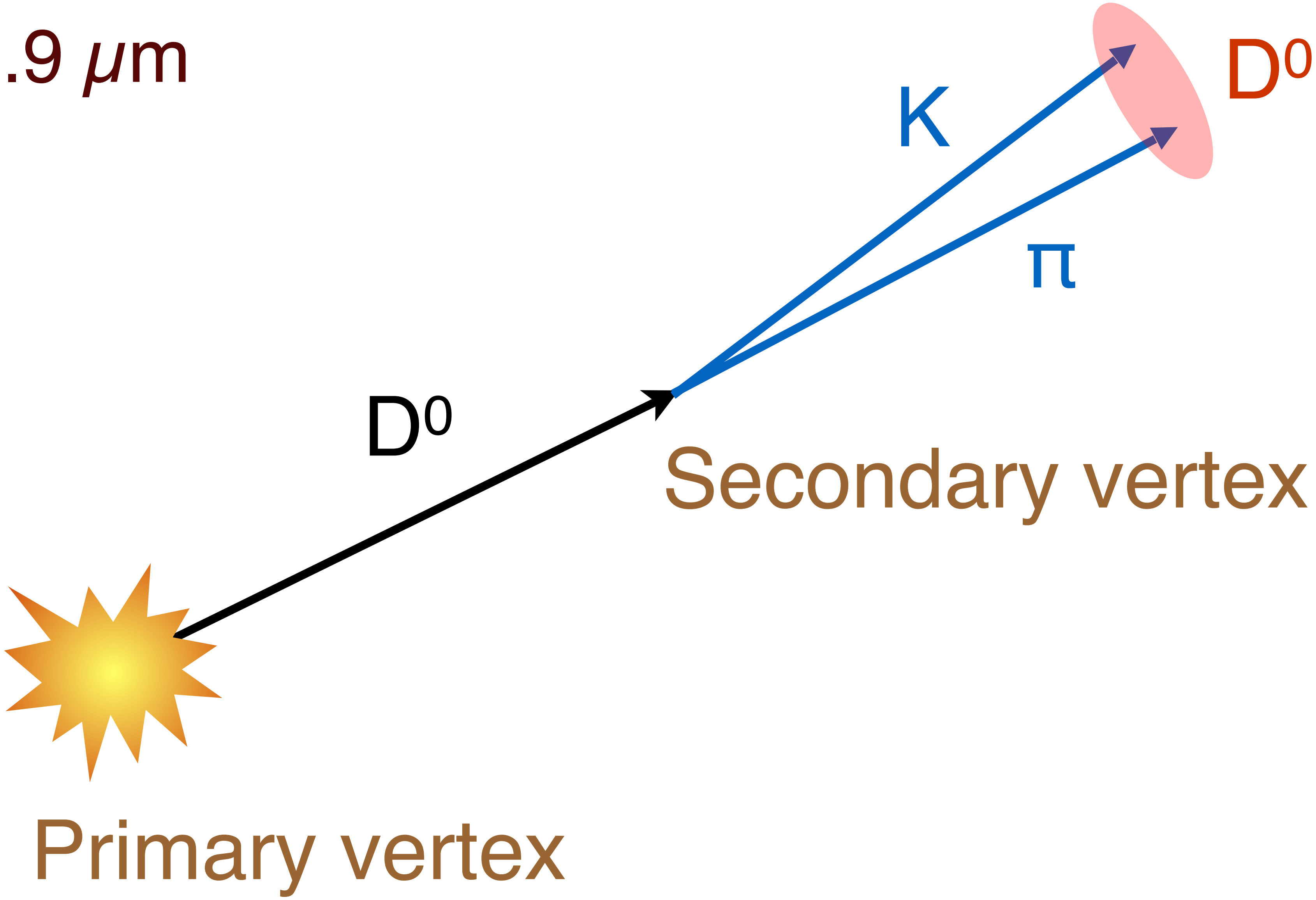
# $D^0$ meson production at 5.02 TeV

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

First Run II heavy flavor analysis

# $D^0$ meson production

- $c \rightarrow D^0$: O(50%) of c cross-section
- $D^0 \rightarrow K\pi$: 3.93 ± 0.04%
- $D^0$ $c\tau$ = 122.9 $\mu$m

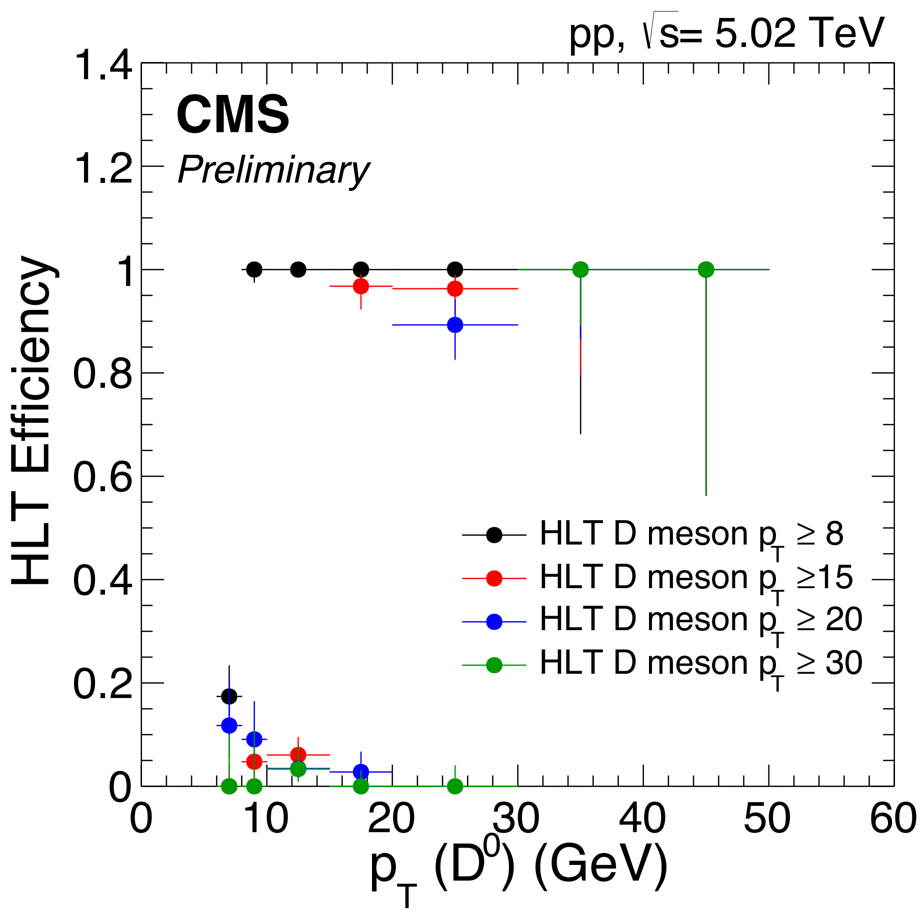


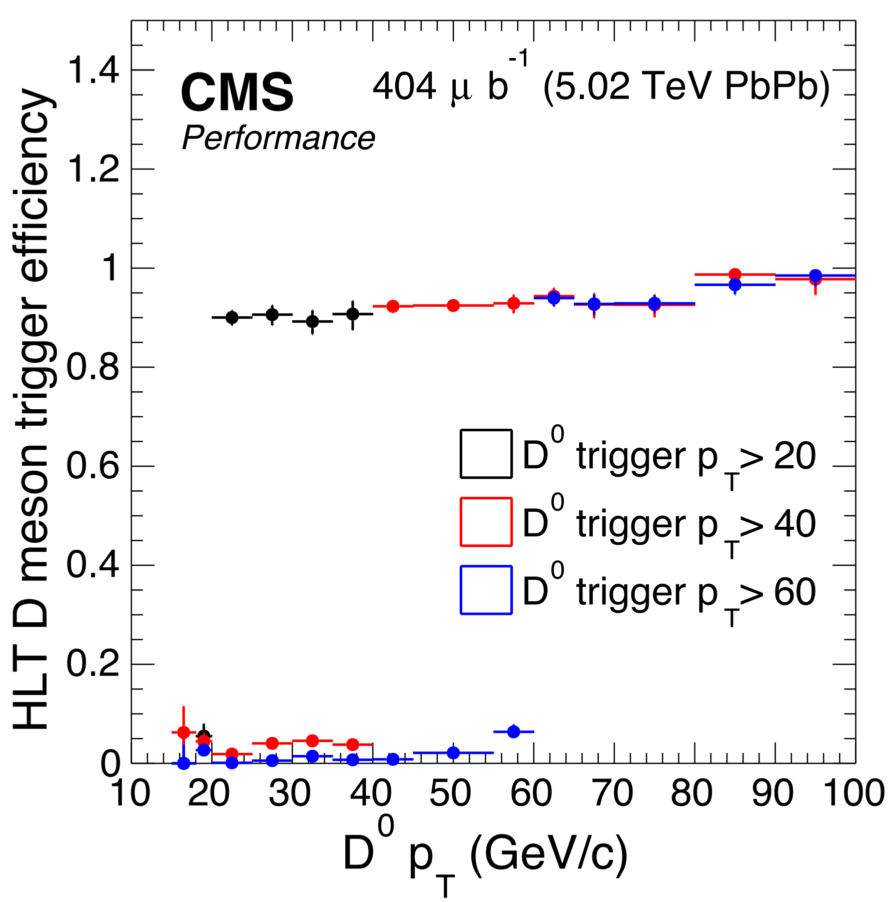
# D⁰ measurements in pp and PbPb

**$D^0 \to K\pi$** in pp and PbPb collisions at **5.02TeV**, Centrality **0-10% and 0-100%, |y|<1**

## Datasets

- **Low pT** ( < 20 GeV/c)
  **MinBias** Events (pp: 2 billions events; PbPb: 150 million events)
- **High pT** ( > 20 GeV/c)
  Events triggered by dedicated **HLT $D^0$ filters** to enhance the statistics at very high pT



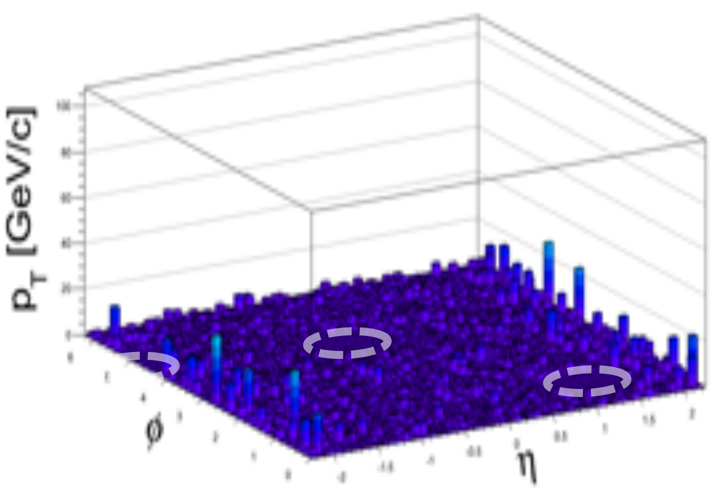



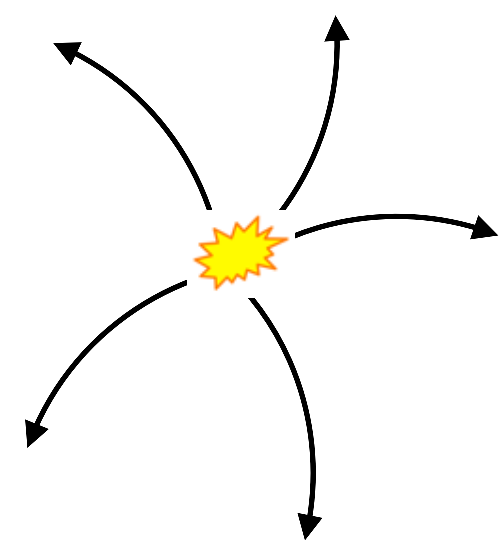
# High-Level-Trigger (HLT) $D^0$ triggers

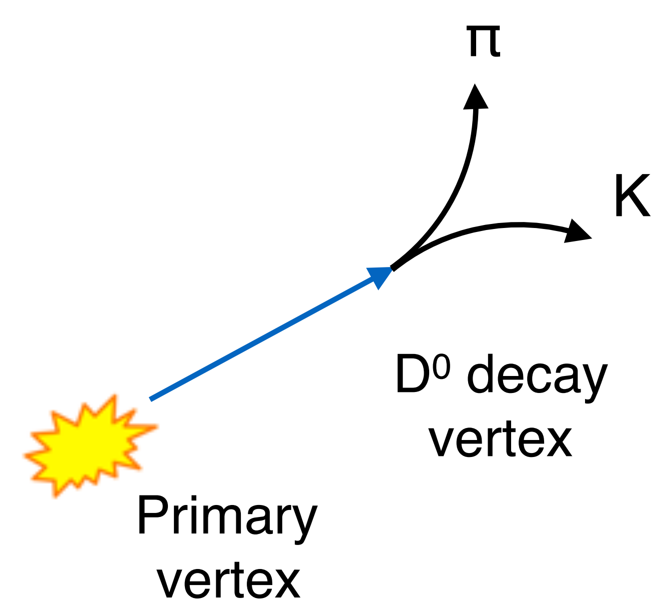
**Hardware L1 jet triggers selection**

**Track selection in software triggers**

**$D^0$ selection**





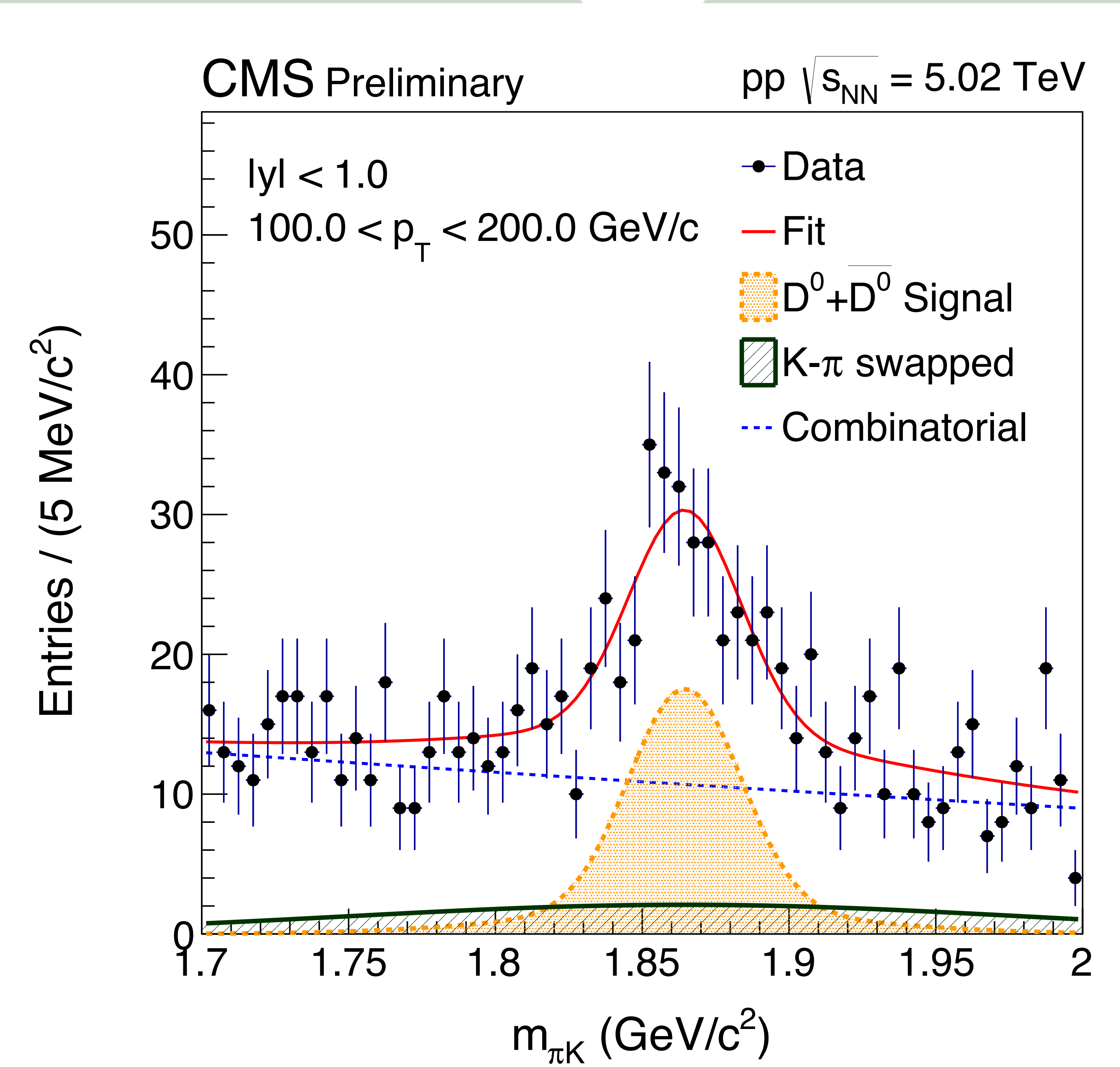

- Level-1 (L1) jet algorithm with online background subtraction

Track seed $p_T$ cut applied:

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

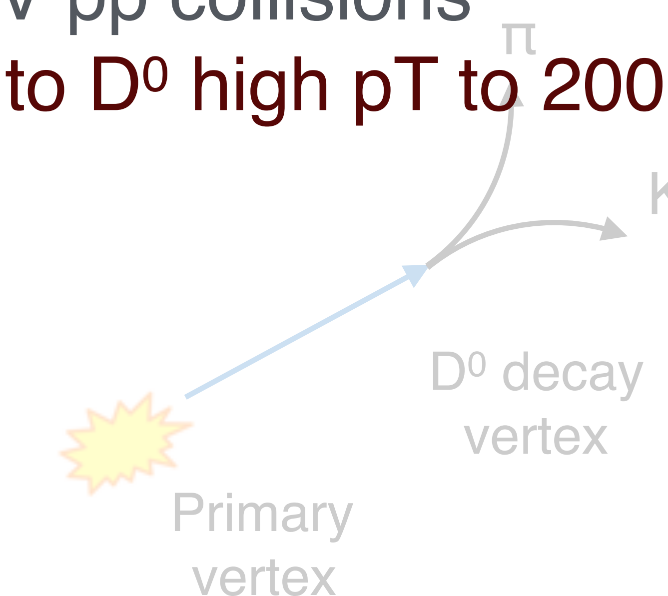
- $D^0$ online reconstruction
- loose selection based on $D^0$ vertex displacement

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




D⁰ selection

- 5.02 TeV pp collisions
- **Extend to $D^0$ high pT to 200 GeV/c**



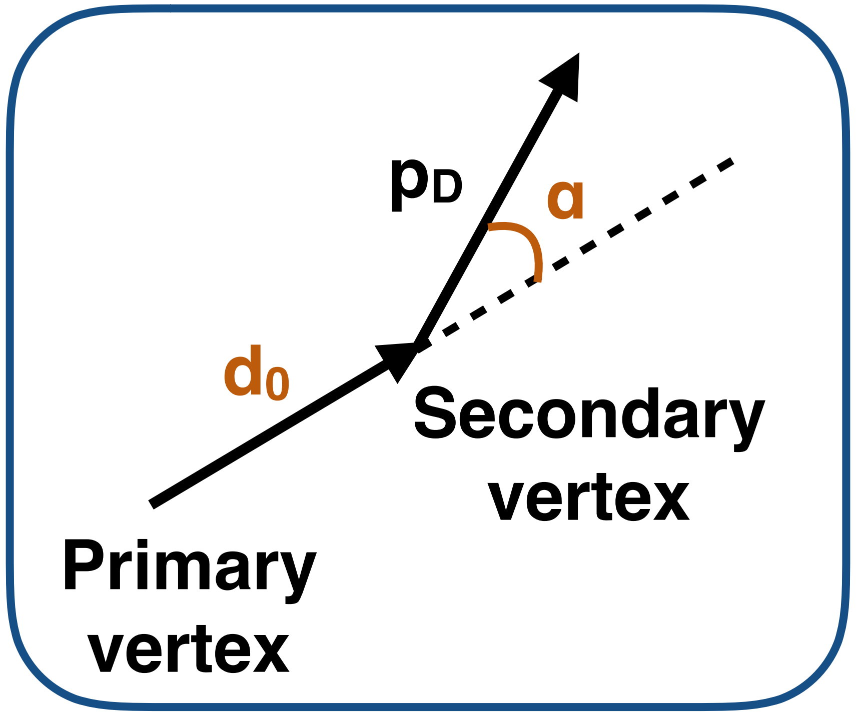

- $D^0$ online reconstruction
- loose selection based on $D^0$ vertex displacement

# $D^0$ measurements in pp and PbPb

**$D^0 \rightarrow K\pi$** in pp and PbPb collisions at **5.02TeV**, Centrality **0-10% and 0-100%**, **|y|<1**

## Analysis strategy

- Primary vertex reconstruction *several tracks*
- $D^0$ candidates (vertex) reconstruction *pairing two tracks + kinematic fitter*
- $D^0$ candidates selection (TMVA) *decay topology*
  - Pointing angel (α) *< ~0.12*
  - 3D decay length ($d_0$) normalized by its error *> ~4*
  - Secondary vertex probability *> ~0.1*
- Raw yields extraction *Invariant mass*
- Cross-sections



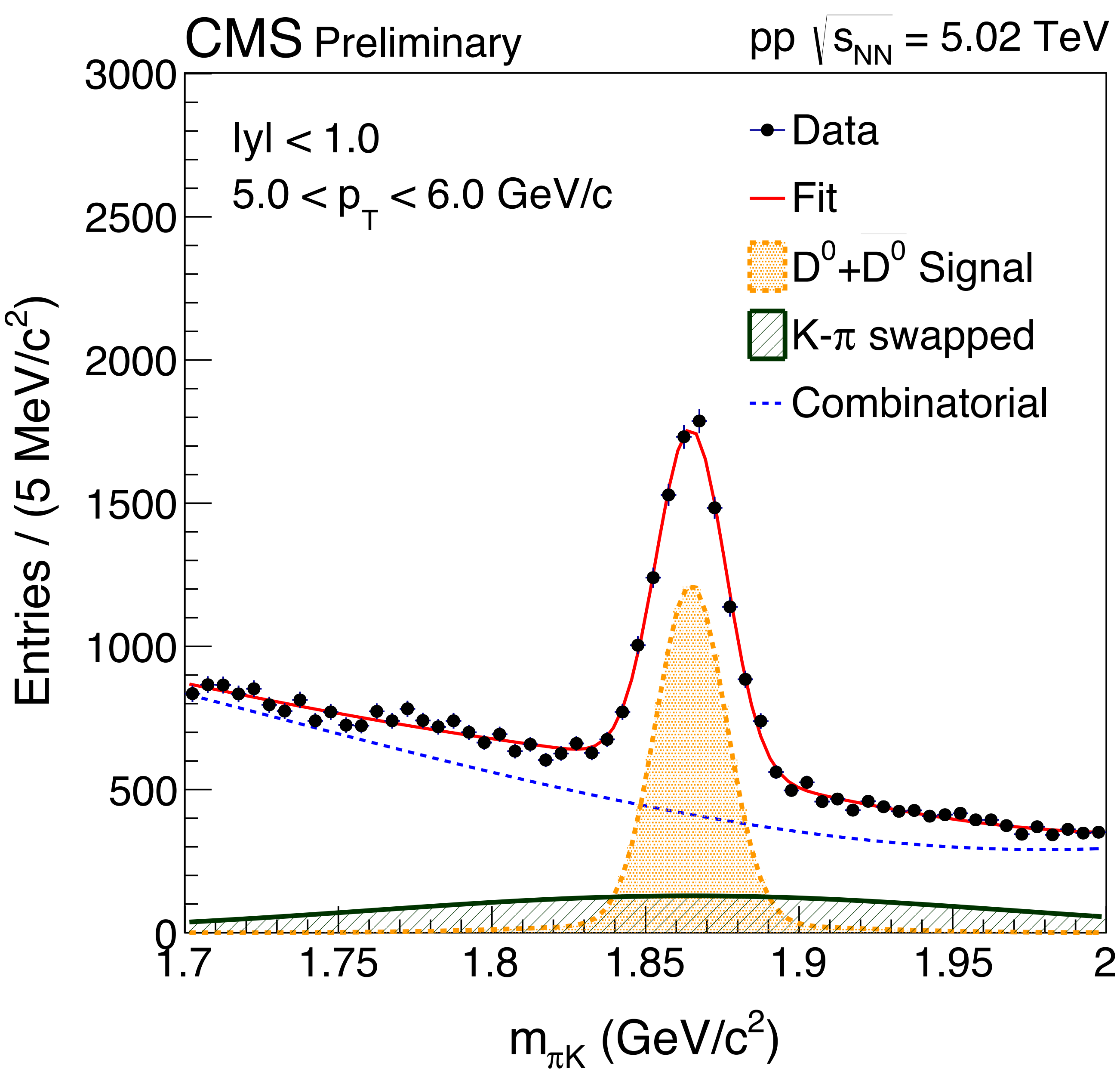
## Raw yields extraction

Mass distributions fitted by

- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-π swapped)

Fix in MC

**No PID**
*Candidates with wrong mass assignment*



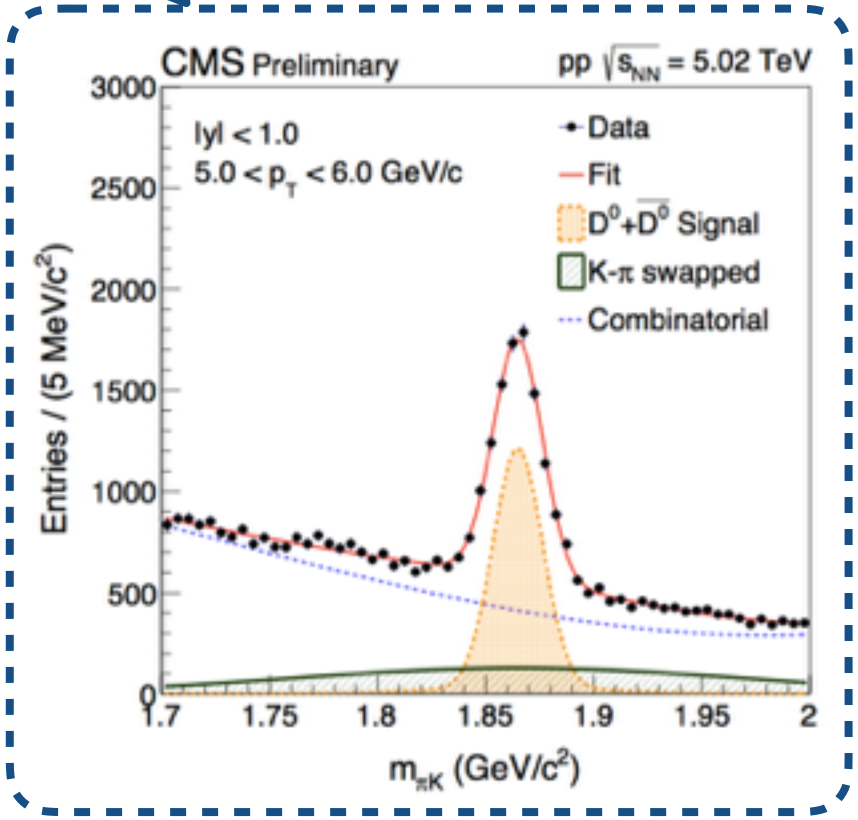
# Obtain cross-section from raw yields

## Raw yields → Cross-sections

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

Prompt $D^0$ Cross-section

Raw yields



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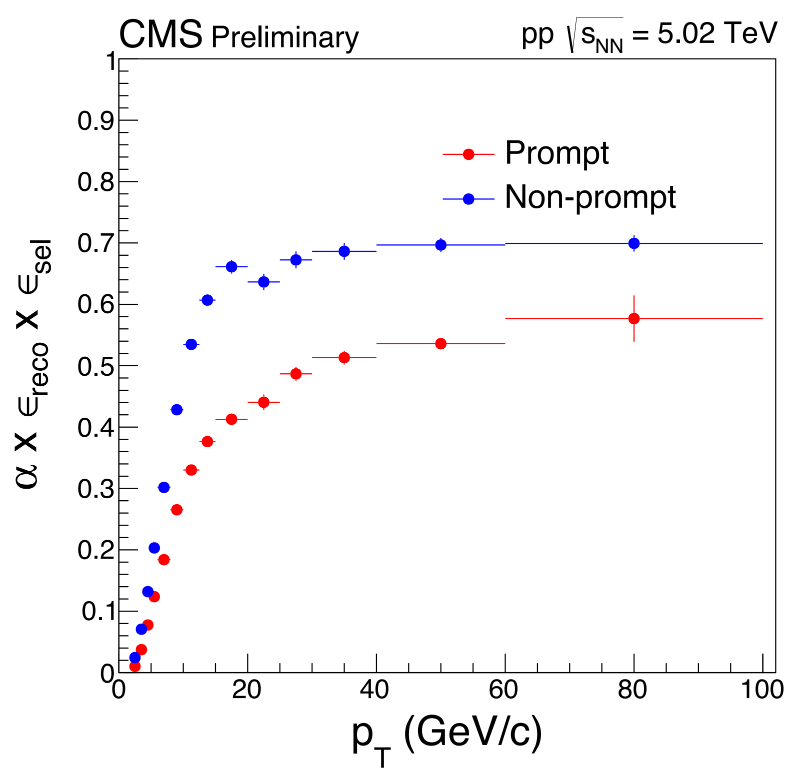
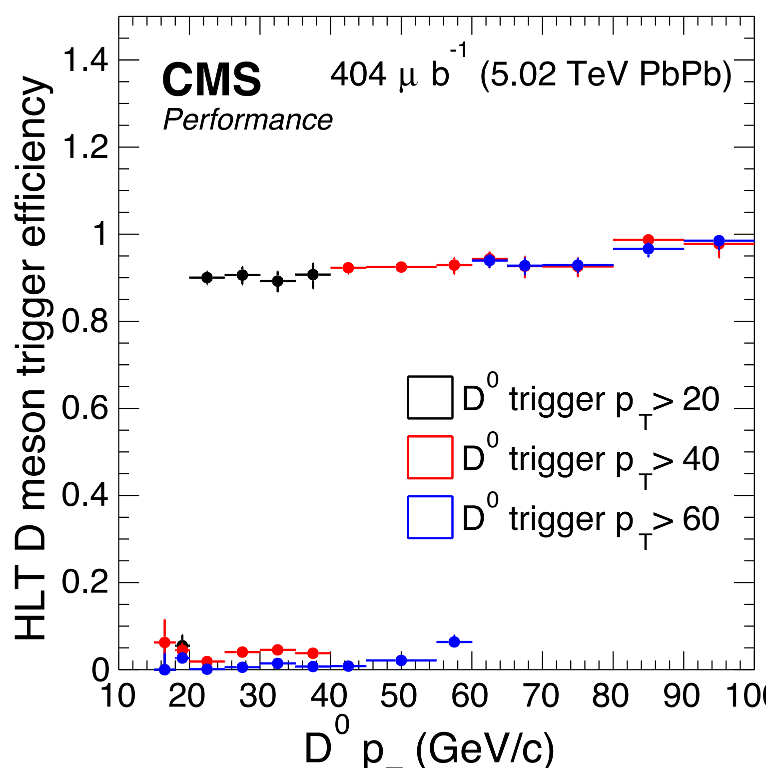
**Acceptance & efficiency**

from MC simulation




**Trigger efficiency**

fit turn on curve



# Obtain cross-section from raw yields

## Raw yields → Cross-sections

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

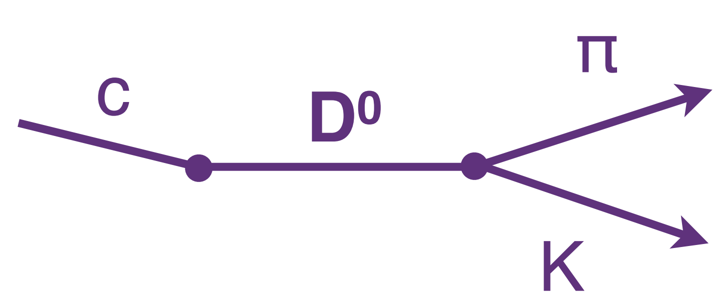
Fraction of prompt $D^0$

Branching fraction

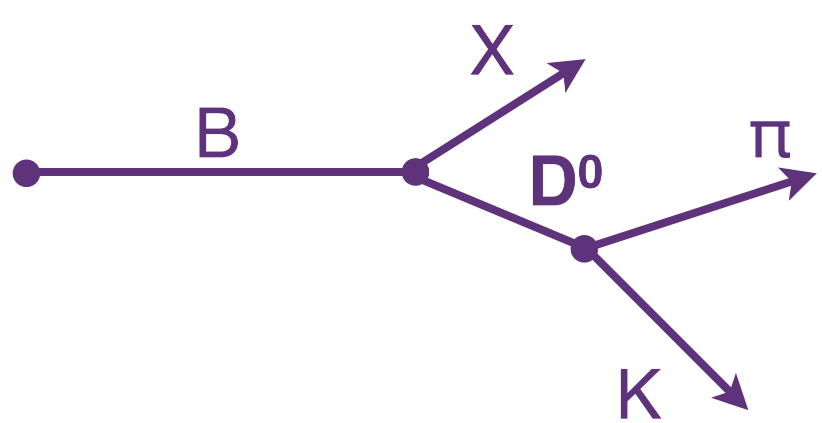
Luminosity

Prompt:
$D^0$ mesons coming from c-quark fragmentation

Prompt:

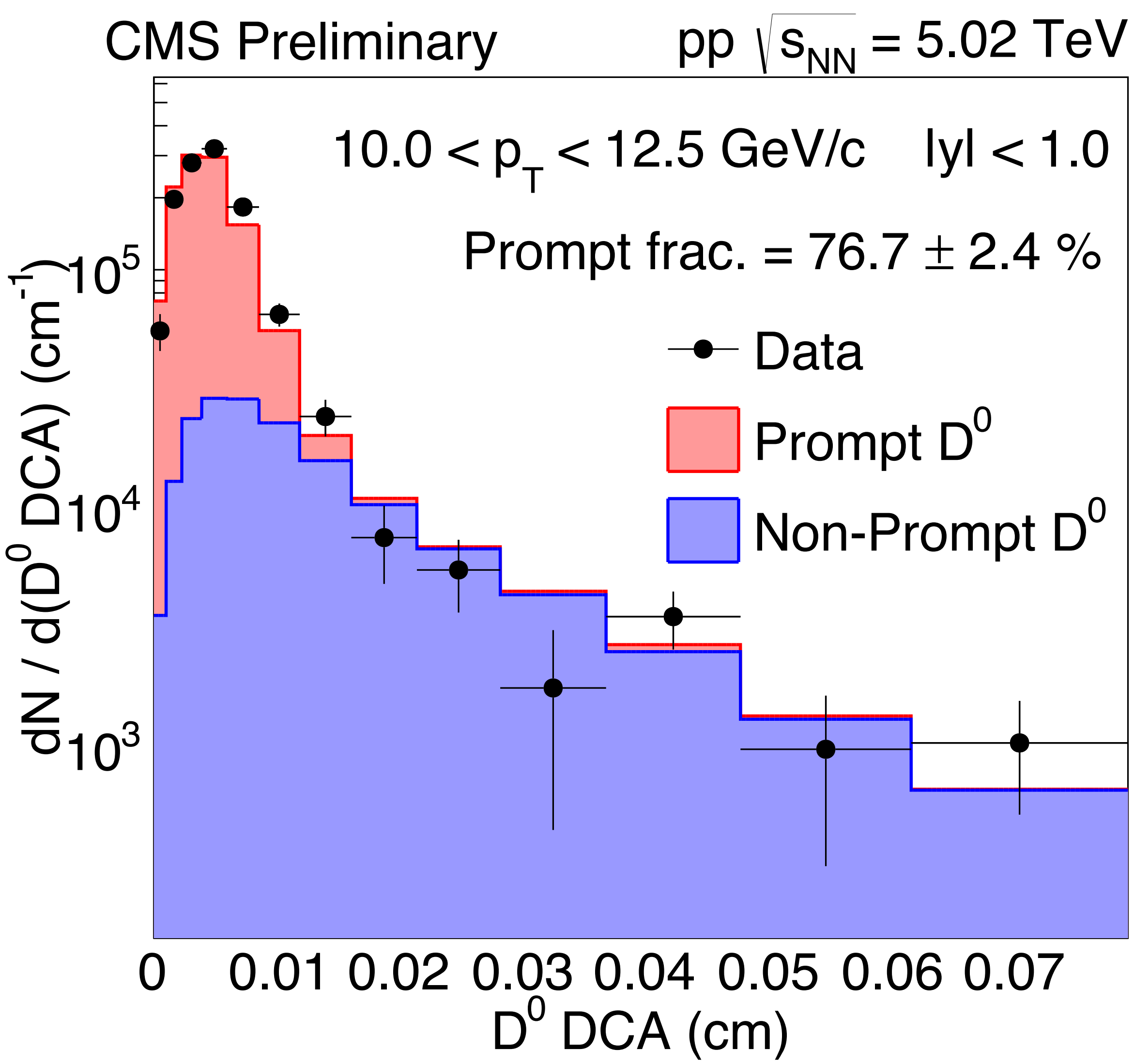



Non-prompt:

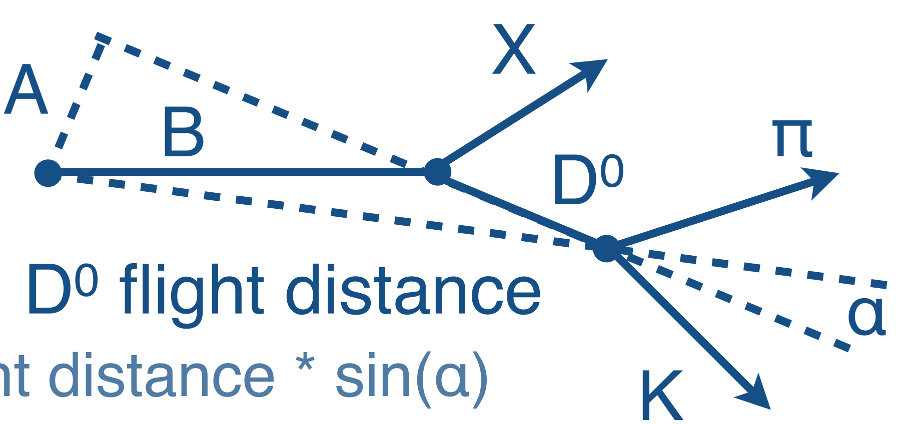


# $f_{prompt}$: Fraction of prompt $D^0$

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




- Different shapes of distance of closest approach (**DCA**) distributions of prompt and non-prompt $D^0$
- The shapes of DCA distributions come from MC
- Fit DCA distributions of data

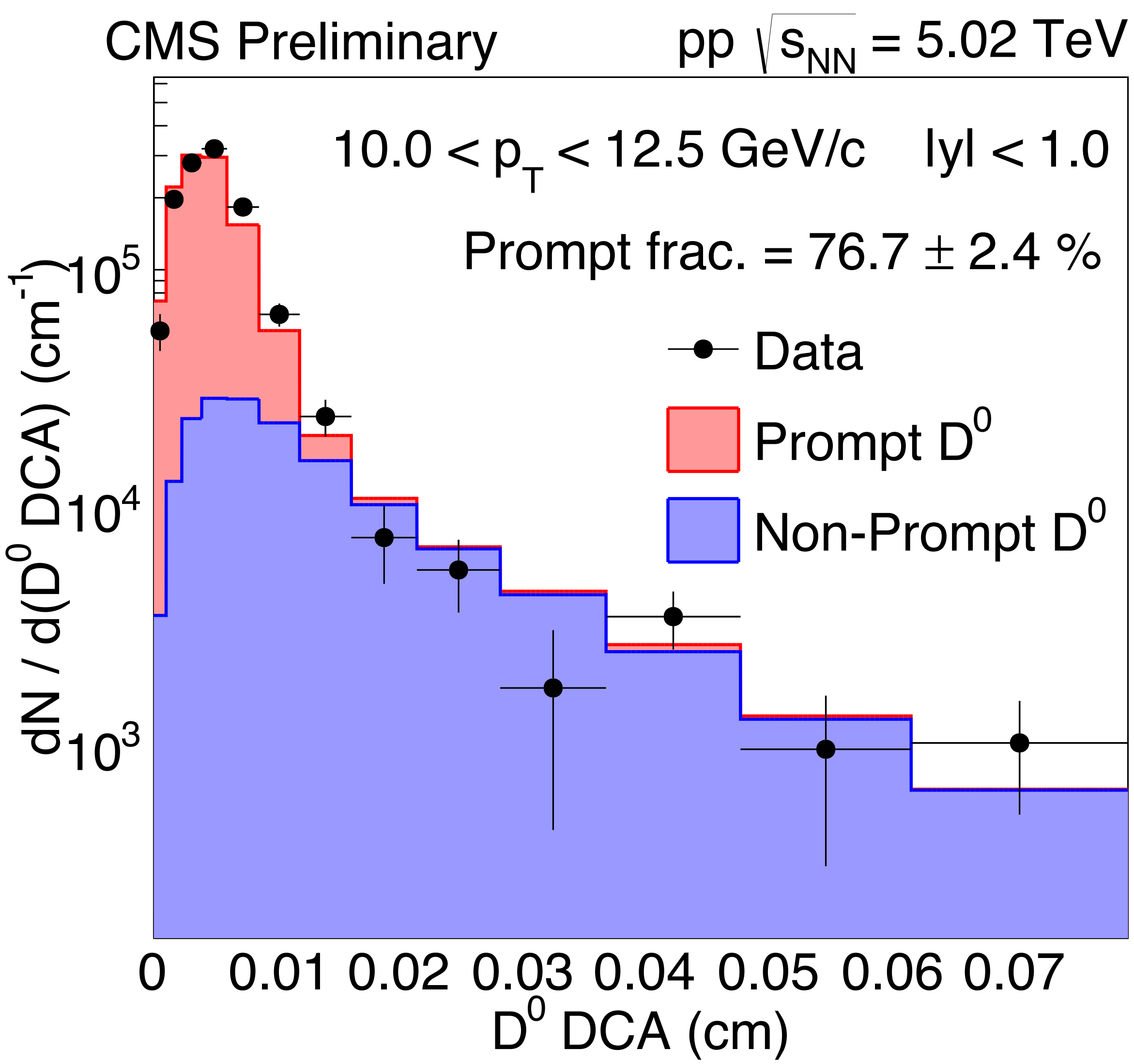


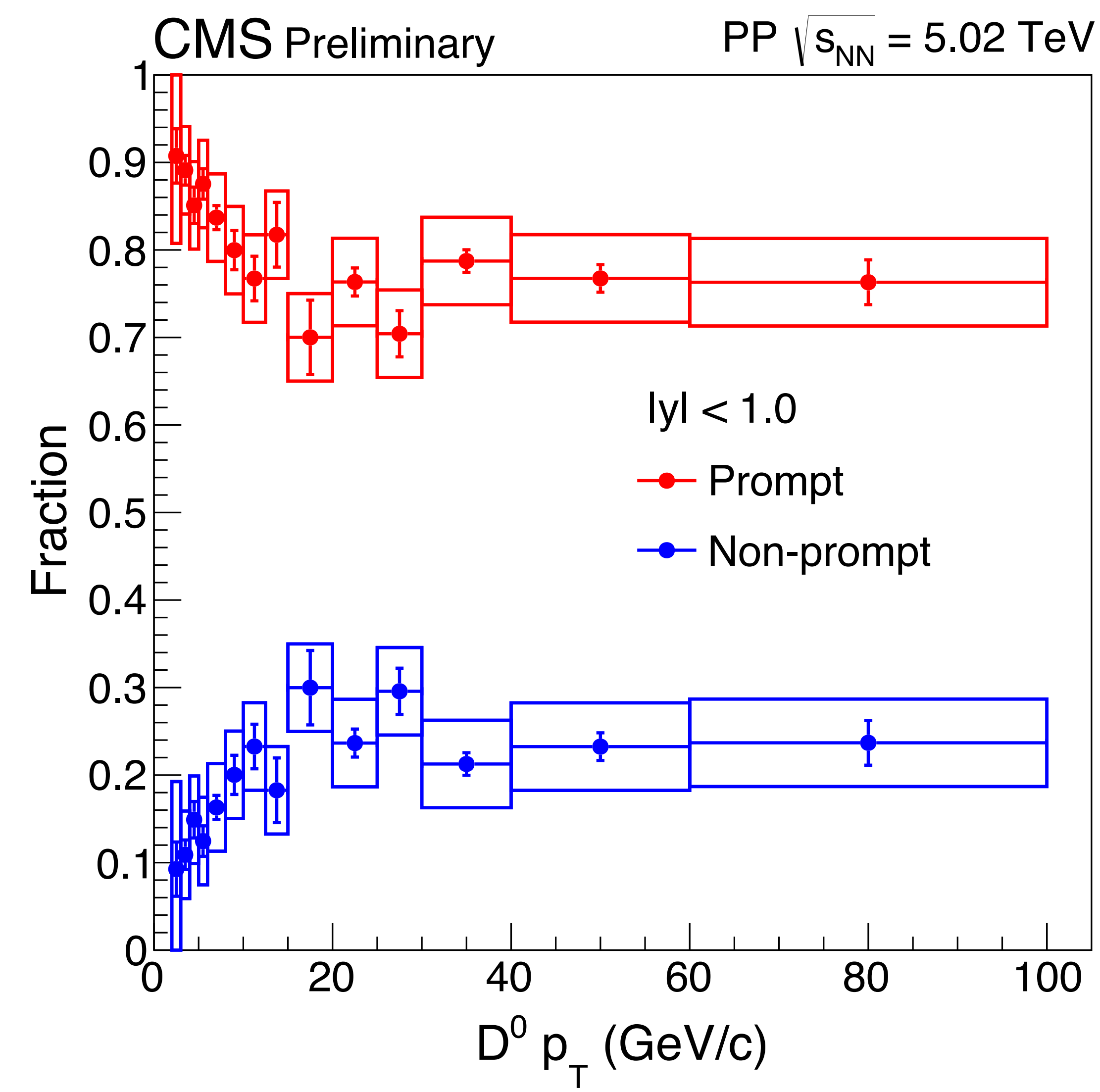

$D^0$ DCA = flight distance * sin(α)

# $f_{prompt}$: Fraction of prompt $D^0$

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

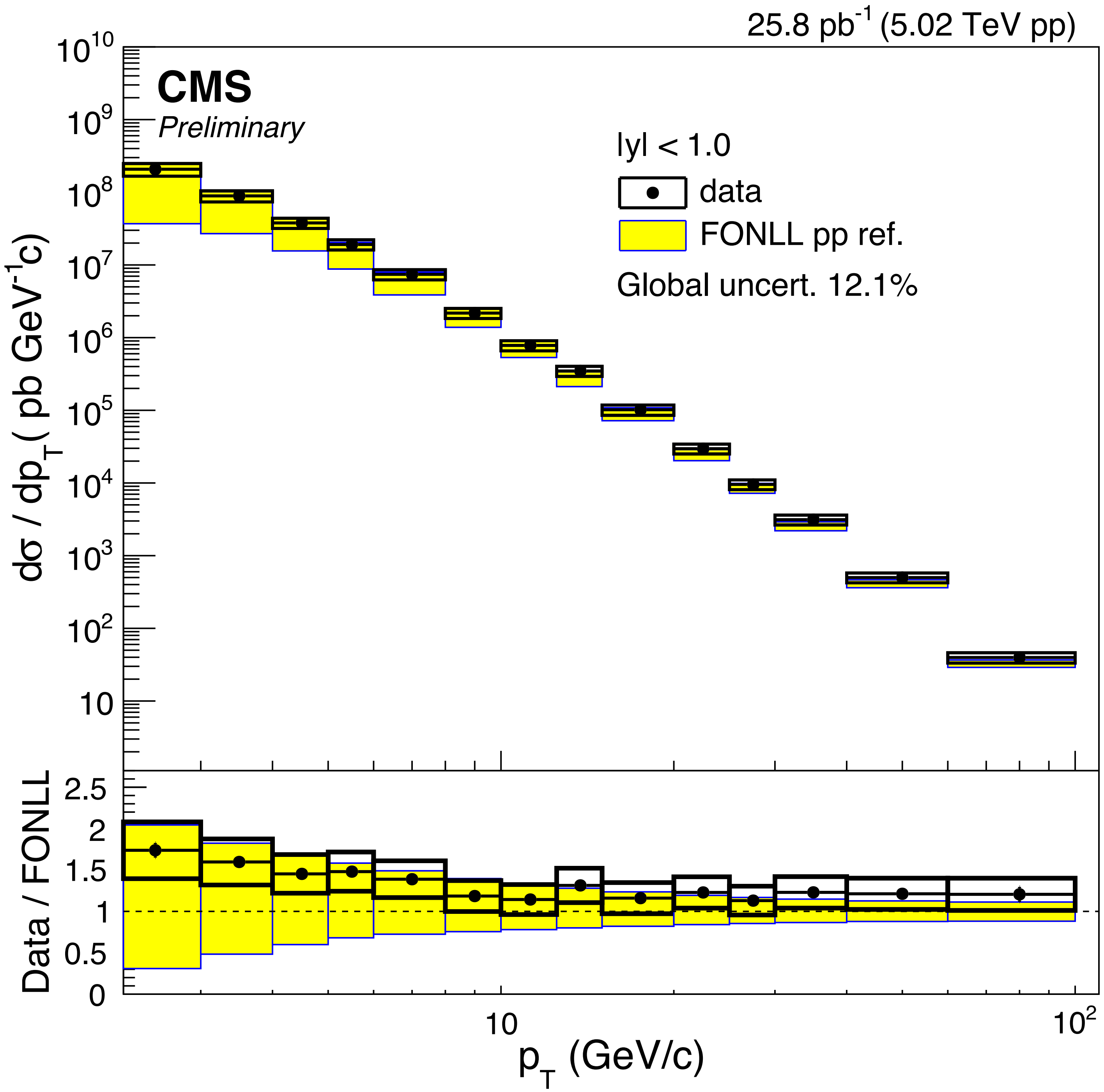
- Consistent with that from FONLL convoluted with MC efficiency




$f_{prompt}$ vs. $D^0$ pT

# $p_T$-differential cross-section in pp

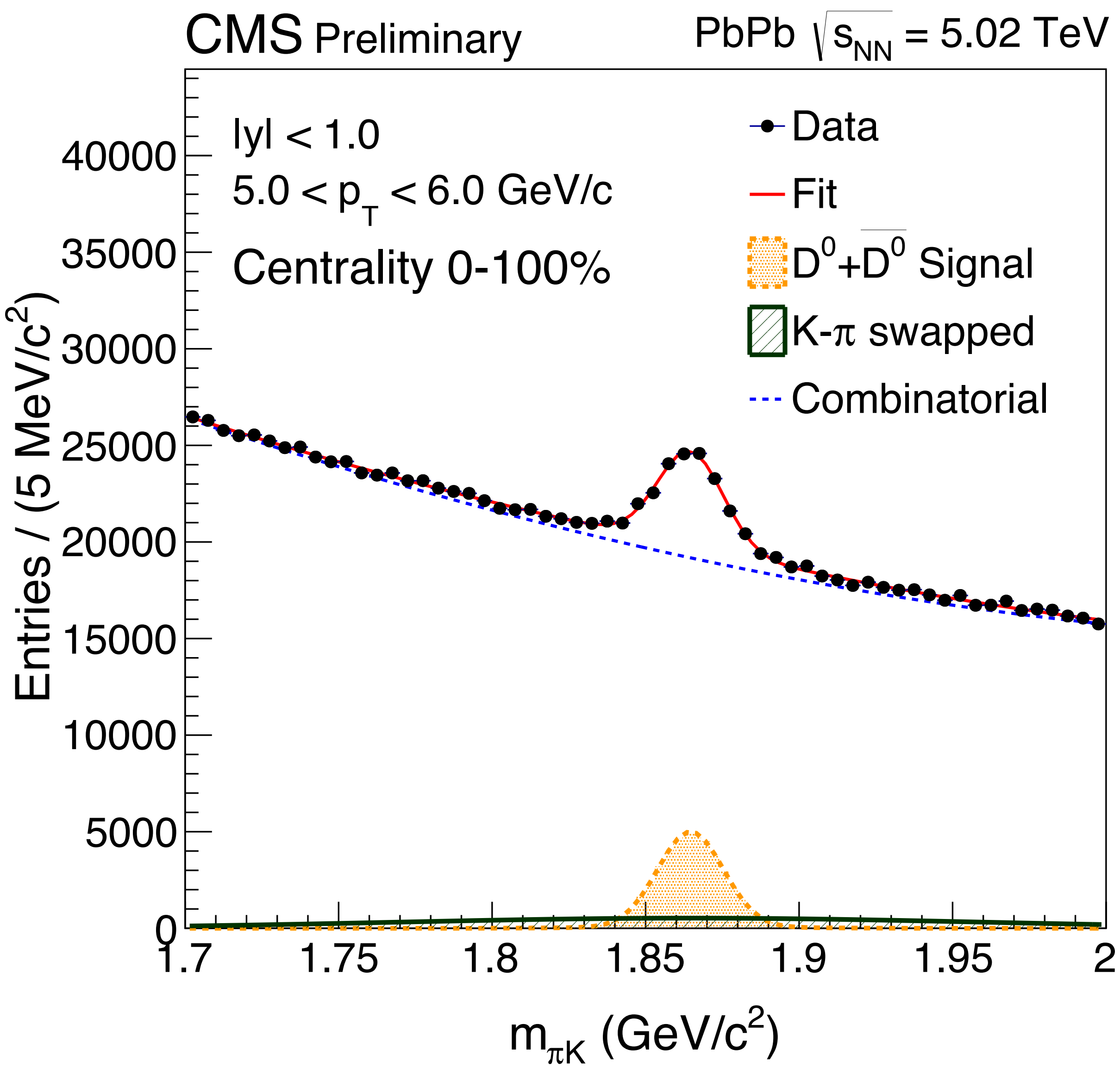


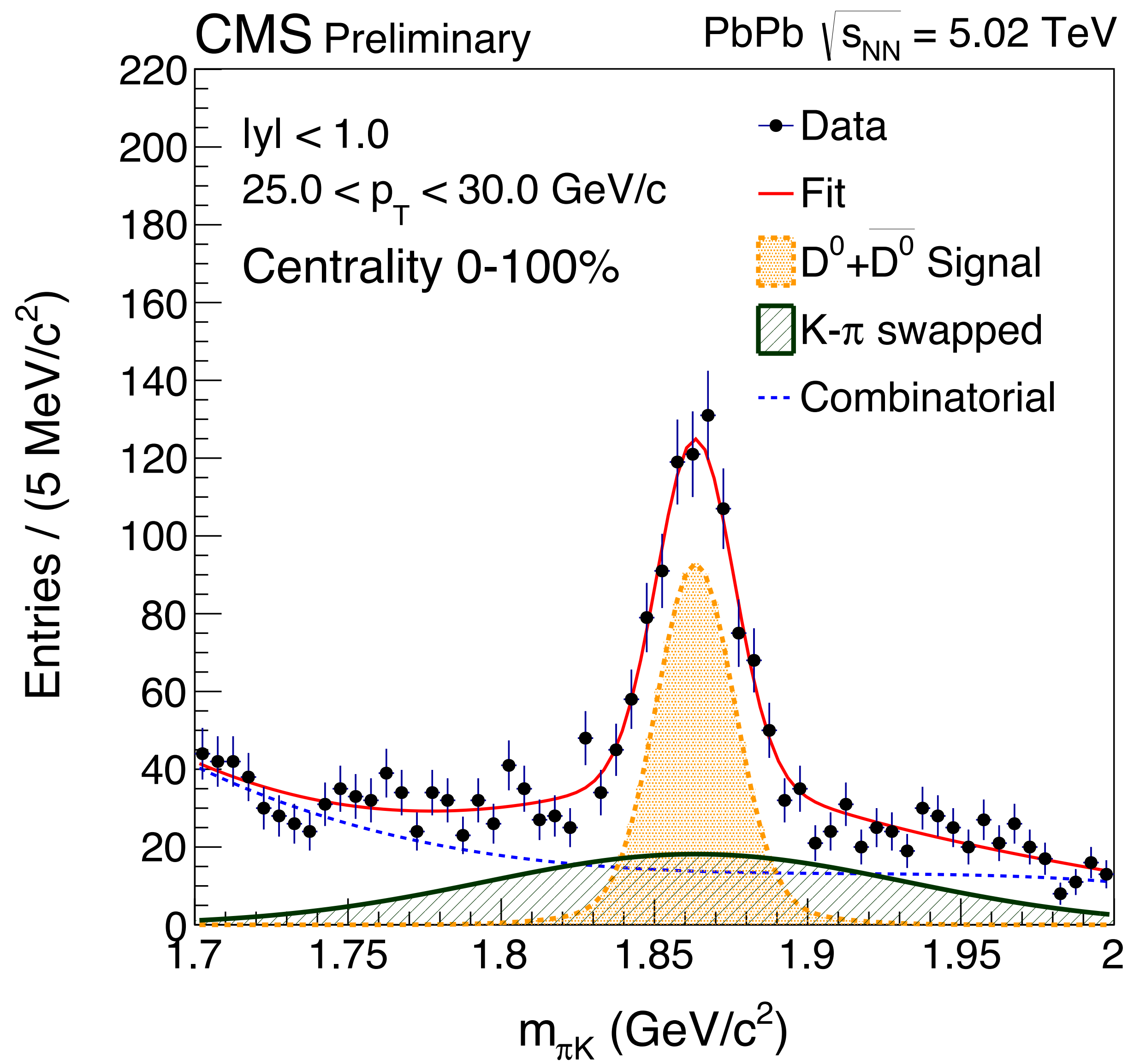

- The first measurement of $D^0$ cross-section in pp collisions at 5.02 TeV
- $p_T$ range covers from 2 to 100 GeV/c in |y| < 1
- Consistent with the upper bound of FONLL predictions [1]

[1] M. Cacciari, M. Greco, P. Nason, “The pT Spectrum in Heavy-Flavour Hadroproduction”, JHEP 007, 9805 (1998)

## Raw yields extraction

5.02 TeV, 0-100%



# Systematic uncertainties summary

**Signal extraction systematics** *~5%*

- Varying signal and background fit functions

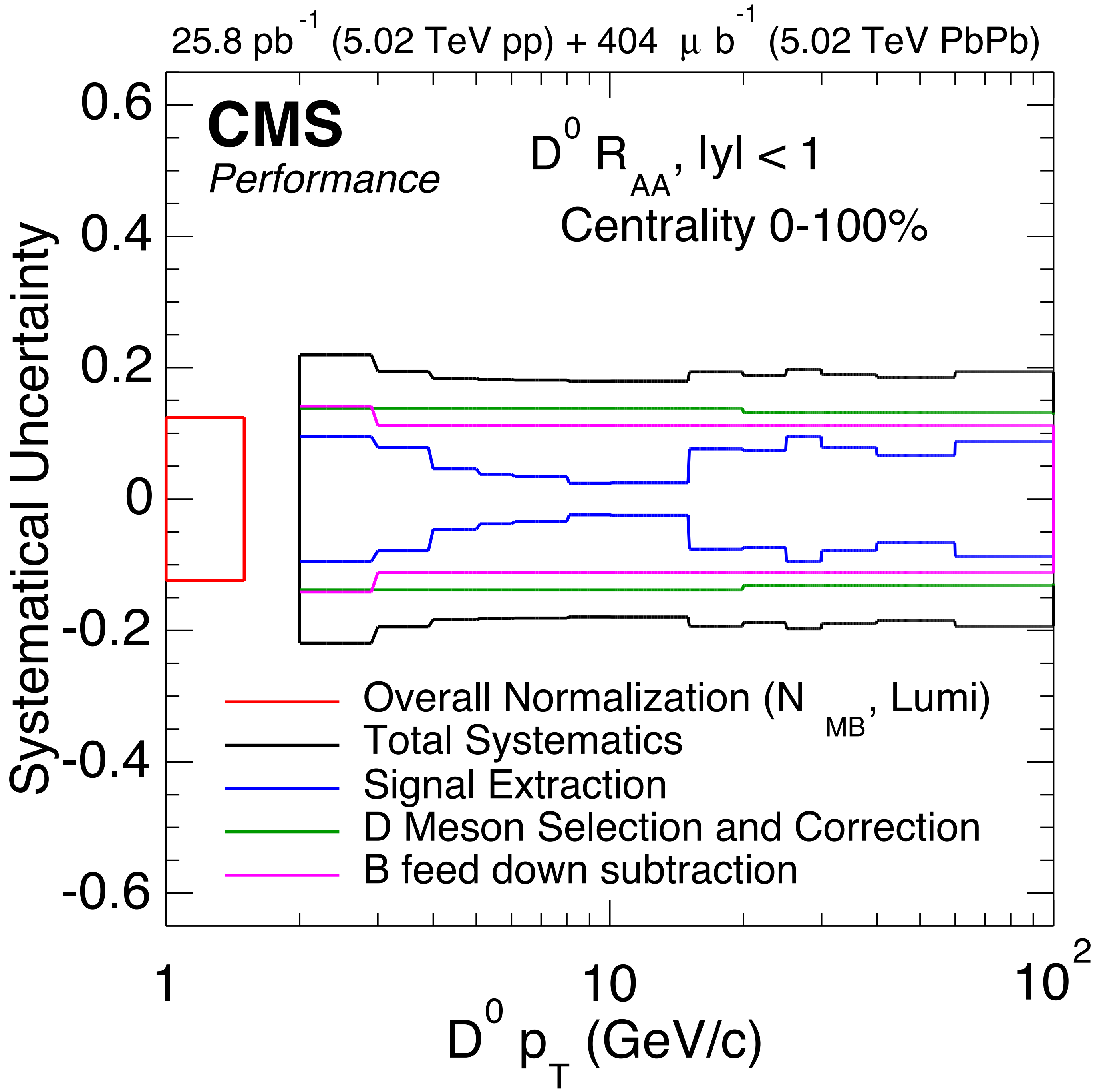
**D meson selection** *~13%*

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

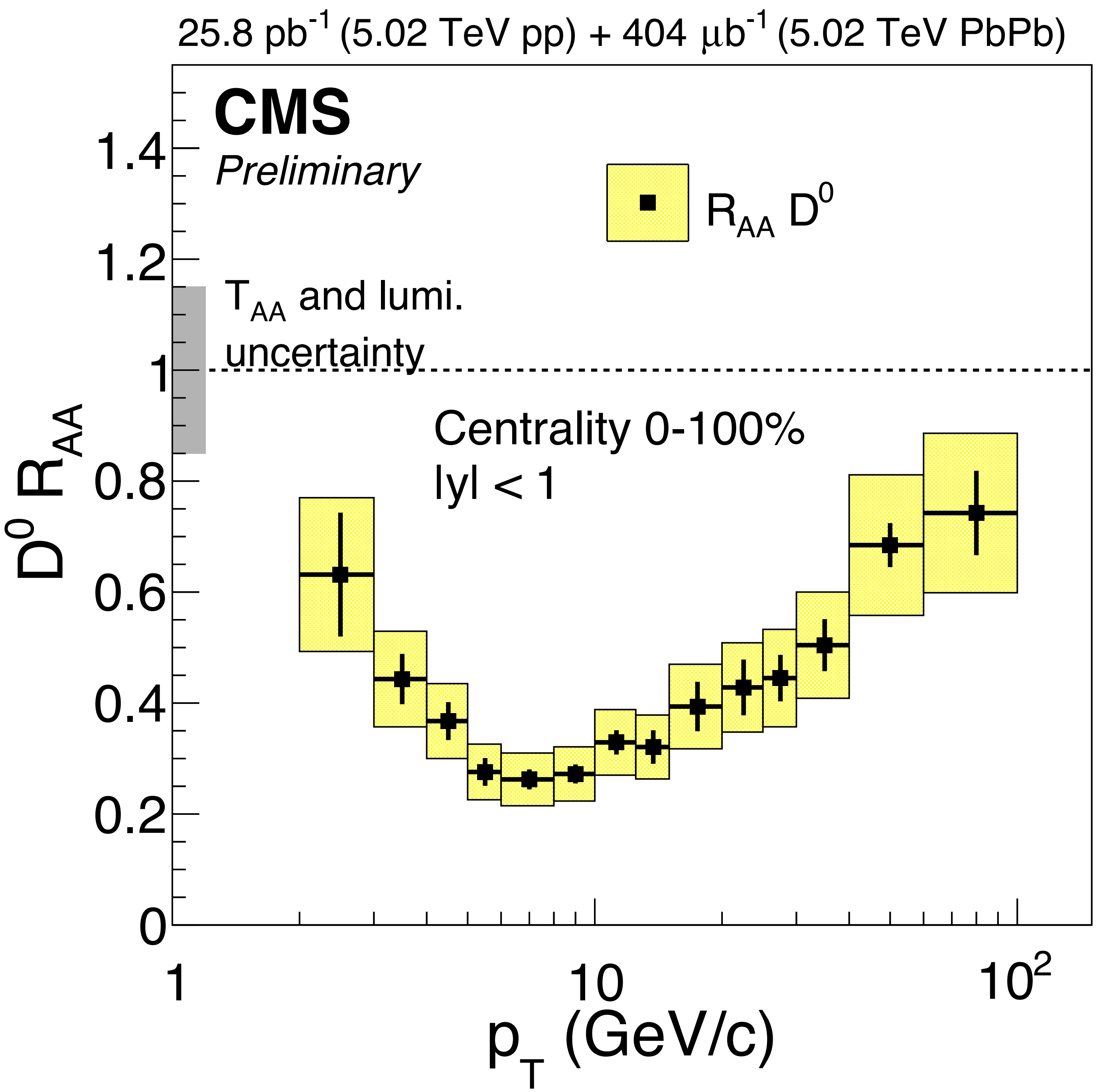
**B-feed down uncertainty** *~8%*

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

**PbPb,** Centrality **0-100%**



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

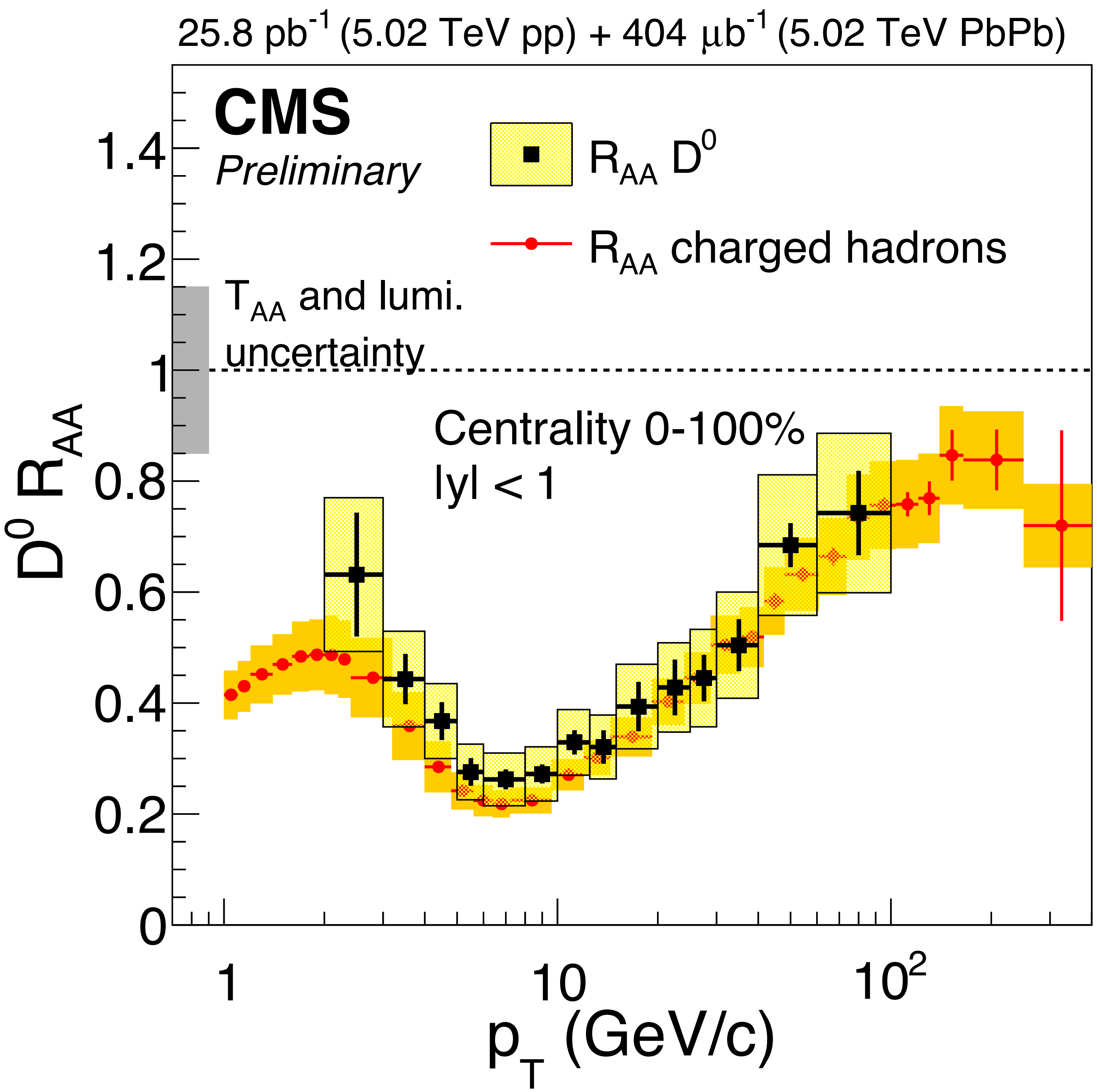



## lyl < 1, Centrality 0-100%

- Strong suppression at pT 5-8 GeV/c
- Less suppression for low and high pT

CMS-PAS-HIN-16-001

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



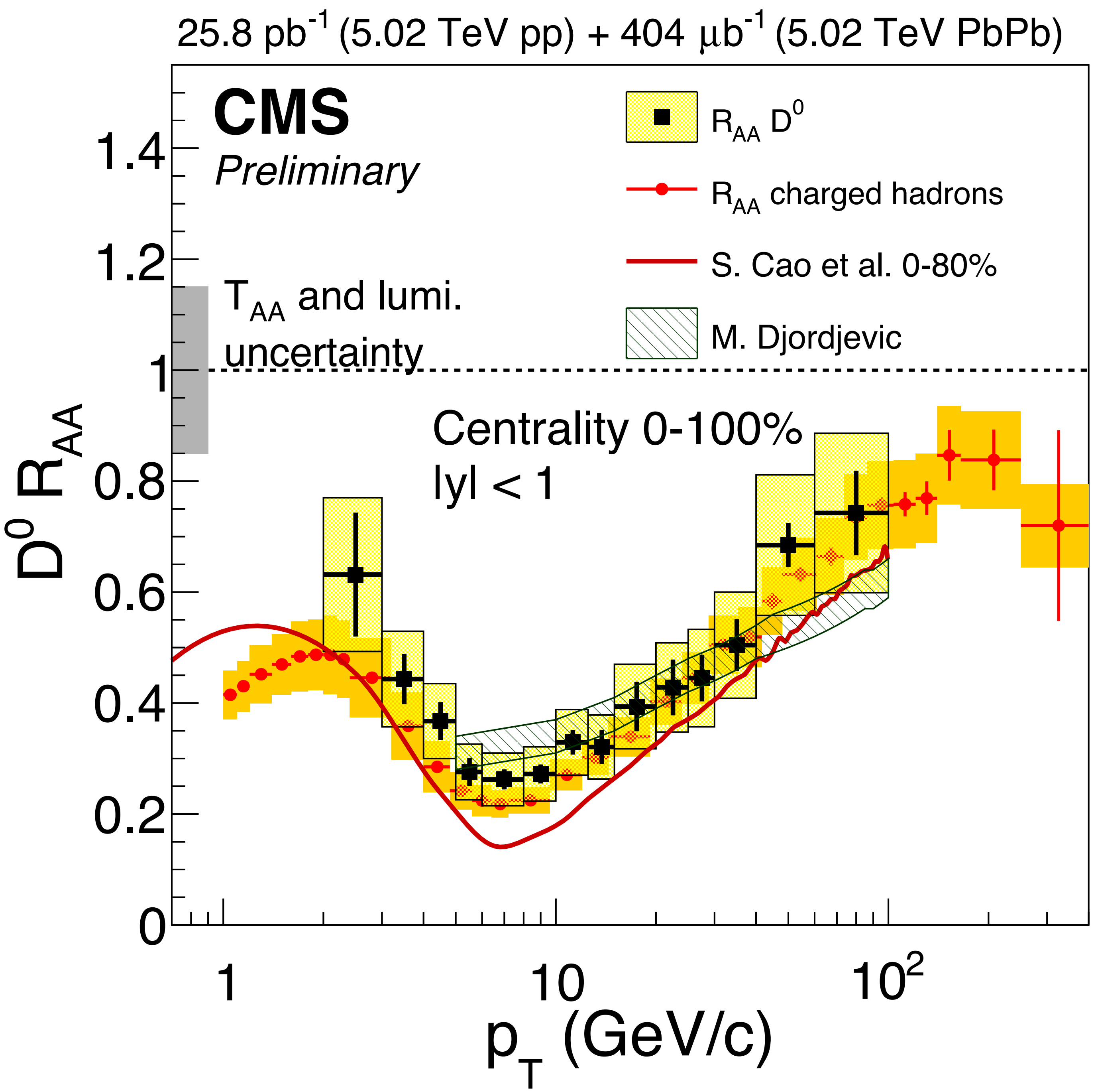

## lyl < 1, Centrality **0-100%**

- Comparison with **charged hadrons** [1]
  - Less suppression at low pT
  - Similar suppression at high pT

[1] CMS-PAS-HIN-15-015

CMS-PAS-HIN-16-001

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




## **lyl < 1,** Centrality **0-100%**

- Comparison with **charged hadrons** [1]
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  - Similar suppression at high pT
- Comparison with **theoretical predictions**
  - S. Cao et al. [2] (*Improved Langevin eq, Linearized Boltzmann*)
  - M. Djordjevic [3] (*pQCD calculations in a finite size optically thin dynamical QCD medium*)

CMS-PAS-HIN-16-001

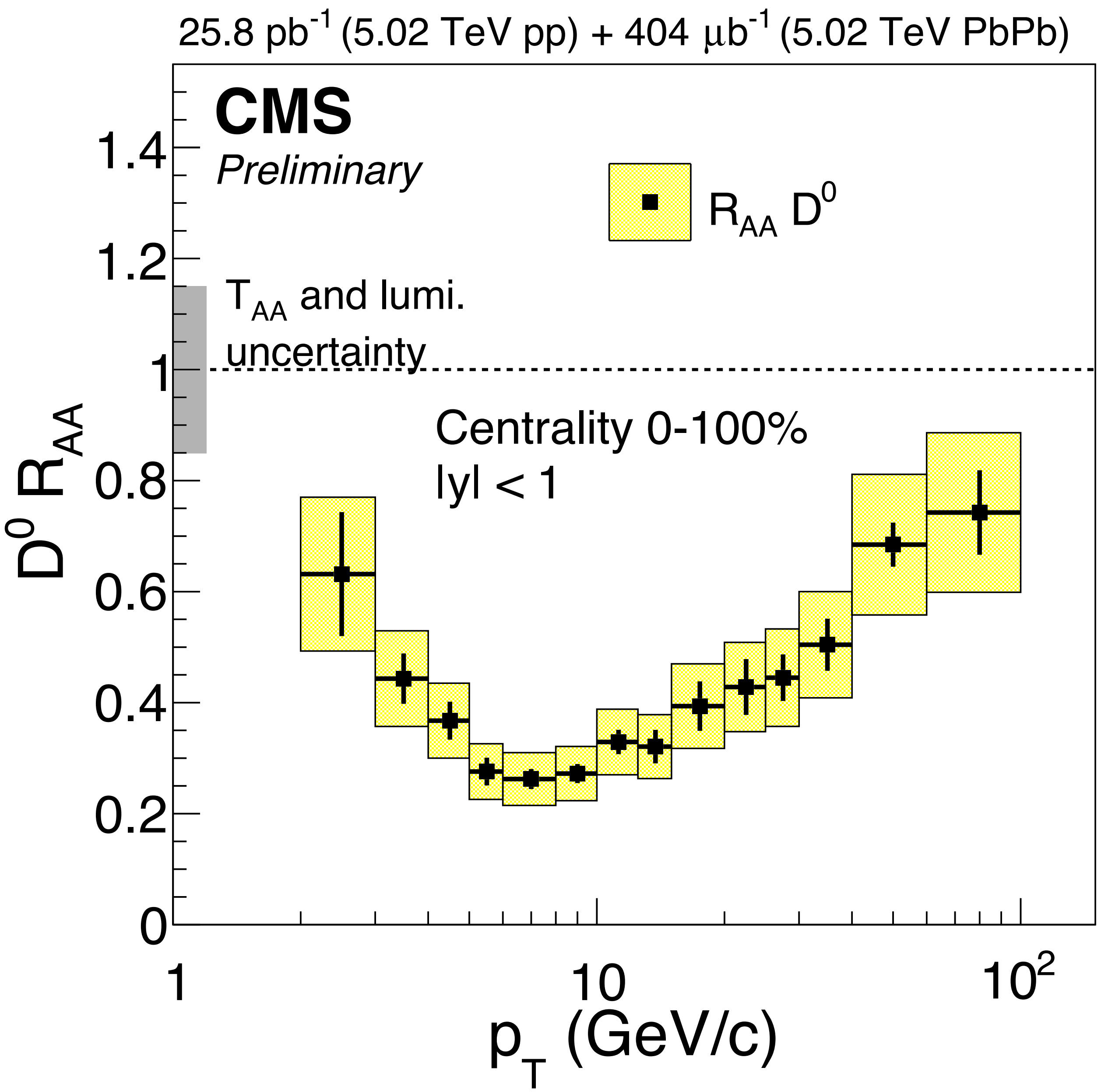

[1] CMS-PAS-HIN-15-015

[2] arXiv:1605.06447v1.

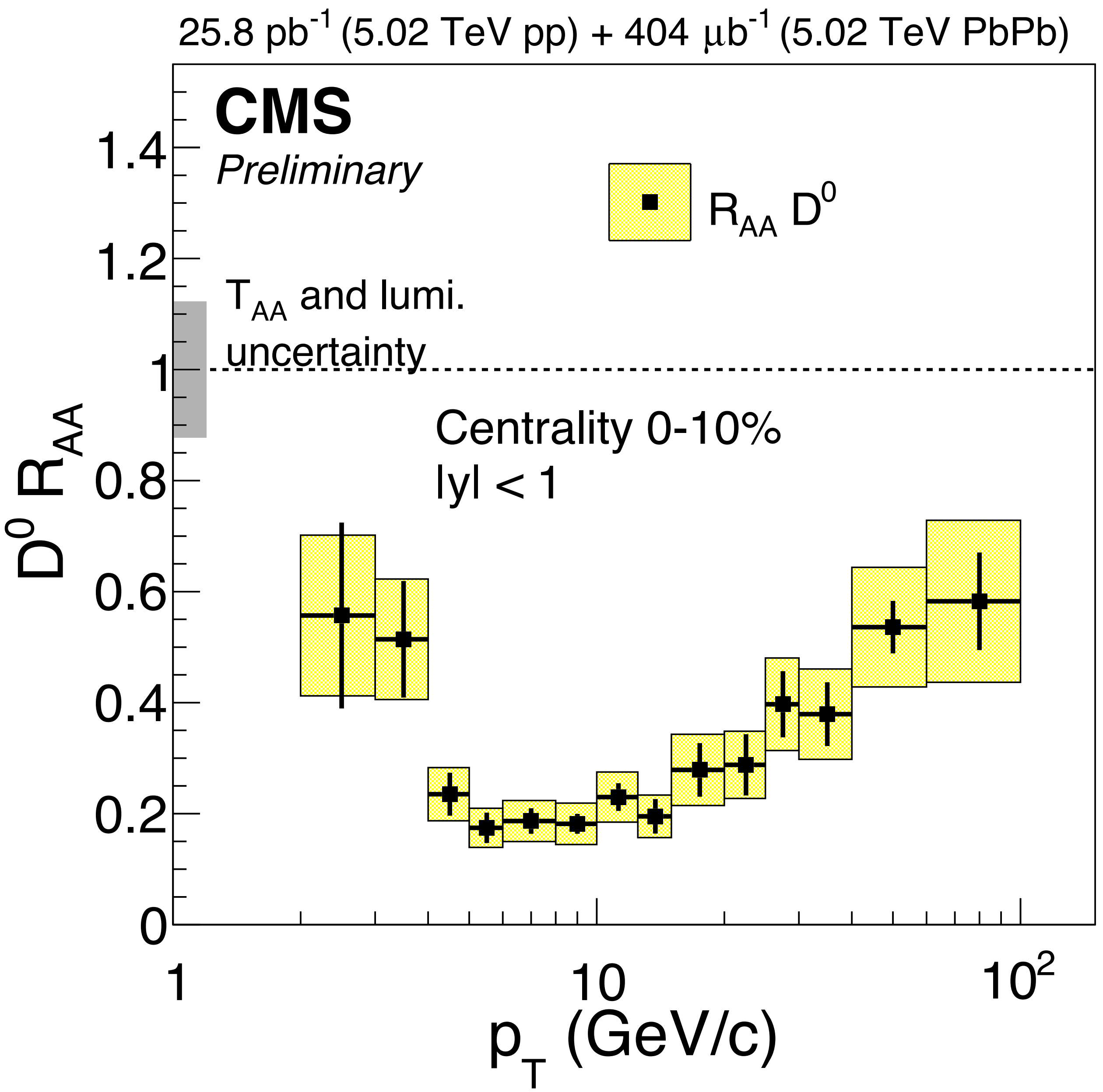
[3] Phys. Rev. C **92** (Aug, 2015) 024918

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

## Centrality **0-100%**

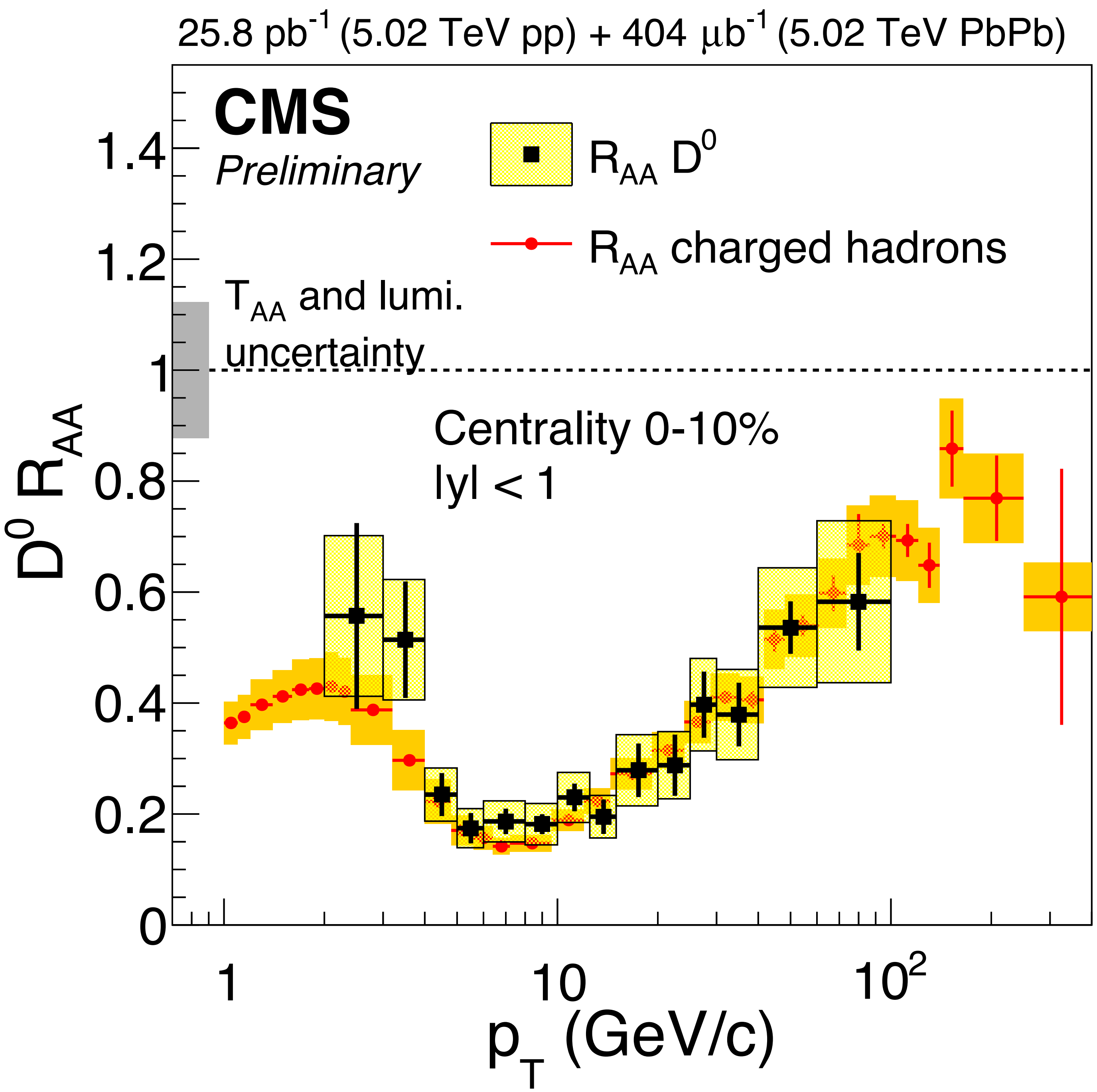



## Centrality **0-10%**




CMS-PAS-HIN-16-001

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



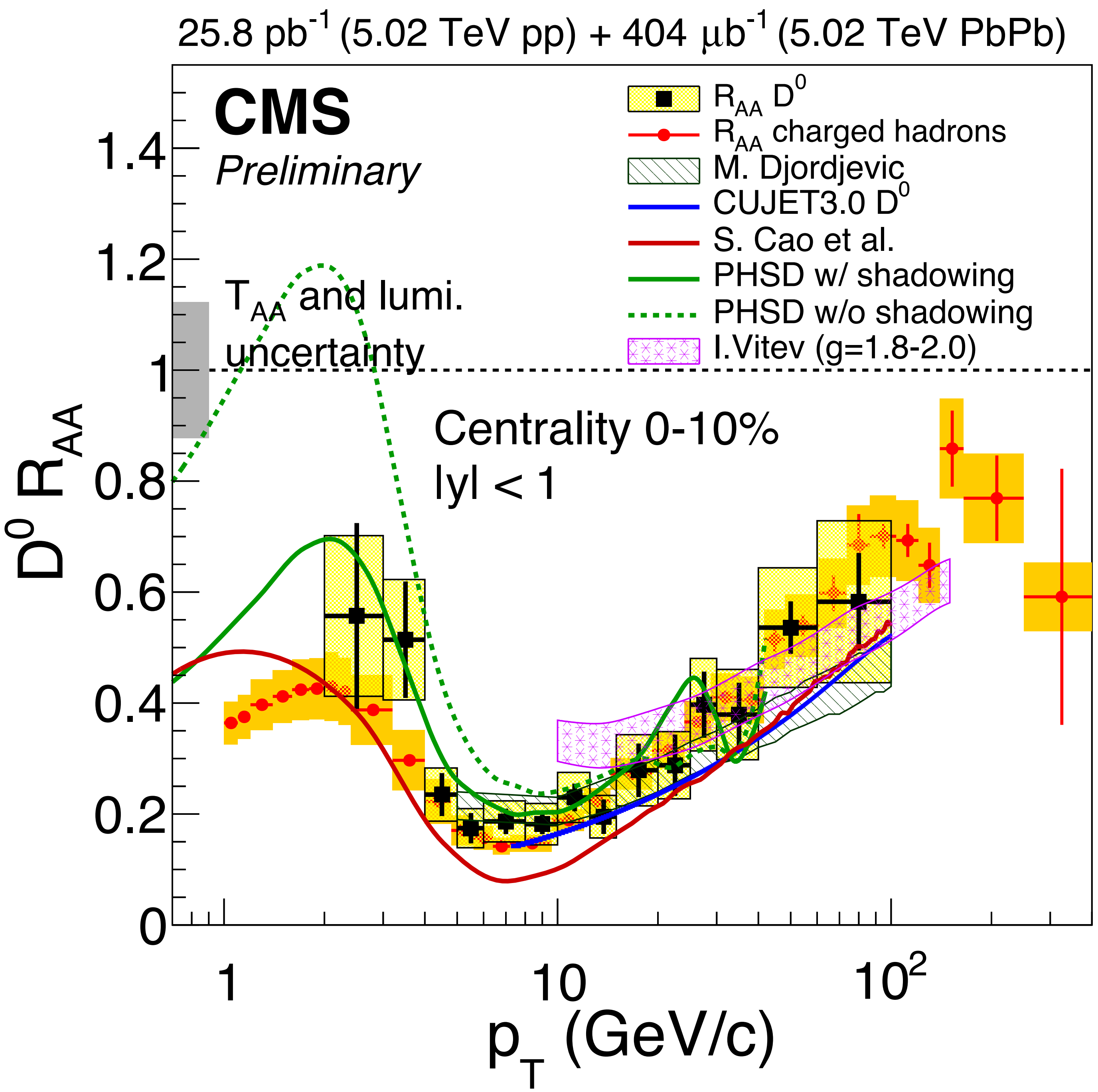

**lyl < 1,** Centrality **0-10%**

- Comparison with **charged hadrons** [1]
  - Similar behavior with 0-100%

[1] CMS-PAS-HIN-15-015

CMS-PAS-HIN-16-001

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




## |y| < 1, Centrality 0-10%

- Comparison with **charged hadrons** [1]
  - Similar behavior with 0-100%
- Comparison with **theoretical predictions**
  - S. Cao et al. [2] (*Improved Langevin eq, Linearized Boltzmann*)
  - M. Djordjevic [3] (*pQCD calculations in a finite size optically thin dynamical QCD medium*)
  - CUJET3.0 [4] (*jet quenching model based on DGLV opacity expansion theory*)
  - PHSD [5] (*Parton-Hadron-String Dynamics transport approach*)
  - I. Vitev [6] (*jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG)*)

CMS-PAS-HIN-16-001


[1] CMS-PAS-HIN-15-015
[2] arXiv:1605.06447v1.
[3] Phys. Rev. C **92** (Aug, 2015) 024918
[4] JHEP **02** (2016) 169
[5] Phys. Rev. C **93** (Mar, 2016) 034906
[6] Phys. Rev. D **93** (Apr, 2015) 074030

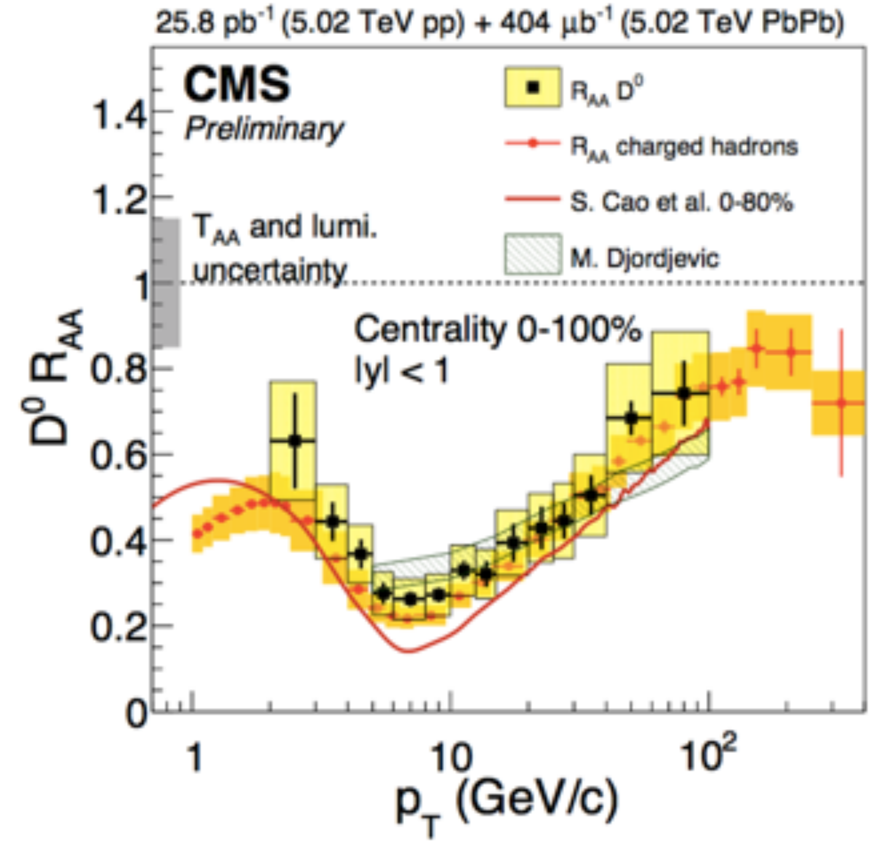
# Summary

# Summary

## Conclusions

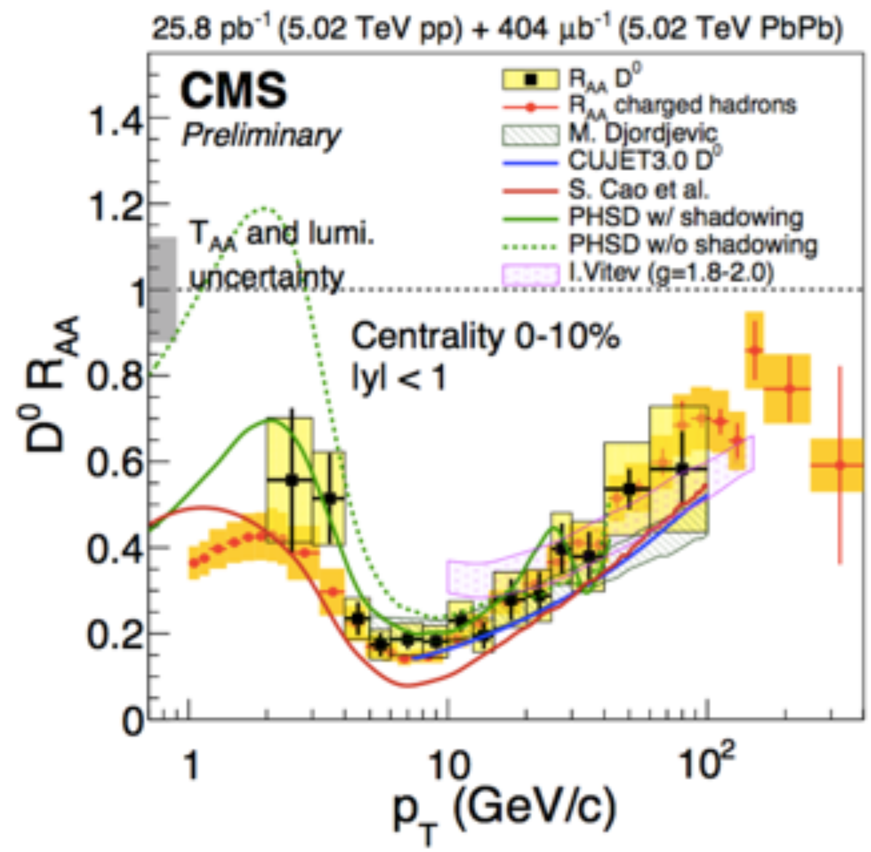
**$D^0$ and charged particle $R_{AA}$ agree up to very high $p_T$**

- Putting strong constraints on theoretical calculations
- Forcing theories to describe HF production in a much wider kinematic range where different processes dominate




## Outlook

- D meson at very low pT
  - Down to ~1 GeV/c
  - The hadronization mechanisms and the cold medium properties
- D meson $v_n$ measurements
  - Collective behavior
- B meson $R_{AA}$
  - Coming soon!

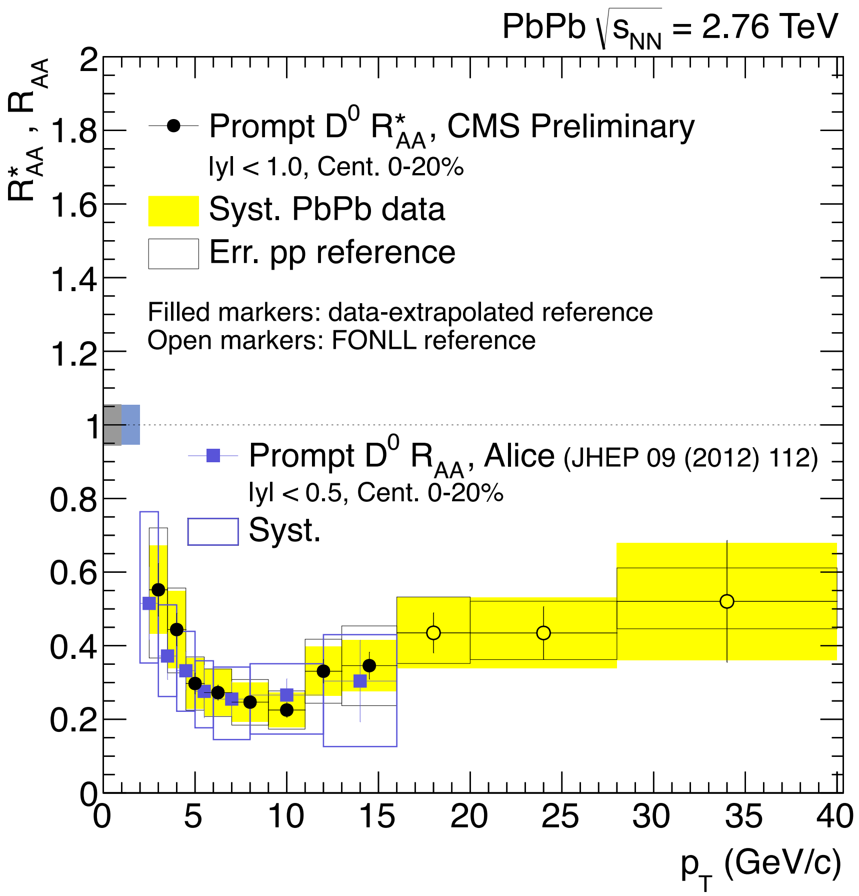


# Back up

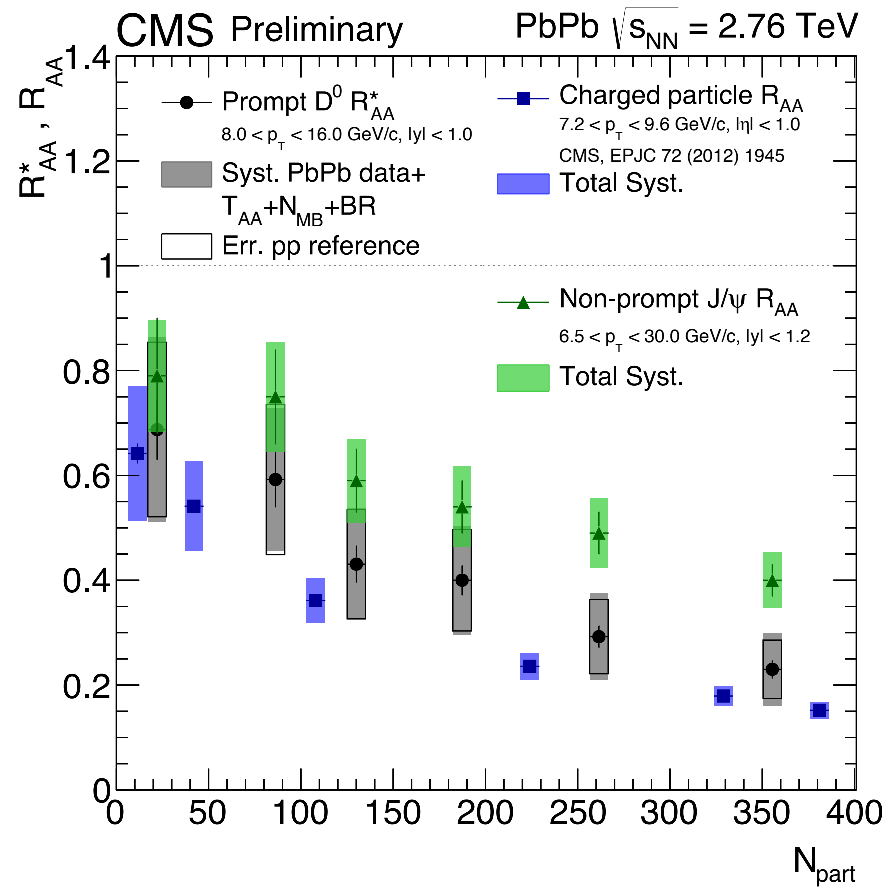
Thanks for your attention!

## PbPb @ 2.76 TeV

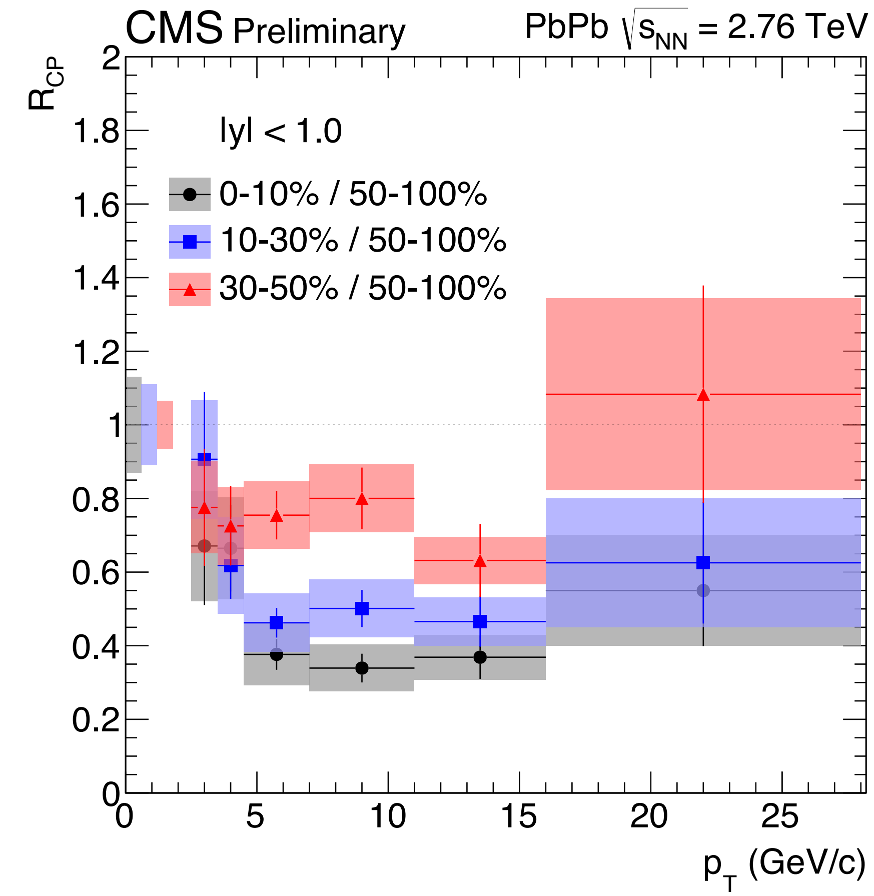
CMS-PAS-HIN-15-005




$R_{AA}$ vs. $p_T$




$R_{AA}$ vs. $N_{part}$



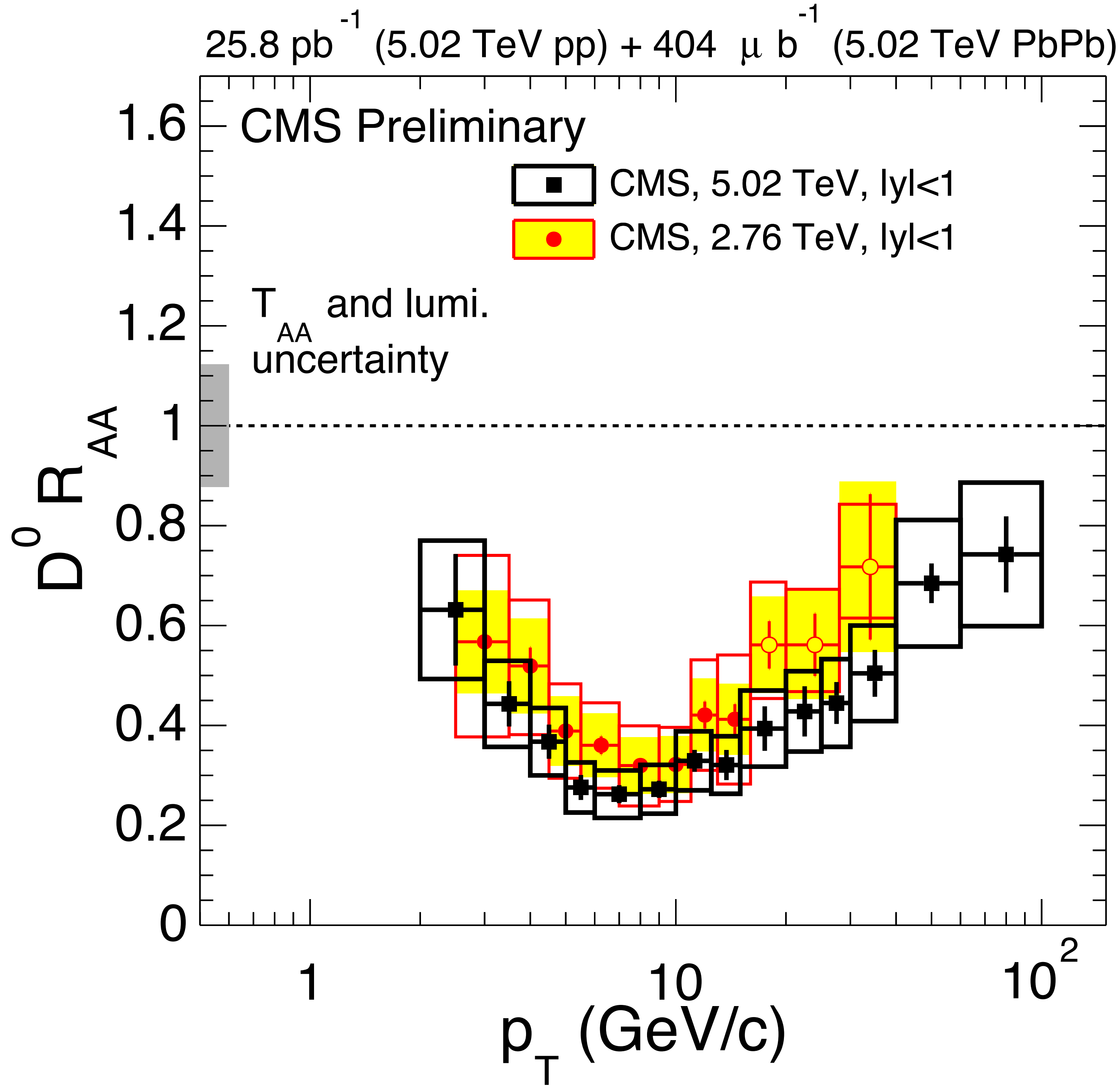

$R_{CP}$ vs. $p_T$

## RunII: pp + PbPb @ 5.02 TeV

- Measurements reaching very high $p_T$ (>100GeV/c) for the first time!
- PP reference directly from data

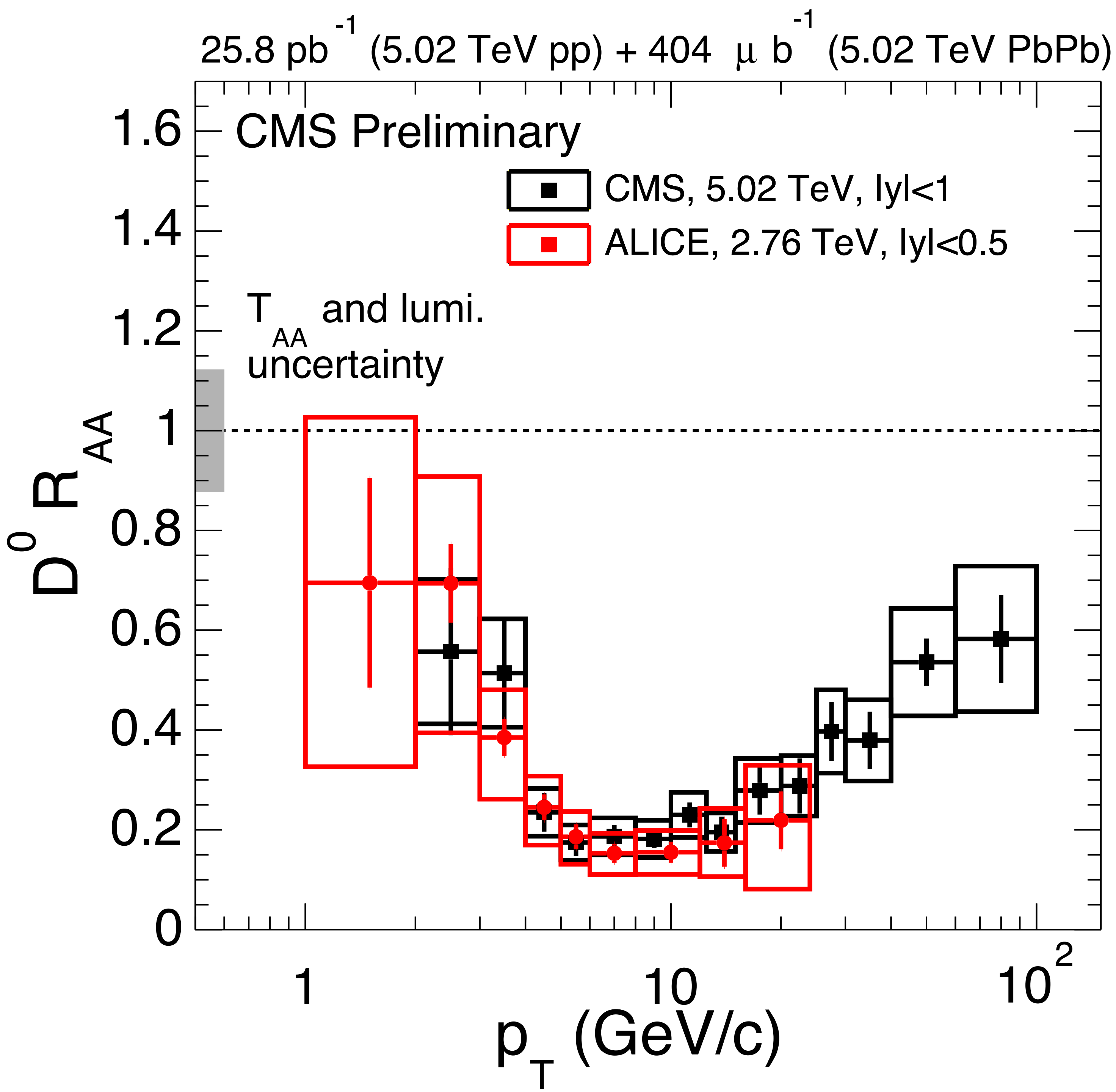
# Comparison with CMS 2.76 TeV

## PbPb 0-100%



# Comparison with ALICE 5.02 TeV

## PbPb 0-10%



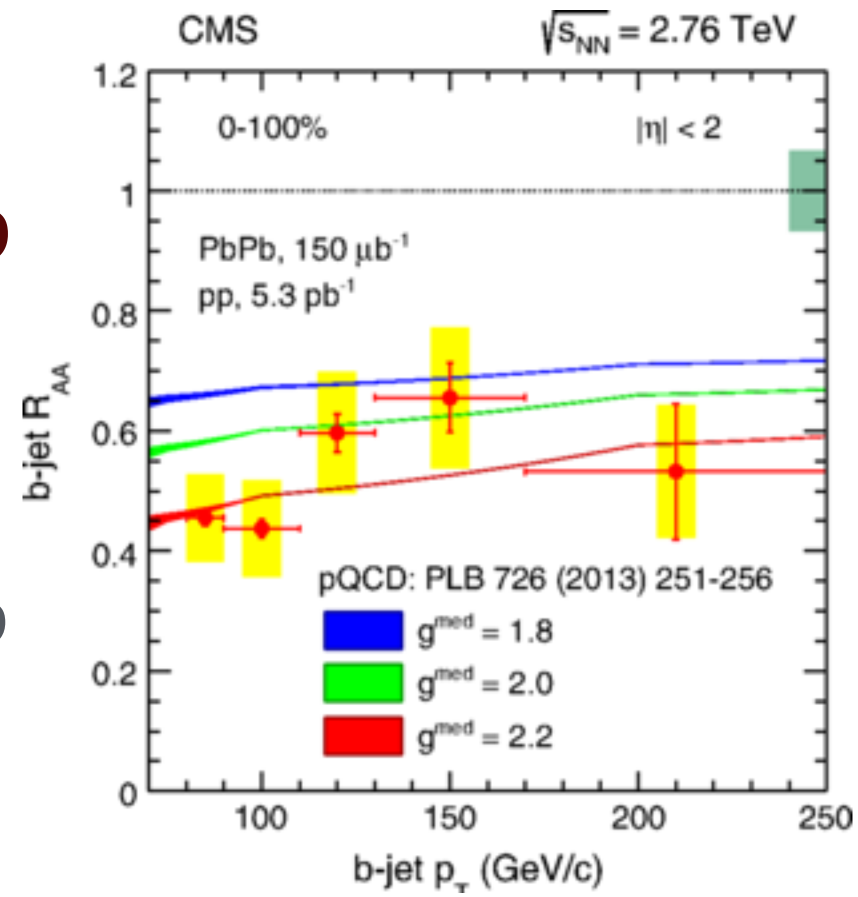

CMS: 0-10%, ALICE: 0-7.5%

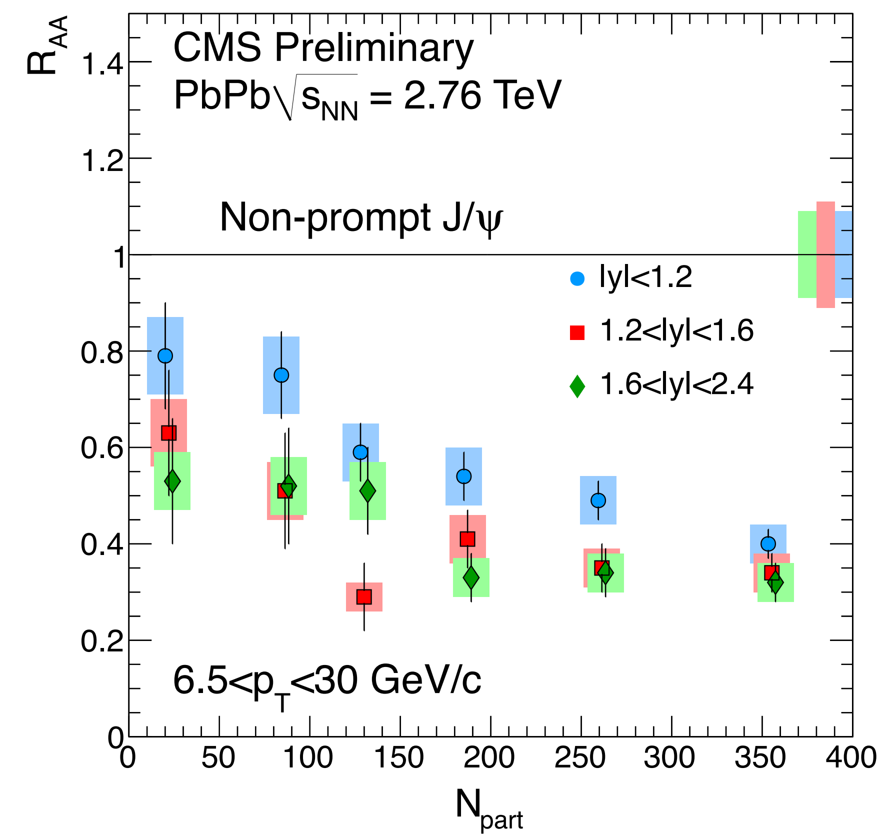
# LHC Run I

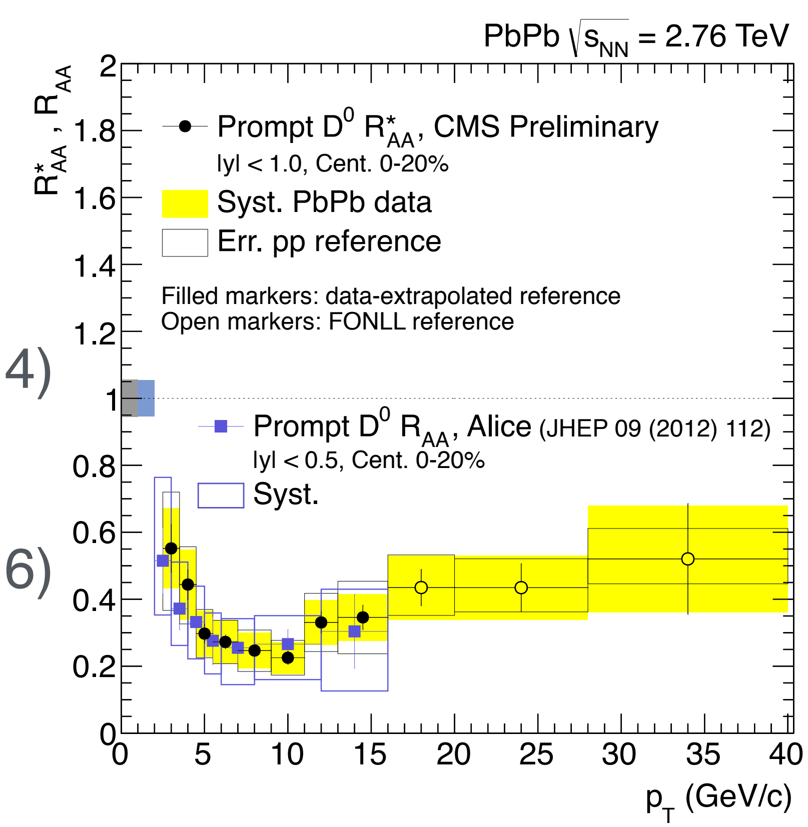
## 2.76 PbPb + 5.02 pPb

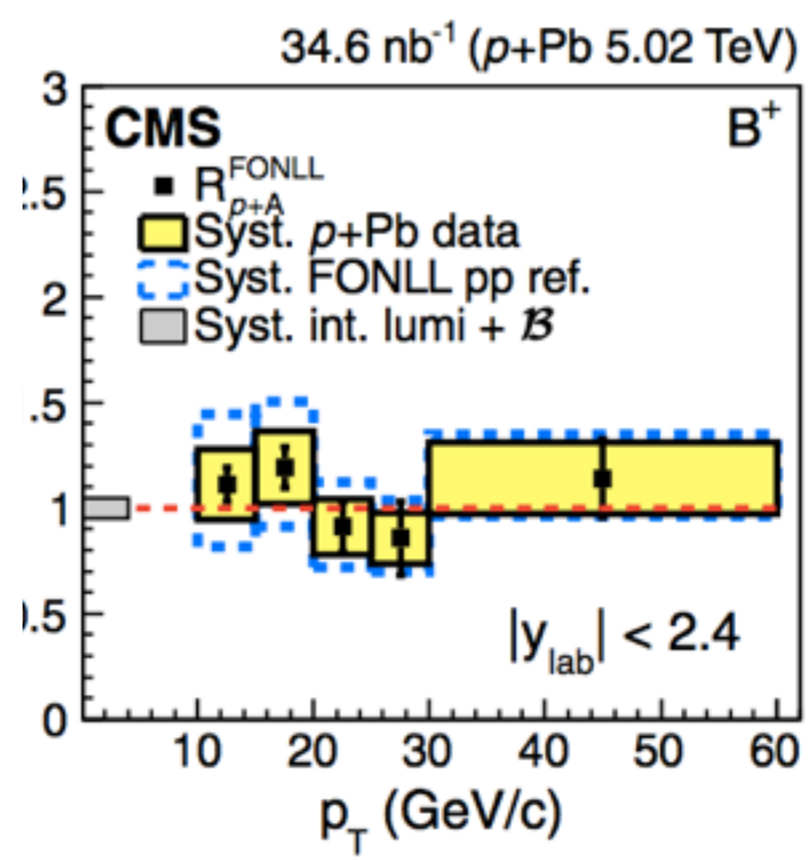
1. **b-jet $R_{AA}$** in PbPb
2. **J/ψ $R_{AA}$** in PbPb
3. **$D^0$ meson $R_{AA}$** in PbPb
4. **B meson $R_{pPb}$** in pPb

① ②
③ ④



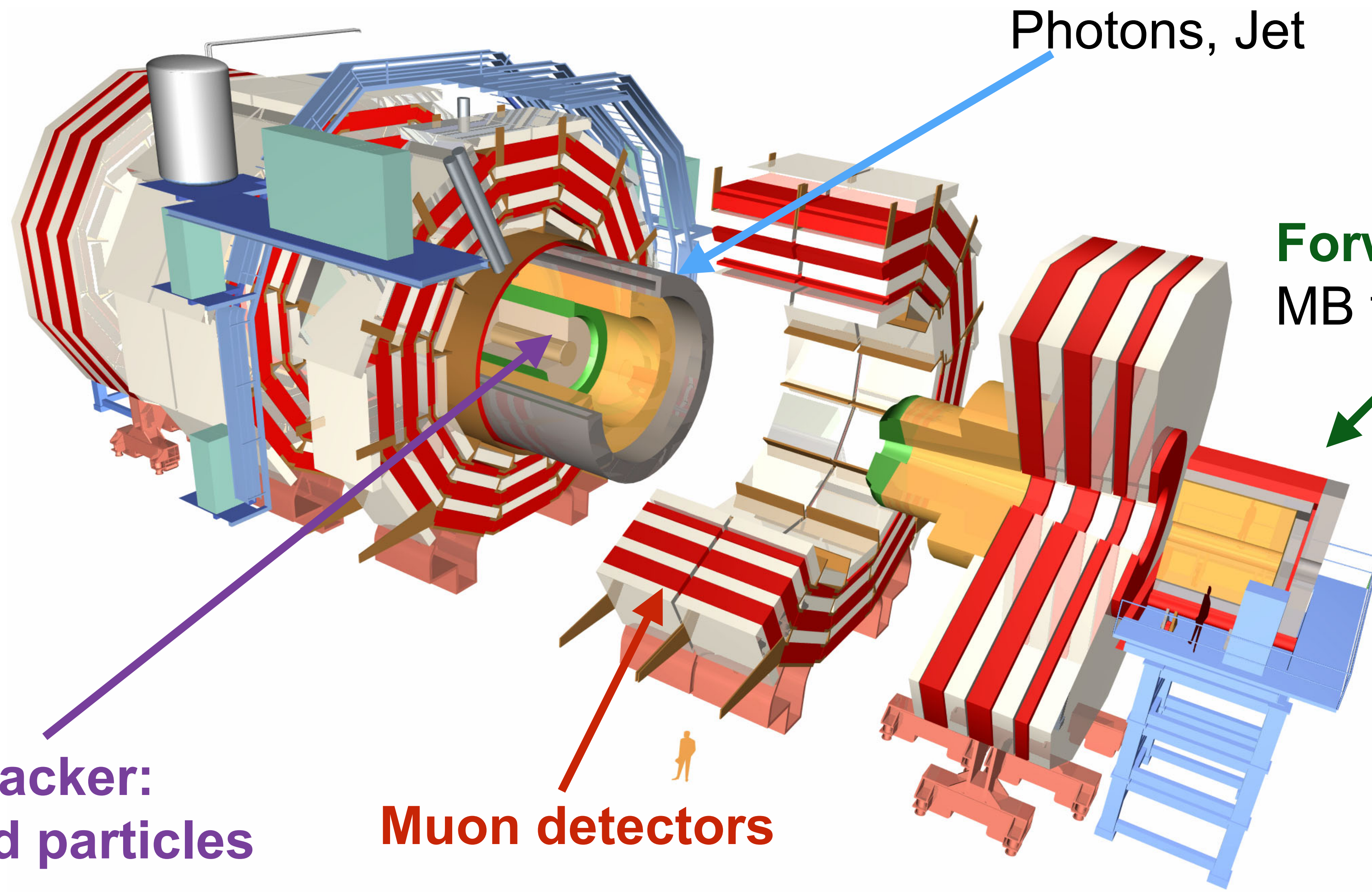




[1] Phys. Rev. Lett. **113,** 132301 (2014)
[2] CMS-PAS-HIN-12-014
[3] CMS-PAS-HIN-15-005
[4] Phys. Rev. Lett. **116,** 032301 (2016)

# CMS detector

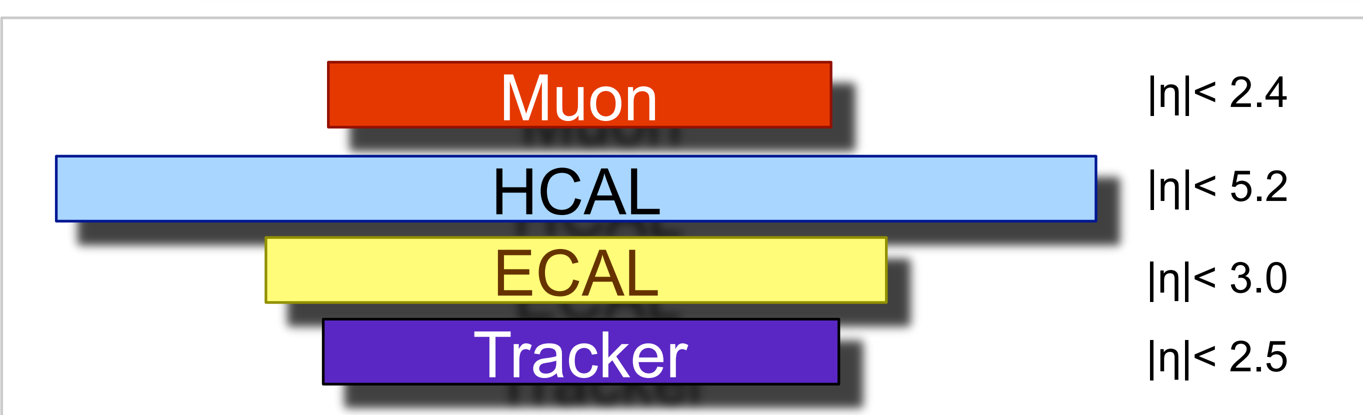
**EM and hadronic calorimeters**
Photons, Jet

**Forward Calorimeter:**
MB triggers, centrality



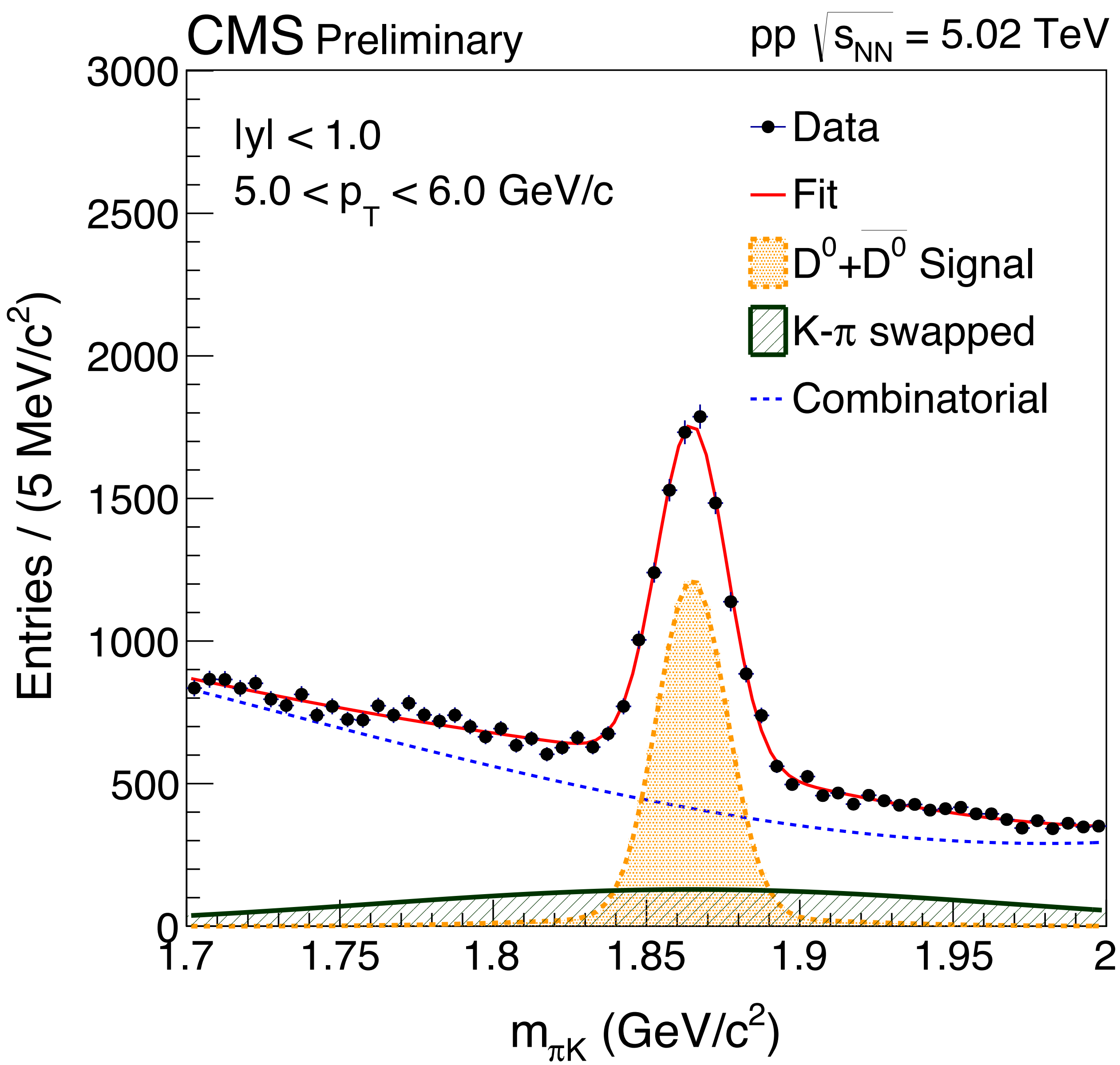
**Inner tracker:**
**charged particles**

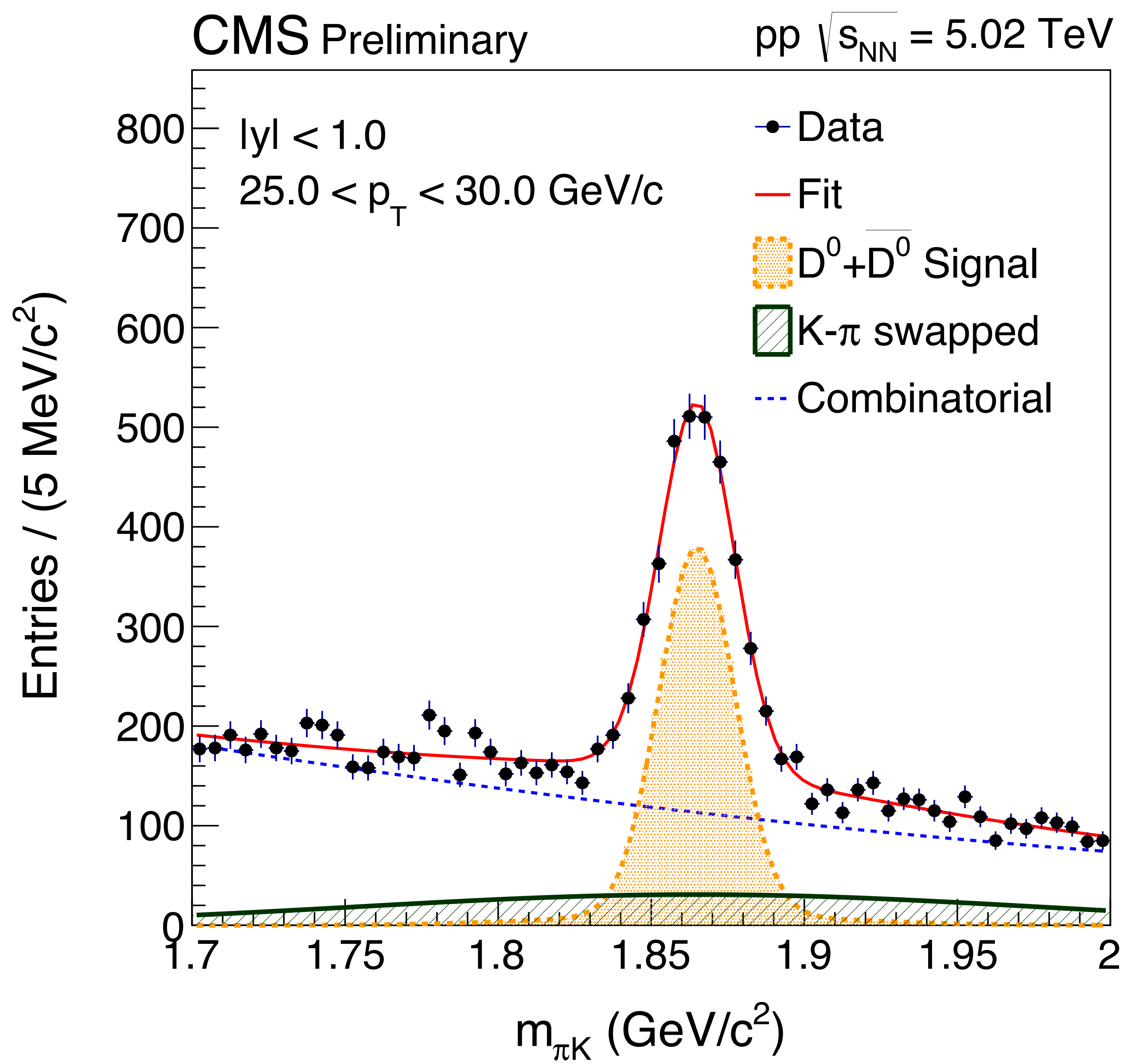
**Muon detectors**



# Mass spectra

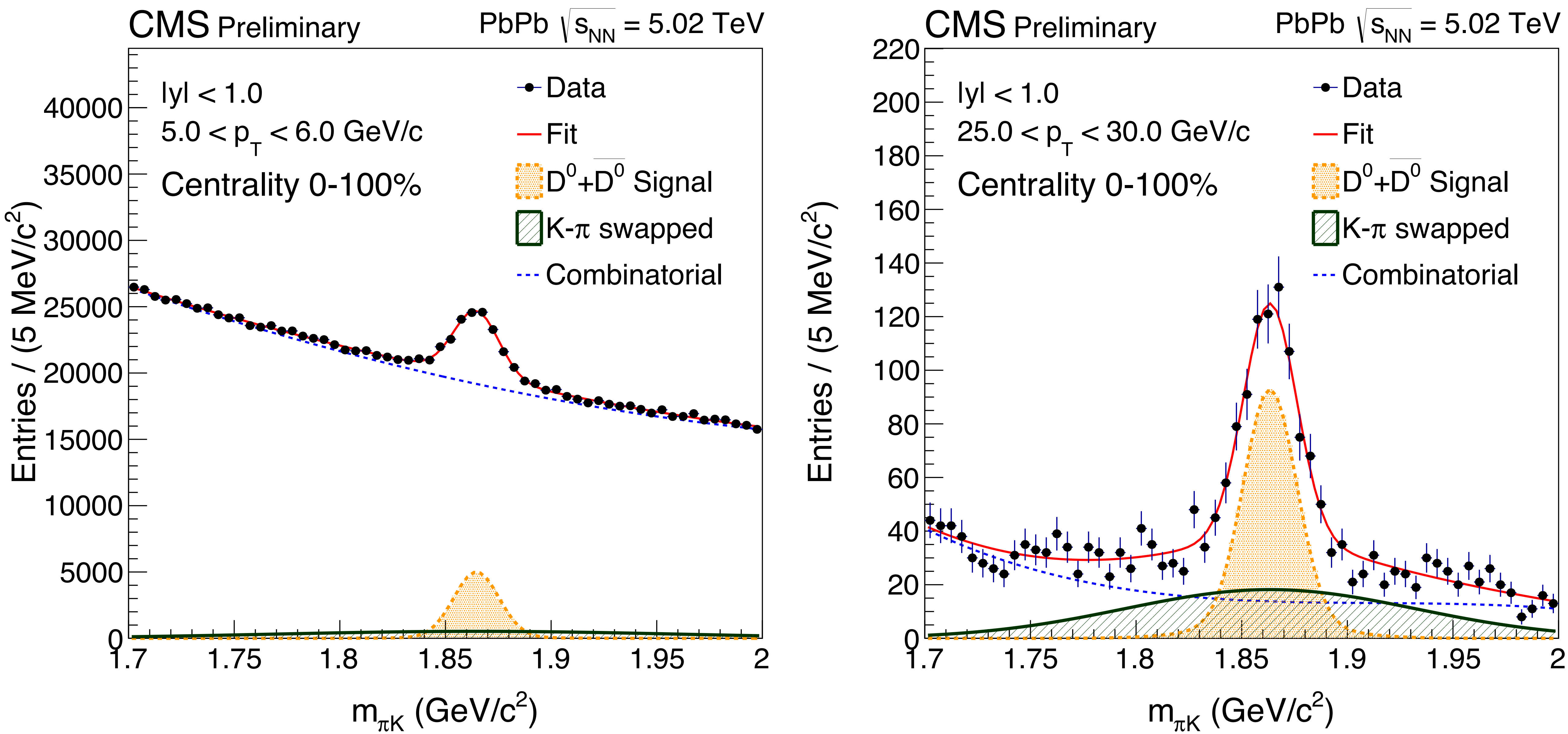
## pp



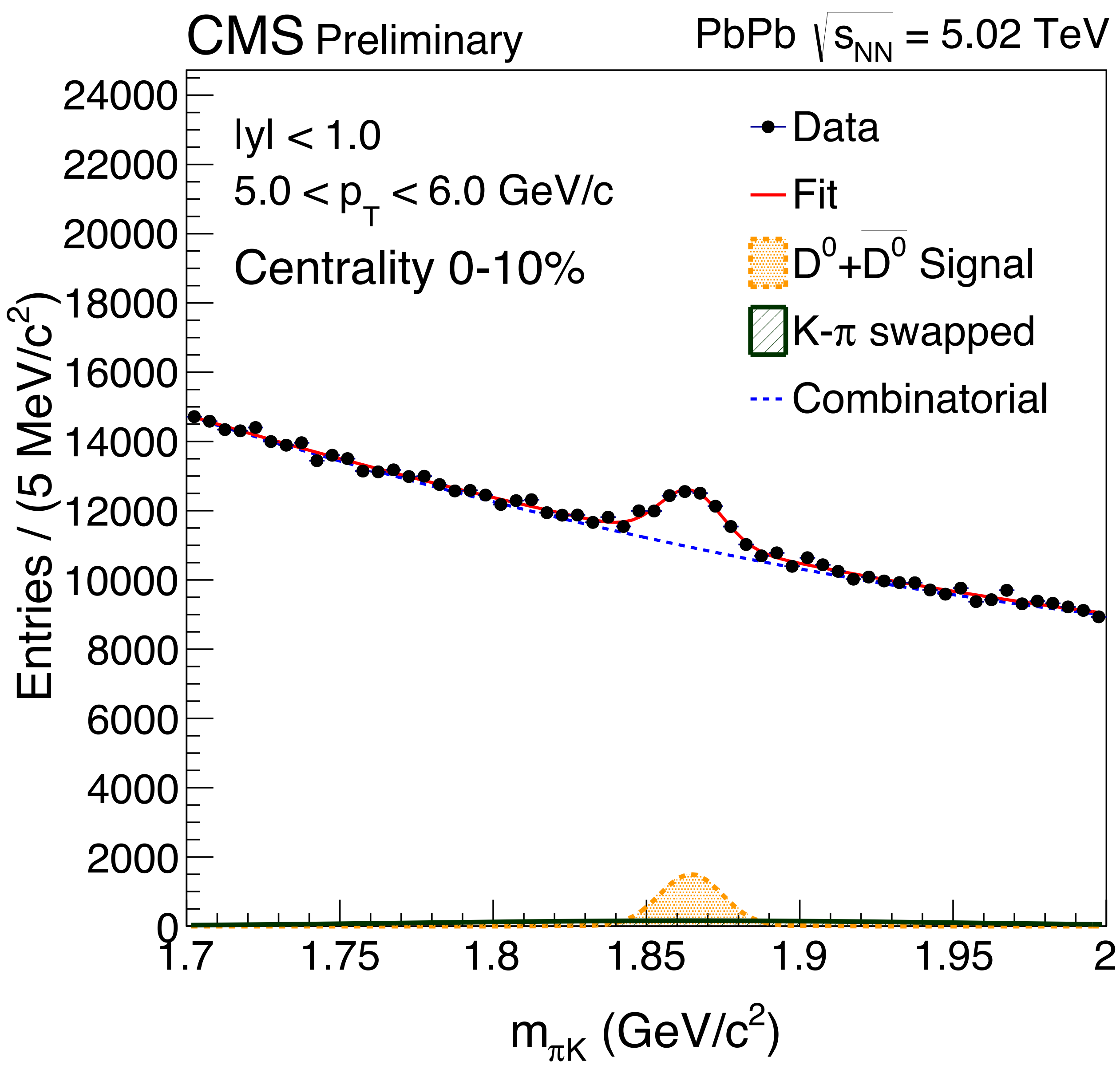



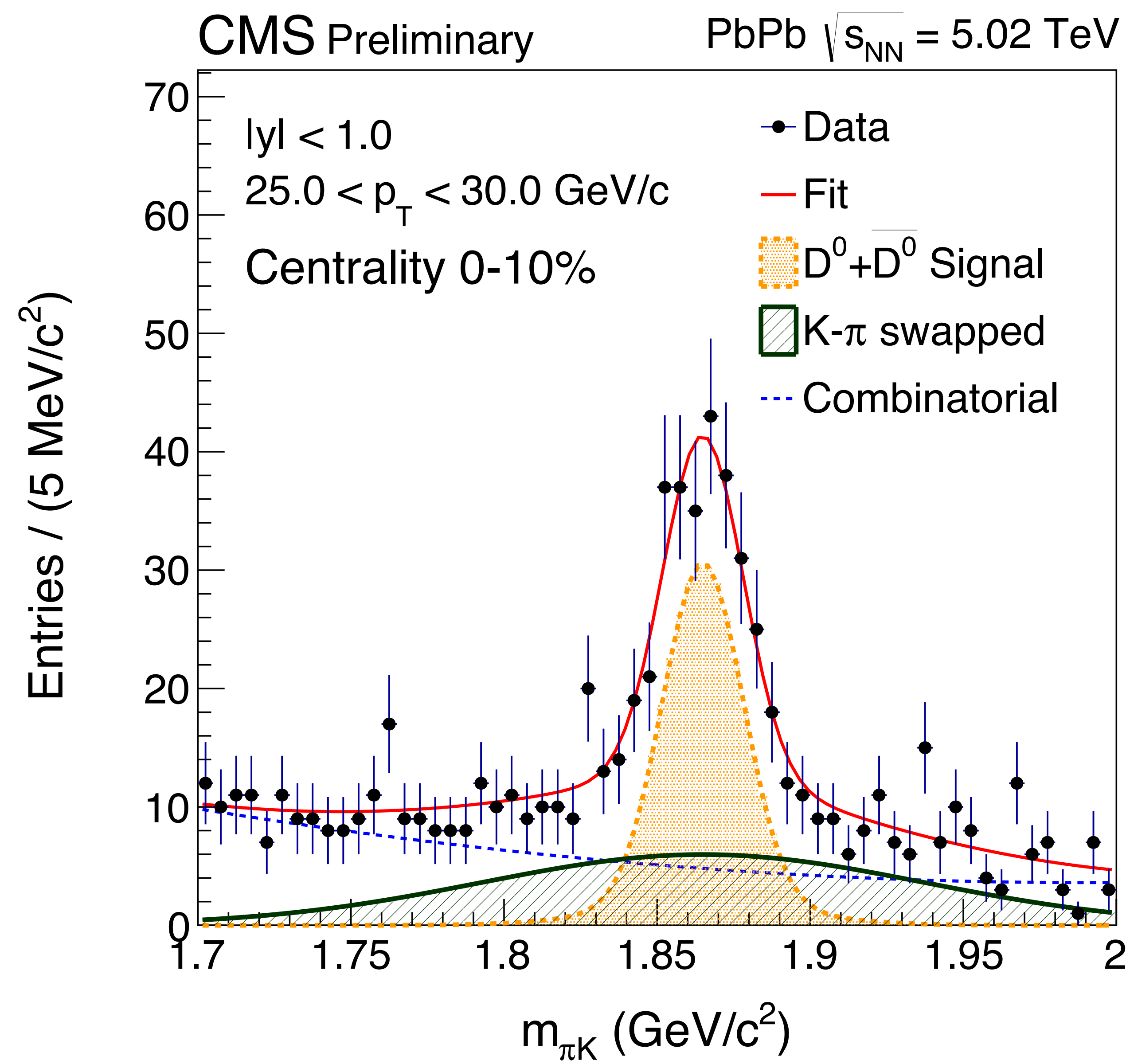
# Mass spectra

## PbPb 0-100%

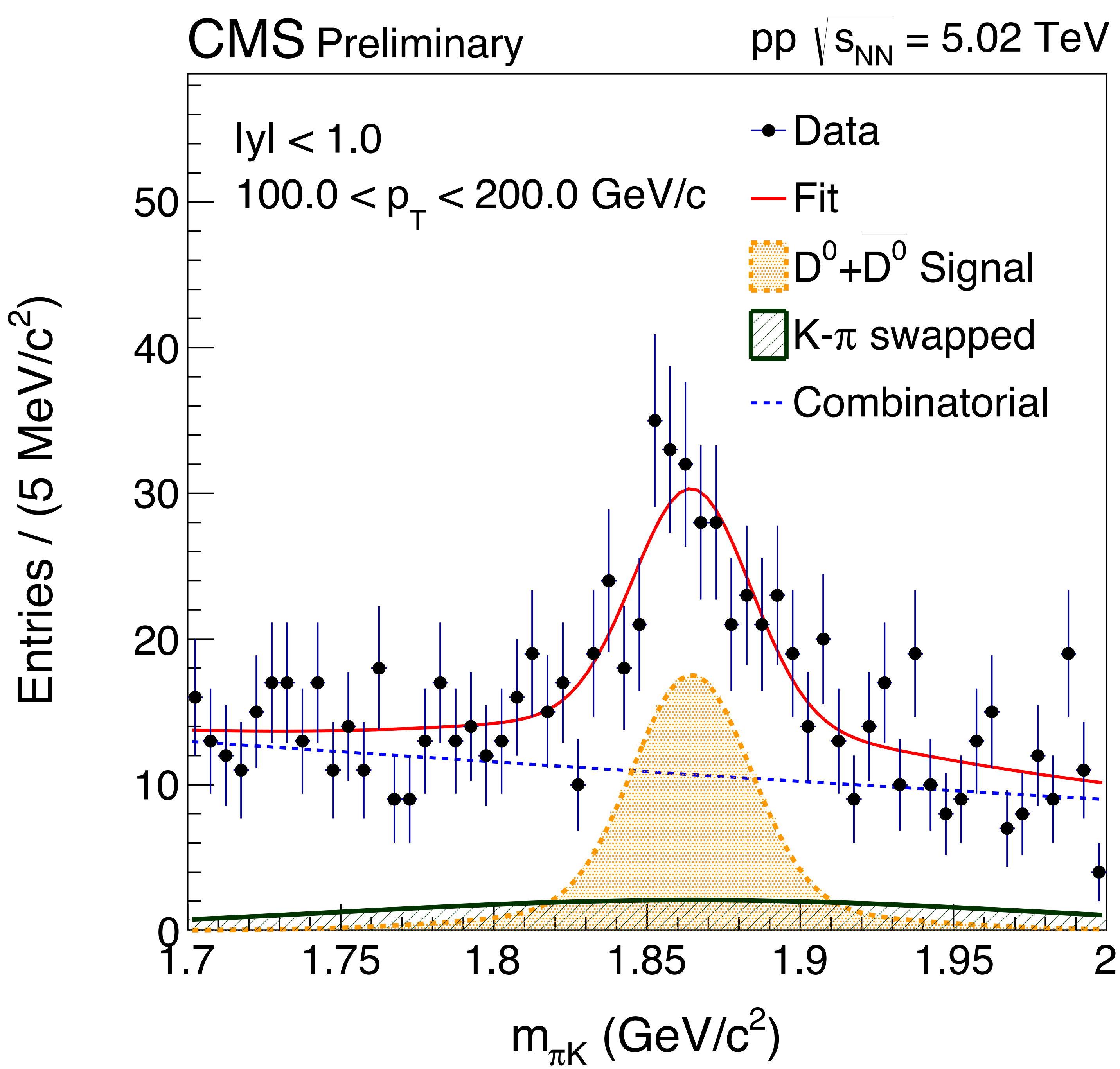


## PbPb 0-10%


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
|y| < 1.0
5.0 < $p_T$ < 6.0 GeV/c
Centrality 0-10%
Data
Fit
$D^0+\overline{D}^0$ Signal
K-π swapped
Combinatorial
Entries / (5 MeV/$c^2$)
$m_{\pi K}$ (GeV/$c^2$)


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
|y| < 1.0
25.0 < $p_T$ < 30.0 GeV/c
Centrality 0-10%
Data
Fit
$D^0+\overline{D}^0$ Signal
K-π swapped
Combinatorial
Entries / (5 MeV/$c^2$)
$m_{\pi K}$ (GeV/$c^2$)

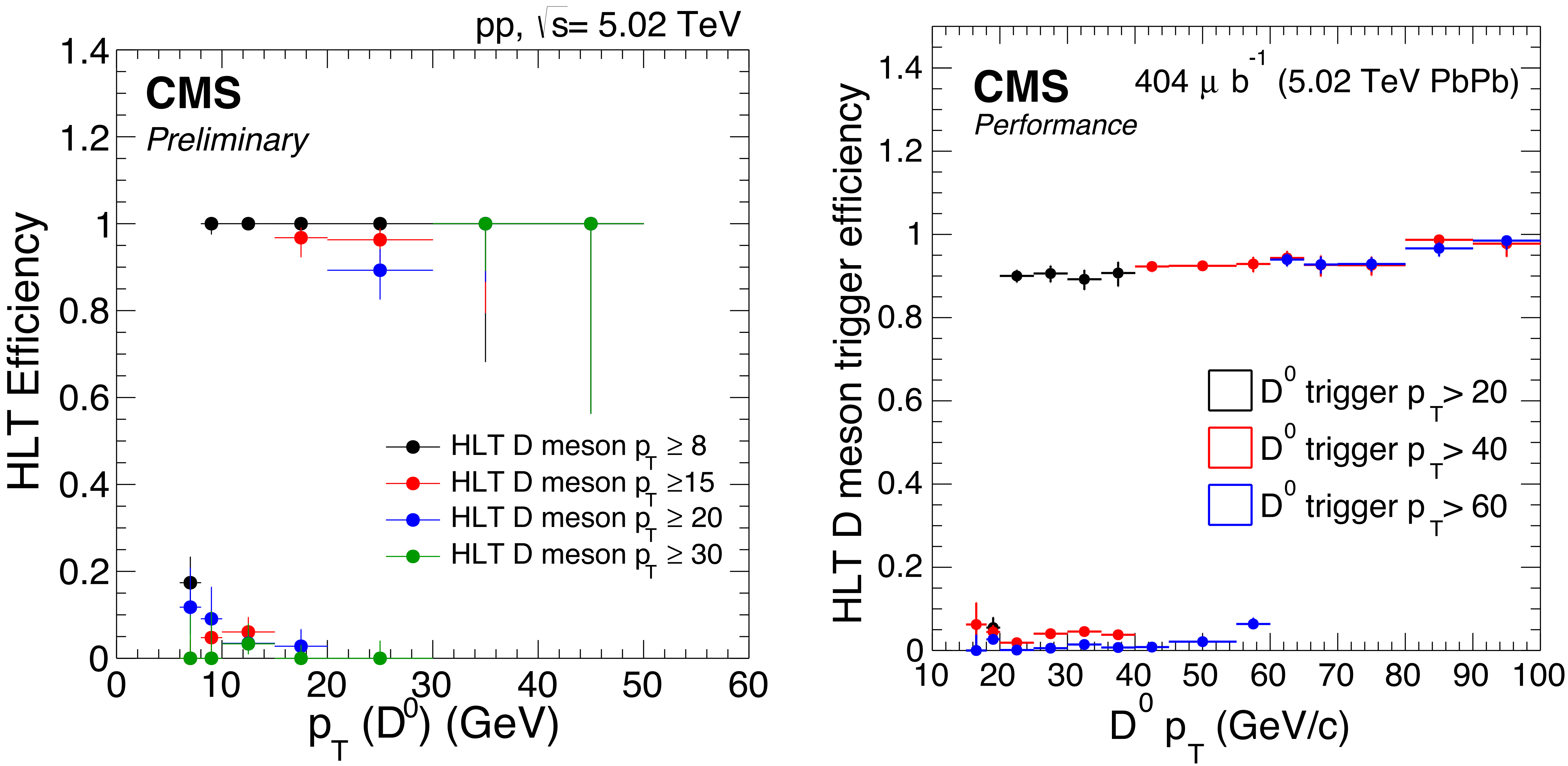
# High-Level-Trigger (HLT) $D^0$ triggers




- 5.02 TeV pp collisions
- Extend to $D^0$ high pT to 200 GeV/c

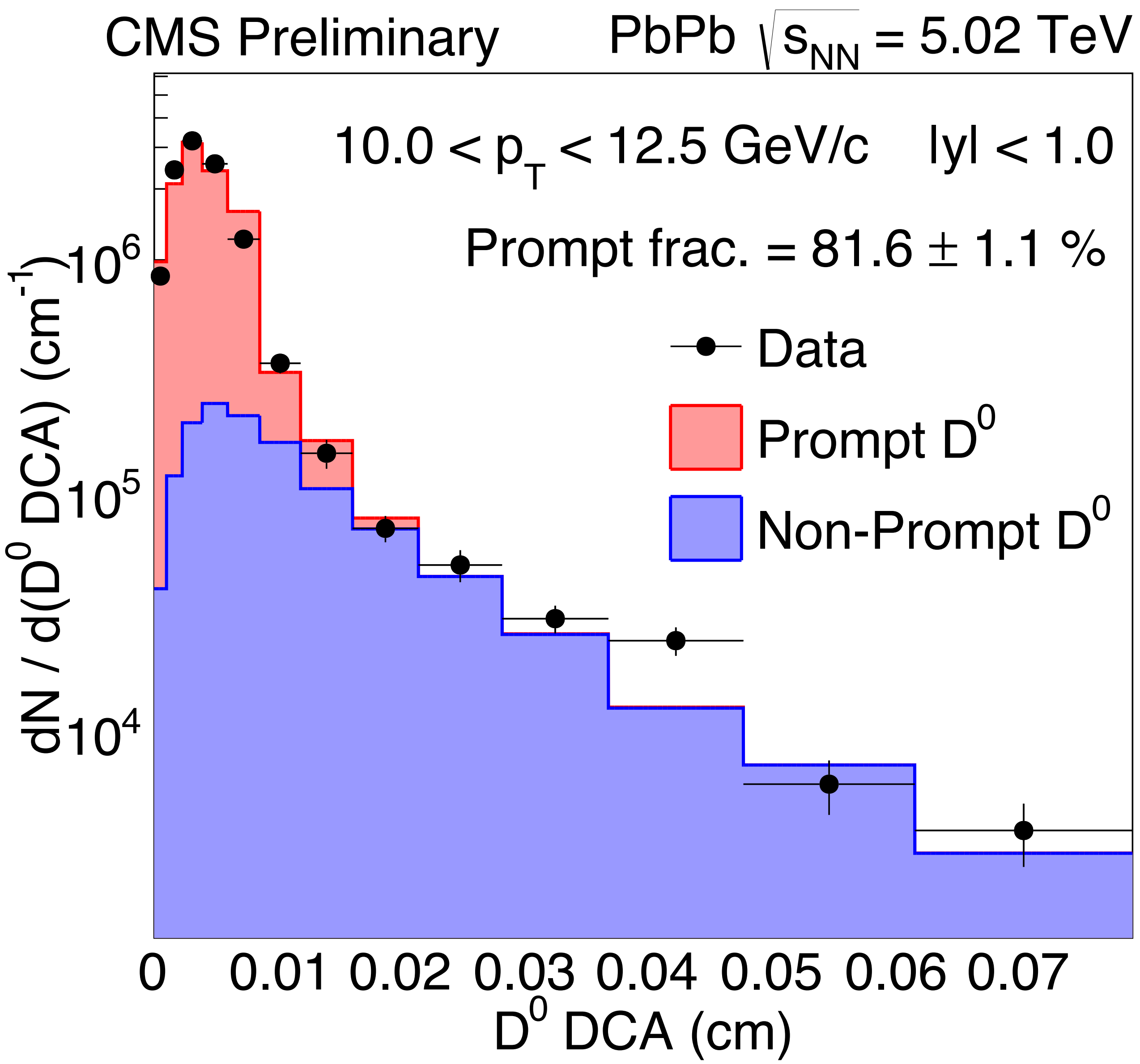
# High-Level-Trigger (HLT) $D^0$ triggers

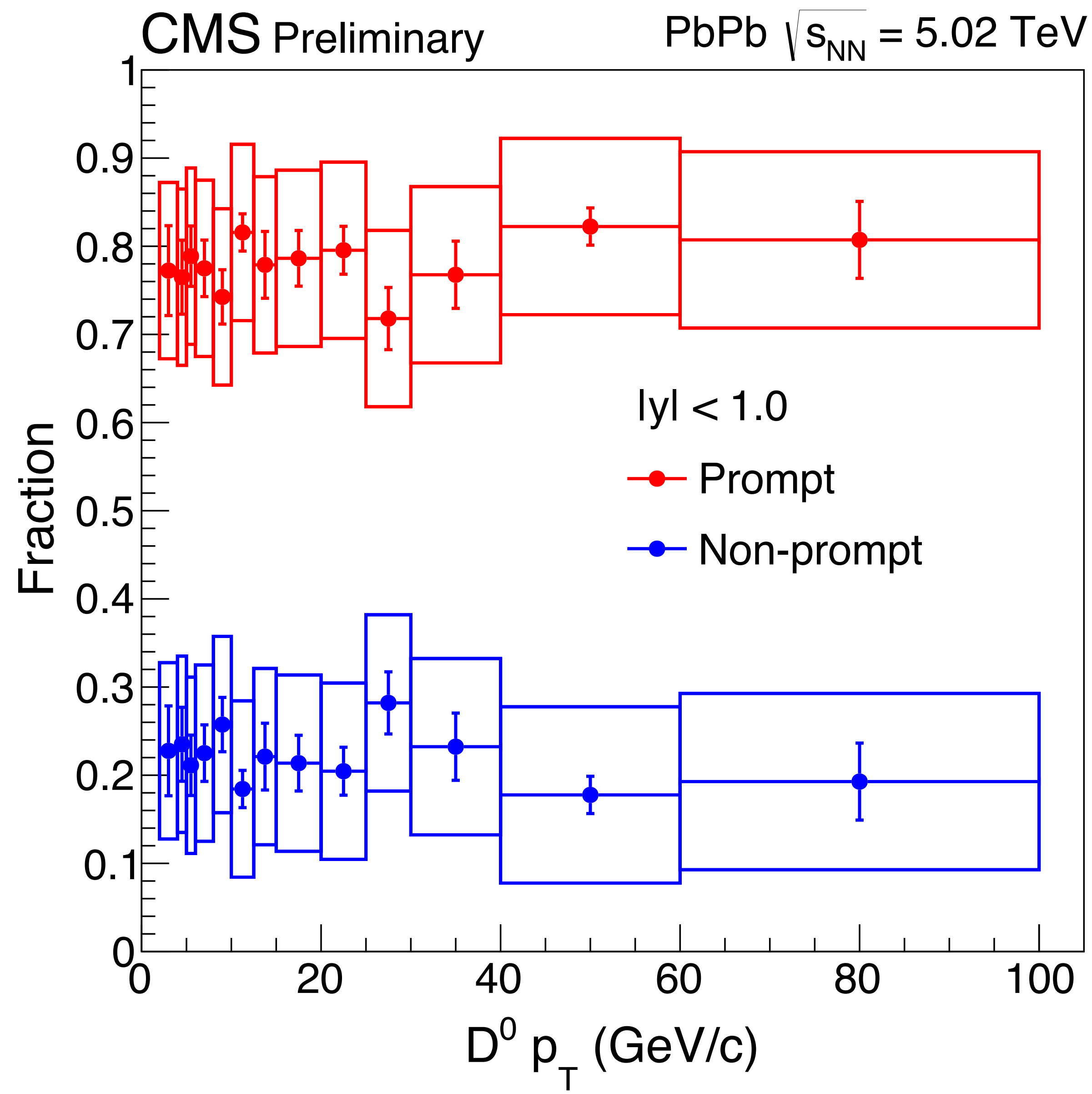
## Triggers performance



# $f_{prompt}$: Fraction of prompt $D^0$

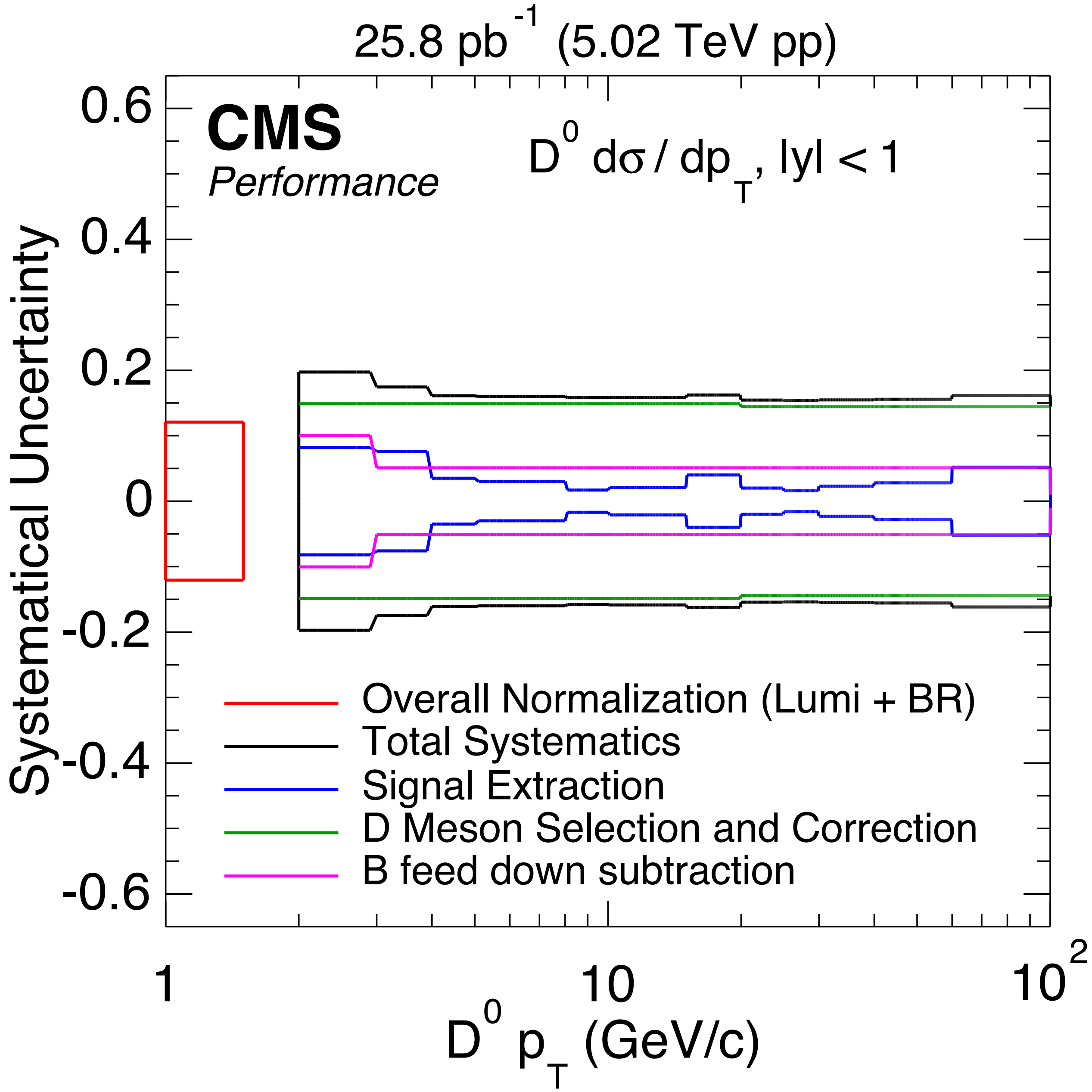
## PbPb



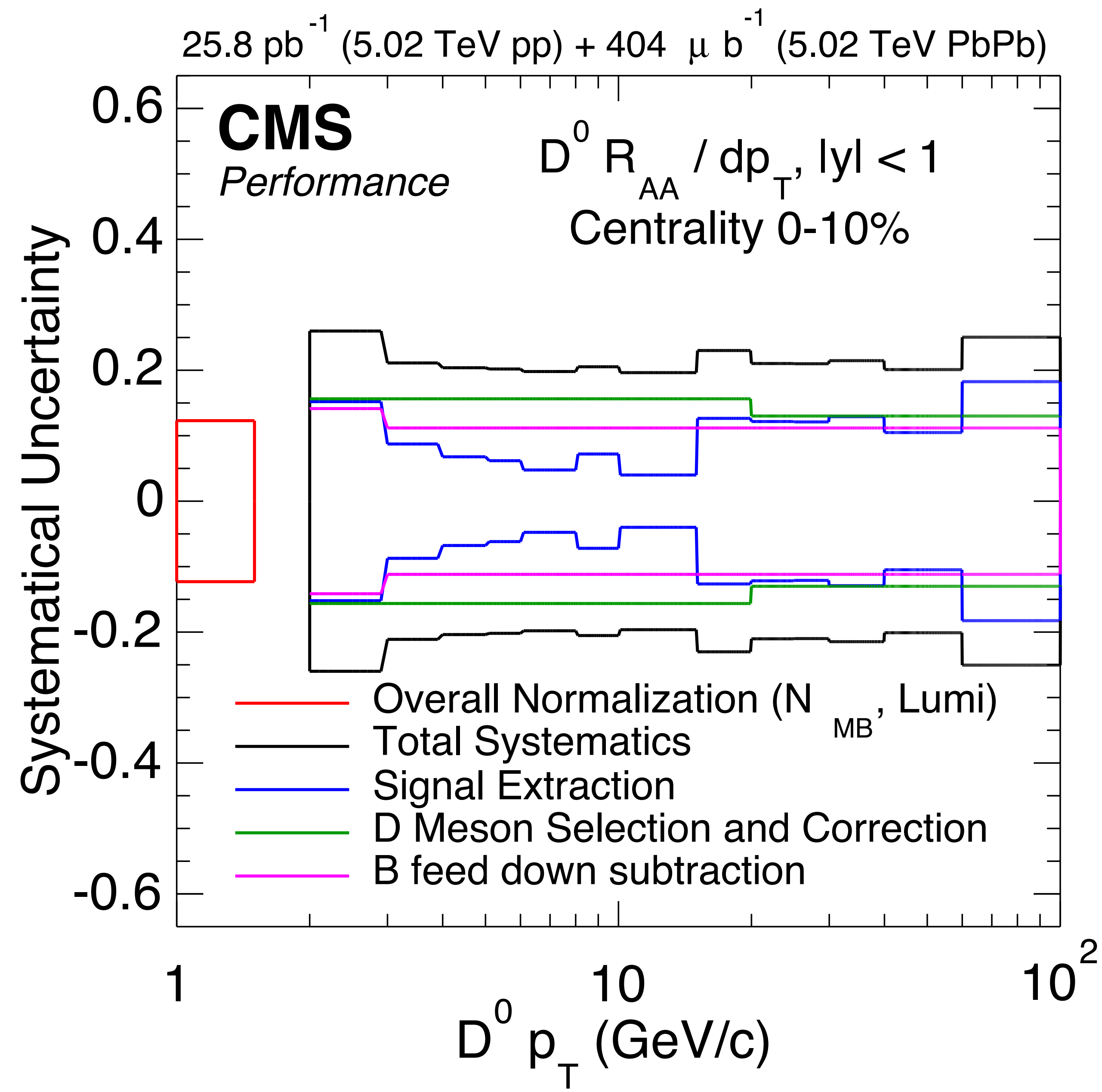



# Systematics

## pp

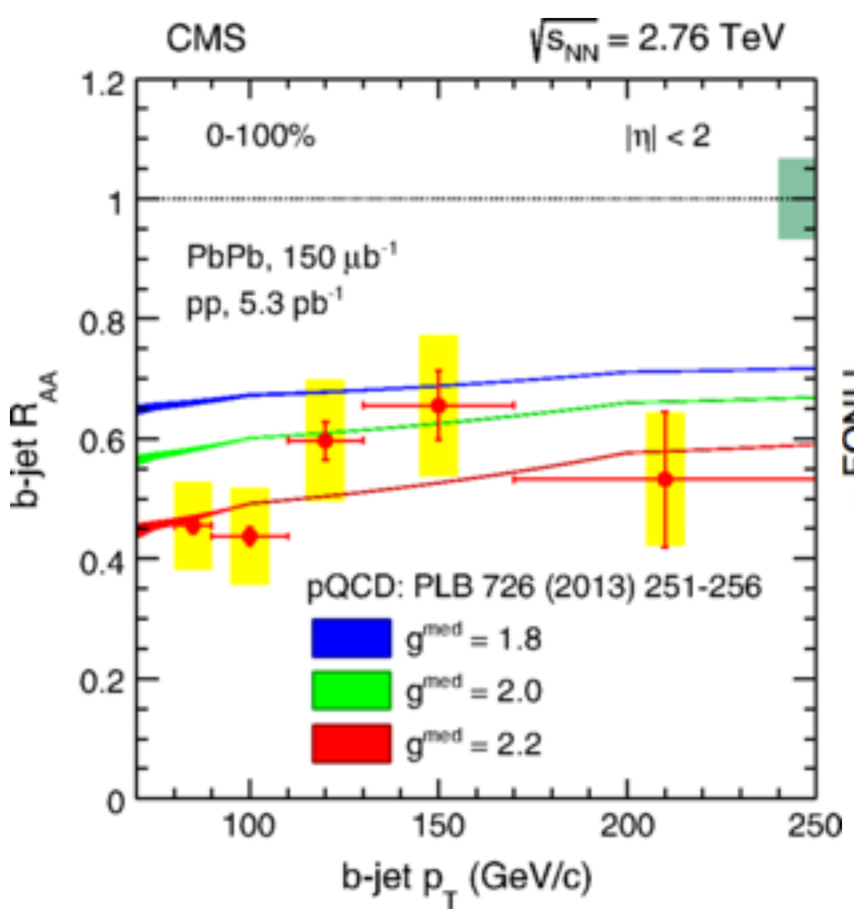



## PbPb 0-10%

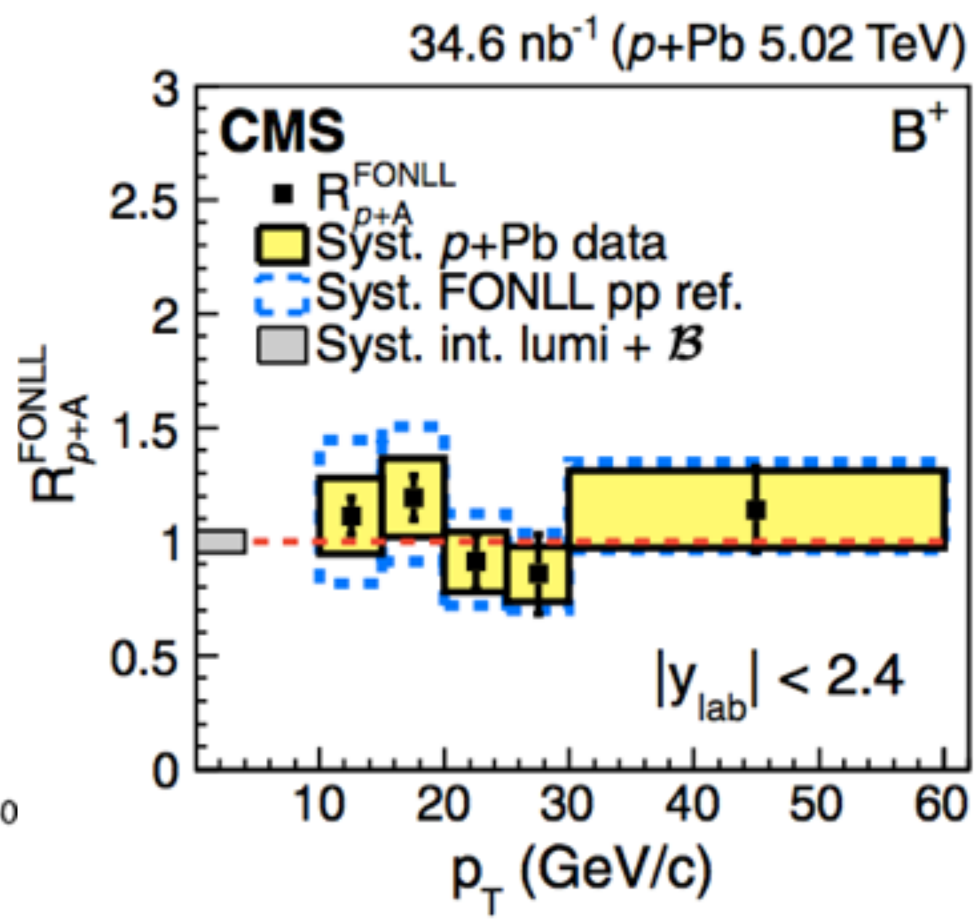


## LHC Run I (2.76 PbPb + 5.02 pPb)

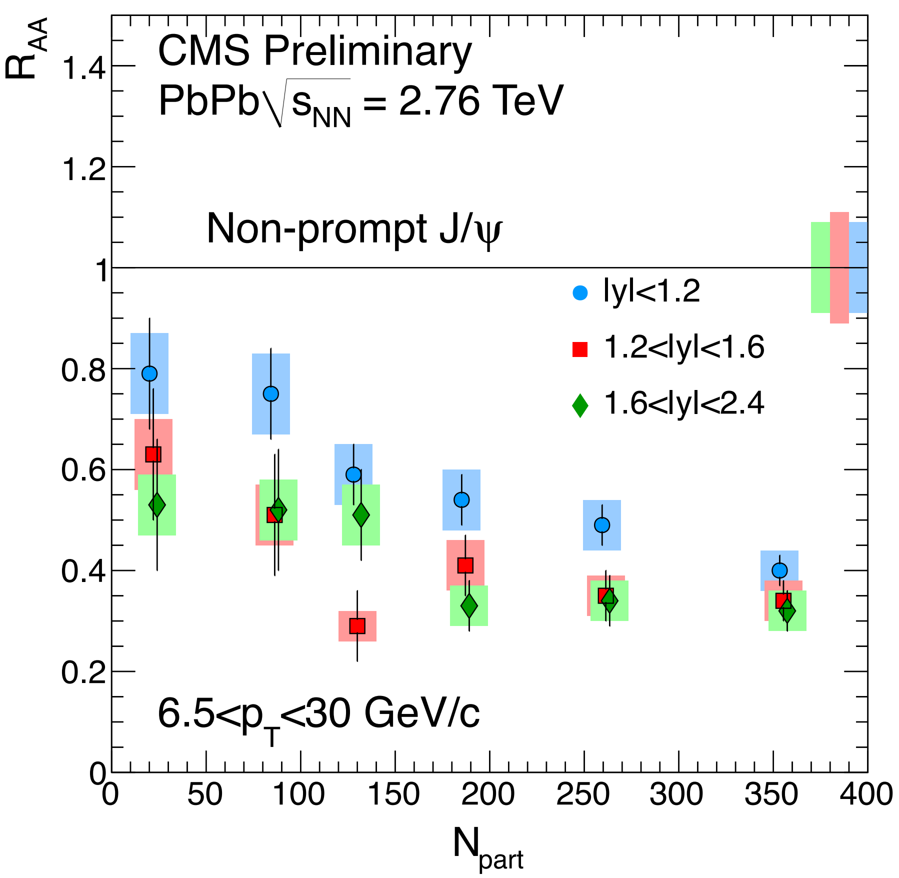
| b-jet $R_{AA}$ in PbPb | B meson $R_{pPb}$ in pPb | J/ψ $R_{AA}$ in PbPb |
|---|---|---|




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




Phys. Rev. Lett. **116,** 032301 (2016)




CMS-PAS-HIN-12-014