D meson nuclear modification factor and azimuthal anisotropy in PbPb at 5.02 TeV with CMS

Jing Wang on behalf of the CMS Collaboration

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Puebla (Mexico)

Why study heavy flavors in HI?

Heavy quarks are good probe of QGP!

- Produced mainly via initial hard scatterings (m_c, m_b >> T_{QGP})
  - ➡ Experience the whole evolution of the medium
- Production cross section calculable with pQCD (m_c, m_b >> Λ_{QCD})
- Strongly interact with the deconfined medium

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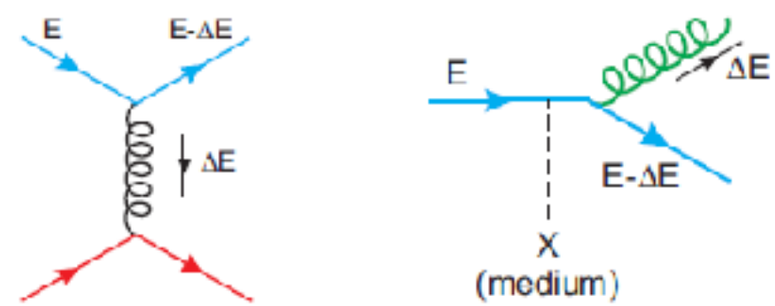
What information can we get?

- ✦ Energy loss in the medium
  - Pictures
    - pQCD: Collisional + Radiative
    - AdS/CFT: drag force
  - Depends on (pQCD)
    - color charge and quark mass (dead cone effect [1])
      - ➡ $\Delta E_g > \Delta E_c > \Delta E_b$
    - medium density and path length



[1] Phys. Lett. B 519 (2001) 199

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      - ➡ $\Delta E_g > \Delta E_c > \Delta E_b$
      - ➡ $R^{light}_{AA} < R^{D}_{AA} < R^{B}_{AA}$
    - medium density and path length
- ✦ Collective flow
  - measurement of the interaction strength

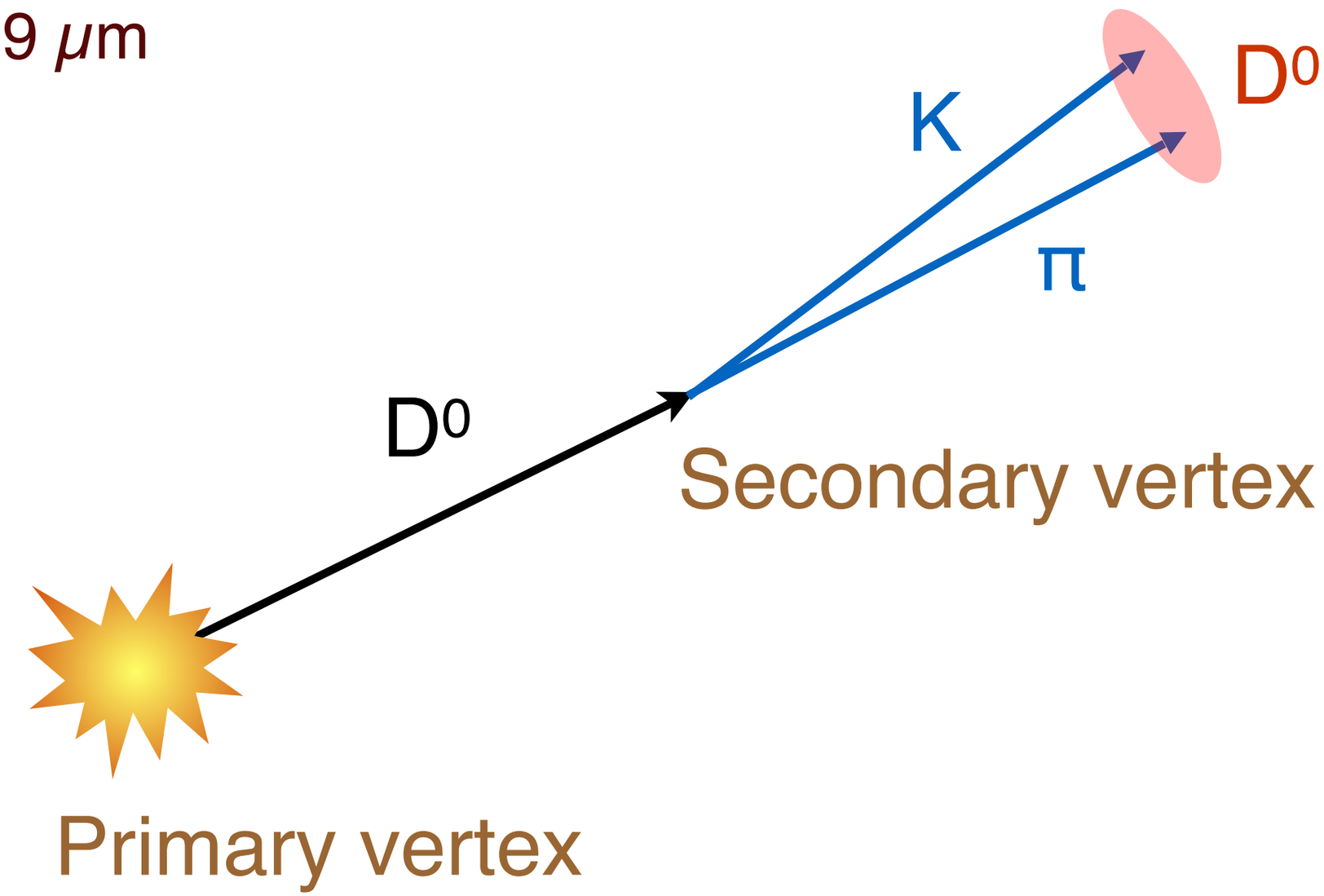
Nuclear modification factor (R_{AA})

Azimuthal anisotropy (v_n)

[1] Phys. Lett. B 519 (2001) 199

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 μm

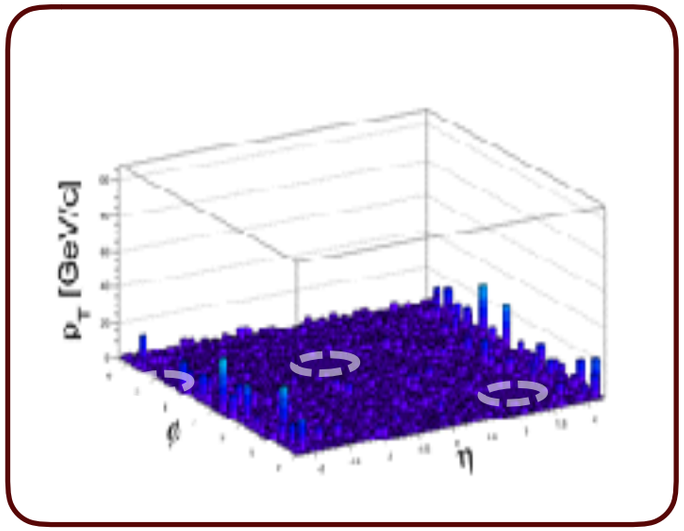


D^0 measurements in pp and PbPb

Datasets

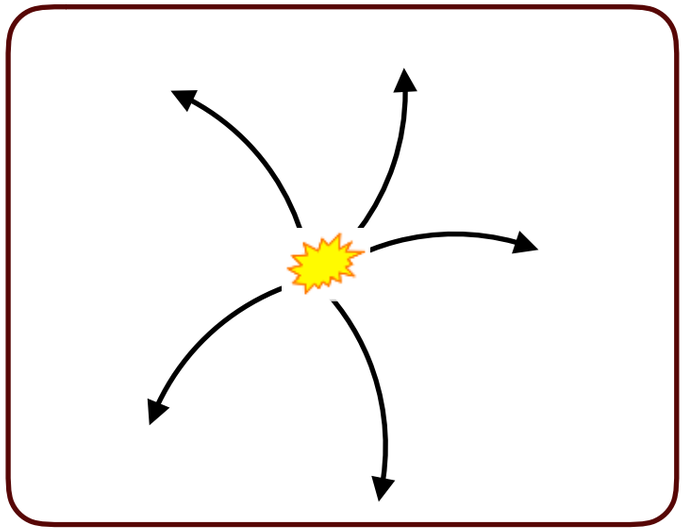
- LHC Run II at 5.02 TeV in 2015
- Large minbias and centrality triggered samples
- Dedicated *HLT D^0 filters* to enhance the statistics at very high p_T

Hardware L1 jet triggers selection



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

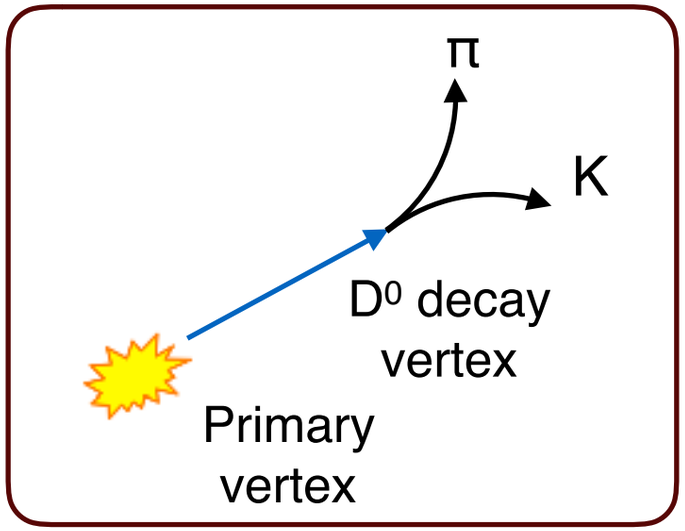
Track selection in software triggers



Track seed p_T cut applied:

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

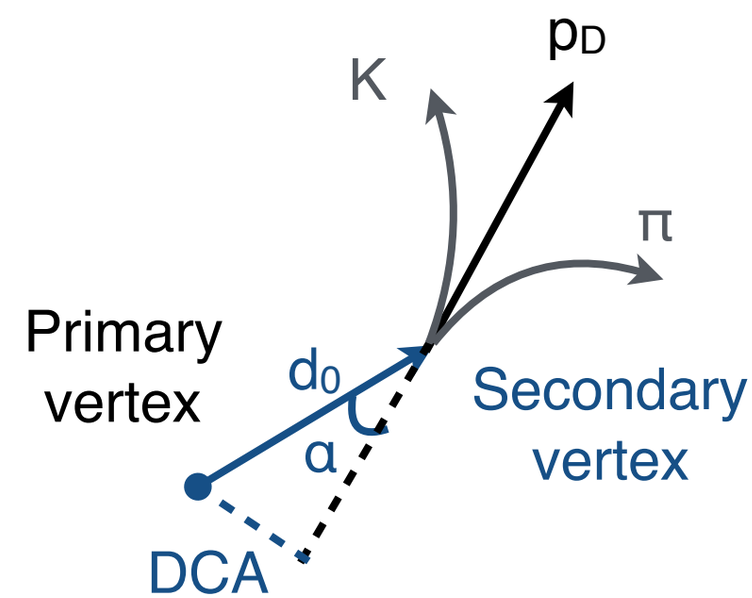
D^0 selection



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

D^0 reconstruction

- Primary vertex reconstruction *several tracks*
- D^0 candidates (vertex) reconstruction *pairing two tracks + kinematic fitter*
- D^0 candidates selection (TMVA) *decay topology*
  - ➡ Pointing angle (α) *< ~0.12*
  - ➡ 3D decay length (d_0) normalized by its error *> ~4*
  - ➡ Secondary vertex probability *> ~0.1*
  - ➡ Distance of Closest Approach (DCA) *< ~0.008 cm*



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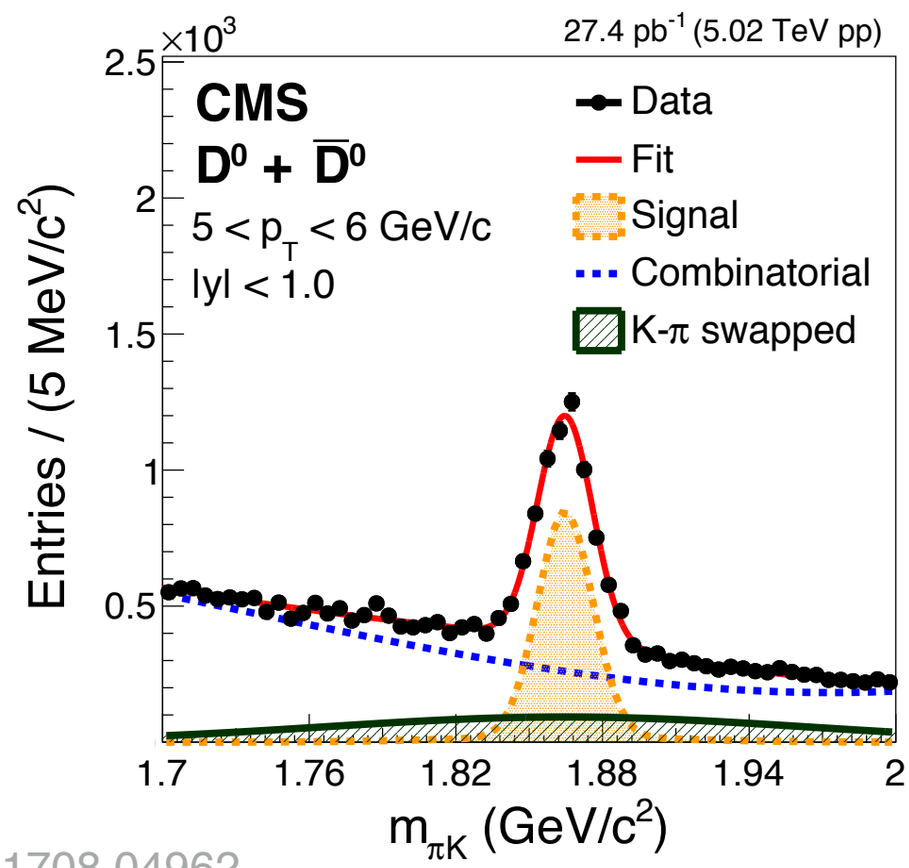
- Raw yields extraction *Invariant mass*



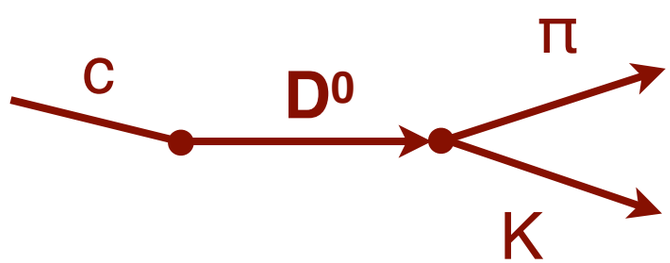
arXiv: 1708.04962

Mass distributions fitted by

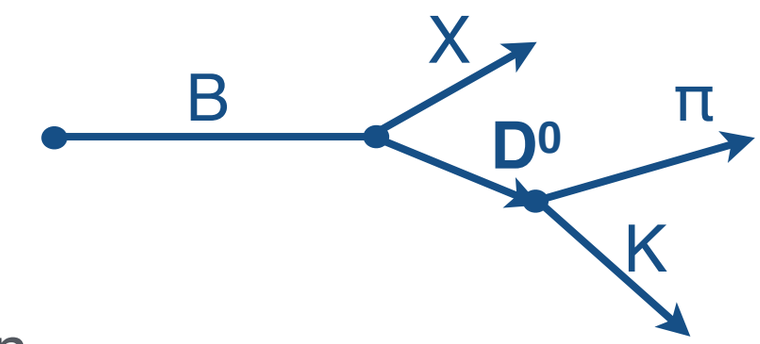
- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-π swapped)
  - No PID: Candidates with wrong mass assignment

Extraction of prompt fraction with data

Prompt:

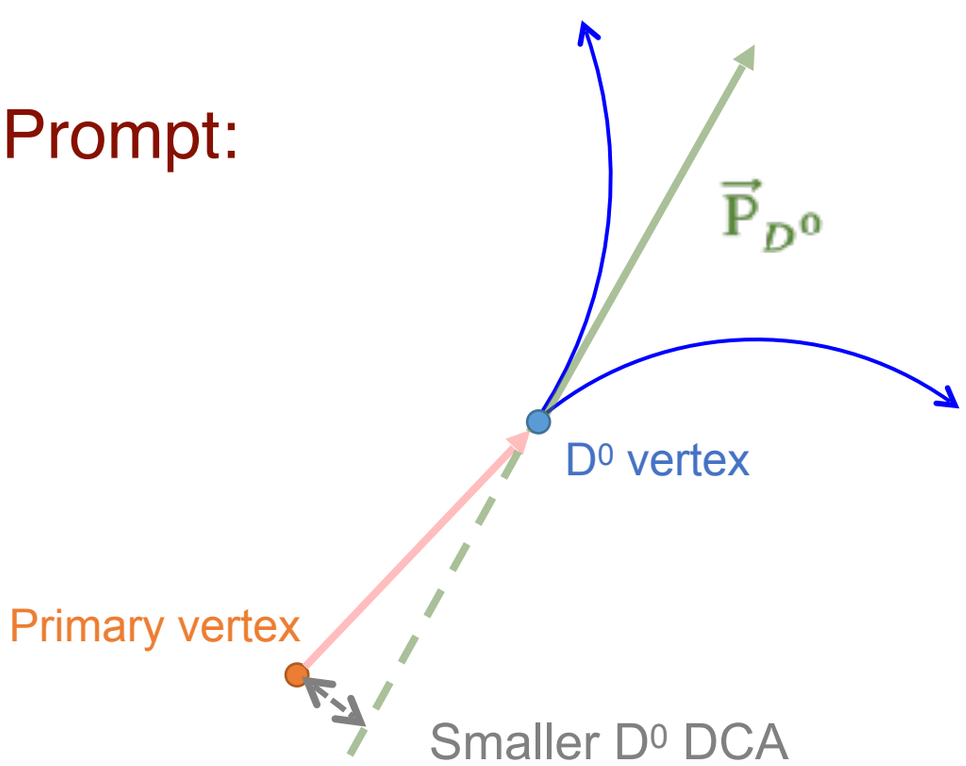


Non-prompt:



- Prompt: D^0 mesons coming from c-quark fragmentation
- Extract prompt fraction with data (new method!)
- Different shapes of ***DCA*** distributions of prompt and non-prompt D^0

Prompt:



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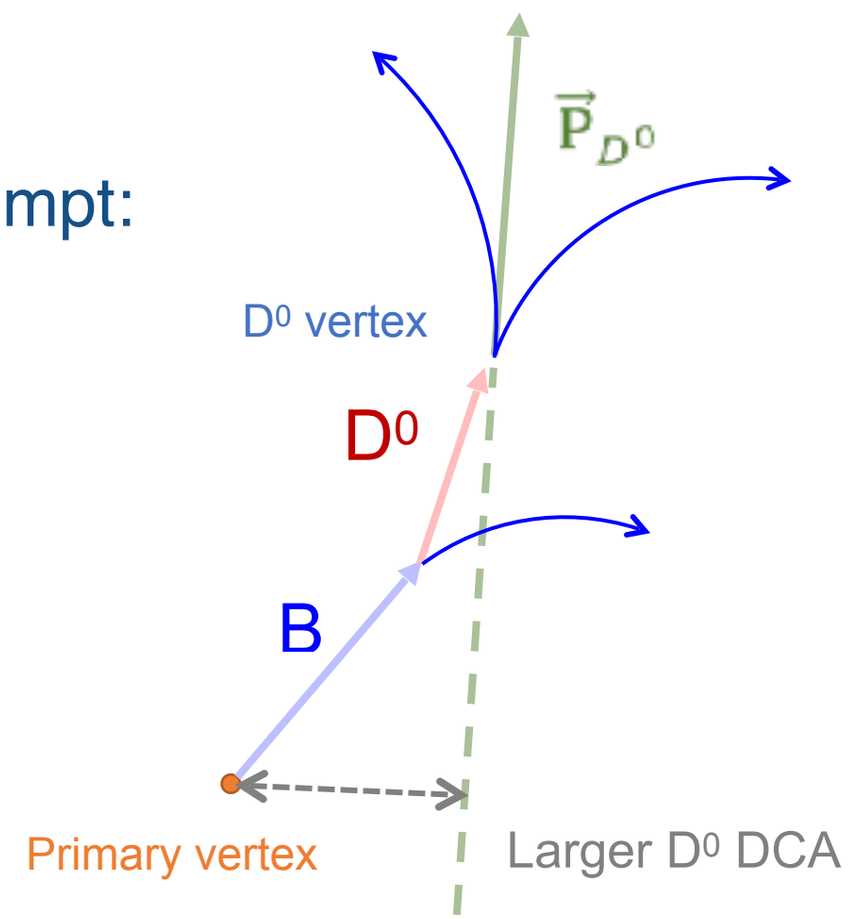

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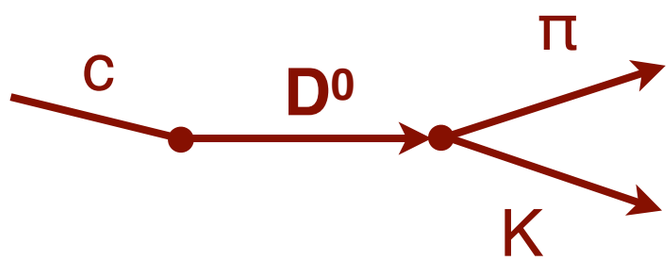

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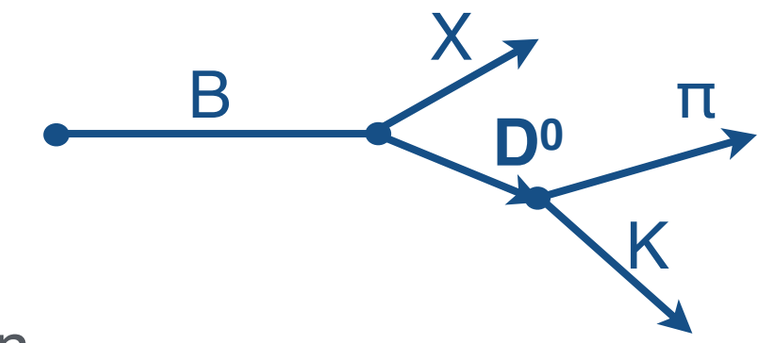

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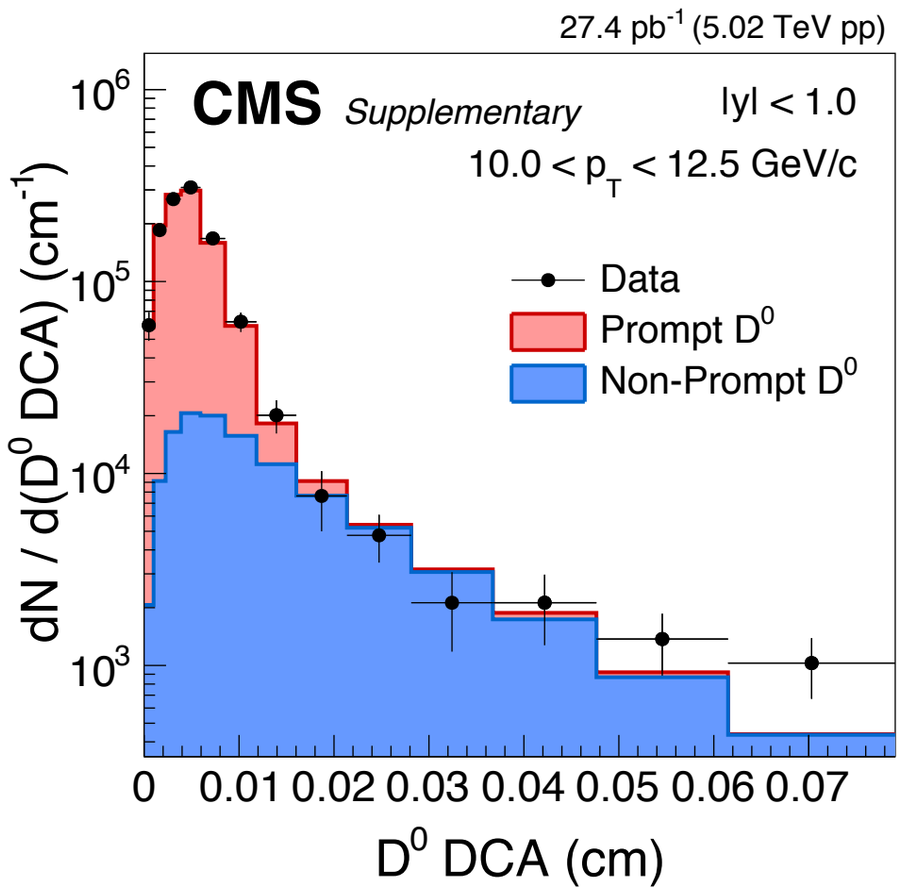
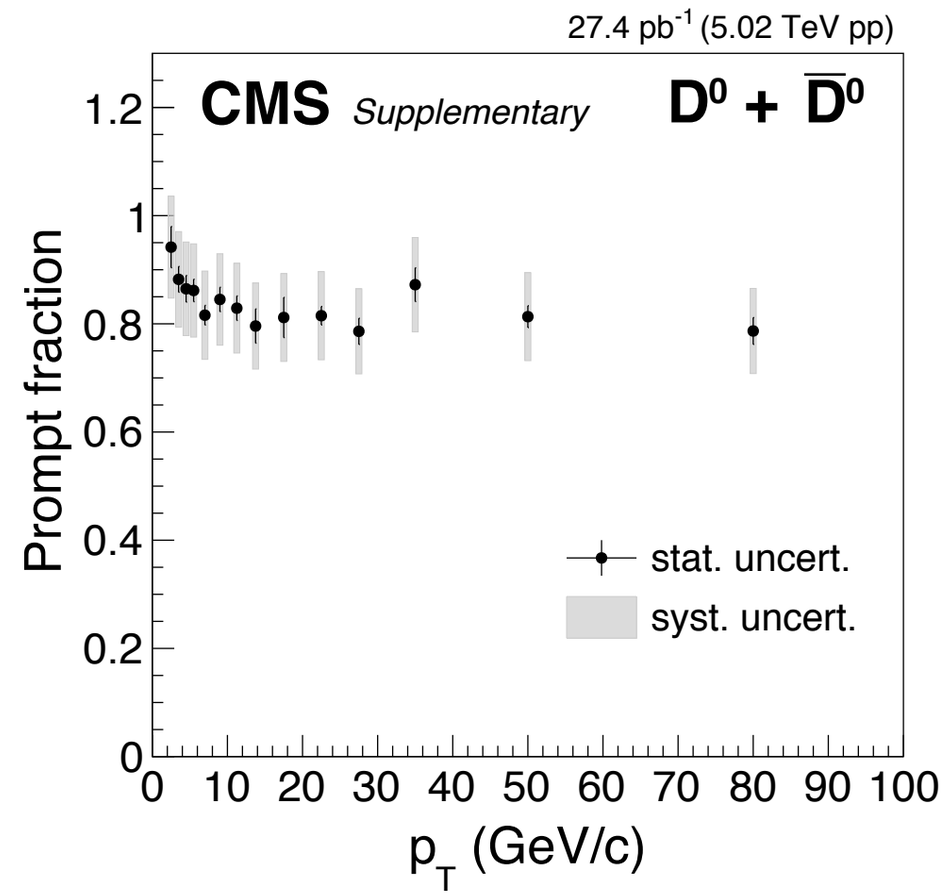
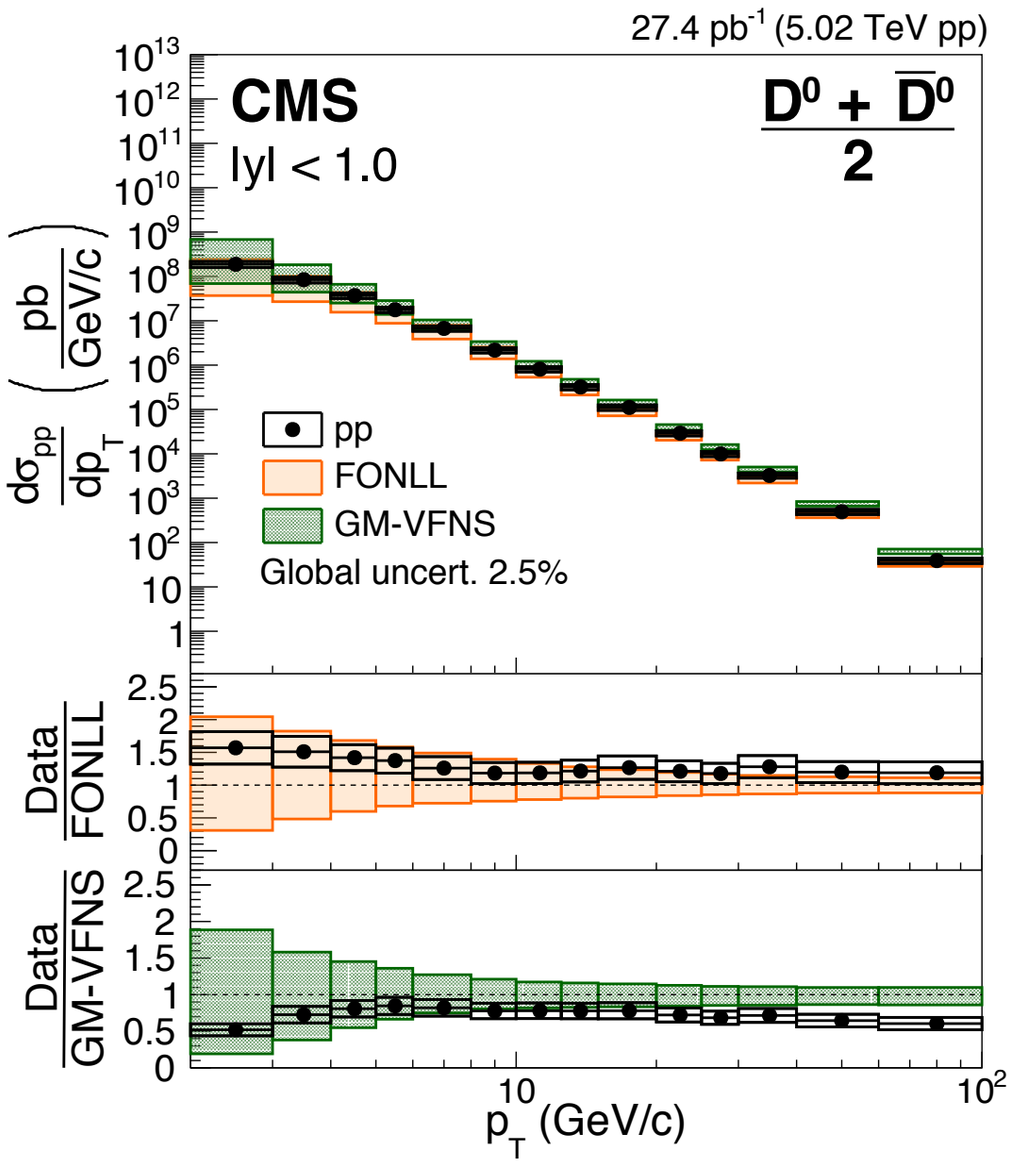
- Extract prompt fraction with data (new method!)
- Different shapes of ***DCA*** distributions of prompt and non-prompt D^0
- The shapes of the template of DCA distributions from MC

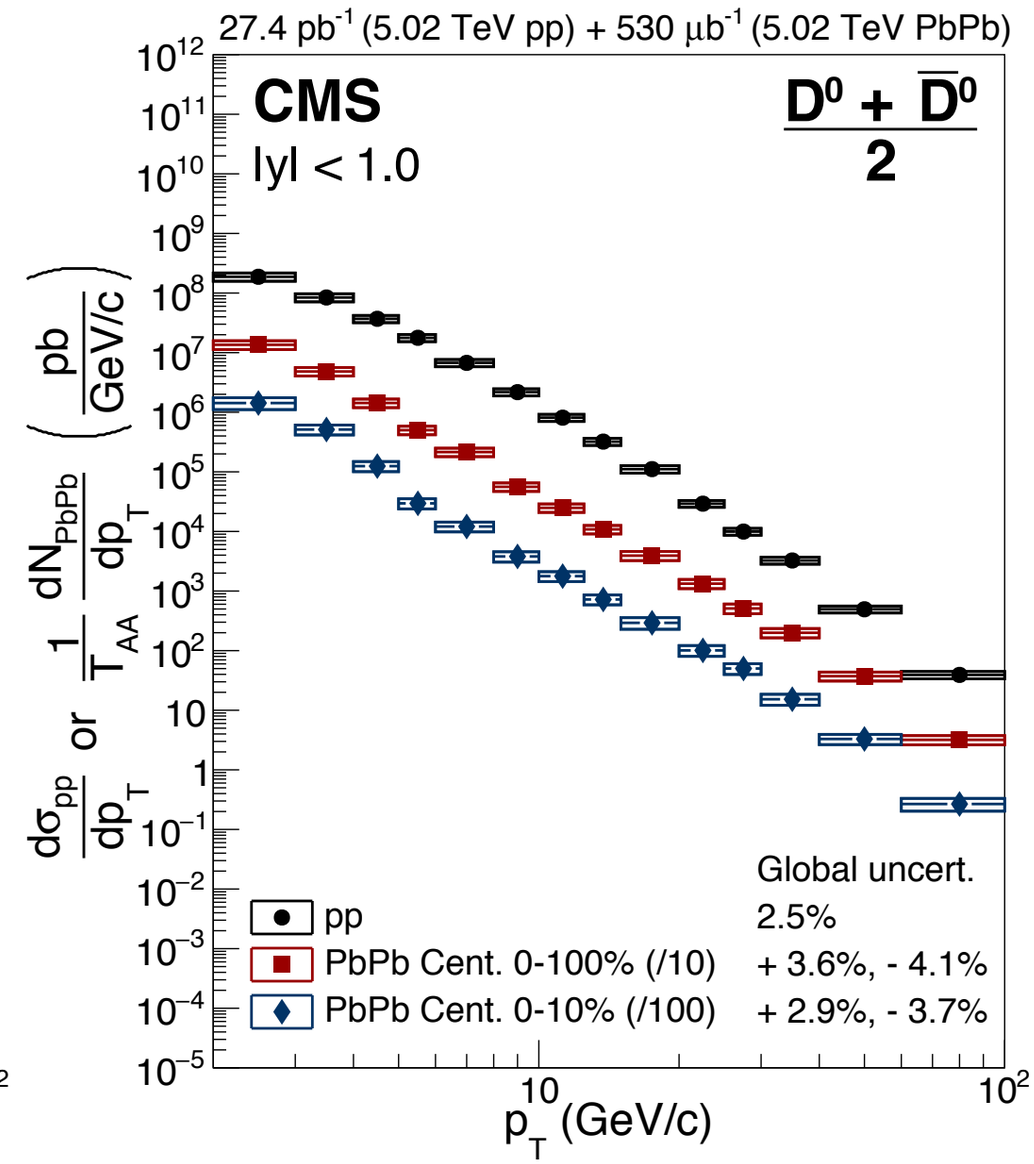




Prompt D^0 p_T-differential cross-section

- p_T range covers from ***2 to 100 GeV/c*** (wide p_T range!)
- Compared with the FONLL [1] and GM-VFNS [2] predictions



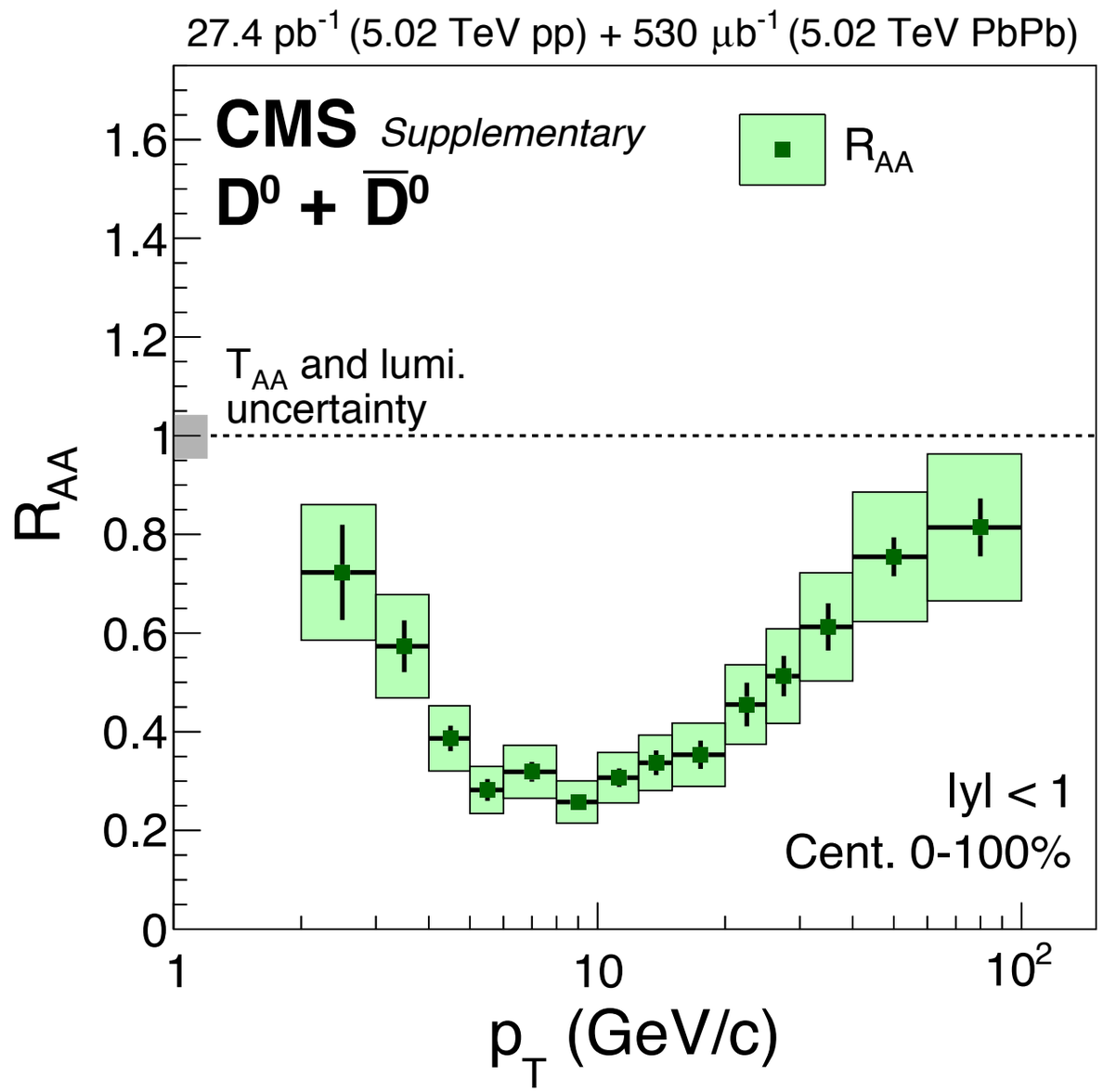


arXiv: 1708.04962

[1] JHEP 05 (1998) 007
[2] Eur. Phys. J. C 72 (2012) 2082

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

|y| < 1, Centrality 0-100%



- Nuclear modification factor

$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} / \frac{d\sigma_{pp}}{dp_T}.$$

- Strong suppression at p_T 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

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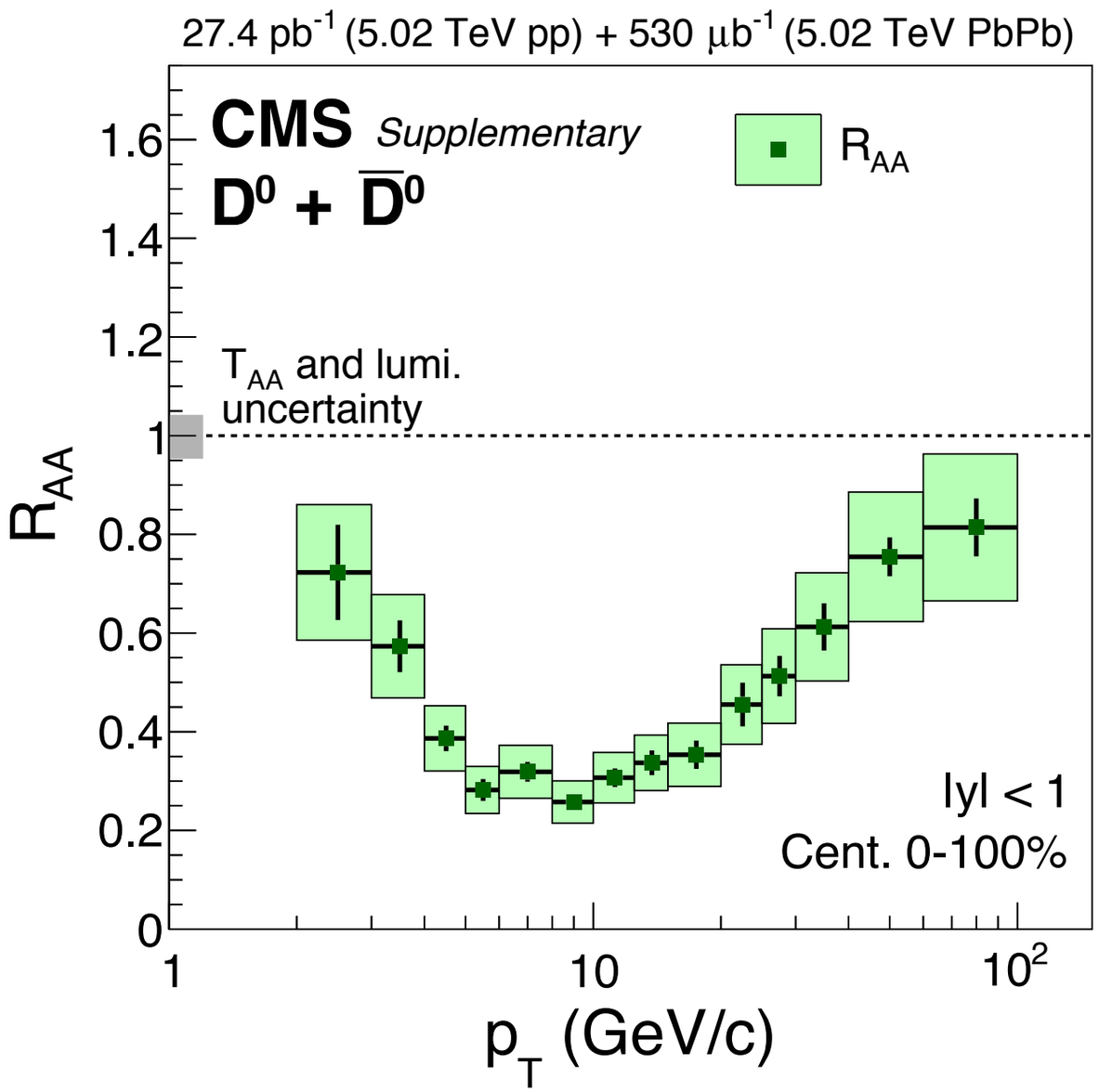
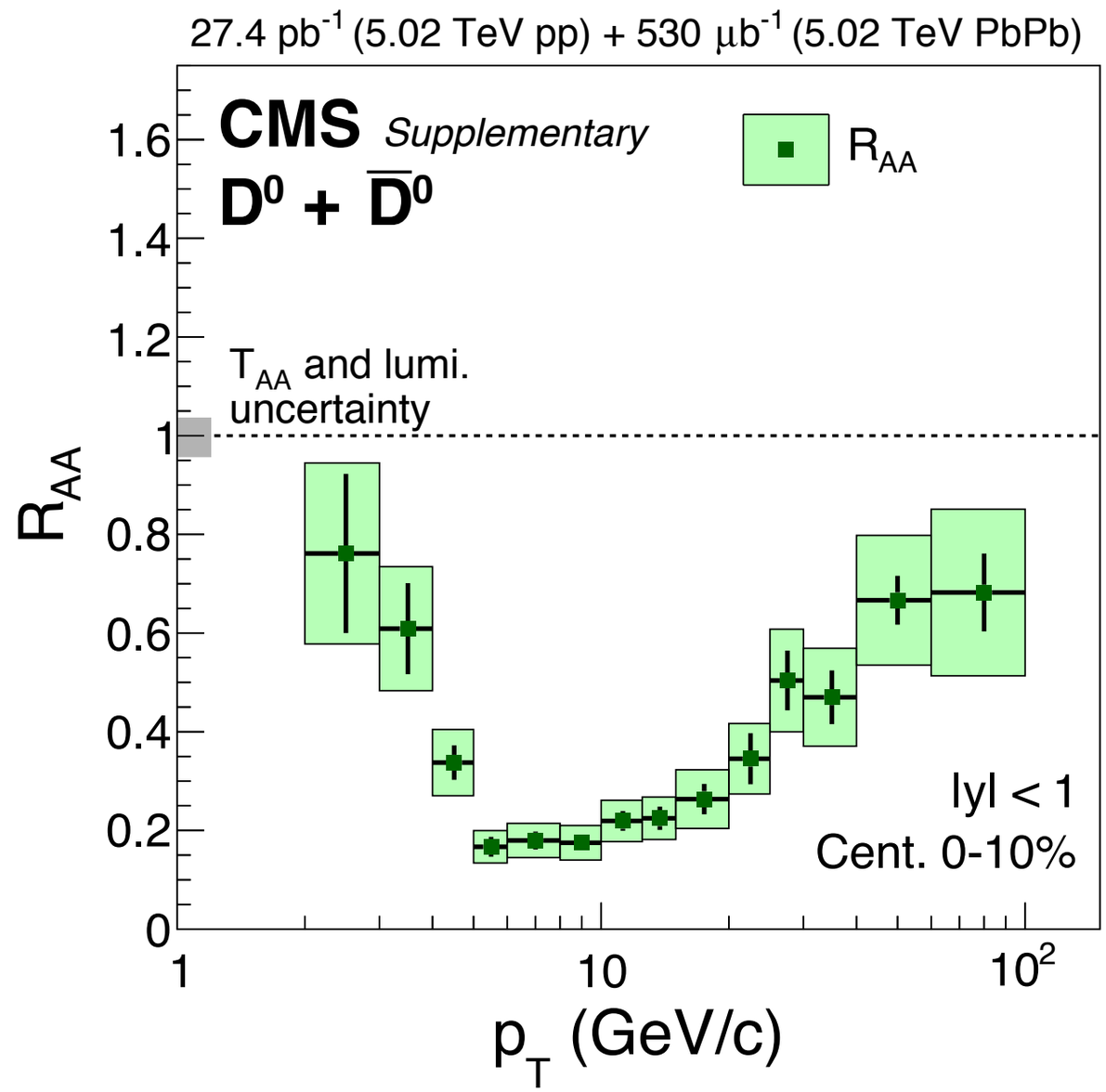
Centrality **0-100%**



Centrality **0-10%**



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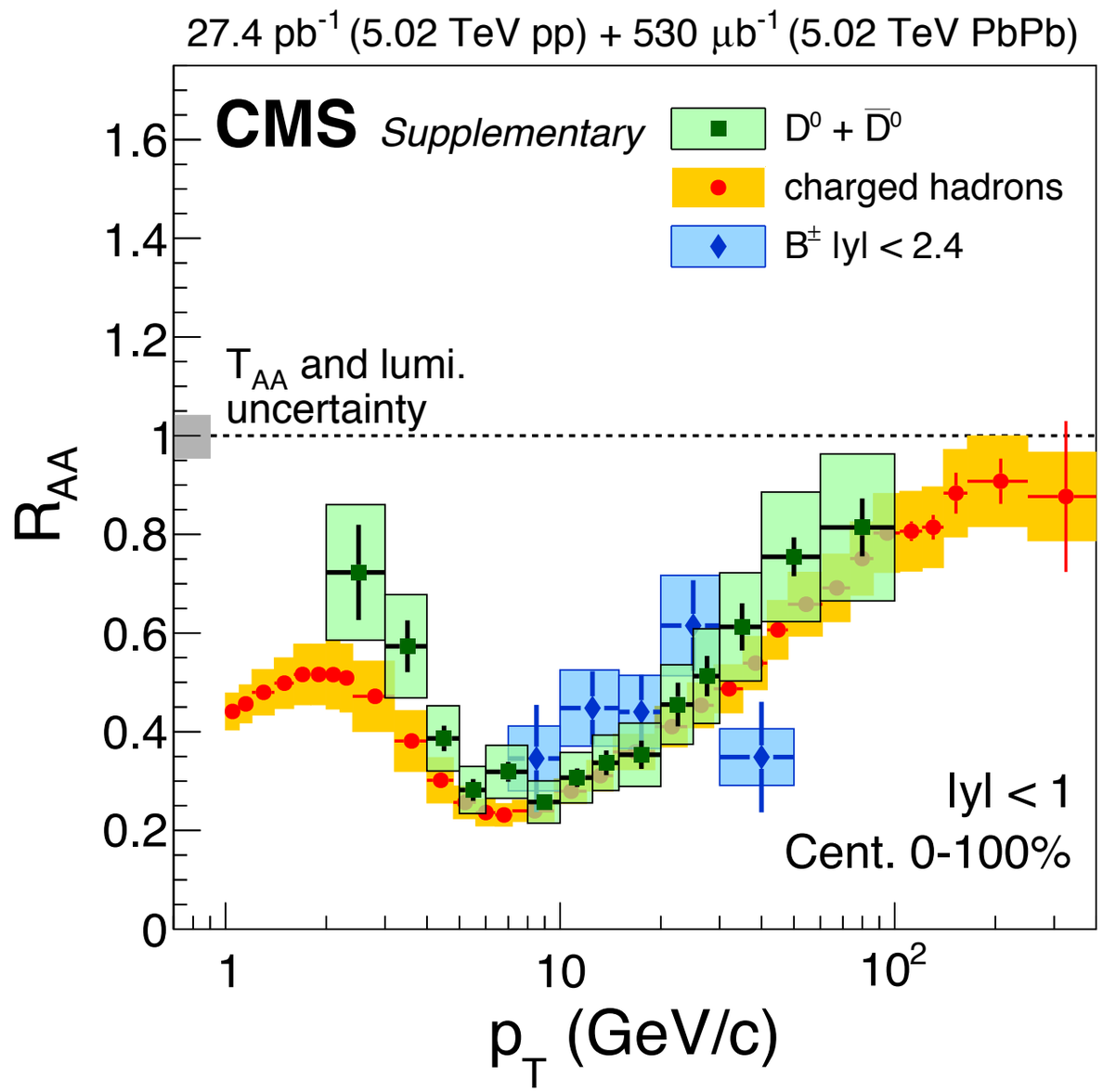

- Comparison with **charged hadrons**
  - ➡ Similar suppression in a wide kinematic range
  - ➡ Hint of less suppression of D^0 at low p_T?
  - ➡ To be studied with higher statistics data to be taken in 2018 and HLLHC
- Comparison with **B^+ meson**
  - ➡ No significant meson flavor dependence of R_{AA} at high p_T with the current accuracy
  - ➡ B→D analysis is on going to reach lower p_T

JHEP 04 (2017) 039
arXiv:1705.04727
arXiv: 1708.04962

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

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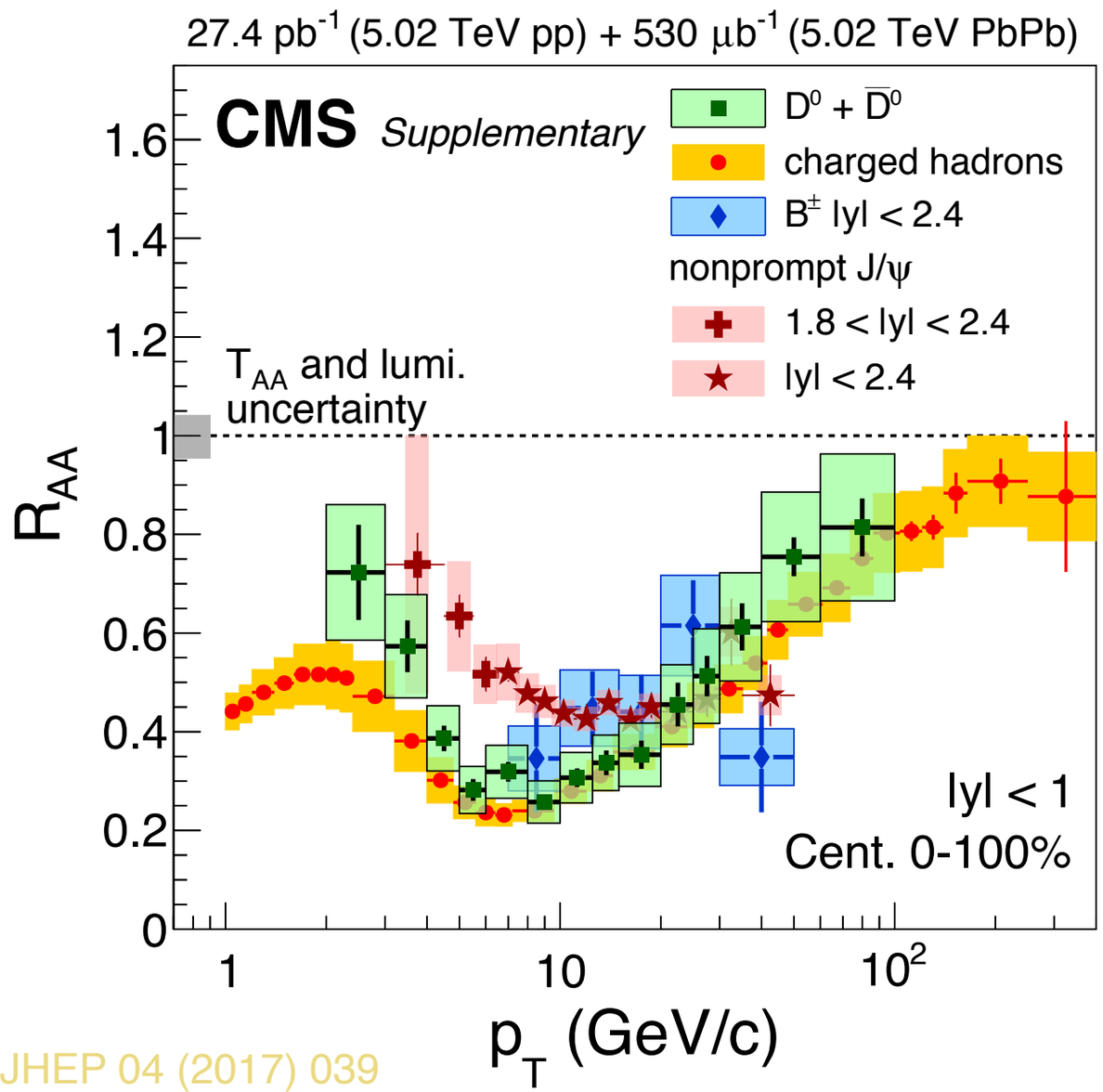

JHEP 04 (2017) 039
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CMS-PAS-HIN-16-025
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- Comparison with **B^+ meson**
  - ➡ No significant meson flavor dependence of R_{AA} at high p_T with the current accuracy
  - ➡ $B \rightarrow D$ analysis is on going to reach lower p_T
- Comparison with **nonprompt J/ψ**
  - ➡ Hint of meson flavor dependence of R_{AA} at low p_T

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

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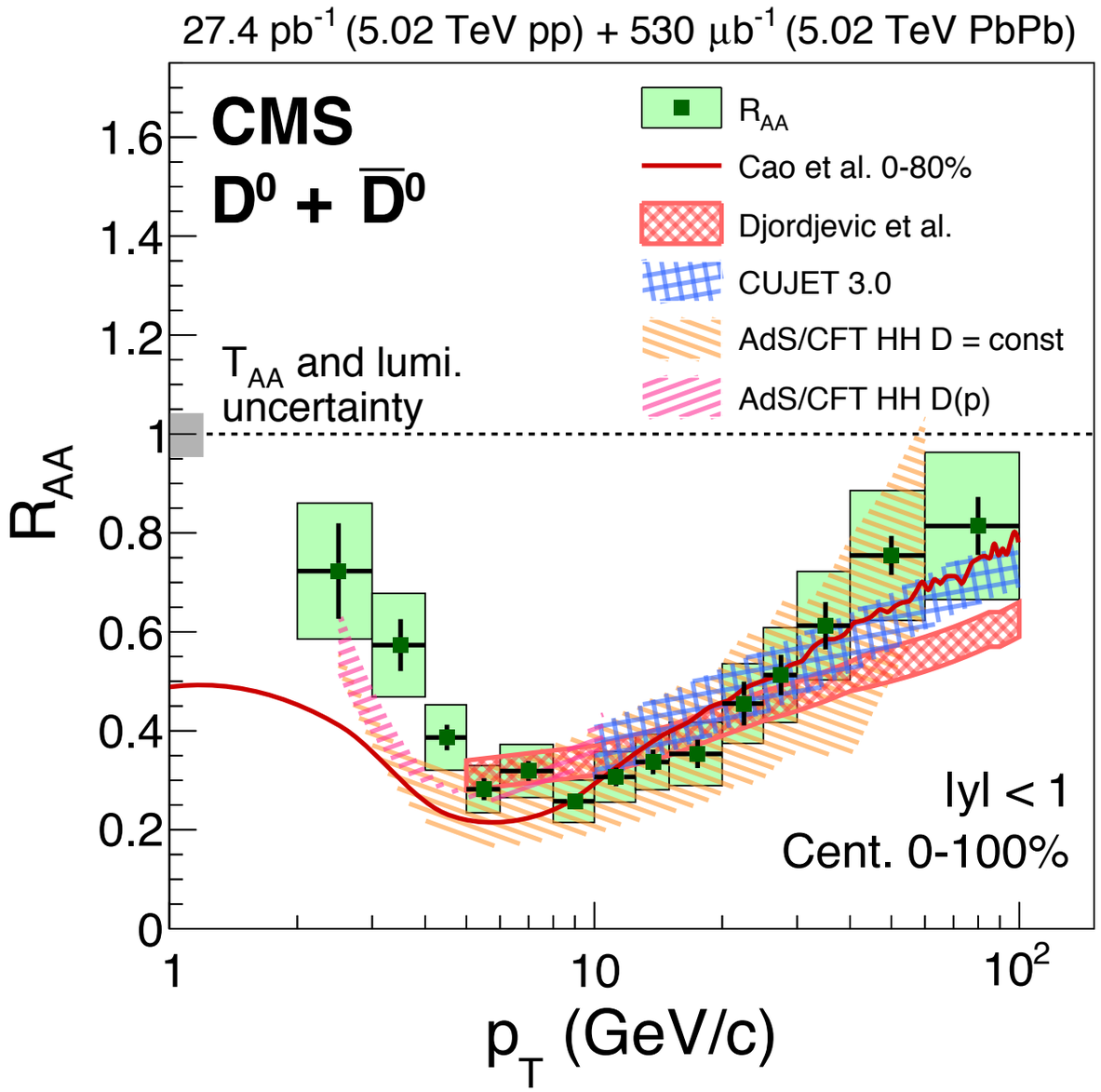

- Comparison with **theoretical predictions**
  - ➡ S. Cao et al. [1] *(Improved Langevin eq, Linearized Boltzmann)*
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  - ➡ CUJET3.0 [3] *(jet quenching model based on DGLV opacity expansion theory)*
  - ➡ AdS/CFT [4] *(a model based on the anti-de Sitter/conformal field theory)*

[1] arXiv:1703.00822
[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019

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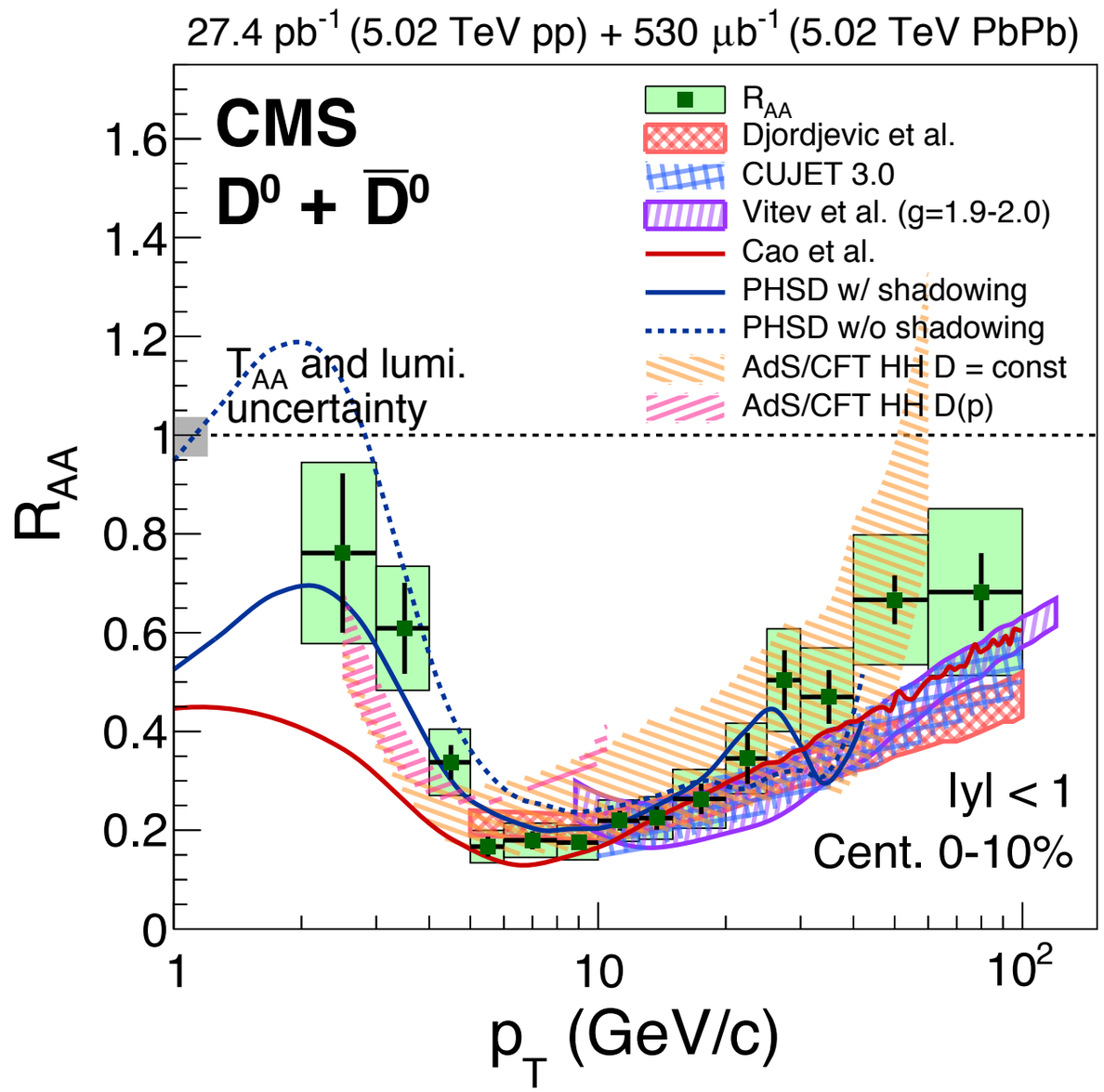

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  - ➡ Vitev et al. [5] *(jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG))*
  - ➡ PHSD [6] *(Parton-Hadron-String Dynamics transport approach)*

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[2] Phys. Rev. C 92 (2015) 024918
[3] JHEP 02 (2016) 169
[4] Phys. Rev. D 91 (2015) 085019
[5] Phys. Rev. D 93 (2016) 074030
[6] Phys. Rev. C 93 (2016) 034906

Azimuthal anisotropy

- The azimuthal anisotropy can be characterized by the Fourier coefficients v_n in the azimuthal angle (ϕ) distribution of the hadron yield

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right),$$

  - ➡ Elliptic flow: v_2
  - ➡ Triangular flow: v_3

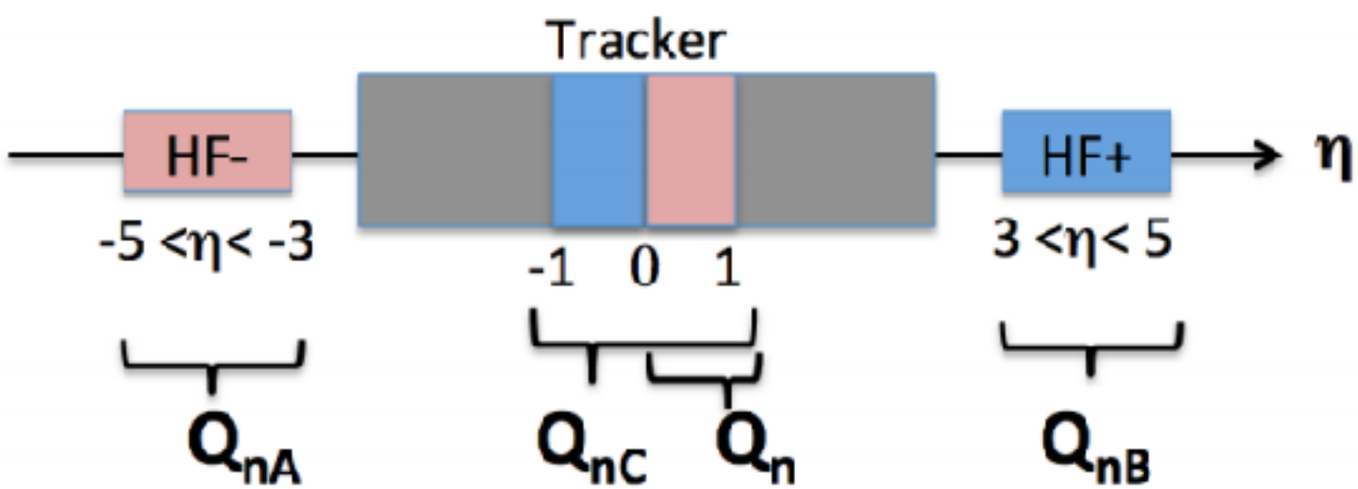
- Azimuthal anisotropy origins from
  - low p_T
    - ➡ collective motion in the thermalized medium
    - ➡ fluctuation (v_3)
  - high p_T
    - ➡ path length dependence of the energy loss

Scalar Product Method

- v_n coefficient can be expressed in terms of Q-vectors as

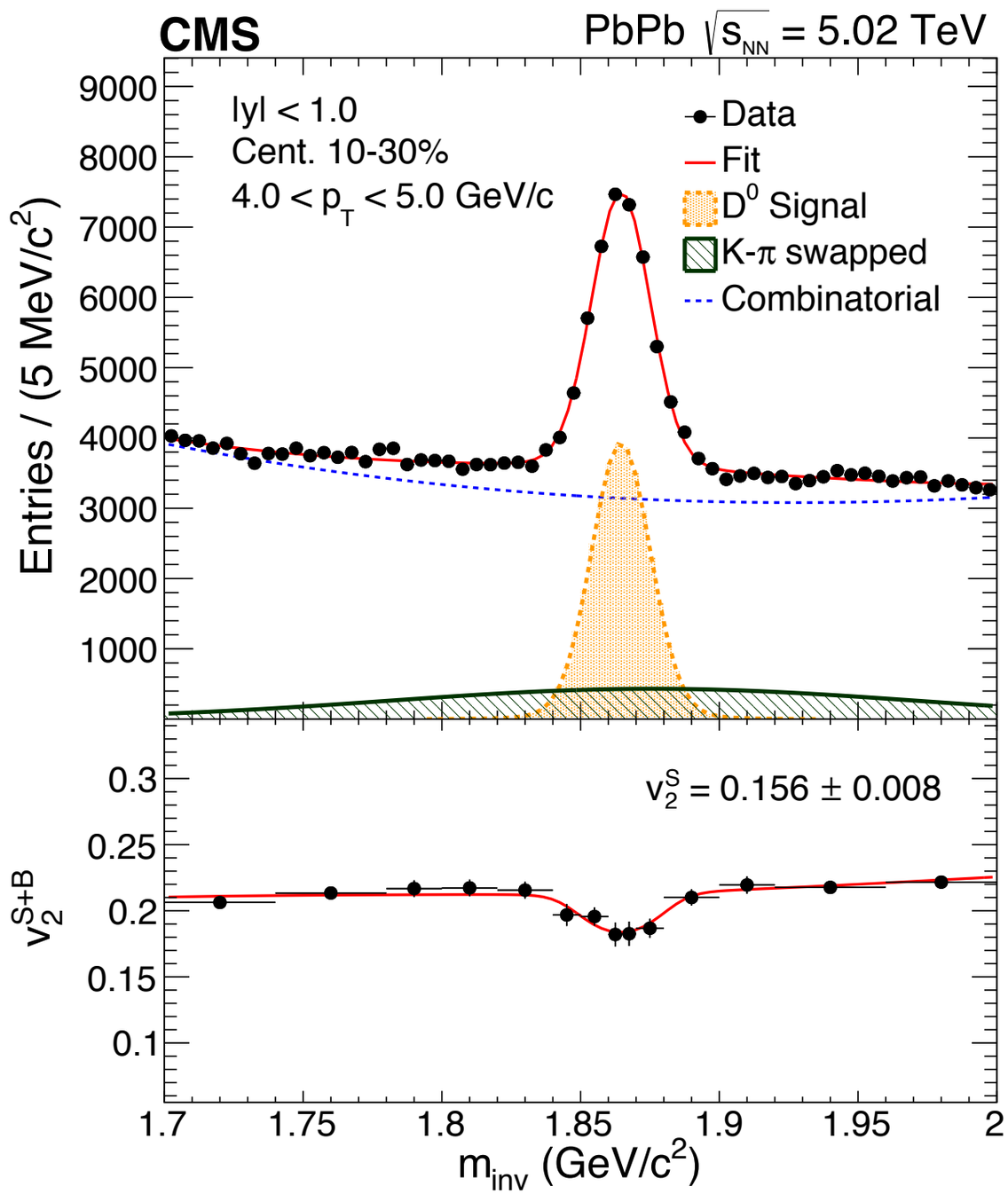
$$v_n\{\mathrm{SP}\} = \frac{\left\langle Q_{n,\mathrm{D}^0} Q^*_{nA} \right\rangle}{\sqrt{\frac{\left\langle Q_{nA} Q^*_{nB} \right\rangle \left\langle Q_{nA} Q^*_{nC} \right\rangle}{\left\langle Q_{nB} Q^*_{nC} \right\rangle}}}, \qquad Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k}$$

Scaling factor from 3 sub events



	A	B	C
sub evts	HF-	HF+	Tracker
M	towers	towers	tracks
ω_k	E_T	E_T	p_T

Extraction of D^0 v_n



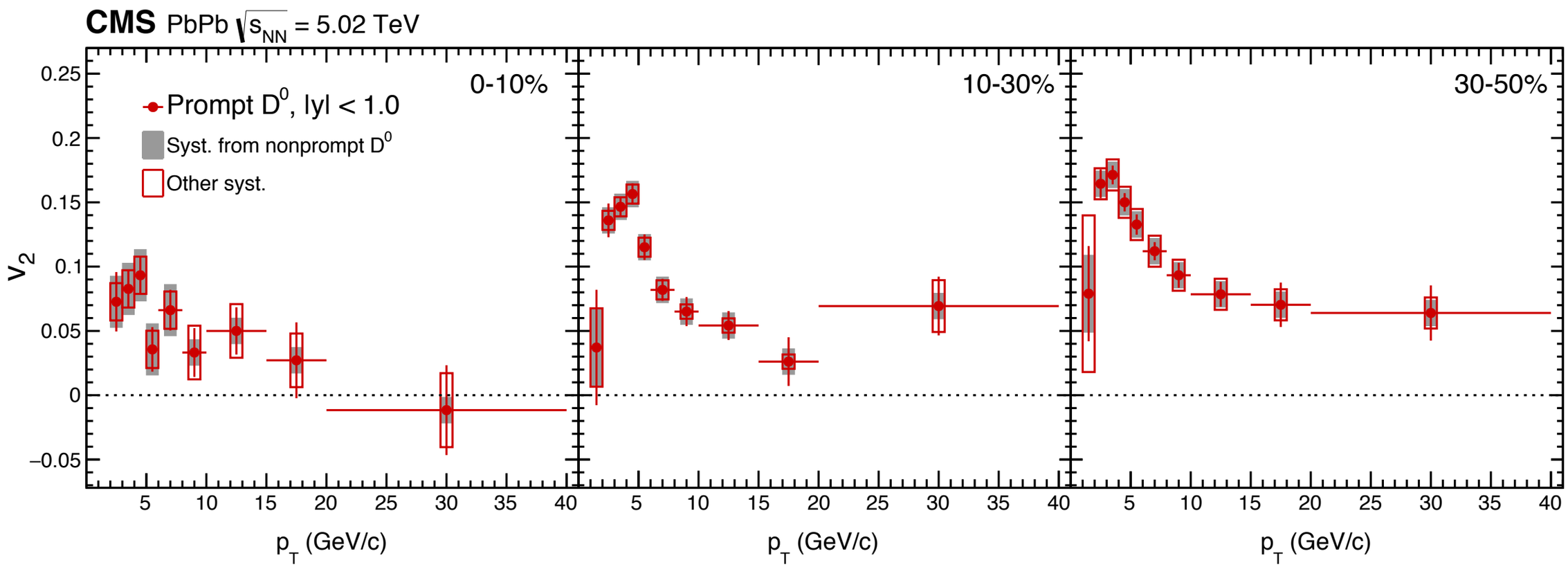
- Simultaneous fit on invariant mass distribution and v_n vs mass

$$v_n^{S+B}(m_{inv}) = \alpha(m_{inv})v_n^S + [1-\alpha(m_{inv})]v_n^B(m_{inv}),$$

- v_n^S: v_n of signal D^0
  - ➡ fit parameter
- other terms:
  - ➡ $v_n^{S+B}(m_{inv})$: v_n of all D^0 candidates
  - ➡ $v_n^B(m_{inv})$: v_n of combinatorial background, modeled by a linear function
  - ➡ $\alpha(m_{inv})$: signal fraction from invariant mass spectra fit

arXiv: 1708.03497

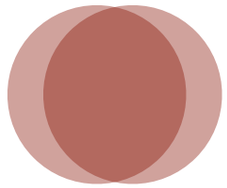
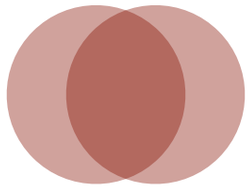
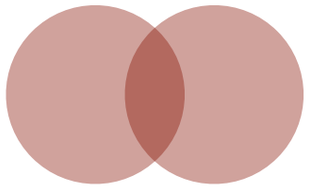
Prompt D^0 v_2 in PbPb at 5.02 TeV

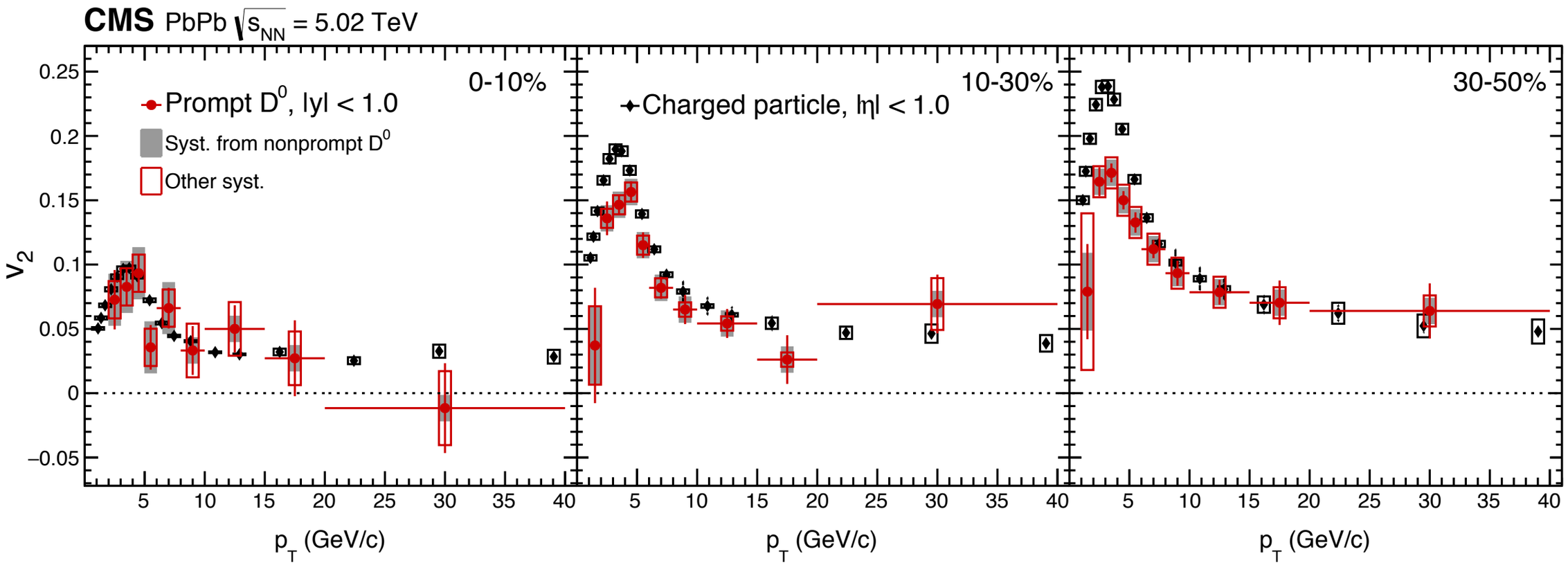


- Positive prompt D^0 v_2 observed in studied p_T range
  - ➡ Low p_T: charm quarks take part in the collective motion
  - ➡ High p_T: indicates path length dependence of energy loss
- Peaks around p_T at 3 GeV/c, then decreases vs p_T

arXiv: 1708.03497

Prompt D^0 v_2 vs. charged particles v_2

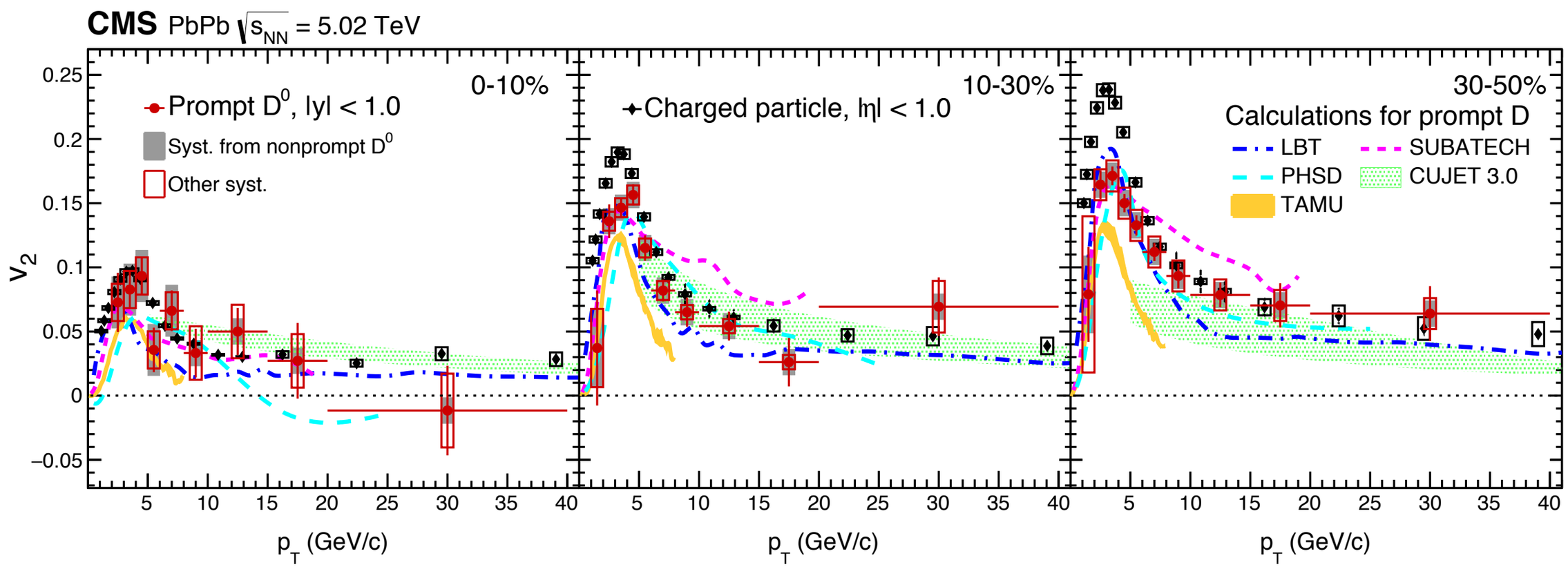






- Low p_T: v_2 (prompt D^0) < v_2 (charged particles)
  - ➡ Difference in most central events is smaller
  - ➡ Hint of smaller centrality dependence than charged particles
- High p_T: v_2 (prompt D^0) ≈ v_2 (charged particles)
  - ➡ consistent with ΔE (charm) ≈ ΔE (light quark) observed in R_{AA}
- Similar p_T dependence

arXiv: 1708.03497

Prompt D^0 v_2 vs. theoretical calculations

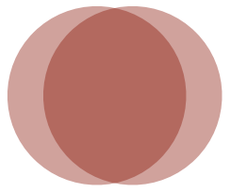
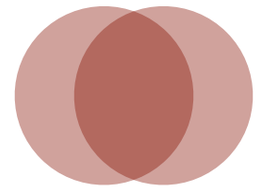
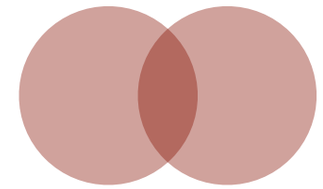


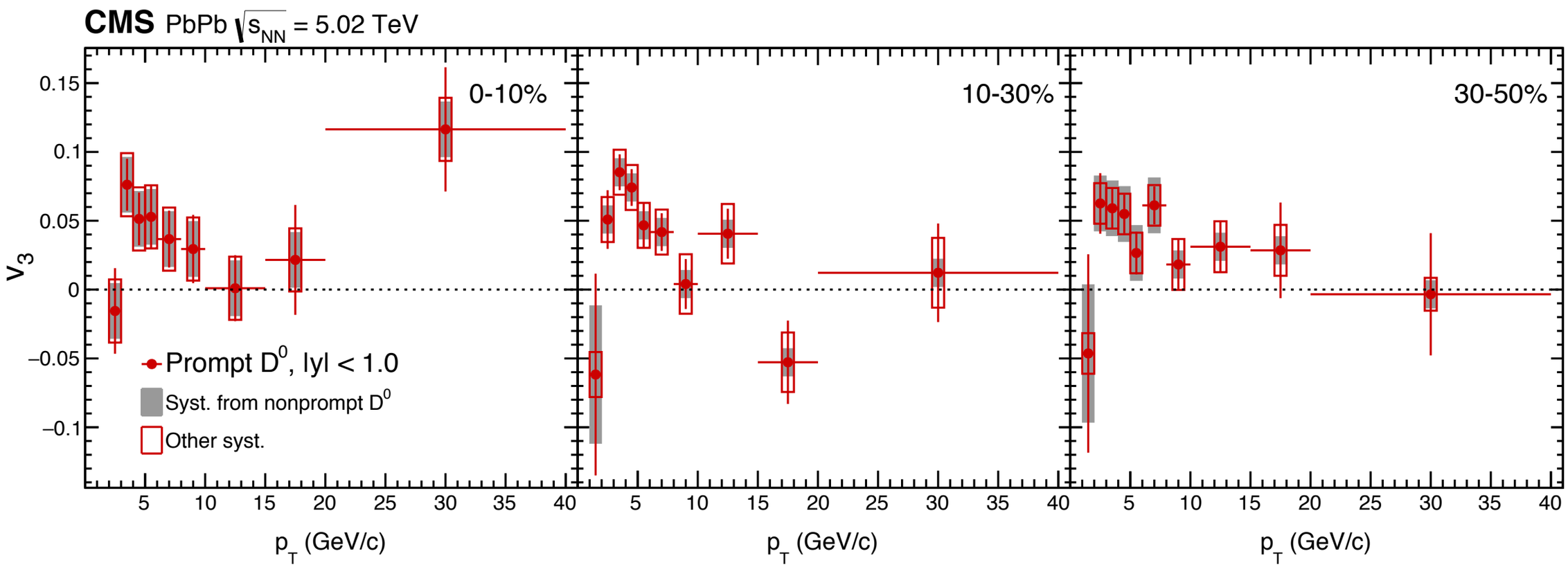
- Models need to describe both R_{AA} and v_n results simultaneously in a wide kinematic range

PRC 94 (2016) 014909
PRC 91 (2015) 014904
PRC 93 (2016) 034906
JHEP 02 (2016) 169
PLB 735 (2014) 445

arXiv: 1708.03497

Prompt D^0 v_3 in PbPb at 5.02 TeV

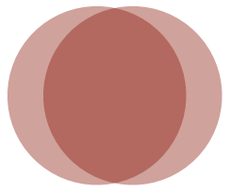
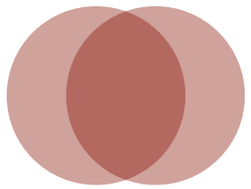
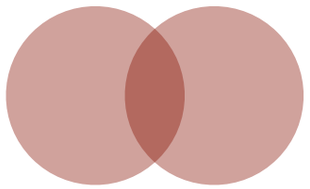




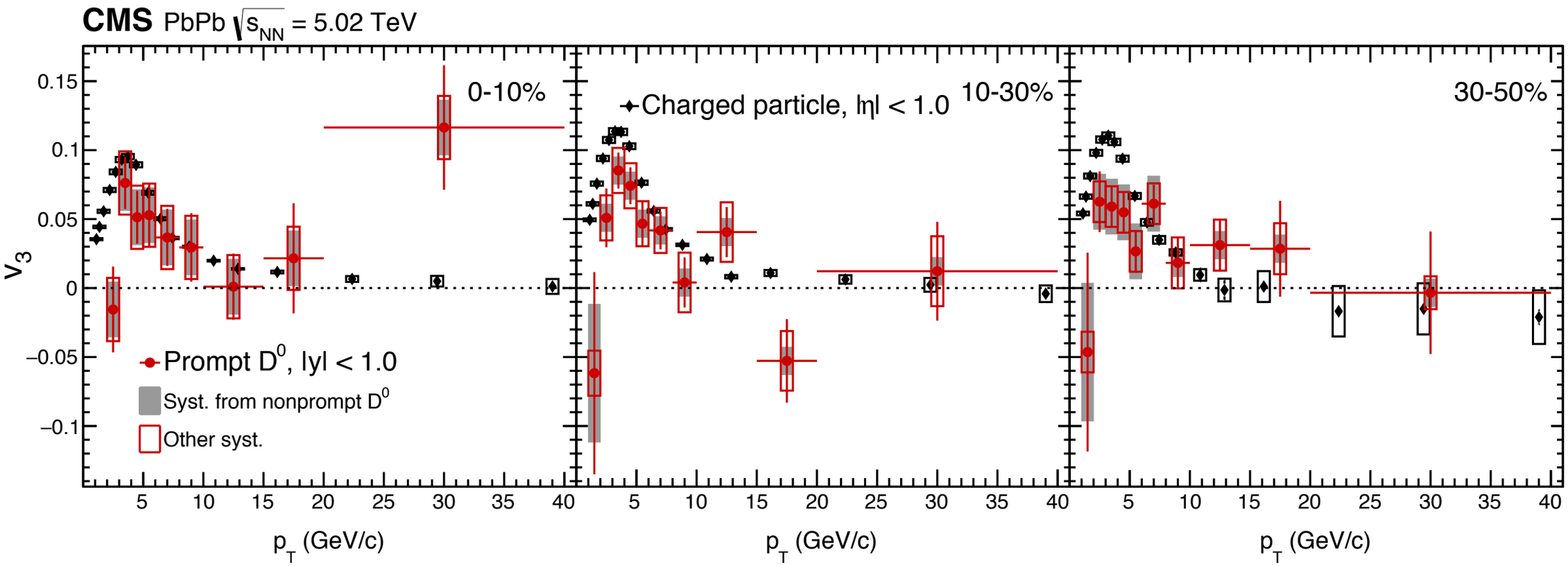


- First measurements of D^0 v_3
- Low p_T: v_3 (prompt D^0) > 0; High p_T: v_3 (prompt D^0) ≈ 0
- Peaks around 3 GeV/c
- Little centrality dependence

arXiv: 1708.03497

Prompt D^0 v_3 vs. charged particles v_3

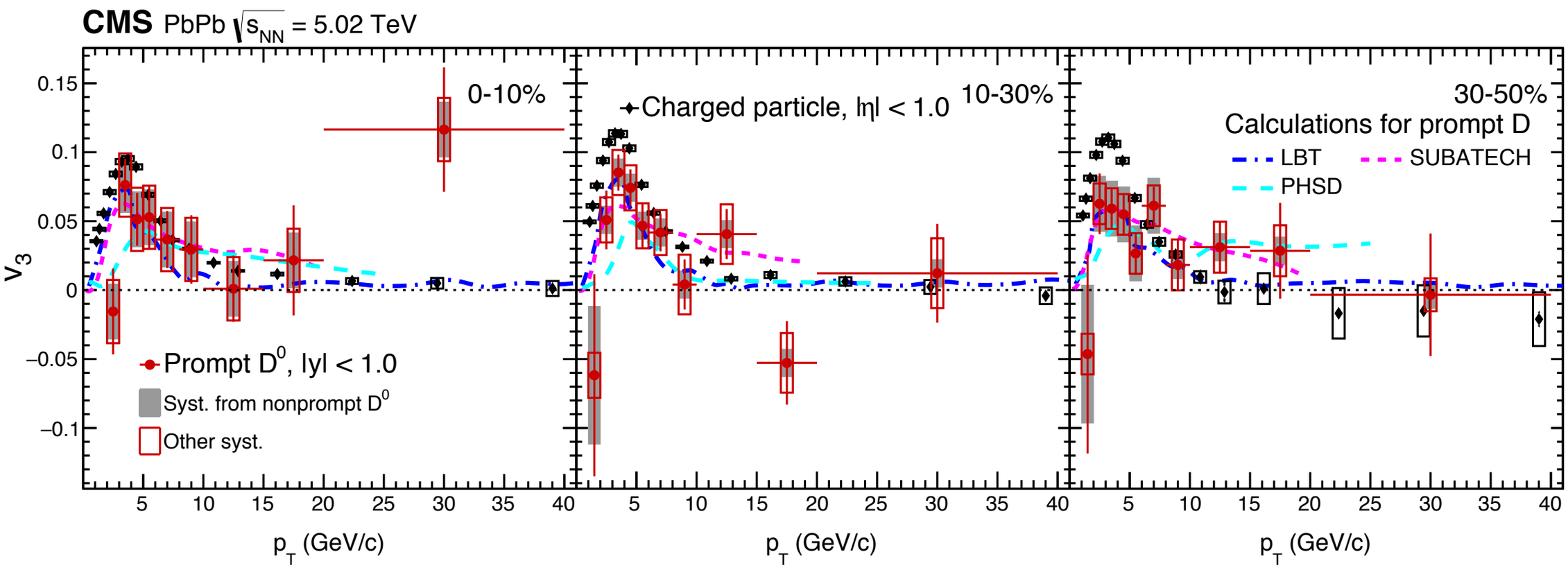






- Low p_T: v_3 (prompt D^0) < v_3 (charged particles)
  - ➡ Difference in most central events is smaller
- High p_T: v_3 (prompt D^0) ≈ v_3 (charged particles)
- Similar p_T dependence
- Both have little centrality dependence

arXiv: 1708.03497

Prompt D^0 v_3 vs. theoretical calculations



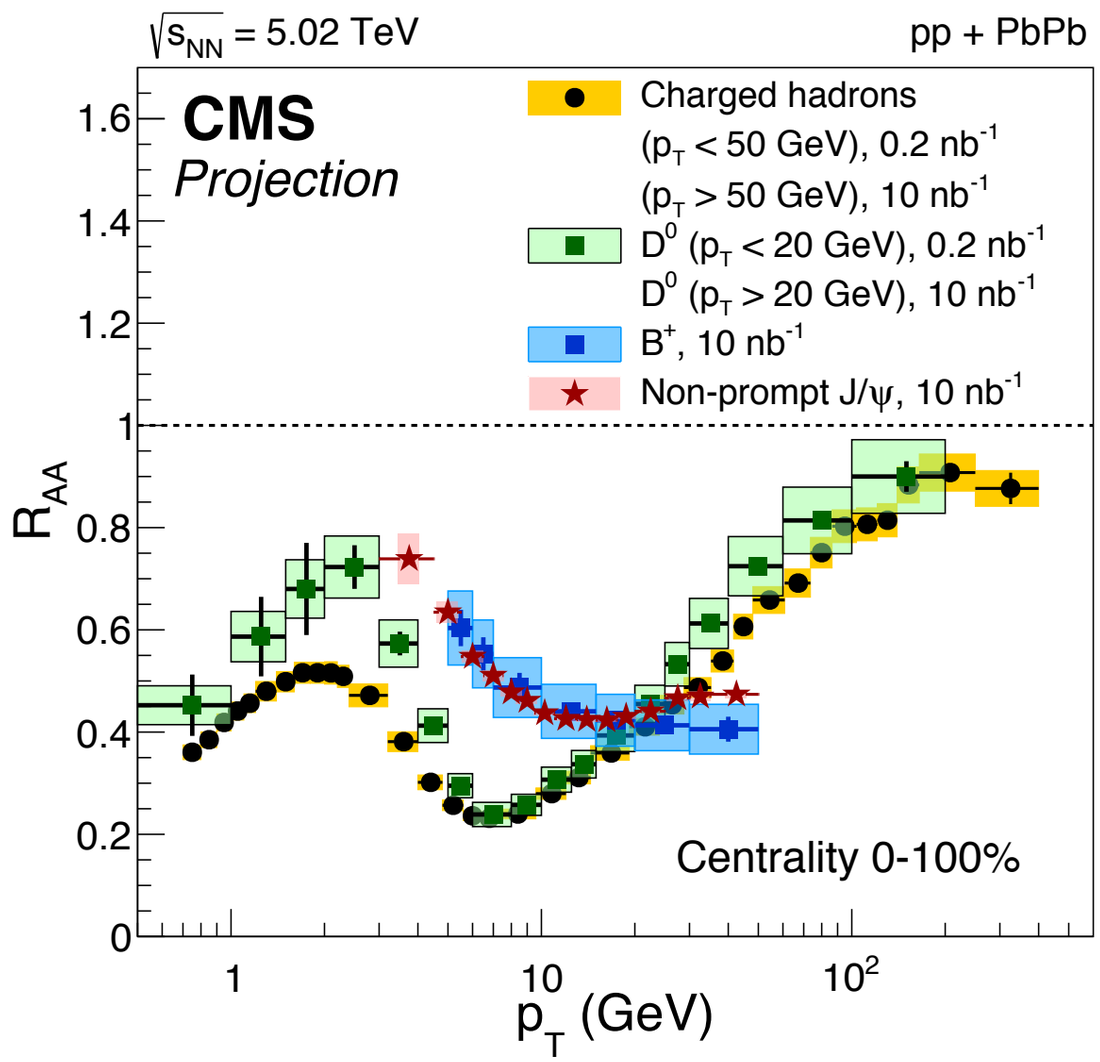
- Models need to describe both R_{AA} and v_n results simultaneously in a wide kinematic range

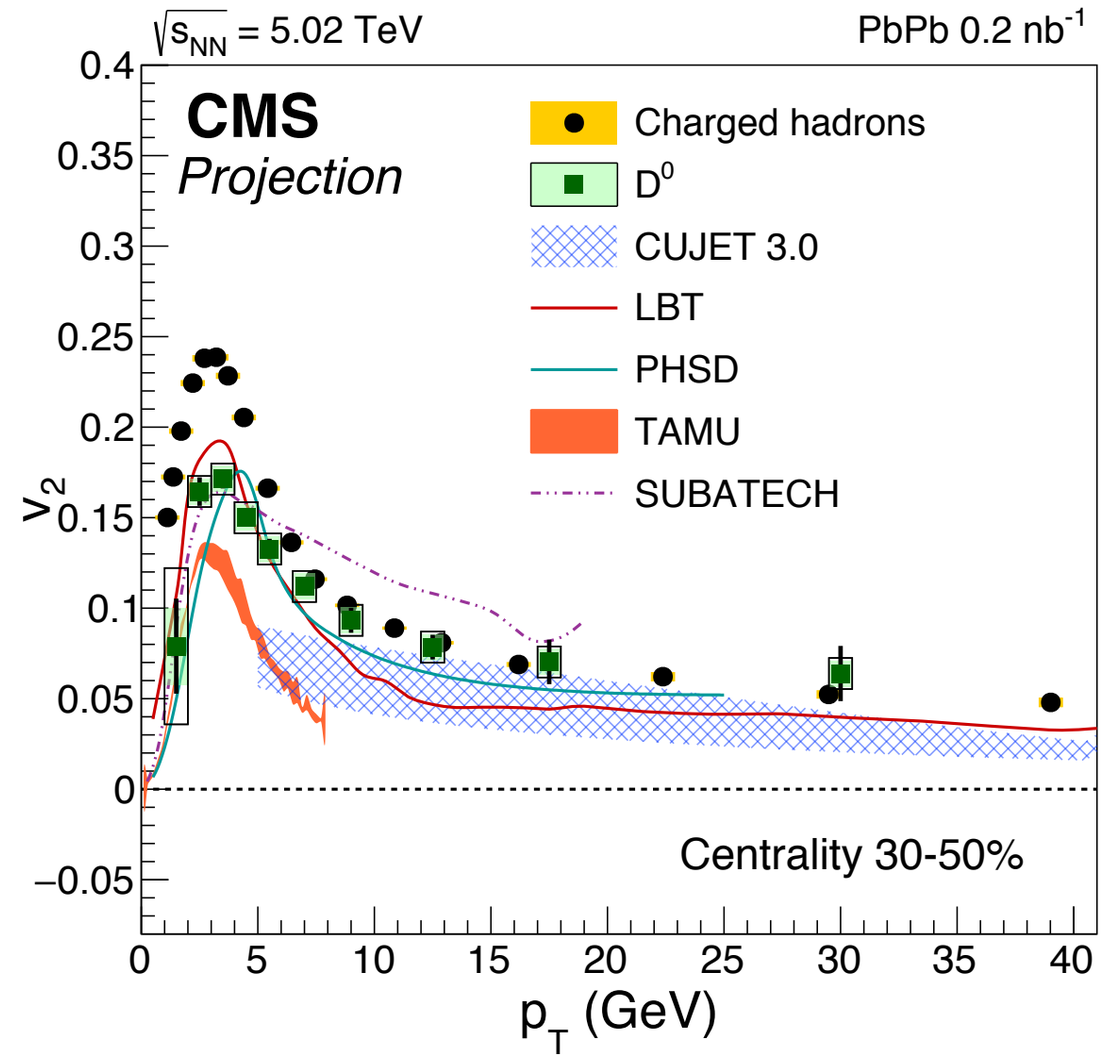
PRC 94 (2016) 014909
PRC 91 (2015) 014904
PRC 93 (2016) 034906

arXiv: 1708.03497

What can be expected at the HL-HLC era?

High-Luminosity LHC!





- A more solid conclusion on the flavor dependence of energy loss will be addressed
- Stronger constraints on the theory models

CMS-FTR-17-002

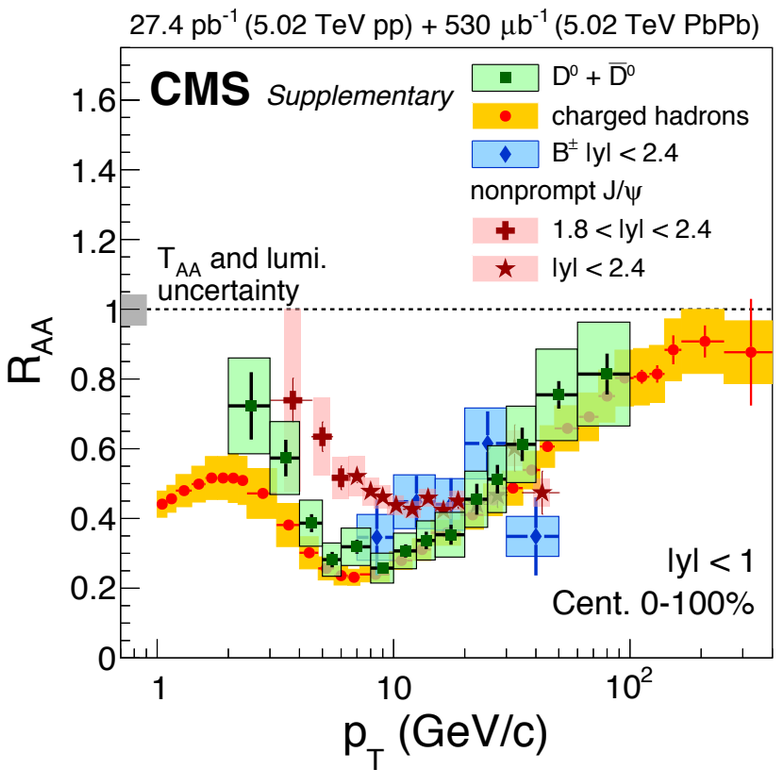
Summary

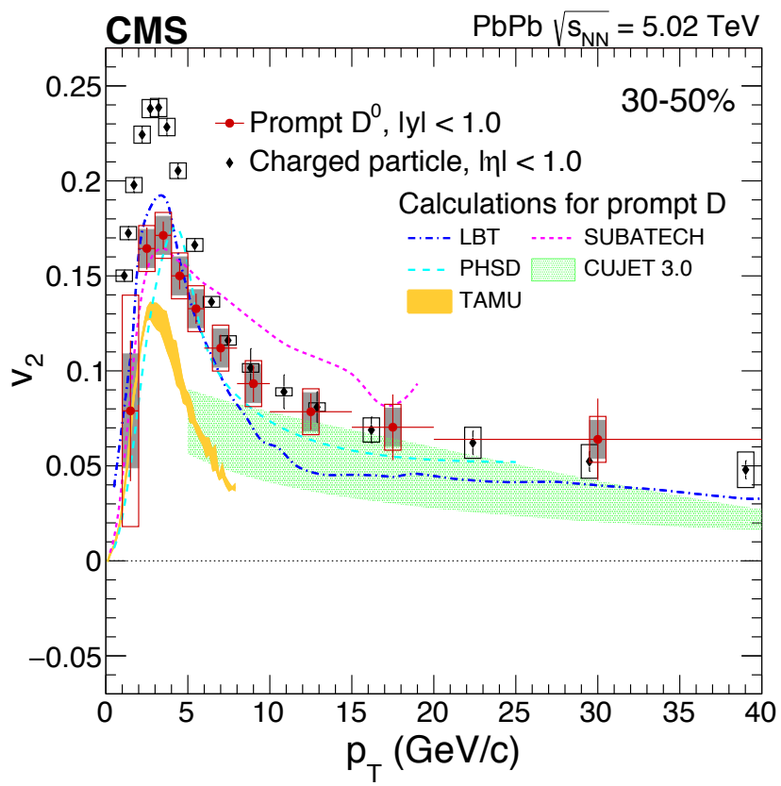
- D^0 R_{AA} in PbPb at 5.02 TeV
  - ➡ Strong suppression
  - ➡ No significant flavor dependence at high p_T
  - ➡ Hint of flavor dependence at low p_T
  - ➡ B→D analysis is on going to reach lower p_T

- D^0 v_2 and v_3 measured in 3 centrality ranges in PbPb at 5.02 TeV
  - ➡ First measurement of D^0 v_3
  - ➡ Low p_T: v_n (prompt D^0) < v_n (charged particle)
  - ➡ High p_T: v_n (prompt D^0) ≈ v_n (charged particle)

- Results provide important inputs for theoretical models

- We can expect much more precise measurements in Run 3 and HL-LHC

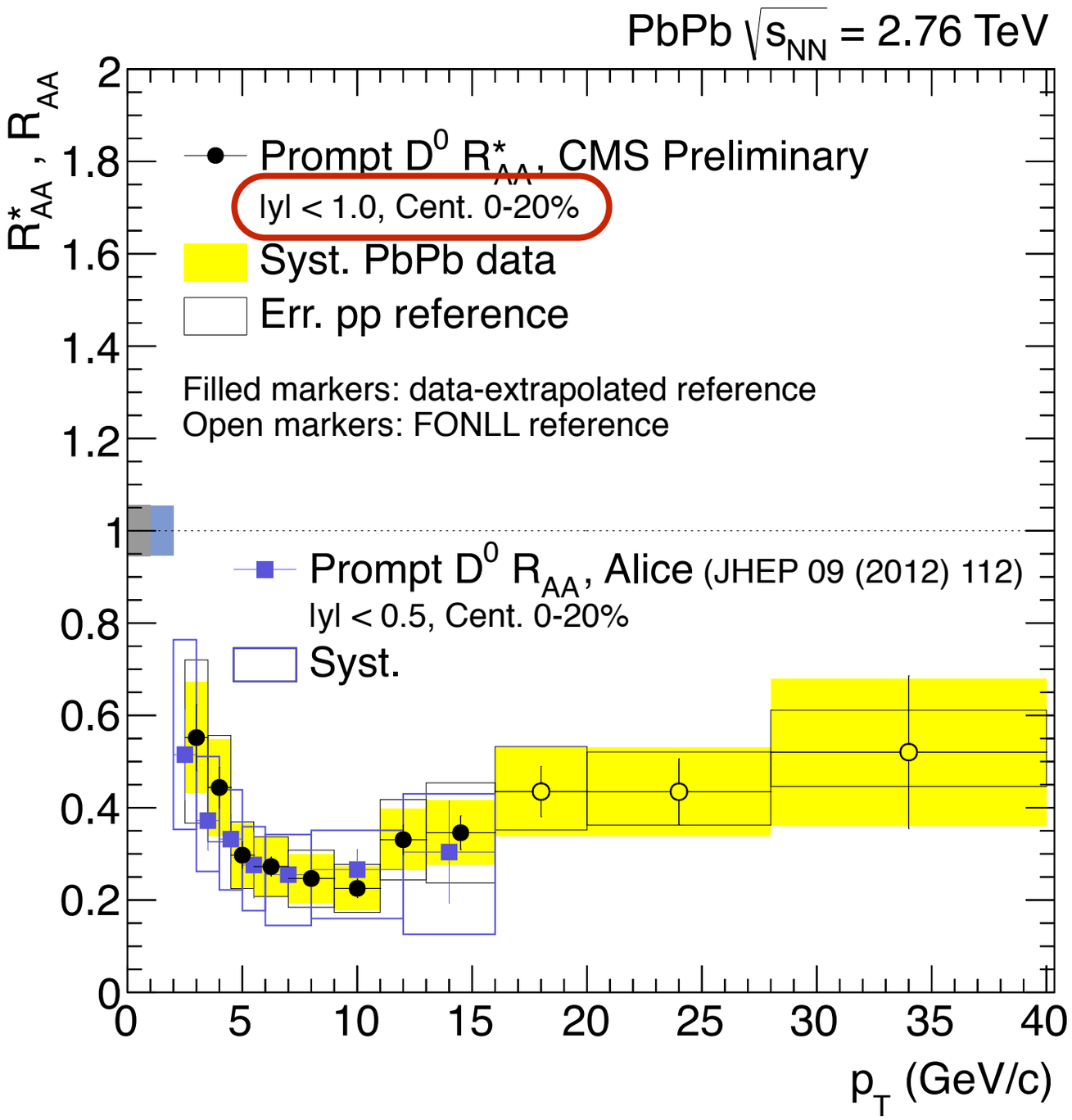




Back up

Thanks for your attention!

D^0 measurements with CMS in Run I



Run I 2.76 TeV

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

Run II 5.02 TeV

- Dataset: MB + D trigger events
- 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

Systematic uncertainties summary

Signal extraction systematics *~5%*

- Varying signal and background fit functions

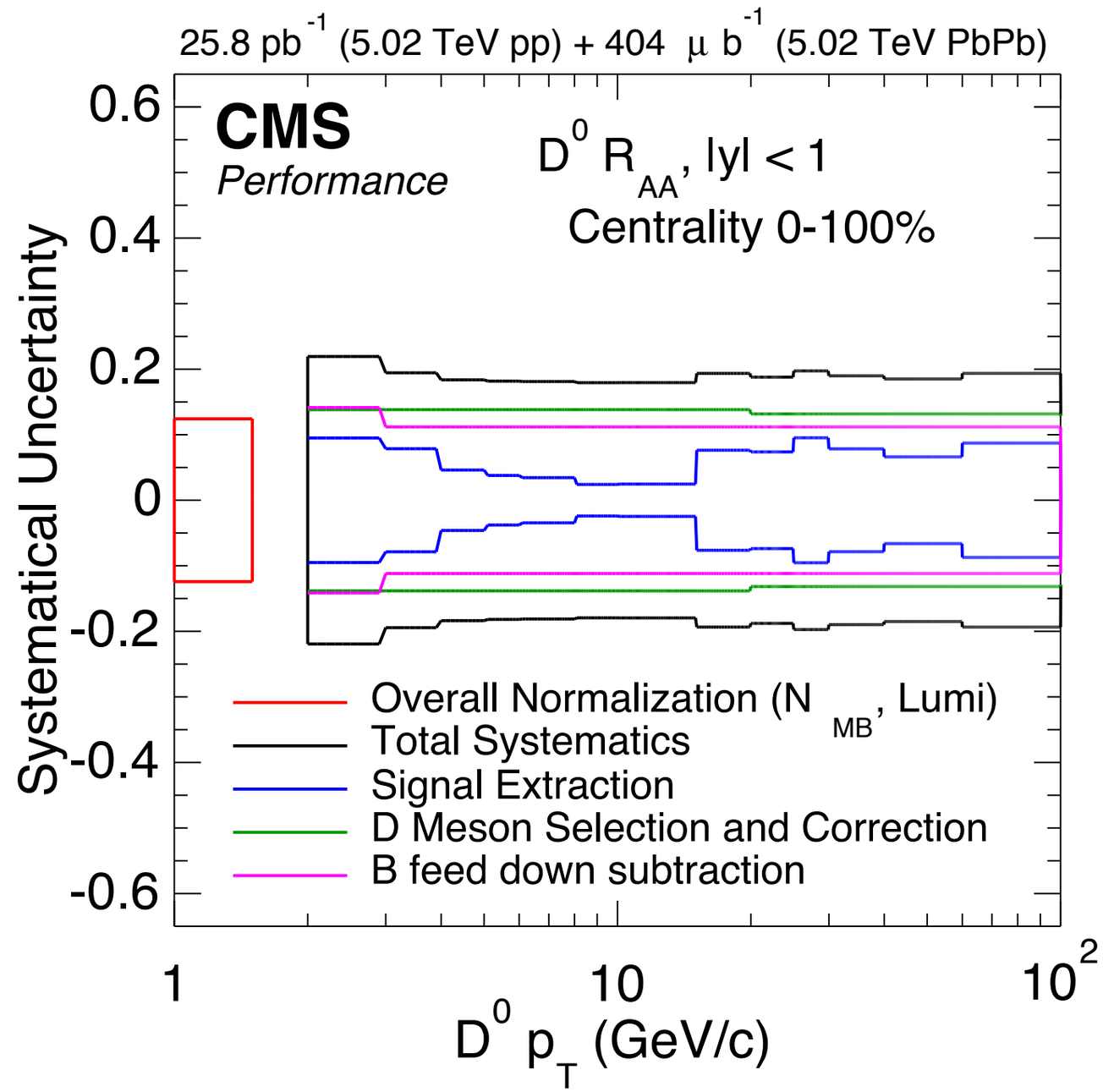
D meson selection *~13%*

- 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)

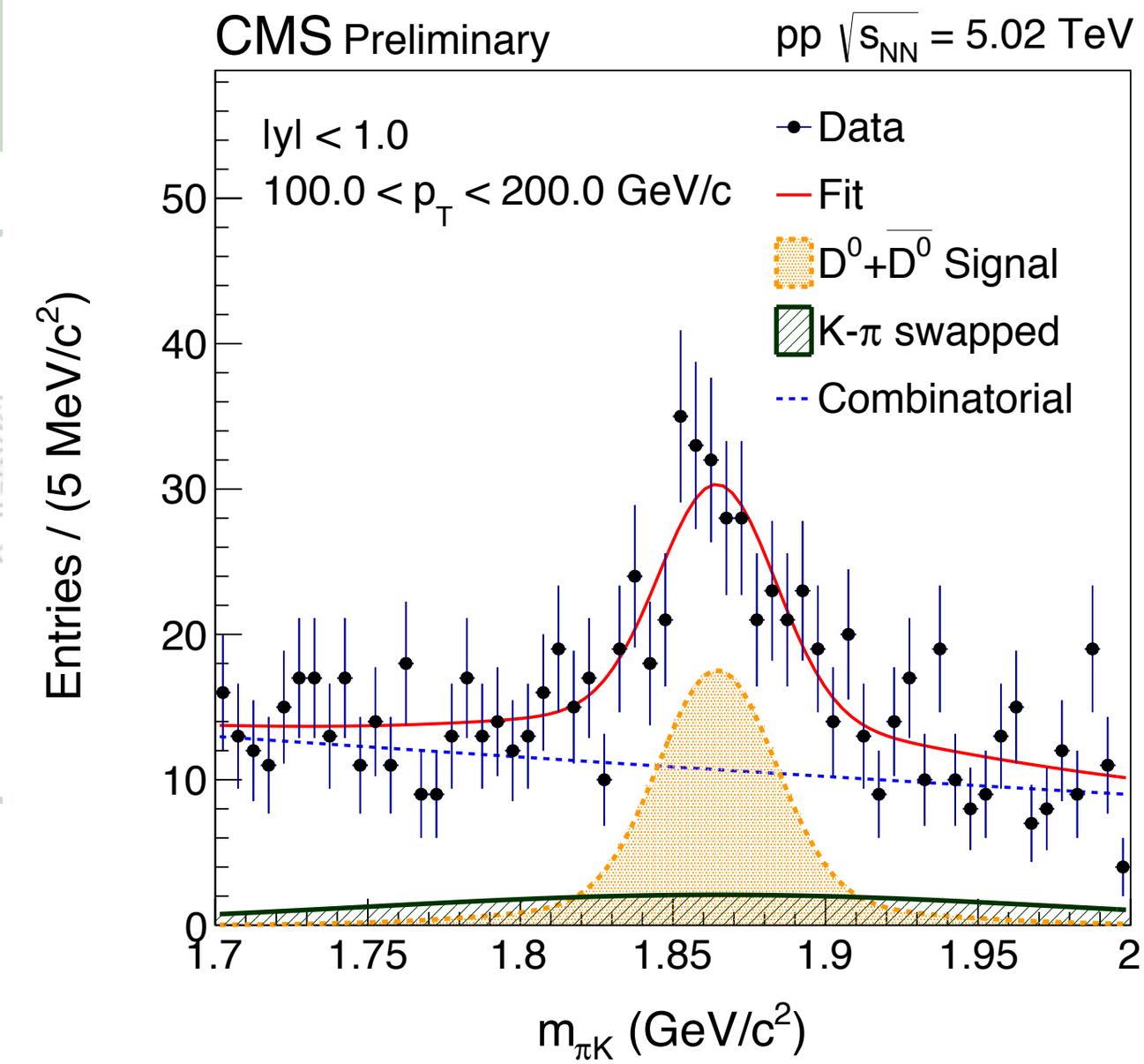
B-feed down uncertainty *~8%*

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

PbPb, Centrality **0-100%**



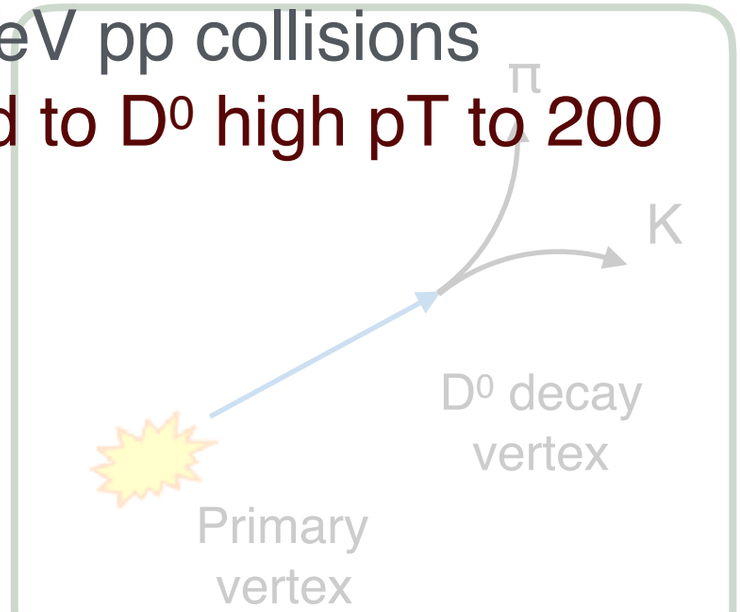
High-Level-Trigger (HLT) D^0 triggers



on in
gers

D^0 selection

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



- applied:
  p
- p_T > 8 GeV for PbPb

background subtraction

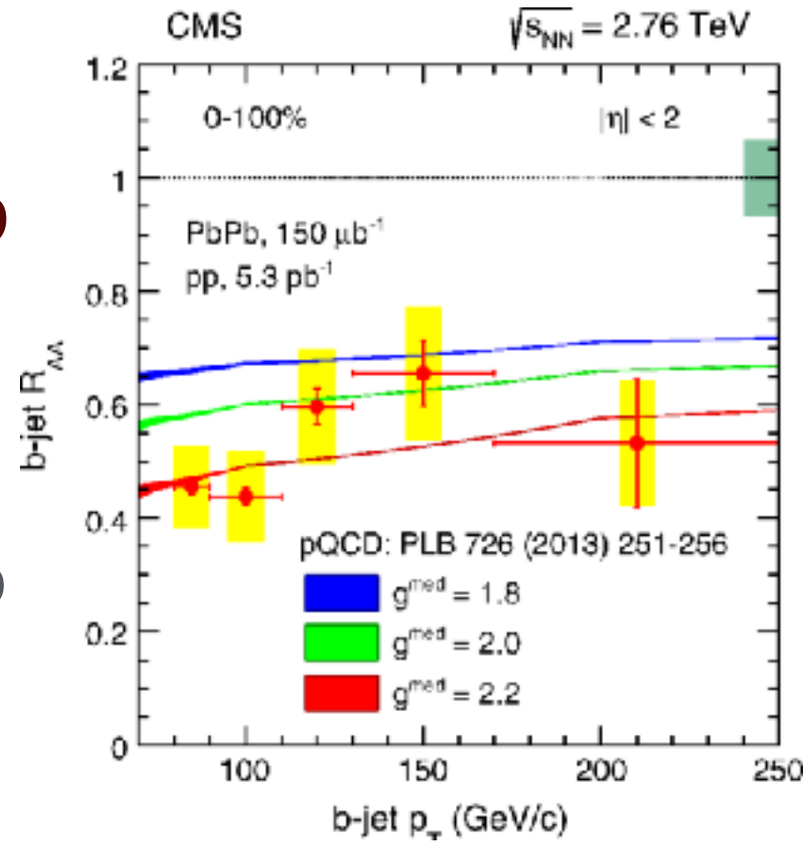
- D^0 online reconstruction
- loose selection based on D^0 vertex displacement

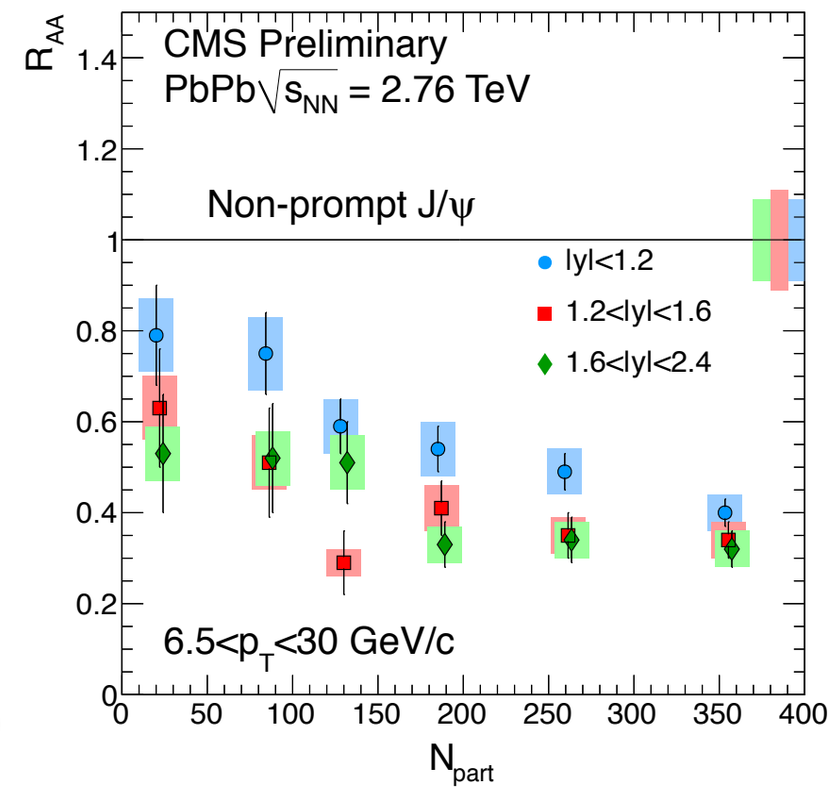
Heavy flavor measurements with CMS

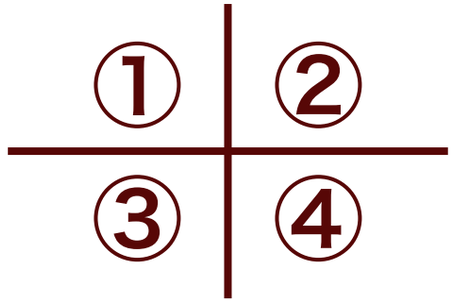
LHC Run I

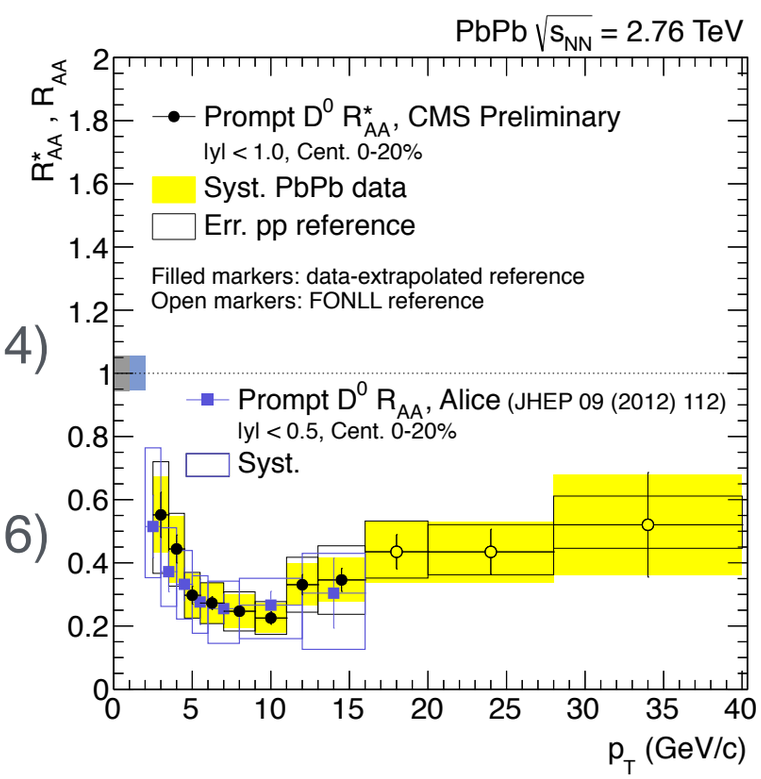
2.76 PbPb + 5.02 pPb

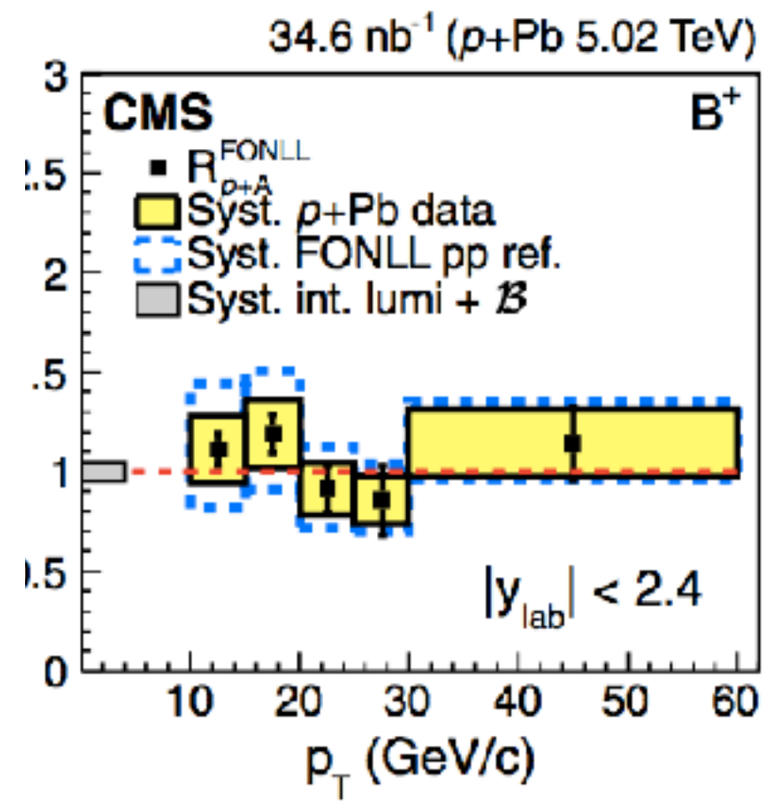
1. **b-jet R_{AA}** in PbPb
2. **J/ψ R_{AA}** in PbPb
3. **D^0 meson R_{AA}** in PbPb
4. **B meson R_{pPb}** in pPb





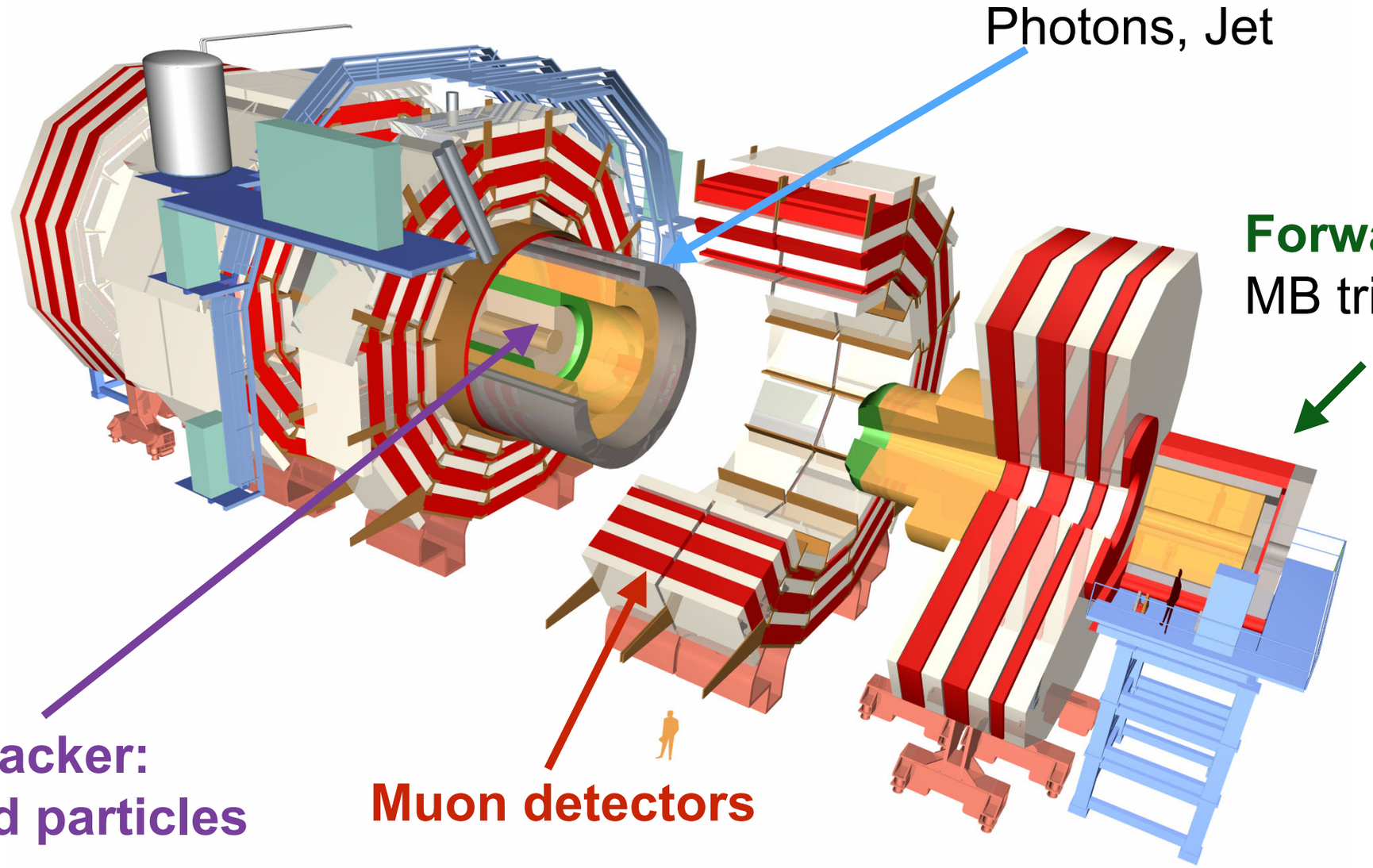


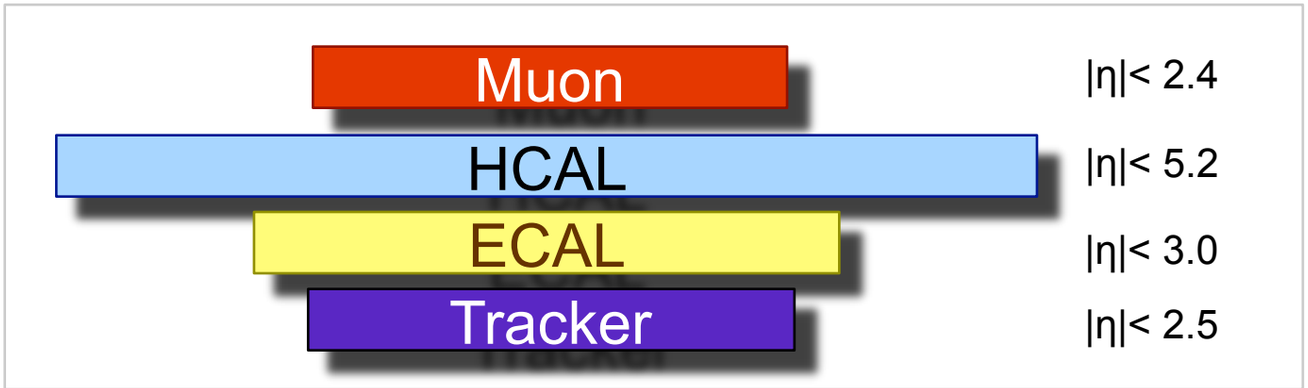




[1] Phys. Rev. Lett. **113,** 132301 (2014)
[2] CMS-PAS-HIN-12-014
[3] CMS-PAS-HIN-15-005
[4] Phys. Rev. Lett. **116,** 032301 (2016)

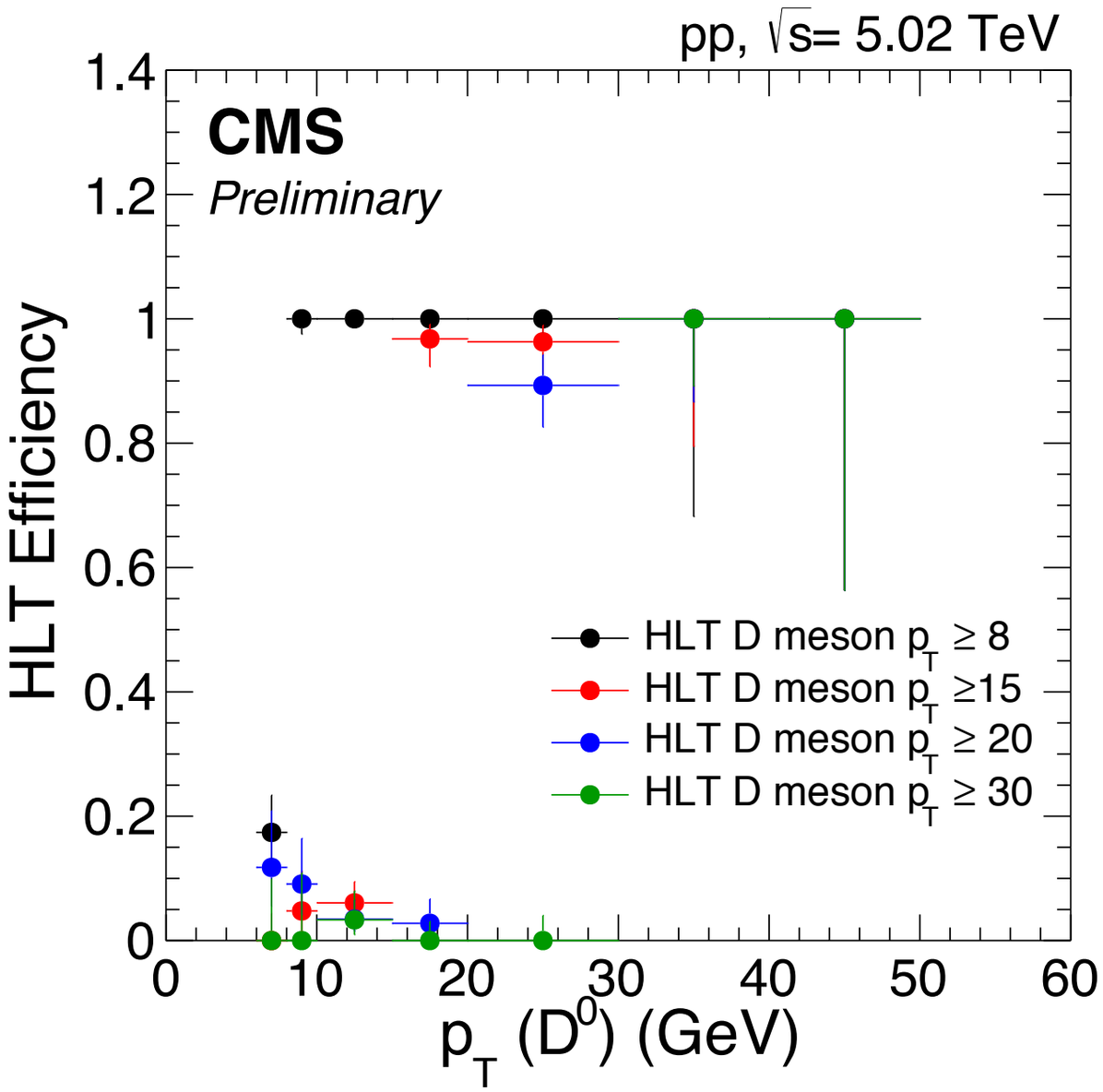
CMS detector

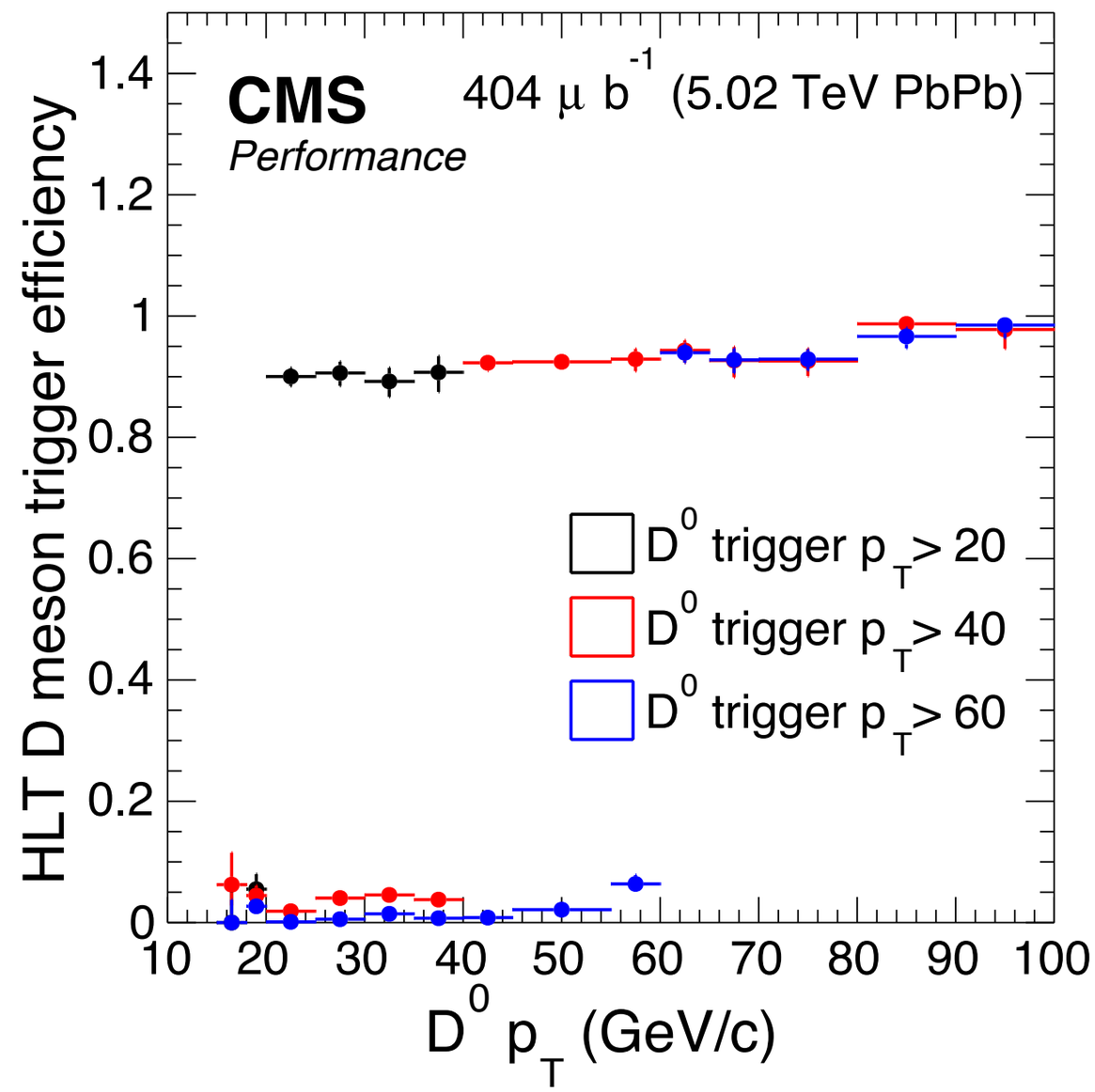




High-Level-Trigger (HLT) D^0 triggers

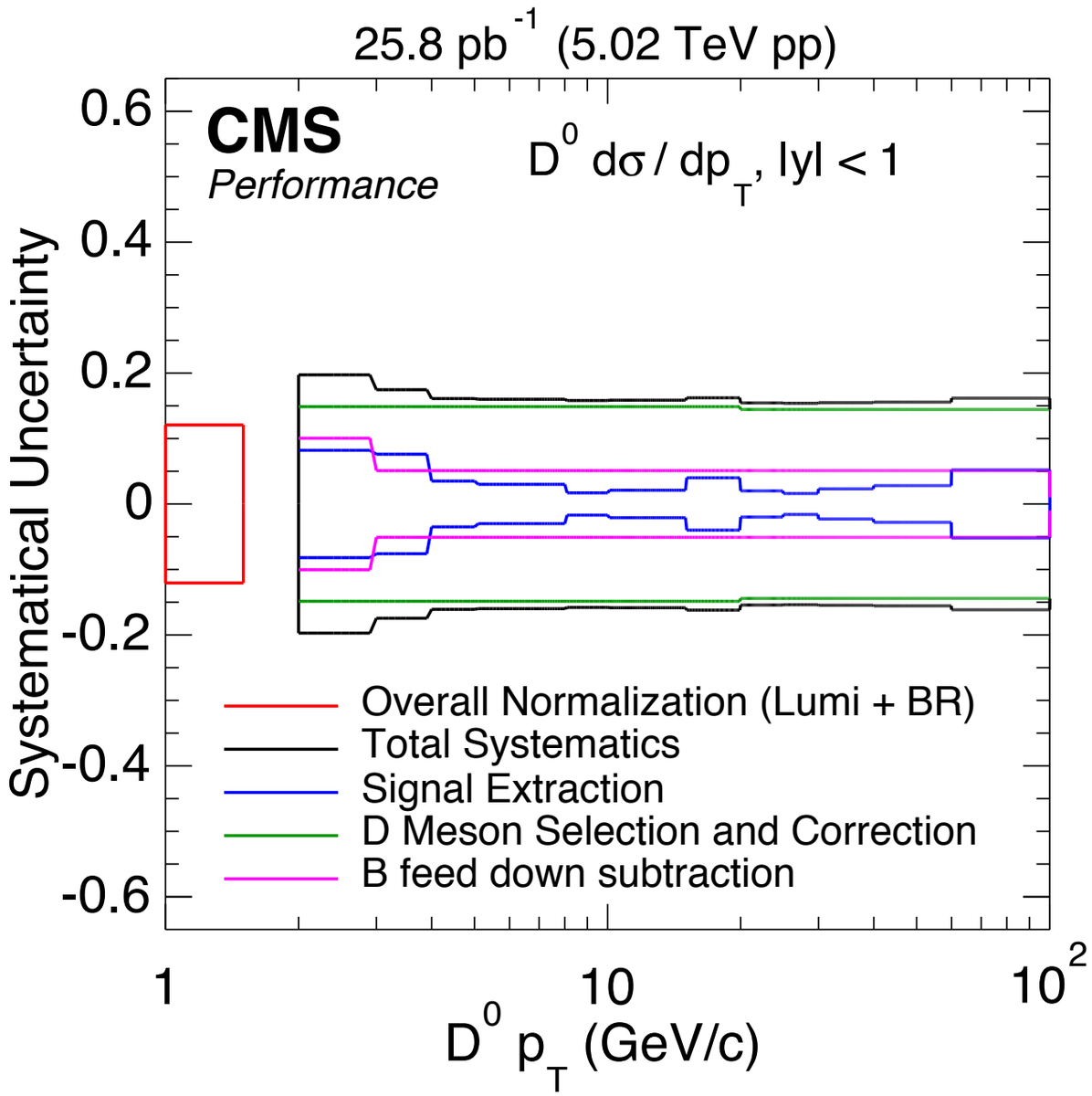
Triggers performance



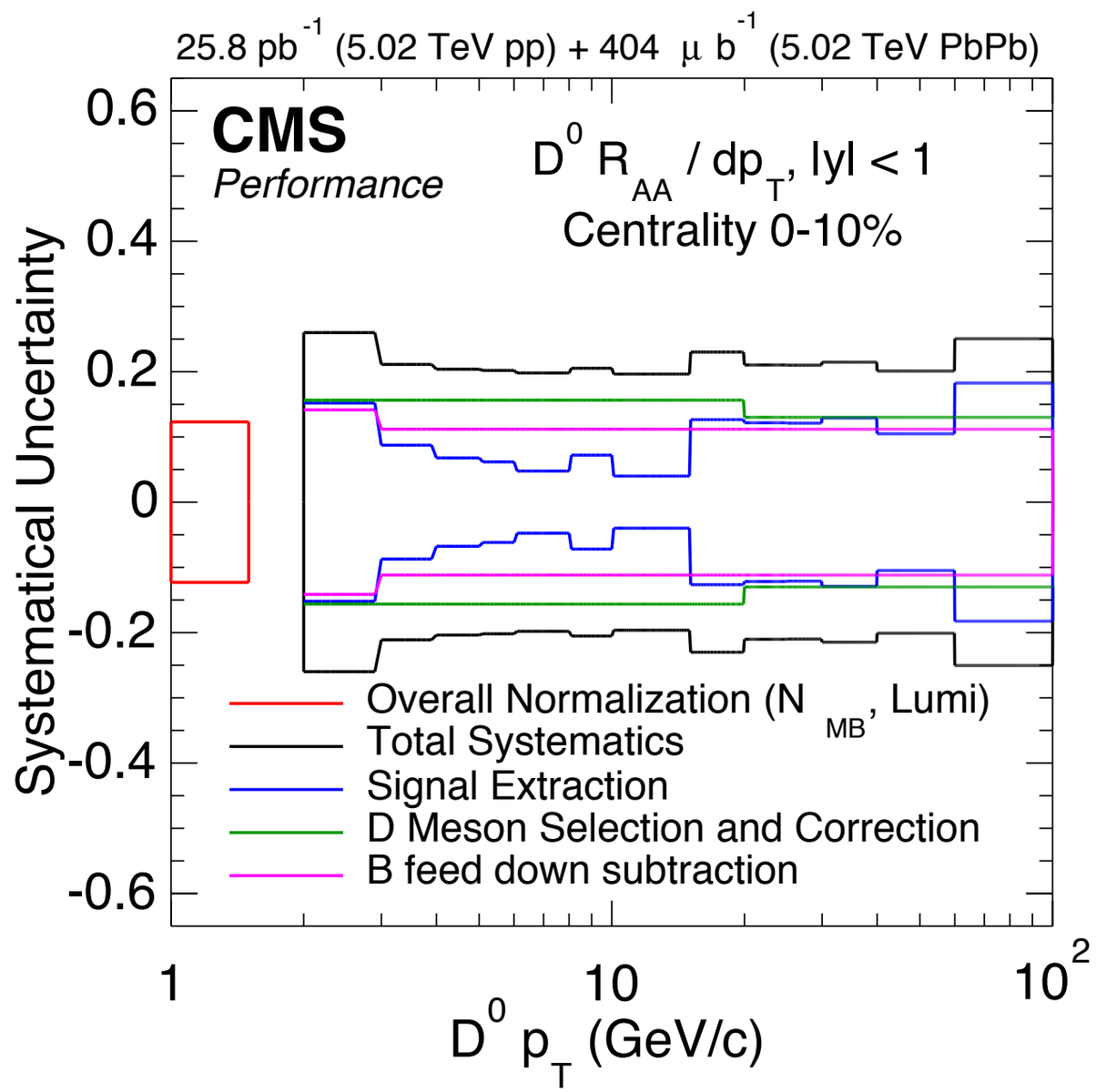


Systematics

pp



PbPb 0-10%



Systematics of fprompt for v_n analysis

- **Systematic uncertainties from non-prompt D^0 are evaluated in a data driven method based on:**
  - **v_n of D^0 with all analysis cut and w/o b_0 cut**
  - **Fractions of prompt D^0 with all analysis cut and w/o b_0 cut**

All analysis cut: $v_{n,1}^{sig} = f_{p,1}\, v_n^{p} + (1-f_{p,1})\, v_n^{np}$

Without b_0 cut: $v_{n,2}^{sig} = f_{p,2}\, v_n^{p} + (1-f_{p,2})\, v_n^{np}$

$$\Rightarrow \quad v_n^{p} = v_{n,1}^{sig} + \frac{1-f_{p,1}}{f_{p,1}-f_{p,2}}\left(v_{n,1}^{sig} - v_{n,2}^{sig}\right)$$

D^0 v_n with all analysis cuts as central value

As systematics from non-prompt D^0