PURDUE
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Open Heavy-flavor Measurements from LHC

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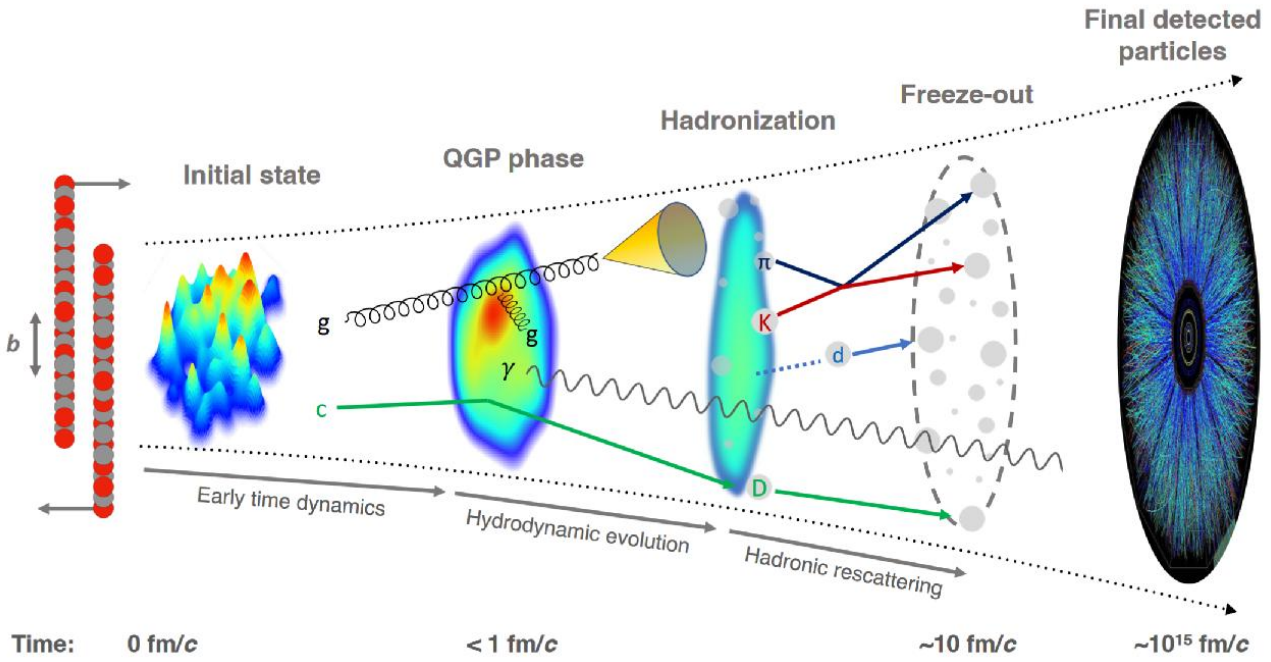
Intersections – CIPANP 2025
Madison, Wisconsin

Evolution of collision

- **Initial states**
  - Pre-equilibrium
  - Highest energy density
- **Quark Gluon Plasma:**
  - Strongly interacting fluid
  - Hydrodynamic evolution
- **Freeze-out & Hadronization**
  - Chemical freeze-out
  - Kinetic freeze-out

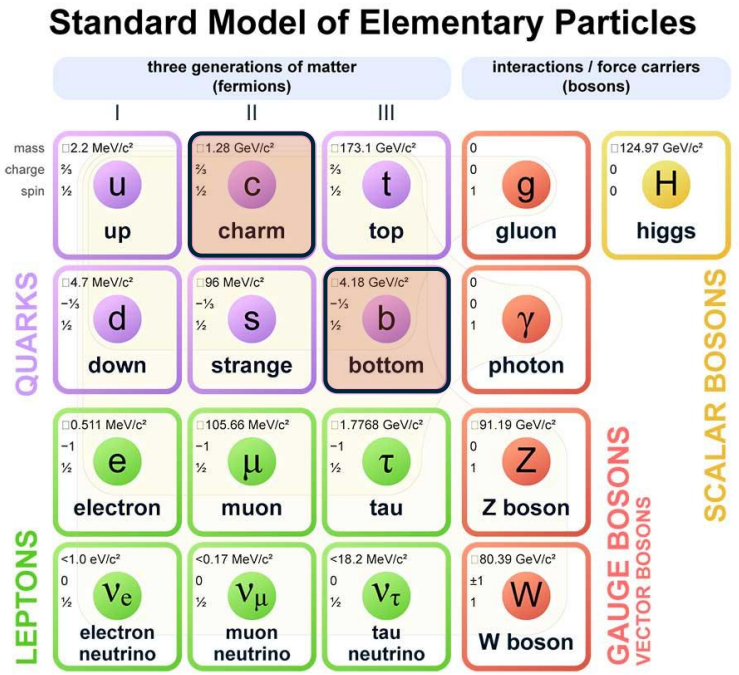


arXiv:2303.17254
Hot QCD White Paper

Heavy Quarks

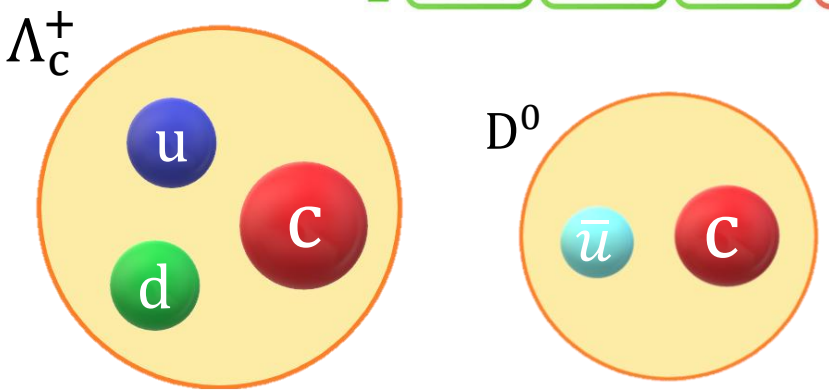
The charm and beauty (bottom) quarks

- Masses much larger than $\Lambda_{\mathrm{QCD}} \sim 200$ MeV
- $m_c \sim 1.27$ GeV/c
- $m_b \sim 4.18$ GeV/c
- Top quark decays fast → no hadronic states

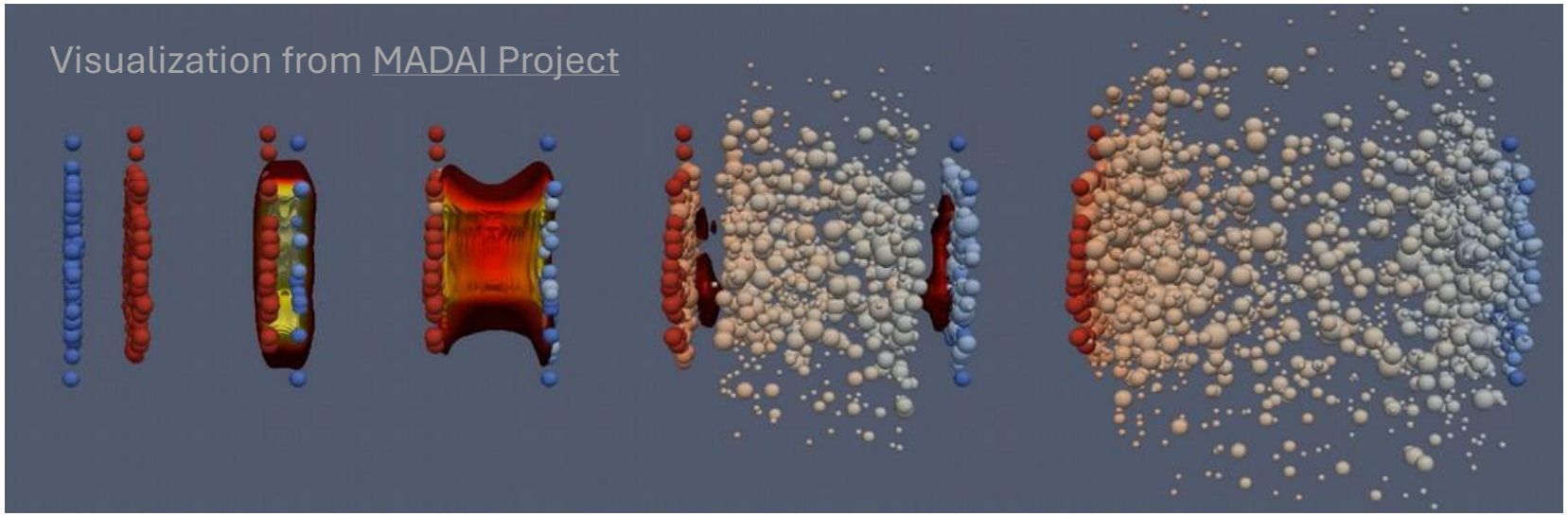


Open heavy-flavor hadrons

- A heavy-quark paired with lighter quarks
- $\Lambda_{\mathrm{C}}(udc), \mathrm{D}^0(\bar{u}c), \Lambda_{\mathrm{B}}(udb), \mathrm{B}^0(\bar{d}b)$



Why Study Heavy Quarks?



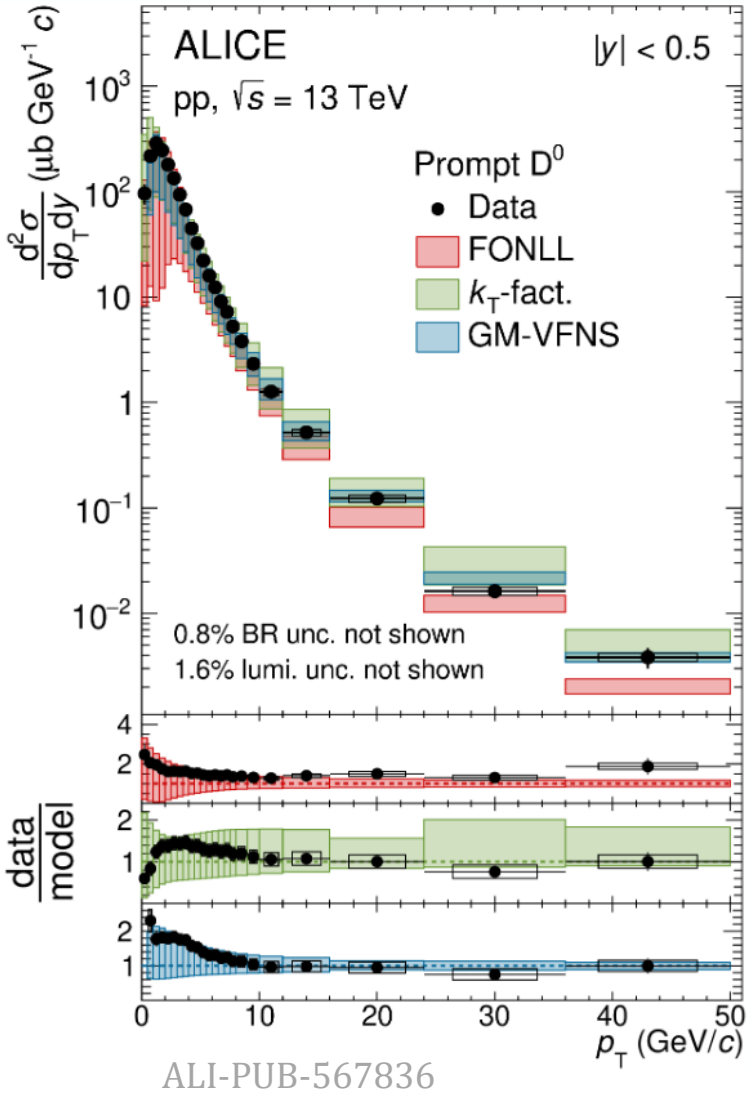
Heavy quarks are formed early in the collision (hard scattering)

- Production can be calculated using pQCD
- Probe of Quark-Gluon Plasma (QGP) medium (in heavy-ion collisions)
- Sensitive to energy loss mechanism and hadronization (fragmentation vs recombination)
- Reference for nuclear modification factor and fragmentation function (in pp collisions)

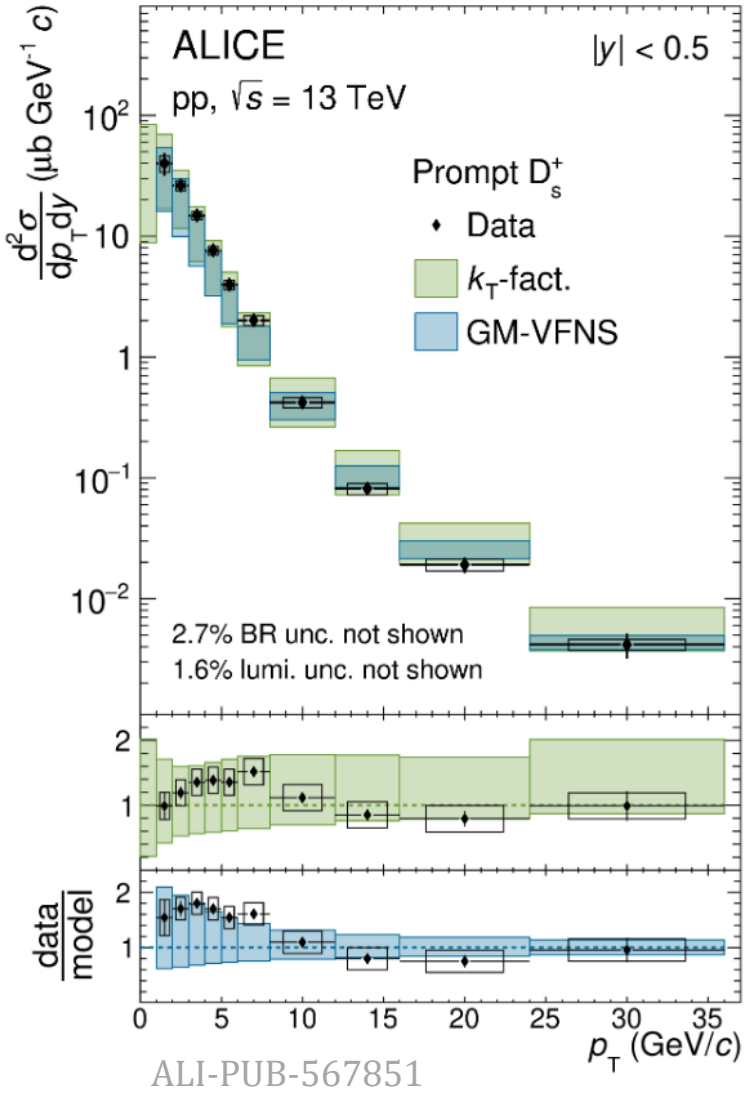
LHC Experiments

- **ALICE**: Optimized for heavy-ion collisions
  - Excellent particle identification (PID) at mid-rapidity
  - Good at reconstructing low-p_{T} heavy-flavor hadrons
- **CMS and ATLAS**: General-purpose detectors with good tracking and calorimetry
  - Capable of measuring high- p_{T} heavy flavors
  - Reconstructing decays to muons and electrons
- **LHCb**: Forward spectrometer, specialized in heavy-flavor physics at forward rapidity
  - Excellent vertex resolution and PID

Prompt D^0 and D_s^+ in pp collisions



ALI-PUB-567836

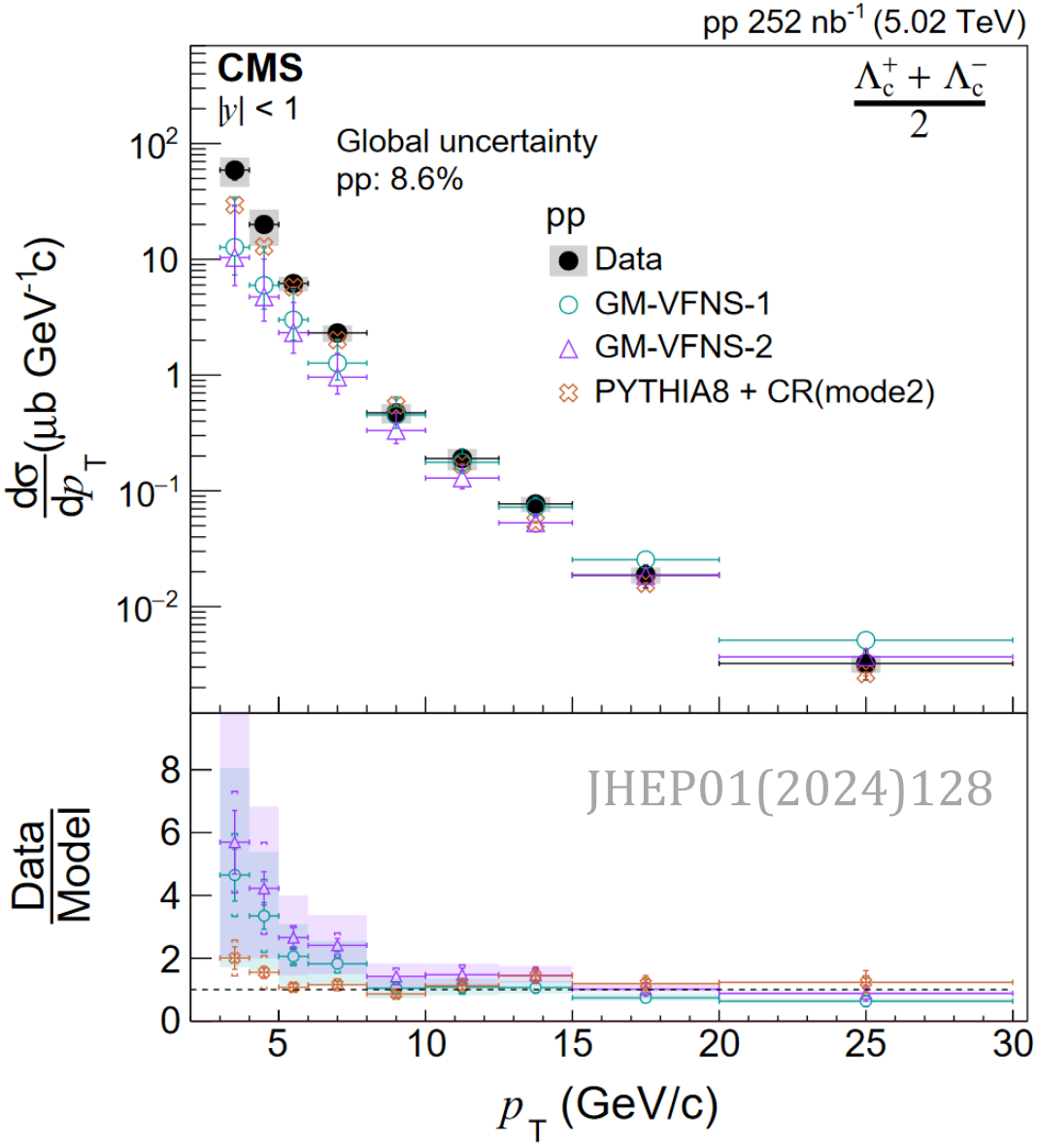


ALI-PUB-567851

- Prompt charm meson produced from hadronization or decay of excited charm hadrons
- p_{T} – differential cross-section described well by p-QCD calculations

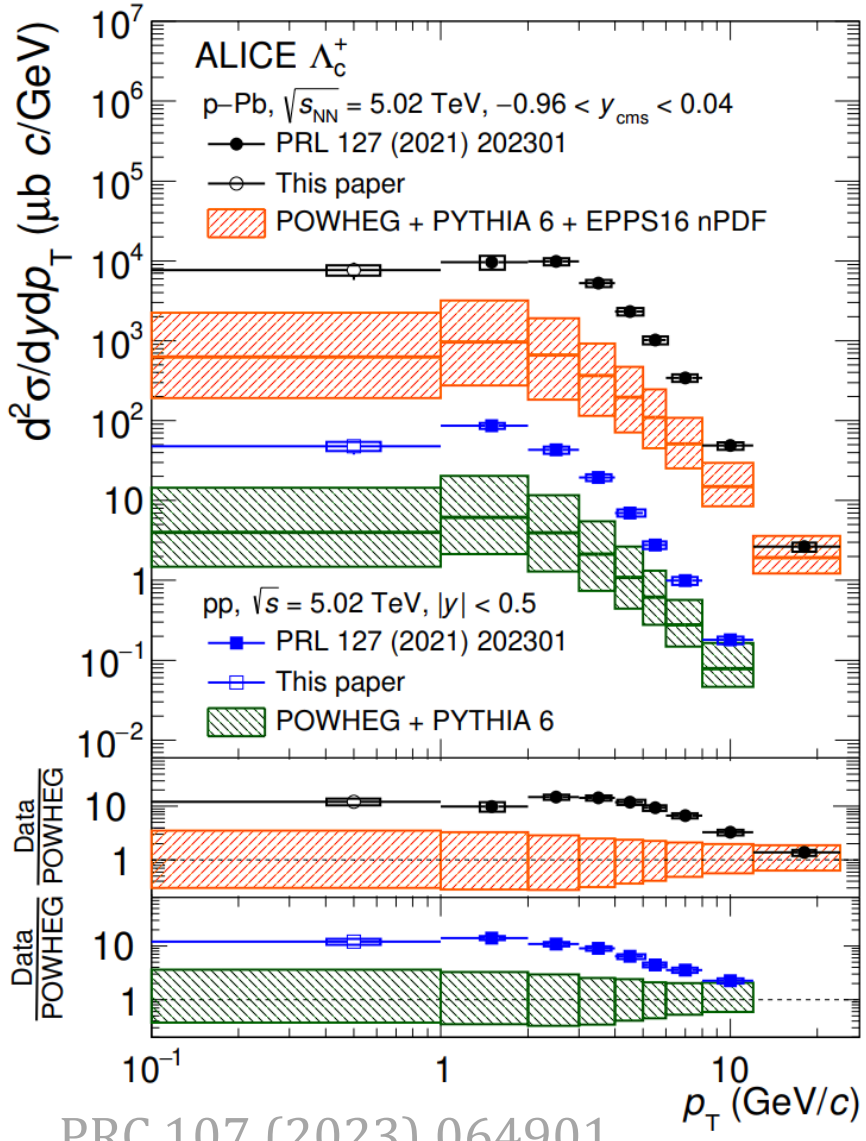
JHEP 12 (2023) 086

Prompt Λ_c^+ in pp collisions



- PYTHIA8+CR(mode2) is consistent with pp data.
  - Final partons in the string fragmentation are color connected to minimize total string length
- GM-VFNS systematically below data for $p_T < 10$ GeV/c
  - Fragmentation tuned from Belle/OPAL (e^+e^- data)
  - Breakdown of the universality of charm quark fragmentation functions?

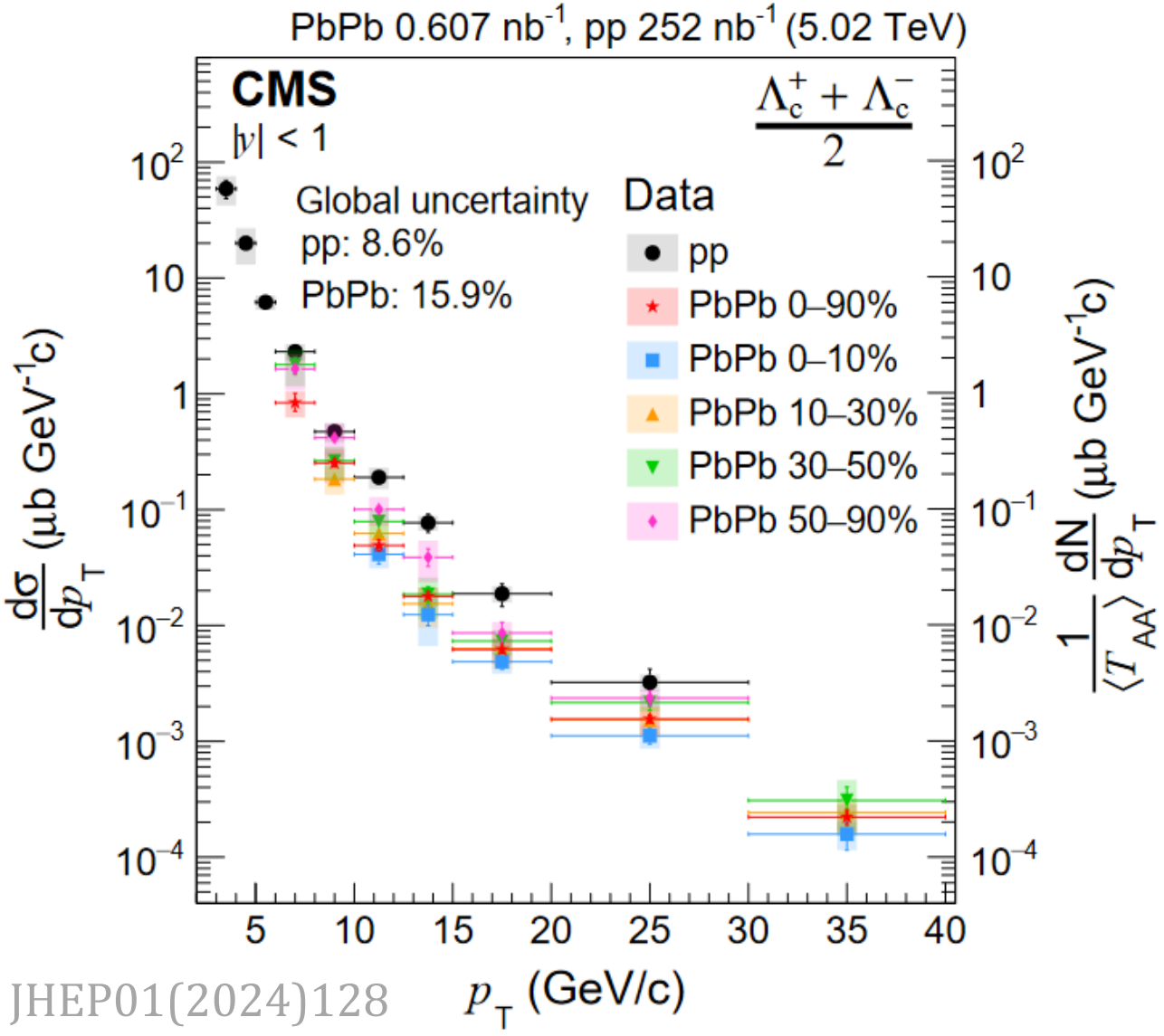
Prompt Λ_c^+ in pp & pPb collisions



PRC 107 (2023) 064901

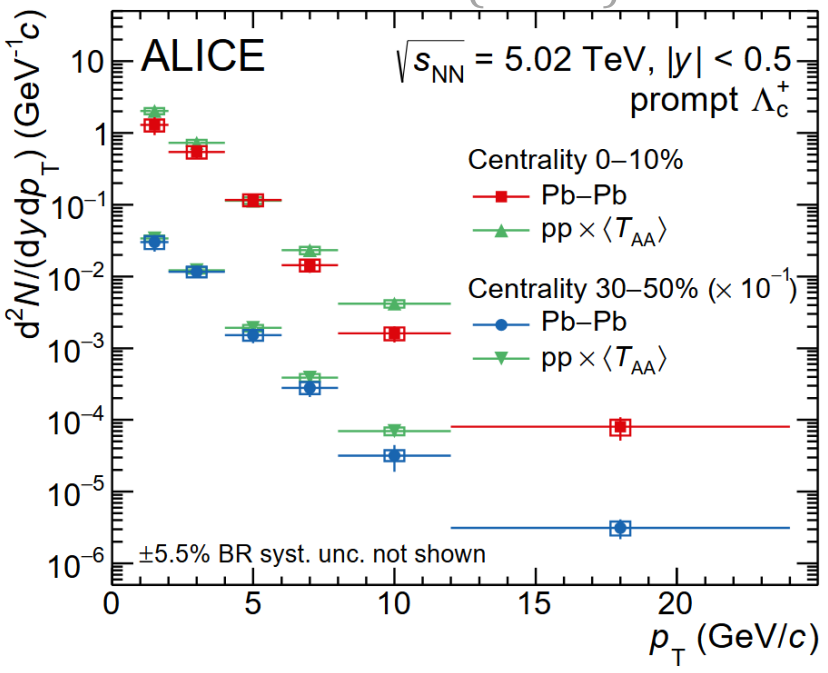
- Λ_c^+ p_T spectra measured in pp and pPb collisions
- Comparison with POWHEG+PYTHIA6 shows the production is underestimated, especially at low p_T

Prompt Λ_c^+ in PbPb collisions



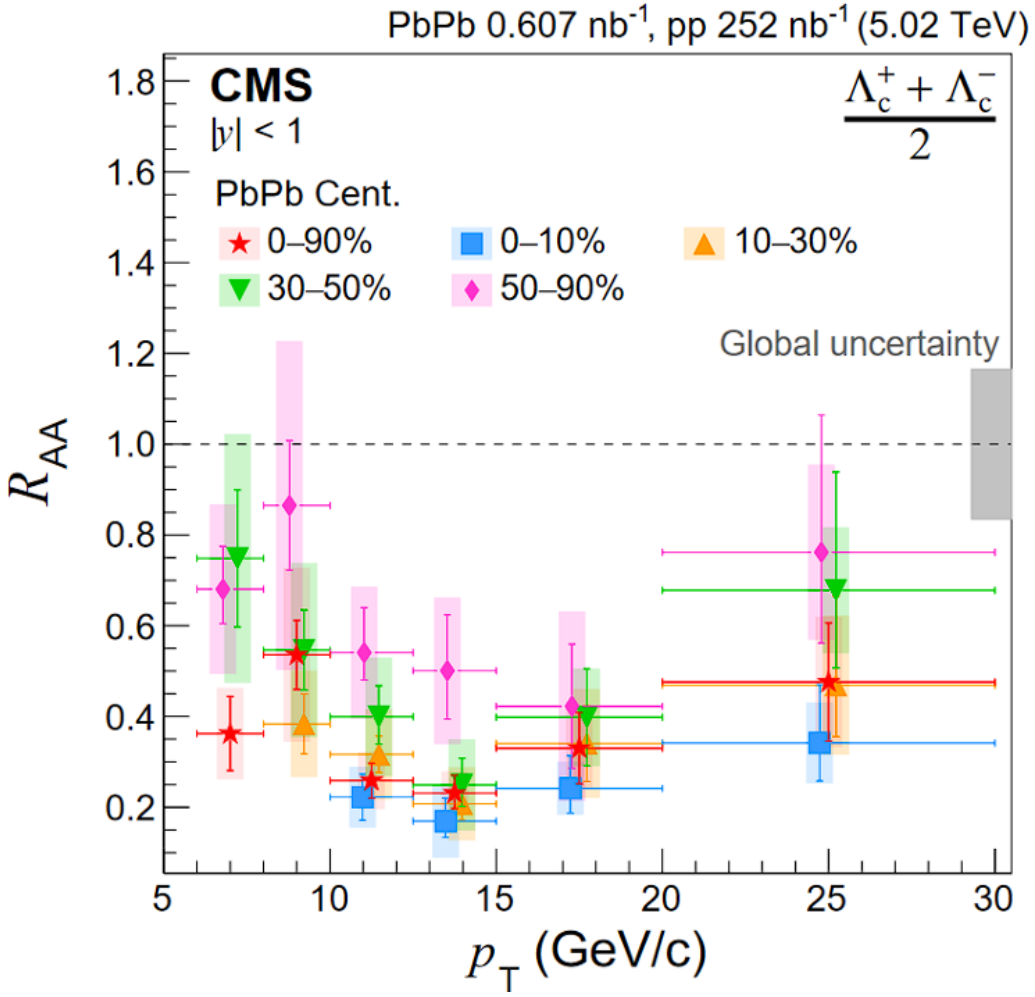
JHEP01(2024)128

PLB 839 (2023) 137796



- Λ_c^+ p_T spectra measured for 4 centrality classes, and inclusive centrality (0-90%)
- For $p_T > 10$ GeV/c, the T_{AA} scaled yields of PbPb systematically lower than cross-section in pp collision.

Prompt Λ_c^+ R_{AA}



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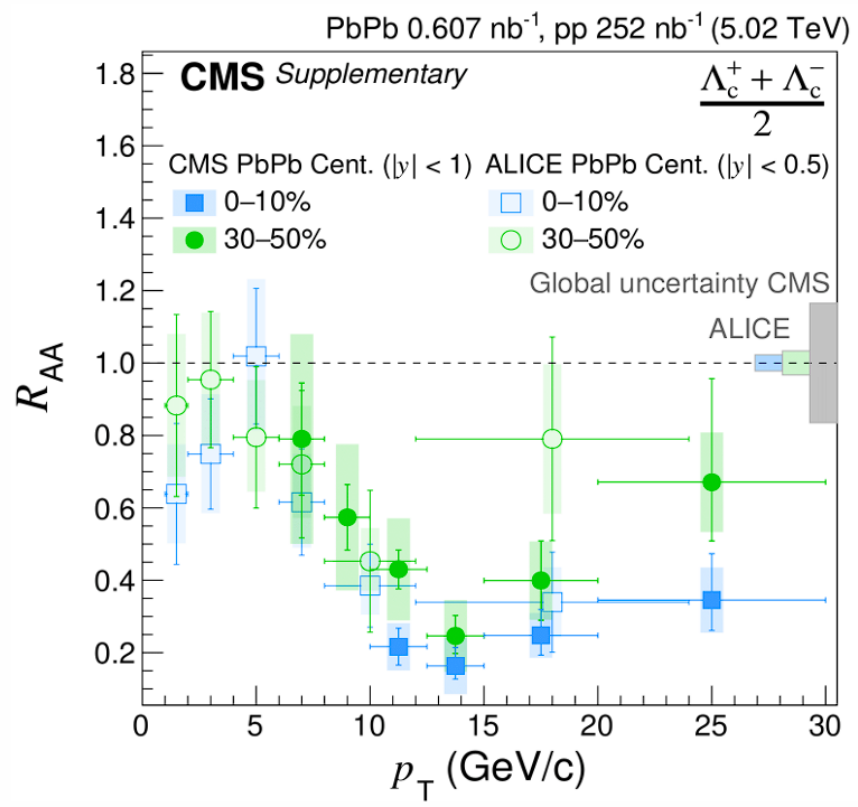
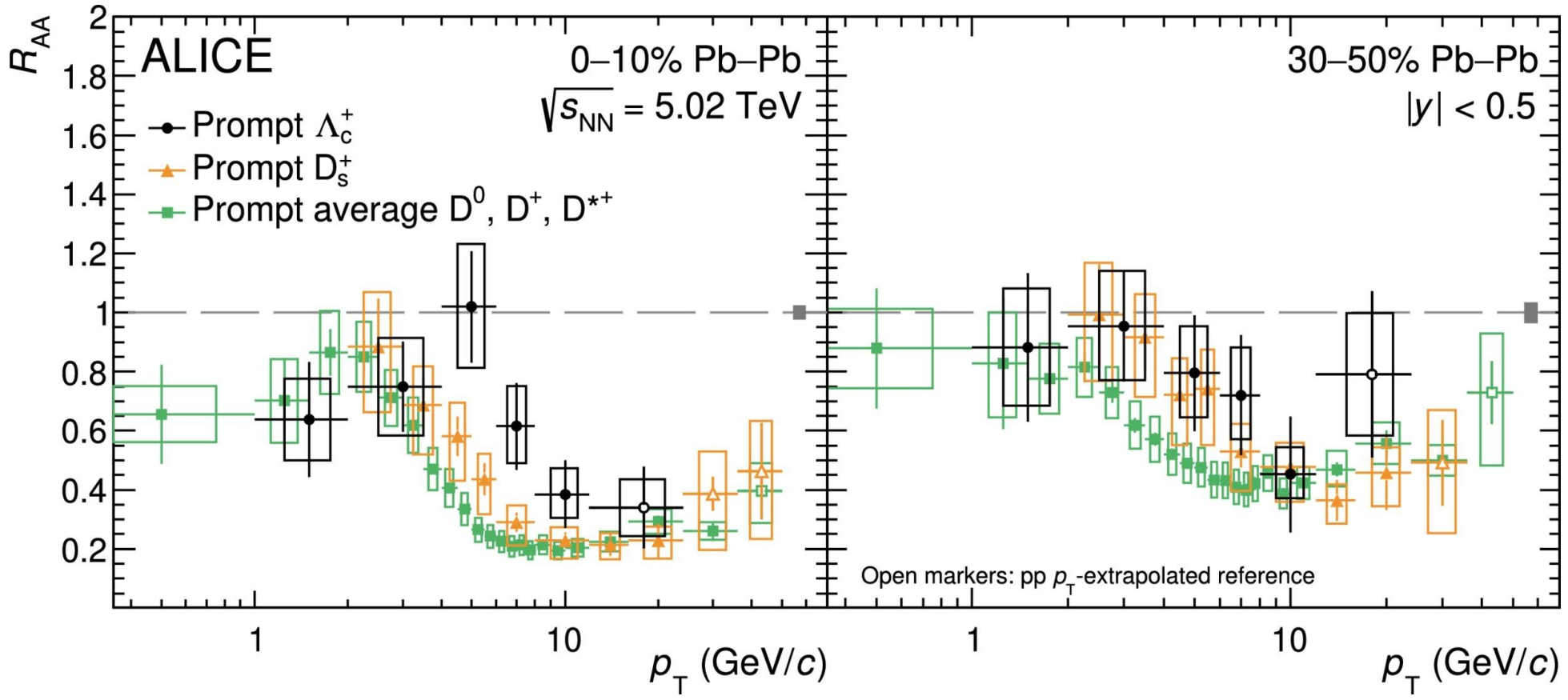


- Larger suppression of Λ_c^+ production for central PbPb collisions
- R_{AA} decreases from low p_T up to ~14 GeV/c, then increases for higher p_T

Prompt Λ_c^+ R_{AA}

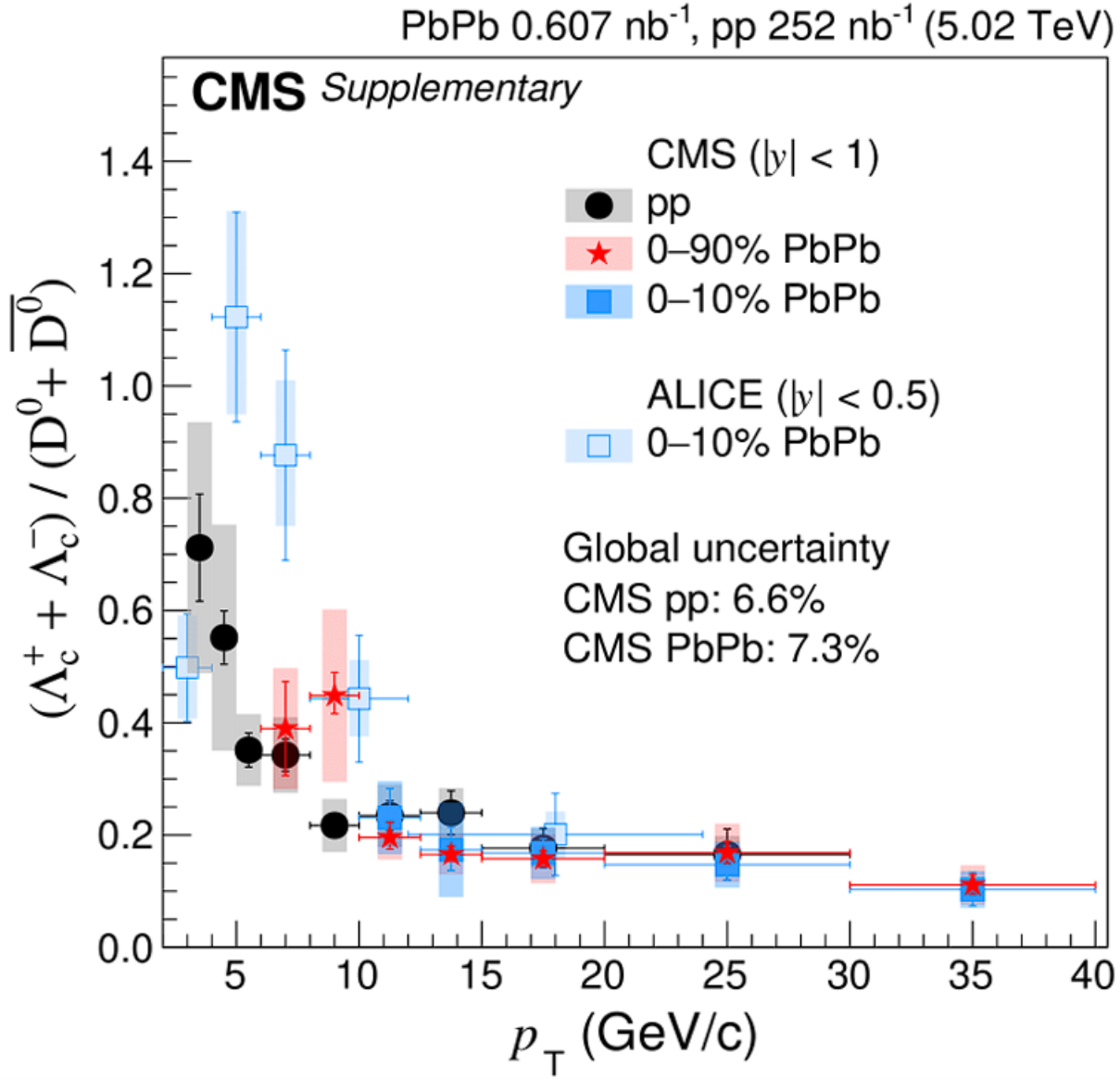
PLB 839 (2023) 137796

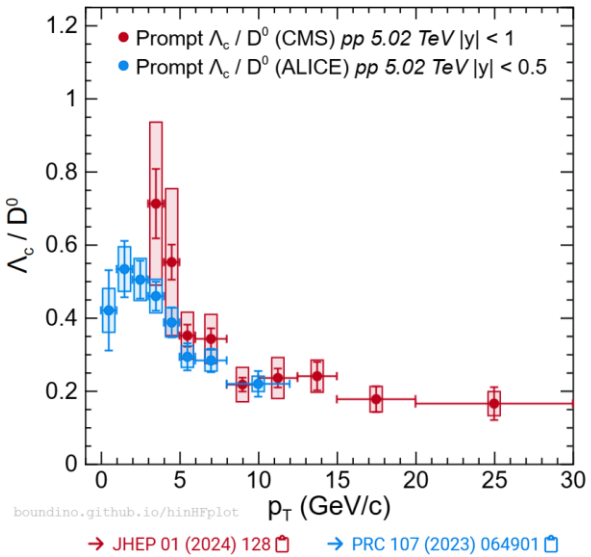


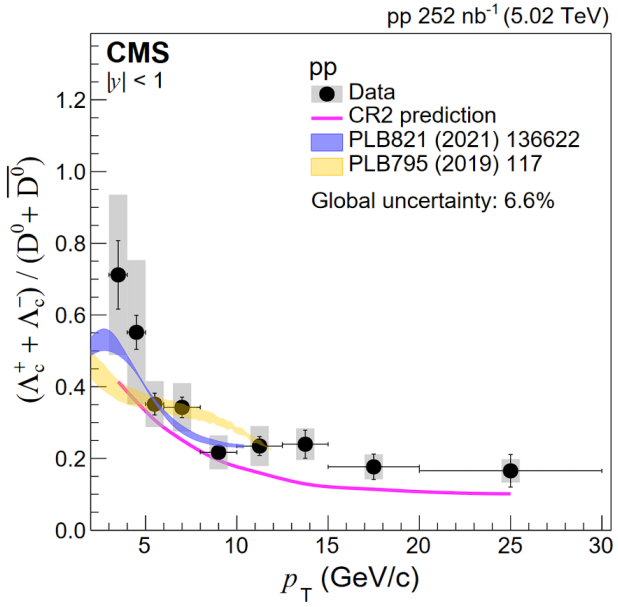
- Similar trend observed for prompt D meson measurements
- For $4-8$ GeV/c in $0-10\%$ centrality, ordering of $D < D_s < \Lambda_c$ is observed

Prompt Λ_c^+/D^0 ratio

JHEP01(2024)128

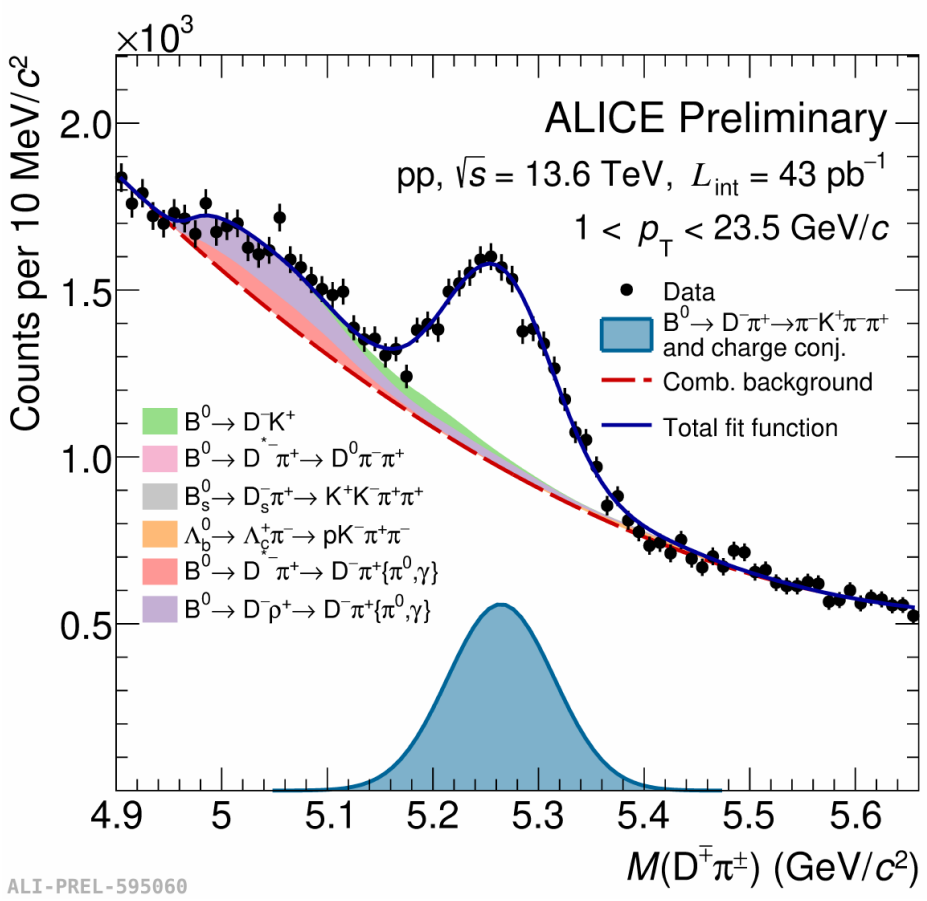


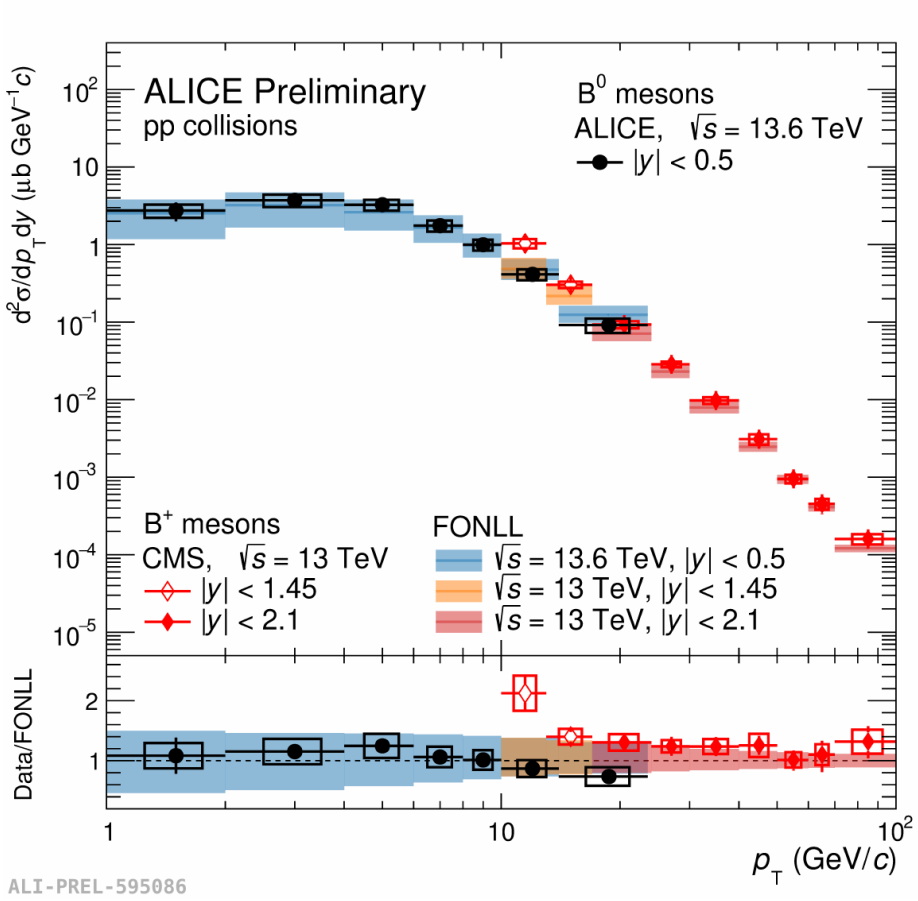




- Λ_c^+/D^0 ratio for PbPb is consistent with pp data for $p_T > 10$ GeV/c.
  - Coalescence process does not play a significant role for high p_T
- Ratio consistent with e^+e^- for higher p_T region
- Results consistent between CMS and ALICE

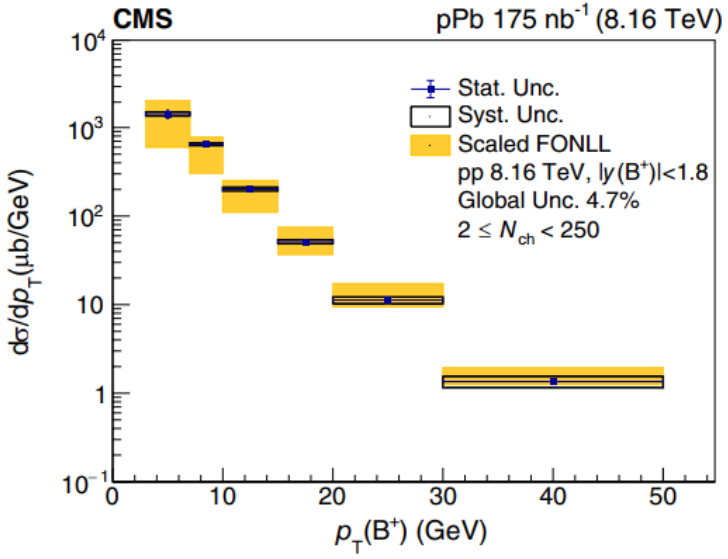
B^0 meson production in pp collisions

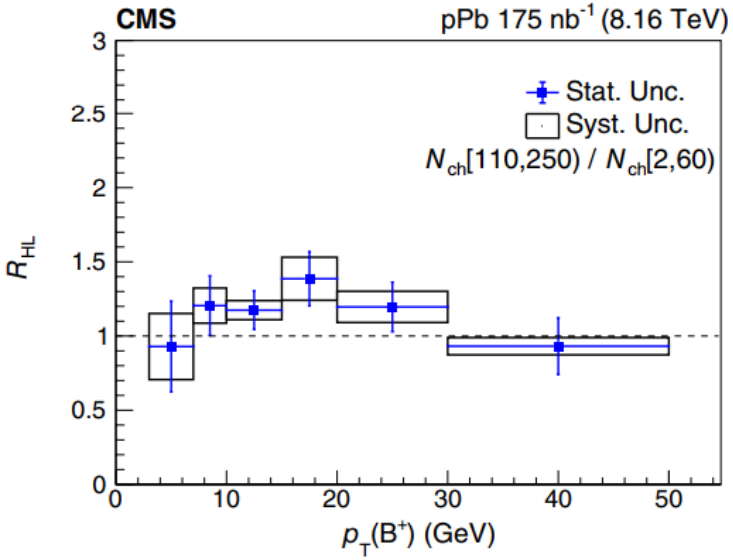


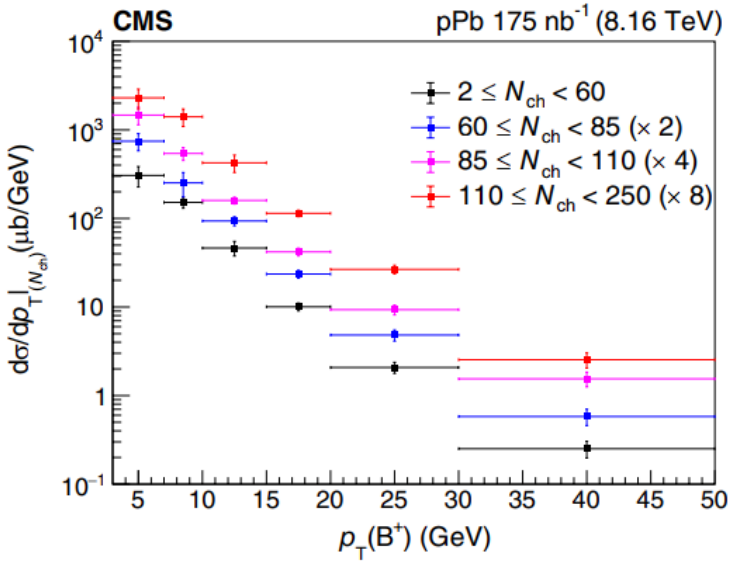


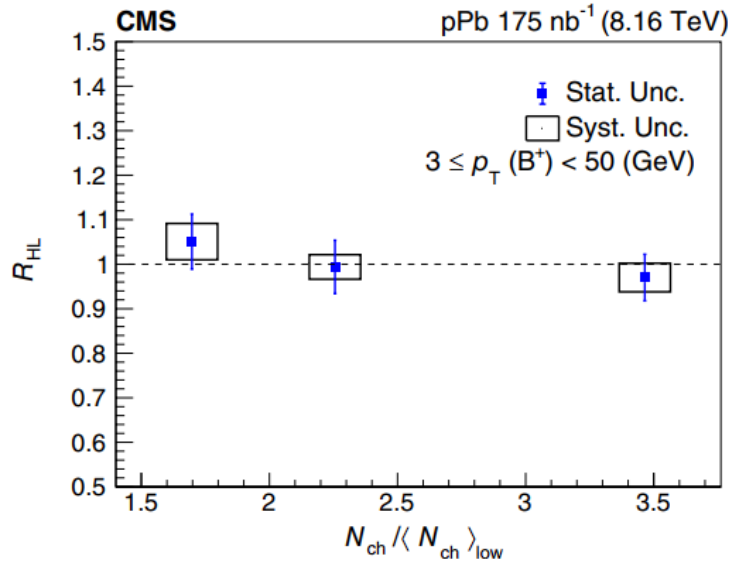
- B^0 measurement (first direct detection) to low p_T
- In agreement with FONLL predictions

B^+ meson production in pPb collisions







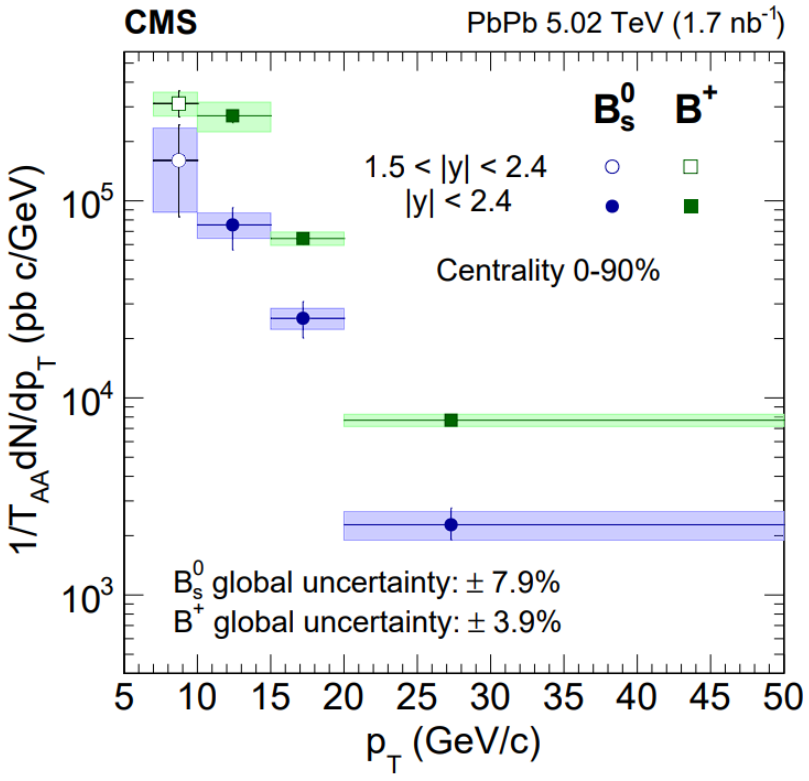


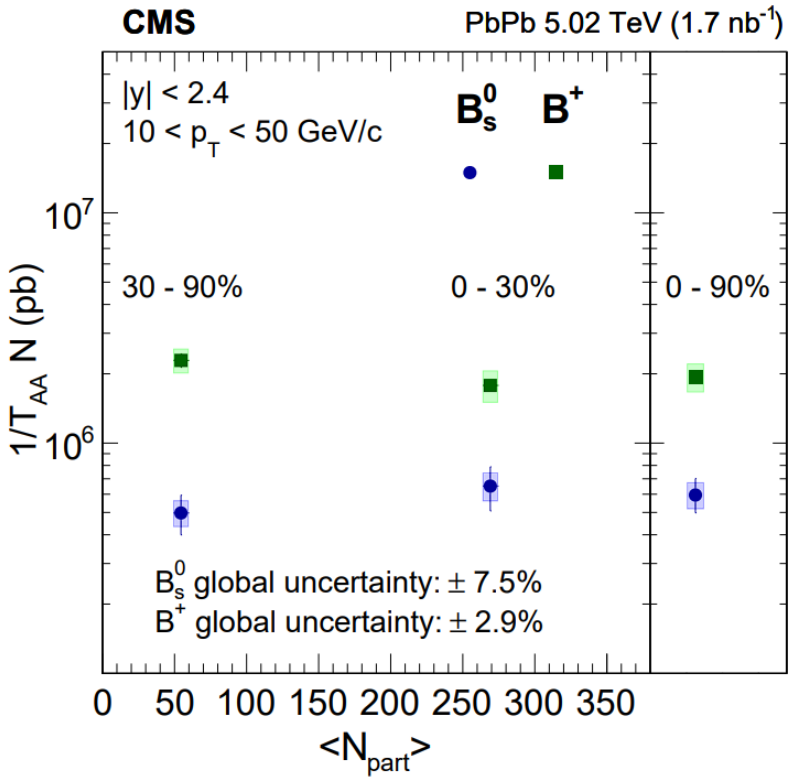
- B^+ production in pPb collisions (first measurement in different N_{ch} classes)
  - $B^+ \rightarrow J/\psi\, K^+$
- Consistent with FONLL predictions
- The production ratio in high and low multiplicity consistent with 1

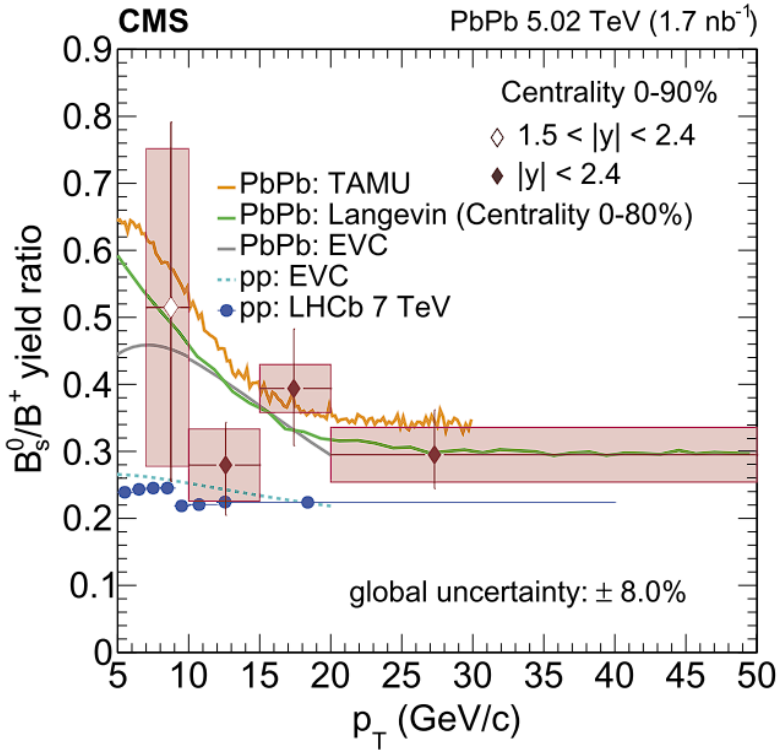
PRL 134 (2025) 111903

B meson production

PLB 829 (2022) 137062



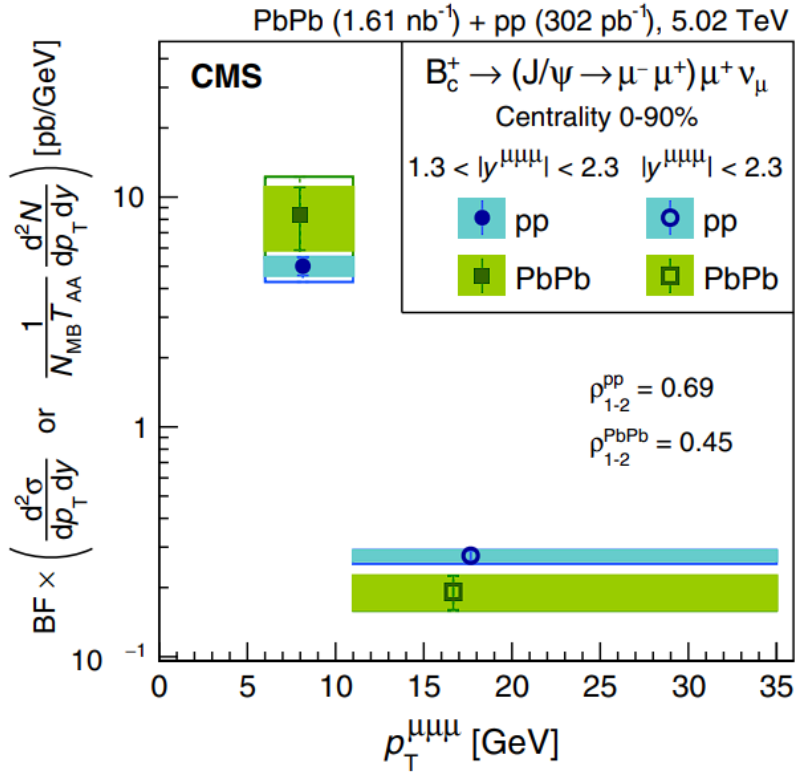


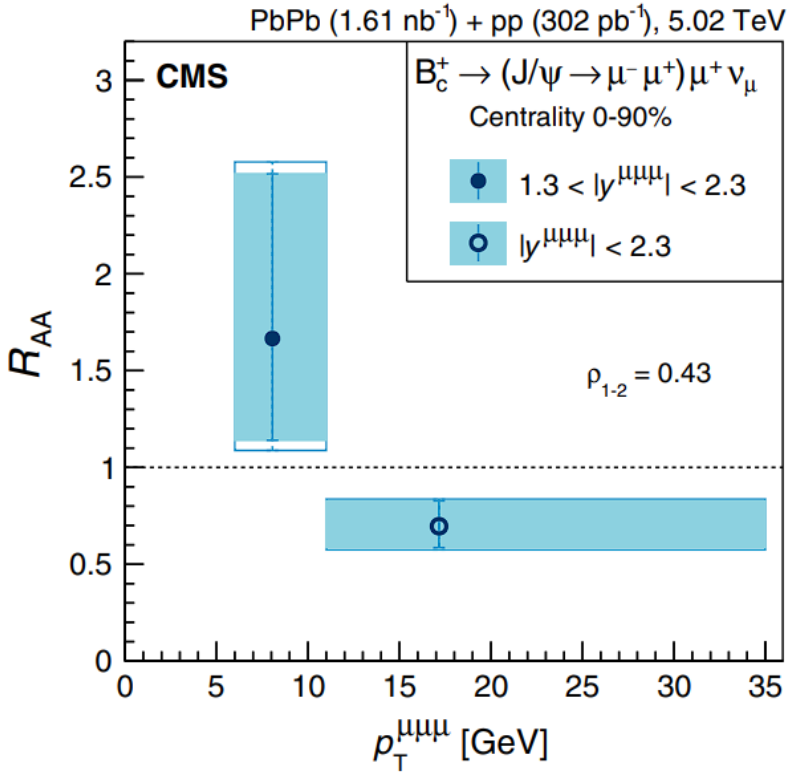


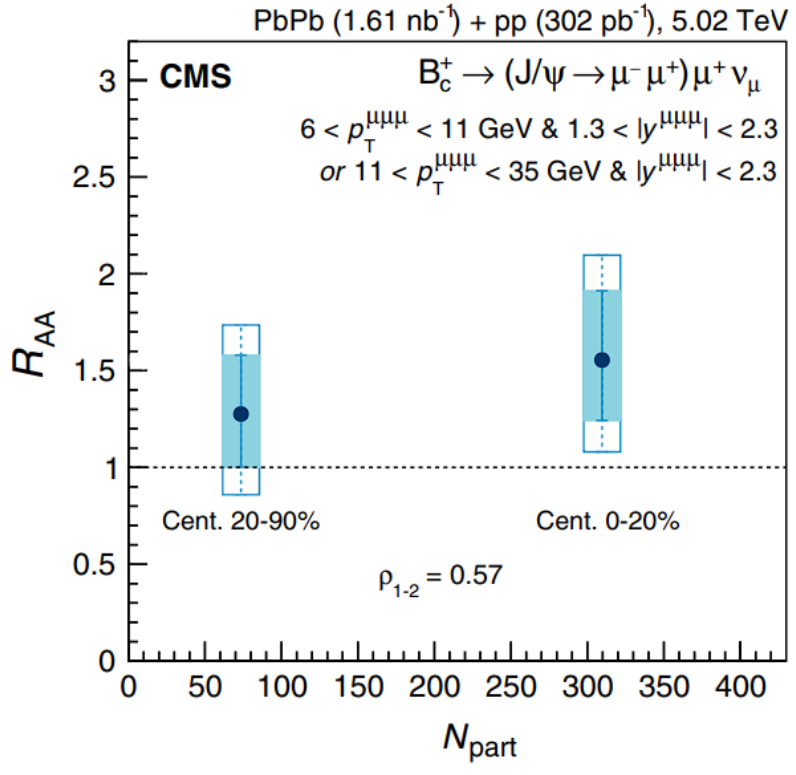
- B^+ & B_s^0 measurement by CMS at high p_T
- Compatible with pp collisions and model predictions

B_c^+ meson production

PRL 128 (2022) 252301





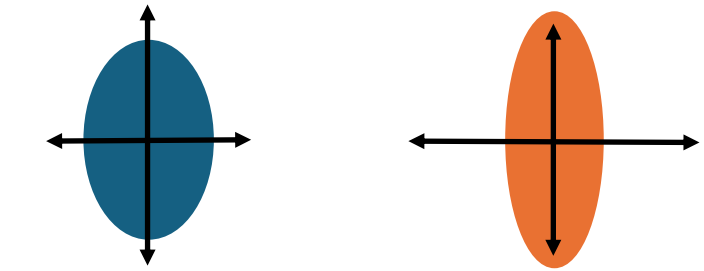


- First B_c^+ measurement by CMS in pp and PbPb collisions
  - Using leptonic decay channel
  - Enhanced production in low p_T and suppression at high p_T

Anisotropic flow (v_n)

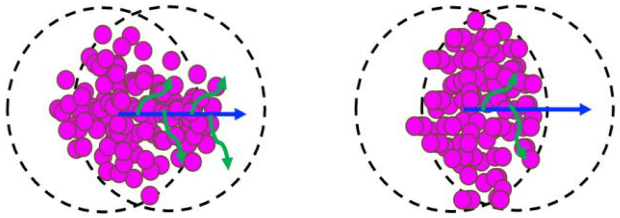
In Heavy-ion collisions (mainly)

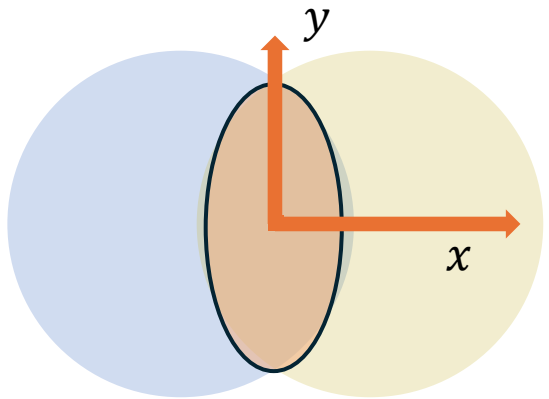
- Non-central collisions → spatial anisotropy
- Anisotropic distribution in ϕ
- Insight into medium interaction



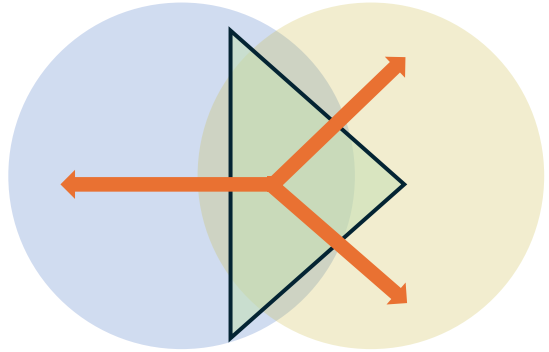
Low ε_2 (q_2)

High ε_2 (q_2)



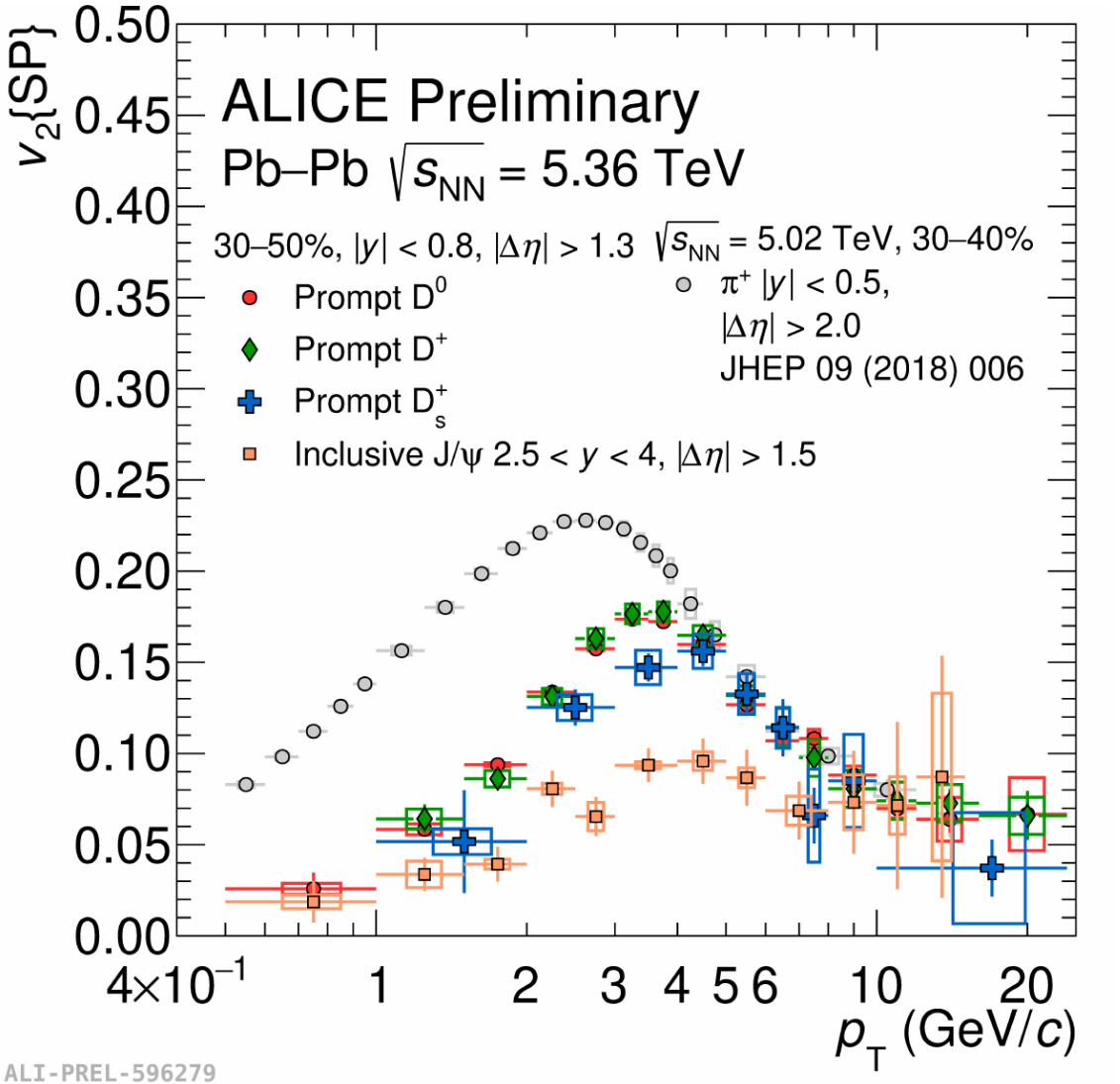


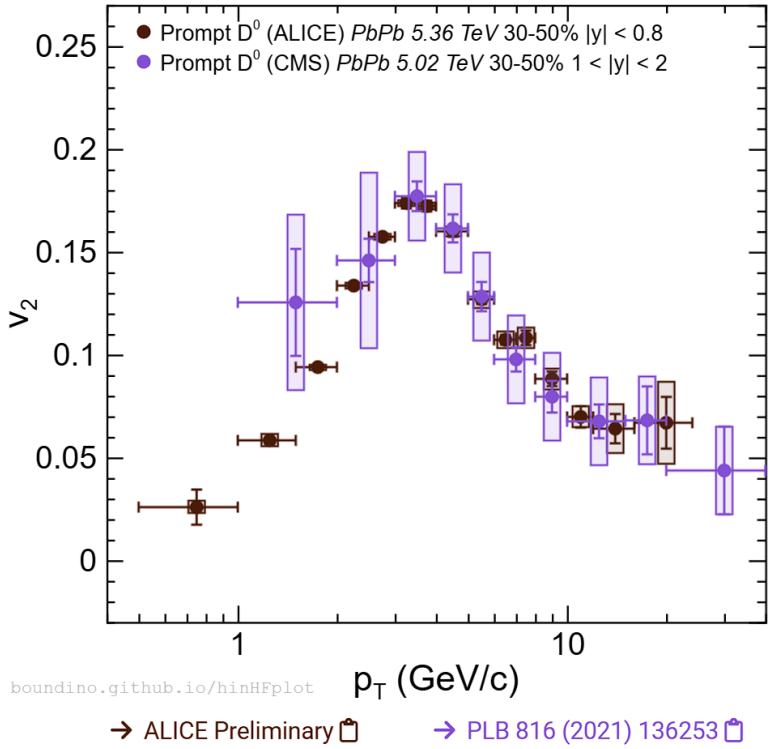
Elliptic flow, v_2



Triangular flow, v_3

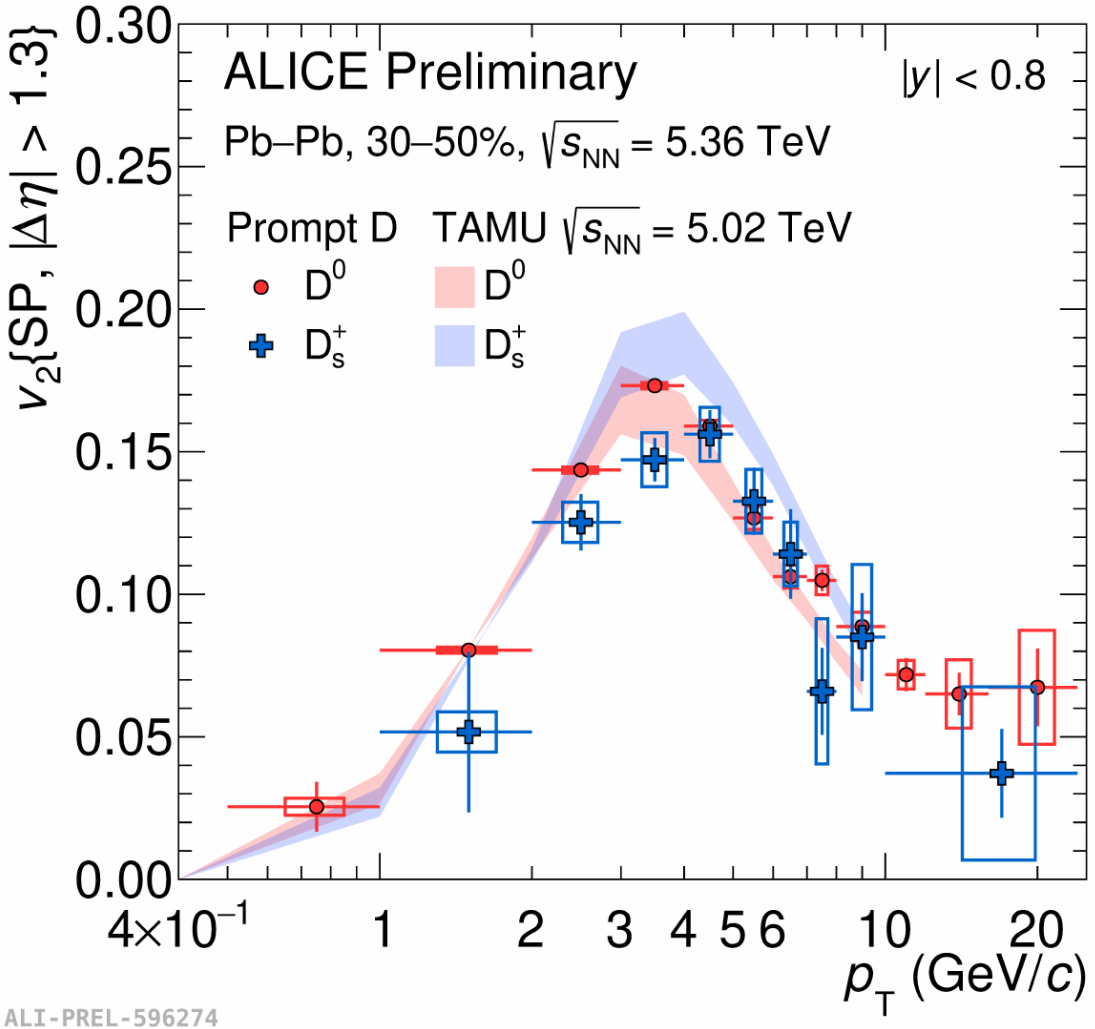
Prompt D flow in PbPb collisions

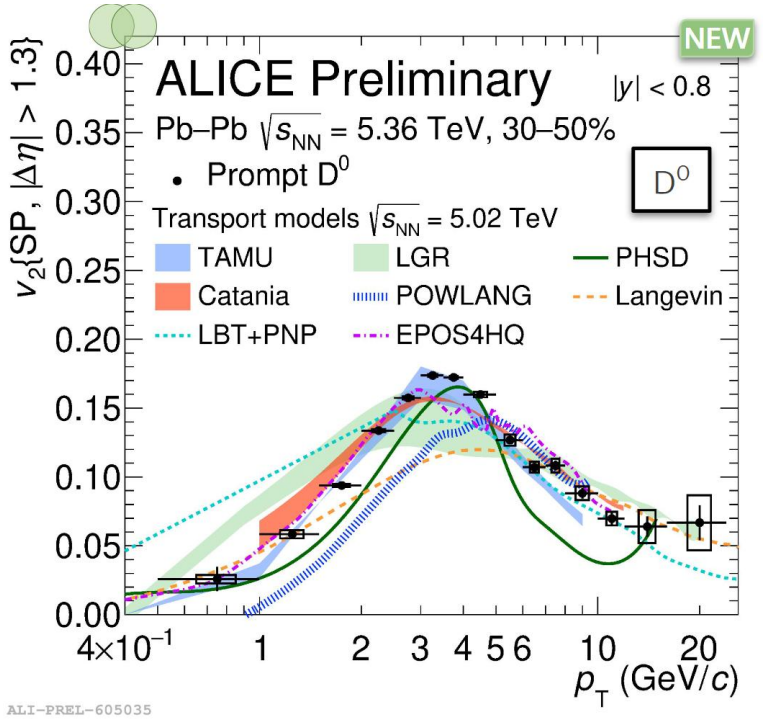




- First measurement of D^0 v_2 below 1 GeV/c
- Consistent with D^+ and D_s^+ ($p_T > 4$ GeV/c)

Prompt D flow in PbPb collisions

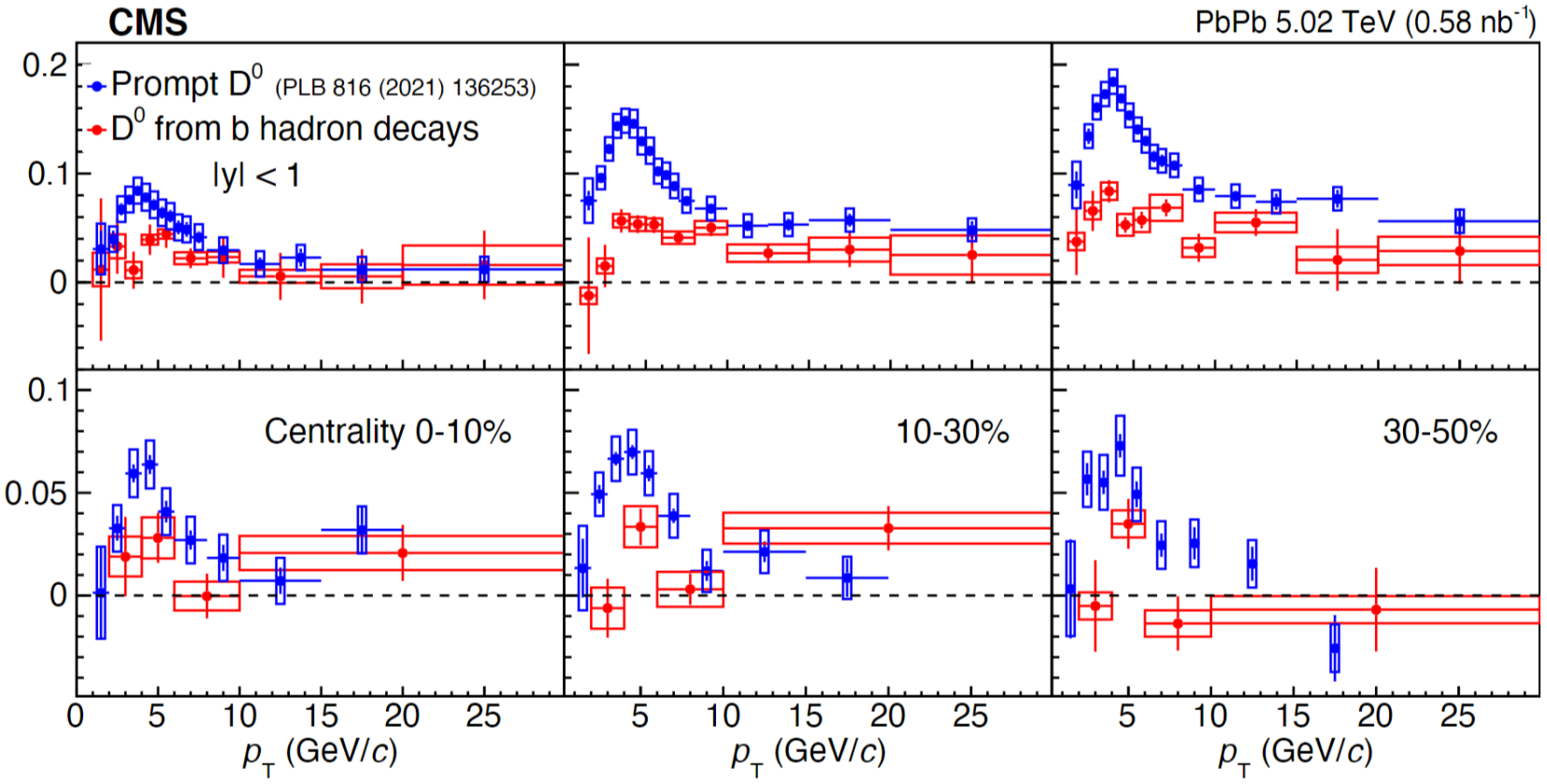


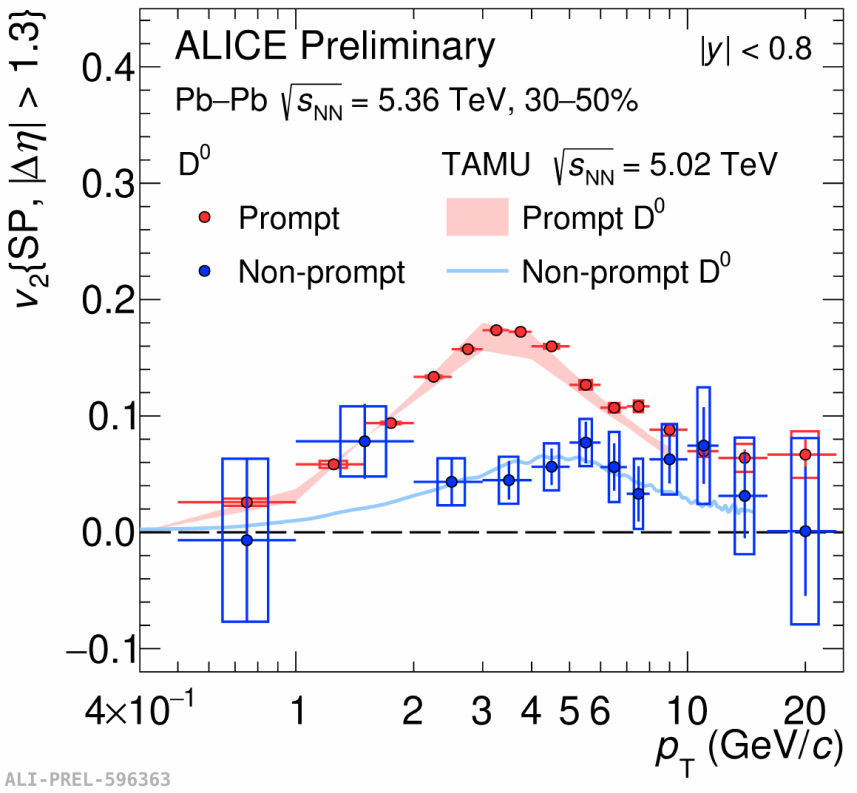


- First measurement of D^0 v_2 below 1 GeV/c
- Consistent with D^+ and D_s^+ ($p_T > 4$ GeV/c)

Prompt/non-prompt D^0 flow

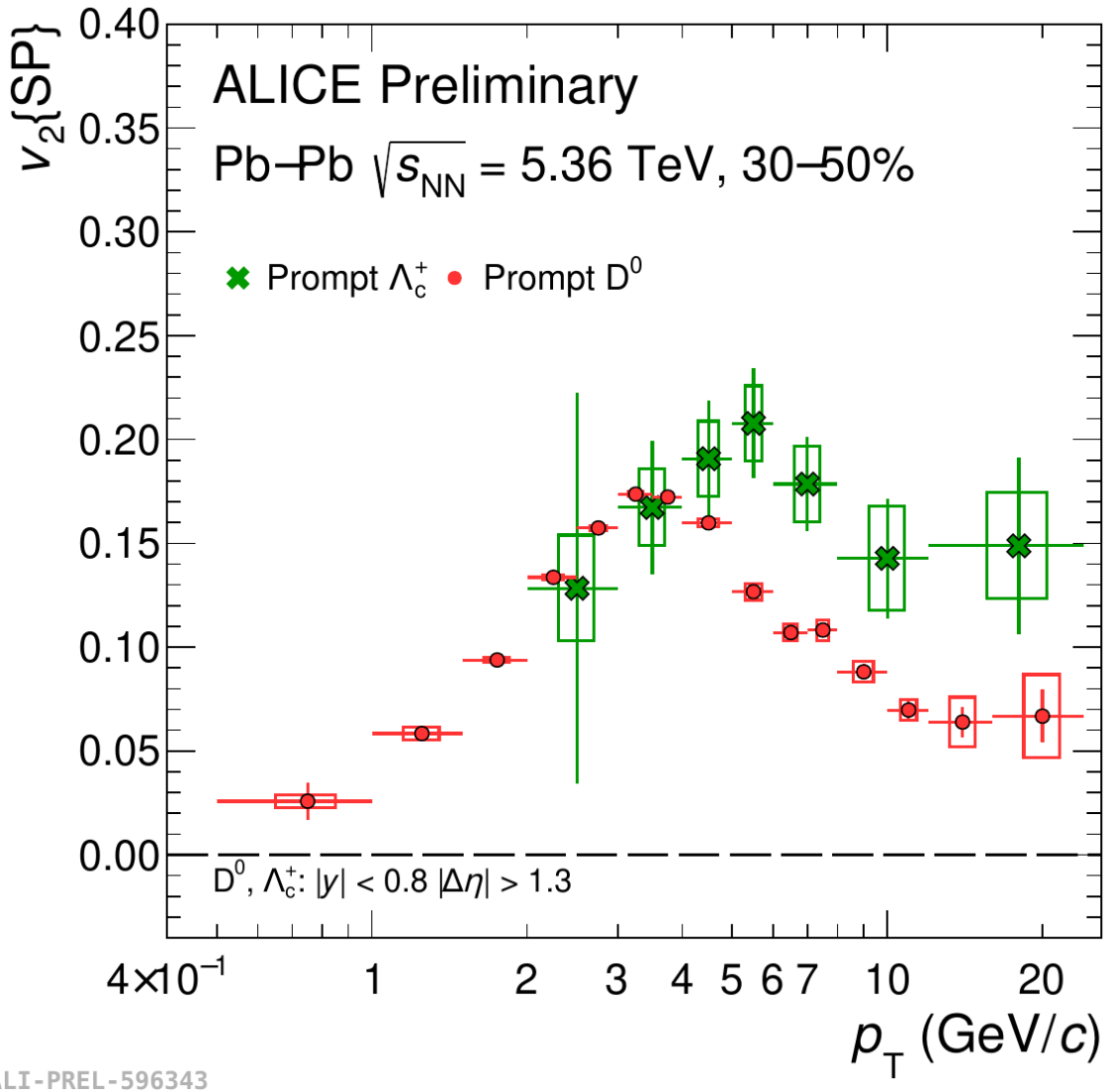
PLB 850 (2023) 138389





- Mass ordering of v_n (b-quark flow < c-quark flow)
- Indication of nonzero v_3 for non-prompt D^0

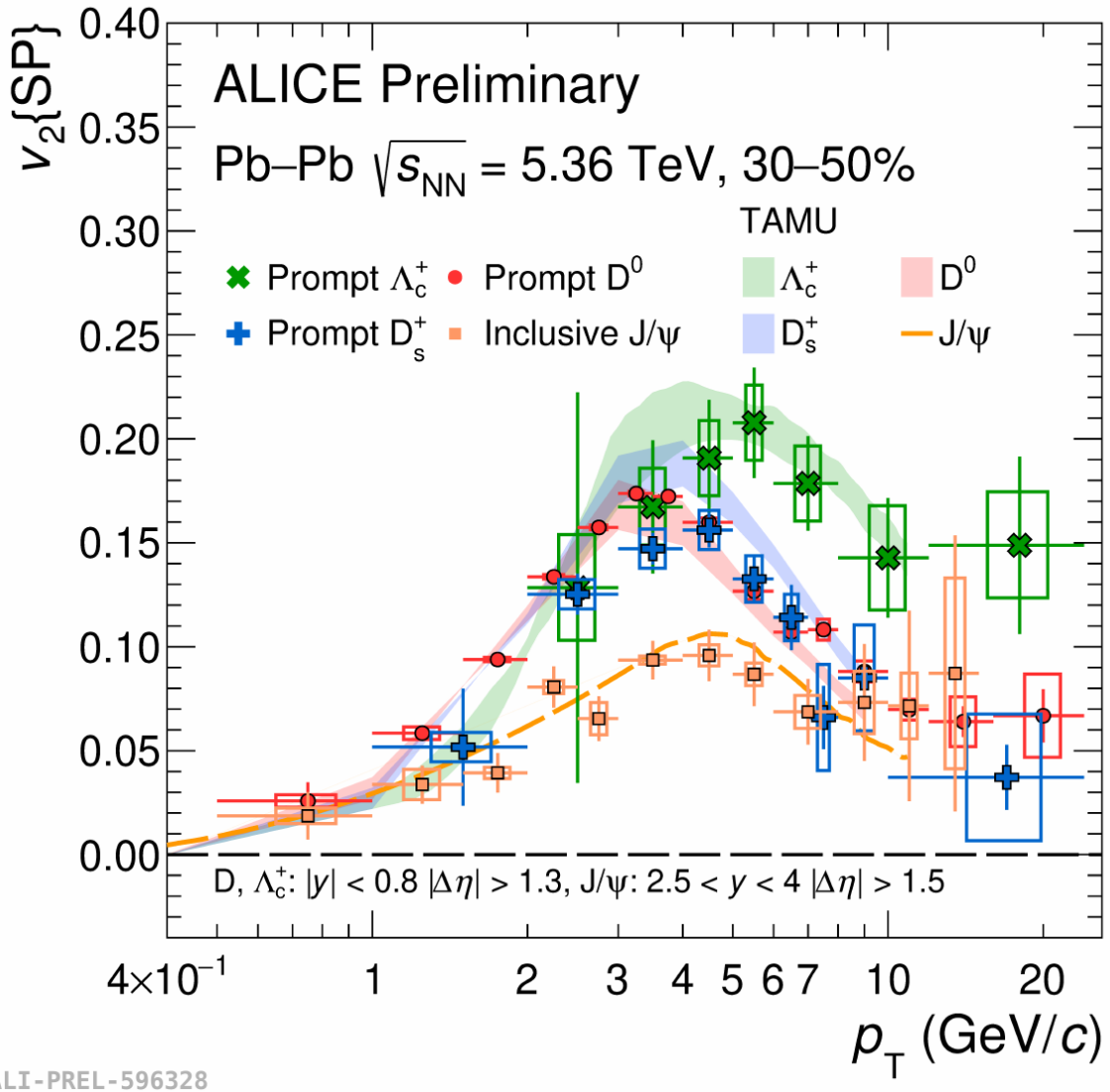
Prompt Λ_c^+ flow in PbPb collisions

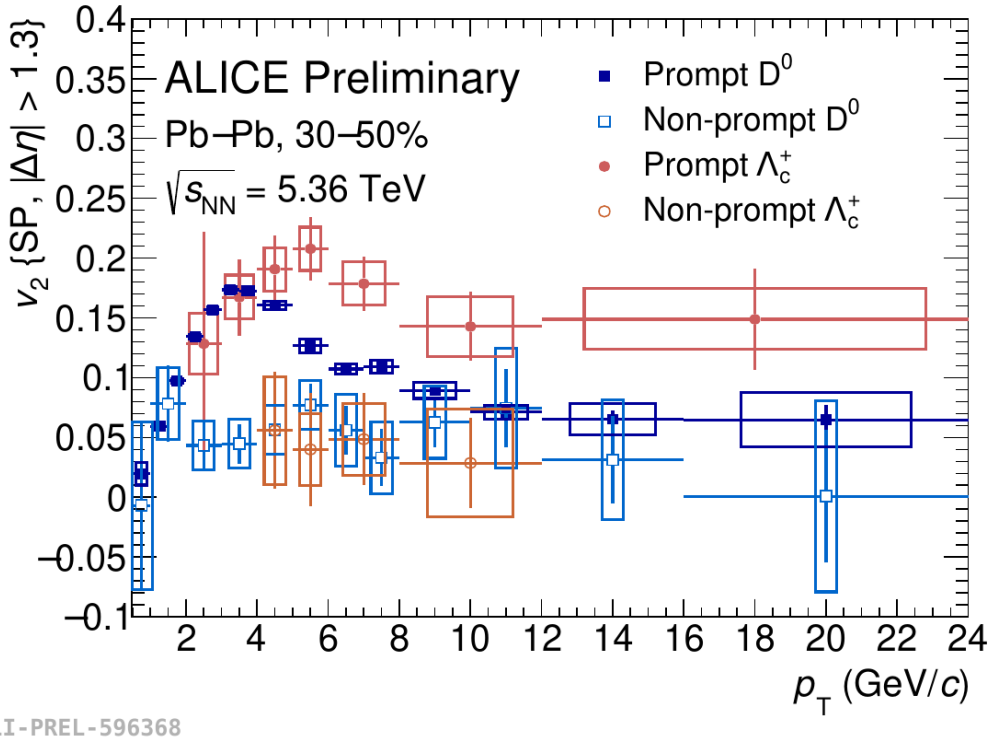


ALI-PREL-596343

- First measurement of Λ_c^+ v_2 in PbPb collisions ($p_T < 3$ GeV/c) in 30-50%
  - Below 4 GeV, v_2 consistent with D
  - Intermediate p_T, larger than D ($3.6\,\sigma$) → "Evidence of charm baryon/meson splitting"

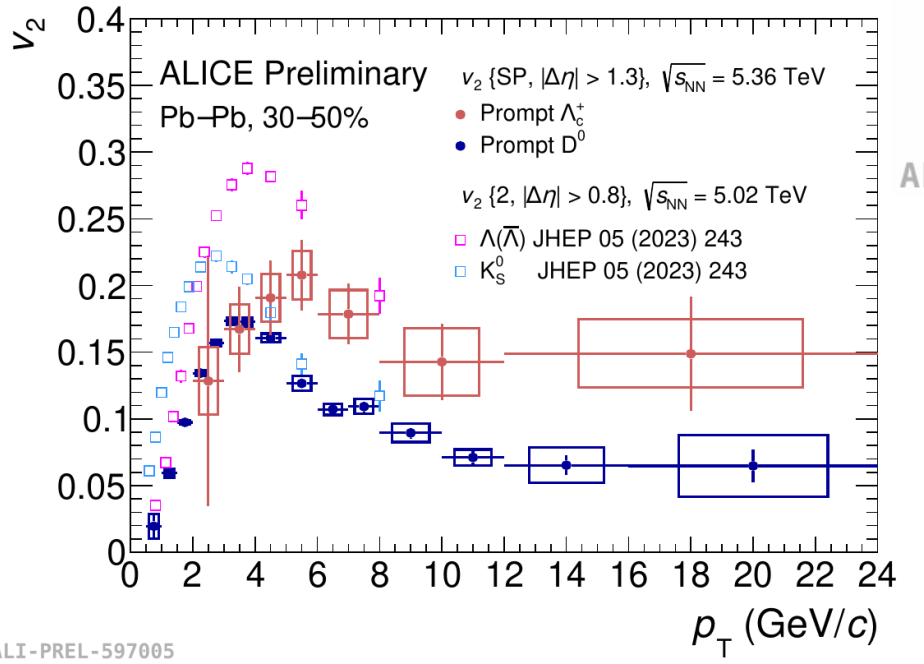
Prompt Λ_c^+ flow in PbPb collisions

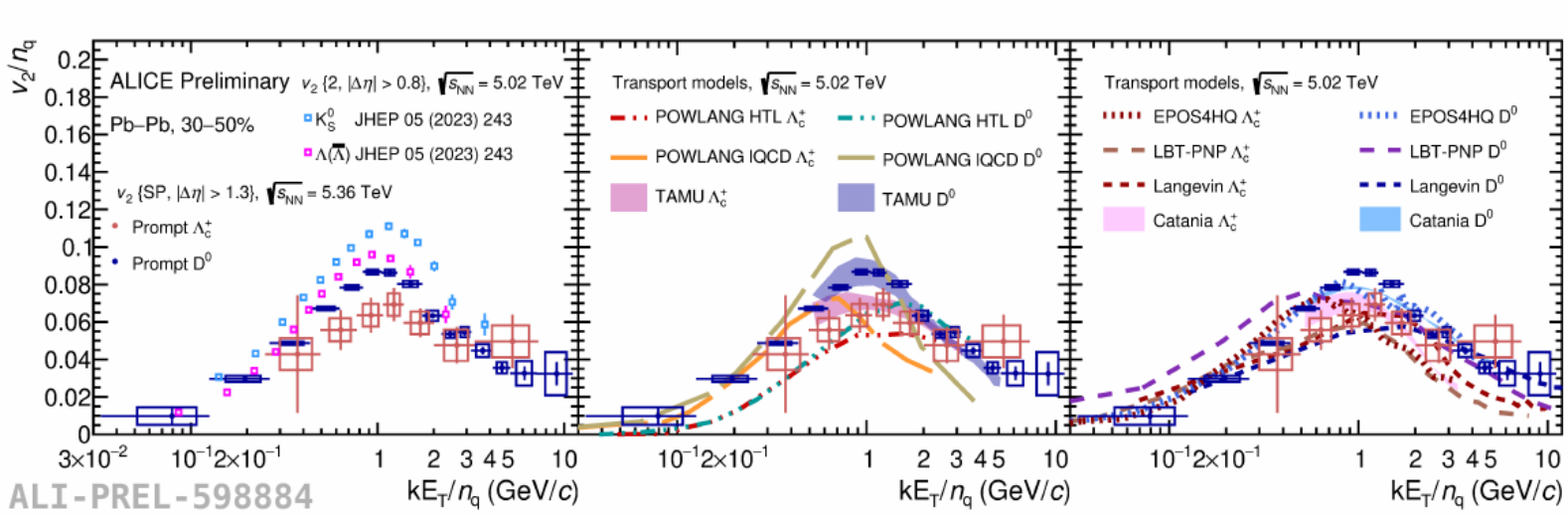




- TAMU predictions consistent
- Beauty-baryon v_2 with non-prompt Λ_c^+
  - Consistent with non-prompt D^0 v_2

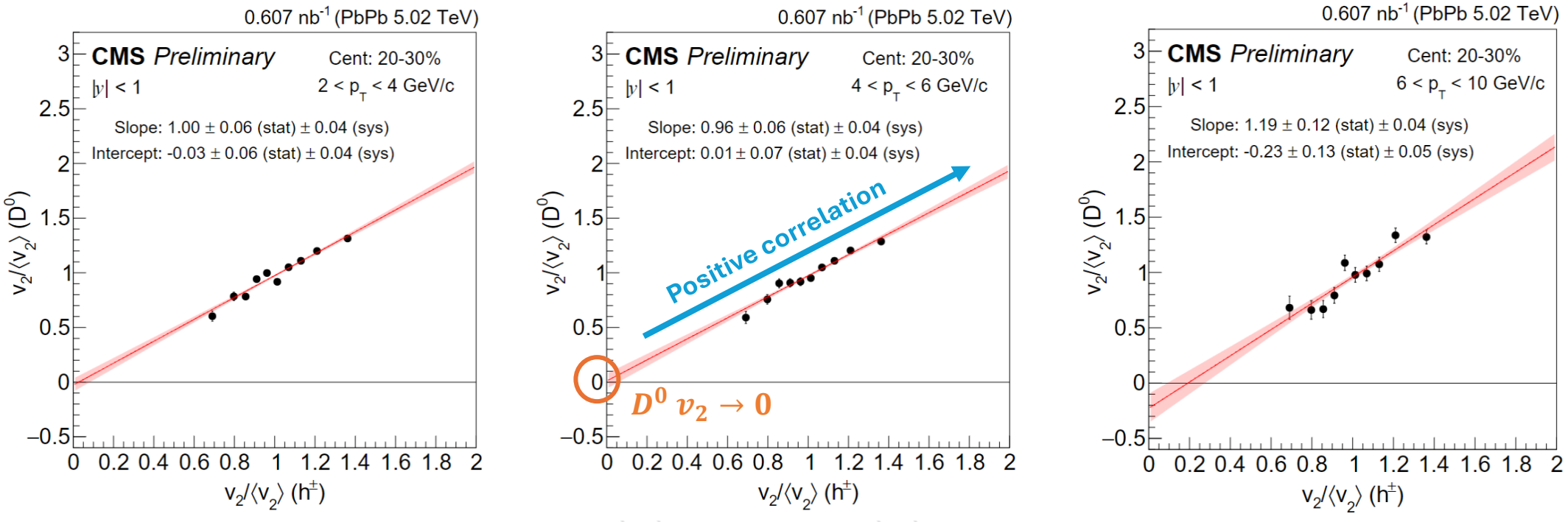
Insight into NCQ scaling





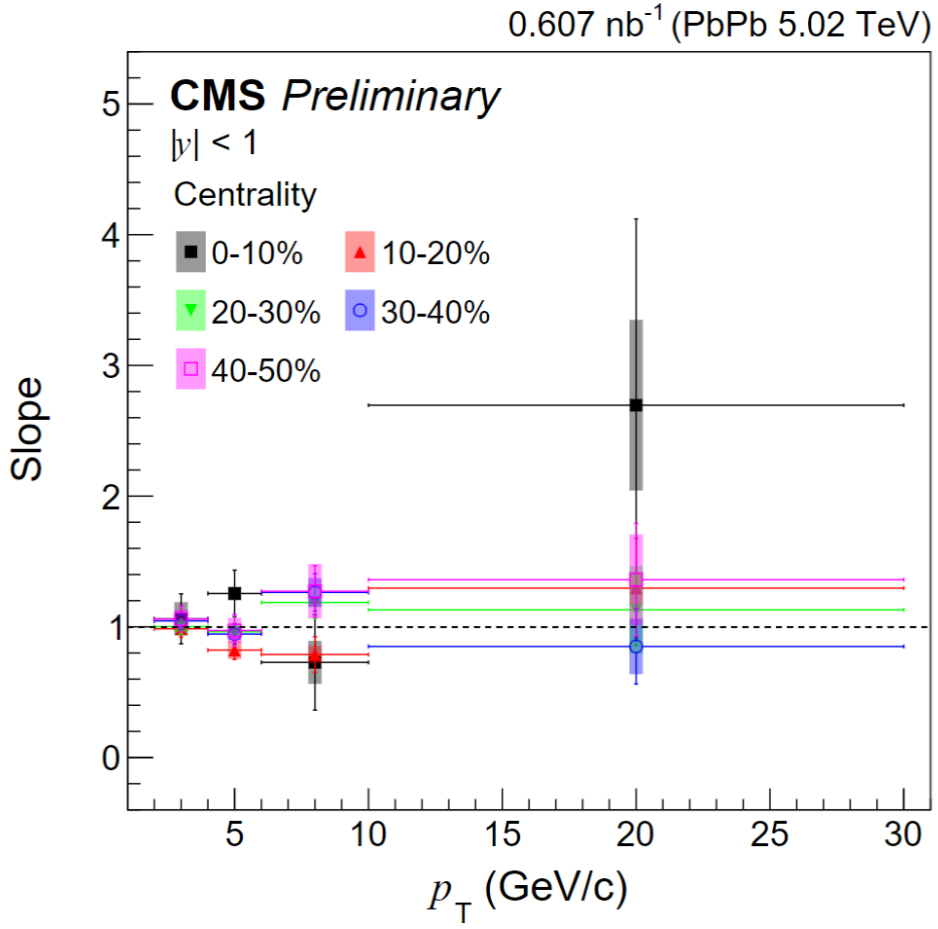
- n_q → number of constituent quarks
- $kE_T = \sqrt{m^2 + p_T^2} - m$
- NCQ scaling is violated for both light and heavy flavors
  - Similar trends for data and model

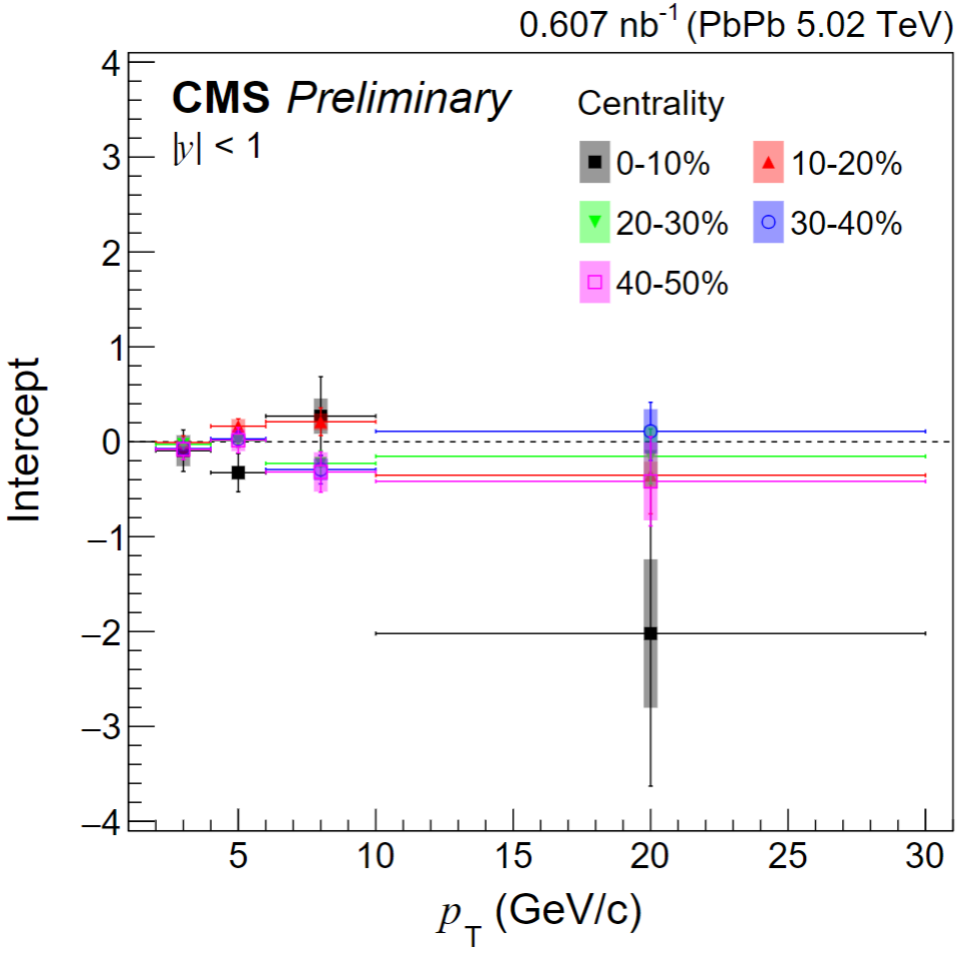
Correlation of prompt D^0 flow



- Correlation plot of prompt D^0 v_2 vs charged particle v_2 ($1 < p_T < 3$ GeV/c) in $|y| < 1$
- Prompt D^0 and charged particle v_2 normalized by the respective q_2-inclusive v_2
- **The low-p_T charged particle v_2 is a proxy for initial shape eccentricity**
- **Approximate linear correlation between prompt D^0 v_2 and charged particle v_2**
  - **Slope (intercept) consistent with unity (zero)**

Correlation of prompt D^0 flow



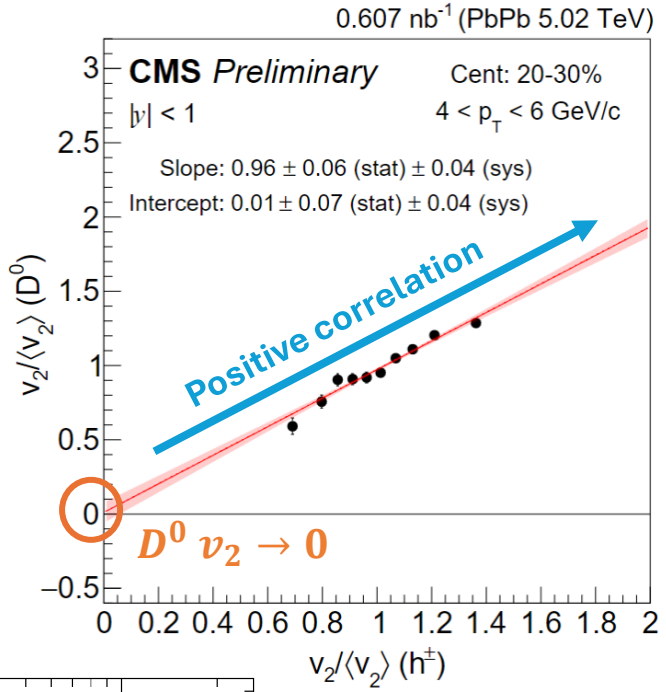


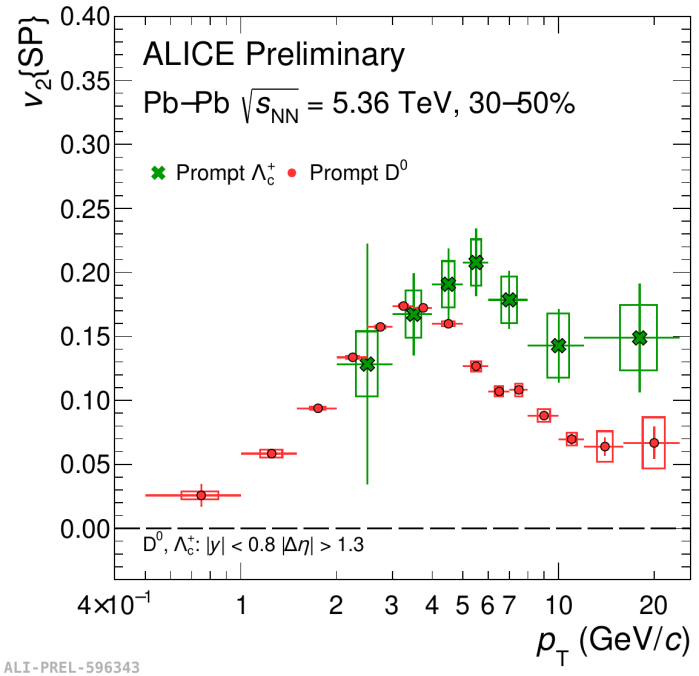
- The slopes of the correlation plots **consistent with unity**

- The intercepts of the correlation plots **consistent with zero**
  - Prompt D^0 $v_2 \rightarrow 0$ when $\epsilon_2 \sim 0$

Summary & Outlook

- **New heavy-flavor measurements from LHC experiments**
  - First measurements of Λ_c^+ v_2 (30-50% centrality)
  - D^0 v_2 measurements in low p_{T} (< 1 GeV/c)
- NCQ scaling broken at low p_{T}, charm baryon-meson splitting at intermediate p_{T}
- D^0 v_2 correlation with light particles shows linear correlation
  - The initial geometry eccentricity is the primary origin of the D^0 meson elliptic flow
- **New insights into QCD with Run3 data from LHC experiments**





ALI-PREL-596343

Thank you!

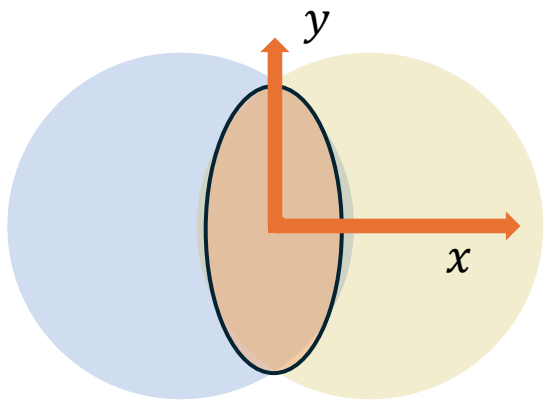
Back-up

Anisotropic flow (v_n)

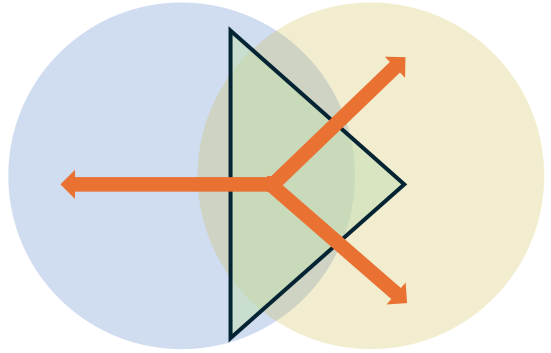
Extracting D^0 flow

- Using flow vectors (Q_n)
  - $Q_n = \sum_{i=1}^{M} \mathrm{w_i} e^{in\phi_i}$
  - M = Multiplicity (#offline reconstructed tracks)
  - $\mathrm{w_i}$ = Weight (E_T for HF, p_T for tracks)
  - ϕ_i = Azimuthal angle of tracks

- Anisotropic flow $(v_n)\{SP\} = \dfrac{\langle Q_n^{D^0} Q_{nA}^* \rangle}{\sqrt{\dfrac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$

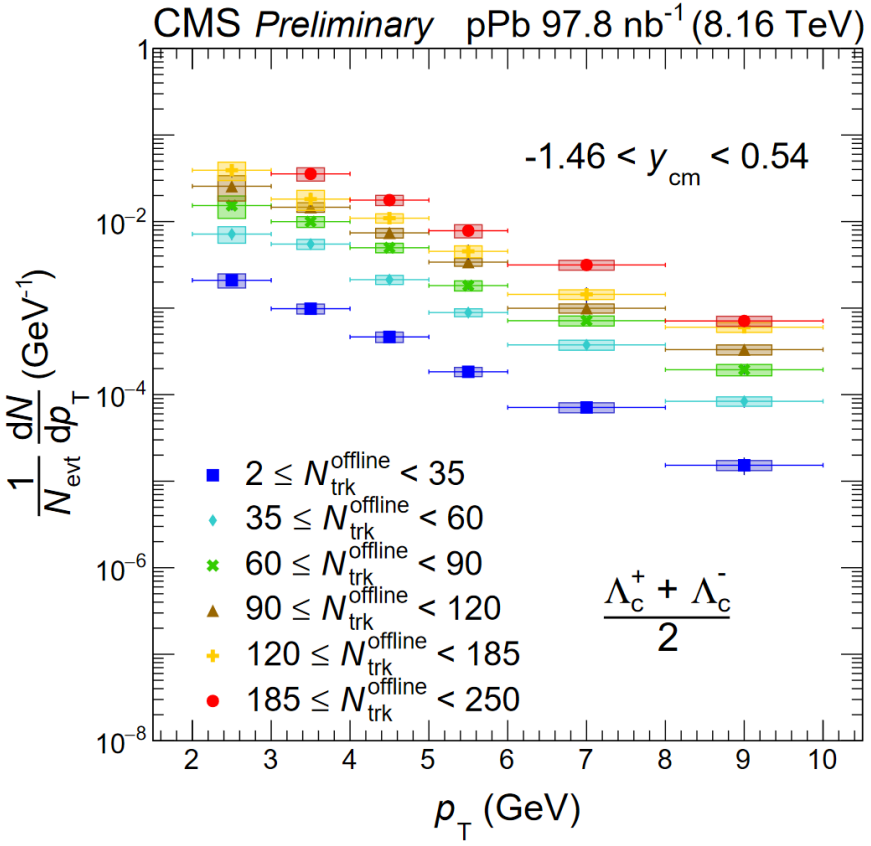


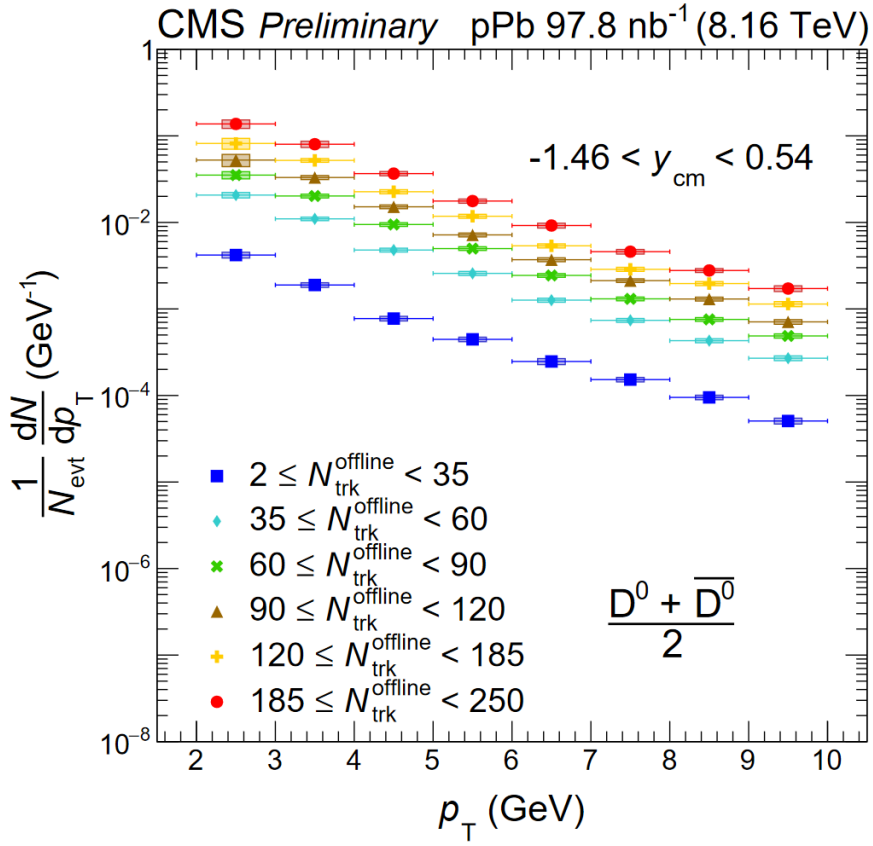
Elliptic flow, v_2



Triangular flow, v_3

Prompt Λ_c^+ & D^0 in pPb collisions



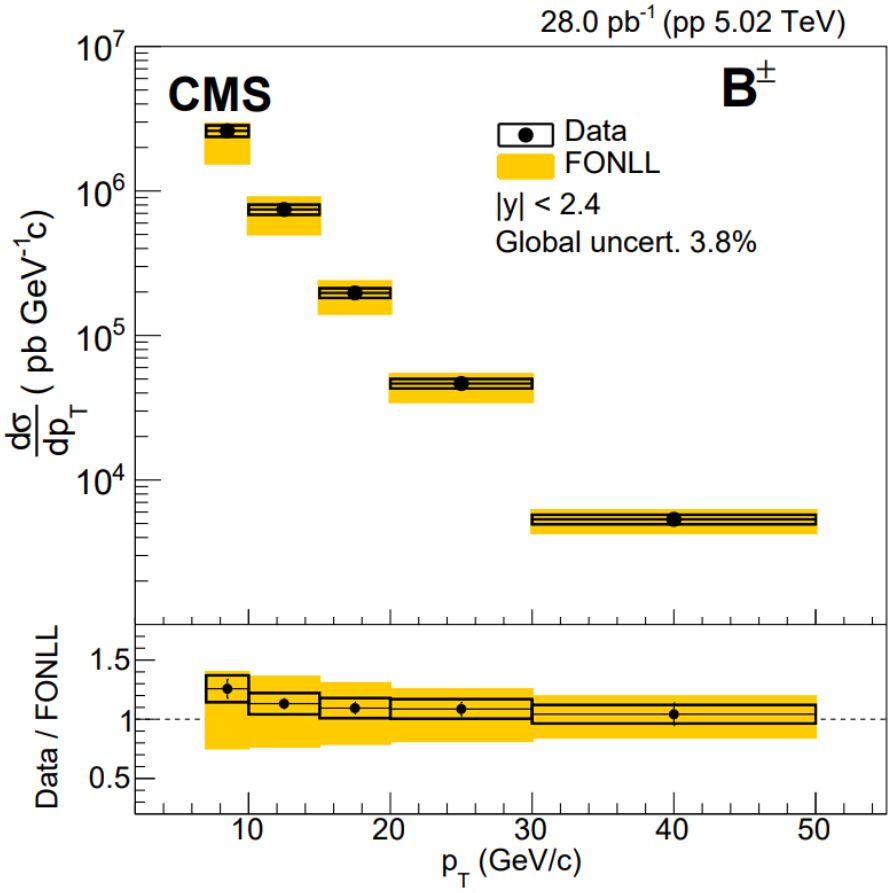


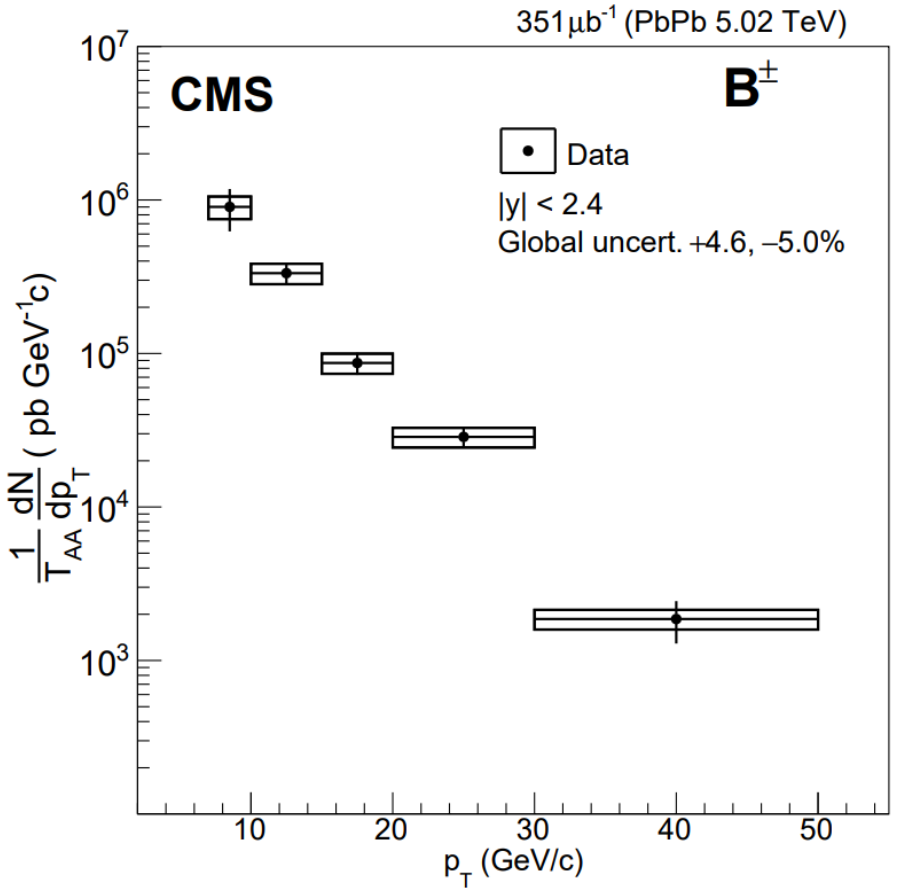
- p_T spectra measured in different multiplicity regions
  - Determined based on number of offline selected tracks
- Increased charm hadron production with higher multiplicity

CMS PAS HIN-21-016

B meson production

PRL 119 (2017)152301





- $B^{\pm}$ measurement by CMS in pp and PbPb collisions
- Data explained well by FONLL