Study of charm quark and QGP medium via Λ_c^+ and D^0 production and collective flow at CMS

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On behalf of the CMS collaboration

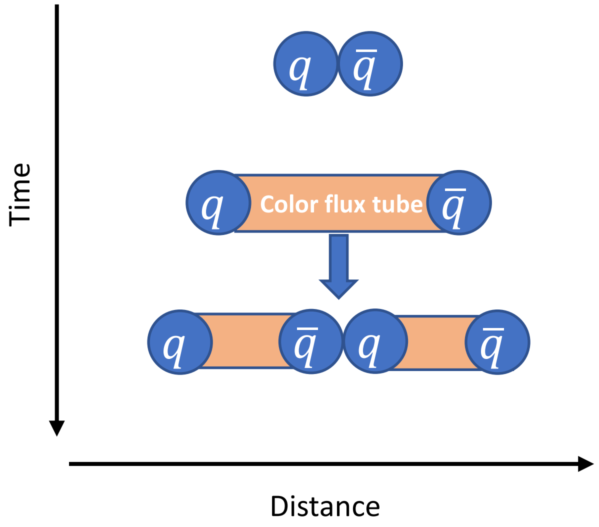
SQM2024

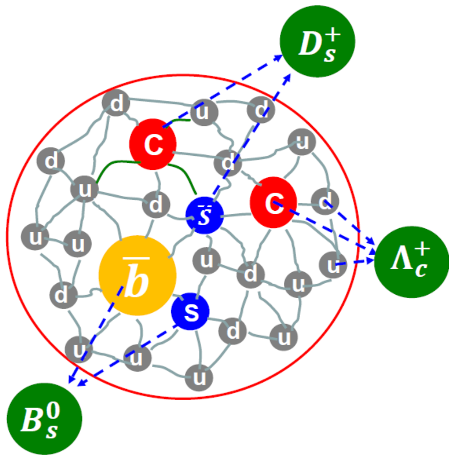
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Motivation

Study of charm quark

- ❑ Heavy quarks formed early in the collision
- ❑ Evolution of collision system
- ❑ Probe energy loss mechanisms
- ❑ Hadronization process:
  - ➢ String fragmentation vs coalescence
  - ➢ $\Lambda_c^+(udc)/D^0(c\bar{u})$ ratio essential for charm quark coalescence
  - ➢ May depend on system size (pp, pPb and PbPb collisions)
- ❑ Anisotropic flow → QGP interaction

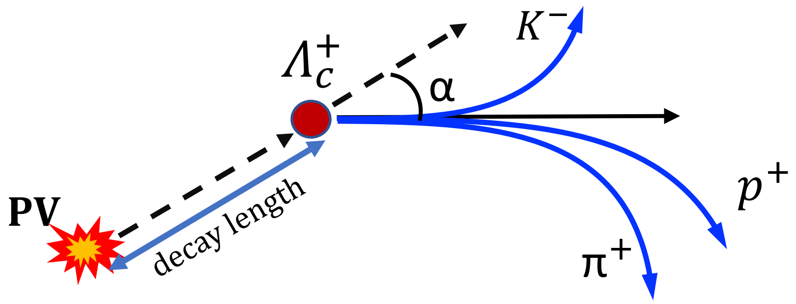




Reconstruction

- Λ_c^+ reconstruction
  - $\Lambda_c^+ \rightarrow p^+K^-\pi^+$ (BR ~ 6.23%)

$p\overline{K^*}(892) \rightarrow pK^-\pi^+$ 1.31%
$\Delta^{++}K^- \rightarrow pK^-\pi^+$ 1.08%
$\Lambda(1520)\pi^+ \rightarrow pK^-\pi^+$ 0.49%
Non resonance = 3.5%



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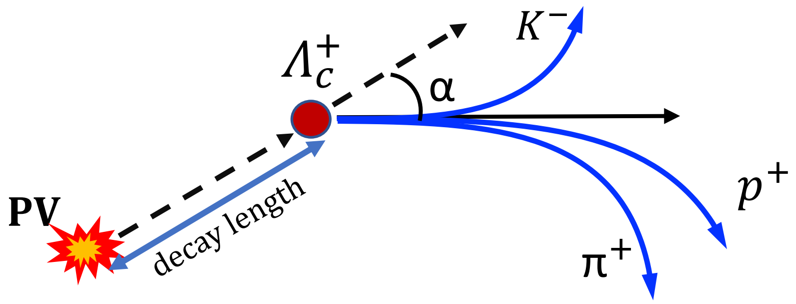
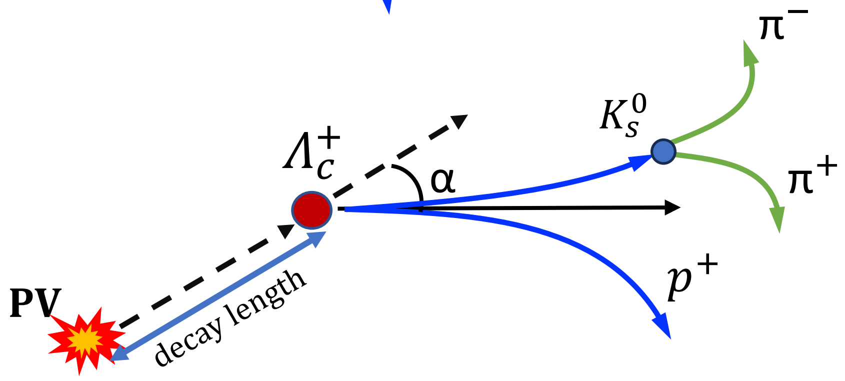
- Λ_c^+ reconstruction (pPb)
  - $\Lambda_c^+ \rightarrow K_S^0 p$ (BR ~ 1.59%)
    - $K_S^0 \rightarrow \pi^+\pi^-$ (BR ~ 69.20%)





- PID (dE/dx) used for proton identification for Λ_c^+ in pPb

Reconstruction

- ❖ Λ_c^+ reconstruction
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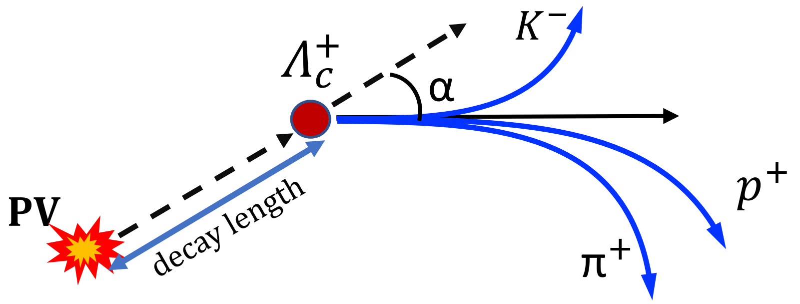
- ❖ D^0 reconstruction
  - ➢ $D^0 \rightarrow K^-\pi^+$ (BR ~ 3.94%)



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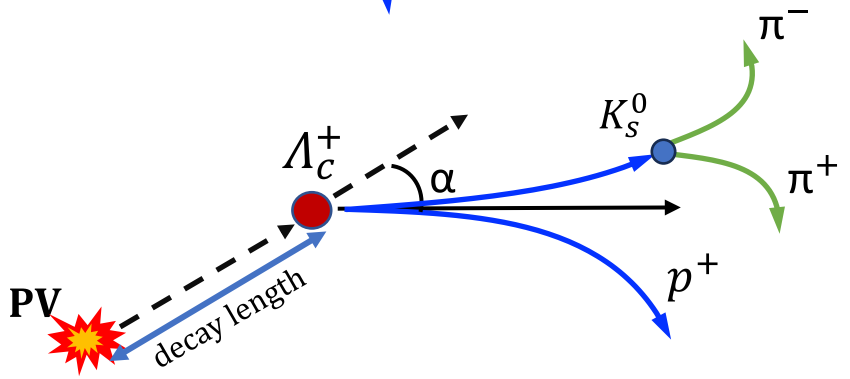
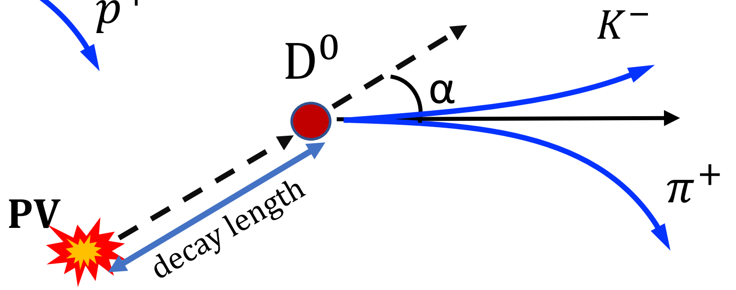
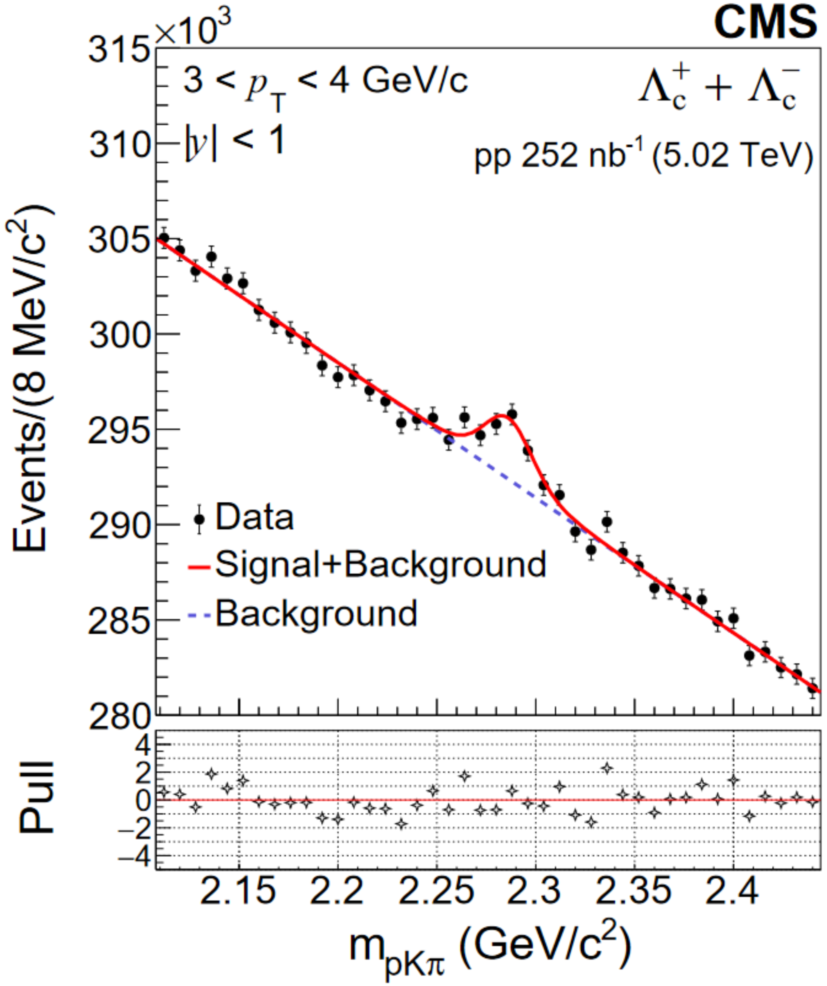


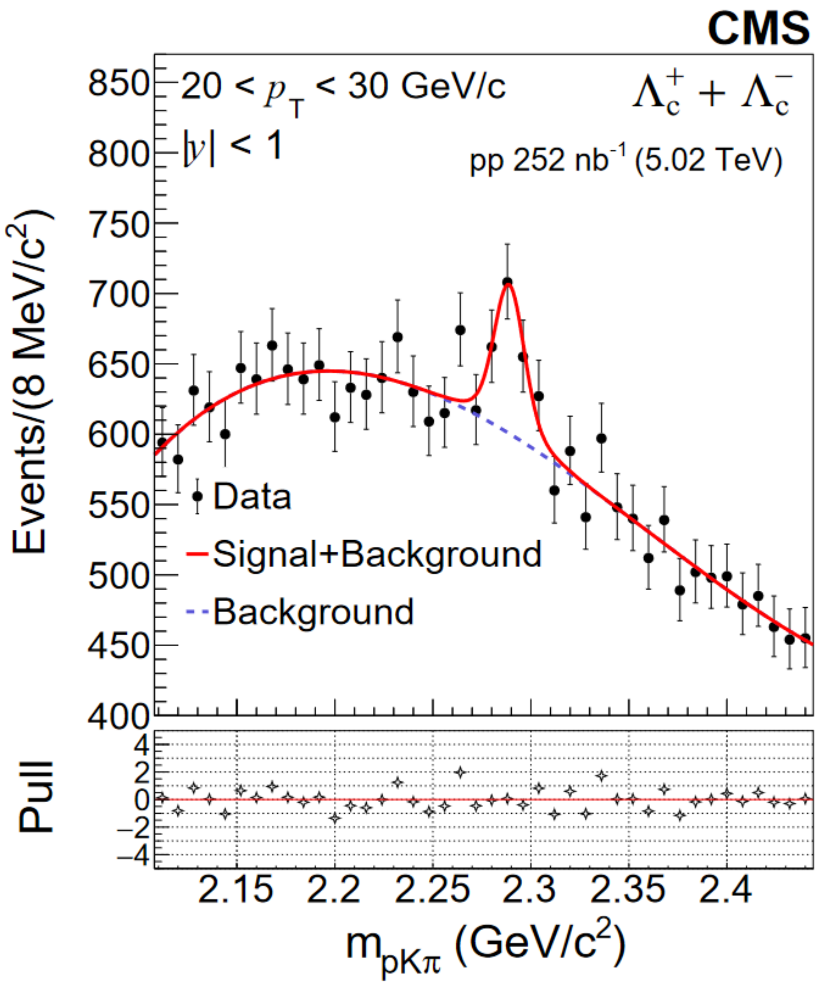


- ❖ All possible combinations of three (two) charged tracks in an event are considered for pp and PbPb

Signal Extraction Λ_c^+ in pp



Low p_T in pp collisions



High p_T in pp collisions

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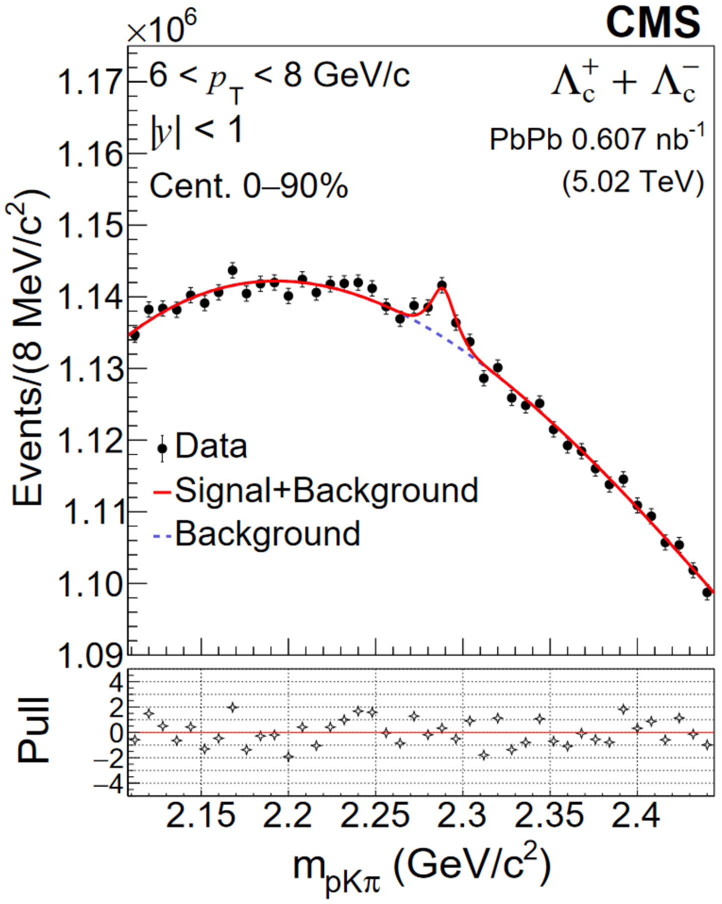
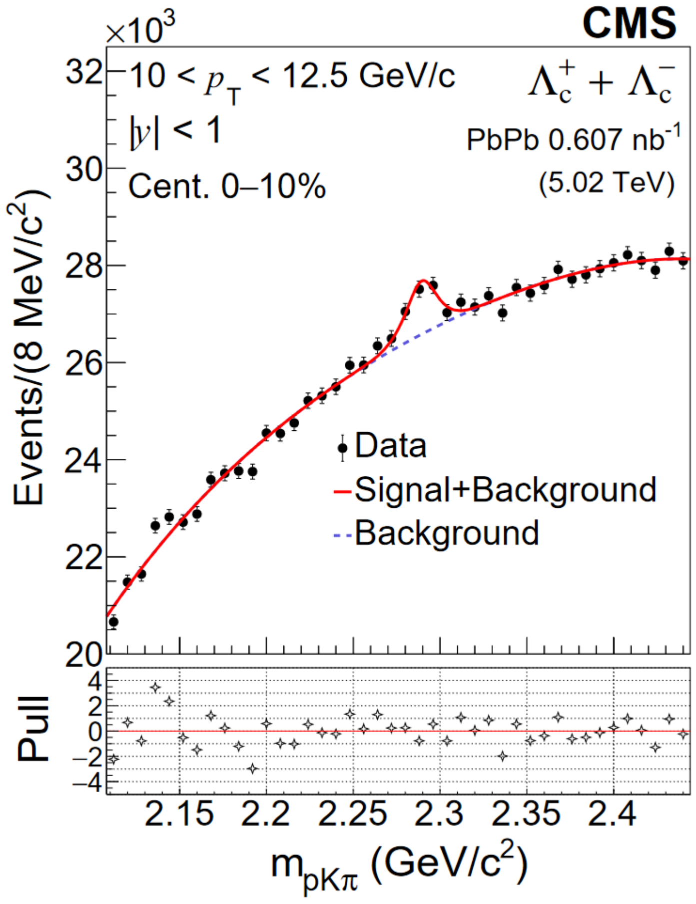
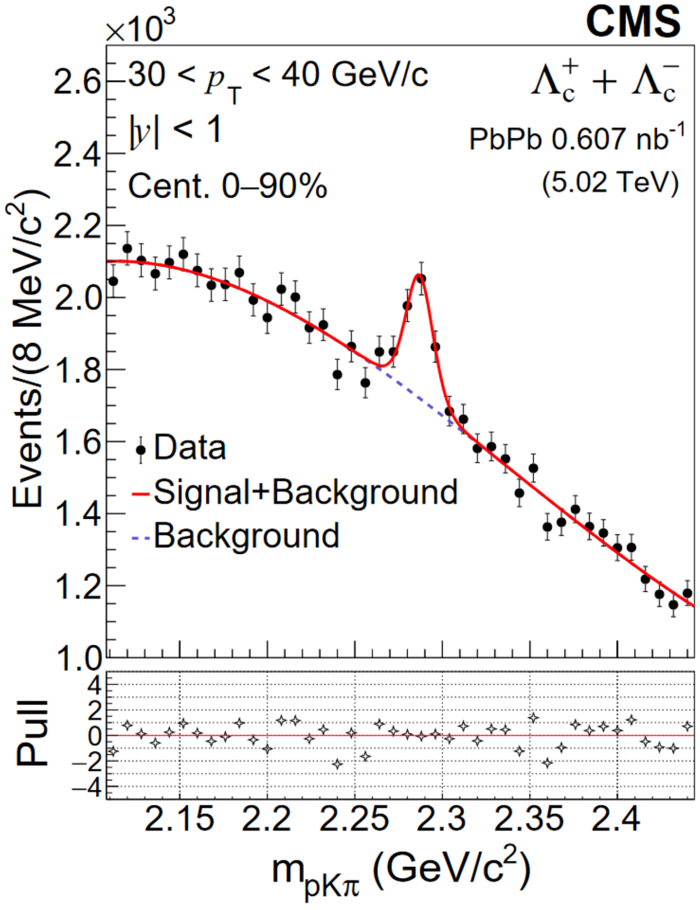
Signal Extraction Λ_c^+ in PbPb



Low p_T in PbPb (0-90%)



Low p_T in PbPb (0-10%)



High p_T in PbPb (0-90%)

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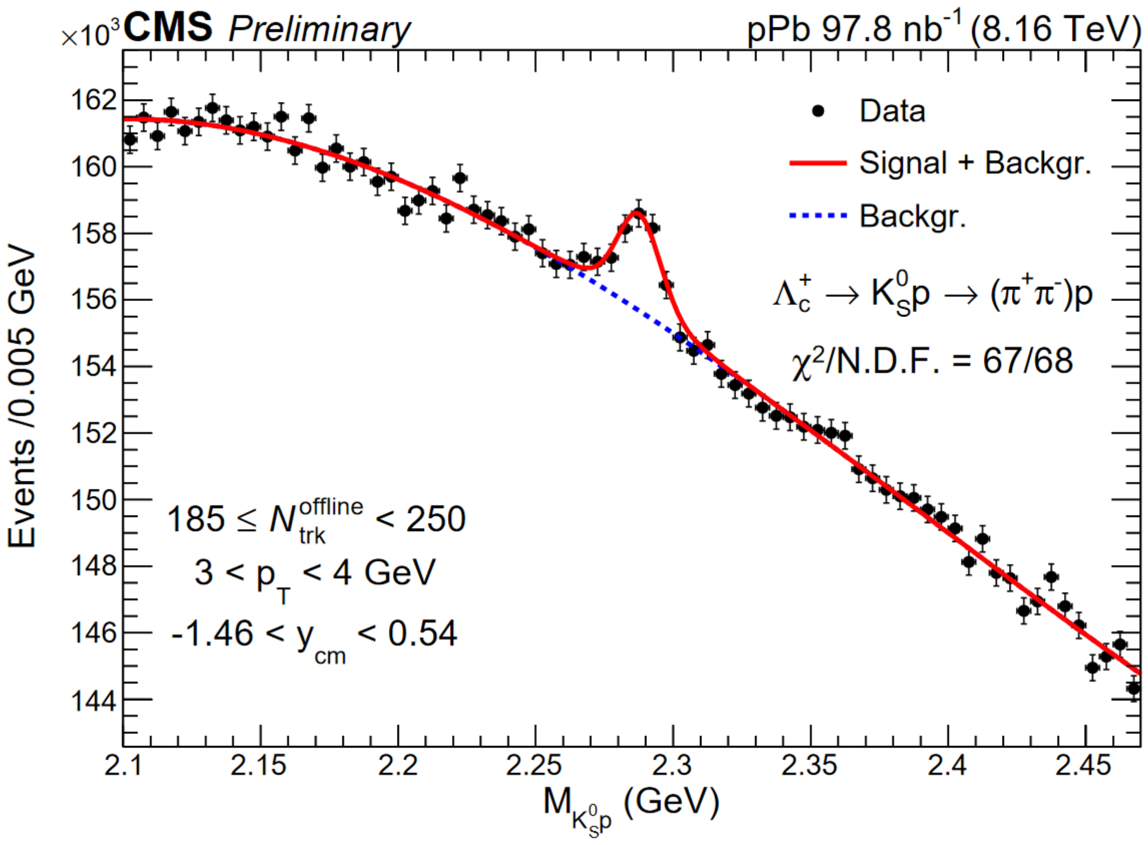
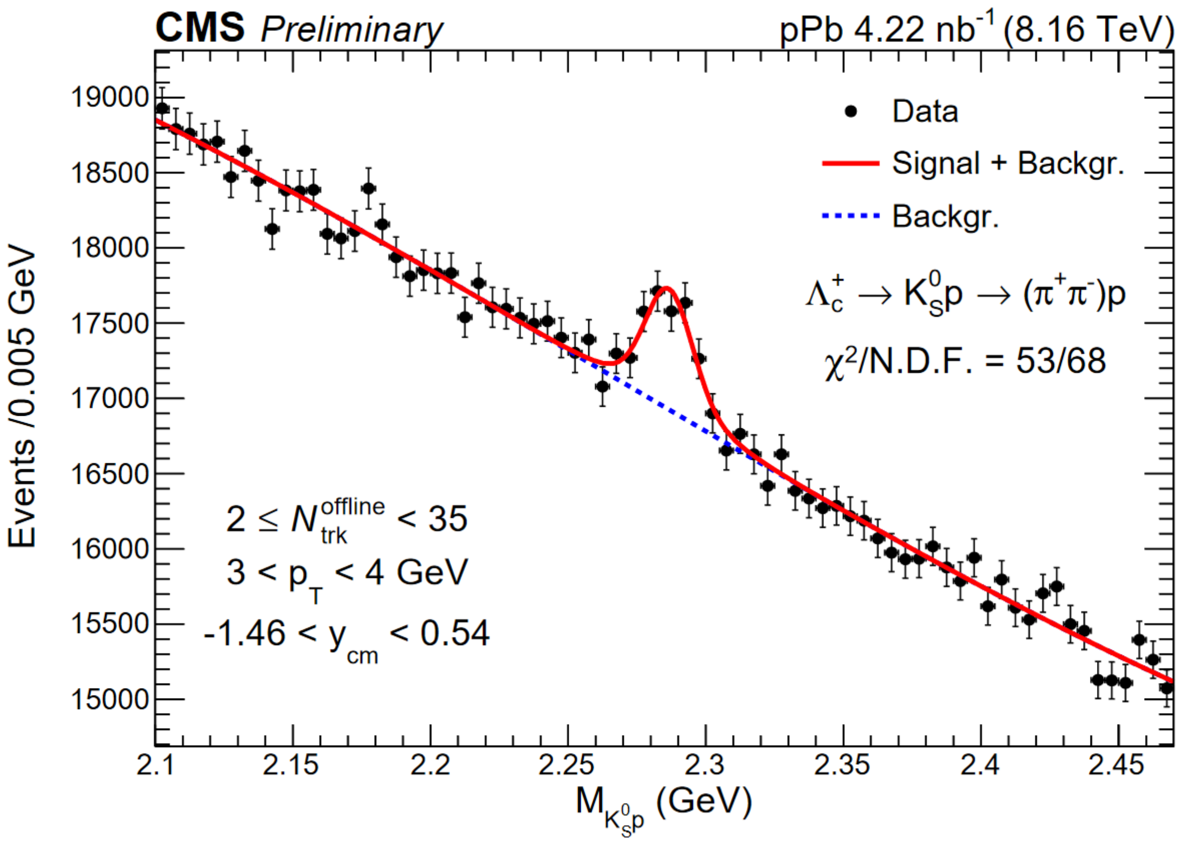
Signal Extraction Λ_c^+ in pPb



Low p_T in pPb (high multiplicity)



Low p_T in pPb (low multiplicity)

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D^0 anisotropy

Azimuthal anisotropy

- ❑ Correlation between D^0 and light particles
- ❑ Studying anisotropy:
  - ➢ Particle production in ϕ

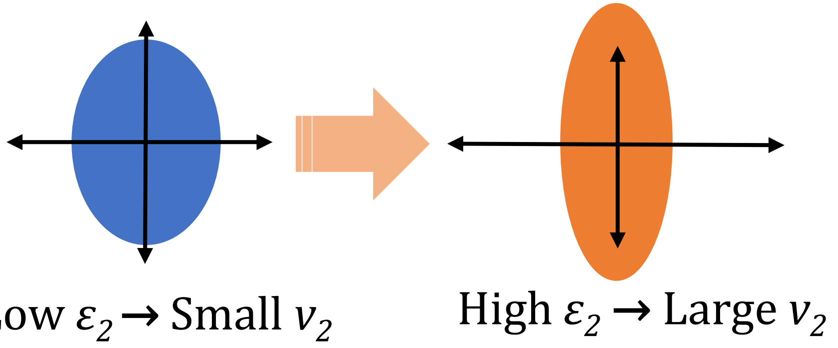
$$\frac{dN}{d\phi} \propto \left(1 + \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right)$$

ϕ → azimuthal angle of D^0

Ψ_n → symmetry plane (Event plane)

Properties:

- ➢ Diffusion
- ➢ Parton energy loss
- ➢ Coulomb effect → Δv_2



Signal Extraction D^0 v_2

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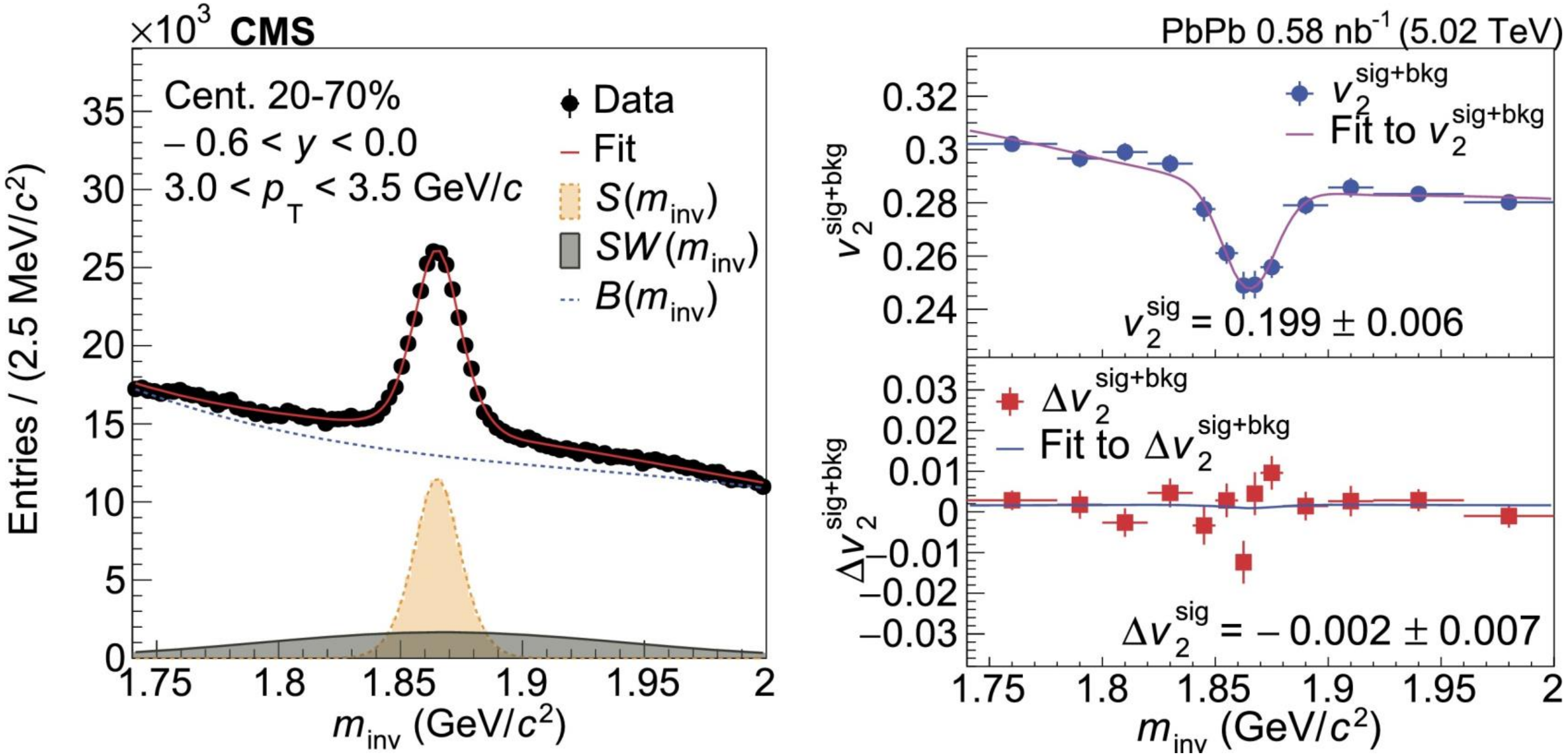
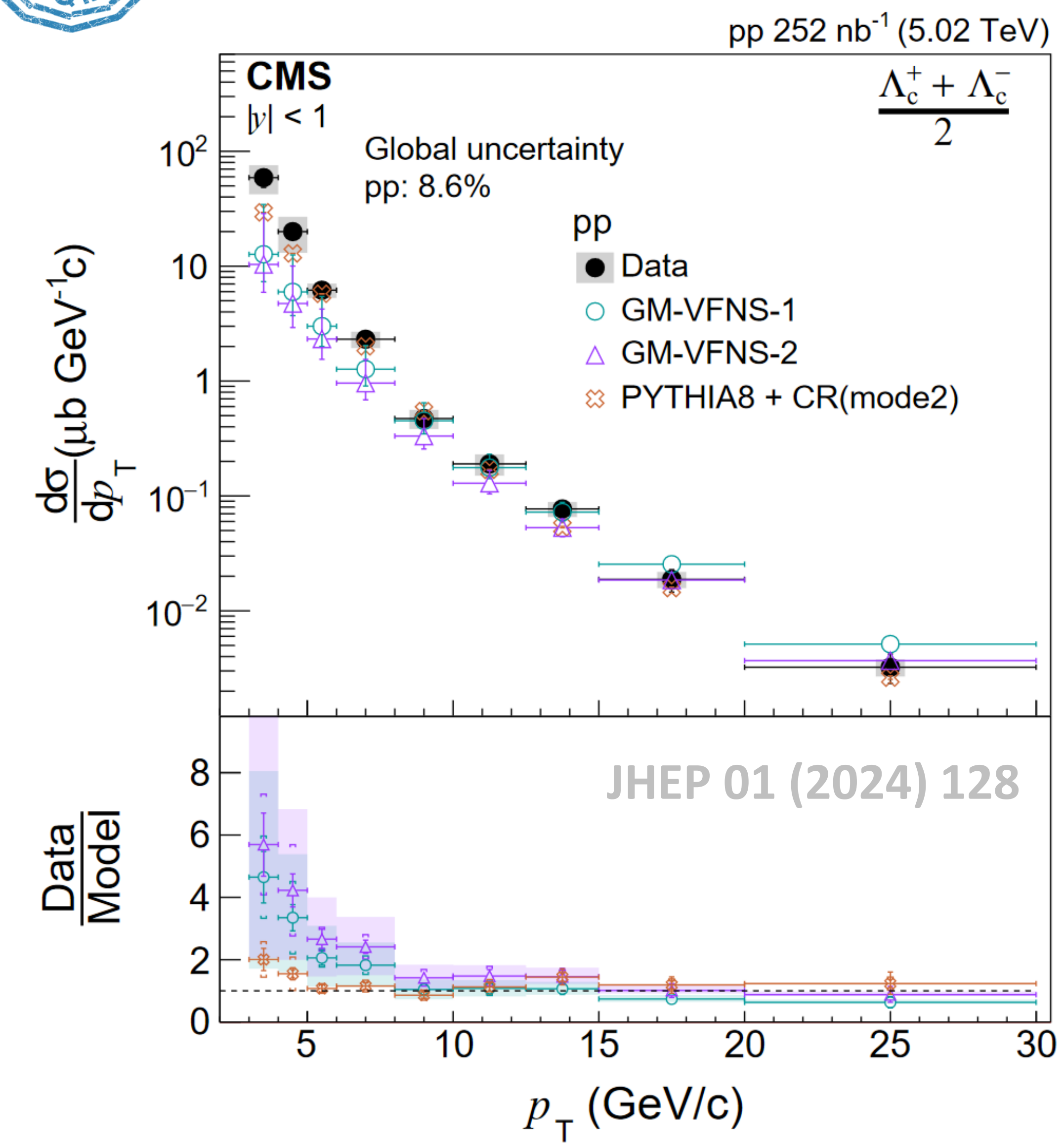
- v_2 is extracted using the scalar product method
- Simultaneous fit of the πK invariant mass and $v_2, \Delta v_2$
- Linear function is assumed for background v_2



Results

Prompt Λ_c^+ p_T spectra in pp



- PYTHIA8+CR(mode2) is consistent with pp data.
  - Final partons in the string fragmentation are color connected to minimize total string length

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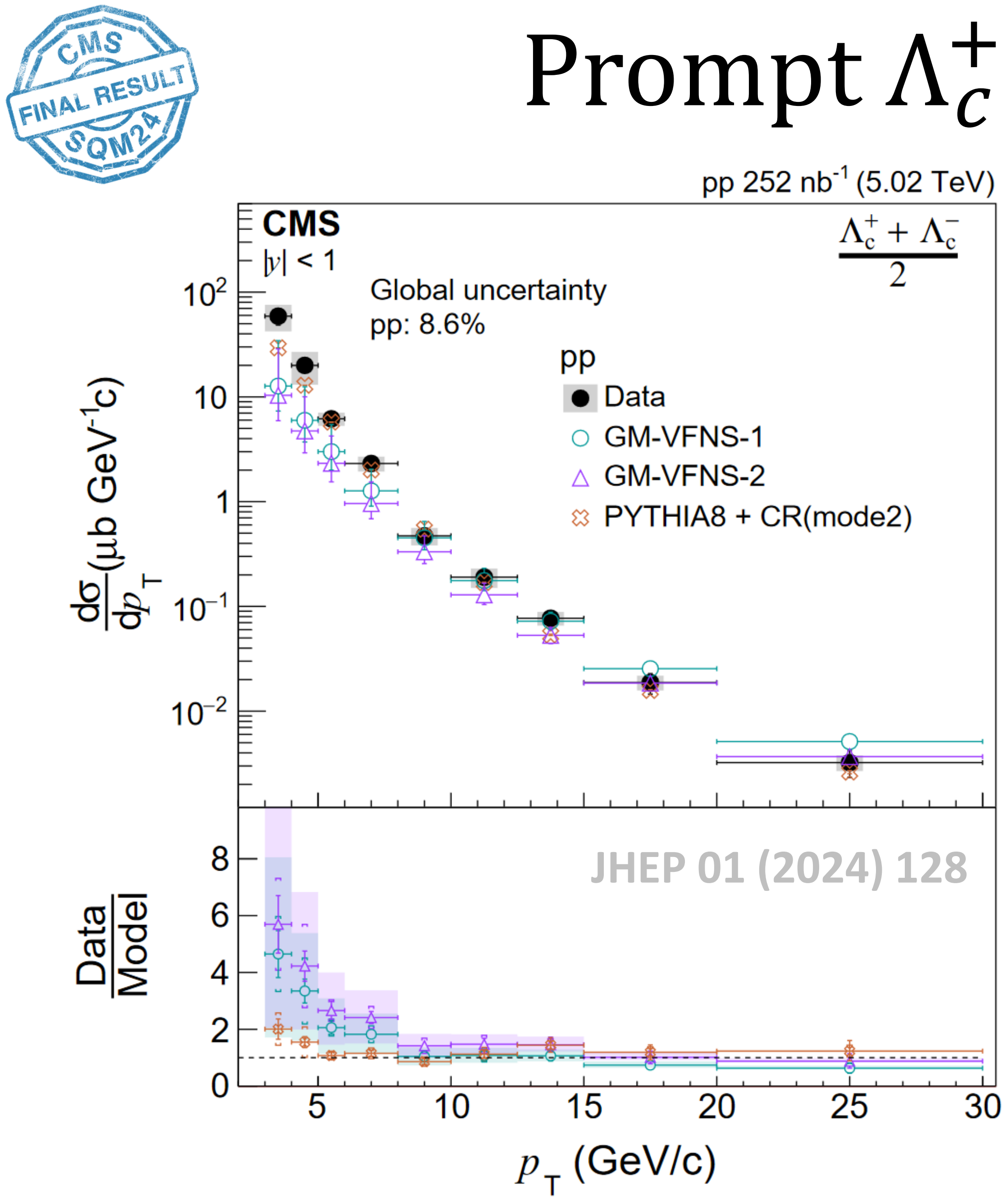
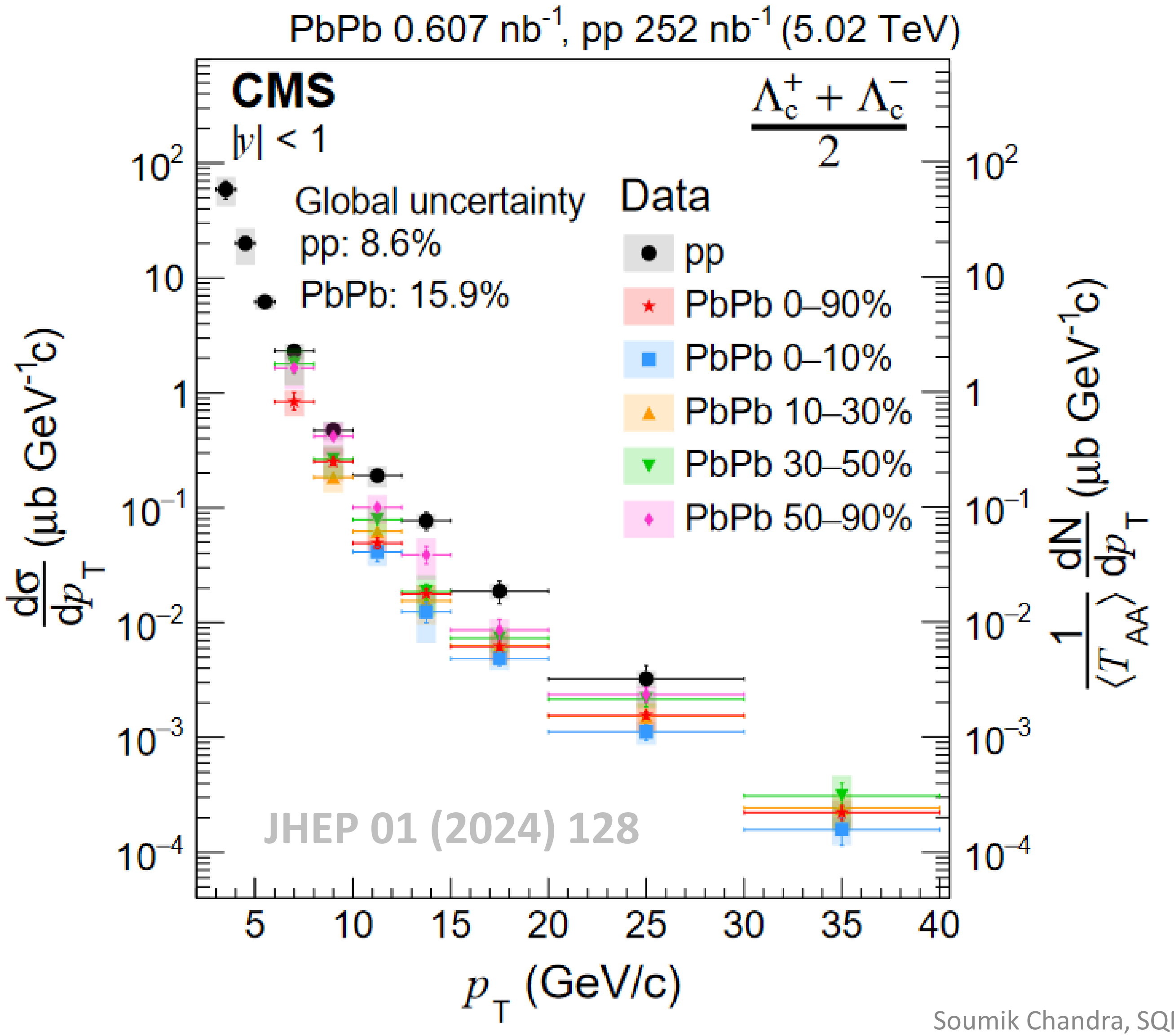


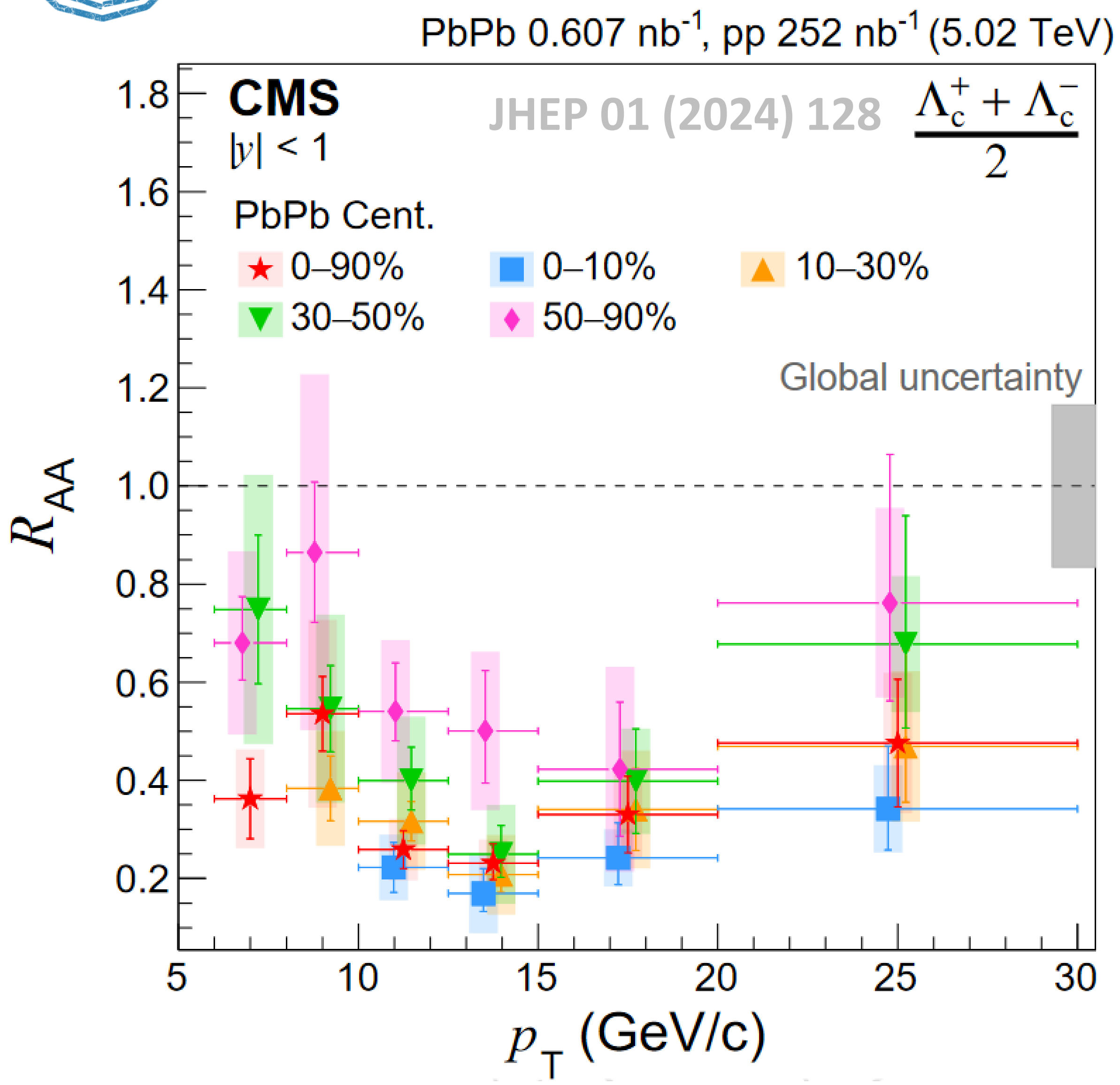
- ❑ PYTHIA8+CR(mode2) is consistent with pp data.
  - ➢ Final partons in the string fragmentation are color connected to minimize total string length
- ❑ GM-VFNS systematically below data for p_T< 10 GeV/c
  - ➢ Fragmentation tuned from Belle/OPAL (e^+e^- data)
  - ➢ Breakdown of the universality of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

Prompt Λ_c^+ p_T spectra in PbPb



- ❑ 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 is systematically lower than that in pp collision.
  - ❑ More suppression for central collisions
  - ❑ Energy loss of charm quark traversing the QGP medium

Prompt Λ_c^+ R_{AA}



- 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

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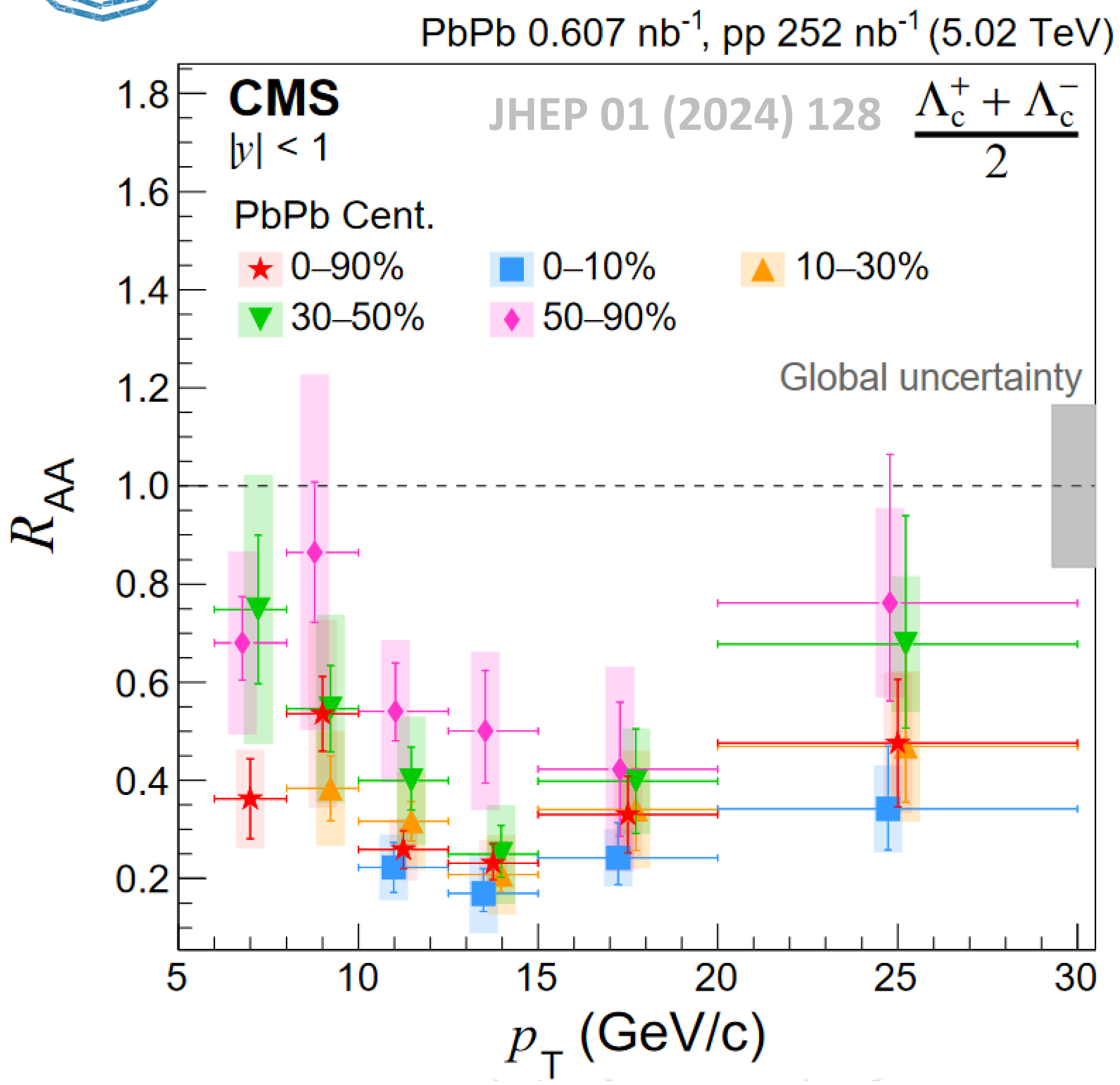
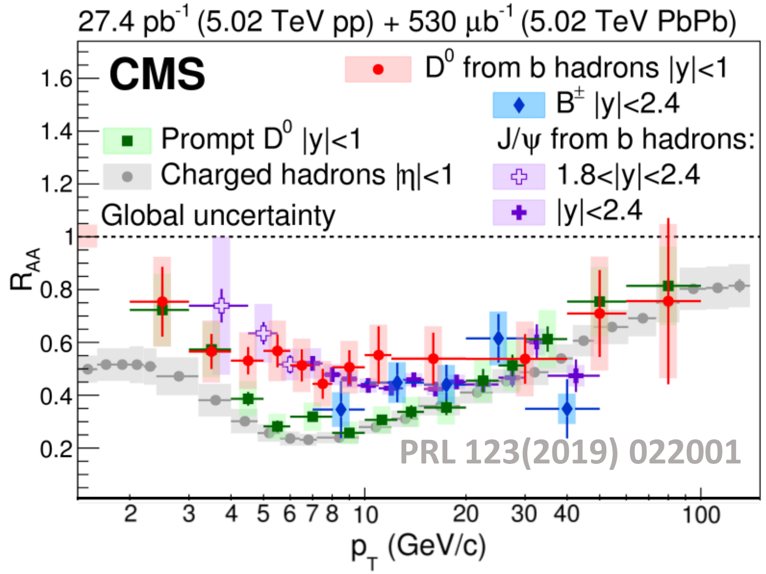
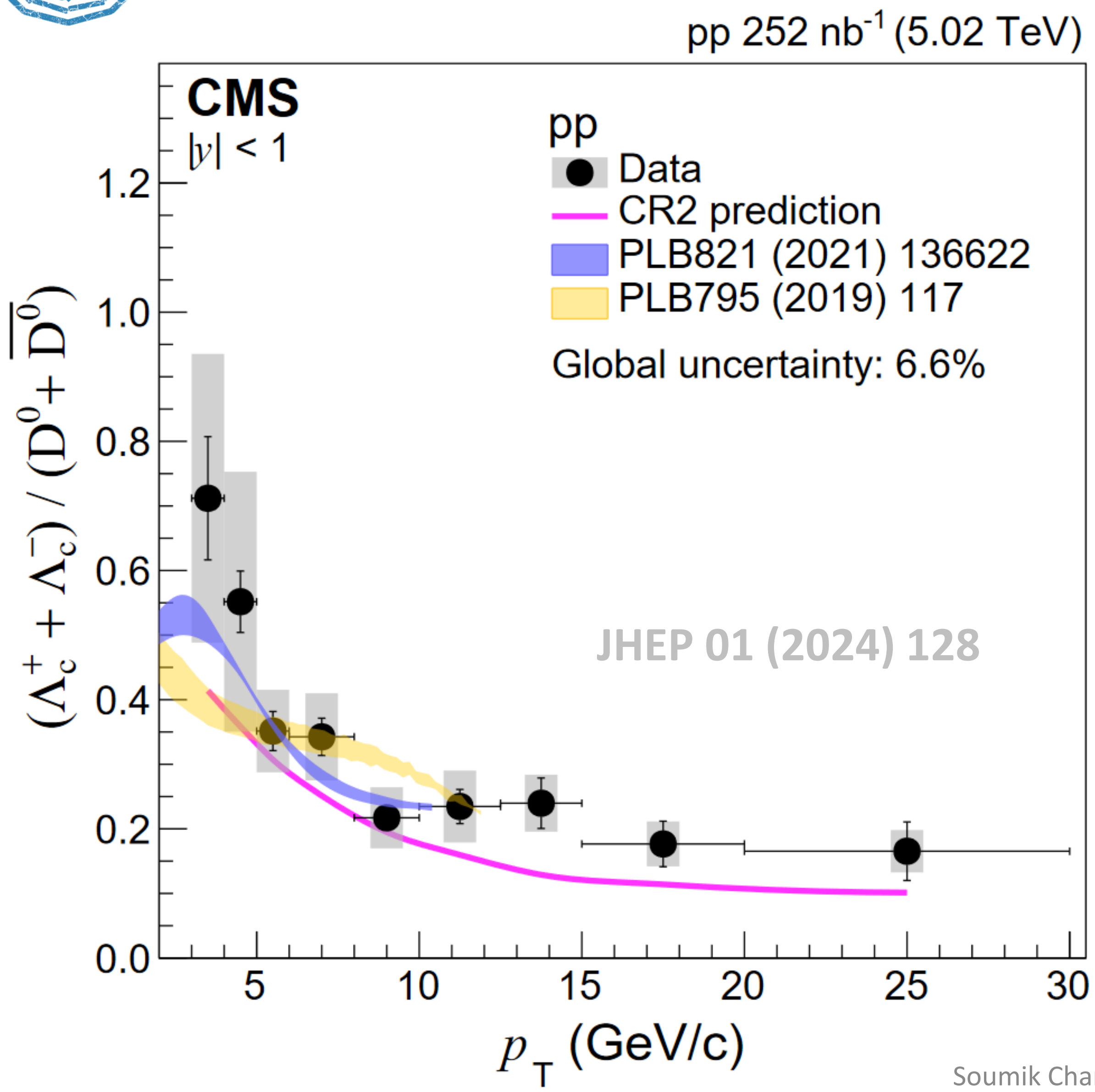


- Larger suppression of Λ_c^+ production for central PbPb collisions
- R_{AA} decreases from low p_T up to ~14 GeV/c, then increases for higher p_T
- Similar trend to other heavy flavor measurements.
  - D^0 R_{AA} minimum at p_T ~ 9 GeV/c



Prompt Λ_c^+/D^0 in pp



- PYTHIA8+CR2 predictions consistent with pp data for $p_T < 10$ GeV/c, systematically lower for p_T range 10-30 GeV/c.

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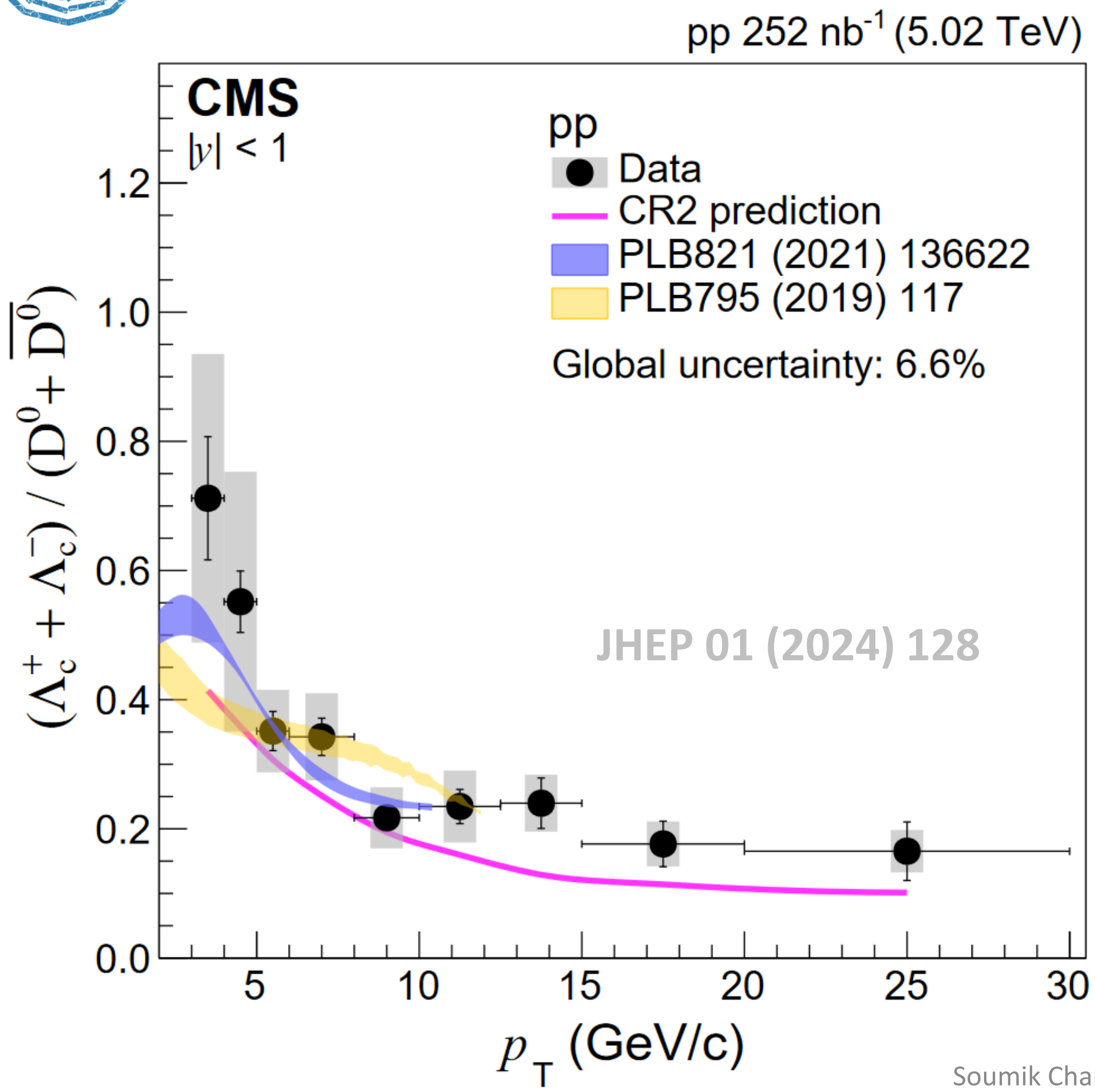

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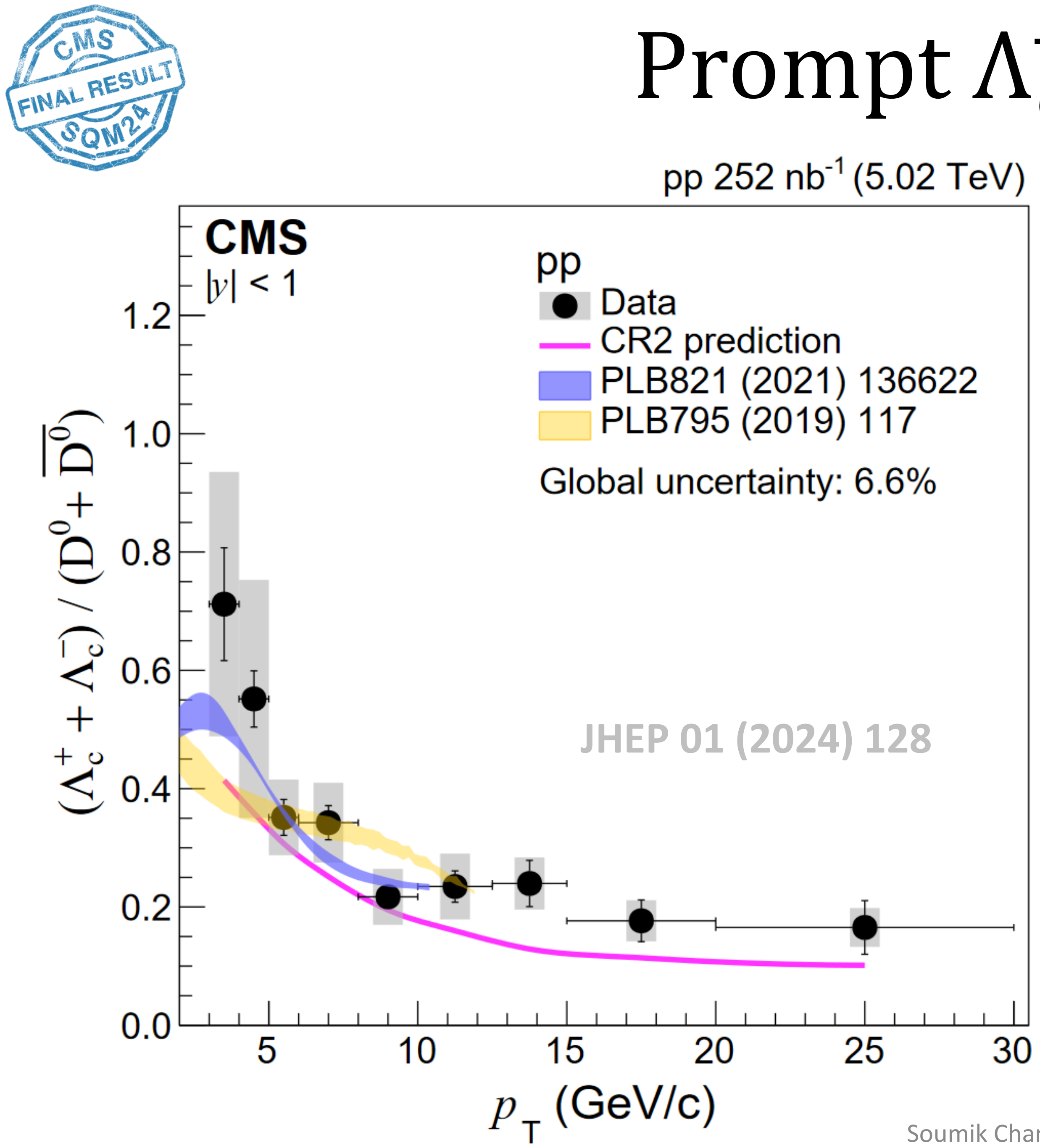

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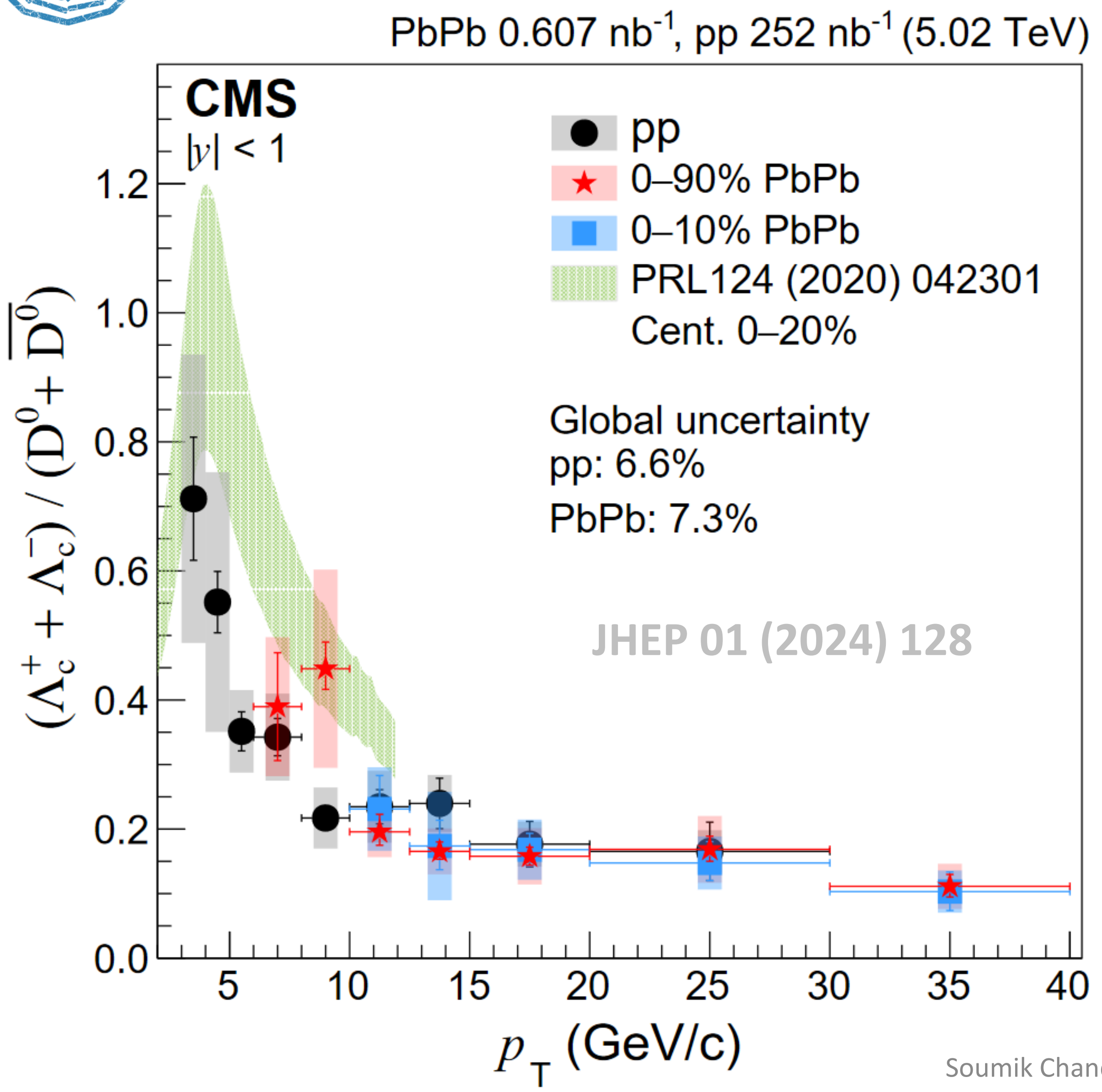
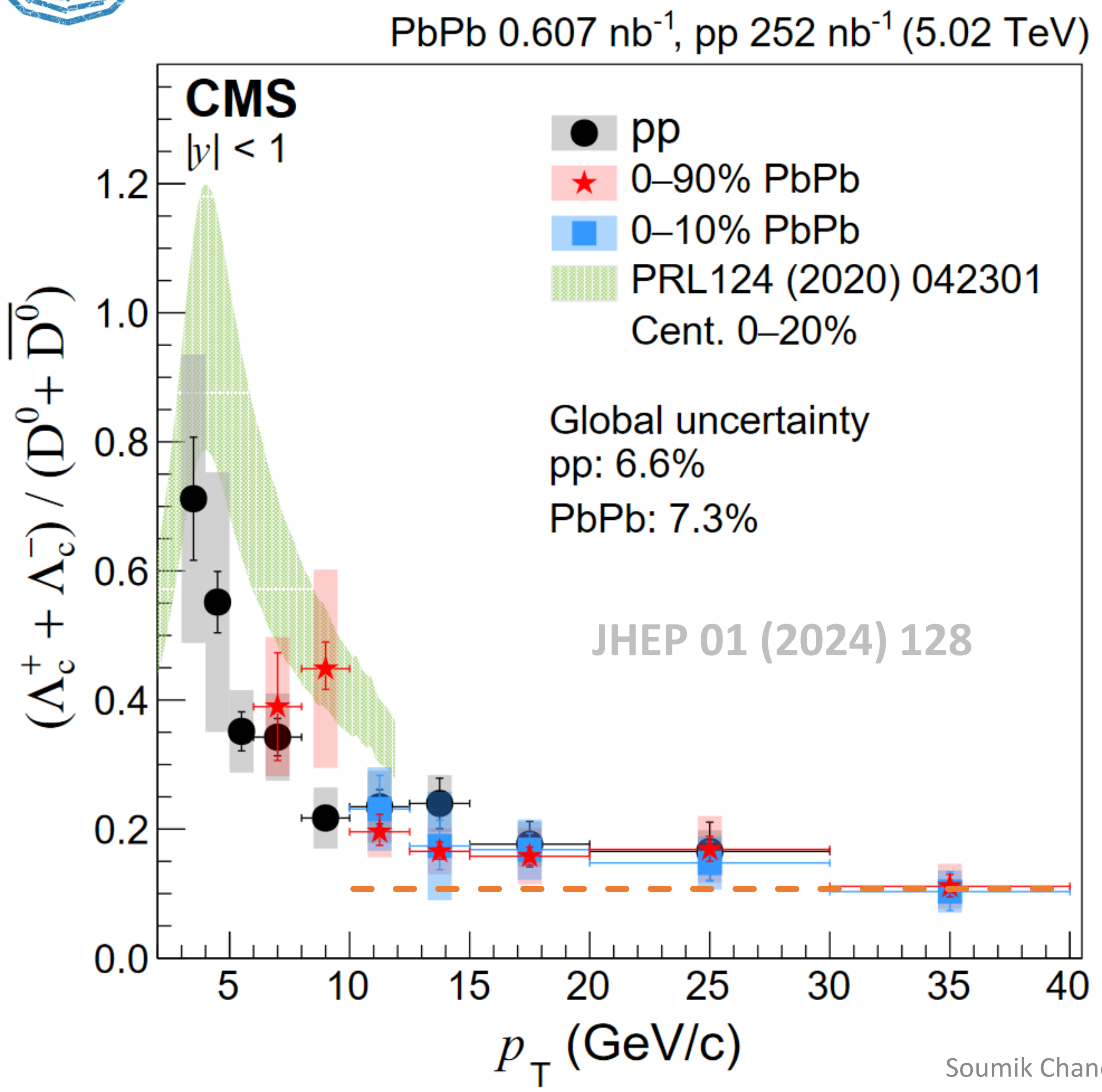
- Catania model including both coalescence and fragmentation consistent with data for $p_T < 10$ GeV/c.
- TAMU model using statistical hadronization approach and including excited charmed baryon states beyond the PDG describes the data reasonably

Prompt Λ_c^+/D^0 in PbPb



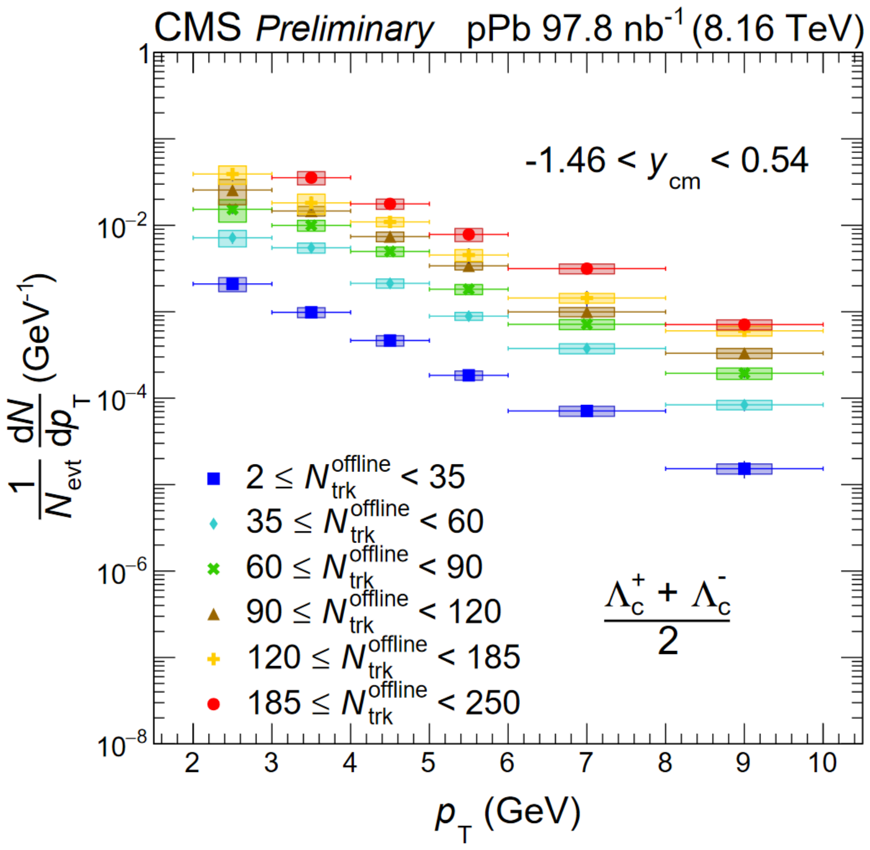
- Λ_c^+/D^0 ratio for PbPb is consistent with pp data for $p_T > 10$ GeV/c.
  - Coalescence process does not play a significant role for high p_T

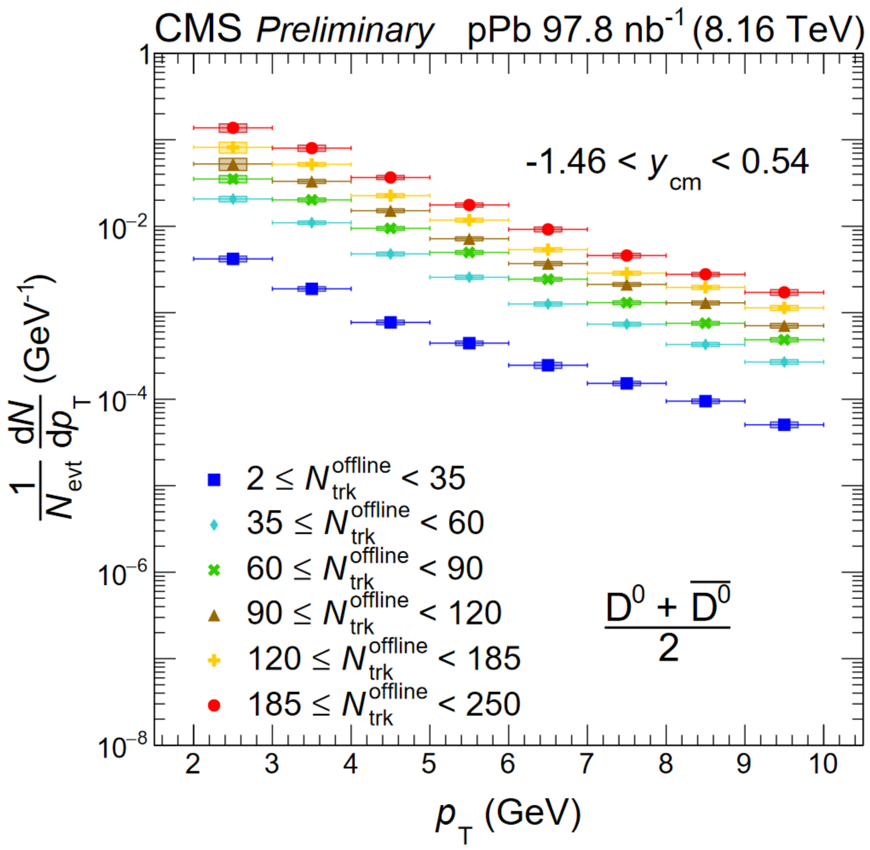
Prompt Λ_c^+/D^0 in PbPb



- 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
- Model for PbPb collisions (0-20% centrality) consistent with data for p_T 10-12.5 GeV/c
  - Four-momentum conserving recombination mechanisms
  - Excited charm baryon states beyond PDG.
- Ratio consistent with e^+e^- for higher p_T region

Prompt Λ_c^+ & D^0 p_T spectra in pPb





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

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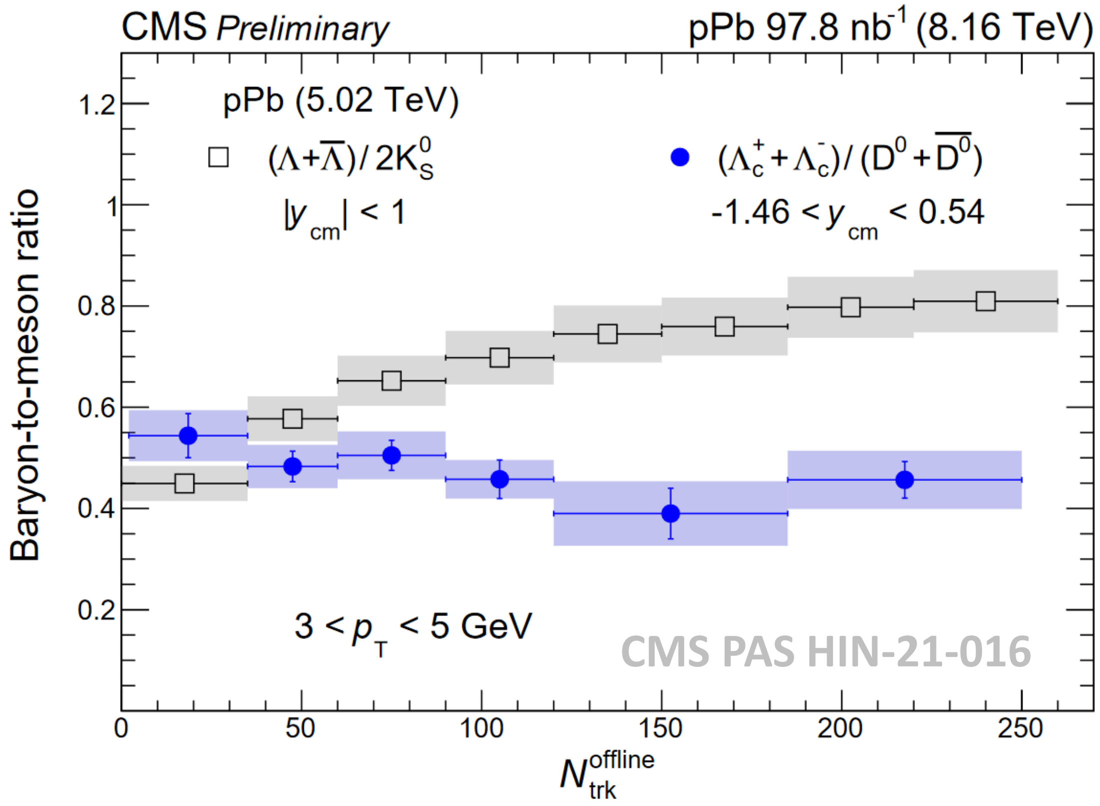
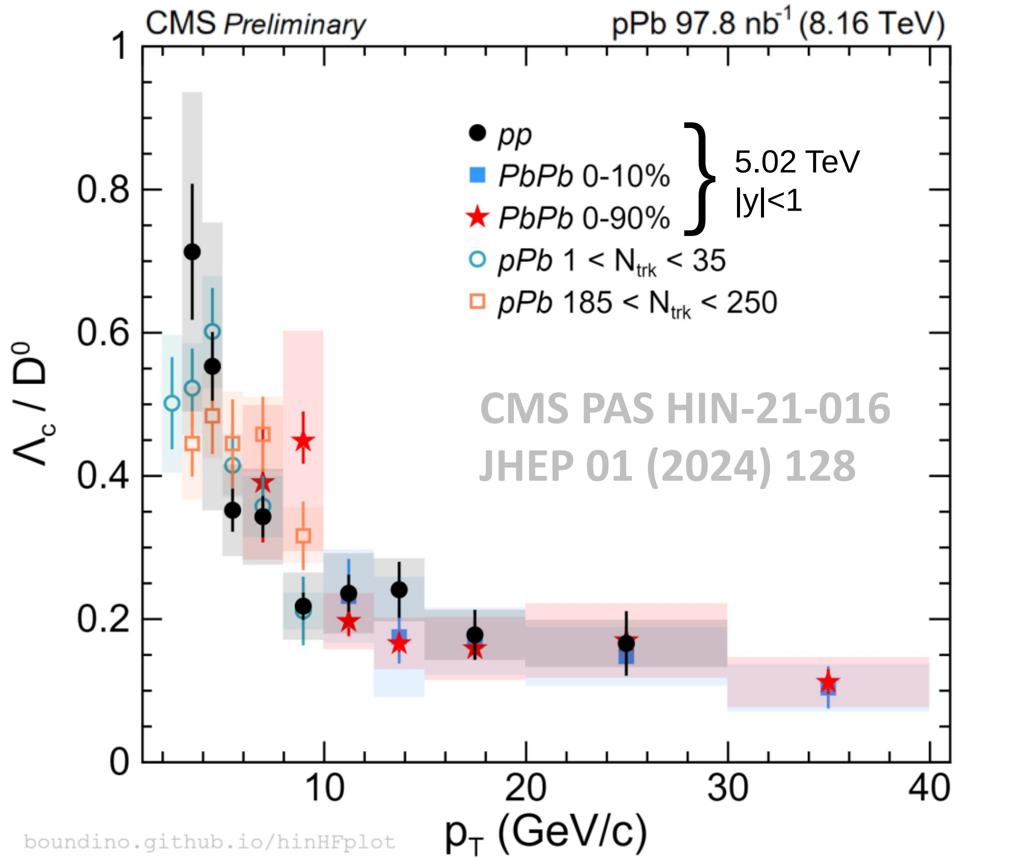
Prompt Λ_c^+/D^0 ratio in pPb





- No significant multiplicity dependence
  - Differs from strange quark trend
- Coalescence process saturates early for charm quark with multiplicity

- Λ_c^+/D^0 ratio decreases with increasing p_T
- Consistent with pp and PbPb results

Anisotropic D^0 flow in PbPb

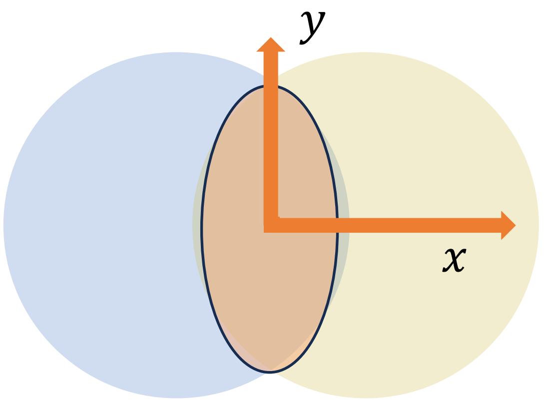
- The flow vector:

$$Q_{n,x} = \sum_{i=1}^{M} \cos(n\phi_i)$$

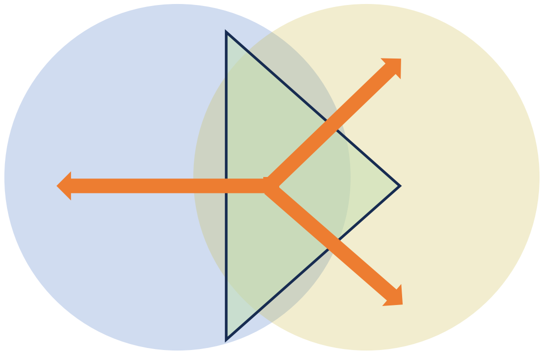
$$Q_{n,y} = \sum_{i=1}^{M} \sin(n\phi_i)$$

- Flow coefficients

$$v_n\{SP\} \equiv \frac{\langle Q_n Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}$$

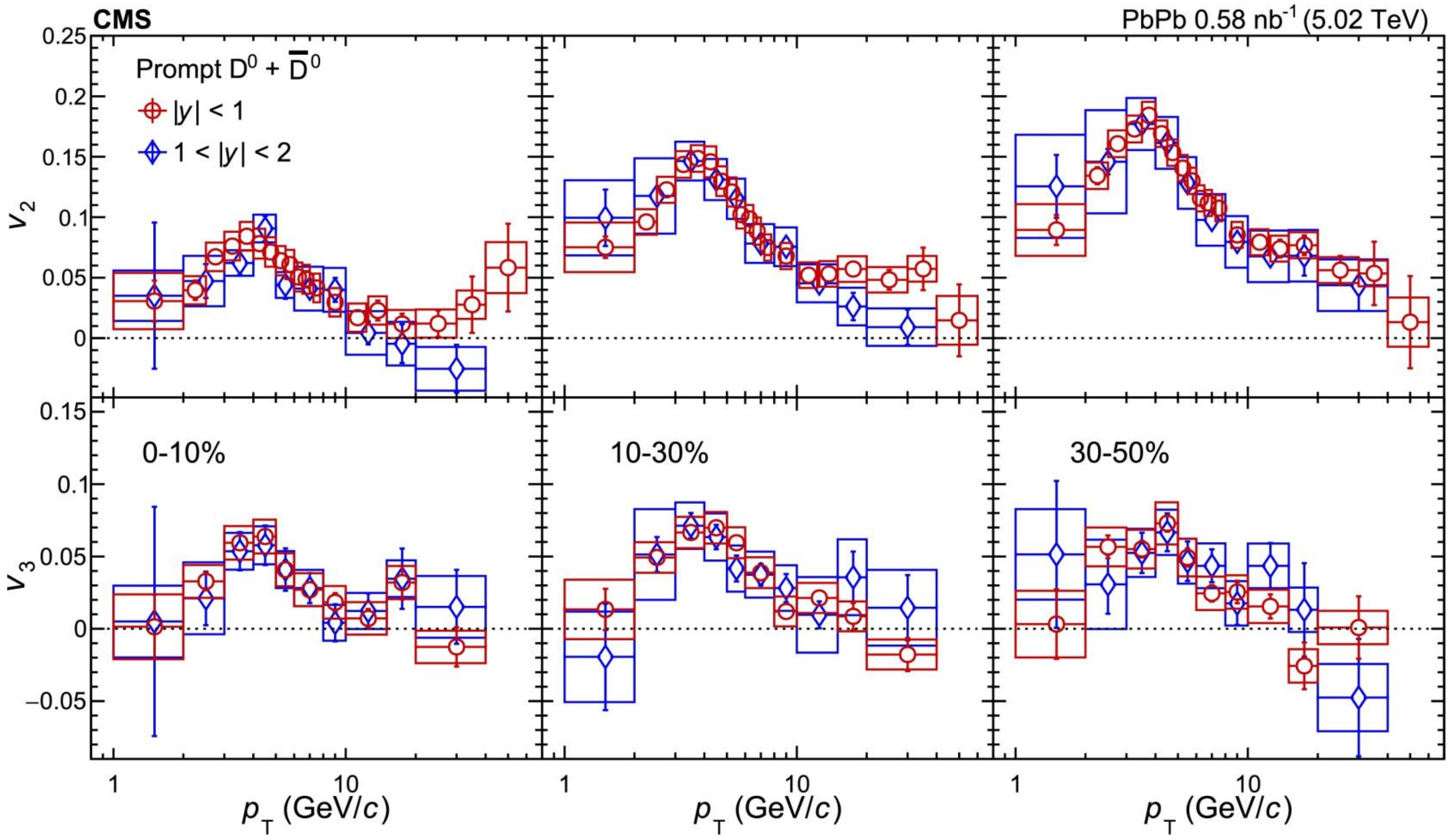


Elliptic flow, v_2



Triangular flow, v_3

Anisotropic D^0 flow in PbPb



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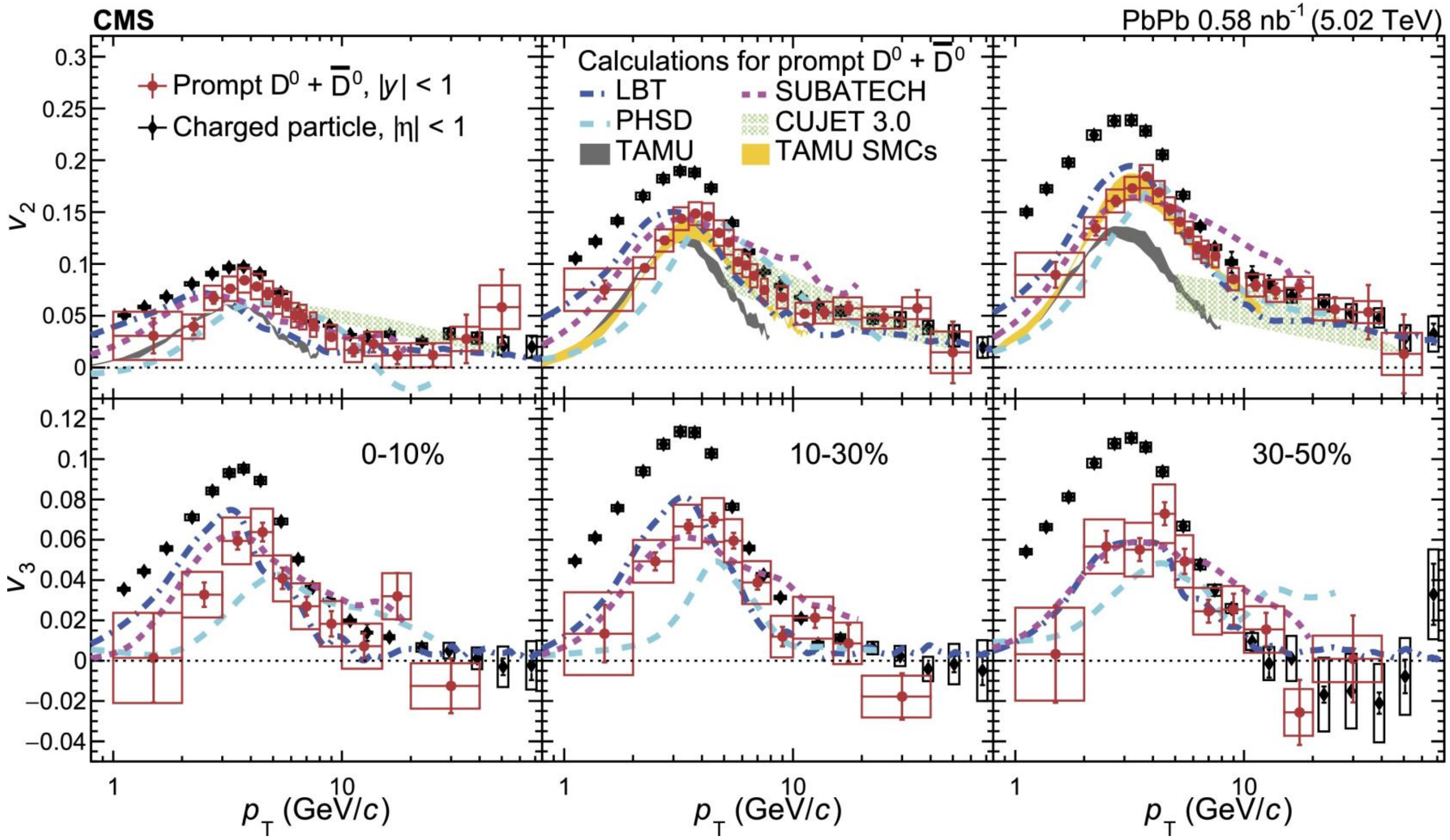
- Strong p_T dependence of v_2 and v_3
- Significant nonzero v_3 up to $p_T \sim 10$ GeV/c
- Significant centrality dependence of v_2, while v_3 is largely independent of centrality

Anisotropic D^0 flow in PbPb



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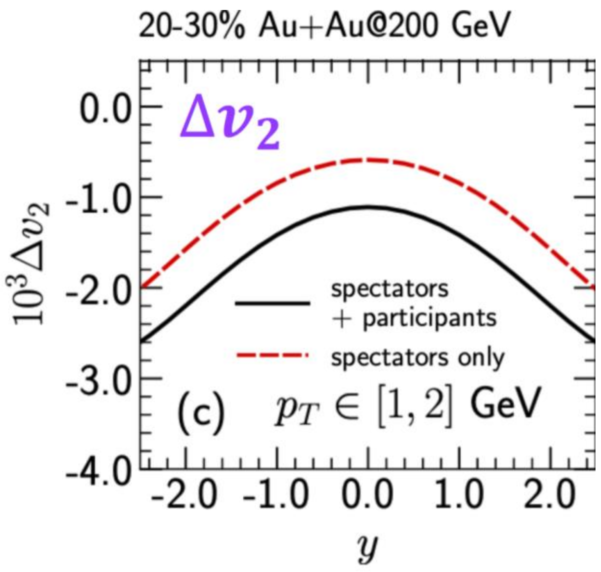
- Comparison with models
- No model explain the data over all centrality and p_T ranges.

CMS FINAL RESULT SQM24

Effect of Coulomb Field

Predictions for pions



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- Constraints on the electric conductivity of the quark-gluon plasma
- Difference in v_2 of D^0 and $\overline{D}^0$ mesons vs rapidity
- Rapidity averaged $\langle \Delta v_2 \rangle = 0.001 \pm 0.001(\text{stat}) \pm 0.003(\text{syst})$
- No evidence of strong Coulomb field observed in charm flow

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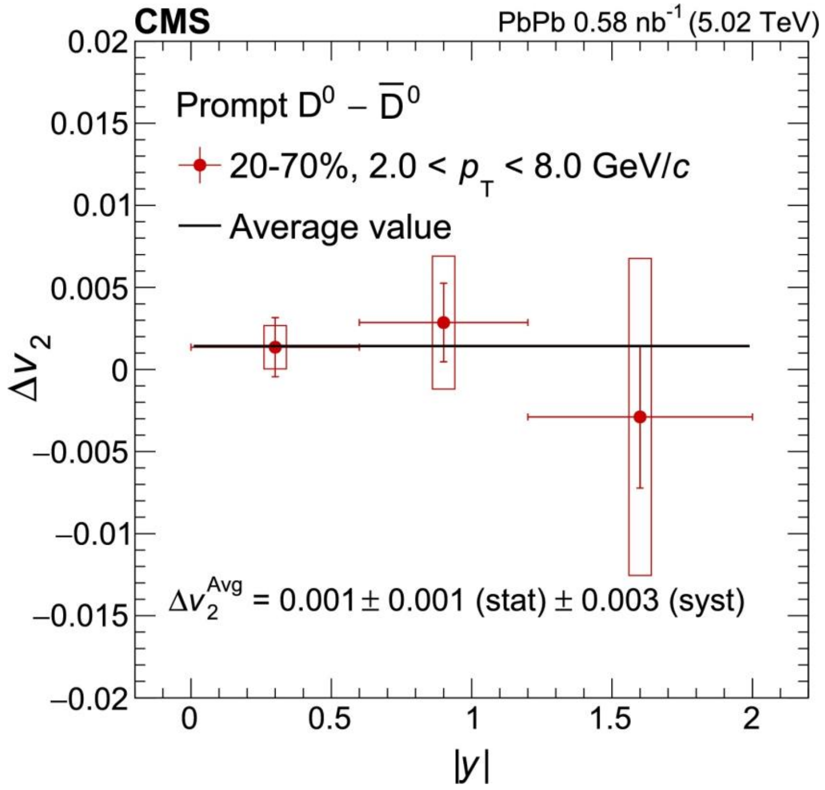

CMS FINAL RESULT SQM24

CMS NEW RESULT SQM24

Summary

- ❑ Λ_c^+ production significantly suppressed in PbPb → charm quark E-loss
- ❑ Λ_c^+ production in pp systematically higher than GM-VFNS calculation (tuned with e^+e^- data)
  - ➢ Breakdown of the universality of charm quark fragmentation functions?
- ❑ For $p_T > 10$ GeV/c, the Λ_c^+/D^0 ratios consistent in pp and PbPb, no significant coalescence contribution
  - ➢ Λ_c^+/D^0 ratios for pp and PbPb converge with e^+e^- for $p_T > 10$ GeV/c
- ❑ No significant multiplicity dependence in pPb
  - ➢ Differs with other quarks, saturation of coalescence?
- ❑ Centrality and p_T dependence of anisotropic flow
  - ➢ No sign of strong Coulomb field in PbPb

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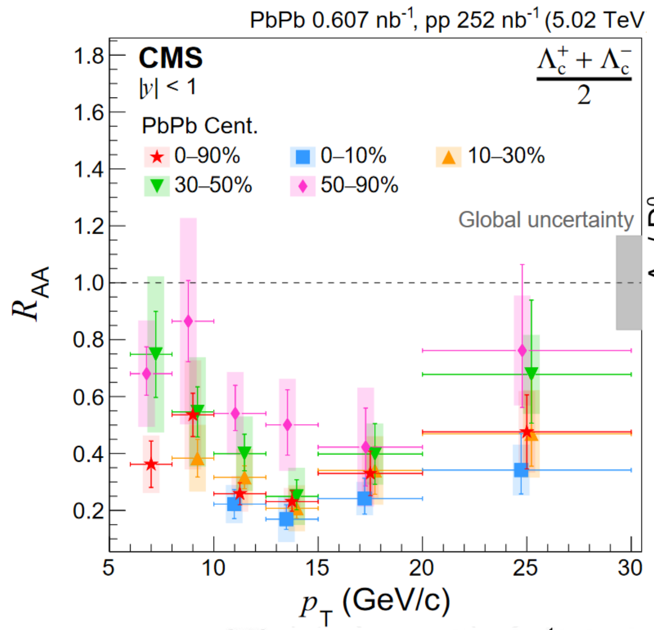

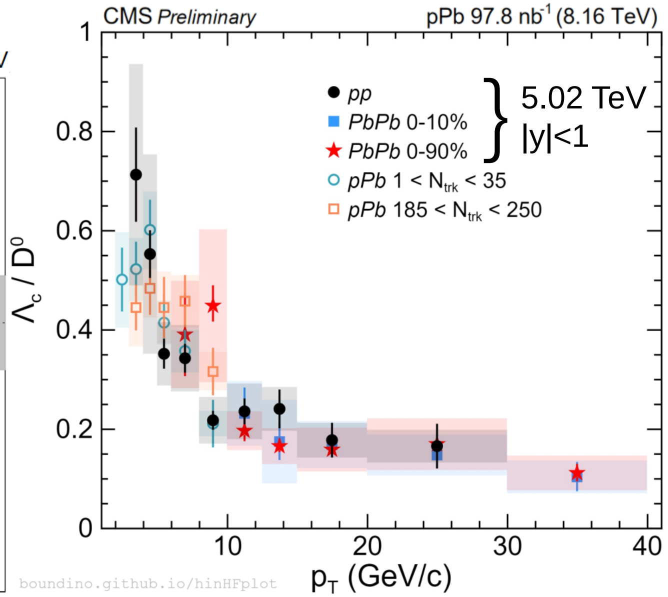

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