New insights on heavy flavor dynamics and hadronization from small to large collision systems from Λ_c^+ production with CMS

Soumik Chandra
Purdue University
on behalf of the CMS collaboration

SQM 2022

Motivation

- Heavy quarks produced at earliest stages of the collision
  - follow the whole evolution of the system
  - provide information on initial states as well as interactions with the QGP medium and hadronization process

- Studying energy loss mechanism
  - different than light quarks

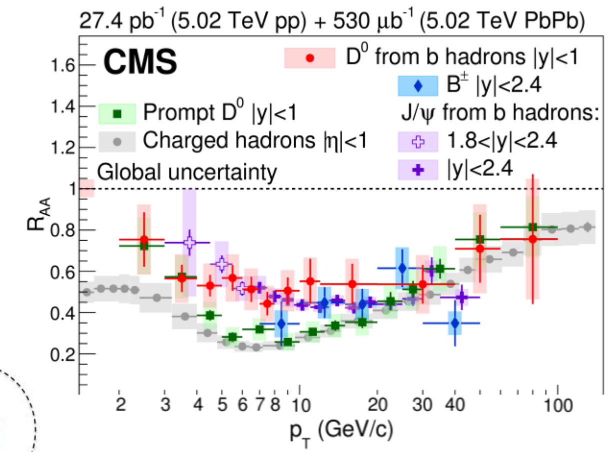
- Hadronization process
  - Fragmentation, coalescence, color reconnection, etc.
  - $\boldsymbol{\Lambda_c^+}(\boldsymbol{udc})$ and $\boldsymbol{D^0}(\boldsymbol{c\bar{u}})$ essential for charm quark coalescence (baryon - meson ratio)

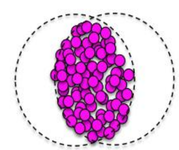
- Collectivity in small systems
  - Initial state correlations or final state effect?
  - Heavy quarks could provide further insight into the origin of collectivity

Heavy flavor in large systems

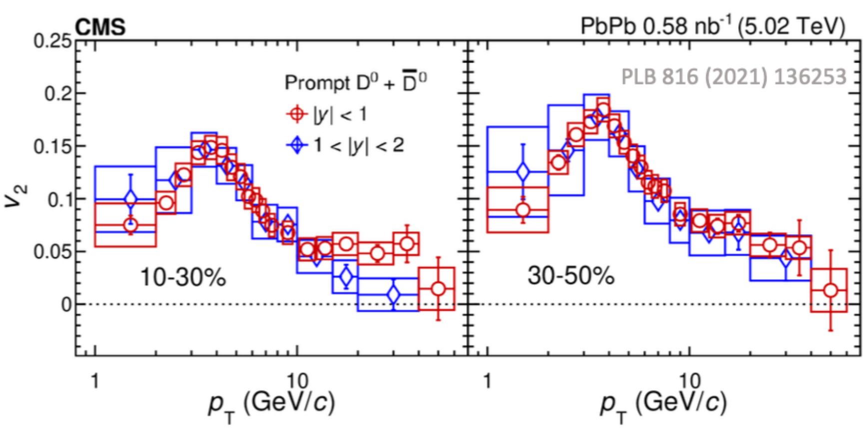
PRL 123(2019) 022001

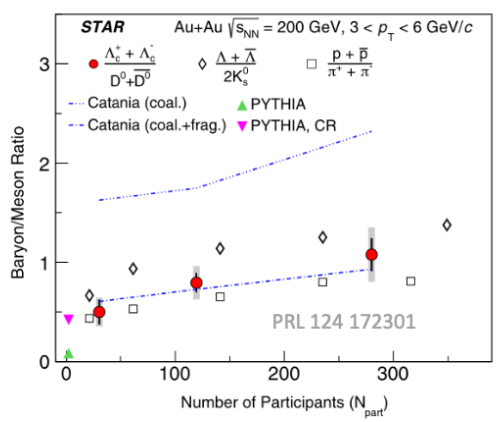
- ❖ Significant v_2 of heavy flavor quarks
- ❖ Heavy flavor suppression
- ❖ Coalescence process:
  - ➢ Baryon/meson ratio enhancement
    - ❑ Both light and heavy flavor hadrons

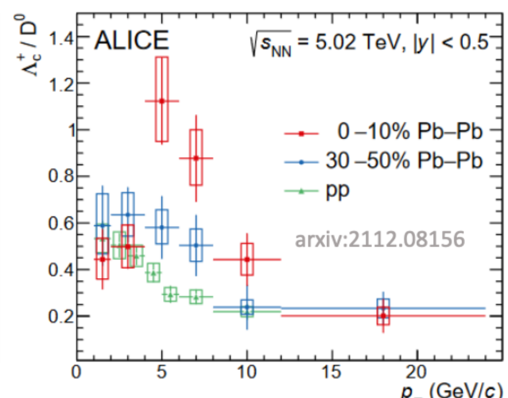




PbPb

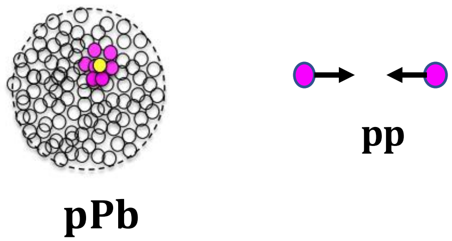


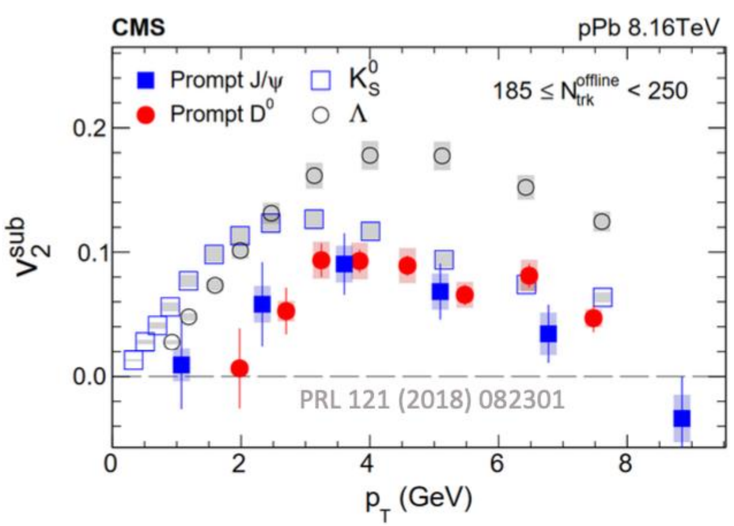


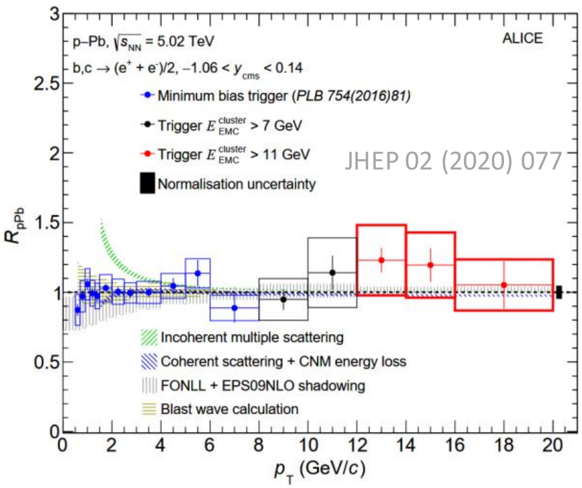


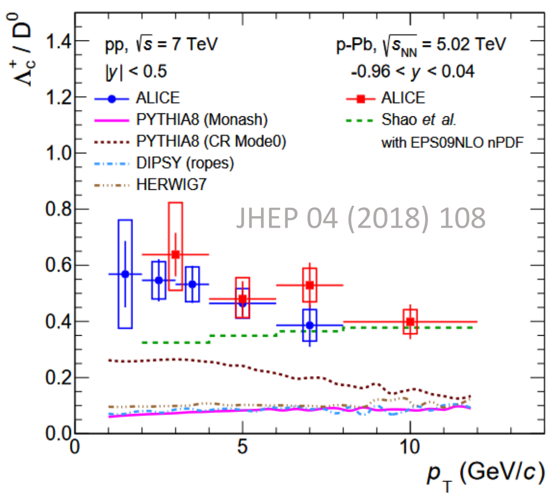
Heavy flavor in small systems

- Significant v_2 of heavy flavor quarks
- No heavy flavor suppression!
- Coalescence process:
  - Baryon/meson ratio enhancement





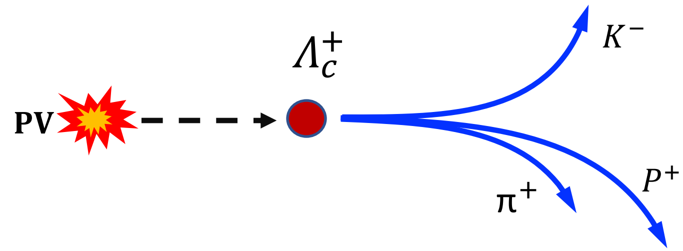




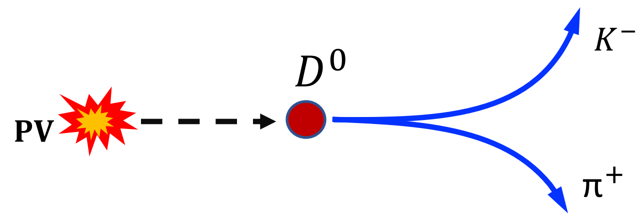
Reconstruction

- 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%



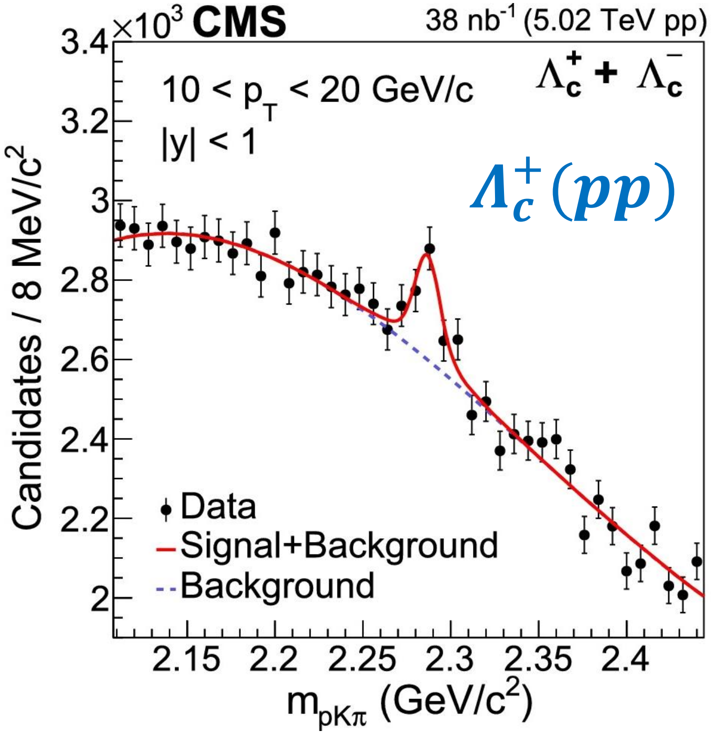
- D^0 reconstruction
  - $D^0 \rightarrow K^-\pi^+$
  - BR ~ 3.93%



- No particle identification → All possible combinations of three (two) charged tracks in an event are taken into account

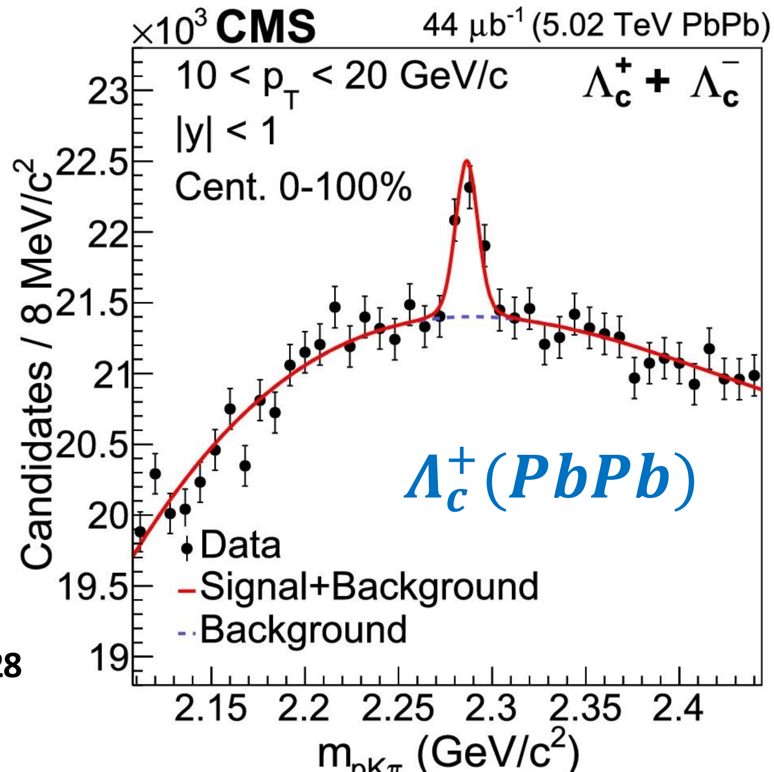
- Additional selection done with TMVA training

Signal Extraction Λ_c



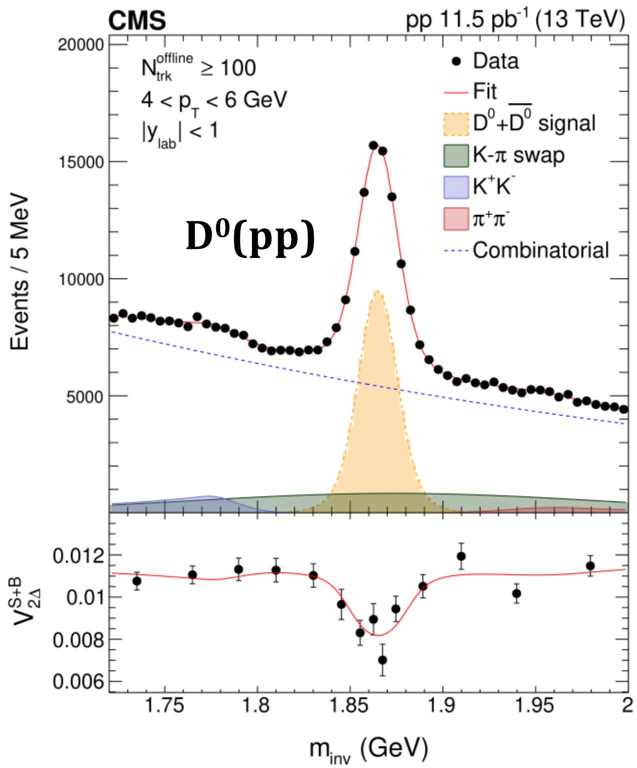
- Combinatorial background: 3rd order Chebyshev polynomial function

- Signal: Double Gaussian



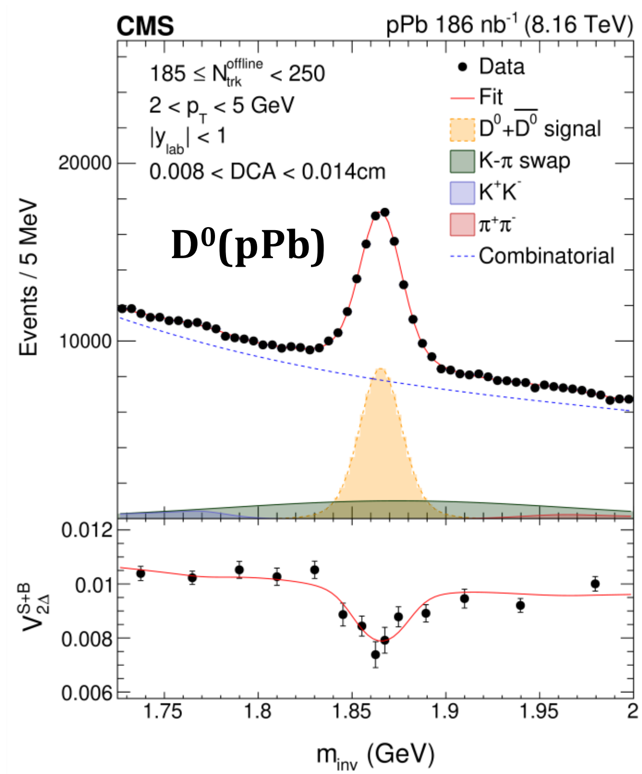
PLB 803 (2020) 135328

Signal Extraction D^0



Simultaneous fit of mass and v_2

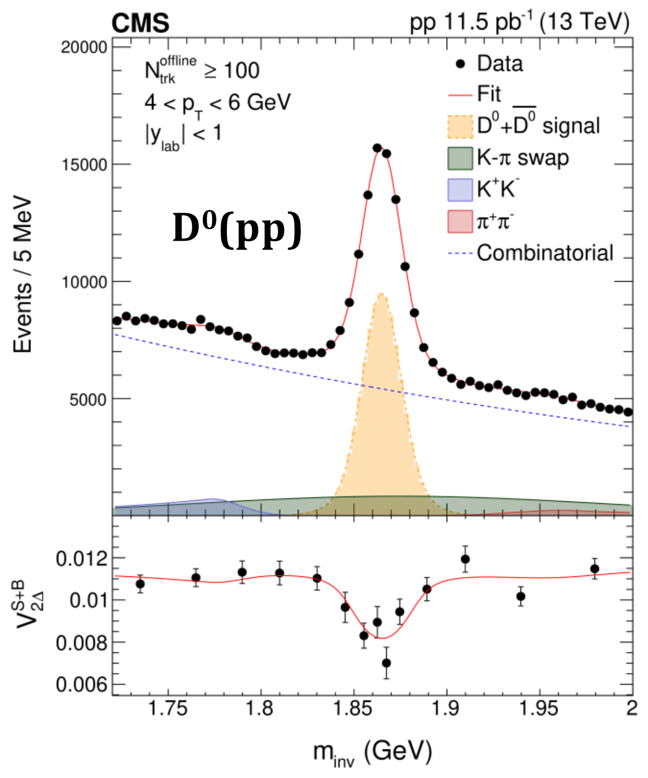
PLB 813 (2021) 136036



Mass Fit:

- $D^0+\overline{D}^0$ signal: Double Gaussian
- K-π swap: Single Gaussian
- KK and $\pi^+\pi^-$: Crystal ball function
- Combinatorial background: 3rd order polynomial

Signal Extraction D^0



Mass Fit:

- $D^0+\overline{D}^0$ signal: Double Gaussian
- K-π swap: Single Gaussian
- KK and $\pi^+\pi^-$: Crystal ball function
- Combinatorial background: 3rd order polynomial

v_2:

- Background $V_{2\Delta}^{B}(m_{inv})$: Linear function

$$V_{2\Delta}^{S+B}(m_{inv}) = \alpha(m_{inv})\, V_{2\Delta}^{S} + [1-\alpha(m_{inv})]\, V_{2\Delta}^{B}(m_{inv})$$

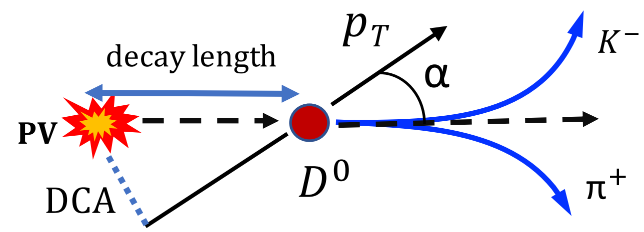
$$\alpha(m_{inv}) = \left[S(m_{inv}) + SW(m_{inv}) + S(m_{K^+K^-}) + S(m_{\pi^+\pi^-})\right] / \left[S(m_{inv}) + SW(m_{inv}) + S(m_{K^+K^-}) + S(m_{\pi^+\pi^-}) + B(m_{inv})\right]$$

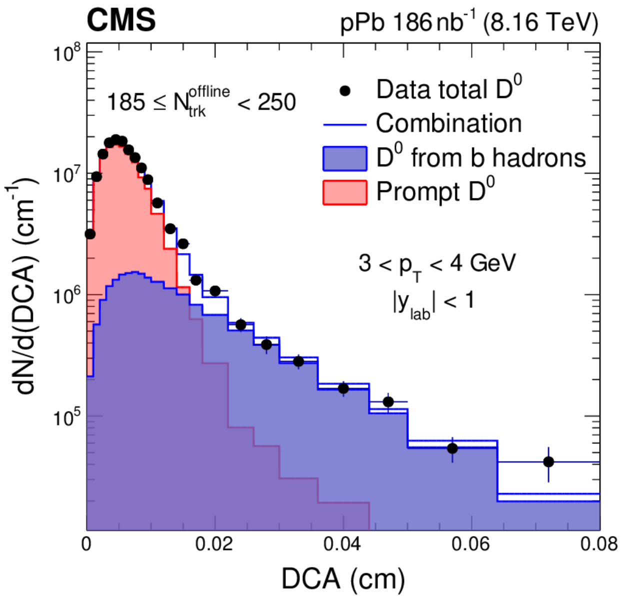
Simultaneous fit of mass and v_2

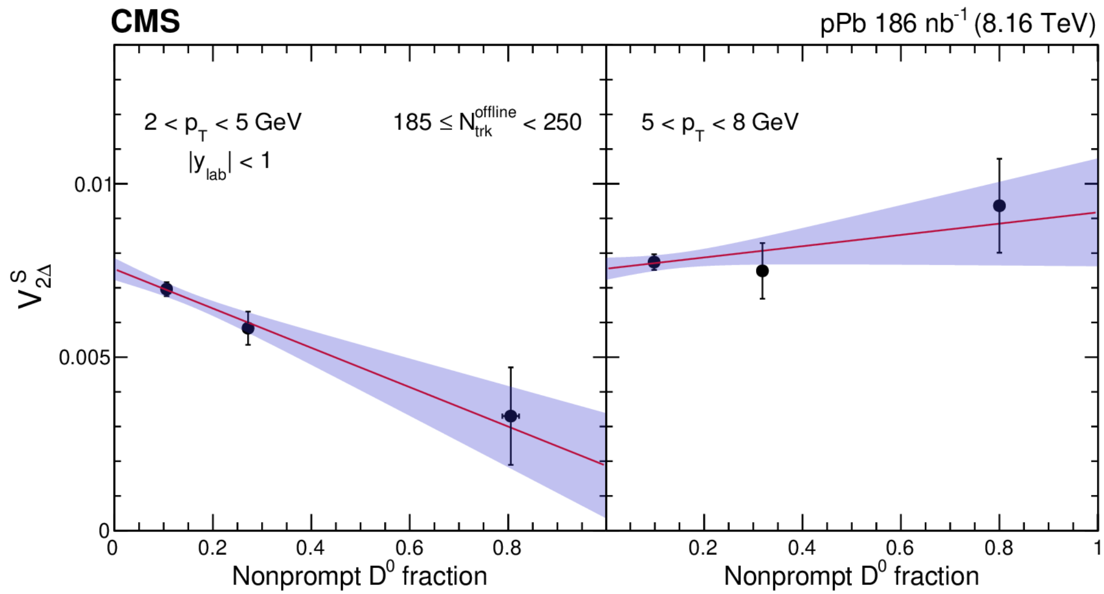
PLB 813 (2021) 136036

Nonprompt D^0 Extraction

- Distance of closest approach (DCA) fit to extract non-prompt fraction
- v_2 vs non-prompt fraction (3 DCA ranges)





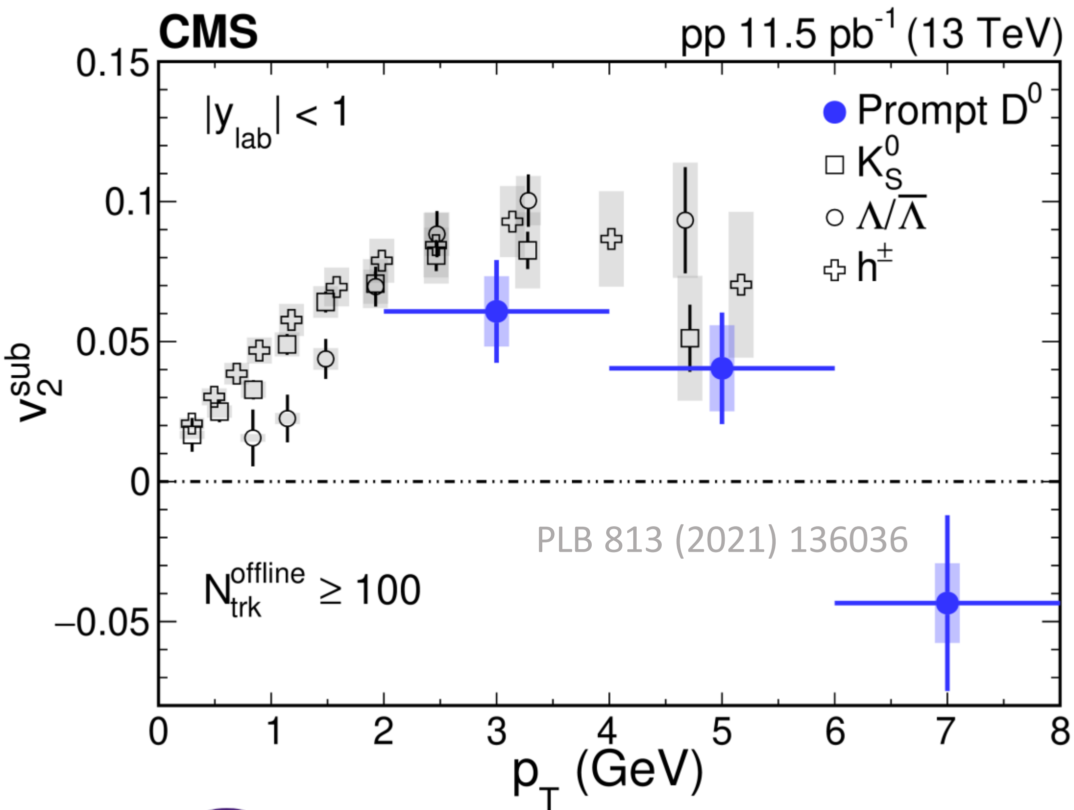


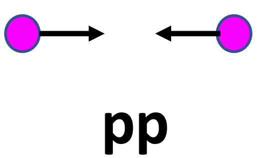
PLB 813 (2021) 136036

Results

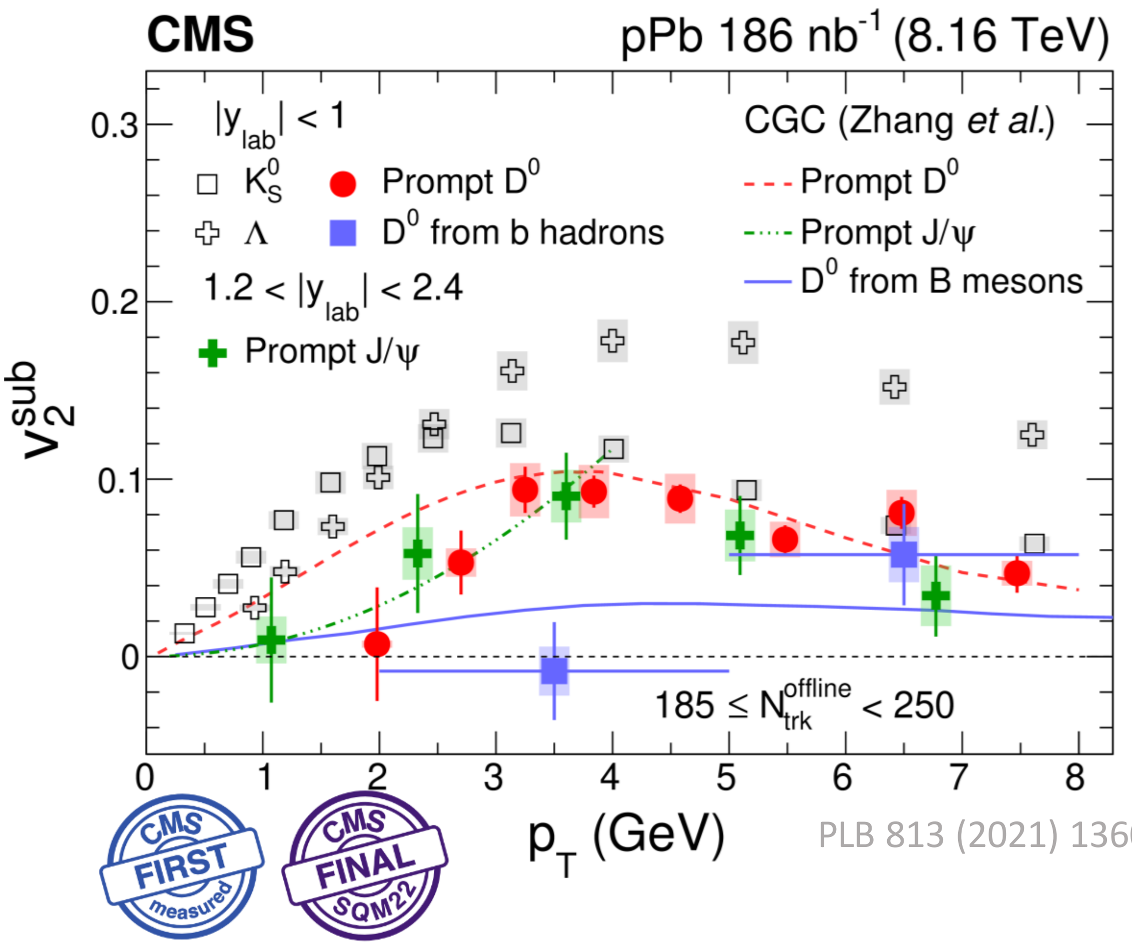
D^0 v_2 in pp collisions

- First measurement of prompt D^0 v_2 in pp collisions
- Indication of nonzero charm flow!
- Comparable with light hadrons



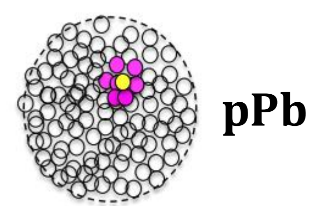


D^0 v_2 in pPb collisions

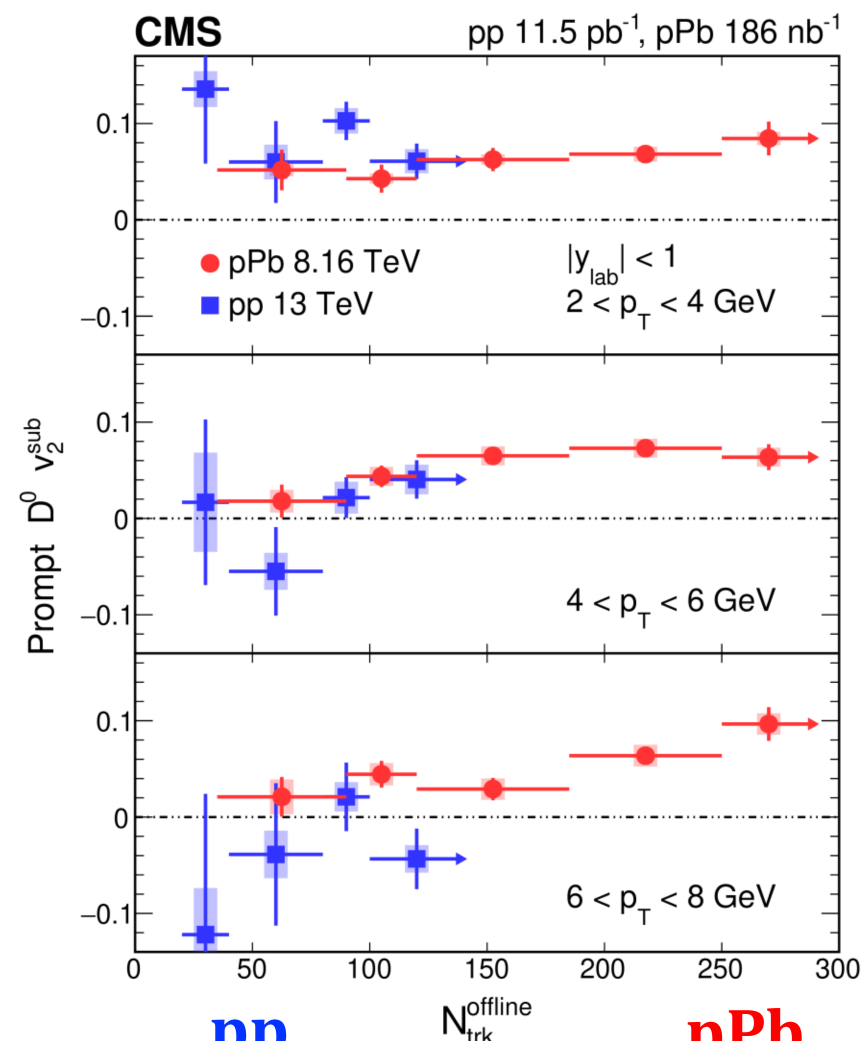


PLB 813 (2021) 136036

- First measurement of b → D^0 v_2
  - v_2 consistent with 0
- Mass hierarchy at lower p_T
- CGC model consistent with data
  - Although with large uncertainties

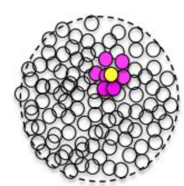


Prompt D^0 v_2 in pp & pPb

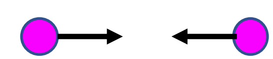


pp **pPb**

- ❑ Positive v_2 of prompt D^0 is observed in high multiplicity events
- ❑ Non-zero v_2 diminish towards low-multiplicity regimes
- ❑ pp & pPb results compatible within the same multiplicity range
  - ➢ With large uncertainties



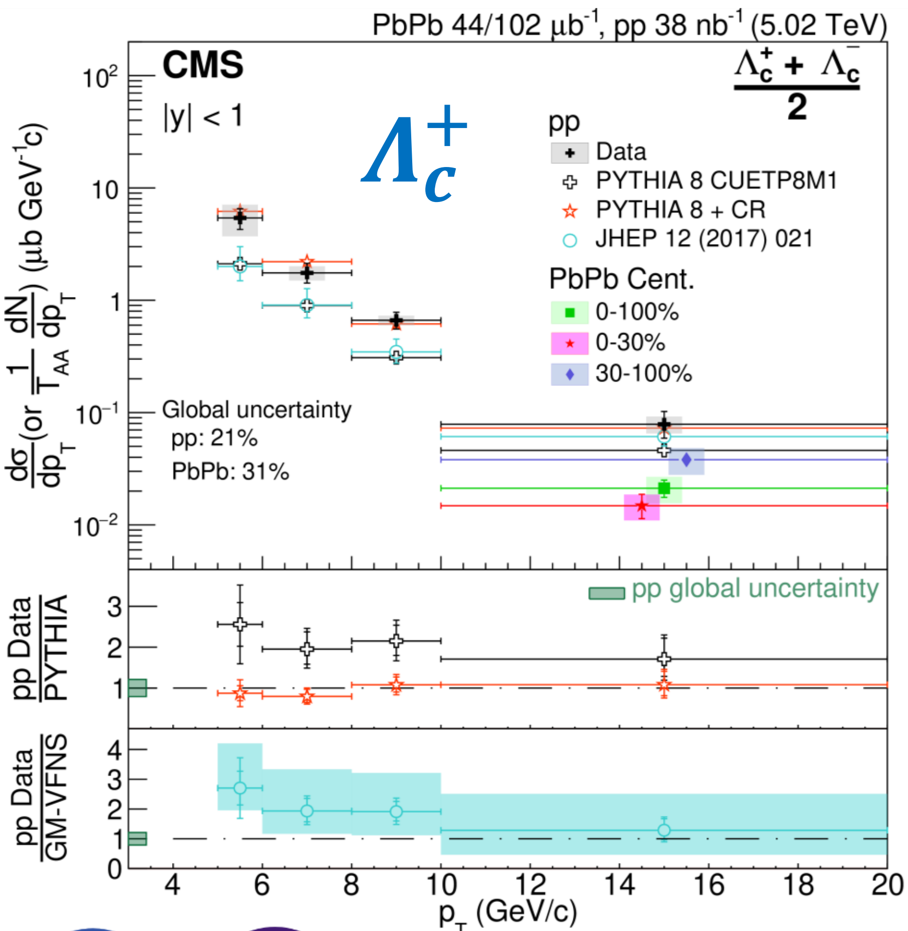
pPb



pp

Λ_c^+: p_T spectra

PLB 803 (2020) 135328

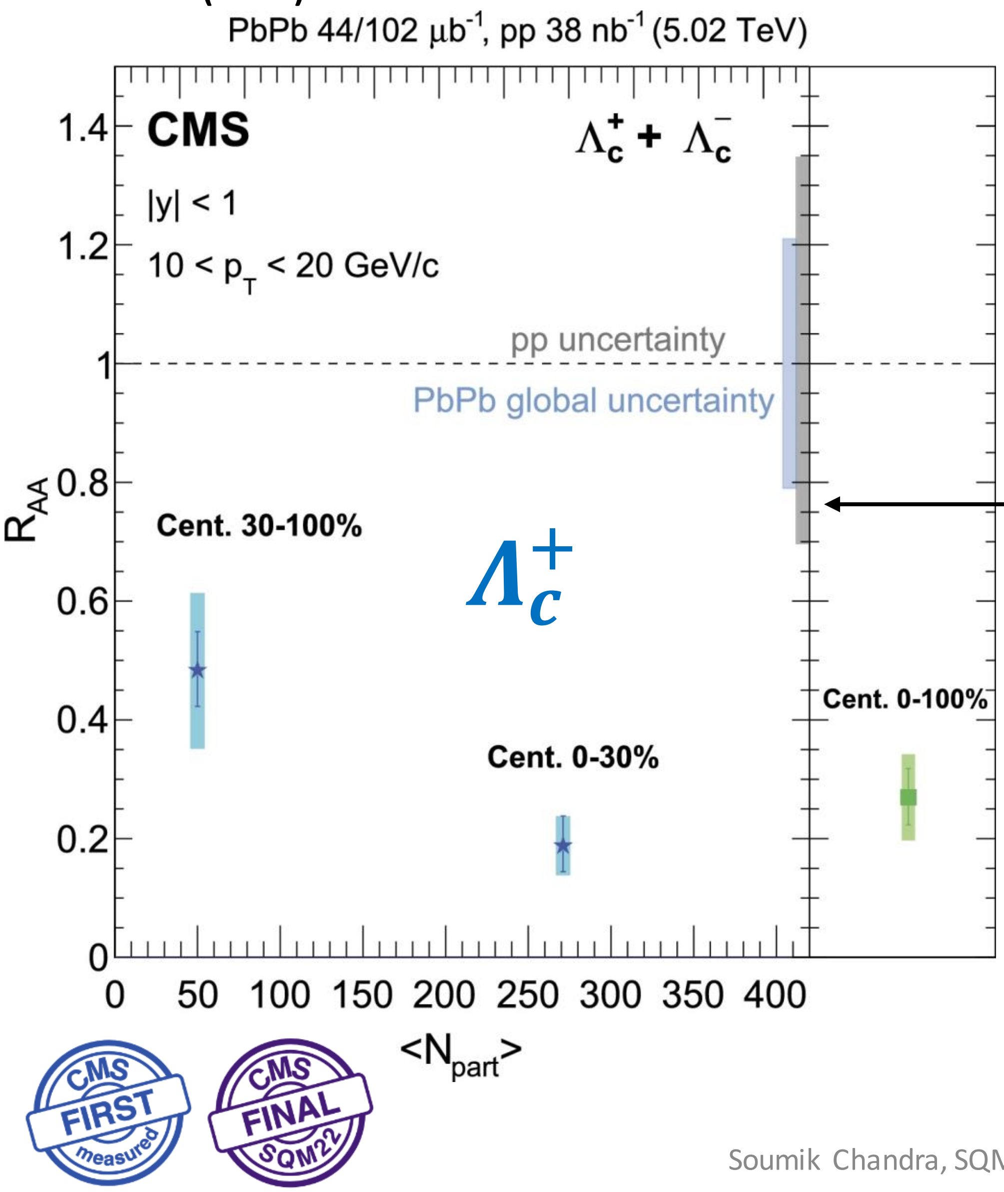


- PYTHIA 8 systematically below data
- PYTHIA 8 + color reconnection (CR) mode 2 consistent with pp data
- GM-VFNS Systematically below data for $p_T < 10$ GeV/c
- T_{AA} scaled yield for PbPb collisions is lower than cross-section in pp collisions.

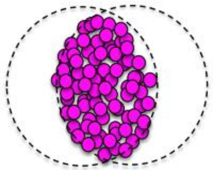
PbPb **pp**

$\Lambda_c^+ : R_{AA}$

PLB 803 (2020) 135328



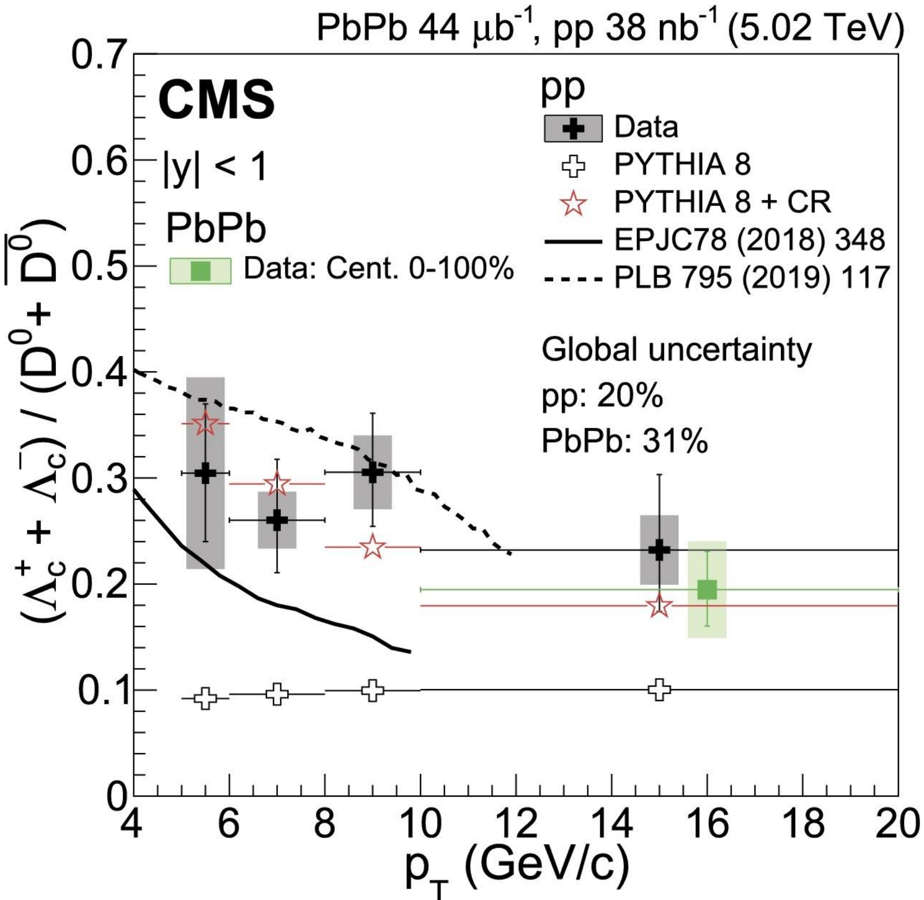
- Indication of Λ_c^+ suppression in PbPb collisions
- Suppression larger in central events
- Cannot draw definite conclusion due to large global uncertainties



PbPb

Λ_c/D^0 enhancement

PLB 803 (2020) 135328



pp **PbPb**

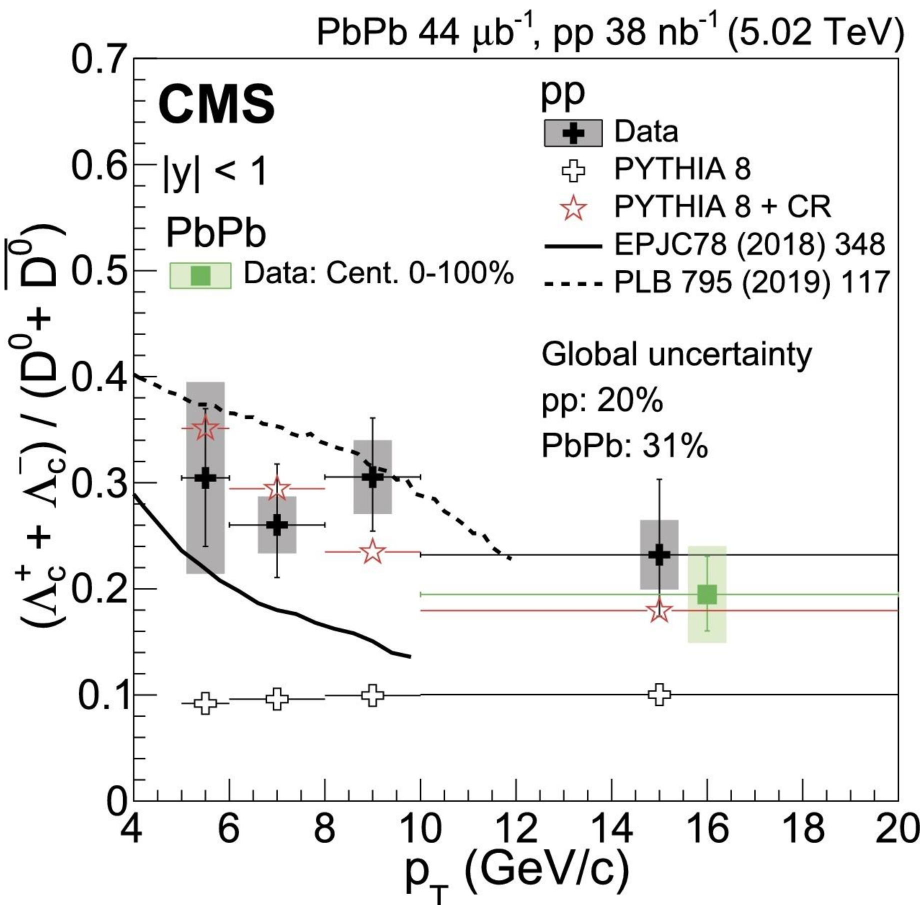
- **Similarity between pp & PbPb results suggest that there is no significant coalescence of Λ_c^+ (10 < p_T < 20 GeV/c)**

- No significant p_T dependence observed within large uncertainties.

CMS FIRST measured
CMS FINAL SQM22

Λ_c/D^0 enhancement

PLB 803 (2020) 135328



pp **PbPb**

- **Similarity between pp & PbPb results suggest that there is no significant coalescence of Λ_c^+ (10 < p_T < 20 GeV/c)**
- No significant p_T dependence observed within large uncertainties
- PYTHIA8 underestimates pp data
- PYTHIA8 + color reconnection – good description of data
- Solid line (Catania) - predicts stronger p_T dependence
  - Coalescence + fragmentation
- Dashed line (TAMU) – reasonable description of data for p_T < 10 GeV/c
  - Includes charm baryon states beyond PDG

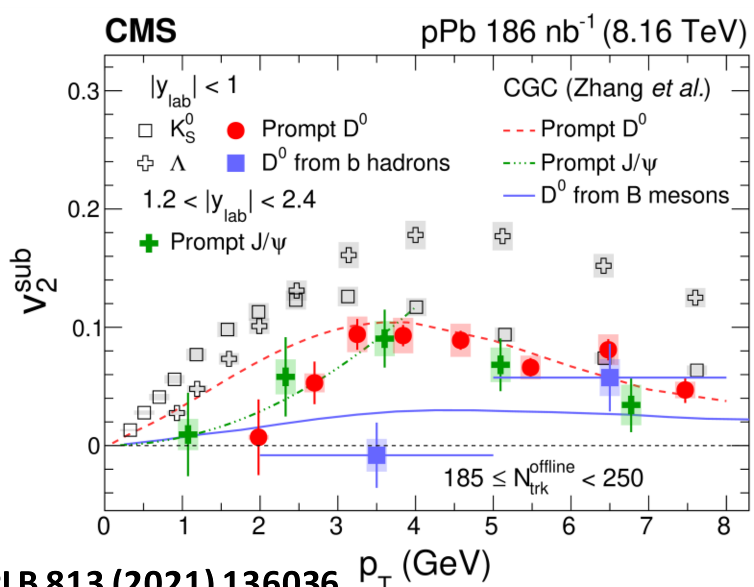
CMS FIRST measured

CMS FINAL SQM22

Summary

- Comprehensive study of heavy flavor in all collision systems
- Significant elliptic flow of charm quark in pPb and indication in pp collisions
- b→D^0 v_2 in pPb consistent with 0
- Suppression of Λ_c^+ consistent with D^0 results in PbPb
- No significant coalescence of Λ_c^+ observed for $10 < p_T < 20$ GeV/c
- Λ_c^+ in pp collisions described well by PYTHIA 8 + CR
- New analysis is ongoing with increased statistics:
  - ~ 13 times for PbPb data
  - ~ 6 times for pp data

PLB 803 (2020) 135328



PLB 813 (2021) 136036