Modification of heavy-quark hadronisation in high-multiplicity collisions

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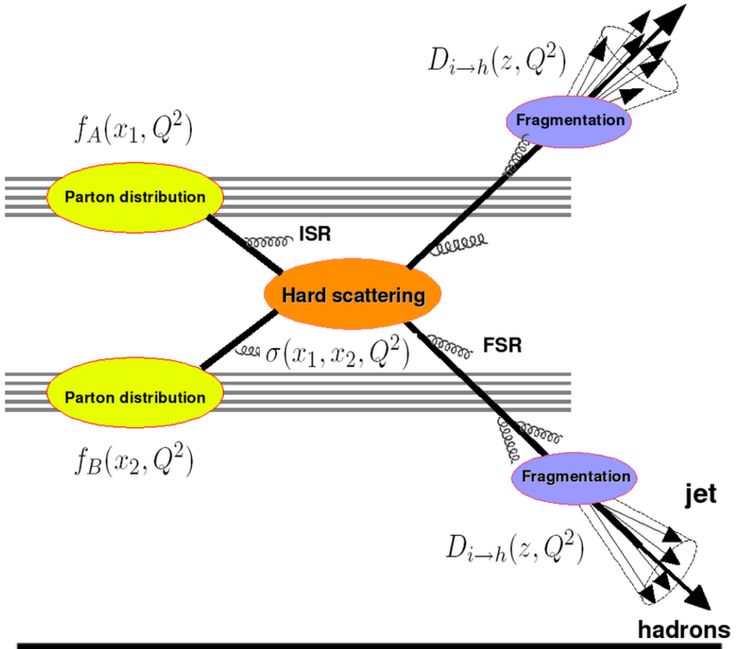
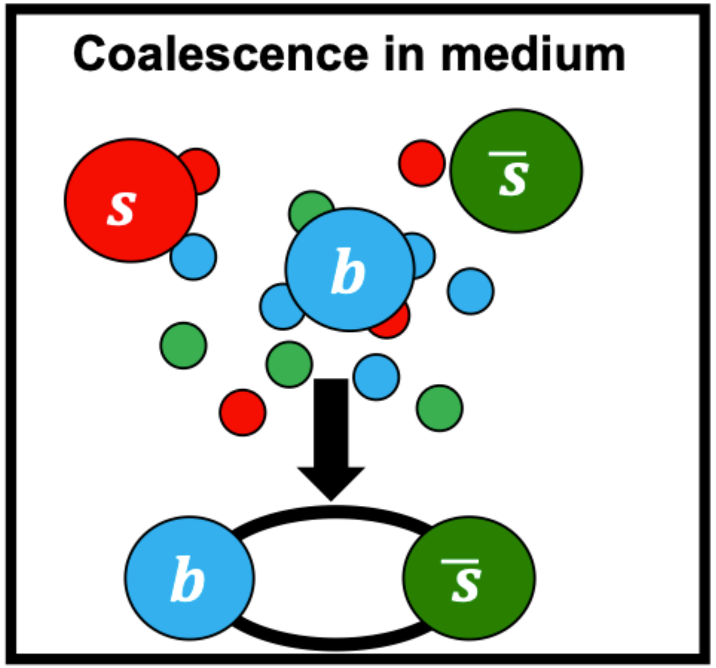
Motivation

- Heavy quark offer unique probes of the hadronization process
  - ➢ Produced at early stages of the collision, production well described.
  - ➢ Fragmentation mechanism: lots of partons produced by outgoing quarks fragment into hadrons, dominates in low multiplicity collisions.
  - ➢ Coalescence mechanism: multiple overlapping quarks in position and velocity phase space combine to form hadrons, occurs in high multiplicity collisions.
- High multiplicity collisions are often accompanied by strangeness enhancement
  - ➢ In big systems (PbPb, AuAu): *s* quarks enhancement mainly come from gluons fusion in QGP.
  - ➢ In small systems (*pp*, *p*Pb): *s* quarks enhancement mechanism is still debated (rope hadronization, dynamical core-corona initialization…).

Baryon/meson ratios are sensitive to hadronization.



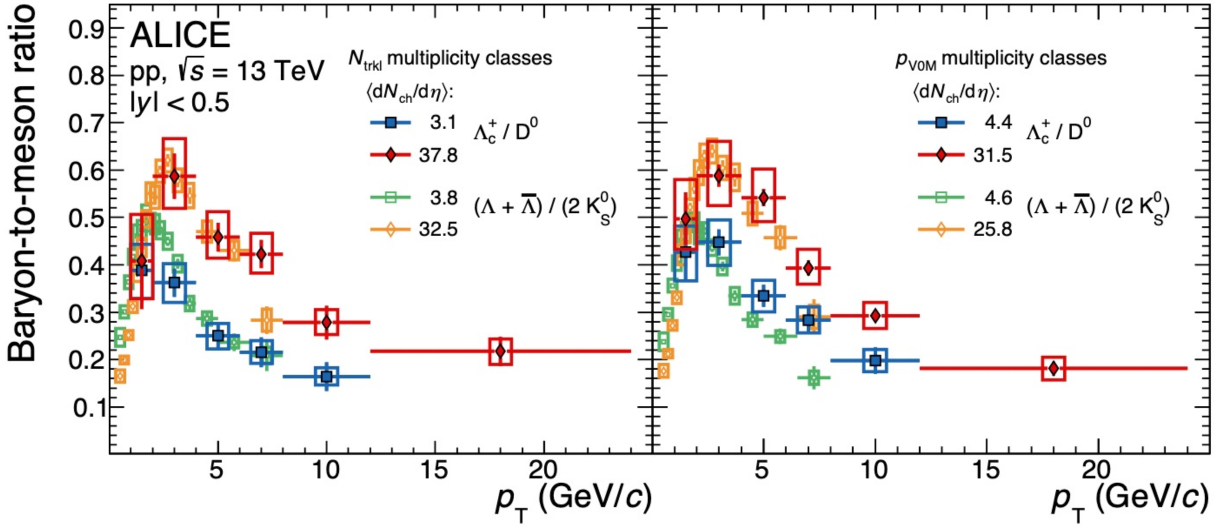
Strange meson/non strange meson ratios are sensitive to hadronization and strangeness enhancement.

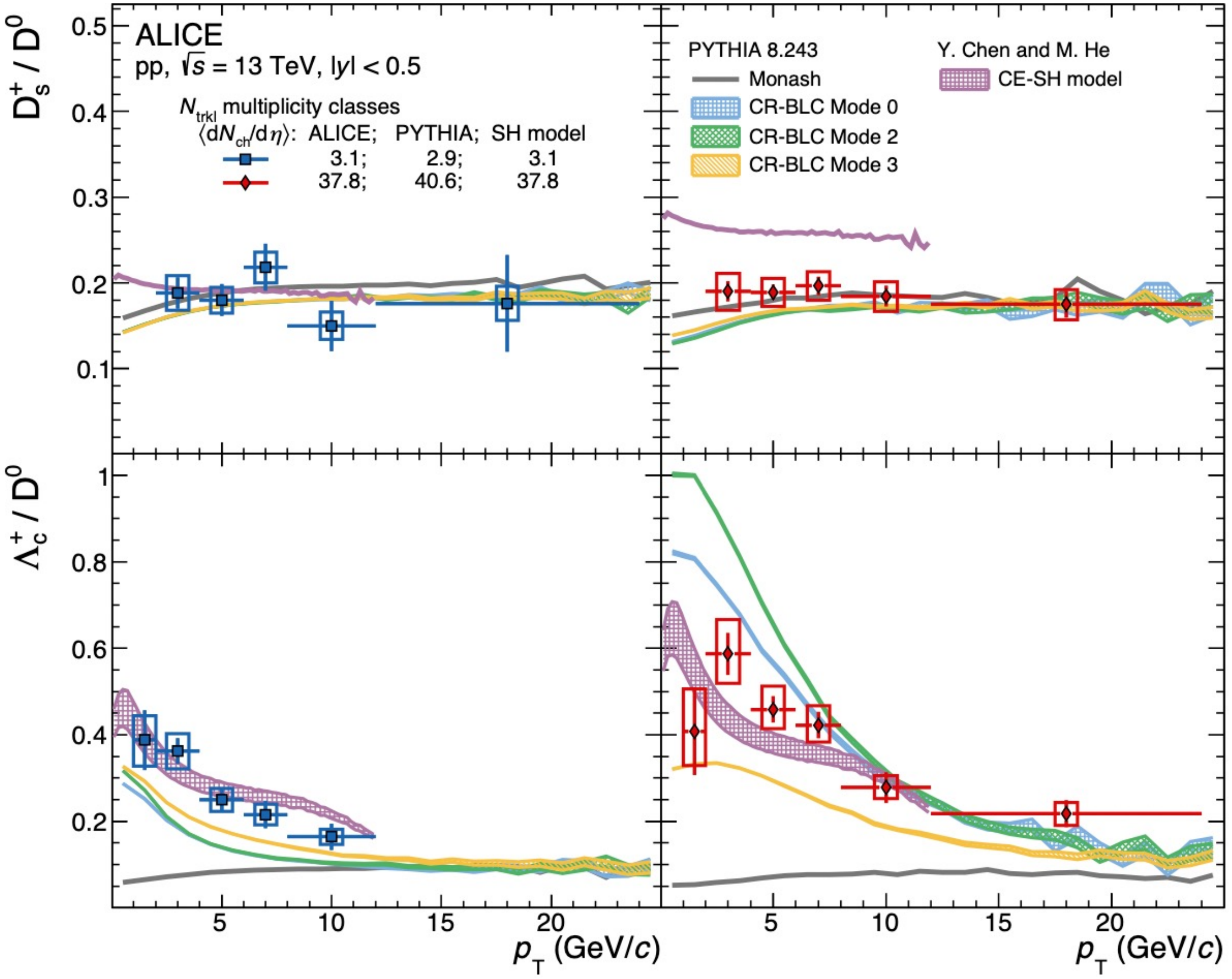


Baryon/Meson ratios

Λ_c^+/D^0 ratios in pp collisions at $\sqrt{s}$ =13 TeV

- The Λ_c^+/D^0 ratios show a significant multiplicity enhancement, with a significance of 5.3σ for $1 < p_T < 12$ GeV/c, comparing the highest multiplicity interval with respect to the lowest one.
- The Λ_c^+/D^0 ratios as a function of p_T show a similar shape and magnitude as the Λ/K_S^0 ratios in comparable multiplicity intervals, suggesting a potential common multiplicity enhancement mechanism for strange and charm hadrons formation.

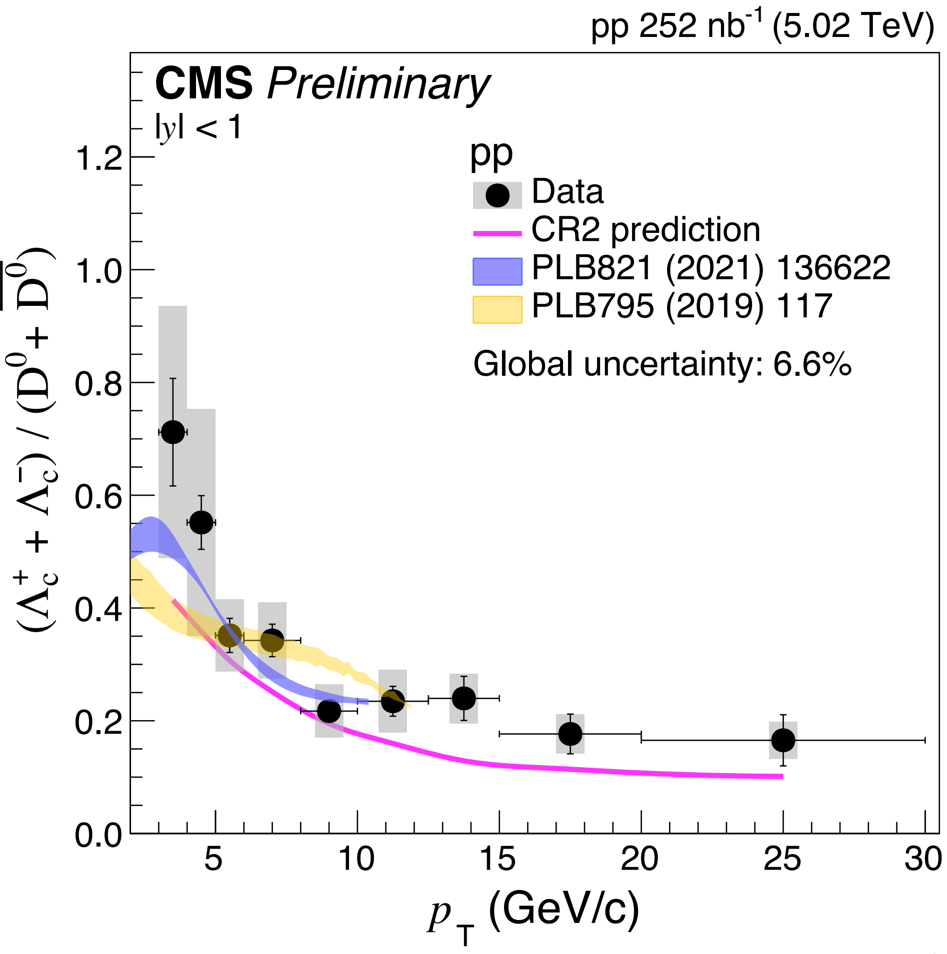


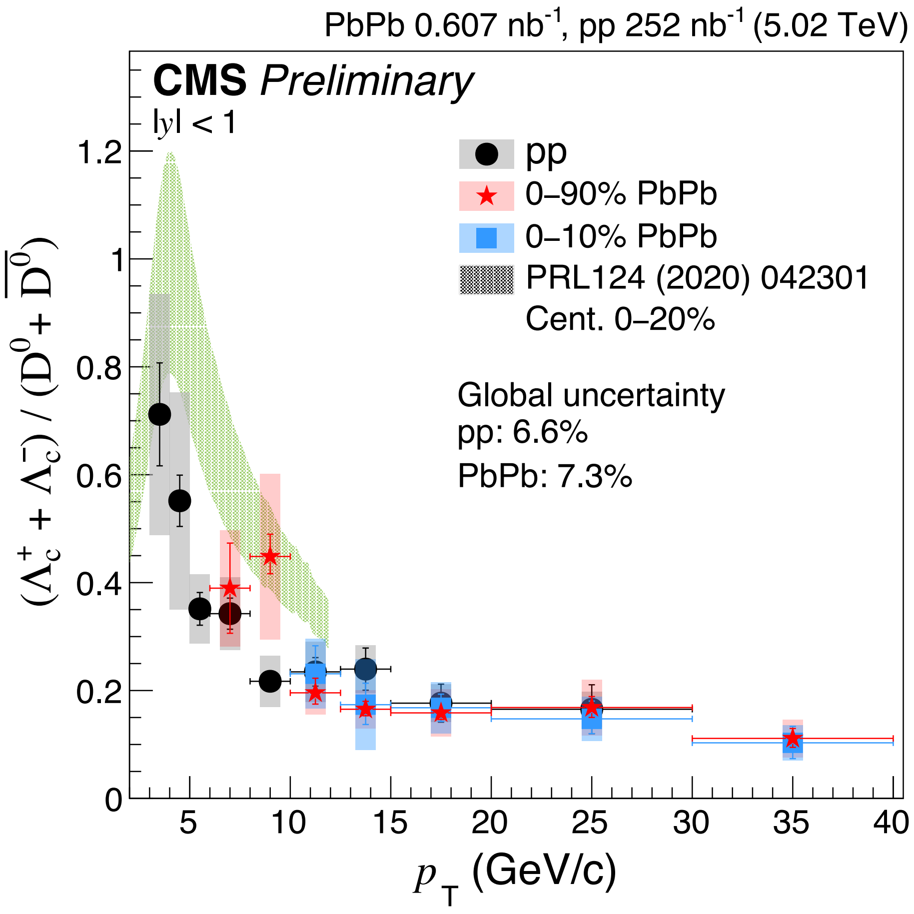


Phys. Lett. B 829 (2022) 137065

Λ_c^+/D^0 ratios in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Λ_c^+/D^0 ratios in pp is consistent with color reconnection for $p_{\mathrm{T}} < 10$ GeV/c, but is systematically lower than observed for the $10 < p_{\mathrm{T}} < 30$ GeV/c range.
- The Λ_c^+/D^0 ratios in PbPb is consistent with pp for $p_{\mathrm{T}} > 10$ GeV/c. This suggests that the coalescence process doesn't play a significant role in high p_{T}.



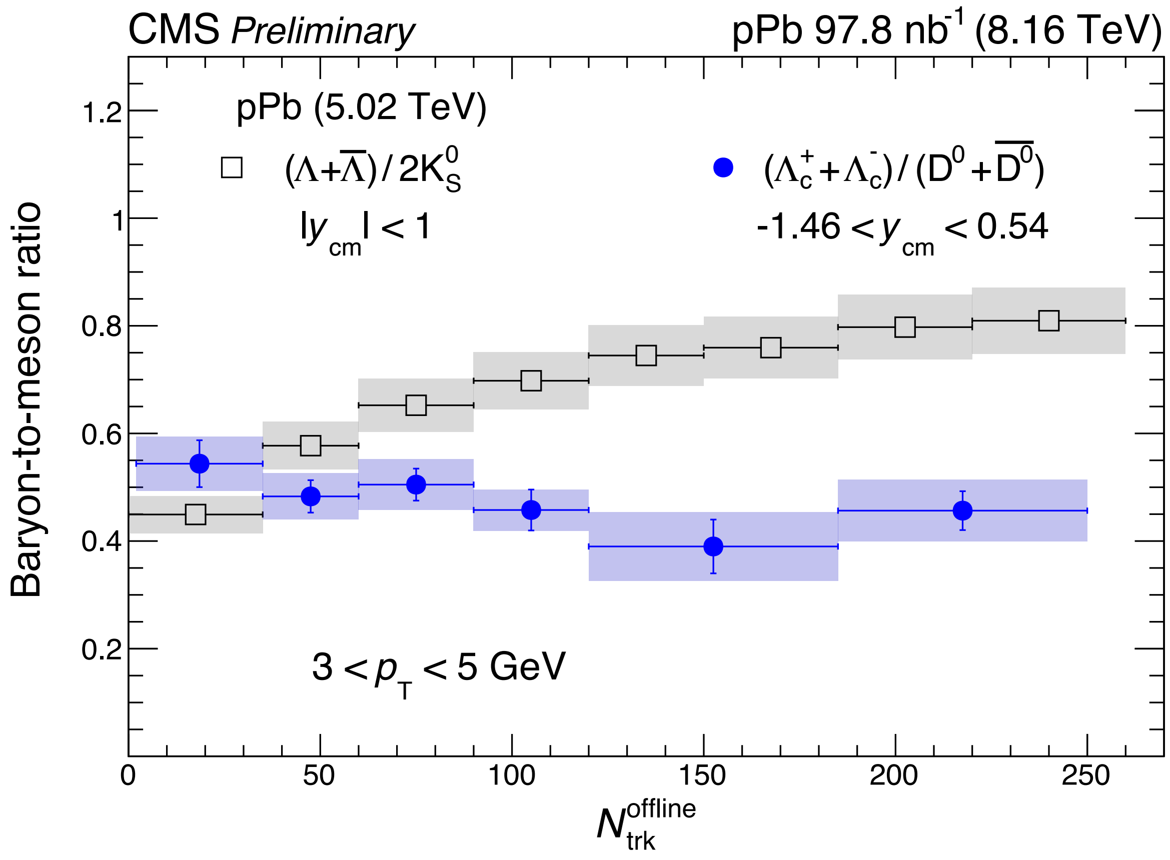


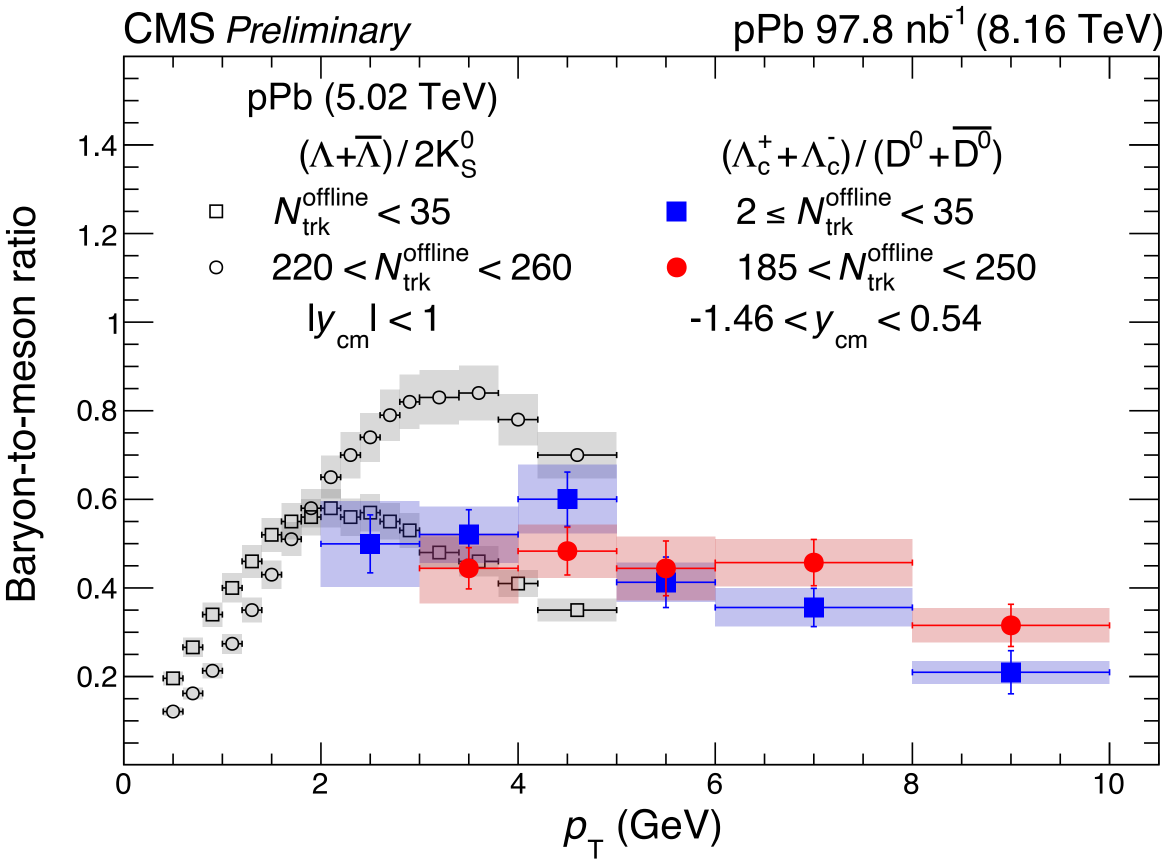
CMS-PAS-HIN-21-004

Λ_c^+/D^0 ratios in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

Almost same kinematic region
System dependent ?

- Λ_c^+/D^0 ratios in pPb has no significant multiplicity dependence.
- The strange hadrons don't show similar multiplicity dependence as charm hadrons, different from the case in *pp* (slide 4).

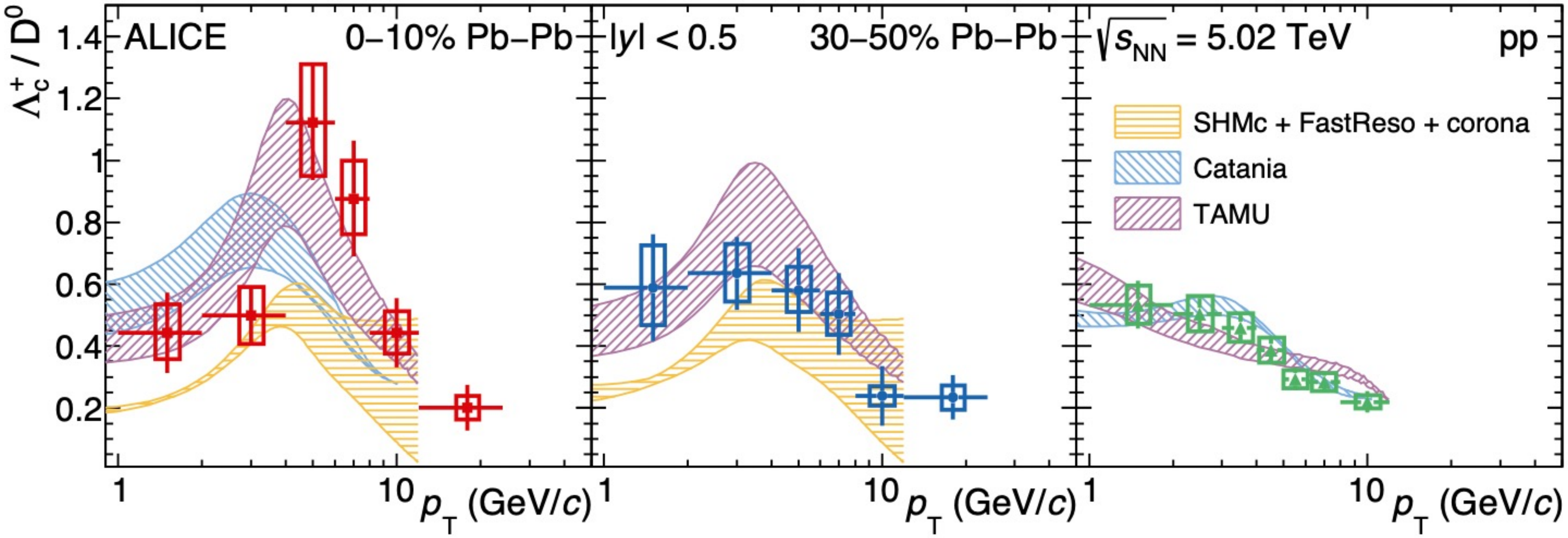




CMS-PAS-HIN-21-016

Λ_c^+/D^0 ratios in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

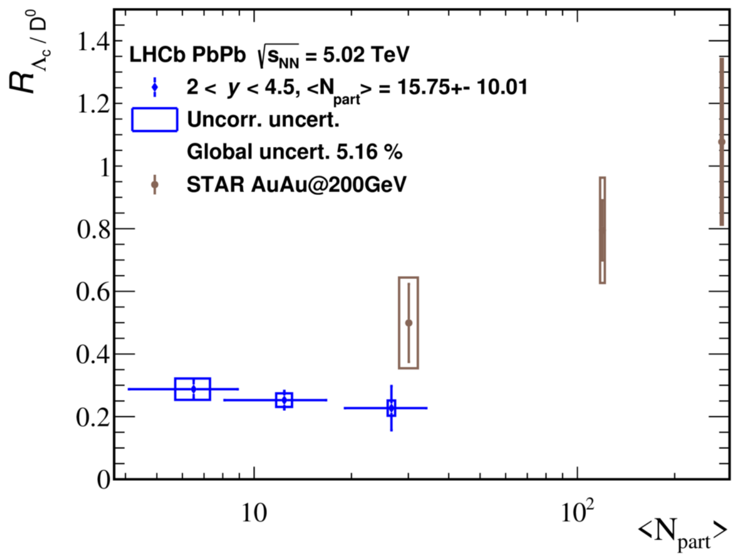
- Coalescence mechanism is expected to be stronger in heavy ion collisions due to the presence of QGP, baryons are more strongly enhanced than mesons under the influence of coalescence mechanisms.
- Recently, both ALICE and LHCb measured Λ_c^+/D^0 ratios in PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV separately.
- ALICE results show Λ_c^+/D^0 ratios increase from *pp* to central PbPb collisions with a significance of 3.7σ for $4 < p_{\mathrm{T}} < 8$ GeV/c.
- This measurements are in agreement with the theoretical calculation that include both coalescence and fragmentation mechanism.

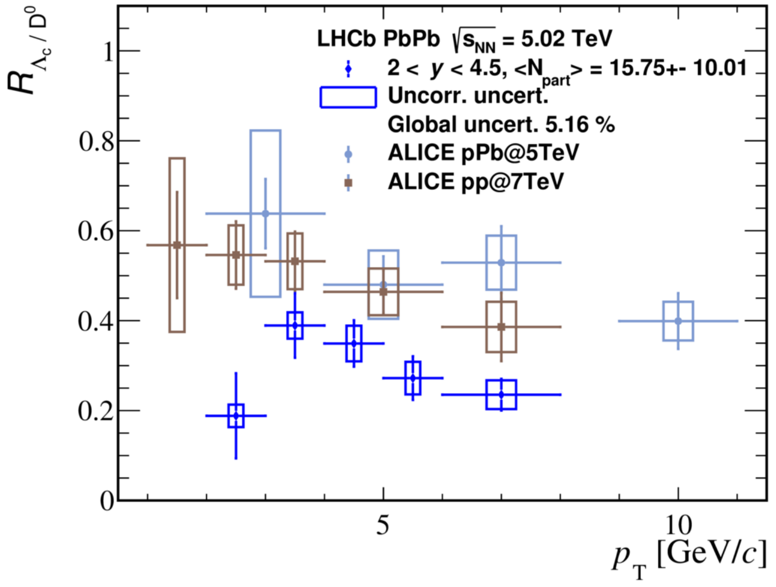


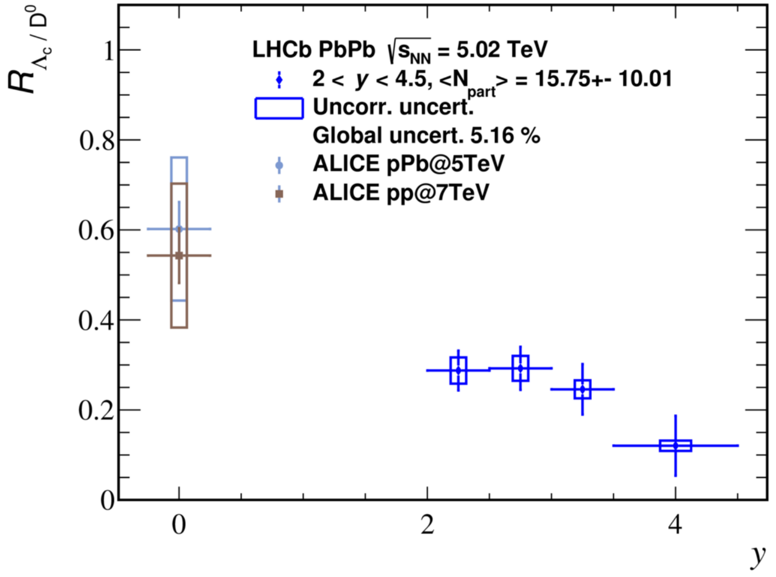
Phys.Lett.B 839 (2023) 137796

Λ_c^+/D^0 ratio in peripheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- In LHCb, Λ_c^+/D^0 is extended to most peripheral PbPb collisions (65–90%) and forward region ($2 < y < 4.5$).
- Λ_c^+/D^0 ratios show no dependence on centrality in 65–90%, but maybe dependence on rapidity.
- Λ_c^+/D^0 ratios are systematically lower than ALICE result, but with higher precision.





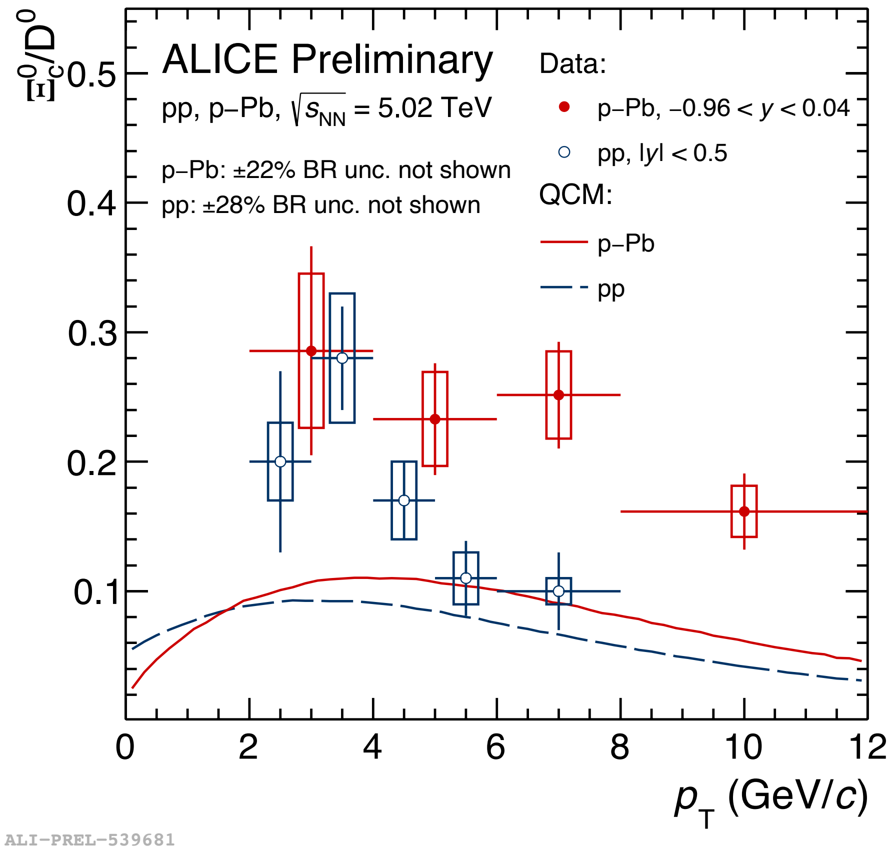


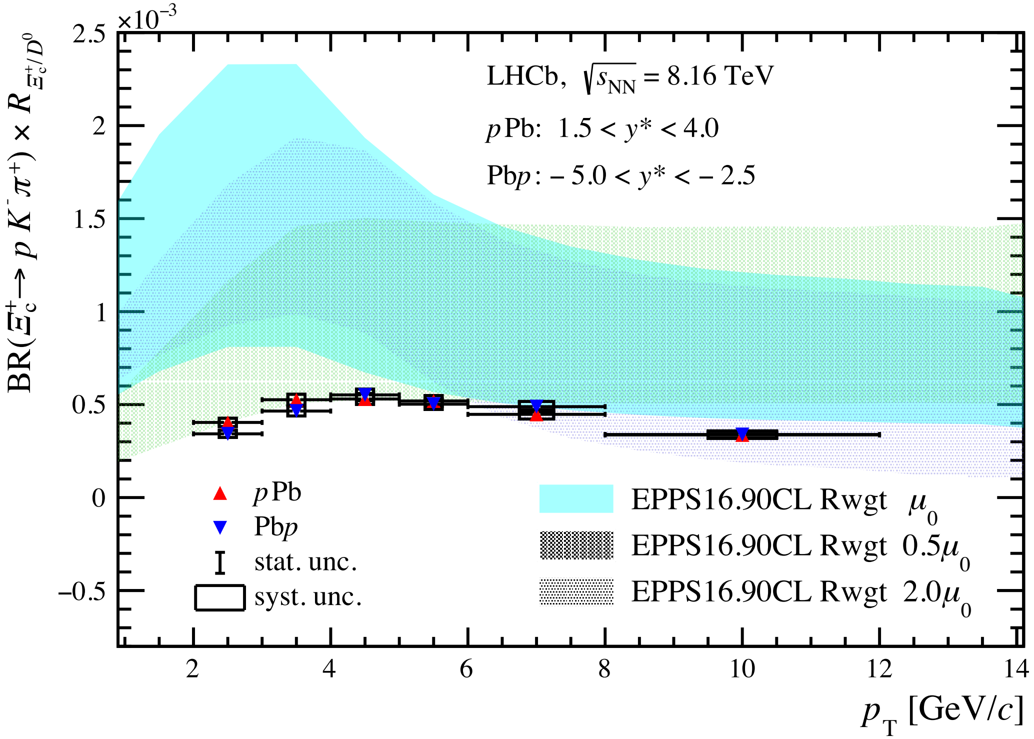
Different rapidity range → Different particle density → Different coalescence contribution ?

arXiv:2210.06939

Ξ_c^0/D^0, Ξ_c^+/D^0 ratios in pPb collisions

- The Ξ_c^0/D^0 ratios measured in pPb collisions are significantly larger than that in pp collisions.
- Generally, proton-lead collisions will produce more multiplicity than pp collisions at the same energy.



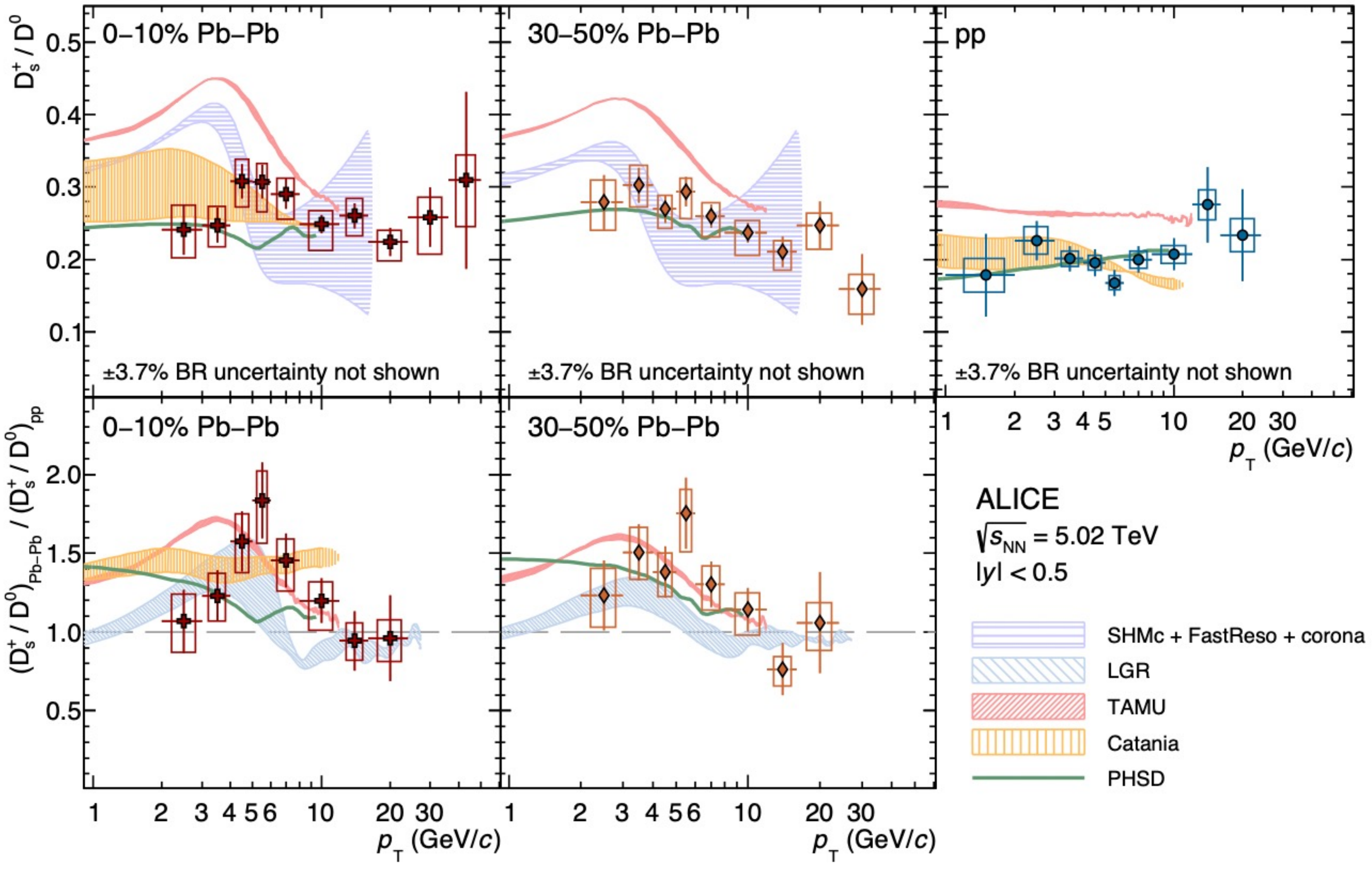


- Due to the asymmetry of the forward single-arm of the LHCb detector, it has pPb(forward) and Pbp(backward) collisions.
- Backward collisions have higher multiplicity on average than forward collisions.
- There is no significant difference in the Ξ_c^+/D^0 ratios between forward and backward collisions.

arXiv:2205.03936
arXiv:2305.06711

Strange meson/Non strange meson ratios

D_s^+/D^0 ratios in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

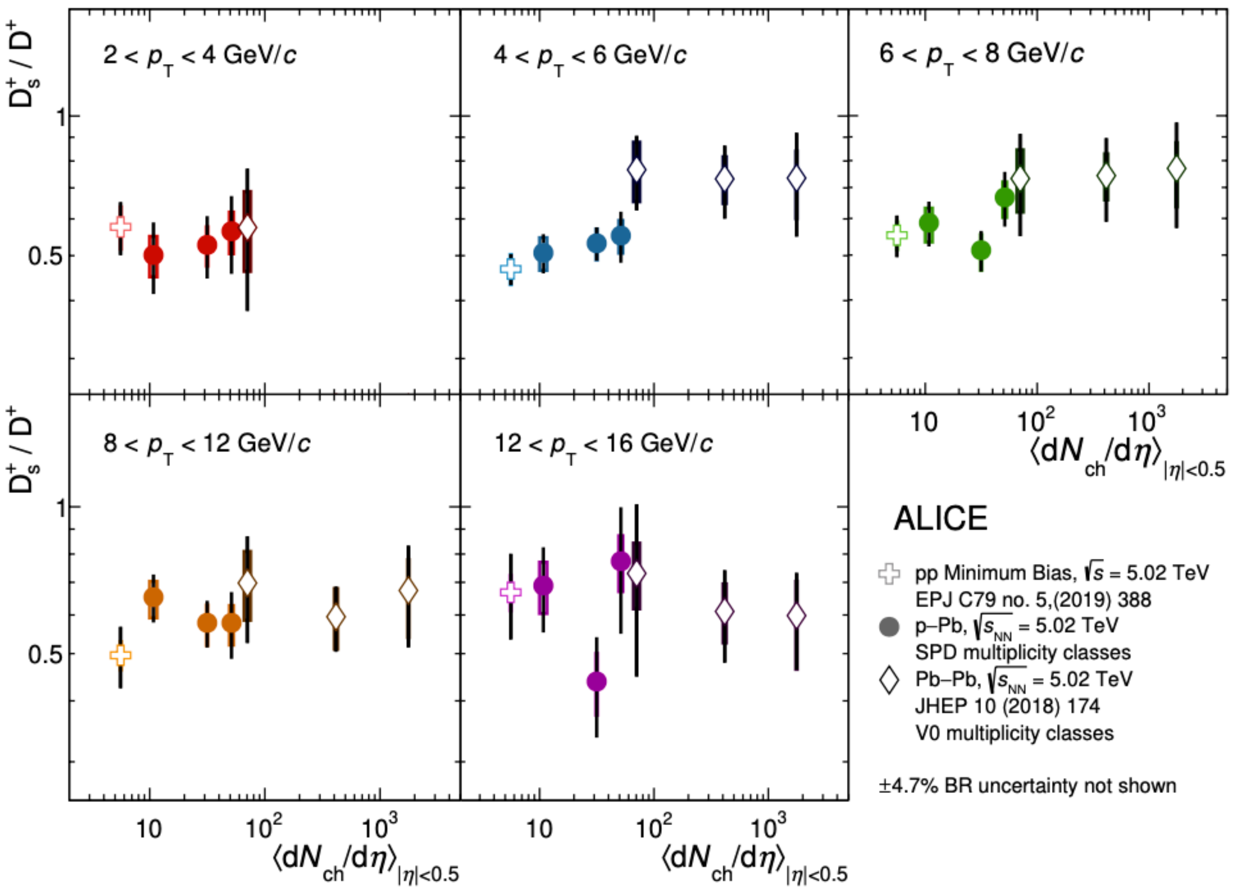


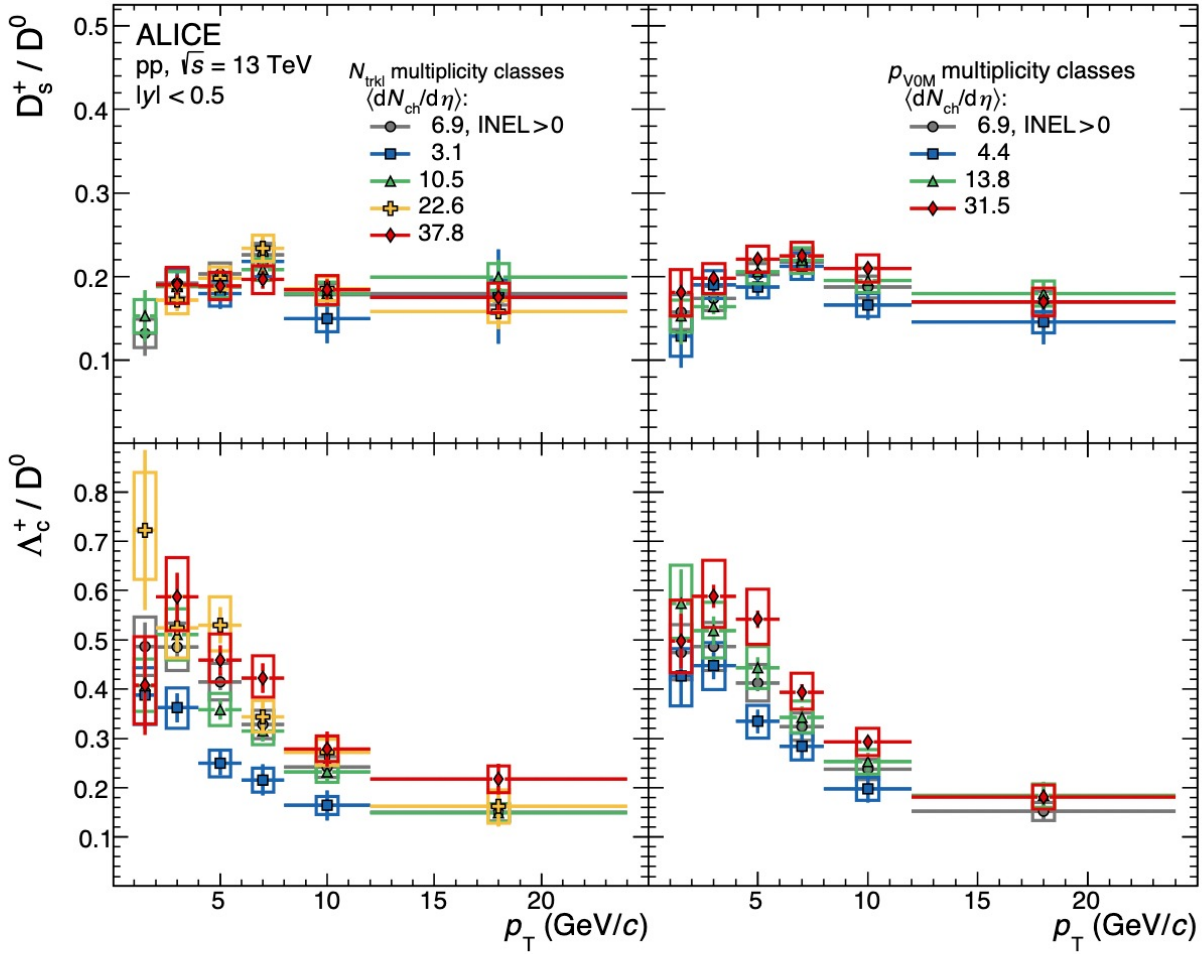
- Since the enhanced *s* quark abundance in the QGP, an increased D_s^+ in heavy-ion collisions relative to *pp* collisions has been predicted. This is also confirmed by ALICE and STAR. Phys. Lett. B 827 (2022) 136986 Phys. Rev. Lett. 127 (2021) 092301
- The *s* quark enhancement was also observed in high-multiplicity *pp* collisions. Nature Phys 13, 535–539 (2017) Therefore, the D_s^+/D^0 ratios increase with multiplicity is also expected to be observed in small system.

Phys. Lett. B 827 (2022) 136986

D mesons ratios in pp and pPb collisions

- The strange to non-strange D_s^+/D^+, D_s^+/D^0 ratios show no significant multiplicity dependence in pp and pPb collisions.

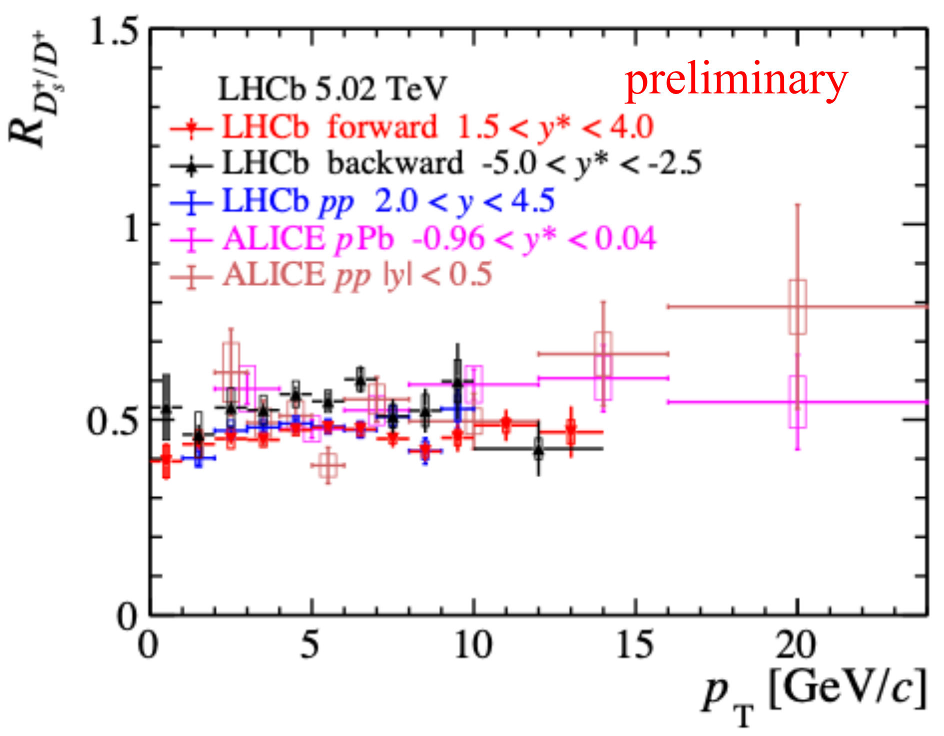


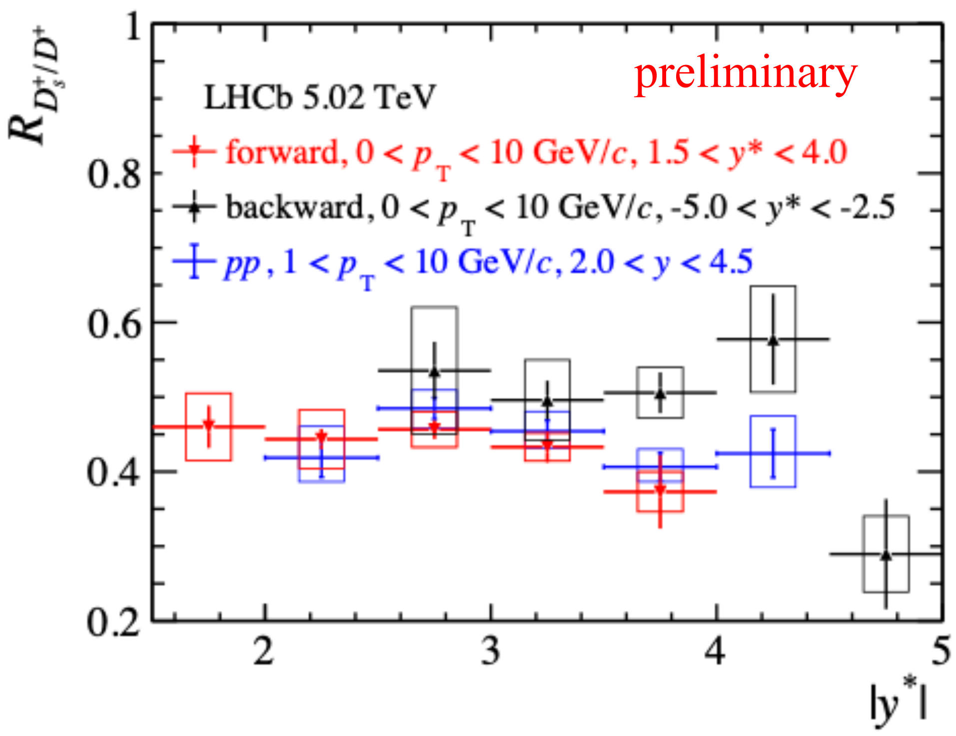


Phys. Lett. B 829 (2022) 137065
JHEP12(2019)092

D_s^+/D^+ ratios in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- D_s^+/D^+ ratios show no dependence on p_{T}.
- D_s^+/D^+ ratios are consistent with the result of LHCb in pp collisions within uncertainties.
- D_s^+/D^+ ratios are consistent with ALICE measurements with higher precision.
- Higher D_s^+/D^+ ratios for backward compared to forward may be due to coalescence contribution.



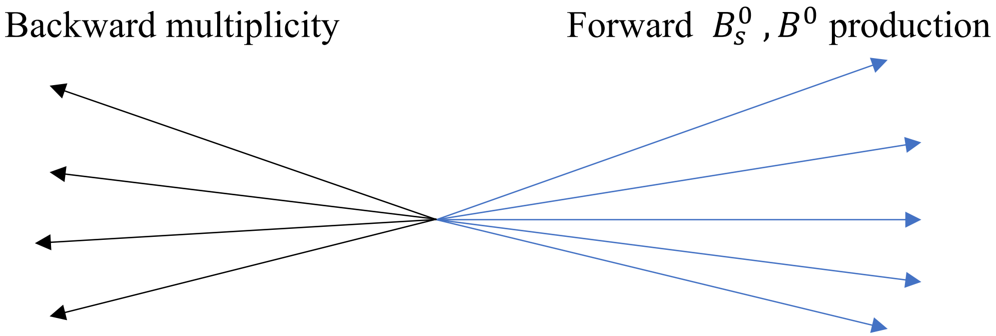


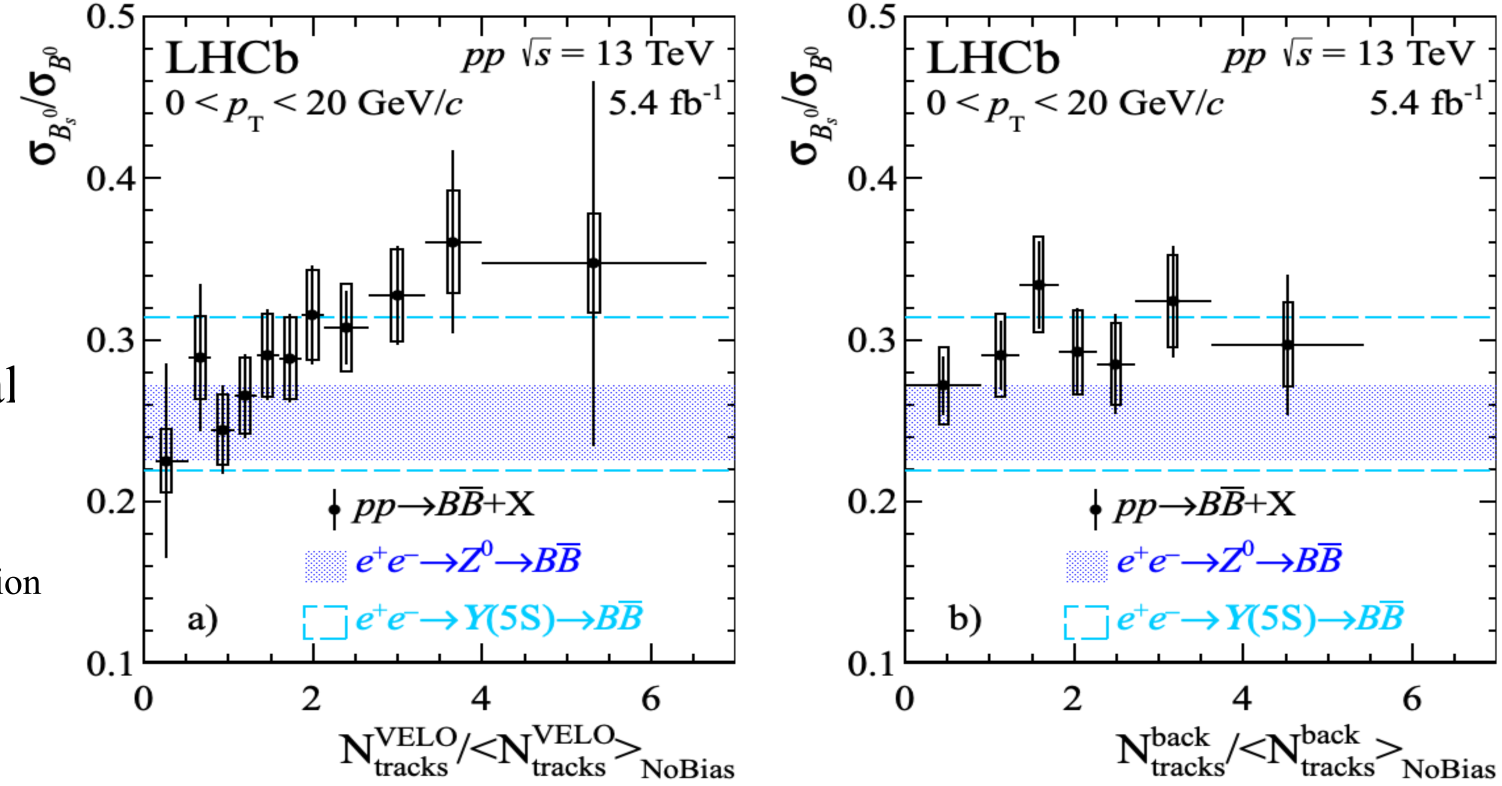
LHCb-PAPER-2023-006 paper in preparing

B_s^0/B^0 ratios in pp collisions at $\sqrt{s} = 13$ TeV

- The B_s^0/B^0 ratios show an increasing trend with the VELO tracks, consistent with fragmentation in vacuum (measured in e^+e^- collisions) at low multiplicity.

- No significant dependence of forward B_s^0/B^0 ratios on backward multiplicity.
- Indicate that the mechanism responsible for the ratios increase is related to the local particle density.

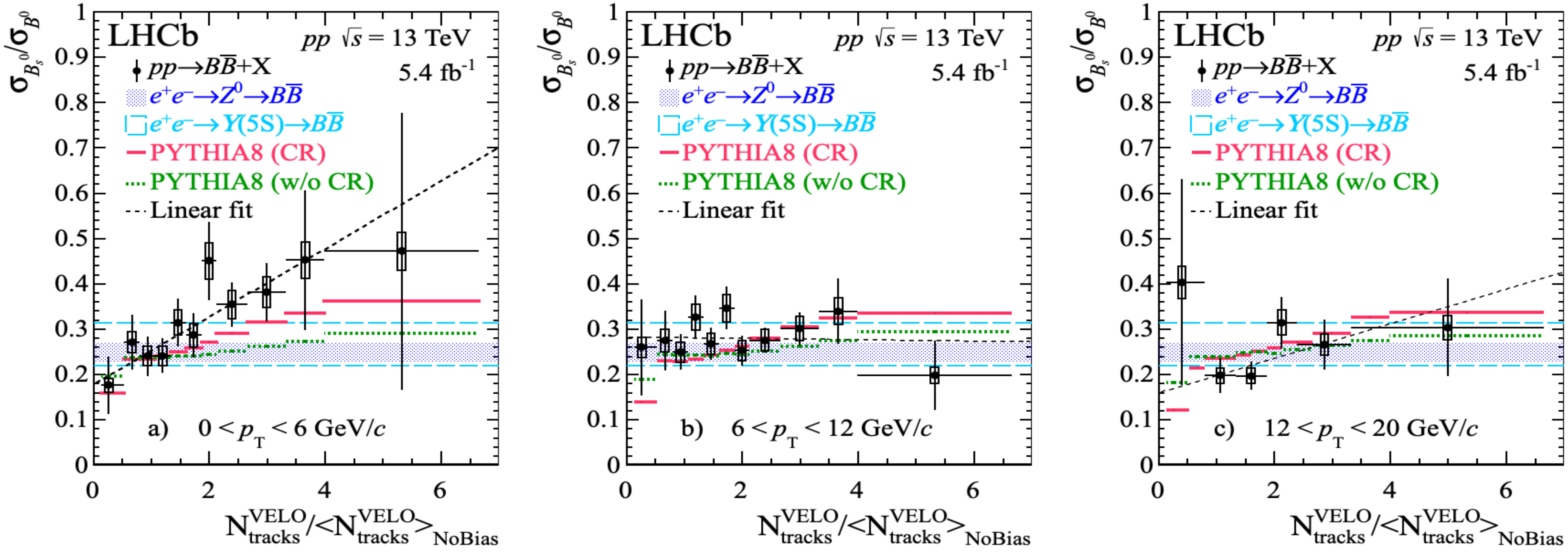




arXiv:2204.13042

B_s^0/B^0 ratios in pp collisions at $\sqrt{s} = 13$ TeV

- The $\sigma_{B_s^0}/\sigma_{B^0}$ ratios increases with multiplicity (slope significance = 3.4σ). Has a closer trend to the PYTHIA8 simulation with color reconnection.
- At low multiplicity, the ratio is consistent with values measured in e^+e^- collisions.
- No significant dependence on multiplicity and consistent with values measured in e^+e^- collisions and PYTHIA8 simulation.
- High p_T b quarks have less overlap with the low p_T bulk of the quarks, thereby dominantly hadronize via fragmentation.



arXiv:2204.13042

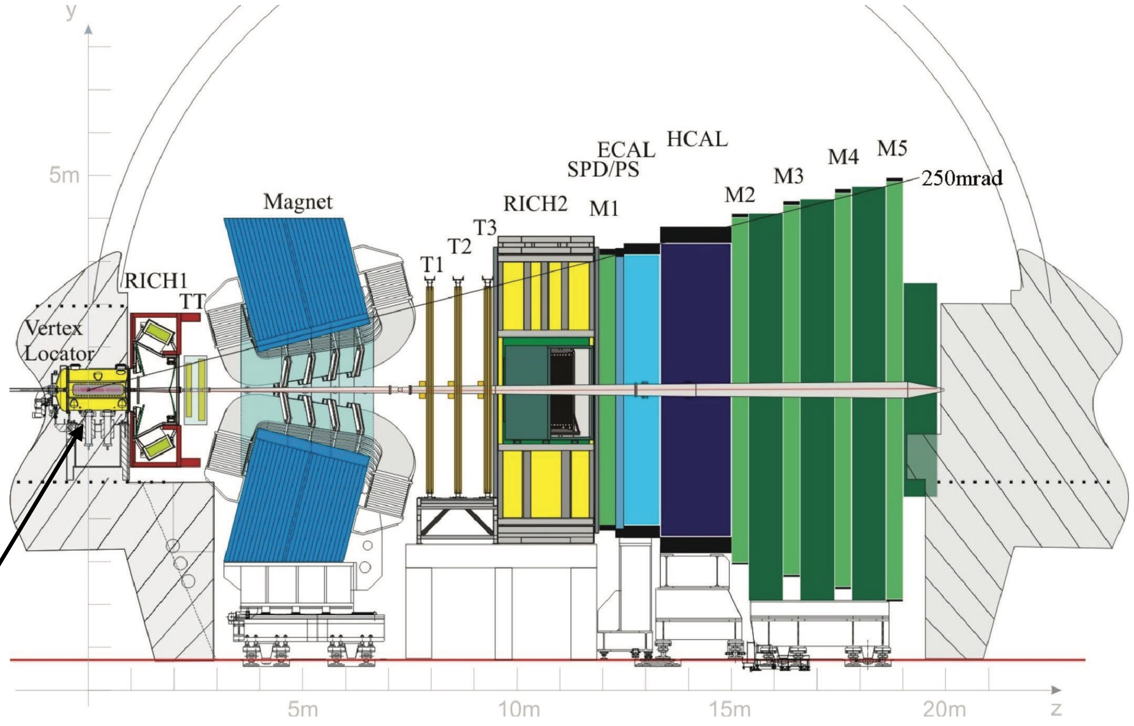
Summary

- In *pp* collisions , the Λ_c^+/D^0 ratios show a significant multiplicity enhancement, but in *p*Pb collisions not. The reason still needs further research.
- In central PbPb collisions, Λ_c^+/D^0 ratios show a significant centrality dependence. This is not the case in peripheral PbPb collisions, which instead show hints of rapidity dependence. This may be due to different coalescence contribution in different rapidity range.
- The Ξ_c^0/D^0 ratios measured in *p*Pb collisions are larger than that in *pp* collisions.
- In *p*Pb collisons, the D_s^+/D^+ ratios show no dependence on p_{T}, but on rapidity. The higher D_s^+/D^+ ratios for backward compared to forward may be due to coalescence contribution.
- In *pp* collisons, the B_s^0/B^0 enhancement is observed at low p_{T} and consistent with our expected coalescence mechanism qualitatively. The ratios has no significant dependence on backwards multiplicity, indicate that the mechanism responsible for the ratio increase is related to the local particle density.

Thanks for listening!

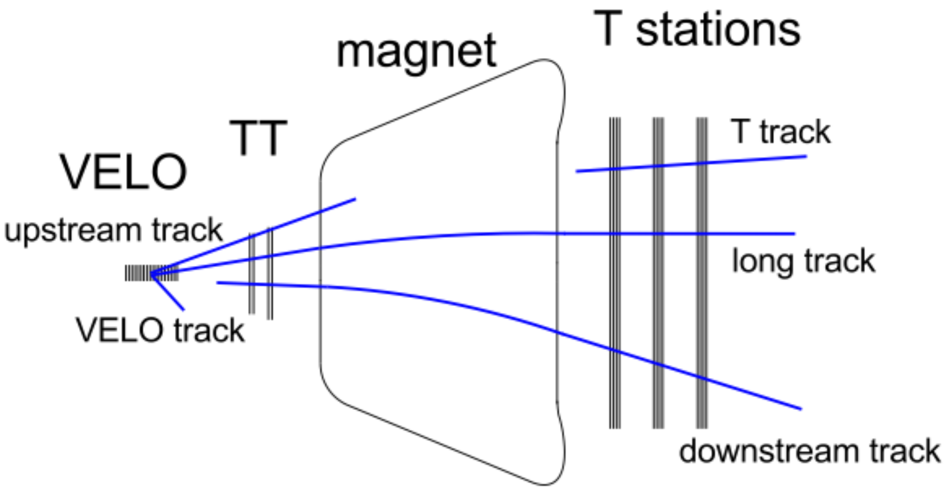
LHCb detector

- A single-arm spectrometer in the forward direction, charm & beauty factory
  - ➢ Vertex Locator (20 μm IP resolution)
  - ➢ Tracking system ($\Delta p/p = 0.5 - 1.0\%$)
  - ➢ PID optimal for μ, p, K, π
    - ❖ $\varepsilon(K \to K) \sim 95\%$
    - ❖ $\varepsilon(\mu \to \mu) \sim 97\%$
  - ➢ Flexible software trigger



VErtex LOcator

- VELO tracks : have hits in the VELO
- Back tracks : subset of VELO tracks, point in the backward direction

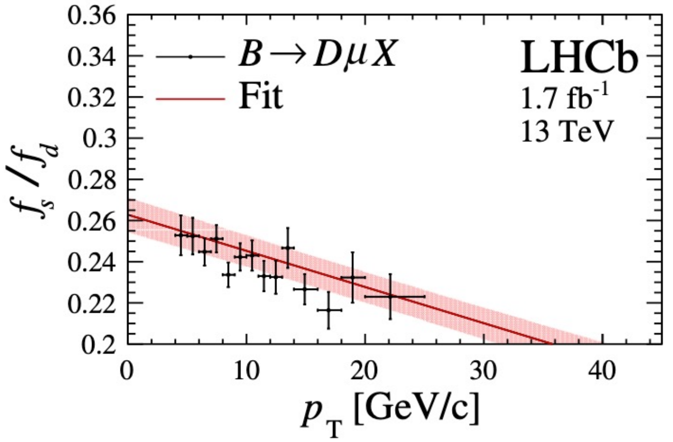


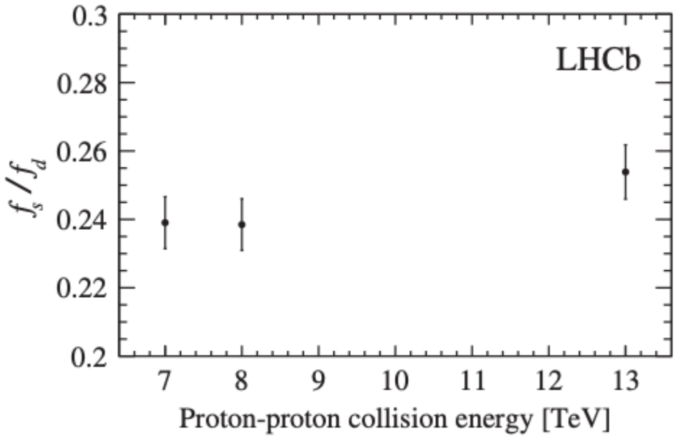
LHCb, JINST 3 (2008) S08005
LHCb, IJMPA 30 (2015) 1530022
JINST 10 (2015) 02 P02007

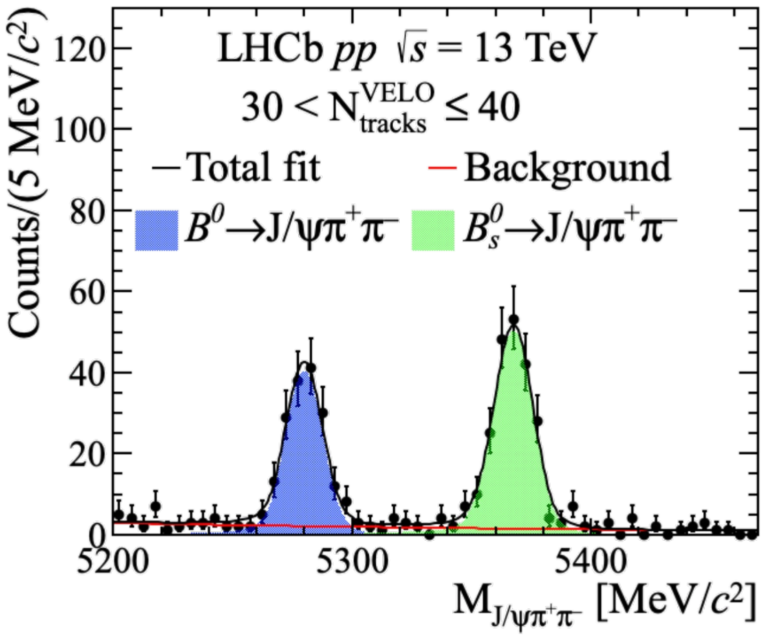
B_s^0/B^0 ratio vs multiplicity in *pp* collisions at $\sqrt{s} = 13$ TeV

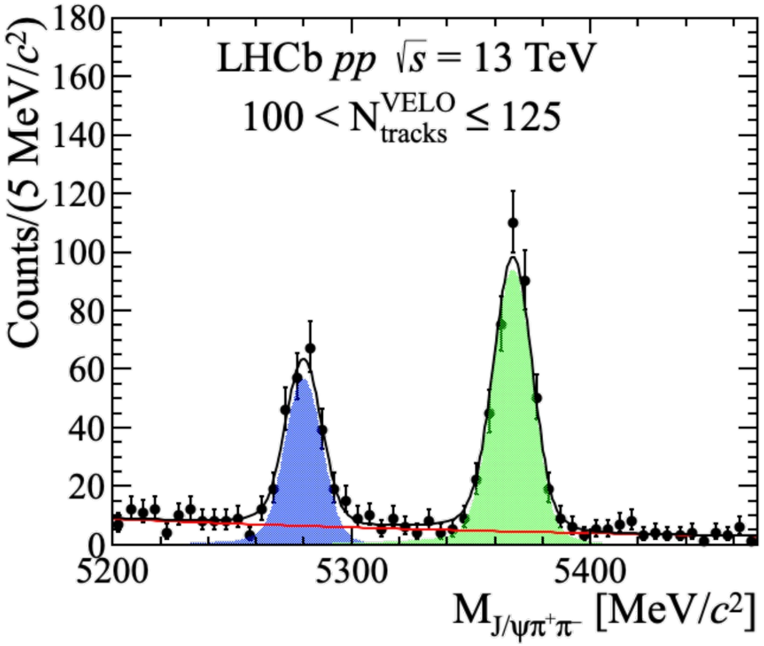
Phys. Rev. D 104(2021) 032005

- Fragmentation fractions are measured with B mesons in *pp* collisions: $\frac{f_s}{f_d} \propto \frac{N_{corr}(B_s^0)}{N_{corr}(B^0)}$
  - ➢ $\frac{f_s}{f_d}$ is observed to depend on the B meson transverse momentum.
  - ➢ No dependence on the collision energy.









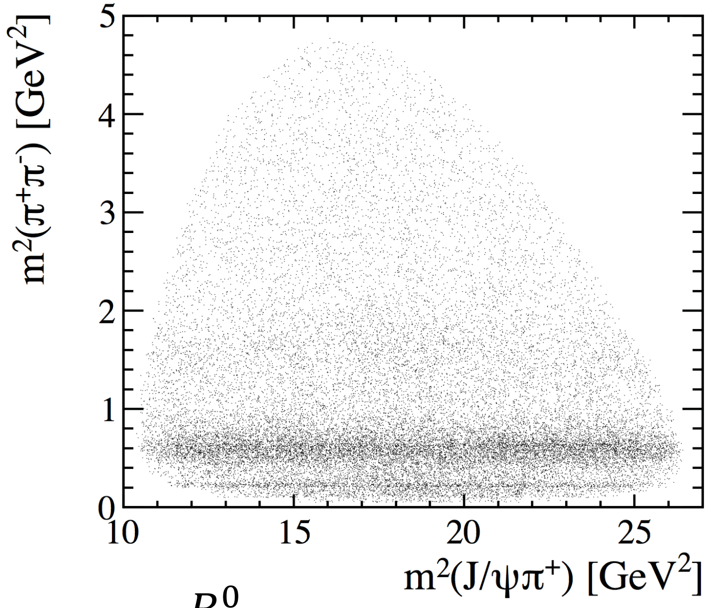
- Both B_s^0 and B^0 are reconstructed via $J/\psi\pi^+\pi^-$, relative corrections are generally close to 1 .

arXiv:2204.13042

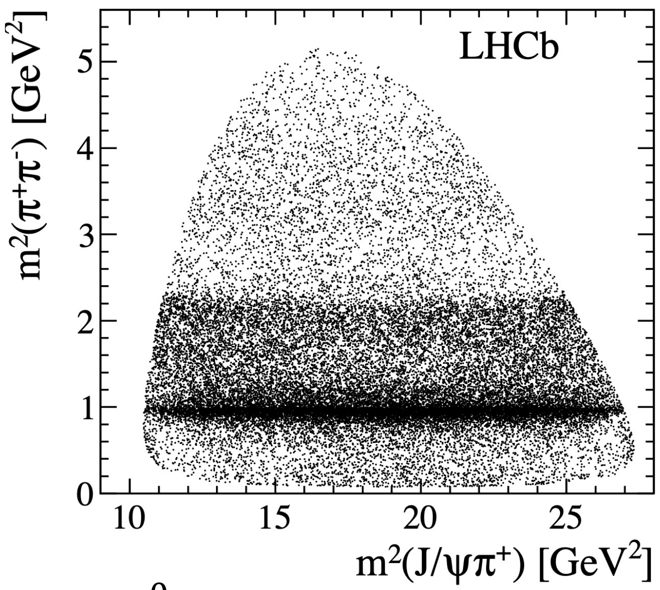
Efficiencies

$$\frac{\sigma_{B_s^0}}{\sigma_{B^0}} = \frac{N_{B_s^0}}{N_{B^0}} \times \frac{\mathcal{B}_{B^0}}{\mathcal{B}_{B_s^0}} \times \frac{\varepsilon^{\mathrm{acc}}_{B^0}}{\varepsilon^{\mathrm{acc}}_{B_s^0}} \times \frac{\varepsilon^{\mathrm{trig}}_{B^0}}{\varepsilon^{\mathrm{trig}}_{B_s^0}} \times \frac{\varepsilon^{\mathrm{PID}}_{B^0}}{\varepsilon^{\mathrm{PID}}_{B_s^0}} \times \frac{\varepsilon^{\mathrm{reco}}_{B^0}}{\varepsilon^{\mathrm{reco}}_{B_s^0}},$$

- $\frac{\varepsilon^{acc}_{B^0}}{\varepsilon^{acc}_{B_s^0}} = 1 \pm 0.01$, $\frac{\varepsilon^{trig}_{B^0}}{\varepsilon^{trig}_{B_s^0}} = 1 \pm 0.01$, $\frac{\varepsilon^{PID}_{B^0}}{\varepsilon^{PID}_{B_s^0}} = 1 \pm 0.01$
- $\frac{\varepsilon^{reco}_{B^0}}{\varepsilon^{reco}_{B_s^0}} = 0.86 \pm 0.04$: Due to the difference in the dipion mass distributions produced in the B_s^0 and B^0 decays.
- Due to the similarities of the B_s^0 and B^0 decays, many systematic uncertainties partially cancel in this ratio of cross sections.



B^0

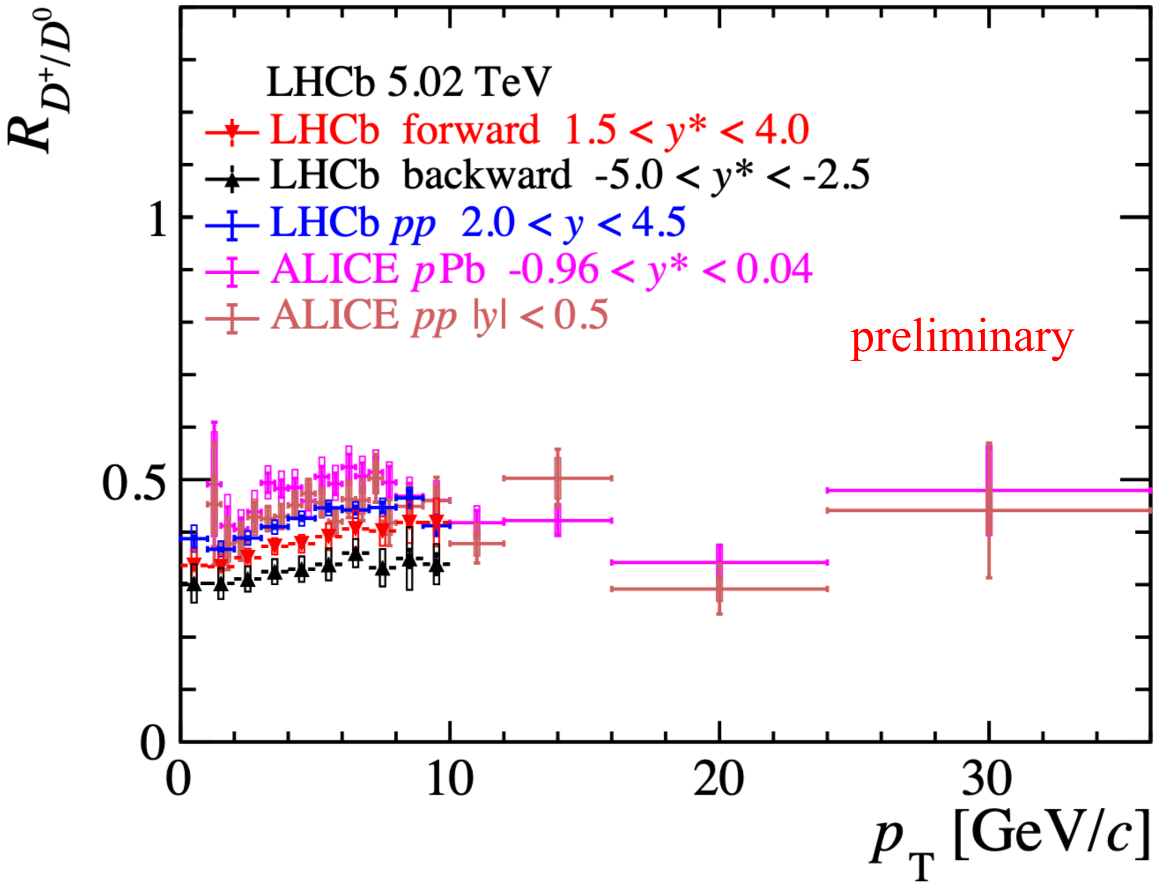


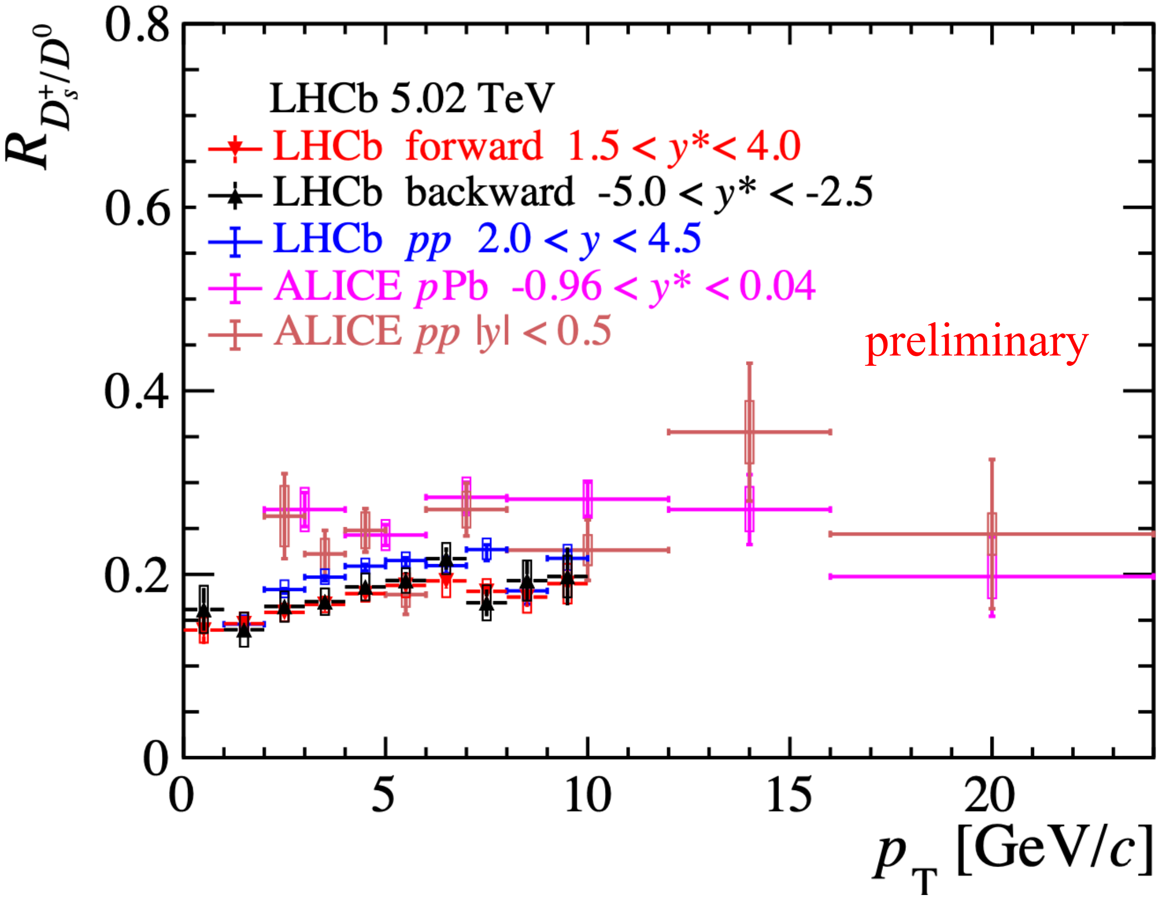
B_s^0

Phys. Rev. D89 (2014) 092006
Phys. Rev. D90 (2014) 012003

D_s^+/D^+ ratios in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- D_s^+/D^0?
- D^+/D^0?

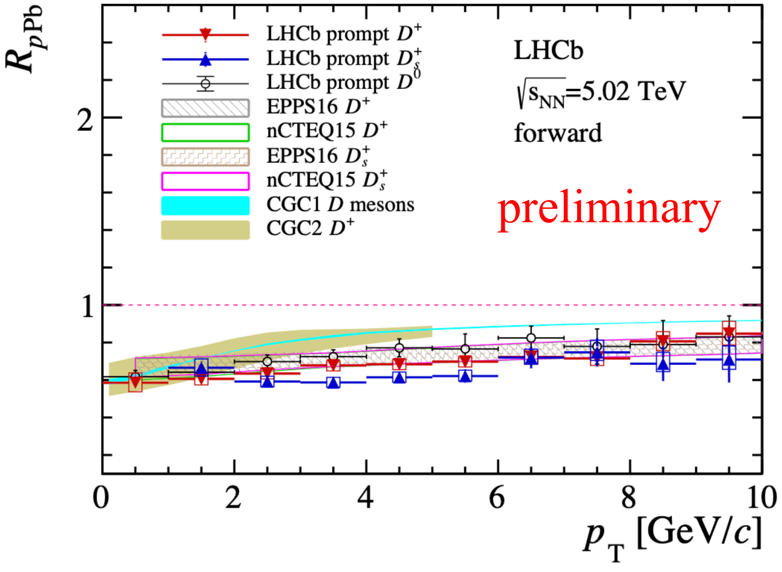


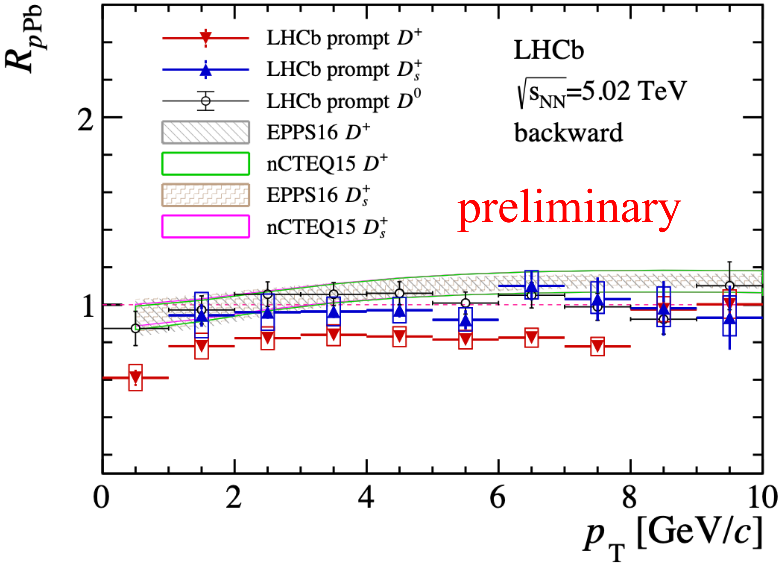


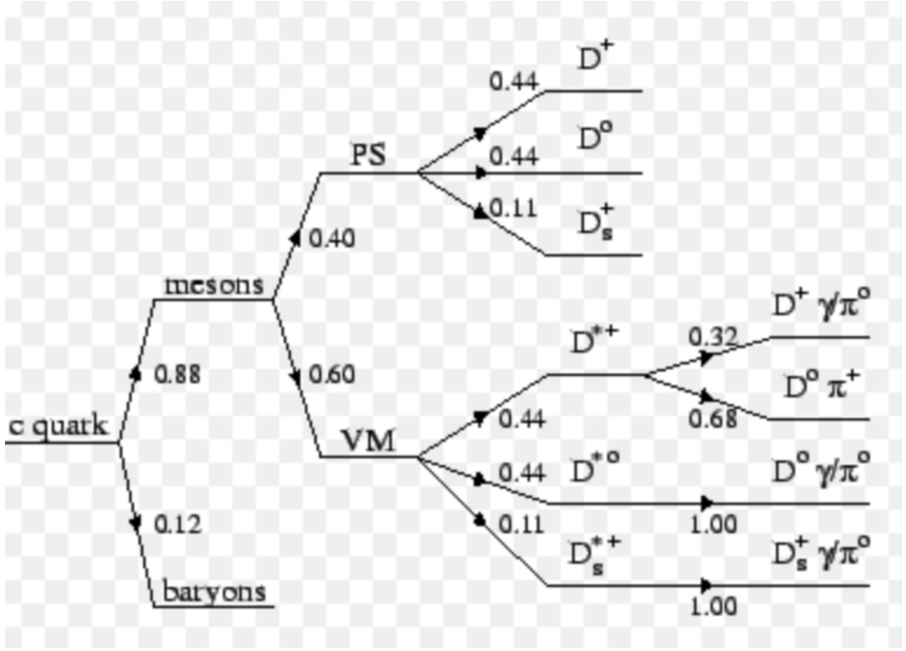
LHCb-PAPER-2023-006

D_s^+/D^+ ratios in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Just D^+ fell down?



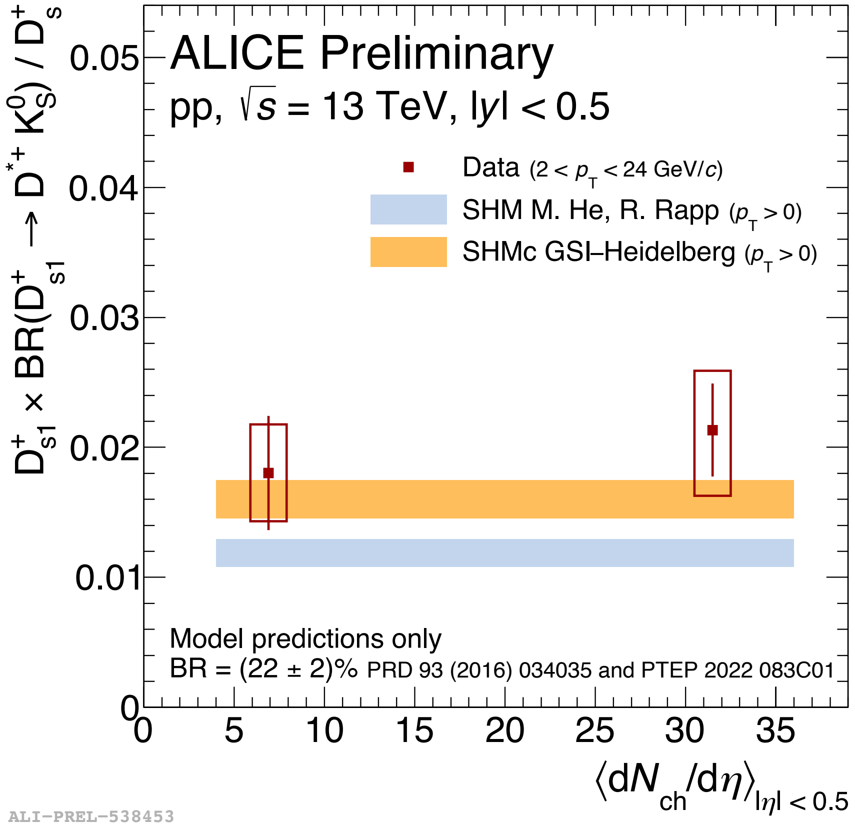




LHCb-PAPER-2023-006

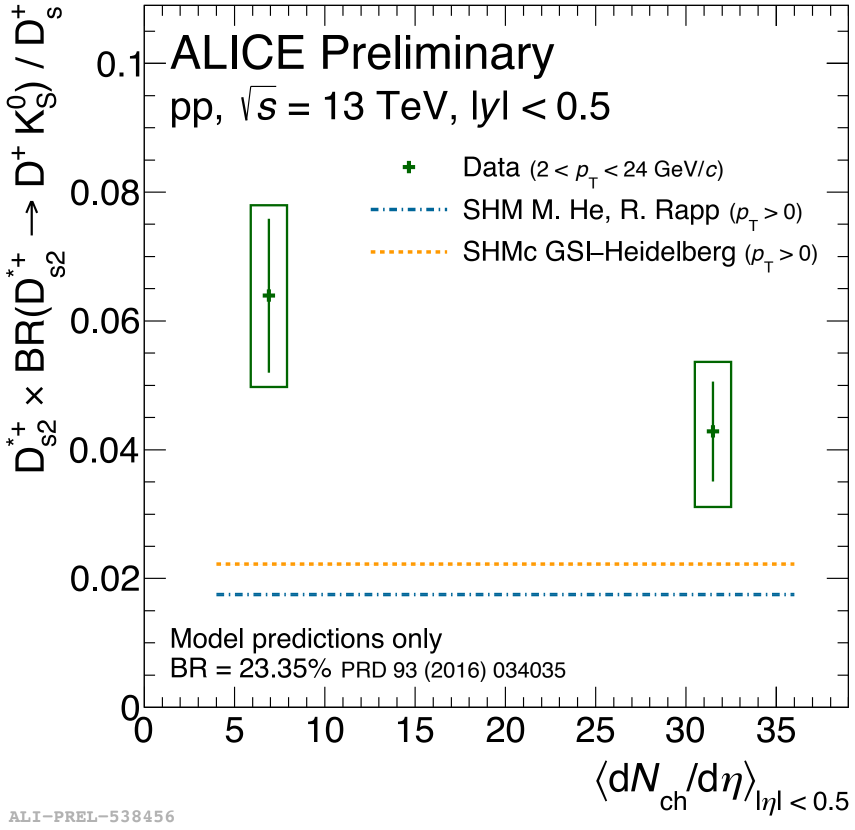
D_{s1}^{+}/D_{s}^{+}, D_{s2}^{*+}/D_{s}^{+} ratios in pp collisions at $\sqrt{s}$ =13 TeV

- D_{s1}^{+} and D_{s2}^{*+} are P-wave excited states of the D_{s}^{+}, isospin and angular momentum $I(J^P) = 0(1^+)$ and $I(J^P) = 0(2^+)$.
- First measurement of D_{s1}^{+} and D_{s2}^{*+} production at the LHC.



$D_{s1}^{+} \rightarrow D^{*+}K_{s}^{0}$

- D_{s1}^{+}/D_{s}^{+} show no multiplicity dependence.
- D_{s2}^{*+}/D_{s}^{+} slightly decreases with multiplicity, which might come from hadronic rescattering during lifetime(τ (D_{s2}^{*+}) ~ 11.61 fm/c, τ(D_{s1}^{+}) ~ 219 fm/c).
- D_{s2}^{*+}/D_{s}^{+} show tension with models, about 2.5σ (1.5σ) at low (high) multiplicity.

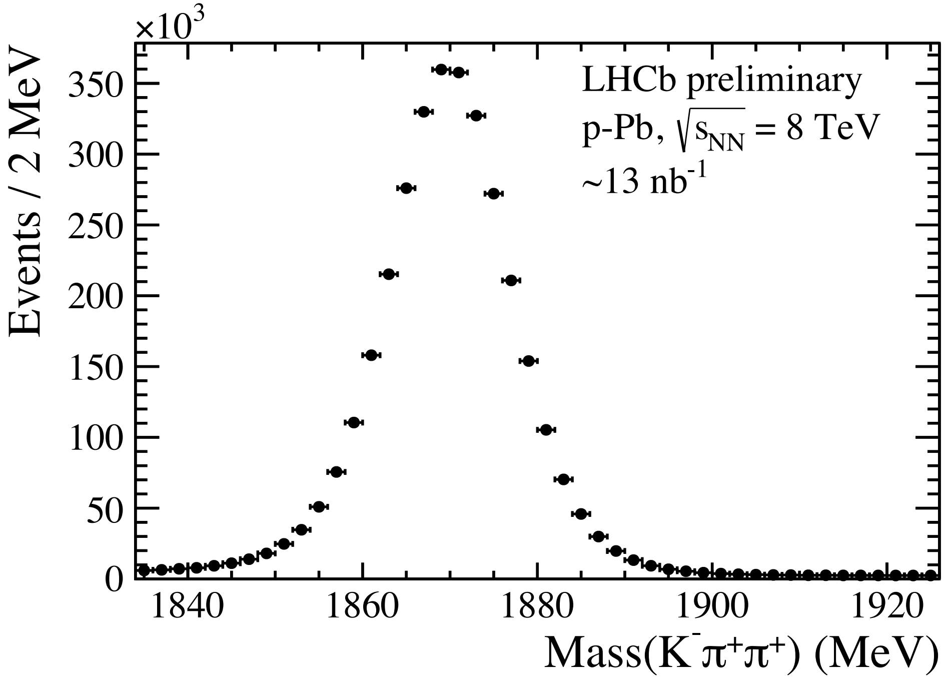


$D_{s2}^{*+} \rightarrow D^{+}K_{s}^{0}$

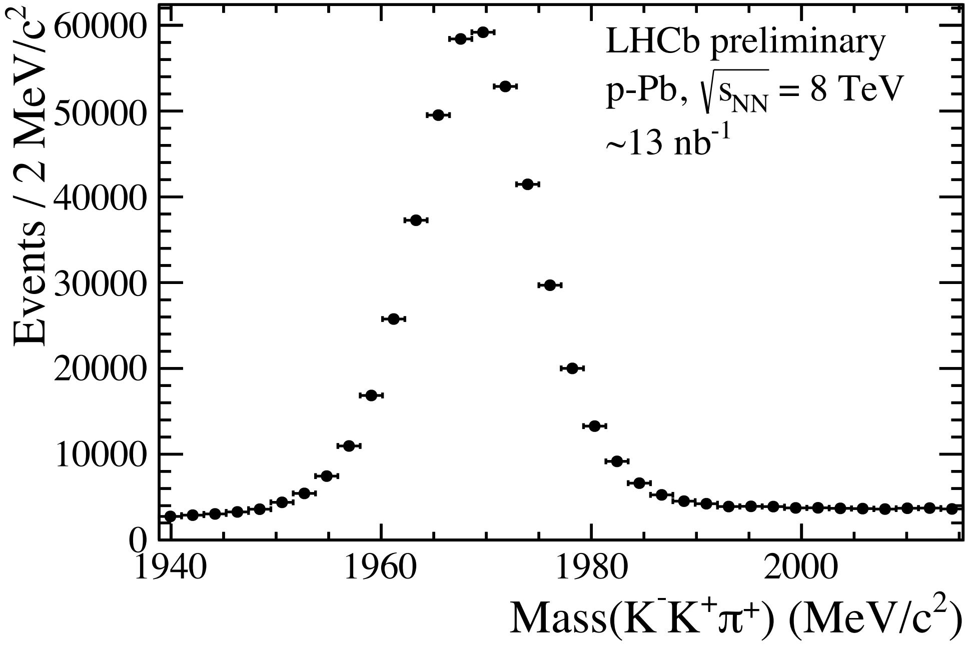
Work in progress: D_s^+/D^+ ratio in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\mathrm{TeV}$

- Compared with 5.02 TeV, the statistics of 8.16 TeV are larger.
- Divided multiplicity dimensions

$$R_{D_s^+/D^+}(p_{\mathrm{T}}, y^*, \mathrm{PV\ nTracks}) = \frac{N(D_s^\pm \to K^\mp K^\pm \pi^\pm)}{N(D^\pm \to K^\mp \pi^\pm \pi^\pm)} \times \frac{\mathcal{B}(D^\pm \to K^\mp \pi^\pm \pi^\pm)}{\mathcal{B}(D_s^\pm \to K^\mp K^\pm \pi^\pm)} \times \frac{\epsilon_{D^+}}{\epsilon_{D_s^+}}$$



$D^+ \to K^-\pi^+\pi^+$



$D_s^+ \to K^+K^-\pi^+$