LHCP 2023

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# Modification of heavy-quark hadronisation as a function of multiplicity

Chenxi Gu, Laboratoire Leprince-Ringuet (École Polytechnique, CNRS-IN2P3)

on behalf of LHCb, ALICE and CMS collaborations

EuroTechPostdoc2 Programme
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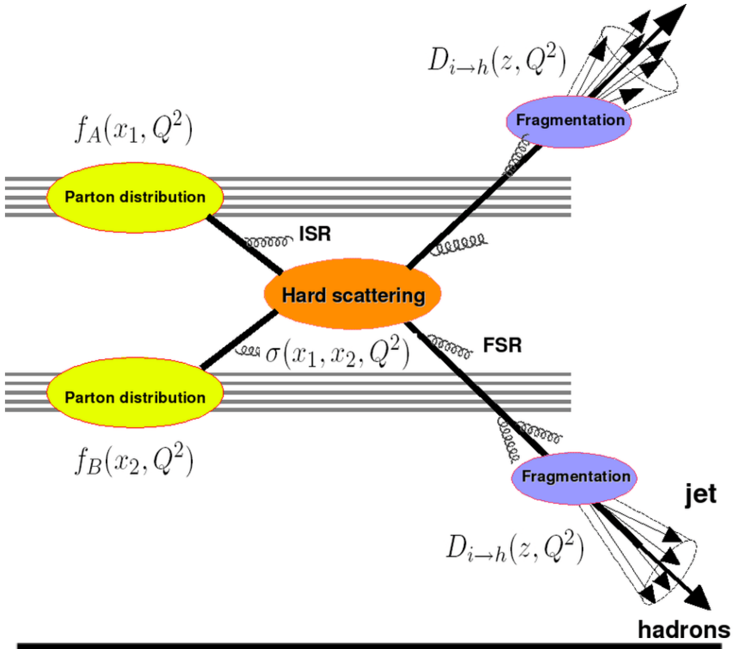
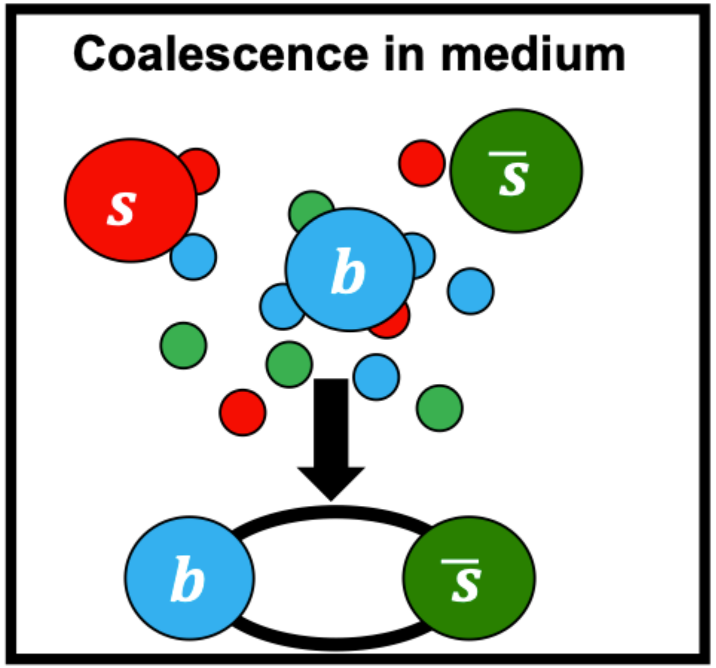
# Motivation

- 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 (color reconnection, rope hadronization, dynamical core-corona initialization…).

Baryon/meson ratios are sensitive to hadronization.



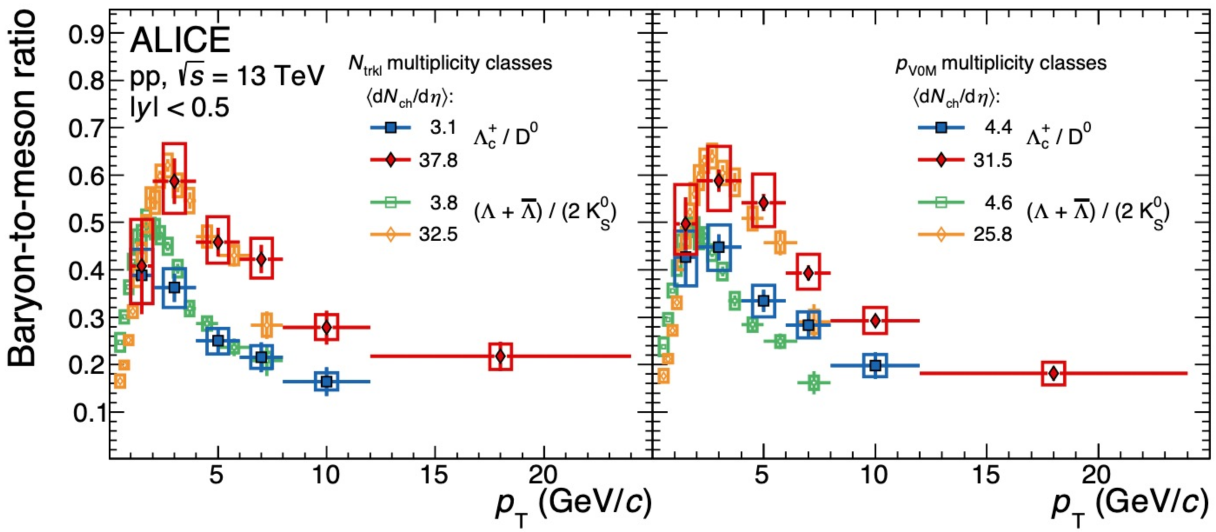

Strange meson/non strange meson ratios are sensitive to hadronization and strangeness enhancement.

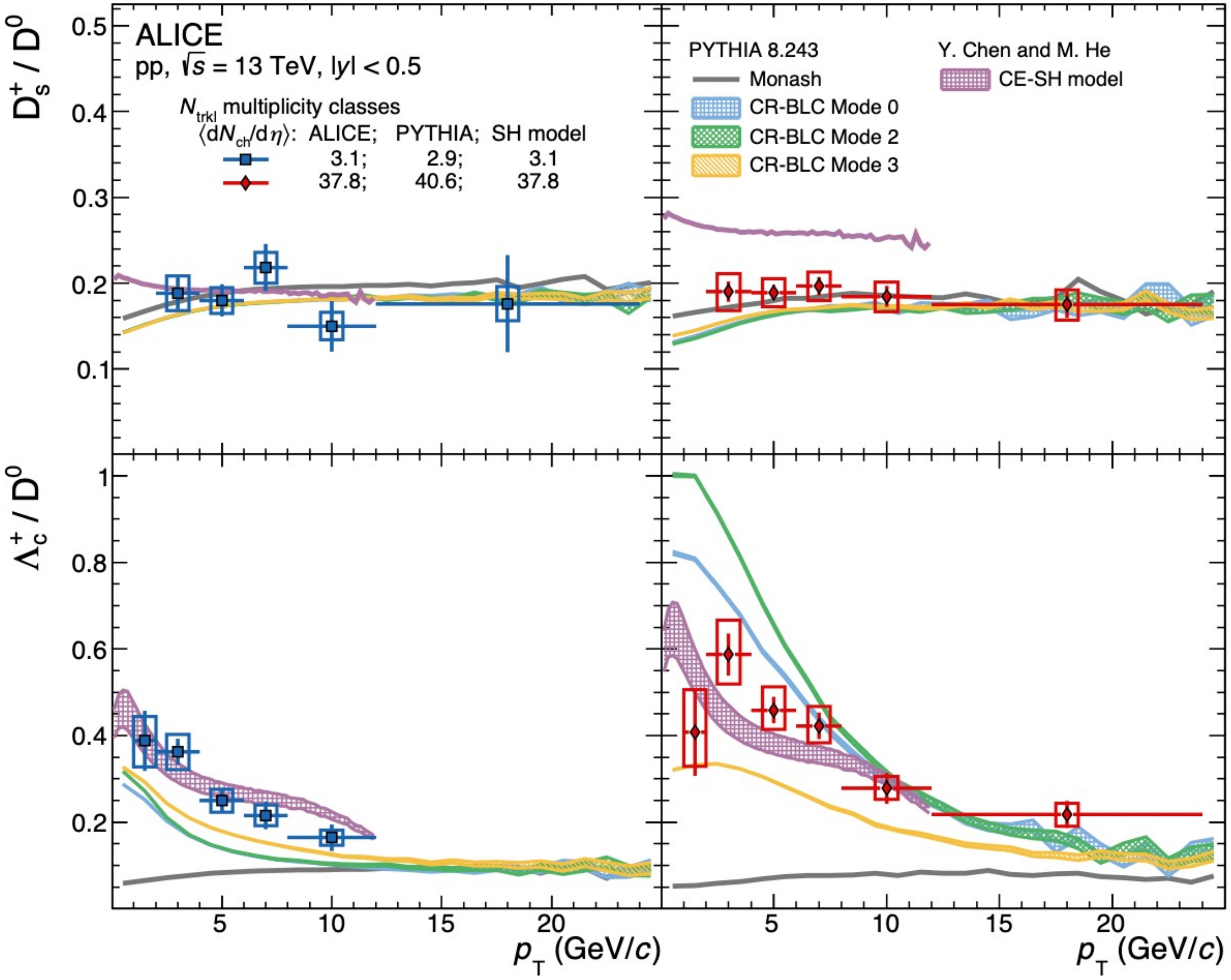


# Baryon/Meson ratios

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

- The $\Lambda_c^+/D^0$ 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 $\Lambda_c^+/D^0$ ratios as a function of $p_T$ show a similar shape and magnitude as the $\Lambda/K_S^0$ ratios in comparable multiplicity intervals, suggesting a potential common multiplicity enhancement mechanism for strange and charm hadrons formation.

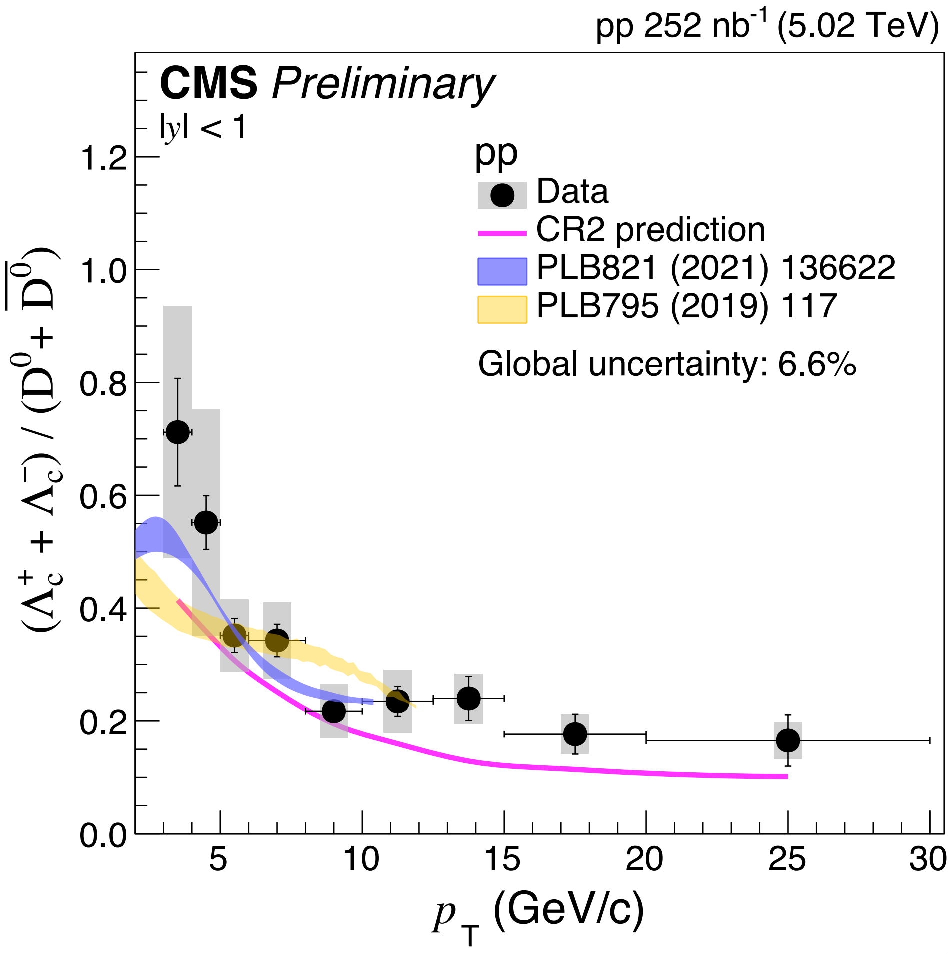


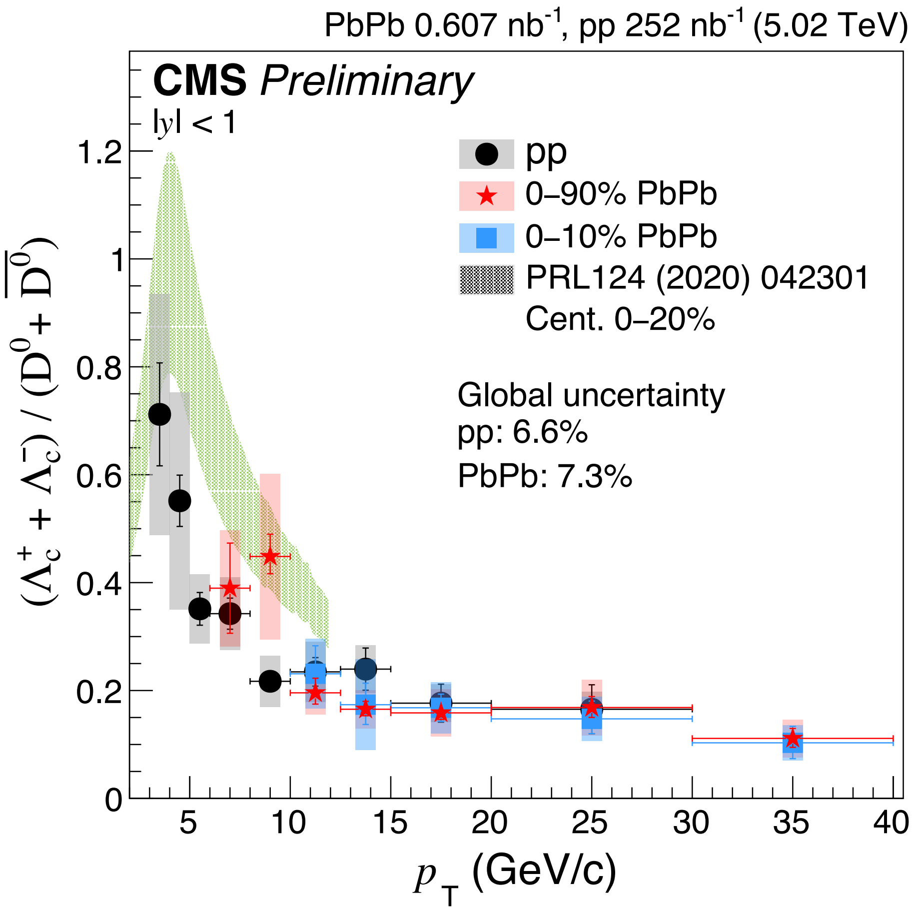




Phys. Lett. B 829 (2022) 137065

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

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





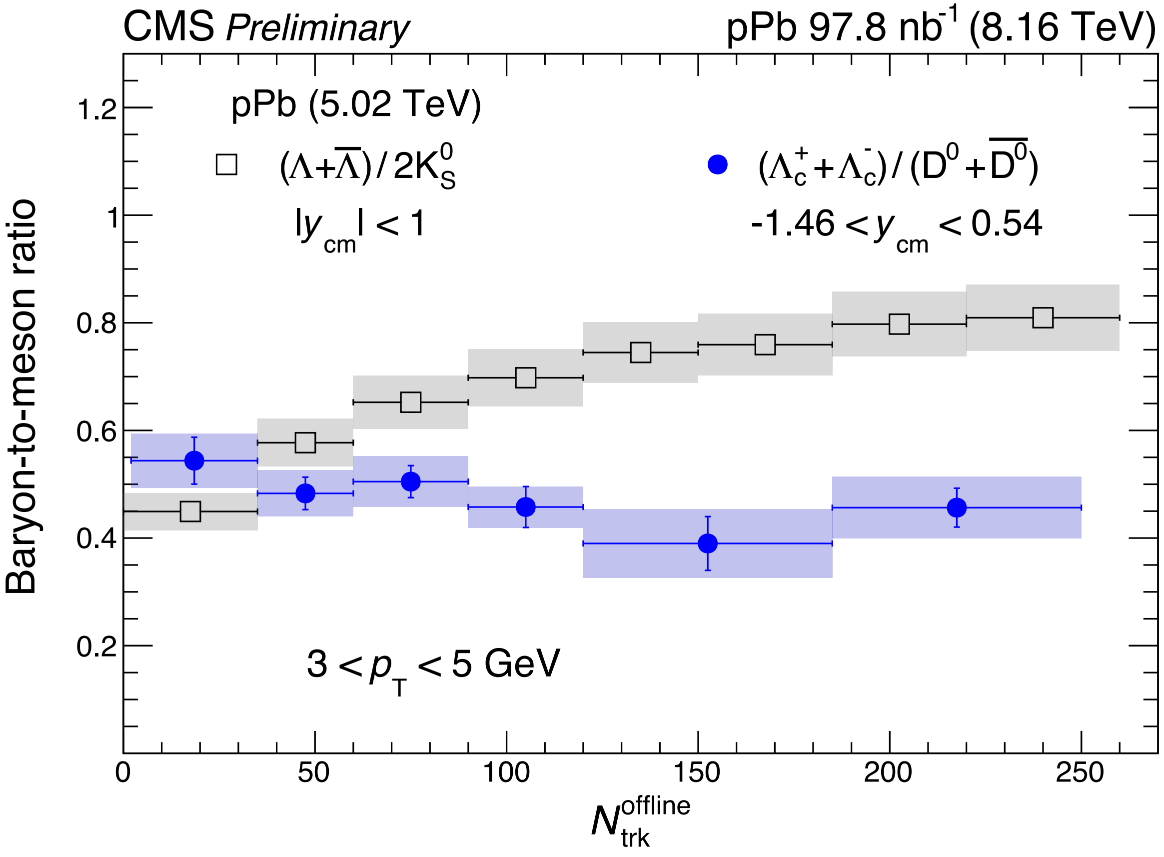

CMS-PAS-HIN-21-004

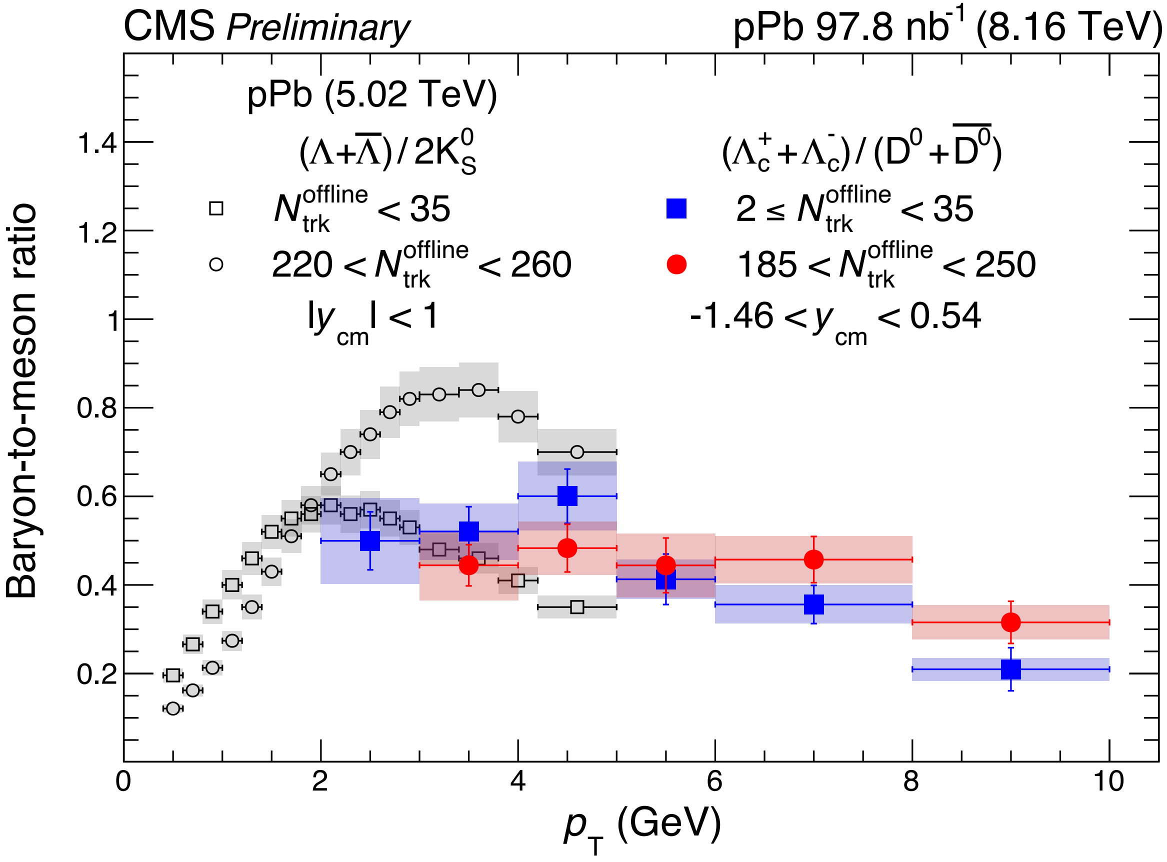
# $\Lambda_c^+/D^0$ ratios in $p$Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Almost same kinematic region

System dependent ?

- $\Lambda_c^+/D^0$ ratios in $p$Pb 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).



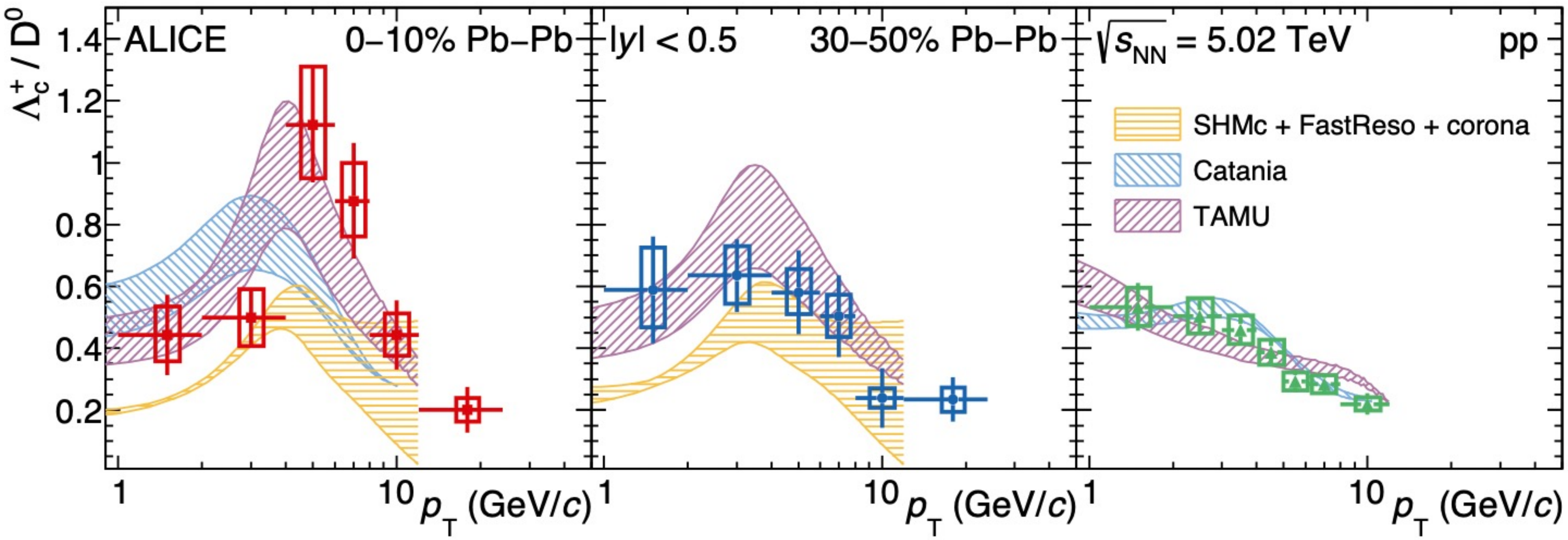






CMS-PAS-HIN-21-016

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

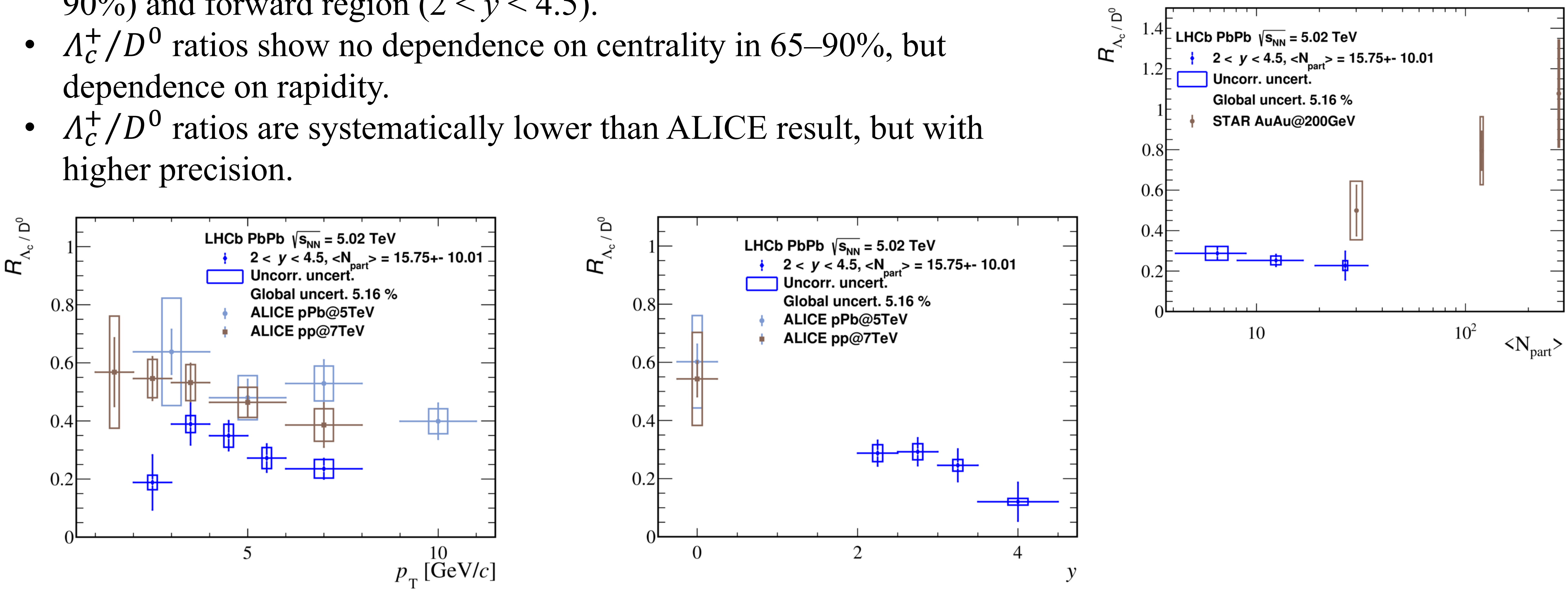
- Coalescence mechanism is expected to be stronger in heavy ion collisions due to the presence of QGP, baryons are more strongly enhanced than mesons under the influence of coalescence mechanisms.
- Recently, both ALICE and LHCb measured $\Lambda_c^+/D^0$ ratios in PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV separately.
- ALICE results show $\Lambda_c^+/D^0$ 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

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

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



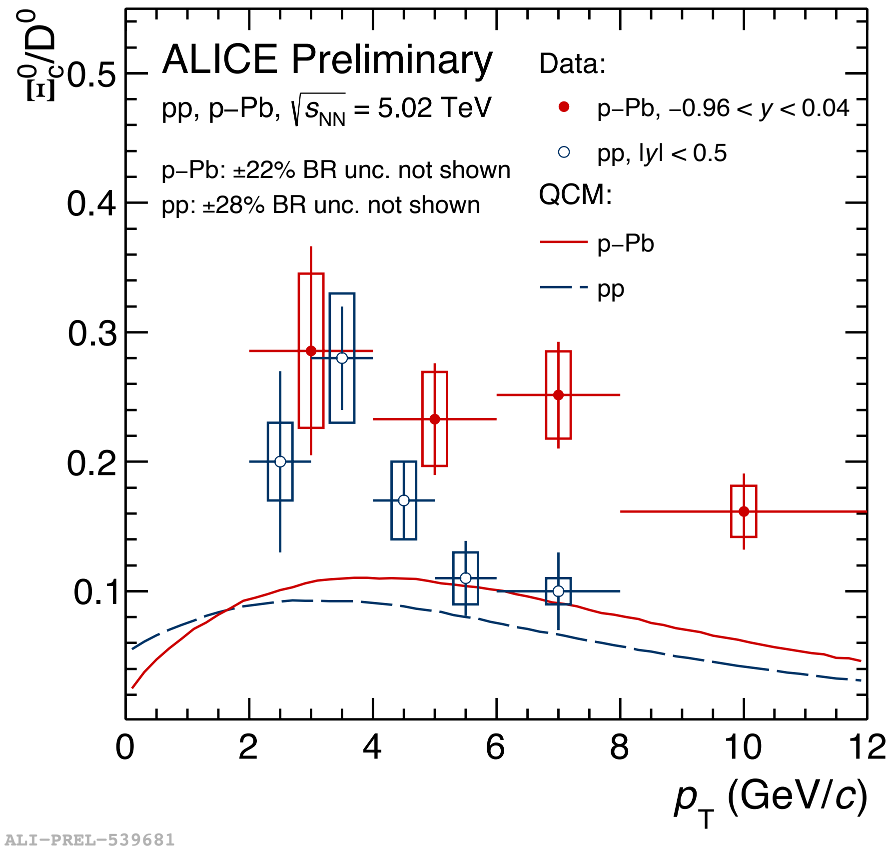

Different rapidity range → Different particle density → Different coalescence contribution ?

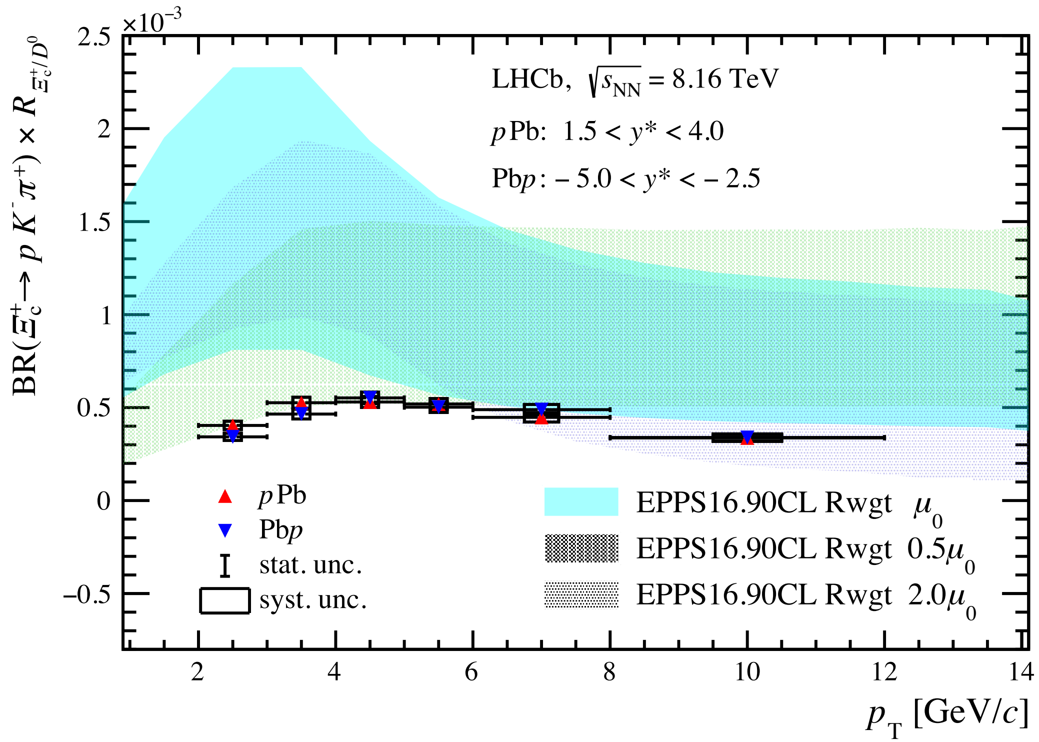


arXiv:2210.06939

# $\Xi_c^0/D^0$, $\Xi_c^+/D^0$ ratios in $p$Pb collisions

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



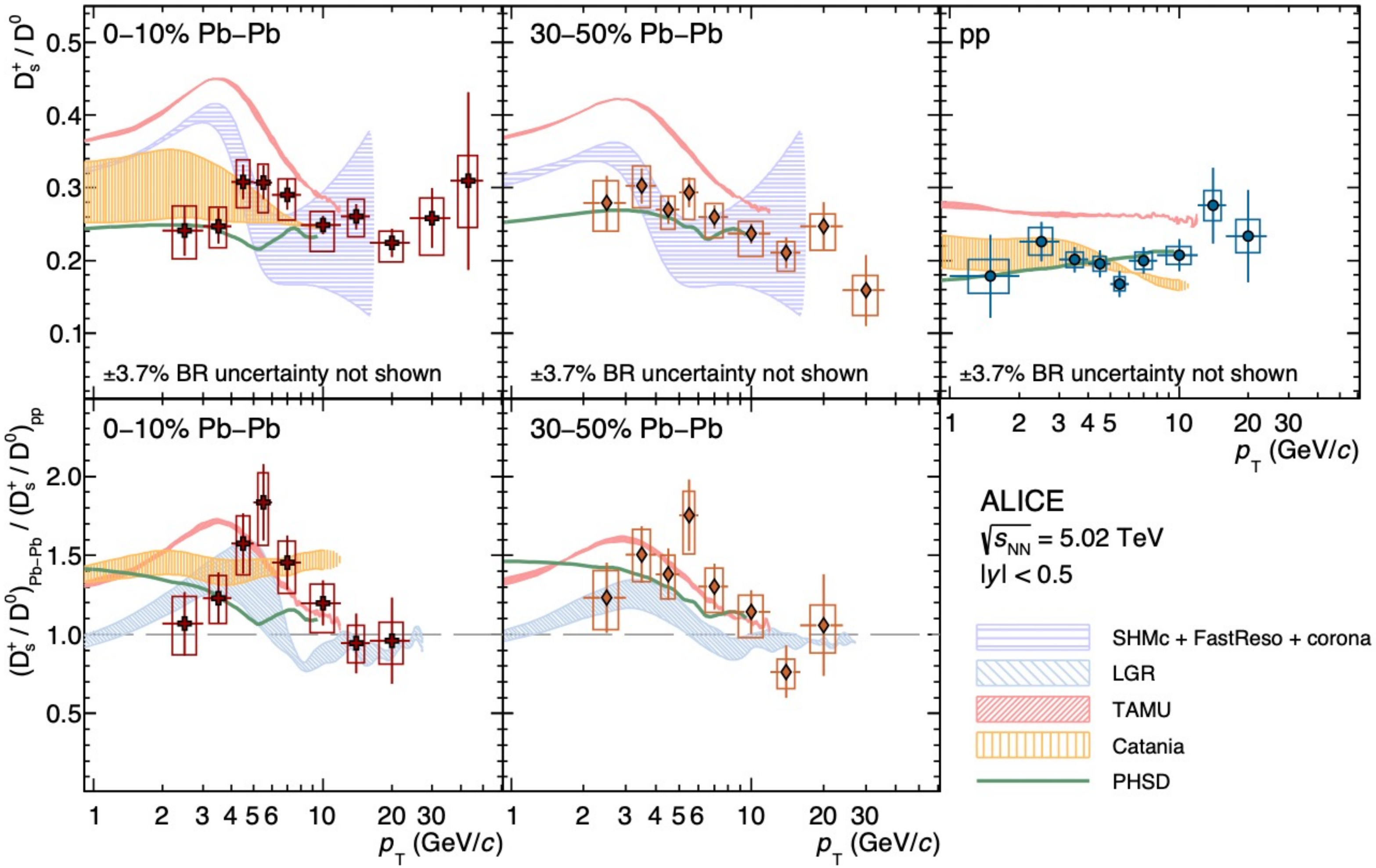




- Due to the asymmetry of the forward single-arm of the LHCb detector, it has $p$Pb(forward) and Pb$p$(backward) collisions.
- Backward collisions have higher multiplicity on average than forward collisions.
- There is no significant difference in the $\Xi_c^+/D^0$ ratios between forward and backward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

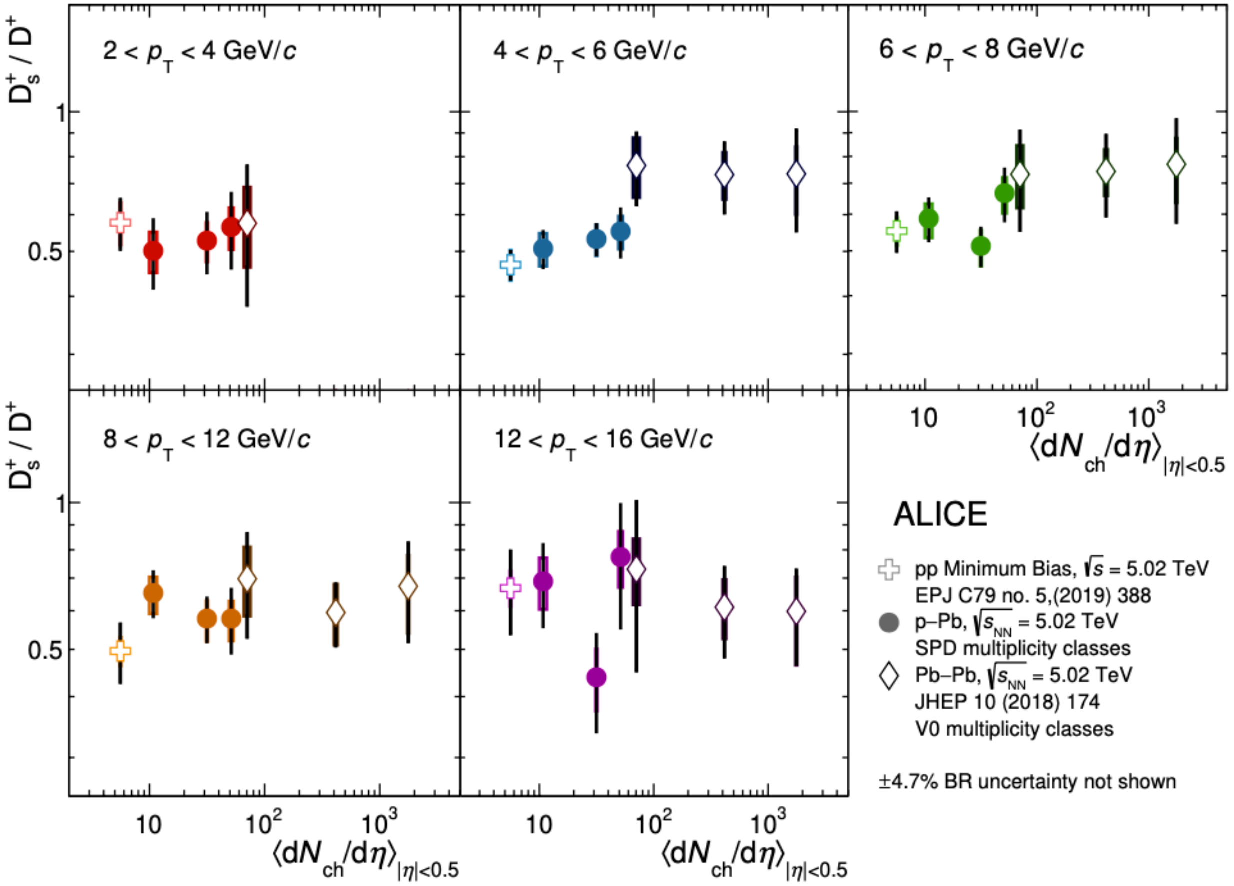


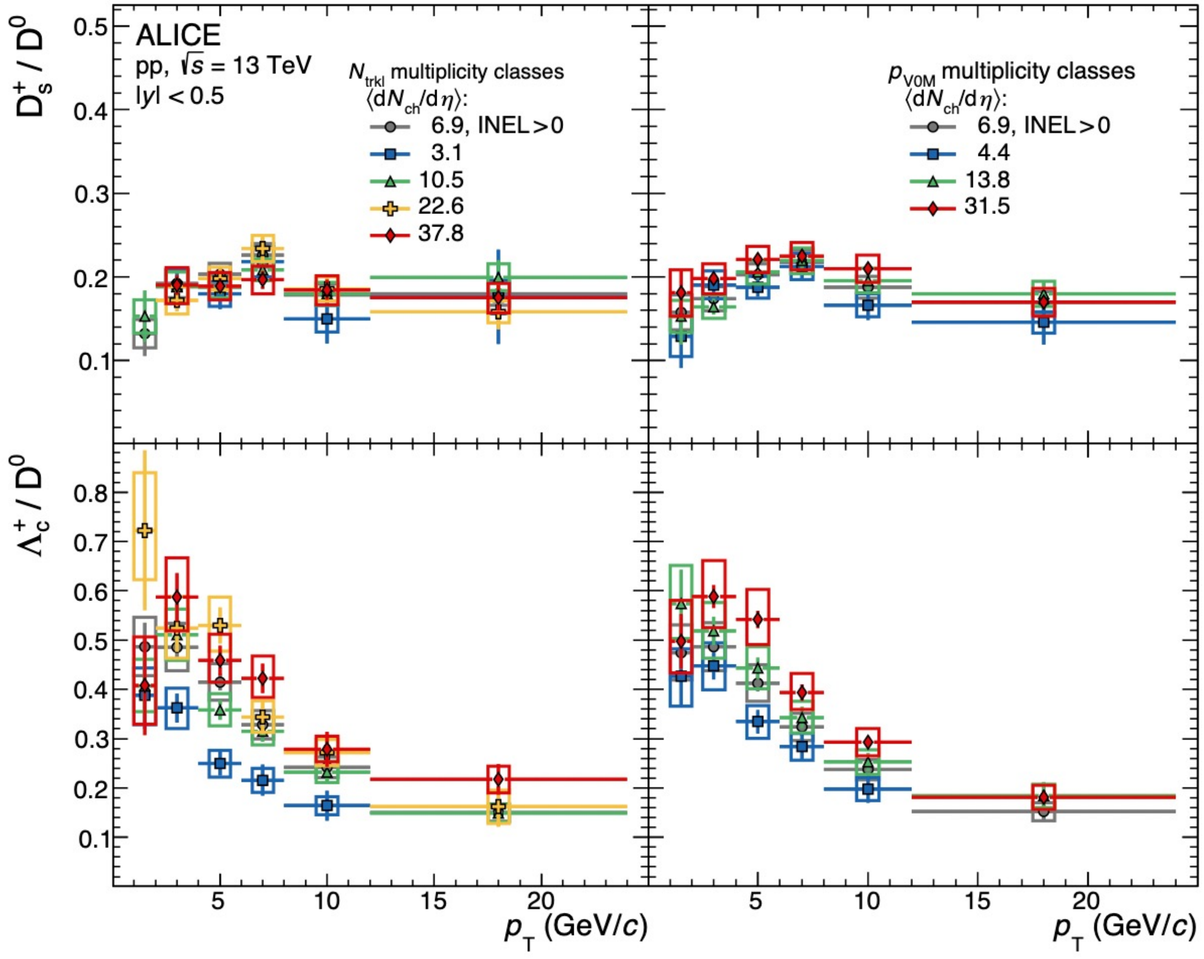

- Since the enhanced *s* quark abundance in the QGP, an increased $D_s^+$ in heavy-ion collisions relative to *pp* collisions has been predicted. This is also confirmed by ALICE and STAR. Phys. Lett. B 827 (2022) 136986 Phys. Rev. Lett. 127 (2021) 092301
- The *s* quark enhancement was also observed 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 $p$Pb collisions

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

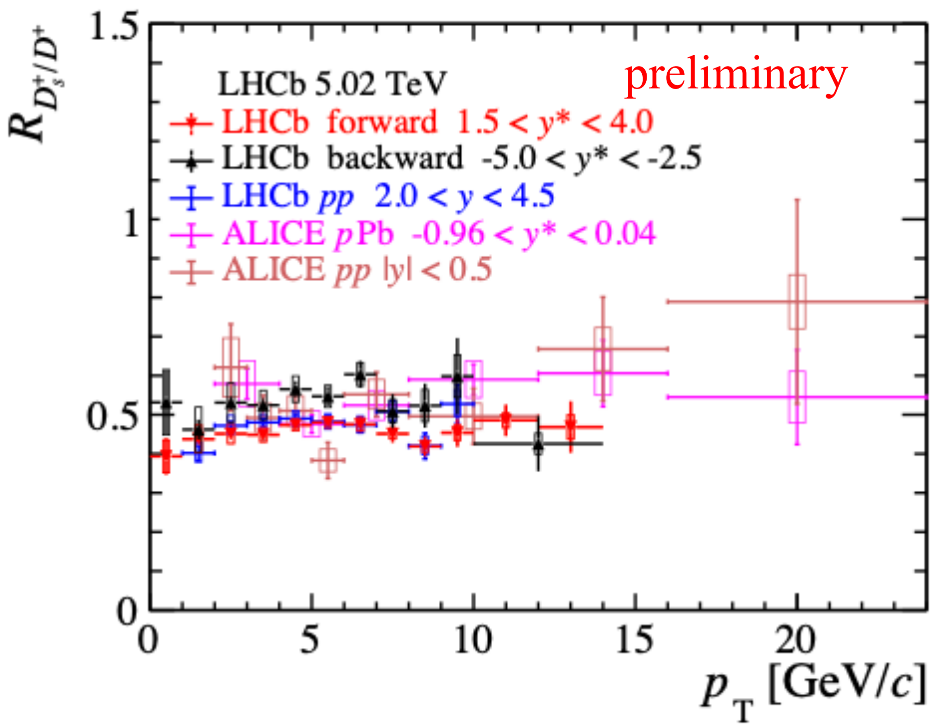


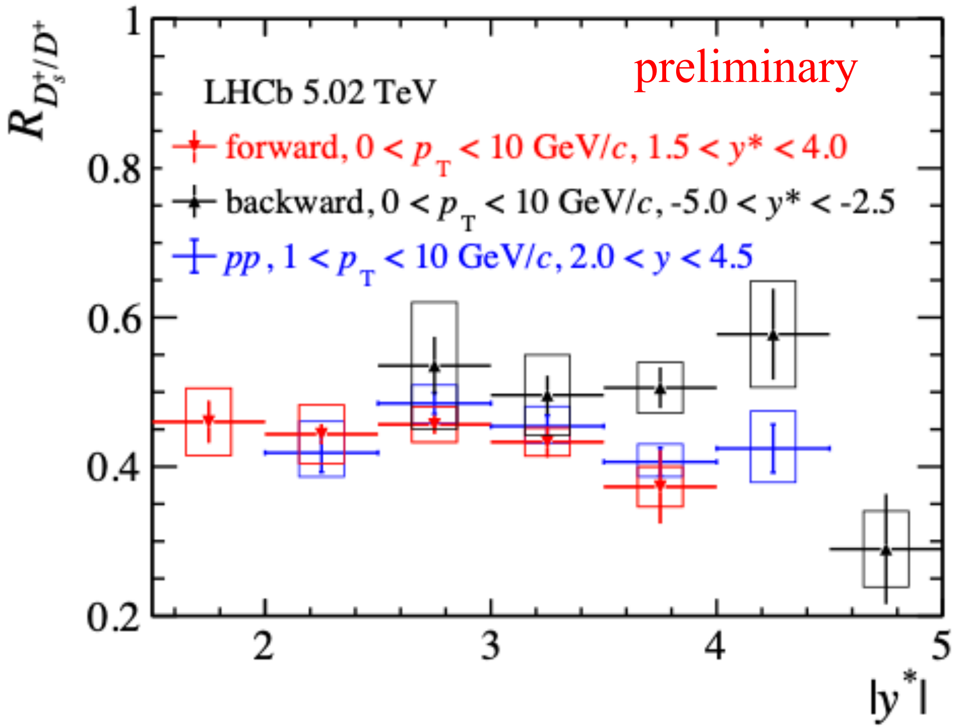




Phys. Lett. B 829 (2022) 137065
JHEP12(2019)092

# $D_s^+/D^+$ ratios in $p$Pb collisions at $\sqrt{s_{NN}} = 5.02$ 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.

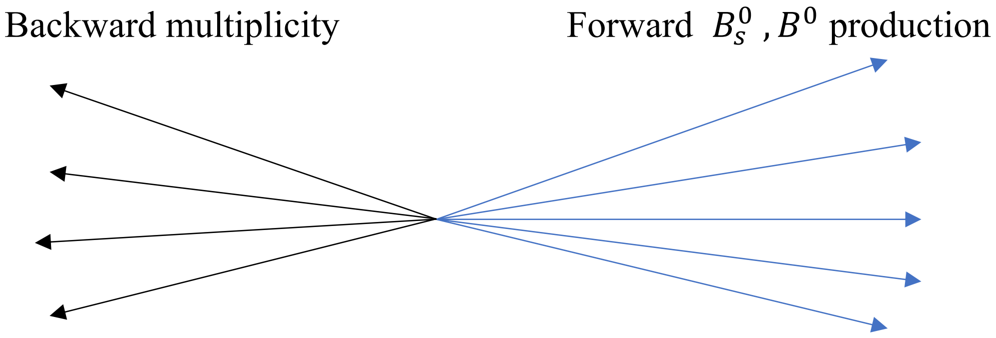


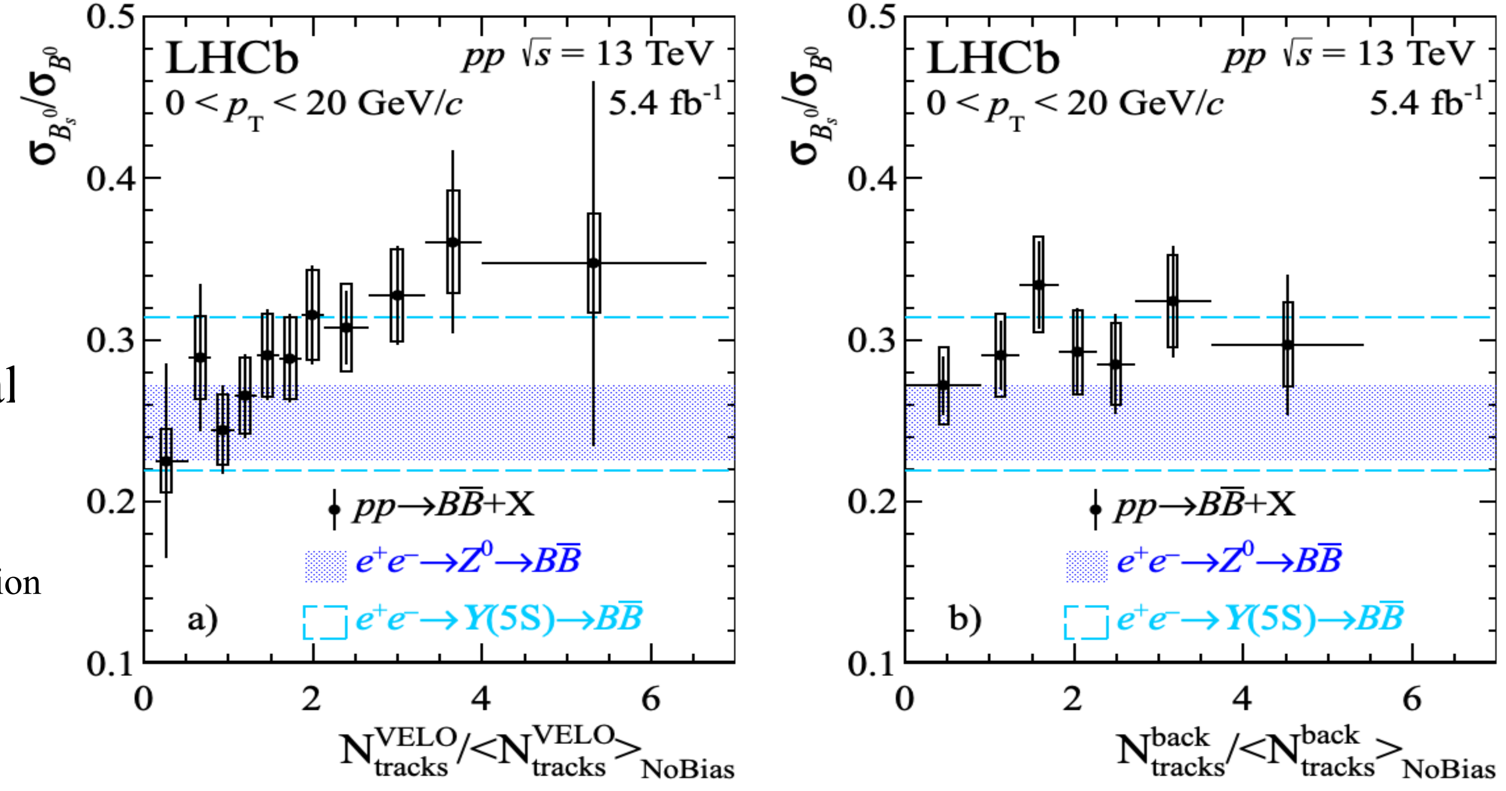




LHCb-PAPER-2023-006 paper in preparing

# $B_s^0/B^0$ 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.



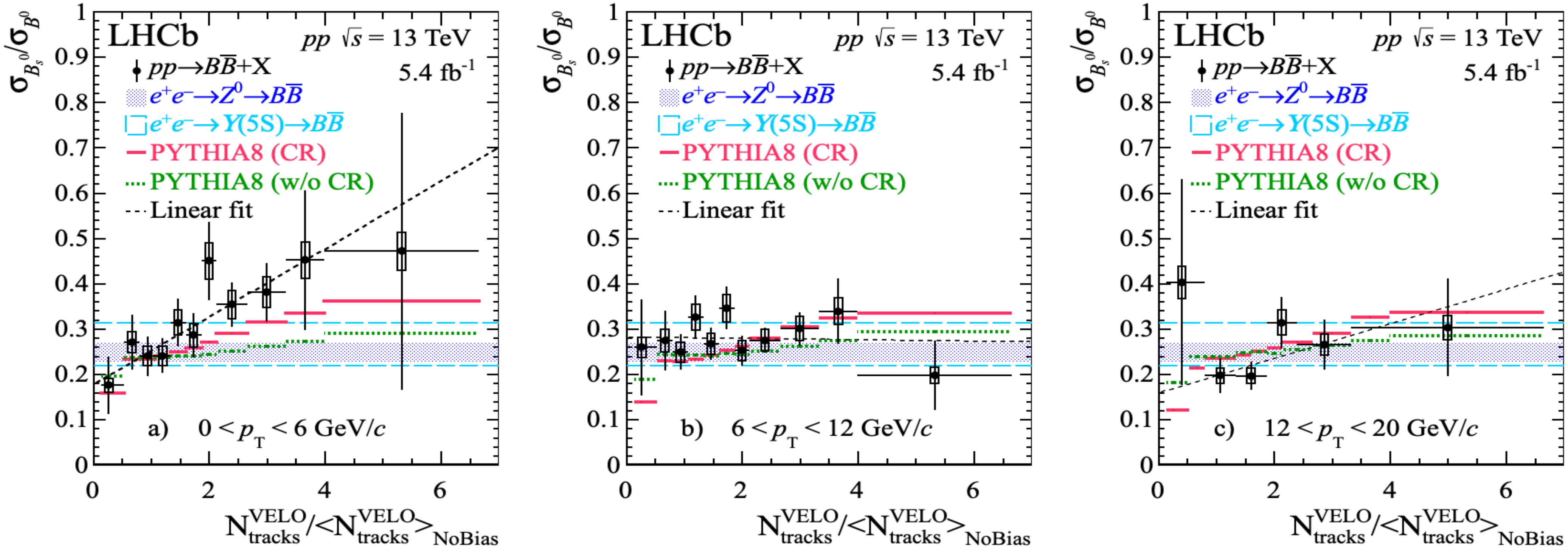






arXiv:2204.13042

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

- The $\sigma_{B_s^0}/\sigma_{B^0}$ ratios increases with multiplicity (slope significance = 3.4$\sigma$). 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

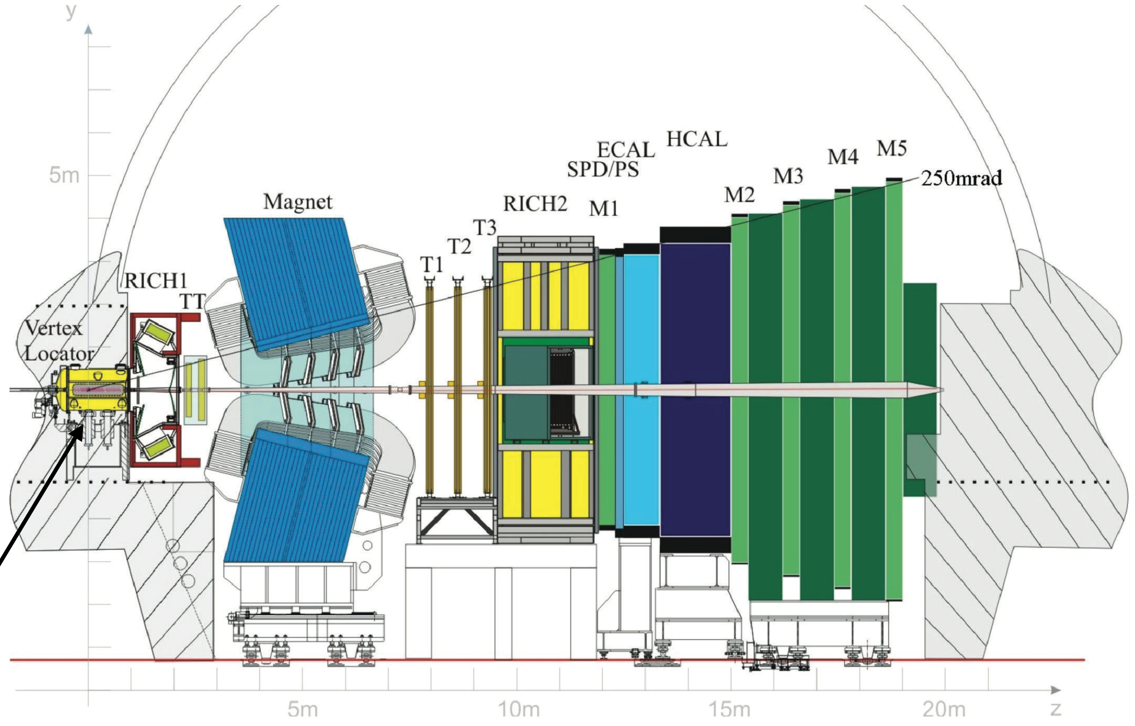
# Summary

- In *pp* collisions , the $\Lambda_c^+/D^0$ ratios show a significant multiplicity enhancement, but in *p*Pb collisions not. The reason still needs further research.
- In central PbPb collisions, $\Lambda_c^+/D^0$ 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 $\Xi_c^0/D^0$ 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 $p_{\mathrm{T}}$, 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 $p_{\mathrm{T}}$ 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!

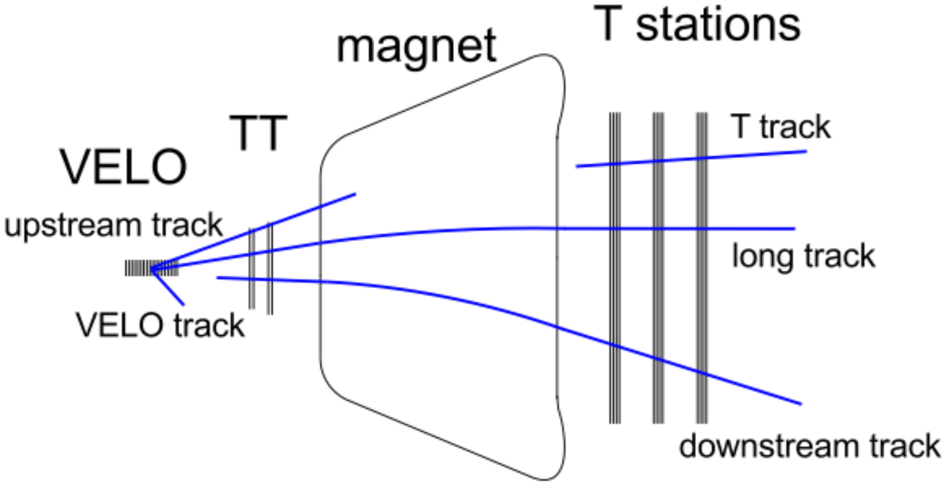
# LHCb detector

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




VErtex LOcator

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

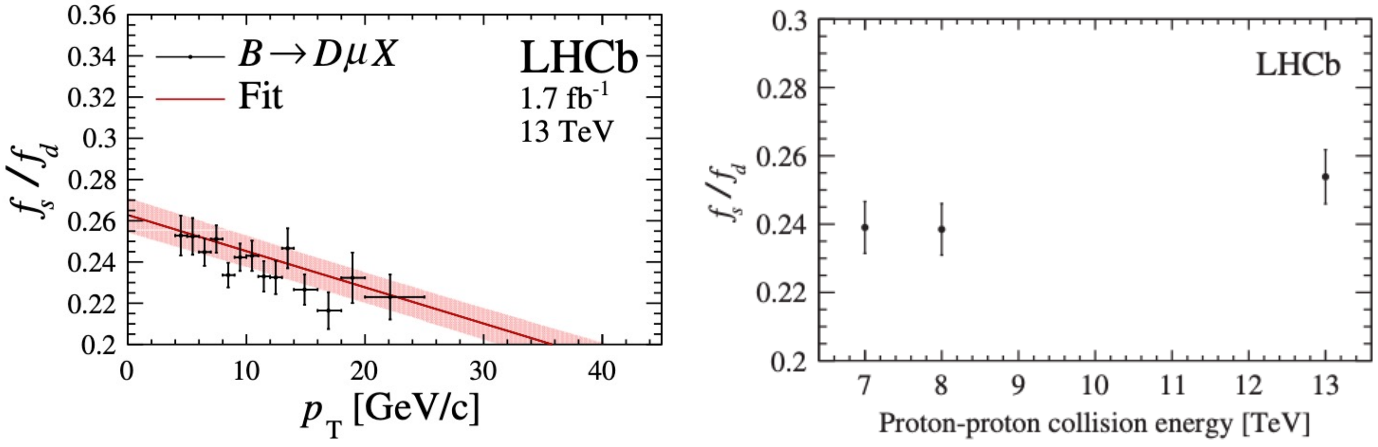


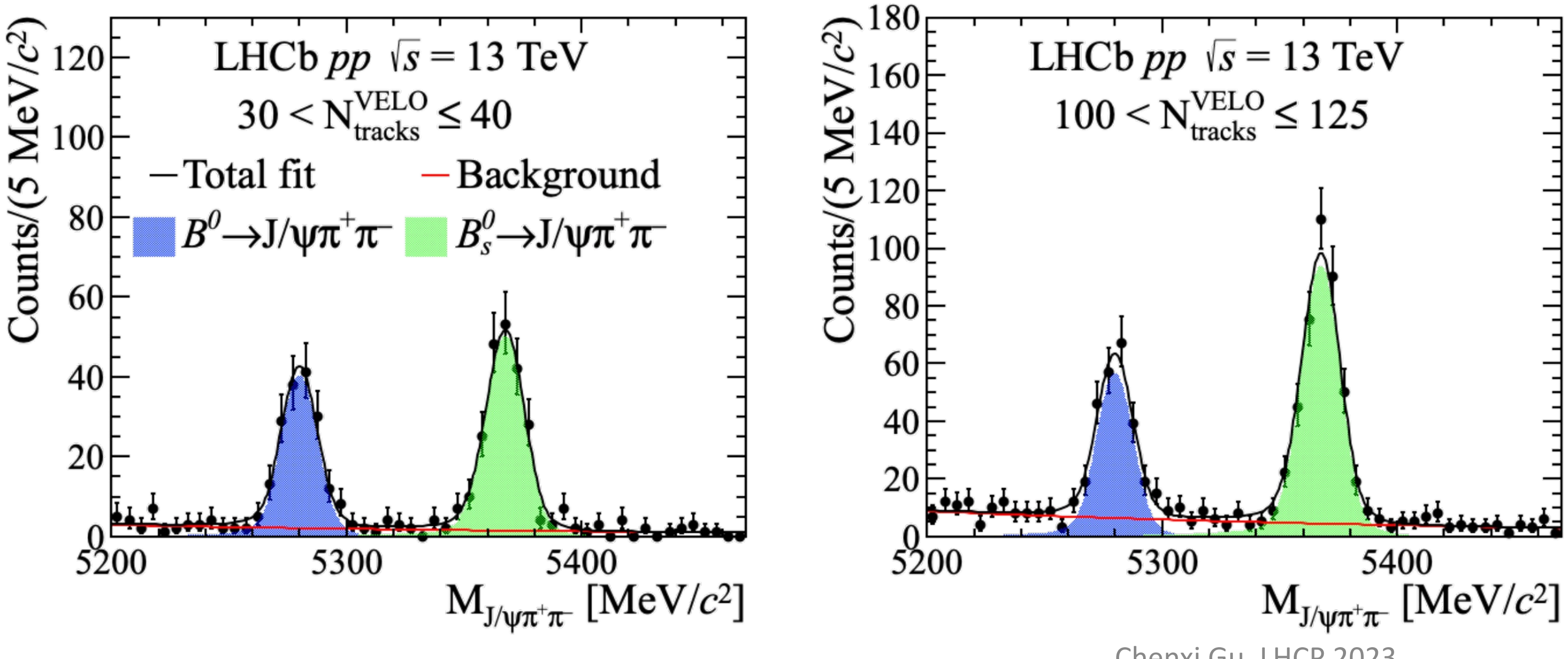

LHCb, JINST 3 (2008) S08005
LHCb, IJMPA 30 (2015) 1530022
JINST 10 (2015) 02 P02007

# $B_s^0/B^0$ 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.



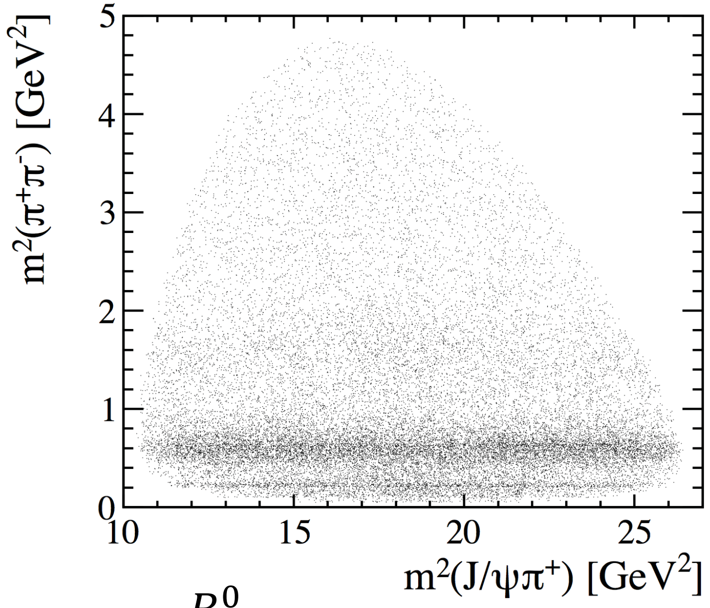

- Both $B_s^0$ and $B^0$ are reconstructed via $J/\psi\pi^+\pi^-$, relative corrections are generally close to 1 .

arXiv:2204.13042

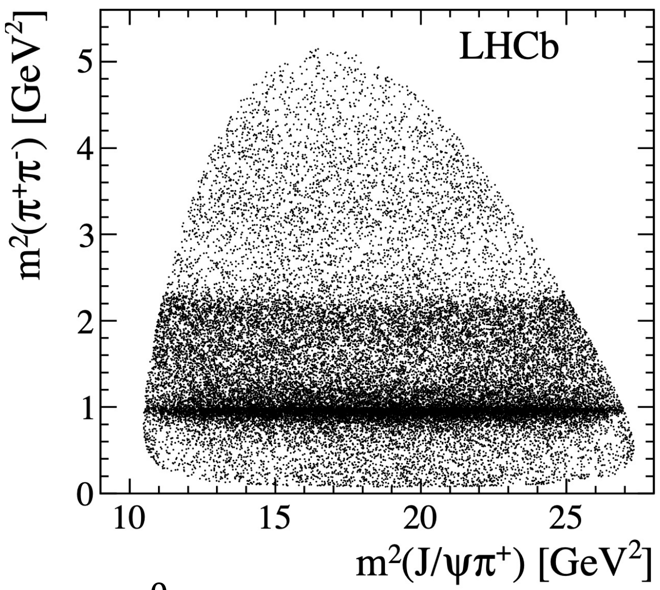
# Efficiencies

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

- $\frac{\varepsilon_{B^0}^{acc}}{\varepsilon_{B_s^0}^{acc}} = 1 \pm 0.01$， $\frac{\varepsilon_{B^0}^{trig}}{\varepsilon_{B_s^0}^{trig}} = 1 \pm 0.01$， $\frac{\varepsilon_{B^0}^{PID}}{\varepsilon_{B_s^0}^{PID}} = 1 \pm 0.01$
- $\frac{\varepsilon_{B^0}^{reco}}{\varepsilon_{B_s^0}^{reco}} = 0.86 \pm 0.04$ : 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.




$B^0$

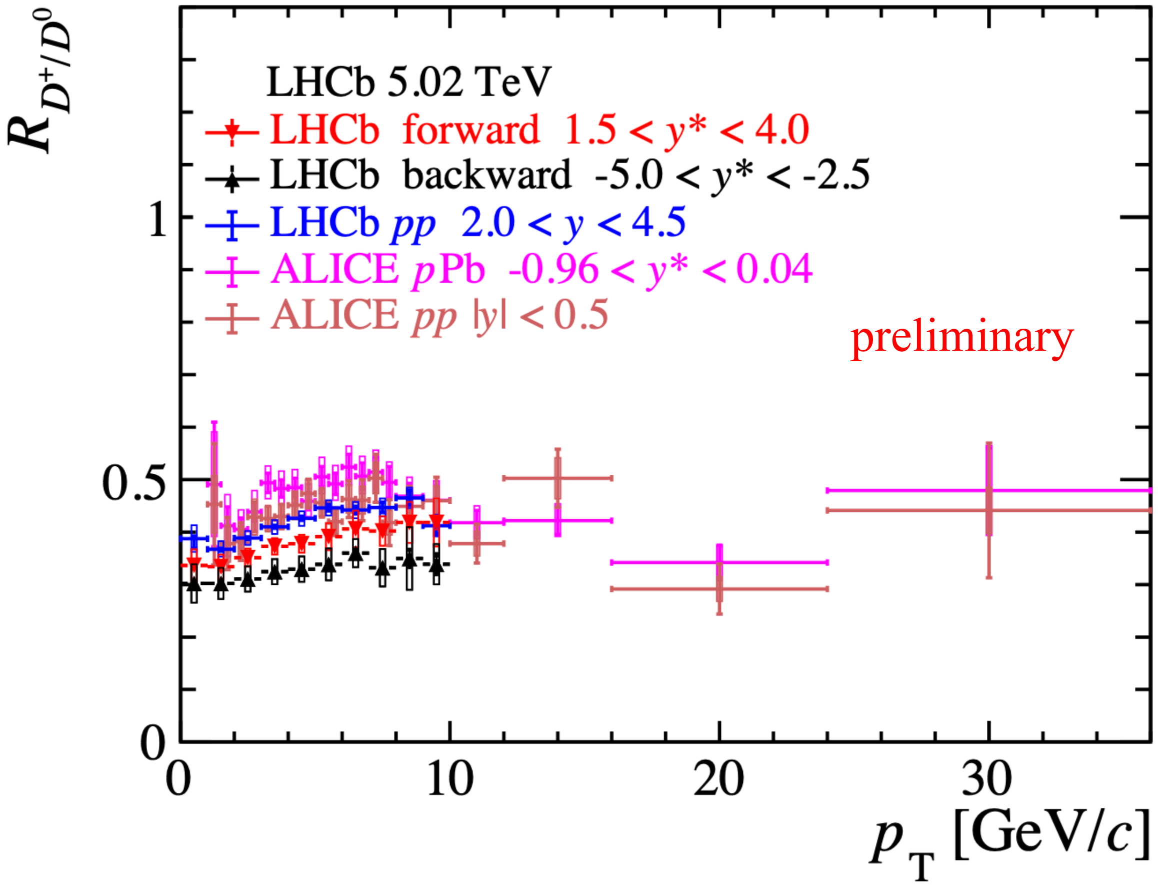


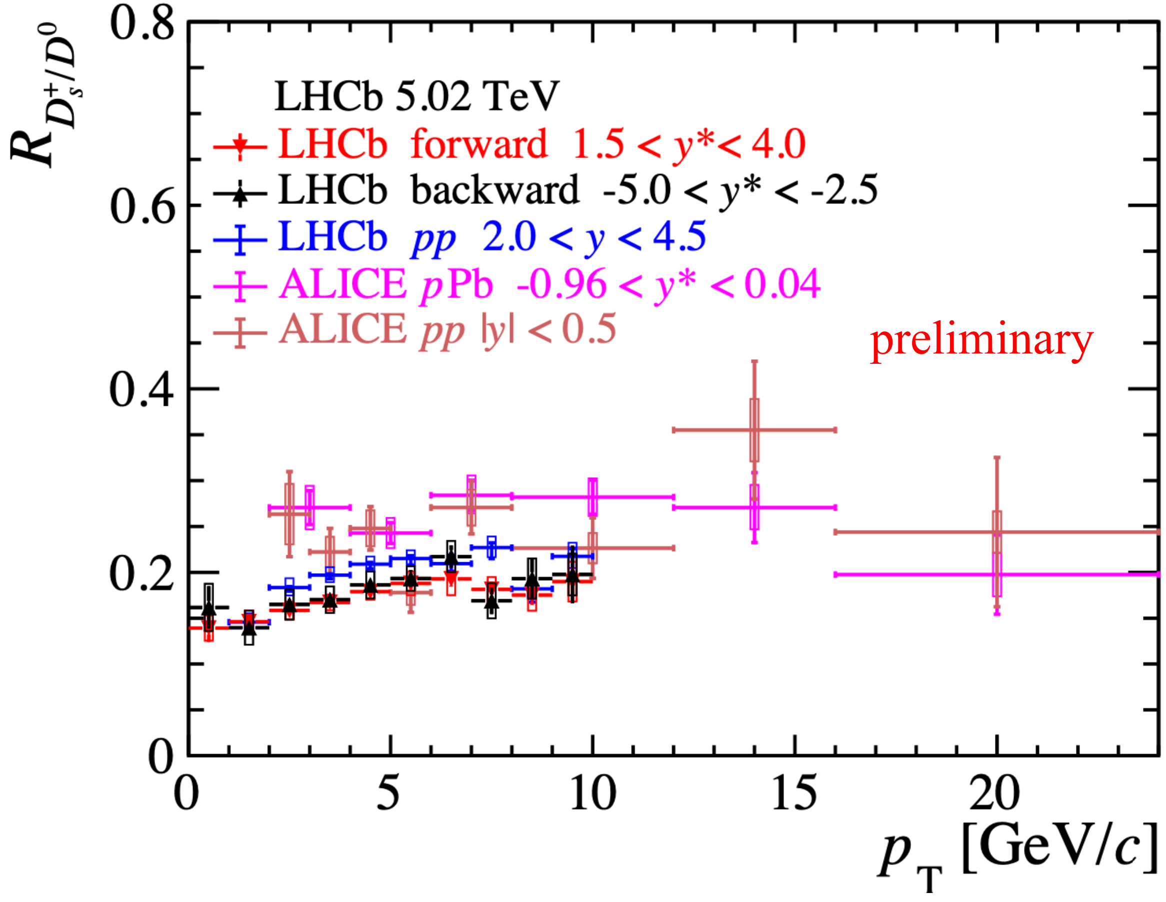

$B_s^0$

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

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

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

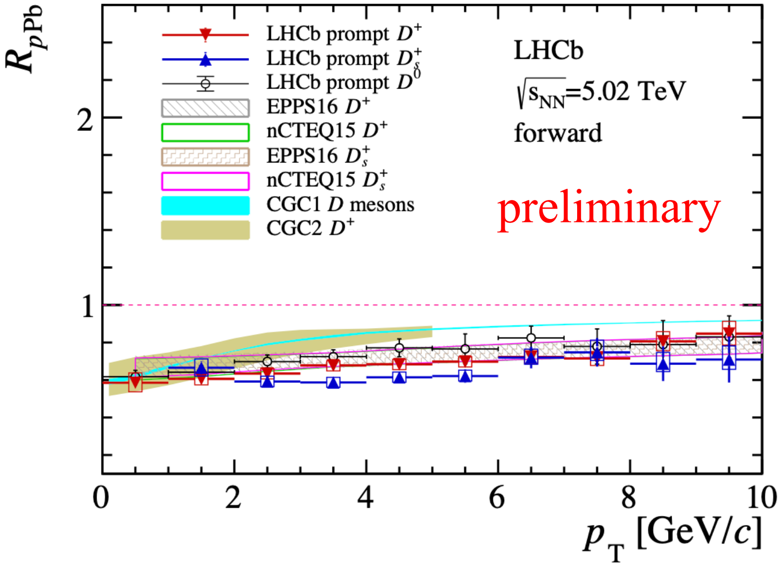


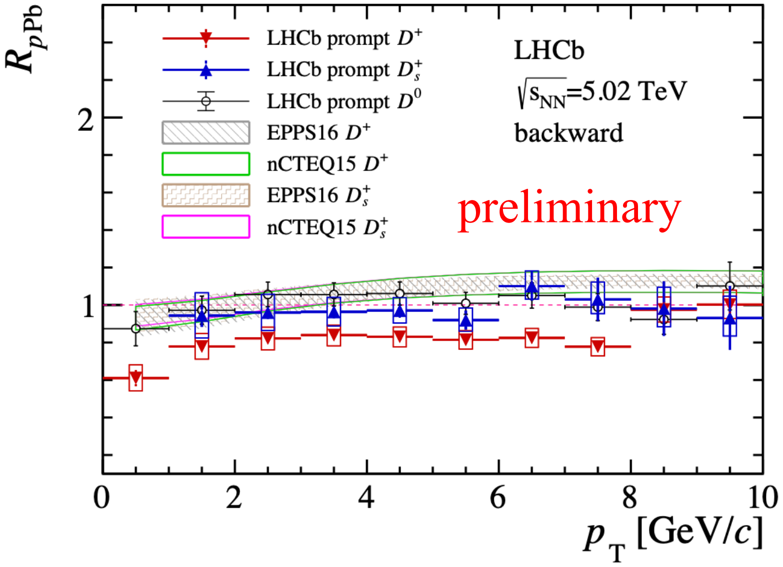



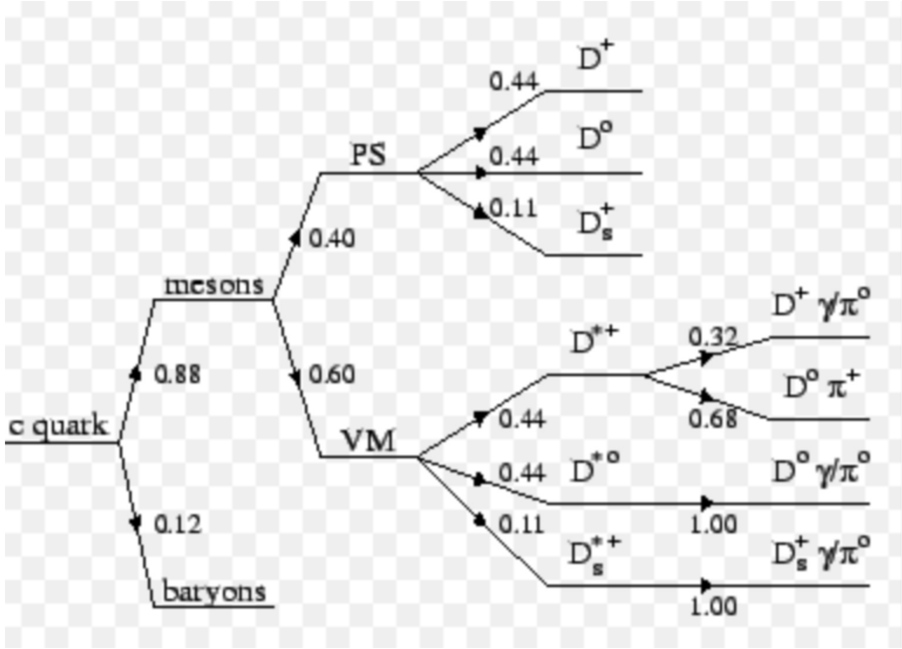

LHCb-PAPER-2023-006

# $D_s^+/D^+$ ratios in $p$Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

- Just $D^+$ fell down?



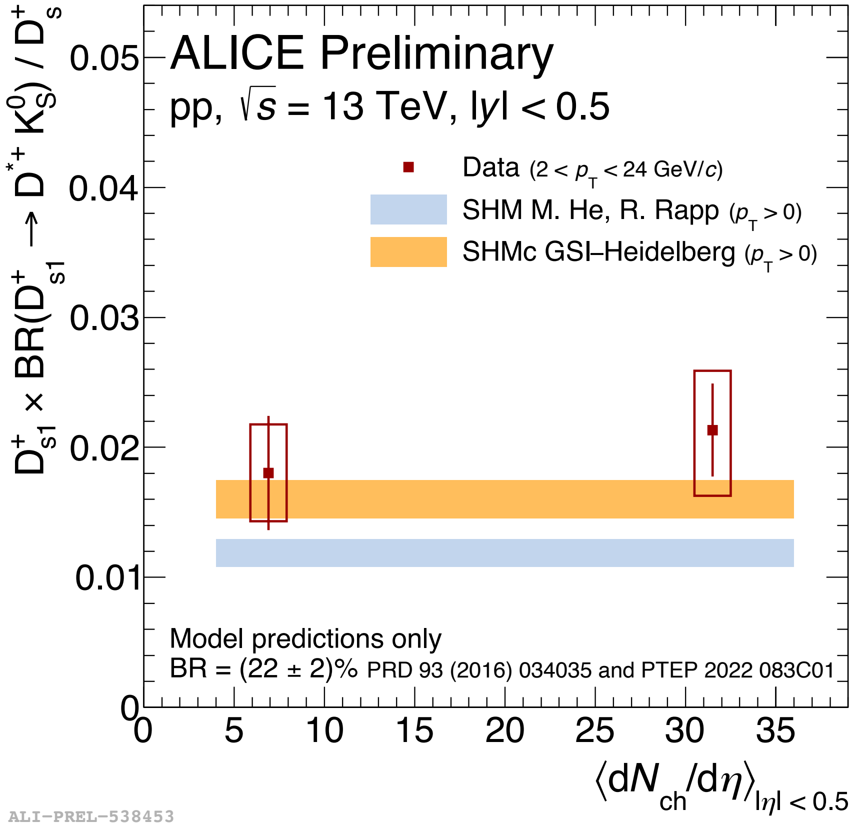




LHCb-PAPER-2023-006

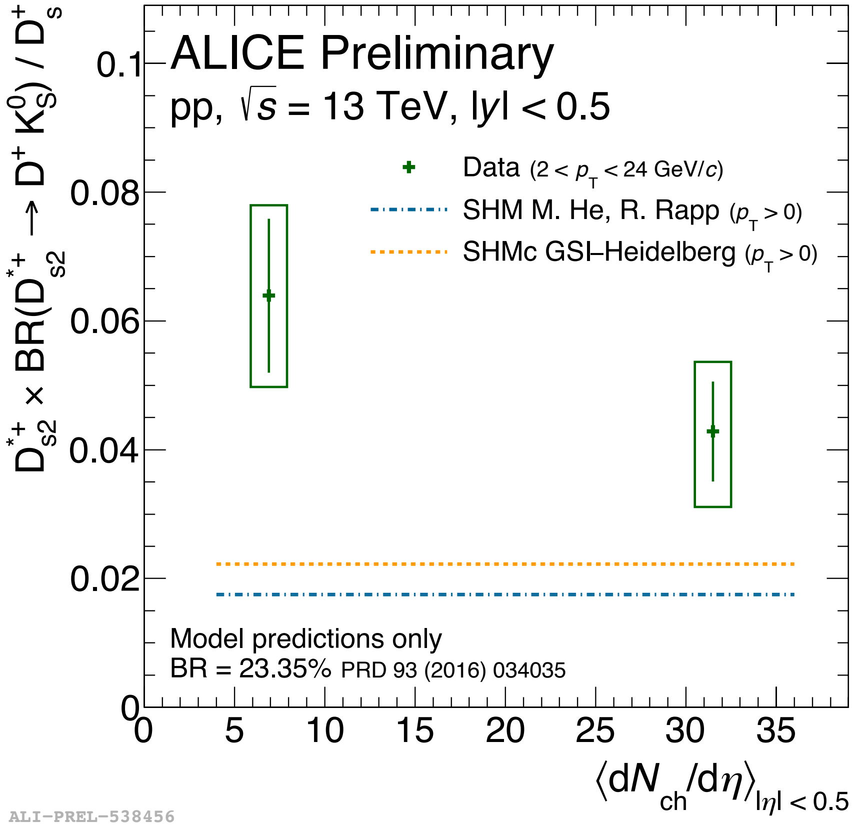
# $D_{s1}^+/D_s^+$, $D_{s2}^{*+}/D_s^+$ ratios in $pp$ collisions at $\sqrt{s}$ =13 TeV

- $D_{s1}^+$ 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.




$D_{s1}^+ \to D^{*+}K_s^0$

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

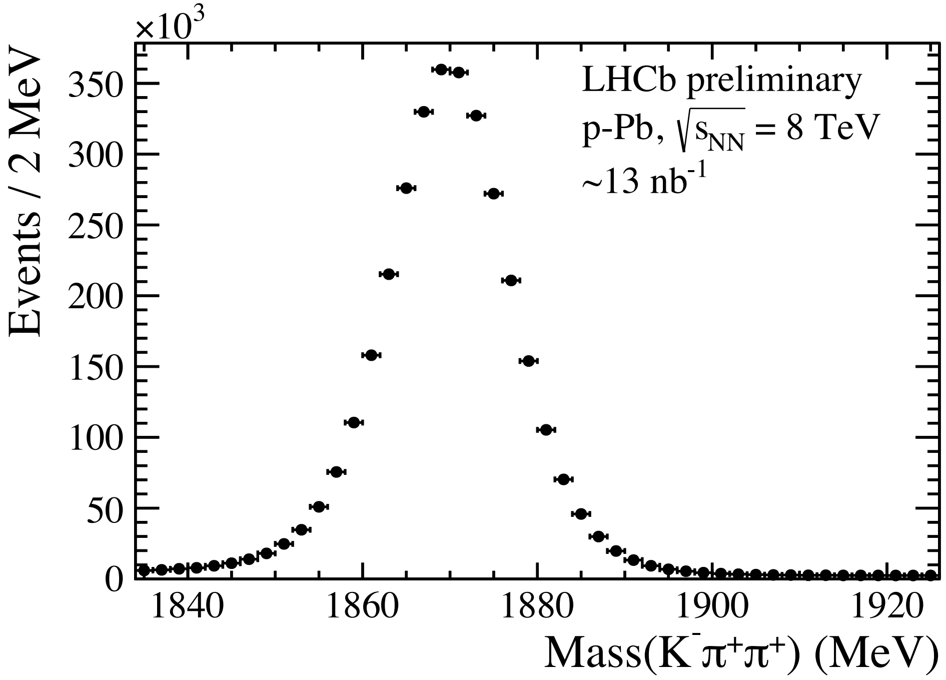



$D_{s2}^{*+} \to D^+K_s^0$

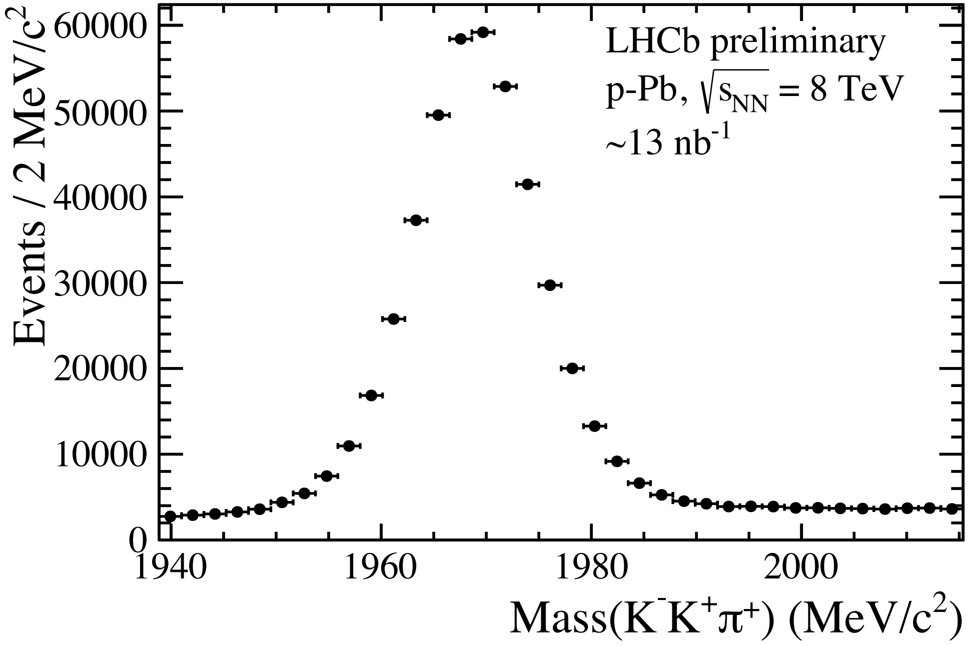
# Work in progress: $D_s^+/D^+$ ratio in $p$Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$TeV

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

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




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




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