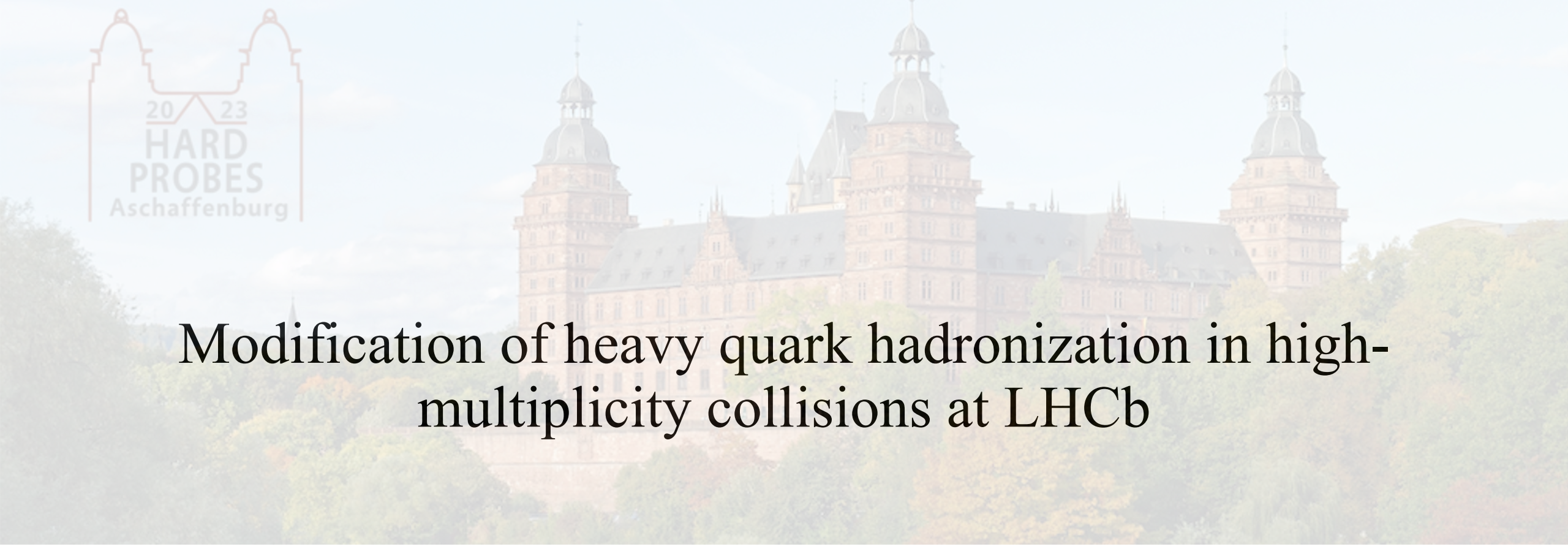


# Modification of heavy quark hadronization in high-multiplicity collisions at LHCb

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

on behalf of the LHCb collaboration

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LHCb

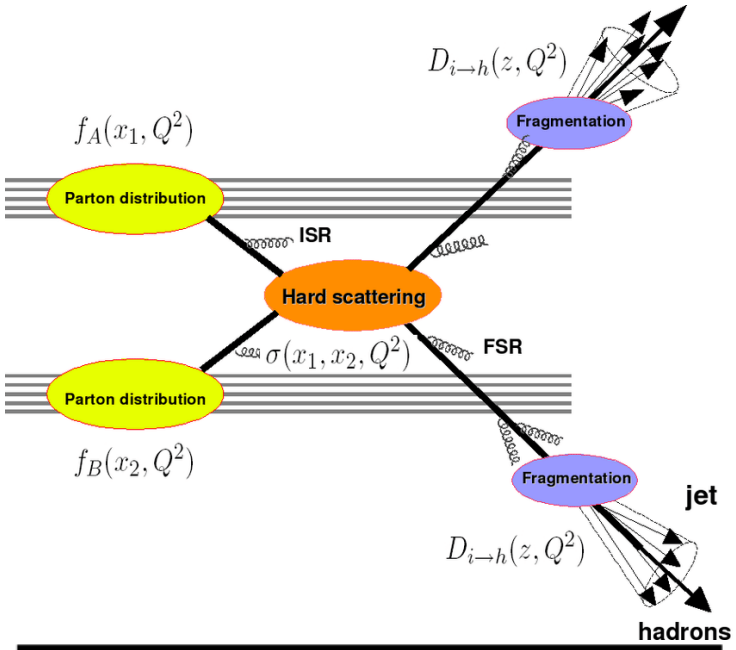
# Outline

- Motivation
- LHCb detector
- Evidence for modification of $b$ quark hadronization in $pp$ collisions arXiv:2204.13042 PRL accepted!
- Measurement of prompt $D_s^+/D^+$ ratios in $p$Pb collisions LHCb-PAPER-2023-006 piping hot!
- Measurement of the $\Lambda_c^+/D^0$ ratios in peripheral PbPb collisions arXiv:2210.06939
- Summary

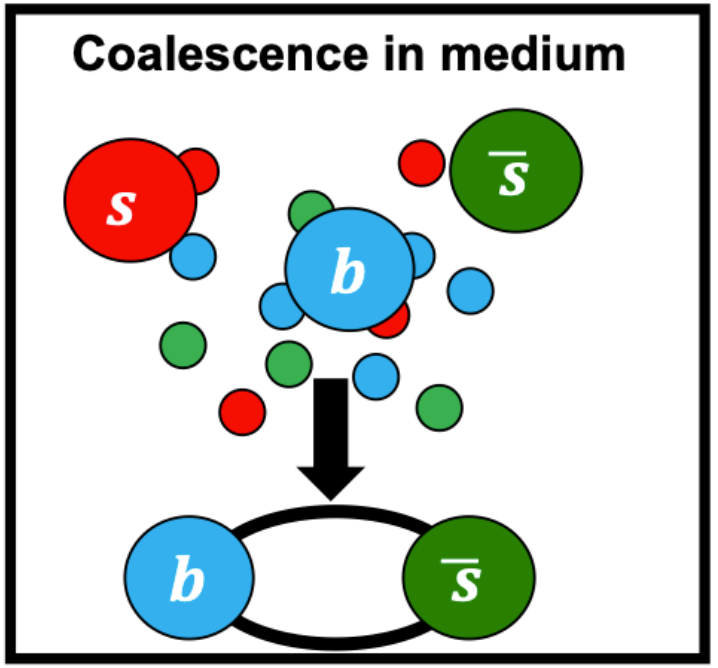
# Motivation

- 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.
  - ➢ Coalescence mechanism: multiple overlapping quarks in position and velocity phase space combine to form hadrons.
- 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 (dynamical core-corona initialization, rope hadronization, color reconnection…).

Baryon/meson ratios are only sensitive to hadronization.

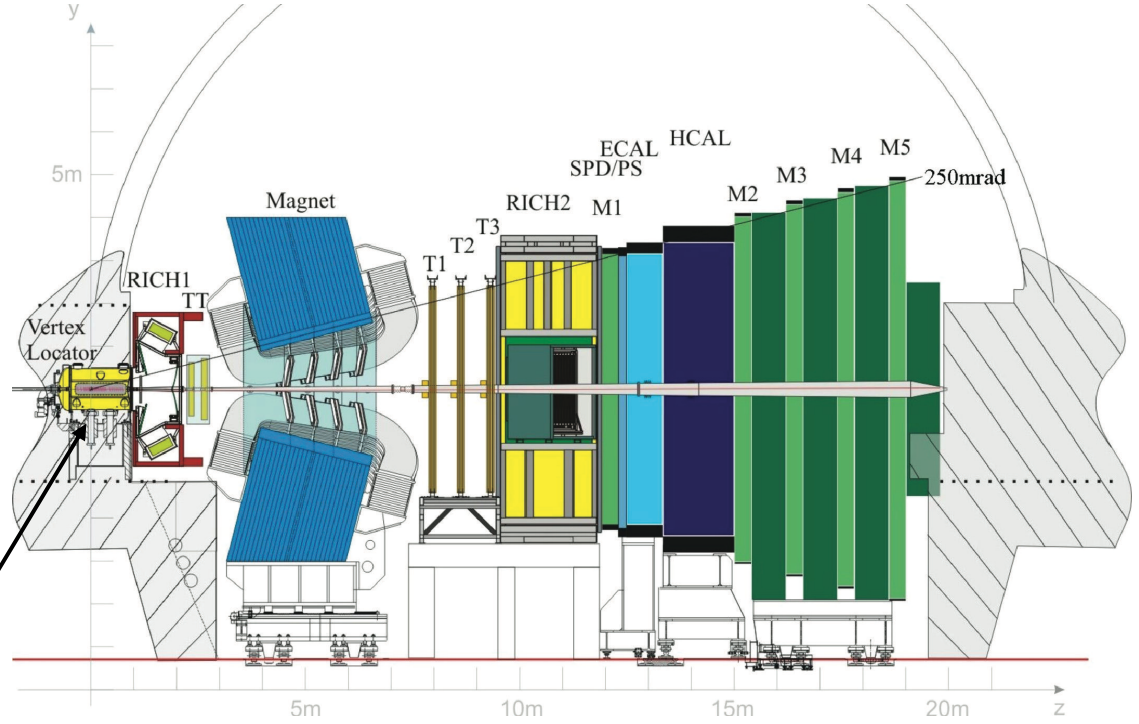



Strange meson/non strange meson ratios are sensitive to hadronization and strangeness enhancement.



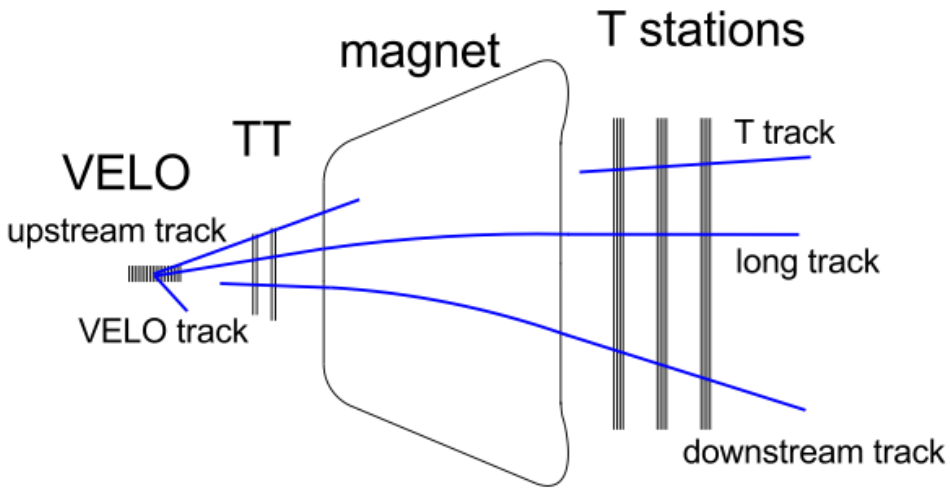
# LHCb detector

- 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, $\pi$
    - ❖ $\varepsilon(K \to K)$~95%
    - ❖ $\varepsilon(\mu \to \mu)$~97%
  - ➢ Flexible software trigger




VErtex LOcator

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



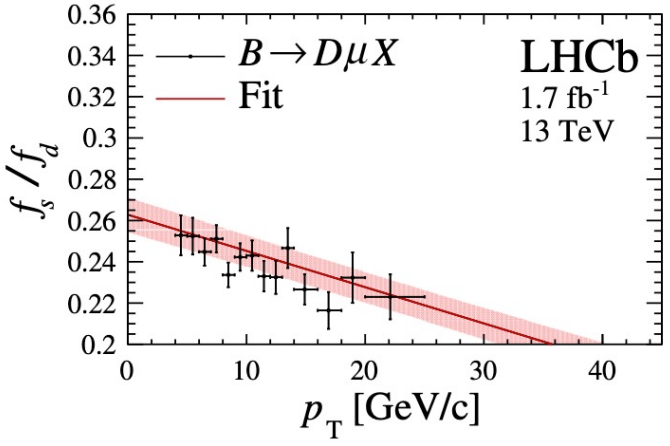


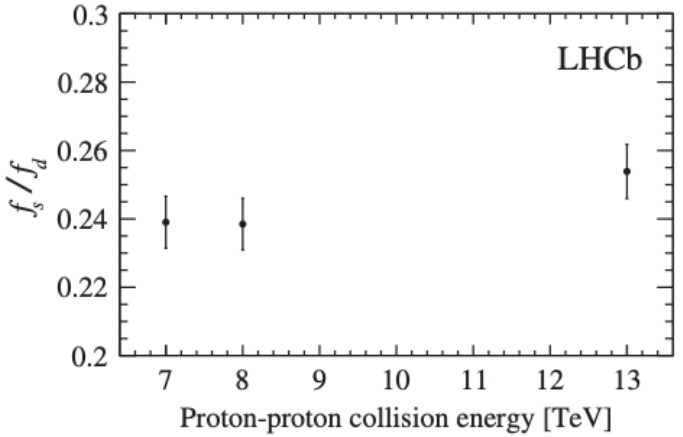
LHCb, JINST 3 (2008) S08005
LHCb, IJMPA 30 (2015) 1530022
JINST 10 (2015) 02 P02007

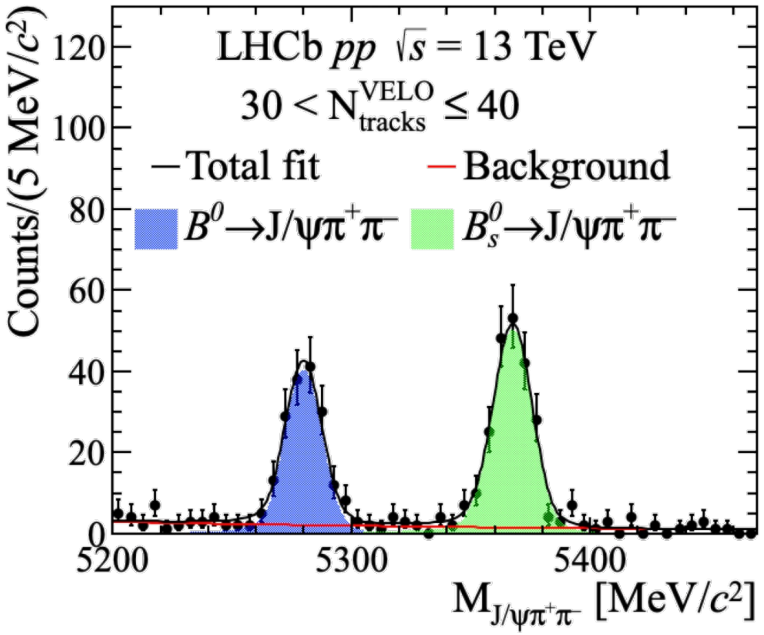
# $B_s^0/B^0$ ratio vs multiplicity in $pp$ collisions at $\sqrt{s_{\mathrm{NN}}} = 13$ TeV

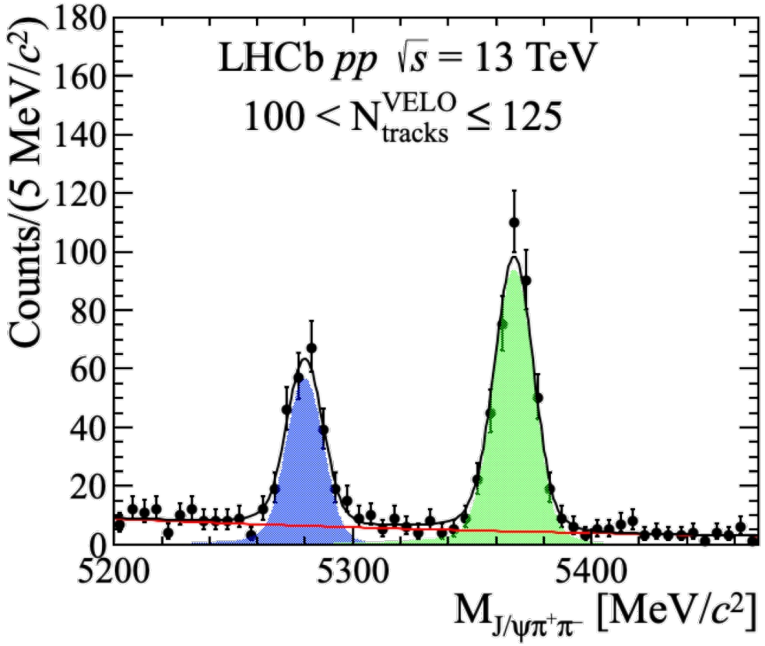
Phys. Rev. D 104(2021) 032005

- 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.



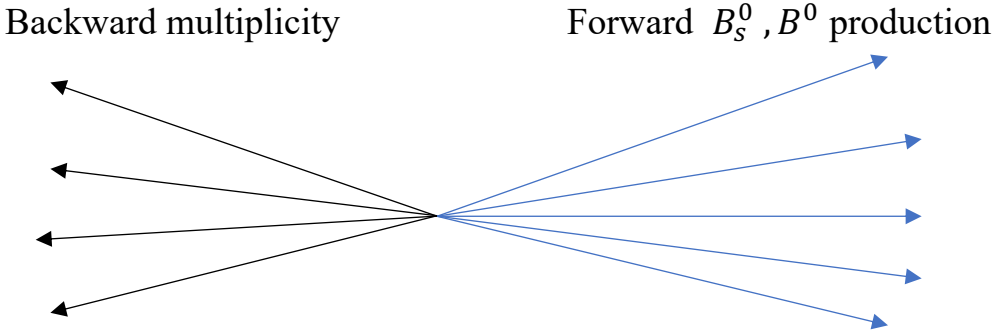

- Both $B_s^0$ and $B^0$ are reconstructed via $J/\psi\pi^+\pi^-$, relative corrections are generally close to 1 .

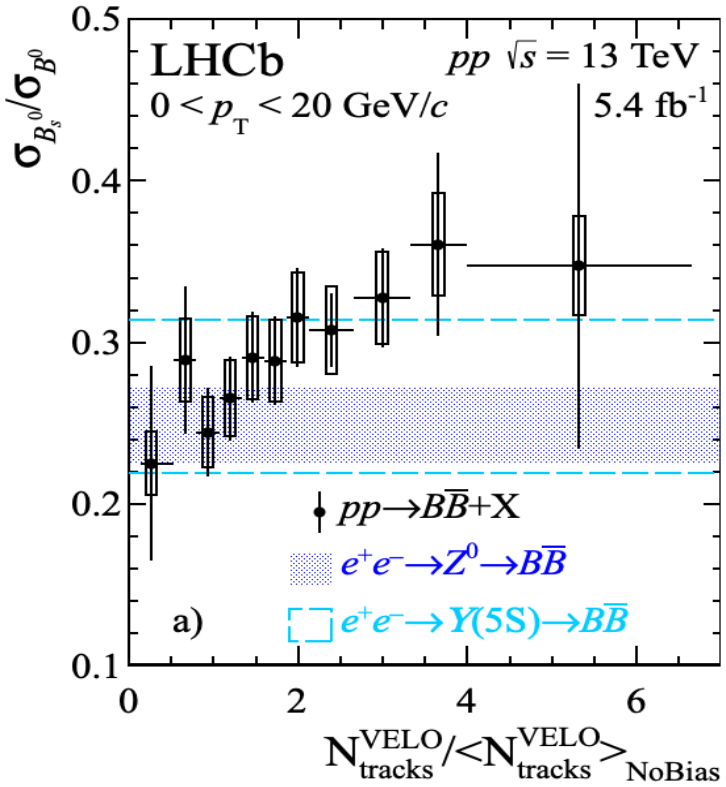
arXiv:2204.13042

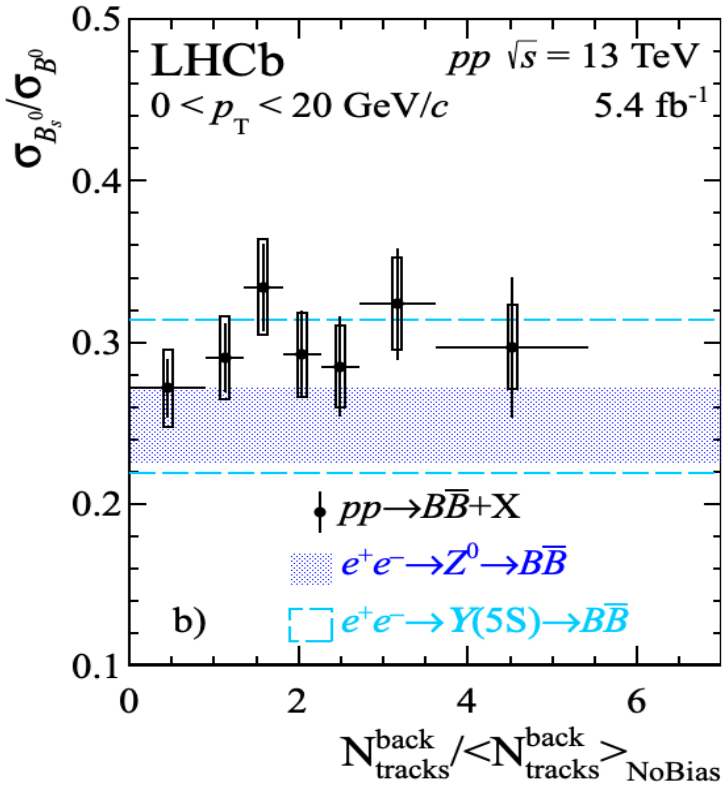
# $B_s^0/B^0$ vs tracks

- The $B_s^0/B^0$ ratio shows 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 ratio increase is related to the local particle density.



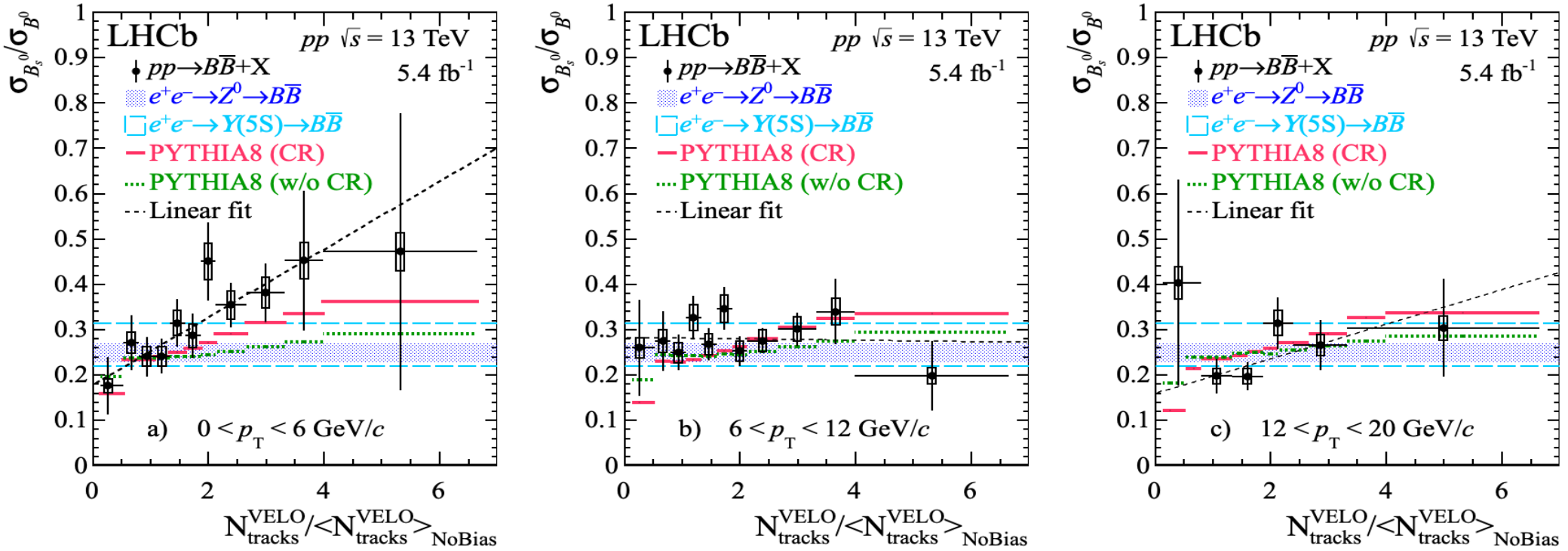






arXiv:2204.13042

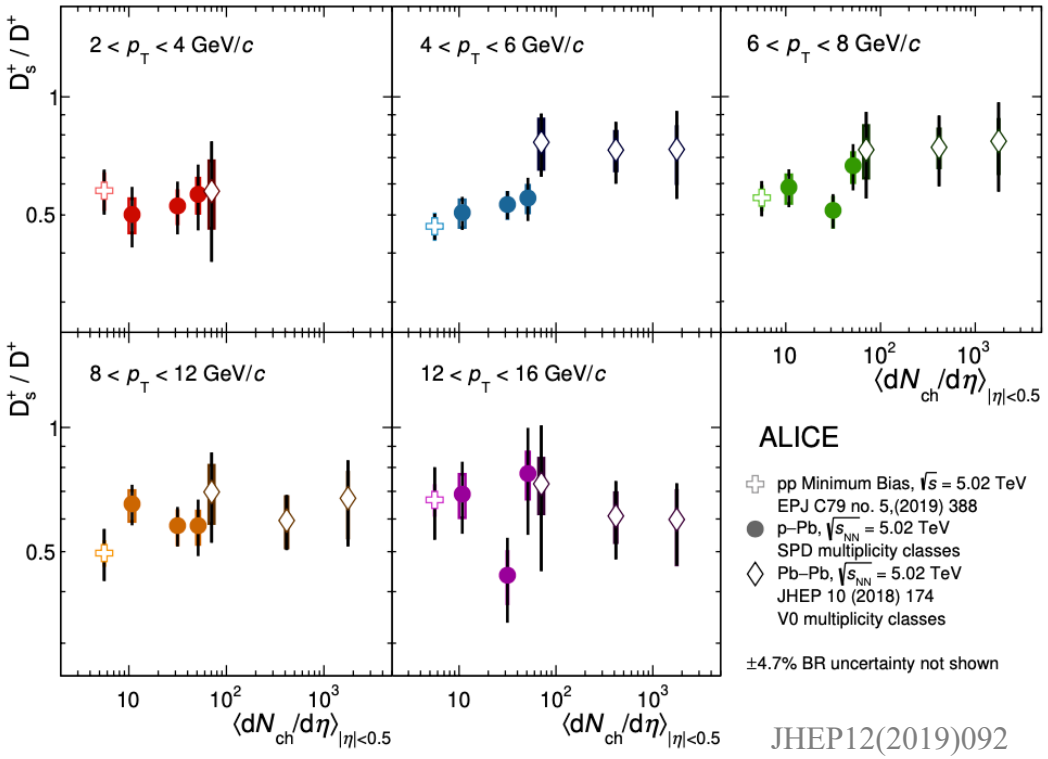
# $B_s^0/B^0$ in different $p_T$ bins

- The $\sigma_{B_s^0}/\sigma_{B^0}$ ratios increases with multiplicity (slope significance = 3.4$\sigma$). Has a closer trend to the PYTHIA8 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.



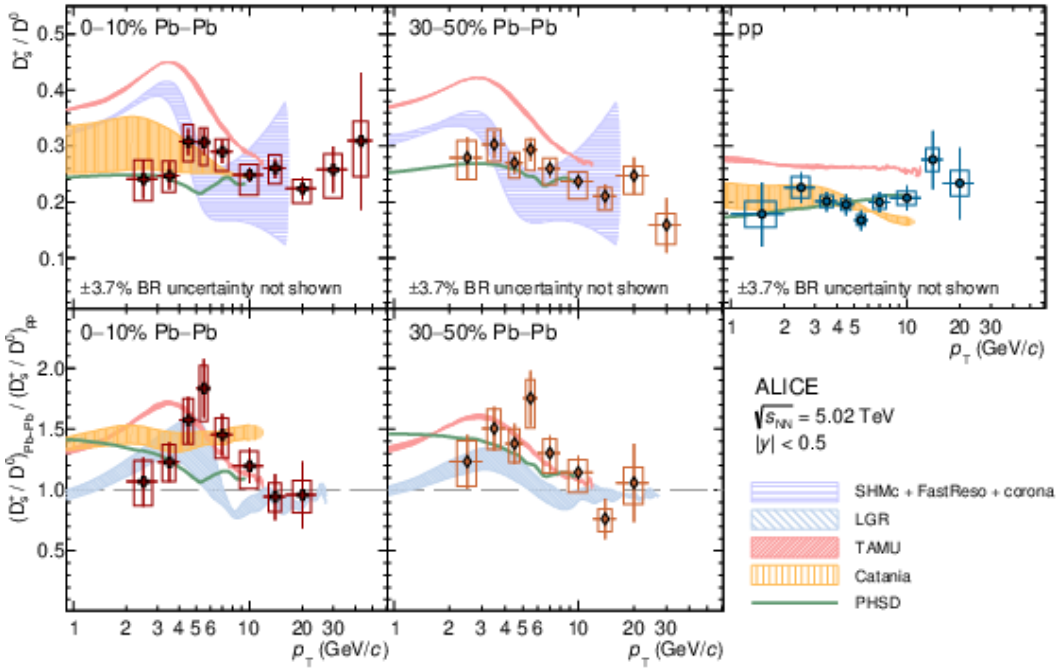
# $D_s^+/D^+$ ratios in $p$Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- 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)




JHEP12(2019)092

Phys. Lett. B 827 (2022) 136986

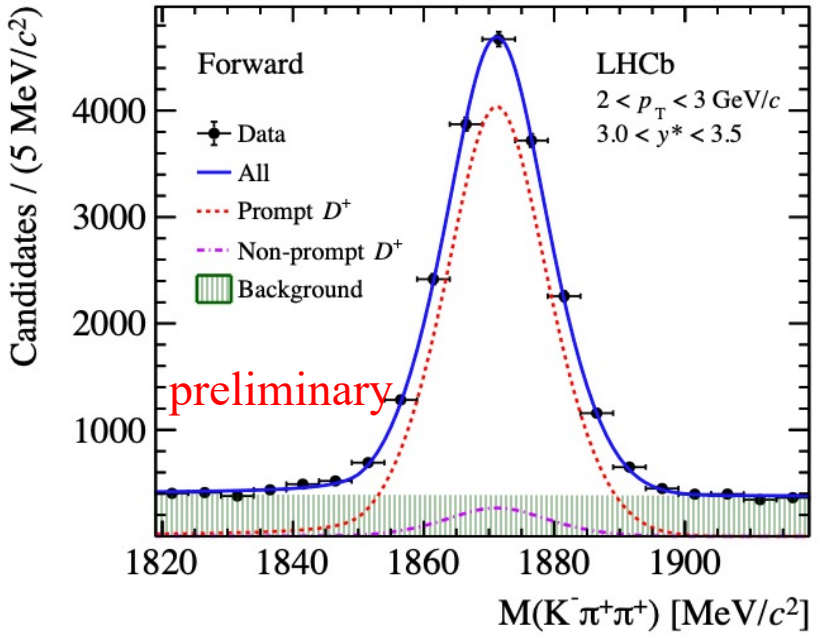


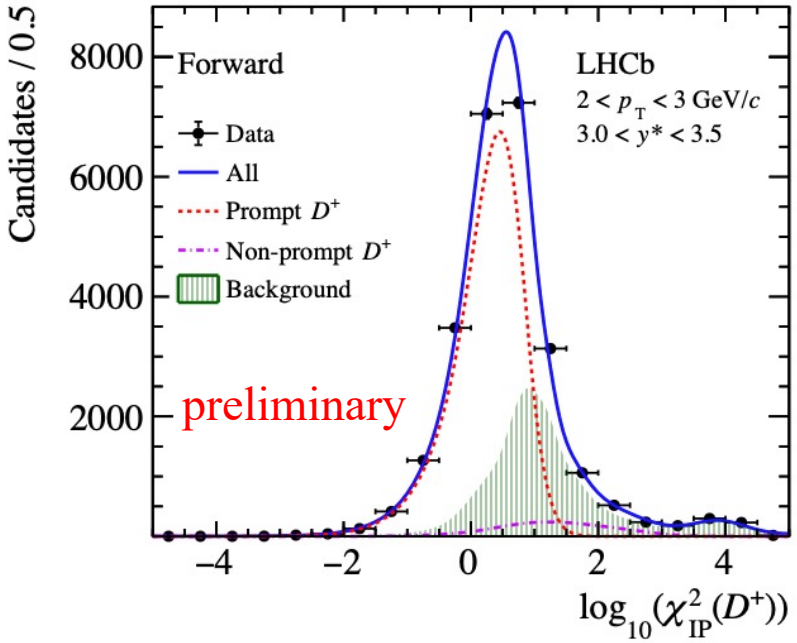

- The *p*Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV data was taken in 2013 with asymmetric collision configuration.
  - Forward : $1.5 < y^* < 4$ (center mass system rapidity)
  - Backward : $-5 < y^* < -2.5$
- Backward collisions have higher multiplicity on average than forward collisions.
  - Forward long track number ~40
  - Backward long track number ~60

LHCb-PAPER-2023-006

# Signal extraction

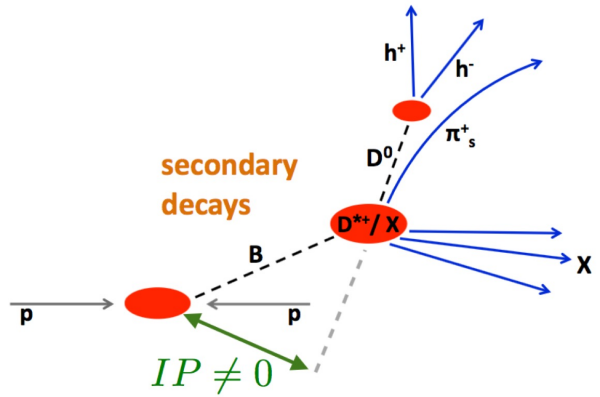
- The prompt and from *b* yields are determined from simultaneous fits to the invariant mass and $\log(\chi^2_{\mathrm{IP}})$ distributions.




➢**Prompt and from b component**: Crystal ball + Gaussian function.
➢**Background**: linear function.

➢**Prompt and from b component**: Bukin function.
➢**Background**: Shape obtained from the data side-band regions.



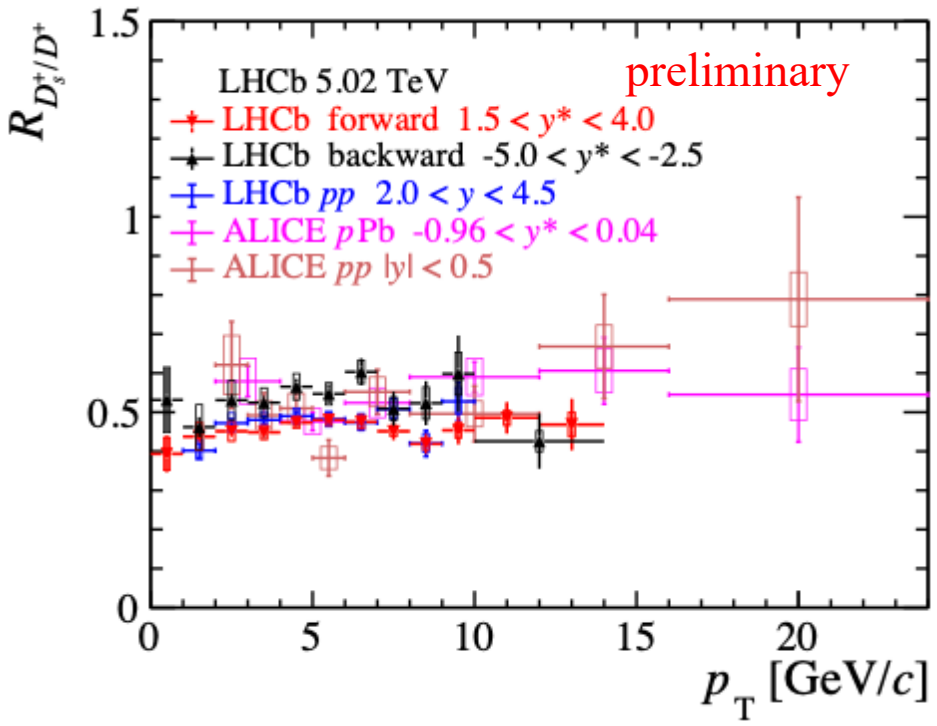

Impact parameter (IP) : the perpendicular distance from the primary vertex to *D* path. The *D* meson with smaller impact parameter is more likely to originate from the primary interaction.

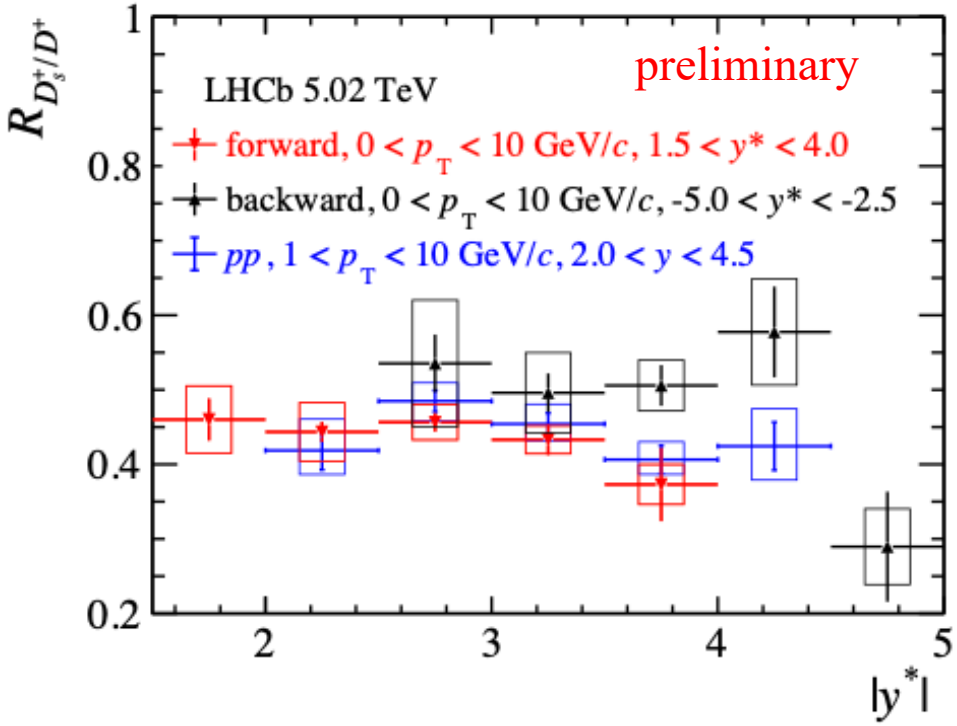


LHCb-PAPER-2023-006

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

- $D_s^+/D^+$ ratios show no dependence on $p_{\mathrm{T}}$.
- $D_s^+/D^+$ 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.



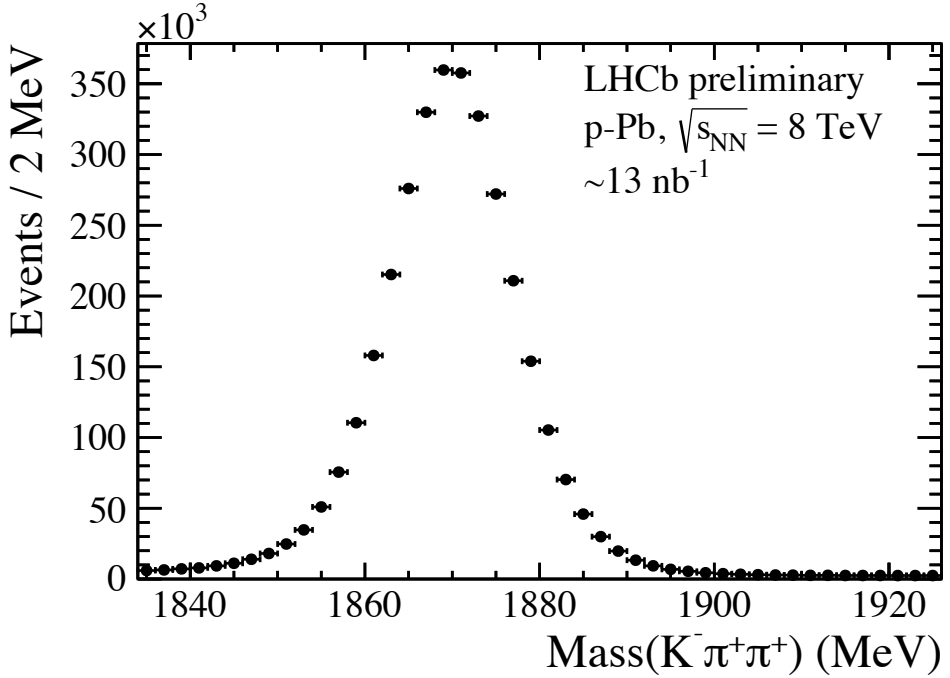



LHCb-PAPER-2023-006

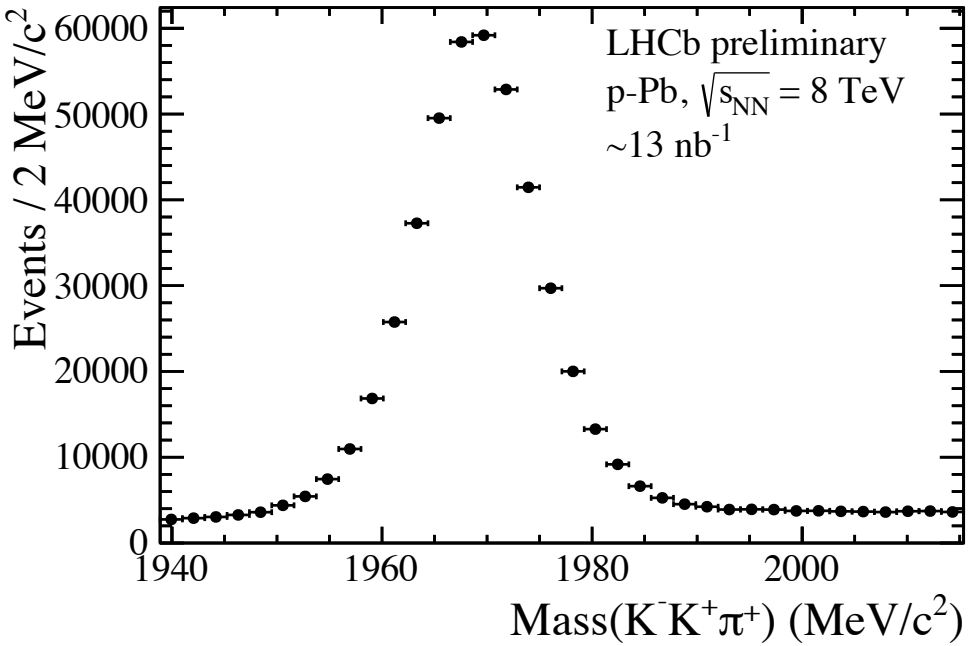
# Work in progress: $D_s^+/D^+$ ratio in $p$Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\mathrm{TeV}$

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

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




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

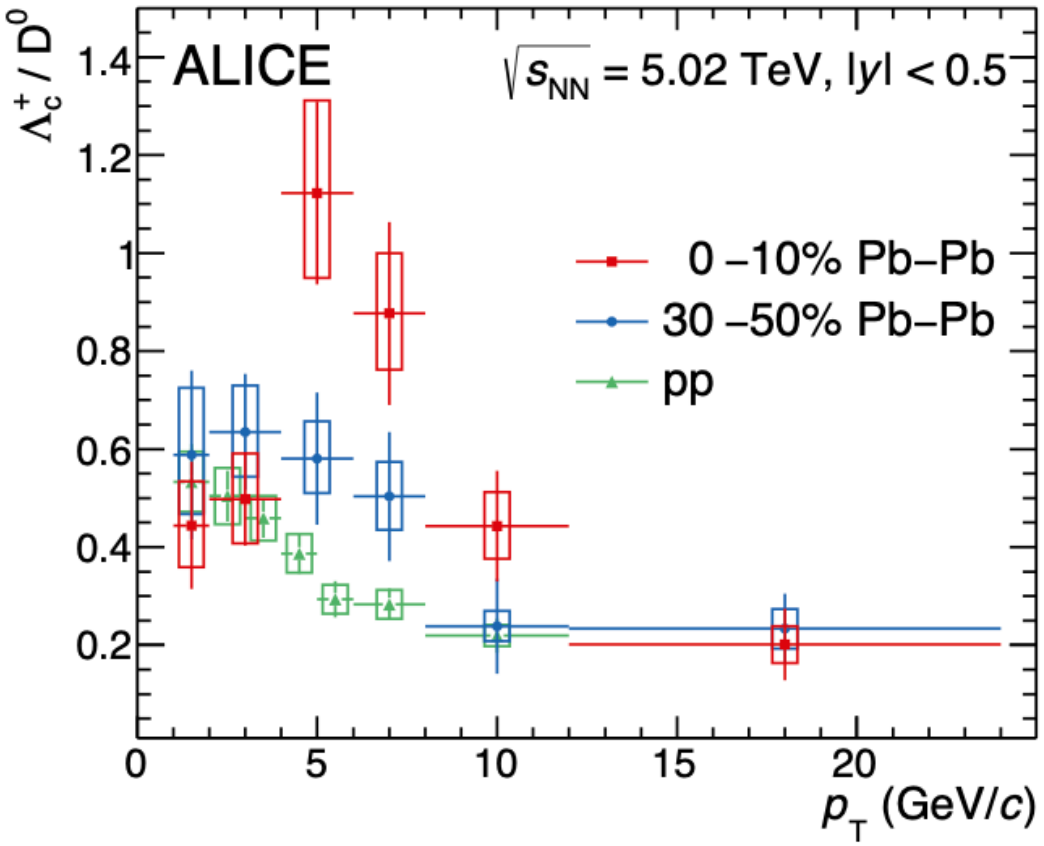



$D_s^+ \to K^+K^-\pi^+$

# $\Lambda_c^+/D^0$ ratios in peripheral 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. $\Lambda_c^+/D^0$ ratio is an excellent tool to study coalescence contribution.
- Recently, ALICE has measured $\Lambda_c^+/D^0$ ratio in PbPb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV at mid-rapidity.

- The PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV data were taken in 2018 with luminosity ~210 $\mu b^{-1}$.
- Due to LHCb hardware limitations, $\Lambda_c^+$ and $D^0$ are measured in the centrality range of about 65–90%. But we can cover forward rapidity, $2 < y < 4.5$.



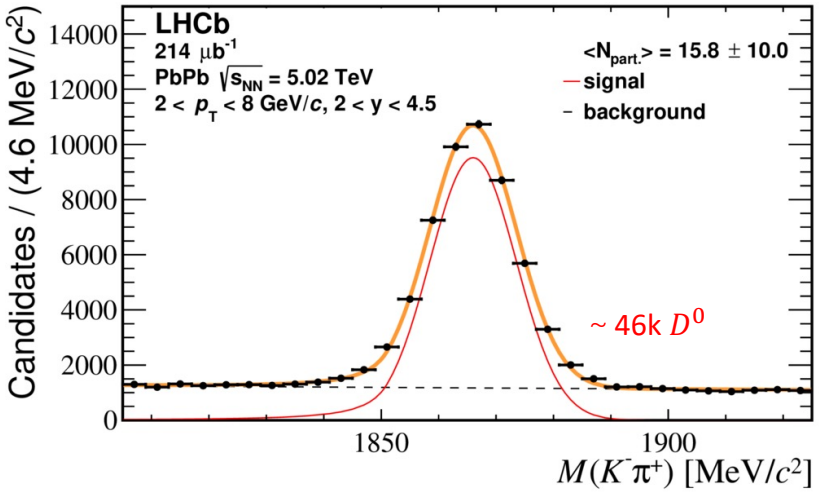

Phys.Lett.B 839 (2023) 137796

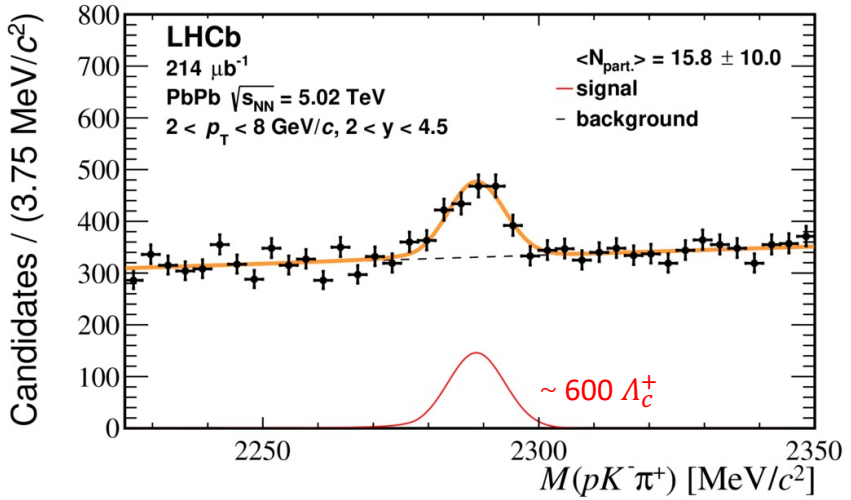


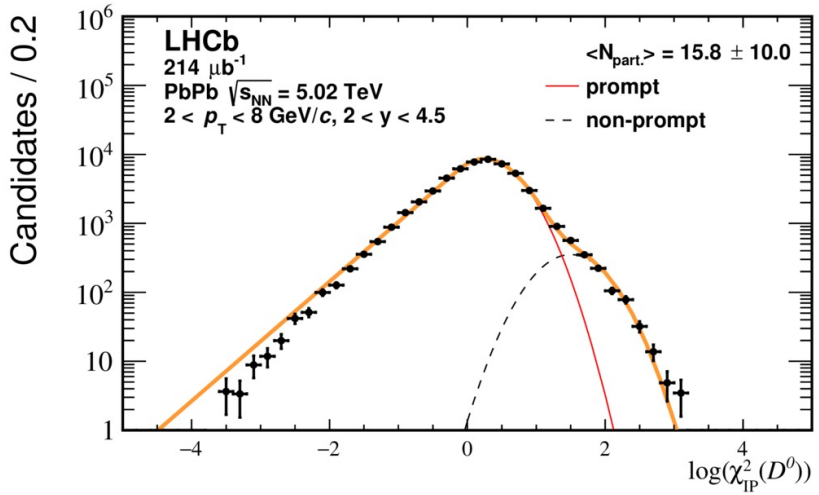
arXiv:2210.06939

# Signal extraction

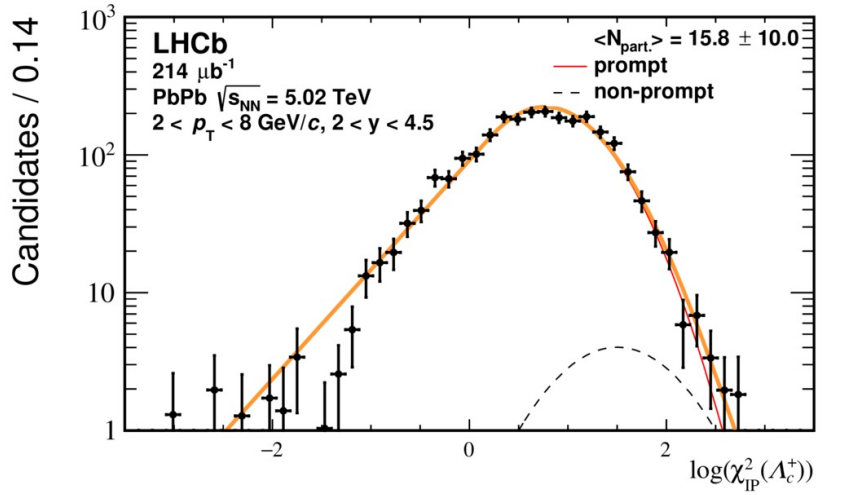
The inclusive signals and prompt signals are determined by invariant mass fitting and $\log(\chi^2_{\mathrm{IP}})$ fitting respectively.




$D^0 \to K^-\pi^+$ & c.c




$\Lambda_c^+ \to pK^+\pi^-$ & c.c

- The inclusive signals are extracted from invariant-mass spectra.
- Fit model: Crystal Ball function + first-order polynomial function

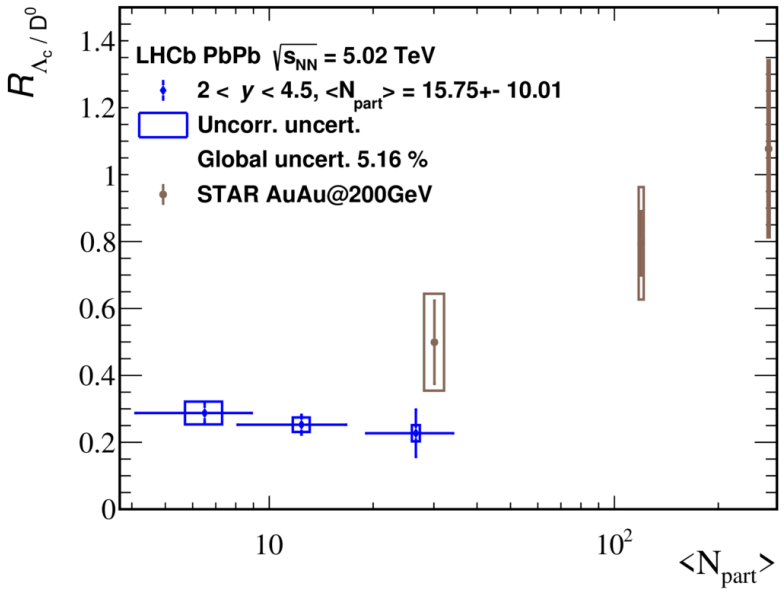
- The prompt signal are extracted from $\log(\chi^2_{\mathrm{IP}})$ distribution.
- Fit model: Crystal Ball function + Gaussian function

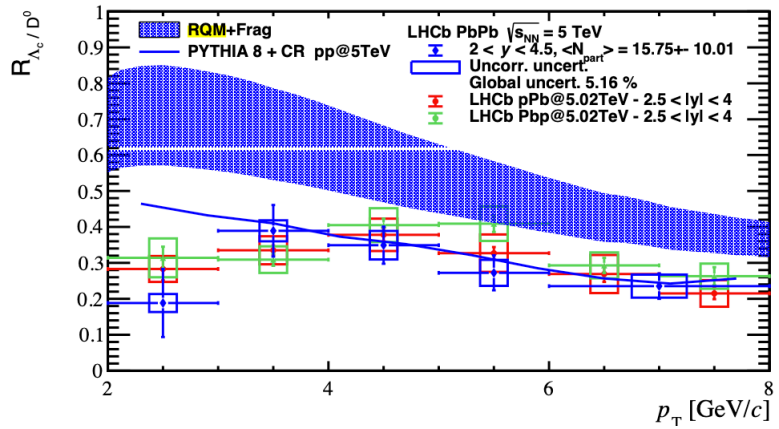


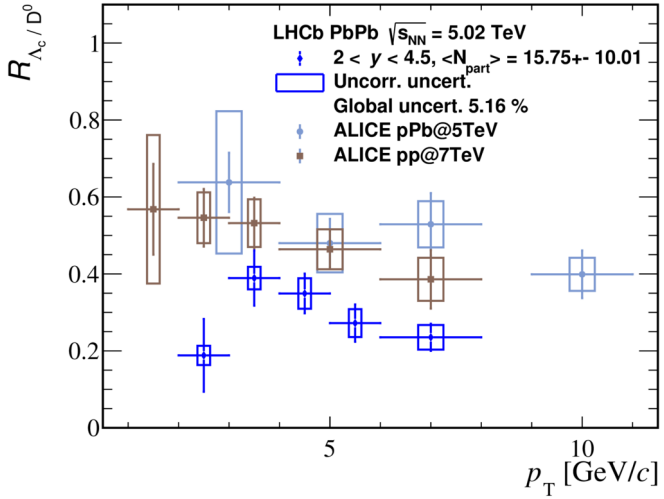
arXiv:2210.06939

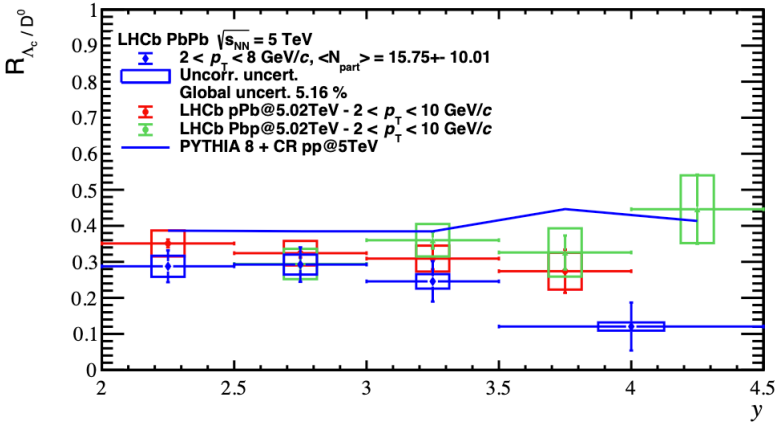
# $\Lambda_c^+/D^0$ ratio in peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

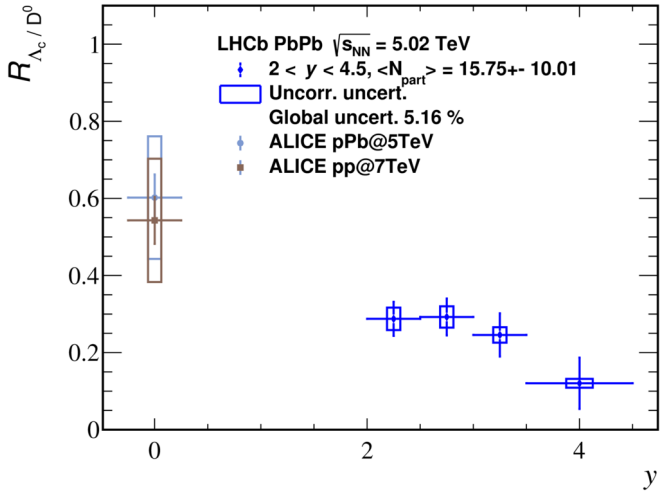
- $\Lambda_c^+/D^0$ ratios show no dependence on centrality.
- $\Lambda_c^+/D^0$ ratios are consistent with the LHCb results in $p$Pb at 5.02 TeV.
- $\Lambda_c^+/D^0$ ratios are systematically lower than ALICE result, but with higher precision.




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

arXiv:2210.06939

# Summary

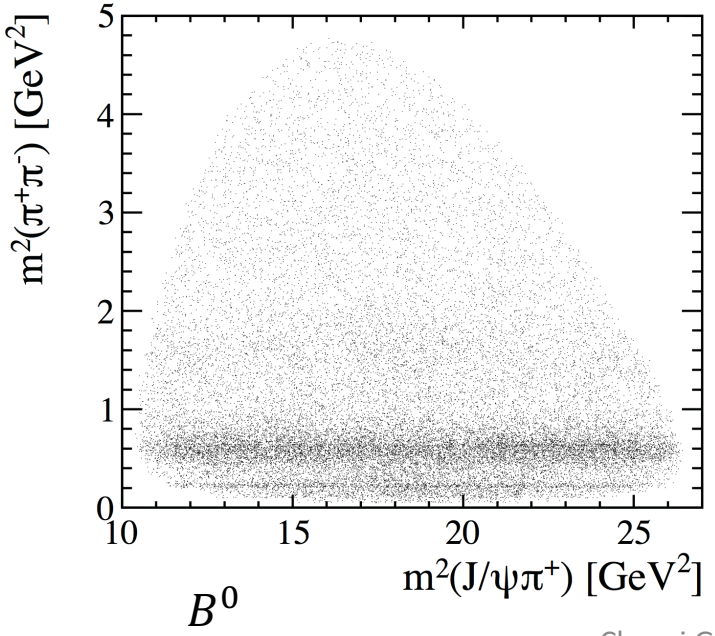
- In $pp$ collisons, the $B_s^0/B^0$ enhancement is observed at low $p_{\mathrm{T}}$ and consistent with our expected coalescence mechanism qualitatively. The ratios has no significant dependence on backwards multiplicity, indicate that the mechanism responsible for the ratio increase is related to the local particle density.
- In $p$Pb collisons, the $D_s^+/D^+$ ratios shows no dependence on $p_{\mathrm{T}}$, but higher $D_s^+/D^+$ ratios for backward compared to forward may be due to coalescence contribution.
- In peripheral PbPb collisions, $\Lambda_c^+/D^0$ ratios show no dependence on multiplicity and consistent with the LHCb results in $p$Pb collisions, The results are systematically lower than ALICE results, it may be due to different coalescence contribution in different rapidity range.

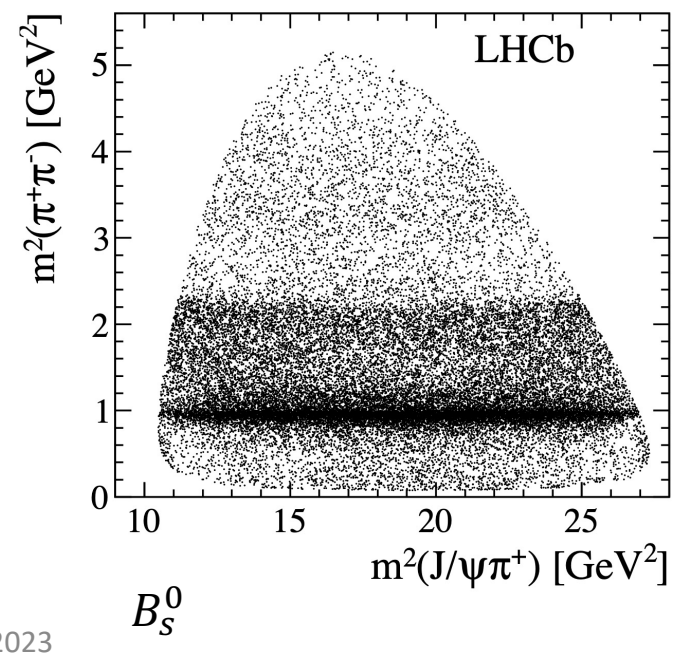
# Thanks for listening!

# Efficiencies

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

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

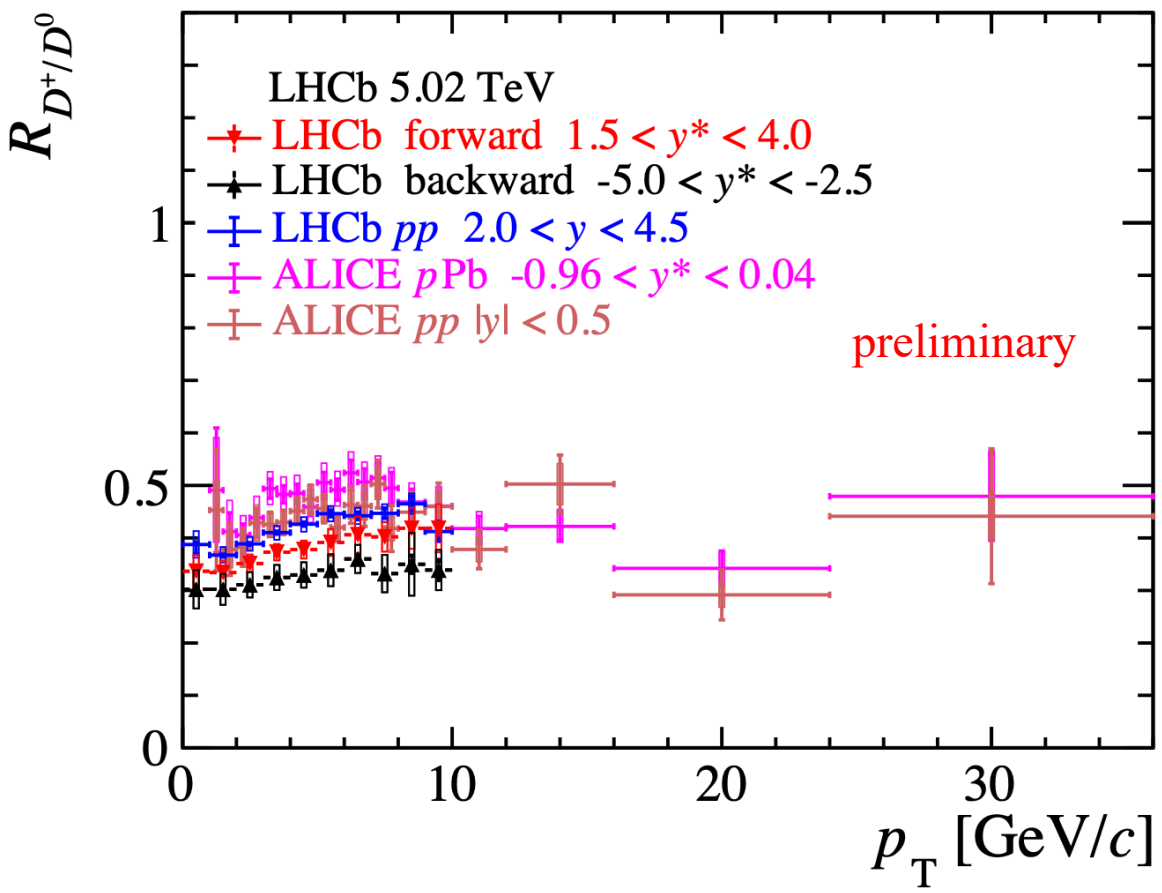


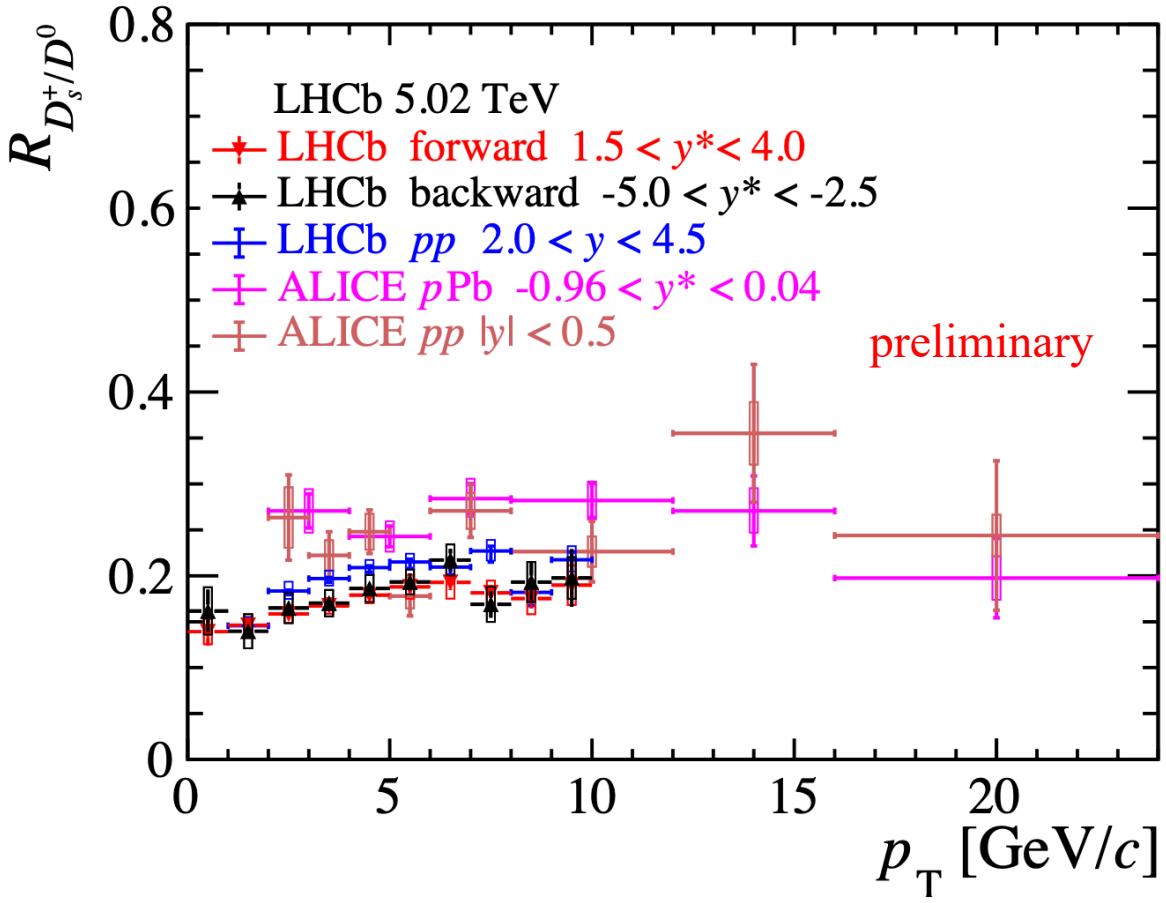




Phys. Rev. D89 (2014) 092006
Phys. Rev. D90 (2014) 012003

# $D_s^+/D^+$ 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Just $D^+$ fell down?