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

Strangeness production in *pp* and *p*Pb collisions

Clara Landesa Gómez
on behalf of the LHCb collaboration

LHCb

IGFAE
Instituto Galego de Física de Altas Enerxías
USC Universidade de Santiago de Compostela
XUNTA DE GALICIA
EXCELENCIA MARÍA DE MAEZTU
CENTROS CIGUS
Cofinanciado por la Unión Europea
Fondos Europeos

Outline

1. The LHCb experiment. Data samples.
2. Heavy strange hadrons in small systems.
3. Recent LHCb results.

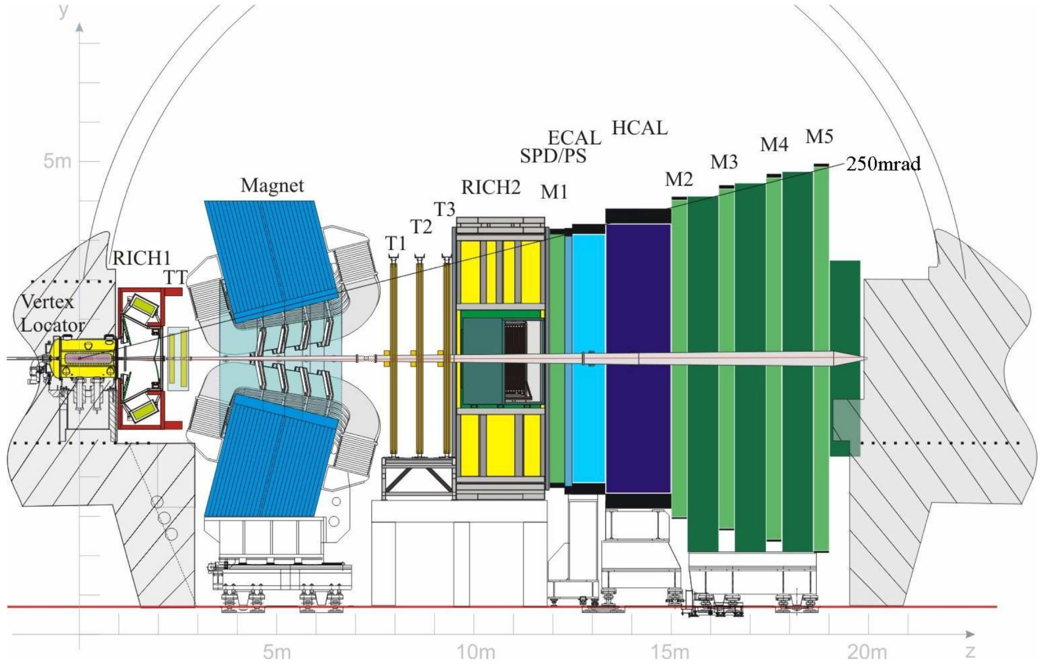
   Measuring system size. Multiplicity proxies.

   - B_s^0/B^0 ratio with multiplicity in pp collisions at 13 TeV .... Phys. Rev. Lett. 131 (2023) 061901
   - $D_s^+/\ D^{+/0}$ratio in pPb collisions at 5 TeV .... JHEP 01 (2024) 070
   - D_s^+/D^+ ratio in pPb collisions at 8 TeV .... arXiv:2311.08490 NEW!
   - Ξ_c^+/Λ_c^+ ratio in pPb at 8 TeV .... Phys. Rev. C 109 (2024) 044901
4. Conclusion and prospects.

The LHCb experiment.

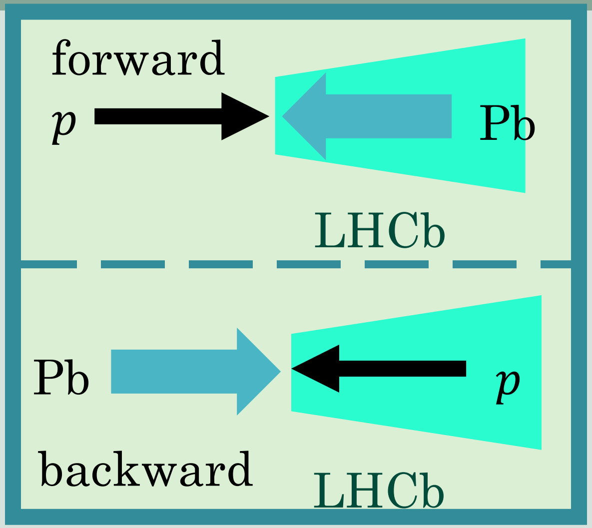
- From heavy flavour physics to general-purpose detector in the forward region.
- Fully instrumented forward detector $2<\eta<5$.
- Excellent tracking, momentum resolution and particle identification.

JINST 3 (2008) S08005

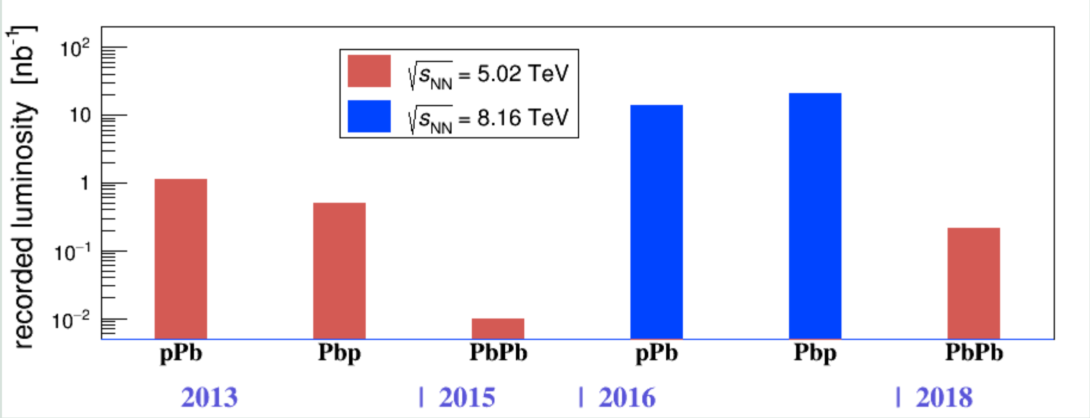


Data samples.

- The results in this presentation are from *small collision systems*.
- pp collisions $\sqrt{s} = 13$ TeV, $\int \mathcal{L}\, dt = 5.4\ \text{fb}^{-1}$
- pPb collisions at $\sqrt{s_{NN}} = 5$ TeV
  - Forward $\int \mathcal{L}\, dt = 1.06\ \text{nb}^{-1}$
  - Backward $\int \mathcal{L}\, dt = 0.52\ \text{nb}^{-1}$
- pPb collisions at $\sqrt{s_{NN}} = 8$ TeV
  - Forward $\int \mathcal{L}\, dt = 12.18\ \text{nb}^{-1}$
  - Backward $\int \mathcal{L}\, dt = 18.57\ \text{nb}^{-1}$



$$y_{\text{lab}} - y^* \approx 0.5 \times \log\left(\frac{A}{Z}\right) = 0.465$$



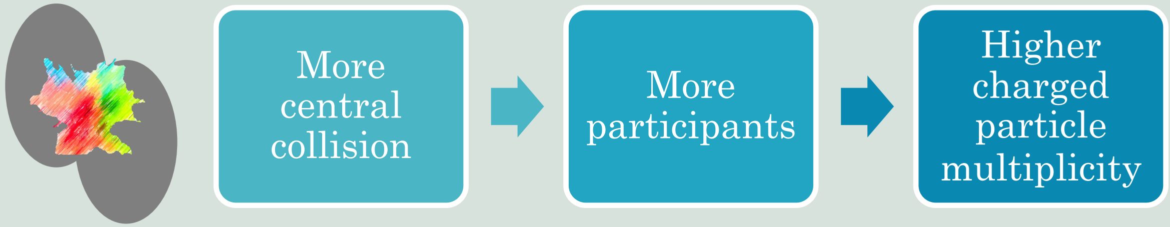
Heavy strange hadrons in small systems.

- Why heavy strange hadrons?
  - Because of their **strangeness** content.
  - Because they offer unique probes of the **hadronization mechanism**.

Heavy strange hadrons in small systems.

Strangeness as a QGP signature

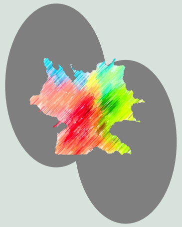
- In PbPb collisions, the enhancement of strange hadrons in high multiplicity (low centrality) events was originally postulated as a QGP signature.

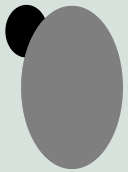


Heavy strange hadrons in small systems.

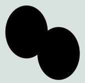
Strangeness as a QGP signature

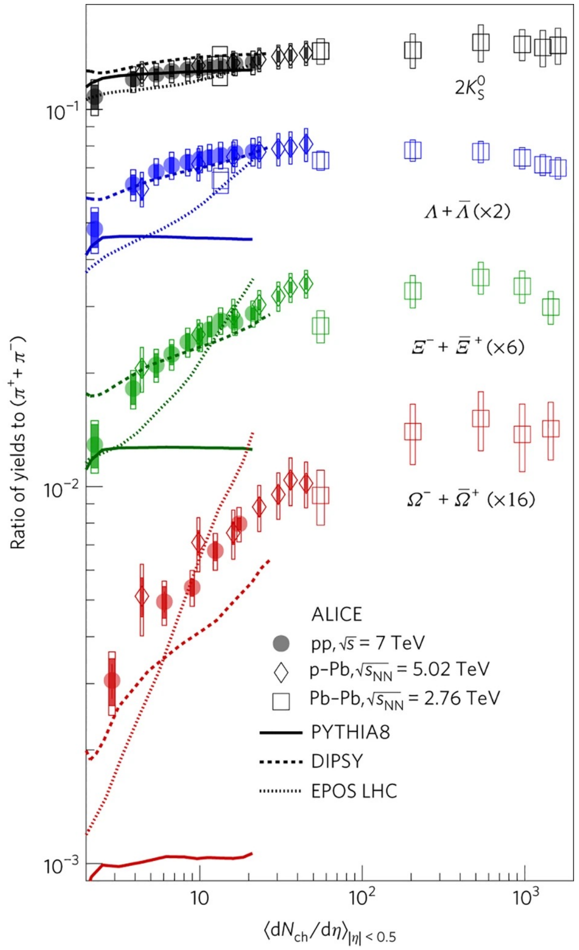
- In PbPb collisions, the enhancement of strange hadrons in high multiplicity (low centrality) events was originally postulated as a QGP signature.





- Recent findings show universal strangeness enhancement with the event charged particle multiplicity in *small systems*.



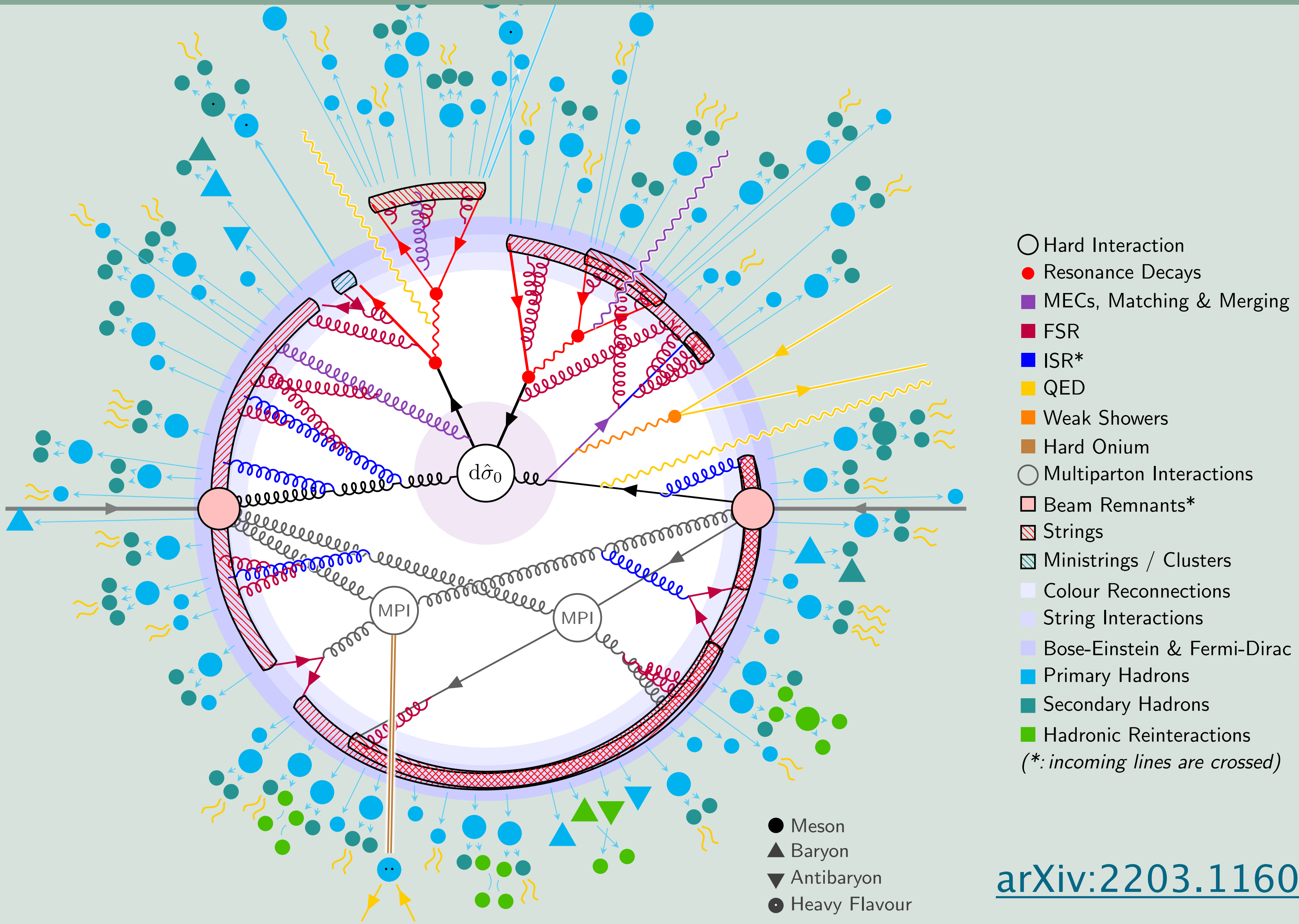


Nature Phys 13, 535-539 (2017)

Heavy strange hadrons in small systems.

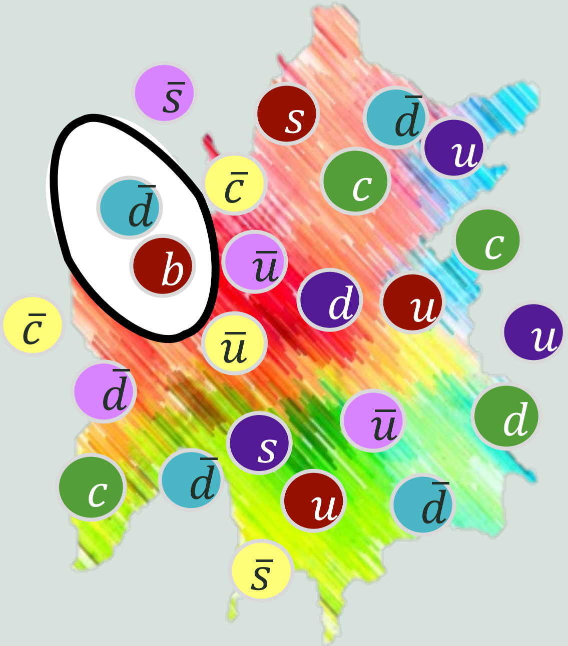
- The hadronization mechanism reflects the properties of the hadronic matter.

  Fragmentation: Showers produced by outgoing partons form into hadrons.

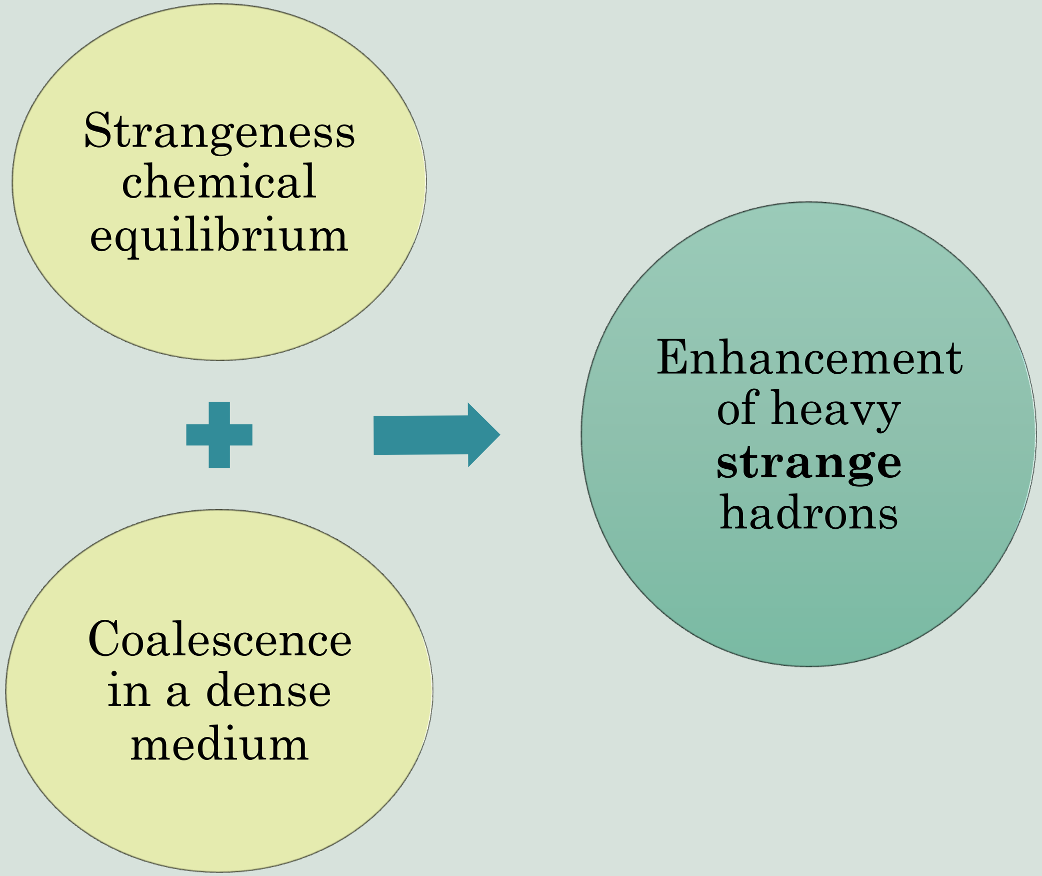


arXiv:2203.11601

- The hadronization mechanism reflects the properties of the hadronic matter.
  - **Fragmentation**: Showers produced by outgoing partons form into hadrons.
  - **Coalescence**: Readily available quarks combine to form colour singlets. Requires multiple quark wavefunctions to overlap in position and velocity.



Heavy strange hadrons in small systems.



Recent LHCb results.

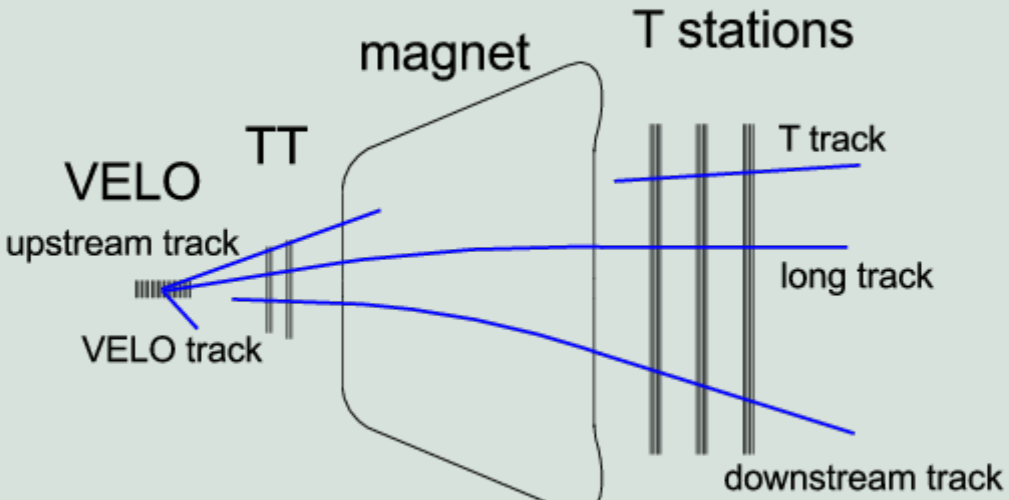
- We present recent LHCb measurements of strange hadrons in the heavy quark sector.
- We focus on the ratios of production of strange over non-strange particles, to study a potential enhancement of strange quarks.

$$R_{S/N} = \frac{\sigma_S}{\sigma_N}$$

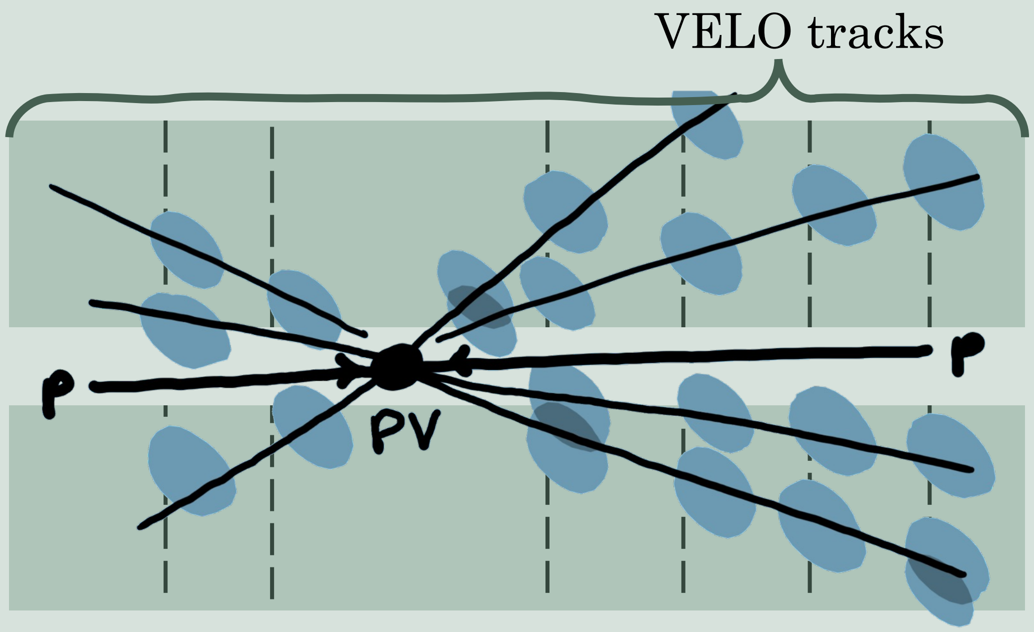
- Some results are presented as a function of the event charged particle multiplicity.

Measuring the system size. Multiplicity proxies.

- N_{tracks}^{VELO}: Total number of charged tracks reconstructed by the VELO detector.

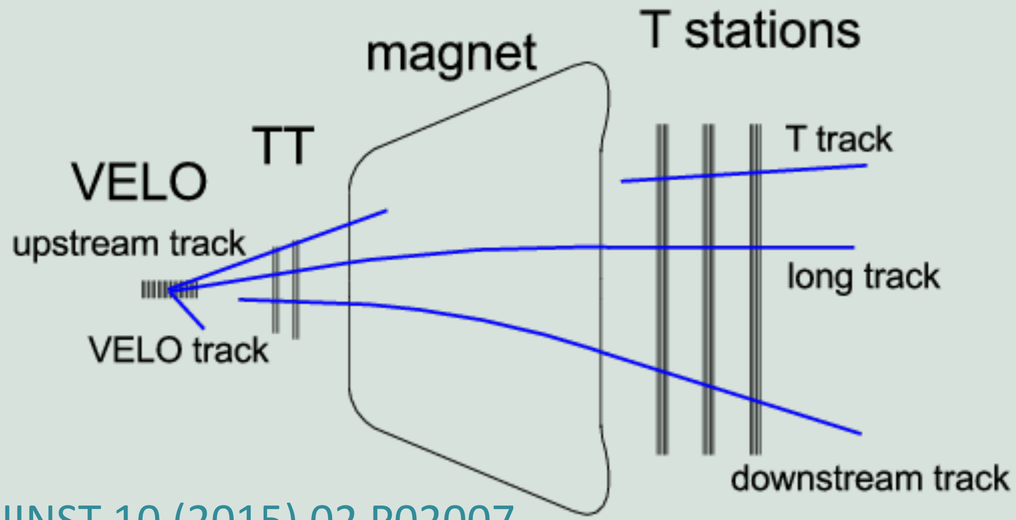


JINST 10 (2015) 02 P02007

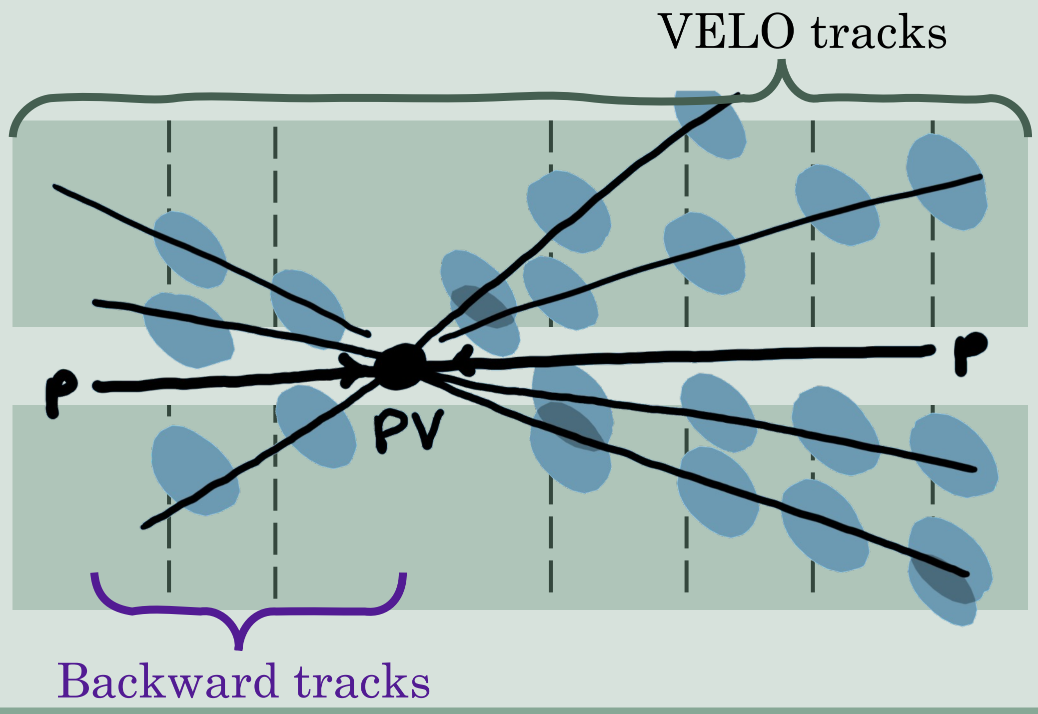


Measuring the system size. Multiplicity proxies.

- $N_{\text{tracks}}^{\text{VELO}}$: Total number of charged tracks reconstructed by the VELO detector.
- $N_{\text{tracks}}^{\text{back}}$: Subset of VELO tracks that point in the backward direction, away from LHCb $(-3.5 < \eta < -1.5)$.

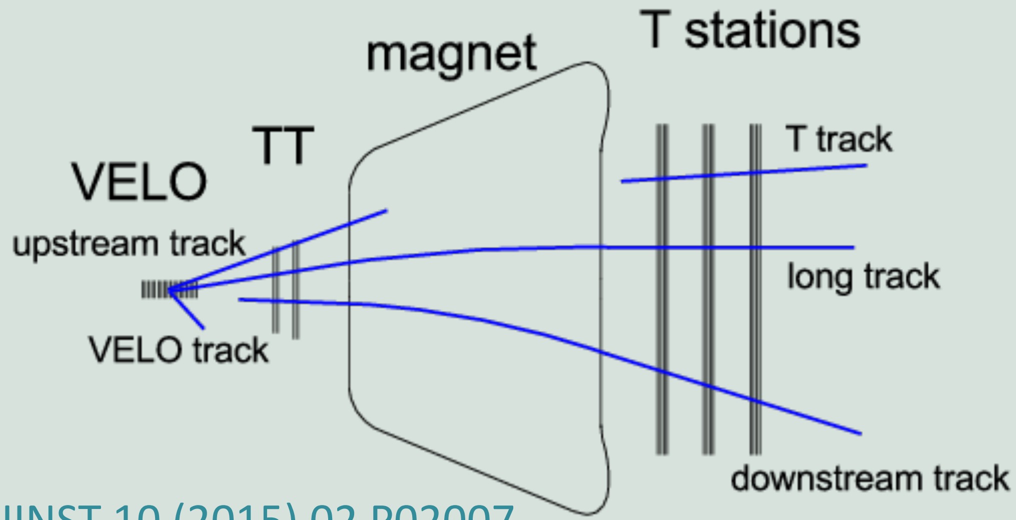


[JINST 10 (2015) 02 P02007]

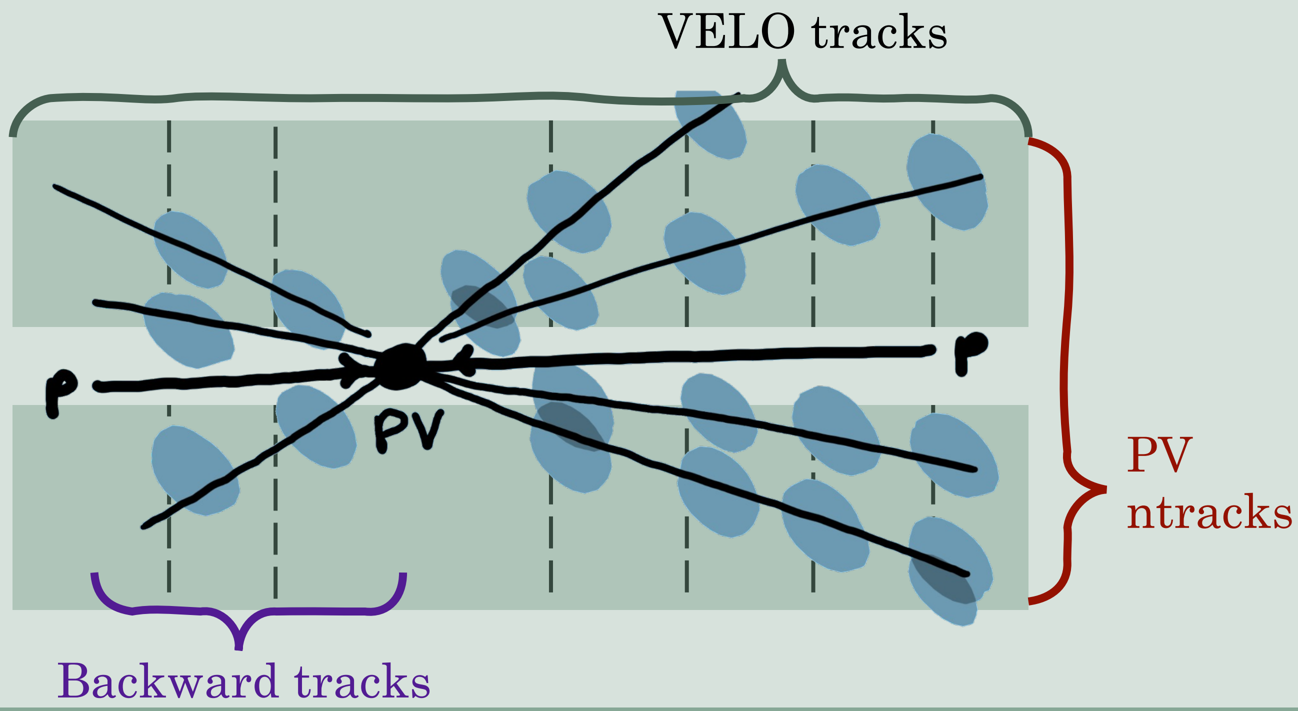


Measuring the system size. Multiplicity proxies.

- $N_{\text{tracks}}^{\text{VELO}}$: Total number of charged tracks reconstructed by the VELO detector.
- $N_{\text{tracks}}^{\text{back}}$: Subset of VELO tracks that point in the backward direction, away from LHCb $(-3.5 < \eta < -1.5)$.
- $N_{\text{tracks}}^{\text{PV}}$: VELO tracks used to reconstruct the primary vertex.

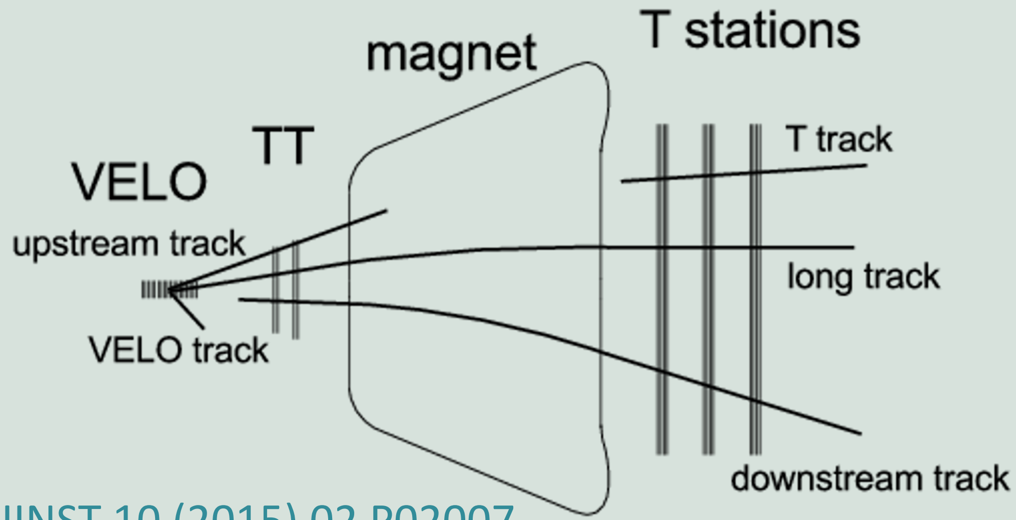


JINST 10 (2015) 02 P02007

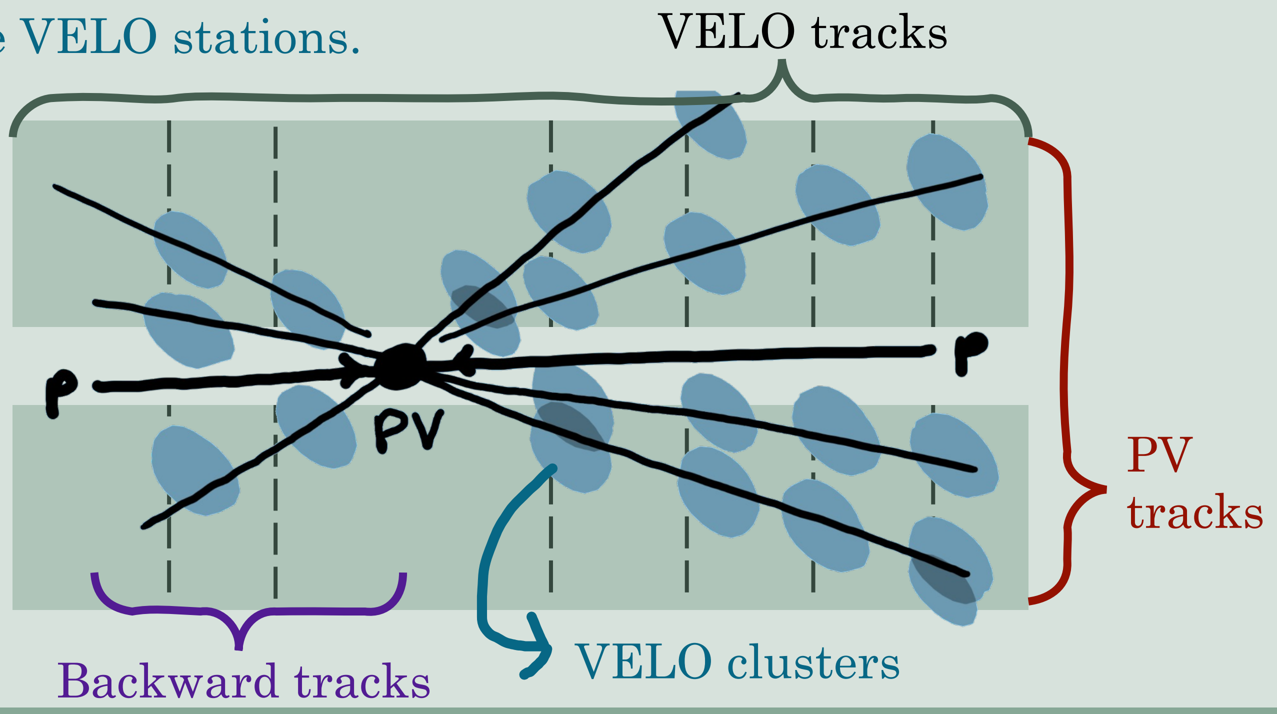


Measuring the system size. Multiplicity proxies.

- N_{tracks}^{VELO}: Total number of charged tracks reconstructed by the VELO detector.
- N_{tracks}^{back}: Subset of VELO tracks that point in the backward direction, away from LHCb ($-3.5 < \eta < -1.5$).
- N_{tracks}^{PV}: VELO tracks used to reconstruct the primary vertex.
- $N_{clusters}^{VELO}$: Number of energy clusters deposited in the VELO stations.



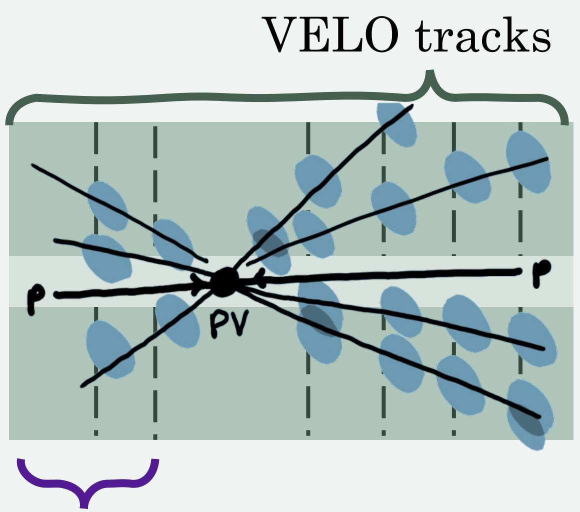
JINST 10 (2015) 02 P02007

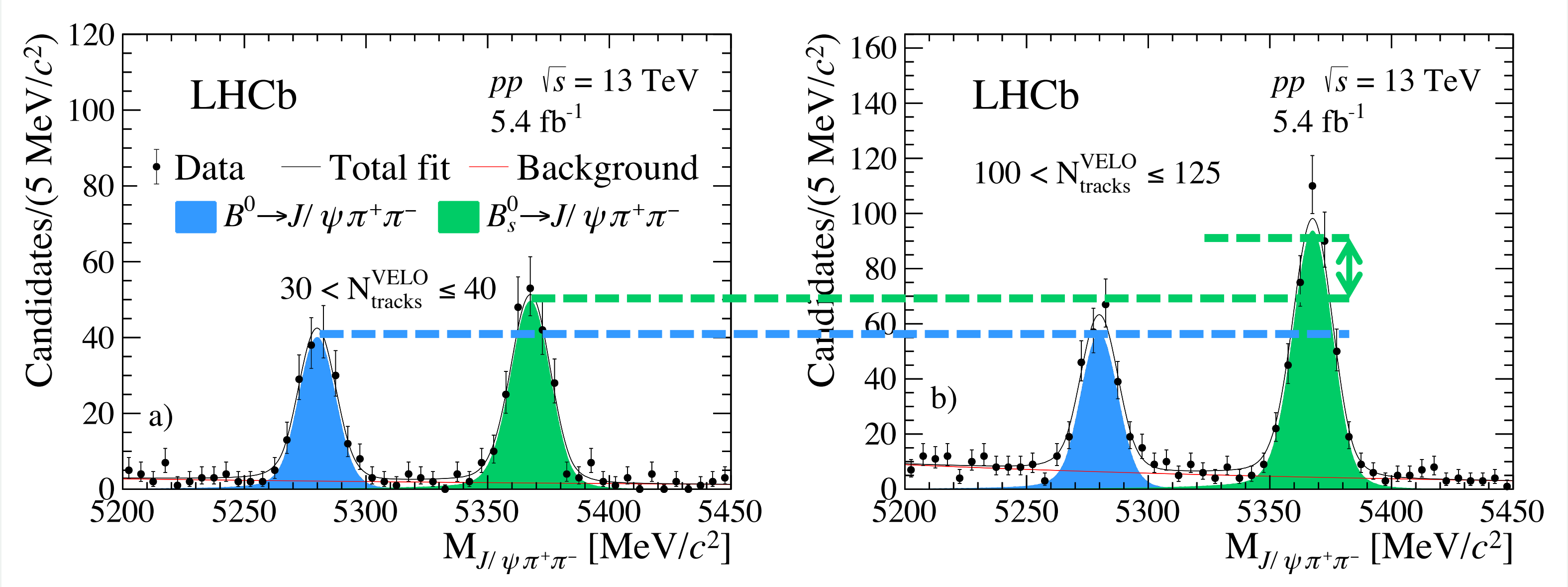


Phys. Rev. Lett. 131 (2023) 061901

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

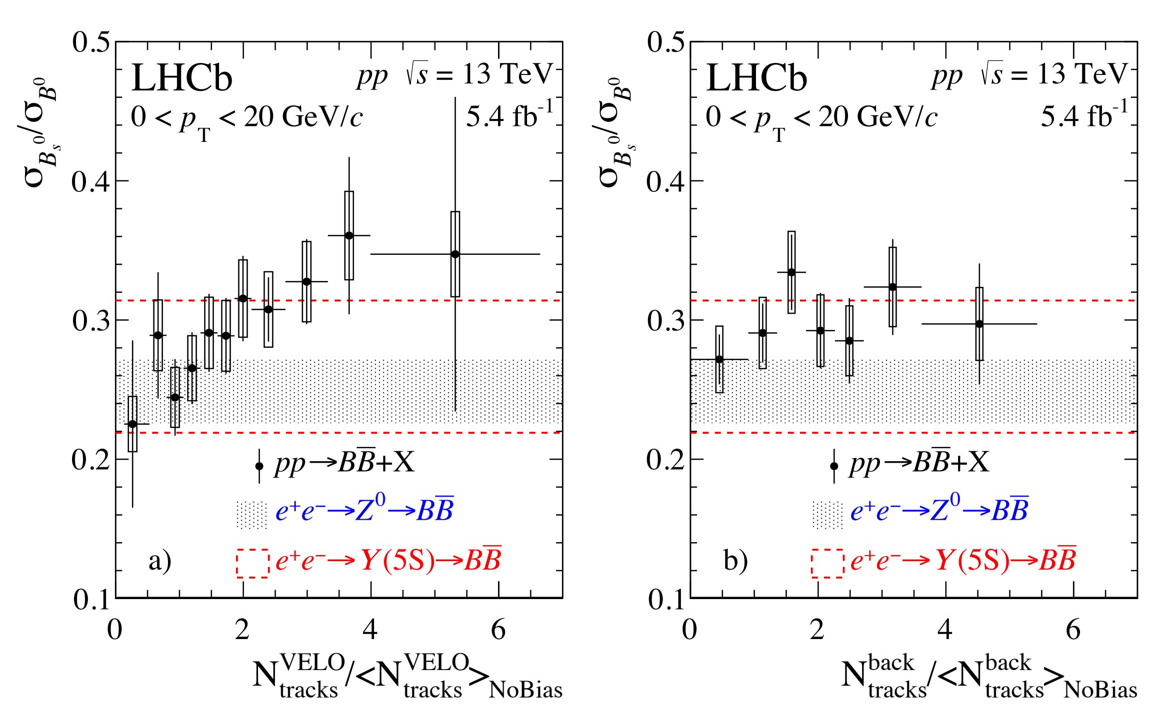
- $B^0_{(s)} \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\pi^+\pi^-$
- The multiplicity is estimated with N_{tracks}^{VELO} and N_{tracks}^{back}.





Apparent increase of the B_s^0 yield compared to B^0 with multiplicity

- Ratio enhancement observed with VELO tracks.
- No significant enhancement with backward tracks. This hints that the mechanism responsible for the increase in the ratio is related to the local particle density.
- Results coherent with e^+e^- measurements at low multiplicity.

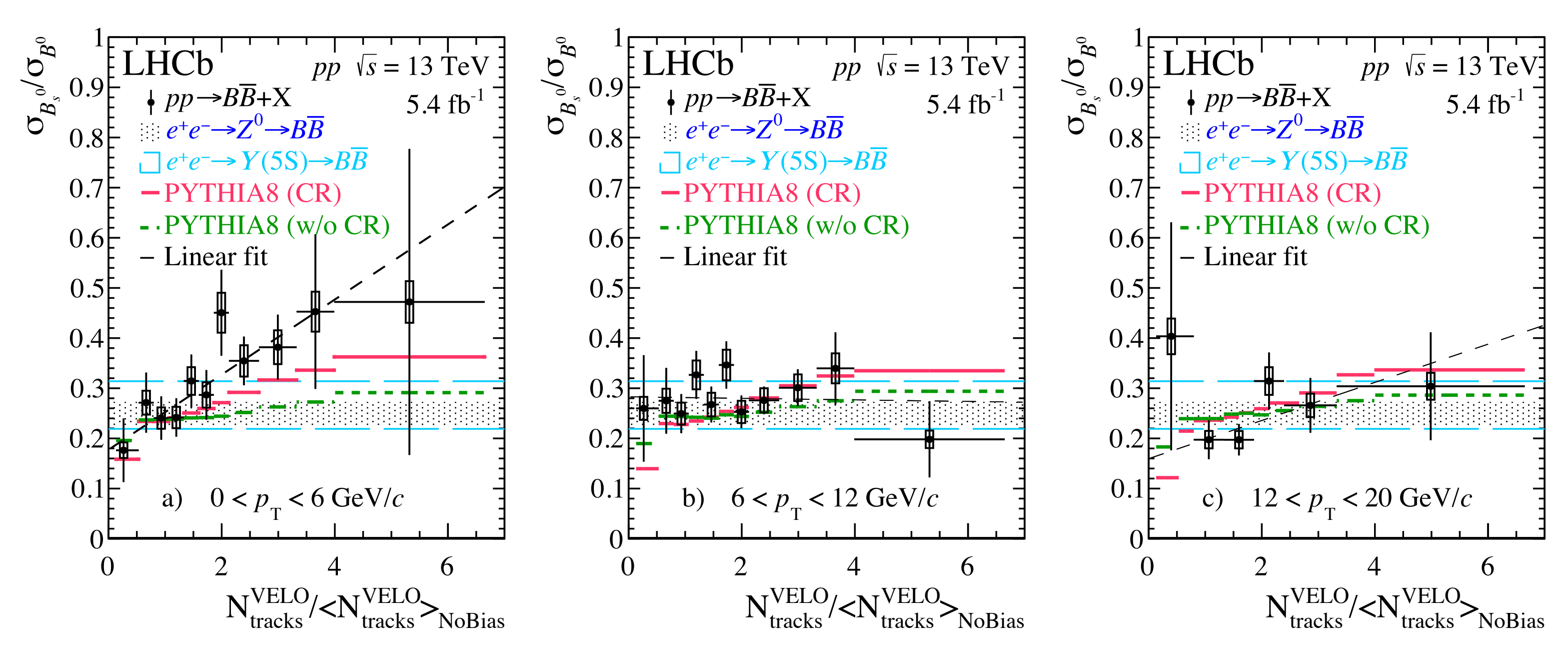


Results quoted in normalised multiplicity

B_s^0/B^0 ratio with multiplicity pp collisions at $\sqrt{s} = 13$ TeV Phys. Rev. Lett. 131 (2023) 061901

- Measurement in p_T bins.
- Ratio enhancement notable at $p_T < 6$ GeV/c

  Qualitatively compatible with coalescence.



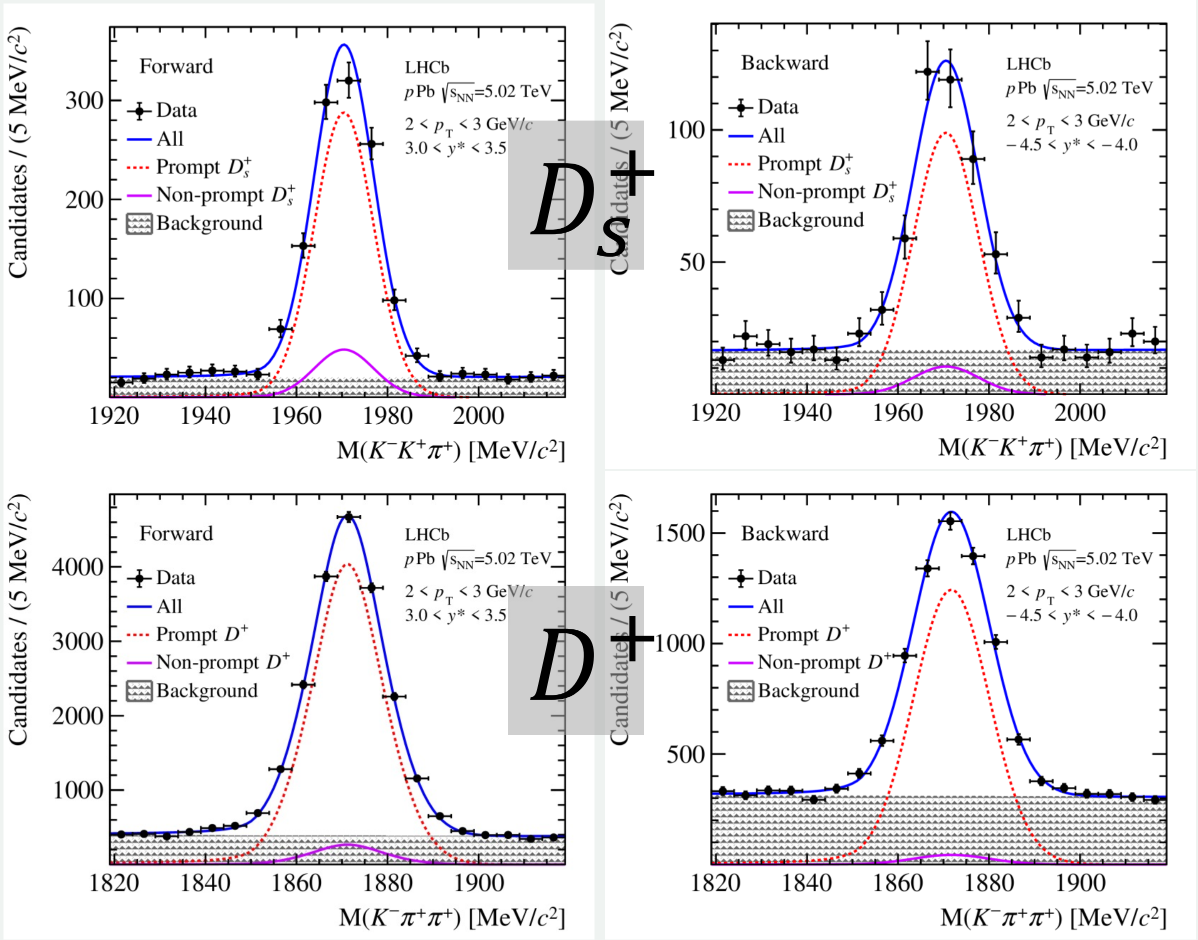
JHEP 01 (2024) 070

D_s^+/D^+ ratio
pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

$D_s^+ \to K^-K^+\pi^+$, BR= $(2.24 \pm 0.15)\%$

$D^+ \to K^-\pi^+\pi^+$, BR= $(9.38 \pm 0.15)\%$

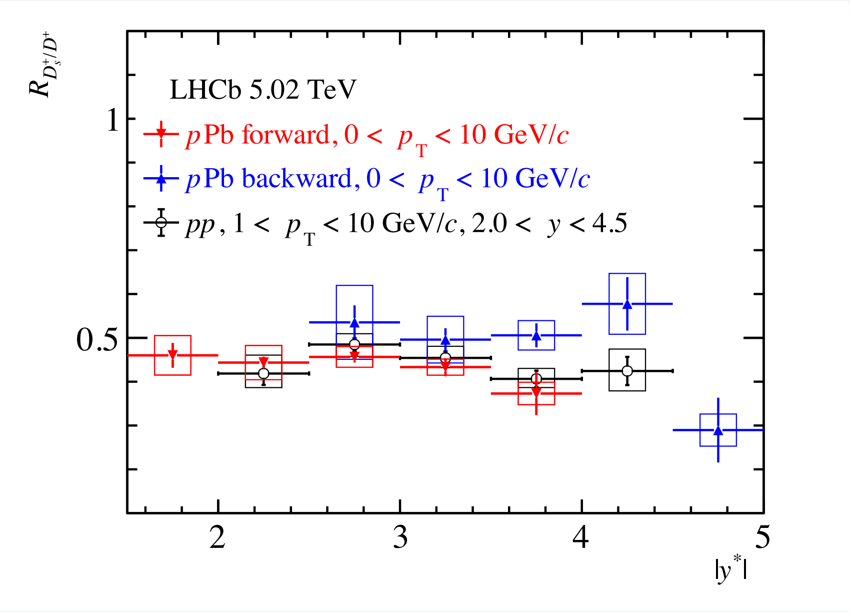
- The prompt contribution is selected by seeking candidates whose momentum points to the interaction vertex.

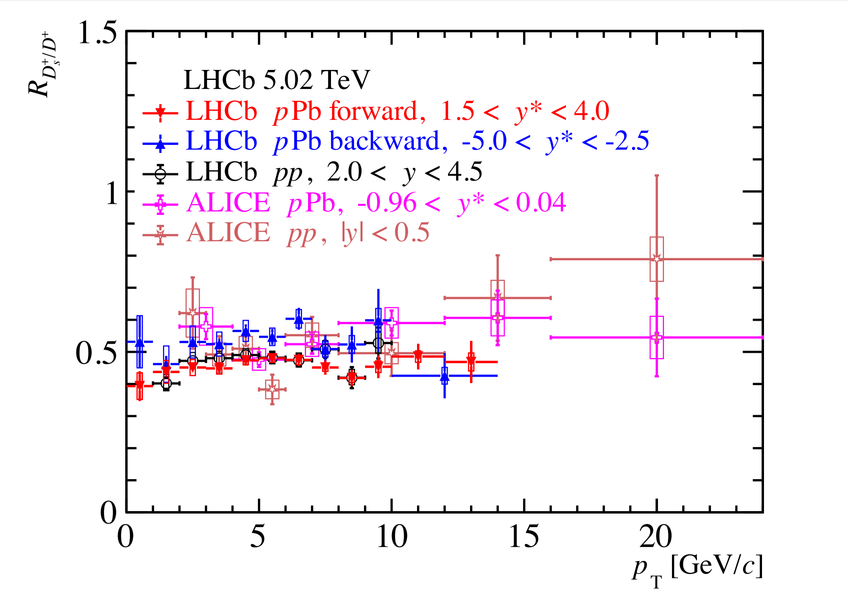


D_s^+/D^+ ratio pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

JHEP 01 (2024) 070

- No enhancement of the yield of strange hadrons at high transverse momentum or rapidity.
- Although not significantly, the ratio of D_s^+/D^+ for backward collisions is systematically above that of forward collisions.



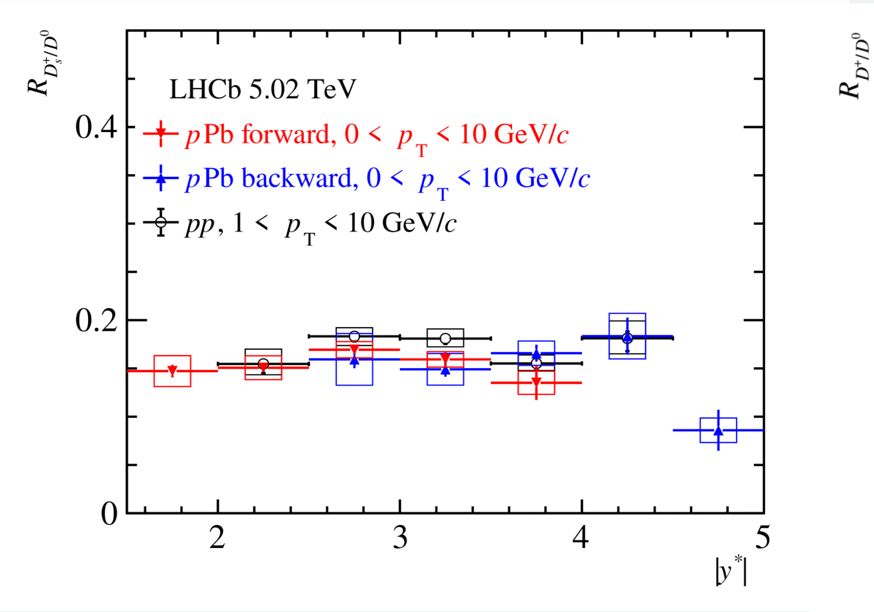


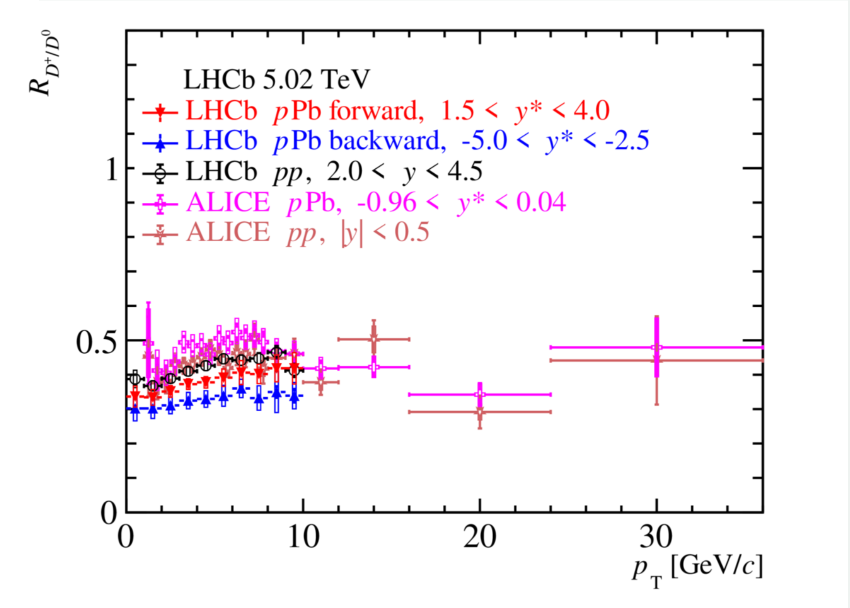
Backward collisions have on average ~1.6 times the multiplicity of forward collisions.

D_s^+/D^0 ratio
pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

[JHEP 01 (2024) 070]
[JHEP10(2017)090]

- No enhancement of the yield of strange hadrons at high transverse momentum or rapidity.
- In this case, the backward results are not systematically above the forward results.





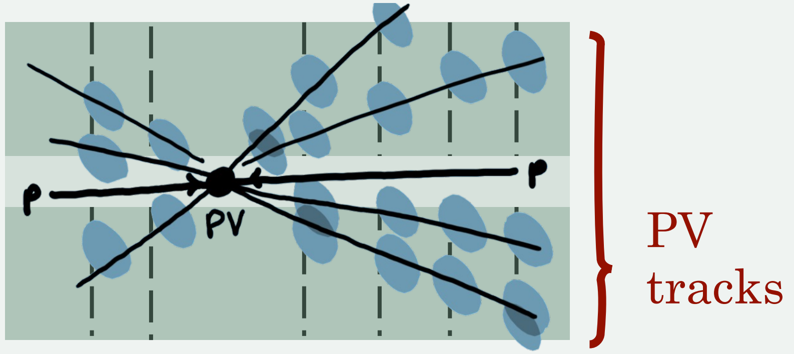
Backward collisions have on average ~1.6 times the multiplicity of forward collisions.

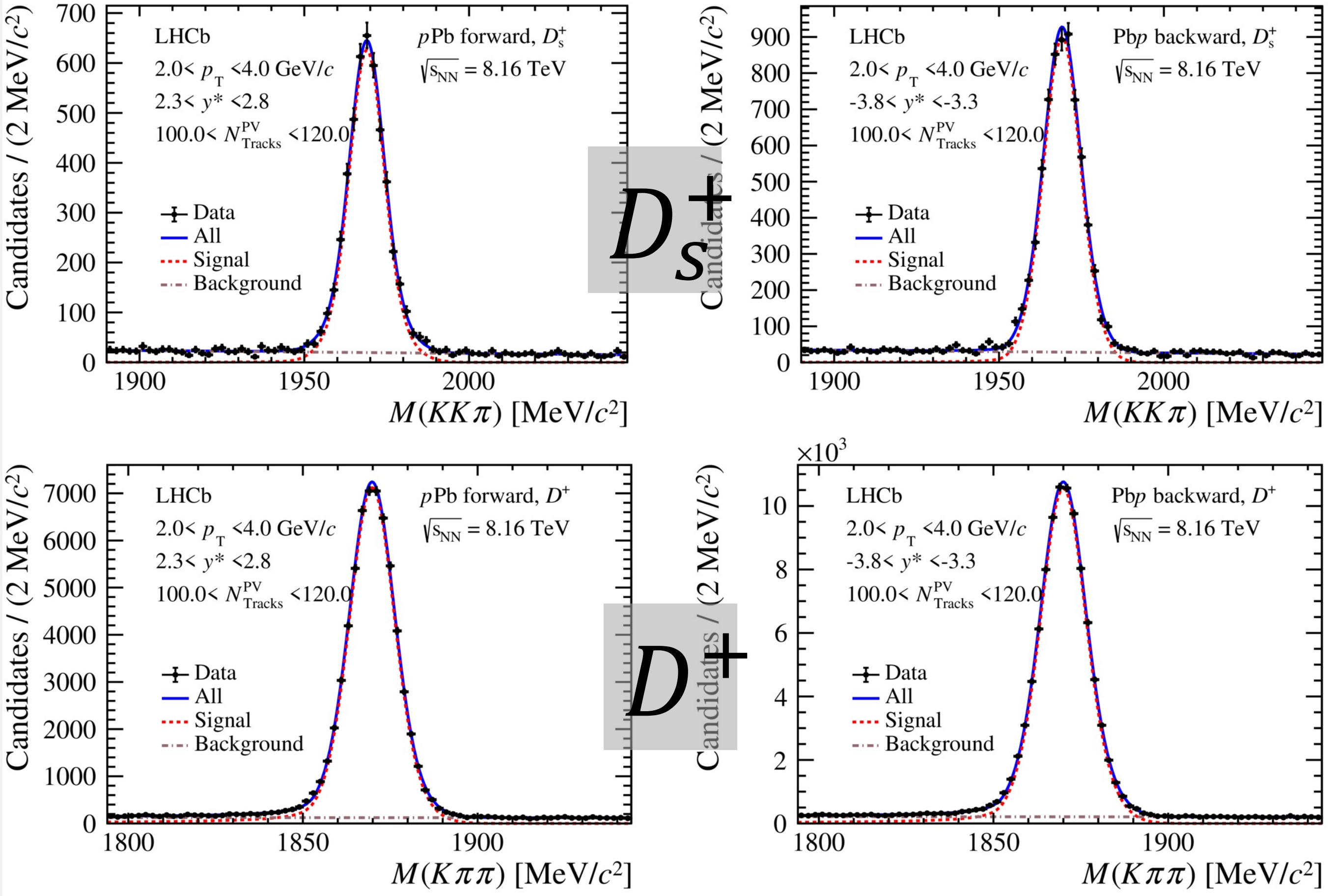
D_s^+/D^+ ratio
pPb collisions at $\sqrt{s_{NN}} = 8$ TeV

$D_s^+ \to K^- K^+ \pi^+$, BR= $(2.24 \pm 0.15)\%$

$D^+ \to K^- \pi^+ \pi^+$, BR= $(9.38 \pm 0.15)\%$

- The prompt contribution is selected.
- The multiplicity is estimated with $\mathrm{N^{PV}_{tracks}}$. $\mathrm{N_{ch}}$ is obtained in the forward region $(2 < \eta < 4.8)$ by applying corrections based on simulation.



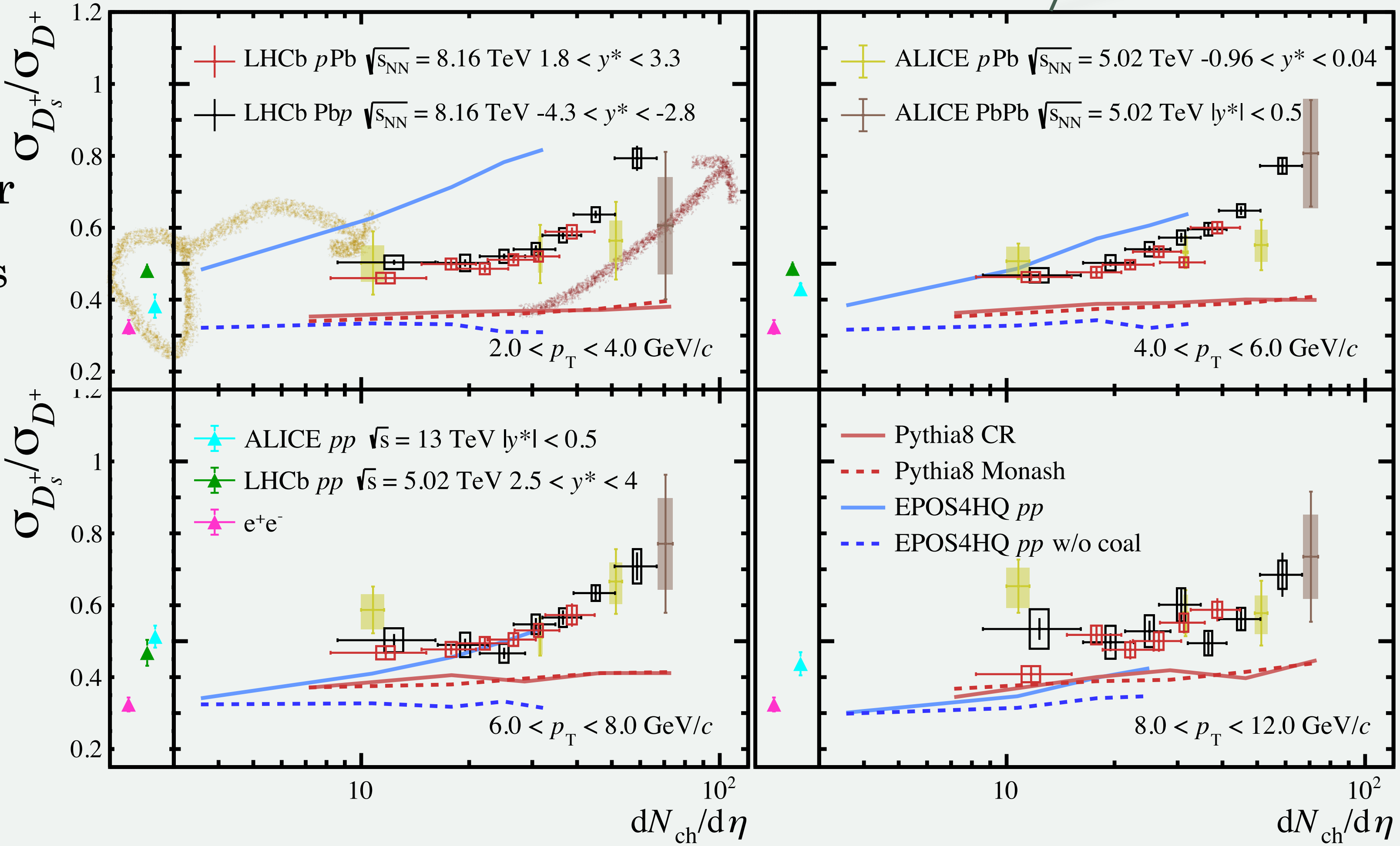


D_s^+/D^+ ratio pPb collisions at $\sqrt{s_{NN}} = 8$ TeV

arXiv:2311.08490 NEW!

$\sigma_{D_s^+}/\sigma_{D^+}$ has an increasing trend with $dN_{ch}/d\eta$ for all p_T intervals.

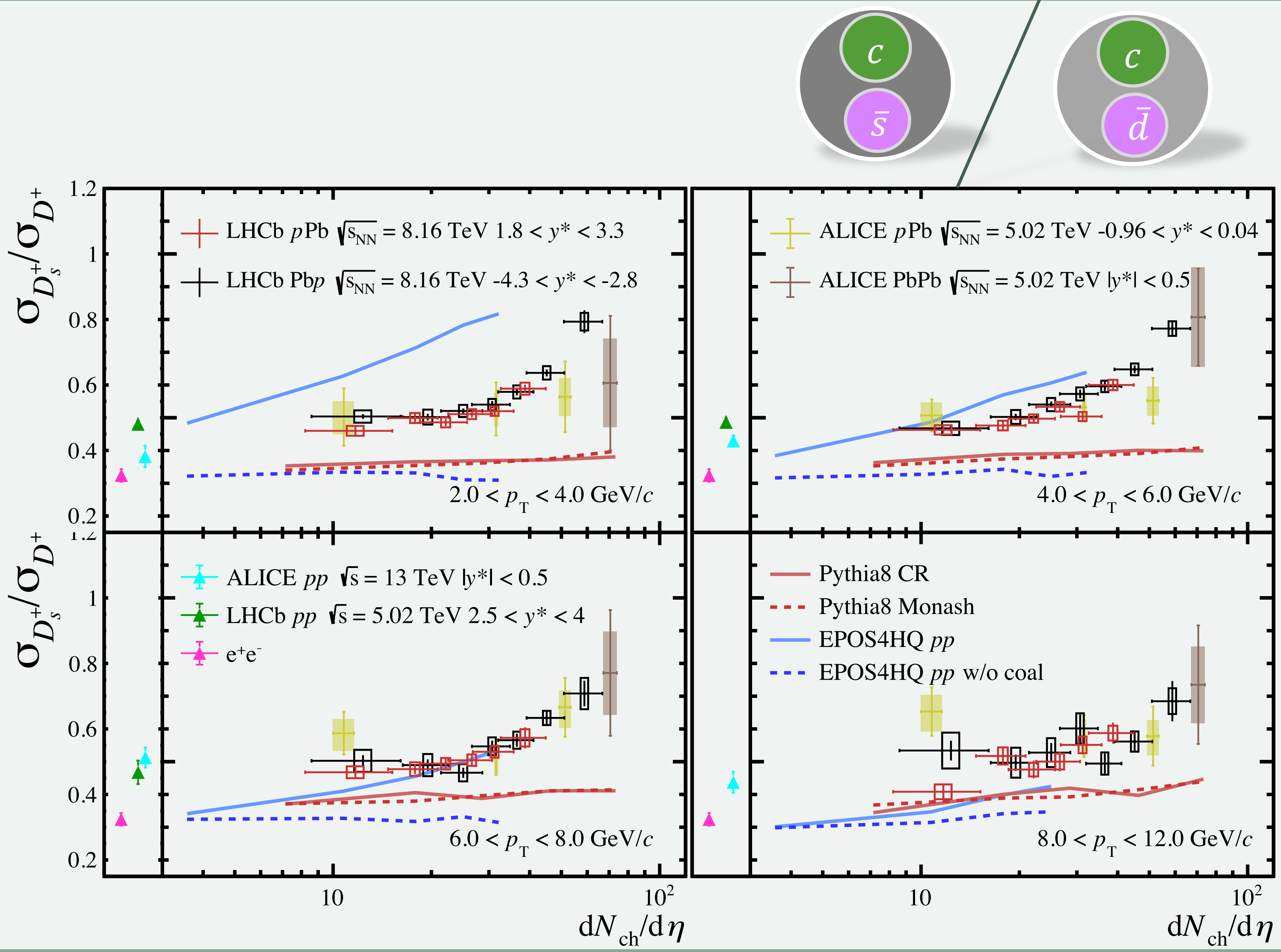
- At low multiplicity, the results resemble those of pp collisions.
- At high multiplicity, a behaviour similar to that of PbPb collisions if observed.
- The trend is similar for forward and backward rapidities.
- More enhancement at low p_T, which is qualitatively compatible with coalescence.



D_s^+/D^+ ratio pPb collisions at $\sqrt{s_{NN}} = 8$ TeV

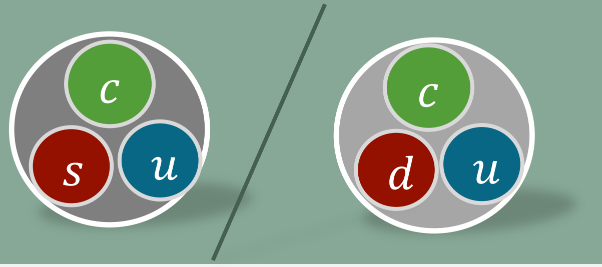
arXiv:2311.08490 NEW!

- All the predictions show some discrepancies with data.
- EPOS4HQ depicts the increasing trend across all p_{T} intervals when accounting for a coalescence hadronization mechanism.



Phys. Rev. C 109 (2024) 044901

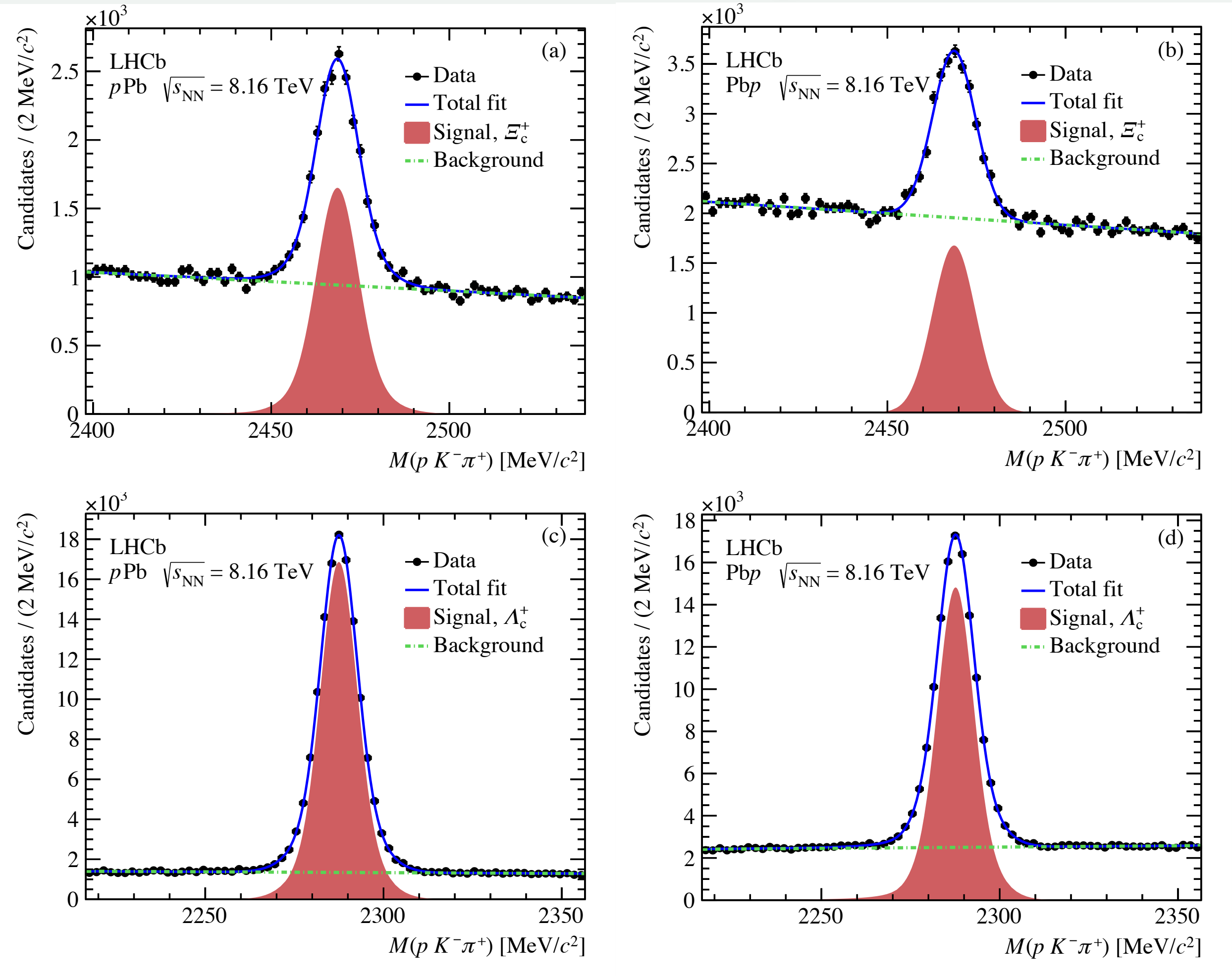
Ξ_c^+/Λ_c^+ ratio
pPb collisions at $\sqrt{s_{NN}} = 8$ TeV

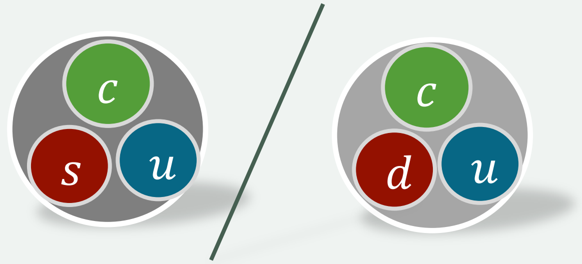


$\Xi_c^+ \to p^+K^-\pi^+$, BR = $(0.62 \pm 0.30)\%$

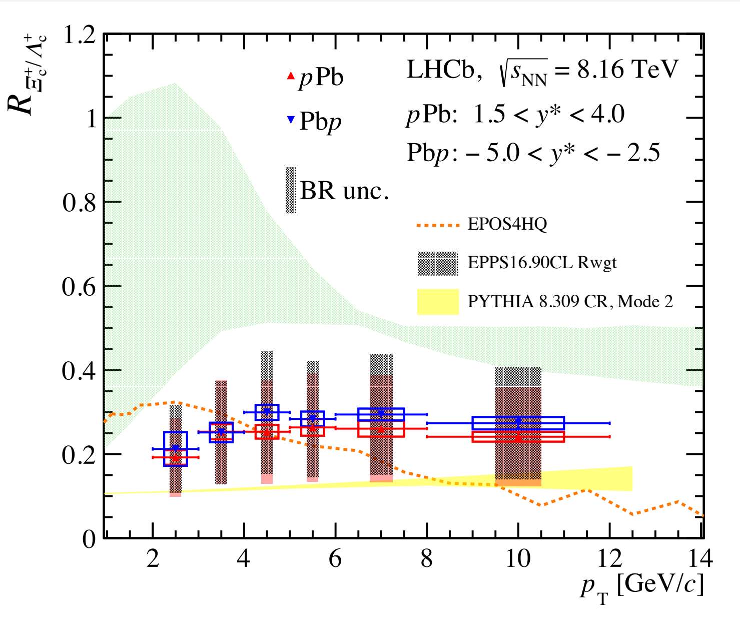
$\Lambda_c^+ \to p^+K^-\pi^+$, BR= $(6.28 \pm 0.32)\%$

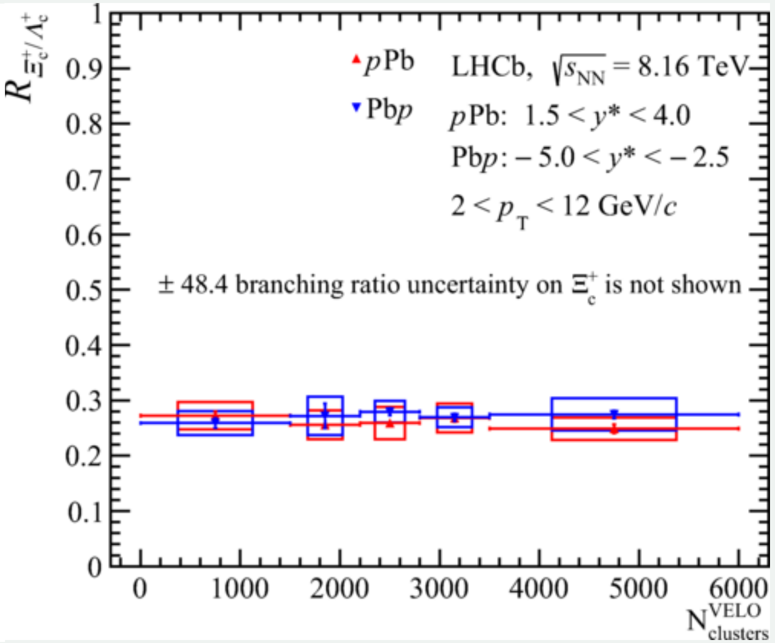
The prompt contribution is selected.

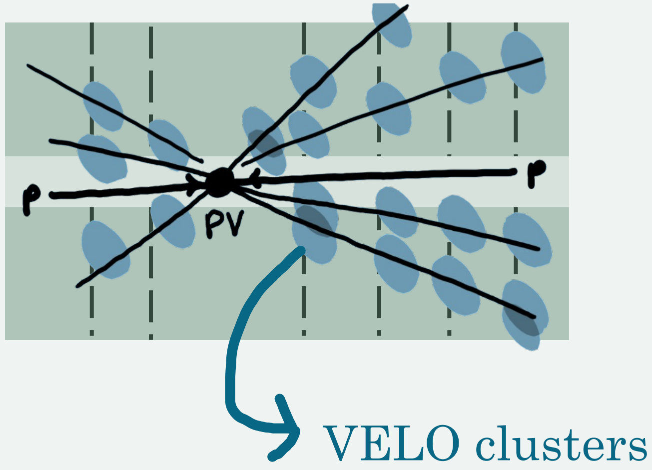




- The Ξ_c^+/Λ_c^+ ratio is roughly constant as a function of p_T and shows the same behaviour in forward and backward collisions.
- No enhancement is shown when studying the dependence with $N_{clusters}^{VELO}$.

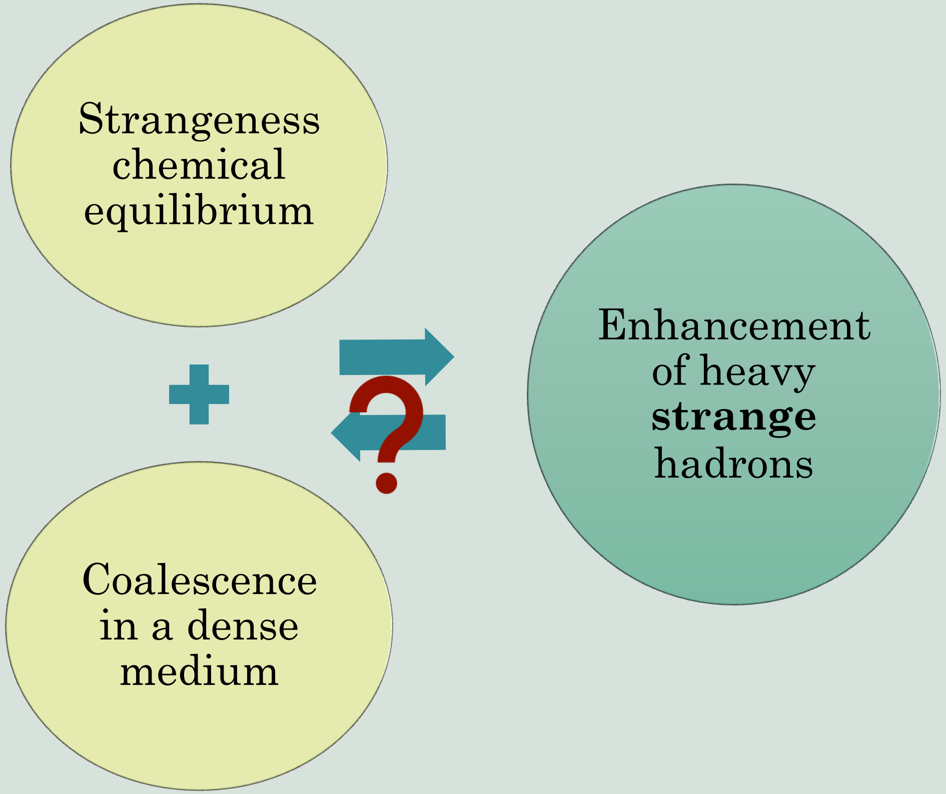






Prospects

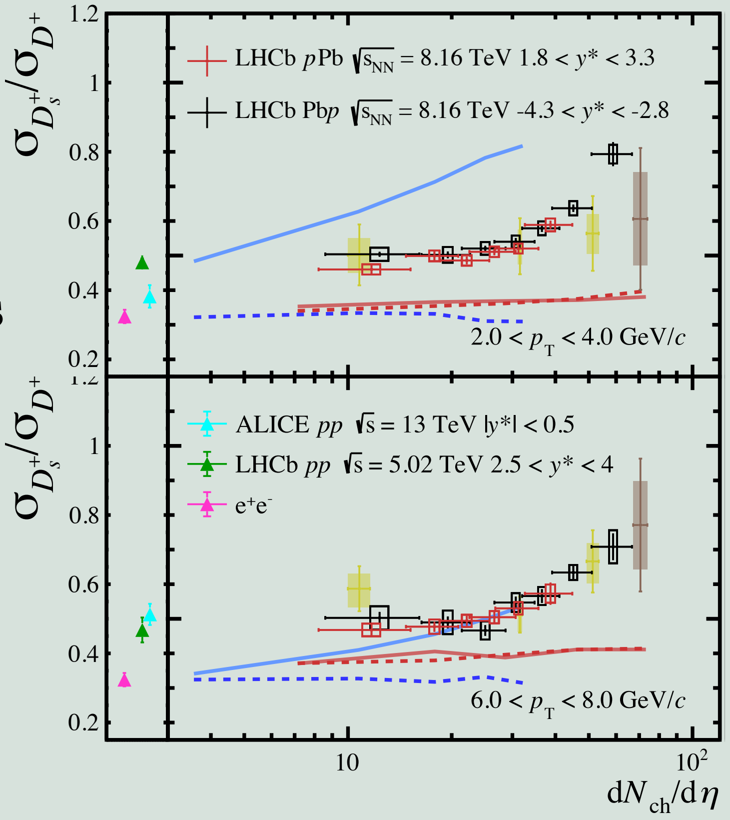
- Unifying multiplicity proxies among analyses may shed light over the interpretation of the results.
- Decorrelating the results from the multiplicity estimator to rule out local effects in charged particle multiplicity.
- Account for $D^{*\,0/+} \rightarrow D^{0/+} + X$ contribution to $D_s^+ / D^{+/0}$ ratios.
- Study strangeness in the light flavour sector.



Conclusions

- The relative production of several strange to non-strange hadrons was studied in small collision systems at the LHCb.
- In pp collisions at $\sqrt{s} = 13$ TeV , there is an observed enhancement of the B_s^0/B^0 ratio at high multiplicity and low p_{T}. This enhancement is not observed when using backward tracks as multiplicity estimator.
- In pPb collisions at $\sqrt{s_{NN}} = 5$ TeV the $D_s^+/D^{0/+}$ the ratios don't show a clear trend with p_{T} or y.
- In pPb collisions at $\sqrt{s_{NN}} = 8$ TeV, a significant enhancement of the D_s^+/D^+ ratio is observed in events with high multiplicity.

  However, the baryon ratio of Ξ_c^+/Λ_c^+ appears to be constant when studied as a function of $\mathrm{N}_{\mathrm{clusters}}^{\mathrm{VELO}}$.



arXiv:2311.08490 NEW!

Supplementary material

Phys. Rev. Lett. 131 (2023) 061901

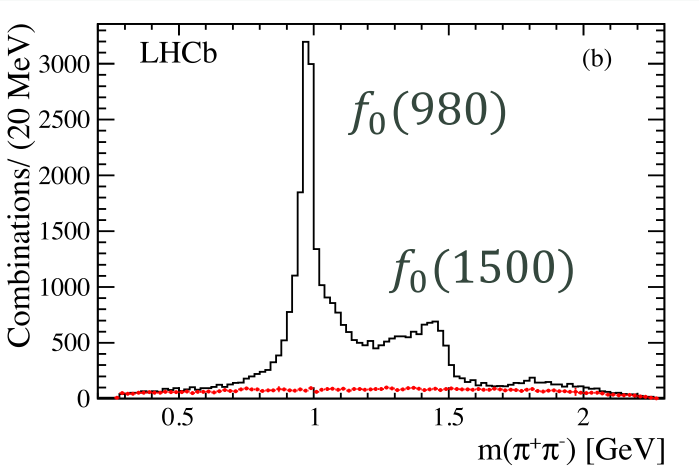
B_s^0/B^0 ratio with multiplicity Efficiency cancelation

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

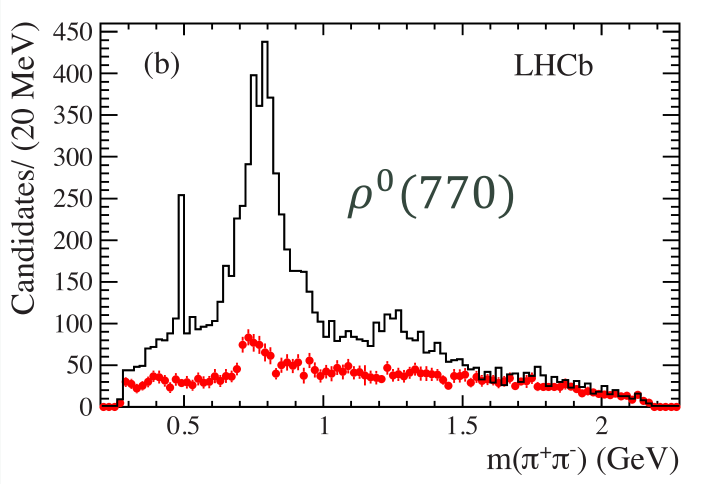
Phys. Rev. D90 (2014) 012003
Phys. Rev. D89 (2014) 092006

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

Due to differences in the $\pi^+\pi^-$mass distribution



$\overline{B_s^0} \rightarrow J/\psi\pi^+\pi^-$

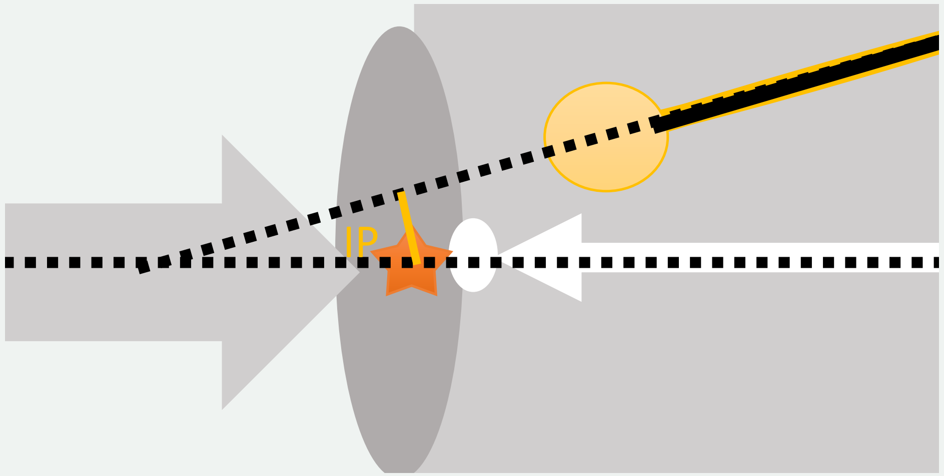


$\overline{B^0} \rightarrow J/\psi\pi^+\pi^-$

Prompt/non-prompt separation the $\log_{10}(\chi^2_{IP})$

χ^2_{IP} is the difference in the vertex-fit χ^2 of a given PV reconstructed with and without the candidate under consideration.

If the candidate is prompt, the χ^2 will improve when taking it into account.

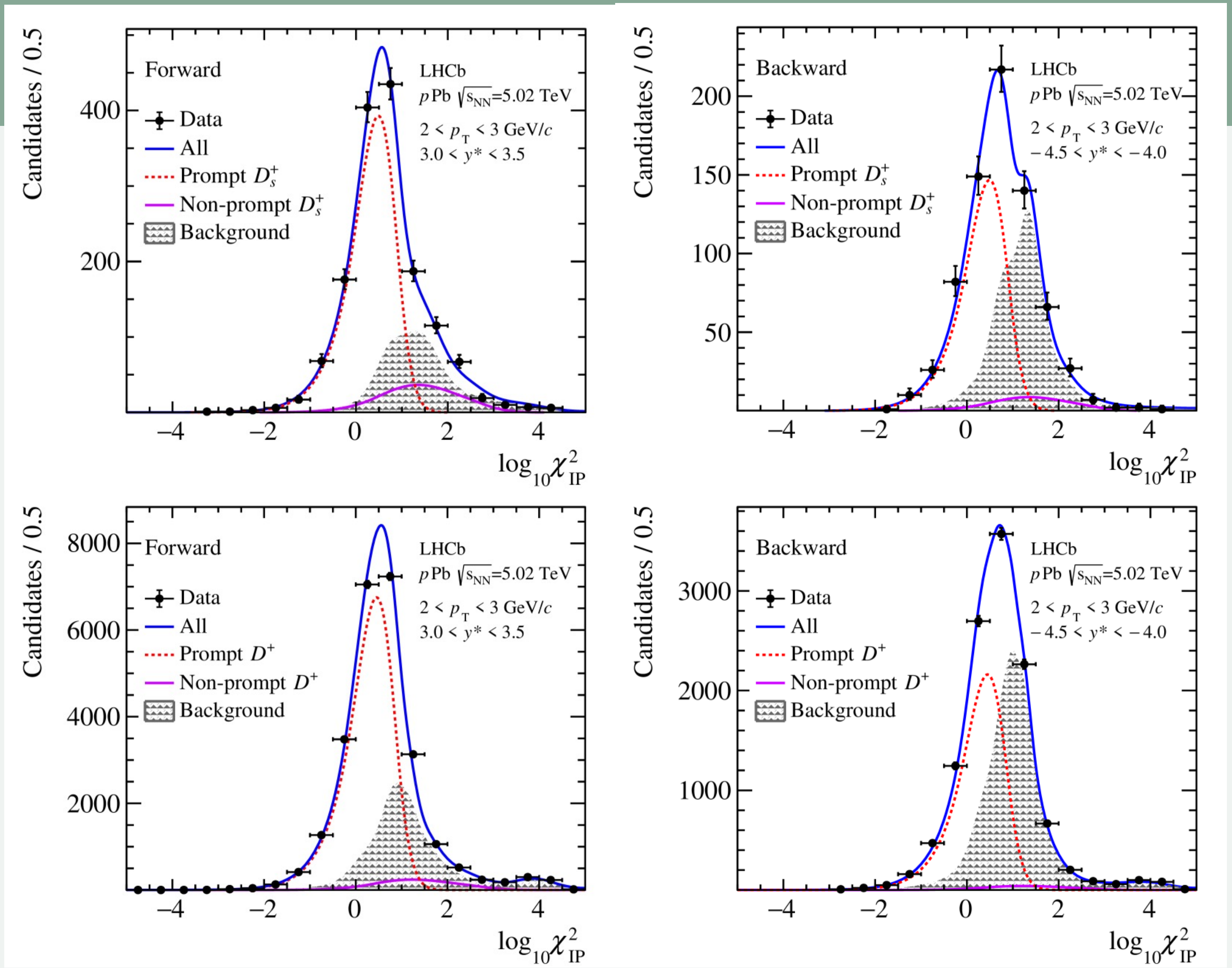


Prompt/non-prompt separation

JHEP 01 (2024) 070

D_s^+/D^+ 5TeV

- In this case, a simultaneous fit to the mass and to the $\log_{10}(\chi^2_{IP})$ is performed.
- The shapes for the (non-) prompt contributions are determined from simulation, modelled with an asymmetric Bulkin curve with tails described by Gaussian functions.
- Width, asymmetry, tail coefficients and peak position of the non-prompt contribution are fixed to MC.
- The background of the $\log_{10}(\chi^2_{IP})$ is fitted by a kernel density estimate function



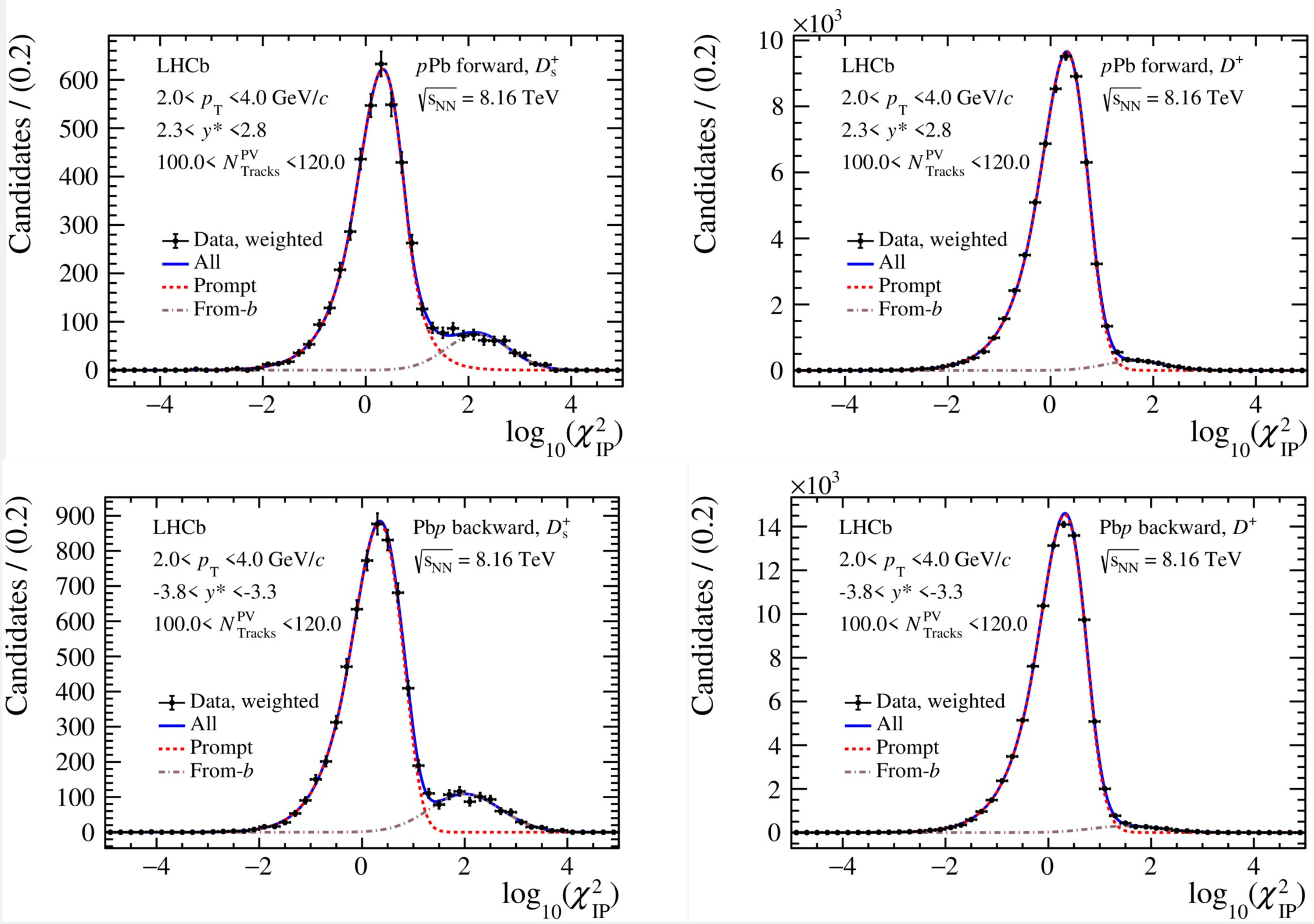
arXiv:2311.08490 NEW!

Prompt/non-prompt separation

D_s^+/D^+ 8TeV

- After background-subtracting the data, a fit to the $\log_{10}(\chi^2_{IP})$ is performed.

- The Bukin function is used to fit each contribution.
- The parameters of the function describing the non-prompt component are fixed from simulation, and the parameters from the prompt component are allowed to float.

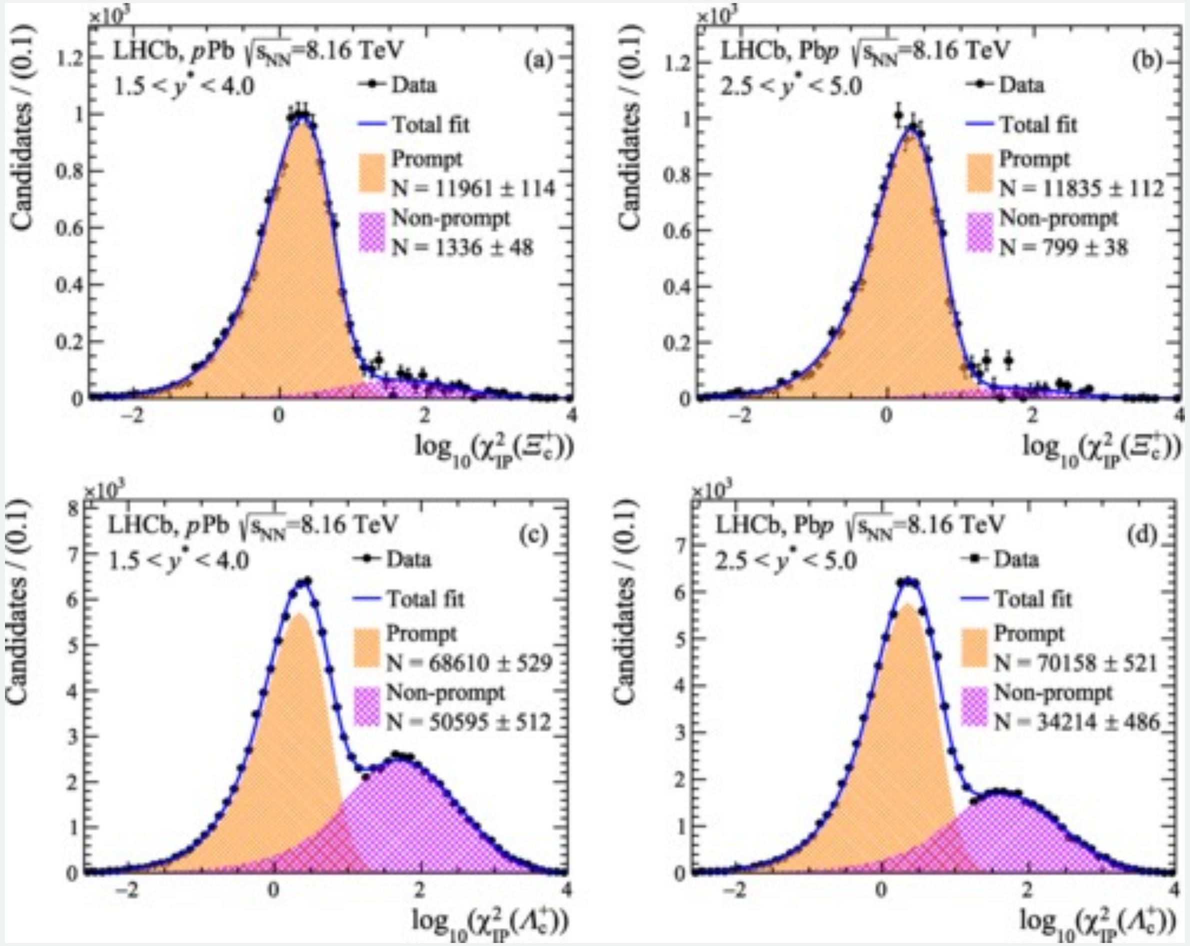


Phys. Rev. C 109 (2024) 044901

Prompt/non-prompt separation

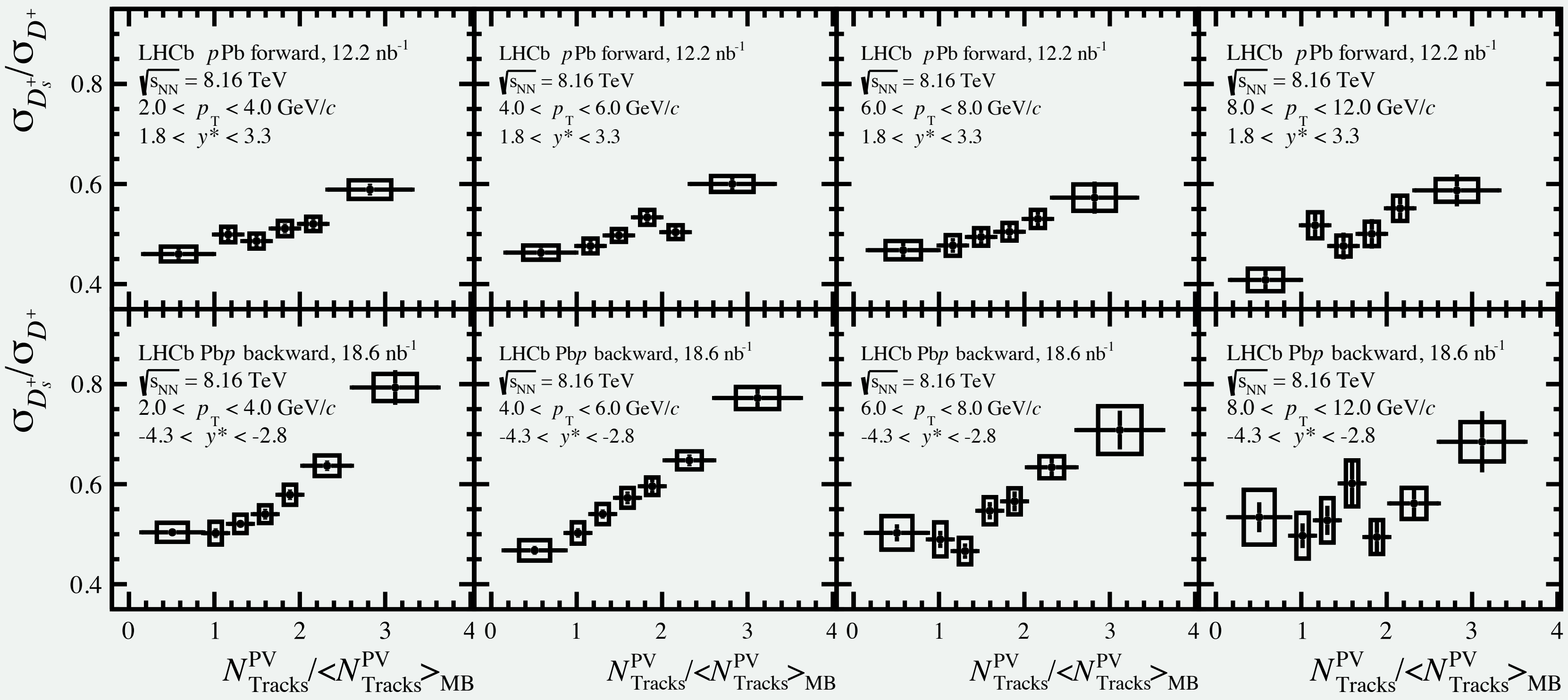
Ξ_c^+/Λ_c^+

- After background-subtracting the data, a fit to the $\log_{10}(\chi^2_{IP})$ is performed.
- The Bukin function is used to fit each contribution with the asymmetry parameters taken from MC and letting the mean and variance to vary.



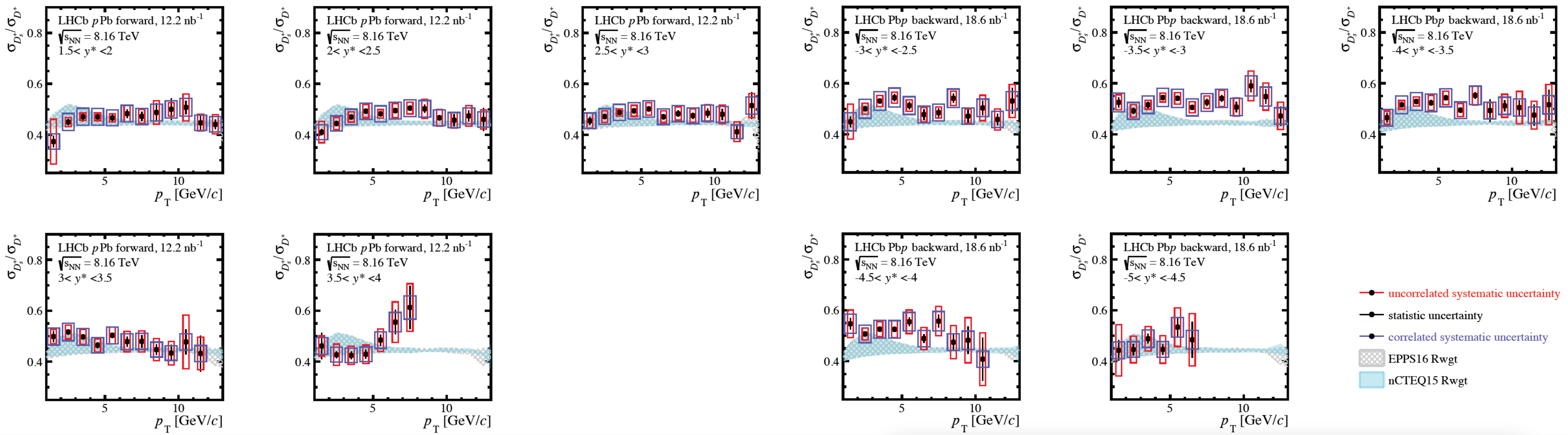
arXiv:2311.08490 NEW!

D_s^+/D^+ ratio
pPb collisions at $\sqrt{s_{NN}} = 8$ TeV



arXiv:2311.08490 NEW!

D_s^+/D^+ ratio
pPb collisions at $\sqrt{s_{NN}} = 8$ TeV



Phys. Rev. C 109 (2024) 044901
Phys. Rev. Lett. 131 (2023) 102301

Ξ_c^+/D^0 ratio
pPb collisions at $\sqrt{s_{NN}} = 8$ TeV

The results are systematically below ALICE's, but they are compatible within uncertainties.