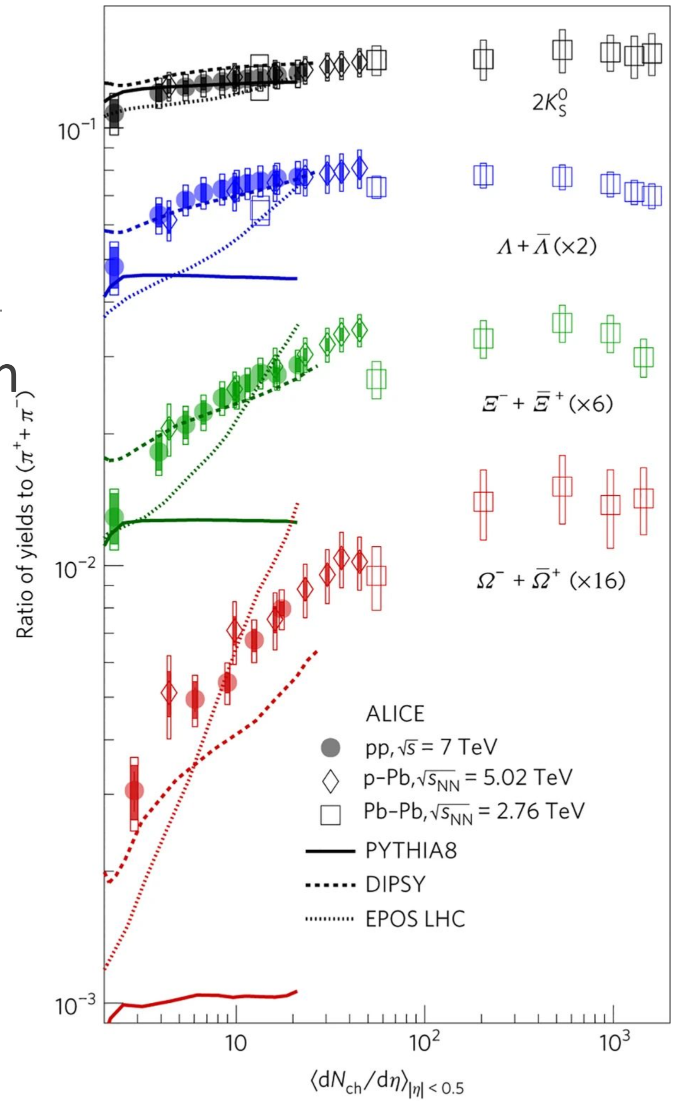
Modified hadronization in small systems at LHCb

Desmond Shangase on behalf of the LHCb Collaboration
University of Michigan
DIS 2023 - March 30th 2023

Motivation

Strangeness enhancement is a signature for QGP production in A-A collisions

- Historically associated with Statistical Hadronization and centrality ⟶ a heavy-ion phenomenon



ALICE, Nature Phys 13, 535–539 (2017)

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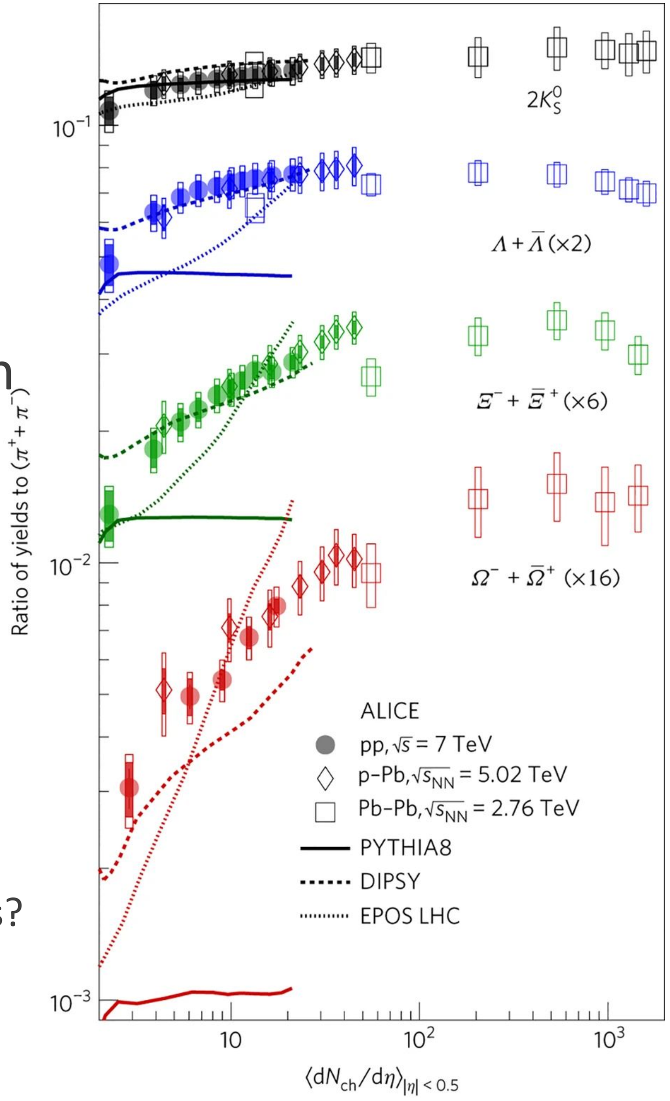
- This raises multiple questions regarding our understanding of hadron production in small systems:
  - Is there QGP droplet formation in p-p?
  - Which modified hadronization schemes are most relevant in small systems?
  - What is the geometric/kinematic dependence in these hadronization mechanisms?



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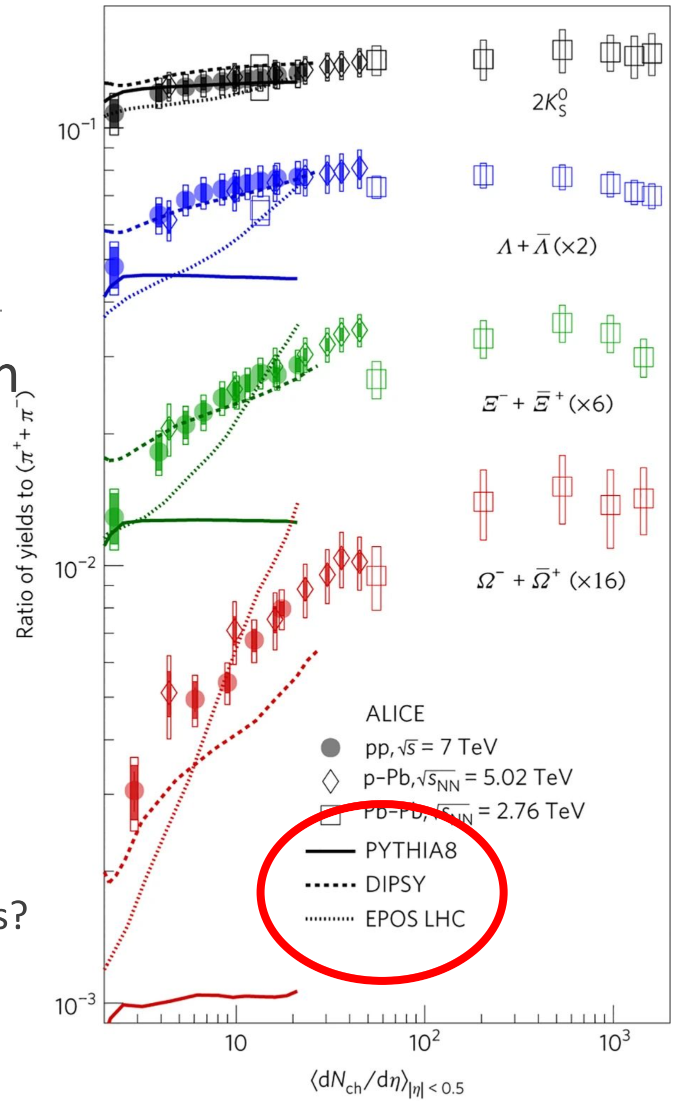

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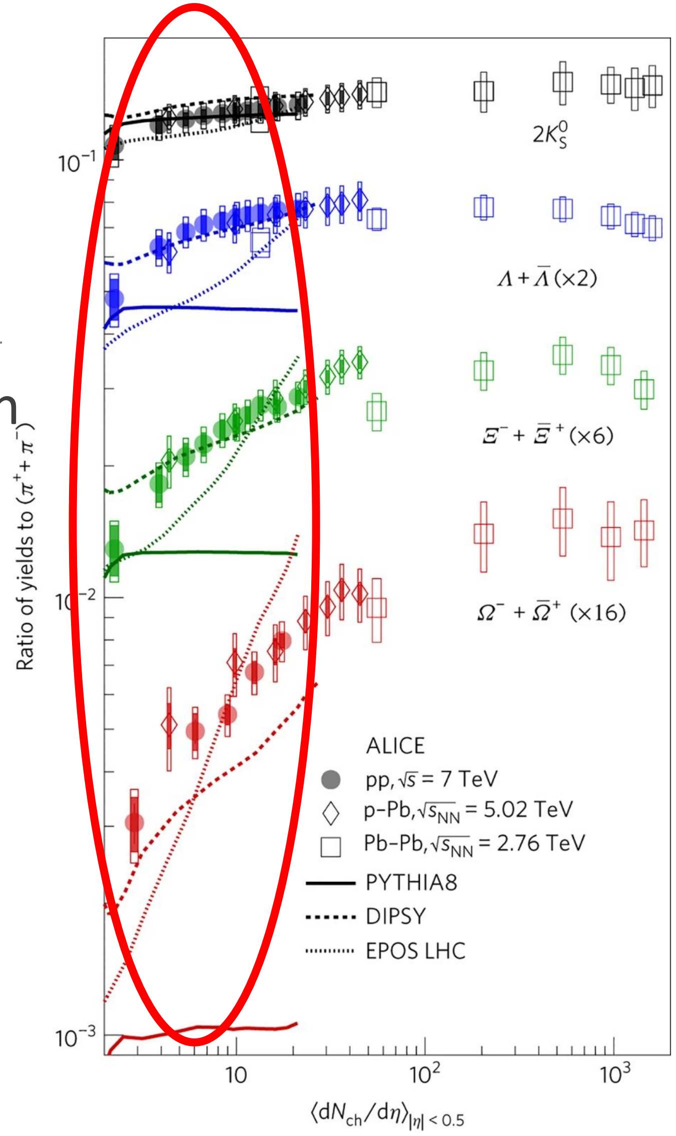
- Particularly useful region to probe
  - Significant constraining power for hadronization models
  - Largest slope (highest sensitivity) in strangeness enhancement
  - Relatively low detector occupancy issues in comparison to heavy-ions



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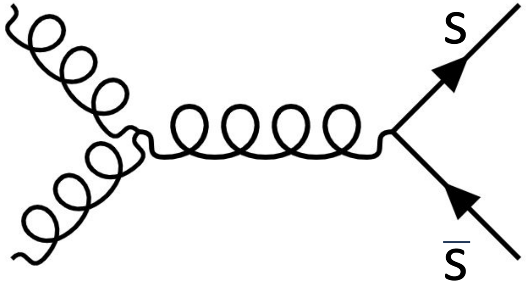
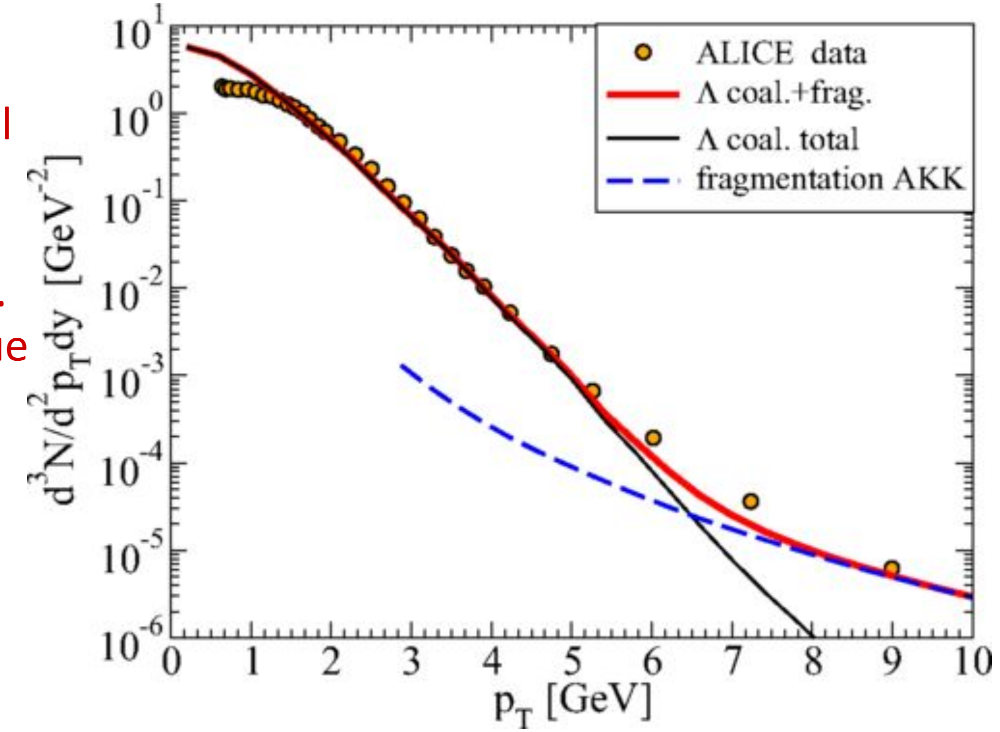
Modified Hadronization



Collisions of high event activity can modify hadron production processes; potentially via medium formation

- **Coalescence**
  - Following QGP production, the medium undergoes a chemical evolution by fusing gluons into strange quark-antiquark pairs (Statistical Hadronization Model*)
  - Quarks coalesce with their phase space neighbors in medium. Hadrons containing strange quarks are more easily formed due to their abundance from QGP evolution
  - The abundance of low-p_T quarks also leads to an increased baryon yield at intermediate momenta



Phys. Rev. C 92, 054904 (2015)

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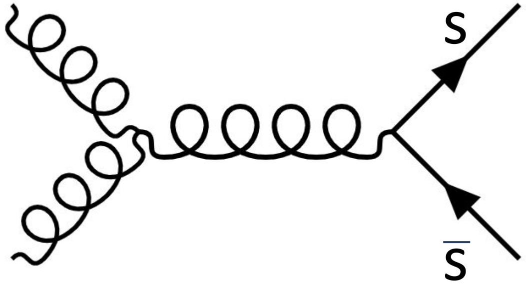
*Phys.Lett.B 113 (1982) 6, Phys.Rev.Lett. 48 (1982) 1066

Modified Hadronization



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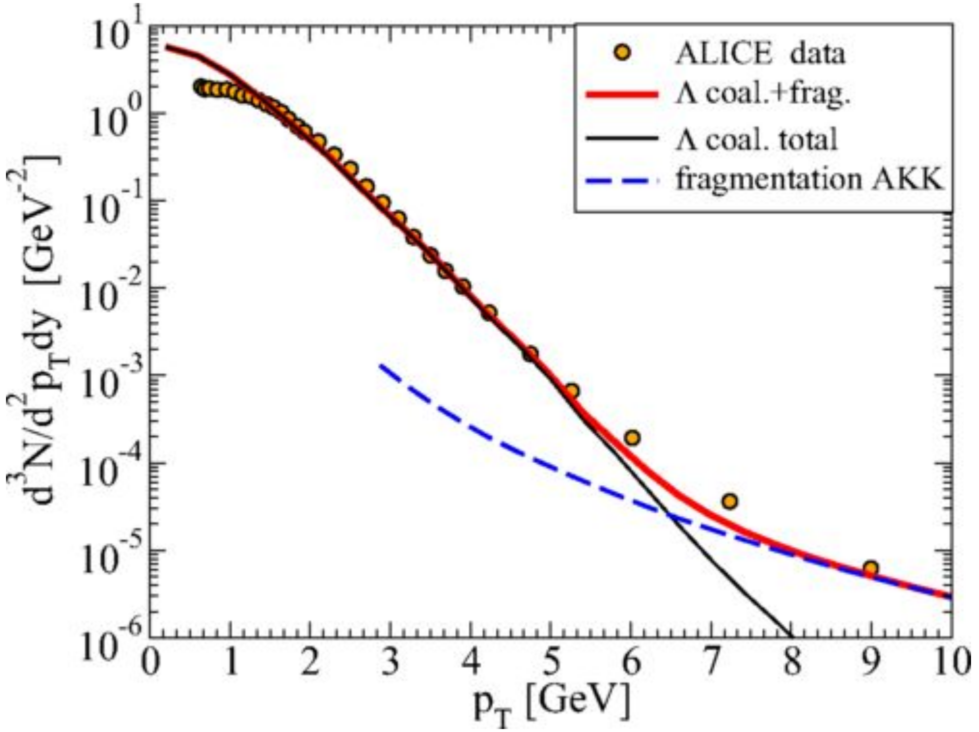
- **Fragmentation**
  - Many models separate the QGP medium into a dense core which undergoes statistical hadronization+coalescence, and a low-density corona which is described by Lund String Fragmentation
  - Combined core-corona models (or coalescence-fragmentation models) have provided better matching with data
  - In addition, models which describe these enhancements with modified String Fragmentation (e.g. Rope Fragmentation) are currently in use by several event generators



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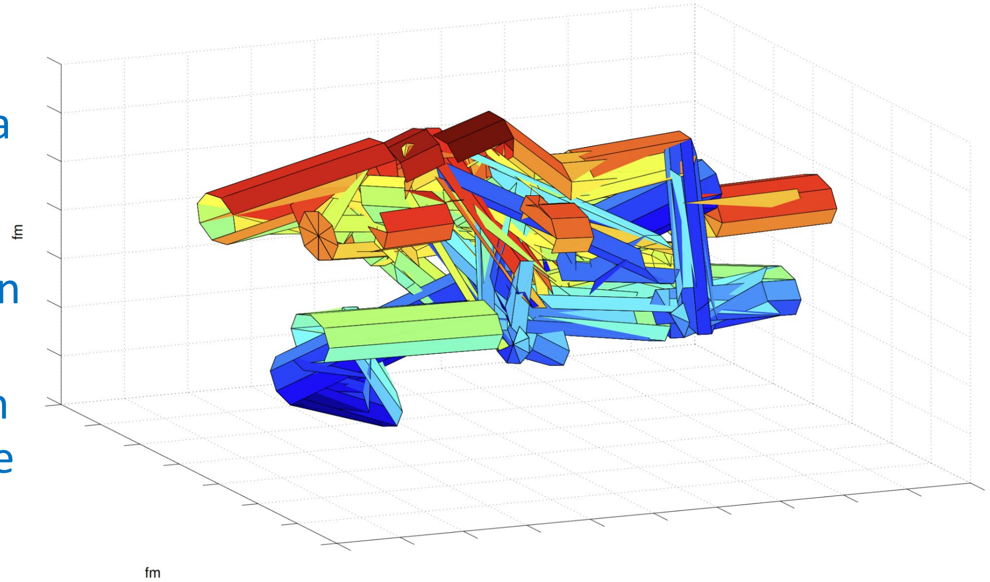

J. High Energ. Phys. 2015, 148 (2015)

Modified Hadronization

What are the dependencies and implications of these various hadronization schemes?

- Can we assume QGP in small systems if core-corona models continue to be successful? (What about modified fragmentation models?)
- In what kinematic ranges do these models contribute significantly?
- Are these phenomena dependent on event activity or local particle densities?
- **(Pseudo)rapidity dependence?**
  - Can non-trivial dependencies be explained entirely by collision geometry & CNM?

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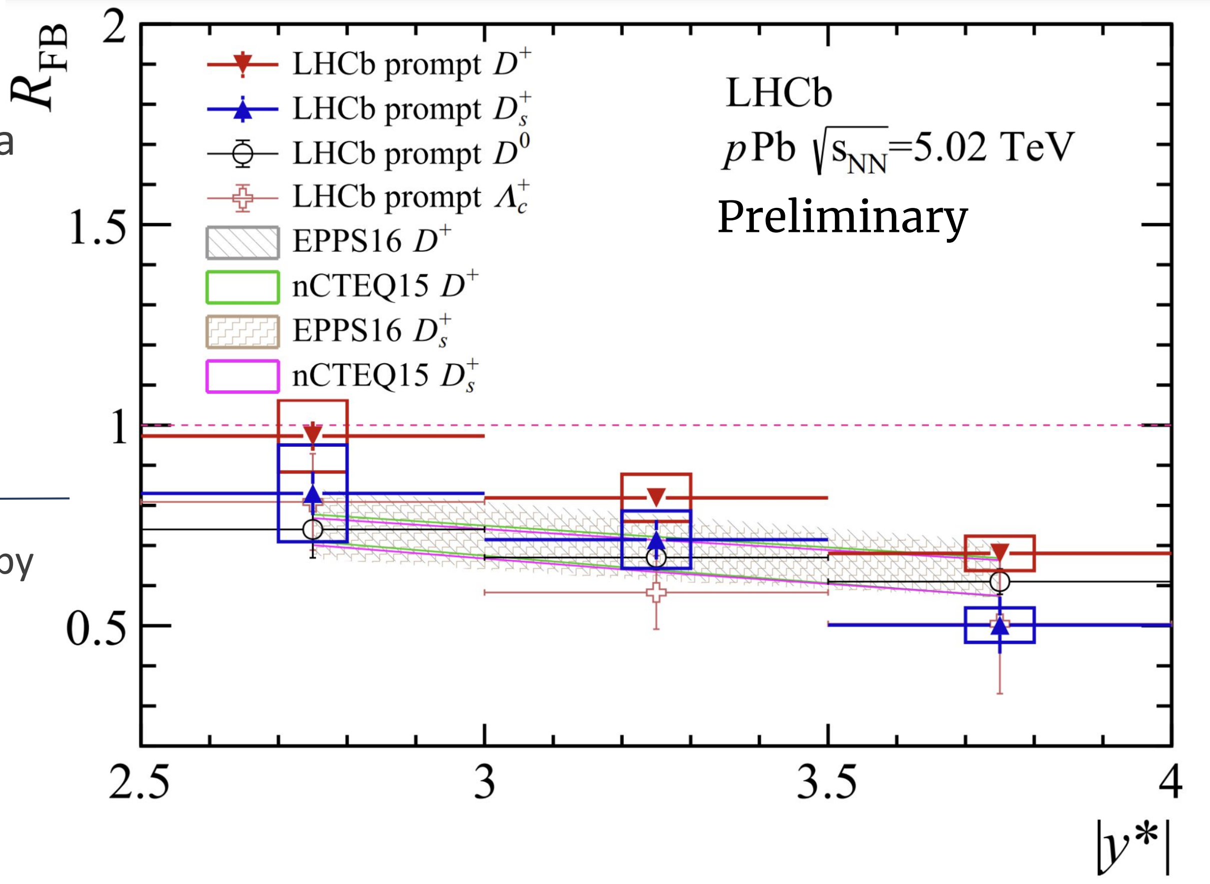

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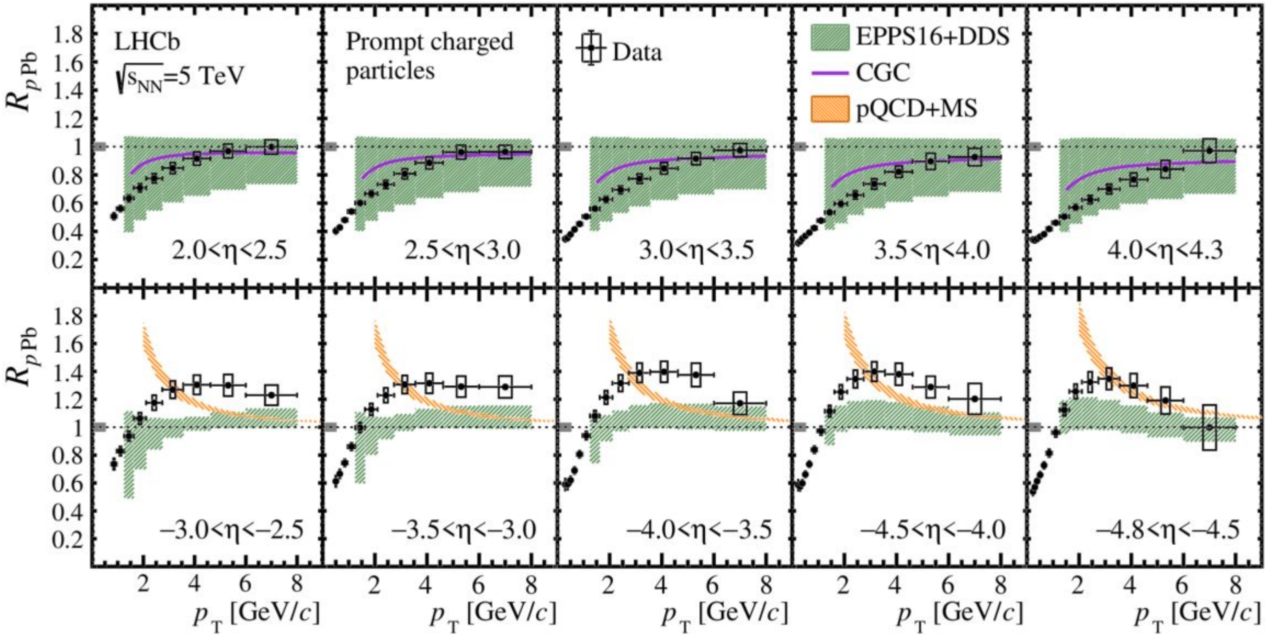

Phys. Rev. Lett. 128, 142004 (2022)

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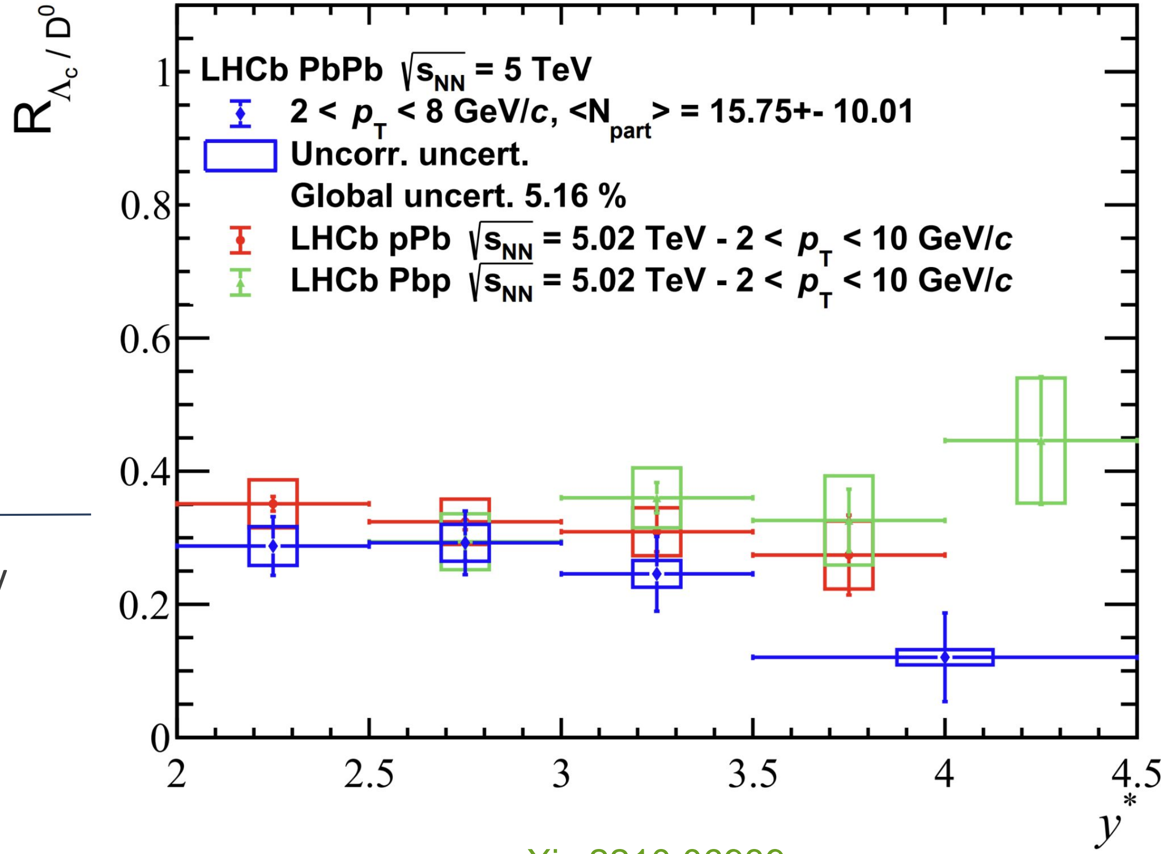

arXiv:2210.06939

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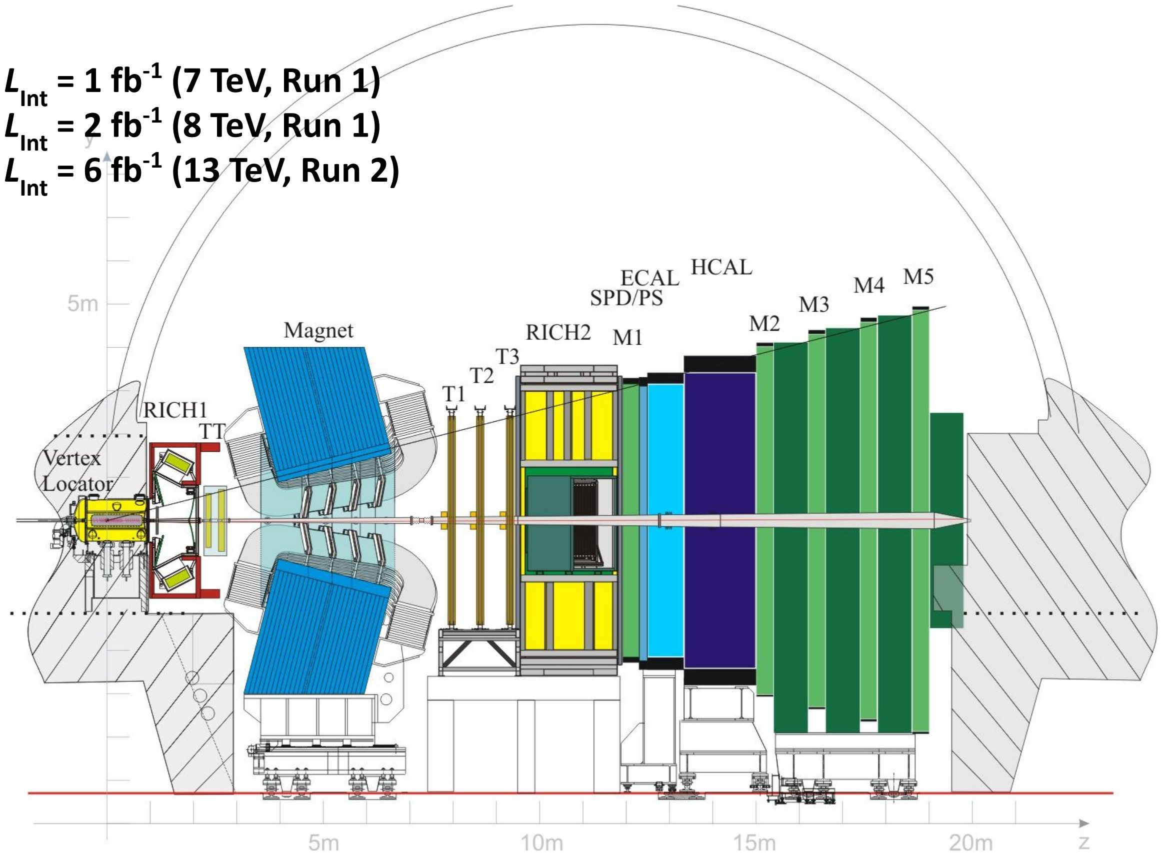
LHCb Detector

Forward arm spectrometer with $2 < \eta < 5$ coverage for reconstructable particles

- Dual RICH PID allows for particle identification for $2 < p_{Track} < 100$ GeV/c
- **Ver**tex **Lo**cator (VELO) allows for precise primary vertex reconstruction and **event activity estimation**
  - Can operate in fixed-target mode during run with a gas target

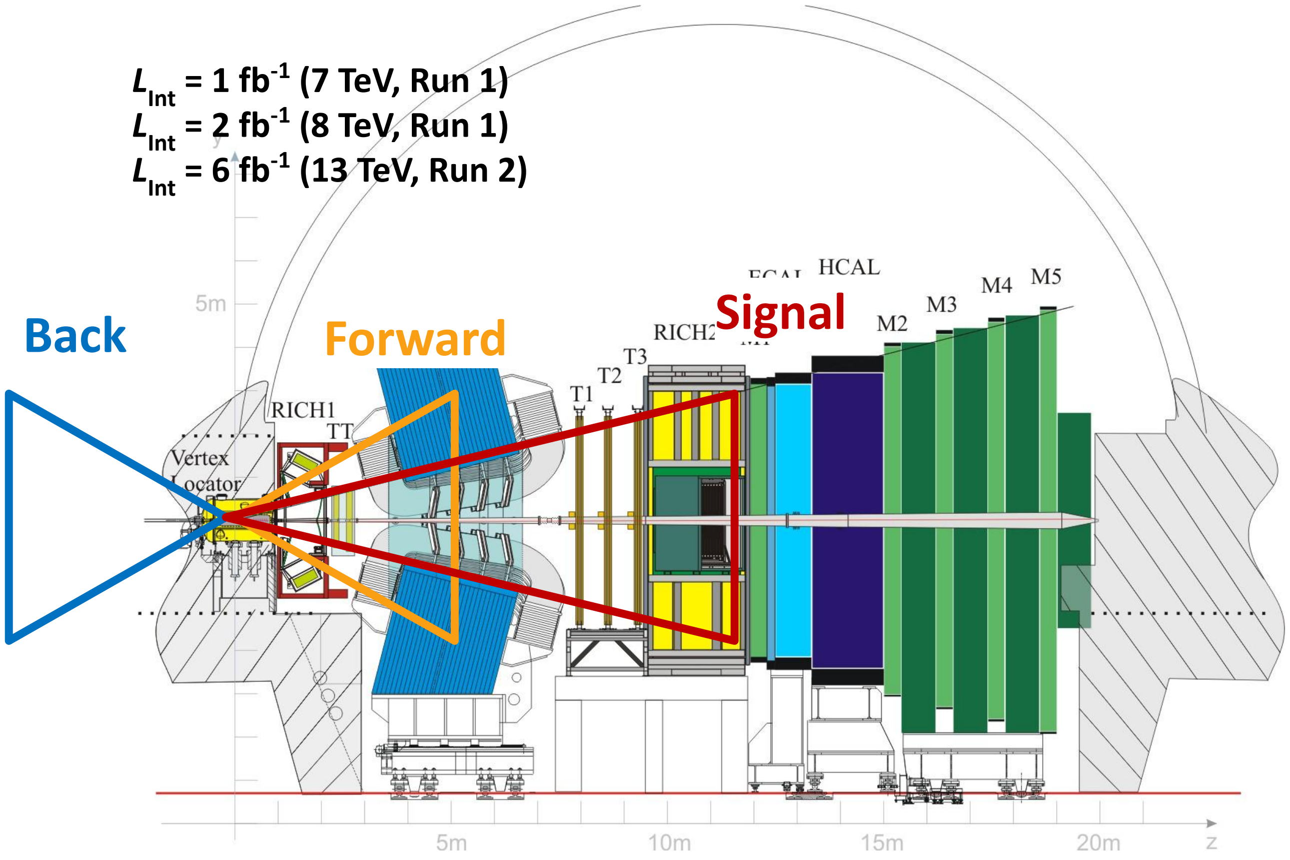


IJMPA 30 (2015) 1530022

Event Characterization

- Will use multiplicity of tracks recorded by VELO as a proxy for event activity
- VELO coverage contains forward ($1.6 < \eta < 4.9$) and backward ($-4 < \eta < -1.5$) regions $\longrightarrow$ Two multiplicity estimators:
  - Backwards: N^{back}_{tracks}
  - Inclusive: N^{VELO}_{tracks}
- Multiplicity estimators with non-overlapping vs. overlapping geometric coverage $\longrightarrow$ local particle density dependence

L_{Int} = 1 fb^{-1} (7 TeV, Run 1)
L_{Int} = 2 fb^{-1} (8 TeV, Run 1)
L_{Int} = 6 fb^{-1} (13 TeV, Run 2)



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  - Backwards: N^{back}_{tracks}
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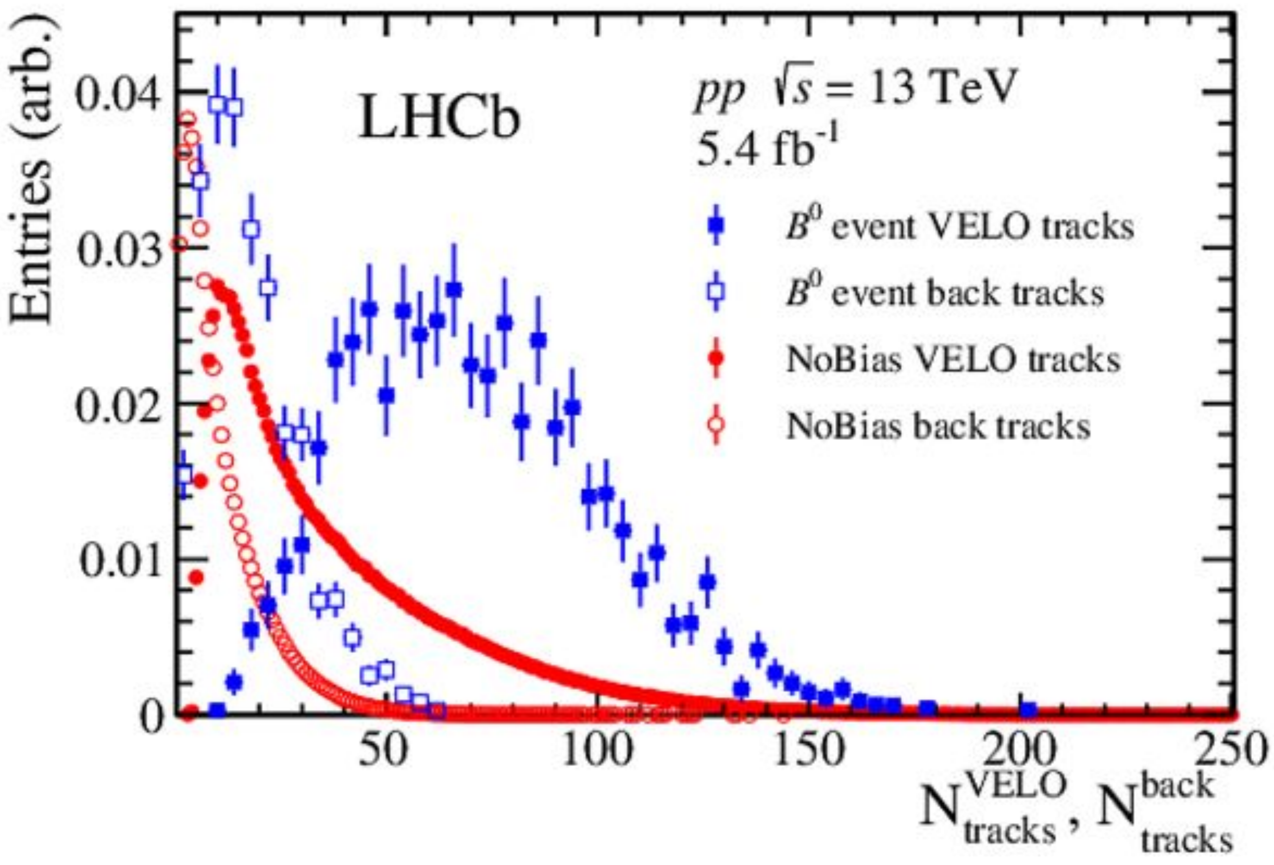
- NoBias events are selected based on the LHC beam clock, which indicates that a bunch crossing has occurred, without any other trigger requirements



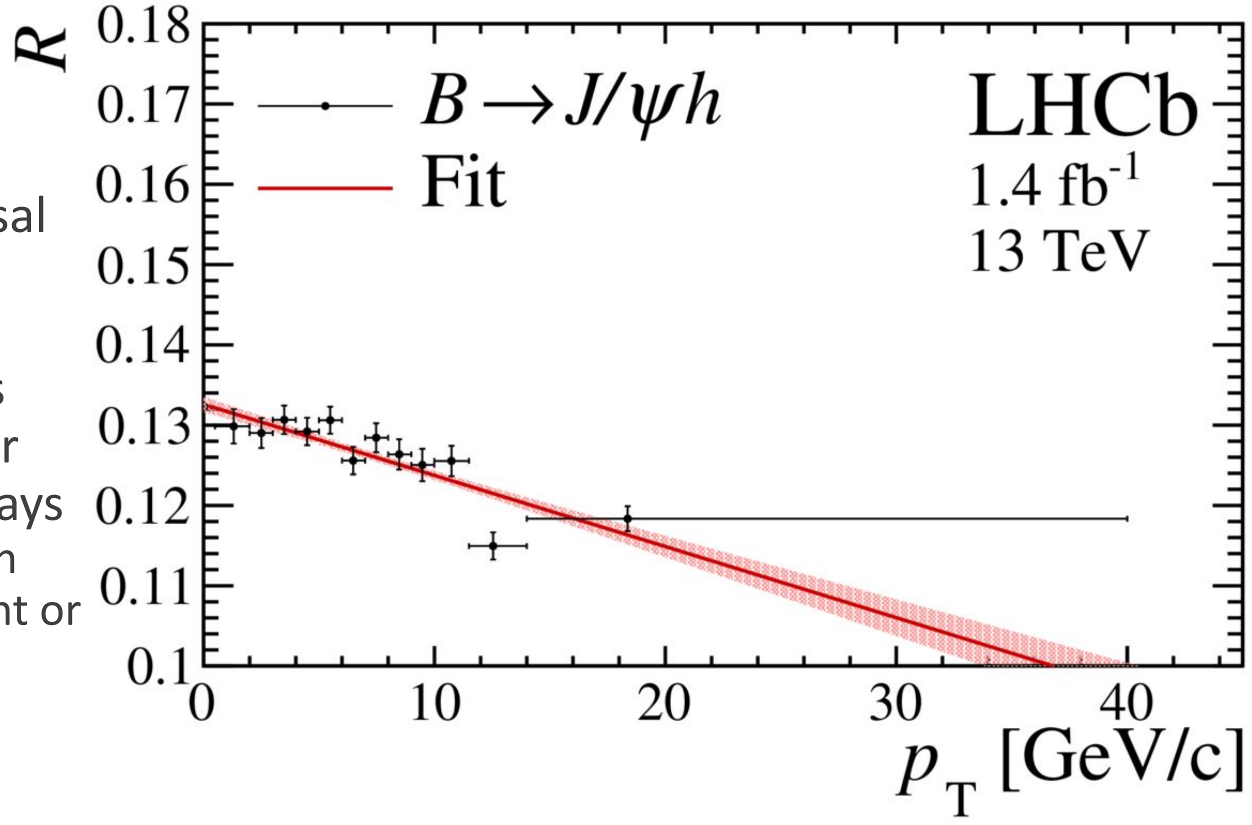
arXiv:2204.13042

Strangeness enhancement in b-quark hadronization

B-mesons are a useful laboratory for investigating strangeness enhancement

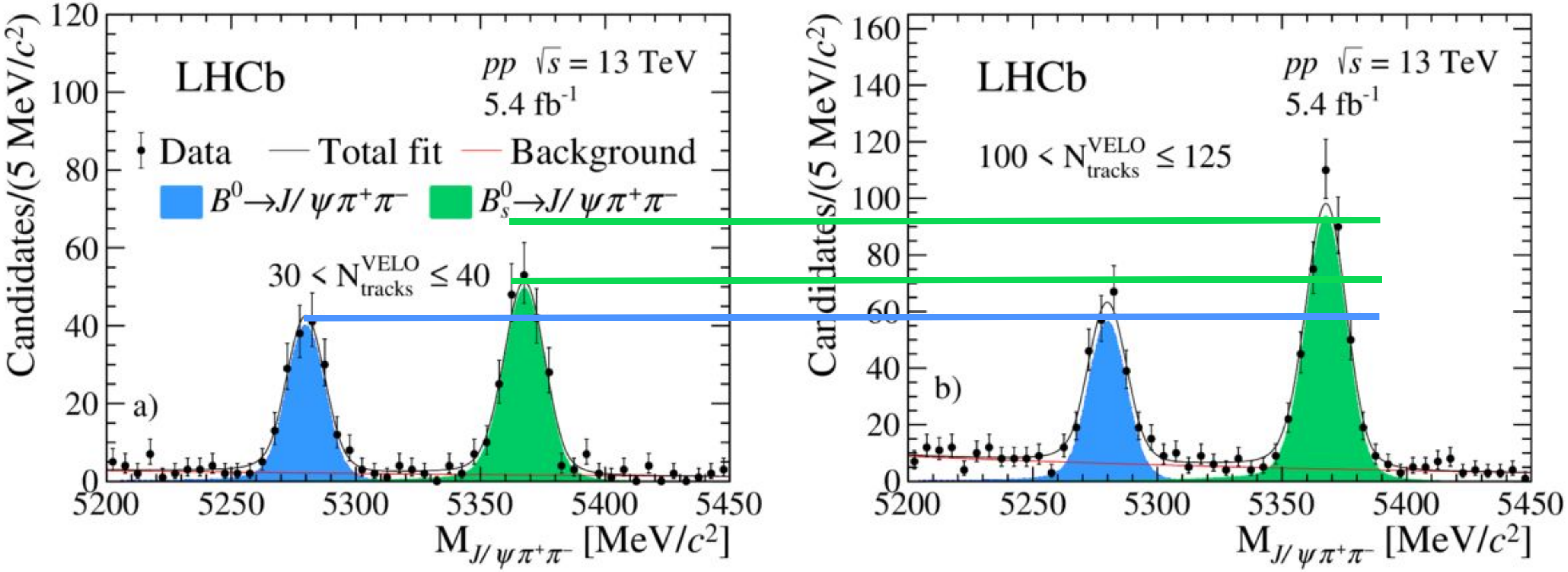
- b-quark fragmentation into B_s^0 (f_s) already measured to be non-universal relative to B^-, B^0 (f_u, f_d) in hadronic collisions systems
- Ratio of fragmentation fractions has been observed to decrease at higher kinematics for various B-meson decays
  - Enhancement at low-p_T could mean contributions from underlying event or bulk

$$R \propto \frac{f_s}{f_d}$$ i.e. relative probability of fragmenting to B_s^0 vs. B^0



Phys. Rev. D 104, 032005 (2021)

Strangeness enhancement in b-quark hadronization



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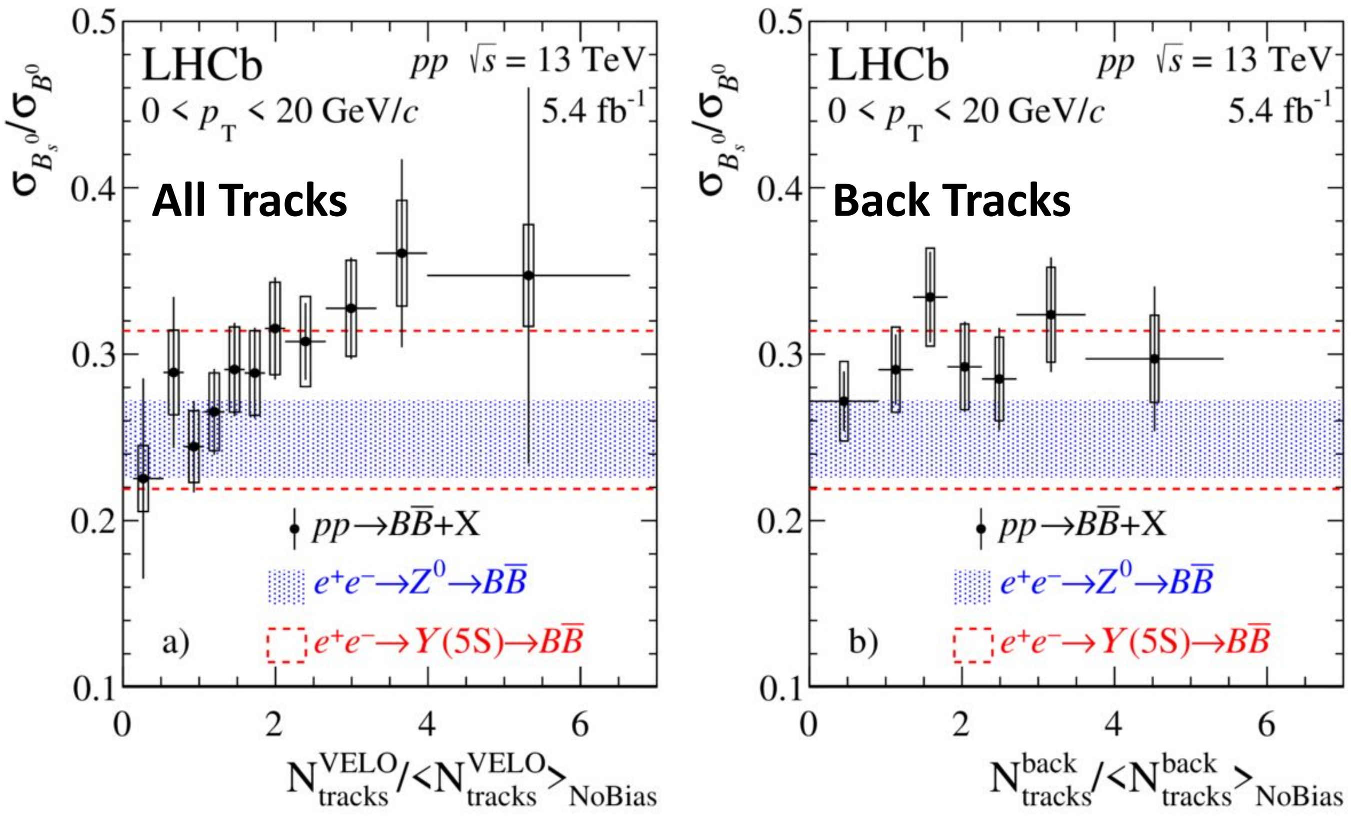
Relative size of B_s^0 mass peak w.r.t. B^0 scales positively with multiplicity → **Strangeness Enhancement**

Let's investigate further…

Strangeness enhancement in b-quark hadronization

- Due to decay and reconstruction similarities, several systematic uncertainties cancel in the ratio
- Vertical error bars (boxes) represent point-to-point uncorrelated (fully correlated) uncertainties
- Positive trend w.r.t. N_{tracks}^{VELO} shows enhancement over e^+e^- results and multiplicity integrated value for p-p ($\sigma_{B_s^0}/\sigma_{B^0} = 0.30 \pm 0.01 \pm 0.03$)



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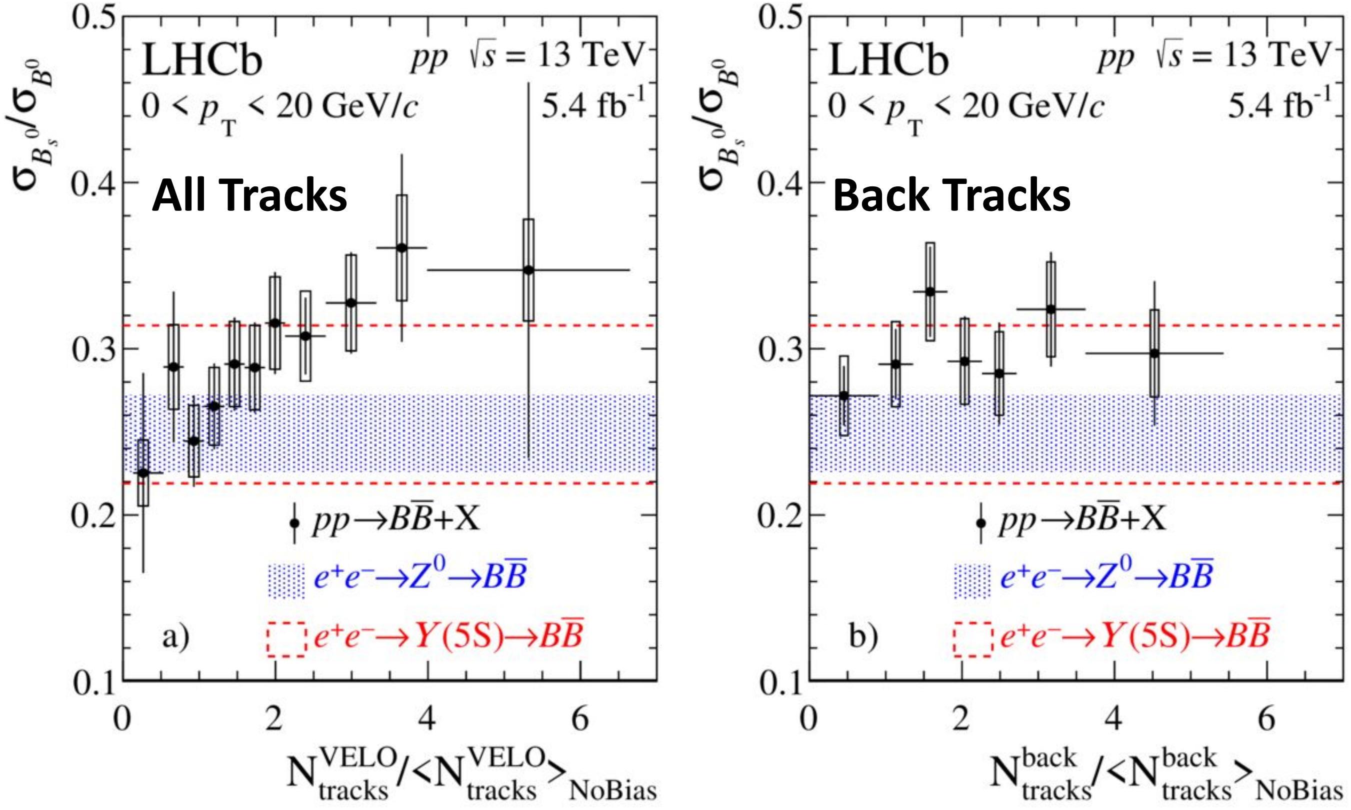
Strangeness enhancement in b-quark hadronization

- Due to decay and reconstruction similarities, several systematic uncertainties cancel in the ratio
- Vertical error bars (boxes) represent point-to-point uncorrelated (fully correlated) uncertainties
- Lack of significant positive trend w.r.t. N^{back}_{tracks} implies that this enhancement could be dependent on local particle densities specifically and thus could be coalescence-related in origin



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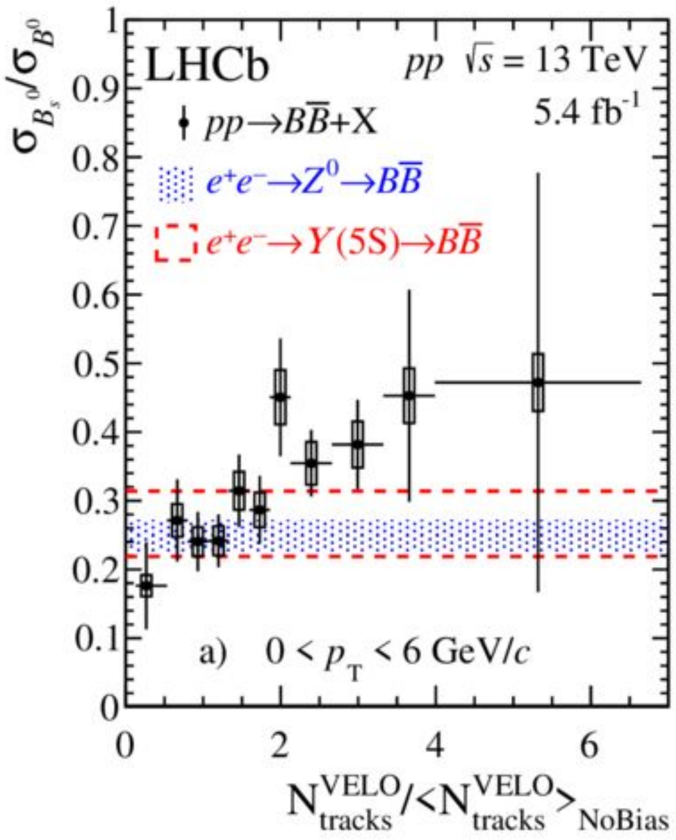
Strangeness enhancement in b-quark hadronization

- Notable enhancement in multiplicity at low (< 6 GeV/c) transverse momentum
  - kinematic range where coalescence effects are historically likely to manifest
- Disappearance of enhancement signal with higher p_T
  - High momentum b's have less overlap in phase space with the low-p_T bulk → hadronize via fragmentation



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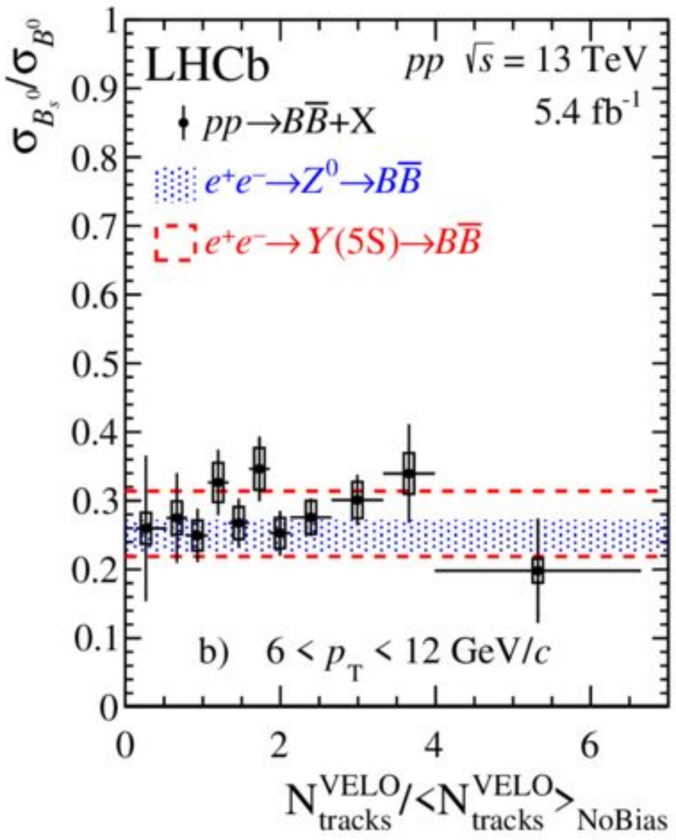

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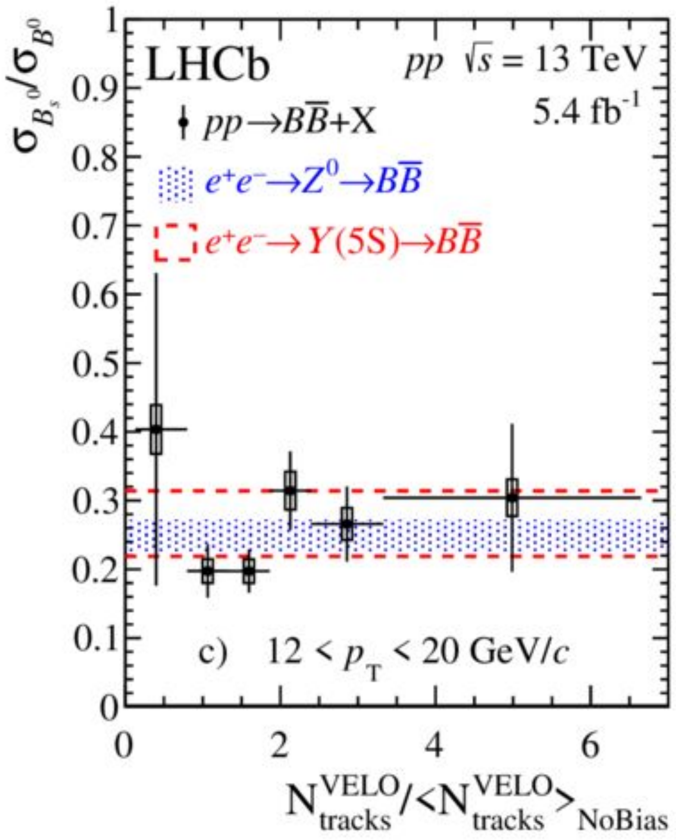

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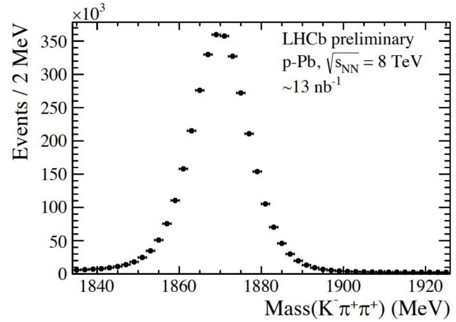
Works In Progress: Upcoming Results from LHCb

- D_s^+ / D^+ at 8 TeV

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



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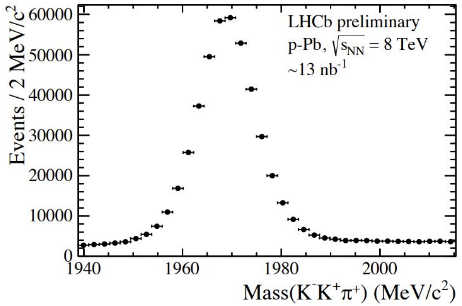

  - Provides further strangeness production in heavy-flavor data
  - Useful in simultaneously probing charm production in small systems
  - Examines $\sqrt{s_{NN}}$ dependence in conjunction with 5 TeV results

- Light flavor strangeness enhancement
  - In p-p and p-A
    - Also, particle production in fixed-target
  - Will provide qualitative comparisons for previous midrapidity results
  - Inclusion of ϕ meson allows for study of hidden strangeness
- Baryon-to-meson ratios
  - complementary observable in constraining core-corona models
  - In various light and heavy-flavor species
    - e.g. Λ, Λ_b, Λ_c, Ξ_c

Stay Tuned…

Summary

- The landscape of strangeness enhancement results has forced us to reconsider our understanding of hadronization mechanisms at play in small systems and probing small systems at forward pseudorapidity provides a new dimension to the current pool of results
- Using distinct multiplicity estimators, LHCb has seen that strangeness enhancement in B mesons is potentially dependent on local particle density rather than overall event activity
- Said enhancement results also seem to appear in the $p_T < 6$ GeV/c range, supporting the hypothesis of possible coalescence in p-p
- Efforts are continuing at the LHCb collaboration to continue probing small systems using a variety of species and collisions systems (p-p vs. p-A)

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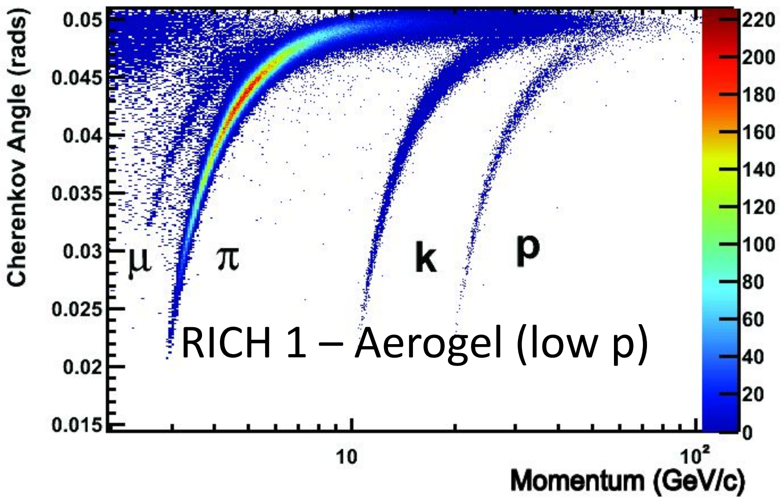
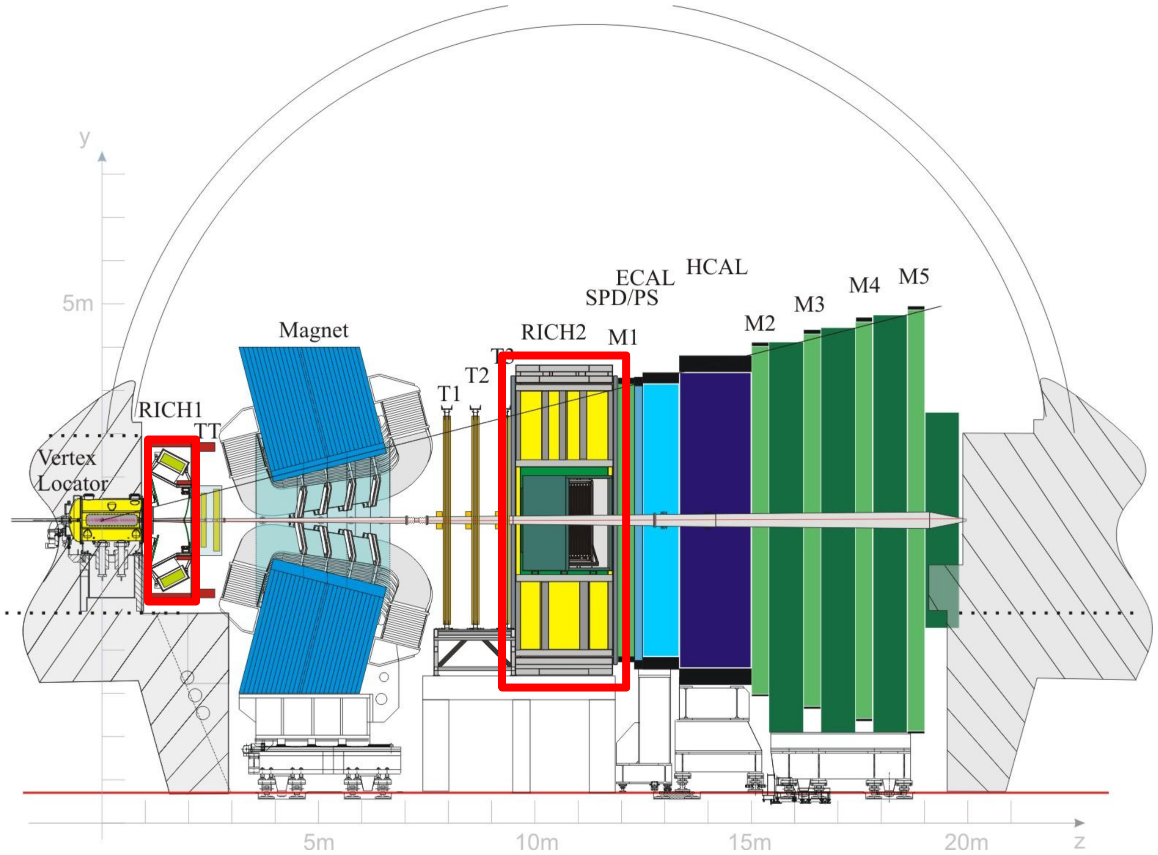
Backup

RICH

Ring **I**maging **CH**erenkov Detector

- Used for PID
  - Specifically separation of light long-lived particles





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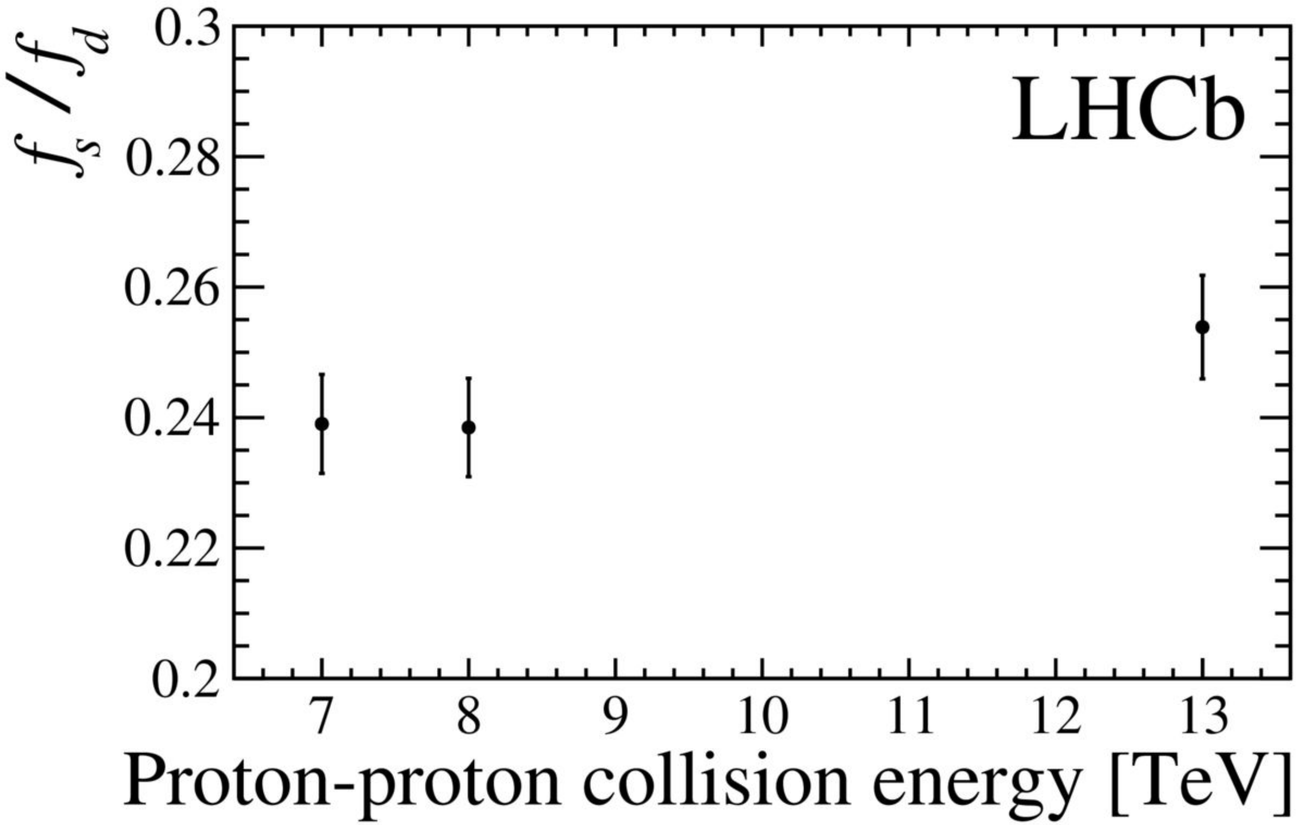
f_s/f_d non-universality



Phys. Rev. D 104, 032005 (2021)

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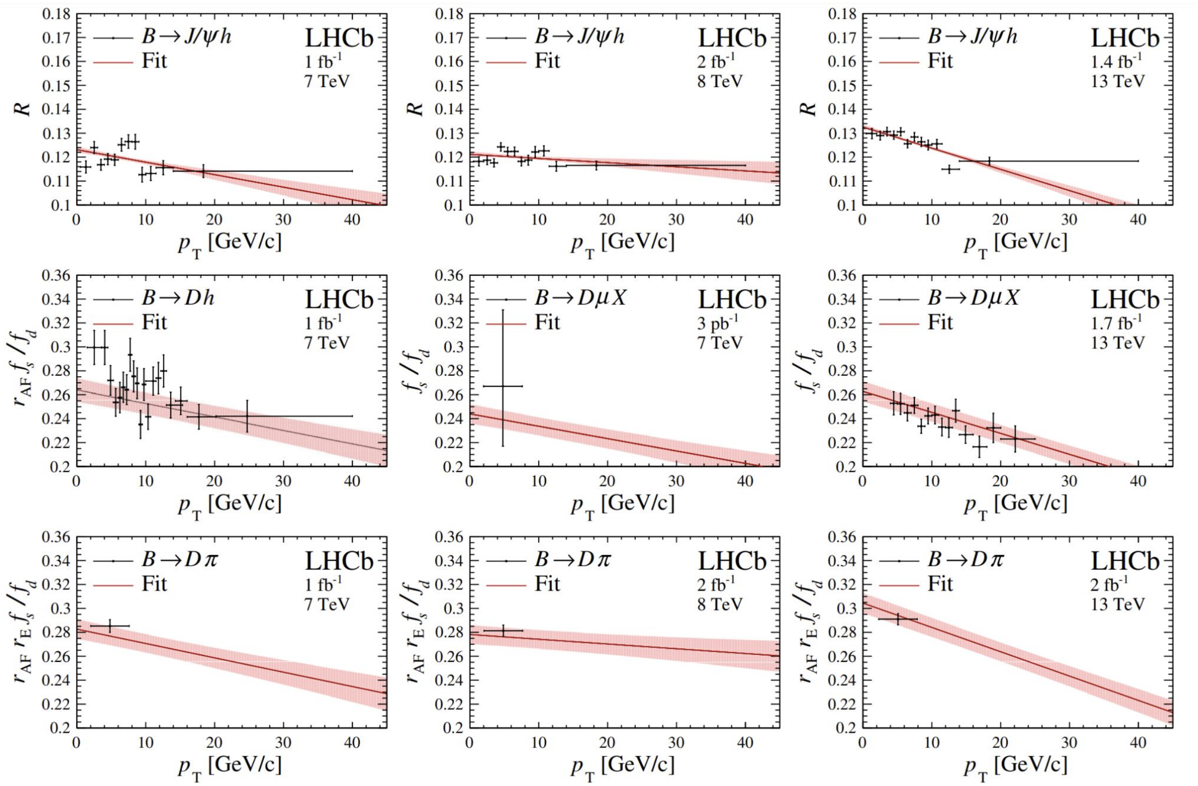

FIG. 1. Measurements of f_s/f_d sensitive observables as a function of the B-meson transverse momentum p_T overlaid with the fit function. The scaling factors r_{AF} and r_E are defined in the text; the variable $\mathcal{R}$ is defined in Eq. (4). The vertical axes are zero suppressed. The uncertainties on the data points are fully independent of each other; overall uncertainties for measurements in multiple p_T intervals are propagated via scaling parameters, as described in the text. The band associated with the fit function shows the uncertainty on the postfit function for each sample.

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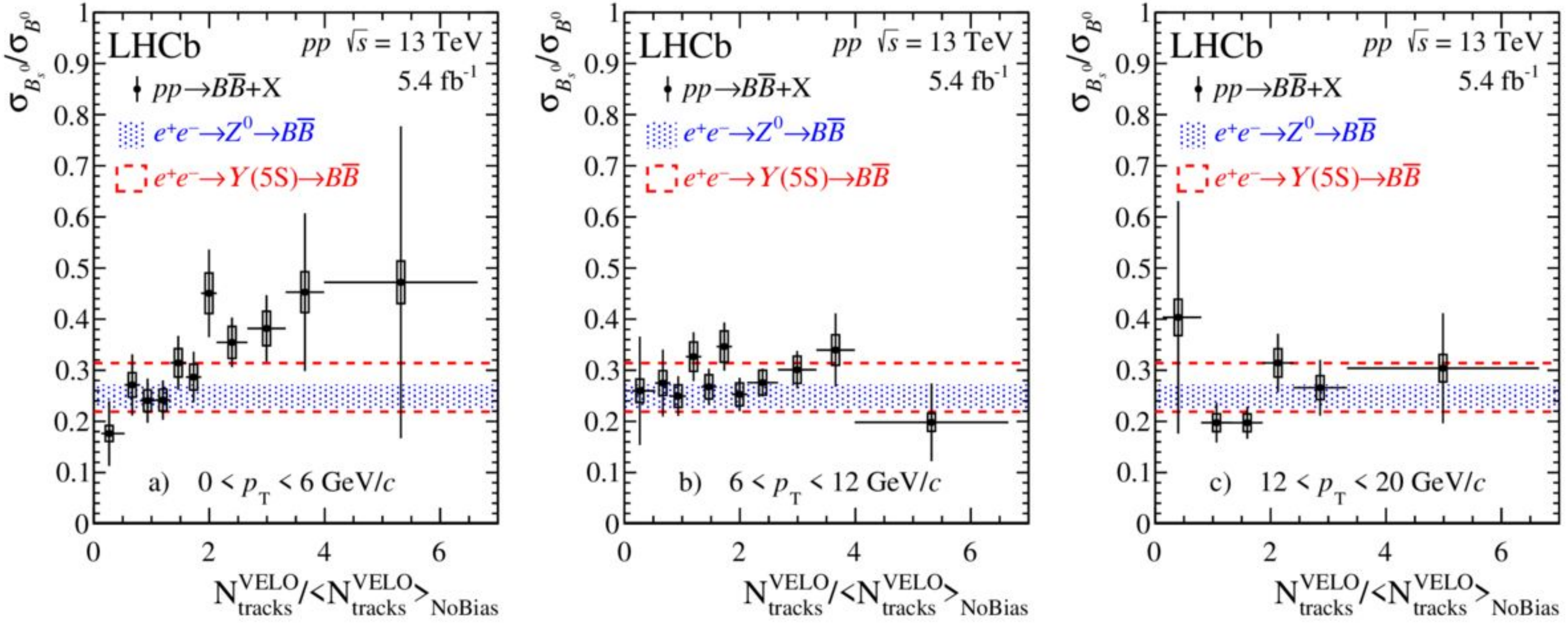
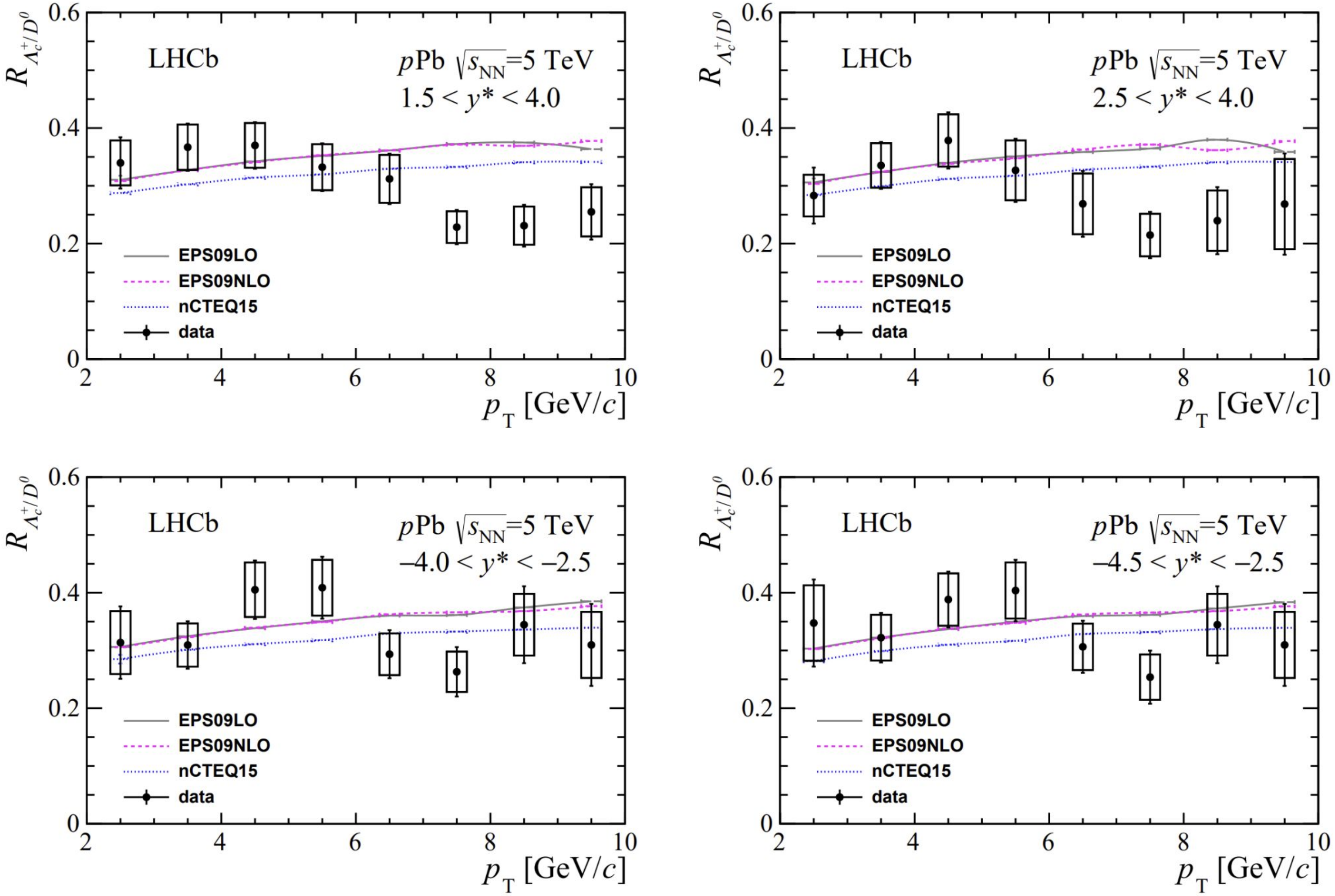


arXiv:2204.13042

Λ_c/D^0 in *p*A

- Multiplicity integrated
- Multiplicity-dependent follow-up in PbPb done recently



J. High Energ. Phys. 2019, 102 (2019)

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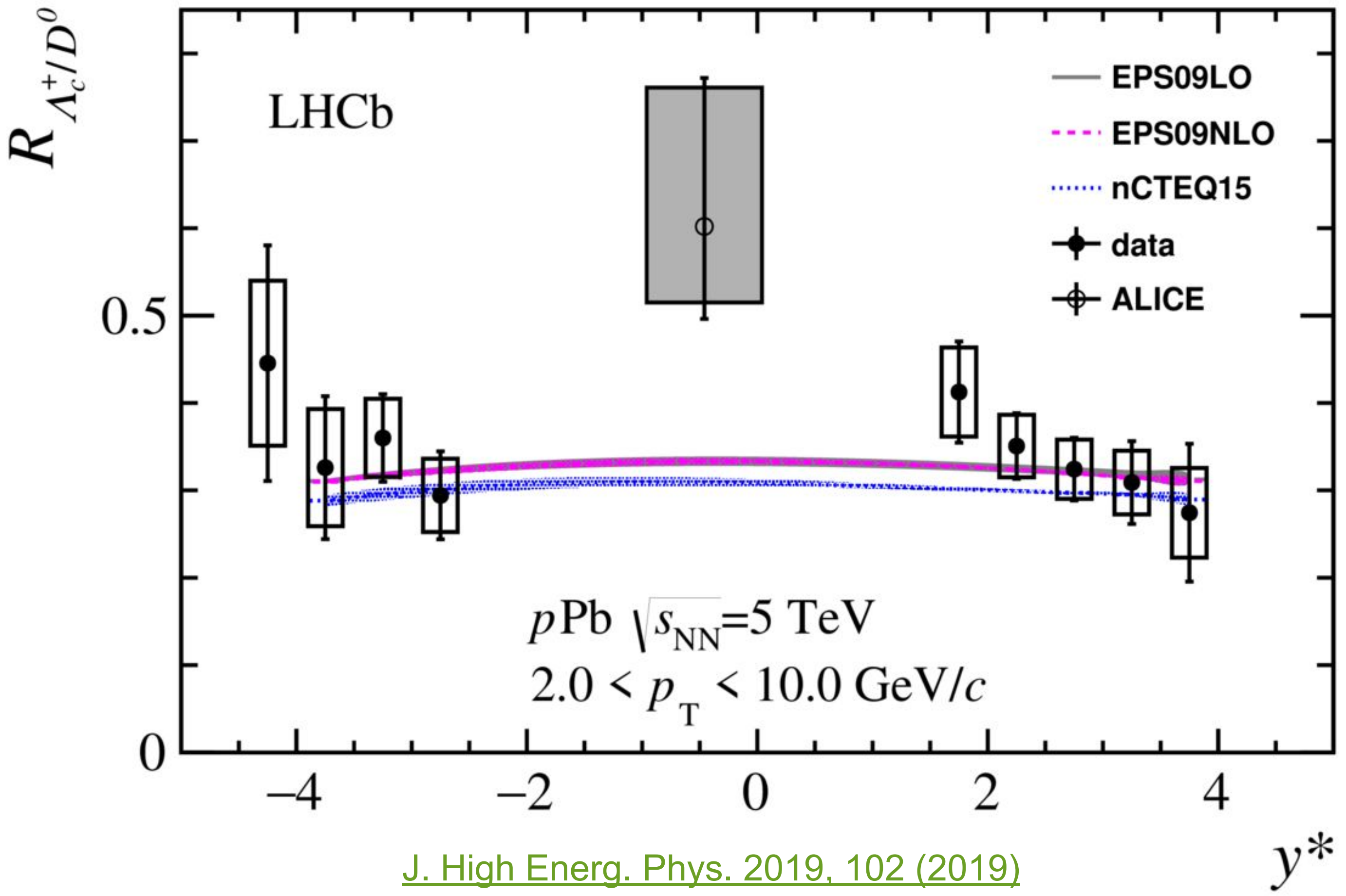

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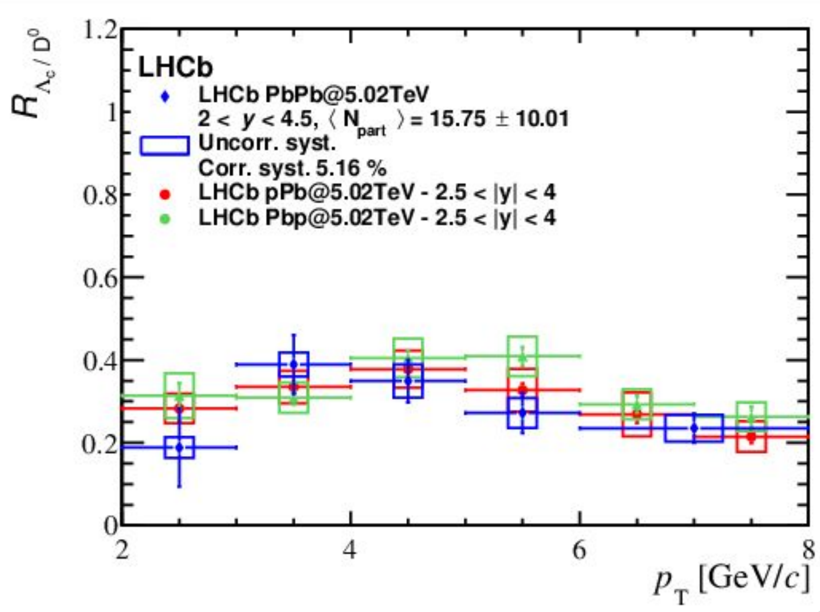
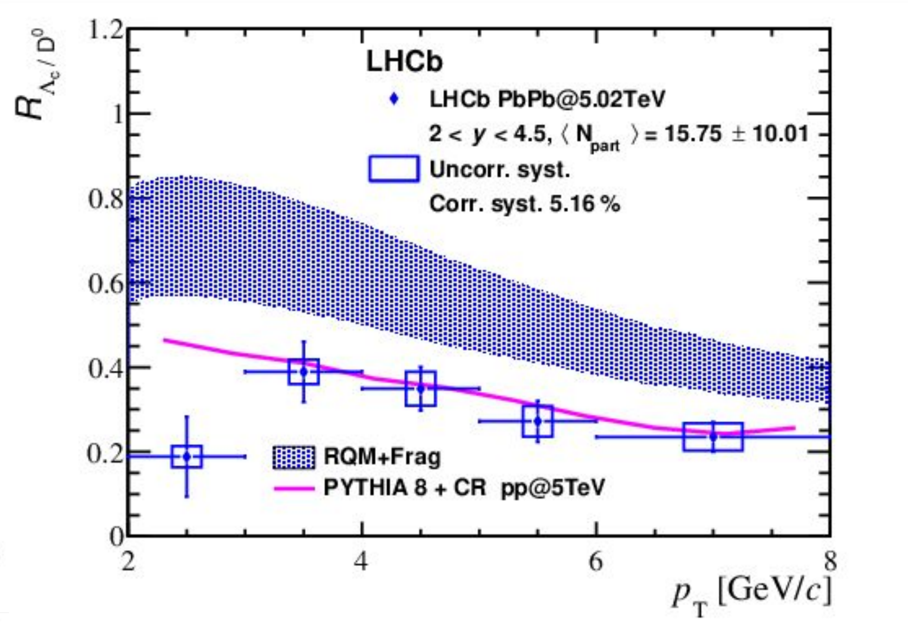
Λ_c/D^0 in PbPb

- No strong multiplicity dependence observed
- Color Reconnection outperforms SHM here





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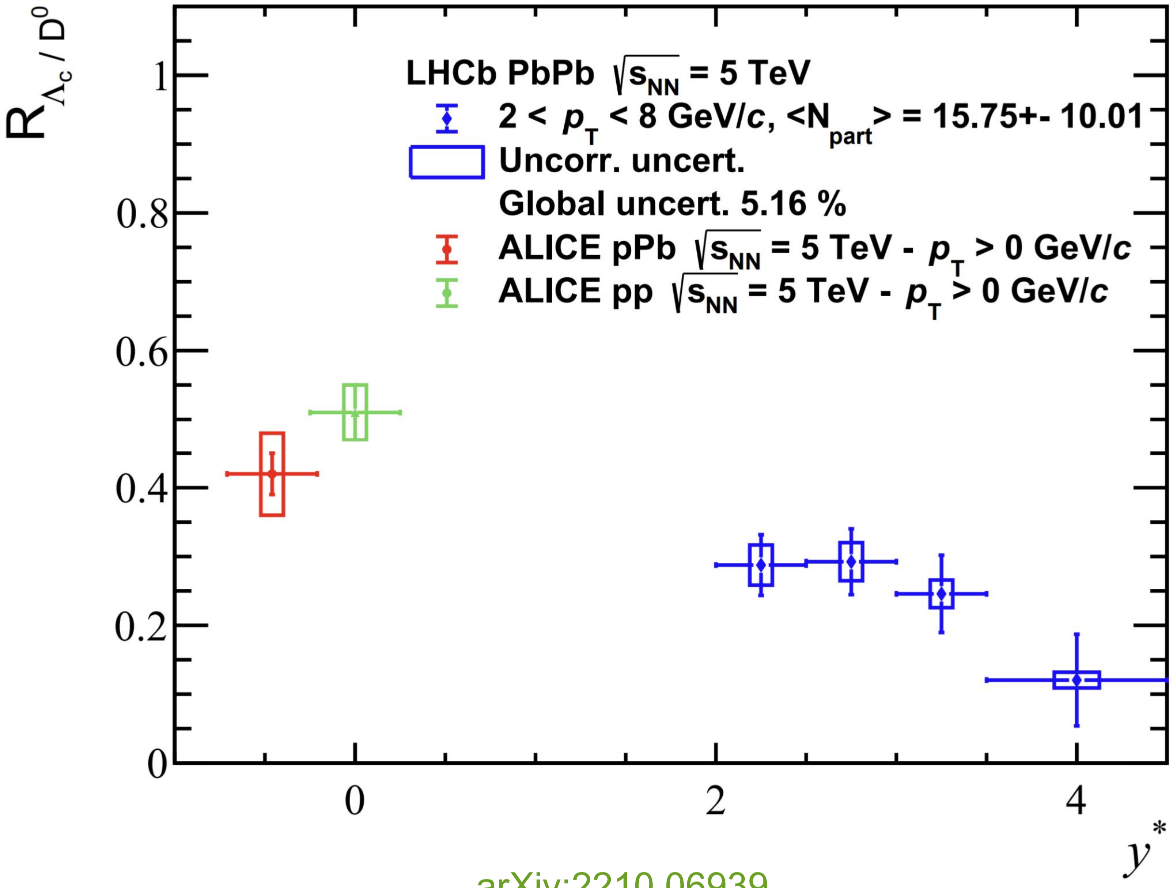

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Multiplicity and Event Characterization

Charged track multiplicity has monotonic correspondence with number of participating nucleons per collision

- Glauber model fits to multiplicity distributions provide a construction for centrality classes, to distinguish events of varying participant number
- QGP and other Heavy-ion phenomena (e.g. v2) are associated with the lowest centrality (i.e. highest Npart)

This relation can be utilized for small-systems