LHCb measurements sensitive to Hadronisation and UE/MPI

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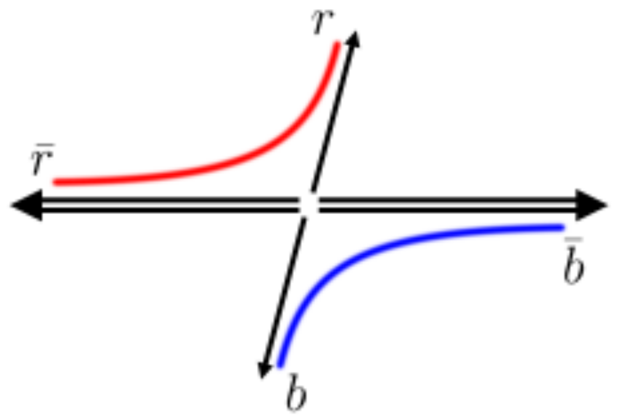
Outline

- Hadronisation
- LHCb experiment
- Enhanced production of Λ_b^0 baryons in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV
  LHCb-PAPER-2023-027
- Observation of strangeness enhancement with charmed meson in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8$ TeV
  LHCb-PAPER-2023-021
- Evidence for modification of b quark hadronization in High-Multiplicity pp collisions at $\sqrt{s} = 13$ TeV
  PRL 131, 061901 (2023)
- Measurement of Ξ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 8$ TeV at LHCb
  LHCb-PAPER-2022-041
- Summary

Hadronisation

How do quarks form hadrons?
- Hard processes: Factorization with in-vacuum fragmentation
- Soft particles: QCD-inspired models
- Coalescence

Soft particles
- Non-perturbative regime
- MC dependent mechanism
  - String model
  - Cluster formation

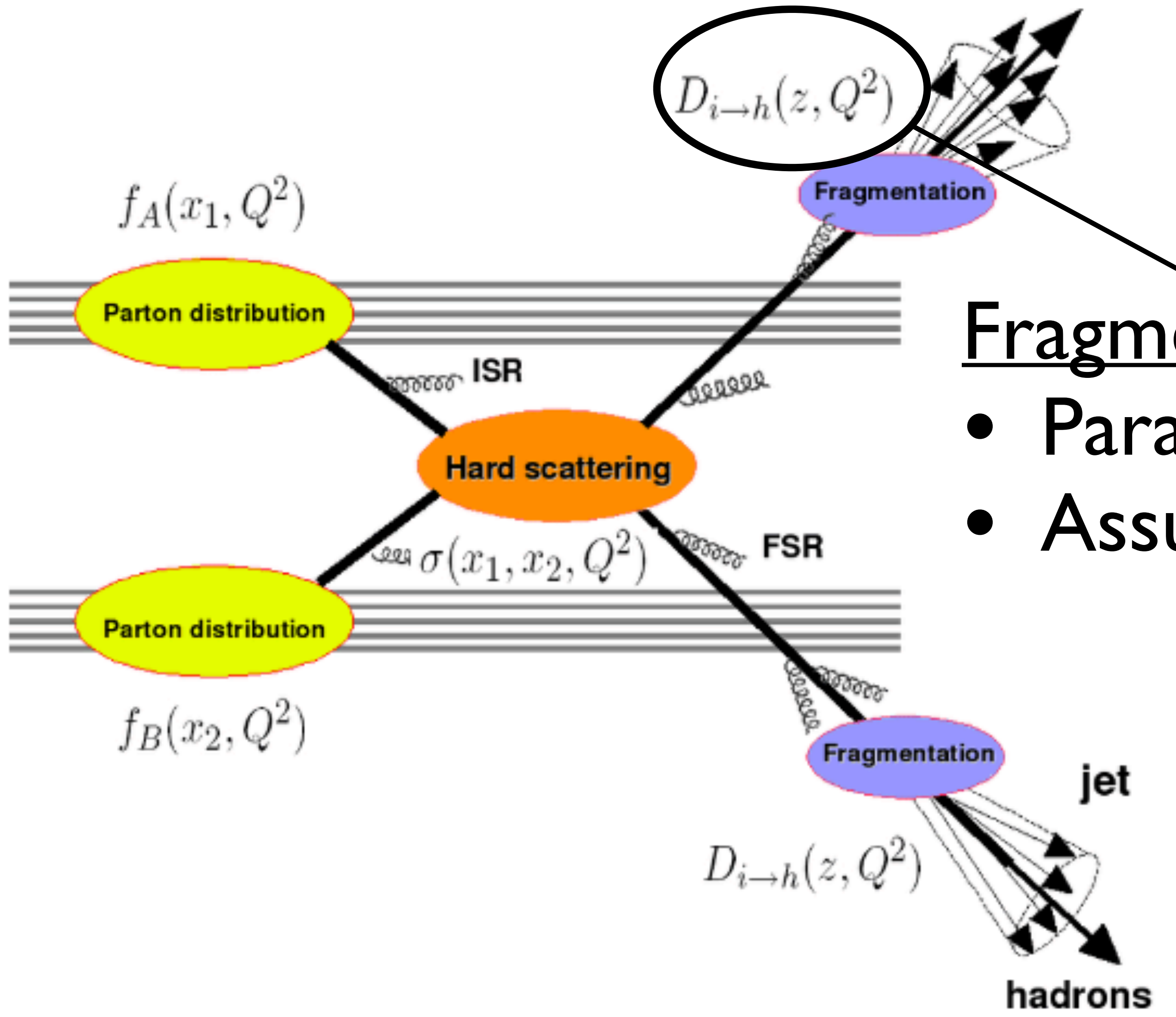


PYTHIA: Lund string model

Hard processes

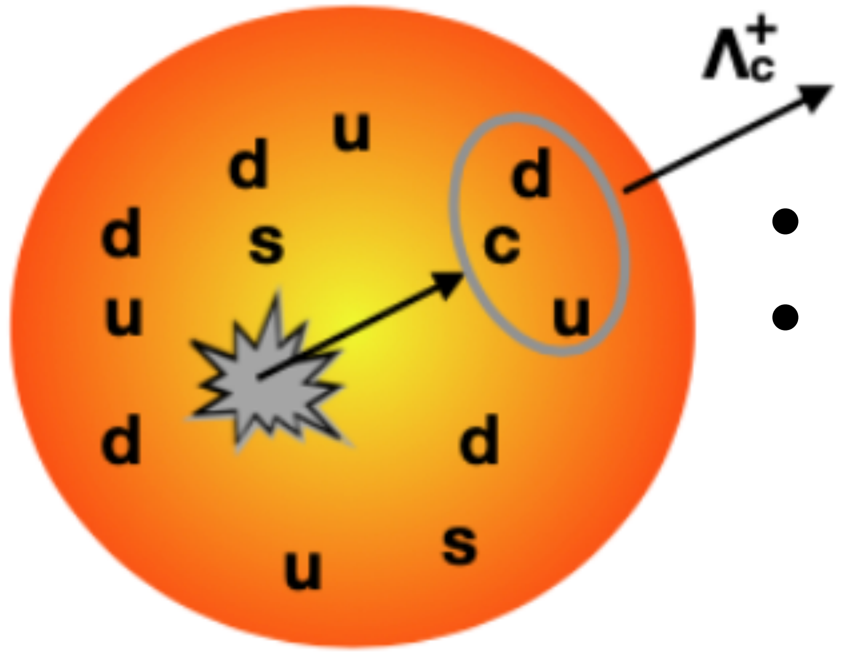
pQCD

$$\sigma_{pp\to hx} = PDF(x_a, Q^2)\cdot PDF(x_b, Q^2)\cdot \sigma_{ab\to q\bar{q}}\cdot D(z, Q^2)$$



Fragmentation function:
- Parametrized on data
- Assumed to be "universal"

Coalescence: Quarks joining by phase space proximity

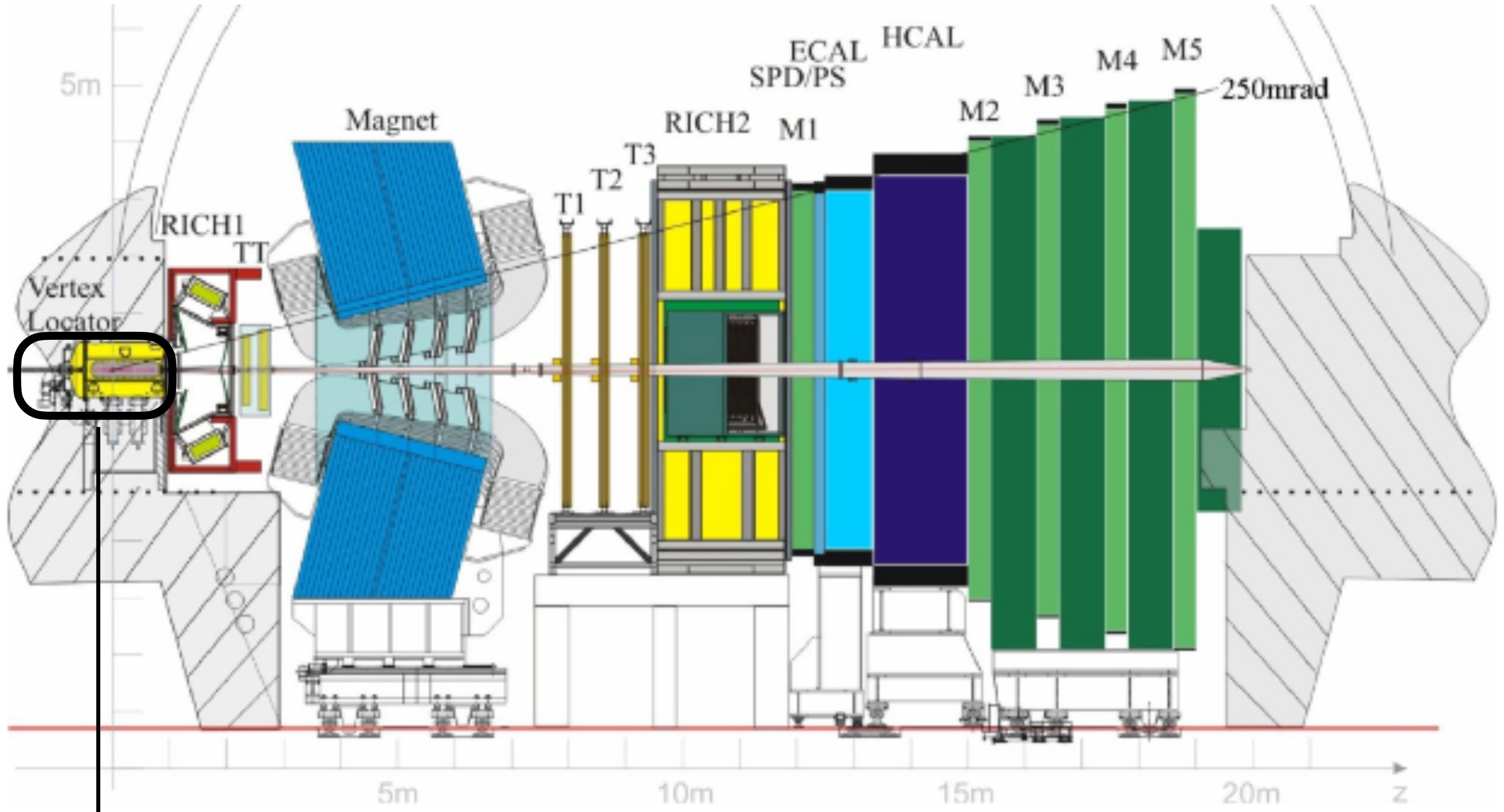


- Initially proposed in QGP
- Some measurements in small systems are compatible with this picture

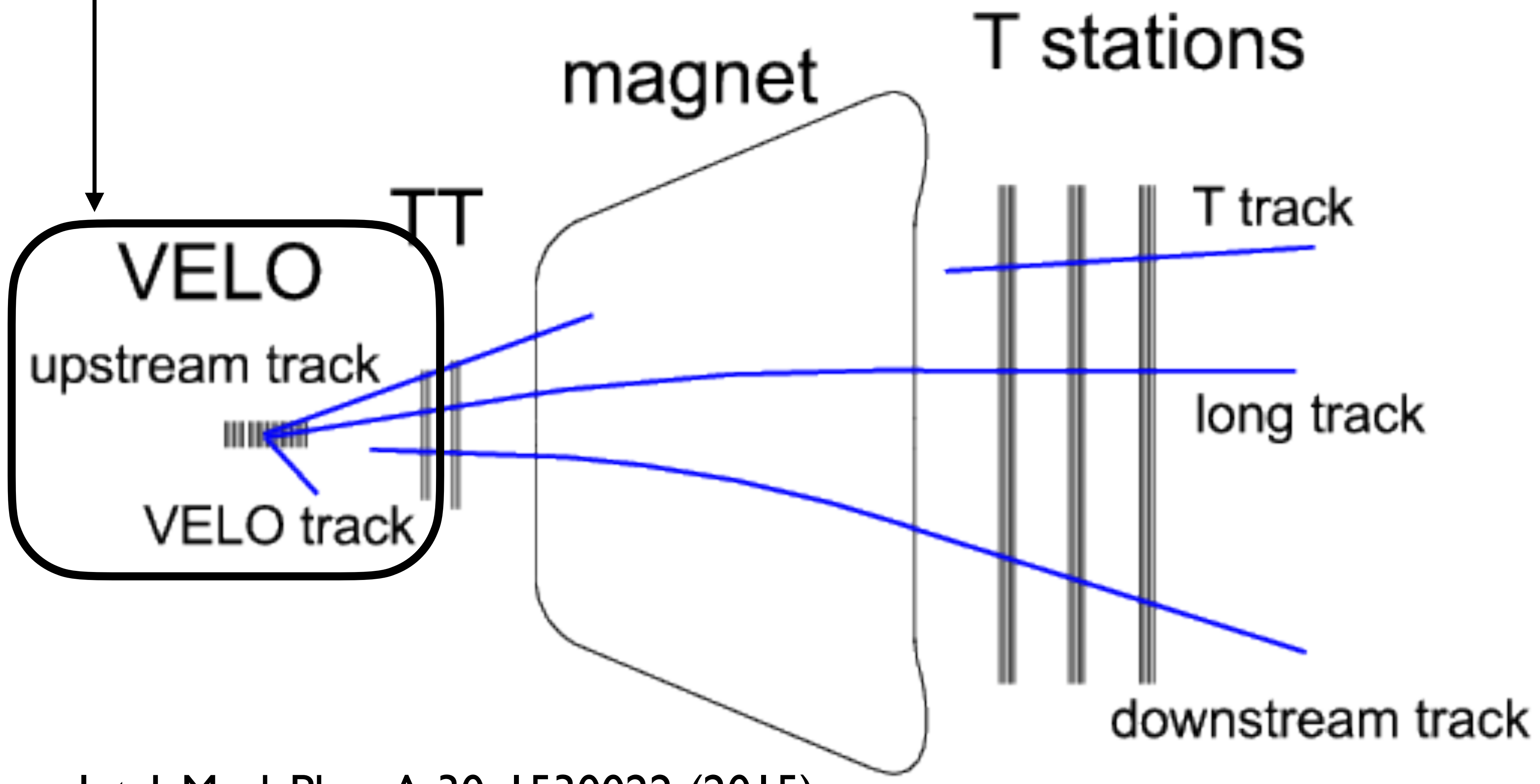
Annual Review of Nuclear and Particle Science 2008 58:1, 177-205

What is the role of coalescence in small systems ?

LHCb experiment



JINST 3 (2008) S08005

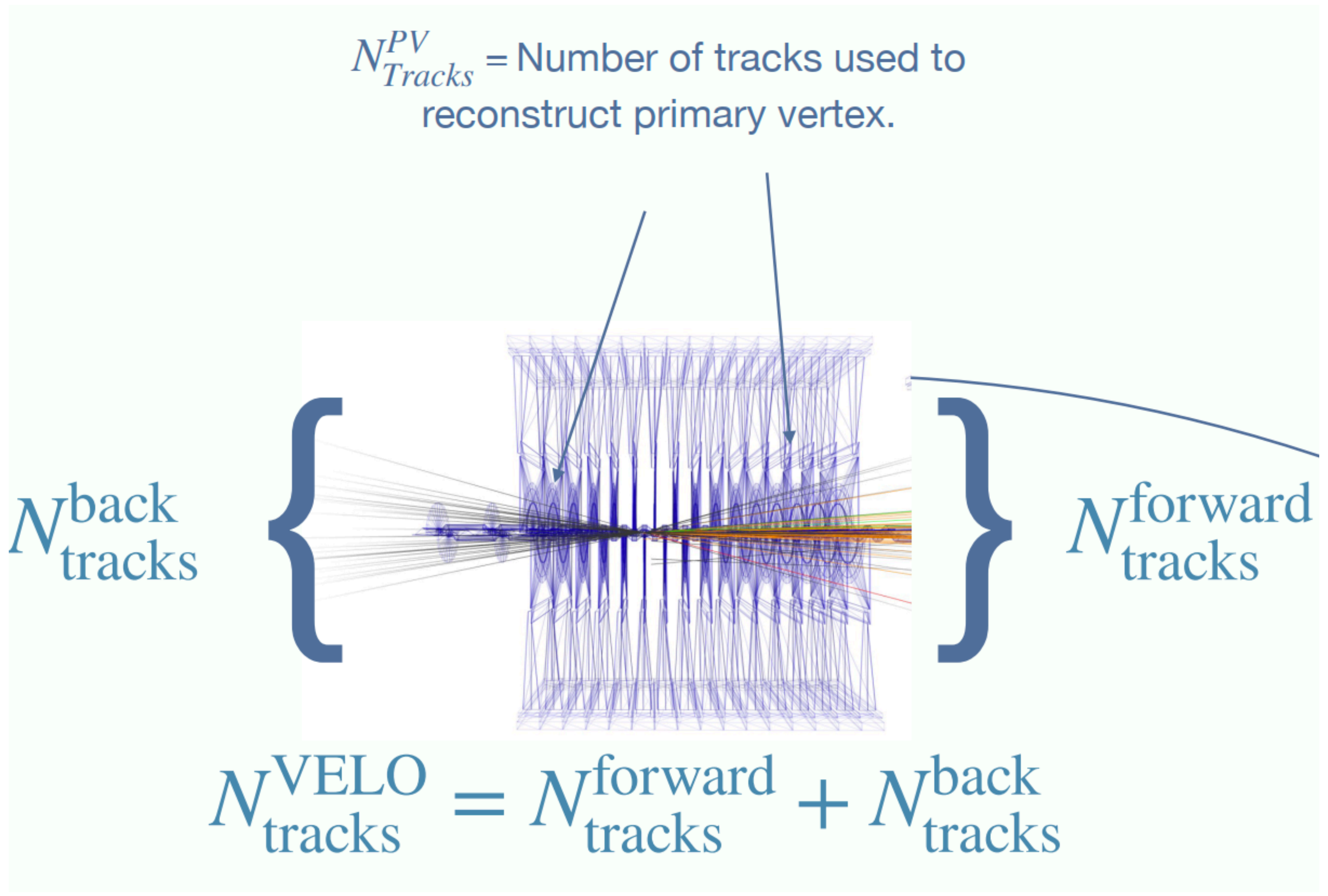


Int. J. Mod. Phys. A 30, 1530022 (2015)

Different tracks in the LHCb experiment

LHCb experiment

- Genial purpose experiment in the forward region, $\eta \in [2,5]$
- Several collisions modes: pp, pPb, PbPb and fixed target modes
- Momentum resolution: $\Delta p/p = 0.5 - 1\,\%$, $p \in [2, 200]\,\mathrm{GeV/c}$
- Primary vertex resolution: $\in [10, 35]\,\mu\mathrm{m}$
- ECAL energy resolution: arXiv:2008.11556
  $13.5\,\%/\sqrt{E/GeV} \oplus 5.2\% \oplus (0.32\,\mathrm{GeV})/E$



Multiplicity selection in forward and backward regions

LHCb experiment

- Q^2: exchanged moments between interacting partons
- x: momentum fraction of the parton with respect to nucleus

$$Q^2 \sim m^2 + p_T^2, \quad x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$$

- **LHCb coverage**
  - Forward, $10^{-6} \leq x \leq 10^{-4}$
  - Backward, $10^{-3} \leq x \leq 10^{-1}$

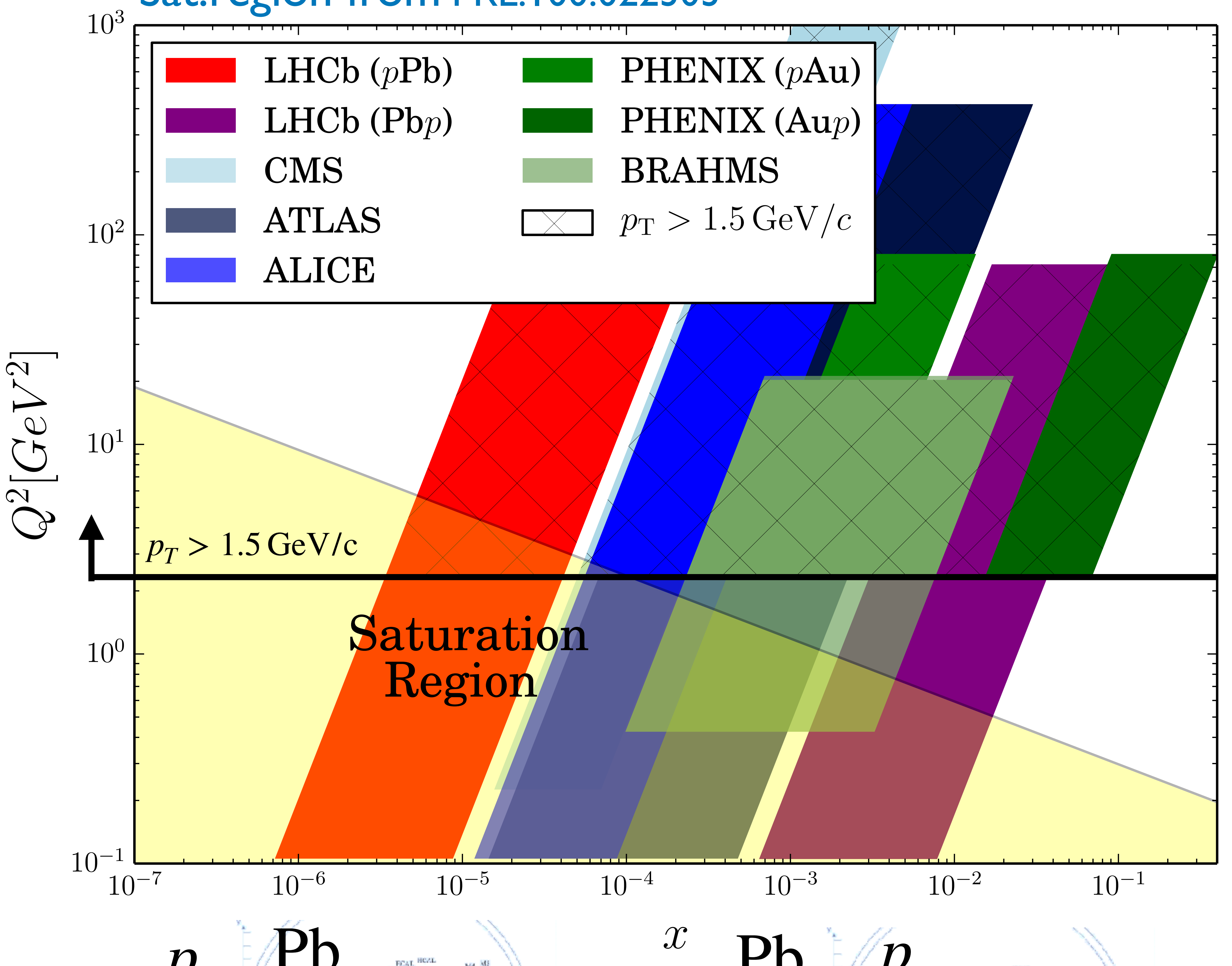
↓

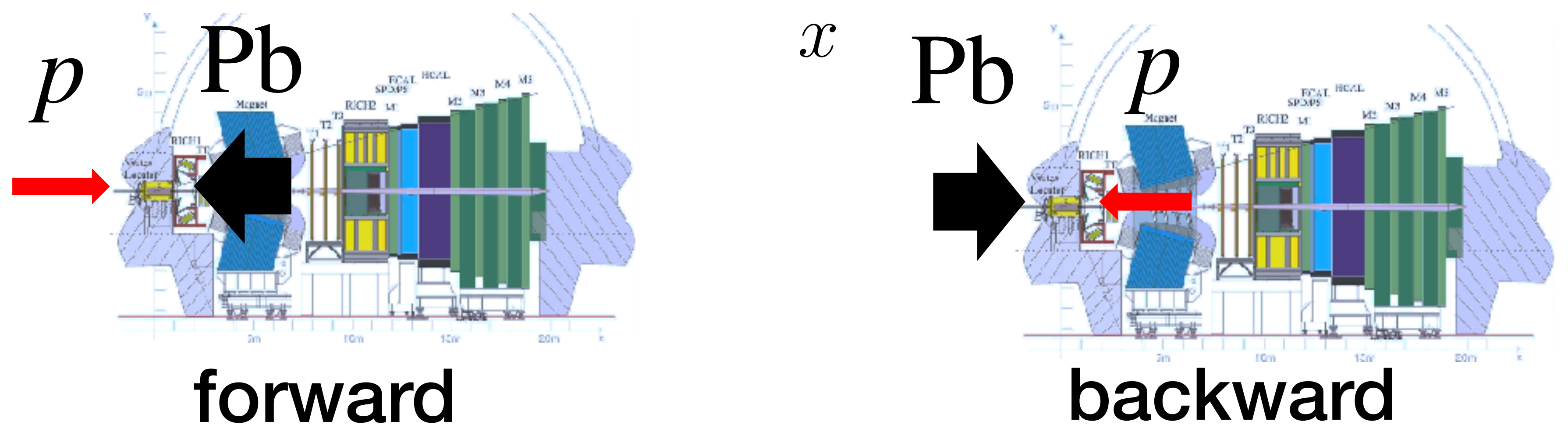
Unique access to low-x physics

LHCb particular capabilities

- Charged and neutral hadron production at small-x
- Capability to study one system in a wide range of x values:
  - Forward/Backward comparison
- Possible access to the *saturation region* →Non-linear dynamics

Sat.region from PRL.100.022303



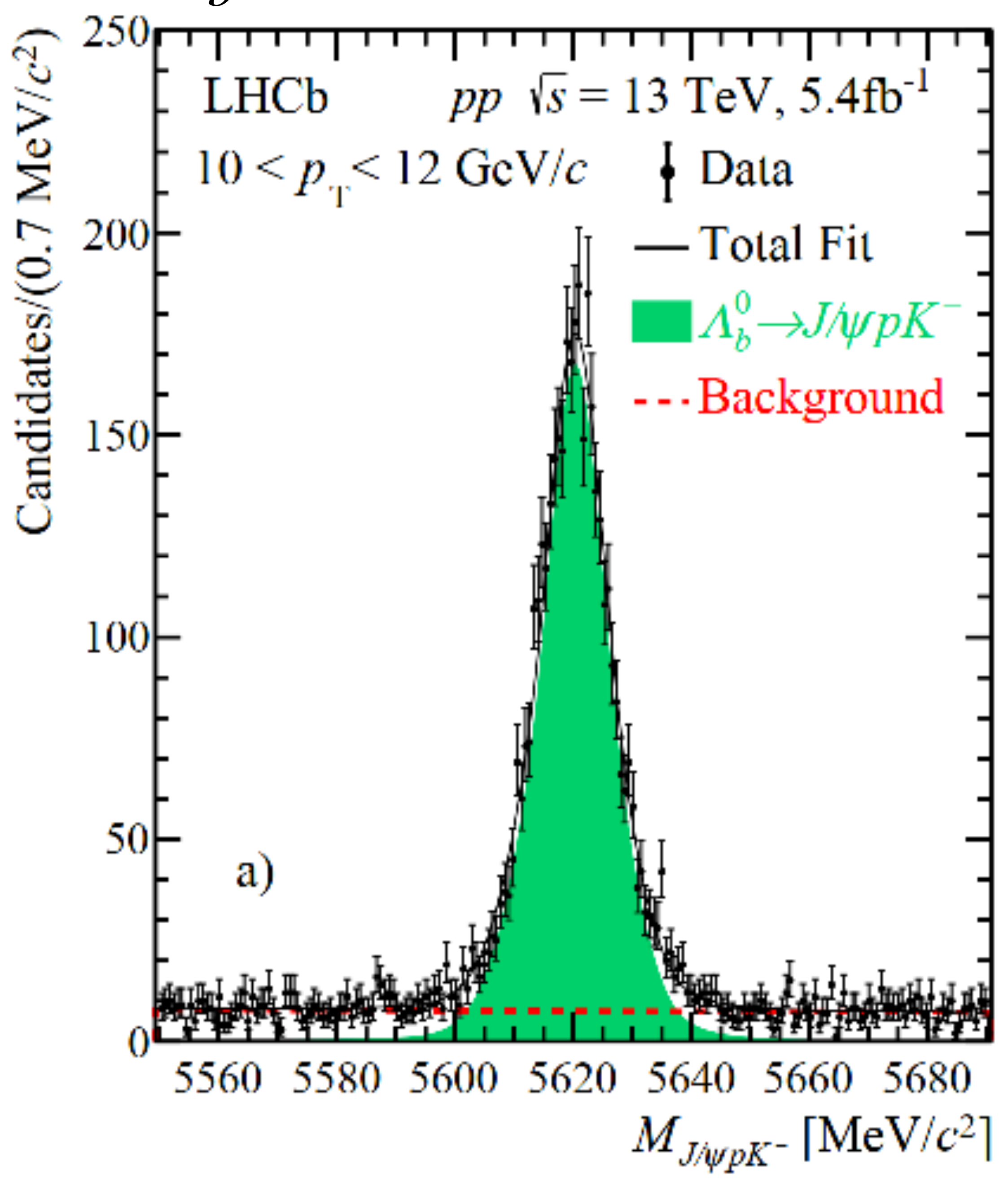


We have a higher multiplicity at backward than at forward

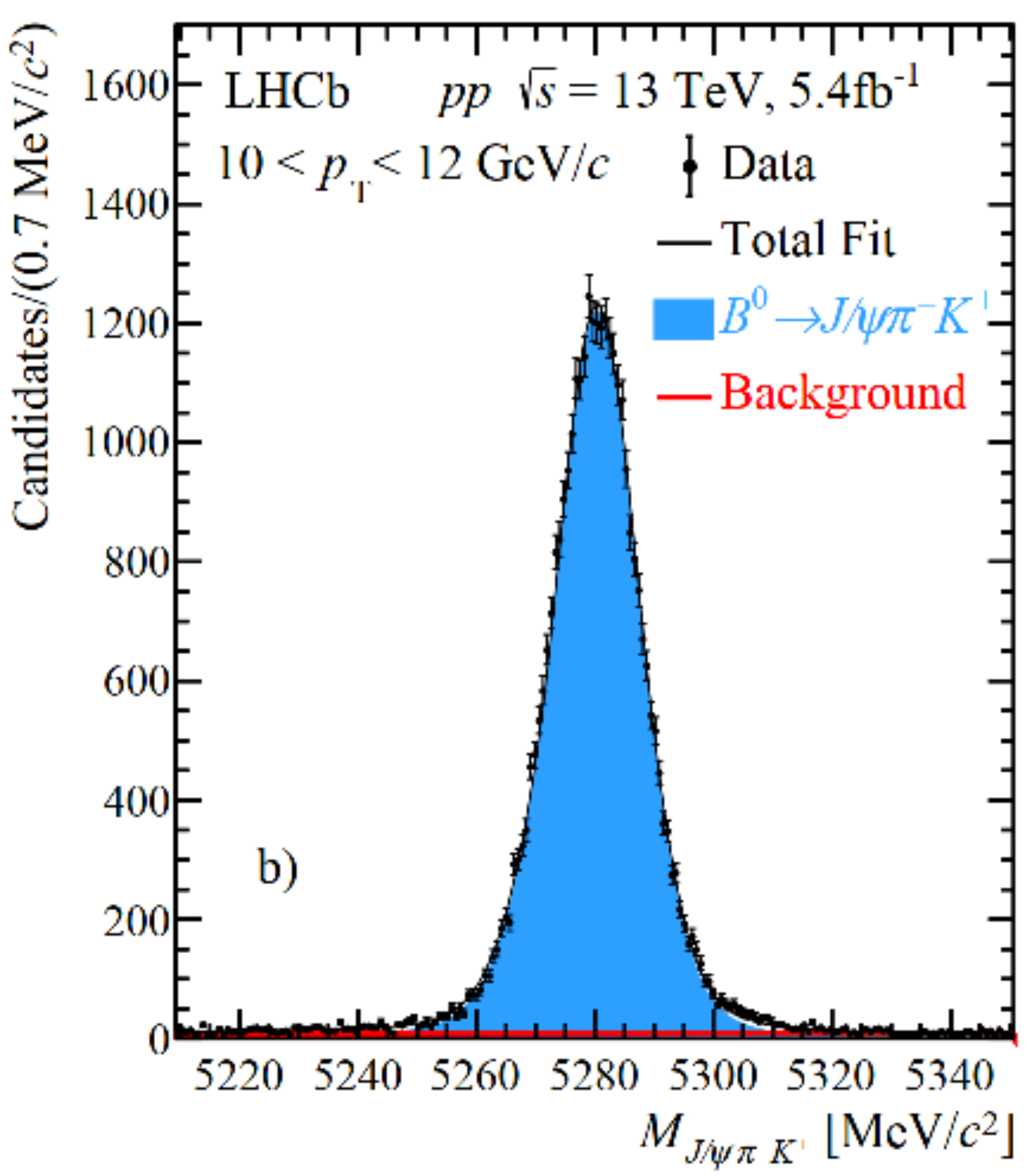
B quark hadronisation

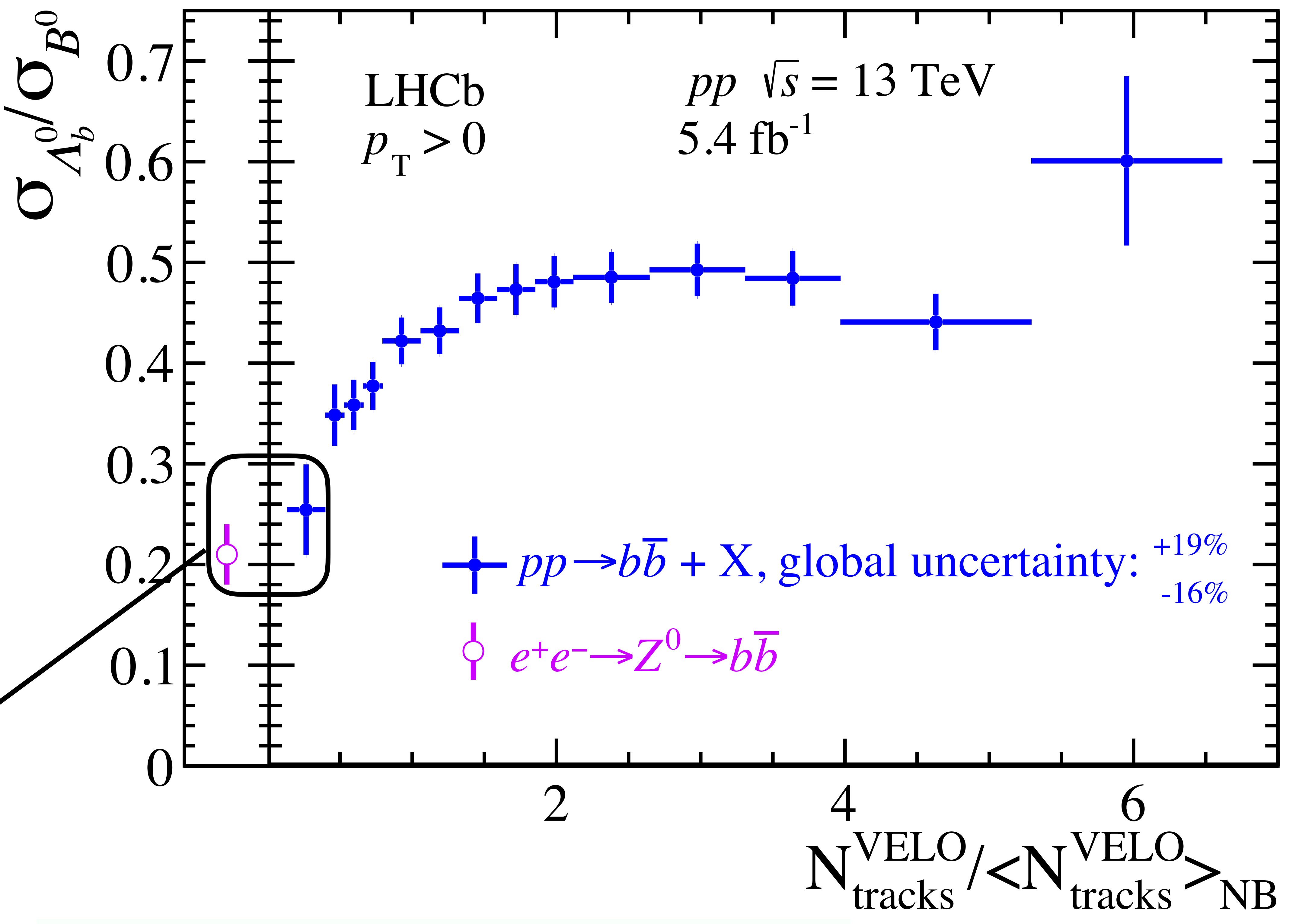
LHCb-PAPER-2023-027

$\Lambda_b^0(5619) = udb$



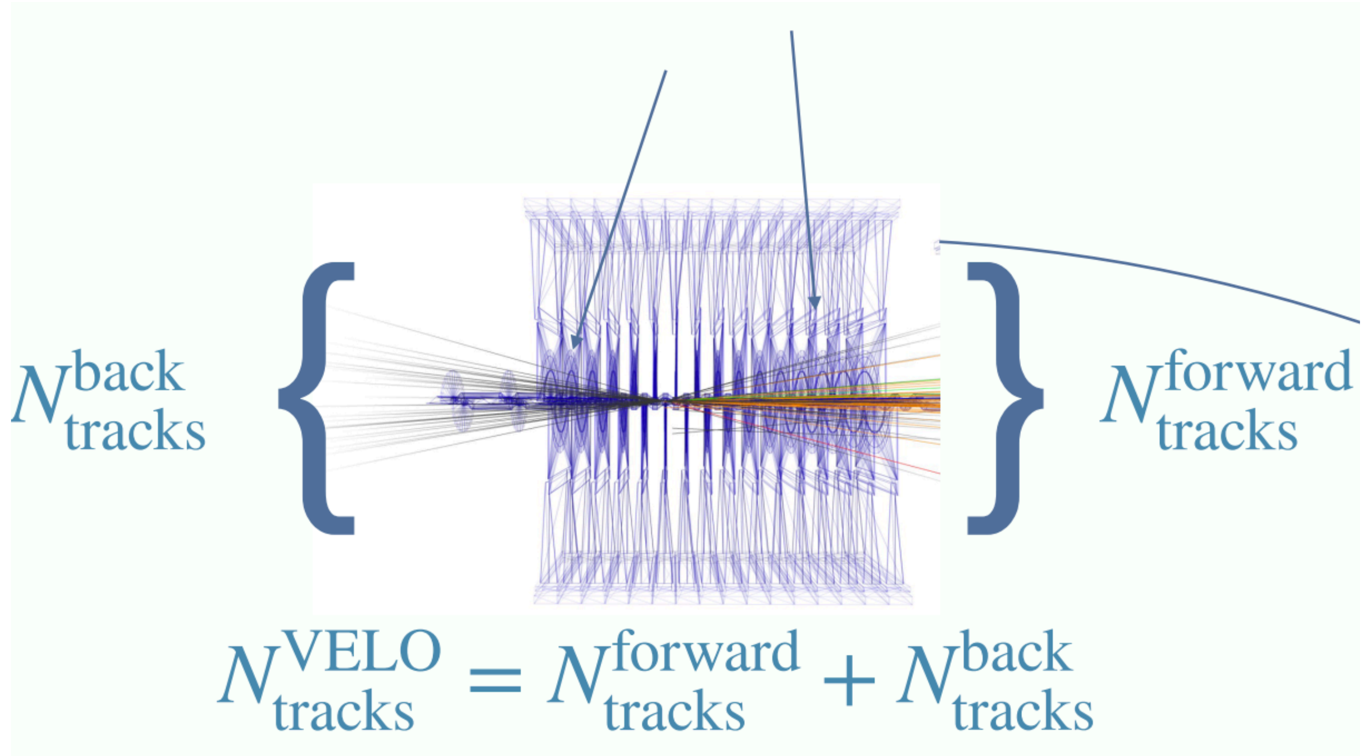
$B_0(5279) = d\bar{b}$





No bias

- Λ_b^0/B^0 production ~100% enhancement with multiplicity
- e+e-: Only fragmentation scenario
- Very low multiplicity events are compatible to e+e-
- Is coalescence emerging a an hadronization mechanism for Λ_b^0 at high multiplicities ?



What do we learn from these studies?

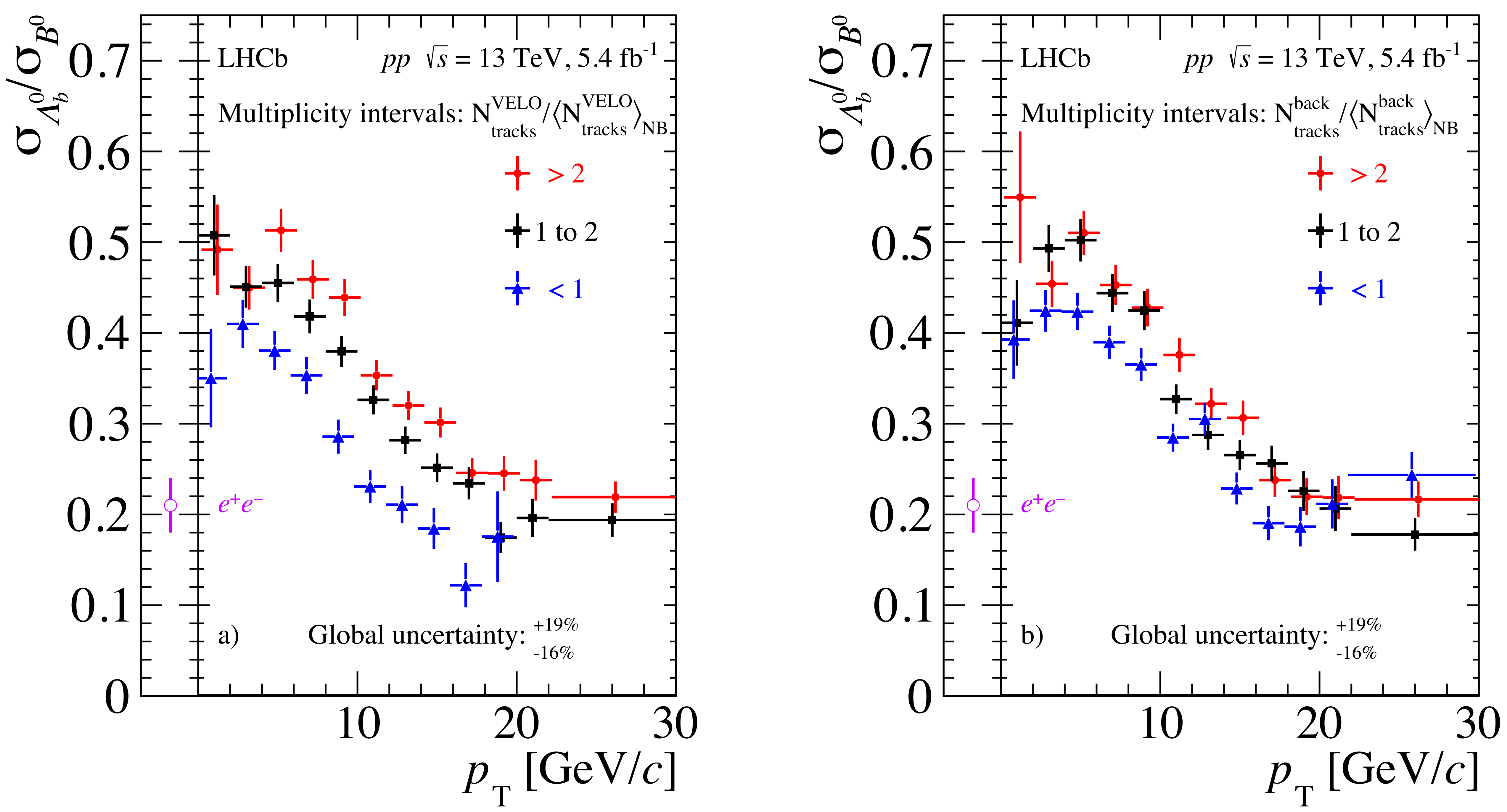
Fragmentation may be not enough to explain B-quark hadronization at LHC

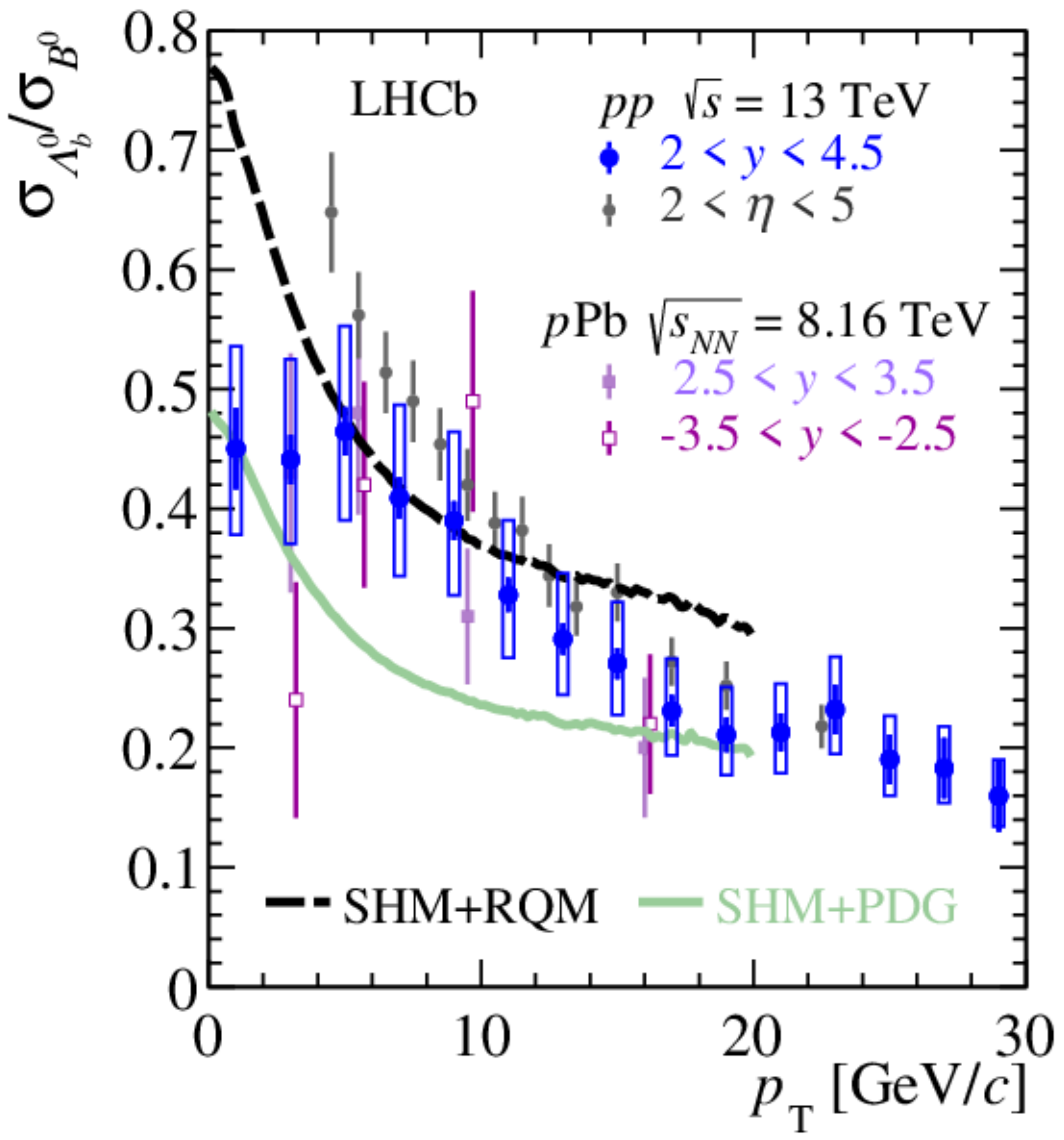
B quark hadronisation

LHCb-PAPER-2023-027

- Systematic uncertainties dominate for $p_T < 18$ GeV/c, with statistical uncertainties becoming dominant at higher pT
- High-pT region is compatible with e+e- result: Fragmentation dominant
- Strong enhancement at low-pT
- The higher the multiplicity the bigger the enhancement
- Weaker multiplicity dependence with backward VELO tracks

$\Lambda_b^0(5619) = udb$; $B_0(5279) = d\bar{b}$



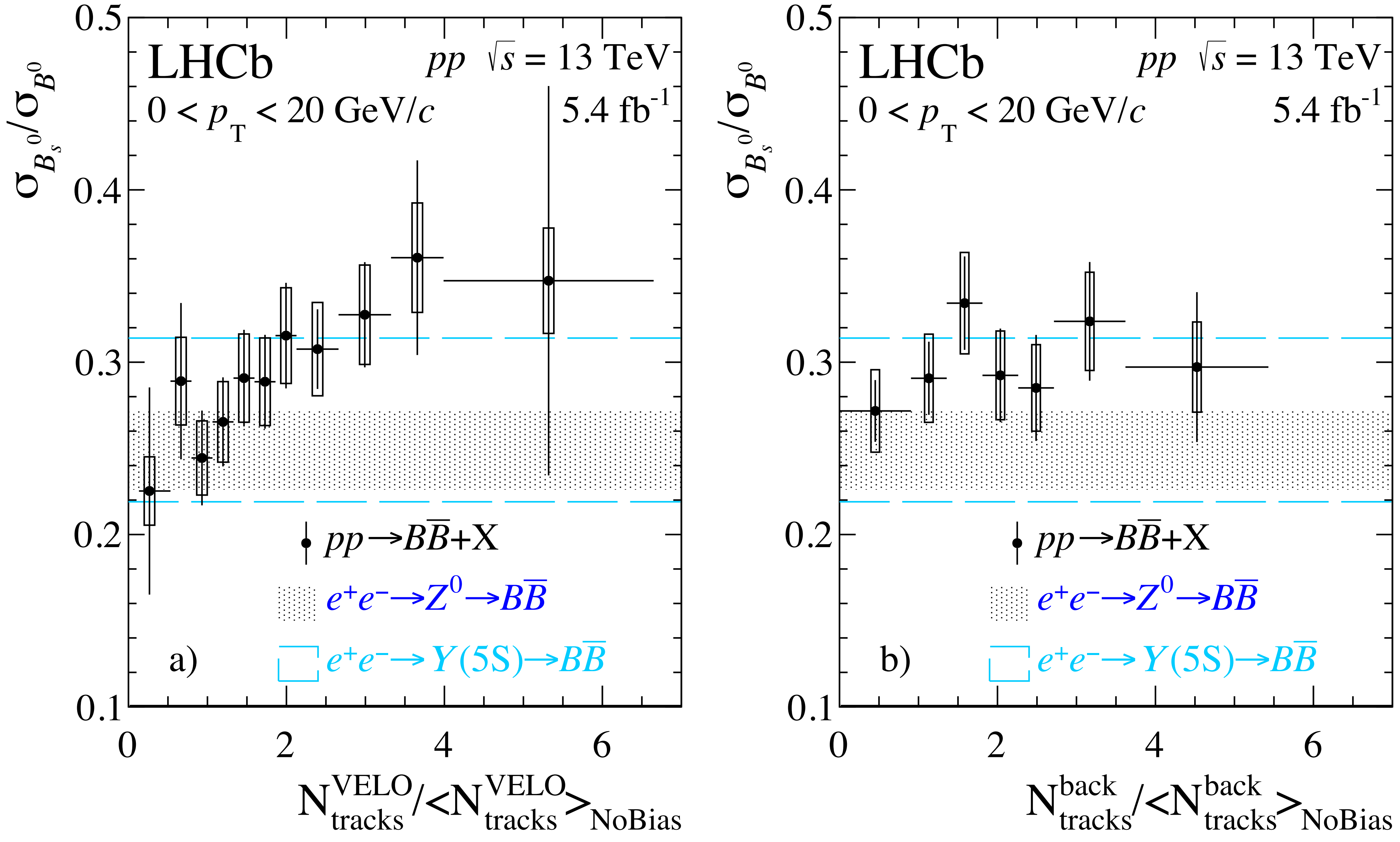


- Λ_b^0/B^0 (blue points) is consistent with previous LHCb pp, pPb results
- The green solid curve uses the measured spectrum of baryons collected by Particle Data Group (PDG).
- The black dashed curve uses the expanded set of excited states from the Relativistic Quark Model (RQM).
- The enhancement of RQM relative to the PDG is attributed to the feed down from thus far unobserved excited b baryons.
- LHCb data tend to favor RQM at $p_T < 15$ GeV/c

B quark hadronisation

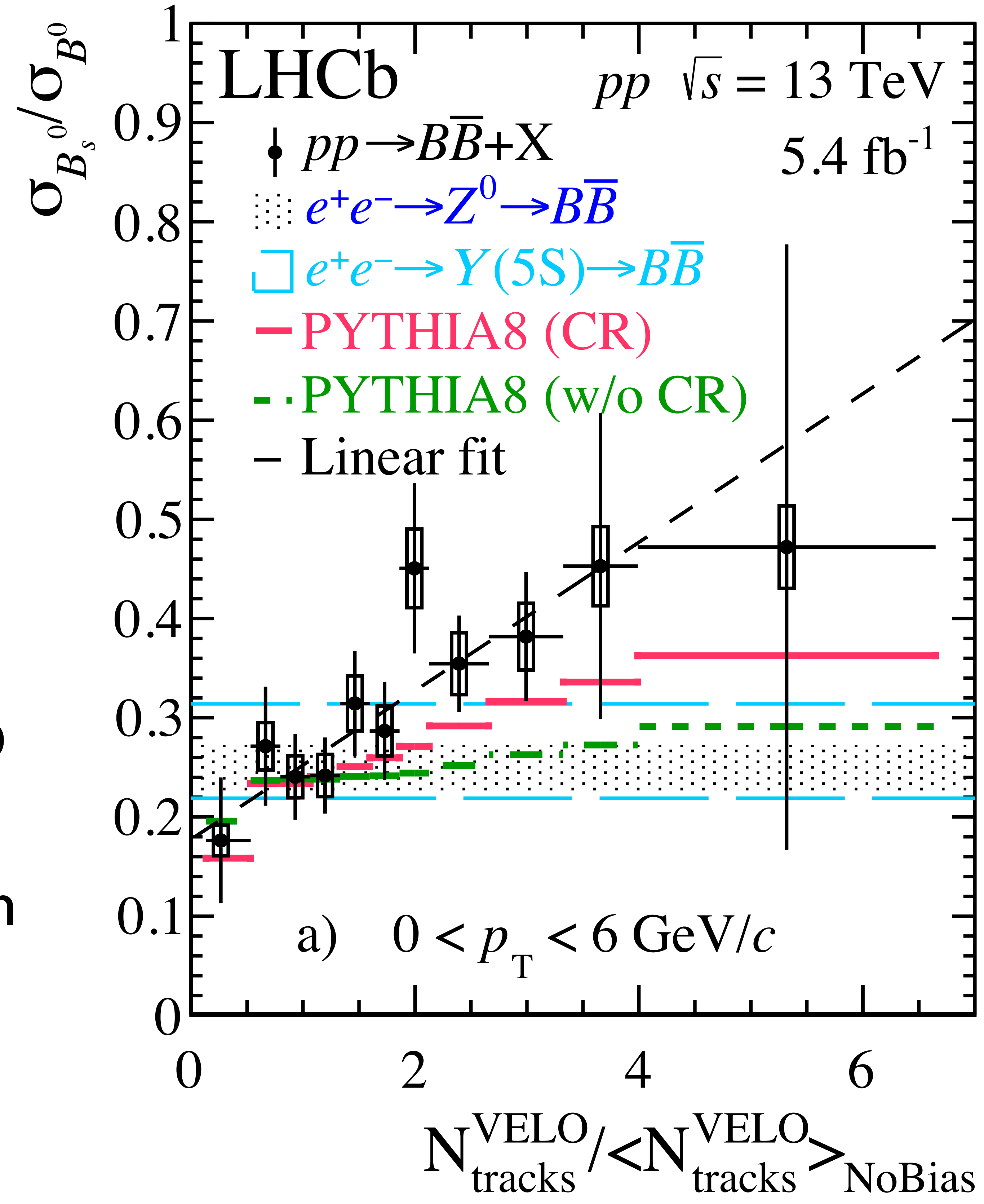
Phys. Rev. Lett. 131, 061901

- B_s^0/B^0 ratio is constant with multiplicity from pQCD
- An increasing trend with multiplicity is observed at LHCb data
- The trend is stronger when measuring as a function of VELO tracks than using only backward tracks
- More data is needed in order to draw a conclusion. Run3 ?



VELO tracks

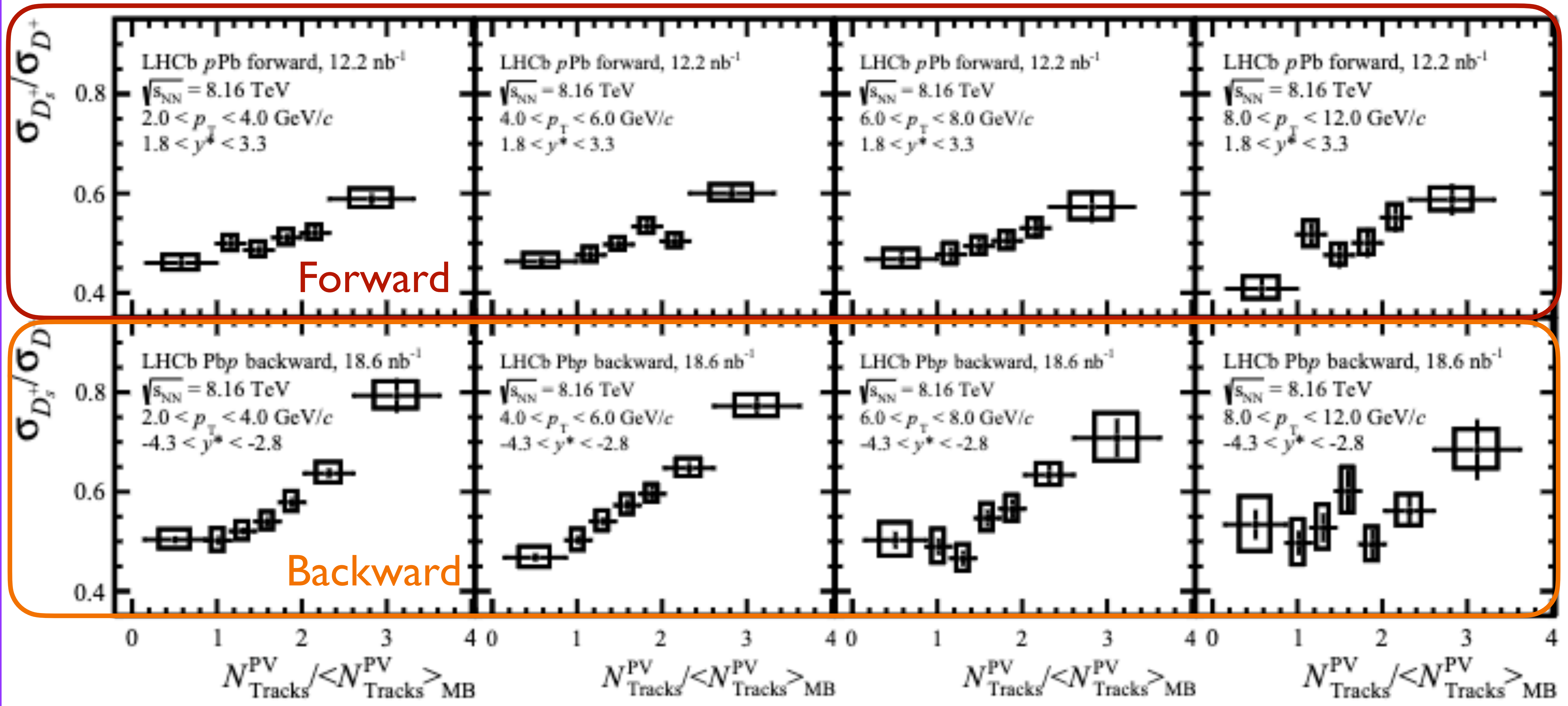
Backward VELO tracks



- B_s^0/B^0 ratio is sensitive to different MPIs models
- Color Reconnection from PYTHIA predicts a stronger increasing for B_s^0/B^0 ratio with multiplicity
- However, we don't have enough precision to discriminate between both models

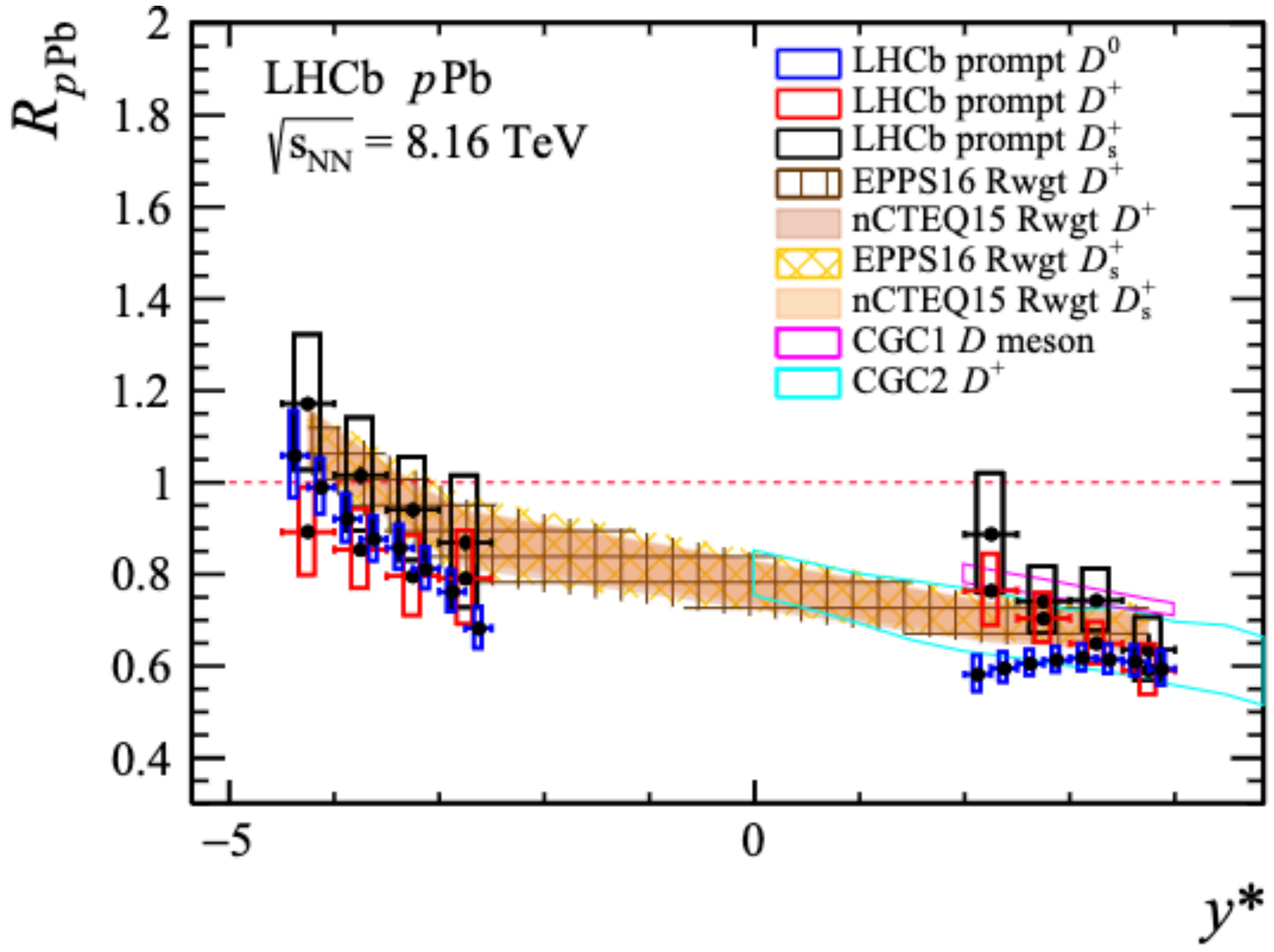
Strangeness enhancement in pPb

LHCB-PAPER-2023-021-002



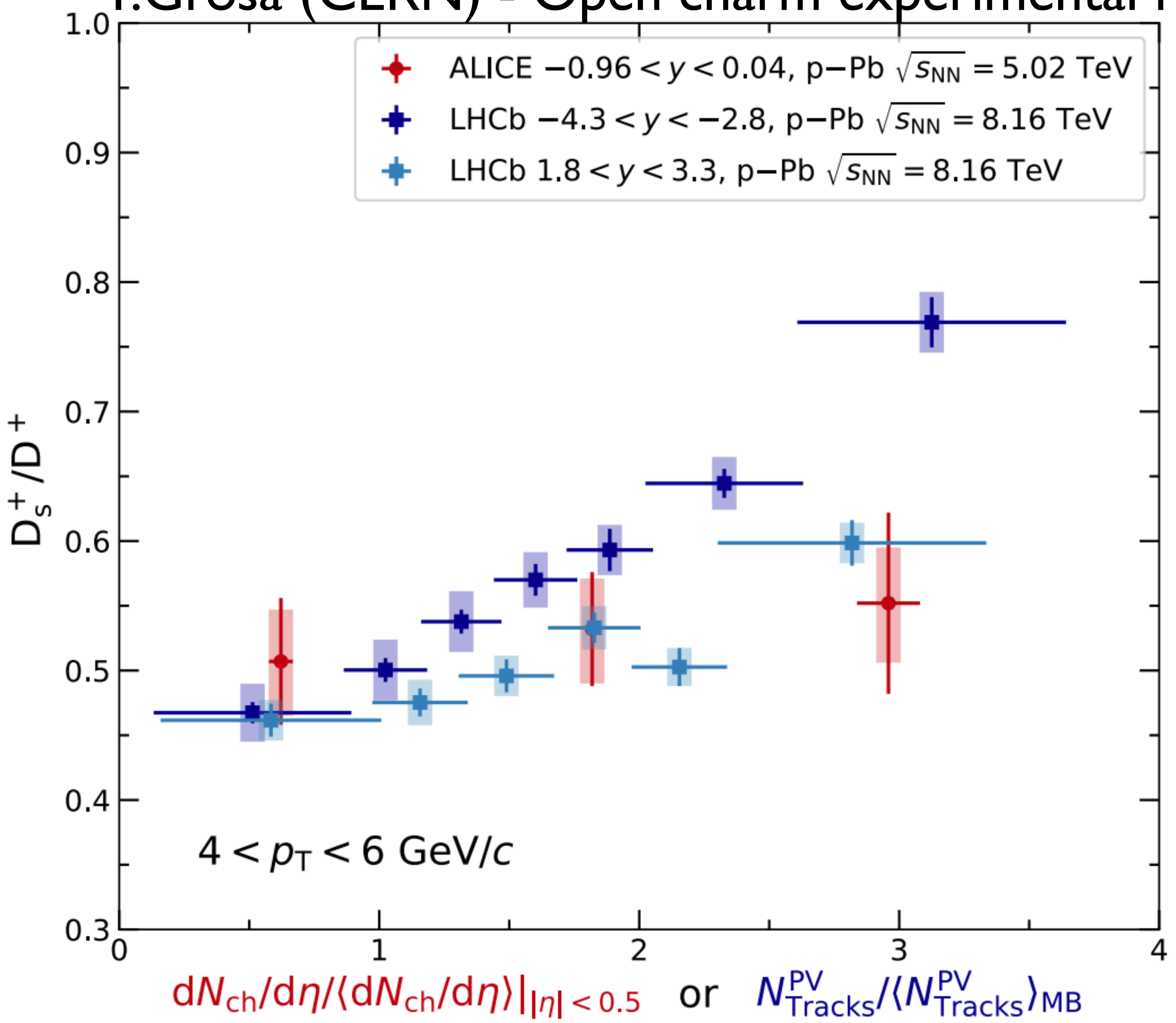
- N^{PV}_{Tracks} → Number of tracks used to reconstruct the primary vertex
- D_s^+/D^+ ratio increases with multiplicity
- Stronger enhancement of D_s^+/D^+ ratio in the backward rapidity
- Does it implies a modification of charm quark hadronization in high multiplicity pPb collisions?

- $R_{pPb} = \frac{1}{A}\frac{d^2\sigma_{pPb}(p_T, y)/dp_T dy}{d^2\sigma_{pp}(p_T, y)/dp_T dy}$
- R_{pPb} is consistent with nPDFs calculations in the forward region
- However, the LHCb result is smaller than the predictions in the backward high pT region
- An interpolation between $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV is done using a power law
- The main systematic uncertainty comes from the pp results and interpolation



Strangeness enhancement in pPb

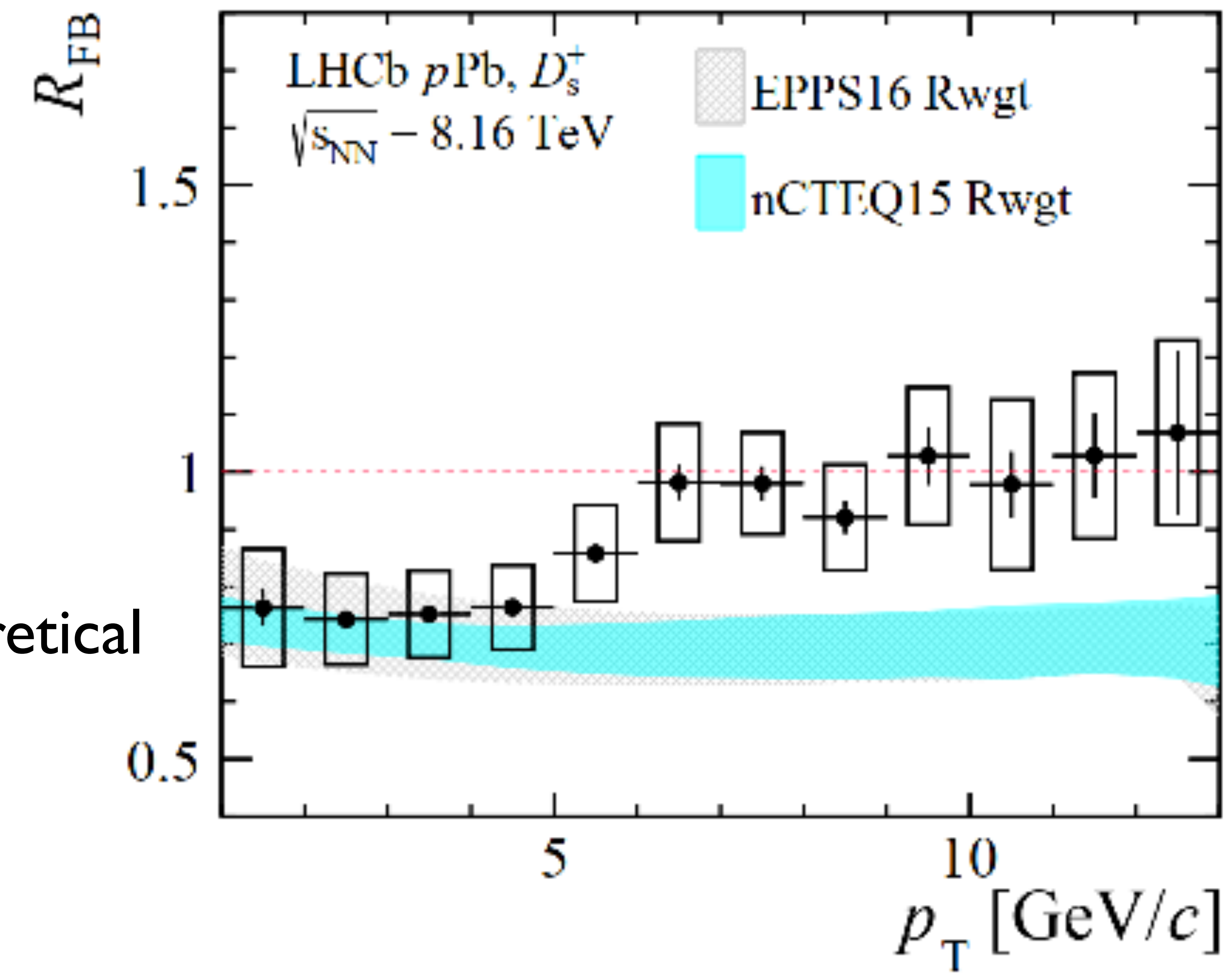
F.Grosa (CERN) - Open charm experimental review - Quark Matter 23



- In Heavy Ions (PbPb, AuAu): s quark enhancement comes from gluon fusion in QGP
- In small systems (pp, pPb): s quark enhancement is not fully explained yet

- ALICE data does not show a strangeness enhancement in the mid-rapidity region
- LHCb data in the forward region agrees with ALICE
- LHCb sees a strangeness enhancement in the backward region
  - Wider multiplicity range
  - Better precision

LHCB-PAPER-2023-021-002

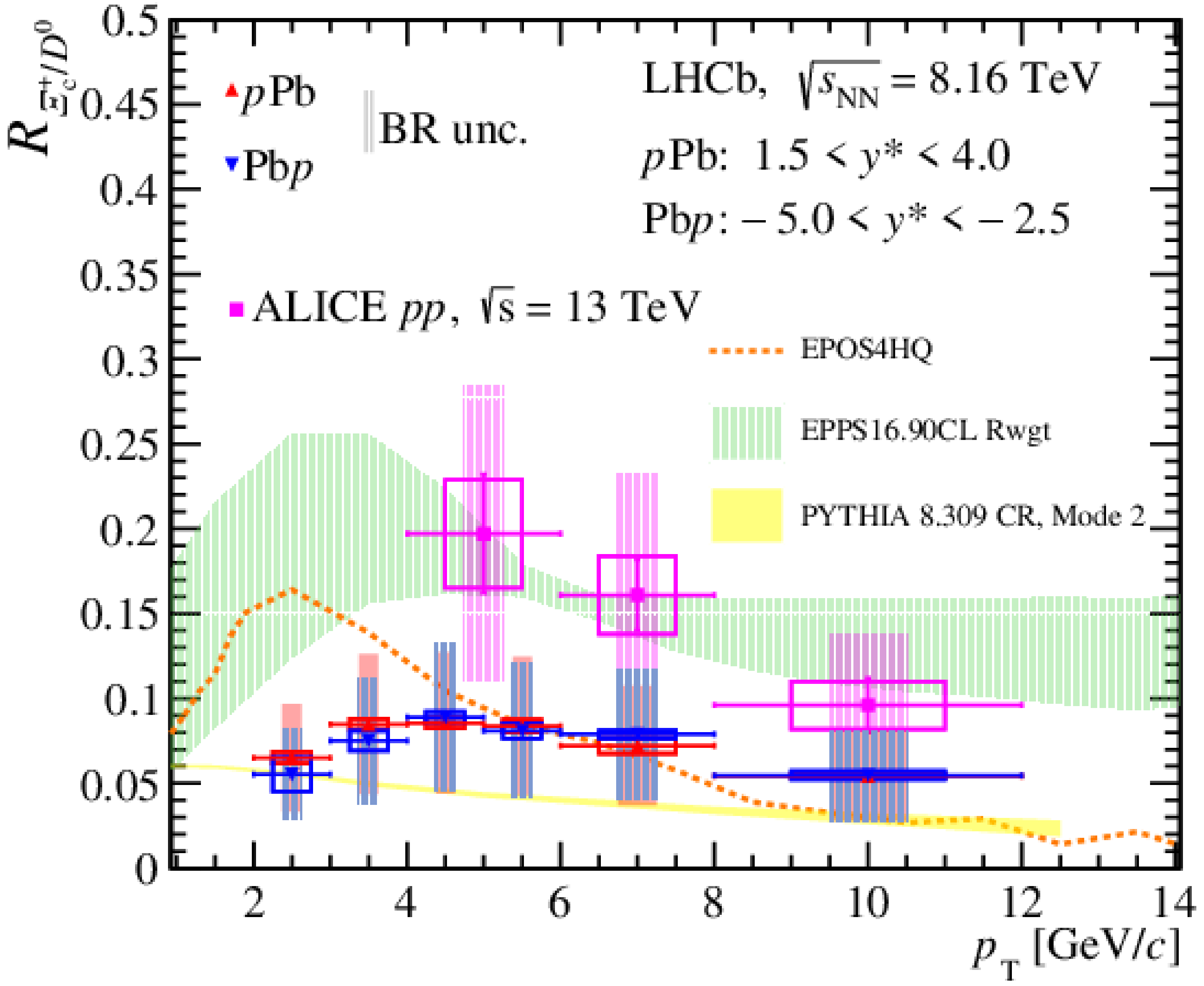


- $$R_{FB} = \frac{d^2\sigma_{pPb}(p_T, +y)/dp_T dy}{d^2\sigma_{Pbp}(p_T, -y)/dp_T dy}$$
- R_{FB} shows a rising trend with pT. Consistent with nPDFs at low PT, larger than theoretical calculations at high pT
- Potential explanations for backward production suppression:
  - Weaker anti-shadowing effect in initial state.
  - Higher energy loss for backward in final state (high pT → low pT)

Measurement of Ξ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 8$ TeV at LHCb

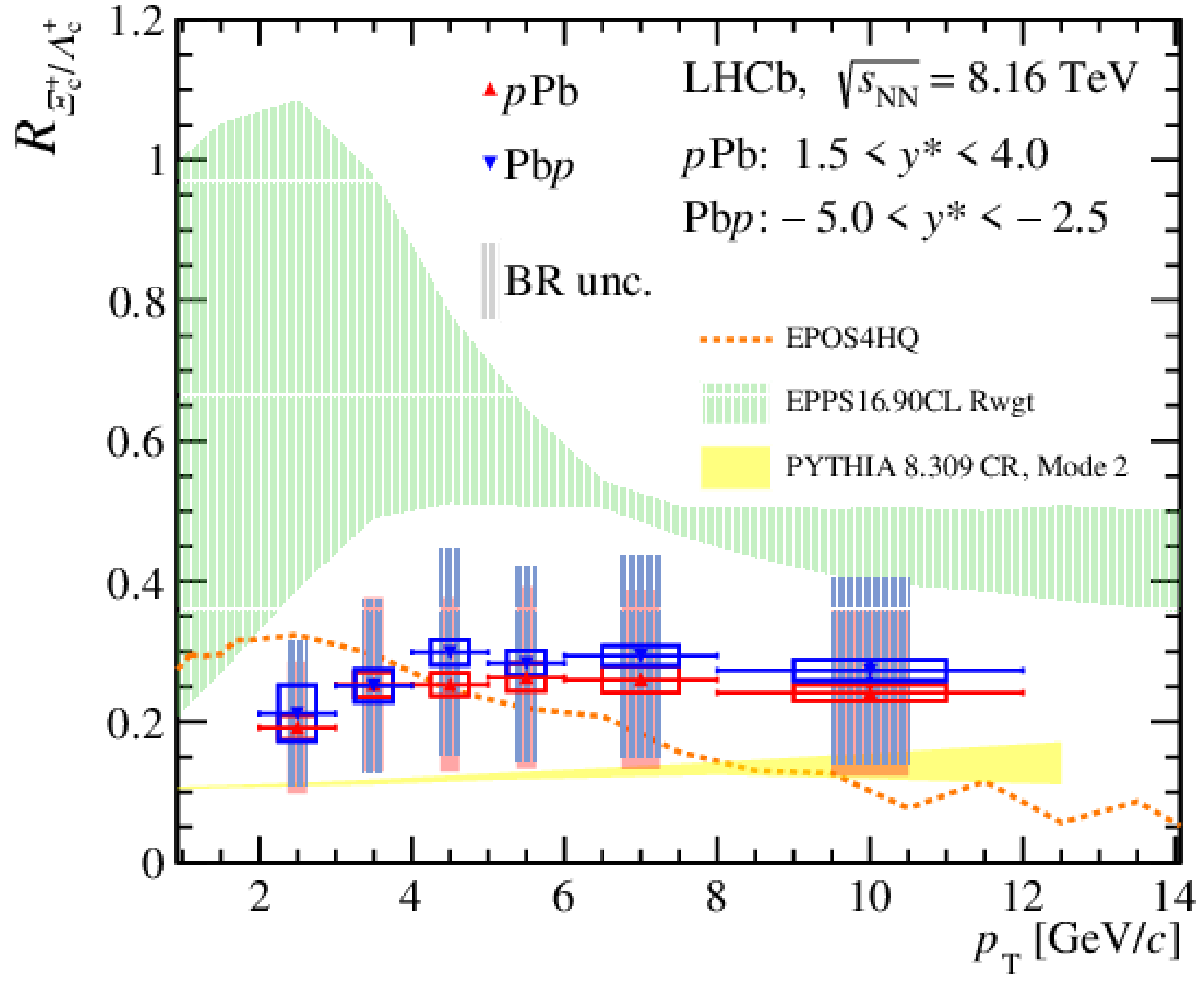
LHCb-PAPER-2022-041

Ξ_c^+(usc) ; $D^0(c\bar{u})$



- Forward and backward results are compatible
- LHCb result for $R_{\Xi_c^+/D^0}$ is systematically lower than ALICE
- The error bars represent the statistical uncertainties, while the boxes indicate the systematic uncertainty
- Low-pT measurement constrains EPPS prediction

Ξ_c^+(usc) ; Λ_c^+(udc)



- EPPS16 model shows a similar trend, but significantly overestimates the data
- Pythia 8.3 with colour reconnection (CR) beyond the leading-colour approximation underestimated the ratio
- EPOS4HQ, the heavy quark extension of the new EPOS4 framework agrees qualitatively at $p_T > 4$ GeV/c
- This is the first time that $R_{\Xi_c^+/D^0}$ and $R_{\Xi_c^+/\Lambda_c^+}$ are measured in this system
- Low-pT measurement constrains EPPS prediction

Summary

- Quark Hadronisation mechanism could depend on Underlying Event properties
- LHCb experiment is a unique place to study this effects
- Enhanced production of Λ_b^0 baryons in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV
    - Low multiplicity and high-pT is compatible with e+e- data
    - Around 100% enhancement is observed in high multiplicity events
- Observation of strangeness enhancement with charmed meson in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8$ TeV
    - No strangeness enhancement is observed at mid-rapidity region for D meson
- Evidence for modification of b quark hadronisation in High-Multiplicity pp collisions at $\sqrt{s} = 13$ TeV
- Measurement of Ξ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 8$ TeV at LHCb

Open questions:

- Is coalescence an important hadronisation mechanism in high multiplicity small collision systems?
- Can feed-down itself explain data?
- There is a modification in quark hadronisation with pseudorapidity?

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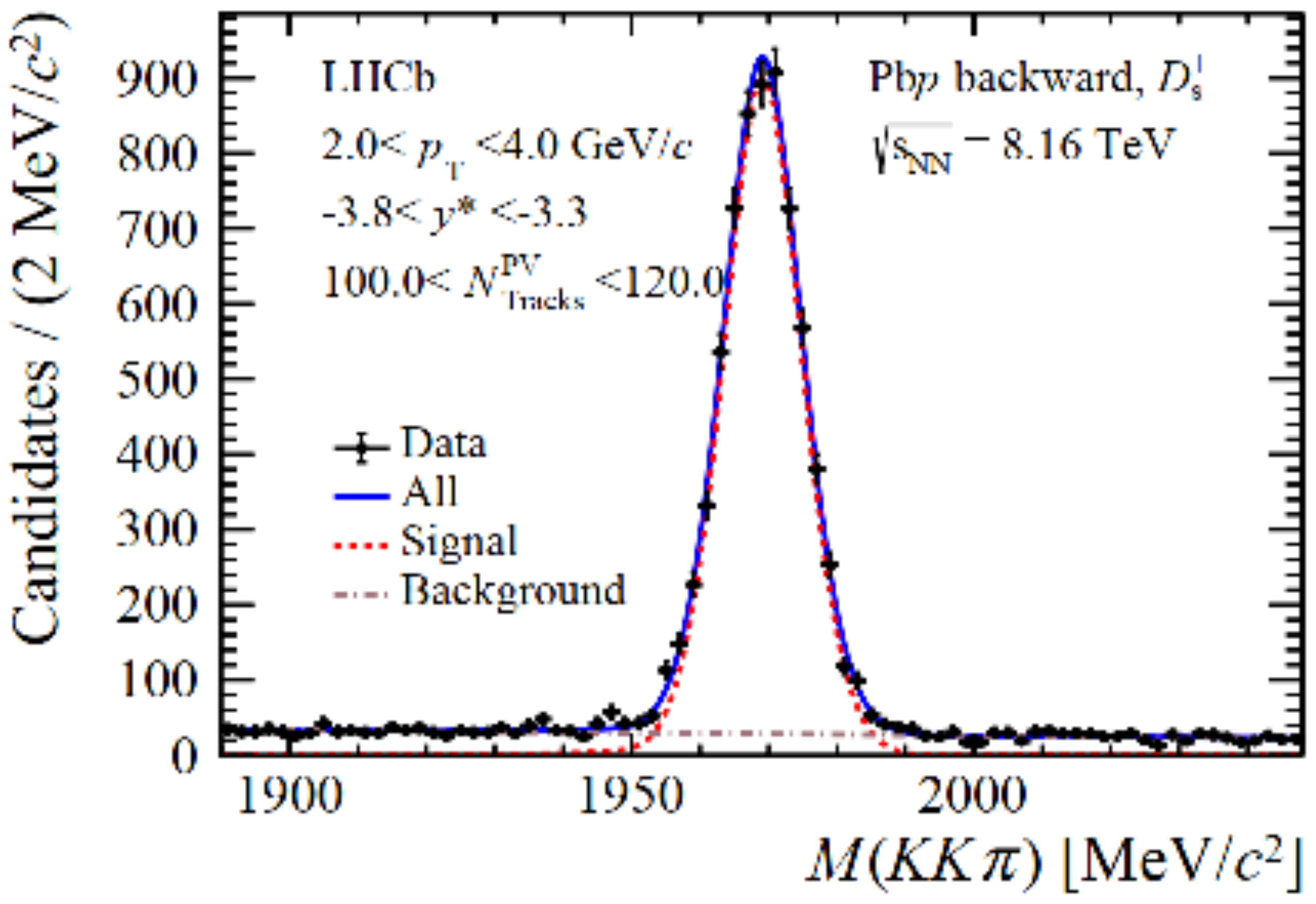
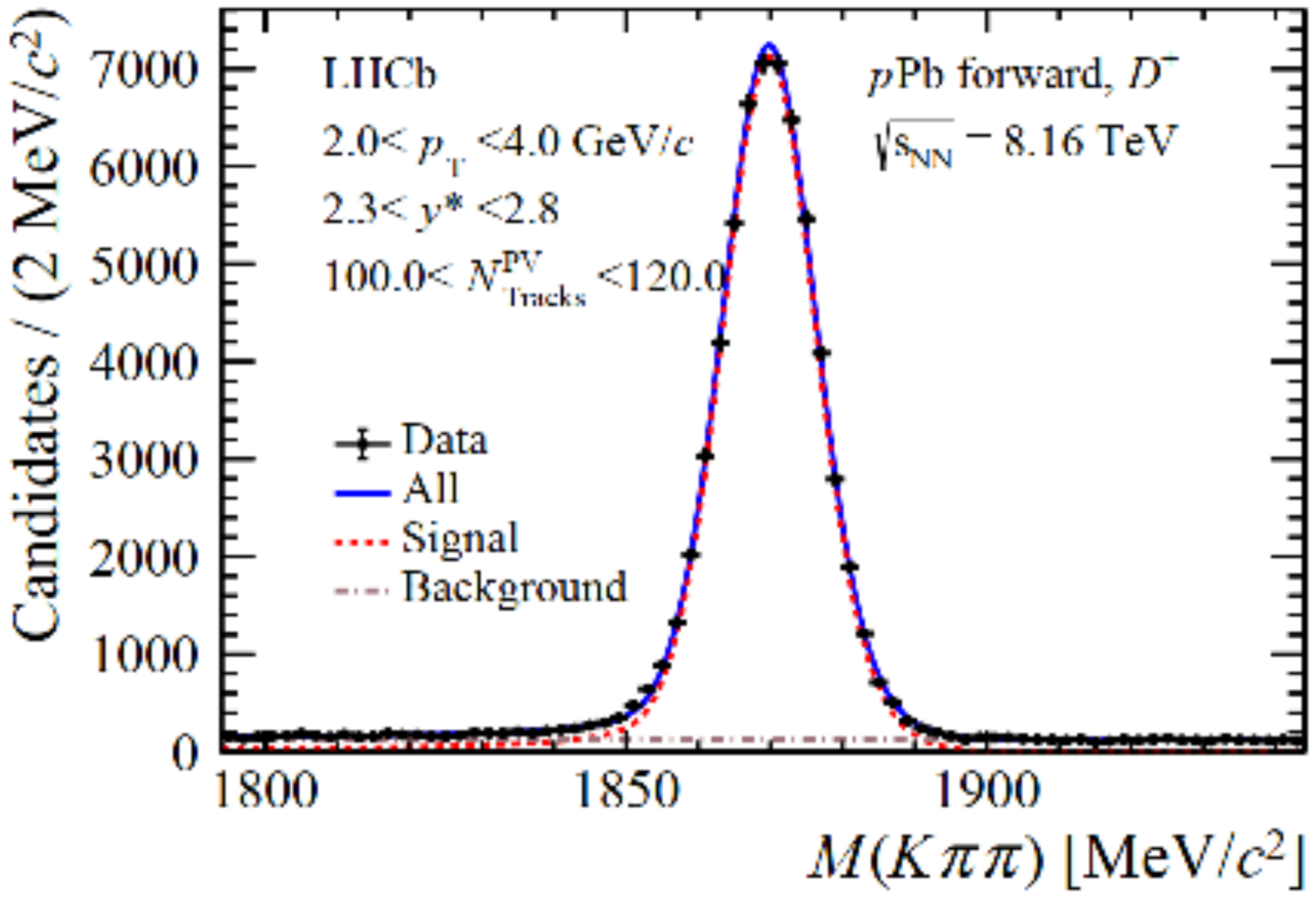
Extra material

$D_s^+(c\bar{s})$



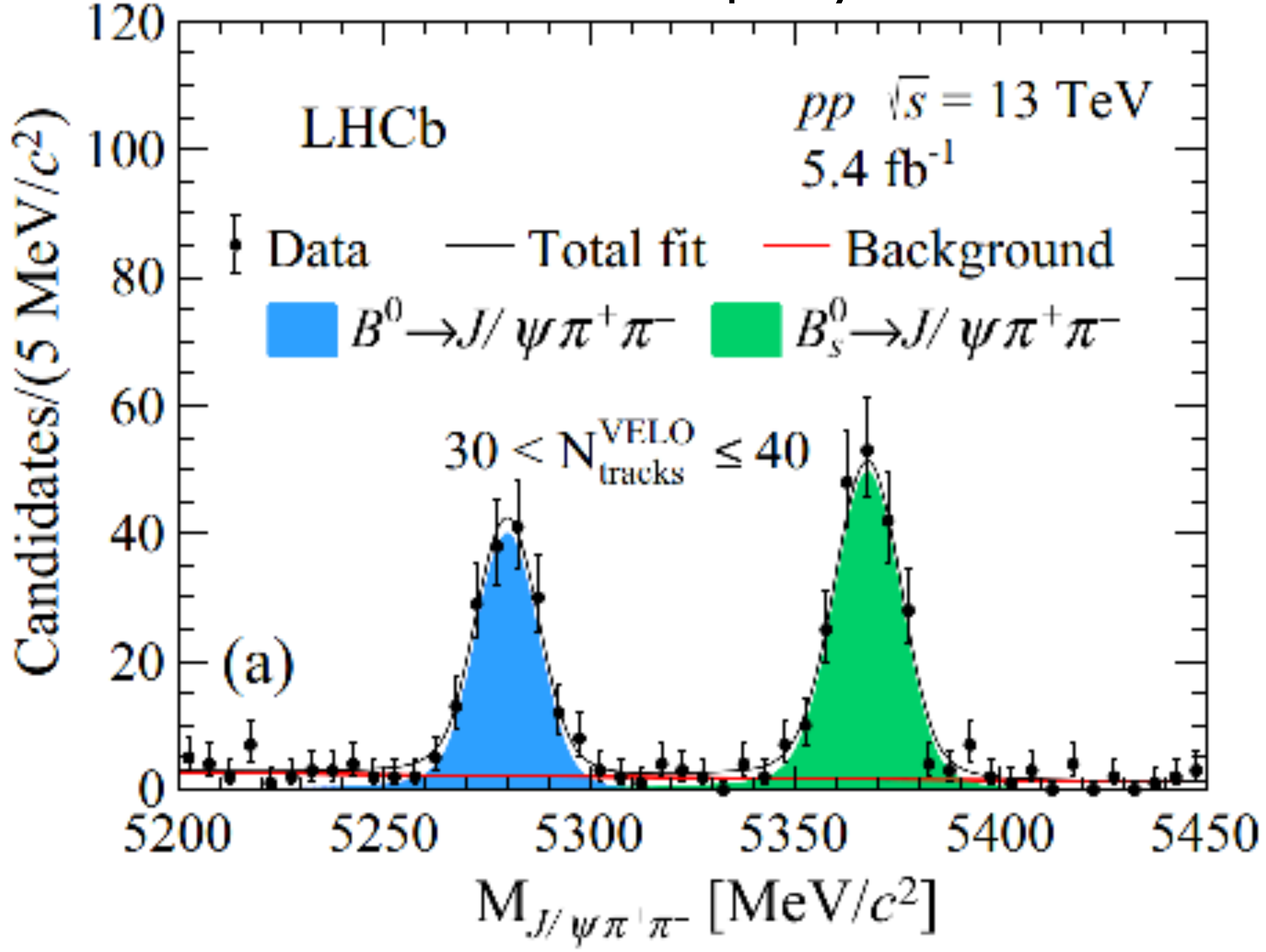
$D^+(c\bar{d})$



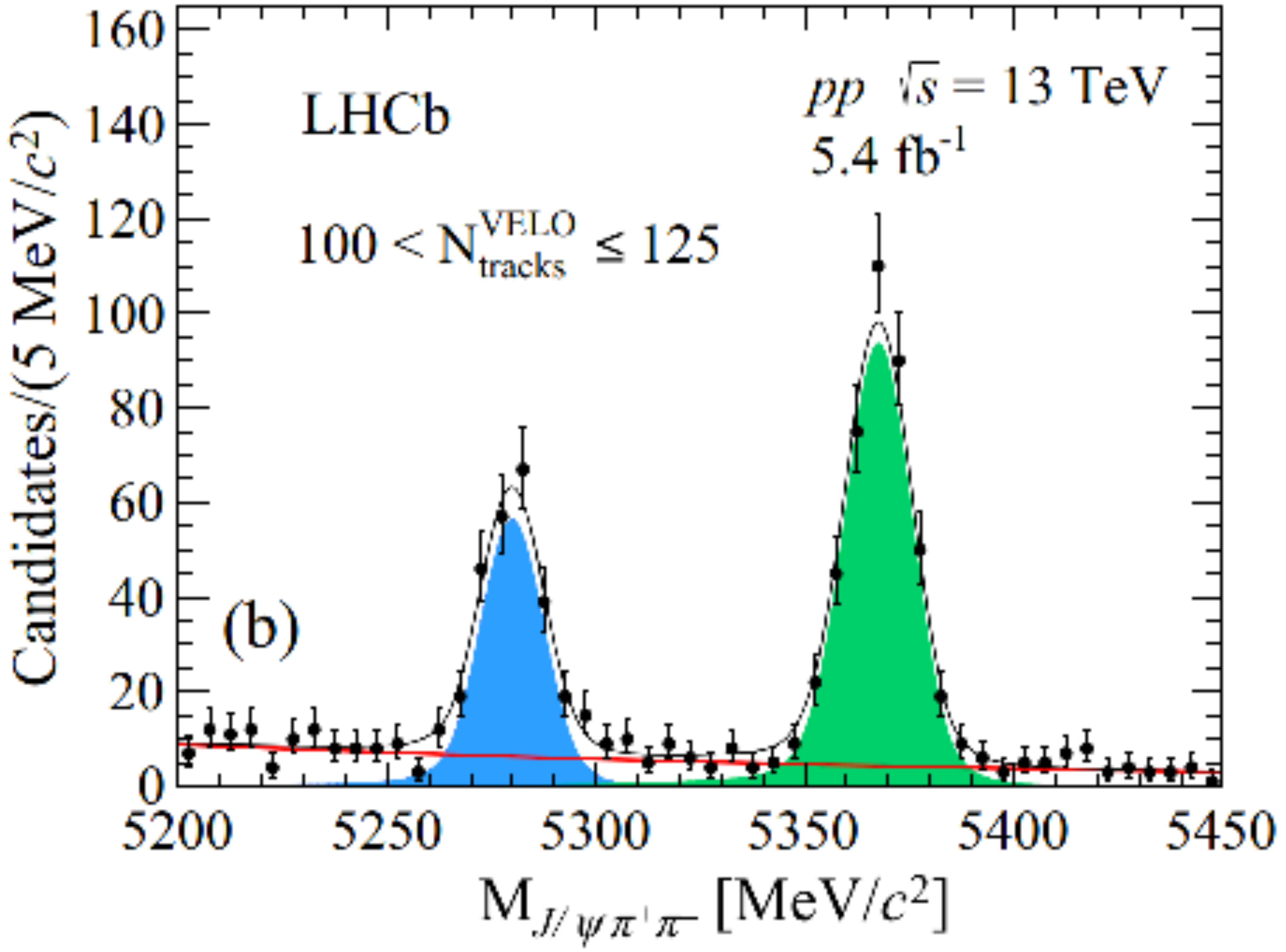
Extra material

PRL 131, 061901 (2023)

Low multiplicity

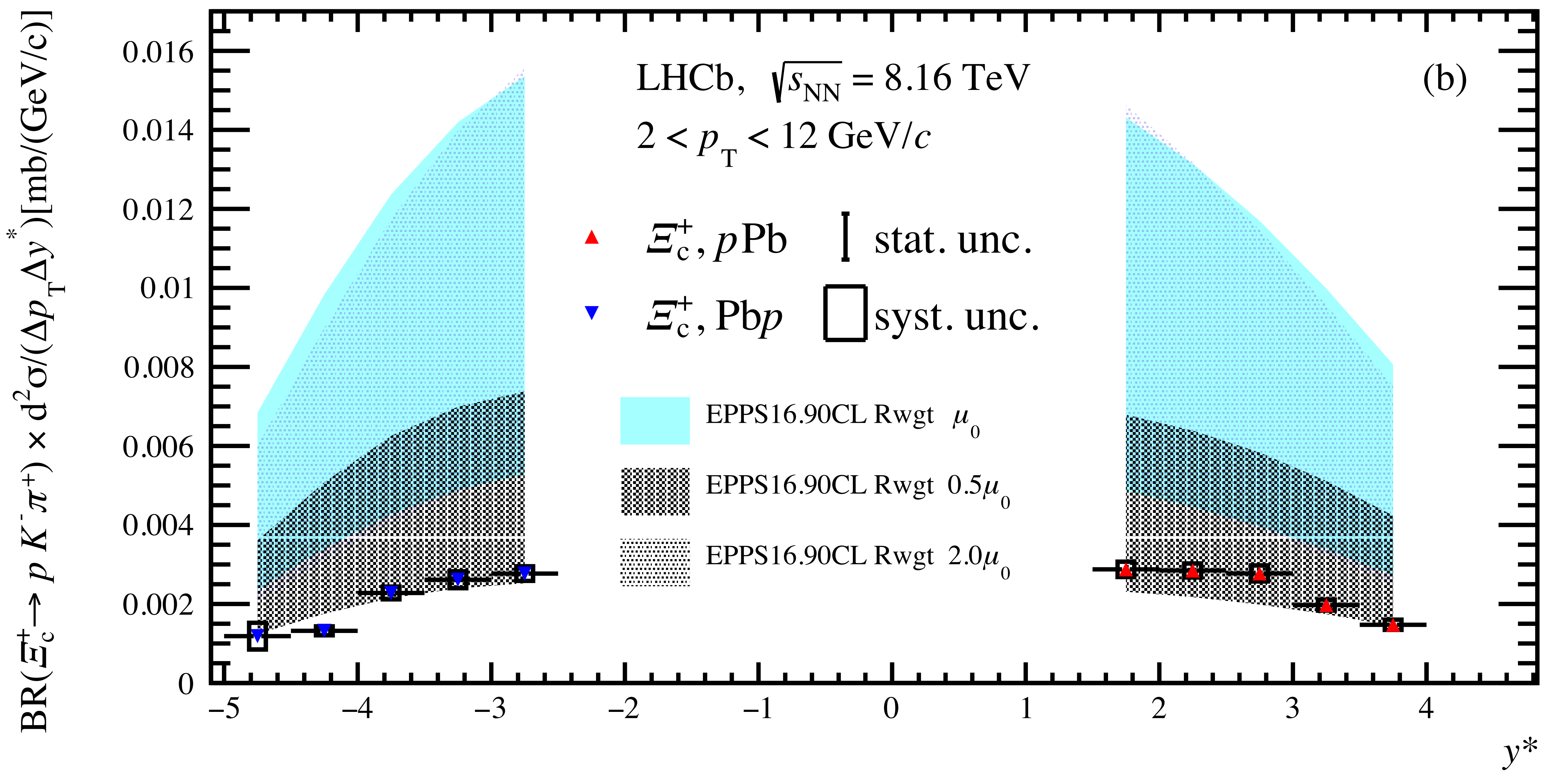


High multiplicity



Measurement of Ξ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 8$ TeV at LHCb

Ξ_c^+(usc) ; $D^0(c\bar{u})$



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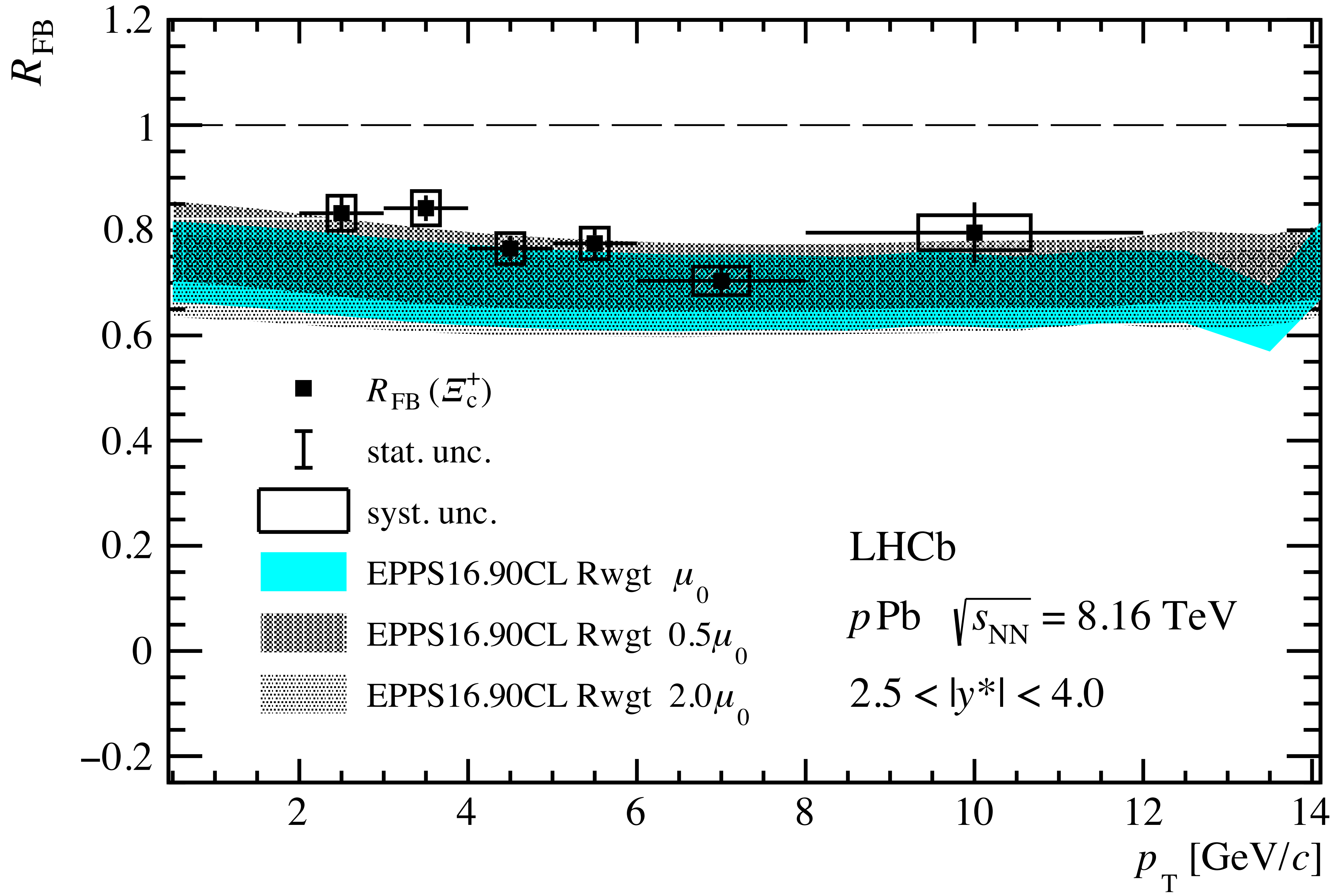
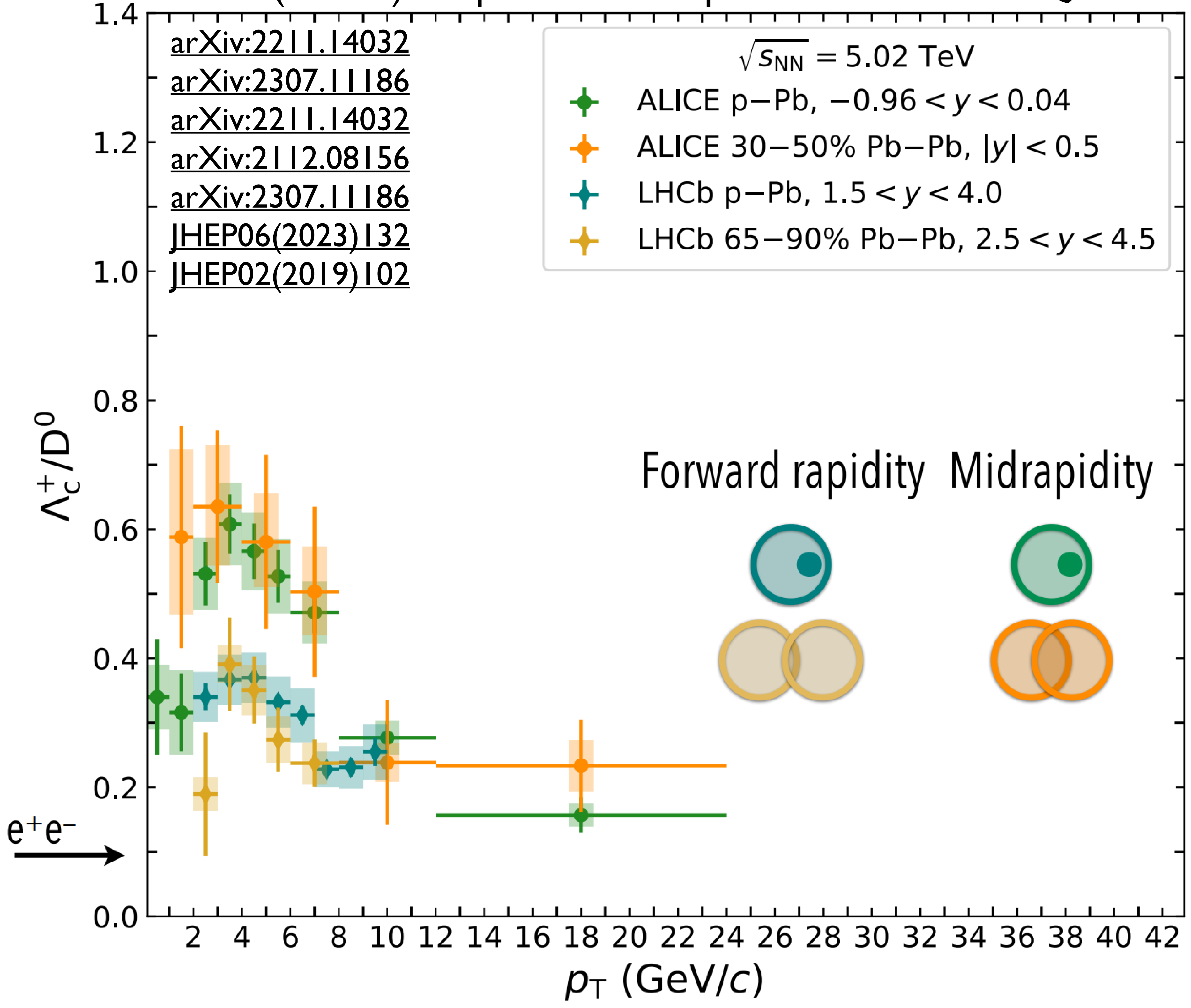


Charm-quark baryonisation

F.Grosa (CERN) - Open charm experimental review - Quark Matter 23



- Strong enhancement of charm baryon-to-meson ratio in pp collisions compared to e^+e^- collisions
  - ➡ Good agreement between ALICE and CMS data
- Modification of the Λ_c^+ / D^0 ratio in p–Pb collisions
  - ➡ Radial-flow like effect or quark recombination
- Similar modification in Pb–Pb collisions, increasing with centrality
- Similar behaviour at forward rapidity, but lower in absolute value
  - ➡ Rapidity dependence?

LHCb data gives unique information about the hadronisation process