Particle production vs multiplicity in small systems

LHCP 2024

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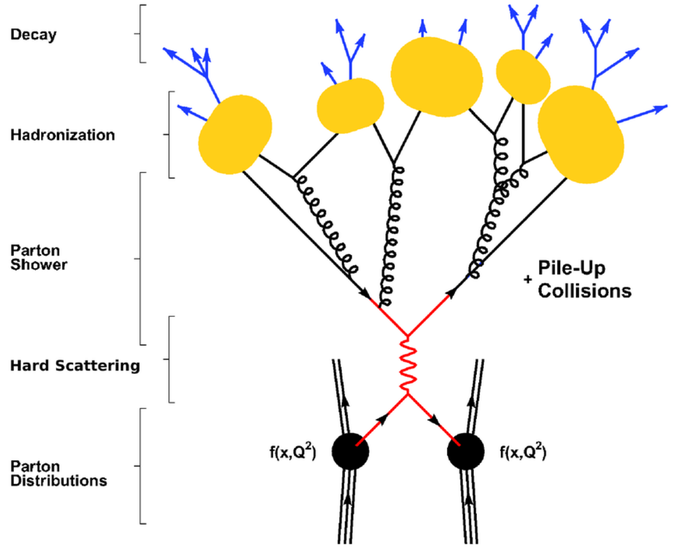
Hadronisation mechanism: Probes

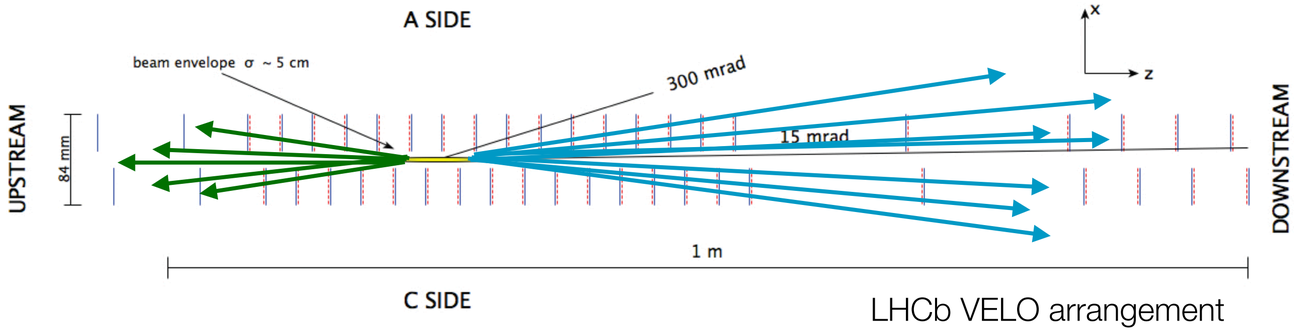


- Heavy quarks production is a powerful probe of hadronisation mechanism:
  - produced at initial stages of collision
  - depend on the parton distribution functions of the incoming nucleons, the hard parton-parton scattering cross-section, and the fragmentation functions
  - hadronisation is assumed to be universal
- Hadronisation mechanism:
  - fragmentation: partons fragment into hadrons at low multiplicity
  - coalescence: quarks overlap in velocity-position space forming hadrons at high multiplicity
  - co-mover effect: loosely bound states can dissociate in the interaction with co-moving particles

Hadronisation mechanism: Observables

- With increase of the size of the collision system QGP effects may appear
- **Production**:
  - kinematic dependencies affected by medium (fragmentation vs coalescence at low vs high p_{T})
  - nuclear modification factor (medium temperature and density, coalescence and co-mover effect)
  - relative ratios (co-mover effect for quarkonia, strangeness enhancement)
- **Correlations**:
  - **multiplicity** dependence (breaking of factorisation of b quark hadronisation in different collision systems)
  - **forward-backward** asymmetries
  - …
- **Many different ways to probe hardronisation and QGP effects**

Multiplicity variables



LHCb VELO arrangement

- Various multiplicity observables are available for different experiments:

  # of primary vertices (PVs), # of tracks associated with a PV, # of clusters in calorimeter…
- For universality an observable has to be normalised to a minimum/no bias average value
- Common choice of variables:
  - LHCb: # of forward tracks (correlated) and # of backward tracks (non-correlated)
  - LHCb, CMS: # of tracks associated with a PV (for LHCb ≈ # of fw + # of bw) - local multiplicity
  - ALICE: deposited charge - local multiplicity
  - ALICE: spherocity - topology in the azimuthal plane

$$S_{\mathrm{O}}^{p_{\mathrm{T}}=1} = \frac{\pi^2}{4} \min_{\hat{n}} \left(\frac{\Sigma_i \left| \hat{p_{\mathrm{T}}}_{,i} \times \hat{n} \right|}{N_{\mathrm{trks}}} \right)^2$$

$\hat{p}_{\mathrm{T}}$ - transverse momentum unit vector
$\hat{n}$ - unit vector that minimizes $S_O^{p_{\mathrm{T}}=1}$
N_{trks} - number of charged particles

Recent results

- Observation of strangeness enhancement with charmed mesons in high-multiplicity $p\mathrm{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV
  - LHCb [arXiv:2311.08490]
- Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pp collisions at $\sqrt{s} = 13$ TeV
  - LHCb [arXiv:2312.15201]
- Evidence for modification of b quark hadronization in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV
  - LHCb [Phys. Rev. Lett. 131, 061901]
- Enhanced production of Λ_b^0 baryons in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV
  - LHCb [Phys. Rev. Lett. 132, 081901]
- Light-flavor particle production in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV as a function of transverse spherocity
  - ALICE [JHEP 05 (2024) 184]
- Investigating strangeness enhancement with multiplicity in pp collisions using angular correlations
  - ALICE [arXiv:2405.14511]
- Measurement of the B^+ differential cross section as a function of transverse momentum and multiplicity in $p\mathrm{Pb}$ collisions at $\sqrt{s} = 8.16$ TeV
  - CMS [CMS PAS HIN-22-001]

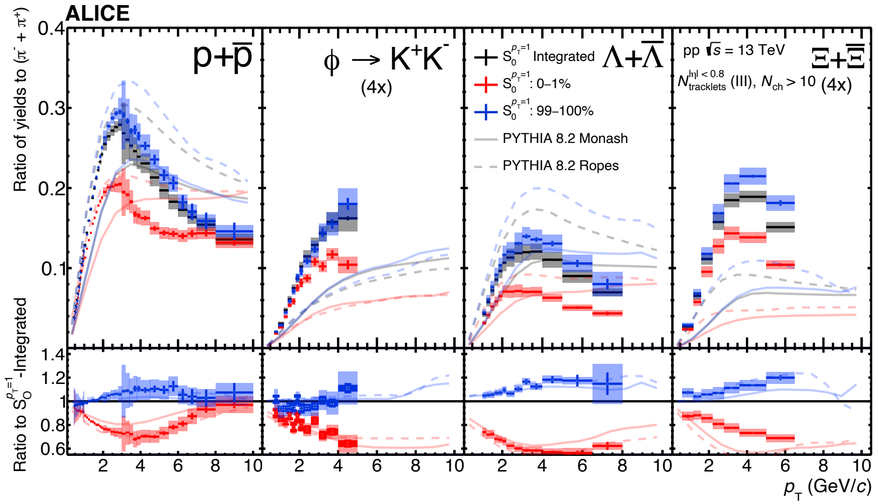
Light-flavour production

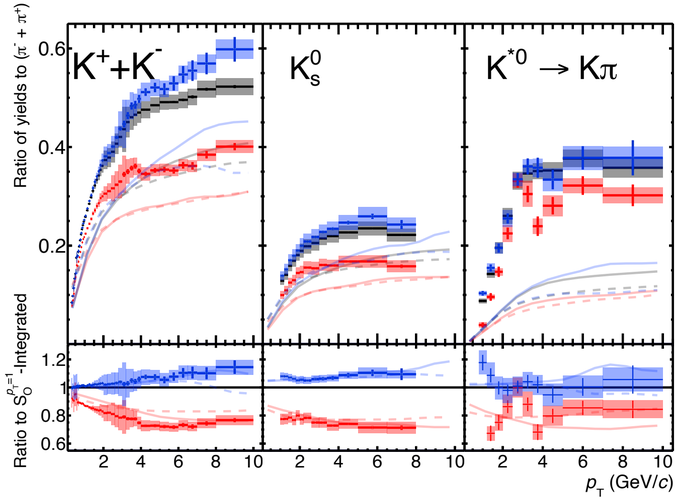
$S_0^{p_T=1}$: 0–1% - jet-like

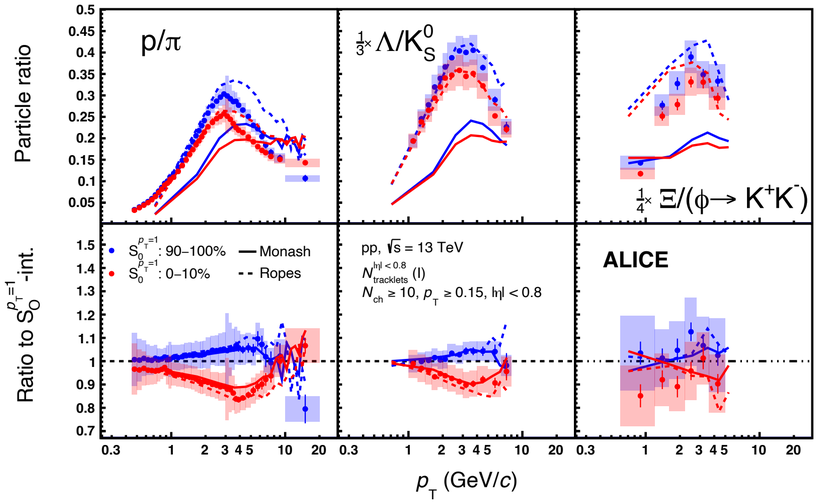
$S_0^{p_T=1}$: 99–100% - isotropic

JHEP 05 (2024) 184

- Production of p, ϕ, Λ, Ξ, K^{*0}, $K^{\pm}$ and K_s^0 in pp collisions at $\sqrt{s} = 13$ TeV
- Enhancement of strange hadrons in events with an isotropic topology, and a strong suppression in events with a jet-like topology
- Baryon-to-meson ratio shows enhancement at mid p_{T}, without depletion of low-p_{T} particles for jet-like events



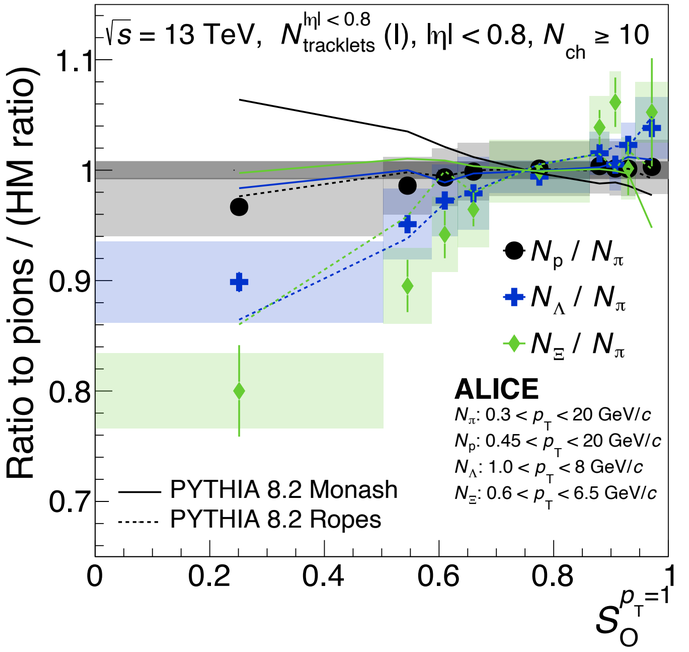




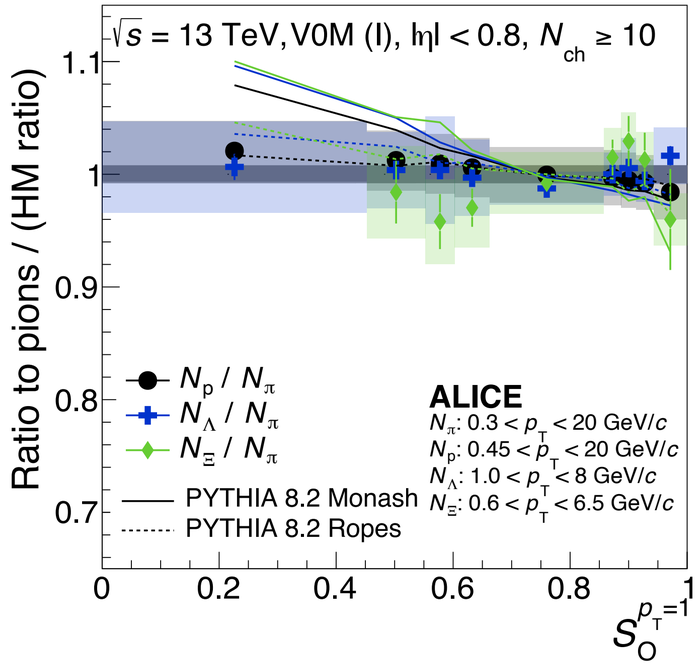
Light-flavour production

JHEP 05 (2024) 184

- Relative integrated strange particle yield to pions as function of $S_O^{p_T=1}$
- Strangeness enhancement achieved by fixing the local charged particle density and varying the azimuthal topology, instead of varying charged-particle density
- **More than one contribution to particle production at high multiplicity**



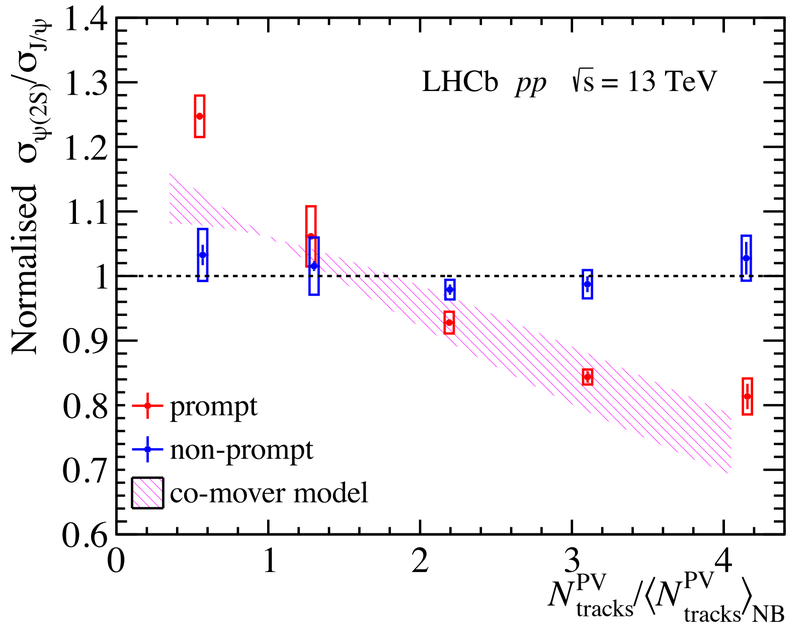
- No significant strangeness enhancement or suppression within systematic uncertainties when multiplicity is estimated using the forward rapidity estimator
- Average high-multiplicity events are dominated by soft processes, when hard processes play little or no role for bulk observables

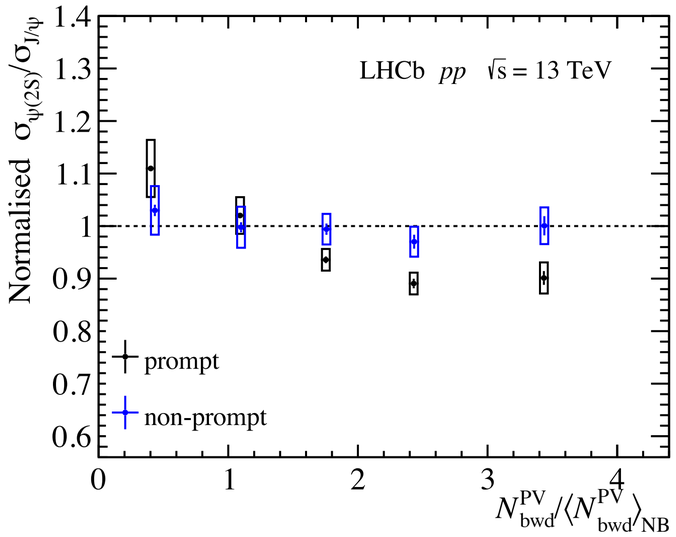


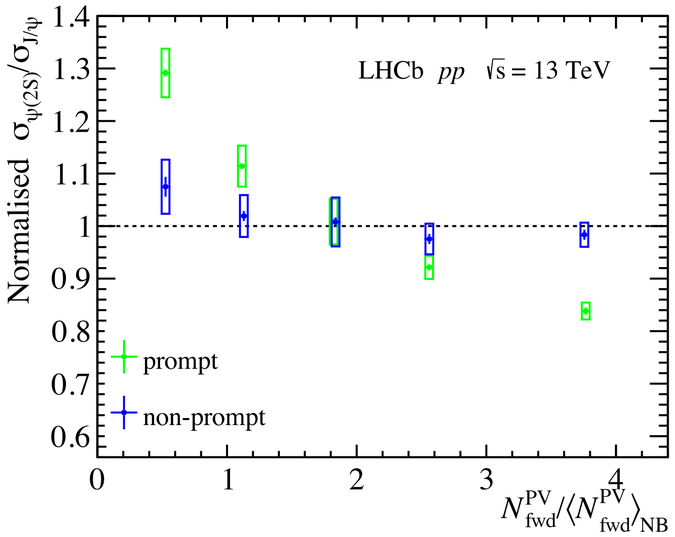
$\psi(2S)/J/\psi$ ratios

arXiv:2312.15201

- Quarkonia production suppression at high multiplicity in small systems may indicate presence of QGP or co-mover effect
- Observation of production ratios can mitigate initial-state effects; however, observed suppression for excited states points to additional existing effects
- **Prompt production ratio decreases with multiplicity**





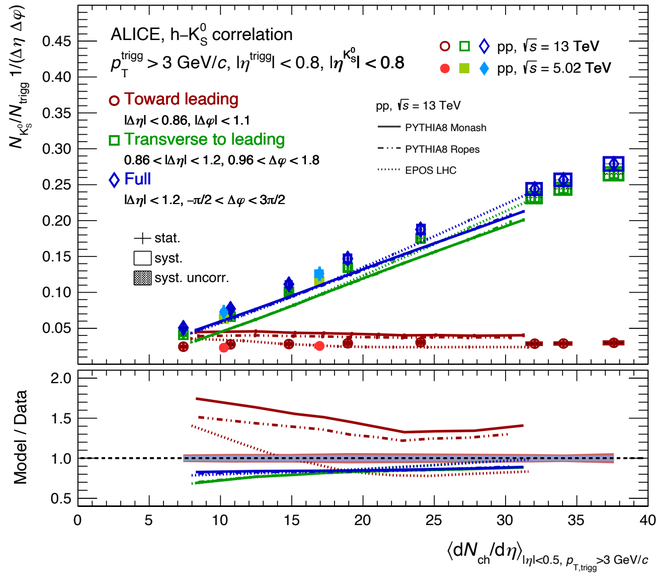


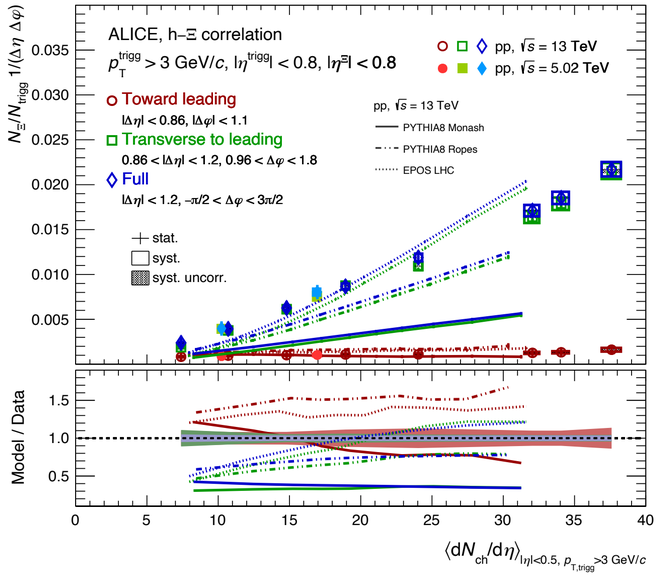
- The effect is less visible for N^{PV}_{bwd} multiplicity, suggesting correlation between suppression and local multiplicity; **possible indication of co-mover effect**
- Weak dependence may be explained by the correlation between N^{PV}_{bwd} and N^{PV}_{fwd}

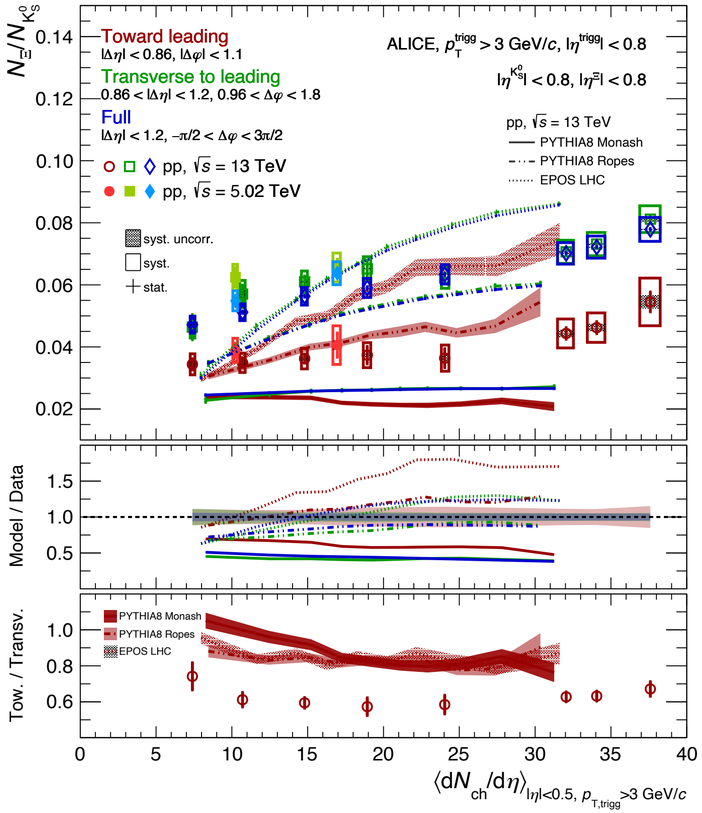
K_s^0 and $\Xi^{\pm}$ production

arXiv:2405.14511

- Production measurement in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV in the direction of the highest-p_{T} charged particle and transverse to it





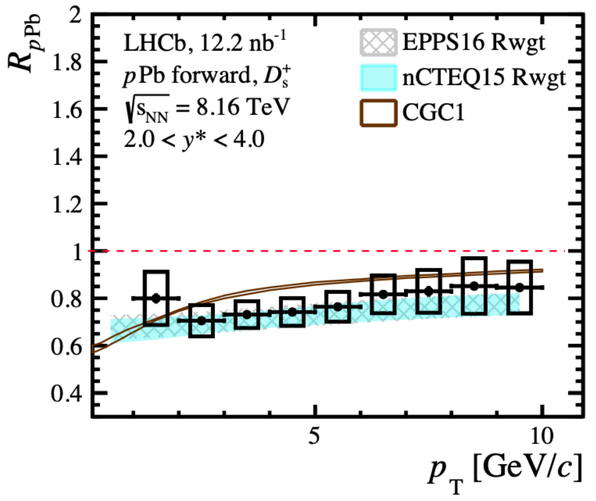


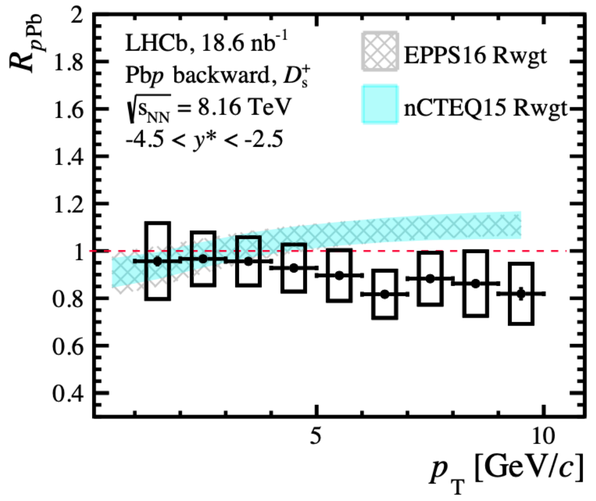
- **Toward-leading p_{T}** (hard scattering processes) **spectra are harder than transverse-to-leading ones** (production related to the underlying event)
- Milder multiplicity dependence in toward-leading yields; contribution of transverse-to-leading process increases with multiplicity
- **Relative $\Xi^{\pm}/K_s^0$ production is favoured in transverse-to-leading processes** (higher strangeness)
- Models cannot quantitatively describe the production

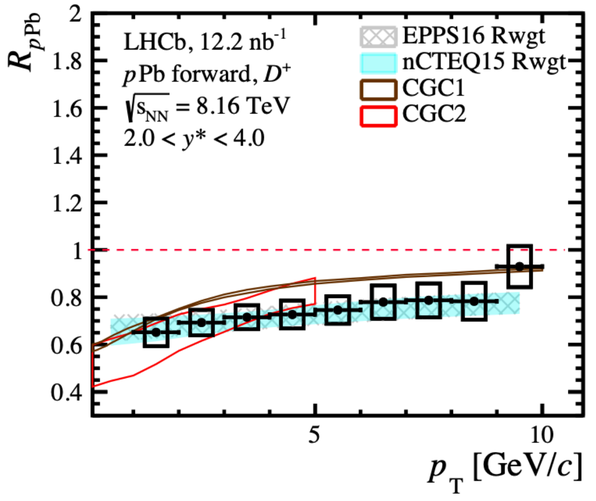
D_s^+/D^+ ratios

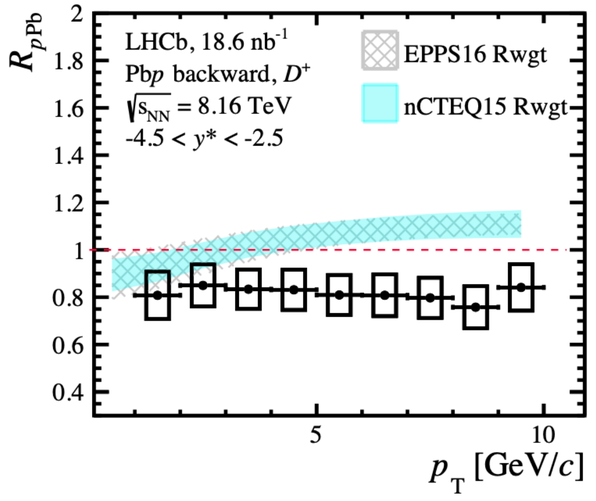
arXiv:2311.08490

- Study of nuclear modification factor $R_{p\mathrm{Pb}}$ provides a test of the universality of hadronisation mechanism
- Theoretical predictions tuned using previous measurements are available
- Results for
  - **forward region** $2.0 < y^* < 4.0$ **show significant suppression** for both D^0 and D_s^0, and in good agreement with predictions
  - **backward region** $-4.5 < y^* < -2.5$ **are below theoretical predictions**, indicating possible final-state effects depending on charm hadronisation





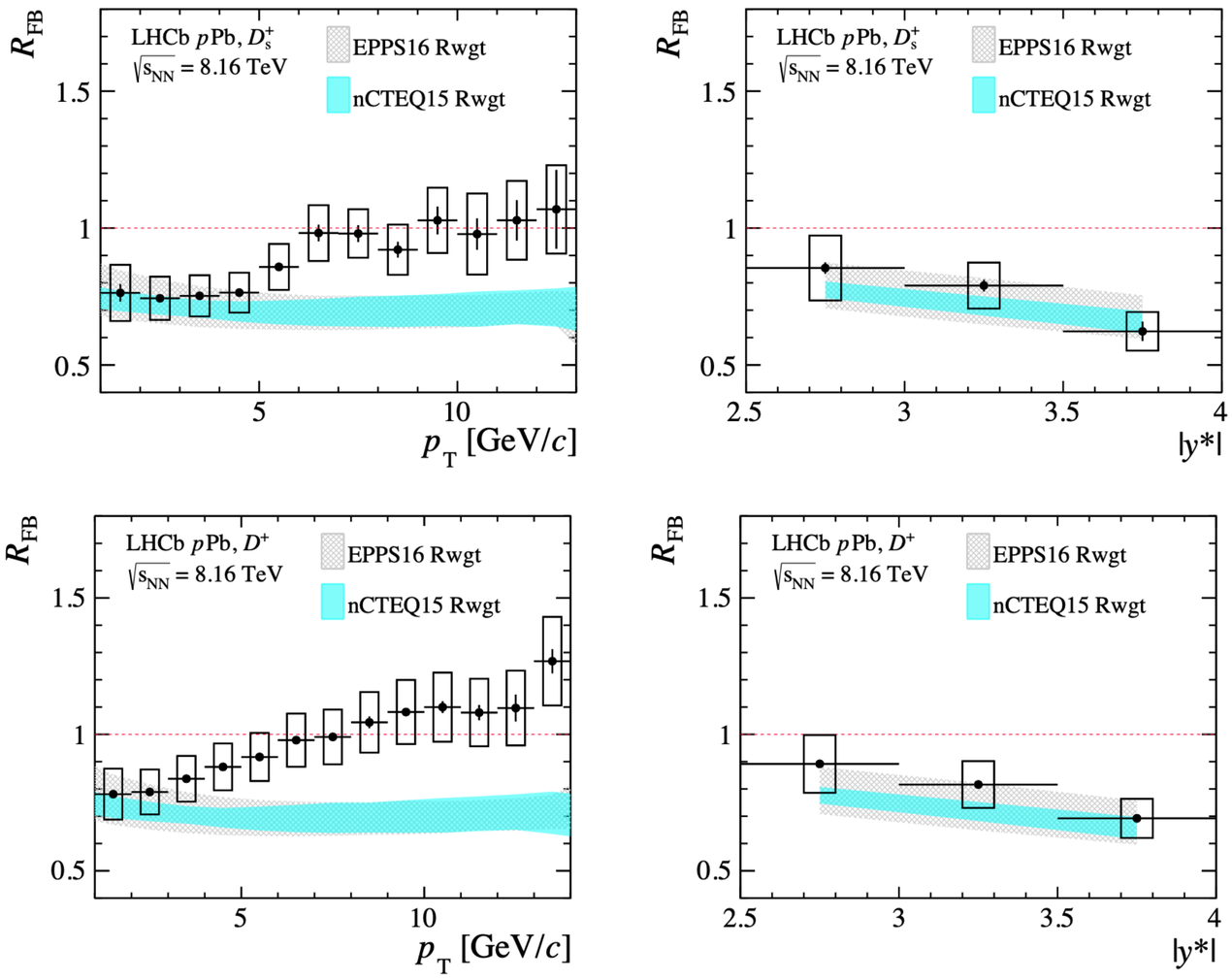




D_s^+/D^+ ratios

arXiv:2311.08490

- Forward-backward asymmetry R_{FB} allows to test production mechanism depending on the longitudinal momentum fraction x carried by a parton
- The results show **strong dependence on p_{T},** contrary to the theoretical prediction;
- The discrepancies for R_{FB} and $R_{p\mathrm{Pb}}$ may originate from the suppression of high-p_{T} $D^0_{(s)}$ mesons at backward rapidity



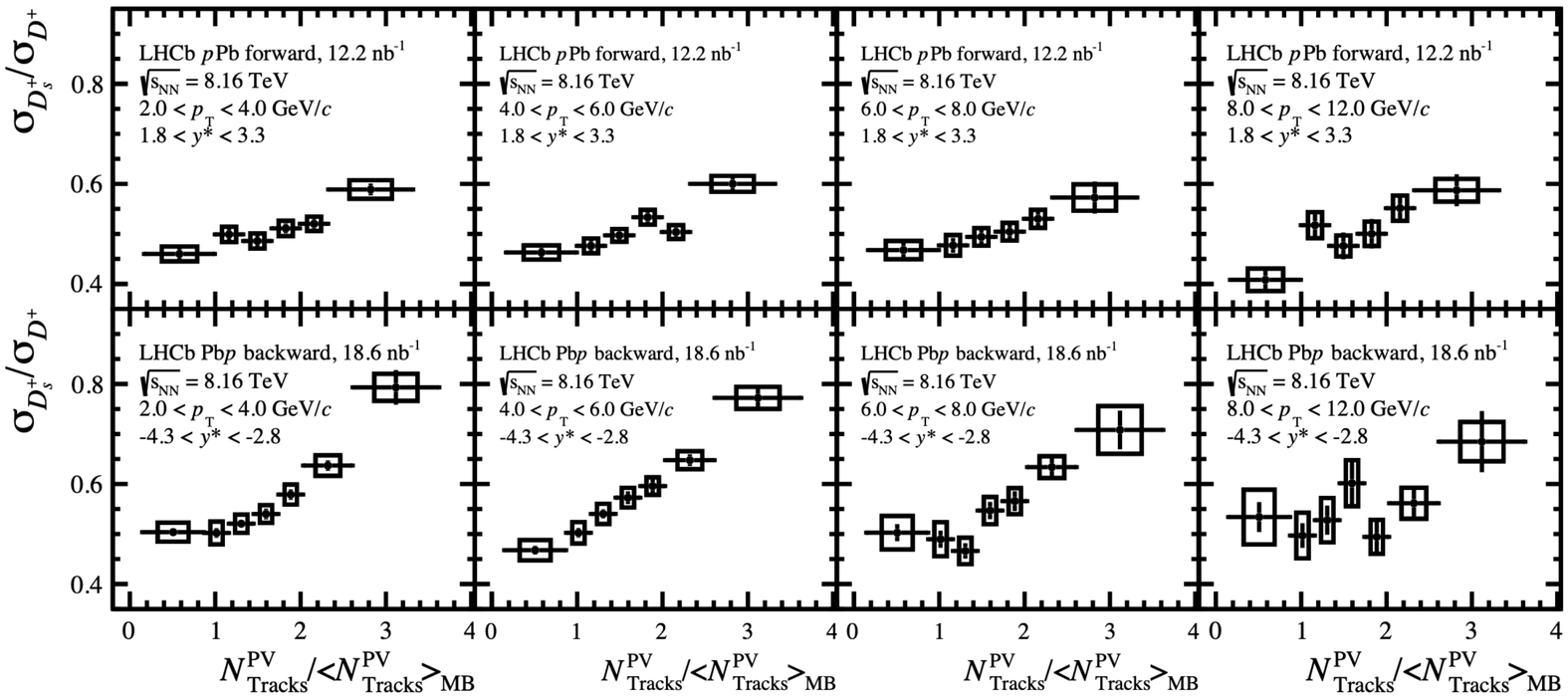
D_s^+/D^+ ratios

arXiv:2311.08490

- Multiplicity dependence of the D_s^0/D^0 ratio demonstrates **strangeness enhancement at high multiplicity**

- Dependence is weaker at high p_{T}; agrees with observations for b quark hadronisation

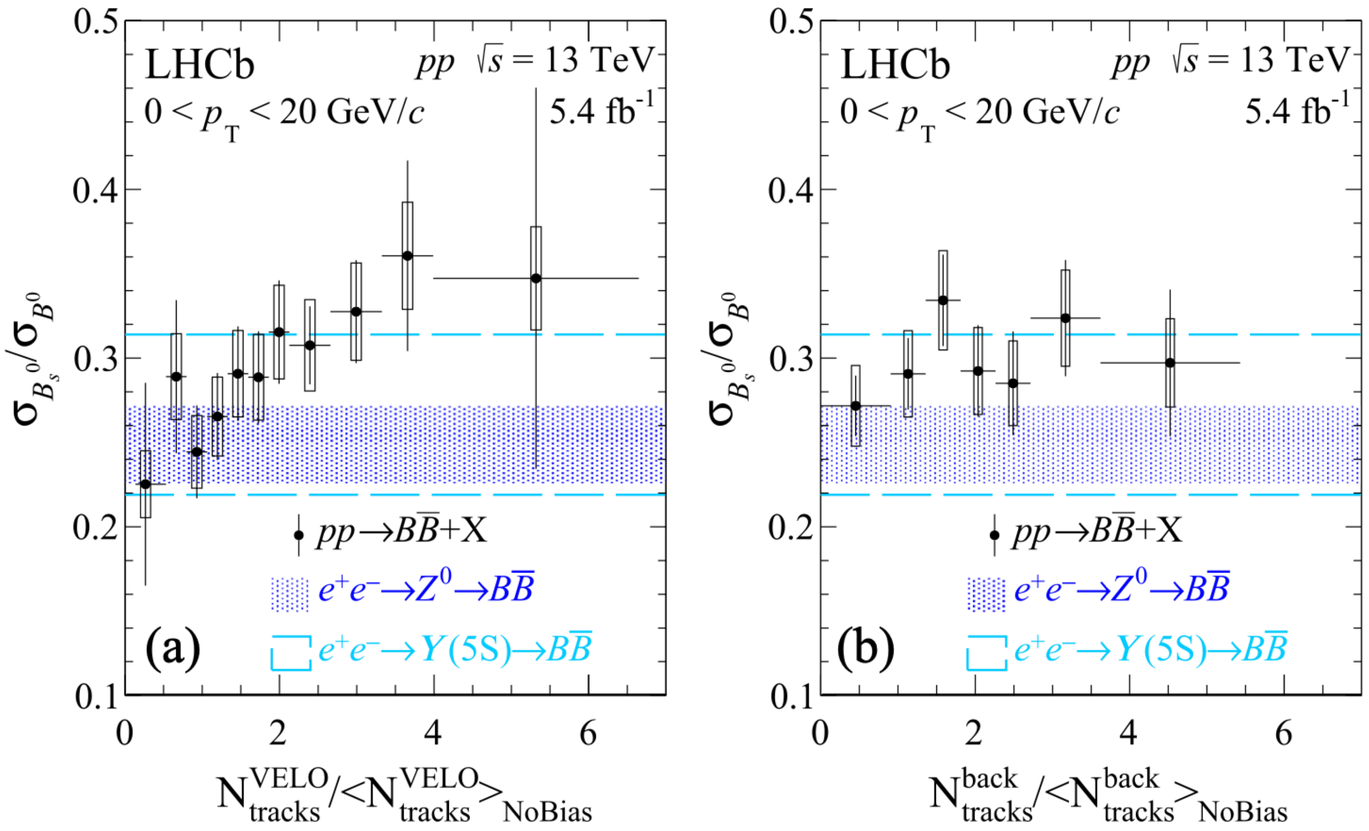
- **First observation** of this effect, consistent with the coalescence mechanism



B_s^0/B^0 ratios

Phys. Rev. Lett. 131, 061901

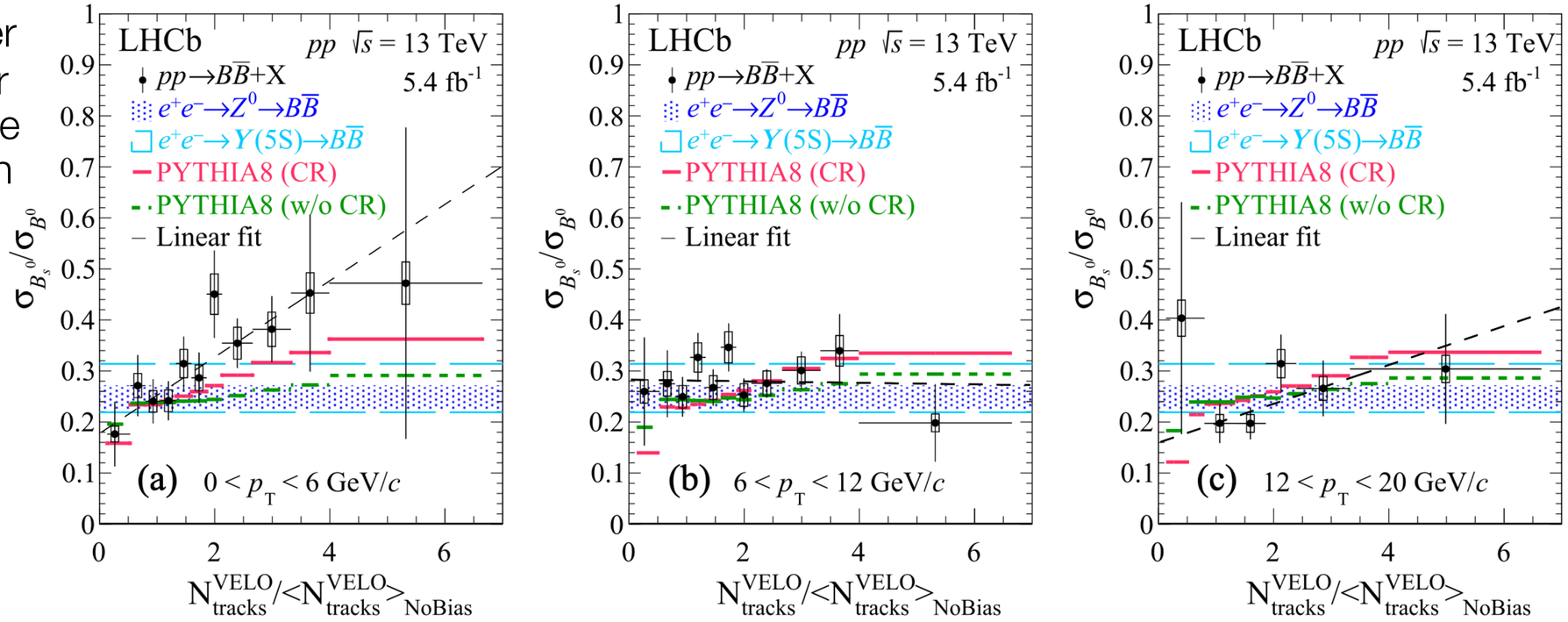
- Dependencies the B_s^0/B^0 ratio studied for two variables:
  - increasing trend for local multiplicity, compatible with results from e^+e^- collisions at low multiplicity (pure fragmentation)
  - no dependence on backward multiplicity
- Results indicate **possible presence of the coalescence mechanism**



B_s^0/B^0 ratios

Phys. Rev. Lett. 131, 061901

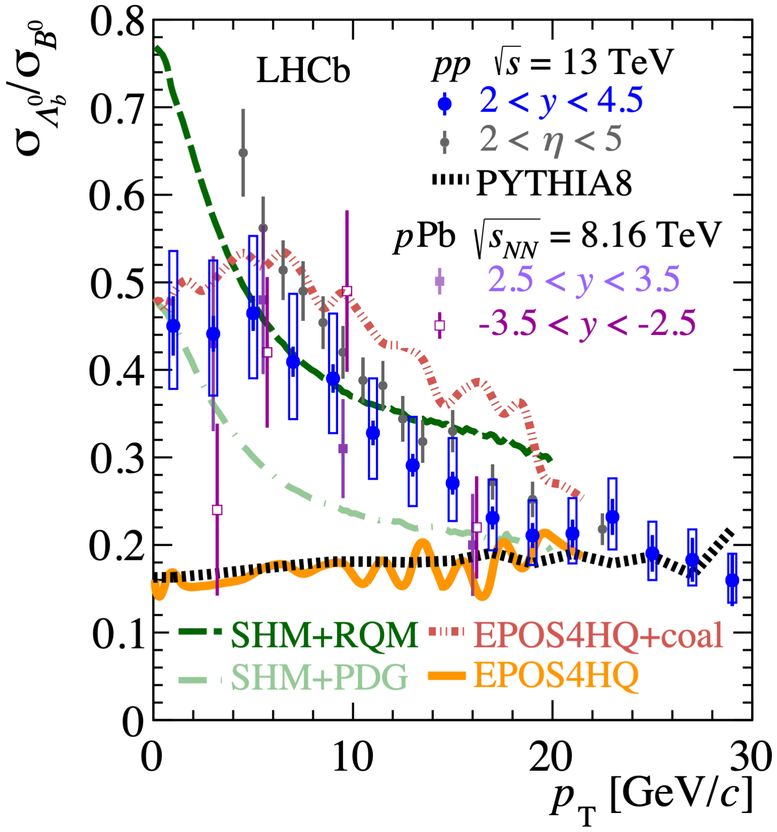
- Ratio increase (3.4σ) at low p_{T}, compatible with results from e^+e^- collisions at low multiplicity
- No significant dependence at high p_{T}, compatible with results from e^+e^- collisions
- All results are in agreement with PYTHIA calculations
- Results at low p_{T} have closer trend to the model with color reconnection; however, agree within uncertainties with both calculations
- **Consistent with the presence of the coalescence mechanism**

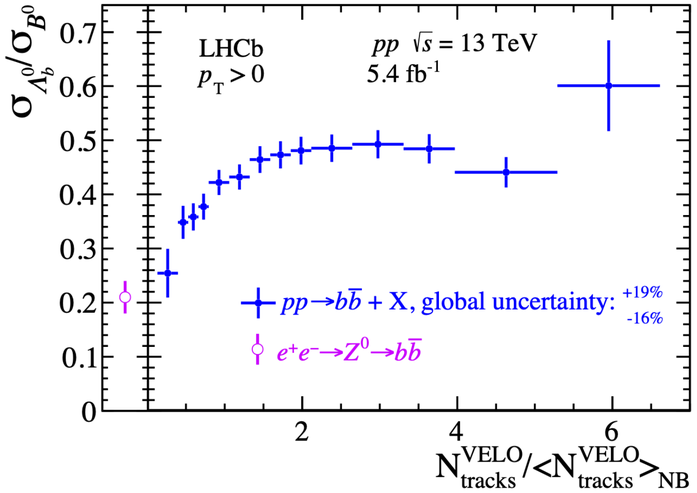


Λ_b^0/B^0 ratios

Phys. Rev. Lett. 132, 081901

- Good agreement with $\Lambda_b^0/(B^0+B^+)$ in pp and Λ_b^0/B^0 in pPb
- Statistical hadronisation
  - with relativistic quark model (RQM) at mid p_{T}
  - with measured spectrum from PDG at low and high p_{T}
- Pure fragmentation describes data only at high p_{T}
- Coalescence may contribute at low p_{T}





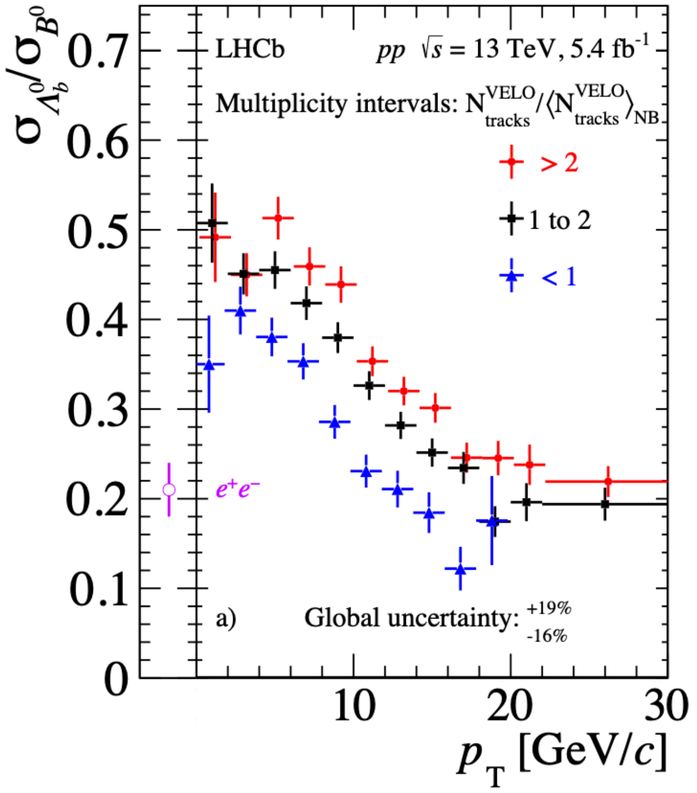
- Multiplicity dependence:
  - approaching e^+e^- collisions data at low multiplicity; fragmentation in vacuum
  - rise and plateau at higher multiplicity; **a hint of additional contribution** to production **from coalescence mechanism**

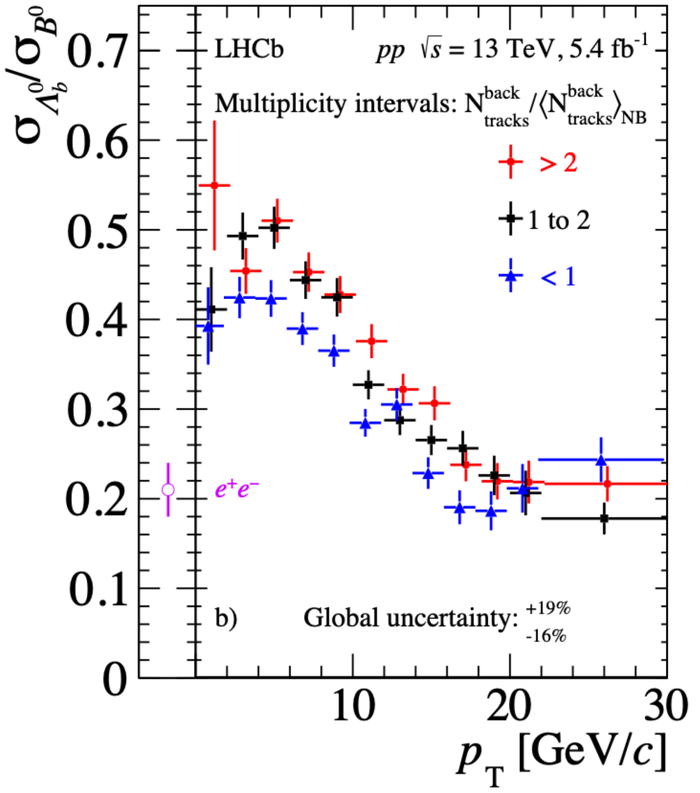
Λ_b^0/B^0 ratios

Phys. Rev. Lett. 132, 081901

- **Significant multiplicity dependence** for both metrics, however, more pronounced for the total number of VELO tracks

- Multiplicity dependence weakens with p_{T} converging to the value measured in e^+e^- collisions
  - low p_{T} : coalescence with b-quark combining with light quarks
  - high p_{T} : b-quark fragmentation in vacuum

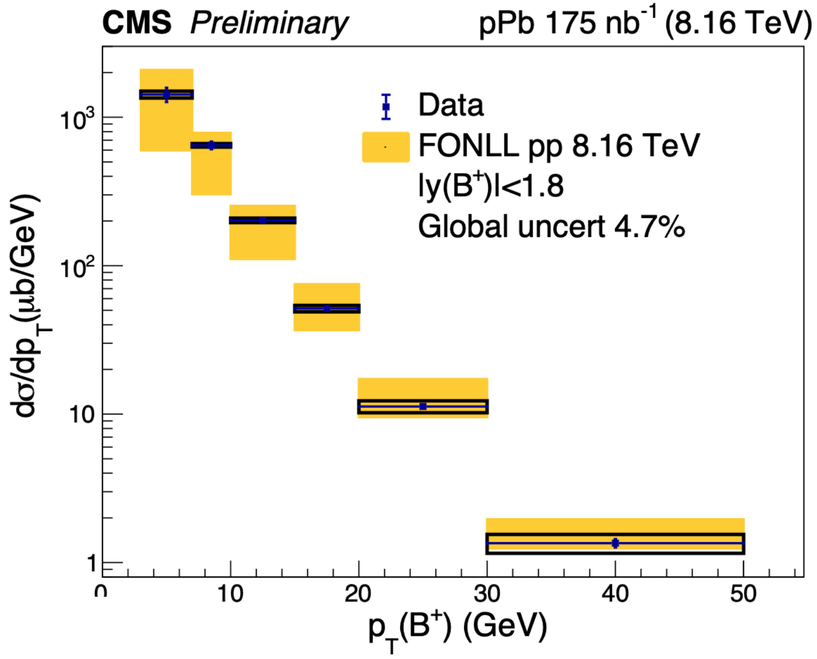


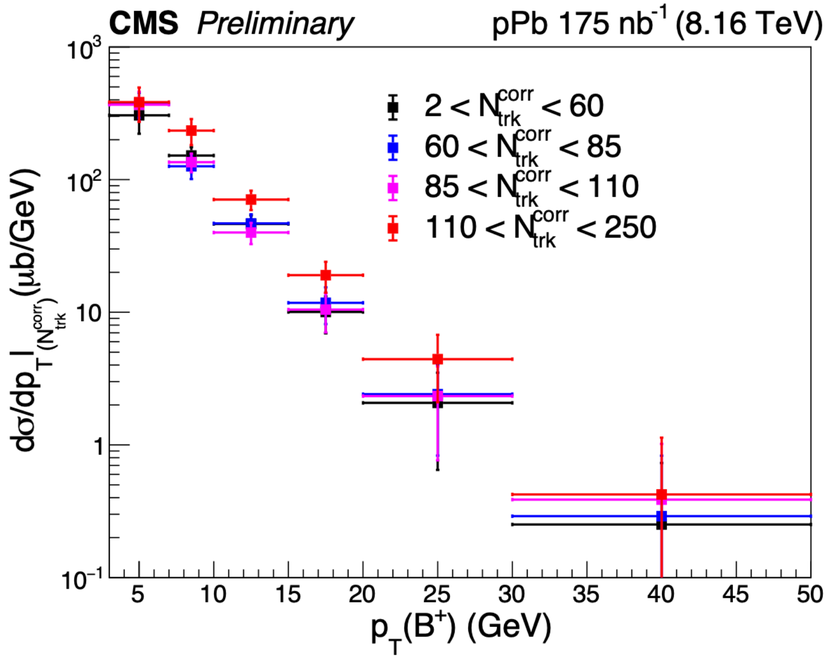


B^+ production

CMS PAS HIN-22-001

- First measurement of B^+ production dependency on multiplicity in $p\mathrm{Pb}$ collisions
- Good agreement of p_T-differential production cross-section with FONLL predictions
  - The predictions are done for pp collisions and scaled by $A = 208$ for $p\mathrm{Pb}$ collisions
- Slightly higher production at high multiplicity





Summary

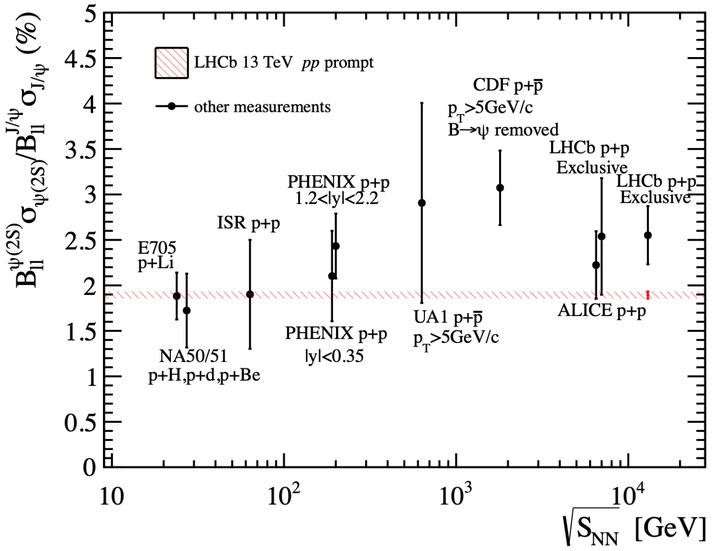
- Multiple measurements indicate presence of additional hadronisation mechanism:
  - strangeness enhancement with local multiplicity increase at low p_{T}
  - absence of dependency on backward multiplicity
  - high p_{T} data are consistent with fragmentation in vacuum (results from $e^{+}e^{-}$)
- Contrary to the theoretical prediction, R_{FB} for $D^{0}_{(s)}$ shows **strong dependence on** p_{T}, and stronger suppression for $R_{p\mathrm{Pb}}$
- Relative $\Xi^{\pm}/K^{0}_{s}$ production is favoured in transverse-to-leading processes
- Prompt $\psi(2S)/J/\psi$ ratio **depends significantly on local multiplicity**, but weaker on backward multiplicity; **possible indication of co-mover effect**
- **Different behaviour** in pp and $p\mathrm{Pb}$ collisions from $e^{+}e^{-}$ is a **hint of breaking universality of hadronisation mechanism**

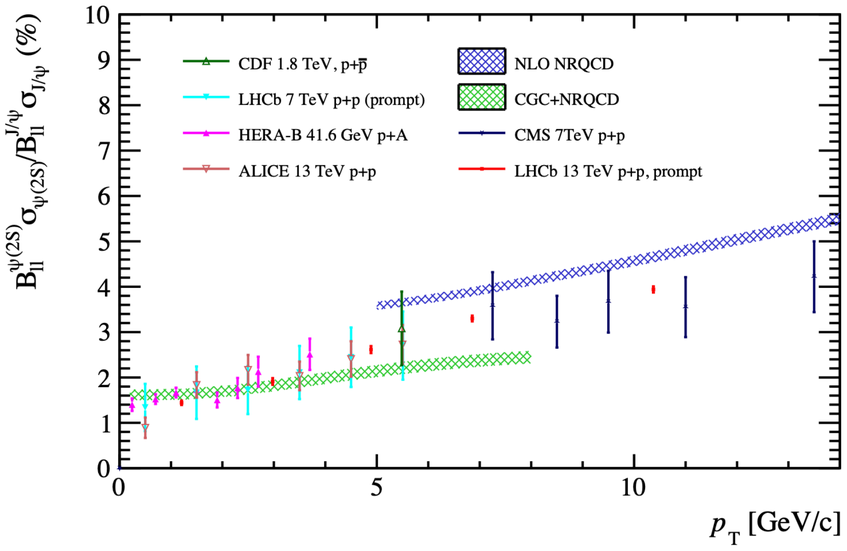
Backup

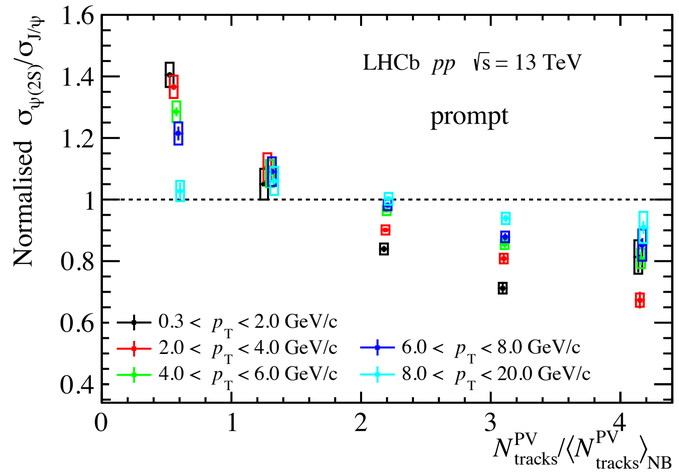
$\psi(2S)/J/\psi$ ratios

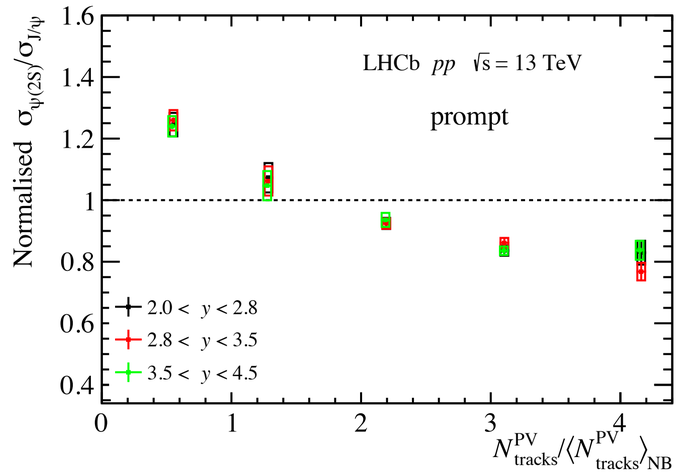
arXiv:2312.15201

- **Different behaviour for prompt ratio in p_T bins**, consistent with other existing measurements:
  - suppression at high multiplicity for low p_T
  - no significant dependence for high p_T
- No dependence on y



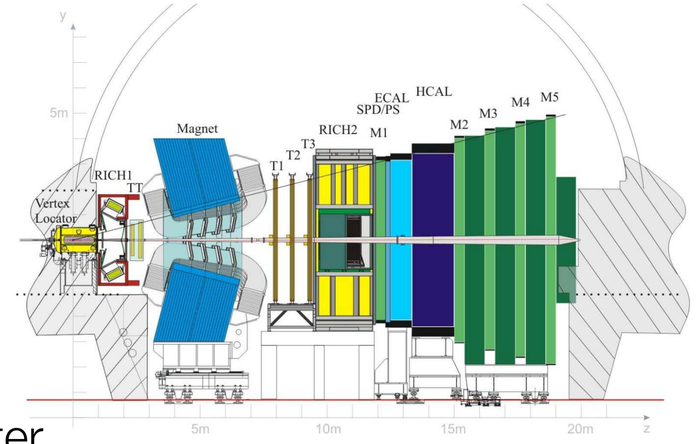






- Integrated and p_T-differential ratios are in good agreement with other existing results

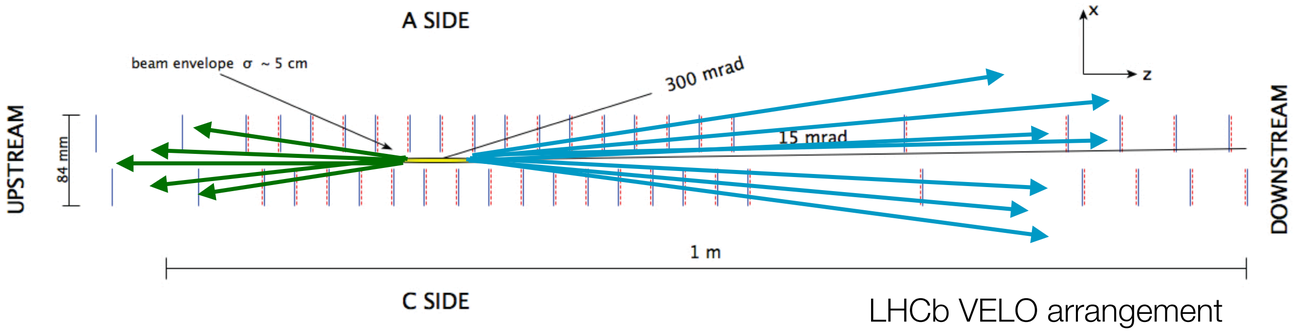
Multiplicity variables



LHCb

- Various multiplicity observables are available for different experiments:

  # of primary vertices (PVs), # of tracks associated with a PV, # of clusters in calorimeter…
- For universality an observable has to be normalised to a minimum/no bias average value
- LHCb is a forward-arm spectrometer covering pseudorapidity range $2 < \eta < 5$
  - LHCb VErtex LOcator (VELO) has sensors in both forward and backward rapidity regions



LHCb VELO arrangement

- Common choice of variables:
  - # of forward tracks
  - # of backward tracks - non-correlated multiplicity
  - # of tracks associated with a PV ≈ # of fw + # of bw - local multiplicity