Hadronization: Open Heavy Flavor at LHCb

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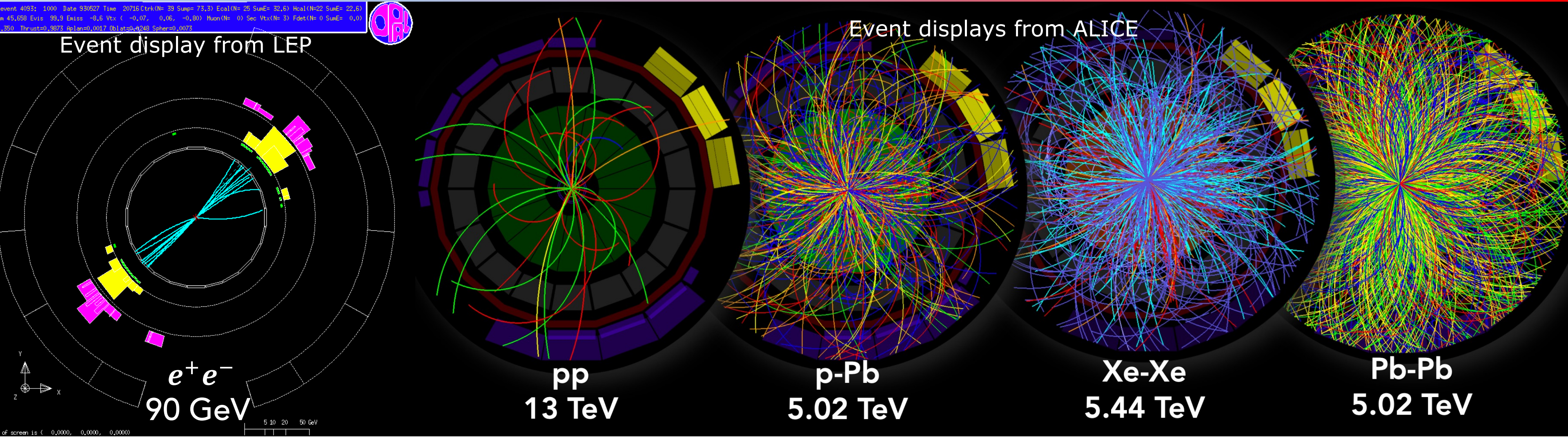
Managed by Triad National Security, LLC, for the U.S. Department of Energy's NNSA.

From vacuum to the QCD medium- hadronization

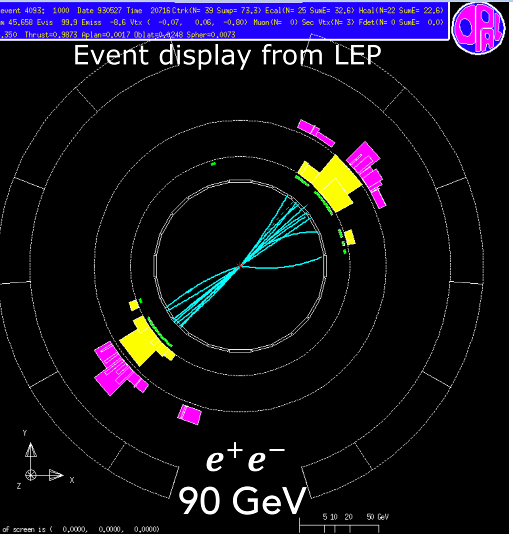
Vacuum (e^+e^-) Diffuse medium (pp,pA) Increasing T, $N_{charged}$ Dense medium (pA, AA)



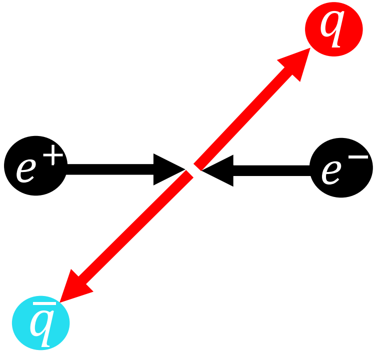
- The defining feature of QCD is **confinement**: quarks and gluons can never be observed as isolated particles
- Instead, they are found only as constituents of color-neutral hadrons

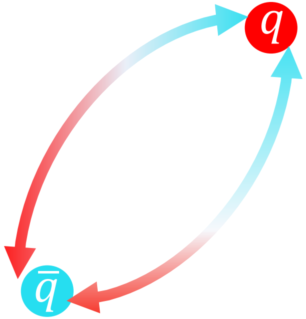
Hadronization mechanisms

Fragmentation in vacuum ($e^+e^- \to q\bar{q}$ event)



Potential between quarks increases until it is energetically favorable to neutralize color charge by creating more quarks out of vacuum.





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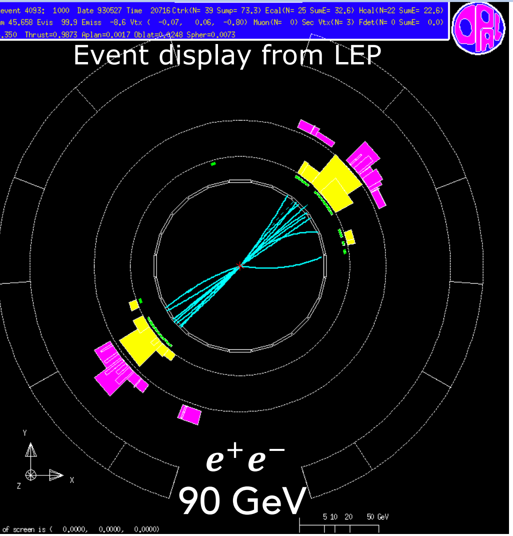

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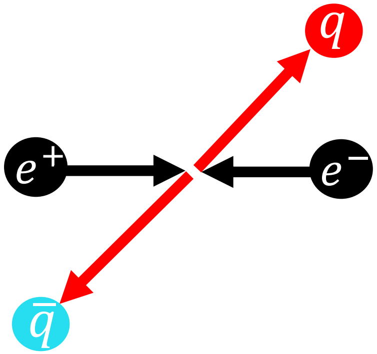

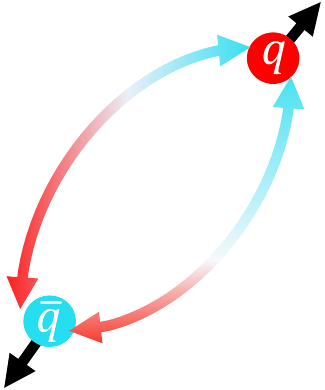

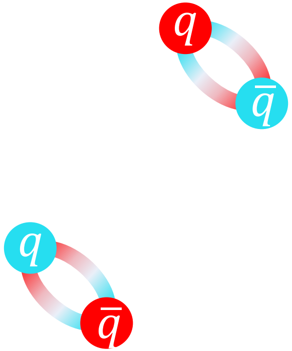

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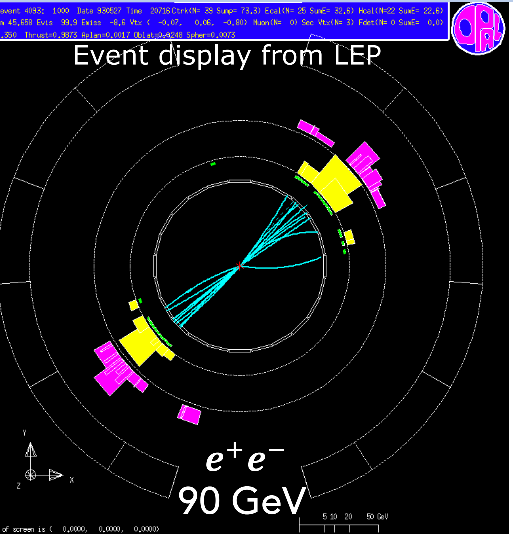

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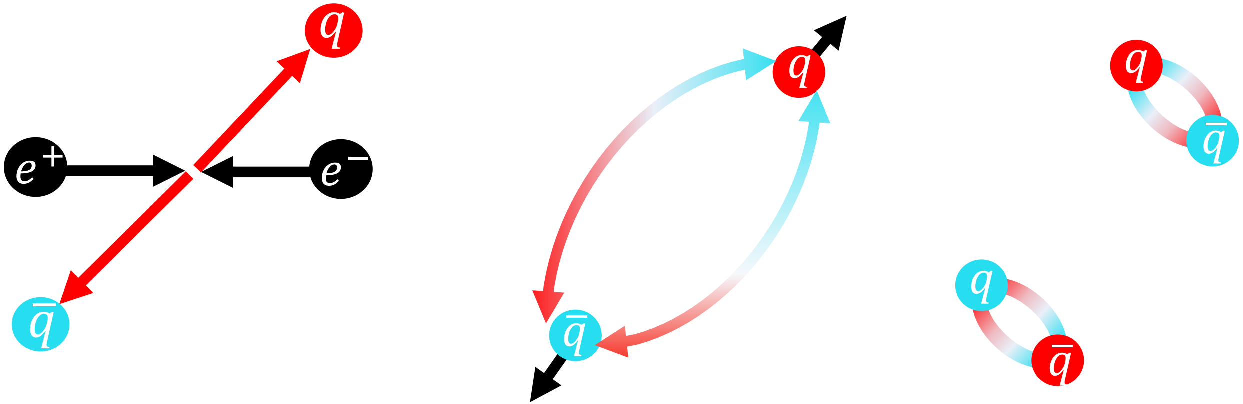
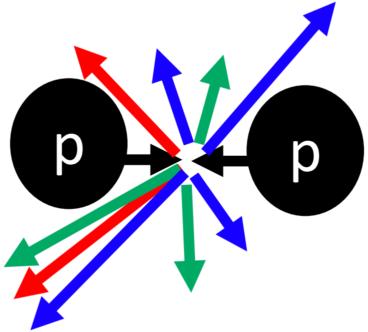
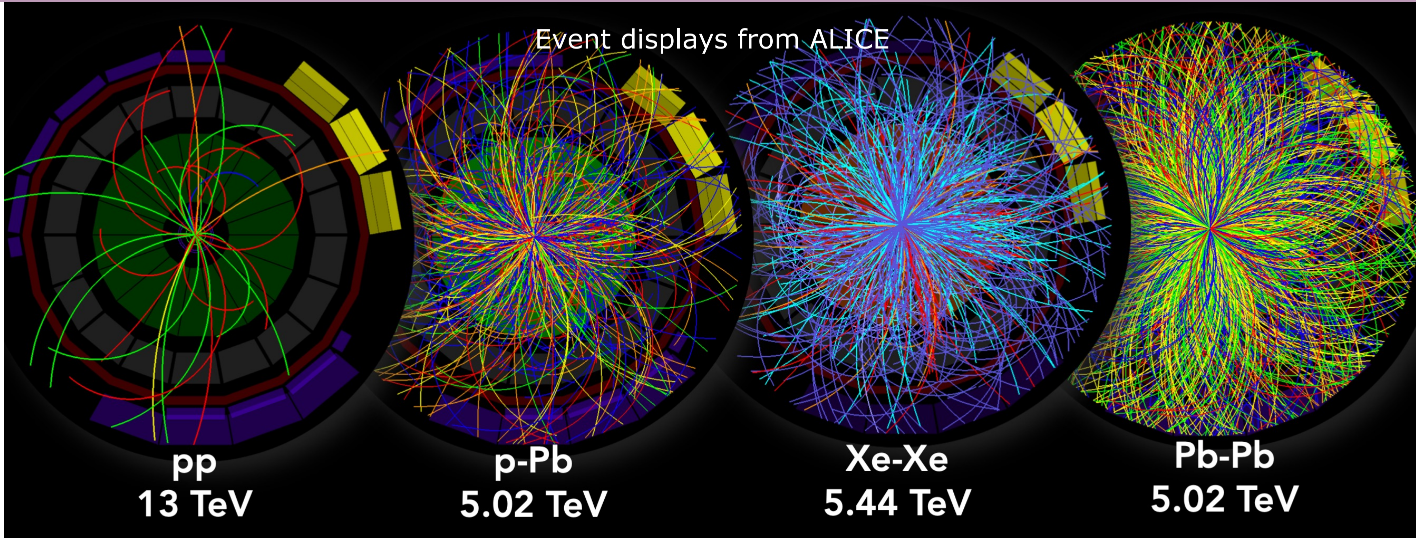


- Models of fragmentation are tuned precisely to data from e^+e^- collisions
- These models **FAIL** to describe particle production in *pp*, *p*A, and AA collisions

Hadronization mechanisms

Quark coalescence

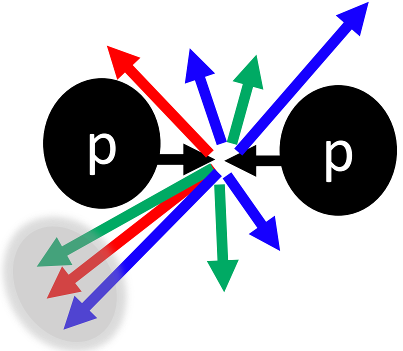


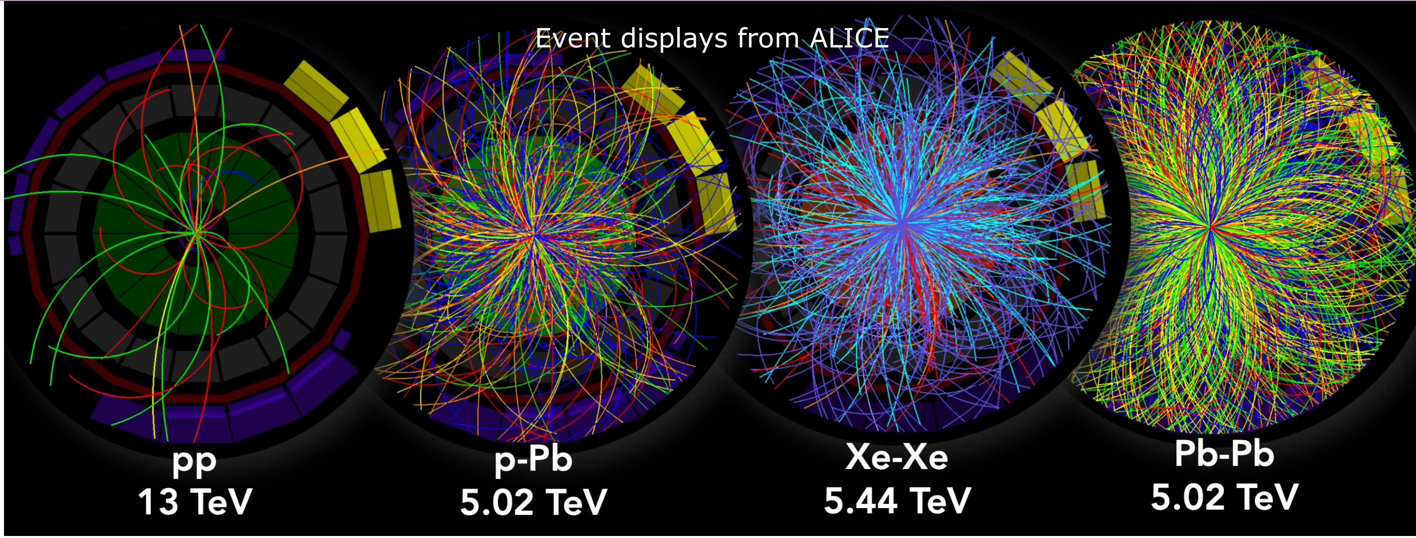


- Quarks that overlap in position/velocity space can coalesce to make color neutral hadrons

Hadronization mechanisms

Quark coalescence

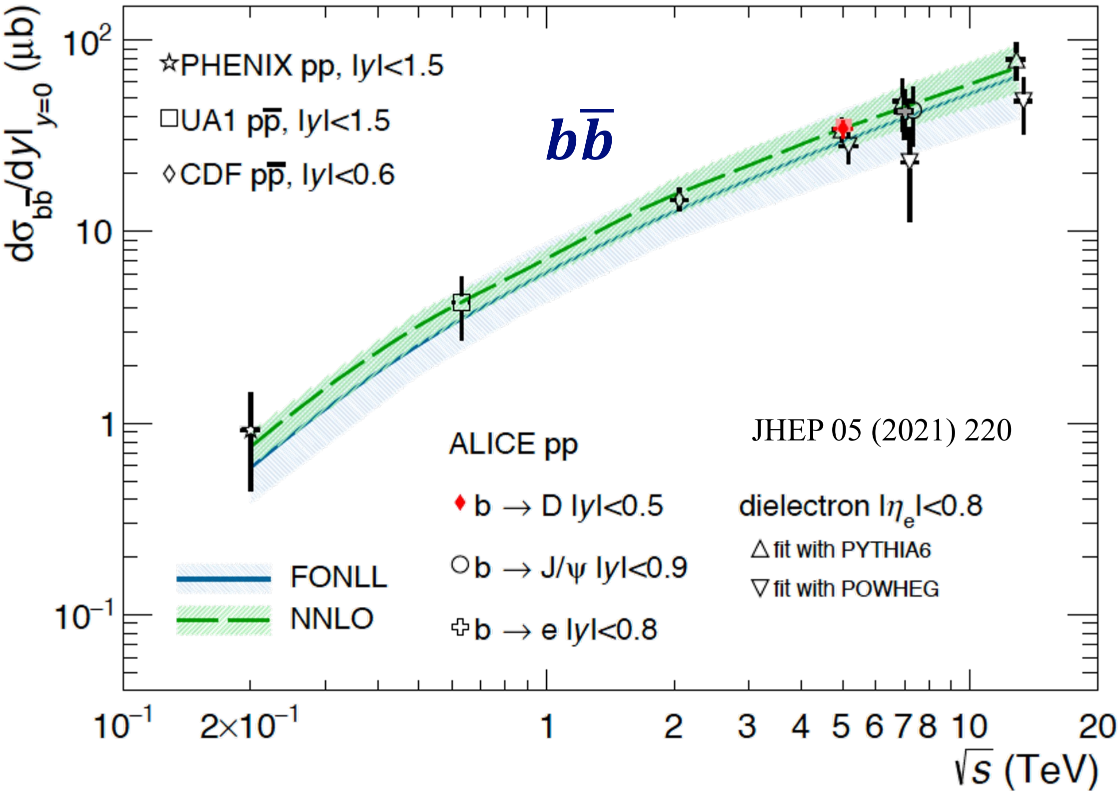




- Quarks that overlap in position/velocity space can coalesce to make color neutral hadrons
- At high density, expect increased production of **hadrons with strange quarks** and enhanced production of **3-quark baryons**

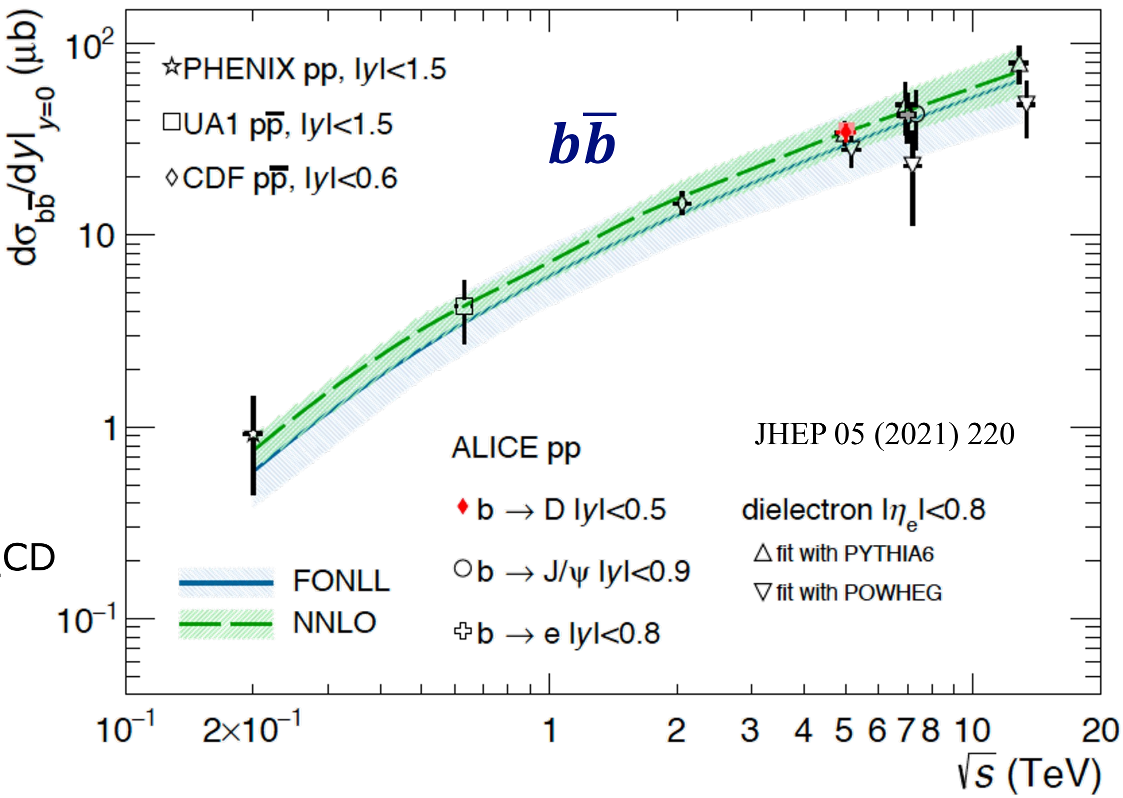
Heavy quark production

- Production of $b\bar{b}$ pairs:
  - Dominated by hard parton-parton interactions
  - Initial stages of a collision
  - Quantity is essentially fixed in the early stages of collisions



Heavy quark production

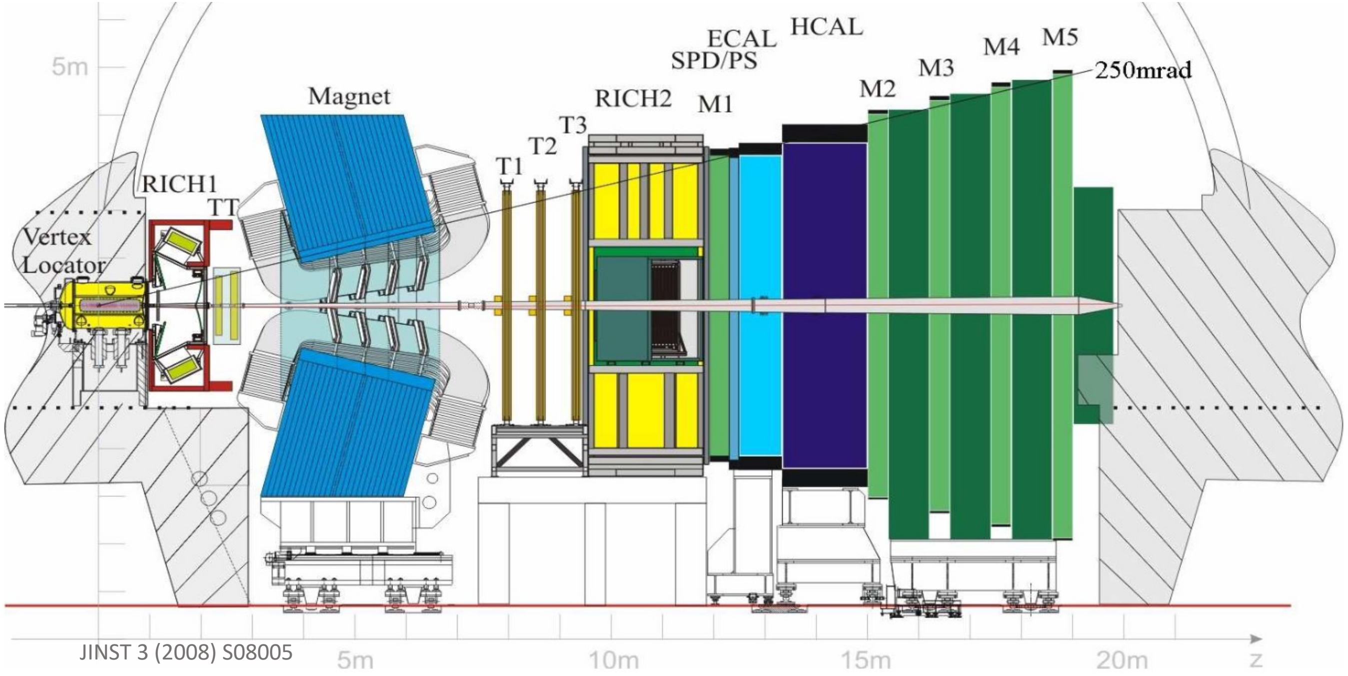
- Production of $b\bar{b}$ pairs:
  - Dominated by hard parton-parton interactions
  - Initial stages of a collision
  - Quantity is essentially fixed in the early stages of collisions
- Cross section is well described by pQCD calculations



We can use *b* quarks produced perturbatively to probe the non-perturbative hadronization process

The Large Hadron Collider beauty (LHCb)

- Precision vertexing
- Fast DAQ at forward rapidity
- $p_T > 0$



JINST 3 (2008) S08005

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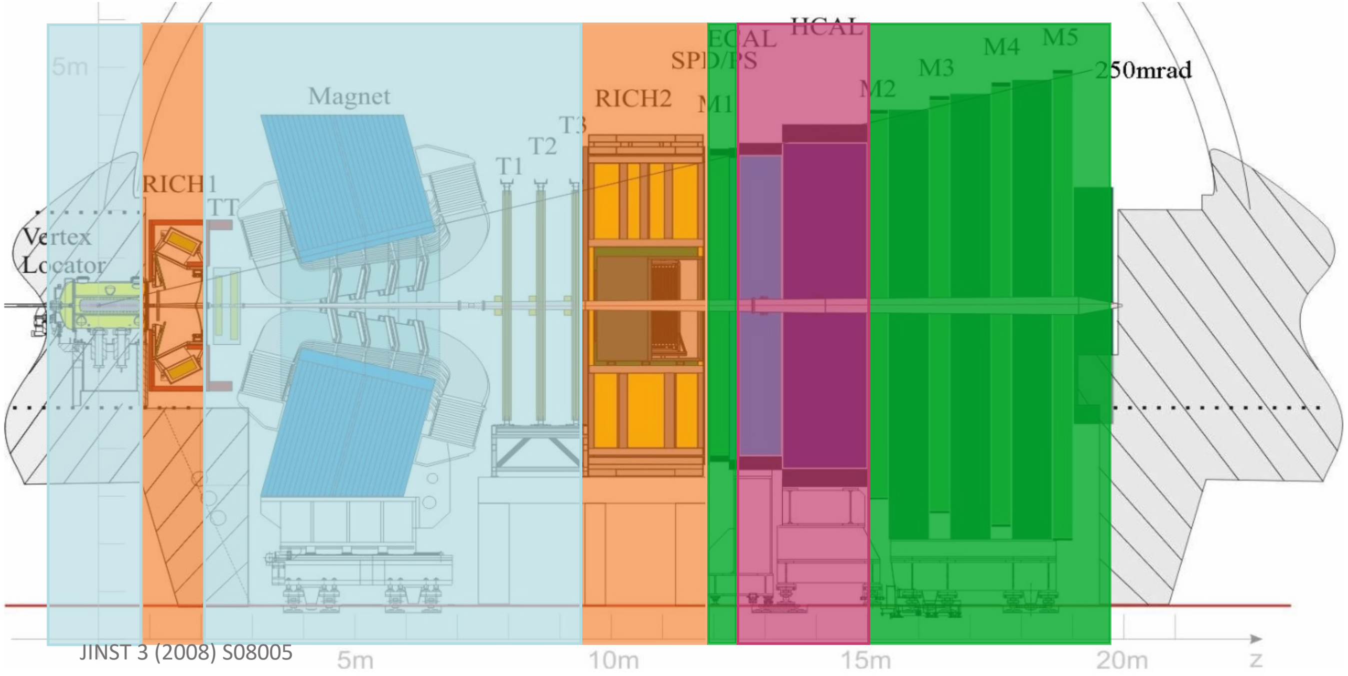

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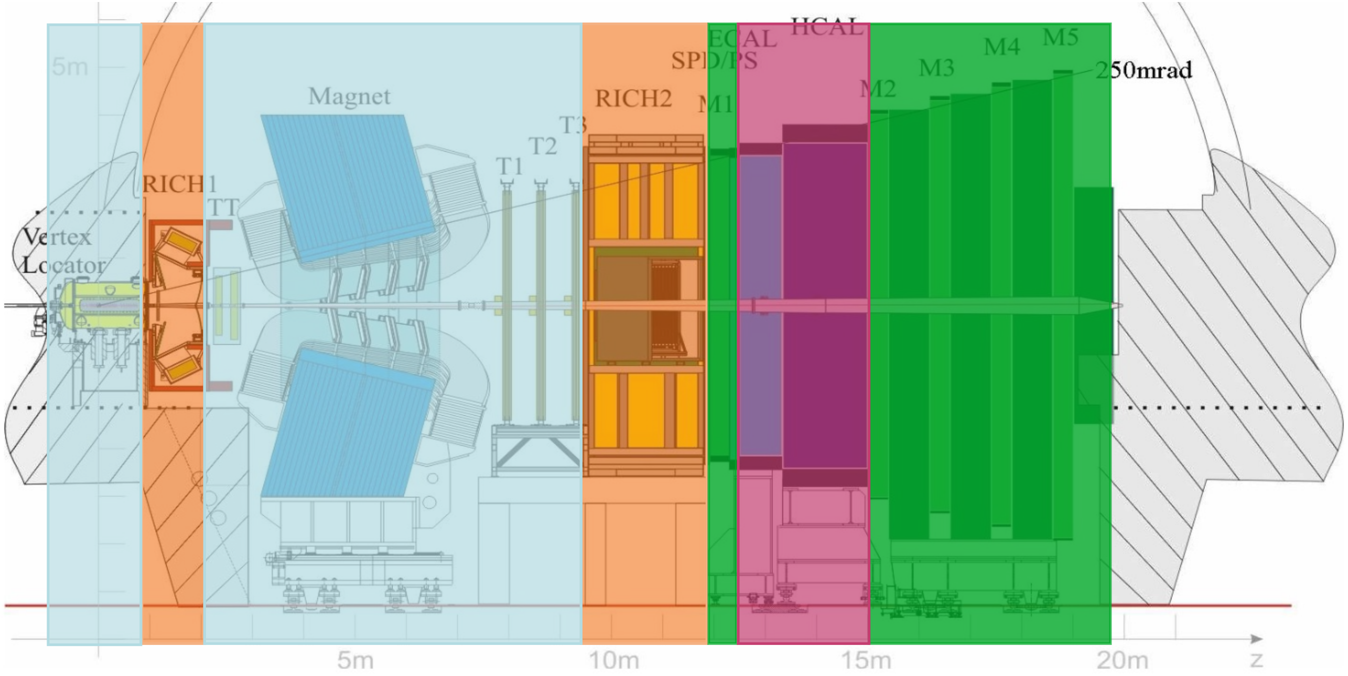
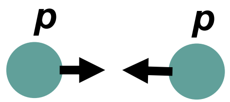


LHCb has unique access to large sets of B baryons and mesons at low p_T

B baryons at LHCb



- The very heavy *b* quarks move slowly at low p_T
  - Slower velocity
  - Larger wavelength
  - Greater overlap with bulk particles
- Should be especially sensitive to coalescence

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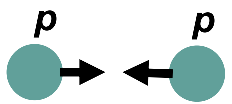

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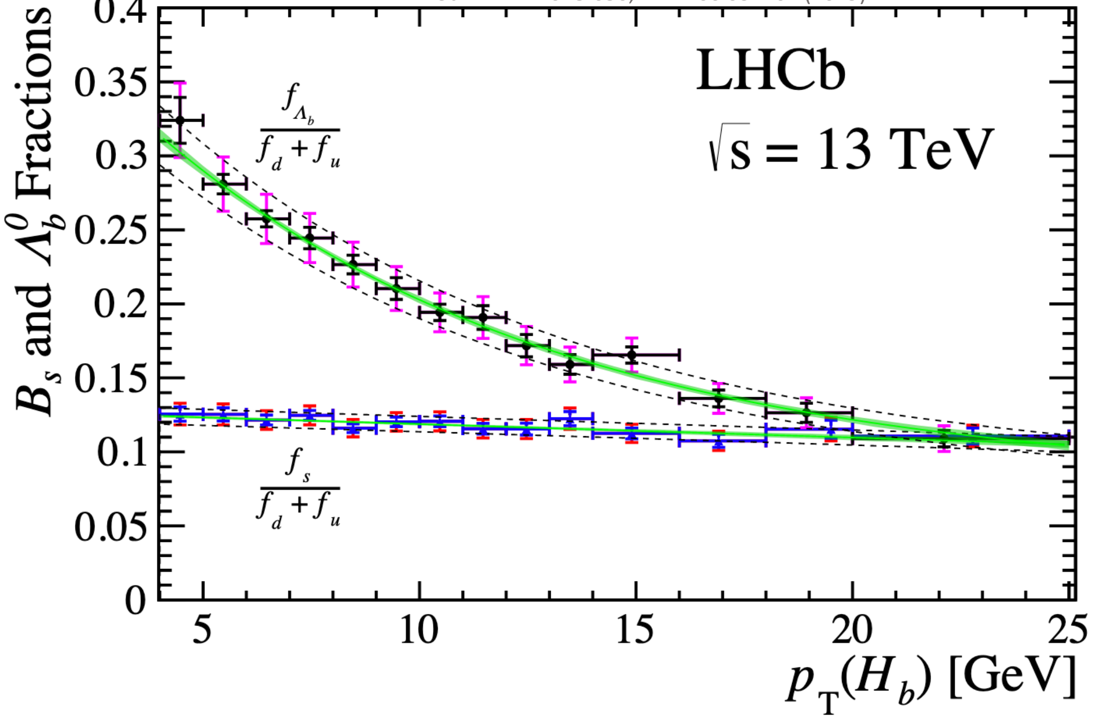
LHCb-PAPER-2018-050, PRD 100 031102 (2019)



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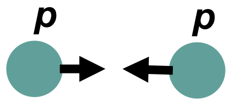

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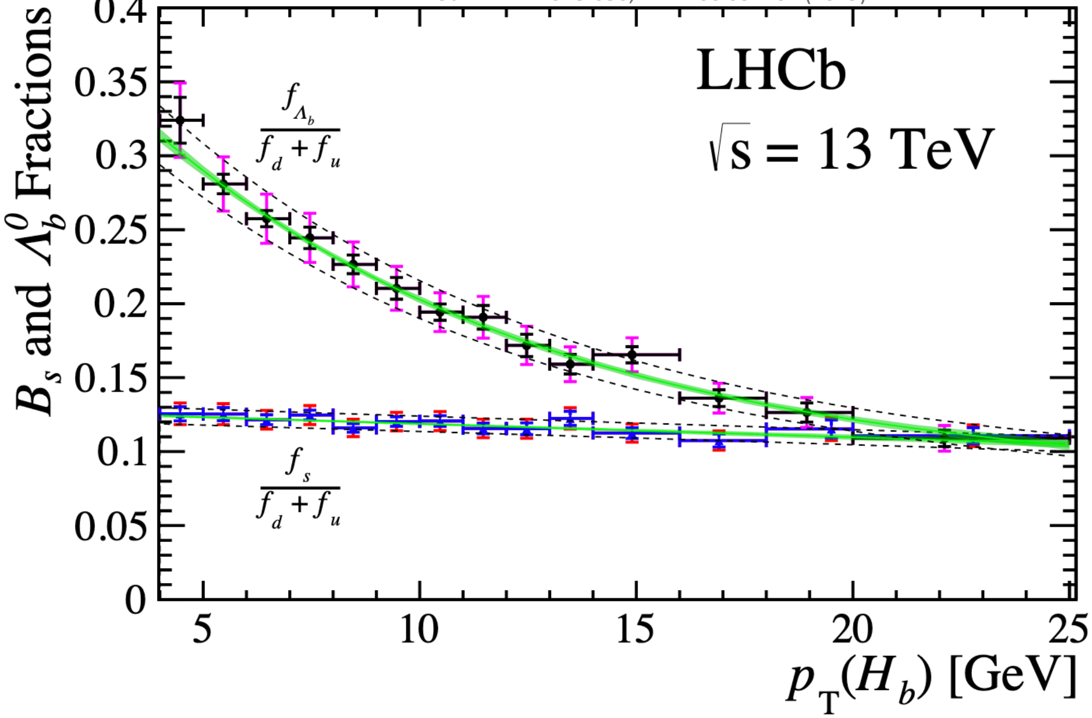
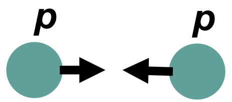


Previous LHCb measurements show dramatic variation of *B* baryon/meson ratio with p_T

Behavior is not explained by fragmentation alone!

B baryons at LHCb



$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} = \frac{N_{\Lambda_s^0}}{N_{B^0}} \times \frac{BR(B^0 \to J/\psi K\pi)}{BR(\Lambda_b^0 \to J/\psi p\pi)} \times \frac{\varepsilon_{B^0}^{acc}}{\varepsilon_{\Lambda_b^0}^{acc}} \times \frac{\varepsilon_{B^0}^{trig}}{\varepsilon_{\Lambda_b^0}^{trig}} \times \frac{\varepsilon_{B^0}^{reco}}{\varepsilon_{\Lambda_b^0}^{reco}} \times \frac{\varepsilon_{B^0}^{PID}}{\varepsilon_{\Lambda_b^0}^{PID}}$$

- Physics quantity of interest

B baryon measurement

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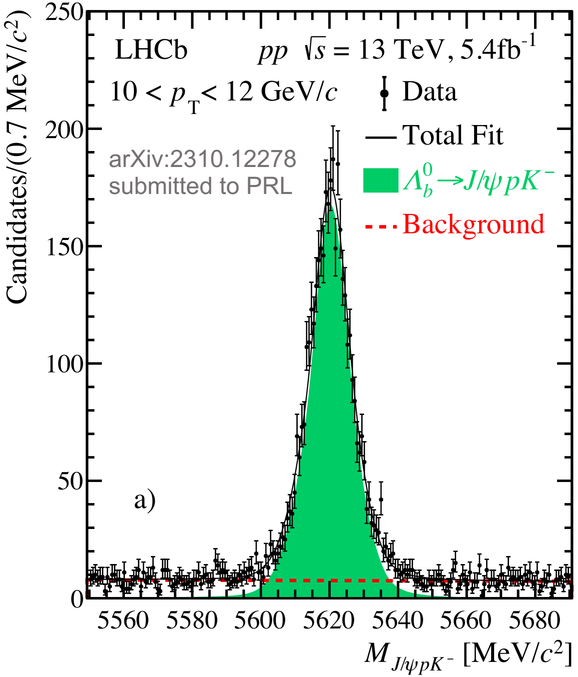
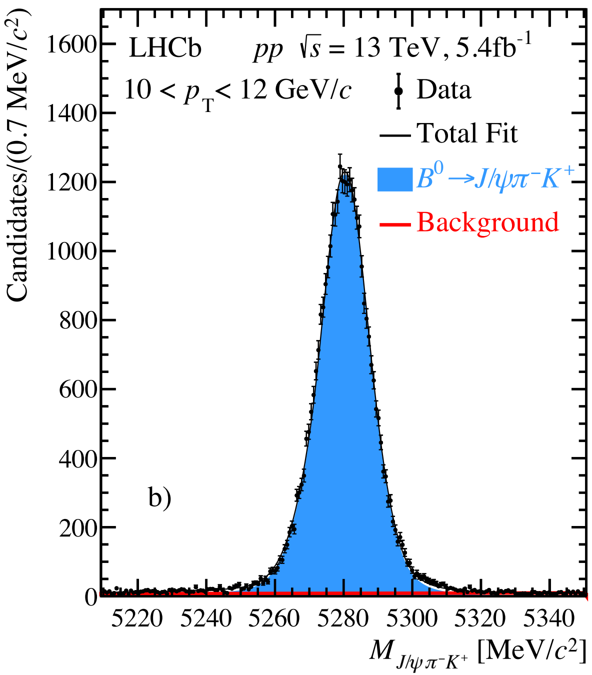
- Counts extracted by fitting mass spectra in multiplicity bins





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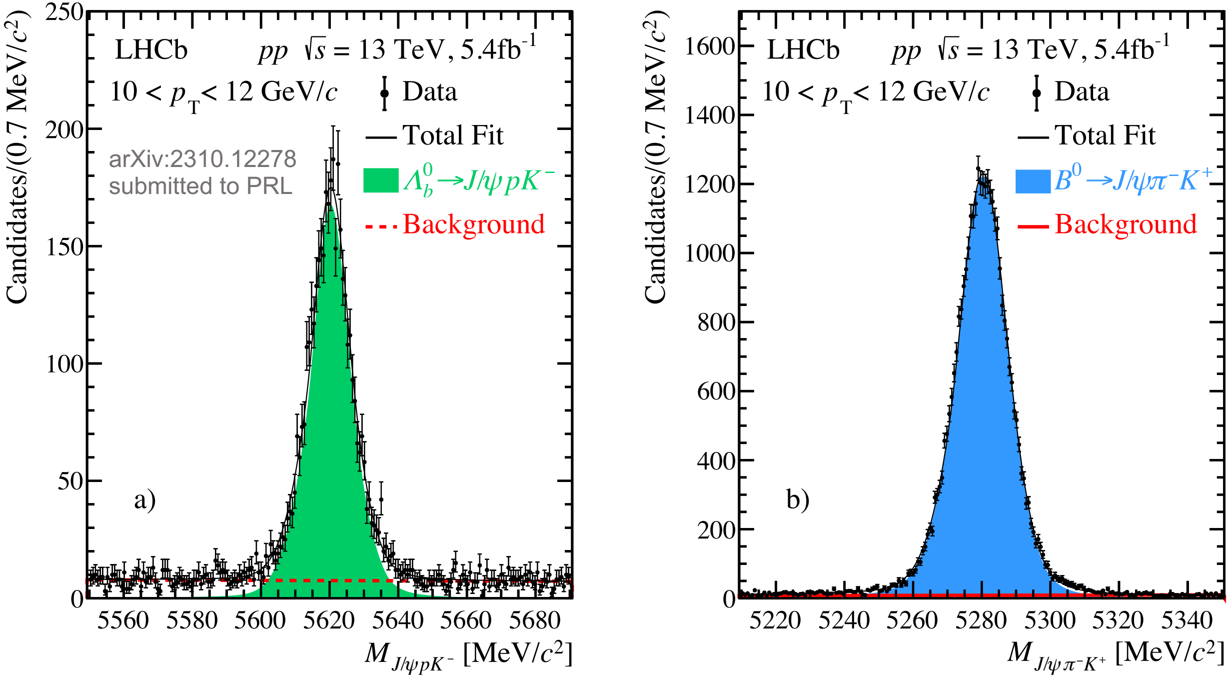
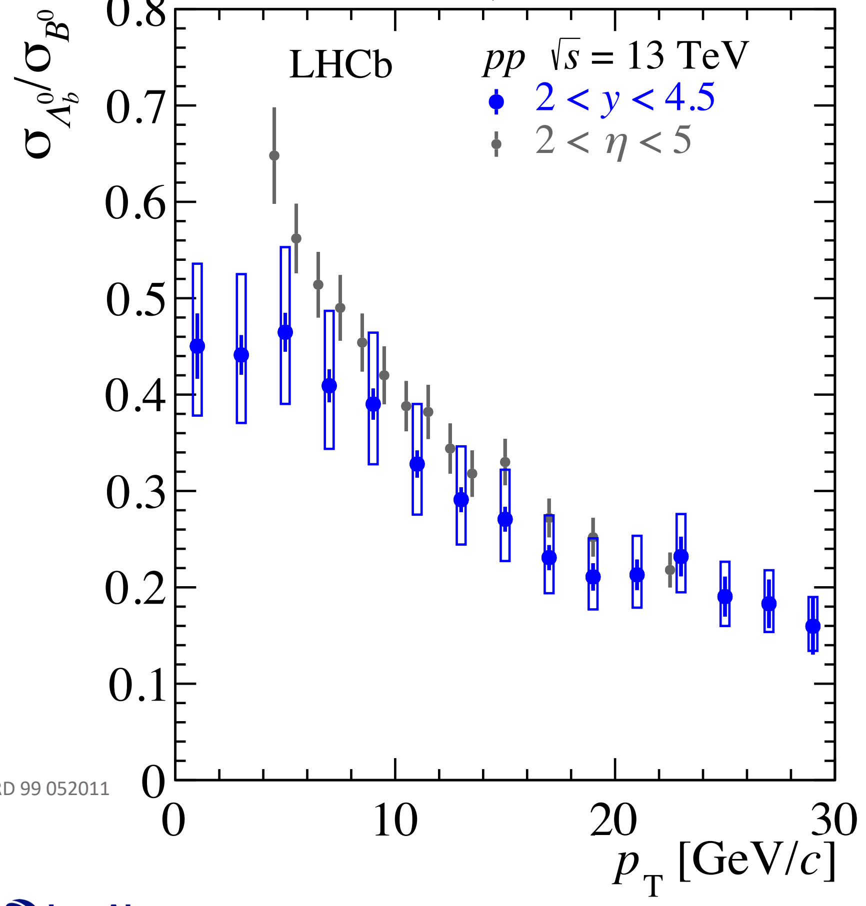
- Physics quantity of interest
- Counts extracted by fitting mass spectra in multiplicity bins
- Branching fractions from PDG
- **Efficiency calculations largely canceled out**



B baryon enhancement

arXiv:2310.12278, submitted to PRL



PRD 99 052011

- Hadronic decays confirm strong dependence on p_T
- Hadronic and semileptonic decay data agree

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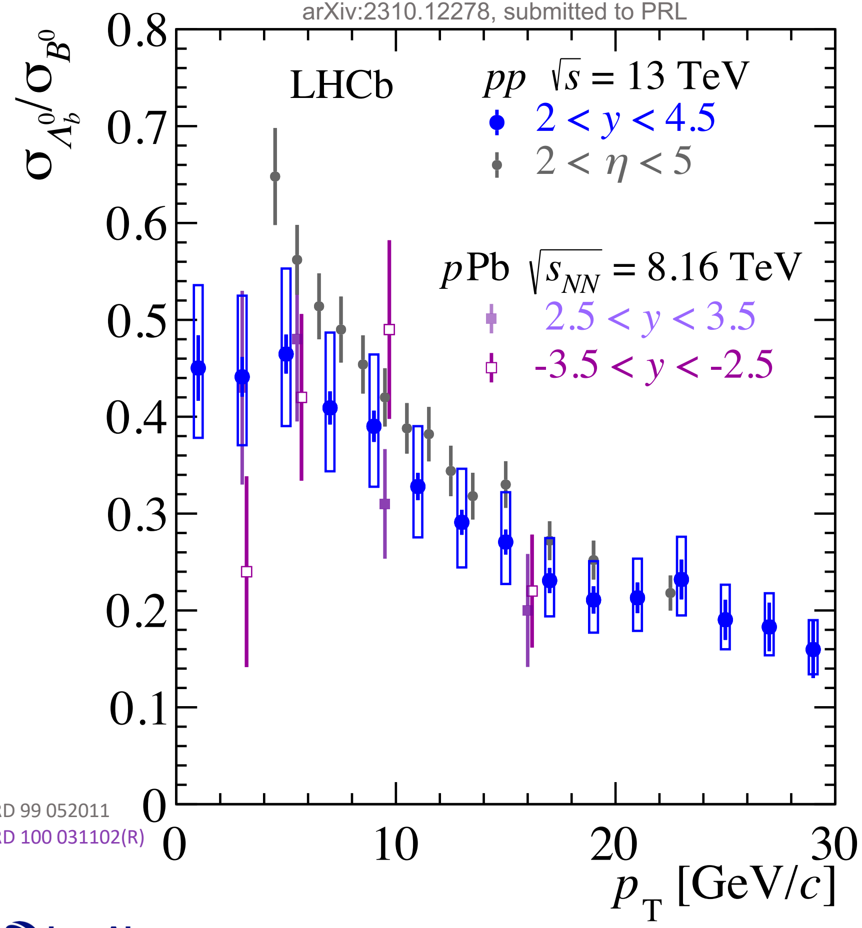

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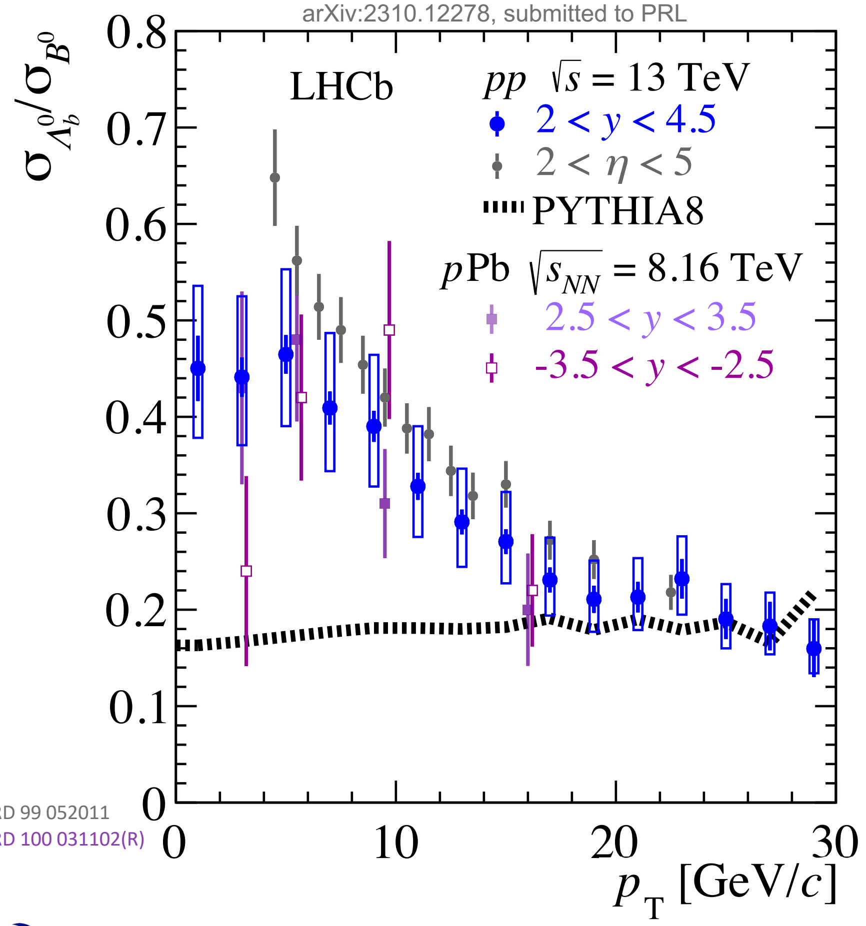

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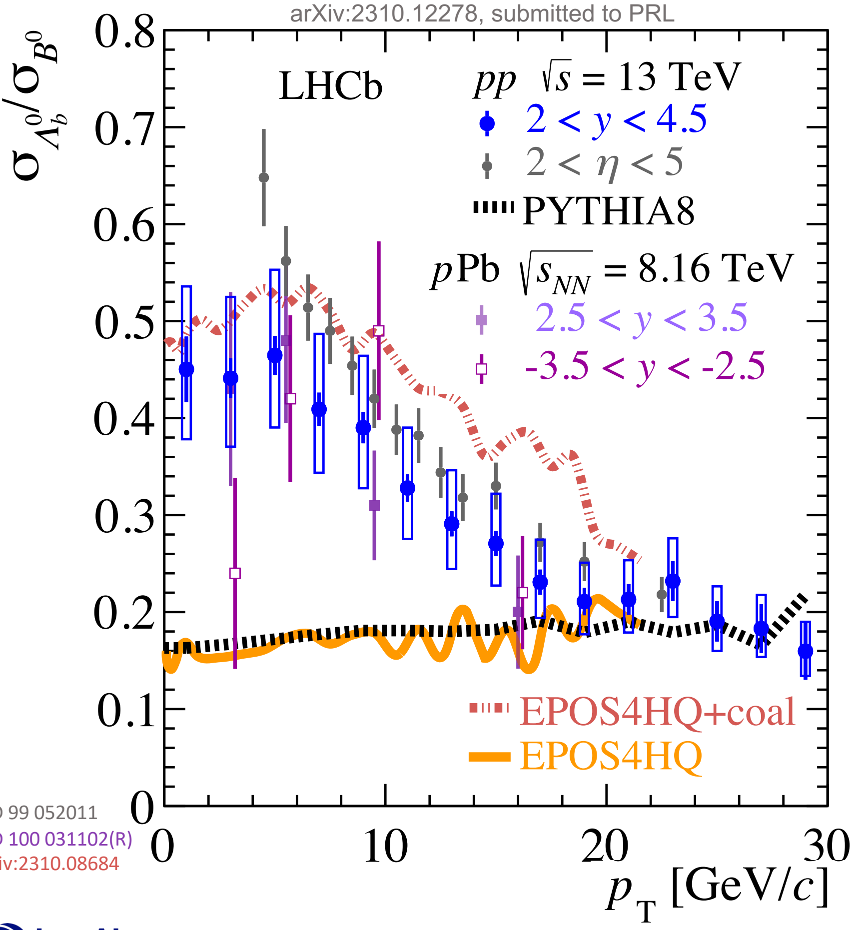

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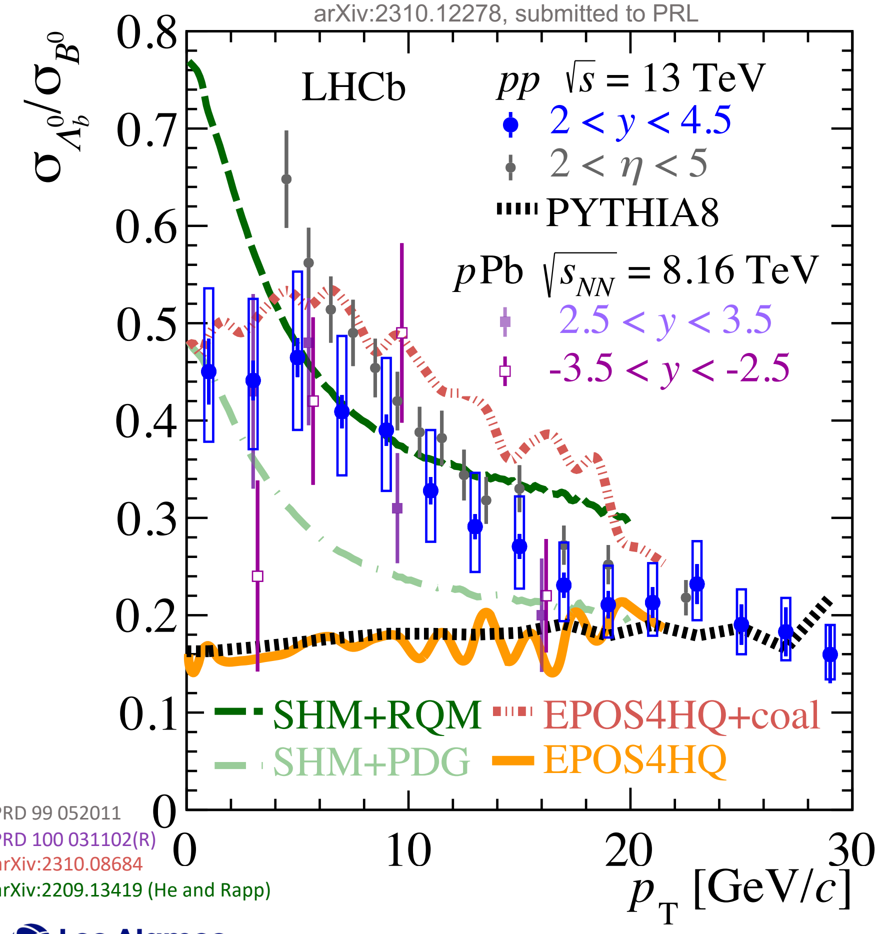

PRD 99 052011
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arXiv:2209.13419 (He and Rapp)

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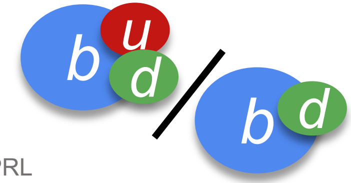
- EPOS4HQ follows the same tend as PYTHIA
- Compare to Statistical Hadronization Model that uses two sets of baryons as input:
  - Expanded set of baryons predicted by the Relativistic Quark Model
  - Known baryons from PDG

B baryon enhancement



- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Baryon/meson ratio shows significant multiplicity dependence
- Expected in scenario where *b* quarks coalesce with light quarks to form baryons

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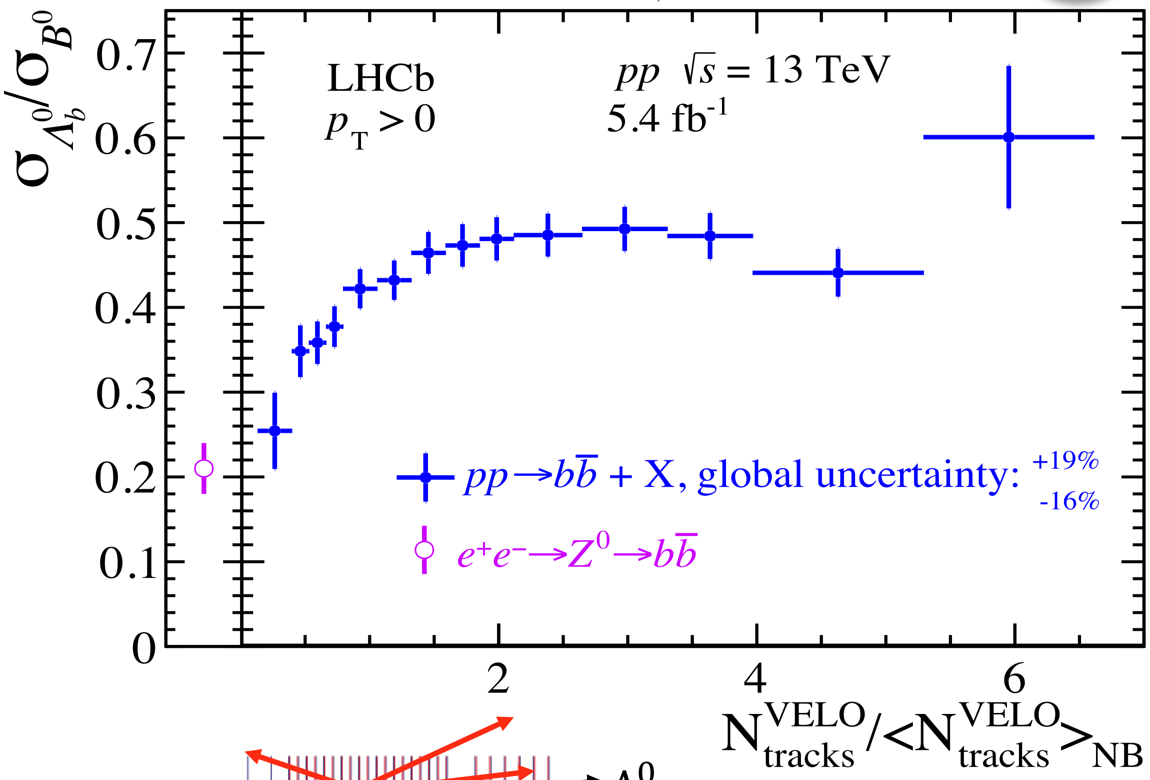

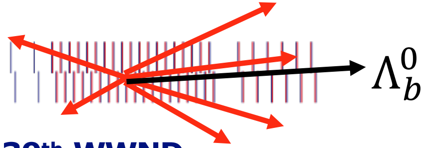

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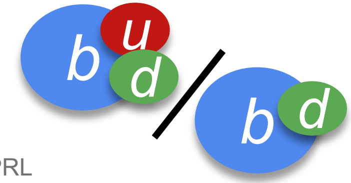

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- Pure fragmentation limit is achieved

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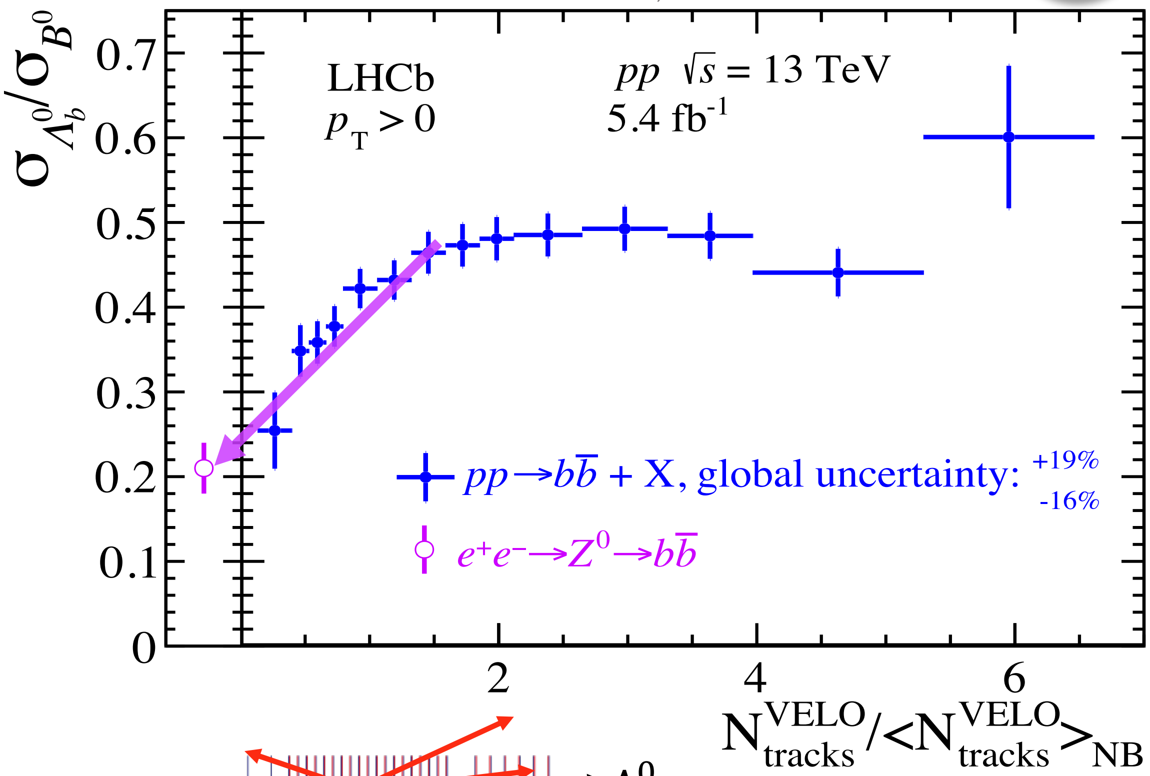

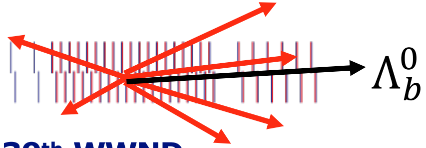

B baryon enhancement

- Clear multiplicity dependence at relatively low p_T
- Distinct ordering of enhancement from low to high multiplicity

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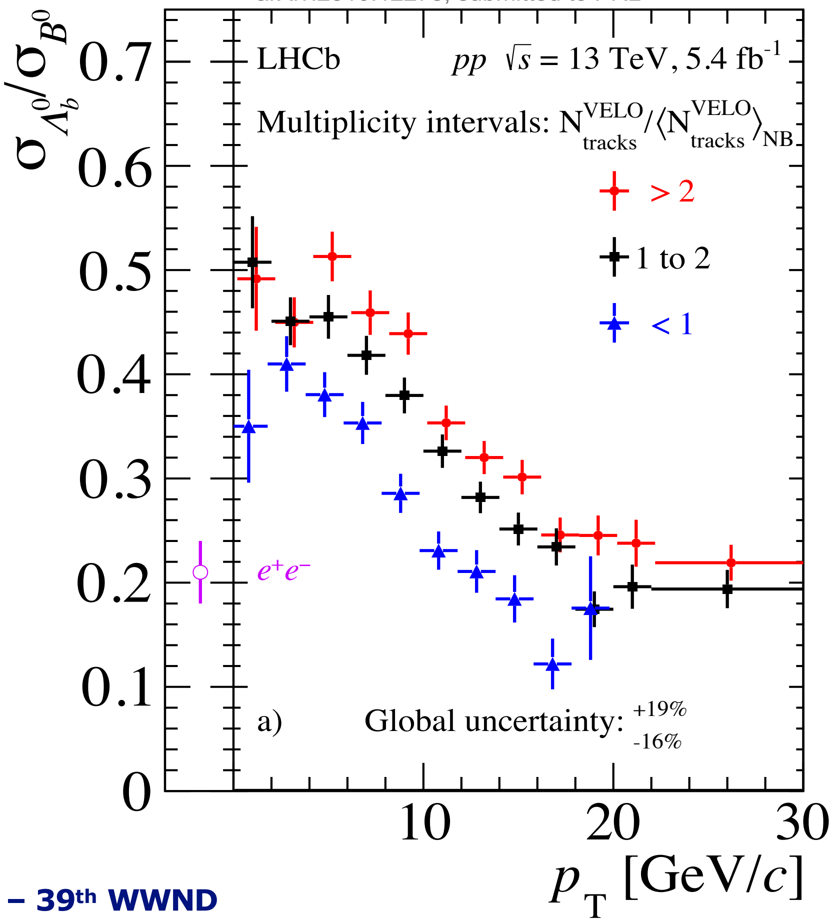

B baryon enhancement

- Clear multiplicity dependence at relatively low p_T
- Distinct ordering of enhancement from low to high multiplicity
- Reproduce e^+e^- result at high p_T where *b* quarks don't interact with bulk and fragment instead

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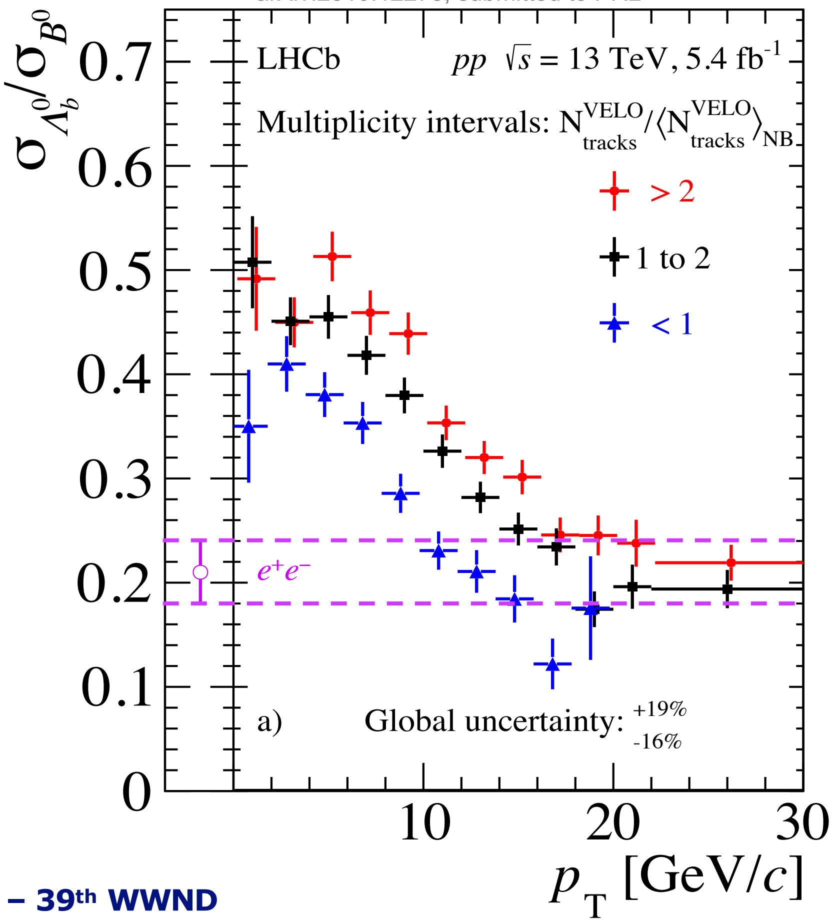
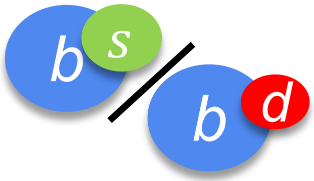
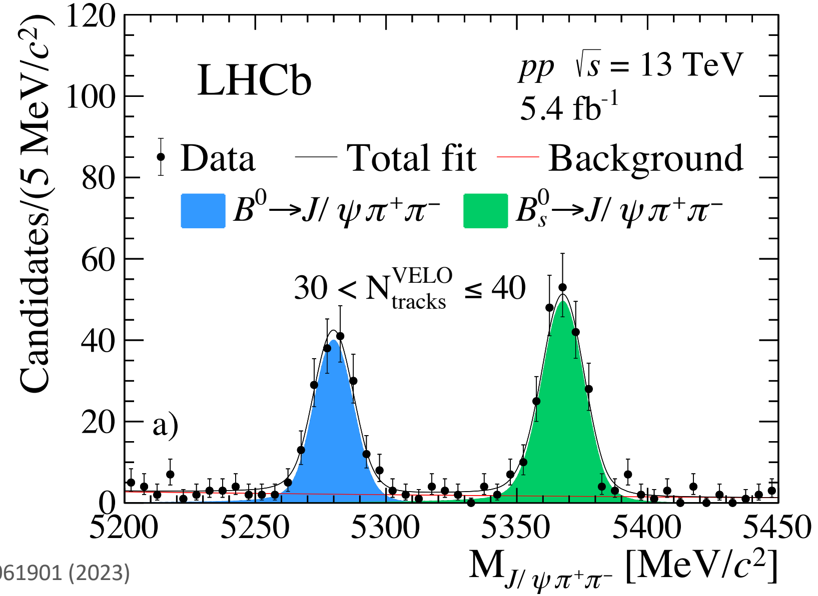


Modification of *b* hadronization

strange B mesons

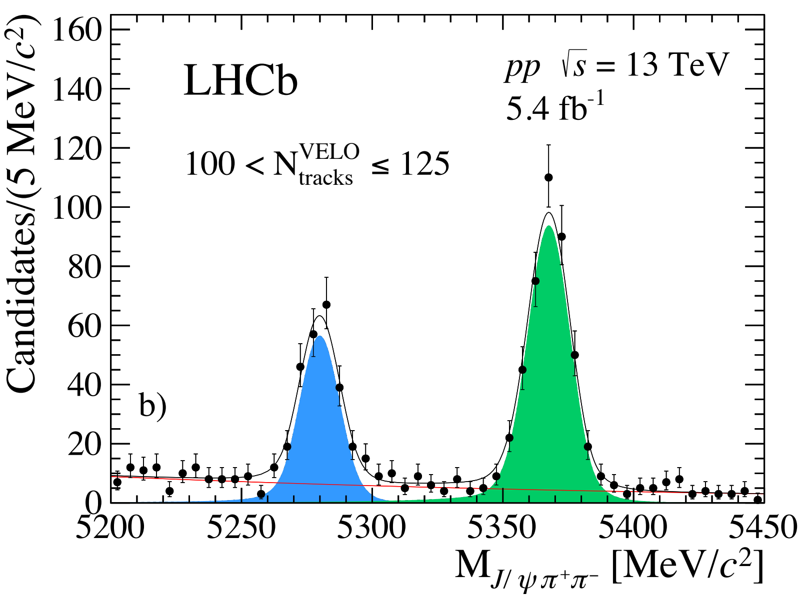


- $s\bar{s}$ production enhanced in high mult events, *Nature Physics* 13 535–539 (2017)
- coalescence should lead to enhanced B_s^0 yields



PRL 131 061901 (2023)

Low multiplicity



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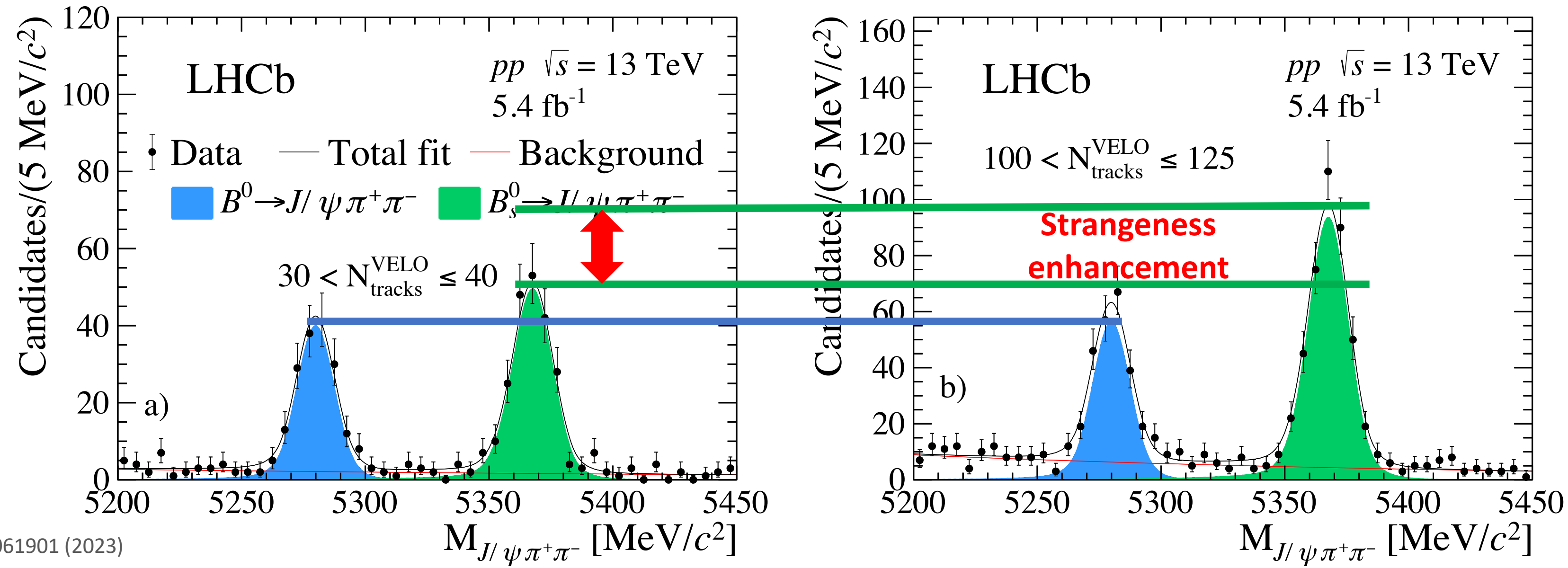

PRL 131 061901 (2023)

Low multiplicity

High multiplicity

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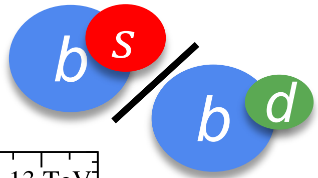

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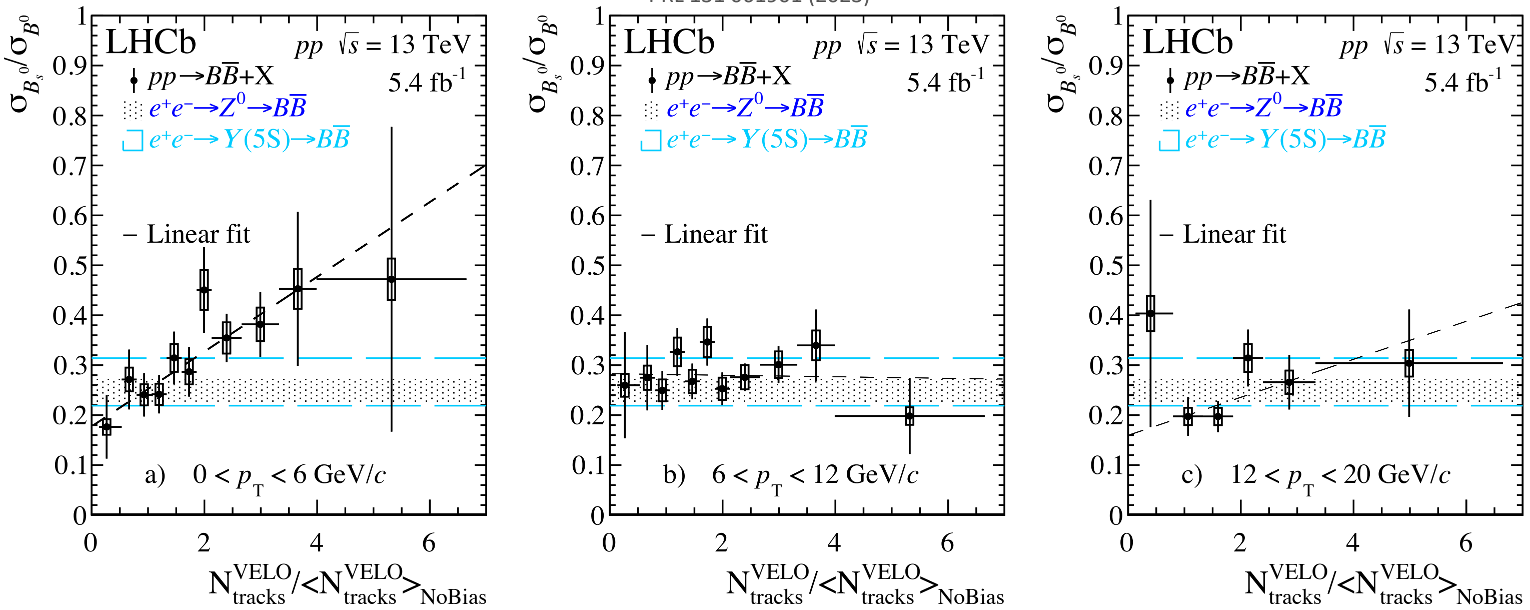

- Evidence of enhancement of B_s^0/B^0 at low p_T
- Low multiplicity data consistent with fragmentation in vacuum measured in e^+e^- collisions
- Higher p_T B mesons show no enhancement

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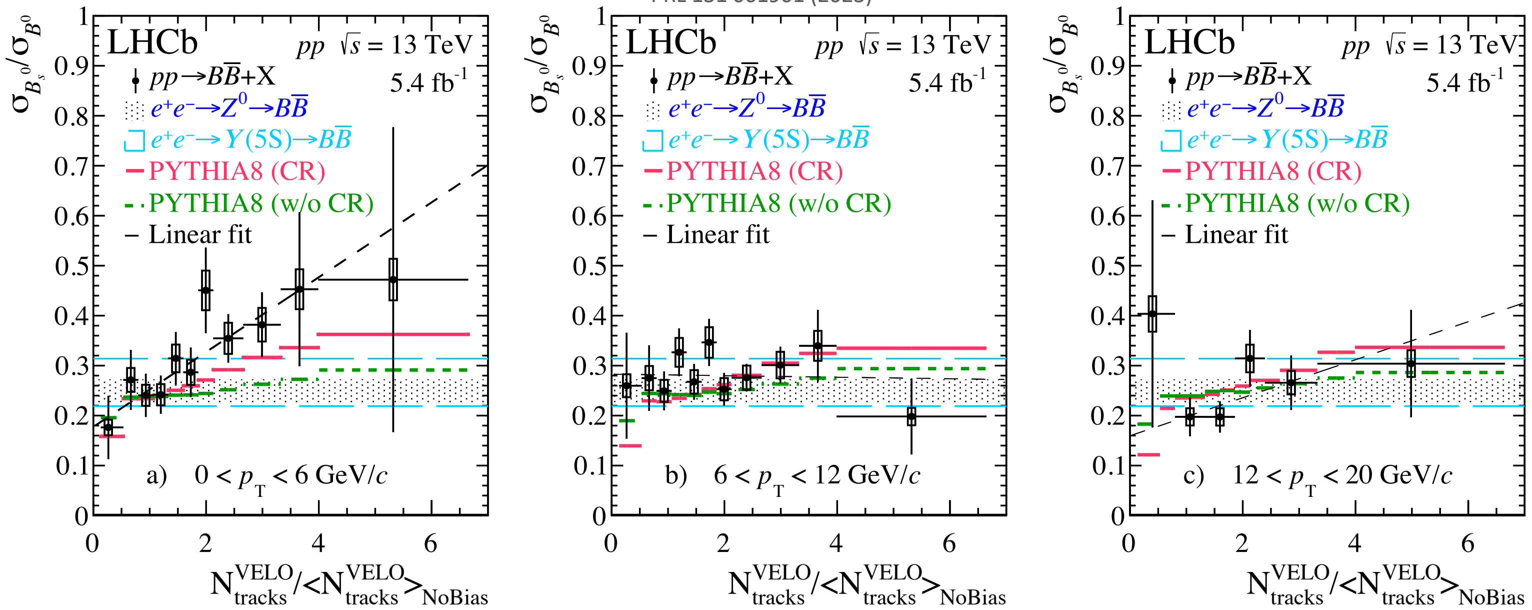

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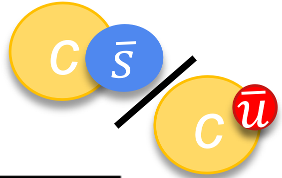
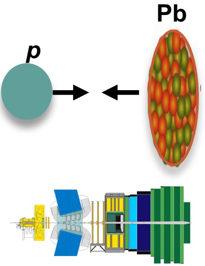
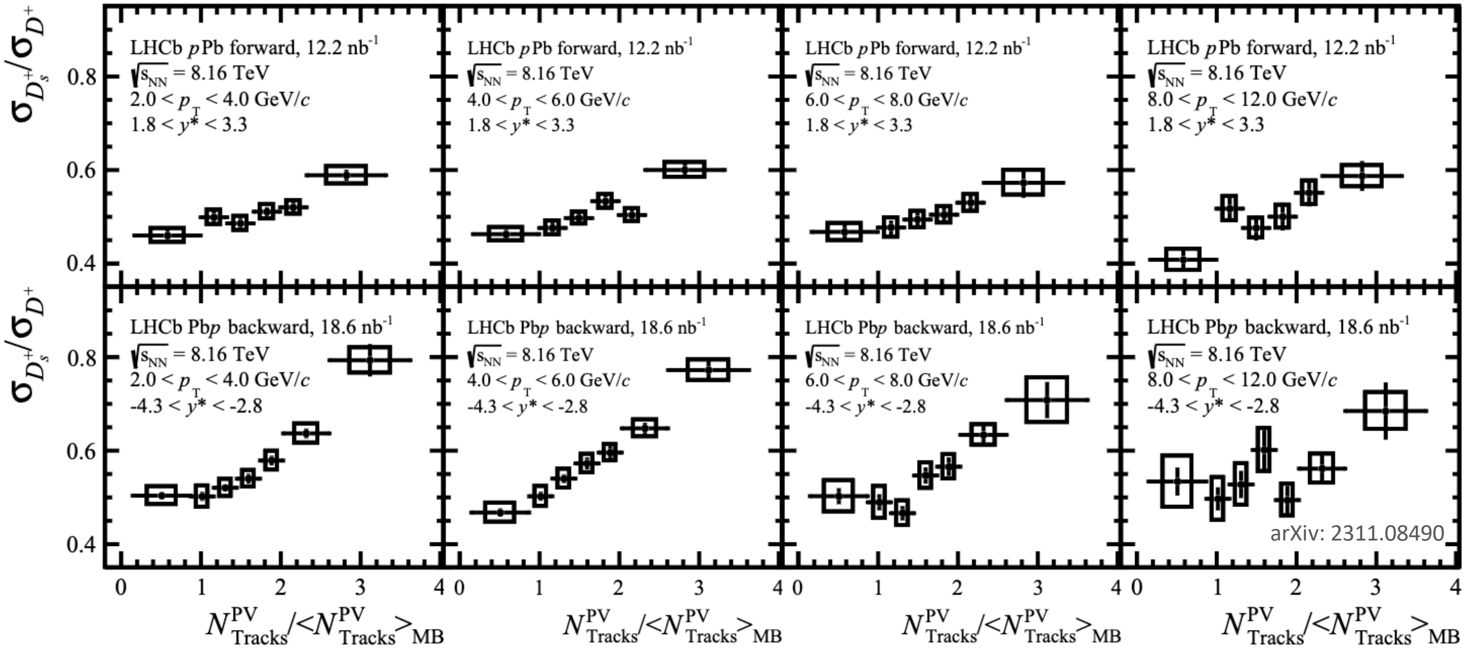
- PYTHIA8 w/color reconnection enabled describes high p_T data, undershoots low p_T

Strangeness enhancement

charm sector



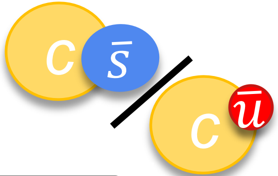


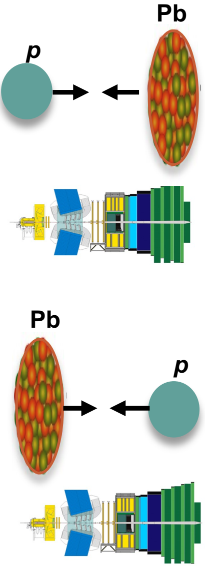


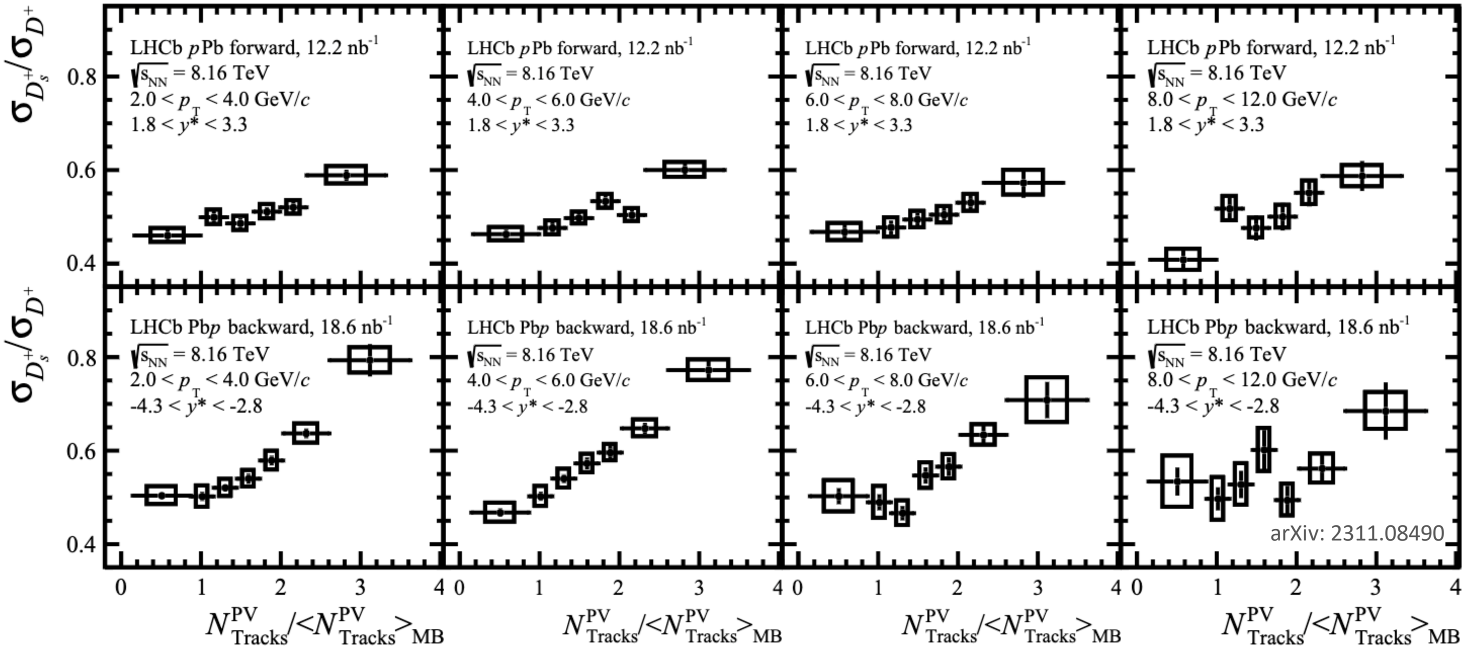
- Low p_T regime shows greater enhancement of strangeness
- Enhancement with increasing particle density in heavy-ion collisions

Strangeness enhancement

charm sector







- Low p_T regime shows greater enhancement of strangeness
- Enhancement with increasing particle density in heavy-ion collisions
- Greater enhancement in the denser hadronic environment (Pb*p*)

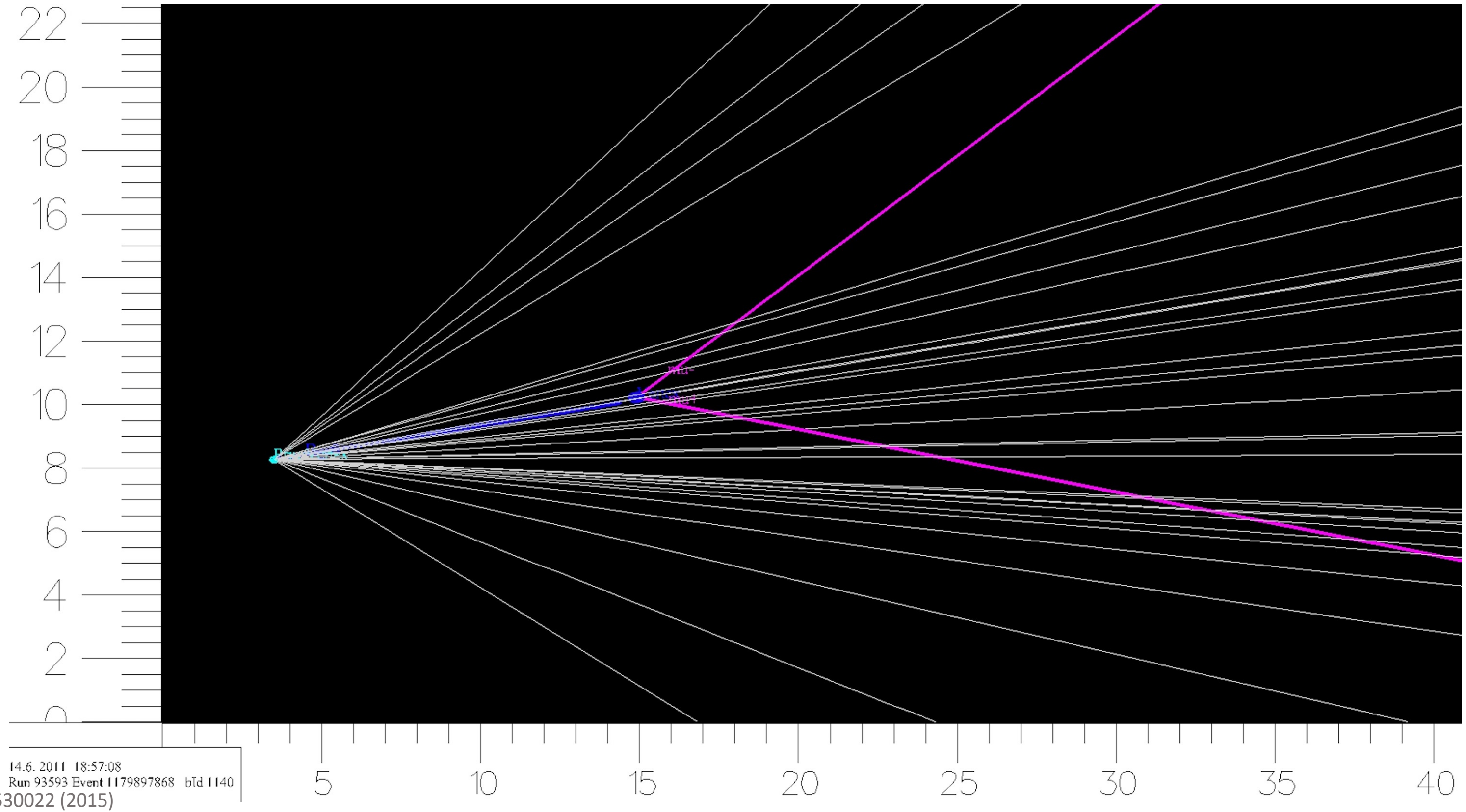
Summary

- LHCb is uniquely well-suited to study hadronization.
- The density of the underlying event has a clear effect on heavy quark hadronization.
- At increasing multiplicity and decreasing p_T, B-baryon production is enhanced, and strangeness enhancement is observed.
- The limit of pure fragmentation (as measured in $e^+e^- \to Z^0 \to b\bar{b}$ at LEP) can be recovered at low multiplicity and high p_T.
- These observations are consistent with expectations from **coalescence** emerging as a new hadronization mechanism in hadron+hadron collisions.

Back up

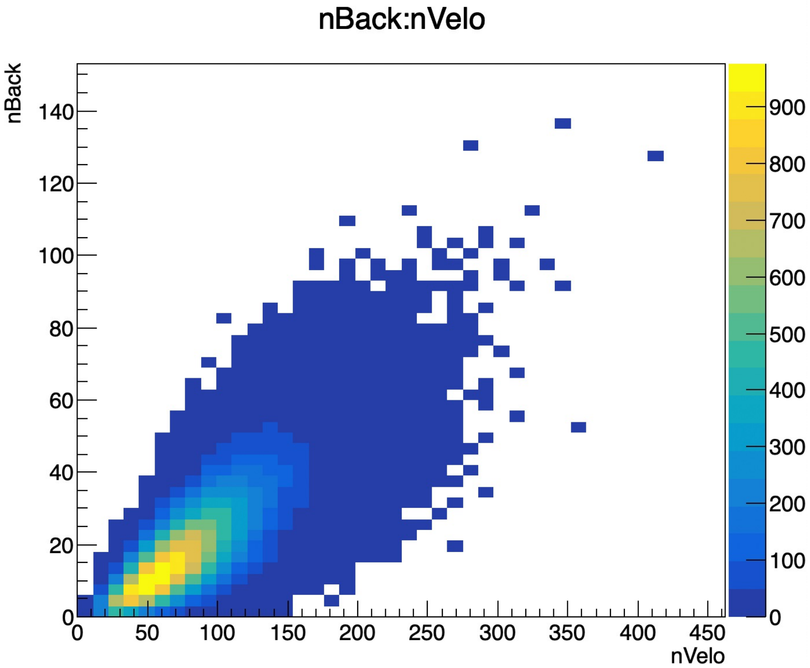
The Large Hadron Collider beauty (LHCb)

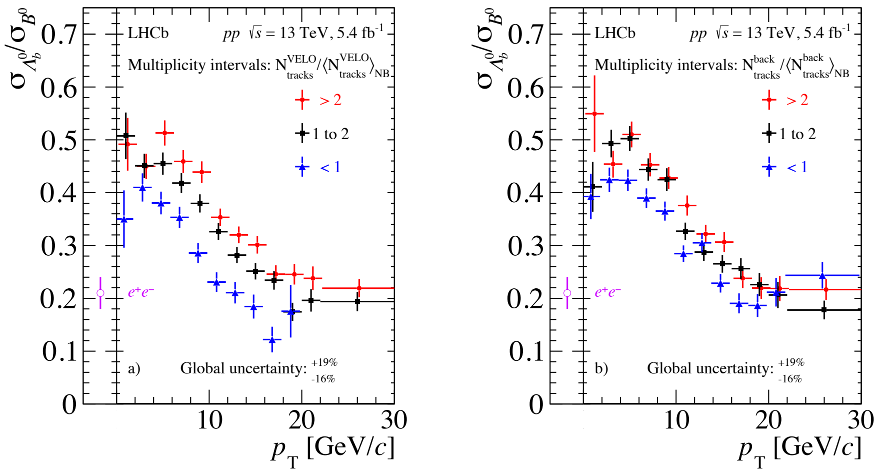
Event display of $B_s^0 \rightarrow \mu^+\mu^-$ candidate



JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

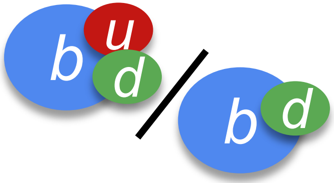
Multiplicity Metrics and correlations





- Strong correlation between nBack and nVelo
- Similar behavior is seen using both metrics

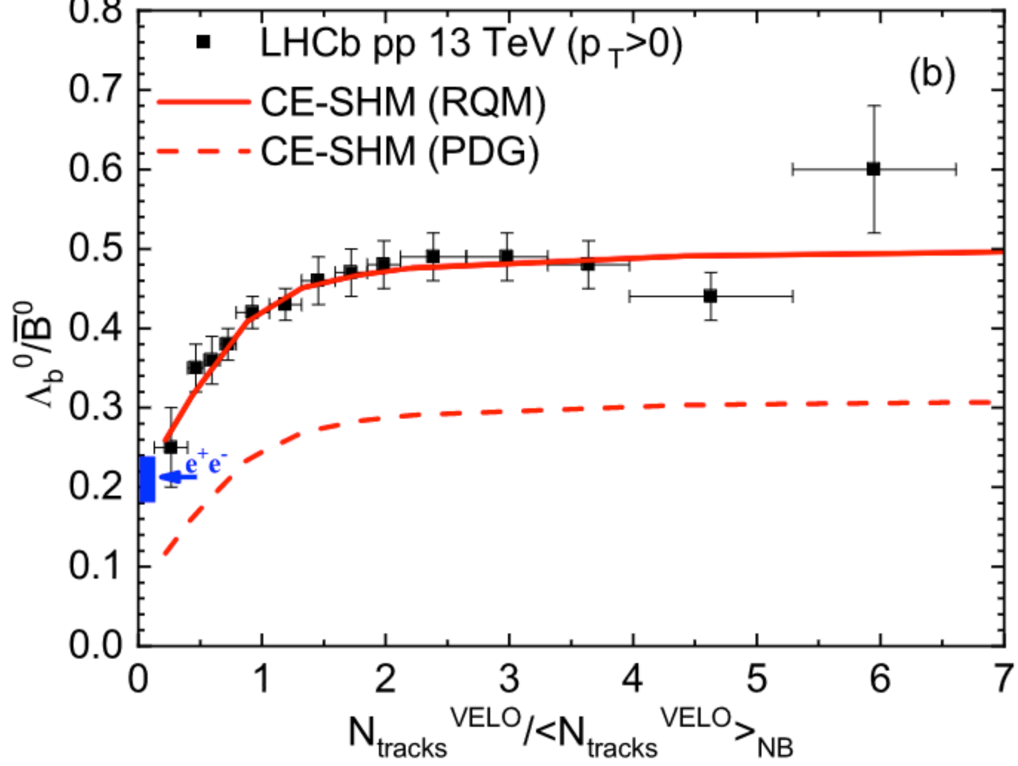
Statistical Hadronization Model



Canonical Ensemble

- Unobserved, predicted b baryons as input to CE-SHM
- Decreasing trend toward low multiplicity (canonical suppression)
- Data favors RQM model
- May indicate the existence of many, not-yet-observed b baryons

arXiv:2402.03692



Statistical Hadronization Model

Canonical Ensemble

$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j]$$

→ Partition function for small systems where relative fluctuations of quantum charges become significant

$$\vec{Q} = (Q, N, S, C, B)$$

→ Quantum charge for specific hadron type

$$(\phi_Q, \phi_N, \phi_S, \phi_C, \phi_B)$$

→ Associated phase angles

$$\langle N_j \rangle^{CE} = \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} z_j \frac{Z(\vec{Q} - \vec{q}_j)}{Z(\vec{Q})}$$

→ Primary mean yield for the j-th hadron