Open Heavy Flavor Highlights from LHCb

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On behalf of the LHCb Collaboration

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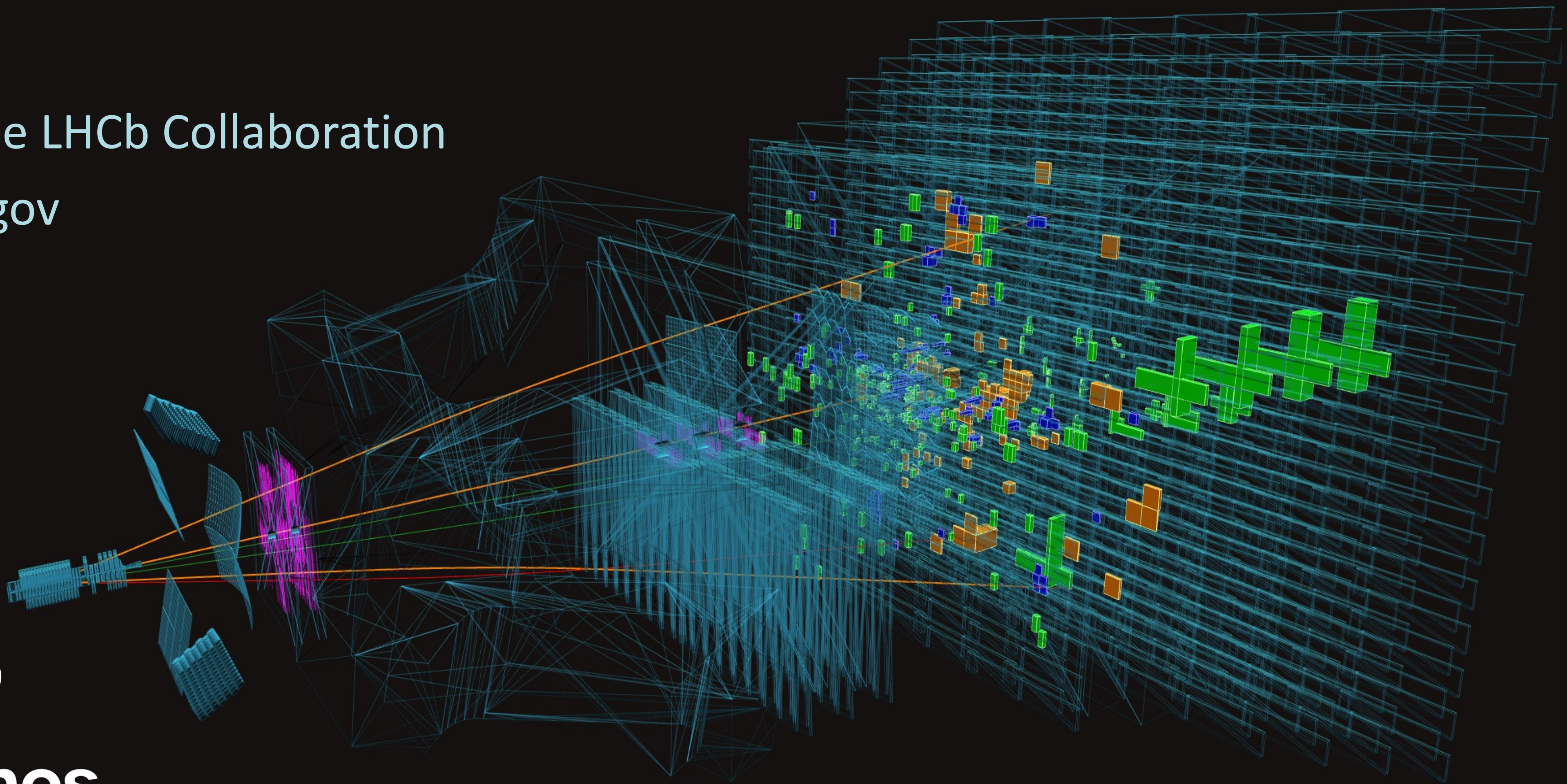


Center for Frontiers in Nuclear Science

Los Alamos NATIONAL LABORATORY

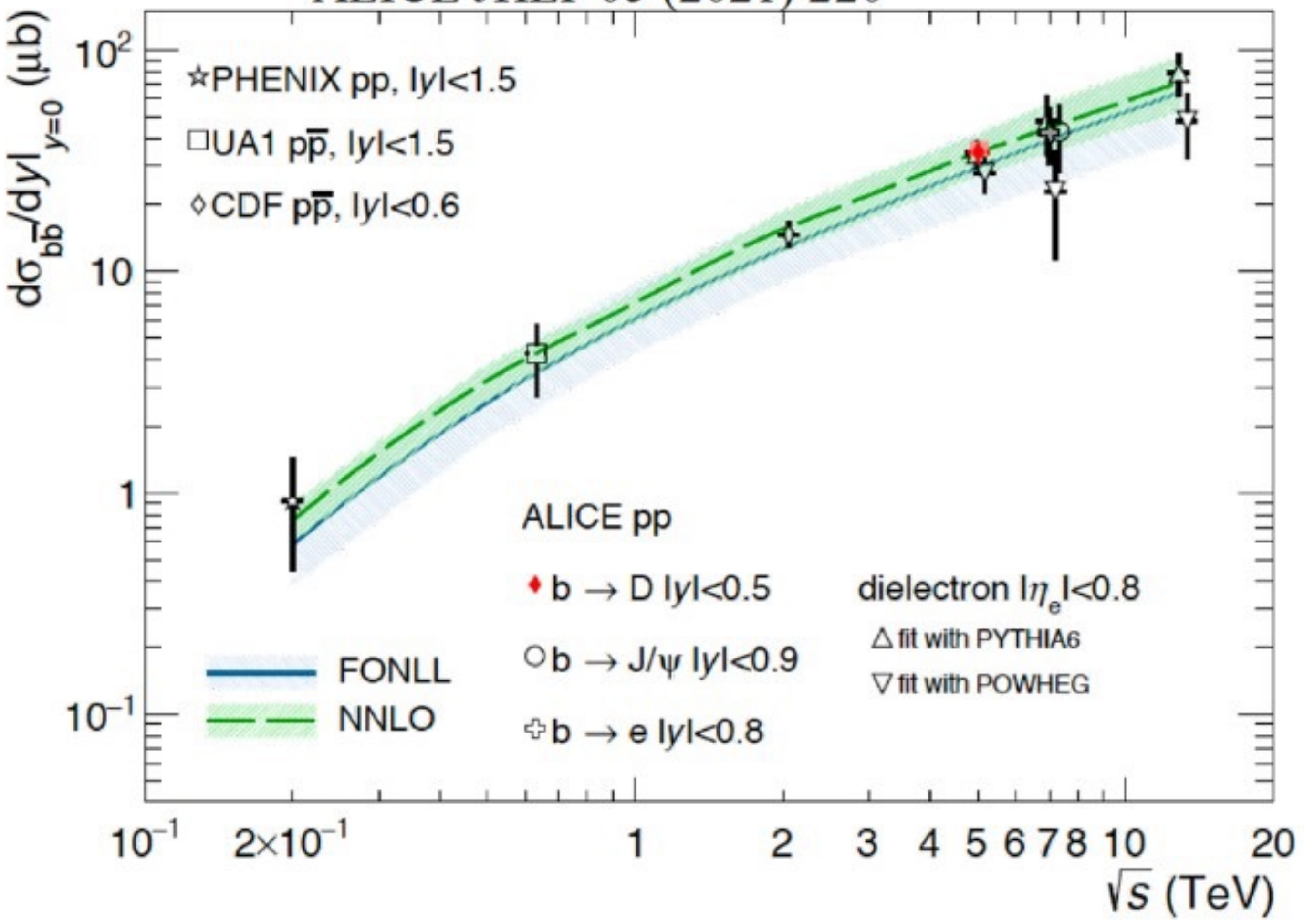
2nd Workshop on Advancing the Understanding of Non-Perturbative QCD Using Energy Flow

What we know

$b\bar{b}$

- No *b* content in the incoming beam particles at colliders
- Production of $b\bar{b}$ pairs:
  - Dominated by hard parton-parton interactions
  - Initial stages of a collision

ALICE JHEP 05 (2021) 220

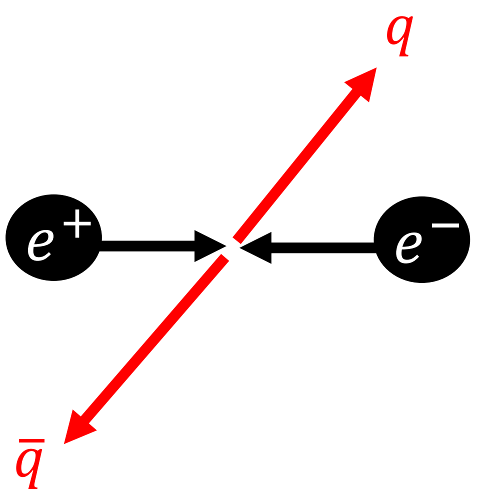


Cross-sections are well described by theory calculations

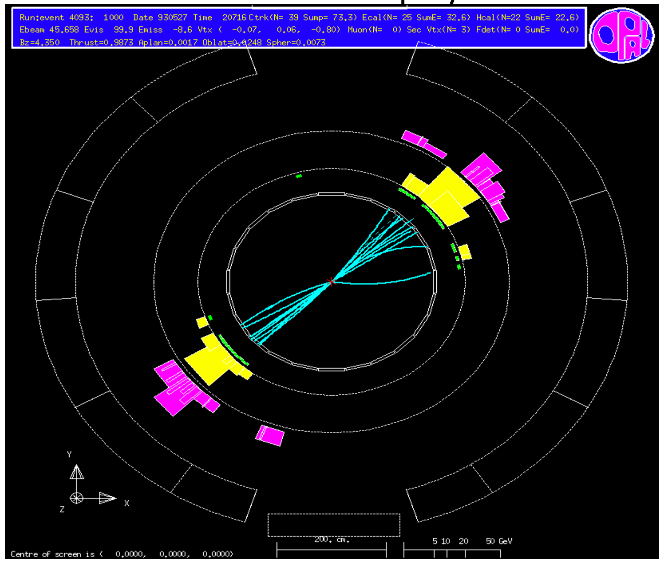
We can use *b* quarks produced perturbatively to probe the non-perturbative hadronization process

Quark confinement

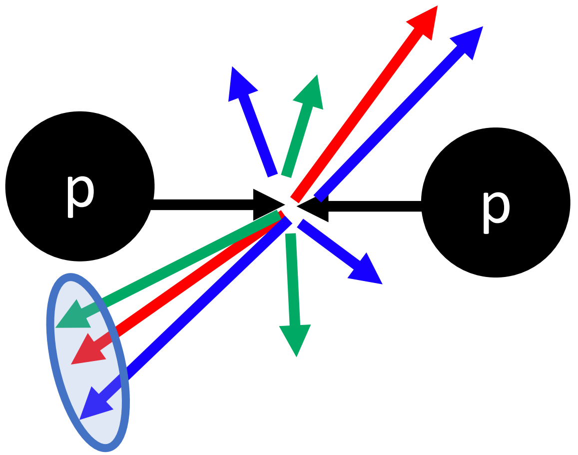
- Models of fragmentation are tuned precisely to data from e^+e^- collisions
- These models **FAIL** to describe particle production in proton+proton, proton+nucleus, and nucleus+nucleus collisions
- Quarks that overlap in position/velocity space to form color neutral hadrons
- Signature is enhanced baryon production (3 quark hadrons)



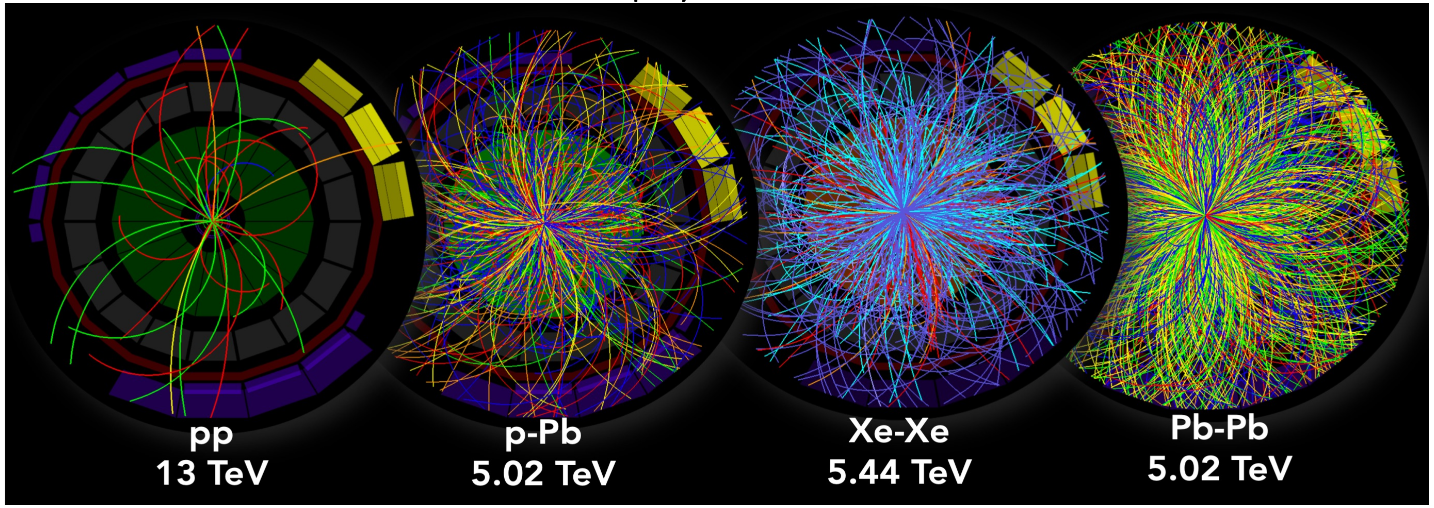
LEP event display



Fragmentation in vacuum



ALICE event display

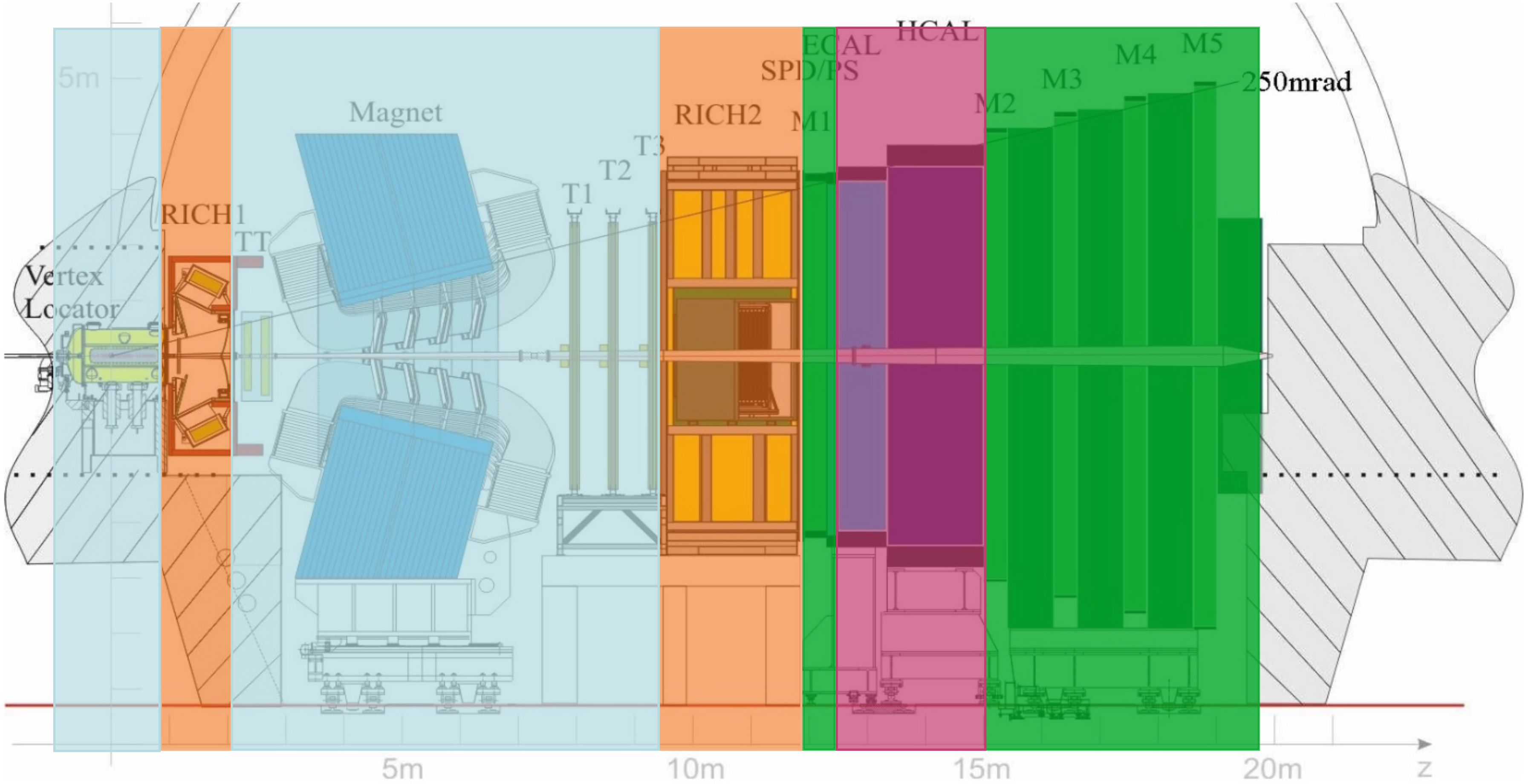


Alternative hadronization mechanism: coalescence

The Large Hadron Collider bottom (LHCb)

The LHCb Detector: Full tracking, particle identification, hadronic and electromagnetic calorimetry and muon ID in $2 < \eta < 5$

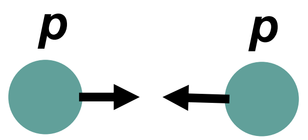
- Precision vertexing
- Fast DAQ at forward rapidity
- Fixed target
  - p beams
  - Pb beams
- $p_T > 0$



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

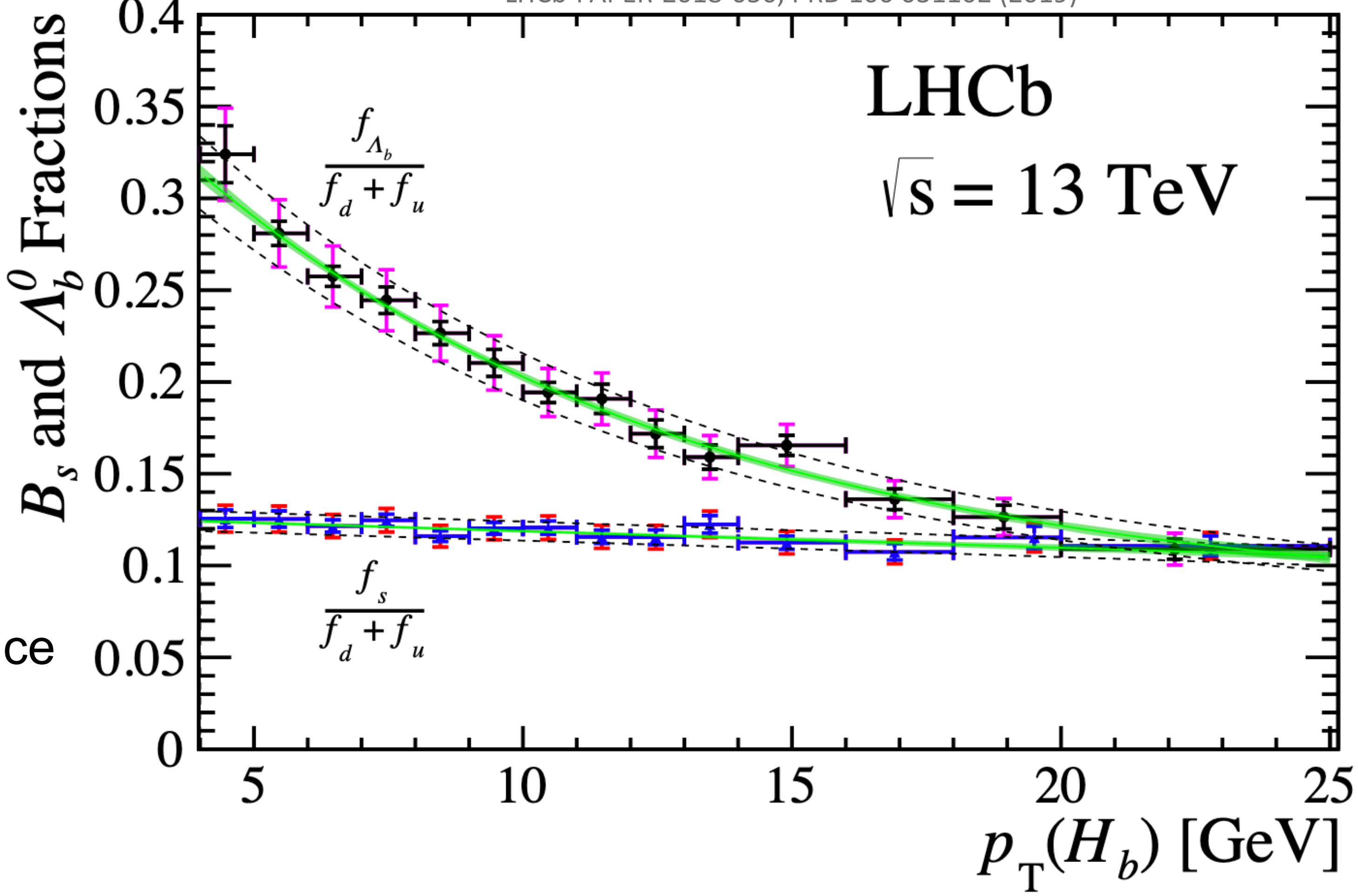
JINST 3 (2008) S08005

Bottom 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
  - Fragmentation in supressed

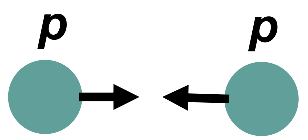
LHCb-PAPER-2018-050, PRD 100 031102 (2019)



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

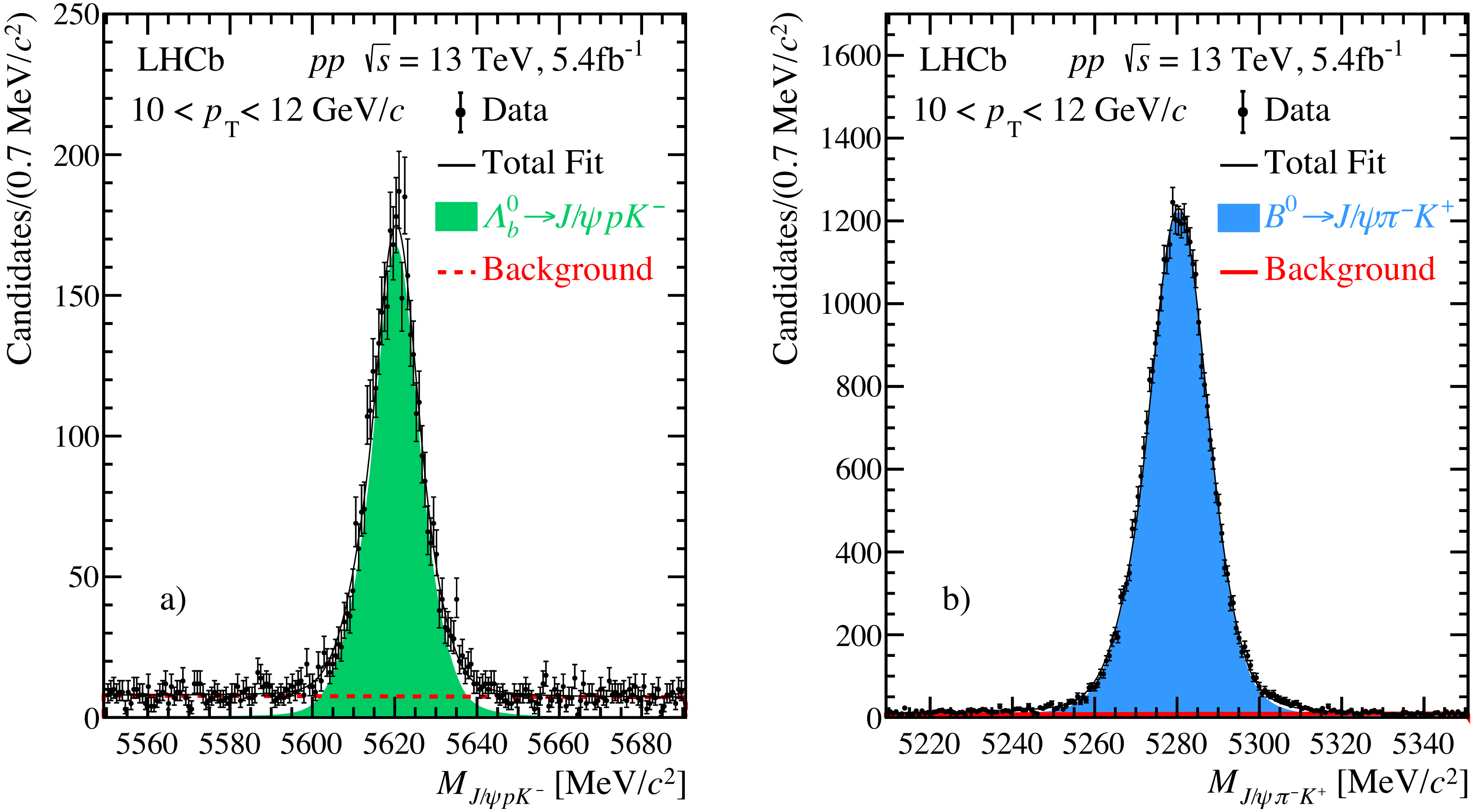
Behavior is not explained by fragmentation alone!

B baryon measurement

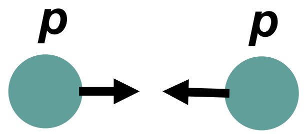


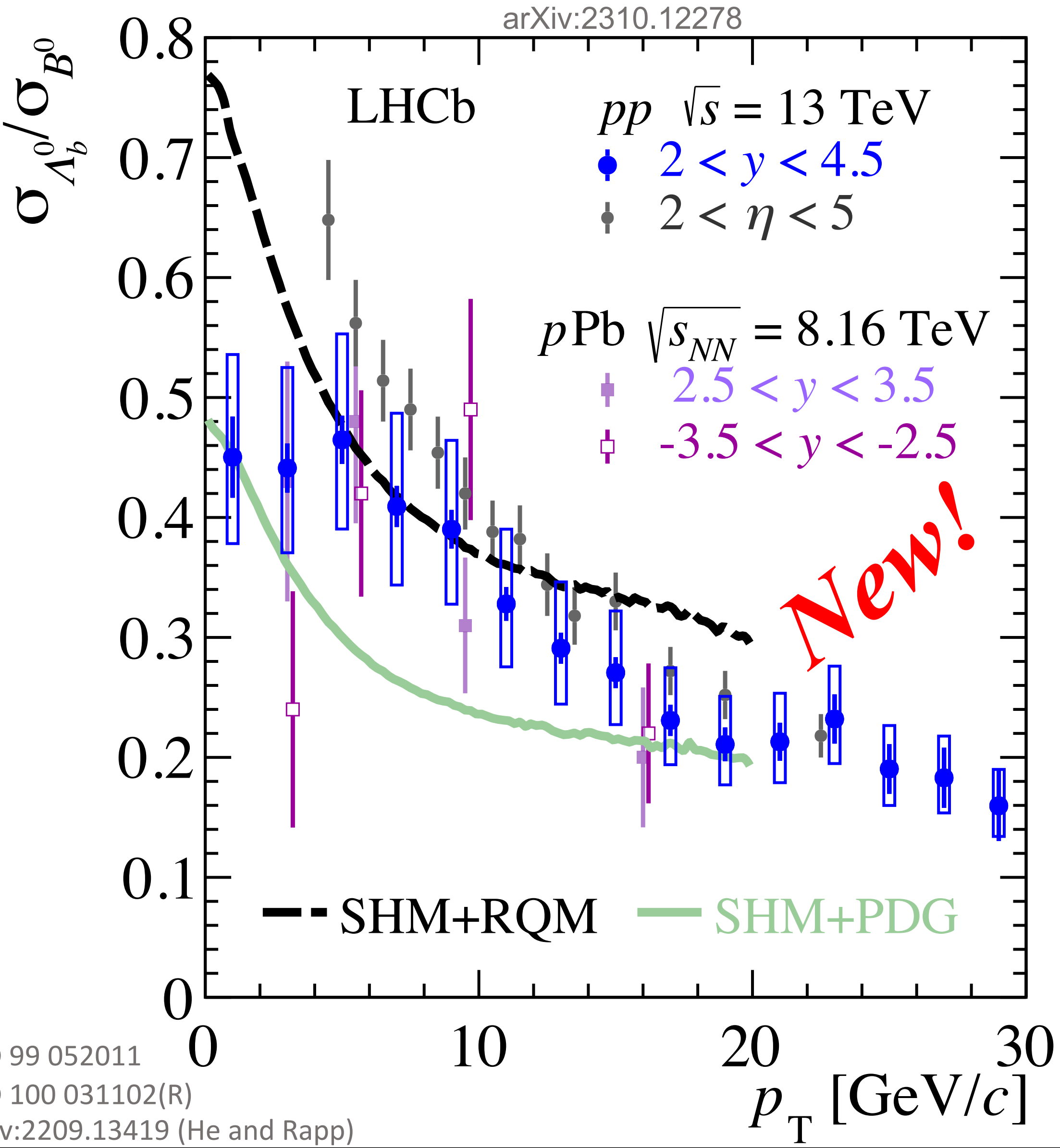
$$\frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} = \frac{N_{\Lambda_s^0}}{N_{B^0}} \times \frac{BR(B^0 \to J/\psi K\pi)}{BR(\Lambda_b^0 \to J/\psi p\pi)} \times \frac{\varepsilon_{B^0}^{acc}}{\varepsilon_{\Lambda_b^0}^{acc}} \times \frac{\varepsilon_{B^0}^{trig}}{\varepsilon_{\Lambda_b^0}^{trig}} \times \frac{\varepsilon_{B^0}^{reco}}{\varepsilon_{\Lambda_b^0}^{reco}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

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



B baryon enhancement

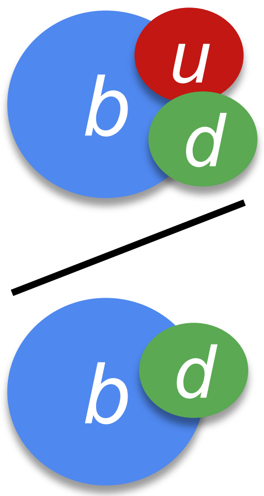


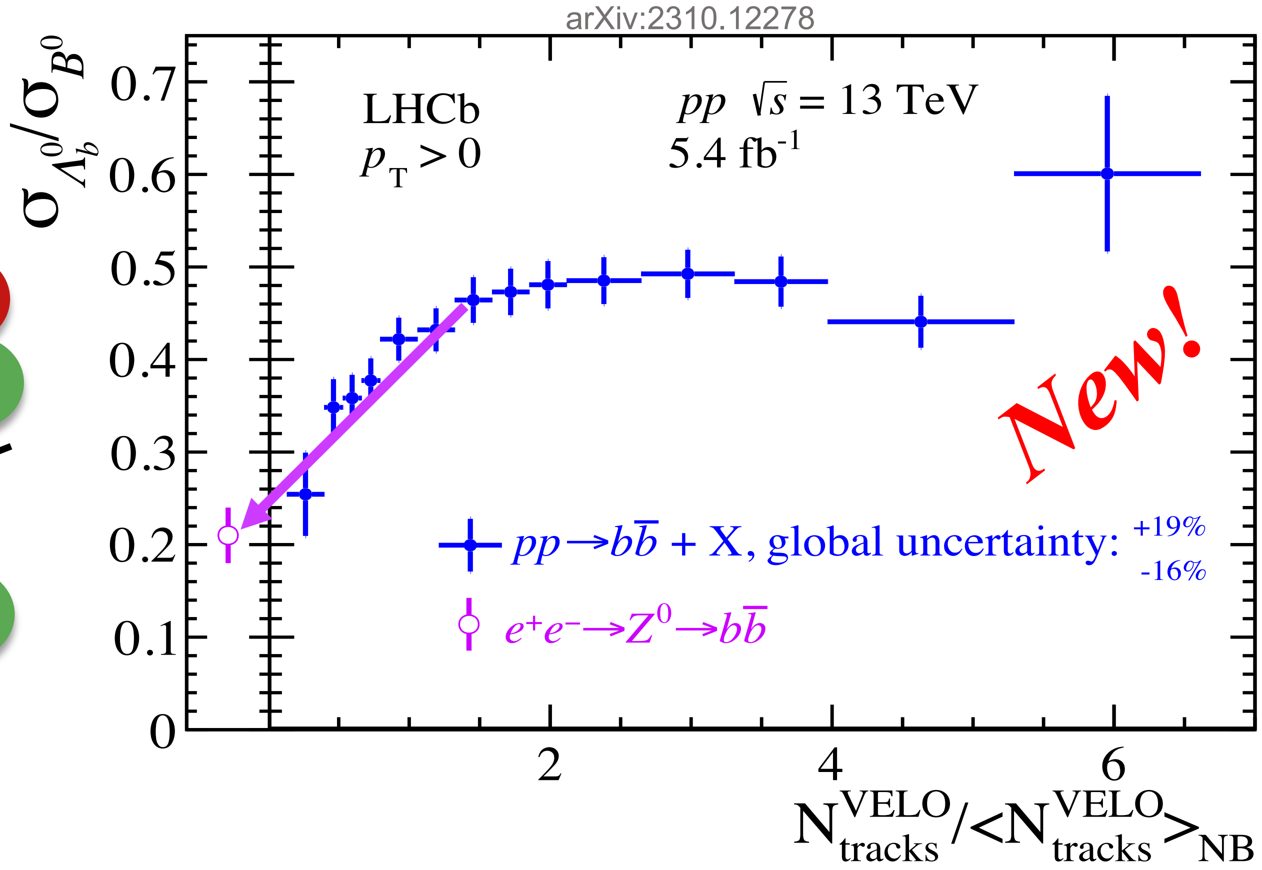


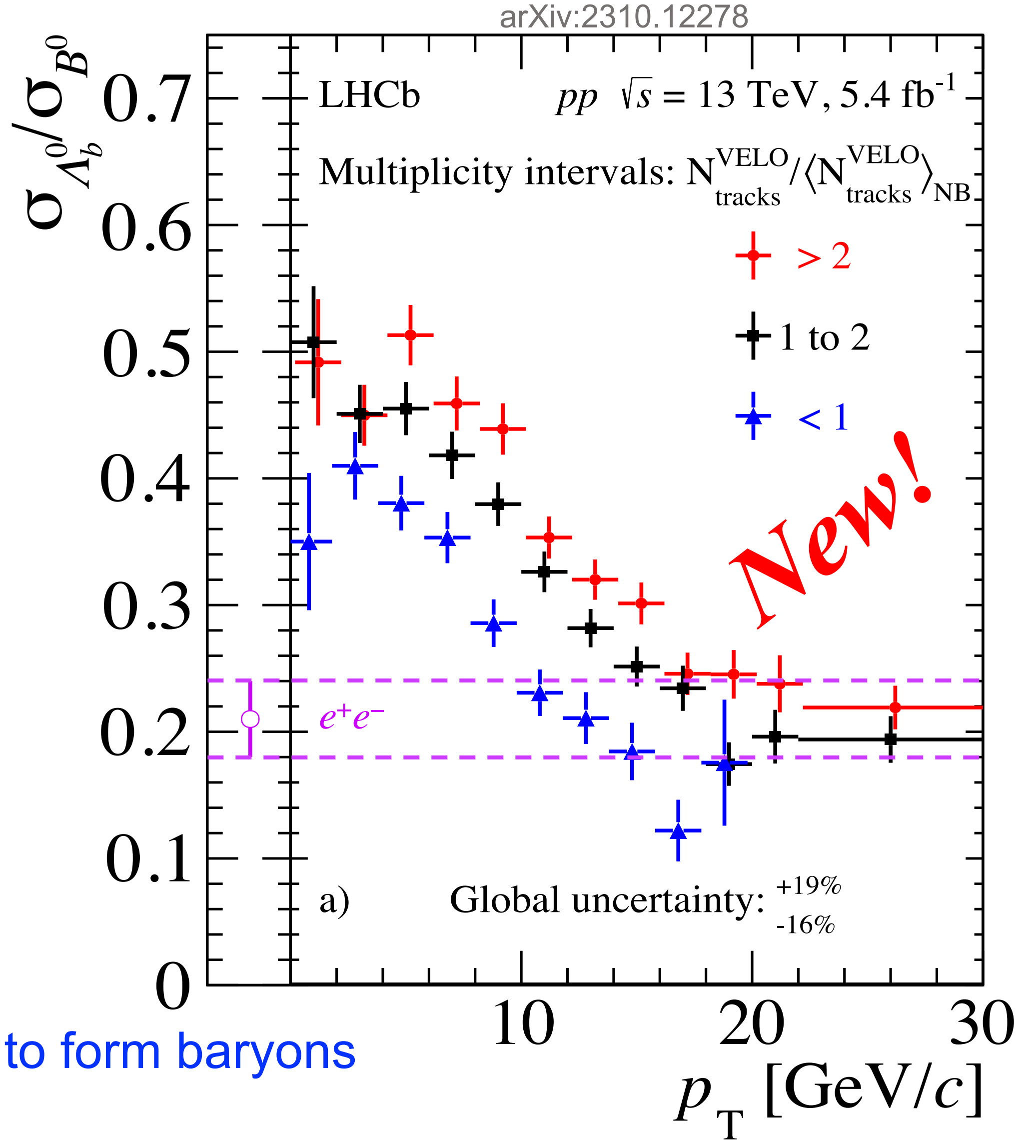
- Hadronic decays show strong dependence on p_T
- Experimental data agrees with *pp* data measured using semileptonic decays
- Data agrees with *p*Pb (within large uncertainties)
- Data agrees more with Relativistic Quark Model input to Statistical Hadronization Model calculations
  - Could indicate there are additional baryons awaiting discovery

PRD 99 052011
PRD 100 031102(R)
arXiv:2209.13419 (He and Rapp)

B baryon enhancement

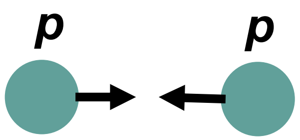


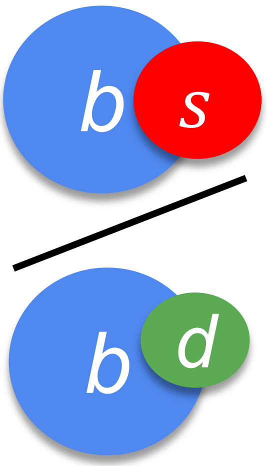


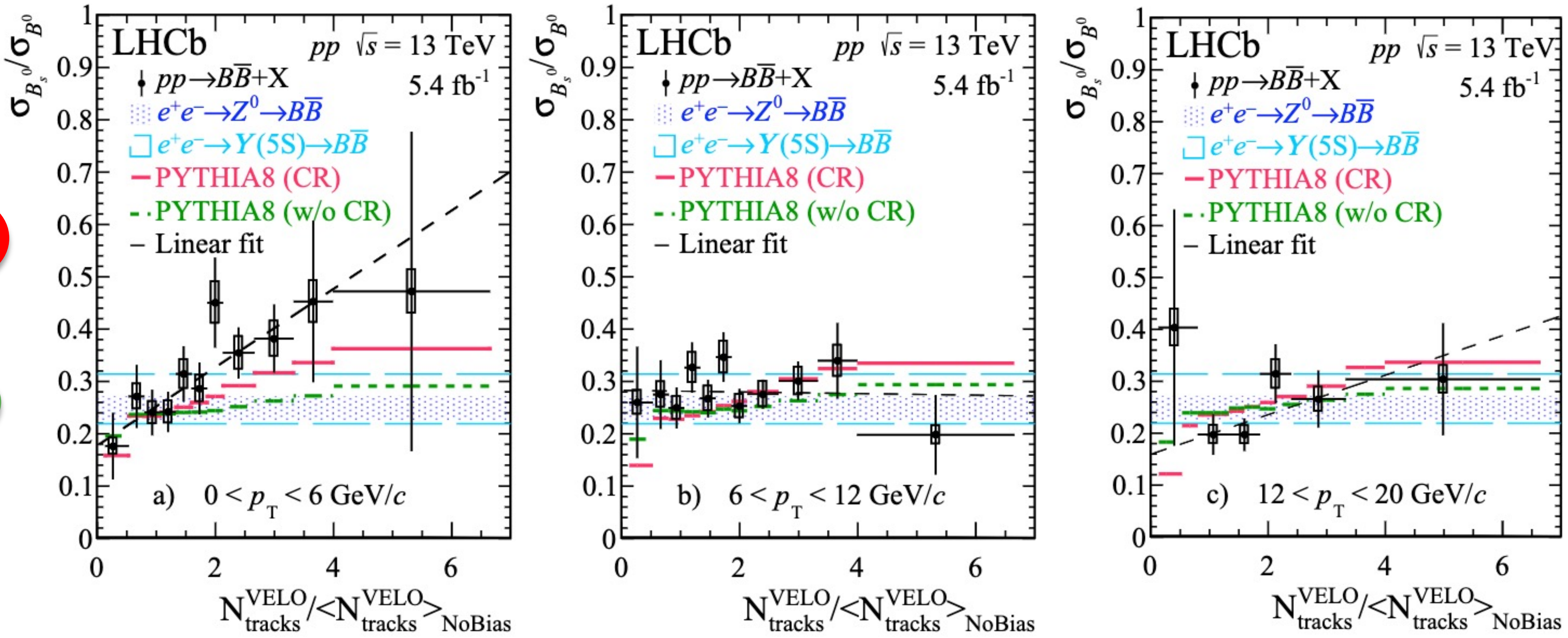


- Expected in scenario where *b* quarks coalesce with light quarks to form baryons
- Pure fragmentation limit is achieved
- All multiplicity bins converge to LEP result at high p_T
- High p_T *b* quarks do not overlap with other quarks and fragment in vacuum, like in e^+e^-

Strangeness enhancement





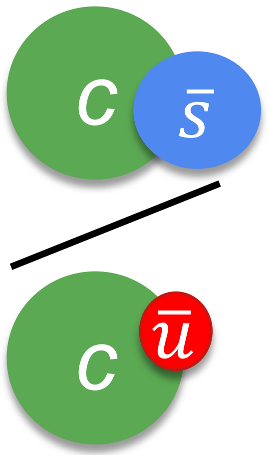


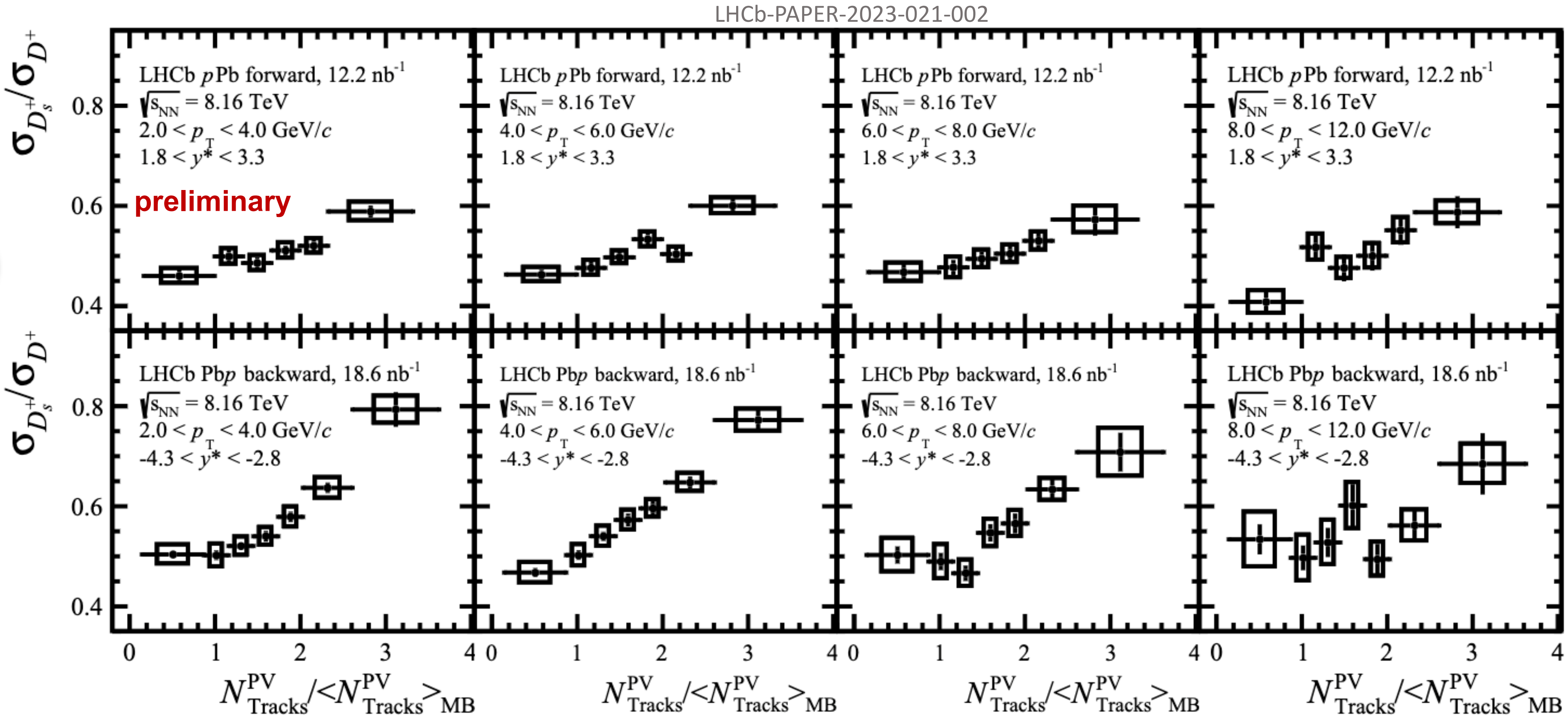
- Enhancement emerges with increasing particle density at lowest p_T
- Data is consistent with e^+e^- value at very low multiplicity and high p_T

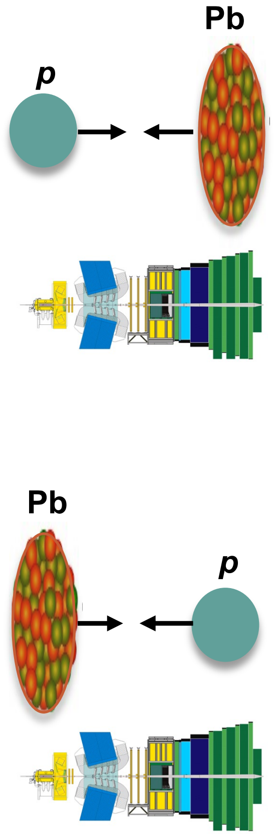
PRL 131 061901 (2023)

$e^+e^- \to Z^0$ & $\Upsilon(5S) \to b\bar{b}$ shows fragmentation is universal!!

Strangeness enhancement in charm







- 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 (Pbp)

Summary

- 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.
- 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.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

LHCb

CERN-EP-2023-208
LHCb-PAPER-2023-027
October 27, 2023

Enhanced production of Λ_b^0 baryons in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV

LHCb collaboration

Abstract

The production rate of Λ_b^0 baryons relative to B^0 mesons in pp collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV is measured by the LHCb experiment. The ratio of Λ_b^0 to B^0 production cross-sections shows a significant dependence on both the transverse momentum and the measured charged-particle multiplicity. At low multiplicity, the ratio measured at LHCb is consistent with the value measured in e^+e^- collisions, and increases by a factor of ~ 2 with increasing multiplicity. At relatively low transverse momentum, the ratio of Λ_b^0 to B^0 cross-sections is higher than what is measured in e^+e^- collisions, but converges with the e^+e^- ratio as the momentum increases. These results imply that the evolution of heavy b quarks into final-state hadrons is influenced by the density of the hadronic environment produced in the collision. Comparisons with a statistical hadronization model and implications for the mechanisms enforcing quark confinement are discussed.

Submitted to Physical Review Letters!

At the LHC, we have shown that the density of the hadronic medium affects hadronization in pp and it will be interesting to see how the nucleus affects the hadronization process at EIC!!

U.S. DEPARTMENT OF ENERGY | Office of Science

Los Alamos National Laboratory is supported by the DOE/Office of Science/Nuclear Physics

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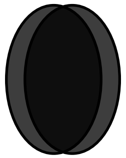
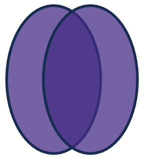
Back up

Baryon enhancement in heavy-ion collisions

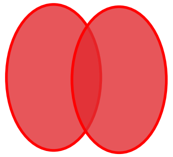
Nuclear overlap in A+A collisions



Central collisions 0-10%



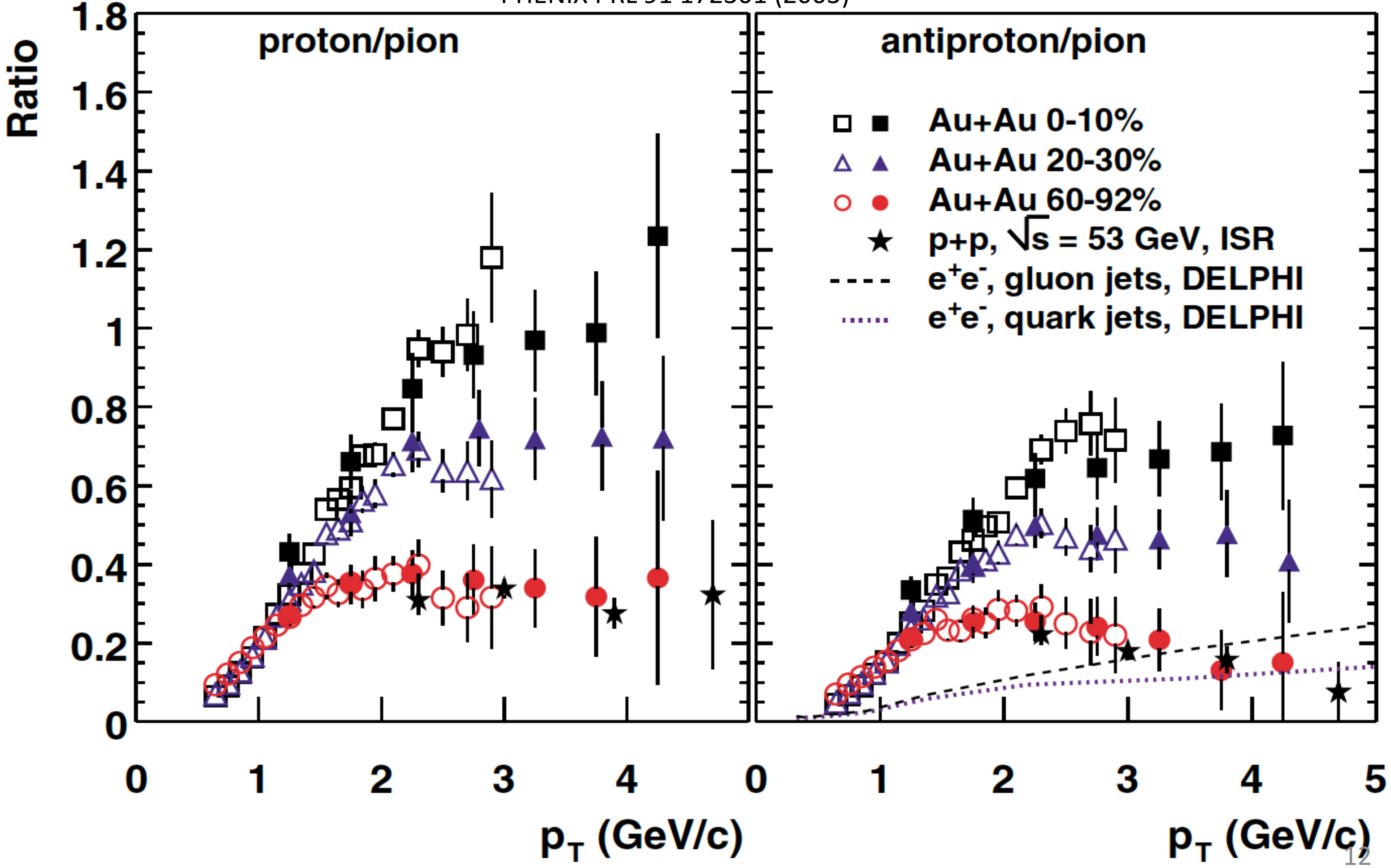
Semi-central collisions 20-30%



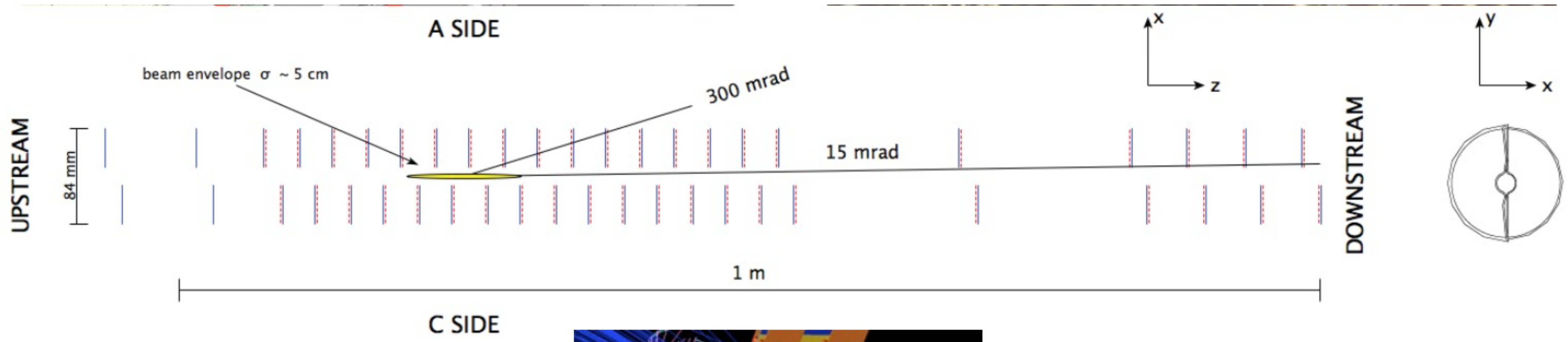
Peripheral collisions 60-92%

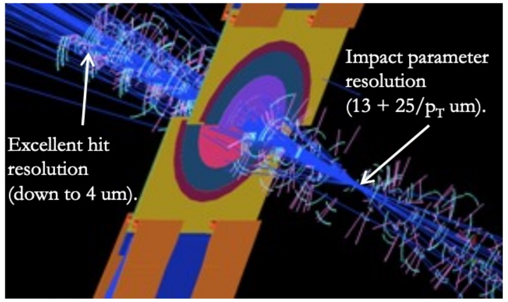
- Light flavor baryon production increases in more central collisions at RHIC
- Models require quark coalescence in order to match baryon production rates

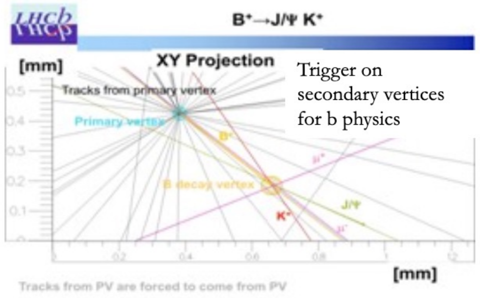
PHENIX PRL 91 172301 (2003)



VELO tracks

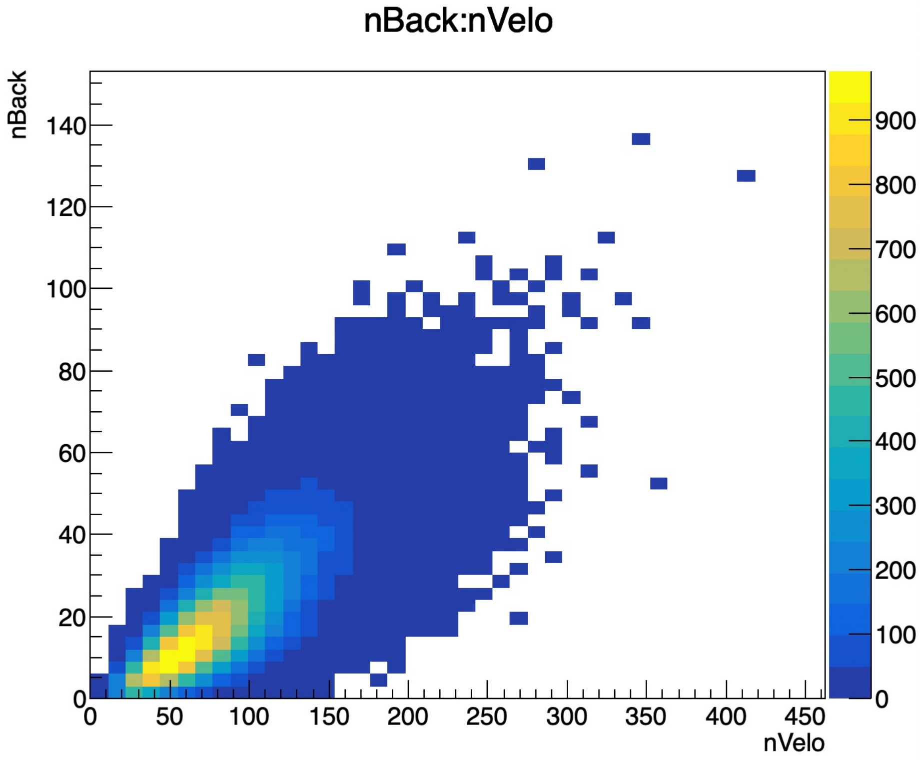




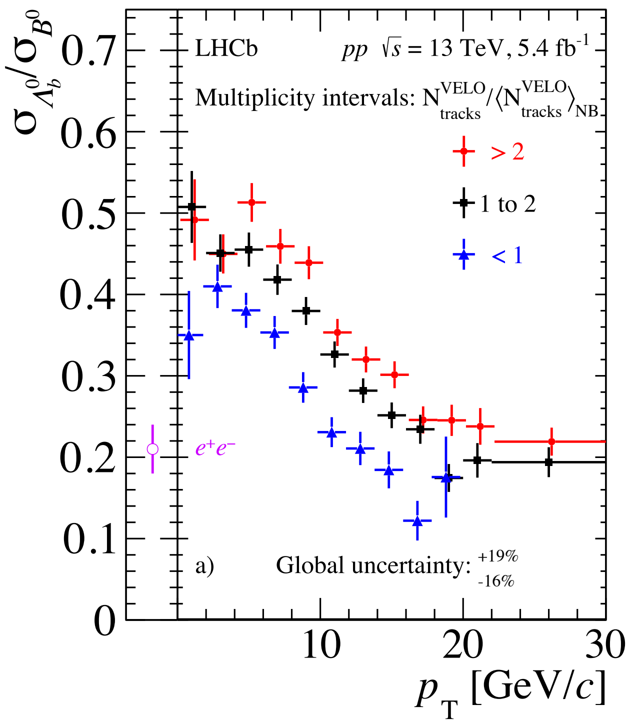


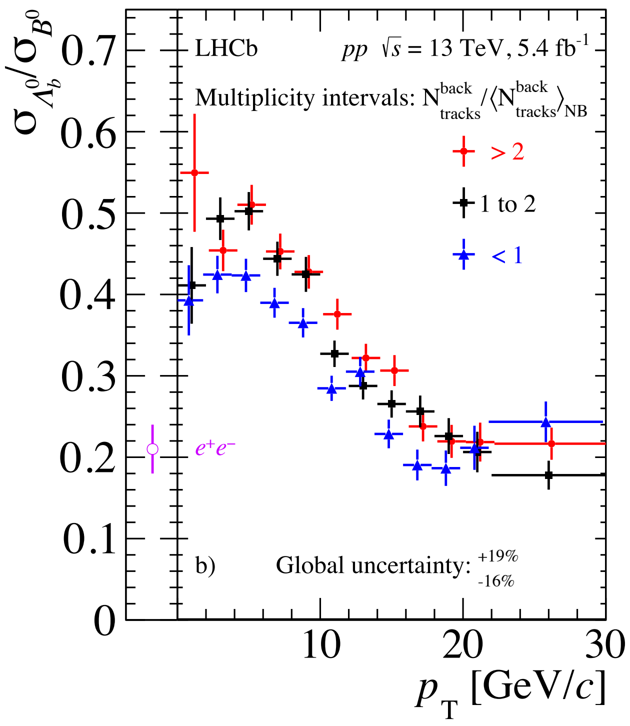
- VErtex LOcator
- Surrounds interaction region
- Precision tracking
- Fast DAQ
- Provides measurements of track coordinates to determine primary interaction vertices and secondary vertices
- Selects bottom (beauty) and charm decays

Multiplicity Metrics



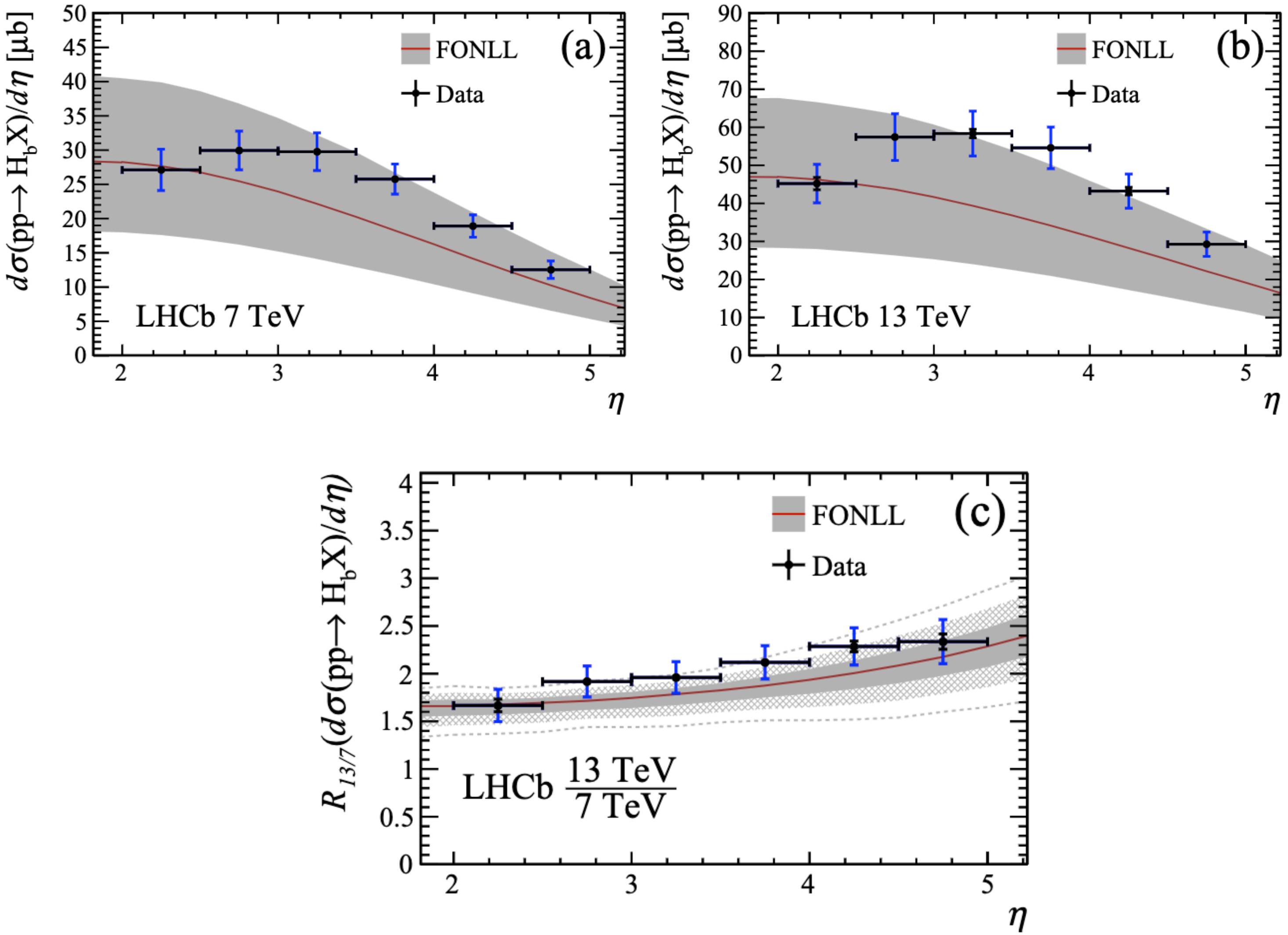
−3.5 < η < −1.5



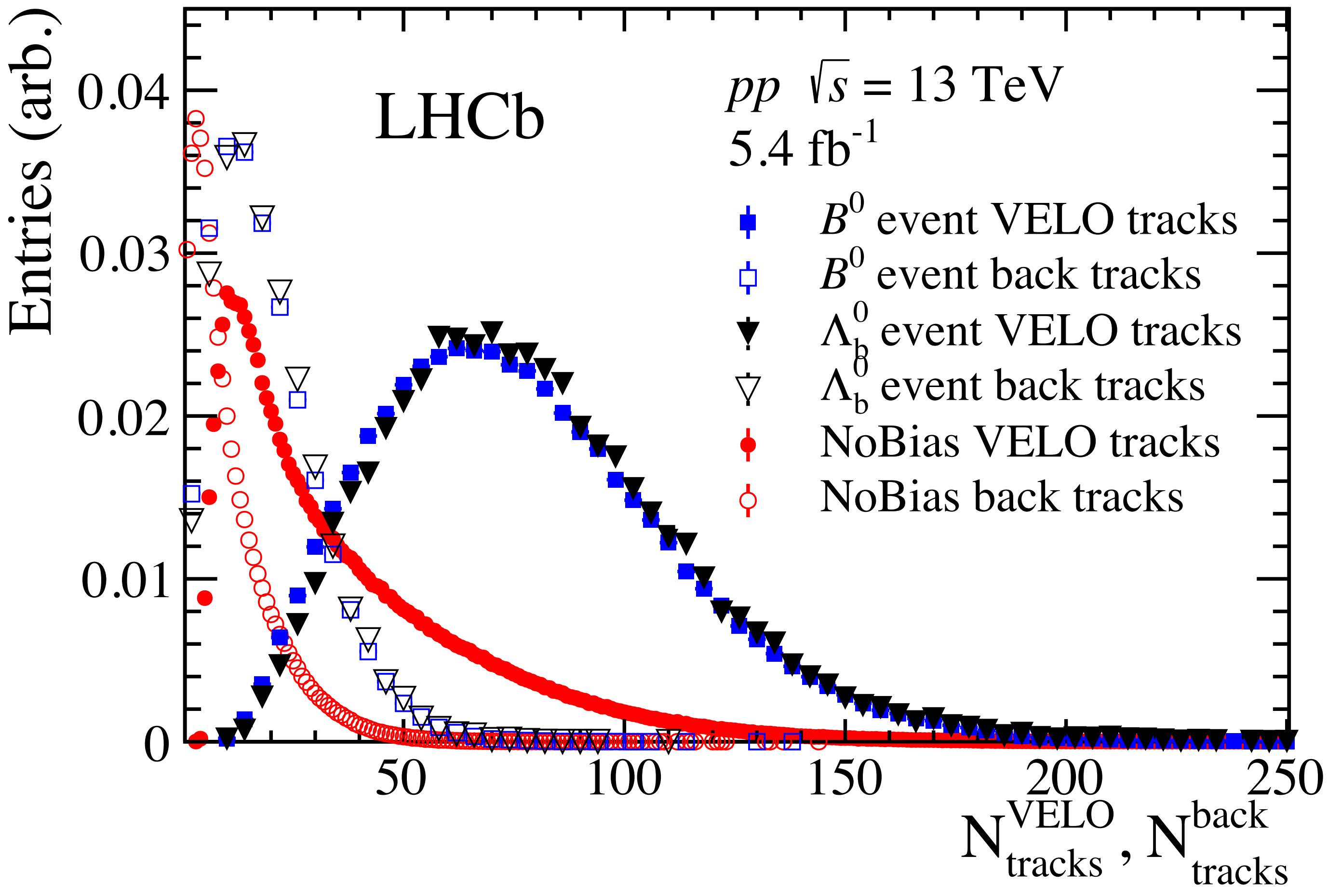


- Strong correlation between nBack and nVelo
- Similar behavior is seen using both metrics

$b\bar{b}$ Cross-section measurements at LHCb



Event characterization



- Event distributions of nVELO and nBack
- signal events with one reconstructed primary vertex