Hadronization of heavy *b* quarks at LHCb

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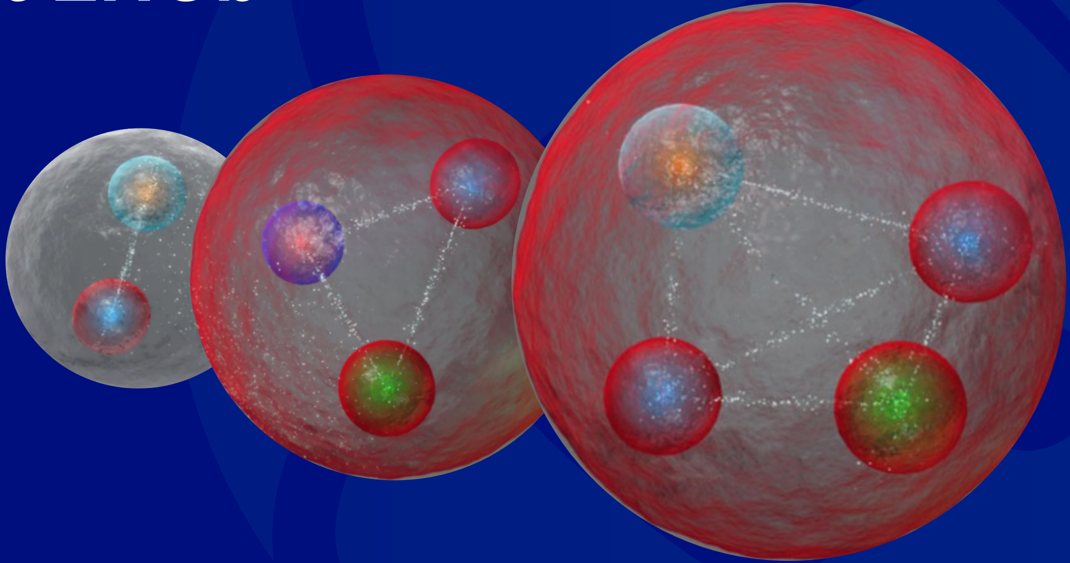
Charleston, SC



Outline

- Hadronization: the bridge between QCD and observable particles
  - In-medium modifications of the hadronization process
- New measurements from LHCb sensitive to hadronization mechanisms
  - Strangeness enhancement in B mesons: Phys Rev Lett 131 061901 (2023)
  - Λ_b baryon enhancement in small systems: Phys Rev Lett 132 081901 (2024)
  - X(3872) enhancement in pPb collisions: 2402.14975 (to appear in PRL)
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Heavy Quark Production

$$\sigma_{AA\to H+X} \propto f_1(x_1, Q^2) \otimes f_2(x_2, Q^2) \otimes \hat{\sigma}(Q^2, x_1, x_2) \otimes D_H(z)$$

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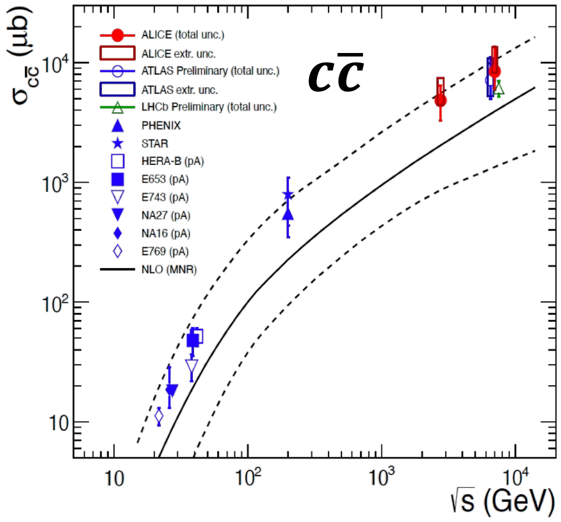
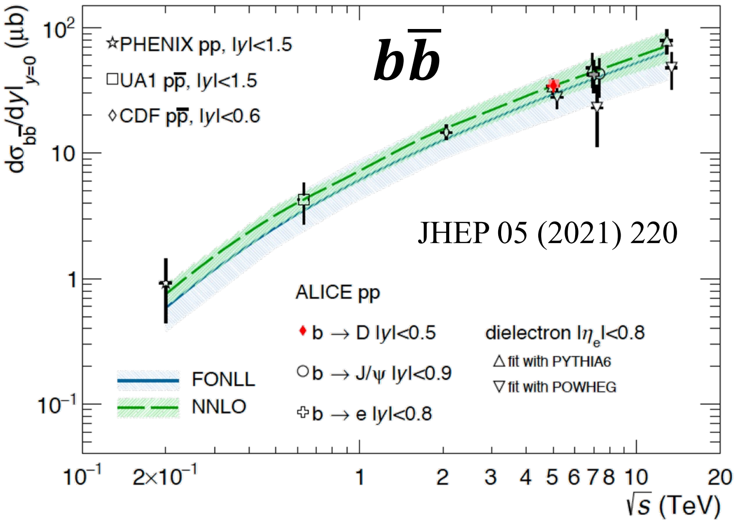
- **Hadron cross sections: measured at experiments**
- **Parton-parton cross sections: calculable by pQCD**

- ~No heavy quarks in beam projectiles
- Number of heavy quarks is essentially fixed in early stages of collisions





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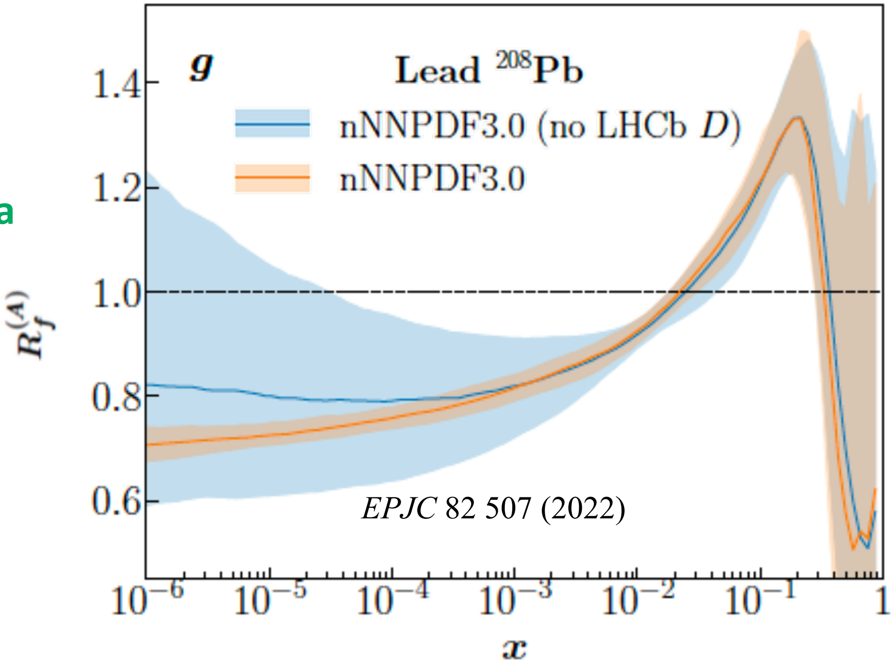
- **Parton distribution functions: constrained by data**

Major recent progress
reducing nPDF uncertainties
by including LHCb charm data



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- **Hadron cross sections: measured at experiments**
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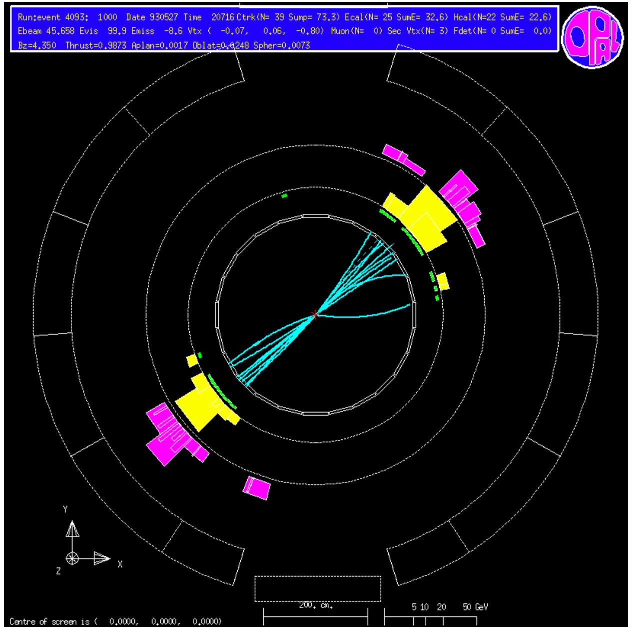
- **Fragmentation functions: constrained by e^+e^- data**

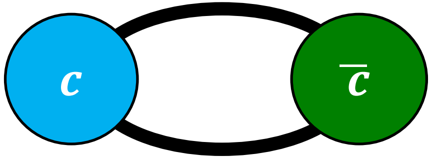
$e^+e^- \to Z \to q\bar{q}$ event



Fragmentation in vacuum

- 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

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br$$



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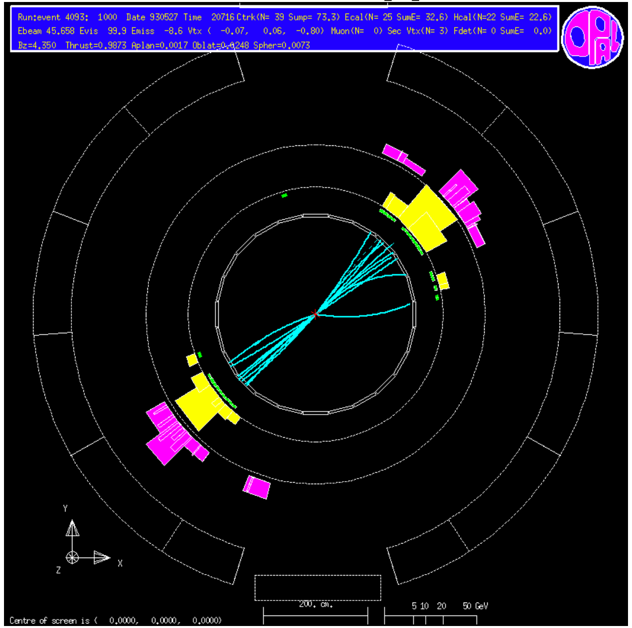

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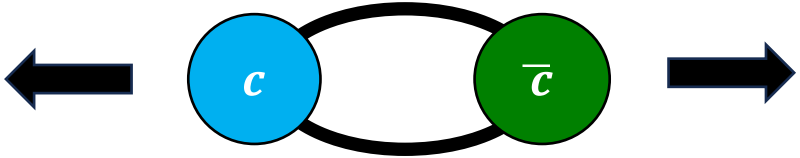
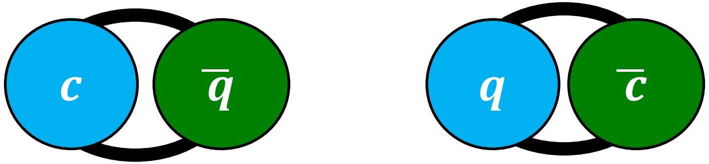


Potential between quarks increases until it is energetically favorable to neutralize color charge by creating more quarks out of vacuum: **fragmentation**



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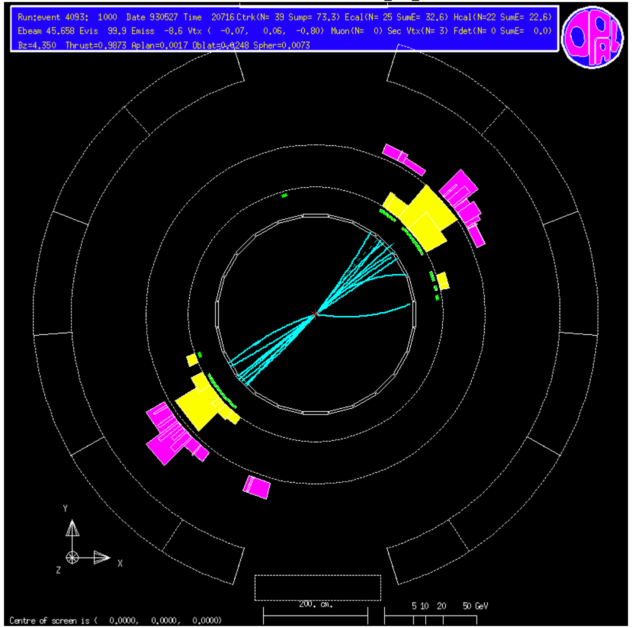

Hadronization is the bridge between observable particles and underlying QCD

Fragmentation in vacuum

- The defining feature of QCD is **confinement**: quarks and gluons can never be observed as isolated particles
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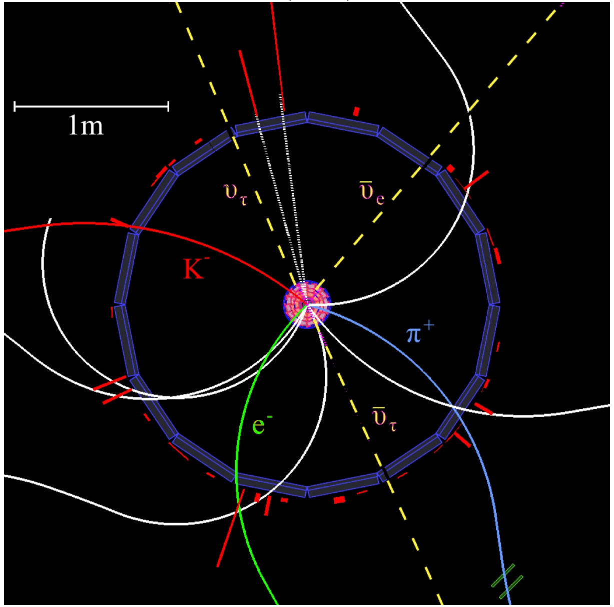
$e^+e^- \to \Upsilon(5S) \to b\bar{b}$ event



b factories:

$e^+e^- \to \Upsilon(5S) \to b\bar{b}$

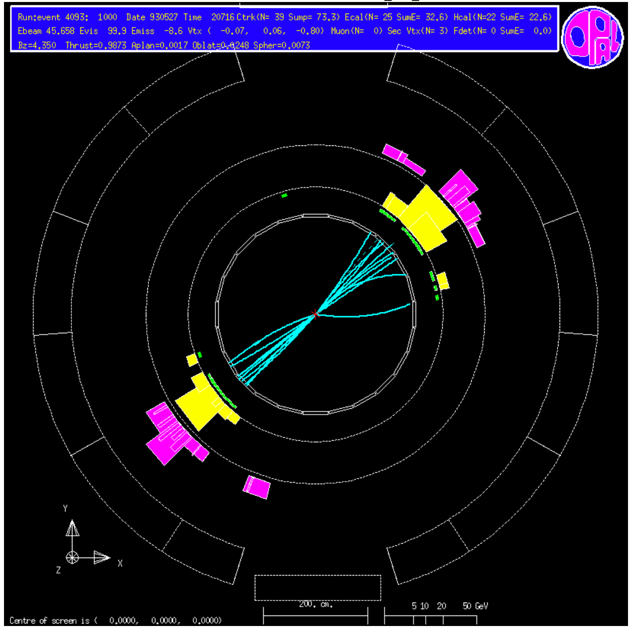
$$B_s/B^0 = 0.26\ ^{+0.05}_{-0.04}$$

LEP

$e^+e^- \to Z \to b\bar{b}$

$$B_s/B^0 = 0.25 \pm 0.02$$

$e^+e^- \to Z \to q\bar{q}$ event



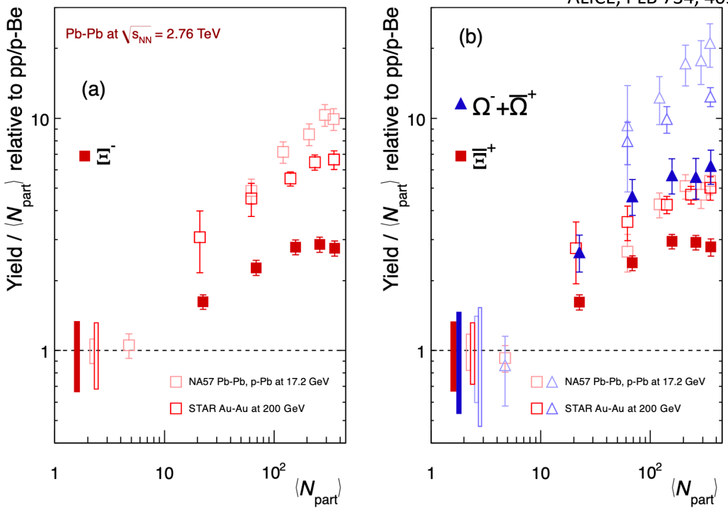
Assumption: hadronization is ***universal*** and ***factorizable*** from rest of collision

Hadronization following deconfinement

In a deconfined plasma, strange quark production is dramatically enhanced

- $T_c \approx 190\ MeV \approx 2m_s$ strange quark pairs can be produced through fusion of thermalized gluons

ALICE, PLB 734, 409 (2014)



"strangeness enhancement"

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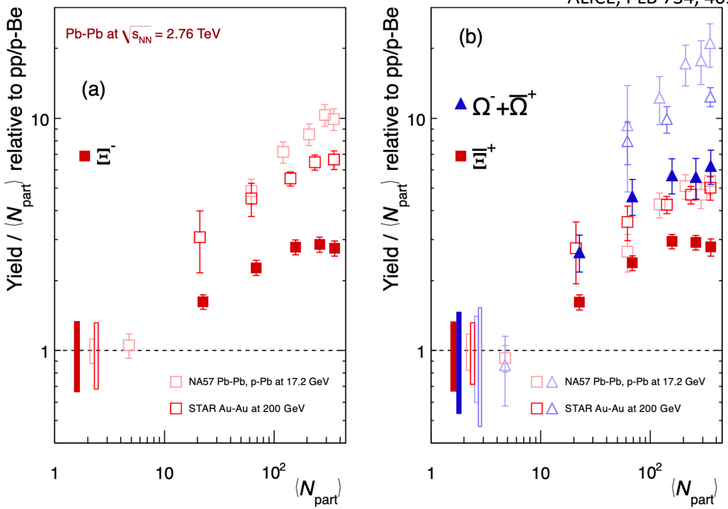
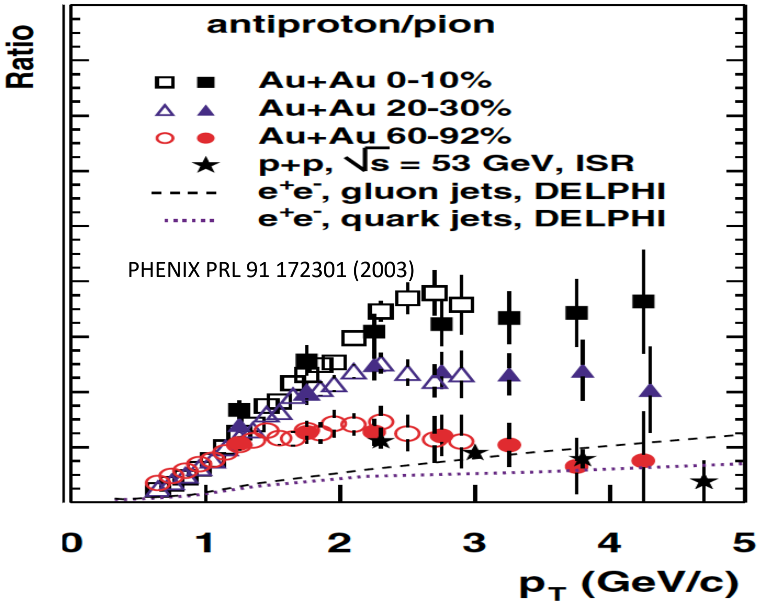


"strangeness enhancement"

Proton/pion ratio dramatically varies between central A+A, p+p, and e+e- collisions

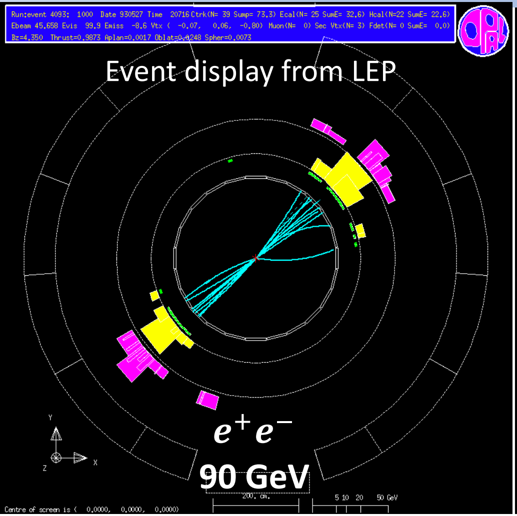


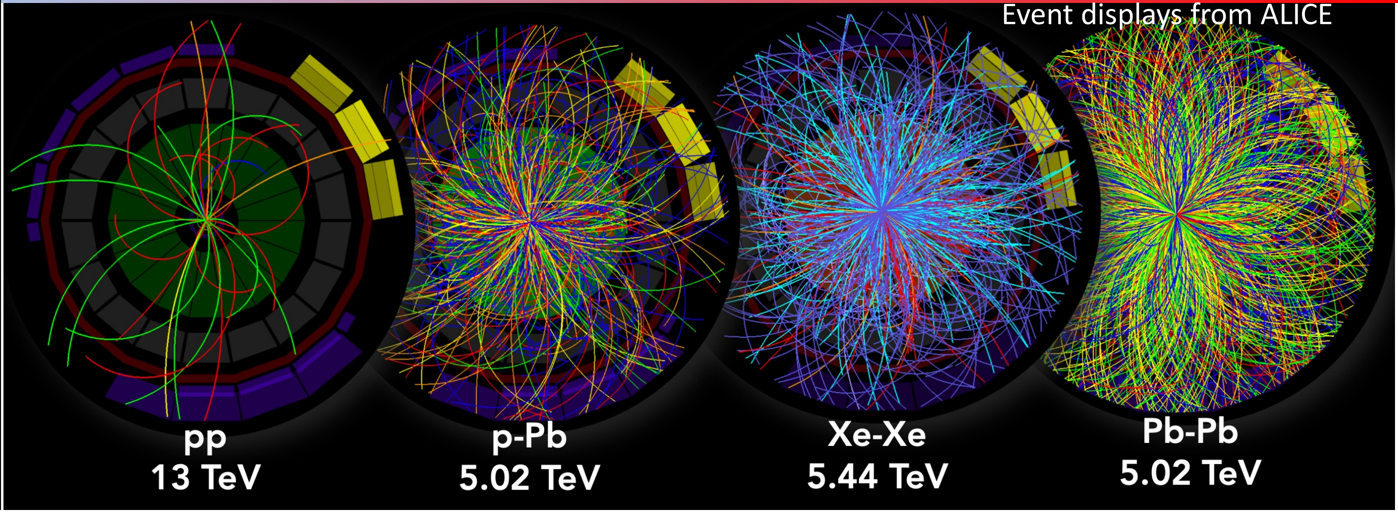
"baryon enhancement"

Dramatic changes in hadron chemistry between collision systems

From vacuum to the QCD medium – quark coalescence

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





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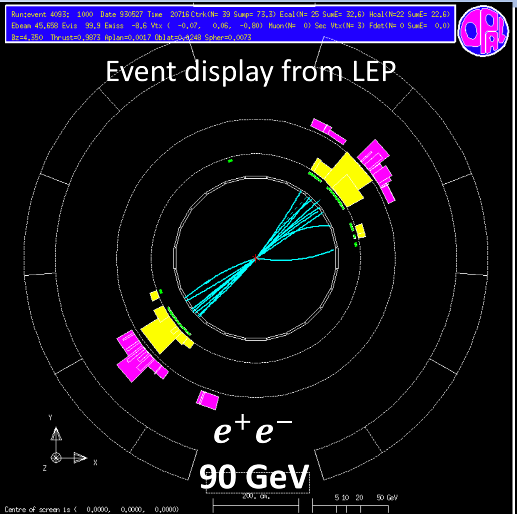

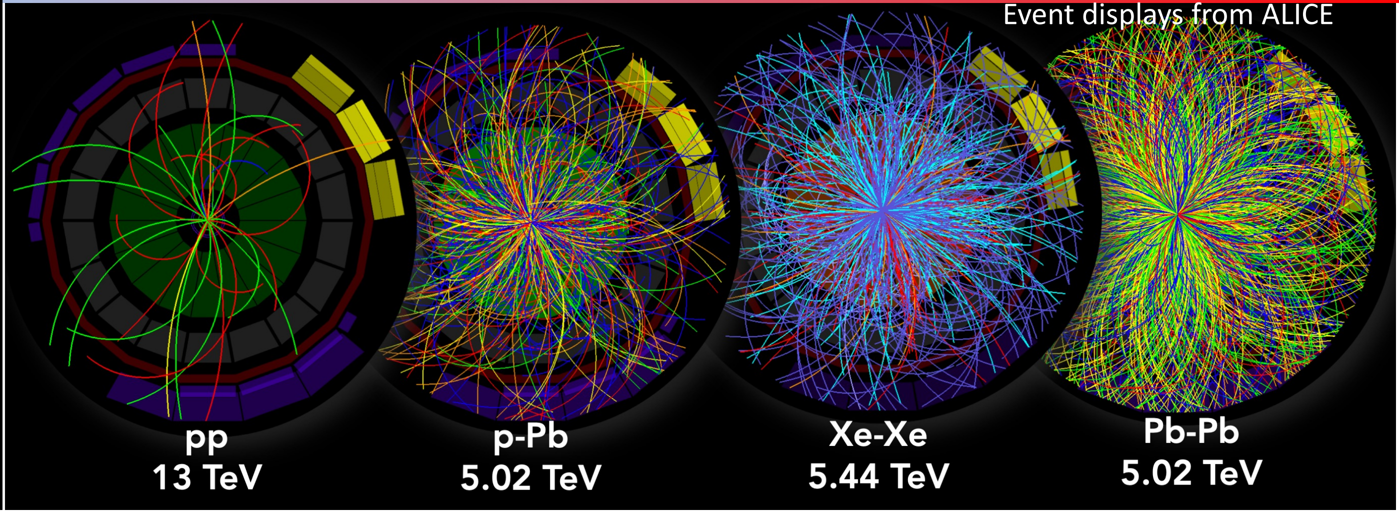

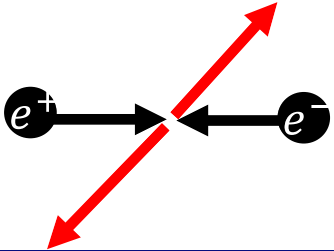

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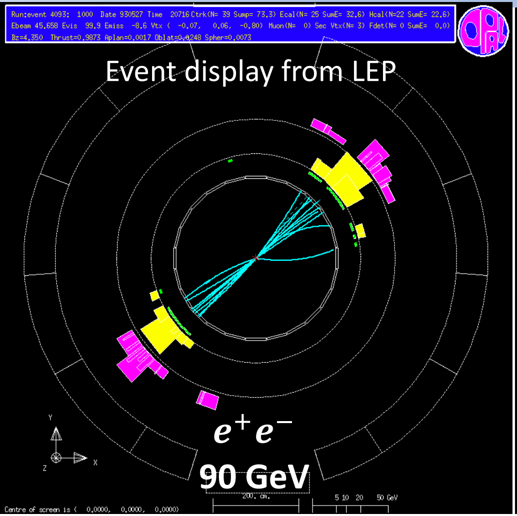
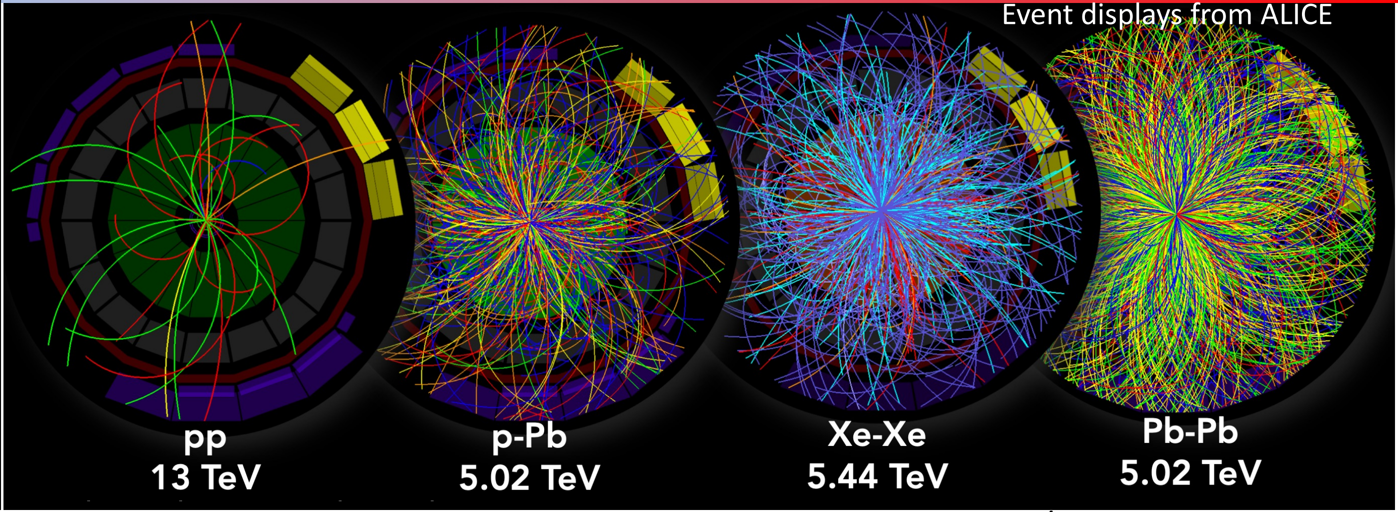
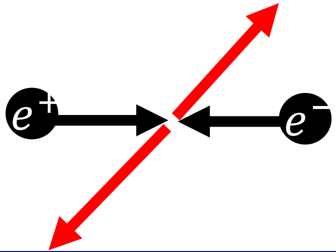
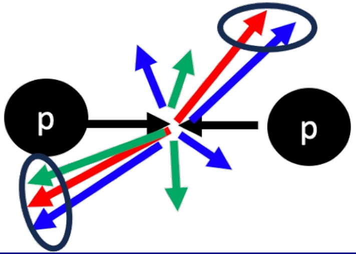






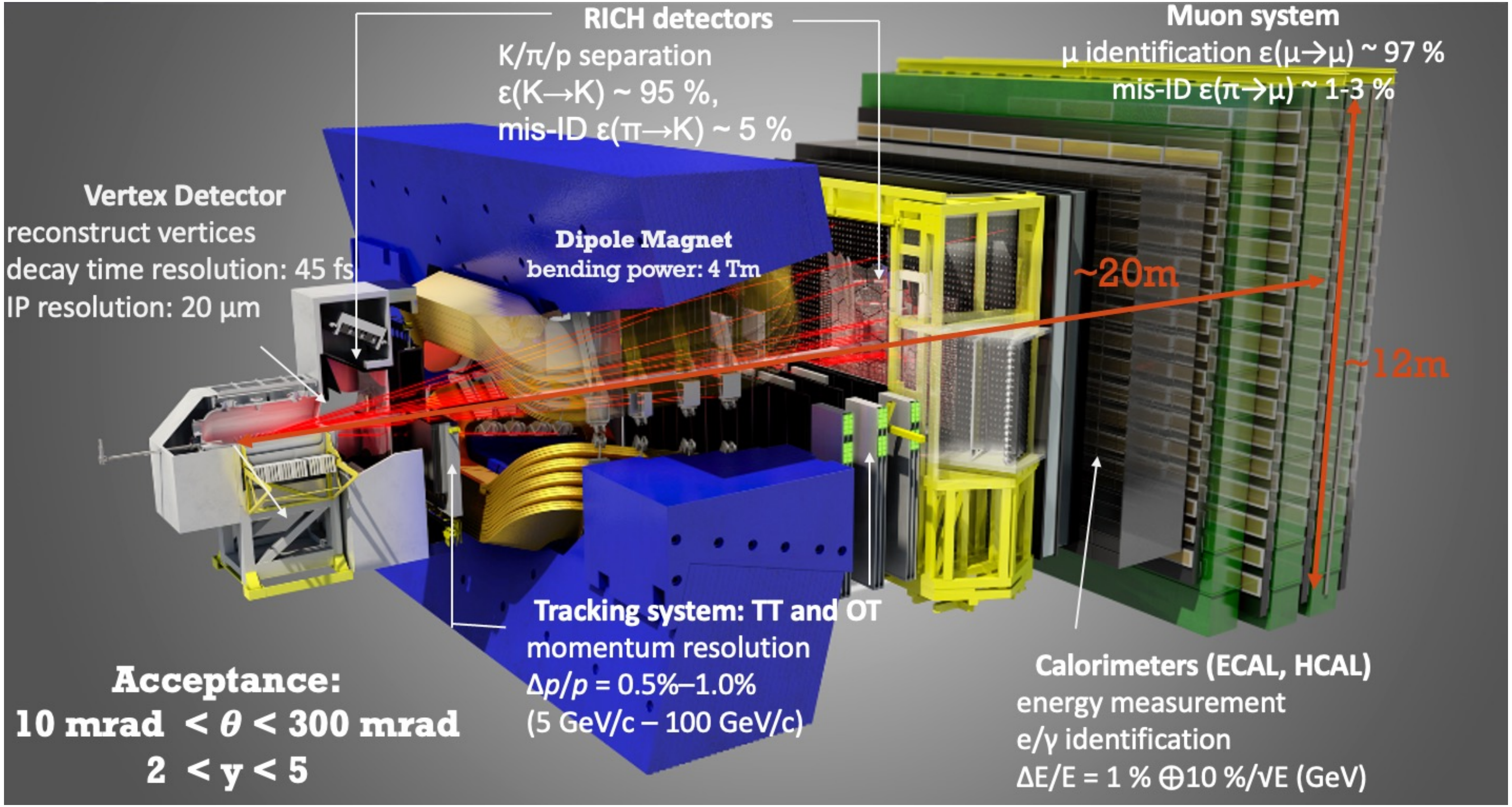


- Quarks that overlap in position/velocity space can coalesce to make color neutral hadrons
- At high density, expect increased production of **hadrons with strange quarks** and enhanced production of **3-quark baryons**
- Expect pure fragmentation at low density

The LHCb detector

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

Unique forward rapidity coverage at the Large Hadron Collider in p+p, p+A, A+A, fixed target collisions



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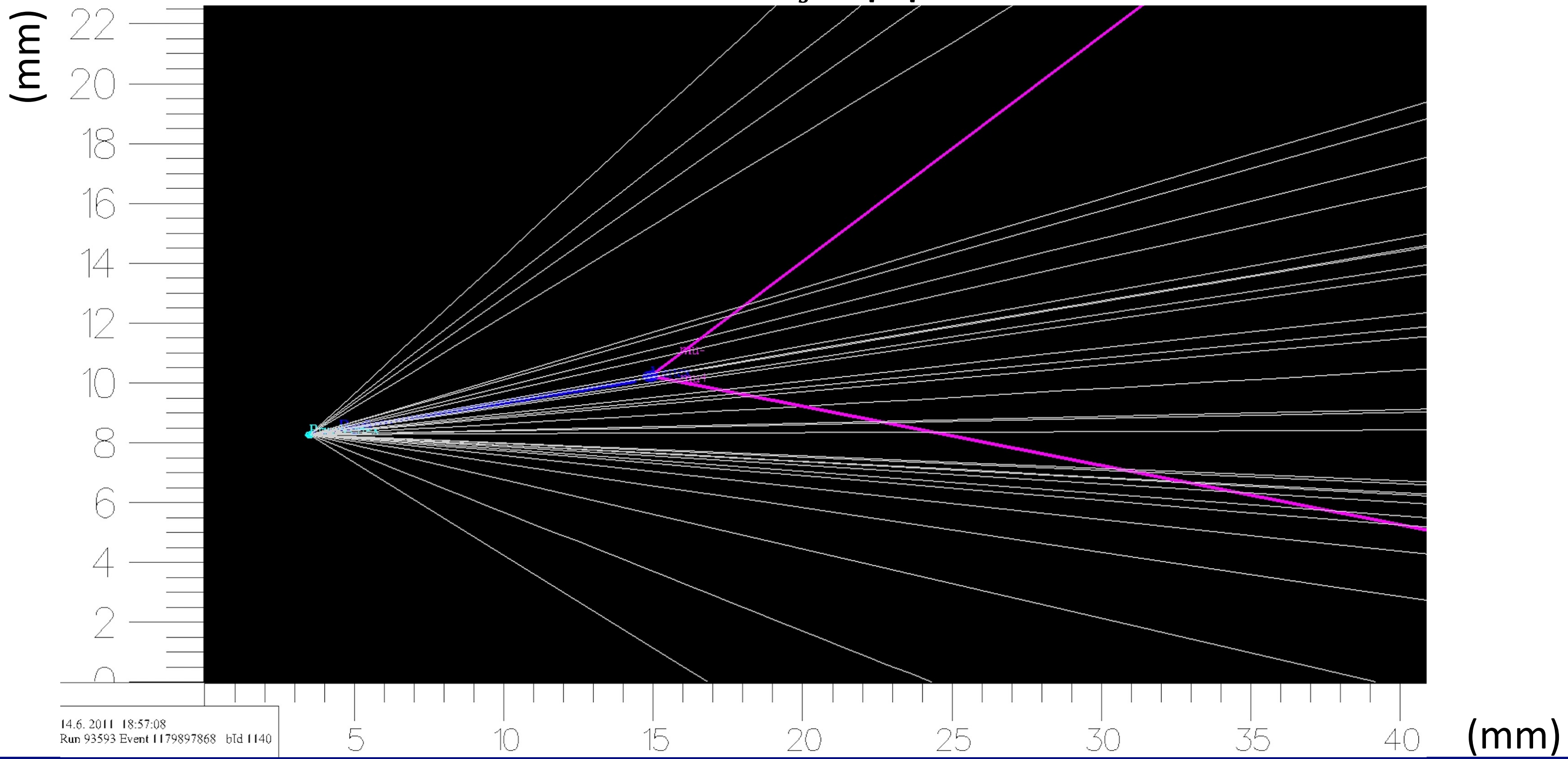
Event display of $B_s^0 \to \mu^+\mu^-$ candidate



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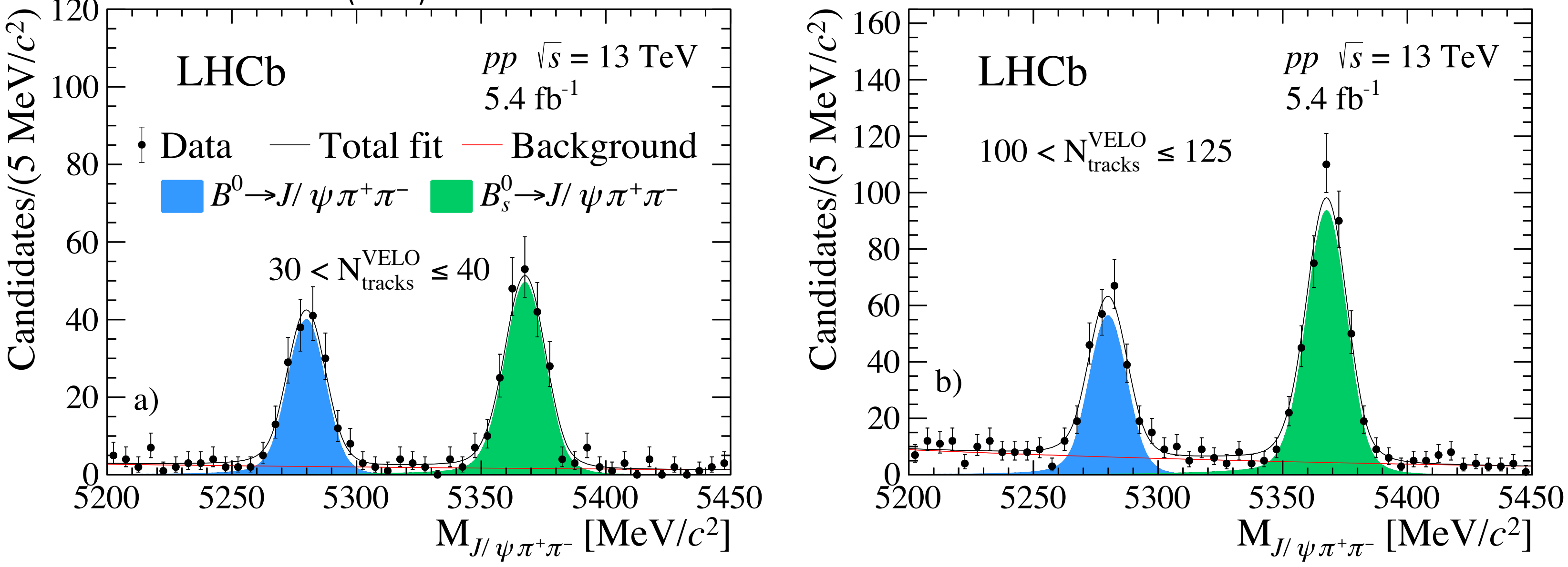
Modification of *b* hadronization – strange B mesons

- Large mass of *b* quarks → low *b* velocity; potential for substantial overlap with other quarks
- coalescence should lead to enhanced B_s^0 yields

PRL 131 061901 (2023)



Low multiplicity – few tracks

High multiplicity – many tracks

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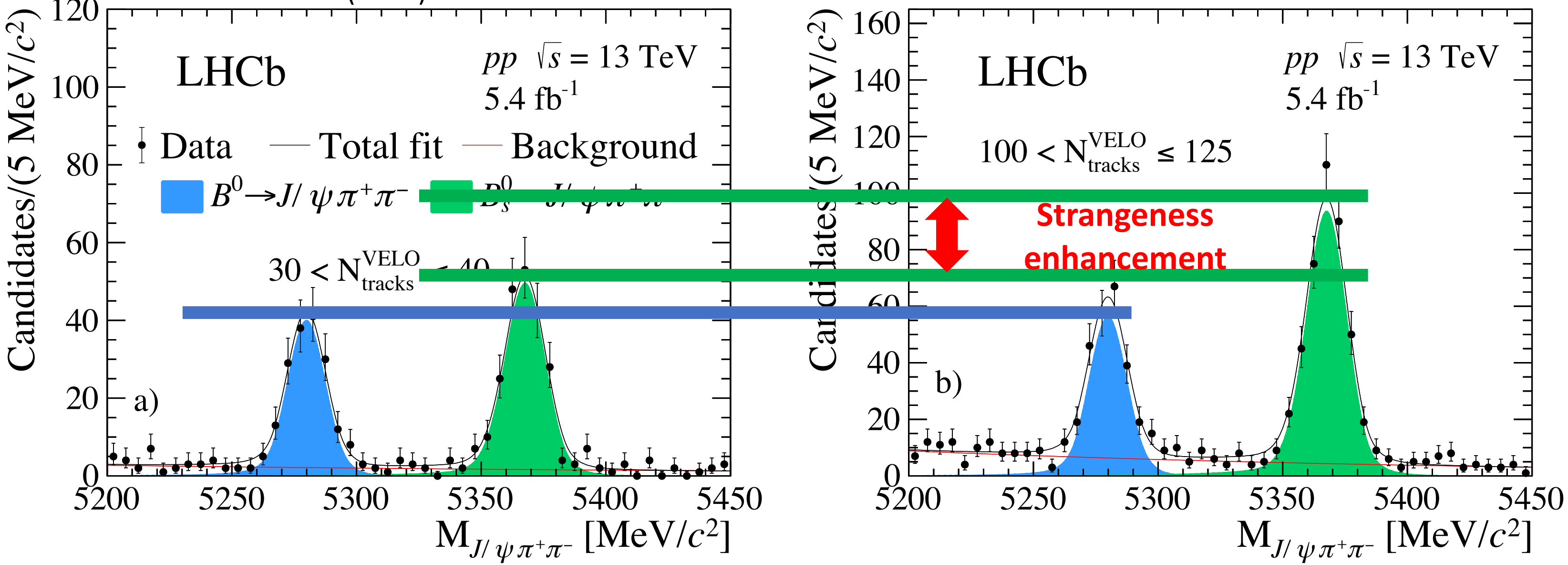

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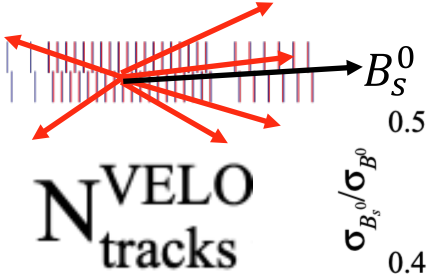

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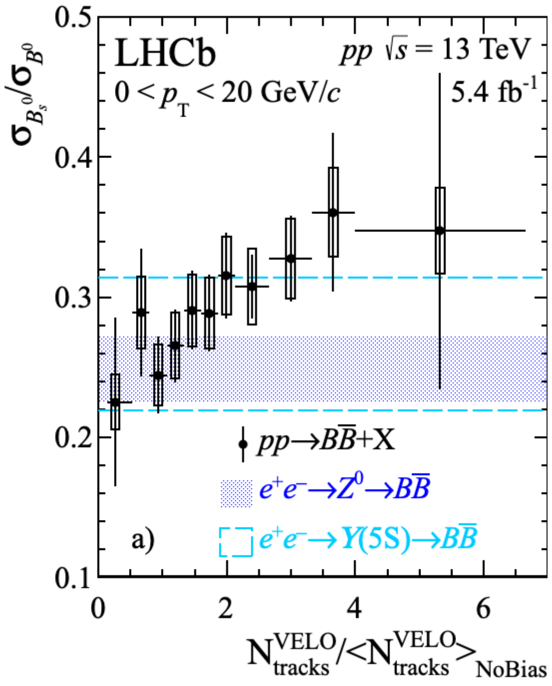
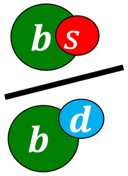


Total VELO multiplicity, dominated by forward tracks



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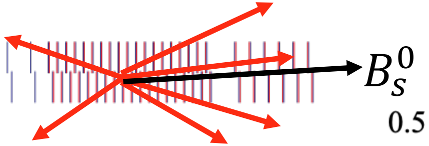

$N_{\text{tracks}}^{\text{VELO}}$

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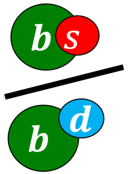
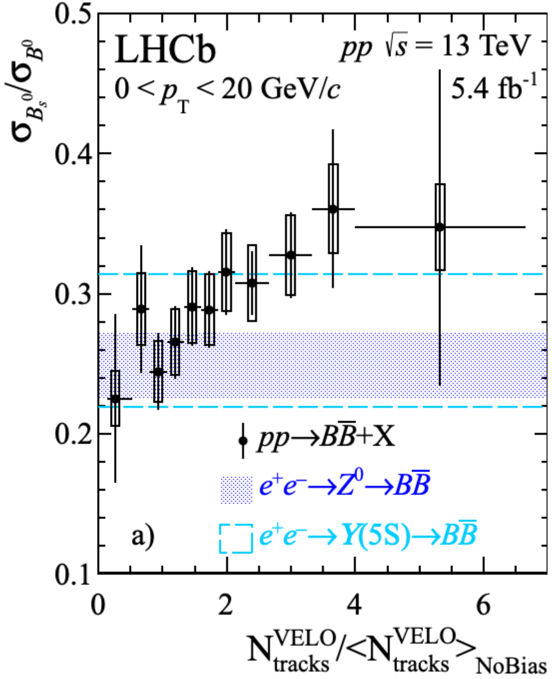
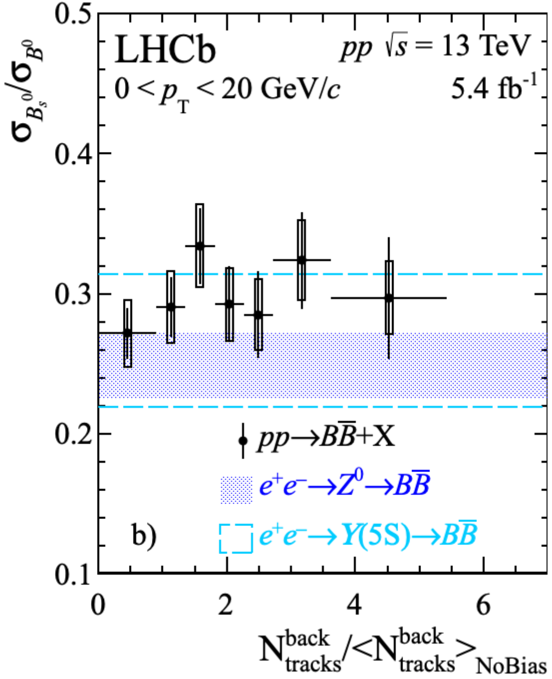
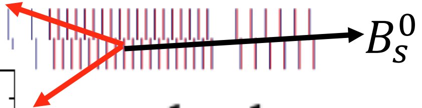








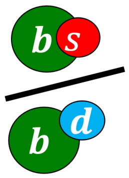
$N_{\text{tracks}}^{\text{back}}$

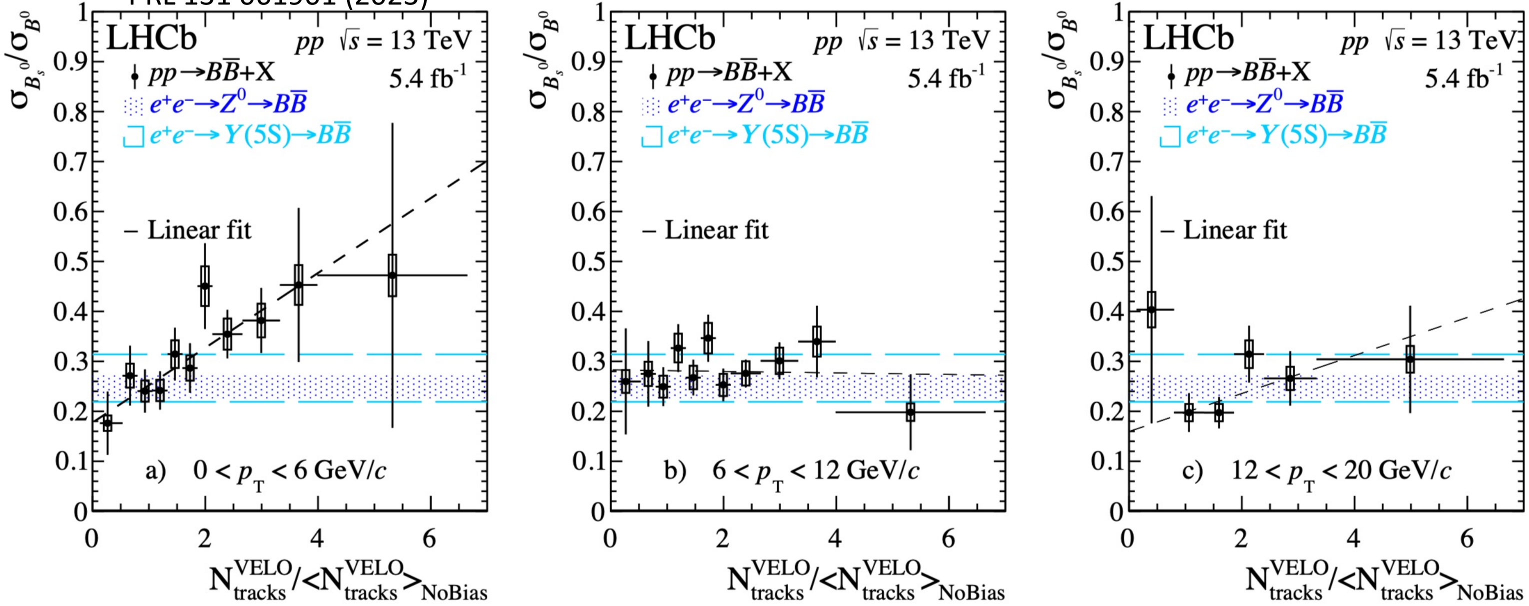
Multiplicity in opposite hemisphere as B mesons

- Enhancement depends on *local* particle density around B mesons

Modification of b hadronization

PRL 131 061901 (2023)

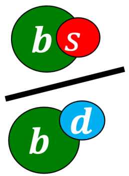


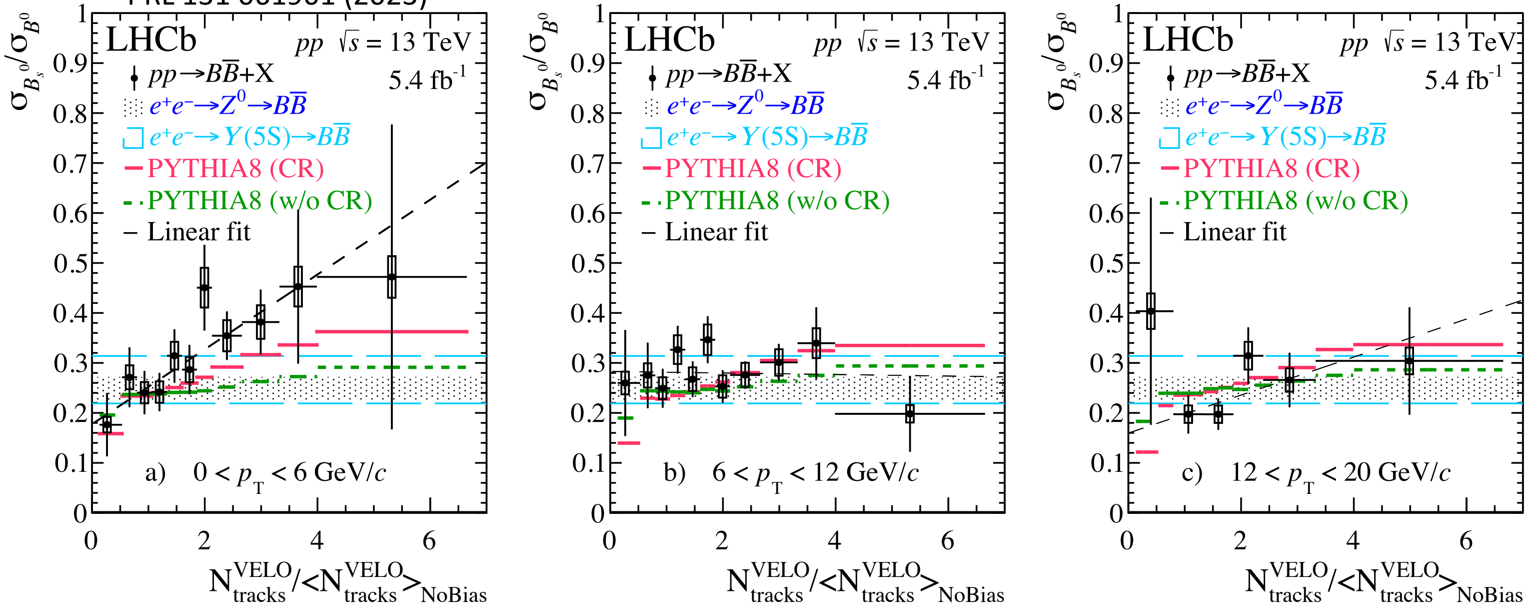


- Evidence for an increase of B_s^0/B^0 at low p_T
- Low multiplicity data consistent with fragmentation in vacuum measured in e^+e^- collisions
- Higher p_T B mesons show no enhancement

Modification of *b* hadronization – PYTHIA8

PRL 131 061901 (2023)





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- Higher p_T B mesons show no enhancement
- PYTHIA8 w/color reconnection enabled describes high p_T data, undershoots low p_T

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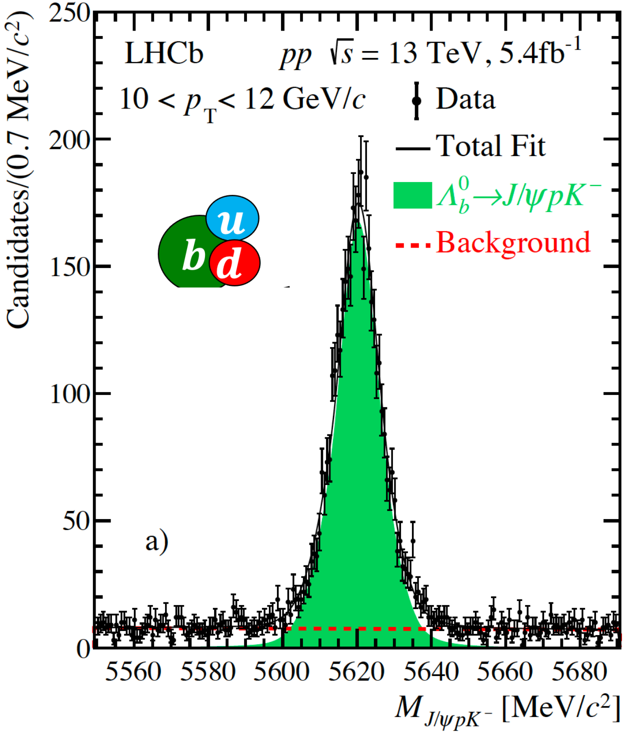
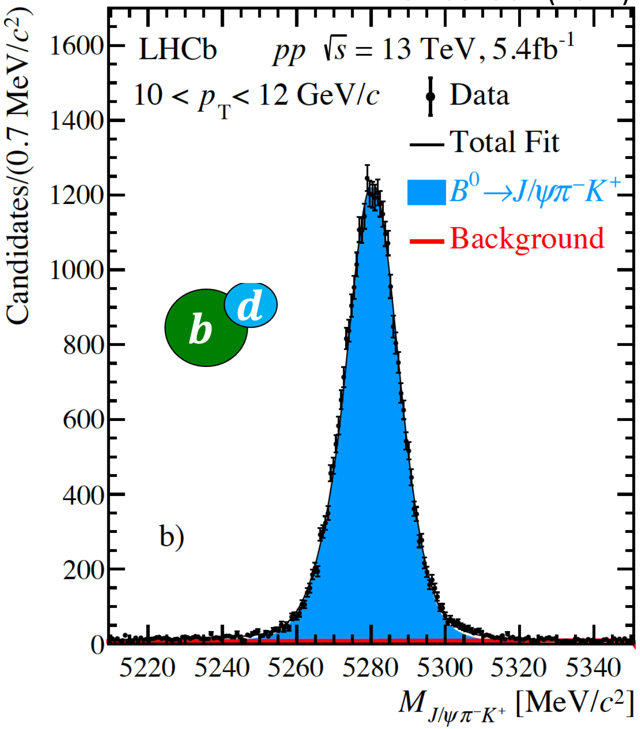
Modification of *b* hadronization – B baryons

- Coalescence provides a new mechanism for baryon formation - 3 quarks overlap
- Baryon enhancement is therefore a signature of coalescence

PRL 132 081901 (2024)





Modification of b hadronization – B baryons

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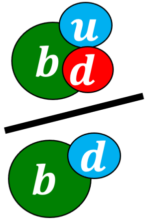

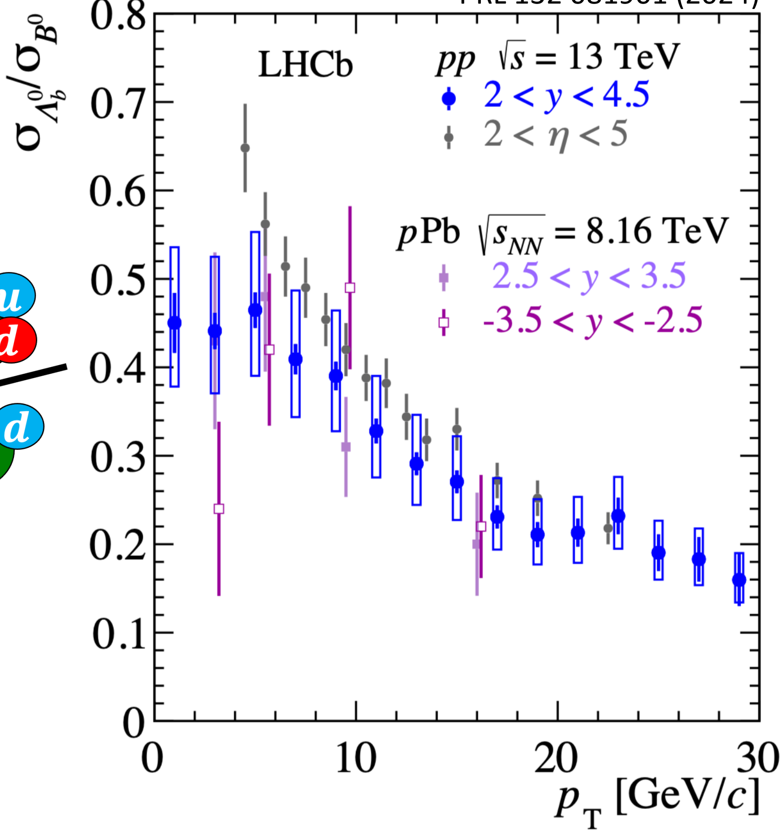

Baryon/meson ratio shows significant p_T dependence

Consistent with previous results (semileptonic decays)

Consistent with pPb results, within large uncertainties

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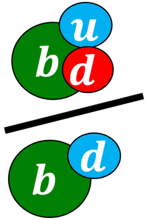

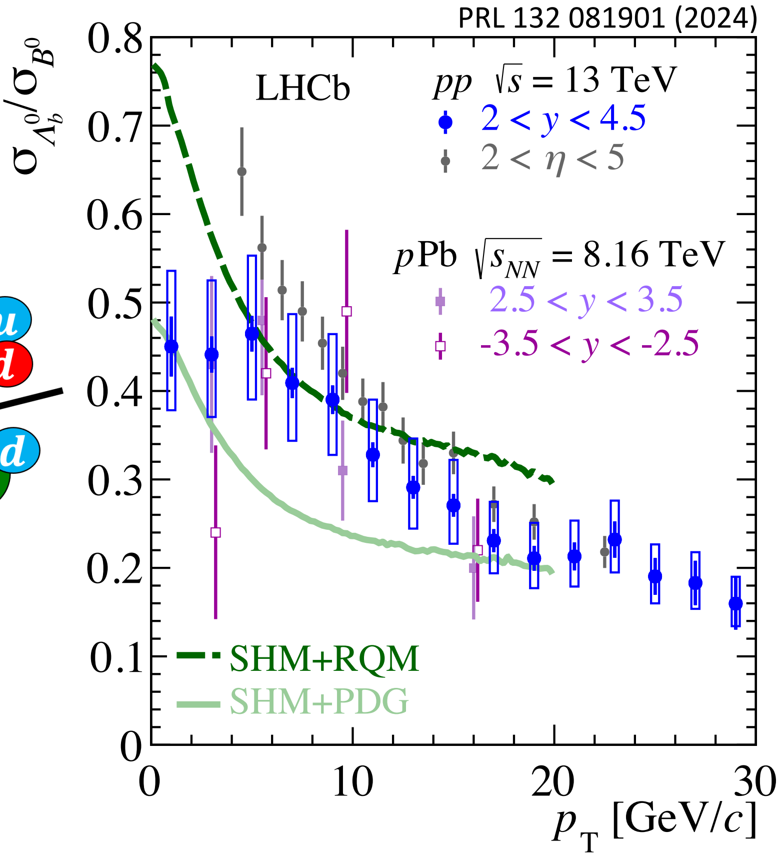

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Compare to Statistical Hadronization Model that uses two sets of baryons as input:

- Known baryon states from PDG
- Expanded set of baryons predicted by the Relativistic Quark Model

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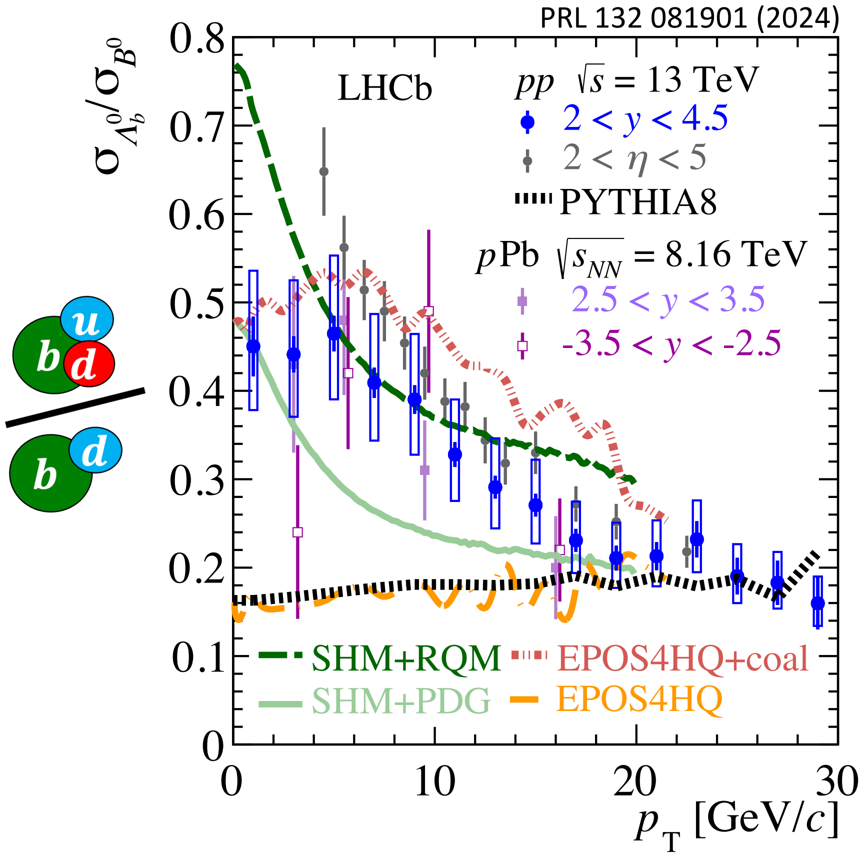

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PYTHIA8 fails to reproduce p_T dependence

EPOS4HQ with only fragmentation also fails

EPOS4HQ with fragmentation+quark coalescence does much better, slightly overpredicts ratio

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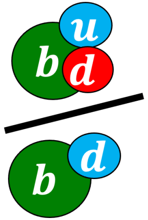

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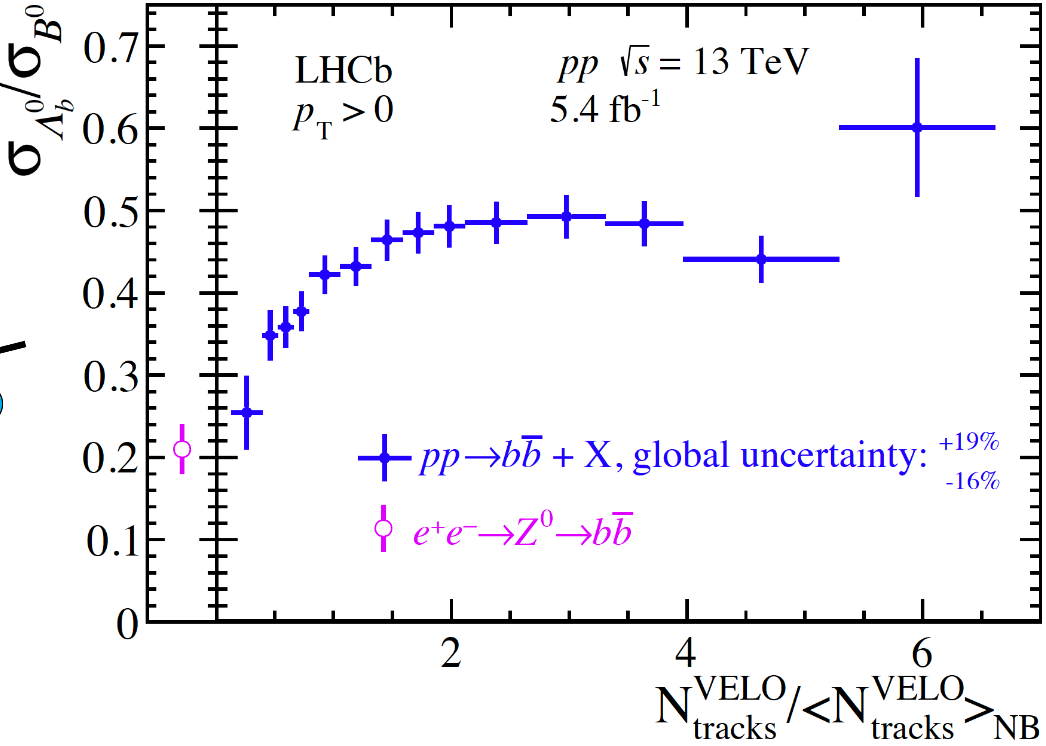
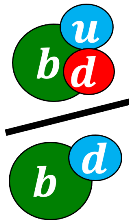
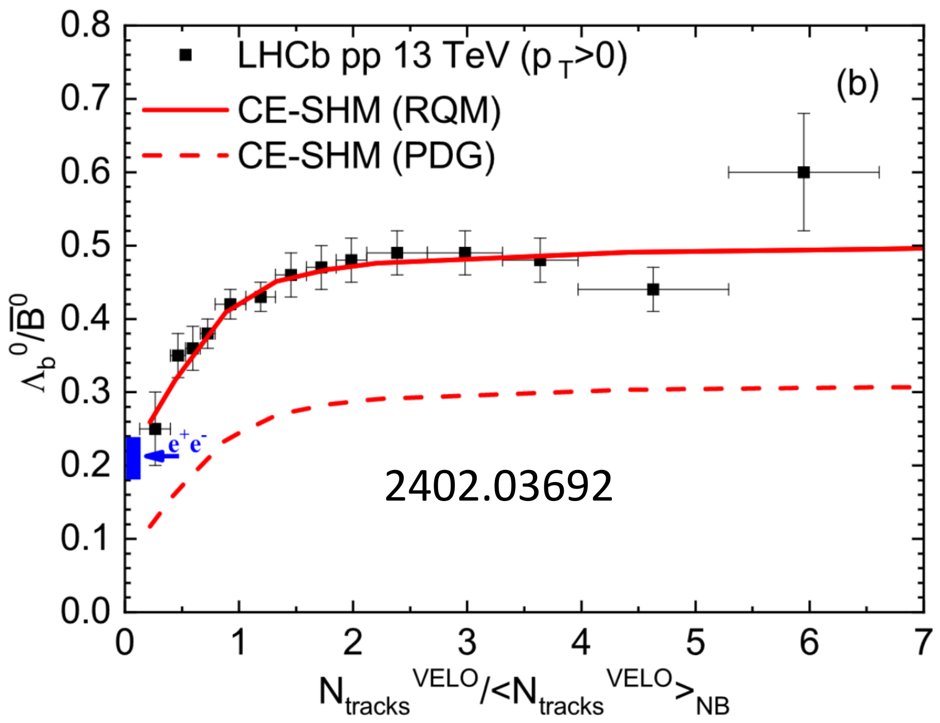


- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

b quarks in low multiplicity collisions have nothing to coalesce with → fragment in vacuum

Modification of b hadronization – B baryons

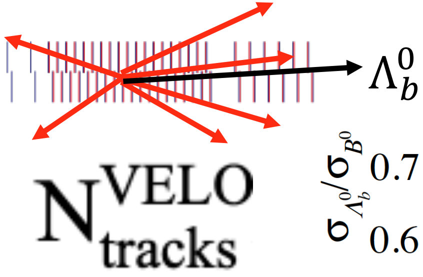


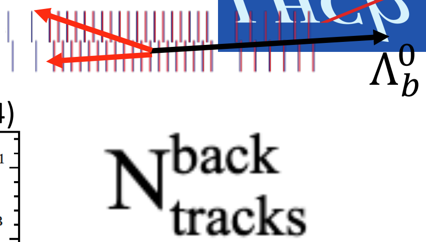


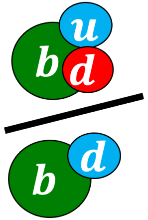
- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

SHM reproduces trend with plateau – all possible baryon states populated at high multiplicity

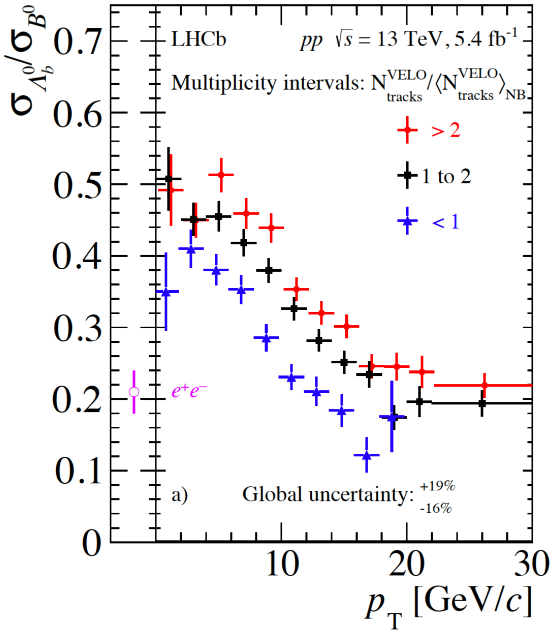
Modification of *b* hadronization – B baryons

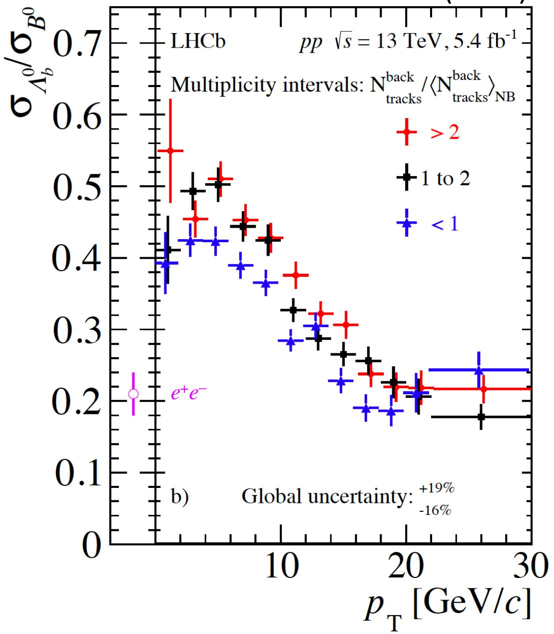






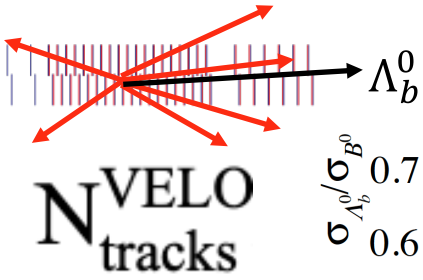
PRL 132 081901 (2024)

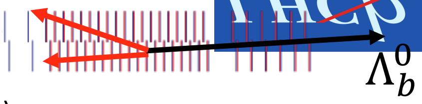


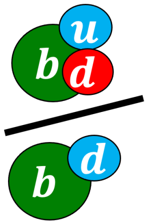


- Clear multiplicity dependence at relatively low p_T

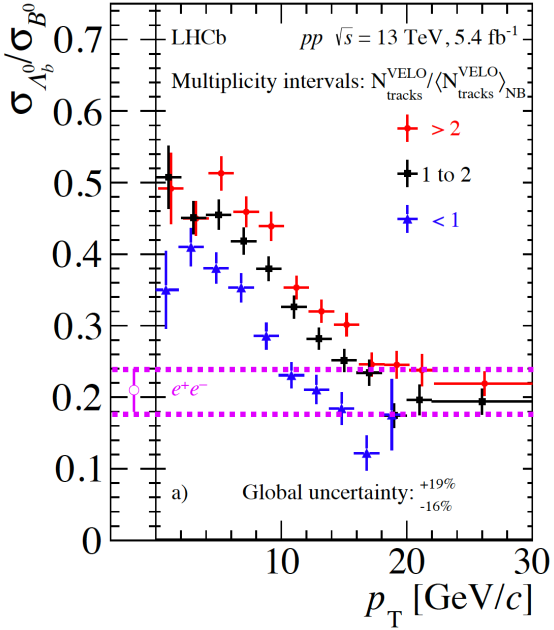
Modification of *b* hadronization – B baryons

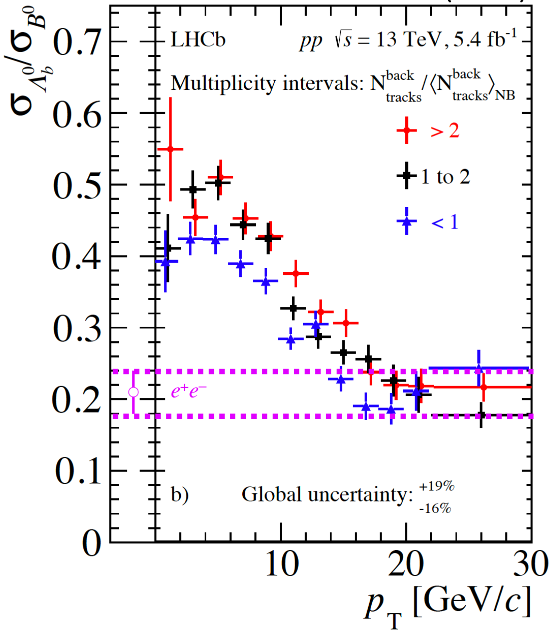






PRL 132 081901 (2024)





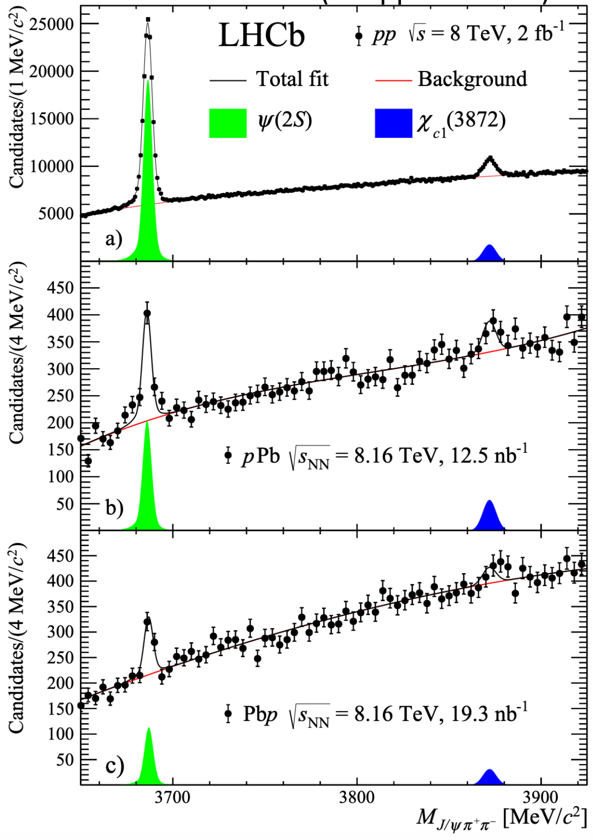
- Clear multiplicity dependence at relatively low p_T
- Reproduce e^+e^- result at high p_T where *b* quarks don't interact with bulk and just fragment

Outline

- Hadronization: the bridge between QCD and observable particles
  - In-medium modifications of the hadronization process
- New measurements from LHCb sensitive to hadronization mechanisms
  - Strangeness enhancement in B mesons: Phys Rev Lett 131 061901 (2023)
  - Λ_b baryon enhancement in small systems: Phys Rev Lett 132 081901 (2024)
  - X(3872) enhancement in pPb collisions: 2402.14975 (to appear in PRL)
- Conclusions

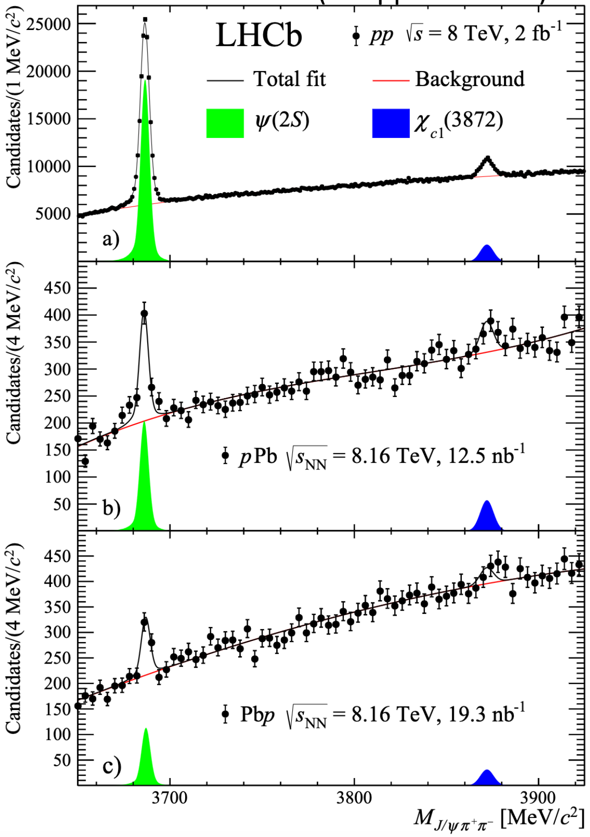
X(3872) in *p*Pb

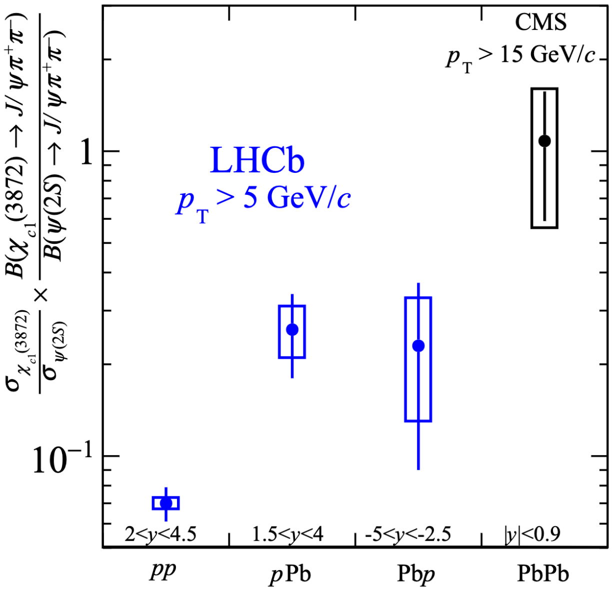
arXiv:2402.14975 (to appear in PRL)



X(3872) in *p*Pb

arXiv:2402.14975 (to appear in PRL)





Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium

Initial state effects (eg shadowing) should largely cancel in ratio

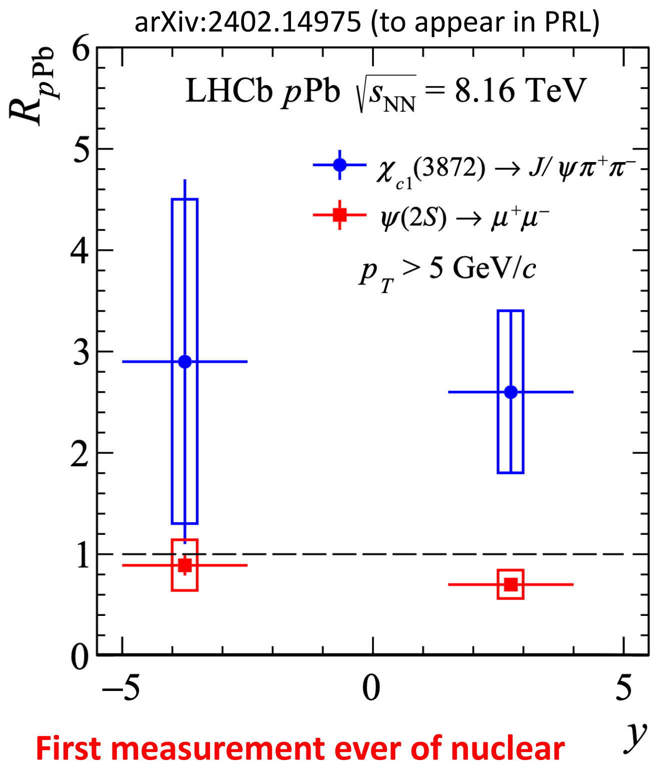
Enhancing effects start to out compete breakup?

- arXiv:2302.03828

Prompt X(3872)/ ψ(2S) = 0.26 ± 0.08 ± 0.05 in forward pPb
Prompt X(3872)/ ψ(2S) = 0.23 ± 0.15 ± 0.10 in backward pPb
Falls between pp (~0.1) and PbPb (~1.0)

AMBIGUITY between X(3872) enhancement and ψ(2S) suppression

X(3872) in *p*Pb

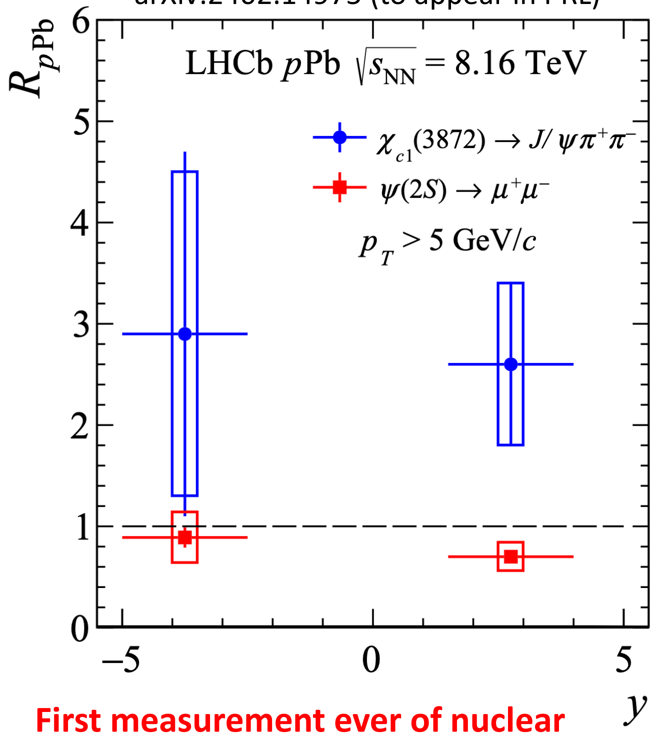


First measurement ever of nuclear modification factor of a tetraquark!

Ambiguity lifted by measuring nuclear modification factors:

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

X(3872) in *p*Pb



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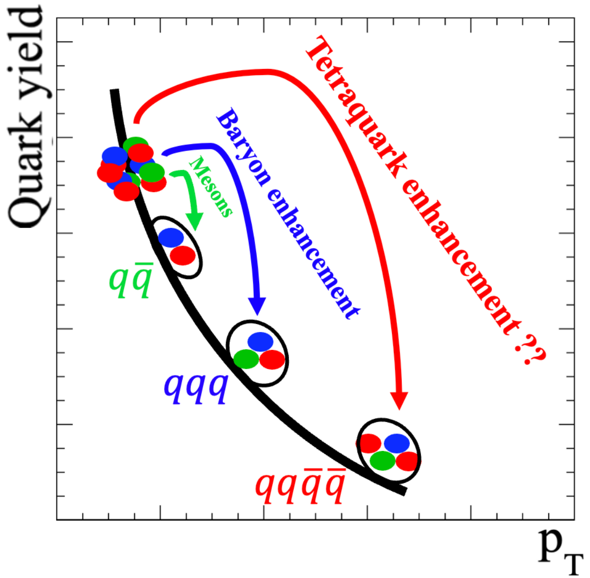
Ambiguity lifted by measuring nuclear modification factors:

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$

Evidence for enhancement of X(3872) in *p*Pb: Coalescence dominating over breakup?

Similar mechanism for baryon enhancement could also increase tetraquark production



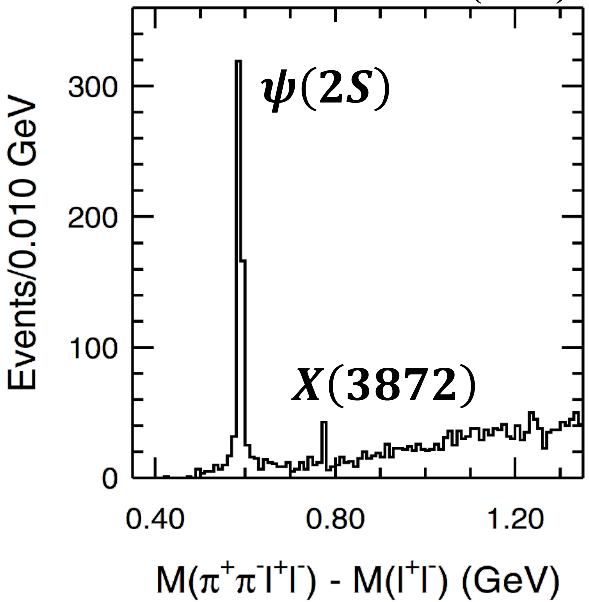
Summary

- **Heavy quarks are extremely versatile for probing non-perturbative QCD**
- QCD creates a rich spectrum of bound states
- Universality of hadronization clearly breaks between different collision systems.
- Clear indications of new hadronization mechanisms that are important at hadron colliders.

Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics and DOE Early Career Awards program

An enduring puzzle: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



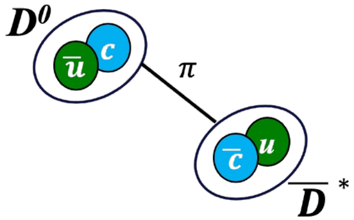
*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

- The first exotic hadron, discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003
- LHCb measured quantum numbers (PRL 110 222001 2013)
  - **Incompatible** with expected charmonium states
- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

$$\left(M_{D^0} + M_{\bar{D}^{*0}}\right) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12\ \text{MeV}/c^2$$

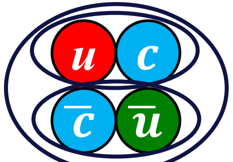
- Large prompt production fraction (~80%) – potentially inconsistent with D meson coalescence in pp*

$D^0\overline{D}^*$ Molecule



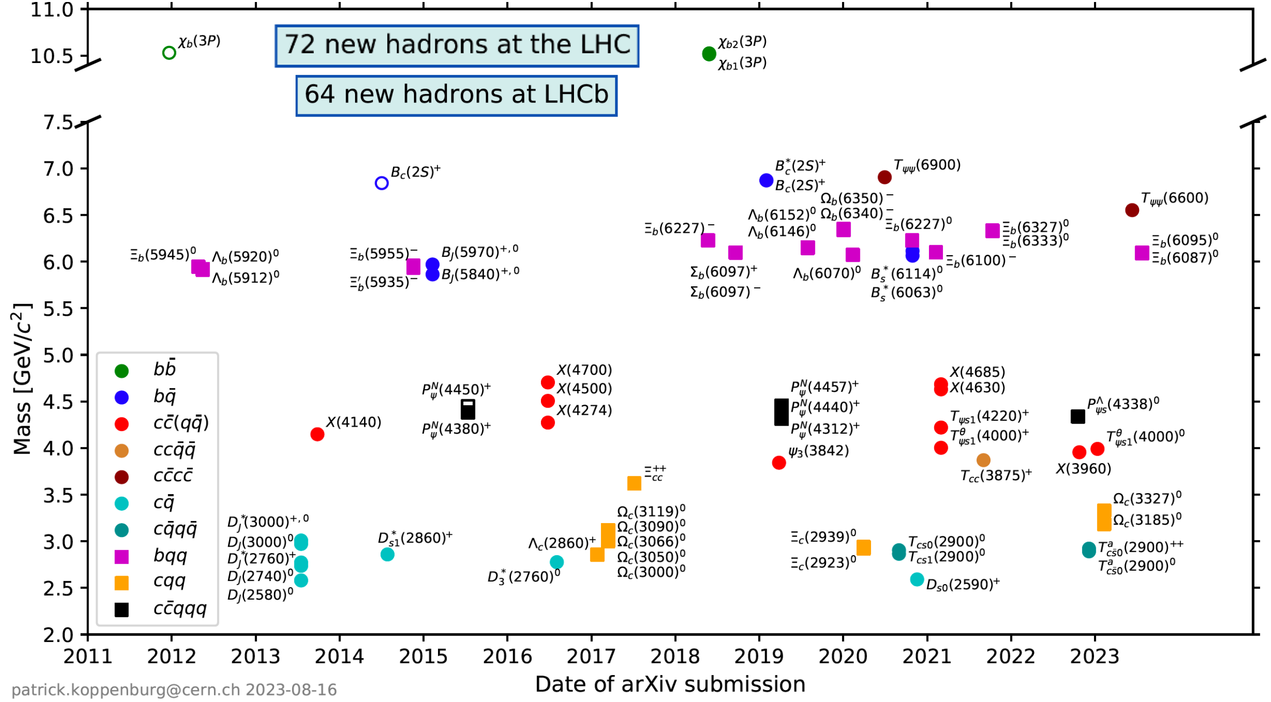
VERY **small binding energy**
VERY **large radius, ~10 fm**

Compact tetraquark

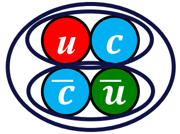


Tightly bound via color exchange between diquarks
Small **radius, ~1 fm**

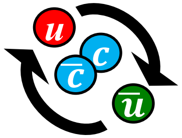
New hadrons discovered at LHC



Compact tetraquark/pentaquark

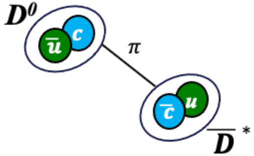


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

Mixtures

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

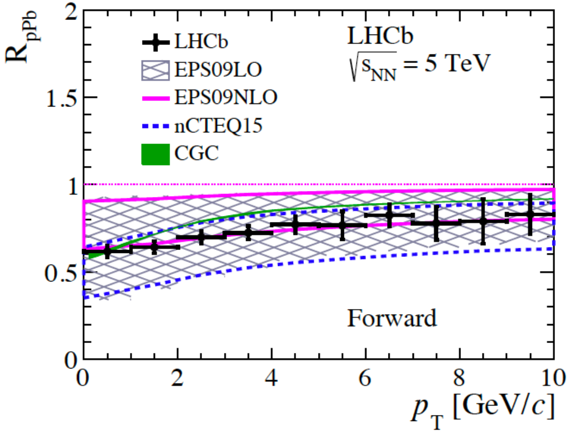
PLB 578 365 (2004)
PRD 96 074014 (2017)

The quark model is rapidly expanding: study of exotics states largely driven by experiment

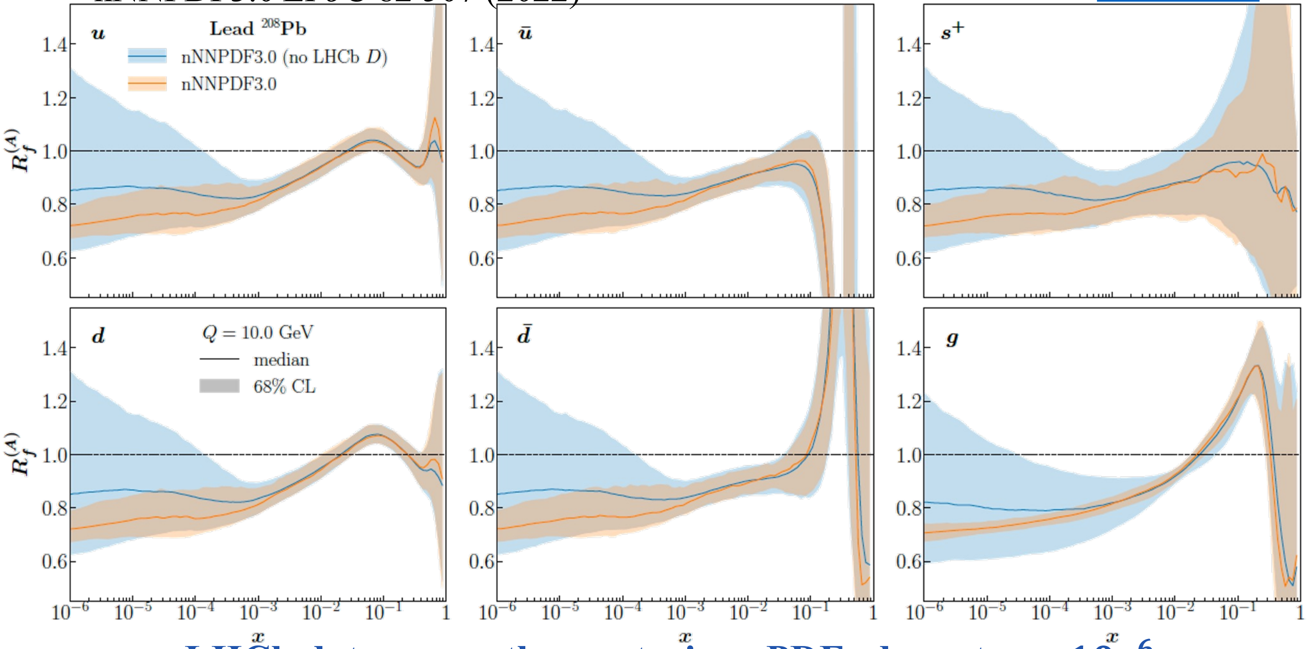
Constraining nPDFs with D mesons

[Tom Boettcher
Tues 16:30]

JHEP 1710 (2017)



nNNPDF3.0 *EPJC* 82 507 (2022)



- LHCb D meson data: significantly more precise than calculations from older nPDF sets
- Now included as constraint in updated nPDF sets

LHCb data currently constrains nPDFs down to $x \sim 10^{-6}$
Places especially stringent bounds on gluon nPDF