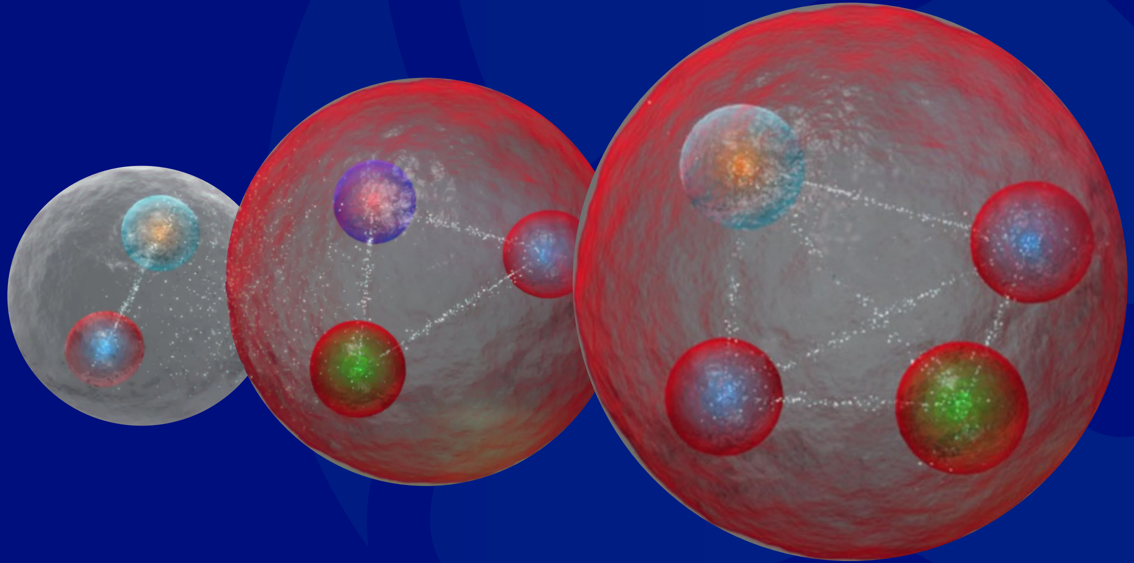
Mesons, baryons, and tetraquarks in the QCD medium

Matt Durham
durham@lanl.gov

Heavy Flavor Seminar
April 15, 2026



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
  - Λ_b Baryon enhancement in small systems
- Exotic multiquark states in-medium
  - X(3872) in pp and pPb
- Future upgrades

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
  - Λ_b Baryon enhancement in small systems

- Exotic multiquark states in-medium
  - X(3872) in pp and pPb

- Future upgrades

Heavy Quark Production

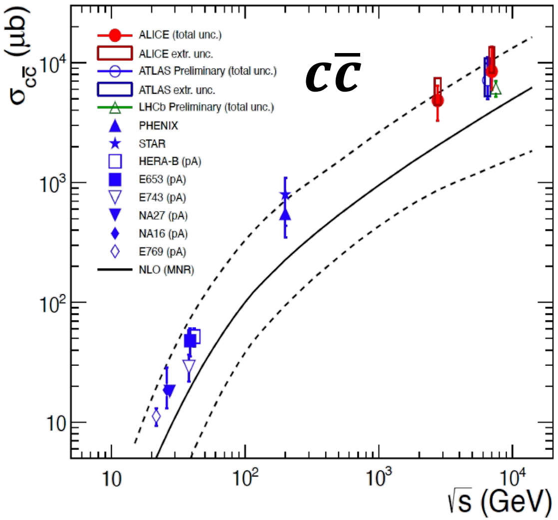
$$\sigma_{AA\rightarrow H+X} \propto f_1(x_1, Q^2) \otimes f_2(x_2, Q^2) \otimes \hat{\sigma}(Q^2, x_1, x_2) \otimes D_H(z)$$

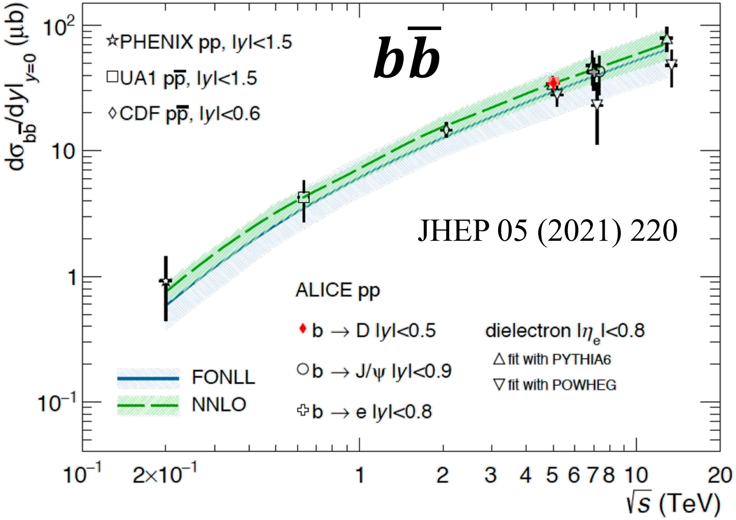
Heavy Quark Production

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

- **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



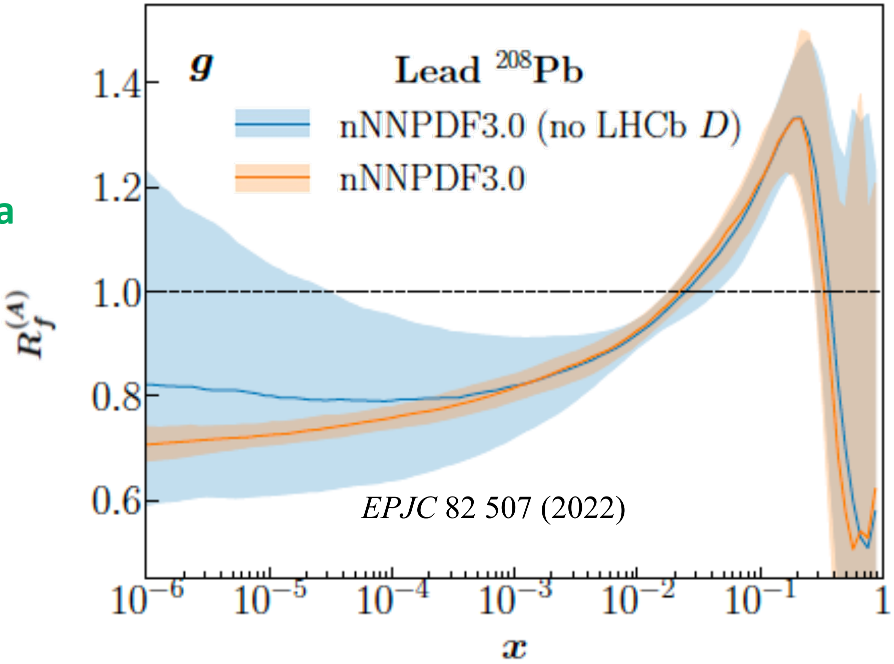


Heavy Quark Production

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

- **Hadron cross sections: measured at experiments**
- **Parton-parton cross sections: calculable by pQCD**
- **Parton distribution functions: constrained by data**

Major recent progress
reducing nPDF uncertainties
by including LHCb charm data

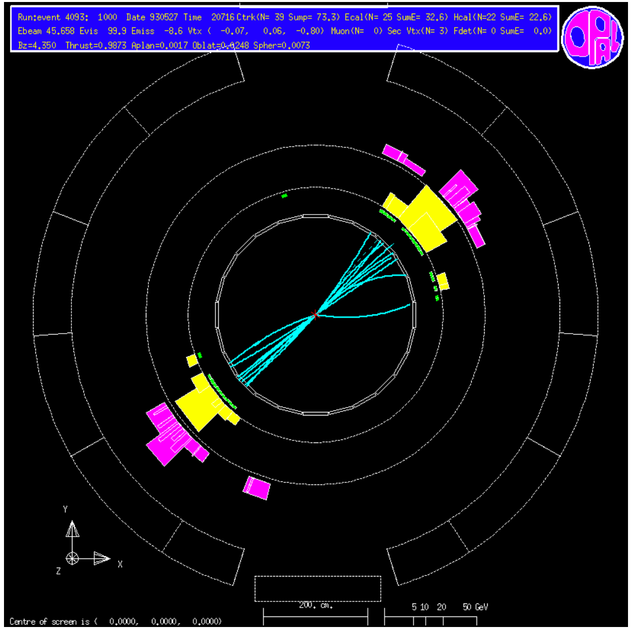


Heavy Quark Production

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

- **Hadron cross sections: measured at experiments**
- **Parton-parton cross sections: calculable by pQCD**
- **Parton distribution functions: constrained by data**
- **Fragmentation functions: constrained by e^+e^- data**

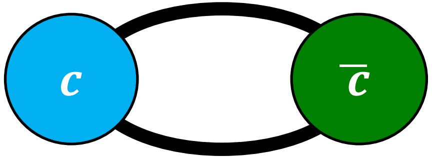
$e^+e^- \to Z \to q\bar{q}$ event



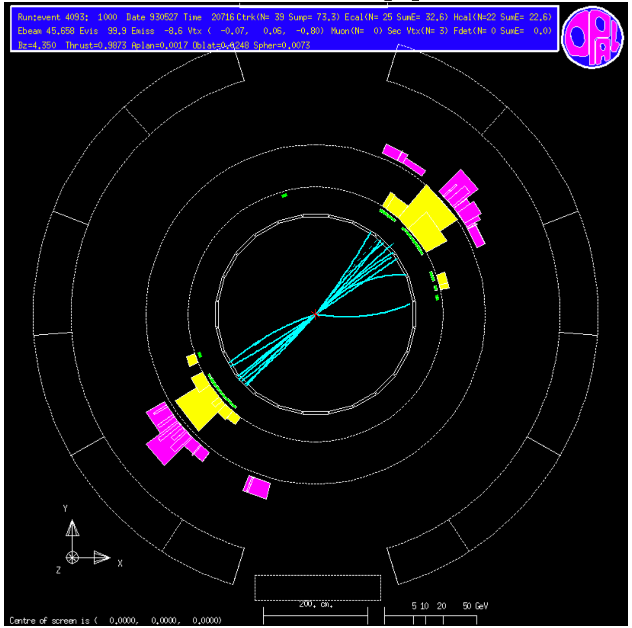
Fragmentation in vacuum

- 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

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



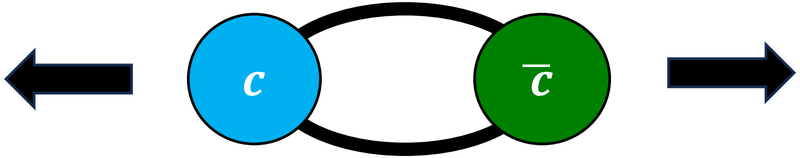
$e^+e^- \to Z \to q\bar{q}$ event



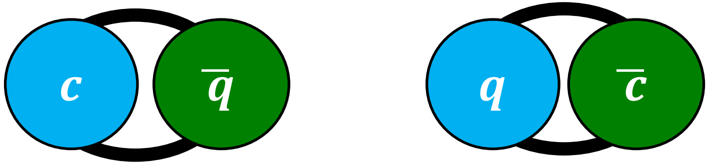
Fragmentation in vacuum

- 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

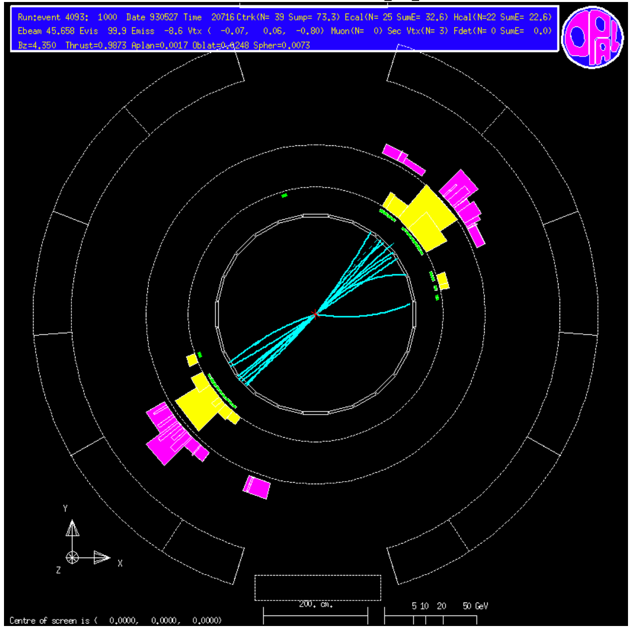
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br$$



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



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

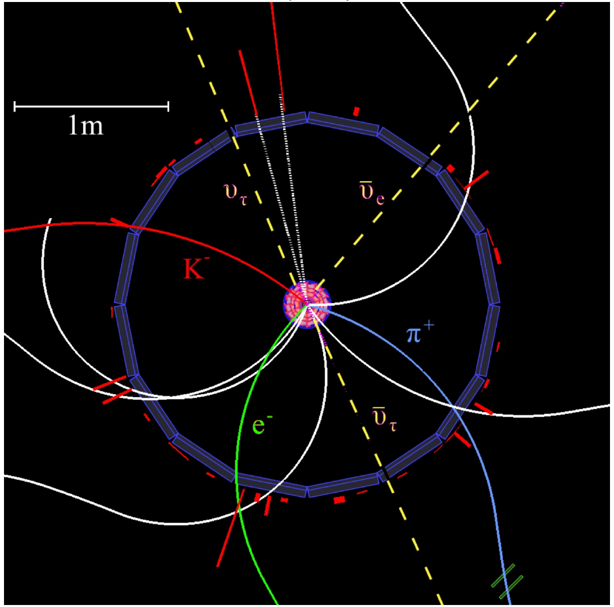


Hadronization is the bridge between observable particles and underlying QCD

Fragmentation in vacuum

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

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



b factories:

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

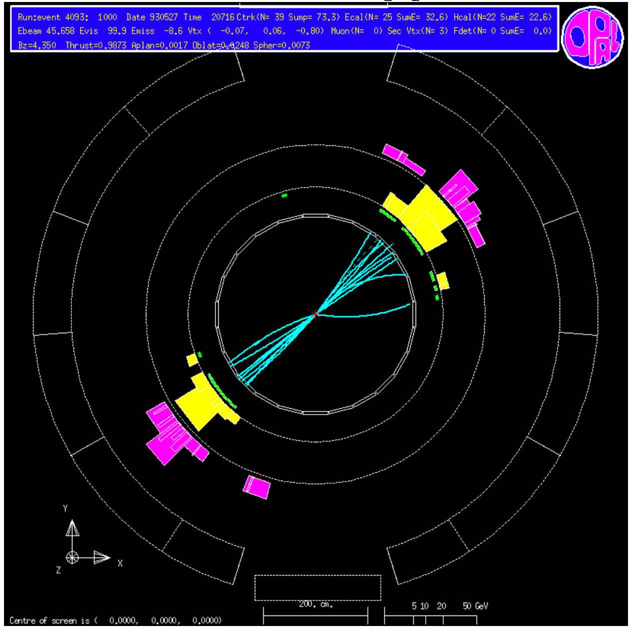
$$B_s/_{B^0} = 0.26\ ^{+0.05}_{-0.04}$$

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



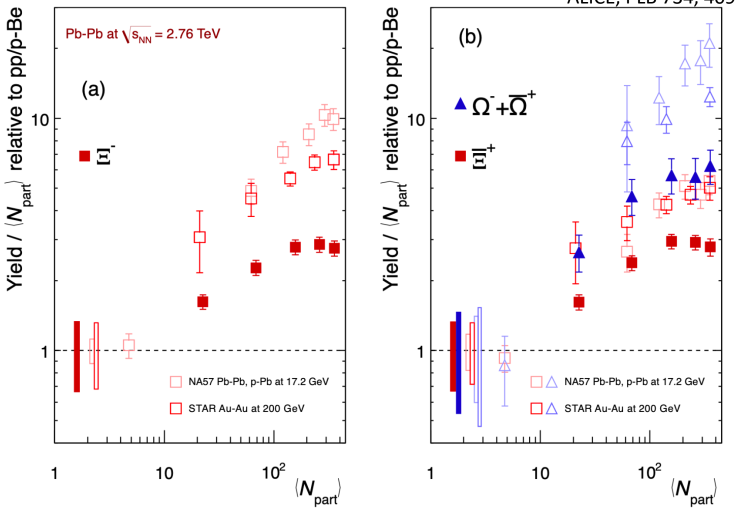
Assumption: hadronization is ***universal*** and ***factorizable*** from rest of collision

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)



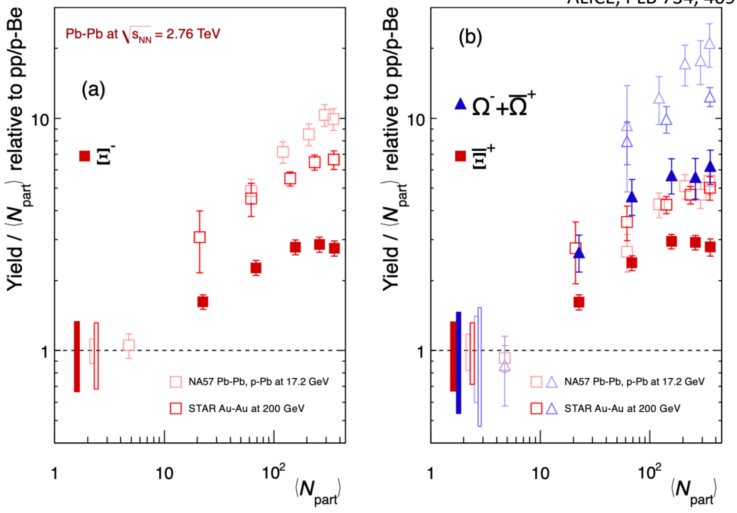
"strangeness enhancement"

Hadronization following deconfinement

In a deconfined plasma, strange quark production is dramatically enhanced

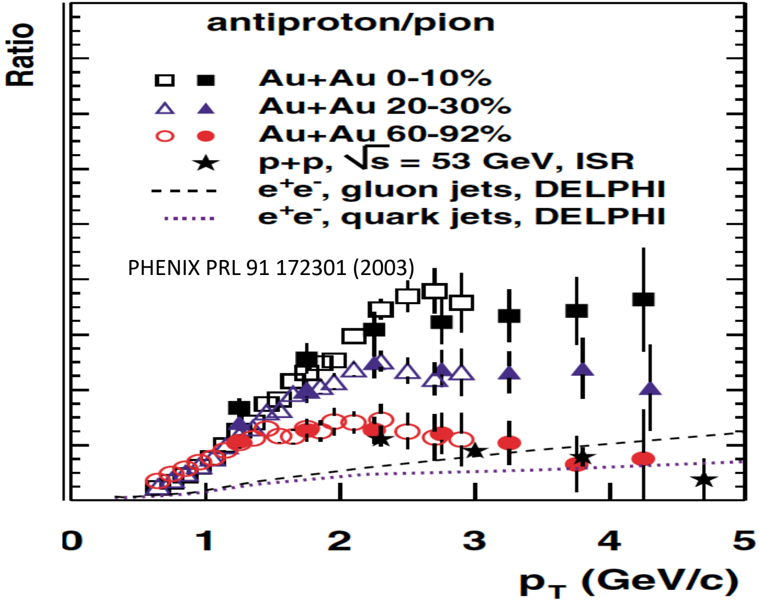
- $T_c \approx 190\ MeV \approx 2m_s$ strange quark pairs can be produced through fusion of thermalized gluons

ALICE, PLB 734, 409 (2014)



“strangeness enhancement”

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



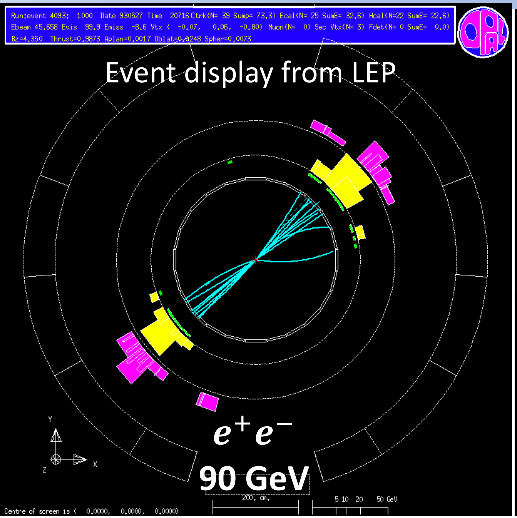
“baryon enhancement”

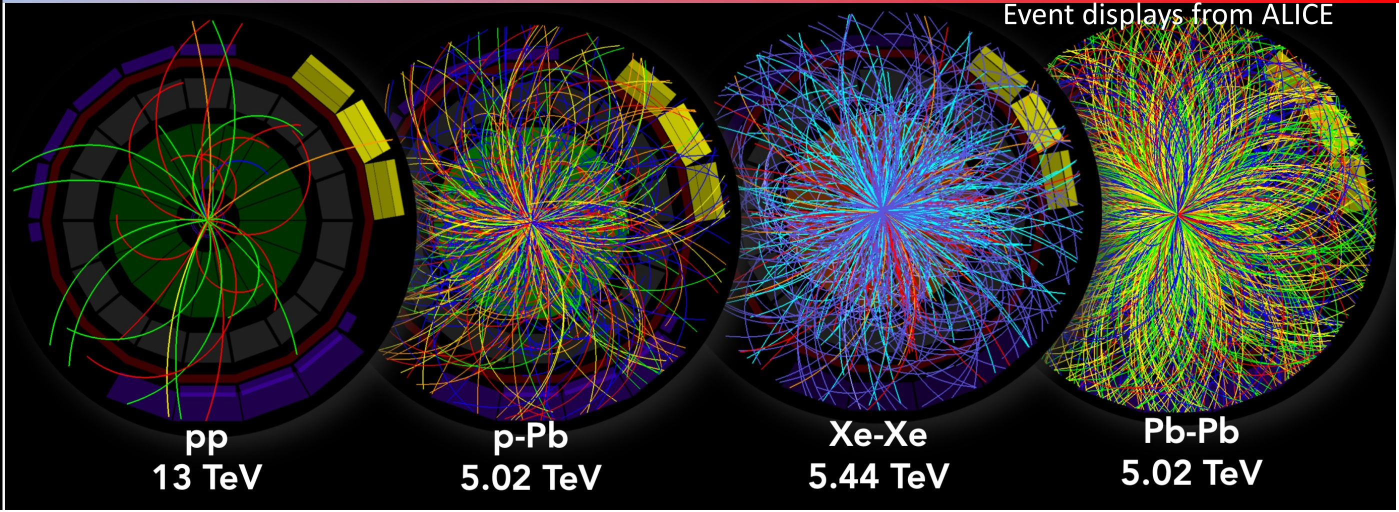
Dramatic changes in hadron chemistry between collision systems

From vacuum to the QCD medium – quark coalescence

Vacuum (e^+e^-) Diffuse medium (pp,pA) Dense medium (pA, AA)

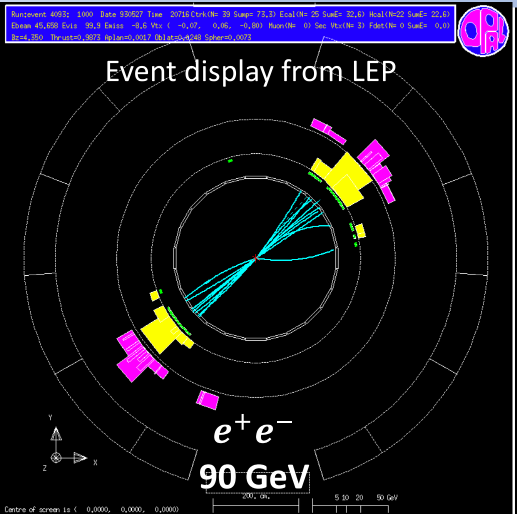
Increasing T, $N_{charged}$

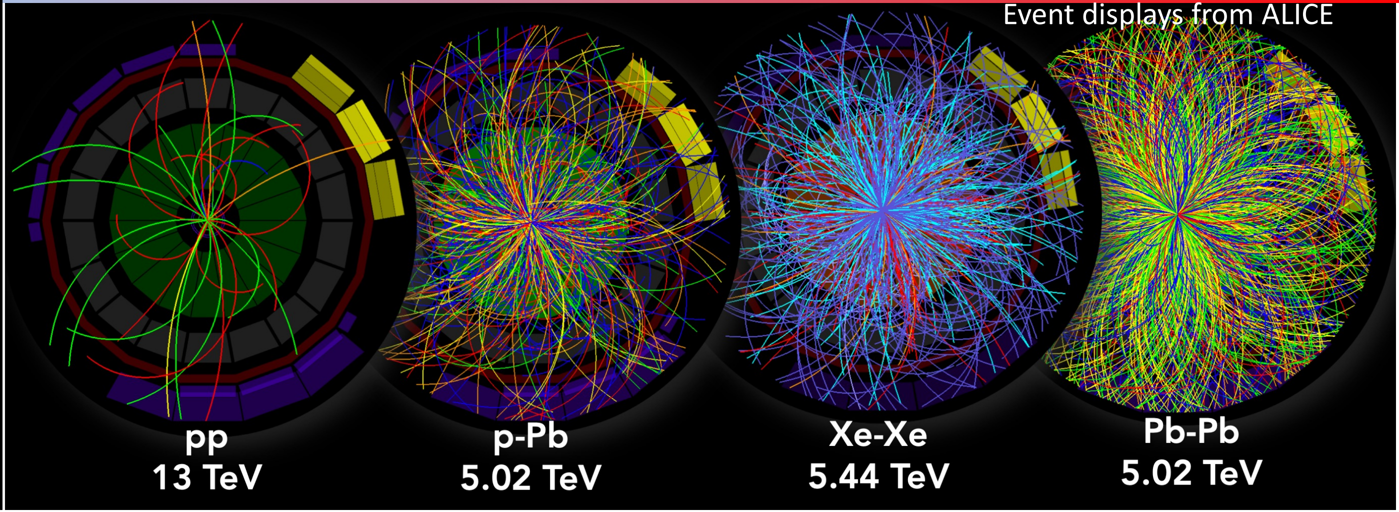


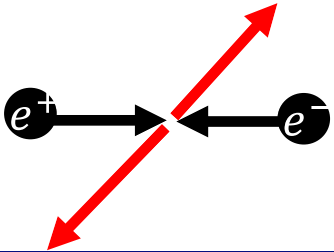


From vacuum to the QCD medium – quark coalescence

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

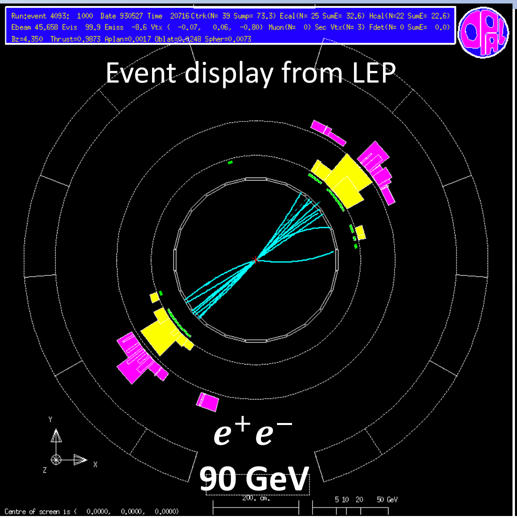


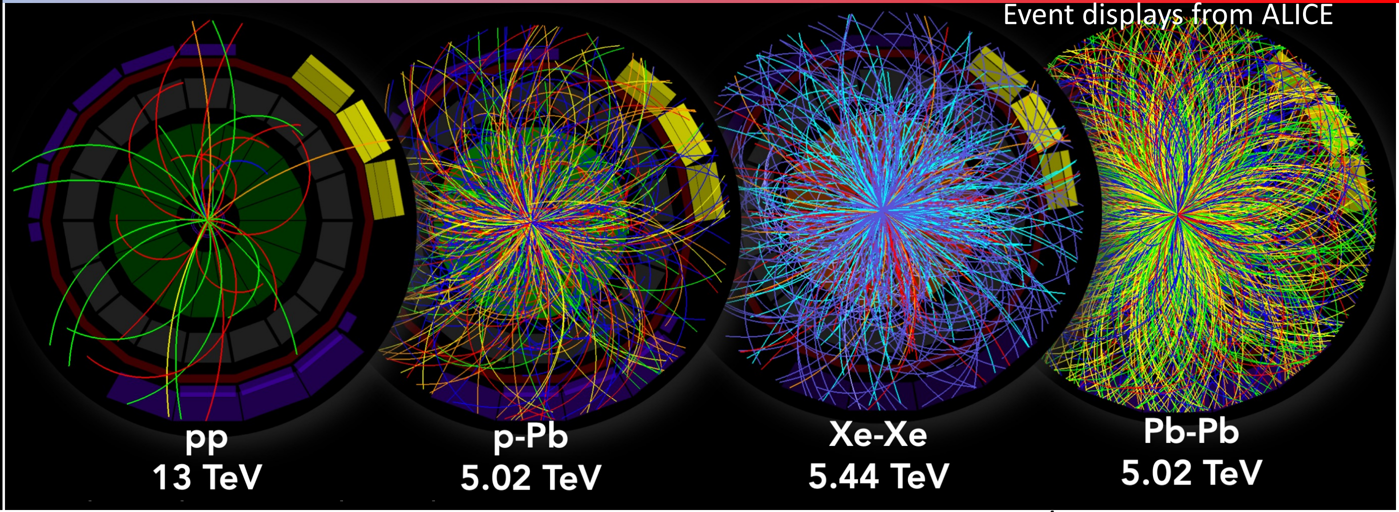


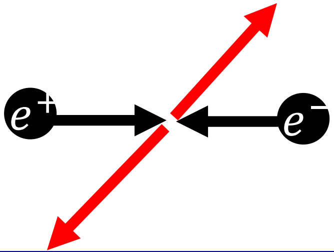


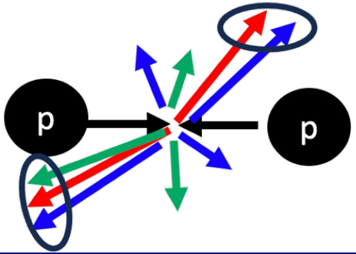
From vacuum to the QCD medium – quark coalescence

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









- 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

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
  - Λ_b baryon enhancement in small systems

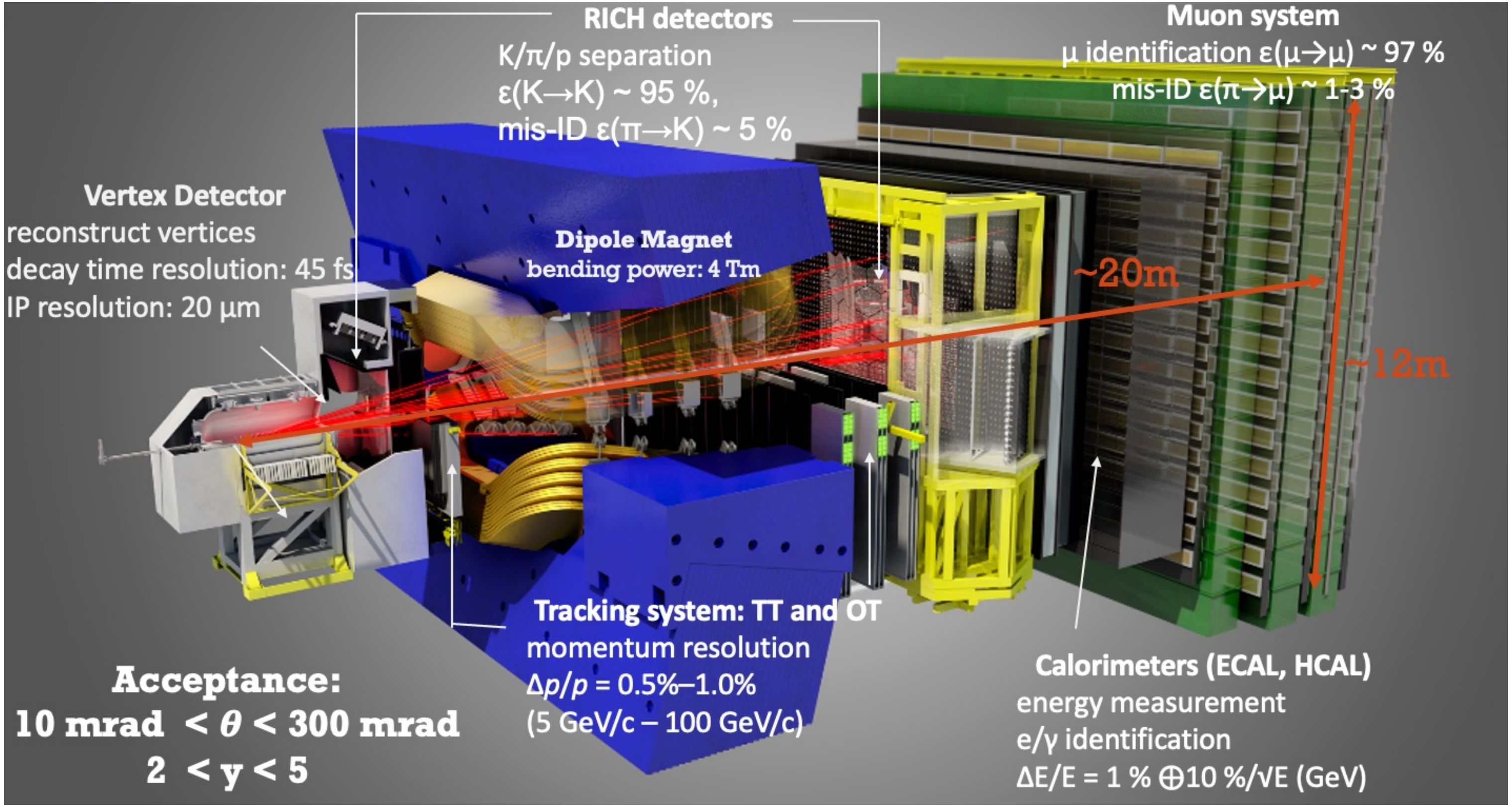
- Exotic multiquark states in-medium
  - X(3872) in pp and pPb

- Future upgrades

The LHCb detector

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

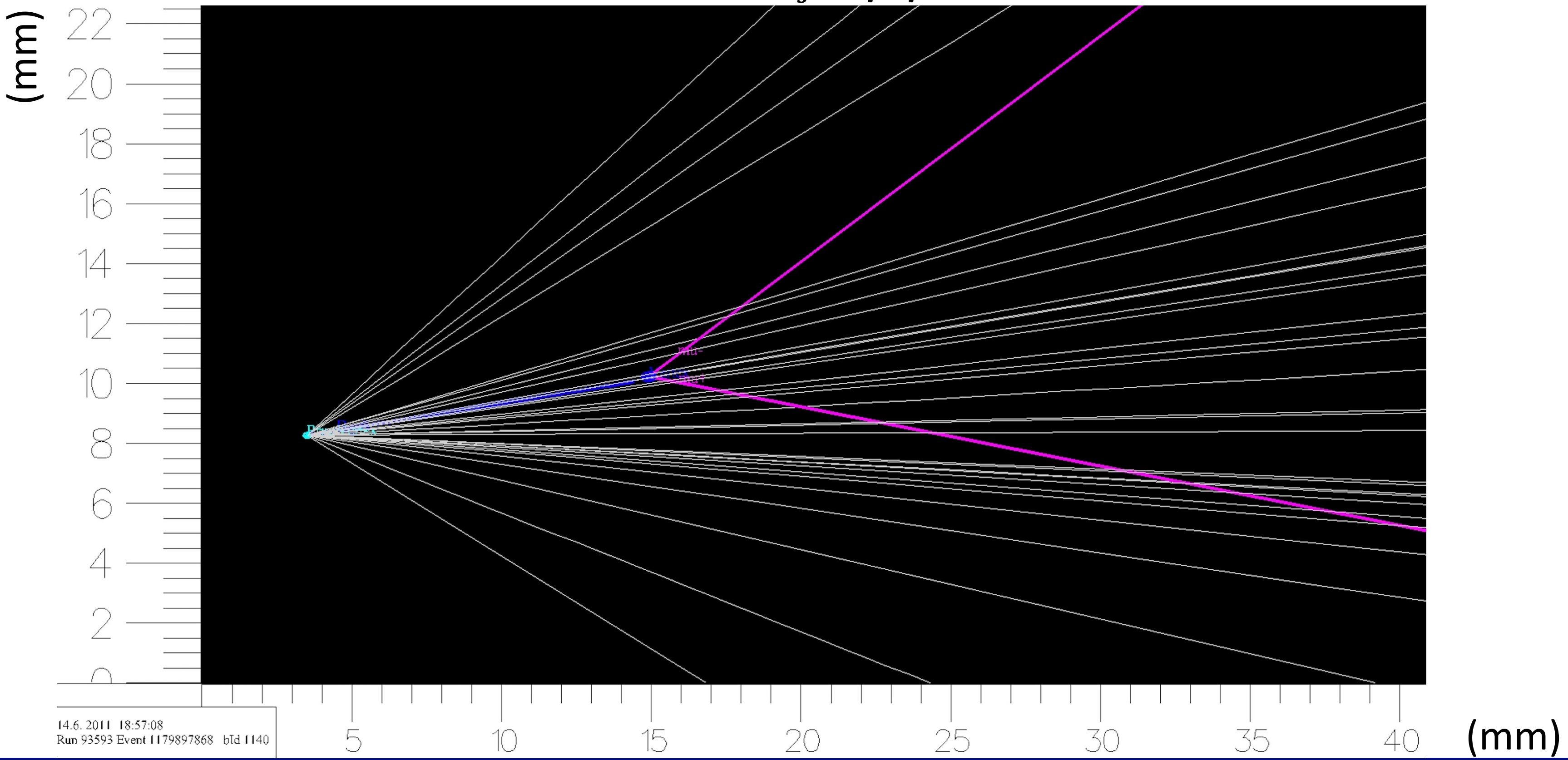
Unique forward rapidity coverage at the Large Hadron Collider in p+p, p+A, A+A, fixed target collisions



The LHCb detector

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

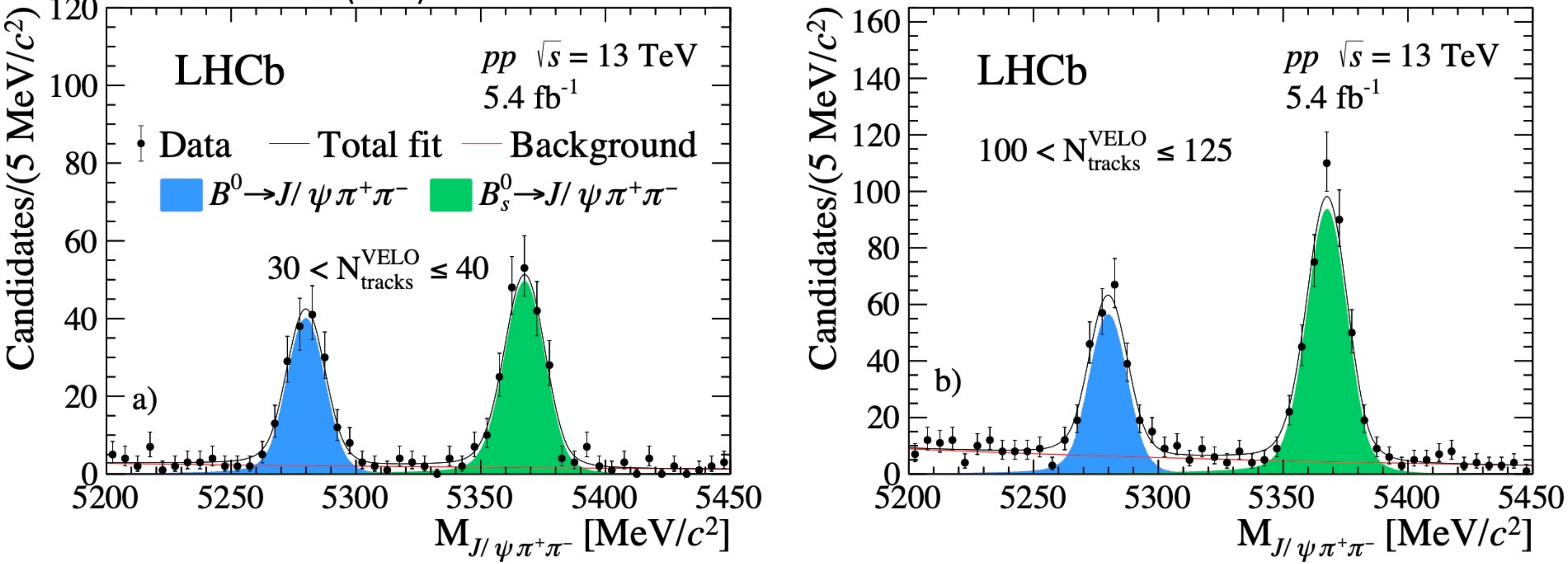
Event display of $B_s^0 \to \mu^+\mu^-$ candidate



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)



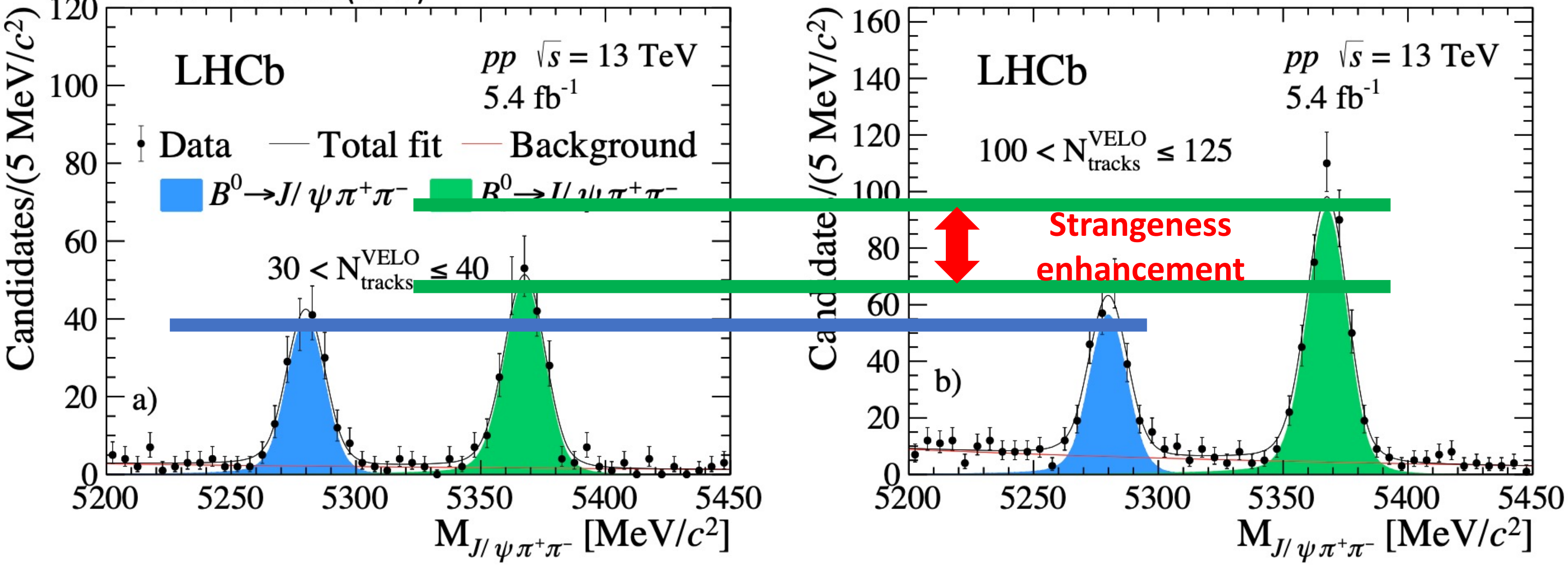
Low multiplicity – few tracks

High multiplicity – many tracks

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

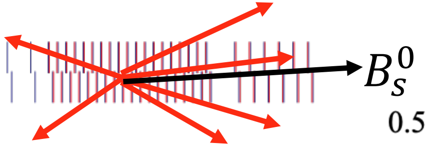
PRL 131 061901 (2023)



Low multiplicity – few tracks

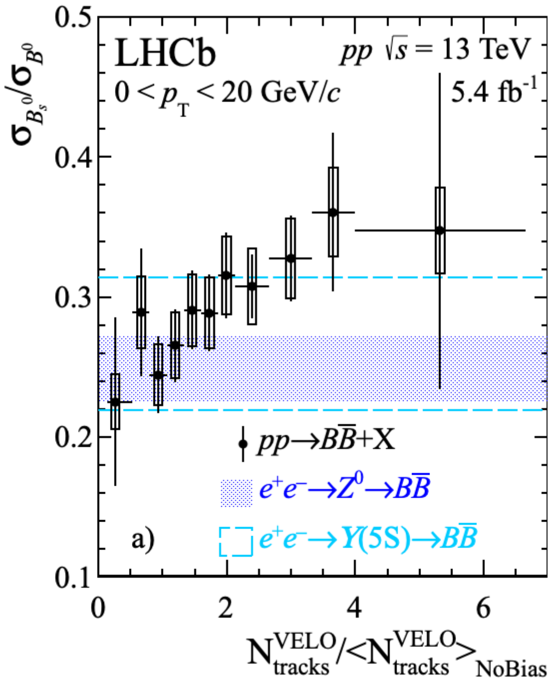
High multiplicity – many tracks

Modification of *b* hadronization – strange B mesons

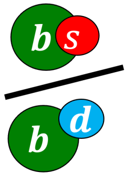


PRL 131 061901 (2023)

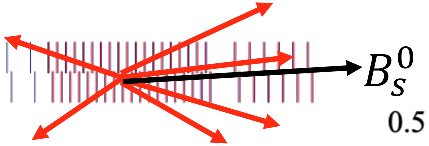
$N_{\text{tracks}}^{\text{VELO}}$



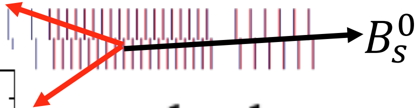
Total VELO multiplicity, dominated by forward tracks



Modification of *b* hadronization – strange B mesons

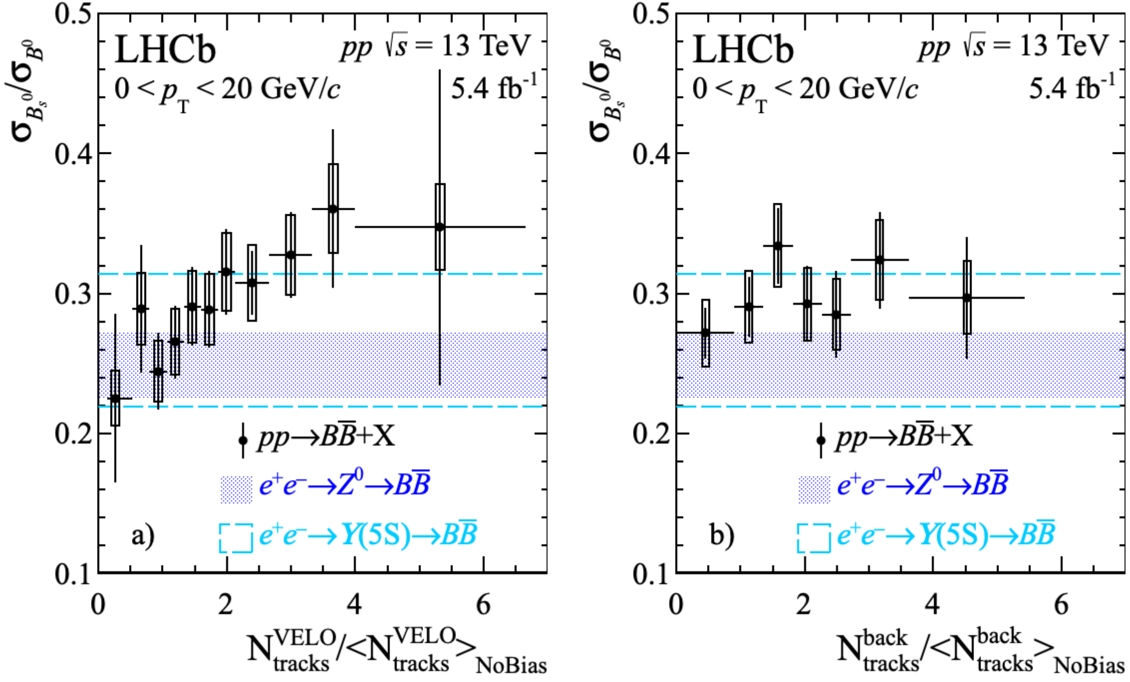


PRL 131 061901 (2023)



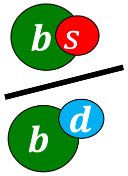
N^{VELO}_{tracks}

N^{back}_{tracks}



Total VELO multiplicity, dominated by forward tracks

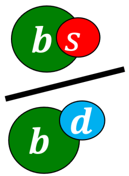
Multiplicity in opposite hemisphere as B mesons

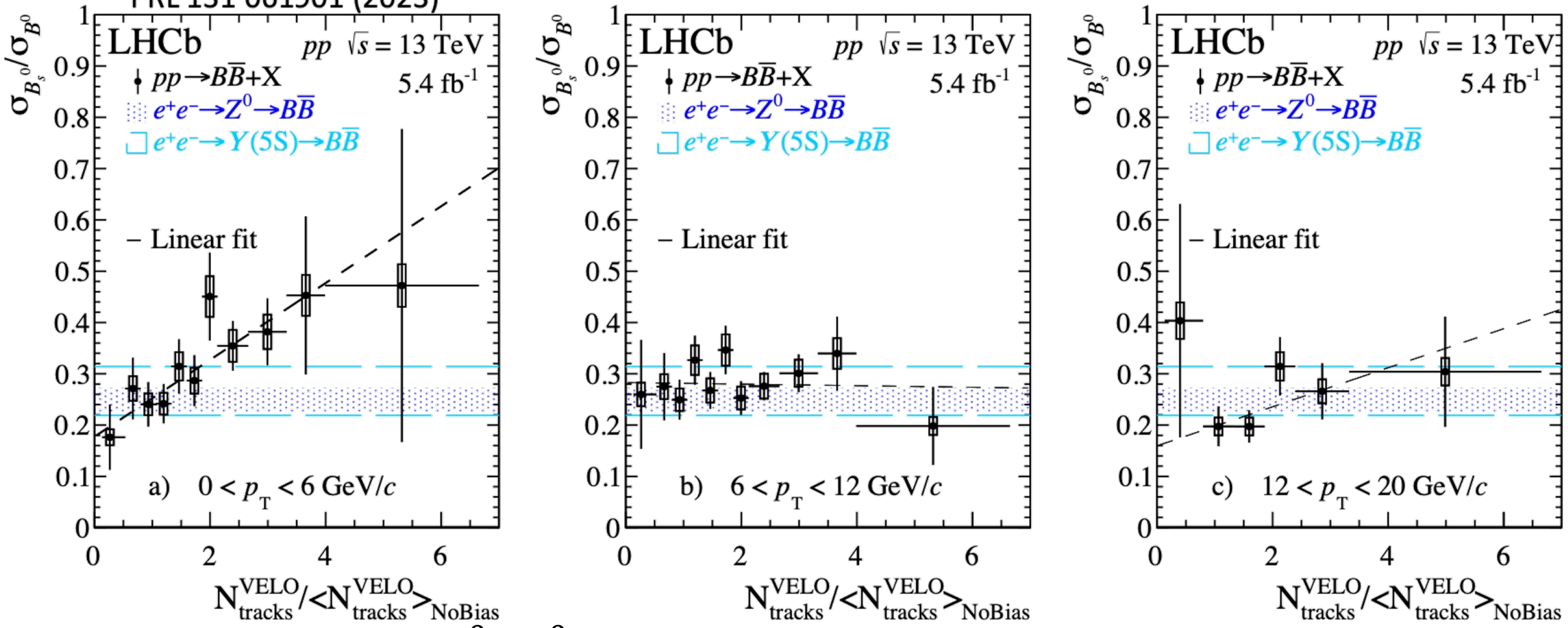


- Enhancement depends on *local* particle density around B mesons

Modification of *b* hadronization

PRL 131 061901 (2023)

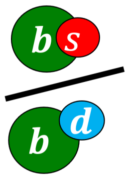


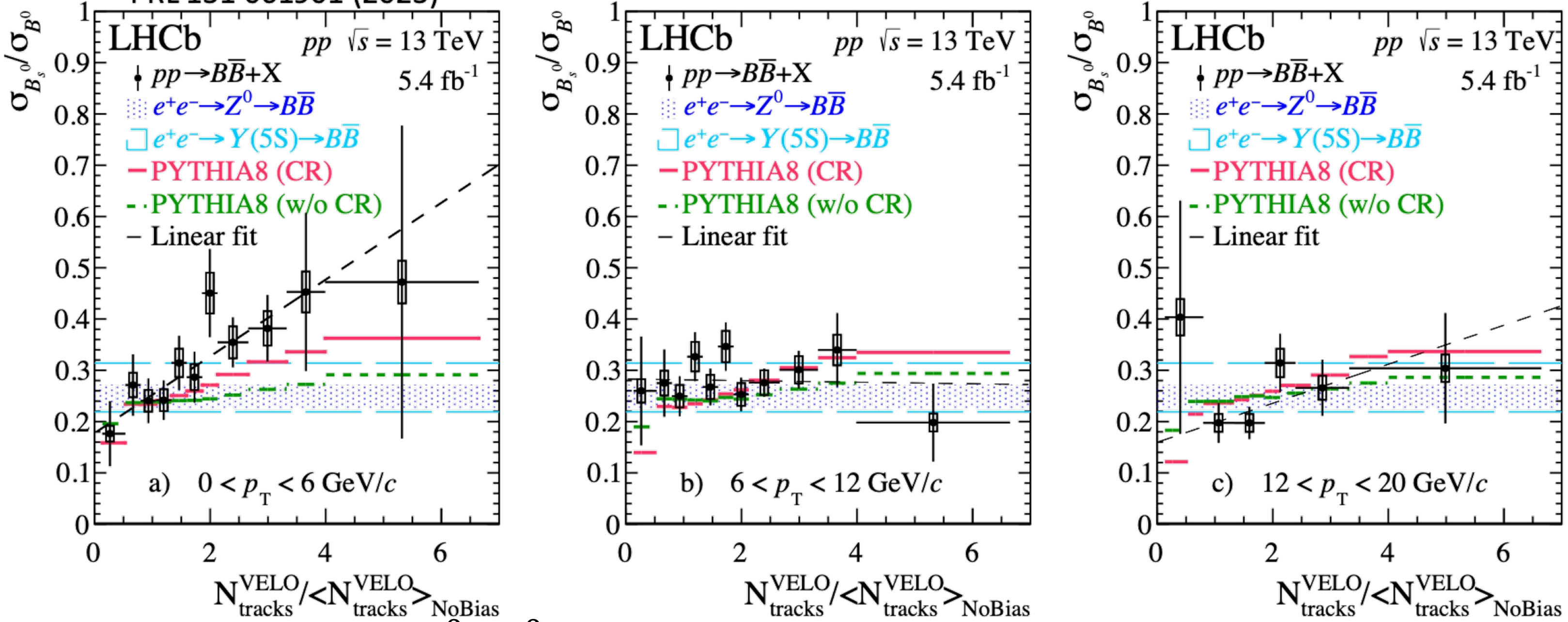


- Evidence for an increase of B_s^0/B^0 at low p_T
- Low multiplicity data consistent with fragmentation in vacuum measured in e^+e^- collisions
- Higher p_T B mesons show no enhancement

Modification of *b* hadronization – PYTHIA8

PRL 131 061901 (2023)



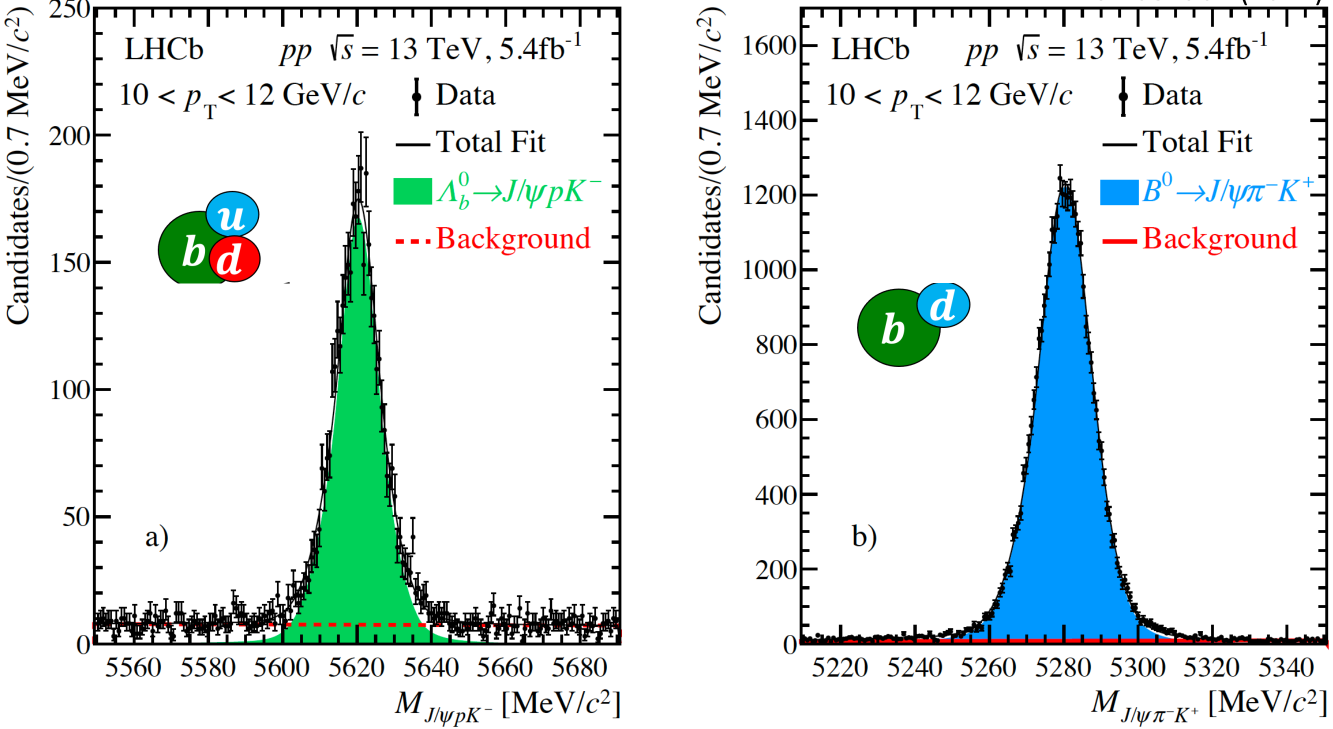


- Evidence for an increase of B_s^0/B^0 at low p_T
- Low multiplicity data consistent with fragmentation in vacuum measured in e^+e^- collisions
- Higher p_T B mesons show no enhancement
- PYTHIA8 w/color reconnection enabled describes high p_T data, undershoots low p_T

Modification of *b* hadronization – B baryons

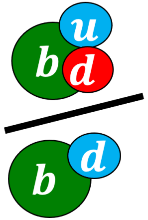
- Coalescence provides a new mechanism for baryon formation - 3 quarks wavefunctions overlap
- Baryon enhancement is therefore a signature of coalescence

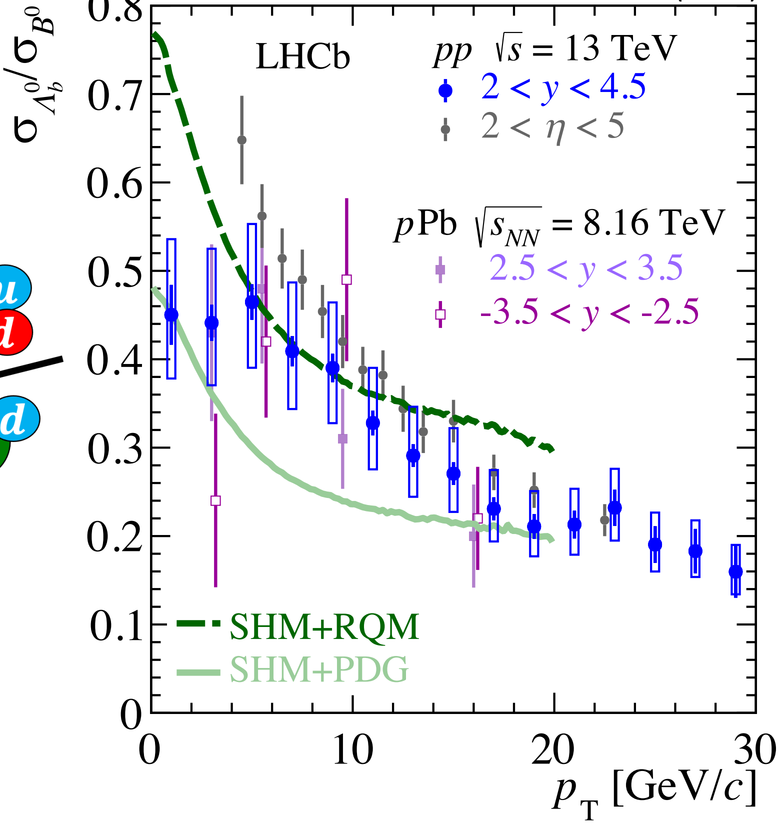
PRL 132 081901 (2024)



Modification of *b* hadronization – B baryons

PRL 132 081901 (2024)





Baryon/meson ratio shows significant p_T dependence

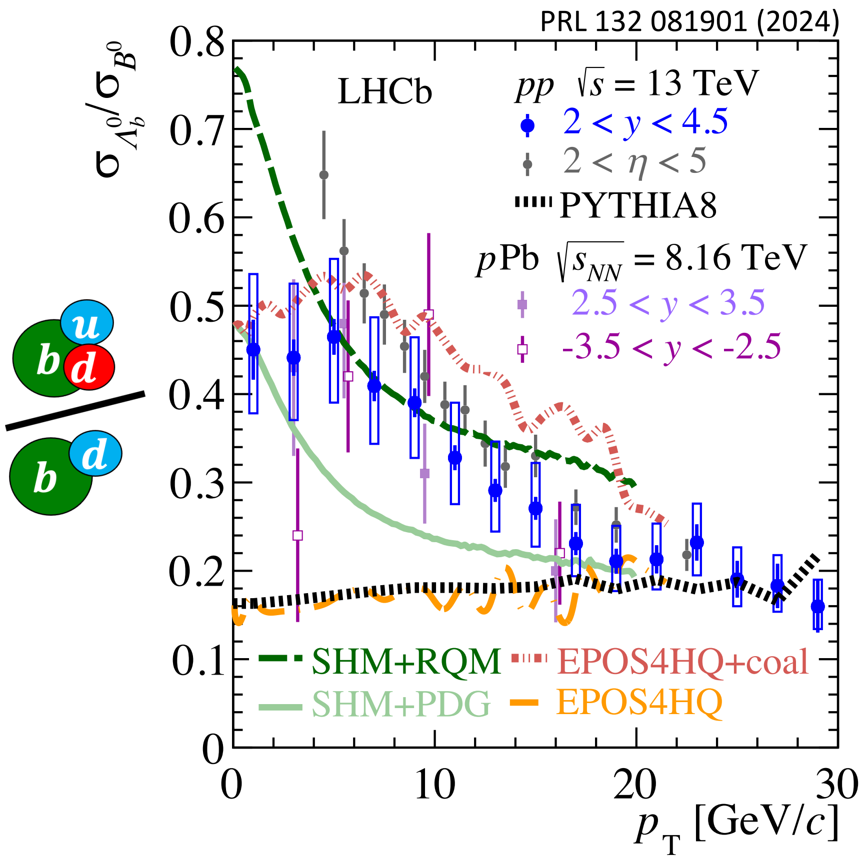
Consistent with previous results (semileptonic decays)

Consistent with pPb results, within large uncertainties

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

Modification of *b* hadronization – B baryons



Baryon/meson ratio shows significant p_T dependence

Consistent with previous results (semileptonic decays)

Consistent with pPb results, within large uncertainties

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

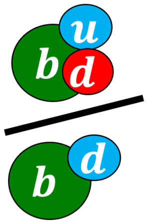
- Known baryon states from PDG
- Expanded set of baryons predicted by the Relativistic Quark Model

PYTHIA8 fails to reproduce p_T dependence

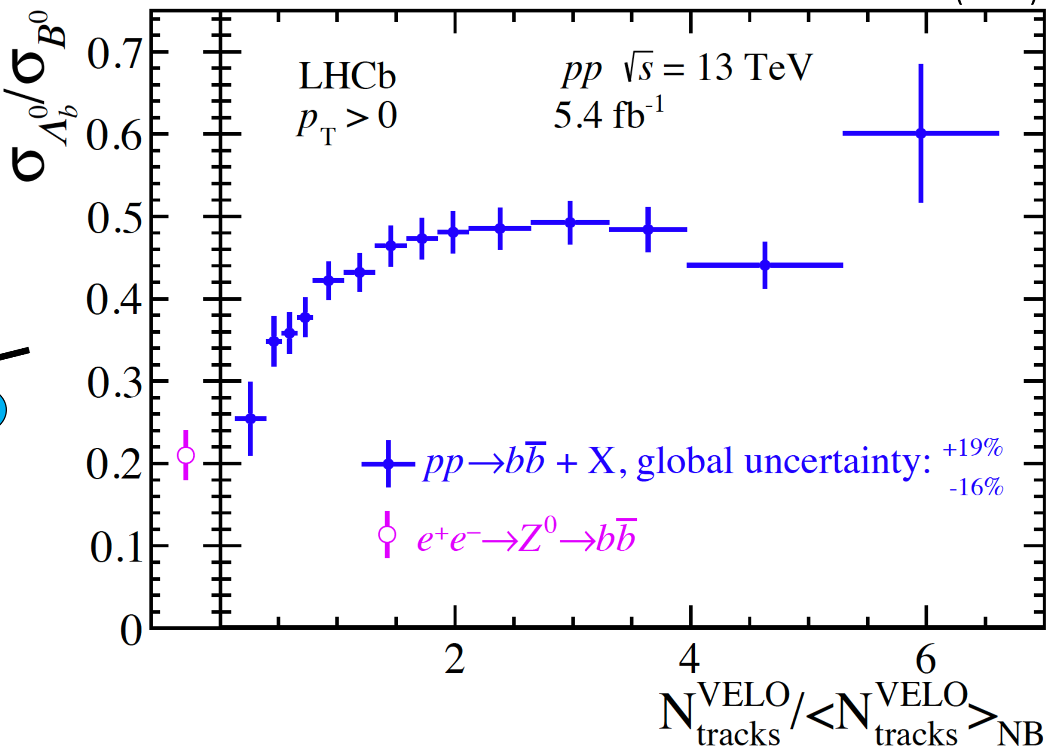
EPOS4HQ with only fragmentation also fails

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

Modification of *b* hadronization – B baryons



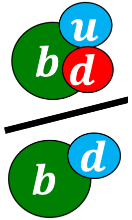
PRL 132 081901 (2024)

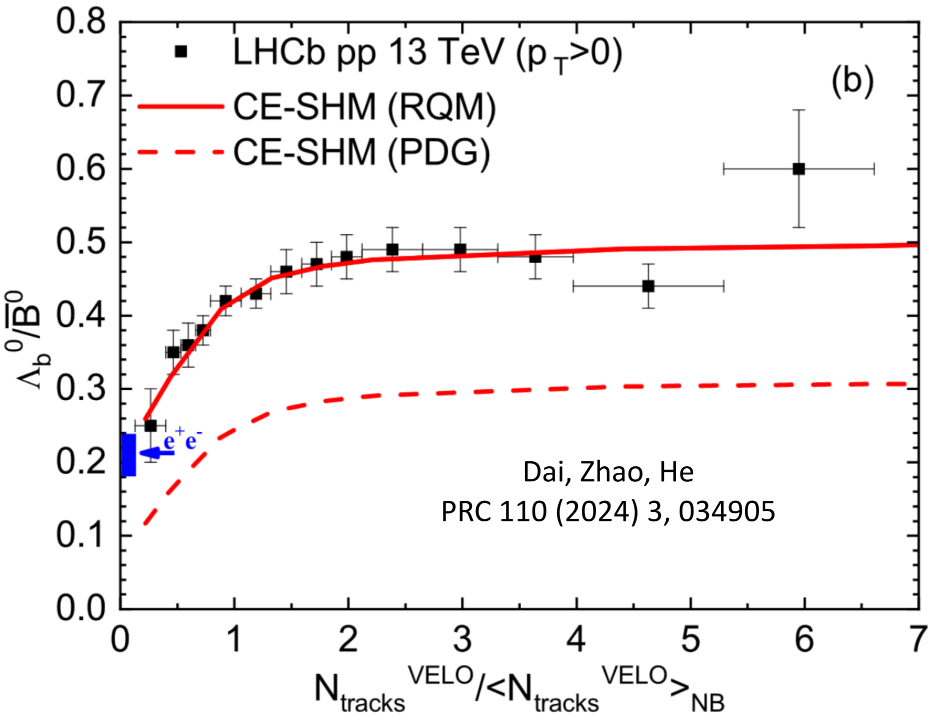


- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

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

Modification of *b* hadronization – B baryons

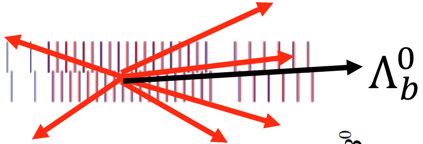




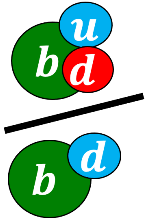
- Baryon/meson ratio shows significant multiplicity dependence
- Increases by a factor of ~2 and plateaus for collisions with >2x average multiplicity
- Reproduce e^+e^- result as multiplicity approaches zero

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

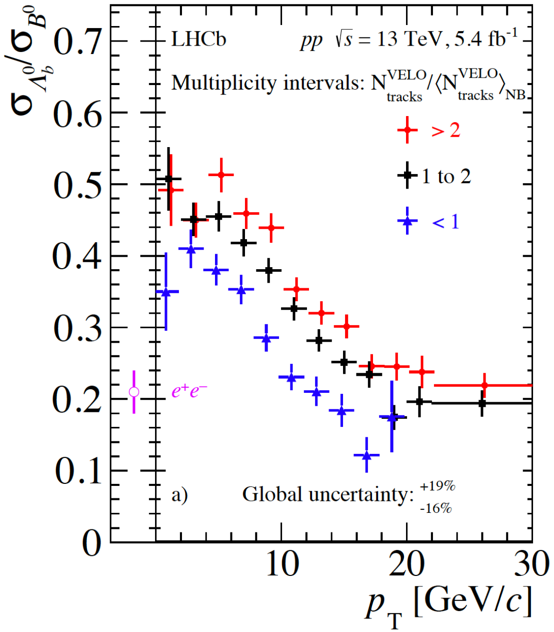
Modification of *b* hadronization – B baryons

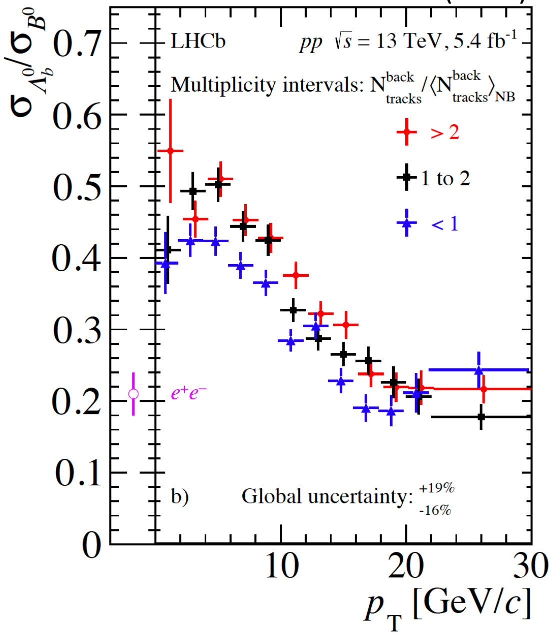


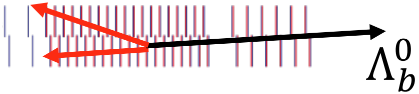
$N^{\mathrm{VELO}}_{\mathrm{tracks}}$



PRL 132 081901 (2024)



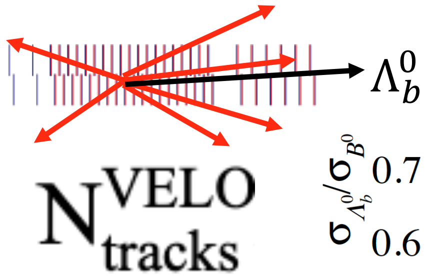


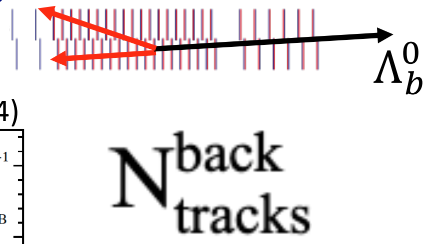


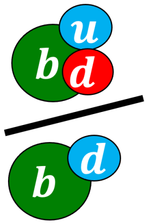
$N^{\mathrm{back}}_{\mathrm{tracks}}$

- Clear multiplicity dependence at relatively low p_T

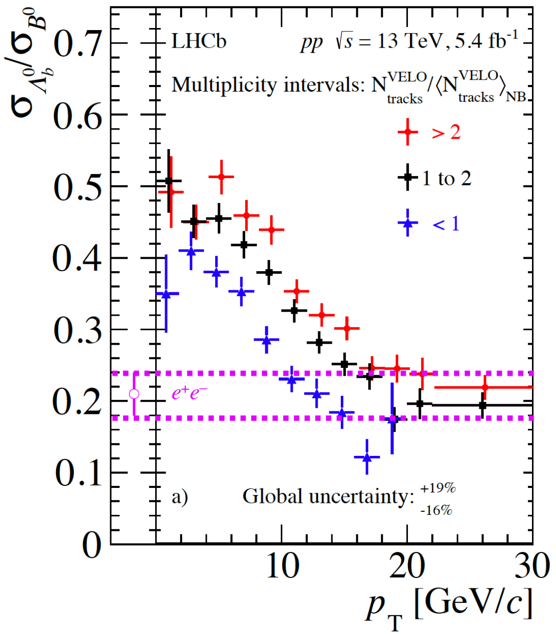
Modification of *b* hadronization – B baryons

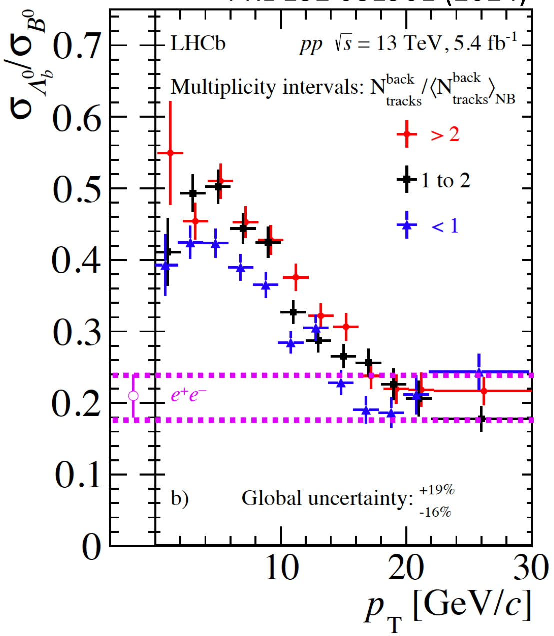






PRL 132 081901 (2024)





- 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

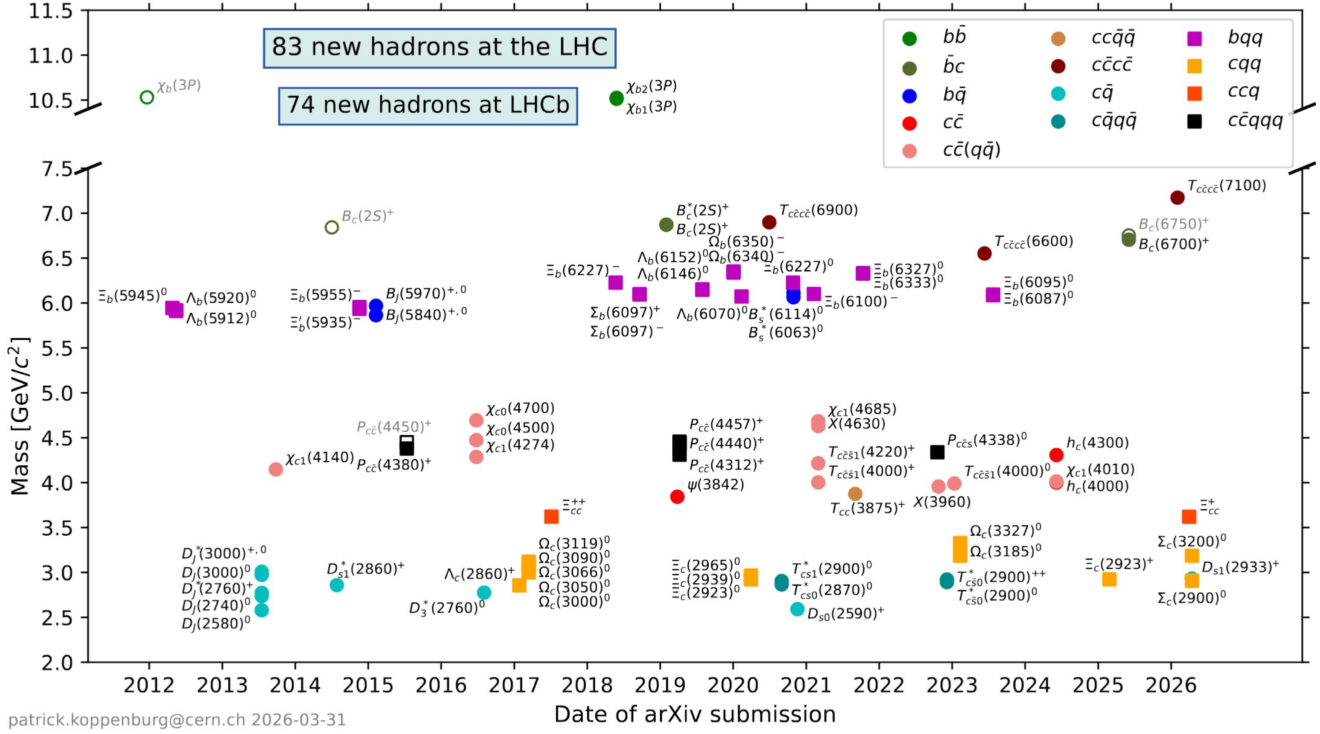
- Hadronization: the bridge between QCD and observable particles
  - In-medium modifications of the hadronization process

- New measurements from LHCb sensitive to hadronization mechanisms
  - Strangeness enhancement in B mesons
  - Λ_b Baryon enhancement in small systems

- Exotic multiquark states in-medium
  - X(3872) in pp and pPb

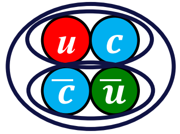
- Future upgrades

New hadrons discovered at LHC

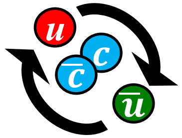


The quark model is rapidly expanding:
study of exotics states largely driven by experiment

Compact tetraquark/pentaquark

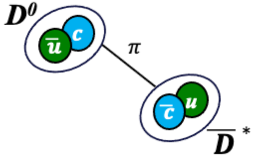


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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

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

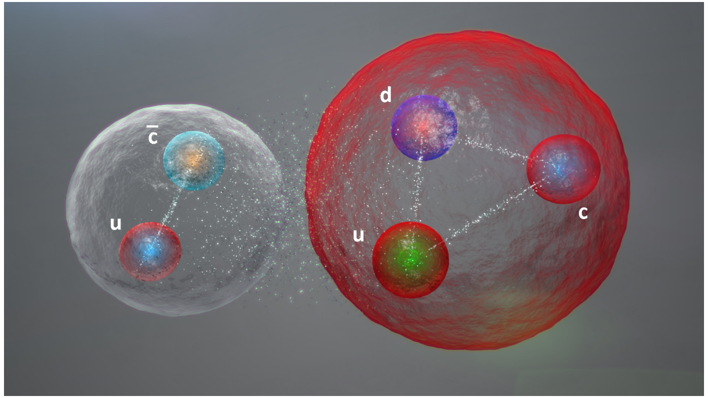
PLB 578 365 (2004)
PRD 96 074014 (2017)

Example: $P_c^{\pm}$ pentaquarks

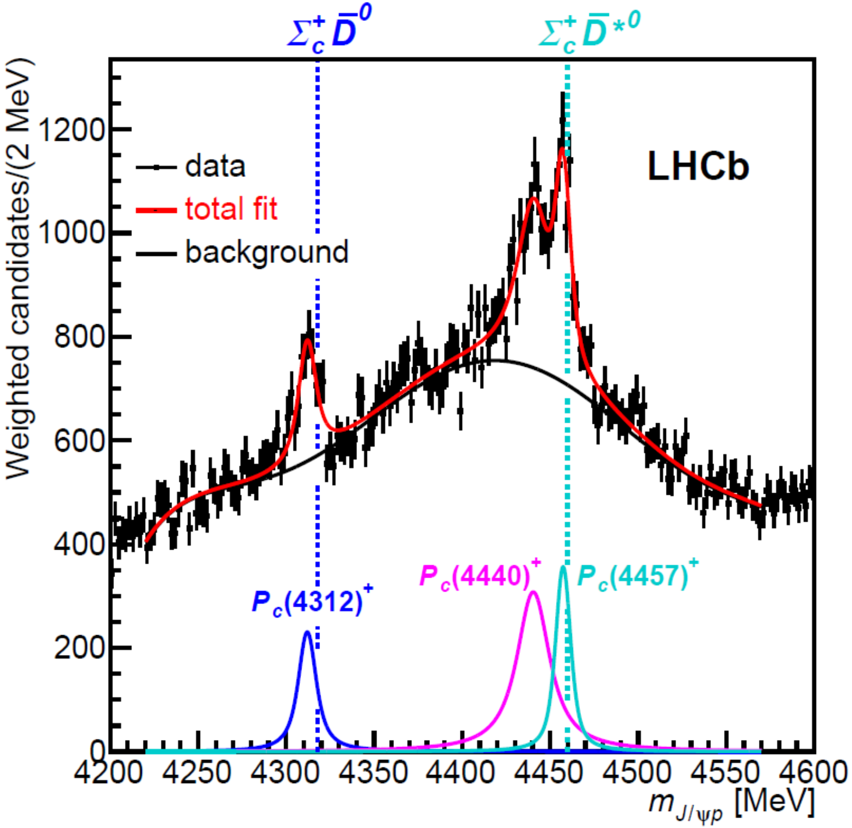
Select daughters from the decay

$$\Lambda_b^0 \rightarrow J/\psi\, p K^-$$

Masses are close to meson+baryon thresholds – candidate hadronic molecule



PRL 122 222001 (2019)



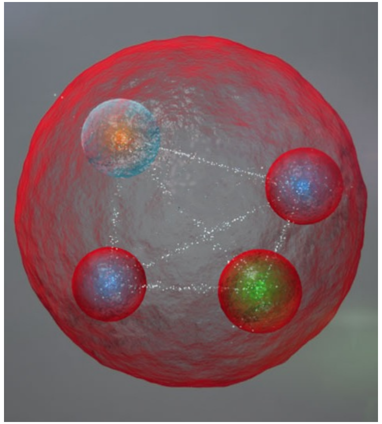
Example: Charged Tetraquark: $Z_c^{\pm}$

Select daughters from the decay

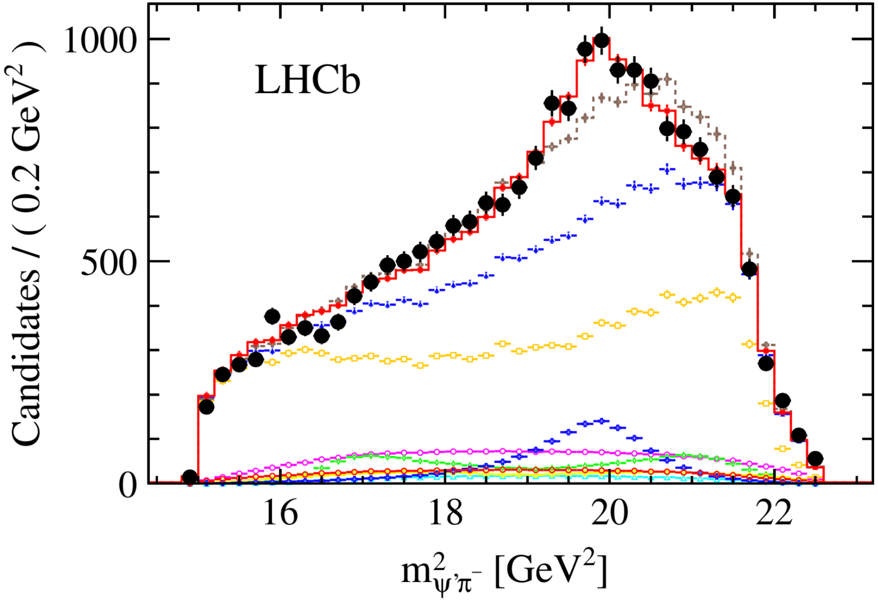
$$B^0 \rightarrow \psi(2S) K^+ \pi^-$$

Charged and contains $c\bar{c}$ pair:
minimal quark content $c\bar{c}q\bar{q}$

Mass not close to hadron+hadron threshold – candidate compact tetraquark

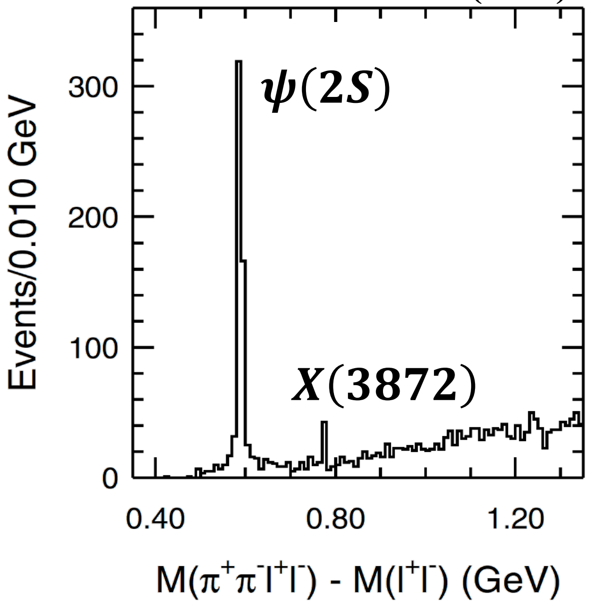


PRL 112 222002 (2014)



An enduring puzzle: X(3872)

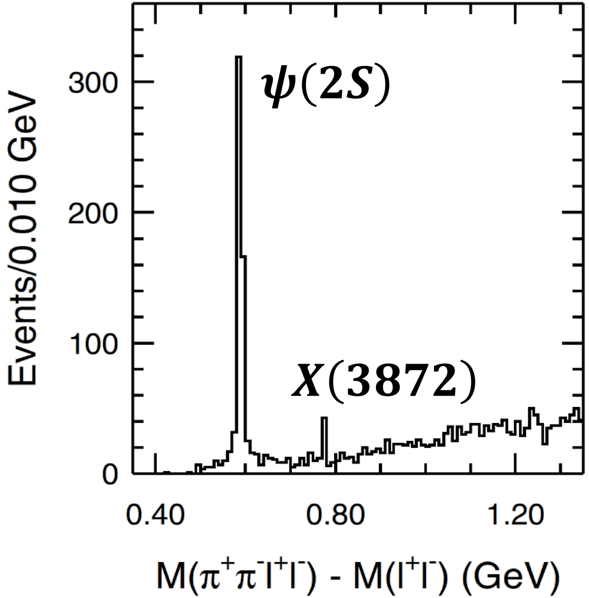
Belle Collaboration
PRL 91 262001 (2003)



- The first exotic hadron, discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003

An enduring puzzle: X(3872)

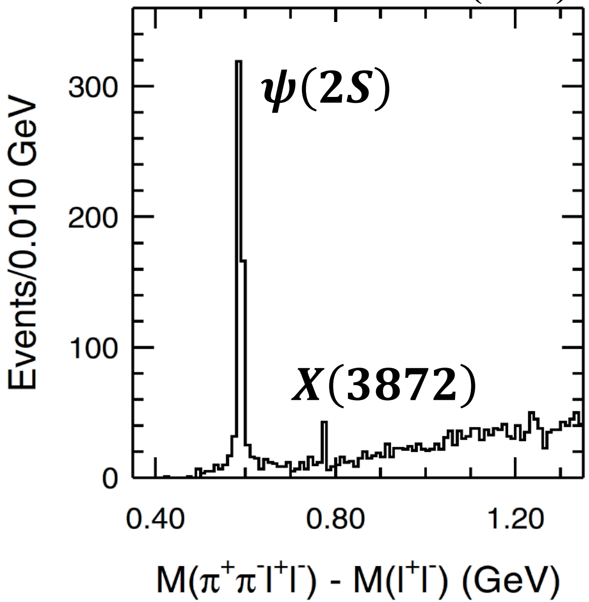
Belle Collaboration
PRL 91 262001 (2003)



- 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

An enduring puzzle: X(3872)

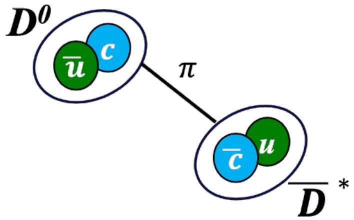
Belle Collaboration
PRL 91 262001 (2003)



- 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:

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

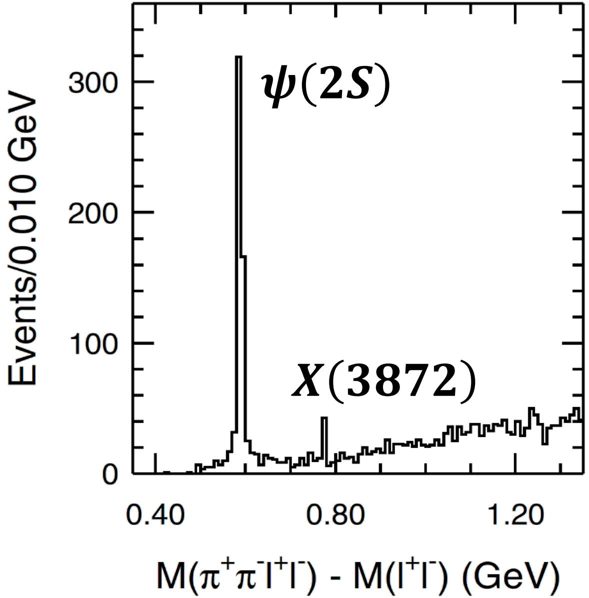
$D^0\overline{D}^*$ ***Molecule***



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

An enduring puzzle: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



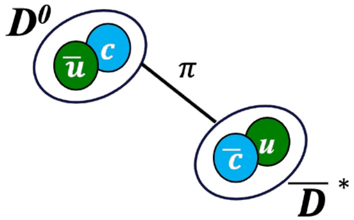
*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

- 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:

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

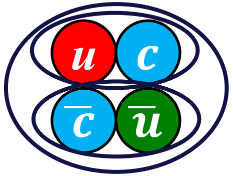
- Large prompt production fraction (~80%) – potentially inconsistent with D meson coalescence in pp*

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



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

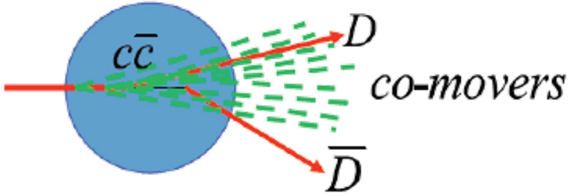
Compact tetraquark



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

Quarkonia in the QCD medium

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of ${}^{\psi(2S)}/_{J/\psi}$ and ${}^{\Upsilon(2S,3S)}/_{\Upsilon(1S)}$
- In general, final state effects are required to explain difference in suppression between states
- Prevalent in regions with high particle multiplicity
- Weakly bound hadronic molecules may show similar effects.

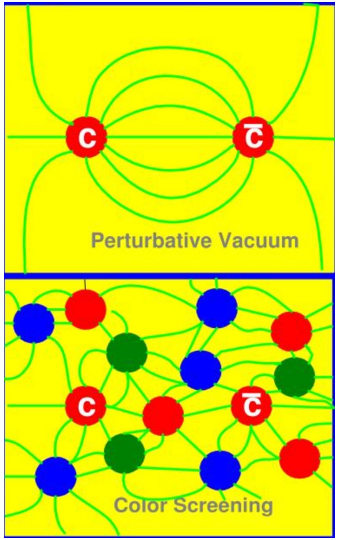


cf. PLB 749 98 (2015)

$D\bar{D}^*$ ***Molecule***

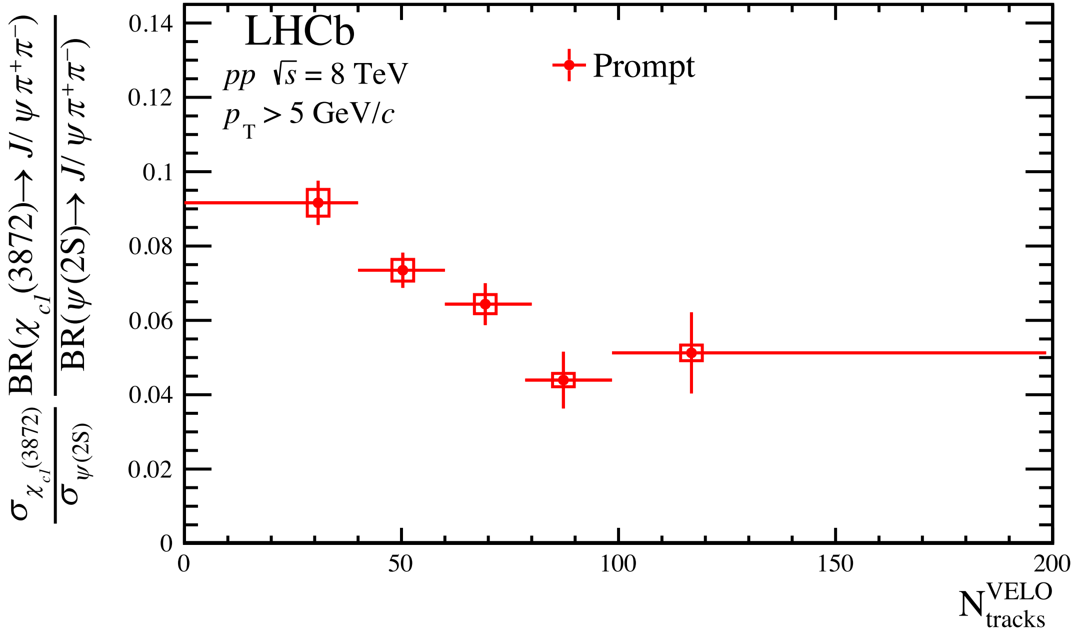
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

Satz, J. Phys. G 32 (3) 2006



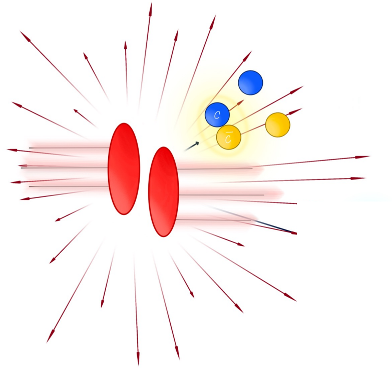
X(3872)/ψ(2S) vs multiplicity

PRL 126, 092001 (2021)

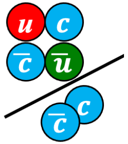


Prompt component:

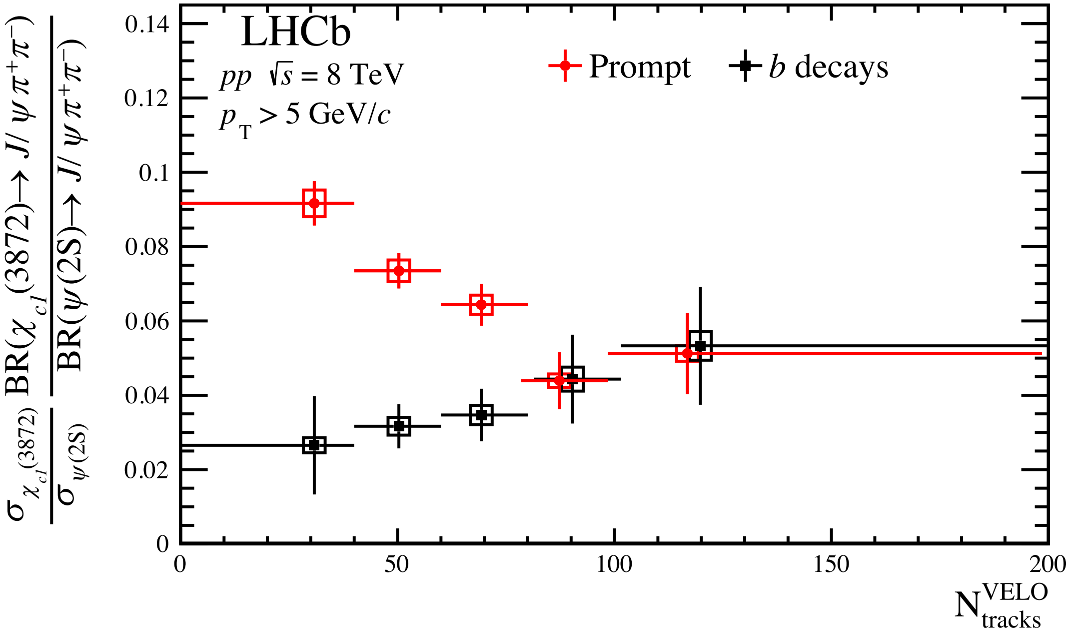
Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases



X(3872)/ψ(2S)



PRL 126, 092001 (2021)

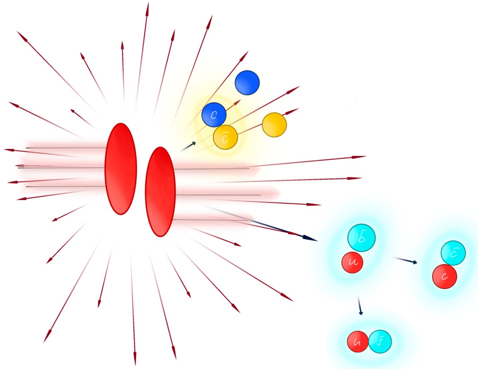


Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

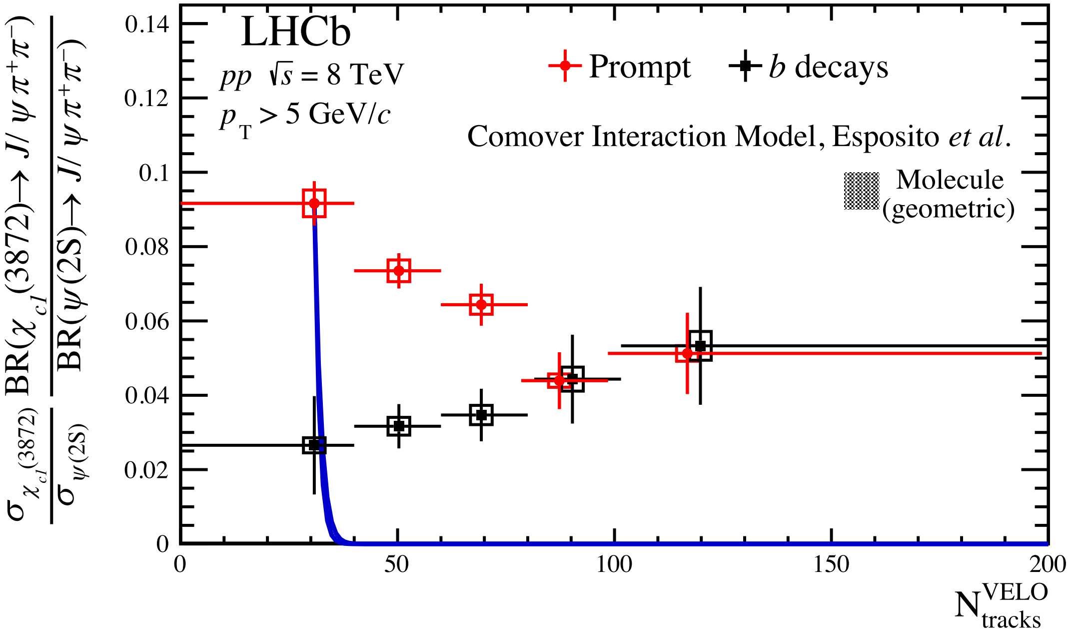
b-decay component:

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.



X(3872)/ψ(2S)

PRL 126, 092001 (2021)



Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

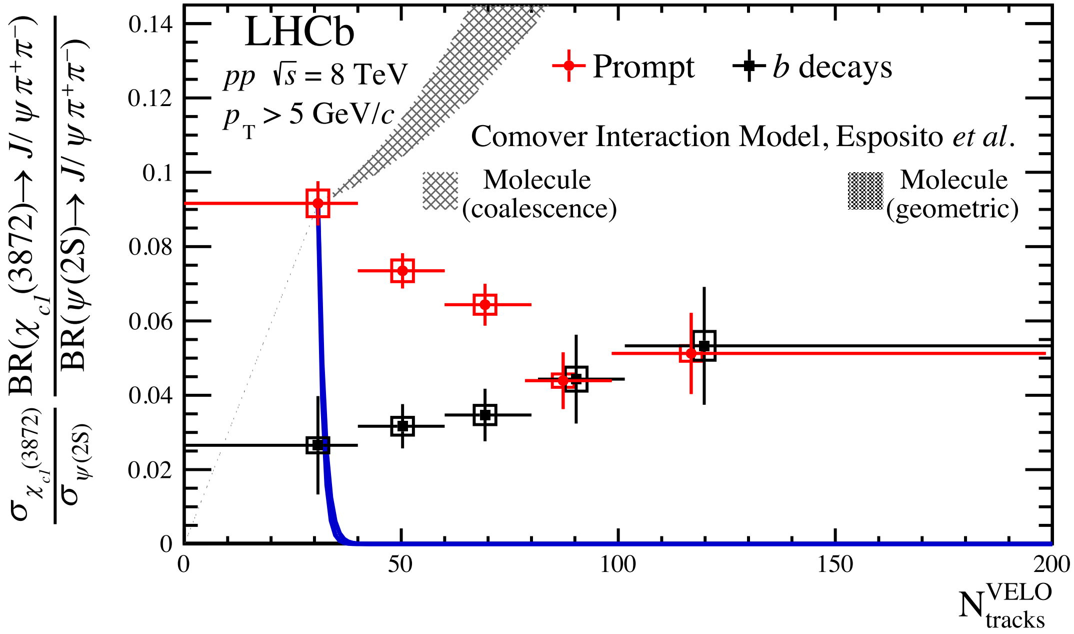
Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

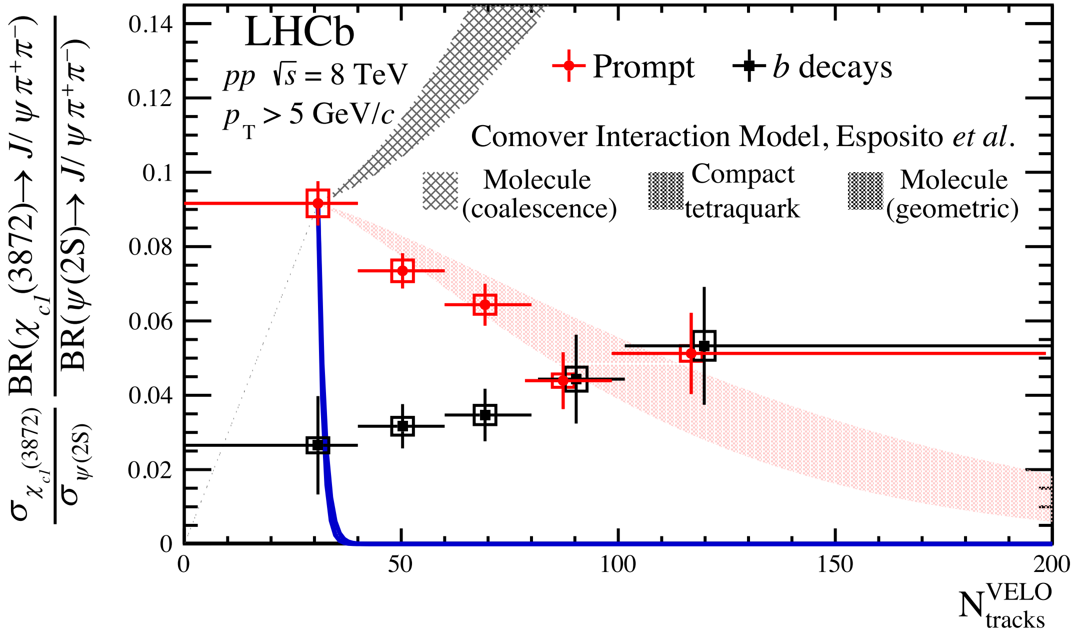
$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Coalescence of D mesons into molecular X(3872) increases ratio

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

$\boldsymbol{b}$-decay component:

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by $\boldsymbol{b}$ decay branching ratios.

Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma \rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c} \right)^n \right\rangle$$

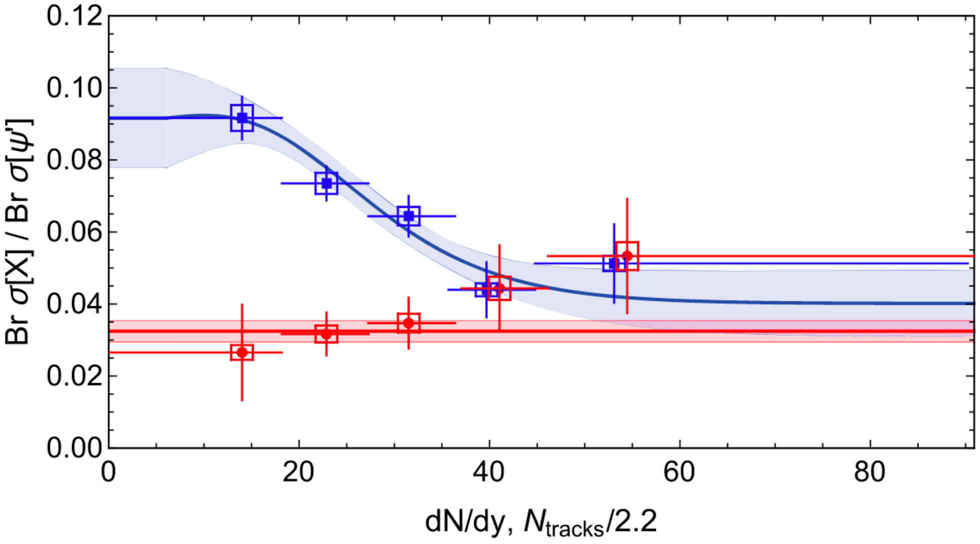
Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Coalescence of D mesons into molecular X(3872) increases ratio

Compact tetraquark of size 1.3 fm gradually dissociated as multiplicity increases – consistent with data

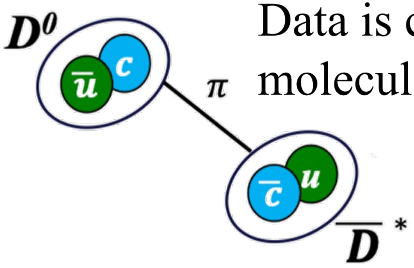
Comover model: constituent interaction

Different method of calculating breakup cross section:
Braaten, He Ingles, Jiang Phys. Rev. D 103, 071901 (2021)



Breakup cross section approximated as sum of cross section for molecule constituents:

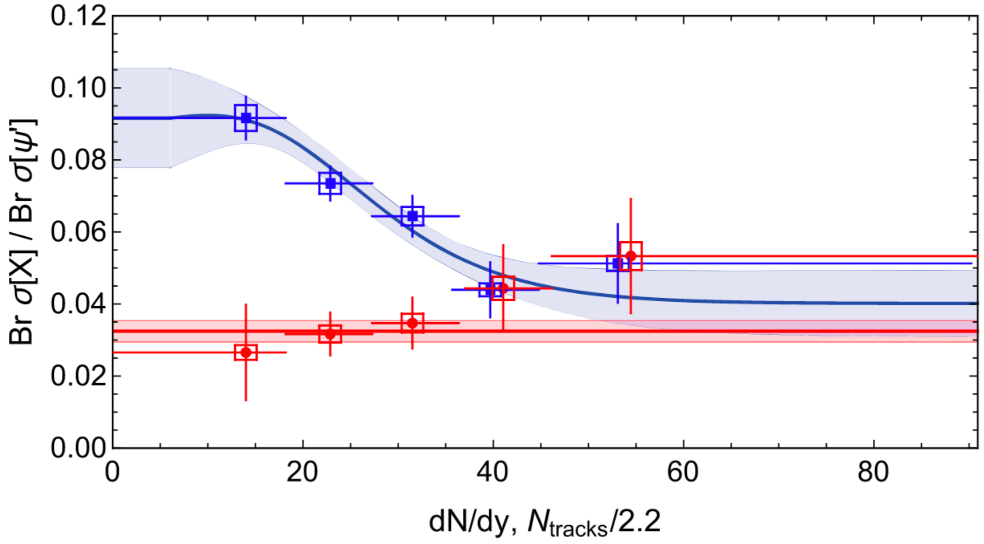
$$\sigma^{\text{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$



Data is consistent with this molecular interpretation.

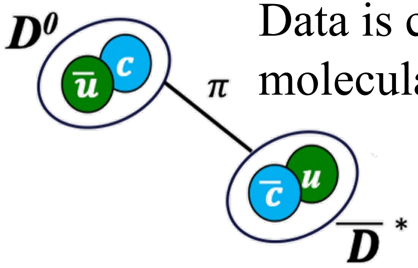
Comover model: constituent interaction

Different method of calculating breakup cross section:
Braaten, He Ingles, Jiang Phys. Rev. D 103, 071901 (2021)



Breakup cross section approximated as sum of cross section for molecule constituents:

$$\sigma^{\text{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$

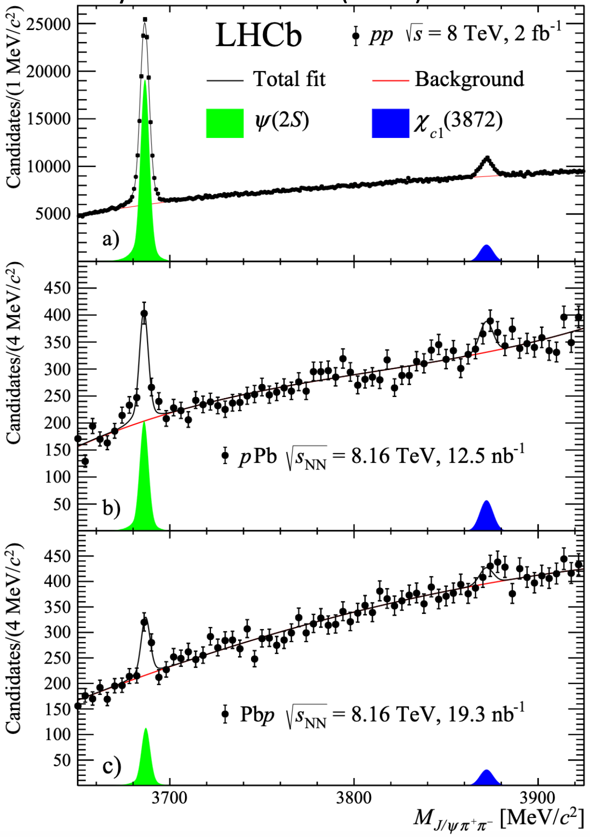


Data is consistent with this molecular interpretation.

If breakup is due to scattering of individual constituents, would all $c\bar{c}$ have equal suppression? Not observed in charmonium or bottomonium systems.

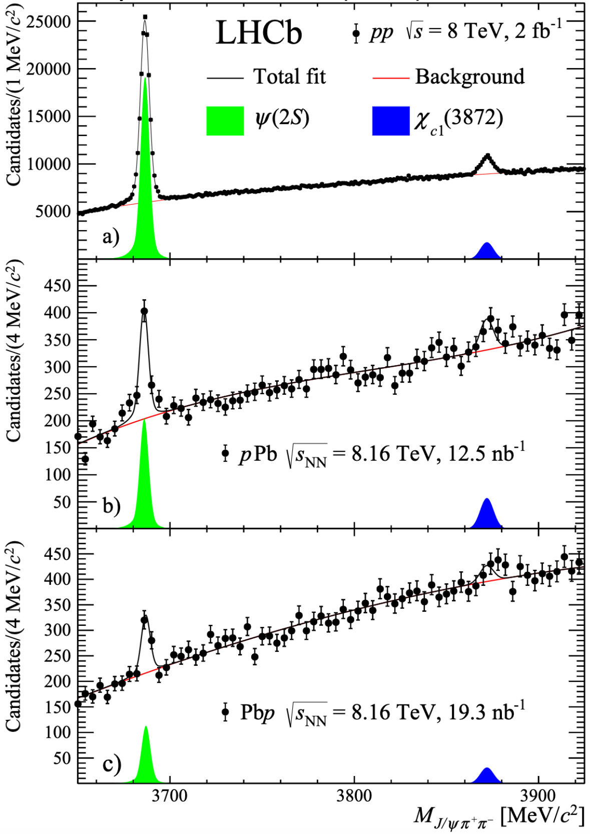
X(3872) in *p*Pb

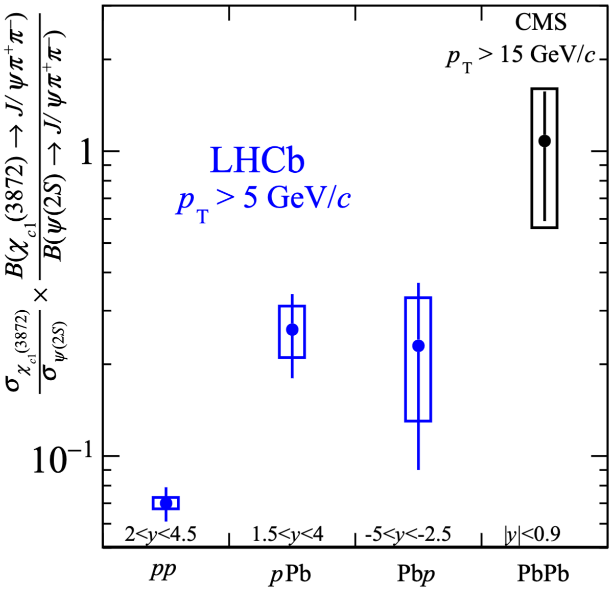
Phys. Rev. Lett. 132 (2024) 242301



X(3872) in *p*Pb

Phys. Rev. Lett. 132 (2024) 242301





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

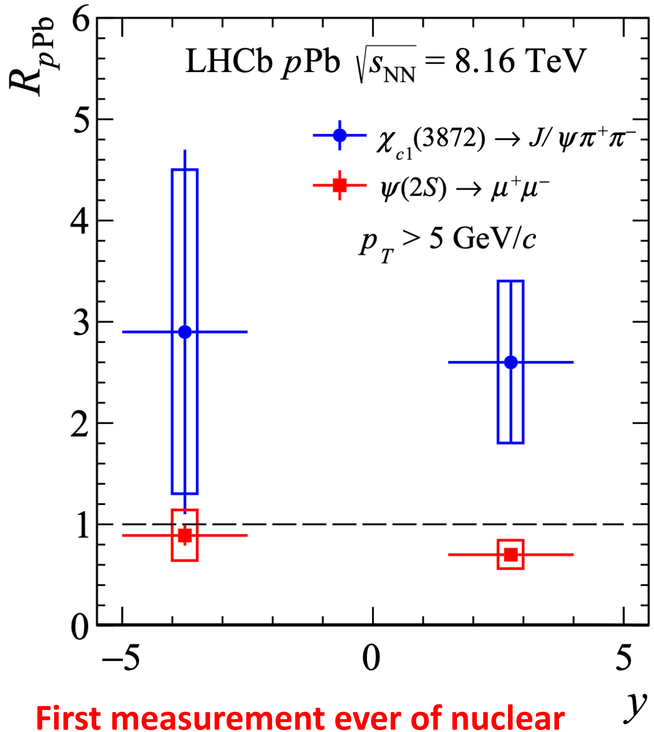
Prompt X(3872)/ ψ(2S) = 0.23 ± 0.15 ± 0.10 in backward pPb

Falls between pp (~0.1) and PbPb (~1.0)

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

X(3872) in *p*Pb

Phys. Rev. Lett. 132 (2024) 242301



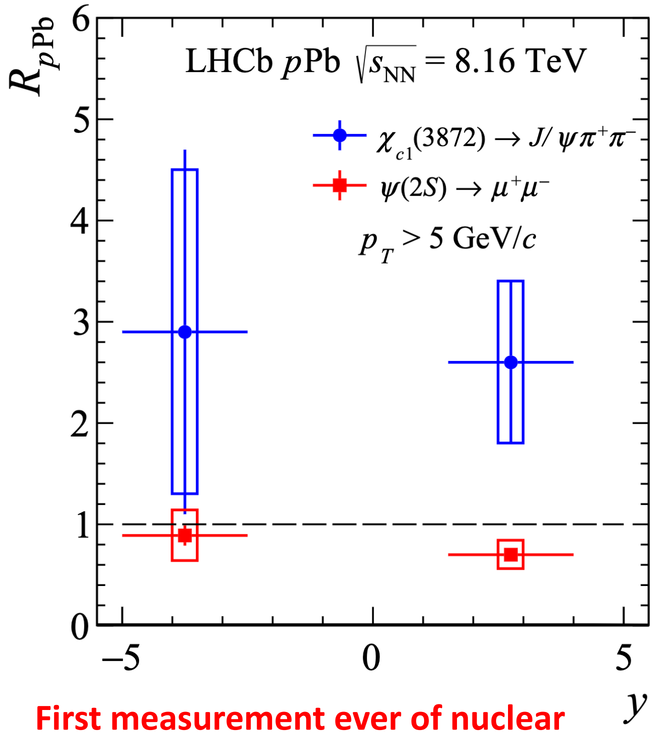
First measurement ever of nuclear modification factor of a tetraquark!

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

Phys. Rev. Lett. 132 (2024) 242301



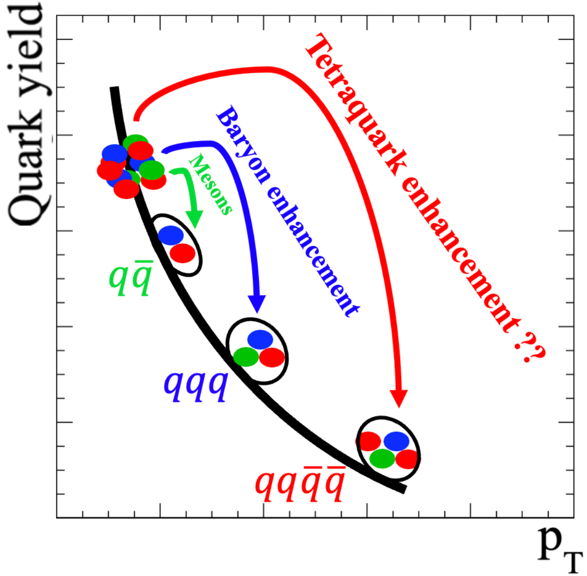
First measurement ever of nuclear modification factor of a tetraquark!

Ambiguity lifted by measuring nuclear modification factors:

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

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

Similar mechanism for baryon enhancement could also increase tetraquark production

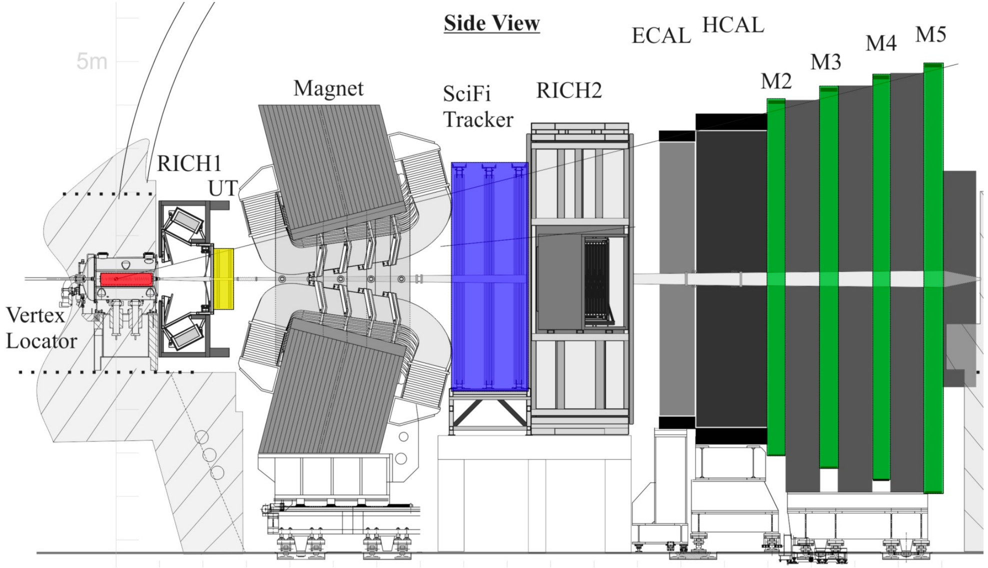


Outline

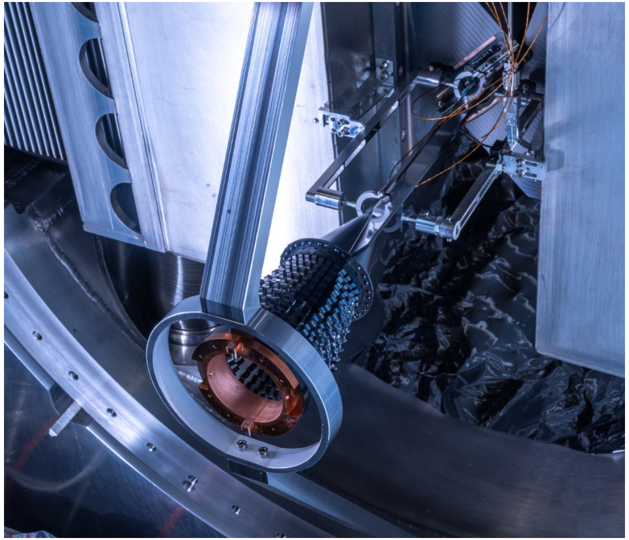
- Hadronization: the link between QCD and observable particles
  - In-medium modifications of the hadronization process
- New measurements from LHCb sensitive to hadronization mechanisms
  - Strangeness enhancement in B mesons
  - Λ_b Baryon enhancement in small systems
- Exotic multiquark states in-medium
  - X(3872) in pp and pPb
- Future plans

LHCb Upgrade 1(a) – Installed

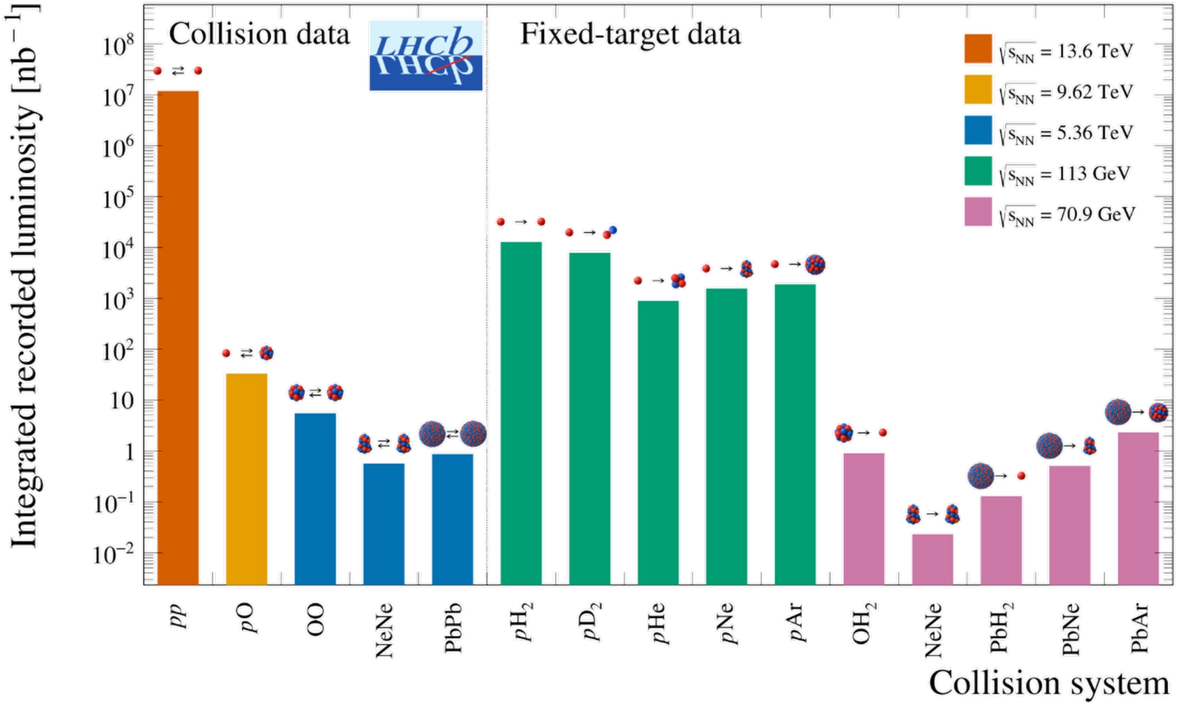
- LHCb has **advanced the state of the art** with full streaming readout in *pp* at 40MHz
- All new tracking system allows reconstruction up to ~30% most central PbPb collisions



- Dedicated gas storage cell has been installed in front of LHCb VELO
- Allows greatly increased rates of beam+gas collisions

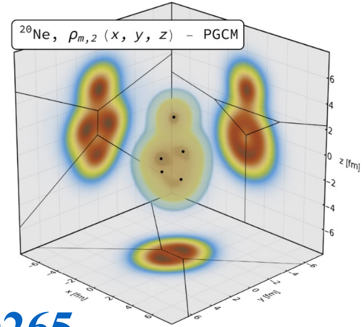


15 new data sets recorded by LHCb in 2025



New data sets all LHCb to probe:

- QCD at highest energies
- CNM and QGP at high temperatures
- (De)confinement at small energy densities
- Totally unique geometries



LHCb is the most versatile heavy ion experiment ever fielded

It sure would be nice to have fixed target at the EIC! [arXiv:2603.00265]

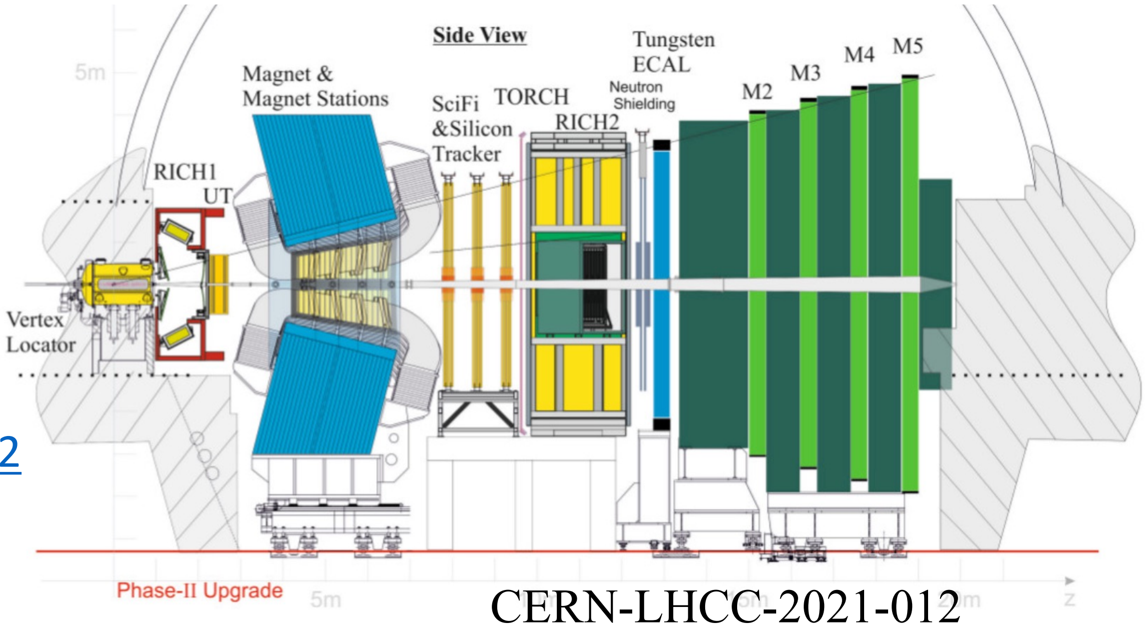
LHCb Upgrade II (Run 5+)

Further upgraded tracking to deal with high *pp* pileup and heavy ion collisions

- Access the full PbPb centrality range
- Precise measurements of B hadrons, exotic states, and more at low p_T in central collisions
- R&D well underway

Discussions beginning for a new era of fixed target physics: Spin polarized target?

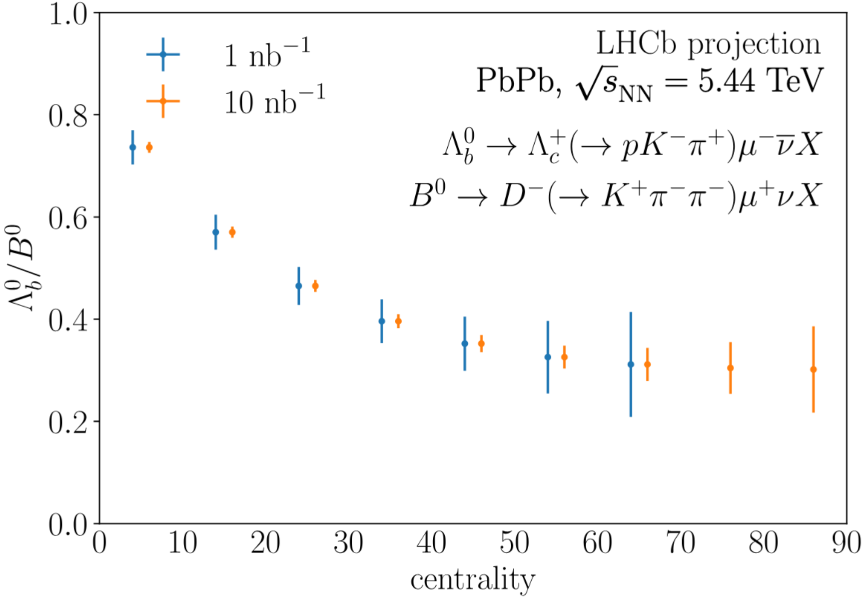
arXiv:1901.08002

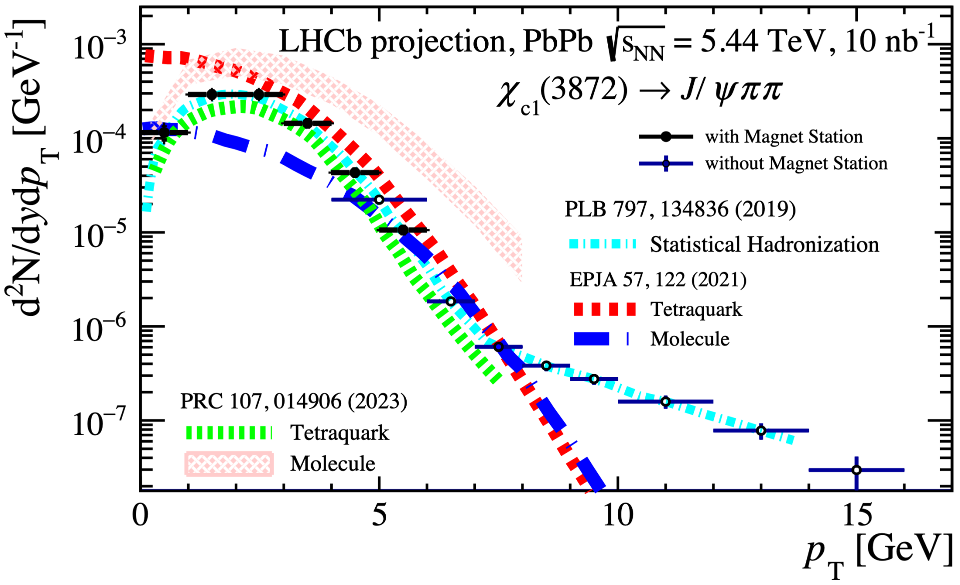


CERN-LHCC-2021-012

Run 5 Projections

arXiv:2503.23093





- Precision access to bottom baryons and mesons in central PbPb collisions

- Measurements of exotic X(3872) at low p_T in PbPb collisions (w/MS)
- Clear discrimination between models

Summary

- **Heavy quarks are extremely versatile for probing non-perturbative QCD**
- The evolution of quarks into observable matter is influenced by the density of other particles produced in the event – clear indications of new hadronization mechanisms that are important for baryon formation.
- QCD creates a rich spectrum of bound states - our knowledge of the allowed configuration of quarks inside hadrons is rapidly growing
- New capabilities from upgrades will expand our reach into QCD

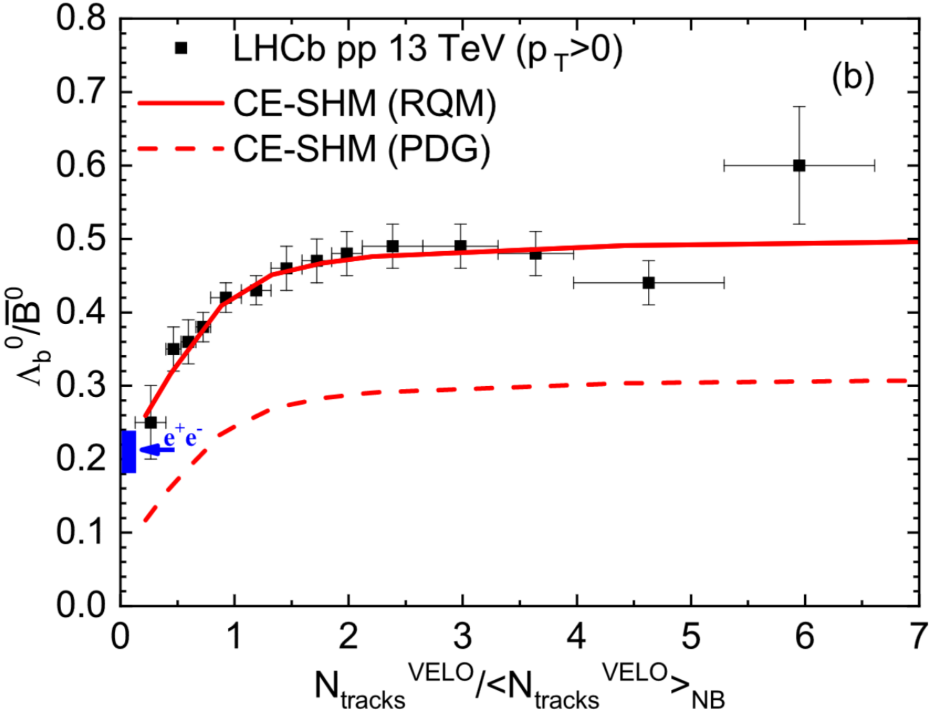
Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics

and DOE Early Career Awards program

BACKUPS

SHM

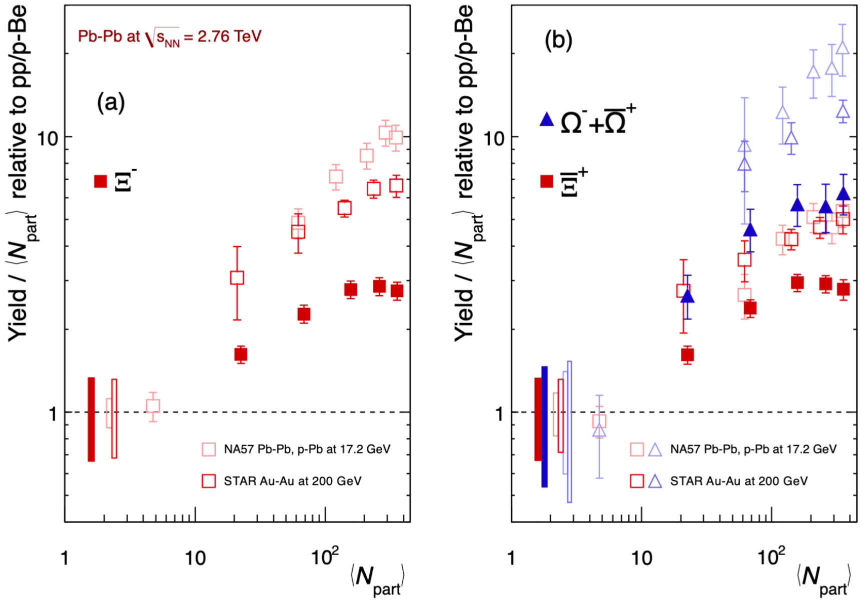
https://arxiv.org/pdf/2402.03692.pdf



Hadronization in heavy ion collisions

In a deconfined plasma, strange quark production is dramatically enhanced

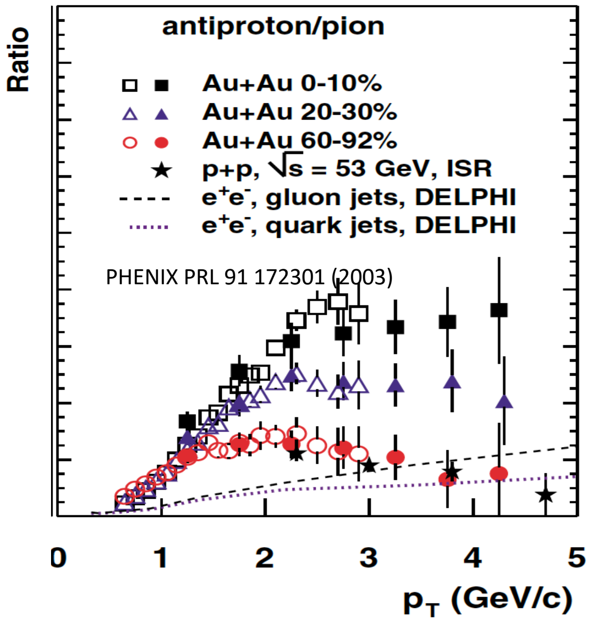
- $T_c \approx 190\ MeV \approx 2m_s$ strange quark pairs can be produced through fusion of thermalized gluons



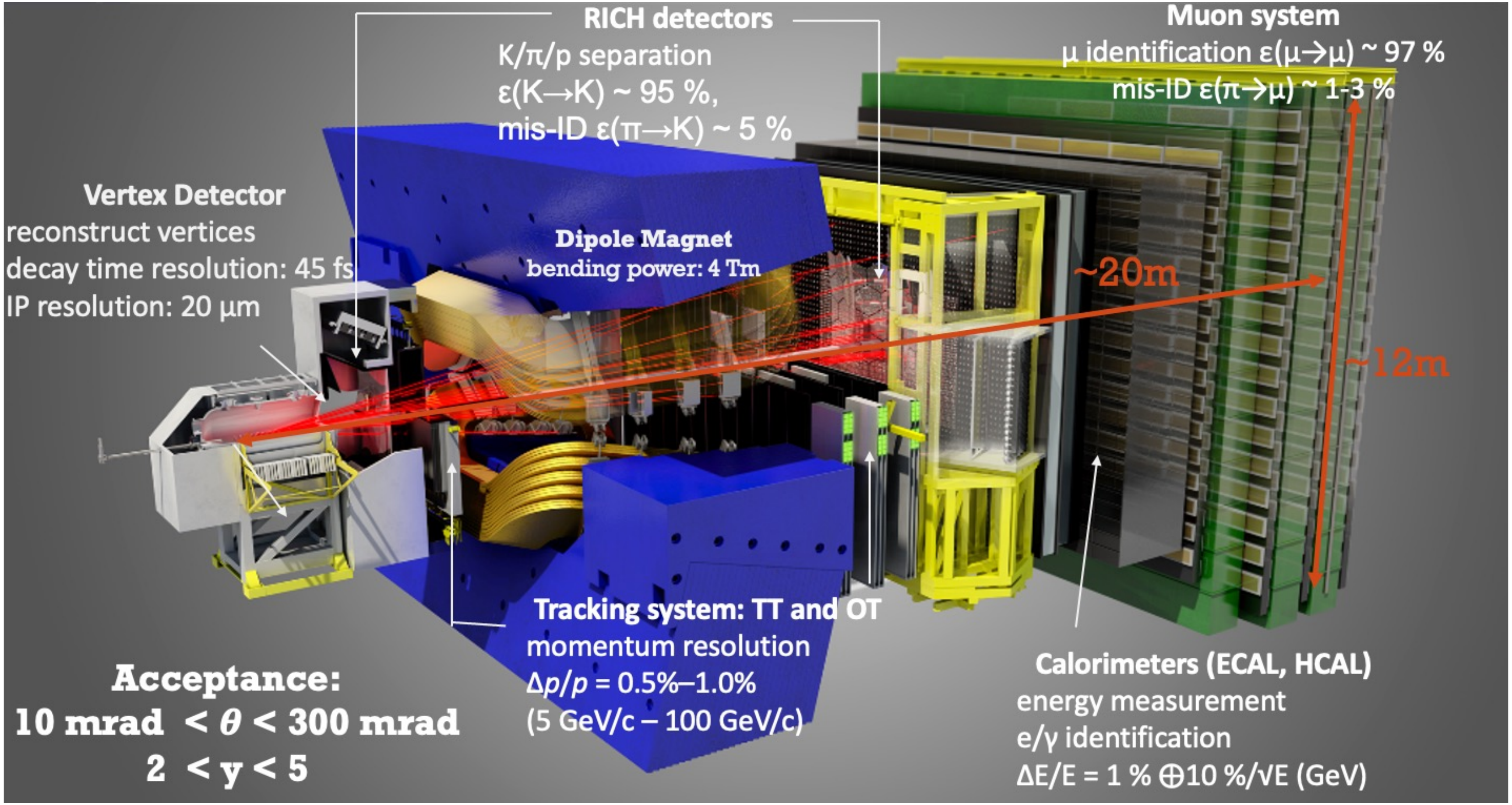
"strangeness enhancement"

Overall baryon production also enhanced

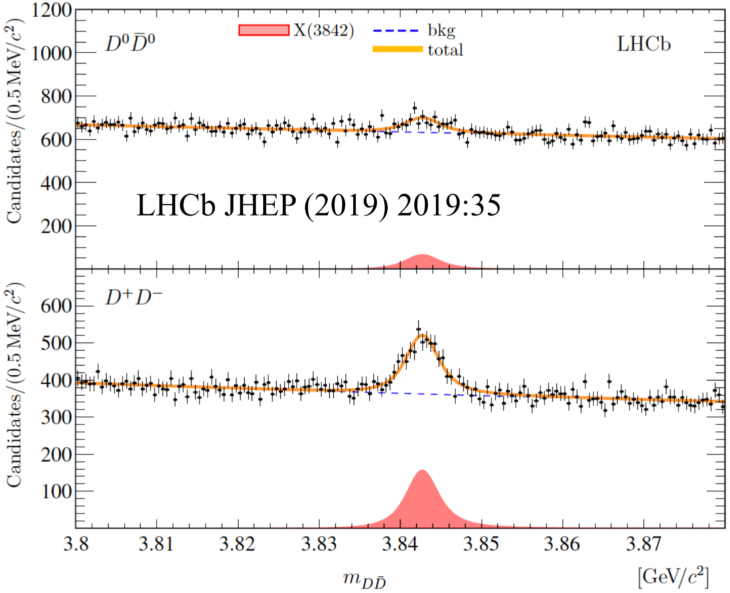
- Models generally require



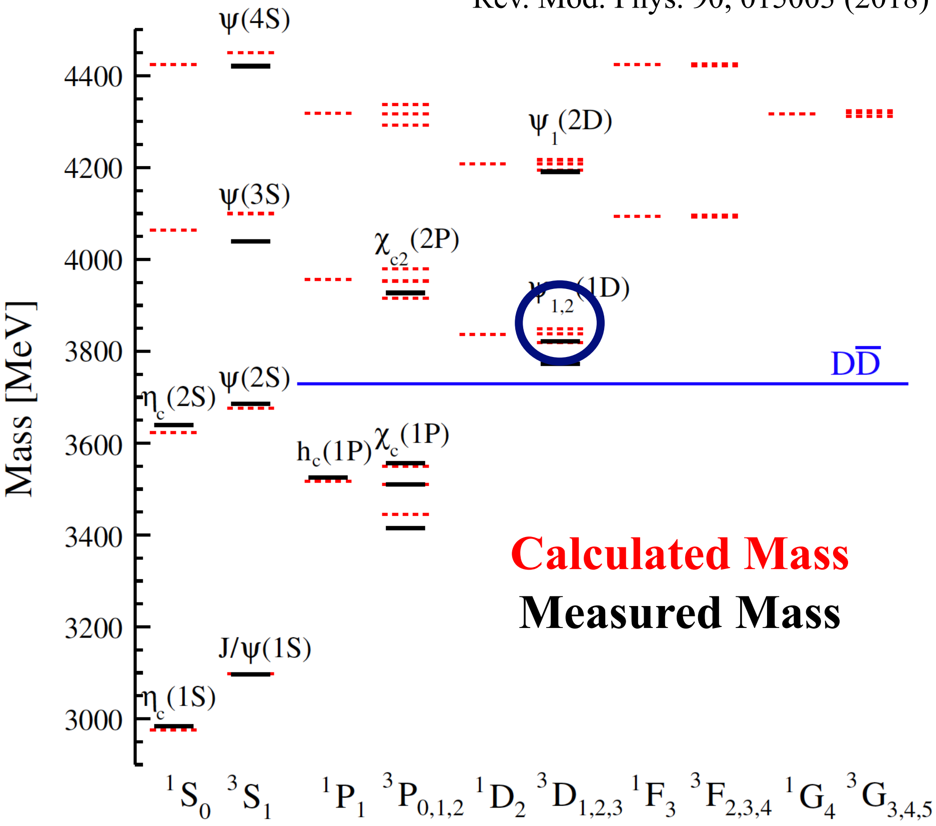
"baryon enhancement"


RICH detectors
K/π/p separation
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %
Muon system
μ identification ε(μ→μ) ~ 97 %
mis-ID ε(π→μ) ~ 1-3 %
Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
IP resolution: 20 μm
Dipole Magnet
bending power: 4 Tm
~20m
~12m
Tracking system: TT and OT
momentum resolution
Δp/p = 0.5%–1.0%
(5 GeV/c – 100 GeV/c)
Calorimeters (ECAL, HCAL)
energy measurement
e/γ identification
ΔE/E = 1 % ⊕10 %/√E (GeV)
Acceptance:
10 mrad < θ < 300 mrad
2 < y < 5

Quarkonia – bound states of heavy quarks



Rev. Mod. Phys. 90, 015003 (2018)



The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: 3842.71 ± 0.16 ± 0.12 MeV
Predicted mass: 3849 MeV

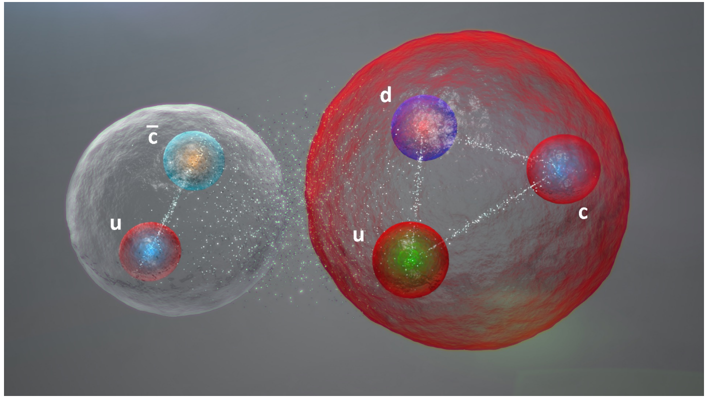
Incredibly rich structure, accessible theoretically and experimentally

Example: $P_c^{\pm}$ pentaquarks

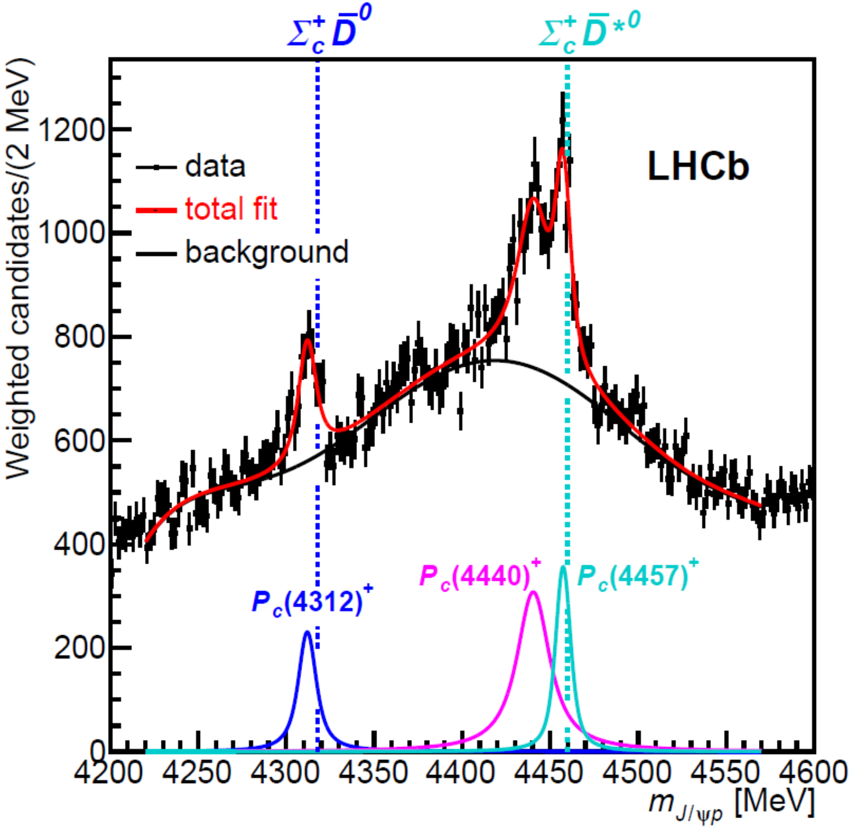
Select daughters from the decay

$$\Lambda_b^0 \rightarrow J/\psi\, p K^-$$

Masses are close to meson+baryon thresholds – candidate hadronic molecule



PRL 122 222001 (2019)



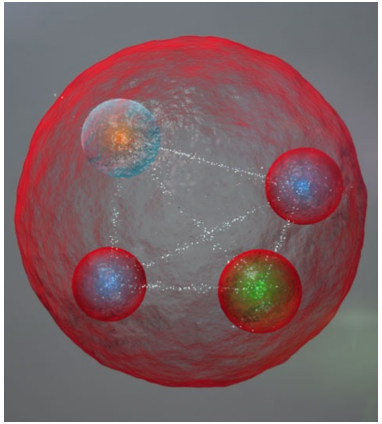
Example: Charged Tetraquark: $Z_c^{\pm}$

Select daughters from the decay

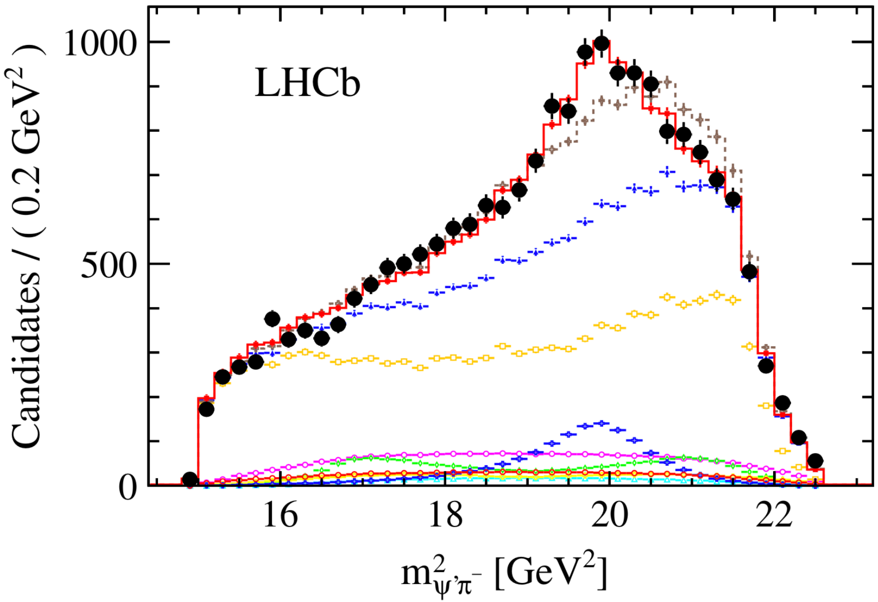
$$B^0 \rightarrow \psi(2S) K^+ \pi^-$$

Charged and contains $c\bar{c}$ pair: minimal quark content $c\bar{c}q\bar{q}$

Mass not close to hadron+hadron threshold – candidate compact tetraquark

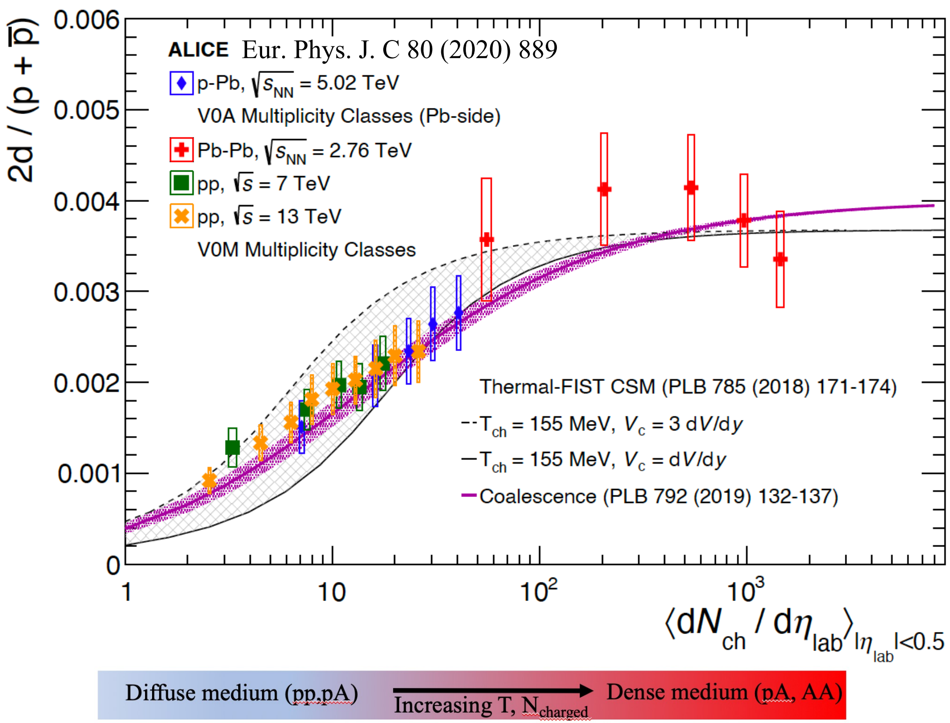


PRL 112 222002 (2014)

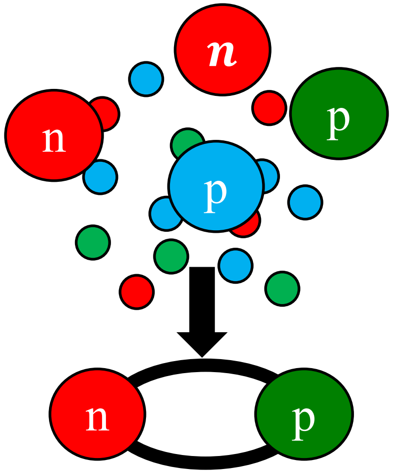


Deuteron production in the QCD medium

Deuteron: weakly bound state of neutron and proton, $E_b \approx 2\ MeV$



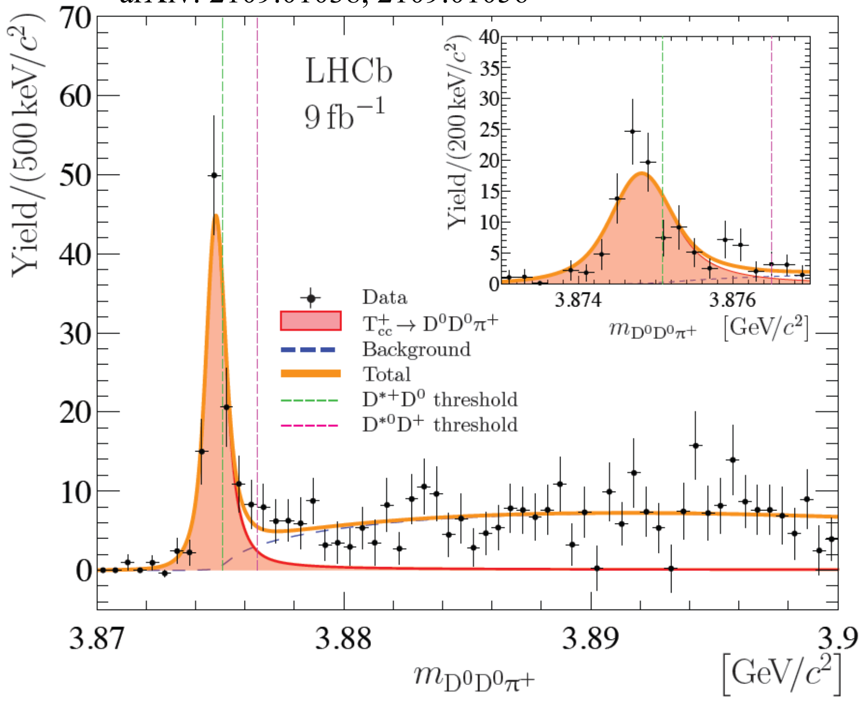
Production relative to protons increases with system density:



Well described by coalescence models.

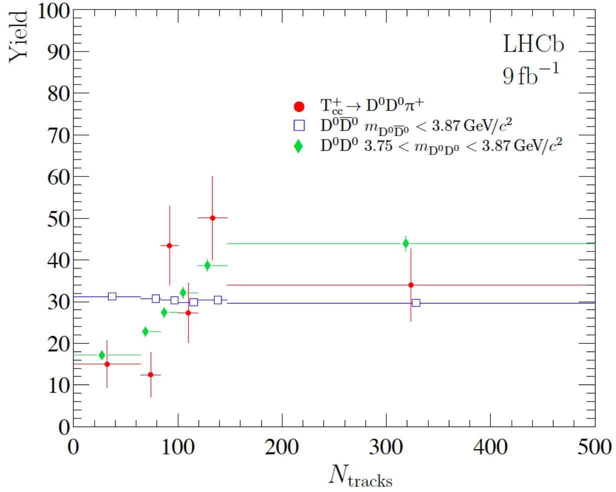
Newest LHCb exotic: T_{cc}^{+}

arXiv: 2109.01038, 2109.01056



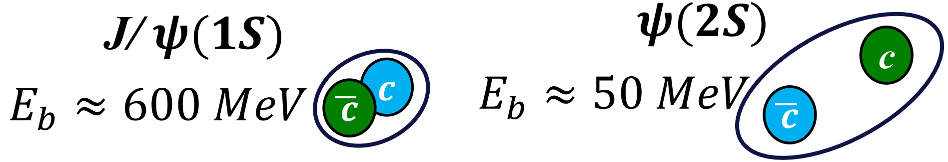
New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

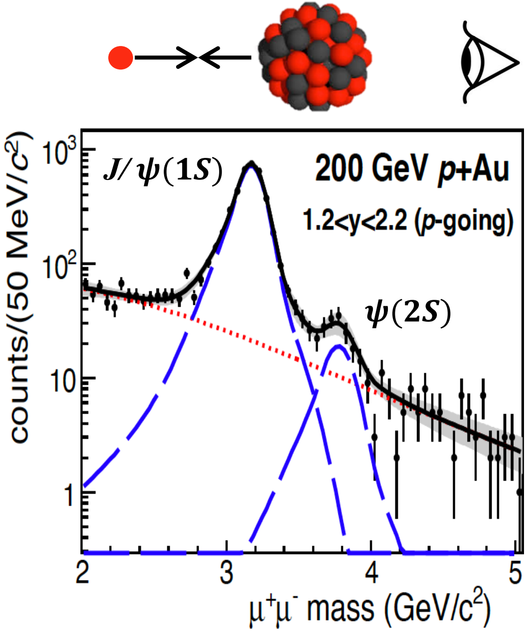
Similar to X(3872), mass quite close to DD threshold
Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$



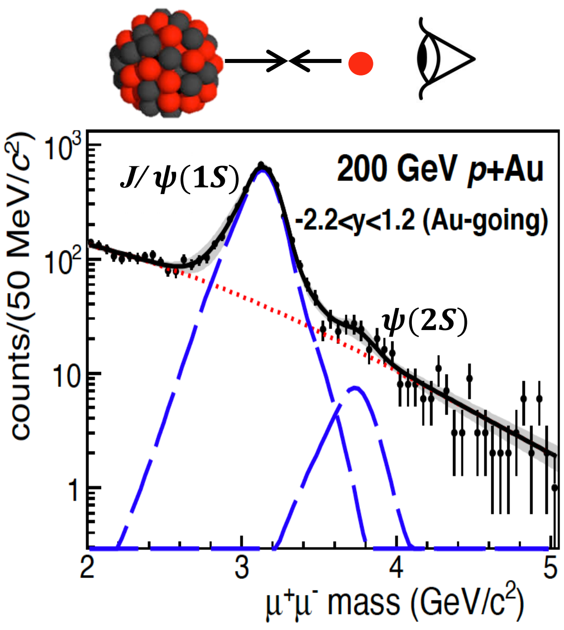
Yield favors higher multiplicity collisions, reminiscent of deuteron.
Evidence for hadronic molecule structure?

Quarkonia in the QCD medium

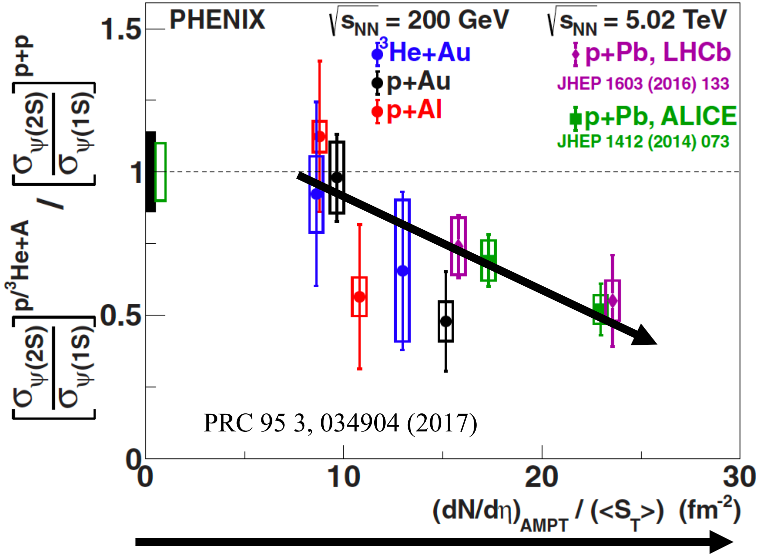




Relatively *low* particle density

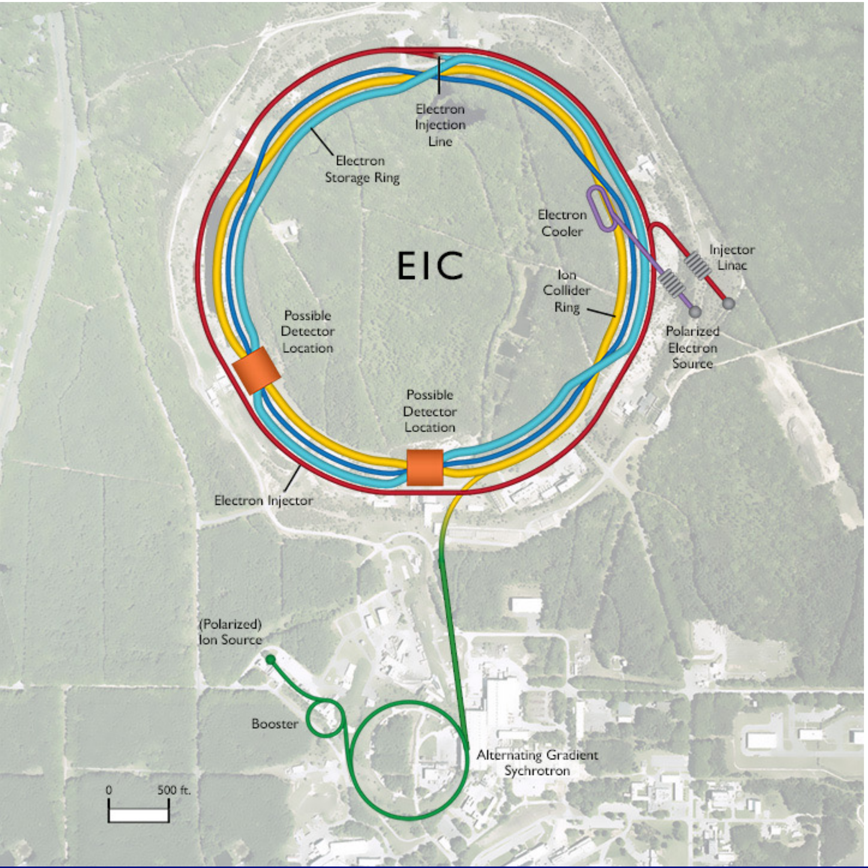


Relatively *high* particle density



Increasing charged particle density

Hadronization at the Electron-Ion Collider



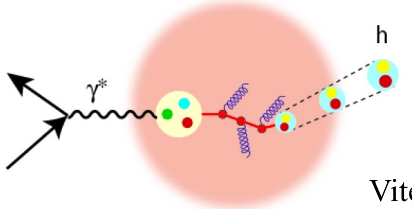
$$\sqrt{s} \sim 20 \ - 100 \ GeV$$

e+*p*, *e*+O, *e*+Al, *e*+Cu, *e*+Au, *e*+U,…

Charm production inside the nucleus probes:

- Parton structure of nucleons
- Parton distribution function modifications
- QCD energy loss

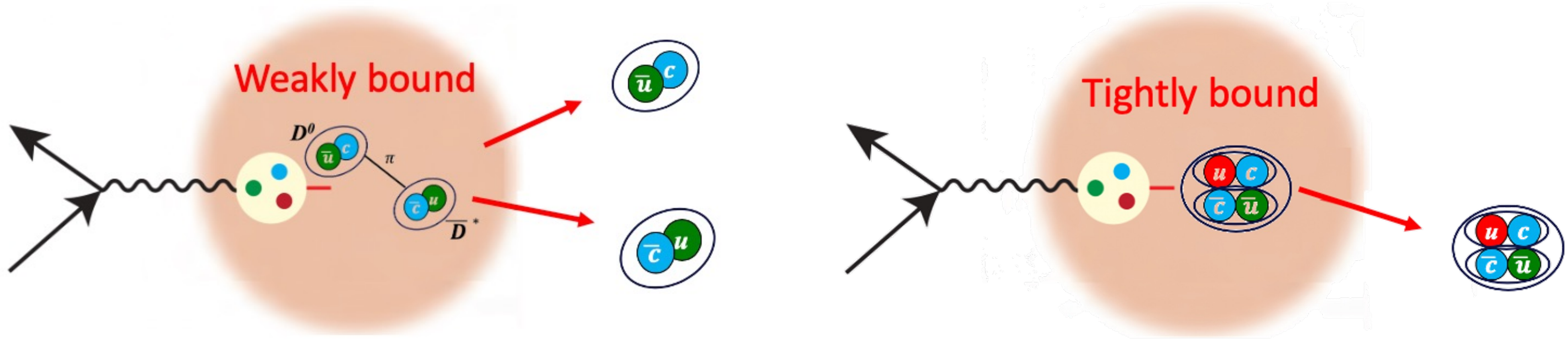
Hadronization inside the nucleus becomes important



Vitev, 1912.10965

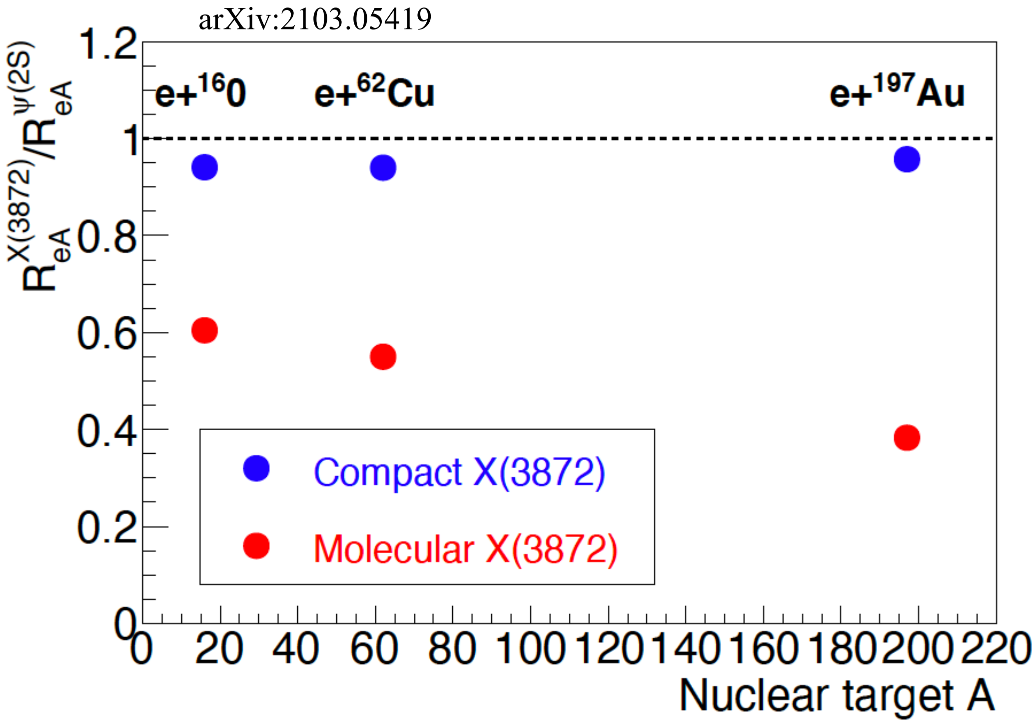
Filtering States with the Nucleus

- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair



- Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906
- Explains trends observed in fixed target data at FNAL, SPS
- Test idea via MC simulation of propagation through nucleus for three cases:
    - $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

Relative modification of X(3872)/ $\psi(2S)$ at EIC



$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Big/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$

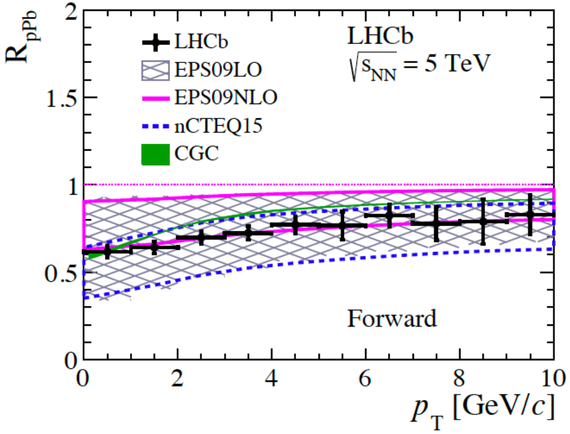
- **Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.**
- **Large difference between model of molecular X(3872) and $\psi(2S)$.**

X(3872) is only an example, model equally applicable for other exotics accessible at EIC

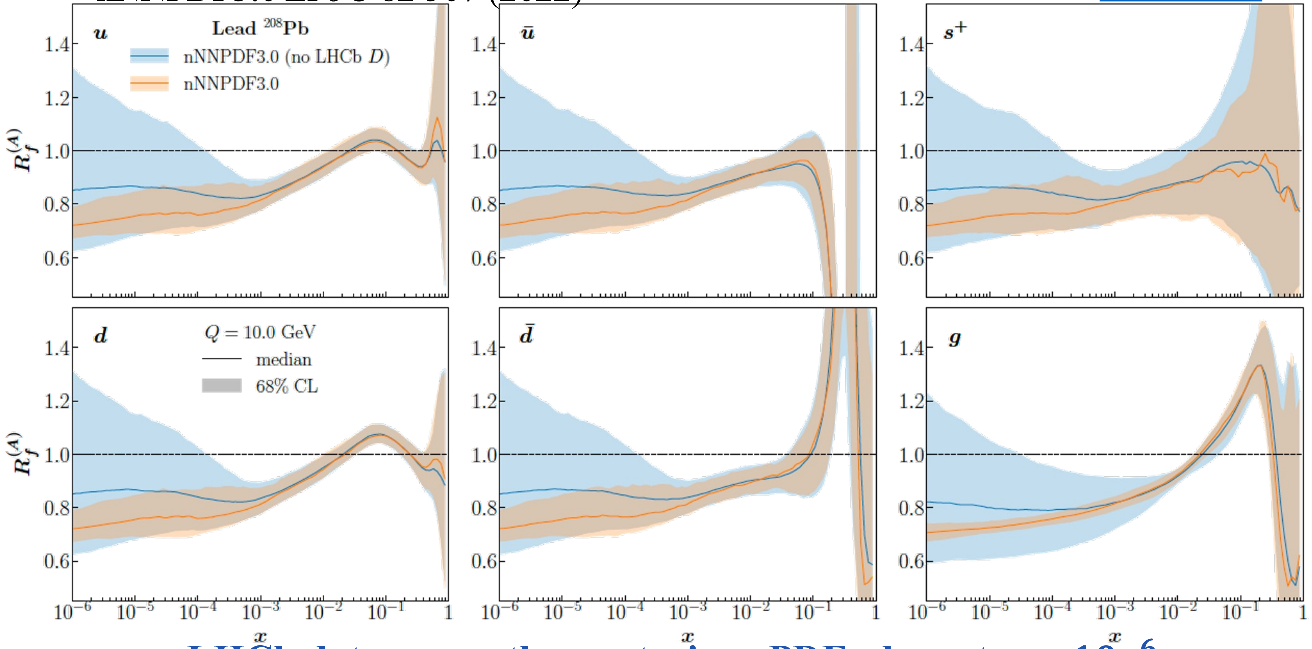
Constraining nPDFs with D mesons

Tom Boettcher
Tues 16:30

JHEP 1710 (2017)



nNNPDF3.0 *EPJC* 82 507 (2022)

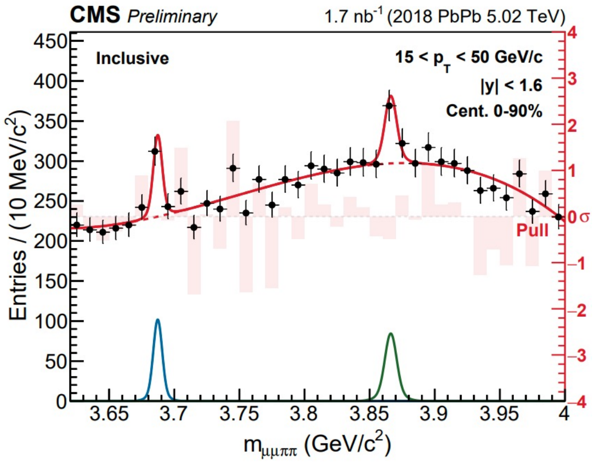


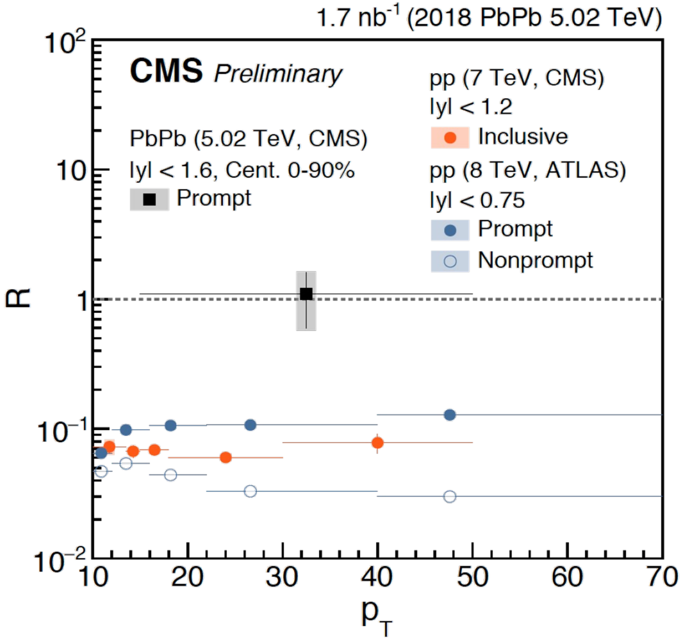
- LHCb D meson data: significantly more precise than calculations from older nPDF sets
- Now included as constraint in updated nPDF sets

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

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





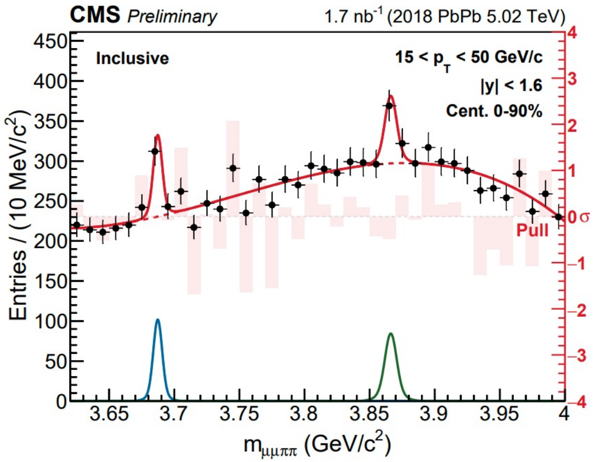
Recombination of X(3872) at pT > 15 GeV?

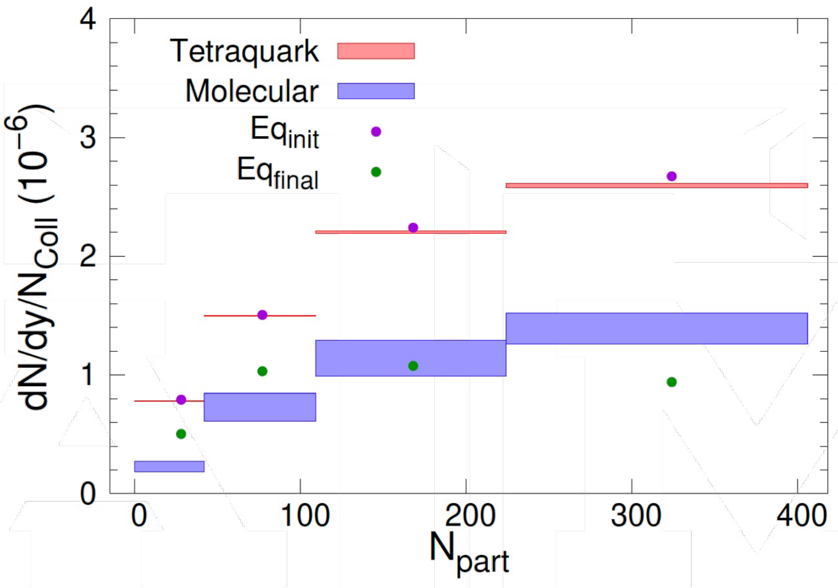
Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





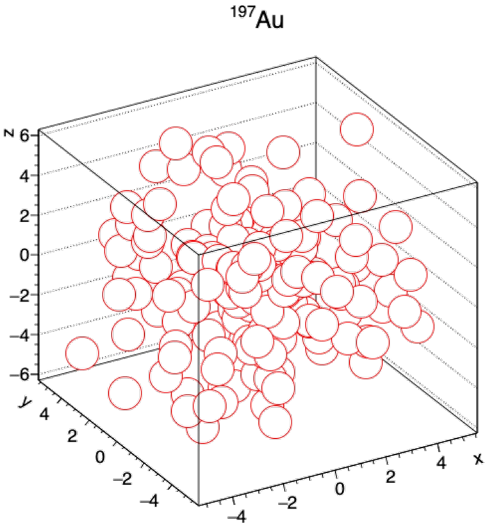
Transport model gives larger yield for compact tetraquark vs. molecule by factor of ~2 in PbPb

Will be tested with future PbPb data sets.

Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Intriguing data! Inconclusive with these uncertainties.



Propagation through Nuclei

- In Monte Carlo simulation, populate a Glauber nucleus, using parameters from PHOBOS model: arXiv:1408.2549
- Randomly select starting point for $Q\bar{Q}$ pair
- Propagate $Q\bar{Q}$ along z axis

- Following model of Arleo *et al.* in Phys Rev C, 61 054906 (2000), expand $Q\bar{Q}$ radius as a function of time:

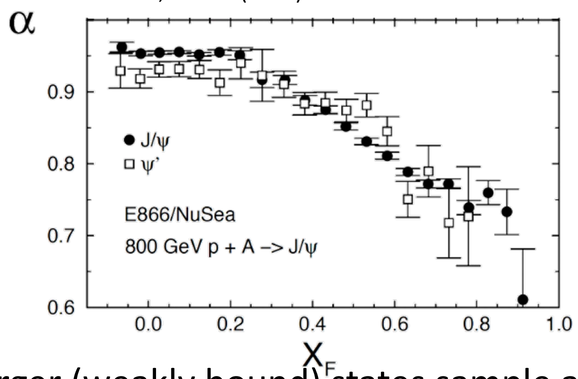
$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}}\ \tau & \text{if } r_{c\bar{c}}(\tau) \leq r_i \\ r_i & \text{otherwise} \end{cases}$$

- Calculate radius-dependent cross section: $\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}}/r_{\psi})^2$
- If the state comes within a distance of $\sqrt{\sigma_{c\bar{c}}/\pi}$ to a nucleon, consider it disrupted.
- Three cases: $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

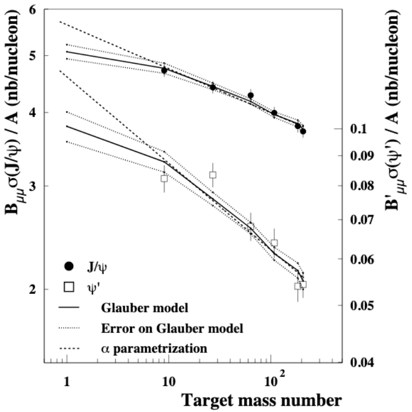
Filtering States with the Nucleus

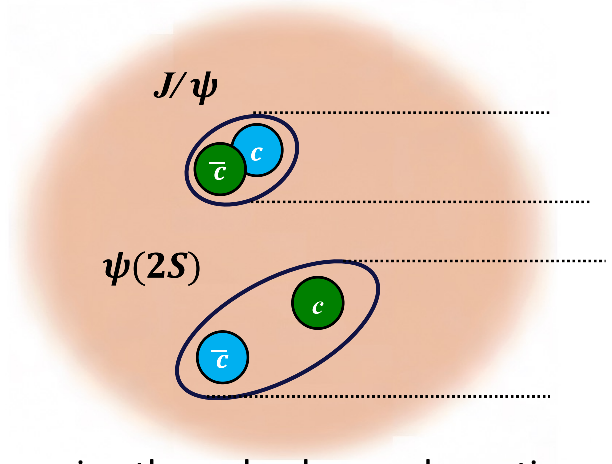
- At the EIC, hadronization inside the nucleus becomes an important effect (Vitev, 1912.10965)
- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260



NA50, EPJC 48 329 (2006)





- Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906
- Explains trends observed in fixed target data at FNAL, SPS
- As expected, fails at RHIC (hadronization occurs outside nucleus) PHENIX PRL 111 202301 (2013)

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Table 1: Charmonium states and binding energies

Satz hep-ph/0512217

state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

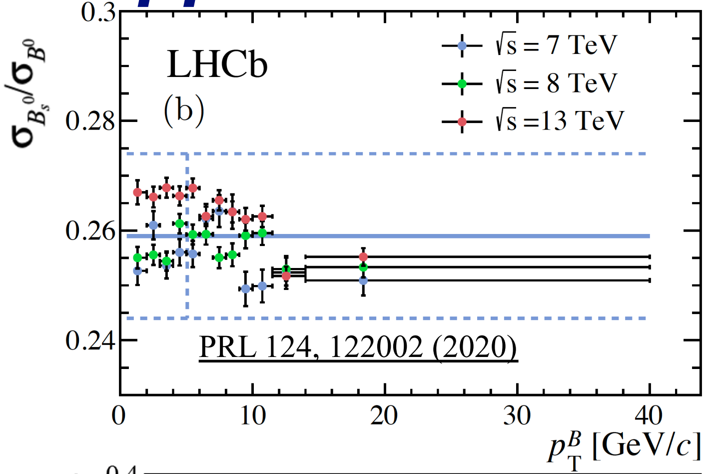
Table 2: Bottomonium states and binding energies

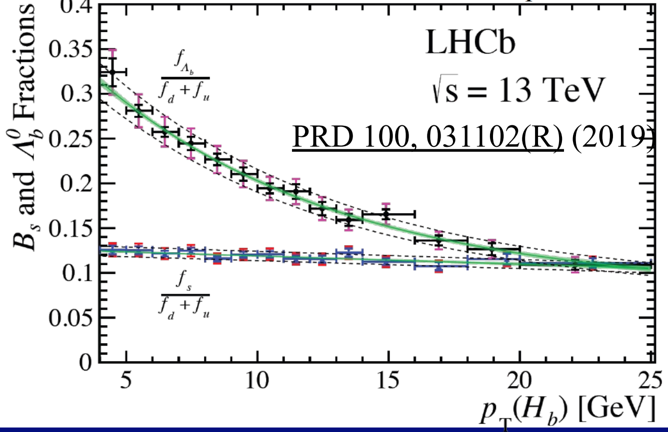
b fragmentation in *pp*

- Production of $b\bar{b}$ pairs is relatively well understood:
  - Negligible *b* content of incoming beams
  - Negligible production of *b* pairs via fragmentation
  - Total *b* cross section well described by pQCD

- *b* quark hadronization is not universal
  - Varies between e^+e^- and pp machines, $\sqrt{s}$, kinematics
  - Inconsistent with assumption of universal fragmentation

- Very similar to observations of **strangeness enhancement** and **baryon enhancement** in heavy ion collisions, typically seen as QGP signatures

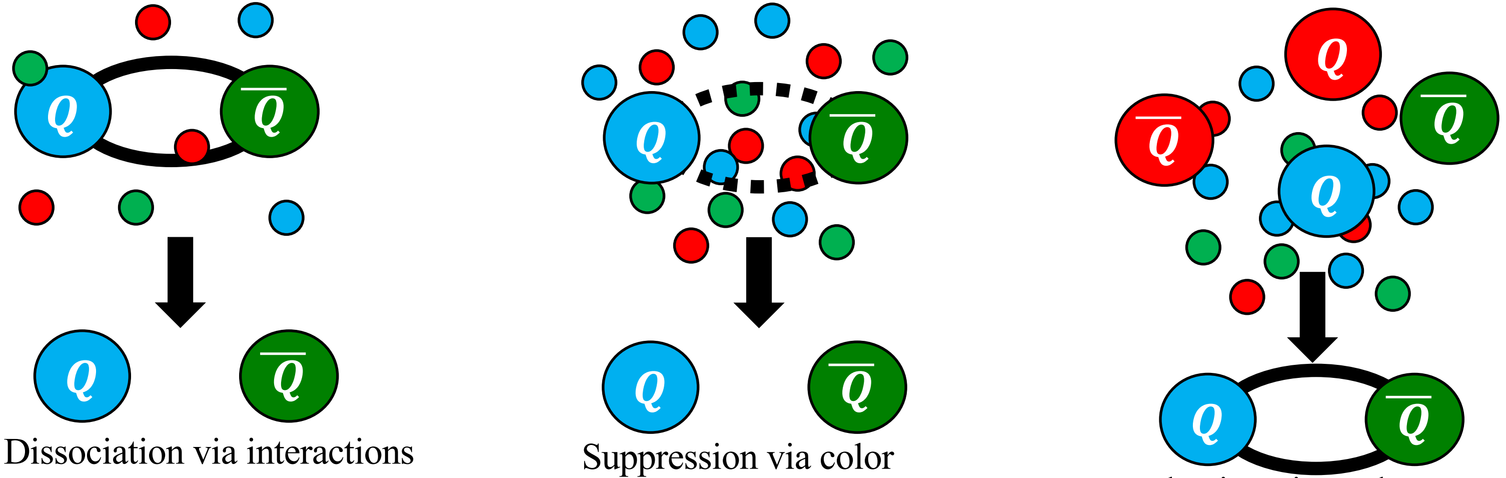




Quarkonia in the QCD medium

Diffuse medium (pp,pA) → Dense medium (pA, AA)

Increasing T, $N_{charged}$



Dissociation via interactions with comoving particles

Suppression via color screening

Production via coalescence

Experimentally, we use different collision systems/kinematic regions to prepare environments where different non-perturbative effects dominate.

Separate prompt/non-prompt production

Simultaneous fit to mass and proper time in each multiplicity bin