Probing Cold Nuclear Matter Effects with Heavy Flavor and Quarkonia in HI

On behalf of the LHC experiments at CERN for LHCP2024

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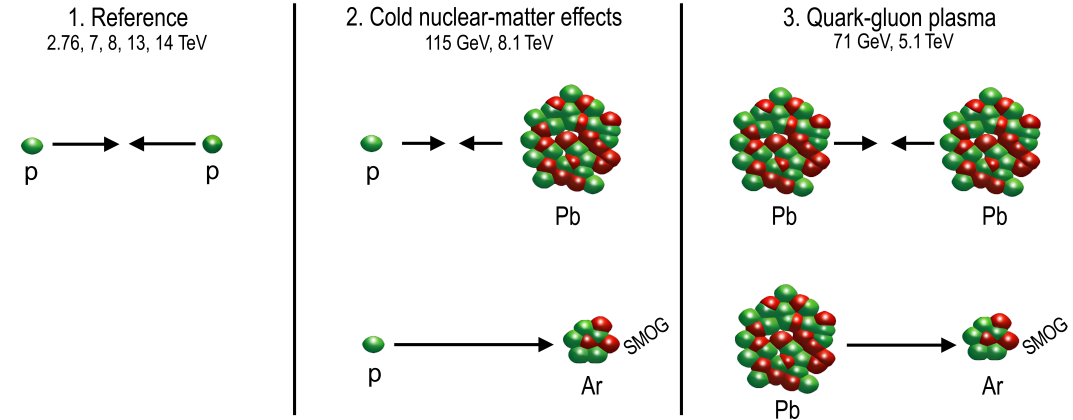
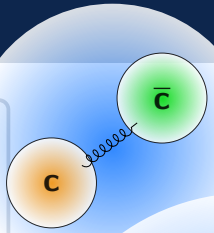
Different Collision Configurations



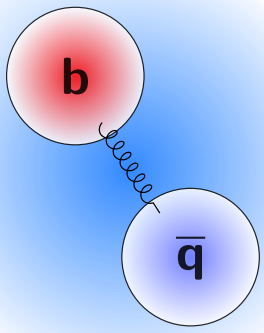
Hard Probes

Probes with heavy quarks are produced in the hard processes happening in the initial stages of the collision.

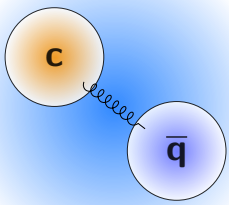
- Quarkonia
- Open Heavy flavor



J/ψ



B



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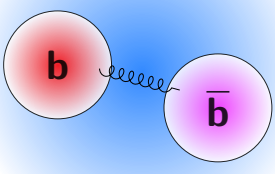
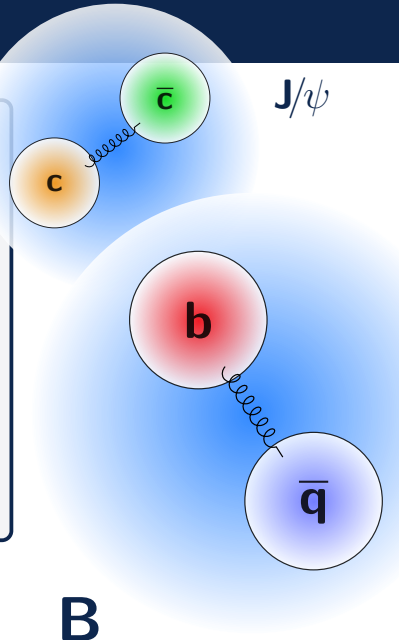


Υ

Hard Probes

Probes with heavy quarks are produced in the hard processes happening in the initial stages of the collision.

- Quarkonia
  - ▷ Used in R_{pA} measurements
  - ▷ Ground to excited state production ratios probe final state effects
- Open heavy flavor
  - ▷ Hierarchical energy loss in the medium
  - ▷ Carries large fraction of energy enabling precise study of hadron density and initial state effects in nucleus
  - ▷ Good probe of hadronization mechanism
  - ▷ Great input to test QCD calculations



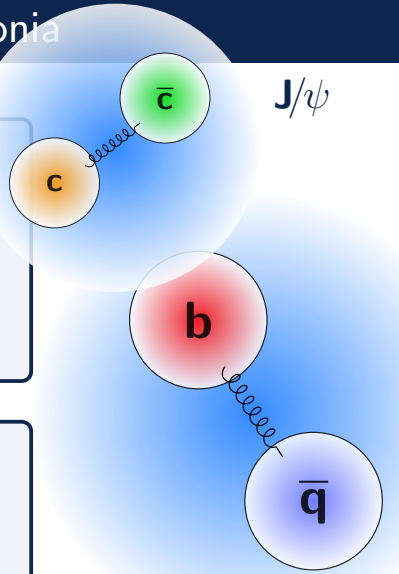
CNM Effects with Heavy Flavor and Quarkonia

In small / medium systems with high multiplicity collisions
QGP-like effects are observed (without deconfinemet):

- Collectivity (vs vacuum-like behavior)
- Quarkonia breakup (co-mover effect)
- Strangeness enhancement (nuclear environment)
- Modification of baryon / meson ratio (multiplicity dependence)

Open questions:

- How can these effects be explained?
- How universal hadronisation is?
- How do the observables change in transition
  from small to large and from low to high density QCD systems?

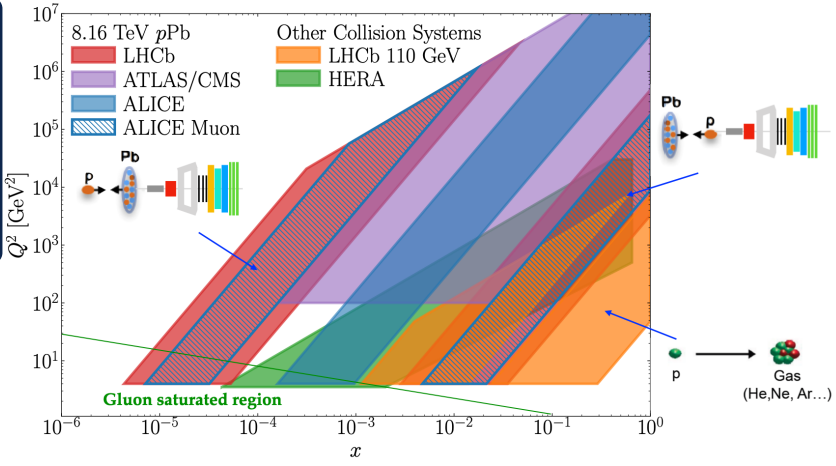


Coverage of Parameter Space

LHCb extends the phase space coverage to high x and low Q^2 regions.
Good for probing:

- Initial state effects
- Cold Nuclear Matter effects

[JP Conf: (2019) 1271 012008]

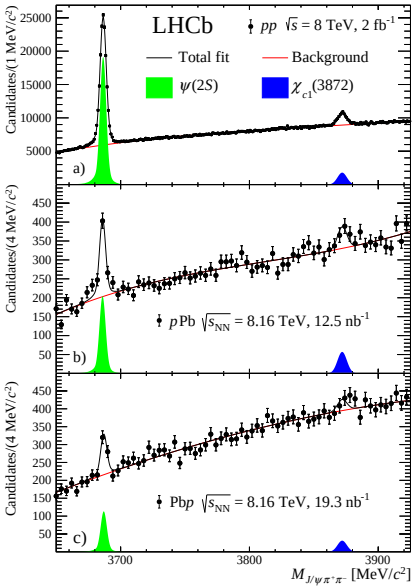


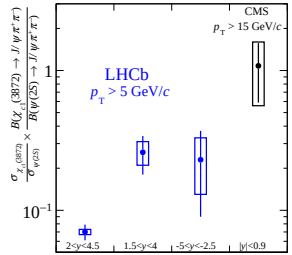
Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pPb

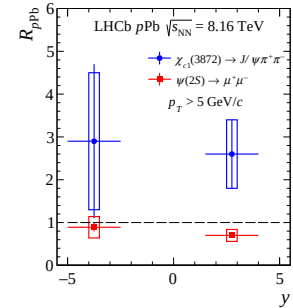
First measurement of the nuclear modification factor of an exotic multi-quark state.

- Good probe of co-mover and coalescence effects
- $\chi_{c1}(3872)$ production is expected to depend on the size of the system
- Tighly bound and molecular states have different predictions

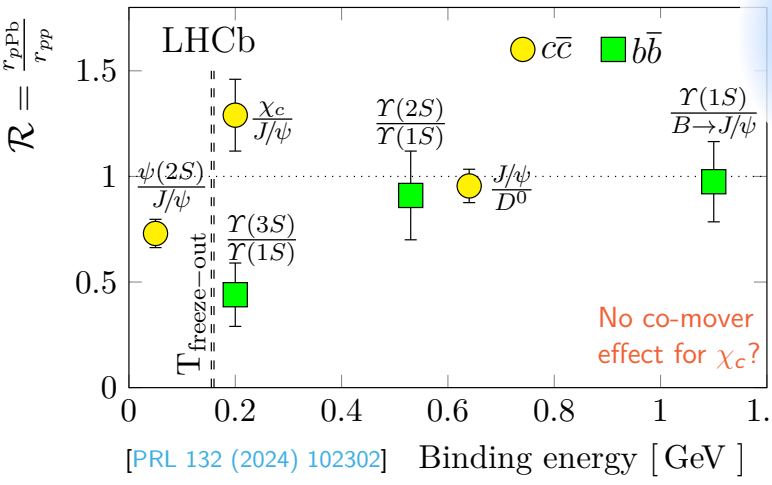
[arXiv:2402.14975]



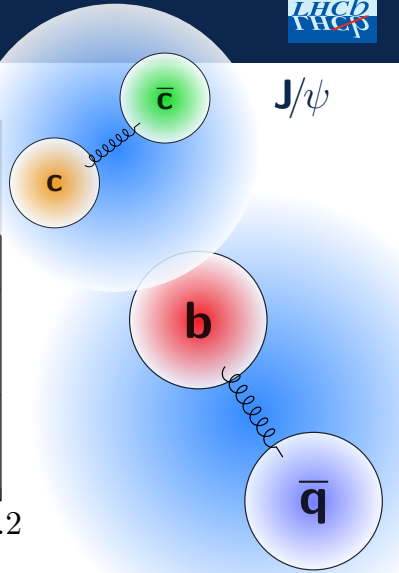




Double Ratio between Quarkonium States



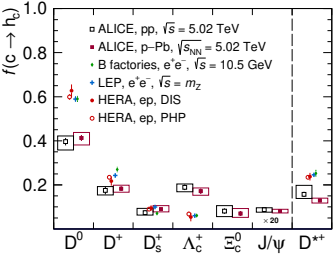
[PRL 132 (2024) 102302]



B

Charm fragmentation fractions and $c\bar{c}$ cross sections in pPb

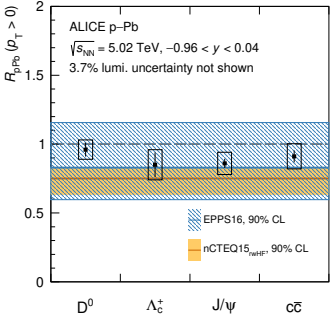
- Charm quark production cross section and the fragmentation fractions to different charm-hadron species, are measured for the first time at midrapidity in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- The cross section is found to be consistent with a binary scaling of pQCD calculations from pp collisions

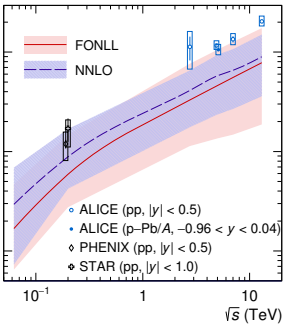


$$R_{\mathrm{pPb}}(c\bar{c}) = 0.91 \pm 0.04\,(\mathrm{stat.})\,{}^{+0.08}_{-0.09}\,(\mathrm{syst.})\,{}^{+0.04}_{-0.03}\,(\mathrm{extr.}) \pm 0.03\,(\mathrm{lumi.})$$

Consistent with unity

[arXiv:2405.14571]

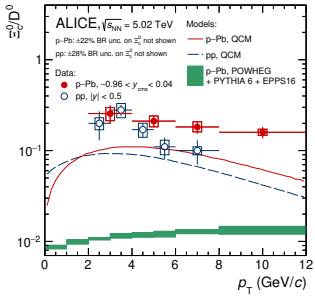


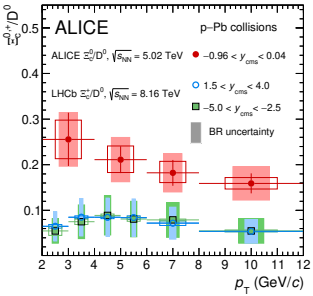


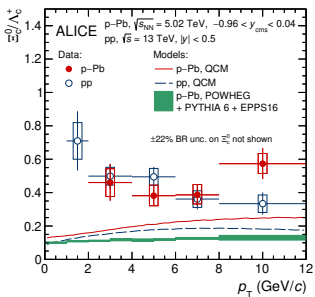
Production cross section of prompt Ξ_c^0 baryons in pPb

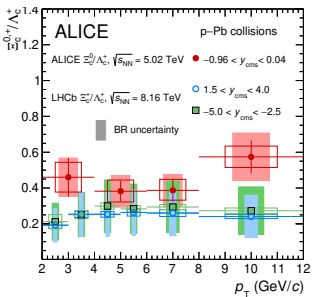
- pQCD models taking into account only CNM effects undersestimate the production cross section of prompt Ξ_c^+ baryons by an order of 40
- Model including quark coalescence brings the prediction closer to the data
- Measured R_{pPb} suggests a possible enhancement of Ξ_c^0 production via CNM effects

[arXiv:2405.14538]



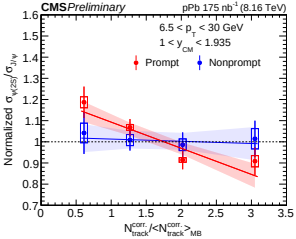


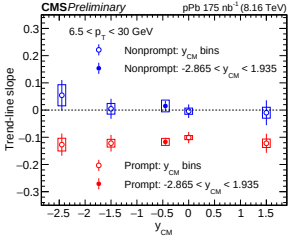


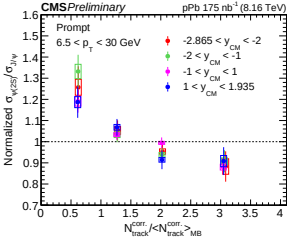


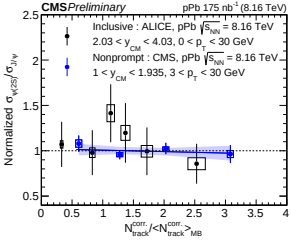
Multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ pPb collisions

- New result from CMS
- Figures already available
- Full text available soon
- Different regions of rapidity are investigated
- A difference between promt and non-promt components is observed
- Suppression of the production ratio of $\psi(2S)/J/\psi$ visible in high multiplicity regions







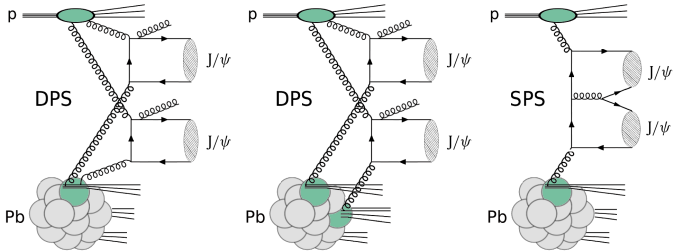


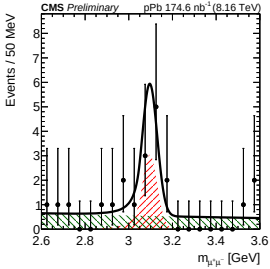
[CMS-PAS-HIN-24-001]

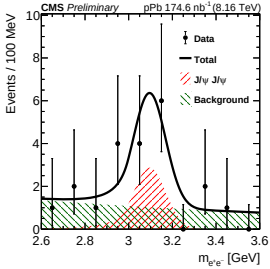
Observation of double - J/ψ production in pPb collisions

- First observation of the concurrent production of two J/ψ mesons in protonnucleus collisions is presented
- After selection requirements 8.5 ± 3.4 events are found for the $J/\psi J/\psi + \mathrm{X}$ final state
- The cross section is measured to be:
  $\sigma(pPb \to J/\psi J/\psi + X) = 22.0$
  $\pm 8.9\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})\,\mathrm{nb}$

[CMS-PAS-HIN-23-013]







Recent Results

LHCb:

- Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV [arXiv:2402.14975]
- Prompt and nonprompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2401.11342]
- Strangeness enhancement with charm in high-mult. pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2311.08490]
- Fraction of χ_c decays in prompt J/ψ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2311.01562]
- Prompt D^+ and D_s^+ production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [arXiv:2309.14206]
- Ξ_c^+ production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2305.06711]
- Charmonium production in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV [arXiv:2211.11645]
- Open charm production and asymmetry in pNe collisions at $\sqrt{s_{NN}} = 68.5$ GeV [arXiv:2211.11633]
- Prompt D^0 nuclear modification factor in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2205.03936]

[JHEP 04 (2024) 111] [JHEP (2023) 01562]
[JHEP 01 (2024) 070] [PRL 131 (2023) 102301]
[EPJC 83 (2023) 541] [PRL 132 (2024) 10232]
[EPJC 83 (2023) 625]

Recent Results

ALICE:

- Charm fragmentation fractions and $c\bar{c}$ cross sections in pPb collisions [arXiv:2405.14571]
- Production cross section of prompt Ξ_c^0 baryons in pPb collisions [arXiv:2405.14538]
- J/ψ production at midrapidity in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV [arXiv:2211.14153]
- $\psi(2S)$ production vs. charged-particle multiplicity in pp and pPb collisions [arXiv:2204.10253]
- Measurements of the production of non-prompt charm hadron states in pPb [study in progress]

CMS:

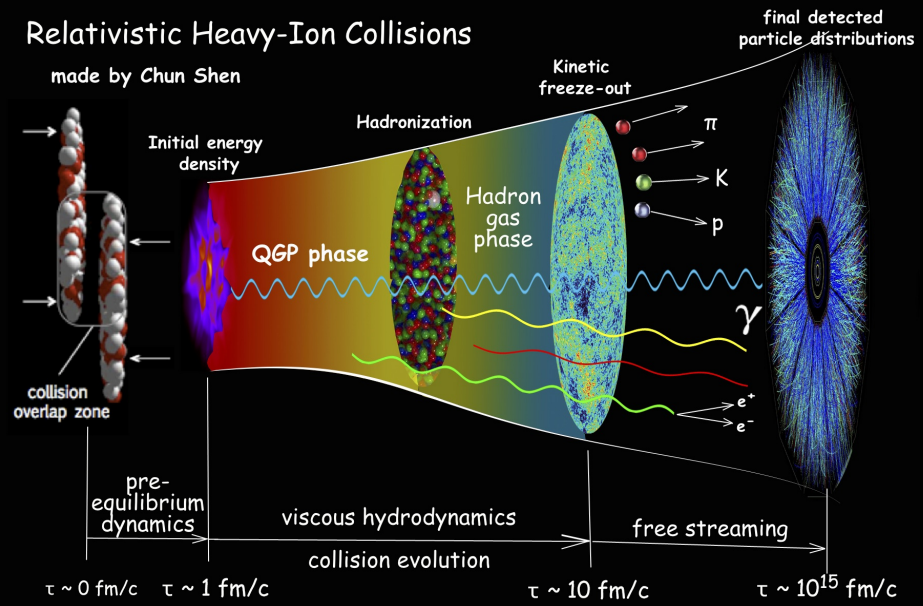
- Multiplicity dependence of the ratio of $\psi(2S)/J/\psi$ pPb collisions [CMS-PAS-HIN-24-001]
- Observation of double - J/ψ production in pPb collisions [CMS-PAS-HIN-23-013]
- B^+ differential cross section as a function of p_T and multiplicity in pPb [CMS-PAS-HIN-22-001]
- Multiplicity dependence of charm baryon and meson production in pPb [CMS-PAS-HIN-21-016]

[JHEP 07 (2023) 137]
[JHEP 06 (2023) 147]

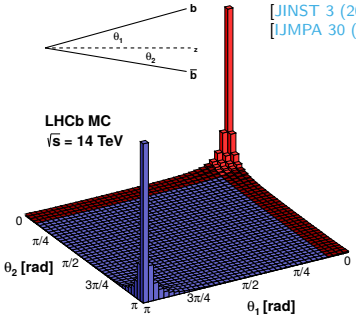
Summary

- Heavy flavor and quarkonia are excellent probes of the CNM
- Recent results from LHCb, ALICE and CMS show a wealth of information on the CNM effects
- The field is rapidly evolving with new results coming out regularly. It will only grow with more data in Run3 and detector upgrades
- The smooth transition in parameters between small and large systems means that a combined effort between the experts in HI, hadron spectroscopy and related fields will be required to better understand and explain the QCD processes related to hot and cold nuclear matter

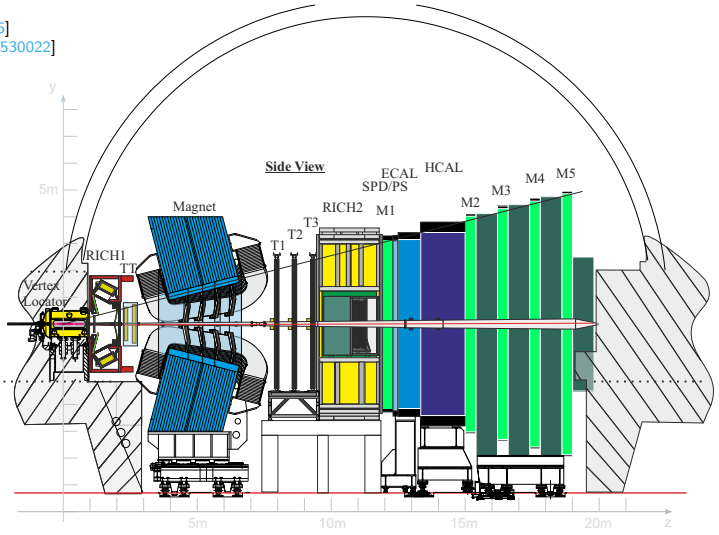
BACKUP SLIDES


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

The LHCb Experiment



[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 07, 1530022]



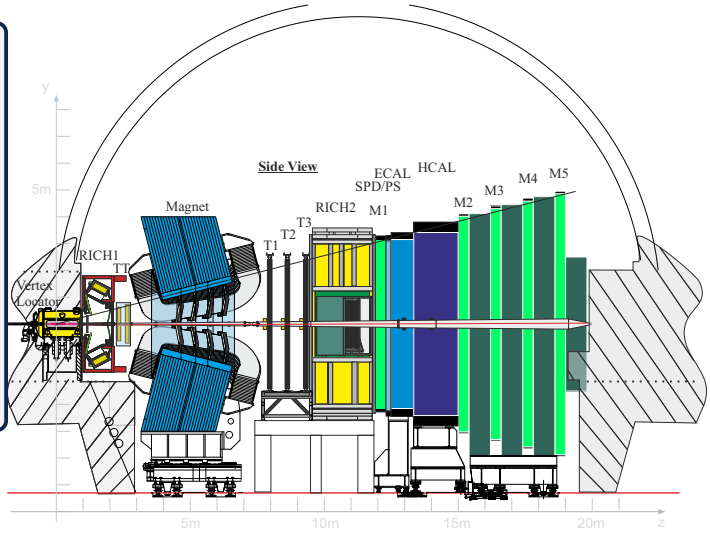
Acceptance:	$2 < \eta < 5$	
Vertex:	σ_{IP}	$\sim 20\ \mu$m
Time:	σ_τ	~ 45 fs
PID:	$\varepsilon(K)$	$\sim 95\%$

The LHCb Experiment

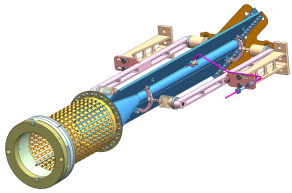
LHCb features relevant to HI physics and CNM studies:

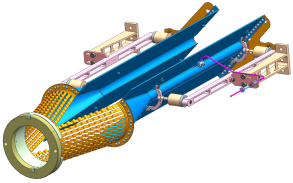
- Excellent p_T resolution
- Excellent hadron, muon, electron and photon PID (with 3-5% mis-ID)
- Precise vertexing
- Excellent impact parameter resolution
  $(15 + 29/p_T\ [\text{GeV}])\ \mu\text{m}$
  (UPC separation)

[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 07, 1530022]

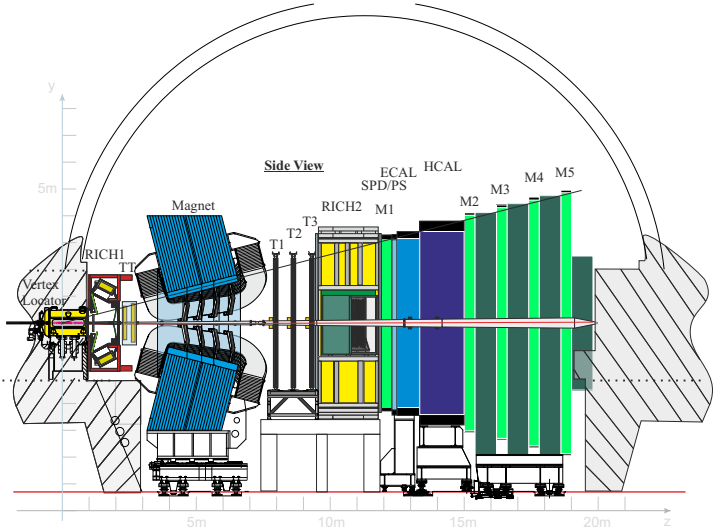


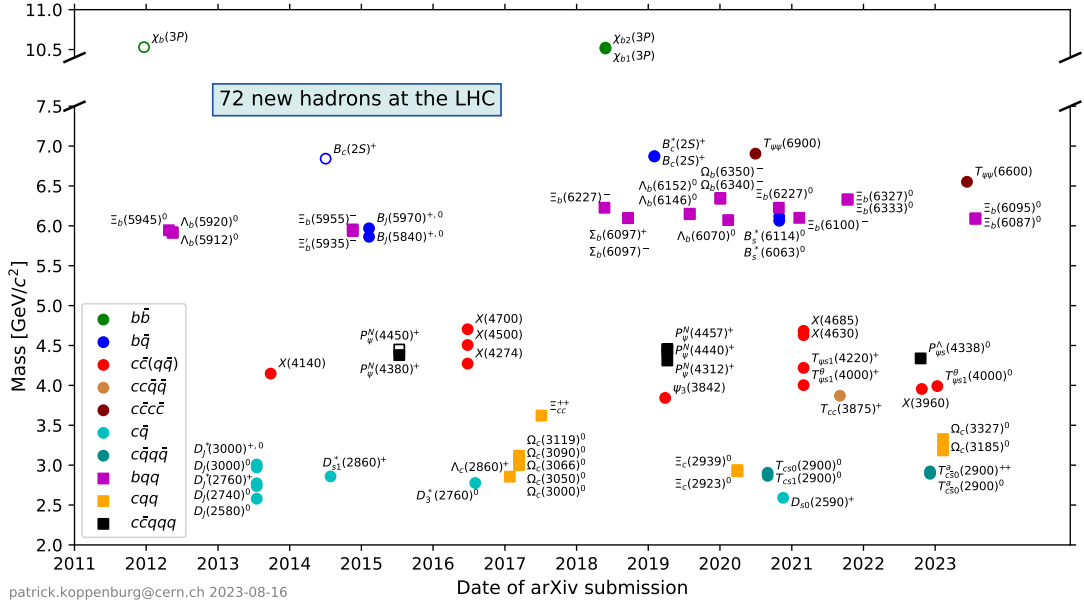
LHCb as a Fixed Target Experiment





[JINST 3 (2008) S08005]
[JINST 9 (2014) P12005]
[LHCB-TDR-020]
[IJMPA 30 (2015) 07, 1530022]





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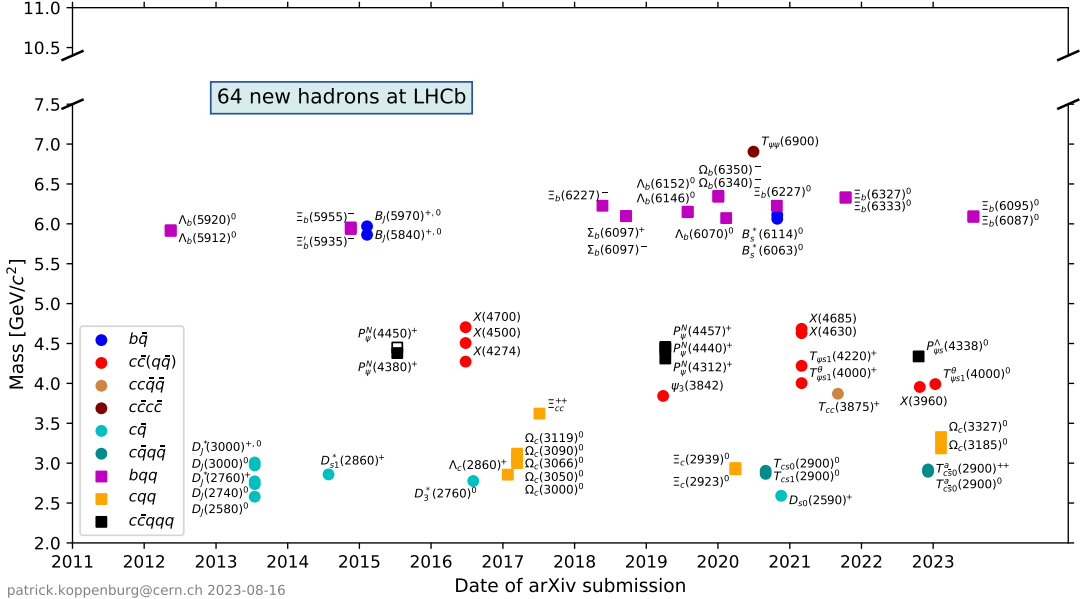

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Helium identification and Observation of Hypertriton in LHCb