Quarkonium production studies in nuclear collisions at LHCb

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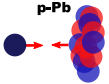
Quarkonia as a probe of nuclear medium

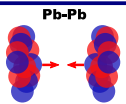
Quarkonia are a fine probe of the nuclear medium in collision of heavy ion:

- The quark pair is created in the initial hard scattering hence experience the full evolution of the system.
- Their heavy mass $m_b > m_c \gg \Lambda_{QCD}$ hence can be described by pQCD.

- Study production mechanism, compare with models to test QCD.
- Baseline for pPb and PbPb.



- Study effects of presence of nucleus in the collision on particle production.
- 'Cold nuclear matter' reference for PbPb data.

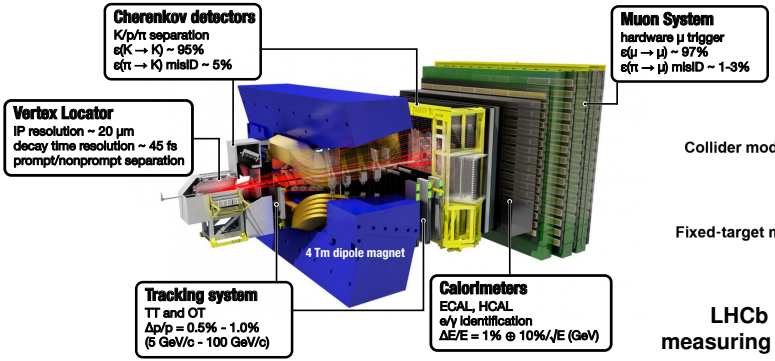


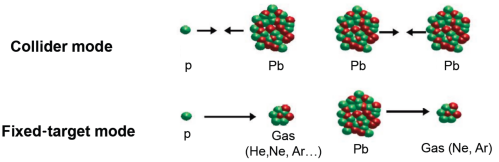
- Map transition from hadronic to partonic matter.
- Study properties of hot nuclear matter.

LHCb detector

doi:10.1142/S0217751X15300227

- Single arm spectrometer fully instrumented in $2 < \eta < 5$ designed to study c and b quarks in pp collisions.
- Has excellent vertexing, tracking, and PID capability, reconstruction down to $p_{\mathrm{T}} = 0$.

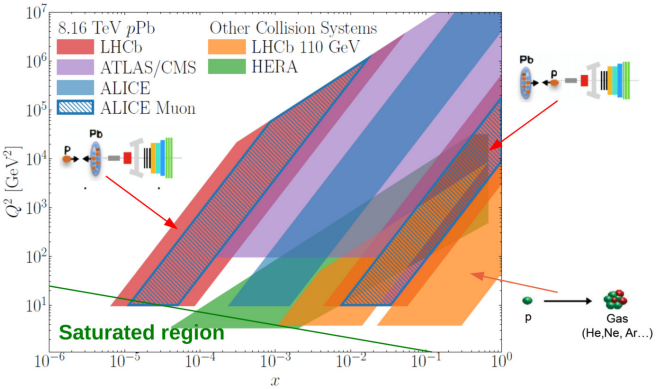




LHCb is now a general purpose detector measuring pp/pPb/PbPb and in fixed target mode.

LHCb as a general heavy ion experiment

arXiv:1904.04130



Large kinematic coverage in pA collisions.

Collider mode

- Constrain (n)PDFs in pp/pPb measurements.
- PbPb data up to 60% centrality.

Fixed target mode:

- Constrain nPDFs.
- Cosmic physics in laboratory.

Ultra-peripheral Collisions of PbPb

- Coherent photoproduction of forward J/ψ probes the gluon nPDFs at small to intermediate Bjorken x.

Recent results

Quarkonia in (nuclear) medium:

- **Measurement of prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV**, LHCb-PAPER-2020-048, arXiv:2103.07349 (submitted to Phys. Rev. C Lett.)

- **Observation of multiplicity-dependent prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions**, Phys. Rev. Lett. 126 (2021) 9, 092001.

Quarkonia photoproduction in nuclear collisions

- **Low-p_{T} J/ψ photo-production in PbPb peripheral collisions at $\sqrt{s_{NN}}$ = 5 TeV with the LHCb experiment**, LHCb-PAPER-2020-043 (to be submitted to Phys. Rev. Lett)

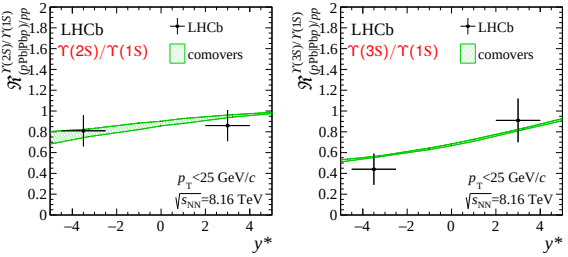
Conventional charmonia in nuclear medium

Production of quarkonia is modified in nuclear collisions compared to that in pp.

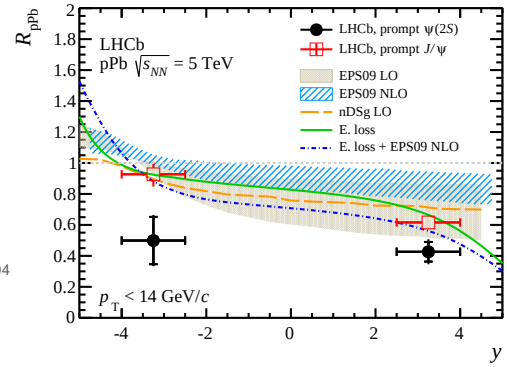
$$R_{p-Pb} = \frac{1}{A} \frac{\sigma_{p-Pb}(\Delta p_T, \Delta y^*)}{\sigma_{pp}(\Delta p_T, \Delta y^*)}$$

Higher excited states are more suppressed, as they are increasingly weakly bound.

LHCb, JHEP 11 (2018) 194



LHCb, JHEP 1603 (2016) 133



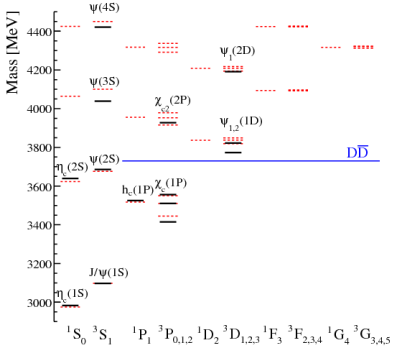
Such difference in suppression of states with the same quark content can be explained with final-state effects.

Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb 8.16 TeV

LHCb, JHEP 1603 (2016) 133

The χ_c are a P-wave charmonia triplet, with masses between those of J/ψ and $\psi(2S)$.

- Their sequential mass differences are < 100 MeV.
- Most commonly measured from $\chi_c \to J/\psi + \gamma$. The branching fractions of $\chi_{c1,2}$ make such measurement possible in pPb.



Measuring χ_c is interesting for three reasons:

1. This is the first measurement in nuclear collision at the LHC.
2. Their cross-section ratio can serve as a probe of sensitivity to nuclear matter effects.
3. They are an important feed-down channel for J/ψ.

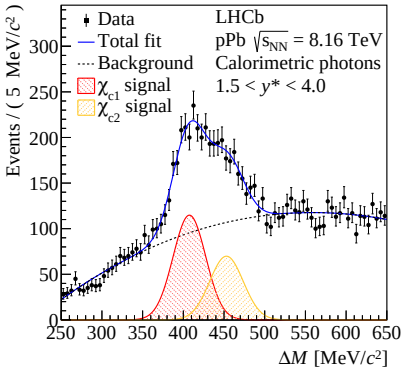
Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb 8.16 TeV (cont'd)

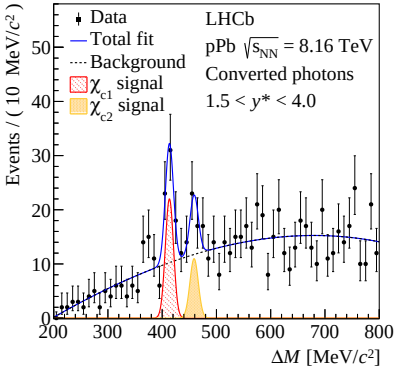
LHCb-PAPER-2020-048
arXiv:2103.07349

LHCb can measure χ_c from their radiative decays $\chi_c \to J/\psi + \gamma$ using two independent sets of photons:

Calorimetric photons, providing reasonable event statistics but affected by poor mass resolution.

Converted photons, which offer excellent mass resolution but are found in few events.





Prompt cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in pPb 8.16 TeV (cont'd)

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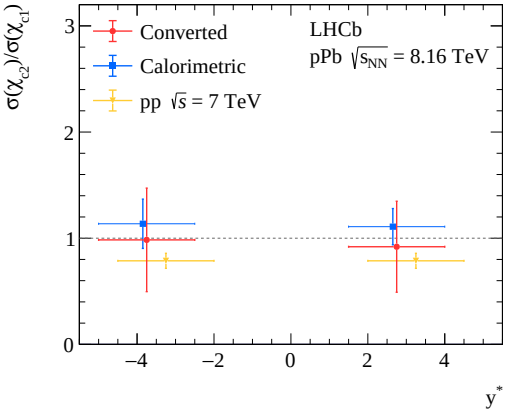


The two set of pPb results were measured with **different kinematic selection**.

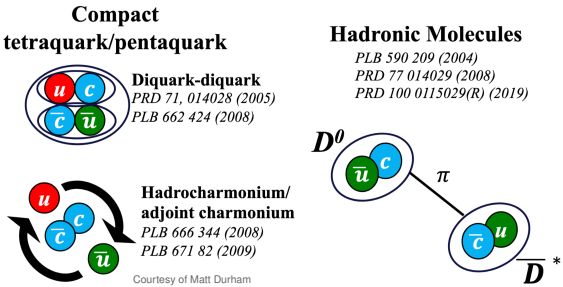
The cross-section ratio shows **no dependence on rapidity**.

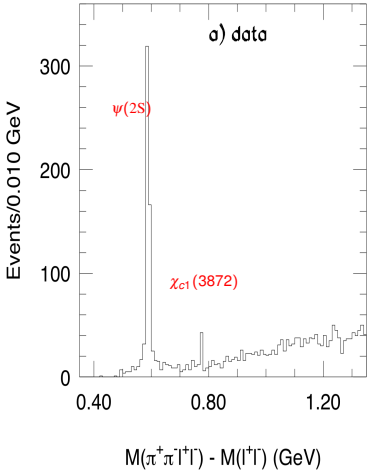
Comparison with pp results from LHCb's 7 TeV measurement with converted photons suggest the **same impact of nuclear effect** on the two states in both rapidity windows.

Multiplicity dependent $\chi_{c1}(3872)$ production in pp 8 TeV

The $\chi_{c1}(3872)$ exotic hadron was first observed in 2003 by Belle in decays of $B \to J/\psi\pi^+\pi^-$.

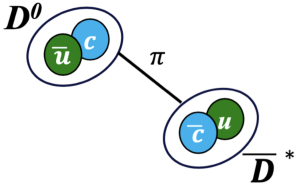
Belle, PRL 91 (2003) 262001





Multiplicity dependent $\chi_{c1}(3872)$ production in pp 8 TeV (cont'd)

The nature of $\chi_{c1}(3872)$ can be scrutinised by studying its multiplicity dependent relative suppression compared to a conventional charmonium state such as $\psi(2S)$.



Hadronic molecule $\Rightarrow$ very weakly bound with a large radius ~ 10 fm.

$$M_{\chi_{c1}(3872)} - M_{\bar{D}} - M_{D^*} = 0.1 \pm 0.27 \text{ MeV}$$

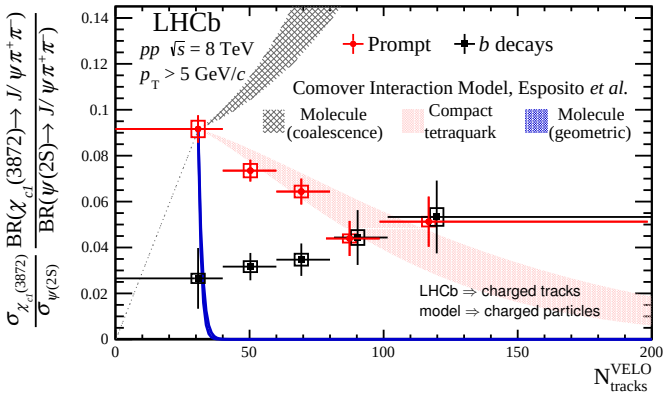
Compact tetraquark $\Rightarrow$ tightly bound with small radius ~ 1 fm.

Multiplicity dependent $\chi_{c1}(3872)$ production in pp 8 TeV (cont'd)

PRL 126 (2021) 9, 092001

- The prompt ratio decreases with multiplicity - stronger suppression of $\chi_{c1}(3872)$ compared to $\psi(2S)$.
- The non-prompt ratio is constant in multiplicity.

Such behaviour is consistent with the idea of a weakly-bound $\chi_{c1}(3872)$ being more dissociated than a more tightly bound $\psi(2S)$.



Comover interaction model by Espacito *et al.*, arXiv: 2006.15044, favours the **compact tetraquark scenario**.

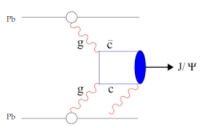
A tweaked model by Braaten *et al.*, arXiv: 2012.13499, suggests the $\chi_{c1}(3872)$ is a **charm-meson molecule**.

Coherent J/ψ photoproduction in PbPb

Coherently produced J/ψ are extensively studied in photon-nucleus interactions in Ultra-Peripheral PbPb Collisions (UPC).

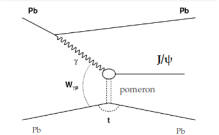
However, such process also occurs in peripheral nuclear collisions, where it is manifested in a low-p_T J/ψ excess.

Hadronic production



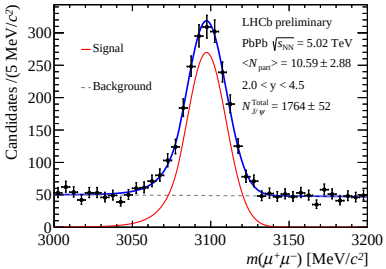
$gg \rightarrow J/\psi$

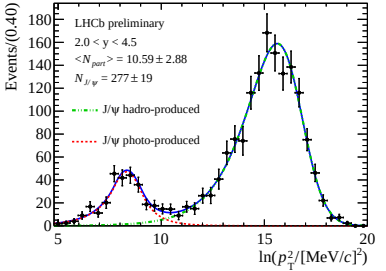
Coherent photo-production



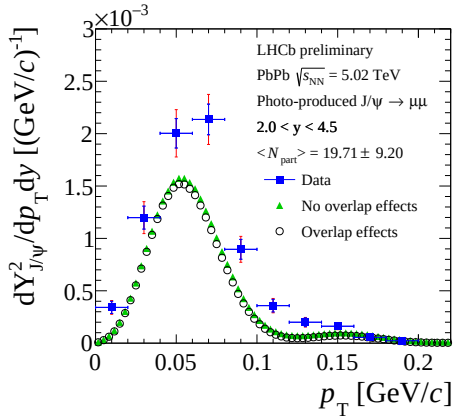
$\gamma(pomeron) \rightarrow J/\psi$

LHCb-PAPER-2020-043





Coherent J/ψ photoproduction in PbPb



LHCb measured photproduced J/ψ as a function of p_T, rapidity, and centrality.

In particular the p_T dependent data are **the most precise results to date**.

Data are qualitatively well reproduced in models with and without overlap effects, **confirming the presence of photoproduction**.

Summary

LHCb is tried and true general purpose experiment with many unique results.

- LHCb performed the first measurement of 1P charmonia in nuclear collisions at the LHC. The cross-section ratio revealed no difference in the nuclear effects acting on the χ_{c1} and χ_{c2} states.
- LHCb measured the multiplicity dependence of $\chi_{c1}(3872)$ in pp collisions - such studies probe the nature of this exotic state through its interaction with the medium. Whether the $\chi_{c1}(3872)$ is a tetraquark or a charm-meson molecule is still a point of debate.
- LHCb's measurement of photoproduced J/ψ in peripheral PbPb collisions is the most precise to date.