Quarkonia measurements in small systems at LHCb

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On behalf of LHCb Collaboration

Qaurkonia As Tools 2021
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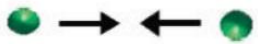
Quarkonia as a probe of nuclear medium

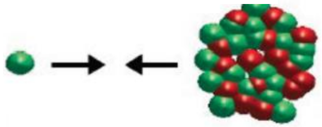
- The study of quarkonium production provides:
  - valuable information on non-perturbative QCD physics.
  - novel signatures for the exploration of new phenomena, multi-quark spectroscopy.
  - probes of proton structure.
  - double parton scattering interactions.
- Quarkonium in high-energy collisions at the LHC:

p-p



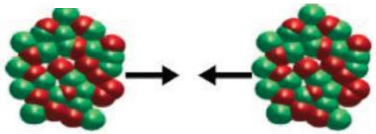
- **Large datasets** collected
- Provide a compelling setting
- **Baseline** for p-Pb and Pb-Pb collisions

p-Pb



- **Compare to p-p:** Probe of the nPDFs in nucleus
- **Reference for PbPb:** Explore the dynamics of heavy-quarks in cold nuclear matter

Pb-Pb

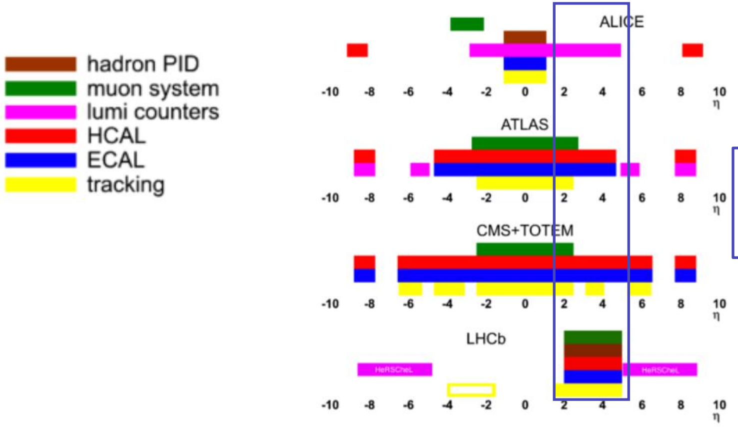


- Probes to study **QGP** (Hot&dense state of matter)
- Sensitive to **initial-to-final-state effects**

LHCb detector

[doi:10.1142/S0217751X15300227]

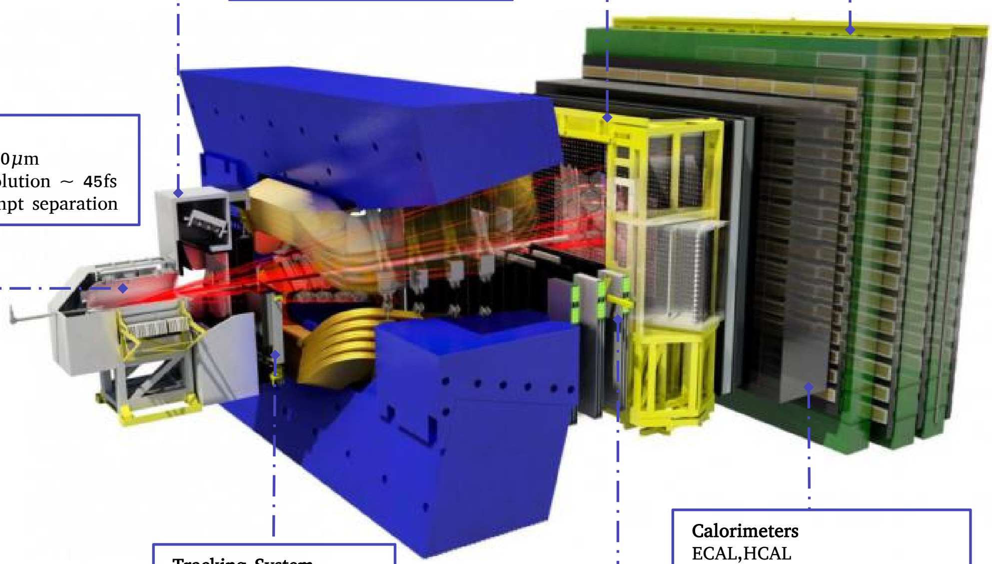
LHCb : Single arm forward spectrometer fully instrumented in pseudo-rapidity range **$2 < \eta < 5$**.
Design for the study of particles containing **b or c quarks**.
Can also use for **heavy ion studies**.



Cherenkove Dectectors
K/p/π separation
$\varepsilon(K \to K) \sim 95\%$
$\varepsilon(\pi \to K) \sim 5\%$ misID

Muon Station
hardware μ trigger
$\varepsilon(\mu \to \mu) \sim 97\%$
$\varepsilon(\pi \to \mu) \sim 1 - 3\%$ misID

Vertex Locator
IP resolution$\sim 20\mu$m
decay time resolution $\sim$ 45fs
prompt/no prompt separation



Tracking System
TT and OT
$\Delta p/p = 0.5\% - 1.0\%$
(5GeV/c - 100GeV/c)

Calorimeters
ECAL,HCAL
e/γ identification
$\Delta E/E = 1\% \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

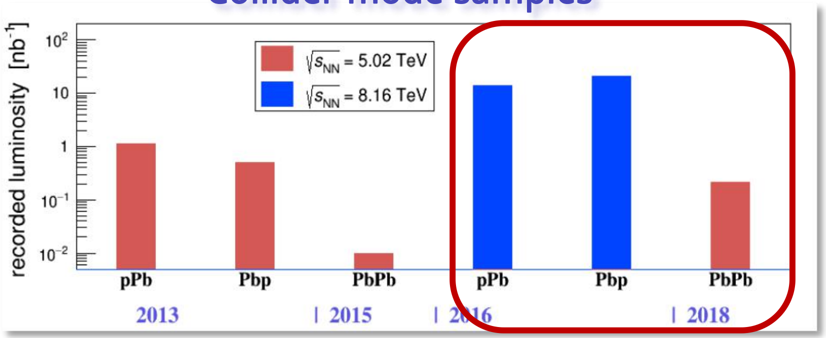
- ※ High precision device down to **very low-p_T**.
- ※ Excellent **p_T and mass resolution**.
- ※ Excellent **particle identification**.
- ※ Precision **vertex reconstruction**.

LHCb running modes

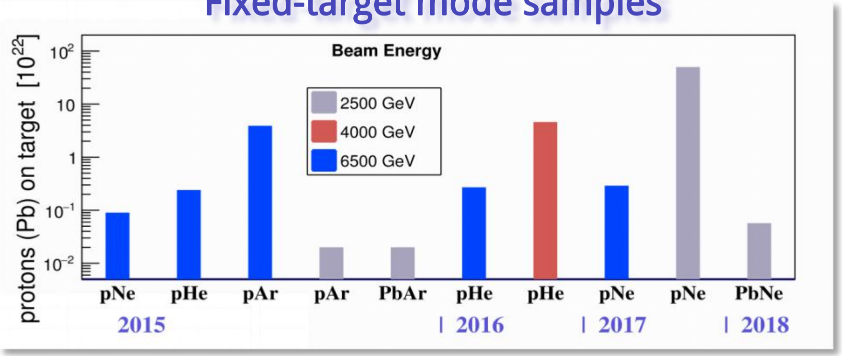
- Both the collider mode and fixed-target mode running at the same time.

[arXiv:1904.04130]

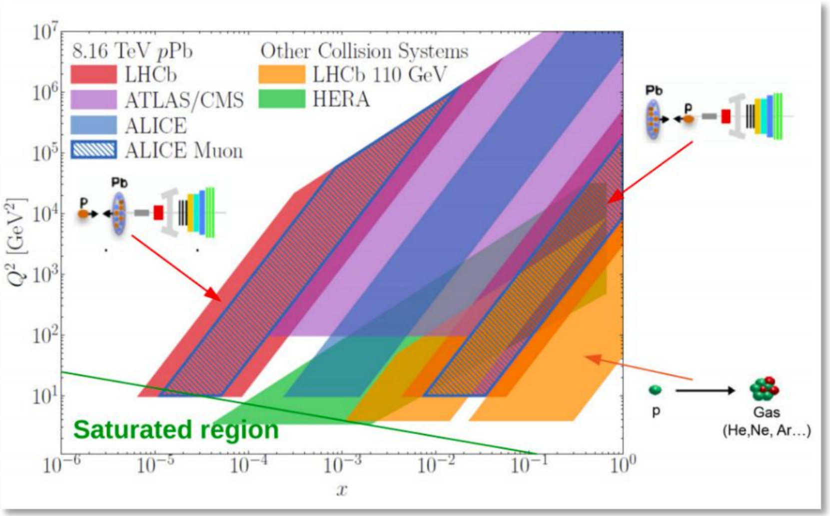
Collider mode samples



Fixed-target mode samples



LHCb can do better in low-x region



- Large kinematic coverage in pA collisions.

1

Measurement of Prompt Cross-section Ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ in pPb Collisions at $\sqrt{s_{NN}} = 8.16$ TeV

LHCb-PAPER-2020-048, arXiv:2103.07349 (Submitted to Phys. Rev. C)

2

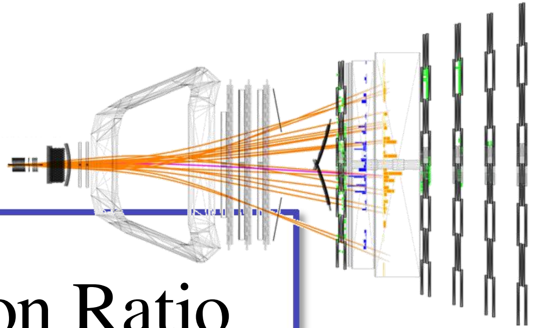
Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions

Phys. Rev. Lett. 126 (2021) 9, 092001

3

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)



Measurement of Prompt Cross-section Ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ in pPb Collisions at $\sqrt{s_{NN}} = 8.16$ TeV

LHCb-PAPER-2020-048
arXiv:2103.07349
(submitted to Phys. Rev. C.)

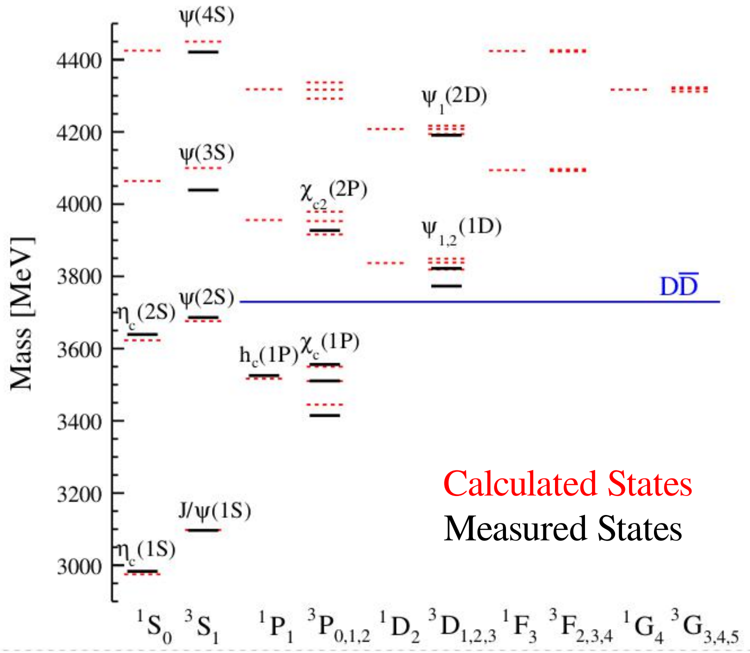
Prompt cross-section ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ in pPb 8.16 TeV

- **The χ_c states($\chi_{c0}, \chi_{c1}, \chi_{c2}$) :**
  - comprise a triplet of orbitally excited 1P charmonia.
  - $M_{J/\psi} < M_{\chi_c} < M_{\psi(2S)}$.
  - Their sequential mass differences are < 100 MeV.

- **Why study χ_c production:**
  - A useful tool to study their sensitivity to final-state nuclear effects.
  - Form an important feed-down contribution to J/ψ production, so as to clarify interpretation of the J/ψ data.
  - Efficiency factors and sources of uncertainty cancel out in the ratio, allowing for a more precise measurement.

- **The χ_c states have beeen measured in nuclear collisions by:**
  - HERA-B collaborations. [Phys. Rev. D79 (2009) 012001]
  - PHENIX collaborations. [arXiv:1305.5516]
  - **To date, the first measurement in nuclear collision at the LHC energy!!**

At LHCb
In 2016 pPb Collisions
At $\sqrt{s_{NN}} = 8.16$ TeV



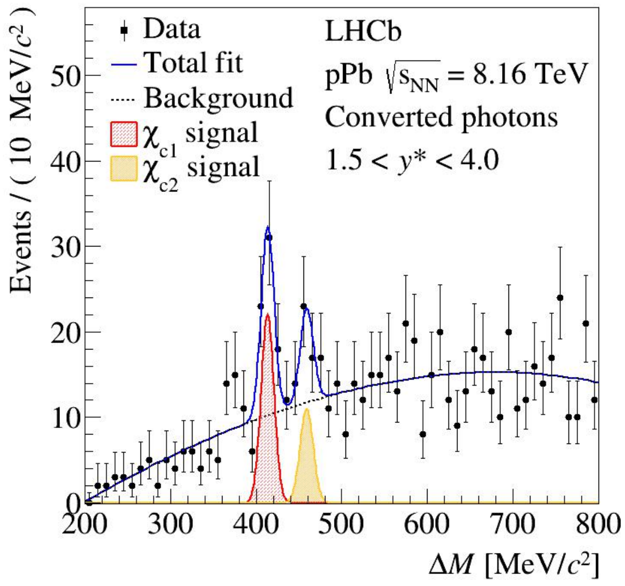
[Rev. Mod. Phys. 90, 015003 (2018)]

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

[arXiv:2103.07349]

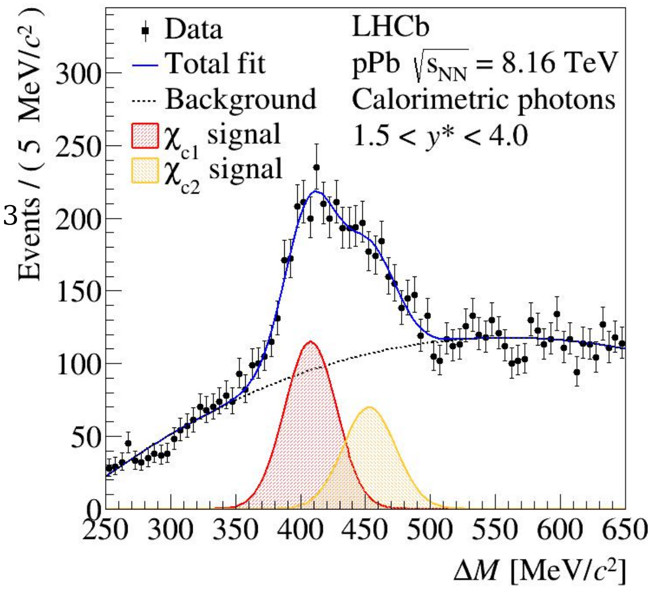
- The χ_c can be measured from their radiative decay: $\chi_c \rightarrow (J/\psi \rightarrow \mu^+\mu^-) + \gamma$, with two types of γ:

- **Converted photons:**
  - The electron and positron tracks were reconstructed in the tracking system.
  - Lower statistics but excellent mass resolution.



$N_{\chi_{c1}} = 41 \pm 9$
$N_{\chi_{c2}} = 21 \pm 8$
$\frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} = 0.51 \pm 0.23$

- **Calorimetric photons:**
  - Reconstructed through their energy deposits in the calorimetric system.
  - Higher statistics but poor mass resolution.



$N_{\chi_{c1}} = 1151 \pm 69$
$N_{\chi_{c2}} = 721 \pm 76$
$\frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} = 0.63 \pm 0.08$

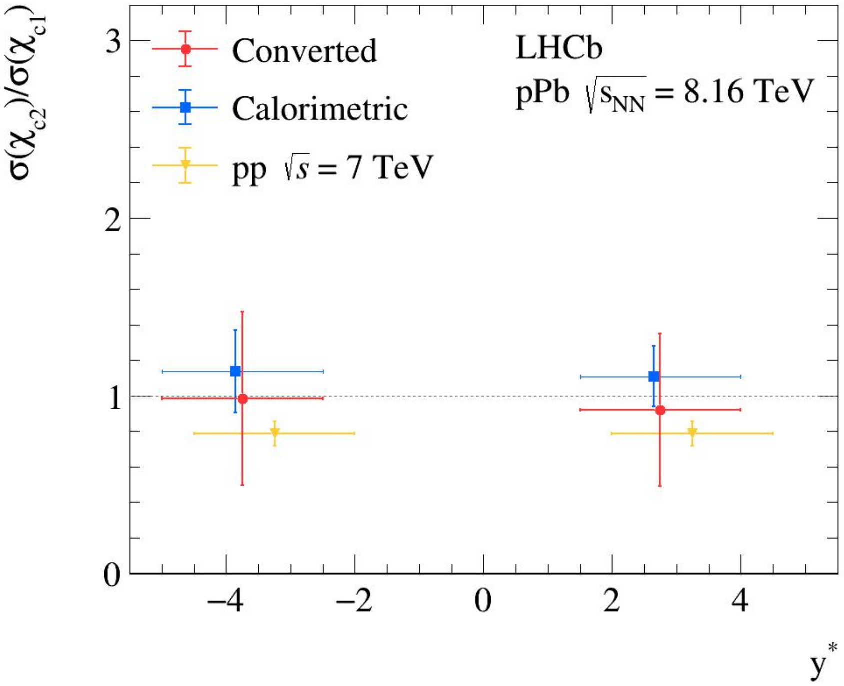
Prompt cross-section ratio $\sigma(\chi_{c1})/\sigma(\chi_{c2})$ in pPb 8.16 TeV

[arXiv:2103.07349]

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c2})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \frac{\varepsilon_{\chi_{c1}}}{\varepsilon_{\chi_{c2}}} \frac{\mathcal{B}(\chi_{c1} \to J/\psi\gamma)}{\mathcal{B}(\chi_{c2} \to J/\psi\gamma)}$$

$$\frac{\varepsilon^{acc}_{\chi_{c1}}}{\varepsilon^{acc}_{\chi_{c2}}} \frac{\varepsilon^{reco}_{\chi_{c1}}}{\varepsilon^{reco}_{\chi_{c2}}}$$

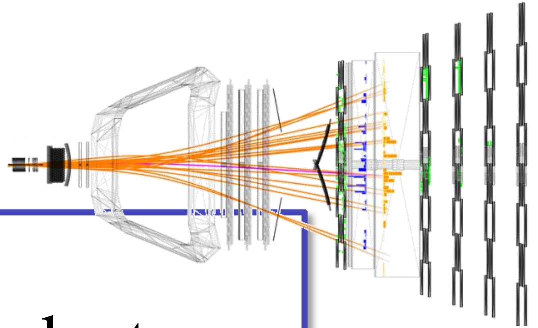
√ simulated events



- The significantly larger yield of the calorimetric sample allows more precise conclusions.
- Relative production of the χ_{c1} and χ_{c2} shows no dependence on rapidity.
- Comparing with p-p data:

$$\mathcal{R} = \frac{\sigma(\chi_{c2})/\sigma(\chi_{c1})|^{pPb}}{\sigma(\chi_{c2})/\sigma(\chi_{c1})|^{pp}} = 1.41 \pm 0.021 \pm 0.18(\text{forward})$$

➡ the nuclear effects have the same impact on both χ_{c1} and χ_{c2} states.



Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions

Phys. Rev. Lett. 126 (2021) 9, 092001

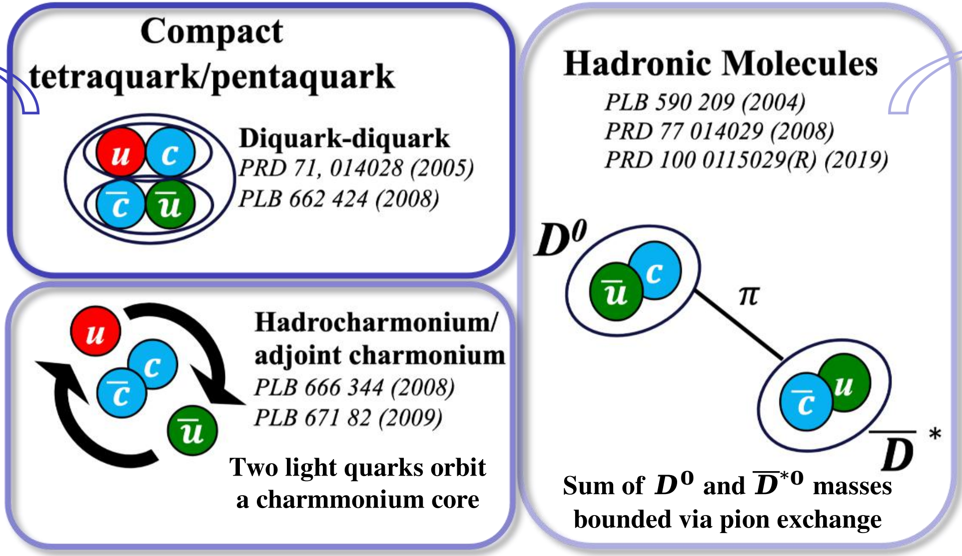
Multiplicity dependent $\chi_{c1}(3872)$ production in pp 8 TeV

[Phys. Rev. Lett. 126 (2021) 9, 092001]

- χ_{c1}(3872) is first discovered in2003 by Belle in decay of B→ $J/\psi\pi^+\pi^-$. [Phys. Rev. Lett. 91, 262001 (2003)]
- The LHCb has since measured the quantum numbers to be $J^{PC} = 1^{++}$. [Phys. Rev. Lett. 110, 222001 (2013)]
- Mass differecnce is consistent with zero:

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

- Multiple explanations explored in literature of χ_{c1}(3872):



- Tightly bound via color
- Exchange between diquarks
- Small radius: ~1fm

- Very small binding energy
- Very large radius: ~ O(10 *fm*)

[Courtesy of Matt Durham@Quark matter 2019]

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

[Phys. Rev. Lett. 126 (2021) 9, 092001]

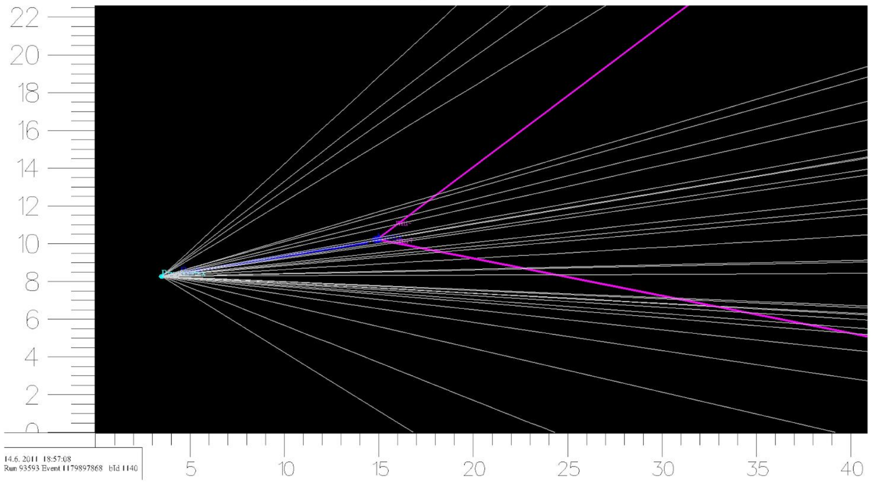
- **Prompt production:**
  - X(3872) produced at collision vertex can be subject to further interactions with co-moving particles produced in the event
  - Interact with other produced particles with break-up cross section
  - Assume no interaction at low multiplicity region
- **Production in b-decays:**
  - Hadrons containing b travel down the beampipe and decay away from the primary vertex and decay in vacuum
  - X(3872) from decays not subject to further interactions
  - Control sample

At LHCb
In pp Collisions
At 8 TeV

High multiplicity pp collisions:

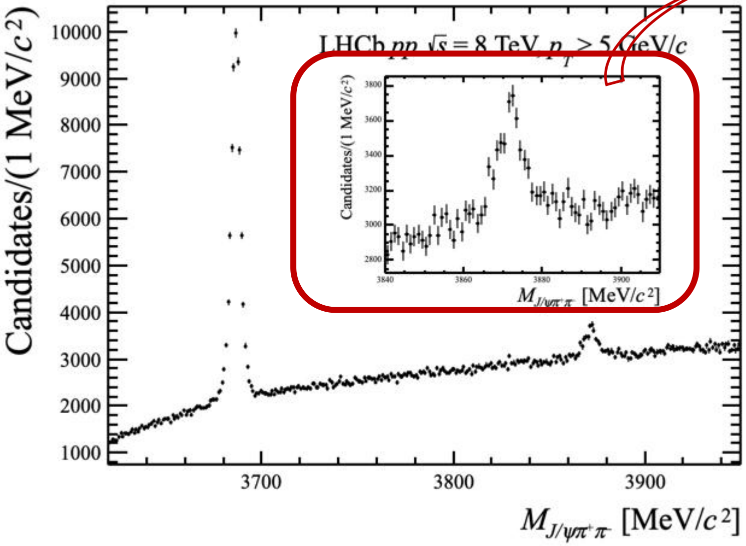
- Provides a testing ground for examing final-state effects observed on quarkonium in pA and AA
- Contributes for new constraints on the structure of $\chi_{c1}(3872)$.

Event display of B0s → $\mu^+\mu^-$ candidate [PRL 118 191801 (2017)]



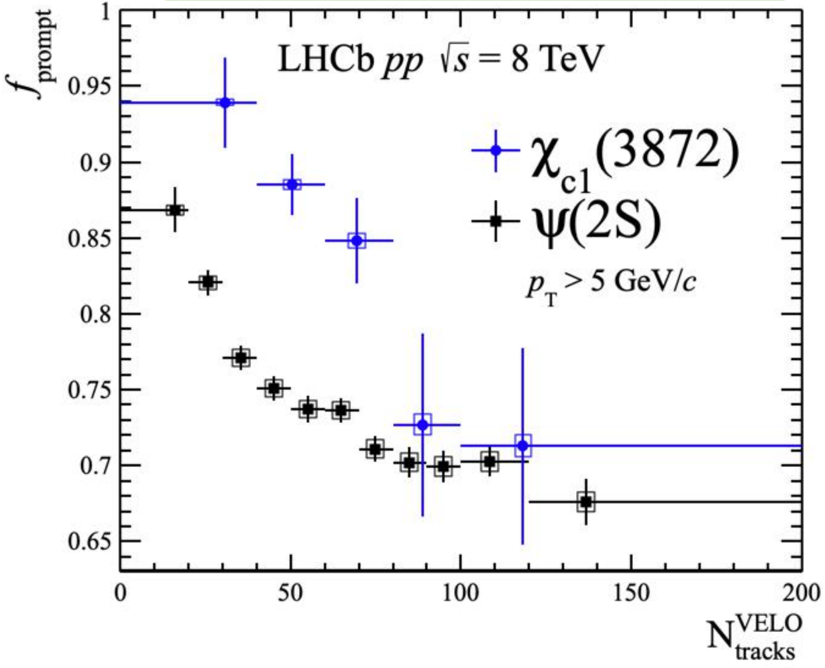
Multiplicity dependent $\chi_{c1}(3872)$ production in pp 8 TeV

[Phys. Rev. Lett. 126 (2021) 9, 092001]



χ_{c1}(3872) resonance

$$f_{prompt} = \frac{N_{prompt}}{N_{prompt} + N_{b-decay}}$$



A clear decrease of f_{promt} is seen as the multiplicity increase:

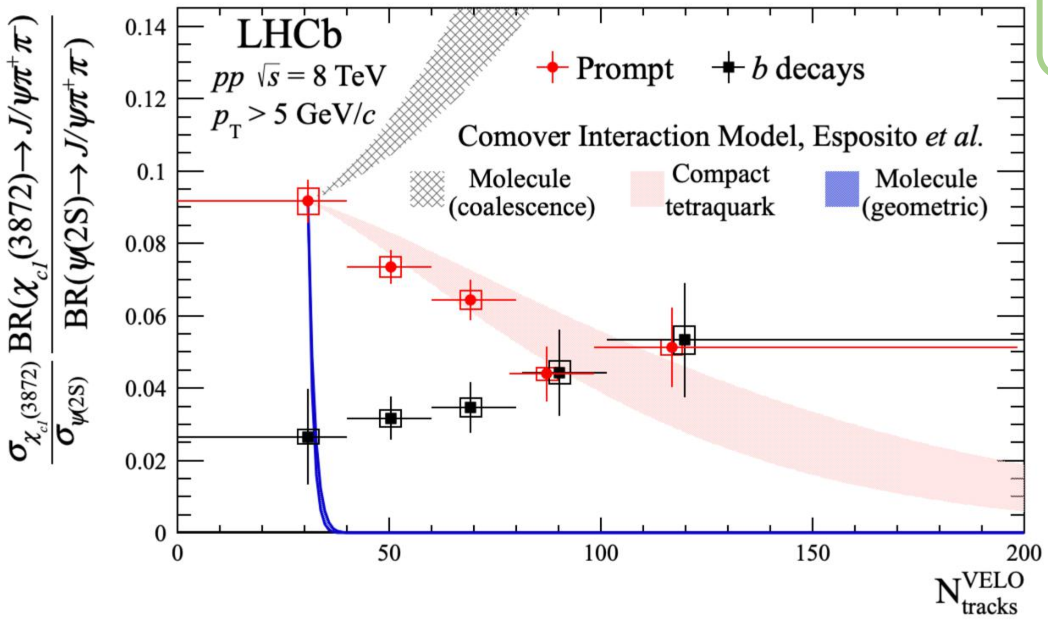
- Events with $b\bar{b}$ production naturally have higher multiplicity, due to their fragmentation into hadrons and subsequent decays.
- The suppression of prompt ψ(2S) and χc1(3872) production via interactions with other particles produced at the vertex.

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

[Phys. Rev. Lett. 126 (2021) 9, 092001]

- The ratio of $\psi(2S)$ and $\chi_{c1}(3872)$ cross section is given by:

$$\frac{\sigma_\chi}{\sigma_\Psi}\frac{\mathcal{B}_\chi}{\mathcal{B}_\Psi} = \frac{N_\chi}{N_\Psi}\frac{f^\chi{}_{prompt}}{f^\Psi{}_{prompt}}\frac{\varepsilon^{acc}_\Psi}{\varepsilon^{acc}_\chi}\frac{\varepsilon^{reco}_\Psi}{\varepsilon^{reco}_\chi}\frac{\varepsilon^{PID}_\Psi}{\varepsilon^{PID}_\chi}$$

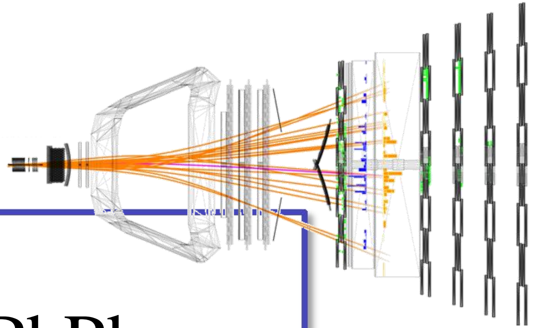


- **Prompt component:**
  $\chi_{c1}(3872)$ production is suppressed relative to $\psi(2S)$ as multiplicity increases.

- **b-decay component:**
  No significant change in relative production, as expected for decays in vacuum.

- 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 χc1(3872) is a **charm-meson molecule.**

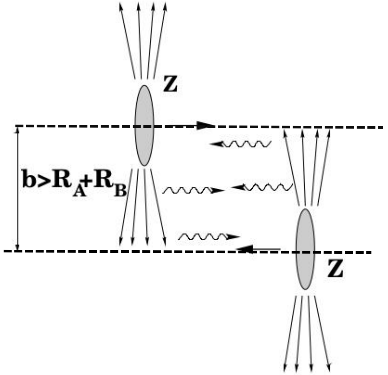


Low-p_T J/ψ photo-production in PbPb peripheral collisions at $\sqrt{s_{NN}} = 5$ TeV with the LHCb experiment

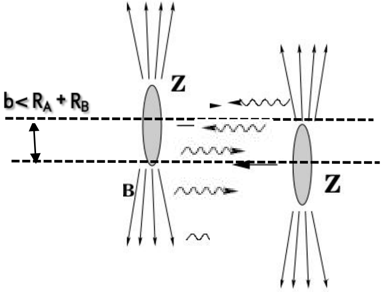
LHCb-PAPER-2020-043
(to be submitted to Phys. Rev. Lett)

Coherent J/ψ photoproduction in PbPb 5 TeV

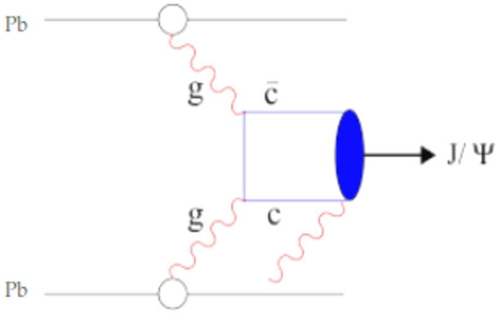
- **Ultra-Peripheral Collisions(UPCs):**
  impact parameter b is **larger than** the sum of the radii Ra and R_b of the two colliding nuclei, thus J/ψ mesons can be coherently produced without nuclear breaking up.
- **Peripheral Collisions:** b is **smaller than** the sum of the radii
- Coherent J/ψ production can also occurs in peripheral collision with very low-p_T excess.



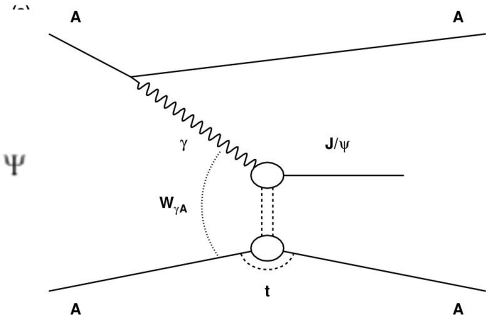
Ultra-Peripheral Collision



Peripheral Collision



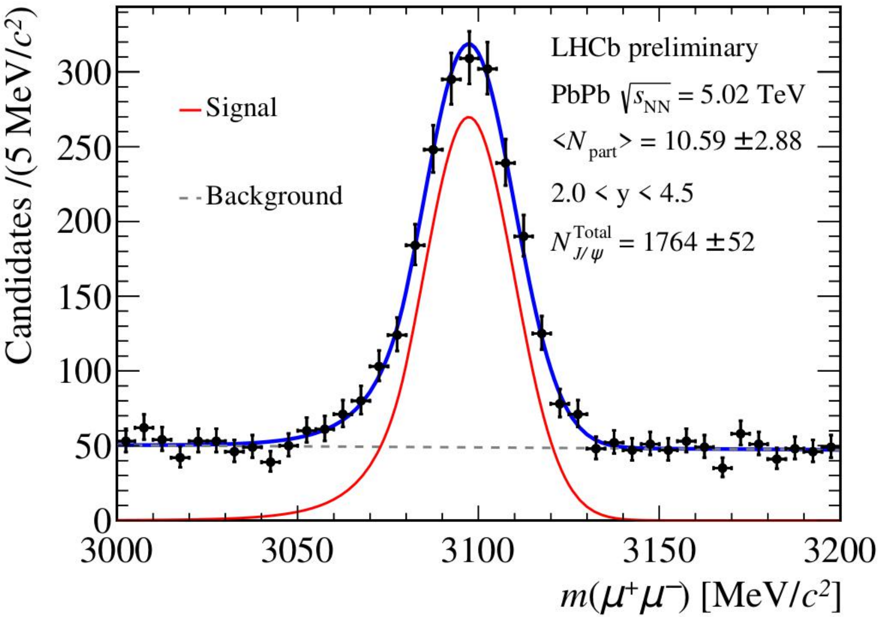
Hadronic production



Coherent production

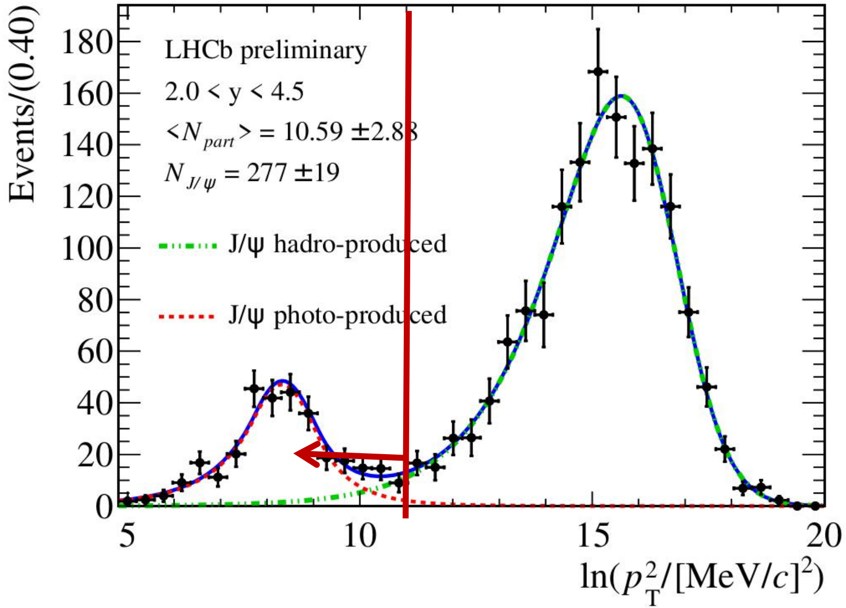
Coherent J/ψ photoproduction in PbPb 5 TeV

[LHCb-PAPER-2020-043]



In one representative bin of centrality for J/ψ mesons with:

p_T <15.0 GeV/c
2.0<y<4.5



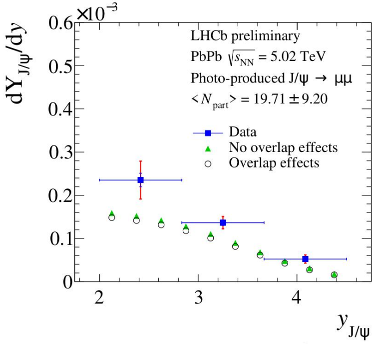
The photo-produced J/ψ candidates are visible in:

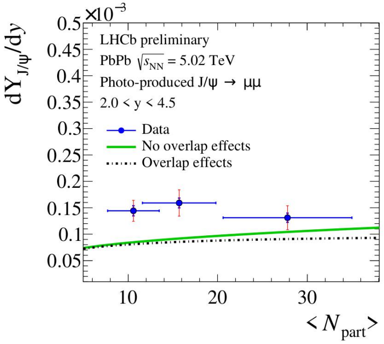
$\log(p_T)^2 < 11$
p_T range: **0 to ~250 MeV/c**

Coherent J/ψ photoproduction in PbPb 5 TeV

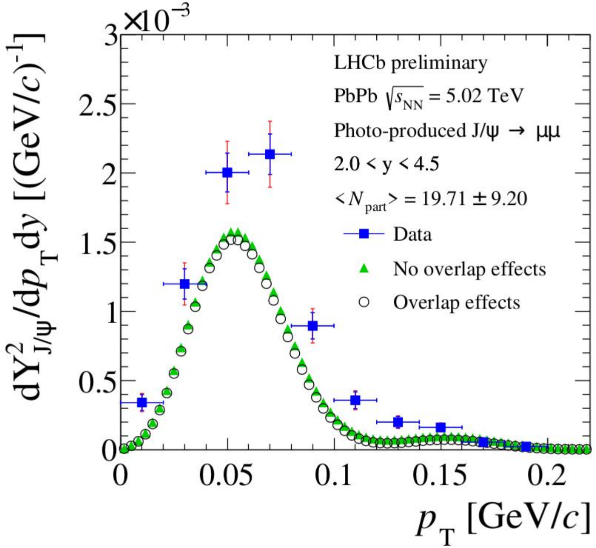
[LHCb-PAPER-2020-043]

The First PbPb Results At LHCb!





$$\frac{dY^i_{J/\psi}}{dy} = \frac{N^i_{J/\psi}}{\mathcal{B}\, N^i_{\rm MB}\, \varepsilon_{\rm tot}{}^i\, \Delta y}, \quad \frac{d^2Y^i_{J/\psi}}{dp_{\rm T}dy} = \frac{dY^i_{J/\psi}}{dy} \times \frac{1}{\Delta p_{\rm T}},$$



- LHCb measured the yield of coherently photo-produced prompt J/ψ events at very low p_T.
- Yields are displayed as a function of **rapidity** and **transverse momentum** of the J/ψ meson in intervals of **Npart**.
- 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.

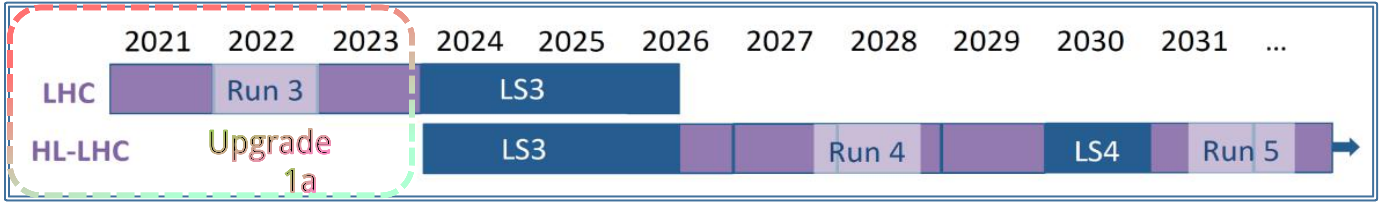
Summary

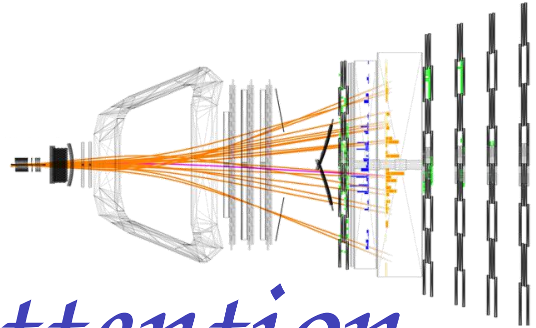
- **LHCb is the dedicated forward detector:**
  - LHCb is a quarkonia friendly detector as proven by many precise results in **pp, pPb and PbPb** collisions!

- **Recent quarkonium results from LHCb have been discussed:**
  - **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 χc1(3872) is a tetraquark or a charm-meson molecule is still a point of debate.
  - Measurement of photo-produced J/ψ in peripheral PbPb collisions is the most precise to date.

  The first PbPb results at LHCb!

- **LHCb's future is bright for quarkonium production studies:**





Many thanks for your attention

Comments are always welcome!