Charmonium production measurements in large systems at LHCb

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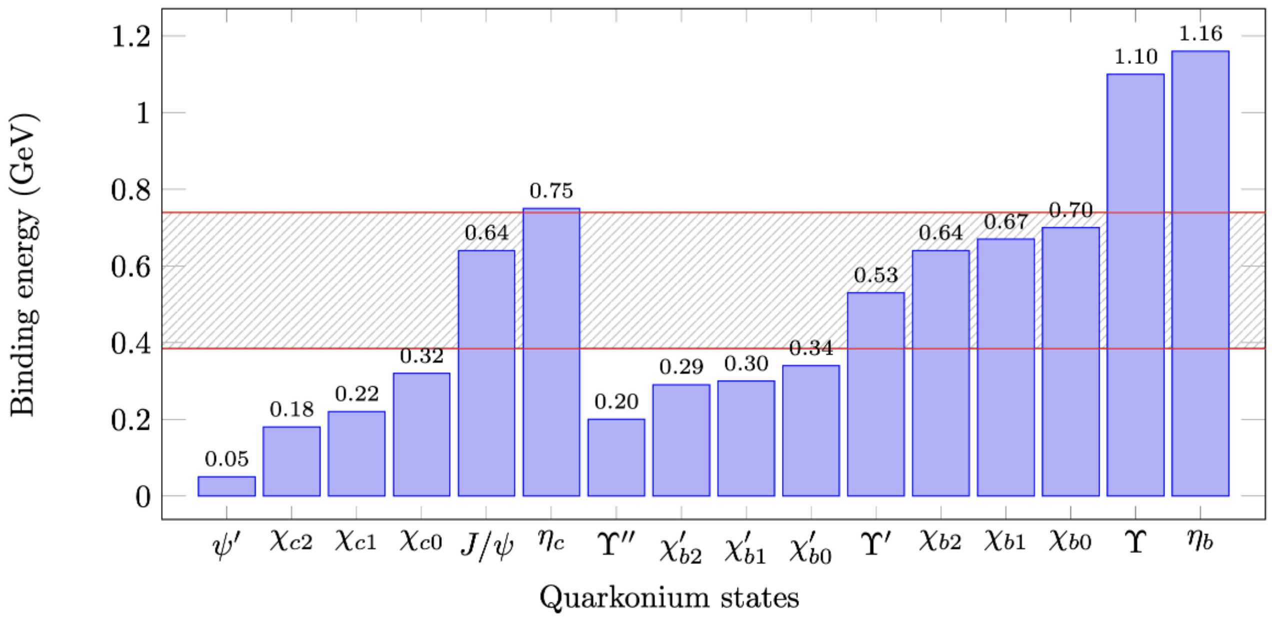
Outline

- Motivation
  - Centrality dependence of charmonium production ratio in PbPb collisions
- LHCb experiment
- Analysis strategy
- New results
- Summary and outlook

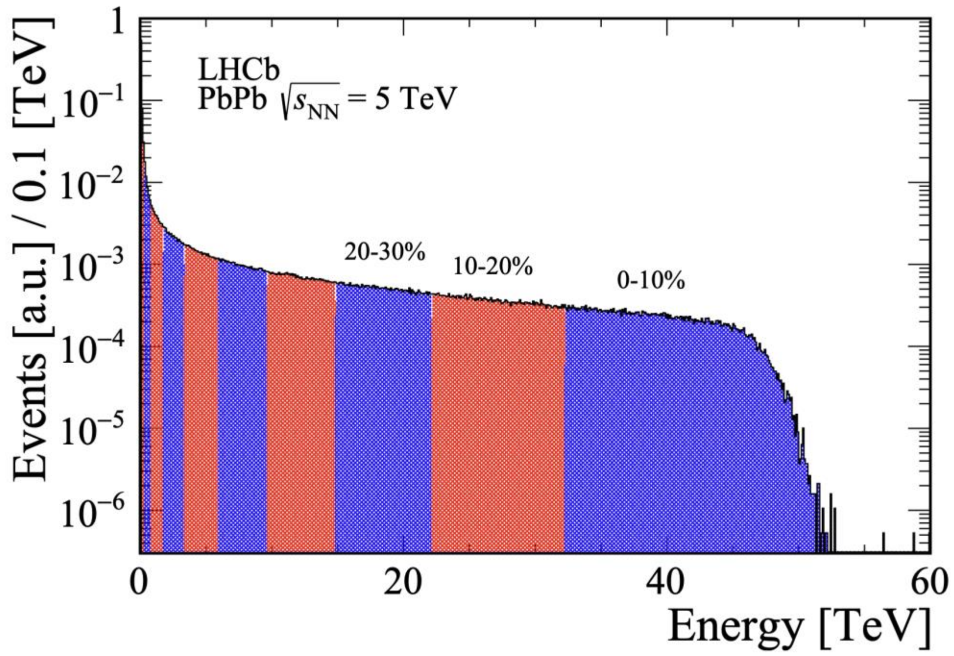
Motivation: Probe for hot nuclear matter effects

T_0~ 385-740 MeV

J. Phys. G32 (2006) R25
Phys. Lett. B754 (2016) 235



JINST **17** P05009

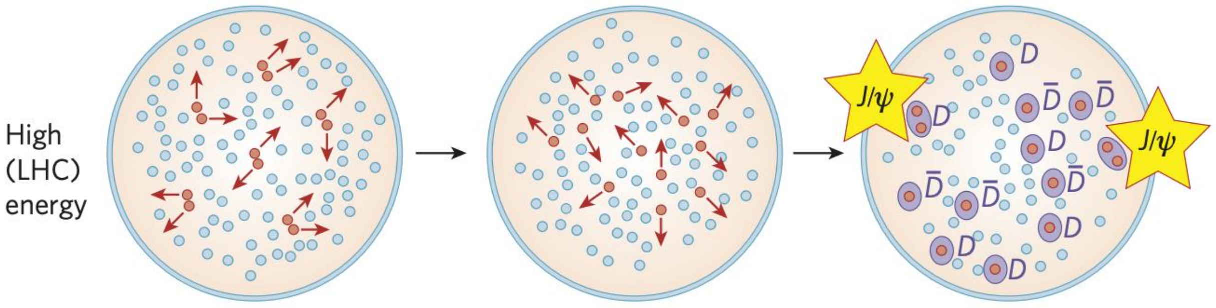


- The quarkonium states would dissociate in the hot and dense medium produced in heavy-ion collisions according to their different binding energies.
  - Stronger dissociation expected for $\psi(2S)$ w.r.t. J/ψ since lower binding energy.
- Relative charmonium yield expected to change with different temperatures achieved in different centrality regions.

Motivation: Charmonium production

- Suppression and re-combination

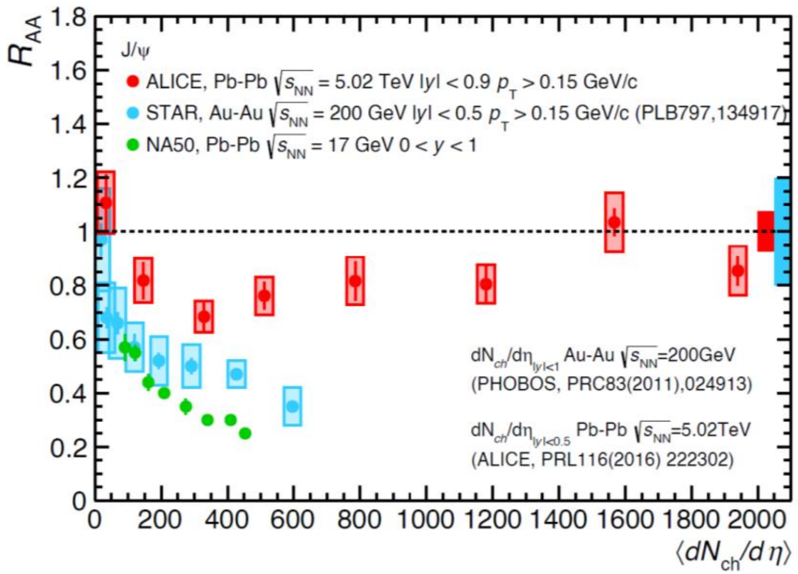
Nature 448 (2007) 302



- Suppression of the charmonium is due to colour screening.
- Regeneration contribution to the charmonium is significantly higher than at RHIC or SPS.

$$R_{AA} = \frac{dN/dp_T|_{PbPb}}{N_{coll}\, dN/dp_T|_{pp}}$$

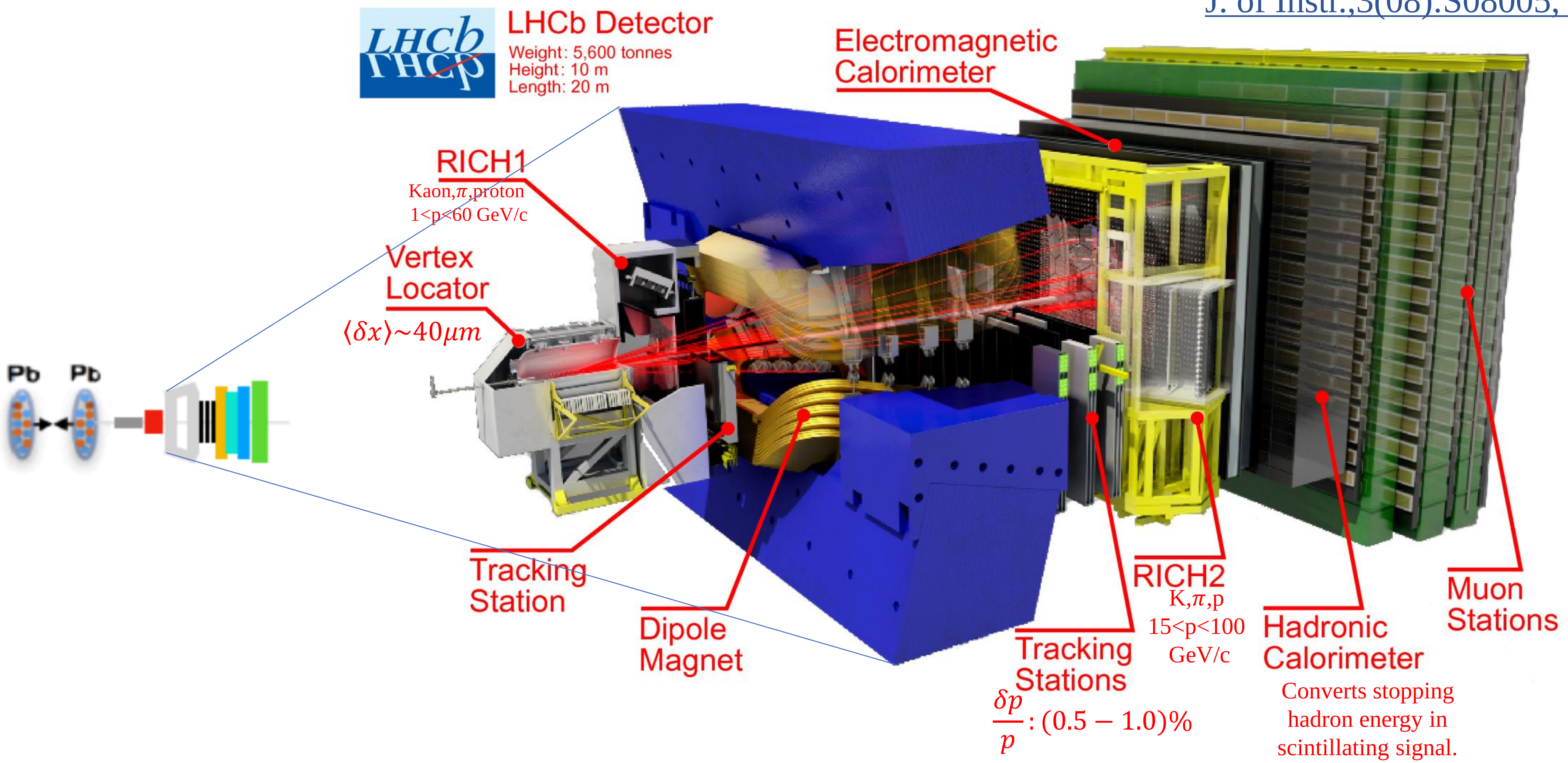
Eur.Phys.J.C 84 (2024) 8, 813



$$R_{AA}^{SPS} < R_{AA}^{RHIC} < R_{AA}^{LHC}$$

LHCb detector

J. of Instr.,3(08):S08005, 2008



Analysis strategy

- $J/\psi(\psi(2S)) \to \mu^+\mu^-$ channel
- Dataset

Year	luminosity (μb^{-1})	center-of-mass energy
2018	228 ± 10	5.02 TeV

Particle Data Group (lbl.gov)

$\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$
$\mathcal{B}(\psi(2S) \to \mu^+\mu^-) = (0.80 \pm 0.06)\%$

- The production ratio is defined as

$$\frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-) \times \sigma(\psi(2S))}{\mathcal{B}(J/\psi \to \mu^+\mu^-) \times \sigma(J/\psi)} = \frac{N(\psi(2S)) \times \varepsilon(J/\psi)}{N(J/\psi) \times \varepsilon(\psi(2S))},$$

where N is the signal yield and ε is the total efficiency.

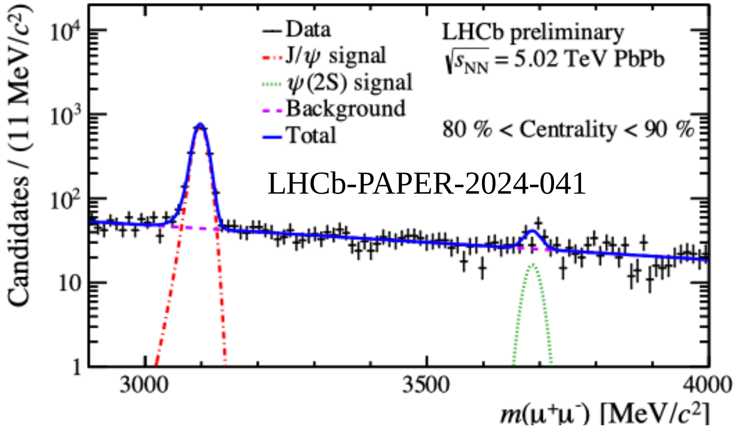
- The event activity is represented by centrality or $\langle N_{part} \rangle$.

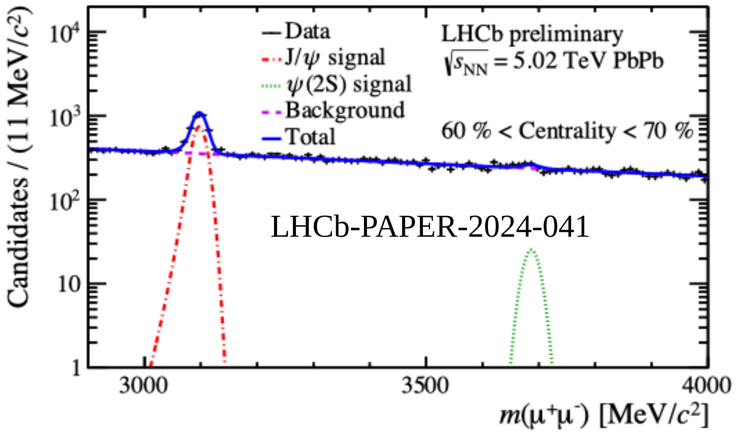
JINST 17 (2022) 05, P05009

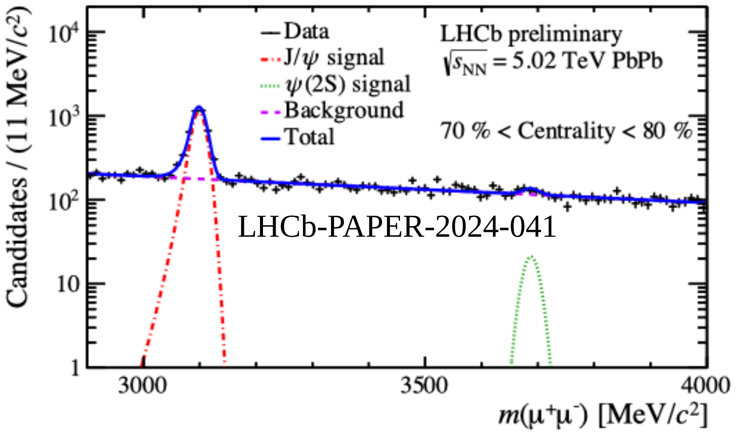
centrality(%)	100 - 90	90 - 80	80 - 70	70 – 60
$\langle N_{part} \rangle$	2.4 – 5.5	5.5 – 13	13 – 26.5	26.5 – 48

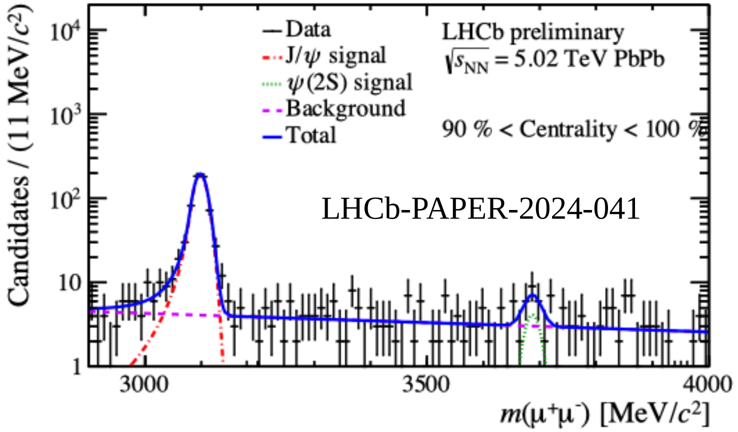
Analysis strategy

- Signal extraction
  - An unbinned extended max-likelihood fit is performed in each centrality bins.
    Signal J/ψ: Crystal ball function,
    Signal $\psi(2S)$: Gaussian function,
    Background: exponential distribution.









Few $\psi(2S)$!

Analysis strategy

- Efficiency determination

  [Phys. Rev. C92 (2015) 034906]

  - Simulated sample with EPOS event generator.
  - The total efficiency is separated into 4 parts: acceptance, reconstruction & selection, muon identification and trigger.
  - The muon identification efficiency is evaluated using calibration sample.
    - An extrapolation of multiplicity for pp calibration sample is used due to the PbPb calibration is unavailable.
  - The simulated sample are reweighted to match the data when calculating efficiency.
    - Kinematic and multiplicity distribution.
  - The estimation of efficiency is also performed in each centrality bins.

Analysis strategy

- Systematic uncertainty

Source	Uncertainty(%)
Signal fit model	0.5 – 2.2
Background fit model	0.5 – 6.3
Reweighting procedure	0.1 – 0.2
Muon identification efficiency	0.1 – 2.8
Simulation sample size	0.5 – 1.0
Trigger efficiency	< 0.1

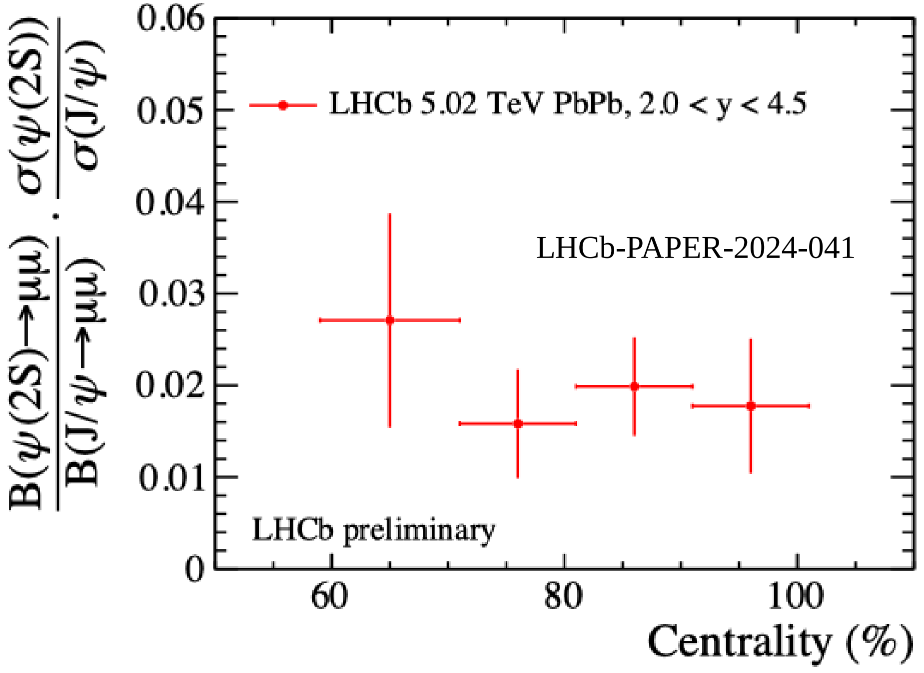
LHCb-PAPER-2024-041

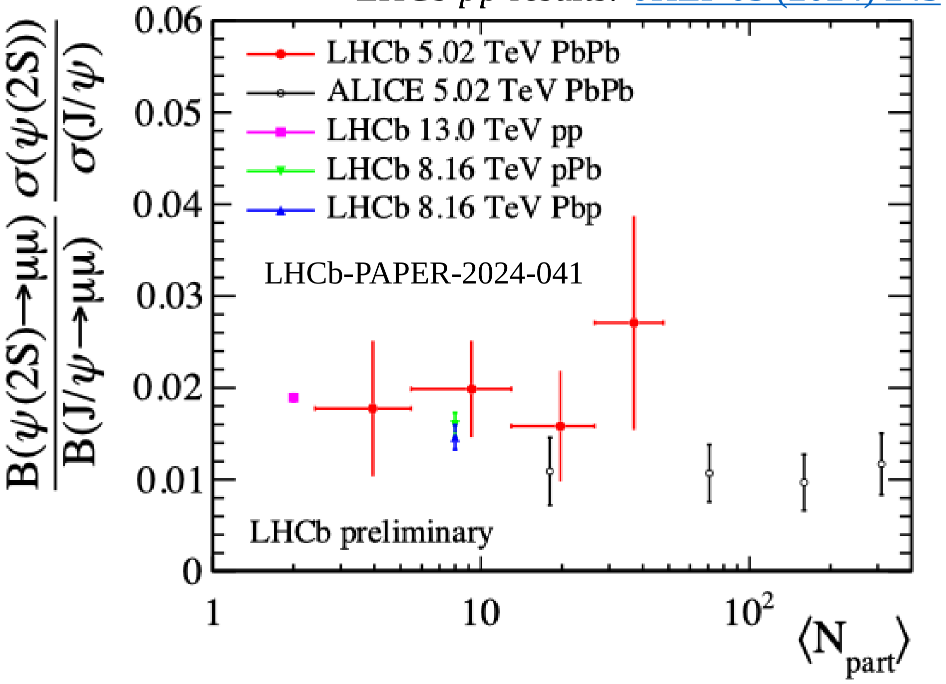
The total systematic uncertainty is computed as the sum in quadrature of each contribution.

New results

- The production ratios as a function of event activity

ALICE results: [Phys. Rev. Lett. 132 (2024) 042301]
LHCb *p*Pb results: [JHEP 04 (2024) 111]
LHCb *pp* results: [JHEP 05 (2024) 243]





- An flat centrality dependence in agreement with ALICE results within the uncertainties.

New results

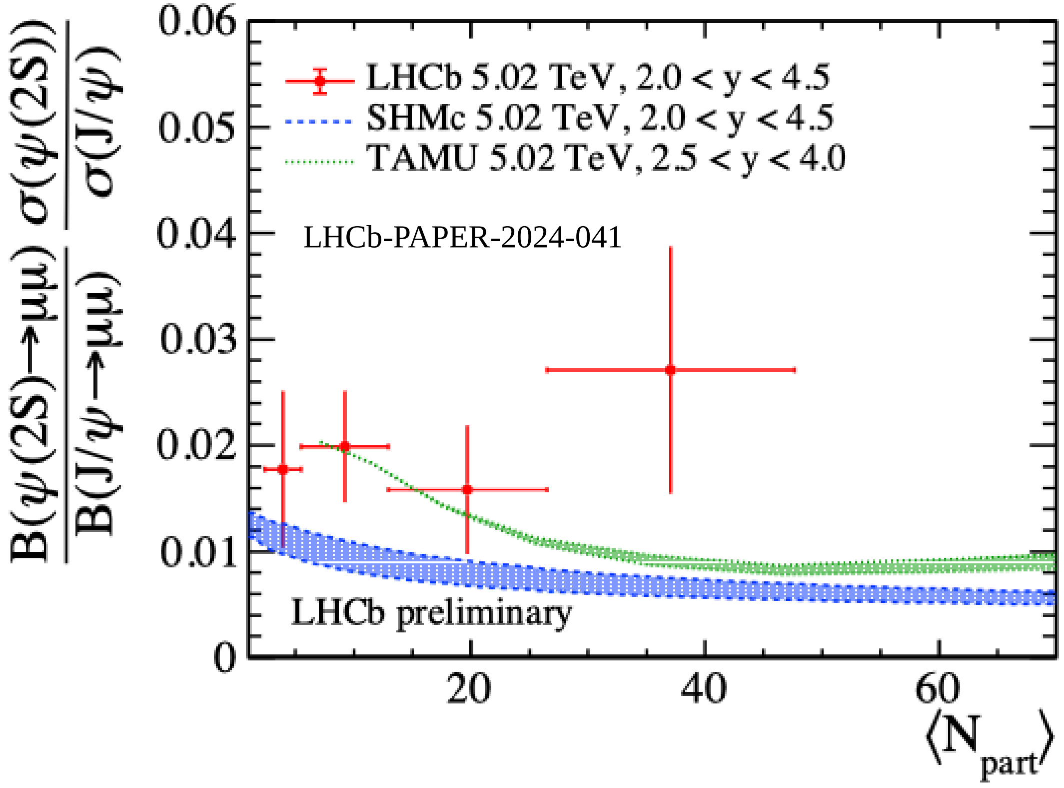
- The production ratios as a function of $\langle N_{part} \rangle$

TAMU: NPA 943 (2015) 147
SHMc: Nature 561 no. 7723 (2018) 32

The TAMU model predictions are in better agreement with the experimental result, especially in the lower multiplicity intervals.

The SHMc tends to slightly underestimate the data although showing a flat ratio trend as a function of the centrality.

Regeneration prefer to be occurred during the medium evolution (TAMU) than the freeze-out (SHMc).



Summary and outlook

- It is the first measurement of prompt charmonium production in large systems at LHCb.
- The production ratio as a function of centrality shows a flat trend and is in agreement with ALICE results.
- The production ratio also compares with 2 theoretical predictions, where TAMU model is in a better agreement while SHMc model has a slightly underestimation.

- The nuclear modification factor ratios are in progress.
- The run3 data would reach the semi-central collisions with higher statistics.

Thanks for listening!

Backup

5.1.5 Centrality classes

After obtaining the simulated distribution of energy deposited in the ECAL, which corresponds only to the hadronic contribution, the distribution can be divided into centrality classes. To determine the ECAL energy boundary values for each class, the simulated distribution is integrated from a value of deposited energy to infinity, until a starting value is found giving a percentage of the total integral. Defining I_T as the total integral of the energy distribution, the ECAL energy requirement for any percentage p of centrality, would be the value of E_p such that

$$\left(p \times 10^{-2}\right) I_T = \int_{E_p}^{\infty} \frac{\mathrm{dN}}{\mathrm{d}E}\mathrm{d}E. \tag{5.5}$$

Similarly, as an example, the centrality class $(10-20)\%$ would correspond to the events depositing an energy E such that $E_{20} < E < E_{10}$.

One million PbPb collisions are simulated using the corresponding nucleon-nucleon cross-section $\sigma_{\mathrm{NN}}^{\mathrm{inel}} = 67.6\,\mathrm{mb}$ for a centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$, and one million PbNe collisions were simulated using the corresponding nucleon-nucleon cross-section $\sigma_{\mathrm{NN}}^{\mathrm{inel}} = 35.4\,\mathrm{mb}$ for a centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 69\,\mathrm{GeV}$. The uncertainty on the nucleon-nucleon cross-sections is considered in the corresponding systematic uncertainty treatment in section 6.2.

The N_{part} and N_{coll} values of every simulated collision are then computed. With these numbers, the number of ancestors N_{anc} is defined as

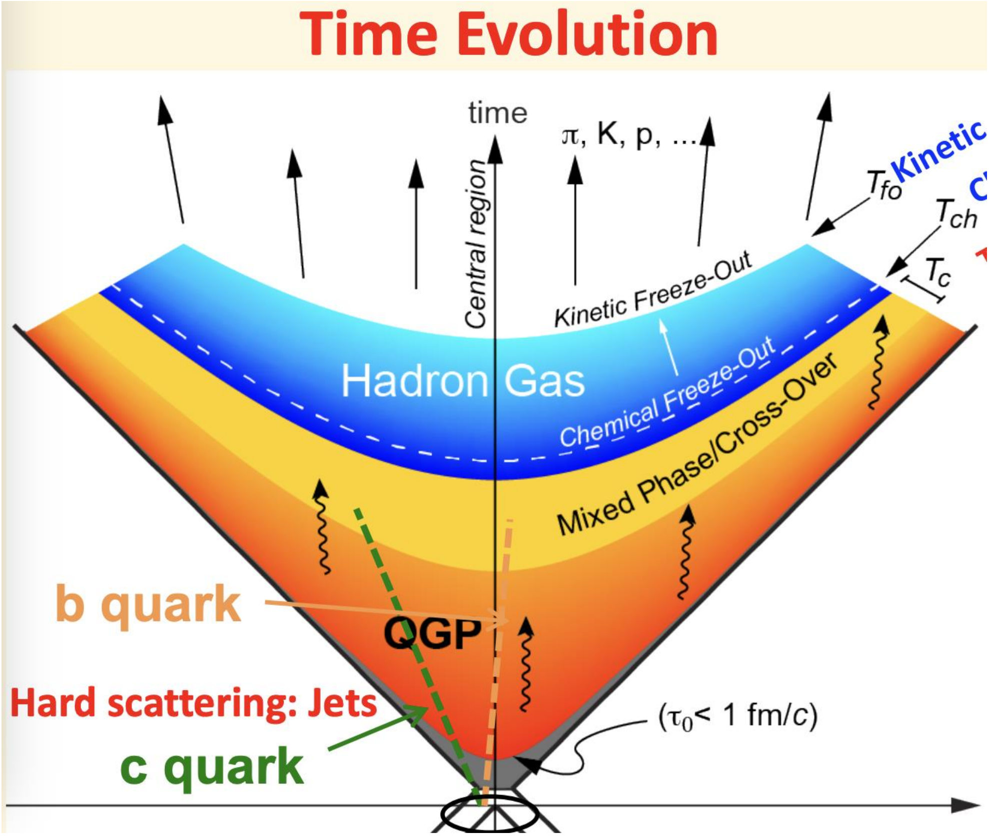
$$N_{\mathrm{anc}} = f \times N_{\mathrm{part}} + (1-f) \times N_{\mathrm{coll}}, \tag{5.1}$$

which effectively scales with the number of sources of particle production, with a relative weight for the participating nucleons and the number of collisions. This is motivated by the fact that the particle multiplicity is expected to scale with N_{part} when soft processes dominate and to scale with N_{coll} when hard processes dominate [17–21]. Below a centre-of-mass energy of about 100 GeV soft processes are expected to dominate. The parameter f determines the fraction of soft processes that contribute to the particle production and has to be determined with a fit. In figure 6, the distributions of N_{part}, N_{coll} and N_{anc} in simulation are displayed with, as an example, $f = 0.751$ for the PbPb case.

To get the distribution of particles originating from the collision, N_{anc} is convoluted with an NBD which has been extensively used to model particle production and has been shown to be a reasonable approach at diverse energy and rapidity regimes [22–26]. The NBD is given in its discrete form by

$$P_{p,k}(n) = \frac{(n+k-1)!}{n!(k-1)!} p^k (1-p)^n, \tag{5.2}$$

with $p = \left(\frac{\mu}{k}+1\right)^{-1}$, where μ and k are parameters related to the mean and spread of the NBD respectively, and n is the number of particles that are produced and deposited energy in the ECAL.


Time Evolution
time
π, K, p, ...
Central region
T_{fo}
Kinetic
T_{ch}
T_c
Kinetic Freeze-Out
Hadron Gas
Chemical Freeze-Out
Mixed Phase/Cross-Over
b quark
QGP
Hard scattering: Jets
c quark
(τ_0< 1 fm/c)