Quarkonium production in LHCb at pp collisions

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on behalf of the LHCb Collaboration

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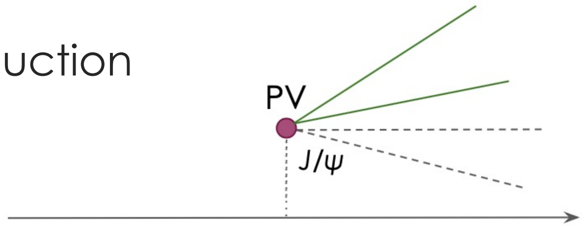
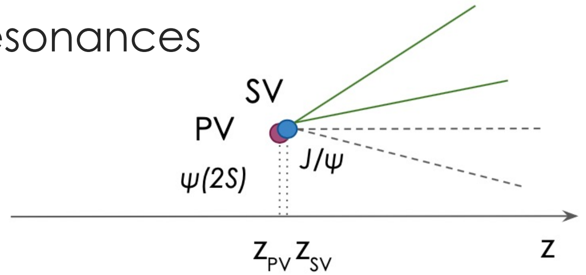
Qarkonium: What and Where from?

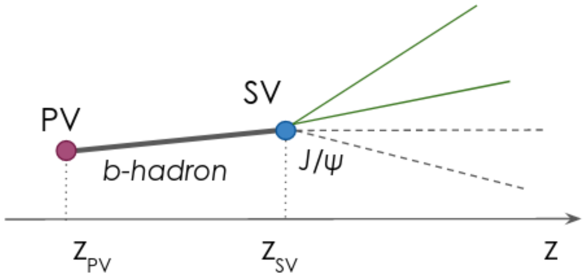
- **What?**
  - a bound state of two heavy quarks (c or b)
- **Where from?**
  - prompt hadroproduction



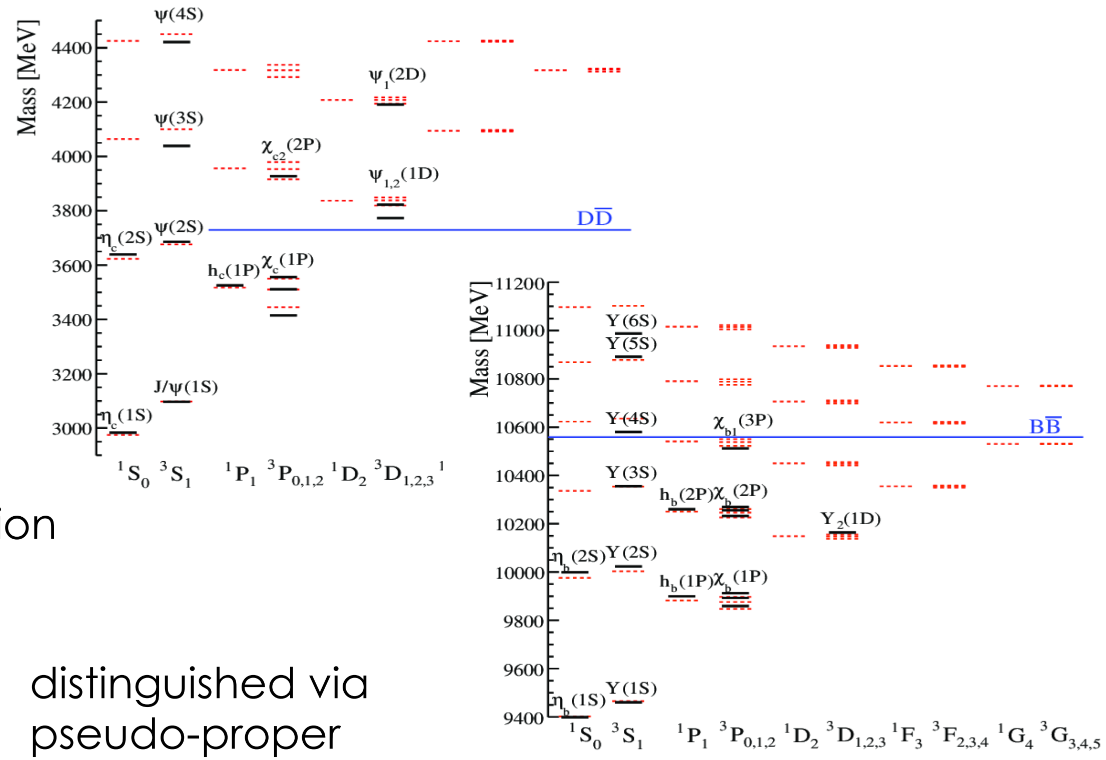
  - decays of higher resonances



  - production in b-hadron decays / non-prompt (charmonium only)



prompt production



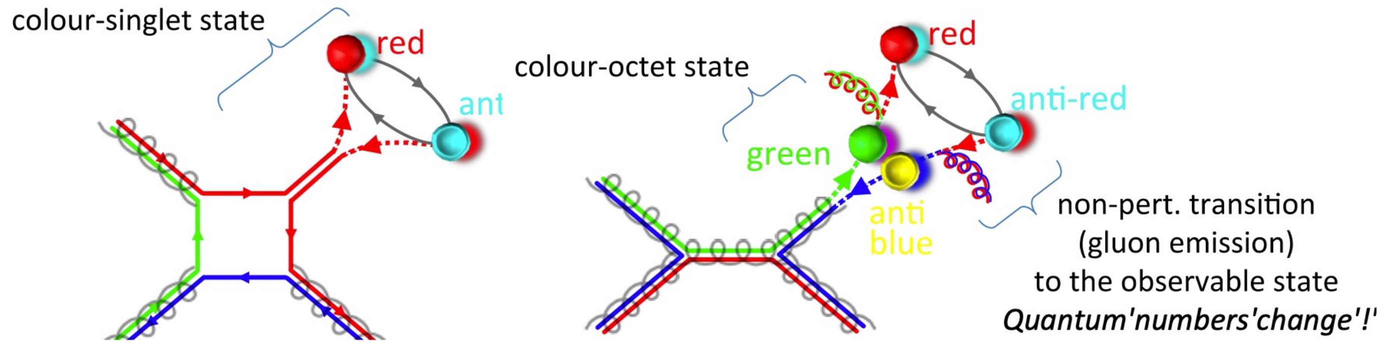
distinguished via pseudo-proper decay time

$t_z = \frac{z_{SV}-z_{PV}}{p_z} M_{q\bar{q}}$ or $\tau = \frac{L_{xy}}{p_T} M_{q\bar{q}}$

PV – primary vertex
SV – secondary vertex

Quarkonium production: Models

- **No consensus on the quarkonium production mechanism**
- Nearly all approaches assume **factorisation** between the **$Q\bar{Q}$ formation** and its **hadronization** into a meson
- Essential difference in various approaches is in the **description of the hadronization:**
  - **Colour evaporation model (CEM):** application of quark-hadron duality; only the invariant mass matters;
  - **Colour-singlet model (CS)**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} as the final-state quarkonium;
  - **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state;



Pictures by Pietro Faccioli

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Quarkonium production: NRQCD

- Two scales of production: hard process of **$Q\bar{Q}$ formation** and soft scale **hadronization of $Q\bar{Q}$**
- **Factorization**: $d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times < O^H(n) >$
  - **Short distance**: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair
  - **Long distance matrix elements (LDMEs)**, non-perturbative part
  - Both **CS** and **CO states** are allowed with varying probabilities; LDMEs from experimental data
- **Universality**: same LDMEs for different √s, prompt production and production in b-decays
- **Heavy-Quark Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states

$$\langle \mathcal{O}^{\eta_c}_{1,8}(^1S_0)\rangle = \frac{1}{3}\langle \mathcal{O}^{J/\psi}_{1,8}(^3S_1)\rangle$$

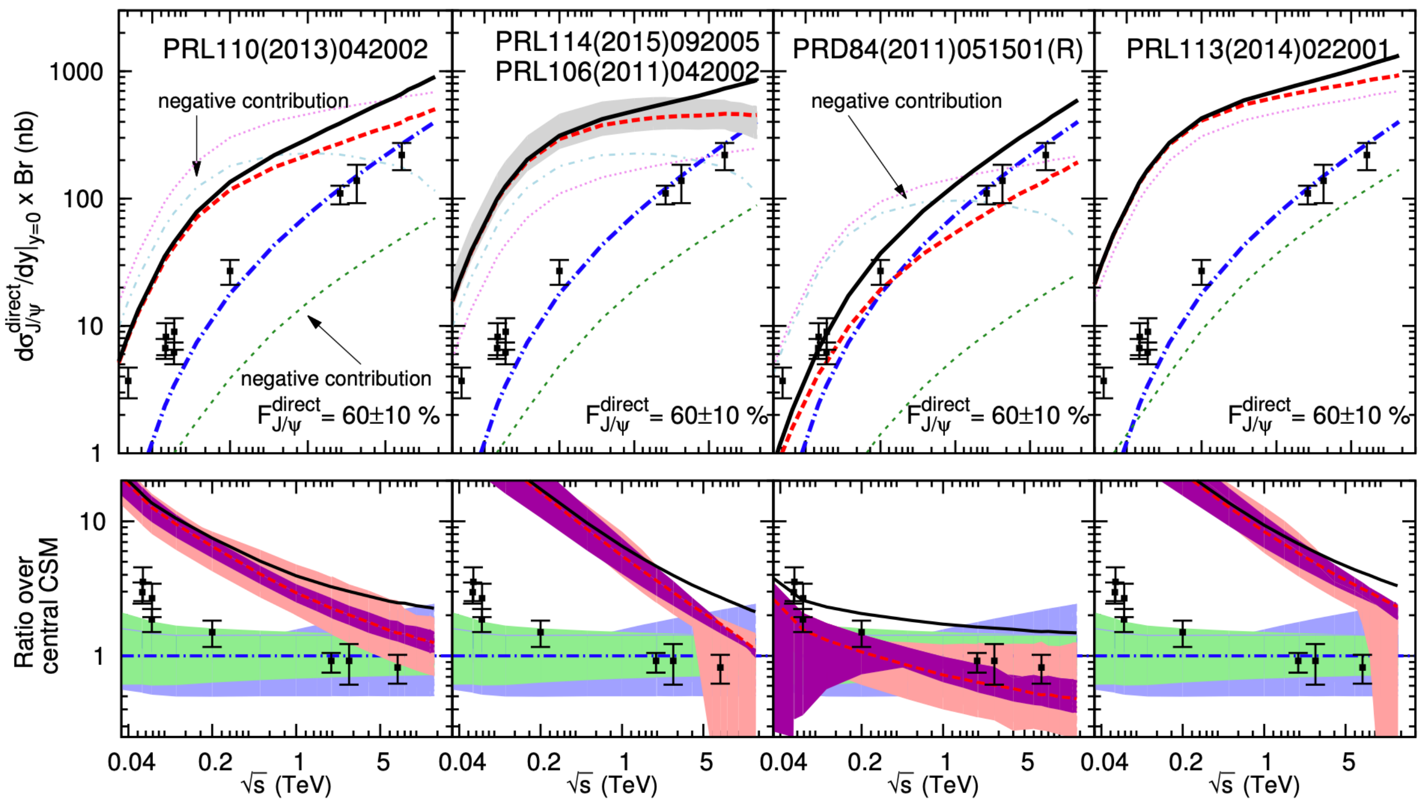
$$\langle \mathcal{O}^{\eta_c}_{8}(^3S_1)\rangle = \langle \mathcal{O}^{J/\psi}_{8}(^1S_0)\rangle$$

$$\langle \mathcal{O}^{\eta_c}_{8}(^1P_1)\rangle = 3\langle \mathcal{O}^{J/\psi}_{8}(^3P_0)\rangle$$

Quarkonium production: Current status

Eur.Phys.J.C 75 (2015) 7, 313
Phys.Rept. 889 (2020) 1-106

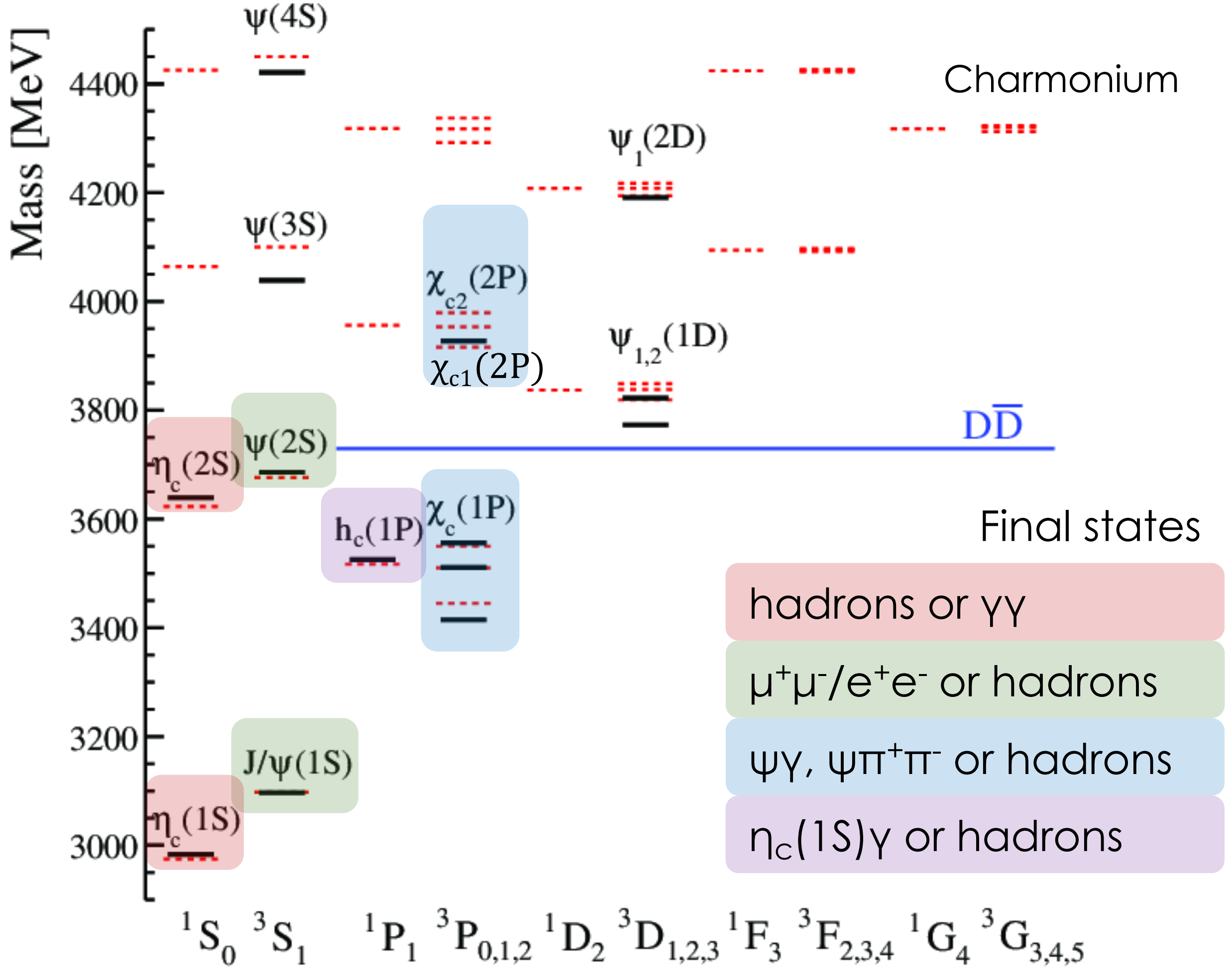
- **Existing challenges**:
  - simultaneous description of **J/ψ production** and **polarization**
  - simultaneous description of **η_c production** and **J/ψ production** and **polarization**
  - negative contribution in the cross-section
  - CEM does not describe P-waves production
  - …
- **New sources of input:**
  - Precise study of pseudoscalar states
  - Asociated quarkonia production
  - Production in heavy-ion collisions
  - Non-conventional qurakonium
  - …

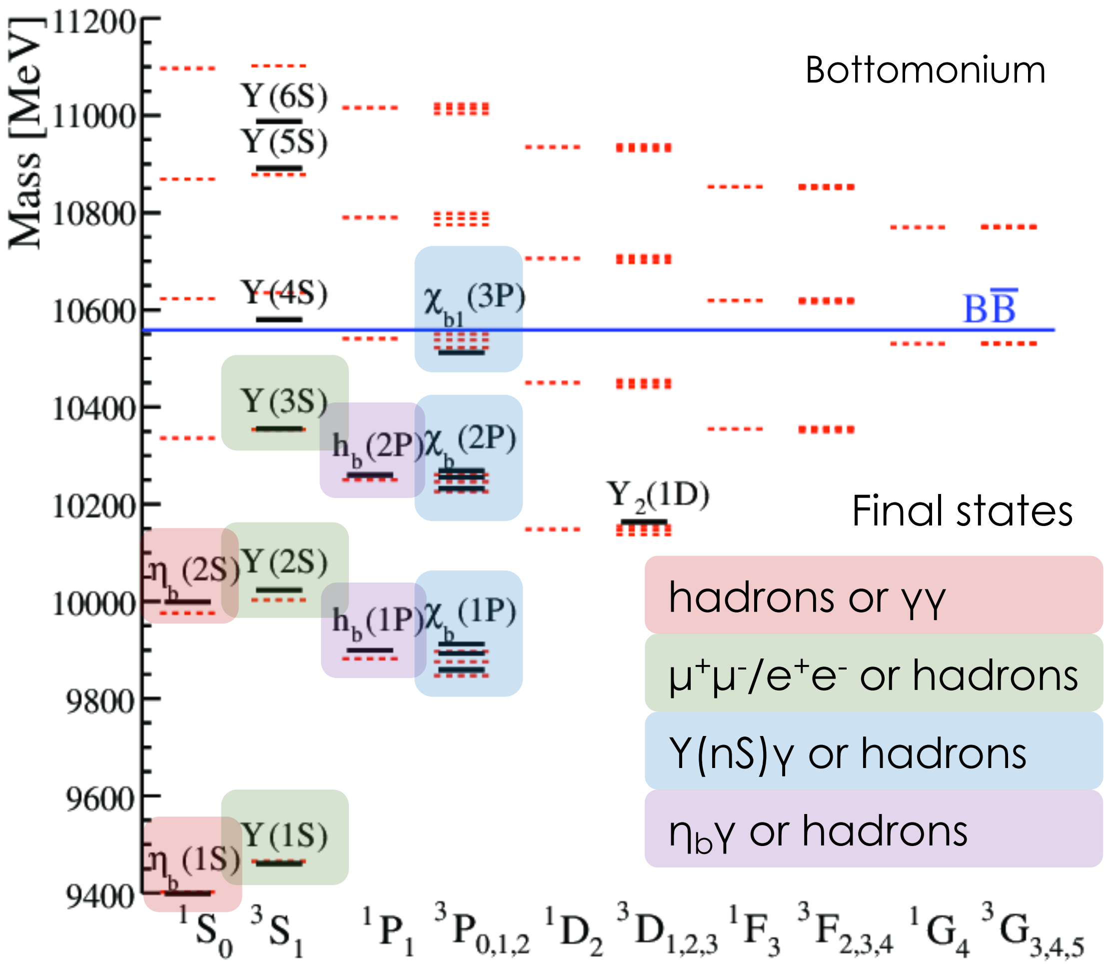


Qarkonium: How to access?

Rev.Mod.Phys 90 (2018) 015003

- Current status of quarkonium spectrum



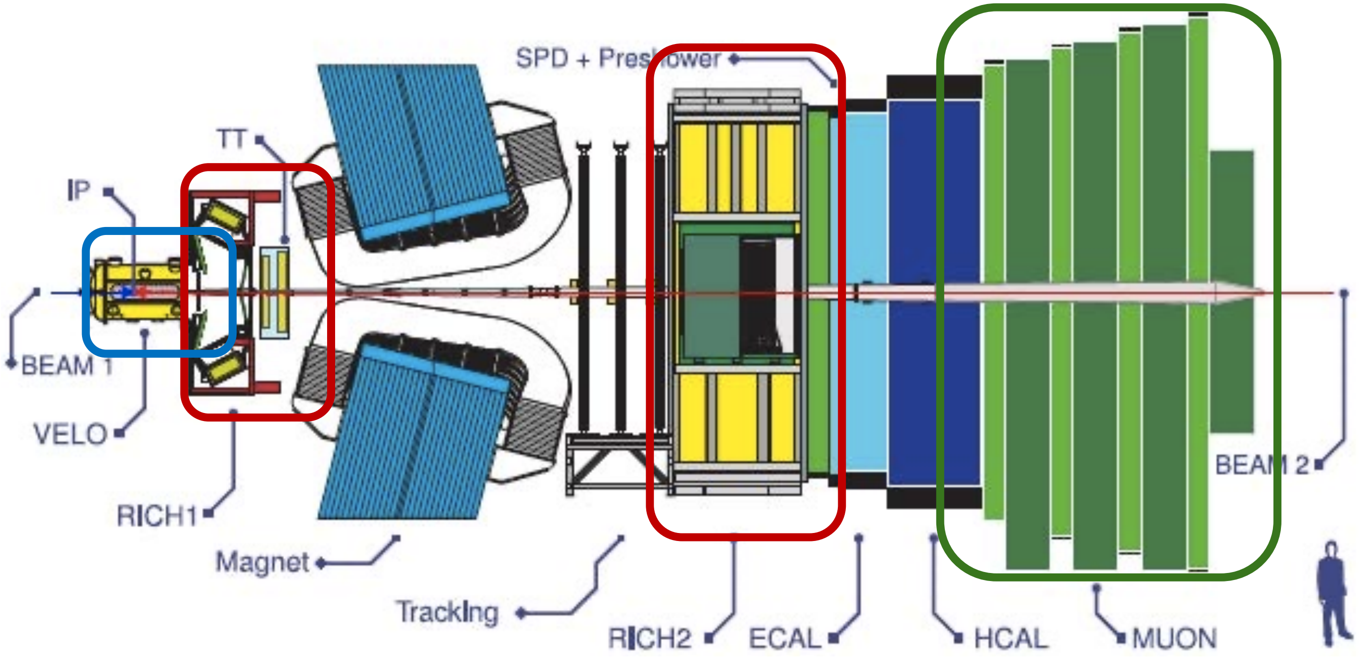


- **Hadronic final states allow to study different quarkonium states simultaneously**

The LHCb experiment: Detector

IJMPA 30 (2015) 1530022

- **Single-arm forward spectrometer:**
  - 10-250 mrad (V), 10-300 mrad (H)
- Forward region $2.0 < \eta < 5.0$,
  - **~4% of solid angle**,
  - but **~40% of heavy quarkonium (HQ) x-section**



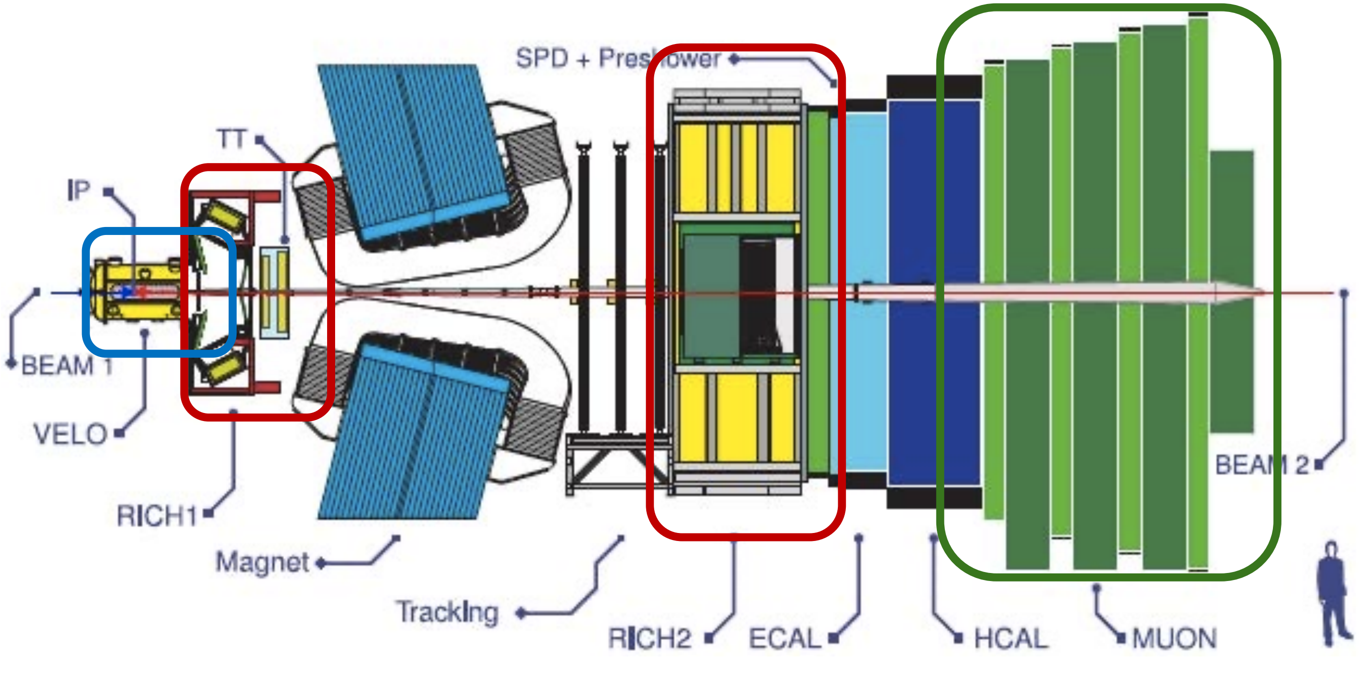
- **Forward peaked HQ production** at the LHC, second *b* in acceptance once the first *b* is in
- Key detector systems for production measurement:
  - **Vertex reconstruction** with **VELO**
  - **Particle identification** with **2 Ring Imaging Cherenkov Detectors (RICH)** and **Muon detector**
  - **Trigger**

The LHCb experiment: Luminosity

IJMPA 30 (2015) 1530022

- **LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:**
  - $\sigma_{b\bar{b}} \sim 0.5$ mb
  - $\sigma_{c\bar{c}} \sim 3.0$ mb

  in LHCb @ √s =13 TeV

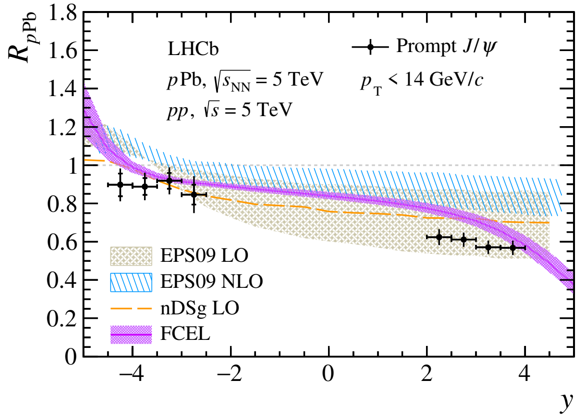


- **Datasets** for *pp* collisions:
  - Run I / 7 TeV / 1.0 fb^{-1}
  - Run I / 8 TeV / 2.0 fb^{-1}
  - Run II / 5 TeV / 0.11 fb^{-1}
  - Run II / 13 TeV / 5.4 fb^{-1}

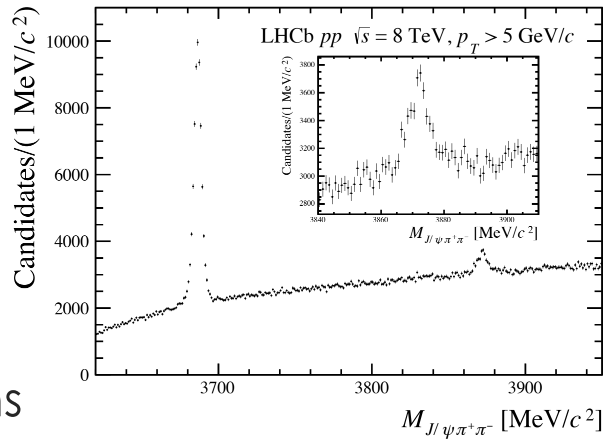
- Absolute cross-section measurement requires **high precision** of **luminosity** determination: LHCb provides ~2% precision [JINST 9 (2014) P12005]

The LHCb experiment: Recent results

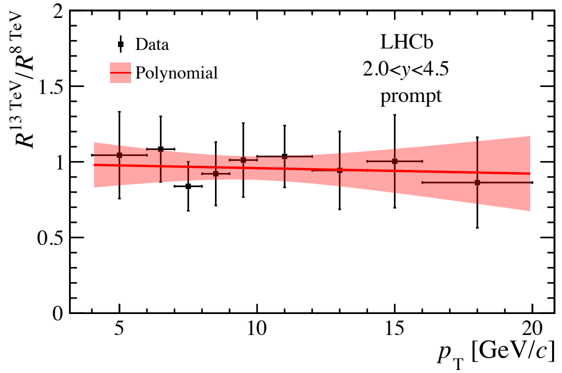
- Measurement of **J/ψ** production cross-sections in pp collisions at √s = 5 TeV: [JHEP11 (2021) 181]



- Observation of **multiplicity-dependent χ_{c1}(3872)** and **ψ(2S)** production in pp collisions: [PRL126 (2021) 092001]



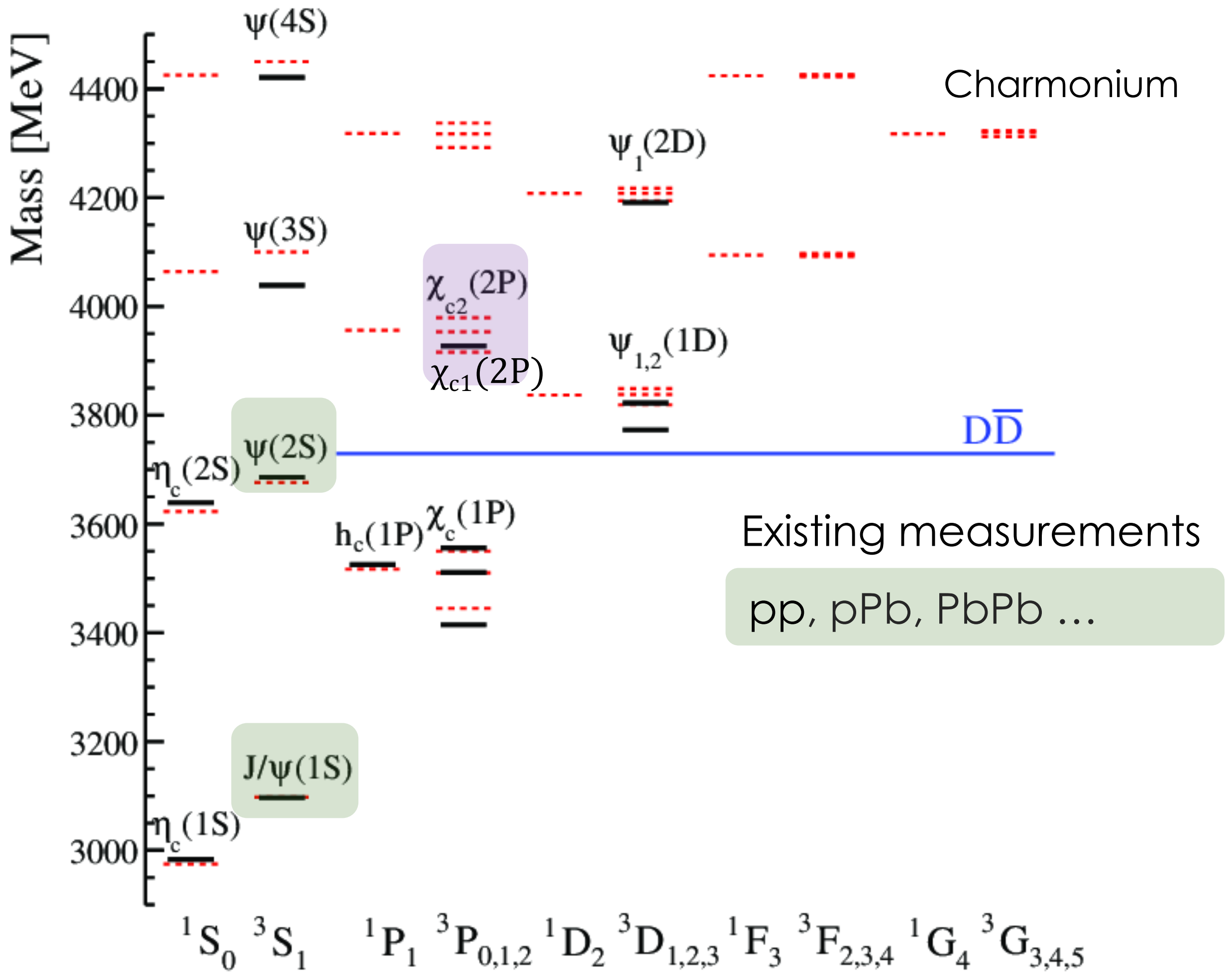
- Measurement of **χ_{c1}(3872)** production in proton-proton collisions at √s=8 and 13 TeV: [JHEP01 (2022) 131]



Quarkonium: Current status

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

- Current status of quarkonium spectrum



- **J/ψ**

- Possible decays: l^+l^- or hadrons

- **The most studied charmonium state**
  - Production and polarization measurements in pp and heavy ion collisions
  - No consistent description of all measurements

J/ψ: Production at $\sqrt{s}$=5 TeV

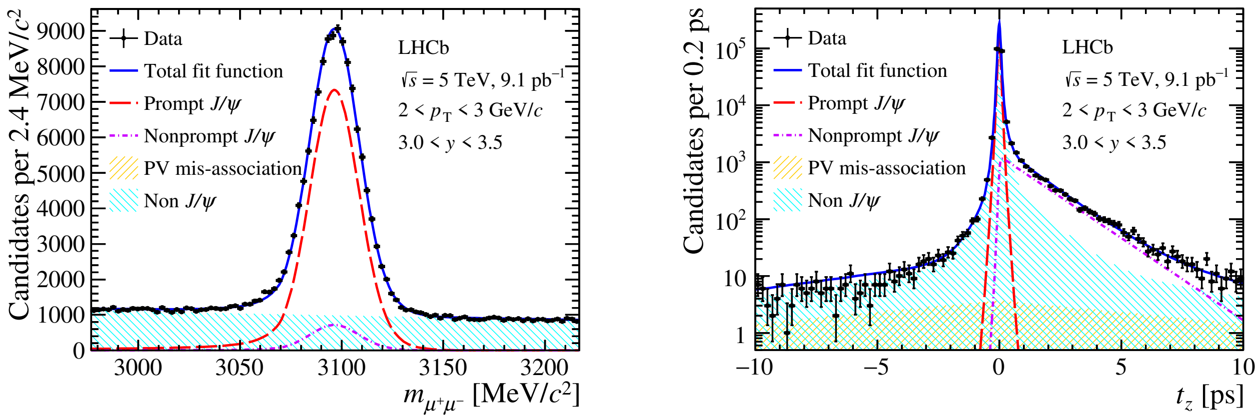
JHEP 11 (2021) 181

- Cross-section determination **in bins[p_T,y]** as a function of p_T(2< p_T< 20 GeV/c) and y(2.0<y<4.5)

$$\frac{d^2\sigma}{dydp_T} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{tot} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

- integrated luminosity
- total efficiency
- number of signal candidates in the given (p_T, y) bin
- bin width

- **Prompt** and ***b*-decay production** distinguished via **combined mass-lifetime fits:**



lifetime value:

$$\boldsymbol{t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{\mu\mu}}$$

- Full kinematic range cross-section
- **Essential input** for the study of **nuclear effects** in heavy ion collisions

J/ψ: Integral and differential cross-section

JHEP 11 (2021) 181

- **J/ψ production** in LHCb @ √**s=5 TeV**

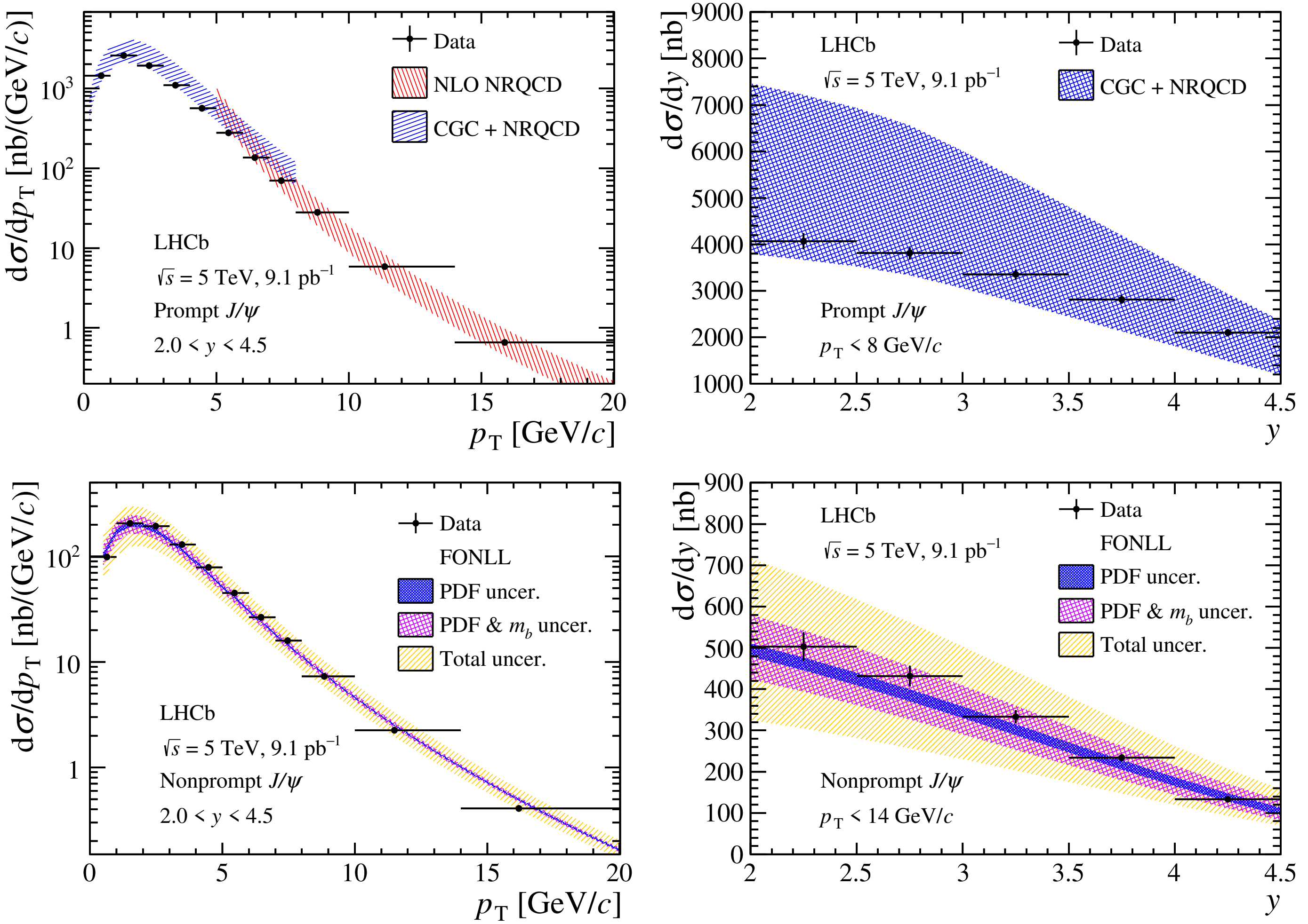
  $0 < p_T < 20\ \text{GeV}/c, 2.0 < y < 4.5$

  $$\sigma^{prompt}_{\psi(2S)} = 8.154 \pm 0.010_{stat} \pm 0.283_{syst}\ \mu b$$
  $$\sigma^{from-b}_{\psi(2S)} = 0.820 \pm 0.0023_{stat} \pm 0.034_{syst}\ \mu b$$

- Reasonable agreement between NRQCD and data for high-p_T

- Small tension with CGC+NRQCD

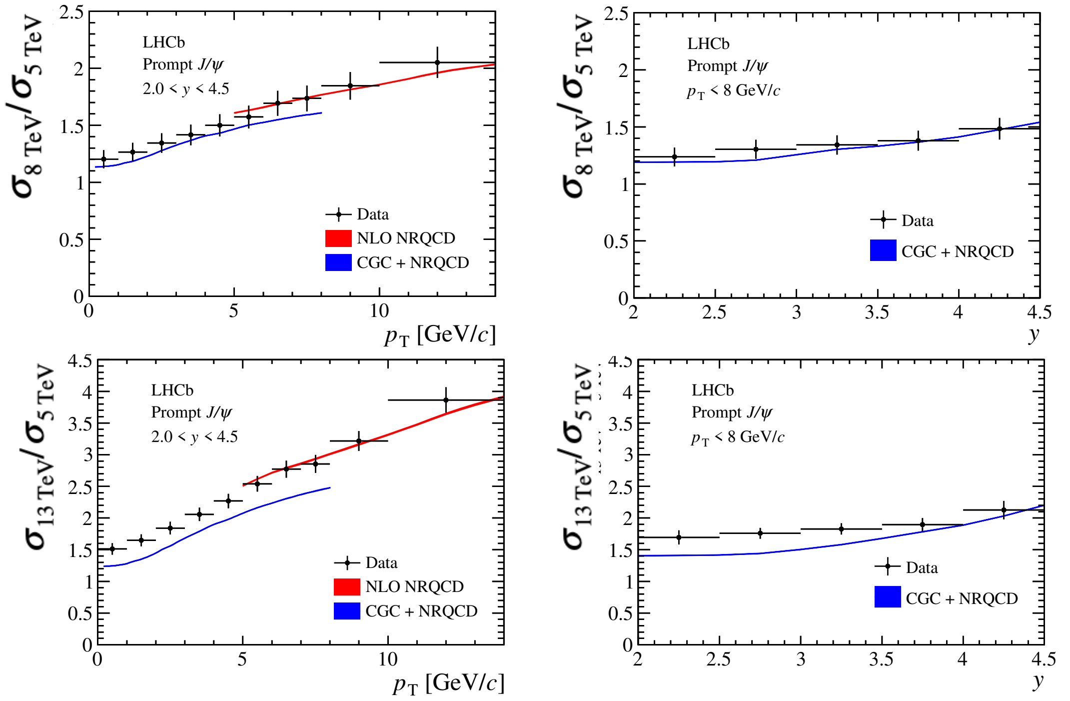
- Good agreement for FONLL



J/ψ: Ratios between different energies

JHEP 11 (2021) 181

- The cross-sections at **5 TeV** are **compared** with those at **8** and **13** TeV
  - cancelled systematic uncertainties: branching fraction and radiative tail
  - partially correlated uncertainties: luminosity, fit model and tracking correction



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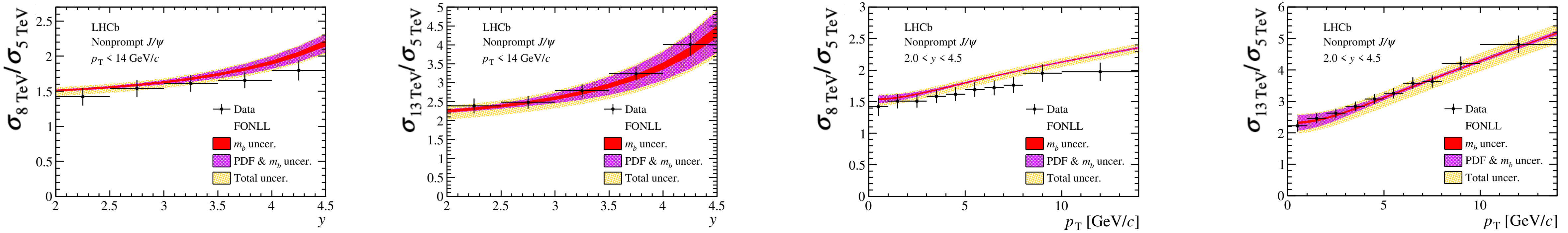
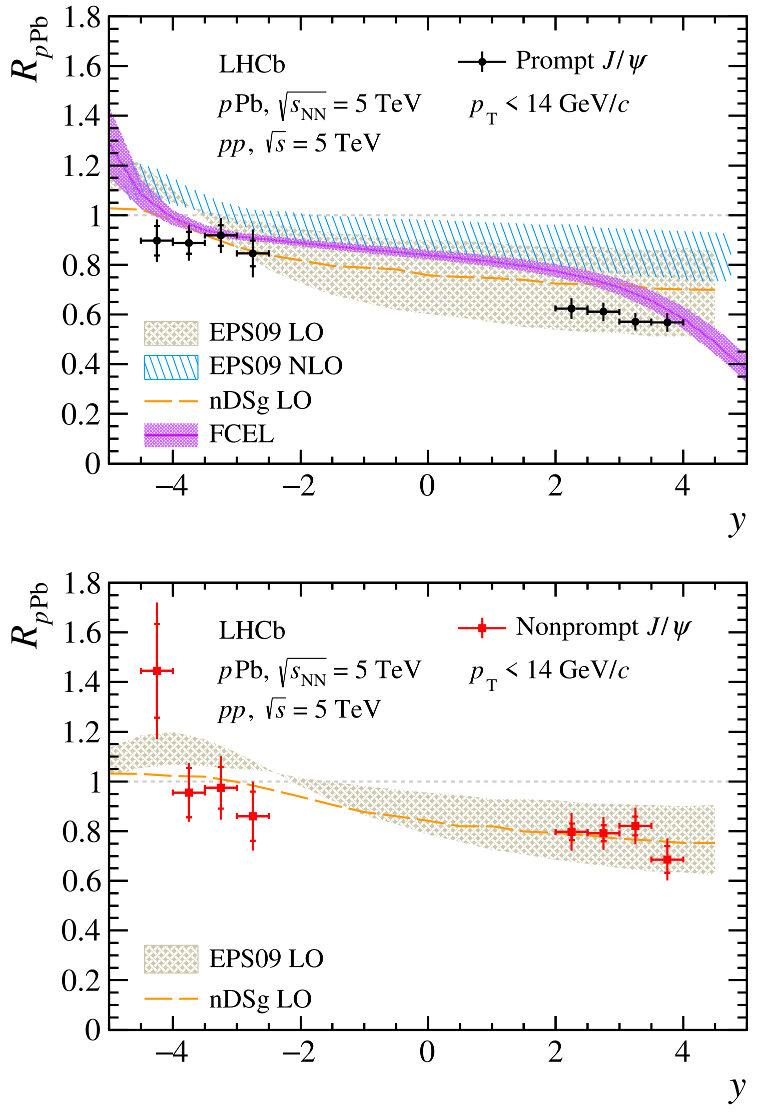


J/ψ: Nuclear modification factor

JHEP 11 (2021) 181

- Previous calculation of R_{pPb} was performed using J/ψ production derived from interpolation of measurements @ 2.76, 7 and 8 TeV [JHEP 02 (2014) 072]
- **Updated R_{pPb}** value based on the direct measurement
  - *p*Pb: 1.5 < y < 4.0
  - Pb*p*: -5.0 < y < -2.5
- For prompt J/ψ the measurement agrees with most theoretical calculations except EPS09 NLO
- Good agreement for non-prompt J/ψ



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Rev.Mod.Phys 90 (2018) 015003

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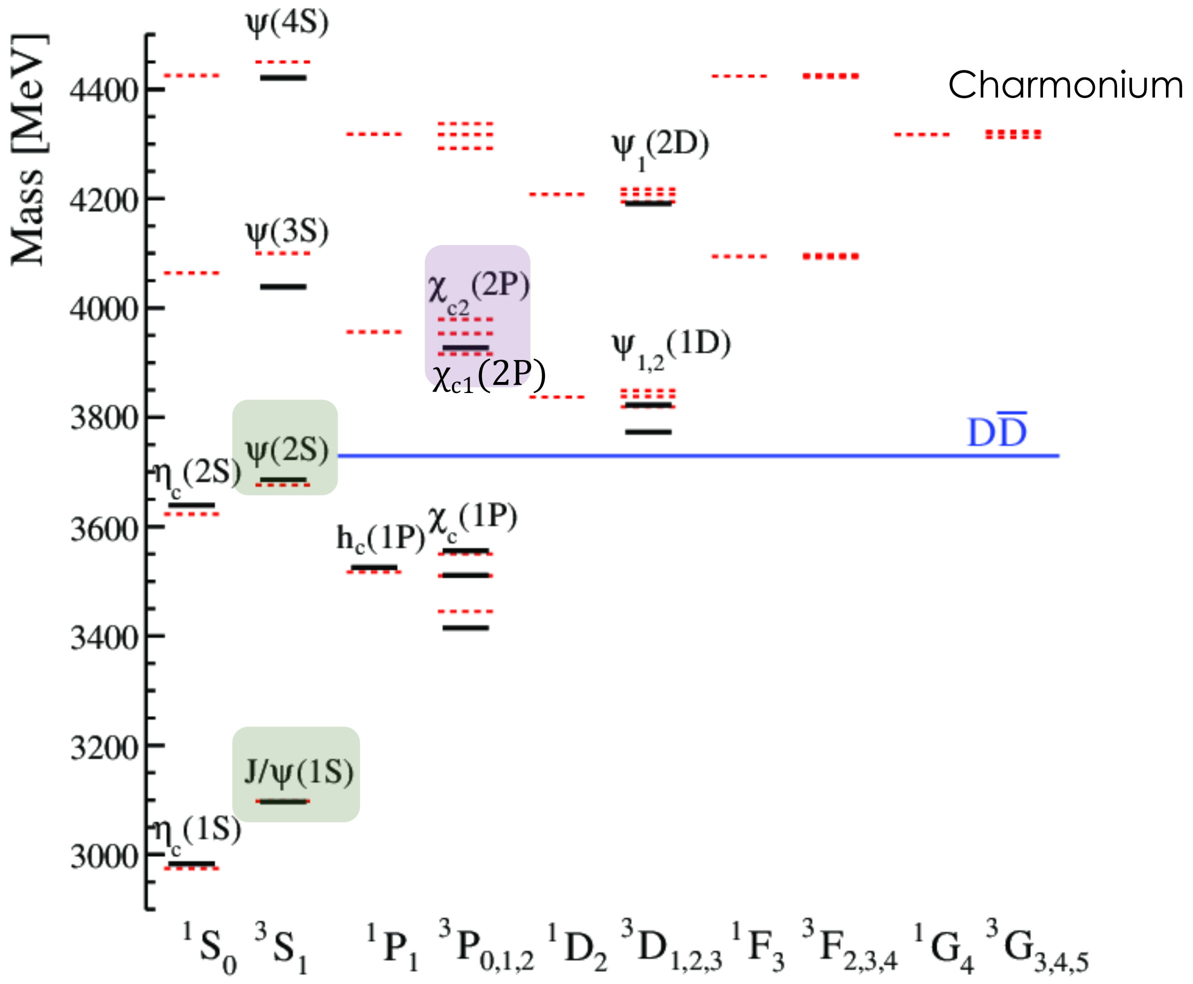
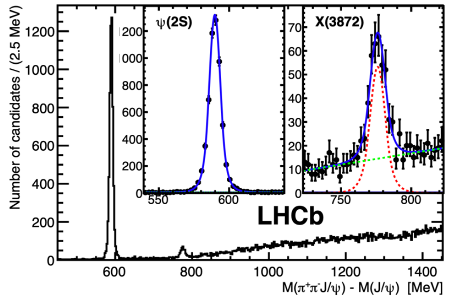


- **X(3872) aka $\chi_{c1}(3872)$**
  - **First exotic state** discovered in $J/\psi\pi^+\pi^-$ decay [PRL 91 262001 (2003)]
  - Charmonium hypothesis **disfavoured** by measured mass and quantum numbers:
    - $M_{D\bar{D}} - M_{X(3872)} = 0.07 \pm 0.12$ MeV$/c^2$ [JHEP 08(2020)123]
    - $J^{PC} = 1^{++}$, with $f_D < 4\%$ @ CL 95% [PRD92 (2015) 011102]
  - Other possible explanations:
    - hadronic molecule
    - tetraquark
    - something else?



X(3872): Production at √s=8 and 13 TeV

JHEP01(2022)131

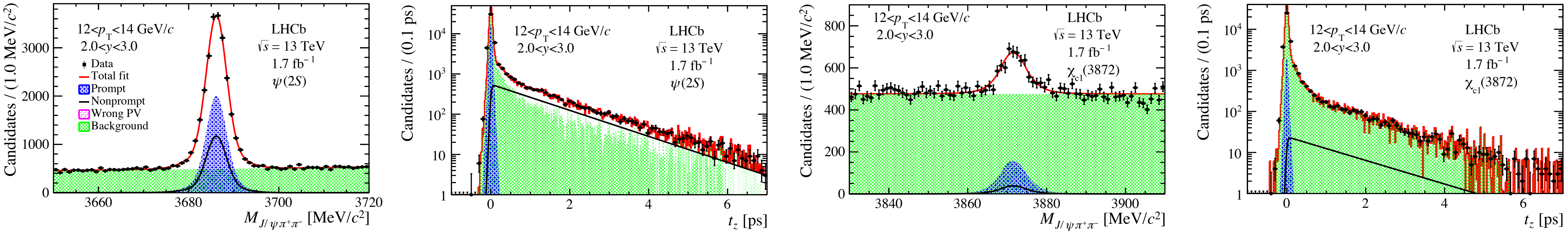
- Cross-section determination:
  - **in bins[p_T,y]** as a function of p_T(0< p_T< 20 GeV/c) and y(2.0<y<4.5)
  - using **$J/\psi\pi^+\pi^-$** decay
  - **ψ(2S) as normalization channel**

$$R \equiv \frac{\sigma_{X(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}(X(3872)\to J/\psi\mu^+\mu^-)}{\mathcal{B}(\psi(2S)\to J/\psi\mu^+\mu^-)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{X(3872)}}$$

o total efficiency

o number of signal candidates in the given (p_T, y) bin

- **Prompt** and ***b*-decay production** distinguished via **combined mass-lifetime fits:**



- Full kinematic range cross-section

X(3872): Ratios at √s=8 and 13 TeV

JHEP01(2022)131

- R(X(3872)/ψ(2S)) in LHCb @ **√s=8 and 13 TeV:**

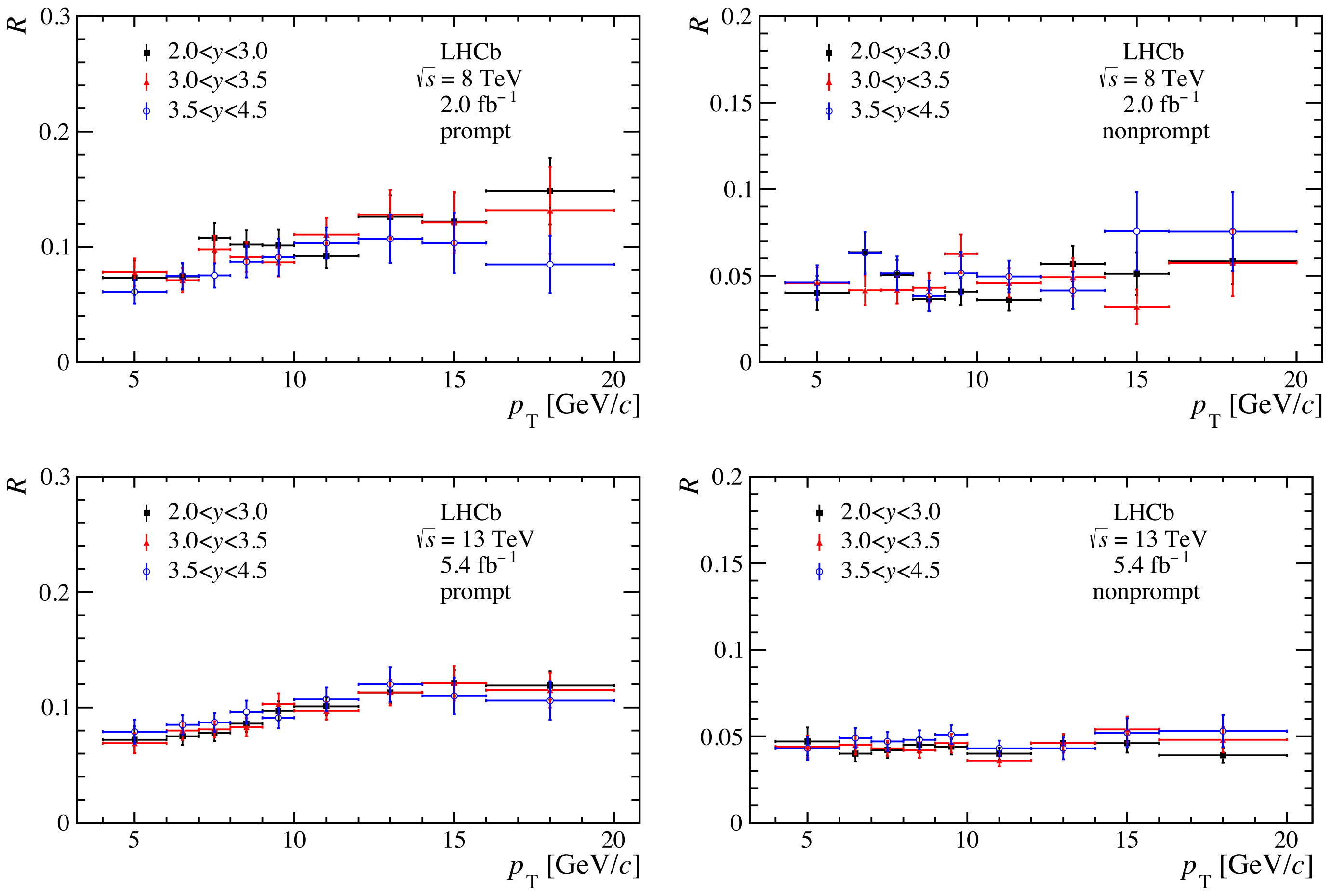
$$4 < p_T < 20\ \mathrm{GeV}/c, 2.0 < y < 4.5$$

$$R_{8TeV}^{prompt} = (7.6 \pm 0.5_{stat} \pm 0.9_{syst}) \times 10^{-2}$$

$$R_{8TeV}^{nonprompt} = (4.6 \pm 0.4_{stat} \pm 0.5_{syst}) \times 10^{-2}$$

$$R_{13TeV}^{prompt} = (7.6 \pm 0.3_{stat} \pm 0.6_{syst}) \times 10^{-2}$$

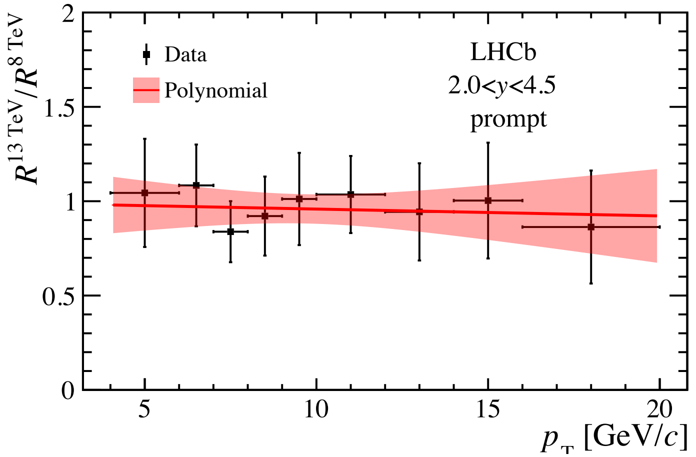
$$R_{13TeV}^{nonprompt} = (4.4 \pm 0.2_{stat} \pm 0.4_{syst}) \times 10^{-2}$$



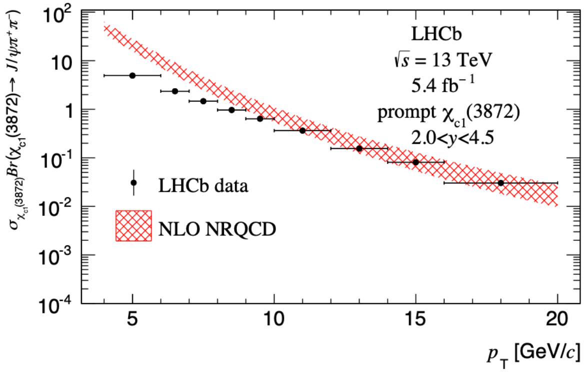
X(3872): Ratios at √s=8 and 13 TeV

JHEP01(2022)131

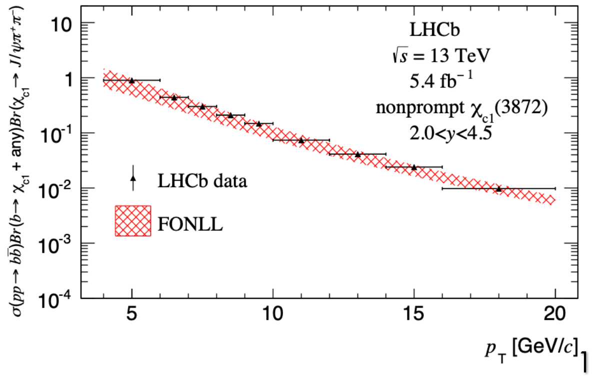
- Double-ratio is computed for prompt production
- A first-order polynomial fit to the double-ratio shows no significant slope => **no significant dependence on √s**



- The absolute X(3872) cross-seciton was estimated using known $\sigma_{\psi(2S)}$ [Eur. Phys. J. C80 (2020) 185] and $\mathcal{B}(\psi(2S) \to J/\psi\mu^+\mu^-)$ [PTEP 2020 (2020) 083C01]



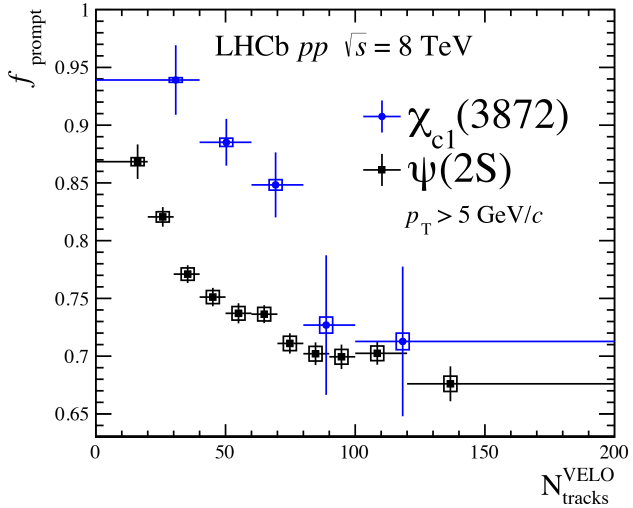
- NRQCD here considers **X(3872)** to be **a mixture of $\chi_{c1}(2P)$ and a $D^0\overline{D}^{*0}$ molecular state**. It shows good agreement with data at p_T>10 GeV/c



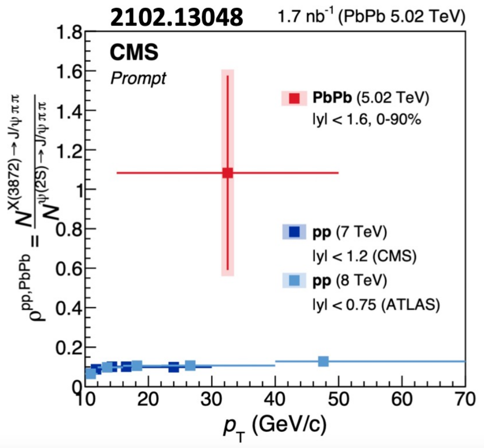
X(3872): Production vs Multiplicity at √s=8 TeV

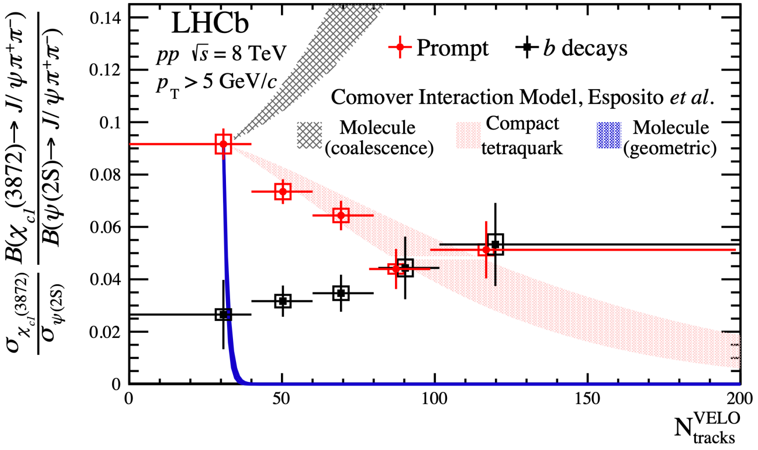
[PRL126 (2021) 092001]

- Event-activity dependence may provide understanding of internal structure
- Decrease in f_{prompt} vs multiplicity:
  - higher multiplicity of events with $b\bar{b}$
  - suppression of prompt via interactions with other particles produced at the vertex
- **Increasing supression of** relative **X(3872)** to ψ(2S) production as multiplicity increases **in prompt**



- **No significant dependence** on multiplicity **in *b*-decays**
- The result in pp collisions **favours tetraquark nature** of the $X(3872)$, when the CMS result in PbPb favours **molecular nature** due to coalescence mechanisms.





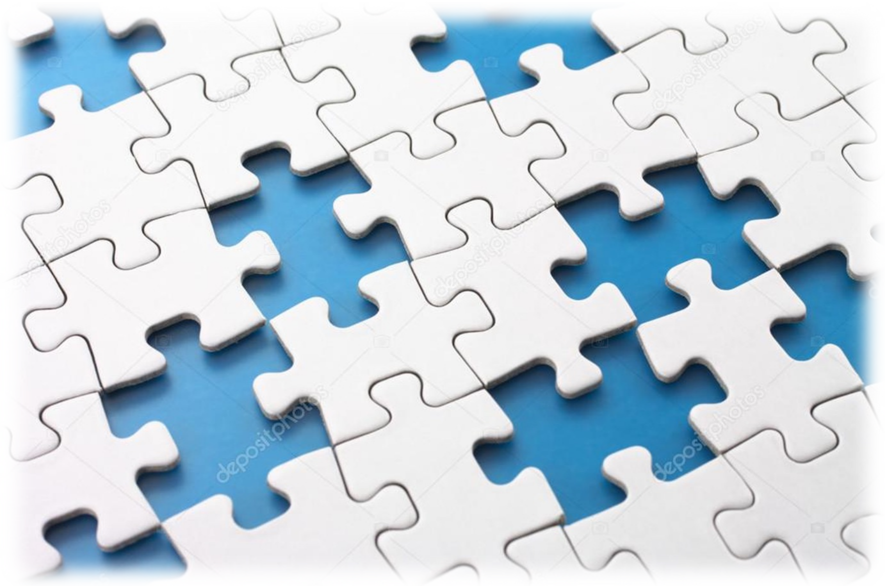
- Upcoming LHCb result in pPb will fill critical gap between pp and PbPb [LHCb-CONF-2022-001]

Summary

- Recent LHCb results on J/ψ and X(3872) production will be useful input to understand quarkonium production mechanism in heavy-ion collisions and the nature of X(3872) and above states

- Comprehensive HF production model is missing
  - new inputs are necessary to improve understanding: asociated production, extention of p_T-region for η_c…

- **Upcoming** interesting results on **single-** and **double-quarkonium production** from **LHCb**
  - would it be possible to have new theory constraints?
  - new models?



Thanks for your attention!