Quarkonium production in pp collisions with ALICE at the LHC

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On behalf of the ALICE Collaboration
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Quarkonium production mechanisms

Quarkonium

- Hard scattering of two gluons in a process which occurs very early in the collision followed by the hadronization of the heavy-quark pair in a bound state.
- Charmonium: bound state of $c\bar{c}$ pair (J/Ψ, Ψ(2S)).
- Bottomonium: bound state of $b\bar{b}$ pair (Υ(1S), Υ(2S) and Υ(3S)).

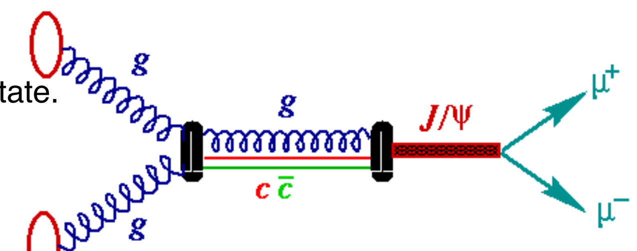


Illustration of the J/Ψ production by gluon fusion. The formed quarkonium decay into a dimuon pair.

Binding into quarkonium state is a non perturbative process, 3 main approaches:

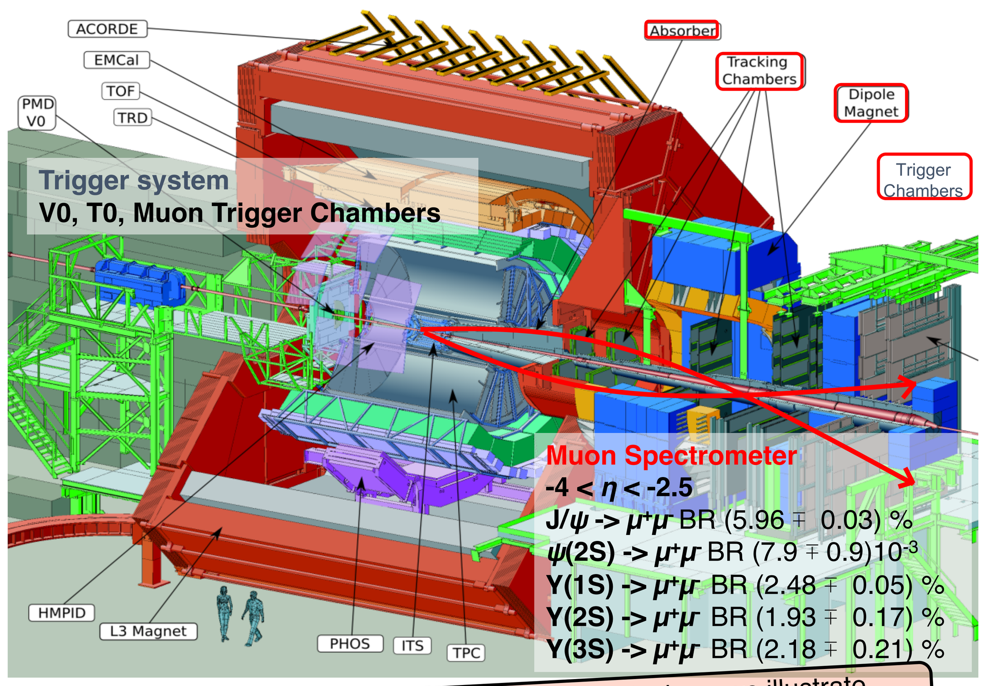
- Color Evaporation Model (CEM) [1,2];
- Color Singlet Model (CSM) [3];
- Non-Relativistic QCD (NRQCD) [4].

Considerable theoretical progresses in recent years [5]
but no consensus on quarkonium production mechanisms in hadronic collisions.

Quarkonium measurements in pp collisions

- Help characterize production mechanisms.
- Charmonia: abundantly produced but difficult interpretation of the inclusive production (large non-prompt contribution).
- Bottomonia: much smaller production cross section but no non-prompt contribution. Heavier mass makes them more suitable for comparison with perturbative QCD calculations.
- Provide a reference baseline for p-A and A-A measurements which in turn quantify cold nuclear matter effects and the Quark-Gluon Plasma (QGP) properties.

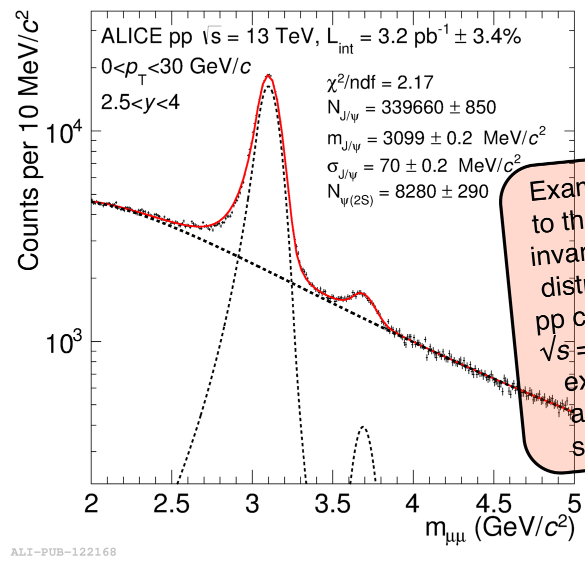
Quarkonium measurements in the dimuon channel with ALICE



Schematic view of ALICE detectors [6]. Red arrows illustrate opposite sign muon pair trajectories through the muon spectrometer.

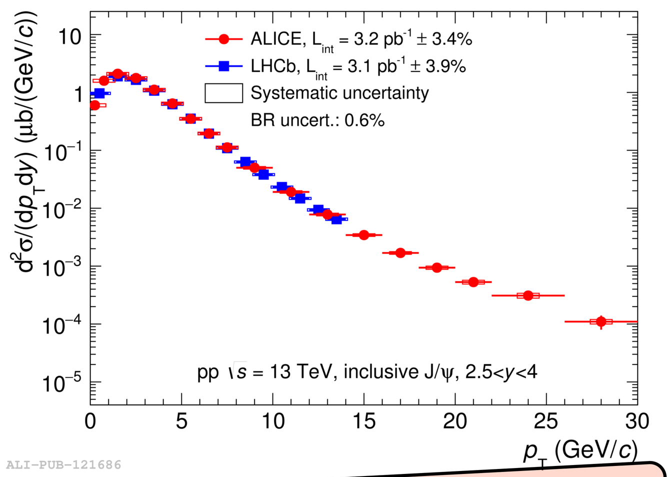
Quarkonium signal extraction:

- fit to the unlike-sign dimuon invariant mass;
- several fitting functions (background + signal);
- various fitting ranges;
- procedure done for each dimuon p_T and y interval.



Example of fit to the dimuon invariant mass distribution in pp collisions at $\sqrt{s}$ = 13 TeV to extract J/Ψ and Ψ(2S) signals [7].

Forward charmonium measurements in pp collisions at $\sqrt{s}$ = 13 TeV



ALICE J/Ψ p_T-differential cross section compared to LHCb (sum of prompt plus non-prompt contributions).

New charmonium measurements at $\sqrt{s}$ =13 TeV [7]

- Data collected in 2015, $\mathcal{L}_{int}$= 3.19 ∓ 0.11 pb^{-1}.
- Inclusive J/Ψ and Ψ(2S) cross section measurements.
- J/Ψ p_T reach extends up to 30 GeV/c.
- Ψ(2S) p_T reach extends up to 16 GeV/c.
- Agreement better than 1σ between ALICE and LHCb [J/Ψ and Ψ(2S) p_T- and y-differential cross sections].

Data/theory comparison at $\sqrt{s}$ =13 TeV [7]

1) Comparison to three independent calculations:

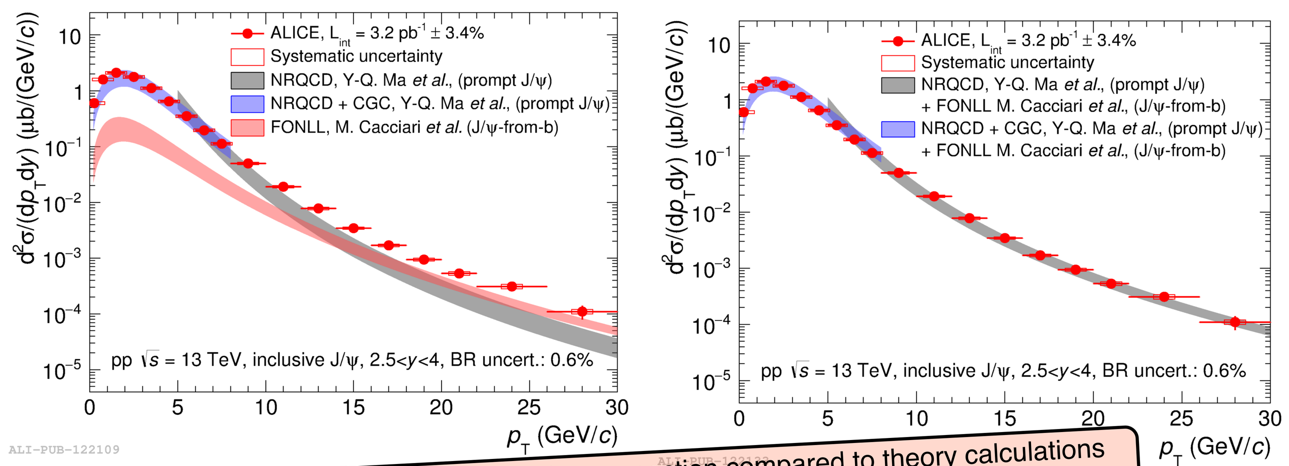
- to a prompt J/Ψ LO NRQCD calculation coupled to a CGC description of the low-x gluons in the proton at low p_T [8];
- to a prompt J/Ψ NLO NRQCD calculation at high p_T [9];
- to a non-prompt J/Ψ FONLL calculation [10].

⇒ For p_T > 15 GeV/c, where the non-prompt contribution is as high as the prompt one, NRQCD underestimates the J/Ψ cross section.

2) Comparison to an *ad hoc* model:

- sum of the non-prompt contribution estimated with FONLL and the prompt contribution with the two NRQCD implementations (uncertainties assumed to be fully uncorrelated).

⇒ Provides a good description of the data over the full p_T range.
⇒ The same conclusion holds for Ψ(2S).

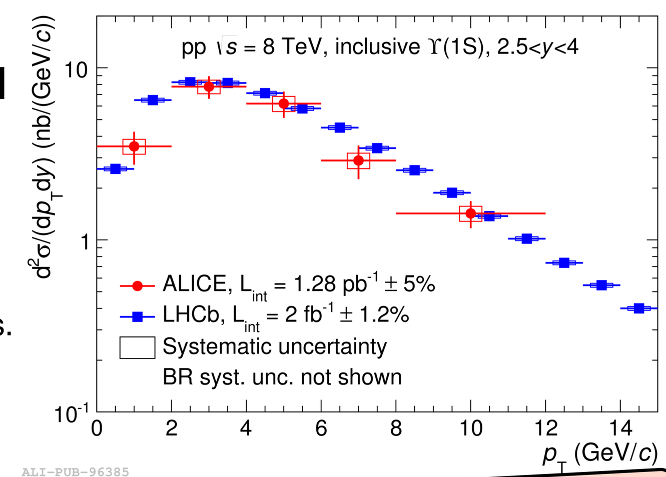


Inclusive J/Ψ p_T-differential cross section compared to theory calculations [7]. (left) Three independent calculations. (right) An *ad hoc* model.

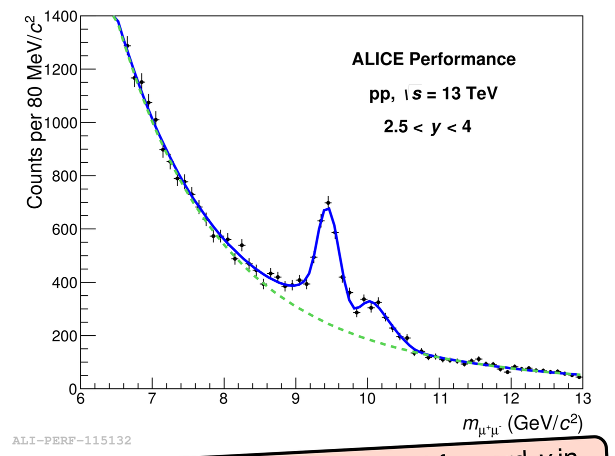
Forward bottomonium measurements

Upsilon measurements at $\sqrt{s}$ = 7 [11] and 8 TeV [12] in pp collisions

- p_T- and y-differential cross sections.
- Υ(3S) measured for the first time with ALICE at $\sqrt{s}$ = 8 TeV.
- ALICE measurements as function of p_T and y are in agreement with LHCb ones.



Υ(1S) p_T-differential cross section in pp collisions at $\sqrt{s}$ = 8 TeV compared to LHCb [12].

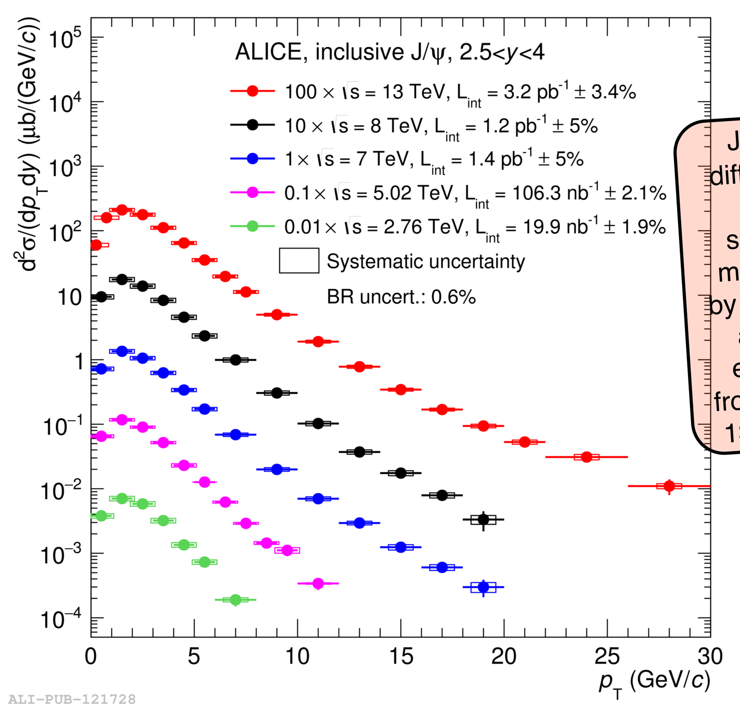


Invariant mass distribution at forward-y in pp collisions at $\sqrt{s}$ = 13 TeV.

ALICE measurements at $\sqrt{s}$ = 13 TeV

- Data collected in 2015.
- Analysis ongoing.

Energy dependence of charmonium production at the LHC



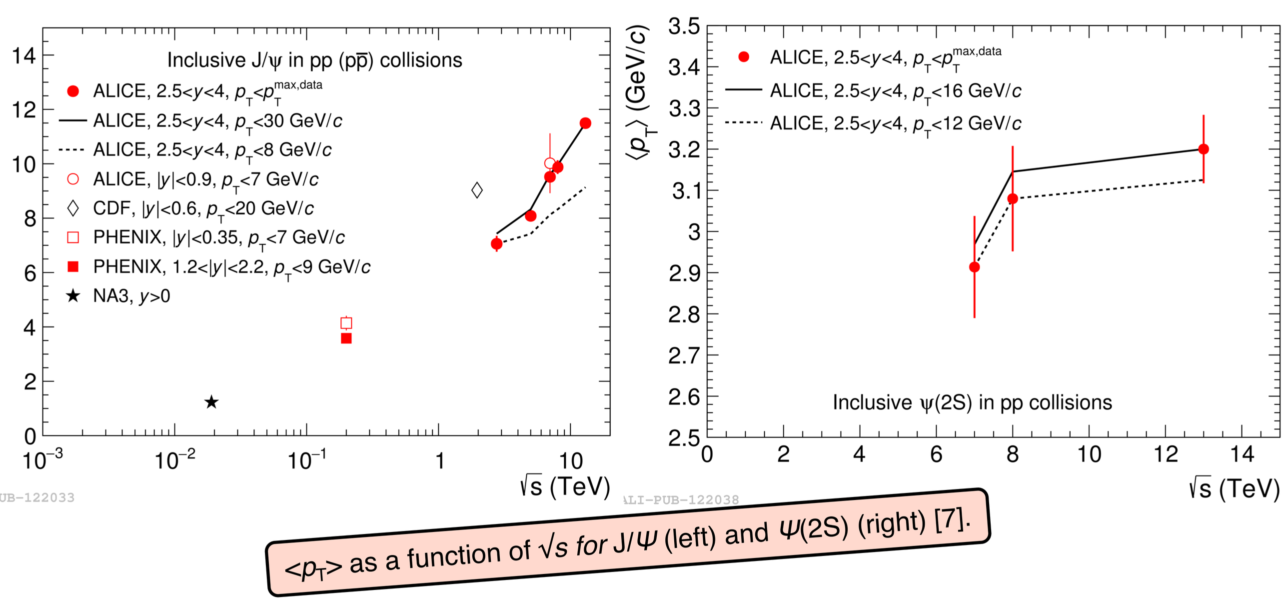
J/Ψ p_T-differential cross sections measured by ALICE at all LHC energies from 2.76 to 13 TeV [7].

Comparison of J/Ψ and Ψ(2S) at different LHC energies [7]

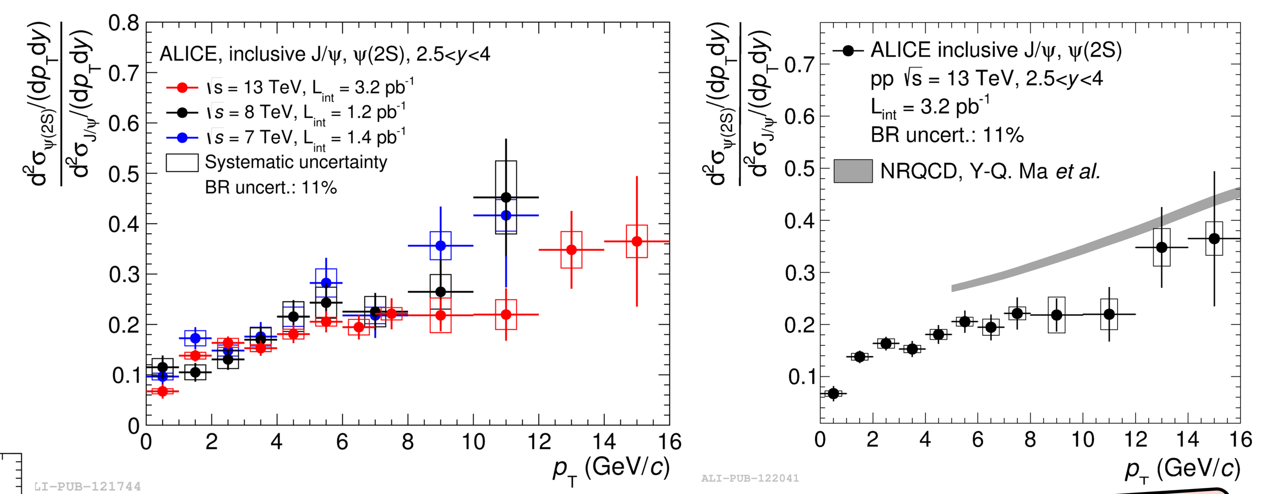
- J/Ψ measured at all LHC energies from 2.76 to 13 TeV (including $\sqrt{s}$ = 5.02 TeV [13]).
- The J/Ψ p_T-differential cross sections indicate a hardening of the spectra with increasing $\sqrt{s}$.
- For $\sqrt{s}$ ≥ 7 TeV a change in the slope is visible for p_T > 10 GeV/c and can be attributed to the onset of the non-prompt J/Ψ contribution to the inclusive cross section.

Better quantification of the hardening of the charmonium p_T spectra with increasing $\sqrt{s}$ [7]

- $\langle p_T \rangle$ extracted from a fit to the charmonium p_T-differential cross sections.
- J/Ψ: ALICE measurements are compared to lower energy measurements (CDF, PHENIX and NA3). A steady increase is observed with a systematically higher value at mid- than at forward rapidity as expected by the hardening of the p_T spectra.
- A similar increase is observed for Ψ(2S).



$\langle p_T \rangle$ as a function of $\sqrt{s}$ for J/Ψ (left) and Ψ(2S) (right) [7].



(left) Ψ(2S)-to-J/Ψ ratios measured by ALICE at $\sqrt{s}$ = 7, 8 and 13 TeV. (right) p_T-differential Ψ(2S)-to-J/Ψ ratio at $\sqrt{s}$ = 13 TeV compared to NRQCD calculation from Ma *et al.*. [7]

Ψ(2S)-to-J/Ψ ratios at $\sqrt{s}$ = 13 TeV [7]

- Steady increase with increasing p_T and small or no dependence on y within uncertainties (not shown here).
- No significant change in shape or magnitude is observed among the three energies within the current uncertainties.
- Impact of the non-prompt charmonium contribution is expected to be small as it enters both in the numerator and the denominator with a similar magnitude.
- Comparison to the high-p_T NLO NRQCD from Ma *et al.*: many of the systematic uncertainties cancel both for data and theory in the ratio and some tensions appear.

Conclusions

➢ ALICE has measured in pp collisions the **inclusive cross sections** as a function of p_T and y at **all LHC energies from 2.76 to 13 TeV for J/Ψ** and starting at 7 TeV for the Ψ(2S).

➢ **New results at $\sqrt{s}$ =13 TeV** significantly extend the p_T reach for charmonium states.

➢ **Outlook: bottomonium** analysis at $\sqrt{s}$ =13 TeV.

➢ **Energy dependence of charmonium production at the LHC**

- Hardening of the J/Ψ p_T-spectra is observed with increasing collision energy.
- Confirmed by $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ measurements.
- Inclusive Ψ(2S)-to-J/Ψ cross section ratios show no $\sqrt{s}$ dependence within uncertainties.
- An excellent agreement is observed between data and theory, provided that the non-prompt contribution to the inclusive cross section is included.

ALICE future (2021) for quarkonium measurements in the dimuon channel: separate experimentally the prompt and the non-prompt contributions with the addition of the Muon Forward Tracker [14].

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