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Quarkonium production in proton-proton collisions with ALICE at the LHC

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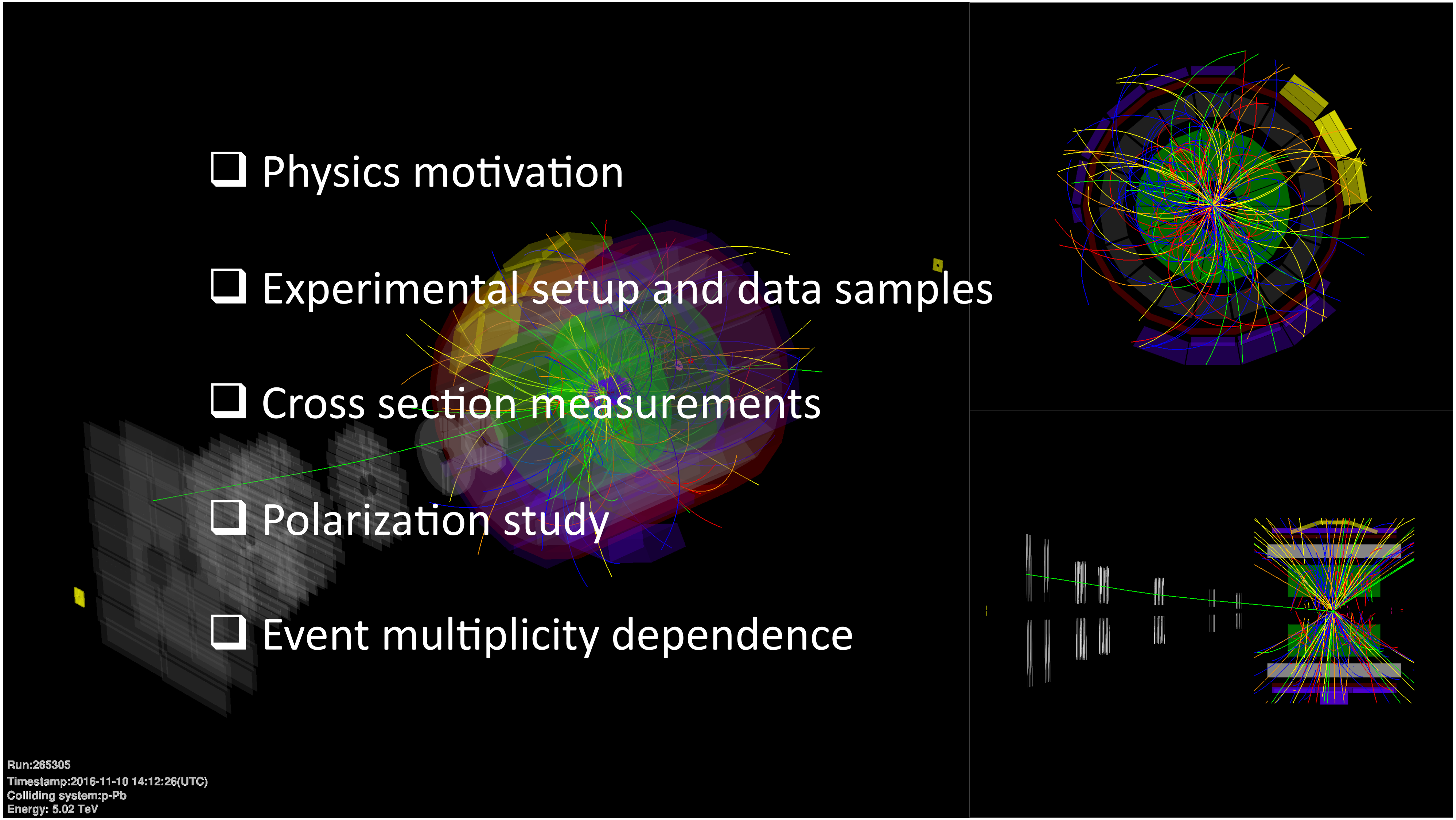
for the ALICE Collaboration

Outline

- ❑ Physics motivation
- ❑ Experimental setup and data samples
- ❑ Cross section measurements
- ❑ Polarization study
- ❑ Event multiplicity dependence

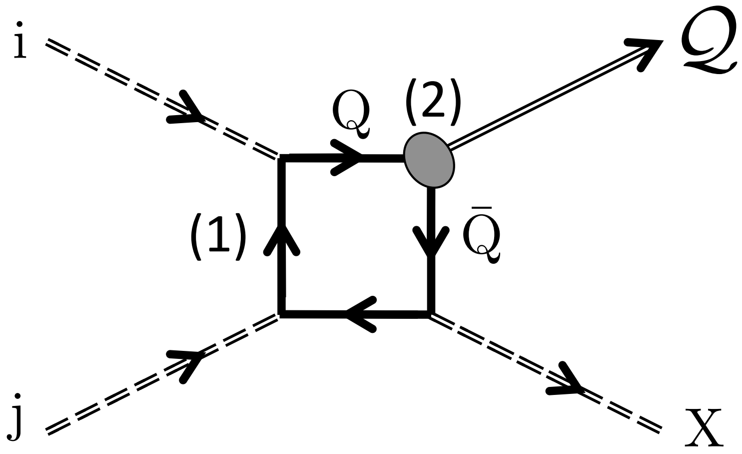


Physics motivation

- Quarkonium $\mathcal{Q}$ = **bound state** of a heavy quark Q and its anti-quark $\bar{\mathrm{Q}}$

- **QCD laboratory** assuming factorization
  (1) **perturbative partonic process** with a momentum transfer > $2m_{\mathrm{Q}}$ (mainly gluon fusion at the LHC)

$$\underbrace{\mathrm{i} + \mathrm{j} \rightarrow (\underbrace{\mathrm{Q}\bar{\mathrm{Q}} \rightarrow \mathcal{Q}}_{(2)}) + \mathrm{X}}_{(1)}$$



  (2) different approaches for the **non-perturbative evolution in a bound state** with a binding energy typically equal to $m_{\mathrm{Q}}v^2$, with v the heavy-quarks velocity in the quarkonium rest frame, $v_c^2 \approx 0.3$ and $v_b^2 \approx 0.1$
  [N. Brambilla et al., Eur. Phys. J. C 71 (2011) 1534 ; A. Andronic et al., Eur. Phys. J. C 76 (2016) 107]

- **Probe** for the study of the hot and dense medium – **Quark-Gluon Plasma (QGP)** – produced in **heavy-ion collisions (Pb-Pb)**

ALICE

Main theoretical approaches

Color-Evaporation Model (CEM) [H. Fritzsch, Phys. Lett. B 67 (1977) 217]

- quark-hadron duality where each $\mathrm{Q\bar{Q}}$ pair evolved in a quarkonium below the open heavy-flavour threshold ($\mathrm{H_Q}$) with a phenomenological energy and process independent probability factor (determined from total cross section) for each quarkonium state
- no polarization prediction

$$\sigma_{\mathcal{Q}} = F_{\mathcal{Q}} \int_{2m_{\mathrm{Q}}}^{2m_{\mathrm{H_Q}}} \hat{\sigma}_{\mathrm{Q\bar{Q}}}(\hat{s})\, d\hat{s}$$

Color-Singlet Model (CSM) [M.B. Einhorn and S.D. Ellis, Phys. Rev. D 12 (1981) 2007]

- no evolution of the quantum state (only color-singlet) between the $\mathrm{Q\bar{Q}}$ production and the quarkonium formation with a wave function computed at zero $\mathrm{Q\bar{Q}}$ separation (i.e. no free parameter)
- partial **longitudinal polarization**

$$\sigma_{\mathcal{Q}} = \hat{\sigma}_{\mathrm{Q\bar{Q}}} \left|\Psi_{\mathcal{Q}}(0)\right|^2$$

Color-Octet Mechanism (COM) [G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D 51 (1995) 1125]

- Non Relativistic QCD (NRQCD) based model introducing Long-Distance Matrix Elements (LDMEs, determined from experimental data) for the hadronization probability in a quarkonium state
- partial **transverse polarization**

$$\sigma_{\mathcal{Q}} = \sum_n \hat{\sigma}^n_{\mathrm{Q\bar{Q}}} \langle \mathcal{O}^n_{\mathcal{Q}} \rangle$$

Note: $\hat{\sigma}_{\mathrm{Q\bar{Q}}}$ is the partonic cross section convoluted with parton distribution functions (PDFs)

Charm versus beauty

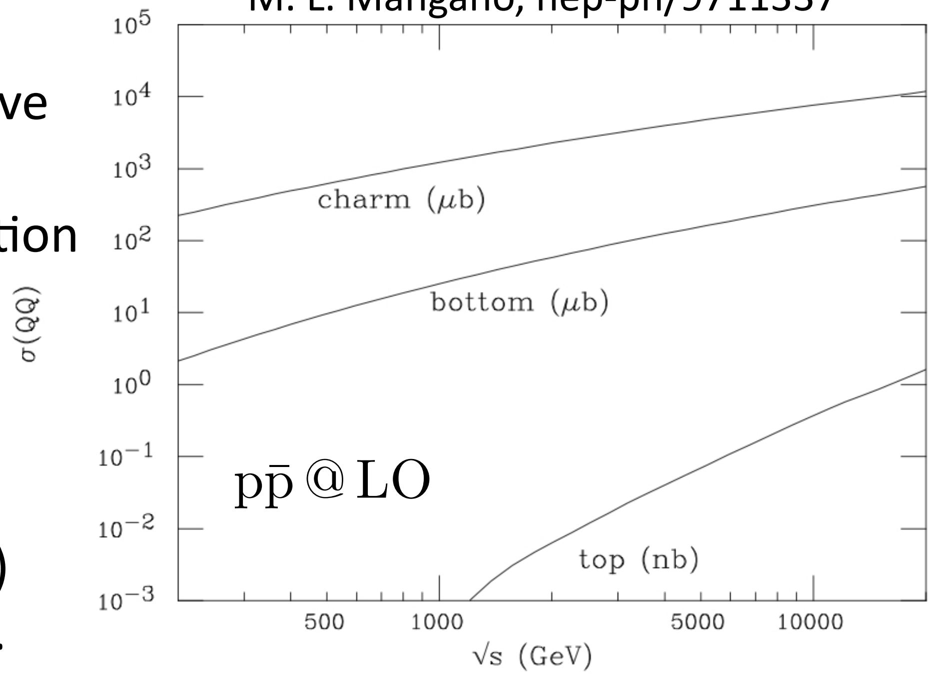
Charmonia

- $(c\bar{c}) = J/\psi,\ \psi(2S)\ldots$
- charm quark lighter ($m_c \approx 1.3$ GeV/c^2)
  - ○ higher production cross section
  - ○ theoretical prediction more sensitive to non perturbative effects
- contamination by non-prompt contribution from b-hadron decay: B → J/ψ + X

Bottomonia

- $(b\bar{b}) = \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S)\ldots$
- bottom quark heavier ($m_b \approx 4.4$ GeV/c^2)
  - ○ lower production cross section, i.e. statistically limited
  - ○ perturbative QCD prediction more robust
- no non-prompt contribution

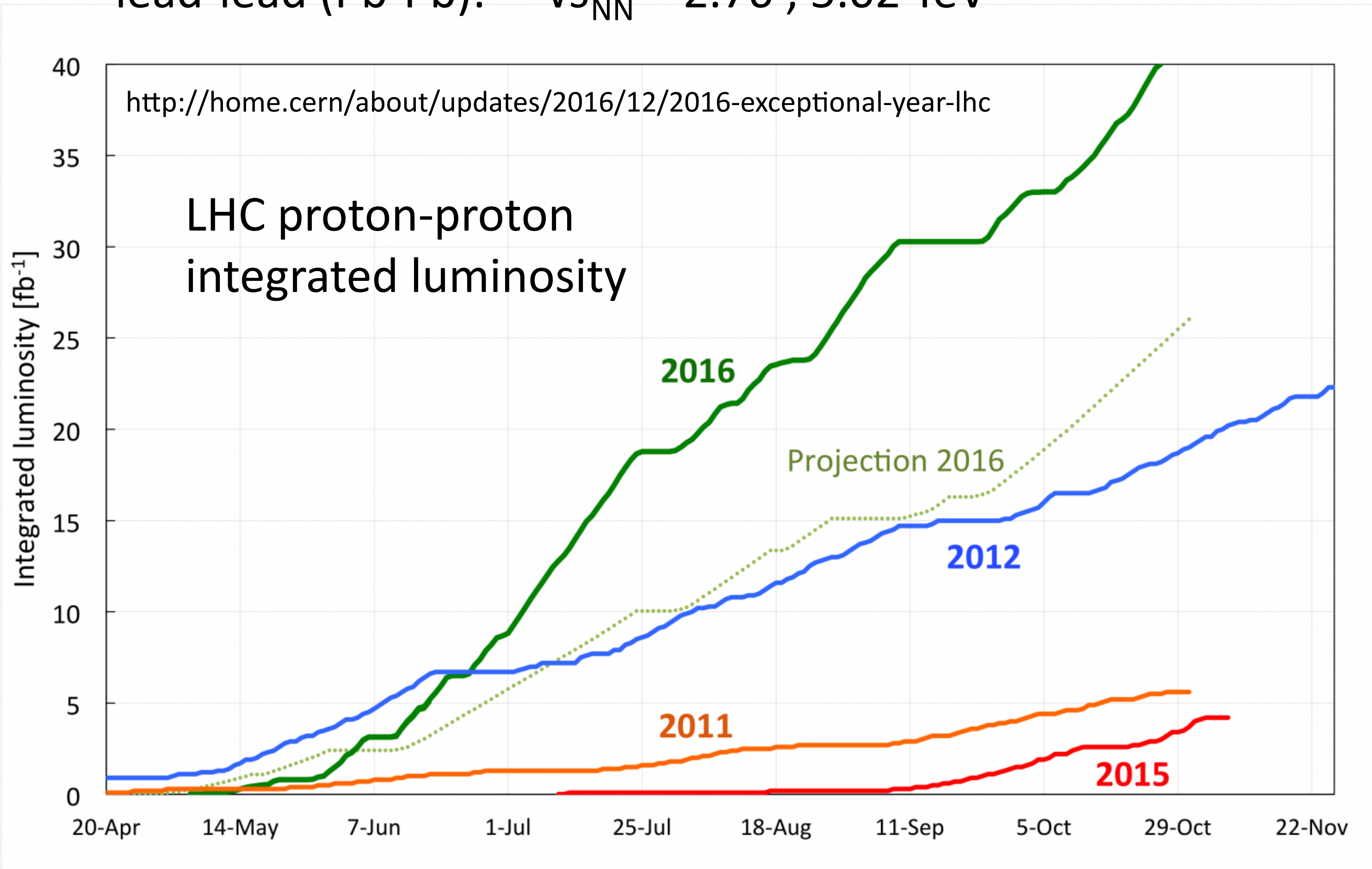
M. L. Mangano, hep-ph/9711337



Large Hadron Collider

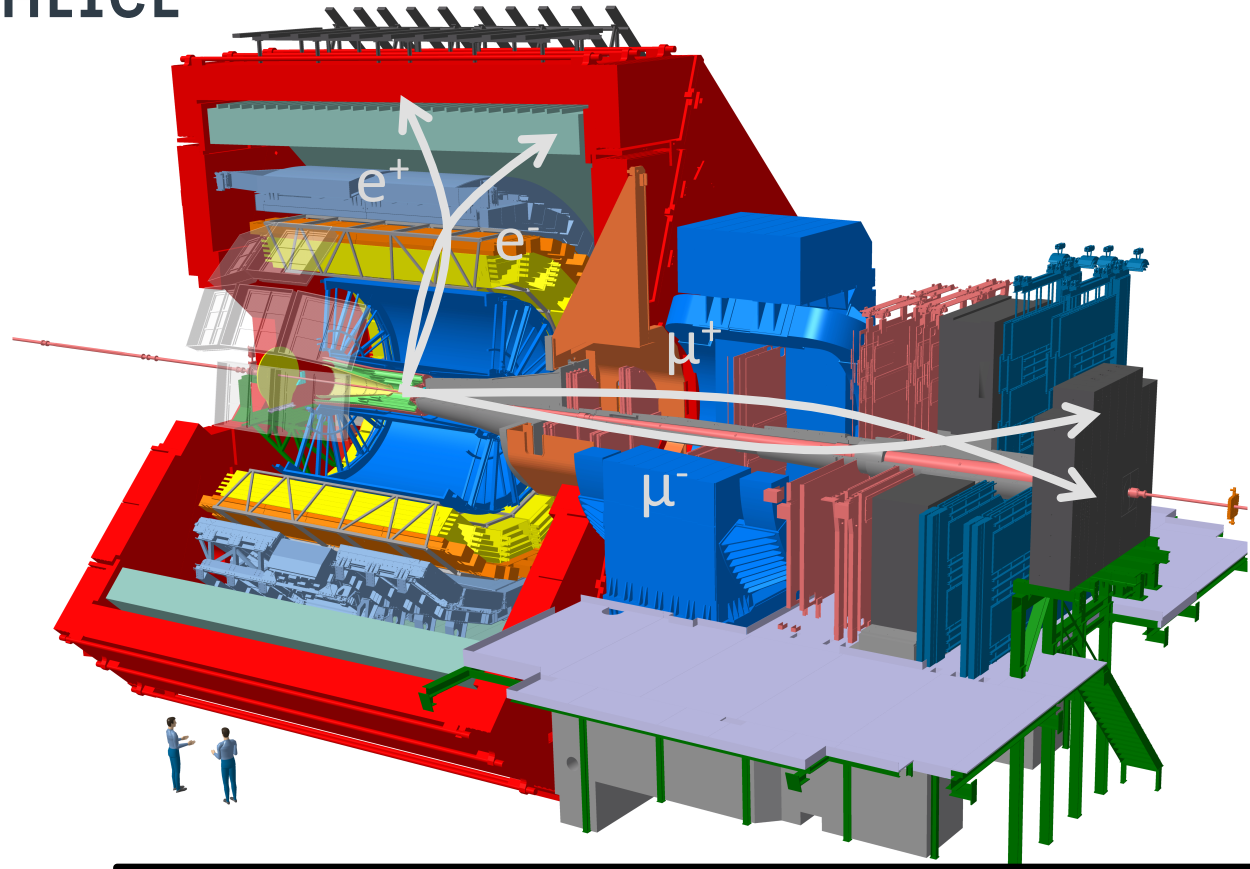
Collision modes

- proton-proton (pp): $\sqrt{s}$ = 0.9 ; 2.76 ; 5.02 ; 7 ; 8 ; 13 TeV
- proton-lead (p-Pb): $\sqrt{s_{NN}}$ = 5.02 ; 8.16 TeV
- lead-lead (Pb-Pb): $\sqrt{s_{NN}}$ = 2.76 ; 5.02 TeV



Quarkonium in ALICE

[J. Instrum. 3 (2008) ; Int. J. Mod. Phys. A 29 (2014)]



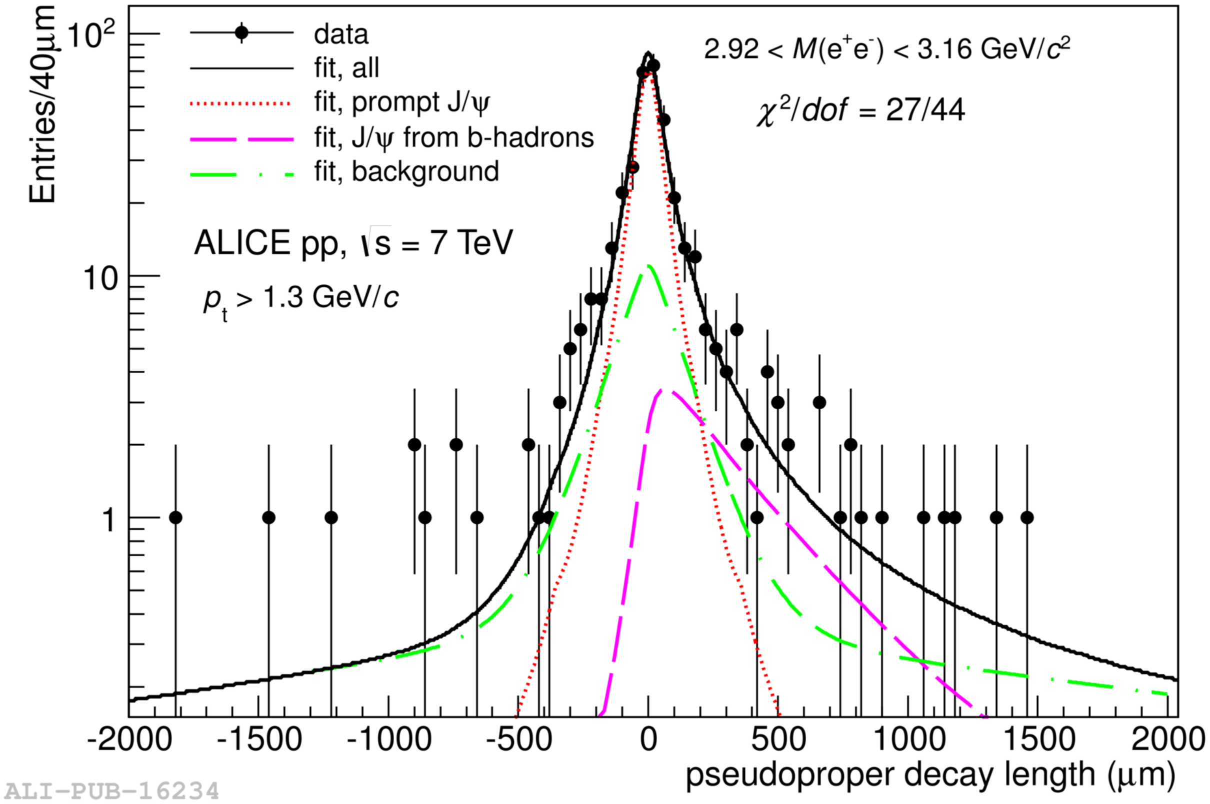
- **Minimum Bias (MB) trigger** with Silicon Pixel Detector (SPD) and V0 hodoscopes
- **$e^{\pm}$ at mid rapidity** with Inner Tracking System (ITS) and Time Projection Chamber (TPC)
- **$\mu^{\pm}$ at forward rapidity** with muon spectrometer
- **Quarkonium reconstruction down to zero p_T**

Analyzed data samples for quarkonia in pp collisions in term of MB luminosity (with dimuon trigger at forward rapidity)

Energy	2.76 TeV	5.02 TeV	7 TeV	8 TeV	13 TeV
$\|y\| < 0.9$	1.1 nb^{-1}		5.6 nb^{-1}		
$2.5 < y < 4$	19.9 nb^{-1}	106 nb^{-1}	1.35 pb^{-1}	1.23 pb^{-1}	3.19 pb^{-1}

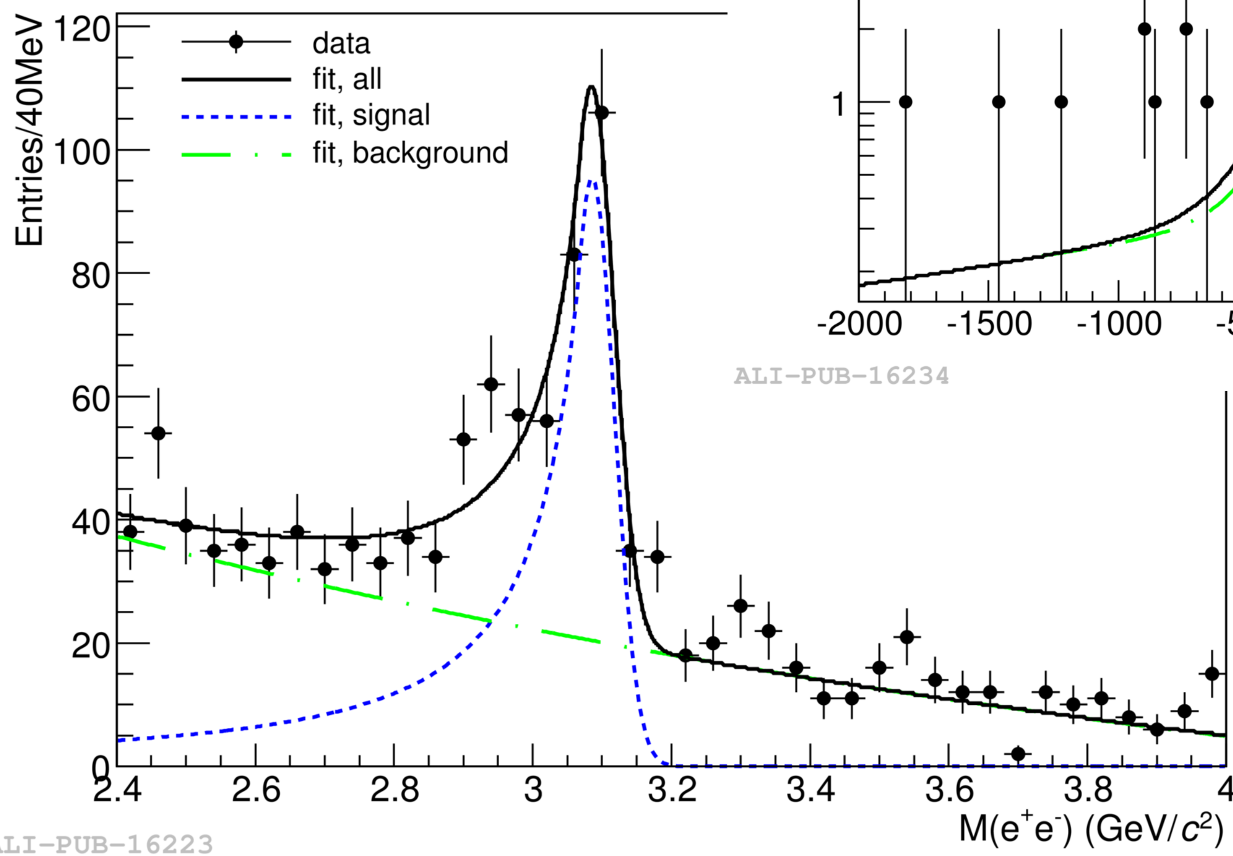
J/ψ reconstruction at mid-rapidity

[JHEP11 (2012)]



e⁺e⁻ invariant mass

- $|y^{ee}| < 0.9$
- $p_T^{ee} > 1.3$ GeV/c



Pseudo proper decay length

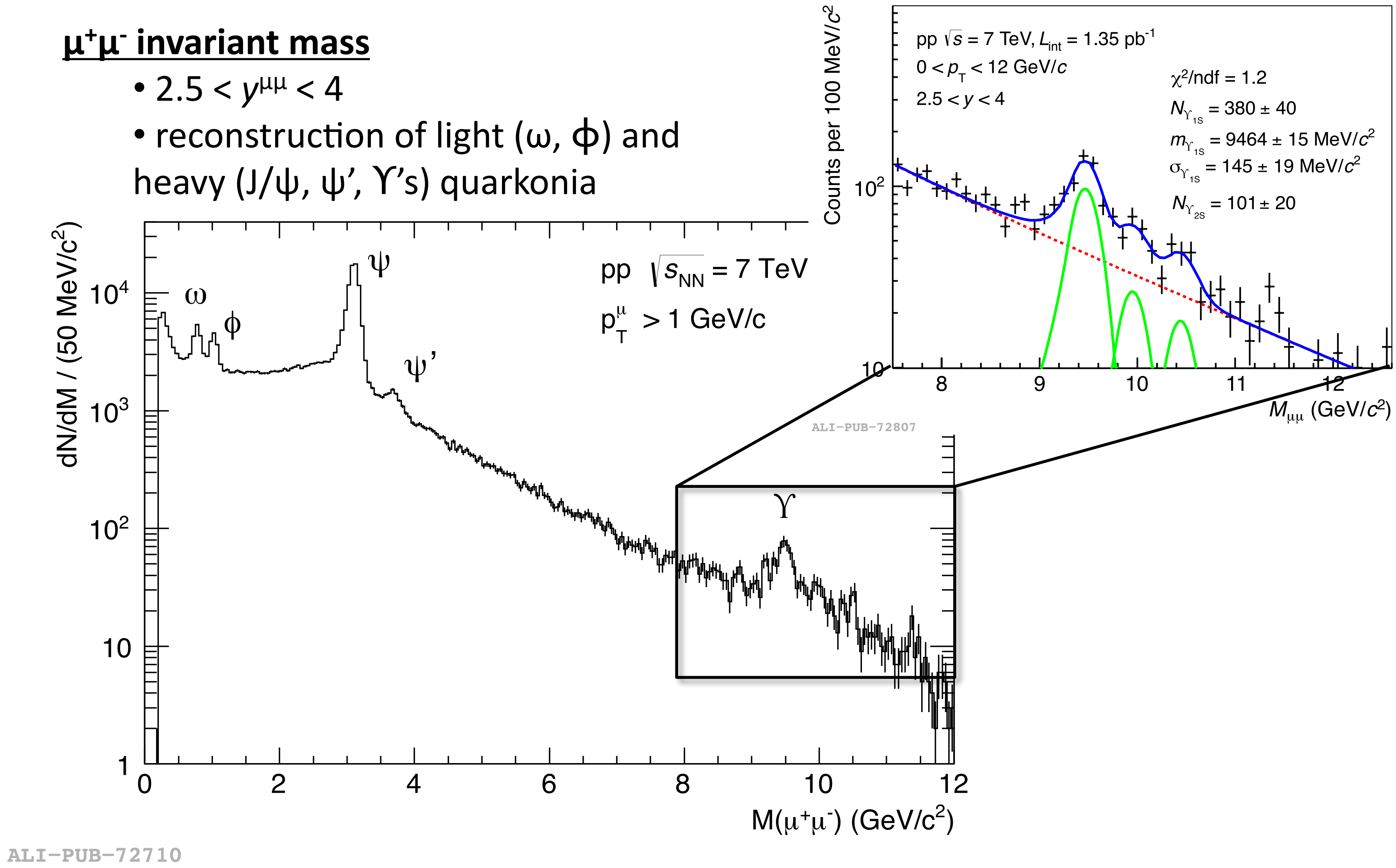
- based on distance between primary and displaced vertices
- separation of prompt J/ψ and J/ψ from b-hadron decay

Quarkonium at forward rapidity

[Int. J. Mod. Phys. A 29 (2014) ; EPJC 74 (2014)]

$\mu^+\mu^-$ invariant mass

- $2.5 < y^{\mu\mu} < 4$
- reconstruction of light (ω, ϕ) and heavy (J/ψ, ψ', Υ's) quarkonia



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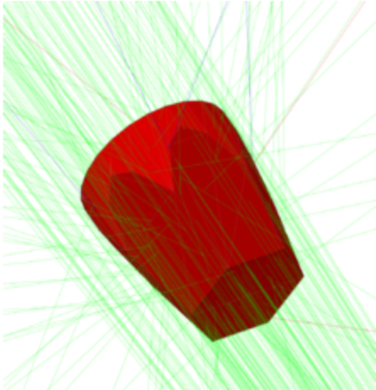
Cross section measurements

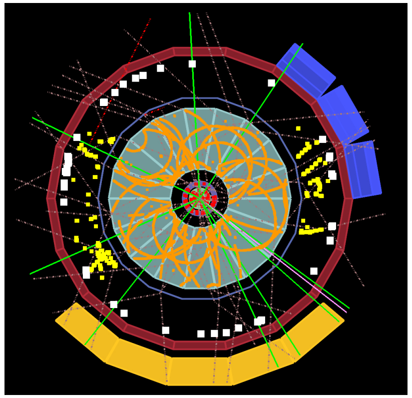
Differential cross section as a function of transverse momentum (p_T) and rapidity (y)

$$\frac{d^2\sigma_{\mathcal{Q}}}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \frac{1}{L_{int}} \frac{N_{\mathcal{Q}}(p_T, y)}{BR_{\mathcal{Q}\to l^+l^-} A\epsilon(p_T, y)}$$

- L_{int} = integrated luminosity of the data sample
- $N_{\mathcal{Q}}$ = number of quarkonium reconstructed in the considered p_T and y range
- $BR_{\mathcal{Q}\to l^+l^-}$ = branching ratio of quarkonium in dilepton
- $A\epsilon$ = acceptance-efficiency correction factor determined via realistic (run-by-run) full simulation:

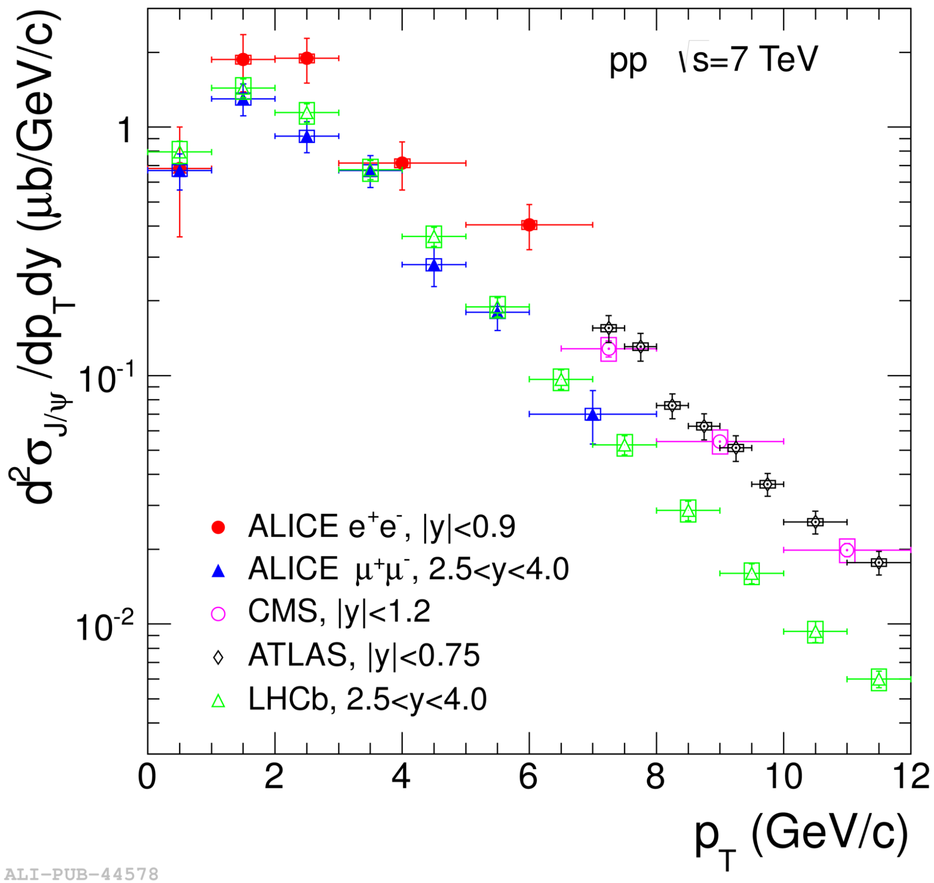
event generator (Pythia, …)	+	transport code (Geant3, …)	+	reconstruction software (like for real data)

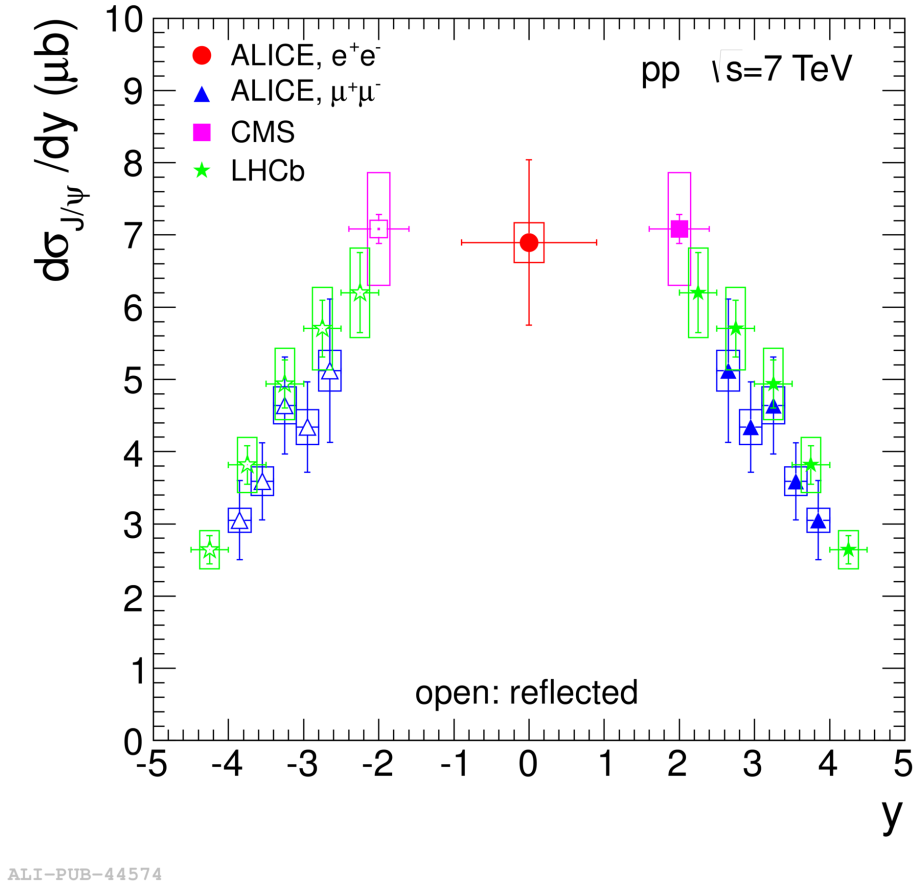




Inclusive J/ψ cross section

[PLB 704 (2011) @ 7 TeV ; PLB 718 (2012) @ 2.76 TeV]





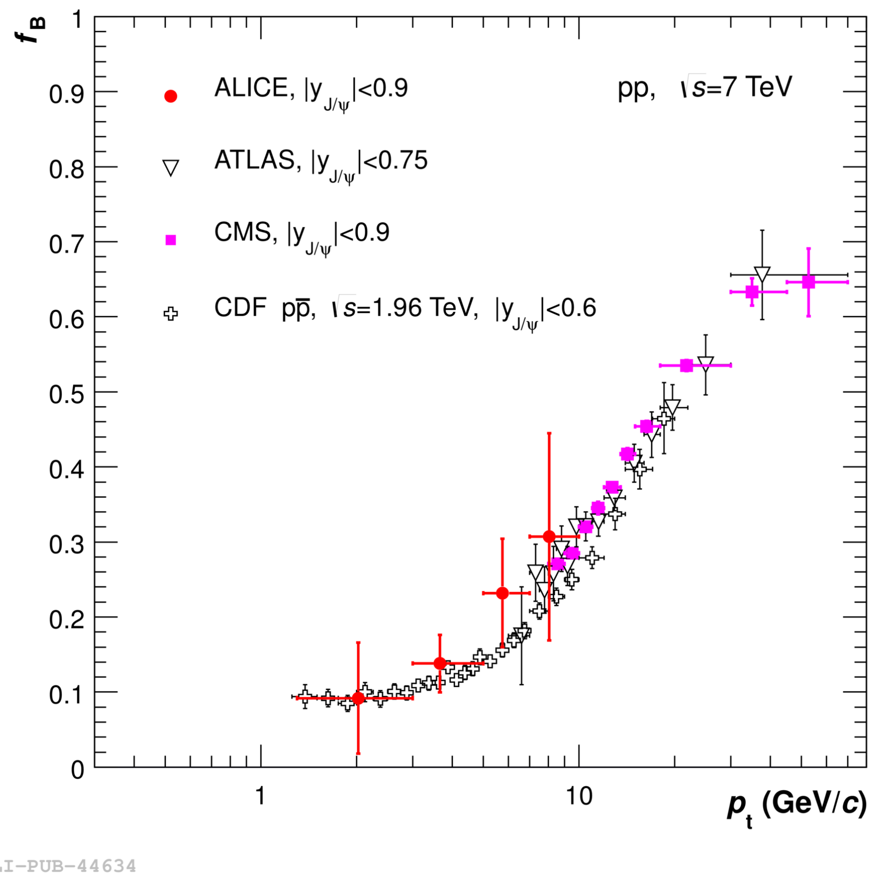
ALICE measurements complement other LHC experiments

- measurement to low p_T even at mid-rapidity
- large rapidity coverage: $|y| < 0.9$ and $2.5 < y < 4$

Non-prompt J/ψ at mid-rapidity

[JHEP 11 (2012) @ 7 TeV]

- Non-prompt J/ψ from b-hadron decay measured with the help of displaced vertex: $c\tau_B \approx 470$ µm
- ALICE extends measurements down to $p_T \approx 1$ GeV/c
- Clear p_T dependence of the fraction of J/ψ from b-hadron decay

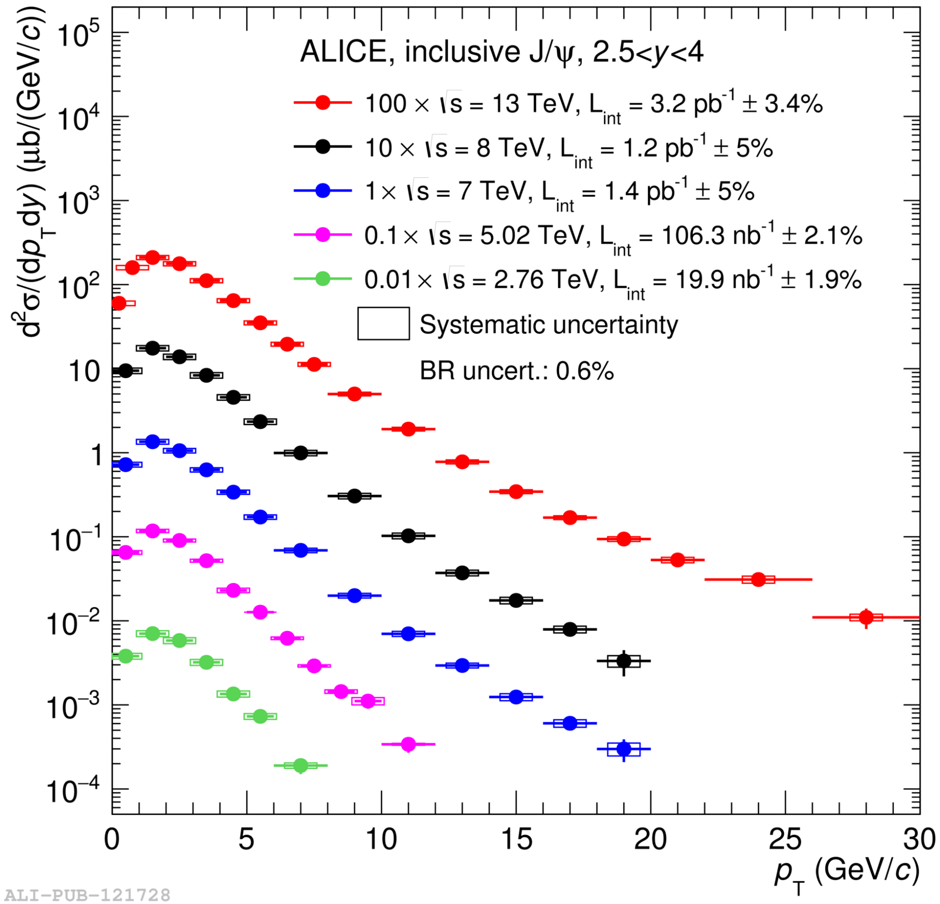


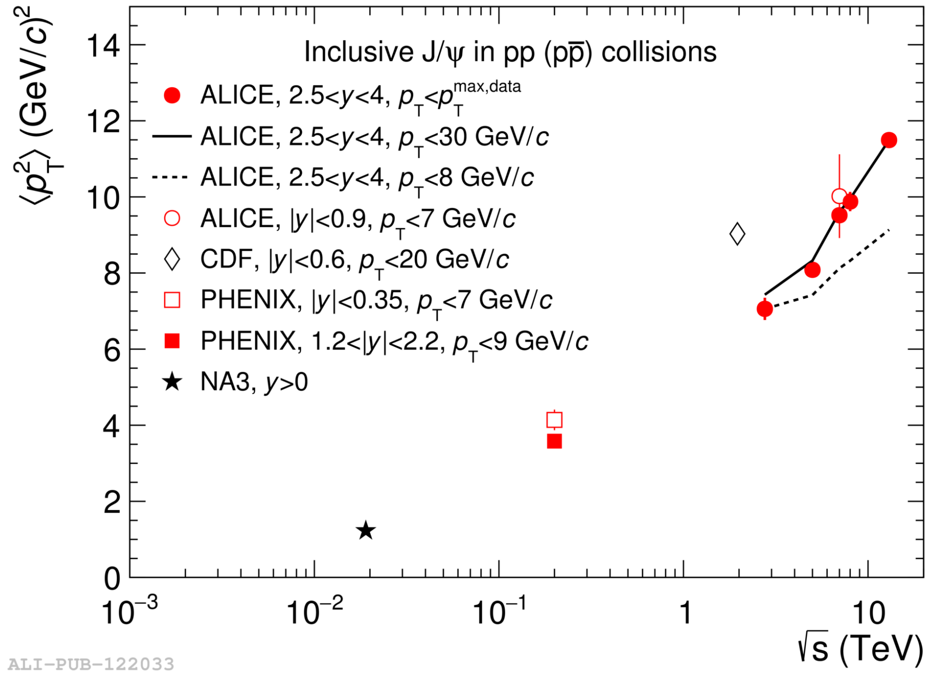
ALICE measurements integrated over the range $|y| < 0.9$ and $p_T > 1.3$ GeV/c

$$f_B = 0.149 \pm 0.037(\mathrm{stat}) \pm^{0.018}_{0.027} (\mathrm{stat}) \pm^{0.025}_{0.021} (\mathrm{pol})$$

Inclusive J/ψ at forward rapidity

[EPJC 74 (2014) @ 7 TeV ; EPJC 76 (2016) @ 8 TeV ;
arXiv:1702.00557 @ 5.02 & 13 TeV]





$$f(p_T) = C \frac{p_T}{\left(1 + \left(\frac{p_T}{p_0}\right)^2\right)^n}$$

- Hardening of the p_T-differential cross section with increasing energy
- $\langle p_T^2 \rangle$ scaling as a function of the centre-of-mass energy with a general trend:

$$\langle p_T^2 \rangle \propto \ln(\sqrt{s})$$

- … but with an hint of a rapidity dependence

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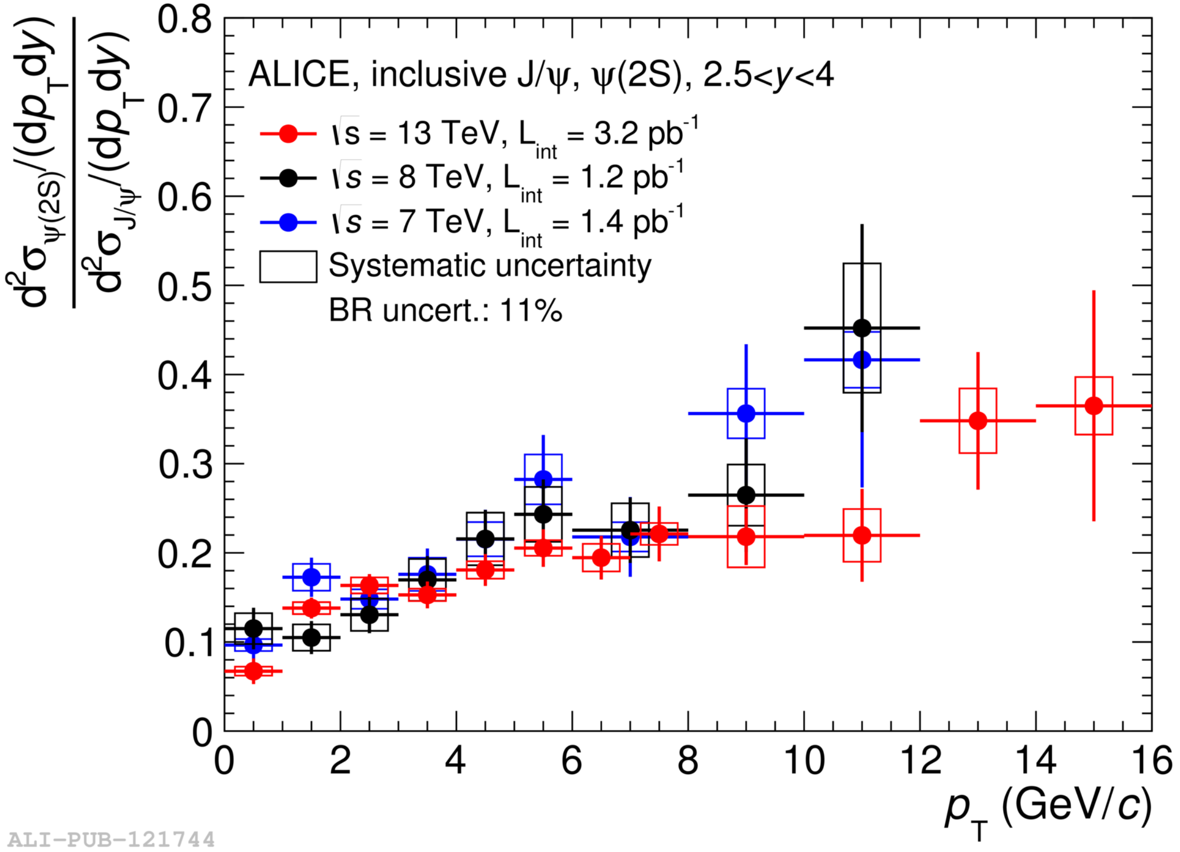
ψ(2S) at forward rapidity

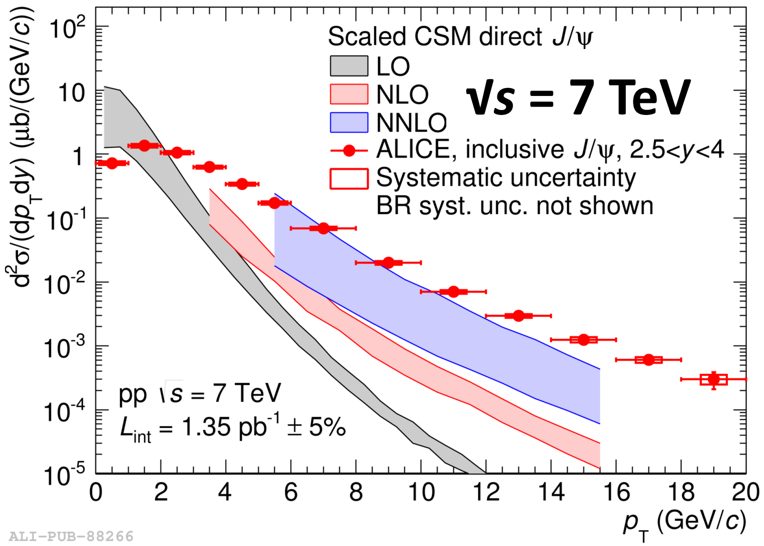
[EPJC 74 (2014) @ 7 TeV ; EPJC 76 (2016) @ 8 TeV ; arXiv:1702.00557 @ 13 TeV]

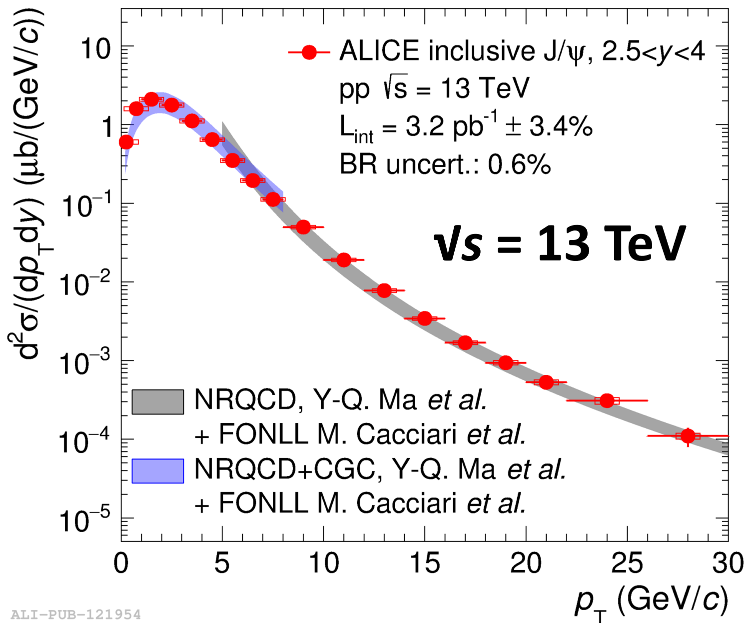


- ψ(2S) production cross section about one order of magnitude lower than for J/ψ
- Increase of ψ(2S) production with transverse momentum
- No energy dependence observed: neither in shape nor in magnitude

J/ψ comparison with theoretical models

[EPJC 74 (2014) @ 7 TeV ; arXiv:1702.00557 @ 13 TeV]





Color-Singlet Model (CSM) [J. Phys. G 38, (2011) 124110]

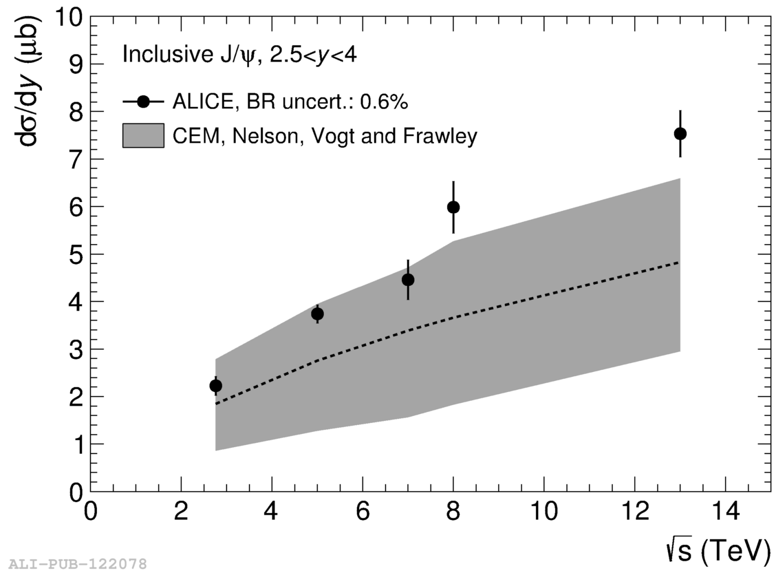
Importance of higher orders of perturbative QCD increases with p_T

Color-Octet Mechanism (NRQCD) [PRL 113 (2014) 192301]

Good p_T description with Color Glass Condensate (CGC) for the low-p_T region and Fixed-Order Next-to-Leading Logarithm (FONLL) for non-prompt J/ψ

Color-Evaporation Model (CEM) [PRC 87 (2013) 014908]

Under estimation of total cross section at forward rapidity ($2.5 < y < 4$) for the highest LHC energies



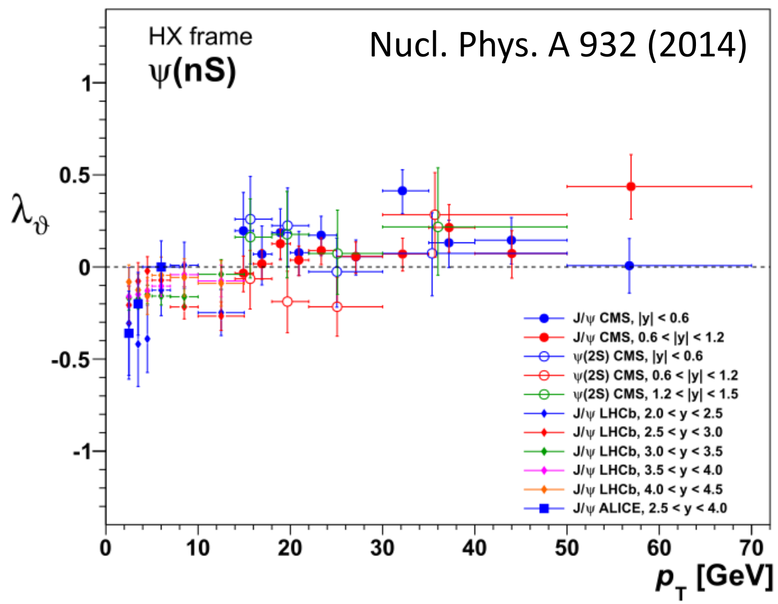
J/ψ polarization

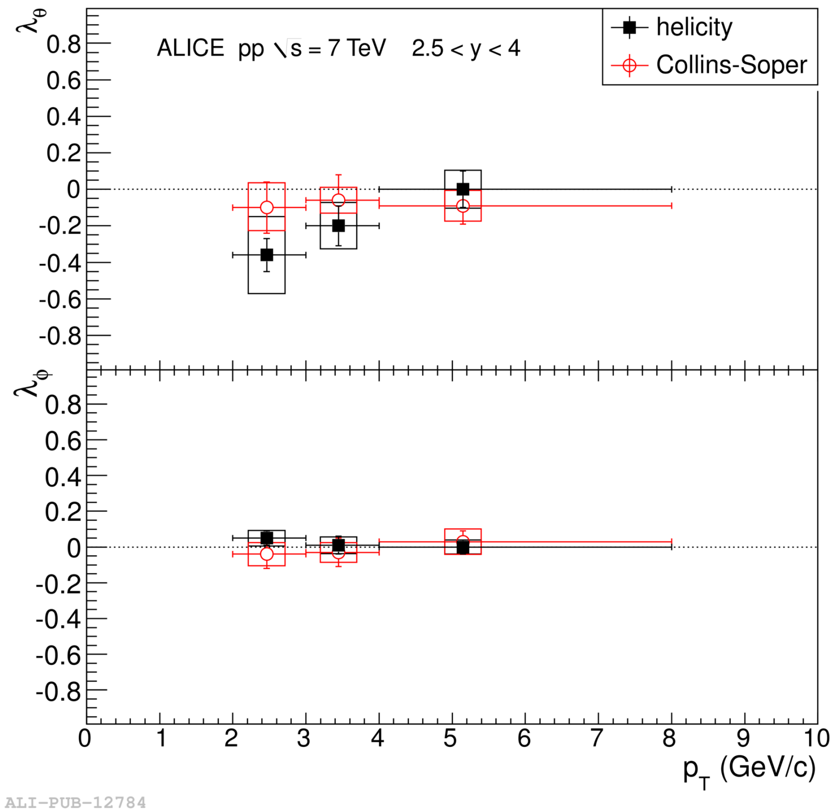
[PRL 108 (2012) @ 7 TeV]

- Quarkonium = vector meson with angular momentum states embedded in three polarization parameters: λ_θ, λ_ϕ, $\lambda_{\theta\phi}$
- Experimental study via angular distributions of leptons in the quarkonium rest-frame, with θ = polar angle and ϕ = azimuthal angle

$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta) \quad ; \quad W(\phi) \propto 1 + \frac{2\lambda_\phi}{3+\lambda_\theta}\cos(2\phi)$$

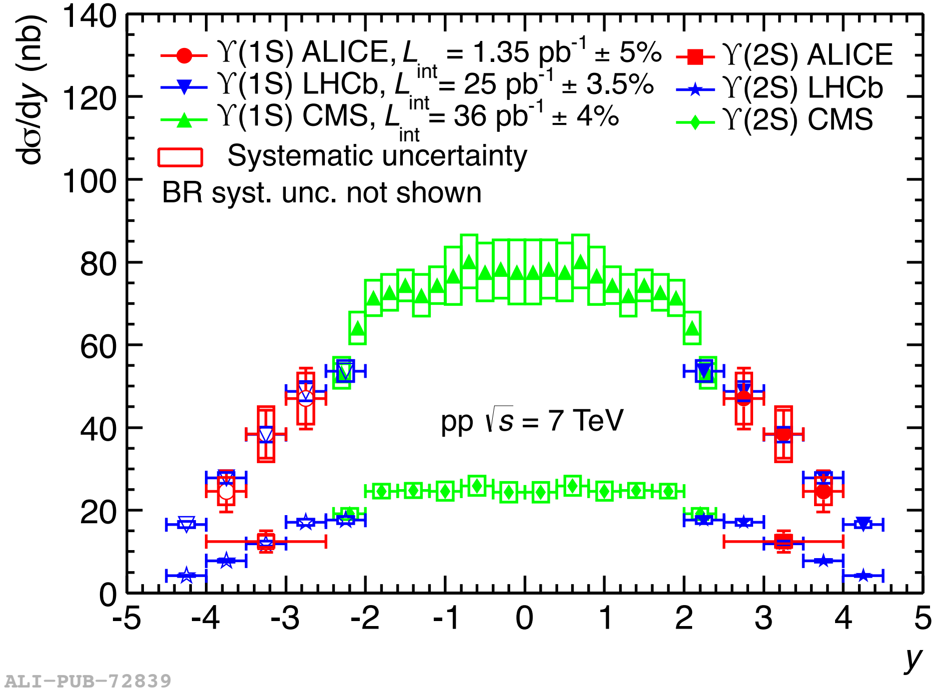
- Measurement performed in different polarization frame for completeness
- No J/ψ polarization observed at low p_T

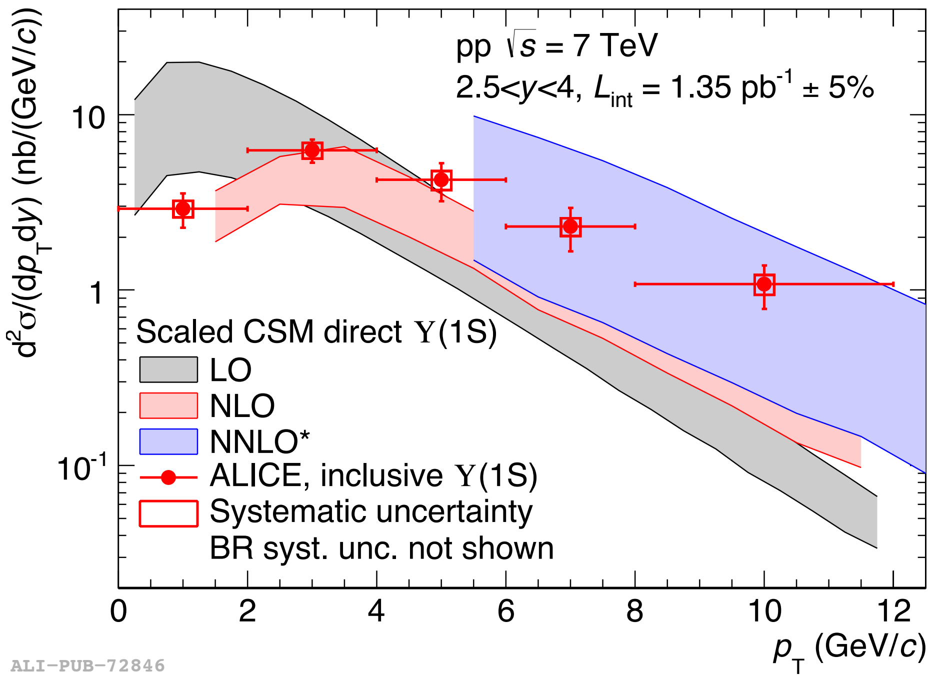




Bottomonium cross section

[EPJC 74 (2014) @ 7 TeV]





Experimental measurements

- Differential cross sections of ϒ(1S) and ϒ(2S) in agreement with LHCb
- ϒ(2S)/ϒ(1S) = 0.28 ± 0.08
- Full rapidity coverage by combining the acceptances of different LHC experiments

Comparison with theoretical models

- High p_T ϒ(1S) show the importance of NNLO contributions [J.-P. Lansberg, Nucl. Phys. A 470, (2013) 910]
- Better matching of CSM prediction with ϒ(1S) than J/ψ

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Event multiplicity dependence

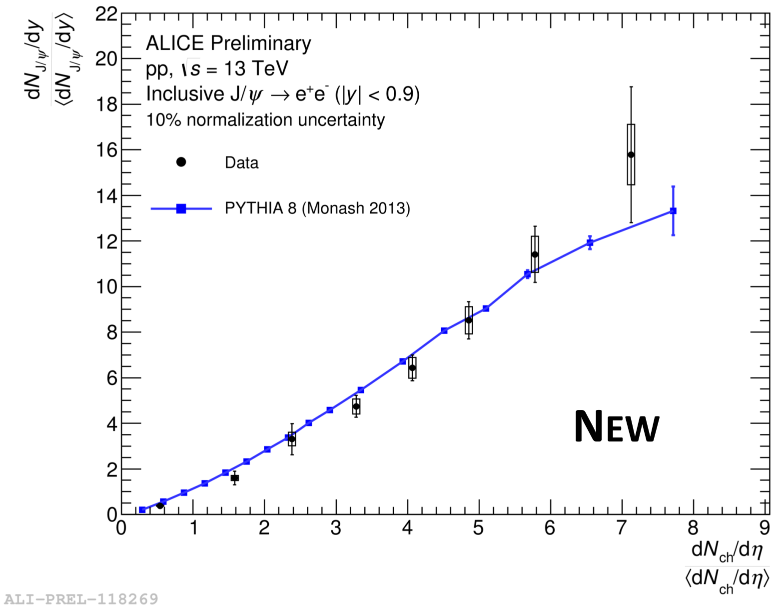
[PLB 712 (2012) @ 7 TeV ; JHEP 09 (2015) @ 7 TeV]

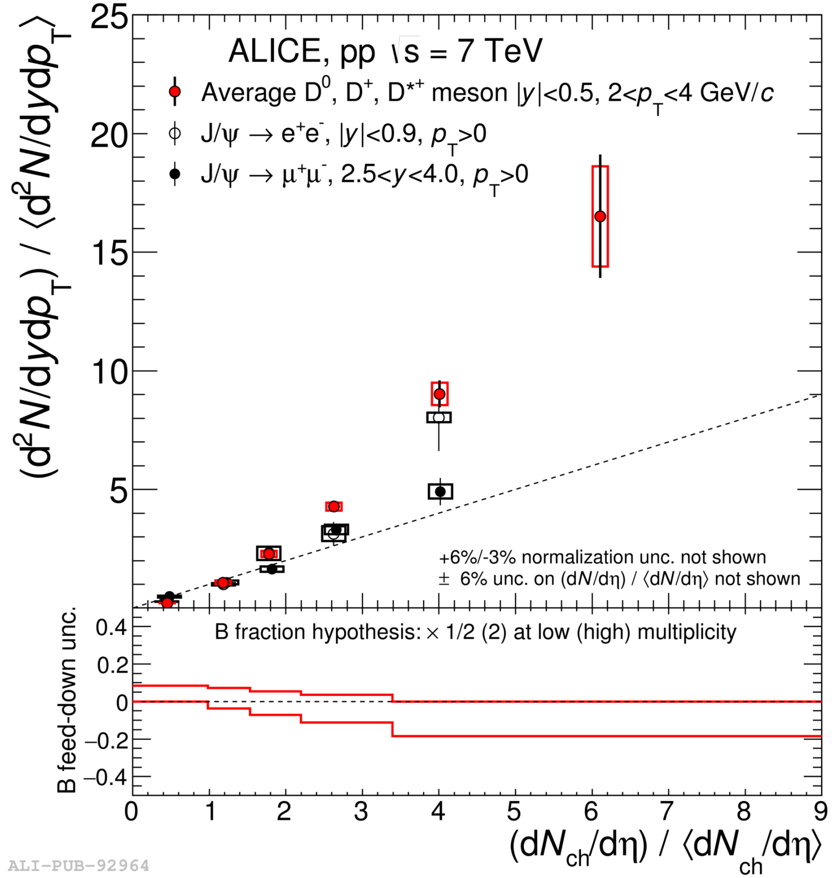
Theoretical motivations

- Multi-Parton Interactions (MPI) in high-energy proton-proton collisions
- Dependence of quarkonium production with underlying event

Experimental measurements

- Non-linear increase of relative J/ψ yield with the relative charged multiplicity N_{ch}
- Similar trend observed for D mesons
- Correct description with MPI approaches: Pythia8 and EPOS3 (not shown)





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In summary

- **Cross section**
  - Measurement of quarkonium cross sections – J/ψ, ψ(2S), ϒ's – in the full LHC energy range: $\sqrt{s}$ = 2.76 – 13 TeV
  - Last results at $\sqrt{s}$ = 13 TeV increase significantly the p_T range
  - Good description of the full p_T spectra with an ad-hoc mixed approach: CGC (low p_T) + NRQCD-COM + FONLL (for non-prompt J/ψ)
  - Measurement of J/ψ from b-hadron decay at mid-rapidity

- **Polarization**
  - Measurement of J/ψ polarization parameters in different frames (HX and CS)
  - Observed zero polarization for J/ψ not reproduced by existing theoretical models: neither CSM (longitudinal polarization) nor COM (transverse polarization)

- **Event multiplicity dependence**
  - Observation of non-linear increase of the relative J/ψ production yield with event multiplicity
  - Correct description by Multi-Parton Interactions (MPI) based generators

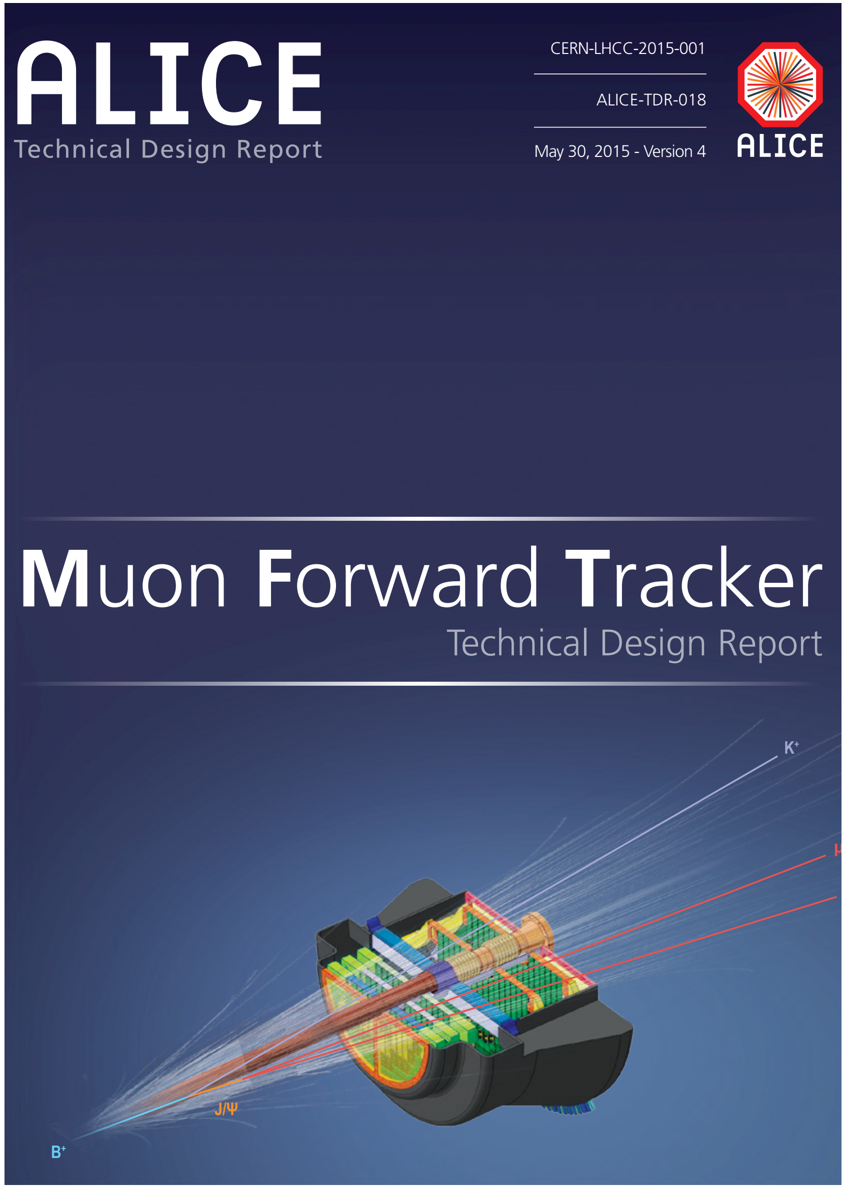
Perspectives

✧ **Much more results to come with the end of LHC run 2**

- more statistics to increase p_T range and to improve ψ(2S) and Υ's measurements
- new analysis, like Υ's versus event multiplicity

✧ **ALICE upgrade for LHC run 3 (2021)**

- new detectors – like the Muon Forward Tracker to separate prompt J/ψ and J/ψ from b-hadron decay at forward rapidity
- improvement of electronics for higher acquisition rate, i.e. still more statistics



Thanks for your attention

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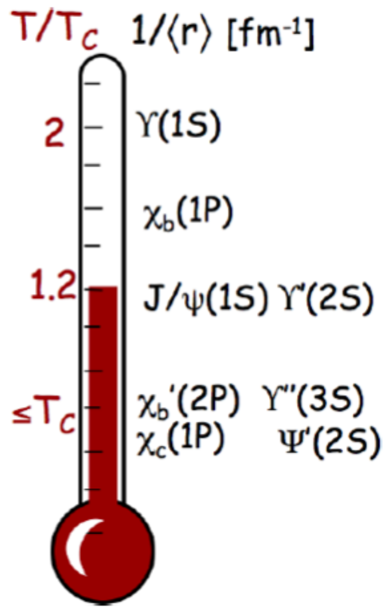
Physics motivation in heavy-ion



✧ Quarkonia are produced in first stages of heavy-ion collisions

➔ sensitive to the properties of the Quark-Gluon Plasma

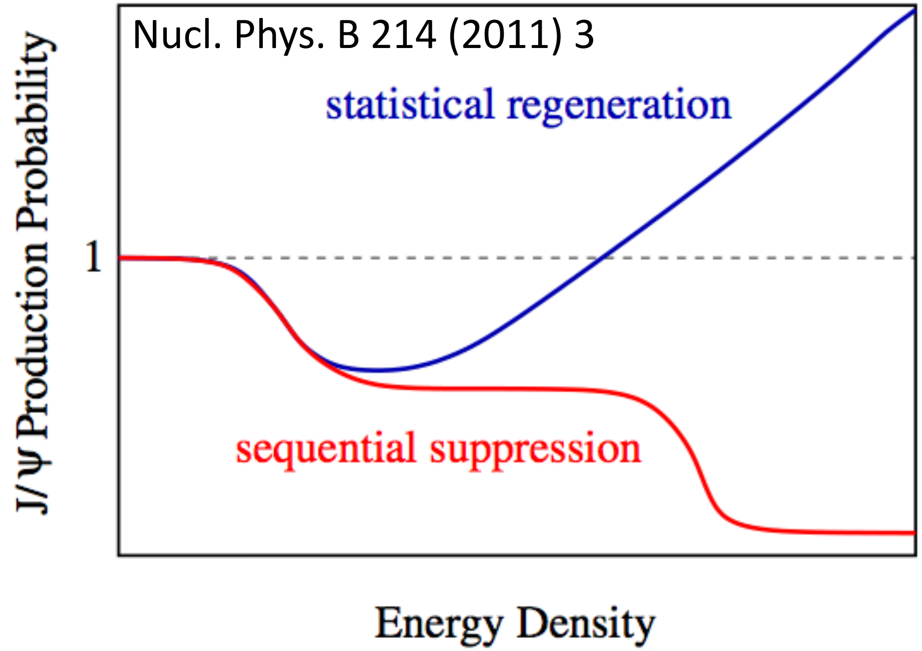
✧ Quarkonium sequential suppression via color screening
[Matsui & Satz, PLB178 (1986) 178]

➔ QGP thermometer [Mocsy, EPJC61 (2009) 705]

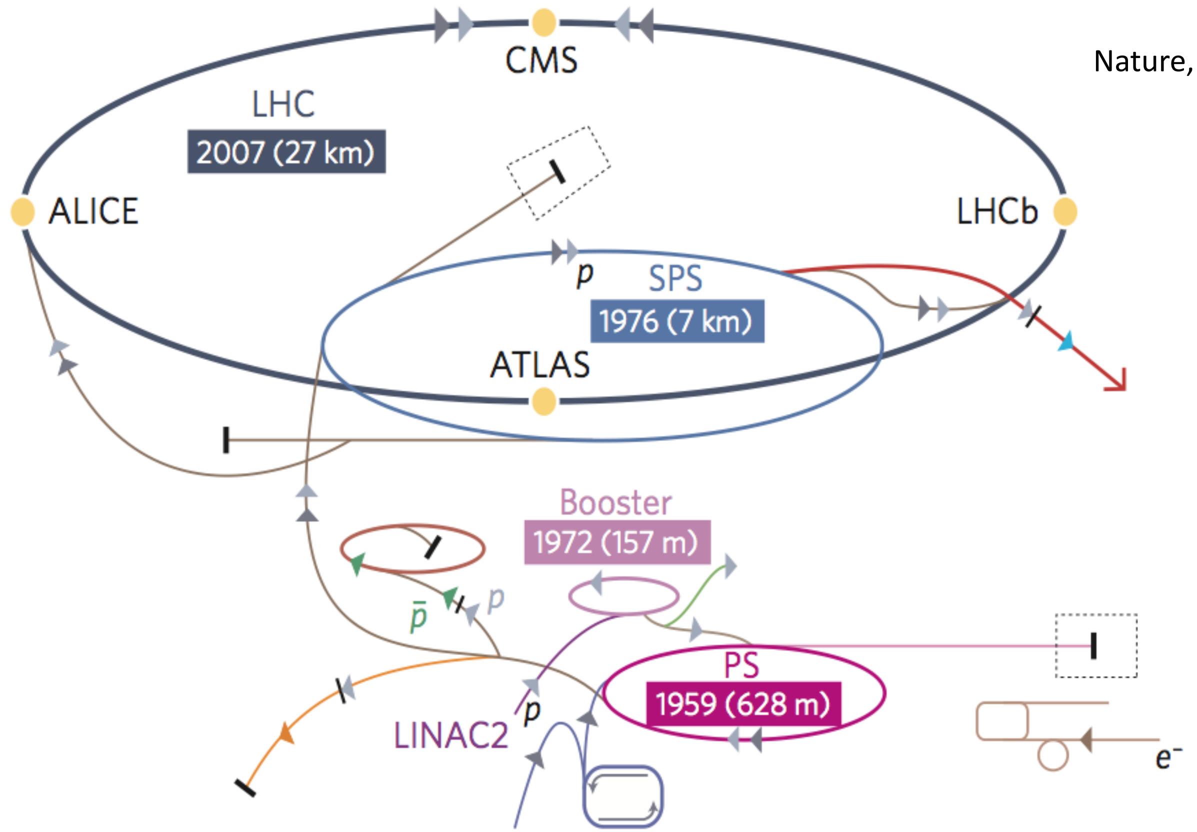
✧ Quarkonium statistical regeneration if large heavy quark event multiplicity
[Braun-Munzinger & Stachel, PLB490 (2000) 196 ; Thews, Schroedter & Rafelski, PRC65 (2001) 054905]

✧ **Advantages of Υ versus J/ψ**

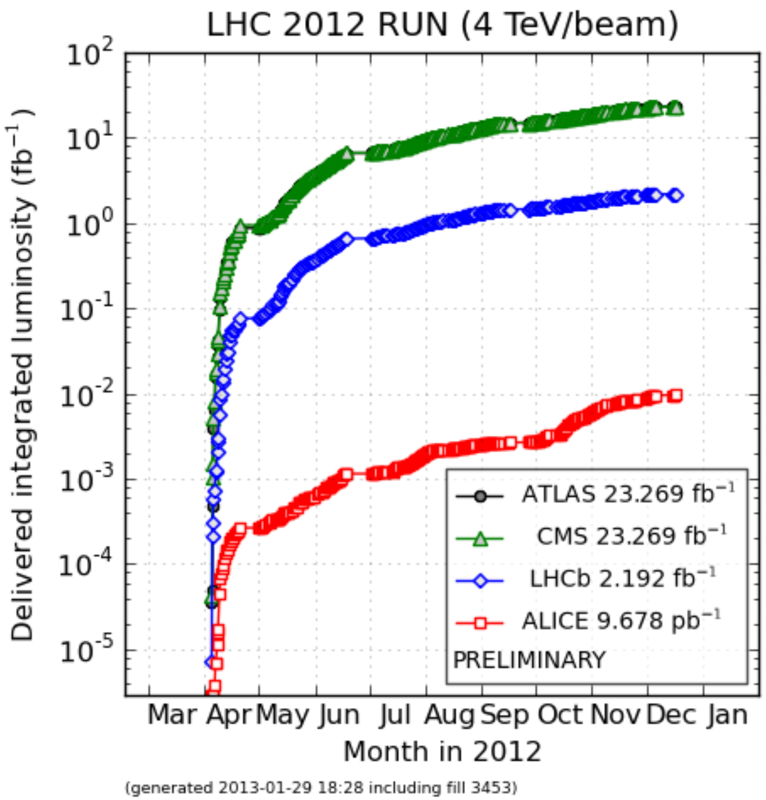
- no feed down from open heavy-flavour hadrons
- less regeneration expected
[L. Grandchamp et al., PRC73 (2006) 064906]



LHC luminosity in ALICE



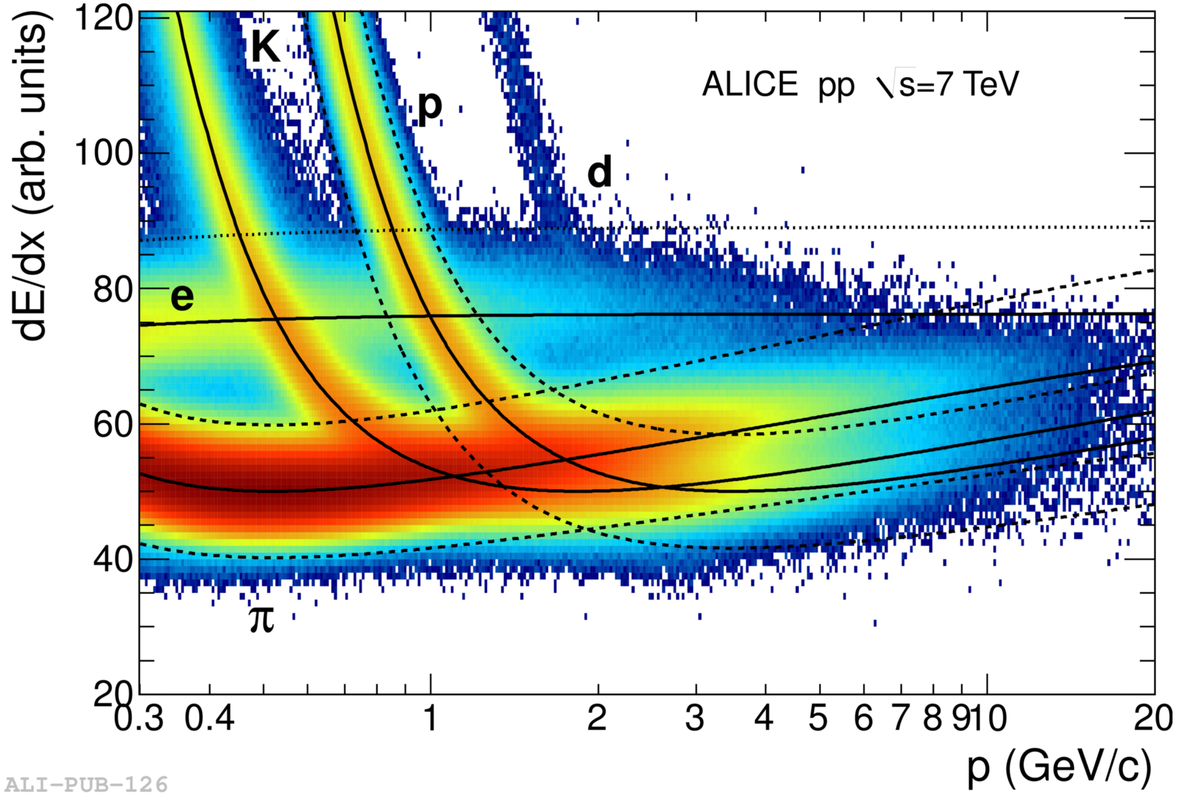
Nature, Vol. 448, 19 July 2007



Electrons identification and pseudoproper decay length

[JHEP 11 (2012) @ 7 TeV]

Specific energy loss in the TPC



Pseudoproper decay length

$$x = \frac{c\, L_{xy}\, m_{J/\psi}}{p_T^{J/\psi}} \quad \text{with} \quad L_{xy} = \frac{\vec{L} \cdot \vec{p}_T^{\,J/\psi}}{p_T^{J/\psi}}$$

and $\vec{L}$ = vector from the primary to the J/ψ decay vertex

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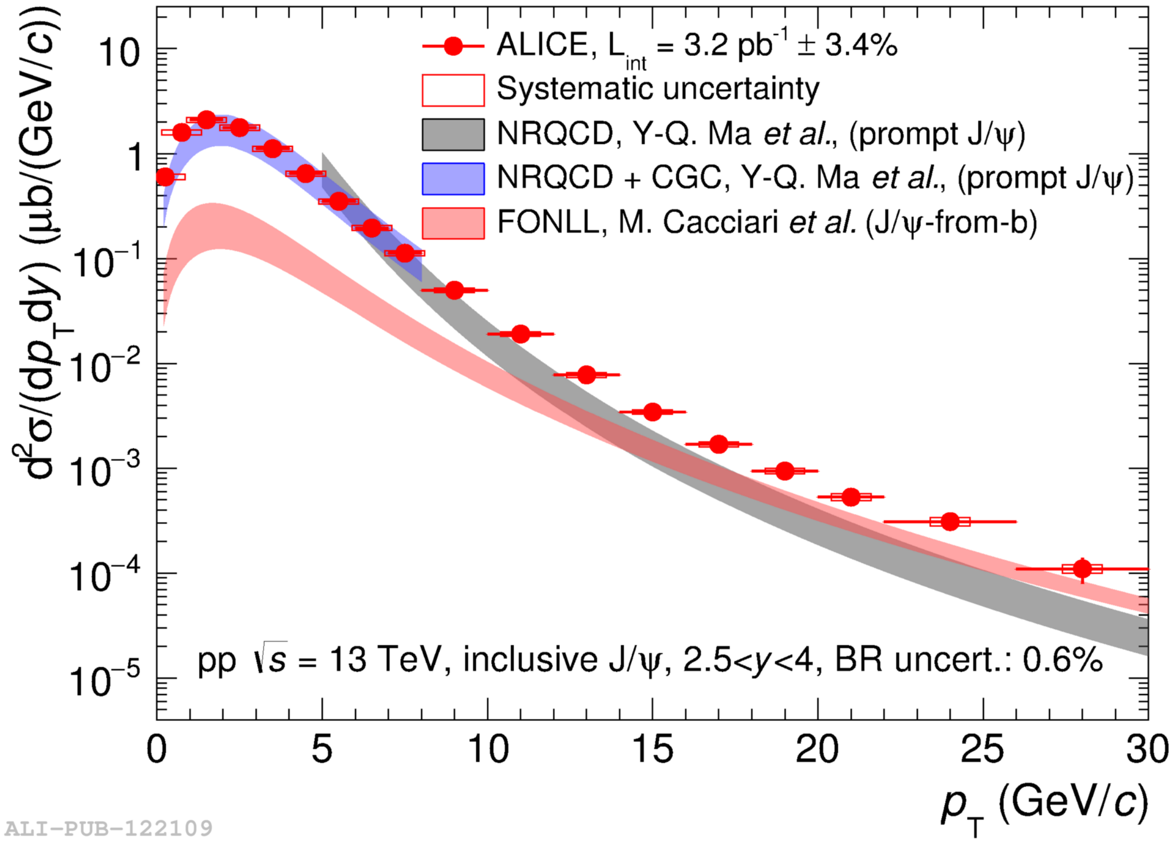
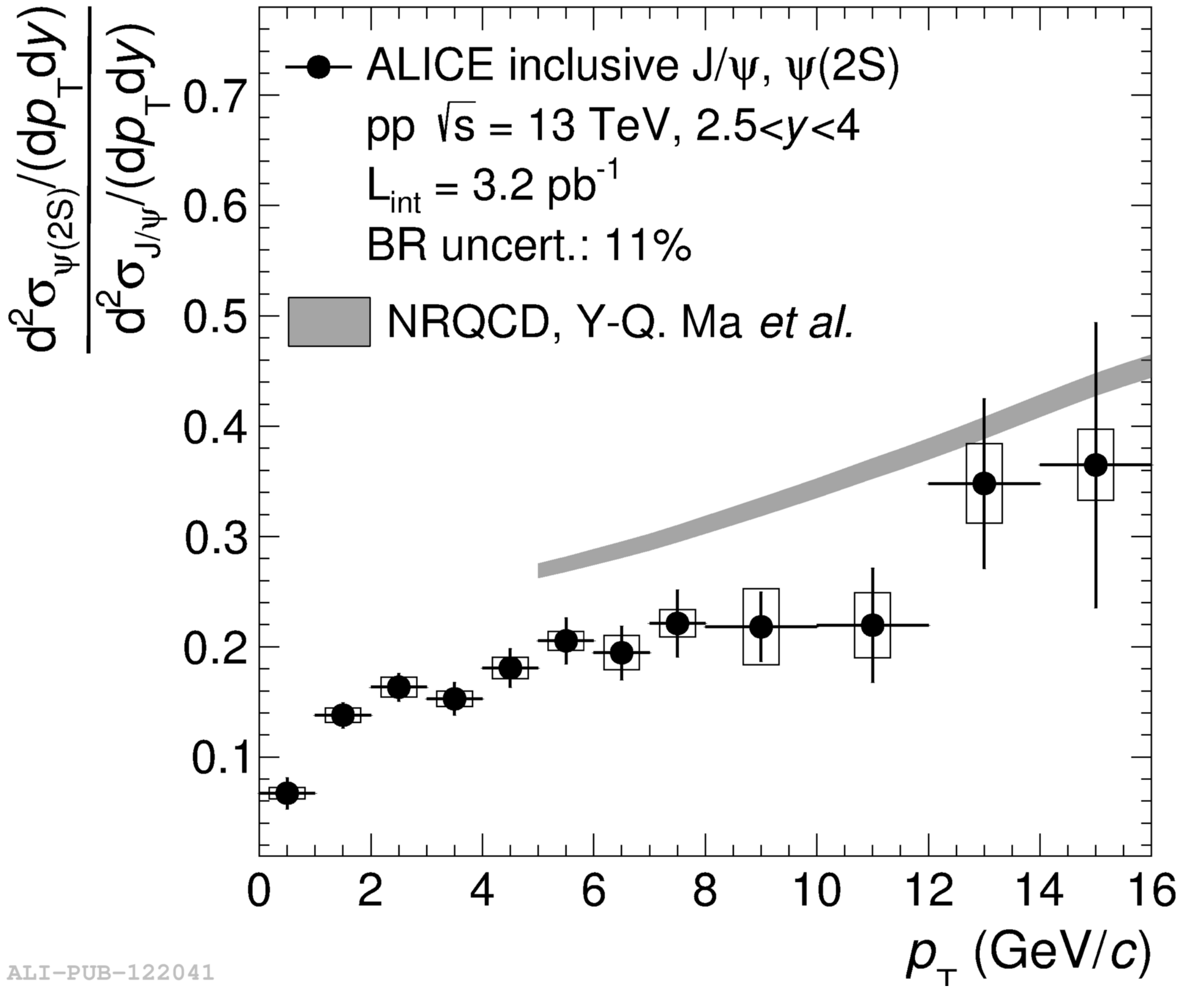
J/ψ comparison to theoretical models

[arXiv:1702.00557 @ 13 TeV]



Ψ(2S) / J/ψ ratio and model

[arXiv:1702.00557 @ 13 TeV]



Muon Forward Tracker expected performances [CERN-LHCC-2015-001]

Longitudinal pseudo-proper decay time

$$t_z = \frac{(z_{J/\psi} - z_{\rm vtx}) \cdot M_{J/\psi}}{p_z}$$