Quarkonia production in **ATLAS** and **CMS** experiments

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On behalf of the **ATLAS** and **CMS** Collaborations

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Introduction

- **Heavy flavour production** is very important for the **understanding** of **QCD**
- LHC's remarkable performance provided **ATLAS and CMS** with over **150 fb^{-1}** of data during Run1 and Run2
  - using these large datasets **new processes** can be observed and more **precise measurements** can be made
- In this talk just a selection of topics

  (1) Measurement of the production cross-section of J/ψ and ψ(2S) mesons at high transverse momentum in pp collisions at $\sqrt{s}$=13 TeV with the **ATLAS** detector ATLAS-CONF-2019-047

  (2) Measurement of the χ_{c1} and χ_{c2} polarisations in proton-proton collisions at $\sqrt{s}$=8 TeV (**CMS**) arXiv:1912.07706

  (3) Measurement of J/ψ production in association with a $W^{\pm}$ boson with pp data at 8 TeV (**ATLAS**) arXiv:1909.13626

  (4) Relative cross sections of the $\mathrm{B_c^+(2S)}$ and $\mathrm{B_c^{*+}(2S)}$ states with respect to the $\mathrm{B_c^+}$ state in proton-proton collisions at $\sqrt{s}$=13 TeV CMS-PAS-BPH-19-001

Measurement of the production cross-section of J/ψ and ψ(2S) mesons at high transverse momentum in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

ATLAS-CONF-2019-047

Quarkonia production in **ATLAS** and CMS experiments

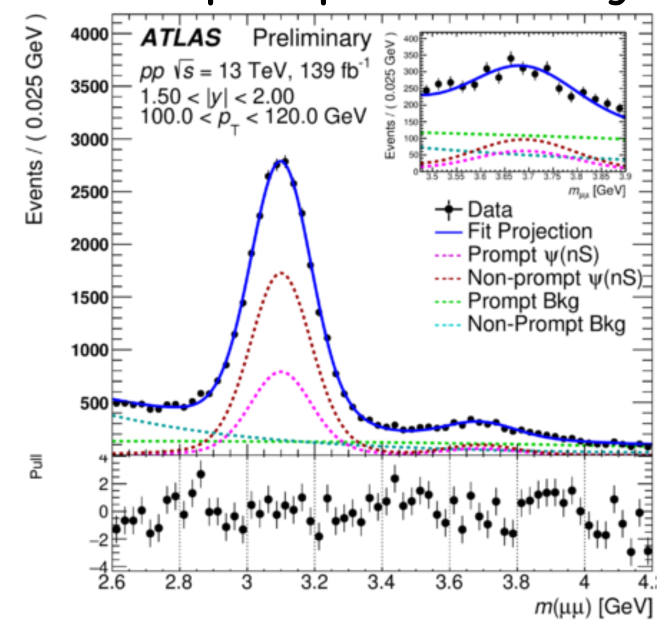
Measurement of the production cross-section of J/ψ and ψ(2S) mesons

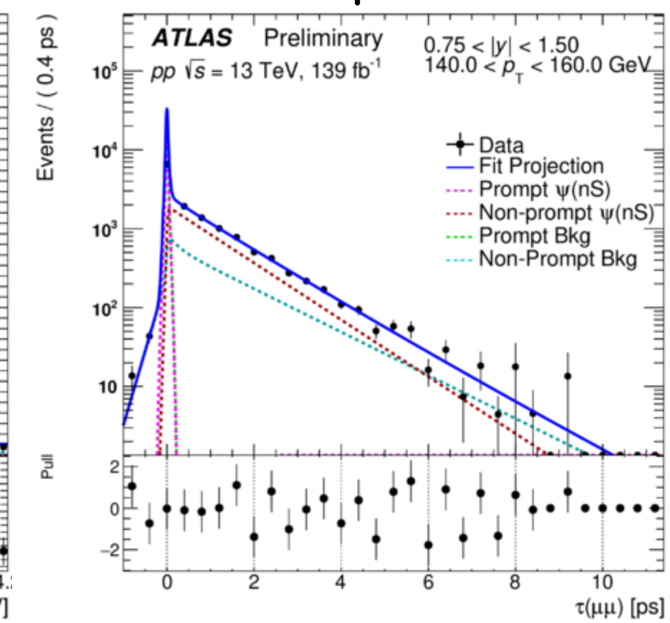
- Quarkonia production provides a unique insight into QCD
  - produced either prompt or non-prompt
- Experimental data can be used to extract values of the Long-Distance Matrix Elements (LDMEs) to help the predictions of quarkonia cross-sections
- Although there are a lot of measurements, a universal library of LDMEs is still challenging to describe simultaneously the
  - quarkonia **polarisations**
  - quarkonia **production in association** with other particles
  - **photo** or **electro** quarkonia **production**
- So, it is important to **widen** the scope of **results** both in terms of **quarkonia production mode** and **kinematic reach**

Quarkonia production in **ATLAS** and CMS experiments

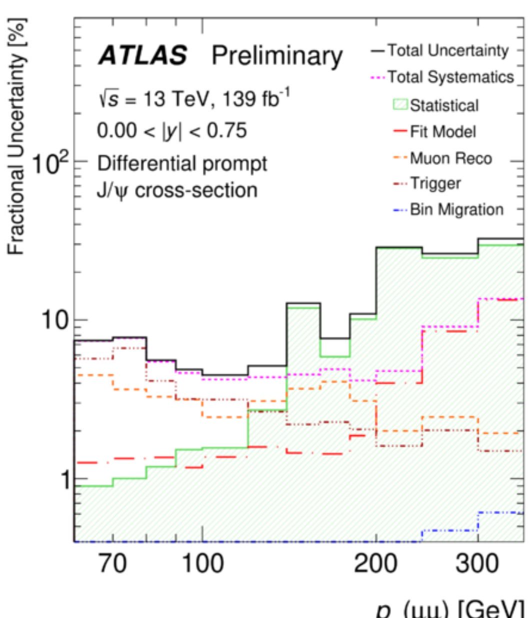
Measurement of the production cross-section of J/ψ and ψ(2S) mesons

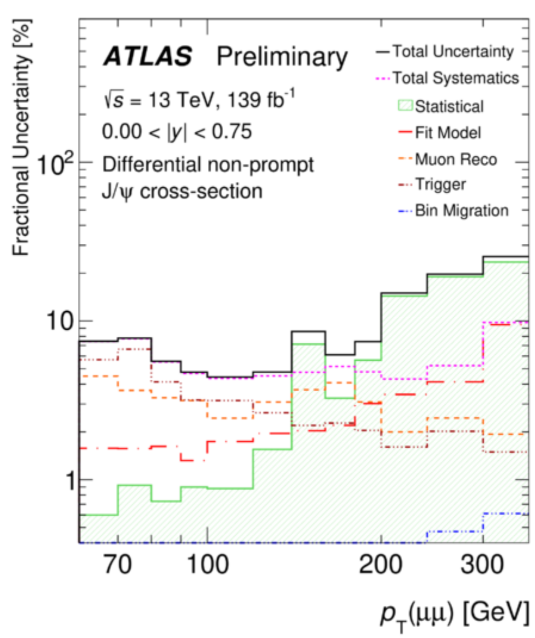
- Use of **single muon triggers** and **full Run-2 dataset** allows to probe high-p_T range
  - previous analysis employed di-muon triggers, limiting the p_T range up to 100 GeV Eur. Phys. J. C 76 (2016) 283
- Fit both di-muon invariant mass and pseudo-proper decay time to separate prompt and non-prompt components

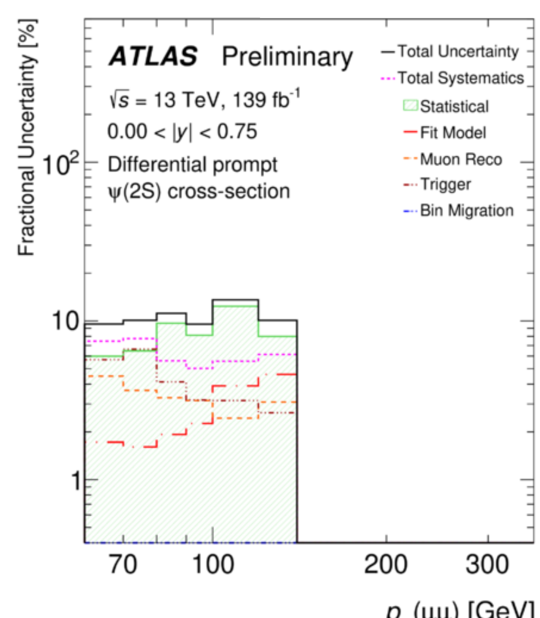


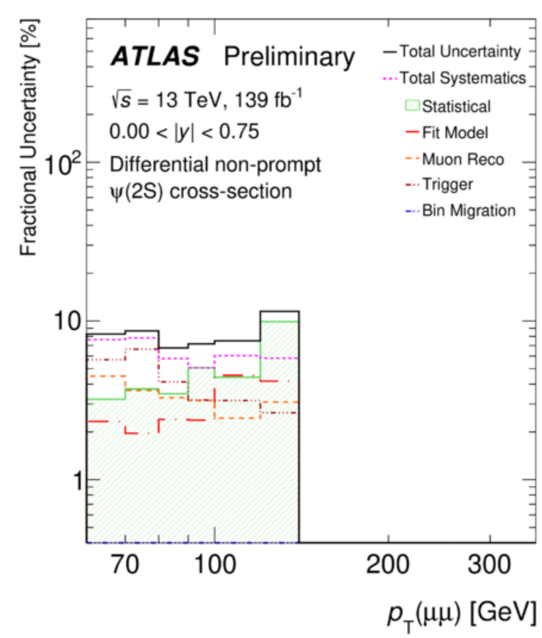


- Measurement **dominated by statistical uncertainty at high p_T**
- At **low p_T** muon reconstruction and trigger contributed to the **systematic uncertainty**





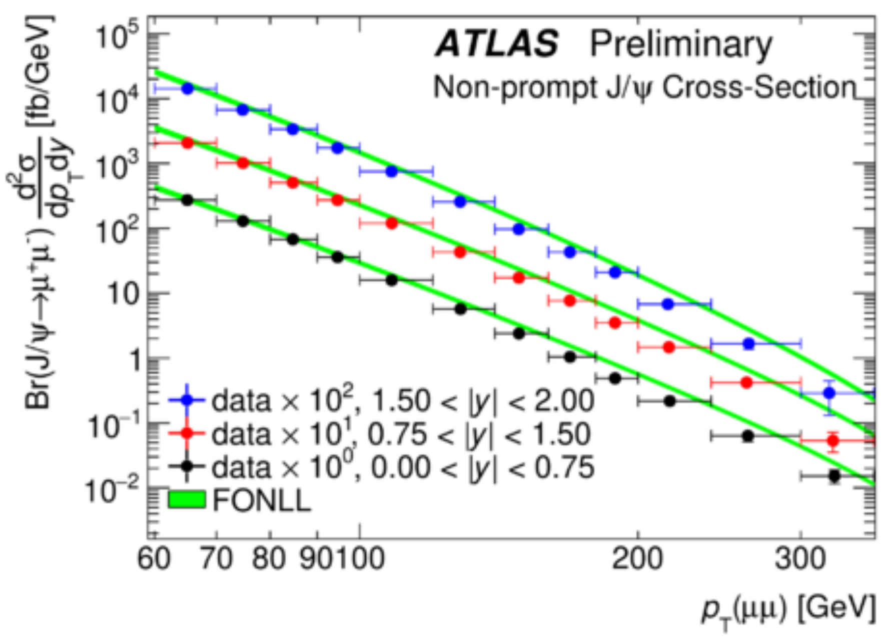


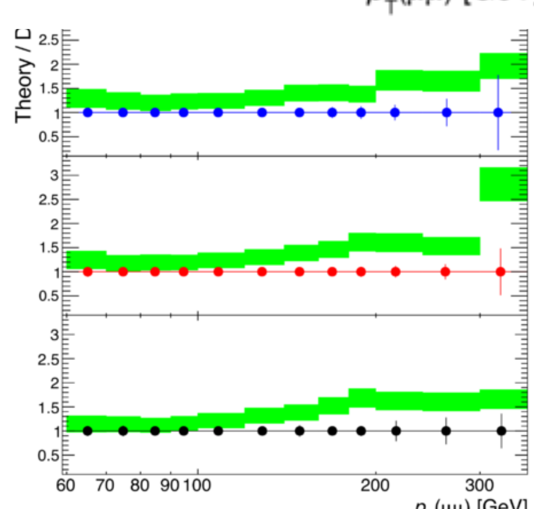


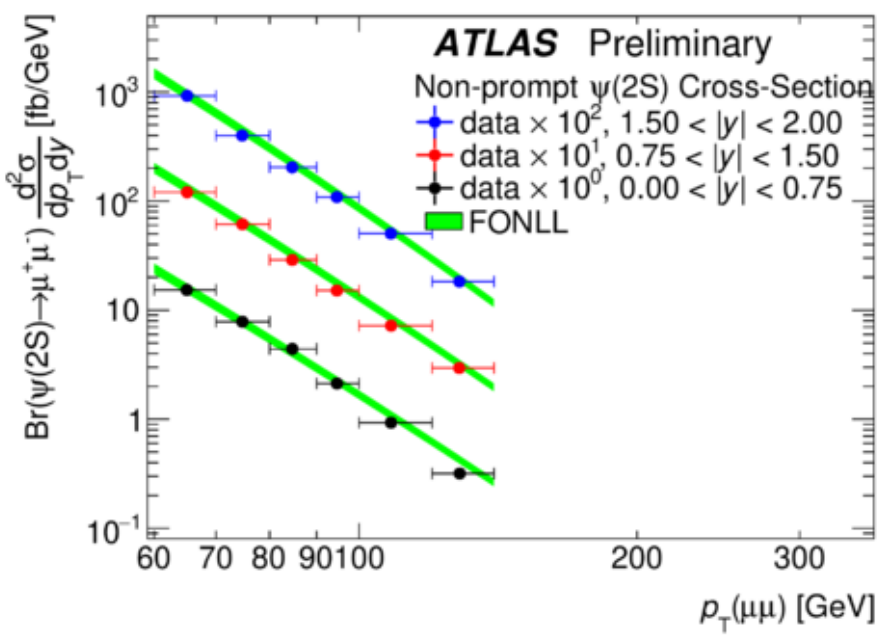
Quarkonia production in **ATLAS** and CMS experiments

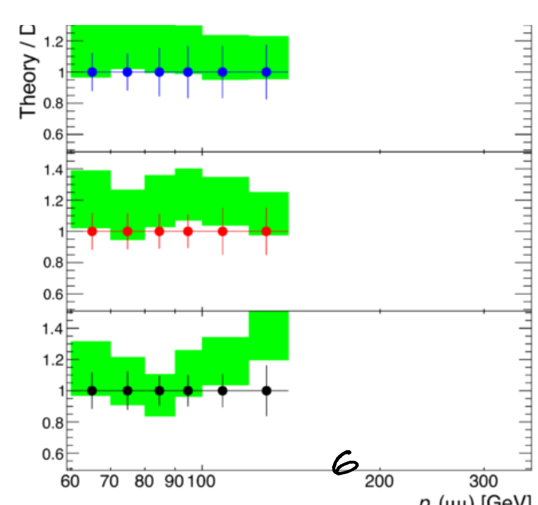
Measurement of the production cross-section of J/ψ and ψ(2S) mesons

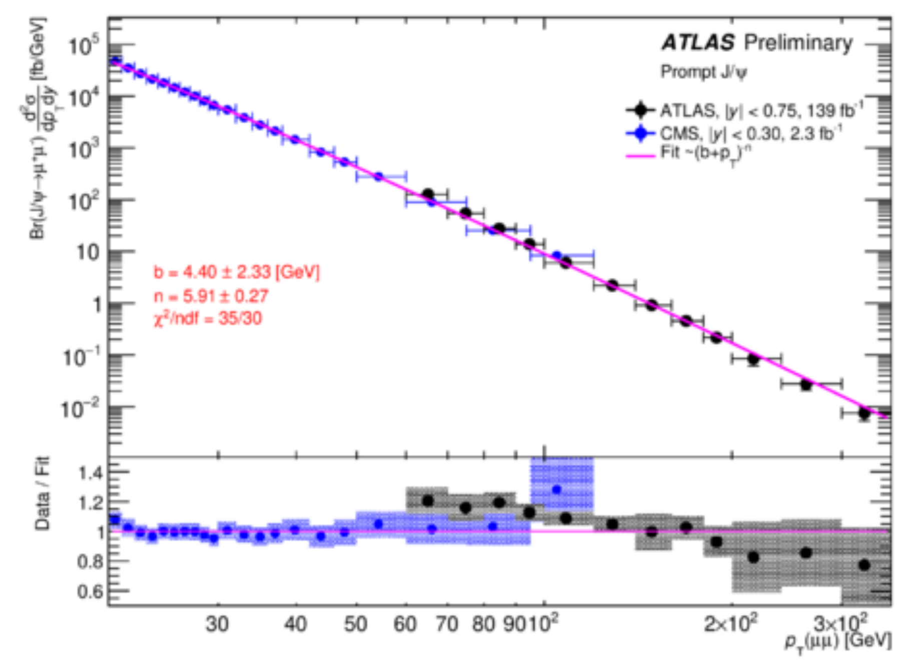
- Comparison of prompt J/ψ cross-section with **CMS** Phys. Lett. B 780 (2018) 251
    - **consistent results in overlap region**
    - parameterisation $(b + p_T)^{-n}$ seems to be consistent with measurement
- **Comparison** of non-prompt production of quarkonia **with FONLL**
    - **good agreement at low p_T**
    - FONLL predicts **higher cross-sections at high-p_T**









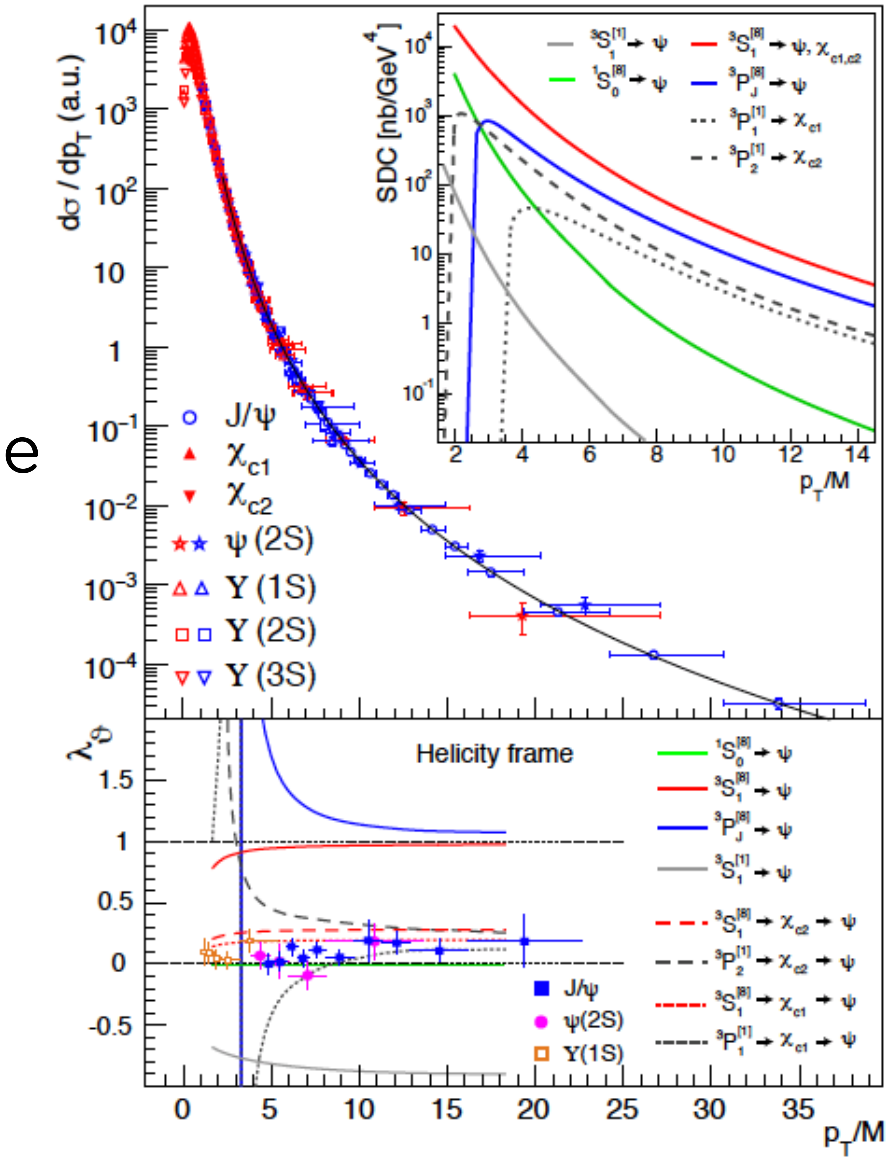


Measurement of the χ_{c1} and χ_{c2} polarisations in proton-proton collisions at $\sqrt{s}$=8 TeV

Phys. Rev. Lett. 124 (2020) 162002 - arXiv:1912.07706

Measurement of the χ_{c1} and χ_{c2} polarisations

- J/ψ, ψ(2S), Υ(1S), Υ(2S) and Υ(3S) **differential cross-sections** measured in ATLAS and CMS have **indistinguishable shapes as a function of p_T/M**
  - which is followed by the χ_{c1} and χ_{c2} states
- For **polarisations**, five S-wave states **compatible with unpolarised scenario**
  - do the χ_{c1} and χ_{c2} states follow?
- In NRQCD, **χ_{c1} and χ_{c2} polarisations** are determined by a single colour octet (CO) parameter
  - can be extracted **employing χ_{c2}/χ_{c1} cross-section ratio**
- The polarisation of the two states should be opposite and almost maximal
  - in case they are similar, will pose a challenge to NRQCD

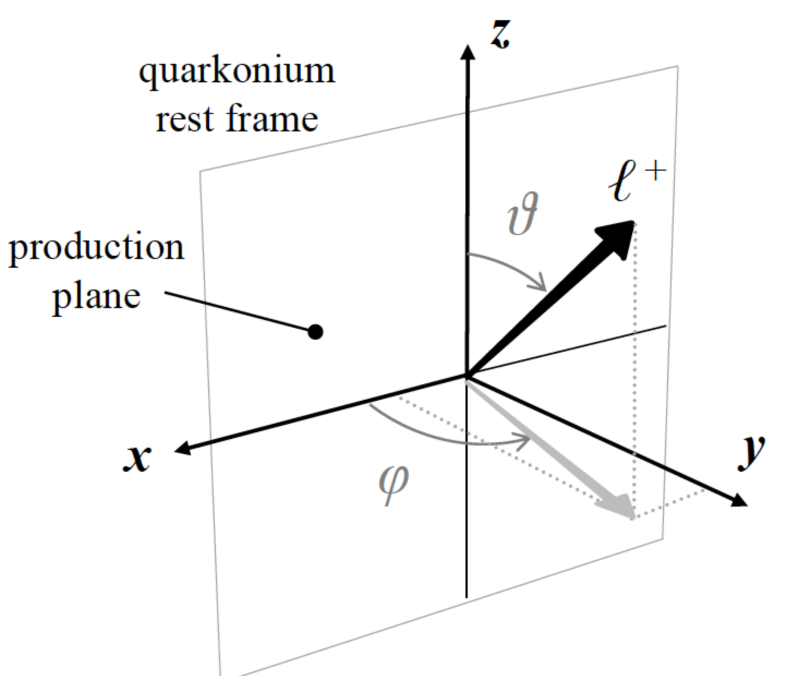


Eur. Phys. J. C 78 (2018) 3

Measurement of the χ_{c1} and χ_{c2} polarisations

- **First measurement** of the **polarisations** of inclusively produced **P-wave quarkonia** using the 8 TeV dataset
- The χ_{c1} and χ_{c2} states are reconstructed via their radiative decays to $J/\psi\gamma$
  - di-muon trigger
  - photon being converted in the tracker
- Polarisation of χ_{cJ} equivalent to the polarisation of its daughter J/ψ
- 3 bins in J/ψ p_T: 8-12, 12-18 and 18-30 GeV
- Angular decay parametrised as

$$1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$



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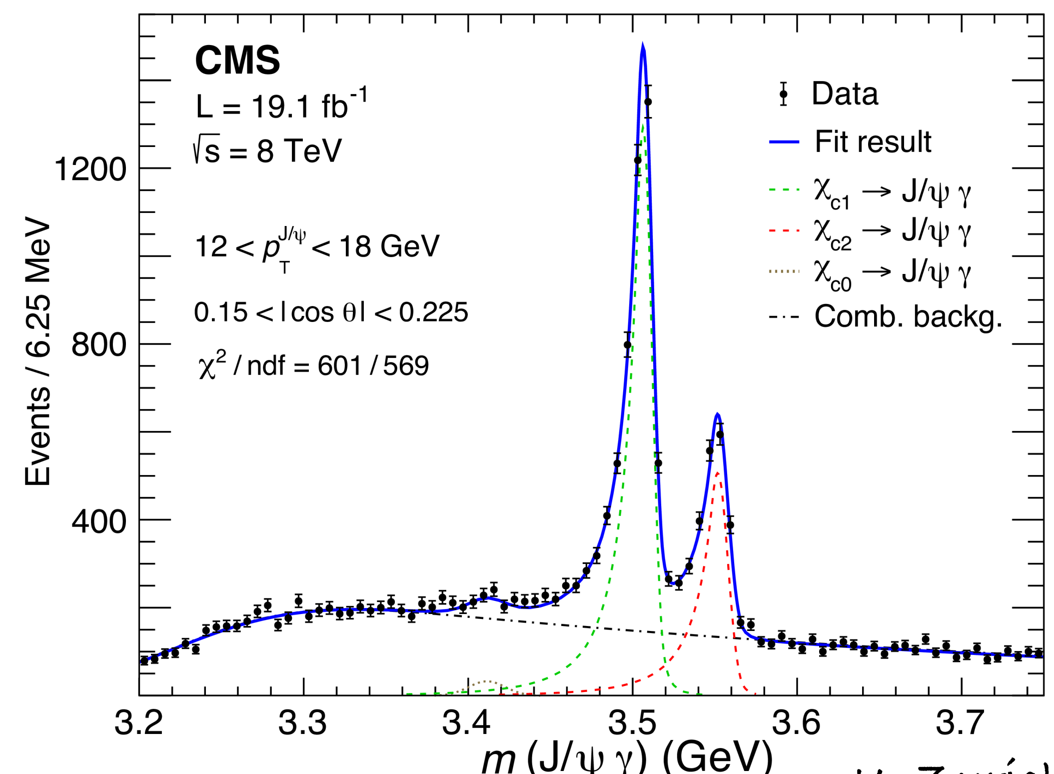

Quarkonia production in ATLAS and **CMS** experiments

Measurement of the χ_{c1} and χ_{c2} polarisations

- χ_{c2}/χ_{c1} yield ratios vs φ and θ measured in data
    - solid and dashed curves indicate the NRQCD and unpolarised scenarios

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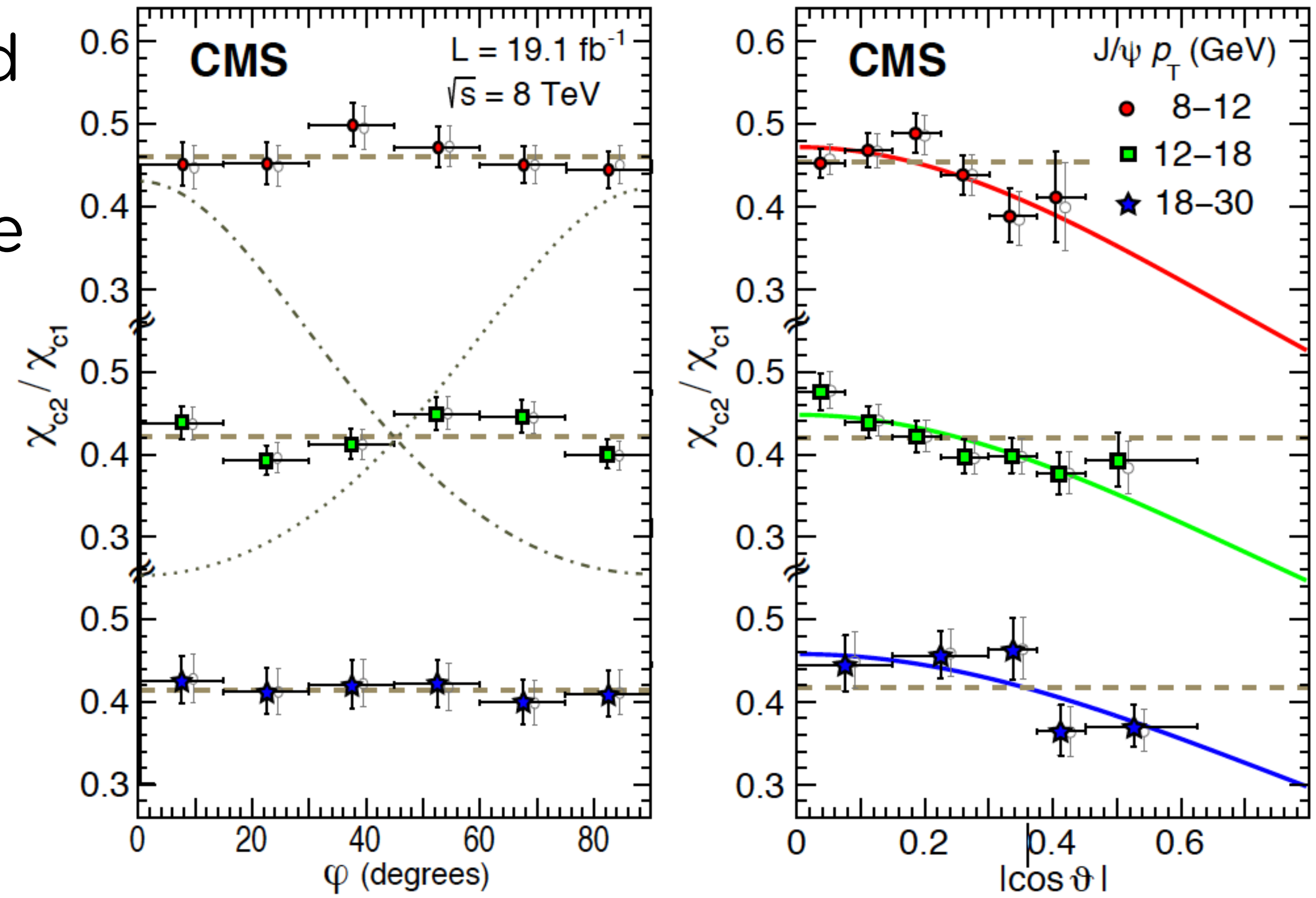
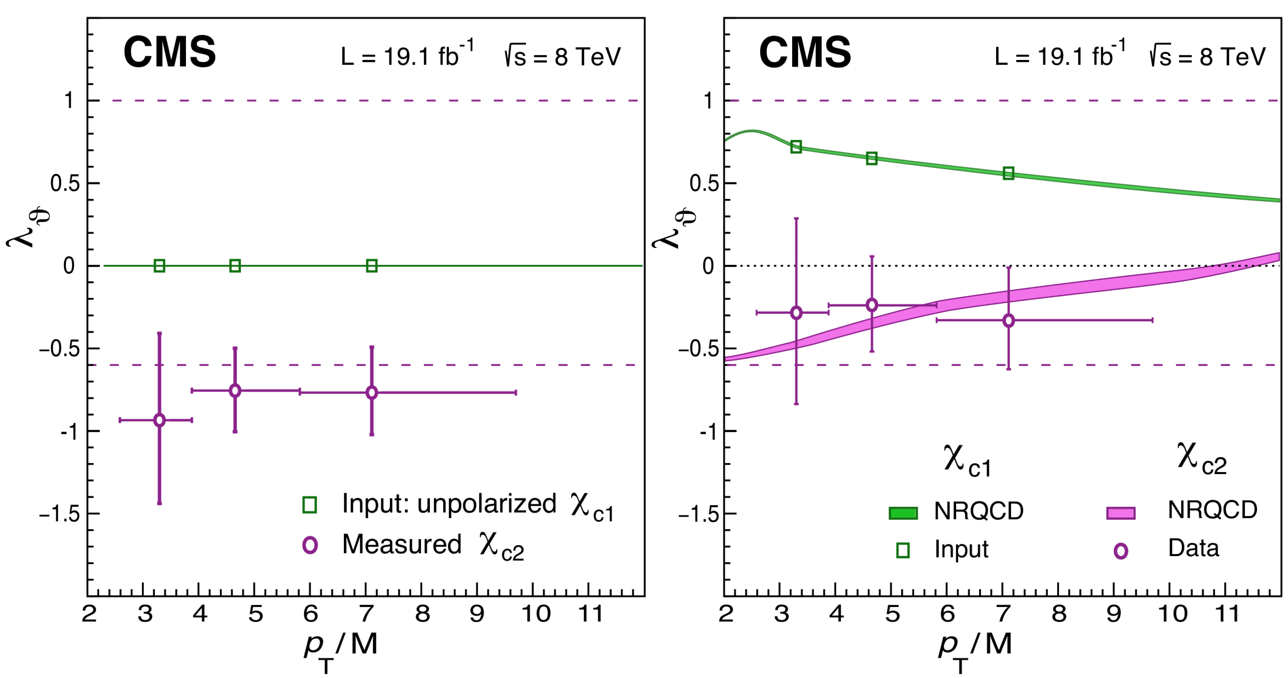
- λ_θ for χ_{c2} according to the unpolarised and NRQCD scenarios
    - **good agreement with the NQCD** while the unpolarised scenario is strongly disfavoured





First significant indication of kinematic differences between the various quarkonia states

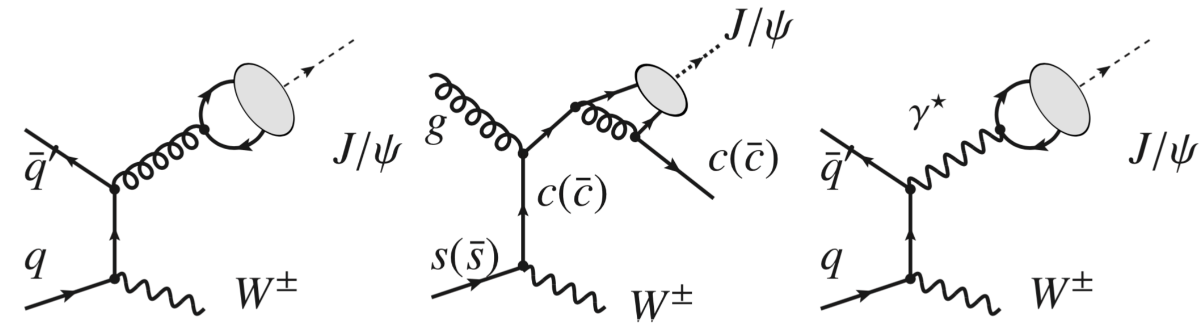
Measurement of J/ψ production in association with a $W^{\pm}$ boson with pp data at 8 TeV

JHEP 01 (2020) 095 - arXiv:1909.13626

Quarkonia production in **ATLAS** and CMS experiments

Measurement of J/ψ production in association with a $W^{\pm}$ boson

- J/ψ **production in association with a W boson** could be used to study **Colour Singlet** and **Colour Octet** contributions
  - W boson requirement in final state selects dedicated CS/CO diagrams
- Two contributions in the final state, where the J/ψ meson and the W boson are potentially produced via either
  - Single Parton Scattering (**SPS**)
  - Double Parton Scattering (**DPS**)
  - indistinguishable on an event-by-event basis
  - use of discriminating variables - azimuthal angle between the two particles
    - flat contribution from DPS - peak at $\Delta\varphi = \pi$ from SPS
- DPS governed by "universal" effective cross-section - σ_{eff}

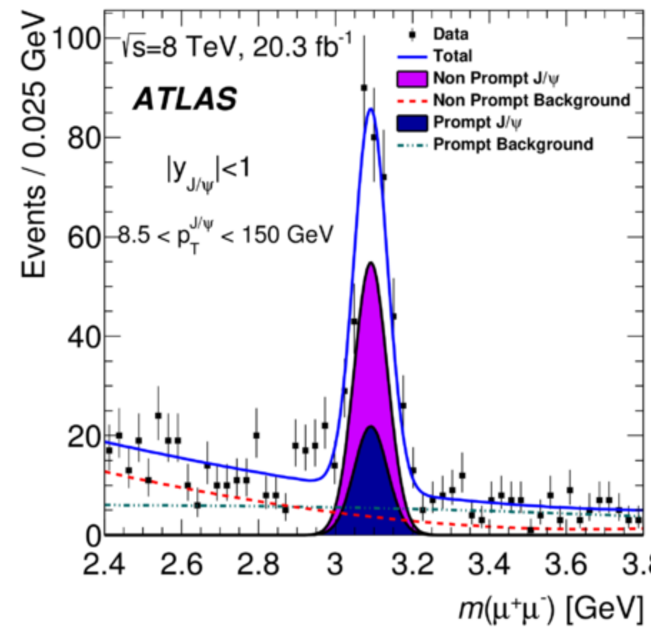


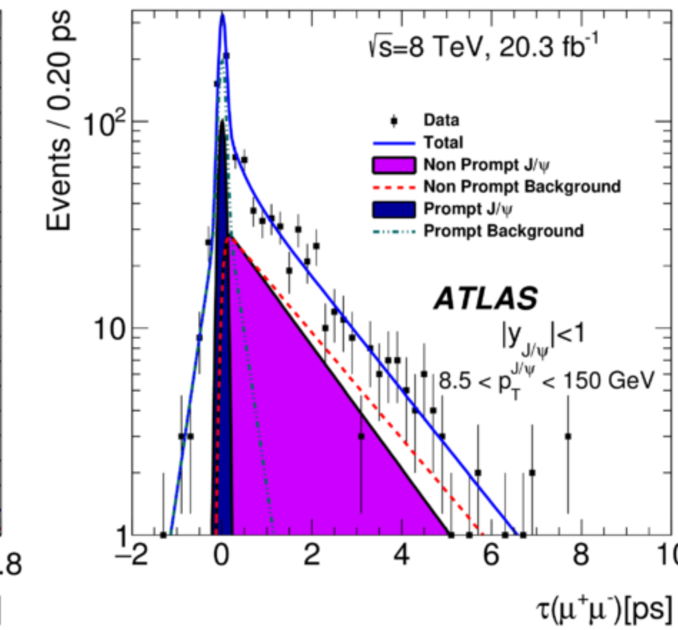
arXiv:1903.09185

Quarkonia production in **ATLAS** and CMS experiments

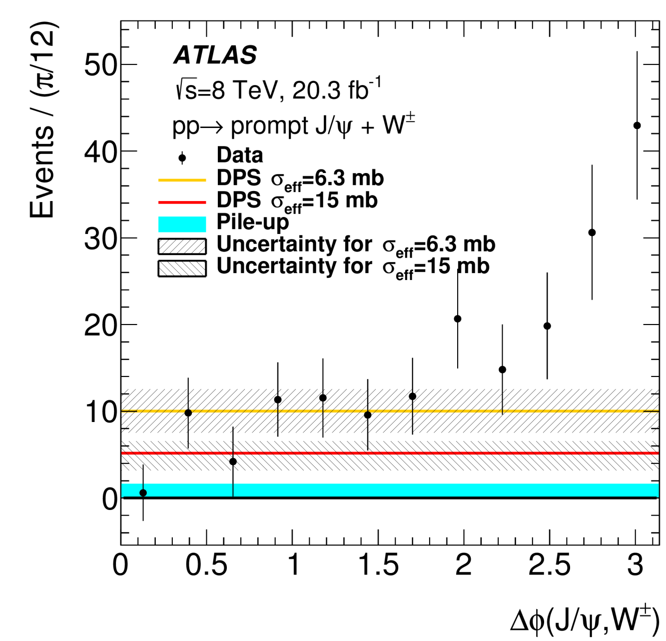
Measurement of J/ψ production in association with a W± boson

- **Measurement of** $R_{J/\psi} = \sigma_{W+J/\psi}/\sigma_W$ using the 8 TeV dataset
- Single high-p_T trigger
- Fit both di-muon invariant mass and pseudo-proper decay time to separate prompt and non-prompt components





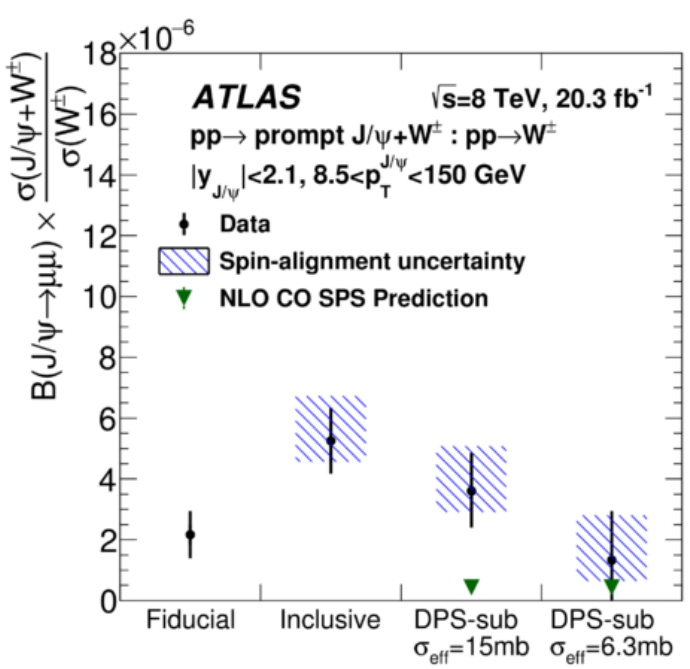
- Double parton scattering component estimation
  - probability that a J/ψ meson is a produced by a second hard process
  - $P_{W+J/\psi} = \sigma_{J/\psi}/\sigma_{\text{eff}}$
  - exact value of σ_{eff} is unknown
    - $\sigma_{\text{eff}} = 15 \pm 3\,(\text{stat.})\,^{+3}_{-3}\,(\text{sys.})\,\text{mb}$ from W+2 jet events
    - $\sigma_{\text{eff}} = 6.3 \pm 1.6\,(\text{stat.}) \pm 1.0\,(\text{sys.})\,\text{mb}$ from prompt J/ψ pair production
    - both values consistent at low Δφ

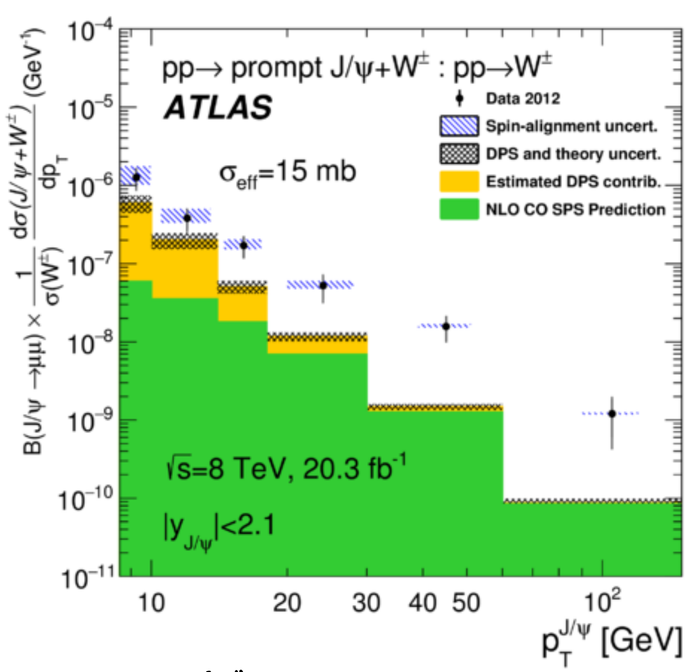


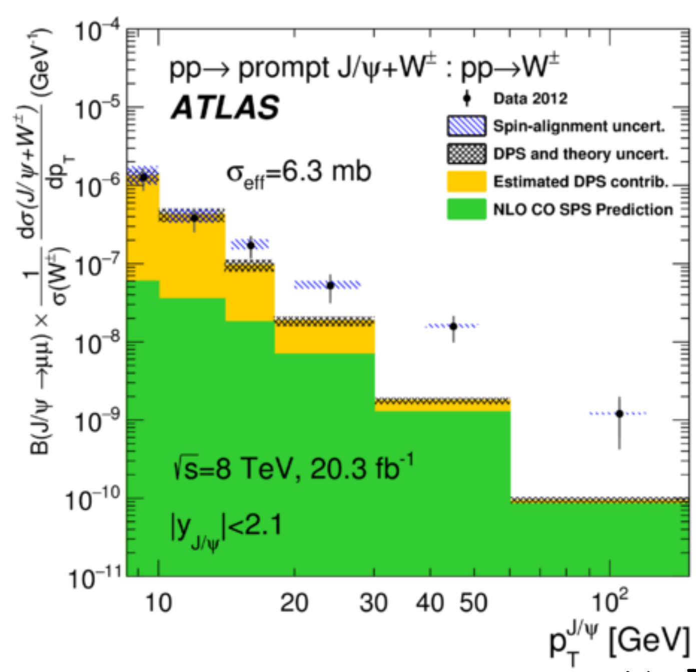
Quarkonia production in **ATLAS** and CMS experiments

Measurement of J/ψ production in association with a $W^{\pm}$ boson

- Systematic uncertainty dominated by the vertex separation between the J/ψ meson and the W boson
- **Fiducial, inclusive** (corrected for the J/ψ spin-alignment) **and DPS-subtracted measurements**
  - DPS-subtracted measured ratio give the opportunity to be compared with theoretical predictions (CO only) - which is found to be in agreement
  - lower σ_{eff} brings the calculated cross-ratio in agreement with measurement
  - **neither σ_{eff} makes the calculations agree with the J/ψ p_T spectrum**
    - probably due to the lack of CS contributions







Relative cross sections of the $\mathrm{B}_{\mathrm{c}}^{+}(2\mathrm{S})$ and $\mathrm{B}_{\mathrm{c}}^{*+}(2\mathrm{S})$ states with respect to the $\mathrm{B}_{\mathrm{c}}^{+}$ state in proton-proton collisions at $\sqrt{s}$=13 TeV

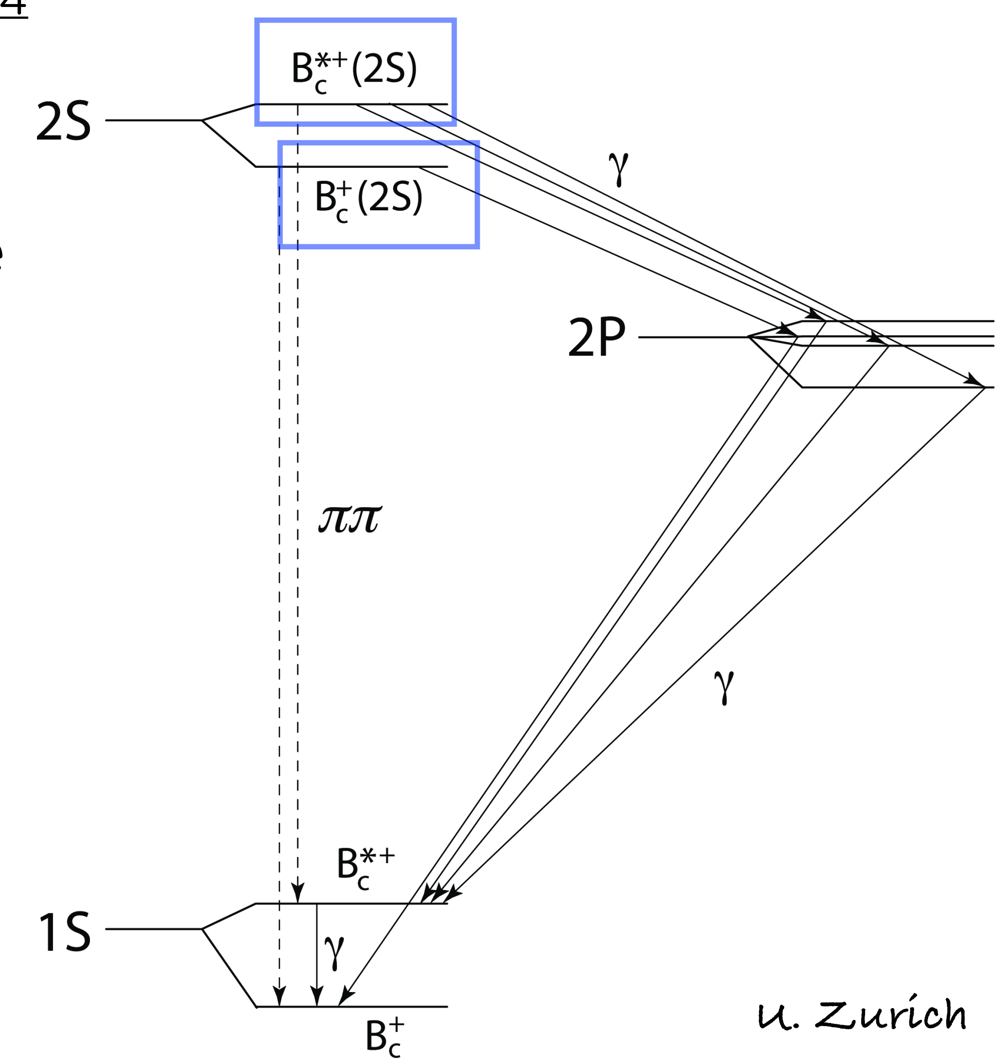
CMS-PAS-BPH-19-001

Quarkonia production in ATLAS and CMS experiments

Relative cross sections of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states with respect to the B_c^+

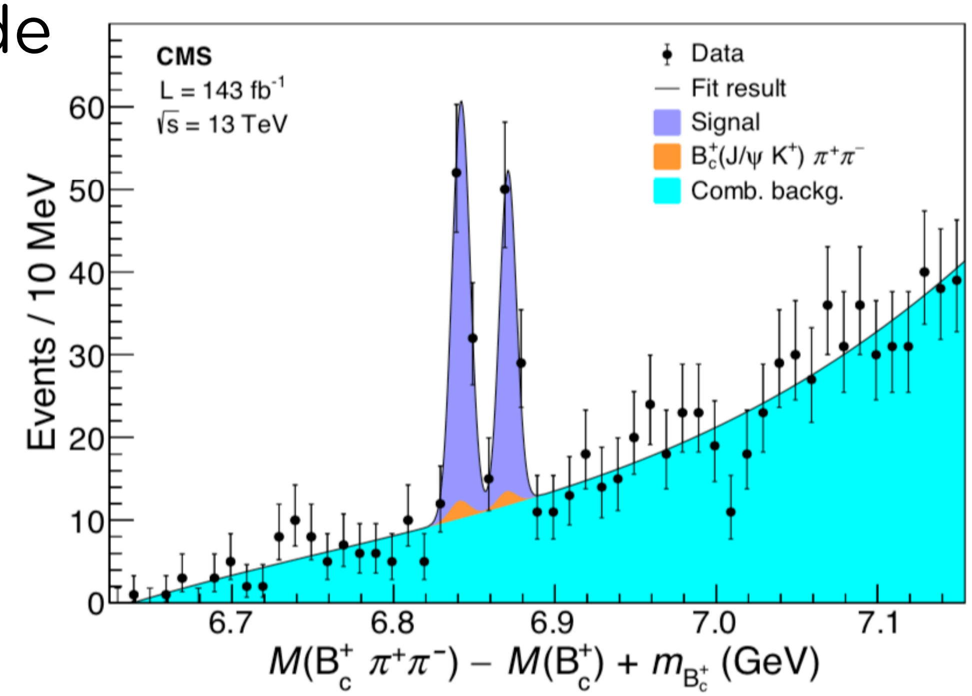
- Although the **charmonia** and **bottomonia** spectra is **well explored**
  - B_c^+ **meson** knowledge is limited
  - different heavy quark flavours allow only transitions through photons or pion pairs
- First discovery of the B_c^+ meson in 1998 by CDF PRL 81 (1998) 2432
  - lowest in mass bound state, of the bc family of mesons
- ATLAS observed the $B_c^+(2S)$ state PRL 113 (2014) 212004
- CMS observed the $B_c^{*+}(2S)$ state PRL 122 (2019) 132001
  - decaying to $B_c^{*+}\pi^+\pi^- \rightarrow B_c^+\gamma\pi^+\pi^-$ - where the soft photon is not detected
  - same final state as $B_c^+(2S) \rightarrow B_c^+\pi^+\pi^-$

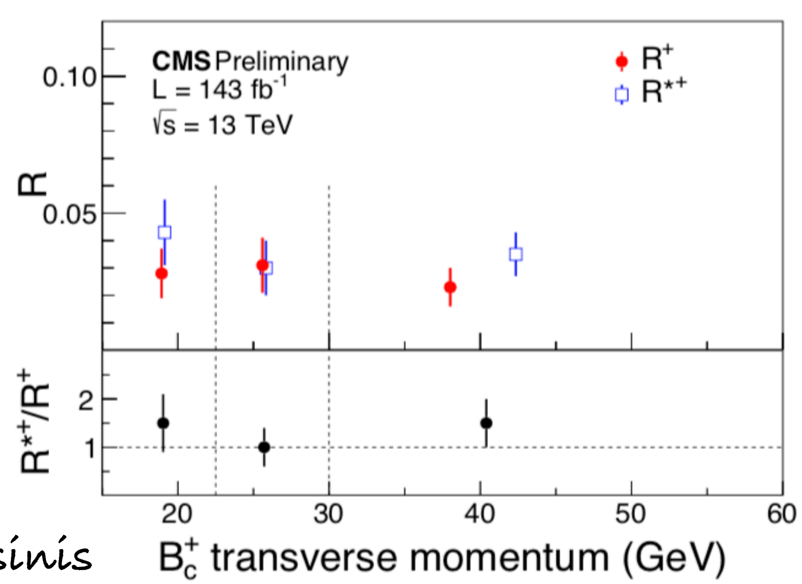
Particle	Predicted Mass [MeV]
B_c	6247 - 6286
B_c^*	6308 - 6341
$B_c(2S)$	6835 - 6882
$B_c^*(2S)$	6881 - 6914

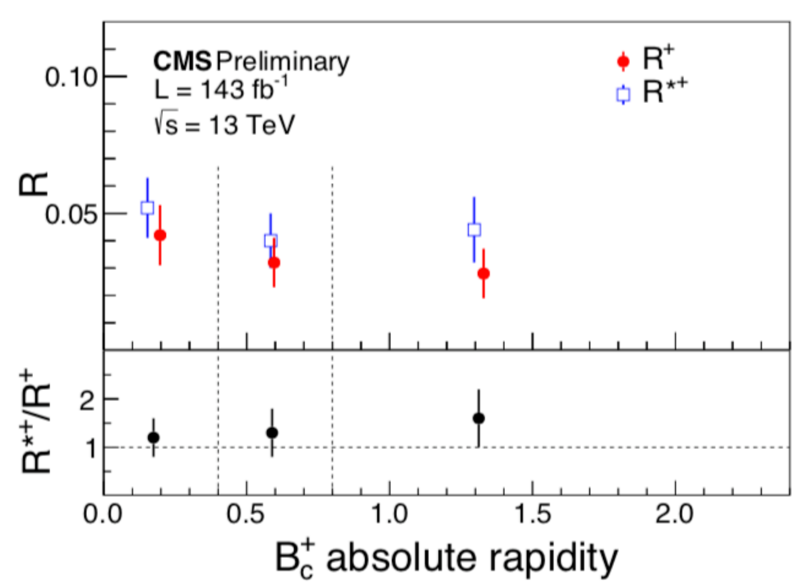


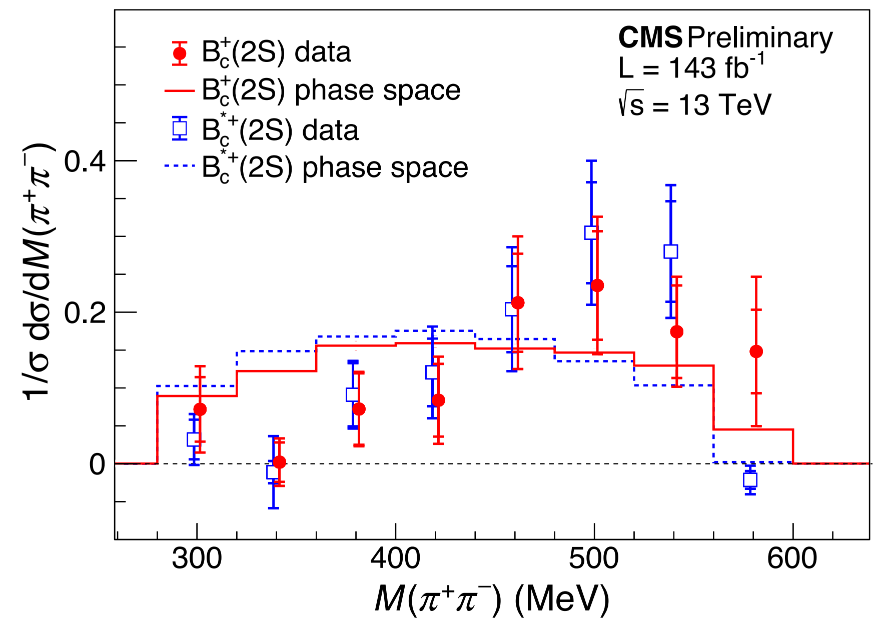
Relative cross sections of the $B_c^+(2S)$ and $B_c^{*+}(2S)$ states with respect to the B_c^+

- **Measurement of cross section ratios** using the 13 TeV dataset
  - di-muon trigger
  - B_c^+ reconstructed through its J/ψπ⁺ decay mode
  - $R^+ \equiv \dfrac{\sigma(B_c^+(2S))}{\sigma(B_c^+)} = 3.57 \pm 0.69\,(\mathrm{stat}) \pm 0.32\,(\mathrm{syst})\,\%$
  - $R^{*+} \equiv \dfrac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+)} = 4.91 \pm 0.69\,(\mathrm{stat}) \pm 0.57\,(\mathrm{syst})\,\%$
  - $R^{*+} / R^+ \equiv \dfrac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+(2S))} = 1.39 \pm 0.35\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst})$
  - no significant variation with the p_T or |y| of the B_c^+ meson is observed
  - shape of di-pion invariant mass is also examined









Summary

- Using Run1 and Run2 datasets **ATLAS** and **CMS** Collaborations increase the number of measurements and contribute towards the understanding of the **quarkonia production**
  - increasing the **precision** and
  - increasing the **kinematic reach** of past measurements
  - probing **rarer processes**
- Many interesting results not covered here are presented in other flavour physics talks

- Only a fraction of available data analysed so far…
  - road ahead includes the exploration of the **available data** from the collaborations - including the **parked CMS data**
  - … and the preparations for the **restart and Run3**!!

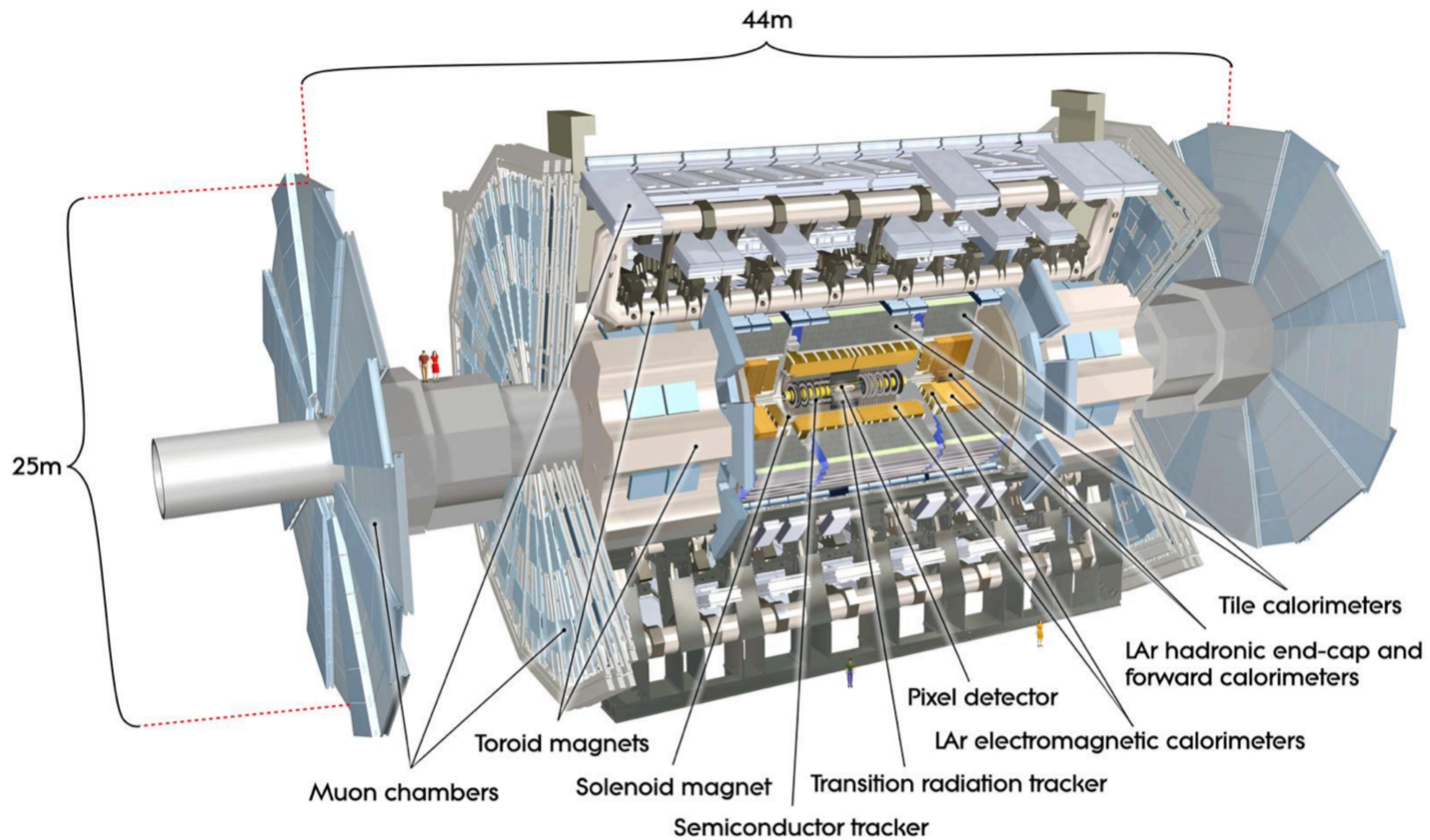
Stay tuned!

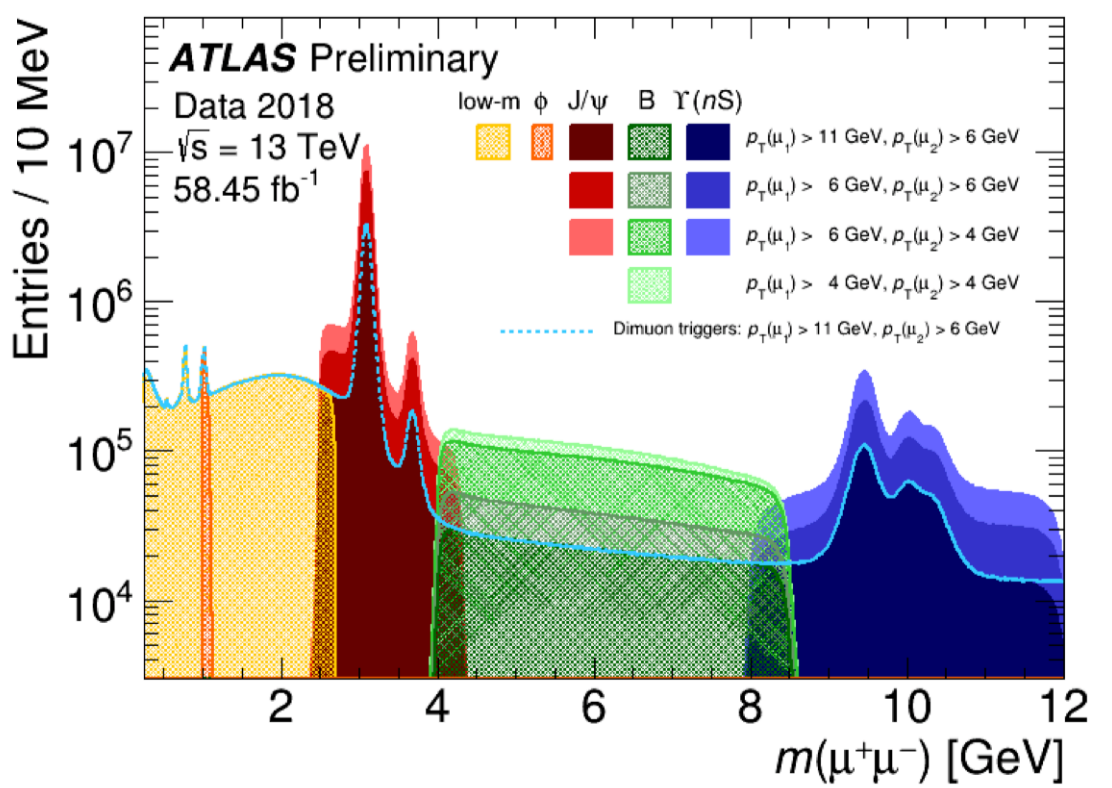
ATLAS results **CMS results**

backup

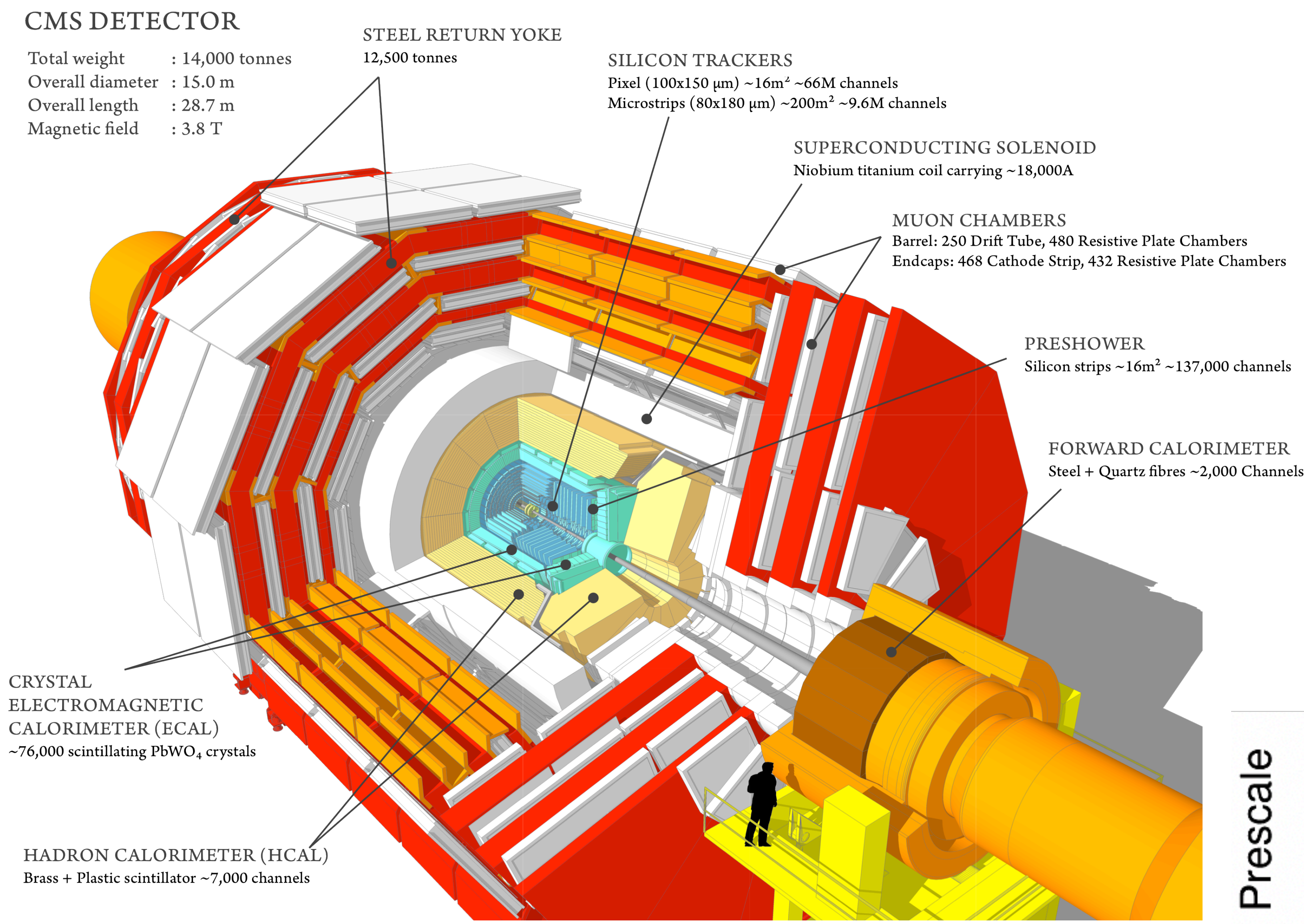
Quarkonia production in **ATLAS** and CMS experiments

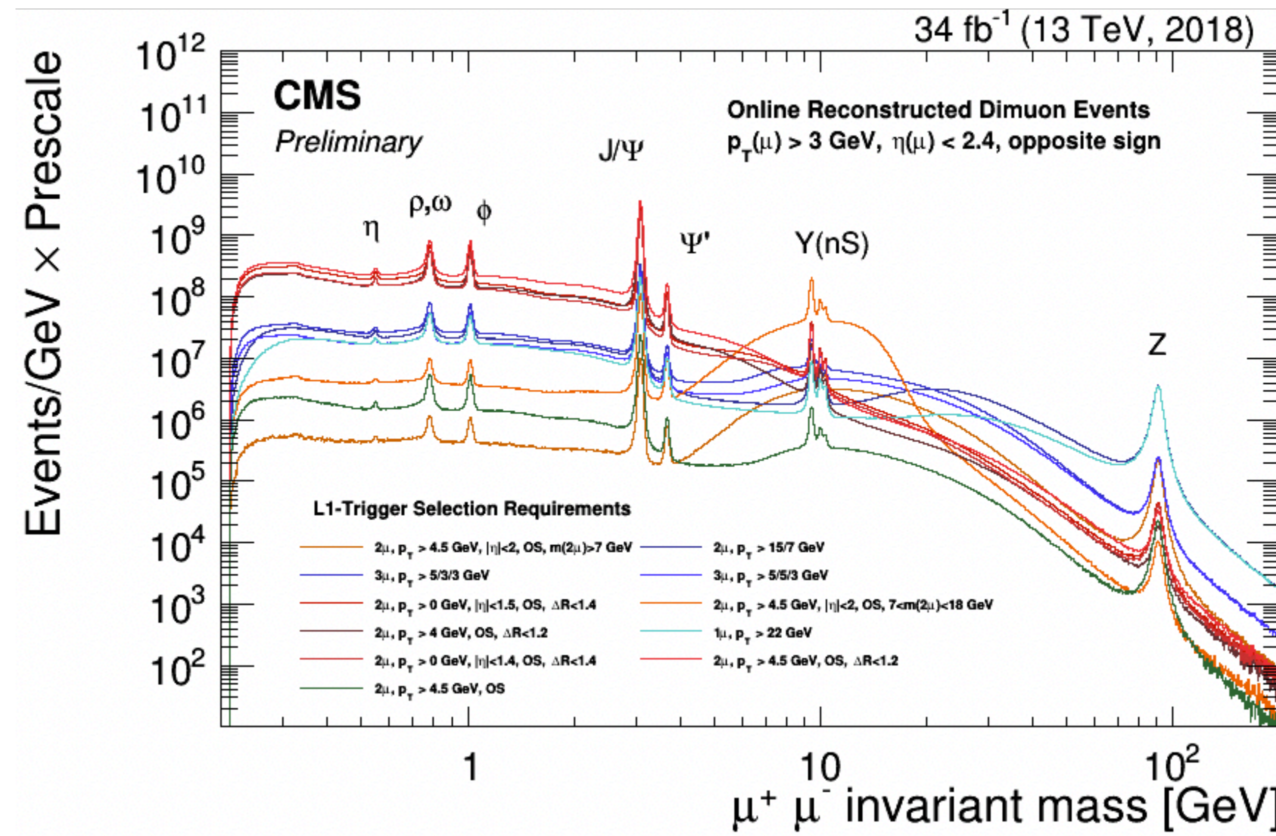
ATLAS detector





CMS detector





Systematics

Source of Uncertainty	Uncertainty [%]	
	$\lvert y_{J/\psi}\rvert < 1$	$1 < \lvert y_{J/\psi}\rvert < 2.1$
J/ψ mass fit	8.7	4.9
Vertex separation	12	15
$\mu_{J/\psi}$ efficiency	2.0	1.6
Pile-up	1.1	1.4
$J/\psi + Z$ and $J/\psi + W^{\pm}(\rightarrow \tau^{\pm}\nu)$	3.5	4.8
Efficiency correction	2.3	2.3

Systematics

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\ \pi^+$ fit model	4.4	4.4	–
$B_c^+\ \pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: dispersion among years	1.8	1.6	0.9
Efficiencies: dipion tracking	4.2	4.2	–
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total systematic uncertainty	8.9	11.5	6.4