Quarkonium production for precision NRQCD

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- First summer school!

Production cross-section measurement

- Number of events N obserbed by an experiment for a decay ($H \to AB\ \dots$):

$$N(H \to AB \dots) = \sigma \times \mathcal{L} \times \varepsilon \times \mathcal{B}(H \to AB \dots)$$

production cross-section | luminosity | detection and reconstruction efficiency | branching ratio

Good final state for studies has **high efficiecny** and **large branching ratio**

- **Cross-section determination**:
  - **absolute**:

$$\sigma = \frac{N(H \to AB \dots)}{\mathcal{L} \times \varepsilon \times \mathcal{B}(H \to AB \dots)}$$

  - **relative**:

$$\frac{\sigma_H}{\sigma_{H'}} = \frac{N_H}{N_{H'}} \times \frac{\mathcal{B}(H' \to A'B' \dots)}{\mathcal{B}(H \to AB \dots)} \times \frac{\varepsilon_{H'}}{\varepsilon_H}$$

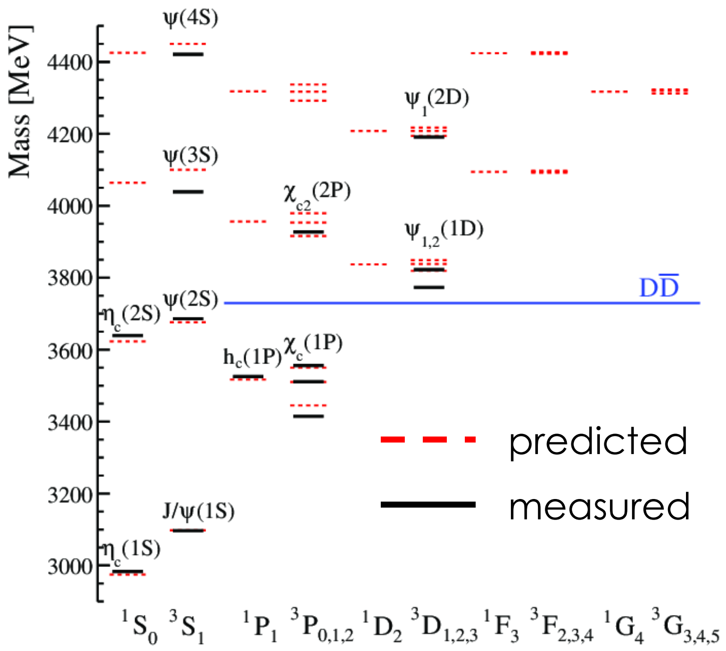
Production studies requre **precise luminosity measurement** or **well-known normalisation channel**

Quarkonia

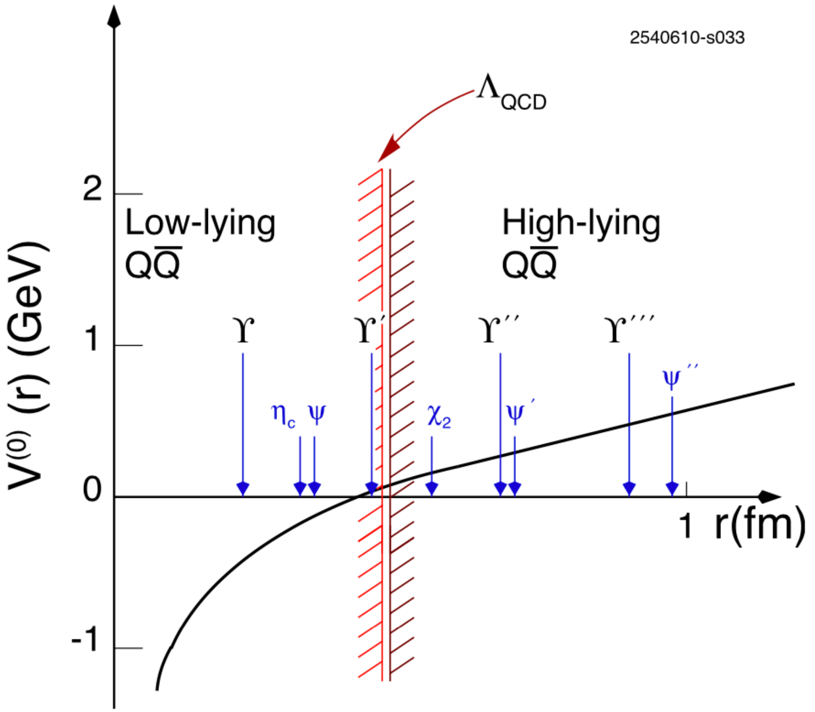
Quarkonium

- A bound state of two **heavy quarks** ($c\bar{c}$ or $b\bar{b}$)
- J/ψ discovery in 1974 – first discovery of c-quark
- **Non-relativistic QCD object**: charmonium: $v^2 \approx 0.3$, bottomonium: $v^2 \approx 0.1$
  - three intrinsic scales $m \gg mv \gg mv^2$
  - simple potential model

v^2 - typical velocity of a heavy quark in the quarkonium rest frame



Ideal probe for different QCD processes

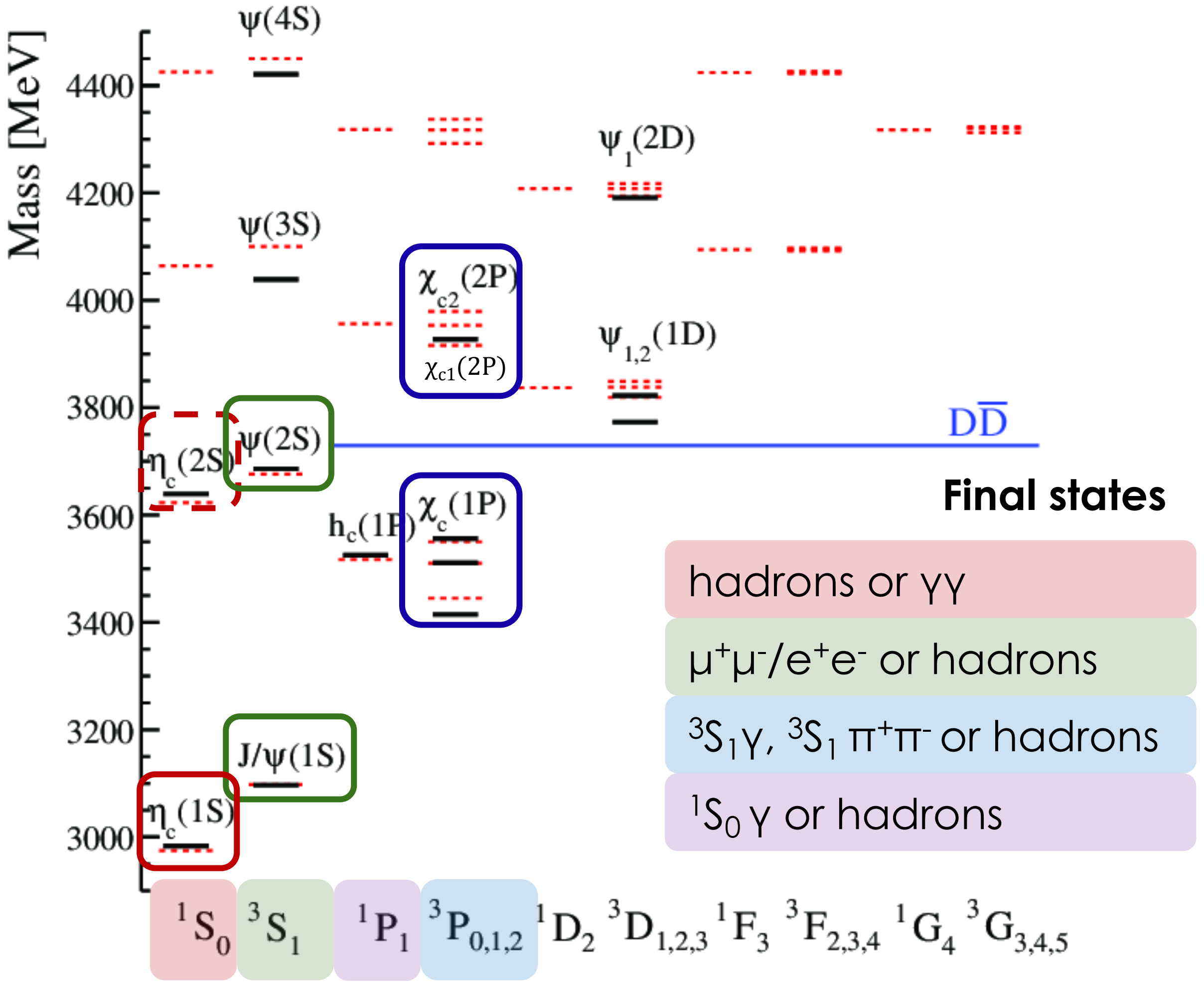


$Q\bar{Q}$ potential as a function of quarkonia radius

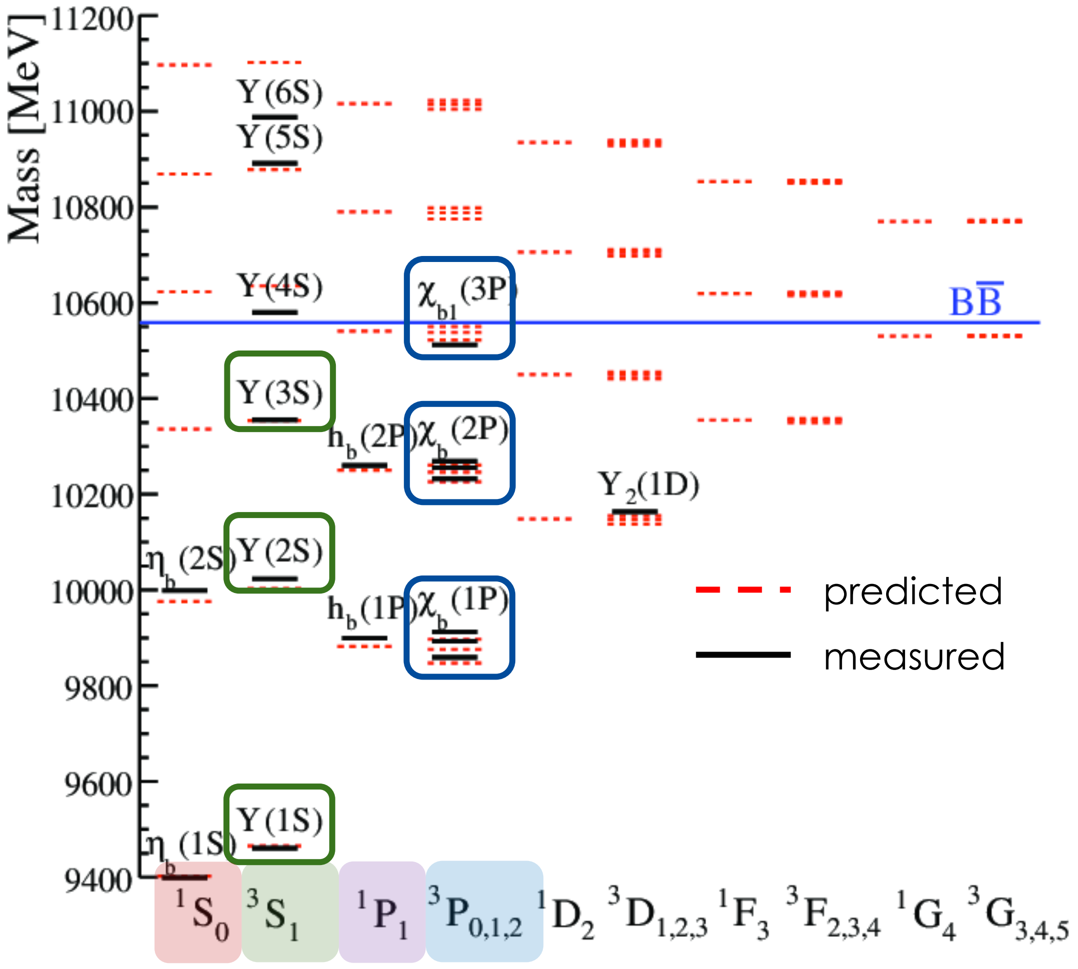
Eur. Phys. J. C 71 (2011) 1534

Qarkonium: Decay modes

Charmonium



Bottomonium



Rev.Mod.Phys 90 (2018) 015003

Hadronic final states allow to study different quarkonium states simultaneously

Quarkonium: (Un)known modes

- *Good* final state for study:
  - large and precise branching ratio ⇒ large signal
  - “easy” to reconstruct ⇒ high efficiency
  - low background ⇒ better precision
  - available for several states ⇒ normalisation
- Branching ratios are studied at flavour factories
- **Lack of information** for some states: challenging to find a decay mode for production studies

$\eta_b(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	hadrons	seen	
Γ_2	$3h^+3h^-$	not seen	
Γ_3	$2h^+2h^-$	not seen	
Γ_4	$4h^+4h^-$	not seen	
Γ_5	$\gamma\gamma$	not seen	
Γ_6	$\mu^+\mu^-$	$<9 \times 10^{-3}$	90%
Γ_7	$\tau^+\tau^-$	<8 %	90%

$h_b(1P)$ DECAY MODES

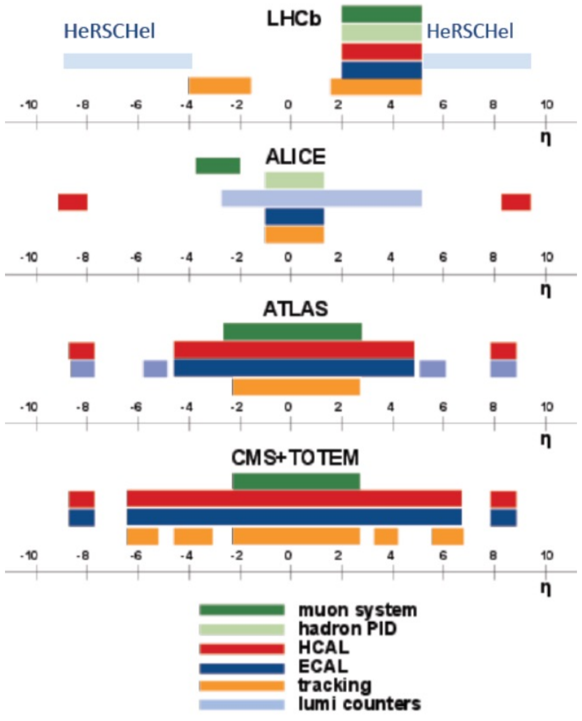
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta_b(1S)\gamma$	(52^{+6}_{-5}) %

Rev.Mod.Phys 90 (2018) 015003

	$\mathcal{B} \times 10^3$								
	$p\bar{p}$	$\phi\phi$	ϕK^+K^-	$\phi\pi^+\pi^-$	$\Lambda\bar{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\bar{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.52 ± 0.16	1.79 ± 0.20	2.9 ± 1.4	unknown	1.09 ± 0.24	9.0 ± 2.6	-	-	5.3 ± 1.8
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.12	0.87 ± 0.09	1.89 ± 0.08	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.33 ± 0.02	0.48 ± 0.07	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.15	forbidden	unknown	unknown	unknown	unknown	unknown	510 ± 60	unknown
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.11 ± 0.01	0.08 ± 0.02	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.03	0.46 ± 0.15	forbidden	1.32 ± 0.34
$\eta_c(2S)$	0.07[1]	unknown	unknown	unknown	unknown	unknown	unknown	forbidden	unknown
$\psi(2S)$	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

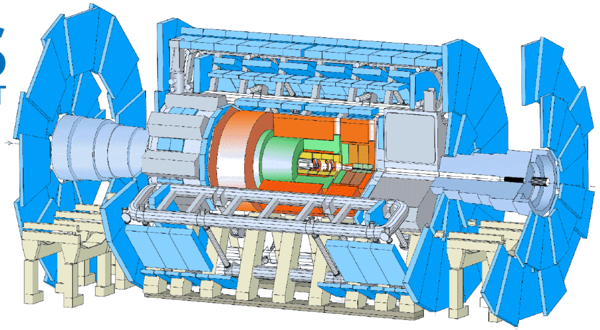
New and more precise measurements are necessary for further studies

LHC detectors hunting for quarkonium



- **ATLAS** and **CMS**: mid-rapidity region, with muons in final state

JINST 3 (2008) S08003



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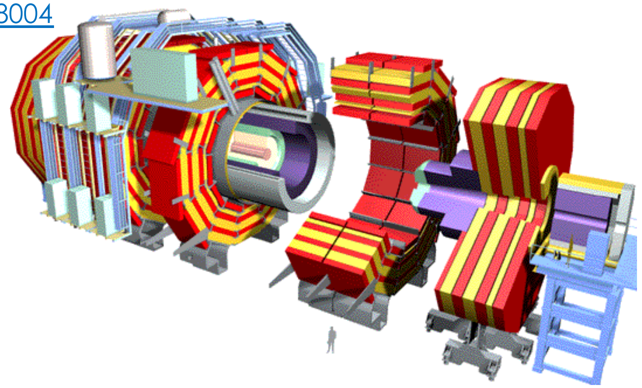
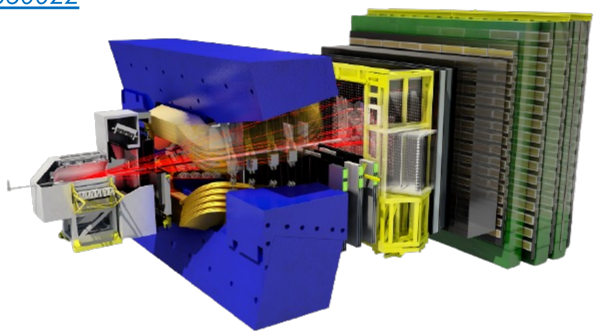


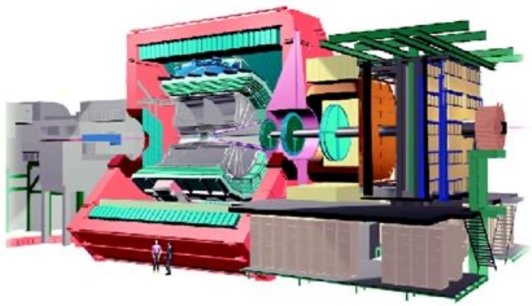
- **LHCb**: forward-rapidity region, with muons and hadrons in final state

IJMPA 30 (2015) 1530022



- **ALICE**: both mid- and forward-rapidity regions, with muons and electrons in final state

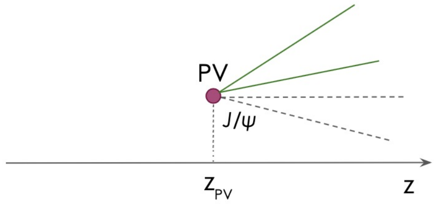
JINST 3 (2008) S08002



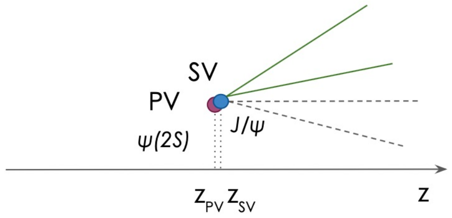
Experiments provide complementary measurements

Quarkonium production @ LHC

- **Origin:**
  - prompt hadroproduction

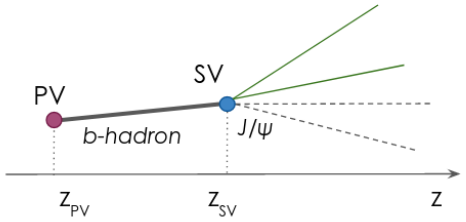


  - decays of higher resonances (feed-down)



  - production in b-hadron decays / non-prompt

(only charmonium)



prompt production

distinguished via pseudo-proper decay time

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

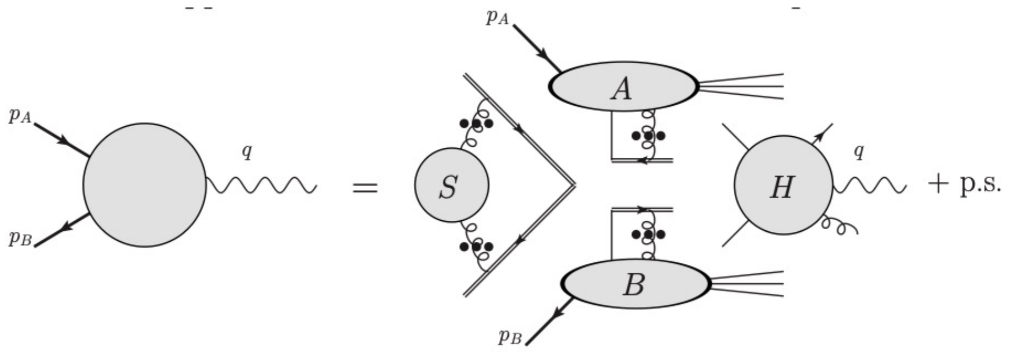
PV – pp collision vertex
SV – decay vertex

- **Existing measurements:**
  - η_c production
  - η_c**(2S)** production in b-decays
  - **J/ψ, ψ(2S)** and **Υ(nS)** production and polarization
  - **J/ψ+J/ψ/jet/Z/W$^{\pm}$, J/ψ+J/ψ+J/ψ** and **Υ(1S)+Υ(1S)** production
  - χ_c production and polarization
  - χ_b production

Understanding quarkonium production is challenging both experimentally and theoretically

Quarkonium production: Assumptions and Models

- Nearly all models assume **factorisation** between the $Q\bar{Q}$ **formation** and its **hadronization** into a meson
  - hard-scale $Q\bar{Q}$ **formation** – calculated as an expansion in powers of α_s
  - soft-scale **hadronization** – non-perturbative; mostly extracted from data; process-independent (**universal**)
- Factorisation depends on a chosen kinematic regime:
  - Collinear, $\sqrt{q^2} \approx q_T \gg \Lambda_{QCD}$
  - Transverse Momentum Dependent, $\sqrt{q^2} \gg q_T \gg \Lambda_{QCD}$
  - k_T or High Energy, $\sqrt{q^2} \gg q_T \gg \Lambda_{QCD}$



V.Bertone. QaT2023

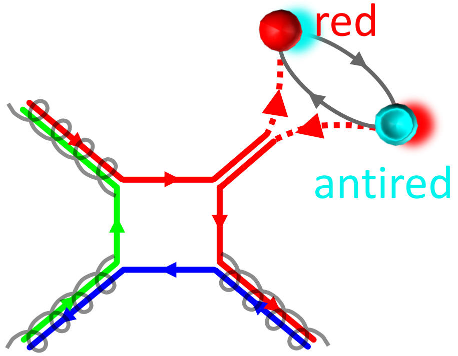
- Additionally, intrinsic scales are used in hadronization description: $m \gg mv \gg mv^2$
- Most advanced models:

Colour Evaporation Model, Colour Singlet Model, Non-relativistic QCD, Fragmentation Function approach

No consensus on the quarkonium production mechanism

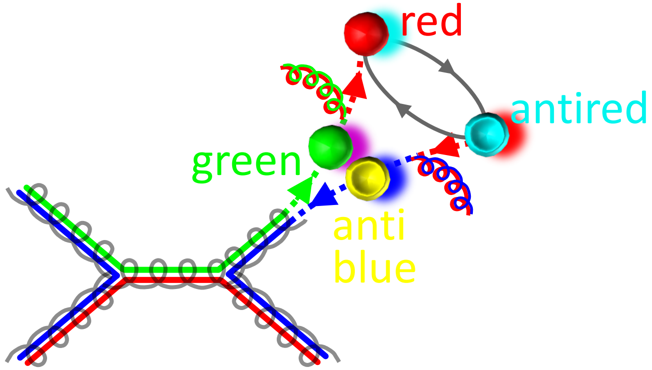
Quarkonium production: Models

- 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;

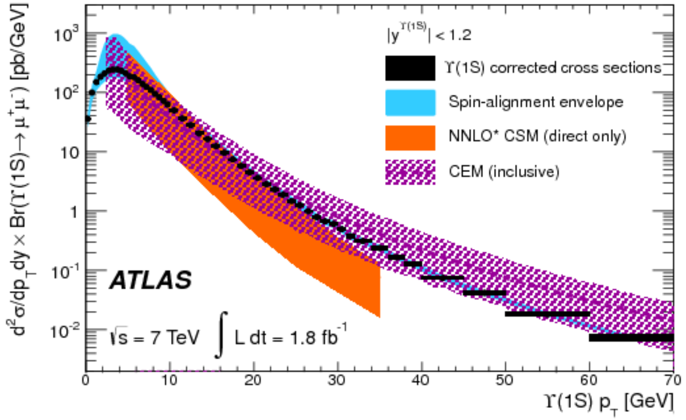


Colour Singlet state

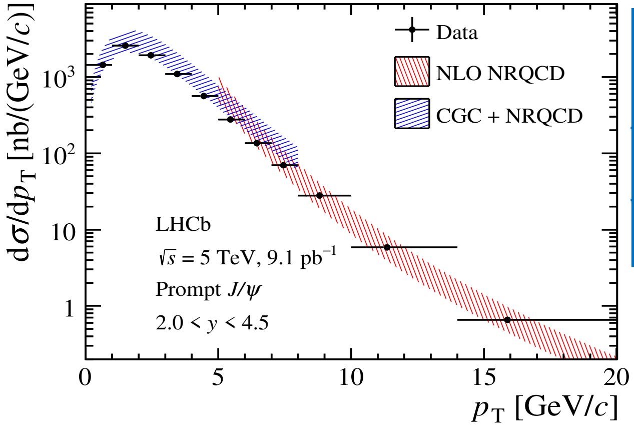
Talk by J.-P. Lansberg



Colour Octet state



PRD 87 (2013) 052004



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NRQCD is found to be the most used, because it is based on an EFT and can be improved systematically

NRQCD: Theory vs Experiment

- **Factorization**: $d\sigma_{A+B\rightarrow H+X} = \sum_n d\sigma_{A+B\rightarrow Q\bar{Q}(n)+X} \times < O^H(n) >$
  - **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: p_T-differential production, feed-down…

- **Universality**: same LDMEs for different √s, prompt production and production in b-decays

⇒ production at all possible √s, associated production, separate prompt and b-decays…

- **Heavy-Quark Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states

⇒ simultaneous studies of several states: η_c+J/ψ, χ_{cJ}+h_c…

$$\langle \mathcal{O}_1^{\chi_{cJ}}(^3P_J)\rangle = \frac{2J+1}{3}\langle \mathcal{O}_1^{h_c}(^1P_1)\rangle$$

$$\langle \mathcal{O}_8^{\chi_{cJ}}(^3S_1)\rangle = \frac{2J+1}{3}\langle \mathcal{O}_8^{h_c}(^1S_0)\rangle$$

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

$$\langle \mathcal{O}_8^{\eta_c}(^3S_1)\rangle = \langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle$$

$$\langle \mathcal{O}_8^{\eta_c}(^1P_1)\rangle = 3\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle$$

Experimental approach

J/ψ, ψ(2S) production

- Production measurement via l^+l final state (e.g. $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$...)

- Cross-section determination in bin[p_T,y]

$$\frac{d^2\sigma}{dydp_T} = \frac{N(q\bar{q} \to l^+l^-)}{\mathcal{L} \times \varepsilon \times \mathcal{B}(q\bar{q} \to l^+l^-) \times \Delta y \times \Delta p_T}$$

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

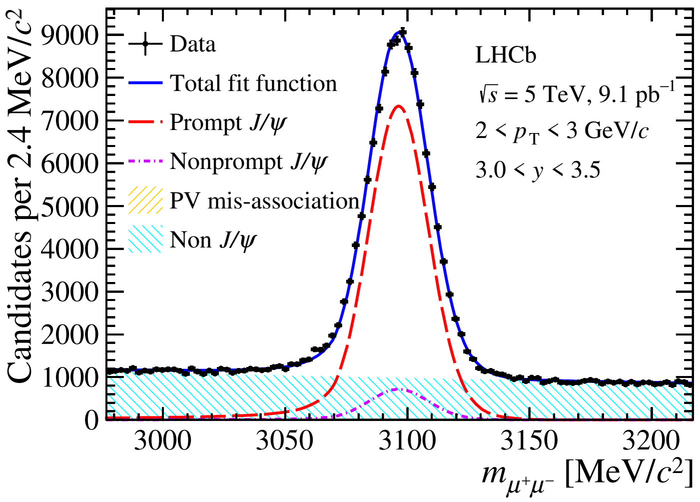
- **Prompt** and ***b*-decay production of charmonium** distinguished via pseudo-proper decay time:

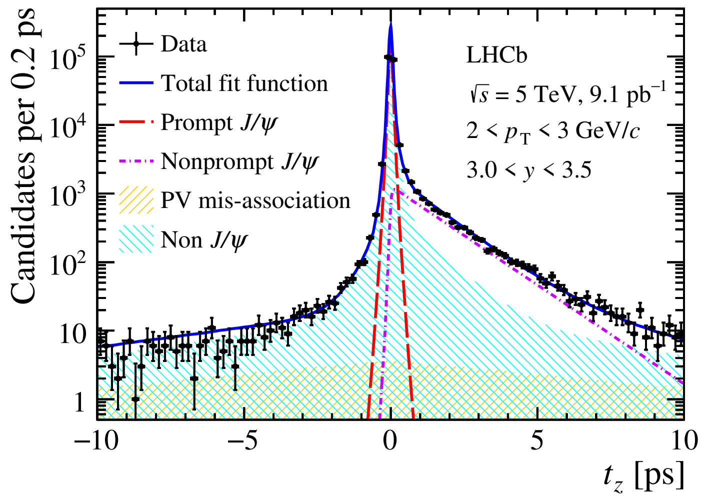
$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

- **Full kinematic range cross-section**

J/ψ and ψ(2S): Combined mass-lifetime fits

- **Prompt** and **from b-decay production** distinguished via decay time value: $t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{\mu\mu}$
- Unbinned maximum likelihood fit in bins of **[p$_T$, y]** to $M_{\mu^+\mu^-}$ and t_z





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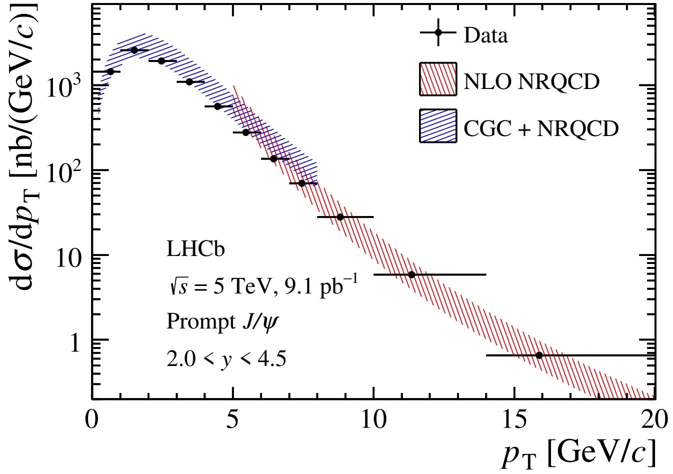
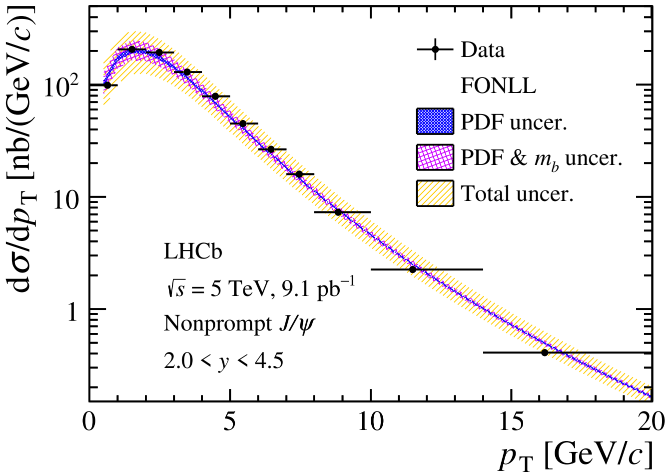
- **Production cross-section:**





Cross-section determination

- **Production cross-section:**

$$\frac{\sigma(A)}{\sigma(B)} = \frac{N_A^P}{N_B^P} \times \frac{\mathcal{B}_{B\to p\bar{p}}}{\mathcal{B}_{A\to p\bar{p}}} \times \frac{\epsilon_{B\to p\bar{p}}}{\epsilon_{A\to p\bar{p}}}$$

$$\frac{\mathcal{B}_{b\to AX}}{\mathcal{B}_{b\to BX}} = \frac{N_A^b}{N_B^b} \times \frac{\mathcal{B}_{B\to p\bar{p}}}{\mathcal{B}_{A\to p\bar{p}}} \times \frac{\epsilon_{B\to p\bar{p}}}{\epsilon_{A\to p\bar{p}}}$$

o From DATA
o From PDG
o From MC

- **Prompt and b-decay separation:**
  - prompt and b-decay production distinguished via **pseudo-proper decay time value:**

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

  - **two different tecnhiques** t_z-cut and t_z-fit technique

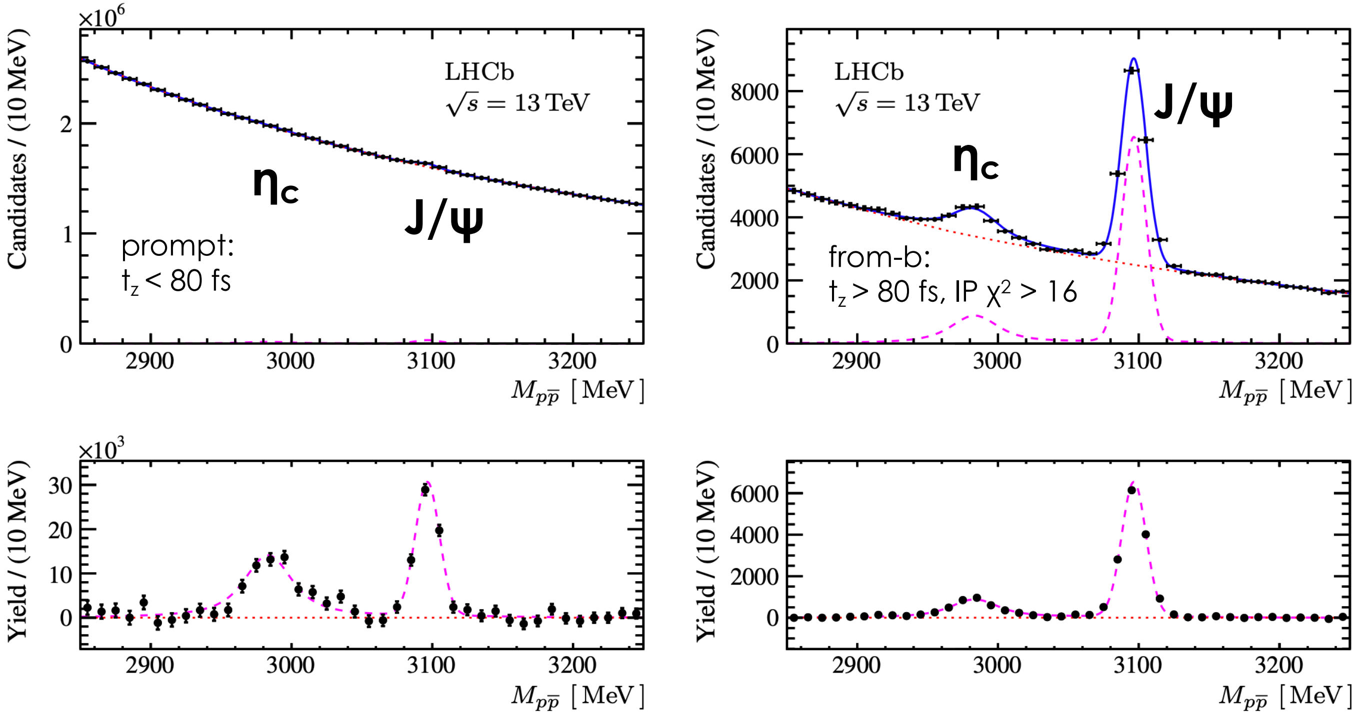
Using ratio allows to reduce systematic uncertainties

- **Final state:** $c\bar{c} \to p\bar{p}$

- **Production studied in the thesis:**
  - J/ψ - normalization channel (p_T<14 GeV/c)
  - $\eta_c(1S)$ – p_T-,y-differential x-section
  - $\eta_c(2S)$, h_c – integrated x-section
  - χ_{cJ}, ψ(2S) – cross-check

$\eta_c(1S)$ production at LHCb at $\sqrt{s}$=13 TeV

- t_z-cut technique: **prompt** and ***b*-decay production** separated using t_z-value



- Relative charmonium yields:

$6.5 < p_T < 14.0\, GeV/c\,, 2.0 < y < 4.5$

$$\frac{N_{\eta_c}^{prompt}}{N_{J/\psi}^{prompt}} = 1.18 \pm 0.10 \qquad \frac{N_{\eta_c}^{from-b}}{N_{J/\psi}^{from-b}} = 0.33 \pm 0.02$$

- Cross-feed probabilities accounted in the simultaneous fit:
  - $\varepsilon^{prompt \to prompt} = 0.965 \pm 0.021$
  - $\varepsilon^{prompt \to from-b} = 0.0002 \pm 0.0001$
  - $\varepsilon^{from-b \to prompt} = 0.066 \pm 0.005$
  - $\varepsilon^{from-b \to from-b} = 0.689 \pm 0.022$

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Challenging backgound conditions for prompt

$\eta_c(1S)$ production at LHCb at $\sqrt{s}$=13 TeV

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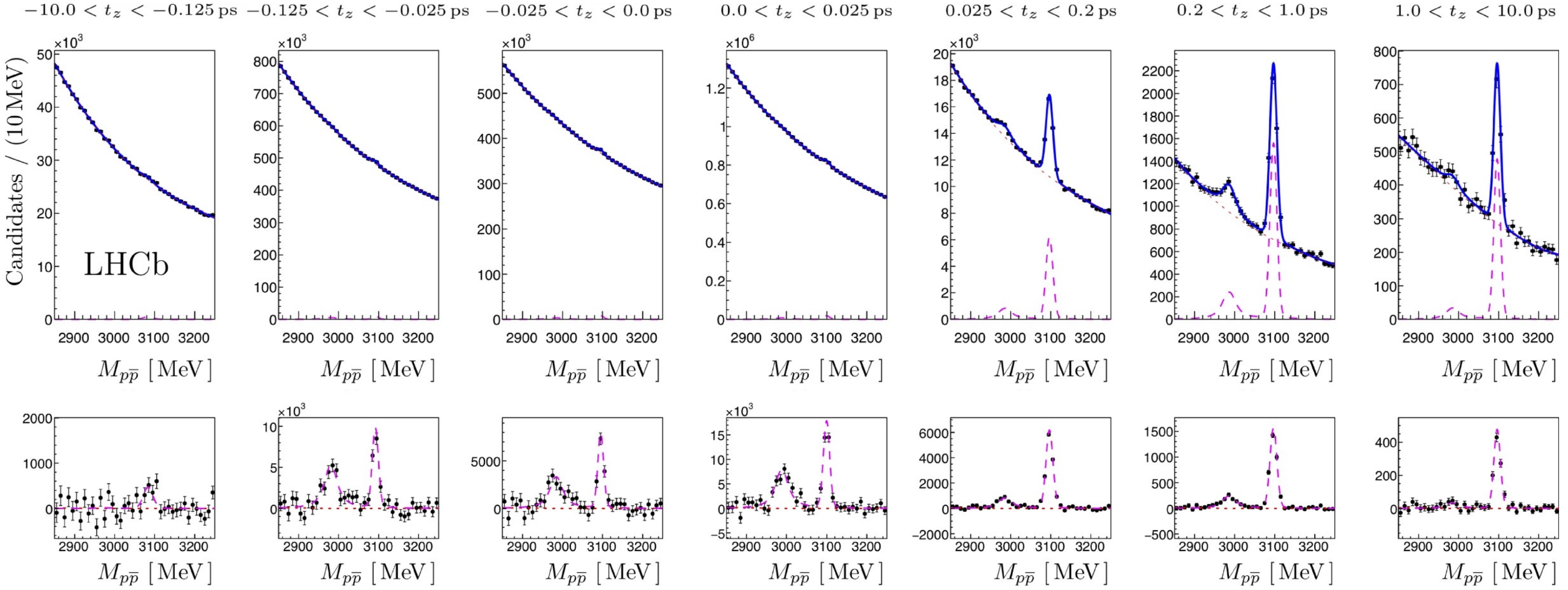
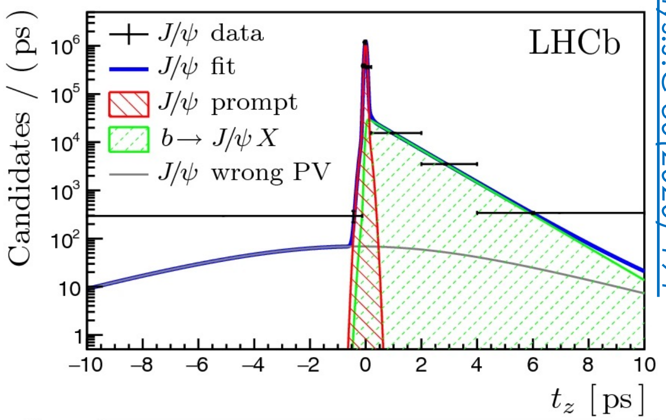
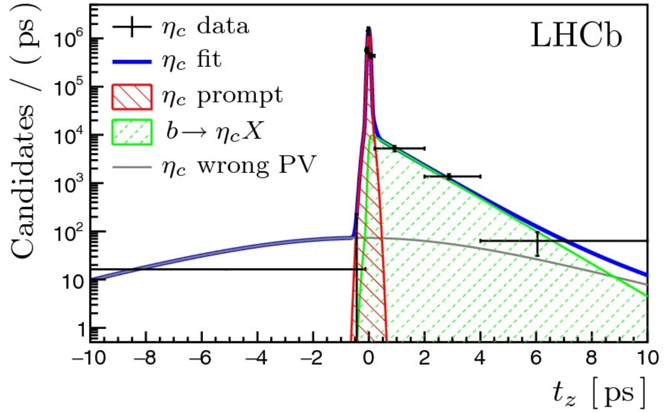
- t_z-fit technique







$6.5 < p_T < 14$ GeV, $2.0 < y < 4.5$

- Simultaneous likelihood **fit to $M_{p\bar{p}}$** in bins of **[p_T, t_z] to extract charmonium yields**
- Simultaneous integral χ² **fit to t_z** in **p_T**-bins **to separate prompt** and **from *b*-decays charmonium**
- Results consistent with t_z-cut technique

Ratio between η_c and J/ψ production

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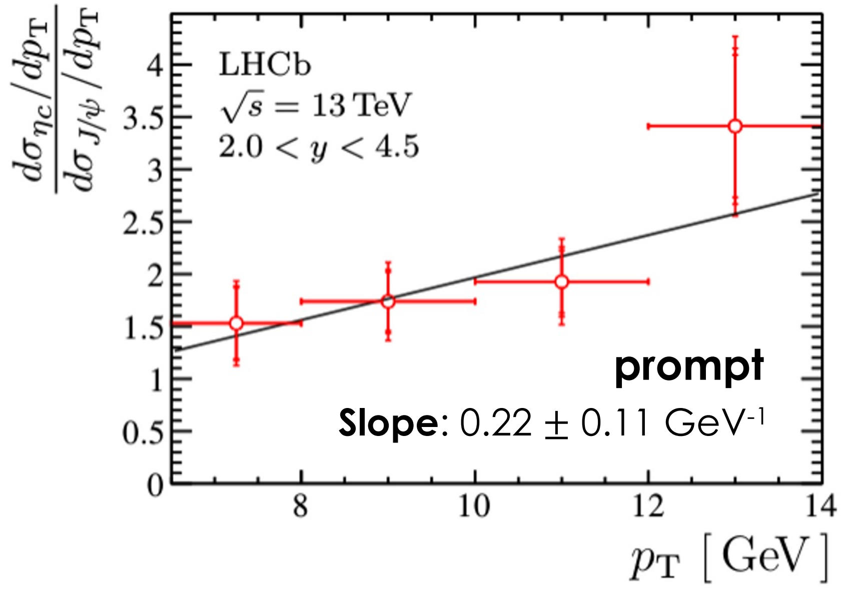
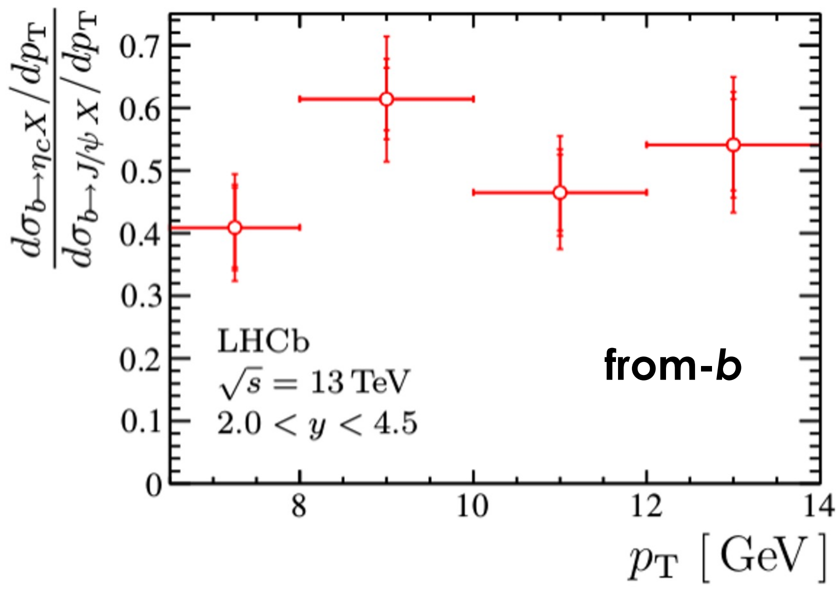
- Relative η_c to J/ψ p_T-differential production cross-sections

$$\frac{d\sigma(\eta_c)/dp_{\mathrm{T}}}{d\sigma(J/\psi)/dp_{\mathrm{T}}} = \frac{N^P_{\eta_c}}{N^P_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$



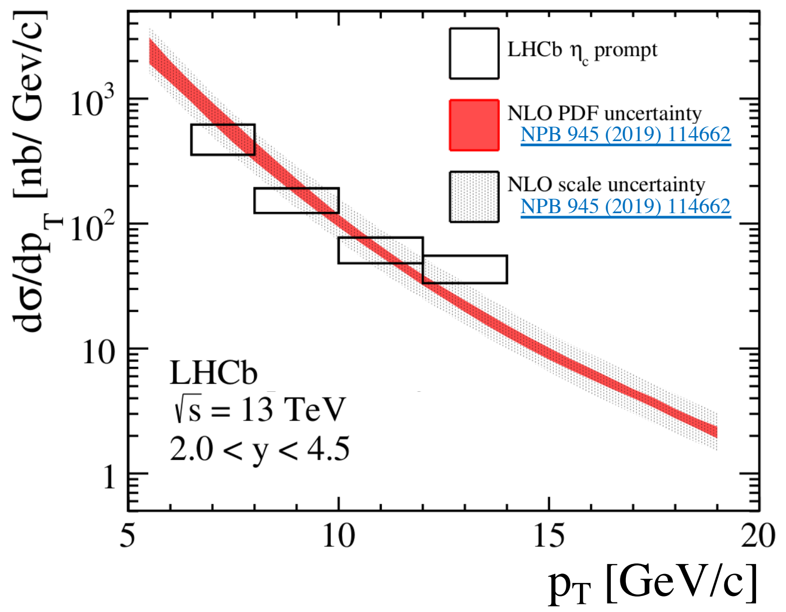


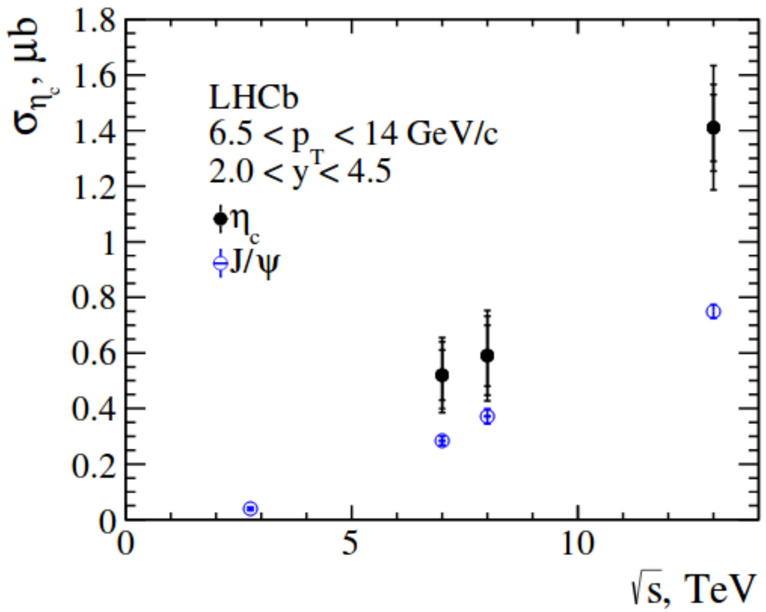
Integrated and differential cross-sections

- Measurement of **integrated** and **p_T -differential production cross-sections**

$$d\sigma(\eta_c)/dp_{\mathrm{T}} = \frac{d\sigma(J/\psi)}{dp_{\mathrm{T}}} \times \frac{N^P_{\eta_c}}{N^P_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

$$\sigma(\eta_c) = \sum_i d\sigma_i(\eta_c)/dp_{\mathrm{T}}$$





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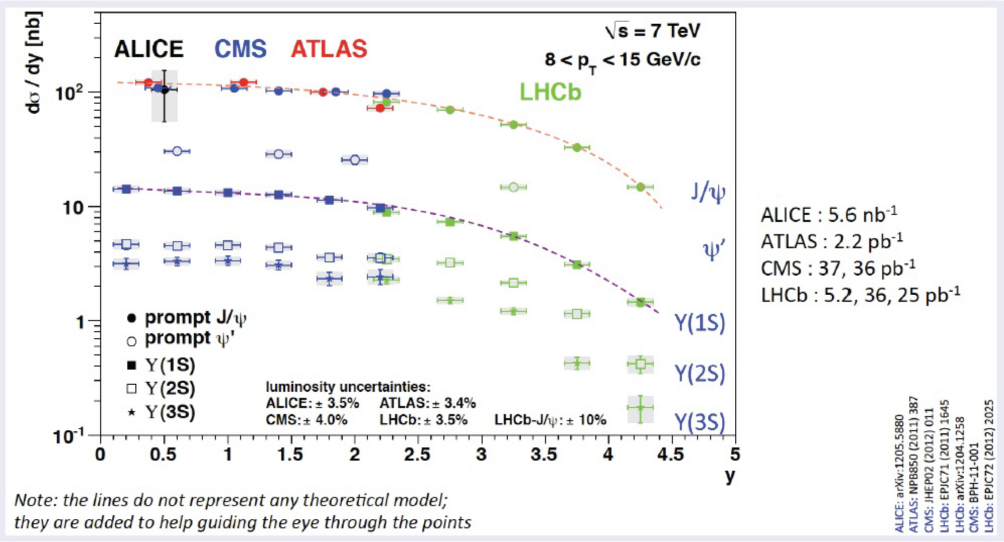
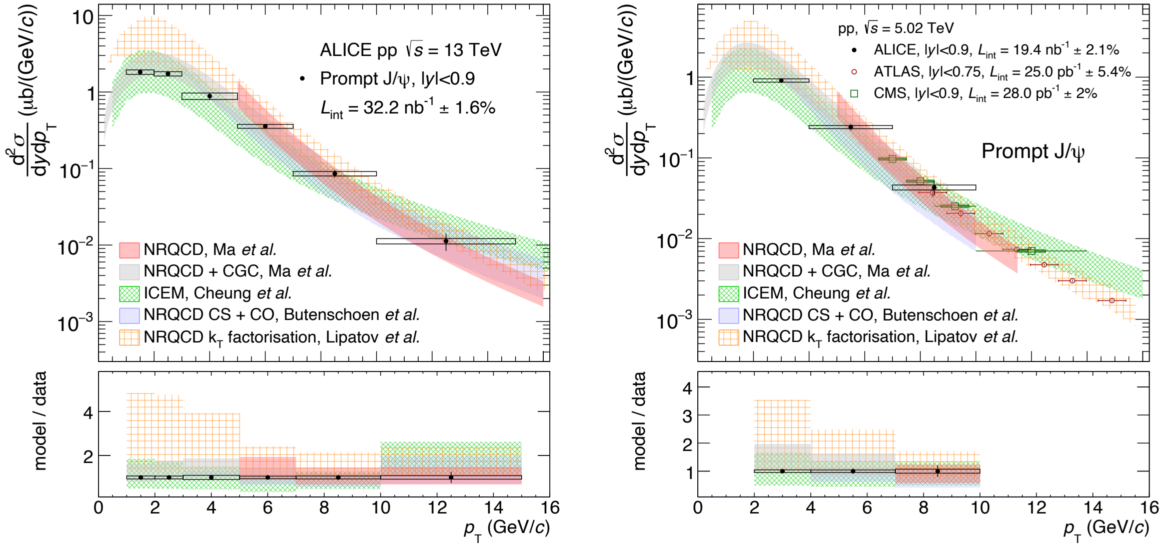
Current status

J/ψ production at the LHC

- J/ψ production and polarisation were studied at different LHC experiments:
  consistent and complementary cross-section measurements

- Description of the production cross-section at different energies





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Explicit prediction for η_c using HQSS relations between η_c and J/ψ LDMEs:

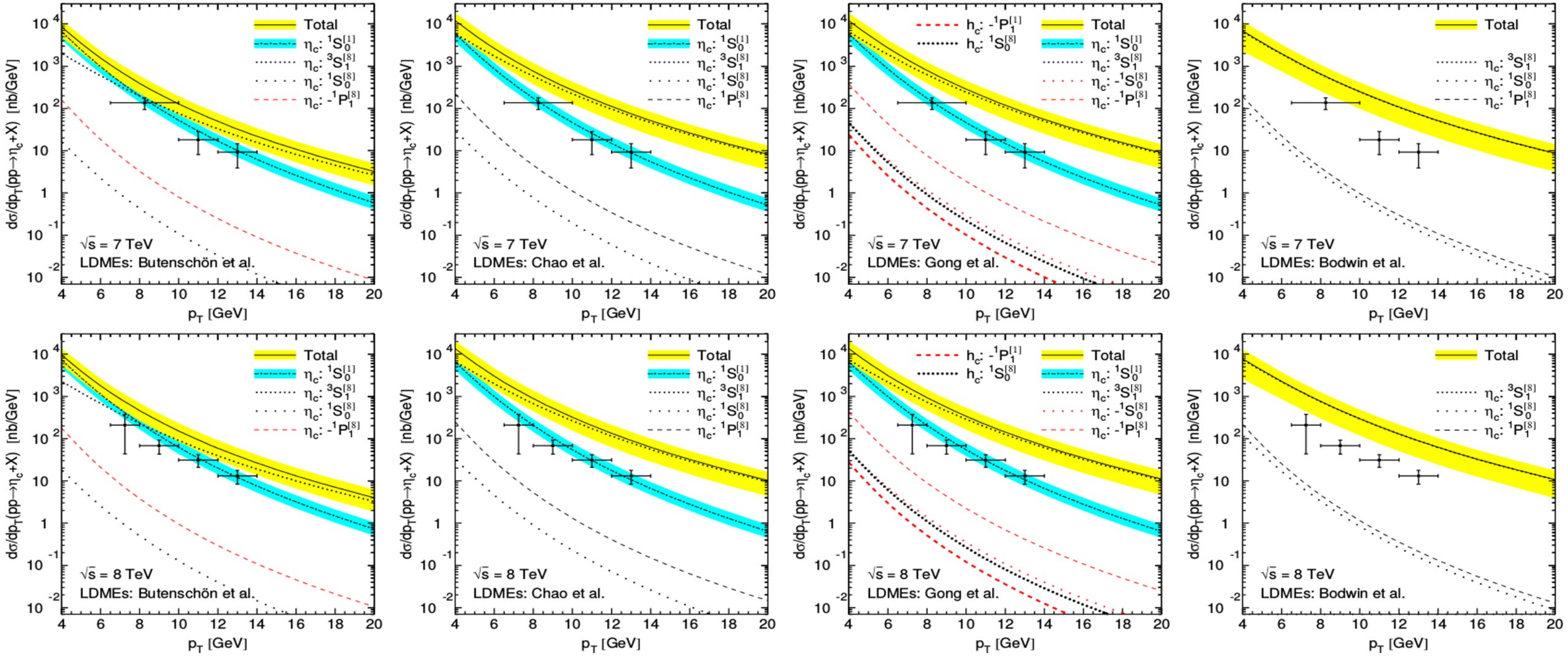
$$\langle \mathcal{O}_{1,8}^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle \mathcal{O}_{1,8}^{J/\psi}(^3S_1)\rangle$$

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

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

η_c production at the LHC

Butenschoen, He, and Kniehl PRL 114(2015), 092004



- **η_c(1S) LDMEs** determined from known HQSS relations for J/ψ and J/ψ production

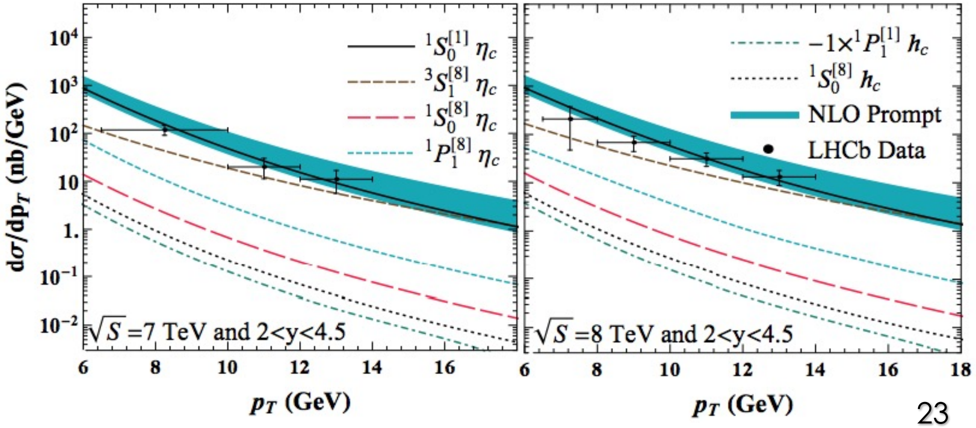
J/ψ prediction (NRQCD CS+CO)

CS prediction

- Direct projection to LHCb data

- **LHCb data saturated by CS contribution,** problem in simultaneous description of η_c production and J/ψ production and polarization

Han, Ma, Meng, Shao, and Chao PRL 114(2015), 092004



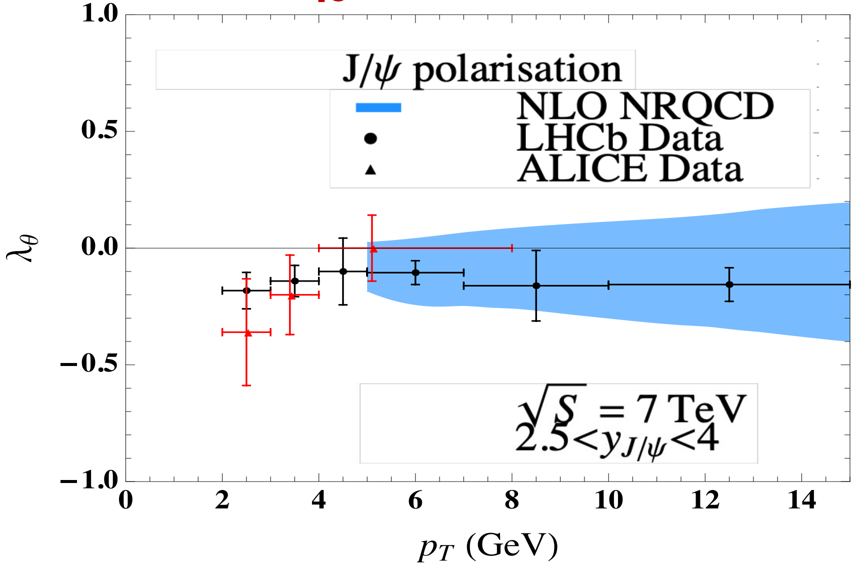
- **Following progress in theory**:
  - using constraints from **fits to J/ψ production measurements and fit to η_c production measurement**, upper limit on CO LMDE extracted:

$$0 < O^{\eta_c}(^3S_1^8) < 1.46\times10^{-3}\ \mathrm{GeV}^3$$

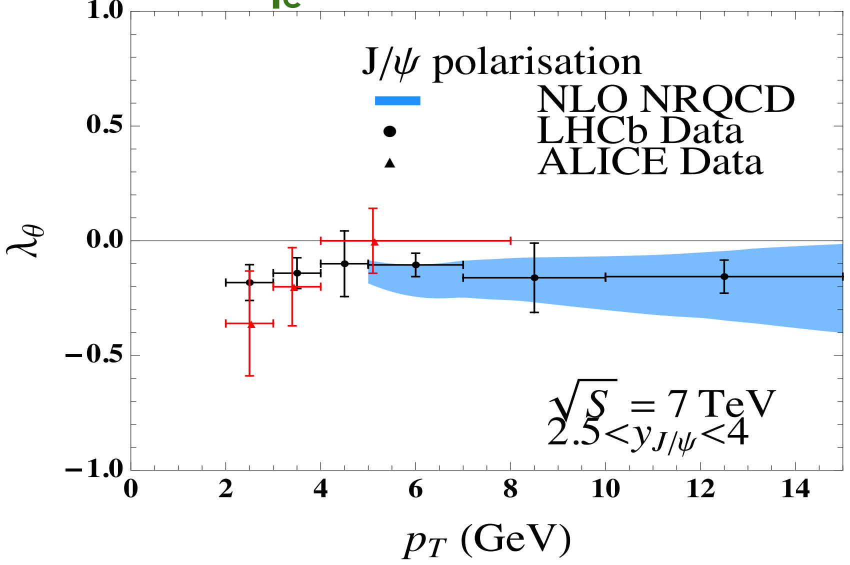
Simultaneous study of η_c and J/ψ production

- **η_c production** @ $\sqrt{s} = 7$ and 8 TeV **sets new constraint on J/ψ polarization**

Before η_c measurements



After η_c measurements



PRL 114(2015) 092004

- **Outcome**:
  - Impressive progress
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?
  - Joint study of hadroproduction and production in inclusive *b*-decays?

Same links for η_c(2S) and **ψ(2S)** are expected ⇒ clean test to confront NRQCD [Lansberg, Shao and Zhang]

η_c(1S): Differential production cross-section

EPJC 80 (2020) 191

- **Relative $\eta_c/J/\psi$** and **absolute η_c** p_T-differential production **cross-sections** @ 13 TeV (**2015-2016** data)

- **η_c(1S) production:**

  $6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

  $$\sigma_{\eta_c}^{prompt} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{J/\psi}\ \mu b$$

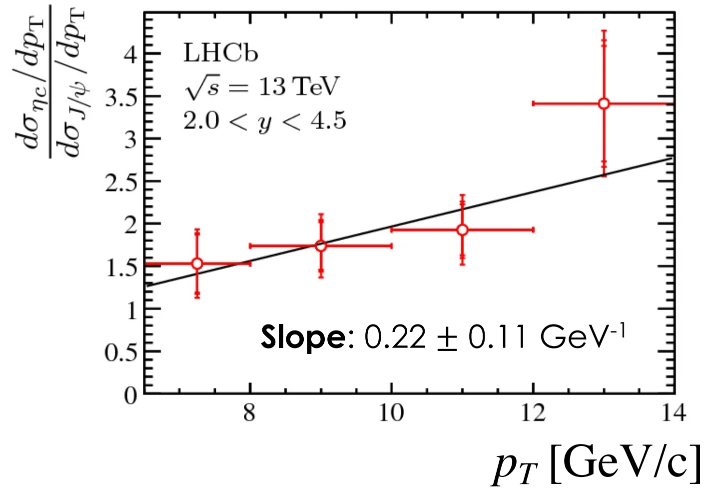
  $$\mathfrak{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{J/\psi})\times 10^{-3}$$

- Results may **provide** important **constraints for J/ψ production and polarization**

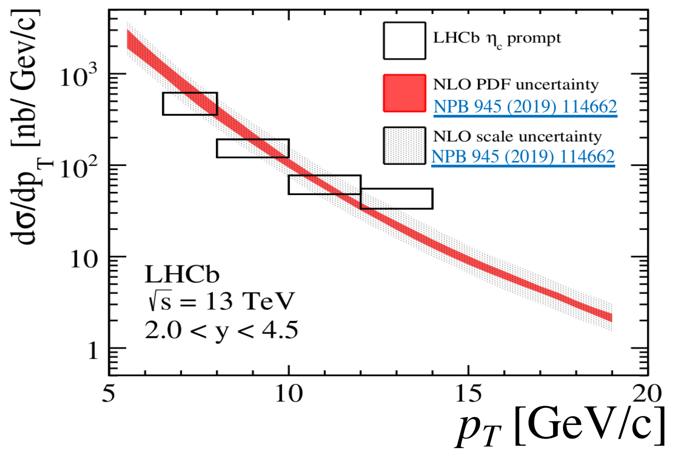
- **η_c(1S) production can be described by CS contribution only;** measurement in **extended p_T is required**: **larger slope** would indicate **possible CO contribution**

Interpretation of η_c(2S)/ψ(2S) much cleaner than for η_c(1S)/J/ψ due to absence of feed-down

Relative production cross-section

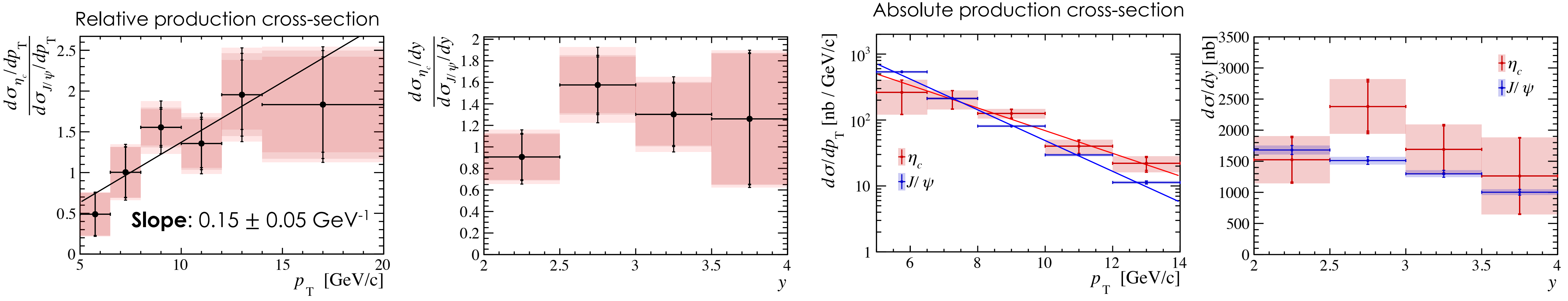


Absolute production cross-section



$\eta_c(1S)$: Differential production cross-section

- **Relative $\eta_c/J/\psi$** and **absolute η_c** p_T- and y-differential production **cross-sections** @ 13 TeV (**2018** data)



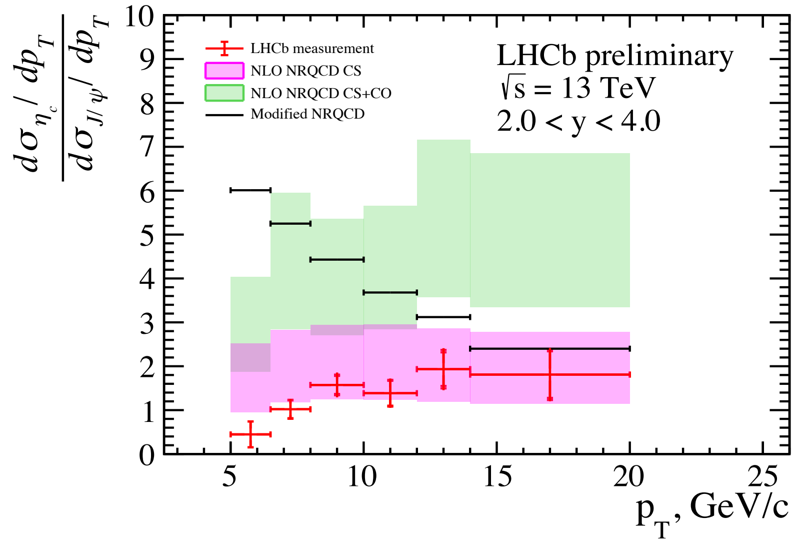
- Extended p_T-range compared to the previous analysis
- The first measurement of y-differrential $\eta_c(1S)$ cross-section

- Slope in p_T-differential ratio of η_c to J/ψ production indicates **different shape and maximum position of p_T-spectra**

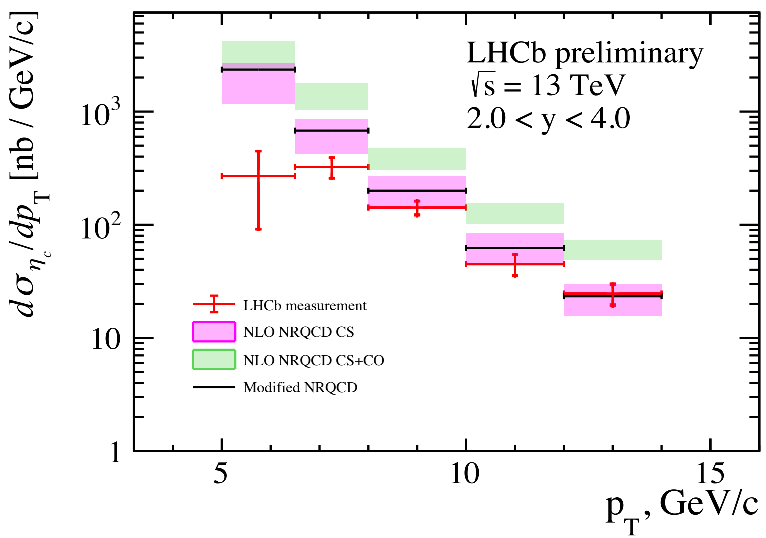
Comparison with theory and outcome

- **Extended p_T-range**:
  - low p_T – probe the transition region between NRQCD and models targeting low p_T region
  - high p_T – sensitive to CO contribution
- Hadroproduction results are compared with NRQCD CS and CO, and modified NRQCD predictions:
  - NRQCD CS describes data for p_T>7 GeV/c
  - **no CO contribution** at high p_T
  - modified NRQCD does not describe η_c to J/ψ production ratio
  - strong motivation to better understand/reduce theoretical uncertainties

Relative production cross-section



Absolute production cross-section



Rapidity-differential study may provide a tool to reduce scale uncertainties

Summary and outlook

- Quarkonia is a great tool to study QCD
- **Persisting challenges**:
  - simultaneous description of **J/ψ production** and **polarization –** **"**polarization puzzle"
  - simultaneous description of η_c and **J/ψ** together with **J/ψ photoproduction -** "HQSS puzzle"
  - negative contribution in the cross-section
  - …

- **New sources of input are required:**
  - New studies of quarkonia decays
  - Study of η_q and χ_q states
  - Associated quarkonia production
  - Production in heavy-ion collisions
  - Non-conventional quarkonium