Quarkonium production in pp collisions at LHC

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HF2022: Heavy Flavours from small to large systems

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IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
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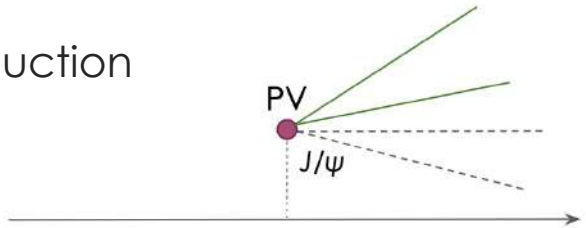
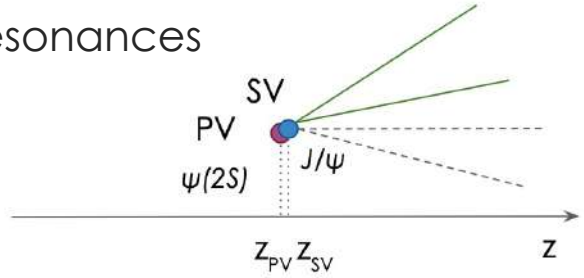
Qarkonium: What and Where from?

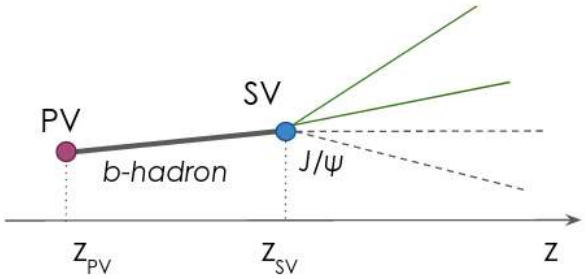
- **What?**
  - a bound state of two heavy quarks (c or b)
- **Where from?**
  - prompt hadroproduction



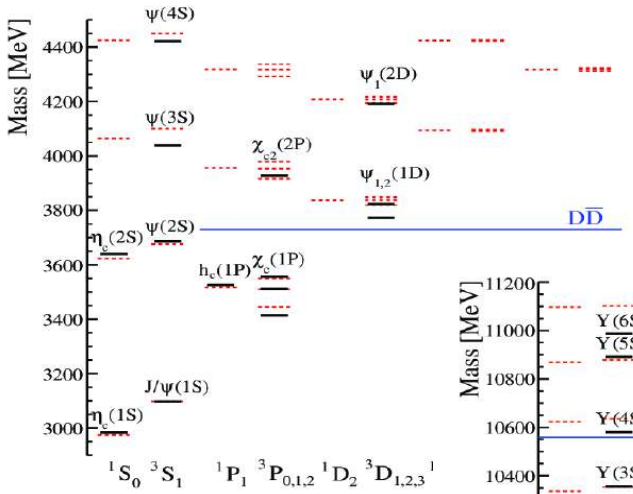
  - decays of higher resonances

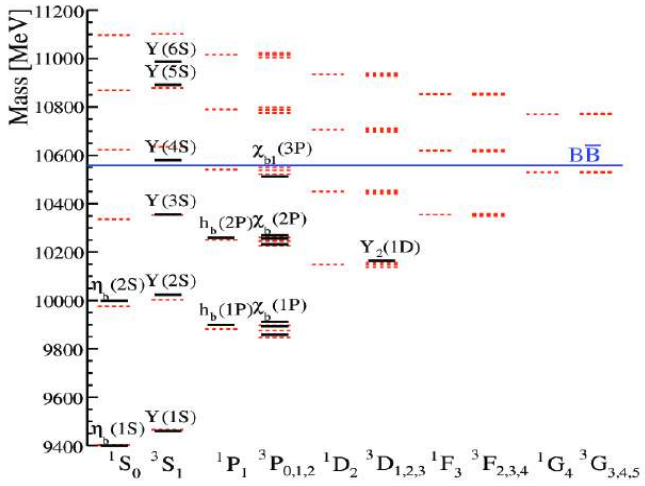


  - production in b-hadron decays / non-prompt (charmonium only)



prompt production





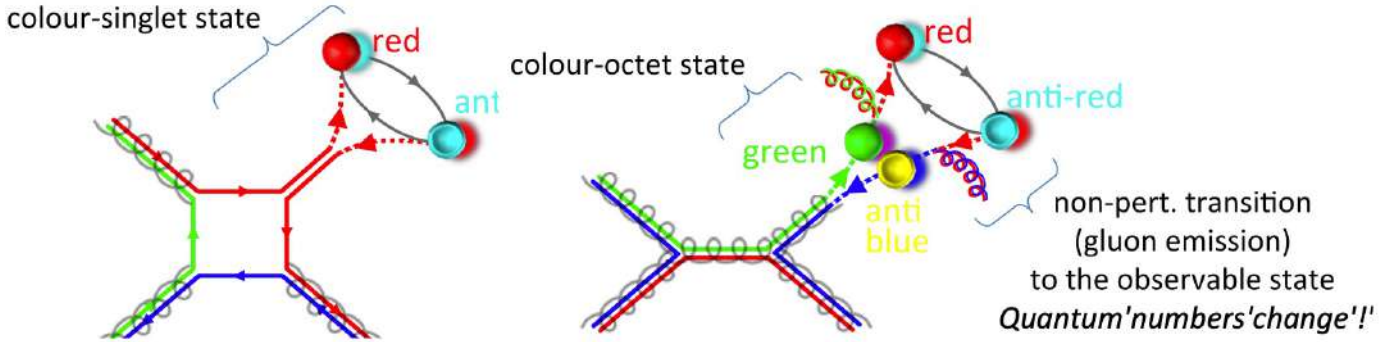
distinguished via pseudo-proper decay time

$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{q\bar{q}}$ 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
- Three common models with the different **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

© talk by J.-P. Lansberg

Quarkonium production: NRQCD

- Two scales of production: hard process of **$Q\bar{Q}$ formation** and soft scale **hadronization of $Q\bar{Q}$**

- **Factorization**: $d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n) \rangle$
  - **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

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

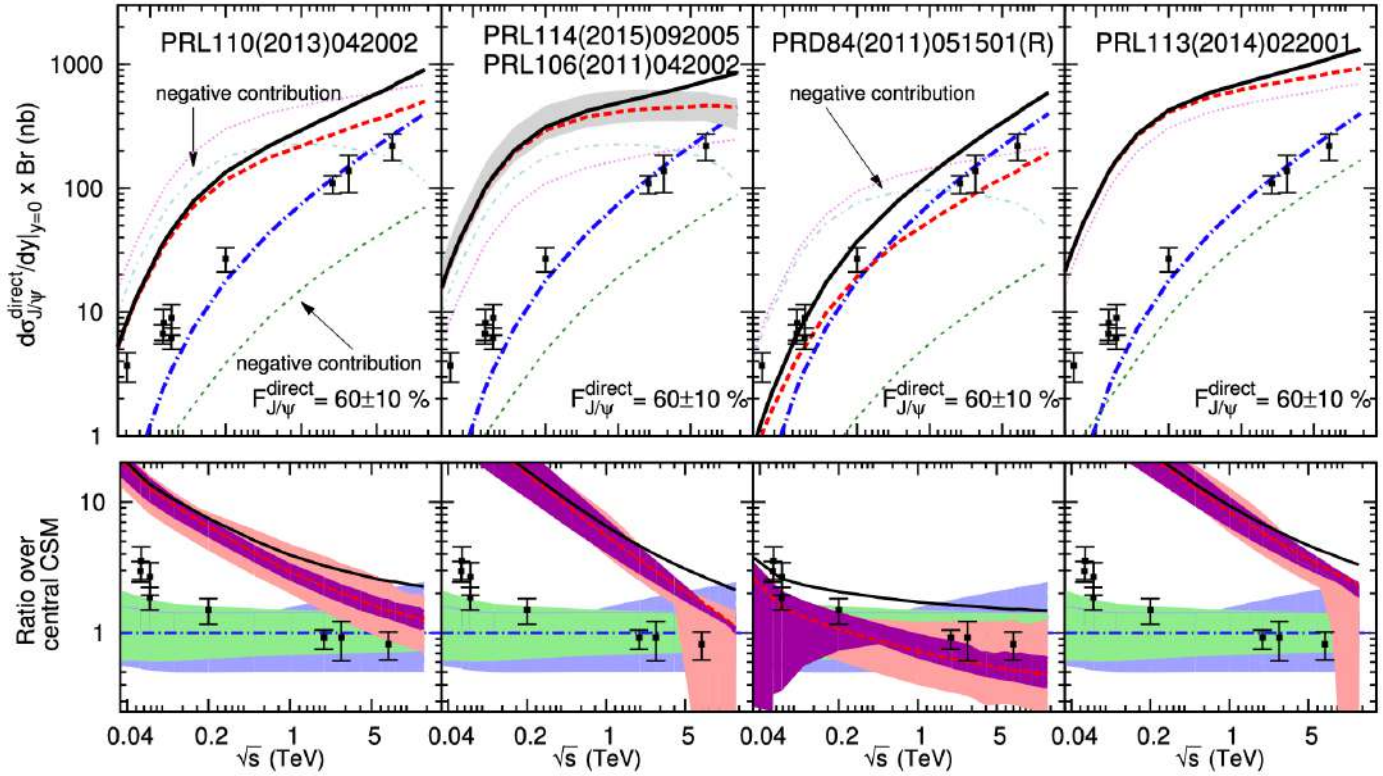
$$\langle \mathcal{O}^{\eta_c}_{8}(^3S_1)\rangle = \langle \mathcal{O}^{J/\psi}_{8}(^1S_0)\rangle$$

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

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 –** "polarization puzzle"
  - simultaneous description of **η_c+ J/ψ** together with **J/ψ photoproduction -** "HQSS puzzle"
  - negative contribution in the cross-section
  - tension with **J/ψ+Z production**
  - CEM does not describe P-waves production
  - …
- **New sources of input:**
  - Study of pseudoscalar states
  - Asociated quarkonia production
  - Production in heavy-ion collisions
  - Non-conventional qurakonium
  - …



LDMEs	J/ψ hadropr.	J/ψ photopr.	J/ψ polar.	η_c hadropr.
Butenschön et al.	✓	✓	✗	✗
Chao et al. + η_c	✓	✗	✓	✓
Zhang et al.	✓	✗	✓	✓
Gong et al.	✓	✗	✓	✗
Chao et al.	✓	✗	✓	✗
Bodwin et al.	✓	✗	✓	✗

talk of Maxim

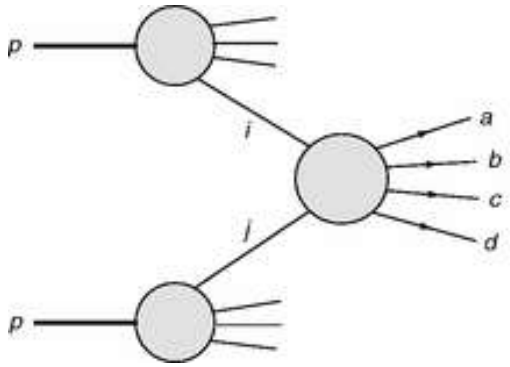
Associated production: DPS and SPS

PRD 84 (2011) 074021
ATL-PHYS-SLIDE-2021-129

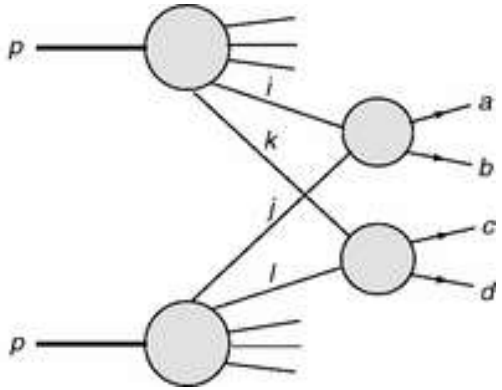
The production of two particles in the same pp collision can be due to

- **Single-Parton Scattering (SPS):**
  - the two particles are produced a single interaction of two partons
  - expected to be "back-to-back" in transverse plane
- **Double-Parton Scattering (DPS):**
  - simultaneous interaction of two pairs of partons, assumed to be uncorrelated
  - DPS "Pocket formula":

$$\sigma_{DPS}^{pp\to\psi_1\psi_2} = \frac{m}{2}\frac{\sigma_{SPS}^{pp\to\psi_1 X}\sigma_{SPS}^{pp\to\psi_2 X}}{\sigma_{eff,DPS}}$$



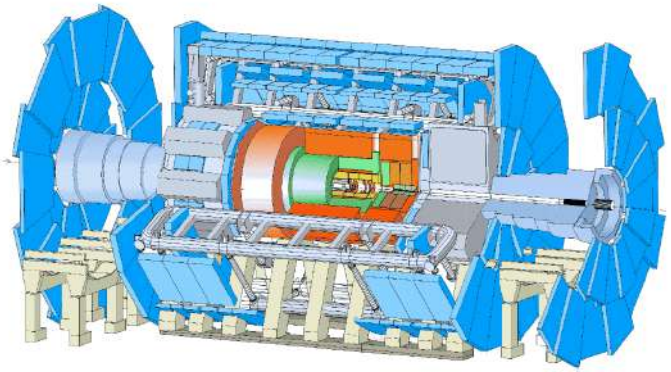
- **Di-J/ψ production:**
  - expected small SPS CO contribution (strongly depends on LDMEs)
  - DPS contribution is important at large J/ψ Δy
  - Feed-down contribution depends on the production mechanism



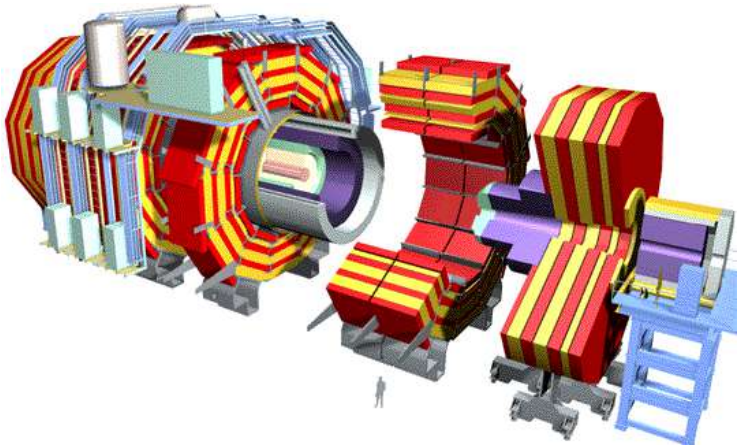
LHC detectors hunting for quarkonium

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

JINST 3 (2008) S08003

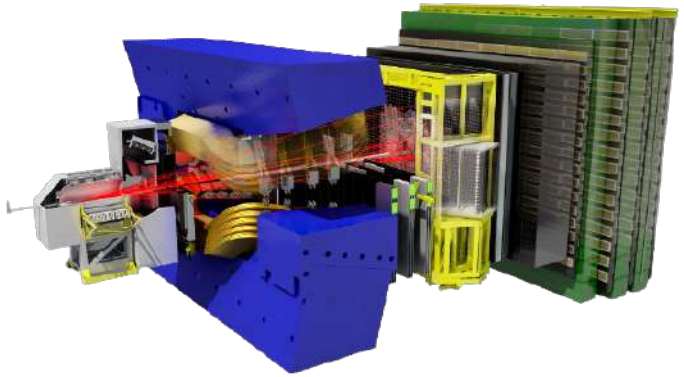


JINST 3 (2008) S08004



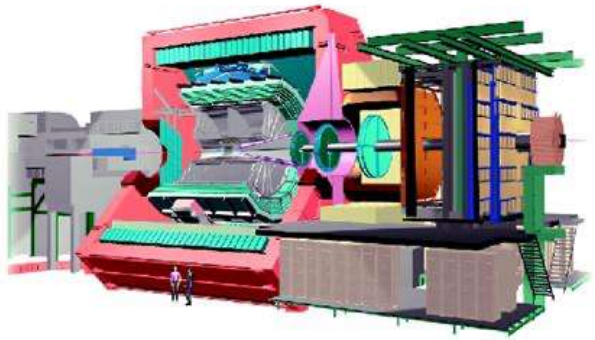
- **LHCb**: forward-rapidity region, with muons and hadrons in final state

IJMPA 30 (2015) 1530022



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

JINST 3 (2008) S08002

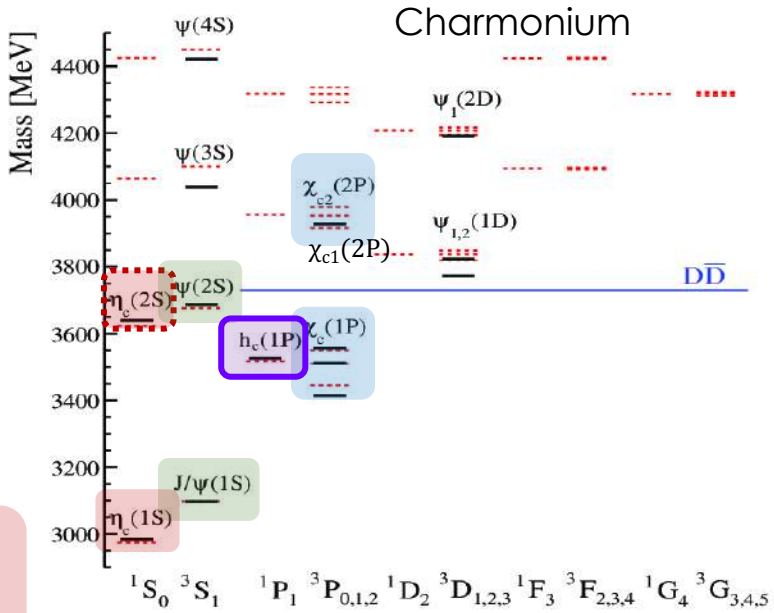


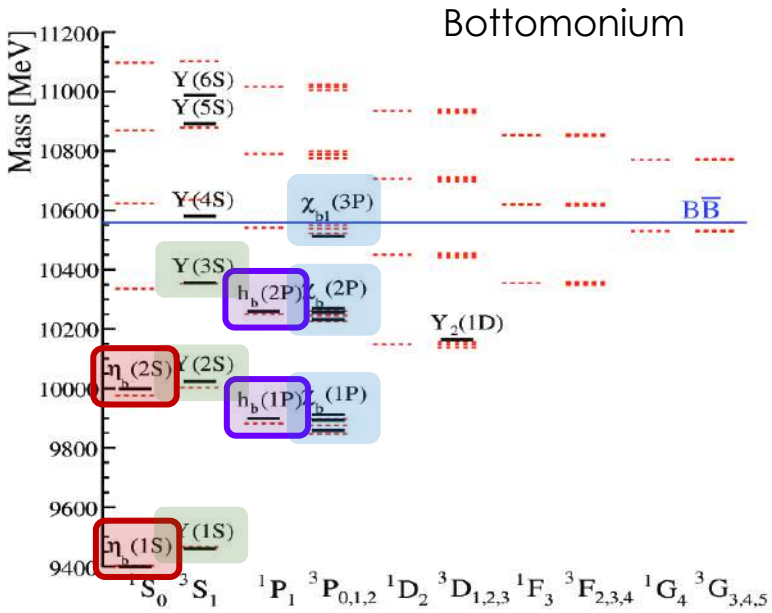
Experiments provide complementary measurements

Qarkonium @ LHC

Rev.Mod.Phys 90 (2018) 015003

- **Final states:**
  - hadrons or γγ
  - $\mu^+\mu^-/e^+e^-$ or hadrons
  - $^3S_1\gamma$, $^3S_1\ \pi^+\pi^-$ or hadrons
  - $^1S_0\ \gamma$ or hadrons
- **Existing measurements:**
  - η_c production
  - $\eta_c(2S)$ 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



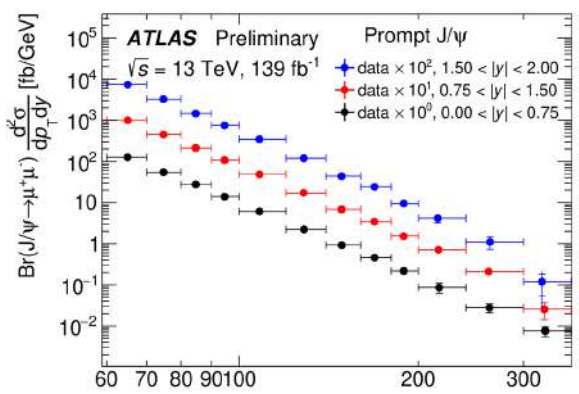


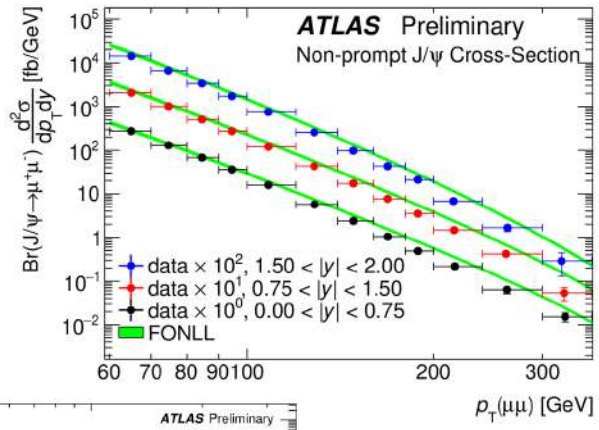
Hadronic final states allow to study different quarkonium states simultaneously

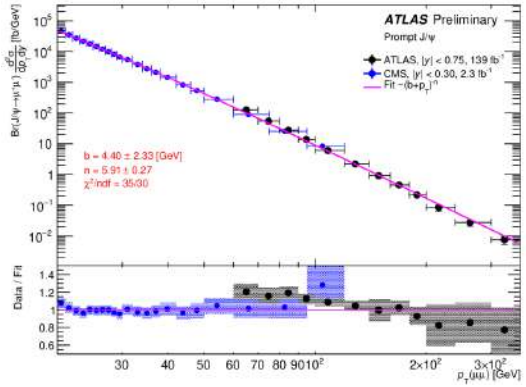
J/ψ: Differential production cross-sections

ATLAS-CONF-2019-047
JHEP 11 (2021) 181

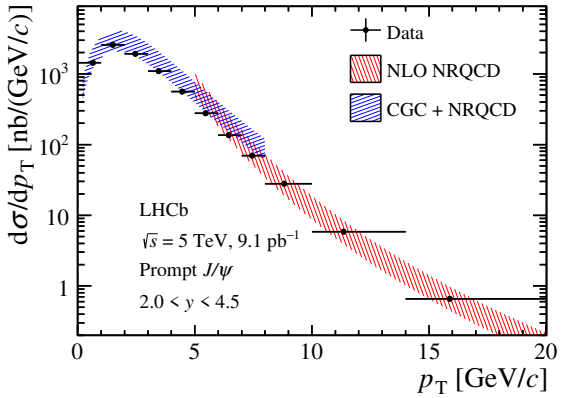
- ATLAS EXPERIMENT prompt and from-b @ 13 TeV
  $60 < p_T < 360\ GeV/c,\ |y| < 2.0$
- Data compared with low-p_T CMS results
- LHCb prompt and from-b @ 5.02 TeV
  $0 < p_T < 20\ GeV/c, 2.0 < y < 4.5$
- J/ψ production:
  $$\sigma_{\psi(2S)}^{prompt} = 8.154 \pm 0.010_{stat} \pm 0.283_{syst}\ \mu b$$

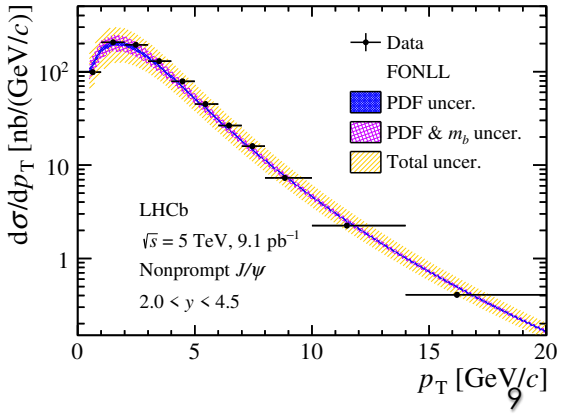






- **Reasonable agreement between NRQCD and data for high-p_T**
- **Small tension with CGC+NRQCD**
- **Good agreement between data and FONLL at low-p_T,** with theory exceeding prediction at high-p_T

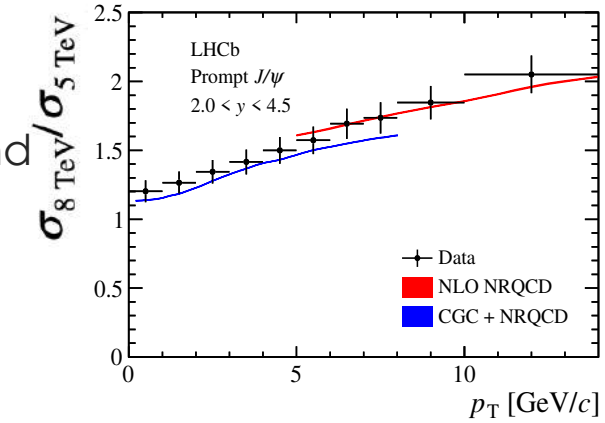


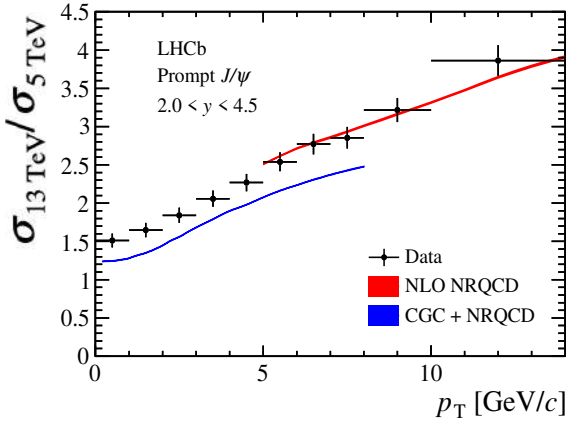


J/ψ: Ratios between energies and R_{pPb}

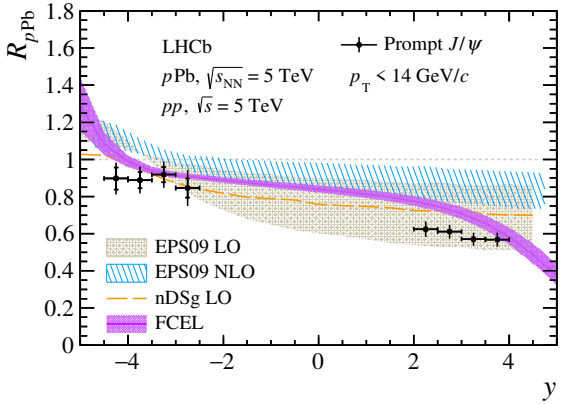
JHEP 11 (2021) 181

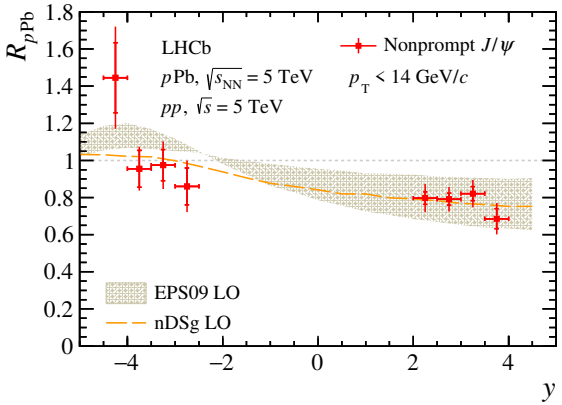
- The cross-sections at **5 TeV** are **compared** with those at **8** and **13 TeV**
  - cancelled systematic uncertainties: branching fraction and radiative tail
  - partially correlated uncertainties: luminosity, fit model and tracking correction





- **Updated R_{pPb}** value based on the direct measurement
  - pPb: 1.5 < y < 4.0
  - Pbp: -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





Single J/ψ hadroproduction production has been studied in all possible configurations

ψ(2S): Differential production cross-sections

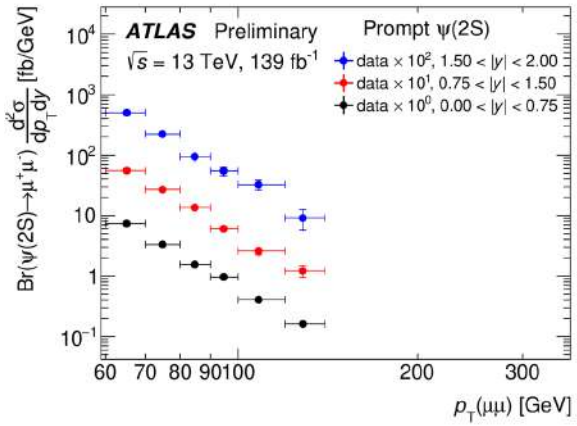
ATLAS-CONF-2019-047
EPJC 80 (2020) 185

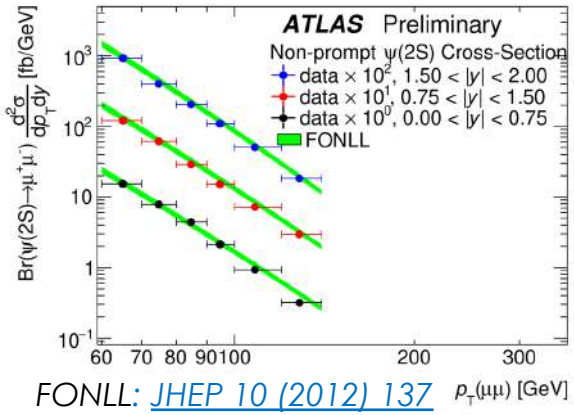
- ATLAS EXPERIMENT prompt and from-b @ 13 TeV
  $60 < p_T < 360$ GeV/c, $|y| < 2.0$

- LHCb prompt and from-b @ 7 and 13 TeV
  $p_T < 20$ GeV/c, $2.0 < y < 4.5$

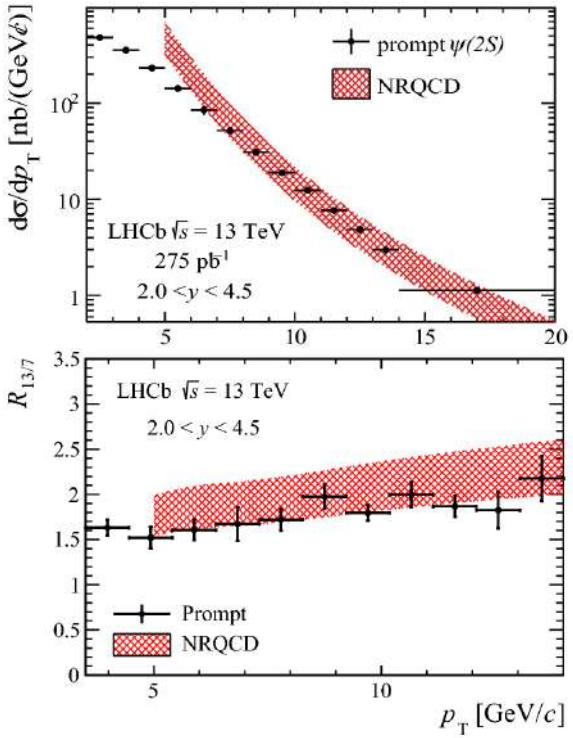
- Complementary measurements in different rapidity regions
- **Reasonable agreement between NRQCD and data** for $p_T > 7$ GeV/c
- **Good agreement with FONLL** for production in b-decays **for both experiments**
- The **cross-section ratios** computed for **8** and **13 TeV**

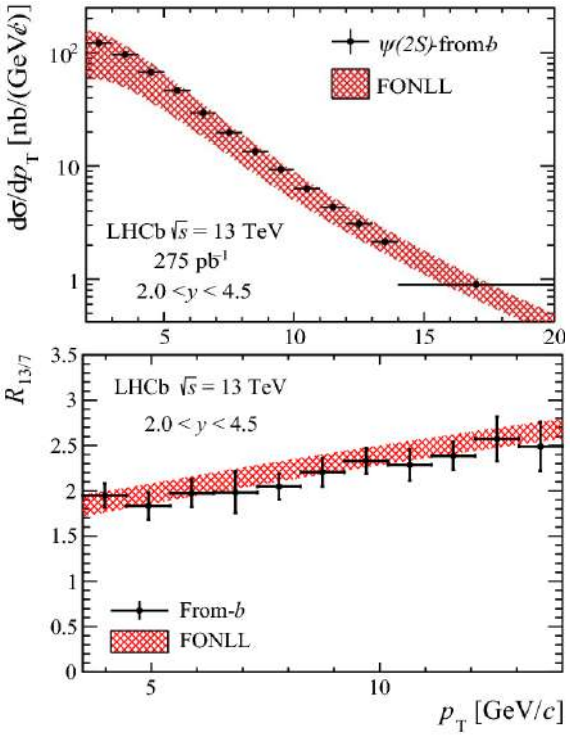
Same situation as for single J/ψ hadroproduction





FONLL: JHEP 10 (2012) 137





NRQCD: JHEP 05 (2015) 103

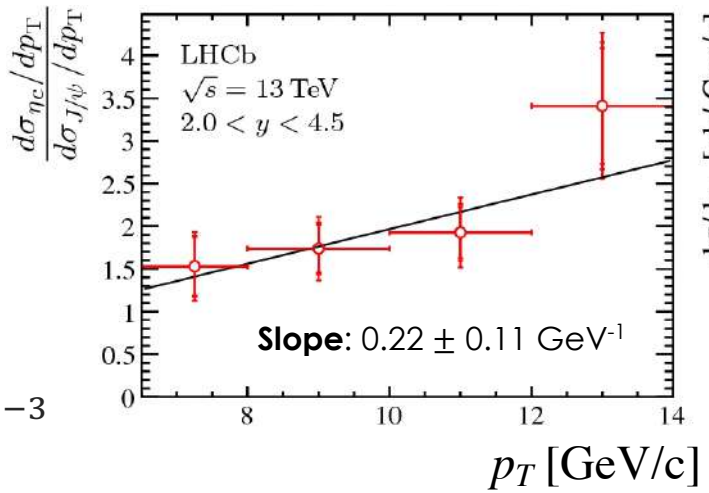
FONLL: EPJC 75 (2015) 610

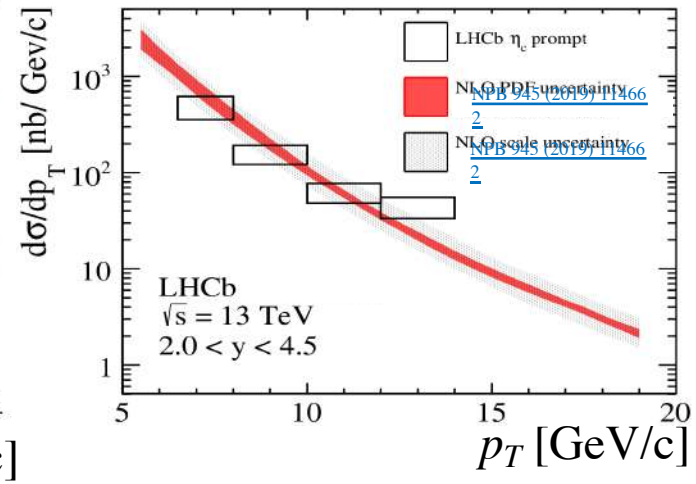
$\eta_c(1S)$: Differential production at $\sqrt{s}$=13 TeV

EPJC 80 (2020) 191

- **relative $\eta_c/J/\psi$** and **absolute η_c** p_T-differential production **cross-sections**

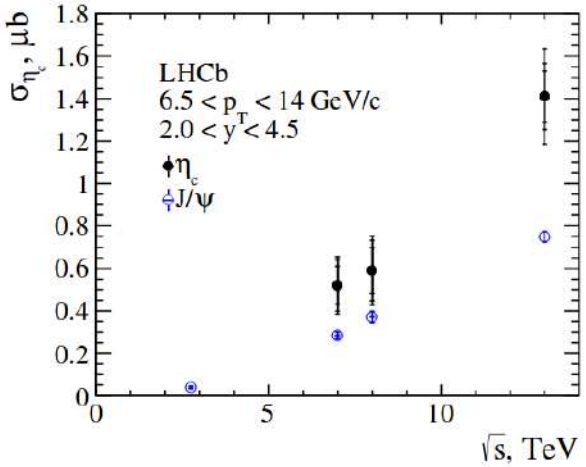
- **$\eta_c(1S)$ production:**
  $6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$
  $$\sigma_{\eta_c}^{prompt} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{J/\psi}\ \mu b$$
  $$\mathfrak{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{J/\psi})\times 10^{-3}$$





- Results may **provide** important **link between J/ψ production and polarization**

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

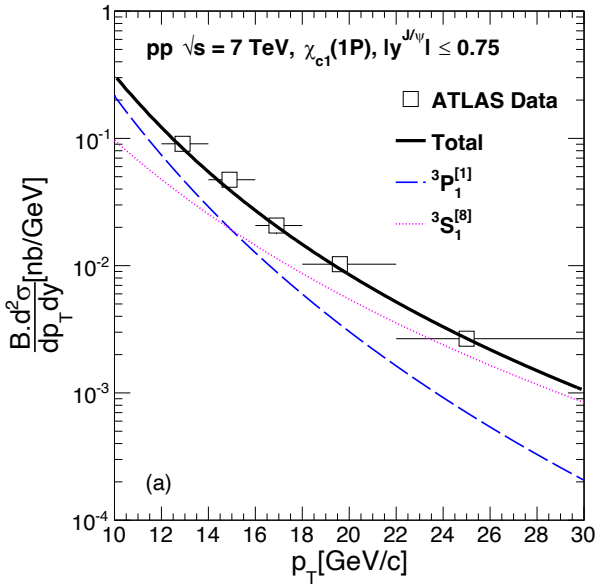


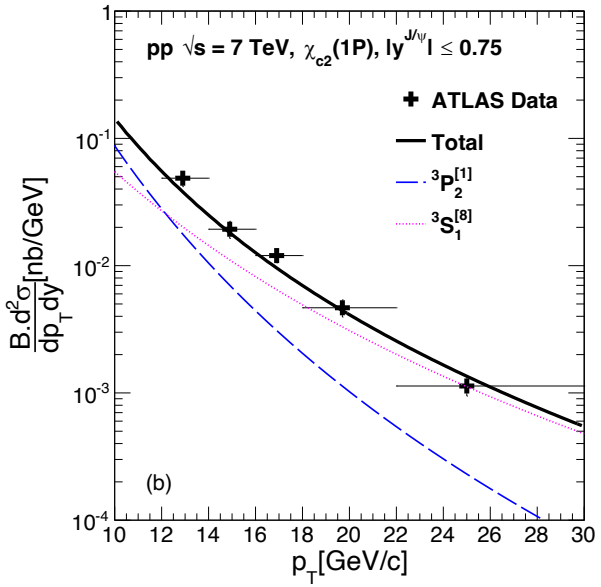
Interpretation of $\eta_c(2S)/\psi(2S)$ much cleaner than for $\eta_c(1S)/J/\psi$ due to absence of feed-down contributions: **dedicated LHCb trigger in 2018**

$\chi_{c1,2}$ production using $\chi_{c1,2} \rightarrow J/\psi\gamma$

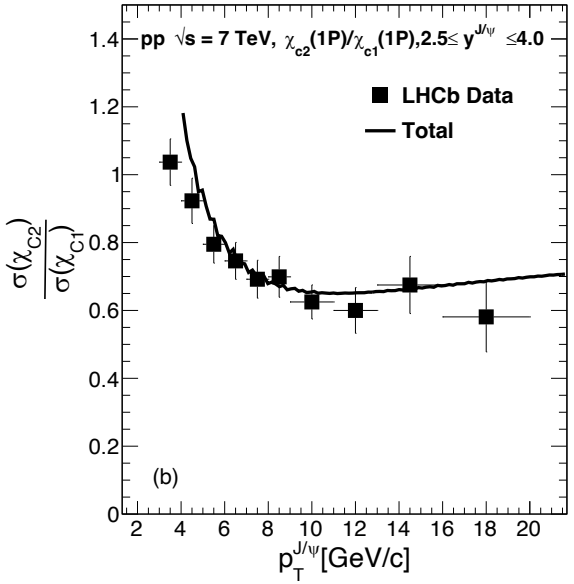
J.Phys.G 44 (2017) 8, 085003

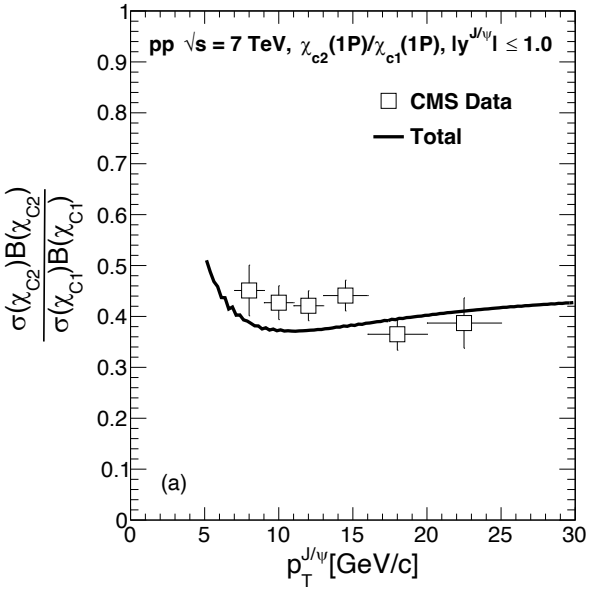
- NRQCD fit for production cross-section
  - absolute =>
  - relative =>





- **CO LDME for χ_c is obtained from fit to data**





- More precise when looking for ratio
- **Small p_T region has to be explored**

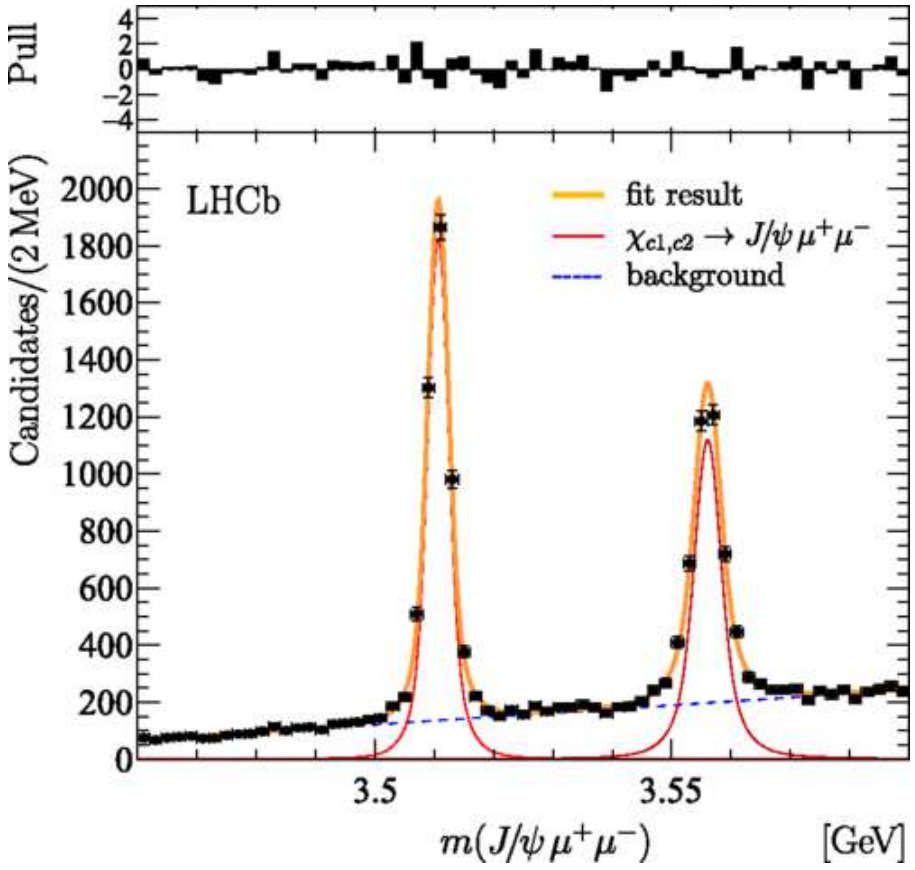
$\chi_{c1,2}$ production using $\chi_{c1,2} \to J/\psi\mu^+\mu^-$

PRL 119 (2017) 22, 221801

- First observation of $\chi_{c1,2} \to J/\psi\mu\mu$ decay modes
- Extremely clean signals
- $\chi_{c1,2}$ resonance parameters measured with world average precision

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

- New channel for production measurement



- **Promising channel for χ_c hadroproduction at low p_T**
- **Similar studies can be done at CMS?**

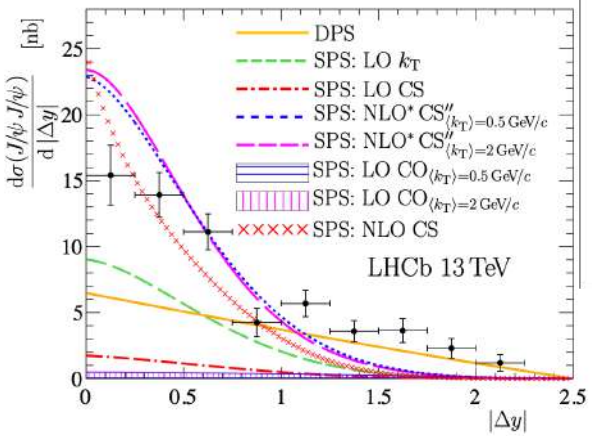
Di-J/ψ: Production

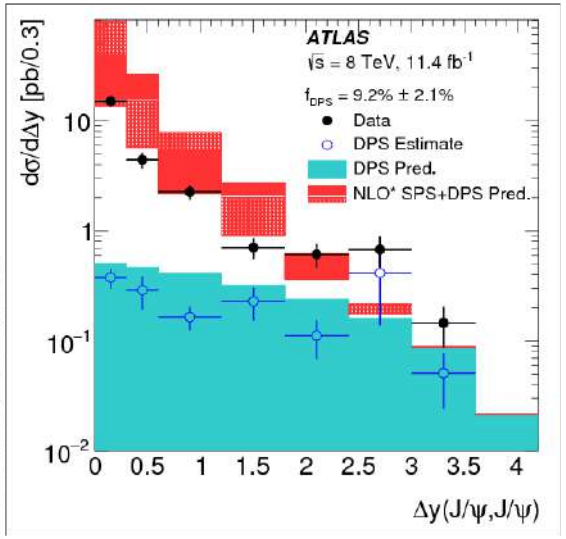
Eur.Phys.J.C 77 (2017) 2, 76
JHEP 09 (2014) 094
JHEP 06 (2017) 047

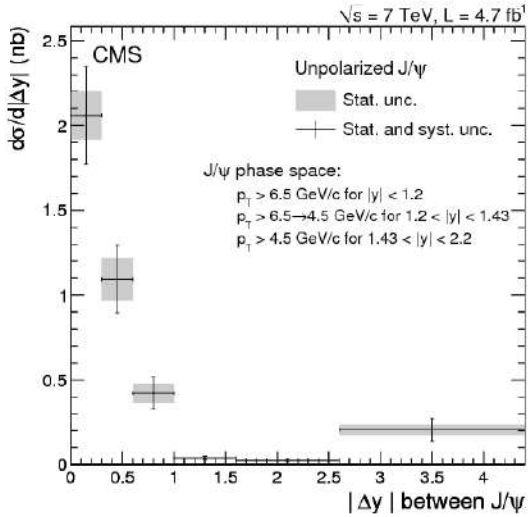
- Di-J/ψ production was measured in different kinematical regions

- ATLAS EXPERIMENT Measurement shows **small DPS contribution**:
  $f_{DPS} = (9.2 \pm 2.1_{stat} \pm 0.5_{syst})\%$

- LHCb Measurement shows **large DPS contribution**:
  $f_{DPS} > 50\%$





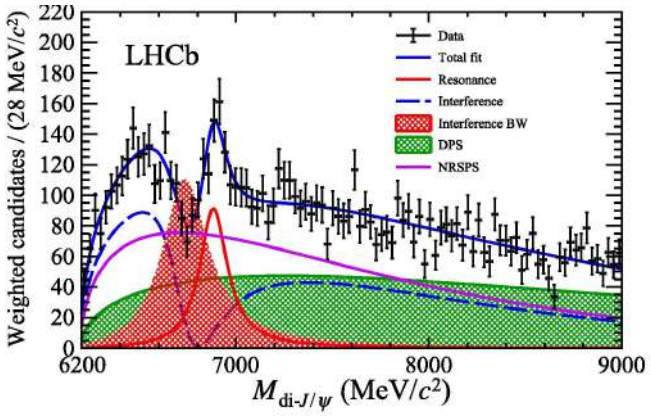


- LHCb result shows lower σ_{eff} than the other LHCb measurements, but higher than ATLAS and CMS results
- An **improvement in the precision for SPS predictions is needed** for a better discrimination between theory approaches
- **Feed-down contribution** can amount up to 40% of SPS contribution and **has to be accounted for**

Di-J/ψ: Search for resonanses

SB 65 (2020)23, 1983-1993
CMS-PAS-BPH-21-003
ATLAS-CONF-2022-040

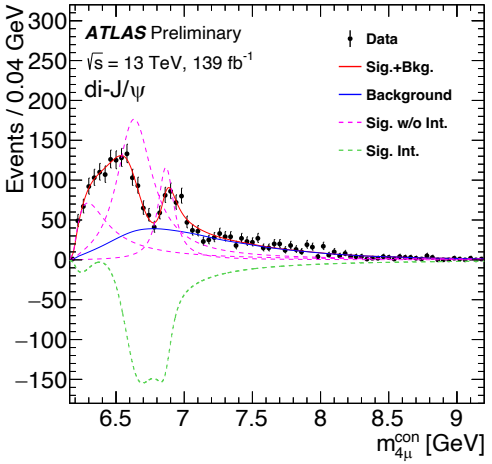
- **First observation of fully heavy tetraquark candidate X(6900)**

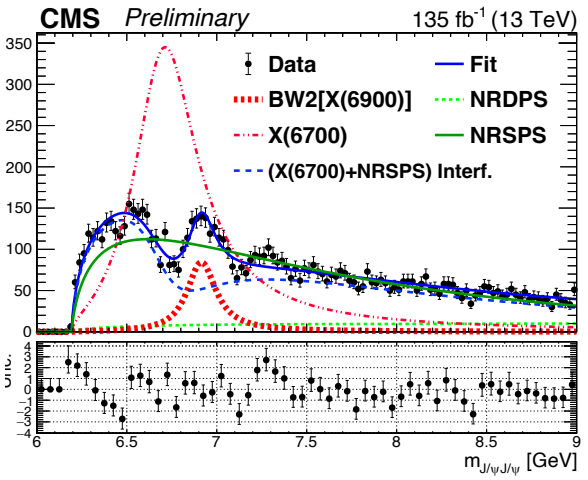


- **Observes similar structure + two more candidates X(6600) and X(7300)**

- Threshold structure with a few possible interpretations:
  - One BW, combination of two BWs, feed-down…

	m [GeV/c²]	Γ [GeV/c²]
LHCb	$6.89 \pm 0.01 \pm 0.01$	$0.17 \pm 0.03 \pm 0.07$
CMS	$6.93 \pm 0.01 \pm 0.01$	$0.12 \pm 0.02 \pm 0.02$
ATLAS	$6.87 \pm 0.03\ ^{+0.06}_{-0.01}$	$0.12 \pm 0.04\ ^{+0.03}_{-0.01}$





- Additional study together with spin-parity measurement required to explain nature of threshold structure

More studies of J/ψ+quarkonium will arrive soon

Di-Υ(1S): Production and search for resonances

PLB 808 (2020) 135578

- **DPS process** can **provide information on partons** p_T, their correlations inside proton and can **help understanding various backgrounds**

- **Υ(1S) pair production for unpolarized case**

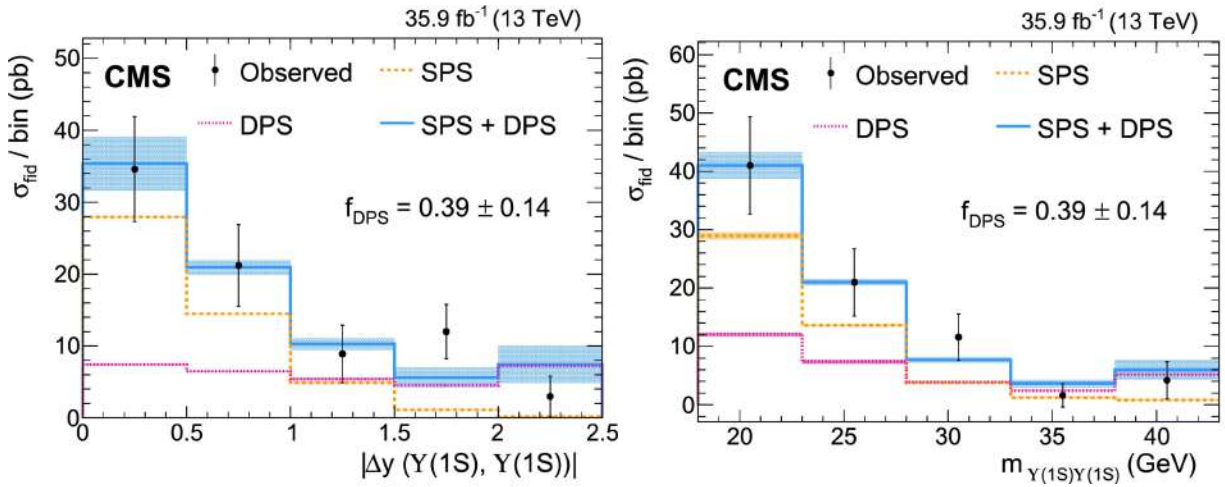
  $\sigma_{\Upsilon(1S)\Upsilon(1S)} = 79 \pm 11_{stat} \pm 6_{syst} \pm 3_{\mathfrak{B}}\, pb$, |y|<2.0

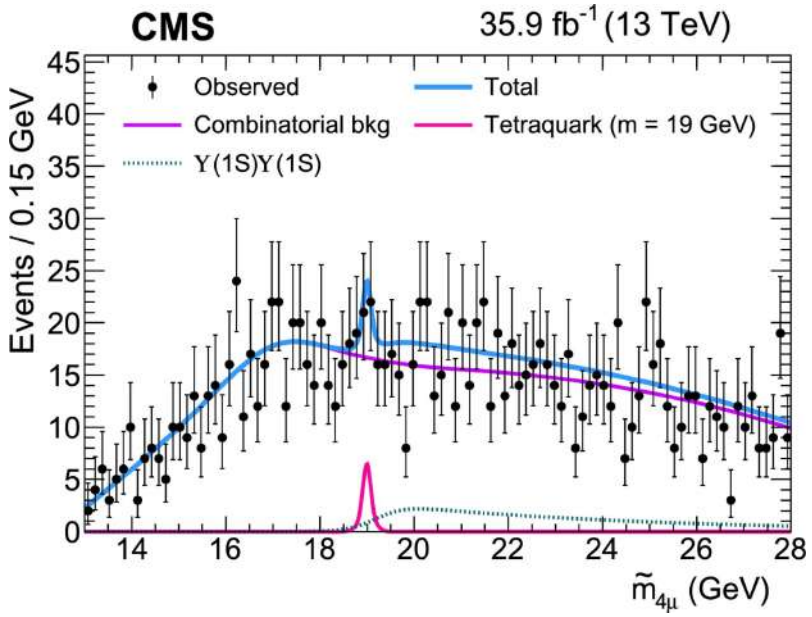
- Charging λ_θ in range[-1, +1] production varies from −60% to +25%

- First measurement of DPS contribution to $\sigma_{\Upsilon(1S)\Upsilon(1S)}$

  $f_{DPS} = (39 \pm 14)\%$

- **No excess** of events compatible with signal is observed **in 4-μ invariant mass spectrum**

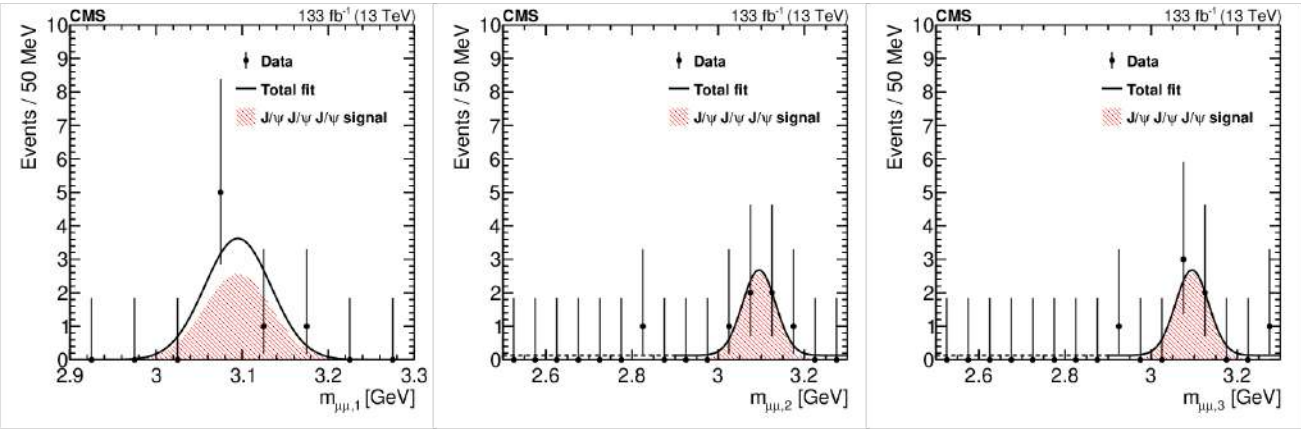




Triple-J/ψ production

arXiv:2111.05370

- **First observation of triple-J/ψ production**



- **Cross-section:**

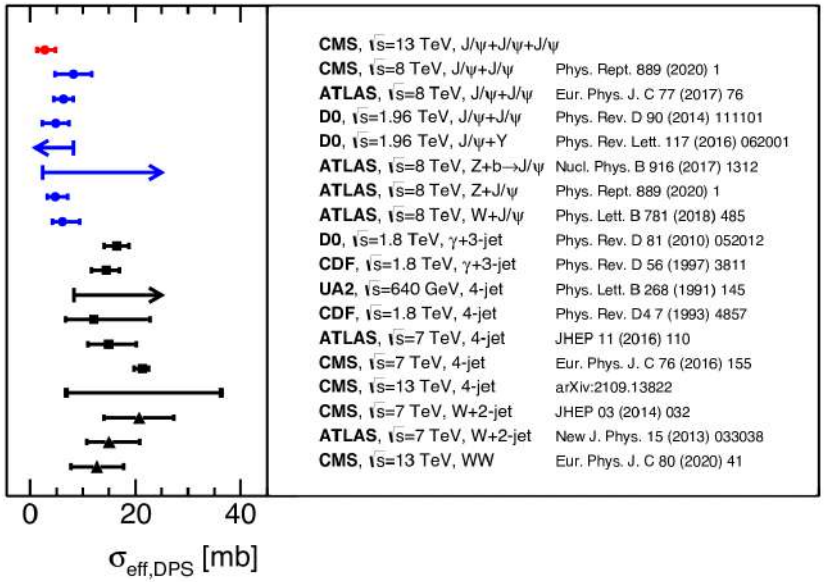
$\sigma_{3J/\psi} = 272^{+141}_{-101}{}_{stat} \pm 16_{syst}\ fb$, $|y_{J/\psi}|<2.4$

- **Contributions of DPS and TPS**:

f_{DPS}~76% and f_{TPS}~20%

$\sigma_{eff,TPS} = (0.82 \pm 0.11)\times\sigma_{eff,DPS}$

$\sigma_{eff,DPS} = 2.7^{+1.4}_{-1.0}{}_{stat}{}^{+1.5}_{-1.0}{}_{syst} mb$

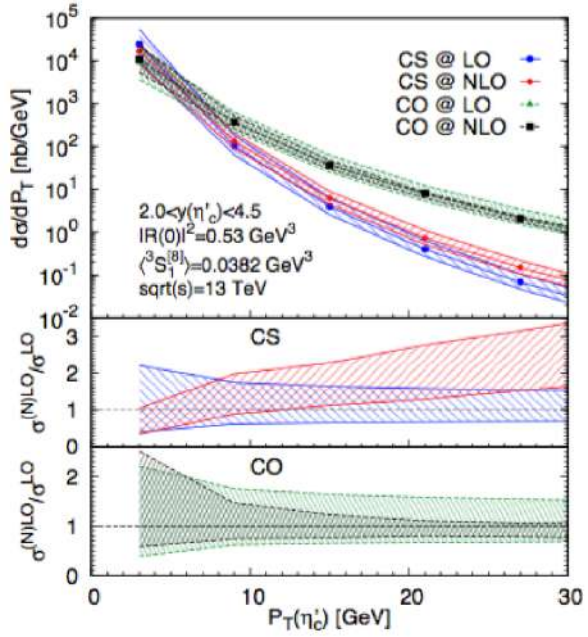


- Measured $\sigma_{eff,DPS}$ is consistent with di-J/ψ results, but lower that jet/W/Z results

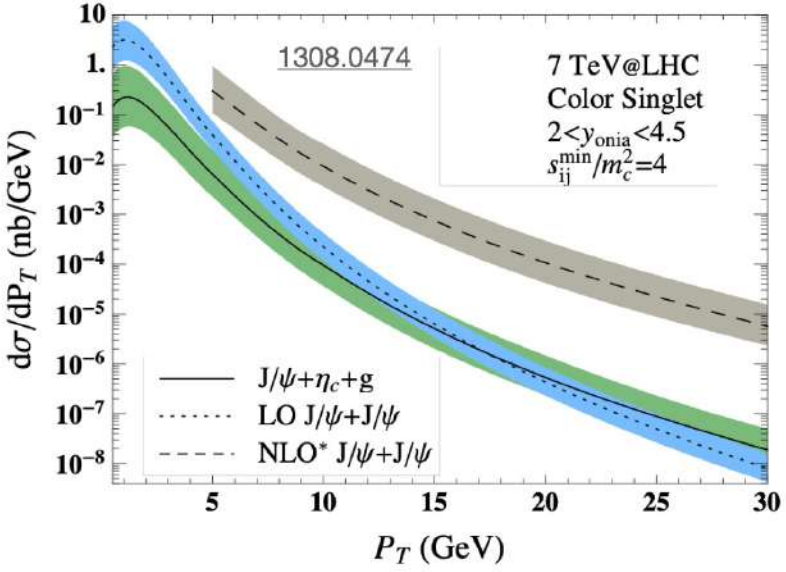
Prospects

Phys.Lett.B 786 (2018) 342-346
Phys.Rept. 889 (2020) 1-106

- **Single quarkonium production:**
  - **$\eta_c(2S)$, h_c** and **$\eta_b(1S)$** production
  - simultaneous study of **$\psi(2S)$** and **$\eta_c(2S)$**
    - ➢ no feed-down from higher stated, clean interpretation
  - decays to **$\Lambda\Lambda$, $\Lambda^*\Lambda^*$, $\Sigma\Sigma$, $\Xi\Xi$** final states
    - ➢ access to new quarkonium states



- **Double quarkonium production:**
  - $J/\psi+\eta_c$
    - ➢ NRQCD predicts suppressed yield w.r.t. $J/\psi+J/\psi$
  - $J/\psi+\Upsilon$
    - ➢ dominant SPS CO
  - $J/\psi+\psi(2S)$, $\psi(2S)+\psi(2S)$
    - ➢ will help to understand feed-down contribution



Summary

- Recent LHC results on quarkonium production will be useful input to understand quarkonium production mechanism in pp and heavy-ion collisions

- Comprehensive HF production model is missing
  - new inputs are necessary to improve understanding: asociated production, production of η_c and h_c …

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

Thanks for your attention!