Charmonium production in proton-proton collisions at LHC

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(On behalf of the LHCb, ATLAS and CMS collaborations)

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Outline

- Introduction
- The LHC detectors
- Recent results since the last workshop
  - ATLAS&CMS: J/ψ and $\psi(2S)$ production at 5.02TeV — *EPJC 78 (2018) 171, EPCJ 77 (2018) 269*
  - LHCb: J/ψ production at 13TeV (update) — *JHEP 1510 (2015) 172, (Err. JHEP 1705 (2017) 063)*
  - CMS: J/ψ and $\psi(2S)$ production at 13TeV — *PLB 780 (2018) 251*
  - ATLAS: $\psi(2S)$ and X(3872) production at 8TeV — *JHEP 1701 (2017) 117*
  - LHCb: χ_{cJ} and $\eta_c(2S)$ production in b-decays — *EPJC 77 (2017) 609*
  - LHCb&CMS: J/ψ production in jets at 13TeV & 5.02TeV — *PRL 118 (2017) 192001, CMS PAS HIN-18-012*
  - LHCb: central exclusive production of J/ψ and ψ(2S) at 13TeV — *preliminary*
  - *LHCb: J/ψ pair production at 13 TeV*
  - *ATLAS: J/ψ pair production at 8TeV*

  See Dr. Stanislav POSLAVSKY
  Double charmonia production in the LHC
- Summary

Charmonium production

- Two scales of production:
  hard process of $c\bar{c}$ **formation** and **hadronization of** $c\bar{c}$ at softer scales
- **Factorization**

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

Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

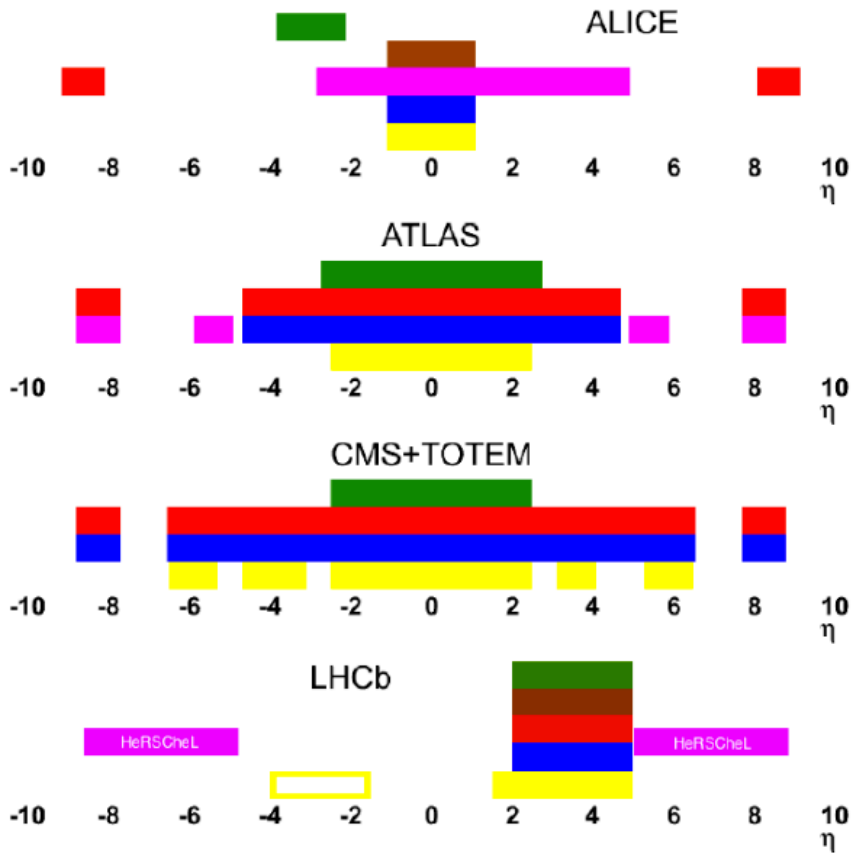
Long distance matrix elements (LDME), non-perturbative part

- **Colour-singlet model (CSM)**: intermediate QQ state is colourless and has the same JPC quantum numbers as the final-state quarkonium
- **NRQCD**: all viable colors and J^{PC} allowed for the intermediate $c\bar{c}$ state, they are adjusted in the long-distance part with a given probability.
- **Long-Distance Matrix Elements** (LDME): taken from experimental data
- **Universality**: same LDME for prompt production and production in b-decays
- **Heavy-Quark Spin-Symmetry (HQSS)**: links between colour-singlet (CS) and colour- octet (CO) LDME of different quarkonium states

QCD model test

- **Powerful QCD tests**, instead of using QCD to estimate observables, use production measurements to calibrate QCD
- New theory developments confronted to new experimental results. Impressive progress in both domains
- **More precision** in conventional studies and **new sources of input**: associated production, isolation, production in pPb and PbPb collisions, ...
- Comprehensive model of **charmonium production** still missing

LHC detectors



Complementary acceptance coverage for production measurements

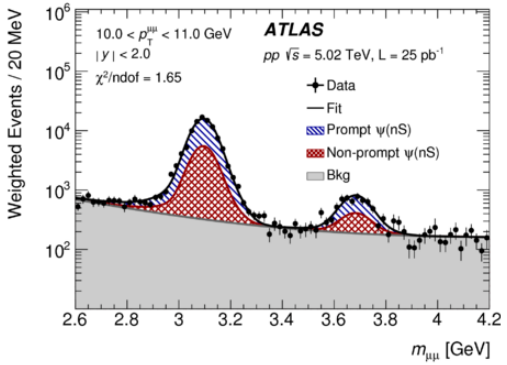
hadron PID
muon system
lumi counters
HCAL
ECAL
tracking

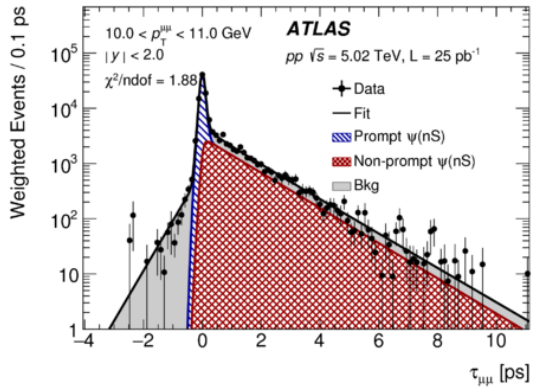
J/ψ and $\psi(2S)$ production at 5.02TeV

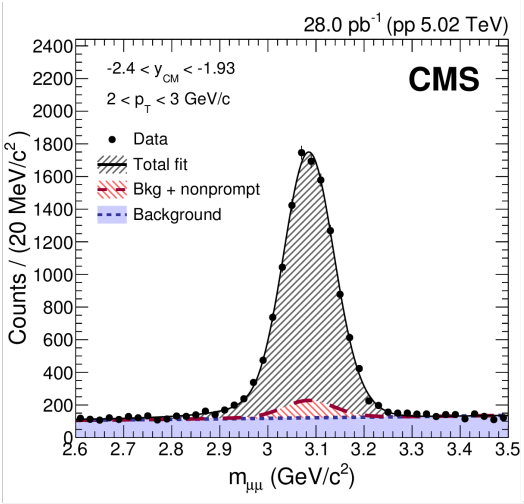
EPJC 78 (2018) 171; EPCJ 77 (2018) 269; arXiv:1805.02248

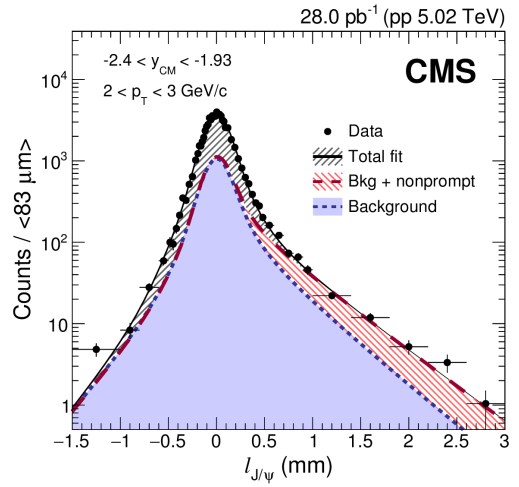
- Measurements on the charmoinum J/ψ and $\psi(2S)$ production cross section in their decays to dimuon in pp collisions, in a study of their production cross section modifications from *pp* to *p*+Pb collisions

- Prompt and *b*-decay non-prompt components are extracted from the fit to lifetime/decay length distribution



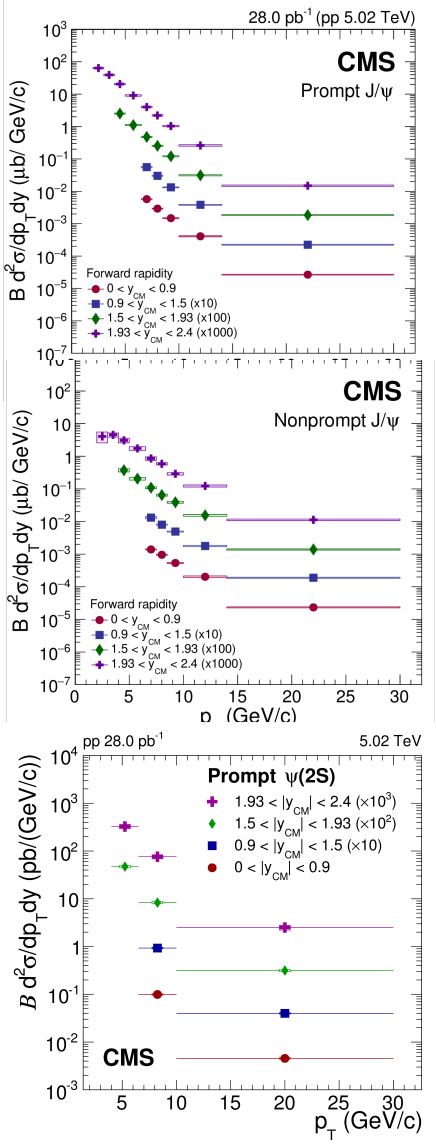


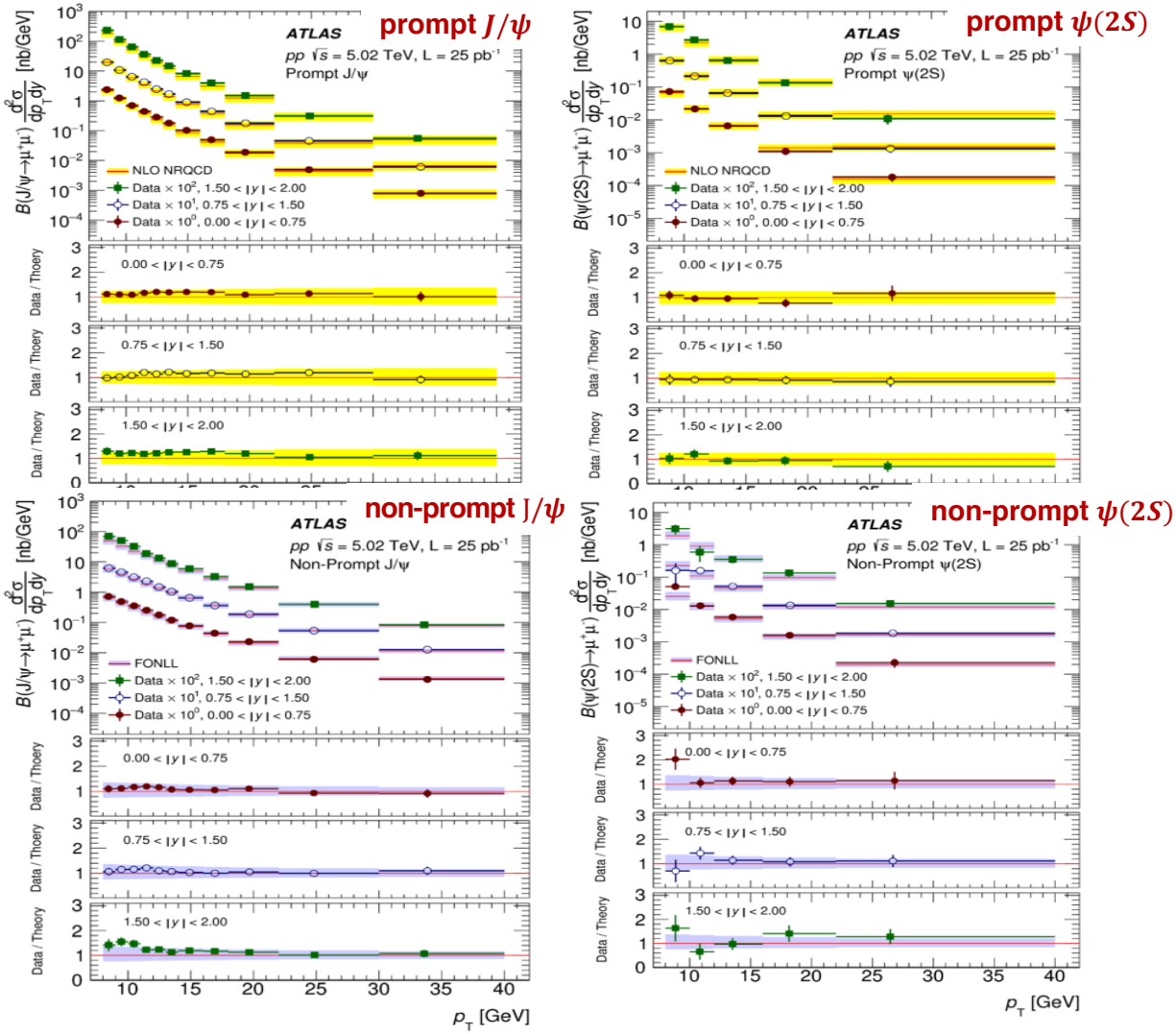




J/ψ and $\psi(2S)$ production at 5.02TeV

EPJC 78 (2018) 171; EPCJ 77 (2018) 269; arXiv:1805.02248





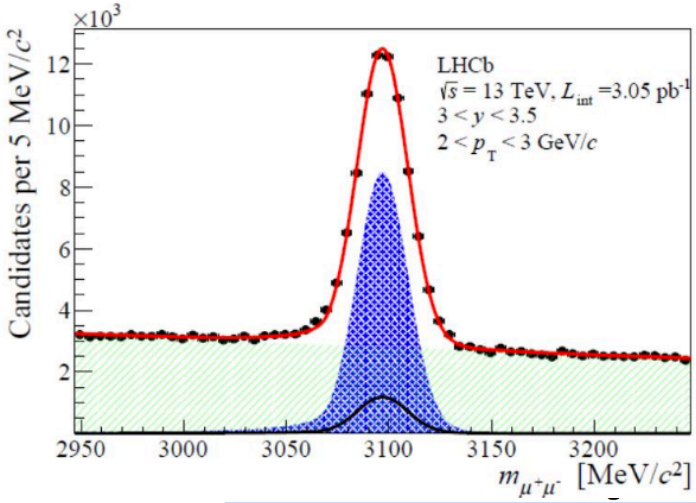
Overall, very good agreement between experiment and theory

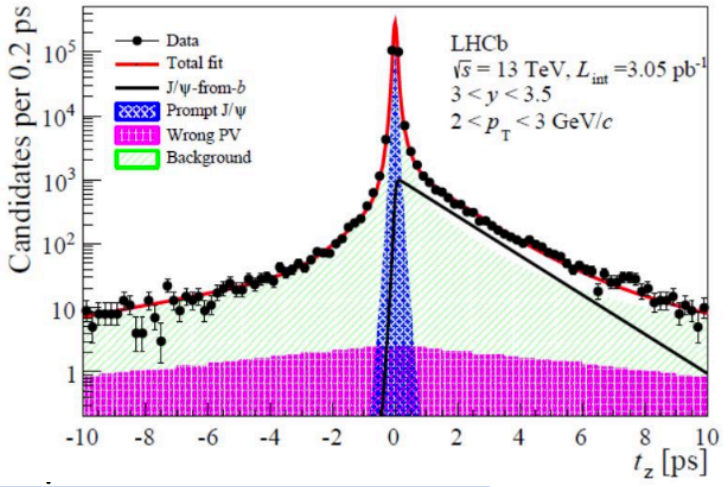
J/ψ production at 13 TeV (update*)

JHEP 1510 (2015) 172 ; (Err. JHEP 1705 (2017) 063)

- Prompt J/ψ production and production in *b*-hadron decays **~3/fb**
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution

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





$$\sigma(\text{prompt } J/\psi, p_{\rm T} < 14\,{\rm GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94\,\mu{\rm b}$$
$$\sigma(J/\psi\text{-from-}b, p_{\rm T} < 14\,{\rm GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14\,\mu{\rm b}$$

$$\sigma(pp \to b\bar{b}X) = 495 \pm 2 \pm 52\,\mu{\rm b}$$

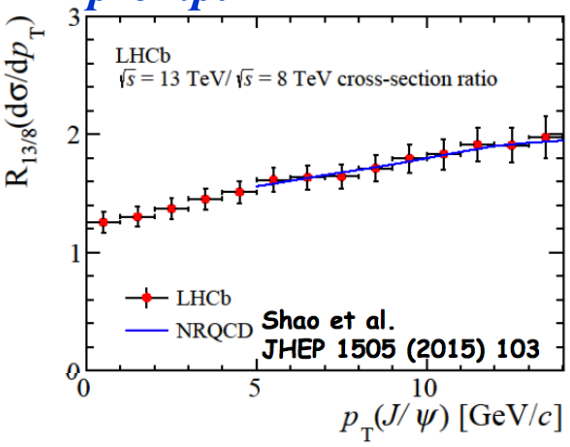
** VELO simulation imperfection in describing radiation damage: track reconstruction efficiency underestimated, particularly at low pseudorapidity and low pT.*

J/ψ production at 13 TeV (update*)

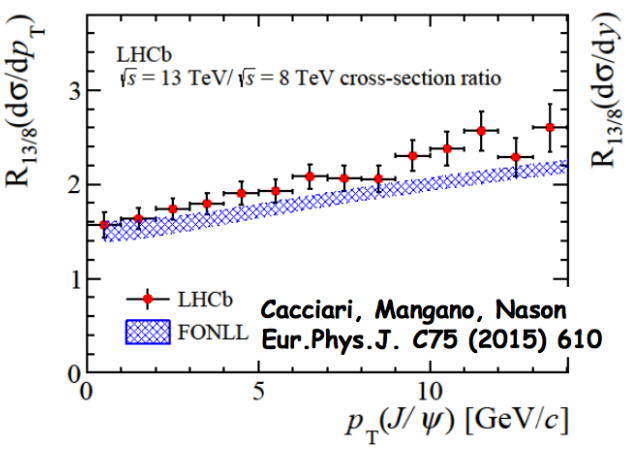
JHEP 1510 (2015) 172 ; (Err. JHEP 1705 (2017) 063)

- Prompt J/ψ production and production in *b*-hadron decays **~3/fb**
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution
- Comparison to 8TeV and theoretical calculations

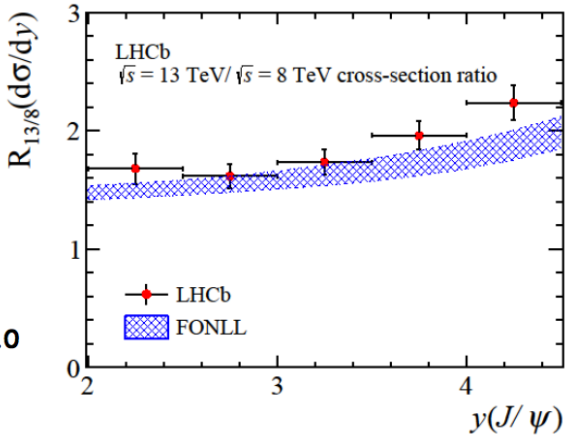
prompt



non-prompt



non-prompt

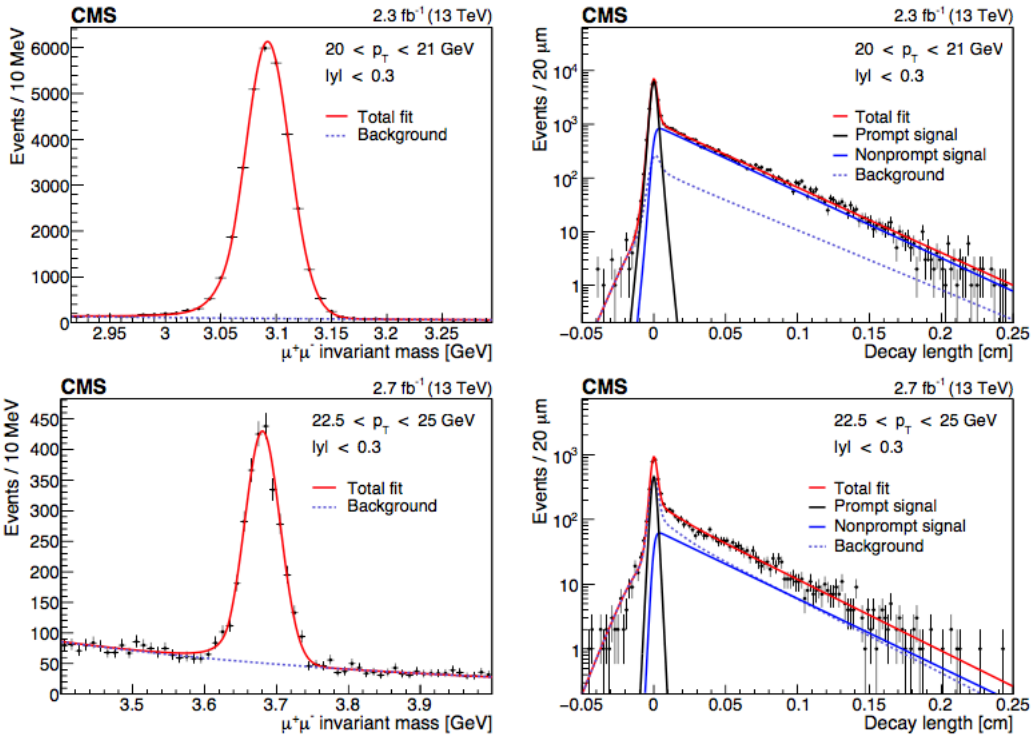


Good agreement between theory and experiment for prompt and *b*-decay production!

J/ψ and ψ(2S) production at 13 TeV

PLB 780 (2018) 251

- Using dimuon channel to reconstruct the two charmonium states **2.3~2.7/fb**
- Prompt and *b*-decay components are extracted from the fit to decay length distributions
- Kinematic region: $|y| < 1.2$

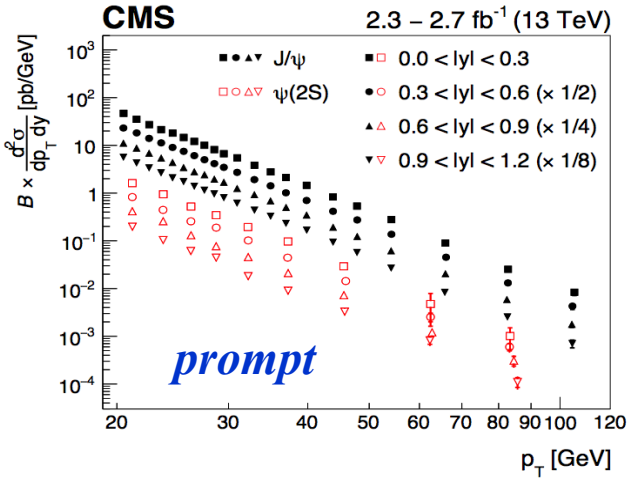


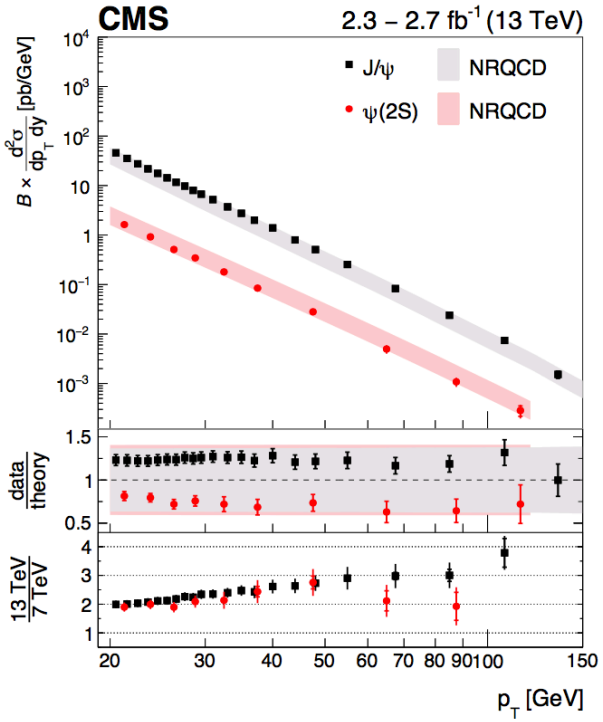
J/ψ and ψ(2S) production at 13 TeV

- Measure the cross sections under the unpolarization scenario, consistent with previous CMS observation
- Full polarization would change the cross sections up to 25%
- The prompt ψ(2S) to J/ψ meson cross section ratio is found to be constant as a function of p_T

PLB 780 (2018) 251

2.3~2.7/fb



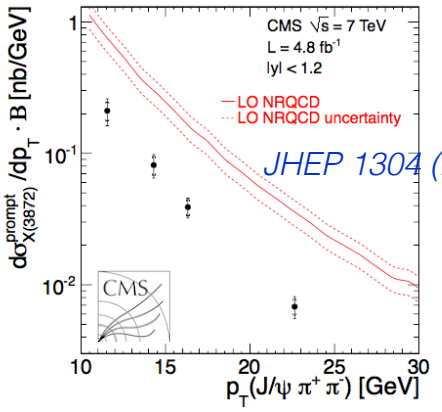


- Theory tends to underestimate (overestimate) the cross section for the J/ψ (ψ(2S)), while staying within 1σ uncertainty.
- The 13 TeV/7 TeV cross section ratios are 1.5~3, changing slowly as a function of dimuon p_T

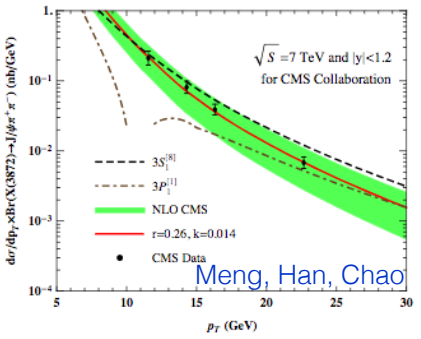
X(3872) production at LHC

- The hidden-charm state X(3872) was discovered by the Belle Collaboration in 2003 [*PRL 91 (2003) 262001*], and subsequently confirmed by CDF, BaBar, and D0.
  ➔ the first observation of an unexpected charmonium state
- LHCb determined its quantum numbers to be 1^{++} [*PRL 110 (2013) 222001*]

- CMS performed a cross-section measurement of promptly produced X(3872) and showed the NRQCD prediction, assuming a $D^0\bar{D}^{*0}$molecule, to be too high
- A later interpretation of X(3872) as a mixed $\chi_{cJ}(2P) - D^0\bar{D}^{*0}$state was adopted in conjunction with the NLO NRQCD model, with the production being dominated by the $\chi_{cJ}(2P)$ component, and showed good agreement with the CMS data [PRD 96 (2017) 074014]



JHEP 1304 (2013) 154



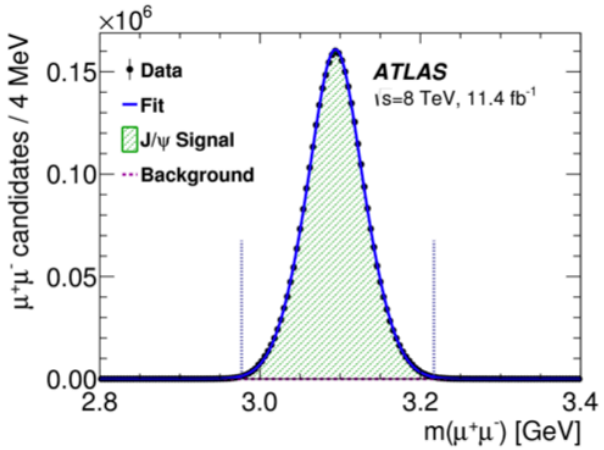
Meng, Han, Chao

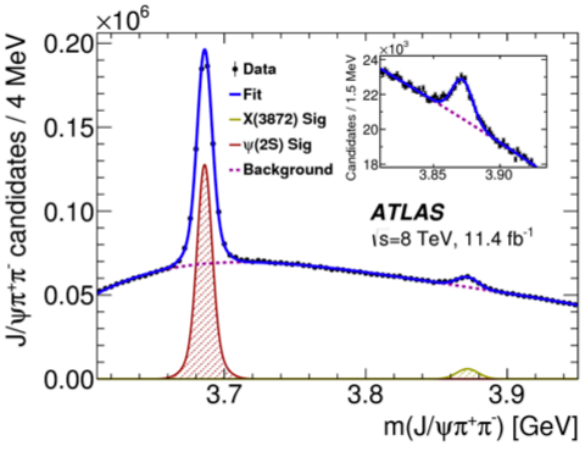
$\psi(2S)$ and X(3872) production at 8TeV

JHEP 1701 (2017) 117

11.4/fb

- ATLAS measures the $\psi(2S)$ and X(3872) production cross section in their decays to $\pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$, as functions of transverse momentum



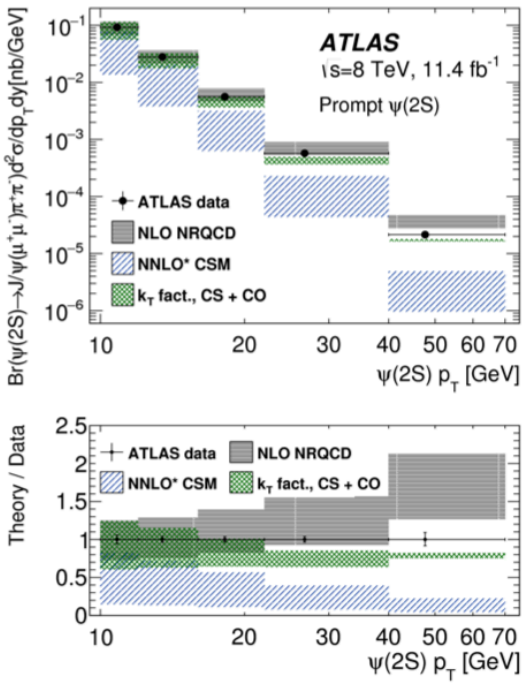


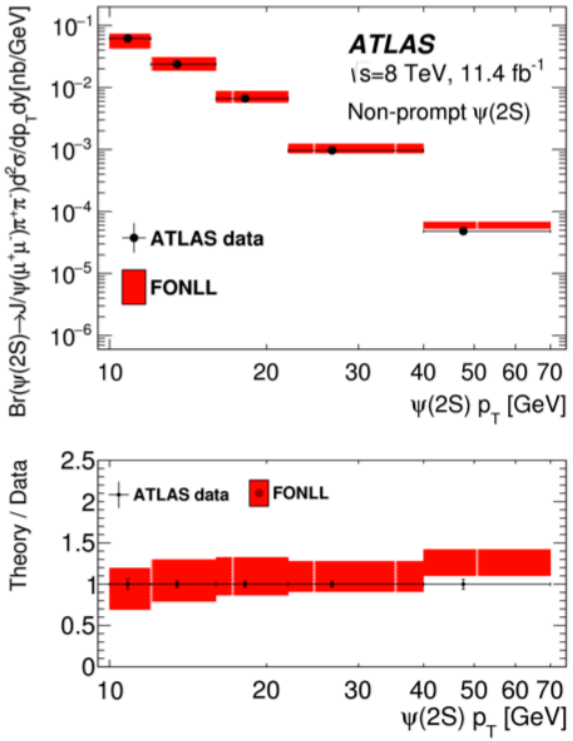
$\psi(2S)$ production cross section at 8TeV

JHEP 1701 (2017) 117

11.4/fb

- Prompt $\psi(2S)$: Predictions made with NLO NRQCD describe the data well with overestimation at high p_T , while CSM significantly underestimates the data at high p_T
- $\psi(2S)$ from b-decays: Predictions made with fixed-order next-to-leading logarithm (FONLL) calculations match the data well over the whole p_T range



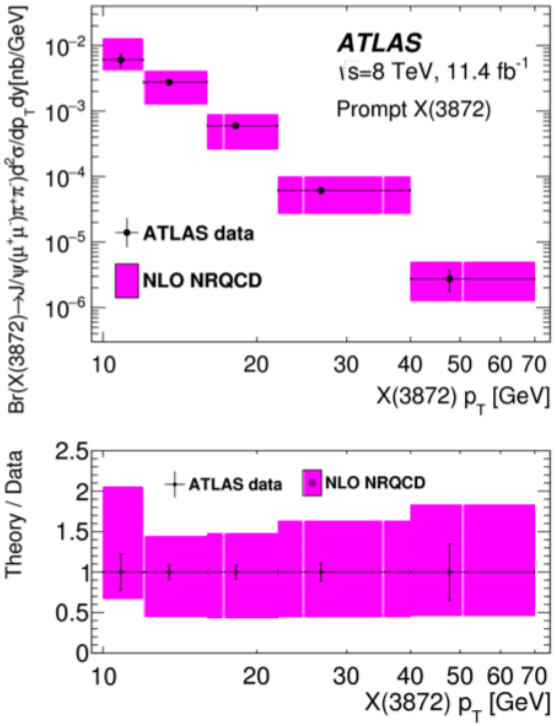


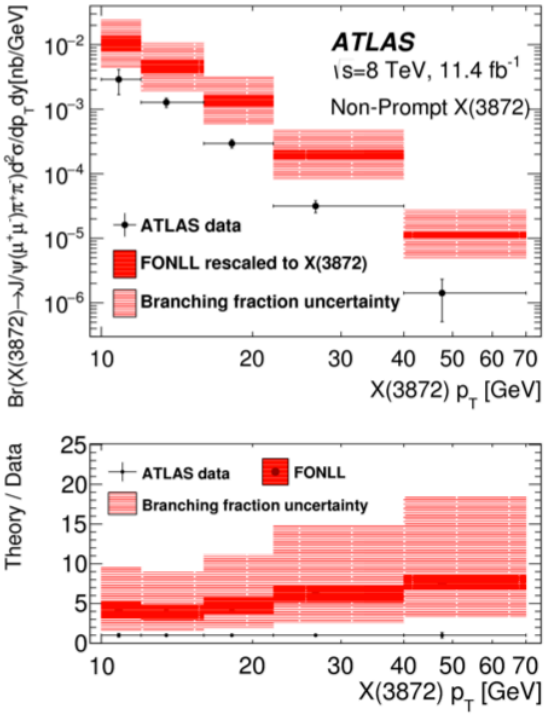
$X(3872)$ production cross section at 8TeV

JHEP 1701 (2017) 117

11.4/fb

- Prompt $X(3872)$: comptiable within theoretical calculations by the prediction of the NLO NRQCD model
- Non-prompt $X(3872)$ from b-decays: the FONLL model overestimates the data by a factor increasing with p_T from~4 to ~8 over the p_T range



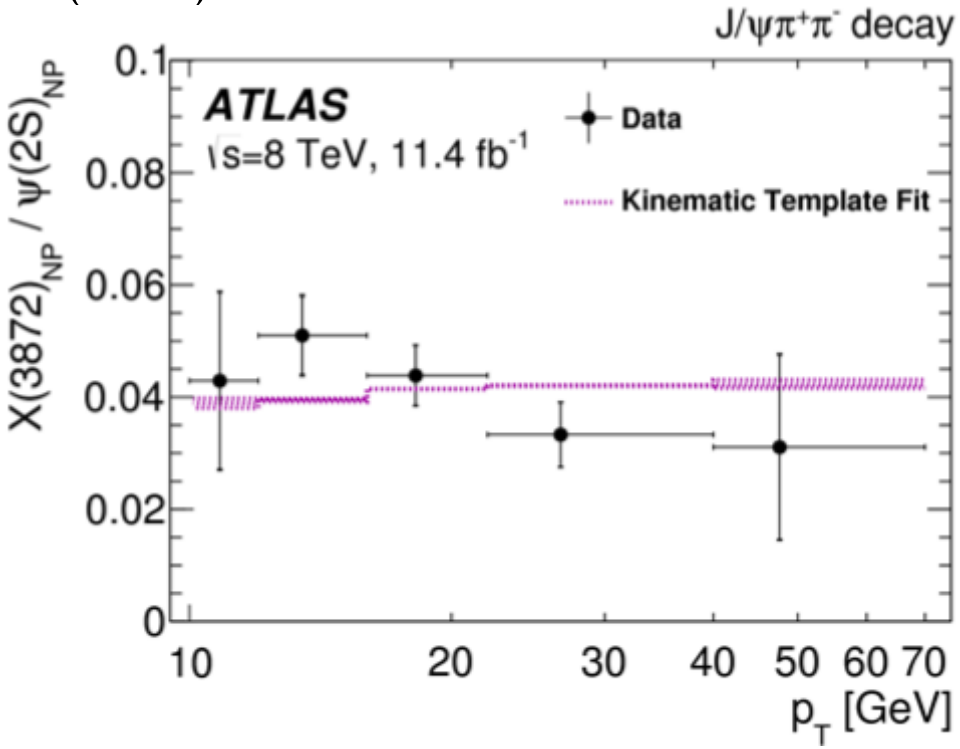


Ratio of $b \to c\bar{c} + X$ decay rates

JHEP 1701 (2017) 117

11.4/fb

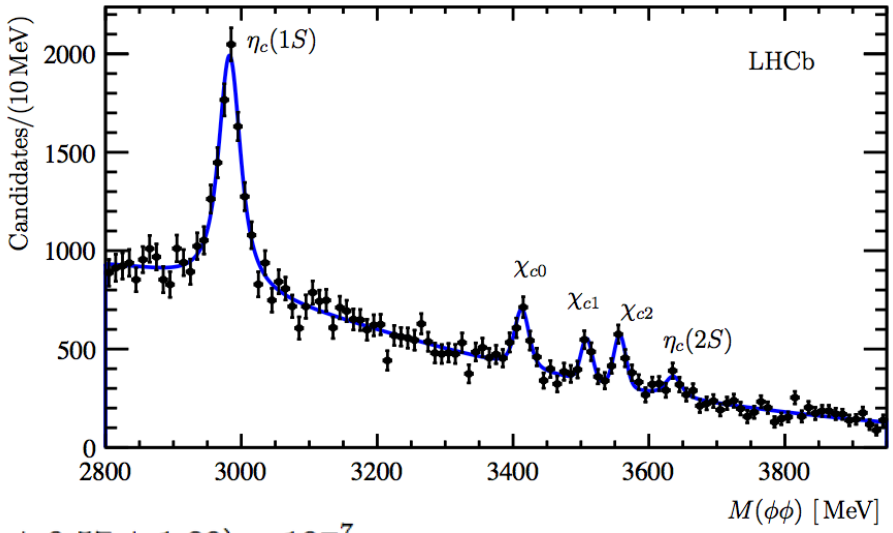
- The measured ratio of non-prompt cross-sections times branching fractions of X(3872) and ψ(2S) is shown
- A ratio of the simulated p_T distributions of non-prompt X(3872) and non-prompt ψ(2S), assuming the same mix of parent *b*-hadrons
- The shape of the template reflects the kinematics of a *b*-hadron decay into ψ(2S) or X(3872)



χ_{cJ} and $\eta_c(2S)$ production in b-decays

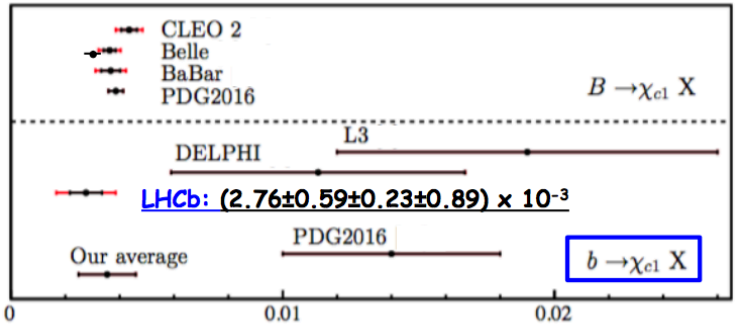
EPJC 77 (2017) 609

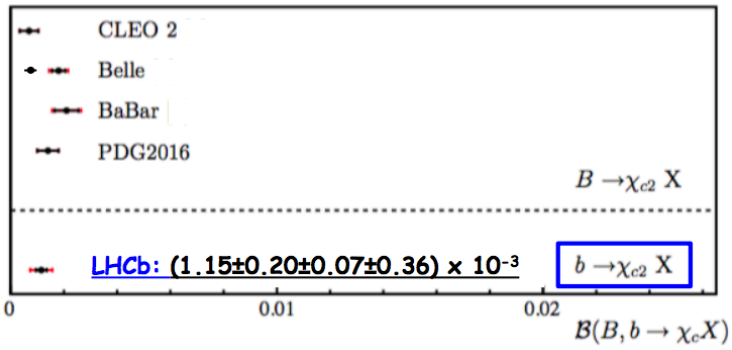
- Charmonium reconstructed via decays to ϕϕ
- Measure the relative production rate to that of the $\eta_c(1S)$ mode
- Results:



$$\mathcal{B}(b \to \chi_{c0} X) = (3.02 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3},$$
$$\mathcal{B}(b \to \chi_{c1} X) = (2.76 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3},$$
$$\mathcal{B}(b \to \chi_{c2} X) = (1.15 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3},$$
$$\mathcal{B}(b \to \eta_c(2S) X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi) = (6.34 \pm 1.81 \pm 0.57 \pm 1.89) \times 10^{-7},$$

- first measurements of χ_{c0} and $\eta_c(2S)$ production in b-hadron decays;
- most precise measurements of χ_{c1} and χ_{c2} production in b-decays



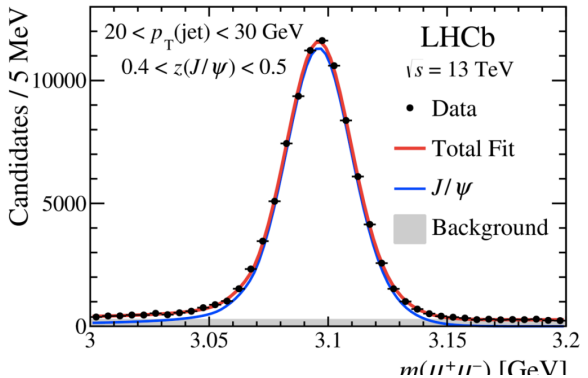


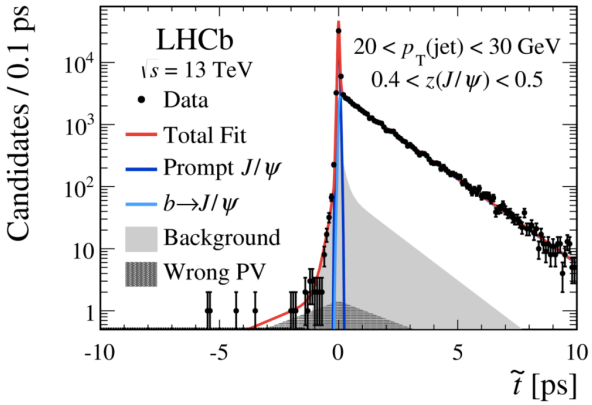
J/ψ production in jets at 13 TeV

PRL 118 (2017) 192001

1.4/fb

- J/ψ produced in direct parton scattering or through parton showering
- Significant J/ψ production in showers can explain lack of observed polarization
- Jet reconstruction by clustering the J/ψ candidate with charged and neutral particle-flow objects with the anti-k_{T} clustering algorithm
- Measure the fraction $z(J/\psi)$ of jet transverse momentum carried by J/ψ:
  - Jets: $p_{\mathrm{T}}(\mathrm{jet}) > 20\ \mathrm{GeV},\ 2.5 < \eta(\mathrm{jet}) < 4$
  - J/ψ: $2.5 < \eta(J/\psi) < 4.5$
- Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution in each bin of $z(J/\psi)$ and p_{T}(jet):

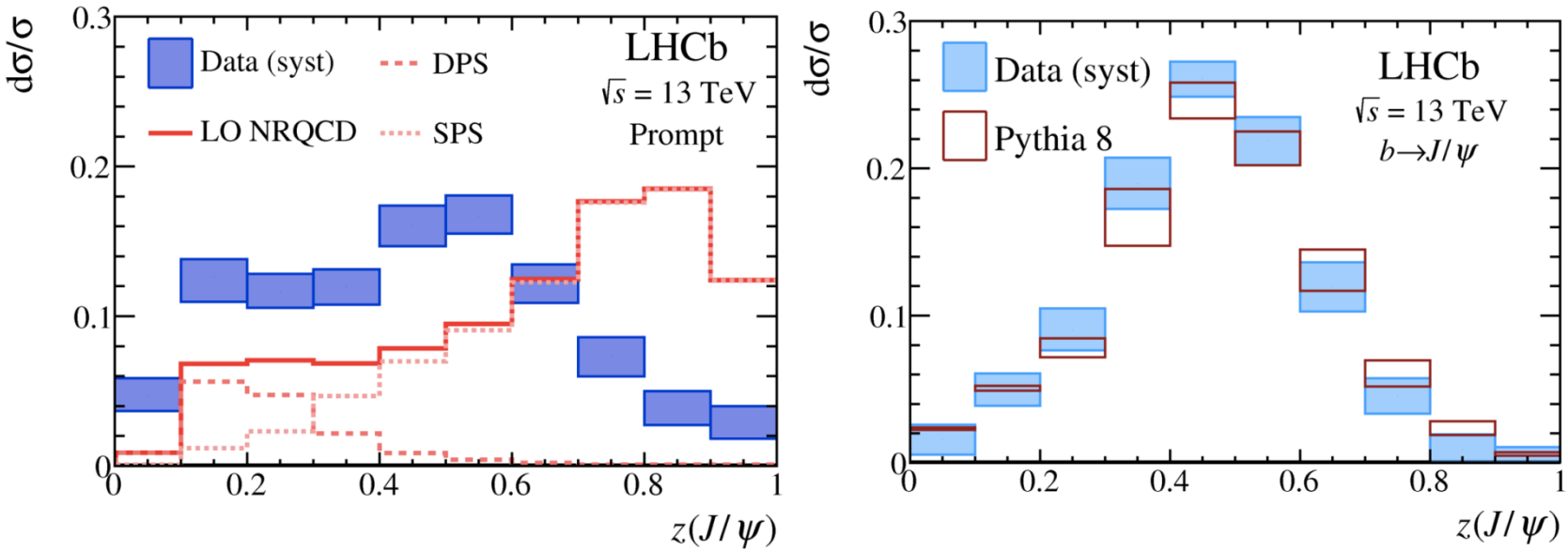




J/ψ production in jets at 13 TeV

PRL 118 (2017) 192001

- The distribution of $z(J/\psi)$, independent for displaced and prompt J/ψ: **1.4/fb**



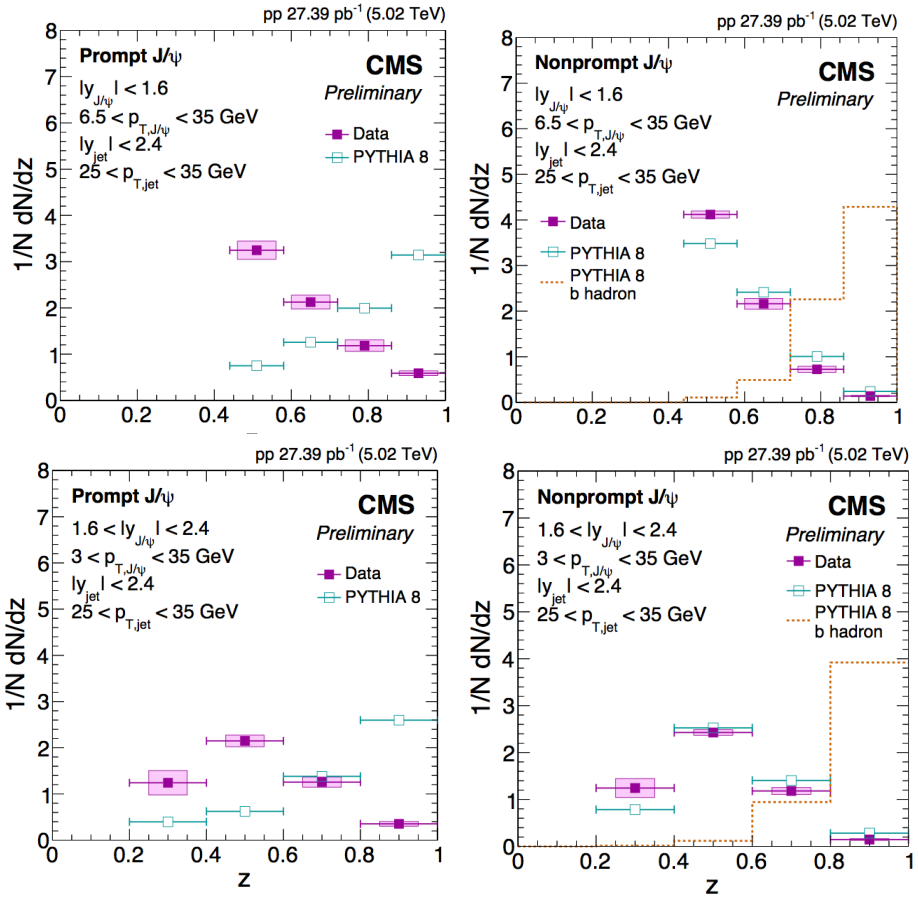
- Prompt $z(J/\psi)$-distribution softer than expected.
- DPS with $\sigma_{\mathrm{eff}} = 31\ \mathrm{mb}$ (PYTHIA default) does not explain the discrepancy.
- Good agreement between data and model for J/ψ from b.

J/ψ production in jets at 5.02 TeV

CMS PAS HIN-18-012

27/pb

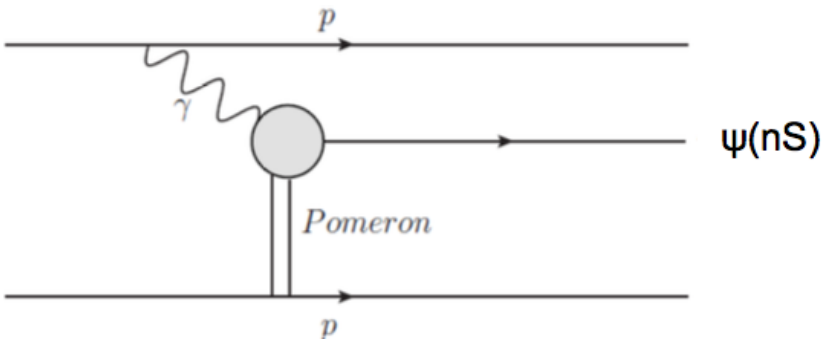
- Similar analysis is performed at CMS, with different kinematic coverage

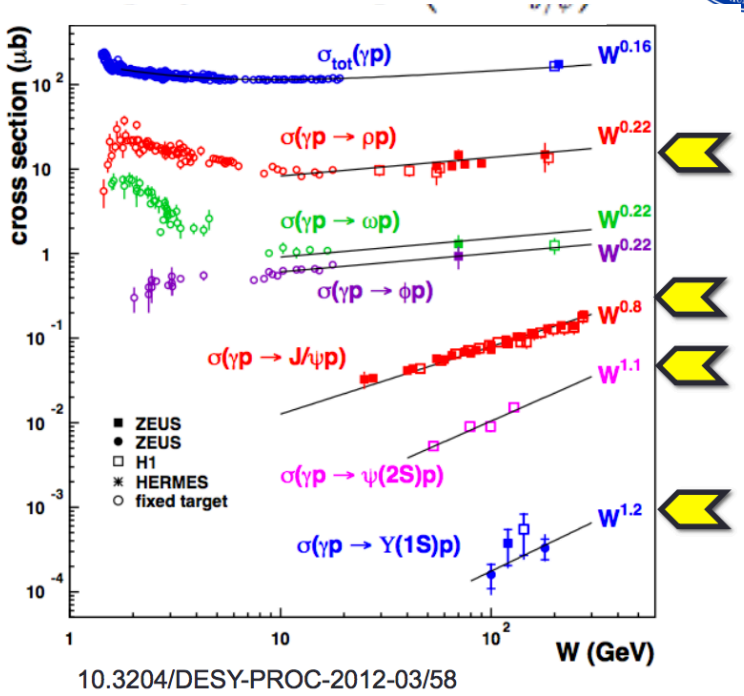


- Confirm the findings of LHCb: non-prompt J/ψ is well modeled by simulation, while the prompt J/ψ production is not.
- Prompt J/ψ in jets tend to carry a smaller fraction of the jet momentum, indicating that they are less isolated than suggested by production models.

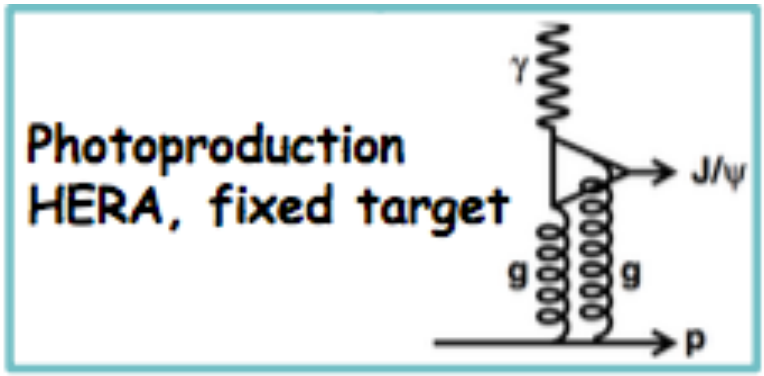
Central Exclusive Production of Charmonia

- Diffractive processes that can be calculated in perturbative quantum chromodynamics (QCD)
- Sensitivity to probing the gluon PDF in the proton
- The LHCb coverage down to the Bjorken variable x~2x10^{-6}





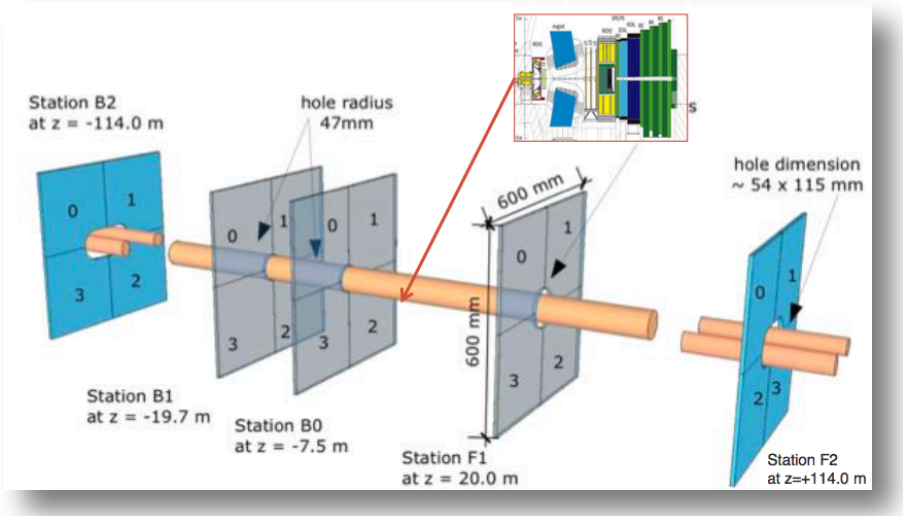
HERA vector meson photo-production results



Central Exclusive Production of J/ψ and ψ(2S) at 13TeV

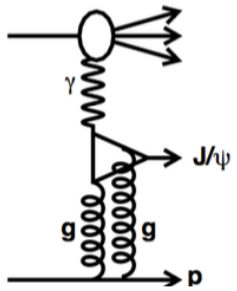
LHCb-CONF-2016-007 & updates

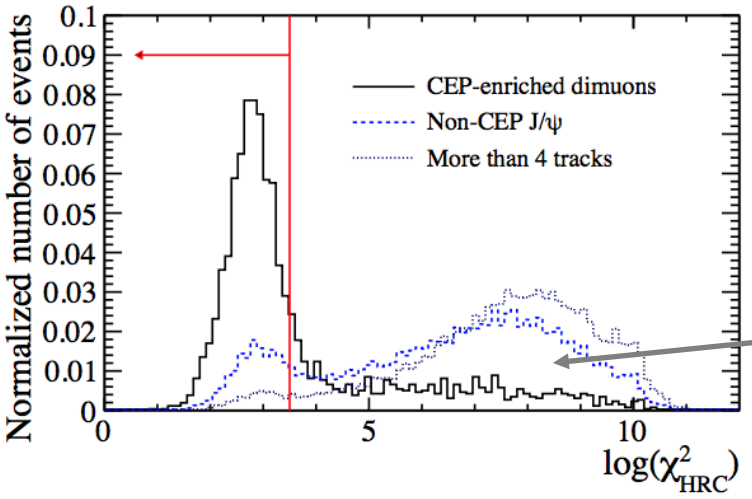
- Dedicated CEP trigger and Herschel veto (high rapidity shower counters) **~0.204/fb**

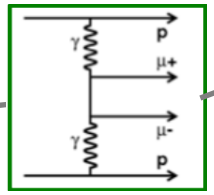


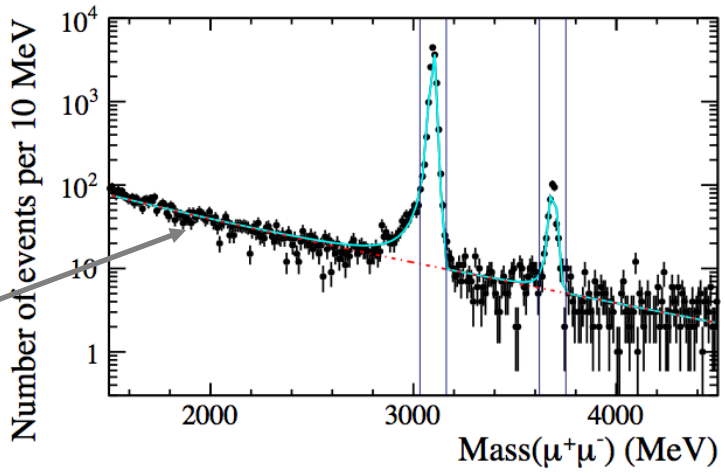
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.

Signal!









Central Exclusive Production of J/ψ and ψ(2S) at 13TeV

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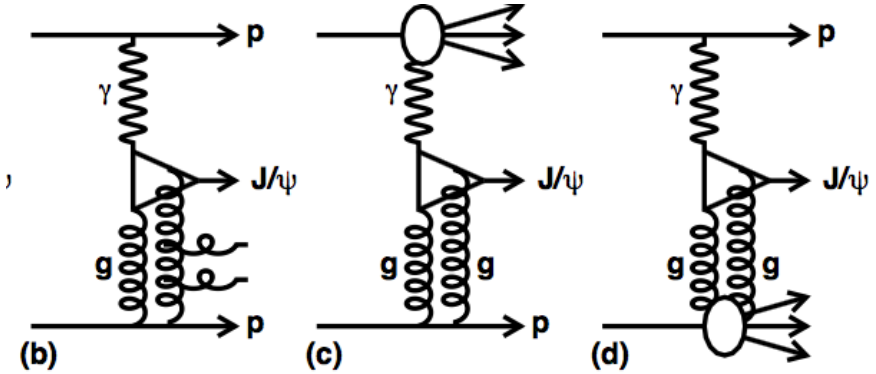
Regge theory: $d\sigma/dt \sim e^{-bP_T^2}$, $b = b_0 + 4\alpha' \log(W/W_0)$ $W^2 = M_{J/\psi} e^y \sqrt{s}$.

b-slope of signal is same with/without Herschel
b-slope of background halved with Herchel
(higher-pT events are vetoed)

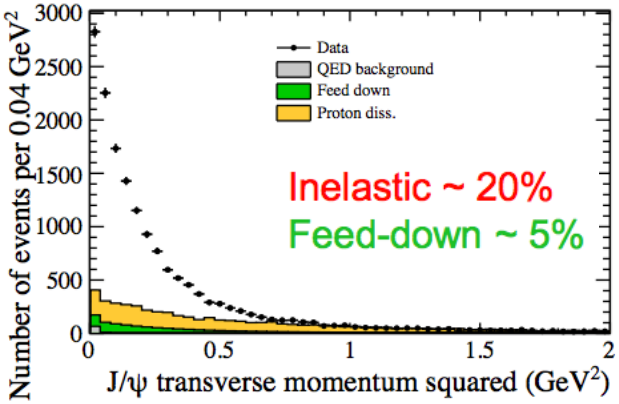
Inelastic backgrounds:

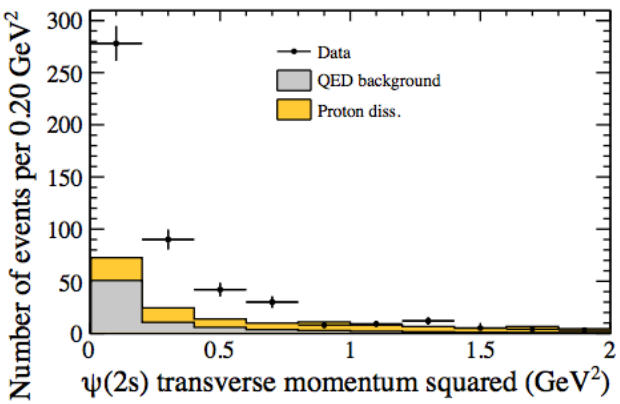
- One/two protons dissociate(s) or additional gluon radiations. Extra particles are undetected.
- P_T shape estimated from data, cross checked with PYTHIA, LPAIR



Feed-down

$\psi(2S) \to J/\psi\pi\pi$: $2.5 \pm 0.2\%$
$\chi_c \to J/\psi\gamma$ $7.6 \pm 0.9\%$
$X(3872) \to \psi(2S)\gamma$ $2.0 \pm 2.0\%$





Central Exclusive Production of J/ψ and ψ(2S) at 13TeV

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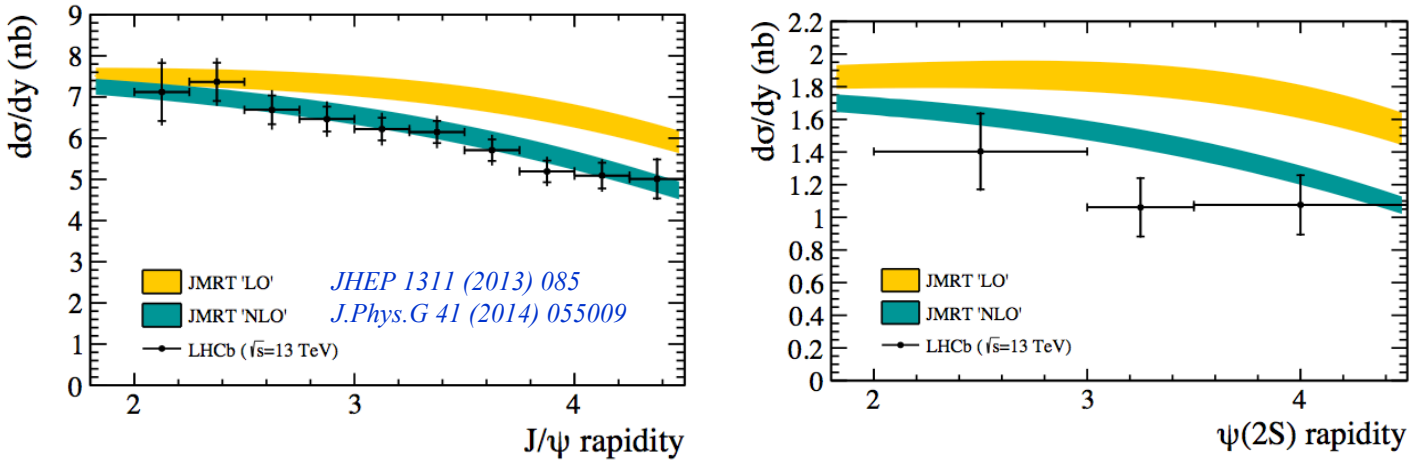
- Differential cross-section compared to theory predictions



- Integrated cross-sections times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta_{\mu^+\mu^-}<4.5) = 399\pm16\pm10\pm16\ \text{pb},$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta_{\mu^+\mu^-}<4.5) = 10.2\pm1.0\pm0.3\pm0.4\ \text{pb}.$$

- **Good agreement with NLO predictions**
- Confirms a hint of NLO importance from the analysis at 7 TeV

Central Exclusive Production of J/ψ and ψ(2S) at 13TeV

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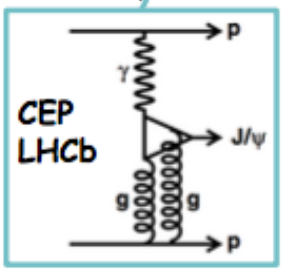
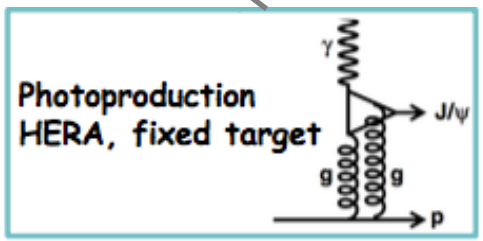
The cross-section for the CEP of vector mesons in pp collisions is related to the photo-production cross-section:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-)$$



Gap survival

Photon flux



$$\text{photon energy } k_\pm \approx (M_{J/\psi}/2)\exp(\pm|y|),$$

HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\text{GeV})^{0.67}\,\text{nb}$

Use this for W- solution (in previously measured region). LHCb measures W+

Central Exclusive Production of J/ψ and ψ(2S) at 13TeV

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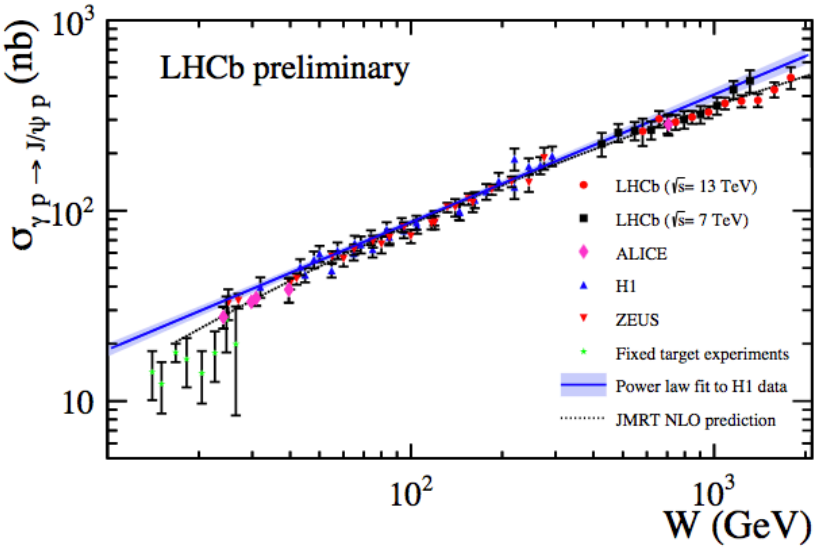

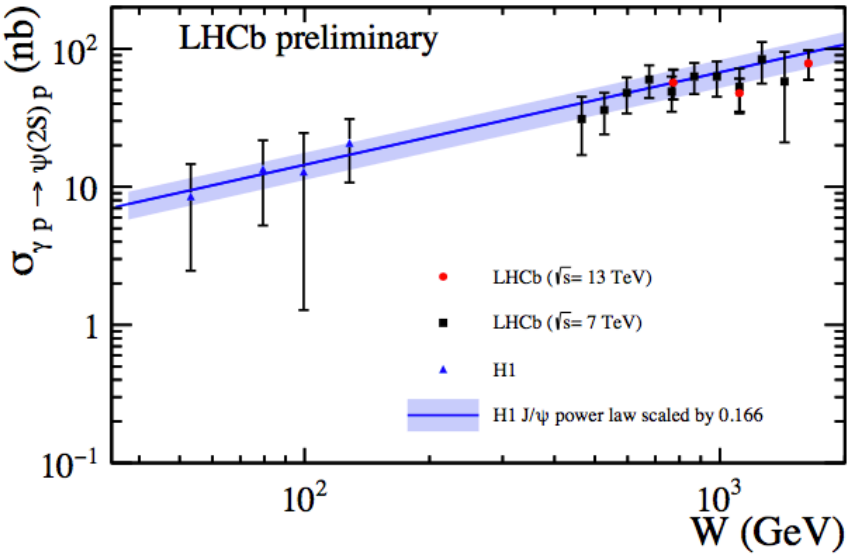

- Good agreement between LHCb results at 7 and 13 TeV
- J/ψ photo-production cross-section: deviation from a pure power-law extrapolation of HERA data;
- Agreement to theory prediction

Summary

- LHC has produced rich results of charmonium production
- We make better understanding of QCD and its effective models: FONLL describes b-hadron production reasonably well, while prompt charmonia still puzzle
- More analyses with data collected in Run-II in the pipe: bigger datasets, better sensitivities
- New complementary probes from associated production, production in jets, CEP, polarizations...
- Stay tuned for more results

Thanks for your attention!