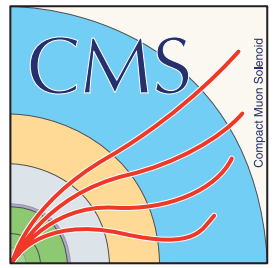
Associated Production of Quarkonium Pairs at LHC

Yajing Wei (Peking University)

On behalf of ALICE, ATLAS, CMS and LHCb collaborations

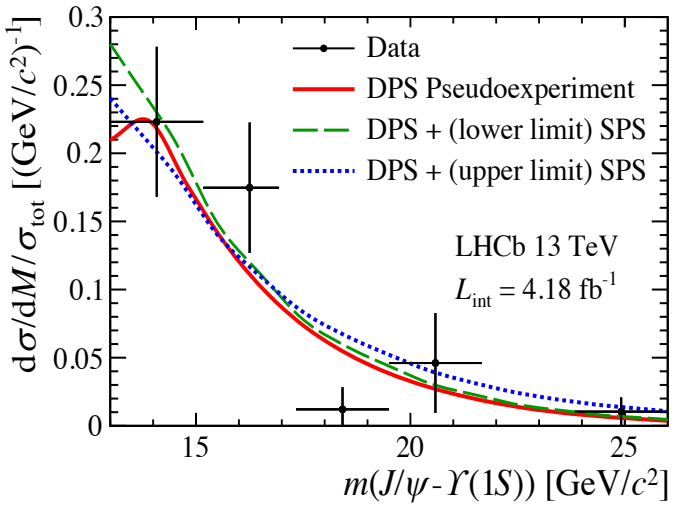
LHCP 2023, 25th May 2023



Outline

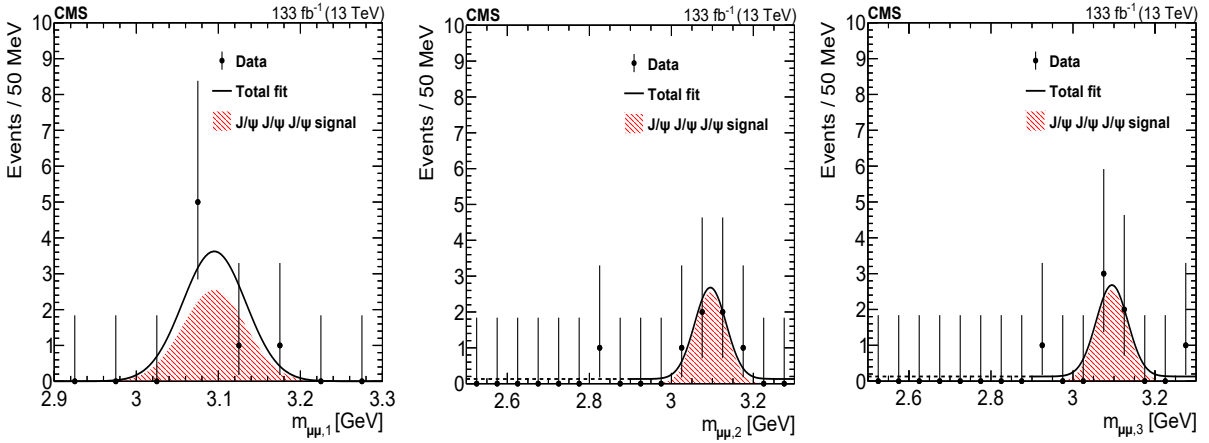
J/ψ and Υ @13 TeV

LHCb-PAPER-2022-047



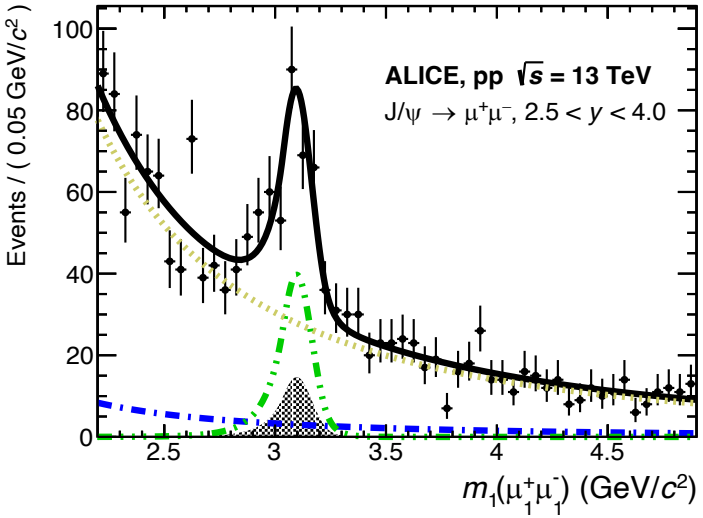
Triple J/ψ @13 TeV

Nat. Phys. 19 (2023) 338



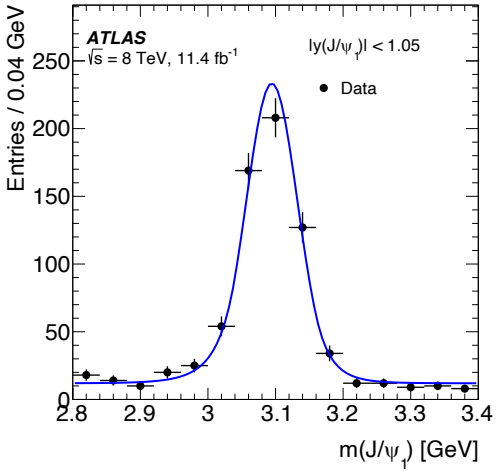
J/ψ pair @13 TeV

arXiv:2303.13431



J/ψ pair @8 TeV

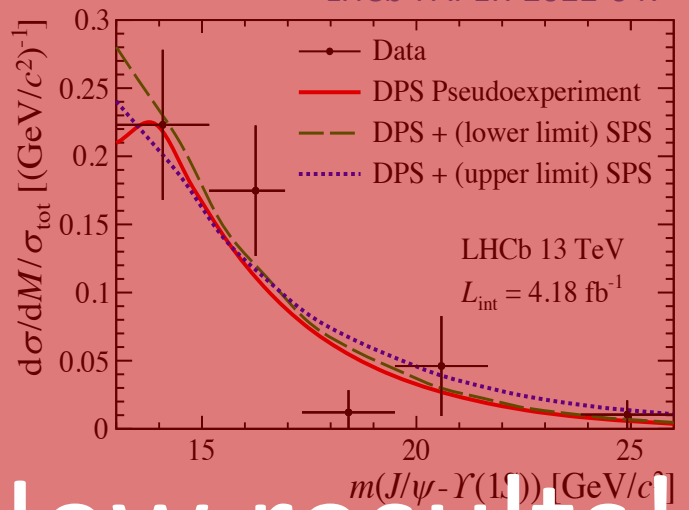
Eur. Phys. J. C77 (2017) 76



Outline

J/ψ and Υ @13 TeV

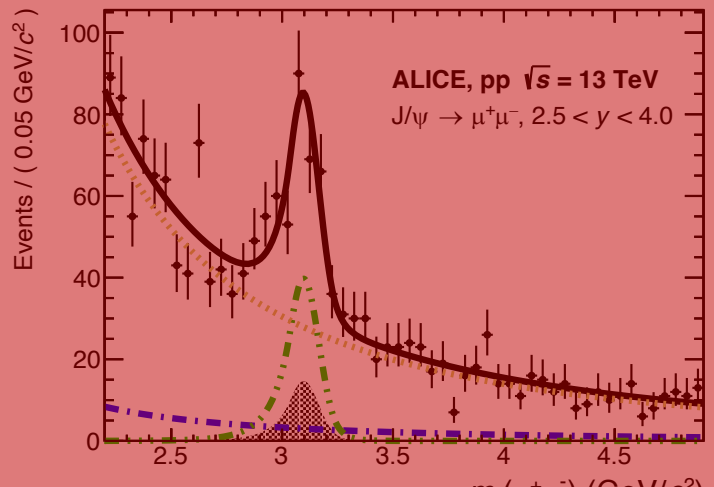
LHCb-PAPER-2022-047



New results!

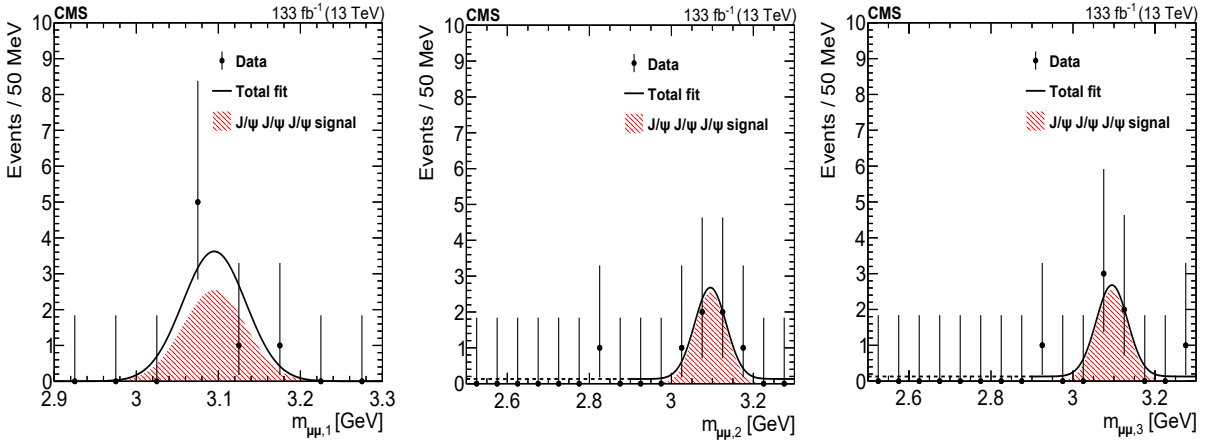
J/ψ pair @13 TeV

arXiv:2303.13431



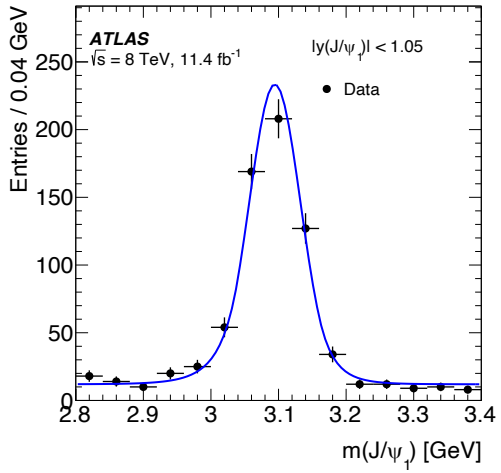
Triple J/ψ @13 TeV

Nat. Phys. 19 (2023) 338

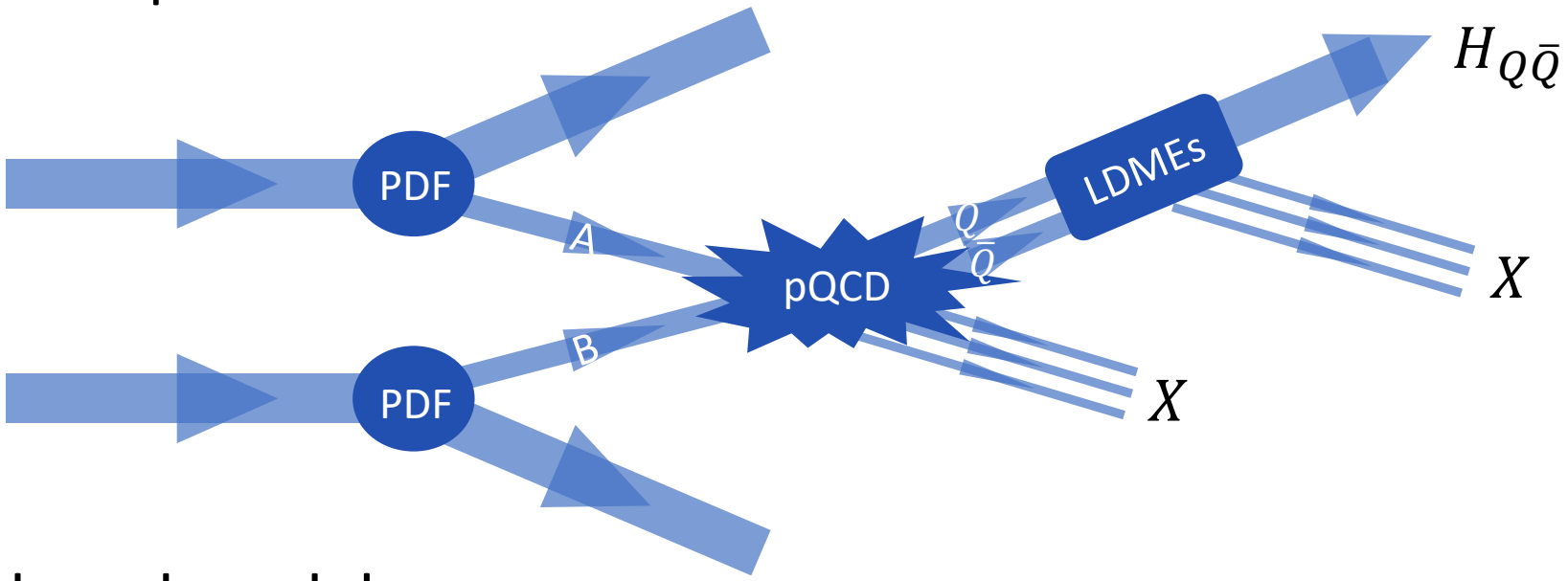


J/ψ pair @8 TeV

Eur. Phys. J. C77 (2017) 76



Quarkonium production

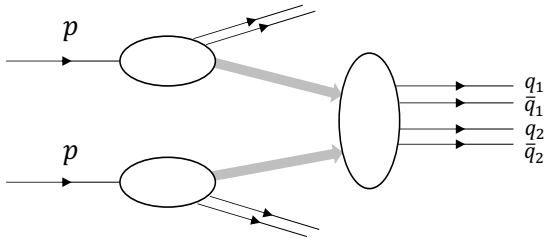


- Well developed models
  - Color singlet model (CSM)
    - ✕ Difficult to predict production cross-sections at high energies
  - Non-relavitistic QCD (NRQCD)
    - ✕ (Lack of) universality of LDMEs (*eg.* inconsistent between η_c and J/ψ)
    - ✕ Cannot describe polarisations and production cross-sections at the same time
- Experimental inputs are needed to test or help constrain models

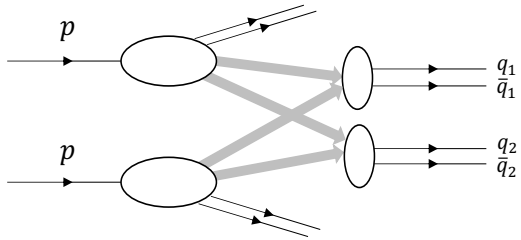
Prog. Part. Nucl. Phys. 122 (2022) 103906

Quarkonium pair production

Single Parton Scattering (SPS)



Double Parton Scattering (DPS)



- SPS: test the production models
- DPS: provide information on parton transverse profile and parton correlations in hadrons

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int d\,x_1 d\,x_2 dx_1' dx_2' d^2b_1 d^2b_2 d^2b$$

SPS parton-level cross-section

$$\times \Gamma_{ij}(x_1, x_2, b_1, b_2) \times \hat{\sigma}_{ik}{}^{Q_1}(x_1, x_1') \hat{\sigma}_{jl}{}^{Q_2}(x_2, x_2') \times \Gamma_{kl}(x_1', x_2', b_1 - b, b_2 - b)$$

Generalised double parton pdf

- Assumptions:
  - transverse and longitudinal components are factorisable $\Gamma_{ij}(x_1, x_2, b_1, b_2) = D_{ij}(x_1, x_2) T_{ij}(b_1, b_2)$
  - no correlations between the two partons $D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), \quad T_{ij}(b_1, b_2) = T_i(b_1) T_j(b_2)$

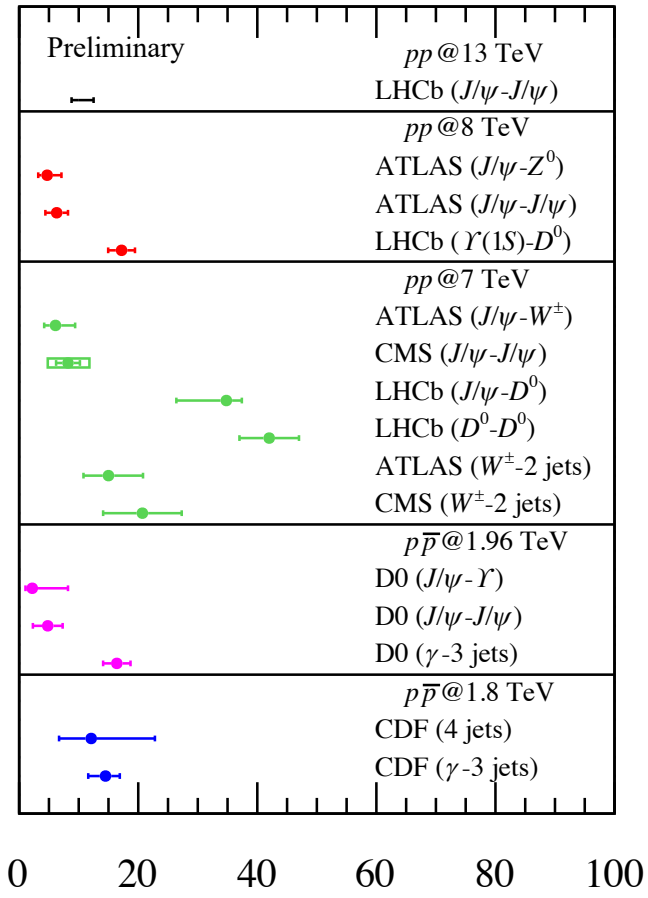
Phys. Rev. D57 (1998) 503

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$

Quarkonium pair production

- J/ψ- J/ψ
  - NA3: π^- interations Phys. Lett. B114 (1982) 457
  - D0: $p\bar{p}$@1.96 TeV Phys. Rev. D90 (2014) 111101
  - CMS : pp@7 TeV JHEP 09 (2014) 094
  - ATLAS : pp@8 TeV Eur. Phys. J. C77 (2017) 76
  - LHCb : pp@13 TeV JHEP 06 (2017) 047
- J/ψ - Υ
  - D0: $p\bar{p}$@1.96 TeV Phys. Rev. Lett. 116 (2016) 082002
- Υ - Υ
  - CMS : pp@8 TeV JHEP 05 (2017) 013

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$

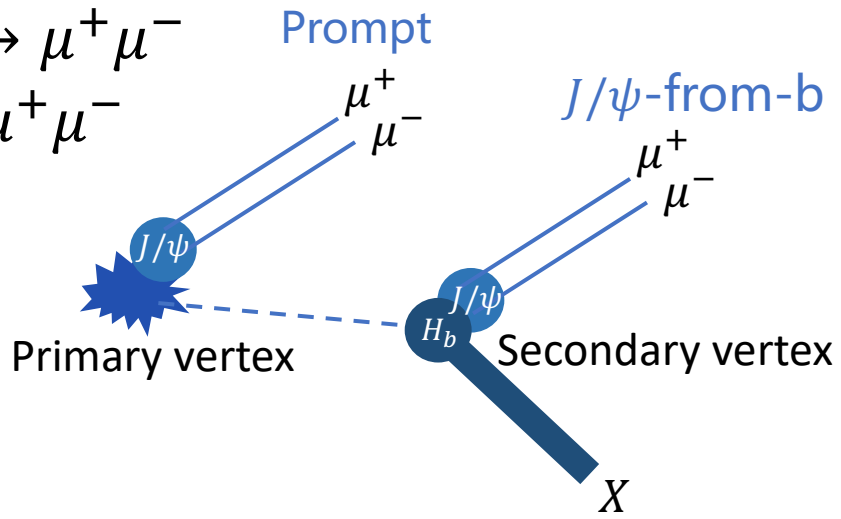


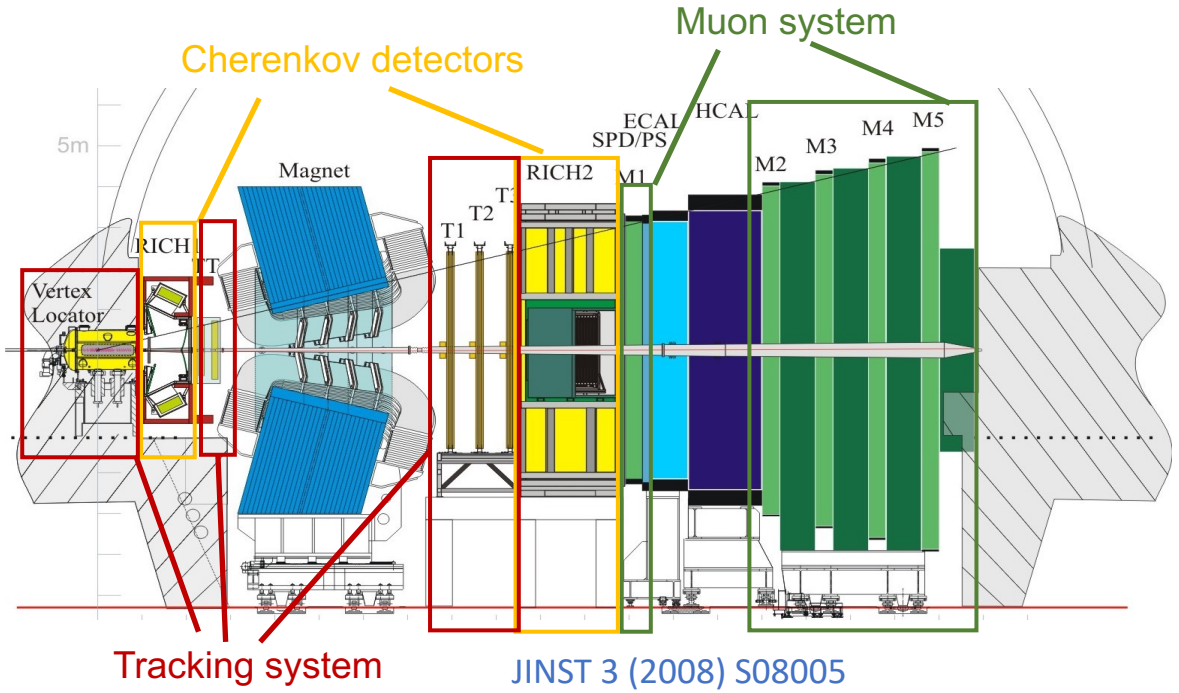
LHCb-PAPER-2022-047

Detailed reference for σ_{eff} is in backup slides

J/ψ - Υ production at $\sqrt{s} = 13$ TeV LHCb-PAPER-2022-047

- Analysis based on subset of Run 2 data ($\mathcal{L} = 4.18\ \text{fb}^{-1}$)
- Prompt production in region:
  - $2 < y < 4.5$
  - $0 < p_{\text{T}}(J/\psi) < 10$ GeV
  - $0 < p_{\text{T}}\ (\Upsilon) < 30$ GeV
- Channels:
  - $J/\psi \to \mu^+\mu^-$
  - $\Upsilon \to \mu^+\mu^-$



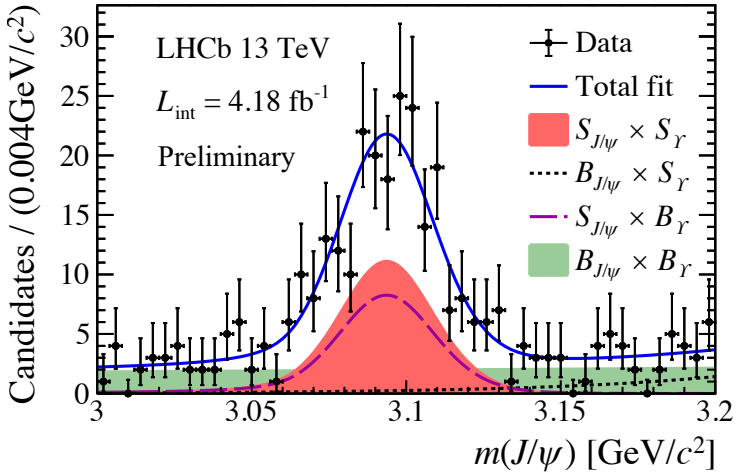


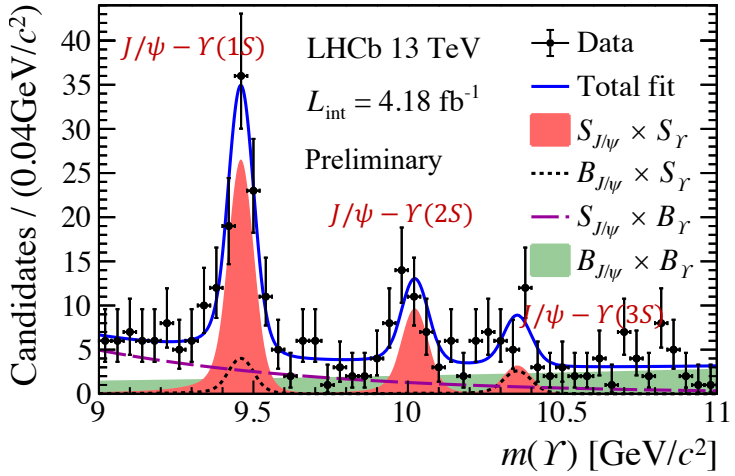
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

J/ψ - Υ production cross-section determination

- $\sigma(J/\psi - \Upsilon) = \dfrac{N}{\mathcal{L} \times \epsilon_{tot} \times \mathcal{B}_{J/\psi \to \mu^+\mu^-} \times \mathcal{B}_{\Upsilon \to \mu^+\mu^-}}$
  - N : signal yield, extracted from J/ψ - Υ 2D invariant mass distribution
  - $\mathcal{L}$: integrated luminosity
  - ϵ_{tot} : detection efficiency, estimated using simulation
  - $\mathcal{B}$: branching fractions

Channel	Significance
J/ψ-$\Upsilon(1S)$	7.9 σ
J/ψ-$\Upsilon(2S)$	4.9 σ





- Signal: Gaussian kernel with power tails
- Background: exponential

LHCb-PAPER-2022-047

J/ψ - Υ production results

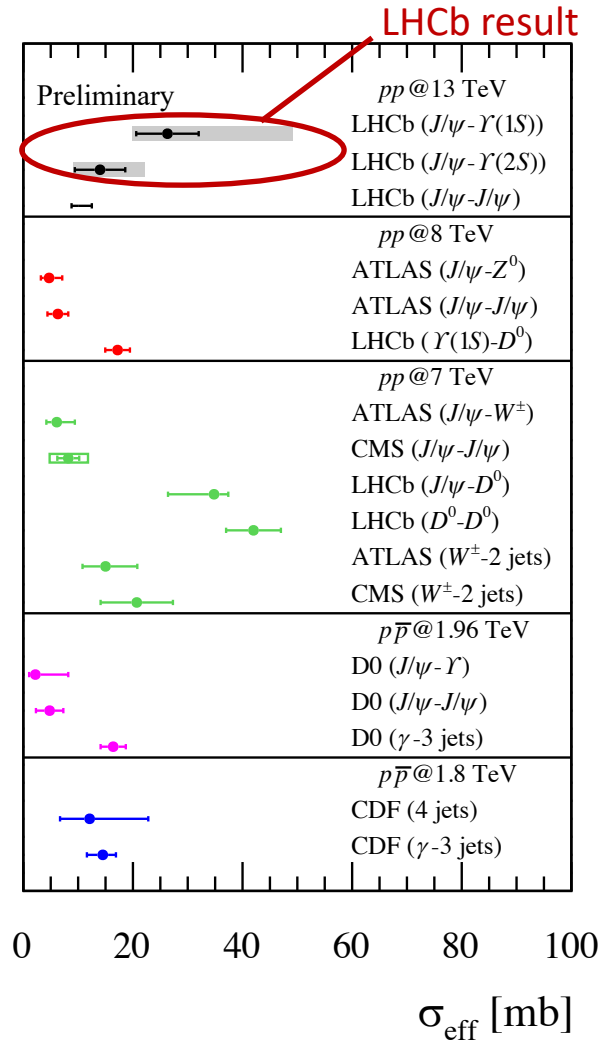
- Cross-sections
  - $\sigma(J/\psi - \Upsilon(1S)) = 133 \pm 22(\text{stat.}) \pm 7(\text{syst.}) \pm 3(\mathcal{B})$ pb
  - $\sigma(J/\psi - \Upsilon(2S)) = 76 \pm 21(\text{stat.}) \pm 4(\text{syst.}) \pm 7(\mathcal{B})$ pb

- $\sigma_{\text{eff}}(J/\psi - \Upsilon) \equiv \frac{\sigma(J/\psi)\times\sigma(\Upsilon)}{\sigma_{\text{DPS}}(J/\psi-\Upsilon)}$
  - σ_{DPS} is estimated by subtracting SPS contribution
    - $\sigma_{\text{sps}}(J/\psi - \Upsilon(1S)) = 20^{+52}_{-15}$ pb
    - $\sigma_{\text{sps}}(J/\psi - \Upsilon(2S)) = 8^{+22}_{-6}$ pb

    Phys. Rev. Lett. 117 (2016) 062001

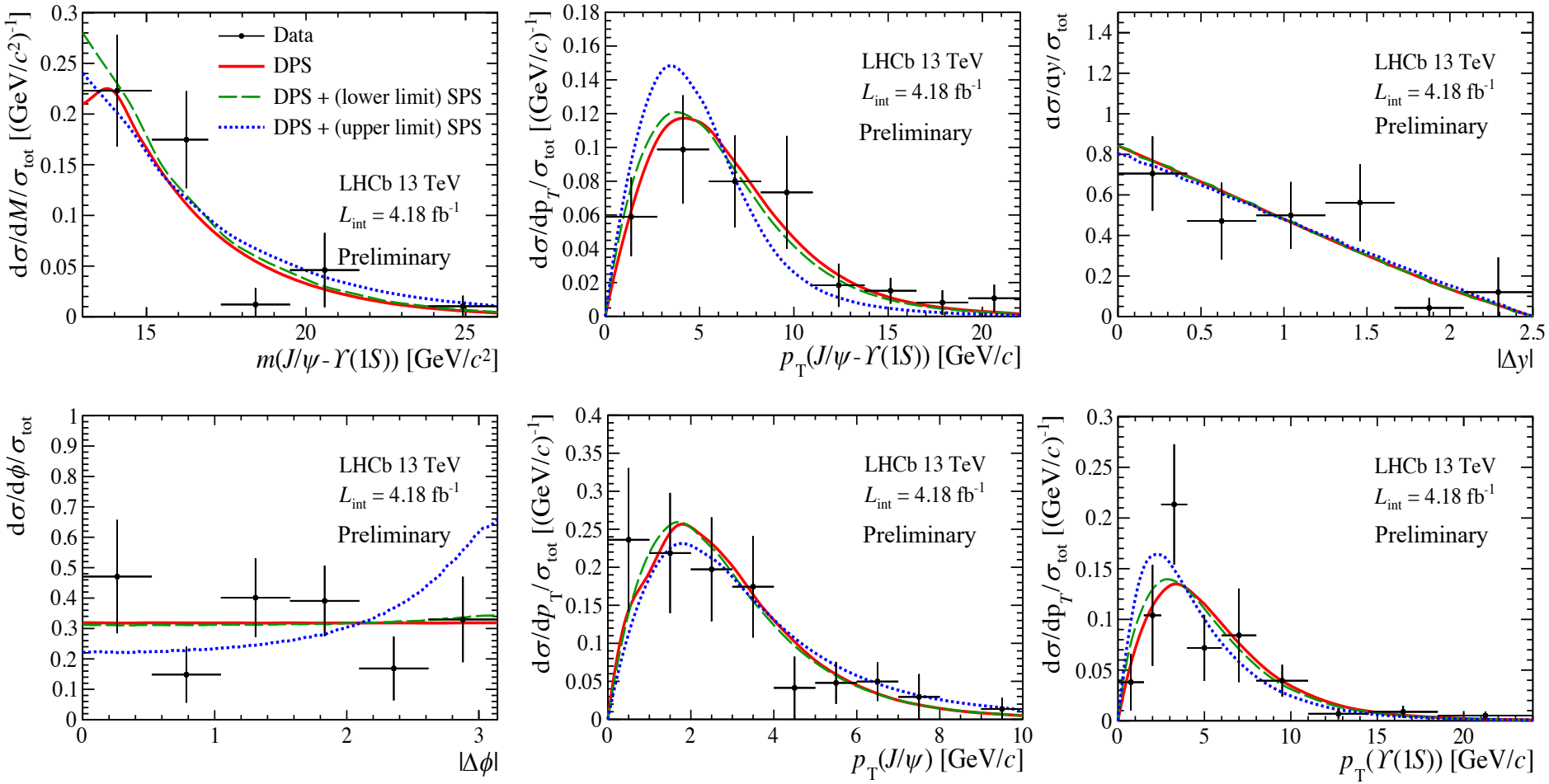
  - $\sigma_{\text{eff}}(J/\psi - \Upsilon(1S)) = 26 \pm 5(\text{stat.}) \pm 2(\text{syst.}) \,^{+22}_{-3}(\text{th.})$ mb
  - $\sigma_{\text{eff}}(J/\psi - \Upsilon(2S)) = 14 \pm 5(\text{stat.}) \pm 1(\text{syst.}) \,^{+7}_{-1}(\text{th.})$ mb

- σ_{eff} result consistent with previous measurements



LHCb-PAPER-2022-047

Kinematic distributions



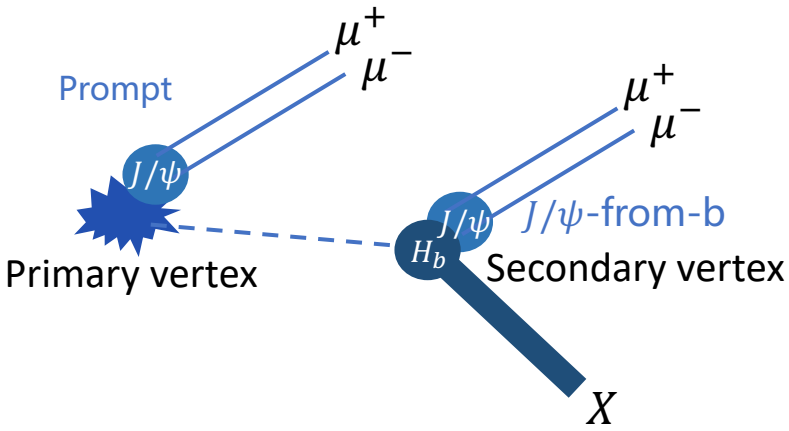
LHCb-PAPER-2022-047

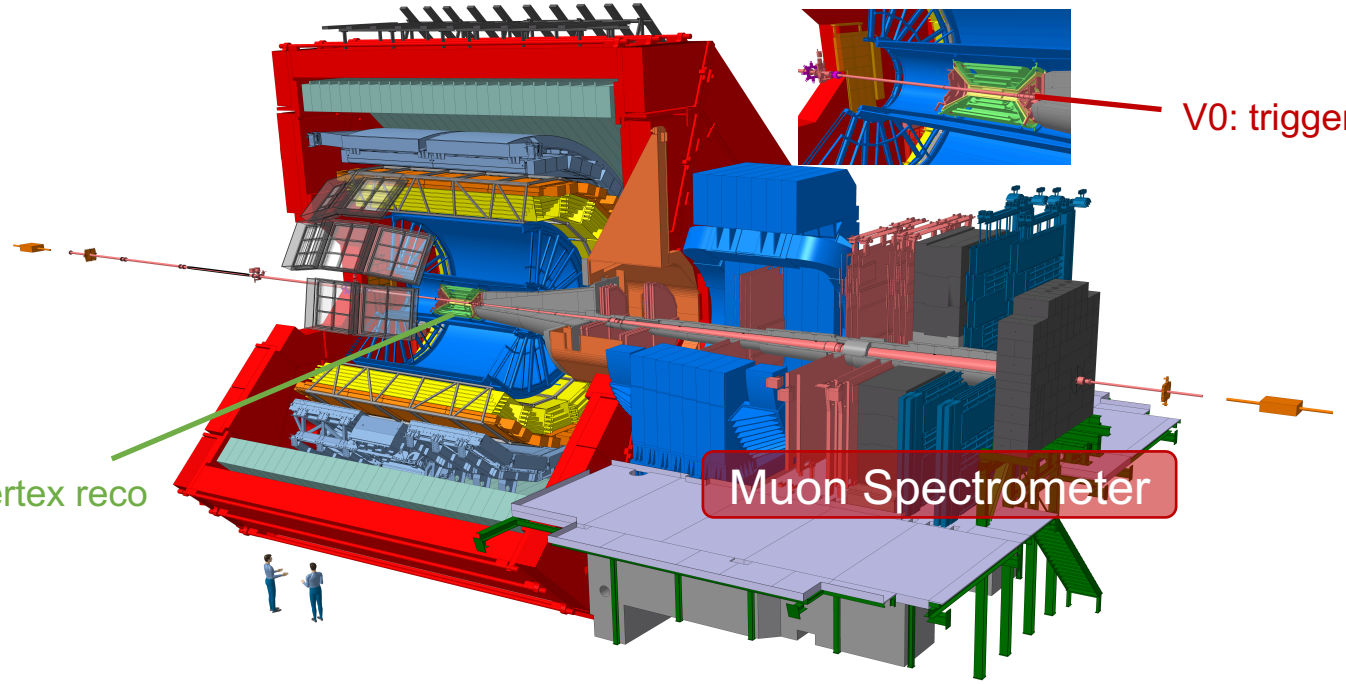
Consistent with both scenarios (DPS only, and DPS + the predicted SPS contributions)

Inclusive J/ψ pair production at $\sqrt{s} = 13$ TeV

arXiv:2303.13431

- pp collision data with $\mathcal{L} = 24.11\ \mathrm{pb}^{-1}$
- Fiducial range
  - $2.5 < y < 4.0,\ p_{\mathrm{T}} > 0$
- Channel: $J/\psi \to \mu^+\mu^-$



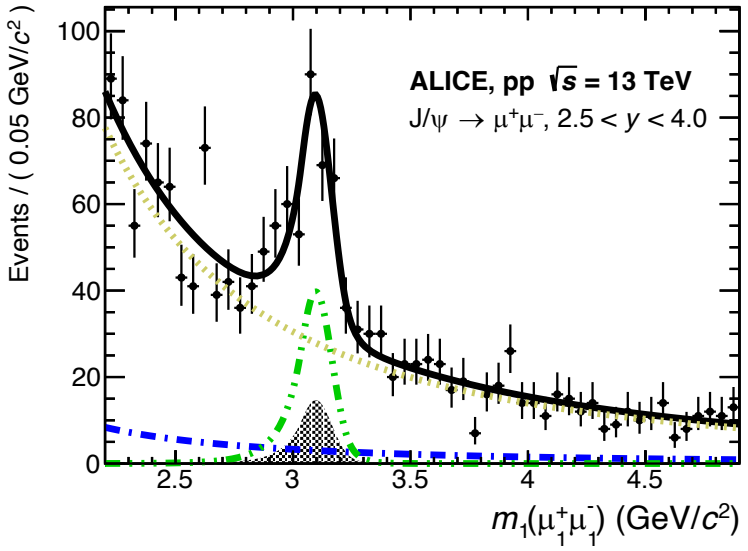


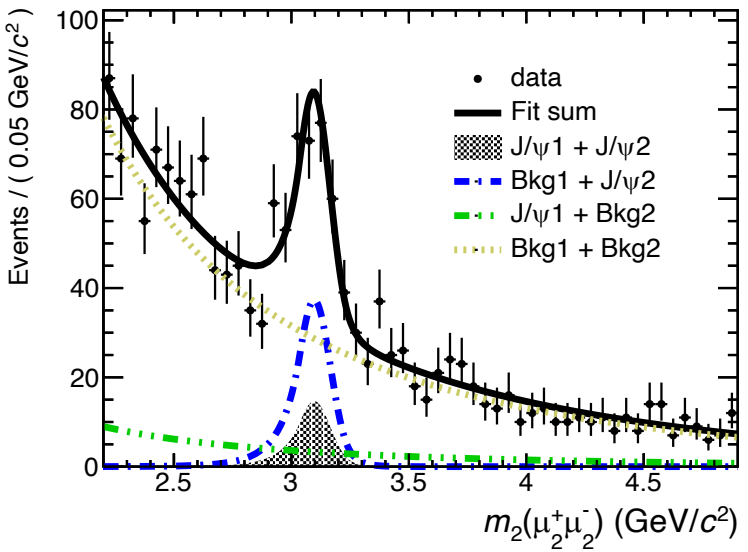
JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

Inclusive J/ψ pair production

$$\sigma(J/\psi - J/\psi) = \frac{N}{\mathcal{L} \times \epsilon_{\mathrm{tot}} \times \mathcal{B}^2_{J/\psi \to \mu^+\mu^-}}$$

- Signal extracted from 2D invariant-mass fit
  - Signal model: Gaussian kernel with power law tails
  - Background:
    - sum of two exponentials
    - exponential of a second order polynomial
    - ratio of a first-order to a second-order polynomials





arXiv:2303.13431

ALICE: results

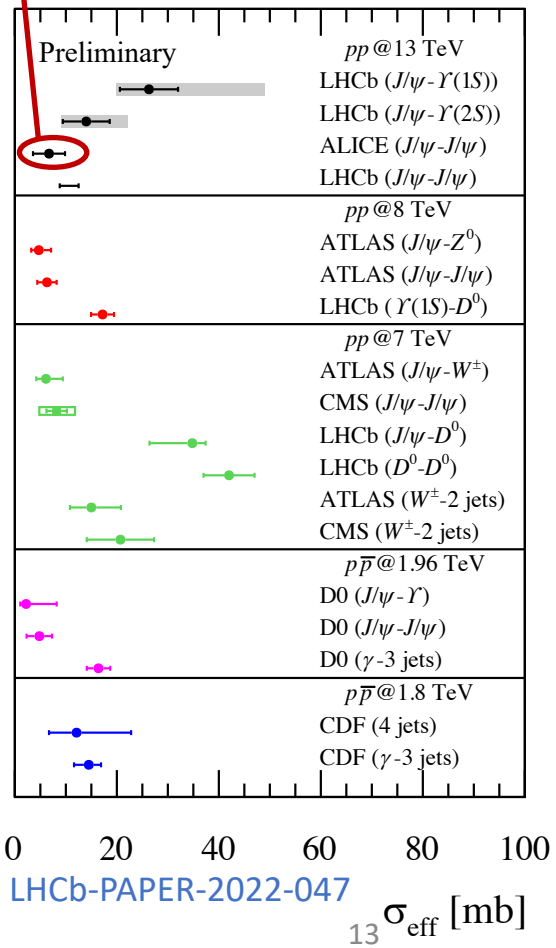
$$\sigma_{\text{non-prompt}}(J/\psi - J/\psi) = \sigma_{b\bar{b}}^{\text{total}} \times \alpha \times B^2(H_b \to J/\psi + X)$$

Acceptance correction factor

- $\sigma(J/\psi - J/\psi) = 10.3 \pm 2.3(\text{stat.}) \pm 1.3(\text{syst.})$ nb
- Prompt cross-section is measured by subtracting non-prompt cross-section from inclusive cross-section
  - $\sigma_{\text{prompt}}(J/\psi - J/\psi) = 7.3 \pm 1.7(\text{stat.})^{+1.9}_{-2.1}(\text{syst.})$ nb
- Assuming only the DPS process contributes: gives lower limit
  - $\sigma_{\text{eff}}(J/\psi - J/\psi) = \frac{1}{2}\frac{\sigma_{\text{prompt}}(J/\psi)^2}{\sigma_{\text{prompt}}(J/\psi - J/\psi)} = 6.7 \pm 1.6(\text{stat.}) \pm 2.7(\text{syst.})$ mb
- Consistent with LHCb $J/\psi - J/\psi$ result measured in slightly different region ($2 < y < 4.5$, $0 < p_{\text{T}} < 10$ GeV)

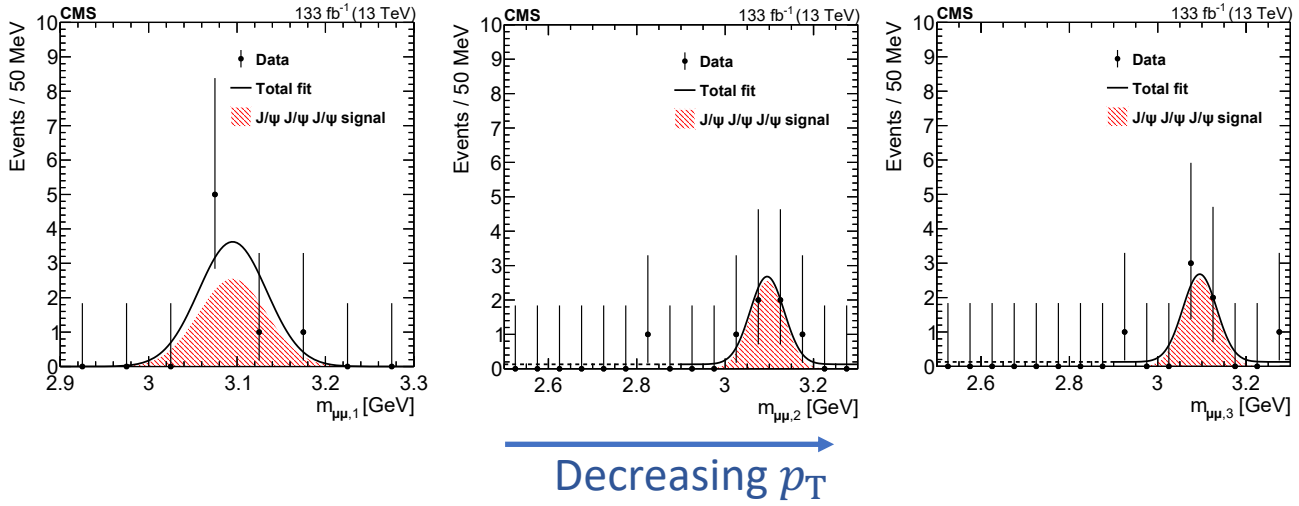
JHEP 06 (2017) 047

ALICE result



LHCb-PAPER-2022-047

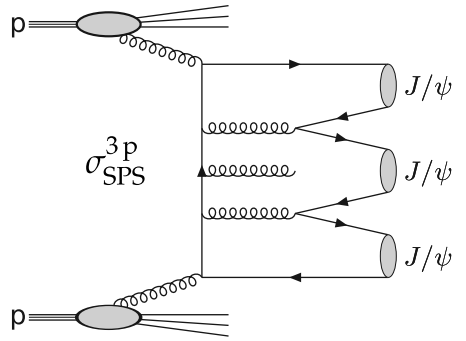
CMS triple J/ψ result



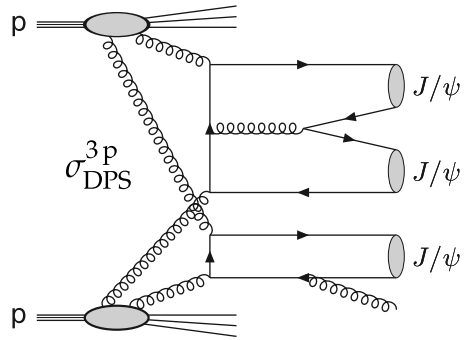
- Inclusive fiducial cross-section
  - $\sigma(pp \to J/\psi J/\psi J/\psi + X) = 272^{+141}_{-104}\ (\text{stat.}) \pm 17\ (\text{syst.})\ \text{fb}$
- Effective DPS cross-section
  - $\sigma_{\text{eff,DPS}} = 2.7\ ^{+1.4}_{-1.0}\ (\text{exp.})\ ^{+1.5}_{-1.0}\ (\text{th.})\ \text{mb}$
- Triple J/ψ production observed
- Dominated by double and triple parton scattering

Pure prompt production:

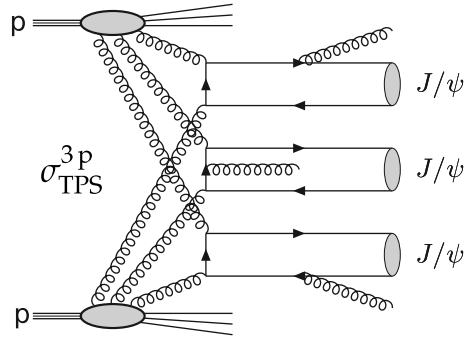
SPS:



DPS:



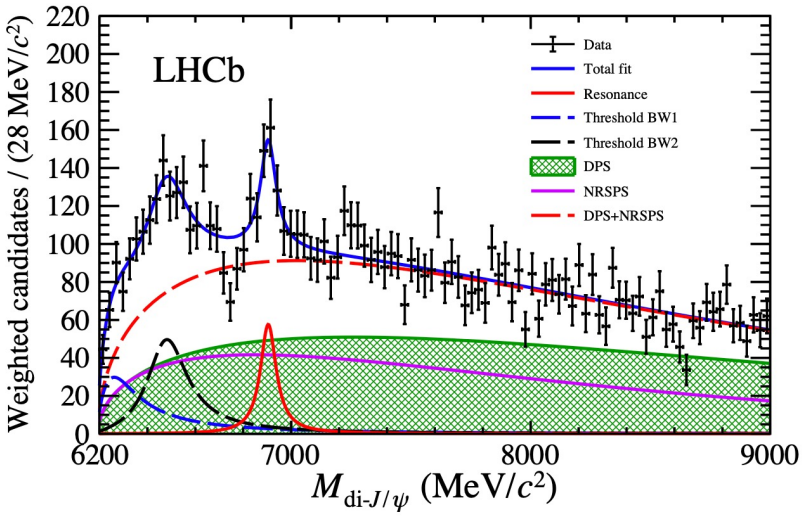
TPS:



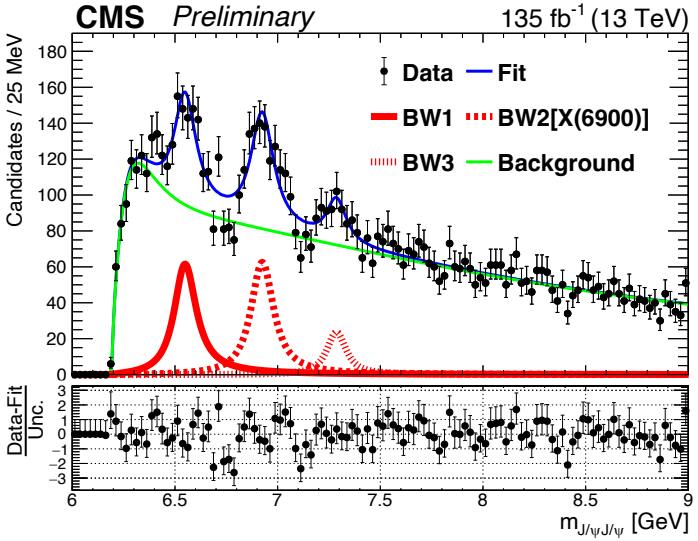
Nat. Phys. 19 (2023) 338

A. Rakotozafindrabe's talk

Double charmonium spectroscopy

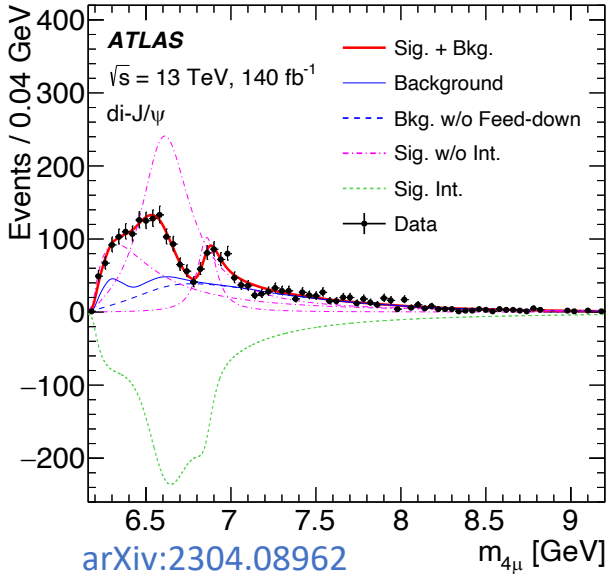


Science Bulletin 65 (2020) 1983



CMS-PAS-BPH-21-003

S. Polikarpov's talk



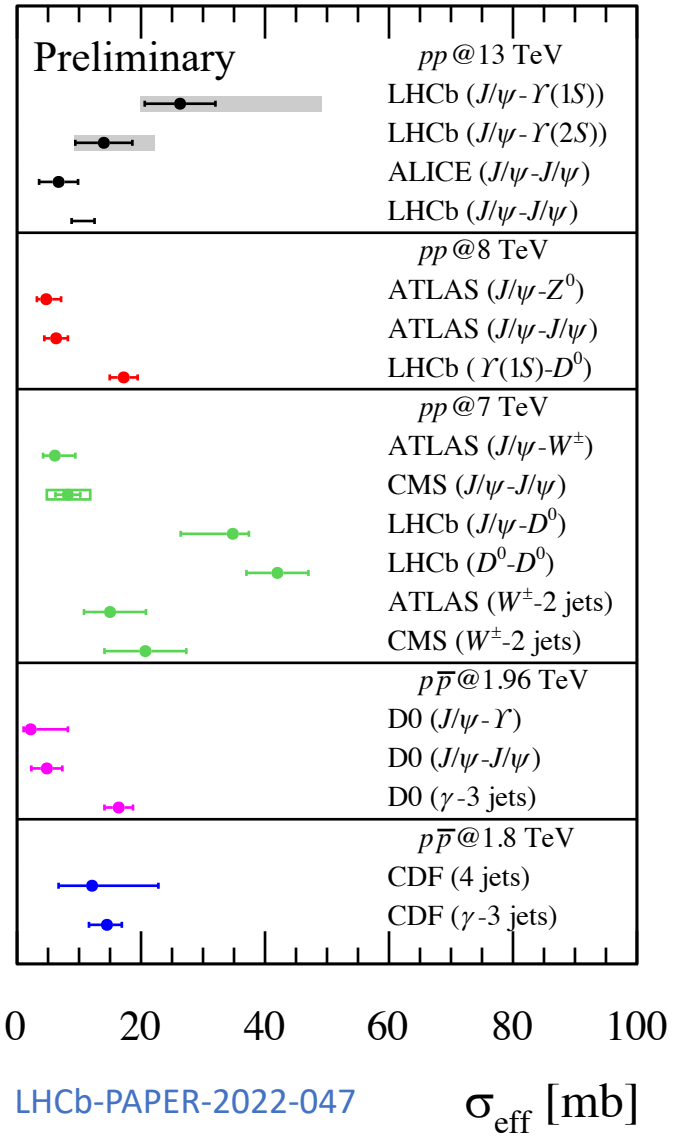
arXiv:2304.08962

- LHCb observed X(6900) in the spectrum of double J/ψ
- Confirmed by CMS and ATLAS
- Interpretation of the states and spectrum is under discussion

Summary

- Actively studied by the LHC experiments
  - Associated production of J/ψ and Υ is studied by LHCb LHCb-PAPER-2022-047
  - ALICE measured the inclusive J/ψ pair production arXiv:2303.13431
  - CMS observed triple J/ψ production Nat. Phys. 19 (2023) 338
  - ATLAS studied double J/ψ production Eur. Phys. J. C77 (2017) 76
- Current measurements are Limited by statistics. Improvements are expected in Run 3
- Improved theory calculations could help distinguish SPS and DPS contributions
- Synergy with the studies of fully heavy exotic states

Thank you for listening!



LHCb-PAPER-2022-047

Backup

Reference to σ_{eff} results

- Figure 1 (a) in H.-S. Shao, “Associated production in pp and heavy ion collisions”, PoS LHCP2020 (2020) 172, arXiv:2009.12555 [hep-ph].

Systematic uncertainties on J/ψ - Υ

Source	$\sigma(J/\psi - \Upsilon(1S))$ (%)	$\sigma(J/\psi - \Upsilon(2S))$ (%)
Signal shape	2.0	2.0
Limited MC size	0.7	1.6
Tracking efficiency	3.3	3.3
PID efficiency	0.5	0.5
J/ψ-from-b fraction	1.1	1.1
Trigger efficiency	1.0	1.0
Radiative tail	2.0	2.0
Vertex fit	0.6	0.6
$\mathcal{B}_{J/\psi\to\mu^+\mu^-}$	0.6	0.6
$\mathcal{B}_{\Upsilon(1S)\to\mu^+\mu^-}$	2.0	-
$\mathcal{B}_{\Upsilon(2S)\to\mu^+\mu^-}$	-	8.8
Luminosity	1.9	1.9
Total	5.5	10.3

Systematic uncertainties on J/ψ - J/ψ

Systematics Source	$\sigma(J/\psi - J/\psi)$ (%)
Signal extraction	7.4
Acceptance-times-efficiency	9.2
$\mathcal{B}_{J/\psi \to \mu^+\mu^-}$	1.1
Luminosity	3.3
Total	12.3