Associated production with onia, double onia production at the LHC

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On behalf of the ATLAS, CMS and LHCb Collaborations

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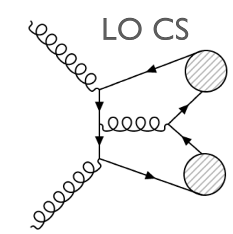
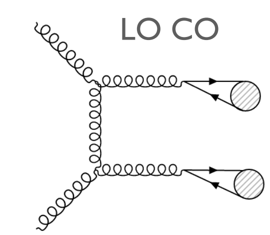
The study of double onia and associated onia production offers new tests of Quantum Chromodynamics (QCD)

Distinguish between production of a heavy quark system in colour-singlet (CS) and colour-octet (CO) states

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

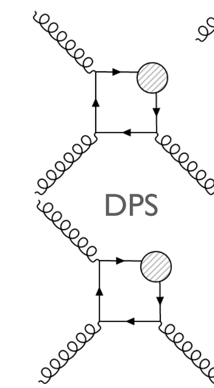
Single Parton Scattering (SPS): the two objects are produced by some process in a single interaction of two partons





Double Parton Scattering (DPS): simultaneous interaction of two pairs of partons, each producing one of the two objects

independent and uncorrelated



$$\sigma^{\mathrm{DPS}}_{A+B} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff}}} \qquad \delta_{AB} = \begin{cases} 1, & A = B \\ 0, & A \neq B \end{cases}$$

σ_{eff} *effective cross section* ~(2 — 20) mb

assumed to be independent of the scattering process and $\sqrt{s}$

DPS not distinguishable on an event-by-event basis from SPS but expected to differ in overall kinematic features, such as angular correlations

Large uncertainties due to possible higher-order SPS contributions, feed-down and limited knowledge of the proton's transverse profile

Associated production with onia

Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

JHEP 04 (2014) 172 arXiv:1401.2831

ATLAS

Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV

Eur. Phys. J. C75 (2015) 229 arXiv:1412.6428

ATLAS

Production of associated Υ and open charm hadrons in pp collisions at $\sqrt{s}$ = 7 and 8 TeV via double parton scattering

JHEP 07 (2016) 052 arXiv:1510.05949

LHCb

Observation of double charm production involving open charm in pp collisions at $\sqrt{s}$ = 7 TeV

J. High Energy Phys., 06 (2012) 141 arXiv:1205.0975

LHCb

$\sqrt{s} = 7$ TeV

$\mathcal{L} = 4.51$ fb^{-1}

$J/\psi \to \mu^+\mu^-$

$W^\pm \to \mu\nu_\mu$

Prompt J/ψ in association with a $W^\pm$

arXiv:1401.2831

fiducial phase space $8.5 < p_T^{J/\psi} < 30$ GeV $|y^{J/\psi}| < 2.1$

$p_T^\mu > 3.5$ GeV $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$ at least one $p_T^\mu > 4$ GeV

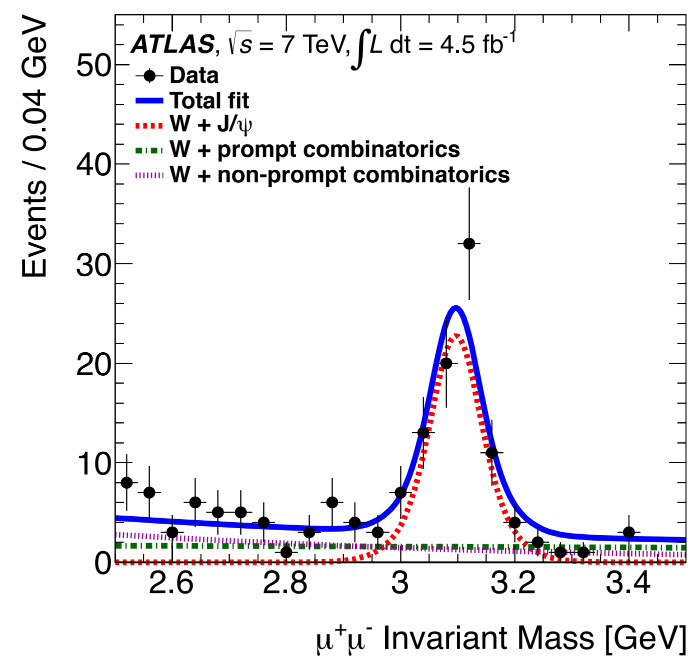
$p_T^\mu > 2.5$ GeV $|\eta^\mu| > 1.3$

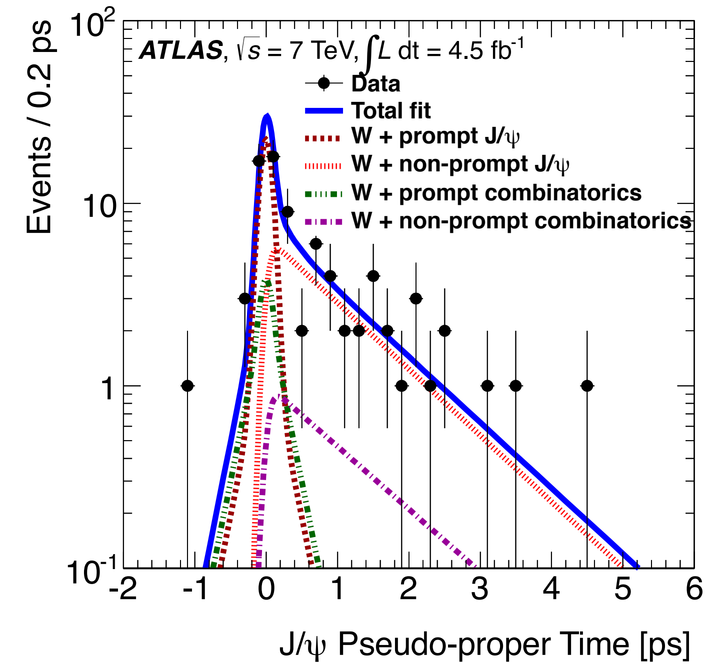
$p_T^{\mu(W)} > 25$ GeV $|\eta^{\mu(W)}| < 2.4$

unbinned maximum likelihood (ML) fit in the J/ψ invariant mass and pseudo-proper time τ to obtain yields for prompt and non-prompt J/ψ and backgrounds

assign weights with sPlot arXiv:physics/0402083

$$\tau \equiv \frac{\vec{L} \cdot \vec{p_T}^{J/\psi}}{p_T^{J/\psi}} \frac{m_{\mu^+\mu^-}}{p_T^{J/\psi}}$$





fit to the weighted W boson transverse mass using templates to extract

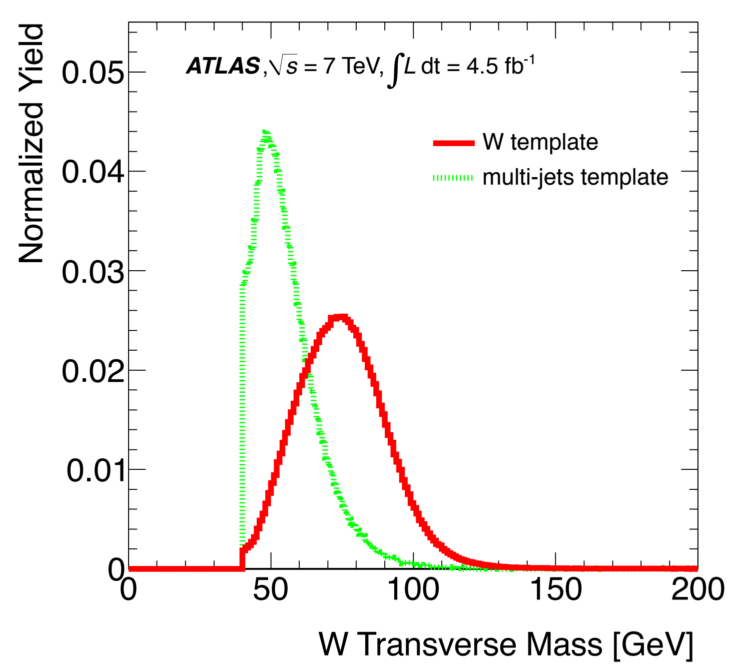
signal yield: $29.2^{+7.5}_{-6.5}$ 5.1σ

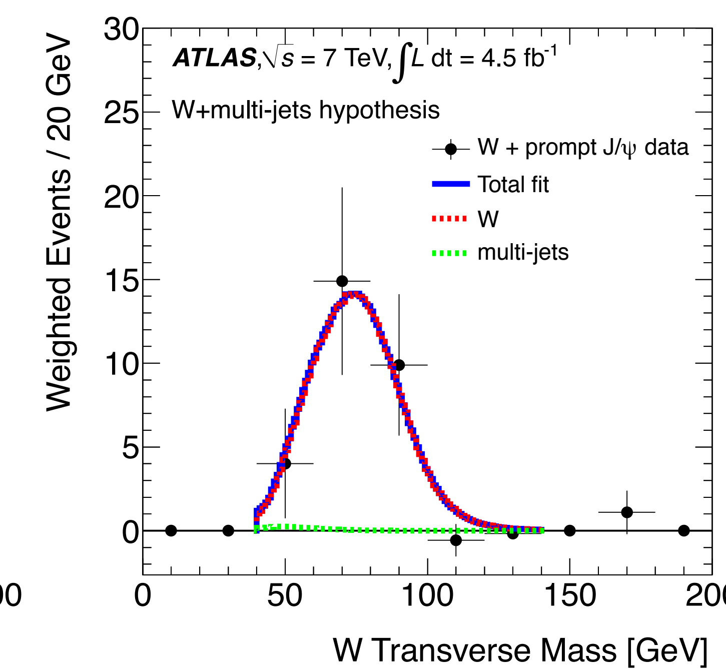
including 1.8 ± 0.2 from pile-up:

DPS yield: 10.8 ± 4.2

assuming $\sigma_{\text{eff}} = 15 \pm 3\,(\text{stat})\,{}^{+5}_{-3}\,(\text{syst})$ mb arXiv:1301.6872

and $\sigma_{J/\psi}$ from arXiv:1104.3038





Prompt J/ψ in association with a $W^{\pm}$

Ratios of the $W^{\pm}+$ prompt J/ψ cross section to the inclusive $W^{\pm}$ cross section normalised to unit rapidity

arXiv:1401.2831

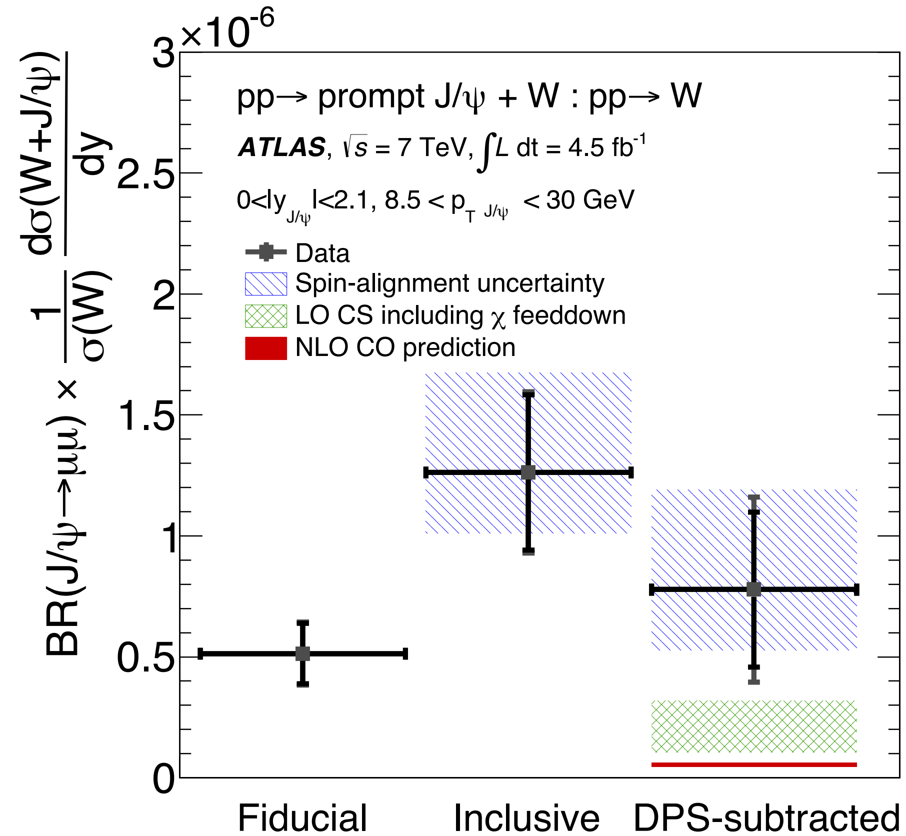
fiducial $R^{\rm fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$

inclusive $R^{\rm incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$

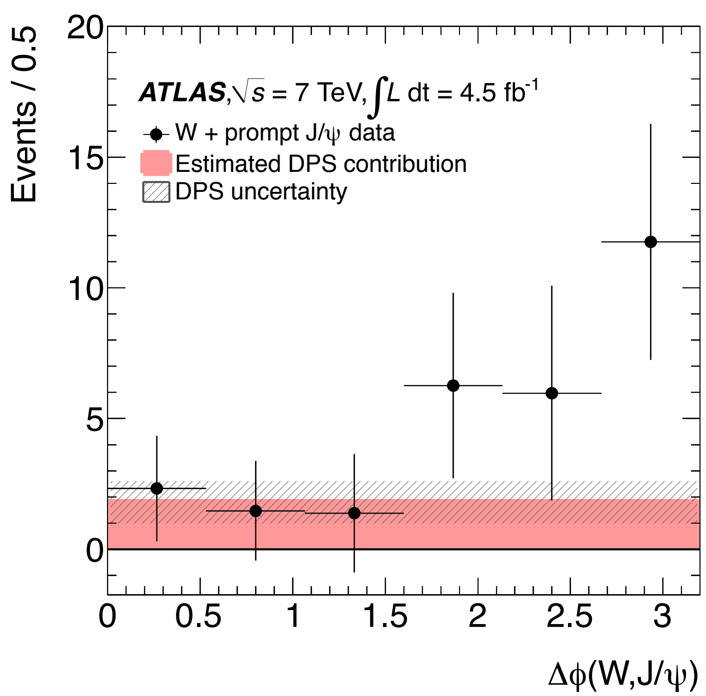
corrected for the fiducial acceptance of the muons from J/ψ
isotropic spin-alignment assumed
last uncertainty from variations with 5 extreme scenarios

DPS subtracted $R^{\rm DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

compared to LO CS and NLO CO predictions



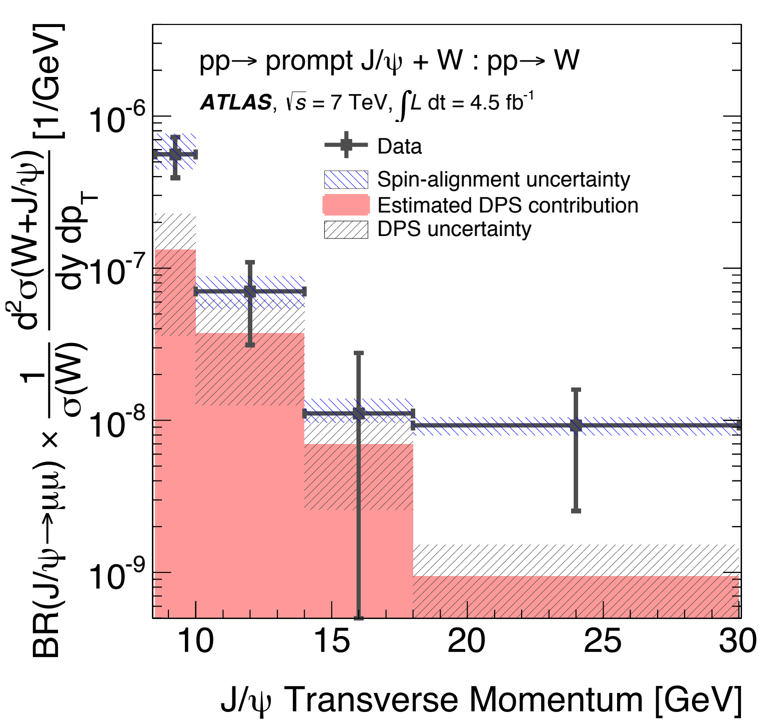
$W + J/\psi$ dominated by CS production



Presence of both SPS and DPS contributions

SPS is the dominant contribution to the total rate at low $p_T^{J/\psi}$

Inclusive differential cross section ratio



Prompt and non-prompt J/ψ in association with a Z

$\sqrt{s} = 8$ TeV

$\mathcal{L} = 20.3$ fb^{-1}

$J/\psi \to \mu^+\mu^-$

$Z \to \ell\ell,\ \ell = \mu, e$

fiducial phase space $8.5 < p_T^{J/\psi} < 100$ GeV $|y^{J/\psi}| < 2.1$

arXiv:1412.6428

$p_T^\mu > 3.5$ GeV $|\eta^\mu| < 1.3$ $|\eta^\mu| < 2.5$

$p_T^\mu > 2.5$ GeV $|\eta^\mu| > 1.3$ at least one $p_T^\mu > 4$ GeV

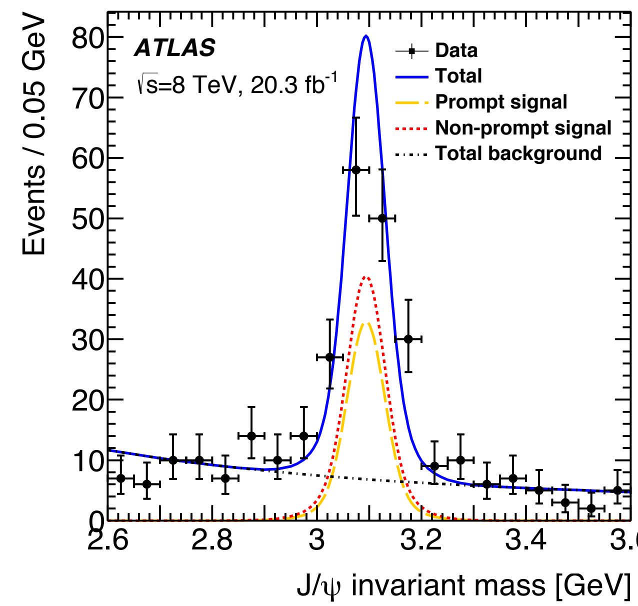
$p_T^{\mu(Z)} > 15$ GeV $|\eta^{\mu(Z)}| < 2.5$

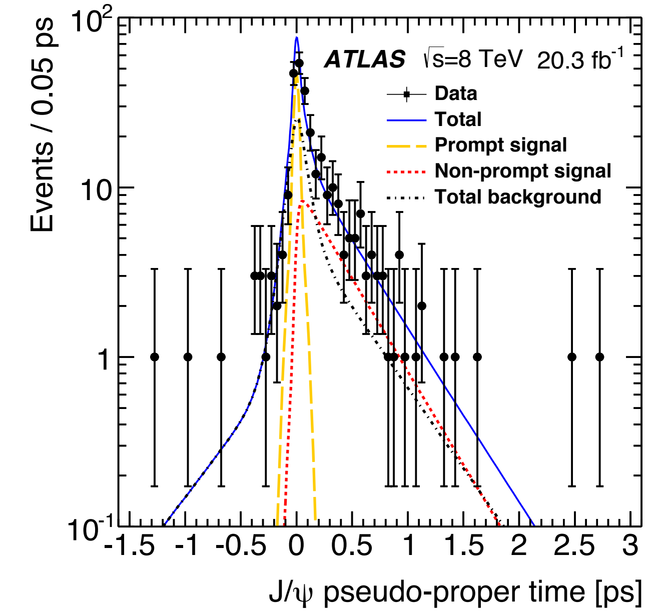
$p_T^{e(Z)} > 15$ GeV $|\eta^{e(Z)}| < 2.47$

unbinned ML fit in J/ψ invariant mass and pseudo-proper time to obtain yields for prompt and non-prompt J/ψ and backgrounds

assign weights with sPlot

signal and multi-jet background templates for weighted Z mass used to extract signal yield separately for $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$





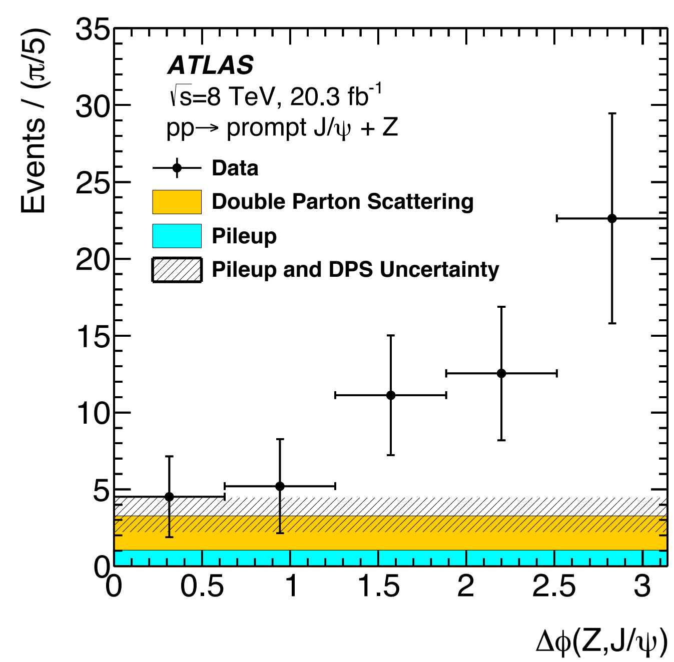
Yields:	prompt	non-prompt
	$56 \pm 10 \pm 5\ (5\sigma)$	$95 \pm 12 \pm 8\ (9\sigma)$
from DPS	$11.1^{+5.7}_{-5.0}$	$5.8^{+2.8}_{-2.6}$

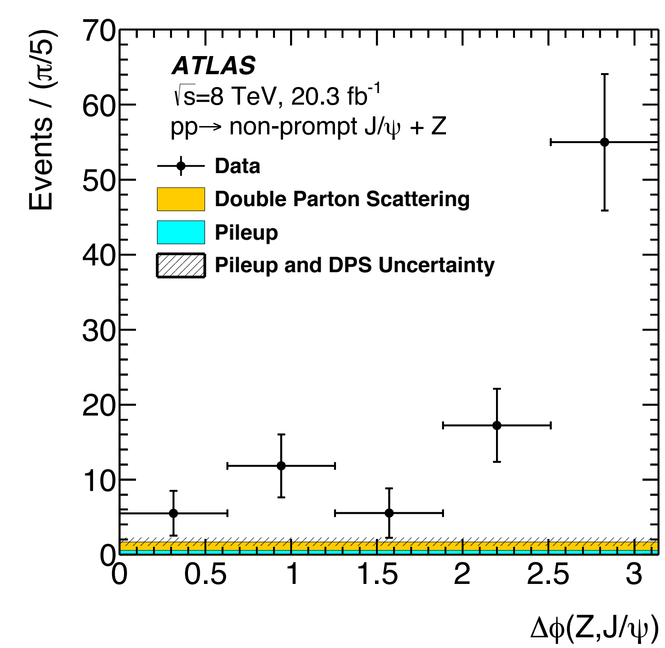
assuming $\sigma_{\text{eff}} = 15 \pm 3\ (\text{stat})\ ^{+5}_{-3}\ (\text{syst})$ mb

arXiv:1301.6872

and $\sigma_{J/\psi}$ from arXiv:1104.3038

assuming all observed signal in the first bin $(< \frac{\pi}{5})$ is due to DPS, a lower limit is set on $\sigma_{\text{eff}} > 5.3$ mb





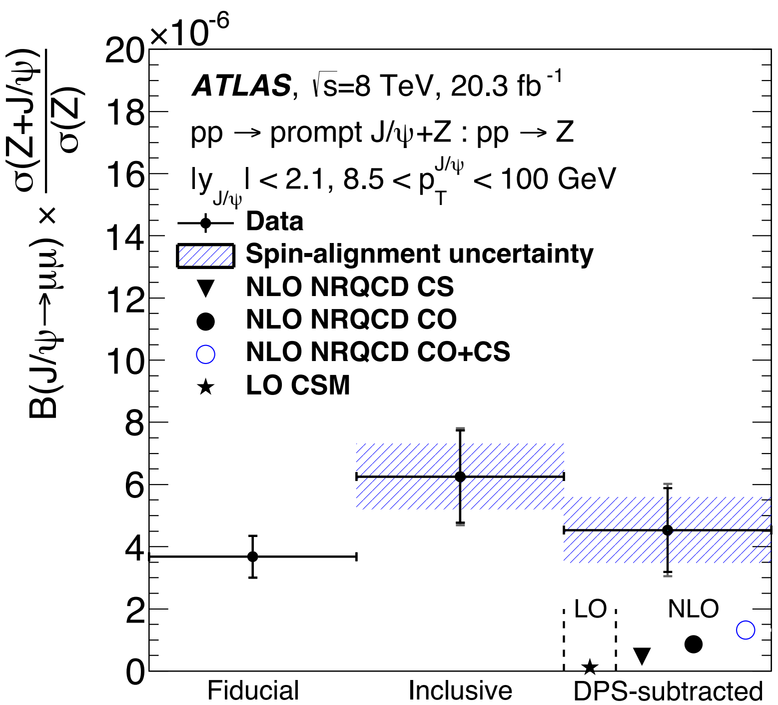
presence of both SPS and DPS contributions

Prompt and non-prompt J/ψ in association with a Z

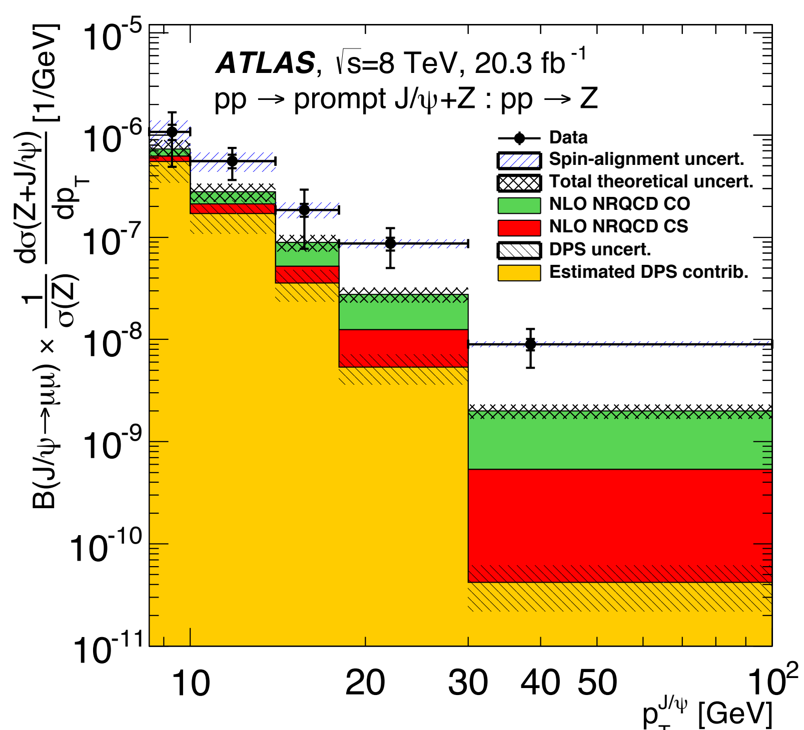
Ratios of the $Z + J/\psi$ cross section to the inclusive Z cross section

arXiv:1412.6428

	prompt	non-prompt
fiducial	${}^{\mathrm{p}}R^{\mathrm{fid}}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{fid}}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$
inclusive	${}^{\mathrm{p}}R^{\mathrm{incl}}_{Z+J/\psi} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{incl}}_{Z+J/\psi} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS subtracted	${}^{\mathrm{p}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (94 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS fraction	${}^{\mathrm{p}}f_{\mathrm{DPS}} = (29 \pm 9)\%$	${}^{\mathrm{np}}f_{\mathrm{DPS}} = (8 \pm 2)\%$



Inclusive differential cross section ratio



a higher production rate predicted through CO than through CS, CO dominant at high transverse momentum

The expected production rate from the sum of CO and CS is lower than the data by a factor of 2 to 5

discrepancy increasing with transverse momentum

Production of associated Υ and open charm hadrons

arXiv:1510.05949
arXiv:1205.0975

$\sqrt{s} = 7\,\text{TeV}\ \ \mathcal{L} = 1\,\text{fb}^{-1}$ fiducial phase space $p_T^{\Upsilon} < 15\,\text{GeV}\quad 2.0 < y^{\Upsilon} < 4.5$

$\sqrt{s} = 8\,\text{TeV}\ \ \mathcal{L} = 2\,\text{fb}^{-1}$ $\quad 1 < p_T^{C} < 20\,\text{GeV}\quad 2.0 < y^{C} < 4.5$

Production of associated J/ψ and open charm hadrons

$\sqrt{s} = 7\,\text{TeV}\ \ \mathcal{L} = 355\,\text{pb}^{-1}$ fiducial phase space $p_T^{J/\psi} < 15\,\text{GeV}\ \ 2 < y^{J/\psi} < 4$

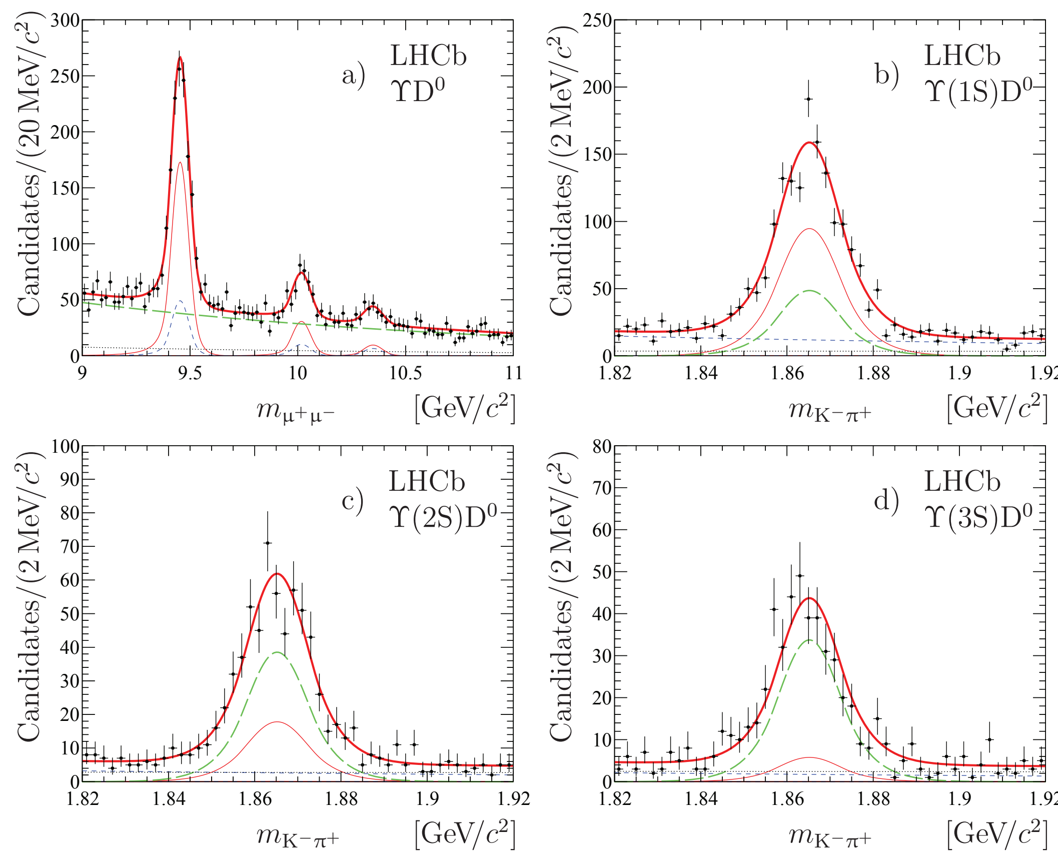
$3 < p_T^{C} < 12\,\text{GeV}\quad 2 < y^{C} < 4$

$$C = D^0\,(K^-\pi^+),\ D^+\,(K^-\pi^+\pi^+),\ D_s^+\,((K^+K^-)_\phi\pi^+),\ \Lambda_c^+\,(pK^-\pi^+)$$

Signal yield from an unbinned extended ML fit to the 2D ΥC and $J/\psi C$ mass distributions:

	D^0	D^+	D_s^+	Λ_c^+
$\Upsilon(1S)$	980 ± 50	556 ± 35	31 ± 7	11 ± 6
	26σ	19σ	6σ	2.5σ
$\Upsilon(2S)$	184 ± 27	116 ± 20	9 ± 5	1 ± 4
	7.7σ	6.4σ	2.5σ	0.9σ
$\Upsilon(3S)$	60 ± 22	55 ± 17	6 ± 4	1 ± 3
	3.1σ	4σ	1.9σ	0.9σ
J/ψ	4875 ± 86	3323 ± 71	328 ± 22	116 ± 14
	$> 8\sigma$	$> 8\sigma$	$> 8\sigma$	7.3σ

background subtracted (weights from sPlot)



ΥC and $J/\psi C$ results

arXiv:1510.05949
arXiv:1205.0975

Model independent production cross sections in the fiducial volume

corrected for acceptance, trigger, reconstruction, selection and particle identification efficiencies

ΥC using trigger matched subsample (~20% yield reduction)

$J/\psi C$ corrected for efficiency of global event cuts

ΥC $\sqrt{s} = 7\,\mathrm{TeV}$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0} = 155 \pm 21 \pm 7\,\mathrm{pb}$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+} = 82 \pm 19 \pm 5\,\mathrm{pb}$$

$\sqrt{s} = 8\,\mathrm{TeV}$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0} = 250 \pm 28 \pm 11\,\mathrm{pb}$$
$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+} = 80 \pm 16 \pm 5\,\mathrm{pb}$$

DPS expectations $\sqrt{s} = 7\,\mathrm{TeV}$

$206 \pm 17\,\mathrm{pb}$

$86 \pm 10\,\mathrm{pb}$

Ratios to inclusive production

$$R^{\Upsilon(1S)D^0} = (6.3 \pm 0.8 \pm 0.2)\%$$
$$R^{\Upsilon(1S)D^+} = (3.4 \pm 0.8 \pm 0.2)\%$$

$$R^{\Upsilon(1S)D^0} = (7.8 \pm 0.9 \pm 0.3)\%$$
$$R^{\Upsilon(1S)D^+} = (2.5 \pm 0.5 \pm 0.1)\%$$

extrapolating down to $p_T^C = 0$ and using fragmentation functions measured at $\Upsilon(4S)$

$$R^{\Upsilon(1S)c\bar{c}} = (7.7 \pm 1.0)\%$$

$$R^{\Upsilon(1S)c\bar{c}} = (8.0 \pm 0.9)\%$$

DPS expectation

$R_{\mathrm{DPS}} \sim 10\%$

in agreement

Significantly larger than SPS predictions: $R_{\mathrm{SPS}} = (0.2 - 0.6)\%$ (LO NRQCD)

$R_{\mathrm{SPS}} = (0.1 - 0.3)\%$ (k_T-factorisation approach)

$J/\psi C$

	D^0	D^+	D_s^+	Λ_c^+
$\sigma_{J/\psi C}$ [nb]	$161.0 \pm 3.7 \pm 12.2$	$56.6 \pm 1.7 \pm 5.9$	$30.5 \pm 2.6 \pm 3.4$	$43.2 \pm 7.0 \pm 12.0$
LO σ^{gg} [nb]	10 ± 6	5 ± 3	1 ± 0.8	0.8 ± 0.5
LO σ^{gg} [nb]	7.4 ± 3.7	2.6 ± 1.3	1.5 ± 0.7	0.9 ± 0.5
σ^{DPS} [nb]	146 ± 39	60 ± 17	24 ± 7	56 ± 22

σ^{DPS} using arXiv:1103.0423

$\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\,\mathrm{mb}$

Phys. Rev. **D56** (1997) 3811

Predictions from gluon-gluon fusion significantly smaller than observed

Better agreement with DPS models

ΥC and $J/\psi C$ results for $\sigma_{\rm eff}$

arXiv:1510.05949
arXiv:1205.0975

$J/\psi C$

	D^0	D^+	D_s^+	Λ_c^+
$\sigma^{\rm eff}_{J/\psi}$ [mb]	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

in good agreement with multi-jet production at the Tevatron $\sigma^{\rm eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb Phys. Rev. **D56** (1997) 3811

Neglecting the SPS contributions: incl. cross sections from arXiv:1509.02372 arXiv:1302.2864

ΥC

$\sqrt{s} = 7$ TeV

$$\sigma_{\rm eff}^{\Upsilon(1S)D^0} = 19.4 \pm 2.6 \pm 1.3 \text{ mb}$$

$$\sigma_{\rm eff}^{\Upsilon(1S)D^+} = 15.2 \pm 3.6 \pm 1.5 \text{ mb}$$

$$\sigma_{\rm eff}^{\Upsilon(1S)D^{0,+}} = 18.0 \pm 2.4 \text{ mb}$$

$\sqrt{s} = 8$ TeV

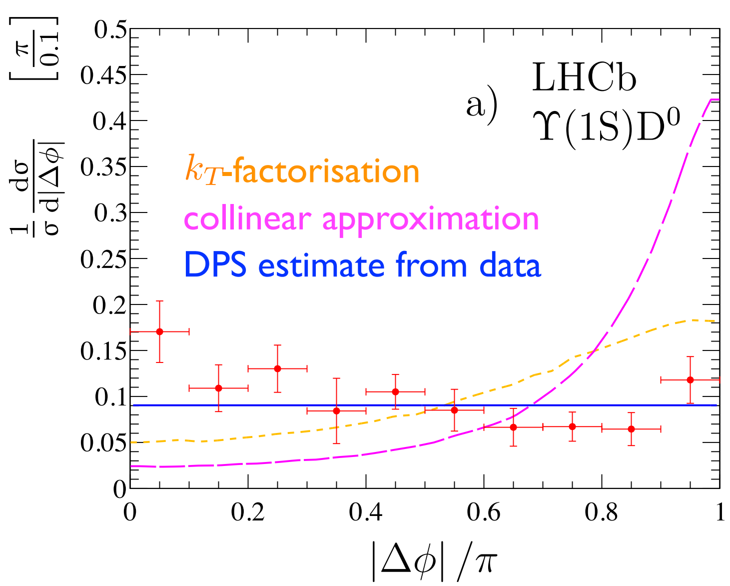
$$\sigma_{\rm eff}^{\Upsilon(1S)D^0} = 17.2 \pm 1.9 \pm 1.2 \text{ mb}$$

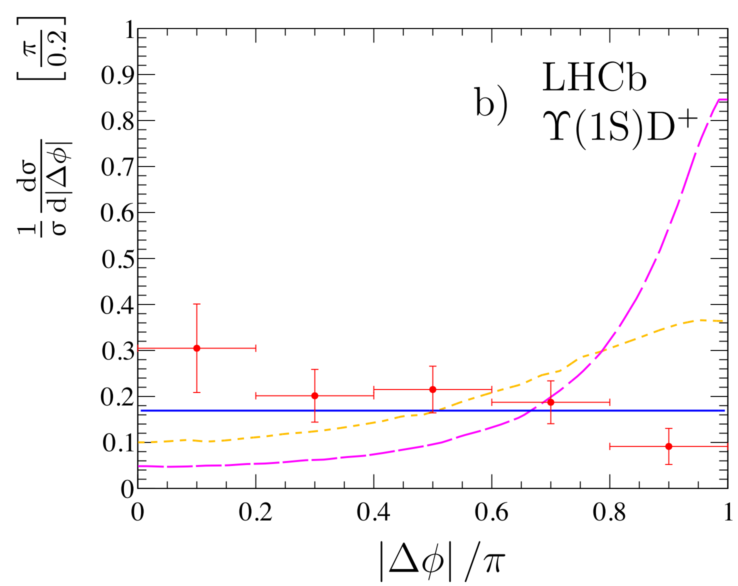
$$\sigma_{\rm eff}^{\Upsilon(1S)D^+} = 22.3 \pm 4.4 \pm 2.2 \text{ mb}$$

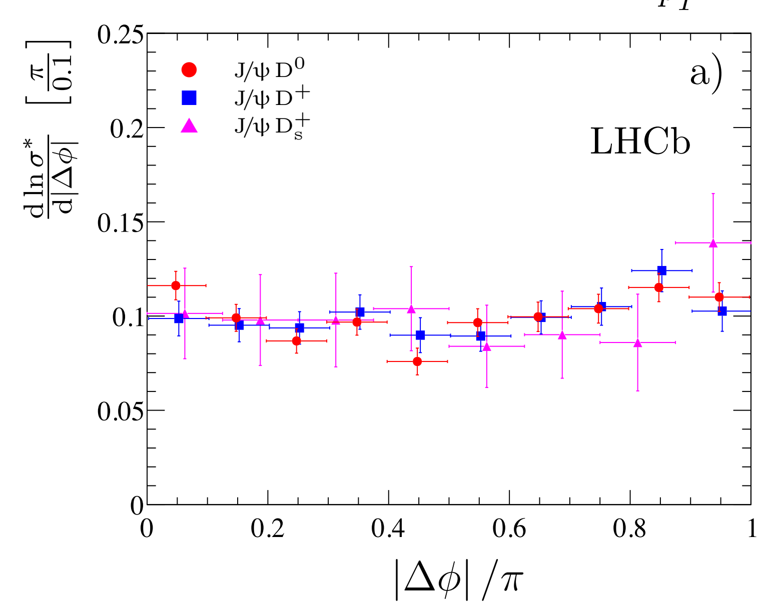
$$\sigma_{\rm eff}^{\Upsilon(1S)D^{0,+}} = 17.9 \pm 2.1 \text{ mb}$$

Average $\sigma_{\rm eff}^{\Upsilon(1S)D^{0,+}} = 18.0 \pm 1.8$ mb in agreement with multi-jet production

Differential distributions for $p_T^{\Upsilon(1S)}$, $p_T^{J/\psi}$, p_T^C, $y^{\Upsilon(1S)}$, y^C, $\Delta\phi$, Δy, $p_T^{\Upsilon(1S)C}$, $y^{\Upsilon(1S)C}$, $m^{\Upsilon(1S)C}$, $\mathcal{A} = \frac{p_T^{\Upsilon(1S)} - p_T^C}{p_T^{\Upsilon(1S)} + p_T^C}$







Good agreement with the DPS expectations as the main production mechanism

Double onia production

Measurement of prompt J/ψ pair production in pp collisions at s√ = 7 TeV

JHEP 09 (2014) 094 arXiv:1406.0484 CMS

Measurement of the prompt J/ψ pair production cross-section in pp collisions at √ s = 8 TeV with the ATLAS detector

Eur. Phys. J. C77 (2017) 76 arXiv:1612.02950 ATLAS

Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV

Submitted to JHEP arXiv:1612.07451 LHCb

Observation of ϒ(1S) pair production in proton-proton collisions at s√= 8 TeV

Accepted by JHEP arXiv:1610.07095 CMS

$\sqrt{s} = 7\ \mathrm{TeV}$
$\mathcal{L} = 4.73\ \mathrm{fb}^{-1}$

J/ψ pair production

fiducial phase space

$p_T^{J/\psi} > 6.5\ \mathrm{GeV}$ $\quad |y^{J/\psi}| < 1.2$

$p_T^{J/\psi}(6.5 - 4.5)\ \mathrm{GeV}$ $\quad 1.2 < |y^{J/\psi}| < 1.43$

$p_T^{J/\psi} > 4.5\ \mathrm{GeV}$ $\quad 1.43 < |y^{J/\psi}| < 2.2$

$3\ \mu$ $\quad p_T^{\mu} > 3.5\ \mathrm{GeV}$ $\quad |\eta^{\mu}| < 1.2$

$p_T^{\mu} > 3.5 \to 2\ \mathrm{GeV}$ $\quad 1.2 < |\eta^{\mu}| < 1.6$

$p_T^{\mu} > 2\ \mathrm{GeV}$ $\quad 1.6 < |\eta^{\mu}| < 2.4$

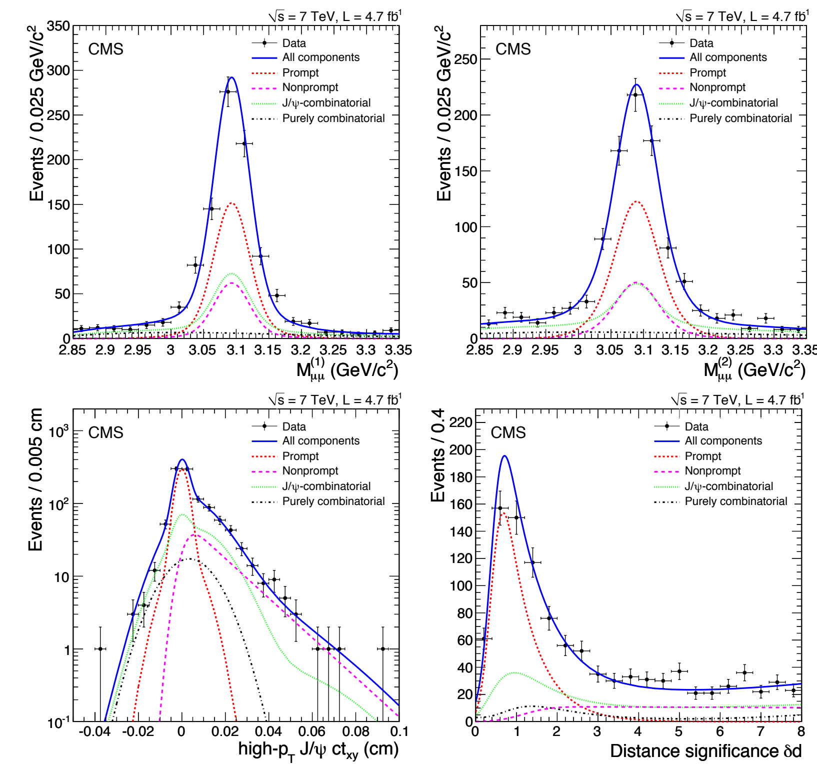
$4^{\mathrm{th}}\ \mu$ $\quad p_T^{\mu} > 3\ \mathrm{GeV}$ $\quad |\eta^{\mu}| < 1.2$

$p^{\mu} > 3\ \mathrm{GeV}$ $\quad 1.2 < |\eta^{\mu}| < 2.4$

arXiv:1406.0484

extended ML fit to the two invariant masses,
the proper-transverse decay length ct_{xy} of the higher-p_T J/ψ and
the separation significance δd between the vertices of the two J/ψ

signal weights with sPlot



$$N_{J/\psi J/\psi} = 446 \pm 23$$

cross section assuming isotropic decays

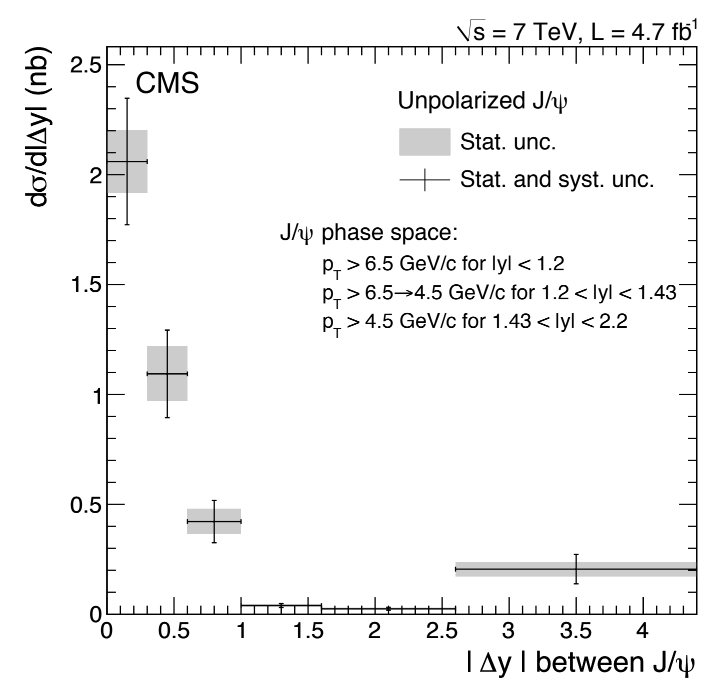
after efficiency and acceptance corrections

$$\sigma_{J/\psi J/\psi} = 1.49 \pm 0.07 \pm 0.13\ \mathrm{nb}$$

The differential cross section in bins of $|\Delta y|$ is sensitive to DPS

non-zero value measured in the bin between 2.6 and 4.4
predicted to be populated via DPS production

$\sigma_{\mathrm{eff}} = 8.2 \pm 2.2\ \mathrm{mb}$ extracted by Lansberg and Shao arXiv:1410.8822



$\sqrt{s} = 8$ TeV
$\mathcal{L} = 11.4\ \mathrm{fb}^{-1}$

Prompt J/ψ pair production

arXiv:1612.02950

fiducial phase space $p_T^{J/\psi} > 8.5$ GeV $|y^{J/\psi}| < 2.1$

$p_T^{\mu} > 2.5$ GeV $|\eta^{\mu}| < 2.3$

unbinned ML fit to the two invariant masses to extract di-J/ψ signal

signal used to create prompt-prompt event weights from a 2D fit to the transverse decay length distributions of the two J/ψ

cross sections reported for two rapidity regions based on the sub-leading J/ψ rapidity

$|y_{J/\psi_2}| < 1.05$

$N_{J/\psi J/\psi} = 3310 \pm 330$

$\sigma^{\mathrm{fid}}_{J/\psi J/\psi} = 15.6 \pm 1.3 \pm 1.2 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})$ pb

$1.05 < |y_{J/\psi_2}| < 2.1$

$N_{J/\psi J/\psi} = 3140 \pm 370$

$\sigma^{\mathrm{fid}}_{J/\psi J/\psi} = 13.5 \pm 1.3 \pm 1.1 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})$ pb

after correcting for muon acceptance and assuming unpolarised production

$\sigma_{J/\psi J/\psi} = 82.2 \pm 8.3 \pm 6.3 \pm 0.9\ (\mathcal{B}) \pm 1.6(\mathcal{L})$ pb

$\sigma_{J/\psi J/\psi} = 78.3 \pm 9.2 \pm 6.6 \pm 0.9\ (\mathcal{B}) \pm 1.5(\mathcal{L})$ pb

the fraction of DPS events is determined by fitting DPS and SPS templates to the data $|\Delta y|$ vs $|\Delta\phi|$

assign DPS and SPS event weights

$f_{\mathrm{DPS}} = (9.2 \pm 2.1 \pm 0.5)\%$ from $|\Delta y|$

$\sigma^{\mathrm{DPS}}_{J/\psi J/\psi} = 14.8 \pm 3.5 \pm 1.5 \pm 0.2\ (\mathcal{B}) \pm 0.3(\mathcal{L})$ pb

$\sigma^{J/\psi J/\psi}_{\mathrm{eff}} = 6.3 \pm 1.6 \pm 1.0(\mathcal{B}) \pm 0.1(\mathcal{L})$ mb

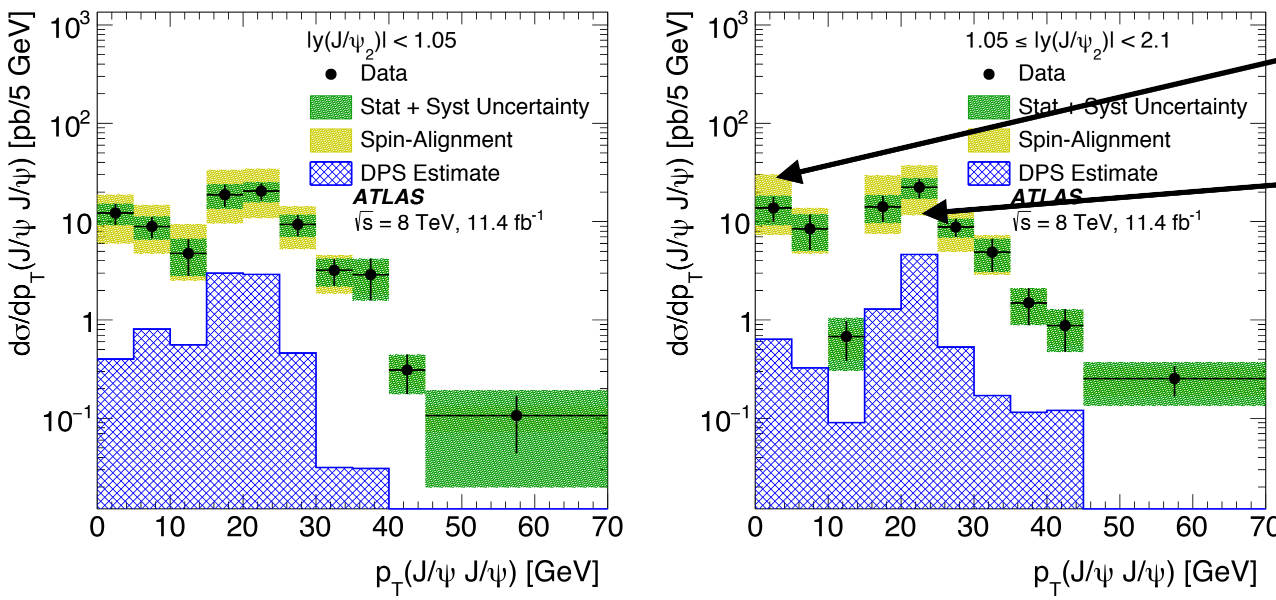
σ^{eff} measured from prompt di-J/ψ lower than from other final states

Prompt J/ψ pair production

arXiv:1612.02950

Differential cross sections as a function of the sub-leading J/ψ p_T, the di-J/ψ p_T and invariant mass

central and forward J/ψ_2 rapidity ranges



events produced back-to-back

events produced together and back-to-back to a gluon

DPS estimate from data

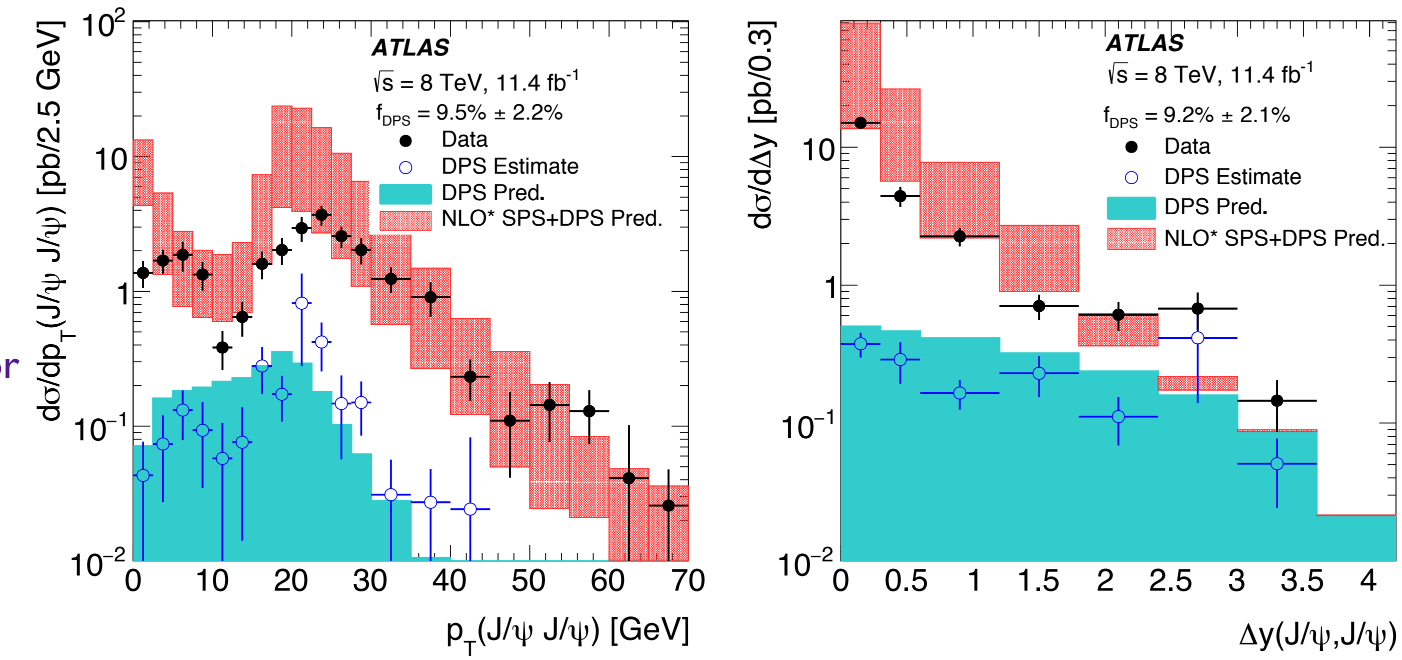
Total and DPS cross sections (full rapidity range) in the muon fiducial volume:

di-J/ψ p_T and invariant mass, Δy and $\Delta\phi$

compared to:

NLO* SPS with a feed-down correction factor

LO DPS normalised to measured



disagreement for large invariant mass, large Δy and in the low-p_T region

Data largely in agreement with NLO* SPS + LO DPS

contributions from feed-down and/or intrinsic parton transverse momentum needed

$\sqrt{s} = 13$ TeV
$\mathcal{L} = 279\ \mathrm{pb}^{-1}$

J/ψ pair production

arXiv:1612.07451

fiducial phase space $p_T^{J/\psi} < 10$ GeV $\quad 2.0 < y^{J/\psi} < 4.5$

$p_T^{\mu} > 650$ MeV $\quad 6 < p^{\mu} > 200$ GeV $\quad 2 < \eta^{\mu} < 5$

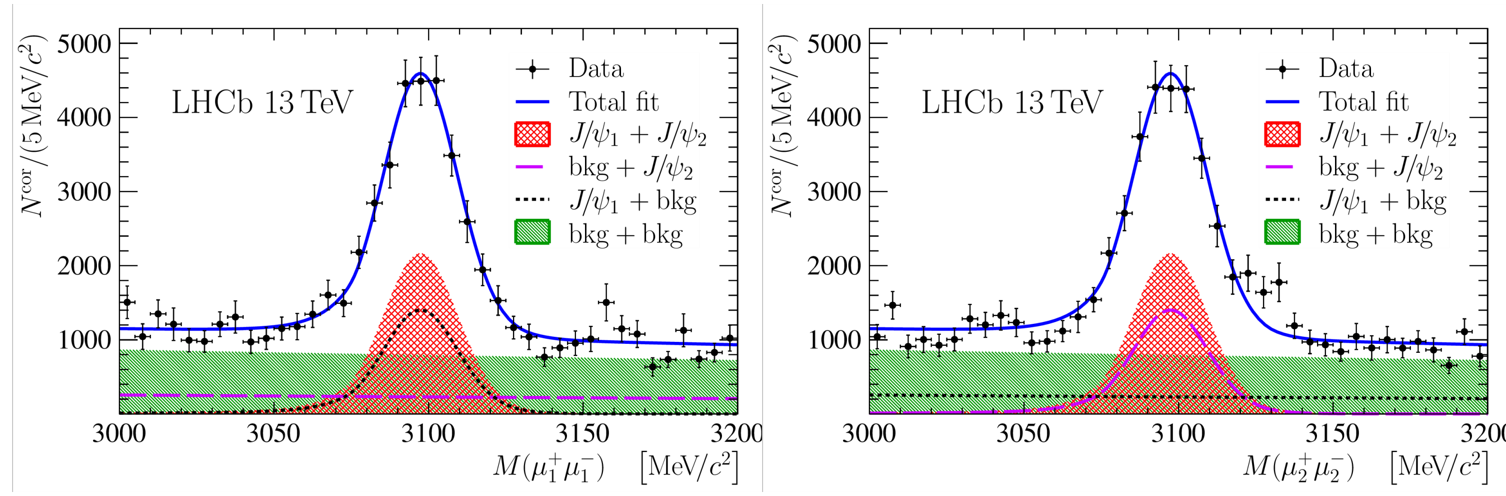
J/ψ_1 and J/ψ_2 assigned randomly

signal yield from an unbinned extended ML fit to the efficiency corrected 2D mass distribution

corrected for acceptance, trigger, reconstruction, selection and particle identification efficiencies

$$N^{\mathrm{cor}} = (15.8 \pm 1.1) \times 10^3$$

fraction of candidates with a J/ψ from b-decays: 4.5%



assuming unpolarised production

$$\sigma_{J/\psi J/\psi} = 15.2 \pm 1.0 \pm 0.9\ \mathrm{nb}$$ $\pm 7\%$ if $\lambda_0 = \pm 20\%$

compare measured $\sigma_{J/\psi J/\psi}$ to theoretical predictions

LO CS	LO CO	LO k_T	NLO* CS''	NLO CS	DPS
$1.3 \pm 0.1^{+3.2}_{-0.1}$	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$15.4 \pm 2.2^{+51}_{-12}$	$11.9^{+4.6}_{-3.2}$	$8.1 \pm 0.9^{+1.6}_{-1.3}$

σ^{DPS} using
arXiv:1509.00771
$\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
CDF Phys Rev **D56** (1997)

if all J/ψ pairs are produced through DPS and $\sigma_{J/\psi}$ from arXiv:1509.00771

$$\sigma_{\mathrm{eff}}^{J/\psi J/\psi} = 7.3 \pm 0.5 \pm 1.0\ \mathrm{mb}$$

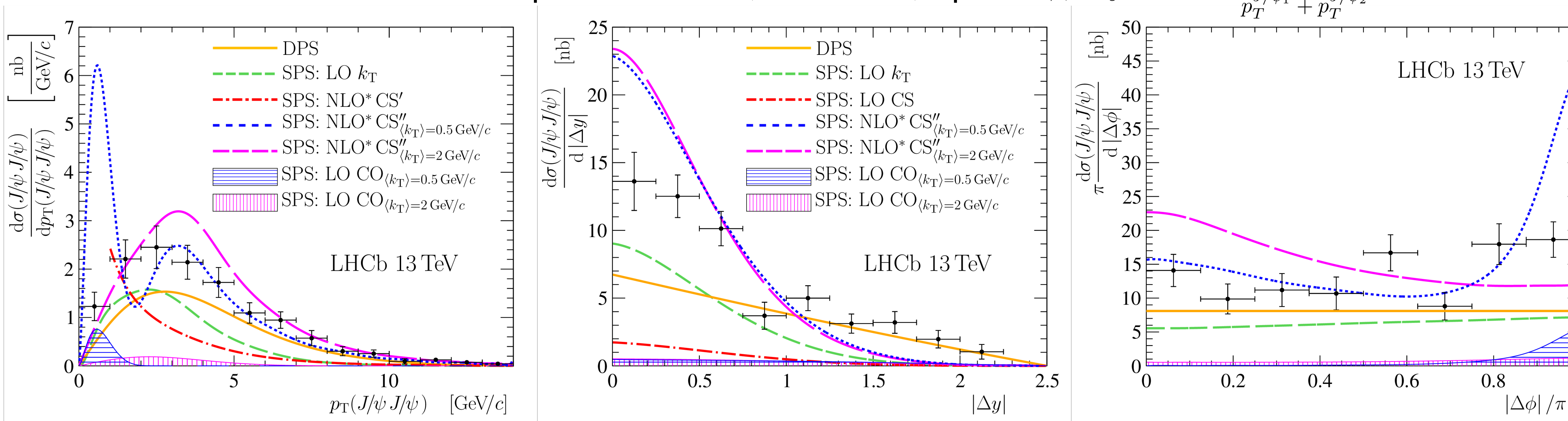
LHCb measurement of $\sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb at $\sqrt{s} = 7$ TeV not precise enough to distinguish between DPS and SPS
arXiv:1407.5973

J/ψ pair production

arXiv:1612.07451

Differential production cross sections:

transverse momenta and rapidities of each J/ψ and the J/ψ pair, $\Delta\phi$, Δy and $\mathcal{A} = \frac{p_T^{J/\psi_1} - p_T^{J/\psi_2}}{p_T^{J/\psi_1} + p_T^{J/\psi_2}}$



DPS estimate from a large number of pseudo experiments

LO CS and NLO* CS″: $\langle k_T \rangle = 0.5\ \mathrm{GeV}/c$ and $\langle k_T \rangle = 2\ \mathrm{GeV}/c$

Neither the DPS model, nor any of the SPS models can describe simultaneously the measured cross section and the differential shapes, however a sum can

A template fit to the differential distributions for the different SPS models is used to get the DPS fraction

$$\frac{d\sigma}{dv} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$$

All fits indicate a large DPS contribution: (42 — 88)%

the CO contribution is significantly smaller than the CS one

including a CO component does not have a large effect on the determination of the DPS fraction

these translate into corresponding values for σ_{eff}: (10 — 12.5) mb ($\sigma_{J/\psi}$ from arXiv:1509.00771)

Smaller than the LHCb measurements in associated onia production

Slightly larger than the central production measurements by ATLAS and CMS

$\sqrt{s} = 8$ TeV
$\mathcal{L} = 20.7\ \mathrm{fb}^{-1}$

$\Upsilon(1S)$ pair production

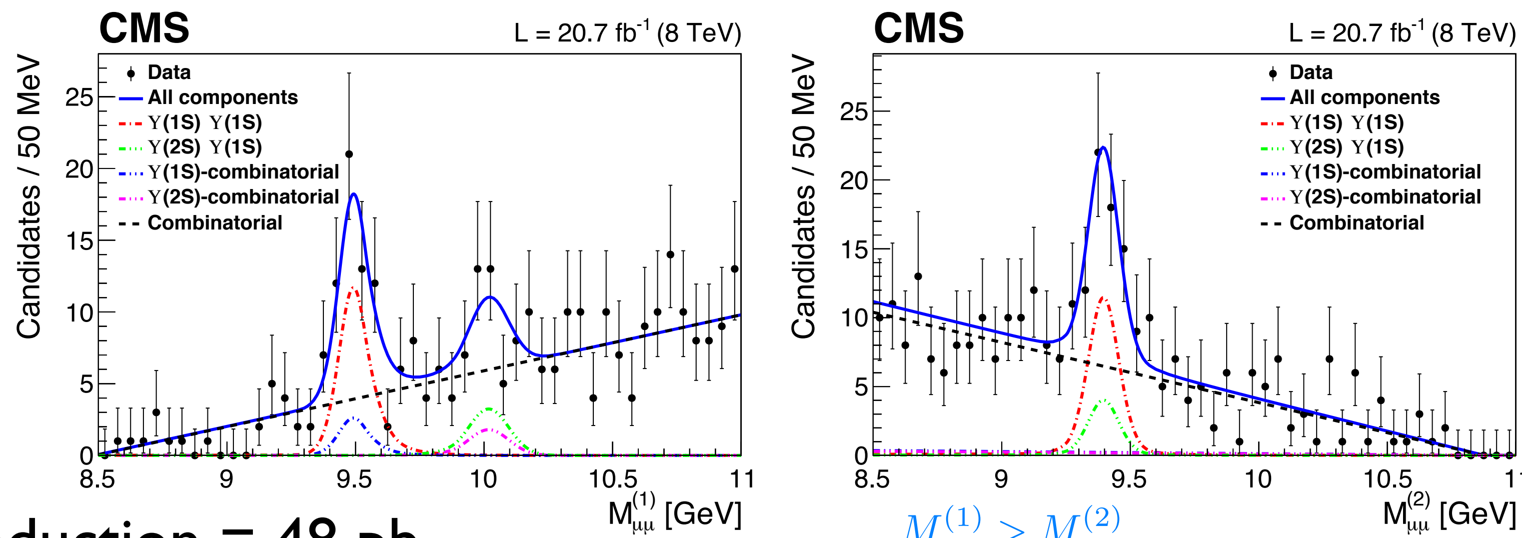
fiducial phase space $|y^{\Upsilon(1S)}| < 2.0$ $\quad p_T^{\mu} > 3.5$ GeV $\quad |\eta^{\mu}| < 2.5$

arXiv:1610.07095

2D unbinned ML fit to $M_{\mu\mu}^{(1)}$ and $M_{\mu\mu}^{(2)}$

$$N_{\Upsilon(1S)\Upsilon(1S)} = 38 \pm 7$$

$$N_{\Upsilon(2S)\Upsilon(1S)} = 13^{+6}_{-5}$$



$M_{\mu\mu}^{(1)} > M_{\mu\mu}^{(2)}$

an SPS prediction for $\Upsilon(1S)$ pair production = 48 pb

cross section assuming isotropic decays

after efficiency and acceptance corrections

$$\sigma_{\Upsilon(1S)\Upsilon(1S)} = 68.8 \pm 12.7 \pm 7.4 \pm 2.8\,(\mathcal{B})\ \mathrm{pb}$$

different polarisations lead to variations in the range -38% to +36%

Assuming a conservatively low value $\quad f_{\mathrm{DPS}} \approx 10\% \quad \sigma_{\mathrm{eff}} \approx 6.6\ \mathrm{mb}$

DPS fraction estimated from $\sigma_{\Upsilon(1S)\Upsilon(1S)}$ and the cross section for $\Upsilon(1S)$ pair production, assuming SPS with feed-down = 48 pb arXiv:1210.5754 $\quad f_{\mathrm{DPS}} \approx 30\% \quad \sigma_{\mathrm{eff}} \approx 2.2\ \mathrm{mb}$

Consistent with the range of values from heavy-quarkonium measurements (2 — 8) mb

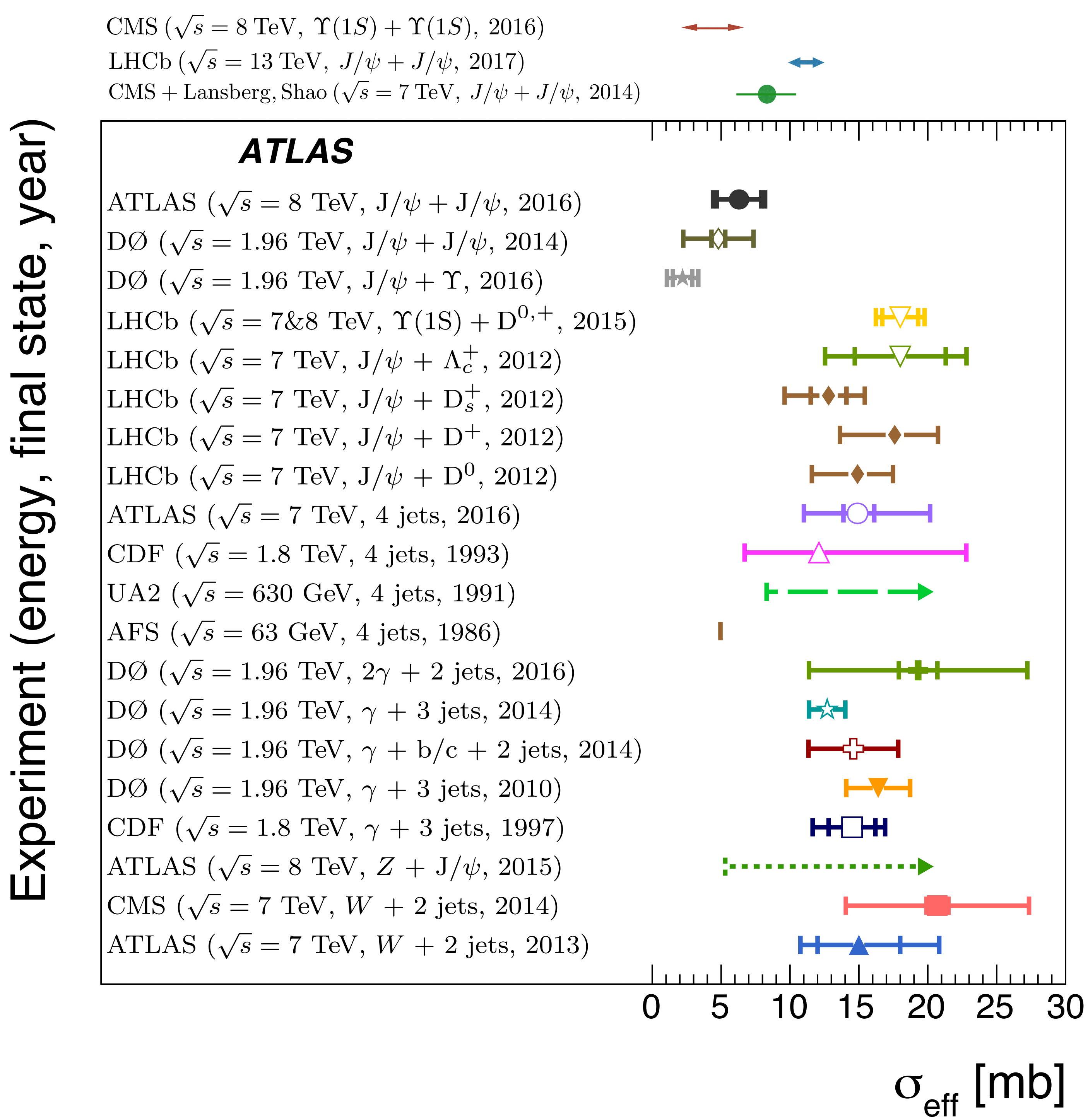
Smaller than multi-jet measurements (12 — 20) mb

Summary

Many results from the LHC experiments shedding light on double onia and associated onia production

Data largely in agreement with NLO* SPS + LO DPS

contributions from feed-down and/or intrinsic parton transverse momentum may be needed



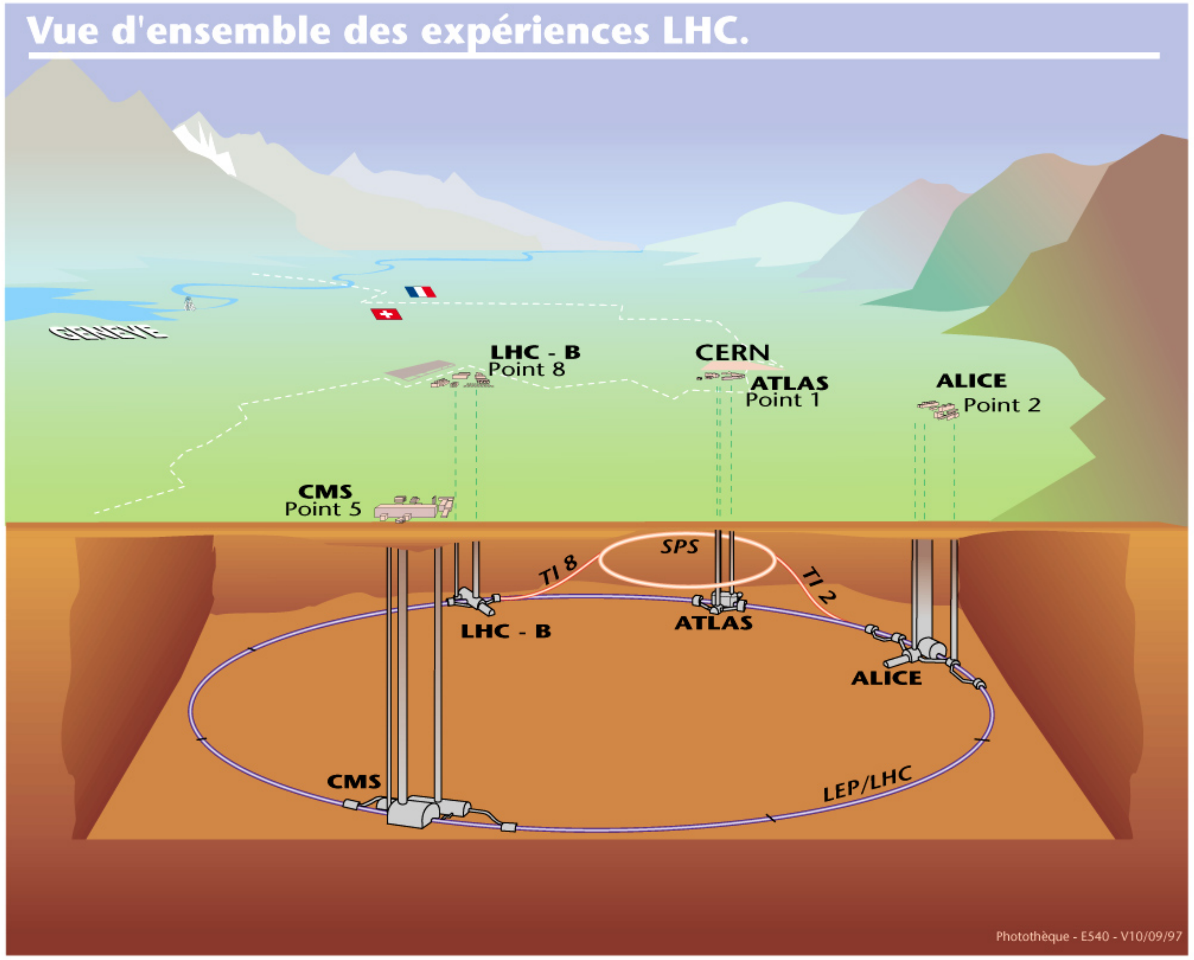
σ^{eff} measured from prompt di-J/ψ generally lower than from other final states

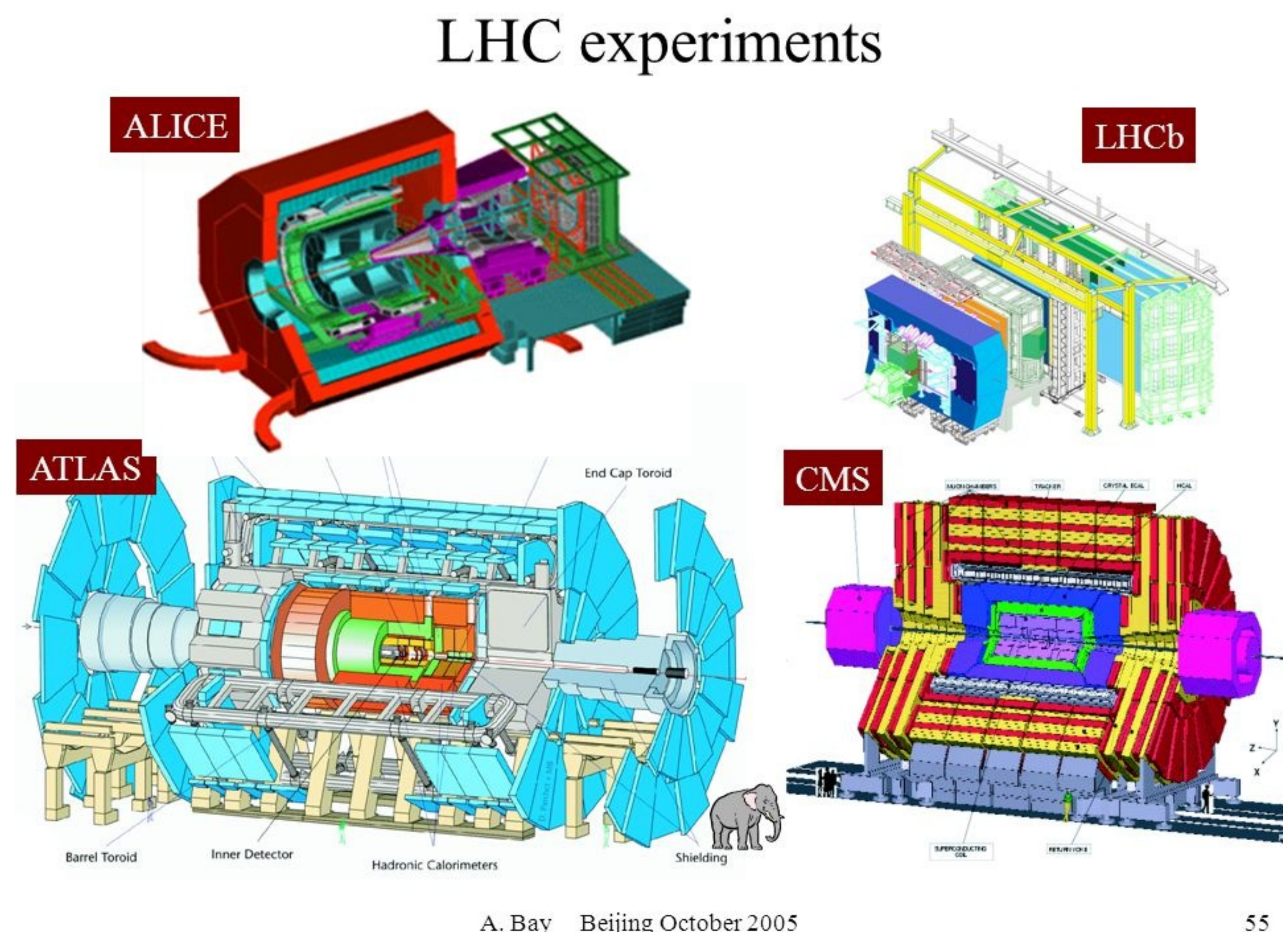
Theoretical predictions of the dependence of σ_{eff} on the process and the centre-of-mass energy are needed

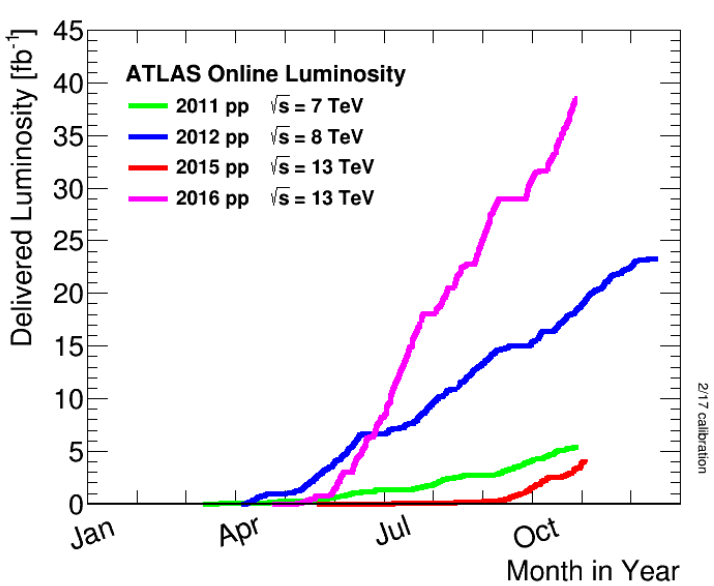
Expect a lot more $\sqrt{s} = 13$ TeV results

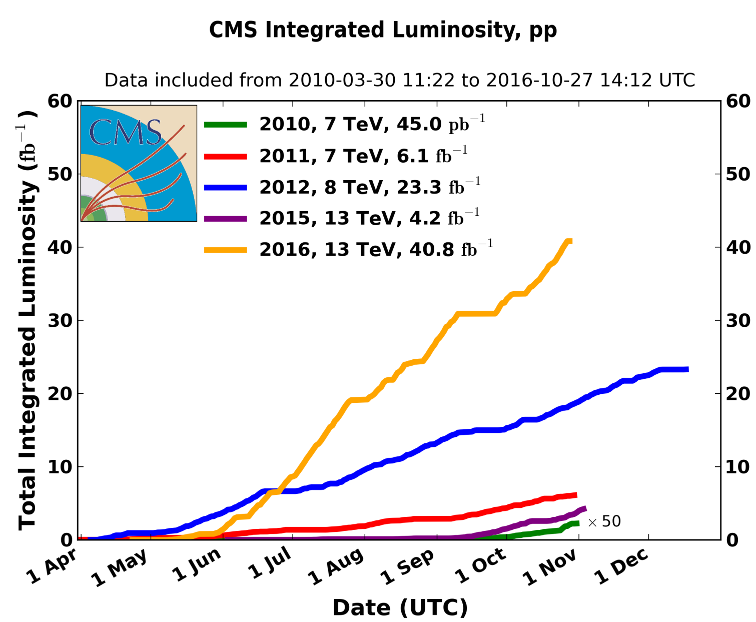
Backup slides

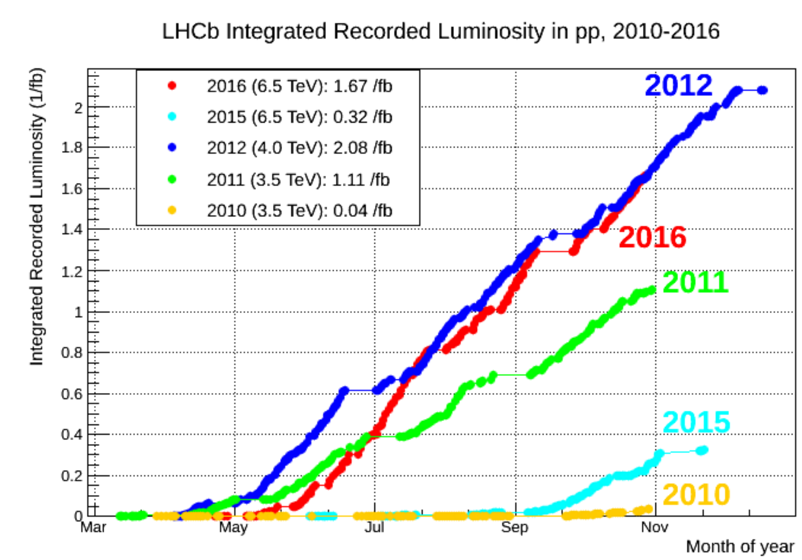
The Large Hadron Collider And Its Experiments







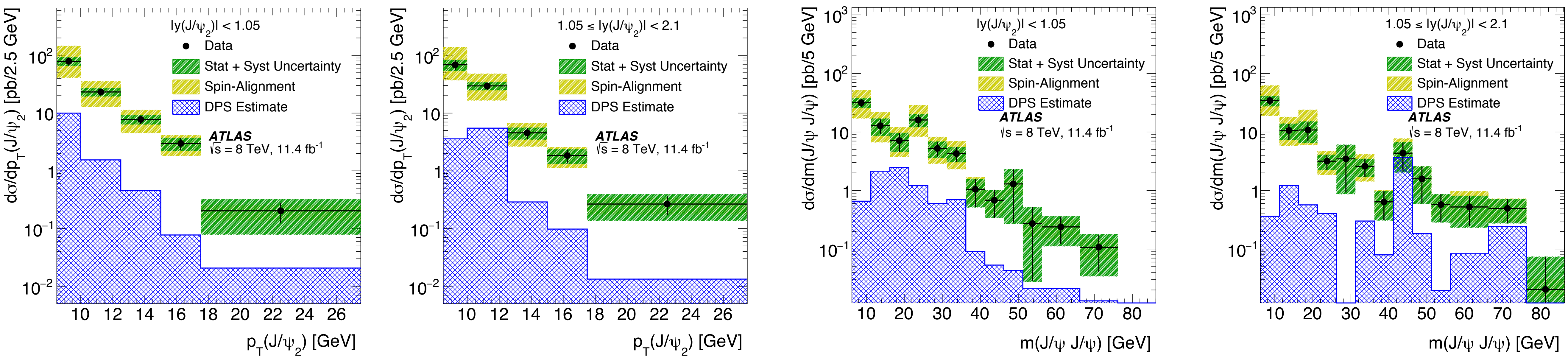




Prompt J/ψ pair production

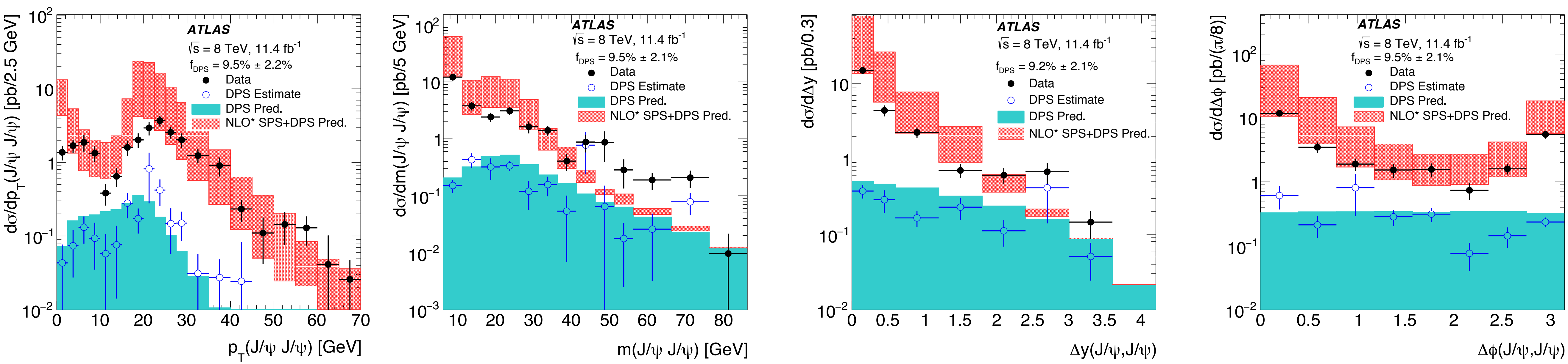
arXiv:1612.02950

Differential cross sections as a function of the sub-leading J/ψ p_T and the invariant mass



Total and DPS cross sections (full rapidity range) in the muon fiducial volume:

di-J/ψ p_T and invariant mass, Δy and $\Delta \phi$



arXiv:1612.02950

Prompt J/ψ pair production

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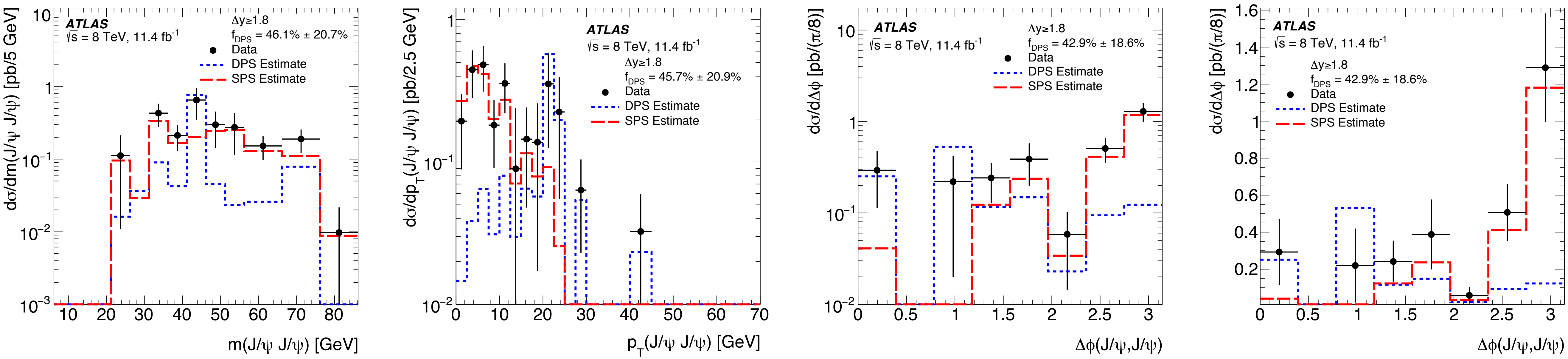
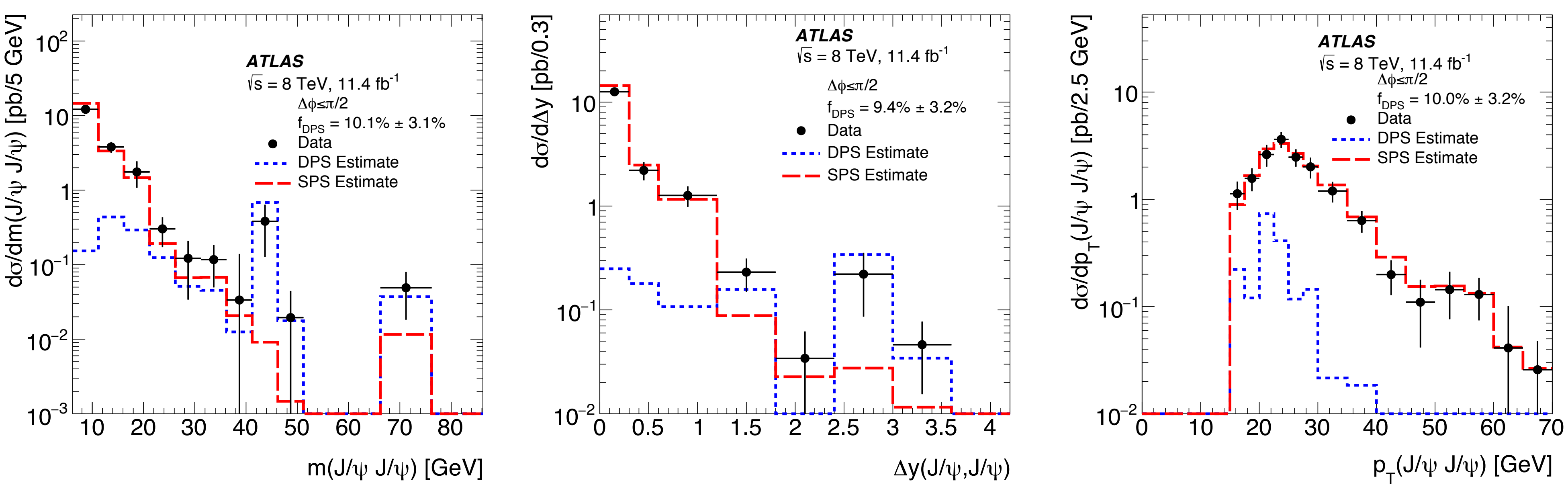
$\Delta y \geq 1.8$



$\Delta\phi \leq \pi/2$



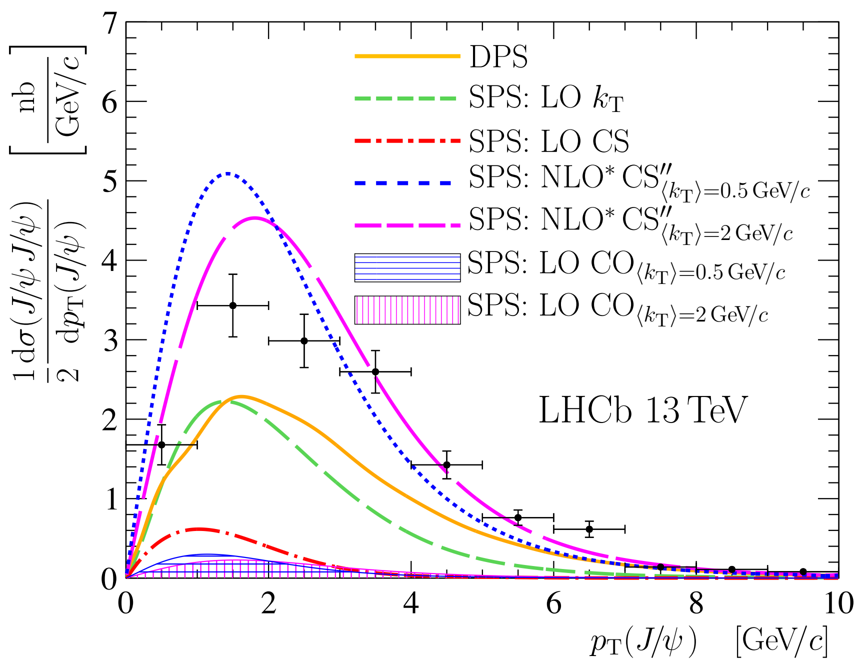
arXiv:1612.02950

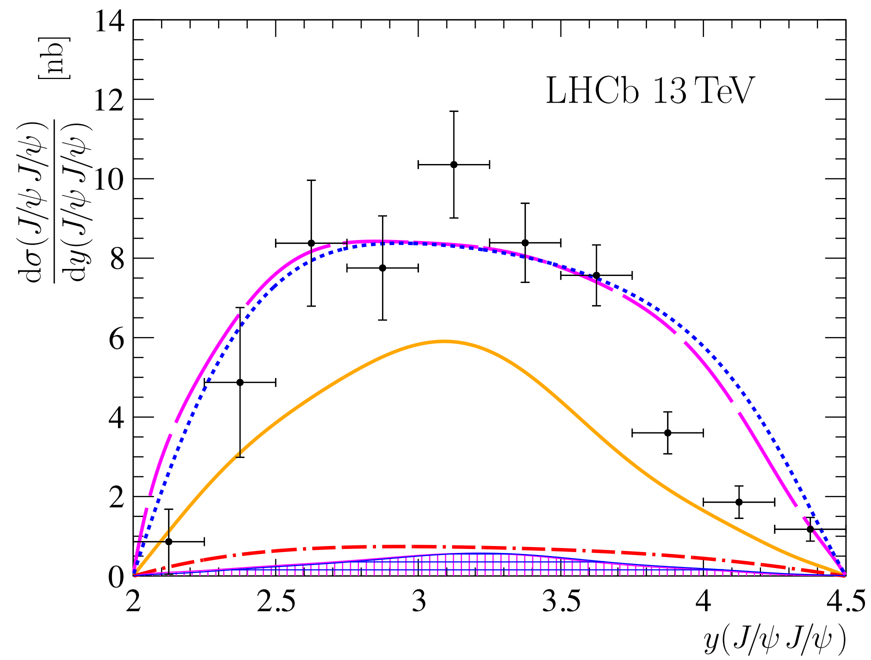
J/ψ pair production

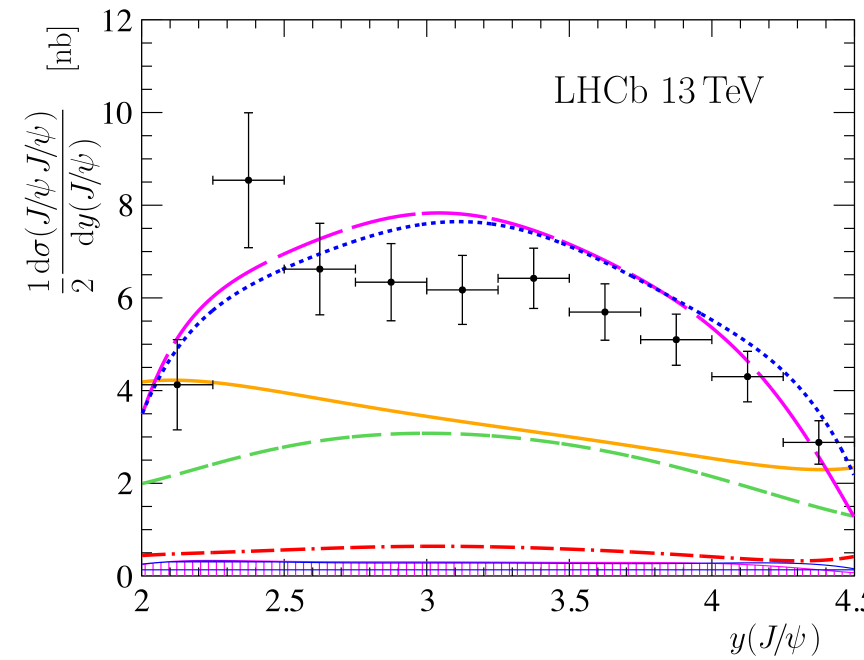
arXiv:1612.07451

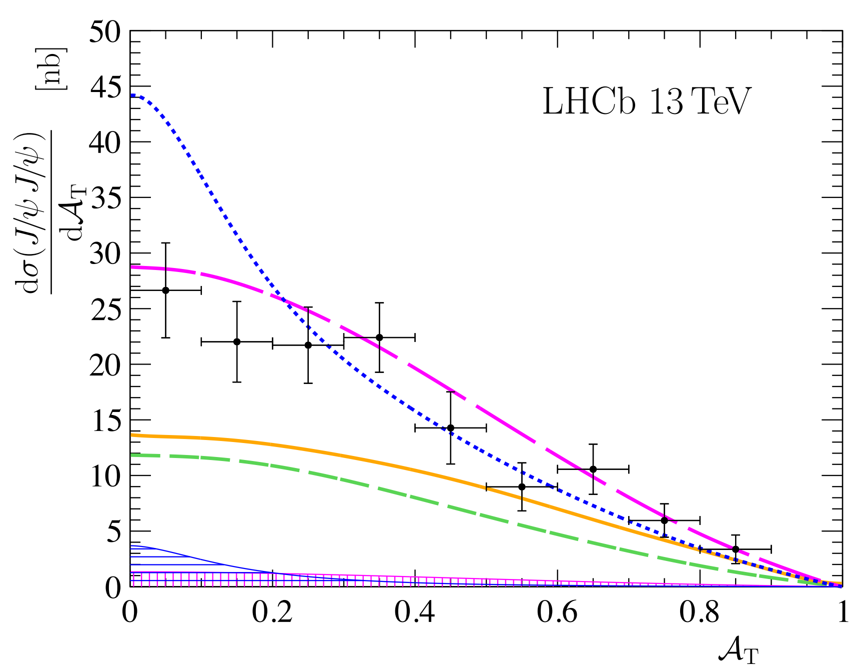
Differential production cross sections:

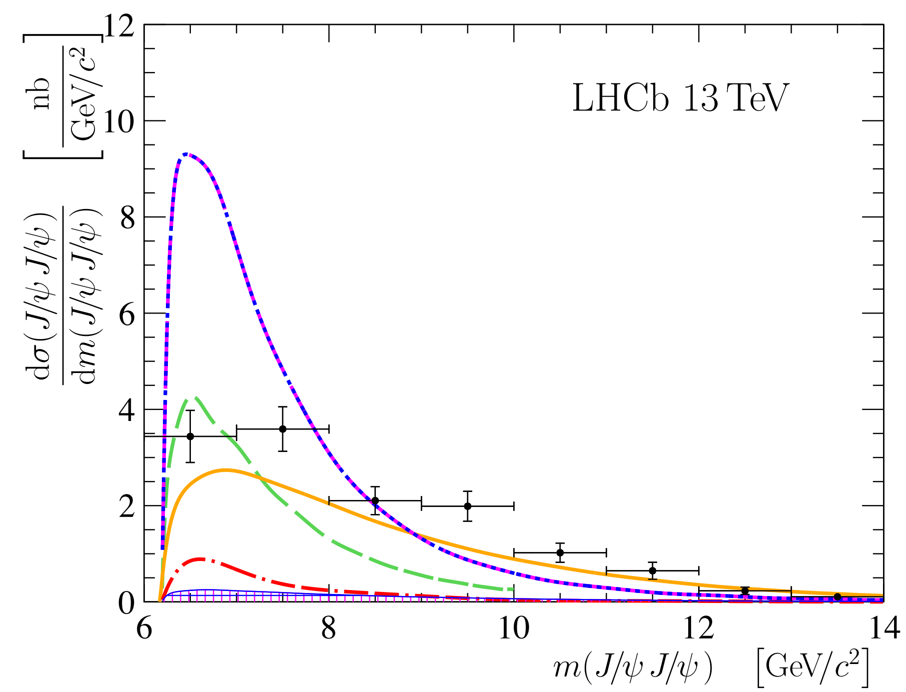
transverse momenta and rapidities of each J/ψ and the J/ψ pair, $\Delta\phi$, Δy and $\mathcal{A} = \frac{p_T^{J/\psi_1} - p_T^{J/\psi_2}}{p_T^{J/\psi_1} + p_T^{J/\psi_2}}$

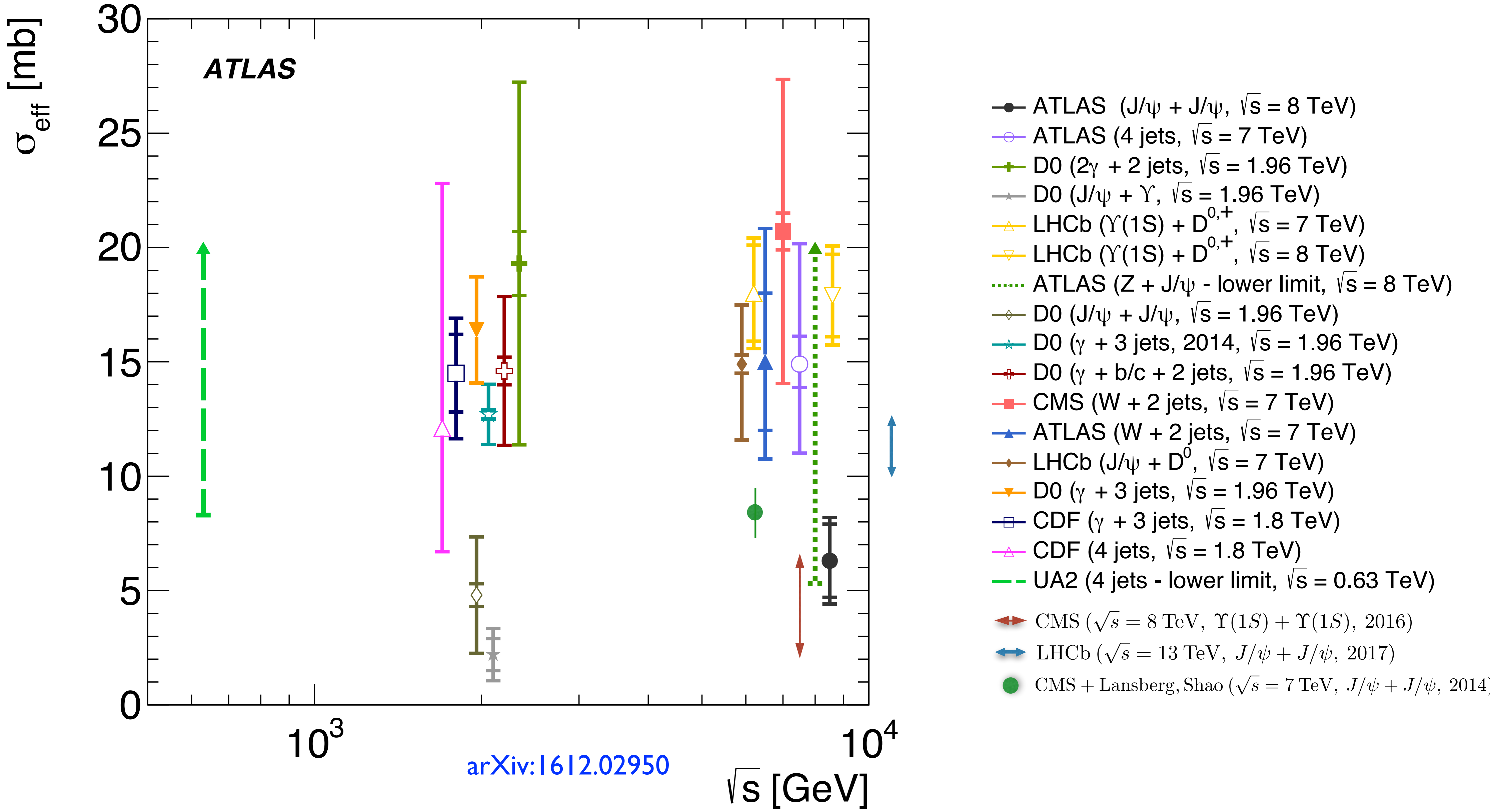




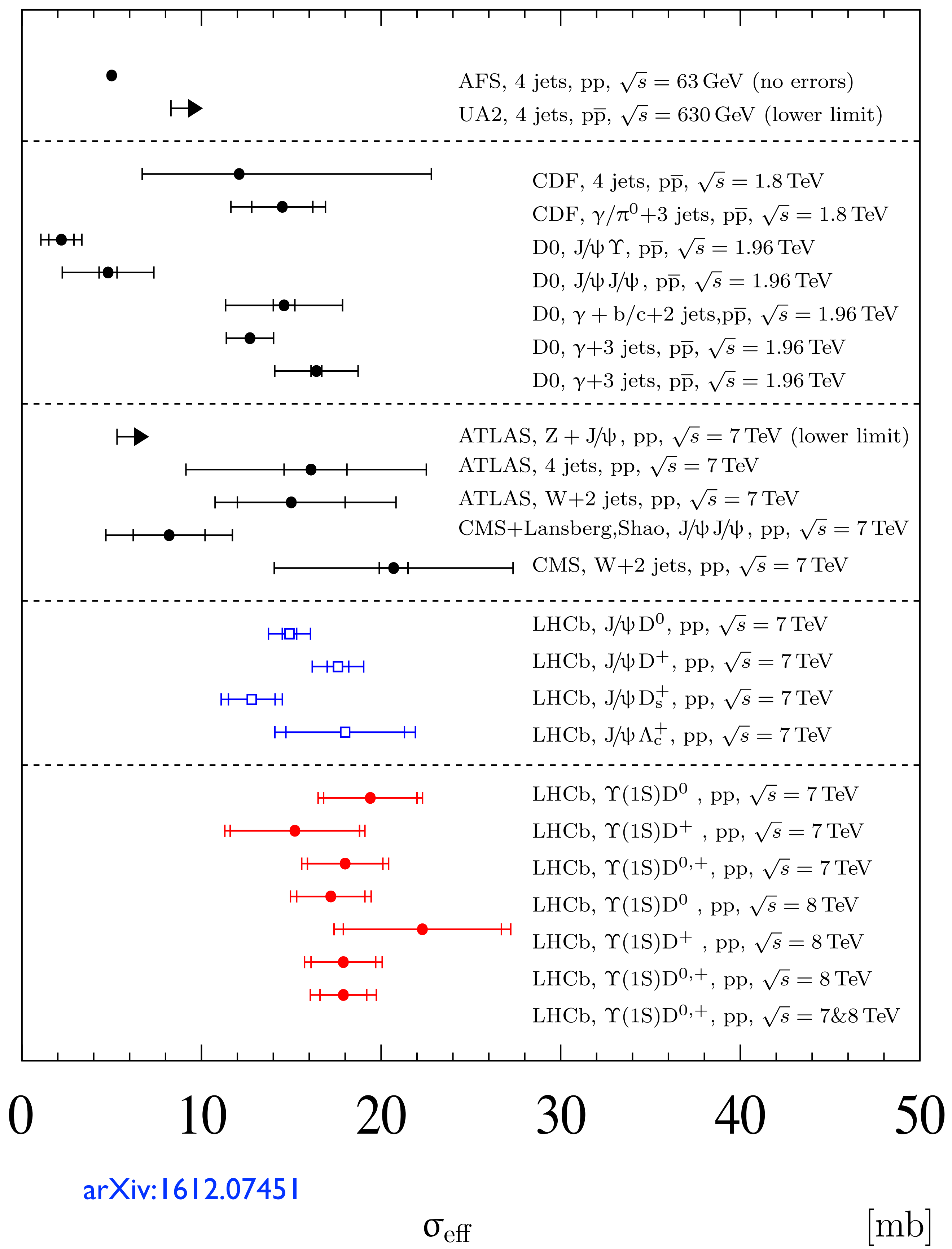








ATLAS
σ_eff [mb]
0
5
10
15
20
25
30
10^3
10^4
√s [GeV]
arXiv:1612.02950
ATLAS (J/ψ + J/ψ, √s = 8 TeV)
ATLAS (4 jets, √s = 7 TeV)
D0 (2γ + 2 jets, √s = 1.96 TeV)
D0 (J/ψ + ϒ, √s = 1.96 TeV)
LHCb (ϒ(1S) + D^{0,+}, √s = 7 TeV)
LHCb (ϒ(1S) + D^{0,+}, √s = 8 TeV)
ATLAS (Z + J/ψ - lower limit, √s = 8 TeV)
D0 (J/ψ + J/ψ, √s = 1.96 TeV)
D0 (γ + 3 jets, 2014, √s = 1.96 TeV)
D0 (γ + b/c + 2 jets, √s = 1.96 TeV)
CMS (W + 2 jets, √s = 7 TeV)
ATLAS (W + 2 jets, √s = 7 TeV)
LHCb (J/ψ + D^0, √s = 7 TeV)
D0 (γ + 3 jets, √s = 1.96 TeV)
CDF (γ + 3 jets, √s = 1.8 TeV)
CDF (4 jets, √s = 1.8 TeV)
UA2 (4 jets - lower limit, √s = 0.63 TeV)
CMS (√s = 8 TeV, ϒ(1S) + ϒ(1S), 2016)
LHCb (√s = 13 TeV, J/ψ + J/ψ, 2017)
CMS + Lansberg, Shao (√s = 7 TeV, J/ψ + J/ψ, 2014)



arXiv:1612.07451