Production of quarkonia states with the ATLAS detector

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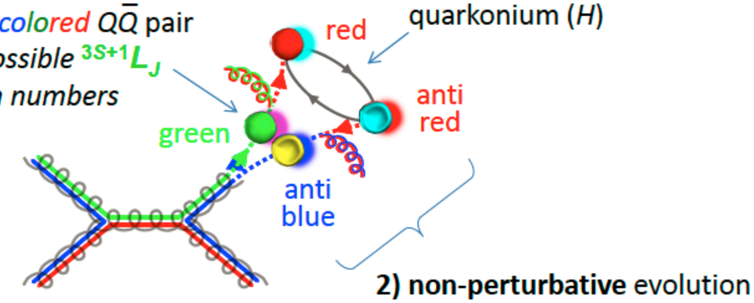
Quarkonium production at the LHC

- The production mechanism of heavy quarkonia is a long-standing and intriguing problem in QCD
  - ❖ Involves both perturbative and non-perturbative QCD
  - ❖ No complete theory yet: *Colour-Singlet Model (CSM) , NRQCD with Colour-Octet Mechanism (COM), k_T* factorization, etc.
  - ❖ Predictions are expected to be more reliable at high p_T region



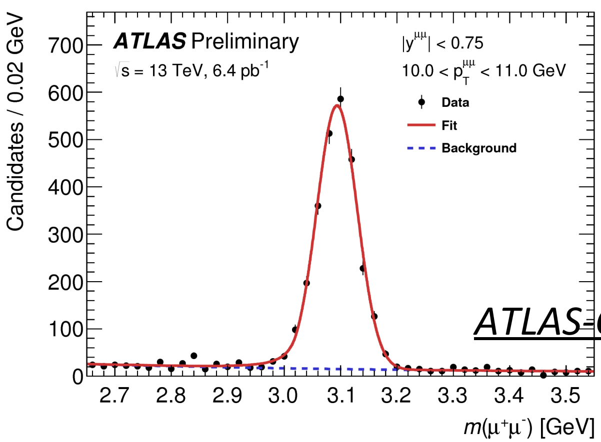
- More recently, through novel exclusive production modes such as di-J/ψ and *W*/*Z*+J/ψ , quarkonia can provide an interesting window into:
  - ❖ Study of multiple parton interactions (MPI)
  - ❖ While also providing new observables for testing production calculations

Quarkonia measurements in ATLAS

- A wide program of studies of quarkonia production is performed with the ATLAS detector:
  - Charmonia and bottomonia production
  - Charmed mesons and beauty mesons
  - Associated production: J/ψ + *W*, J/ψ + *Z* and J/ψ + J/ψ

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

- Mostly in exclusive decays with di-/multi-muon final states, which allows to trigger low-p_T objects

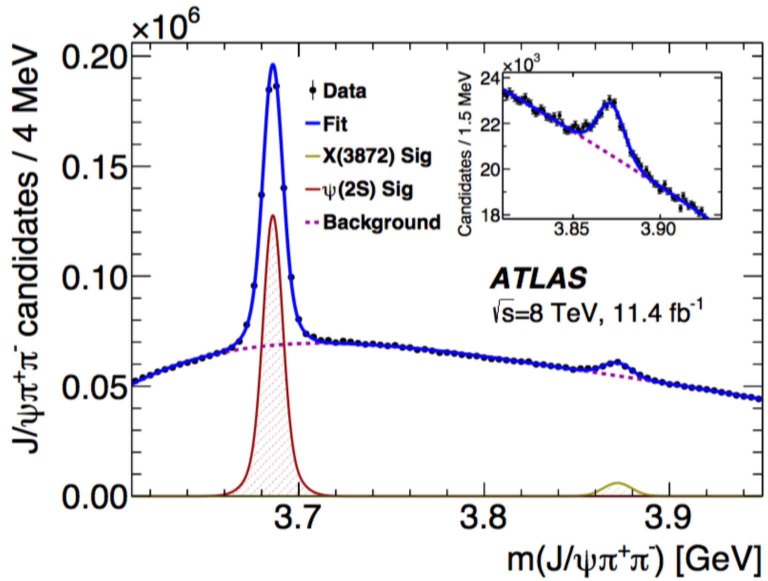


ATLAS-CONF-2015-030

- Recent results:
  - ψ(2S) and X(3872) production measurements at 8 TeV
  - Prompt J/ψ pair production measurements at 8 TeV

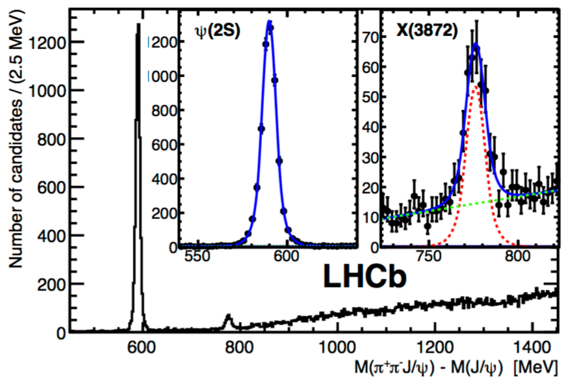
ψ(2S) and X(3872) production measurements

JHEP01(2017)117



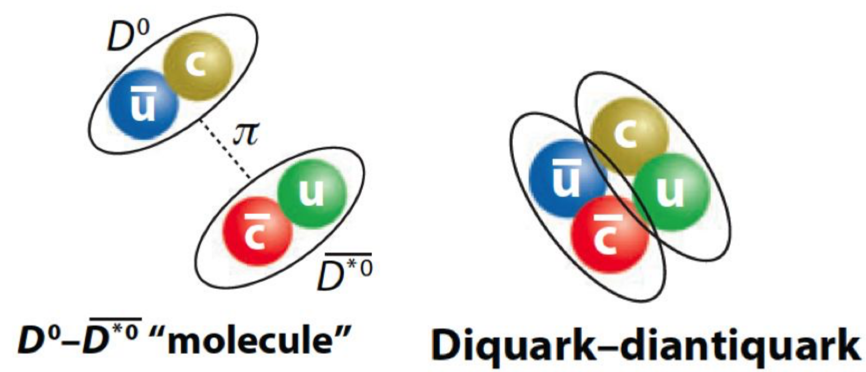
What is X(3872)?

- "Exotic" resonance first observed by Belle in 2003
- Soon after confirmed by BaBar, CDF, D0 and now LHC experiments
- $J^{PC} = 1^{++}$; mass = 3871.69 ± 0.17 MeV → very close to the D^0D^{0*} threshold



Phys. Rev. Lett. 110, 222001 (2013)

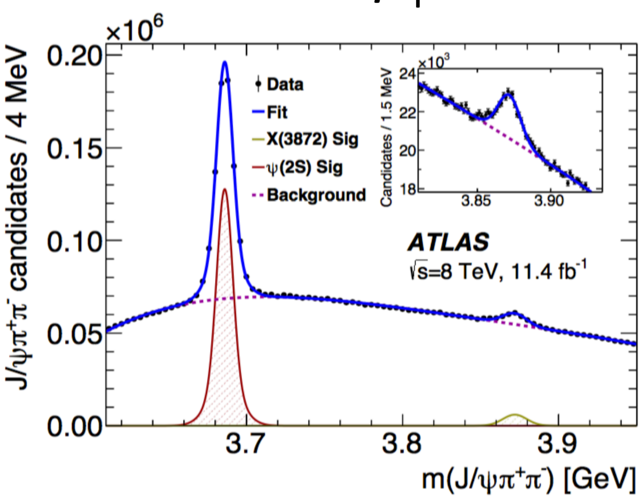
- What is it? No clear picture yet!
  - Loosely bound $D^0 – D^{0*}$ molecule
  - A mixture of $\chi_{c1}(2P)$ -(D^0D^{0*})
  - Tetraquark (diquark – diantiquark)



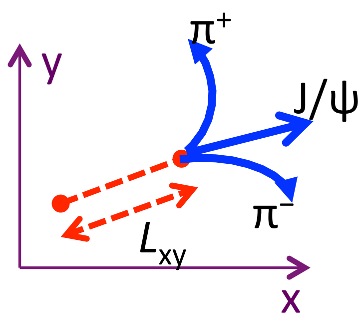
ATLAS presents a new measurement that may help answer some of these questions, and/or create new ones

Overview of the analysis

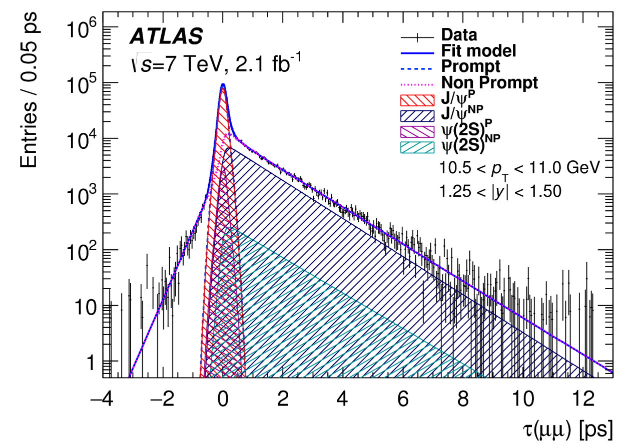
- Decay mode: $J/\psi\ \pi^+\pi^-$, with $J/\psi \rightarrow \mu^+\mu^-$, 11.4 fb^{-1} of 8 TeV ATLAS data
- Rapidity range $|y|<0.75$, p_T range of $J/\psi\ \pi^+\pi^-$ = (10 – 70) GeV
- Corrections for detector geometry and efficiencies are applied on a per-event basis
- The production cross sections of the ψ(2S) and X(3872) states are measured in five p_T bins



$$\tau = \frac{L_{xy}\, m}{c\, p_T}$$



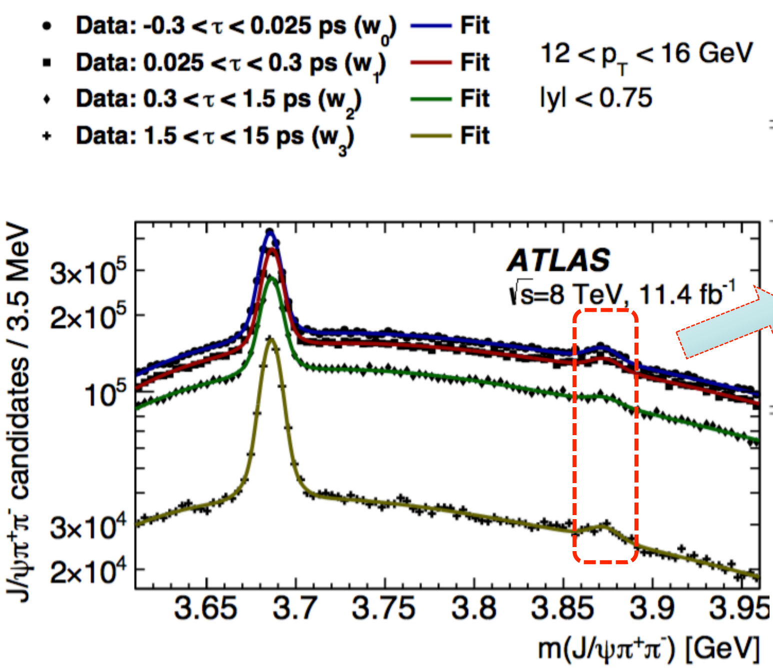
Eur. Phys. J. C 76(5), 1-47, (2016)



- Fits on effective pseudo-proper lifetime τ performed to separate the signal into prompt and non-prompt components

Inclusive ψ(2S) and X(3872) signals extraction

- In each p_T bin, events are further split into 4 τ bins
- Mass fit in each (p_T , τ) bin to determine the ψ(2S) and X(3872) yields



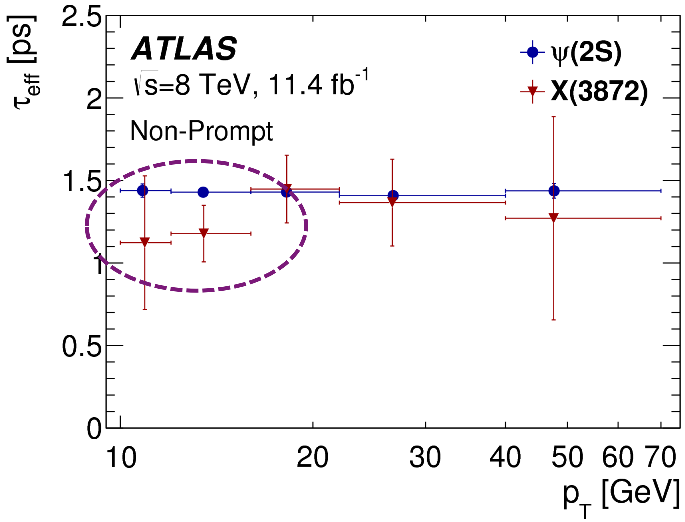
τ window	Corrected yields of $X(3872)$ [×10[4]] vs. p_T [GeV] 10–12	12–16	16–22	22–40	40–70
w_0	10.8 ± 2.3	10.55 ± 0.76	3.53 ± 0.26	1.19 ± 0.11	0.093 ± 0.030
w_1	9.3 ± 2.7	8.21 ± 0.71	2.60 ± 0.24	0.72 ± 0.11	0.039 ± 0.023
w_2	4.1 ± 1.7	3.83 ± 0.63	1.29 ± 0.21	0.45 ± 0.10	0.036 ± 0.023
w_3	2.06 ± 0.81	2.09 ± 0.34	0.98 ± 0.13	0.30 ± 0.06	0.020 ± 0.014

Extracted signal yields can be used directly for total production cross section
→ Need lifetime analysis to separate prompt and non-prompt

Lifetime fit (1)

- Perform lifetime fit to the 4 τ bins in each p_T bin, separately for ψ(2S) and X(3872): $F^i(\tau) = (1 - f^i_{NP})F^i_P(\tau) + f^i_{NP}F^i_{NP}(\tau),$

Single lifetime fit (1L):
With only one single "effective pseudo-proper lifetime" $\boldsymbol{\tau_{eff}}$ fitted to the data.



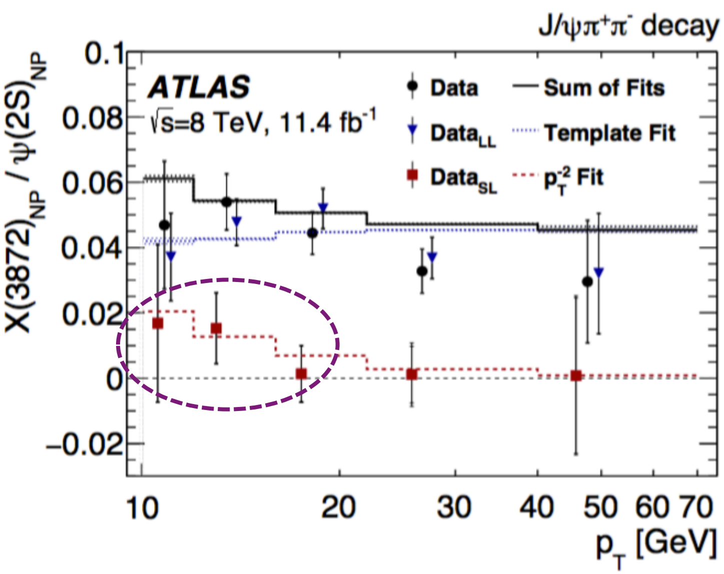
The signal from X(3872) at low p_T tends to have shorter lifetimes
→ Possibly hinting at a different production mechanism at low p_T?

Lifetime fit (2)

- Perform lifetime fit to the 4 τ bins in each p_T bin, separately for ψ(2S) and X(3872): $F^i(\tau) = (1 - f^i_{NP})F^i_P(\tau) + f^i_{NP}F^i_{NP}(\tau),$

Two lifetime fit (2L):
To further separate the short-lived ($B^\pm_c$) and long-lived ($B^\pm$, B^0, B_s mesons and *b*-baryons) components:

$$F^i_{NP}(\tau) = (1 - f^i_{SL})F_{LL}(\tau) + f^i_{SL}F_{SL}(\tau).$$



τ_{SL} =0.40±0.05 ps
τ_{LL} =1.45±0.05 ps

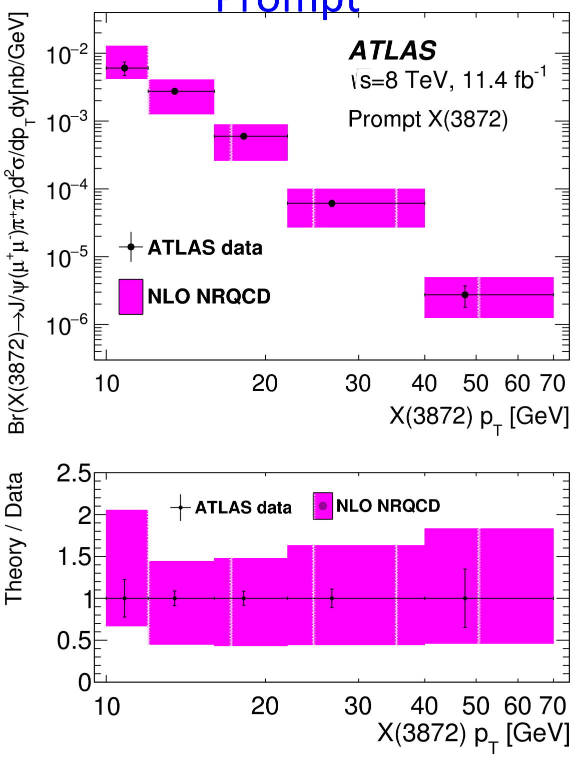
Using the ratio of short-lived of X(3872)/ψ(2S), the fraction of non-prompt X(3872) from short-lived sources is determined:

$$\frac{\sigma(pp \to B_c)\mathcal{B}(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt } X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%,$$

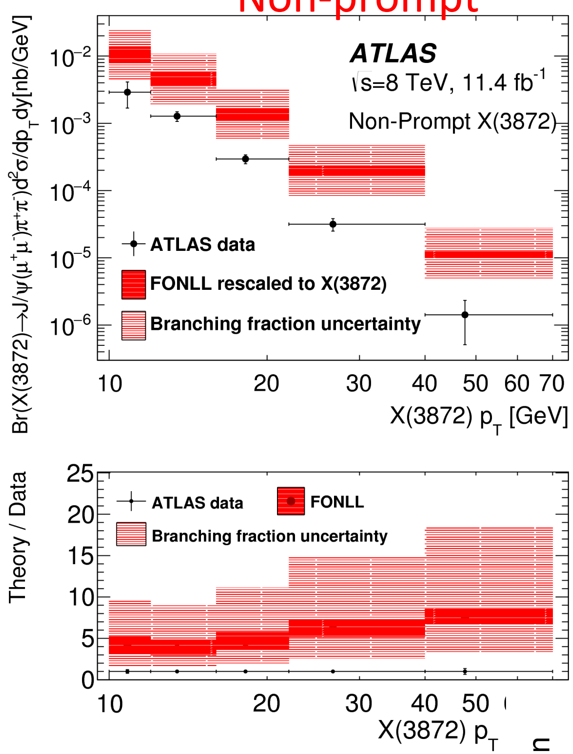
→ Suggested strong enhancement of X(3872) production in B_c decays ?

X(3872) differential cross sections:

Prompt



Non-prompt



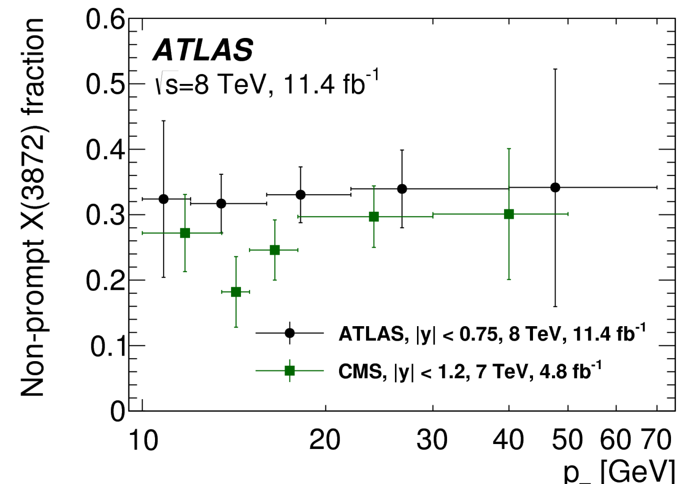
Prompt:

- ❖ Described well by NLO NRQCD (X(3872) considered as a mixture of $\chi_{c1}(2P)$ -(D^0D^0*))

Non prompt:

- ❖ FONLL clearly overshoots the data: factor of 4 to 8, increasing with p_T

Non-prompt fraction

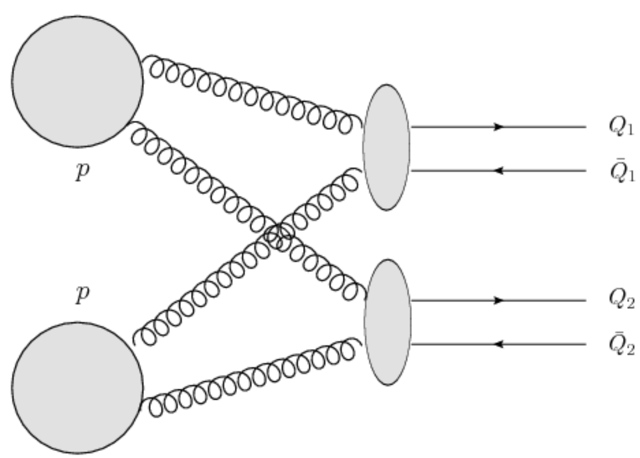


Non-prompt fraction of X(3872):

- ❖ No visible p_T dependence
- ❖ Consistent with CMS result within errors

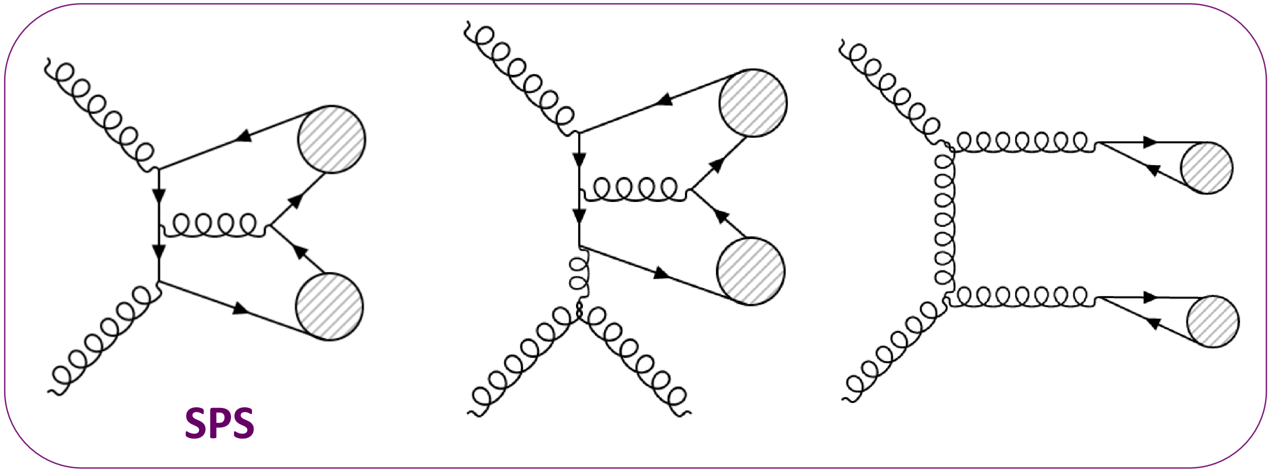
Prompt J/ψ pair production measurements

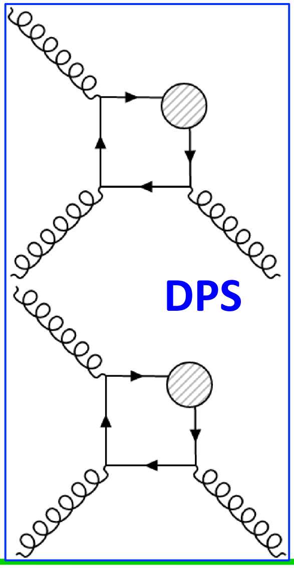
Eur. Phys. J. C77 (2017) 76



Why measure J/ψ pair production?

- Quarkonia pair production:
  - Depends heavily on the production mechanism
  - Sensitive to high order QCD corrections
  - Dominated by single parton scattering (SPS), but double parton scattering (DPS) can also play an important role
- DPS:
  - Probe proton structure
  - Background to new physics searches





Overview of the analysis

ATLAS EXPERIMENT

- Focused on prompt–prompt (**PP**) di-J/ψ production, with the decay $J/\psi \rightarrow \mu^+\mu^-$, 11.4 fb^{-1} of 8 TeV ATLAS data
- Corrections for detector geometry and efficiencies are applied to data
- The PP di-J/ψ signal is extracted sequentially by removing the background:
  - Non-J/ψ background, non-prompt background, pile-up background

Total number of events observed: **1210**
After background subtraction: **1160 ± 70**

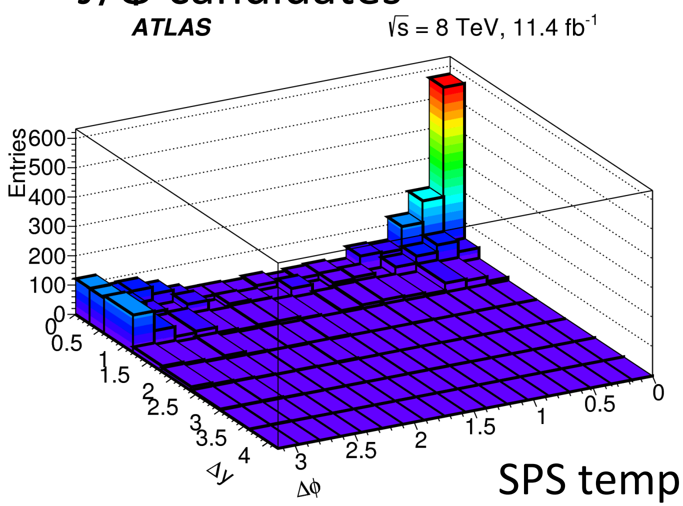
- Differential cross-sections are measured
- SPS and DPS components are determined, and the effective cross-section of DPS **σ_{eff}** is measured

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}},$$

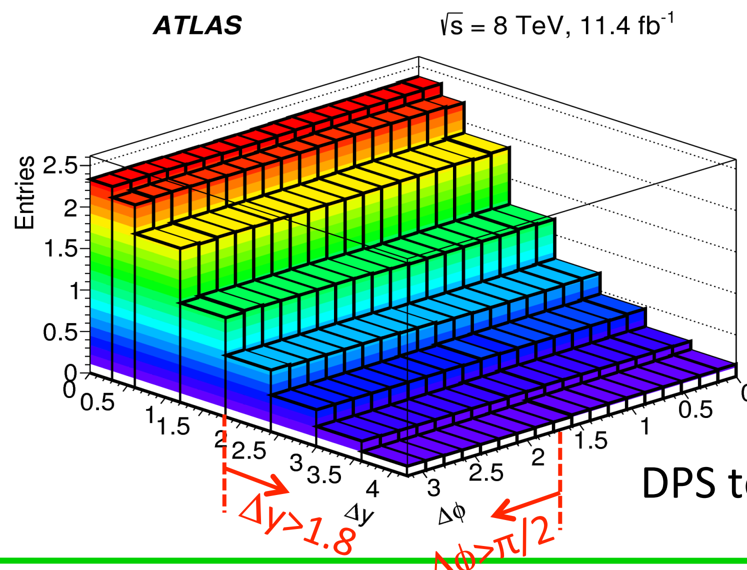
- ❖ Related to the size of the transverse space between partons inside the proton
- ❖ Approximately process and energy independent

DPS extraction

- Not easy to predict SPS distributions:
  - Depends on perturbative QCD corrections of various orders and on *J*/ψ production models
- A data-driven model-independent approach is exploited:
  - DPS template is simulated by combining re-sampled *J*/ψ mesons from two different random events in the di-*J*/ψ sample, normalized to DPS enriched data
  - SPS template is then obtained by subtracting the DPS template
  - SPS and DPS event weights are derived in 2D map of |Δϕ| and |Δy| of the two *J*/ψ candidates

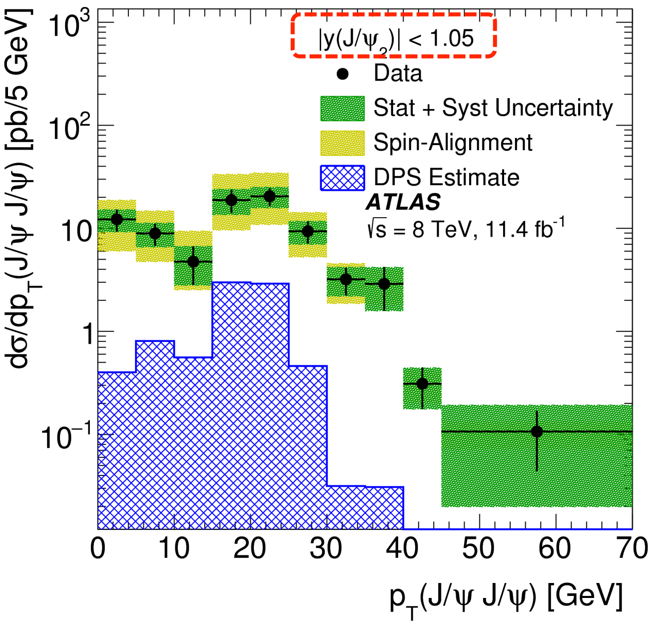


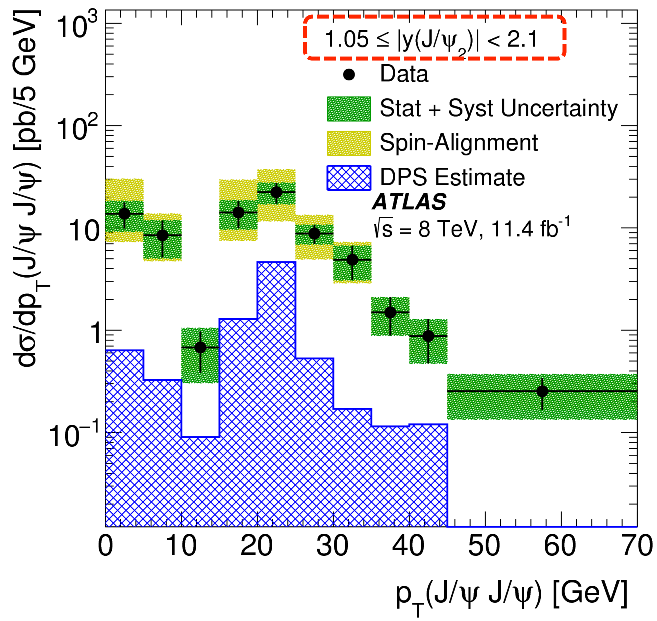
SPS template



DPS template

Differential cross section results





Measured in the J/ψ fiducial volume (p_T > 8.5 GeV, |y| < 2.1)

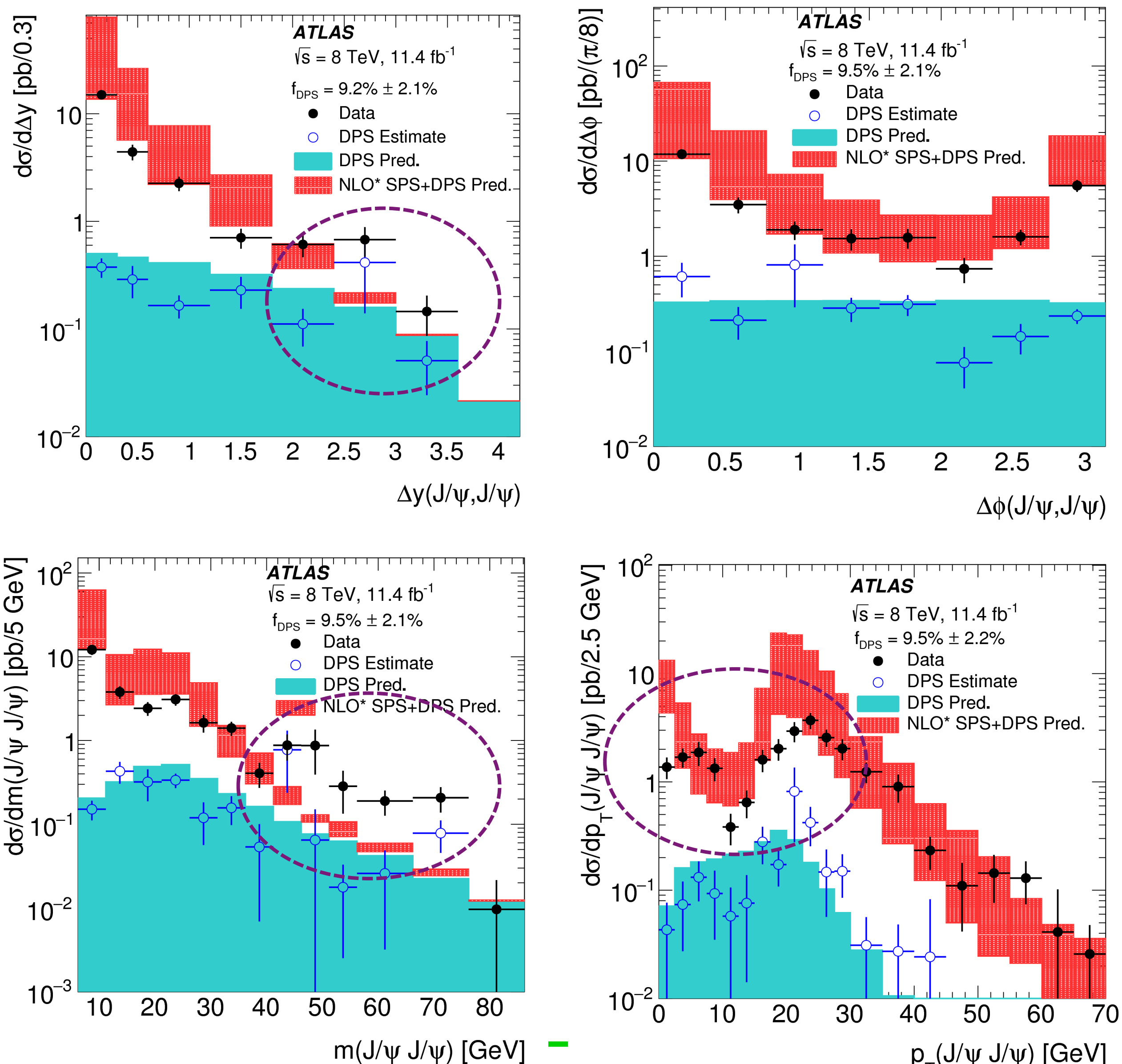
- With assumption of unpolarised *J*/ψ mesons
- Variations due to the maximal *J*/ψ spin-alignment scenarios also shown (yellow band)
- DPS-weighted distributions are also shown

Two peaks structure in dσ/dp_T (*J*/ψ *J*/ψ):

- Low p_T : *J*/ψ are produced back-to-back → ***away*** topology
- High p_T : two *J*/ψ are produced in the same direction → ***towards*** topology (only included in NLO calculation)

A relatively large inclusive DPS fraction: f_{DPS} = 9.2 ± 2.1 (stat) ± 0.5 (syst) %

Differential cross section results (2)

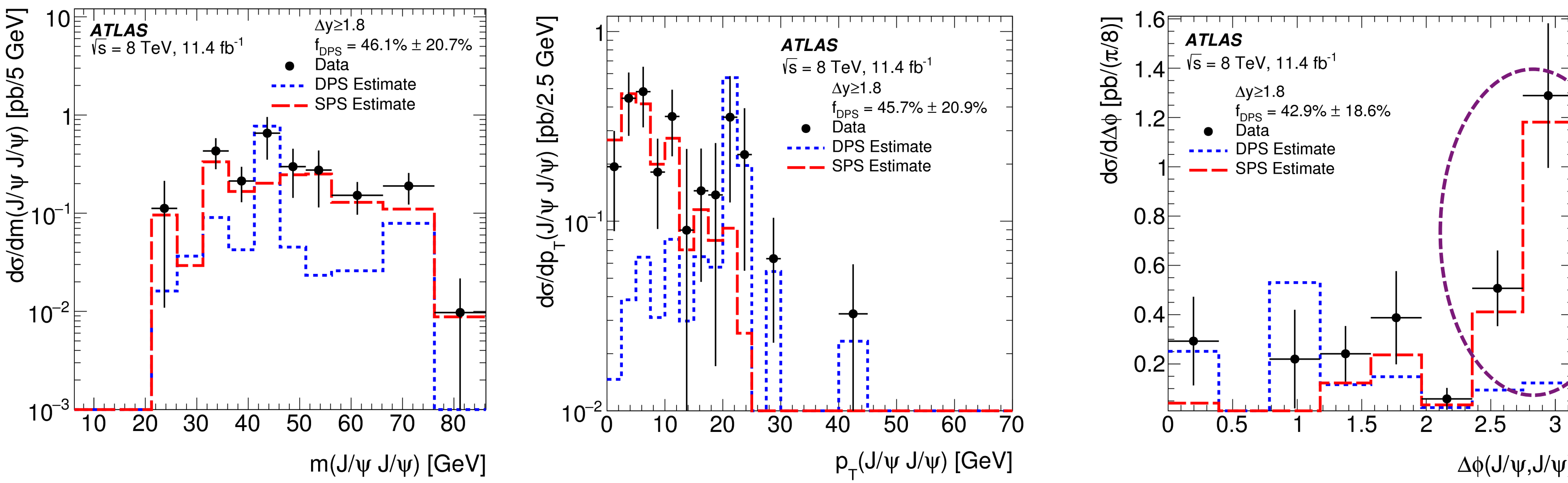


Differential cross sections in muon fiducial volume :

- DPS predictions are normalized to measured f_{DPS} → shape comparison
- NLO SPS is scaled by 1.85 to account for *feed-down*
- Total data deviates from LO DPS + NLO* SPS prediction at large Δy, large invariant mass, and in the low-*p*T region → *"away"* topology

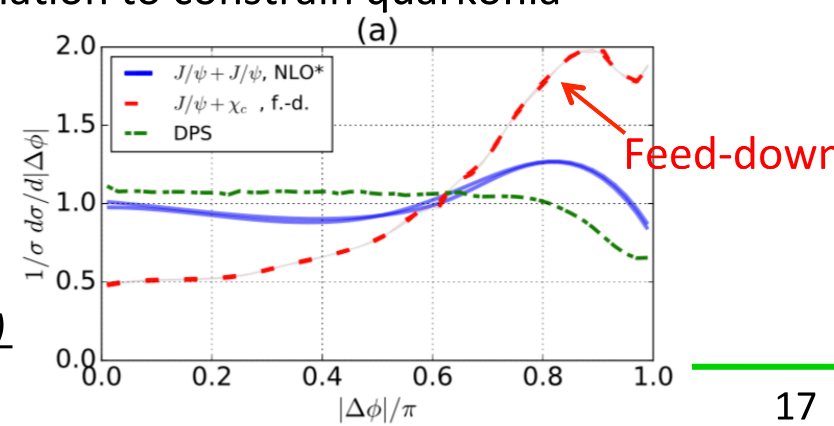
Differential cross section results (3)

- To study the properties of the discrepancies seen, a requirement of $\Delta y \geq 1.8$ is imposed



❖ SPS peaked at $\Delta\phi = \pi$ → non-constant contribution from feed-down?

❖ Further studies needed, and would provide information to constrain quarkonia production models



A.K. Likhoded *et al*, Phys. Rev. D 94, 054017 (2016)

Effective cross-section of DPS

- Effective cross section measurement:

$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{J/\psi,J/\psi}_{\text{DPS}}} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}},$$

σ_{eff} = **6.3 ± 1.6 (stat) ± 1.0 (syst) ± 0.1 (BF) ± 0.1 (lumi) mb.**

$\sigma_{J/\psi}$ is obtained from ATLAS measurements [*Eur. Phys. J. C 76 (2016) 283*]

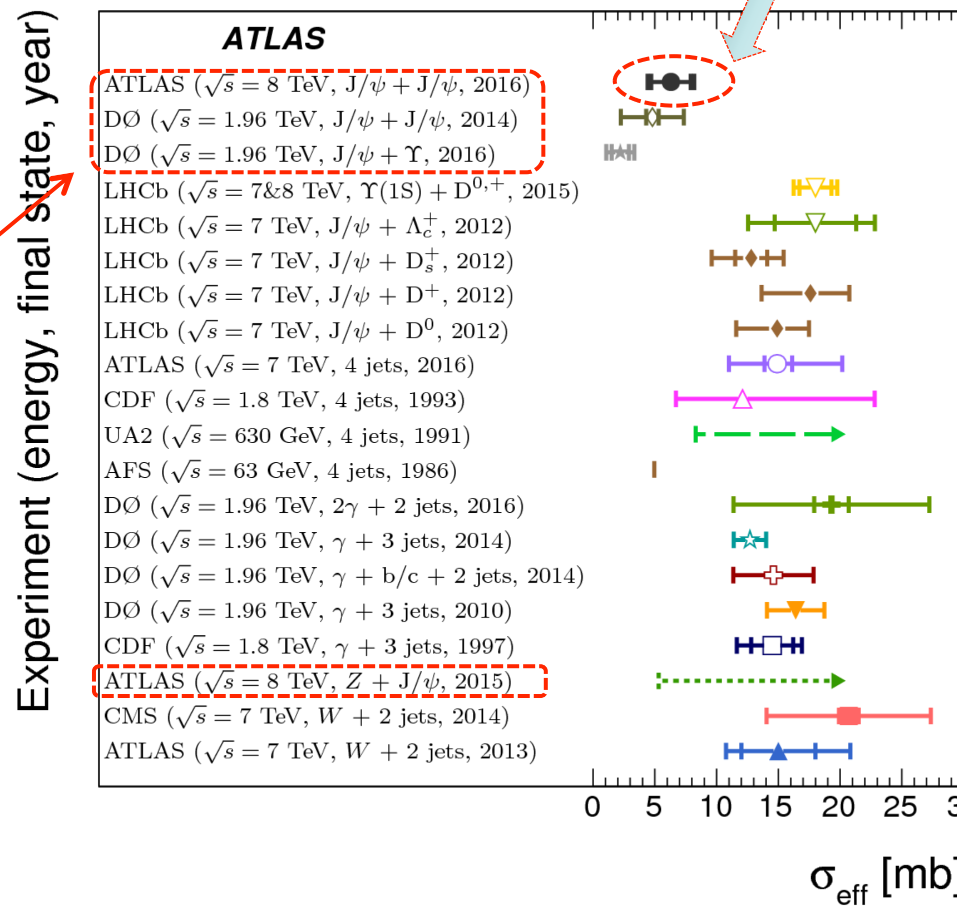
$\sigma_{J/\psi}$ = 429.8 ± 0.1 (stat) ± 38.6 (syst) nb

Close to **D0** results from *quarkonium final stats*, lower than for other measurements

J/ψ production is gluon dominated → suggested smaller average transverse distances between gluons than between quarks in the proton ?

Latest measurements from LHCb @ 13 TeV *arXiv:1612.07451*

σ_{eff} = **9.2±3.9 (stat) mb ~ 14.4 ± 4.9 (stat) mb**



Summary

- Prompt and non-prompt production of $\psi(2S)$ and $X(3872)$ states in the $J/\psi\pi^+\pi^-$ decay mode are studied with 8 TeV data:
  - Prompt production is described reasonably well by NRQCD with previously determined LDMEs, some deviation in the high p_T region
  - A significant fraction of non-prompt X(3872) produced in decays of B_c , measured to be

$$\frac{\sigma(pp \to B_c)\mathcal{B}(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt } X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%,$$

- Prompt di-J/ψ production are studied with 8 TeV data:
  - Differential cross-section as a function of the sub-leading J/ψ p_T, di-J/ψ p_T, and di-J/ψ mass
  - NLO SPS + LO DPS describes data well, except some excess at large Δy and invariant mass
  - The effective cross section for DPS is measured to be:

σ_{eff} = **6.3 ± 1.6 (stat) ± 1.0 (syst) ± 0.1 (BF) ± 0.1 (lumi) mb**.

- More results with 13 TeV data are coming

Backup

ψ(2S)/X(3872): Event selection

- Trigger: Di-muon trigger with 4 GeV pT threshold on each muon
- Muon cuts:
  - pT > 4 GeV, |η| < 2.3
  - Good trigger object matching (ΔR < 0.01)
- J/ψ cuts:
  - $\chi^2_{dimu\_vtx}$ < 200, p_T > 8 GeV & |y| < 2.3
  - | m(J/ψ) - m(J/ψ)PDG | < 120 MeV
- π cuts:
  - Opposite sign, pT > 600 MeV, |η| < 2.4
- $J/\psi\pi^+\pi^-$ background suppression cuts:
  - $P(\chi^2_{J/\psi\pi\pi}) > 4\%$
  - Opening angle ΔR(J/ψ, π±) < 0.5
  - Q = m(J/ψπ+π-) - $m(J/\psi)_{PDG}$ – m(π+π-) < 300 MeV

ψ(2S)/X(3872): systematic uncertainties

- Min., Med. and Max. values for the contributions of various sources of systematic uncertainties across the p_T bins:

Differential cross sections

Source of uncertainty	$\psi(2S)$[%] Min	Med	Max	$X(3872)$[%] Min	Med	Max
Statistical	0.9	1.4	5.4	7.3	9.9	63
Trigger eff.	1.0	1.3	2.5	1.1	1.3	2.6
Muon tracking	2.0	2.0	2.0	2.0	2.0	2.0
Muon reconstruction eff.	0.2	0.2	0.3	0.2	0.2	0.4
Pion reconstruction eff.	2.5	2.5	2.5	2.5	2.5	2.5
Bkgd suppression req.	0.8	0.8	3.0	2.0	3.0	6.0
Mass fit model variation	0.6	0.8	1.2	0.9	1.6	2.6
Short-lifetime variation	0.1	0.2	0.3	0.2	0.7	1.7
Long-lifetime variation	0.6	1.0	1.2	0.3	0.6	0.9
Lifetime resolution model	0.4	1.5	4.0	0.6	2.6	3.4
Total systematic	3.5	3.6	6.4	4.1	4.9	7.5
(2L-fit − 1L-fit) / 2L-fit (prompt)	−0.1	−0.4	−0.6	−0.3	−0.5	−3.4
(2L-fit − 1L-fit) / 2L-fit (non-prompt)	+0.1	+0.4	+0.7	+0.1	+1.4	+9.8

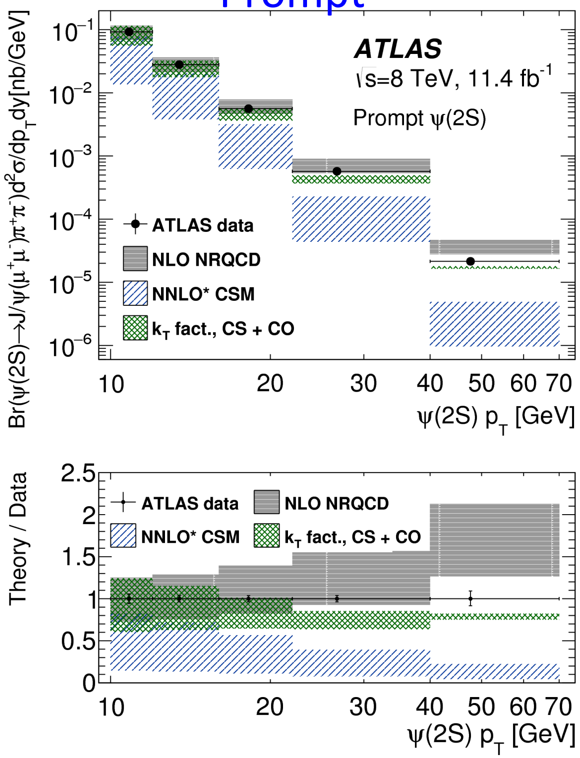
Non-prompt fractions

Absolute uncertainty [%]								
f^{ψ}_{NP} Min	Med	Max	f^{X}_{NP} Min	Med	Max	f^{X}_{SL} Min	Med	Max
0.4	0.5	1.4	4.2	5.8	17.8	16.4	25.8	63
0.1	0.1	0.3	0.1	0.1	0.4	0.0	0.1	0.1
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1
0.4	0.5	0.7	0.3	0.3	0.4	0.0	0.3	0.4
0.8	1.1	1.4	0.6	0.7	0.7	0.1	0.1	0.7
0.1	0.1	0.2	0.2	0.6	1.8	1.0	1.3	2.4
0.2	0.7	1.7	0.4	1.0	2.9	1.8	3.6	12.1
0.0	0.1	0.1	0.1	0.4	0.8	0.3	0.7	2.8
0.3	0.4	0.4	0.2	0.2	0.3	3.3	4.0	4.4
1.3	1.5	2.4	1.0	1.4	3.6	4.1	4.9	13.5
+0.4	+0.6	+0.9	+0.9	+3.1	+9.1	–	–	–

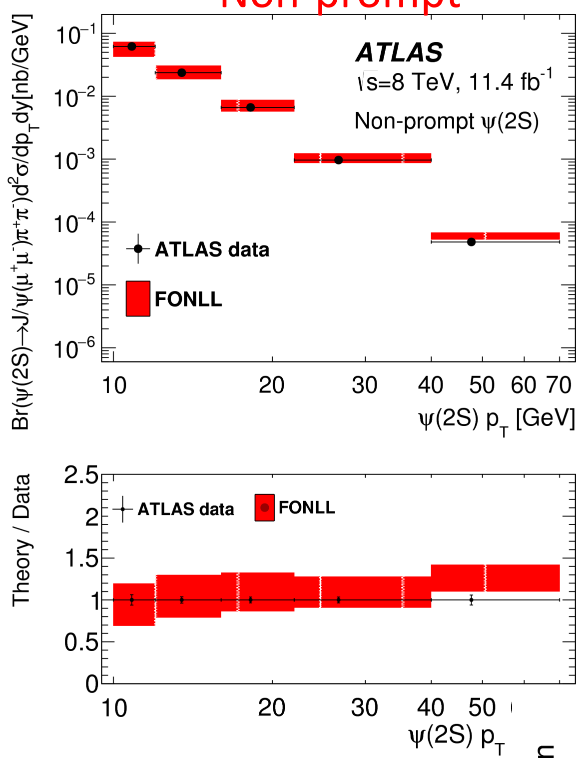
Typically, for X(3872) errors are statistically dominated
For ψ(2S) statistical and systematic errors are similar in size

ψ(2S) differential cross sections:

Prompt



Non-prompt

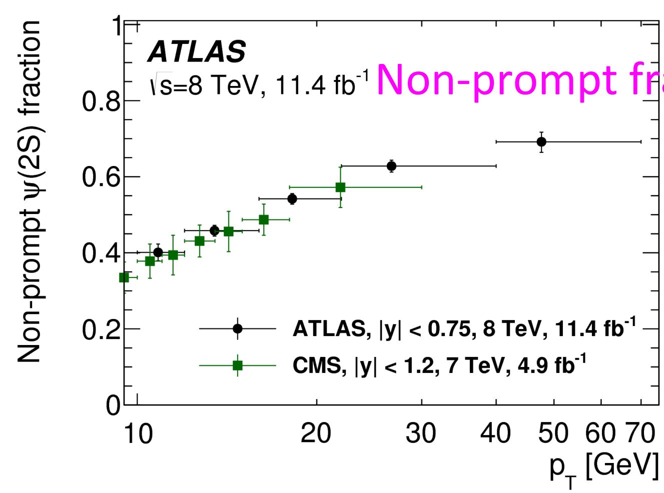


Prompt:

- ❖ Predictions matcht data well at low p_T , deviates at high p_T

Non-prompt:

- ❖ Fixed-order next-to-leading-logarithm (FONLL) describes data well



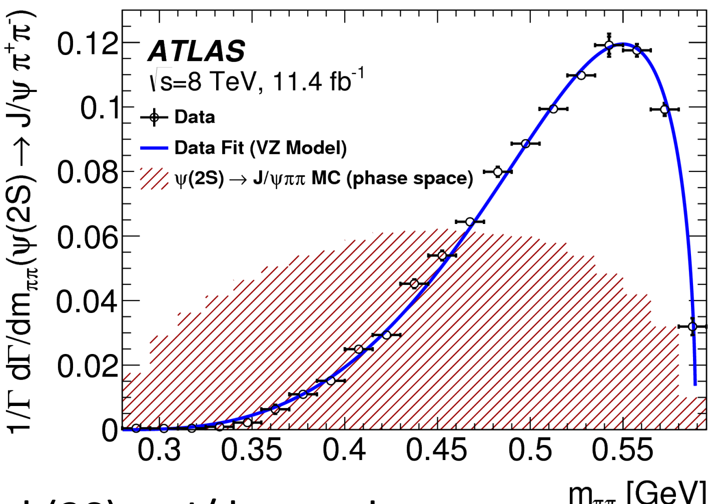
Non-prompt fraction

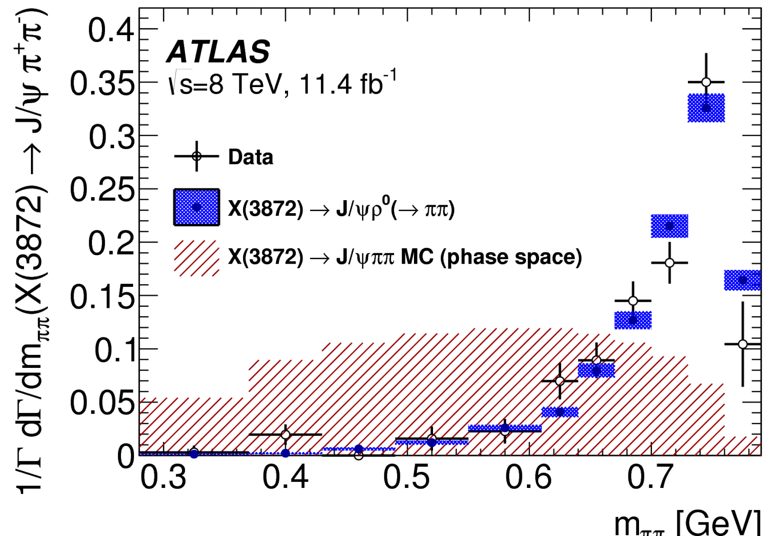
Non-prompt fraction:

- ❖ Grows with p_T as expected
- ❖ Little dependence on energy
- ❖ Agrees well with CMS at 7 TeV

Di-pion mass distribution

- Measured invariant mass distributions of the di-pion system in the decays of ψ(2S) and X(3872) into $J/\psi\pi^+\pi^-$





In ψ(2S) to J/ψπ+π- decays:

- ❖ Dipion mass distribution peaks at high masses
- ❖ Fit to Voloshin-Zakharov function

$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS},$$

- ❖ Found λ = 4.16 ± 0.06(stat) ± 0.03(syst) in agreement with previous measurements

In X(3872) to J/ψπ+π- decays:

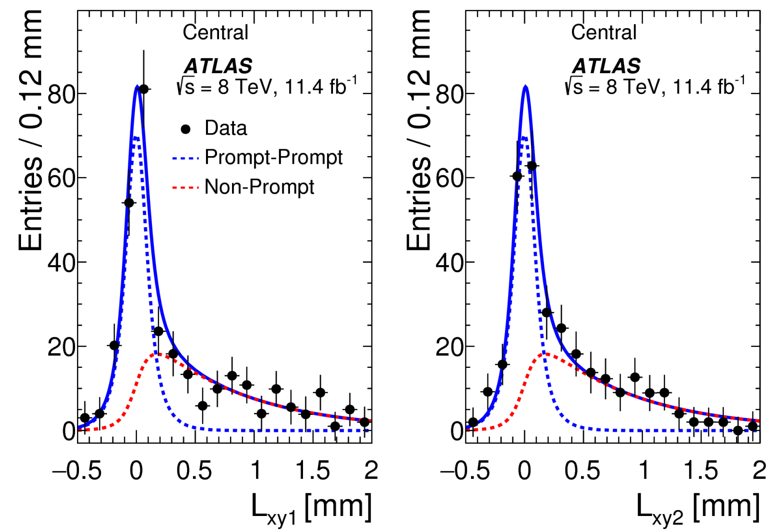
- ❖ Dipion mass distribution has an even sharper peak at high masses
- ❖ In agreement with simulation where the di-pion system is produced via ρ_0 meson decay
- ❖ Also in agreement with previous observations

Di-J/ψ: Event selection

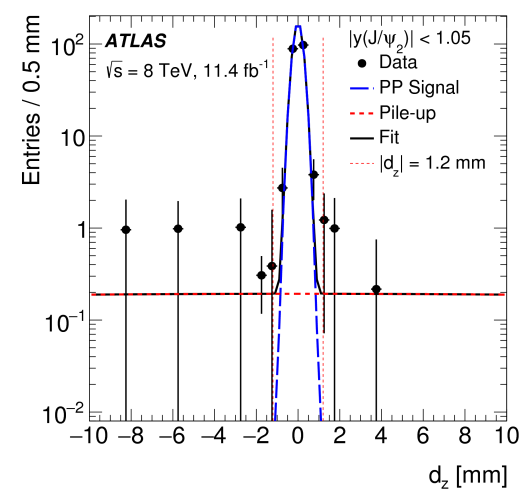
- Trigger: Di-muon J/ψ trigger with 4 GeV pT threshold on each muon
- Muon cuts:
  - pT > 2.5 GeV, $|\eta| < 2.3$
  - Muons from triggered J/ψ must have pT > 4 GeV.
- J/ψ cuts:
  - $2.8 \leq m_{\mu\mu} \leq 3.4$ GeV for each J/ψ candidate
  - $p_T > 8.5$ GeV and $|y_{J/\psi}| < 2.1$
  - Distance of the J/ψ decay vertices in the *z*-plane: $|d_z| < 1.2$ mm.
  - L_{xy} error < 0.3 mm.

Background subtraction

- The PP di-J/ψ signal is extracted sequentially by removing the background
  - ❖ Non-J/ψ background:
    Perform a 2D fit of $m(J/\psi 1)$ against $m(J/\psi 2)$
  - ❖ Non-prompt background:
    Extract PP signal from a fit of the transverse decay length L_{xy} of each J/ψ



  - ❖ Pile-up background:
    Estimated from a fit to the d_z (distance of the J/ψ decay vertices long the beam direction)



Total number of events observed: **1210**
After background subtraction: **1160 ± 70**

Di-J/ψ: Systematic uncertainties

- Sources of systematic uncertainty:

Systematic uncertainty: di-J/ψ cross-section [%]		
Source	$\lvert y(J/\psi_2)\rvert < 1.05$	$1.05 \le \lvert y(J/\psi_2)\rvert < 2.1$
Trigger	± 7.5	± 8.3
Muon reconstruction	± 1.1	± 1.3
Kinematic acceptance	± 0.4	± 1.1
Mass model	± 0.1	± 0.1
Mass bias	± 0.2	± 0.2
Prompt–prompt model	± 0.2	± 0.01
Differential f_{PP} corr.	± 0.6	± 0.3
Pile-up	± 0.03	± 0.4
Total	$\pm$ 7.7	$\pm$ 8.5
Branching fraction	± 1.1	
Luminosity	± 1.9	

Cross-section measurement

- Trigger is the dominant source of the systematic uncertainty due to the trigger selection.

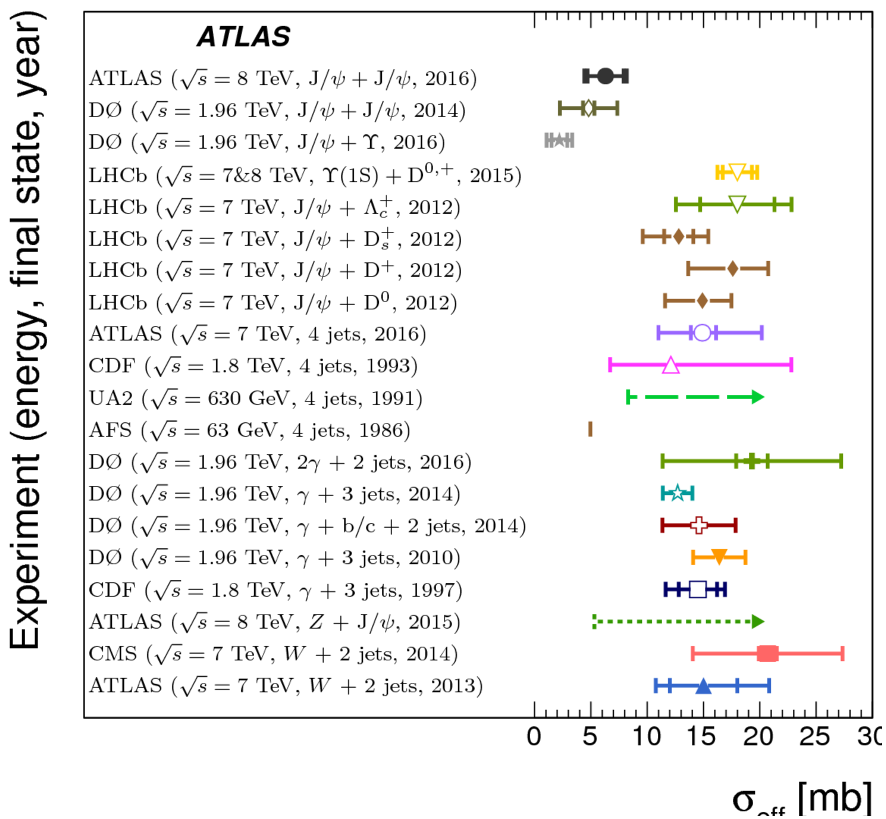
Systematic uncertainty: f_{DPS} [%]	
Source	Relative uncertainty [%]
Trigger	± 0.7
Muon reconstruction	± 0.1
Mass model	± 0.01
Mass bias	± 0.02
Prompt–prompt model	± 0.1
Differential f_{PP} corr.	± 0.1
Pile-up	± 0.8
DPS model	± 5.6
Total	$\pm$ 5.7

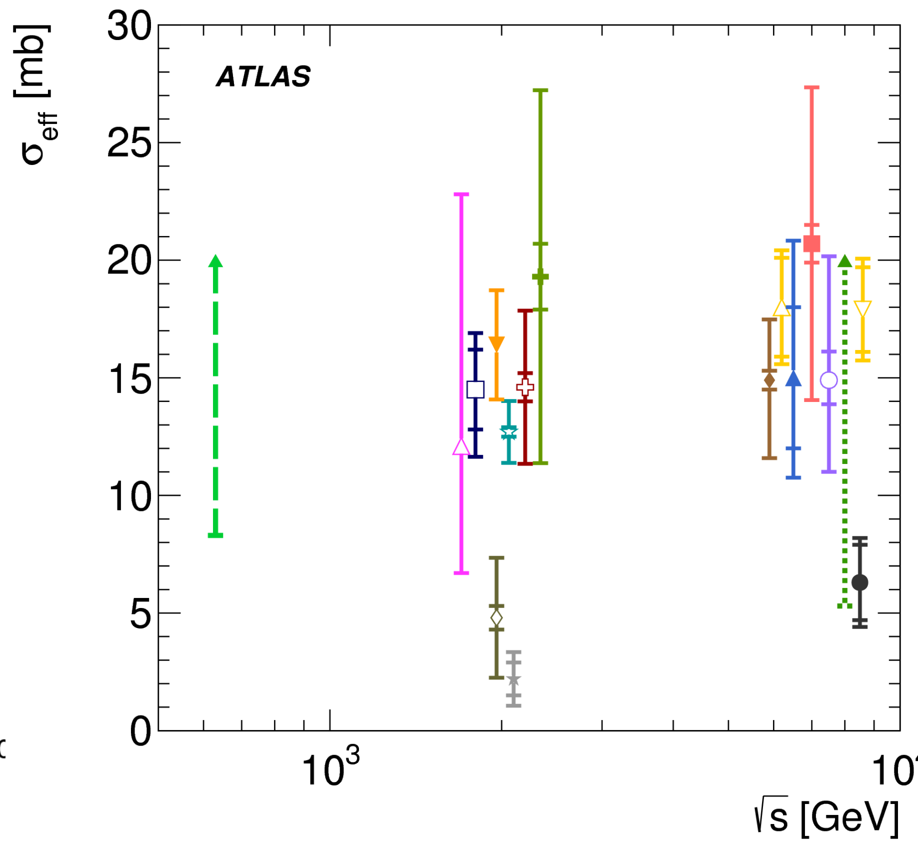
f_{DPS} measurement

- Many of the systematic uncertainties cancel

σ_{eff}

-





Variable	LO k_T	NLO* CS″	
		$\langle k_T \rangle = 2\,\mathrm{GeV}/c$	$\langle k_T \rangle = 0.5\,\mathrm{GeV}/c$
$p_T(J/\psi\, J/\psi)$	11.3 ± 1.6	10.1 ± 4.4	11.0 ± 1.3
$y(J/\psi\, J/\psi)$	—	9.2 ± 3.9	10.0 ± 3.9
$m(J/\psi\, J/\psi)$	11.4 ± 1.2	11.3 ± 1.5	11.3 ± 1.5
$\lvert\Delta y\rvert$	14.4 ± 4.9	14.0 ± 4.4	14.2 ± 4.7

← Latest measurements from LHCb @ 13 TeV *arXiv:1612.07451* DPS fits for different SPS models. The uncertainty is statistical only