Associated production of quarkonium in ATLAS

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School and Workshop "Frontiers of QCD"
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`New observables’ in quarkonium production

- Despite 40+ years’ history, we still have no clear and reliable picture of quarkonium production in hadronic -- and other -- collisions

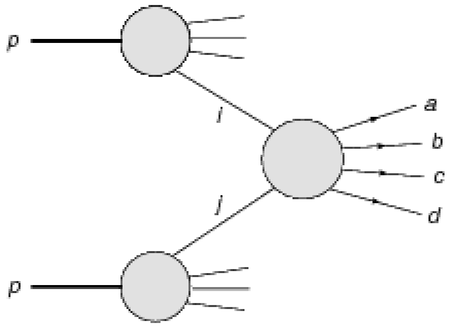
- New energy frontiers and higher luminosities at LHC allow exploration of other reactions that may help understand better the dynamics of quarkonium production

- Simply speaking, more equations (experimental constraints) may help determine unknowns better, even if some new unknowns are introduced

- Examples of these `new observables’: associated production of quarkonium with other objects, such as:
  - other quarkonium (LHCb, CMS, now ATLAS)
  - W or Z bosons (ATLAS)
  - others to come ?

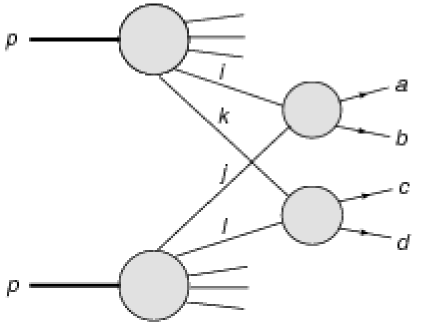
The production of two objects in the same pp collision can be due to

Single-Parton Scattering (SPS):



the two objects are produced via a subprocess in a single interaction of two partons

Double-Parton Scattering (DPS):

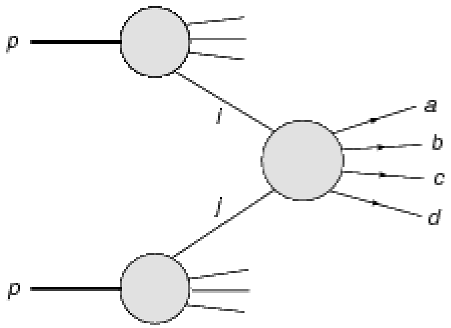


simultaneous interaction of two pairs of partons, each producing one of the two objects, assumed to be uncorrelated

E. Berger et al. Phys.Rev. D84 (2011) 074021 arXiv:1107.3150 [hep-ph]

SPS

- **Single-Parton Scattering (SPS) can be treated in the usual way, once the subprocess cross section is calculated**
- **After all, this is just "another subprocess"**
- **If the final particles are colourless, all the usual factorisation theorems are valid**

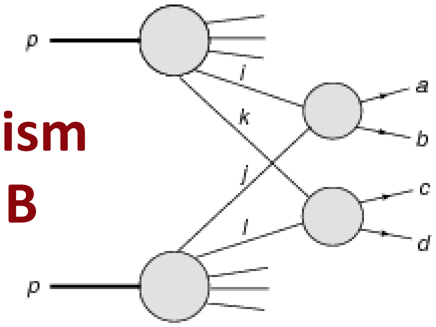


- **(at least as valid as for other subprocesses, may be more)**
- **Since the initial partons are unlikely to have large transverse momenta, the final state objects are expected to be produced back-to-back in transverse plane**
- **(up to some smearing due to initial- and final-state radiation etc)**

DPS

- **Double-Parton Scattering (DPS) can be treated in as two subprocesses happening simultaneously in the same pp collision**

- **Assuming the masses and momenta are much smaller than collision energy, one can ignore correlations due to overall Energy-momentum conservation**



- **So one can apply the usual parton model / QCD formalism TWICE, once for subprocess A and once for subprocess B**

- **The problem is the cross sections are dimensional, and one needs a dimensional factor σ_{eff} as a scale**

$$\sigma^{\text{DPS}}_{A+B} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

σ_{eff} **~(2 - 20) mb**, **assumed (hoped?) to be independent of process and** $\sqrt{s}$

Separating DPS and SPS

- DPS not distinguishable from SPS on event-by-event basis

- However, they are expected to differ in kinematic features, such as angular correlations, so can be separated on a statistical basis

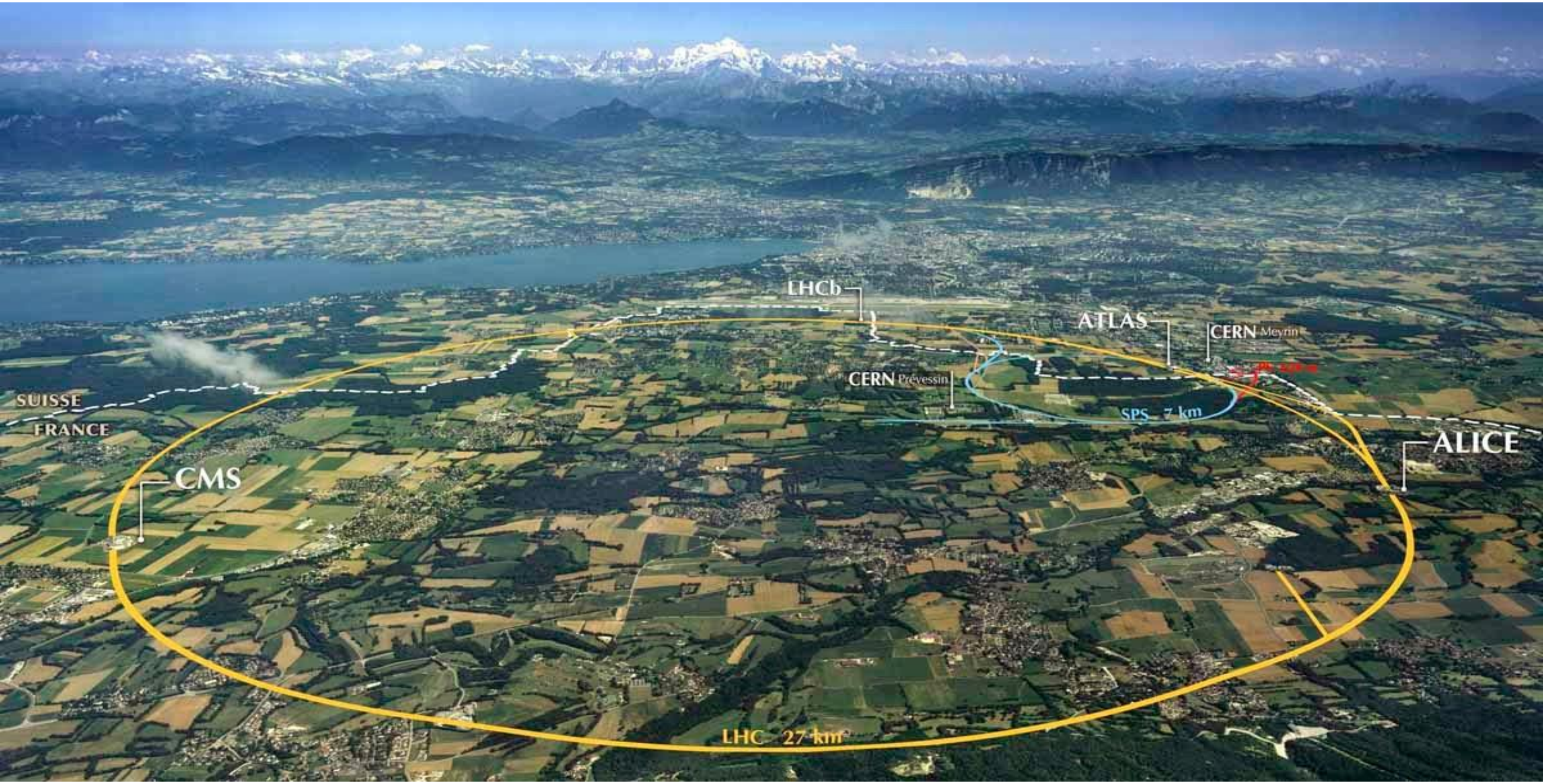
- But there usually are large uncertainties in separation:

  - possible higher-order SPS contributions and feed-down

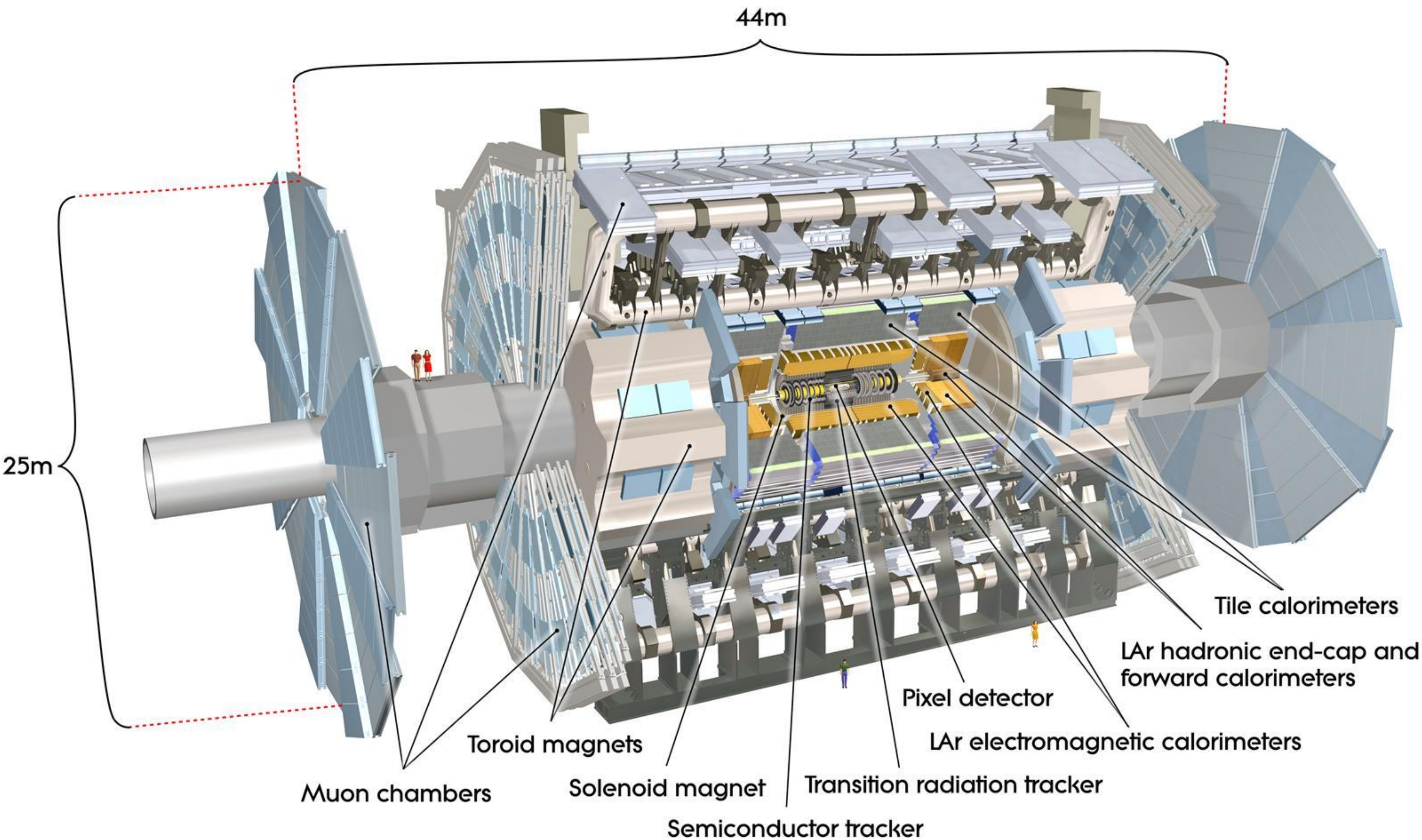
  - limited knowledge of proton's transverse profile

- At the end of the day, both SPS and DPS are part of the same QM aplitude, so need to be careful with things like unitarity and gauge invariance

ATLAS: experimental facility



The ATLAS detector



ATLAS results covered in this talk

$J/\psi + W^{\pm}$ **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**

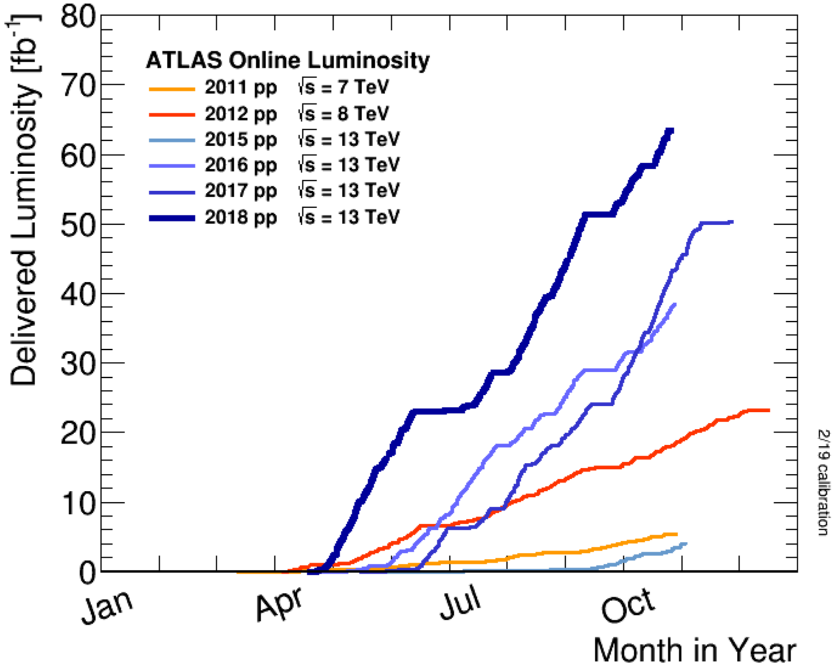
JHEP 04 (2014) 172 arXiv:1401.2831

$J/\psi + Z^0$ **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

$J/\psi + J/\psi$ **Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector**

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



Triggers, fiducial cuts, integrated luminosities

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$J/\psi + W^{\pm}$

Trigger: single muon, p_T > 18 GeV

$\sqrt{s} = 7$ TeV

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

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

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

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 $|\eta^{\mu(W)}| < 2.4$

$J/\psi + Z^0$

Trigger: single muon or electron, p_T > 24 GeV

$\sqrt{s} = 8$ TeV

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

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

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

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

$p_T^\mu > 3.5$ 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 $|\eta^{e(Z)}| < 2.47$

$J/\psi + J/\psi$

Trigger: 2 muons, p_T > 4 GeV, around J/ψ mass

$\sqrt{s} = 8$ TeV

$\mathcal{L} = 11.4\ \text{fb}^{-1}$

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

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

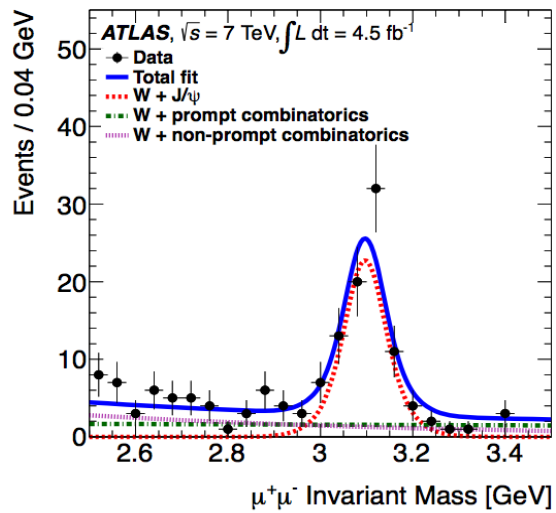
J/ψ + W± : selection and yields

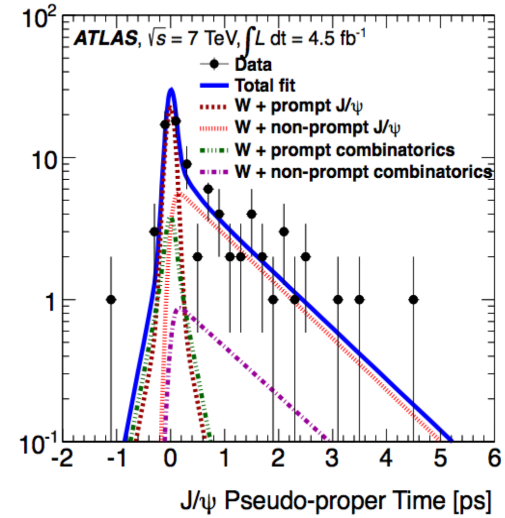
Unbinned maximum likelihood (ML) fit in the J/ψ invariant mass and pseudo-proper time τ to obtain yields for prompt and non-prompt J/ψ and background

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 templates to the weighted W boson transverse mass to extract

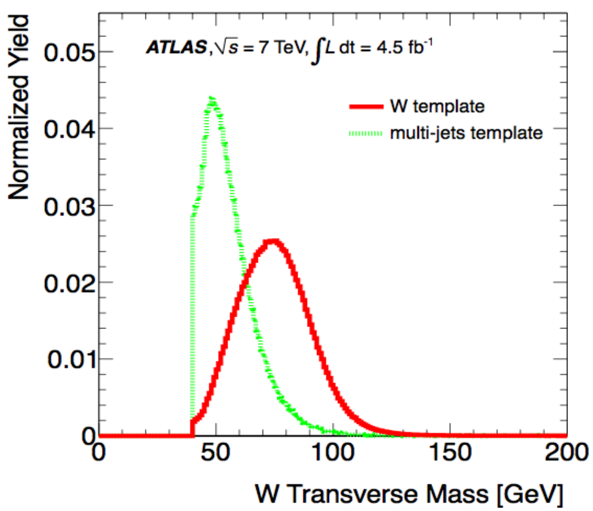
signal yield: $29.2^{+7.5}_{-6.5}$

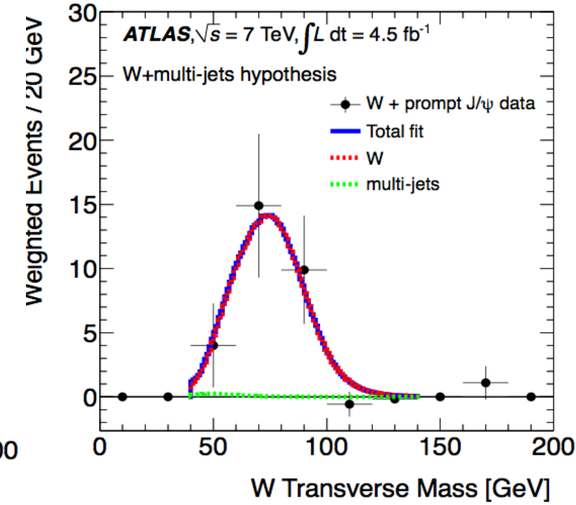
including 1.8 ± 0.2 from pile-up:

DPS yield: 10.8 ± 4.2

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

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





Ratios of the W + J/ψ prompt cross section to the inclusive W cross section

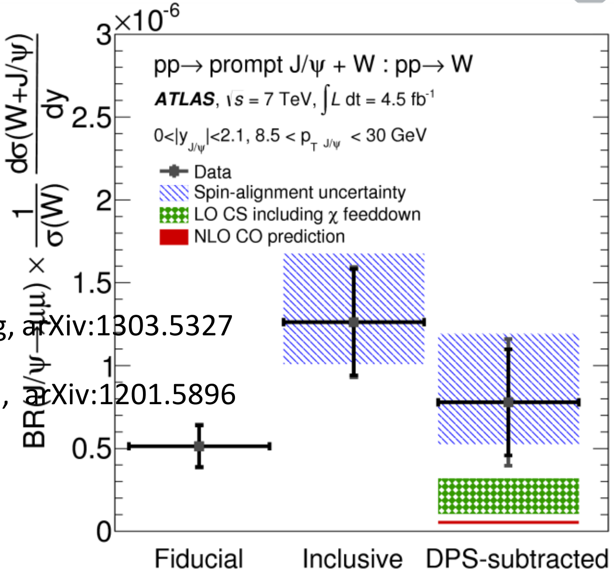
fiducial $R^{\text{fid}}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$

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

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

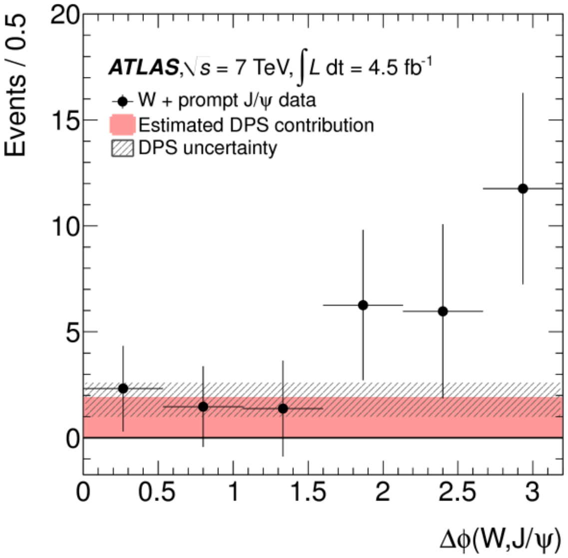
DPS subtracted $R^{\text{DPS sub}}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

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



LO CS: Lansberg, arXiv:1303.5327

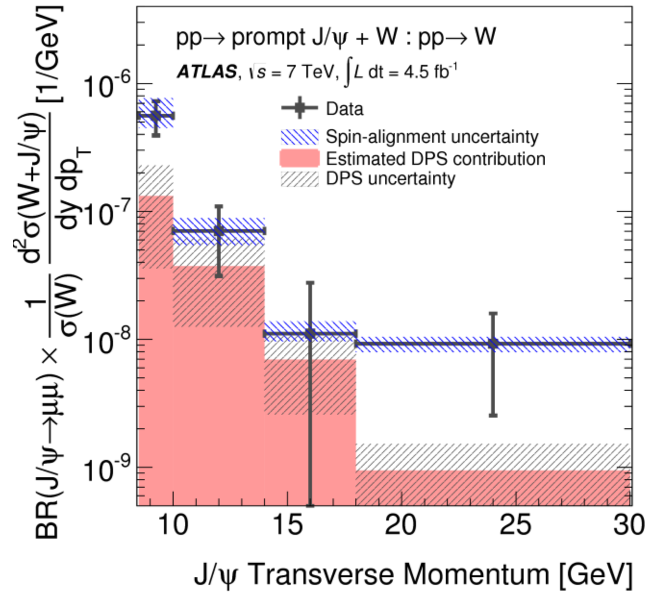
NLO CO:Gavin, arXiv:1201.5896



Presence of both SPS and DPS contributions

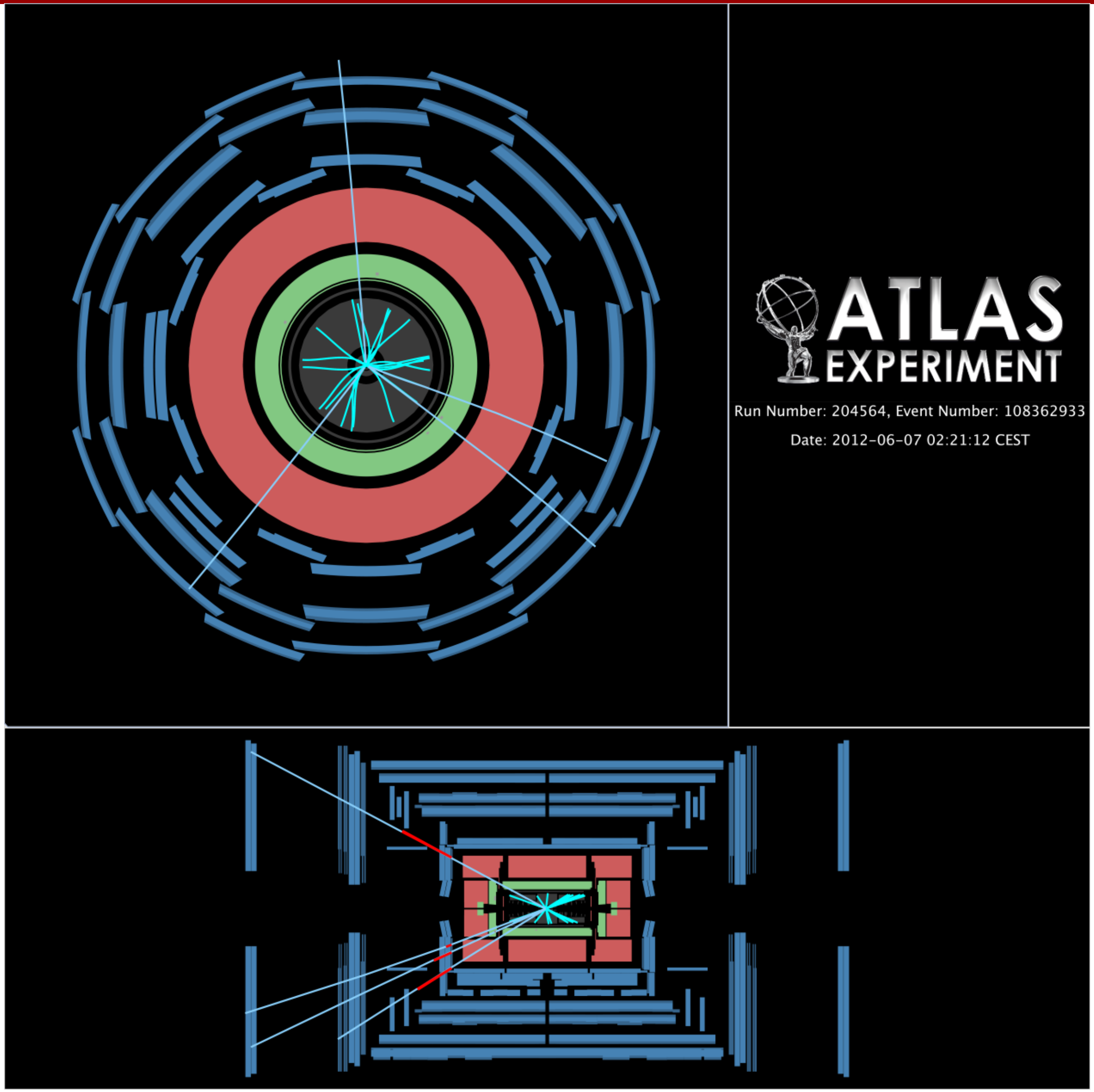
Inclusive differential cross section ratio

SPS is the dominant contribution to the total rate at low p_T



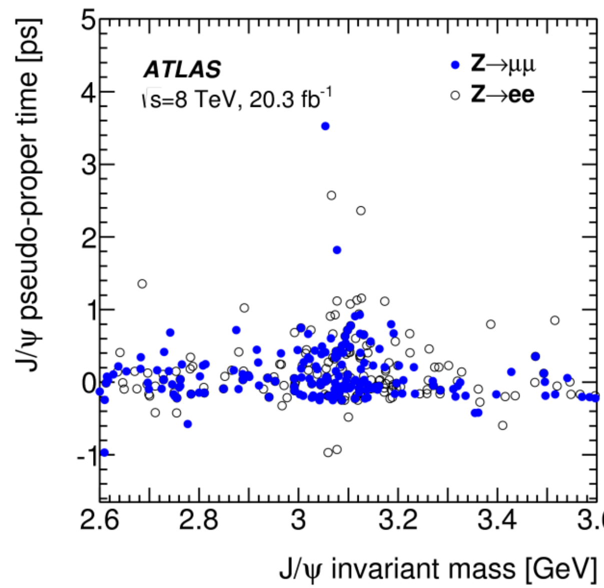
arXiv:1401.2831

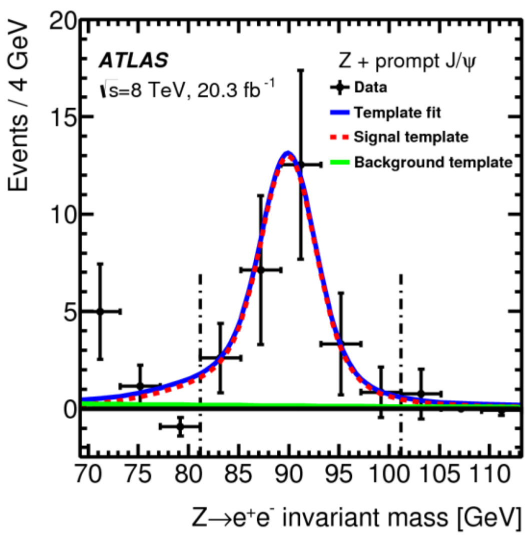
J/ψ + Z^0 : event candidate

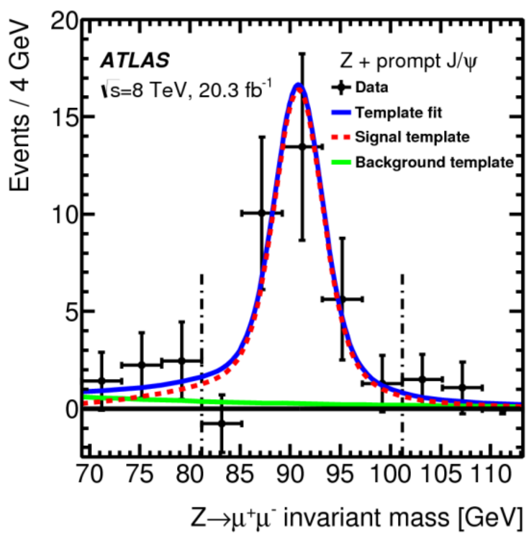


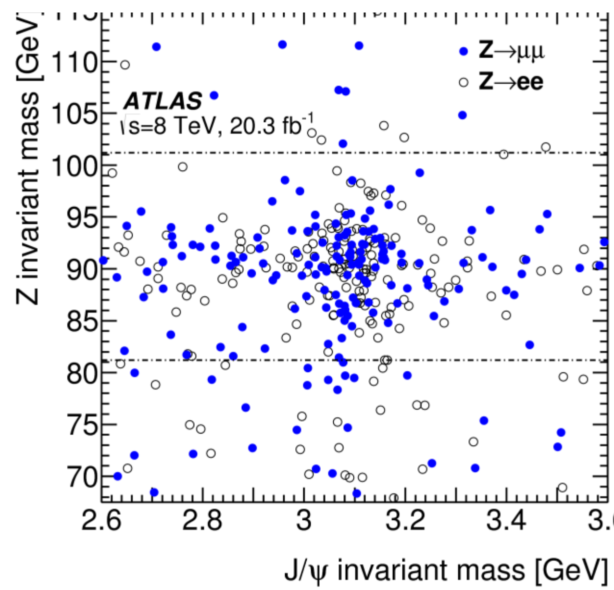
J/ψ + Z^0 : masses and lifetimes

- Identify events with a Z boson (decaying into electrons or muons) AND another pair of muons around the J/ψ mass range
- 2D J/ψ mass and lifetime distribution fits used to assign sPlot weights to events with prompt and non-prompt J/ψ signal candidates and backgrounds
- Weighted Z candidates fitted with Z signal and multi-jet background templates





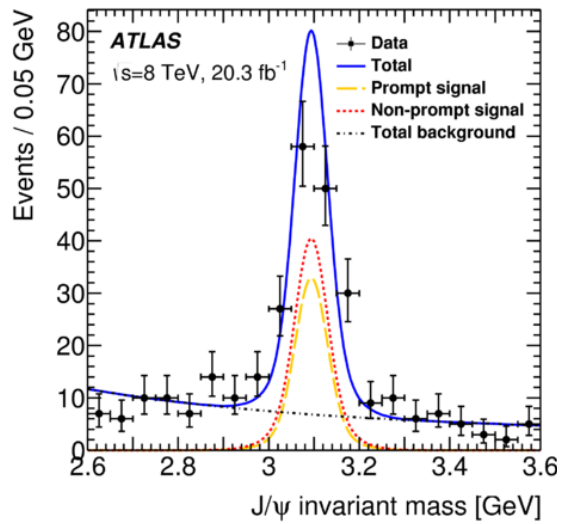


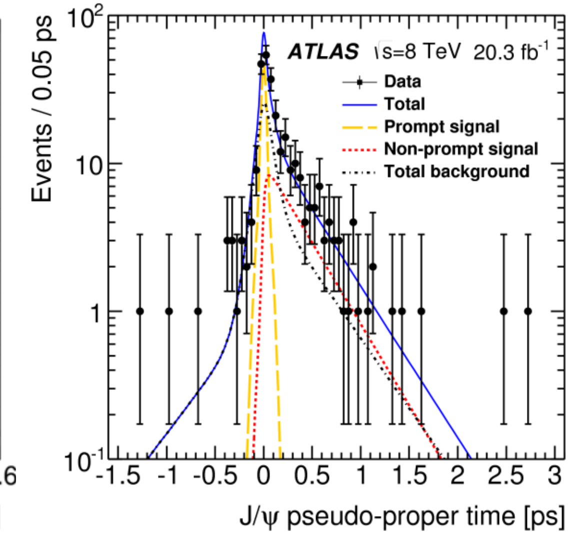


J/ψ + Z⁰ : event selection and yileds

Some J/ψ are prompt, some are non-prompt

Unbinned ML fit in J/ψ mass and lifetime is used to extract prompt and non-prompt yields





Yields: prompt non-prompt

$56 \pm 10 \pm 5\ (5\sigma)$ $95 \pm 12 \pm 8\ (9\sigma)$

DPS: $11.1^{+5.7}_{-5.0}$ $5.8^{+2.8}_{-2.6}$

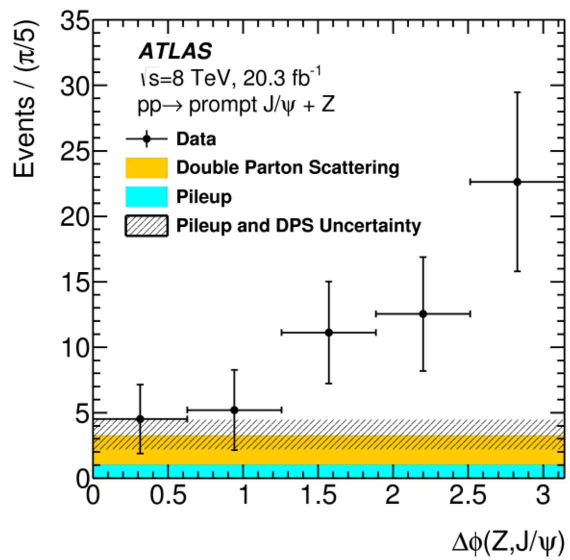
(assuming $\sigma_{\mathrm{eff}} = 15 \pm 3\ (\mathrm{stat})\ ^{+5}_{-3}\ (\mathrm{syst})\ \mathrm{mb}$

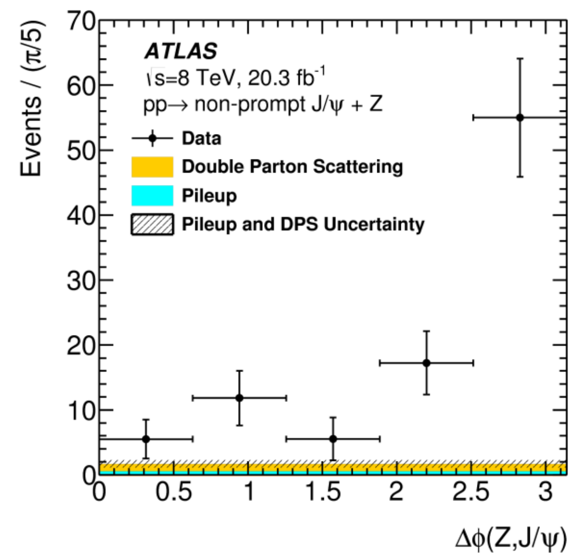
arXiv:1301.6872

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

If all signal in the first Δϕ bin is due to DPS, a lower limit is set:

$\sigma_{\mathrm{eff}} > 5.3\ \mathrm{mb}$

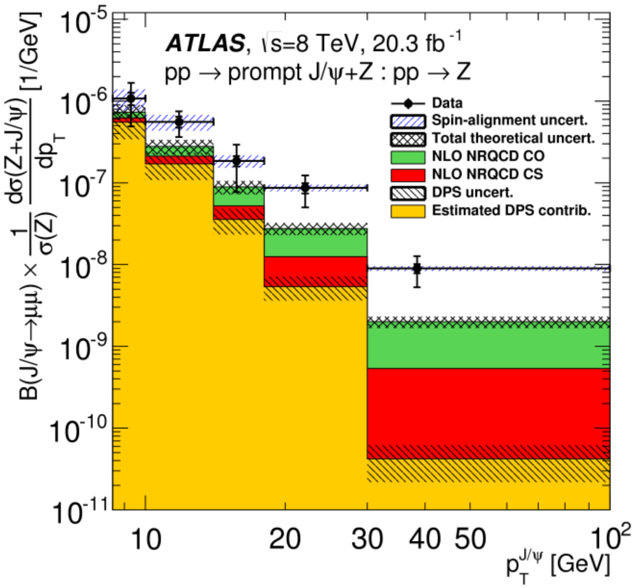




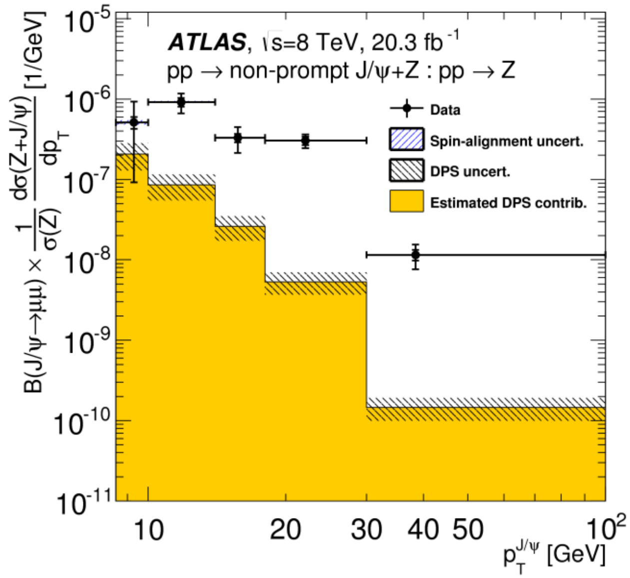
J/ψ + Z⁰ : cross sections

Ratios of the Z + J/ψ cross section to the inclusive Z cross section

	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	${}^{\mathrm{p}}f_{\mathrm{DPS}} = (29 \pm 9)\%$	${}^{\mathrm{np}}f_{\mathrm{DPS}} = (8 \pm 2)\%$



LO: Gong, arXiv:1210.2430
NLO: Mao, arXiv:1102.0398



- A higher production rate predicted through CO than 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

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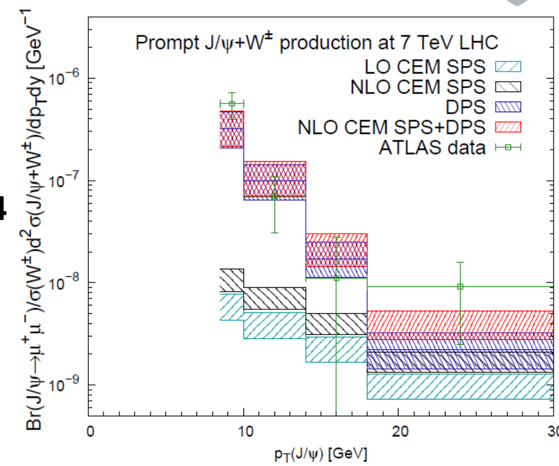
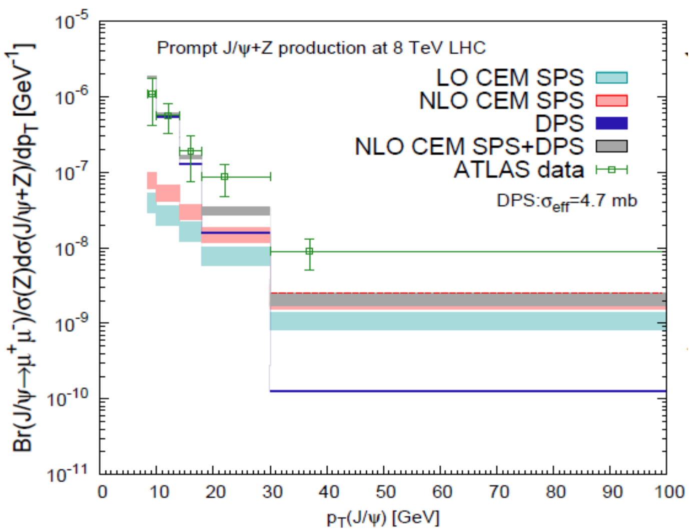
Analysis of prompt J/ψ + W production, using improved CEM for SPS, may indicate that smaller σ_{eff} is needed for DPS

Lansberg et al arXiv:1707:04



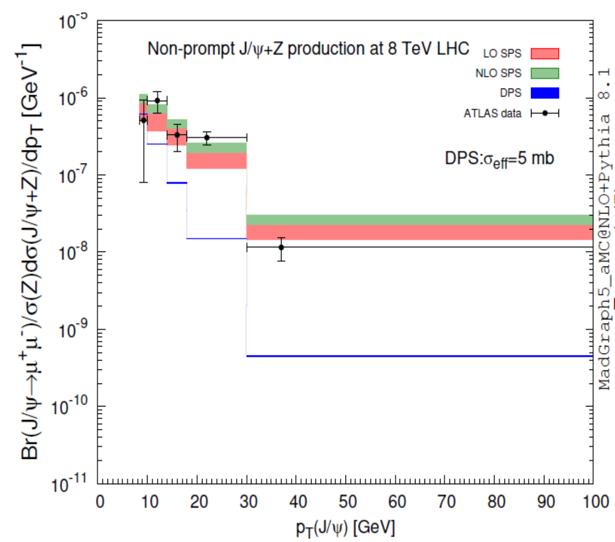


Analysis of prompt J/ψ + Z production also `needs' larger DPS (smaller σ_{eff}), but even that may not be enough at high p_T

Lansberg et al arXiv:1608.03198

However, non-prompt Z + J/ψ production seems to be saturated by SPS, leaving little room for large DPS contributions

Lansberg et al arXiv:1611.09303



J/ψ + J/ψ: yields and cross sections

arXiv:1612.02950

- **Unbinned ML fit to the two dimuon 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**

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

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

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

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

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

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

- **Correcting for muon acceptance and assuming unpolarised production**

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

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

- **the fraction of DPS events is determined by fitting DPS and SPS templates in Δy, Δϕ to the data, assign DPS and SPS event weights**

$$f_{\rm DPS} = (9.2 \pm 2.1 \pm 0.5)\%$$

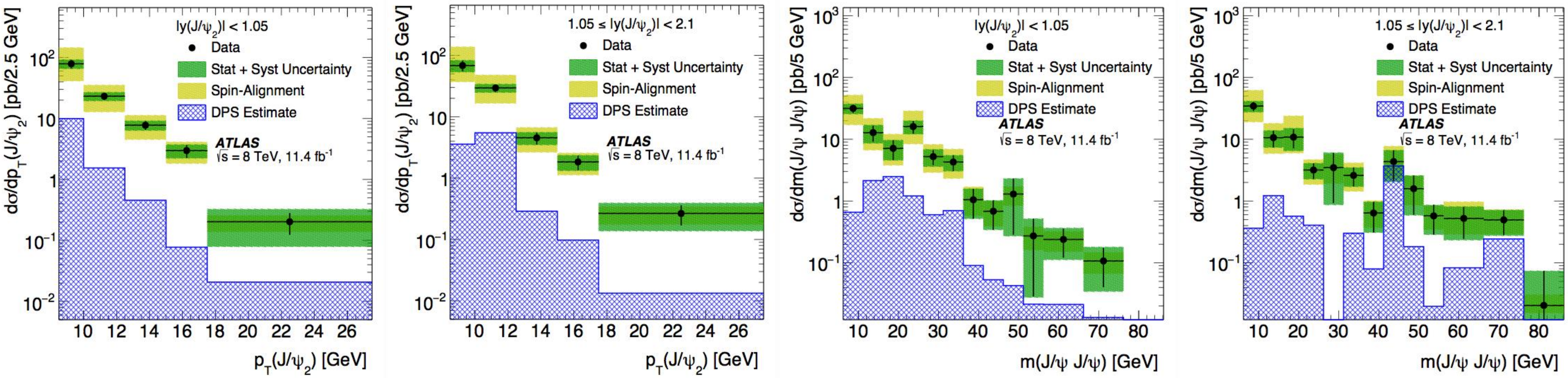
$$\sigma^{\rm DPS}_{J/\psi J/\psi} = 14.8 \pm 3.5 \pm 1.5 \pm 0.2\,(\mathcal{B}) \pm 0.3(\mathcal{L})\ {\rm pb}$$

- **$\sigma^{\rm eff}$ measured from prompt di- J/ψ is lower than from other final states:**

$$\sigma_{\rm eff}^{J/\psi J/\psi} = 6.3 \pm 1.6({\rm stat}) \pm 1.0({\rm syst}) \pm 0.1({\rm BF}) \pm 0.1({\rm lumi})\ {\rm mb}$$

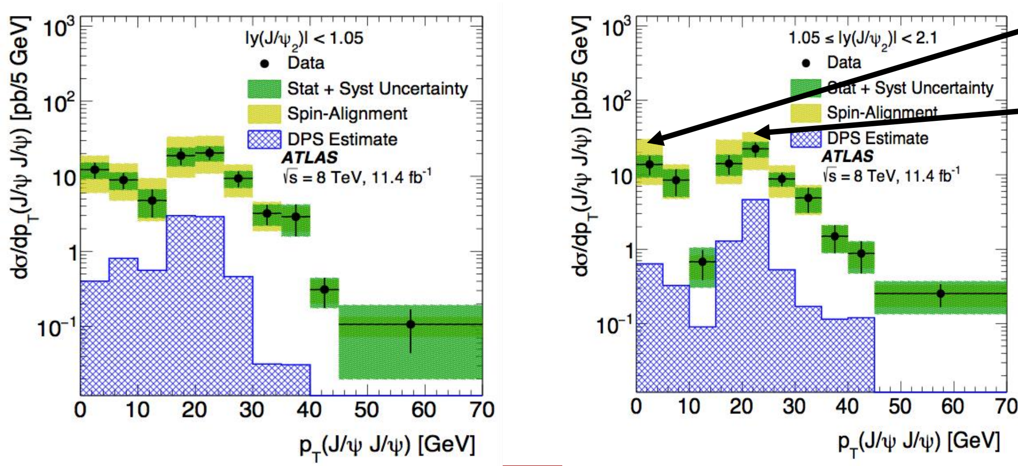
J/ψ + J/ψ: differential cross sections

as a function of the sub-leading $J/\psi\ p_T$ | as a function of the invariant mass



All for central (left) and forward (right) rapidity regions, with data-driven DPS estimates shown in blue

as a function of di-$J/\psi\ p_T$



onia produced back-to-back

onia produced together, and back-to-back to a jet

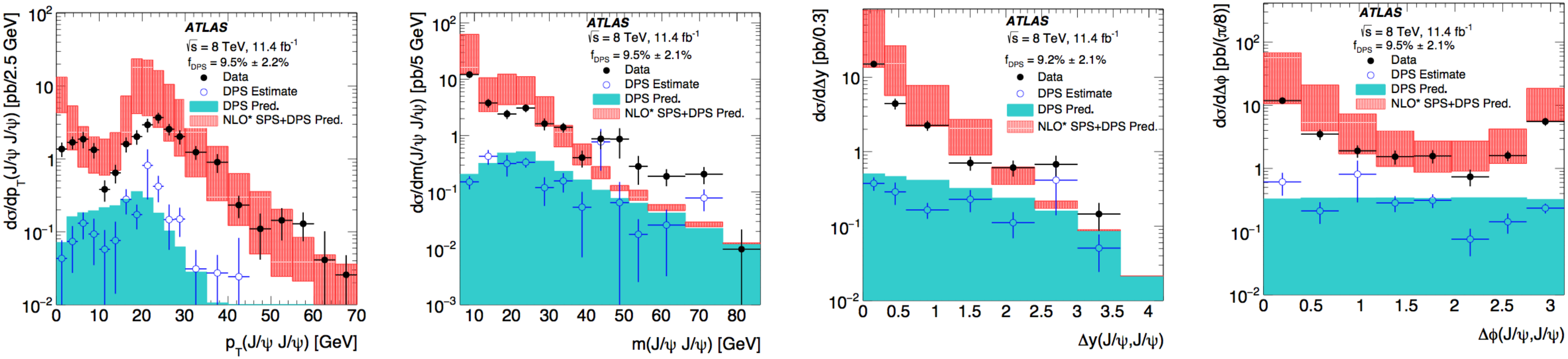
arXiv:1612.02950

J/ψ + J/ψ: more differential distributions

arXiv:1612.02950

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

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



Data points arecompared to:

NLO* SPS (with a feed-down correction factor)

obtained using HELAC-Onia with matrix elements from

Lansberg, Shao arXiv:1410.8822, 1308.0474

LO DPS (normalised to measured)

Borschensky arXiv:1610.00666

Data largely in agreement with NLO* SPS + LO DPS

Some localised disagreements for large invariant mass, large Δy and low p_T

More realistic predictions for feed-down and a better treatment of parton transverse motion are needed

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

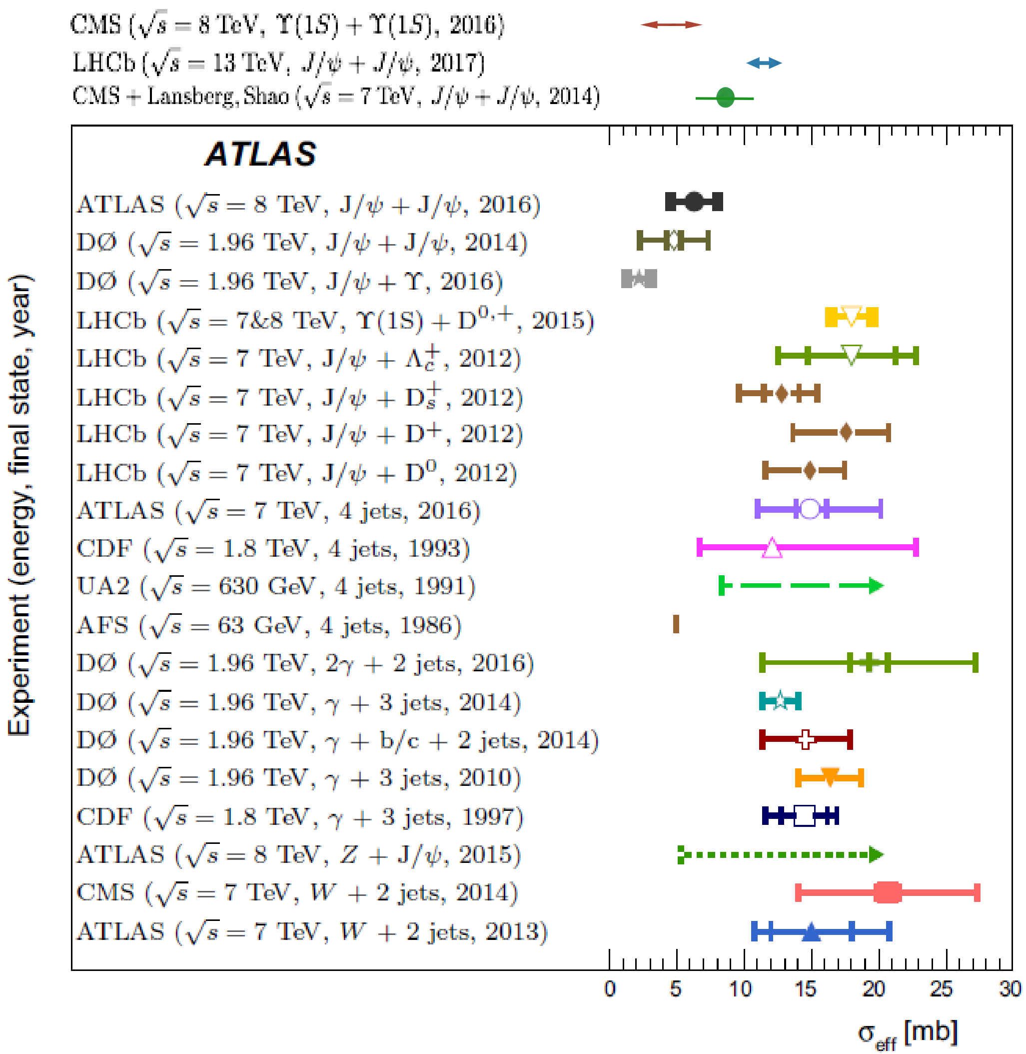
Observation of Υ(1S) pair production in proton-proton collisions at s√= 8 TeV

Accepted by JHEP arXiv:1610.07095

CMS

Summary

- Many results from the LHC experiments are now shedding light on double onia and associated onia production -- expect a lot more using 13 TeV data



- Some measured SPS contributions are well above theoretical predictions
- DPS contributions provide insight into the transverse profile of the proton, but our understanding is somewhat limited
- σ_{eff} measured from prompt di-onia lower than from other final states
- Theoretical predictions of the dependence of σ_{eff} on the process and energy are needed
- There are some signs of improved understanding, but more work still to be done

THANKS!