ATLAS results on quarkonia and heavy flavour production

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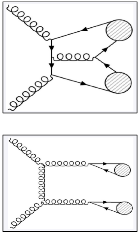
Outline

- Associated quarkonia production:
  - J/ψ and $W^{\pm}$ boson at $\sqrt{s} = 7\,\text{TeV}$ – JHEP 1404 (2014) 172
  - J/ψ and Z boson at $\sqrt{s} = 8\,\text{TeV}$ – Eur.Phys.J. C 75 (2015) 229
- $\psi(2S)$ and $X(3872)$ production at $\sqrt{s} = 8\,\text{TeV}$ – JHEP 1701 (2017) 117

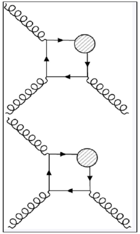
Associated production of vector boson with quarkonia

Motivation:

- Probes the production mechanisms of quarkonium (is not fully understood in hadron collisions)
- New tests of QCD at the perturbative/non-perturbative boundary;
- Further constraints on the contributions from colour-singlet (*CS*) and colour-octet (*CO*) production processes, and their properties;
- Two principal possibilities to produce two objects in a *pp* collision:
  - 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.



SPS



DPS

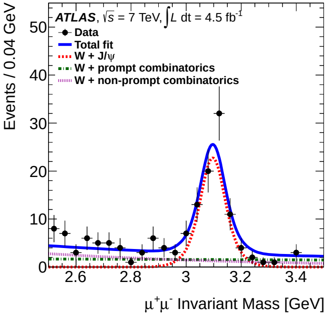
Associated production of $J/\psi + W^{\pm}$

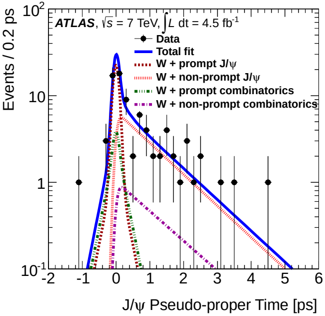
JHEP 1404 (2014) 172

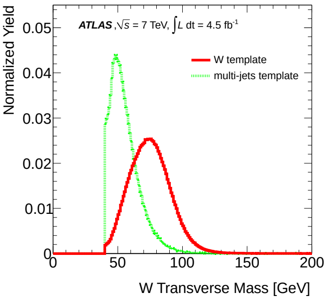
- The first observation of the production of prompt $J/\psi + W^{\pm}$ events in hadronic collisions;
  - Use 4.5 fb^{-1} @ 7 TeV data;
  - $J/\psi \to \mu^{+}\mu^{-}$ and $W^{\pm} \to \mu^{\pm}\nu_{\mu}$ – at least three identified muons;
  - Additional muon must combine with the events missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$)
  - The $W^{\pm}$ boson transverse mass $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}(\mu)E_{\mathrm{T}}^{\mathrm{miss}}(1 - cos(\phi^{\mu} - \phi^{\nu_{\mu}}))}$
  - $27.4^{+7.5}_{-6.5}$ prompt $J/\psi + W^{\pm}$ events were observed with a statistical significance of 5.1σ.

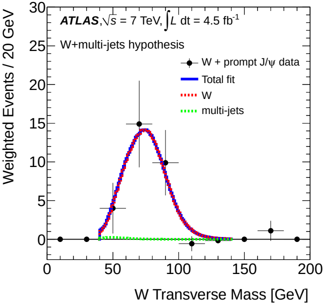
Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

(*) of which 1.8 ± 0.2 originate from pileup





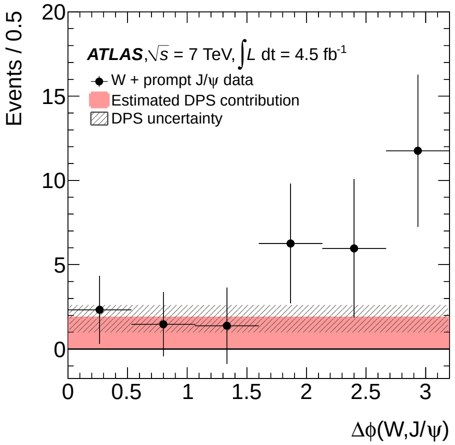




Associated production of $J/\psi + W^{\pm}$: double parton scattering:

JHEP 1404 (2014) 172

- J/ψ and $W^{\pm}$ candidates originate from two different parton interactions in the same *pp* collision
- The probability is $P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{eff}$
  - σ_{eff} is assumed to be universal across processes and energy scales
  - $\sigma_{eff} = 15 \pm 3(stat.)^{+5}_{-3}(syst.)$ mb – New J. Phys. 15 (2013) 033038
  - The prompt J/ψ cross section from the ATLAS measurement – Nucl. Phys. B 850 (2011) 387-444
  - The total number of *DPS* events in the signal yield is estimated to be 10.8 ± 4.2 events.
- A uniform distribution in the azimuthal angle between the $W^{\pm}$ and J/ψ momentais expected from DPS, under the assumption that the two interactions are independent.
- Peak near π and a tail extending towards zero in data distribution $\Longrightarrow$ *SPS* and *DPS* events are present;



Associated production of $J/\psi + W^{\pm}$: cross-section ratios

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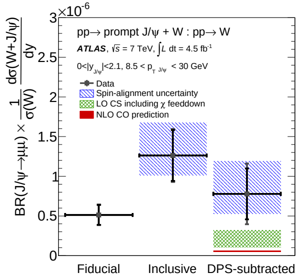
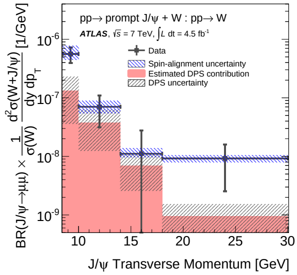
- Fiducial – production cross-section ratio in the J/ψ fiducial region
  $R^{fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$
- Inclusive – after correction for J/ψ acceptance
  $R^{incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$
- DPS-subtracted – after subtraction of the double parton scattering component
  $R^{DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$
- Predictions – LO CS: $(10 - 32) \times 10^{-8}$, LO CO: $(4.6 - 6.2) \times 10^{-8}$



- *SPS* is dominant at low J/ψ transverse momenta
- *DPS* estimate accounts for a large fraction of the observed signal ($\sim$ 40%)
- *CS* mechanism is expected to be the dominant contribution to the cross section

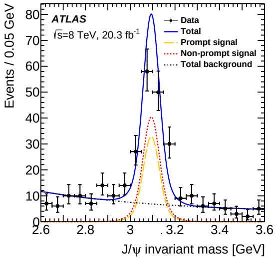
$y_{J/\psi} \times p_T^{J/\psi}$ Bin	Inclusive (SPS+DPS) ratio $dR^{incl}_{J/\psi}/dp_T$ ($\times 10^{-6}$)	DPS ($\times 10^{-6}$)
$(0, 2.1) \times (8.5, 10)$	0.56 ± 0.16(stat) ± 0.04(syst) $^{+0.21}_{-0.11}$(spin)	0.13 ± 0.10
$(0, 2.1) \times (10, 14)$	0.070 ± 0.039(stat) ± 0.006(syst) $^{+0.019}_{-0.016}$(spin)	0.04 ± 0.03
$(0, 2.1) \times (14, 18)$	0.011 ± 0.017(stat) ± 0.001(syst) $^{+0.003}_{-0.002}$(spin)	0.007 ± 0.004
$(0, 2.1) \times (18, 30)$	0.0092 ± 0.0067(stat) ± 0.0006(syst) $^{+0.0012}_{-0.0013}$(spin)	0.0009 ± 0.0006

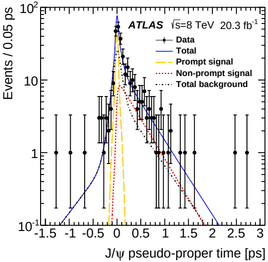


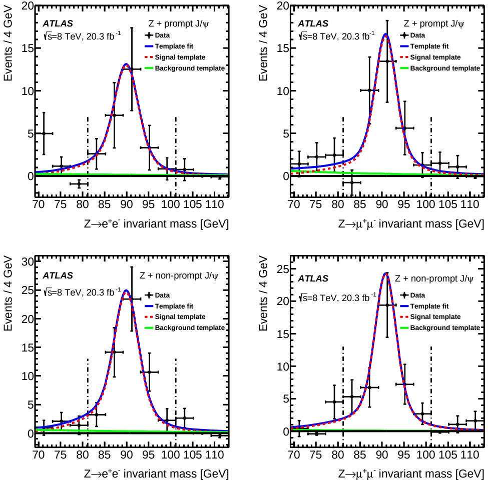
Associated production of $J/\psi + Z$

Eur.Phys.J. C 75 (2015) 229

- The first observation and measurement of associated Z and J/ψ production
  - Use 20.3 fb^{-1} @ 8 TeV data;
  - $J/\psi \to \mu^+\mu^-$ and $Z \to \mu^+\mu^-$, $Z \to e^+e^-$ – two pairs of leptons with opposite charge; regions)





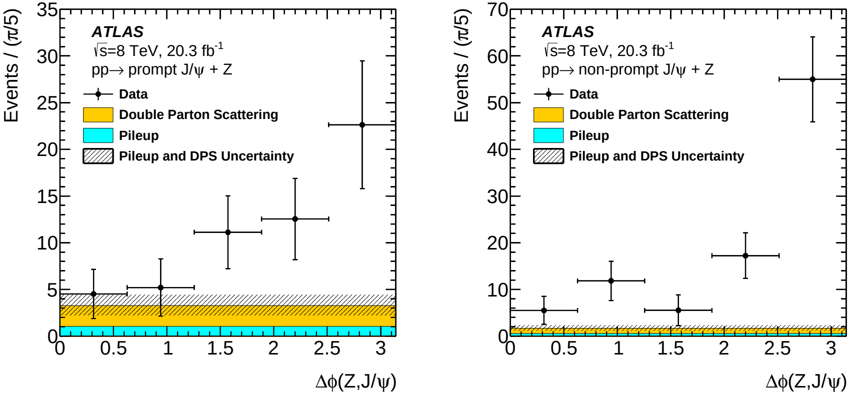


Process	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	Total Events found	Total From pileup
Prompt signal	$24 \pm 6 \pm 2$	$32 \pm 8 \pm 5$	$56 \pm 10 \pm 5$	$5.2^{+1.8}_{-1.3}$
Non-prompt signal	$54 \pm 9 \pm 3$	$41 \pm 8 \pm 7$	$95 \pm 12 \pm 8$	$2.7^{+0.9}_{-0.6}$
Background	$61 \pm 11 \pm 6$	$77 \pm 13 \pm 7$	$138 \pm 17 \pm 9$	

Associated production of $J/\psi + Z$: double parton scattering

Eur.Phys.J. C 75 (2015) 229

- The probability is $P_{J/\psi|Z} = \sigma_{J/\psi}/\sigma_{eff}$
  - $\sigma_{eff} = 15 \pm 3(stat.)^{+5}_{-3}(syst.)$ mb – New J. Phys. 15 (2013) 033038
  - The total number of *DPS* events in the signal yield is estimated to be $11.1^{+5.7}_{-5.0}$ for prompt and $5.8^{+2.8}_{-2.6}$ for non-prompt components.
  - Both *DPS* and *SPS* contributions may be present in the data:



Associated production of $J/\psi + Z$: cross-section ratios

Eur.Phys.J. C 75 (2015) 229

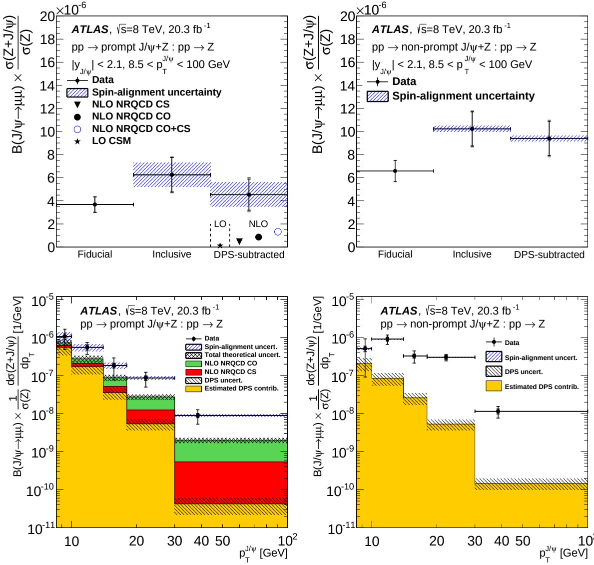
- Cross-section ratios:

$$ {}^{p}R^{fid}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7} $$
$$ {}^{np}R^{fid}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7} $$

$$ {}^{p}R^{incl}_{Z+J/\psi} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7} $$
$$ {}^{np}R^{incl}_{Z+J/\psi} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7} $$

$$ {}^{p}R^{DPS\ sub}_{Z+J/\psi} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7} $$
$$ {}^{np}R^{DPS\ sub}_{Z+J/\psi} = (94 \pm 15 \pm 5 \pm 5) \times 10^{-7} $$

- *DPS* contributions:
  - $(29 \pm 9)\%$ for prompt production
  - $(8 \pm 2)\%$ for nonprompt production
- Prediction:
  LO CS $(11.6 \pm 3.2) \times 10^{-8}$ – $(46.2^{+6.0}_{-6.5}) \times 10^{-8}$
  LO CO $(25.1^{+3.3}_{-3.5}) \times 10^{-8}$,
  NLO CO $(86^{+20}_{-18}) \times 10^{-8}$ $\Rightarrow$ *CO* should have a higher production rate then *CS*
- Data: expected production rate from *CO + CS* is lower than the data by a factor of 2 to 5



$\psi(2S)$ and $X(3872)$ production

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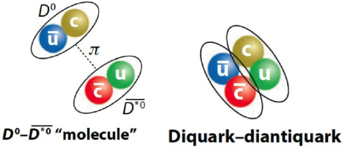
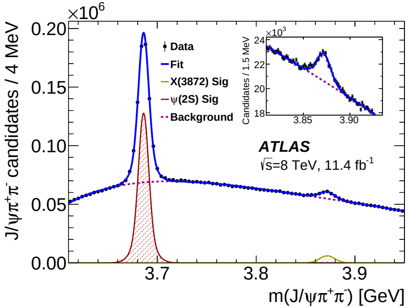
- $X(3872)$ was observed by Belle in 2003, later confirmed by others, $J^{PC} = 1^{++}$
- No clear theoretical picture yet
  - Tetraquark (diquark + diquark)
  - Loosely bound $D^0\bar{D}^{*0}$ molecule
  - $\chi_{c1}(2P)$ state, or the mixture with $D^0\bar{D}^{*0}$
- ATLAS measurement can help to answer some of the questions
  - Measure in $J/\psi\pi^+\pi^-$ mode, together with well known $\psi(2S)$ state
    - helps to reduce systematics in ratios
  - Use 11.4 fb^{-1} @ 8 TeV data
    - Limit to $|y| < 0.75$ for the best mass resolution
    - $\sim$ 470k $\psi(2S)$ and $\sim$ 30k $X(3872)$
  - Use 4 bins of pseudo proper lifetime to extract prompt/non-prompt components





Effective $X(3872)$ lifetime hypotheses

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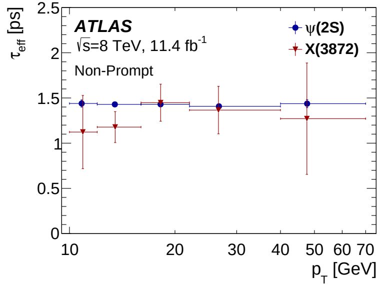
- Single lifetime hypothesis
  - same lifetime for $\psi(2S)$ and $X(3872)$ in each p_T bin
  - effective $X(3872)$ lifetime shorter in low-p_T bins $\Rightarrow$ different production mechanism at low p_T
  - Measure the $X(3872)/\psi(2S)$ non-prompt production cross sections ratio

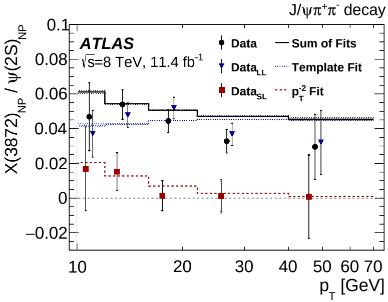
    $R_B = \frac{\mathcal{B}(B\to X(3872)+\text{any})\mathcal{B}(X(3872)\to J/\psi\pi^+\pi^-)}{\mathcal{B}(B\to\psi(2S)+\text{any})\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)}$

    $R_B^{1L} = (3.95 \pm 0.32(\text{stat.}) \pm 0.08(\text{syst.})) \times 10^{-2}$



- Double lifetime hypothesis: long-lived (LL) and short-lived (SL) components
  - LL – $B^\pm$, B^0, B_s, b-barions; SL – B_c;
  - τ_{LL} determined from $\psi(2S)$ fits, allowing for some SL contribution
  - τ_{SL} from simulation, varying B_c lifetime
  - Calculate $X(3872)$ fraction from B_c

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



$X(3872)$ production cross-section

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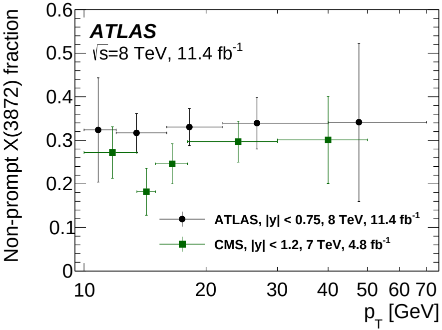
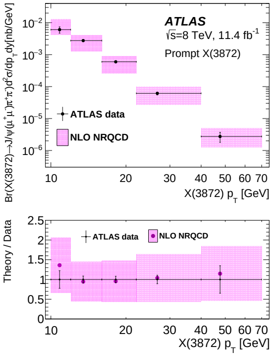
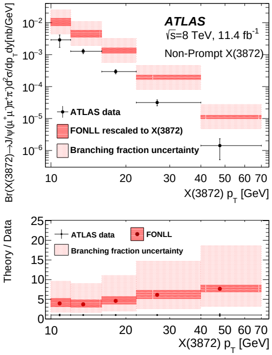
- Prompt production described well by NRQCD
  - $X(3872)$ considered as a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$ molecule
- Non-prompt compared to FONLL calculations
  - Predictions for $\psi(2S)$ recalculated using kinematic template of $X(3872)/\psi(2S)$
  - Factor 4–8 above the data, larger discrepancy at high p_T
- Non-prompt production fraction: no p_T dependence, agreement with CMS data







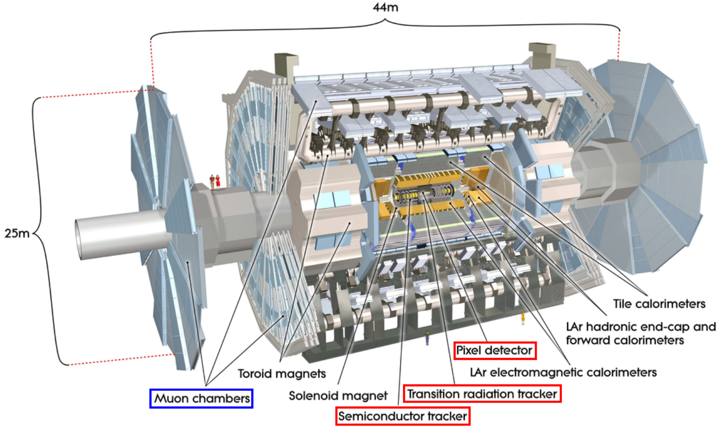
Summary

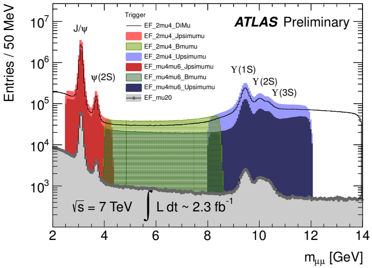
- A selection of ATLAS results was presented
  - Associated production:
    - production of $J/\psi + W$
    - production of $J/\psi + Z$
  - Exotic states: $X(3872)$ measurement
- Many interesting results not covered, e.g.
  - Associated production: prompt J/ψ pairs – Eur. Phys. J. C 77 (2017) 76
  - Heavy flavours production: onia production in pPb and PbPb– – Eur. Phys. J. C 78 (2018) 171
  - b hadron pair production at $\sqrt{s} = 8$ TeV – JHEP 1711 (2017) 062
  - J/ψ and $\psi(2S)$ production at $\sqrt{s} = 7, 8$ TeV – Eur. Phys. J. C 76 (2016) 283
  - D mesons production at $\sqrt{s} = 7$ TeV – Nucl. Phys. B 907 (2016) 717
  - Search for resonances in $B_s^0 \pi^{\pm}$ system – Phys. Rev. Lett. 120 (2018) 202007
- Full Run-2 dataset is still be fully exploited – waiting for many new results!

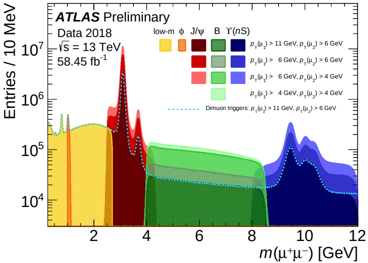
Thank you very much!

Backup slides

ATLAS detector and trigger







Definitions

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

$$\tau \equiv \frac{\vec{L}\cdot\vec{p}_{\mathrm{T}}^{J/\psi}}{p_{\mathrm{T}}^{J/\psi}} \cdot \frac{m_{\mu^+\mu^-}}{p_{\mathrm{T}}^{J/\psi}}$$

$$\begin{aligned} R_{J/\psi}^{\mathrm{fid}} &= \frac{\mathrm{BR}(J/\psi\to\mu^+\mu^-)}{\sigma_{\mathrm{fid}}(pp\to W^{\pm})} \cdot \frac{\mathrm{d}\sigma_{\mathrm{fid}}(pp\to W^{\pm}+J/\psi)}{\mathrm{d}y} \\ &= \frac{N^{\mathrm{ec}}(W^{\pm}+J/\psi)}{N(W^{\pm})}\frac{1}{\Delta y} - R_{\mathrm{pileup}}^{\mathrm{fid}}, \end{aligned}$$

$$\begin{aligned} R_{J/\psi}^{\mathrm{incl}} &= \frac{\mathrm{BR}(J/\psi\to\mu^+\mu^-)}{\sigma_{\mathrm{fid}}(pp\to W^{\pm})} \cdot \frac{\mathrm{d}\sigma(pp\to W^{\pm}+J/\psi)}{\mathrm{d}y} \\ &= \frac{N^{\mathrm{ec+ac}}(W^{\pm}+J/\psi)}{N(W^{\pm})}\frac{1}{\Delta y} - R_{\mathrm{pileup}}, \end{aligned}$$

Fiducial phase space: $8.5 < p_T^{J/\psi} < 30$ GeV, $|y_{J/\psi}| < 2.1$

$J/\psi + Z$

$$\tau := \frac{L_{xy} m^{J/\psi}}{p_{\mathrm{T}}^{J/\psi}}$$

$$\begin{aligned} R_{Z+J/\psi}^{\mathrm{fid}} &= \mathcal{B}(J/\psi\to\mu^+\mu^-)\frac{\sigma_{\mathrm{fid}}(pp\to Z+J/\psi)}{\sigma_{\mathrm{fid}}(pp\to Z)} \\ &= \frac{1}{N(Z)}\sum_{p_T\ \mathrm{bins}}[N^{\mathrm{ec}}(Z+J/\psi) - N_{\mathrm{pileup}}^{\mathrm{ec}}], \end{aligned}$$

$$\begin{aligned} R_{Z+J/\psi}^{\mathrm{incl}} &= \mathcal{B}(J/\psi\to\mu^+\mu^-)\frac{\sigma_{\mathrm{incl}}(pp\to Z+J/\psi)}{\sigma_{\mathrm{incl}}(pp\to Z)} \\ &= \frac{1}{N(Z)}\sum_{p_T\ \mathrm{bins}}[N^{\mathrm{ec+ac}}(Z+J/\psi) - N_{\mathrm{pileup}}^{\mathrm{ec+ac}}], \end{aligned}$$

Fiducial phase space: $8.5 < p_T^{J/\psi} < 100$ GeV, $|y_{J/\psi}| < 2.1$

Backgrounds

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

- Production of $W^{\pm}$ bosons in association with b quarks, subsequent b-hadron decay to J/ψ rejected using the fit;
- Decays of $B_c \to J/\psi \mu \nu_\mu X$ – negligible background;
- The production of Z bosons vetoing events where a pairing of muons has an invariant mass within 10 GeV of the Z boson mass;
- Multi-jet production – the $m_{\mathrm{T}}(W^{\pm})$ distribution of signal events is fit to a sum of a multi-jet template and a $W^{\pm}$ boson signal template.

$J/\psi + Z$

- Background estimation using MC:
  - $Z \to \tau\tau$ or $W \to \ell\nu$ background;
  - Top quark processes involving $t\bar{t}$ or single top production;
  - The single-top Wt process;
  - Diboson (WZ, WW and ZZ) production.
- Background estimation using data:
  - Multi-jet production – selecting non-isolated leptons. The $m_{\mathrm{T}}(Z)$ distribution of signal events is fit to a sum of a multi-jet template and a Z boson signal template.

$X(3872)$

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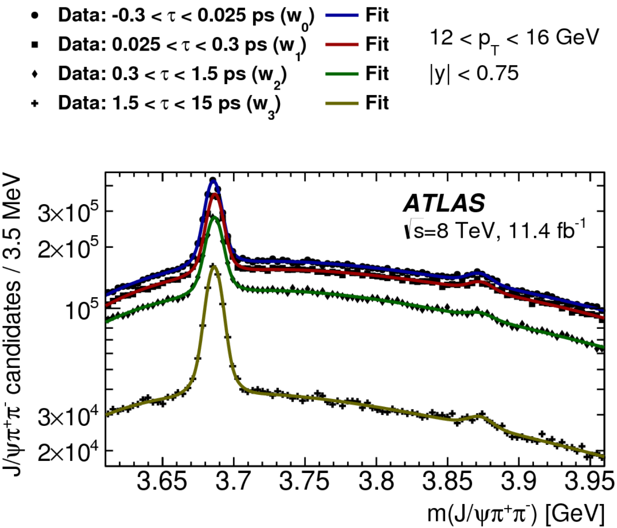
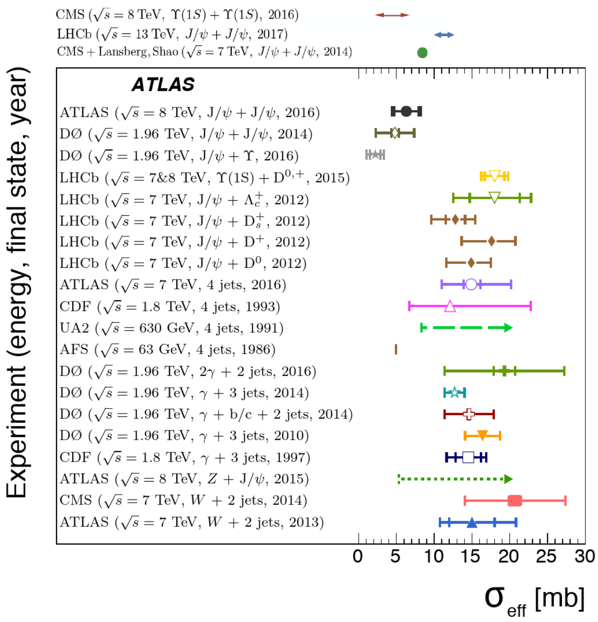


Measurement overview – Eur. Phys. J. C 77 (2017) 76



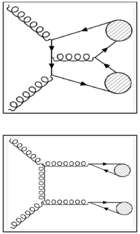
Studying associated production

- Multiple possibilities to produce two objects A, B in a pp collision
  - Single Parton Scattering (*SPS*)
    - described by specific process cross-section σ_{AB}^{SPS} – higher-order *"real"* associated production
  - Double Parton Scattering (*DPS*)
    - individual process cross-sections σ_A, σ_B
    - effective cross-section σ_{eff} accounting for probability of the two processes to happen in a single pp collision

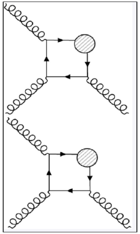
$$\sigma_{AB} = \sigma_{AB}^{\text{SPS}} + \sigma_{AB}^{\text{DPS}} = \sigma_{AB}^{\text{SPS}} + \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}}$$

- DPS/SPS separation is intrinsically uncertain
  - Limited knowledge of σ_{eff}
  - Higher-order SPS contributions can undermine assumptions
  - Experimentally one can measure N_A, N_B, and N_{AB}, with different efficiencies, lumi etc

$$f_{\text{DPS}} = \frac{\sigma_{AB}^{\text{DPS}}}{\sigma_{AB}} = \frac{\sigma_A \sigma_B}{\sigma_{AB}\sigma_{\text{eff}}} \times \frac{1}{1+\delta_{AB}} \sim \frac{1}{\sigma_{\text{eff}}} \times \frac{N_A N_B}{N_{AB}} \times \frac{1}{1+\delta_{AB}}$$



SPS



DPS