Studies of associated charmonium production at ATLAS

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(http://www.coepp.org.au/)

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Outline

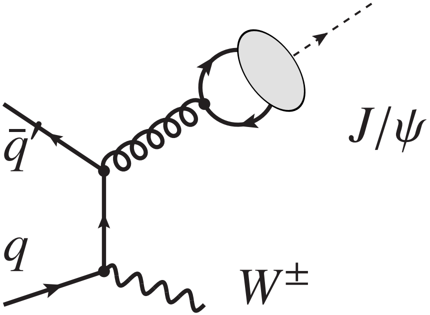
1. **J/ψ production in association with $\{W, Z\}$**
   - Associated $J/\psi\, W$ and $J/\psi\, Z$ production processes
   - Double parton scattering as a source of $J/\psi\, W$ and $J/\psi\, Z$
2. **Quarkonium studies at ATLAS**
3. **Associated production:**
   - selection criteria
   - acceptance
4. **Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV**
5. **Prompt J/ψ in association with Z^{0} at $\sqrt{s} = 8$ TeV**
6. **Summary**

Associated J/ψ {W, Z} production

Kniehl/Palisoc/Zwirner, PRD 66, 114002 (2002);
Li/Song/Zhang/Ma, 83, 014001 (2011); Lansberg/Lorce, PLB 726, 218 (2013)

provides rich observables for probing $\mathcal{Q}$ production mechanisms

J/ψ W: a clear color octet signal?



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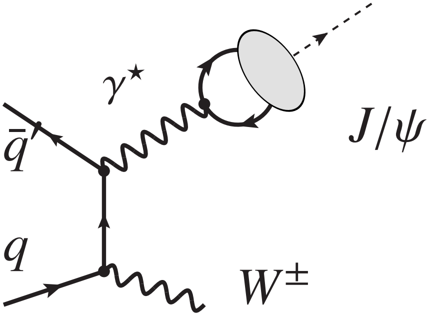

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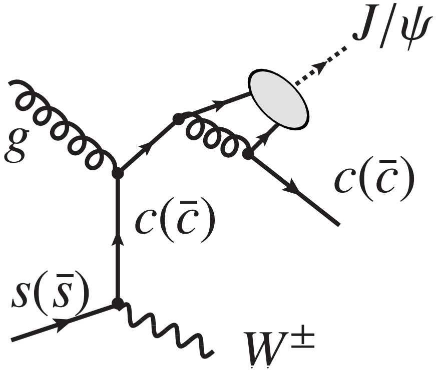

Associated $J/\psi\,\{W, Z\}$ production

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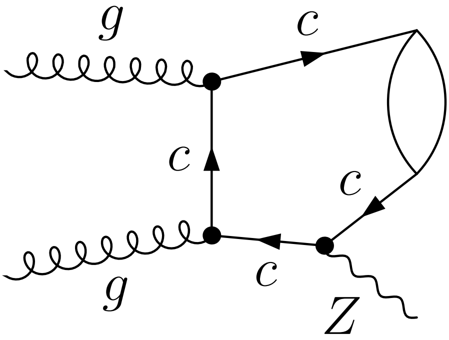

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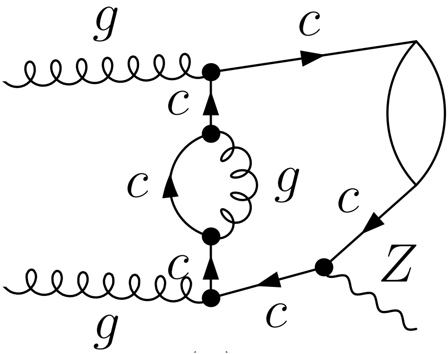

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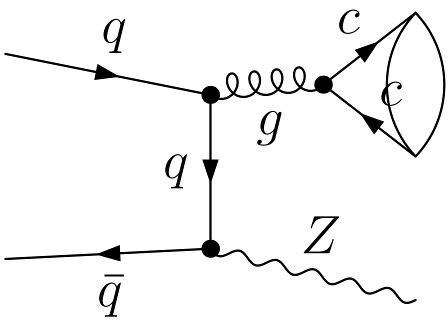

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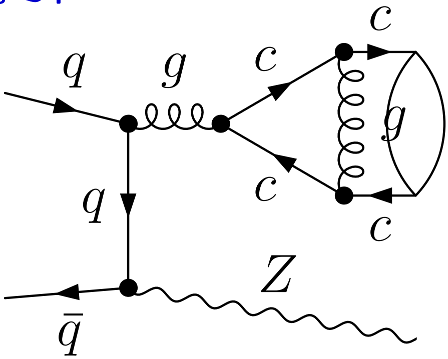

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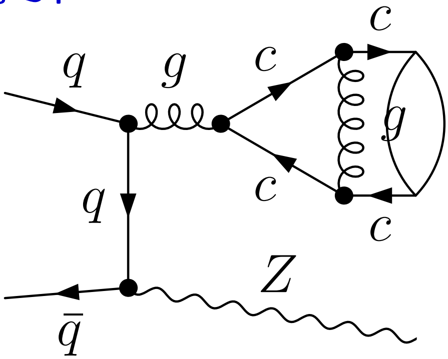

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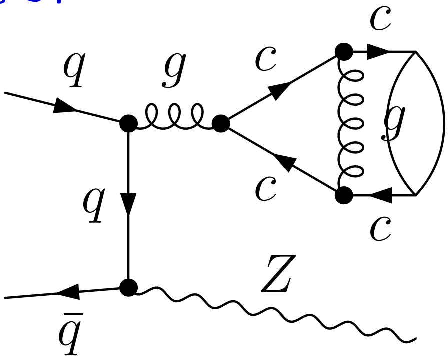

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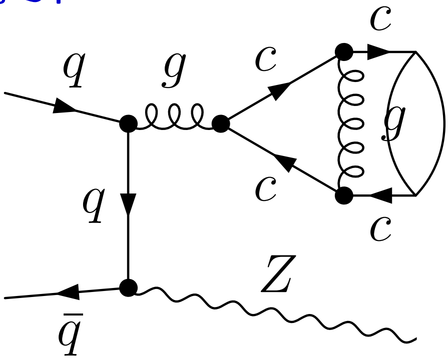

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- $H \rightarrow \mathcal{Q} + \{\gamma, W, Z\}$ measurements

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Grifols/Gunion/Mendez, PLB 197, 266 (1987);
Clarke/Foot/Volkas, JHEP 02 (2014) 123 ...

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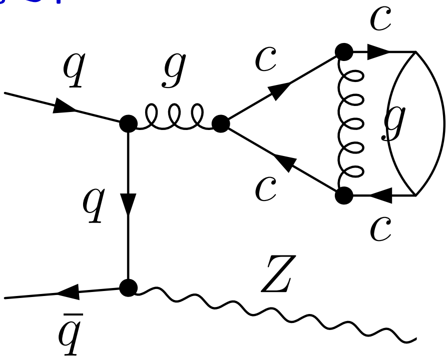

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- $H \to \mathcal{Q} + \{\gamma, W, Z\}$ measurements
- BSM tests — charged Higgs, new light scalars, ...

Associated J/ψ {W, Z} production

Geoff Bodwin's talk on Monday at this meeting:

Theoretical Aspects Quarkonium Production in Vacuum

Geoffrey Bodwin (ANL)

What do we need from experiment?

- Measurements of additional production processes
  - double-charmonium production
  - $J/\psi + Z$, $J/\psi + W^{\pm}$
  - $J/\psi +$ jet

Double parton scattering as a source of J/ψ {W, Z}

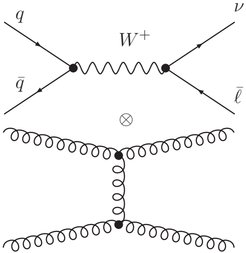
ATLAS Collaboration, New J. Phys. 15, 033038 (2013)

$J/\psi\{W, Z\}$ can also be produced by double parton scattering.

We rely on our study of $W + 2\,\text{jet}$ production, in the usual model of DPS: extraction of two partons from each of proton 1 and proton 2,

$$\mathrm{d}\hat{\sigma}^{\text{DPS}}_{W+2j} = \frac{m}{2\sigma_{\text{eff}}(s)} \int \mathrm{d}x_{i_1}\mathrm{d}x_{j_1}\mathrm{d}x_{i_2}\mathrm{d}x_{j_2}\; f_{i_1 j_1}(x_{i1},\, x_{j_1},\, \mu_F)\, f_{i_2 j_2}(x_{i2},\, x_{j_2},\, \mu_F)$$
$$\mathrm{d}\hat{\sigma}_{i_1 i_2 \to W}(x_{i_1},\, x_{i_2},\, s)\, \mathrm{d}\hat{\sigma}_{j_1 j_2 \to 2j}(x_{j_1},\, x_{j_2},\, s)$$

with *factorization* $f_{ij}(x_i,\, x_j,\, \mu_F) = f_i(x_i,\, \mu_F) f_j(x_j,\, \mu_F)(1 - x_i - x_j)\Theta(1 - x_i - x_j)$



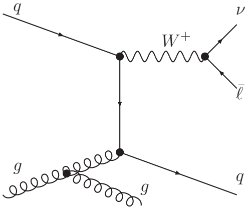
and modelling the DPS sub-processes

$$\hat{\sigma}_W(s) = \sigma_W(s)$$

and

$$\hat{\sigma}_{2j}(s) = \sigma_{2j}(s)$$

cf. DIRECT PROD^N:



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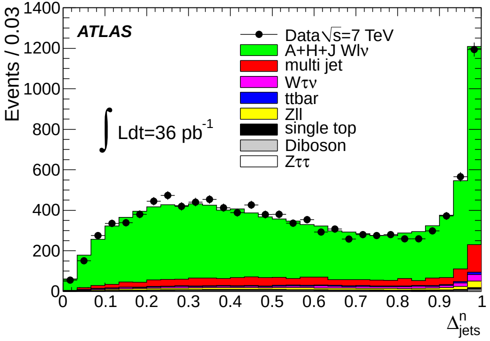
$36\,\mathrm{pb}^{-1}$ of $\sqrt{s} = 7\ \mathrm{TeV}$ data from the 2010 run

$W \to e\nu\ (\mu\nu)$: $p_T^{\ell} > 20\ \mathrm{GeV}$, $|\eta^{\ell}| < 2.47\ (2.4)$, $E_T^{\mathrm{miss}} > 25\ \mathrm{GeV}$, $m_T > 40\ \mathrm{GeV}$

two jets: $p_T > 20\ \mathrm{GeV}$, $|y| < 2.8$ (anti-k_T, $R = 0.4$; isolation from e (μ))

- 5% (8%) bkgd: subtracted



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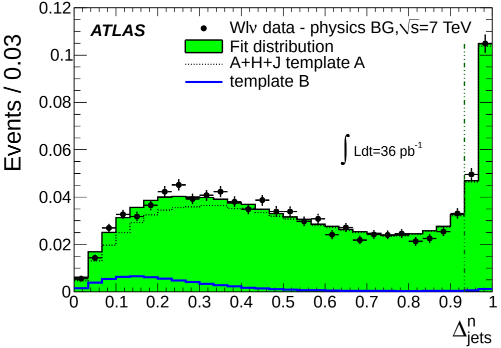
$$\Delta^n_{\text{jets}} = \frac{\left|\vec{p}_T^{\,J_1} + \vec{p}_T^{\,J_2}\right|}{\left|\vec{p}_T^{\,J_1}\right| + \left|\vec{p}_T^{\,J_2}\right|}$$



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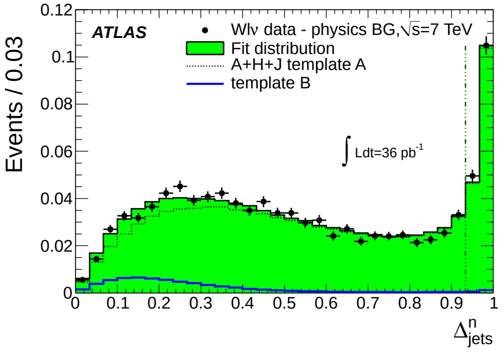
- $W + 0\,\mathrm{jet}$ & low-pileup 2 jet samples for determination of σ_W and σ_{2j}



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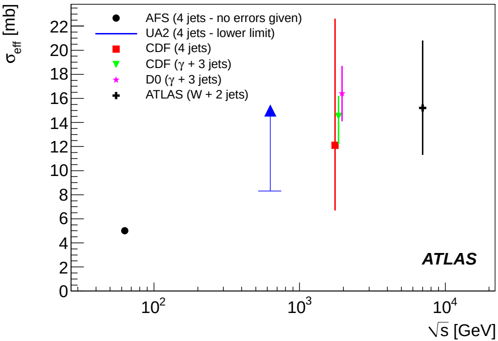


- $\sigma_{\text{eff}}(7\ \text{TeV}) = 15 \pm 3\,(\text{stat.})\,^{+5}_{-3}\,(\text{syst.})\,\text{mb}$: consistent with $\approx$ TeV meas^{ts}; conditions comparable to associated $J/\psi\,\{W,Z\}$ production

Quarkonium studies at ATLAS: analyses

Production cross-sections:

J/ψ differential, prompt & non-prompt	NPB 850, 387 (2011)
$\Upsilon(1S)$ fiducial	PLB 705, 9 (2011)
$\Upsilon(nS)$ differential	PRD 87, 052004 (2013)
$\chi_{c1,c2}$ differential, prompt & non-prompt	JHEP 07 (2014) 154
$\psi(2S)$ differential, prompt & non-prompt	JHEP 09 (2014) 079

Spectroscopy:

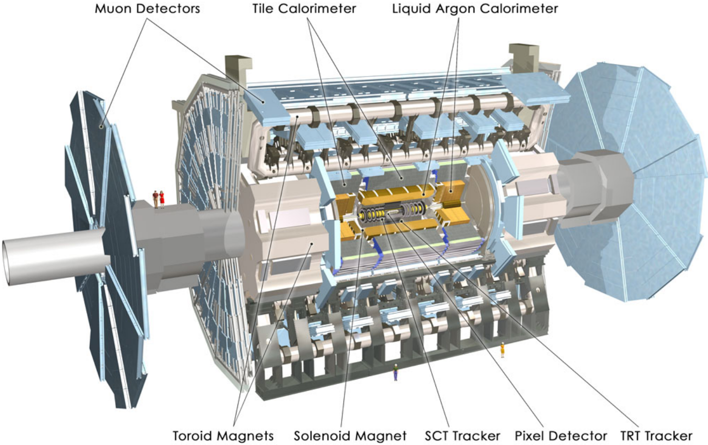
$\chi_{bJ}(nP)$; $\chi_{bJ}(3P)$ first observation	PRL 108, 152001 (2012)
$X_b \to \pi^+\pi^-\Upsilon(1S)$ search	PLB 740, 199 (2015)

Associated production:

prompt J/ψ in association with $W^\pm$	JHEP 04 (2014) 172
prompt J/ψ in association with Z^0	`arXiv:1412.6428` $\to$ EPJC

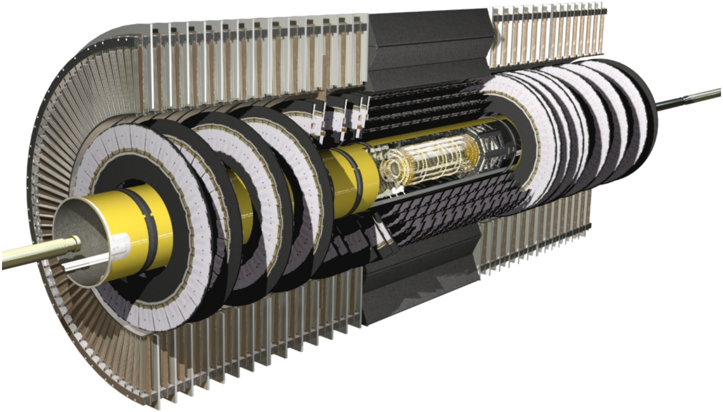
Quarkonium studies at ATLAS: the detector

optimized for a range of high-p_T discovery physics
in $\sqrt{s} = 14\ \mathrm{TeV}$ pp collisions



Quarkonium studies at ATLAS: the detector

typical quarkonium analysis: ATLAS is $\approx$ a large {Si pixel & strip, TRT} vertexing and tracking system, surrounded by trigger and muon ID



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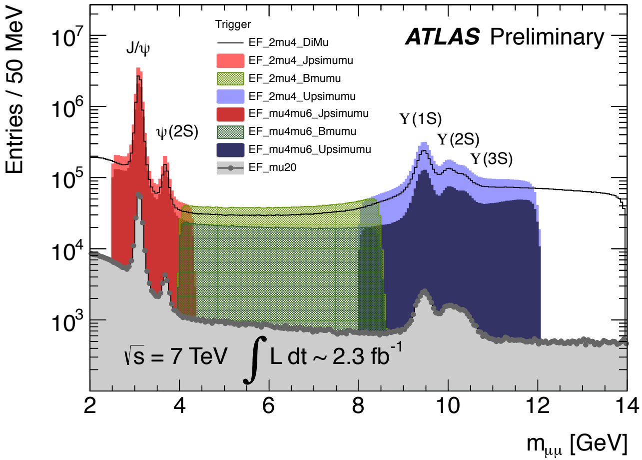

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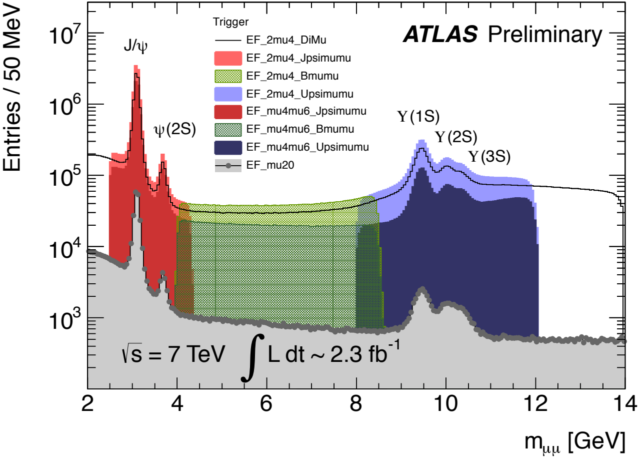

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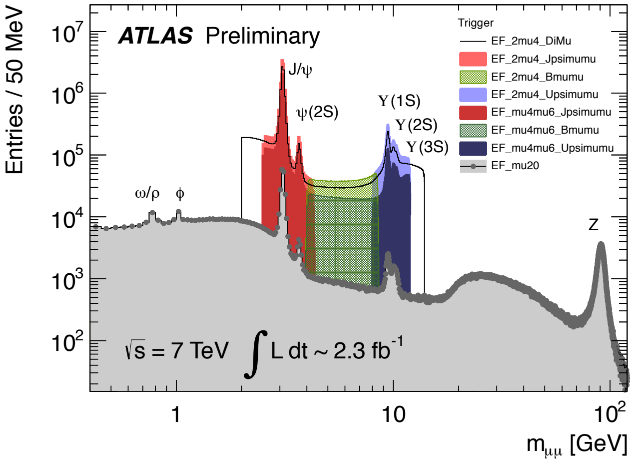
- $J/\psi\,\{W, Z\}$: trigger on W/Z lepton; better J/ψ acceptance



Associated production: selection criteria

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

μ: $|\eta| < 2.5$; $p_T > 3.5\ (2.5)$ GeV for $|\eta| < (>) 1.3$; within $10\,\mathrm{mm}$ of PV along z

ψ: $|y| < 2.1$, $p_T > 8.5$ GeV; ≥ 1 $p_T > 4$ GeV muon; ≥ 1 "combined" muon

$J/\psi\, W^{\pm}$:

- $p_T^{\psi} < 30$ GeV, $m_{\mu\mu} \in (2.5, 3.5)$ GeV
- single-muon trigger: $p_T > 18$ GeV
- $W^{\pm}$ decay muon matches trigger; $|\eta| < 2.4$, $p_T > 25$ GeV, combined closest approach PV $< 1\,\mathrm{mm}$ in z transverse $d_0/\sigma(d_0) < 3$; isolated
- Z^0 veto: W decay & OS ψ muons
- $E_T^{\mathrm{miss}} > 20$ GeV; calculation includes clusters with $|\eta| < 4.9$
- $m_T > 40$ GeV

$J/\psi\, Z^0$:

- $p_T^{\psi} < 100$ GeV, $m_{\mu\mu} \in (2.6, 3.6)$
- single μ or e trigger: $p_T > 24$ GeV
- ≥ 1 decay ℓ must match trigger; μ: $|\eta| < 2.4$ and $p_T > 25$ GeV; e: "medium" ID, $p_T > 25$ GeV

μ: $|\eta| < 2.5$, $p_T > 15$ GeV, combined

e: $|\eta| < 2.47$, $p_T > 15$ GeV, "loose" ID, isolated

- $|m(\ell^+\ell^-) - m_Z| < 10$ GeV
- J/ψ & Z^0 vertices $< 10\,\mathrm{mm}$ in z

Associated production: acceptance

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

For a J/ψ of a given $(|y|,\, p_T)$, the acceptance $\mathcal{A}$ is the probability that *the muons pass the* $(\eta,\, p_T)$ *selection requirements*.

Depends on the J/ψ spin alignment: the distribution $W(\cos\vartheta, \varphi)$

$$
\begin{aligned}
&\propto \frac{\mathcal{N}}{(3+\lambda_\vartheta)} \left(1 + \lambda_\vartheta \cos^2\vartheta\right. \\
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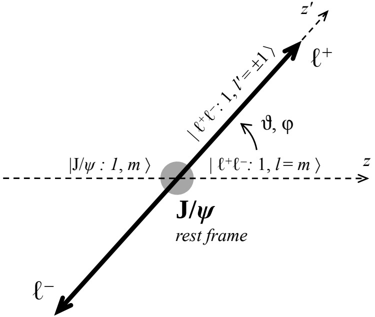

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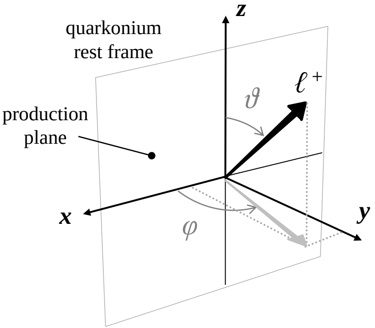

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reflection-odd terms unobservable (parity)

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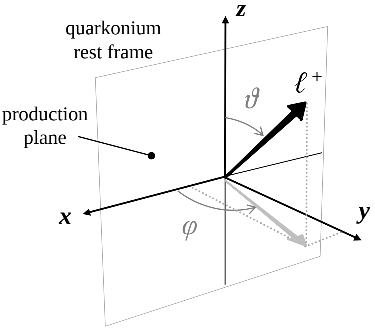

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Depends on the J/ψ spin alignment: the distribution $W(\cos\vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3+\lambda_\vartheta)} \left(1 + \lambda_\vartheta \cos^2\vartheta \right.$$

$$+ \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

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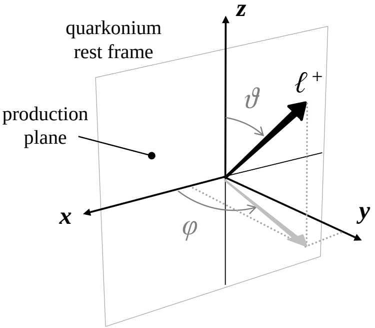

For inclusive production:
reflection-odd terms unobservable (parity)

- limited range of $(\lambda_\vartheta,\, \lambda_\varphi,\, \lambda_{\vartheta\varphi})$ allowed

Associated production: acceptance

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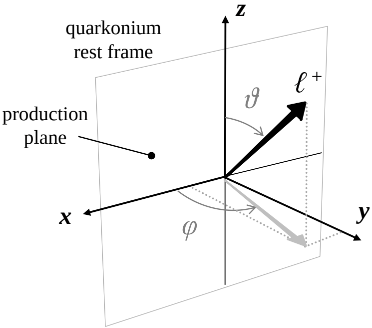


For inclusive production:
reflection-odd terms unobservable (parity)

- limited range of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ allowed
- LHC experiments quote results for each of a set of working points

Associated production: acceptance $\mathcal{A}(|y|, p_T; \text{FLAT})$

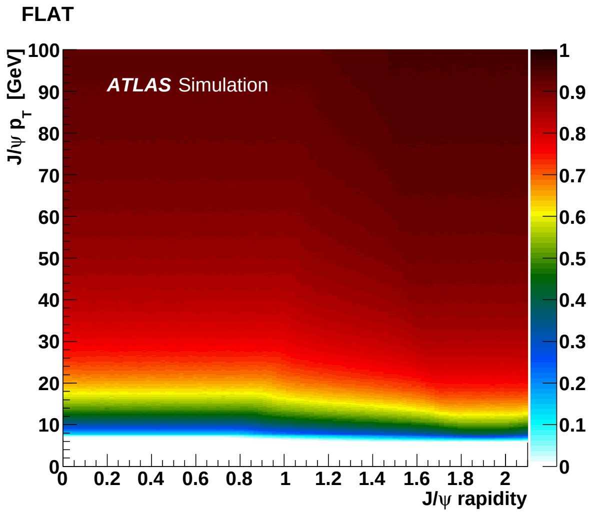
ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428 ($J/\psi\, Z^0$)

$$W(\cos\vartheta, \varphi) \propto (1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

$(\lambda_\vartheta,\ \lambda_\varphi,\ \lambda_{\vartheta\varphi}) =$
$(\ 0,\ \ 0,\ \ 0)$

unpolarized production

isotropic distribution



Associated production: acceptance $\mathcal{A}(|y|, p_T;$ LONG)

ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428 ($J/\psi\, Z^0$)

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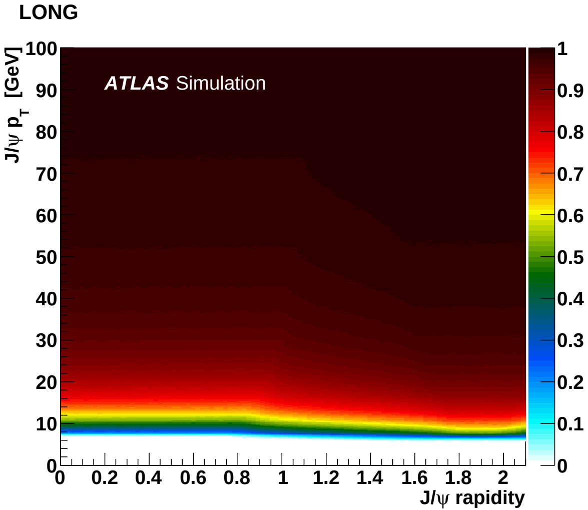
$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$

$(-1, \quad 0, \quad 0)$

J/ψ polarization:
longitudinal along z

$\theta \sim 90^\circ$ preferred:
$\approx$ equal sharing of p_T
between muons



Associated production: acceptance $\mathcal{A}(|y|, p_T; T+0)$

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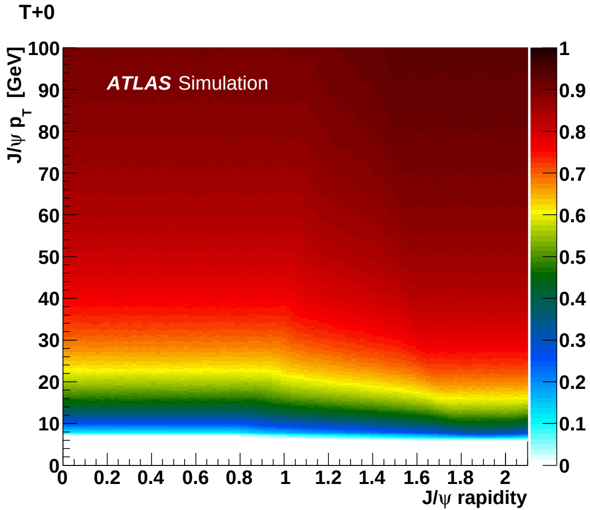
$(+1,\quad 0,\quad 0)$

J/ψ polarization:
transverse along z

$\theta \sim \{0, 180\}^\circ$ preferred:
one μ emerges backward
in the Υ rest frame



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longitudinal along y

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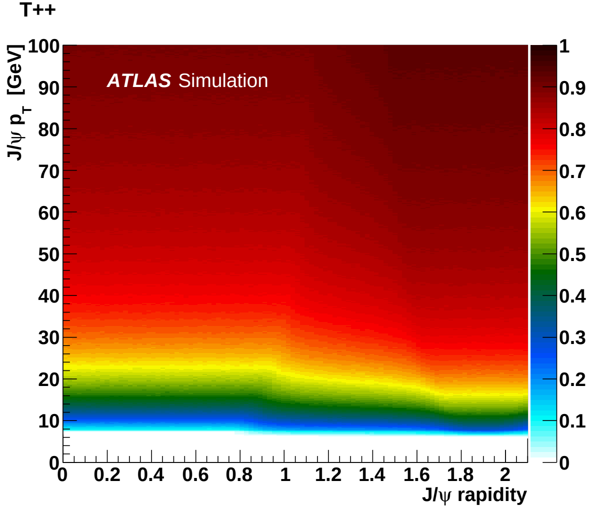

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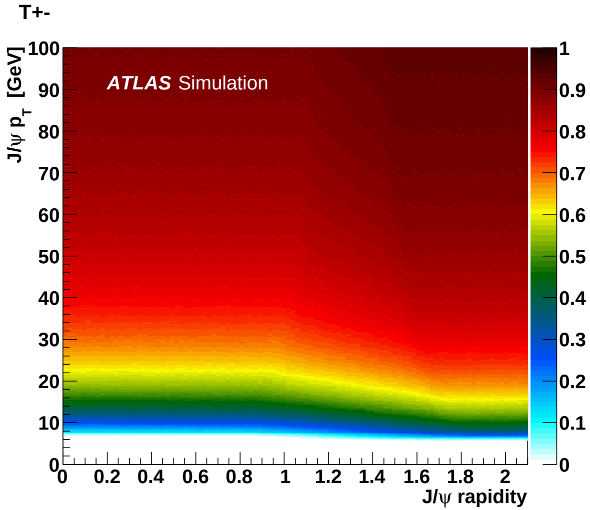
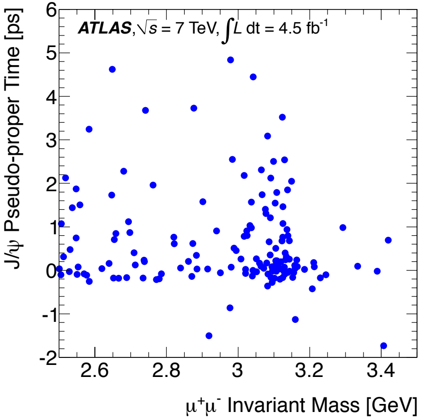


Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

Looking at the events in **dimuon invariant mass $m_{\mu\mu}$** from the vertex fit, and **pseudo-proper time** $\tau \equiv \frac{\vec{L} \cdot \vec{p}_T^{\,\psi}}{p_T^{\psi}} \cdot \frac{m_{\mu\mu}}{p_T^{\psi}}$, where $\vec{L} = \vec{r}^{\,\psi} - \vec{r}^{\,PV}$



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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  78 with $|y| \leq 1.0$,
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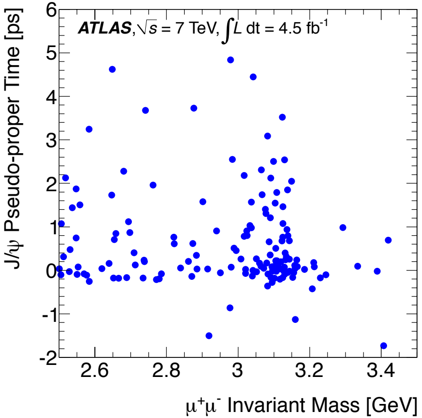

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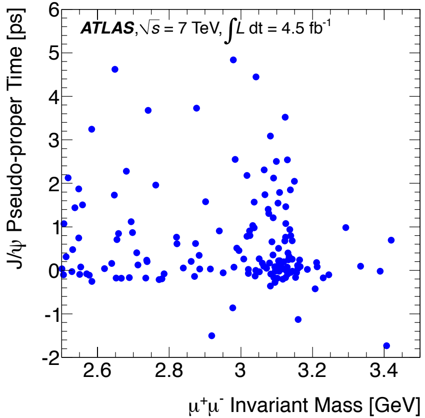

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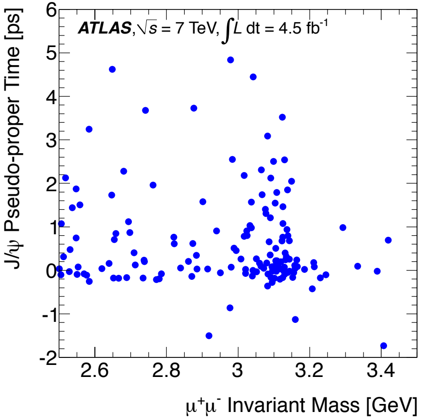

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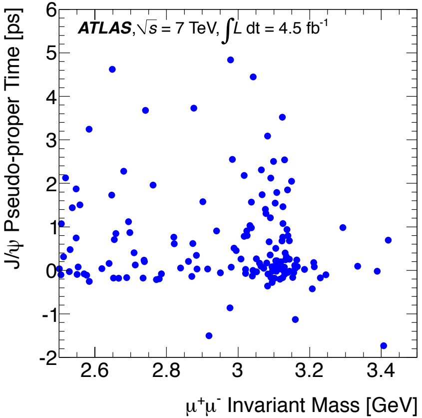

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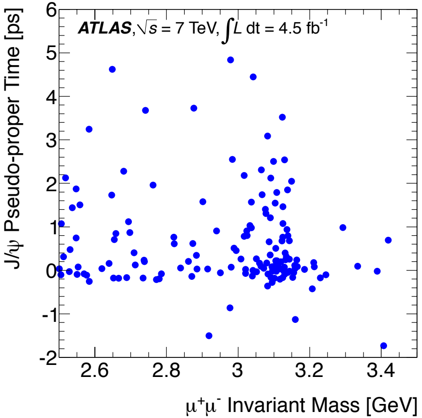

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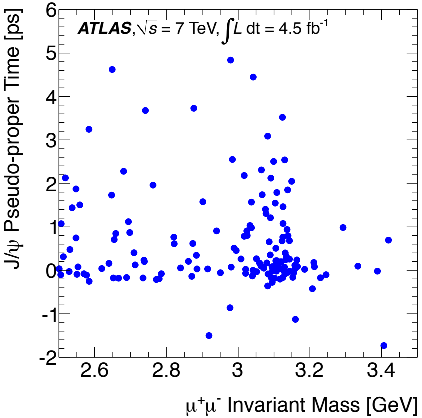

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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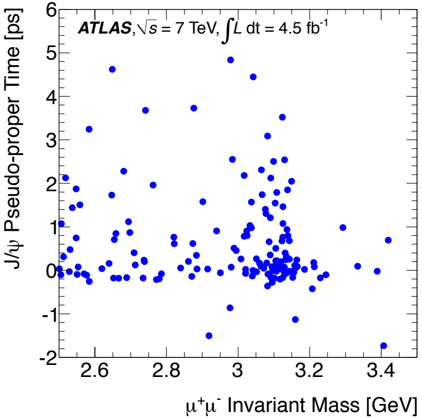
- done separately in the 2 $|y|$ bins

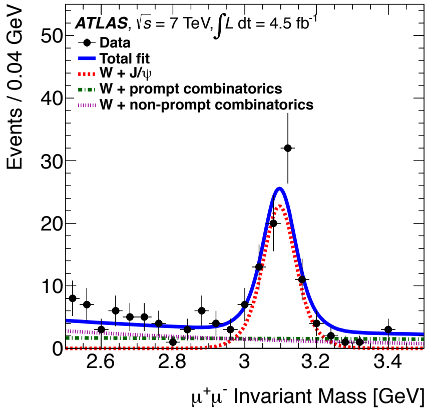


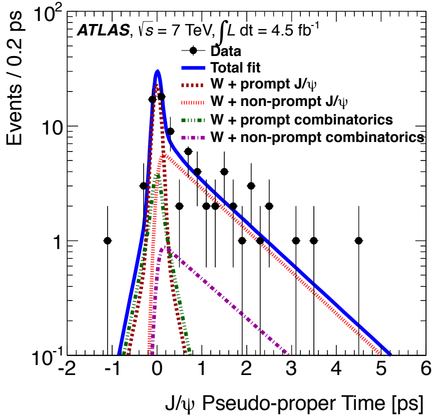
Prompt J/ψ in association with $W^\pm$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

same technique used in charmonium production measurements:

2D fit to ($m_{\mu\mu}$, τ) to distinguish prompt ψ, non-prompt ψ, prompt bkgd, non-prompt bkgd



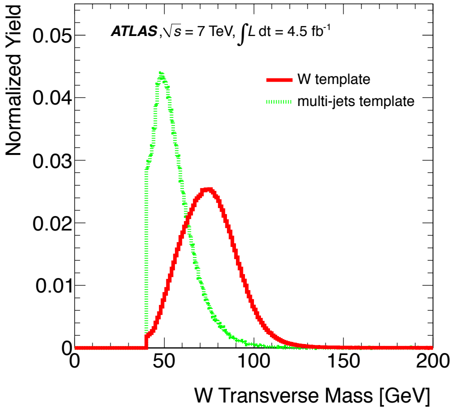


Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

transverse mass $m_T = \sqrt{2 p_T^{\mu} E_T^{\text{miss}} (1 - \cos(\phi^{\mu} - \phi^{\text{miss}})]}$,

to distinguish $W^{\pm}$ signal from multi-jet bkgd events producing $\{\mu, E_T^{\text{miss}}\}$



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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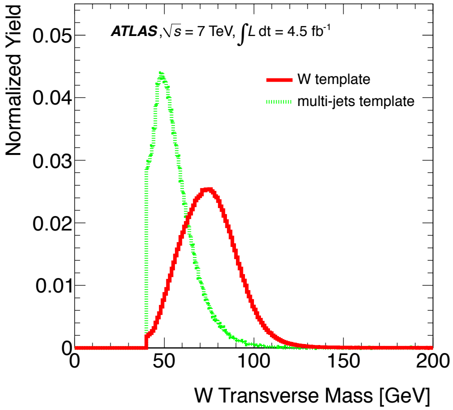
  $W^{\pm}$: MC simulation
  multi-jet: non-isolated μ sample



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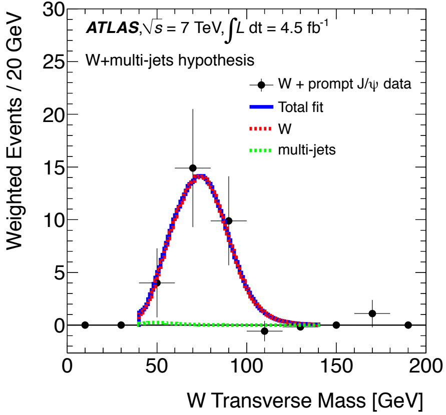
  to pick out the signal, and ...



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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multijets:	0.1 ± 4.6
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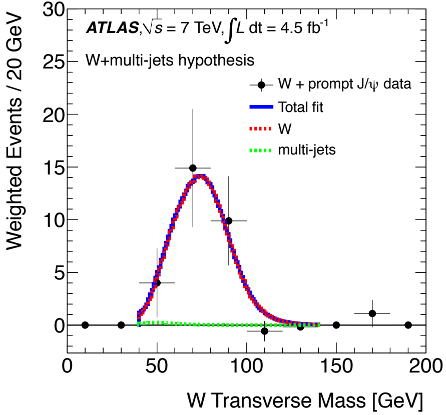

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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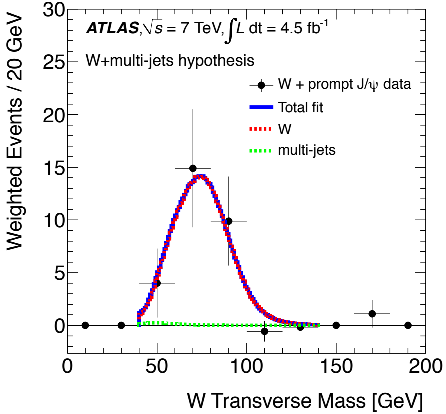
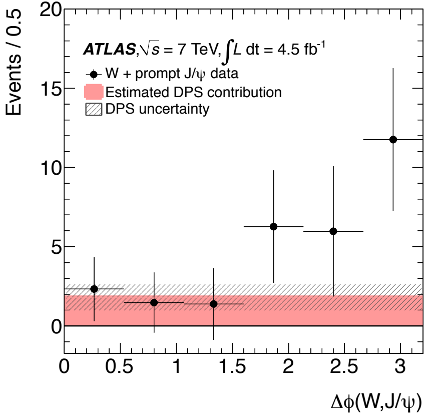
- *cf.* pileup: 1.8 ± 0.2 events
  estimated from W-inclusive, $\mathcal{L}$, Δz, measured σ_{ψ}



Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

azimuthal angle difference between $W^{\pm}$ and J/ψ ($_s\mathcal{P}lot$-weighted), to distinguish DPS (assumed $\approx$ flat in $\Delta\phi$) from direct production



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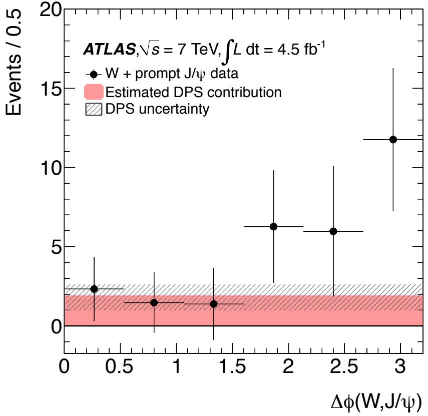

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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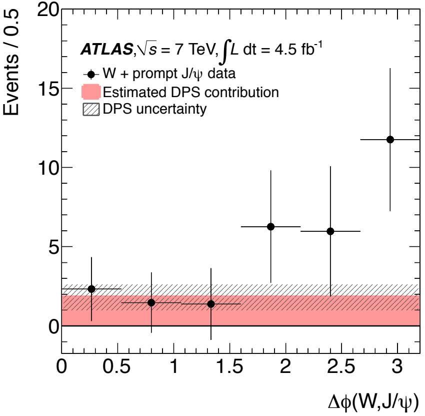

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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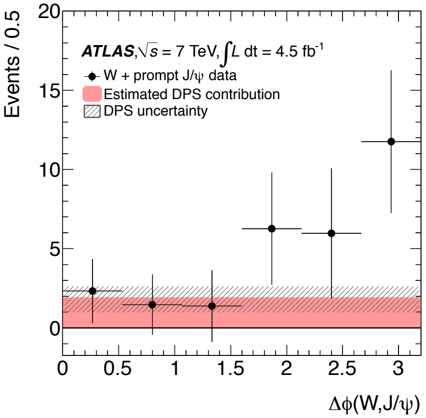

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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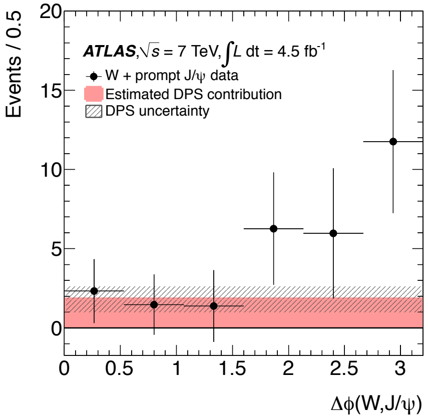
  $\longrightarrow$ 10.8 ± 4.2 events, $\lesssim 40\%$ of the sample



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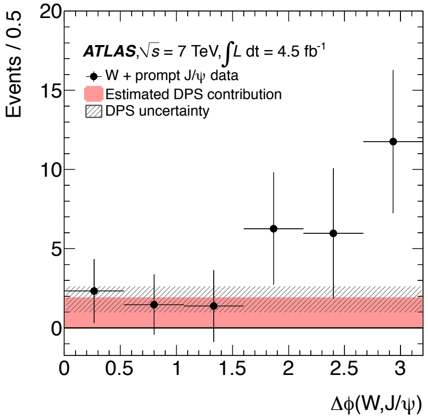

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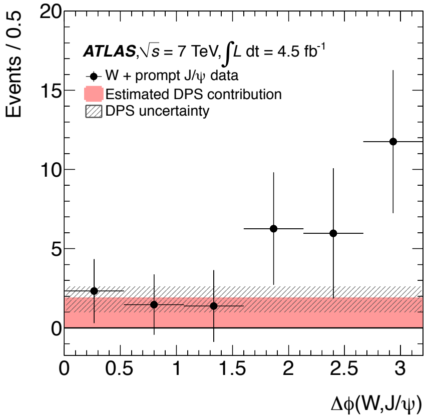
- direct CS, CO: peaked $\Delta\phi \to \pi$



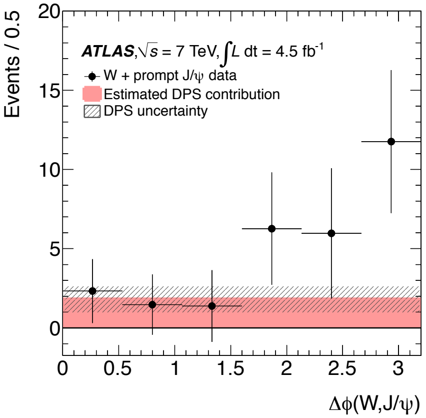
Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

azimuthal angle difference between $W^{\pm}$ and J/ψ (${}_s\mathcal{P}lot$-weighted), to distinguish DPS (assumed $\approx$ flat in $\Delta\phi$) from direct production

- DPS rate: estimated from
  - DPS ansatz $P_{\psi|W} = \sigma_{\psi}/\sigma_{\text{eff}}$
  - ATLAS $\sigma_{\text{eff}} = 15 \pm 3^{+5}_{-3}\,\text{mb}$

  $\longrightarrow 10.8 \pm 4.2$ events,
  $\lesssim 40\%$ of the sample
- DPS shape validated* w `Pythia 8`
- direct CS, CO: peaked $\Delta\phi \to \pi$



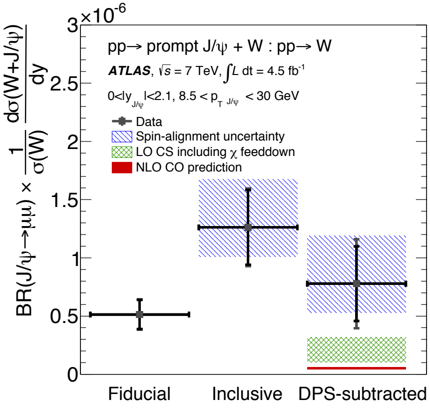
No fit here; my paraphrase:

to the extent that we can trust the DPS rate, and the qualitative results on shape, we have evidence for (direct) associated $J/\psi\ W$

Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

Results as **ratios w.r.to inclusive W** prod^n (measured without J/ψ cuts): 1.48×10^7 events, consistent w NNLO pQCD



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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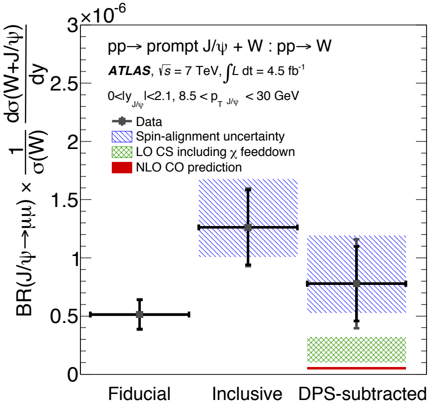

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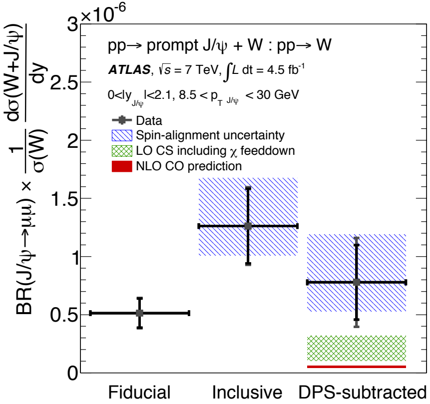

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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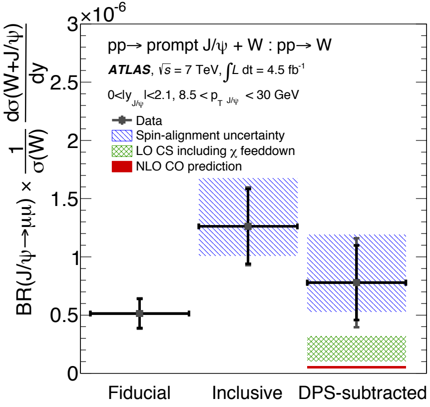

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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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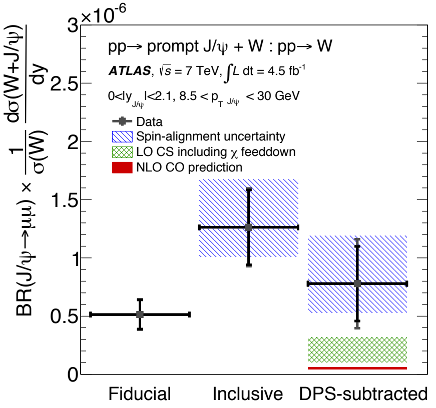
- spin-alignment uncertainty introduced at this step: size $\approx$ other uncertainties



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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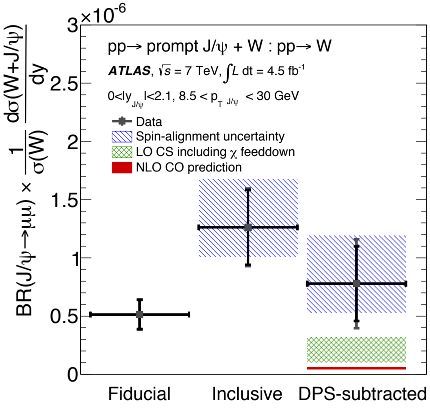

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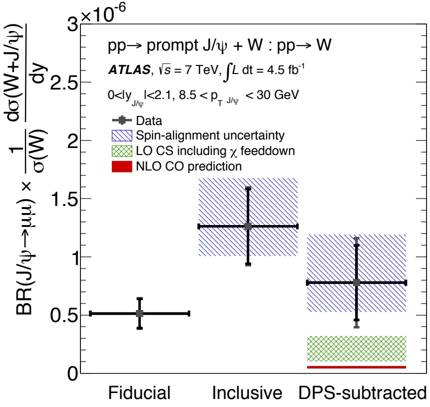
- (pileup subtracted from both)
- DPS-subtracted *cf.* theory:

$$\boxed{R = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}}$$



10–32 in LO CS: PLB 726, 218 (2013)

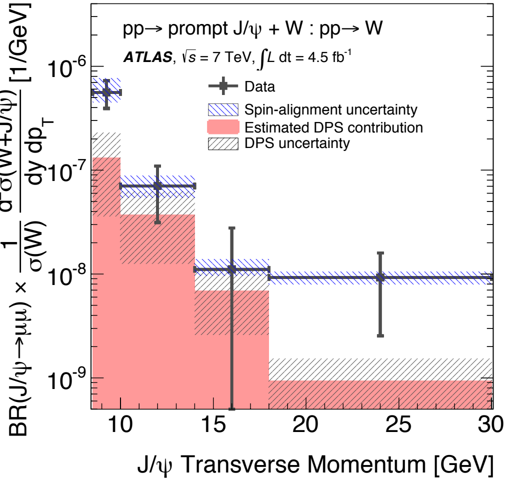
5–6 in NLO CO: PRD 83, 014001 (2011)

Prompt J/ψ in association with $W^{\pm}$ at $\sqrt{s} = 7$ TeV

ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

results in p_T^{ψ} bins: DPS ansatz $d\hat{\sigma}^{DPS}_{\psi W} \propto \frac{1}{\sigma_{eff}(s)} \int d^4\{x_i\}\, f \cdot f \, d\hat{\sigma}_{\psi}\, d\hat{\sigma}_W$

gives the p_T dependence as well as the rate for DPS



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ATLAS Collaboration, J. High Energy Physics 04 (2014) 172

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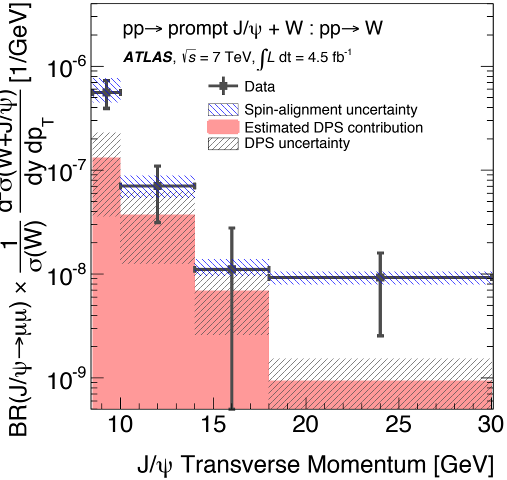
another qualitative statement: *the excess at high p_T provides further warrant (independent of $\Delta\phi$) of a non-DPS-like component*



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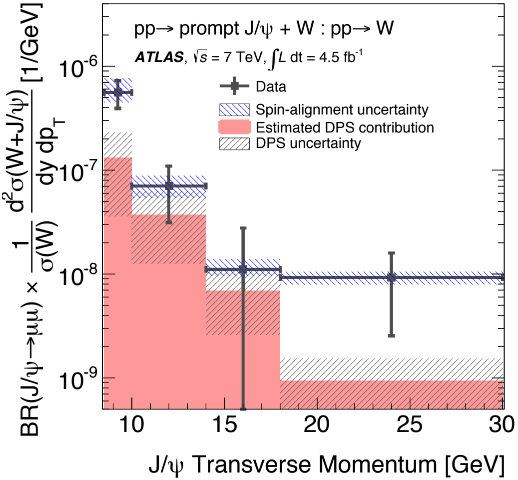

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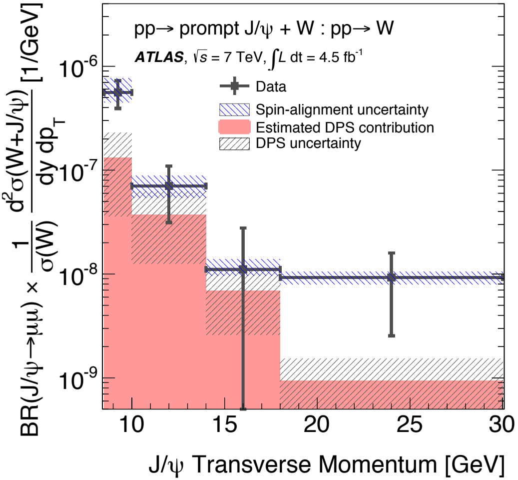
---

we see $J/\psi\, W$ production, consistent with expected DPS contribution + associated prod^n at a higher rate than th^y

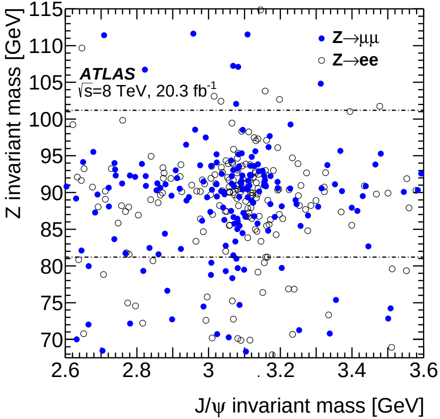


Prompt J/ψ in association with Z^0 at $\sqrt{s} = 8$ TeV

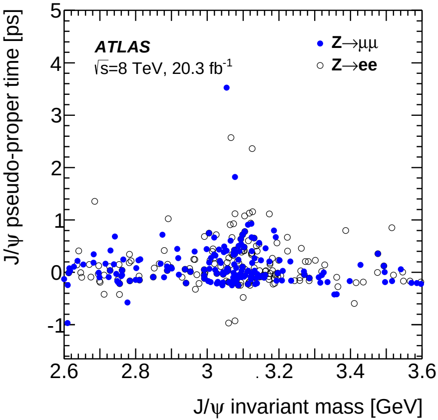
ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

2012 sample: $20.3\,\mathrm{fb}^{-1} \longrightarrow$ 290 events, 139 $\psi_{\mu\mu}\, Z_{\mu\mu}$ + 151 $\psi_{\mu\mu}\, Z_{ee}$

signal evident in (m_ψ, m_Z)



prompt & non-prompt in τ

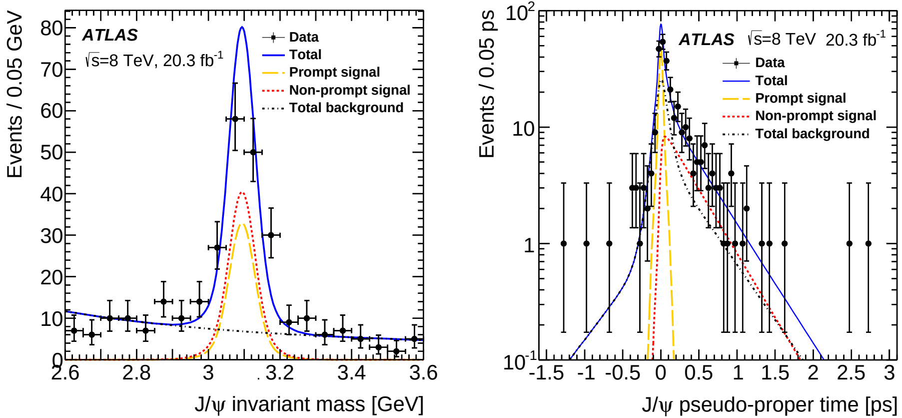


Prompt J/ψ in association with Z^0 at $\sqrt{s} = 8$ TeV

ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

2D fit to $(m_{\mu\mu}, \tau)$ to distinguish prompt ψ, non-prompt ψ, prompt bkgd, non-prompt bkgd

fitted simultaneously w 10^5 inclusive $\psi \to \mu\mu$ events w same selection to determine parameters (*cf.* $\mathcal{G}$-constraint method used for $\psi\, W$)

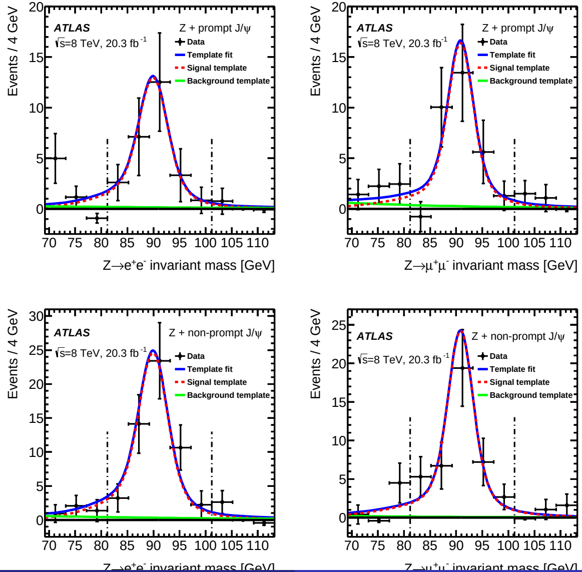


Prompt J/ψ in association with Z^0 at $\sqrt{s} = 8$ TeV

ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

change $m_T \mapsto m_Z$
provides extra power;

- MC signal template
- multi-jet bkgd from data, inverting ℓ isolation requirements
- of 56 ± 10 prompt ψ: 0 ± 4 ee, 1 ± 4 $\mu\mu$ background events
- 95 ± 12 non-prompt ψ: 1 ± 5 ee, 0 ± 5 $\mu\mu$ background events



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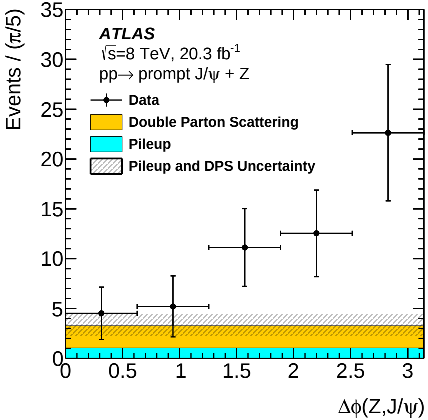
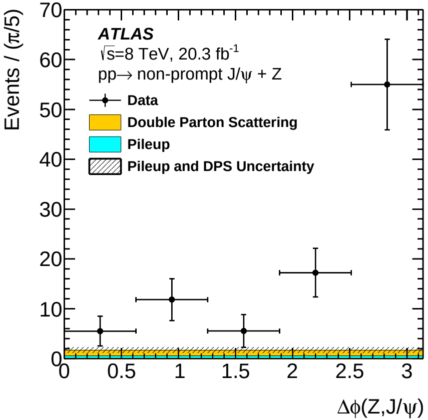
ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

Analogous calculations for

pileup:	$5.2^{+1.8}_{-1.3}$ events	$2.7^{+0.9}_{-0.6}$ events
DPS calculation	$11.1^{+5.7}_{-5.0}$ events	$5.8^{+2.8}_{-2.6}$ events





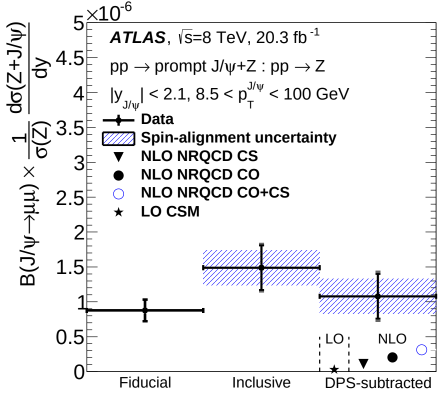
Prompt J/ψ in association with Z^0 at $\sqrt{s} = 8$ TeV

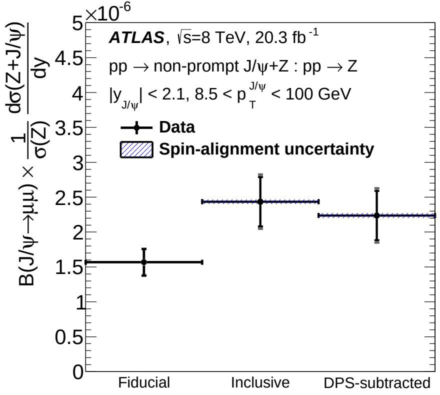
ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

Again: fiducial, inclusive (w spin-alignment uncert.), and DPS-subtracted cross-section ratios; exceeds theory estimates at both

LO: JHEP 03 (2013) 115; note disagreements with

NLO: JHEP 02 (2011) 071; erratum ibid. 12 (2012) 010

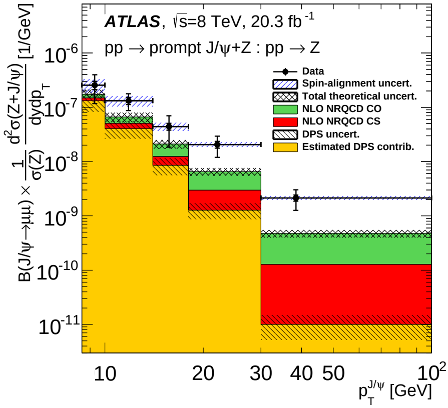


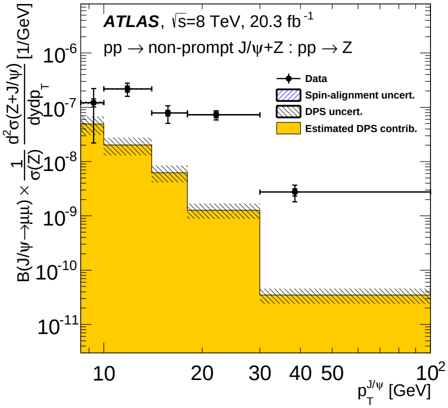


Prompt J/ψ in association with Z^0 at $\sqrt{s} = 8$ TeV

ATLAS Collaboration, ATLAS–BPHY–2014–01, arXiv:1412.6428

As p_T increases, the data excess over color singlet + octet + DPS grows, and the spin-alignment uncertainty becomes negligible





Summary

- ATLAS has measured associated $J/\psi\, W$ and $J/\psi\, Z$ production
- in both cases, we find clean samples, for both prompt and non-prompt J/ψ
- the double parton scattering (DPS) contribution is estimated using the standard ansatz, and our σ_{eff} measurement at $\sqrt{s} = 7$ TeV
- we see evidence for associated production, both in overall rates and in its p_T spectrum
- the rates are in excess over available theoretical predictions
- this is an ideal ATLAS/CMS measurement, robust against high rates & thresholds

BACKUP: acceptance for V $\rightarrow \mu^+\mu^-$

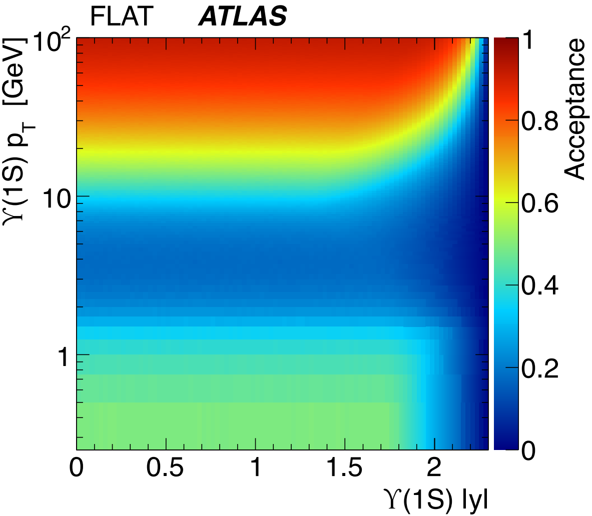
Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

for a given $(|y|, p_T)$,
$\mathcal{A}$ is the probability that *both muons fall within the fiducial volume:*

- $p_T^\mu > 4\ \mathrm{GeV}$
- $|\eta^\mu| < 2.3$

$4\ \mathrm{GeV}$ trigger thresholds
$\longrightarrow$ pronounced structure

straightforward extension to $\pi^+\pi^-\mu^+\mu^-$ and more complex final states



BACKUP: polarization for V $\rightarrow \mu^+\mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

for ($J^{PC} = 1^{--}$) $|V\rangle = b_{+1}\,|+1\rangle + b_{-1}\,|-1\rangle + b_0\,|0\rangle$ decaying $\rightarrow \ell^+\ell^-$,

- the angular distribution $W(\cos\vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3+\lambda_\vartheta)}\,(1 + \lambda_\vartheta \cos^2\vartheta$$

$$+\ \lambda_\varphi \sin^2\vartheta \cos 2\varphi\ +\ \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

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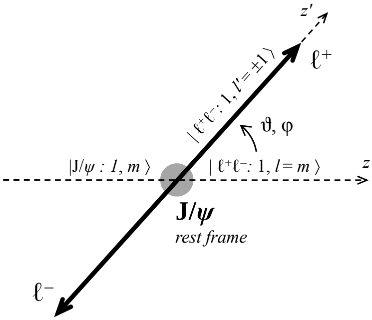

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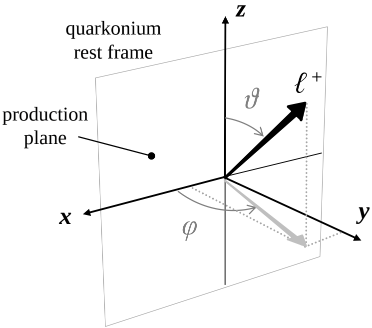
- inclusive production: p_1, p_2, and V only;
  we ($\sim$ must) choose (x, z) : production plane



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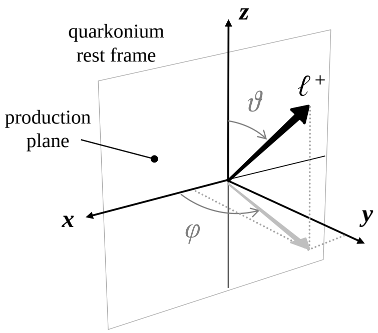

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- reflection-odd terms unobservable (parity)

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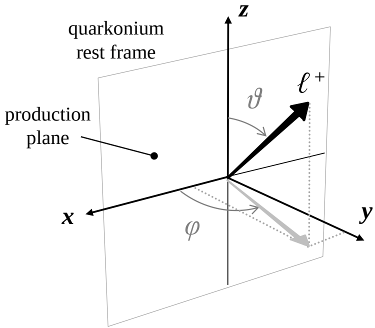

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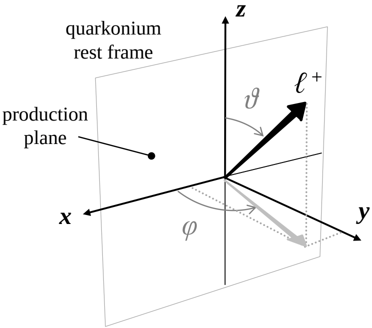
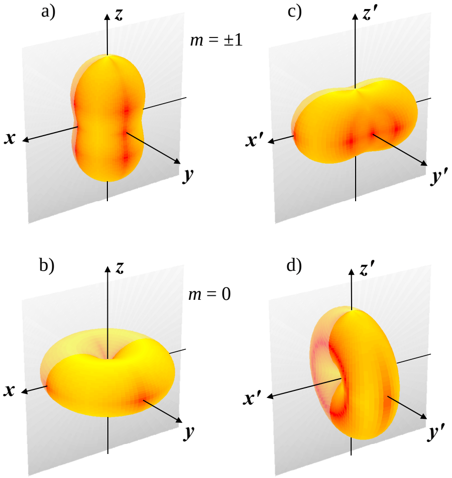


- inclusive production: p_1, p_2, and V only;
  we ($\sim$ must) choose (x, z) : production plane
- reflection-odd terms unobservable (parity)
- full angular distributions $(\lambda_\vartheta,\ \lambda_\varphi,\ \lambda_{\vartheta\varphi})$ in general needed ...

BACKUP: polarization for V $\to \mu^+\mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

- L: polarized $\begin{cases} \text{transversely} \\ \text{longitudinally} \end{cases}$



BACKUP: polarization for $V \to \mu^+\mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

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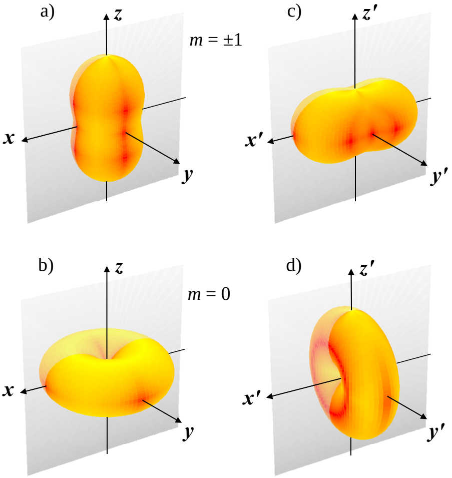

BACKUP: polarization for V $\rightarrow \mu^+\mu^-$

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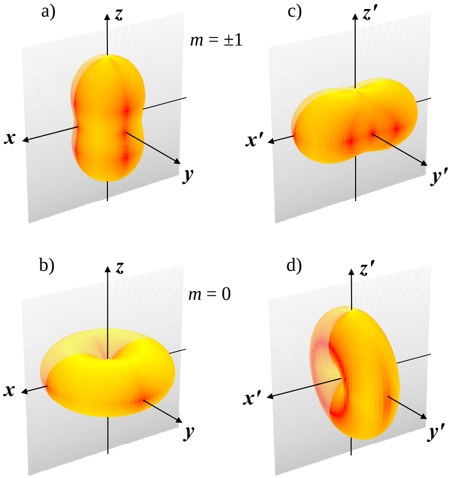
- integration over azimuth $\varphi \longrightarrow$



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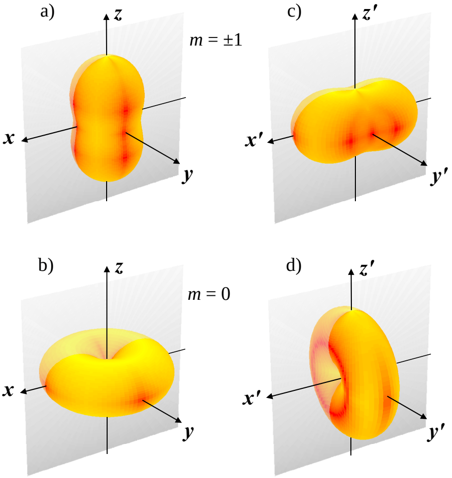
- L: polarized $\begin{cases}\text{transversely} \\ \text{longitudinally}\end{cases}$
- R: meas^t frame rotated by 90°
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like



BACKUP: polarization for V $\to \mu^+\mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

- L: polarized $\begin{cases} \text{transversely} \\ \text{longitudinally} \end{cases}$
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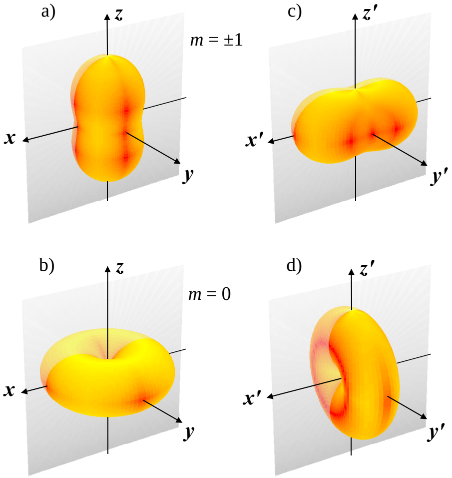

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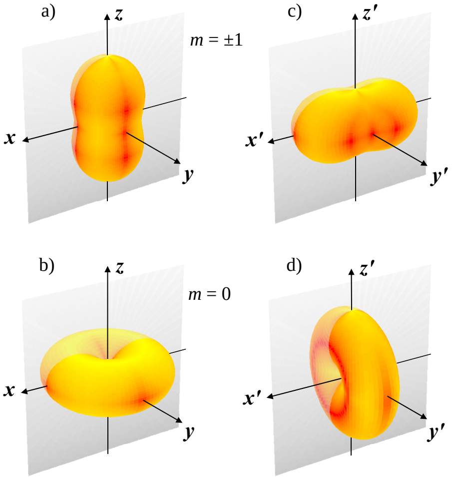

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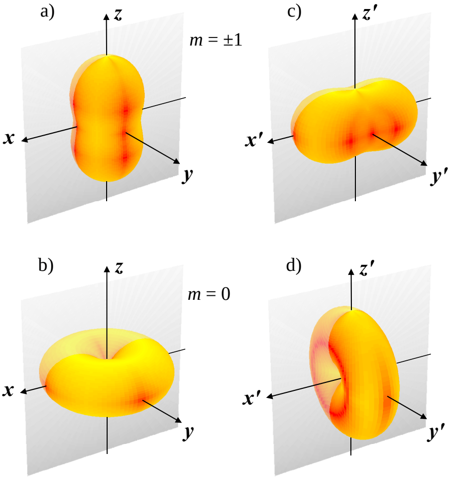
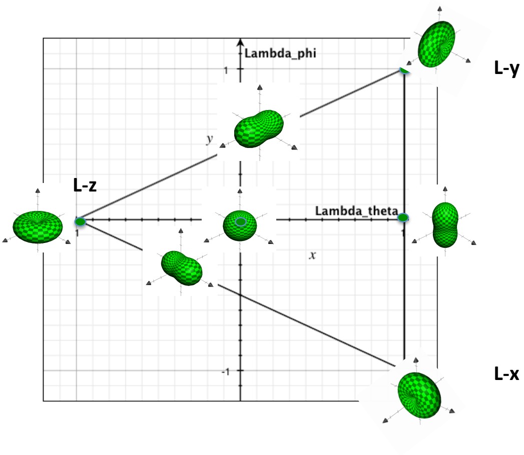
- *experimental acceptance* is also typically a f^n of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$

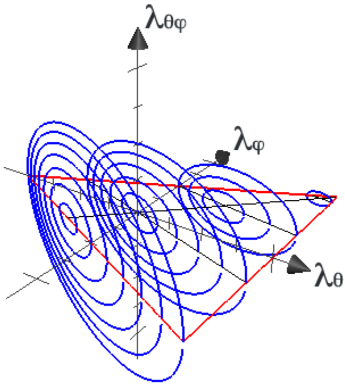


BACKUP: polarization for V $\rightarrow \mu^+\mu^-$

Sandro Palestini, Physical Review D 83, 031503(R) (2011)

- limited range of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ values allowed





BACKUP: polarization for V $\to \mu^+\mu^-$

Sandro Palestini, Physical Review D 83, 031503(R) (2011)

- limited range of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ values allowed
- LHC experiments quote results for each of a set of working points