Double parton scattering and vector boson plus quarkonium associated production

Darren Price

New Observables in Quarkonium Production,

ECT*, Trento, March 1st 2016

Introduction

Wide range of detailed measurements of various quarkonium species production now available (and associated predictions!)

Other observables like polarisation provide additional constraints on theory.

High production rates at hadron colliders allow not just study of inclusive quarkonium production, but test more **exclusive final states**

Additional constraints on theory, and on universality of CO LDMEs

One such "new observable" is associated vector boson plus quarkonium

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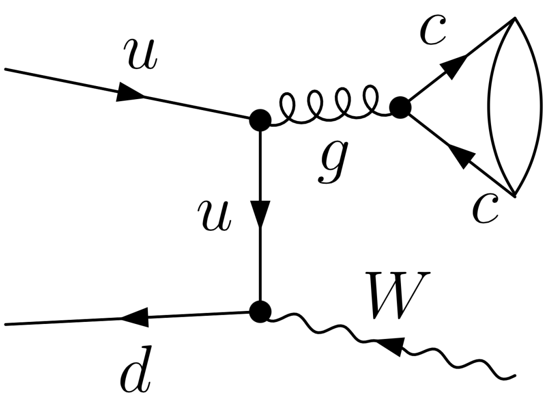
> "including the NLO QCD corrections up to the $\alpha_s^3 v^7$ order, there are only color-octets $c\bar{c}[^1S_0^{(8)}]$, $c\bar{c}[^3S_1^{(8)}]$ and $c\bar{c}[^3P_J^{(8)}]$ $(J = 0, 1, 2)$, but no color-singlet contribution exists in the $pp \to J/\psi + W + X$ process. Therefore, the $J/\psi + W$ production at the LHC is an ideal ground to study the COM."



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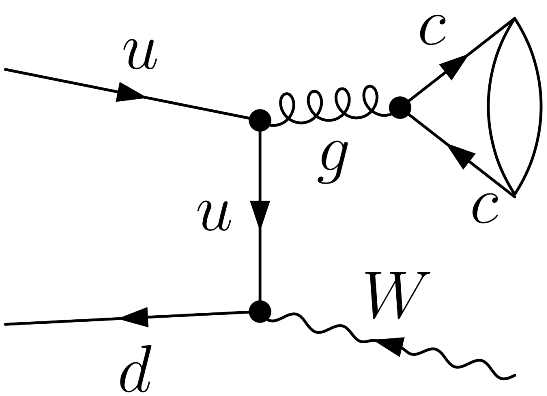
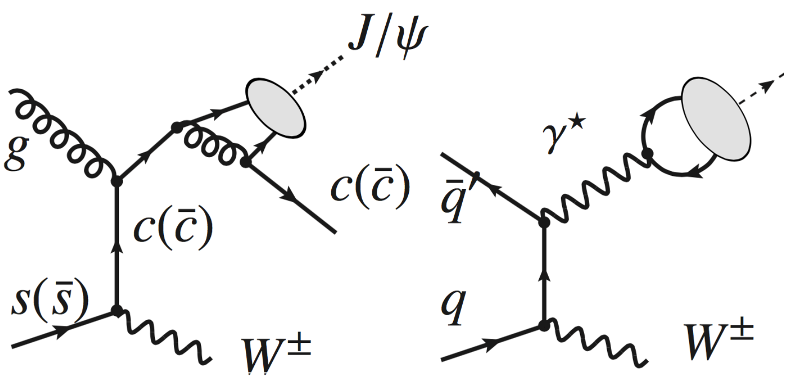


Lansberg, Lorce, [Phys.Lett. B726 (2013) 218-222, Phys.Lett. B738 (2014) 529-529] point out that this is not necessarily the case:

"We have shown that the LO CSM contributions to direct $J/\psi + W^{\pm}$ are not negligible compared to the contribution arising from CO transitions which were previously thought to be dominant."



CDF search for Upsilon(nS)+W/Z

First experimental search for associated vector boson plus quarkonia came from CDF at 1.8 TeV [Phys.Rev.Lett. 90 (2003) 221803] **in the context of a SUSY $H^{\pm} \to W\Upsilon$ search**

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Since superseded by Run-2 search [Phys. Rev. D 91, 052011 (2015)].

	$\Upsilon + W \to e\nu$	$\Upsilon + W \to \mu\nu$	$\Upsilon + W \to \ell\nu$	$\Upsilon + Z \to ee$	$\Upsilon + Z \to \mu\mu$	$\Upsilon + Z \to \ell\ell$
N_{sig}	0.019±0.004	0.014±0.003	0.034±0.007	0.0048±0.0011	0.0037±0.0008	0.0084±0.0018
N_{bg} (fake Υ)	0.7±0.4	0.4±0.3	1.1±0.5	0.07±0.07	0.04±0.04	0.1±0.1
N_{bg} (fake W/Z)	0.06±0.04	0	0.06±0.04	0	0	0
N_{bg} ($\Upsilon + Z$)	0.0006±0.0001	0.0033±0.0007	0.0039±0.0009			
N_{bg} (total)	0.8±0.4	0.4±0.3	1.2±0.5	0.07±0.07	0.04±0.04	0.1±0.1
N_{obs}	0	1	1	0	1	1

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Look for excesses over predicted Vϒ rate 0.47 (W) and 0.18 (Z) pb (null result)

Since superseded by Run-2 search [Phys. Rev. D 91, 052011 (2015)].

	$\Upsilon+W\to e\nu$	$\Upsilon+W\to\mu\nu$	$\Upsilon+W\to\ell\nu$	$\Upsilon+Z\to ee$	$\Upsilon+Z\to\mu\mu$	$\Upsilon+Z\to\ell\ell$
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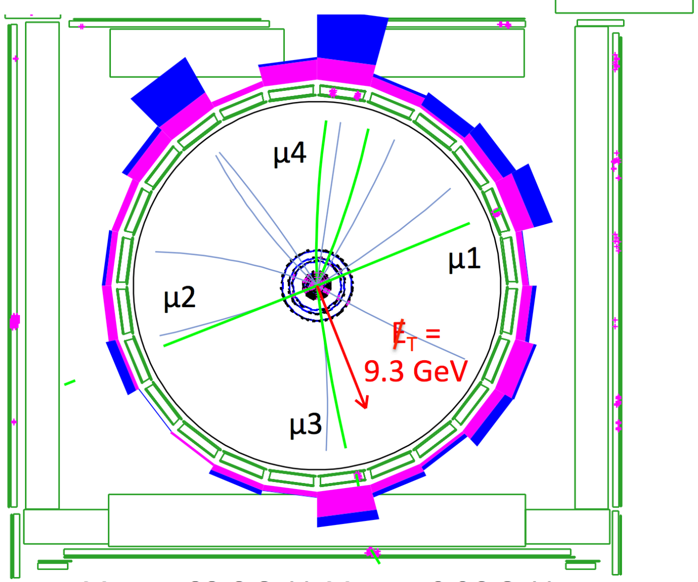
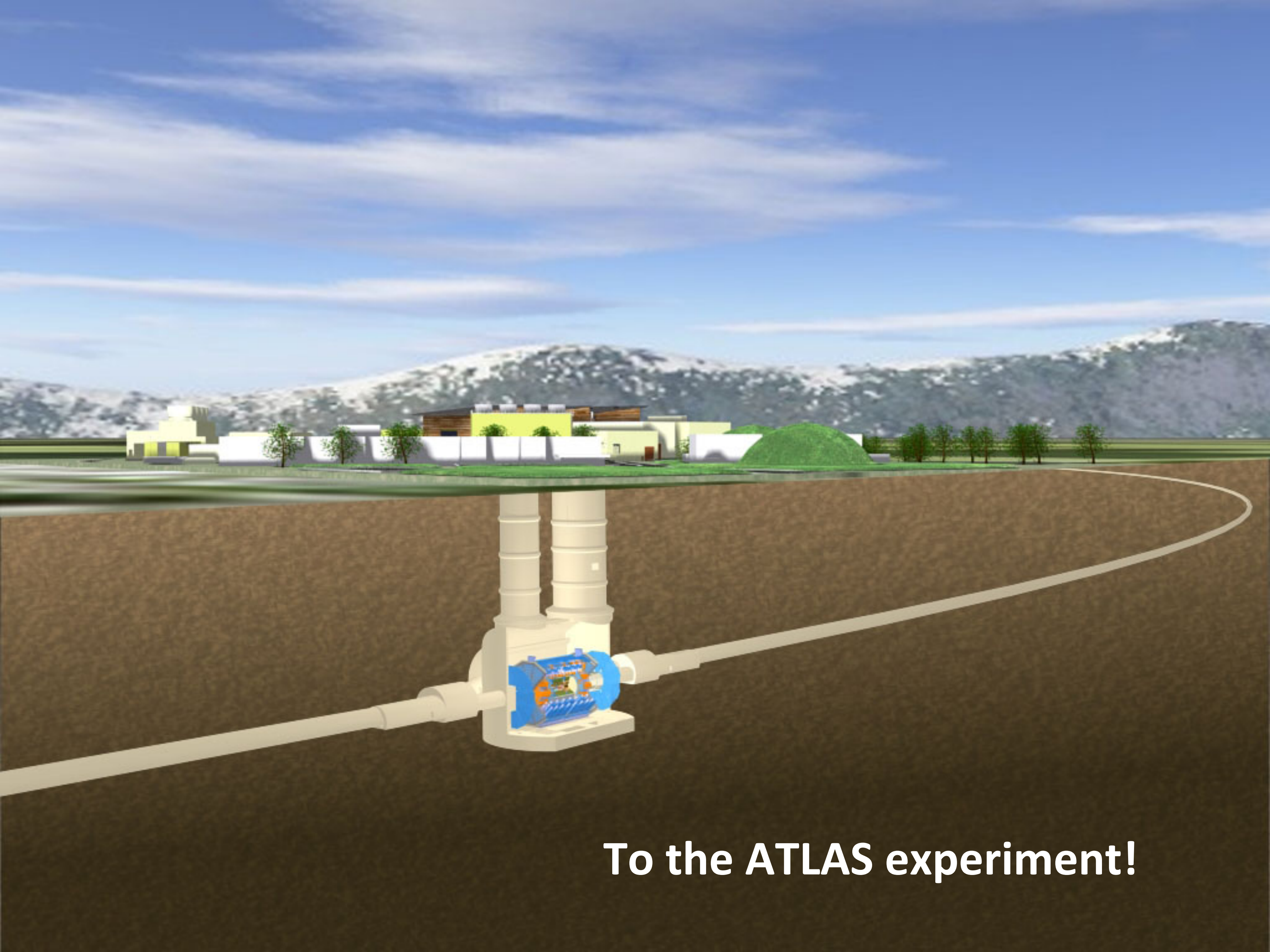
One Wϒ candidate for 1.2±0.5 background expected; set limits on production

	ΥW	ΥZ
90% C.L. expected limit (pb)	4.4	9.9
90% C.L. observed limit (pb)	4.4	16
95% C.L. expected limit (pb)	5.6	13
95% C.L. observed limit (pb)	5.6	21
Run I 95% C.L. observed limit (pb)	93	101

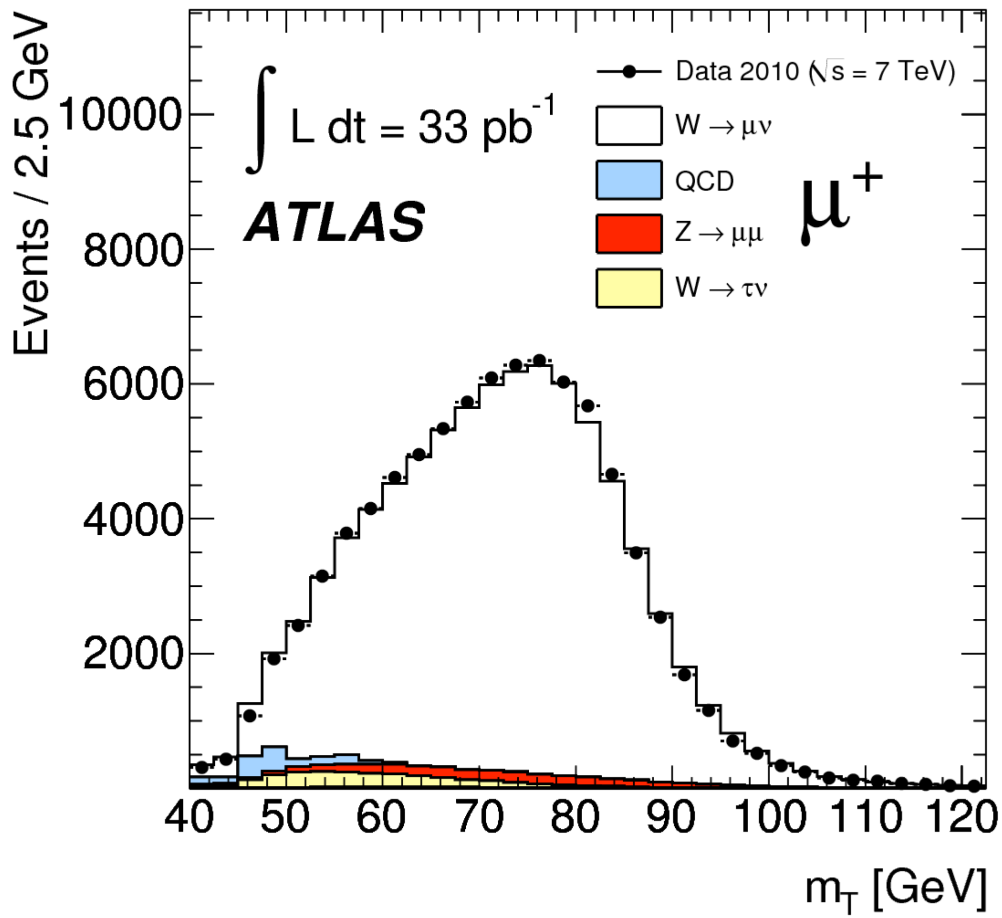


$M_{\mu1\mu2}$ = 88.6 GeV, $M_{\mu3\mu4}$ = 9.26 GeV


To the ATLAS experiment!

Searching for W bosons + J/ψ at ATLAS

A strength of the general purpose detectors like ATLAS is triggering on and reconstructing vector bosons:

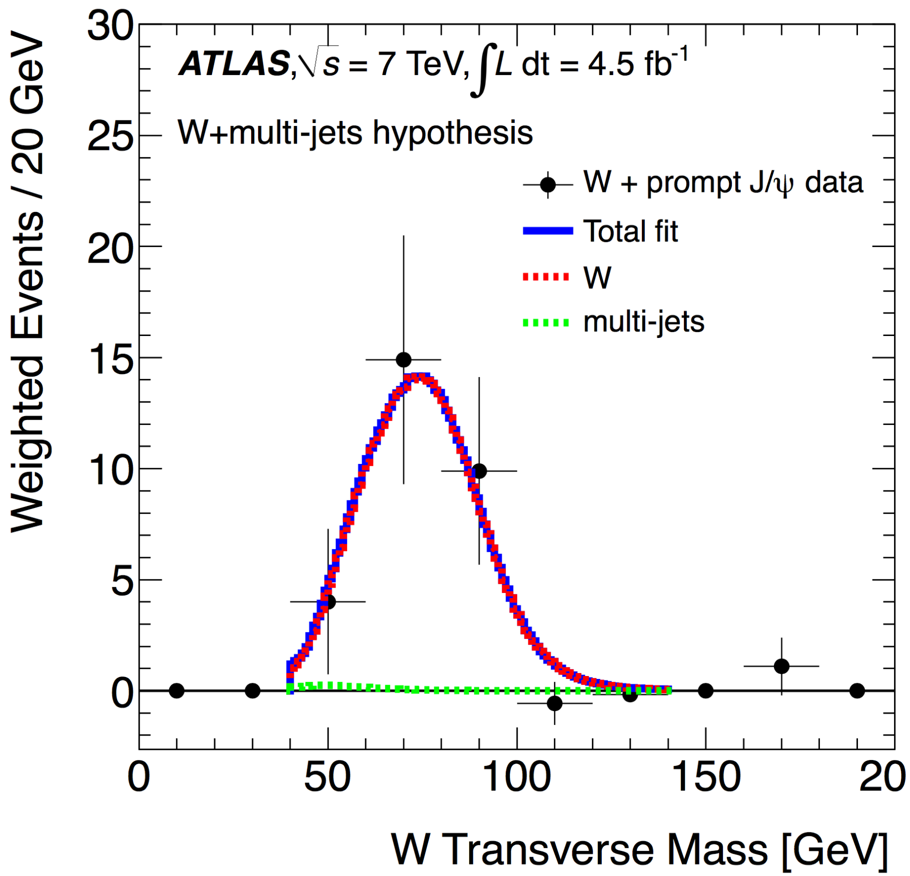


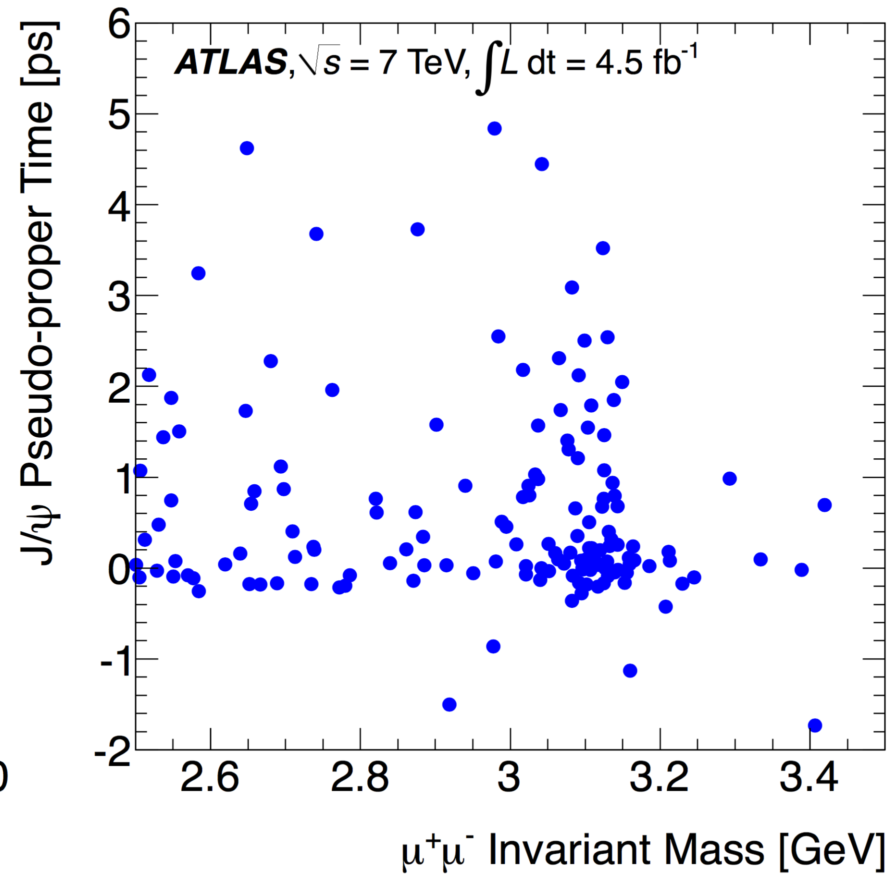
$$m_T = \sqrt{2 p_{T,\ell} p_{T,\nu} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

Searching for W bosons + J/ψ at ATLAS

JHEP 1404 (2014) 172; arXiv:1401.2831

Using 4.5 fb^{-1} of 7 TeV pp collision data select W(→μν) boson candidates with a J/ψ(→μμ) candidate in the same event.
(Additional ID criteria applied to suppress fake-W backgrounds)



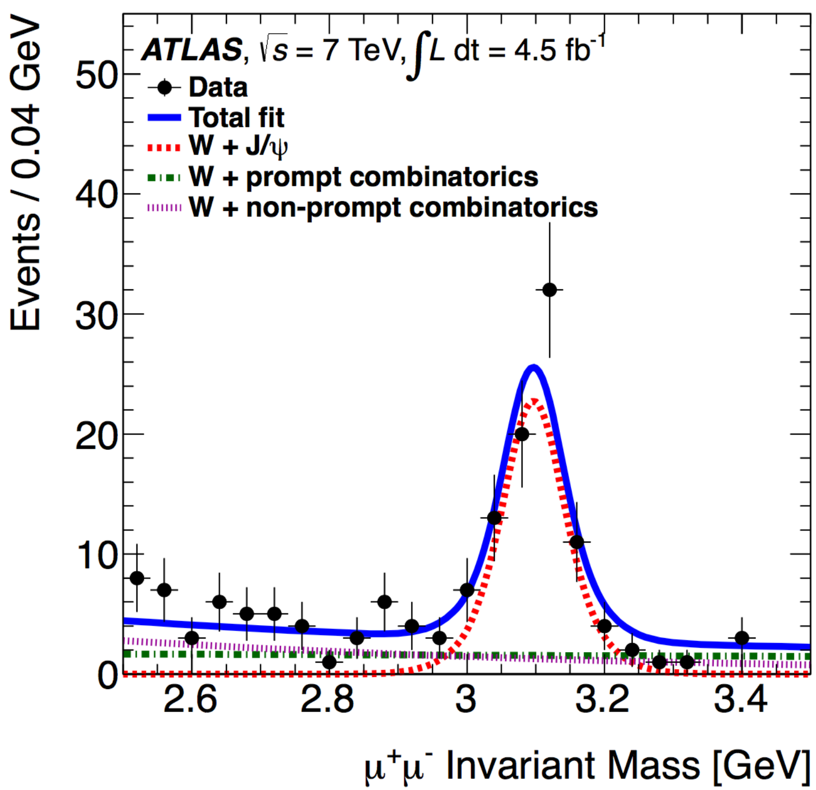


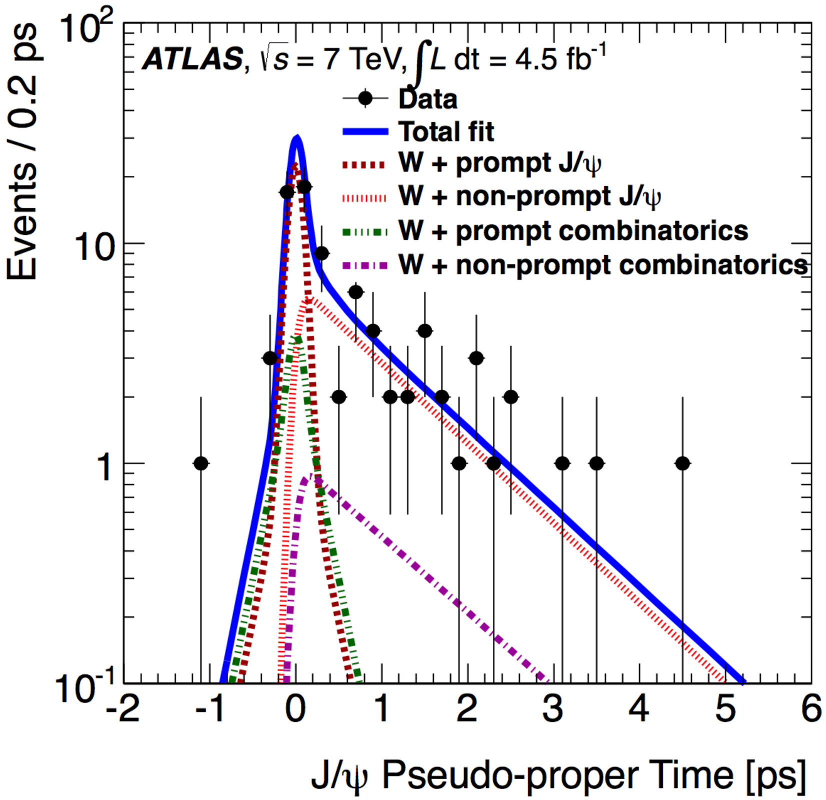
A signal?

W + prompt J/ψ extraction

JHEP 1404 (2014) 172; arXiv:1401.2831

Use standard unbinned mass-lifetime fits to the J/ψ to isolate prompt signal component (non-prompt interesting too however, as probe of W+b)





W + prompt J/ψ backgrounds

JHEP 1404 (2014) 172; arXiv:1401.2831

Assessment of backgrounds from QCD multijet, $B_c \rightarrow J/\psi\ \mu^{\pm}\nu X$, top production, W+b signal leakage, mis-reconstructed Z, combinatorial backgrounds.

Important background to assess from "*pile up*": when W and J/ψ produced in different proton–proton collisions that occur in the same bunch crossing

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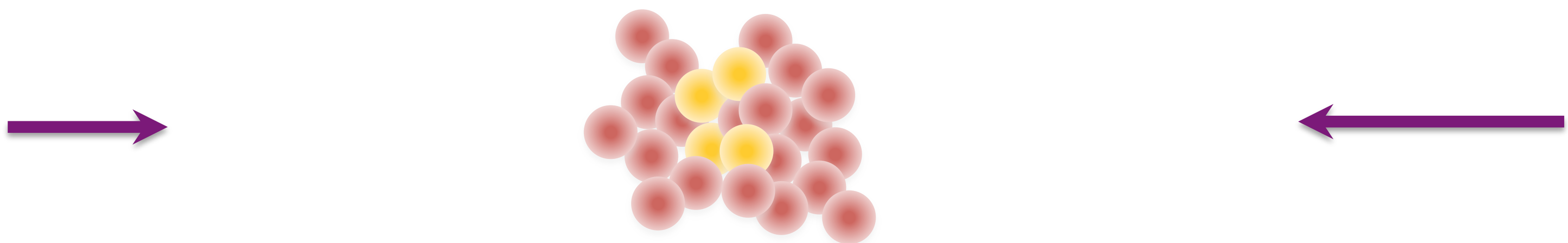

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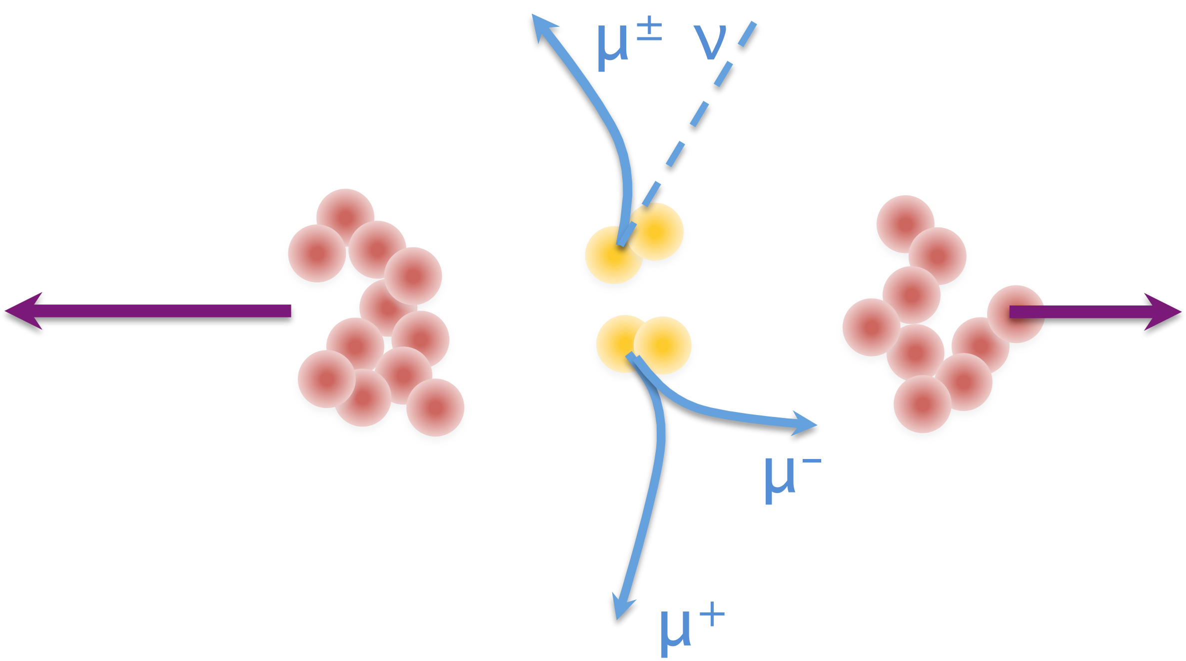

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Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
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

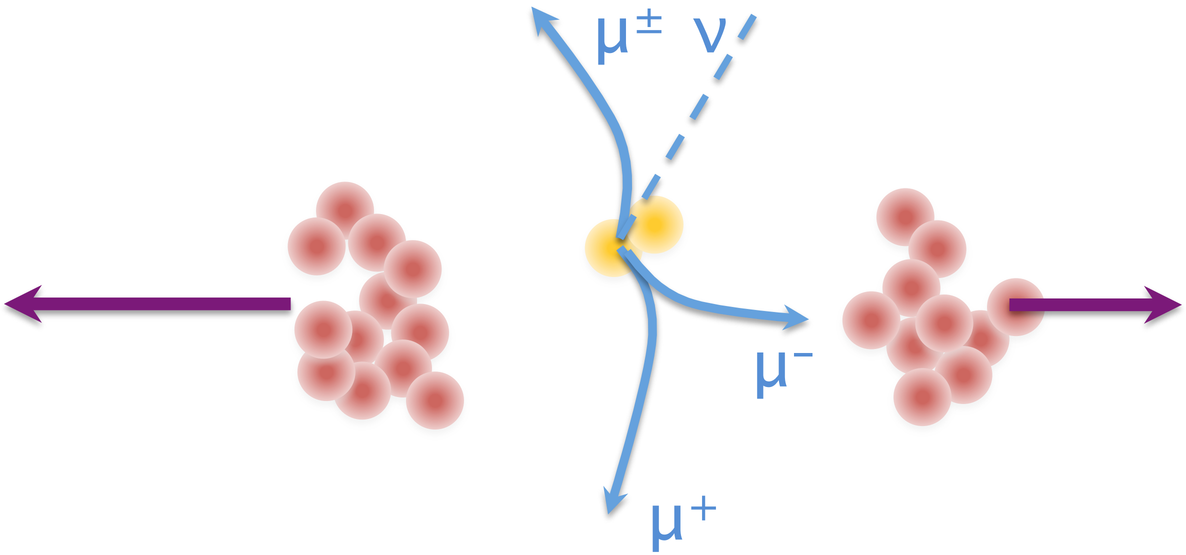
(*) of which 1.8 ± 0.2 originate from pileup

This is a rare process! One of the rarest that could have been discovered in the Run-1 LHC dataset.

Double parton scattering

JHEP 1404 (2014) 172; arXiv:1401.2831

W+prompt J/ψ data can arise from single parton scattering processes, but double parton scattering may also play a role



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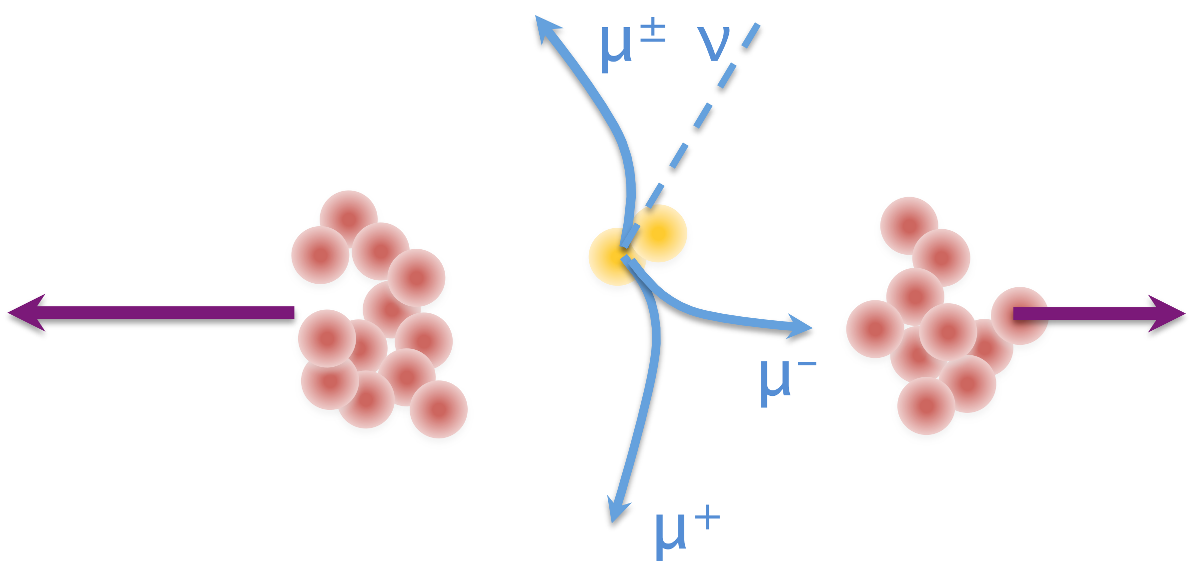
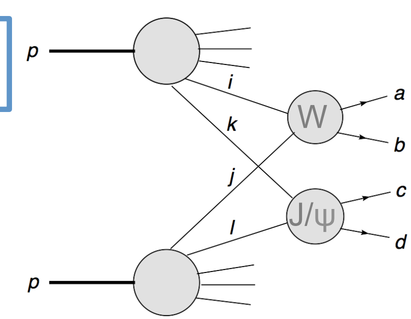


Measured directly in this analysis

From ATLAS measurement prompt J/ψ arXiv:1104.3038

$$d\sigma^{\text{DPS}}_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{\text{eff}}}$$

From ATLAS measurement W+2jets arXiv:1301.6872



Double parton scattering

JHEP 1404 (2014) 172; arXiv:1401.2831

Determine expected rate of DPS if σ_{eff} is as for Wjj production ~ 15 mb

DPS ansatz assumes independent hard scatters.

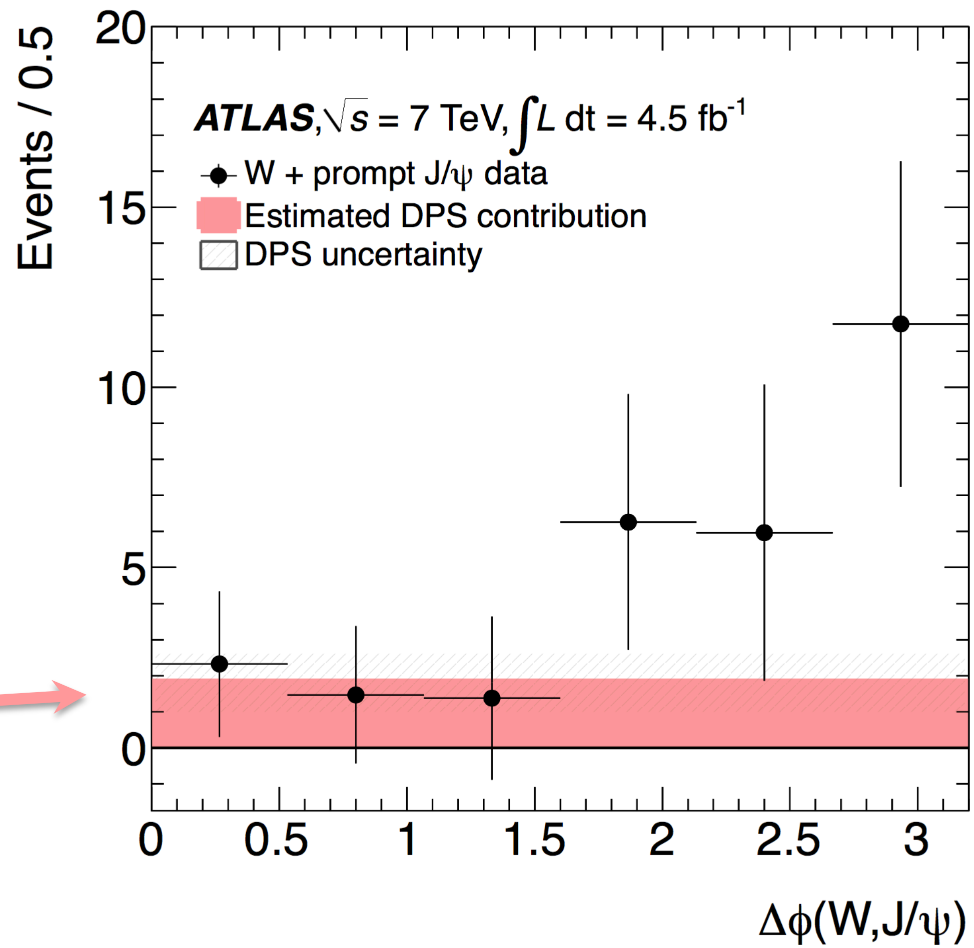
$$d\sigma^{\mathrm{DPS}}_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{\mathrm{eff}}}$$

Must fail at some point, otherwise can have $x_1+x_2>1$, but work under assumption of reasonable approximation

Estimate DPS contribution to the signal using the data

Expect SPS signal to peak near π in Δϕ(W, J/ψ)

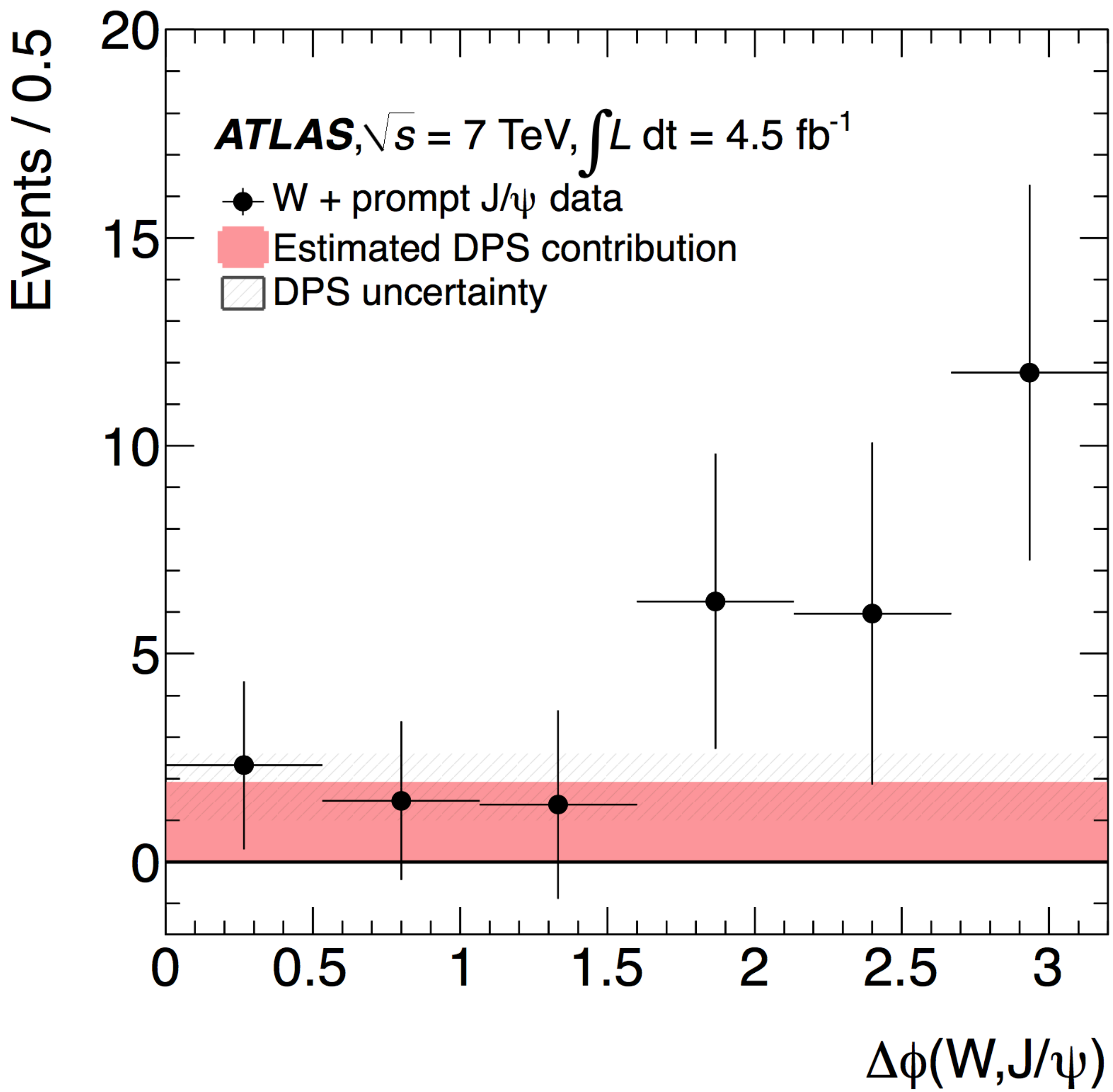
This is *not* a fit!



SPS and DPS contributions to W+J/ψ

JHEP 1404 (2014) 172; arXiv:1401.2831

No reliable SPS event simulation, but data supports estimated DPS rate



SPS and DPS contributions to W+J/ψ

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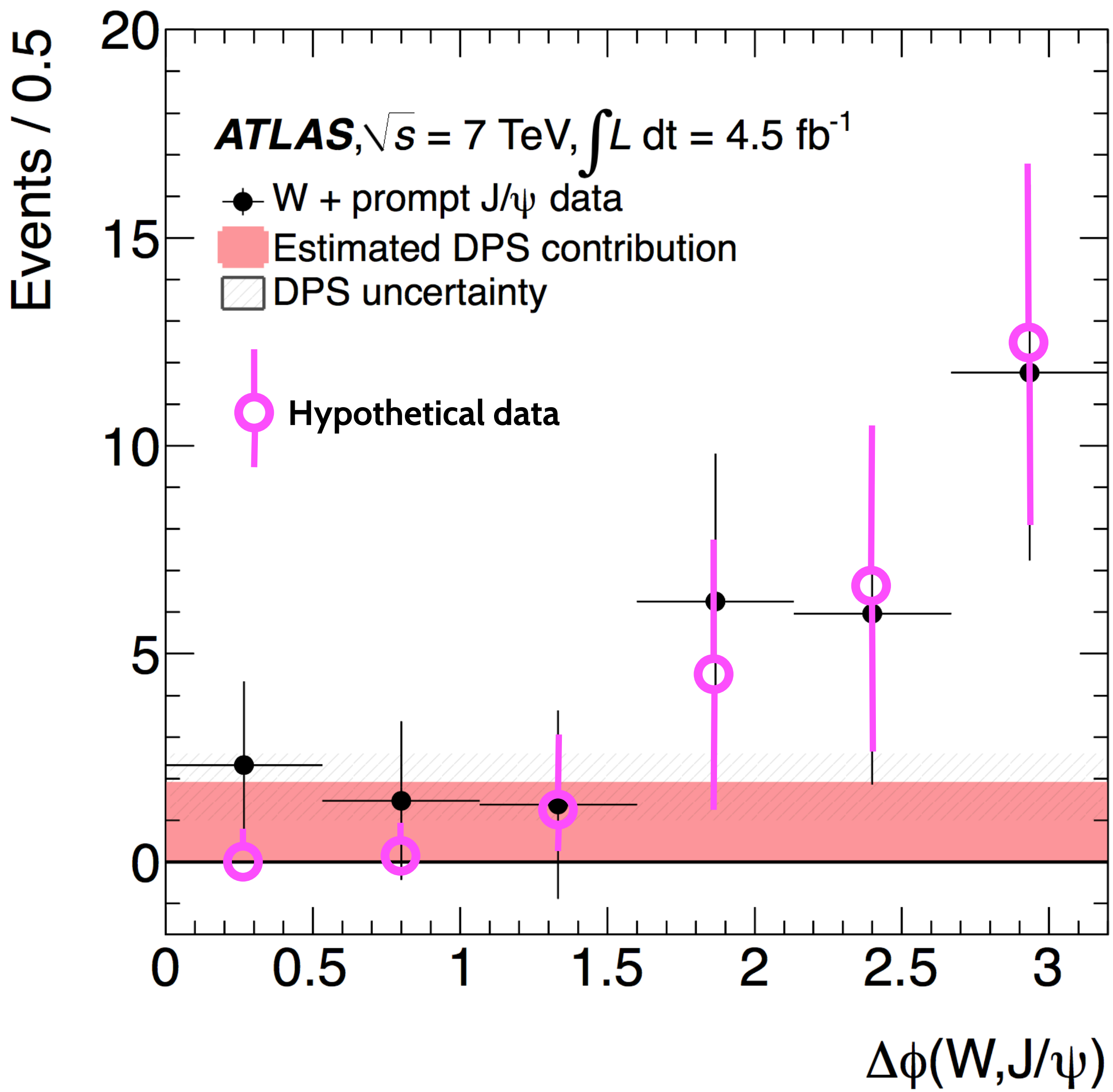
Might imagine data like this if significant DPS correlations…



W + prompt J/ψ production rates

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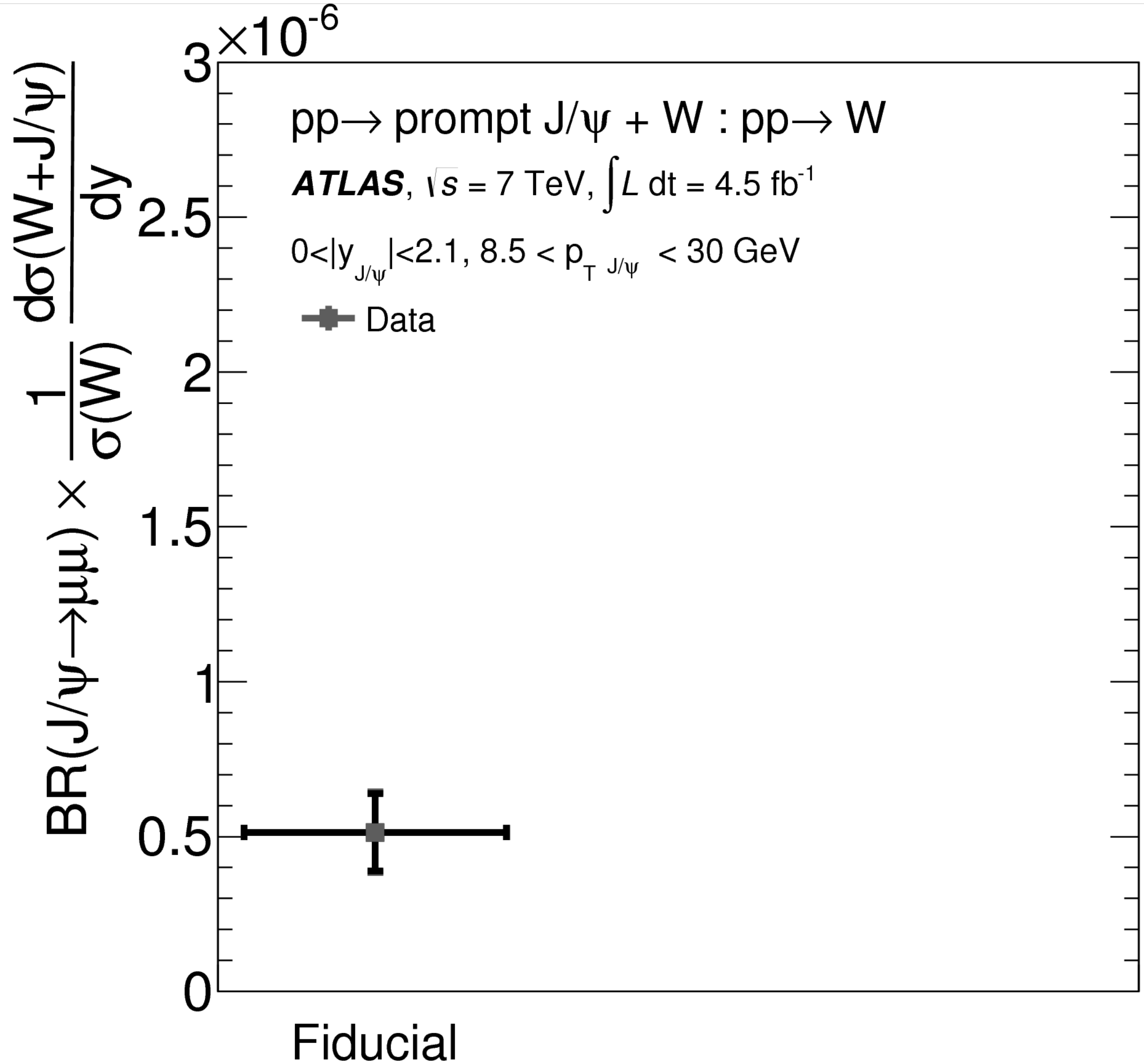
Correcting for detector effects / efficiencies can extract rate:



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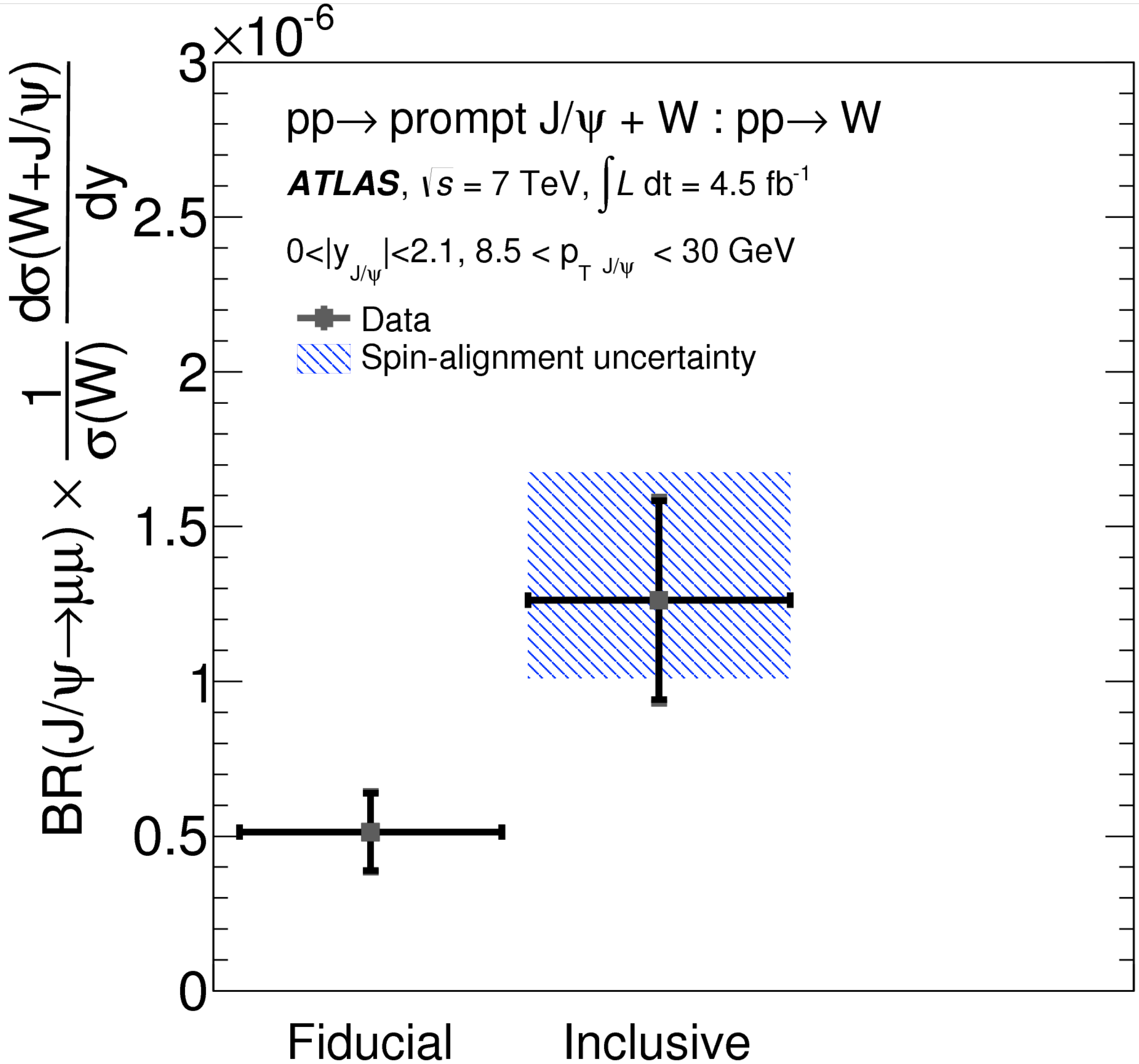

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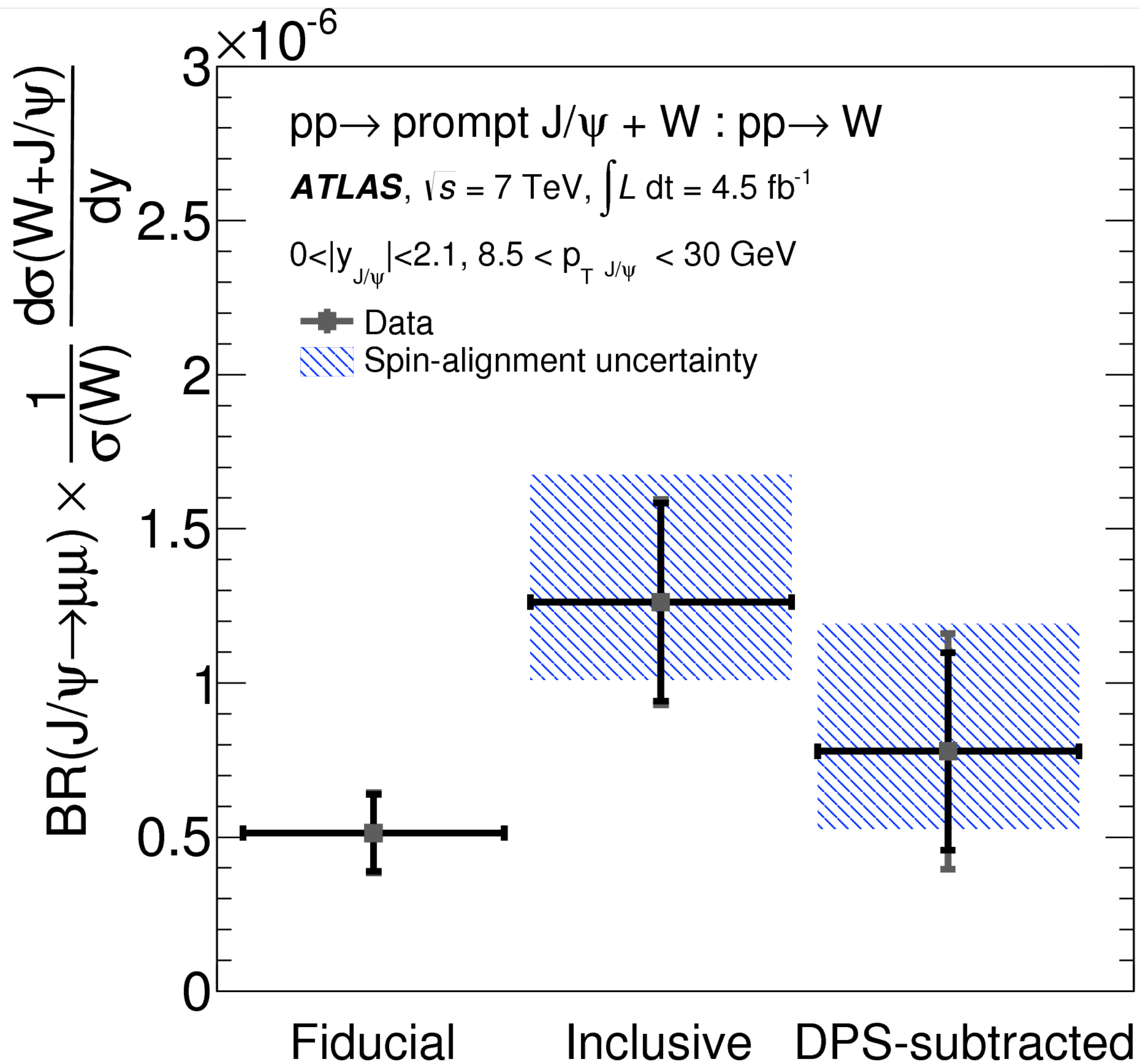

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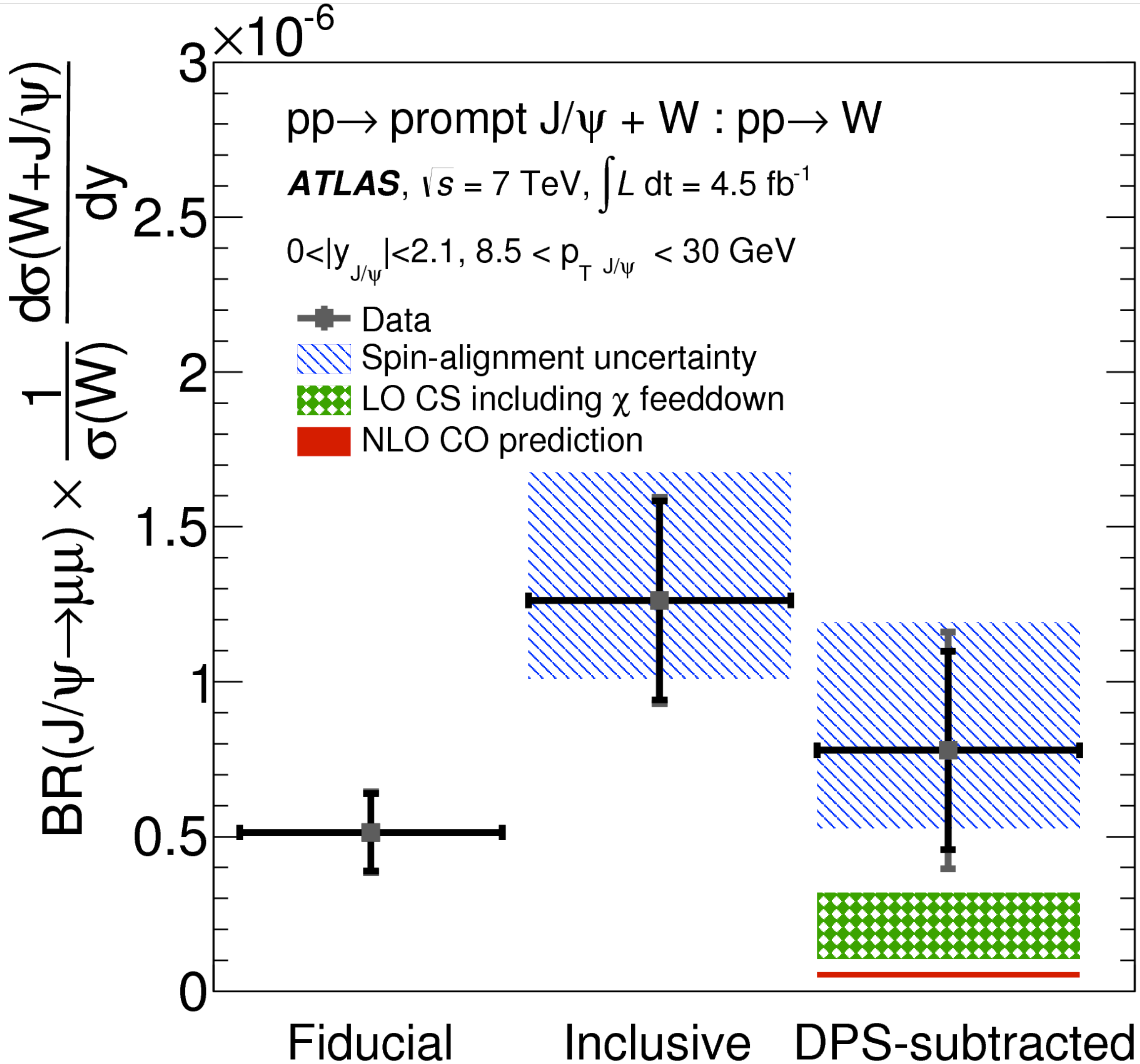

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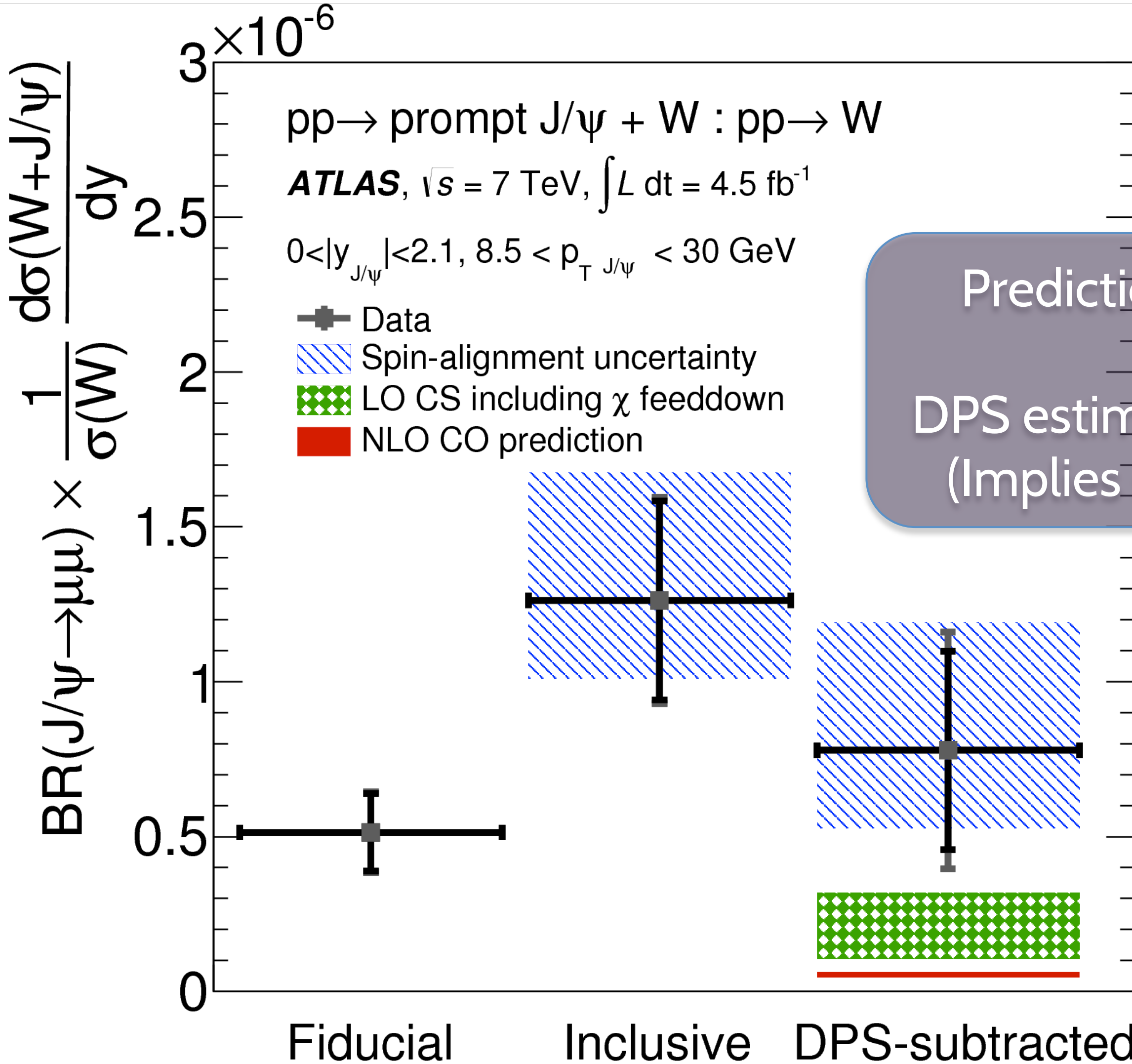

Predictions too low?

DPS estimate too small?
(Implies smaller σ_{eff})?

W + prompt J/ψ production rates

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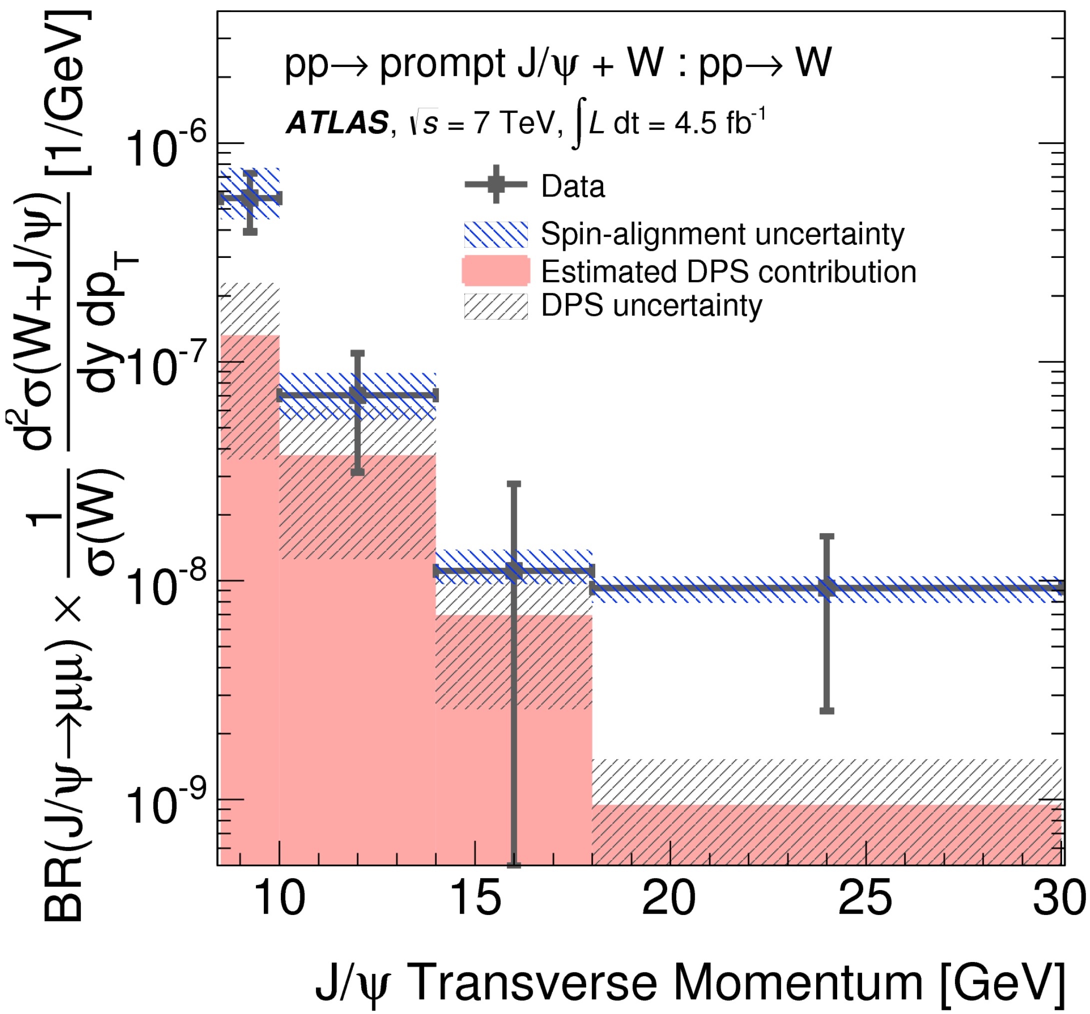
Can go further and measure differential rate, with DPS component re-evaluated from data in each p_T interval



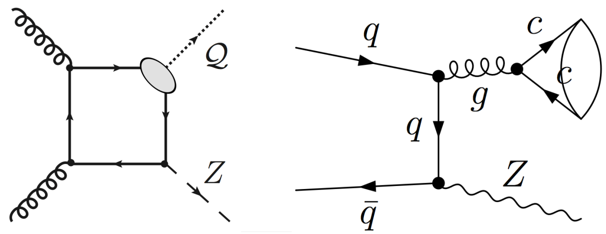
Both single and double parton scattering components observed in data

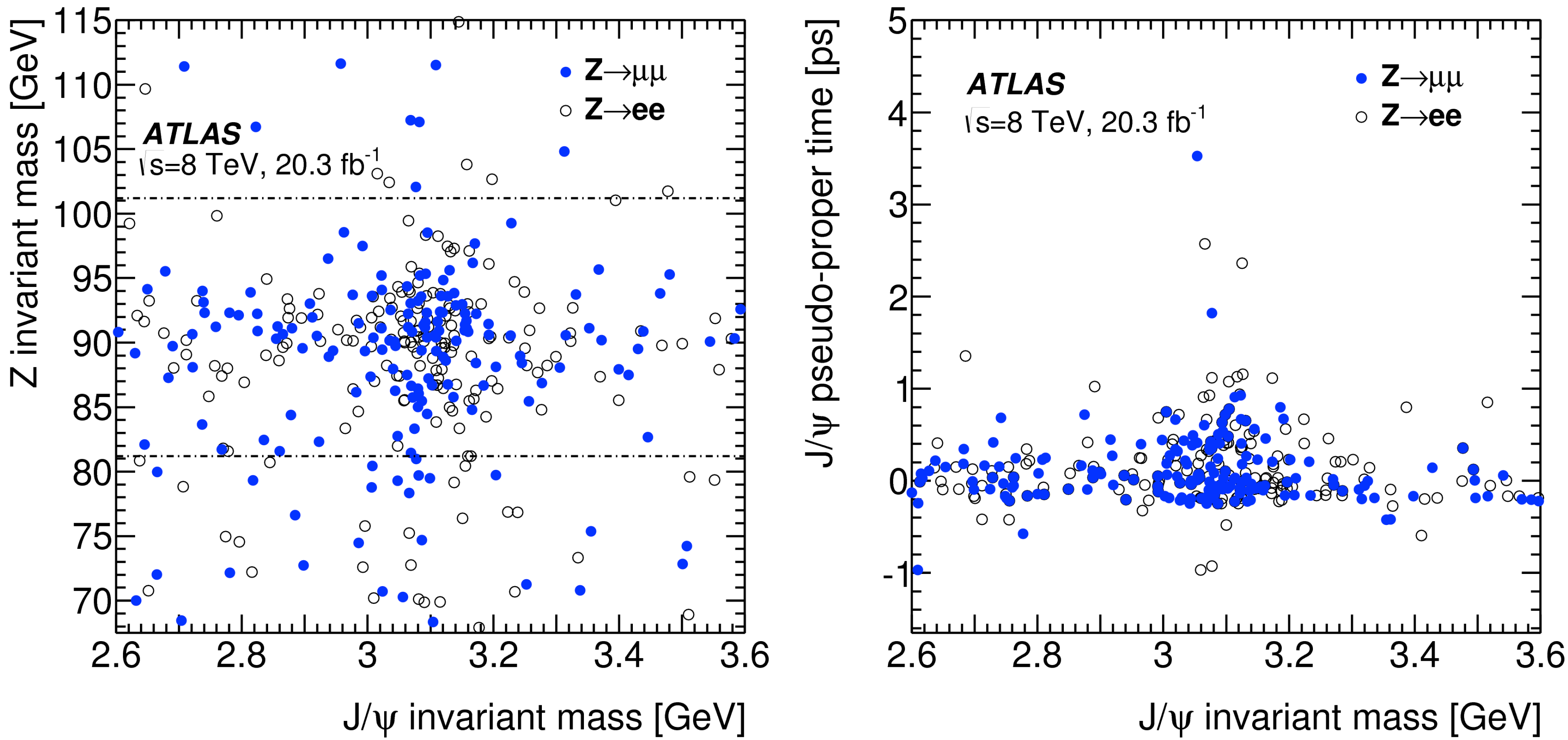
(f_{DPS}≈40%!)

Searching for Z+J/ψ production

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

ATLAS also searched for Z+J/ψ associated production, 8 TeV data, 20.3 fb^{-1}.





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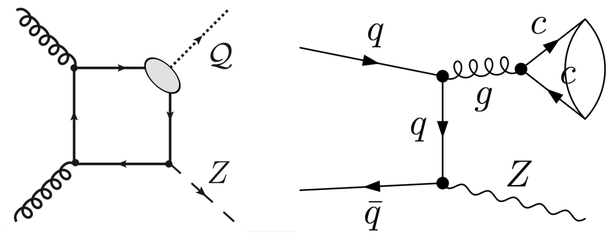

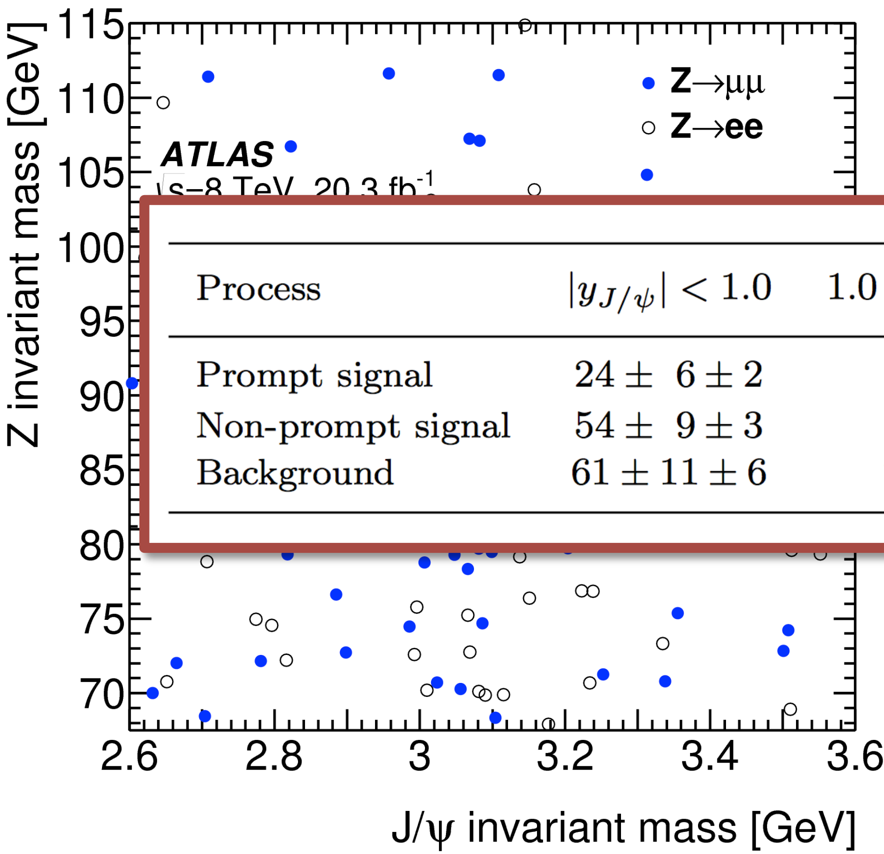

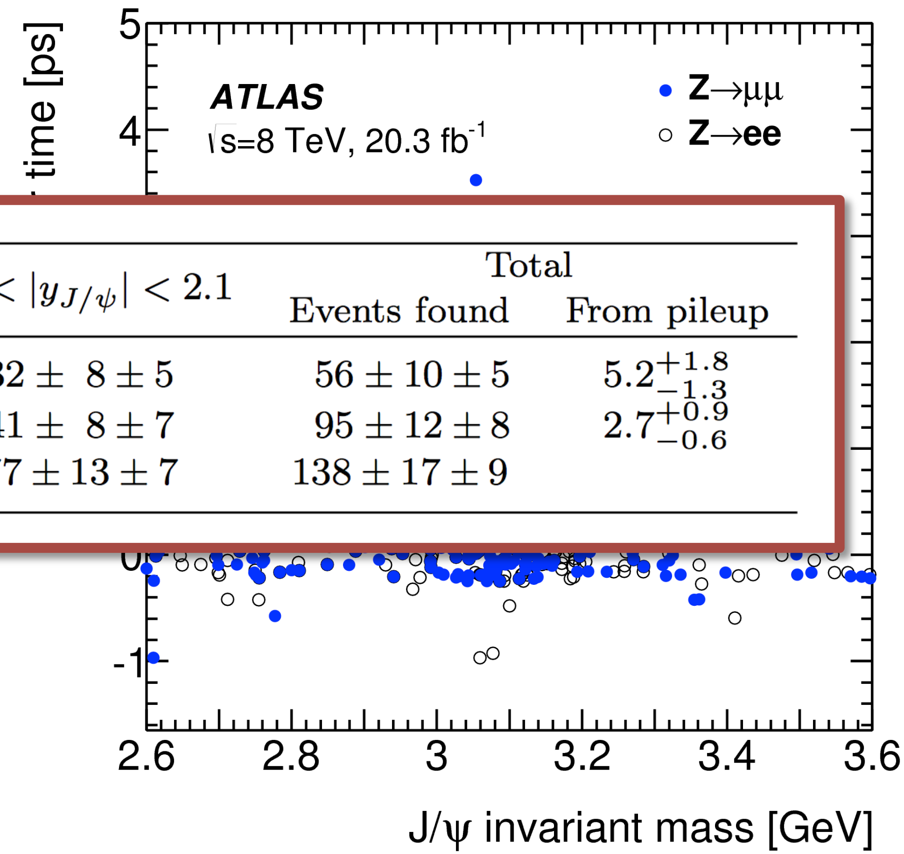

Process	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	Total Events found	Total From pileup
Prompt signal	$24 \pm 6 \pm 2$	$32 \pm 8 \pm 5$	$56 \pm 10 \pm 5$	$5.2^{+1.8}_{-1.3}$
Non-prompt signal	$54 \pm 9 \pm 3$	$41 \pm 8 \pm 7$	$95 \pm 12 \pm 8$	$2.7^{+0.9}_{-0.6}$
Background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

Searching for Z+J/ψ production

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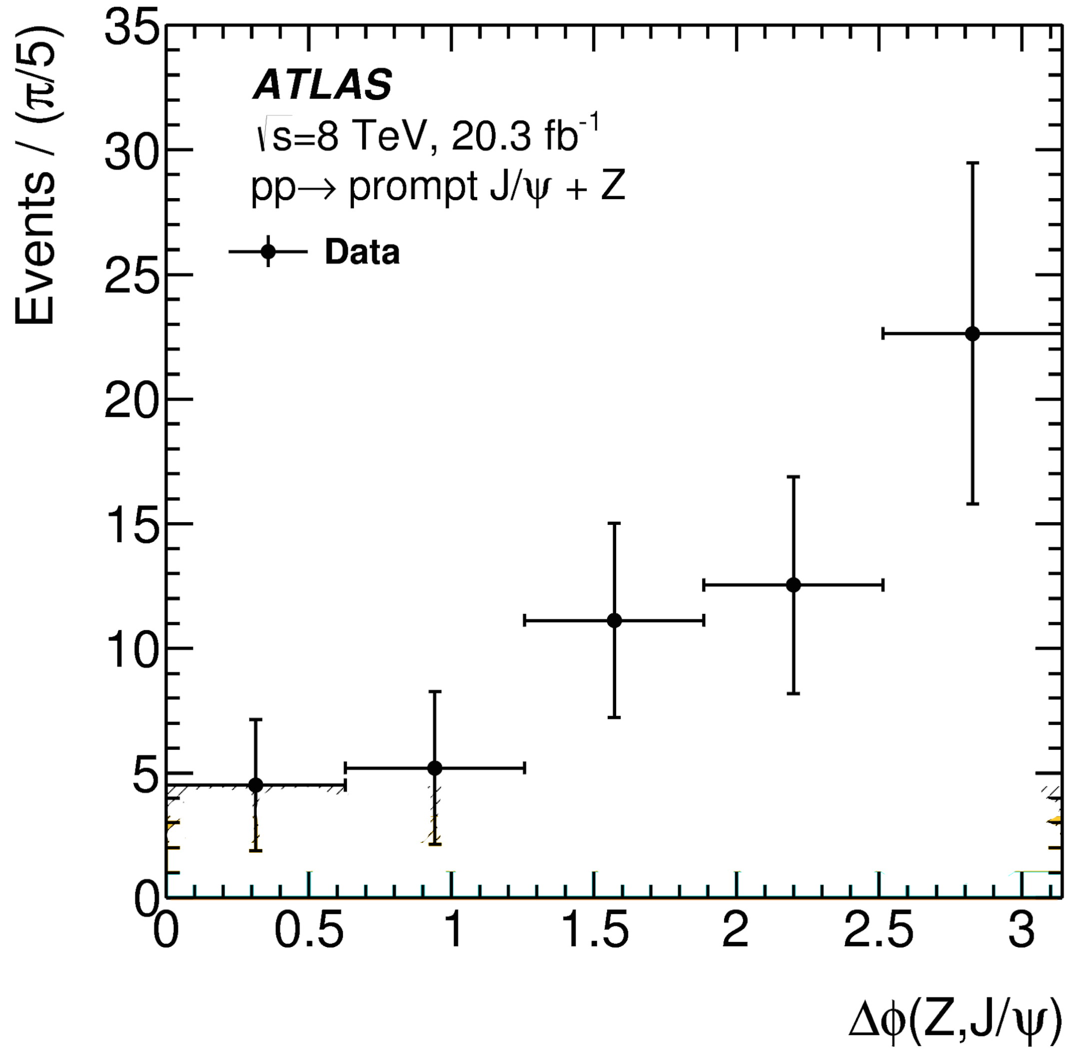
Extract signal, split by prompt/non-prompt, and assess backgrounds. Double parton scattering component again estimated from data and cross-checked on azimuthal angular correlation distribution



Extracting the DPS component

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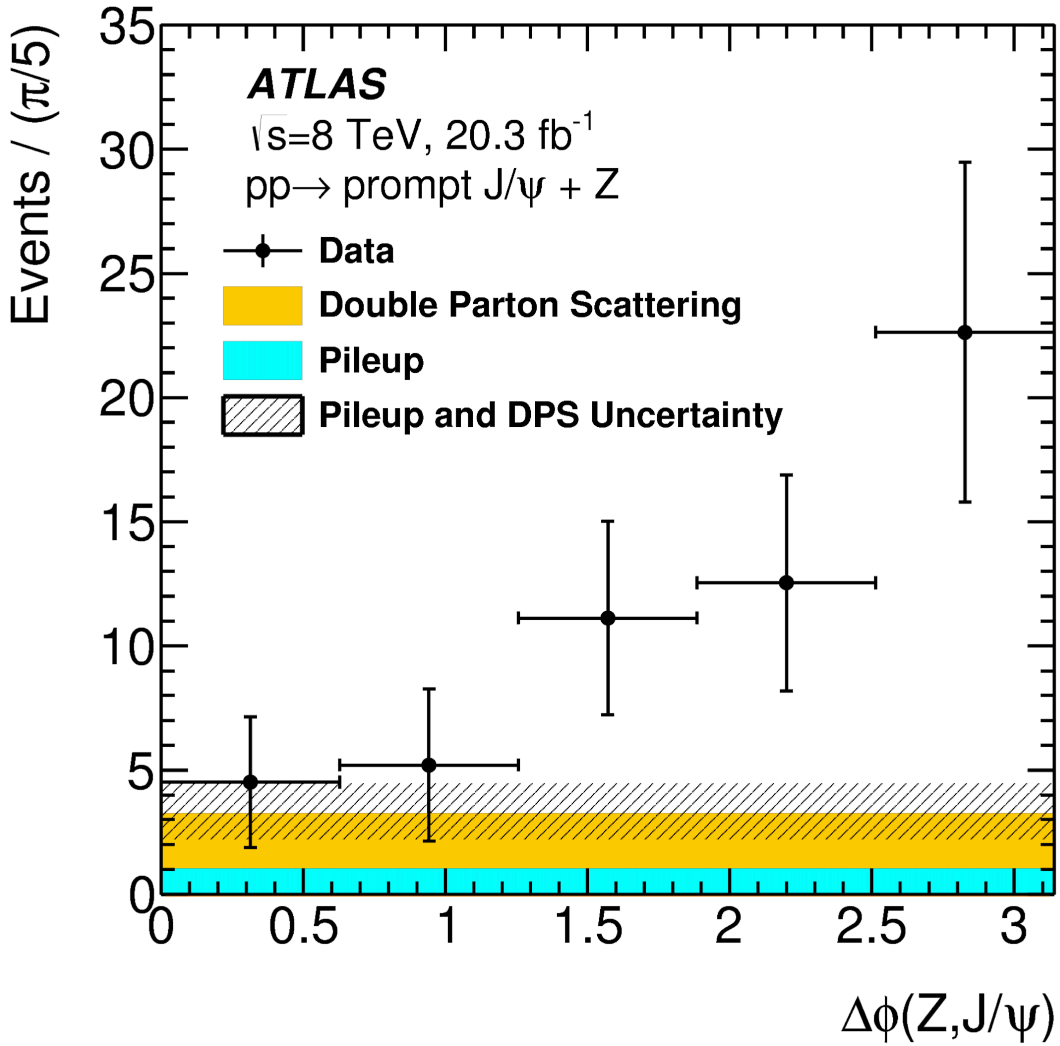

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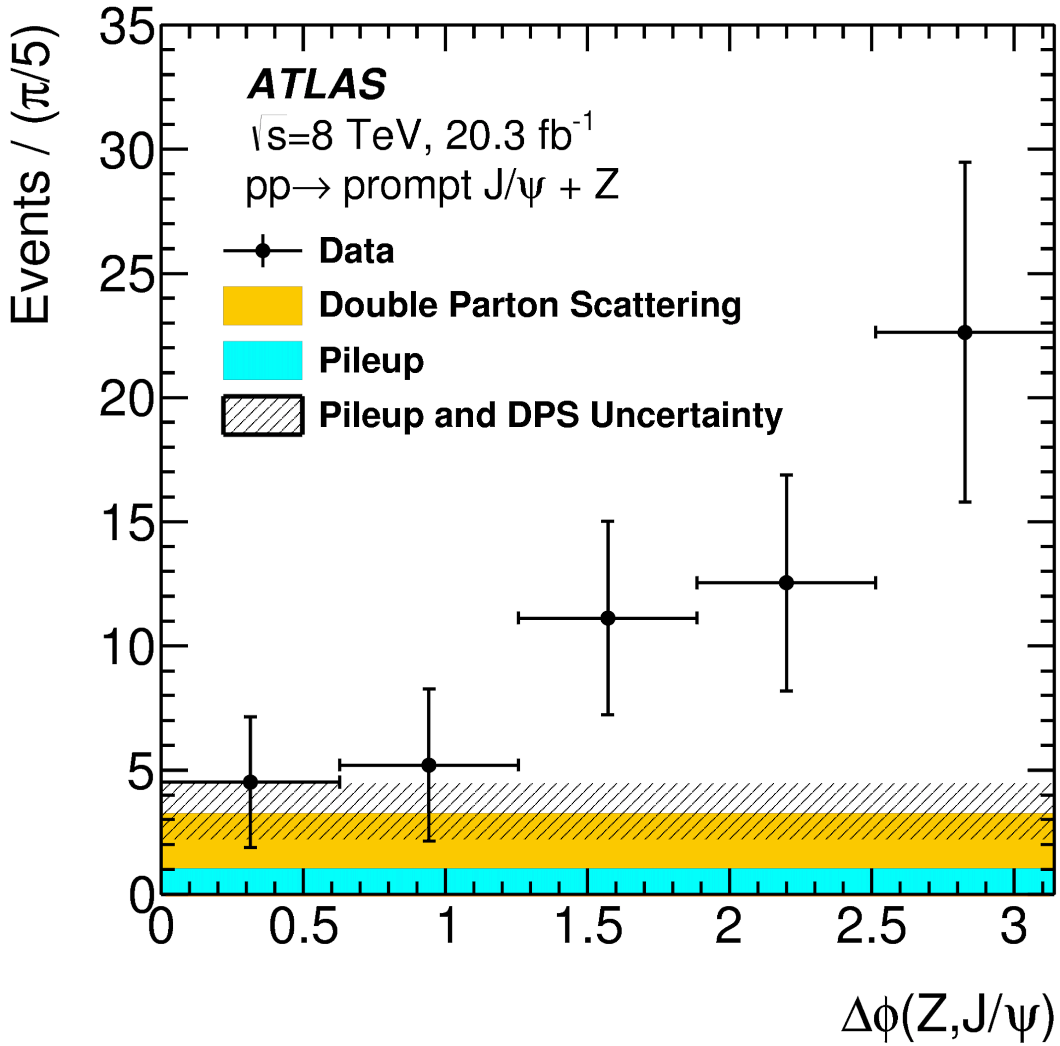
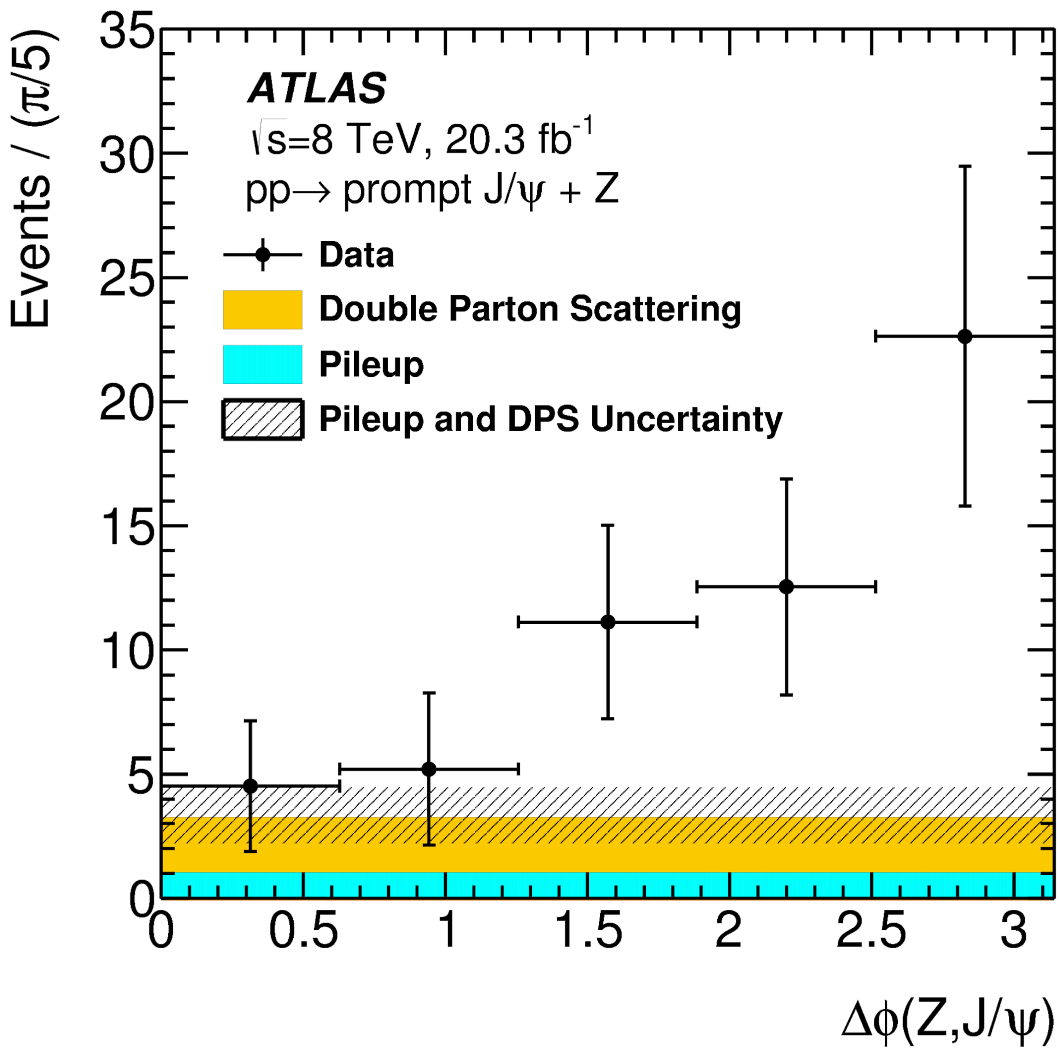


Extracting the DPS component

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

Worth emphasising again: this is not a fit to this distribution, but data *supports* this *rate* of DPS (but can say no more than that): **theory limited – thoughts?**



Extracting the DPS component

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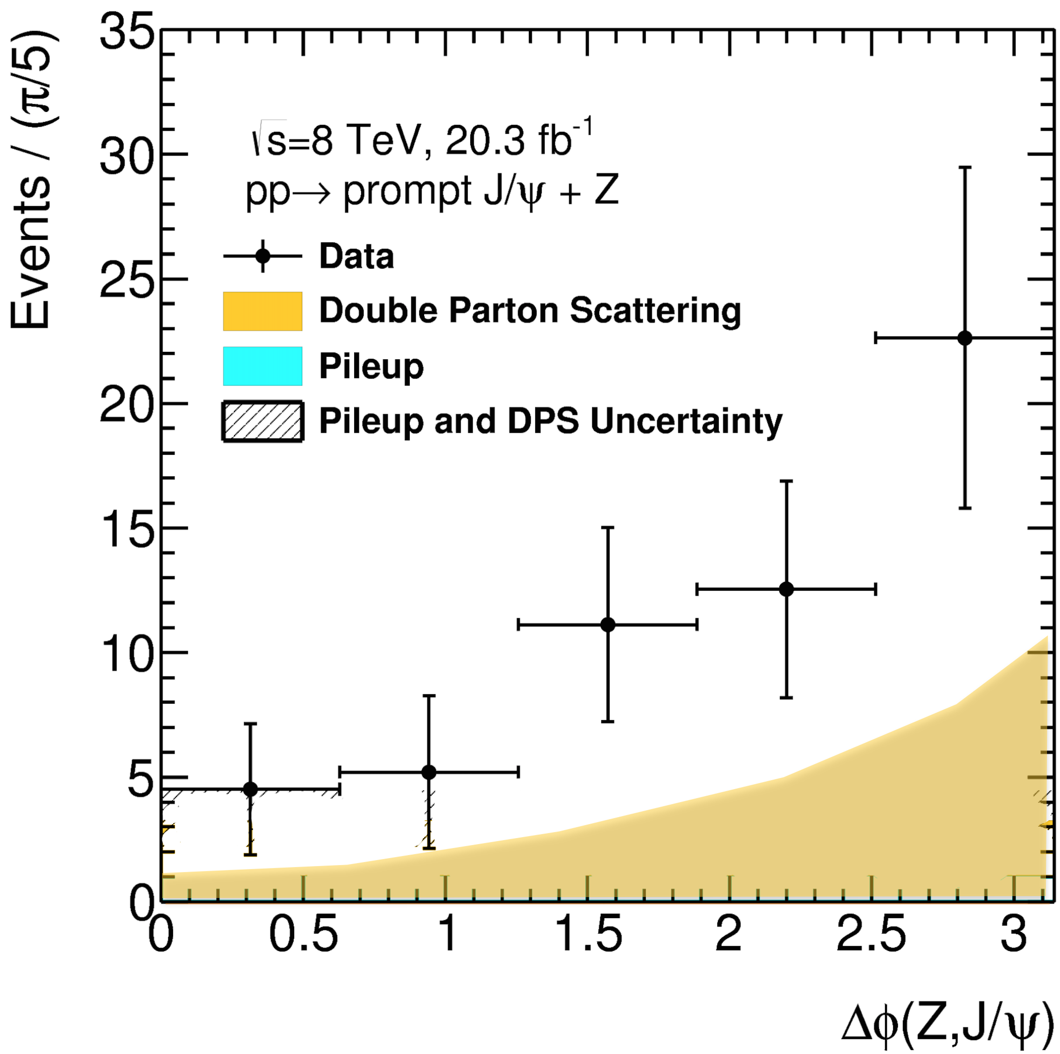
Instead of independent scatters, could redistribute rate of DPS for example:



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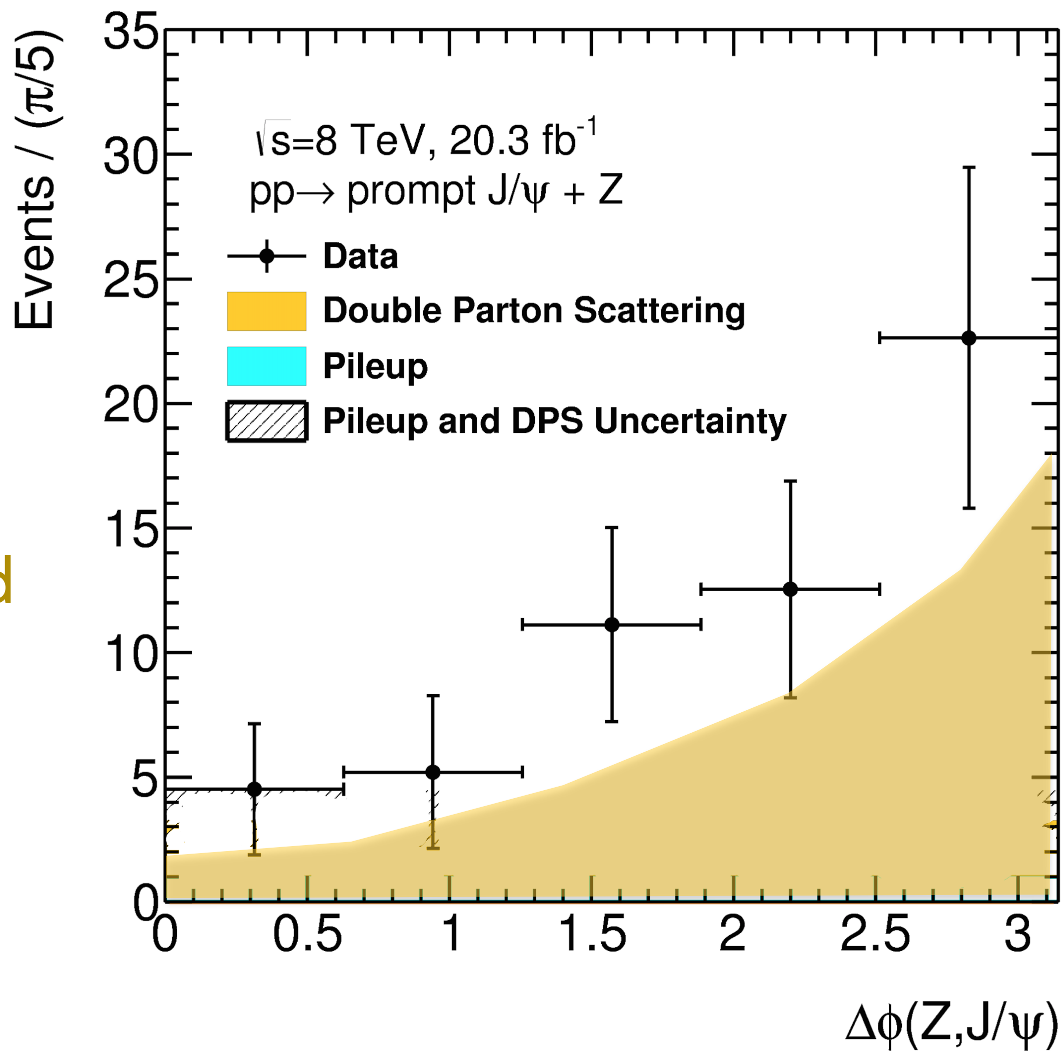
Enhanced DPS rate = reduced σ_{eff}



Theory input very welcome here!

Extracting the DPS component

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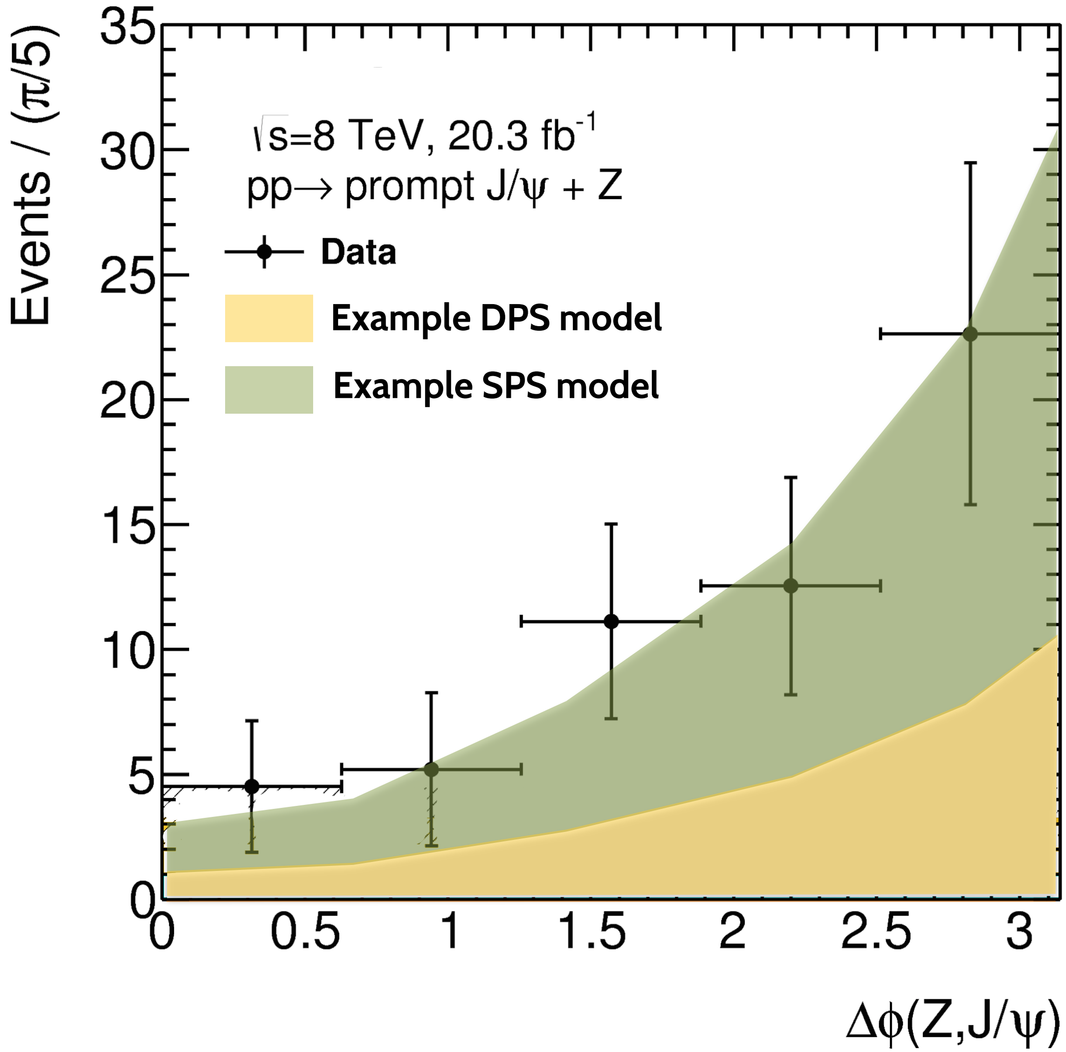
A dream of full event simulation for SPS and DPS processes: would allow us to do so much more…

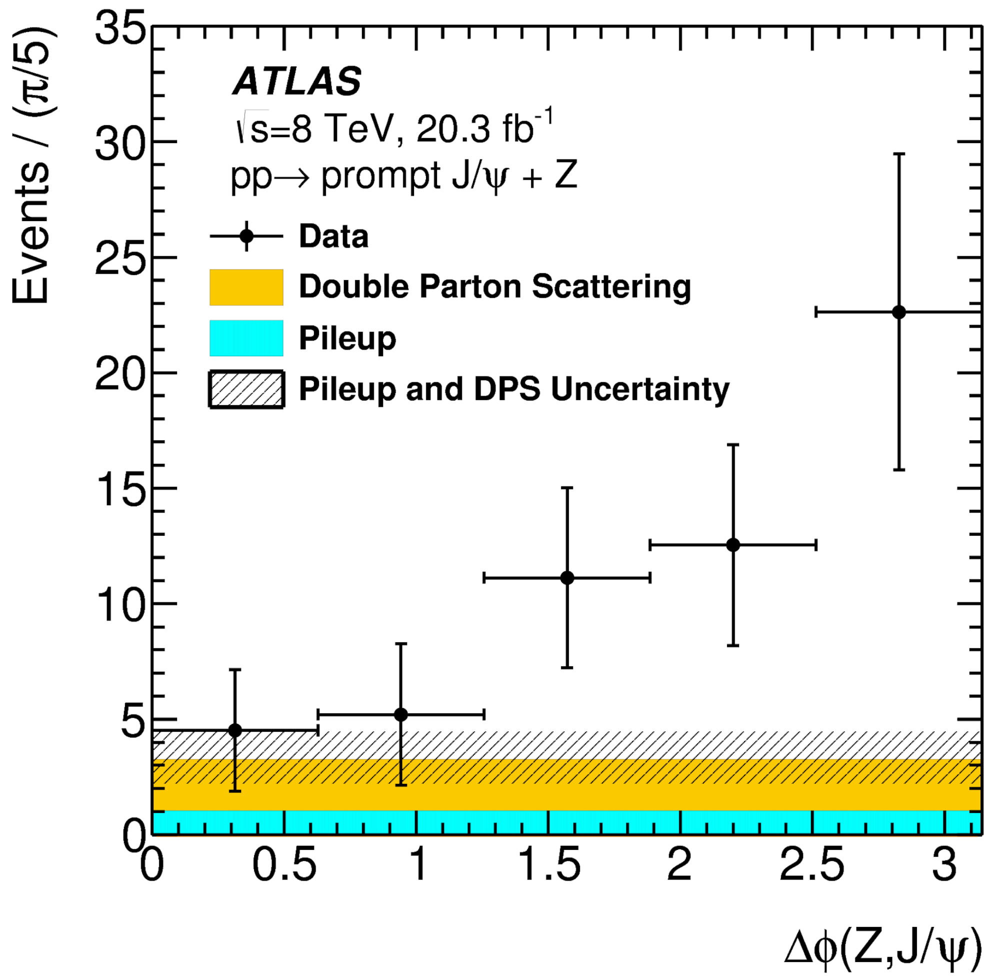


What can we say about DPS already?

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

What can we say about the effective DPS cross-section?

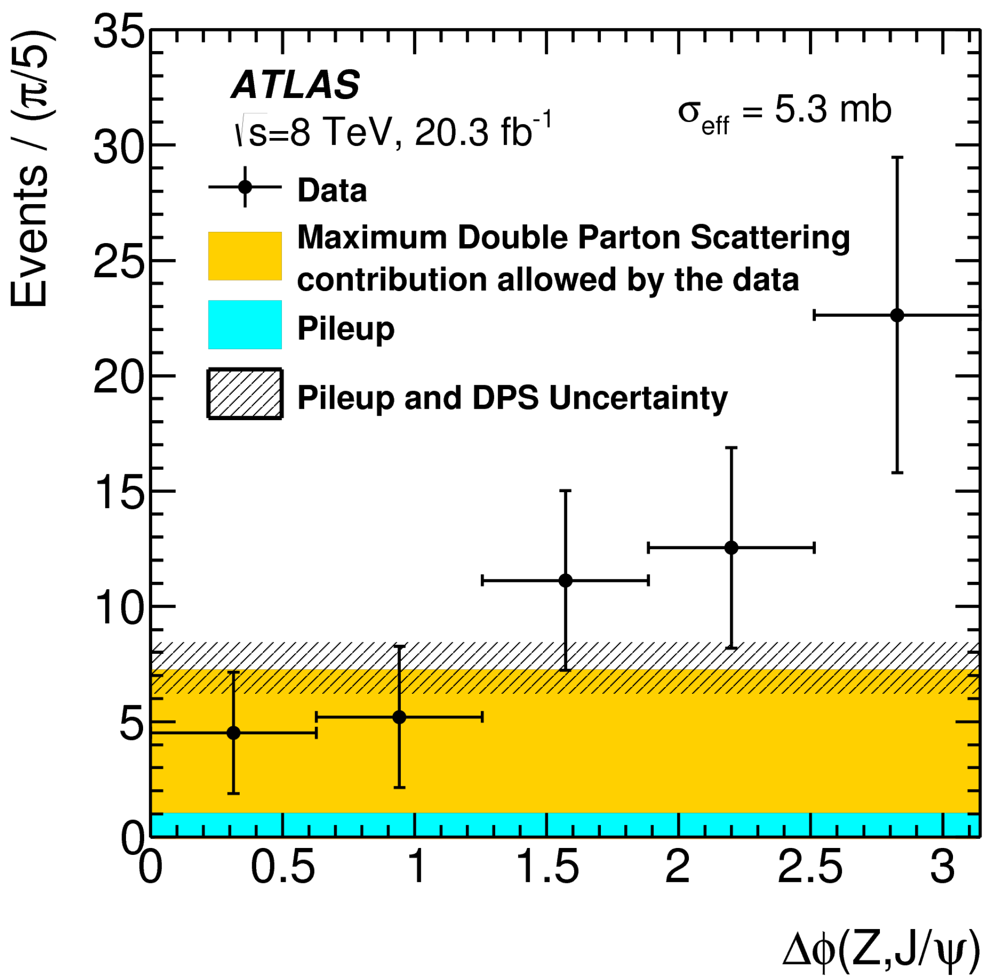
Assuming independent scatters, DPS maximal when SPS contribution to low $\Delta\phi$ tail is negligible:



What can we say about DPS already?

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

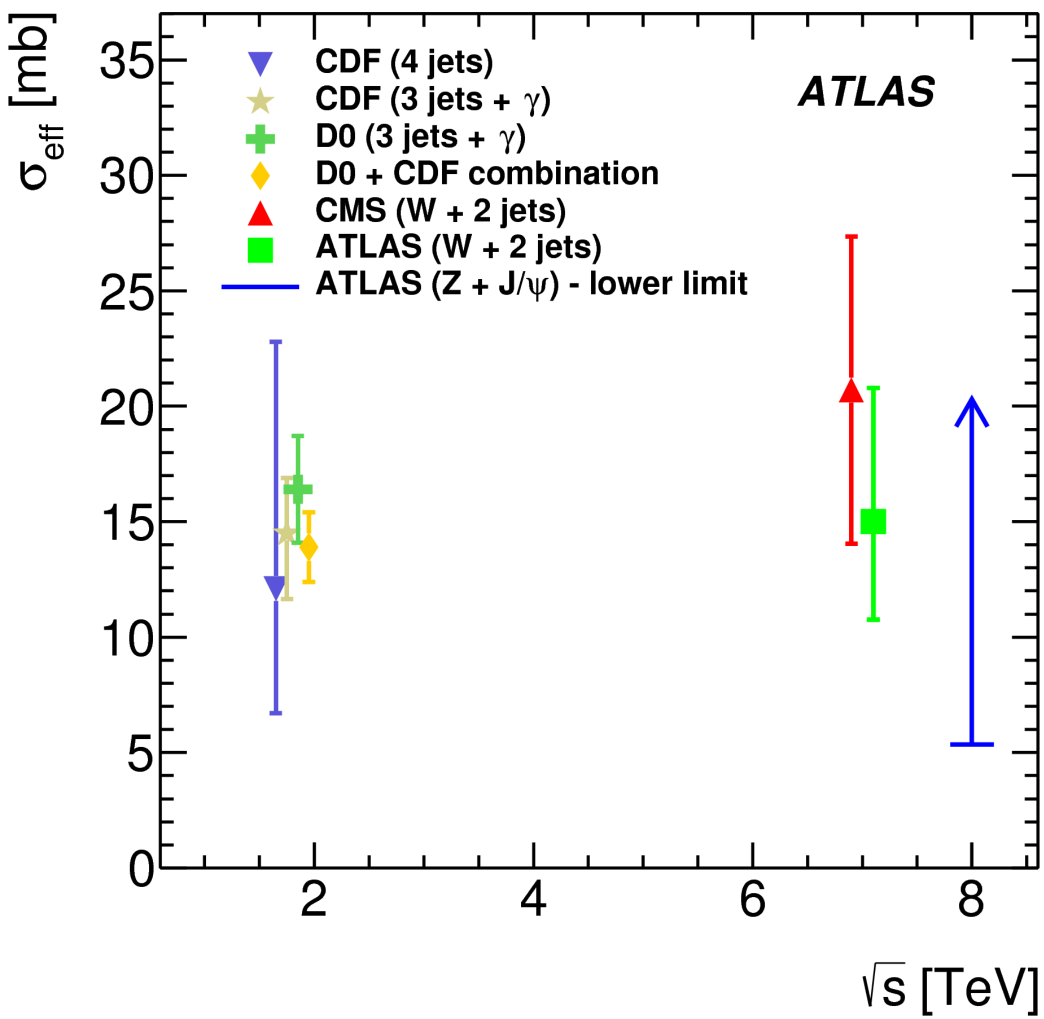
Enhance DPS rate until not supported by the data in tail: maximum DPS rate allowable corresponds to minimum σ_{eff}:



Limits on the effective cross-section

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

Enhance DPS rate until not supported by the data in tail: maximum DPS rate allowable corresponds to minimum σ_{eff}:



W+J/ψ is not like W+jets:

Data wants value lower than for W+jets production (15 mb)

Some theory predictions expect up to 18 mb [Eur.Phys.J. C74 (2014) 2926]

Find a minimum of 5.3 mb (3.7 mb) at 68% (95%) C.L

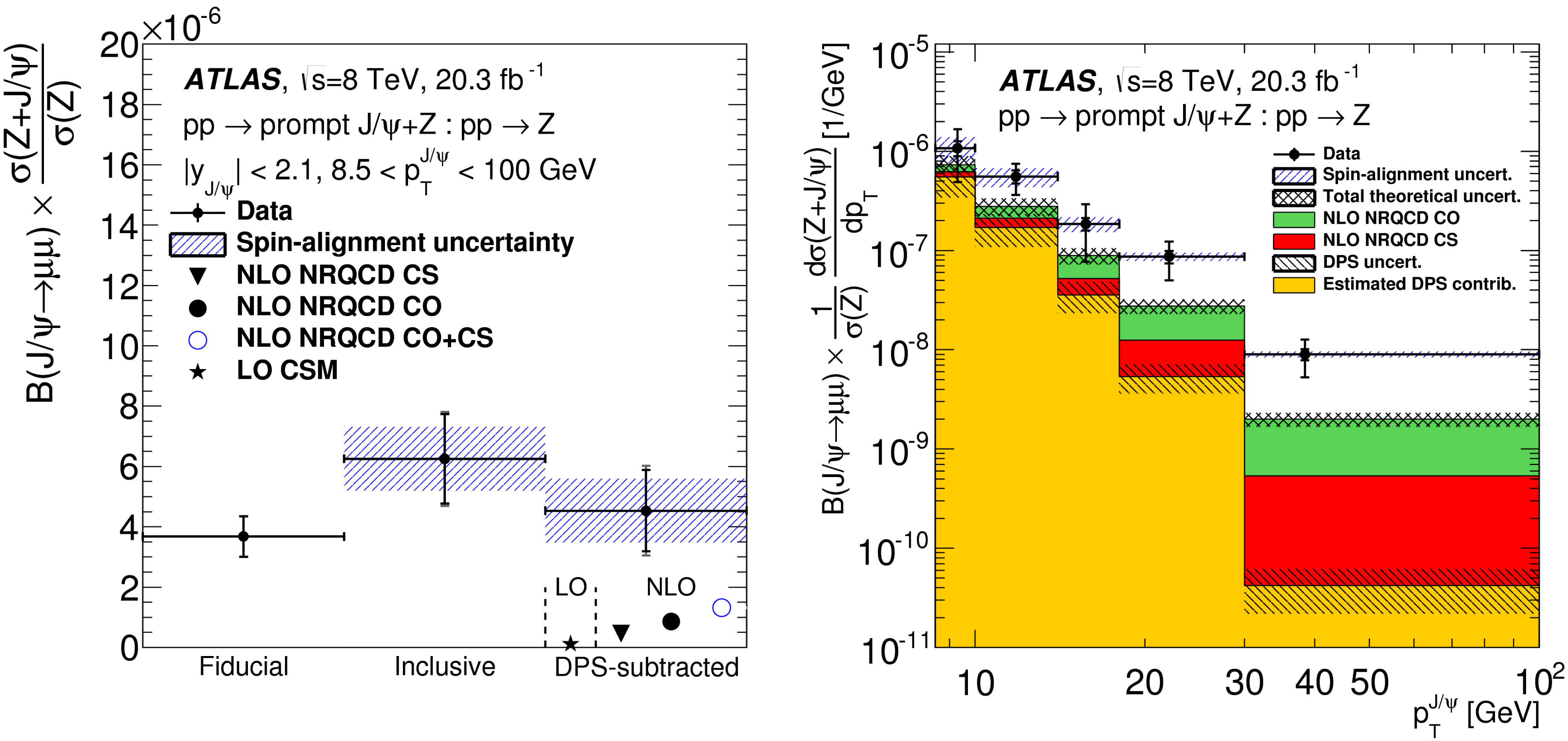
Need SPS theory to derive maximum!

Z+J/ψ production rates

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

Measurement of production rate finds similar picture to W+J/ψ production

Significant deficits at large p_T do not appear explainable by DPS modification

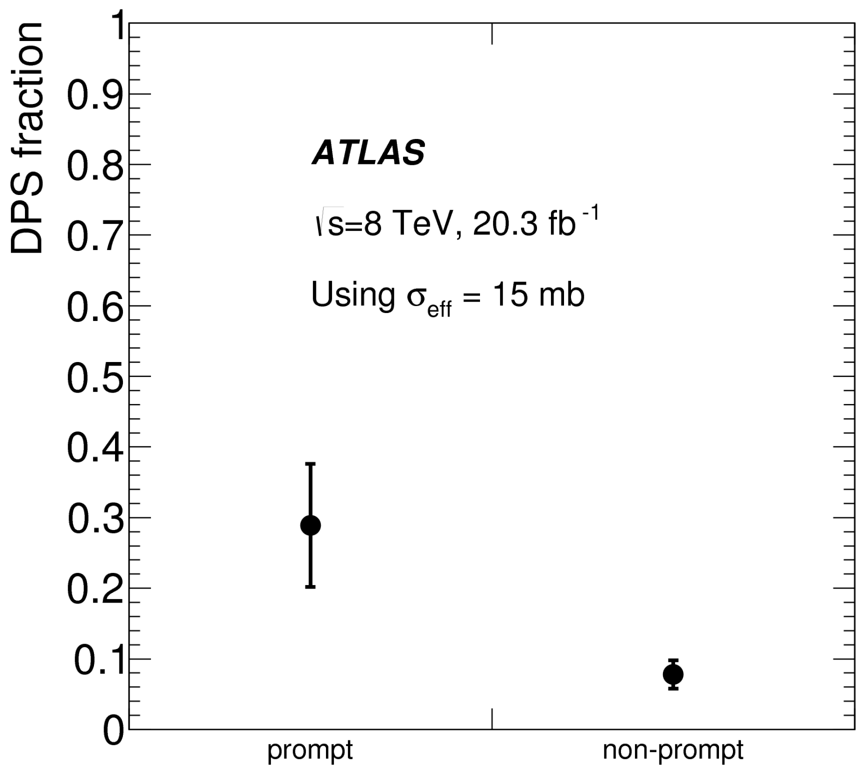


DPS contributions are important

Eur.Phys.J. C75 (2015) 5, 229; arXiv:1412.6428

Worth bearing in mind that estimates of DPS contribution to V+onia signals can be as large as 30 (40)% for Z (W).

If associated production data used to constrain LDMEs, DPS should be taken into account!



$$\langle \text{Total } W+\psi \rangle = \langle W+\psi \rangle + \kappa \times \langle \text{inclusive } \psi \rangle$$

Future prospects

Vector boson plus quarkonium studies have a promising future at the LHC

Vector boson can be triggered on with high acceptance * efficiency, can assume approximate lumi + parton density scaling (assuming no BSM source!)

W+J/ψ at 13 TeV
Can expect up to O(2) [parton density] * O(6) [luminosity] * O(2) [lepton channels] = 24 times statistics by end of 2016 = **~750 prompt signal events**
10–15% total uncertainties, modest increase in p_T reach

Z+J/ψ at 13 TeV
O(2) [pdf] * O(1) [lumi] = **120 prompt signal events** by end of 2016

Conclusions

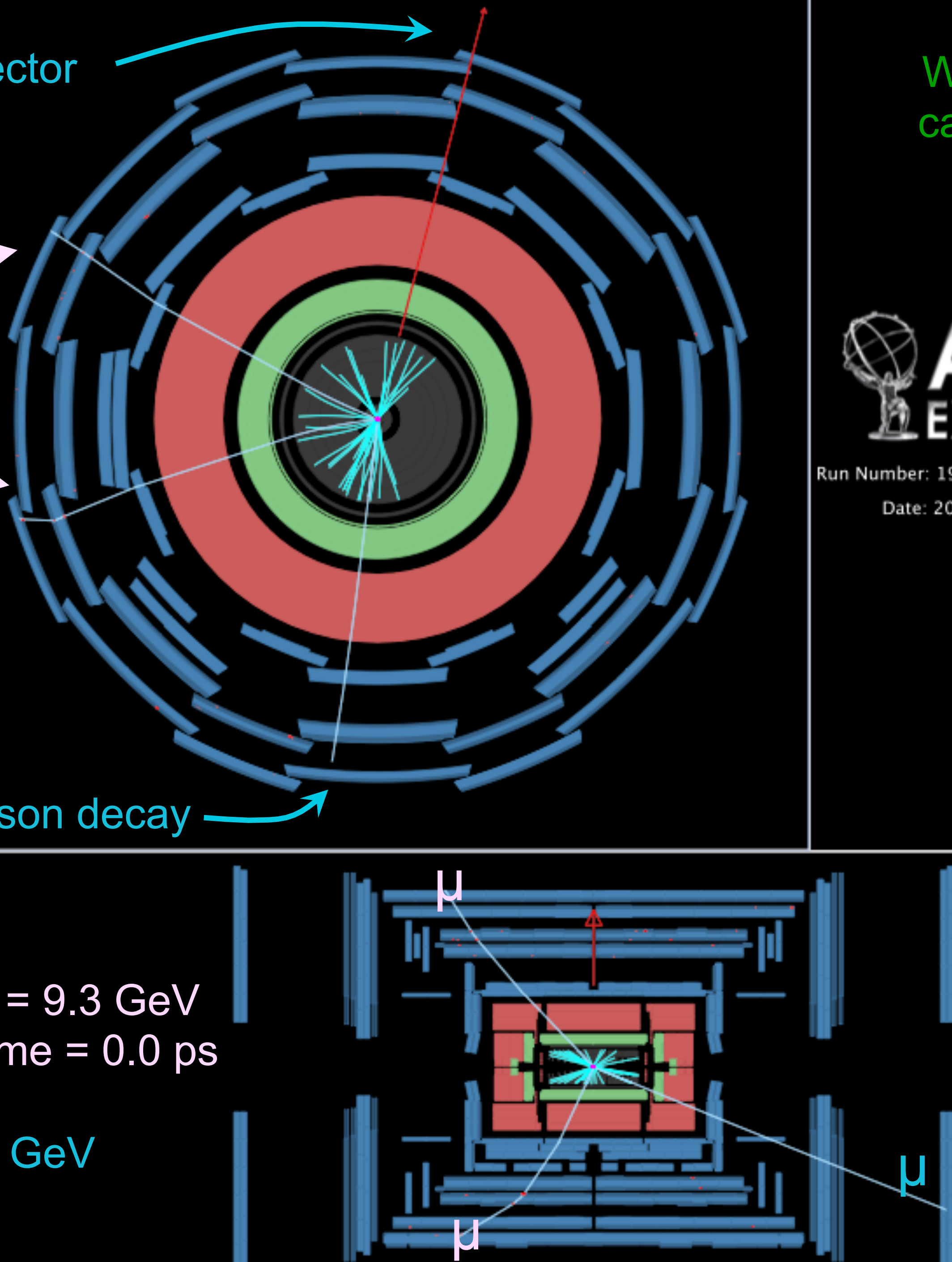
Study of associated vector boson plus quarkonium offers new probes of single parton scattering but also a novel avenue for study of DPS.

Picture of colour octet versus colour singlet dominance in such SPS processes is not currently so clear, and theory undershoots the data.

- Thoughts on how to handle DPS estimation?
- What observables should be measured (SPS and for DPS)?
- Getting reliable showered predictions of observables key to a precision understanding of the SPS process, or, observables insensitive to hadronisation?
- More detailed simulation of DPS contributions very welcome.
- DPS is a 30%+ contribution, should be taken into account carefully in any global fits.
- Is excess at high quarkonium p_T understood? Possible mechanisms?

Backup

W + prompt J/ψ candidate event



J/ψ candidate p_T = 9.3 GeV
Pseudo proper time = 0.0 ps

W boson p_T = 39 GeV