MANCHESTER 1824
The University of Manchester

ATLAS EXPERIMENT

Associated production of heavy flavour

Darren Price, University of Manchester

UK Flavour 2017, Durham, UK, September 6th '17

Measuring associated HF production

So you want to measure the associated production of HF at ATLAS?

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Pros ✓

Cons ✗

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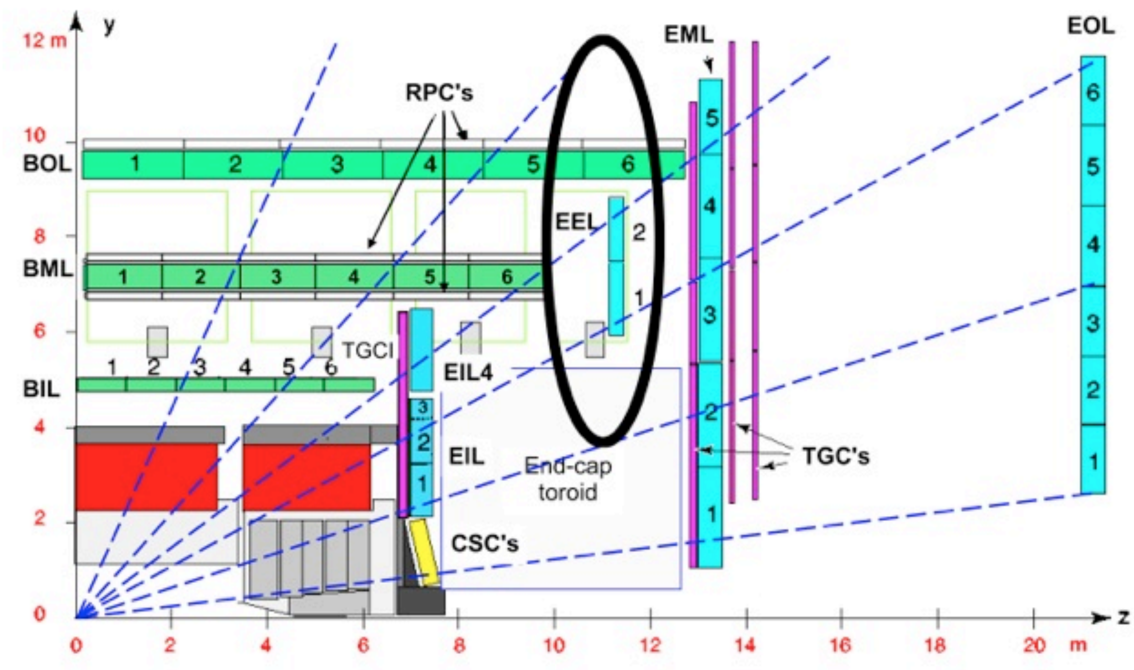
Cons ✗

Wide rapidity and ~hermetic azimuthal coverage

Muon $p_T(\mu)$>2.5 (3.5) GeV, $|\eta(\mu)|\epsilon$ (1.3,2.5] (ϵ[0,1.3])
Tracking to p_T~100 MeV (in principle)



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Pros ✓

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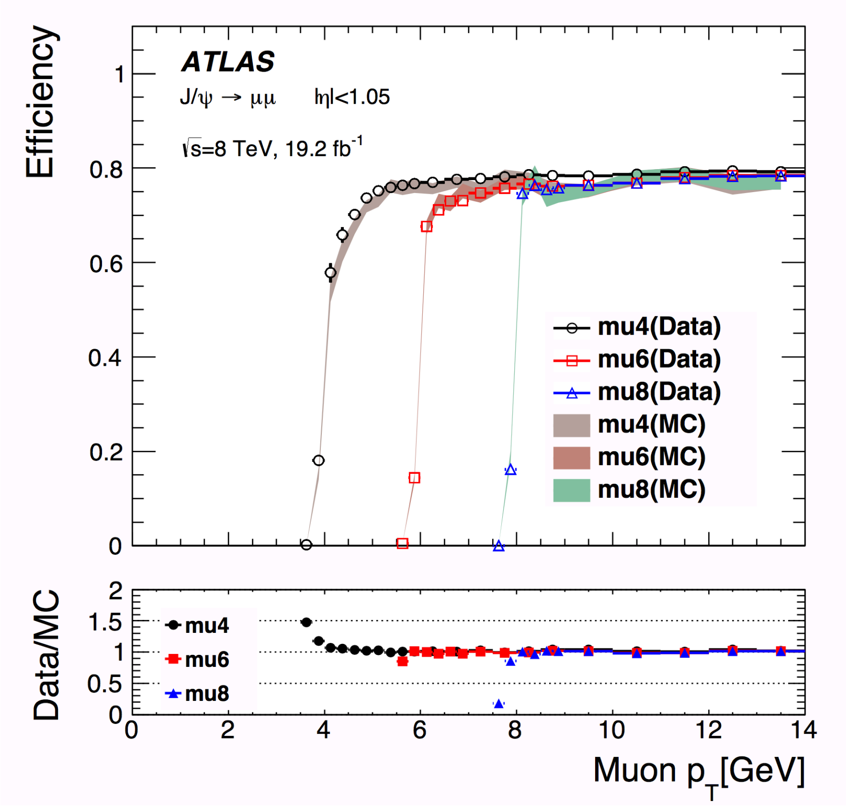
Cons ✗

Triggering restrictions



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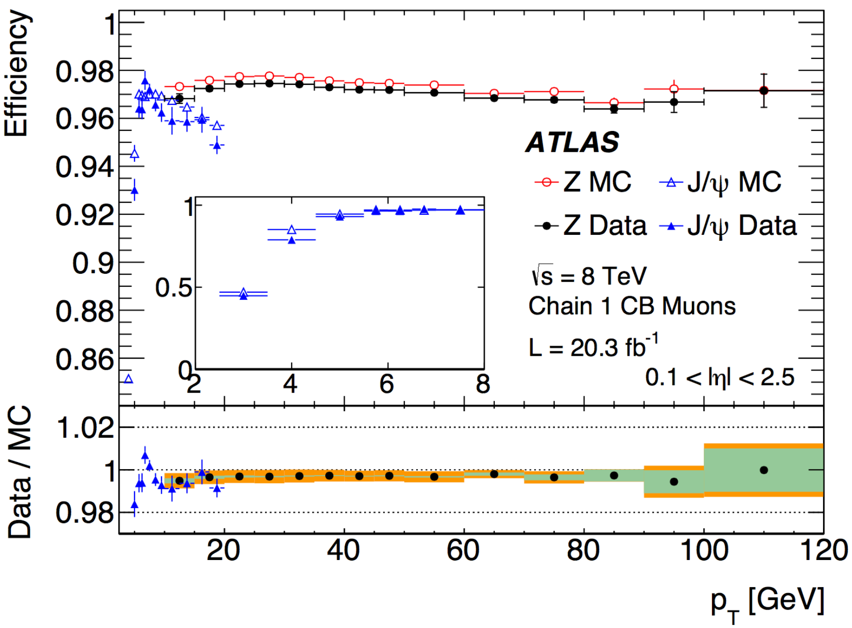
Muon reconstruction performance



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So you want to measure the associated production of HF at ATLAS?

Pros ✓	Cons ✗
Wide rapidity and ~hermetic azimuthal coverage	Triggering restrictions
Muon reconstruction performance	**Associated production relatively rare**

Measuring associated HF production

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Pros ✓

Wide rapidity and ~hermetic azimuthal coverage

Muon reconstruction performance

Associated production relatively rare

Cons ✗

Triggering restrictions

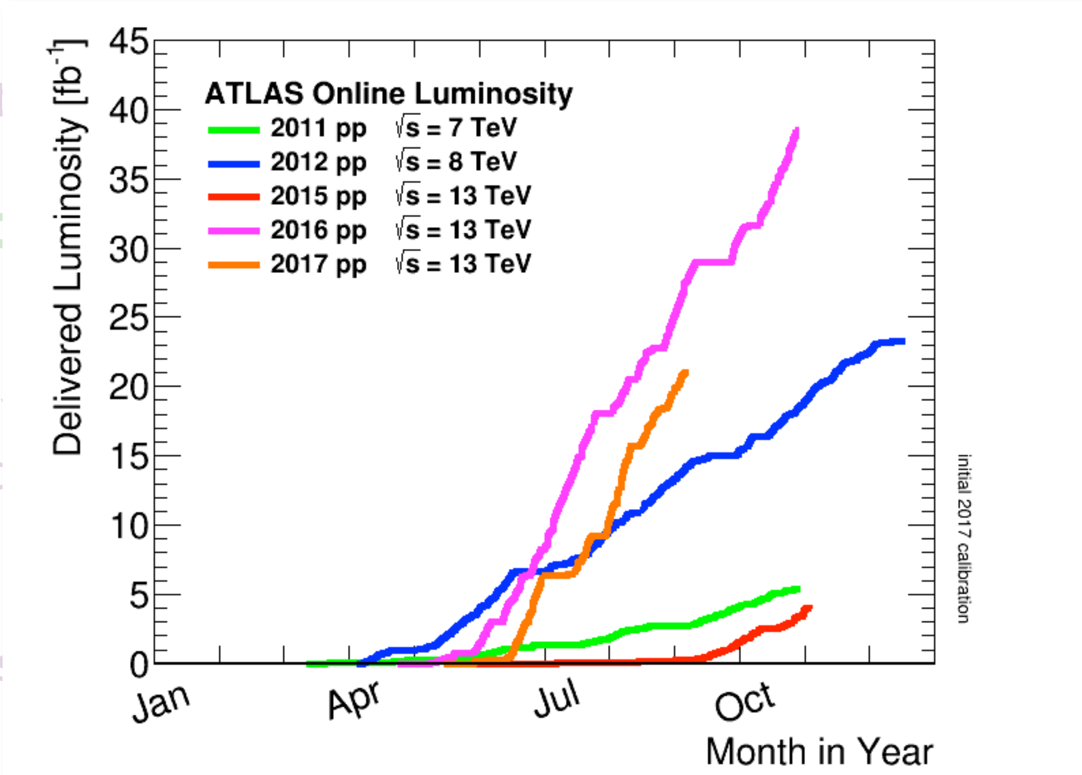
Associated production relatively rare

Measuring associated HF production

So you want t… ATLAS?

Wide rapidit… s
azimuthal cc

Muon recon… n relatively rare



Associated production relatively rare

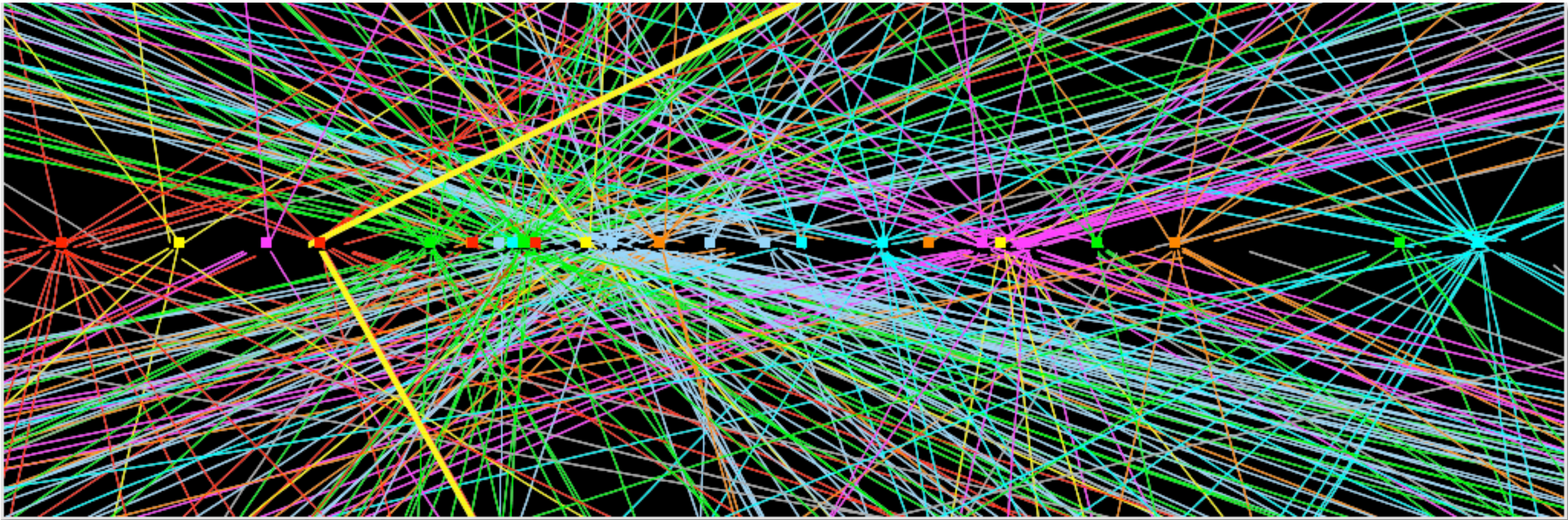
ATLAS has lots of pp collisions! ☺

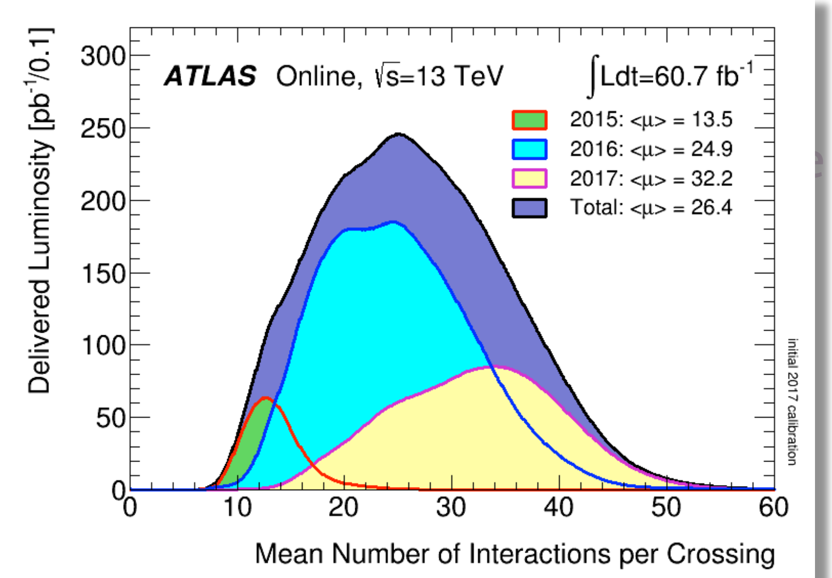
Measuring associated HF production

So you want to measure the associated production of HF at ATLAS?

Pros ✓	Cons ✗
Wide rapidity and ~hermetic azimuthal coverage	Triggering restrictions
Muon reconstruction performance	Associated production relatively rare
Associated production relatively rare *ATLAS has lots of pp collisions!* ☺	**Pileup** *ATLAS has lots of pp collisions!* ☹

Measuring associated HF production





Pileup

ATLAS has lots of pp collisions! ☹

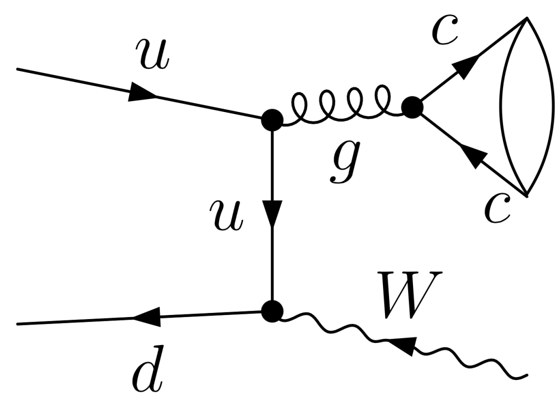
Searching for W bosons + J/ψ at ATLAS

Barger, Fleming, Phillips [Phys.Lett. B371 (1996) 111-116]:

> "$\psi + W$ production offers a clean test of the color-octet mechanism, "

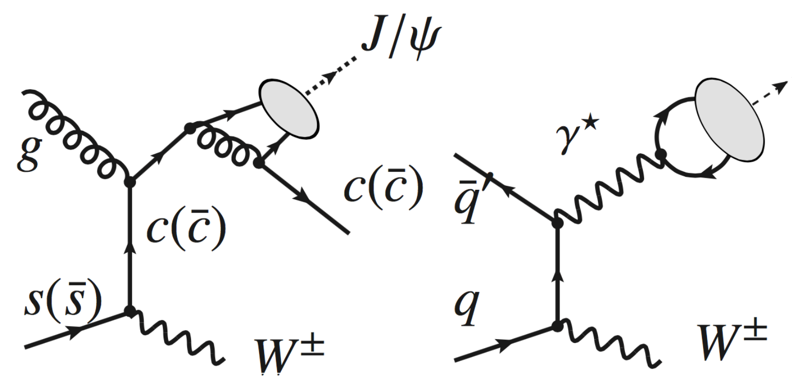
Li, Song, Zhang, Ma [Phys. Rev. D 83, 014001 (2011)]:

> " 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. "



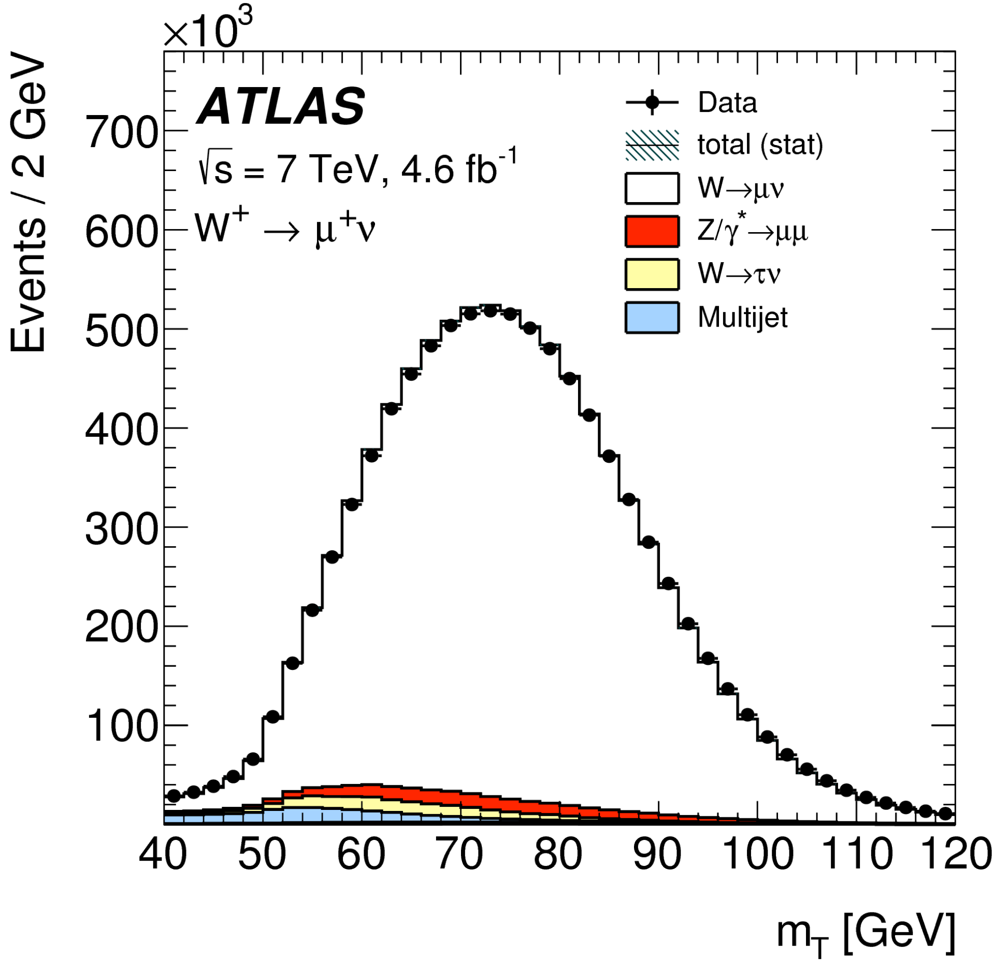
Lansberg, Lorce, [Phys.Lett. B726 (2013) 218-222, Phys.Lett. B738 (2014) 529-529] point out that this is not necessarily the case:

> " 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. "



Searching for W bosons + J/ψ at ATLAS

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



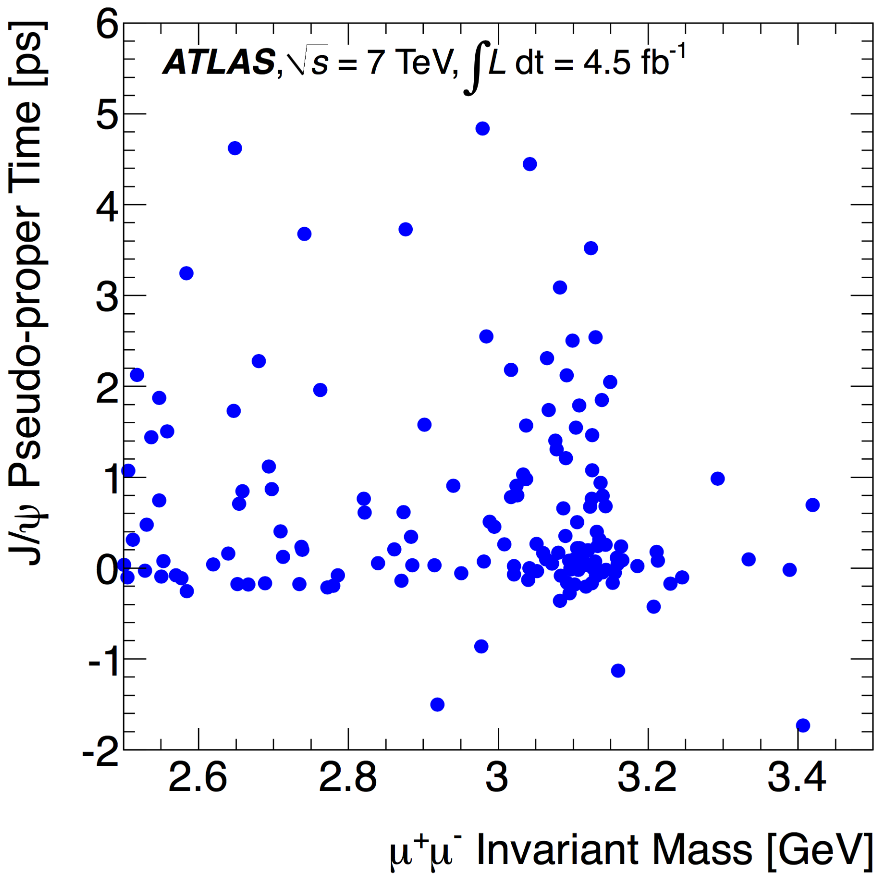
$$m_T = \sqrt{2 p_{T,\ell} p_{T,\nu} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

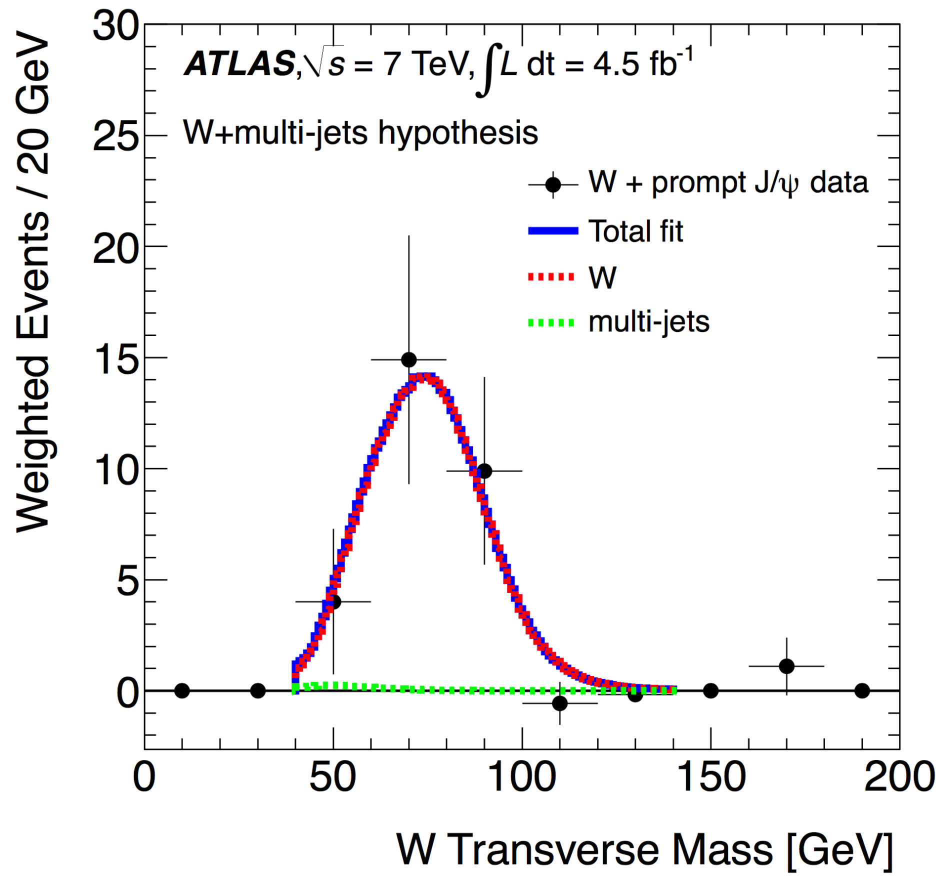
Searching for W bosons + J/ψ at ATLAS

JHEP 1404 (2014) 172

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: purity over efficiency)





A signal?

W + prompt J/ψ backgrounds

JHEP 1404 (2014) 172

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

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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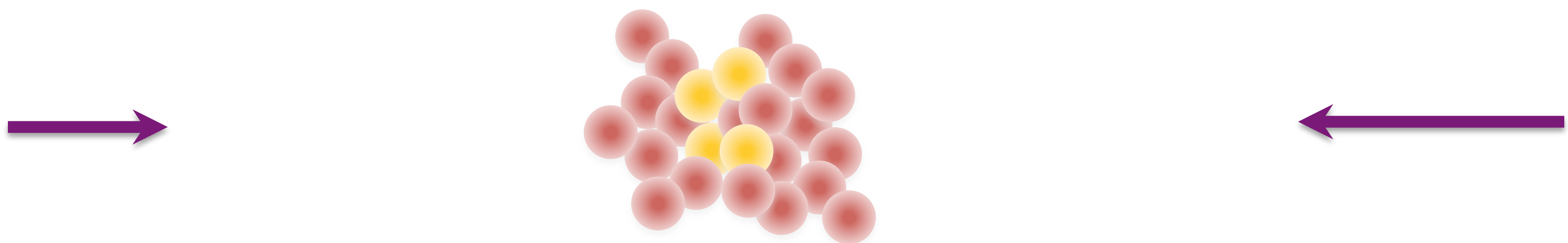

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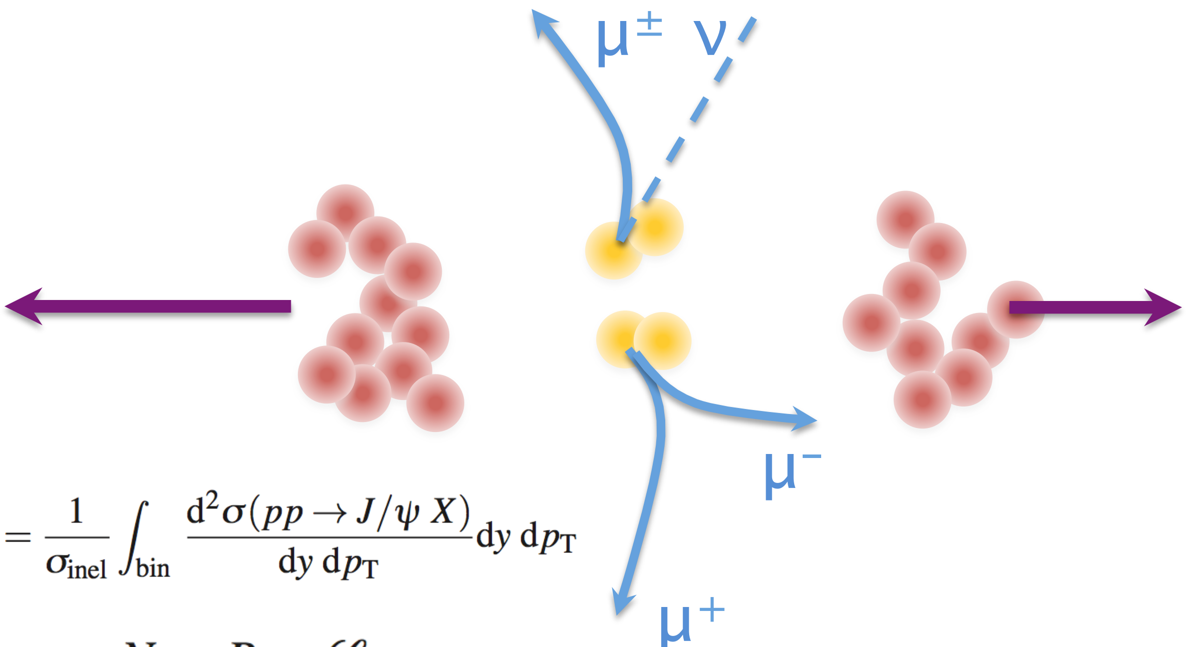


$$P_{J/\psi} = \frac{\sigma^{\rm bin}_{J/\psi}}{\sigma_{\rm inel}} = \frac{1}{\sigma_{\rm inel}} \int_{\rm bin} \frac{{\rm d}^2\sigma(pp \rightarrow J/\psi\ X)}{{\rm d}y\ {\rm d}p_{\rm T}} {\rm d}y\ {\rm d}p_{\rm T}$$

$$N_{\rm pileup} = N_{\rm extra} P_{J/\psi} \mathscr{L} \sigma_{W^{\pm}}$$

W + prompt J/ψ backgrounds

JHEP 1404 (2014) 172

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

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

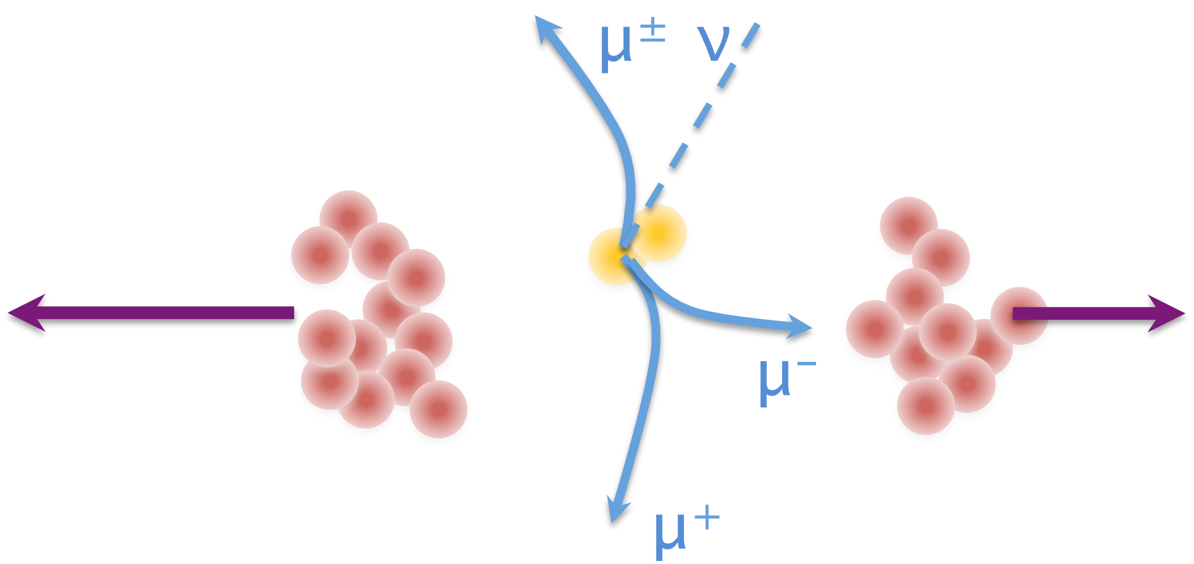
(*) of which 1.8 ± 0.2 originate from pileup

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

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

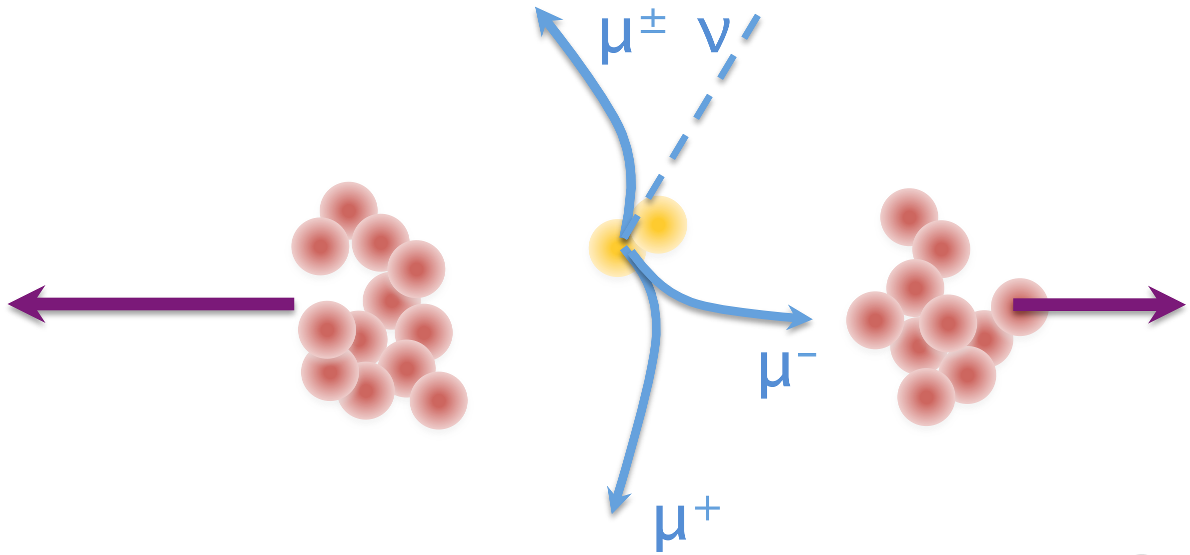


Double parton scattering

JHEP 1404 (2014) 172

W+prompt J/ψ data can arise from single parton scattering processes, but double parton scattering may also play a role: **important part of signal!**

Statistical phenomenon: not distinguishable on event-by event basis

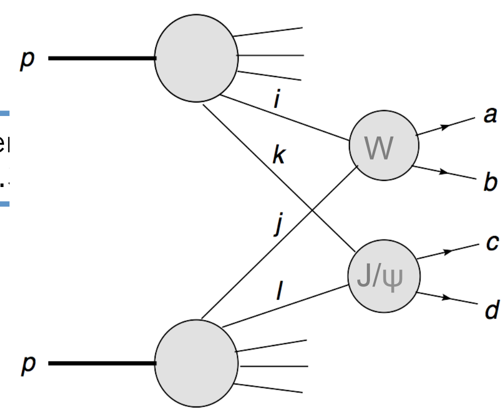


Measured directly in this analysis

From ATLAS measurement prompt J/ψ arXiv:1104..

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

From ATLAS measurement W+2jets arXiv:1301.6872



Double parton scattering

JHEP 1404 (2014) 172

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

DPS ansatz assumes independent hard scatters.

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

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

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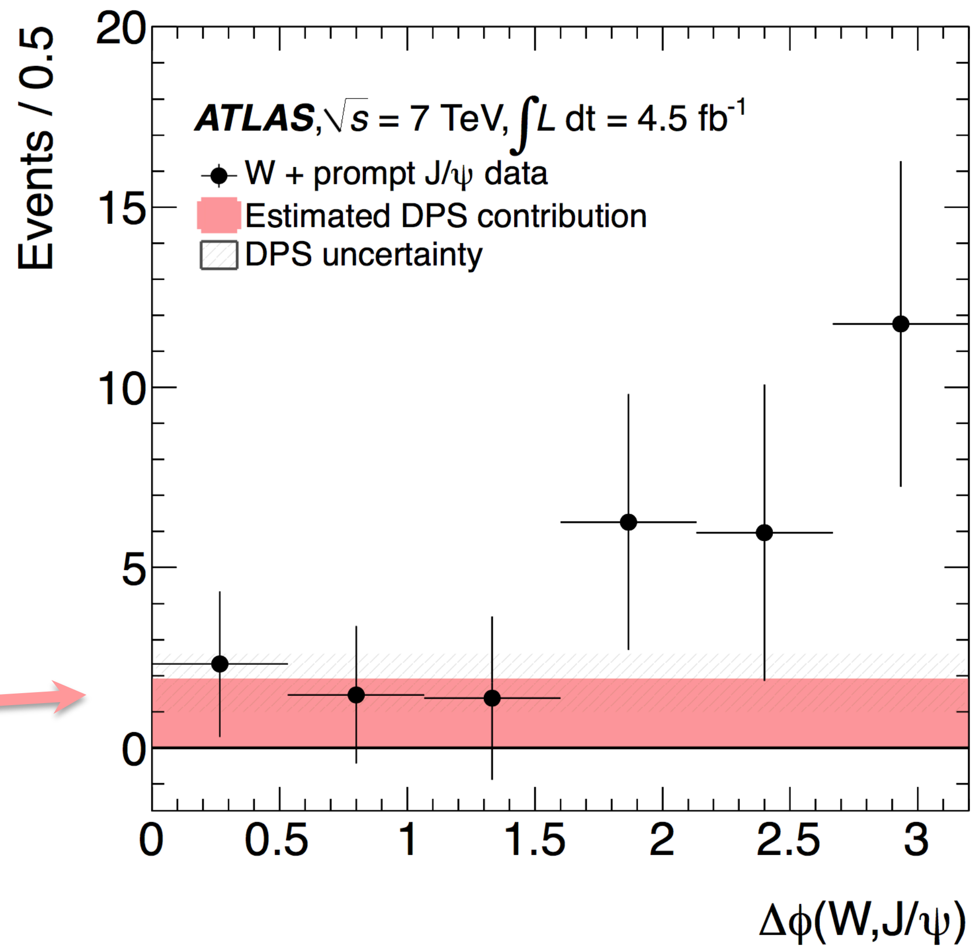
Estimate DPS contribution to the signal using the data

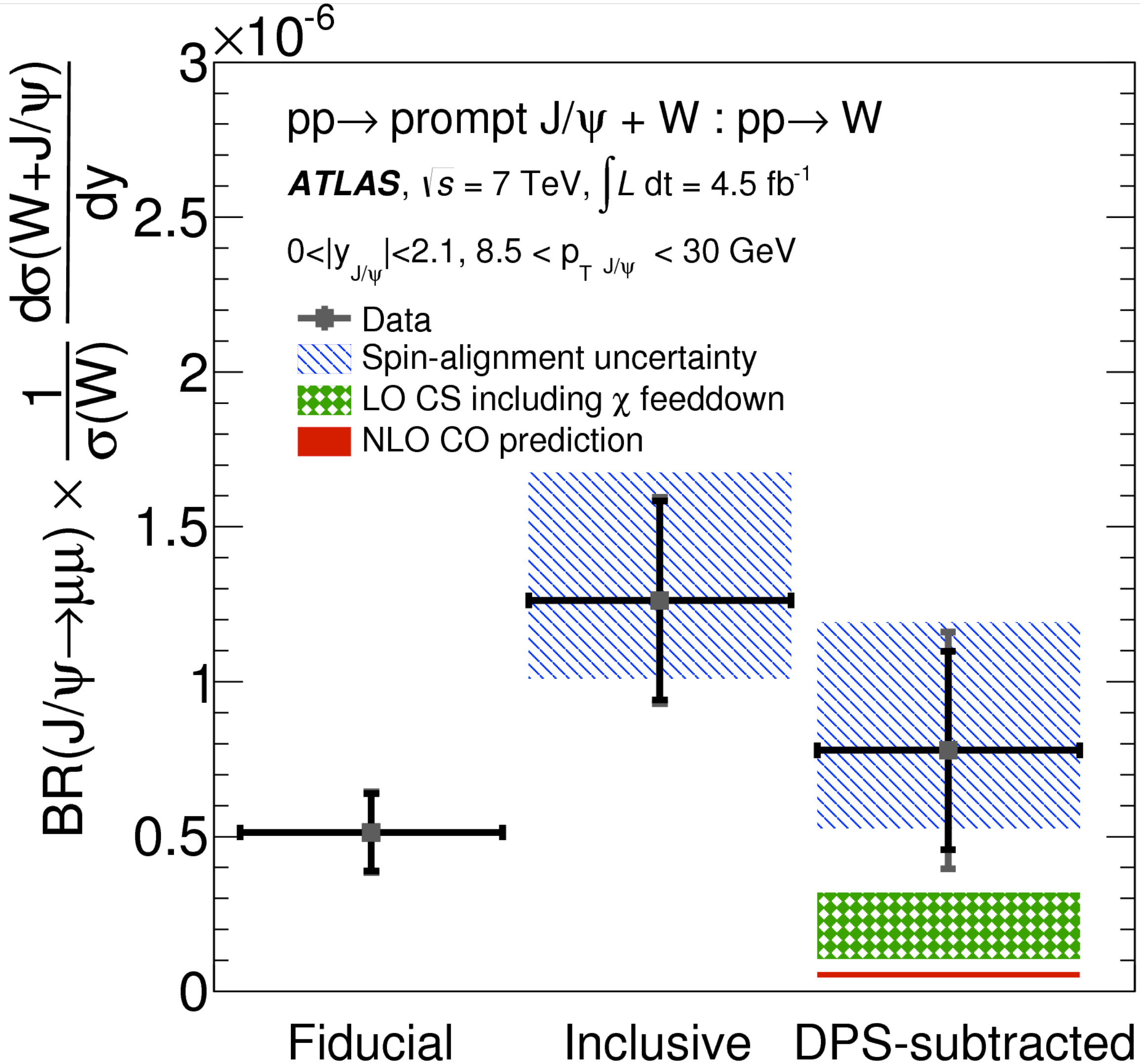
This is *not* a fit!



W + prompt J/ψ production rates

JHEP 1404 (2014) 172

Correcting for detector effects / efficiencies can extract rate:



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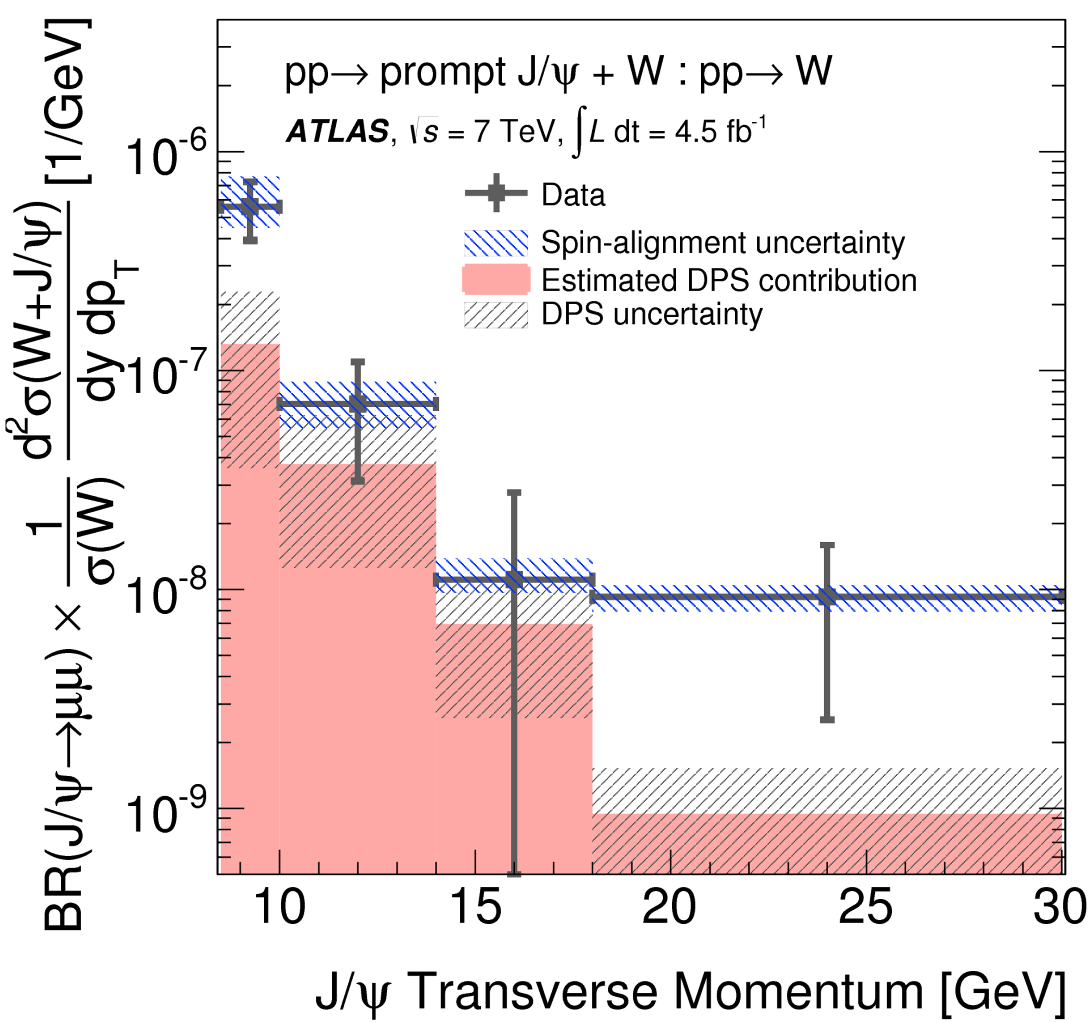
Can go further and measure differential rate,
DPS component re-evaluated from data in each p_T interval



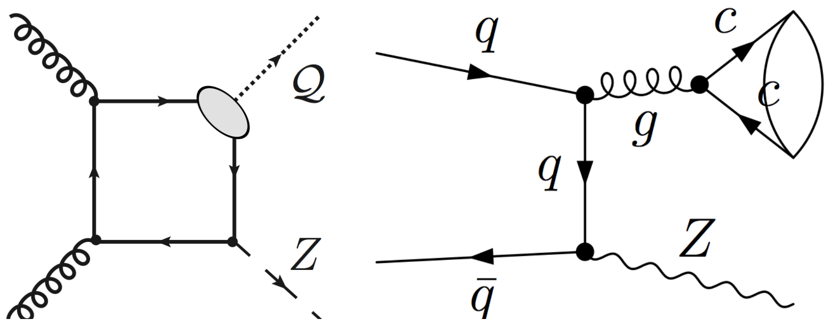
Both single and double parton scattering components observed in data

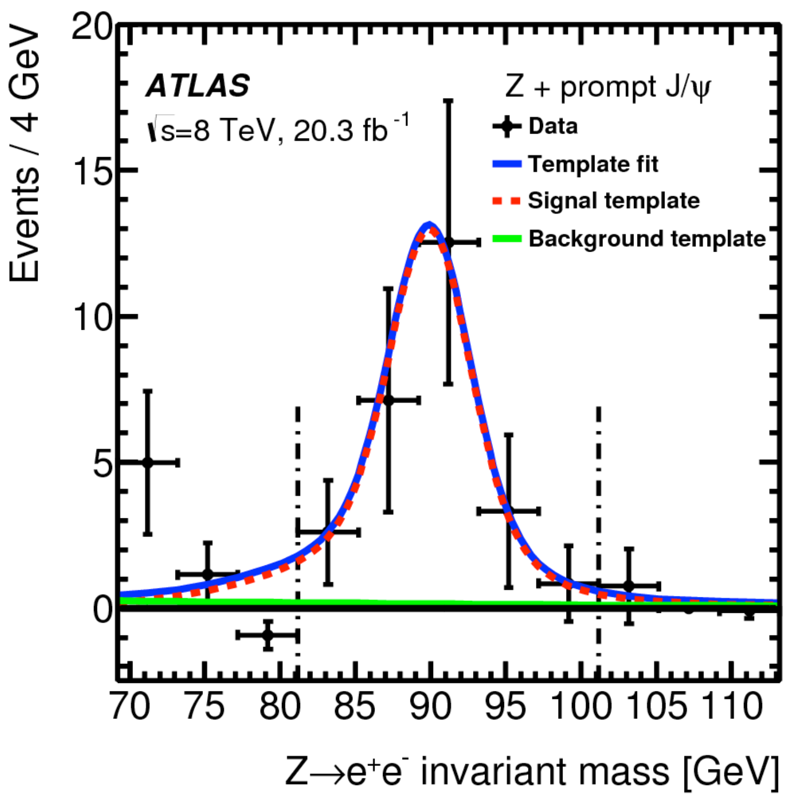
(f_{DPS}≈40%!)

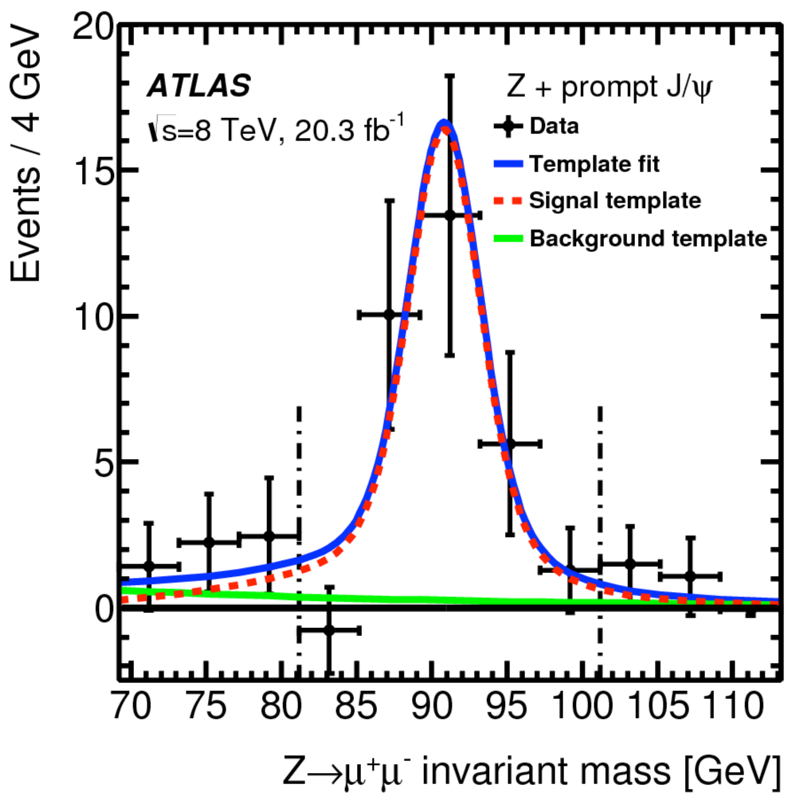
Searching for Z+J/ψ production

Eur.Phys.J. C75 (2015) 5, 229

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







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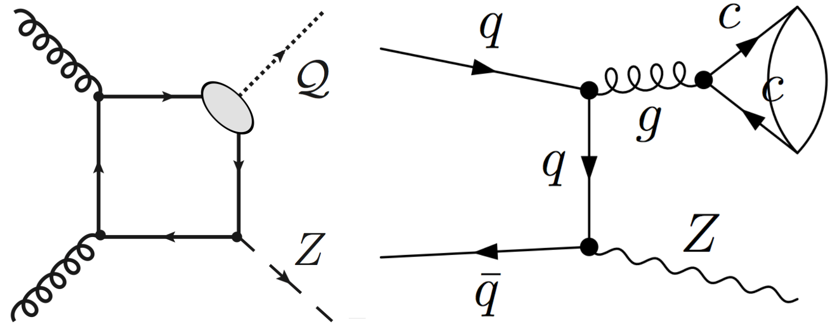

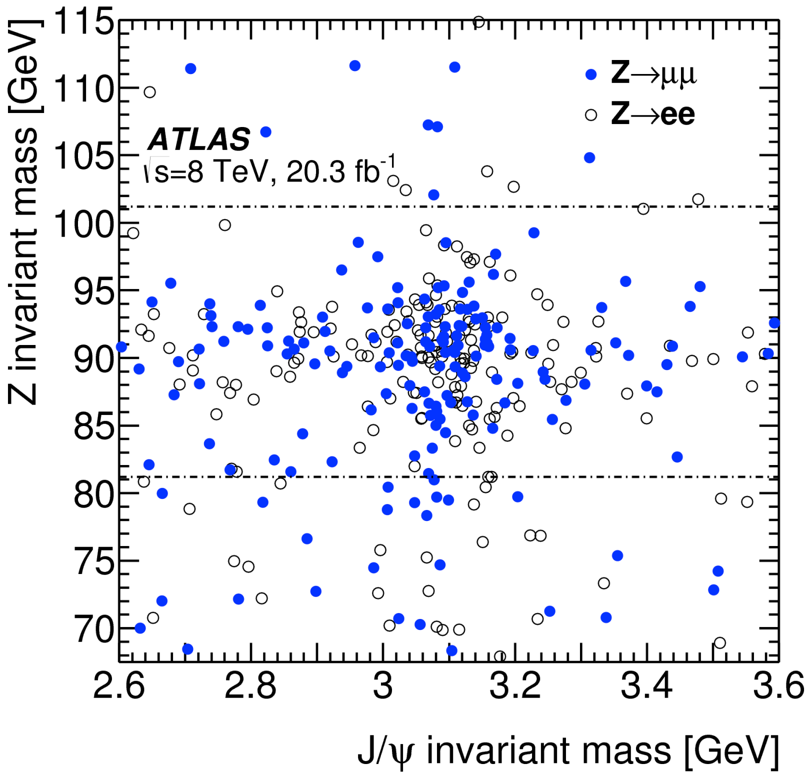

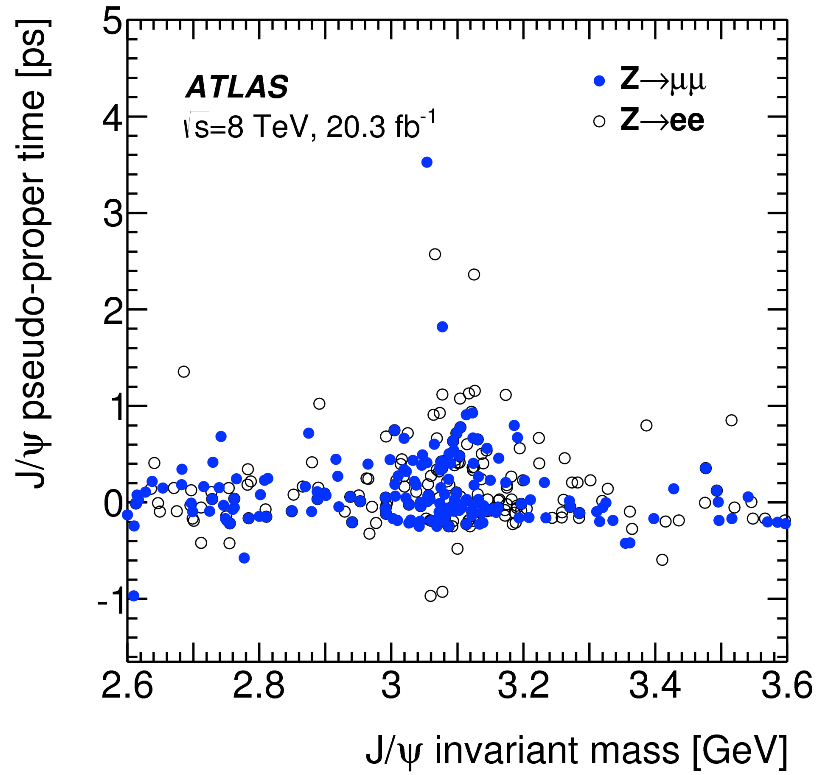

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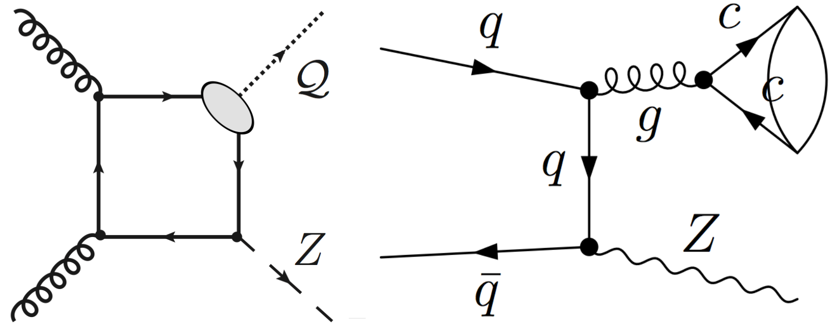

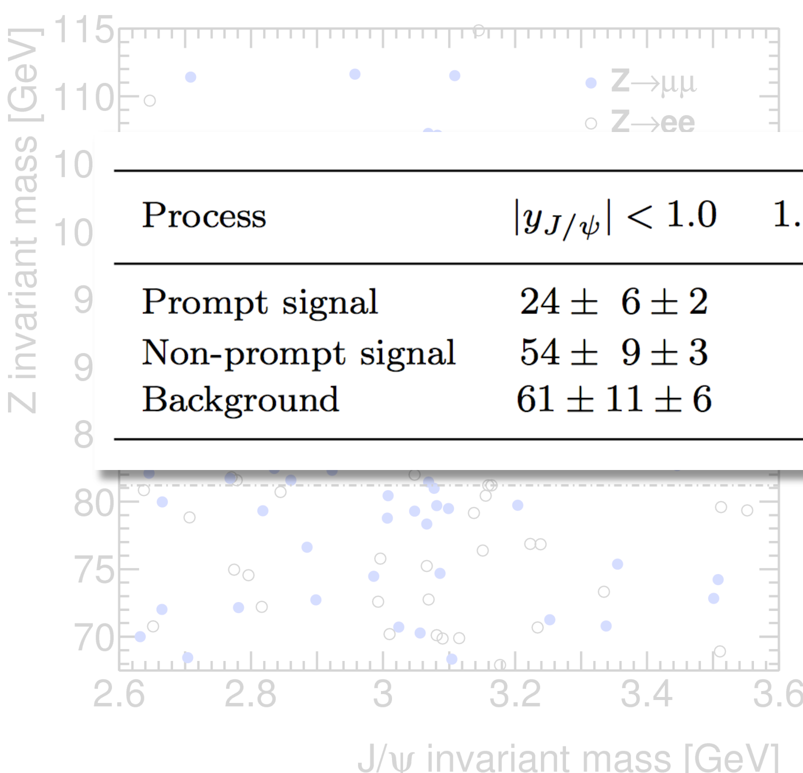

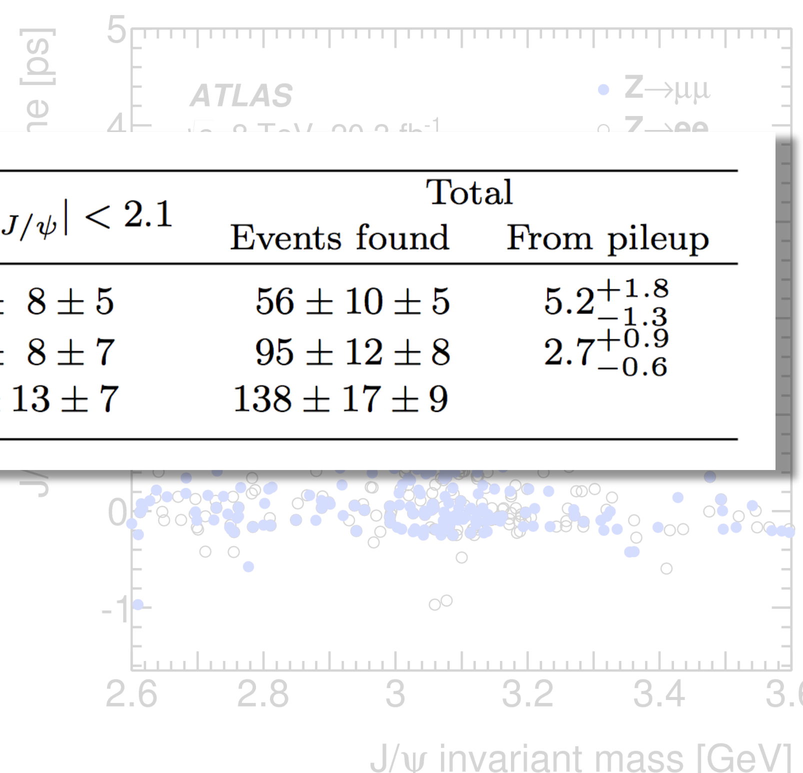

Process	$\lvert y_{J/\psi}\rvert < 1.0$	$1.0 < \lvert y_{J/\psi}\rvert < 2.1$	Total: Events found	Total: From pileup
Prompt signal	$24 \pm 6 \pm 2$	$32 \pm 8 \pm 5$	$56 \pm 10 \pm 5$	$5.2^{+1.8}_{-1.3}$
Non-prompt signal	$54 \pm 9 \pm 3$	$41 \pm 8 \pm 7$	$95 \pm 12 \pm 8$	$2.7^{+0.9}_{-0.6}$
Background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

Extracting the DPS component

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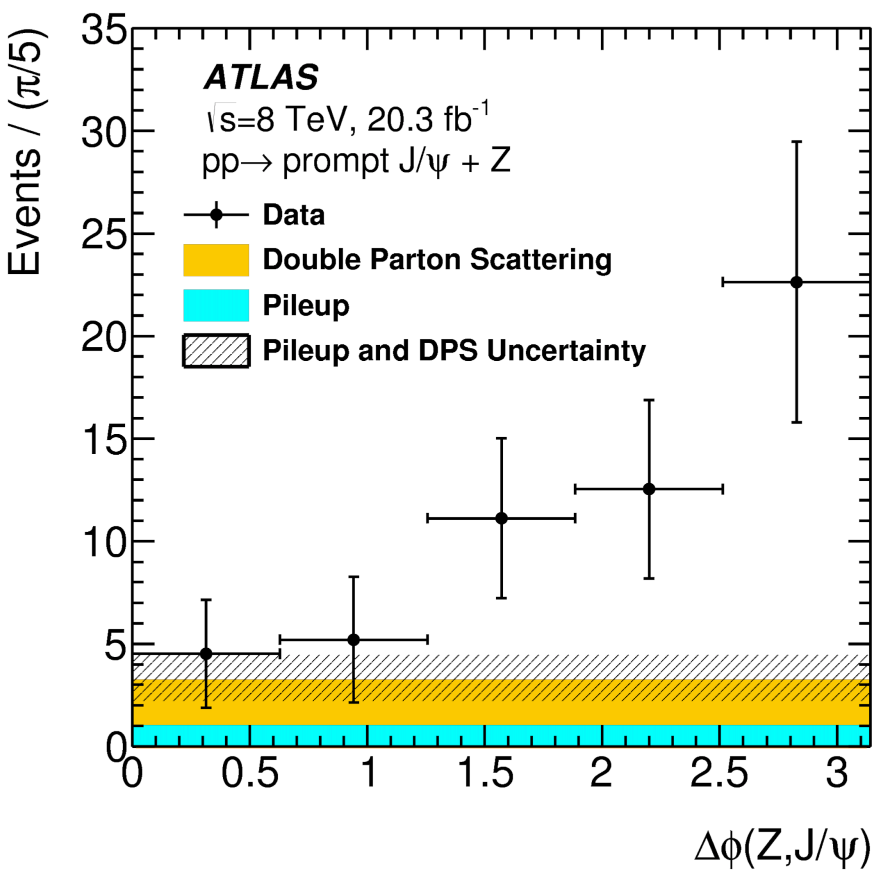
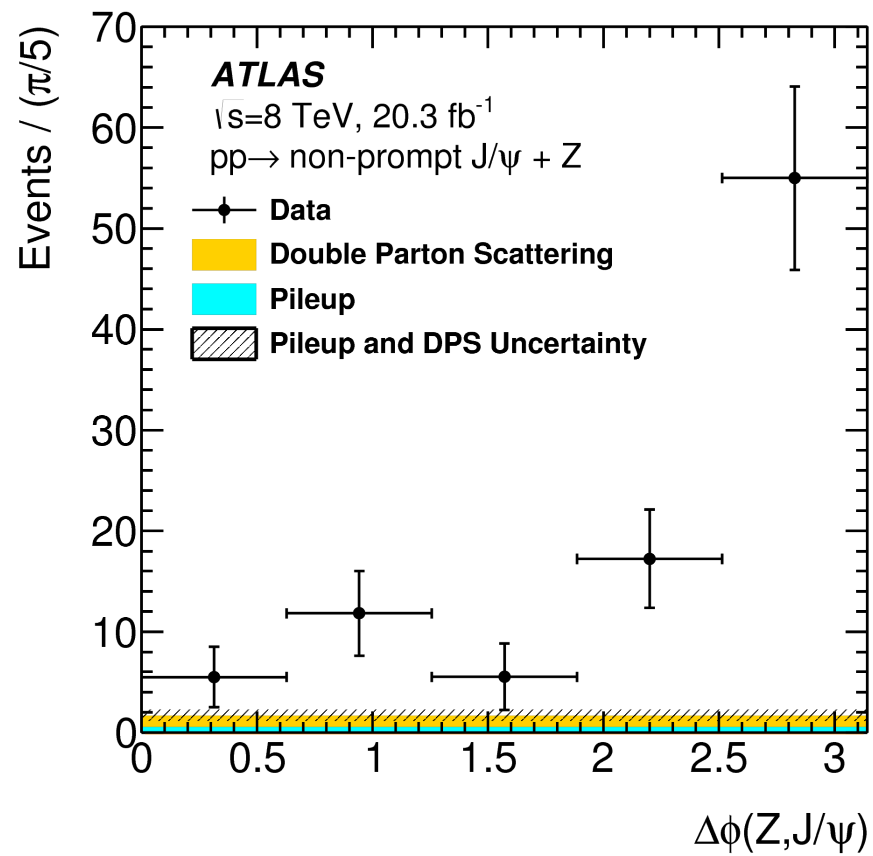
Extract signal, split by prompt/non-prompt, and assess backgrounds.

Double parton scattering component again estimated from data and cross-checked on azimuthal angular correlation distribution

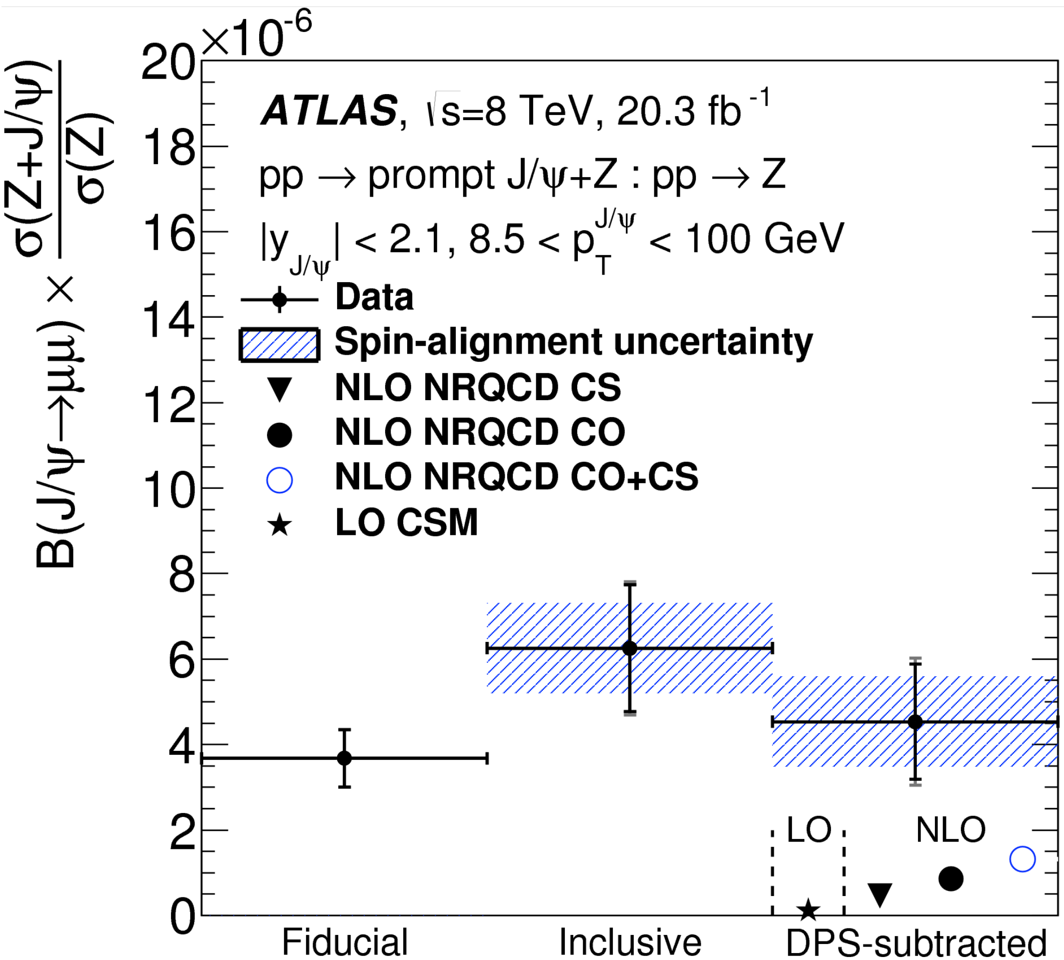




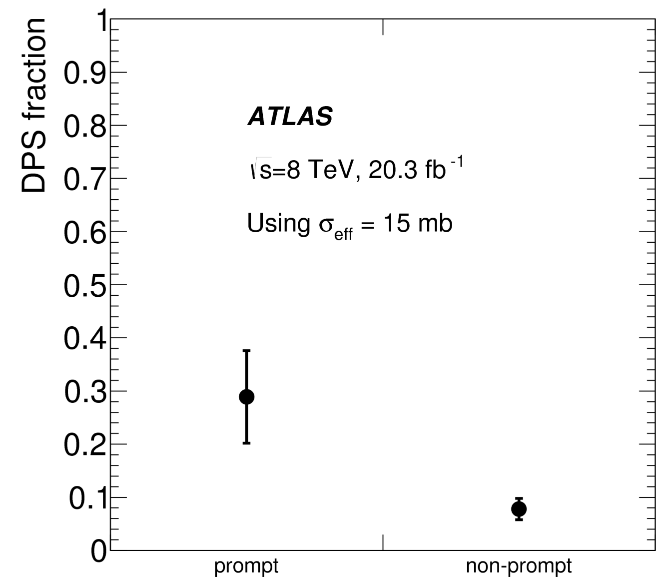
Z + prompt J/ψ production rates

Eur.Phys.J. C75 (2015) 5, 229

Correcting for detector effects / efficiencies can extract rate:



DPS fraction for prompt and non-prompt estimated:



Z + prompt J/ψ production rates

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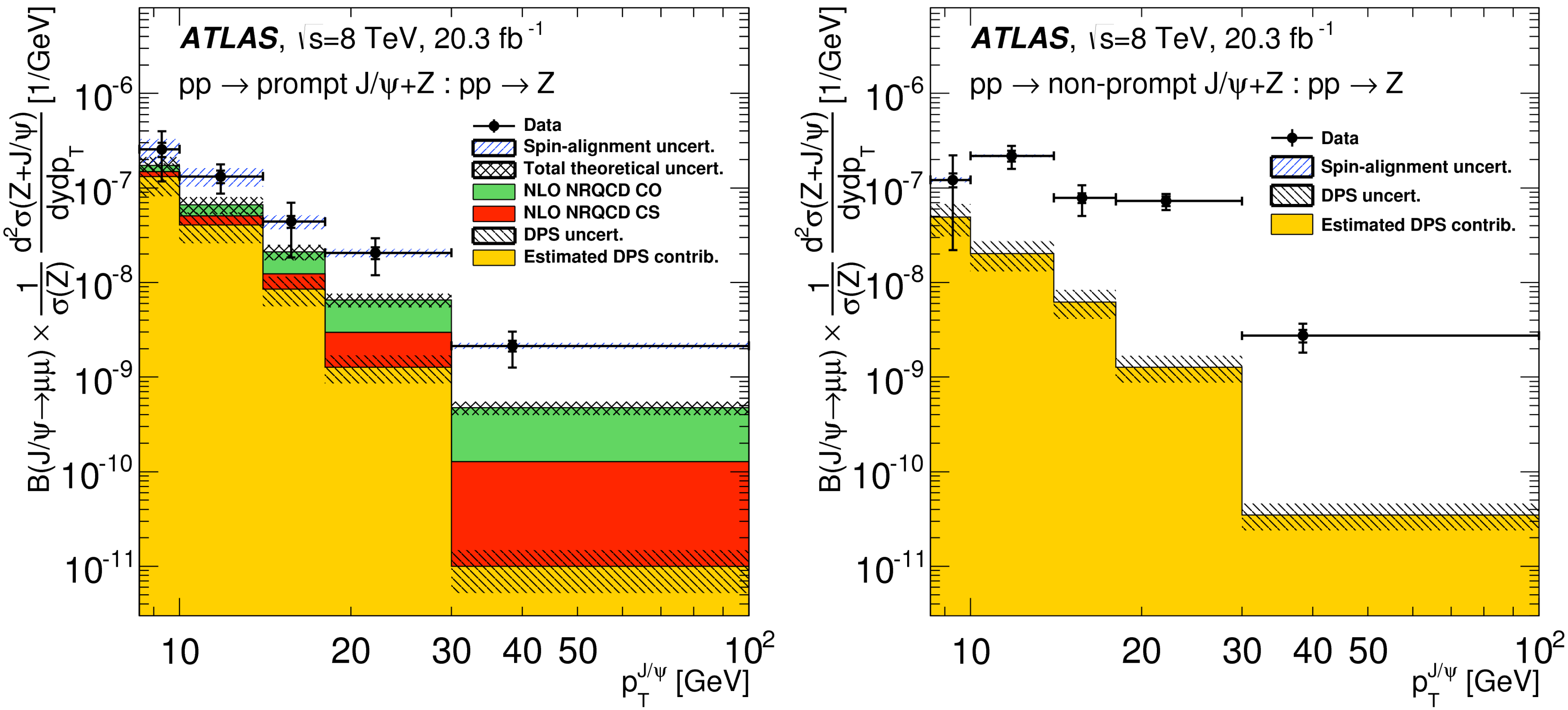
Measure differential rate versus J/ψ p_T for prompt and non-prompt production



Z + prompt J/ψ production rates

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Nucl.Phys. B916 (2017) 132

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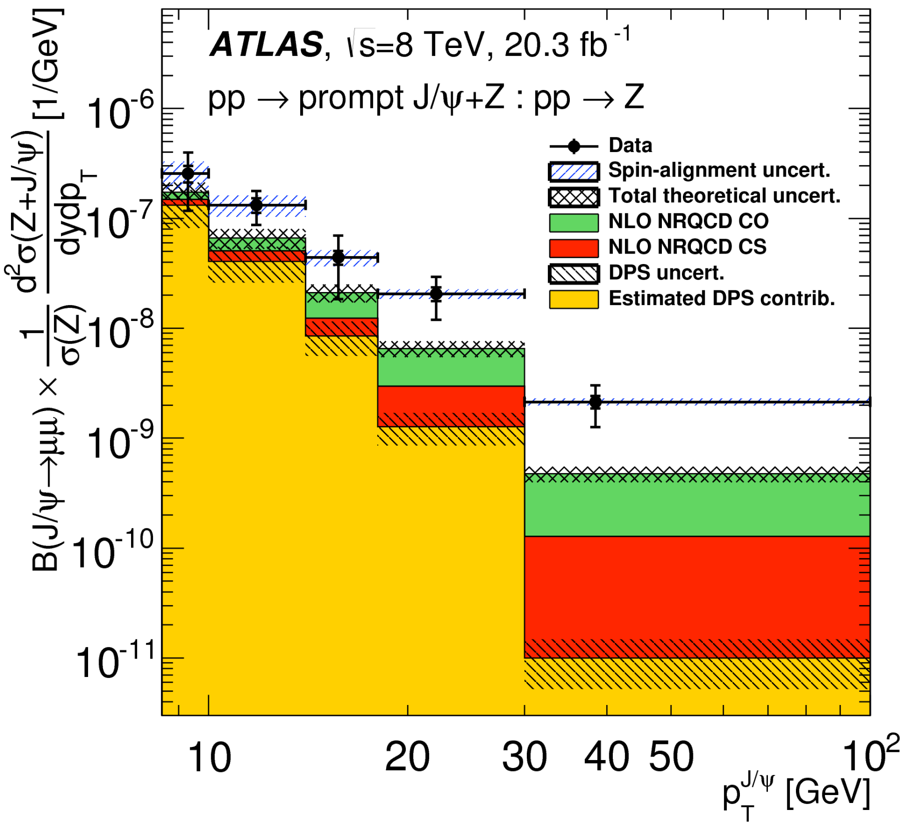
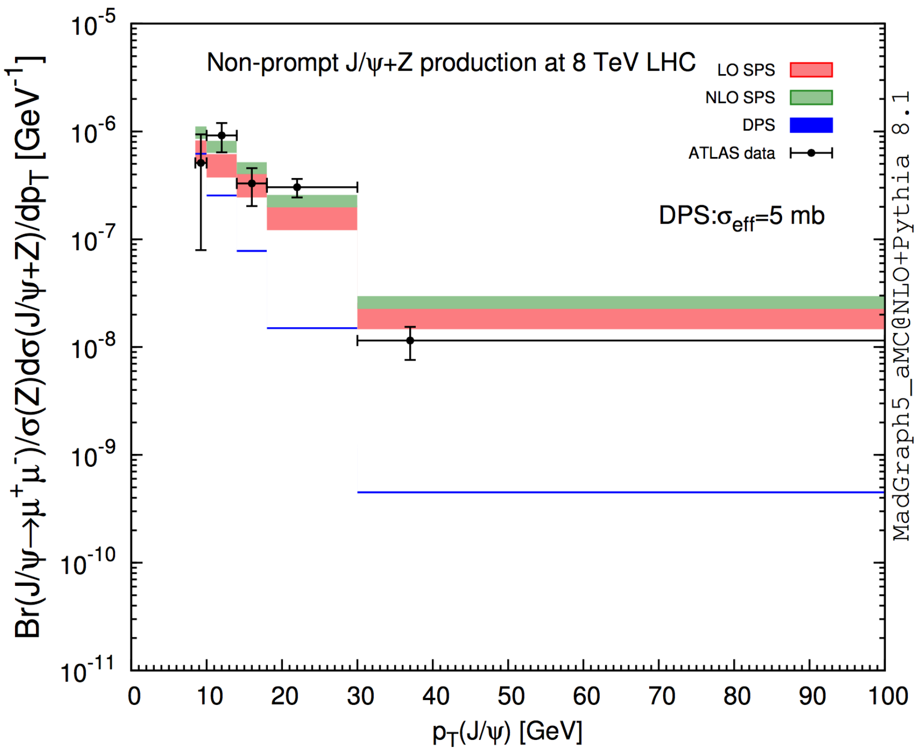


Probe of low b-quark p_T in Z+b



Z + J/ψ: limits on σ_{eff}

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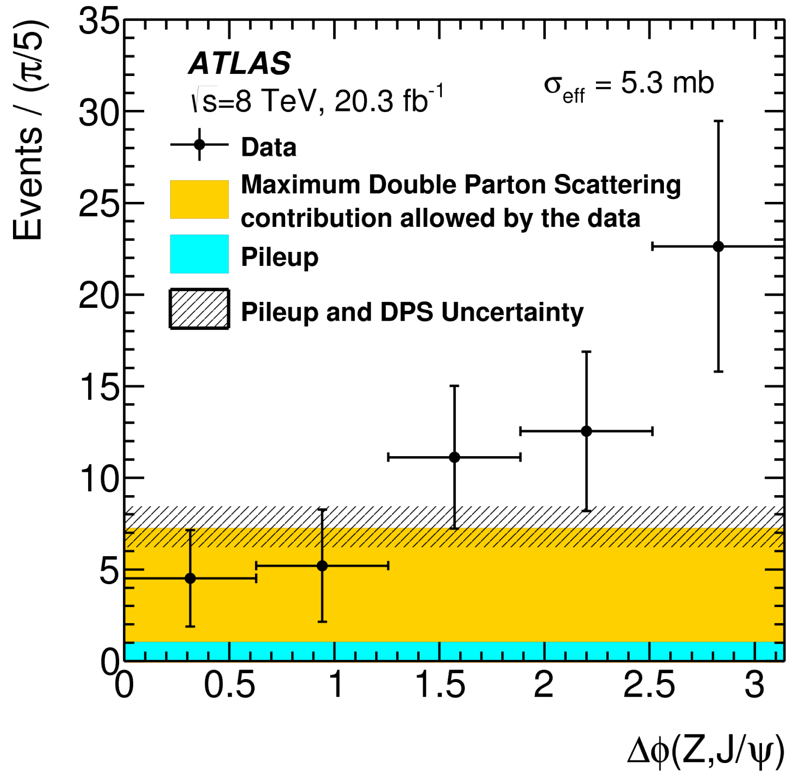
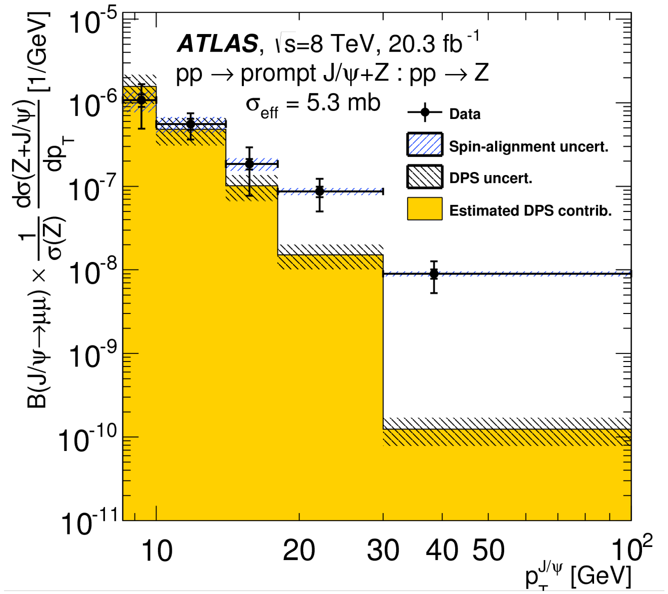
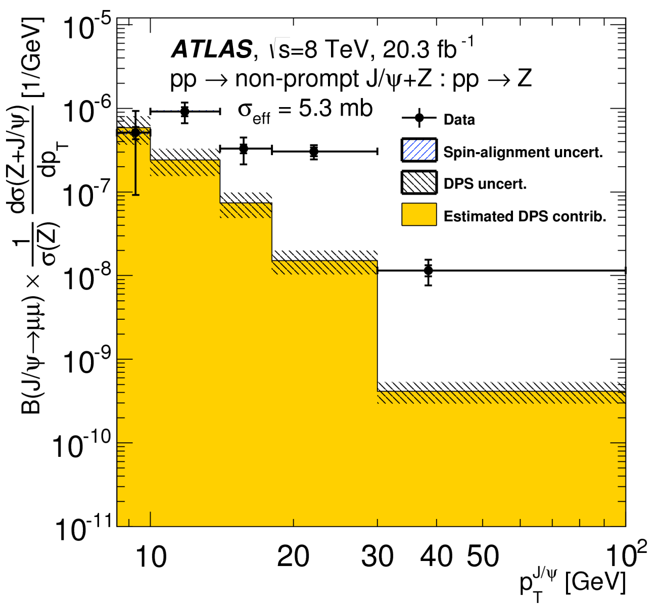
Can extract limits on maximum DPS / lowest σ_{eff} from fit to data







Prompt J/ψ pair production

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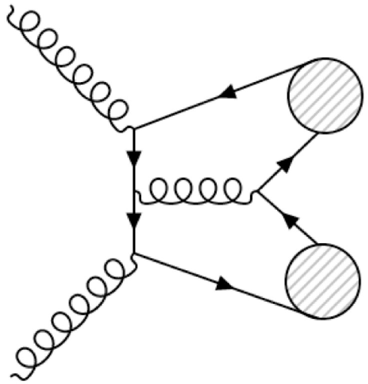
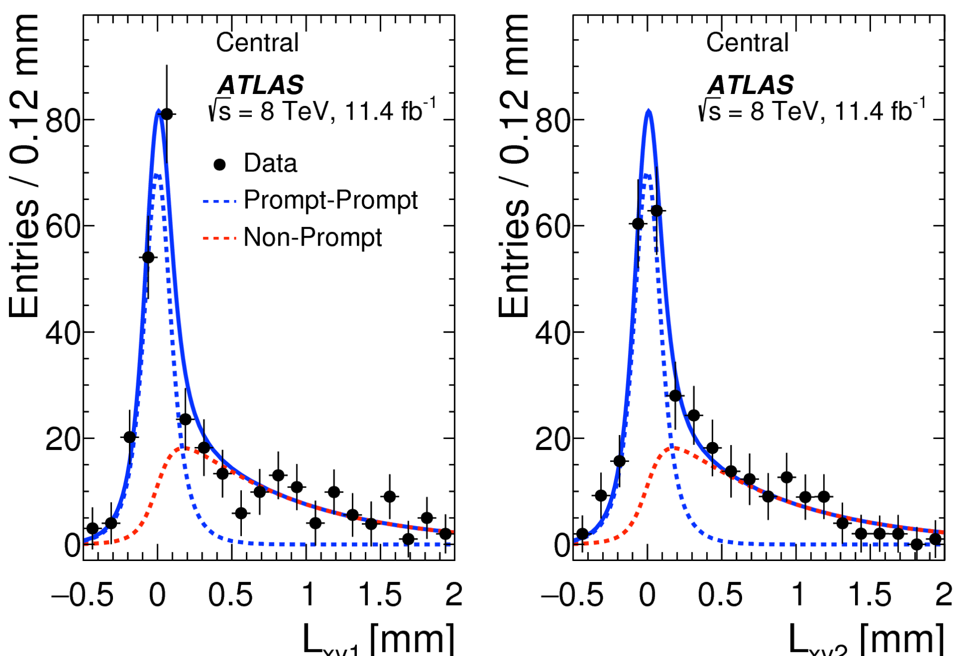
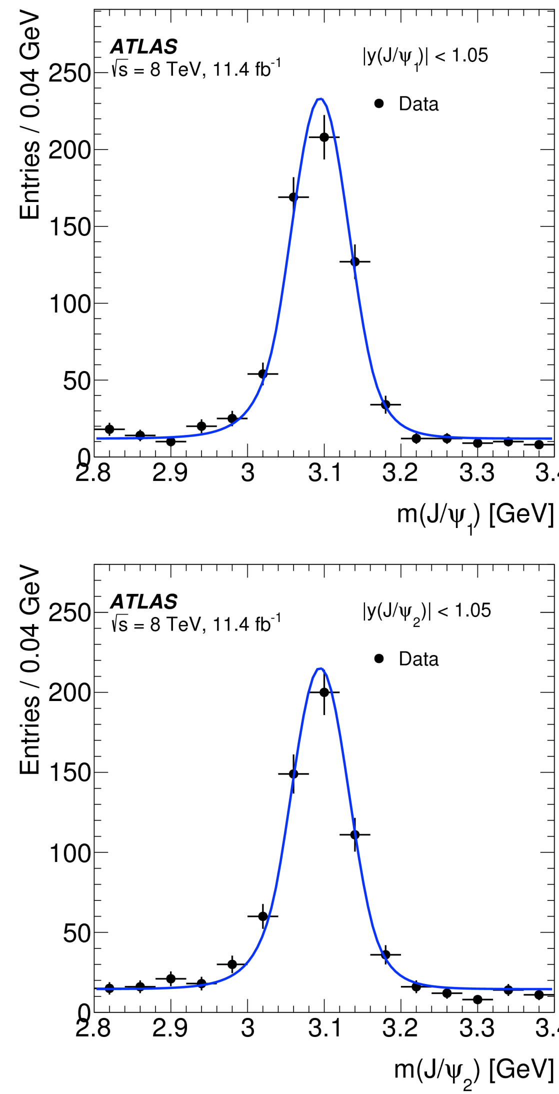
Four muon final state, 8 TeV data, 11.4 fb^{-1}
Unbinned ML fit to two di-muon invariant mass







Prompt J/ψ pair production: DPS

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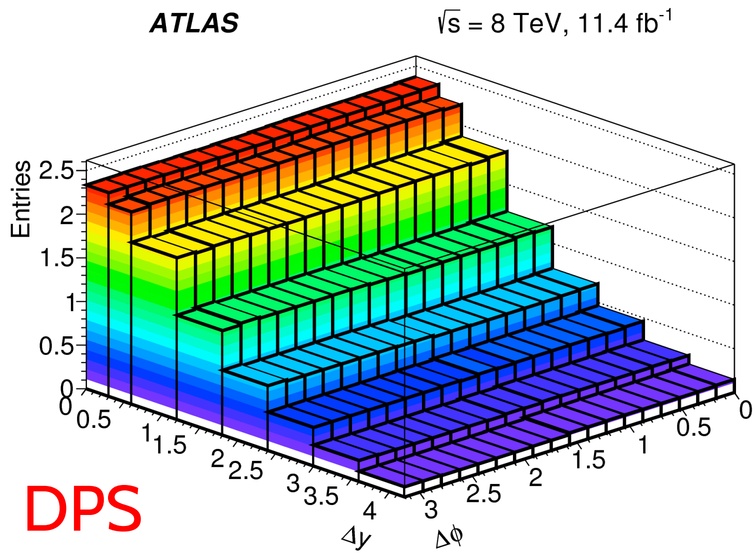
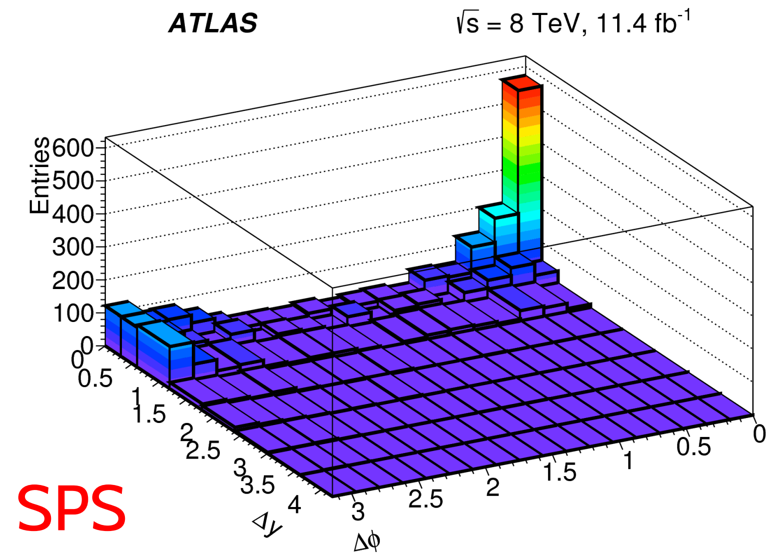
Use data-driven approach to derive kinematic templates for DPS contribution





DPS from J/ψ candidates event-mixing seeded by DPS-enriched $\Delta y \geq 1.8$ and $\Delta\phi \leq \pi/2$ region.

Normalisation of DPS fixed from data in DPS-enriched region.

Prompt J/ψ pair production rates

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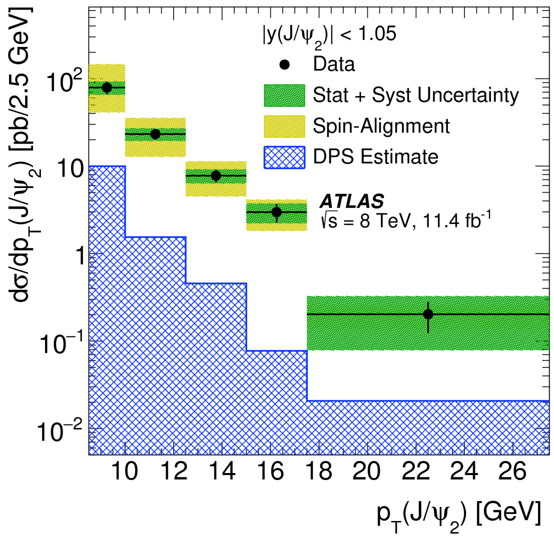
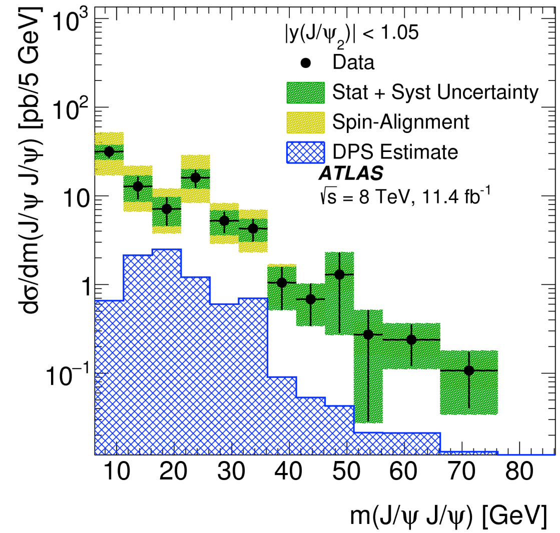
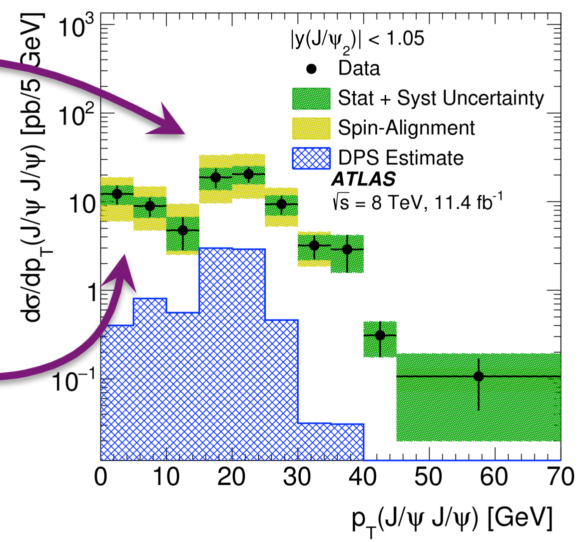
Total prompt J/ψ pair differential production rates (and DPS estimate):





Low p_T region:
J/ψ produced back-to-back

High p_T region:
J/ψ boosted, only modelled by NLO



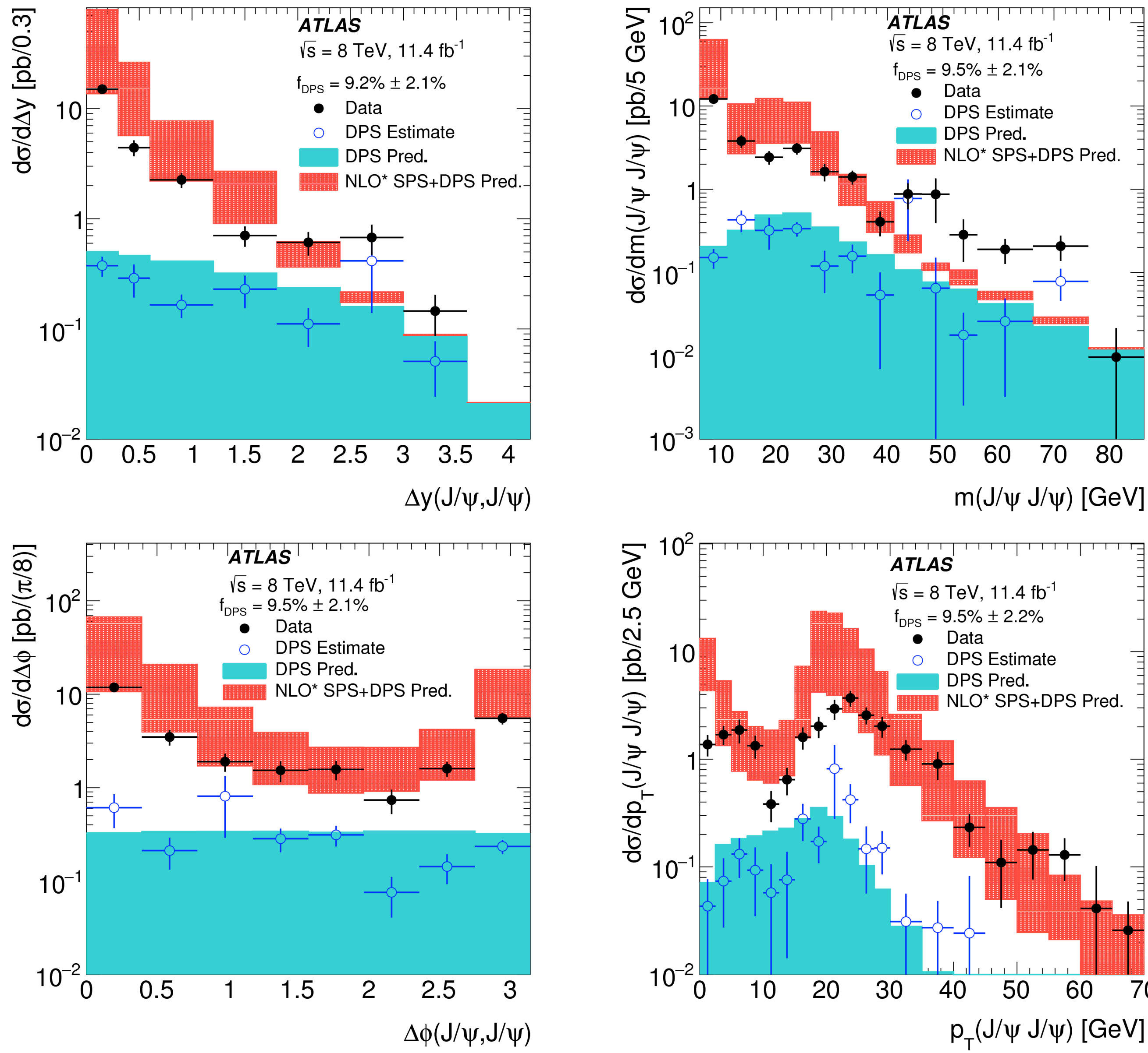
Prompt J/ψ pair production rates

Eur. Phys. J. C77 (2017) 76

Data-driven DPS
compared to
LO DPS prediction
Phys. Rev. D 95, 034029 (2017)

Fraction of DPS from data-driven est. ~9%

SPS NLO singlet predictions (HELAC-Onia) describe data: some discrepancies at low p_T and high mass*



The emergence of a puzzle in DPS

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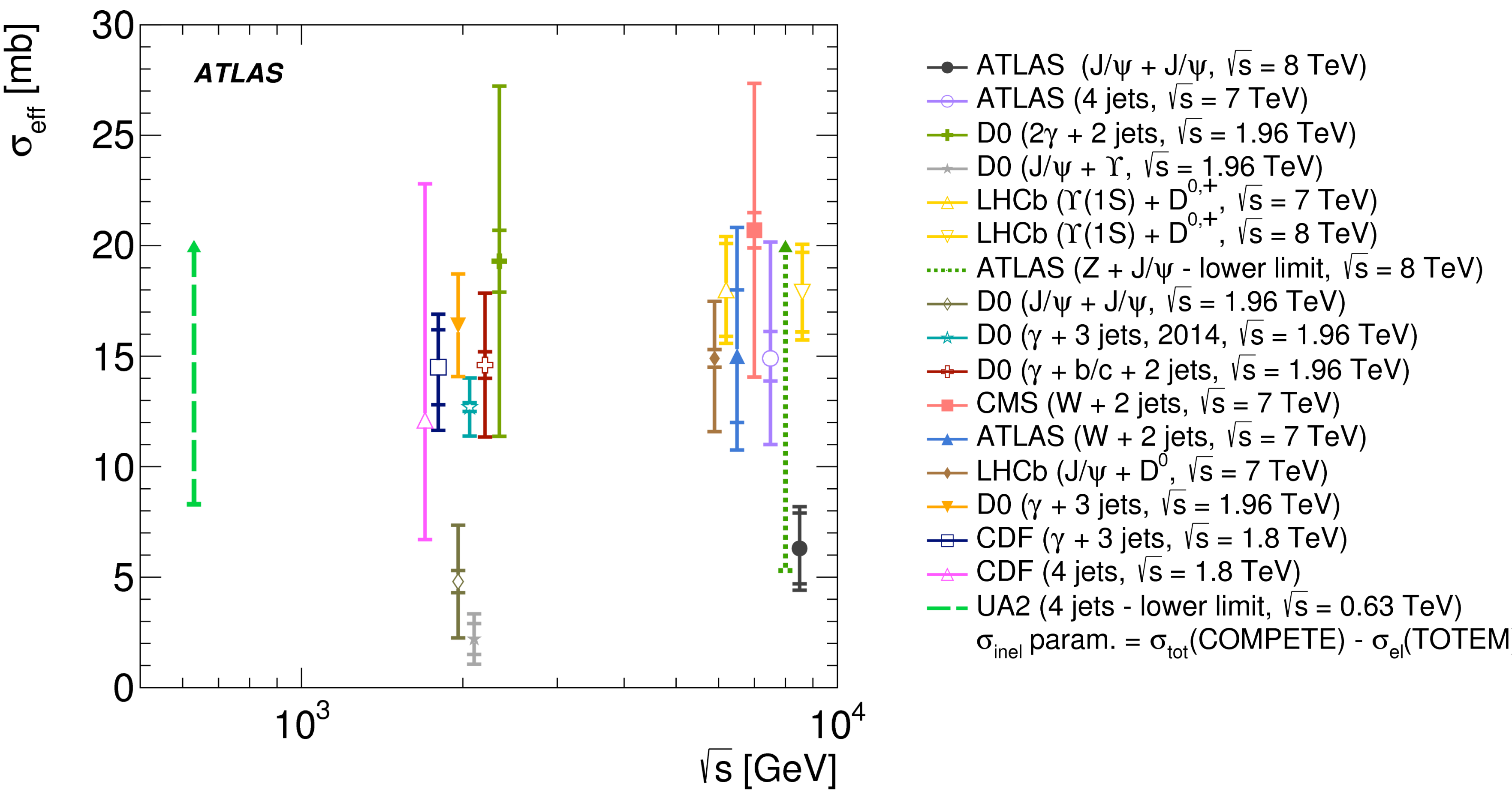
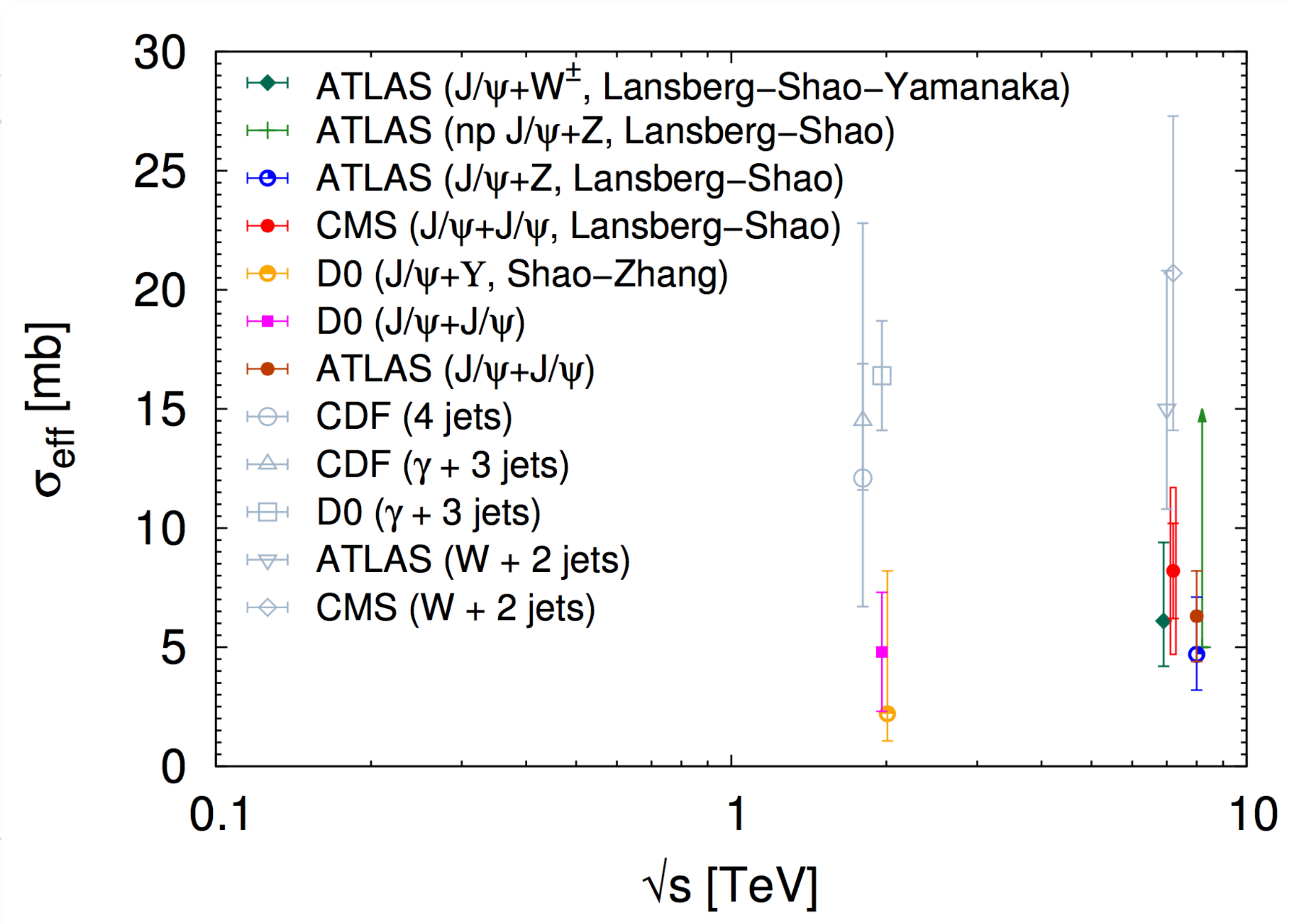
New associated production measurements reveal interesting patterns



The emergence of a puzzle in DPS

arXiv:1707.04350

New associated production measurements reveal interesting patterns

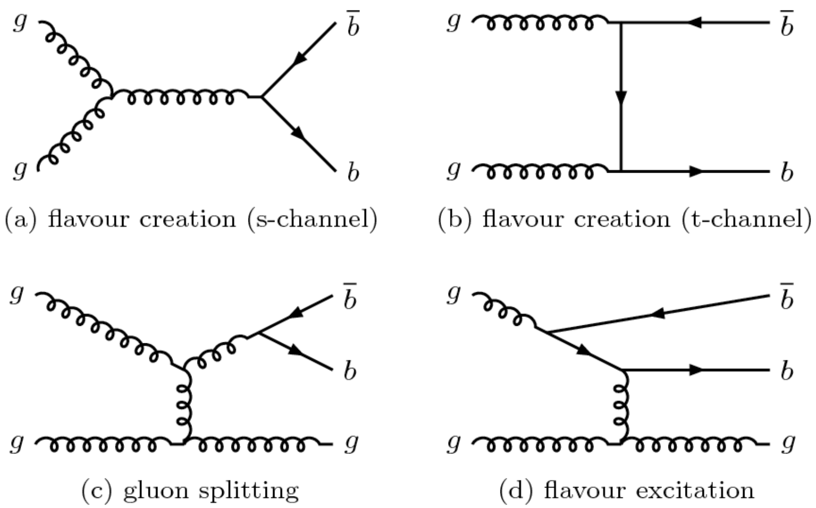


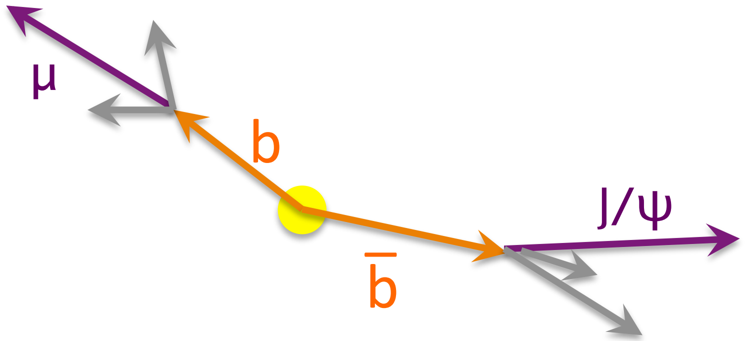
Finally seeing breakdown of basic picture of double parton interactions?

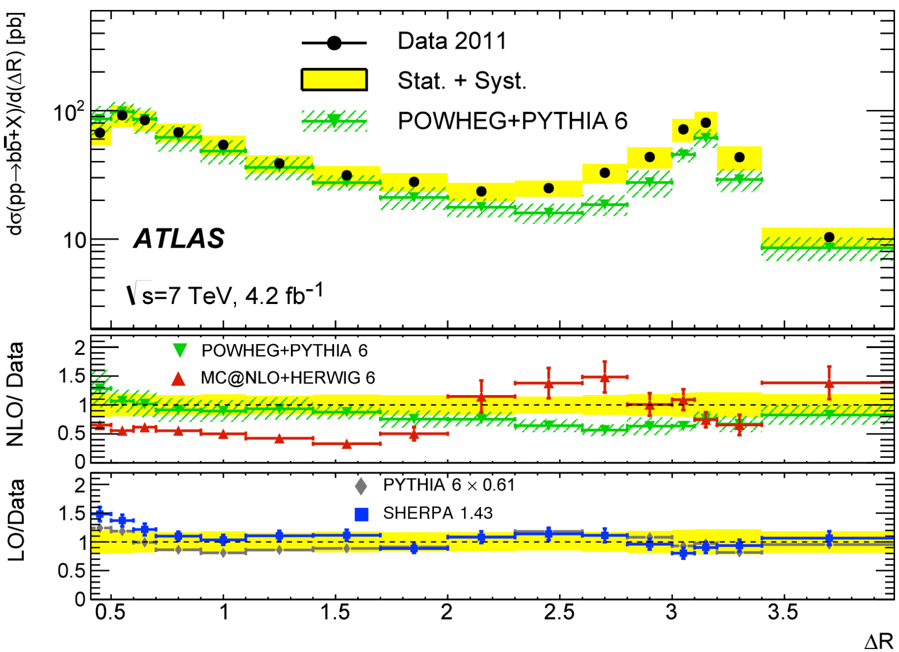
$b\bar{b}$ correlations

arXiv:1705.03374; JHEP

Study bb~ production with J/ψ+μ final states (as proxy for the b)





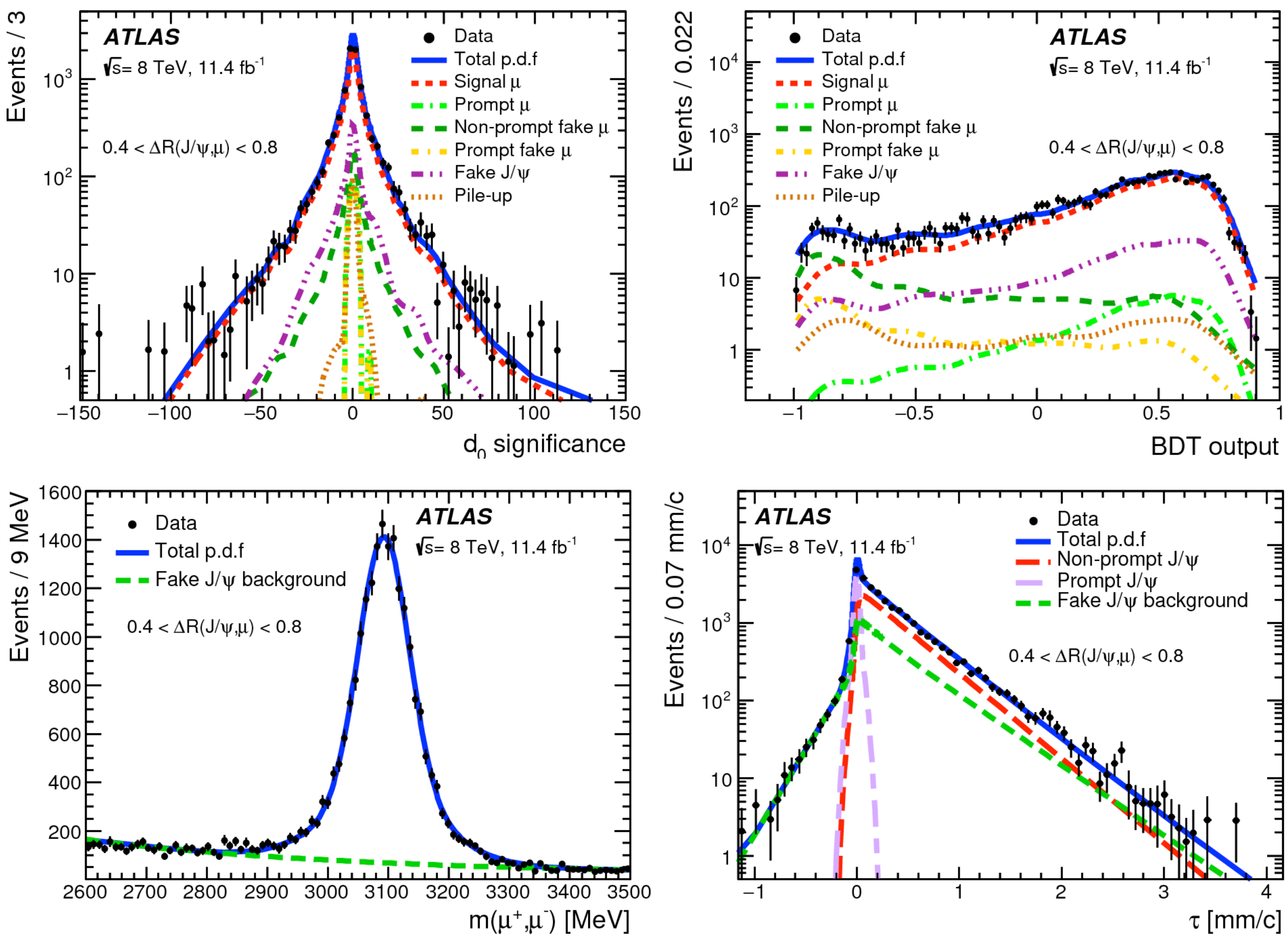


Driven by restrictions on probing b-production modelling issues with jets:

bb production: isolating signal

arXiv:1705.03374; JHEP

Simultaneous fit to d_0 significance / BDT output (*trained against instrumental backgrounds*) for signal third muon yields in high-lifetime J/ψ selection



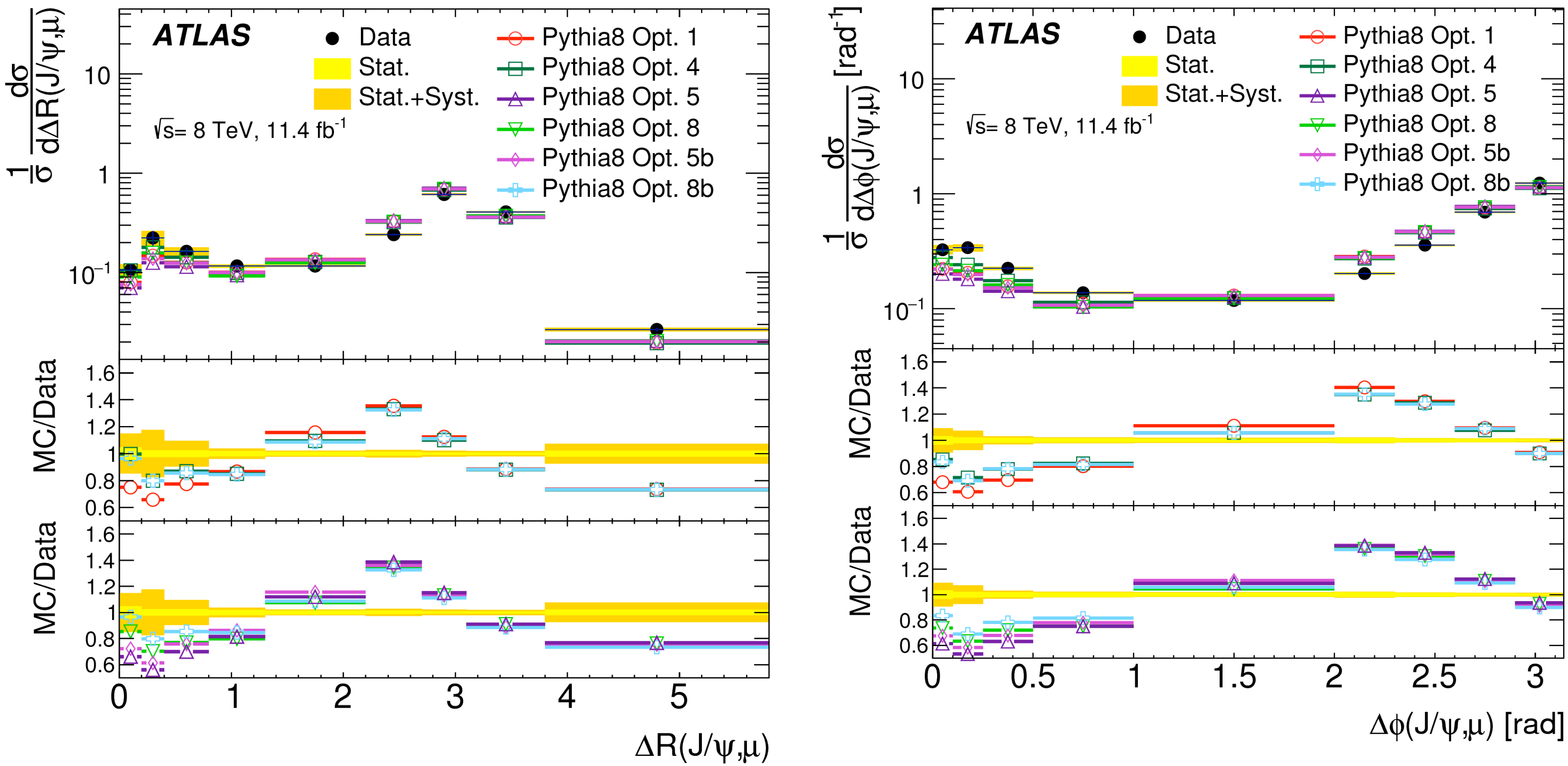
bb production: Pythia model comparison

arXiv:1705.03374; JHEP

Differential rates compared to Pythia with different gluon splitting parameters

Pythia8 does not reproduce shapes of the angular distributions very well

p_T-based splitting kernels give a better description at low ΔR (options 1,4)



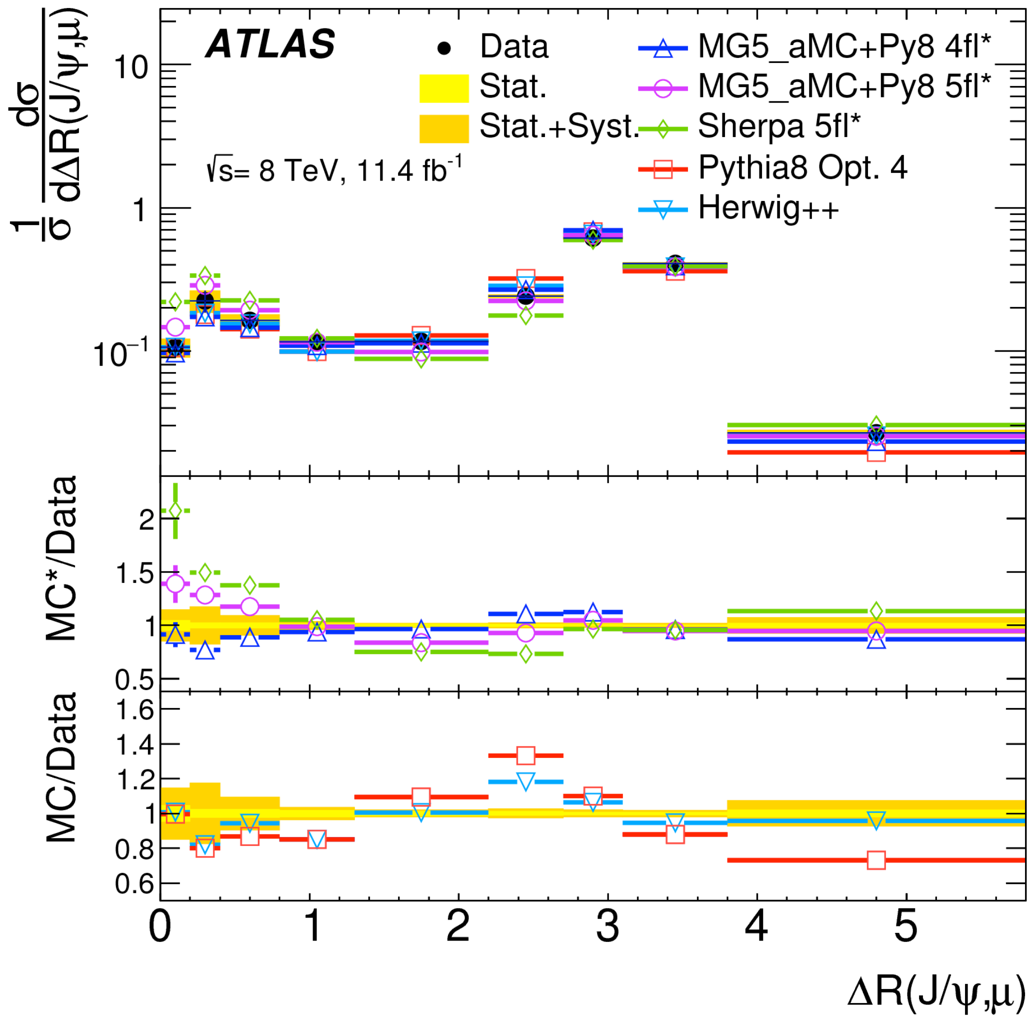
bb production: MC comparison

arXiv:1705.03374; JHEP

Herwig++ generally better description than Pythia8

MG5_aMC 4-flavour and 5-flavour sit on either side of the data

4-flavour closer in shape to the data



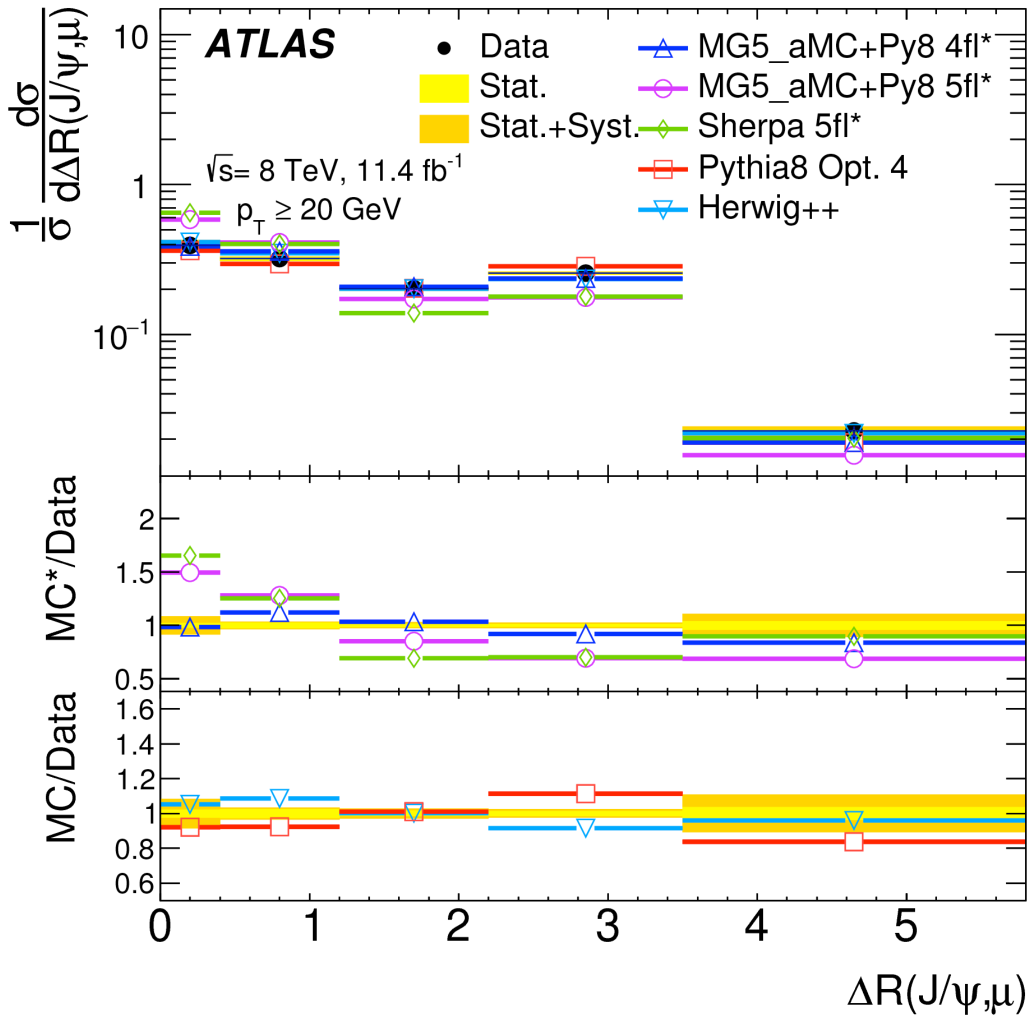
bb production: MC comparison

arXiv:1705.03374; JHEP

Probing higher p_T:

Differences between MF5 4-flavour and MG5 5-flavour emphasised

MG5 5-flavour moving further from data (and similar to Sherpa)



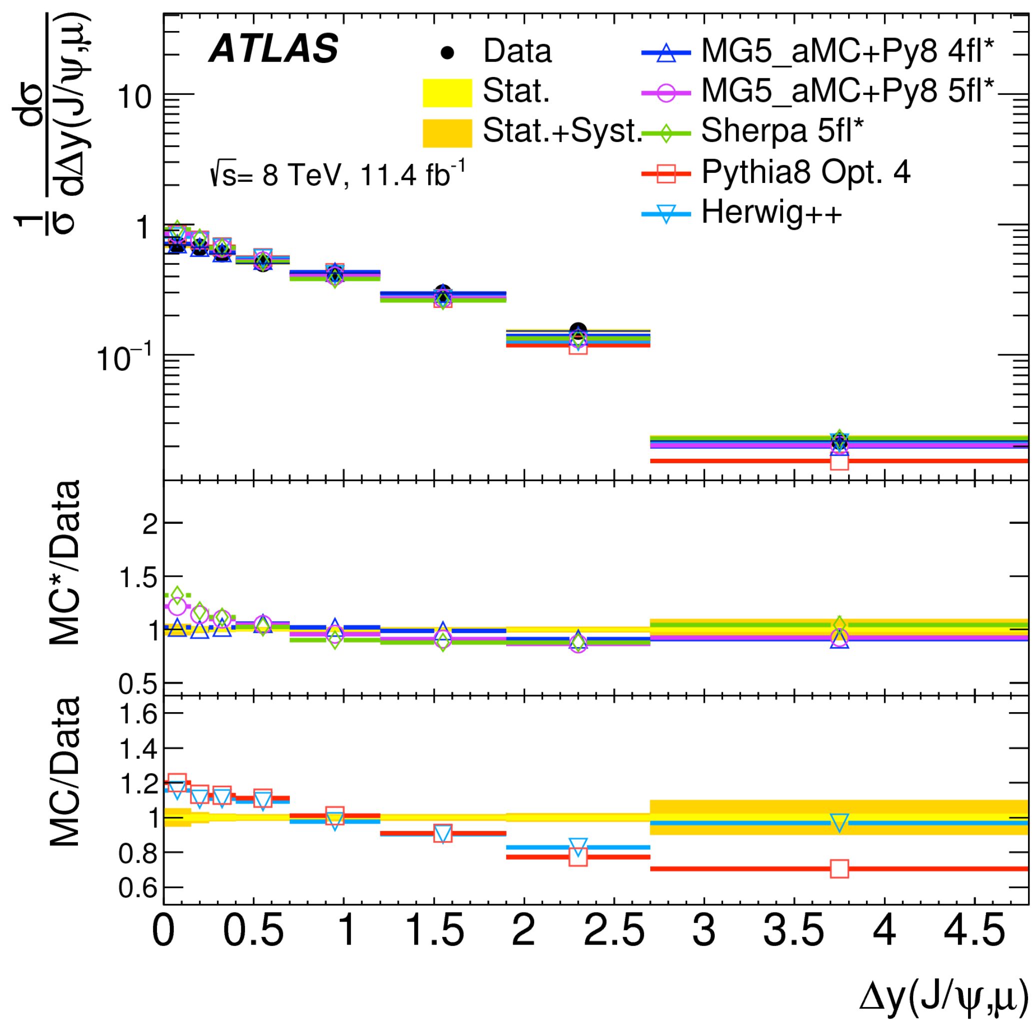
bb production: MC comparison

arXiv:1705.03374; JHEP

For Δy MG5 and Sherpa both give a good description

Herwig++ and Pythia perform poorly as Δy increases

No single generator is able to well-describe all bb spectra studied (more in paper): best overall MG5_aMC 4-flavour



Outlook and future perspectives

Associated production measurements at ATLAS have a positive outlook: robust against trigger rate / pile-up constraints

Aside from tests of QCD production, and DPS, interesting "spin-offs" possible!

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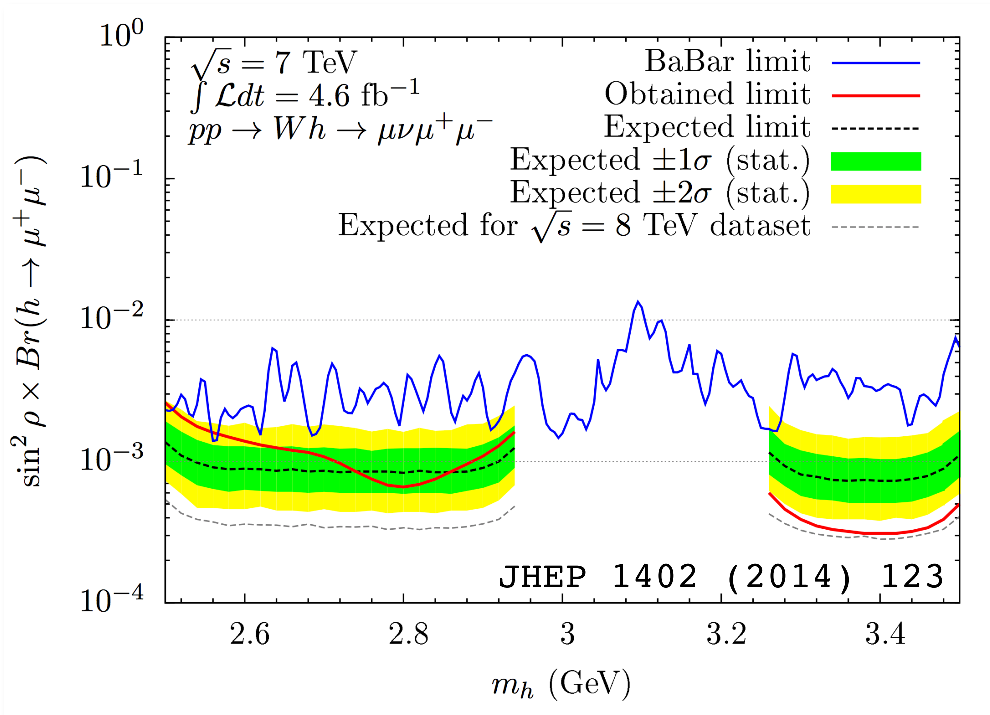
Associated light scalar Higgs boson mixing with SM Higgs (W+J/ψ):



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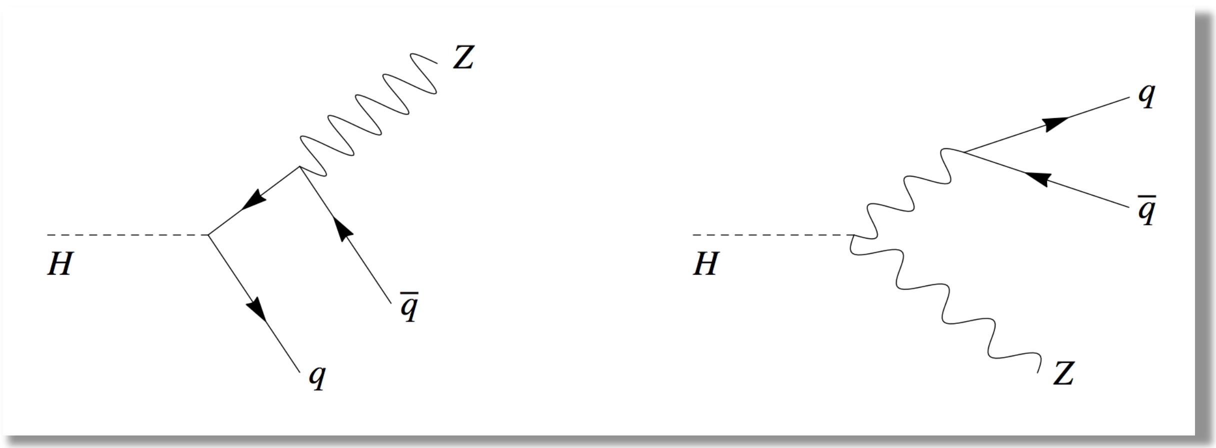
Rare Higgs decays: direct probe of quark Yukawa couplings (Z+J/ψ):



e.g. arXiv:1407.0695, arXiv:1406.7102

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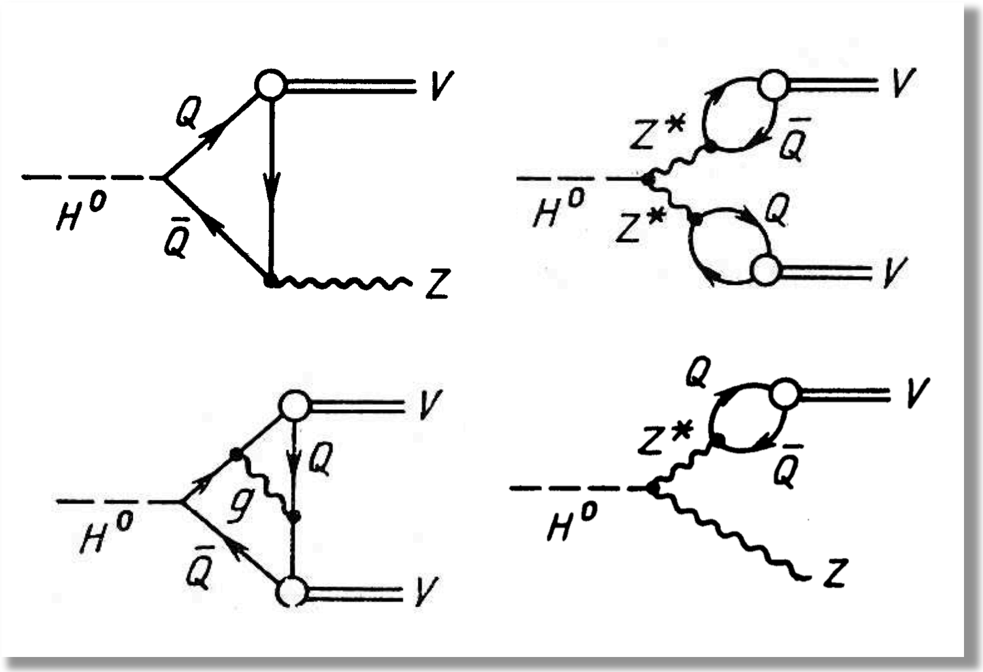
New light states with rare quarkonia decays (Z+J/ψ, di-J/ψ):



Yad. Fiz. 46 (1987) 864–868.
[Sov. J. Nucl. Phys.46,493(1987)].

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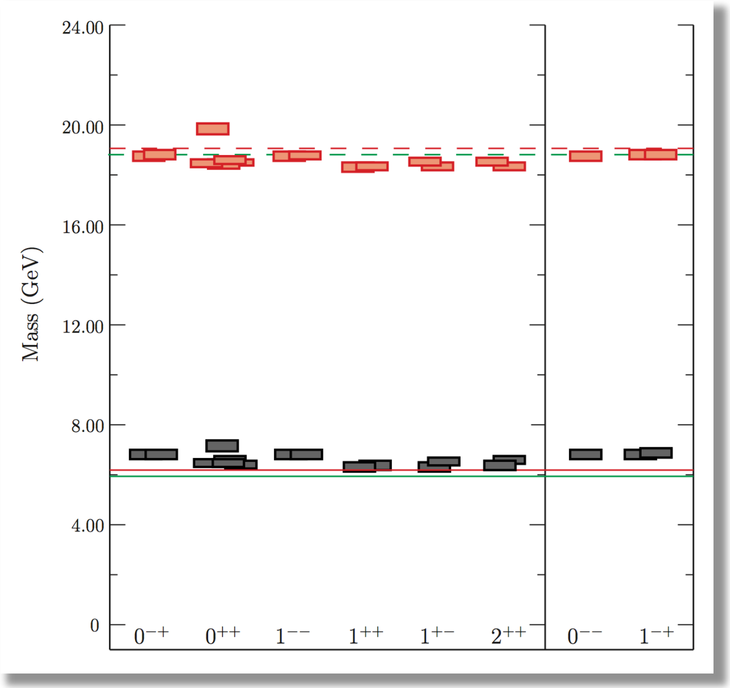
Predict rich spectroscopy of exotic doubly-hidden charm/beauty tetraquarks



e.g. arXiv:1611.00348, arXiv:1605.01647

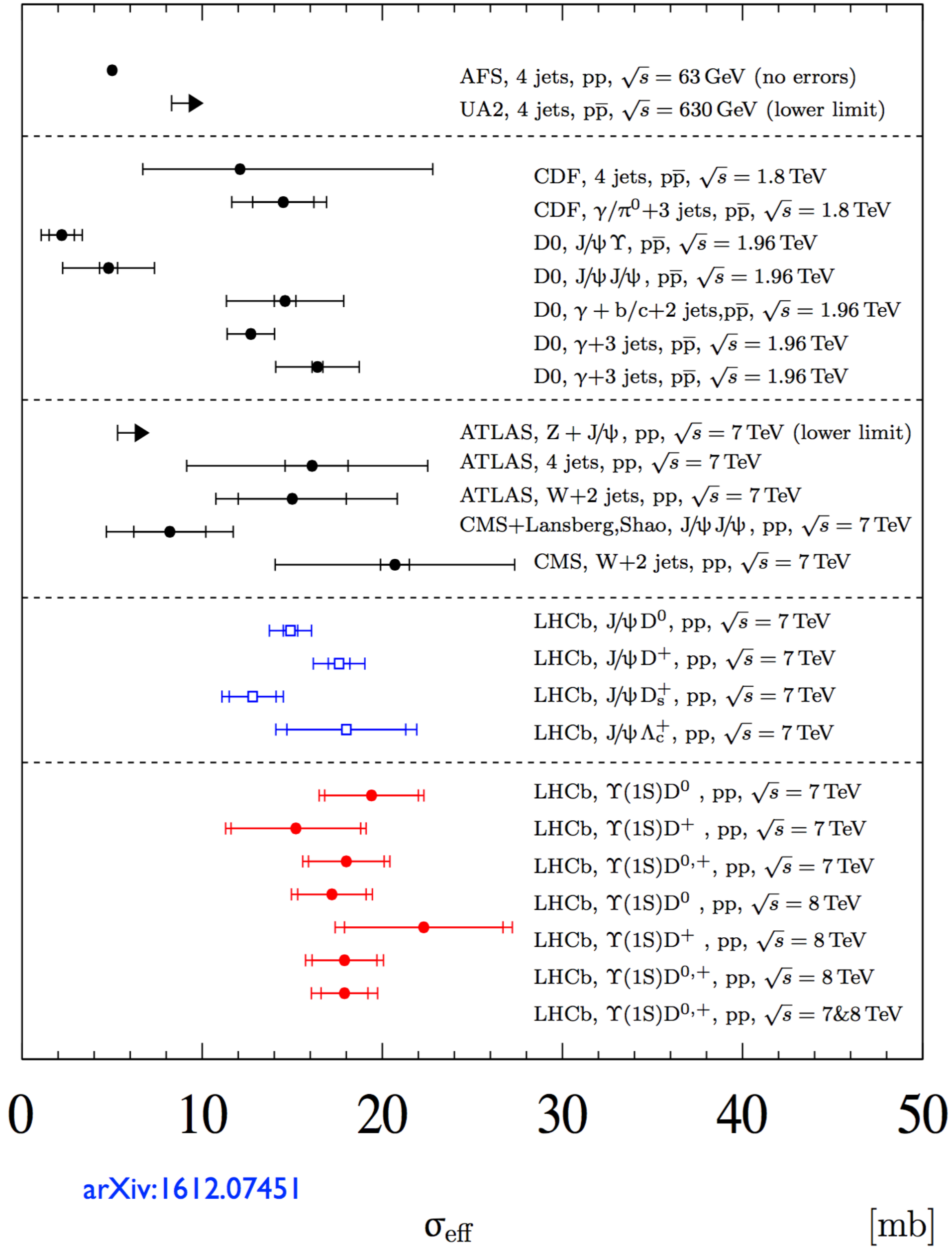
Conclusions

Associated production of heavy flavour a (relatively) rare process that ATLAS is well-suited to explore:

- New tests of QCD HF calculations
- Novel probes of aspects proton structure
- Complementary tests of W/Z+b-quark production
- Future sensitivity to rare decays of Higgs, new light scalars, quark Yukawa couplings, exotic tetraquarks…

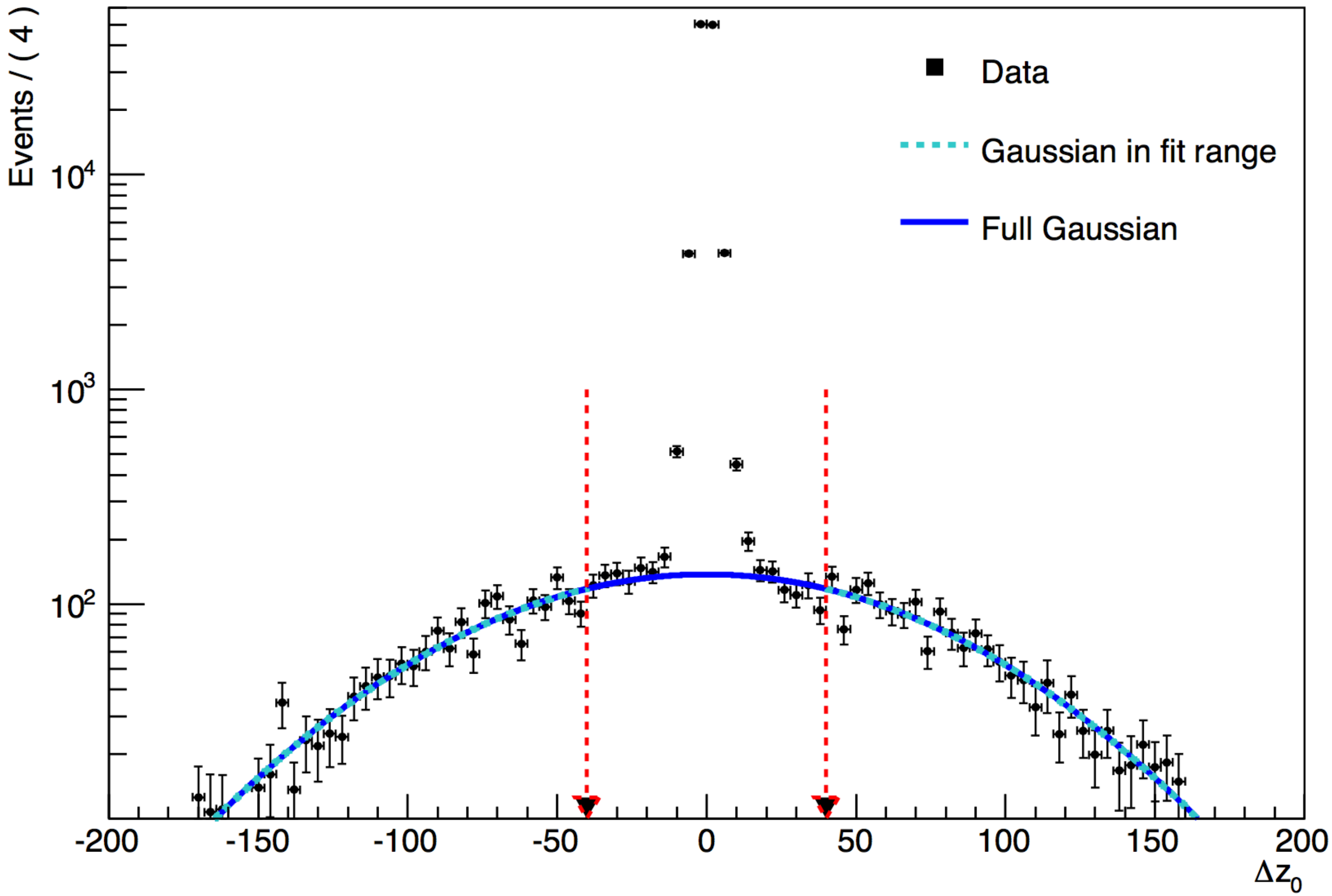
Backup

DPS



arXiv:1612.07451

Pile-up


Events / (4)
10^4
10^3
10^2
Data
Gaussian in fit range
Full Gaussian
-200
-150
-100
-50
0
50
100
150
200
Δz_0