V+J/ψ Production at ATLAS

Peter Onyisi

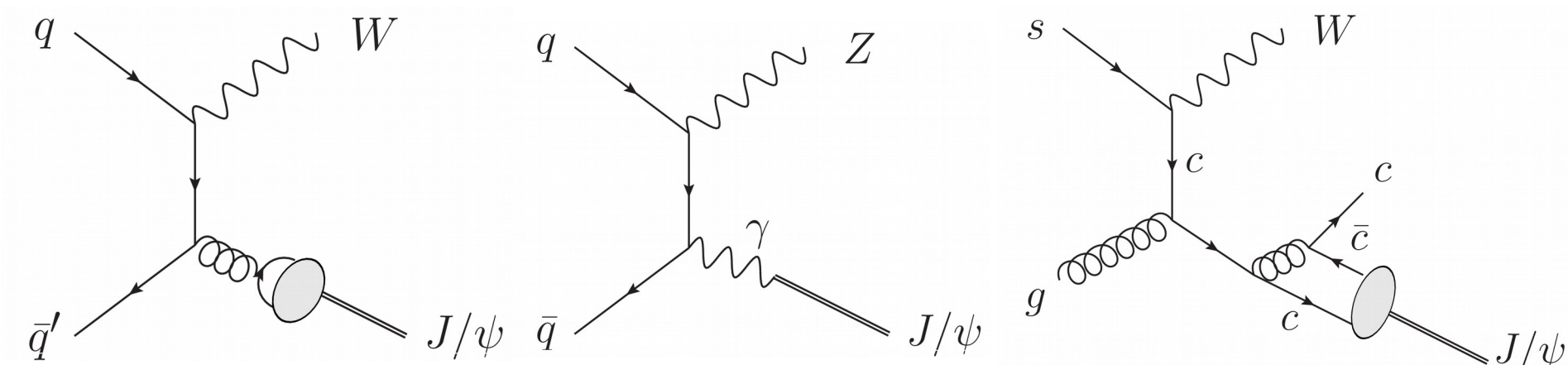
QWG, 7 June 2016

TEXAS
The University of Texas at Austin

ATLAS
EXPERIMENT

Introduction

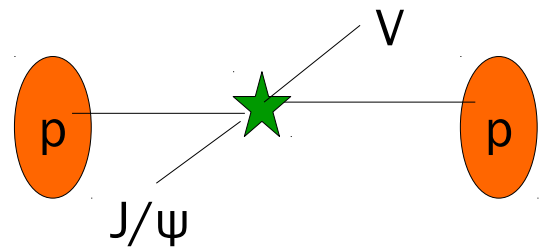
- Associated production of (W/Z) + J/ψ provides interesting information complementary to more inclusive J/ψ modes
  - vector boson production "filters" for $q\bar{q}$ initial state
  - can probe for double parton scattering
  - non-prompt yield is indirect measure of *b*-hadron production
- Will show results for
  - Z+J/ψ @ 8 TeV, 20.3 fb^{-1} [EPJ C75 229 (2015)]
  - W+J/ψ @ 7 TeV, 4.5 fb^{-1} [JHEP 04(2014) 172]



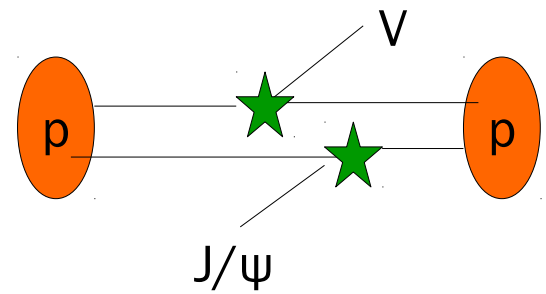
Color octet ($\alpha_s^2\alpha$) Color singlet (α^3) Color singlet ($\alpha_s^3\alpha$)

Contributions

- Single parton scattering

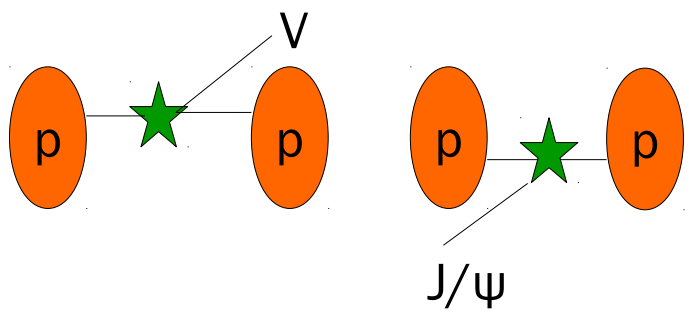


- Double parton scattering



real V + prompt J/ψ

- Pileup



- V+b: in particular t ⟶ Wb
- Fake V: in particular fake W candidates
- Combinatorics

Experimental Method

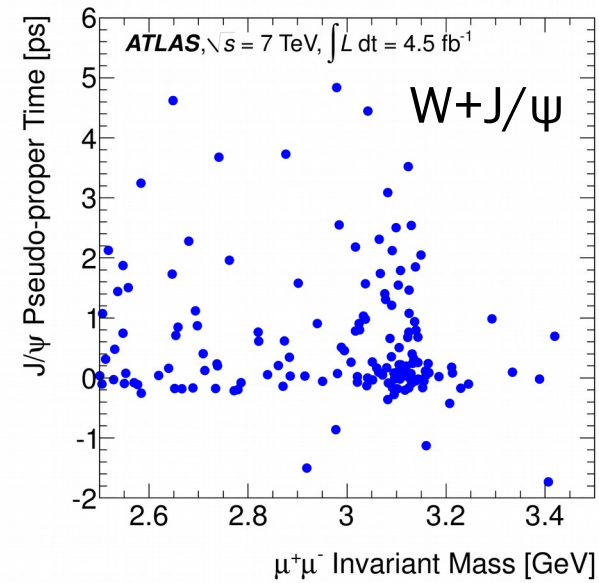
- Reconstruct $J/\psi \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ or $Z \rightarrow (\mu\mu, ee)$.
  - Trigger events on high-p_T leptons from W and Z (unprescaled)
  - Require all tracks consistent with production in the same *pp* collision
- Fit for prompt & non-prompt J/ψ yields
  - use information to confirm real W or Z production
- Apply acceptance/efficiency corrections
- Estimate various background/signal contributions

Reconstruction

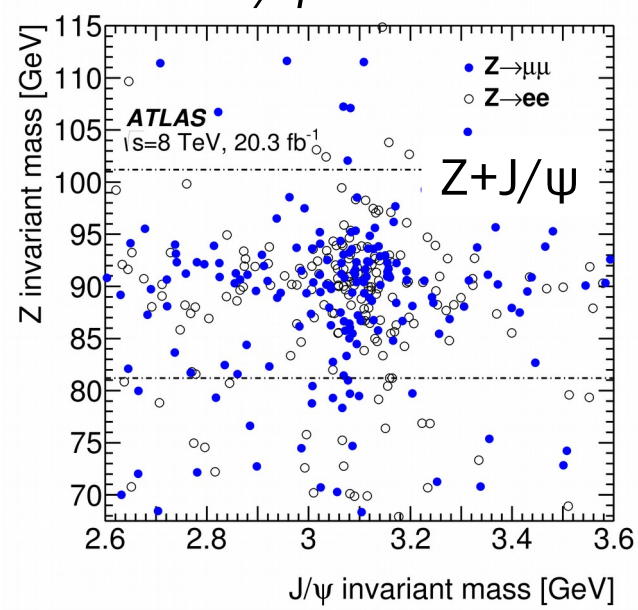
- Merge "high-" and "low-p_T" techniques (MET, vertexing, ...)
- For J/ψ muons, use multiple muon reconstruction techniques to gain efficiency at low p_T

$$\tau := \frac{L_{xy} m^{J/\psi}}{p_T^{J/\psi}}$$

J/ψ displacement vs mass



Z vs J/ψ masses

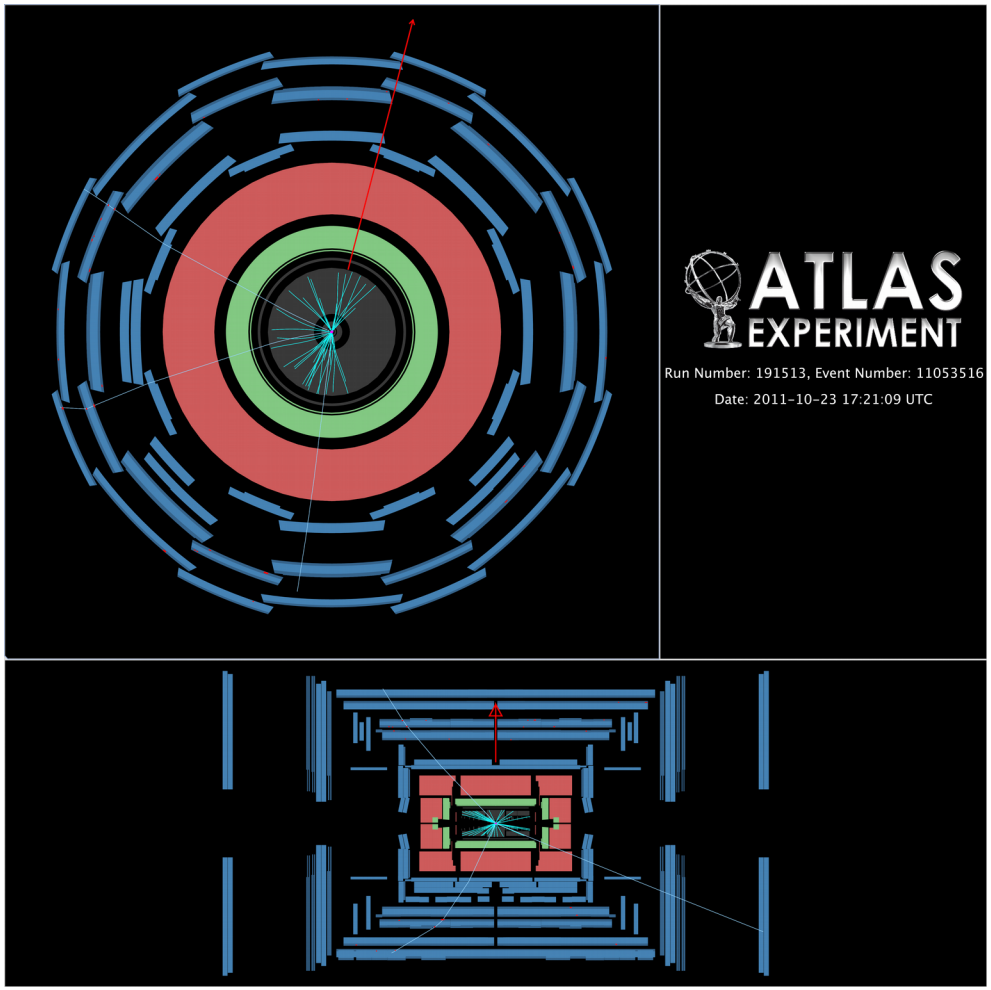


Selections for Z+J/ψ analysis

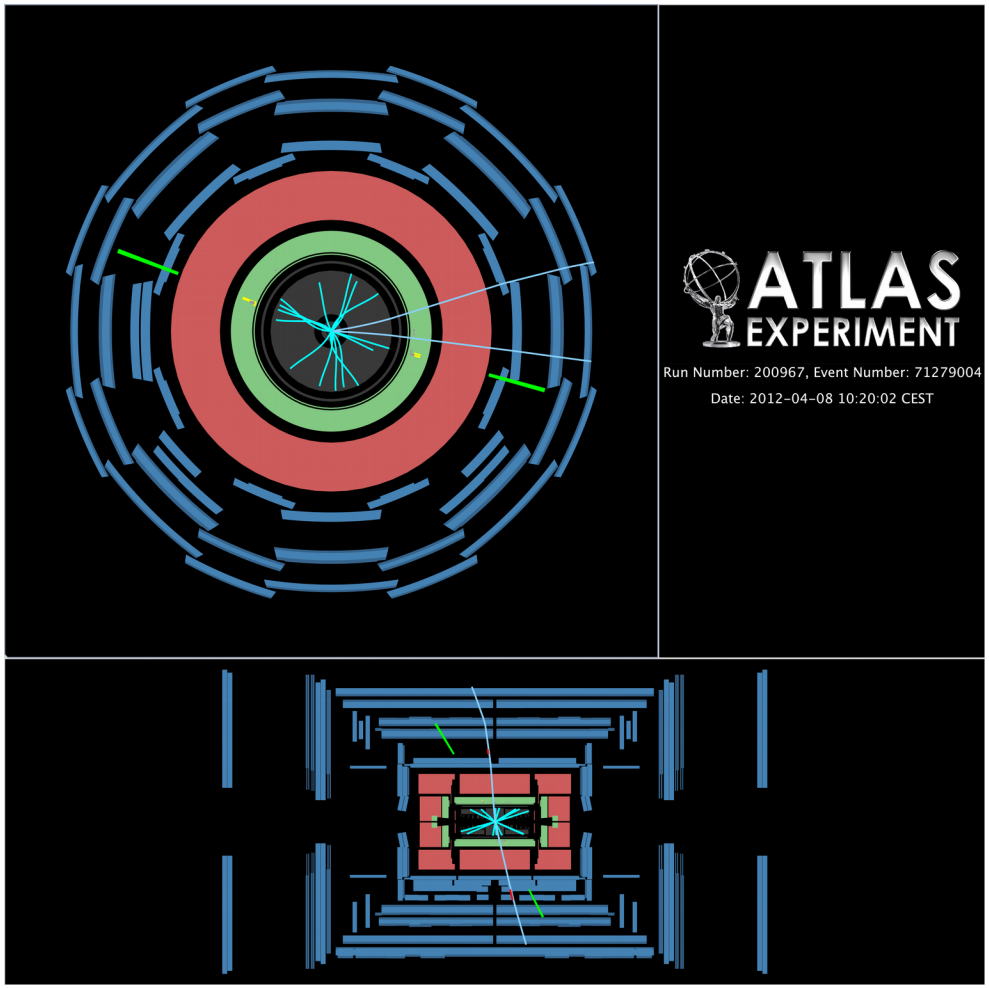
Z boson selection
p_T (trigger lepton)> 25 GeV, p_T (sub-leading lepton)> 15 GeV
$\lvert\eta(\text{lepton from } Z)\rvert < 2.5$
$\lvert m^Z - 91.1876 \text{ GeV}\rvert < 10$ GeV
J/ψ selection
$2.6 < m^{J/\psi} < 3.6$ GeV
$8.5 < p_T^{J/\psi} < 100$ GeV, $\lvert y_{J/\psi}\rvert < 2.1$
p_T (leading muon)> 4.0 GeV, $\lvert\eta(\text{leading muon})\rvert < 2.5$
either p_T (sub-leading muon)> 2.5 GeV, $1.3 \leq \lvert\eta(\text{sub-leading muon})\rvert < 2.5$
or p_T (sub-leading muon)> 3.5 GeV, $\lvert\eta(\text{sub-leading muon})\rvert < 1.3$

Event Displays

$W\ (\rightarrow \mu\nu) + J/\psi\ (\rightarrow \mu\mu)$



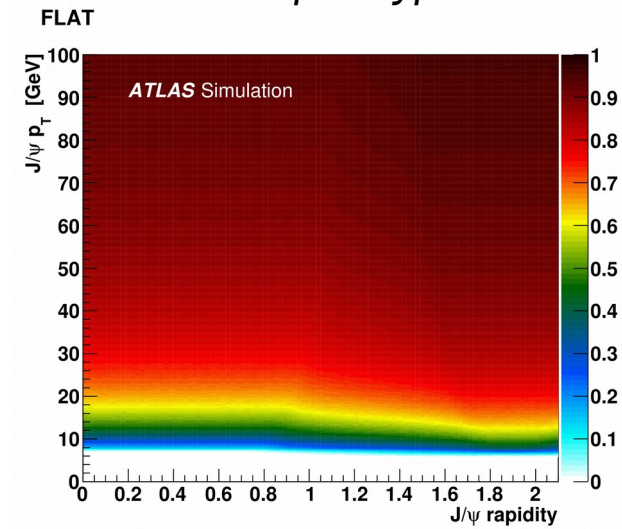
$Z\ (\rightarrow ee) + J/\psi\ (\rightarrow \mu\mu)$

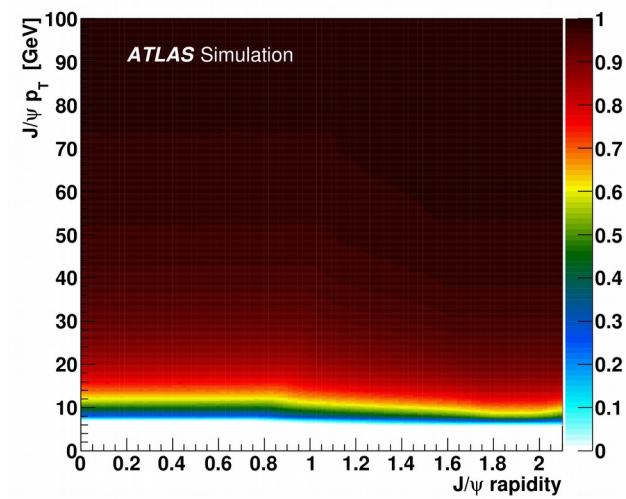


Efficiency/Acceptance Corrections

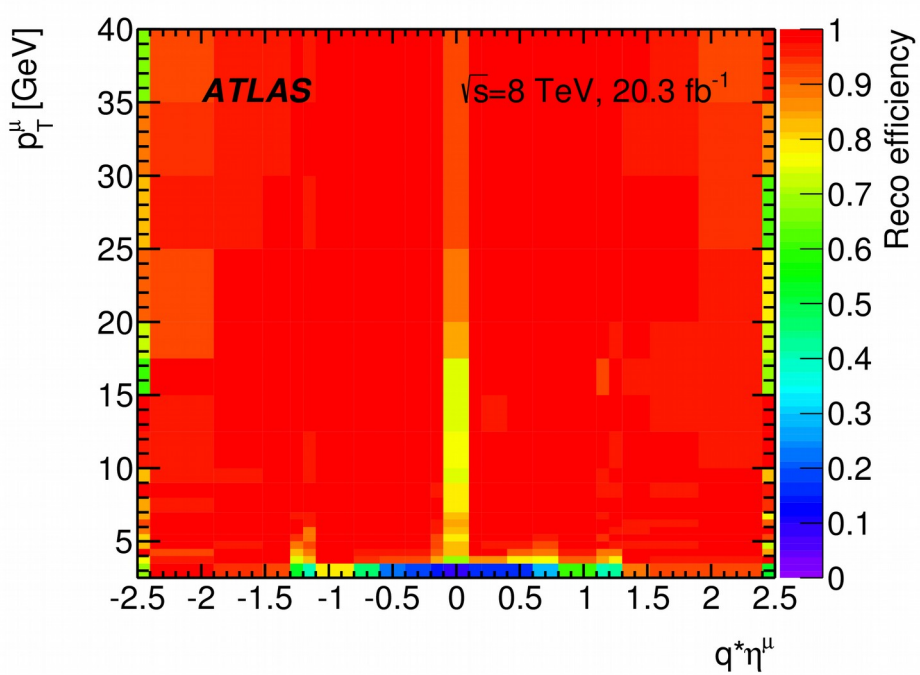
- Measure both *fiducial* and *inclusive* cross sections for $p_T(J/\psi) > 8.5$ GeV
  - Fiducial: μ within detector acceptance, only efficiency corrections applied
  - Inclusive: extrapolate to unobserved μ, needs J/ψ spin assumptions

J/ψ acceptance maps different spin hypotheses





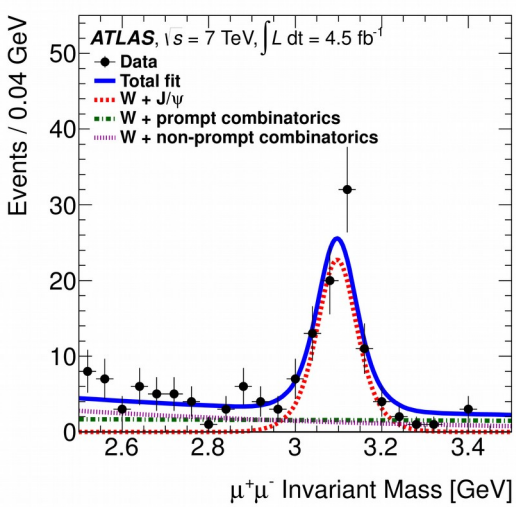
μ efficiency map, combined+segment tagged



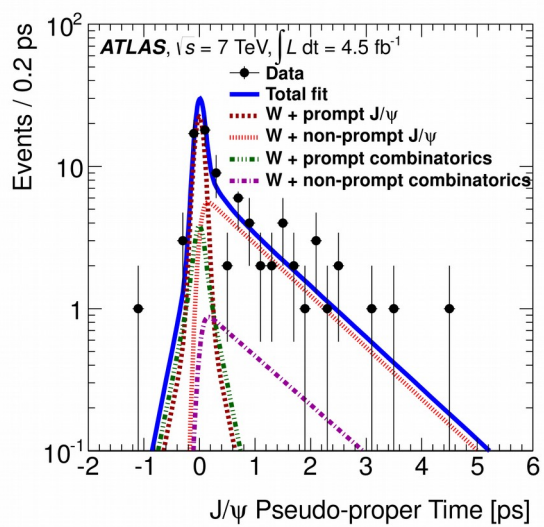
$$\frac{d^2N}{d\cos\theta^\star\, d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

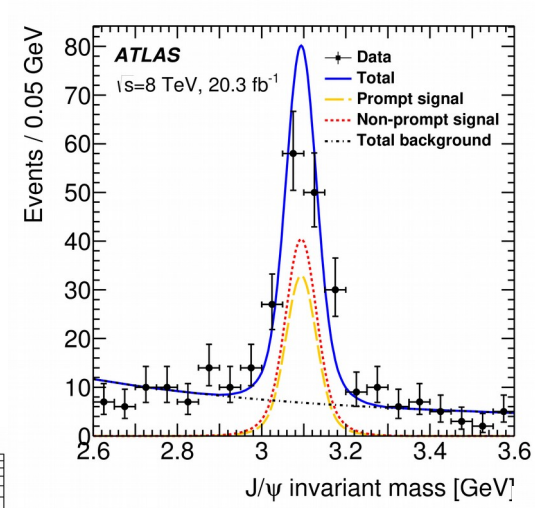
Fitting J/ψ Candidates

- Fit candidate mass and vertex position
  - separate prompt J/ψ, non-prompt J/ψ, and combinatoric bkg
- Unbinned likelihood fit lets us use sPlot to weight events and make additional distributions



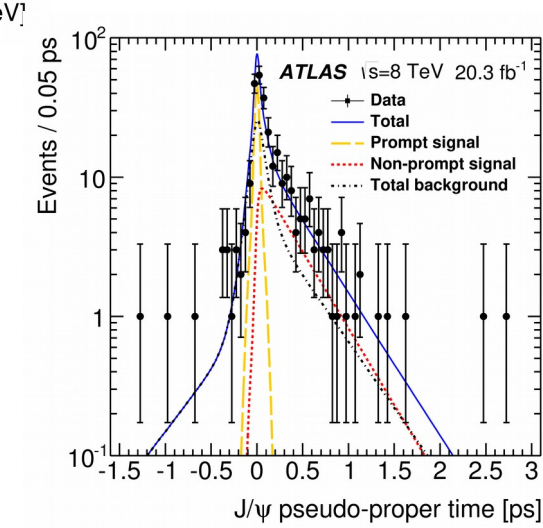
W+J/ψ





sPlot: Pivk & Le Diberder NIM A555, 356

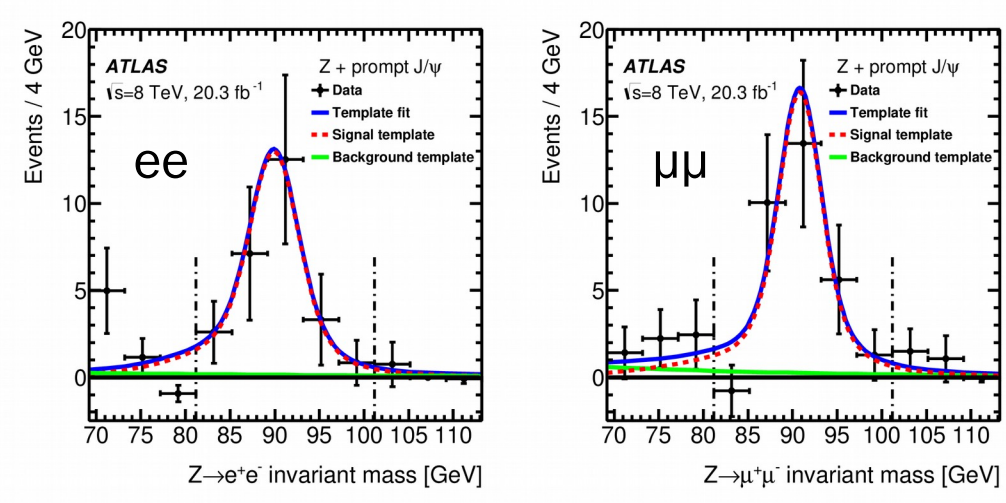
Z+J/ψ



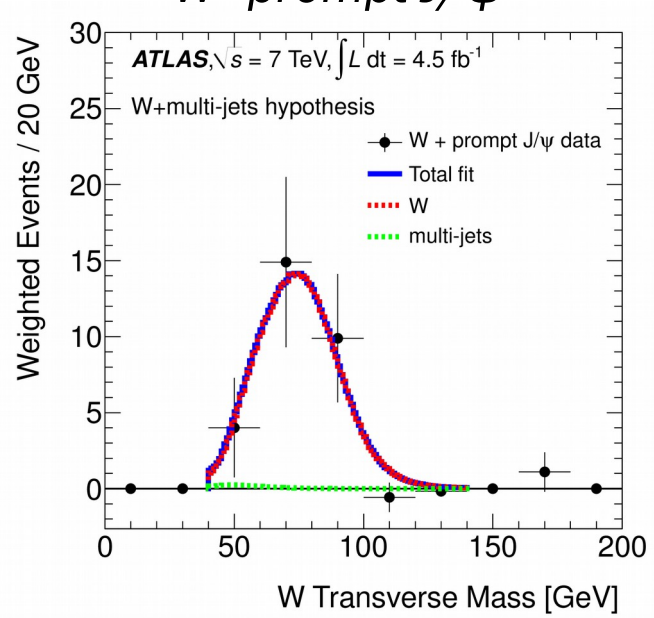
Evidence for Vector Bosons

- Use sPlot weights to project $M(\ell\,\ell)$ [for Z] or $M_T(\mu, \text{MET})$ [for W]
- >5σ evidence for W+prompt J/ψ, Z+prompt J/ψ, Z+non-prompt J/ψ

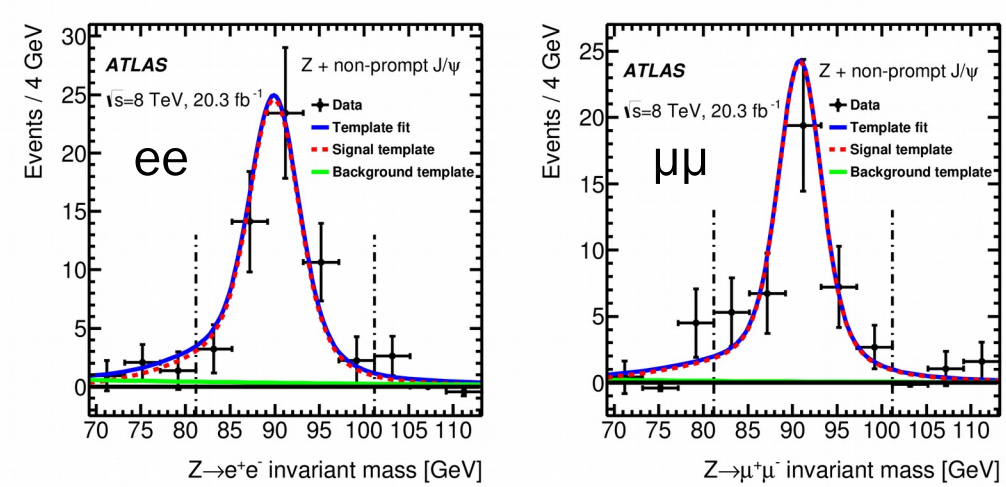
Z+prompt J/ψ



W+prompt J/ψ

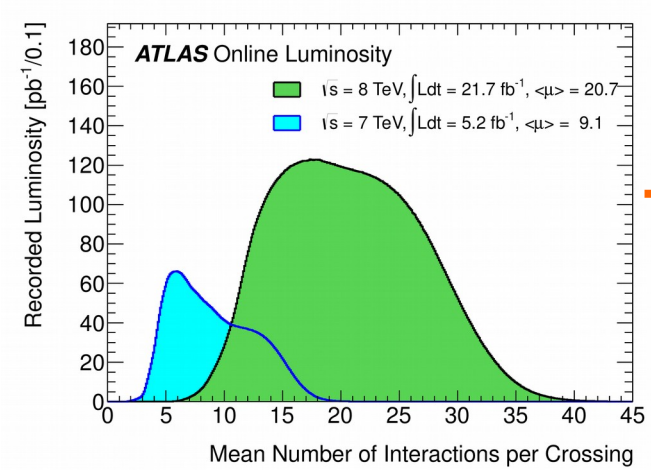


Z+non-prompt J/ψ



Backgrounds: Pileup

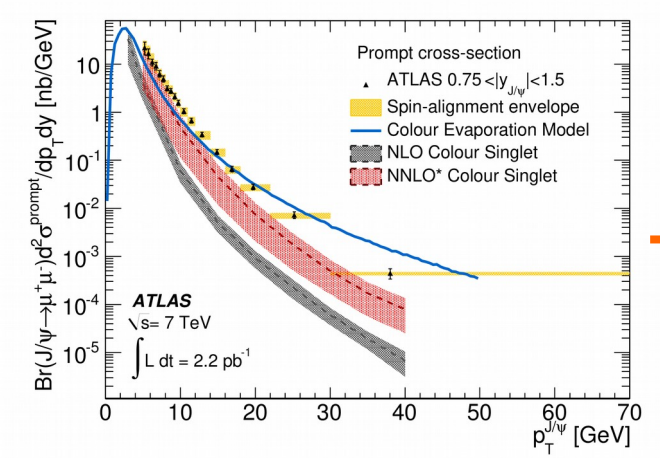
- Multiple *pp* collisions per bunch crossing; non-zero chance of overlapping *pp* → W and *pp* → J/ψ in same BC
- Use known pileup profiles & cross sections to estimate how often two collisions are so close we confuse them



avg # of extra vertices within 1cm of primary:

7 TeV [W] = 0.81 ± 0.08
8 TeV [Z] = 2.3 ± 0.2

ATLAS
Nucl Phys B
850 387 (2011)



events due to pileup:

W+prompt: 1.8 ± 0.2
Z+prompt: $5.2^{+1.8}_{-1.3}$
Z+non-prompt: $2.7^{+0.9}_{-0.6}$

Double Parton Scattering

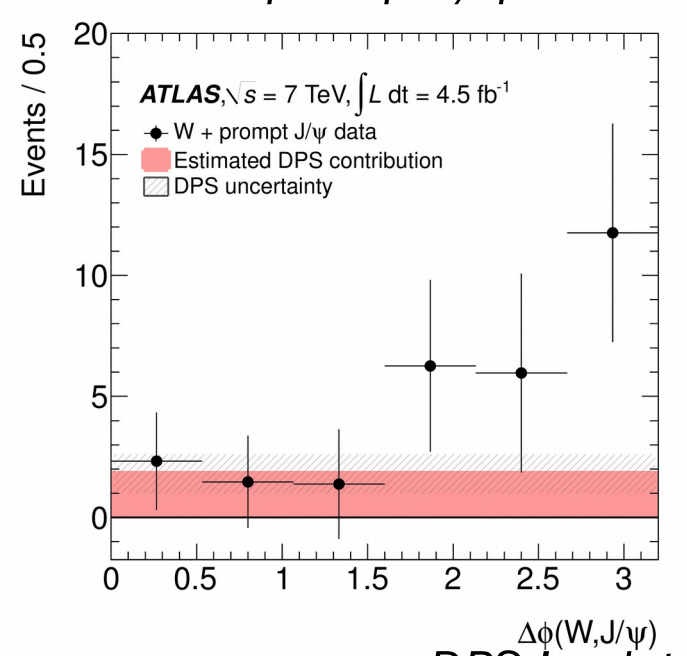
- Indistinguishable event-by-event from single parton scattering
- Use a factorization formalism to estimate contribution

$$\sigma_{V+J/\psi,\mathrm{DPS}} = \frac{\sigma_V \sigma_{J/\psi}}{\sigma_{\mathrm{eff}}}; \qquad \sigma_{\mathrm{eff}} = 15 \pm 3(\mathrm{stat})^{+5}_{-3}(\mathrm{sys})\ \mathrm{mb}$$

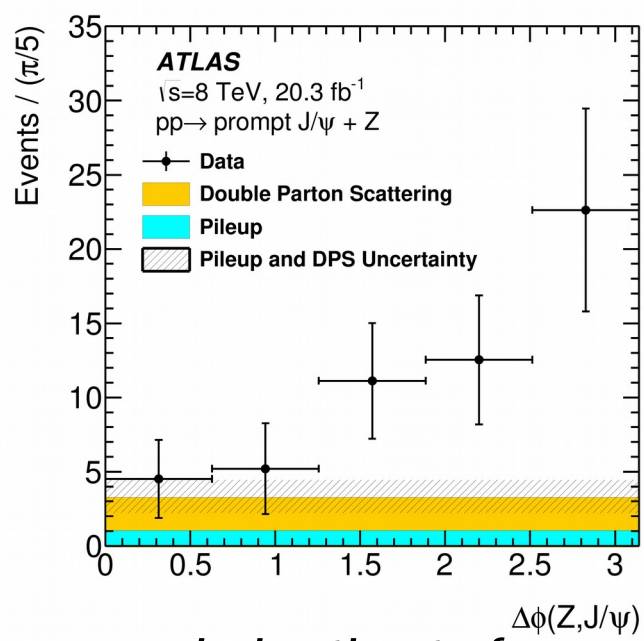
input from W+2jet measurement

- Assuming scatters are uncorrelated, expect DPS to be flat in Δφ(V, J/ψ), but SPS to be back-to-back

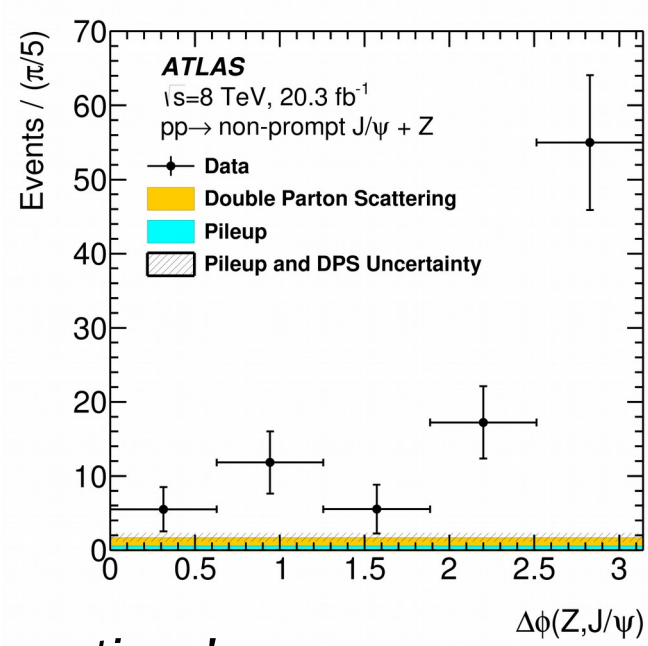
W+prompt J/ψ



Z+prompt J/ψ



Z+non-prompt J/ψ



DPS in plots is an a priori estimate from assumptions!

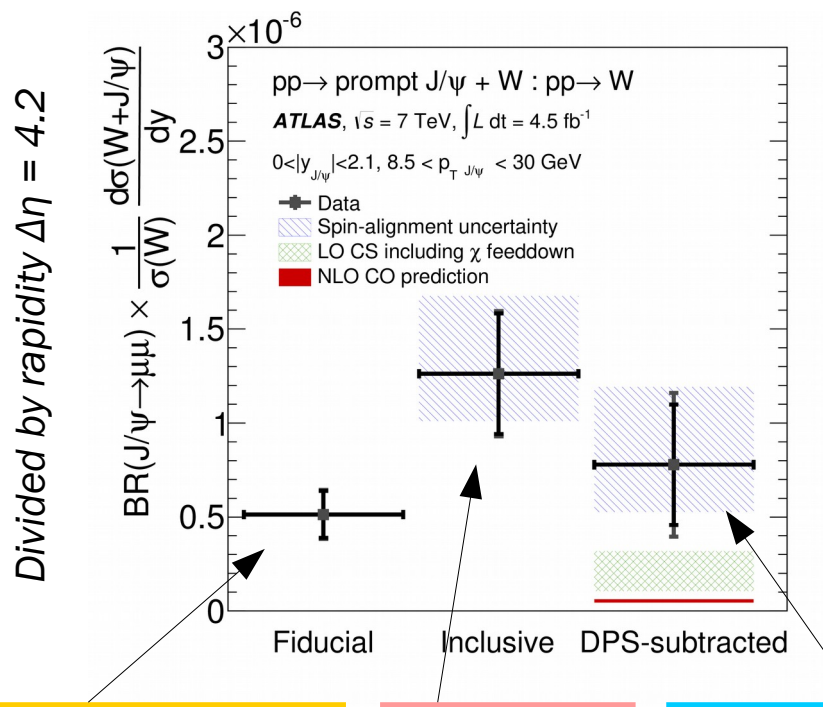
Results: W+prompt J/ψ

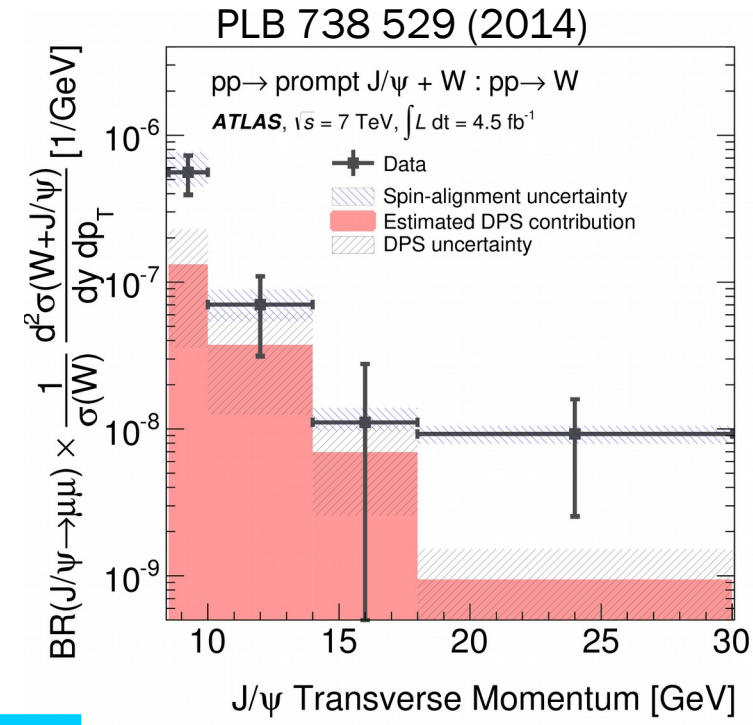
- Divide observed cross sections by σ(W) to cancel W acceptance uncertainties

Li, et al., PRD83 014001 (2011)

- Results in excess of *a priori* predictions
  - Potentially explained by missing CS diagrams

Lansberg, Lorcé, PLB 726 218 (2013); PLB 738 529 (2014)





Fiducial acceptance only
Actually measured by expt

Corrected for acceptance

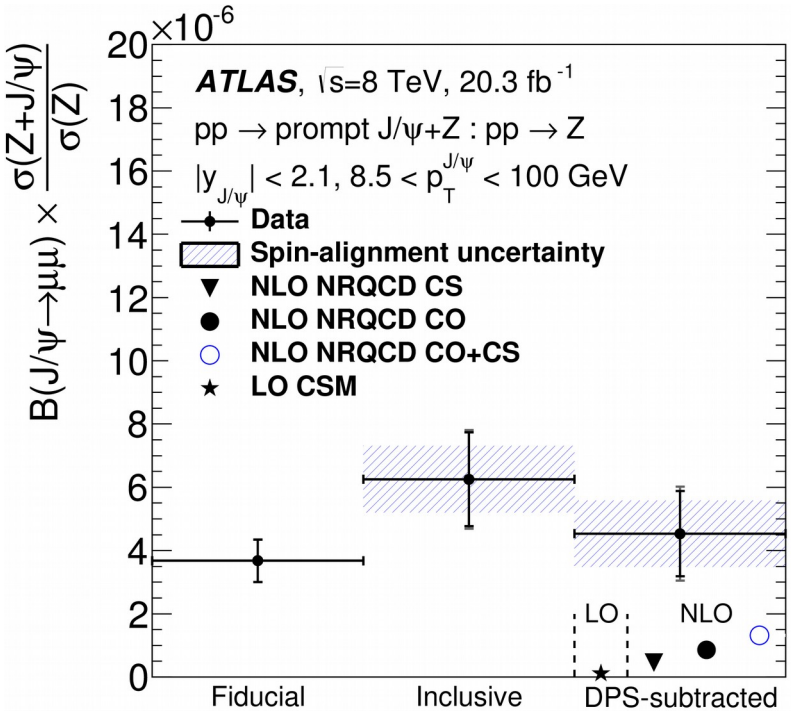
Subtract estimate of DPS cross section

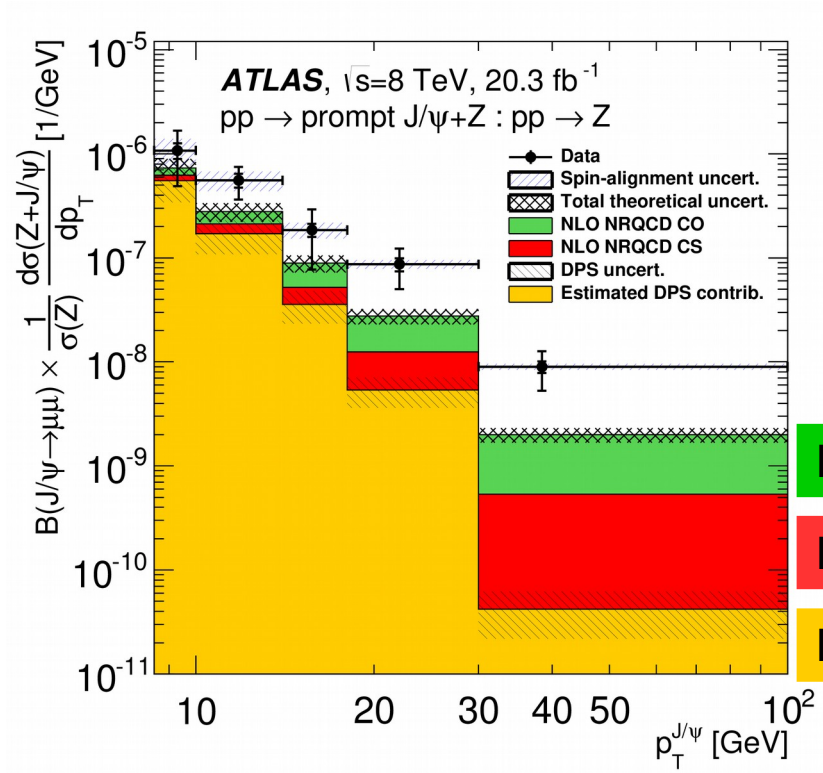
Results: Z+prompt J/ψ

- Divide by σ(Z)
- Again, excess over expectations
- Prompt events have a stiffer $p_T(J/\psi)$ spectrum than in W events?

NRQCD: Mao et al., JHEP 1102 071 (2011)
CSM: Gong et al., JHEP 1303 115 (2013)

Not divided by Δη





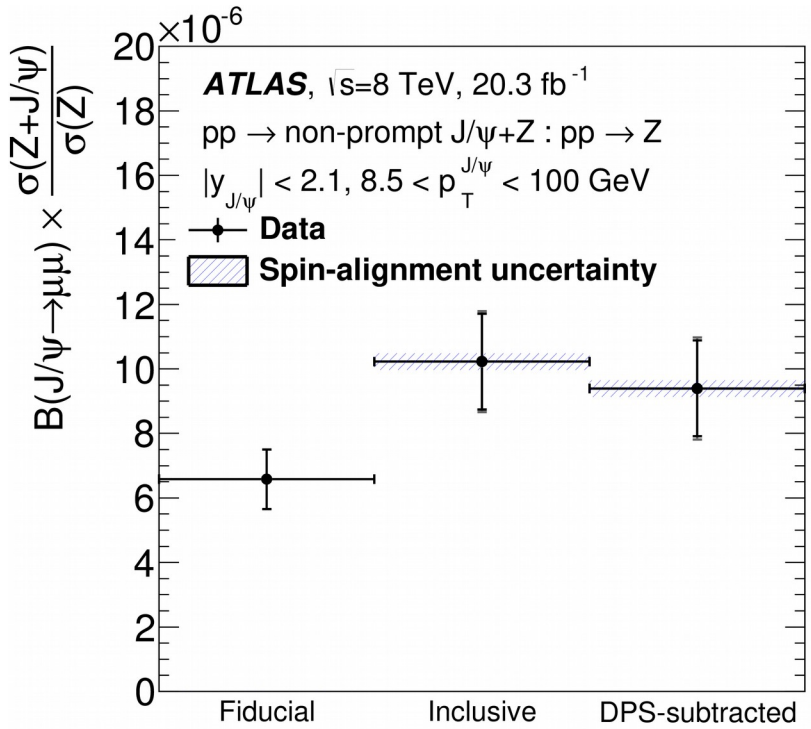
DPS+CS+CO

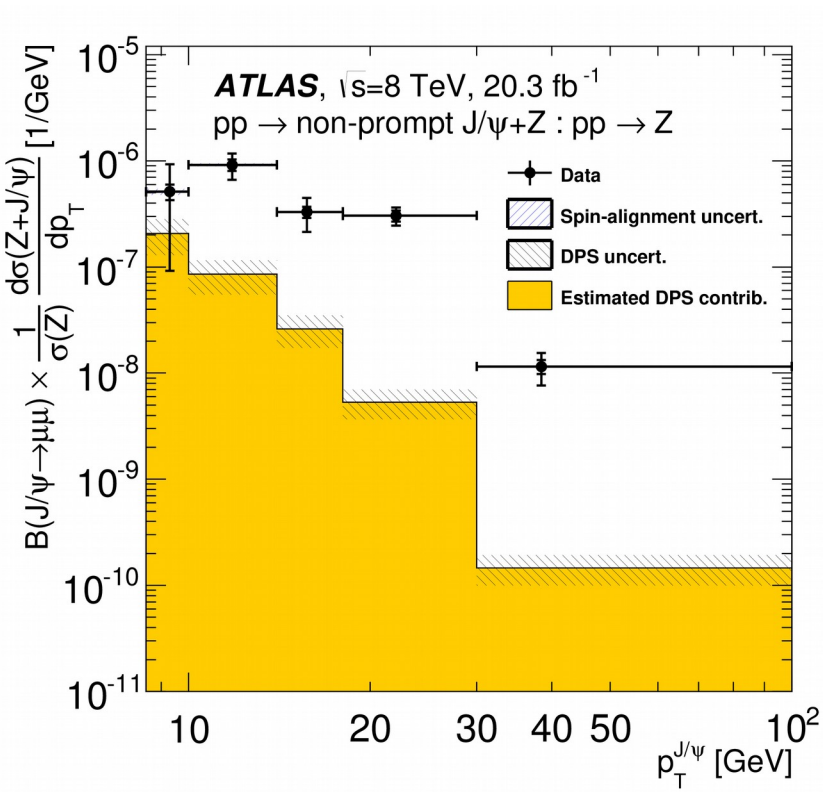
DPS+CS

DPS only

Z+non-prompt J/ψ

- Much harder spectrum ⟶ smaller acceptance corrections
- In future, could extract information on Z+b from this





Double Parton Scattering

- Estimate the DPS cross section using

$$\sigma_{V+J/\psi,\mathrm{DPS}} = \frac{\sigma_V \sigma_{J/\psi}}{\sigma_{\mathrm{eff}}}$$

where σ_{eff} is hypothesized to be universal in this regime

  - compare against ATLAS W+2j result

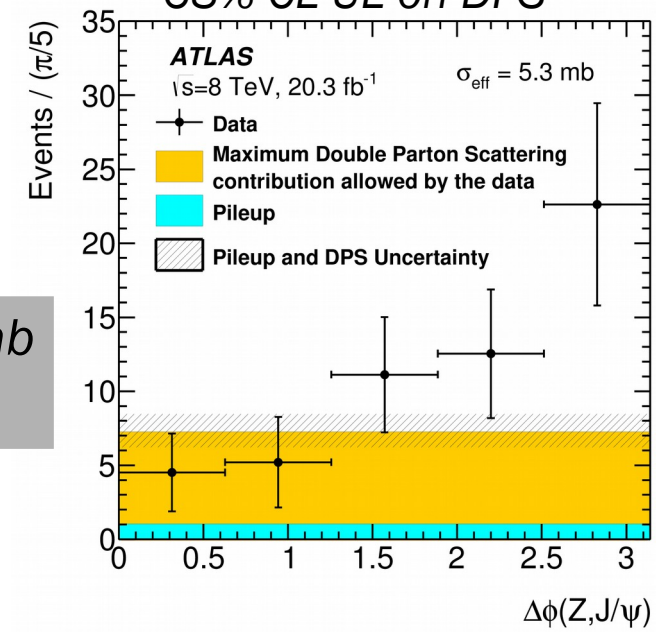
- Larger $\sigma_{eff} \rightarrow$ smaller $\sigma_{V+J/\psi,DPS}$

- Set lower limit on on σ_{eff} by letting DPS saturate the observed σ(Z+prompt J/ψ) for Δφ(Z, J/ψ) ~ 0

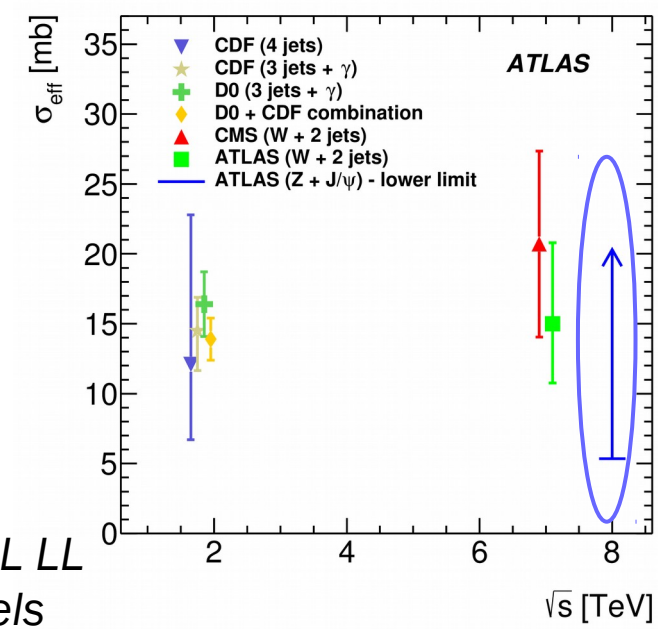
  - σ_{eff} could be even lower, but that requires azimuthal correlation between scatters

  - good predictions of SPS process will allow more reliable extraction of DPS

68% CL UL on DPS



σ_{eff} > 5.3 mb @ 68% CL



Comparison of 68% CL LL on σ_{eff} to other channels

Summary & Outlook

- Observation of associated W+J/ψ and Z+J/ψ provides constraints on quarkonium production models & double parton scattering
  - for $p_T(J/\psi) > 8.5$ GeV and $|\eta_{J/\psi}| < 2.1$, rate is a 3-4 x 10^{-6} of the total W and Z production rate
- These analyses are statistically limited
  - can trigger on W and Z, so mostly unaffected by trigger evolution for Run 2 and beyond
  - more stats ⟶ further differential measurements
  - systematics dominated by unknown acceptance near threshold
- Better models for V+J/ψ SPS production needed
  - improve DPS understanding
  - reduce acceptance errors