Associated quarkonium production at ATLAS as a new probe of QCD

David Bertsche – The University of Oklahoma
for the ATLAS Collaboration

QCD@LHC, Queen Mary University of London
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The University of Oklahoma

Motivation

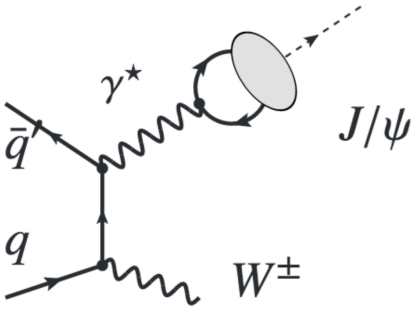
Quarkonium production measurements usually focus on **inclusive** sample properties

- e.g. spin alignment, differential cross sections

The high luminosities available at the LHC make it possible to study the **rare** process of quarkonia in **association** with other particles

- e.g. other quarkonia, vector bosons, jets, top, …

Example of colour-singlet J/ψ + W production
arxiv:1303.5327



There are two possible associated production modes

- **Single Parton Scattering**: particles come from the same hard scatter
- **Double Parton Scattering**: particles come from two hard scatters within the same proton collision

Important experimental motivation for ATLAS

- We can parasitically use a high bandwidth trigger without relying on dedicated quarkonia triggers

Potential to be useful in other measurements

- Background for rare $Z \to l^+l^- J/\psi$ decay and $H \to Z Z^*$
- Probes heavy flavour + W/Z (using J/ψ as b-quark proxy)
- Rare Higgs to quarkonia and associated V-boson
- Higgs to charm couplings
- Other new physics

Motivation

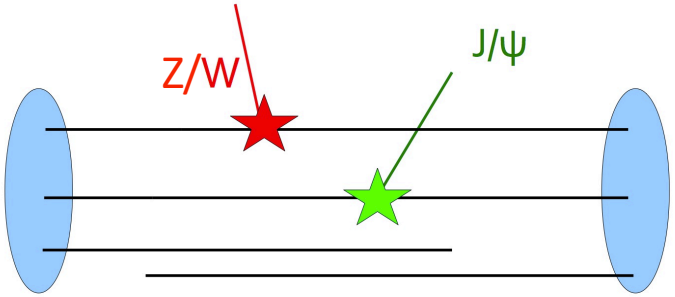
Single parton scattering (SPS)

- Both particles come from the same parton interaction
- Enhances sensitivity to a subset of matrix elements allowing tests/development of theoretical models
- This tests potential differences of the p_T spectra of singlet and octet production modes between V-boson+onia or inclusive production
- Possibility of resonant production from Higgs or New Physics

Double parton scattering (DPS)

- Each particle from independent parton interaction
- Difficult to address theoretically but is often invoked to explain observations (e.g.) rates of multiple heavy-flavour production
- To calculate σ_{eff}, the quarkonia can be fully reconstructed; experimentally cleaner than alternative methods (e.g. W + 2 jets)
- Wider range of measurements of DPS – more realistic models, allows tests of factorisation

DPS is **indistinguishable** on per event basis. We seek observables to disentangle them e.g. $\Delta\phi$ opening angle distributions – but can we do this well enough to be useful?



Measurement Summary

Two measurements present production of **prompt** J/ψ in association with W or Z bosons. These studies

- establish with > 5σ significance the observation of associated quarkonia production with electroweak bosons
- present a cross-section measurement ratio
- provisionally assess the amount of double vs single parton scattering, or present the distributions that are likely to be able to separate them

These are just the first steps, more data and different combinations of particles are needed – these studies are continuing.

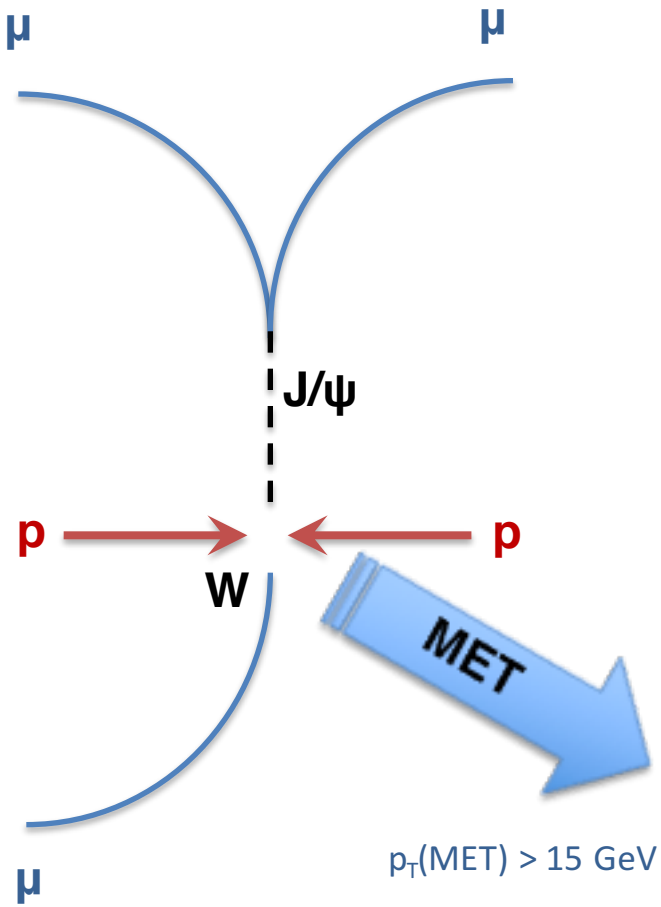
	∫L	√s	Citation
J/ψ + W	4.6 fb-1	7 TeV	JHEP 04 (2014) 172
J/ψ + Z	20.3 fb-1	8 TeV	Eur. Phys. J. C75 (2015) 229

Analysis Steps Overview

1. Selection of relevant μμμμ, μμee or μμμ+MET events
2. Pile-up contamination estimation
   - W/Z and J/ψ come from two different proton-proton interactions
3. Per candidate J/ψ efficiency and acceptance corrections
4. Signal and background weights and yield extraction
   - Using an unbinned, simultaneous, maximum likelihood fit in 2D (mass & lifetime) to separate the prompt and non-prompt J/ψ components
5. Differential cross-section evaluation
   - Cross section ***ratios*** σ(J/ψ + W,Z) / σ(W,Z) presented: most uncertainties cancel
6. Generation of relevant distributions
7. DPS contribution estimation
   - DPS contribution can be ***estimated*** with a calculation using the inclusive J/ψ cross section and the DPS σ_{eff} measurement from W + 2 jets

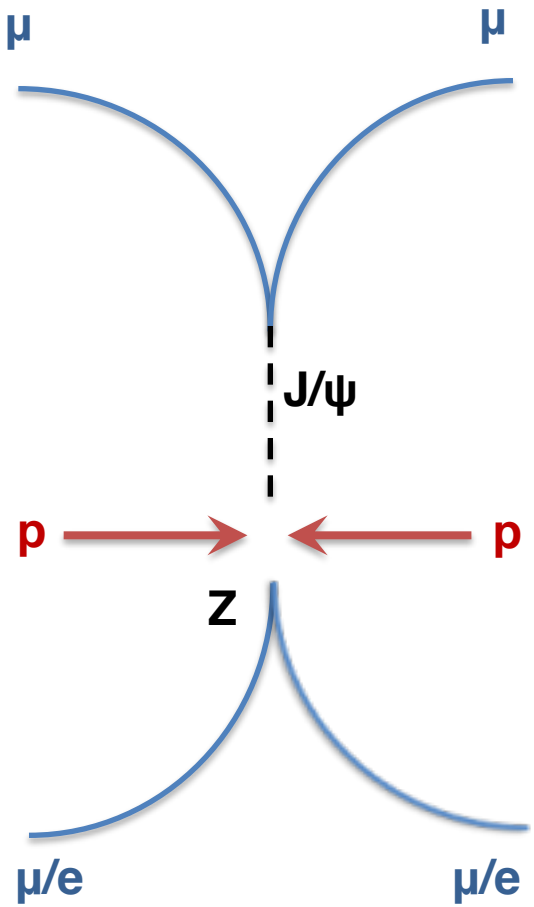
Final State

Triggers: Single high p_T electron/muon
J/ψ fiducial cuts: The same same for both analyses (after the acceptance corrections)



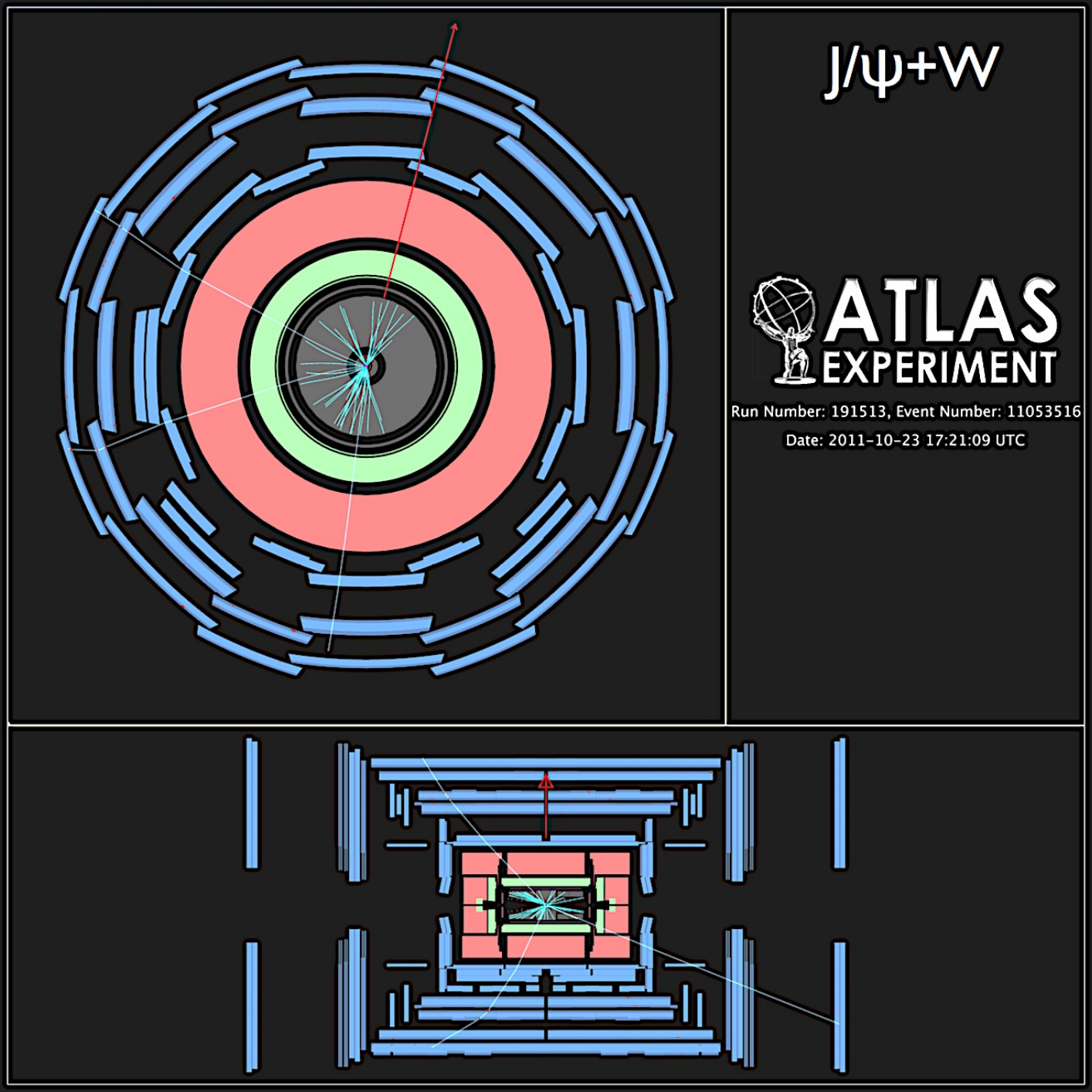
$p_T(\mu) > 25$ GeV
must match trigger

$p_T(MET) > 15$ GeV

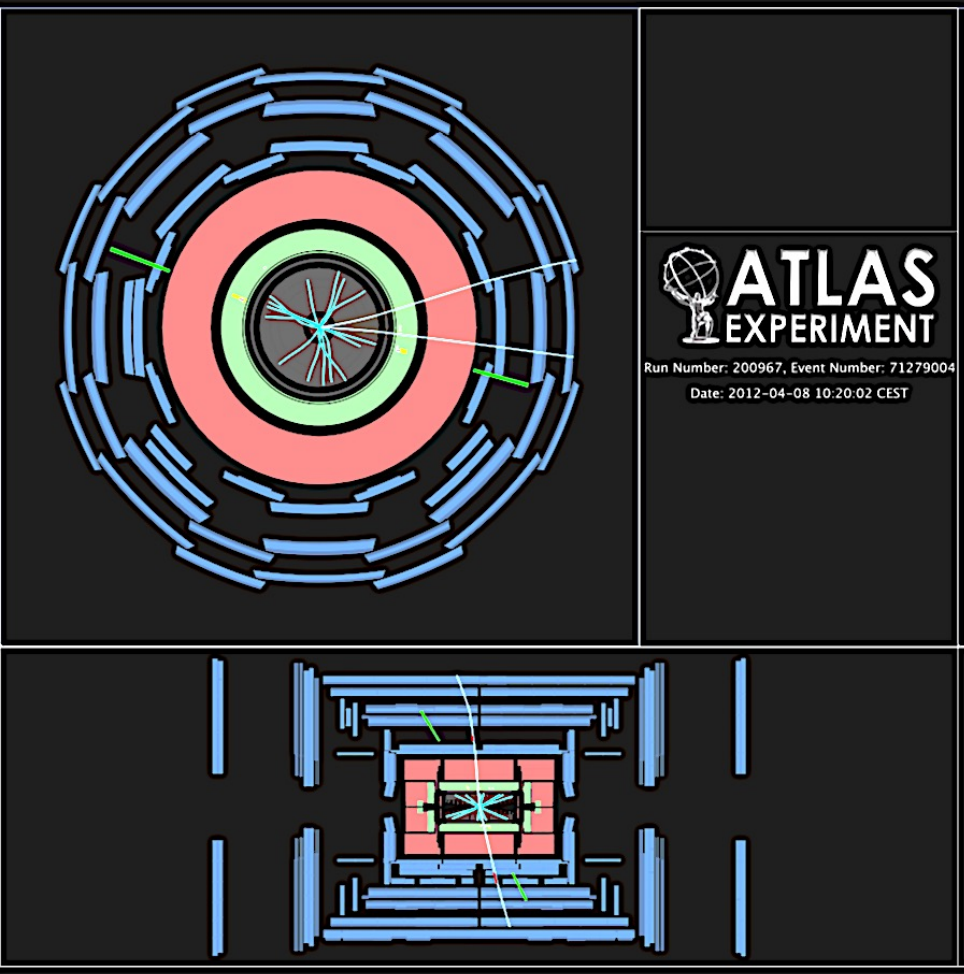


$p_T(\mu/e) > 25$ GeV
must match trigger

$p_T(\mu/e) > 15$ GeV


J/ψ+W
ATLAS
EXPERIMENT
Run Number: 191513, Event Number: 11053516
Date: 2011-10-23 17:21:09 UTC

J/ψ+Z(ee)


ATLAS
EXPERIMENT
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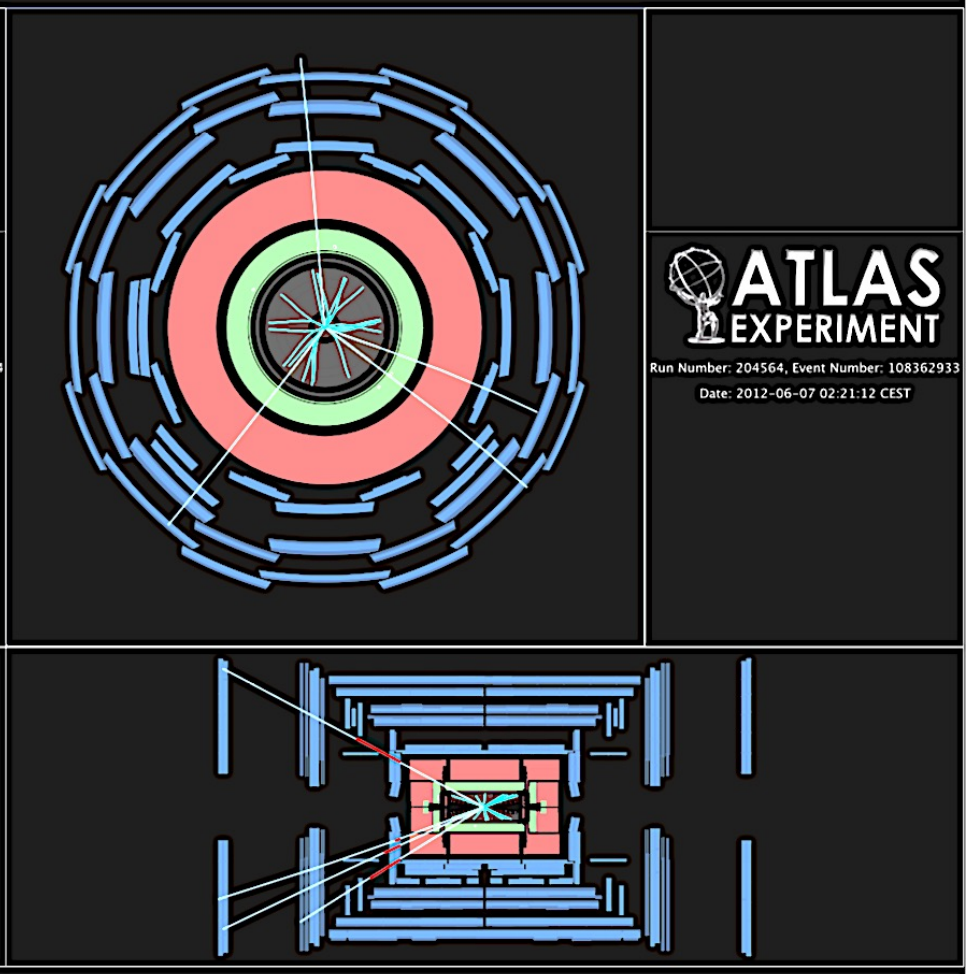
Date: 2012-04-08 10:20:02 CEST

J/ψ+Z(μμ)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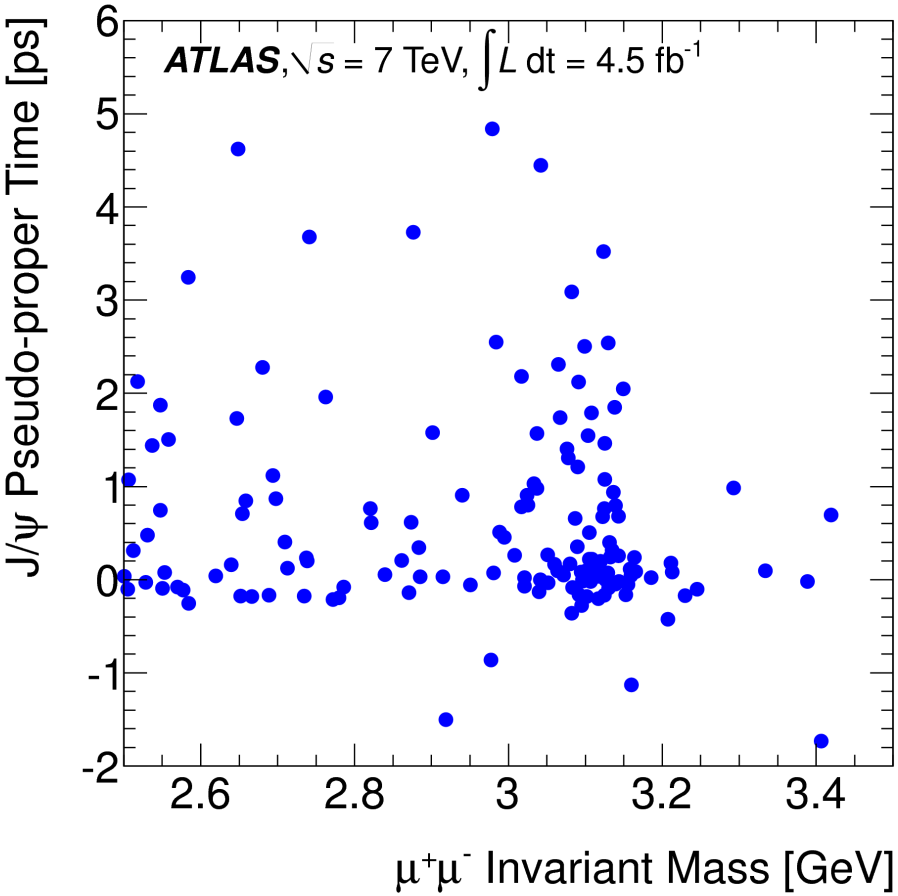
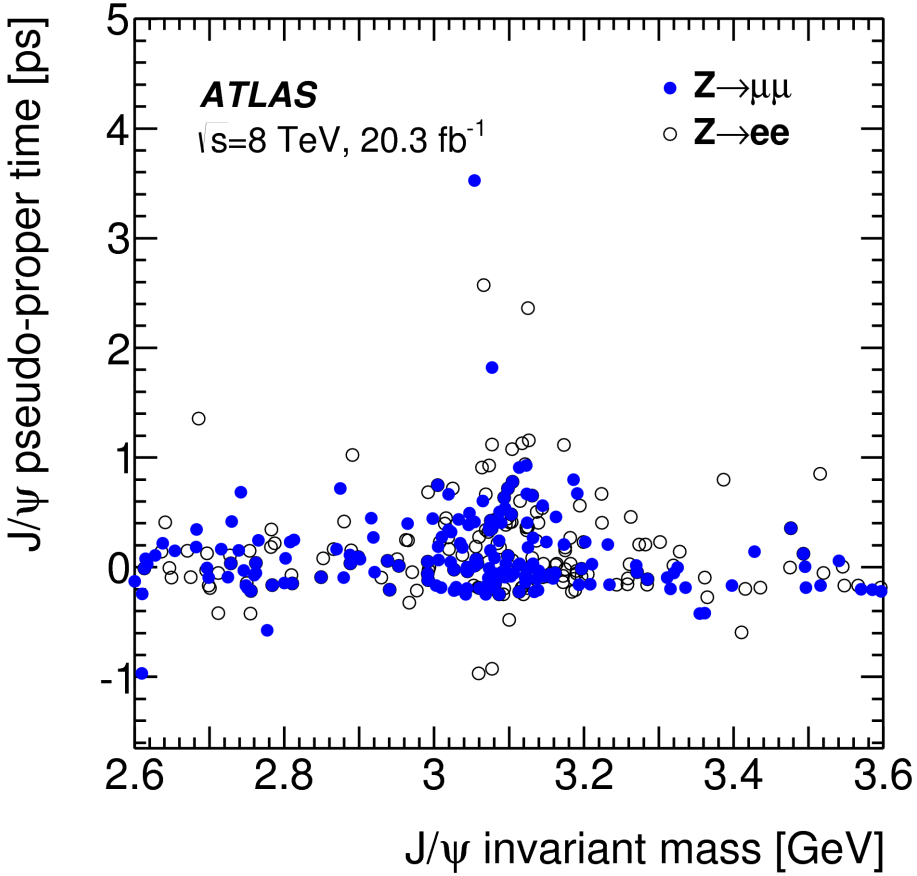
Date: 2012-06-07 02:21:12 CEST

Candidates

J/ψ+W



J/ψ+Z



Corrections and Yield Extraction

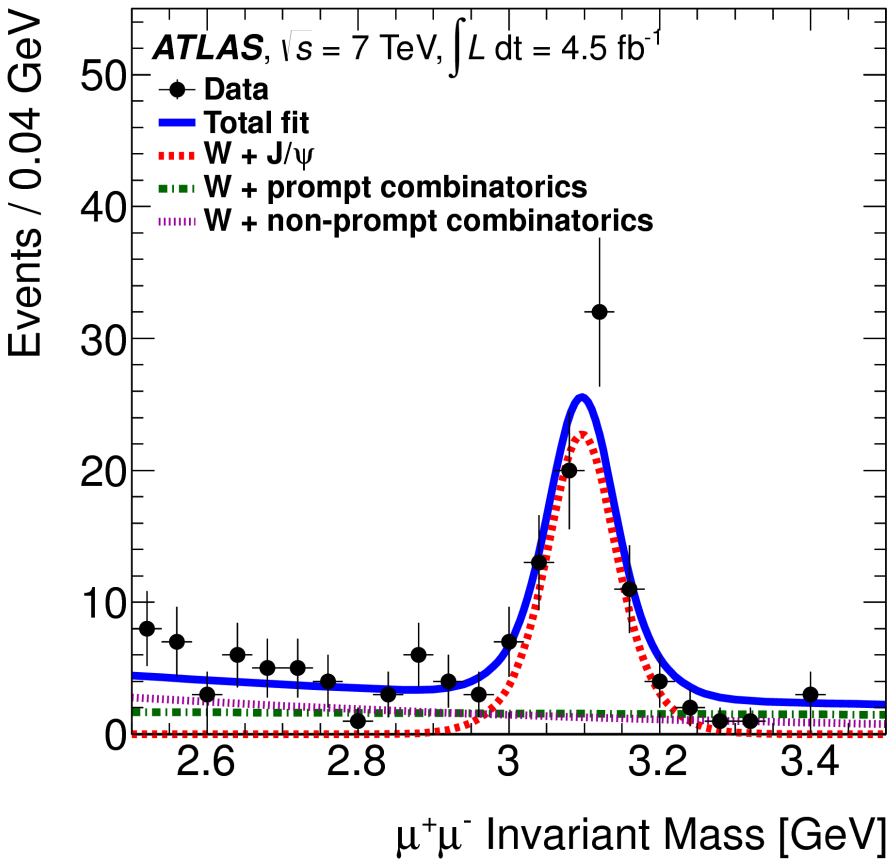
- Acceptance and efficiency corrections derived from MC and applied per candidate
  - A range of acceptance corrections, covering the extremes of J/ψ polarisation scenarios

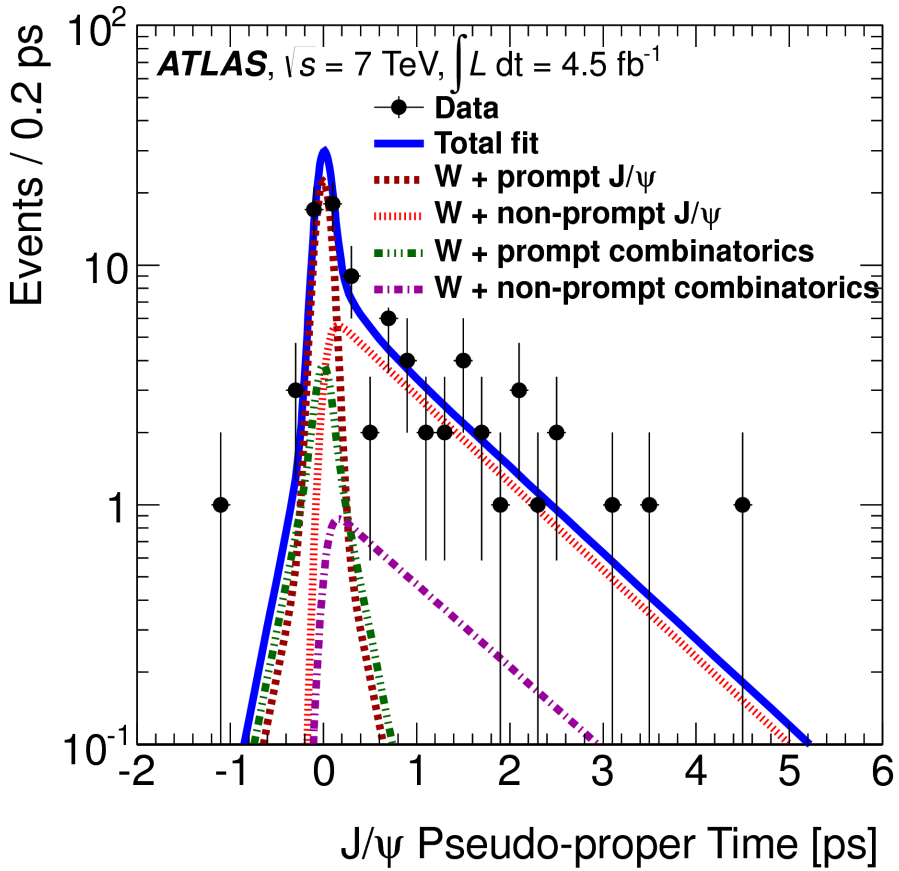
- Signal weights extracted using an 2D maximum likelihood fit with discriminants:
  - J/ψ candidate mass
  - J/ψ candidate pseudo-proper time

- Four categories of events are described in the fits
  - W, Z candidate + real prompt J/ψ **(SIGNAL)**
  - W, Z candidate + real non-prompt J/ψ **(SIGNAL)**
  - W, Z candidate + two combinatorial muons forming a prompt-like lifetime distribution
  - W, Z candidate + two combinatorial muons forming a non-prompt-like lifetime distribution

- Yield extracted by fitting weighted distributions

Corrections and Yield Extraction: J/ψ+W

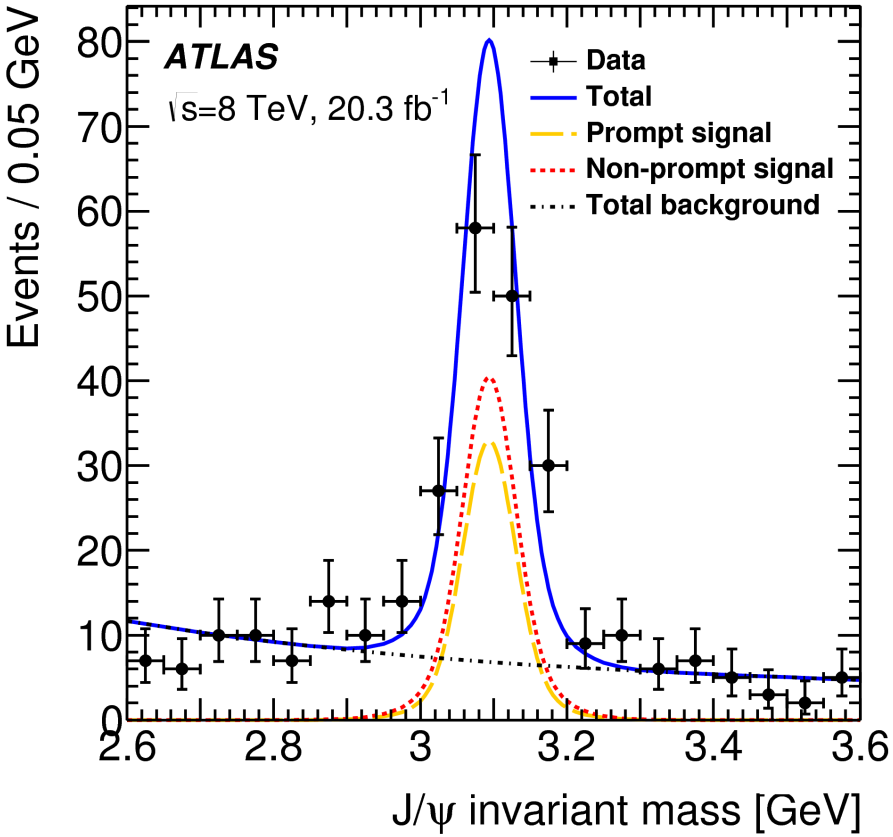


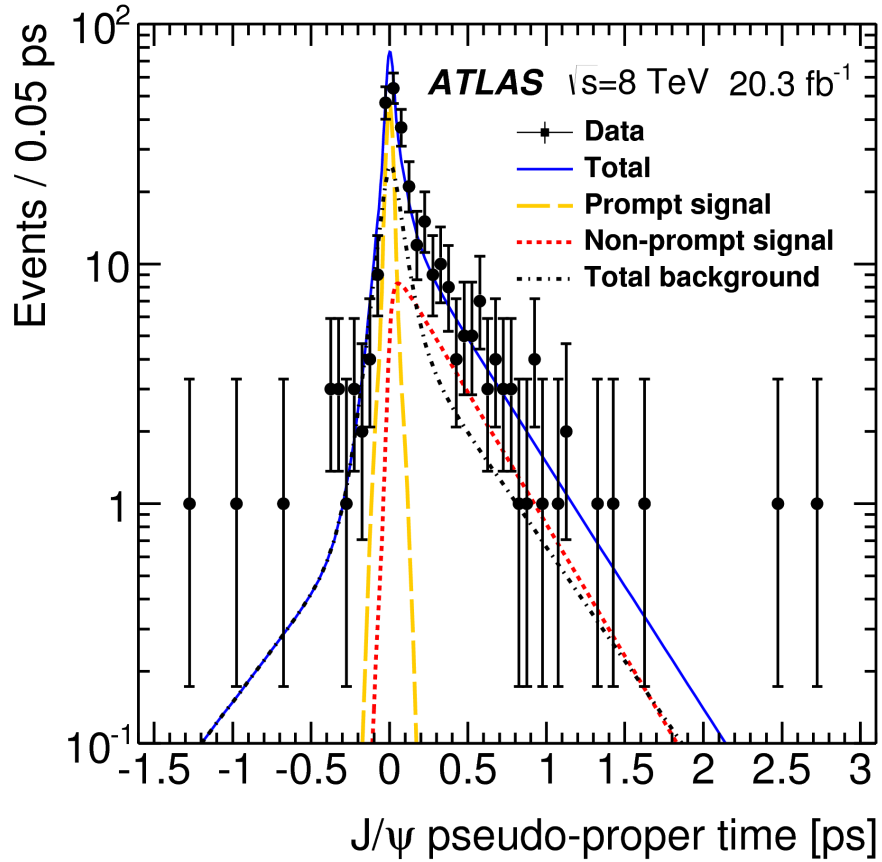


The signal weights are extracted by applying an unbinned, simultaneous, maximum likelihood, 2D fit to the mass and lifetime distributions

Signal significance = 5.1σ for prompt J/ψ+W

Corrections and Yield Extraction: J/ψ+Z





The signal weights are extracted by applying an unbinned, simultaneous, maximum likelihood, 2D fit to the mass and lifetime distributions

Signal significance > 5σ for prompt J/ψ+Z and non-prompt J/ψ+Z

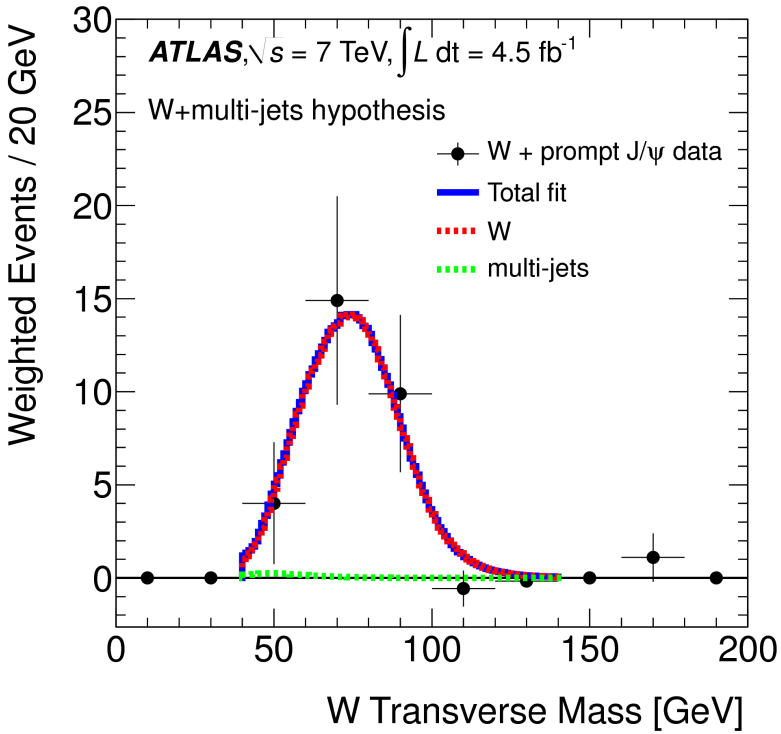
Backgrounds

The backgrounds not covered by the fits were found to be negligible:

- fake W/Z (from multi-jet/top)

  Template fit of m_T(W)estimates
  0.1 ± 4.6 multi-jet events in
  J/ψ+W sample

  Simulation of $t\bar{t}$ events estimates
  < 0.28 events at 95% CL in
  J/ψ+W sample



- Contamination from $B_c \rightarrow J/\psi \mu^{\pm} \nu \mu X$

Backgrounds

EXCEPT real J/ψ and real W/Z produced in different proton-proton collisions in the same bunch crossing ("pile-up background")

Calculate N_{extra} pile-up vertices around a W, Z candidate, from known pile-up characteristics

→

Calculate probability of any of these yielding a J/ψ using

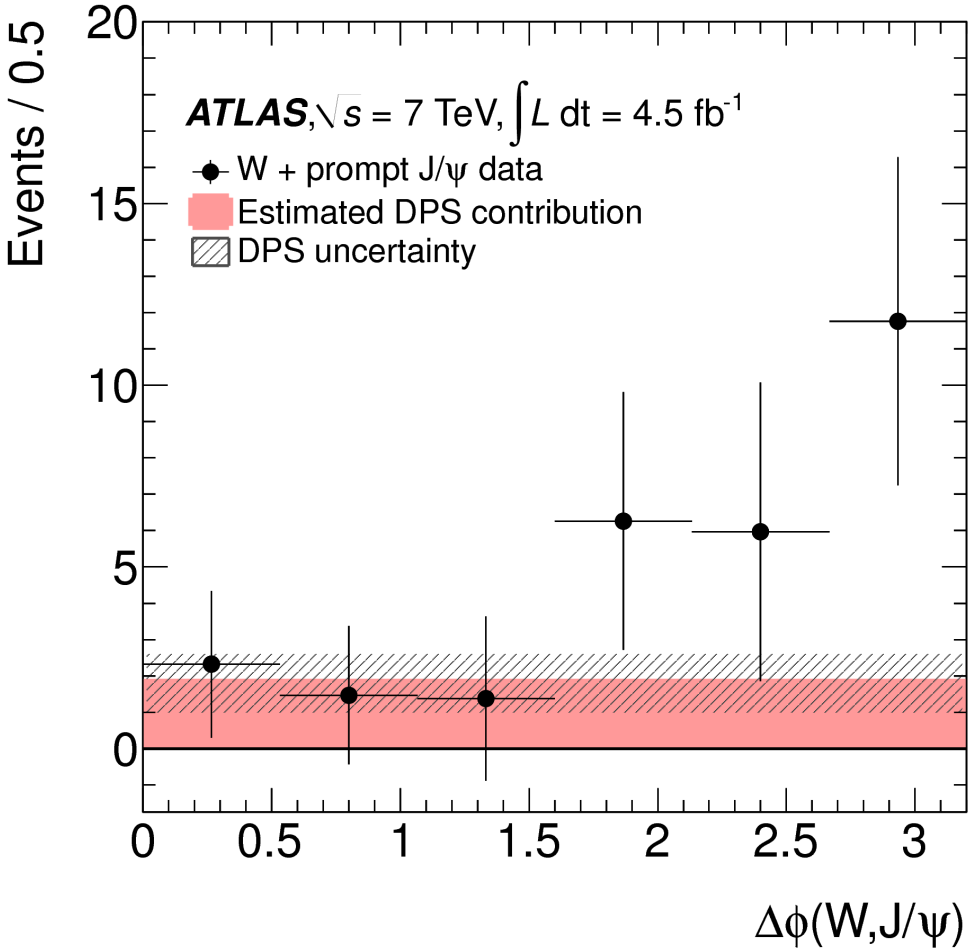
$$P^{ij}_{J/\psi} = \sigma^{ij}_{J/\psi}/\sigma_{\text{inel}}$$

→

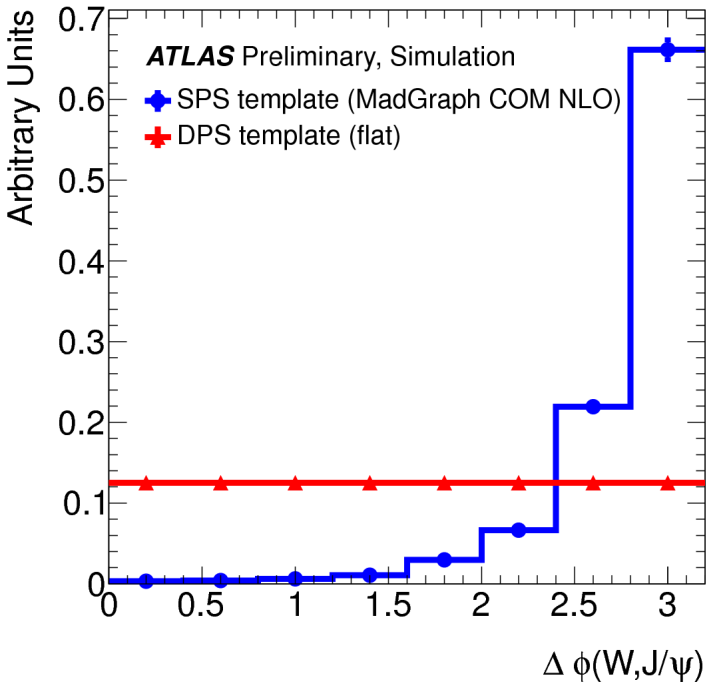
Pile-up contamination estimate:
1.8 ± 0.2 events in J/ψ+W
$5.2^{+1.8}_{-1.3}$ prompt J/ψ+Z
$2.7^{+0.9}_{-0.6}$ non-prompt J/ψ+Z

$N_{pileup\_background\_events}$ = **2.3 ± 0.2** for the J/ψ+Z
$N_{pileup\_background\_events}$ = **0.81 ± 0.08** for the J/ψ+W

J/ψ+W results: azimuthal opening angle

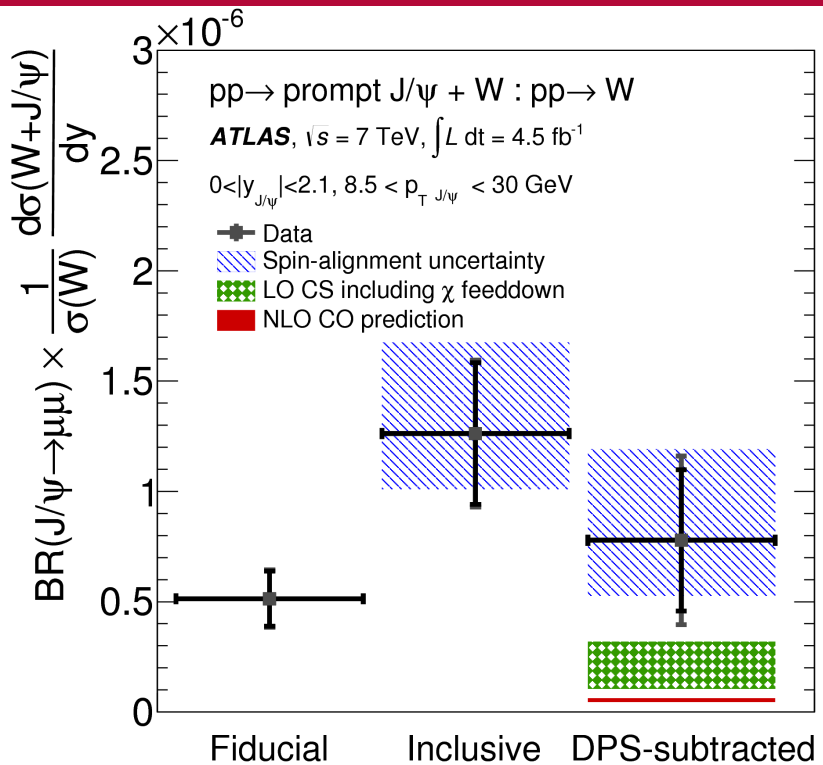


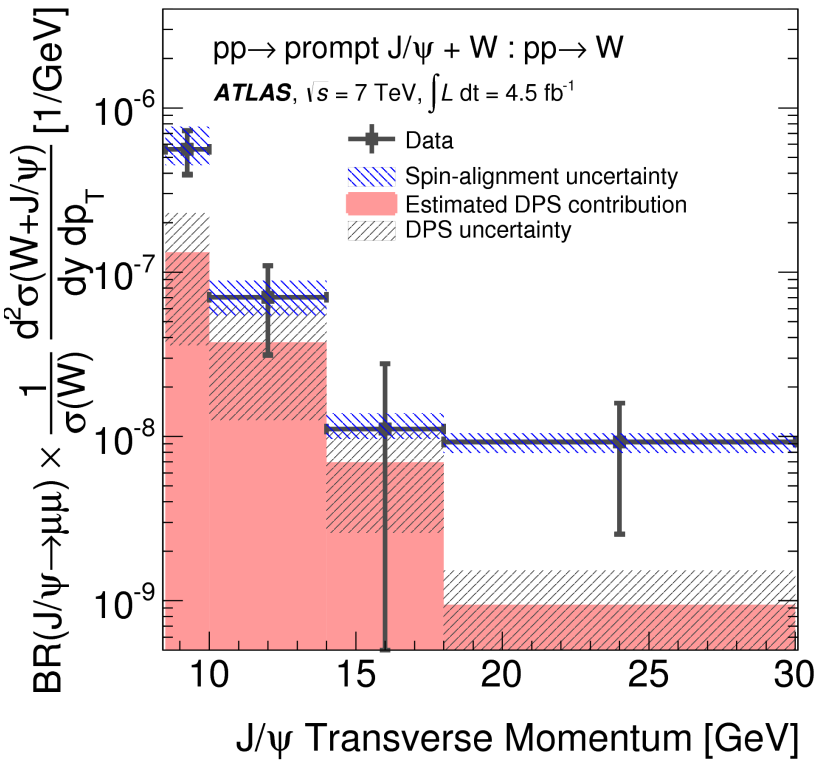
DPS processes are expected to give a flat azimuthal opening angle (Δϕ) distribution



Possible indication of DPS and SPS J/ψ+W production.

J/ψ+W results: Cross-Section





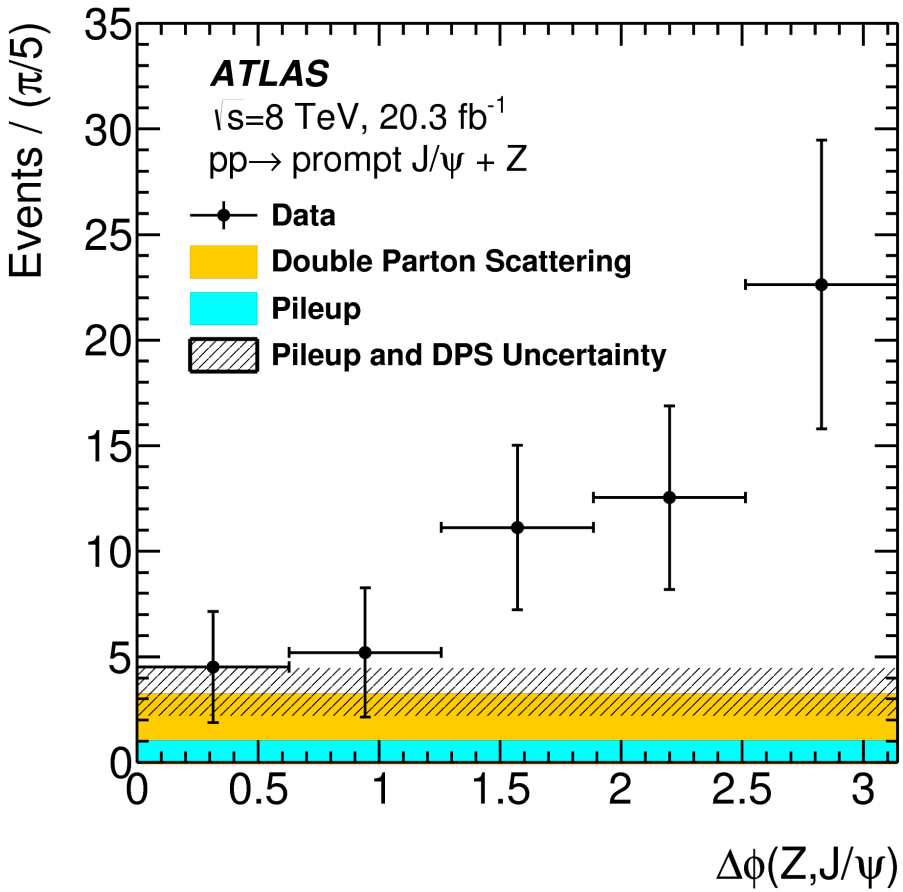
Fiducial means no J/ψ acceptance corrections.
Inclusive contains all corrections, also presented in $p_T^{J/\psi}$ bins.
DPS-subtracted to compare with theory: appears theory doesn't fully account for SPS contribution

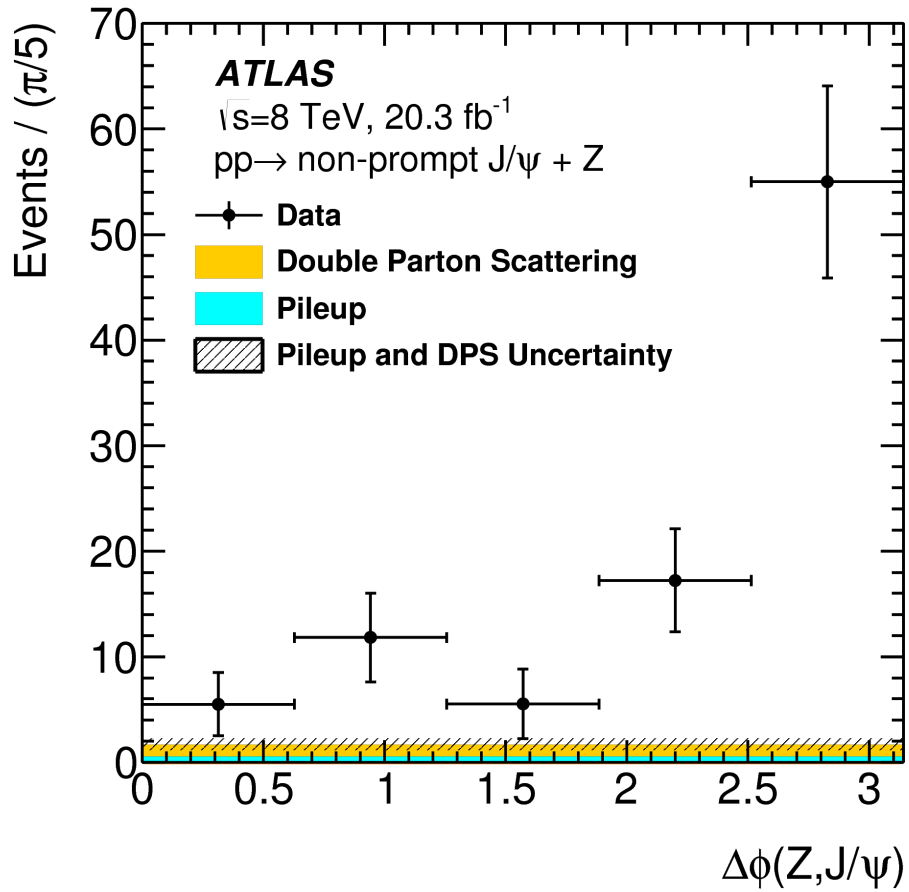
DPS estimated experimentally from measurement of σ_{eff}(W+2*jets*)=15mb
Deviations between data and theory may be due to:

- Theory underestimate of SPS rate
- Theory underestimate of DPS rate, or factorisation ansatz breakdown

CS prediction: PL B 738 (2014) 529-529
LO CS = leading-order colour-singlet
NLO CO = next-to-leading-order colour-octet

J/ψ+Z results: azimuthal opening angle

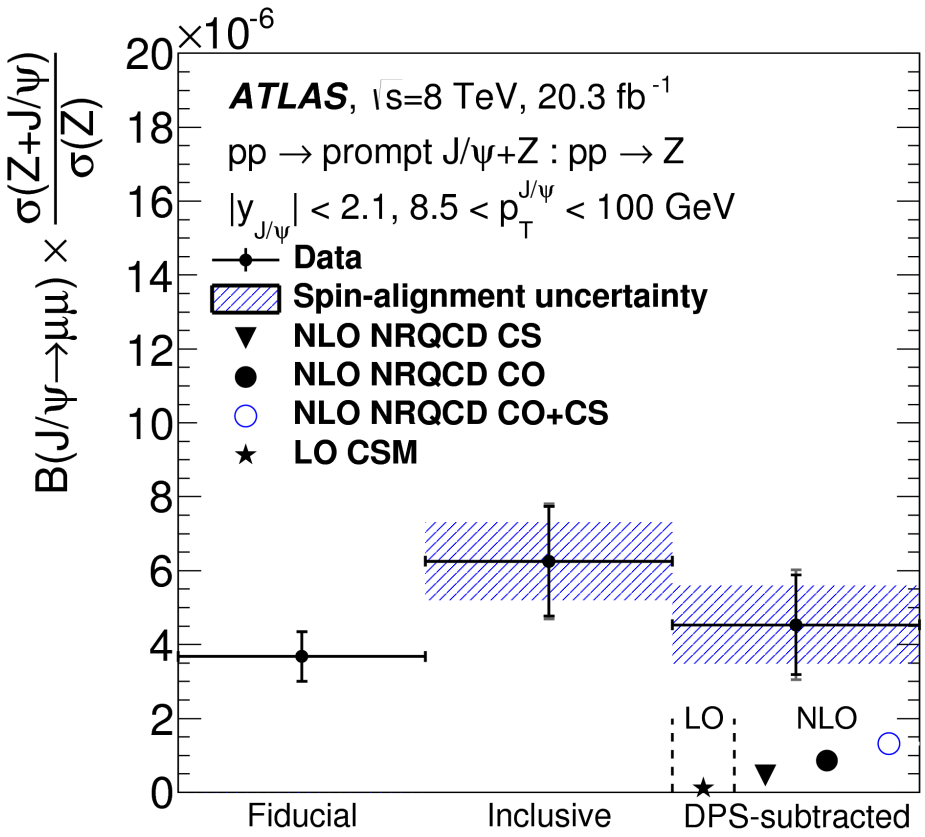


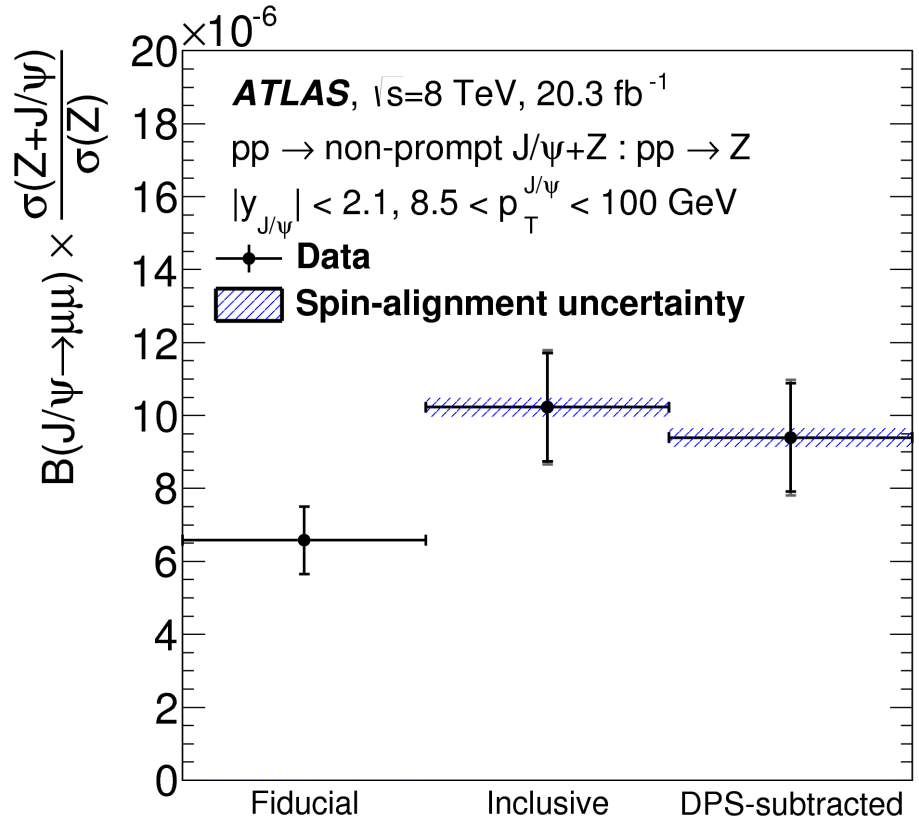


DPS dominates the first bin.

The same pattern is observed in the azimuthal opening angle as with the J/ψ+W.

J/ψ+Z results: total cross-sections



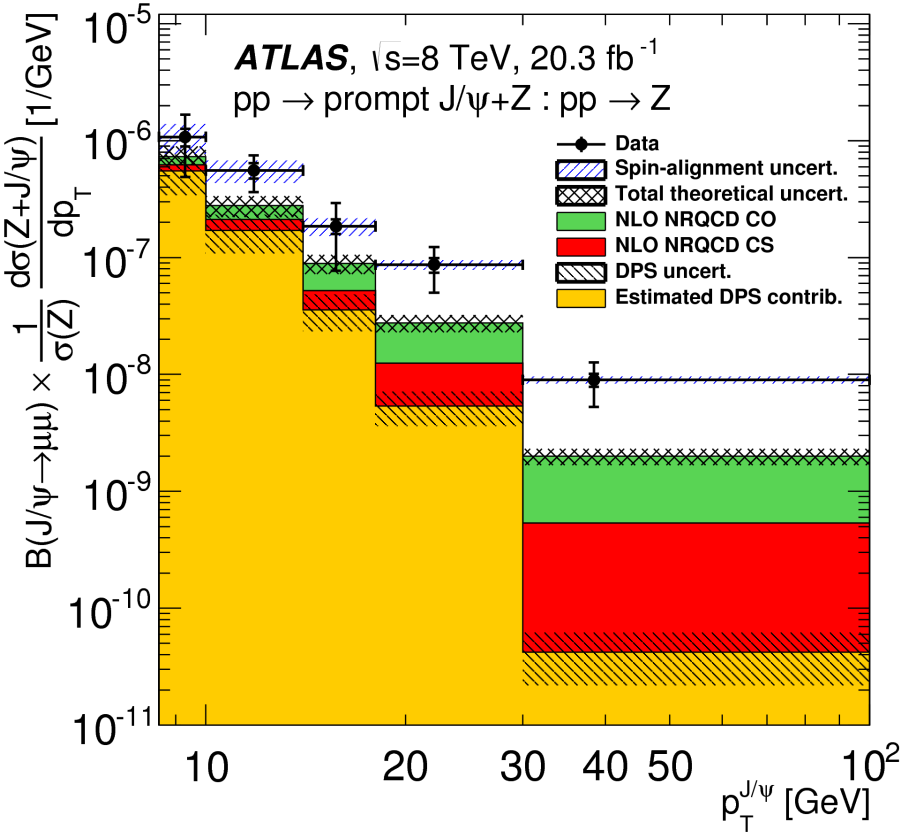


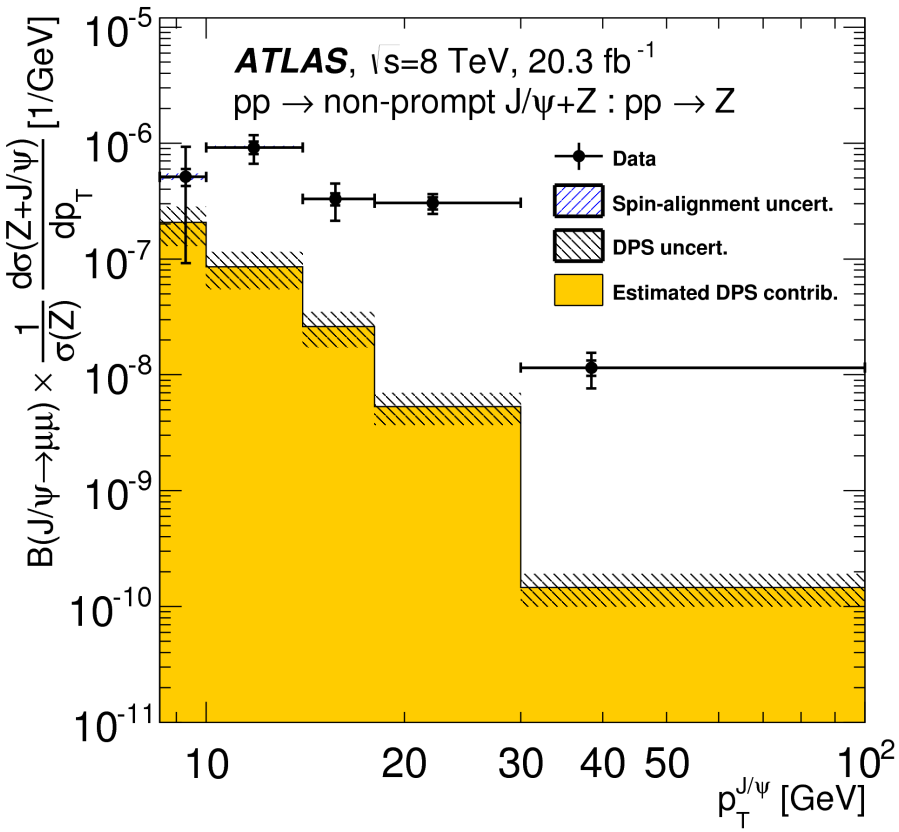
Again, theory appears to underestimate SPS production.
(Note: NLO NRQCD does feed-down a component not included in these predictions.)

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

NLO NRQCD CS = next-to-leading-order non-relativistic-QCD colour-singlet
NLO NRQCD CO = next-to-leading-order non-relativistic-QCD colour-octet
LO CSM = leading-order colour-singlet-mechanism

J/ψ+Z results: differential cross-sections

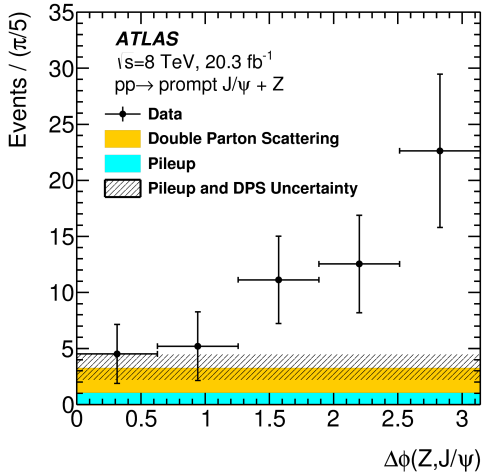


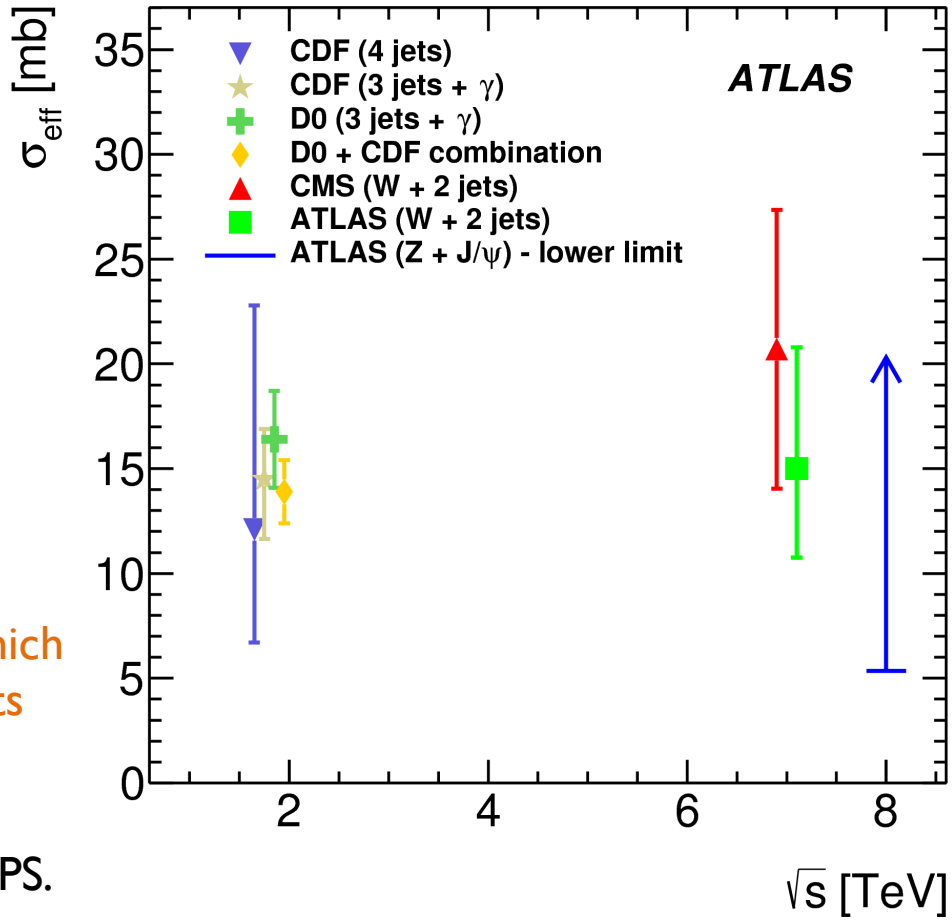


The lowest $p_T^{J/\psi}$ bin is mostly DPS and the highest bins are SPS dominated.
The theory discrepancy becomes more pronounced with increasing $p_T^{J/\psi}$.

J/ψ+Z results: lower limit on σ_{eff}

Again considering the first bin of this Δϕ plot to be due to DPS…





…we set an upper limit on level of DPS contributing to the observed signal

- corresponding to a lower limit on σ_{eff} which is in agreement with other measurements

These are early results, but they show the possibility of using quarkonia for studying DPS.

WANTED: models for the SPS contribution to V+J/ψ, particularly as a function of Δϕ
→ To allow better estimate of the DPS component
→ To allow measurement of σ_{eff} and DPS kinematics

Outlook and conclusions

- The LHC experiments have made excellent first steps in studying the production of quarkonia in association with other particles.

- These processes will help to address issues of:
  - singlet versus octet production of quarkonia
  - double parton scattering
  - resonant production

- Given low production rates, clean experimental signatures and high mass associated particles, we should collect significant numbers of these decays in LHC Run-2 while staying within reasonable trigger thresholds.

The outlook for these studies is positive.

Additional Information

ATLAS J/ψ +W: Event/object selection

Final state requirement	$\mu^+\mu^-\mu^\pm$ + MET
Trigger	Single μ > 18 GeV
Muon selections	3 muons,1 matched to trigger, $\lvert\eta\rvert<2.5$, pT>2.5 (3.5) for $\lvert\eta\rvert<1.3$ (>1.3), all with z0 < 10 mm w.r.t PV
J/ψ selections	$\mu^+\mu^-$, one > 4 GeV, at least one combined, $2.5 < m_{\mu\mu} < 3.5$ GeV, $8.5 < p_T(J/\psi) < 30$ GeV, $\lvert y(J/\psi)\rvert < 2.1$
MET selections	MET > 20GeV
W selections	One muon, matched to trigger: $p_T > 25$ GeV, $\lvert\eta\rvert<2.4$, $z_0 < 1$mm, $d_0/\sigma(d_0) < 3$, isolated $m_T(W) \equiv\sqrt{[2pT(\mu)*MET*(1-\cos(\phi_\mu-\phi_{MET}))]} > 40$ GeV

ATLAS J/ψ +Z: Event/object selection

Final state requirement	$\mu^+\mu^-\mu^+\mu^-$ or $\mu^+\mu^-e^+e^-$
Trigger	Single μ,e > 25 GeV

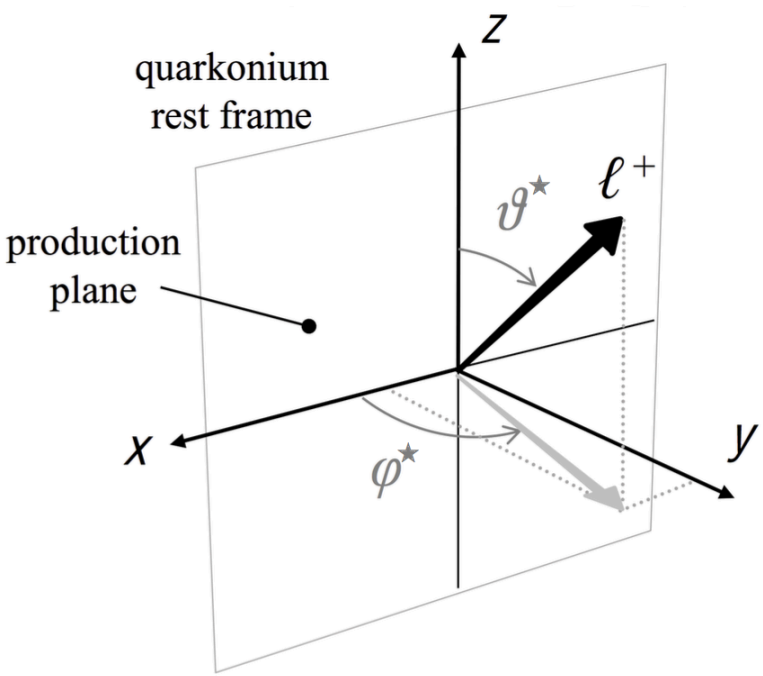
Z boson selection	
p_T (leading lepton)> 25 GeV, p_T (sub-leading lepton)> 15 GeV $\lvert\eta(\text{lepton from } Z)\rvert < 2.5$ $\lvert m(Z) - 91.1876\ \text{GeV}\rvert < 10$ GeV	+ one lepton must have fired the trigger +must fit to vtx
J/ψ selection	
$8.5 < p_T(J/\psi) < 100$ GeV, $\lvert y(J/\psi)\rvert < 2.1$ p_T (leading muon)> 4.0 GeV, $\lvert\eta(\text{leading muon})\rvert < 2.5$ OR $\left\{ \begin{array}{ll} p_T \text{ (sub-leading muon)} > 2.5 \text{ GeV}, & 1.3 \leq \lvert\eta(\text{sub-leading muon})\rvert < 2.5 \\ p_T \text{ (sub-leading muon)} > 3.5 \text{ GeV}, & \lvert\eta(\text{sub-leading muon})\rvert < 1.3 \end{array} \right\}$	+must fit to vtx

J/ψ+Z selections	J/ψ and Z vertices must less than 10mm apart

J/ψ Spin Alignment Uncertainty

J/ψ kinematic acceptance depends on an uncertain spin alignment: we use extreme values to assess this uncertainty.

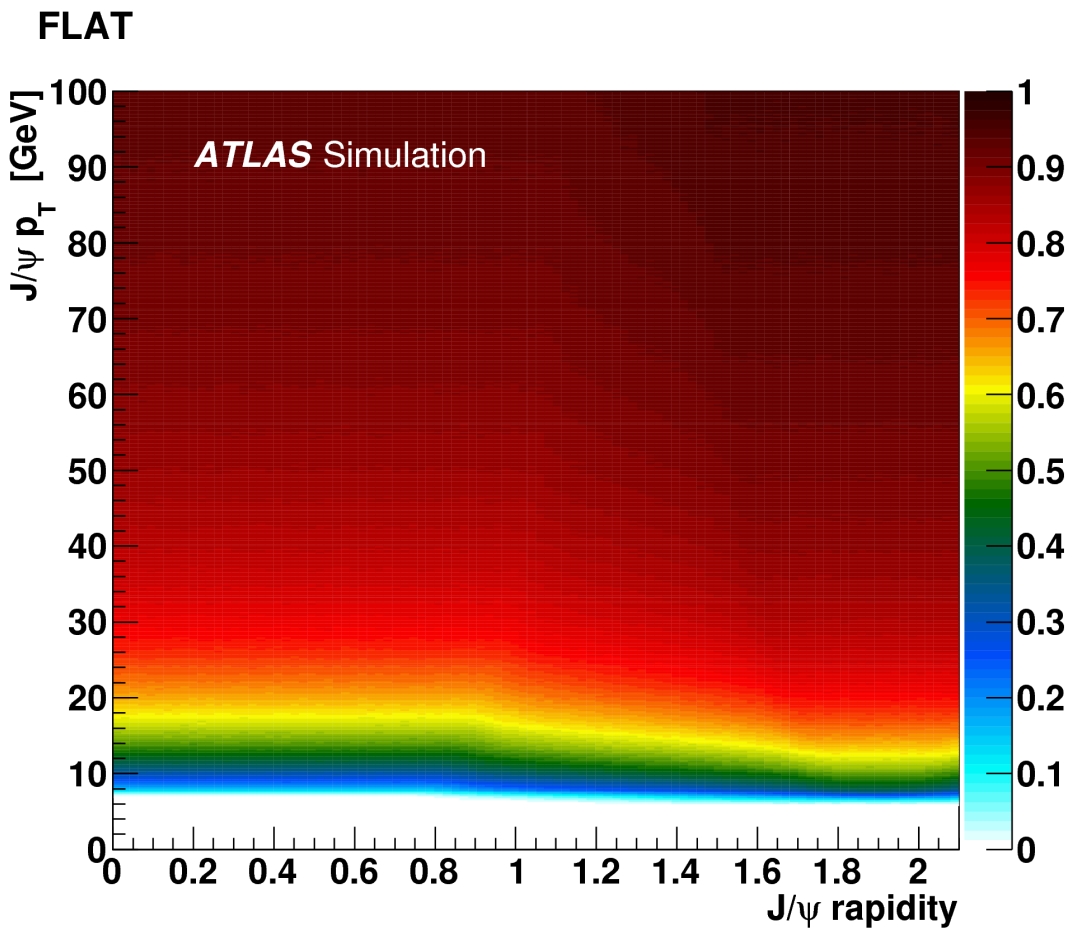
$$\frac{d^2N}{d\cos(\vartheta^*)d\varphi^*} \propto 1+\lambda_\theta \cos^2(\vartheta^*)+\lambda_\phi \sin^2(\vartheta^*)\cos(2\varphi^*)+\lambda_{\theta\phi}\sin(2\vartheta^*)\cos(\varphi^*)$$



	Angular coefficients		
	λ_θ	λ_ϕ	$\lambda_{\theta\phi}$
Isotropic *(central value)*	0	0	0
Longitudinal	−1	0	0
Transverse positive	+1	+1	0
Transverse zero	+1	0	0
Transverse negative	+1	−1	0

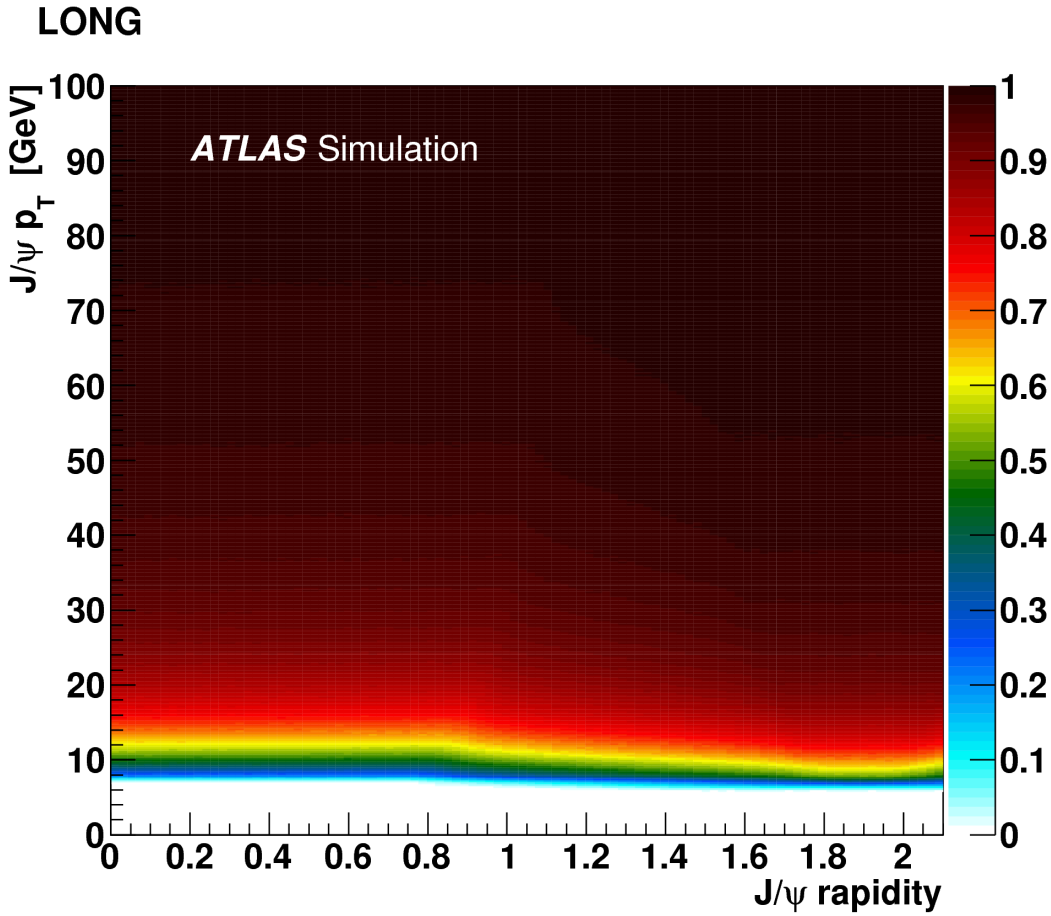
J/ψ Acceptance Maps

J/ψ kinematic acceptance depends on an uncertain spin alignment: we use extreme values to assess this uncertainty.



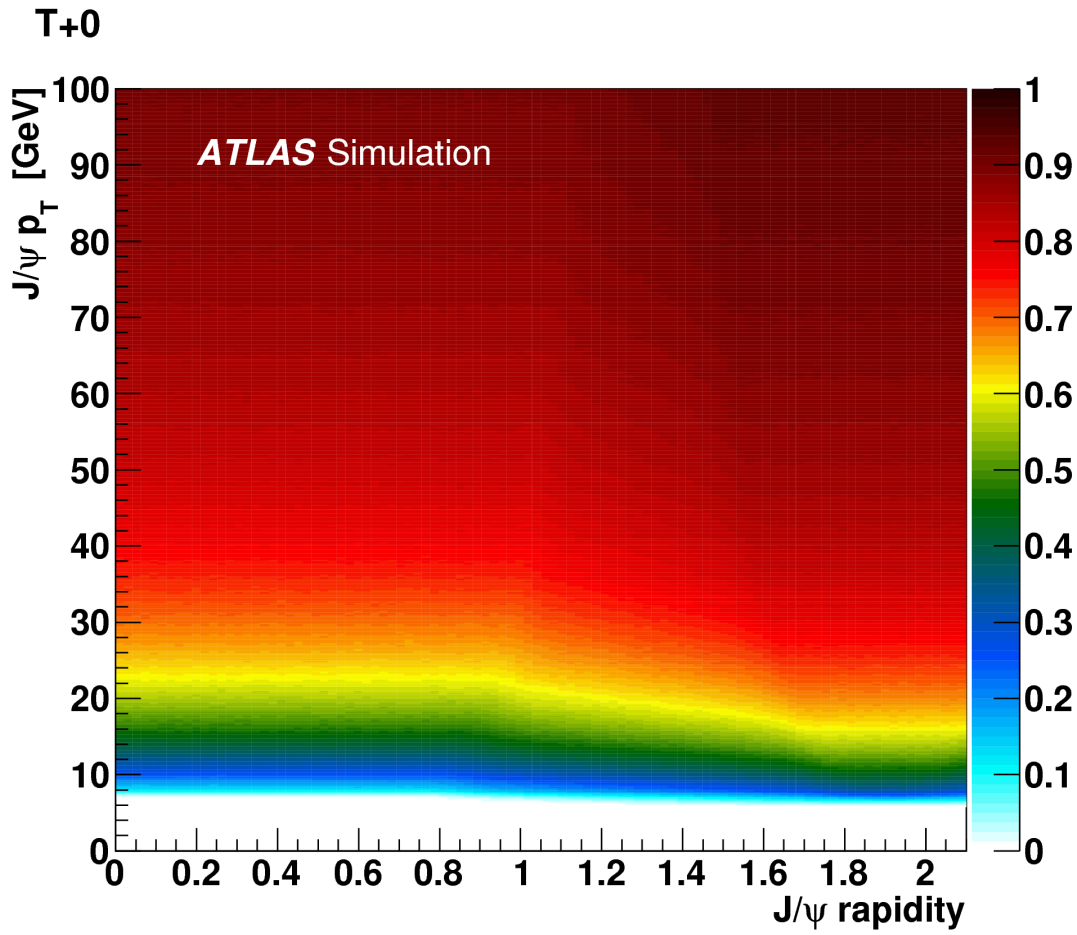
The J/ψ acceptance for the isotropic (FLAT) spin-alignment scenario following Nucl. Phys. B 850 (2011) 387.

J/ψ Acceptance Maps



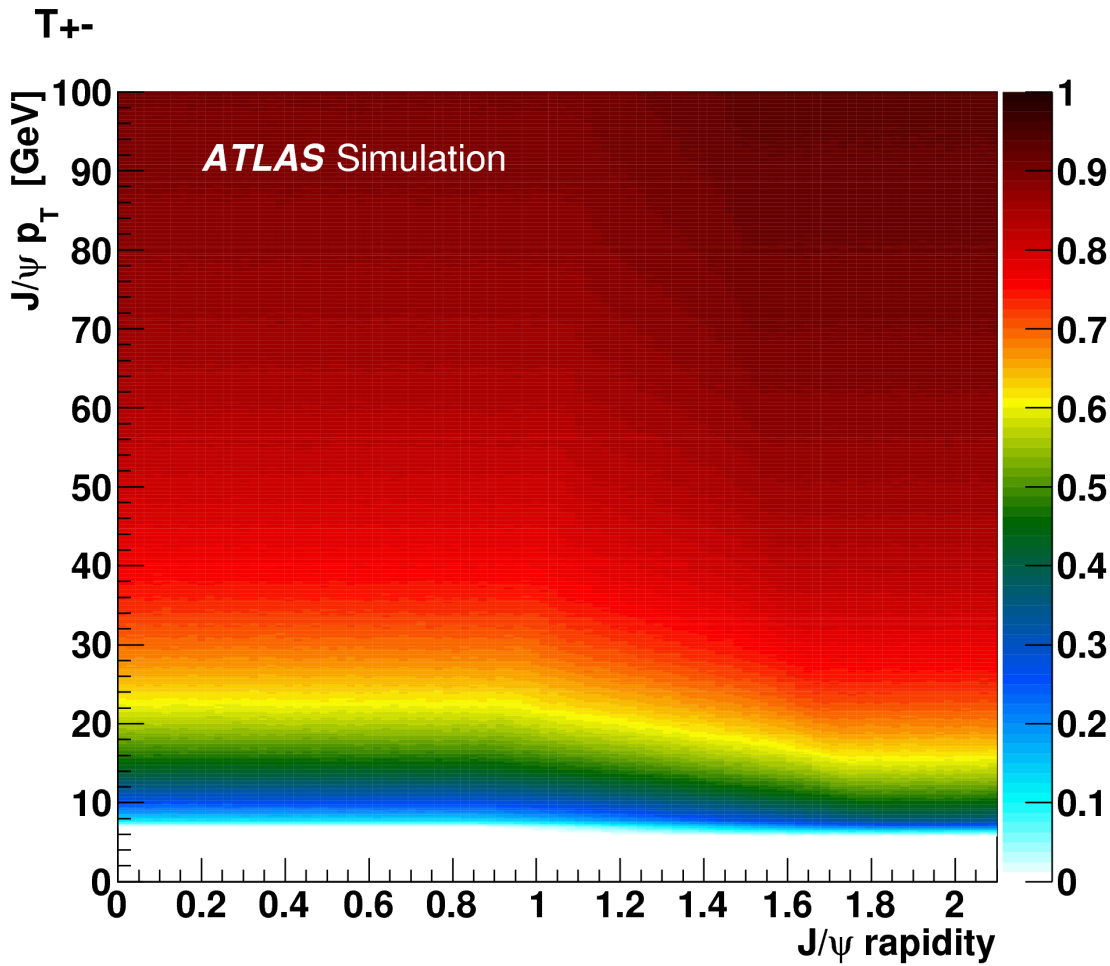
The J/ψ acceptance for the extreme spin-alignment scenario longitudinal (LONG) following Nucl. Phys. B 850 (2011) 387.

J/ψ Acceptance Maps



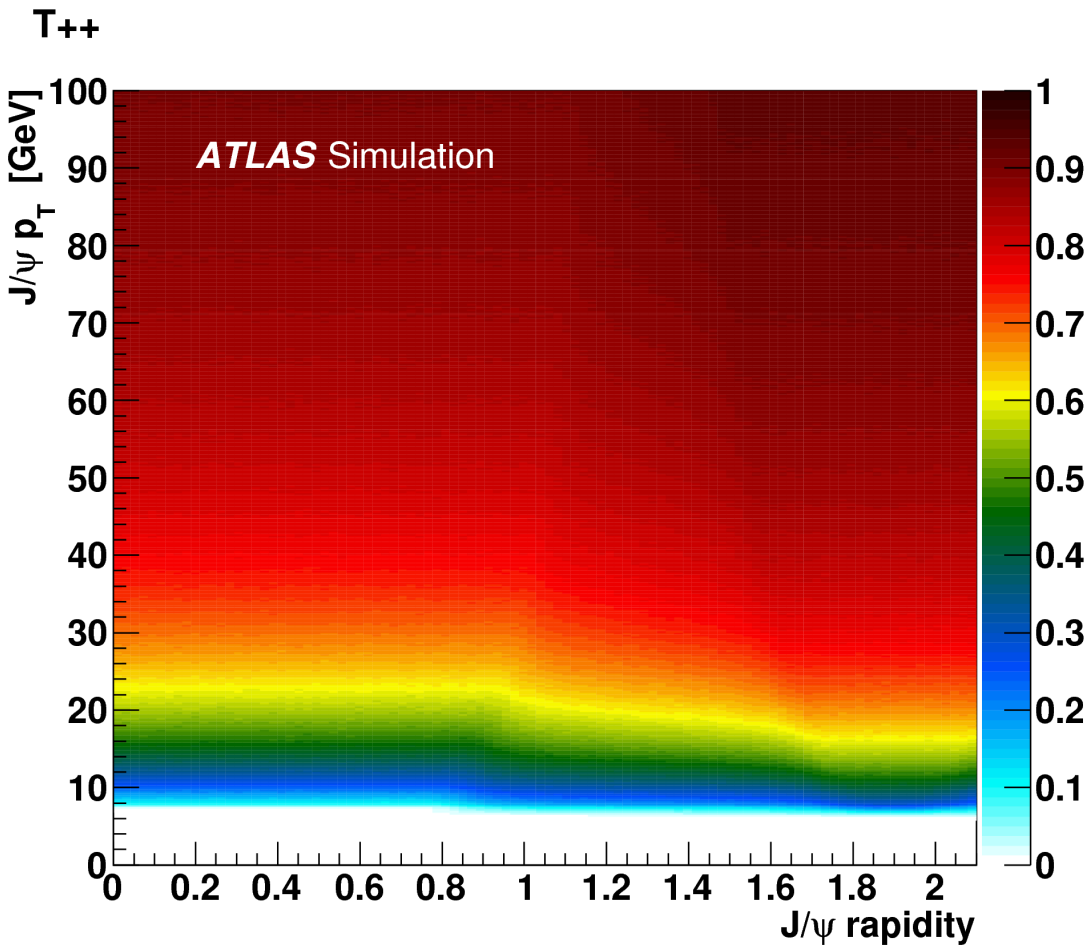
The J/ψ acceptance for the extreme spin-alignment scenario transverse 0 (T+0) following Nucl. Phys. B 850 (2011) 387.

J/ψ Acceptance Maps



The J/ψ acceptance for extreme spin-alignment scenario transverse M (T+-) following Nucl. Phys. B 850 (2011) 387.

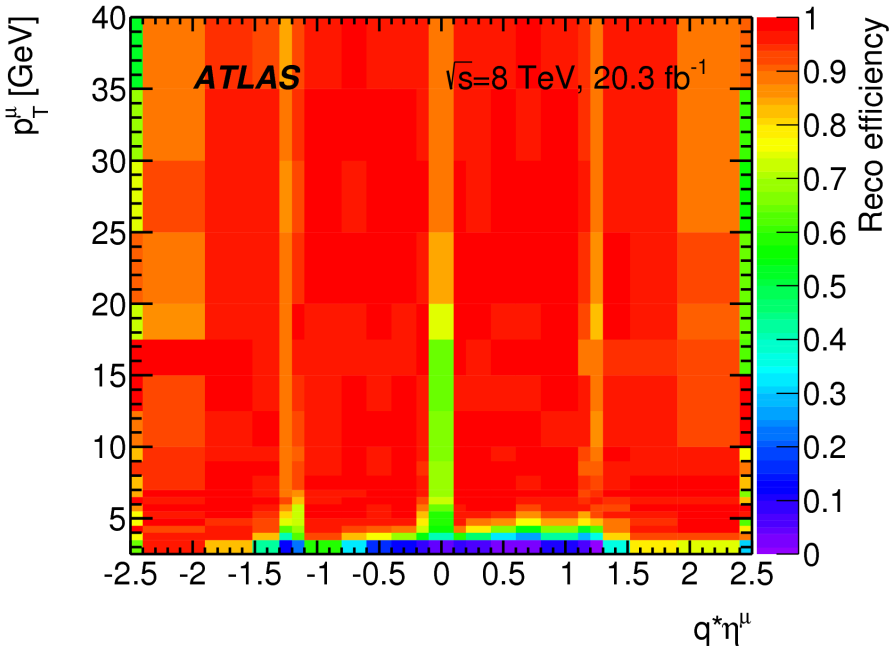
J/ψ Acceptance Maps



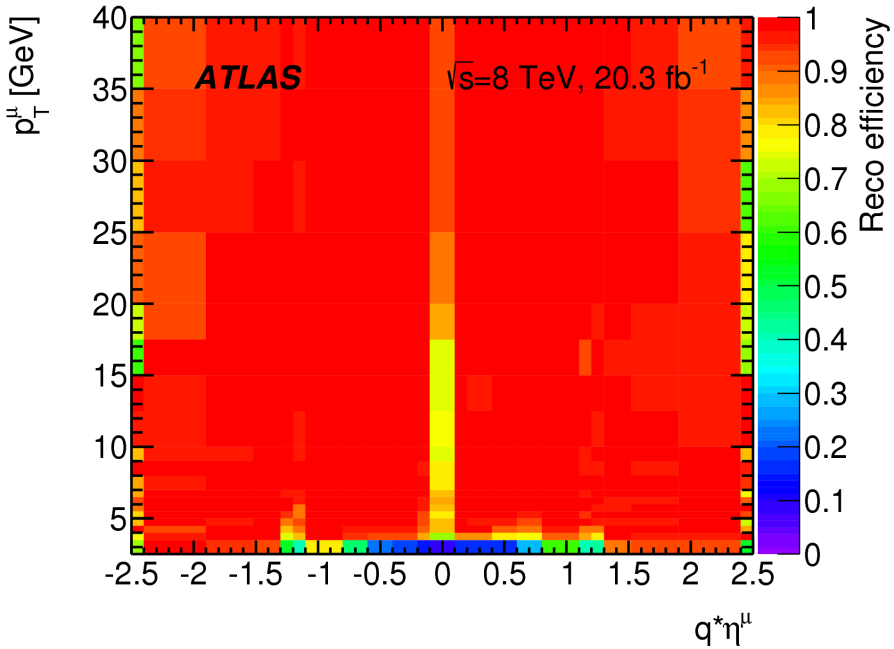
The J/ψ acceptance for extreme spin-alignment scenarios transverse P (T++) following Nucl. Phys. B 850 (2011) 387.

J/ψ Muon Reconstruction Efficiency Maps

The two J/ψ muons are independently efficiency weighted based on p_T and pseudo-rapidity (η)



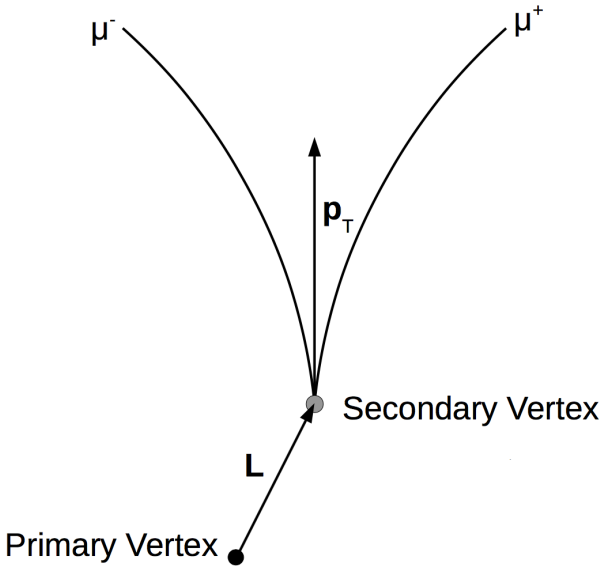
Low p_T reconstruction efficiencies for combined muons.



Low p_T reconstruction efficiencies for segment-tagged muons.

J/ψ pseudo-proper decay time (τ)

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



Allows us to distinguish between prompt and non-prompt J/ψ

Where:

L_{xy} = $\mathbf{L} \cdot \mathbf{p_T}^{J/\psi} / p_T^{J/\psi}$

L = the vector from the primary decay vertex to the J/ψ decay vertex

$m^{J/\psi}$ = the world-average mass of the J/ψ meson

$\mathbf{p_T}^{J/\psi}$ = the transverse momentum of the J/ψ

$p_T^{J/\psi}$ = $|\, \mathbf{p_T}^{J/\psi} \,|$

J/ψ+Z Theory References

- arXiv:1407.5821
- arXiv:1407.4038
- arXiv:1210.2430
- arXiv:1102.0398