ATLAS measurements of associated vector boson plus quarkonium production at the LHC

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Motivation

- Measurements of quarkonium production usually focus on properties of **inclusive** samples (differential cross sections, spin alignment)
- Huge LHC luminosities provide samples of quarkonia produced in association with additional objects
  - Other quarkonia, vector bosons, jets, top, …
- Two possible production modes
  - *single parton scattering*: objects from same diagrams, resonant or non-resonant
  - *double parton scattering*: each object from a separate hard scatter within the same proton collision
- Additional experimental motivation - highly important for ATLAS and CMS
  - additional object often needed for other physics reasons (SM measurements, Higgs, searches) → can "parasitically" use large-bandwidth trigger menus without relying on dedicated quarkonia triggers

Motivation

- *Single parton scattering (SPS)*
  - Both objects from the same diagrams
  - Enhances sensitivity to different matrix elements → new opportunities to test/develop theoretical models
  - Relative contributions of singlet versus octet production vs p_T may be different than inclusive production: measurements will help to address this long-running question
  - Possibility of resonant production from Higgs or New Physics

- *Double parton scattering (DPS)*
  - Each object from independent scatter
  - Difficult to address theoretically but are often invoked to explain (e.g.) rates of multiple heavy-flavour production
  - Quarkonia can be fully reconstructed → experimentally cleaner than alternatives methods (e.g. W+ 2 jets)
  - Wider range of measurements of DPS → more realistic models, allows tests of factorisation

Indistinguishable on an event-by-event basis. Can we find observables to disentangle the two statistically? → Expect differences in (e.g.) Δy and opening angle distributions between SPS and DPS… but can we do this well enough to be useful?

Summary of measurements

- Two measurements presented here of production of **prompt** J/ψ in association with W or Z bosons
- Each of these studies
  - establish beyond doubt the observation of associated quarkonia production
  - present a cross-section measurement
  - make provisional assessments of the degree of double/single parton scattering, or present the distributions that are likely to be able to separate them
- Very early days - more data and different combinations of objects are needed - studies should continue in 2015

	Experiment	∫ L	√s	Citation
J/ψ + W	ATLAS	4.6 fb^{-1}	7 TeV	JHEP 04 (2014) 172
J/ψ + Z (NEW)	ATLAS	20.3 fb^{-1}	8 TeV	To be released shortly

Analysis overview

1. Selection of relevant μμμμ, μμee or μμμ+MET events
2. Estimation of contamination from pile-up
3. Efficiency and acceptance corrections per candidate
4. Signal and background weights extraction
5. Signal and background yield extraction
6. Differential cross section evaluation
7. Production of relevant pair-wise distributions
8. Estimation of DPS contribution

Cross section *ratios*
$\sigma(J/\psi + W,Z) / \sigma(W,Z)$ presented:
most uncertainties cancel

W/Z from the the "primary" interaction, J/ψ from another

DPS contribution can be *estimated* with a simple calculation using the inclusive J/ψ cross section and DPS σ_{eff} (from W + 2 jets)

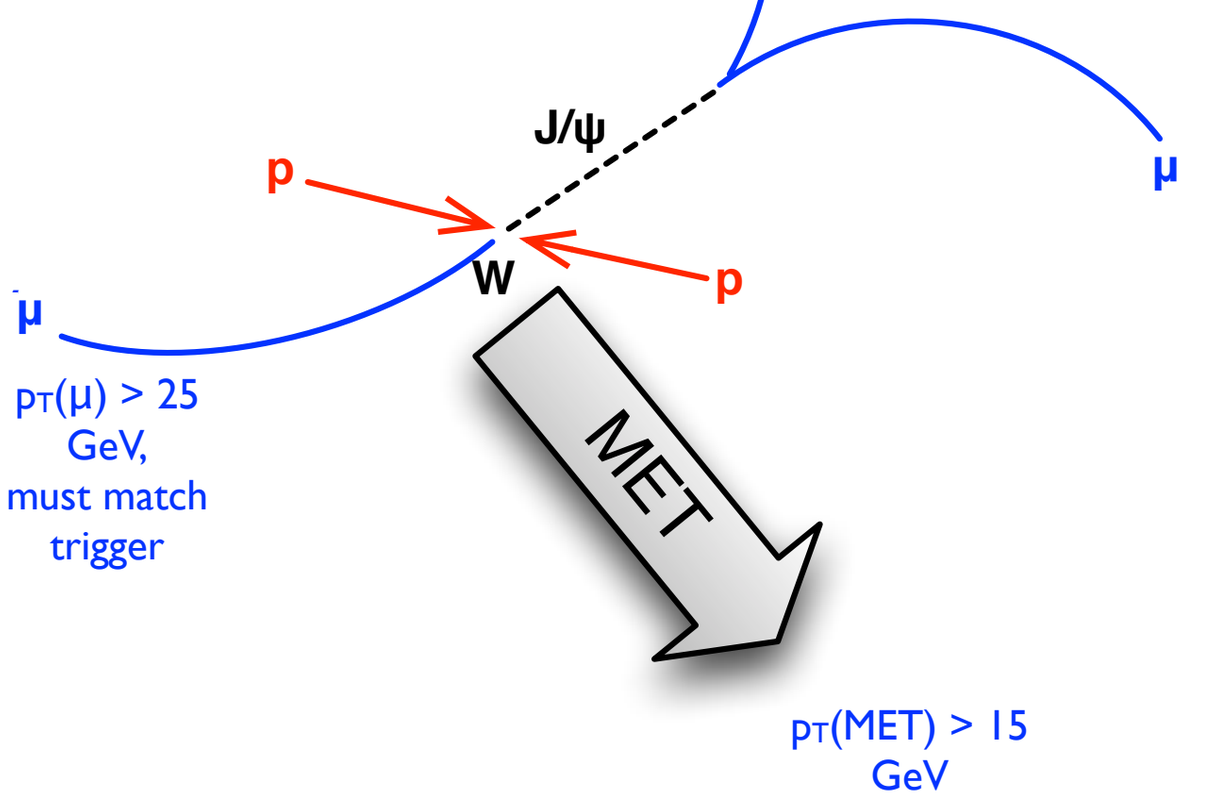
Final state

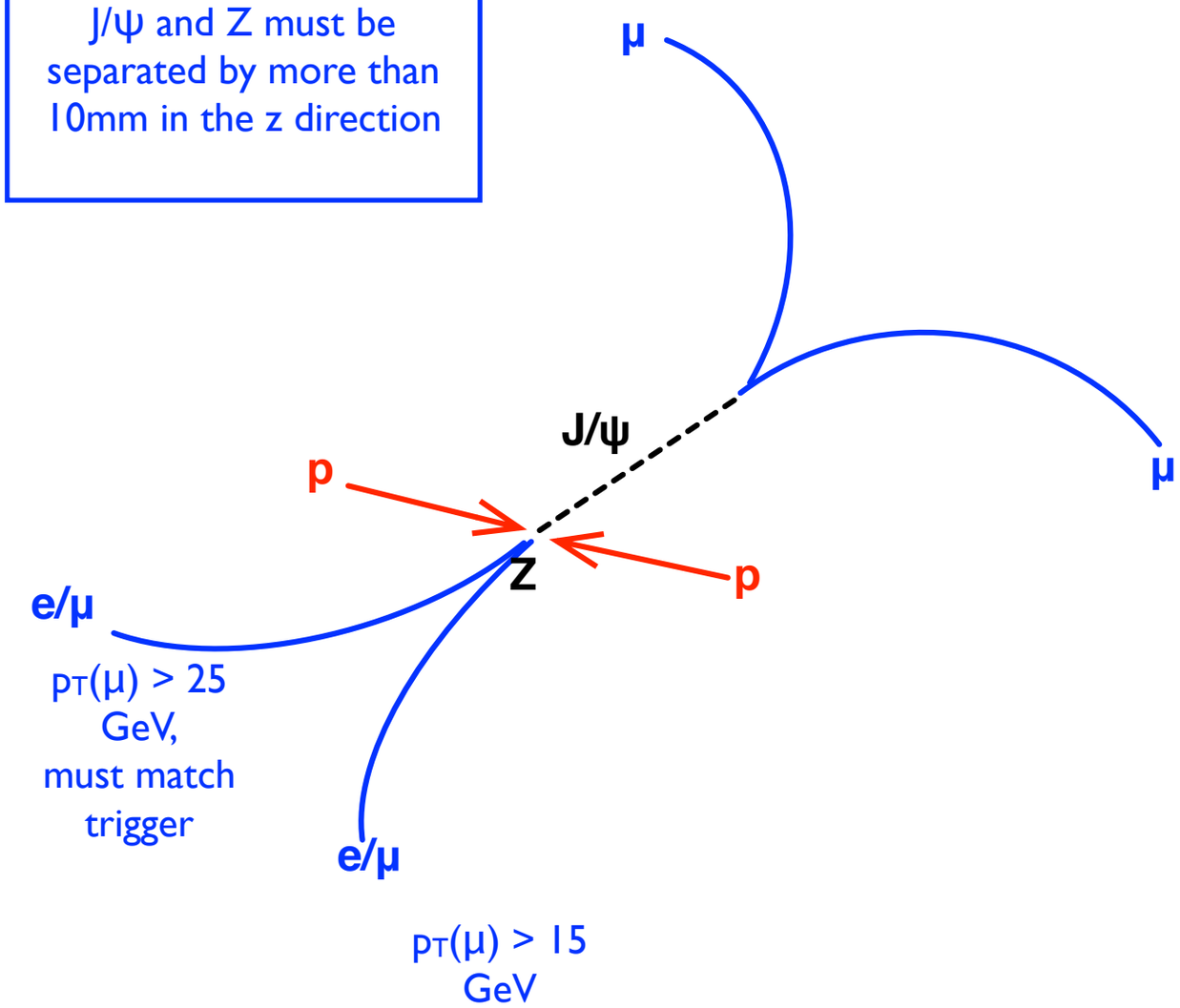
Triggers: single high pT muon/electron

Selections used in the pile-up estimation…

All three muons must have a point of closest approach to the interaction (in z) of less than 10mm.

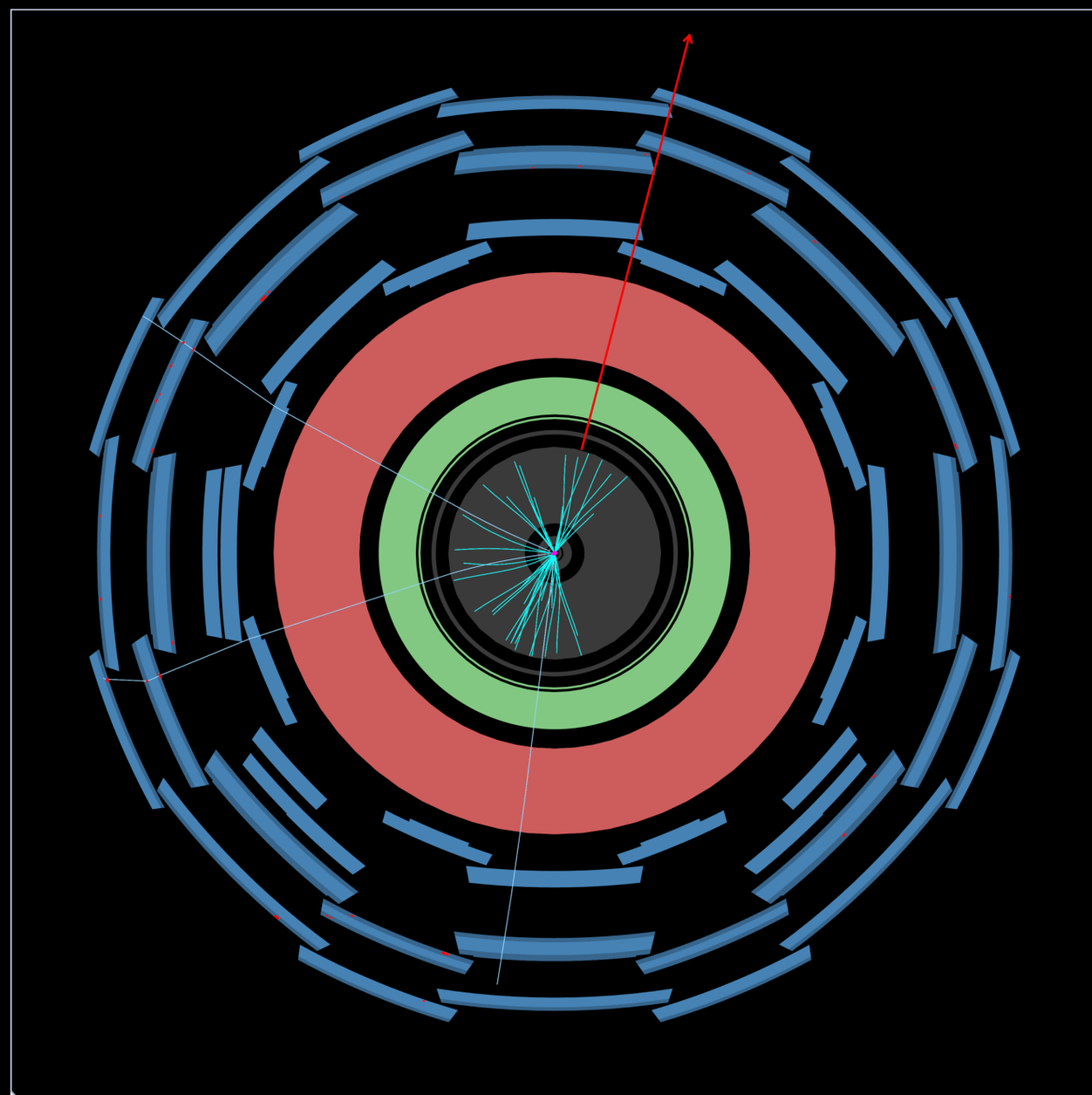
Vertices formed by the J/ψ and Z must be separated by more than 10mm in the z direction





J/ψ fiducial cuts are the same for both analyses after the acceptance corrections

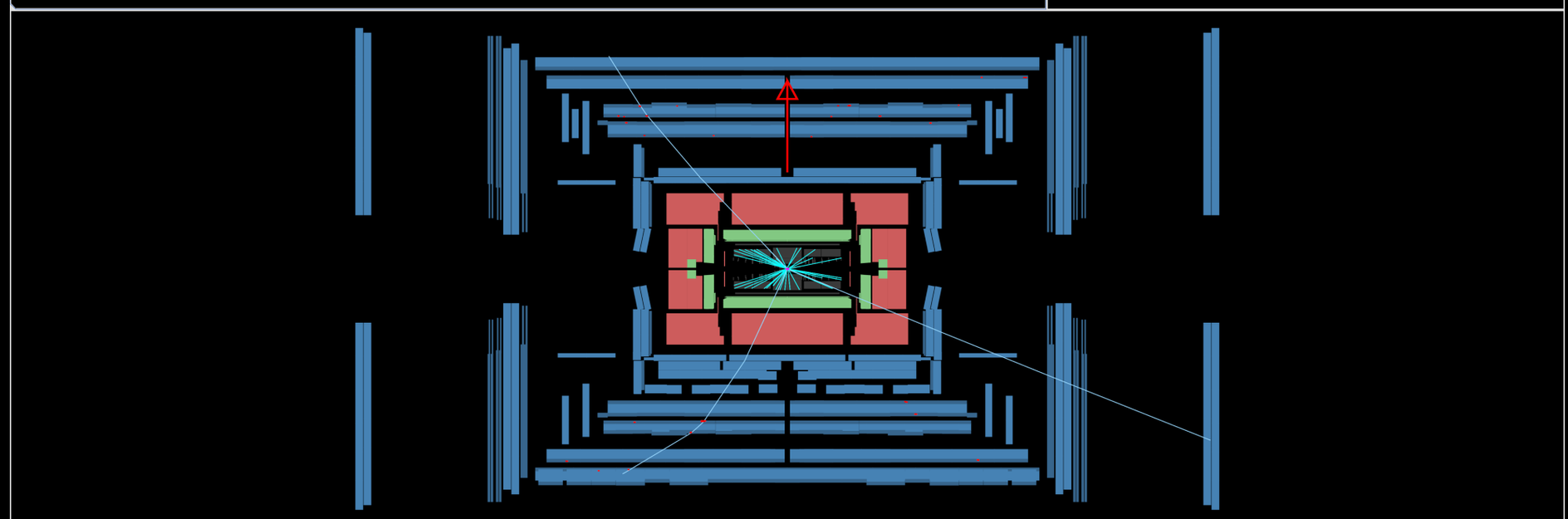
J/ψ+W



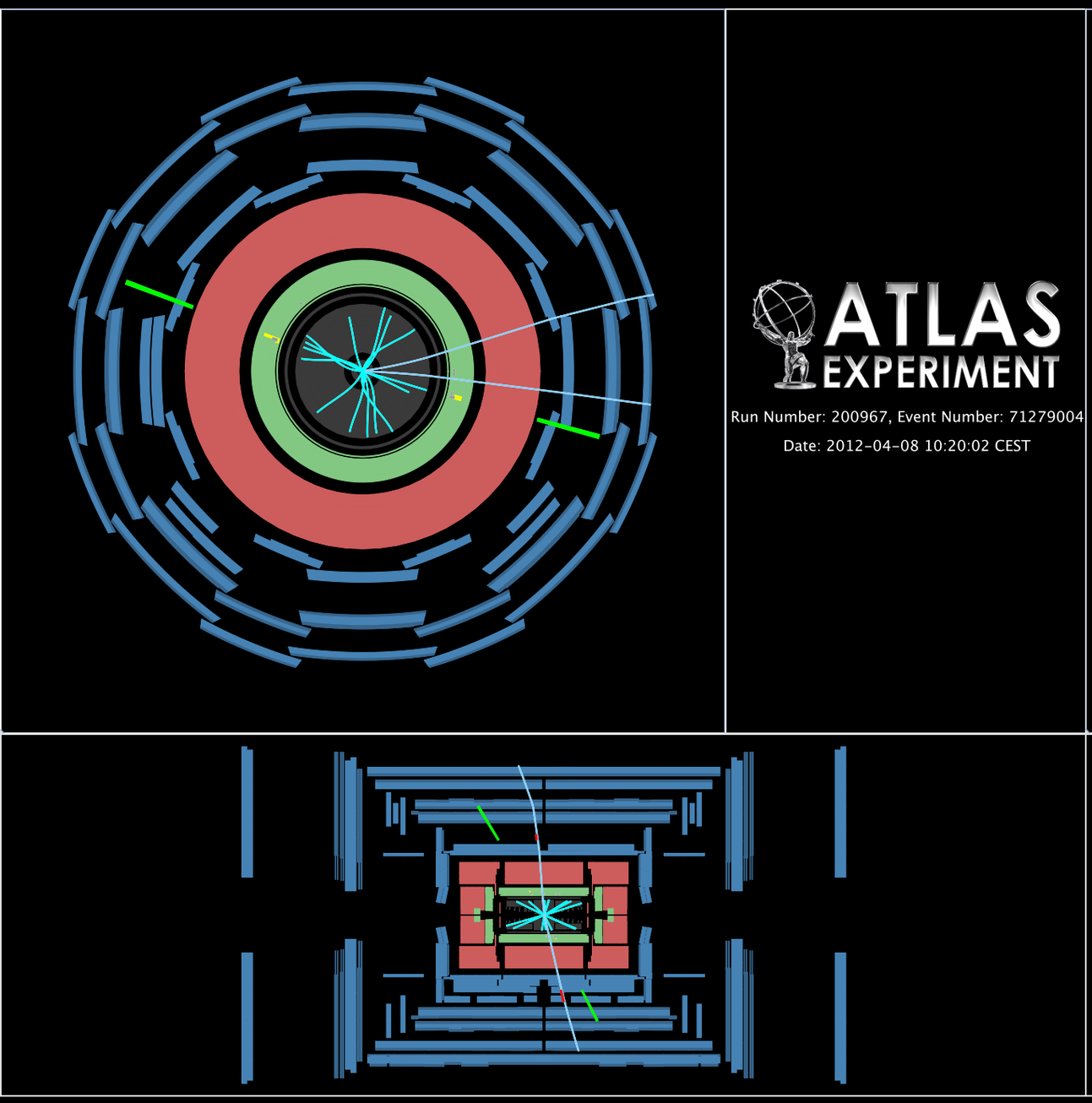
ATLAS EXPERIMENT

Run Number: 191513, Event Number: 11053516

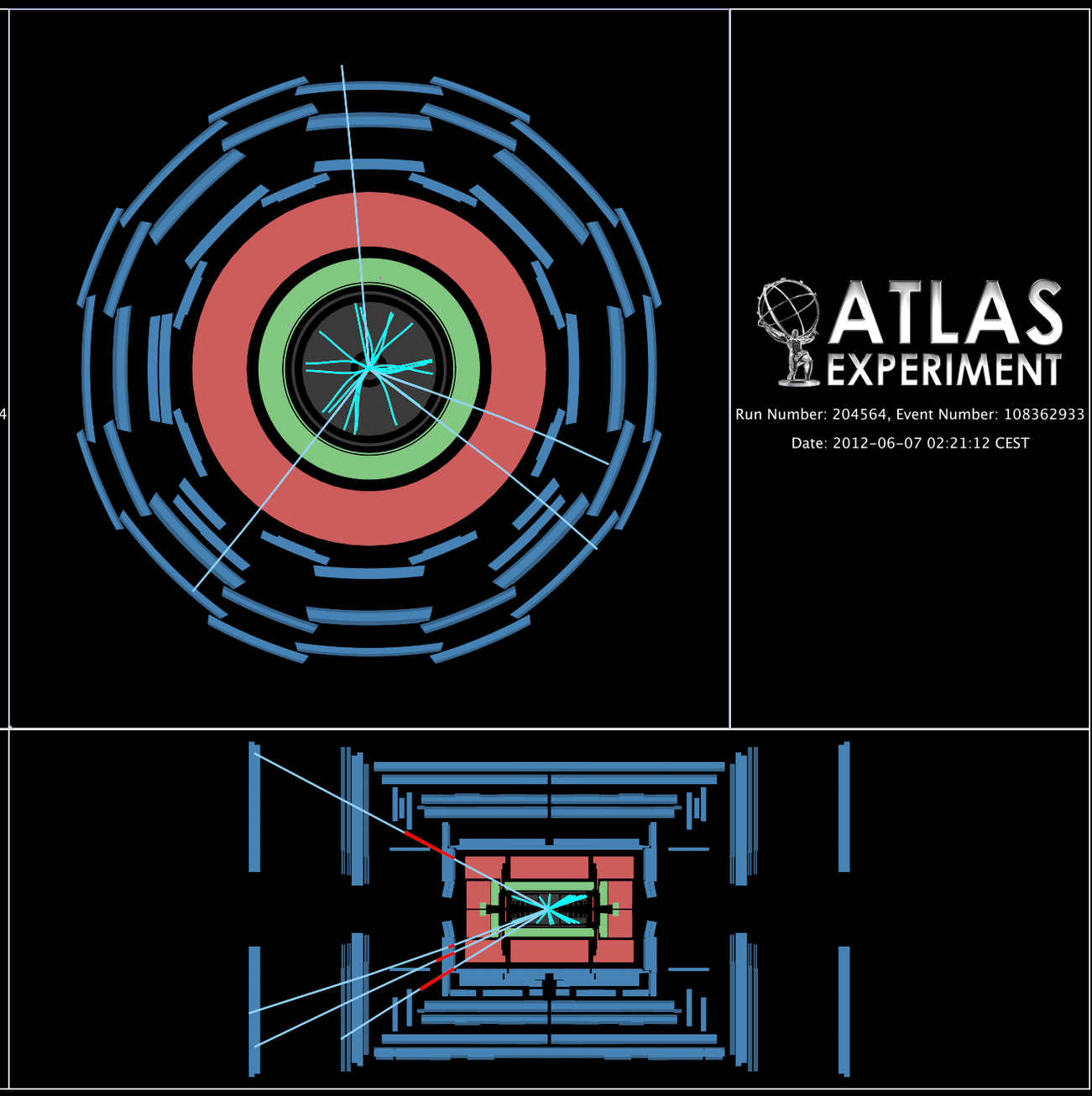
Date: 2011-10-23 17:21:09 UTC



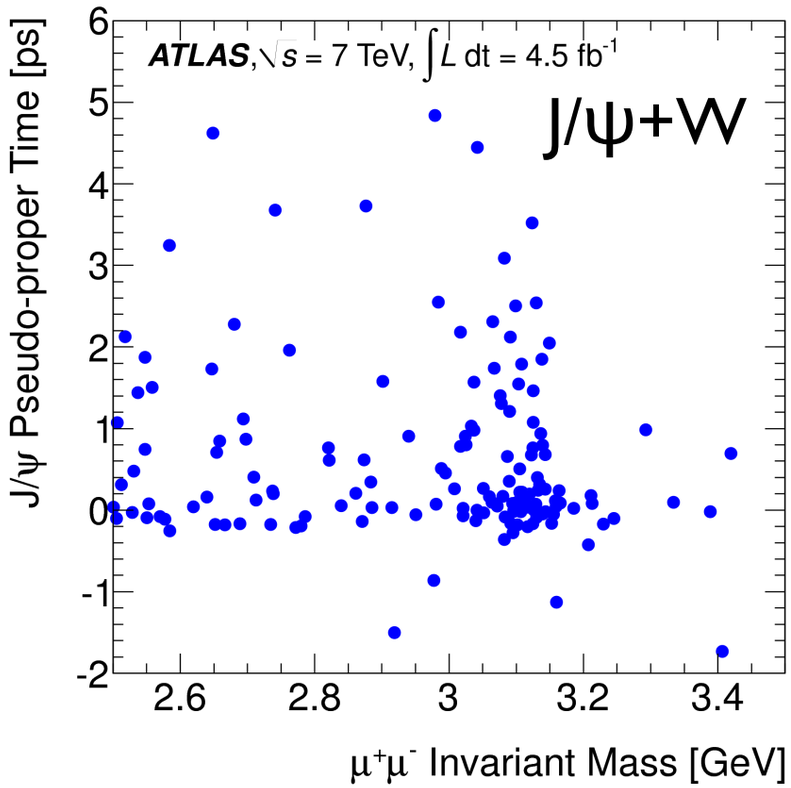
J/ψ+Z(ee)

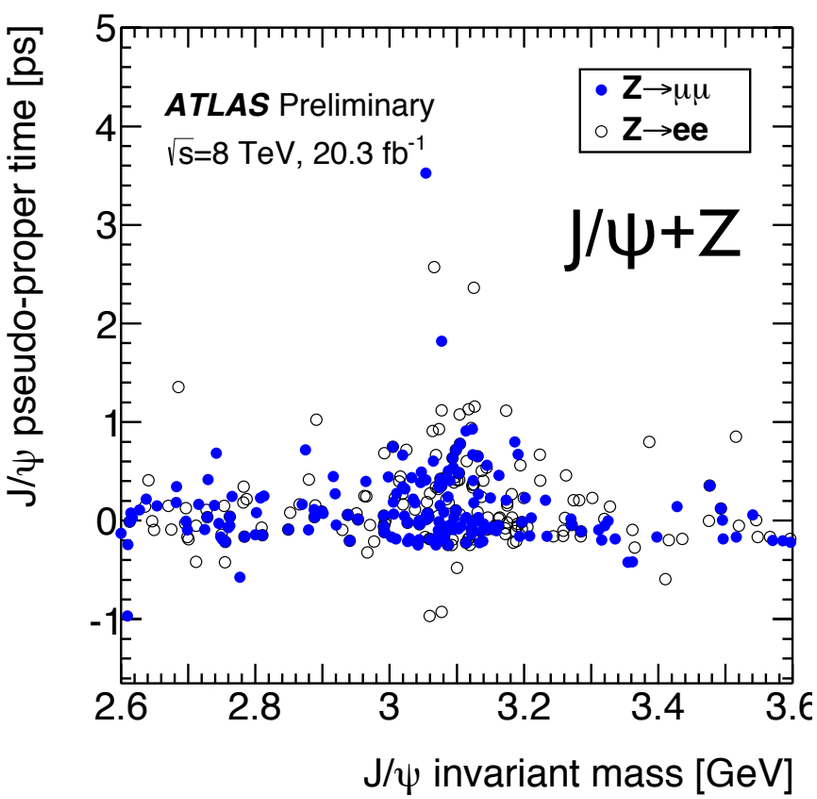

ATLAS
EXPERIMENT
Run Number: 200967, Event Number: 71279004
Date: 2012-04-08 10:20:02 CEST

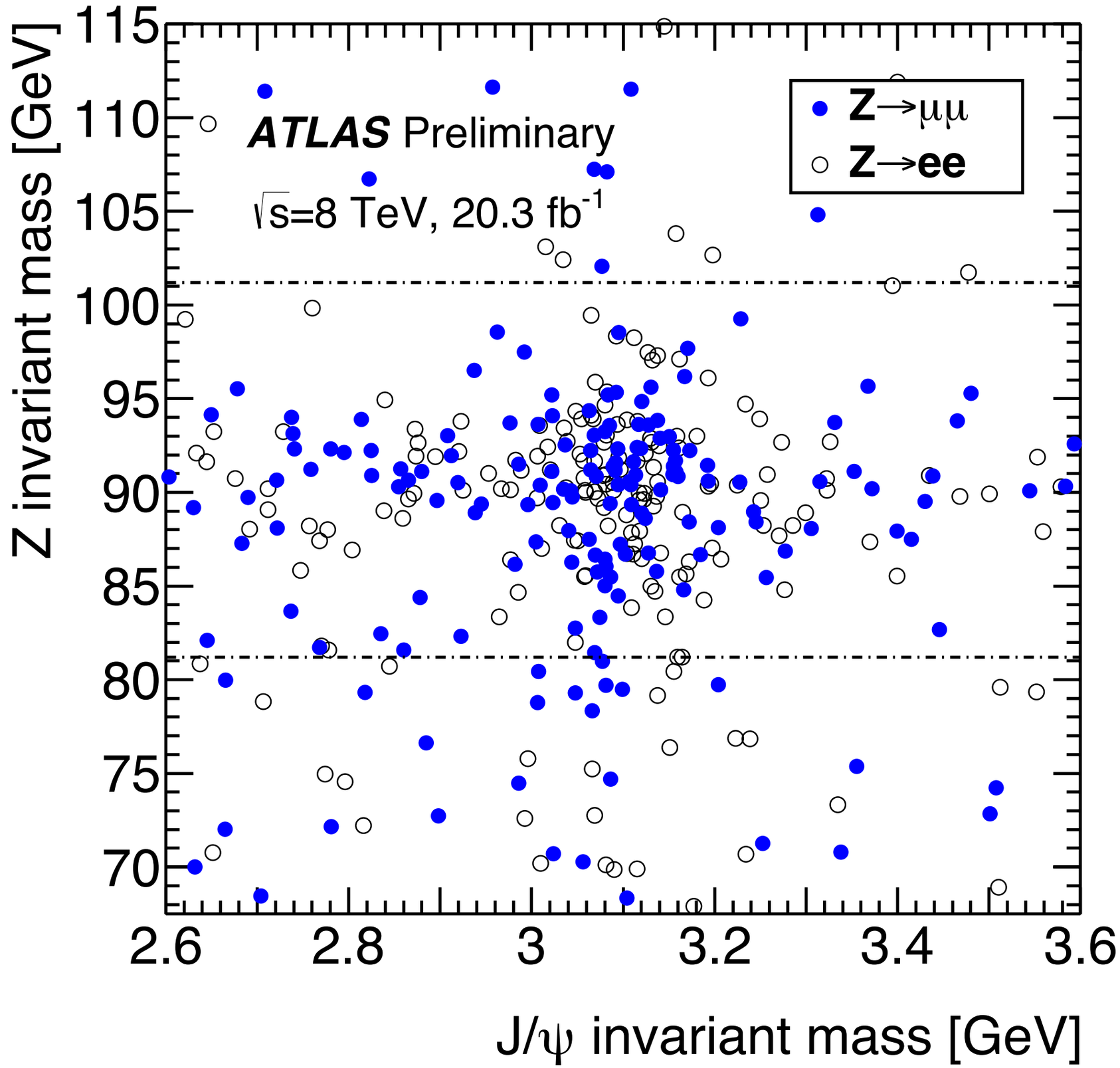
J/ψ+Z(μμ)


ATLAS
EXPERIMENT
Run Number: 204564, Event Number: 108362933
Date: 2012-06-07 02:21:12 CEST

Candidates


ATLAS, √s = 7 TeV, ∫L dt = 4.5 fb-1
J/ψ+W
J/ψ Pseudo-proper Time [ps]
μ+μ- Invariant Mass [GeV]


ATLAS Preliminary
√s=8 TeV, 20.3 fb-1
Z→μμ
Z→ee
J/ψ+Z
J/ψ pseudo-proper time [ps]
J/ψ invariant mass [GeV]


ATLAS Preliminary
√s=8 TeV, 20.3 fb-1
Z→μμ
Z→ee
Z invariant mass [GeV]
J/ψ invariant mass [GeV]

Corrections and yield extraction

- Acceptance and efficiency corrections derived from MC and applied per candidate
  - Range of acceptance corrections, constructed under extreme polarisation scenarios, are deployed
- Signal weights extracted using sPlot with the following discriminants:
  - Masses of the two J/ψ candidates
  - L_{xy} of the two J/ψ candidates
- Four categories of event are described in the fits
  - W, Z candidate + real prompt J/ψ **(SIGNAL)**
  - W, Z candidate + real non-prompt J/ψ **(measured for J/ψ+Z)**
  - 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

Backgrounds

- Backgrounds not covered by the fits found to be negligible:
  - fake W/Z (from top/multi-jet)
  - Contamination from Bc → $J/\psi\mu^{\pm}\nu_{\mu}X$
- **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

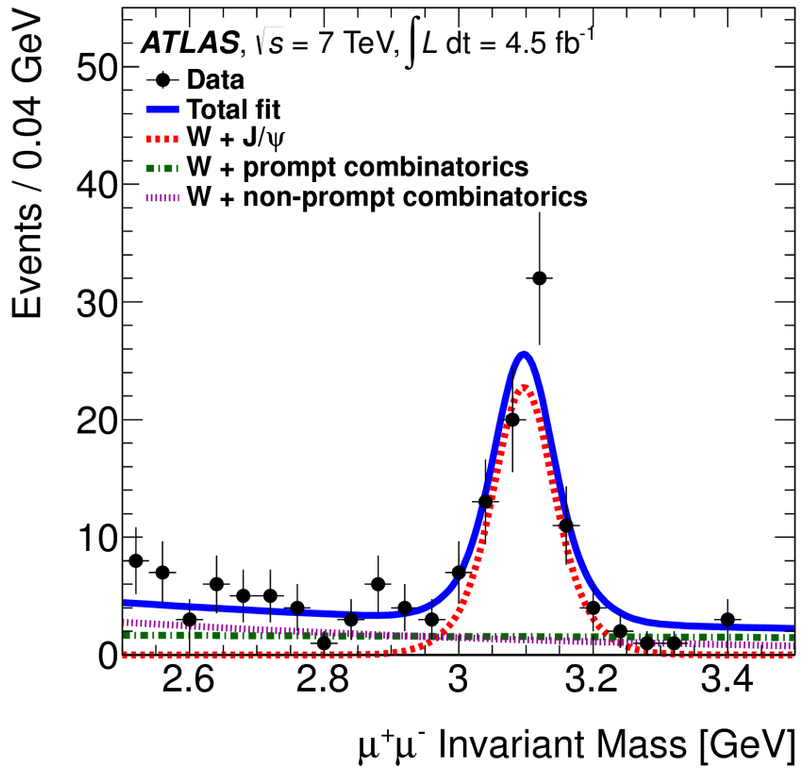
$$P^{ij}_{J/\psi} = \sigma^{ij}_{J/\psi}/\sigma_{\text{inel}}$$

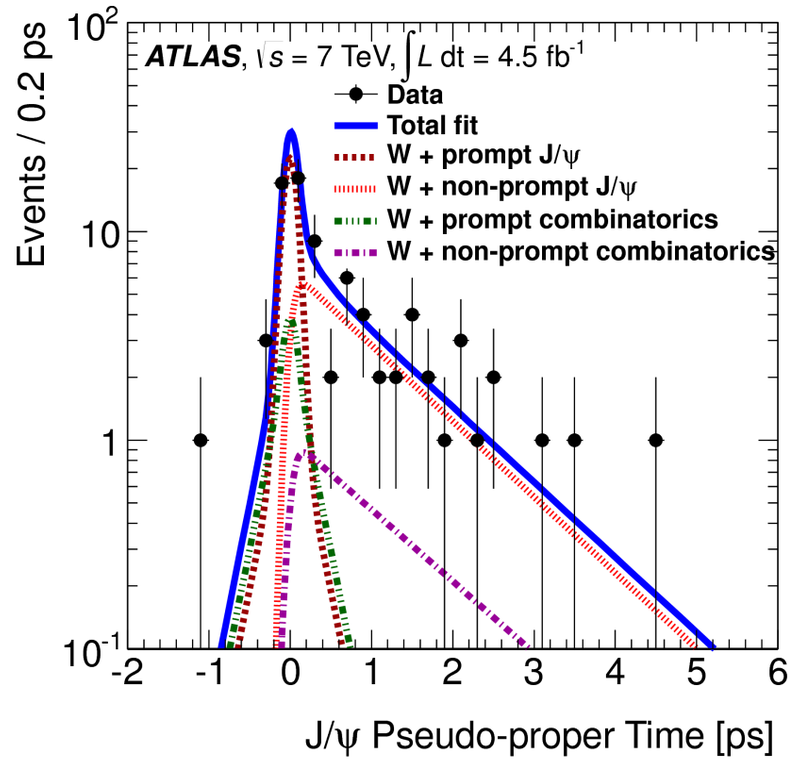
→

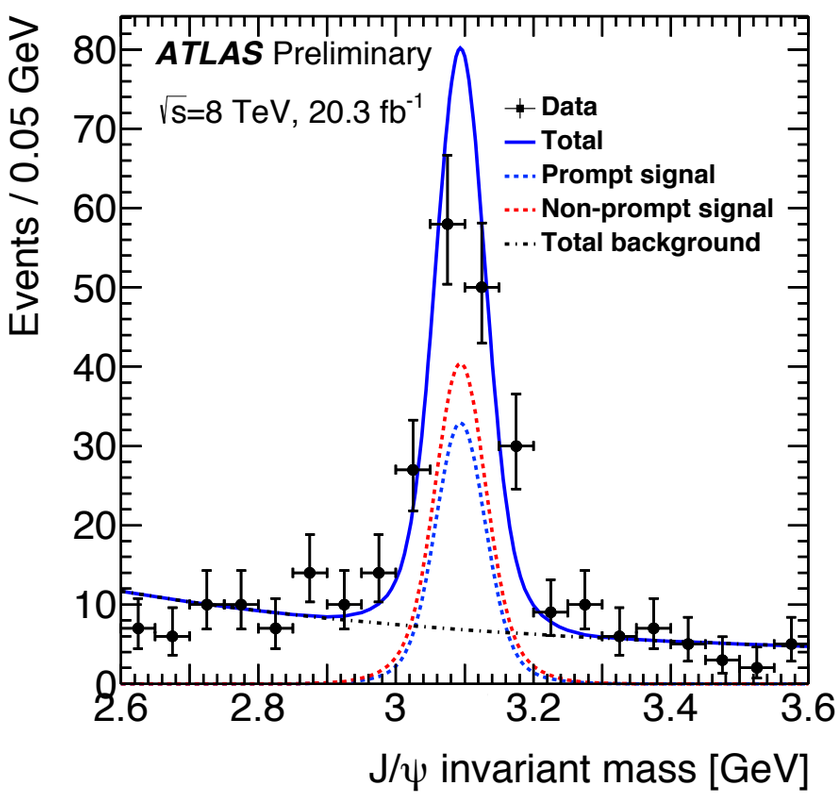
Pile-up contamination estimate:
1.8 ± 0.2 events in J/ψ+W
$5.2^{+1.8}_{-1.3}$ prompt J/ψ+Z
$2.7^{+0.9}_{-0.6}$ non-prompt J/ψ+Z

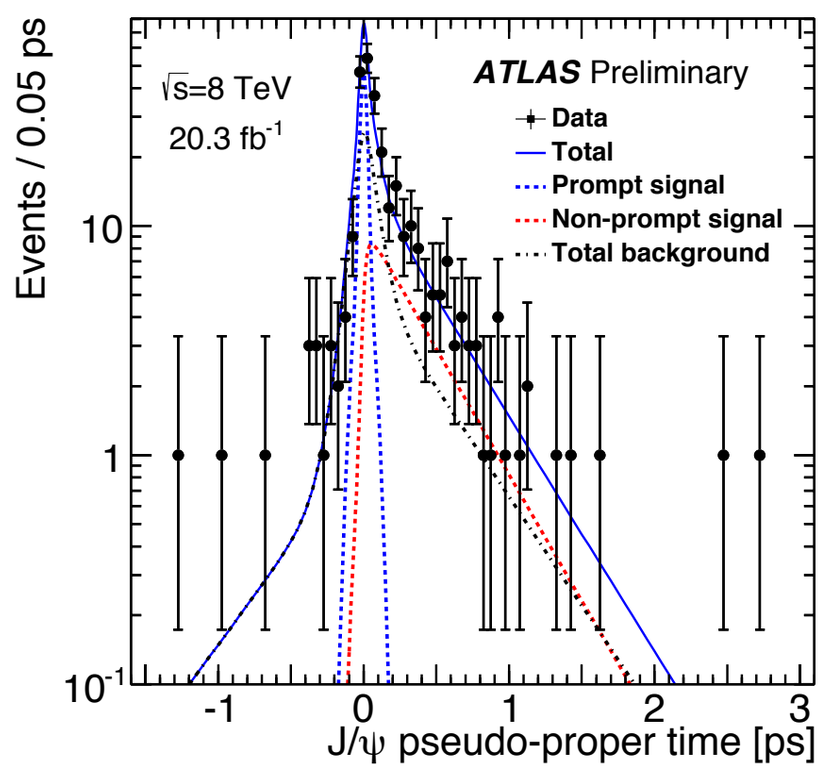
N_{extra} = **2.3 ± 0.2** for the J/ψ+Z
N_{extra} = **0.81 ± 0.08** for the J/ψ+W

Corrections and yield extraction





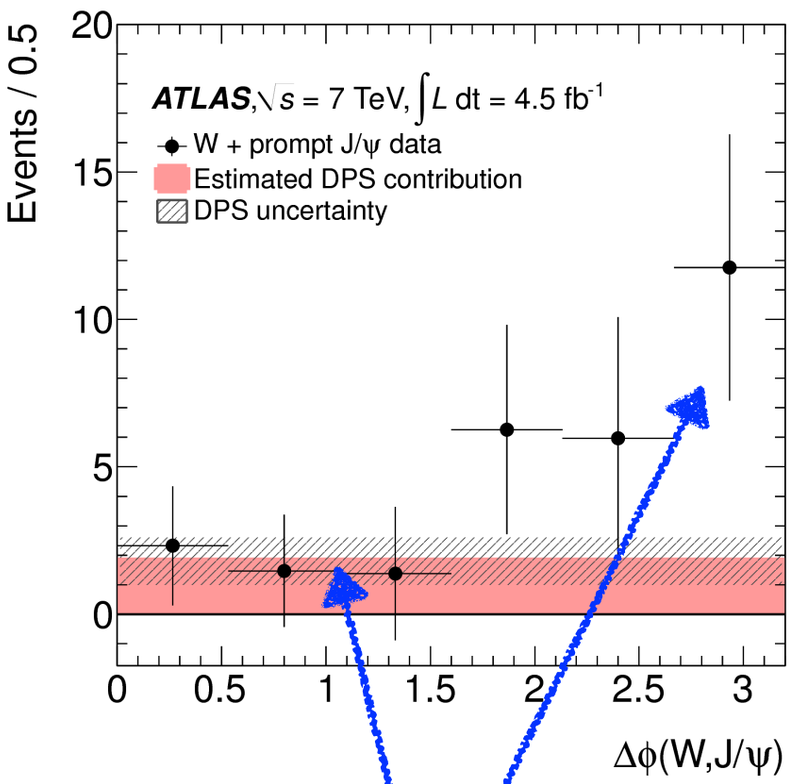


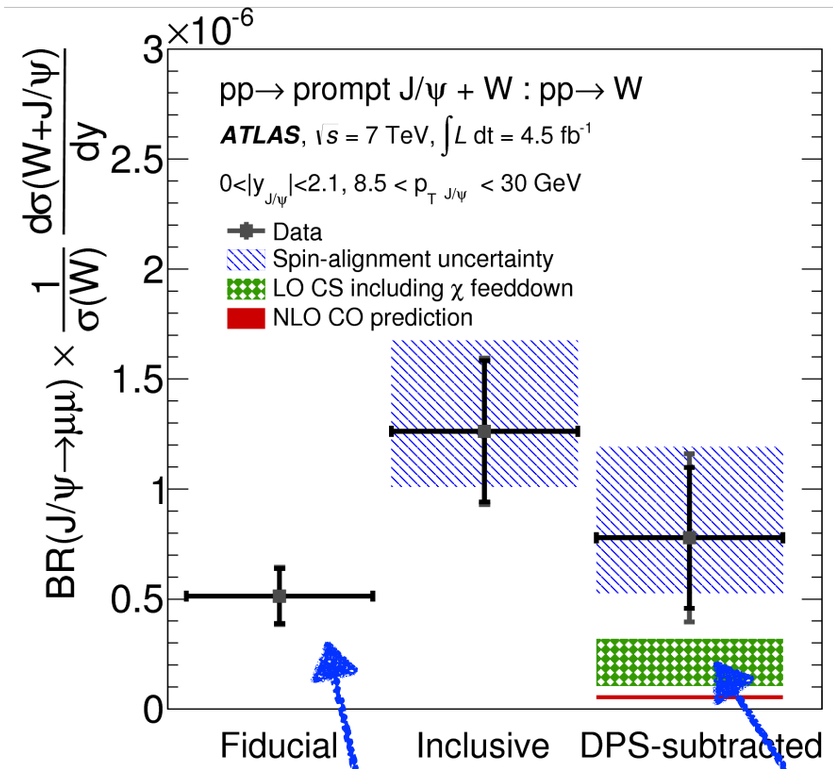


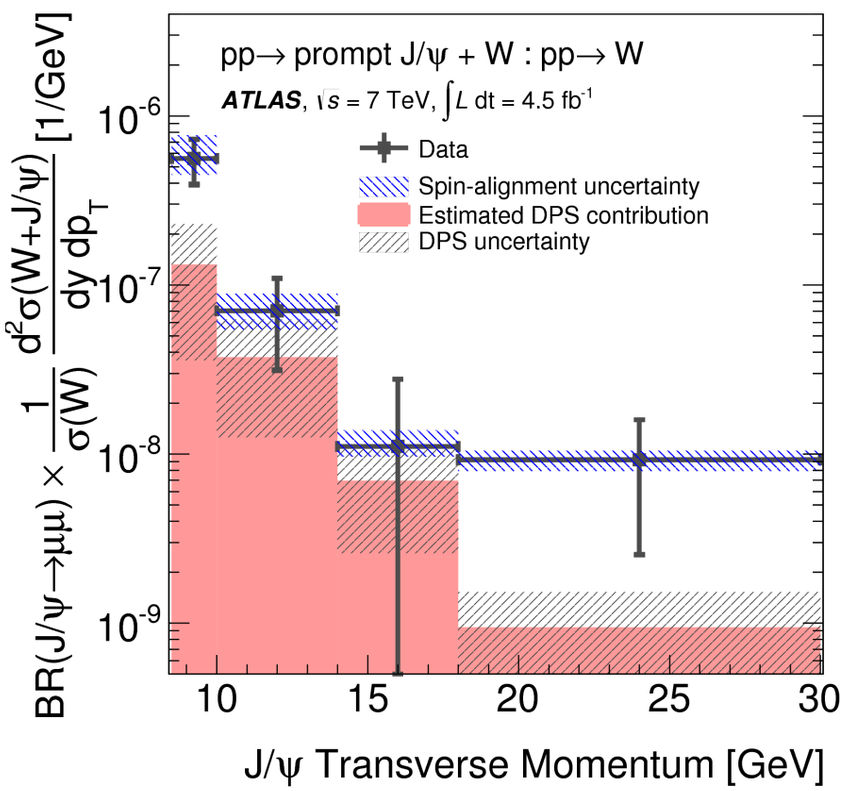
- Signal weights extracted using the mass and lifetime distributions
- Differential cross section ratio calculated by slicing the weighted sample into kinematic bins and evaluating the yield in each bin

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

J/ψ+W results







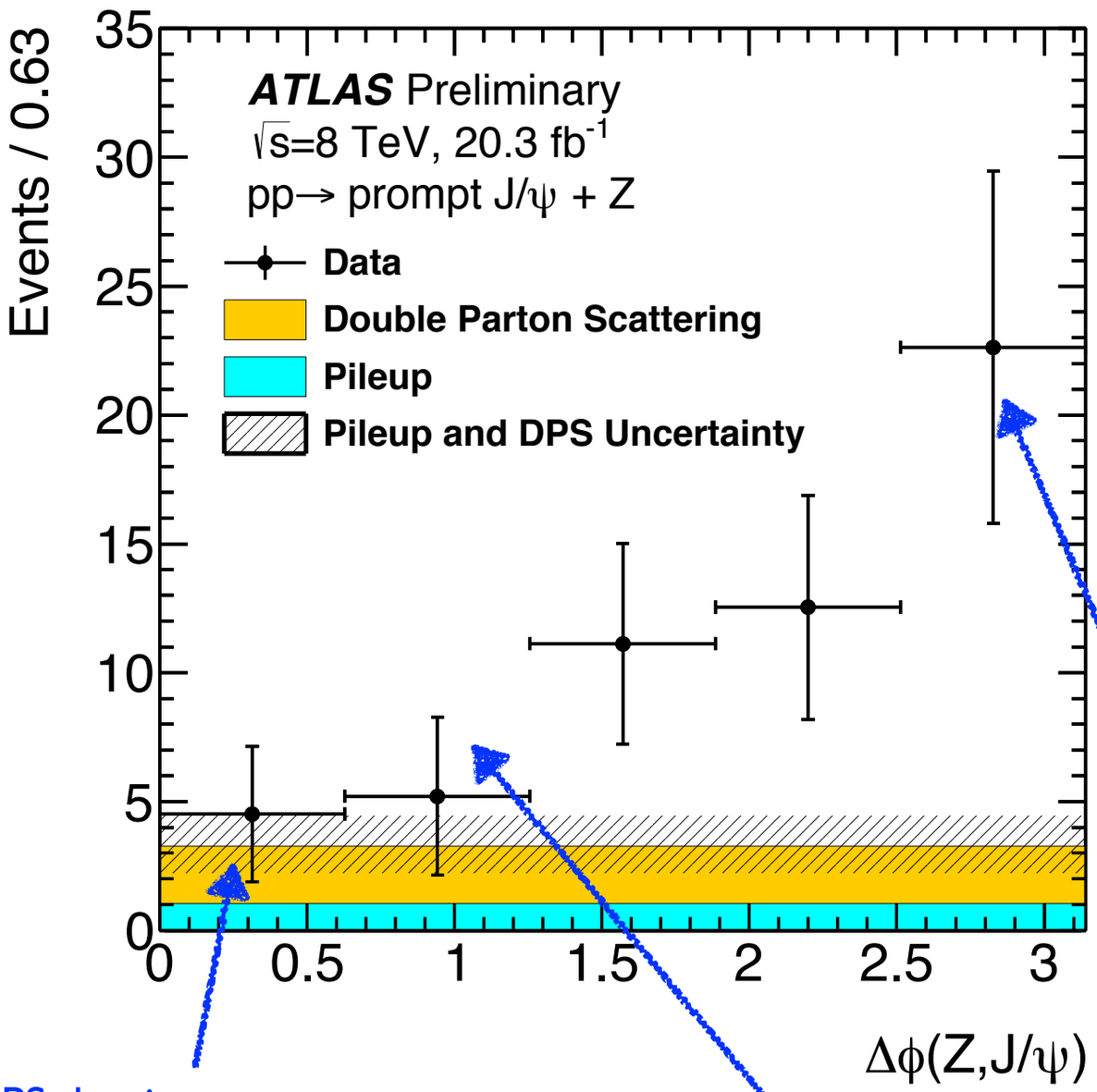
Naively, one expects DPS to be flat in azimuthal opening angle if the two processes are entirely uncorrelated…
so is this an indication of DPS and SPS J/ψ+W production?

No acceptance corrections

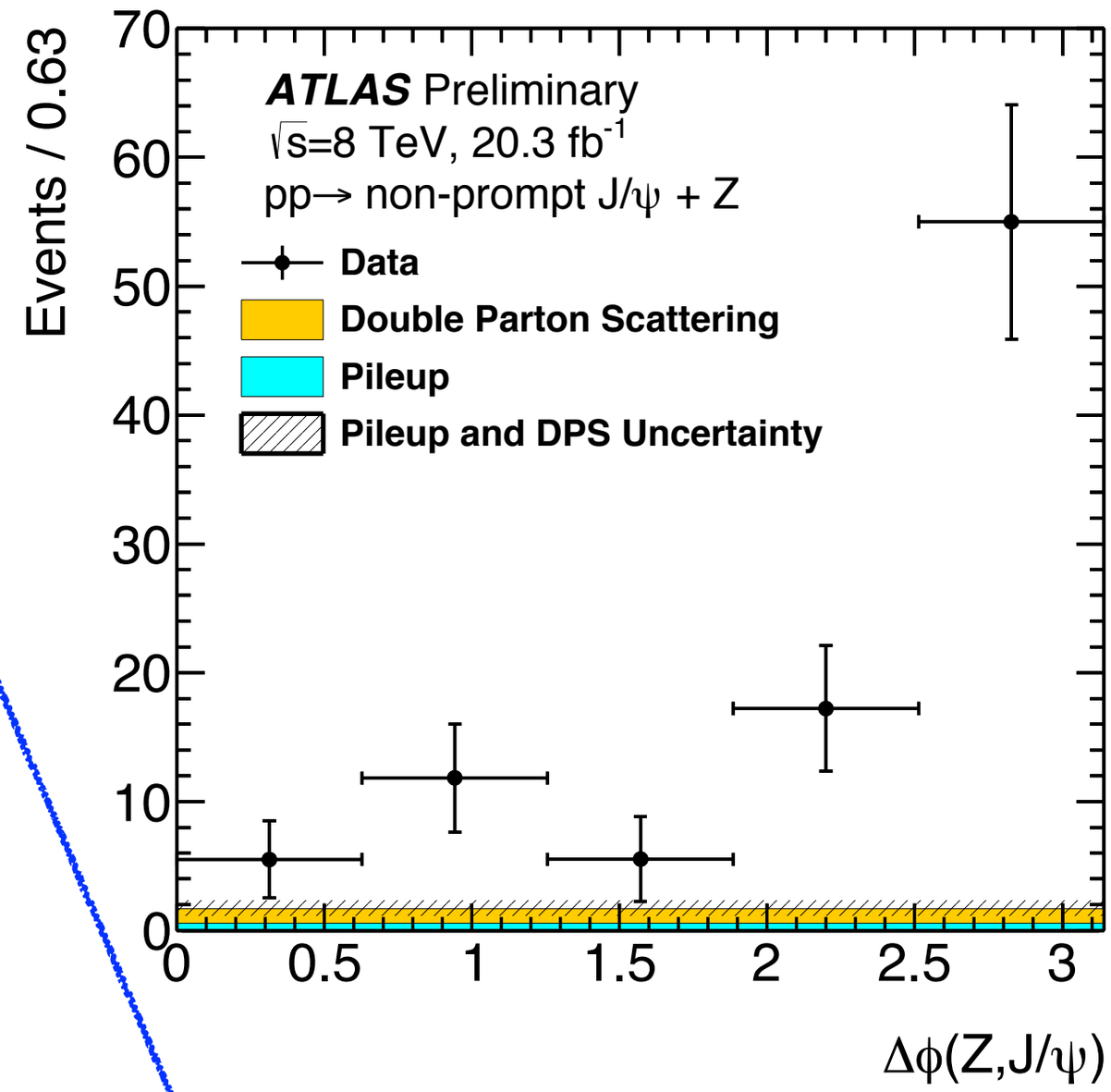
Looks as though the estimated SPS contribution isn't fully accounted for by theory
… note this erratum to the CS prediction: PL B 738 (2014) 529-529 - reduces CS component

J/ψ+Z results: azimuthal opening angle

Prompt



Non-prompt



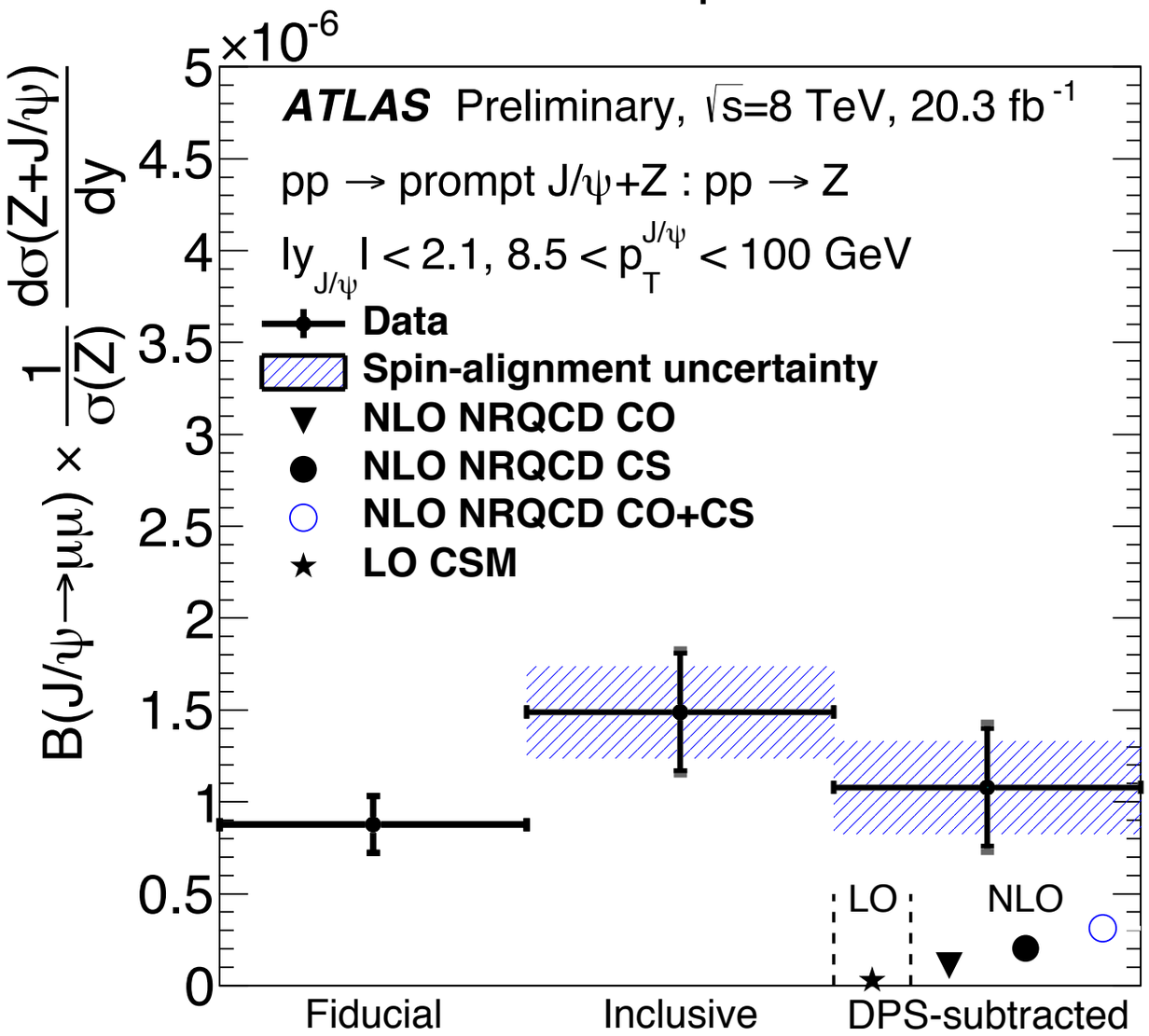
DPS dominates this bin

Same pattern is observed in the azimuthal opening angle as with the W

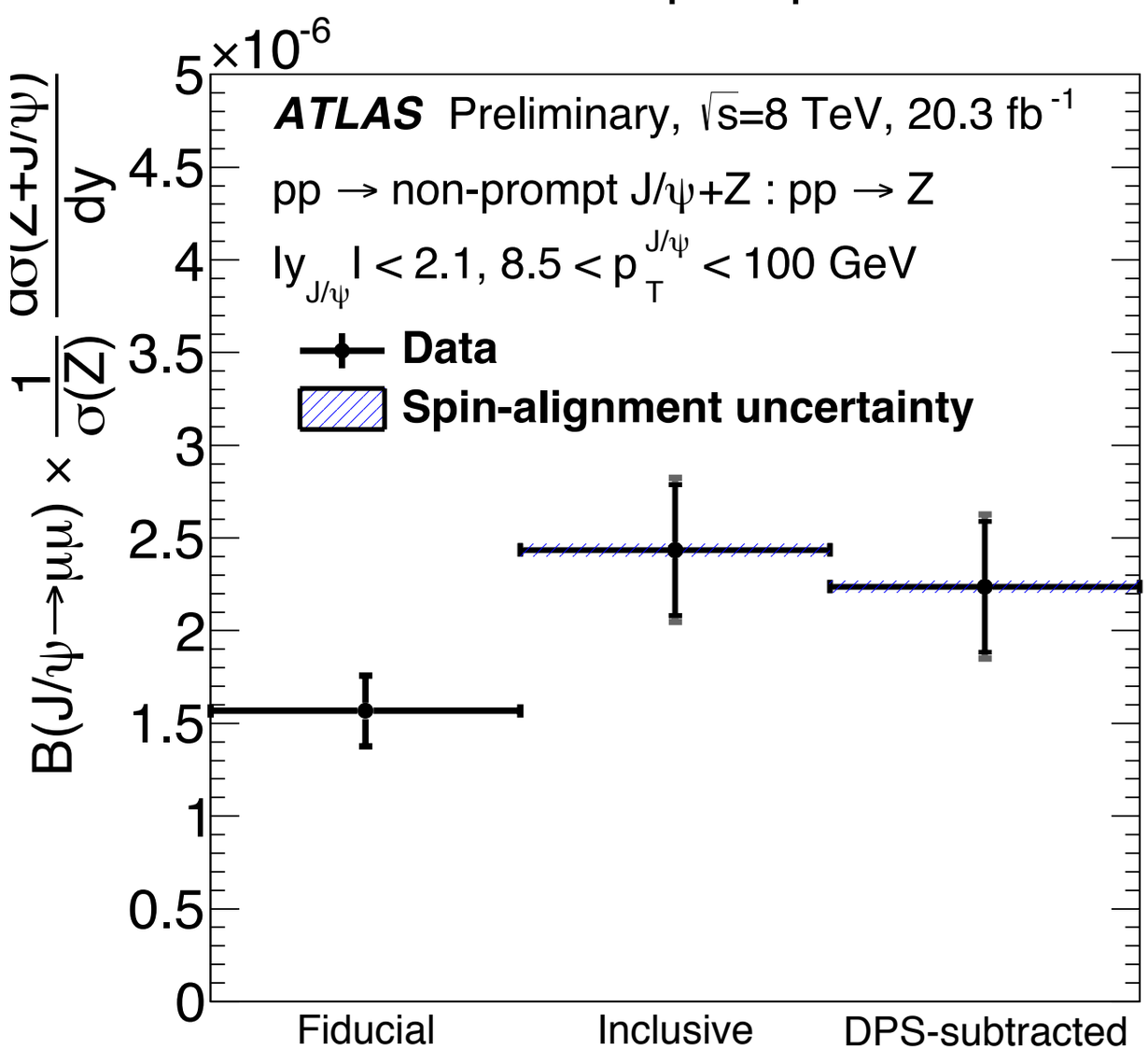
Again the DPS band is an *estimate*

J/ψ+Z results: total cross sections

Prompt



Non-prompt

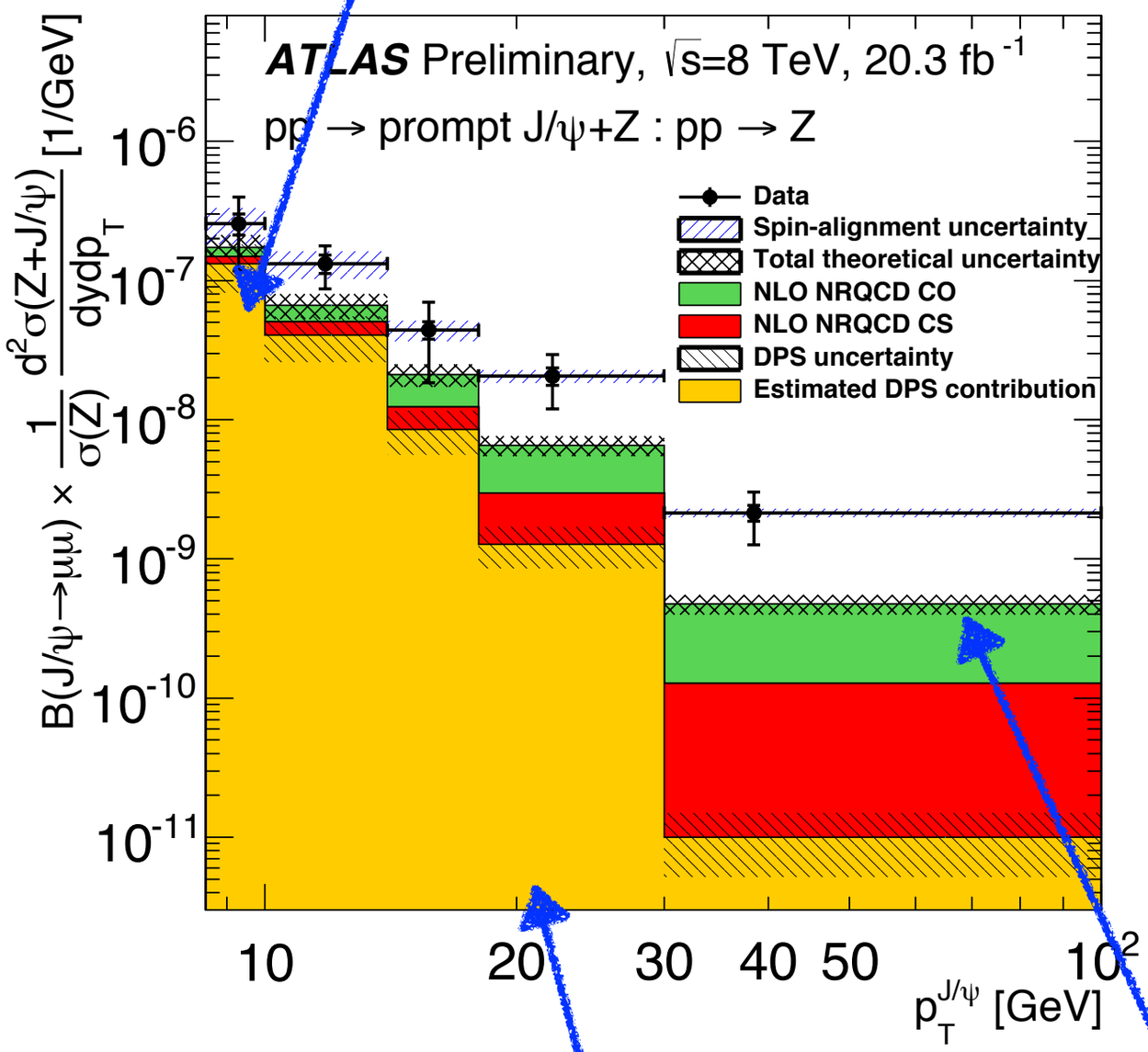


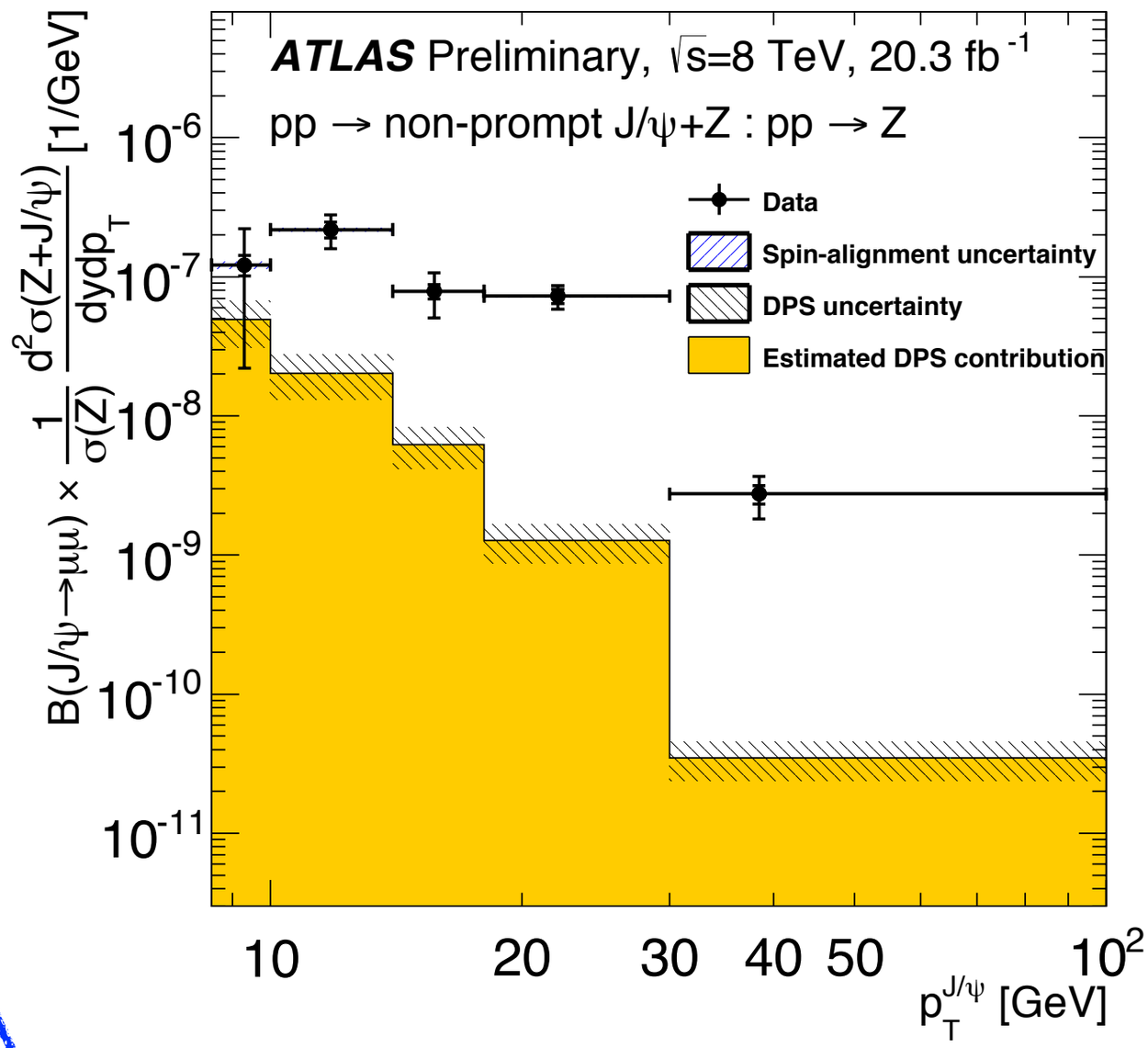
NRQCD: JHEP 1102 (2011) 071 (Mao et al.)
CSM: JHEP 1303 (2013) 115 (Gong et al.)

Theory may be under-estimating SPS production
(but the experimental errors almost cover it)
NLO NRQCD with both octet and singlet contributions does
Feed-down component not included in these predictions

J/ψ+Z results: differential cross sections

Lowest pT bin ~mostly DPS



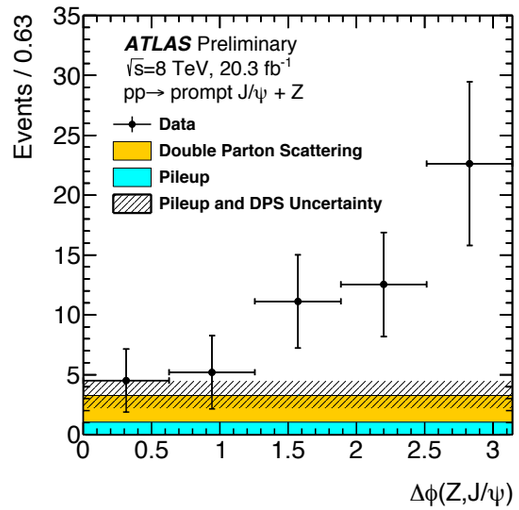


SPS drops off less steeply with p_T than DPS so highest bins are SPS dominated

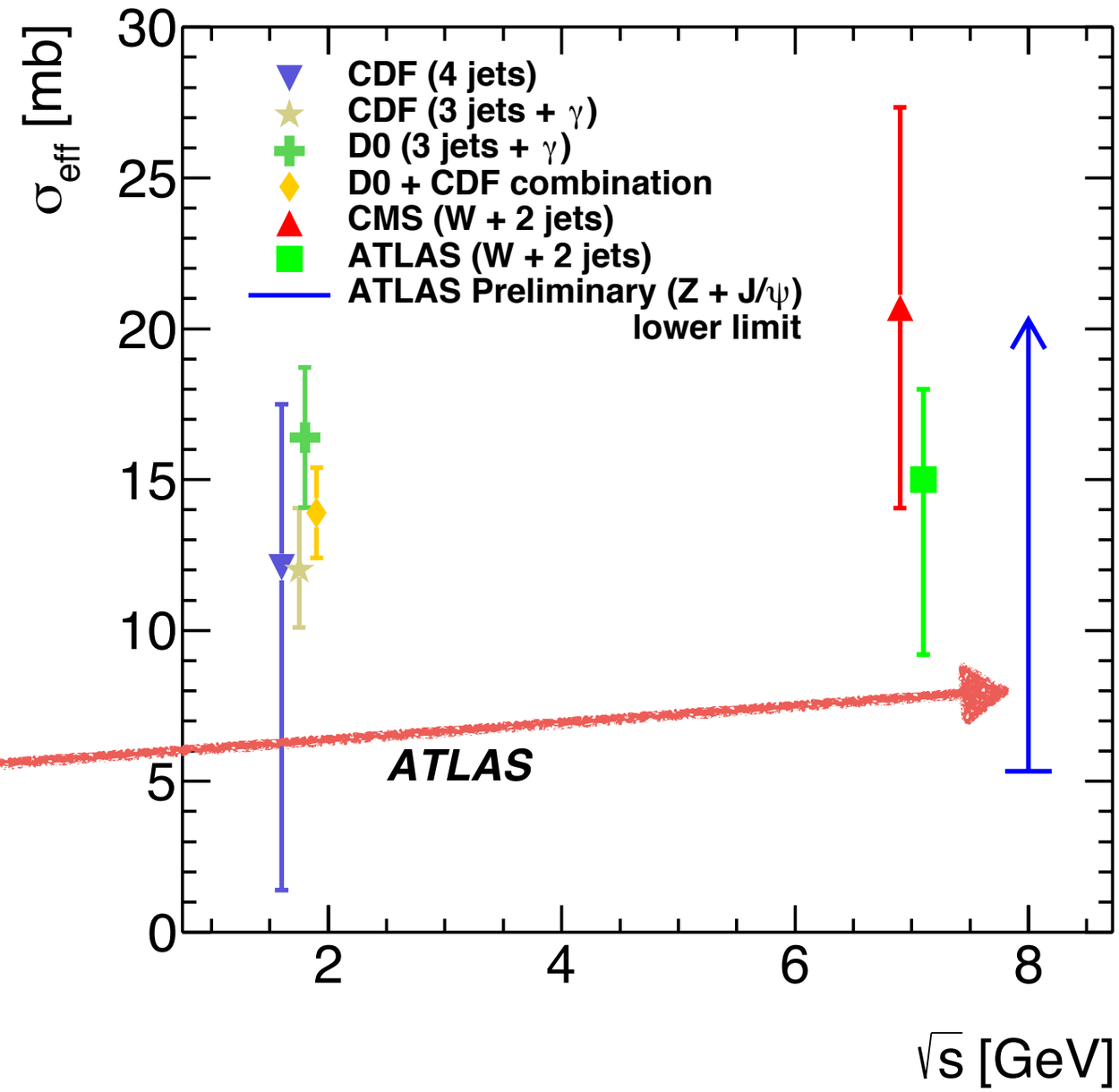
Theory discrepancy gets more pronounced with increasing p_T c.f. inclusive spectra, where NRQCD now does a reasonable job

J/ψ+Z results: lower limit on σ_{eff}

- Back to this plot…
- Assuming that the first bin is due to DPS…



- … can 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



- Very early days, but shows that using quarkonia for studying DPS is a realistic prospect

WANTED: models for the SPS contribution to V+J/ψ, particularly as a function of $\Delta\phi$

→ allows better estimate of the DPS component

→ allows 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 objects
  - $J/\psi+J/\psi$, $J/\psi+W$, $J/\psi+Z$
- These processes will help to address issues of:
  - singlet versus octet production of quarkonia
  - double parton scattering
  - resonant production
- Due to the low production rate, clean experimental signature and use of higher mass objects, we should be able to collect significant numbers of these decays in LHC Run-2 whilst staying within reasonable trigger thresholds
  - Very positive outlook for these studies

Supplementary slides

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
J/ψ selection
$8.5 < p_{\mathrm{T}}(J/\psi) < 100$ GeV, $\lvert y(J/\psi)\rvert < 2.1$
p_{T} (leading muon)> 4.0 GeV, $\lvert\eta(\text{leading muon})\rvert < 2.5$
OR $\left\{ \begin{array}{ll} p_{\mathrm{T}} \text{ (sub-leading muon)} > 2.5 \text{ GeV}, & 1.3 \leq \lvert\eta(\text{sub-leading muon})\rvert < 2.5 \\ p_{\mathrm{T}} \text{ (sub-leading muon)} > 3.5 \text{ GeV}, & \lvert\eta(\text{sub-leading muon})\rvert < 1.3 \end{array} \right\}$

+ one lepton must have fired the trigger

+ must fit to vtx

+ must fit to vtx

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

J/ψ+Z theory references

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