Quarkonium Particles and Tracking Detectors at the LHC

New Fellow
Show and Tell

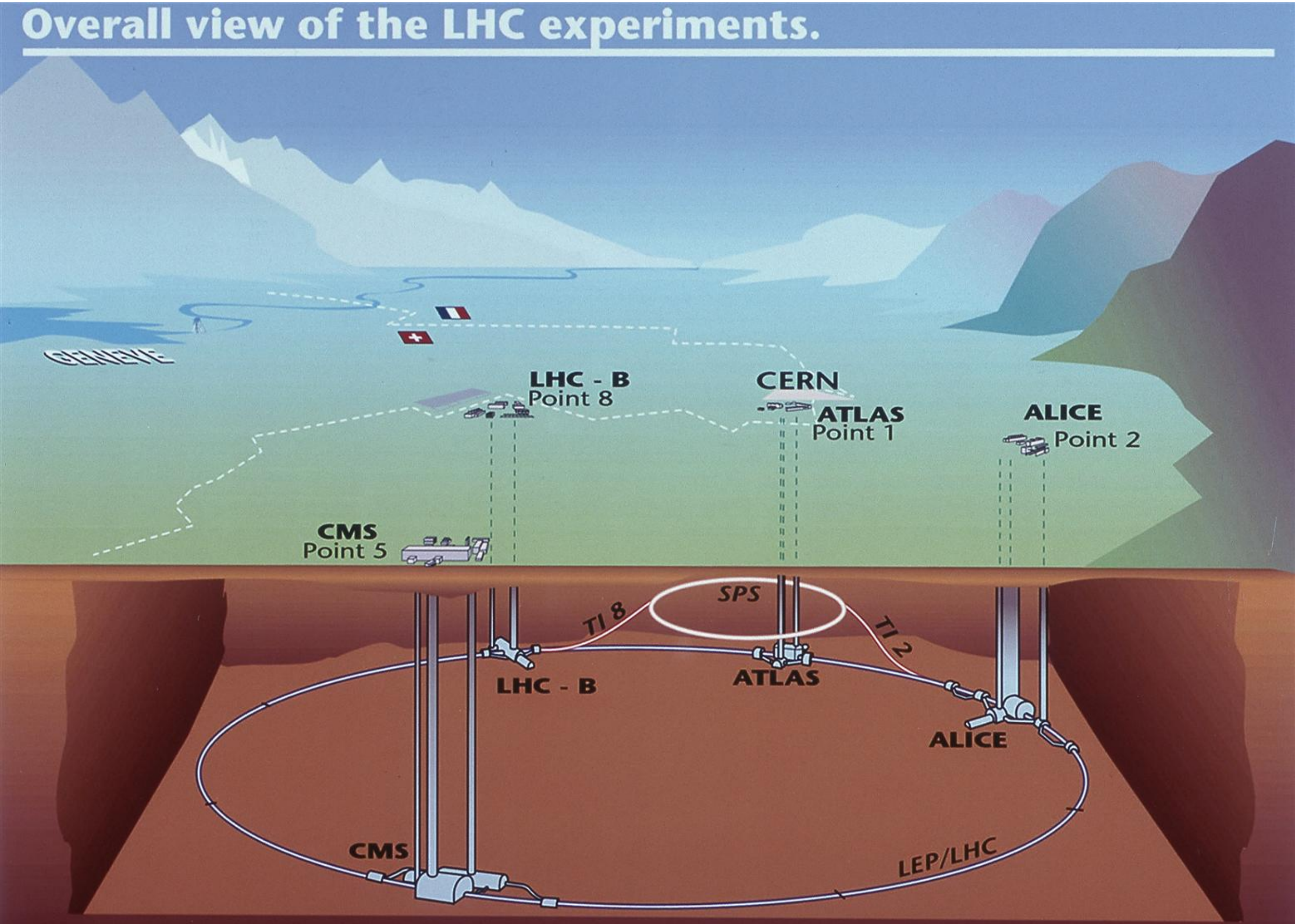
David Bertsche

November 29th 2016

- Born near Lyon, France to American aid workers
- Raised in Congo (DRC) and Botswana
- University in Indiana
- Engineer in Seattle (Boeing 787, Air Force One)
- Masters at the University of Oklahoma
- PhD at CERN on ATLAS
- Joined DESY CMS in September

Hobbies:
Running, Choir (Bass)

The Large Hadron Collider (LHC)



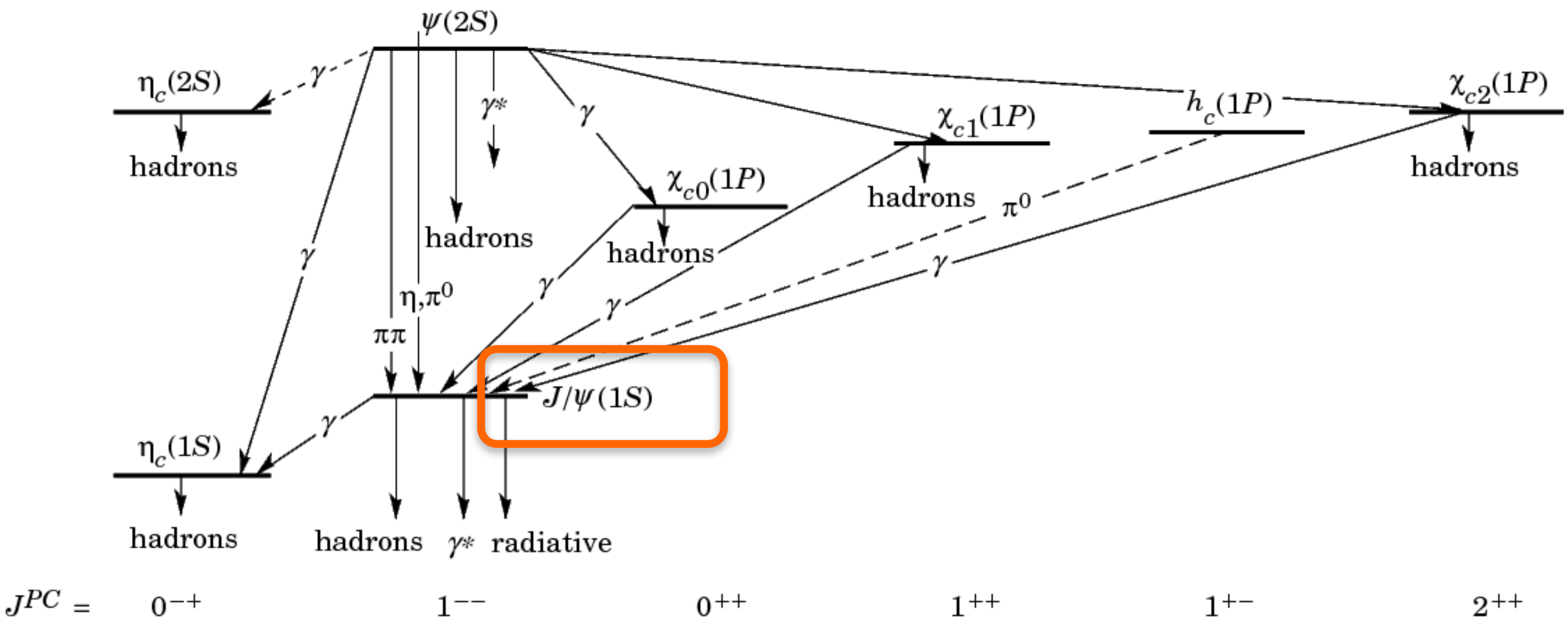
CERN

Est. 1954

- 27 km circumference
- ~100 m underground
- Began operations 2008
- Accelerates *protons* to 99.9999 % *c*
- *proton-proton* collisions briefly create exotic particles
- Detectors quickly photograph them

Quarkonium Production at the LHC

- Offers a unique window to **strong** interaction and **proton** structure



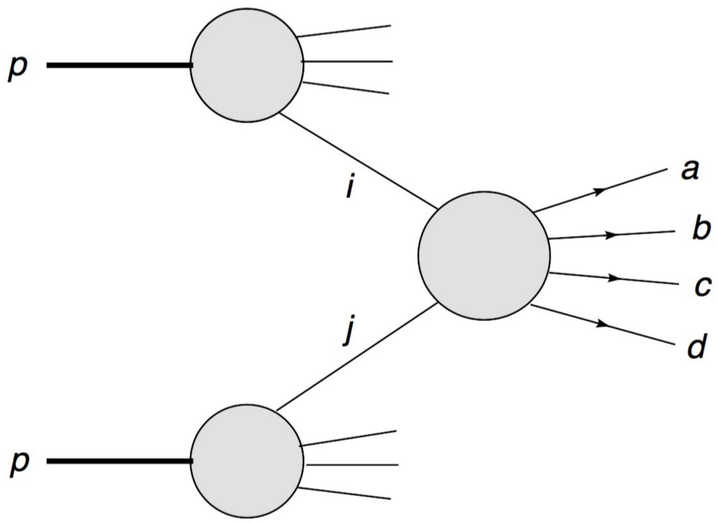
Two production mechanisms:

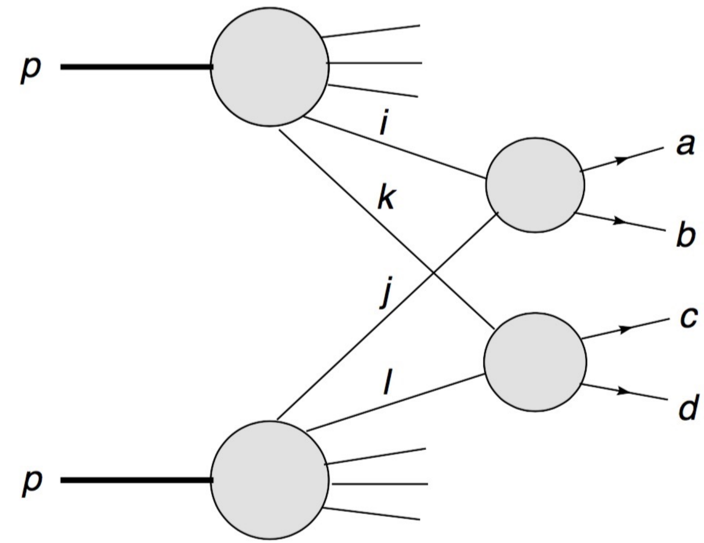
Prompt: Produced directly in the proton-proton interaction or through feed-down

Non-Prompt: Produced in decays of long lived *b*-hadrons

Associated Measurements

We measure the production of J/ψ in association with another particle.



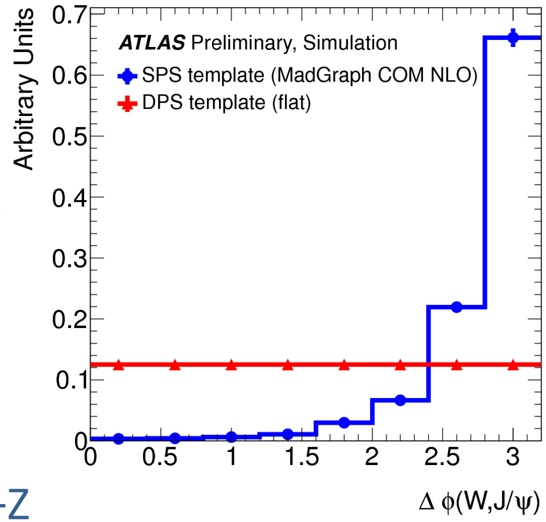


- **Single Parton Scattering**: particles come from the same hard scatter
- **Double Parton Scattering**: particles come from two hard scatters

SPS and DPS are **indistinguishable** on per event basis. We seek observables to disentangle them e.g. Δϕ opening angle distributions

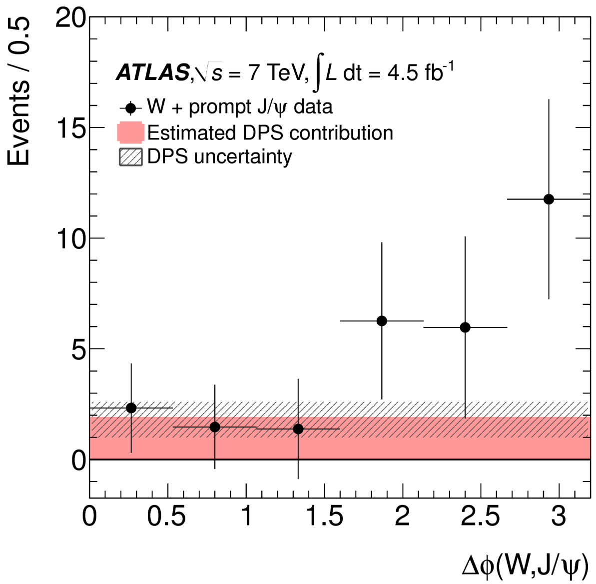
Azimuthal opening angle

Expected opening angle (Δϕ) distribution

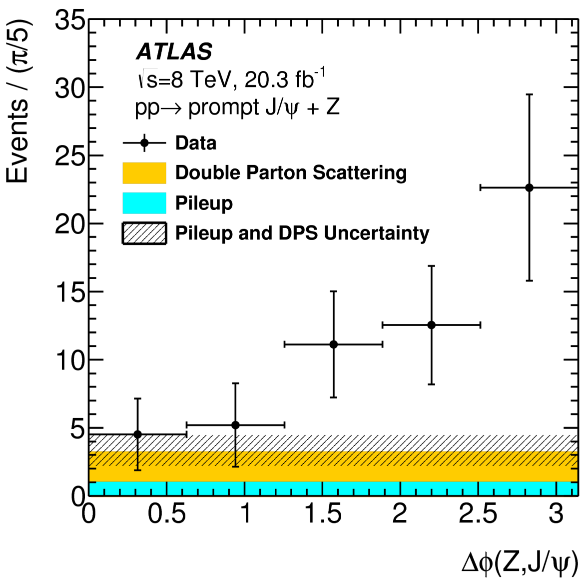


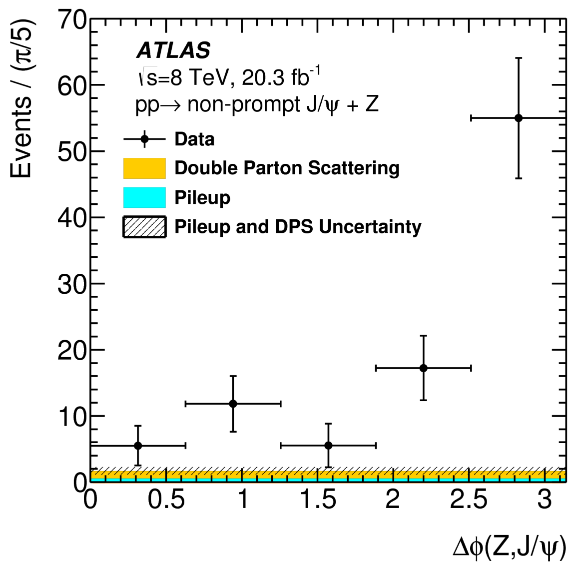
Results give indications of SPS and DPS production

J/ψ+W

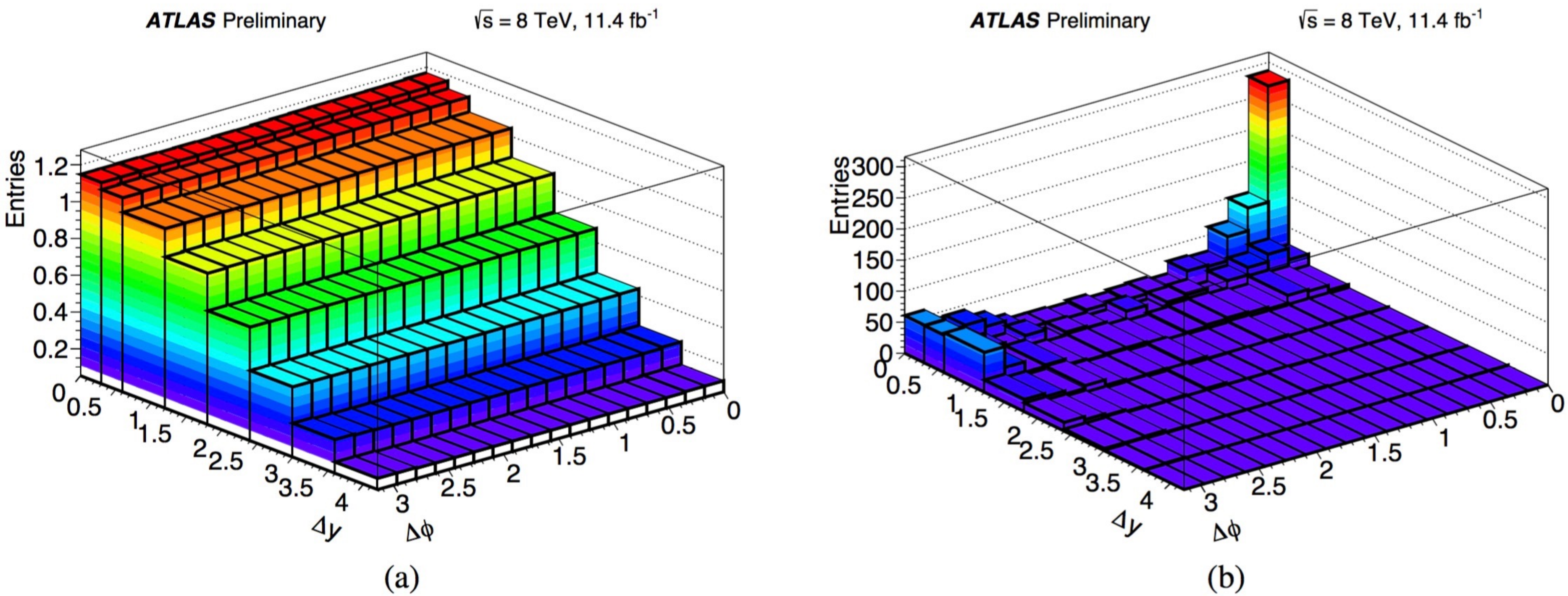


J/ψ+Z





Azimuthal opening angle

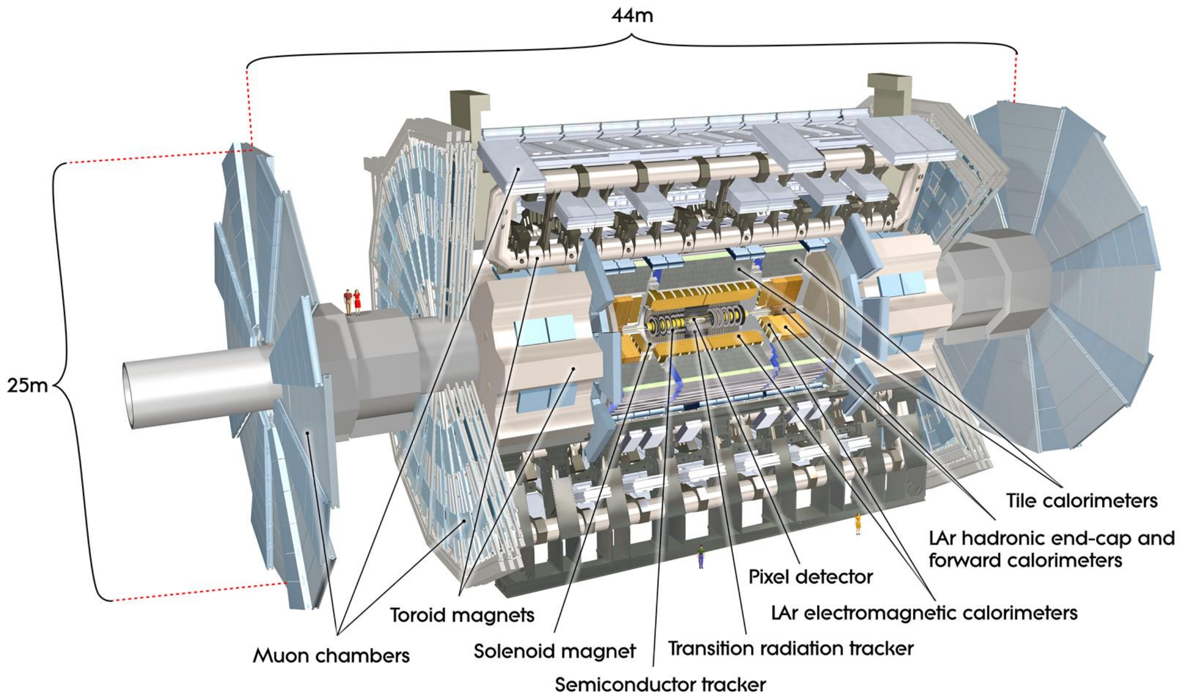


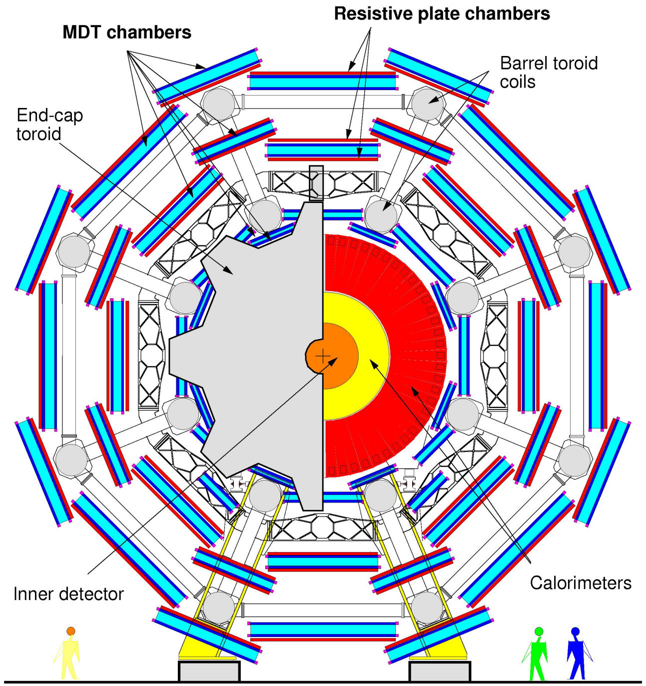
The 2-D **data-driven** templates of Δy vs. Δϕ for J/ψ + J/ψ

(a) DPS: independent J/ψ pairs, normalized to data
(b) SPS: subtracting (a) from data

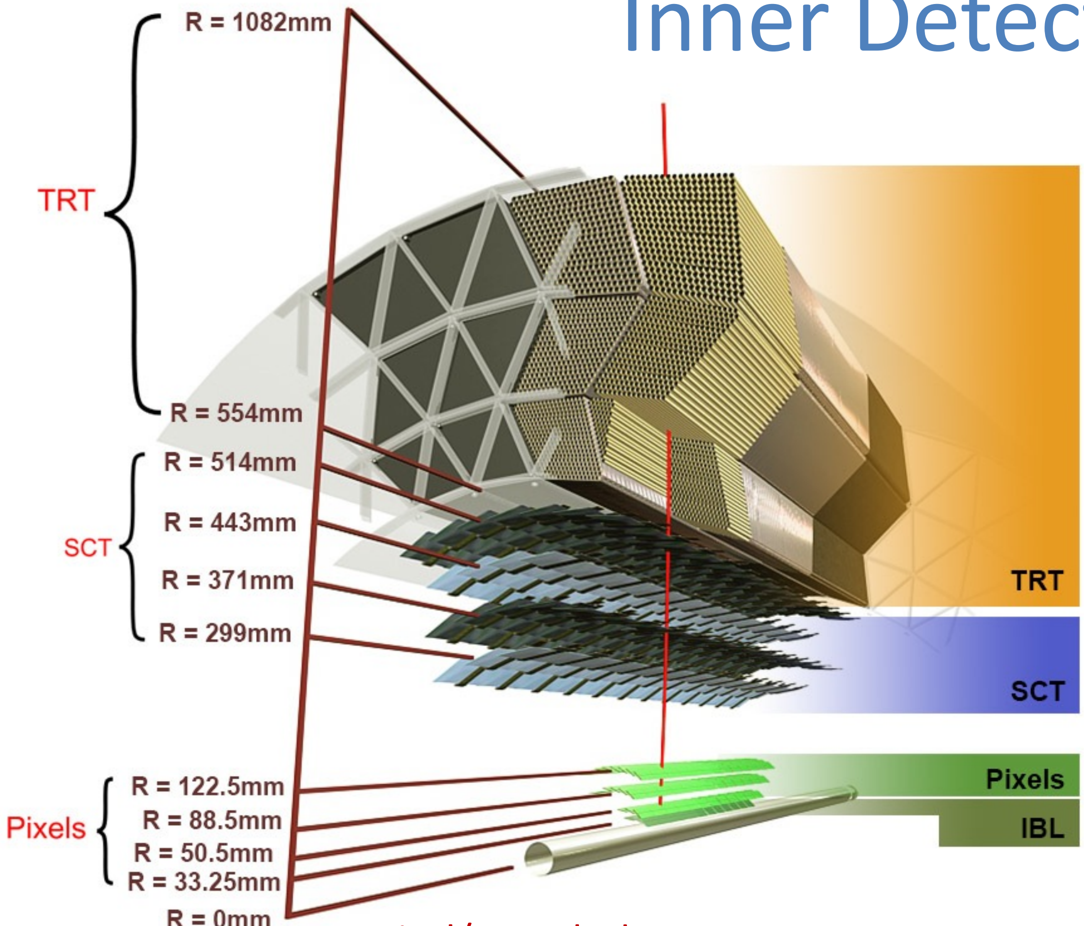
ATLAS EXPERIMENT

- Photographs exotic particles created by the *p-p* collision
- Weight: 7,000 tons
- 46 m long; 25 m diameter
- ~3,000 collaborators, >177 institutes, 38 countries
- Layers have specialized functions





Inner Detector



Pixel/IBL sub-detector

Enclosed by the Solenoid

- Performs:
  - Tracking
  - Vertex Identification

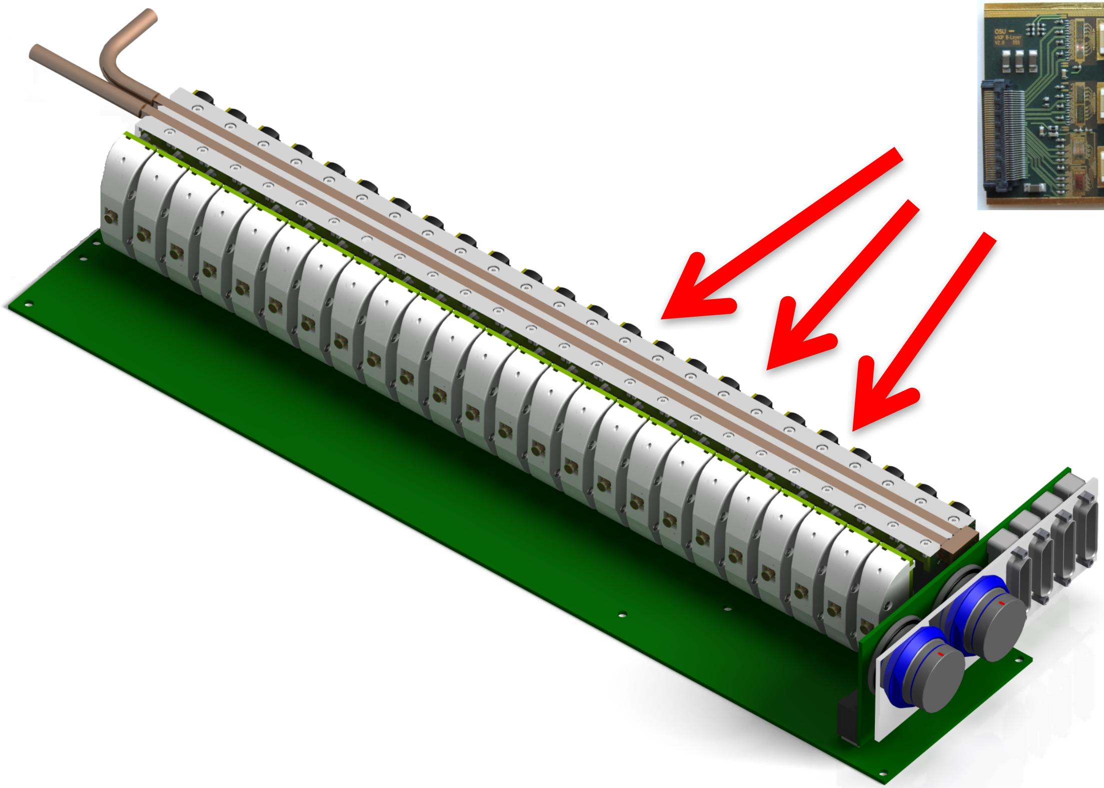
3 technologies used:

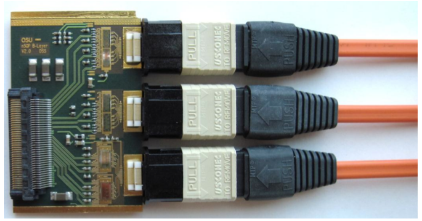
- Silicon pixels
- Silicon strips
- Straw tubes

Red track shows hypothetical charged particle of:
p_T = 10 GeV and η=0.3

Opto-box

- The Pixel and IBL produce **electronic** signals, which must be converted to **optical** signals for read out
- Special attention was given to ensure proper **shielding**, **grounding**, **cooling, high reliability**, and **environmental tolerance** during the **custom design** and manufacturing of the optical modules.





24 **opto-boards** convert signals between electrical and optical form by using **v**ertical-**c**avity **s**urface-**e**mitting-**l**asers (VCSELs).

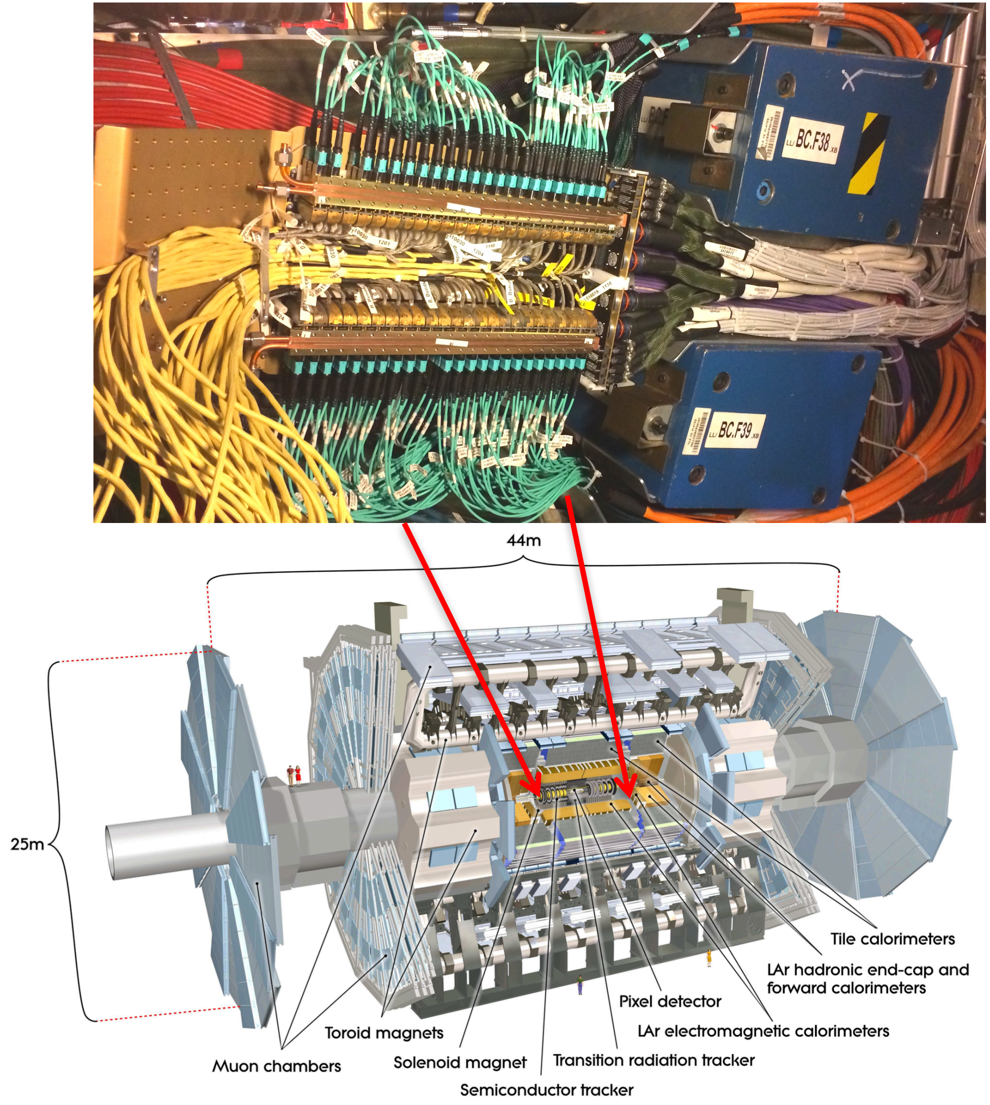
Opto-box

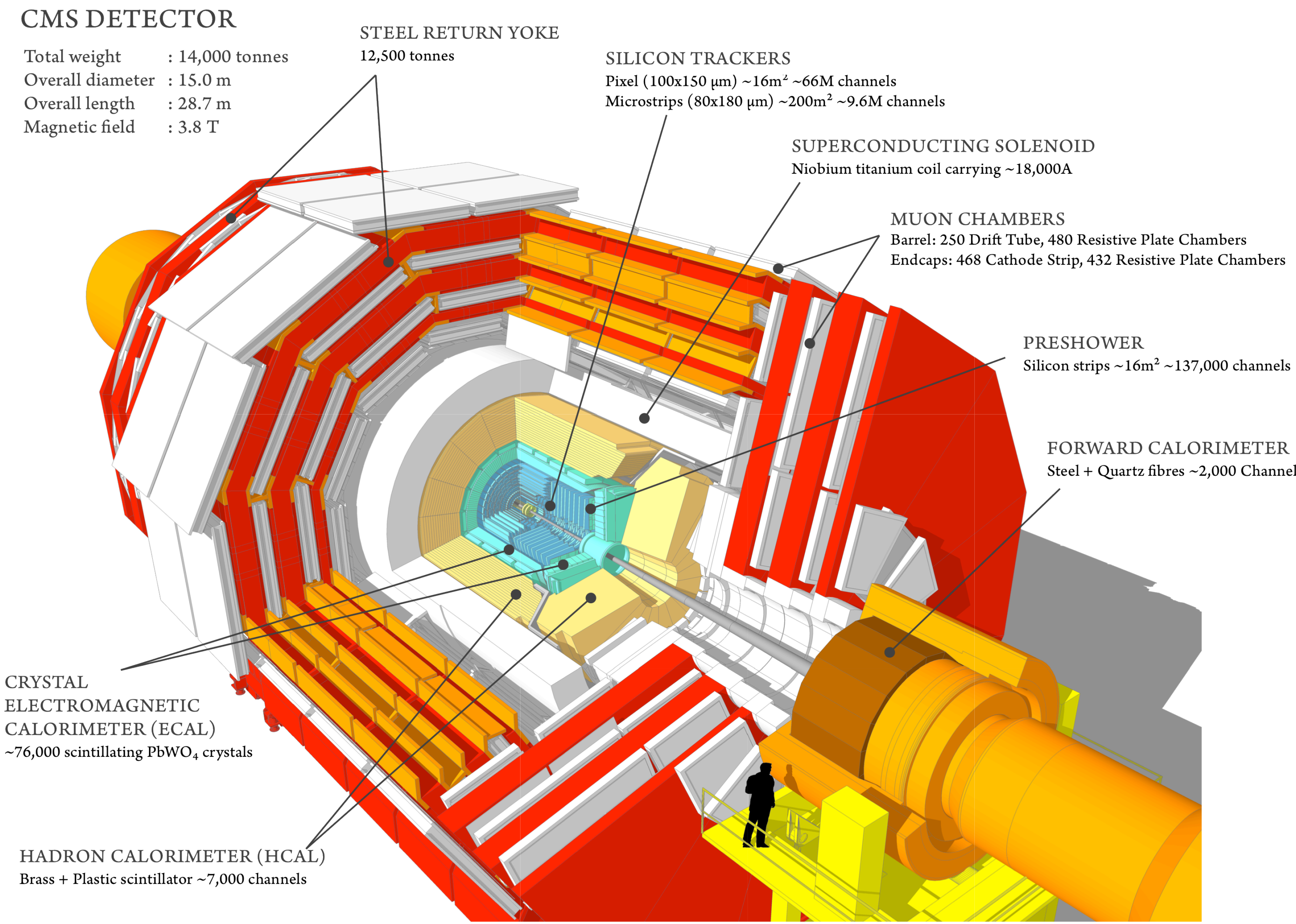
During the LHC long shut down (LS1) we **redesigned and installed** new optoelectronic signal transceiver modules.

This **increases ease of access** to the system

They provide **reliable, tightly integrated**, and **serviceable** mini-crates and modules for the optoelectronic data transfer system.

They are currently operational as an integral part of **data collection** for **LHC run 2**.

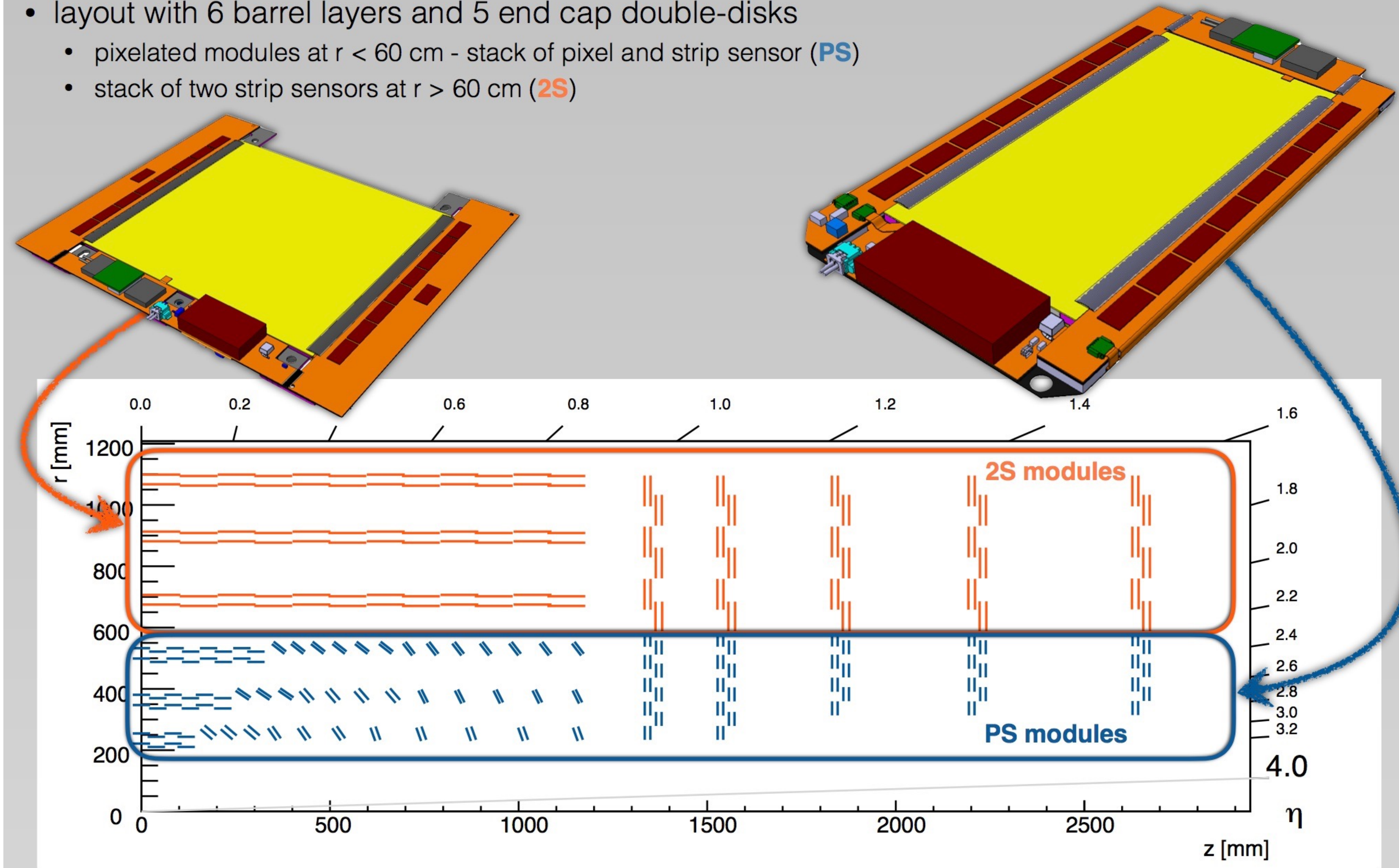




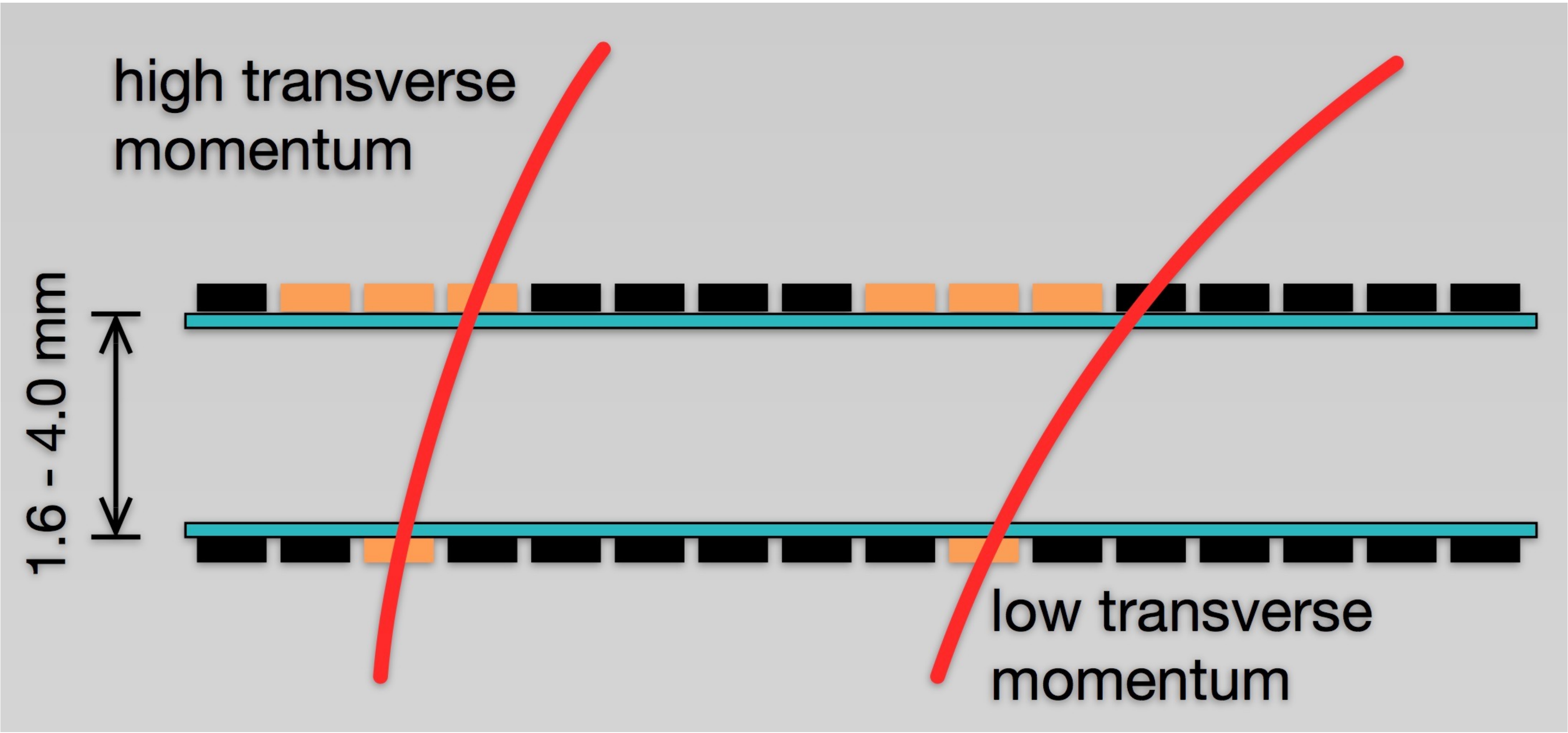
- ~2000 scientists and engineers
  > 20 years to design and build
- Is about 15 m wide and 21.5 m long
- Weighs twice as much as the Eiffel Tower – about **14,000t**
- Largest, most powerful **magnet** of its kind ever made

Phase II Tracker Upgrade

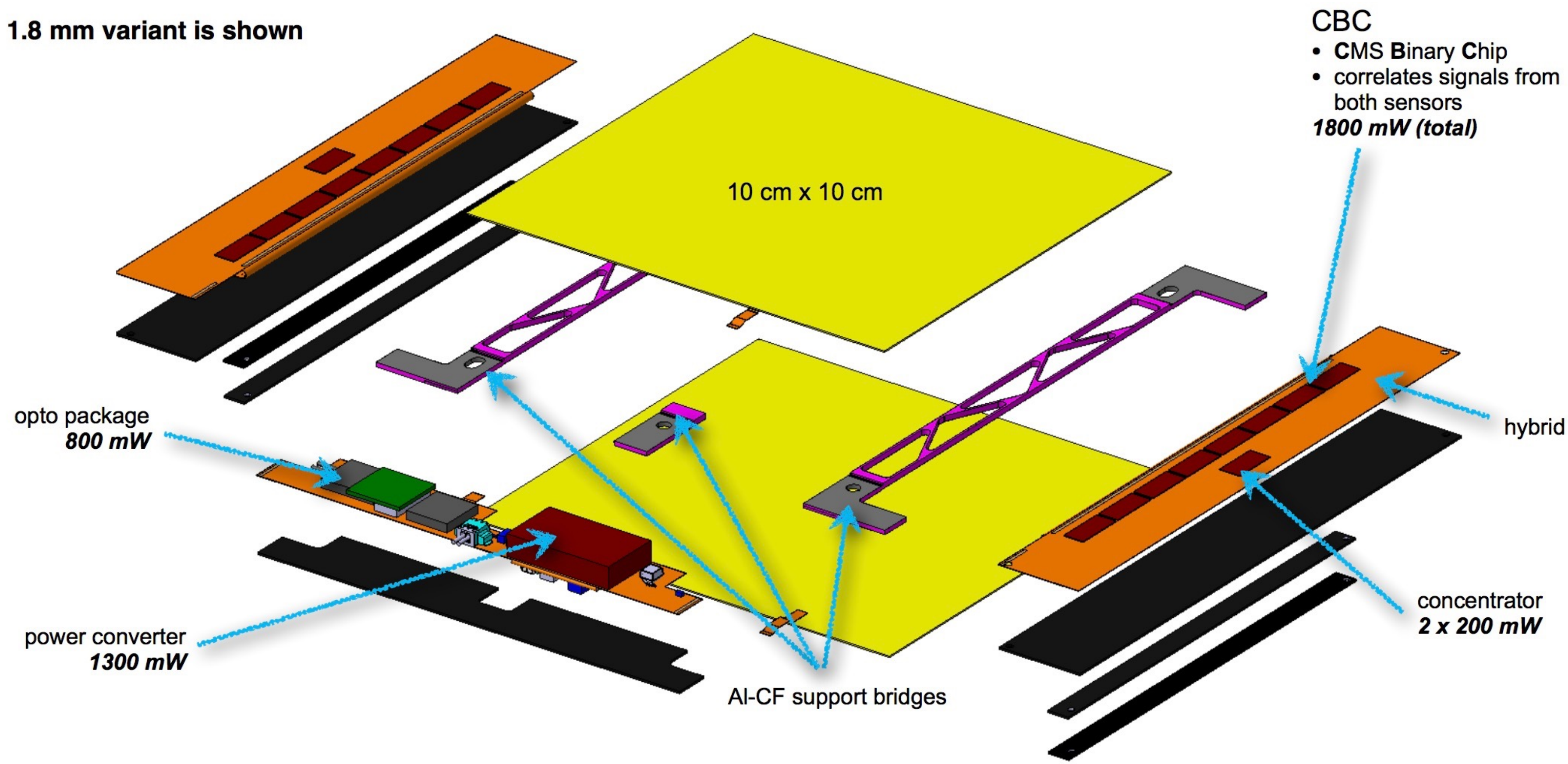
- layout with 6 barrel layers and 5 end cap double-disks
  - pixelated modules at r < 60 cm - stack of pixel and strip sensor (**PS**)
  - stack of two strip sensors at r > 60 cm (**2S**)



Modules will have on-board transverse momentum discrimination



Components of the 2S module

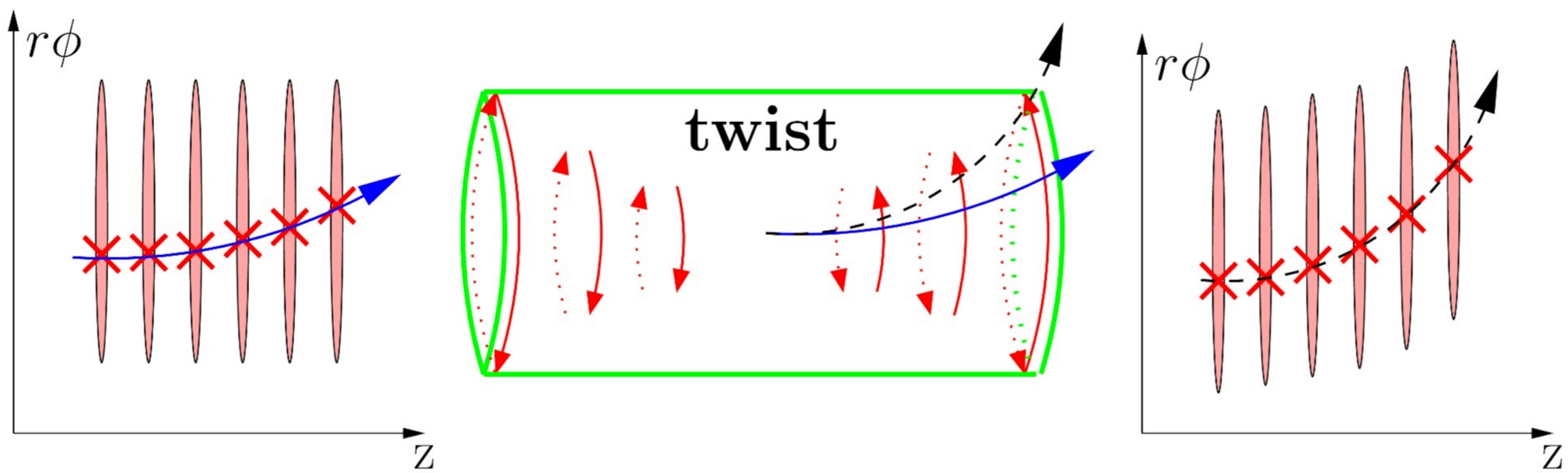


Phase I Alignment

χ^2 minimization fits are very insensitive to twist misalignments – called weak modes

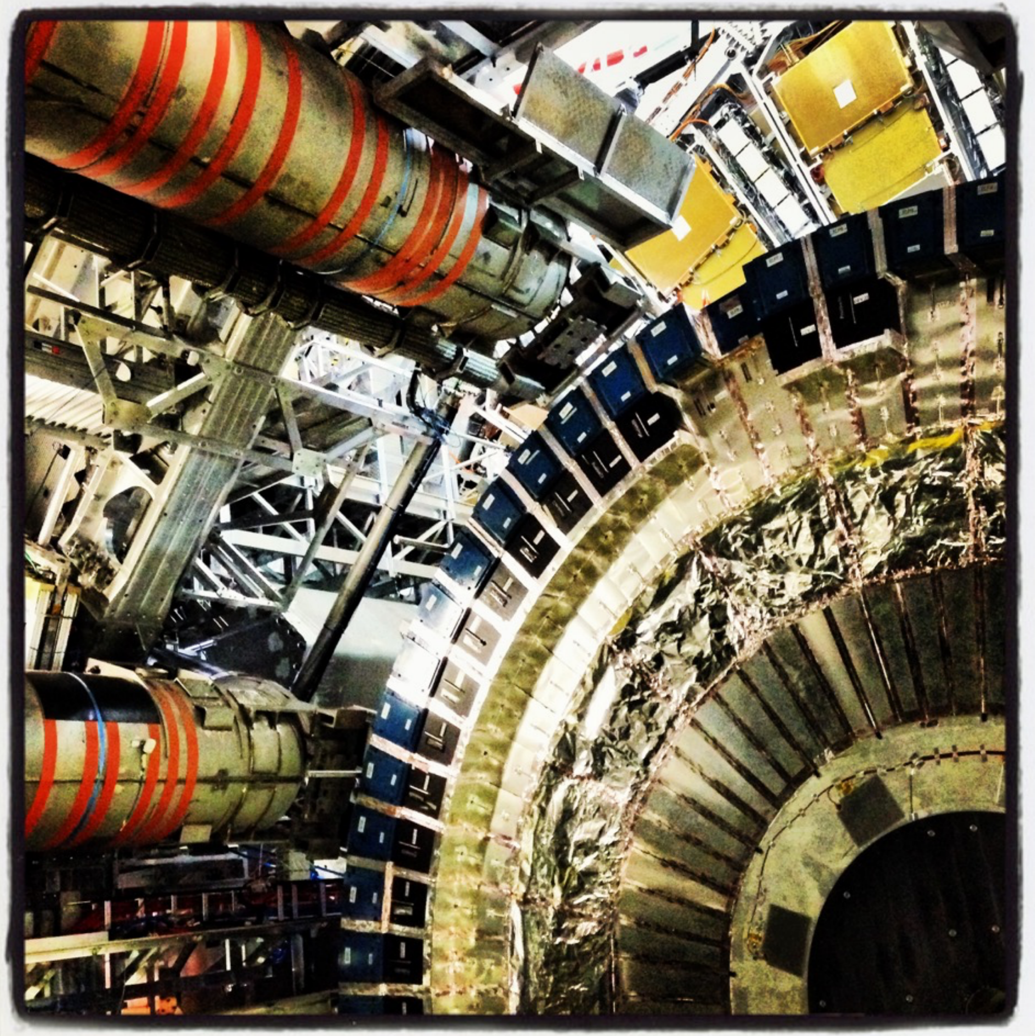
They are studied separately using:

- cosmics (which break cylindrical symmetry)
- Z ->μμ (which are precisely reconstructed)



Modules are coherently shifted along ϕ

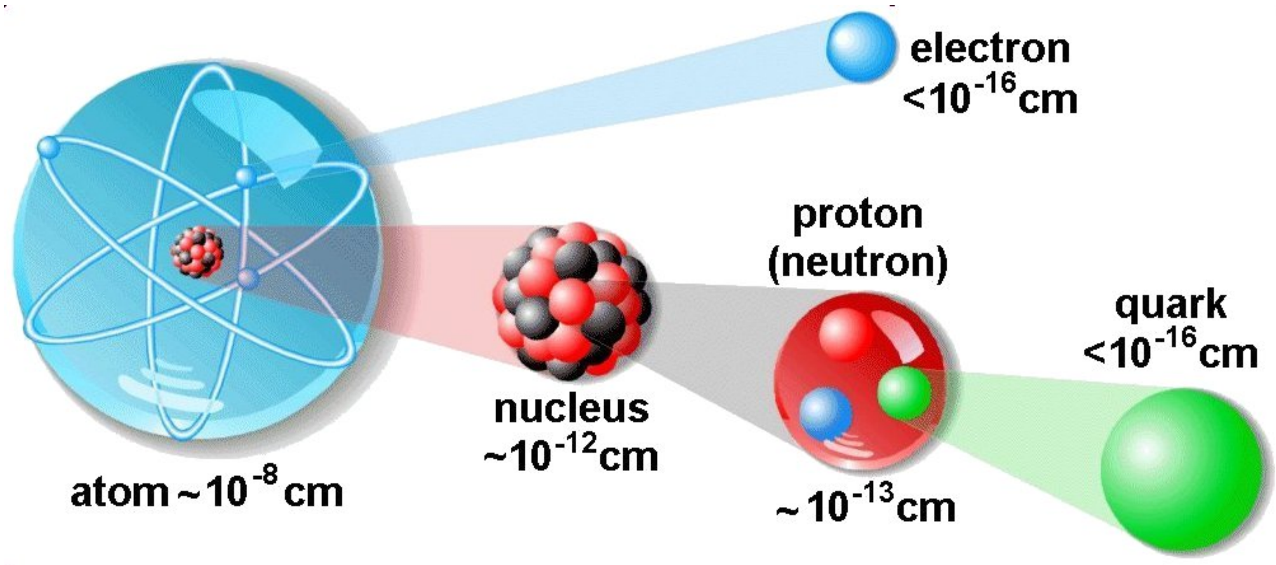
Backup Slides




Q2A

Particle Physics - What is everything made of and what holds it together?

- 460 - 370 B.C. **Democritus** — All matter is made of indivisible particles called **atoms**
- ~1900 **Stoney, Thompson, Rutherford** — Explore atomic structure. Discover/measure **electron, proton**
- Early 1900's **Compton**, **de Broglie** — Discovered **quantum** (particle) nature of x rays, photons are particles. Proposed that matter has **wave properties**
- 1950's --- *Beginning of a proliferation of particle discoveries, modern era of collider experiments* ---
- 1968-69 **Bjorken**, **Feynman** — Propose **quark** model based on SLAC data



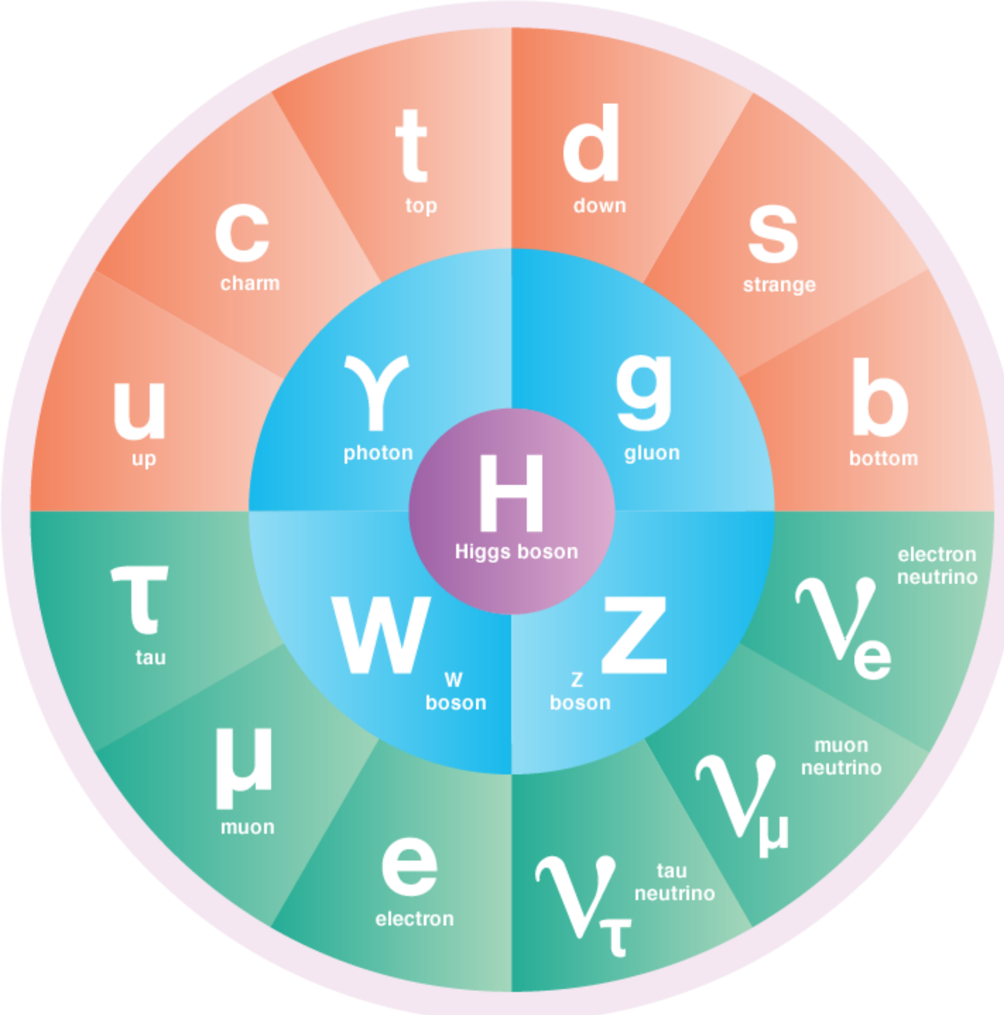
Standard Model of Particle Physics

Field theory, Particles have associated fields.

- 3 principles:
  - Relativity
  - Quantum Mechanics
  - Gauge Invariance

- Outside Ring
  Fermions: matter particles – spin 1/2
- Center
  Bosons: force carriers – integer spin

- All Standard Model fundamental particles now discovered:
  - electron: ~1898
  - Higgs: 2012



Motivation

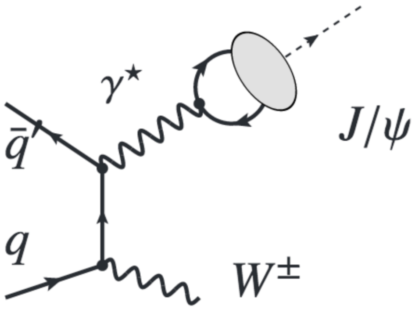
Quarkonium production measurements usually focus on **inclusive** sample properties

- 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



Important experimental motivation for ATLAS

- We can make use of existing high bandwidth high-p_T triggered data rather than relying on dedicated quarkonia triggers

Potential to be useful in other measurements

- Background for rare decays: $Z \rightarrow l^+l^- J/\psi$, $H \rightarrow Z Z^*$ and final states: Z+4-jets, W^+W^-+2-jets
- 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

Measurements Summary

Three measurements present production of J/ψ in association with W bosons, Z bosons or another J/ψ.

These studies:

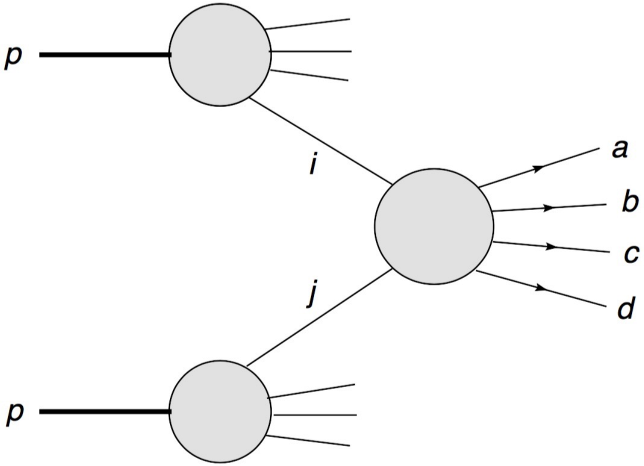
- establish with > 5σ significance the observation of associated quarkonia production
- present a cross-section measurement (or measurement ratio)
- assess the amount of double vs single parton scattering

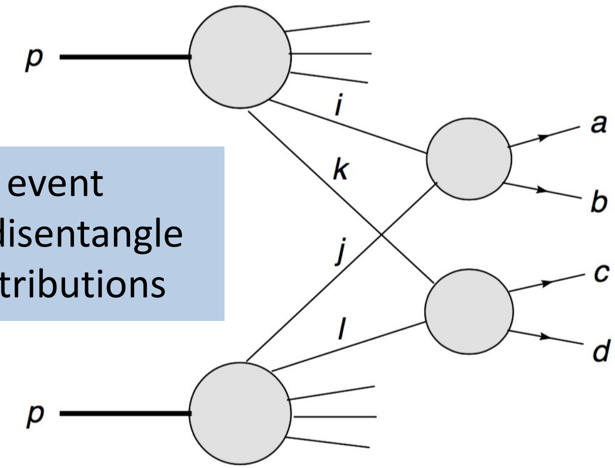
There are two possible associated production modes

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

	∫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
J/ψ + J/ψ	11.4 fb^{-1}	8 TeV	ATLAS-CONF-2016-047

SPS vs DPS





DPS is **indistinguishable** on per event basis. We seek observables to disentangle them e.g. Δϕ opening angle distributions

Single parton scattering (SPS)

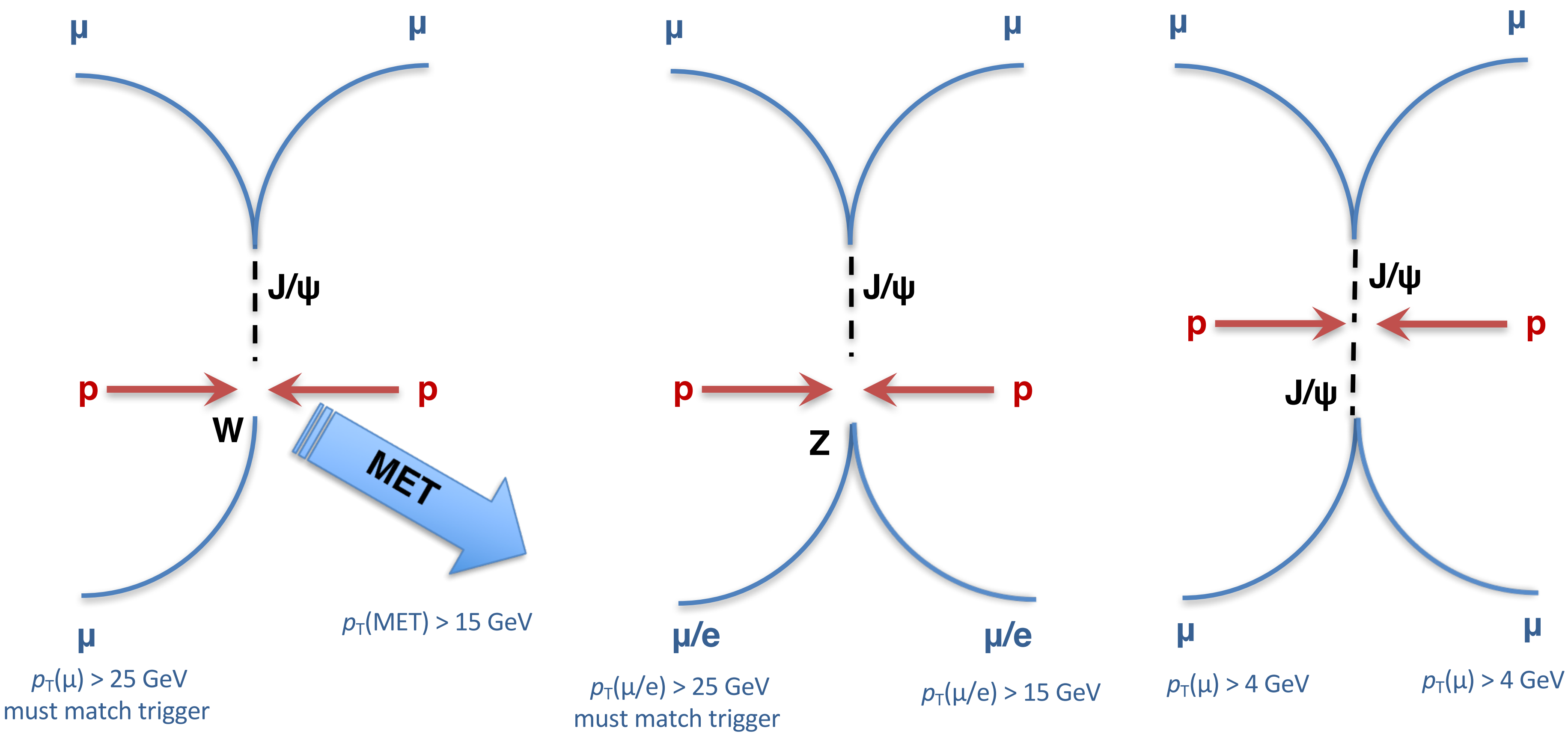
- Both particles come from the same parton interaction
- Enhances sensitivity to a subset of matrix elements allowing tests/development of theoretical models
- This tests potential differences of the p_T spectra of singlet and octet production modes between V-boson+onia or inclusive production
- Possibility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

Final States

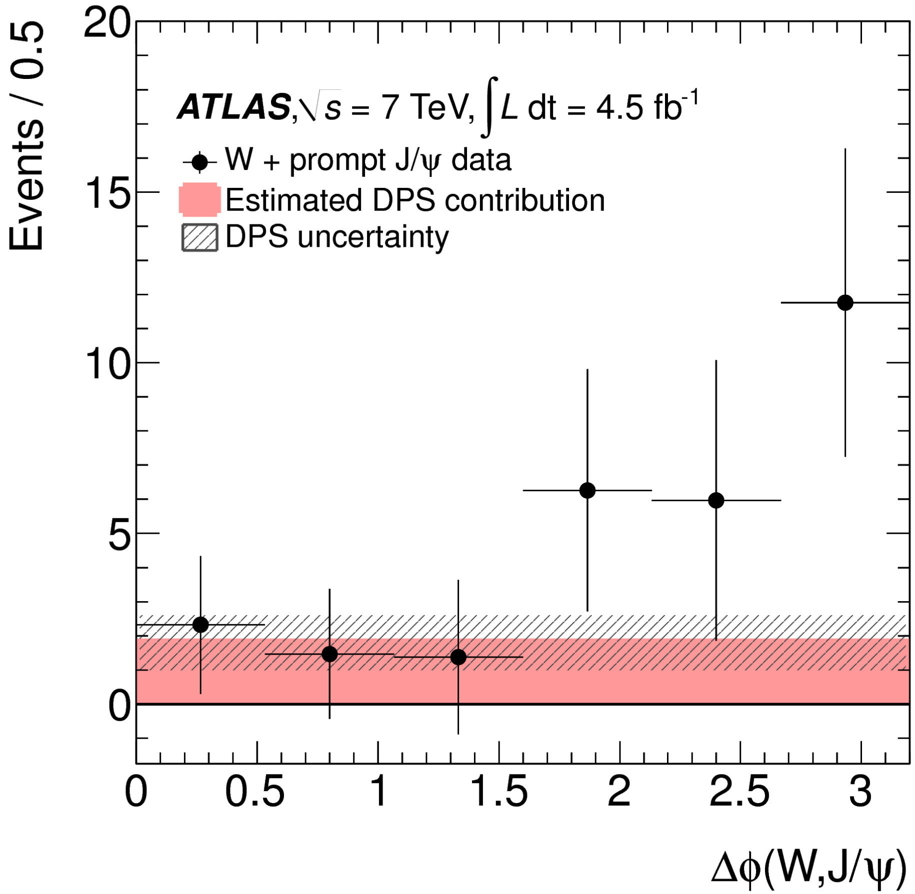
Triggers: Single high p_T electron/muon or di-muon
J/ψ fiducial cuts: Similar for all (after the acceptance corrections)



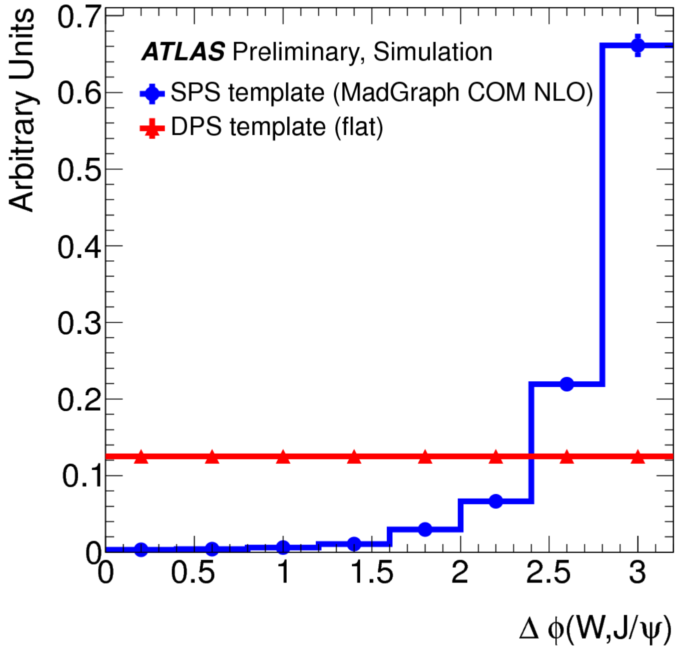
J/ψ+V-boson: Analysis Steps Overview

1. Selection of relevant μμμμ, μμee or μμμ+MET events
2. Pile-up contamination estimation
   - J/ψ associated particle 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, J/ψ) / σ(W,Z, J/ψ) 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

J/ψ+W results: azimuthal opening angle

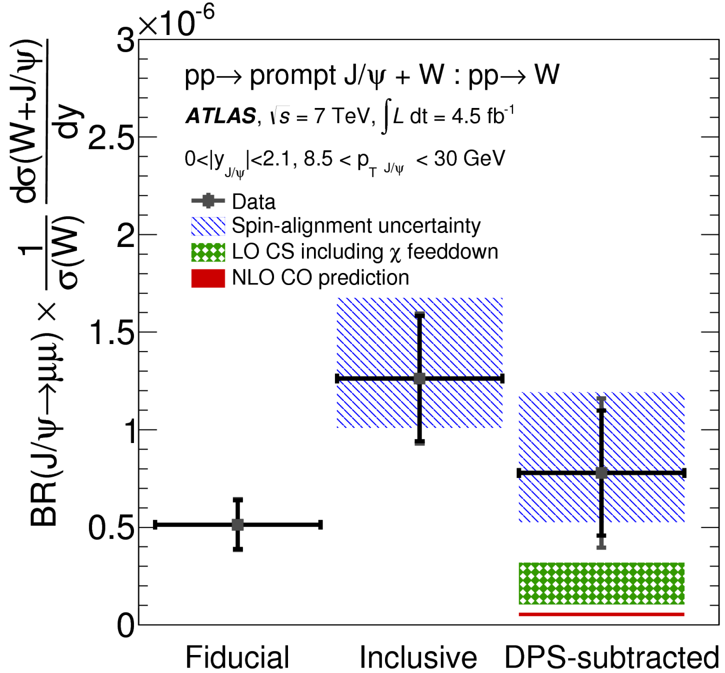


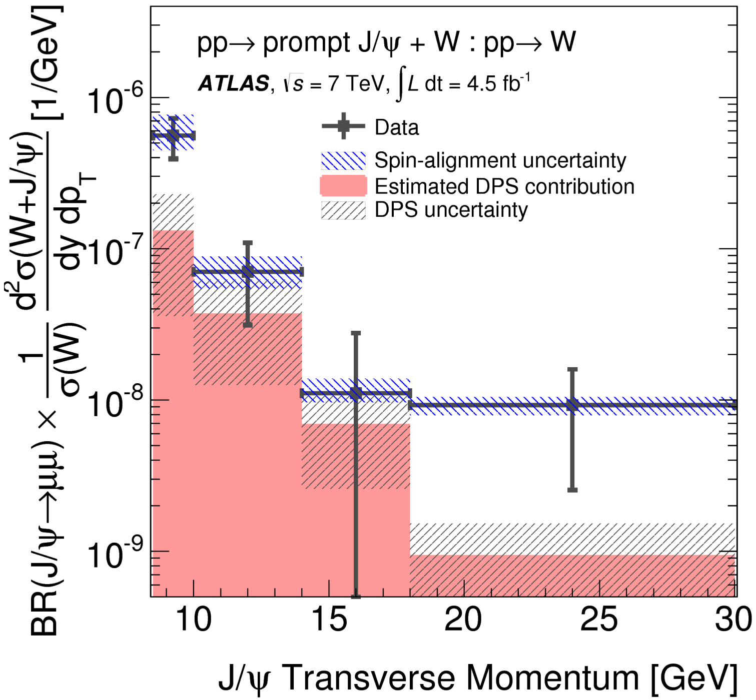
DPS processes are expected to give a flat azimuthal opening angle (Δϕ) distribution



Possible indication of SPS J/ψ+W production.

J/ψ+W results: Cross-Section



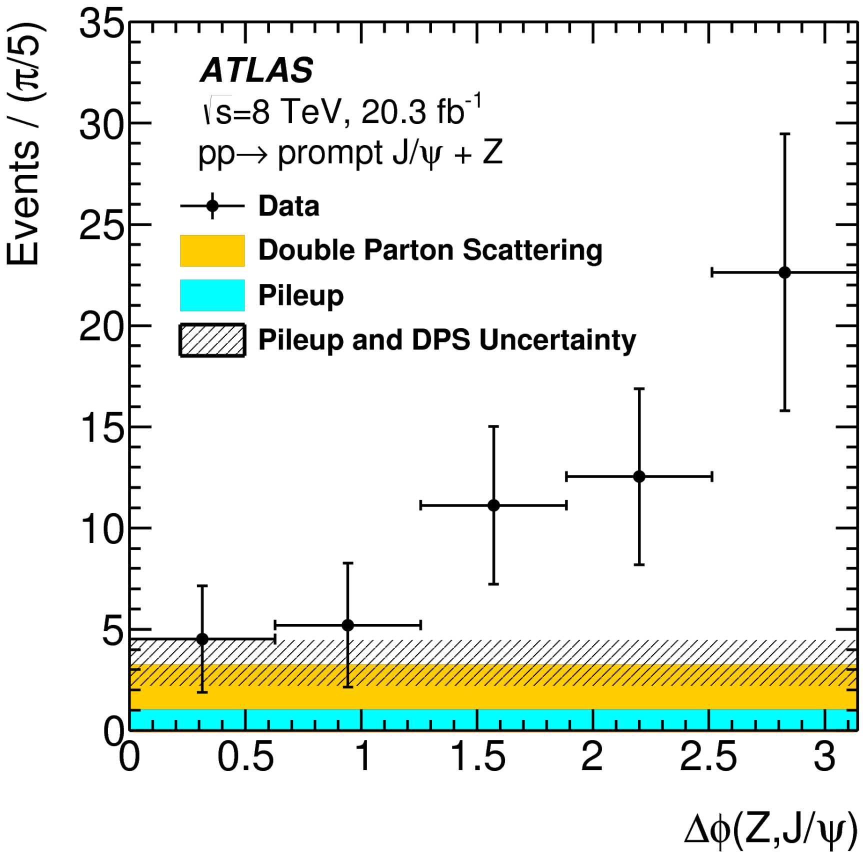


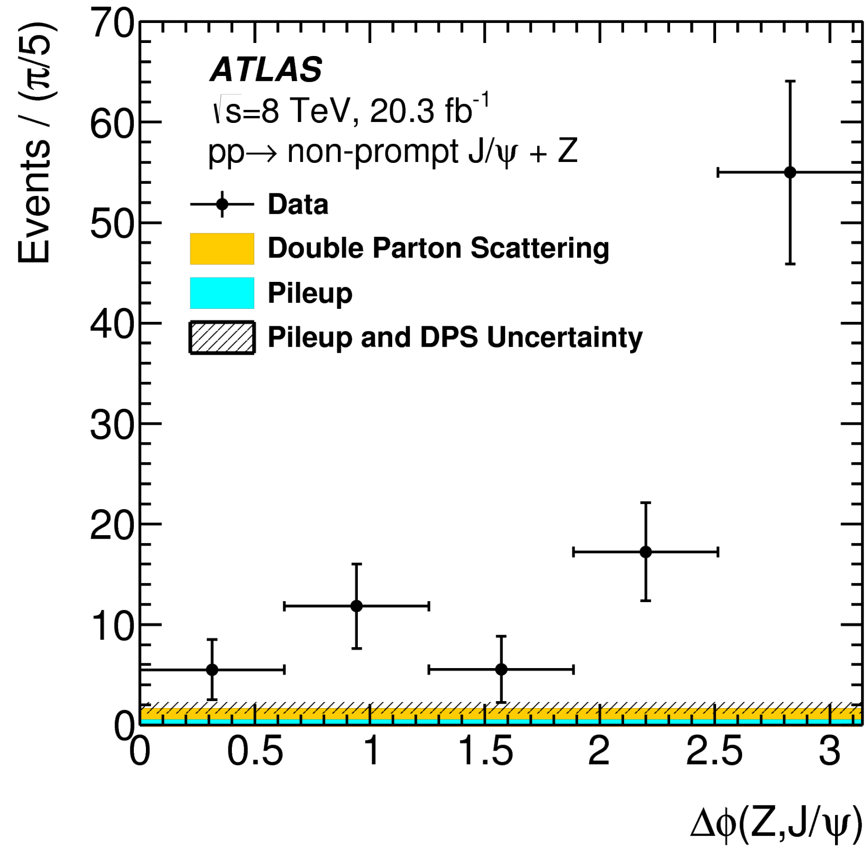
Fiducial means no J/ψ acceptance corrections.
Inclusive contains all corrections, also presented in $p_T^{J/\psi}$ bins.
DPS-subtracted to compare with theory: appears theory doesn't fully account for SPS contribution

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

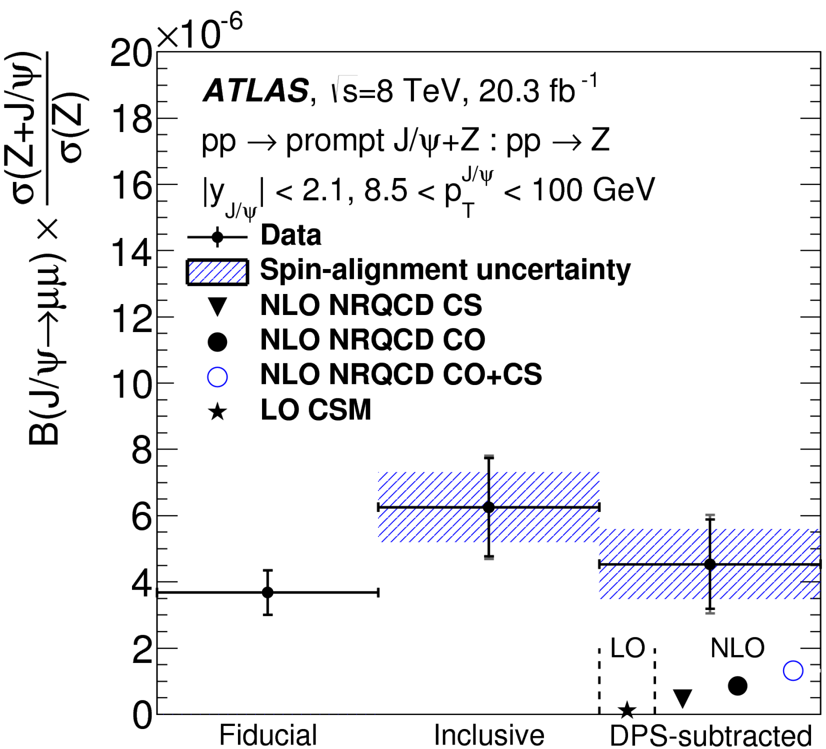


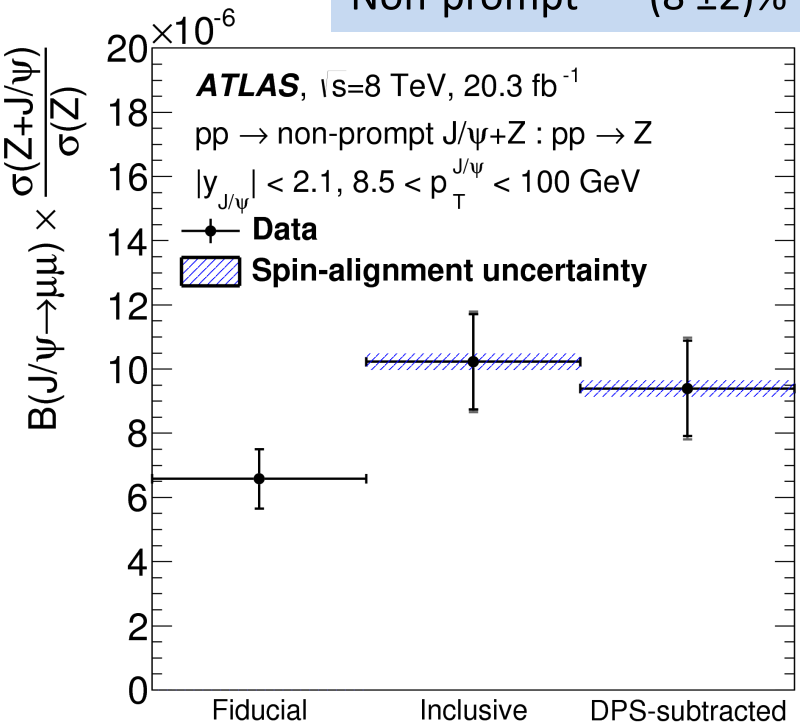


With σ_eff = 15 mb estimate, low Δϕ(Z,J/ψ) data dominantly from DPS.
A similar pattern in observed as with the J/ψ+W data on slide 8.

J/ψ+Z results: total cross-sections

	DPS Fraction
Prompt	(29±9)%
Non-prompt	(8 ±2)%



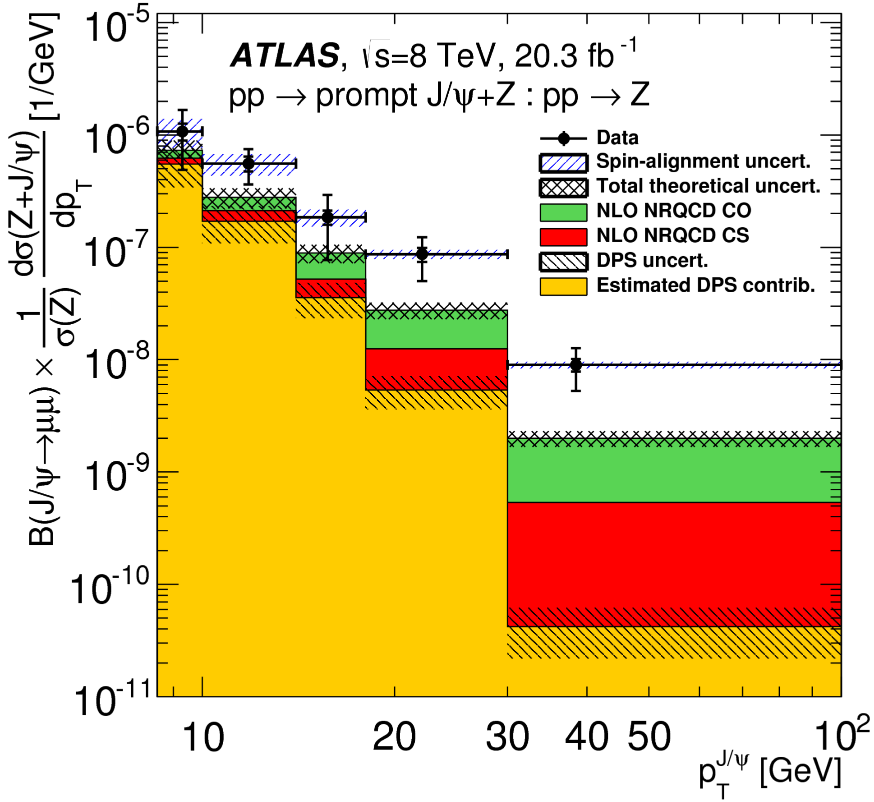


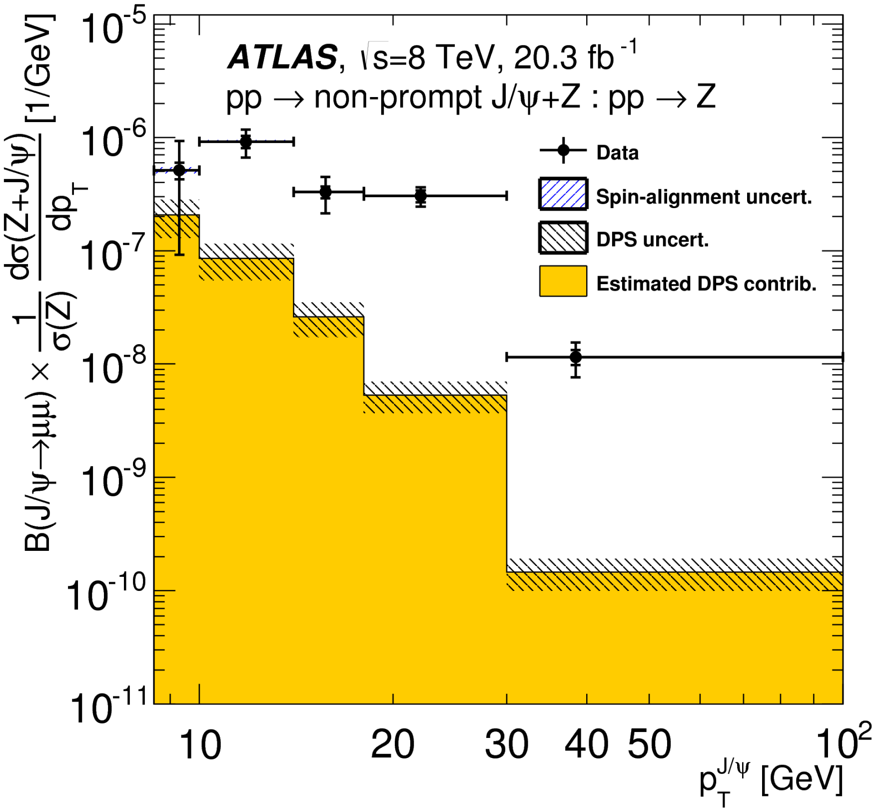
Again, theory appears to underestimate SPS production.
(Note: NLO NRQCD does feed-down a component not included in these predictions.)

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

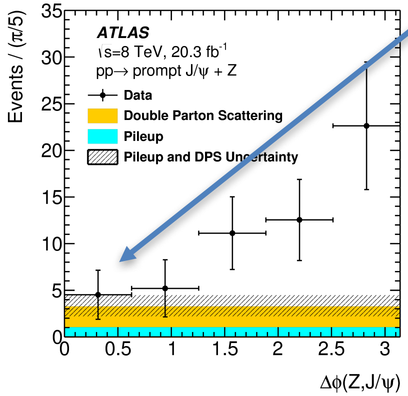


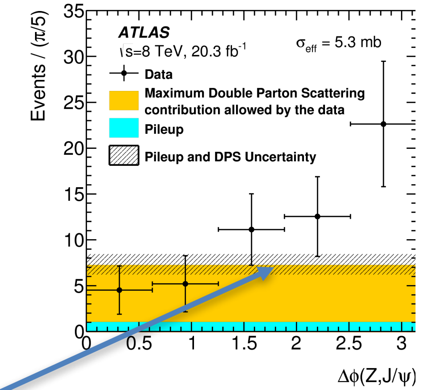


The lowest $p_T^{J/\psi}$ bin is mostly DPS and the highest bins are SPS dominated.
The theory discrepancy becomes more pronounced with increasing $p_T^{J/\psi}$.

J/ψ+Z results: lower limit on σ_{eff}

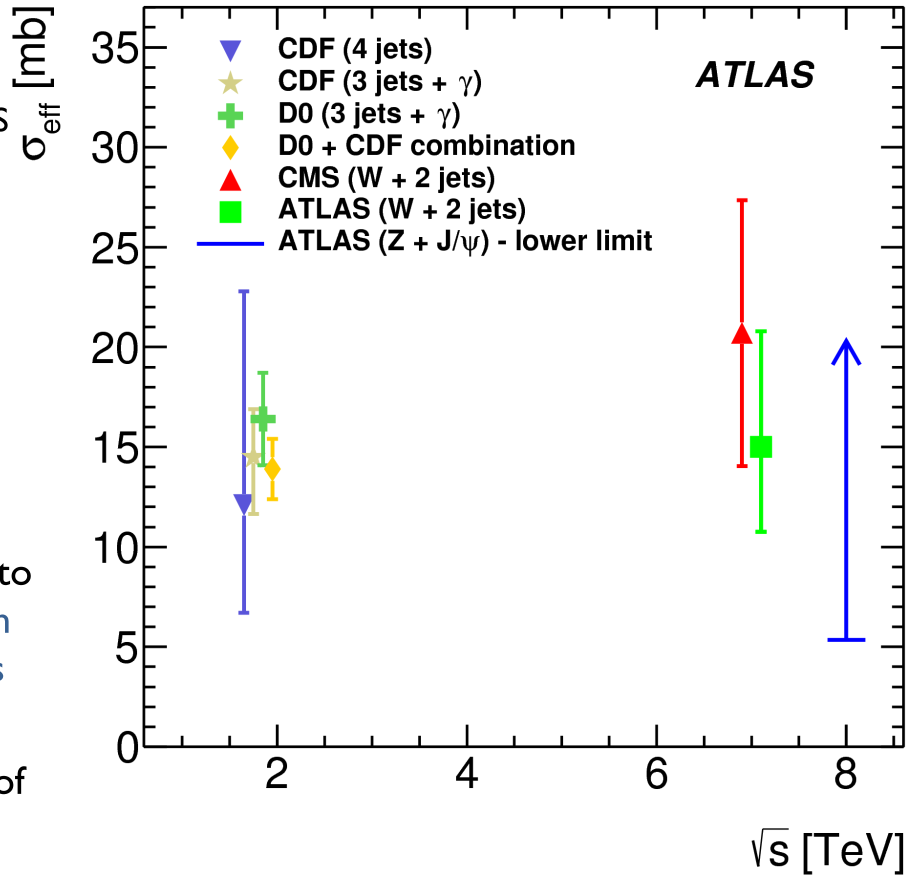
Again considering the first bin of this Δϕ plot to be due to DPS





…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

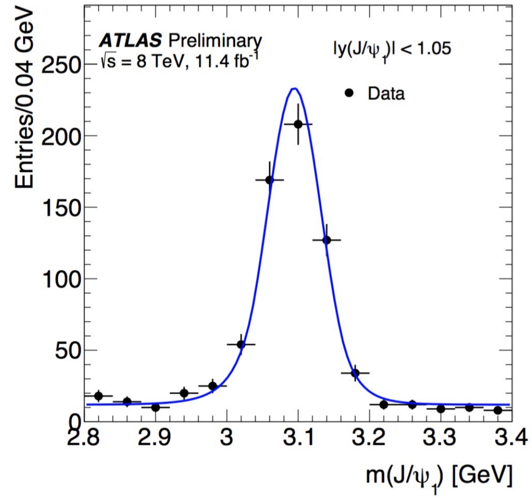
J/ψ + J/ψ: Analysis Steps Overview

1. Selection of relevant μμμμ events
2. Pile-up contamination estimation
   - J/ψ associated particle 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 σ(J/ψ + J/ψ) presented
6. Generation of relevant distributions
7. DPS contribution estimation
   - DPS contribution can be ***estimated*** using a data driven method

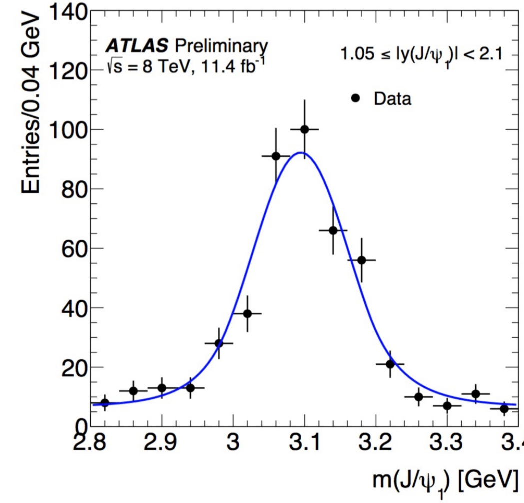
J/ψ+J/ψ: Candidates

The 1-D projections of the invariant mass spectrum fit of the leading J/ψ (a) (b)

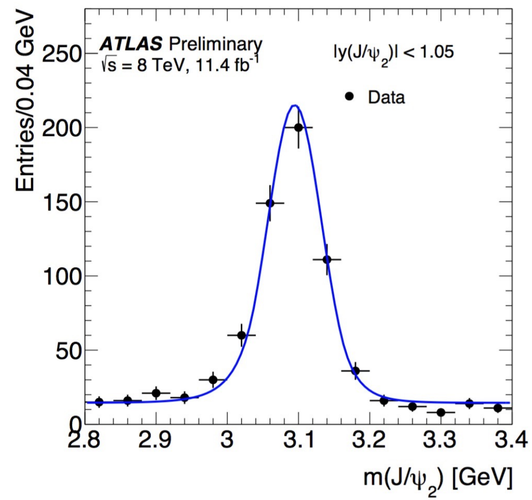
And the sub-leading J/ψ (c) (d)



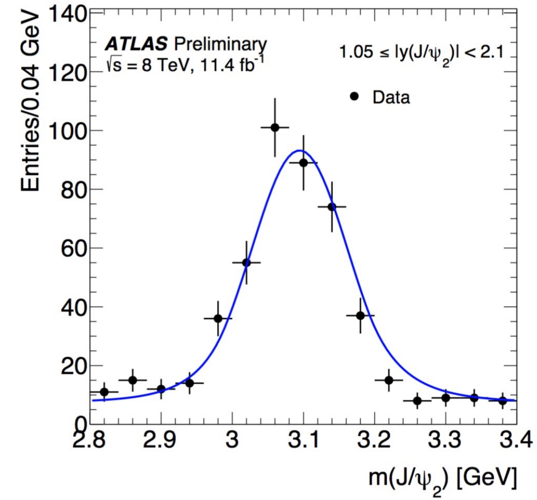
(a)



(b)



(c)



(d)

J/ψ+J/ψ: 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

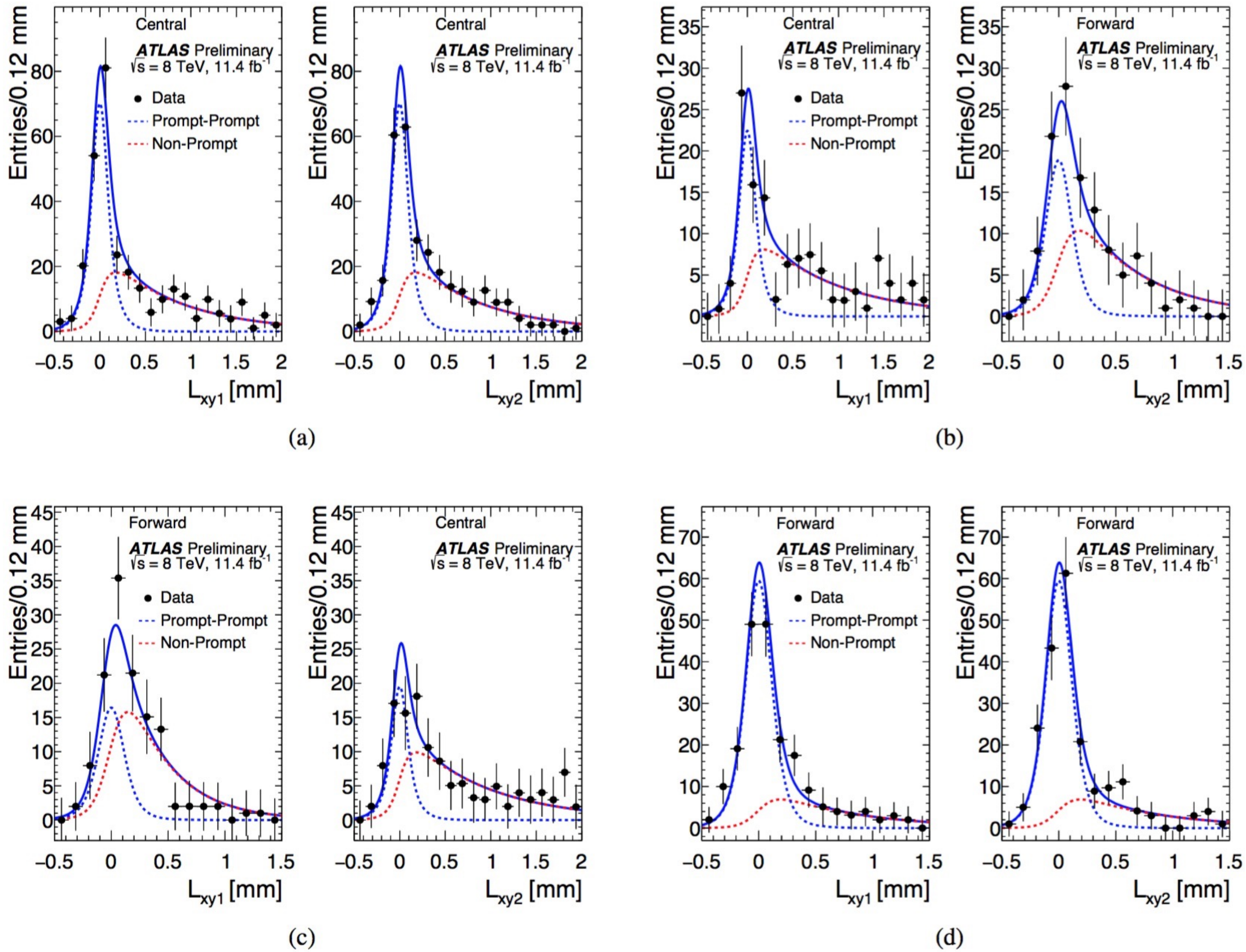
- Signal weights extracted using an 2D maximum likelihood fit with discriminants:
  - J/ψ candidate mass
  - J/ψ candidate pseudo-proper time

- Three categories of events are described in the fits
  - real prompt J/ψ + real prompt J/ψ **(SIGNAL)**
  - real non-prompt J/ψ + anything **(Background)**
  - non J/ψ + anything **(Background)**

- The remaining background not covered by the fit is due to pileup.

- Yield extracted by fitting weighted distributions

J/ψ+J/ψ: Corrections and Yield Extraction



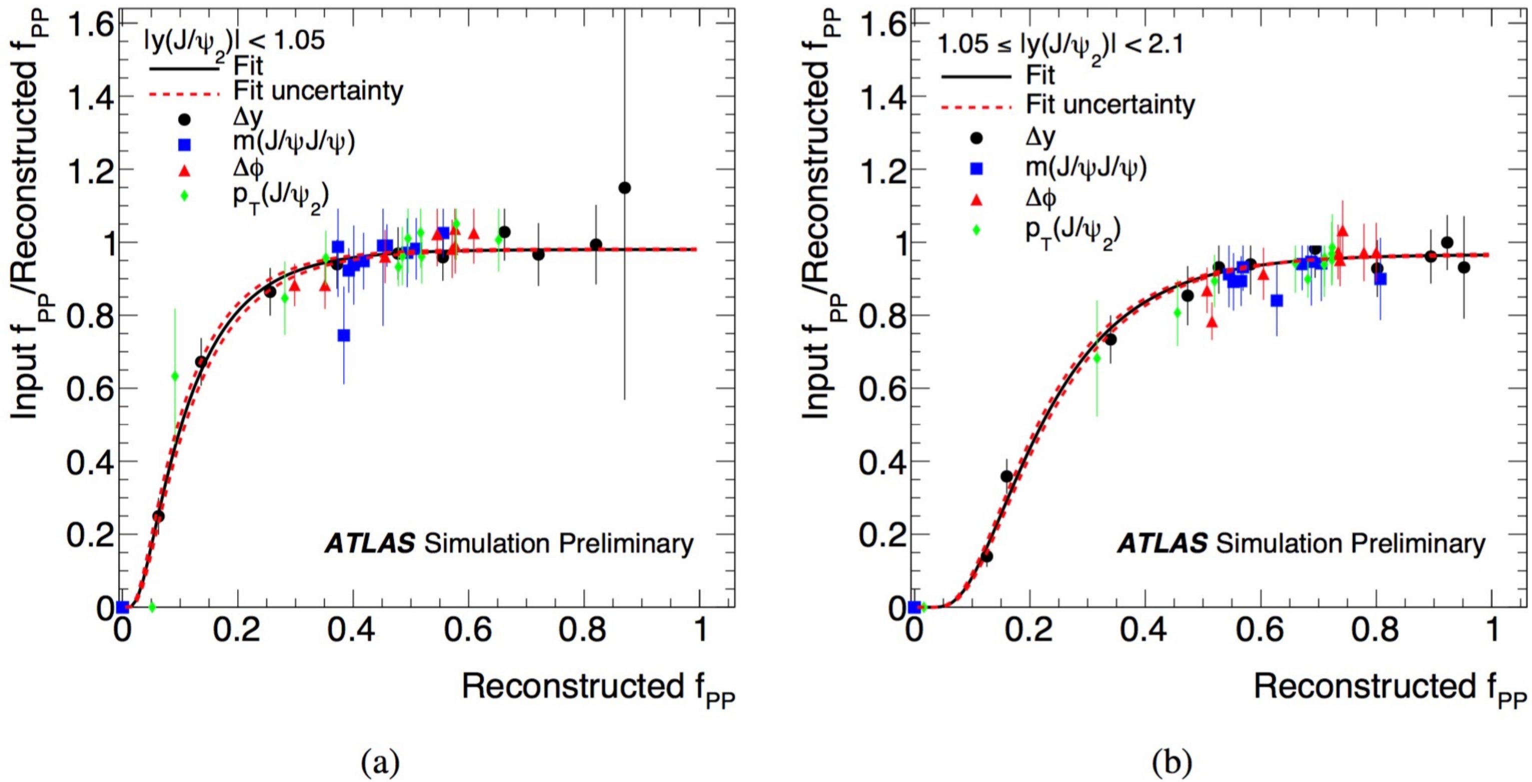
Transverse Invariant

$$\tau(\mu\mu) = \frac{L_{\mathrm{xy}} \cdot m(\mu\mu)}{p_{\mathrm{T}}(\mu\mu)}$$

Transverse

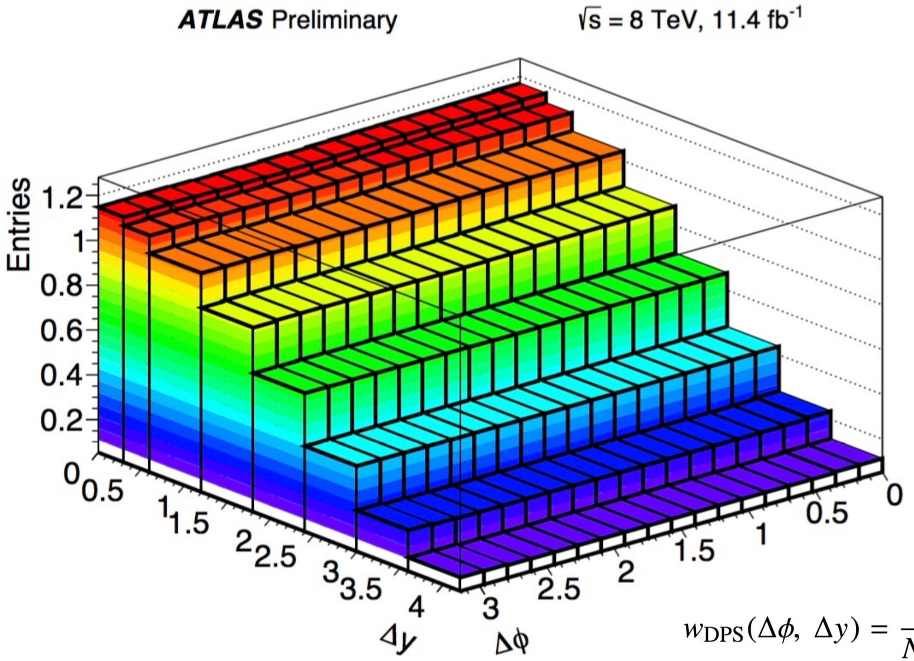
- Background subtracted decay length spectra, L_{xy1} and L_{xy2} of the leading and sub-leading J/ψ
- Shows **prompt-prompt signal** and **non-prompt background**

J/ψ+J/ψ: Correction Factor



- Corrects possible bias in extracted differential PP distributions
- MC samples generated using Pythia8B

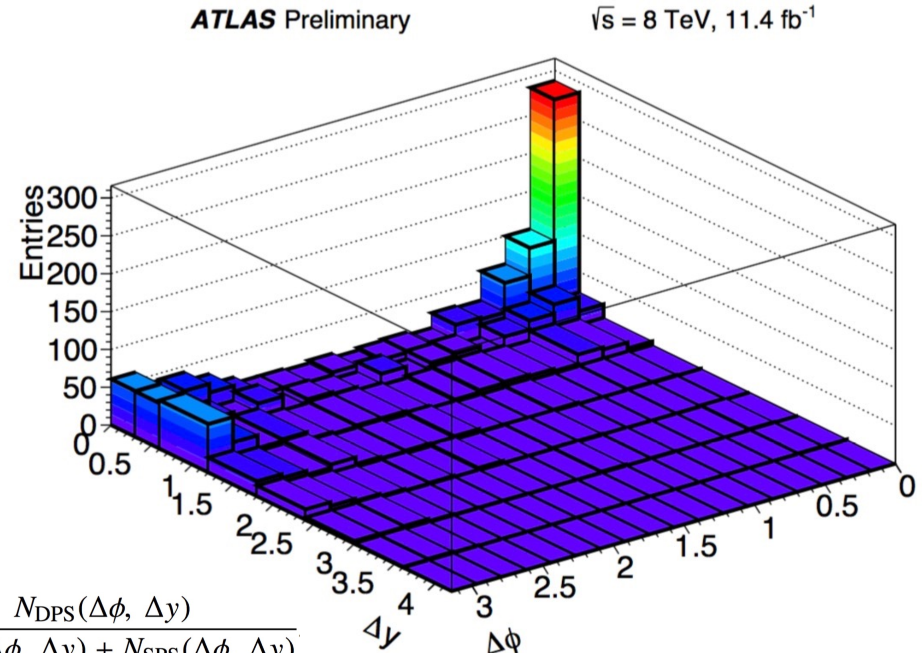
J/ψ+J/ψ: DPS templates



(a)

$$w_{\mathrm{DPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\mathrm{DPS}}(\Delta\phi,\ \Delta y)}{N_{\mathrm{DPS}}(\Delta\phi,\ \Delta y) + N_{\mathrm{SPS}}(\Delta\phi,\ \Delta y)}$$

$$w_{\mathrm{SPS}}(\Delta\phi,\ \Delta y) = \frac{N_{\mathrm{SPS}}(\Delta\phi,\ \Delta y)}{N_{\mathrm{DPS}}(\Delta\phi,\ \Delta y) + N_{\mathrm{SPS}}(\Delta\phi,\ \Delta y)}$$



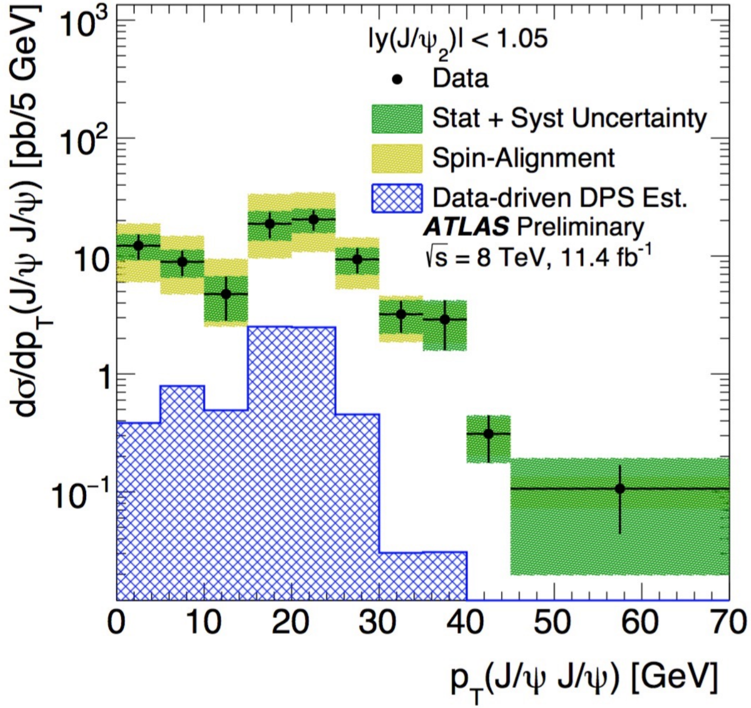
(b)

The 2-D **data-driven** templates of Δy vs. Δφ:

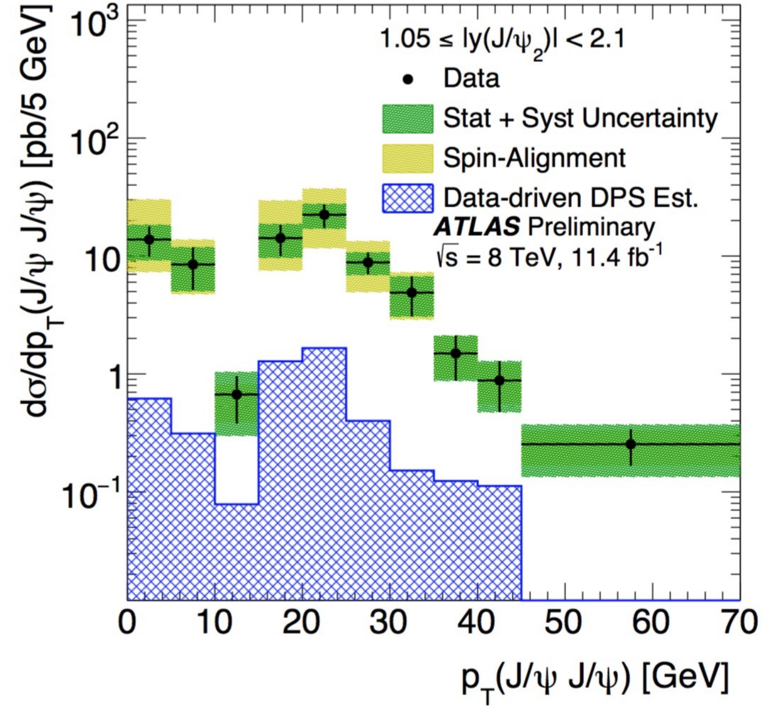
(a) DPS obtained by combining J/ψ pairs from different events and normalizing to the data
n.b. This simple model assumes no correlation between the scatters

(b) SPS obtained by subtracting the normalized DPS template from the data

J/ψ+J/ψ results: differential cross-sections, dσ/dp$_T$(J/ψ J/ψ)



(a)



(b)

Shown separately:

- Uncertainty due to the choice of J/ψ spin-alignment (systematic error)
- Data-driven DPS distribution
    - fraction of DPS events = f_{DPS} = 6.6 ± 0.8 (stat.) ± 0.2 (syst.) % in muon fiducial region

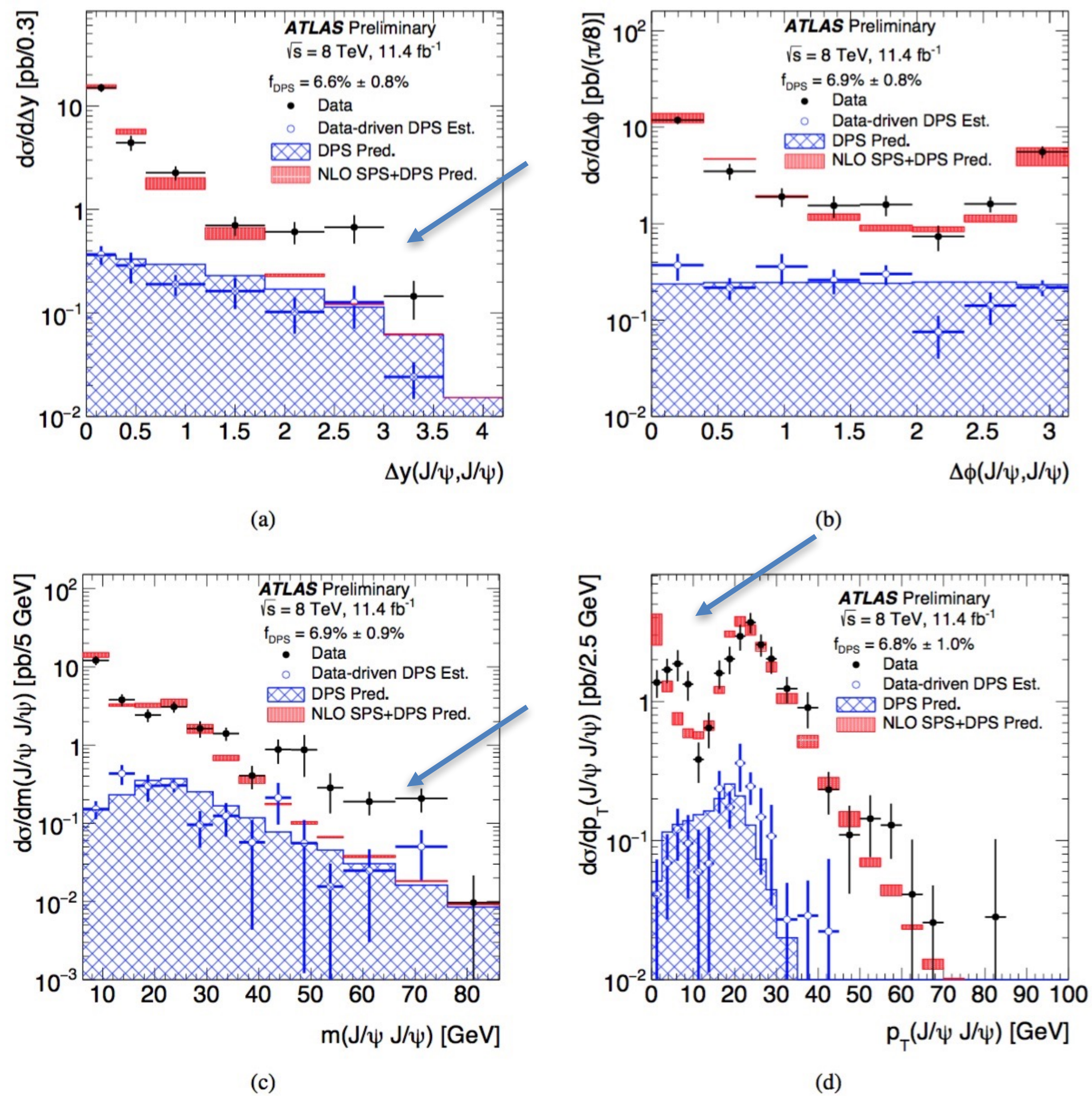
J/ψ+J/ψ results

DPS and **total** differential cross sections

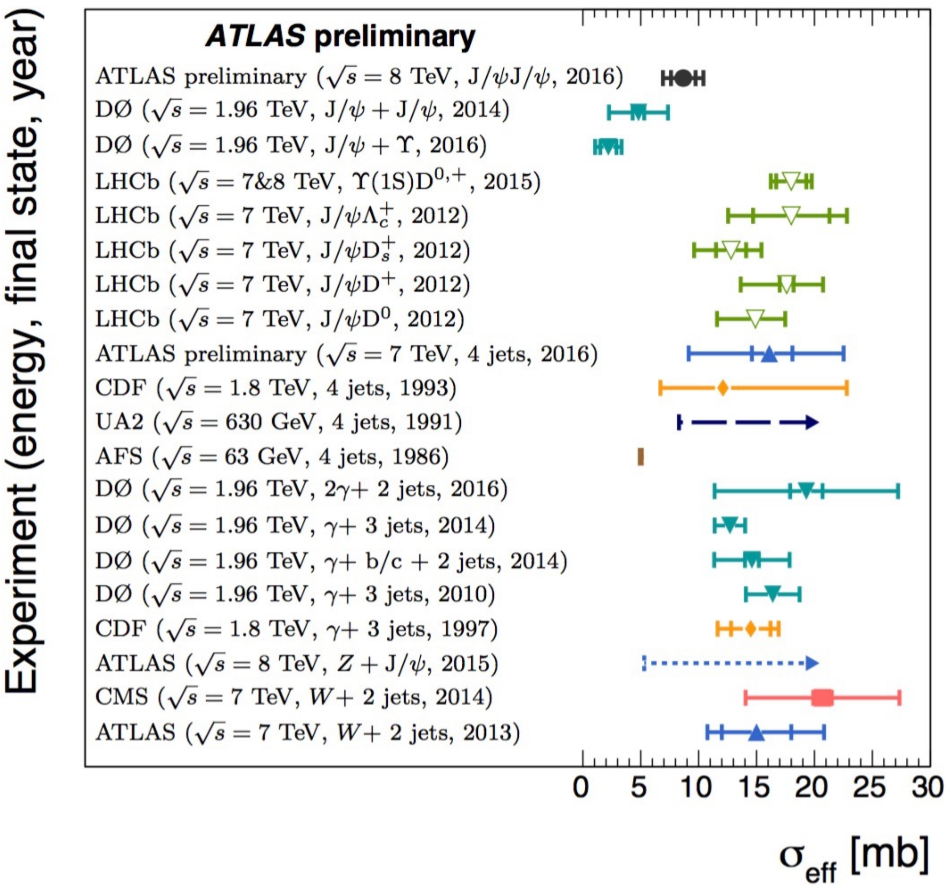
Measured DPS σ **consistent** with theory -- supports the data-driven DPS model used

Predicted NLO SPS cross-section **underestimates** measurement – especially at

- Large Δy
- Large m(J/ψ, J/ψ)
- Low p_T(J/ψ, J/ψ)



J/ψ+J/ψ results: σ_{eff}



$$\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{\sigma_{\text{DPS}}^{J/\psi,J/\psi}} = \frac{1}{2}\frac{\sigma_{J/\psi}\sigma_{J/\psi}}{f_{\text{DPS}} \times \sigma_{J/\psi J/\psi}}$$

f_{DPS} = fraction of DPS events = 6.6 ± 0.8 (stat.) ± 0.2 (syst.) %

f_{DPS} value taken from the well known Δy distribution

Difference between σ_{eff} and $\sigma_{inelastic}$ measures the proton correlation or “clumpiness”

This measurement agrees with past results – but possible evidence for non-universality of σ_{eff} ?

Outlook and conclusions

- The LHC experiments have made excellent steps in studying associated quarkonia production.

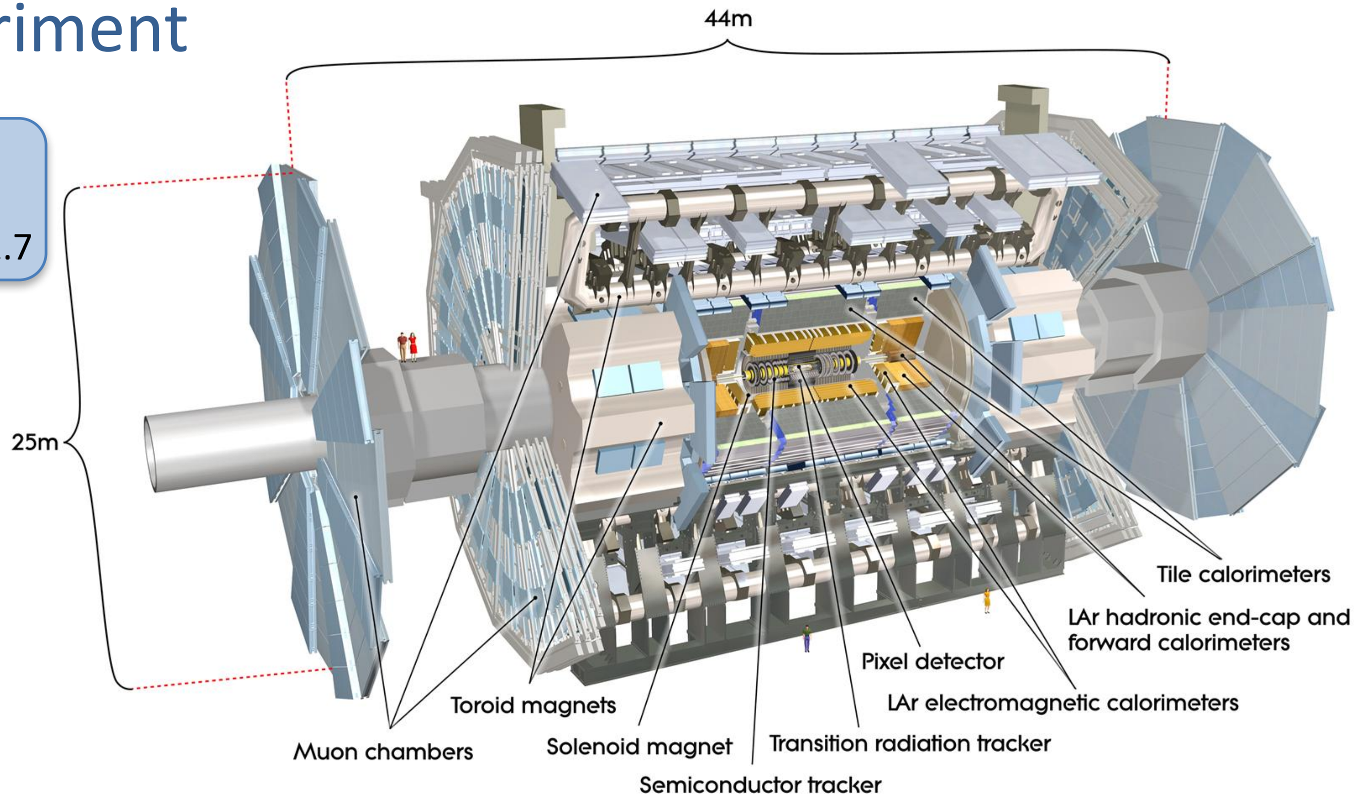
- These processes will help to address issues of:
    - double parton scattering
    - singlet versus octet production of quarkonia
    - resonant production

- Given low production rates, clean experimental signatures, 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.

ATLAS Experiment

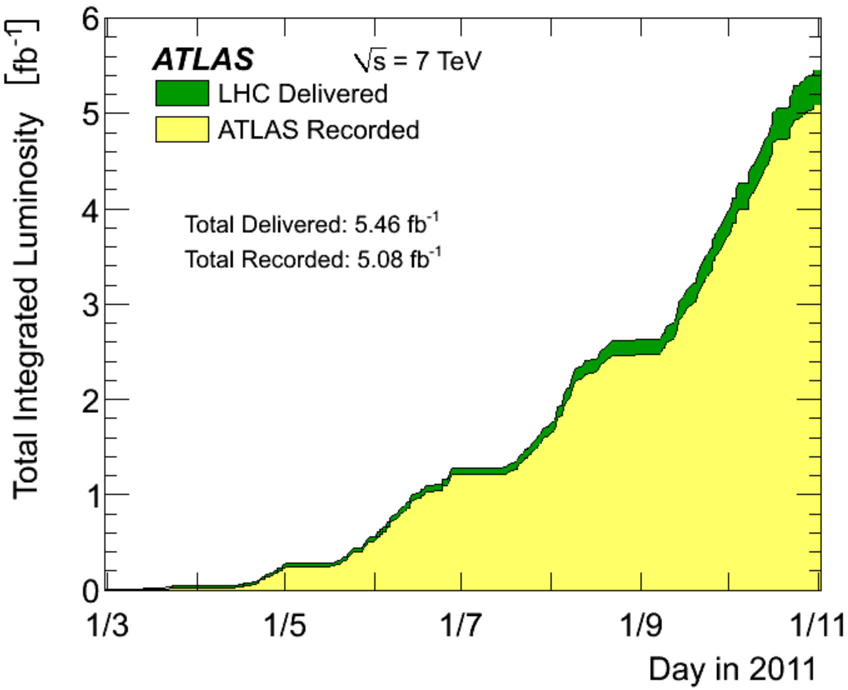
Muon Spectrometer
Triggering $|\eta|<2.4$
Precision Tracking $|\eta|<2.7$

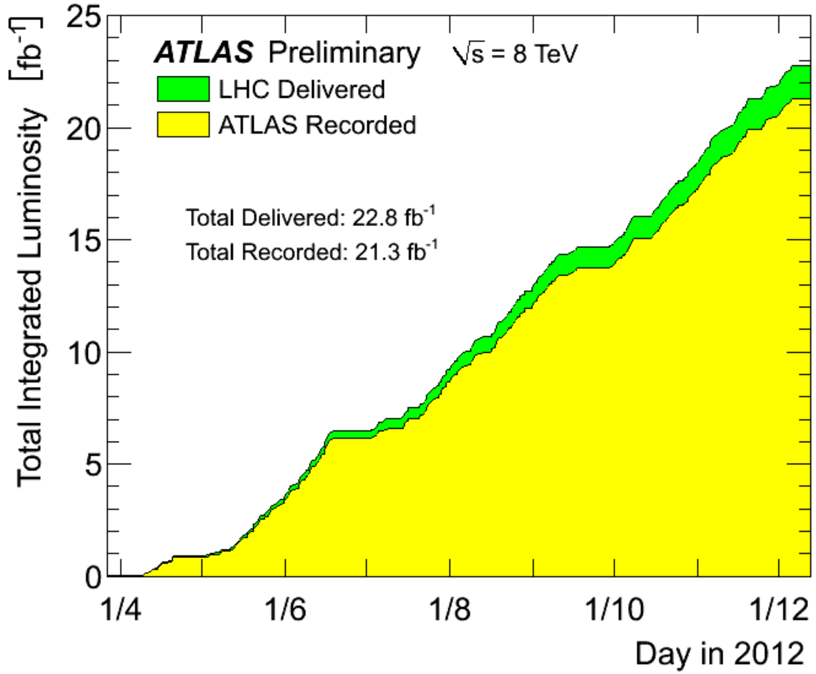


Inner Detector
p_T>0.4 GeV $|\eta|<2.5$
<u>New for Run 2</u>: Insertable B-Layer (IBL)
Additional inner-most pixel layer (r=33mm) and lower x/X_0 beam pipe

Resolution in $m_{\mu+\mu-}$
~50 MeV for J/ψ and 150 MeV for $\Upsilon(nS)$
Resolution in b-hadron proper decay time ~100 fs

Datasets (*pp*)





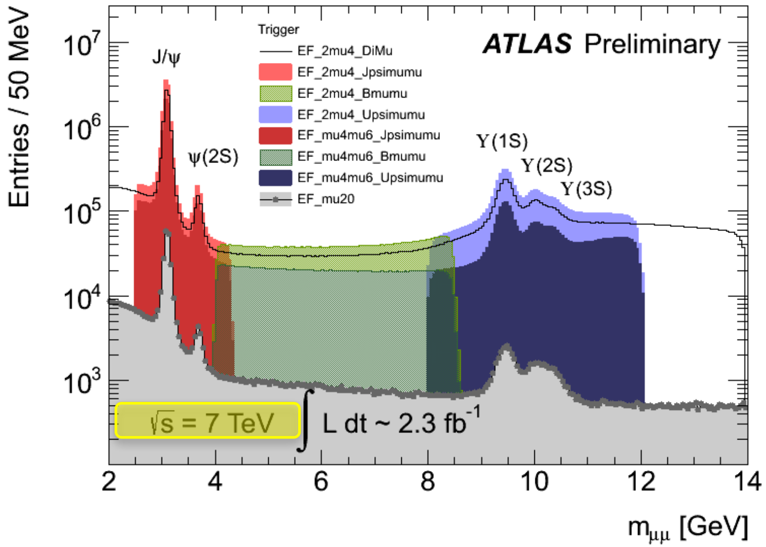
7 TeV data, 5.08 fb^{-1}
50 ns bunch spacing
Peak: 3.7 x 10^{33} cm^{-2}s^{-1}

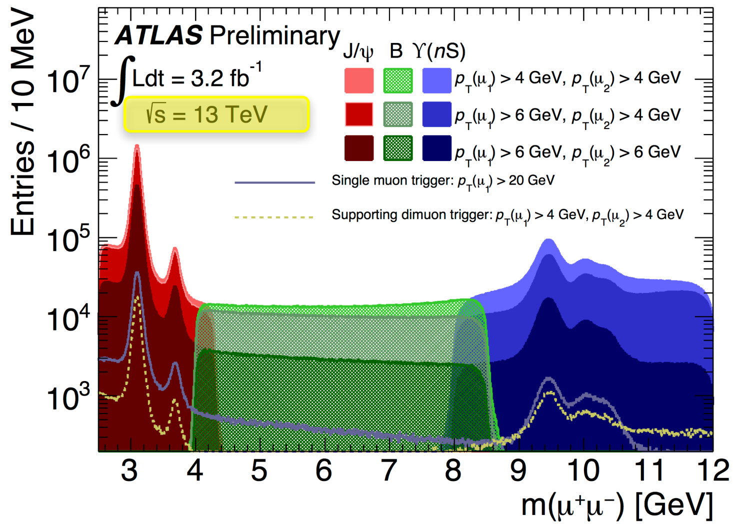
8 TeV data, 21.3 fb^{-1}
50 ns bunch spacing
Peak: 7.7 x 10^{33} cm^{-2}s^{-1}

Triggering for Heavy Flavor Physics

Quarkonia : J/ψ → μμ , ϒ → μμ
Exclusive: B → J/ψ(μμ) X decays
Rare decays: B → μμ(X) decays

- Trigger on low-p_T 4,6 GeV dimuons
- Large gain in yields w.r.t single muon triggers
- 20 MHz collision rate, ~400 Hz recorded
- HF physics concentrates on low p_T di-muon signatures





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, $\|\eta\|<2.5$, pT>2.5 (3.5) for $\|\eta\|<1.3$ (>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, $\|y(J/\psi)\| < 2.1$
MET selections	MET > 20GeV
W selections	One muon, matched to trigger: $p_T > 25$ GeV, $\|\eta\|<2.4$, $z_0 < 1$mm, $d_0/\sigma(d_0) < 3$, isolated $m_T(W) \equiv \sqrt{[2pT(\mu)*MET*(1-\cos(\phi_\mu-\phi_{MET}))]} > 40$ GeV

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

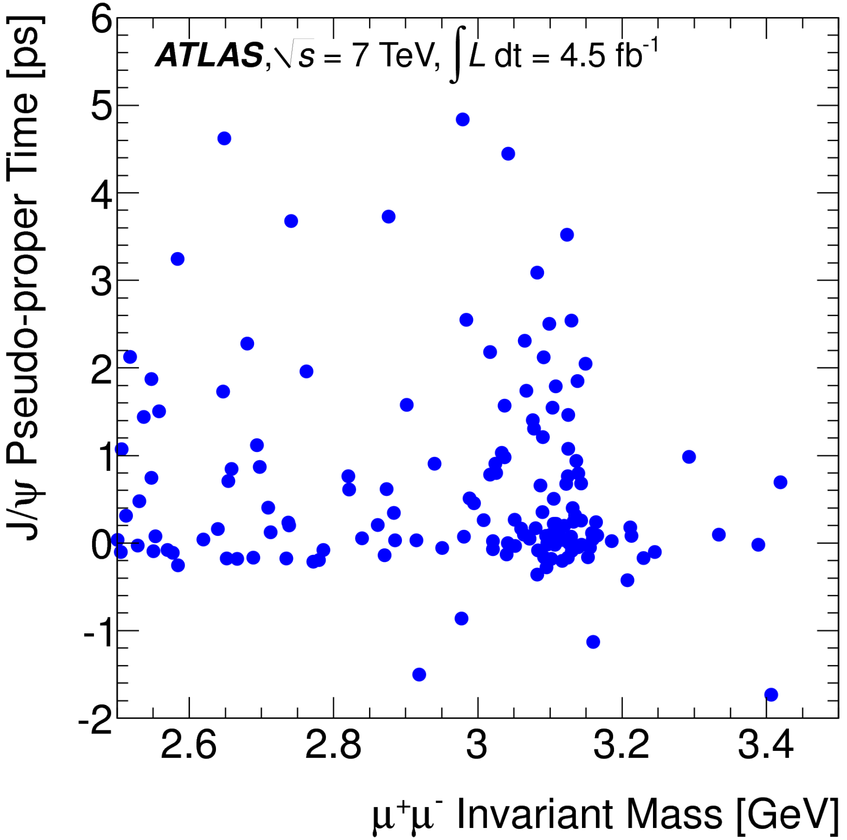
J/ψ+Z selections	J/ψ and Z vertices must less than 10mm apart

J/ψ + J/ψ : Event/object selection

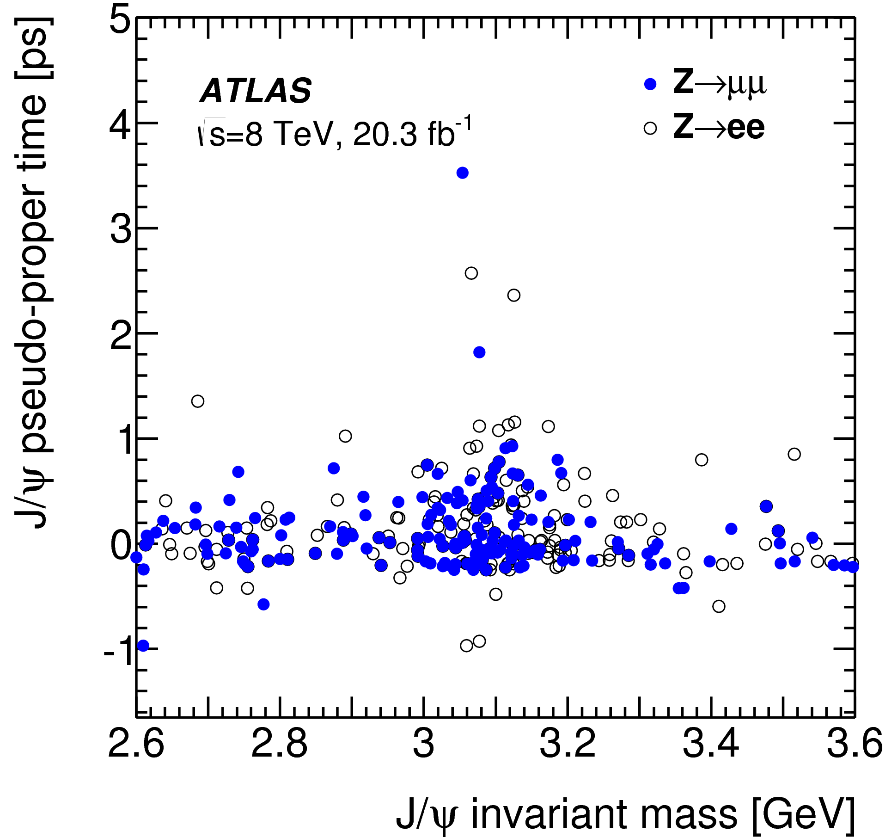
Final State Requirement	$\mu^+\mu^-\mu^+\mu^-$
Trigger	di-muon trigger
Muon Selections	$pT > 4$ GeV and invariant mass $2.5 < M(\mu\mu) < 4.3$ GeV $2.8 \leq M(\mu\mu) \leq 3.4$ GeV $\|\eta\mu\|<2.3$ and $pT\mu > 2.5$GeV.
J/ψ Selections	At least one ID track matched to a MS track from each J/ψ candidate. $\|yJ/\psi\|<2.1$and$pJ/\psi > 8.5$GeV For the triggered J/ψ, each reconstructed muon must have an ID track matched to a MS track. The distance between the two J/ψ decay vertices along the beam direction $\|dz\| < 1.2$ mm The uncertainty of the measurement of decay length, *L*xy, is required to be less than 0.3 mm

J/ψ+V-boson: Candidates

J/ψ+W



J/ψ+Z



J/ψ+V-boson: Corrections and Yield Extraction

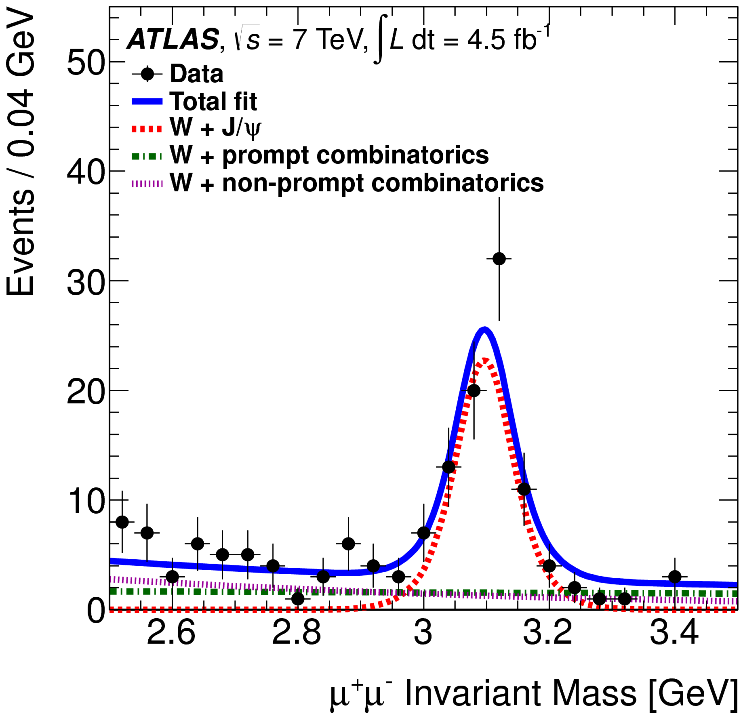
- Acceptance and efficiency corrections derived from MC and applied per candidate
  - A range of acceptance corrections, covering the extremes of J/ψ polarisation scenarios

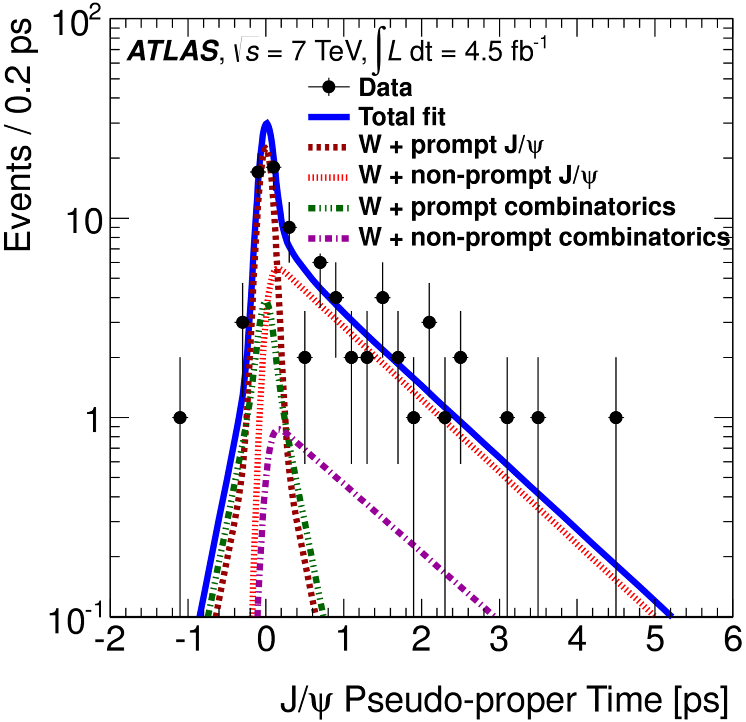
- Signal weights extracted using an 2D maximum likelihood fit with discriminants:
  - J/ψ candidate mass
  - J/ψ candidate pseudo-proper time

- 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

J/ψ+V-boson: Corrections and Yield

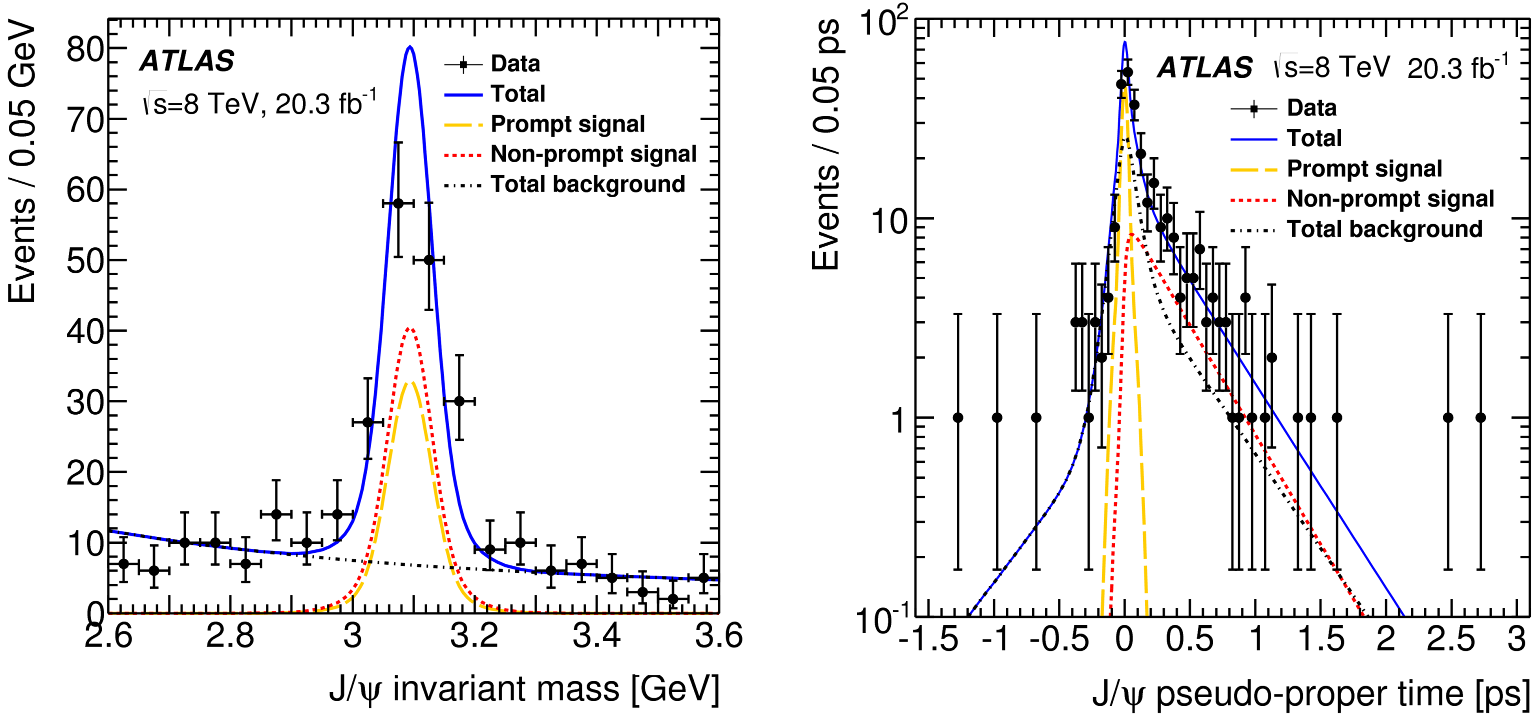




The signal weights are extracted by applying an unbinned, simultaneous, maximum likelihood, 2D fit to the mass and lifetime distributions

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

J/ψ+V-boson: Corrections and Yield Extraction:



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

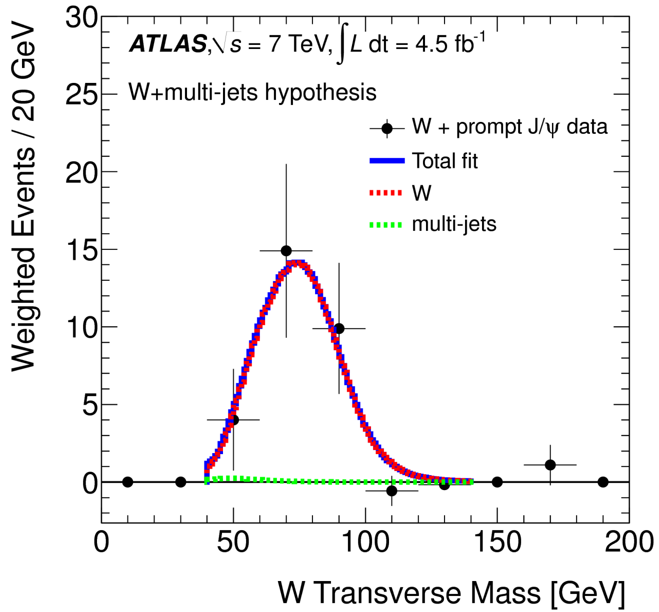
J/ψ+V-boson: Backgrounds

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 $B_c \to J/\psi\mu^{\pm}\nu\mu X$

J/ψ+V-boson: 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

→

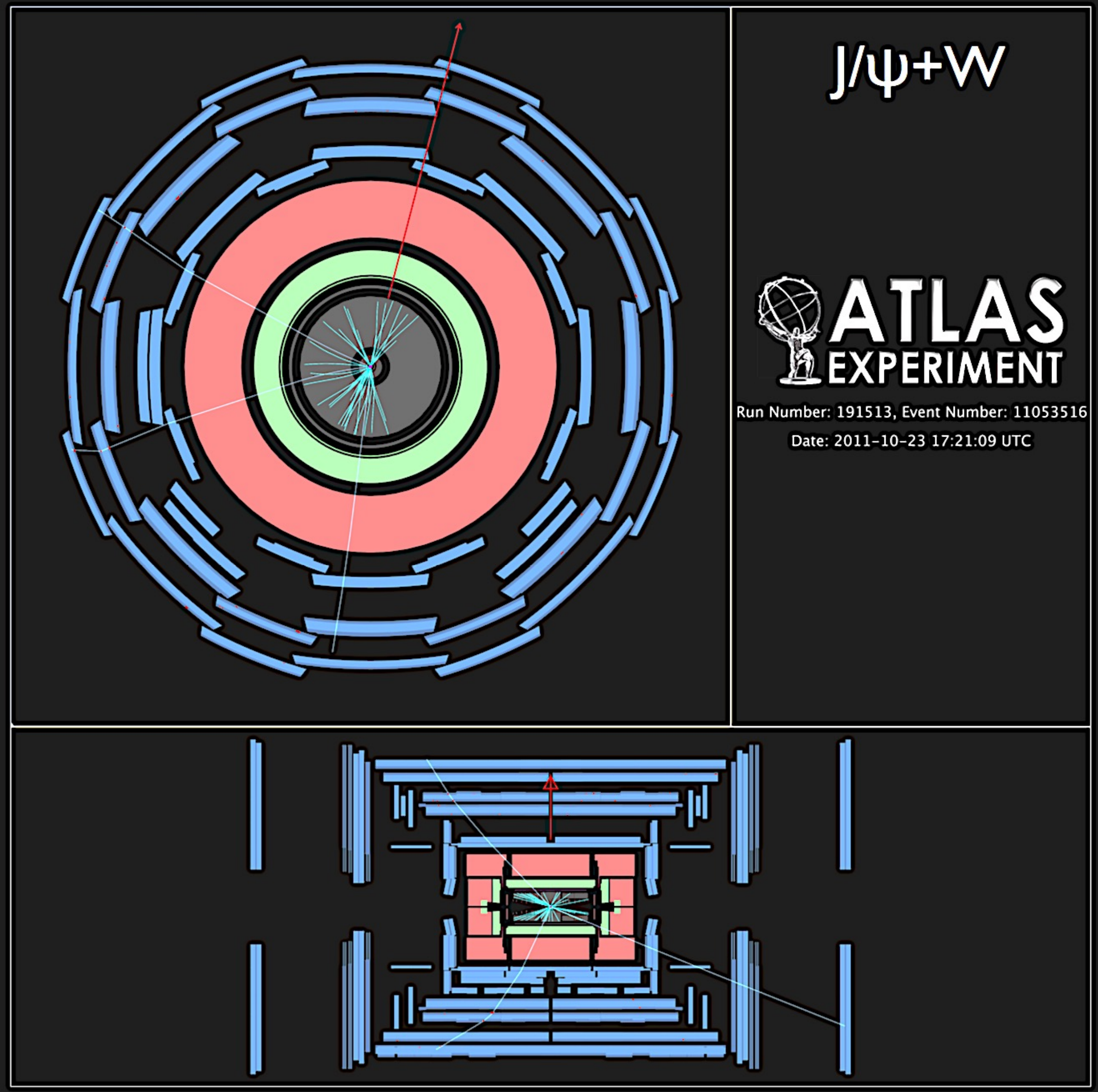
Calculate probability of any of these yielding a J/ψ using

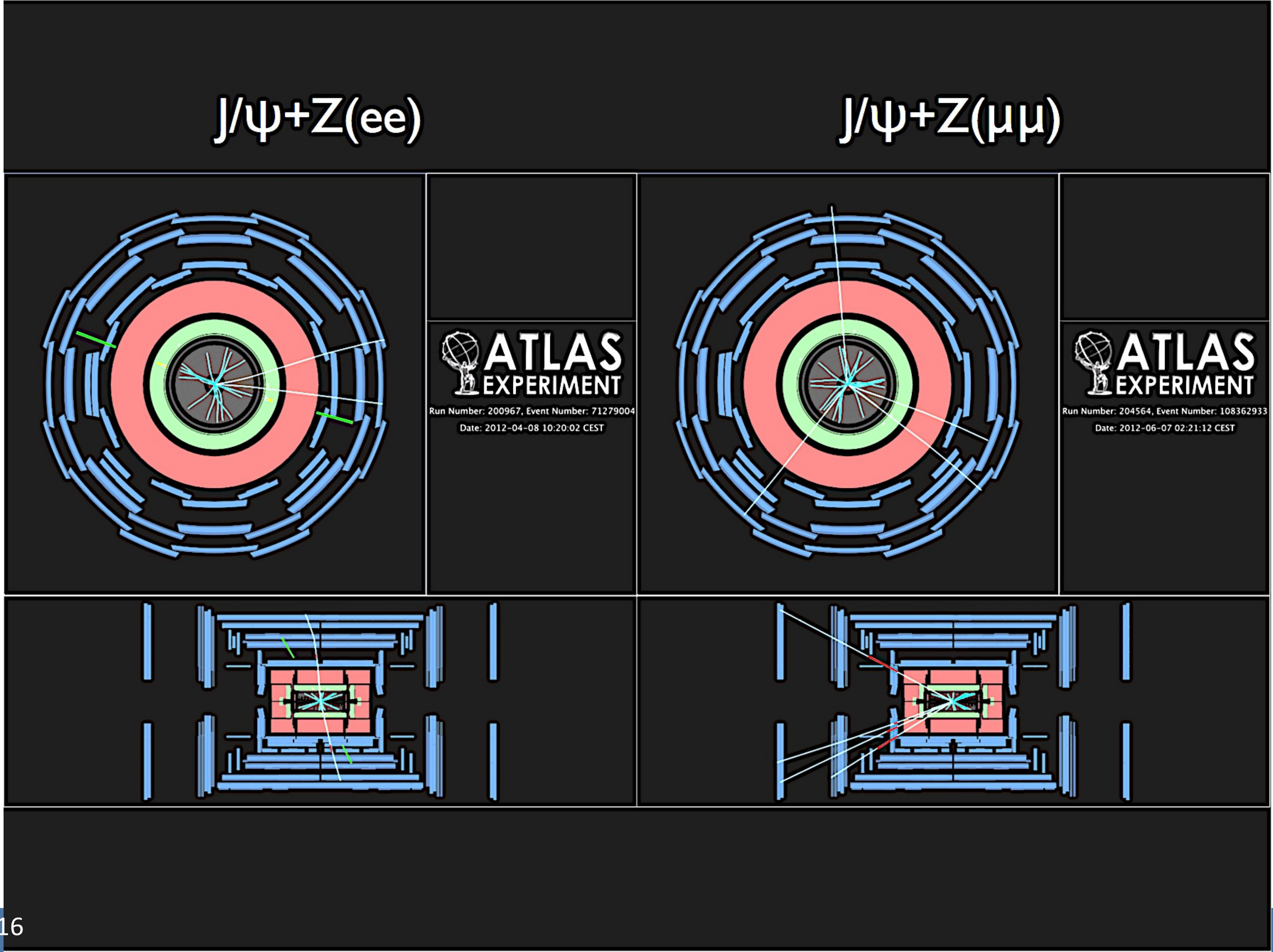
$$P^{ij}_{J/\psi} = \sigma^{ij}_{J/\psi}/\sigma_{\text{inel}}$$

→

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

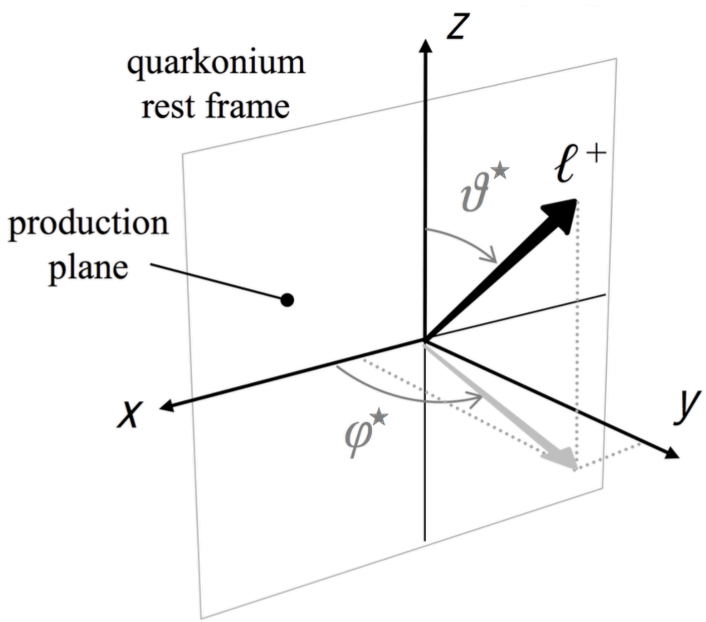

J/ψ+W
ATLAS
EXPERIMENT
Run Number: 191513, Event Number: 11053516
Date: 2011-10-23 17:21:09 UTC


J/ψ+Z(ee)
J/ψ+Z(μμ)
ATLAS EXPERIMENT
Run Number: 200967, Event Number: 71279004
Date: 2012-04-08 10:20:02 CEST
ATLAS EXPERIMENT
Run Number: 204564, Event Number: 108362933
Date: 2012-06-07 02:21:12 CEST

J/ψ Spin Alignment Uncertainty

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

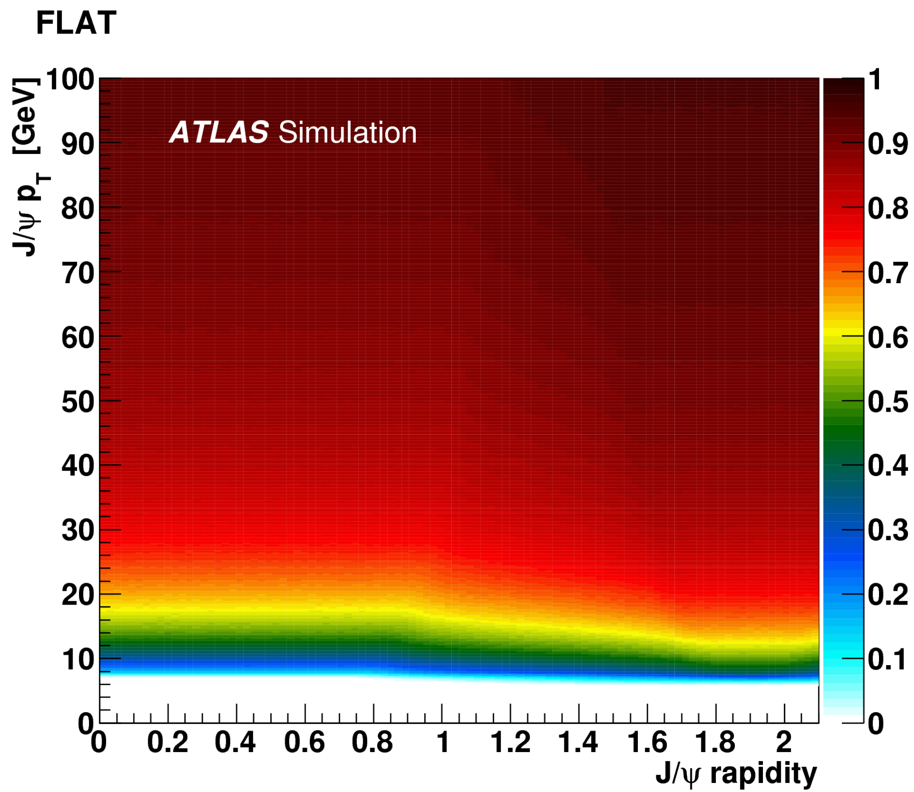
$$\frac{d^2N}{d\cos(\vartheta^*)d\varphi^*} \propto 1+\lambda_\theta \cos^2(\vartheta^*)+\lambda_\phi \sin^2(\vartheta^*)\cos(2\varphi^*)+\lambda_{\theta\phi}\sin(2\vartheta^*)\cos(\varphi^*)$$



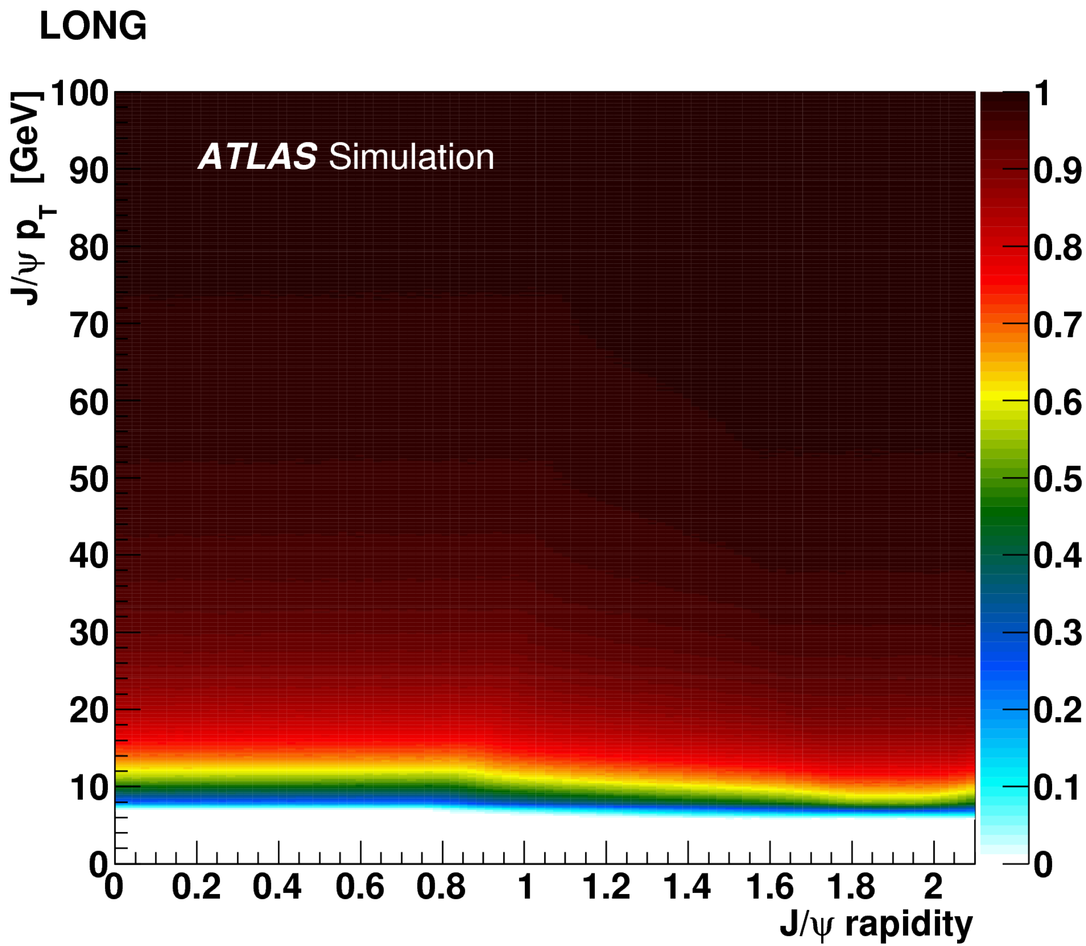
	Angular coefficients		
	λ_θ	λ_ϕ	$\lambda_{\theta\phi}$
Isotropic *(central value)*	0	0	0
Longitudinal	−1	0	0
Transverse positive	+1	+1	0
Transverse zero	+1	0	0
Transverse negative	+1	−1	0

J/ψ Acceptance Maps

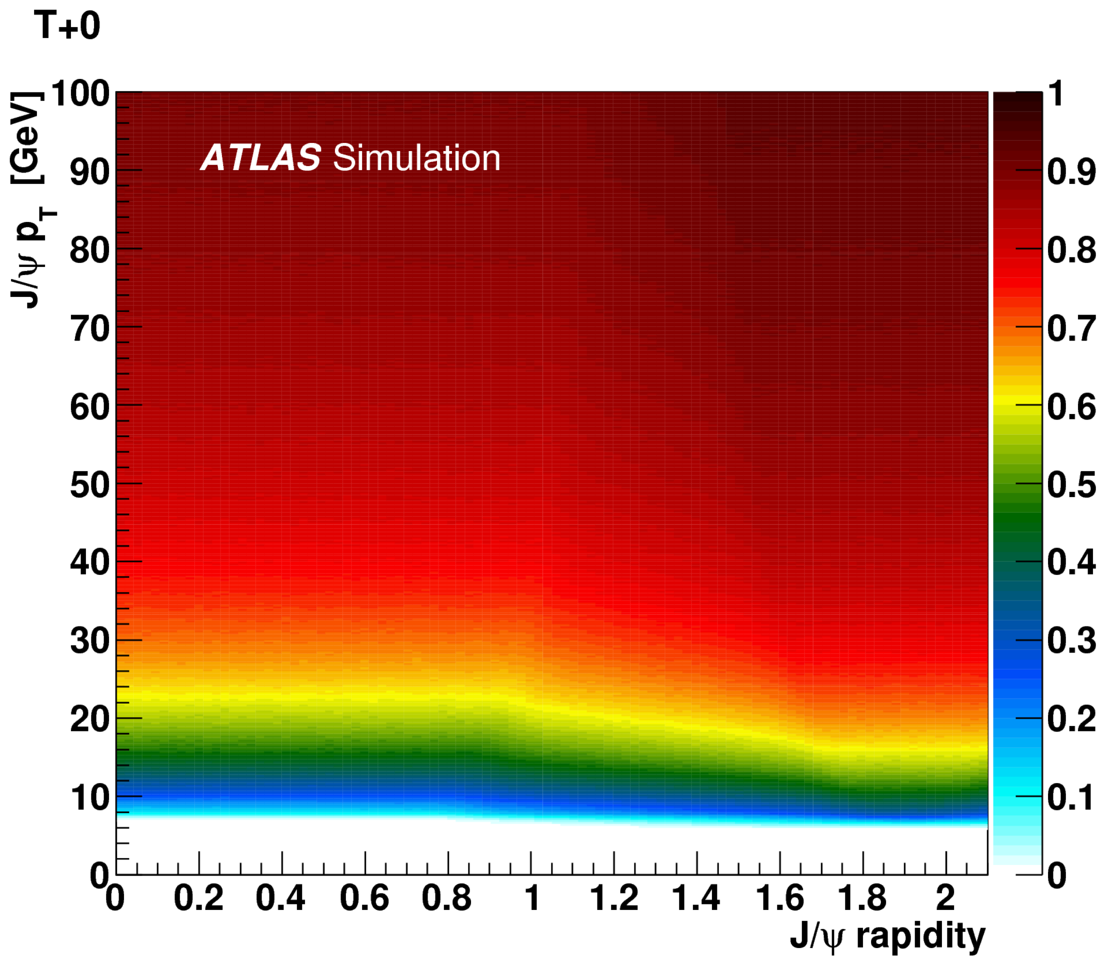
J/ψ kinematic acceptance depends on an uncertain spin alignment: we use extreme values to assess this uncertainty.



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

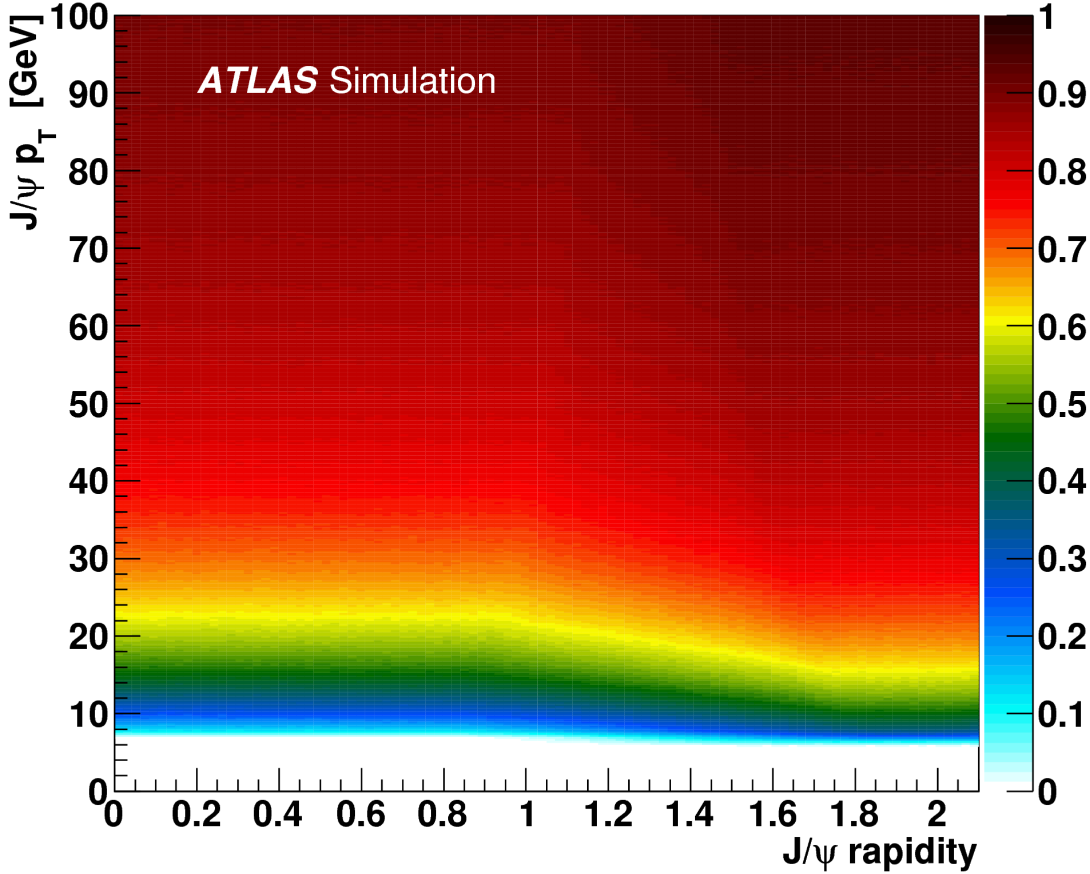


The J/ψ acceptance for the extreme spin-alignment scenario longitudinal (LONG) following Nucl. Phys. B 850 (2011) 387.

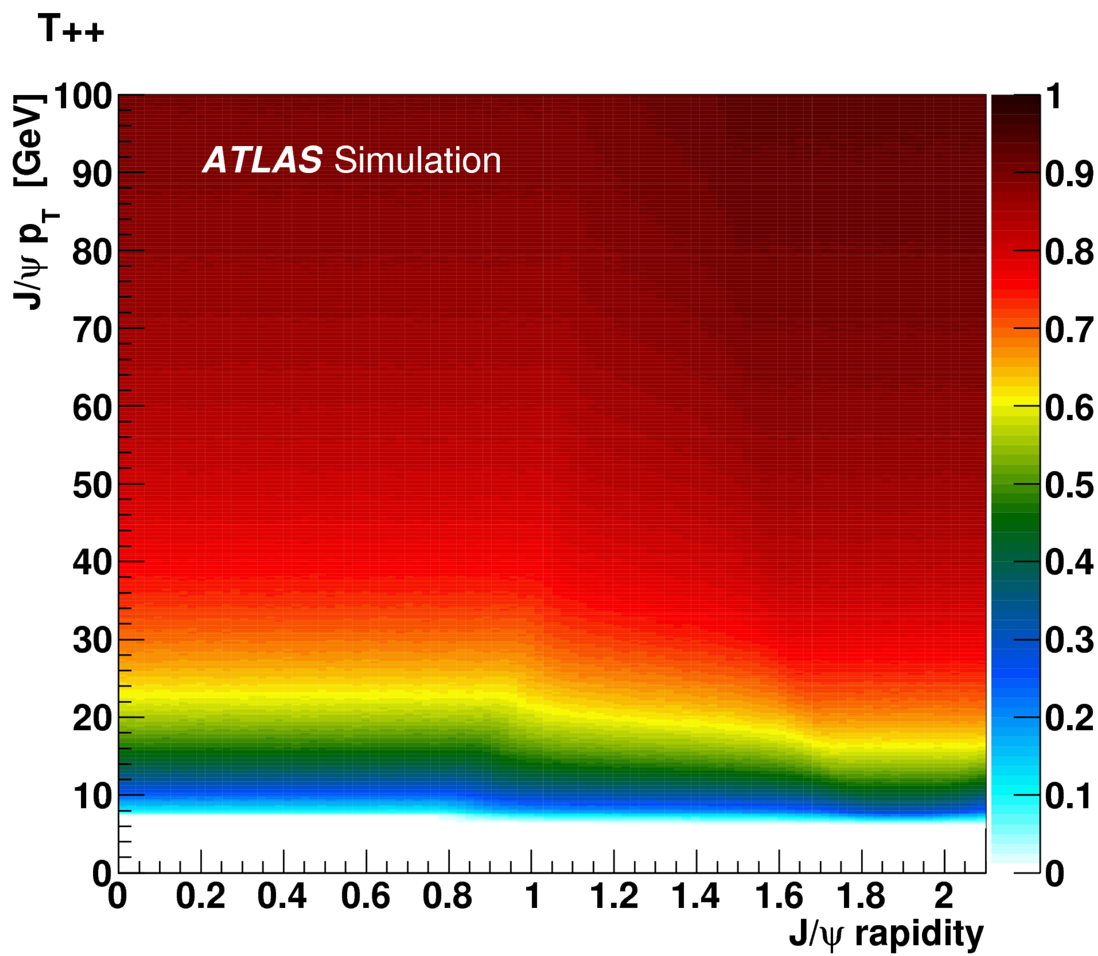


The J/ψ acceptance for the extreme spin-alignment scenario transverse 0 (T+0) following Nucl. Phys. B 850 (2011) 387.

T+-



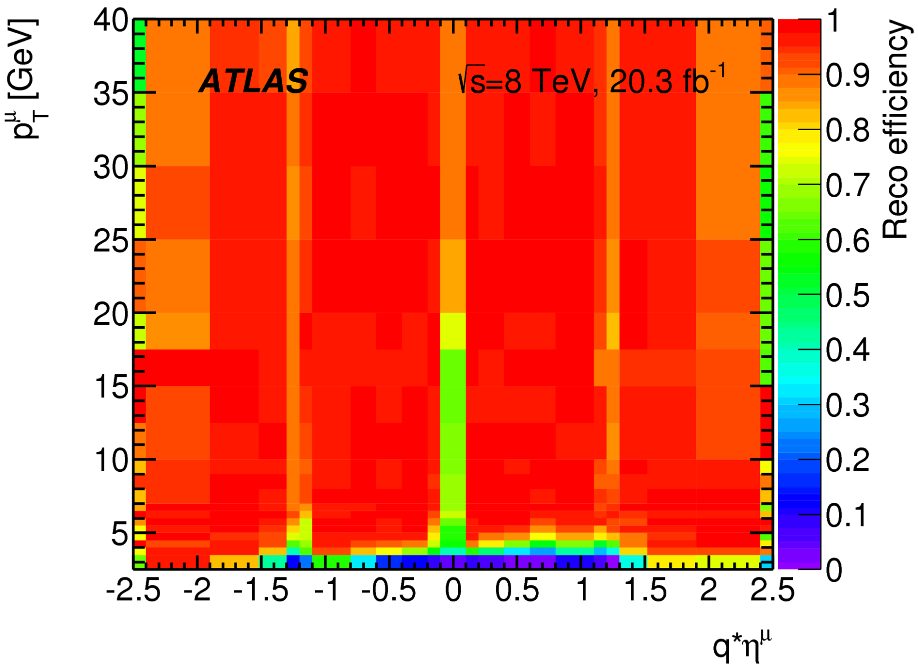
The J/ψ acceptance for extreme spin-alignment scenario transverse M (T+-) following Nucl. Phys. B 850 (2011) 387.



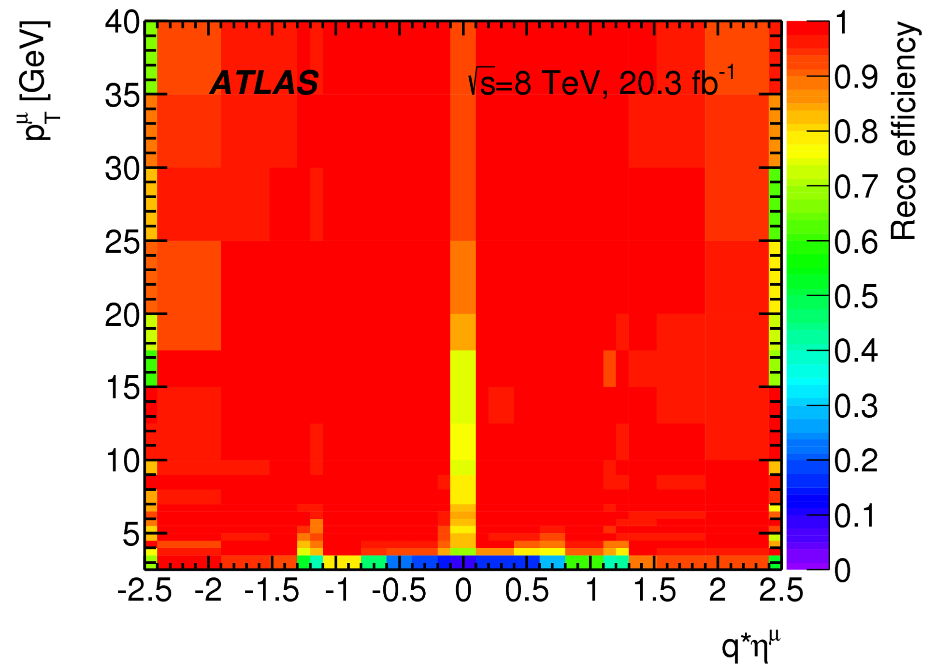
The J/ψ acceptance for extreme spin-alignment scenarios transverse P (T++) following Nucl. Phys. B 850 (2011) 387.

J/ψ Muon Reconstruction Efficiency Maps

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

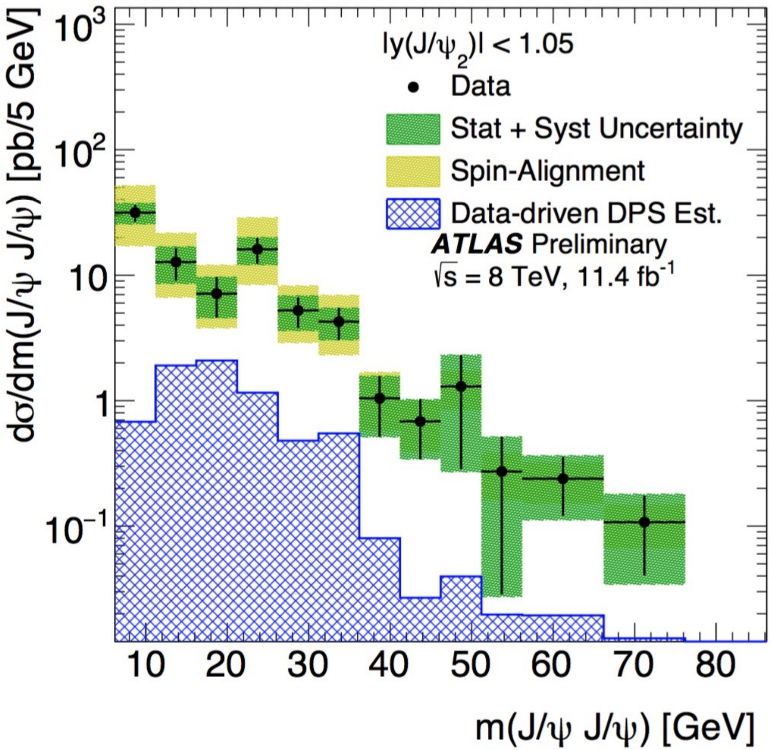


Low p_T reconstruction efficiencies for combined muons.

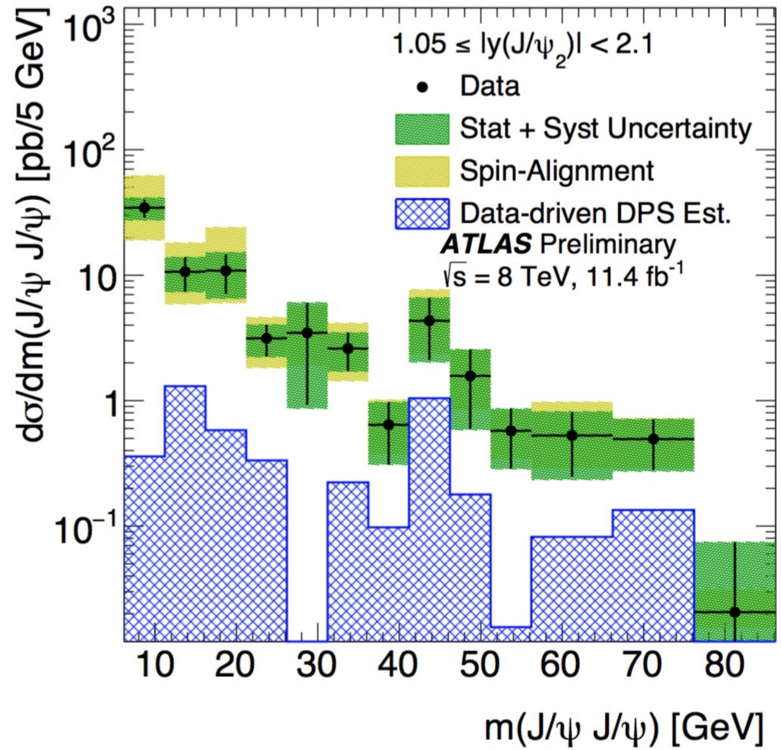


Low p_T reconstruction efficiencies for segment-tagged muons.

J/ψ+J/ψ results: differential cross-sections, dσ/dm(J/ψ J/ψ)



(a)



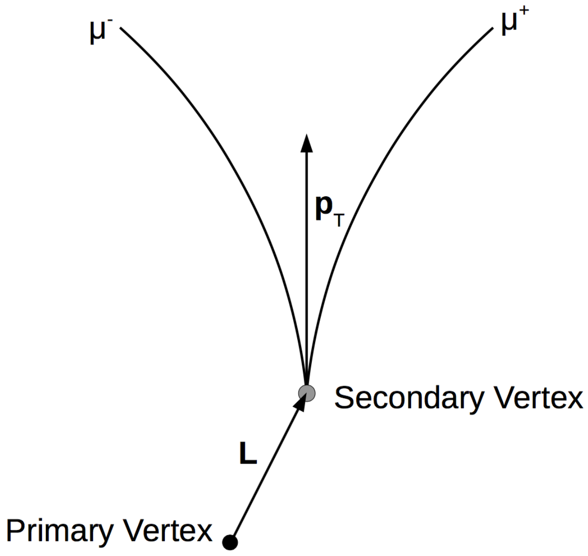
(b)

Shown separately:

- Uncertainty due to the choice of J/ψ spin-alignment
- Data-driven DPS distribution

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