ATLAS results on quarkonia and its associated production

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on Behalf of ATLAS collaboration

Outline

- ATLAS tracking performance relevant to the presented measurements

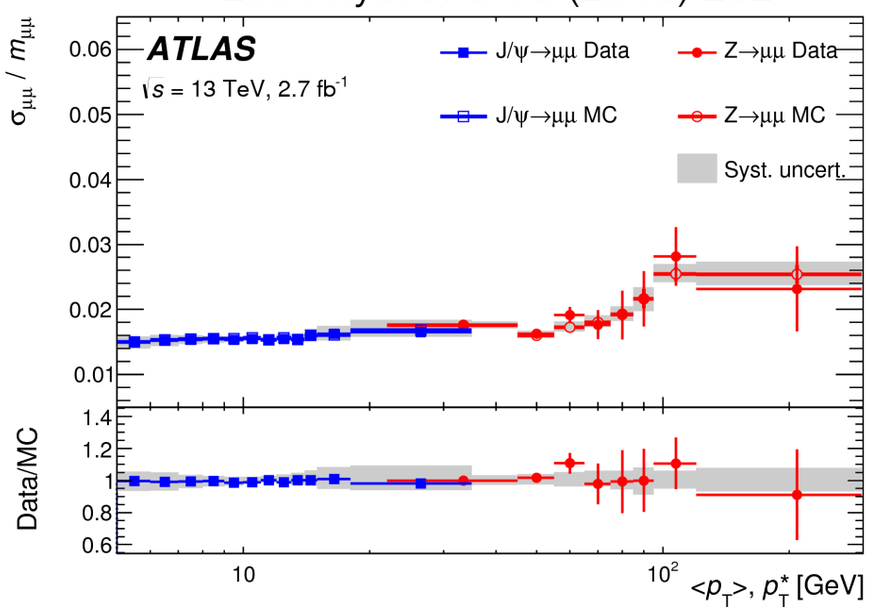
- J/ψ production in association with a $W^{\pm}$ boson at 8 TeV, in ATLAS, arXiv:hep-ex 1909.13626

- Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 8 TeV in ATLAS, Eur. Phys. J. C77 (2017) 76, arXiv:1612.02950

- Associated production of prompt and non-prompt J/ψ mesons with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV in ATLAS, Eur. Phys. J. C75 (2015) 229, arXiv:1412.6428

ATLAS tracking performance relevant to measurements presented here

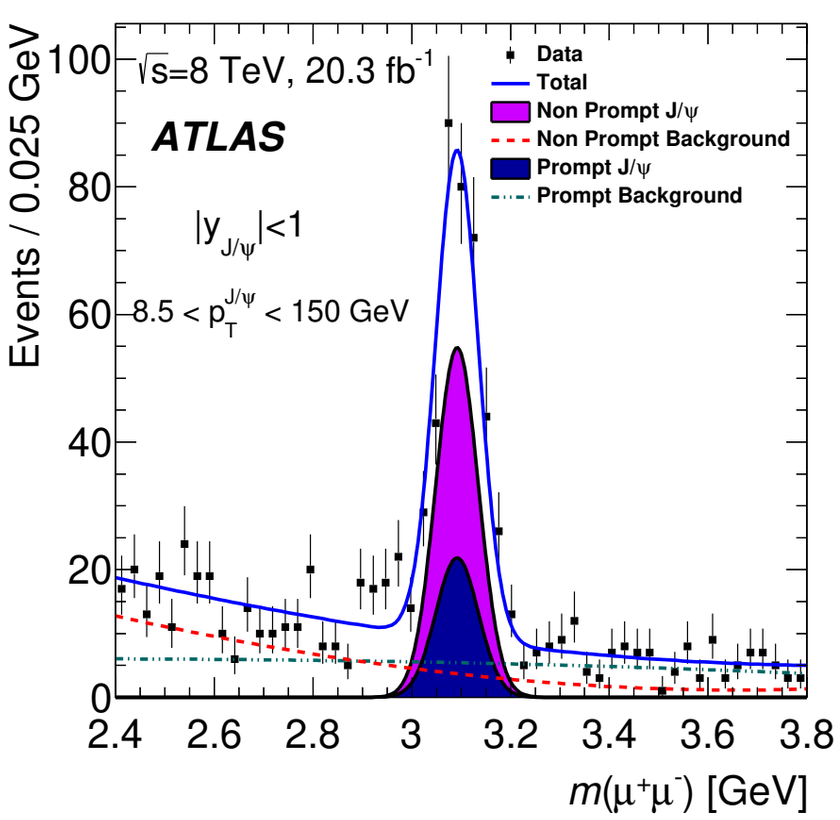
Eur. Phys. J. C 76 (2016) 292

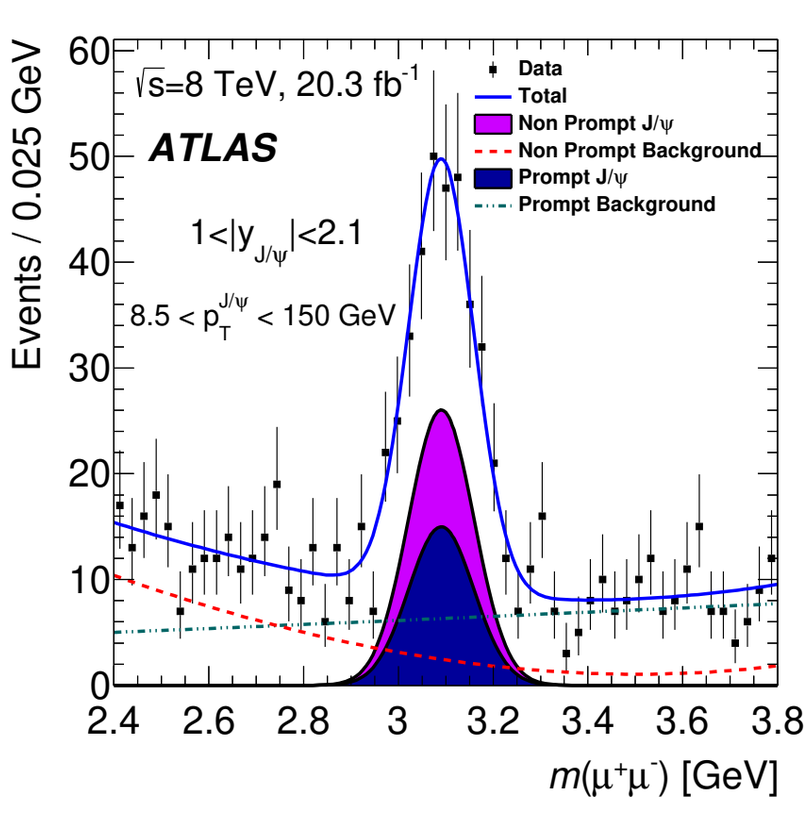


- Relative mass resolution in di-muon states J/ψ, Z in ATLAS has a long plateau at 1.6% (4-40 GeV) and is raising to 2.5% after 80 GeV. The values given for the combined Inner detector -Muon Detector tracking.

- The ATLAS J/ψ mass resolution for pT (8.5 - 150 GeV) in $|\eta| < 1$ is 35 MeV and in $1 < |\eta| < 2.1$ is 90 MeV.

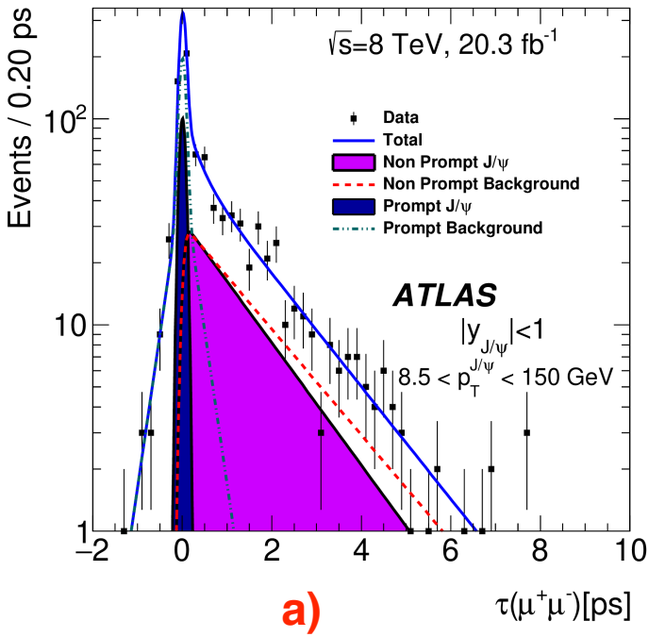
arXiv:hep-ex 1909.13626





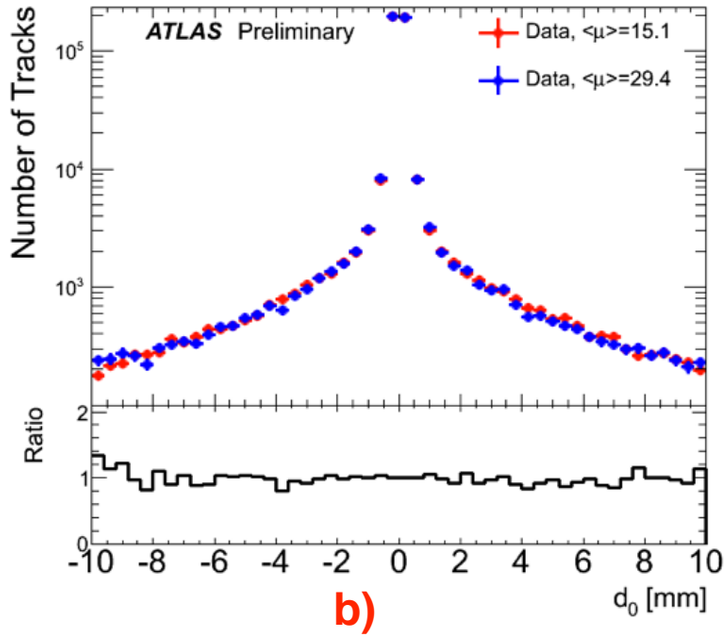
ATLAS tracking performance relevant to measurements presented here, cont

arXiv:hep-ex 1909.13626



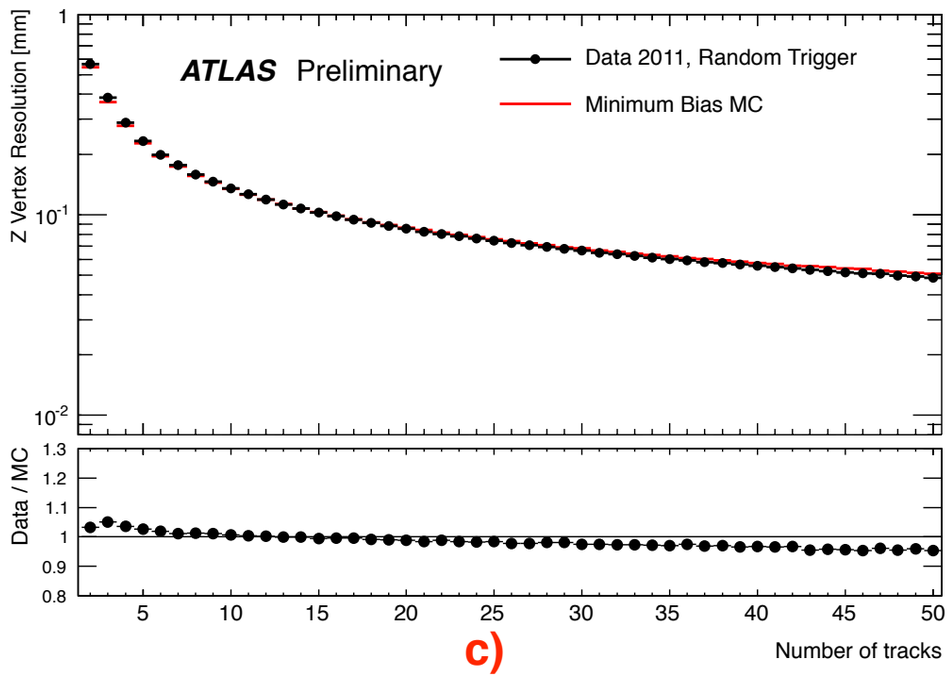
a)

ATLAS-CONF-2012-042



b)

- The separation of the prompt/non-prompt J/ψ's relies on the good decay time resolution (fig. a), which is connected with the precise impact parameter d0 resolution of the reconstructed muon tracks.
- With increasing pileup a stability of d0 resolution (fig. b) is important feature of ATLAS Inner detector performance.



c)

- For the associated J/ψW production the Primary vertex z-resolution is essential in estimation of Bg from J/ψ and W produced in different p-p interactions. PV z-resolution of ATLAS during 7 TeV data taking is shown in fig c.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/InDetTrackingPerformanceApprovedPlots#Figures

J/ψ production in association with a W± boson at 8 TeV, in ATLAS arXiv:hep-ex 1909.13626

Motivation

- Associated prompt J/ψW$^{\pm}$ production is described in QCD as a clear signature of Colour Octet (CO) processes.

  L. Gang, et al, QCD corrections to J/ψ production in association with a W boson at the LHC Phys. Rev. D **83** (2011) 014001.

- Prompt J/ψ production is a mixture of Colour Singlet (CS) and CO production mechanisms, the tests of QCD are more complicated. The J/ψW$^{\pm}$ provides a straight CO test.

- To extract the CO production, J/ψW$^{\pm}$ must be produced in Single-Parton-Scattering (SPS) interaction.

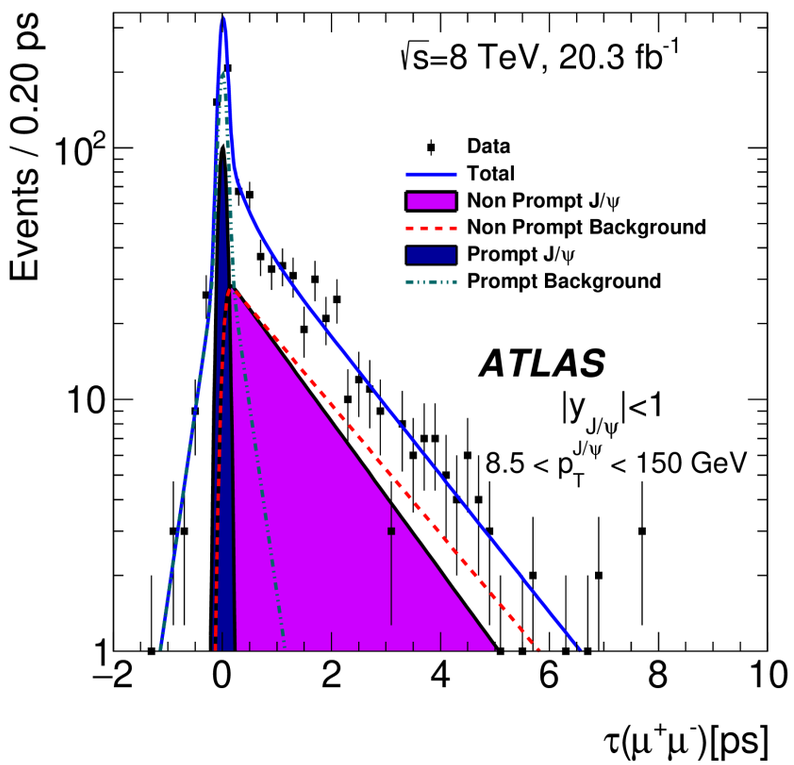
- Extracting a fraction of Double-Parton-Scattering (DPS) (the same p-p collision) is essential part of the measurement.

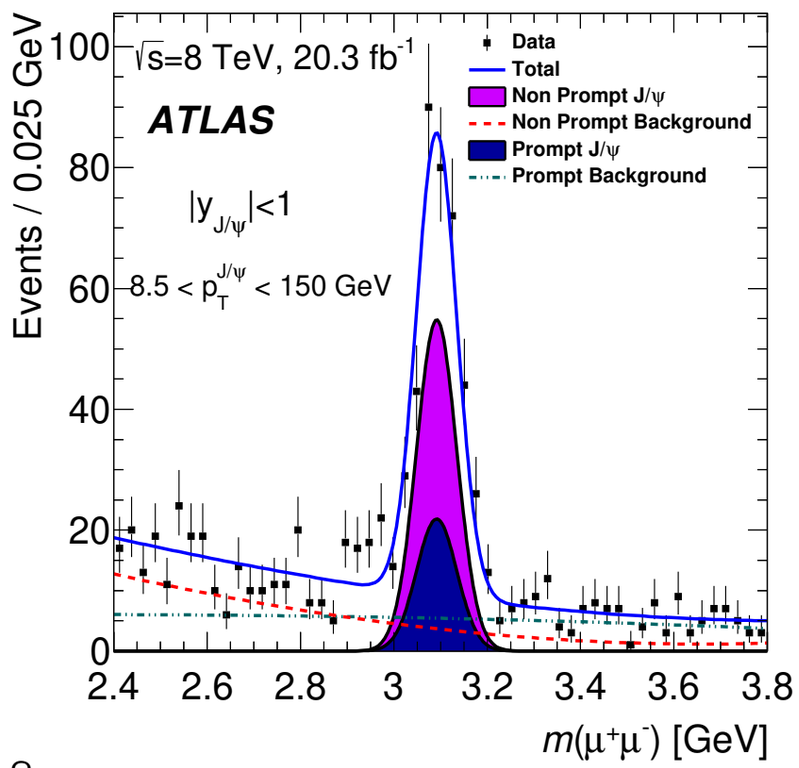
Signal selection

- **Data taken for**
  - 20.3 fb^{-1} of pp collision data at 8 TeV
  - Single-muon trigger p_T > 24 GeV, stable beams, and fully operational sub-detectors.
- **$W^{\pm} \rightarrow \mu^{\pm}\nu$ selections**
  - at least one isolated muon originating < 1 mm from PV along z-axis ($|z_0|$<1mm) and with $|d_0|/\sigma(d_0)$ <3
  - Missing transverse momentum E_T^{miss} > 20 GeV
  - $m_T(W)$ > 40GeV, $m_T(W) \equiv$ sqrt($2p_T(\mu) * E_T^{miss} * (1 - \cos(\phi_\mu - \phi_\nu))$), where ϕ_μ and ϕ_ν are azimuthal angles of the muon from the $W^{\pm}$ boson decay and of the missing transverse momentum E_T^{miss} respectively.
- **J/ψ → μ μ selections**
  - 8.5 < p_T(J/ψ) <150 GeV ; $p_T(\mu 1)$ > 4 GeV; $p_T(\mu 2)$ > 3.5 (2.5) GeV in barrel (endcap), J/ /ψ vertex < 10 mm from PV along z-axis

Backgrounds

- **Inclusive $W^{\pm}$ sample backgrounds**
  - $W\pm \rightarrow \tau^{\pm}\nu$, $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$, diboson, $t\bar{t}$ and single top modelled with MC simulations as well as signal $W\pm \rightarrow \mu^{\pm}\nu$
  - After accounting for all background events contributing 80%, a total $W^{\pm}$ yield of $(6.446 \pm 0.035)\ 10^{7}$ events was determined.
- **J/ψ → prompt/ non-prompt**
  - separated by fit to pseudo-proper decay time applied simultaneously with the mass fit





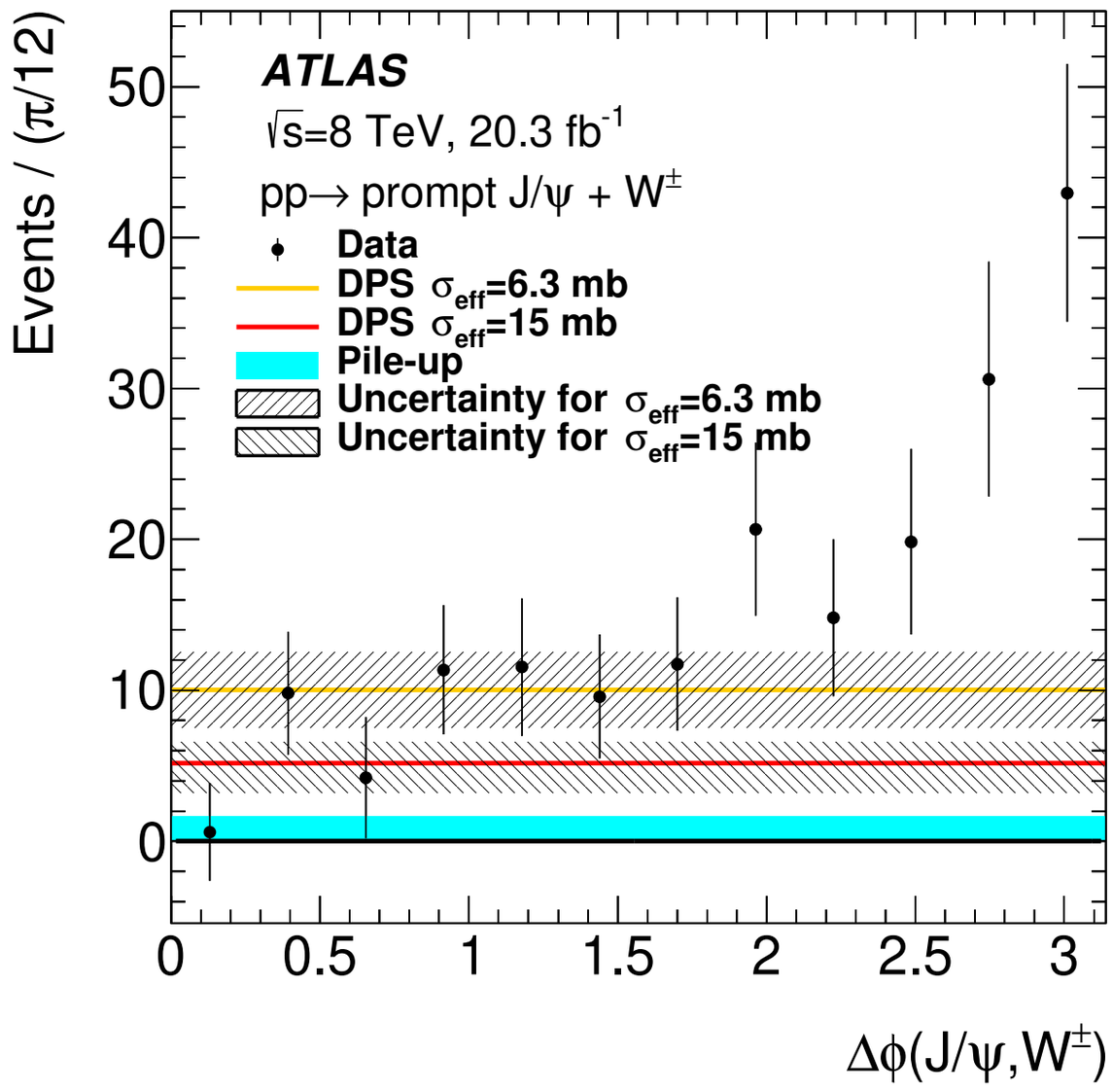
backgrounds for associated production J/ψ + $W^{\pm}$

- **The signal topology:** prompt J/ψ + $W^{\pm}$ with $W^{\pm} \rightarrow \mu^{\pm}\nu$
- **Backgrounds:**
  - prompt J/ψ+$W^{\pm}$ with $W^{\pm} \rightarrow \tau^{\pm}\nu$, (2.3 ± 0.1)% determined by MC
  - prompt J/ψ+Z with Z→ μμ or Z → $\tau\tau$, (9.5 ± 0.5)% determined from ATLAS measured σ(*pp* →*J*/ψ + *Z*)/ σ(*pp* → *Z*) and from MC
  - Bc → J/ψ $\mu^{\pm}\nu$ - negligible
- **Background effects due to pileup:**
  - Background events due to pileup are flat in azimuthal angles diff between J/ψ + $W^{\pm}$ - same as DPS. So an independent pileup Bg estimation is important.
  - Pileup bg J/ψ and $W^{\pm}$ produced in different pp collision in the same bunch crossing
  - Since the selected J/ψ and $W^{\pm}$ are already close to PV , z0 < 10 mm pileup Bg remaining after z0-cut determined as (10.5 ± 1.2)%
  - The procedure used
    - known distribution of the number of collisions per bunch crossing,
    - re-shaped for the selected inclusive $W^{\pm}$ events
    - renormalised by a ratio σ(*pp* →*J*/ψ) / inelastic cross section in each *J*/ψ p_T-η bin
    - applying z0 < 10 mm

J/ψ + $W^{\pm}$ from DPS

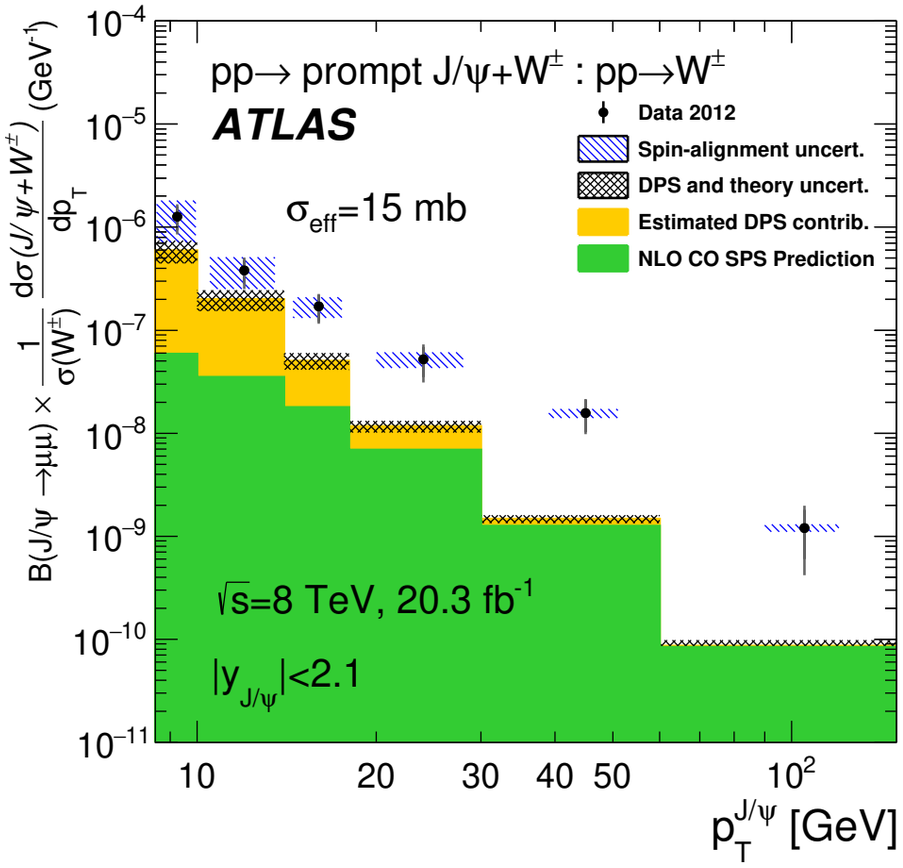
- **DPS:** J/ψ + $W^{\pm}$ produced from different partons in the same pp collision.
- DPS mechanism is not CO hence the DPS fraction has to be determined
- **Measuring DPS contribution:**
  - use effective cross section, $\boldsymbol{\sigma_{eff}}$, which is the effective transverse overlap area of the interacting partons.
  - admitting that $\boldsymbol{\sigma_{eff}}$ may not be fully process-independent, two $\boldsymbol{\sigma_{eff}}$ are used σ_{eff} = 15 mb and 6.3 mb, determined in the measurements respectively
    - Measurement of hard double-parton interactions in W(→ lν) + 2 jet events at 7 TeV with the ATLAS detector, New J. Phys. **15** (2013) 033038, arXiv: 1301.6872 [hep-ex].
    - Measurement of the prompt J/ψ pair production cross-section in pp collisions at √s = 8 TeV with the ATLAS detector, Eur. Phys. J. C 77 (2017) 76, arXiv: 1612.02950 [hep-ex].
  - J/ψ production cross section $\sigma_{J/\psi}$ measured in Eur. Phys. J. C 75 (2015) 229, arXiv: 1412.6428 [hep-ex],
  - Probability $P_{J/\psi\ W\pm}$ that a J/ψ is produced by a second hard process in an event containing a $W^{\pm}$ boson: $\boldsymbol{P_{J/\psi\ W\pm} = \sigma_{J/\psi} / \sigma_{eff}}$. This is done in each *J*/ψ p_T-η bin.
- Using σ_{eff} = 15 mb or 6.3 mb gives 31 % or 75% DPS fractions respectively

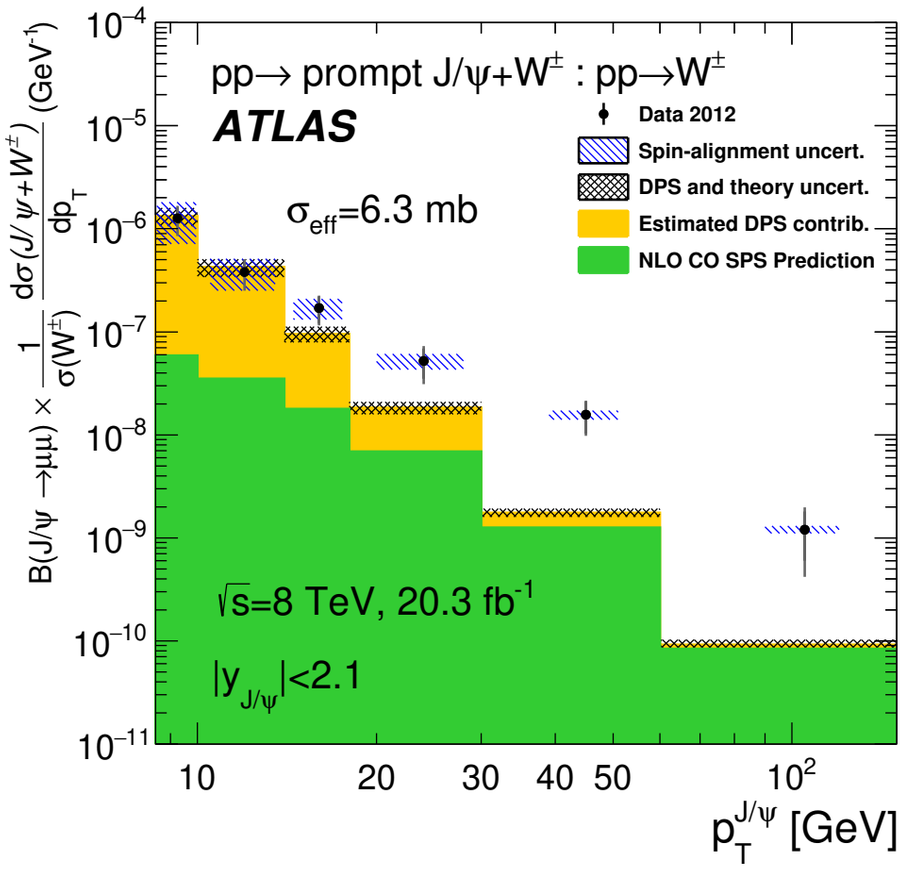
J/ψ + $W^{\pm}$ composition



- opening angle $\Delta\phi(J/\psi,W^{\pm})$ for prompt J/ψ + $W^{\pm}$,uncorrected for acceptance, with pileup and DPS contributions. Peak at $\Delta\phi \simeq \pi$ is assumed to come primarily from SPS events.

Cross section Ratio: $\sigma(J/\psi + W^{\pm}) / \sigma(W^{\pm})$





- The differential cross-section ratio $\sigma(J/\psi + W\pm) / \sigma(W\pm)$ for data and the QCD NLO CO predictions for SPS part.
- Due to uncertainty in double-parton-scattering cross-section σ_{eff}, two different values are used for comparisons of theory with data.
- A smaller σ_{eff} brings the QCD closer to the measured value; however, neither σ_{eff}, is able to correctly model the p_T dependence, possibly because colour-singlet processes are not included in the QCD prediction.

Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 8 TeV in ATLAS

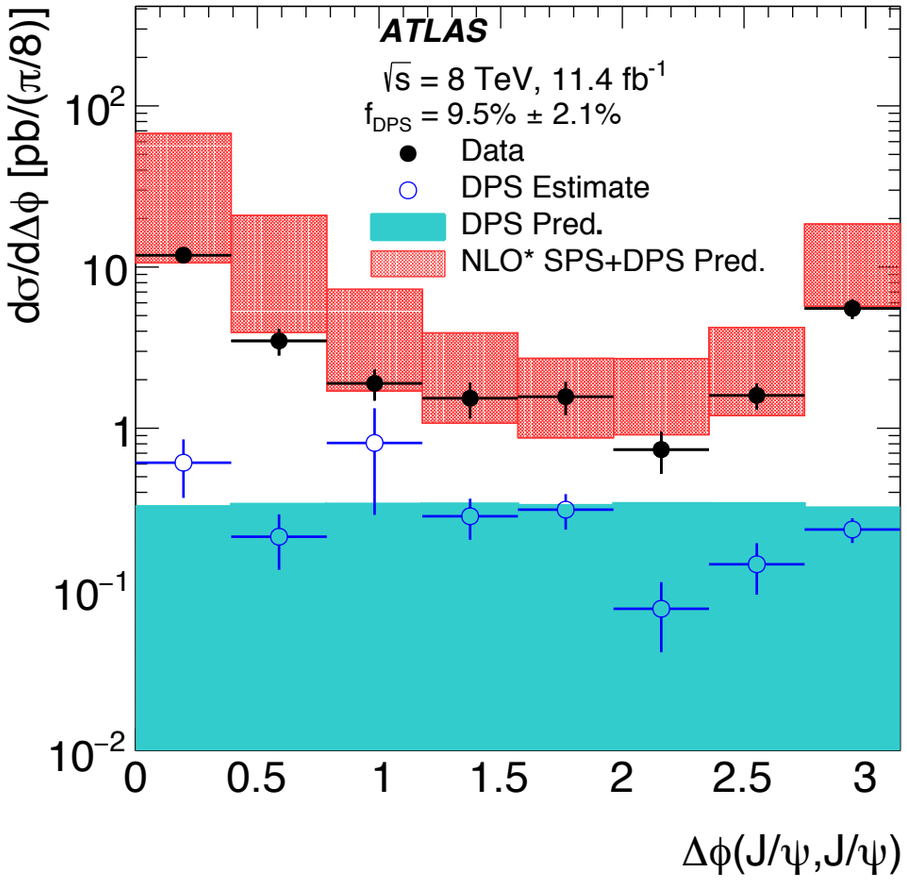
Motivation, goals of the measurement

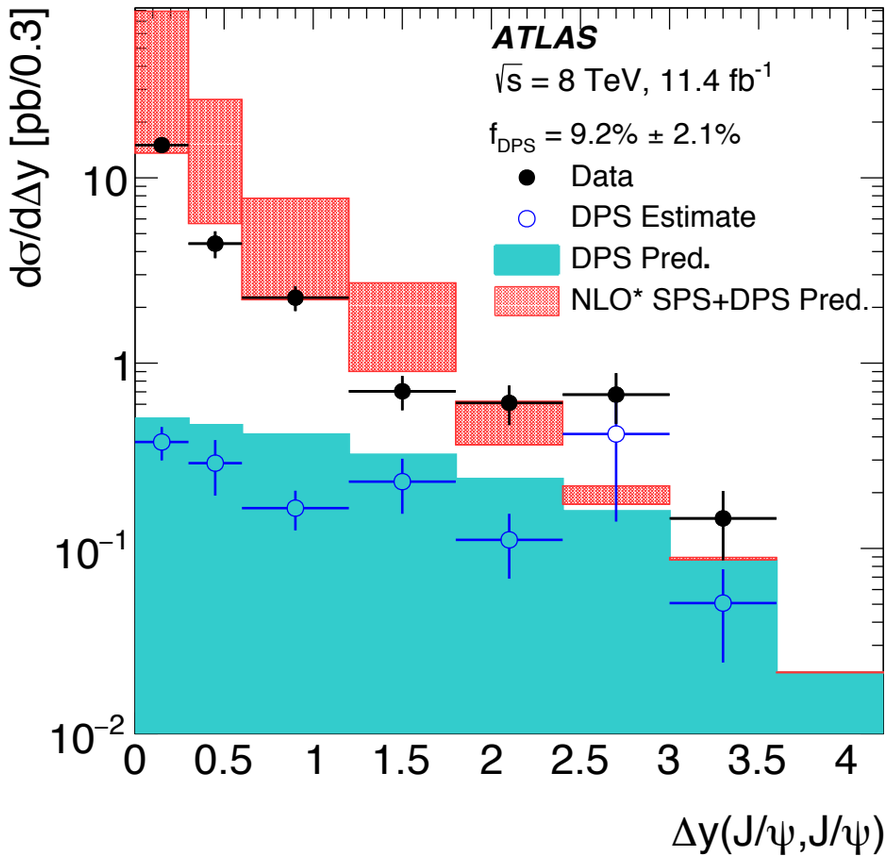
- Differential cross sections are measured for the associated production of two prompt J/ψ - to test QCD, especially NLO and higher-order perturbative corrections.

- Fraction of DPS production is measured in data-driven way, not depending on the effective cross-section σ_{eff} from outside source.

- The analyses provides an independent measurement of $\sigma_{eff.}$ It was extracted based on the measured inclusive di-*J/ψ* cross-section and the fraction of DPS events, as well as the prompt *J/ψ* cross-section in the corresponding fiducial volume.

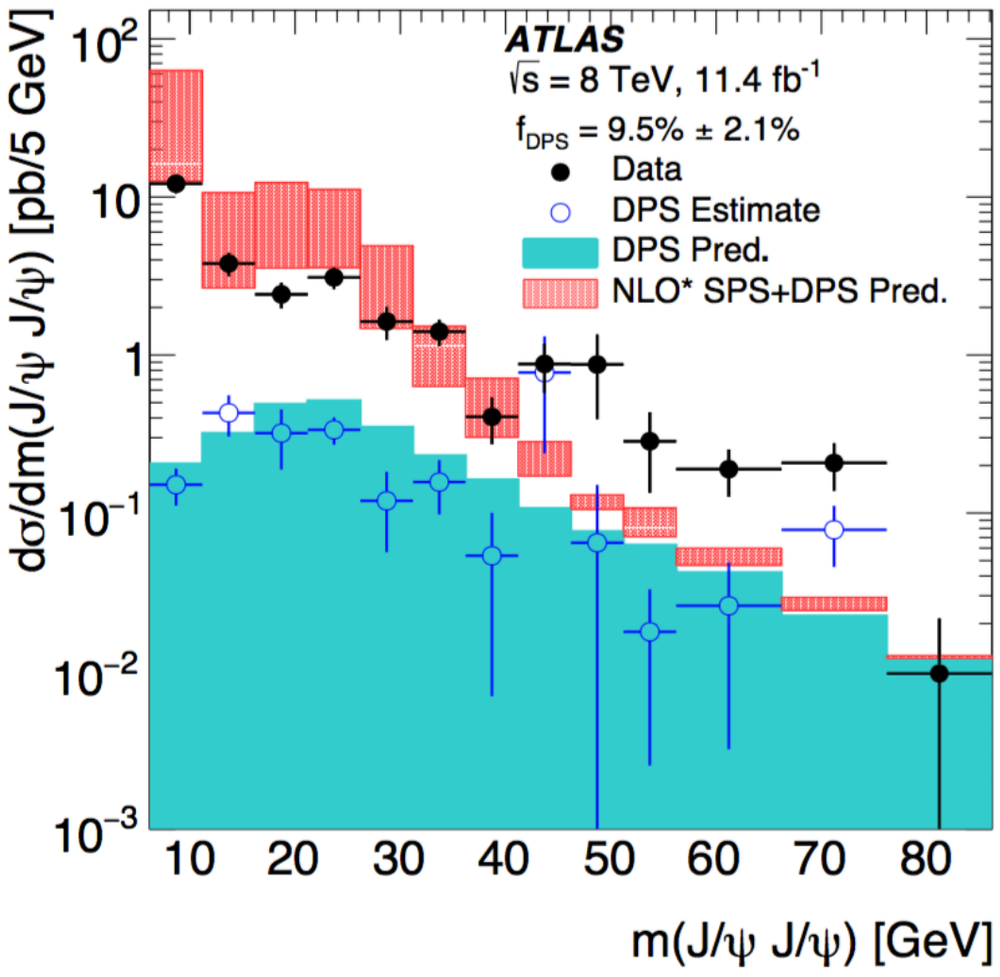
DPS fraction measurement

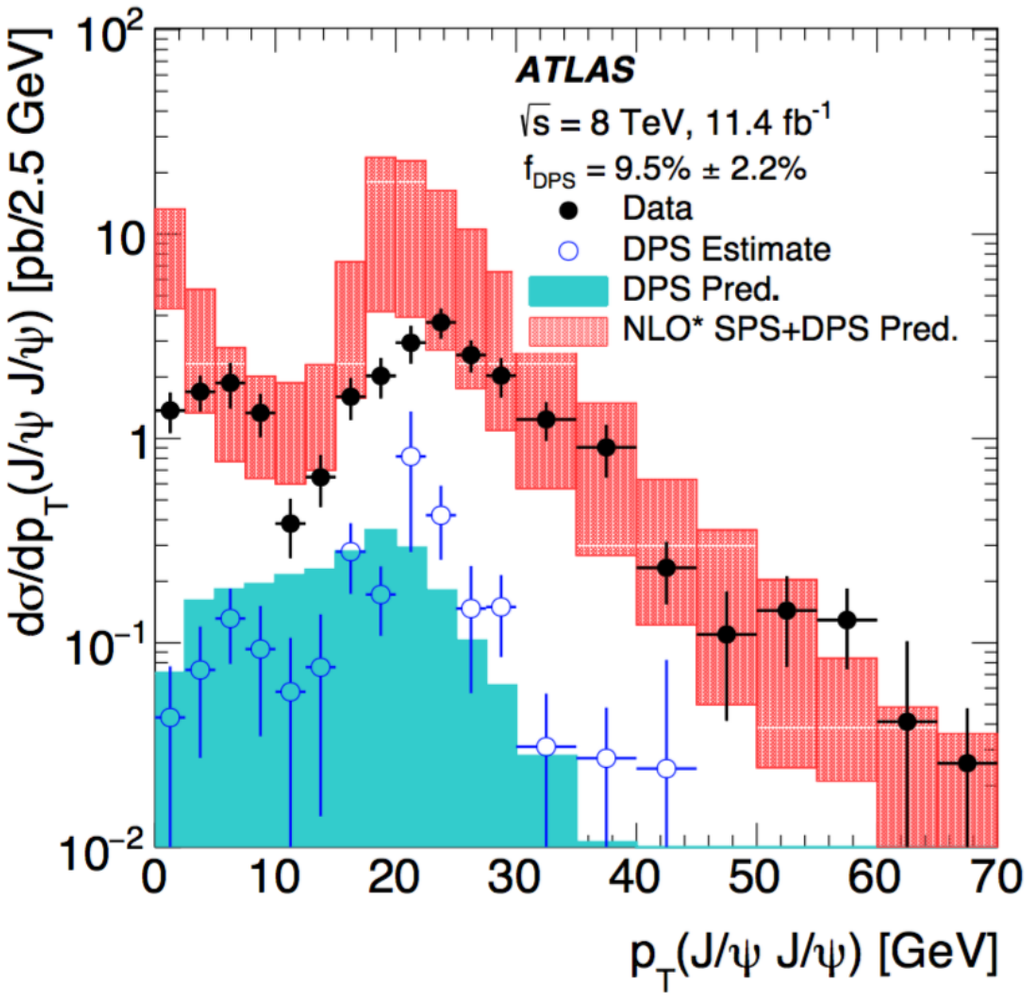




- DPS fractions determined in data-driven way.
- In each Δϕ-Δη bin the DPS template created by combining *J/ψ's* from two independent events from different bunch crossings.

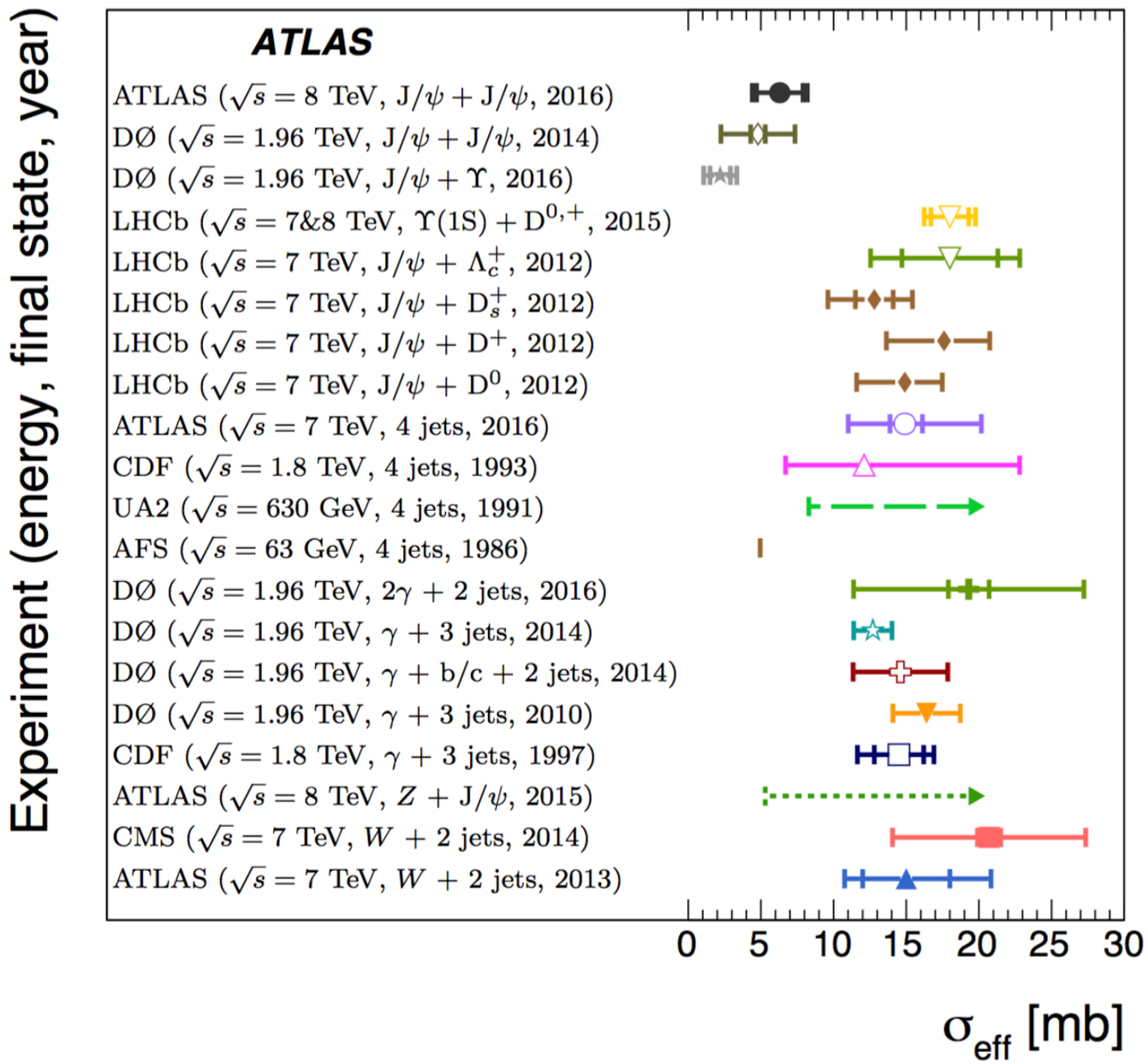
Cross section: σ(J/ψ +J/ψ)





- Differential cross-section σ(J/ψ J/ψ) was measured as a function of di-J/ψ variables: ***Δ*ϕ**, ***Δη*,** pT, m(J/ψ J/ψ).
- DPS, SPS data driven results are in reasonable agreement with the Theory for both DPS and NLO SPS.

the effective cross section σ_{eff}

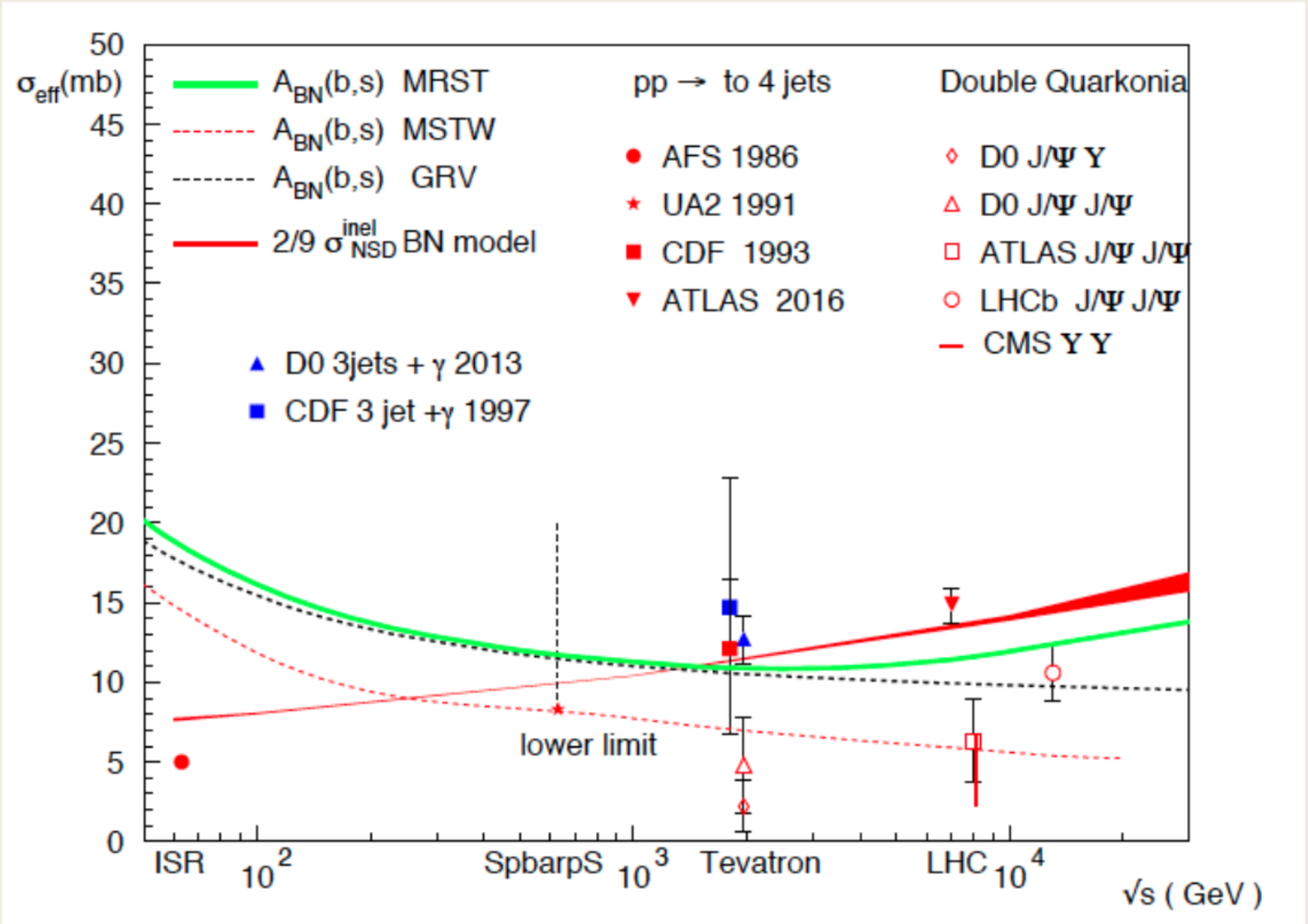


- **The ATLAS compilation**
- The effective cross section **σ_{eff}** was extracted from the measured DPS, σ(J/ψ) and σ(J/ψJ/ψ):

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

- σ_{eff} values for double Onia: (J/ψJ/ψ) ATLAS, D0 and (J/ψΥ) D0 are smaller than the rest. More data would be helpful.
- σ_{eff} are independent of energy

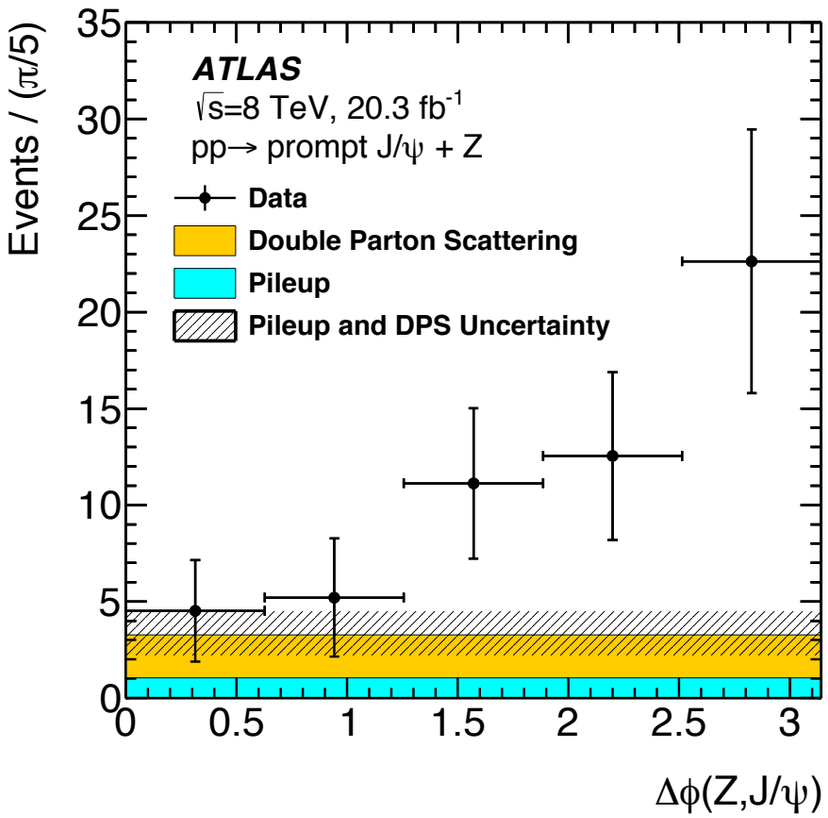
Comparison of two models with data

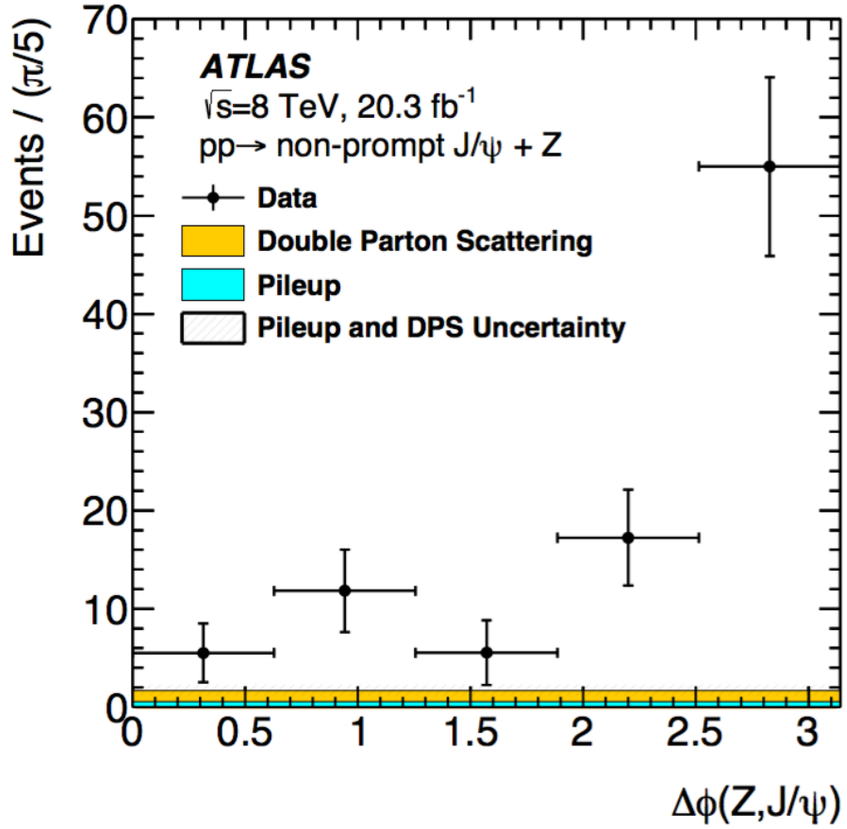


GP,Grau,Pacetti,Srivastava
1911.06672

Associated production of prompt and non-prompt J/ψ mesons with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV in ATLAS, Eur. Phys. J. C75 (2015) 229

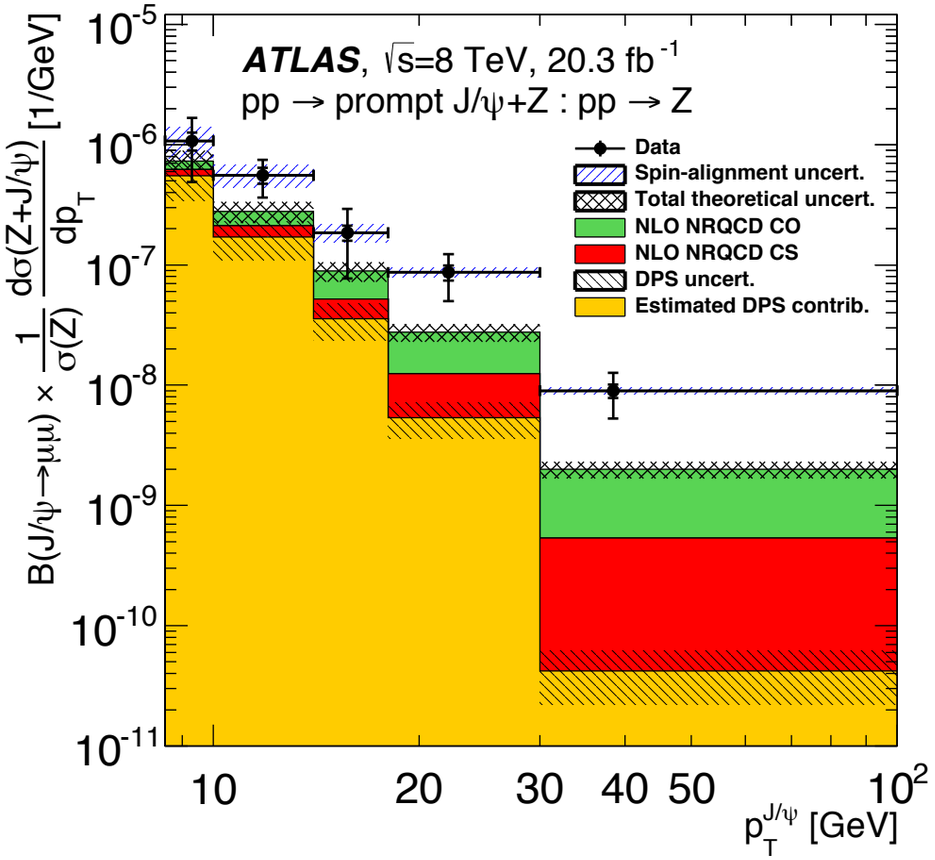
DPS fraction in σ(J/ψ + Z)

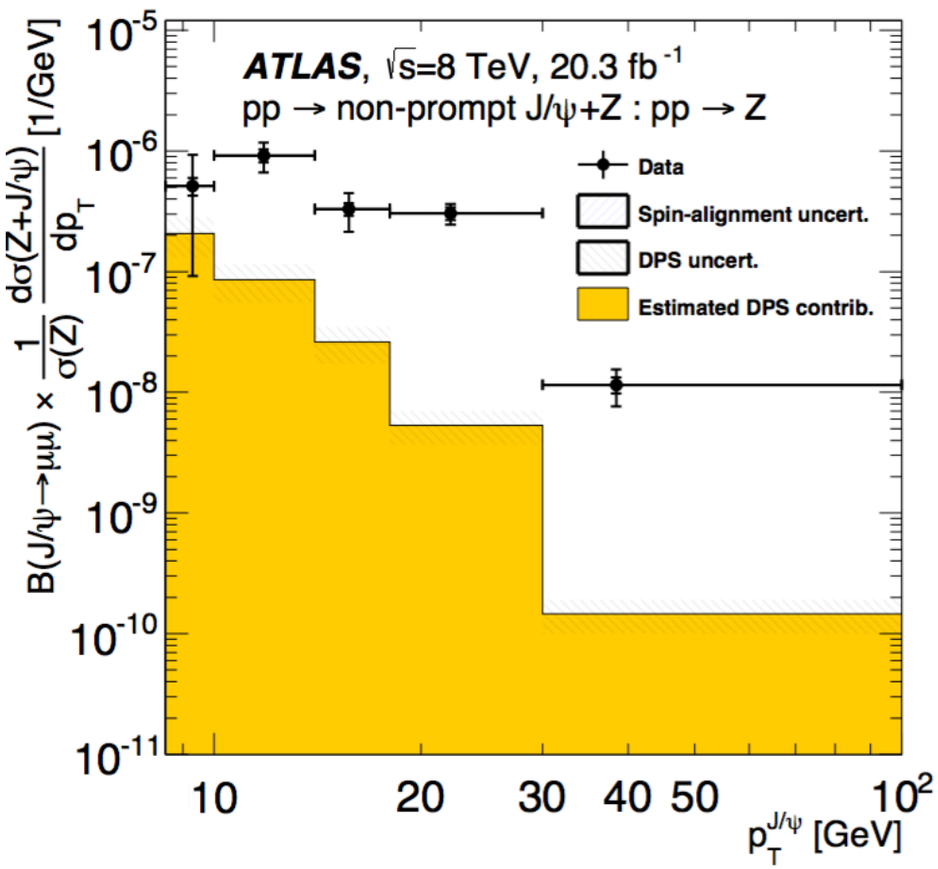




- DPS contribution measured using an input σ_{eff} ATLAS in W + 2-jet, Based on the assumptions that σ_{eff} is process-independent

Cross section: σ(J/ψ + Z)/ σ(Z)





- The cross-section ratios σ(J/ψ + Z)/ σ(Z) are compared to theory: CS and CO processes in the non-relativistic QCD (NRQCD) formalism.
- Theoretical calculations consider only SPS. To allow direct comparison the measured DPS cross sections are subtracted.
- The predicted production rate from the sum of CS and CO contributions is lower than the data by a factor of 2 to 5.

Summary

- Associated production of J/ψ with bosons $W^{\pm}$ and Z and the double J/ψ production performed by ATLAS.

- Differential cross sections compared to QCD predictions

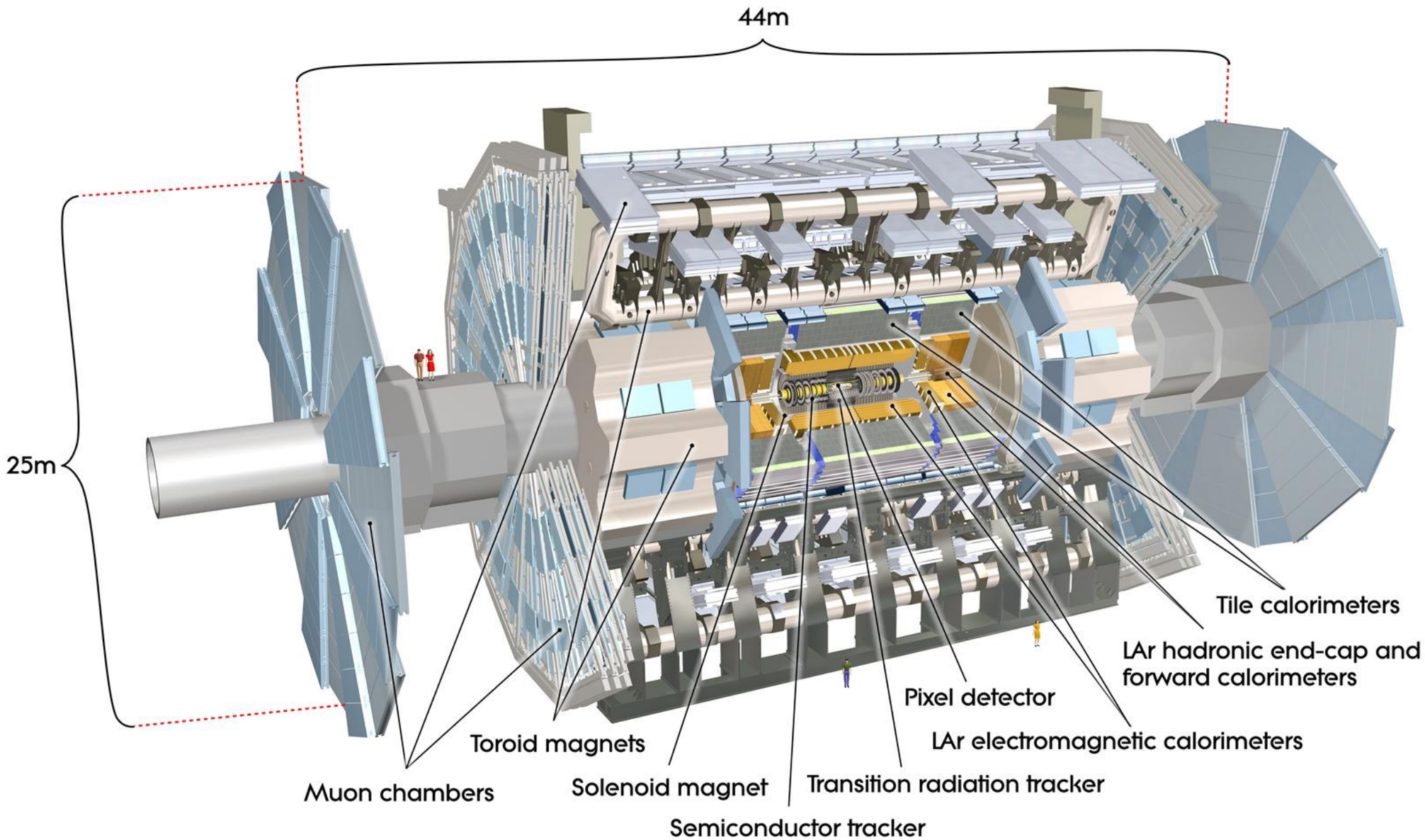
- For better comparisons with theory a Double Parton Scattering is extracted from Single Parton Scattering with help of σ_{eff} measured in ATLAS W + 2-jet as well as in double J/ψ.

- The value of σ_{eff} in the double J/ψ measured in ATLAS corresponds to the D0 double J/ψ, while both are different from σ_{eff} measured in other processes.

- More statistics and more detailed measurements would be desirable from 14 TeV LHC data.

Backup

ATLAS detector



Motivation, prompt, non-prompt J/ψ with Z boson

- In the Standard Model, a single parton–parton interaction can produce a J/ψ meson in association with a Z boson either through a "prompt" QCD subprocess, or through the production of a Z boson with a b-quark and its sub- sequent decay into a J/ψ ("non-prompt" production).

- Associated production J/ψZ has been measured for both prompt and non-prompt J/ψ, relative to inclusive production of Z → μμ or Z → ee.

- The production of a gauge boson in association with a J/ψ sets a high energy scale for the scattering process and results in an improvement in the perturbative convergence of the calculations that has troubled the accuracy of quarkonium production models in the past.

- A fraction of double-parton scattering (DPS) interactions is estimated .