Heavy Flavour Spectroscopy and Production at ATLAS

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Outline

Introduction of heavy flavour physics program at ATLAS

Three topics:

1. Search for the X(5568) in $B_s^0\pi^\pm$ final states (PRL 120, 202007 (2018))

2. Observation of an Excited $B_c^\pm$ Meson State (PRL 113, 212004 (2014))

3. Gauge boson in association with J/Ψ (JHEP 04 (2014) 172, EPJC (2015) 75:229)

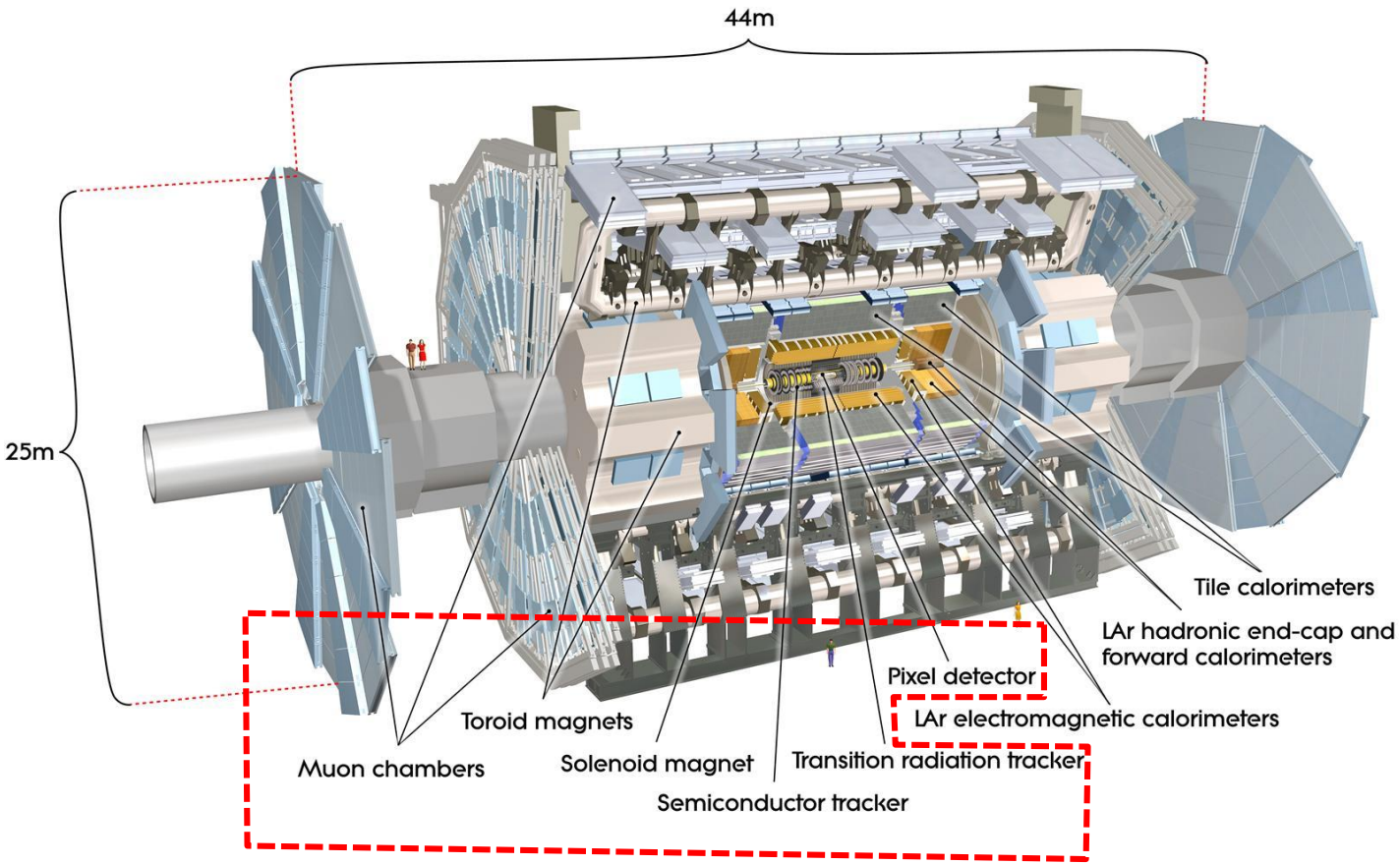
Summary

Heavy Flavour physics program at ATLAS

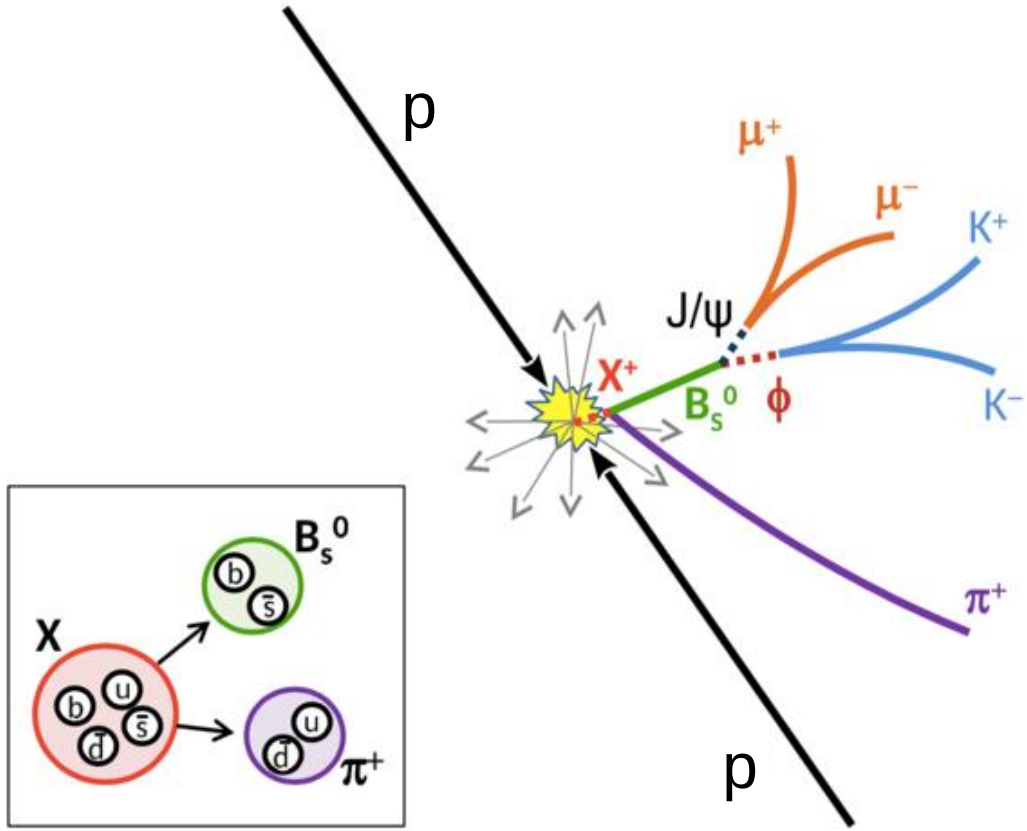
- Precision measurement to find hint of derivation from SM: rare decays, such $B_s^0 \to \mu^+\mu^-$ branching fraction measurement……

- Production and decay of heavy flavour hadrons to understand the strong interaction, such as the discovery of $B_c(2S)$……

- Usually, two muons with a common vertex with invariant mass near J/Ψ are required: the inner tracker and muon detector are used



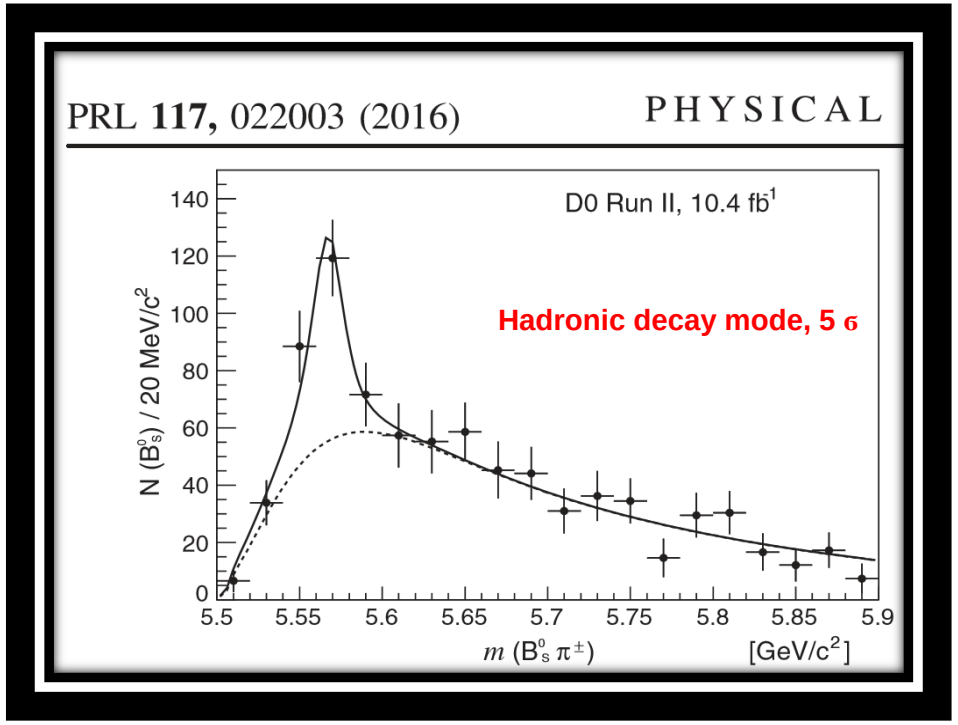
Search for the X(5568) in $B_s^0\pi^\pm$ final states

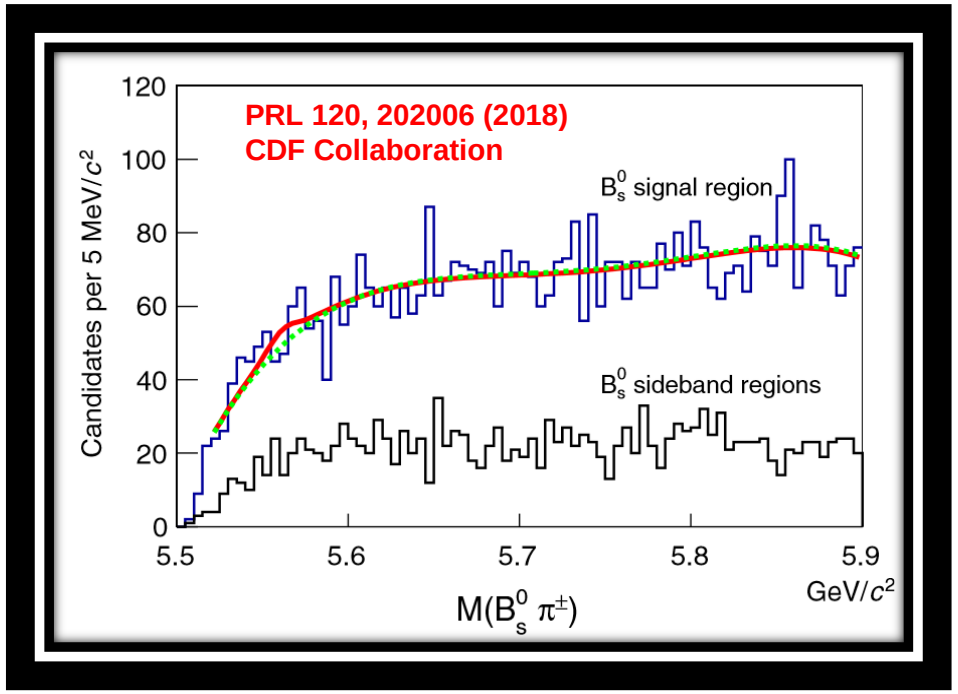


D0 Collaboration reported evidence of the X(5568) -> $B_s^0\pi^\pm$, B_s^0 ->J/Ψ ϕ, and reported consistent result in the semi-leptonic decay of B_s^0 :

Mass ~ 5568 MeV; Width ~ 20 MeV
Good candidate for tetraquark state

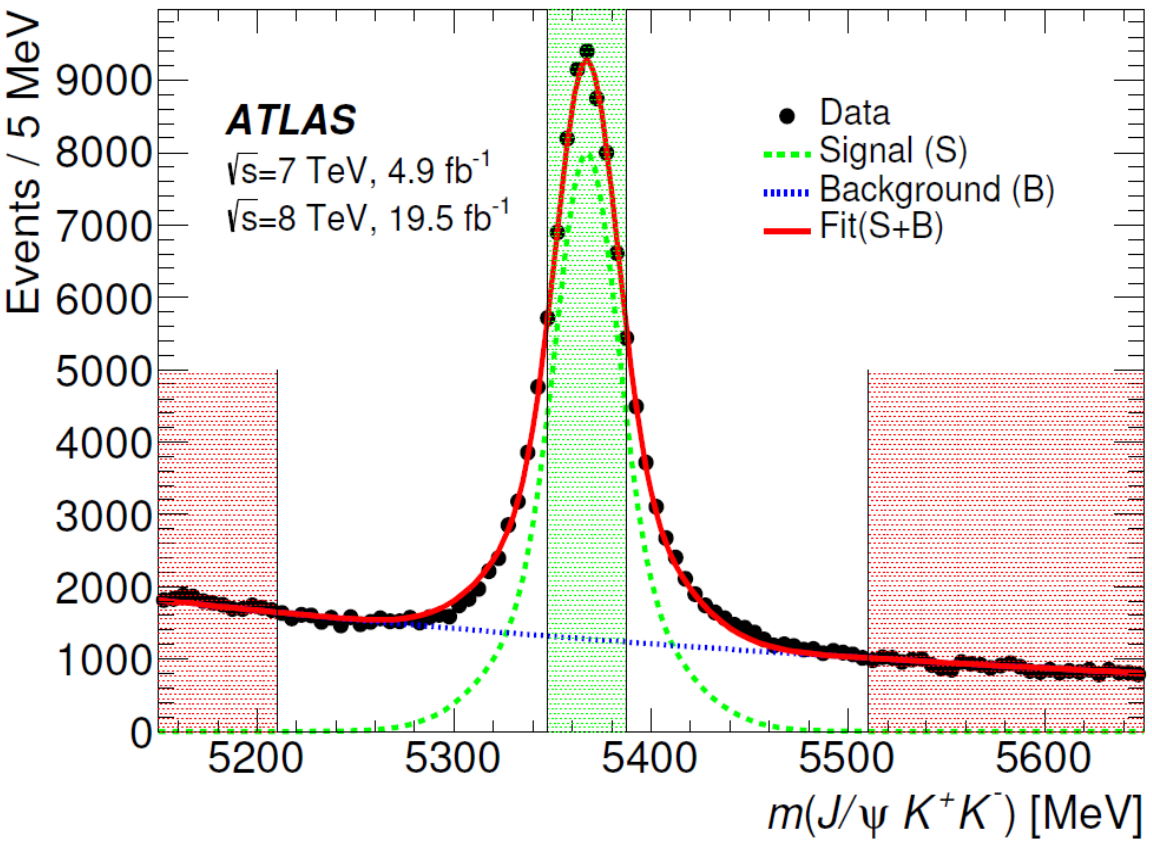
LHCb, CMS at LHC and CDF at Tevatron revealed no signal with similar techniques.





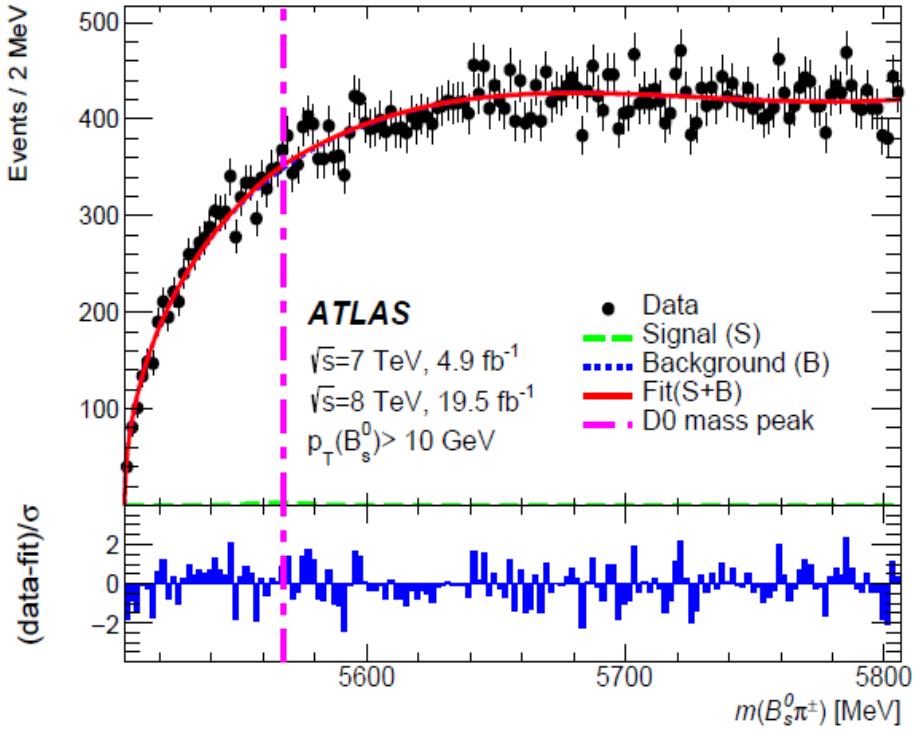
Search for the X(5568) in $B_s^0\pi^\pm$ final states

- Di-muon trigger is used
- Four final states from B_s^0 -> J/Ψ ϕ -> μμ KK are fitted to a common vertex
- Mass constrain of J/Ψ-> μμ; mass cut on 1008.5<m(KK)<1030.5 MeV
- Decay time of B_s^0 > 0.2 ps
- Primary vertex is chosen as the one with least a0, calculated based on the B_s^0 vertex and momentum direction
- One track assumed to be π from the primary vertex

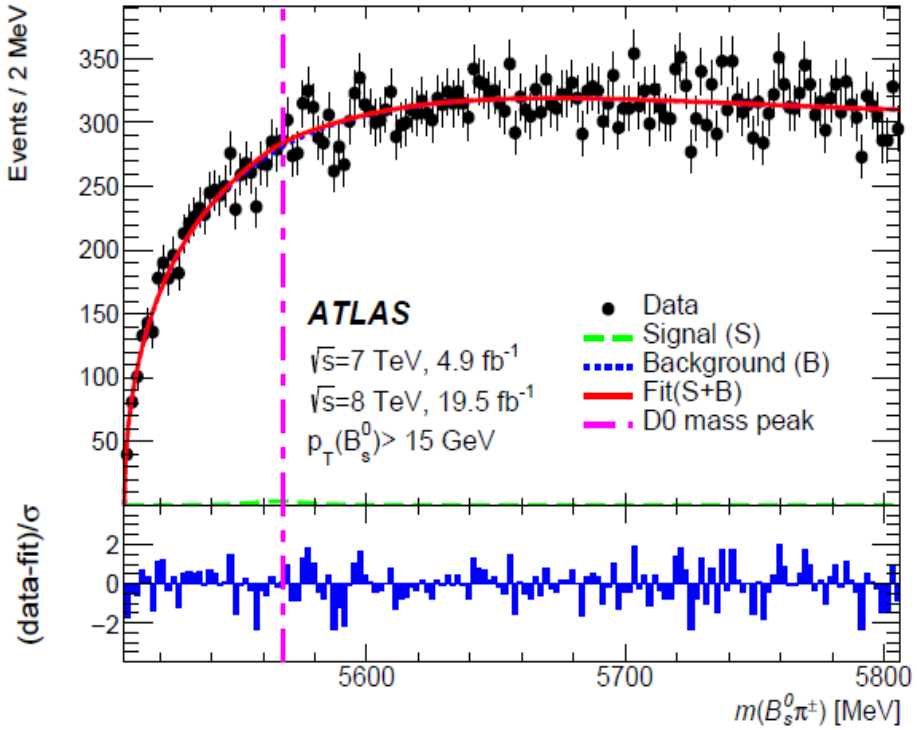


S: double Gaussian; B: Exponential

Search for the X(5568) in $B_s^0\pi^\pm$ final states



$p_T(B_s^0) > 10$ GeV



$p_T(B_s^0) > 15$ GeV

No obvious X(5568) is observed!

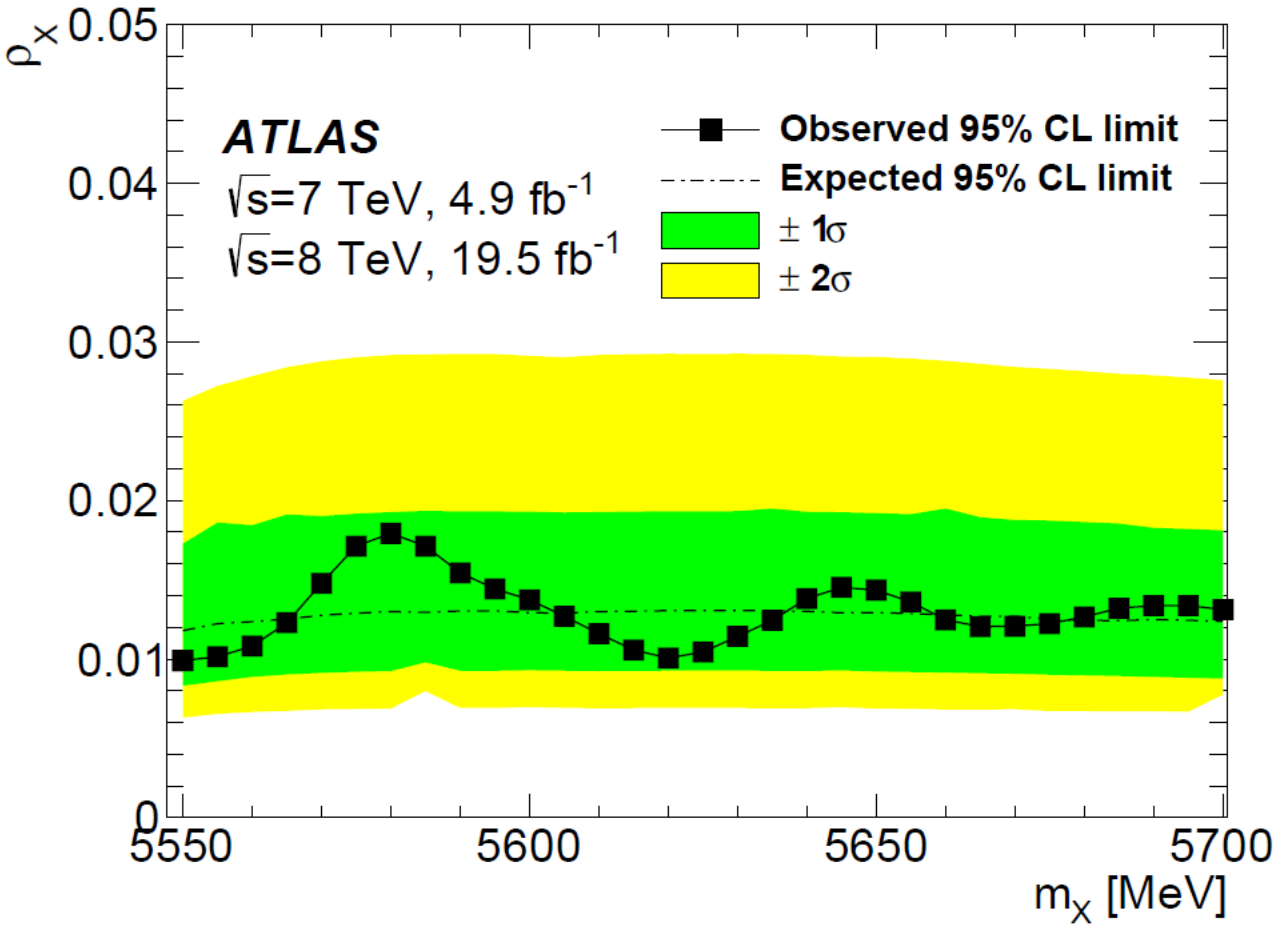
Search for the X(5568) in $B_s^0\pi^\pm$ final states

Mass range: 5550-5700 MeV

Width: 21.9 MeV

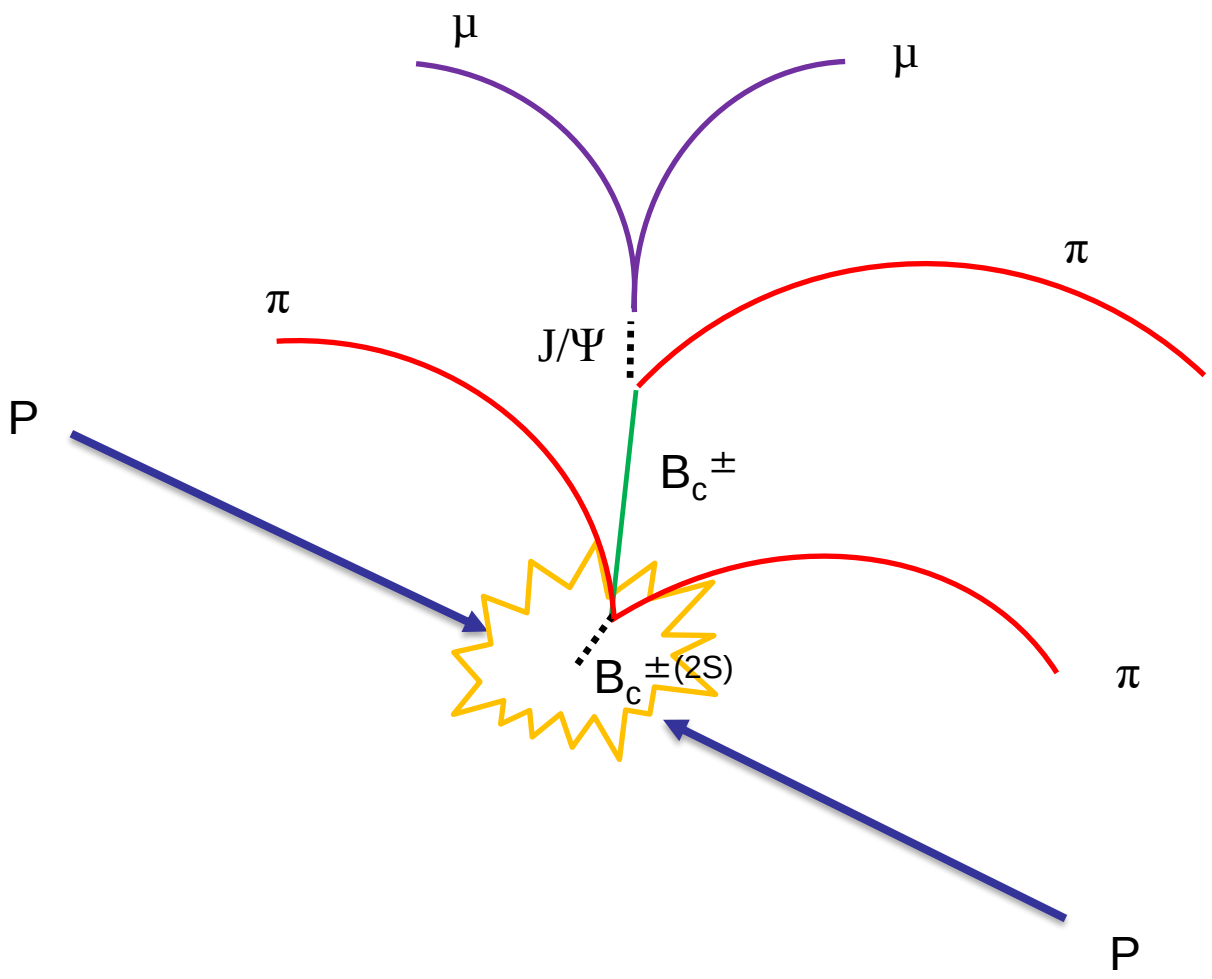
$P_T(B_s^0) > 10$ GeV

Upper limit on the production rate is set



$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\text{rel}}(X)}$$

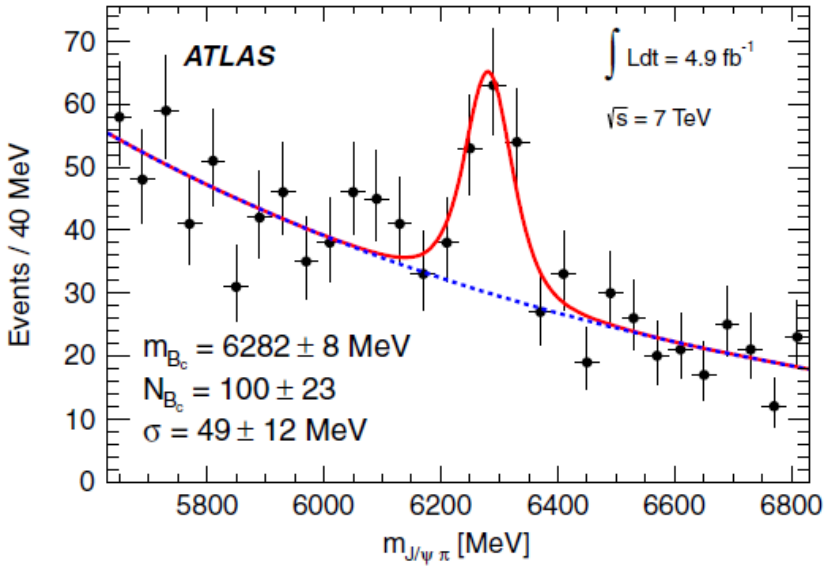
Observation of an Excited $B_c^{\pm}$ Meson State



Observation of an Excited $B_c^{\pm}$ Meson State

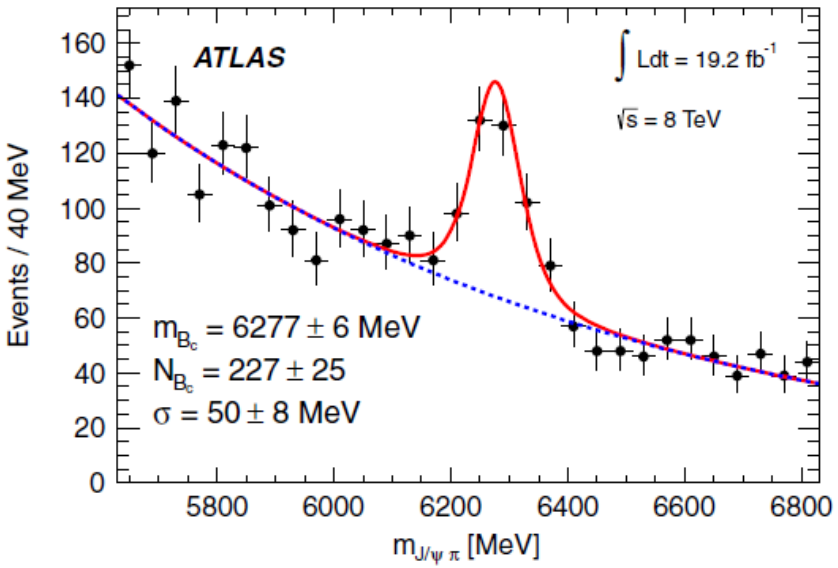
1. Select the J/Ψ into two opposite charged muons:

   pT(high) > 6 GeV; pT(low) > 4 GeV; vertex fit;
   mass constrain to PDG;



2. Select $B_c^{\pm}$ by adding a pion:

   pT > 4 GeV; common vertex to J/Ψ;
   cut on the impact parameter of the pion;
   pT (Bc±) > 15 GeV (18 GeV) for 7 TeV (8 TeV)



Observation of an Excited $B_c^{\pm}$ Meson State

3. Select two pions from the primary vertex:

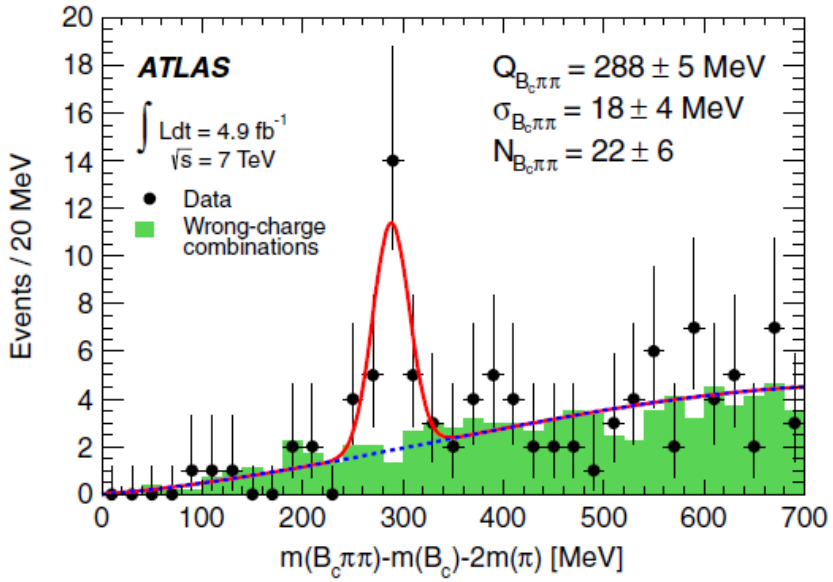
   pT > 400 MeV

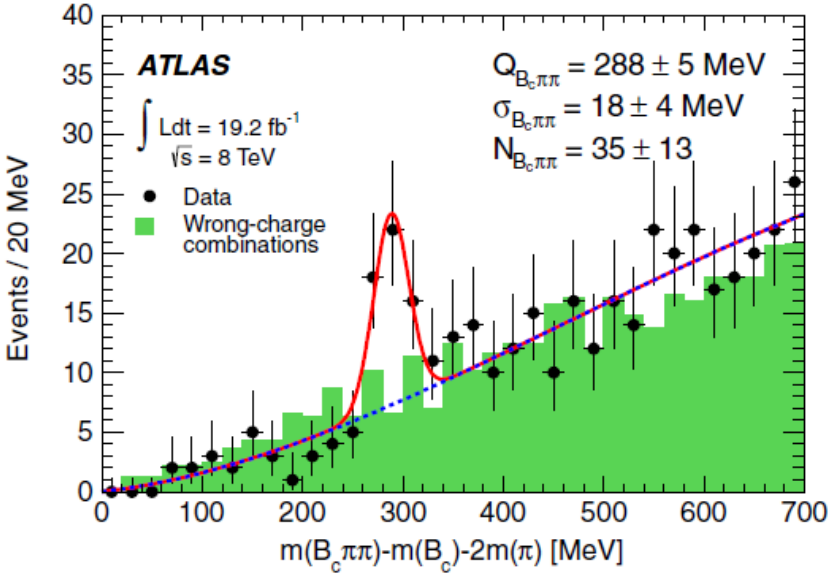
4. Fit the mass difference distribution:

   Gaussian for signal, third-order polynomial for background

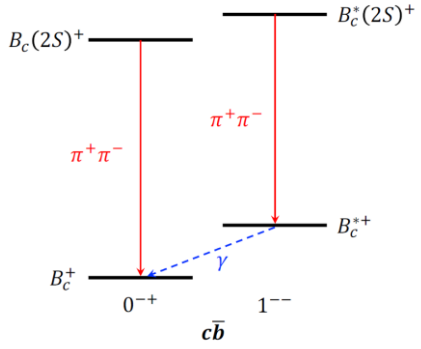
Significance of the new structure

> 5 σ

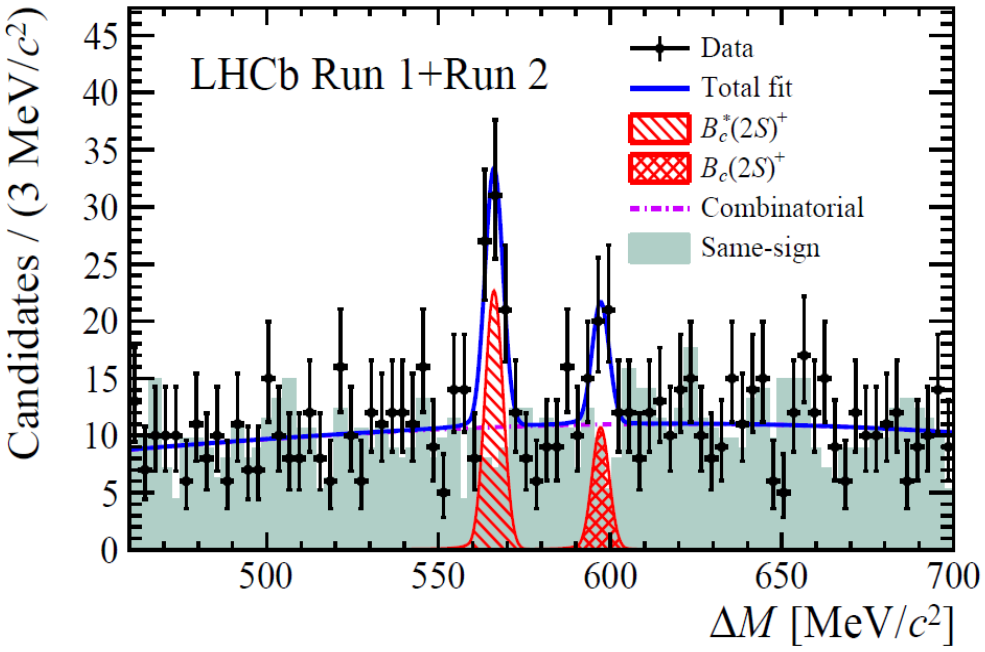




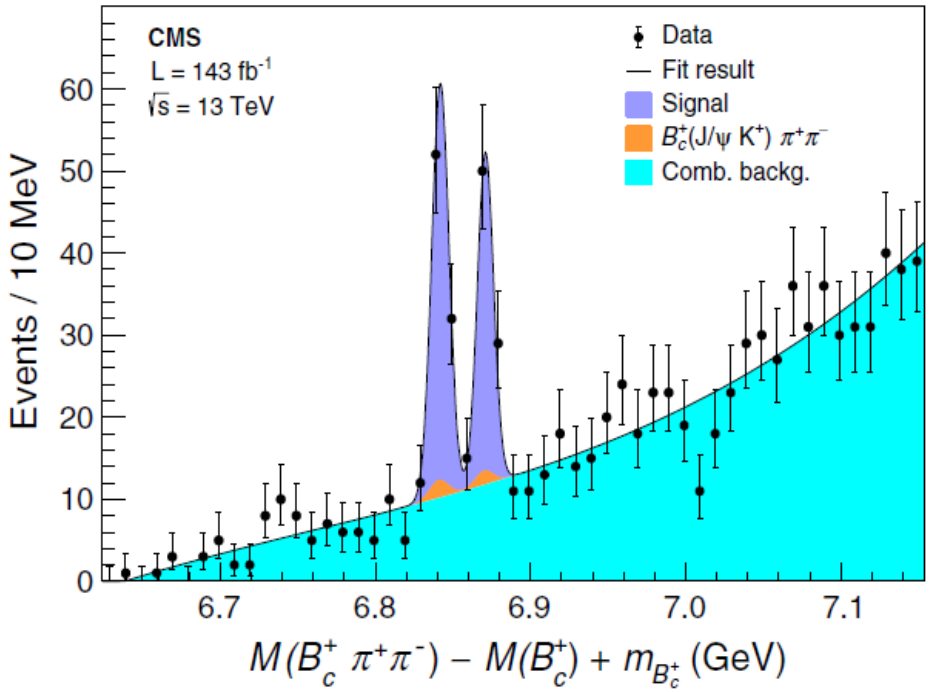
Fine structure?



With the similar technique but larger sample, both CMS and LHCb observed two structures, and updated results on ATLAS to be expected .



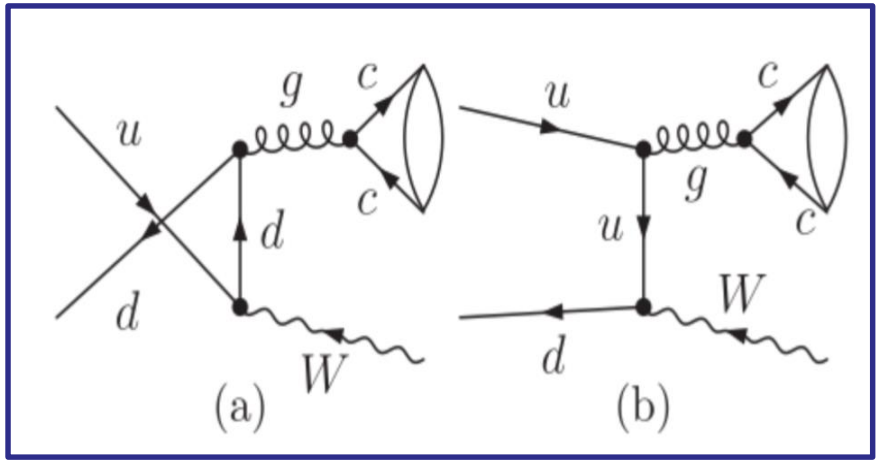
arXiv:1904.0008



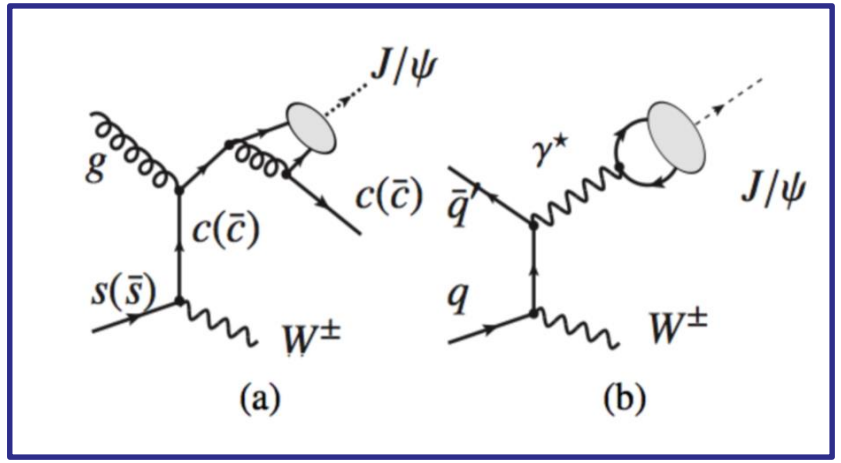
PHYSICAL REVIEW LETTERS 122, 132001

Gauge boson in association with J/Ψ

- **Is the CO really dominated?**



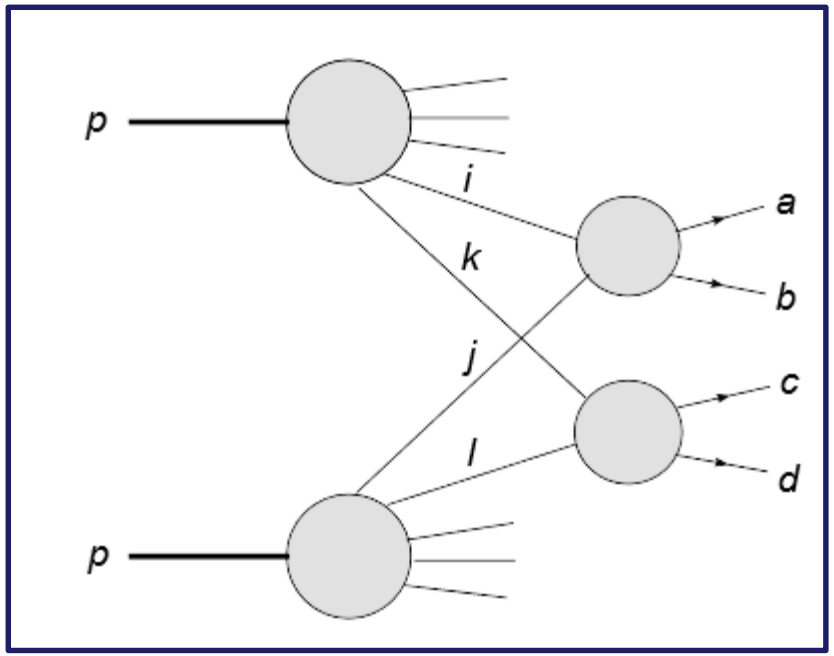
Colour Octet Model



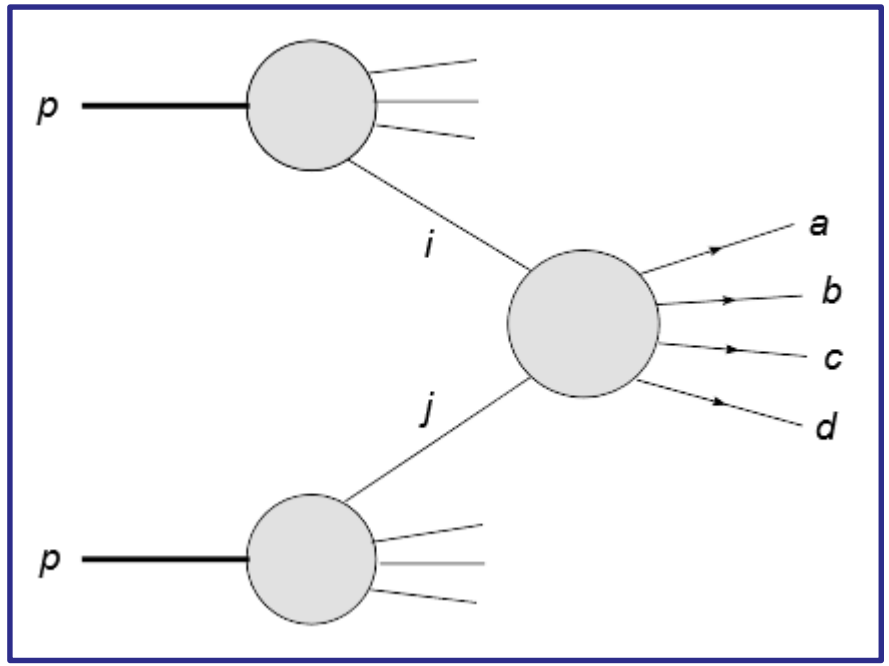
Colour Singlet Model

Motivation

- **SPS or DPS?**



Double Parton Scattering



Single Paton Scattering

General information

W+J/Ψ:

4.5 fb^{-1} at 7 TeV

$W \rightarrow \mu\nu$, $J/\Psi \rightarrow \mu\mu$; three muons + missing transverse energy

Prompt J/Ψ only

Z+ J/Ψ:

20.3 fb^{-1} at 8 TeV

$Z \rightarrow ee$ or $\mu\mu$, $J/\Psi \rightarrow \mu\mu$; four leptons

Both prompt and non-prompt J/Ψ

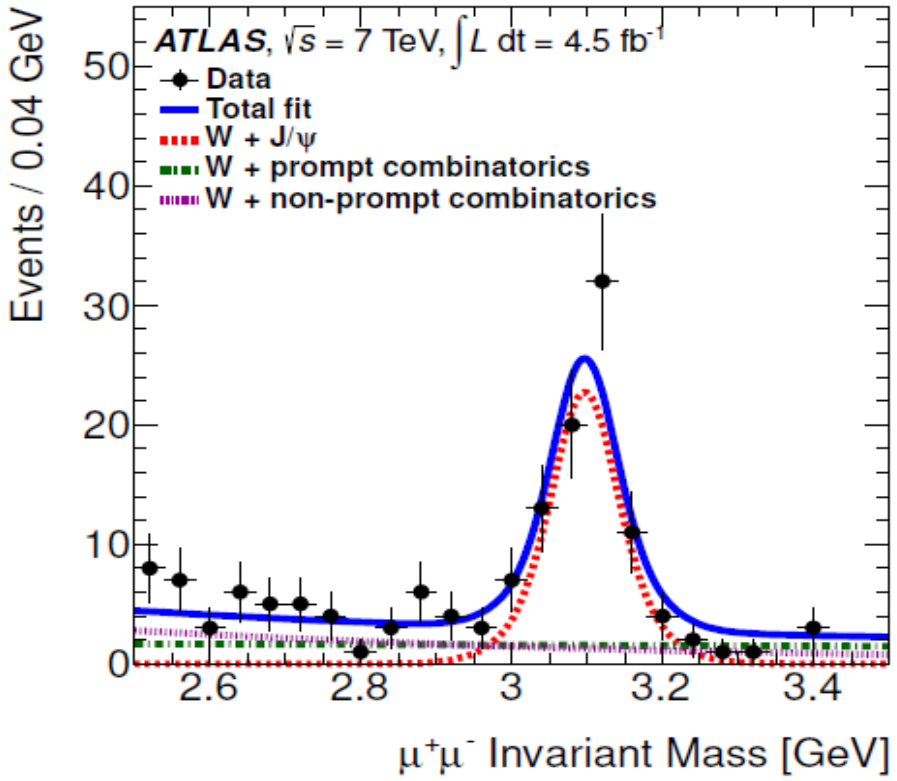
Pseudo-proper time definition:

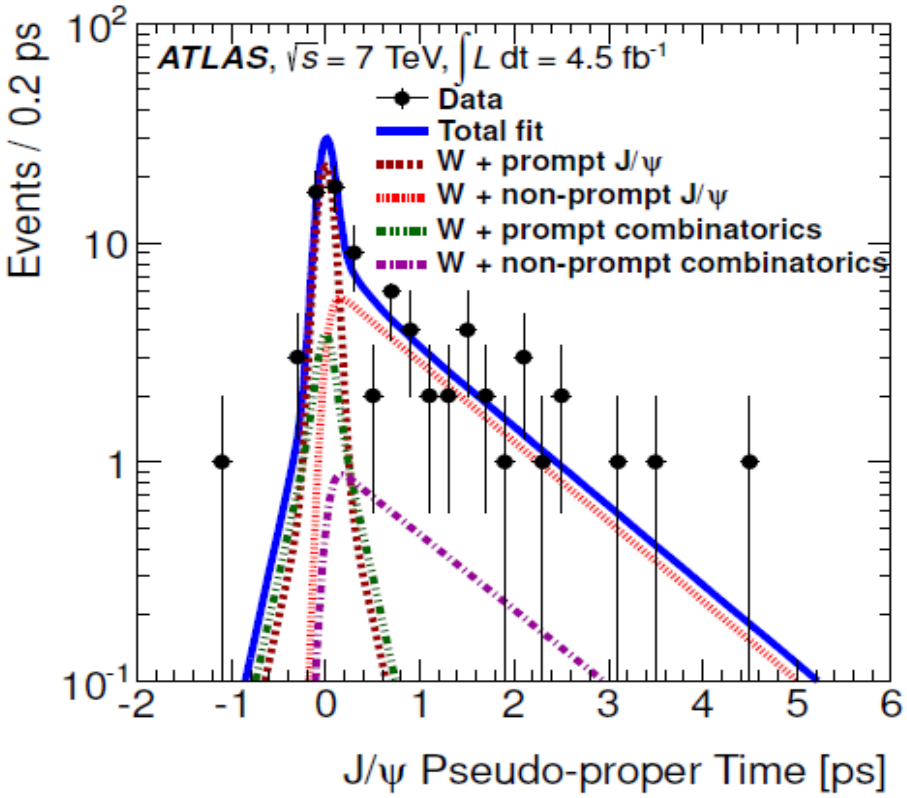
$$\tau := \frac{L_{xy} m^{J/\psi}}{p_T^{J/\psi}}$$

Methodology: step 1

W+J/Ψ

Select the J/Ψ with two opposite charged muons; separate the prompt and non-prompt by fitting the pseudo-proper time distributions (2D fit: mass and time):



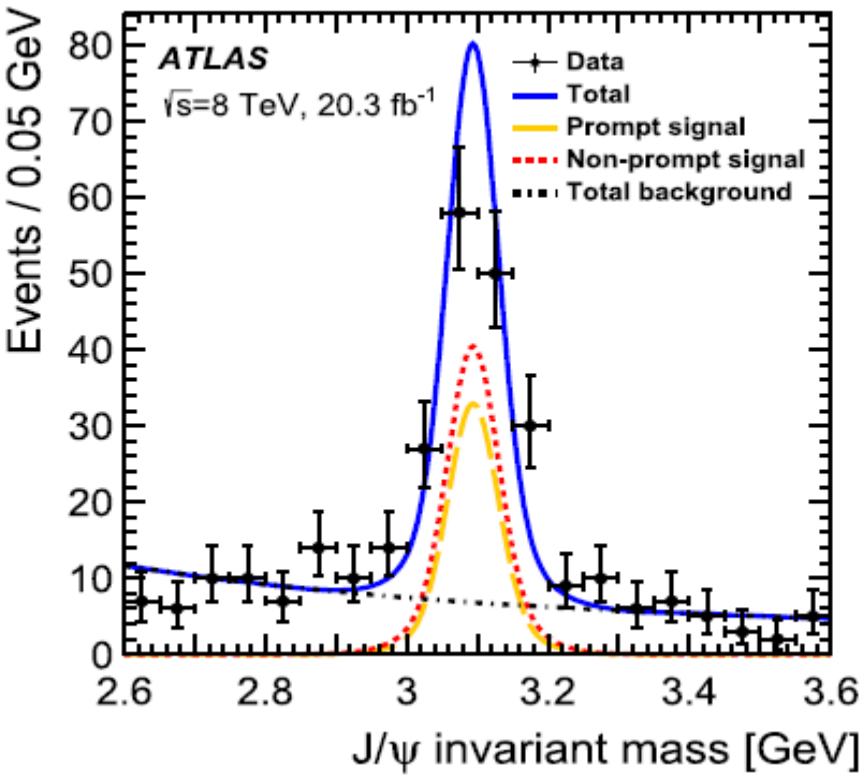


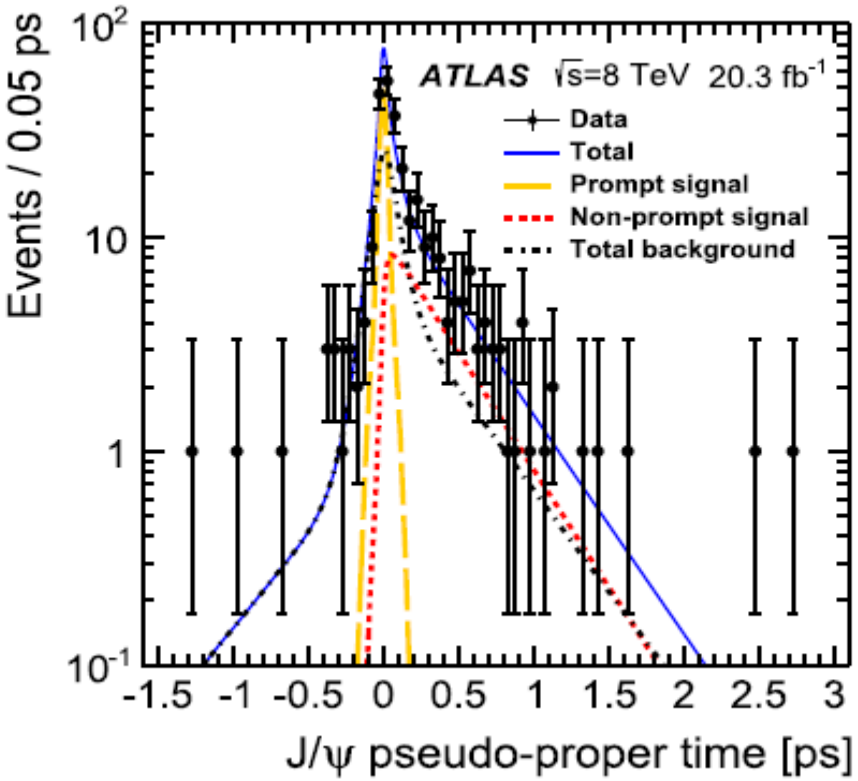
Two rapidity regions of are fitted separately, due to different resolution.
(different multi-scattering status and different magnetic field)

Methodology: step 1

Z+J/Ψ

Select the J/Ψ with two opposite charged muons; separate the prompt and non-prompt by fitting the pseudo-proper time distributions (2D fit: mass and time):



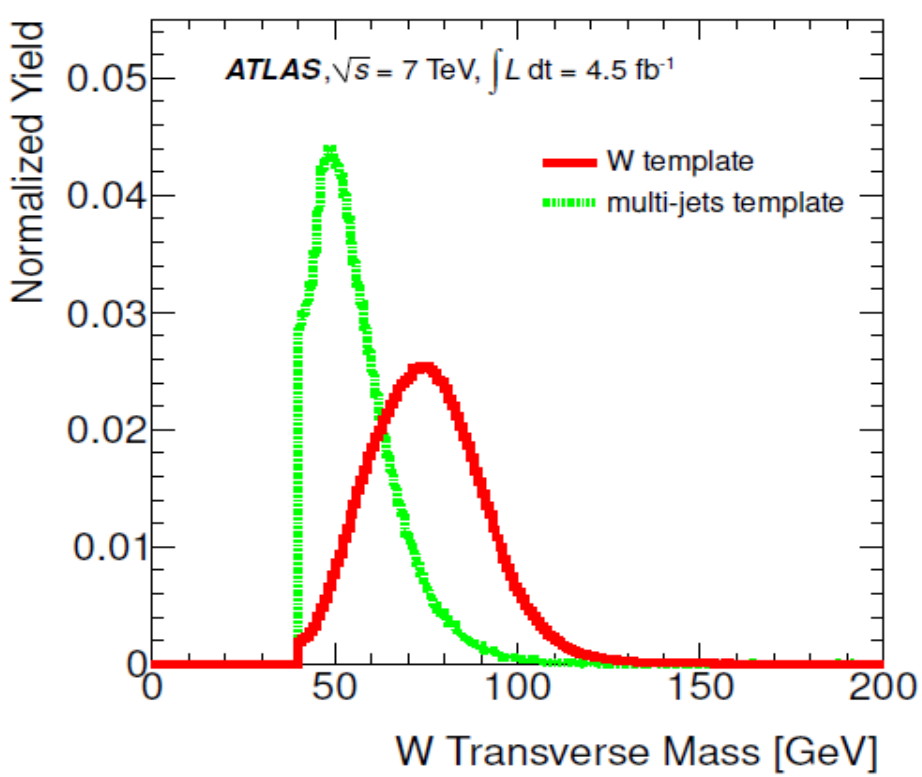


Two rapidity regions of are fitted separately, due to different mass resolution.
(different multi-scattering status and different magnetic field)

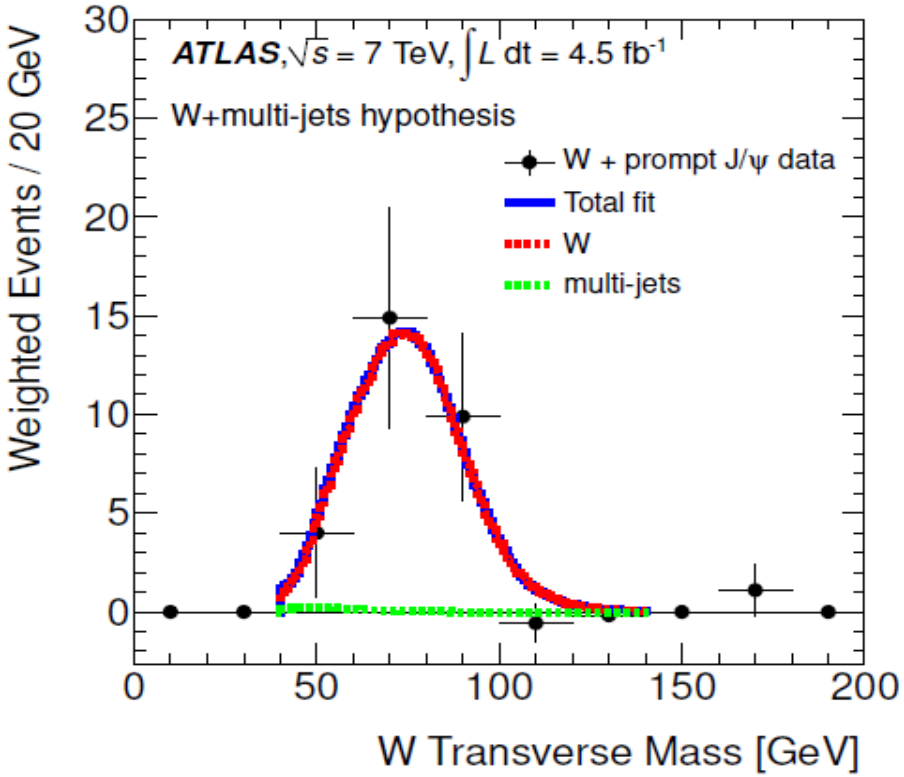
Methodology: step 2

W+J/Ψ

Fit the transverse mass or invariant mass for W or Z (event weight gotten from previous fit is applied):



(a)



(b)

W template is from MC; multi-jet is data driven.

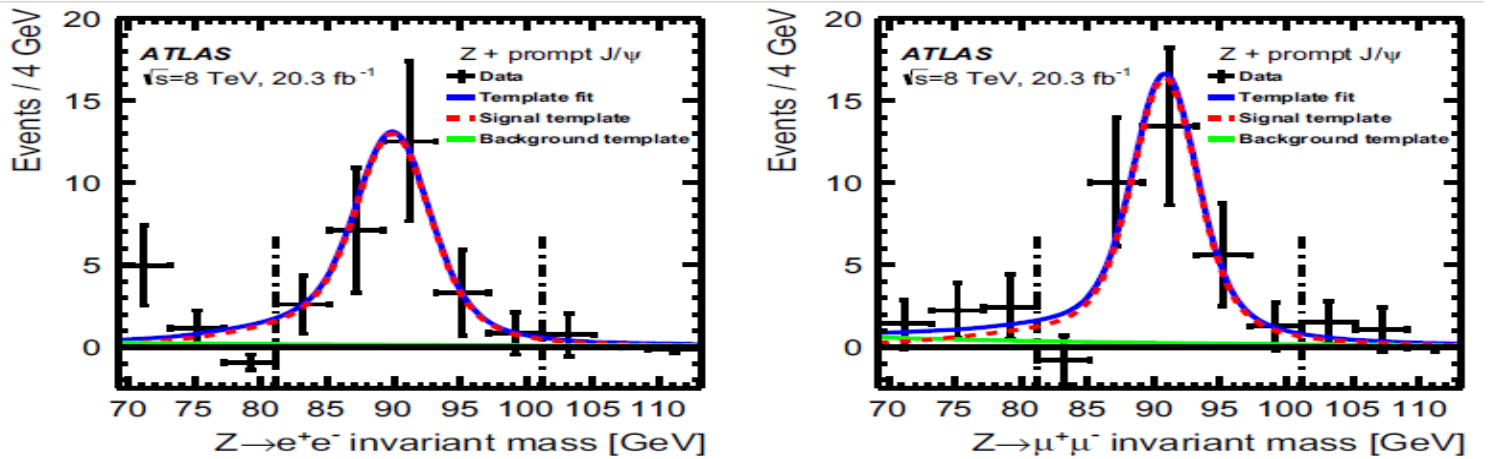
Methodology: step 2

Z+J/Ψ

Fit the transverse mass or invariant mass for W or Z (event weight gotten from previous fit is applied):

Prompt Z to ee

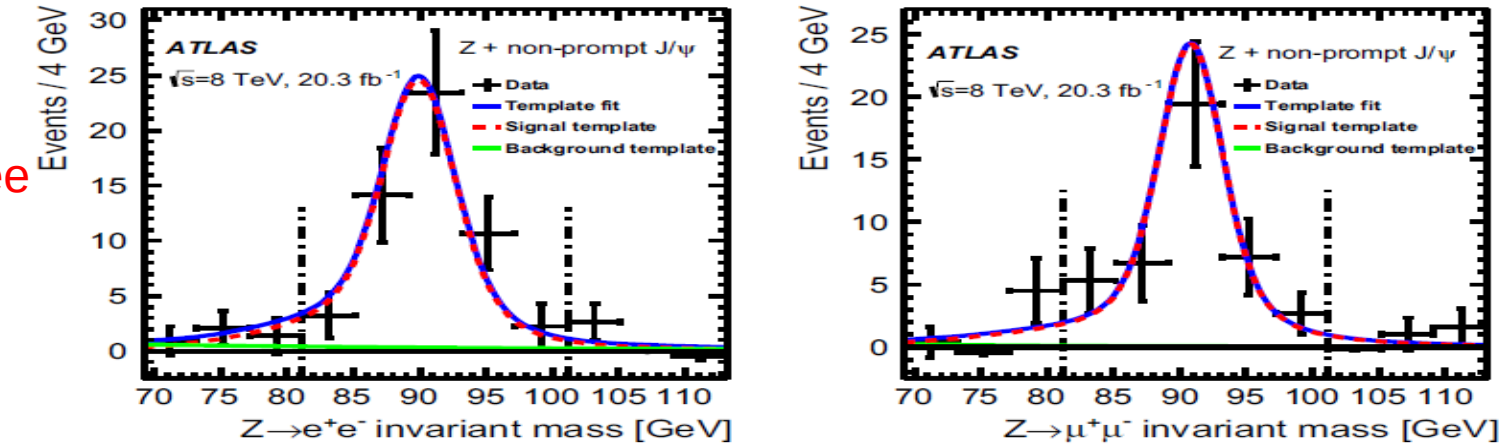
Prompt Z to μμ



(a)

Non-Prompt Z to ee

Non-prompt Z to μμ



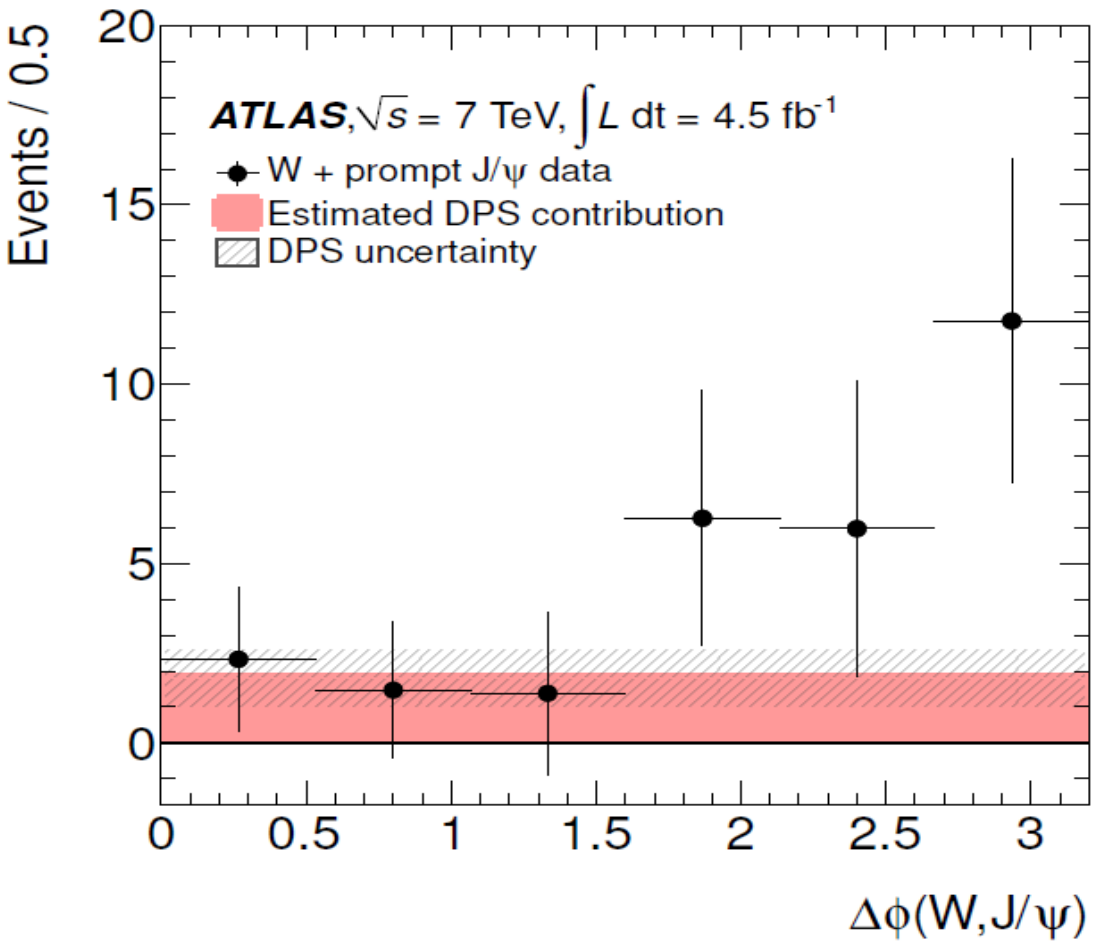
(b)

Signal: Gaussian convolved with a BW. Background: exponential.

Methodology: step 3

W+J/Ψ

Δϕ (boson, J/Ψ) used to separate SPS and DPS, and the latter has flat distribution:



Methodology: step 3

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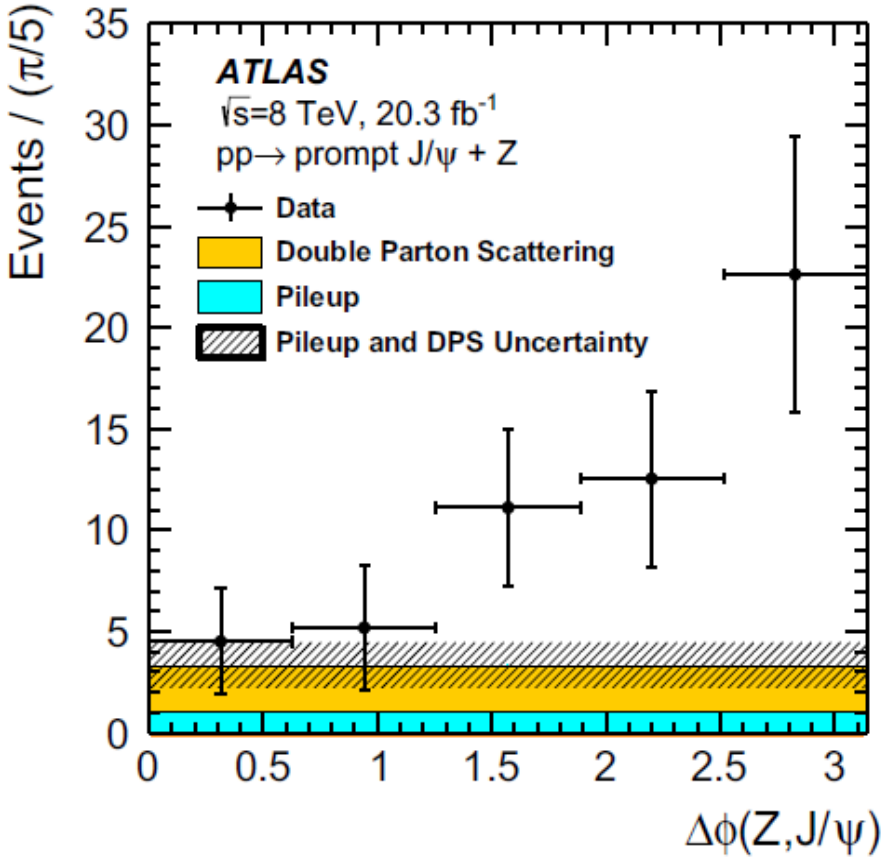
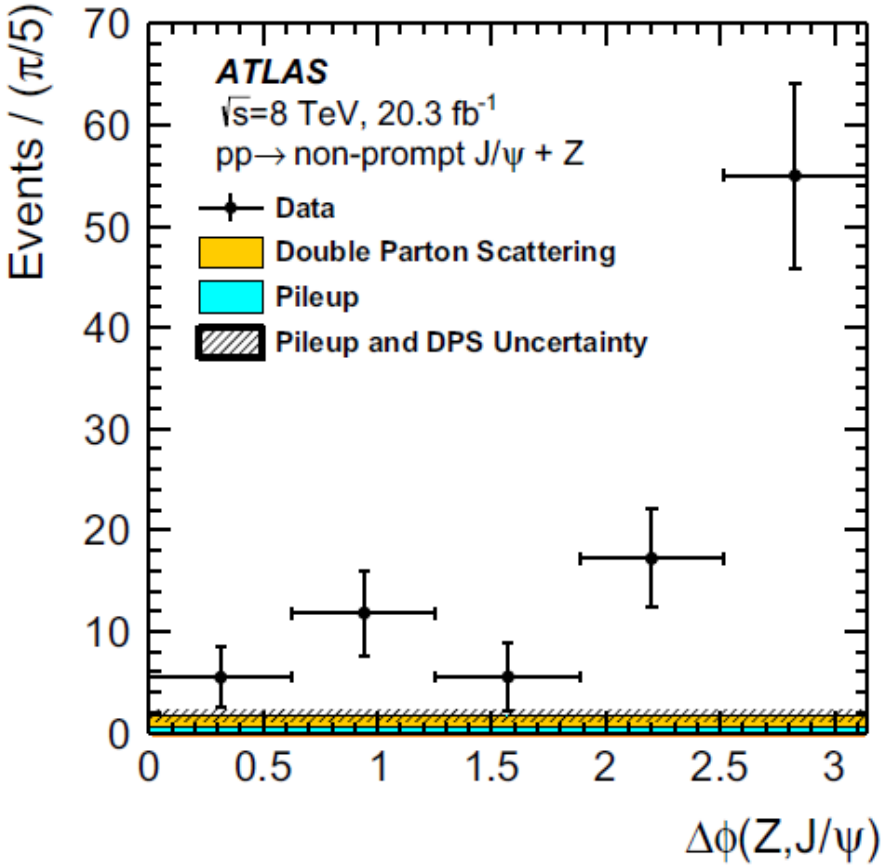


Prompt

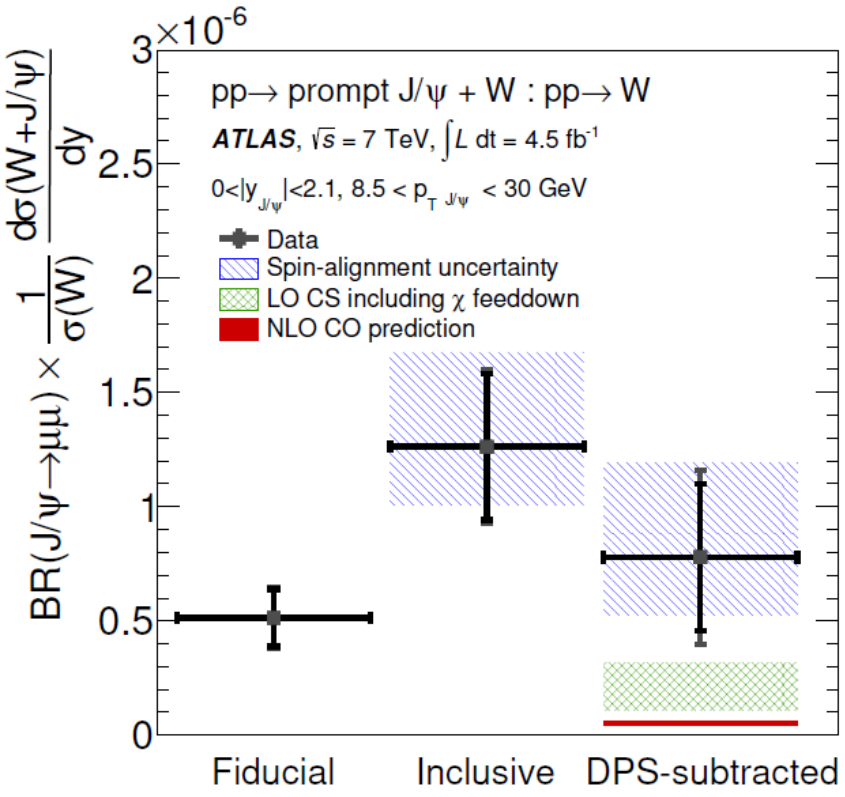


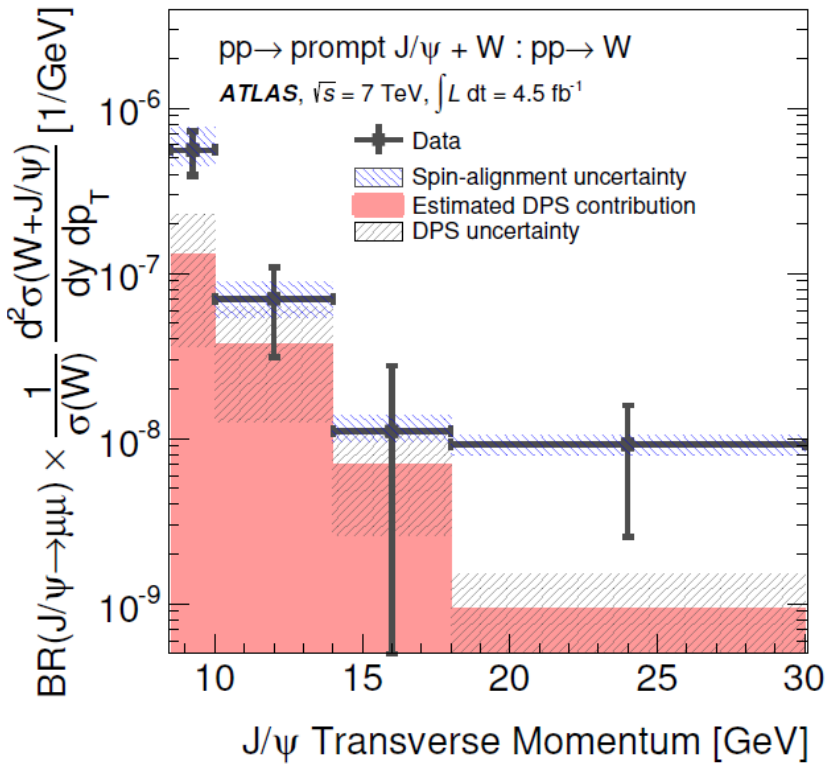
Non-Prompt

W+J/Ψ Results

1. **Observed the process: 5.1 σ**
2. **LO CS is more consistent with data, compared to NLO CO**
3. **SPS is dominant at low J/Ψ transverse momenta.**

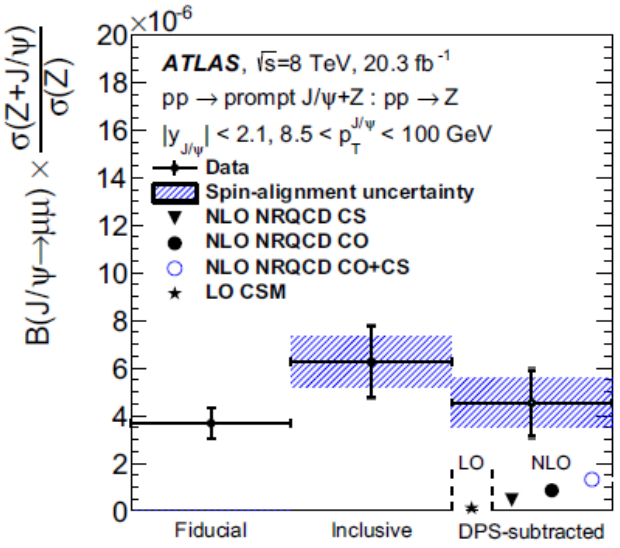
$$R^{\text{fid}}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$$
$$R^{\text{incl}}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$
$$R^{\text{DPS sub}}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$$

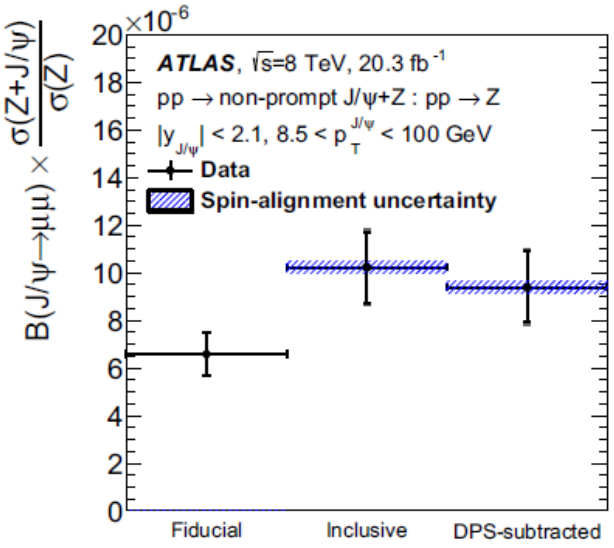




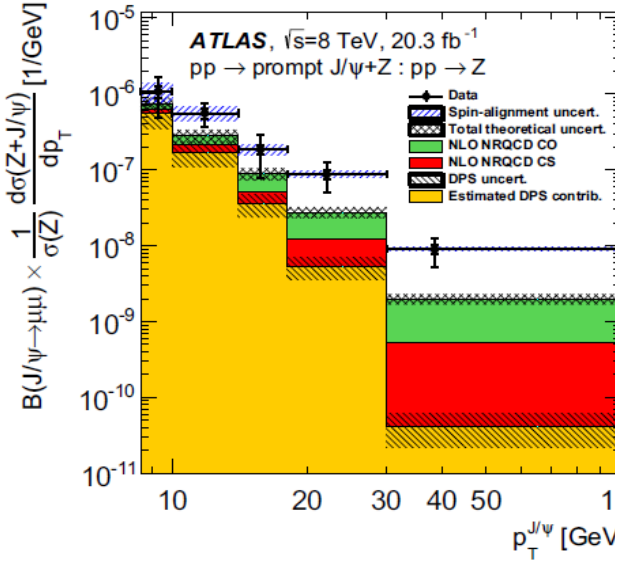
Z+J/Ψ Results

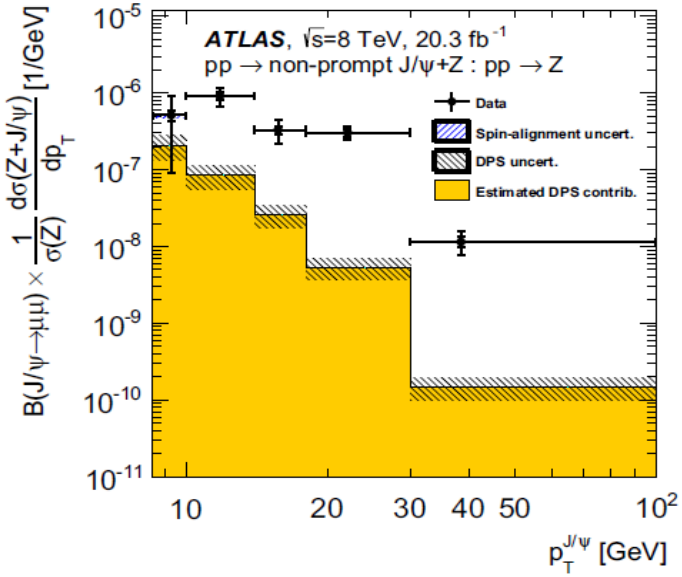
	prompt >5 σ	non-prompt >5 σ
fiducial	${}^{\mathrm{p}}R^{\mathrm{fid}}_{Z+J/\psi} = (36.8 \pm 6.7 \pm 2.5) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{fid}}_{Z+J/\psi} = (65.8 \pm 9.2 \pm 4.2) \times 10^{-7}$
inclusive	${}^{\mathrm{p}}R^{\mathrm{incl}}_{Z+J/\psi} = (63 \pm 13 \pm 5 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{incl}}_{Z+J/\psi} = (102 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS subtracted	${}^{\mathrm{p}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (45 \pm 13 \pm 6 \pm 10) \times 10^{-7}$	${}^{\mathrm{np}}R^{\mathrm{DPS\,sub}}_{Z+J/\psi} = (94 \pm 15 \pm 5 \pm 3) \times 10^{-7}$
DPS fraction	${}^{\mathrm{p}}f_{\mathrm{DPS}} = (29 \pm 9)\%$	${}^{\mathrm{np}}f_{\mathrm{DPS}} = (8 \pm 2)\%$





A higher production rate is predicted through colour-octet transitions than through colour-singlet processes, but the expected production rate from the sum of singlet and octet contributions is lower than the data by a factor of 2 to 5;
Momentum dependence is observed.





Summary

1. X(5568) is searched with ATLAS data, but no hint;
2. Excited $B_c^{\pm}$ Meson State is observed with ATLAS data;
3. Both W+J/Ψ and Z+J/Ψ are observed with ATLAS data; in the two processes, DPS is evident;

Thank you very much!