Measurement of di-J/psi events at ATLAS

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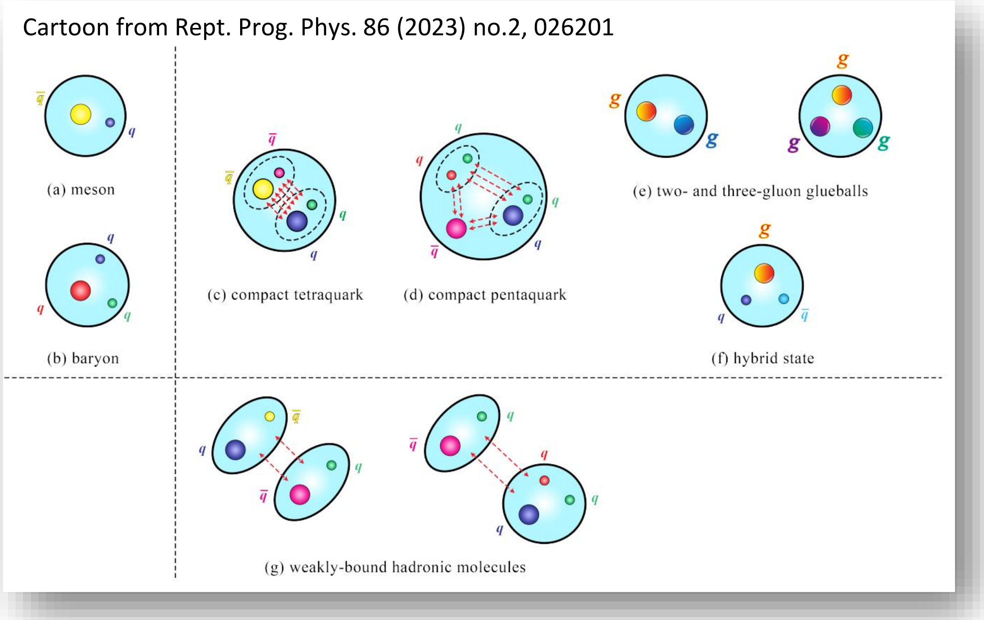
For ATLAS collaboration

COMPASS "Analysis Phase" mini-workshop, April 19th, 2023

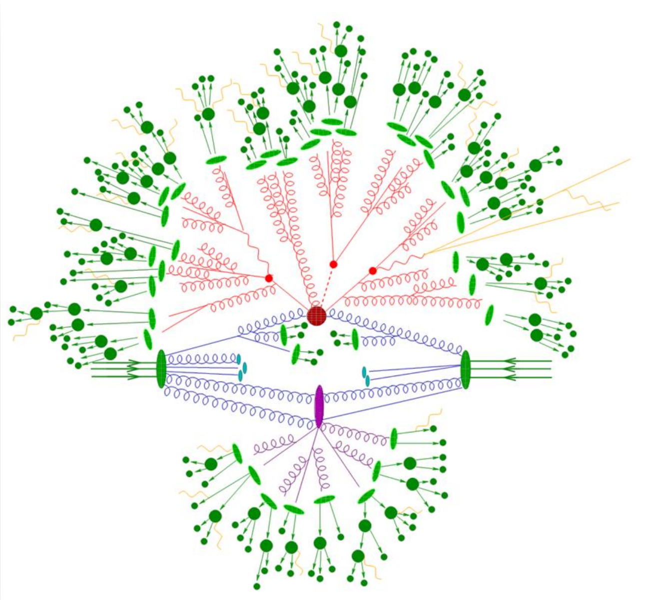
Spectroscopy x Production

- ❑ Desire I: explore zoo of particles composed of quarks, gluons
    - ❖ mesons, baryons
    - ❖ exotic hadrons
    - ❖ multi-quark (gluon) states

- ❑ Desire II: understand at QCD scales how particles are produced and distributed …
    - ❖ perturbative, non-perturbative QCD
    - ❖ prompt, non-prompt
    - ❖ single (double) parton interactions
    - ❖ across different platforms

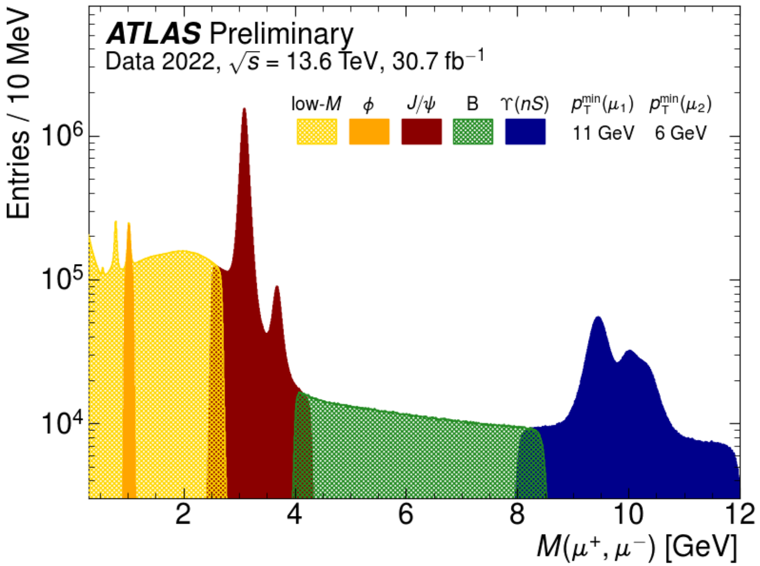

Cartoon from Rept. Prog. Phys. 86 (2023) no.2, 026201

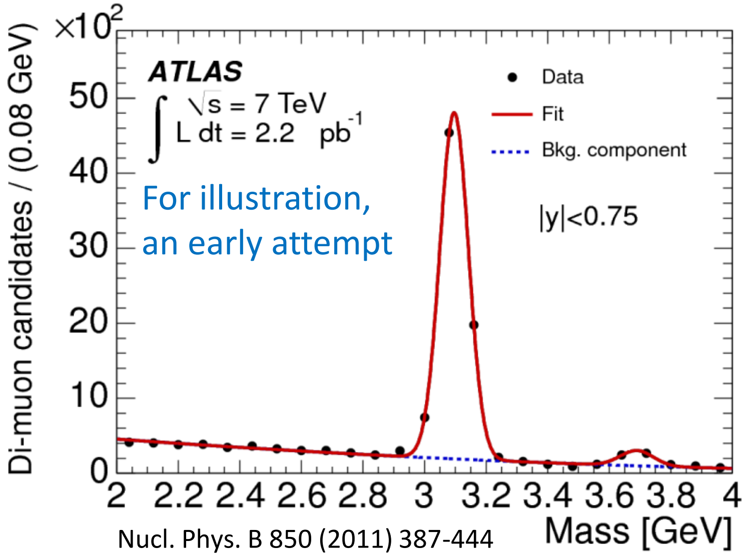
Bump hunting, property measurements



(Differential) Cross-section measurements

J/psi events





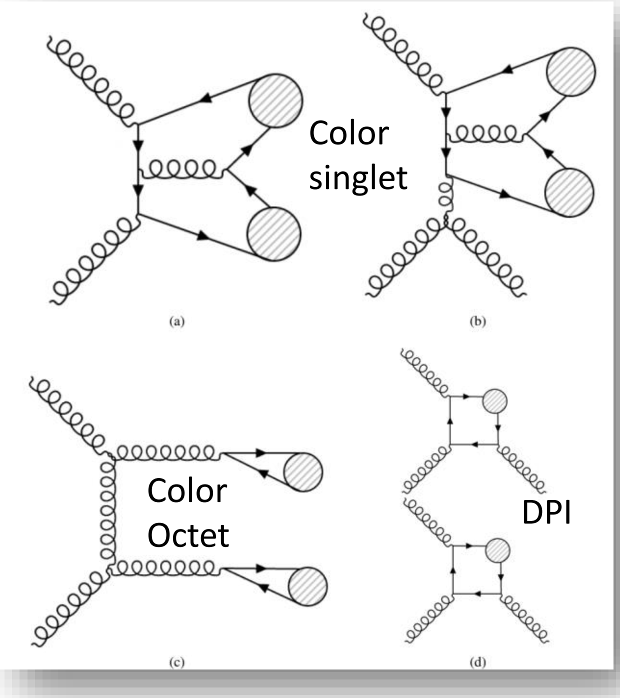
For illustration, an early attempt

Nucl. Phys. B 850 (2011) 387-444

- Abundantly produced and well accessible through its dimuon decays
- Standard candle for detector calibration, especially for low pT muons
- Reference point for triggering, opening a window for flavor physics at the high lumi., general-purpose detectors
    - Higher states / hadrons decaying to J/psi => rare decay, exotic hardon searches
    - Precision measurements (searches) with J/psi => critical inputs to theoretical models

Complementarity in kinematics, interplay between ATLAS/CMS, with other experiments (BELLE-II, COMPASS, LHCb, ALICE…), and next generation tau-charm factories

Double J/psi events



Doubled the difficulties of measurements:

- **O(10) pb fiducial cross-sections ➔** rare process,
  - Analogy to electroweak diboson/Higgs production
  - Not accessible at lower luminosity machines
- **Higher CME requirement ➔** not accessible at traditional charm-tau factories
  - LHC experiments (yes), B factory (?), next-gen. tau-charm factories (?)
- **More complicated decay final states w.r.t. single J/psi ➔** may not be fully efficient in single-arm detectors, general purpose detectors like ATLAS, CMS can be promising

Doubled the physics potentials

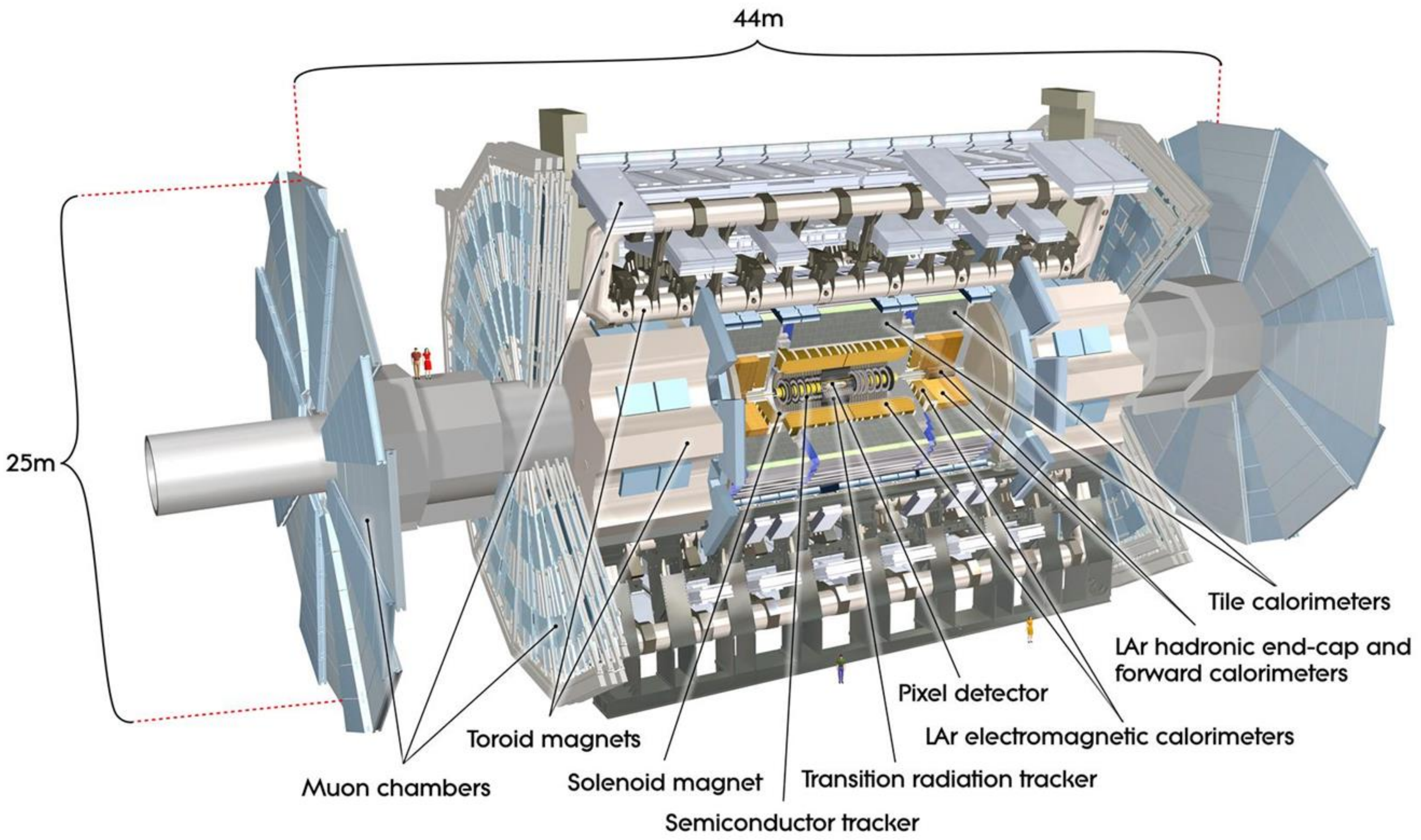
- **Stringent test of QCD** (a.k.a. in the rare process domain)
- **Sizable DPI contribution** (insights on less touched territories of hadron structure)
- **Backgrounds to resonances decays to J/psi pairs** (e.g., search for cccc tetraquark)
- **Backgrounds to low mass resonance searches at charm-bottom energies**
  - e.g., SUSY, dark sector, QCD resonances decaying to four low pT muons

Covered in this talk

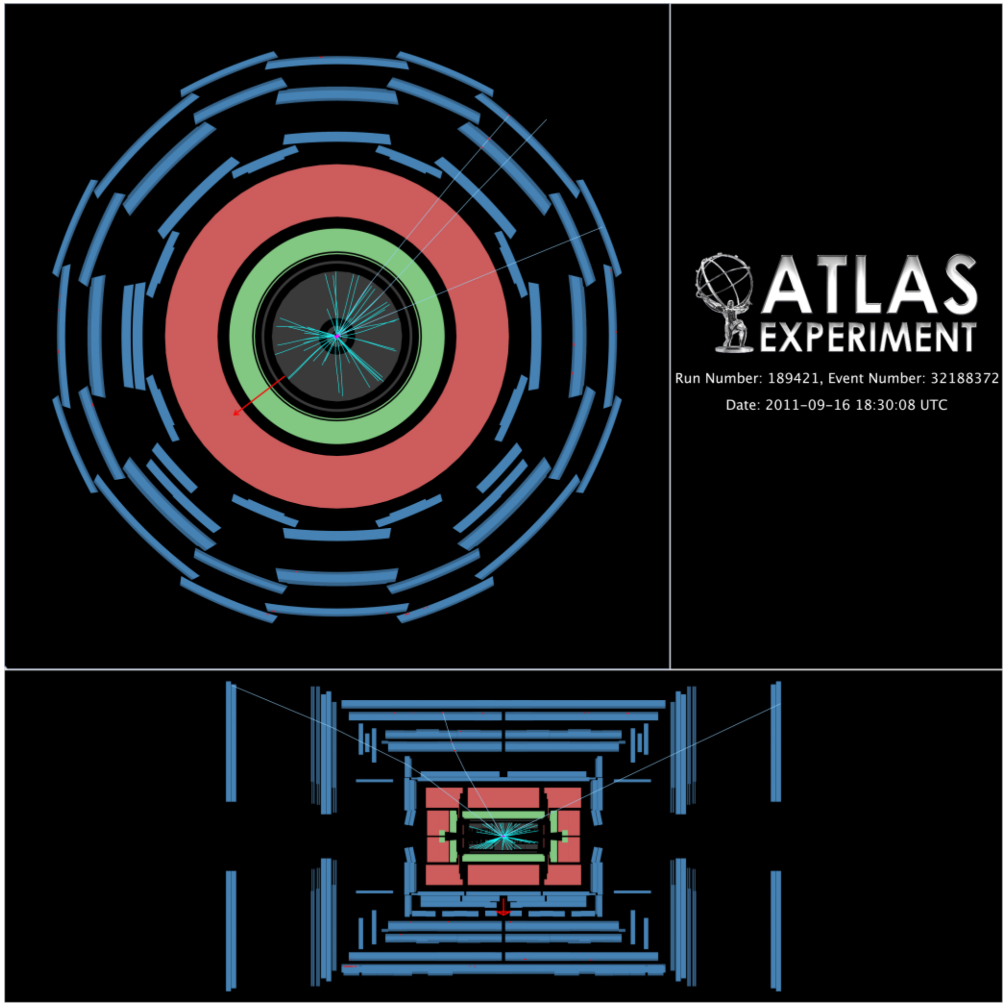
- ☐ A short overview on experimental instrument and techniques
- ☐ Di-J/psi measurement at ATLAS with 8 TeV data [EPJC 77 (2017) 76]
  - ❖ With reference to J/psi + W measurements with 8 TeV [JHEP 01 (2020) 095]
- ☐ Efforts on 13 TeV data at ATLAS
  - ❖ single J/psi measurement [ATLAS-CONF-2019-047]
  - ❖ search for resonances decaying to di-J/psi [arXiv:2304.08962]

Focus on discussing these ATLAS results, would not have time to cover complementarity discussions between ATLAS, CMS, and other experiments

ATLAS detector



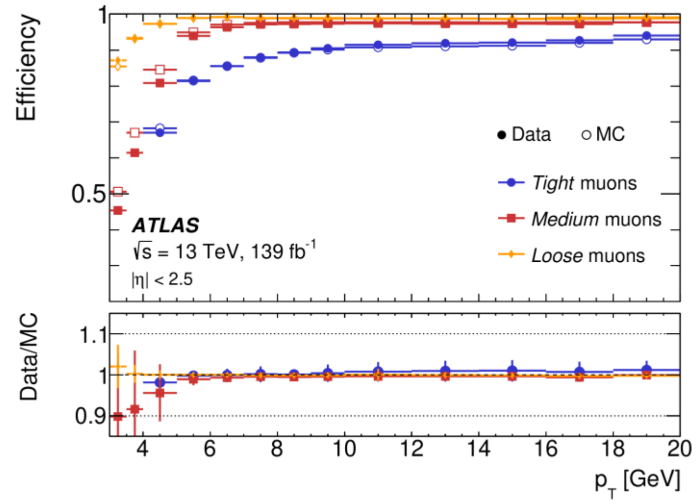
Experimental handles



A display of 3μ+MET final state from W+J/psi production

- No traditional pID (p/K/π etc.) at ATLAS, but we have clear ID of high-pT objects such as muons, electrons, …
- Muons can be reconstructed down to 2.5-3 GeV pT, with pT resolution ~ 1%
  - Inner tracker dominates the resolution in concerned phase space, while muon detector crucial for identifying the muons and triggering the events
- J/psi → di-μ is the channel we typically rely on (which could be combined with tracks, with mass hypotheses applied to select on higher exotic states, etc.)
- O(50) μm vertex precision in x-y, and ranging from O(50) μm to mm in z → enable to separate prompt and non-prompt contributions

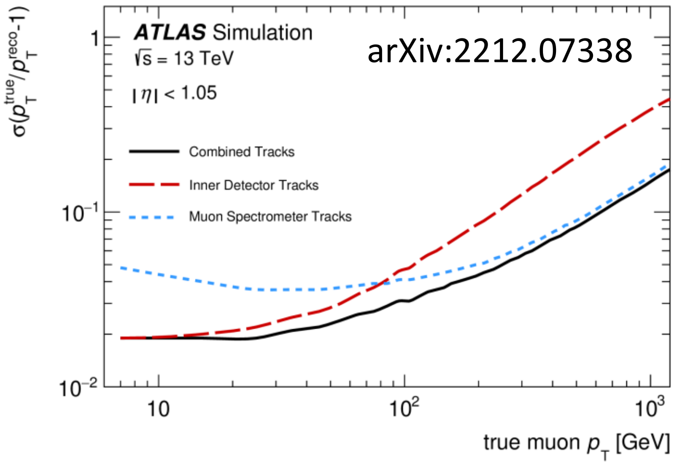
Examples about object performance



Eur. Phys. J. C 81 (2021) 578

Ability to identify muons with small pT

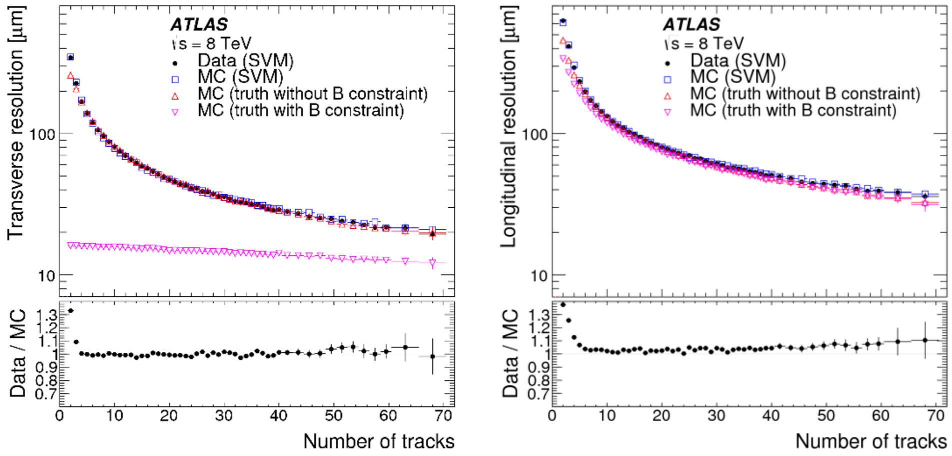
- ➢ Lower threshold around 2-3 GeV due to MIP energy loss in calorimeter
- ➢ Optimized for rejecting non-prompt muons from light flavor hadron decays



arXiv:2212.07338

Visualization of muon pT reso.

Eur. Phys. J. C 77 (2017) 332



Vertex spatial reso. in a nutshell

8 TeV Di-J/psi measurement at ATLAS

EPJC 77 (2017) 76

Di-J/psi measurement at 8 TeV

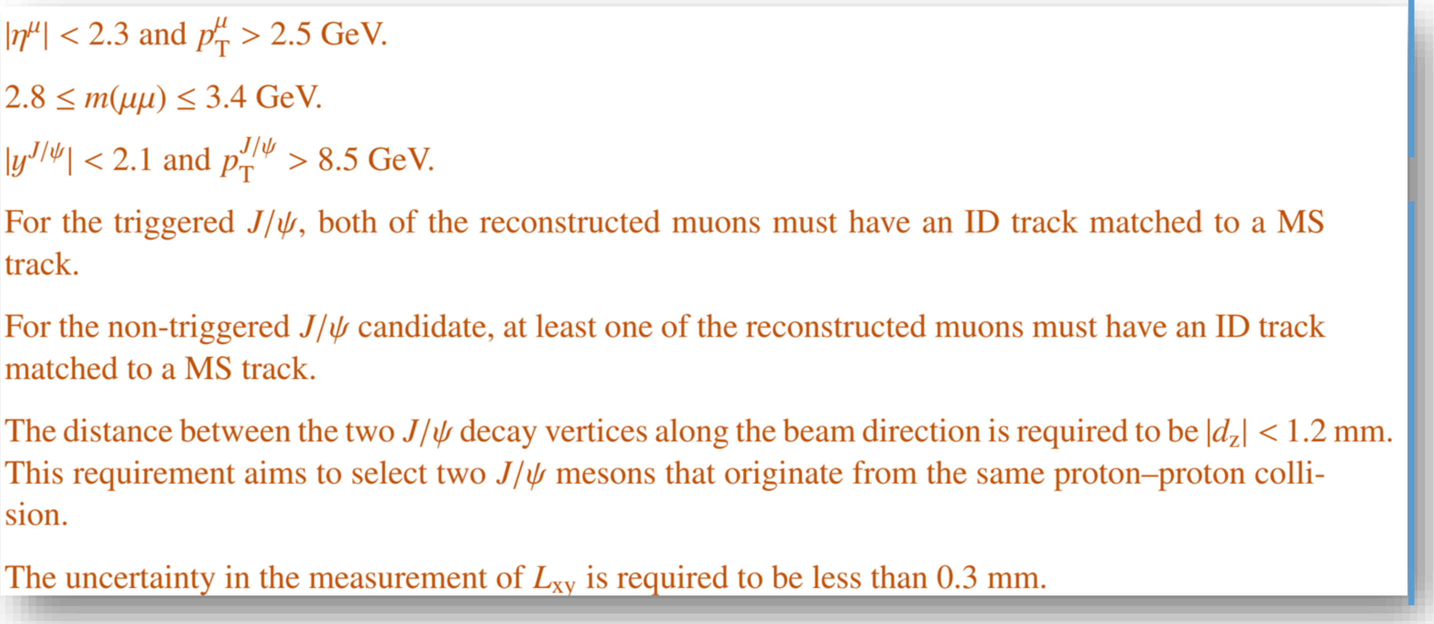
A glance of how di-J/psi candidate events are selected

Trigger:

Data set taken with 2μ trigger in J/psi mass range, trigger selections:
pT > 4 GeV, and 2.5 < m($\mu\mu$) < 4.3 GeV

Defines the fiducial region

Offline:



$|\eta^{\mu}| < 2.3$ and $p_{\mathrm{T}}^{\mu} > 2.5$ GeV.

$2.8 \leq m(\mu\mu) \leq 3.4$ GeV.

$|y^{J/\psi}| < 2.1$ and $p_{\mathrm{T}}^{J/\psi} > 8.5$ GeV.

For the triggered J/ψ, both of the reconstructed muons must have an ID track matched to a MS track.

For the non-triggered J/ψ candidate, at least one of the reconstructed muons must have an ID track matched to a MS track.

The distance between the two J/ψ decay vertices along the beam direction is required to be $|d_{\mathrm{z}}| < 1.2$ mm. This requirement aims to select two J/ψ mesons that originate from the same proton–proton collision.

The uncertainty in the measurement of L_{xy} is required to be less than 0.3 mm.

Instrument quality selection

Signal region

Extract signals from signal region

Events in Signal Region

Correct for acceptance, efficiency, branching fraction, etc.

Events in Fiducial Region

Fit mass spectra to extract the di-J/psi events

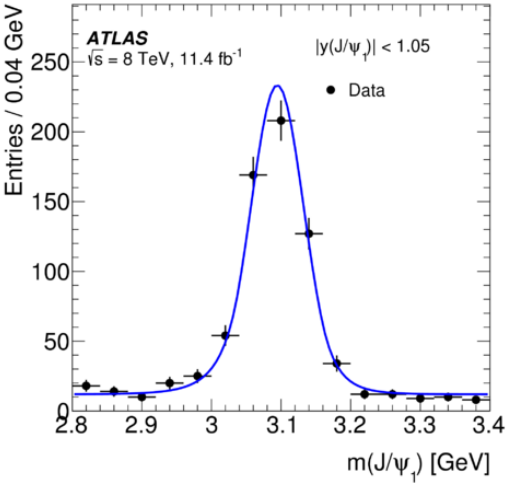
Di-J/psi in Fiducial Region

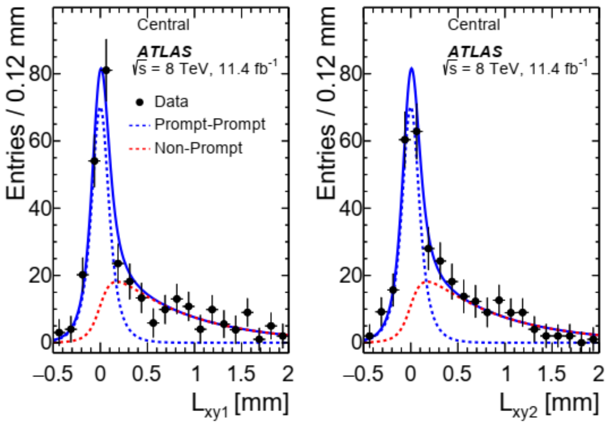
Applied as weights to events

Fit vertex observables to extract prompt/ non-prompt di-J/psi events

(non-) Prompt Di-J/psi in Fiducial Region

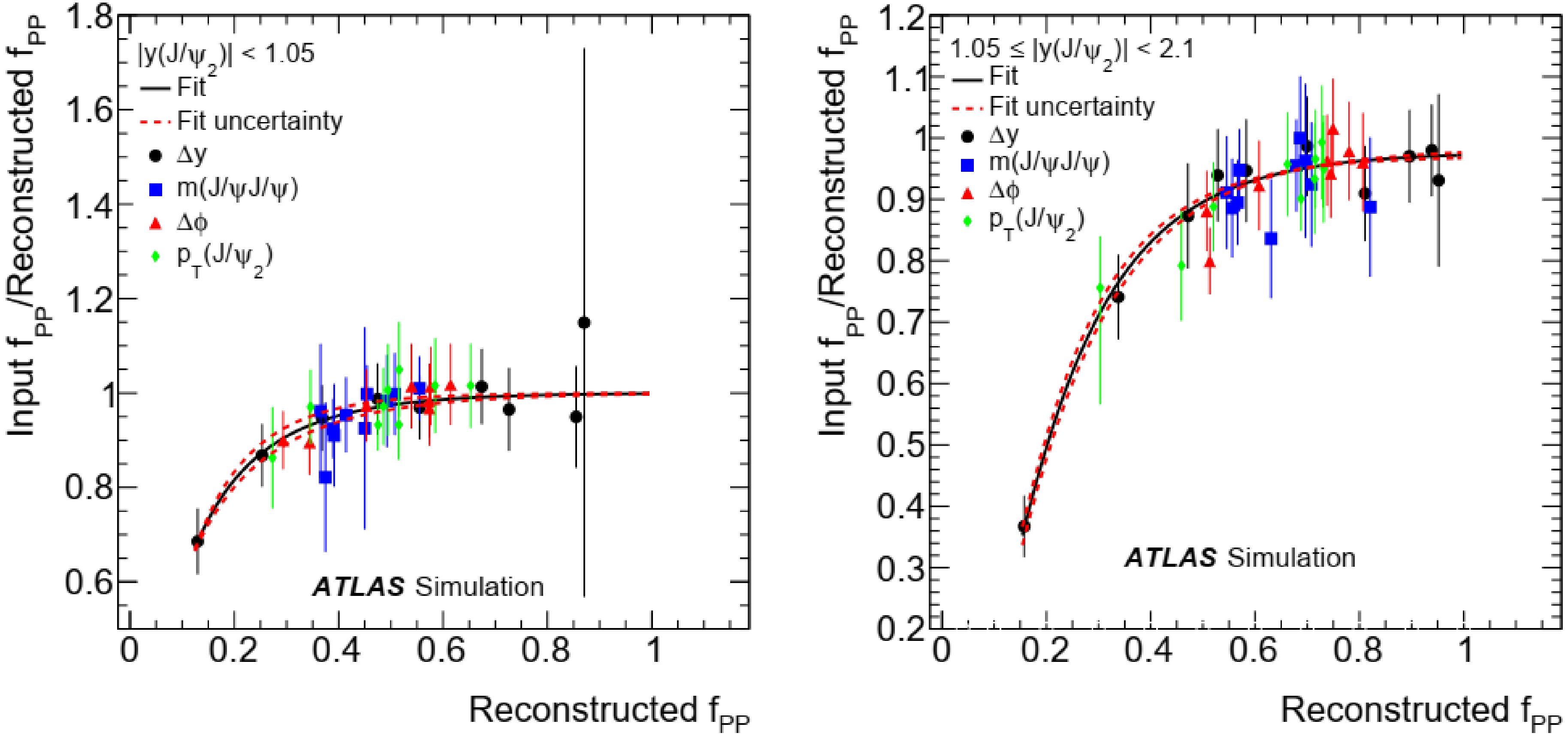
- Simulation based corrections, PYTHIA8 with CTEQ6L1 and AU2 tune
- Unpolarized J/psi considered, while correction of extreme polarization provided





J/psi pairs ordered by pT, Lxy stands for x-y distance between J/psi vertex and primary vertex

Extra Corrections on prompt fraction extraction



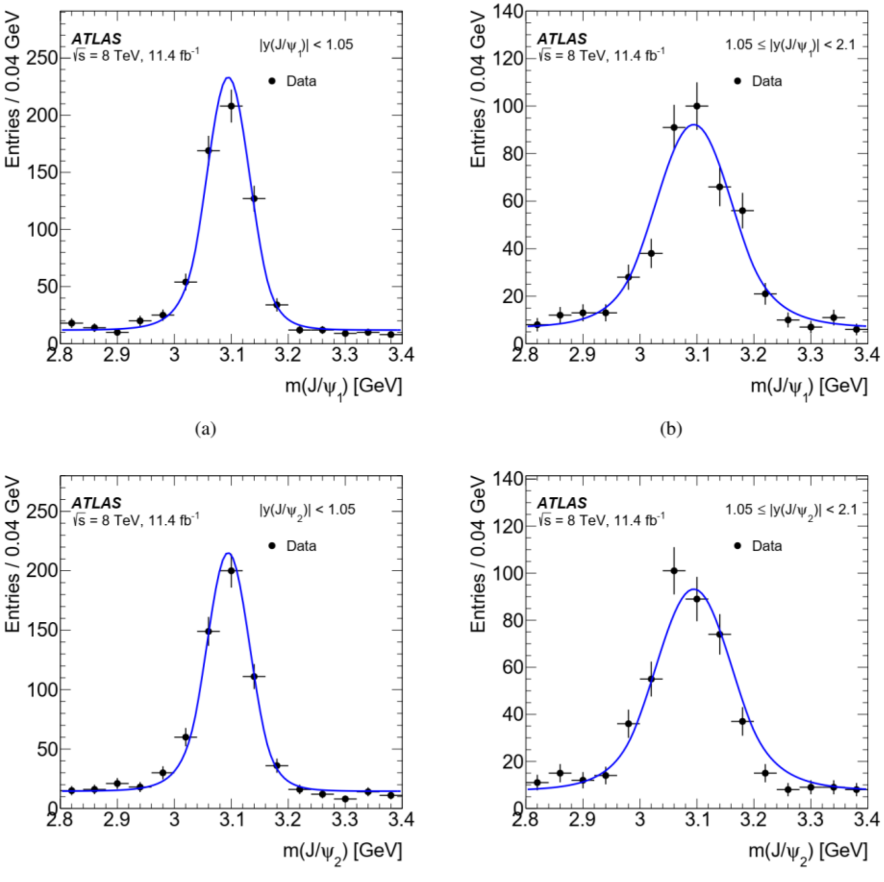
The last step (previous page) accounts for averaged prompt fraction (f_{PP}) across kinematic bins, simulation-based corrections are offered for each bins

Statistical Fits

Unbinned fits to kinematic distributions

Crystal ball signal + flat background

$$P = P_{\rm sig} \times CB\,(m(J/\psi_1)) \times CB(m(J/\psi_2)) \;+\; P_{\rm bkg} \times P_0$$

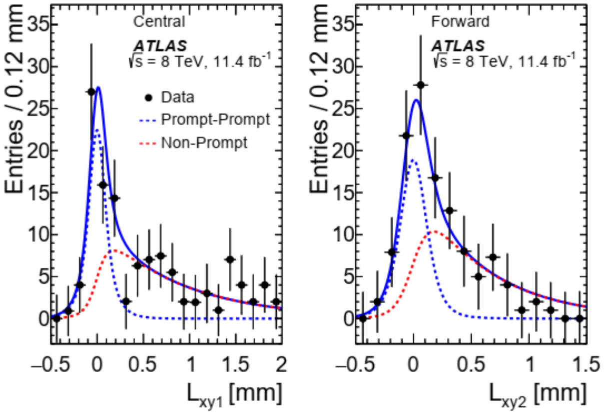


(a) (b)

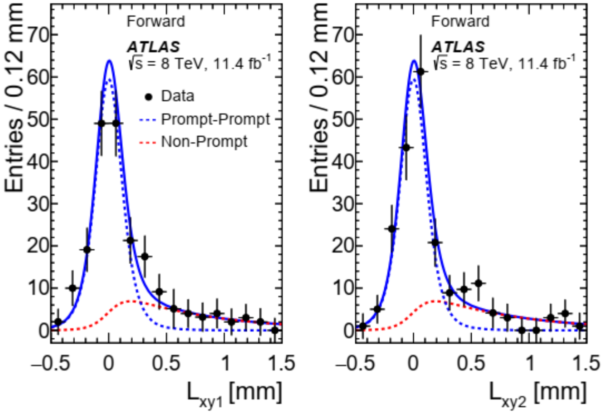
(c) (d)

Physical functions convoluted with resolution function R

$$R = G_1(L_{\rm xy}) + G_2(L_{\rm xy}) + G_3(L_{\rm xy}) + G_4(L_{\rm xy})$$
$$S = \delta(L_{\rm xy}) * R$$
$$N = \frac{1}{\tau}\exp(-L_{\rm xy}/\tau) * R.$$



(b)



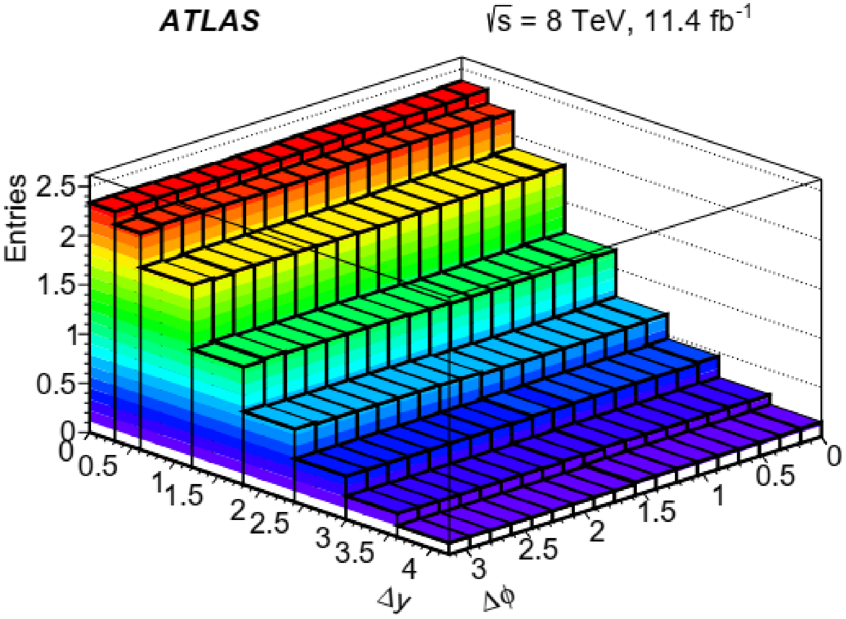
(d)

Extraction of DPI contributions

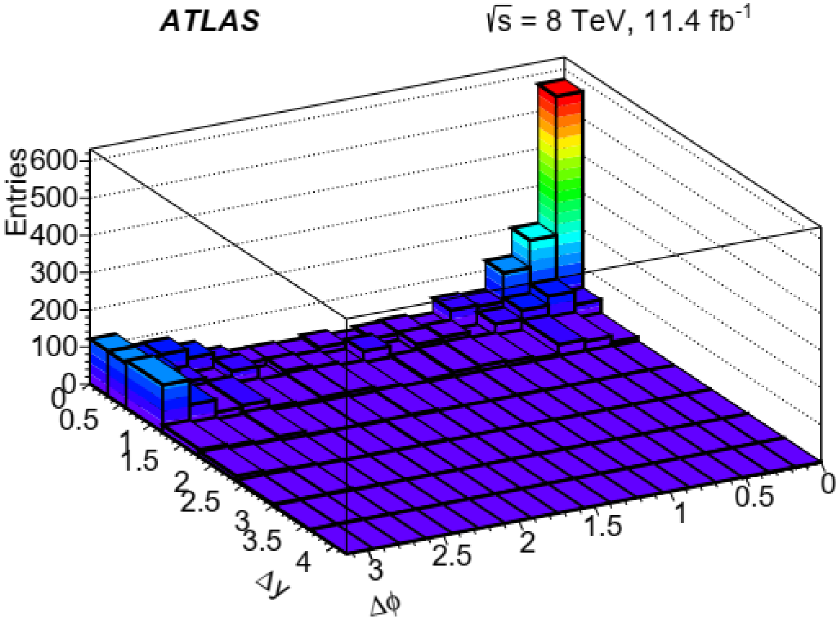
Another important outcome of this work is to examine the DPI/SPI fractions inside prompt di-J/psi production

2D template from data built based on the assumption that DPI di-J/psi is a random mixture of two SPI J/psi, with rate constraint by factorisation formula

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

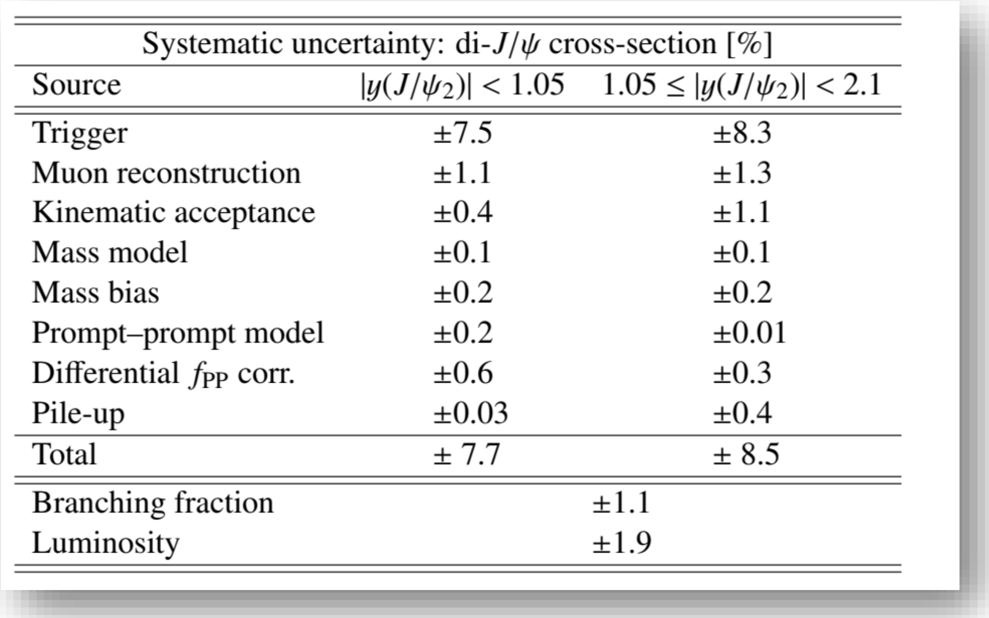


DPI template from data

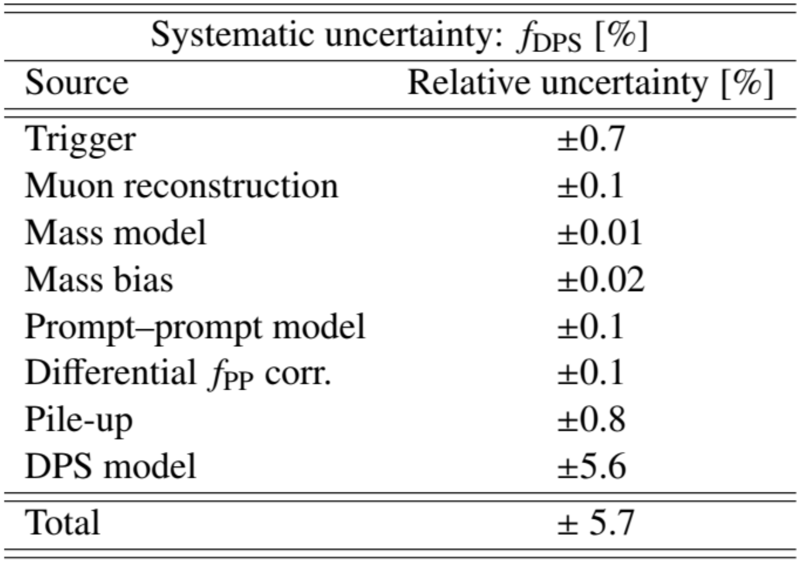


SPI template from data subtracting DPI

Uncertainties



Systematic uncertainty: di-J/ψ cross-section [%]		
Source	$\lvert y(J/\psi_2)\rvert < 1.05$	$1.05 \leq \lvert y(J/\psi_2)\rvert < 2.1$
Trigger	±7.5	±8.3
Muon reconstruction	±1.1	±1.3
Kinematic acceptance	±0.4	±1.1
Mass model	±0.1	±0.1
Mass bias	±0.2	±0.2
Prompt–prompt model	±0.2	±0.01
Differential f_{PP} corr.	±0.6	±0.3
Pile-up	±0.03	±0.4
Total	± 7.7	± 8.5
Branching fraction	±1.1	
Luminosity	±1.9	



Systematic uncertainty: f_{DPS} [%]	
Source	Relative uncertainty [%]
Trigger	±0.7
Muon reconstruction	±0.1
Mass model	±0.01
Mass bias	±0.02
Prompt–prompt model	±0.1
Differential f_{PP} corr.	±0.1
Pile-up	±0.8
DPS model	±5.6
Total	± 5.7

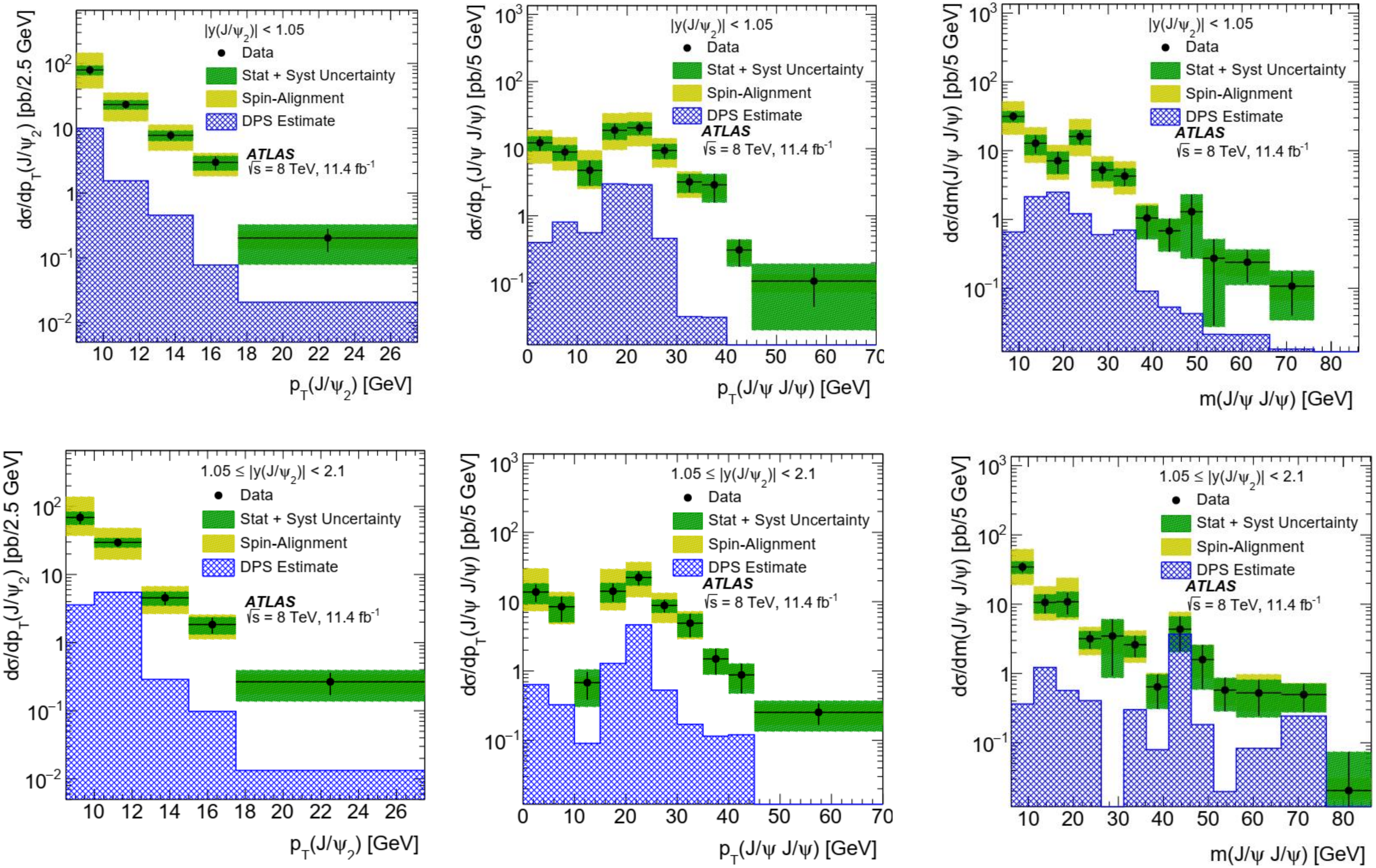
Presentation of a thorough assessment of typical uncertainty sources for cross-section measurement and for DPI measurement

➔ Statistical uncertainty of the data important

➔ Trigger uncertainty dominates the overall systematic unc. (conservative approach)

Results

Differential measurements presented for two rapidity bins



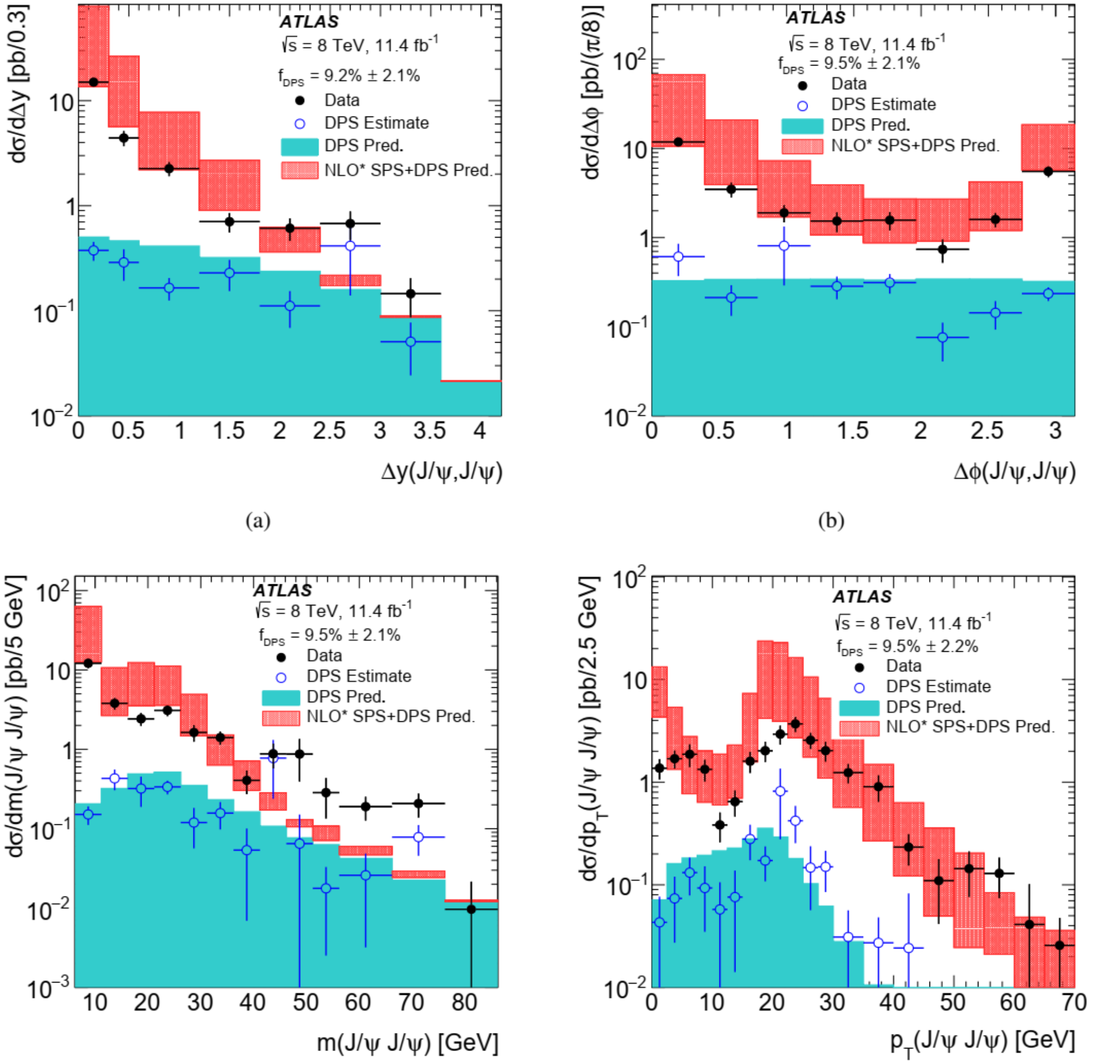
Measurement v.s. Prediction

Comparison to theoretical predictions:

SPI NLO QCD Pred. from HELAC-Onia and CTEQ PDF [1410.8822][1308.0474]

DPI LO Pred. assumes factorisation

➔ Generally reasonable agreement, but SPI/DPI fraction, shape modelling may be improved (?)



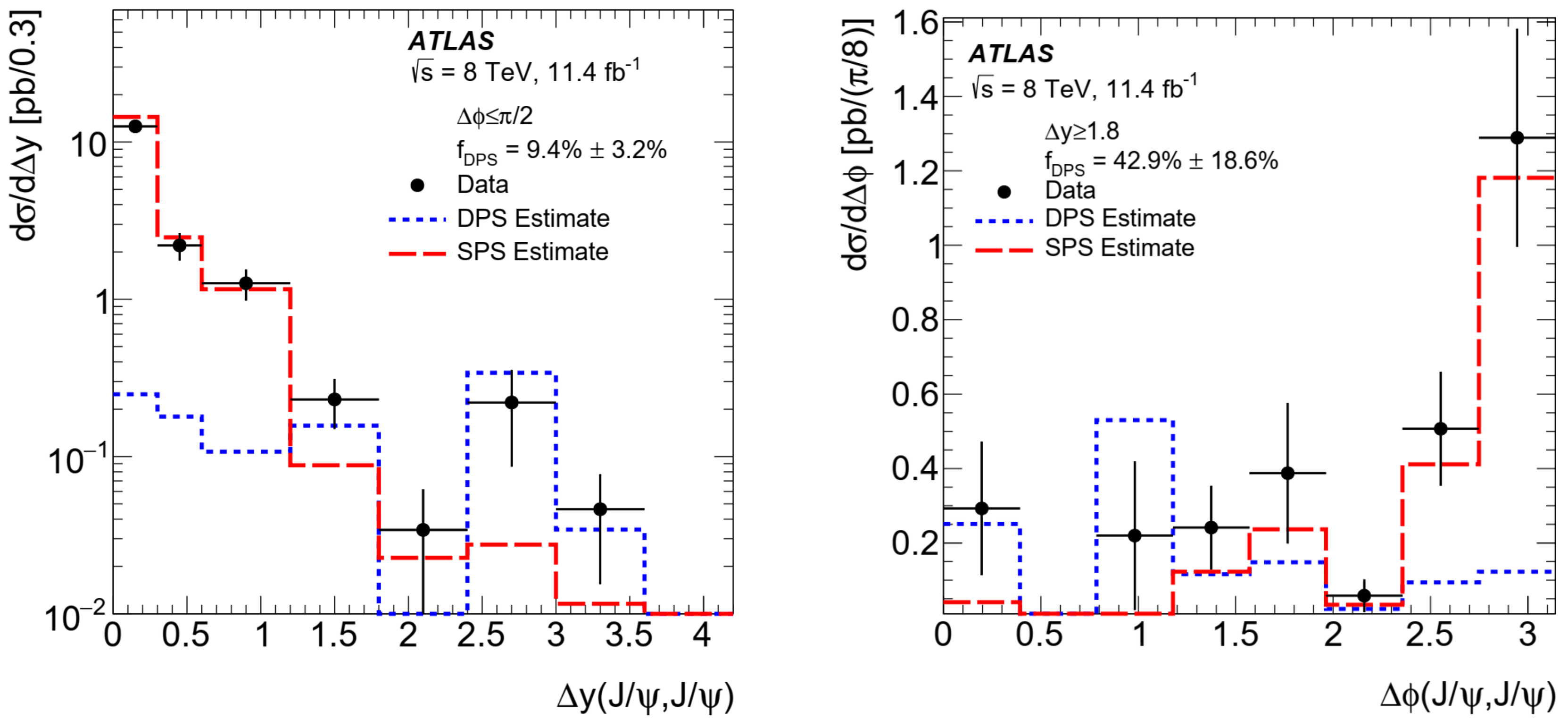
(a)

(b)

(c)

(d)

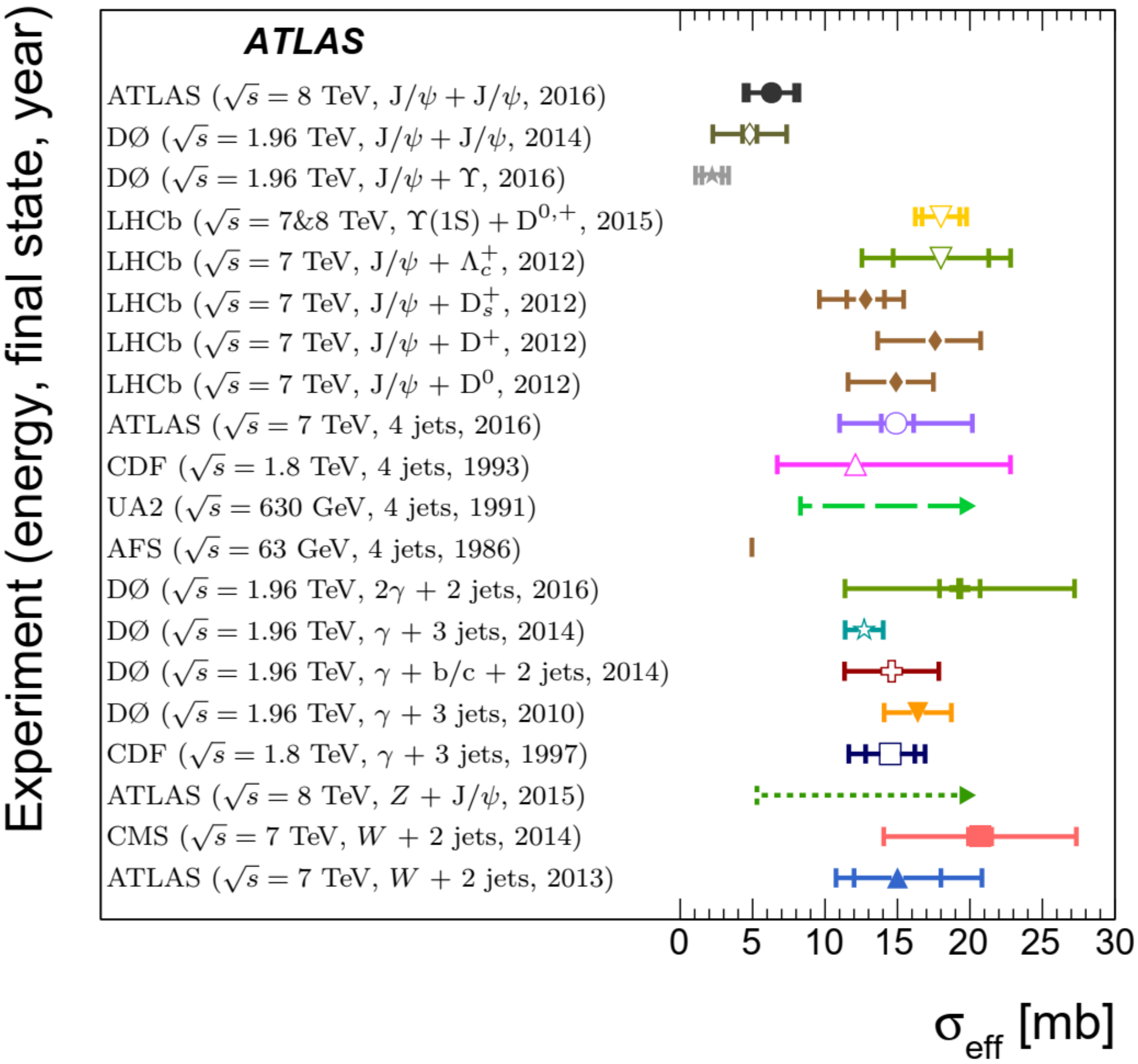
More investigations



With cuts on delta(Y) or delta(phi), SPI-depleted regions are used to examine the discrepancies:

⇒ Hinted about feed-down SPI contributions contributing to large delta(Y)

Effective cross-section measurement



Fitted DPI cross-section converted to the DPI effective σ

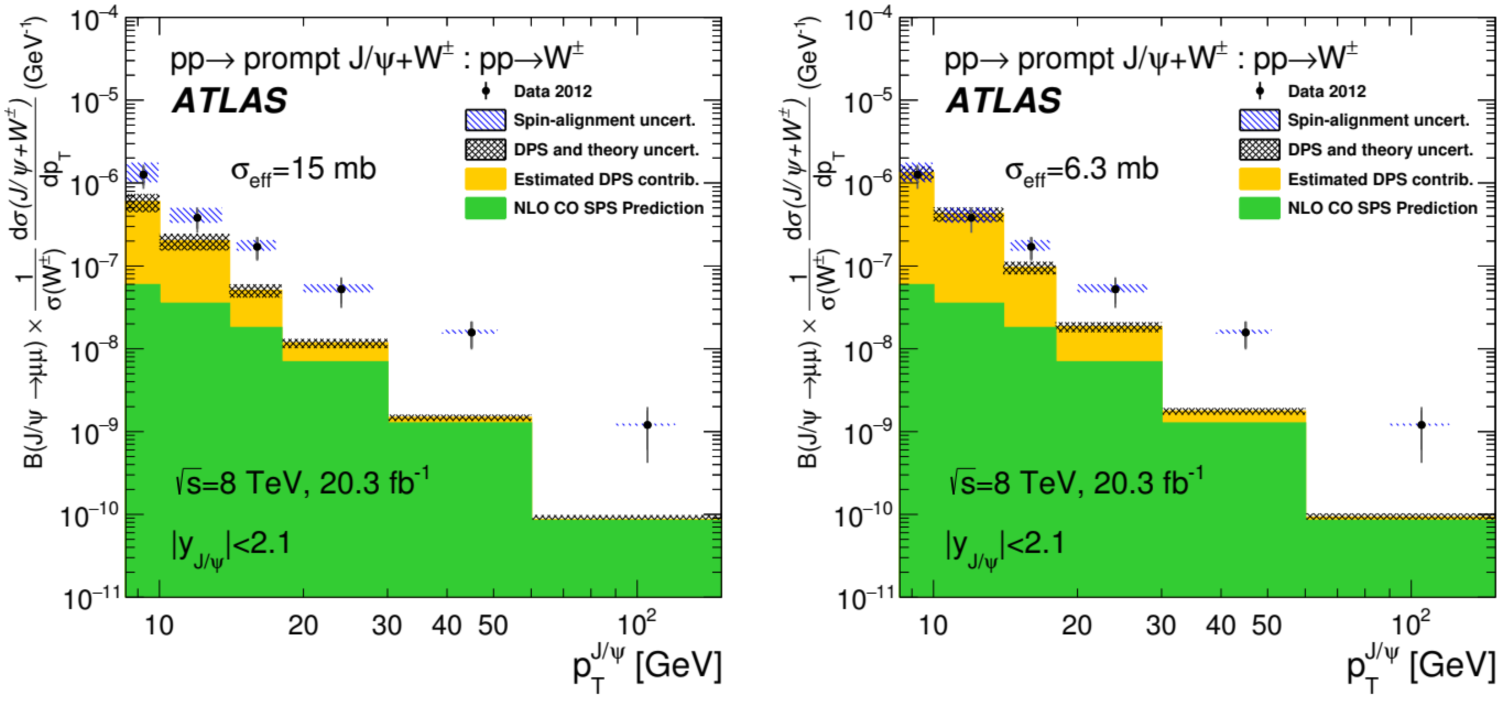
⇒ An important ingredient added to the global picture

⇒ The deviation across different measurements need more attention

Ref: 8 TeV W + J/psi measurements

JHEP 01 (2020) 095

Interesting measurement of this kind to probe associated multi-body production



Enhanced DPI production in low pT of J/psi, also hinted a better match to data with smaller σ(eff)

Color-octet alone may not describe high pT …

13 TeV J/psi efforts at ATLAS

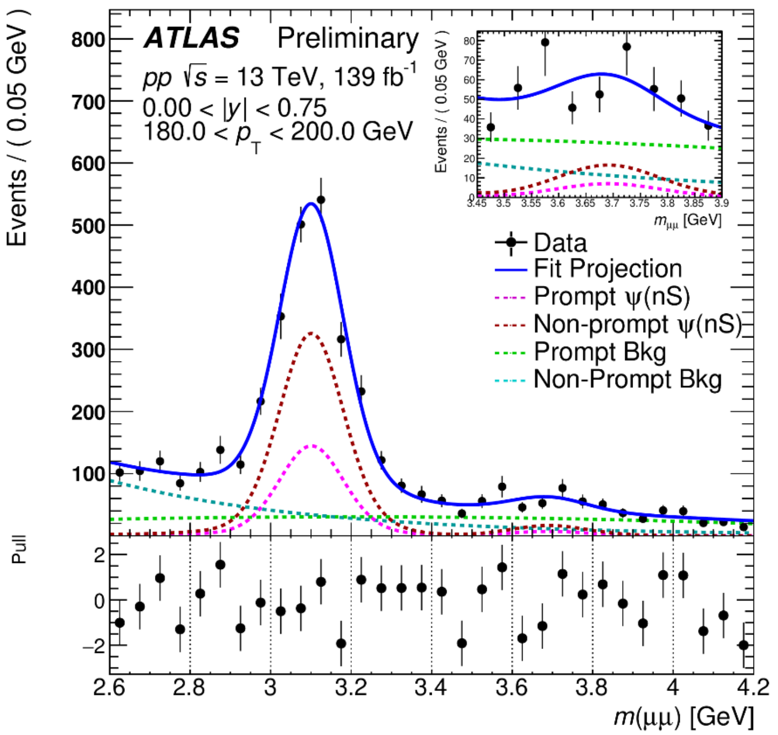
ATLAS-CONF-2019-047, arXiv:2304.08962

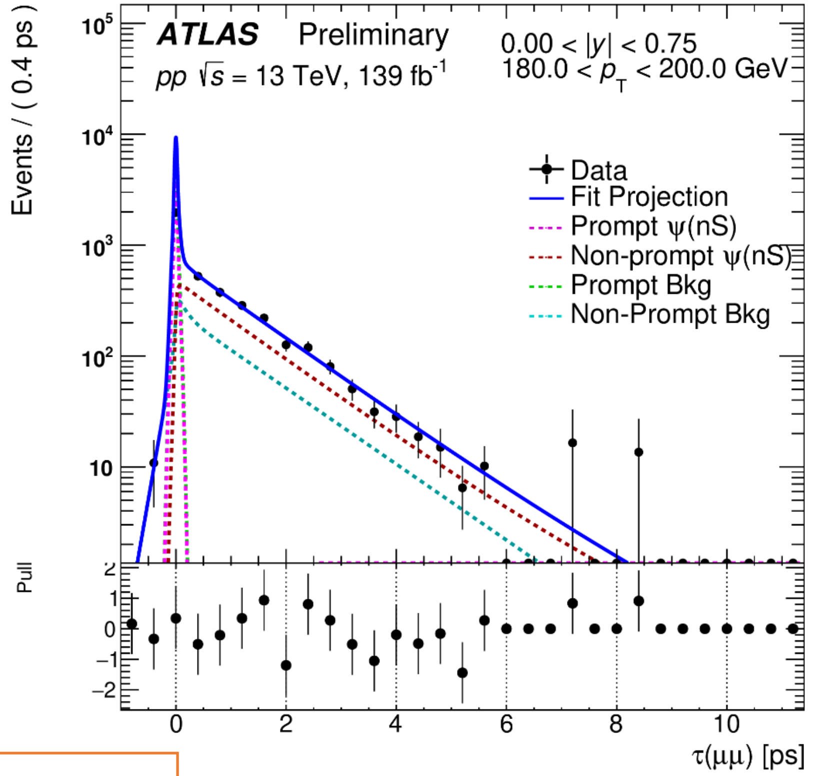
Disclaimer: topics here are slightly off the axis, also given the commonly used techniques, will focus on discussing results

13 TeV J/psi measurements

ATLAS-CONF-2019-047

The overall methodology goes similar, but fitting models get more complicate due to extensive amount of J/psi data





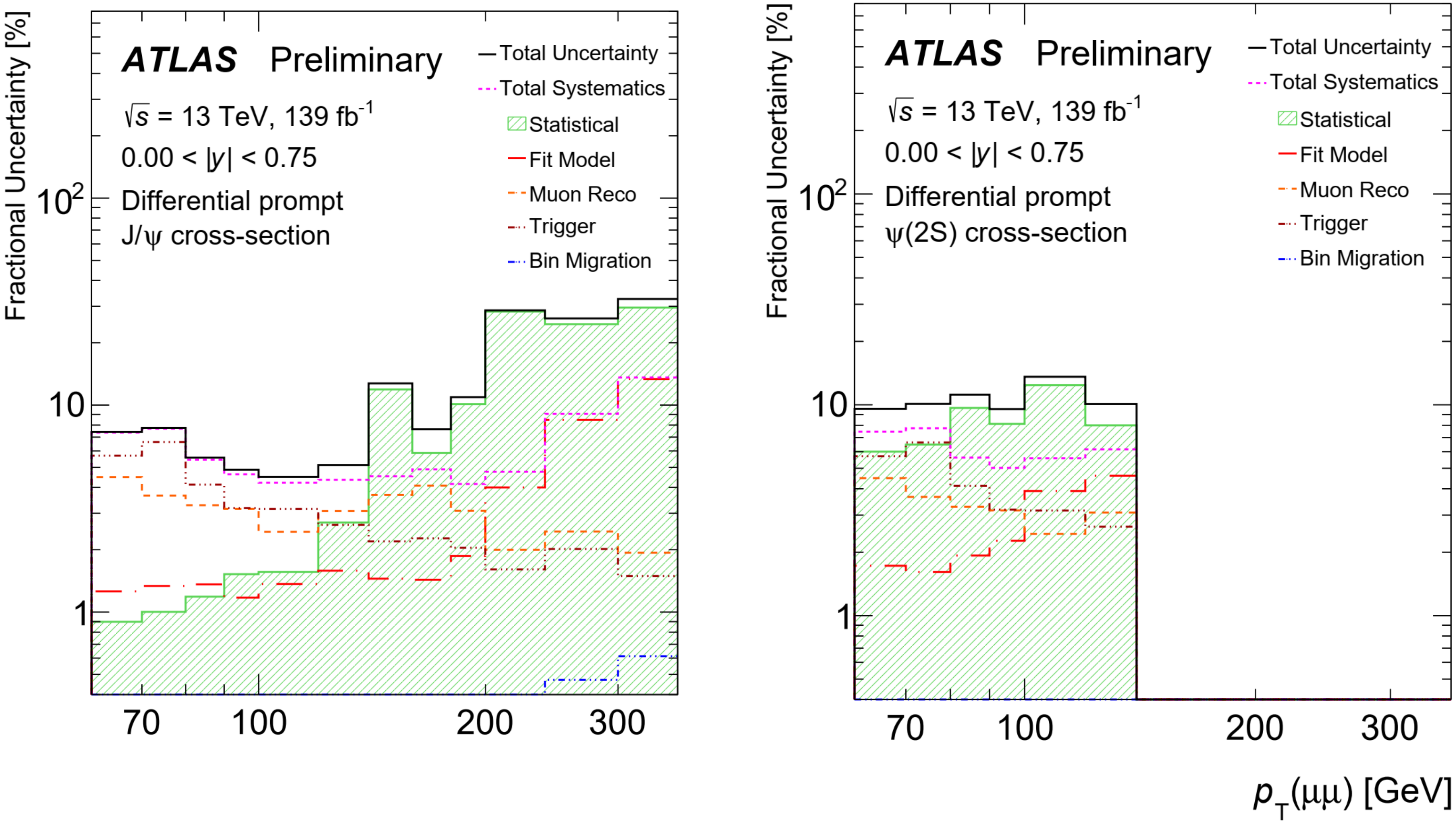
- J/psi and psi(2s) simultaneously
- Largest possible pT range to cover
- Comprehensive studies of fitting performance
- Precision J/psi measurements

Use of pseudo-proper time

$$\tau = \frac{m}{p_T}\frac{L_{xy}}{c}$$

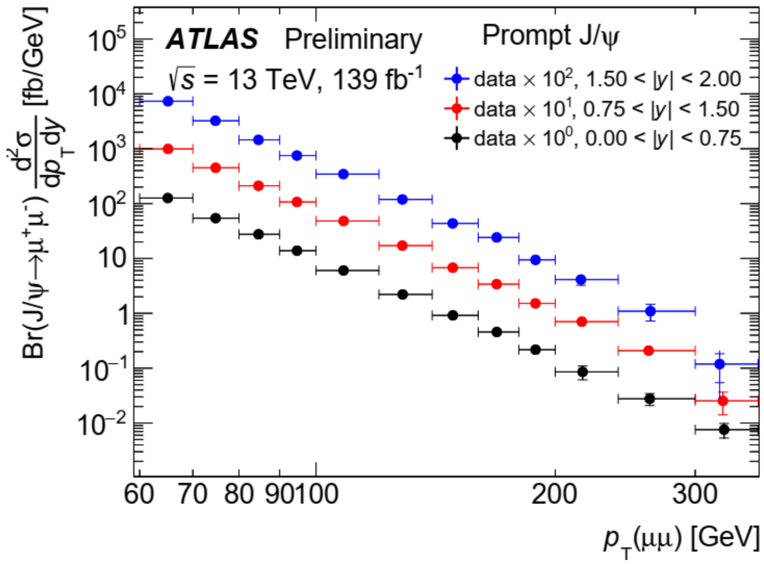
13 TeV J/psi measurements

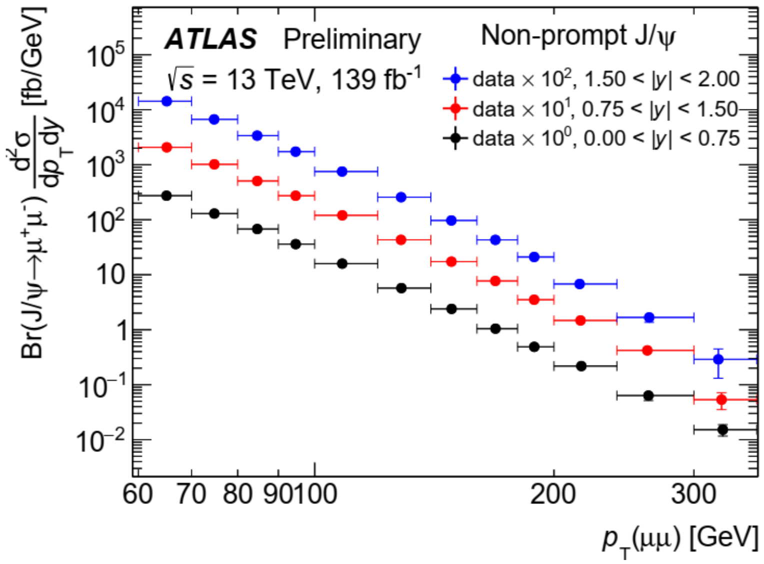
Representative uncertainty breakdowns

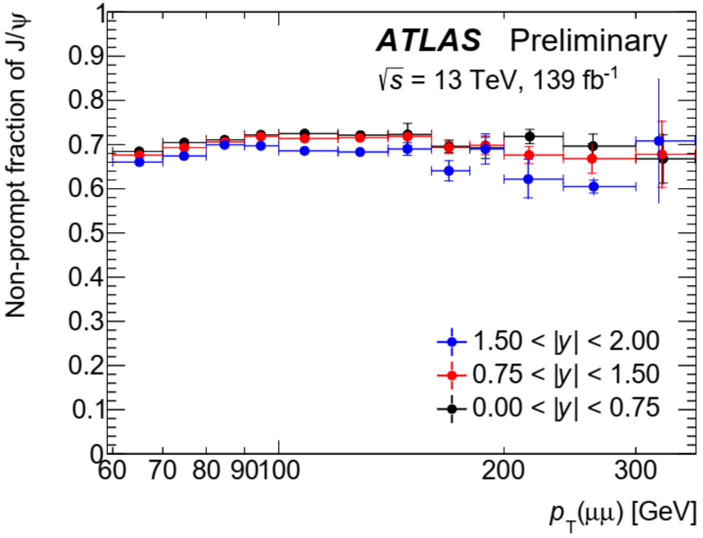


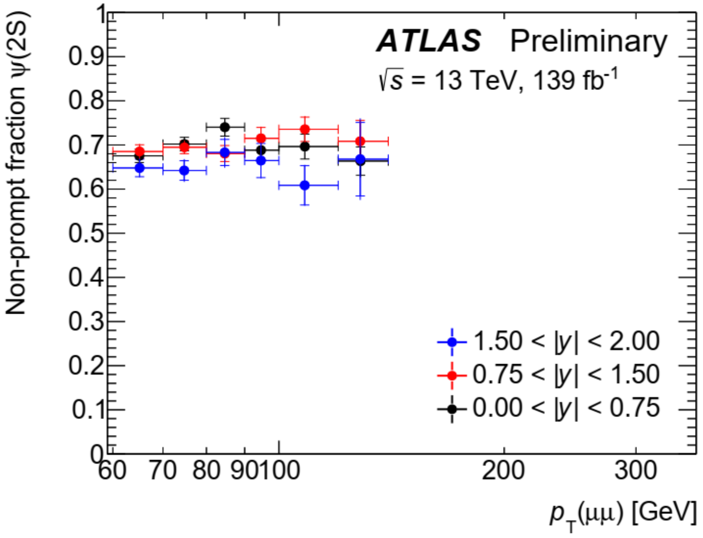
13 TeV J/psi measurements

Beautiful, precise O(10%) measurement up to 300 GeV







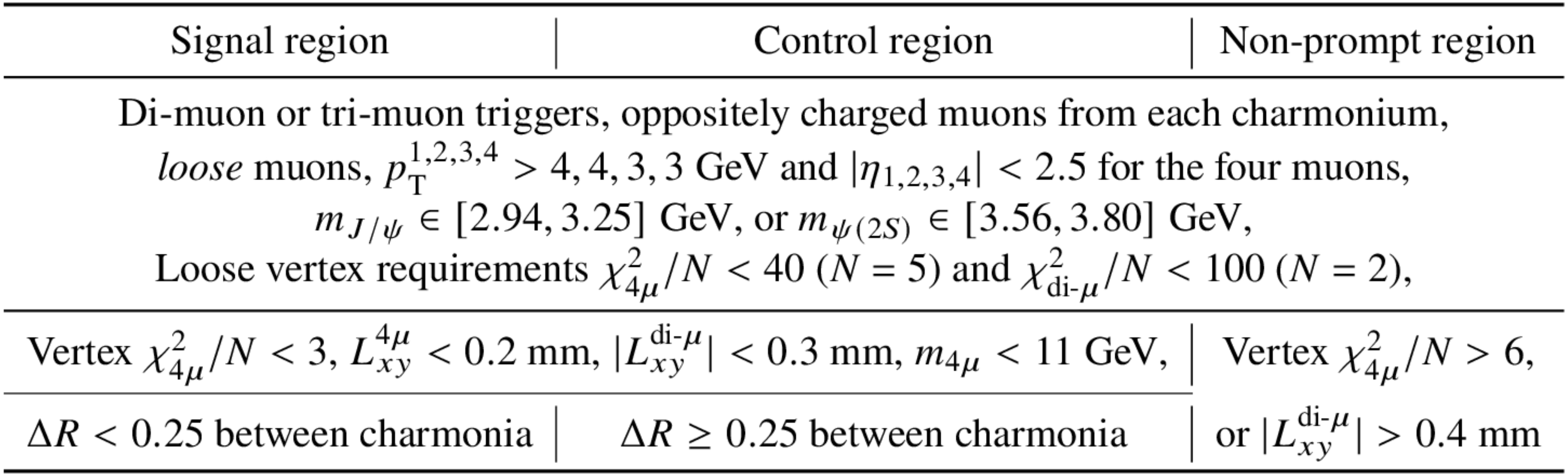


Join the party: hunt for di-J/psi resonances

arXiv:2304.08962

Or see ATLAS-CONF-2022-040

A particular candidate is X(6900) → di-J/psi

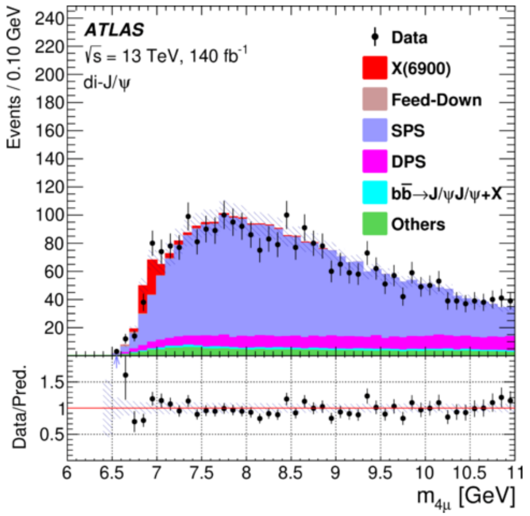


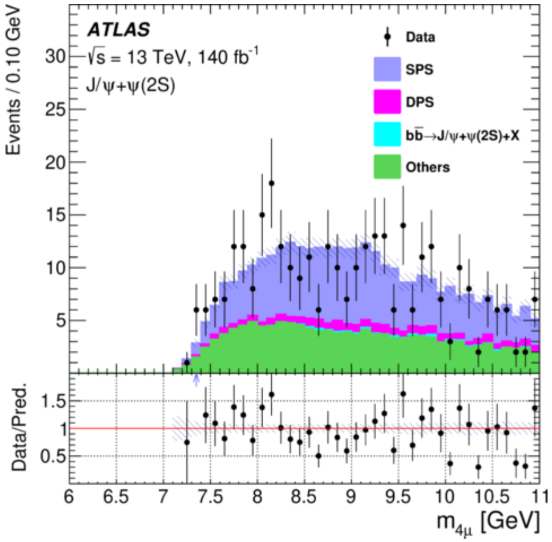
Signal region	Control region	Non-prompt region
Di-muon or tri-muon triggers, oppositely charged muons from each charmonium, *loose* muons, $p_{\mathrm{T}}^{1,2,3,4} > 4, 4, 3, 3$ GeV and $\lvert\eta_{1,2,3,4}\rvert < 2.5$ for the four muons, $m_{J/\psi} \in [2.94, 3.25]$ GeV, or $m_{\psi(2S)} \in [3.56, 3.80]$ GeV, Loose vertex requirements $\chi^2_{4\mu}/N < 40$ $(N = 5)$ and $\chi^2_{\text{di-}\mu}/N < 100$ $(N = 2)$,		
Vertex $\chi^2_{4\mu}/N < 3$, $L^{4\mu}_{xy} < 0.2$ mm, $\lvert L^{\text{di-}\mu}_{xy}\rvert < 0.3$ mm, $m_{4\mu} < 11$ GeV,		Vertex $\chi^2_{4\mu}/N > 6$, or $\lvert L^{\text{di-}\mu}_{xy}\rvert > 0.4$ mm
$\Delta R < 0.25$ between charmonia	$\Delta R \geq 0.25$ between charmonia	

- Very low pT muons are expected => offline threshold limited by trigger and reco.
- In searching mode, define control regions to control the background models
- Di-J/psi production (SPS, DPS, non-prompt) from MC but corrected with CR
- Unblinded fit with signal (multi-resonance interfering) and background to the m(4μ) distributions, simultaneously for SR/CR

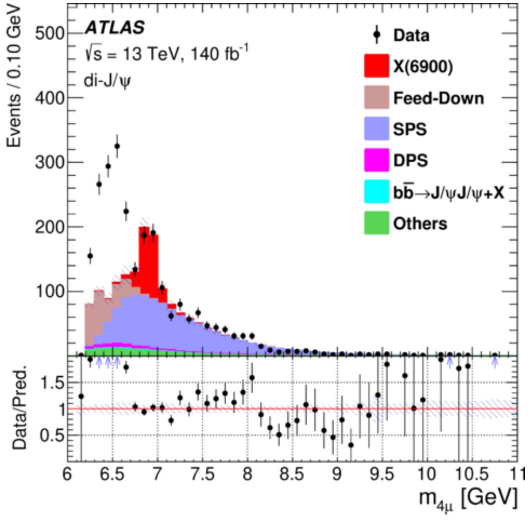
Hunt for di-J/psi resonances

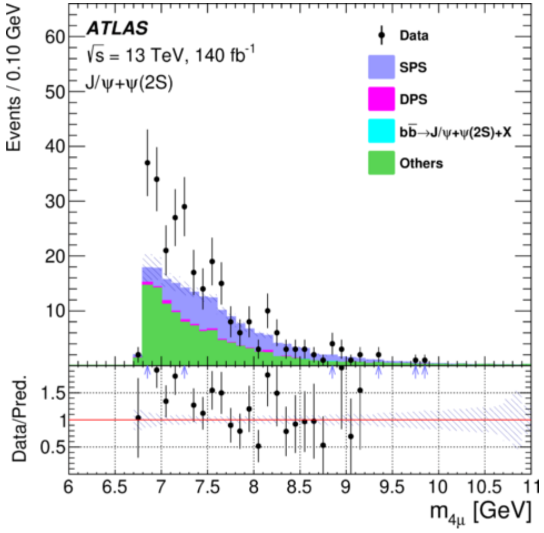
CR





SR

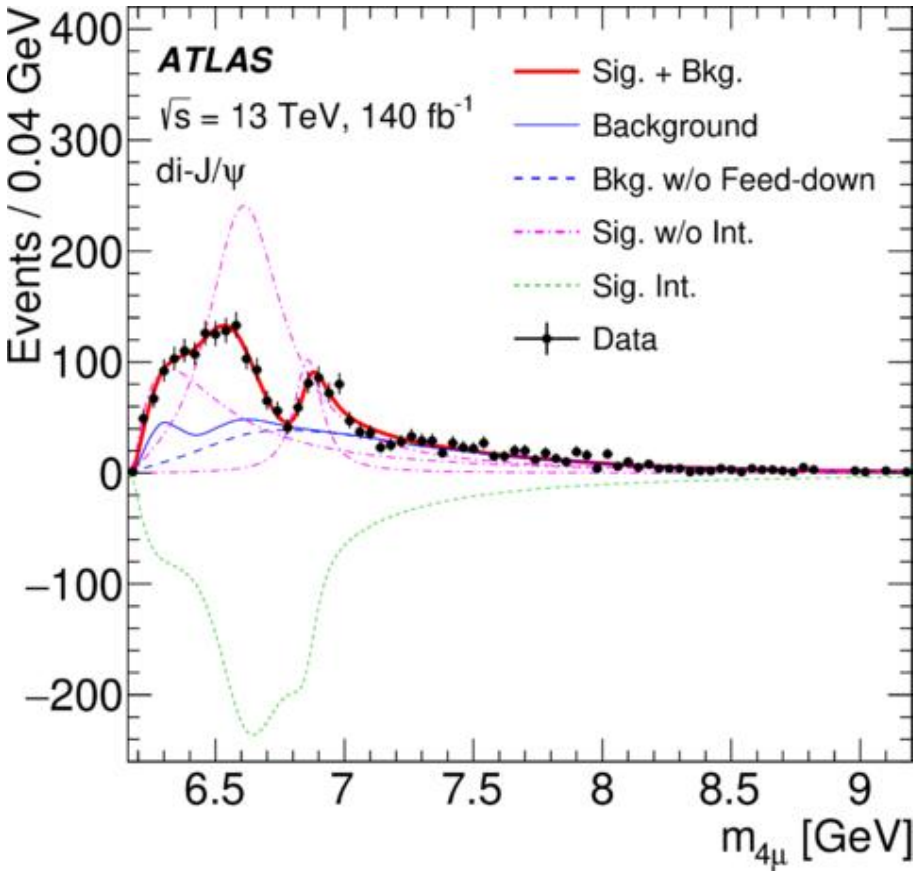




Confidence of MC background modelling is visible in the different regions,

Apart from the sought for region of X to be fitted into signal models

Hunt for di-J/psi resonances



In general, it is evident that a narrow peak at 6.9 GeV with a broad structure below is observed, which might be a combination of multiple structures

$\Rightarrow$ Echoing the observation from LHCb

$\Rightarrow$ Disclosure of the full picture needs more follow-ups

Summary

- A report of 8 TeV di-J/psi measurement was presented, with relevant discussions concerning 13 TeV efforts
- With increasing amount of data sets, and stable methodology, measurements went more and more precise => better constraining power to understand QCD models, and a variety of effects
- Comprehensive understanding of J/psi, di-J/psi encouraged a direct look into more rare, complex phenomena, such as tetraquark resonances => evident results were shown for 6.9 GeV
- Careful study of different effects, improvement of measurement techniques could bring these studies to a next level, stay tuned!

Thanks!