Quarkonium physics at the LHC

(with a slight bias towards ATLAS)

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Lancaster University

Synergies between LHC and EIC in Quarkonium physics
ECT* Trento 8 July 2024

Outline

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- **Production**
- **Spectroscopy**
- **Polarisation**
- **New observables / Onia as a tool**

Apology:

- **Huge amount of data from various experiments**
- **Despite my best efforts, not everything got covered in this talk**

PRODUCTION

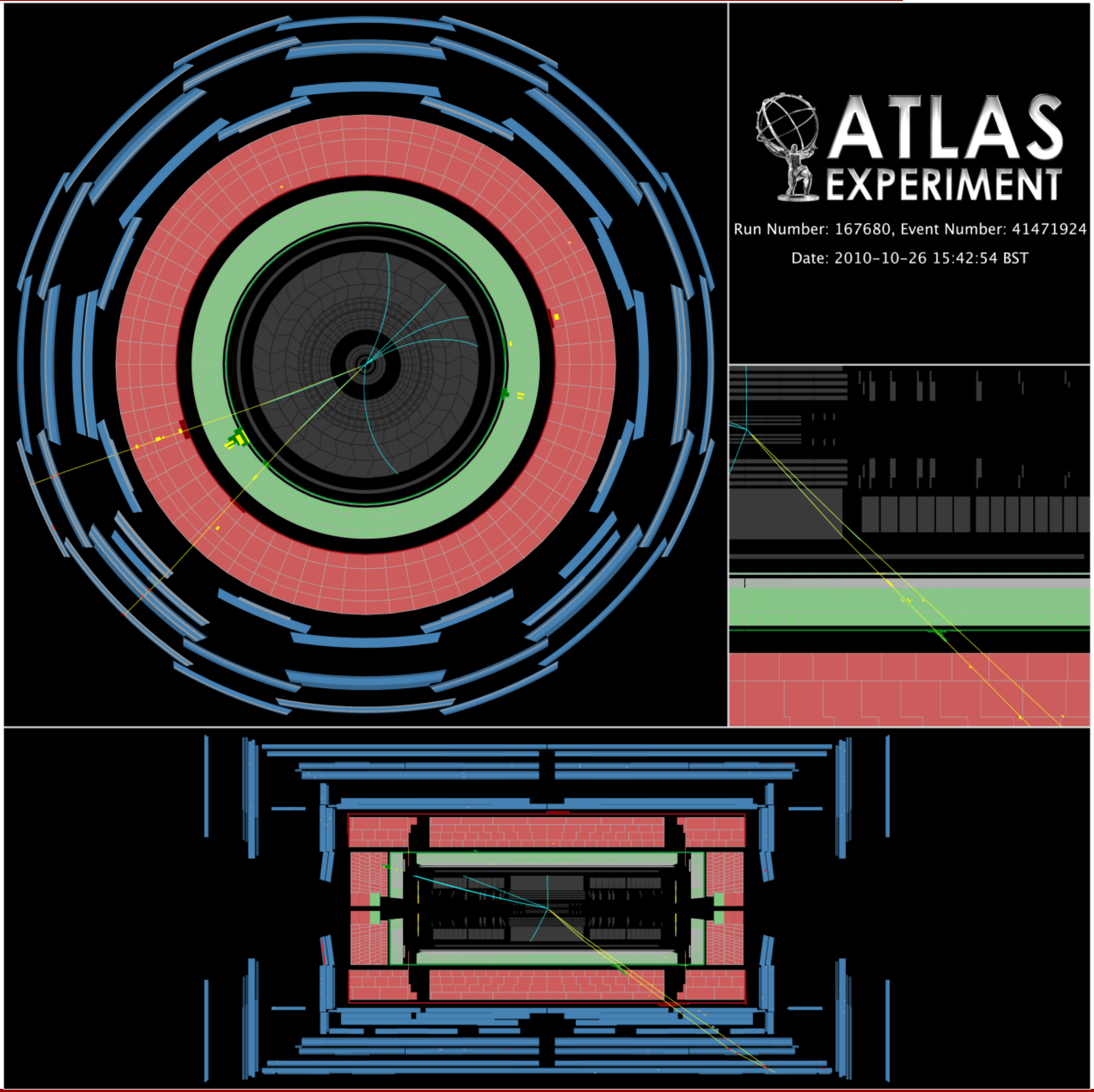
ATLAS event display:
$\chi_c \to J/\psi(\mu^+\mu^-)\,\gamma$

Cross section views perpendicular and parallel to the beam line

Two muon tracks spanning the Inner Detector and the Muon System

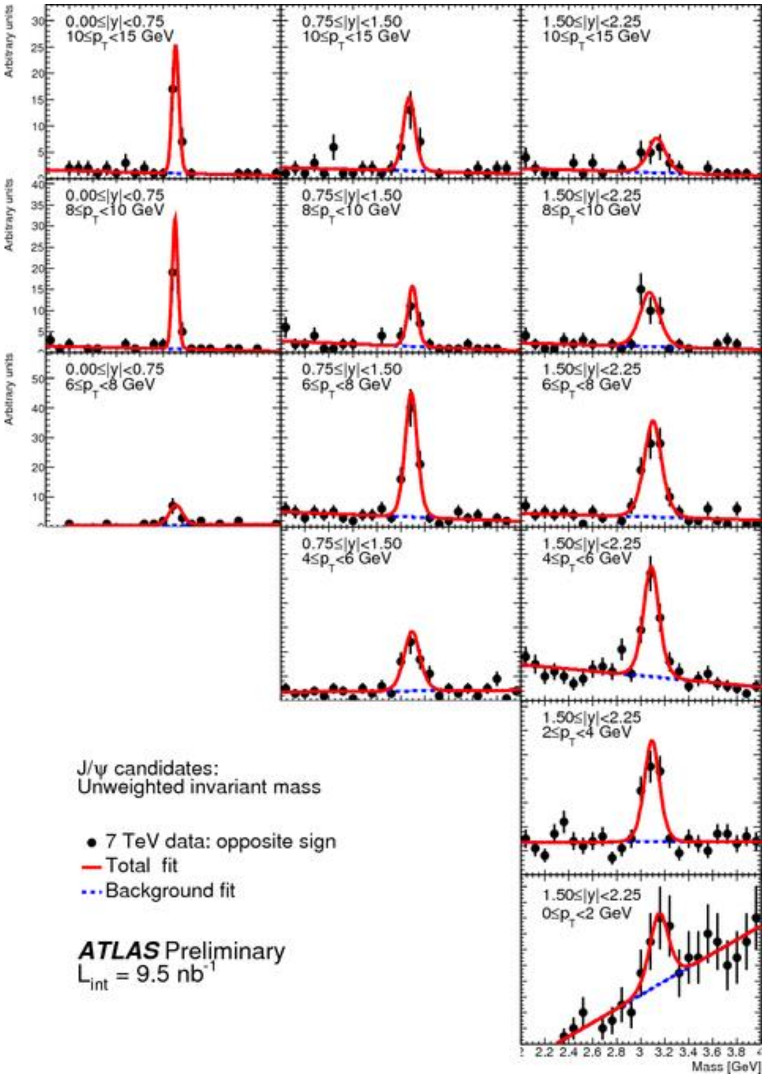
A photon tower in Eclectromagnetic Calorimeter

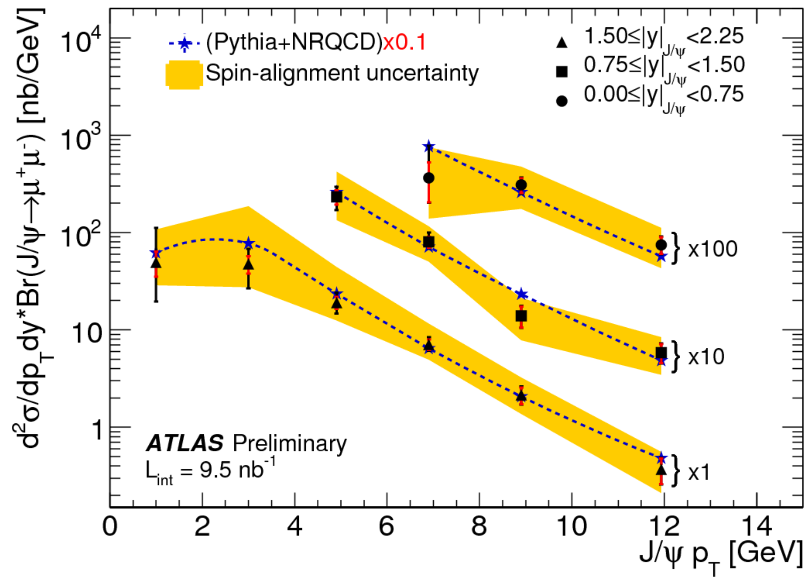
Invariant mass in the χ_c region

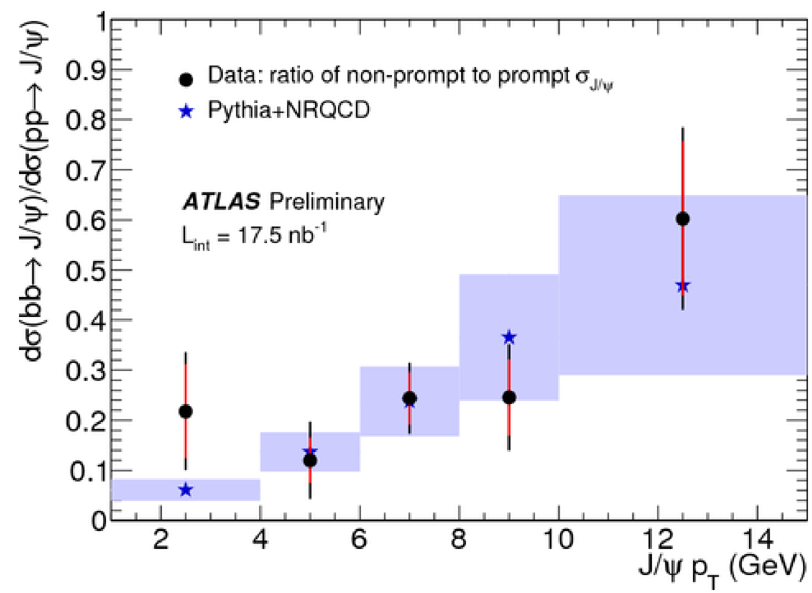


Early days: ATLAS, 7 TeV, 9.5/nb

ATLAS-CONF-2010-062

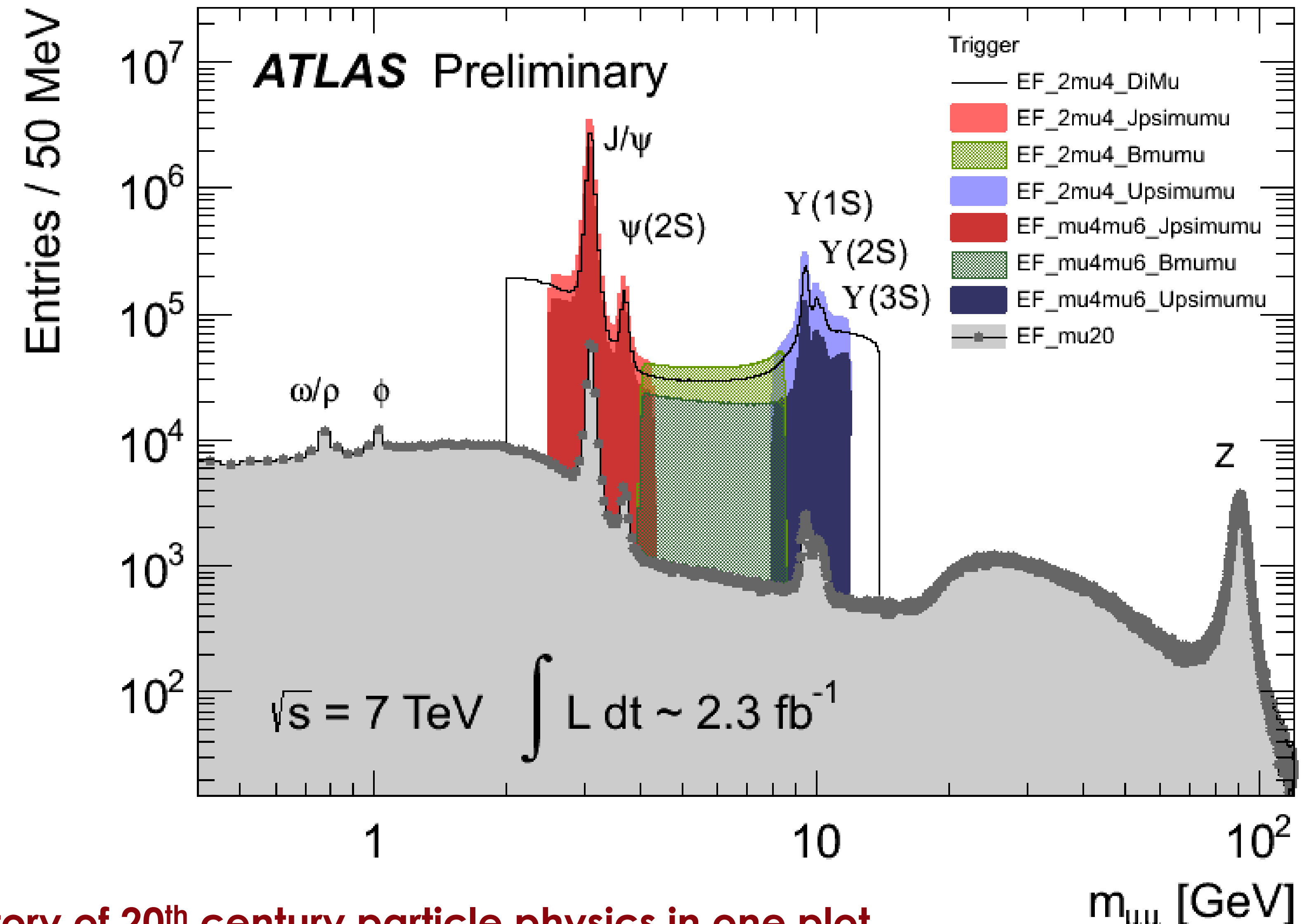






2010 MinBias + L1 single-muon triggers

Muon and dimuon triggers in ATLAS



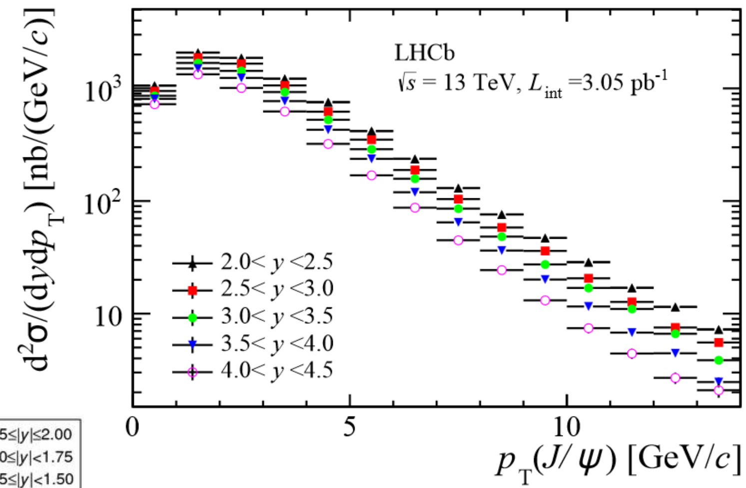
History of 20th century particle physics in one plot

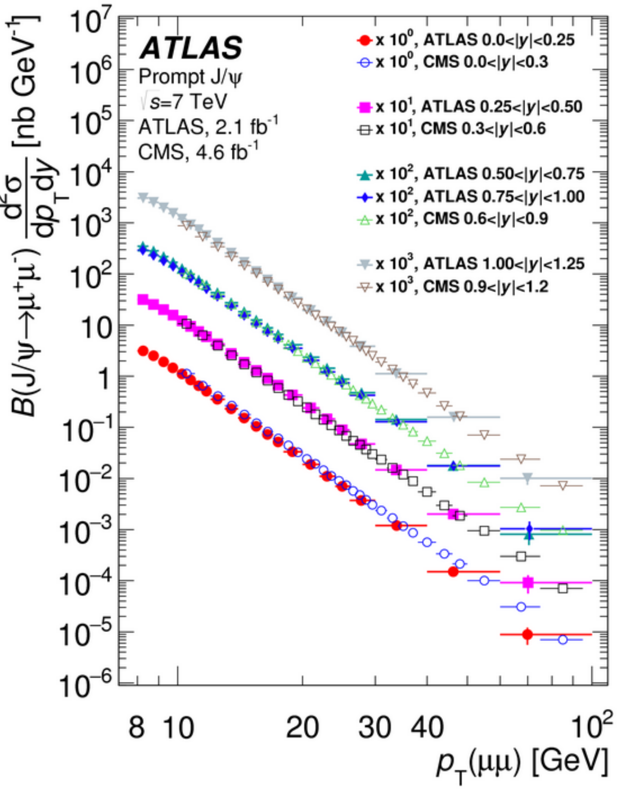
Prompt J/ψ production: LHC 7 TeV

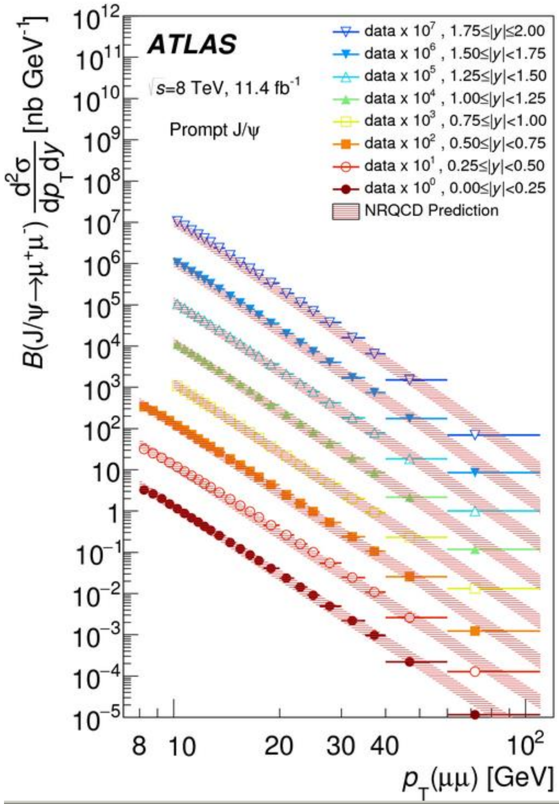
Detailed distributions in a number of bins in pT and rapidity

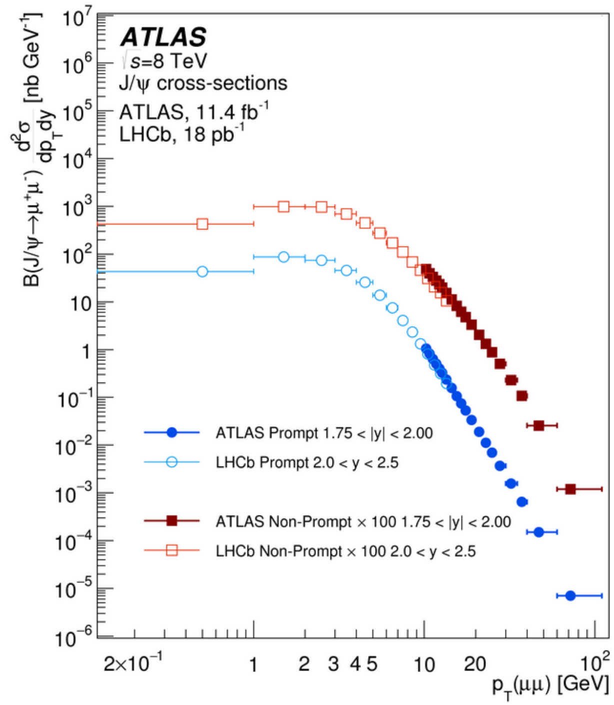
Low pT inaccessible for ATLAS, CMS at high energy / luminosity

Good consistency between ATLAS, CMS and LHCb where overlap

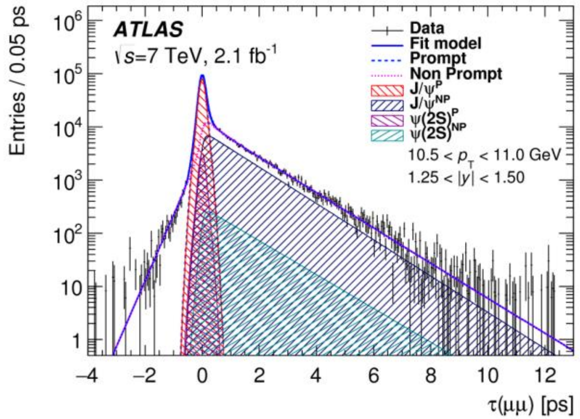


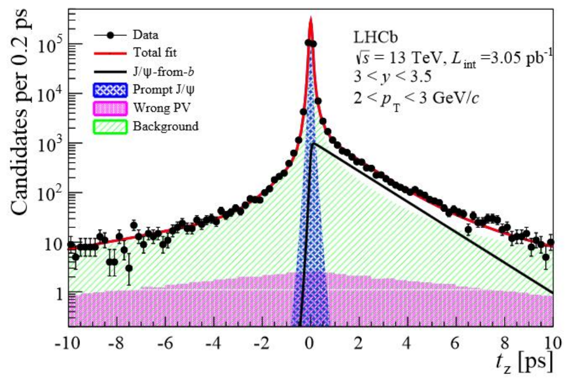


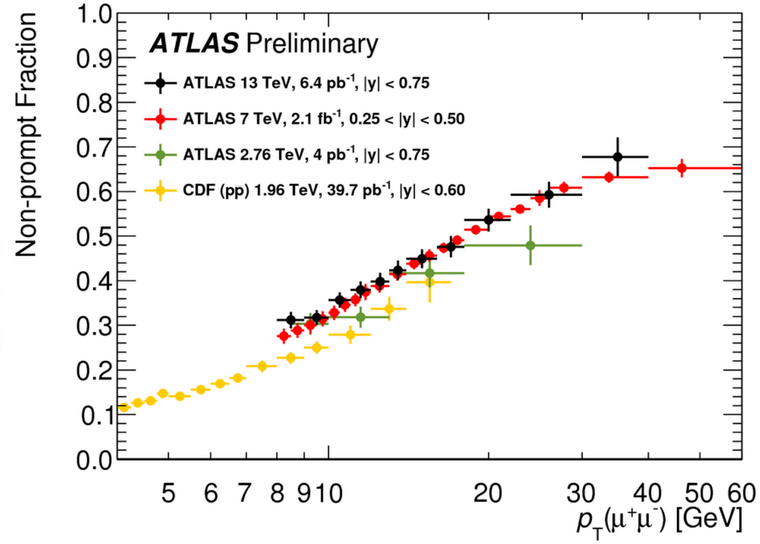




Prompt-nonprompt separation & NP fraction





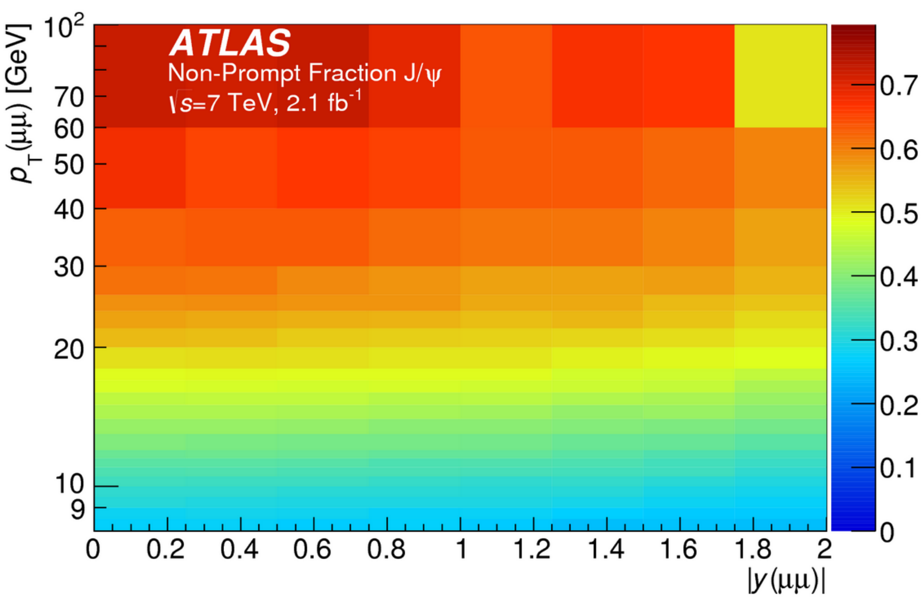


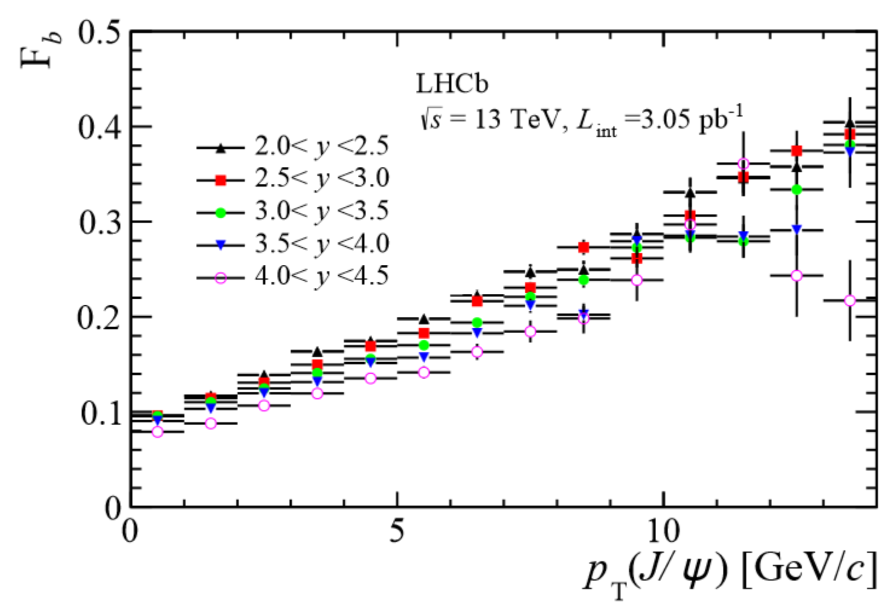
Strong pT dependence

No dramatic evolution with energy

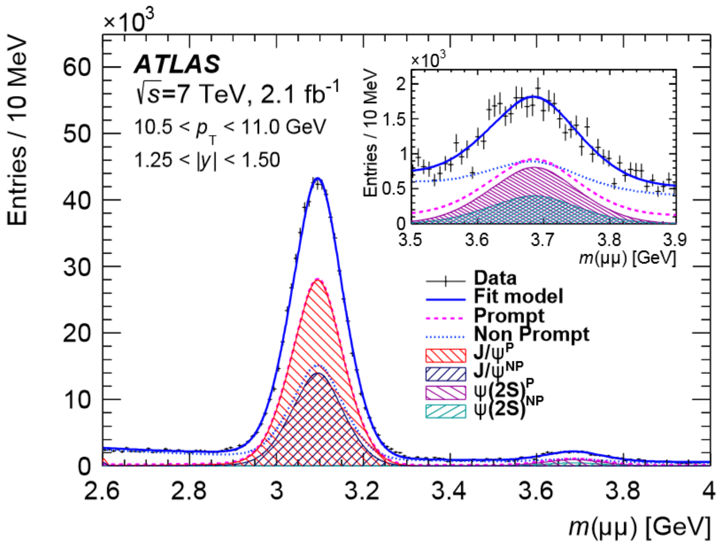
Some dependence on rapidity forward

$$l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T}$$





ψ(2S) production in dimuon decay mode



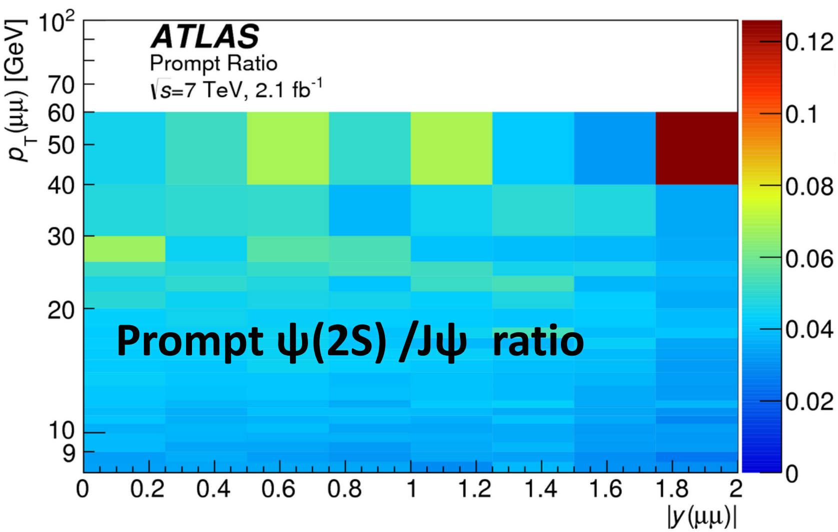
ψ(2S) more challenging: lower stats, higher background

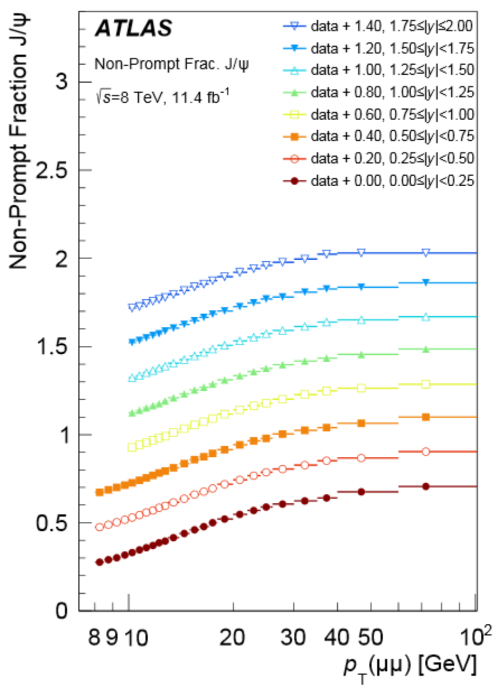
Production mechanism should be theoretically cleaner

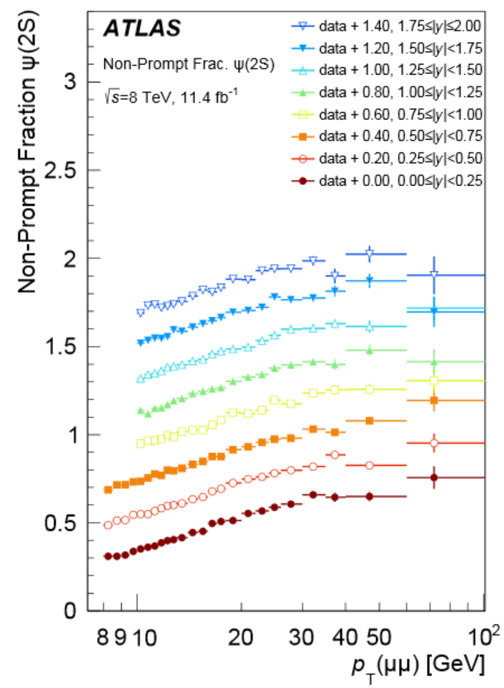
Curiously, non-prompt fraction very similar to J/ψ

Prompt ψ(2S) /Jψ ratio close to constant

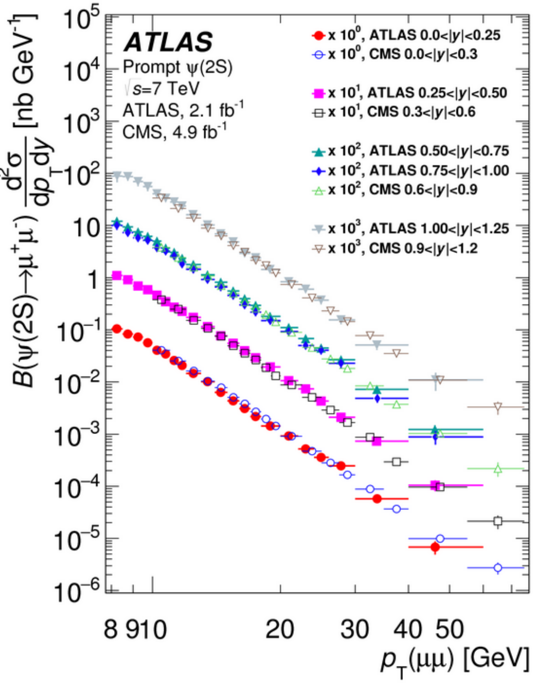
Can these facts be understood within our current picture?







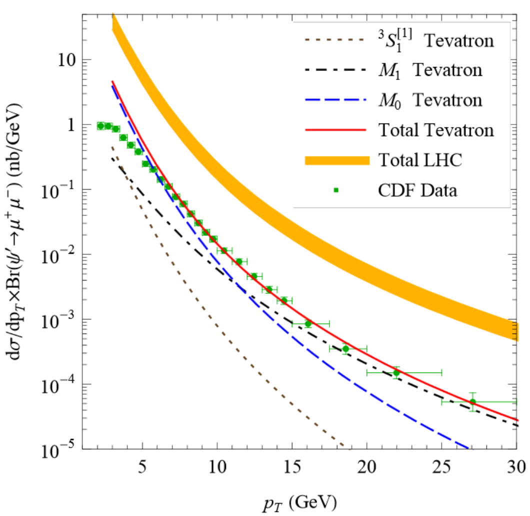
Prompt ψ(2S) production

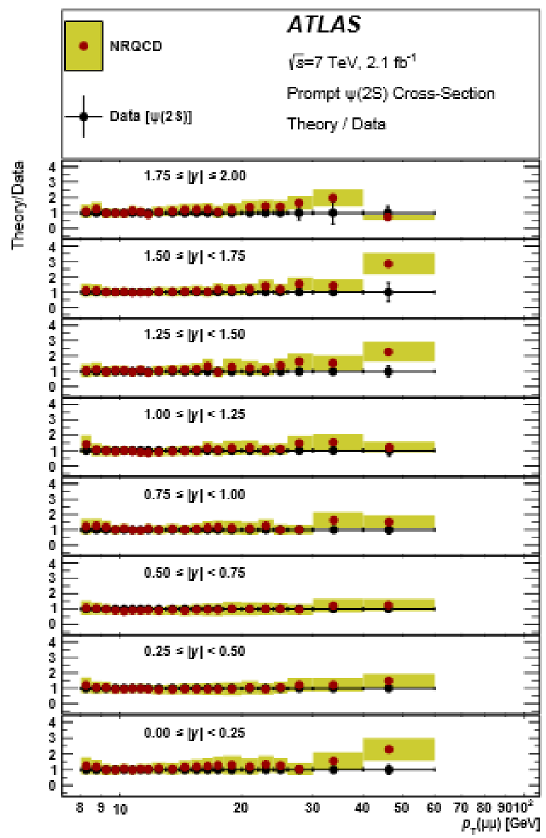


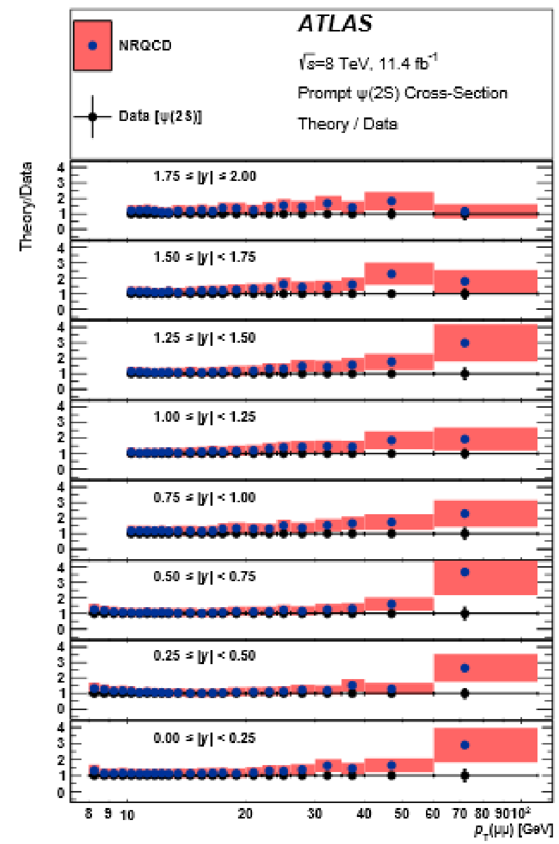
Again, ATLAS and CMS consistent

Could be used to extract some LDMEs (Ma,Wang,Chao,arXiv:1009.3655)

LDMEs from Tevatron fits in decent agreement with LHC data (maybe peeling slightly high at highest pT?)







$\chi_c \rightarrow J/\psi(\rightarrow\mu\mu)\gamma$

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P-wave charmonium production theoretically and experimentally tricky to handle

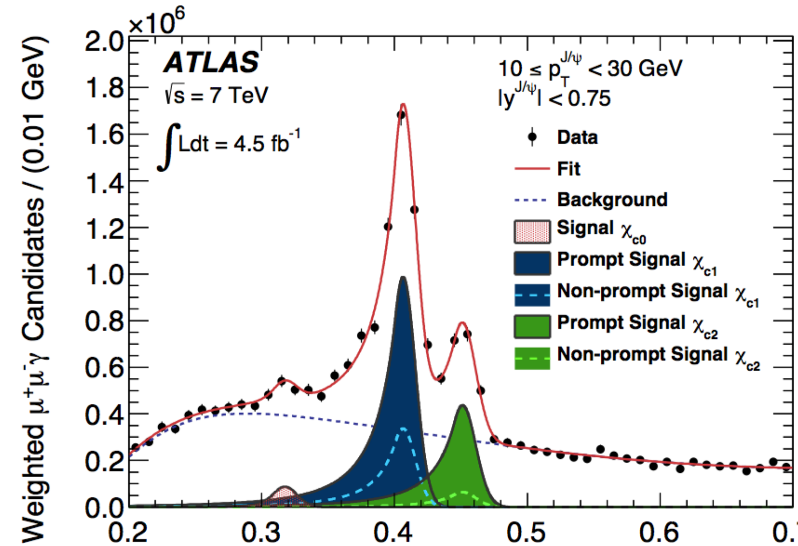
Important to understand this production channel to get a complete picture of quarkonium production.

Experimentally challenging:

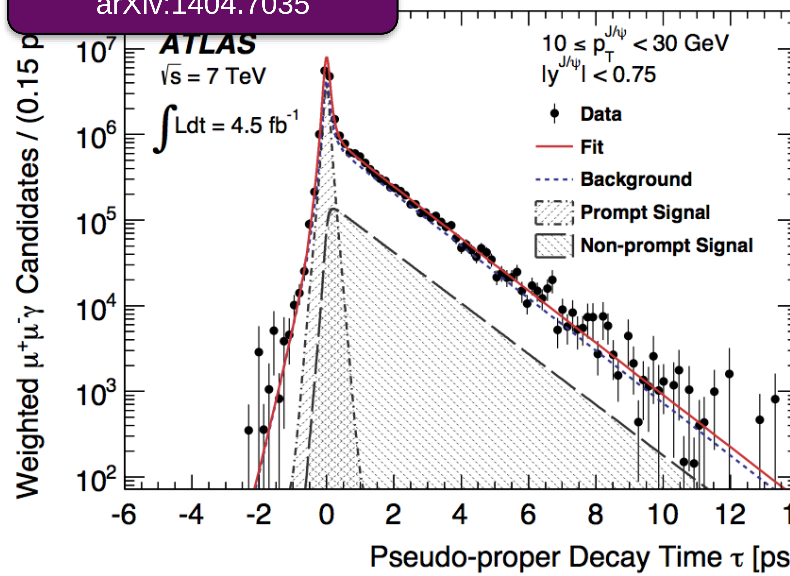
- low p_T muons
- precise reconstruction of soft (p_T>1 GeV) photon through conversions
  – low efficiencies

Perform unbinned maximum likelihood fit on acceptance- and efficiency-corrected mass and lifetime.

Extract prompt and non-prompt production cross section of various χ_c states



Published in JHEP
arXiv:1404.7035



Prompt $\chi_c \rightarrow J/\psi\gamma$ and $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio

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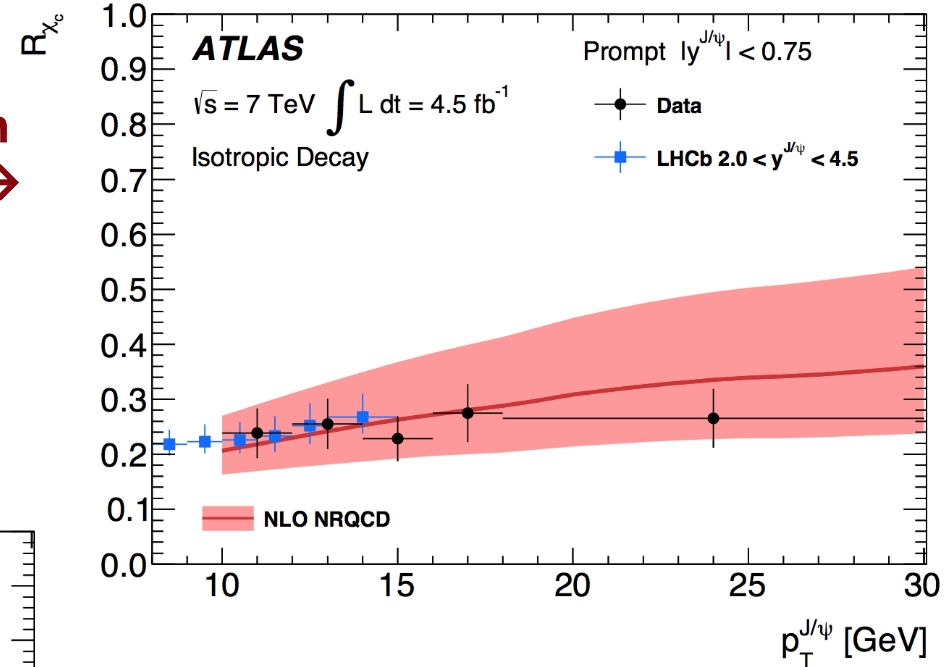
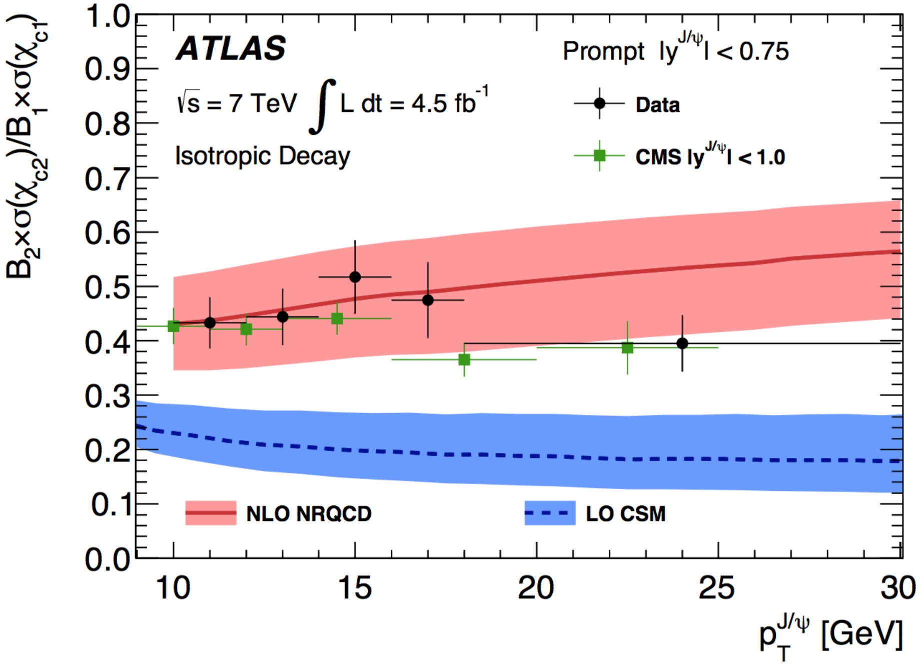
Fraction of prompt J/ψ produced in χ_c feed-down (right)→

Data show that between 20–30% of prompt J/ψ are produced in χ_c decays





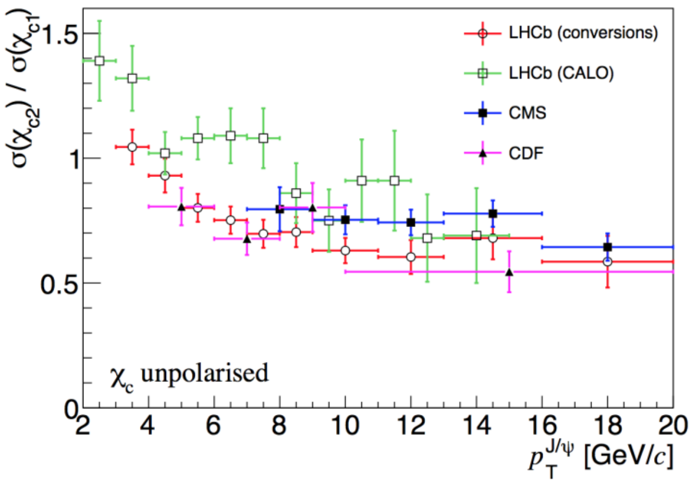
Prompt χ_c cross-section ratio ← (left)

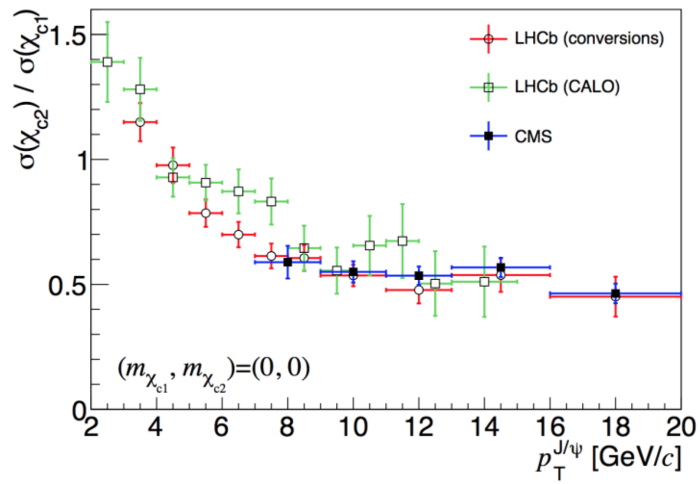
Data show more χ_{c1} than χ_{c2}

Ratio sensitive to possible presence of colour octet contributions in NRQCD

Published in JHEP
arXiv:1404.7035

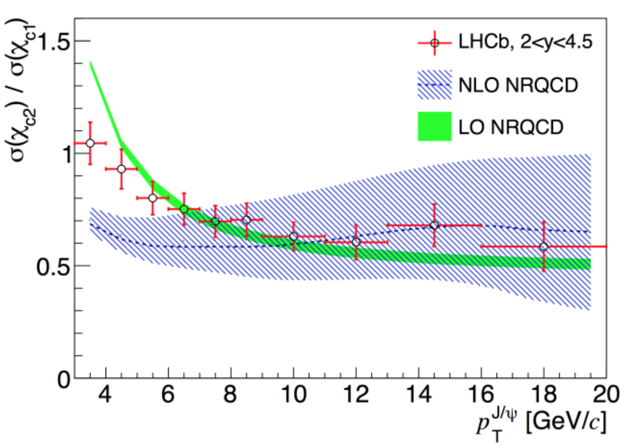
Comparison of relative χ_c rates

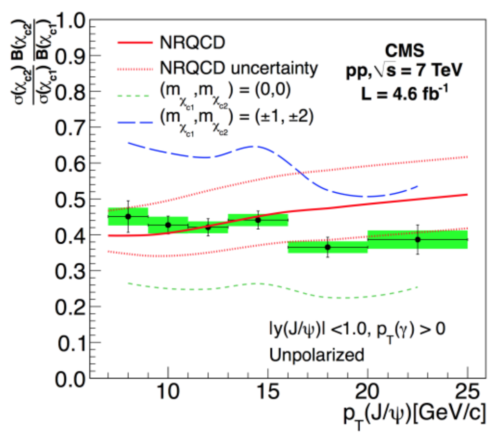


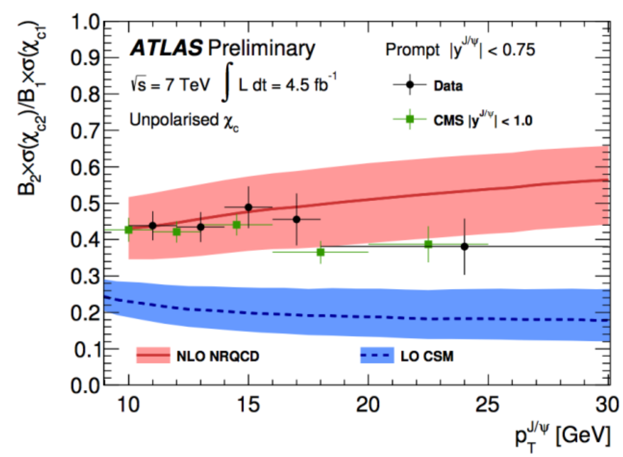


Data reasonably consistent with each other, NRQCD yields mixed results

Naively χ_{c2} should be enhanced at low p_T, as seen in LHCb data



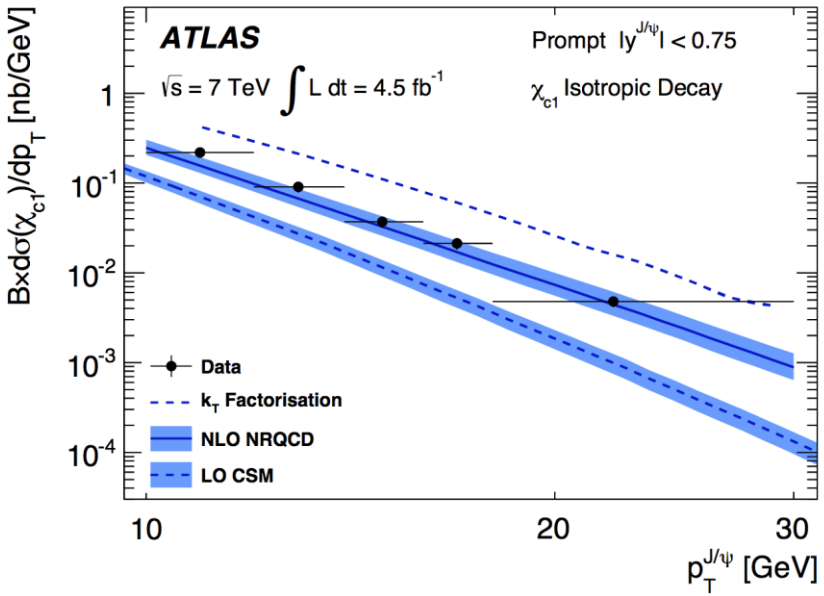


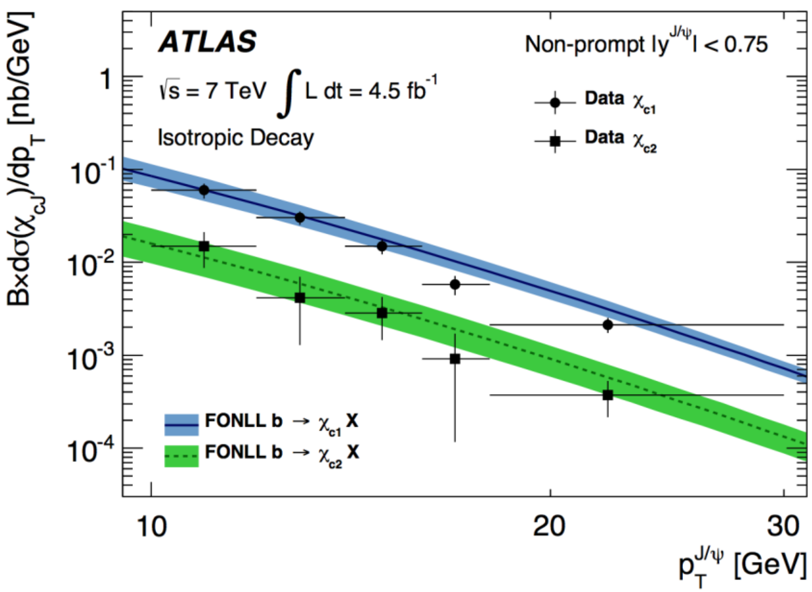


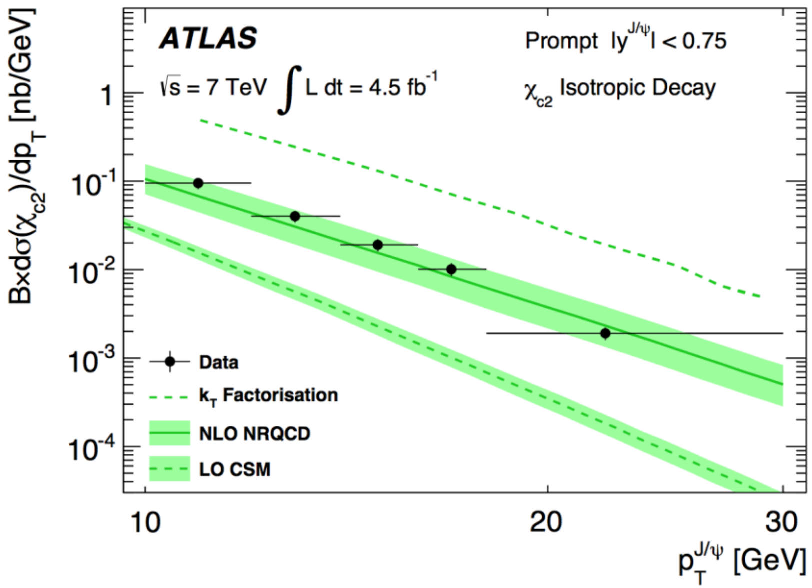
Absolute χ_c production rates

First absolute prompt (right) and non-prompt (below) χ_{c1} and χ_{c2} differential cross sections, compared to predictions

NRQCD / FONLL able to describe the data, but some hints at high-p_T excess in the latter?







Pseudoscalar quarkonium production at LHCb

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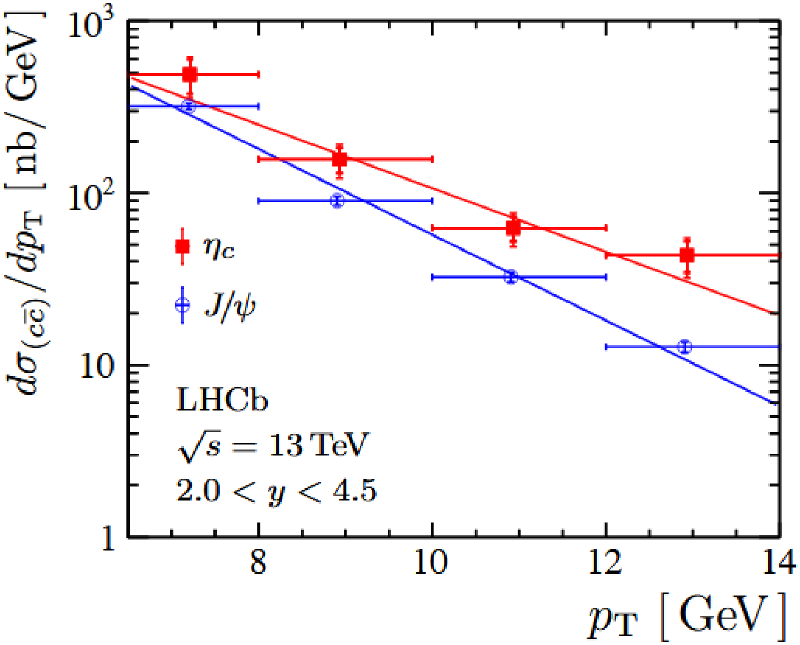
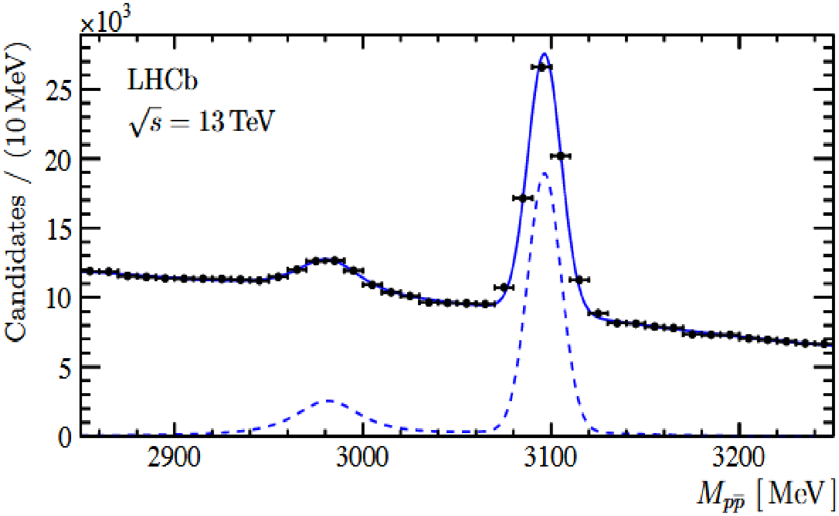
- **Two-gluon fusion into pseudoscalar quarkonium is also a viable process!**

LHCb collaboration, arXiv:1911.03326

- **J/ψ and η_c production was measured at 13 TeV *in proton-antiproton decay mode***
- **Separated into prompt production and from B decays**
- **Even measured the mass difference to be 113.0+/-0.3 +/- 0.1 MeV**
- **J/ψ seems softer than η_c – does this make sense?**





Results from LHC on Upsilon production, 7-8 TeV

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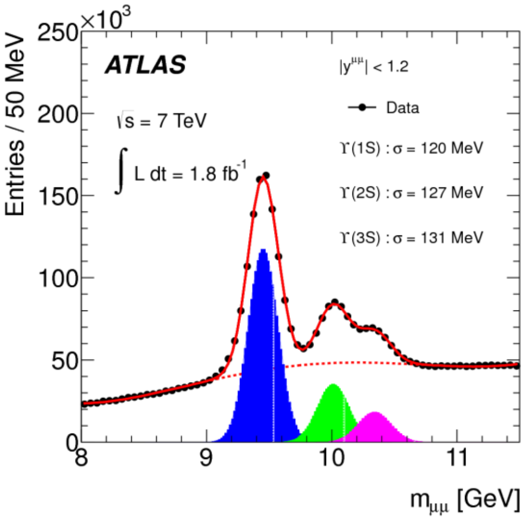
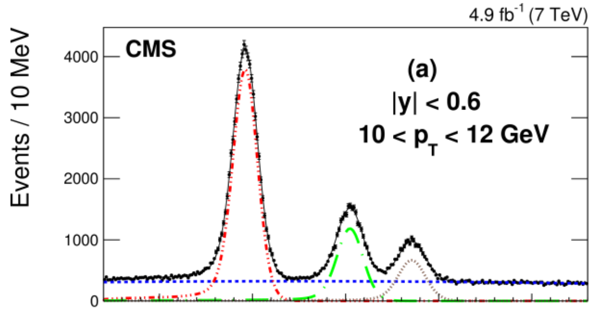
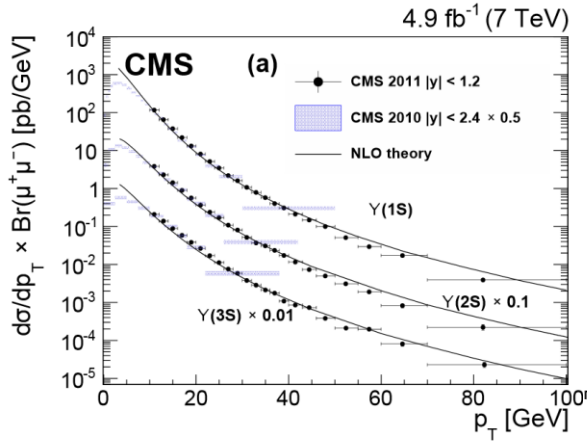
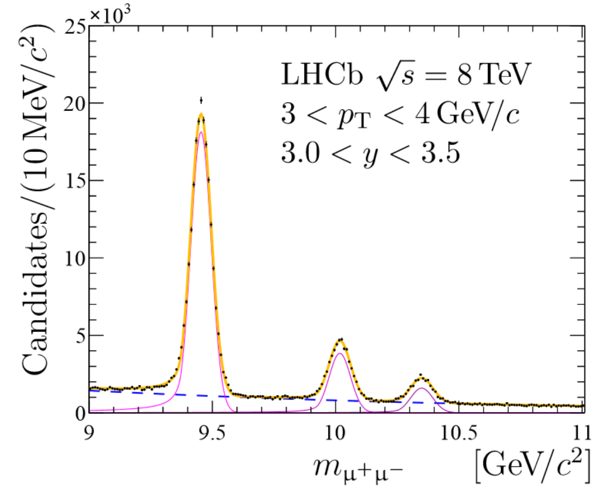


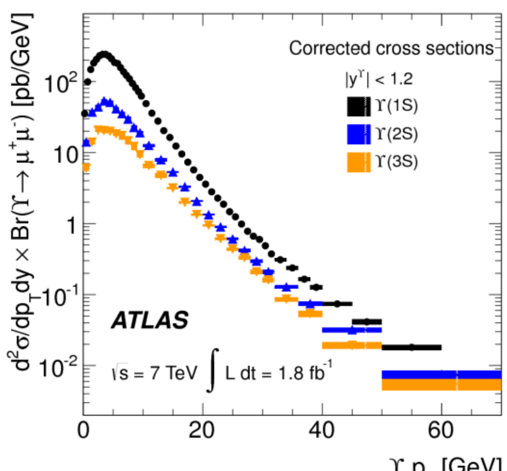


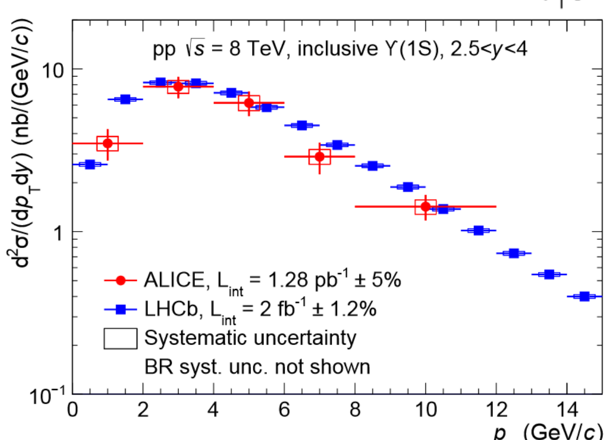
Good mass resolution allows for better separation between the Upsilon states

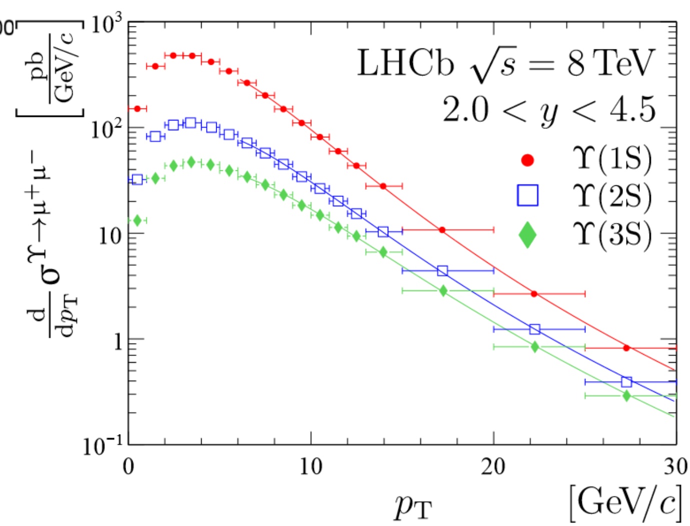




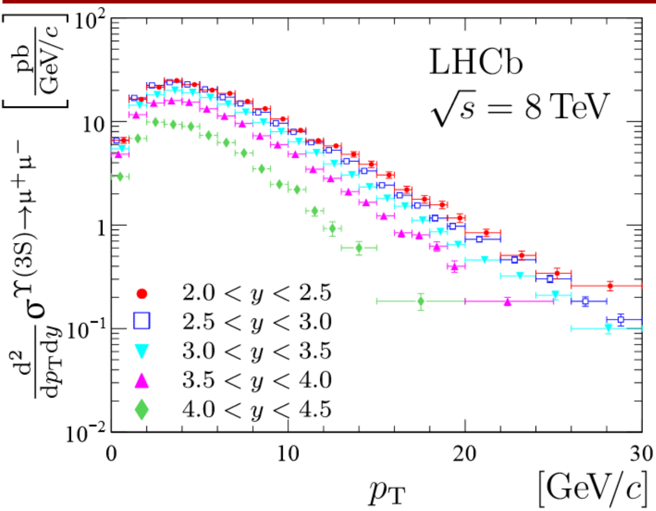
Very detailed data on production of all three ϒ states is available from all LHC collaborations





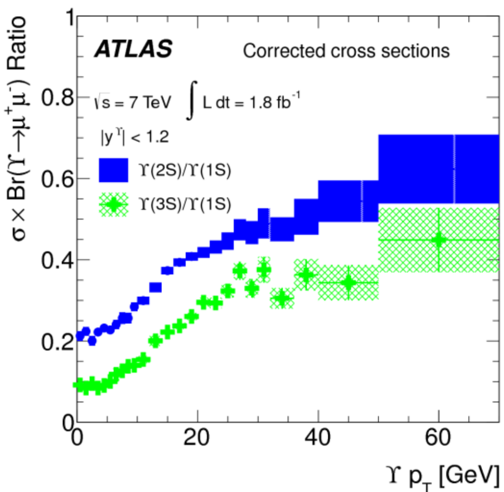


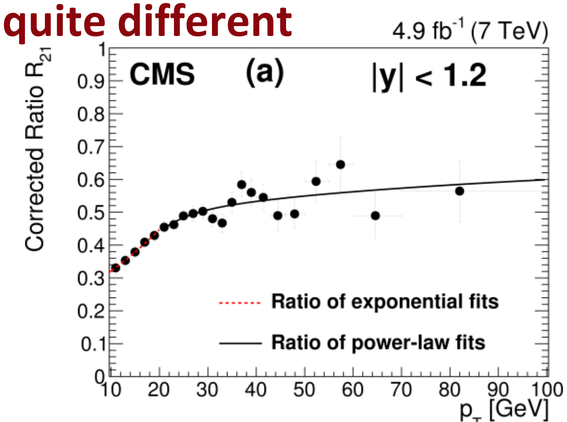
Ratios

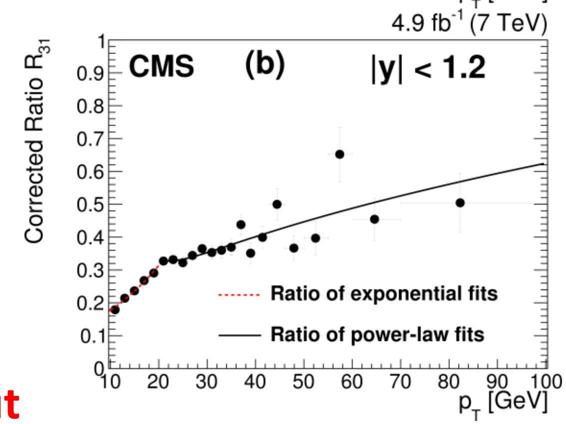


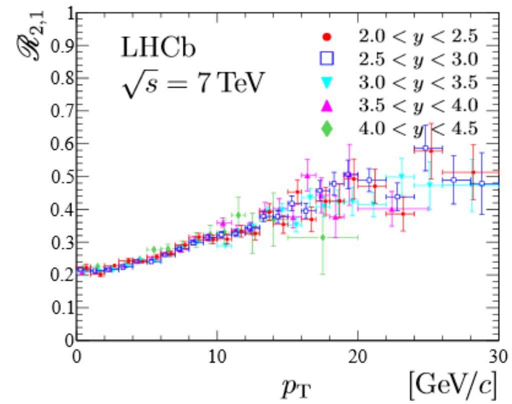
Ratios ϒ(3S)/ϒ(1S) and ϒ(2S)/ϒ(1S) show strong dependence on pT, hinting on a superposition of several mechanisms

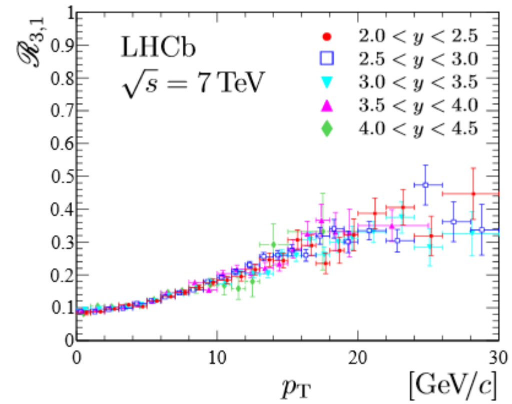
But no dependence on y, even at high y where pT spectra are quite different











LHCb (EPJ C74 (2014) 3092):

feed-down from C-even states is about 50% for all three ϒ(nS) states

There is no "clean" state here like ψ(2S)

Can these experimental facts be reconciled within our current picture of production?

CMS: Quarkonium production at 13 TeV

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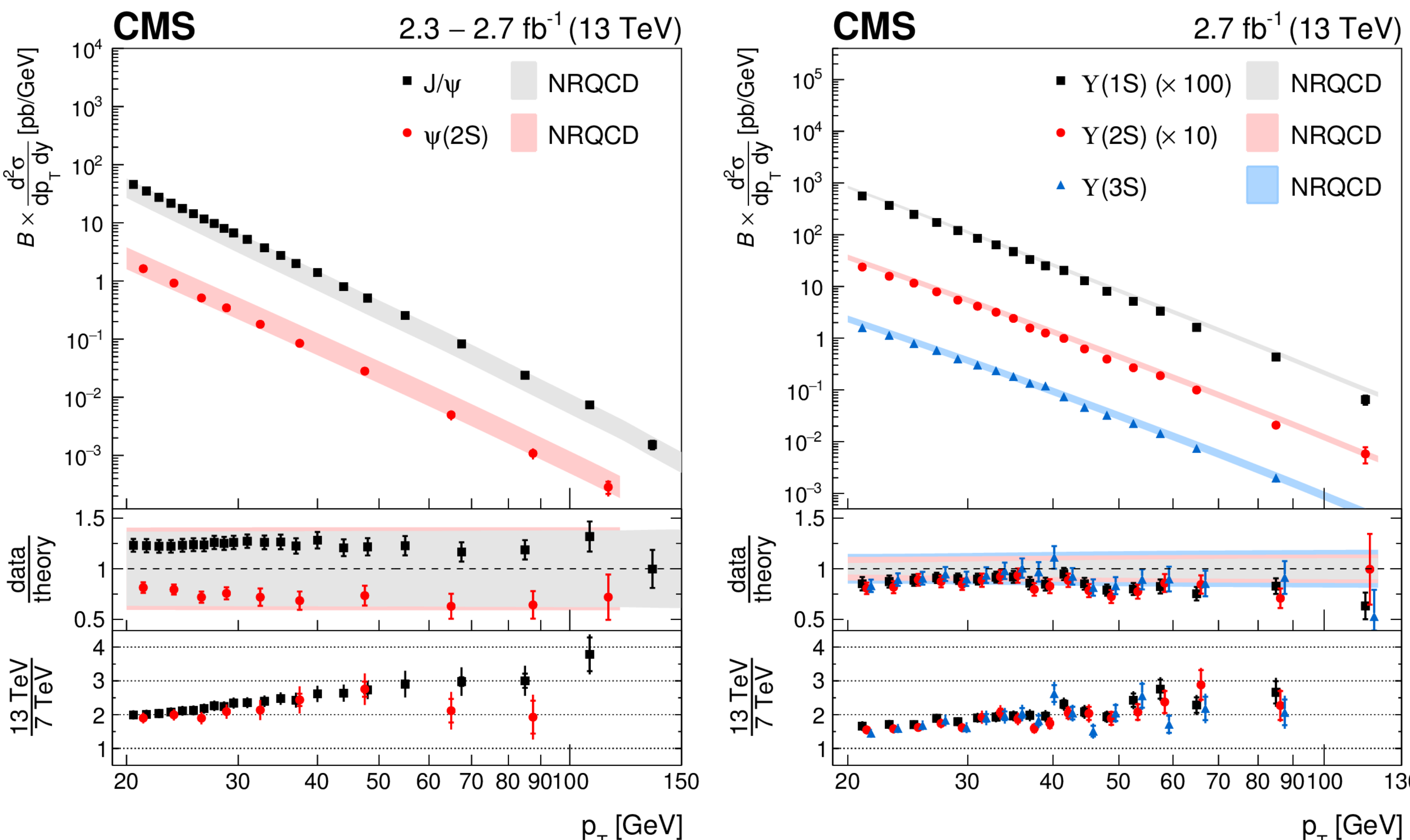


arXiv:1710.11002

ATLAS latest: charmonium at 13 TeV

arXiv:2309:17177 **EPJC 84 (2024) 169**

2D unbinned maximum likelihood fit is done to obtain raw yields - $N_{\psi}^{P,NP}$

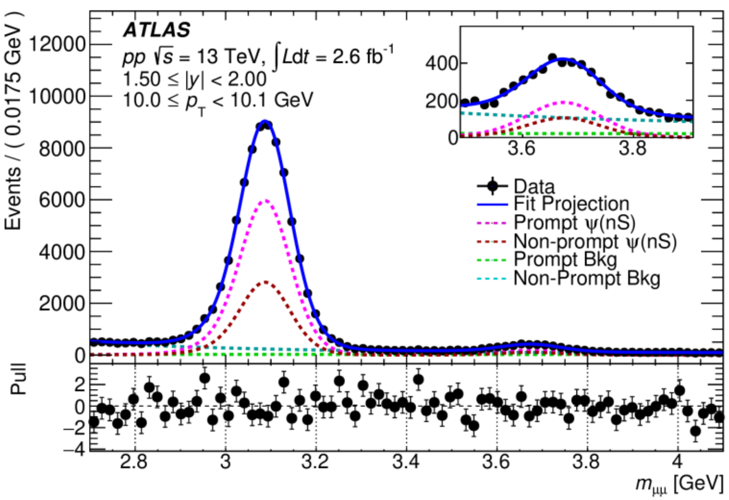
$$PDF(m,\tau) = \sum_{i=1}^{7} \kappa_i f_i(m) \cdot (h_i(\tau) \otimes R(\tau)) \cdot C_i(m,\tau).$$

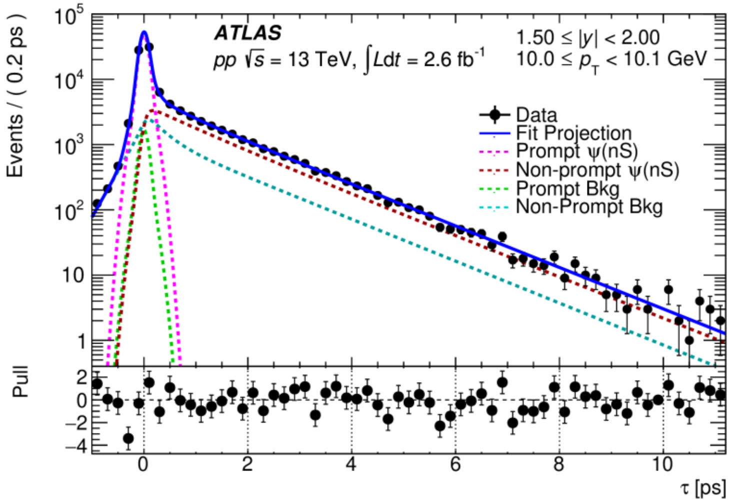
i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\delta(\tau)$
2	J/ψ	NP	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\omega_2 E_1(\tau) + (1-\omega_2)E_1(b\tau)$
3	$\psi(2S)$	P	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$E_2(\tau)$
5	Bkg	P	P	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\|\tau\|)$

Prompt ψ candidates are distinguished from those originating from b-hadron decays through the separation L_{xy} of the primary vertex and the ψ decay vertex.

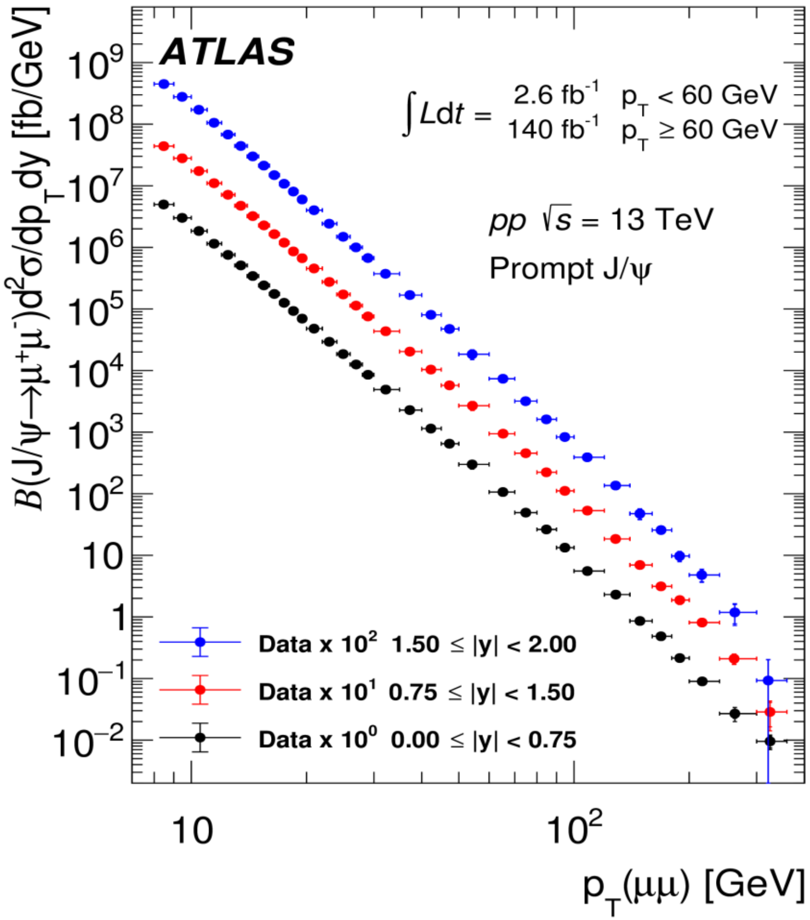
The pseudo-proper time:

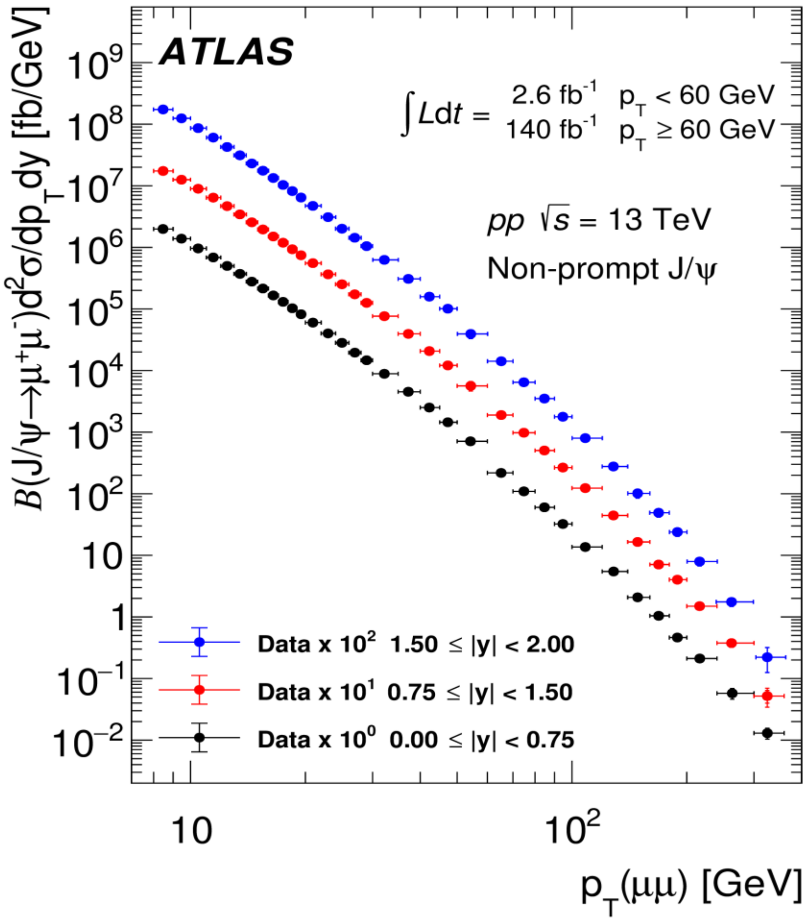
$$\tau = \frac{m_{\mu\mu}}{p_{\mathrm{T}}} \frac{L_{xy}}{c}$$





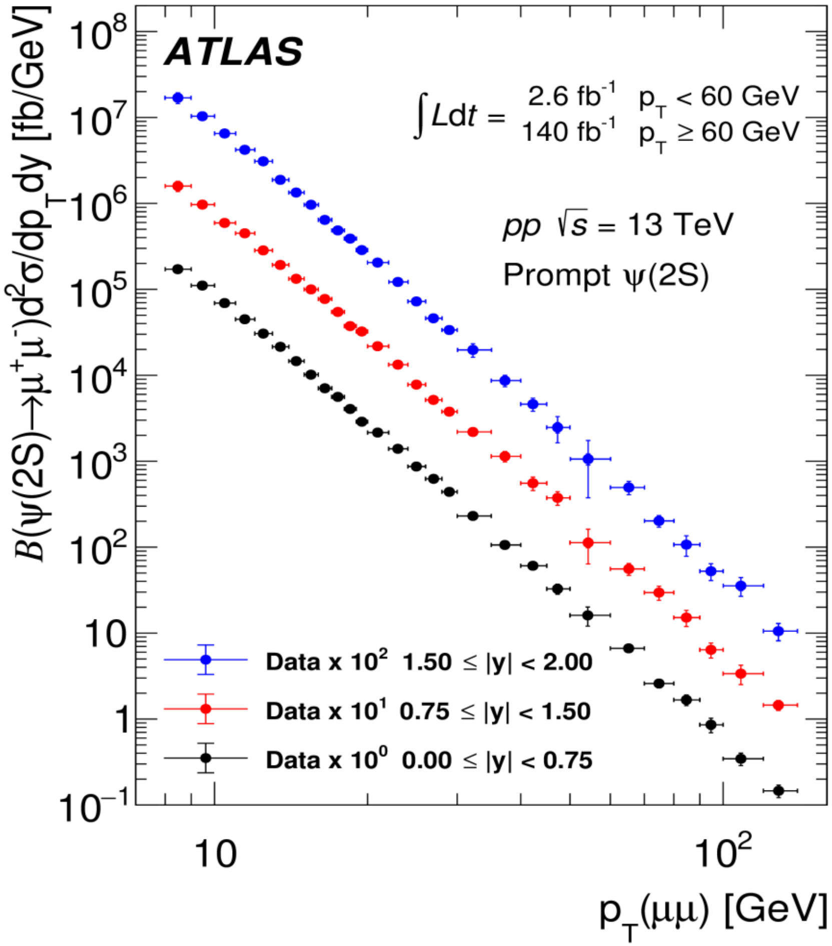
Results: 1 - J/ψ differential cross sections

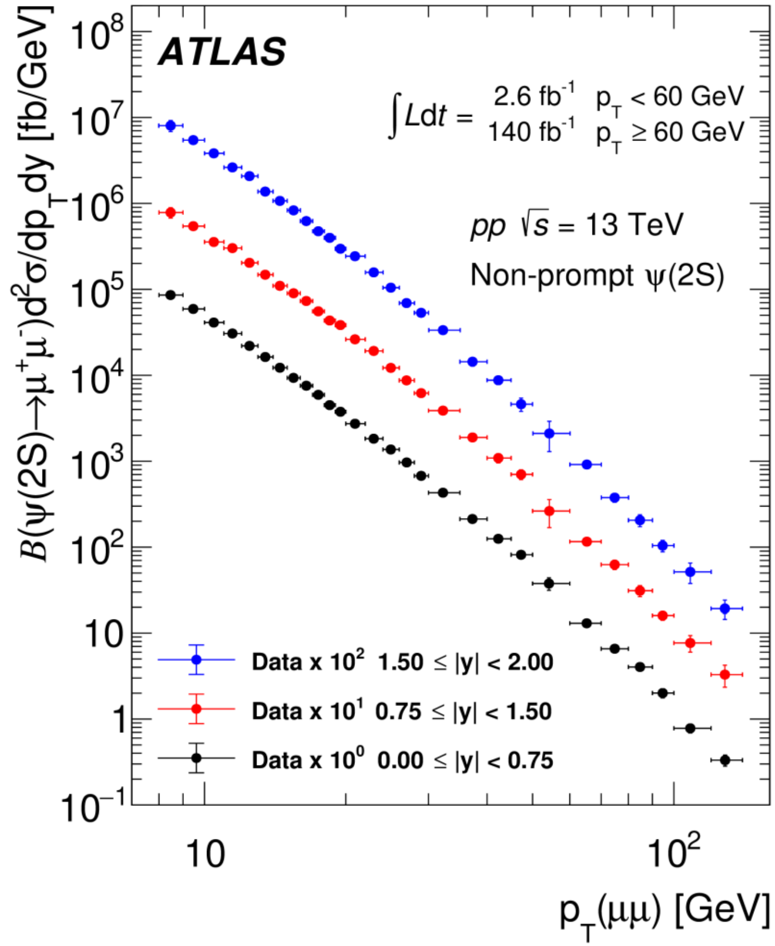




- **Three rapidity ranges shifted for visual clarity**
- **Widest pT range achieved so far: 8 GeV to 360 GeV**
- **Almost 9 orders of magnitude variation of cross section**

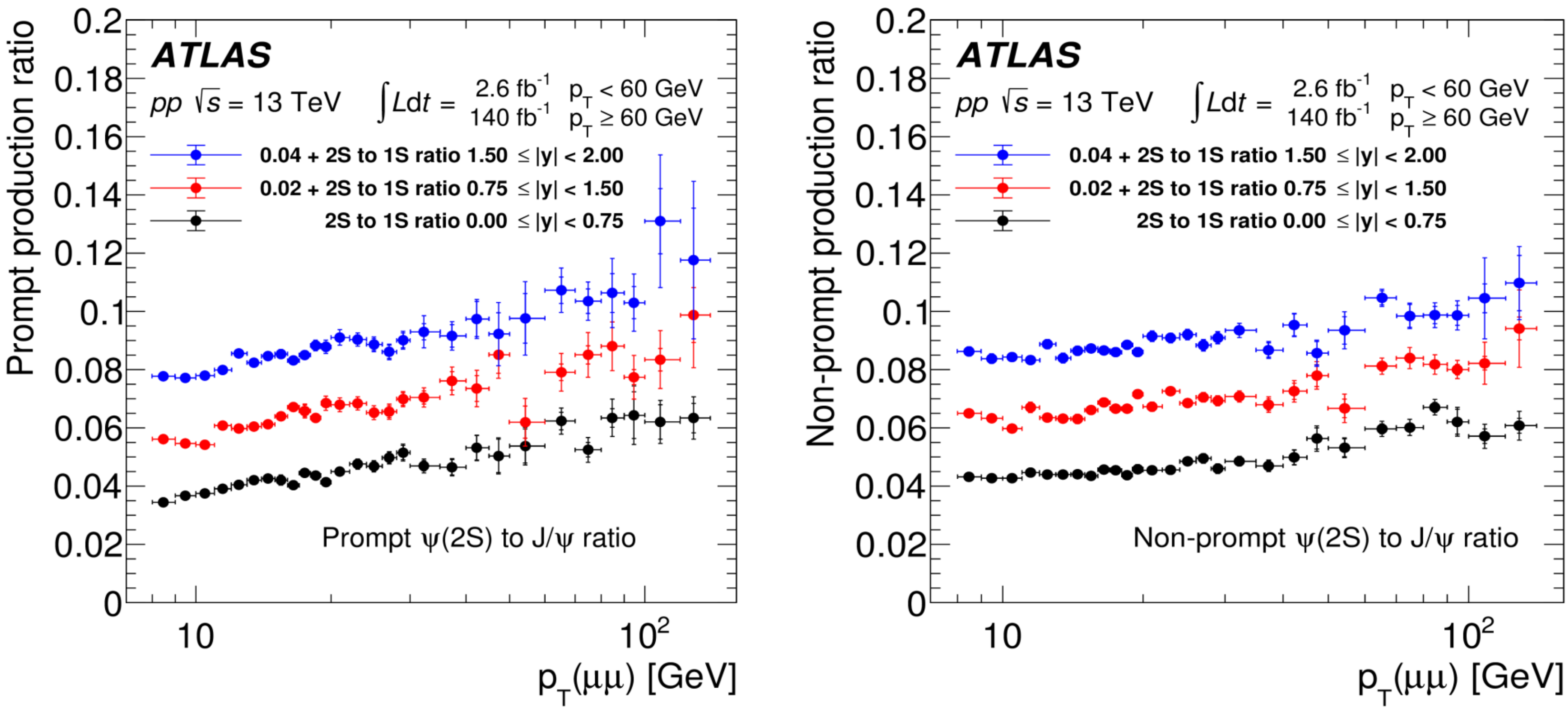
Results: 2 - ψ(2S) differential cross sections





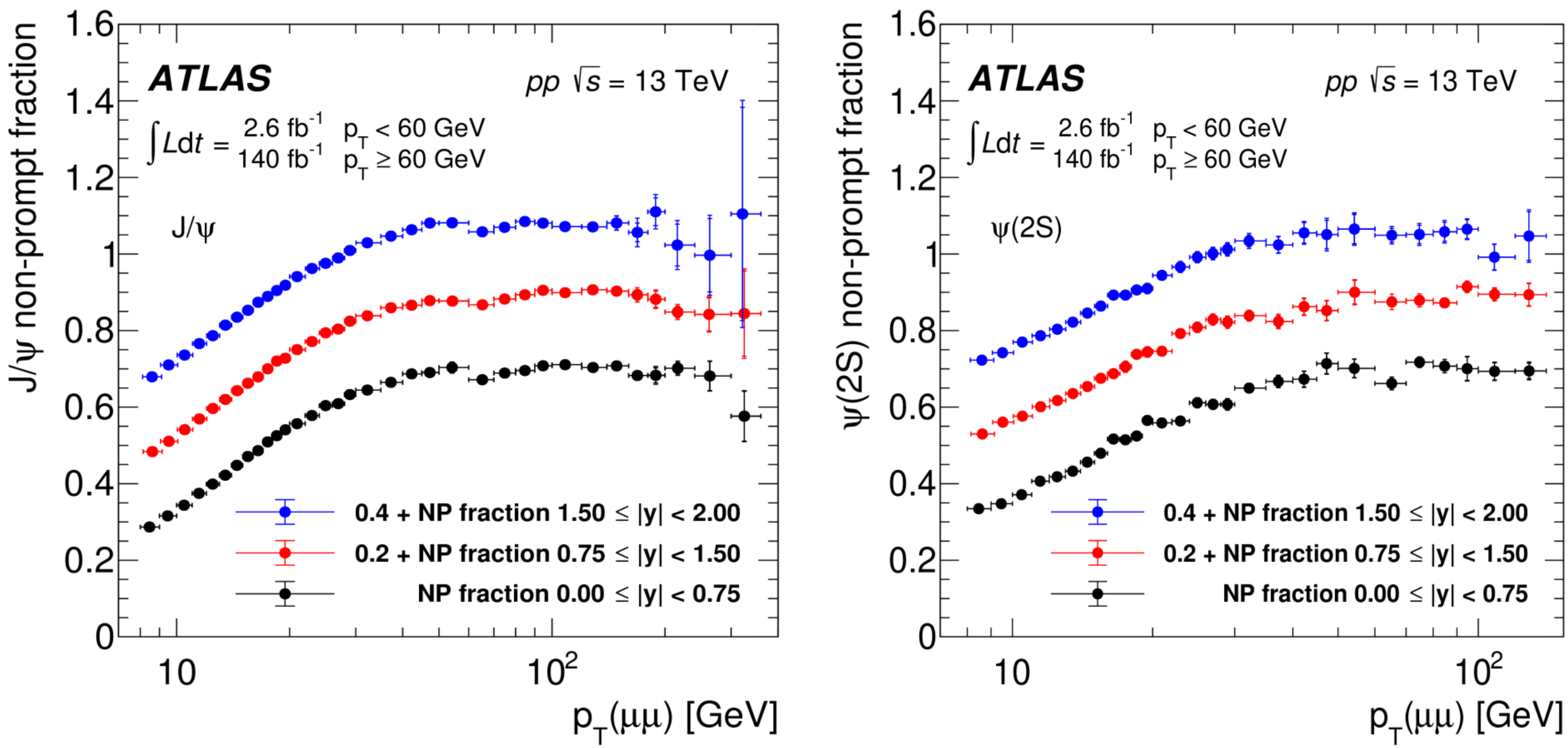
- **Three rapidity ranges shifted for visual clarity**
- **Widest pT range so far: 8 GeV to 140 GeV**
- **More than 6 orders of magnitude variation of cross section**

Results: 3 - ψ(2S)-to-J/ψ production ratios



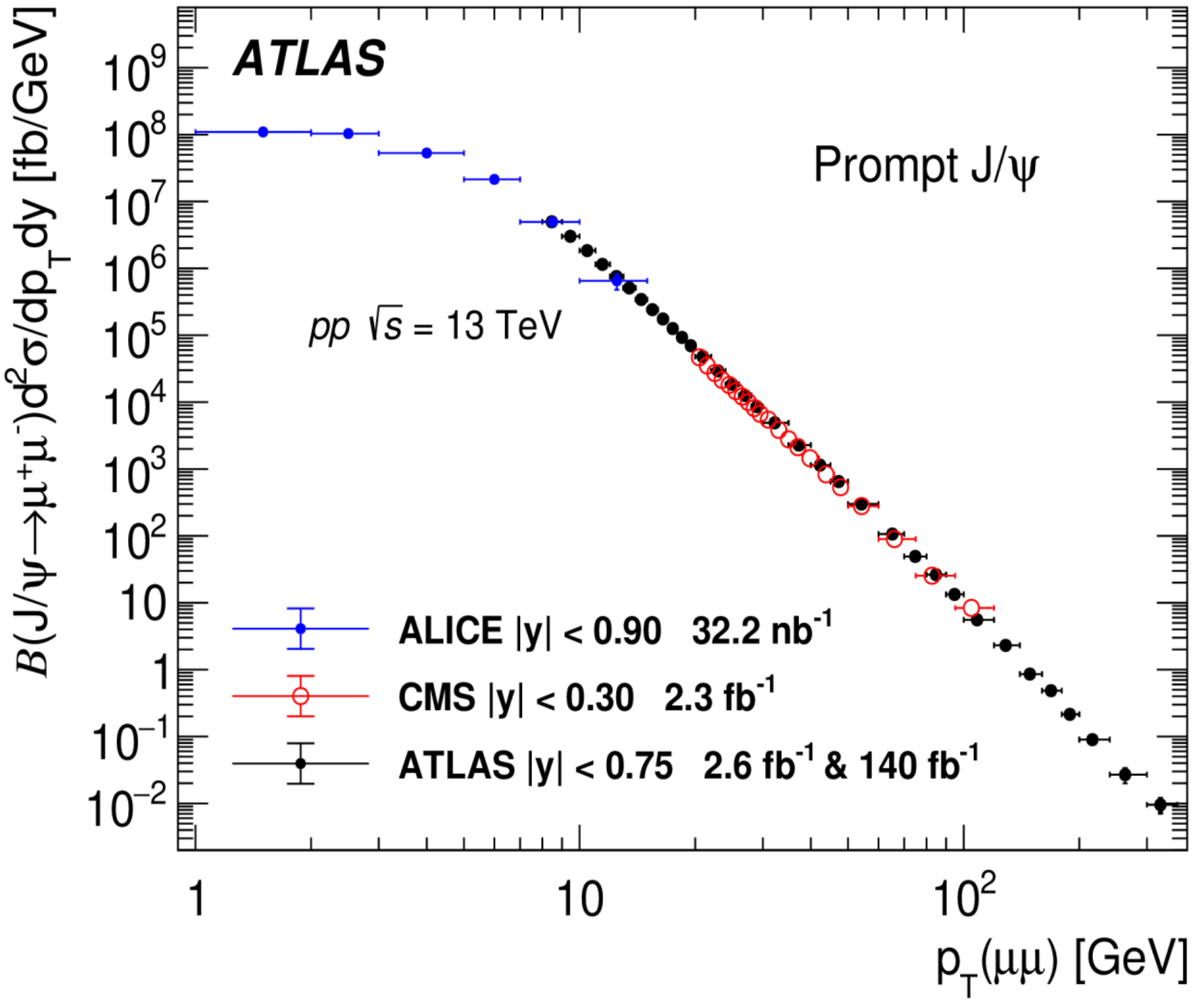
- **Three rapidity ranges shifted for visual clarity**
- **Seem independent of rapidity**
- **Prompt ratio increases faster with pT**

Results: 4 – Non-prompt fractions



- Three rapidity ranges shifted for visual clarity
- Fast increase at low pT, stabilise after 50 GeV
- Similar behaviour for J/ψ and ψ(2S)
- Step at 60 GeV (trigger change) – Spin alignment to blame?

Measurement comparison, central *y*



- ALICE [1 – 15] GeV]
  JHEP 03 (2022) 190
- CMS [20 – 120] GeV
  Phys. Lett. B 780 (2018) 251
- ATLAS [8 – 360] GeV
  arXiv:2309:17177
  EPJC 84 (2024) 169

POLARISATION

Spin alignment / polarisation of quarkonia

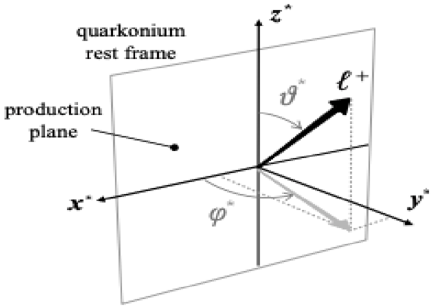


Figure from P. Faccioli

General angular dependence for ψ → mu^+mu^- decay:

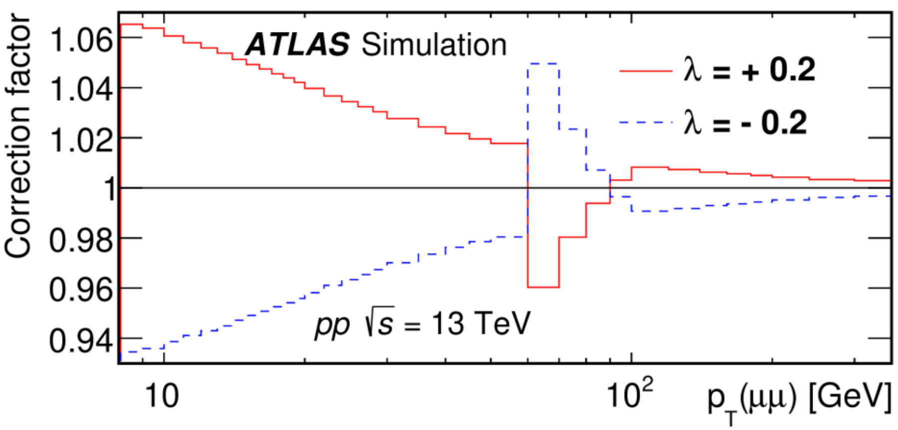
$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

Coefficients λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ are related to the spin-density matrix elements of the dimuon spin wave function for various polarisations.

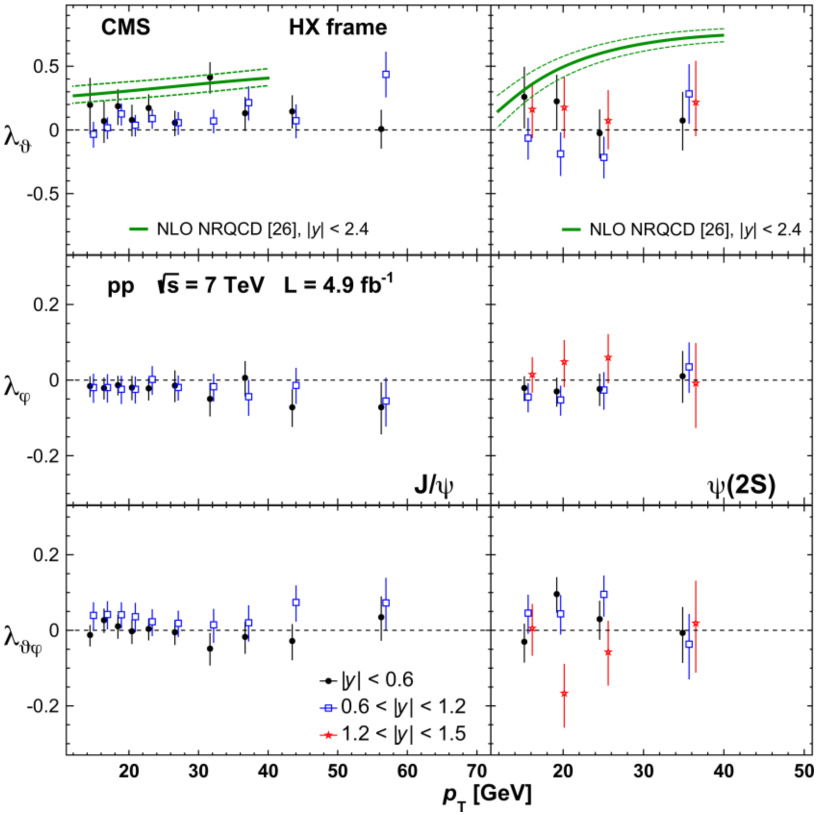
- **Dependence of acceptance on λ_ϕ and $\lambda_{\theta\phi}$ is weak, but λ_θ can be significant.**
- **Nominal analyses usually assumes "isotropic" production, all $\lambda = 0$.**
- **If quarkonia are produced polarised, need to apply correction factors!**
- **Could be different for prompt and non-prompt production**

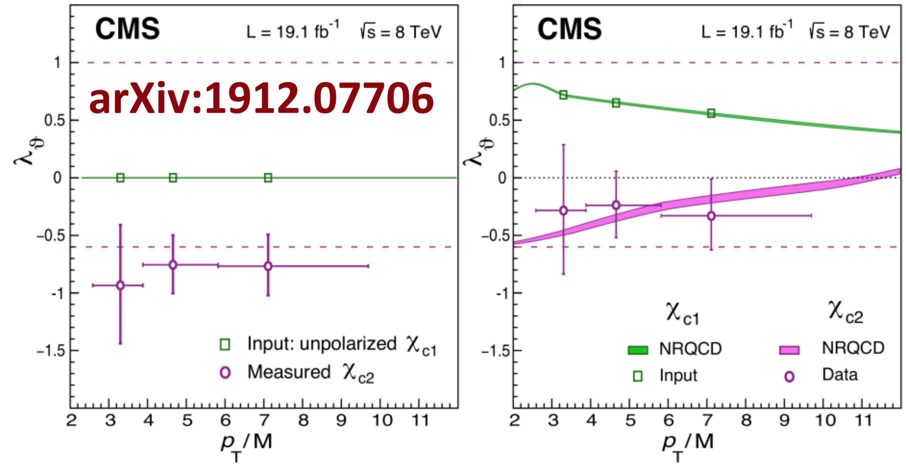
Cross section correction factor

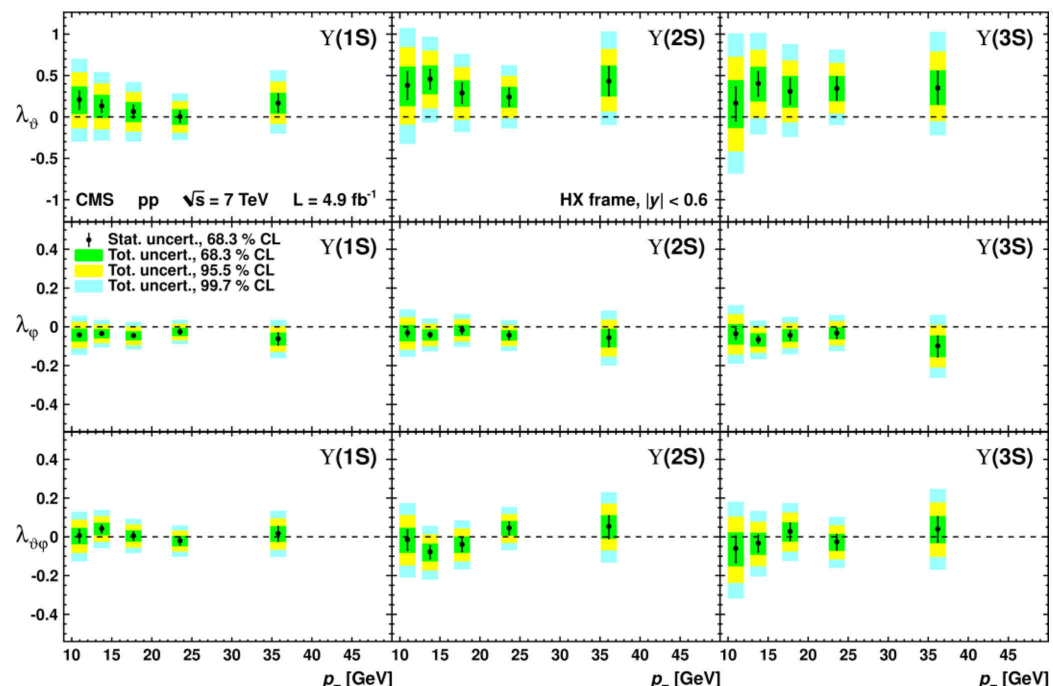
for ATLAS 13 TeV measurement



CMS: charmonium polarisation, 7-8 TeV







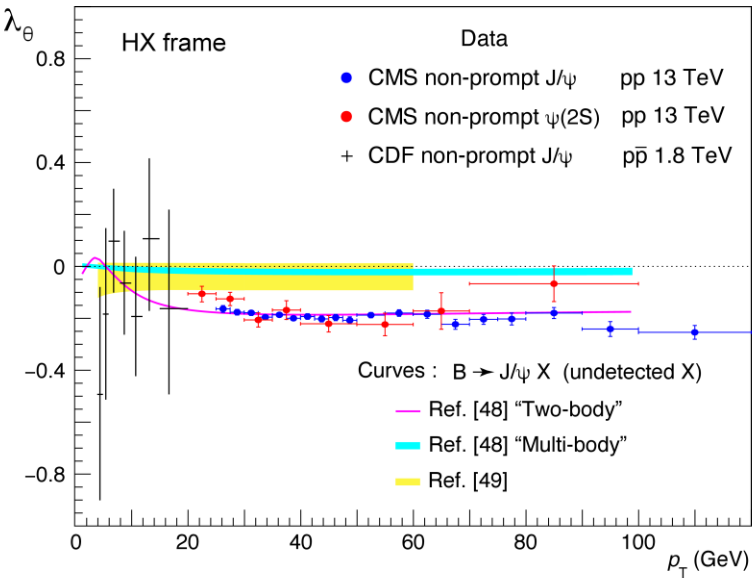
CMS:

Polarisations of (prompt) J/ψ, ψ(2S)

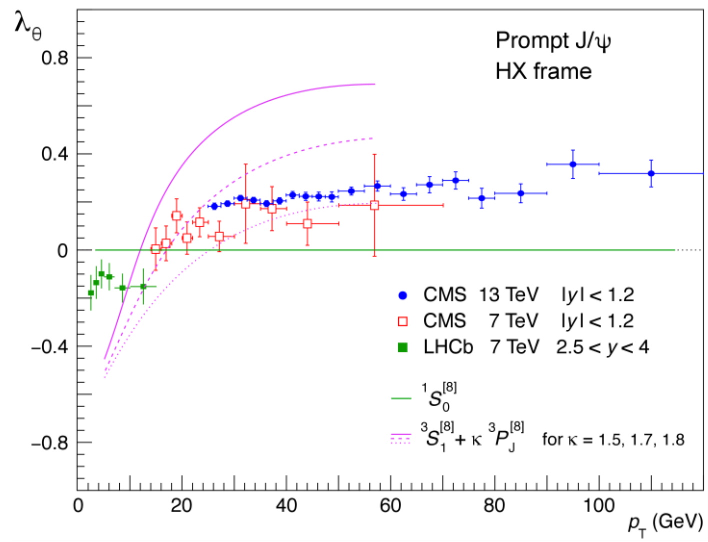
Even for χ1 and χ2 states

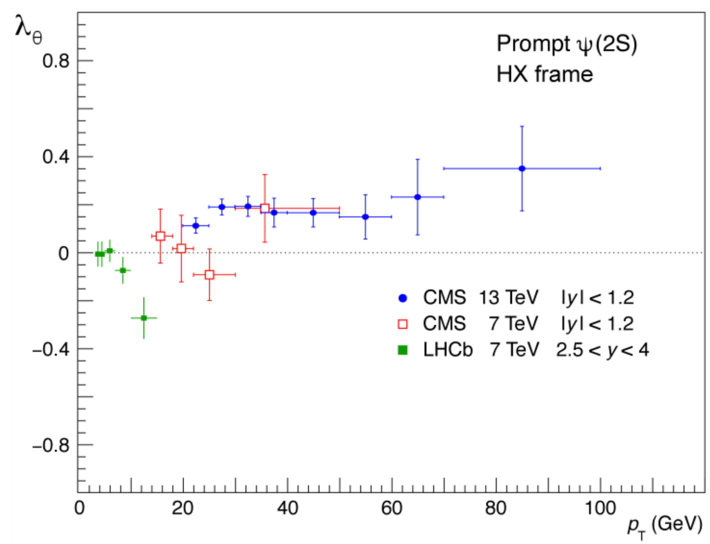
All three Υ states

CMS: P / NP charmonium polarization at 13 TeV



arXiv:
2406.14409





Very fresh from CMS:

Non-prompt ψ(2S) or J/ψ slightly longitudinal, -0.2

Prompt ψ(2S) or J/ψ slightly transverse, +0.2

pT dependence fairly weak after ~30 GeV

SPECTROSCOPY

First observation of the $\chi_{bJ}(3P)$ state

Significance of the new peak calculated through the difference of log-likelihoods with and without the peak in the fit: $D = \log (L_{with} / L_{without})$

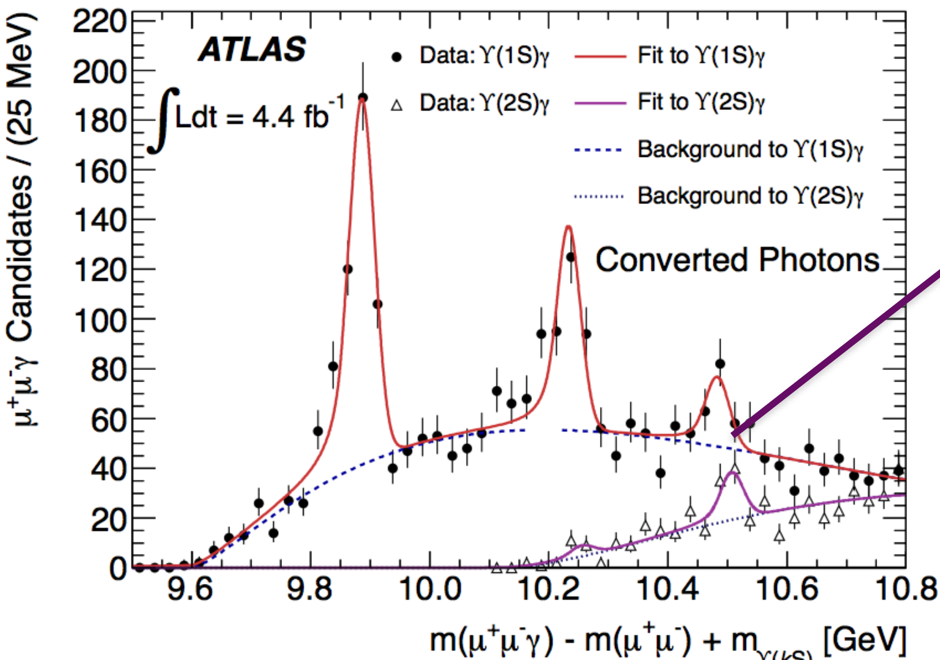
With moderately large numbers involved, -2D is distributed as $\Delta\chi^2$

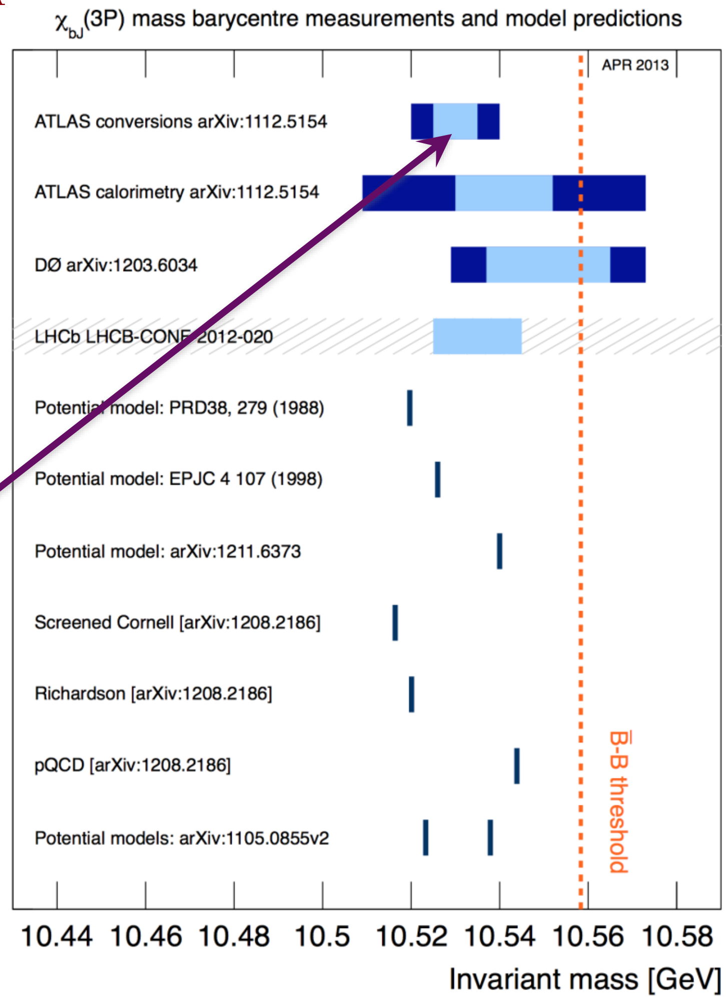
The "with" hypothesis won, with significance in excess of 6σ

Since then, confirmed by DØ and LHCb,

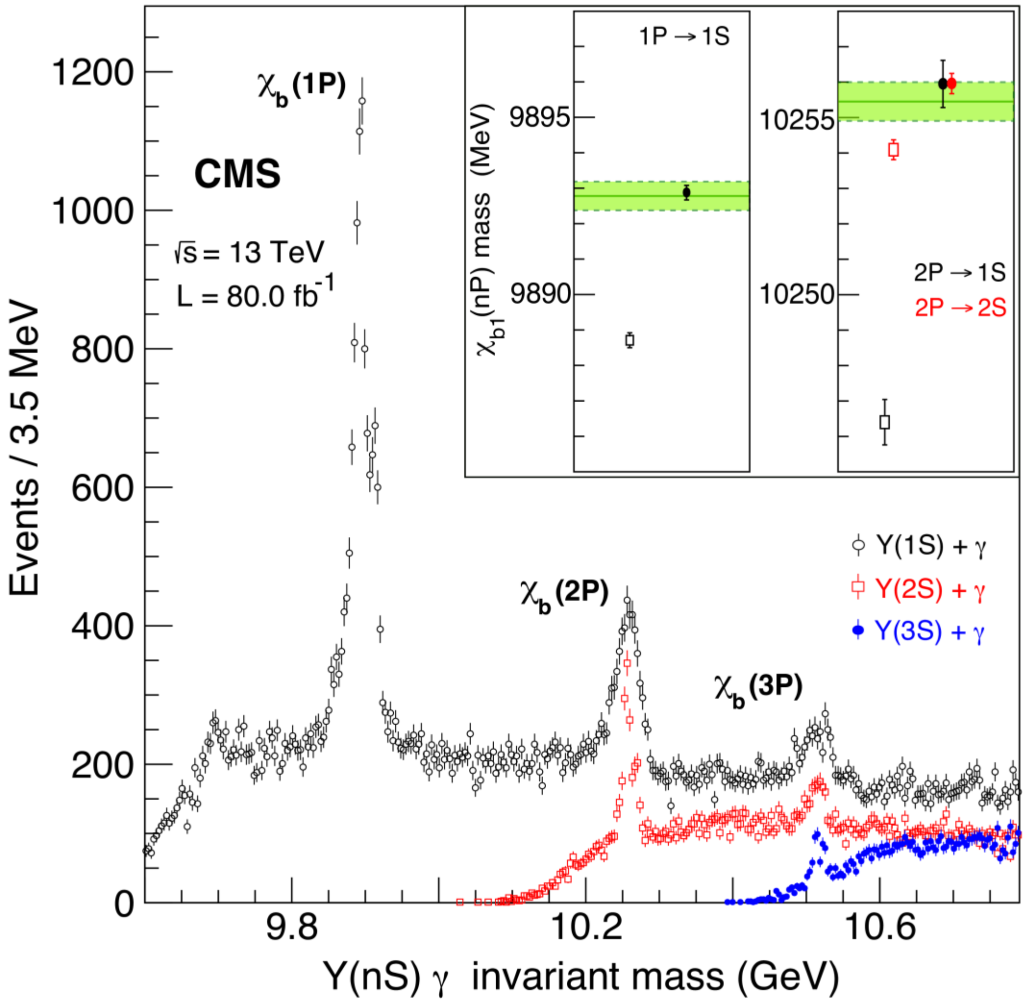
light blue: statistical,
dark blue statistical+systematic
[No quoted systematic for LHCb observation]

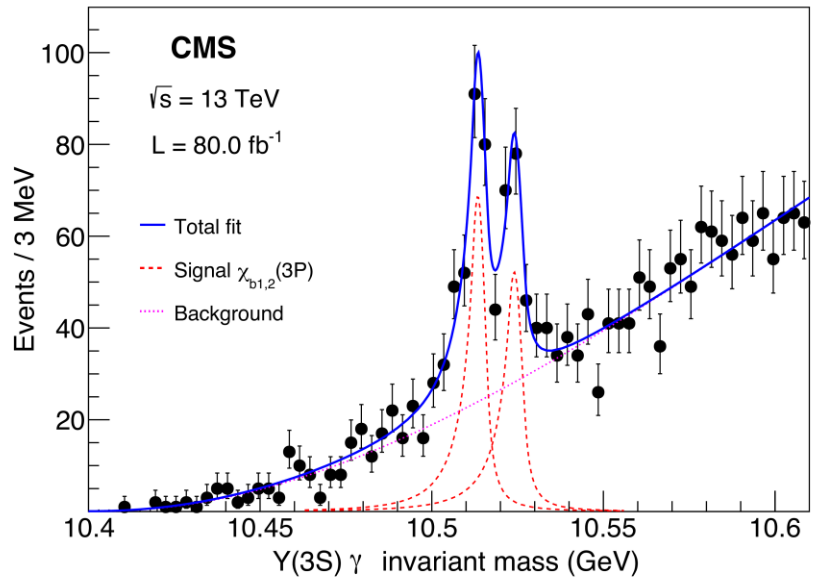
PRL 108 (2012) 152001





CMS: chi_B with better resolution





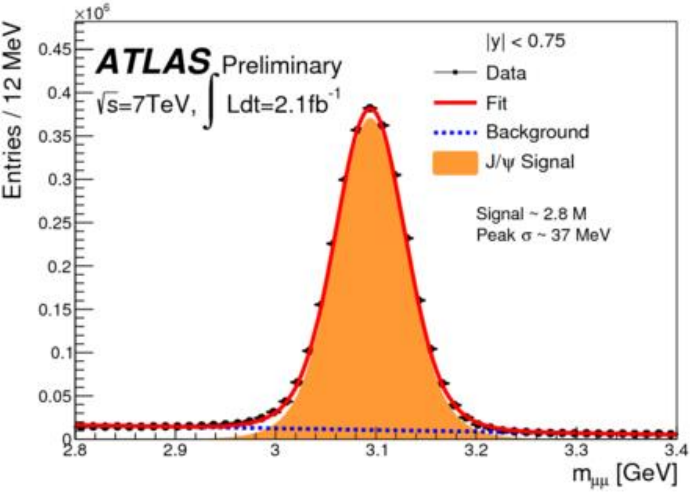
Even resolved χ_b(3P1) and χ_b(3P2)

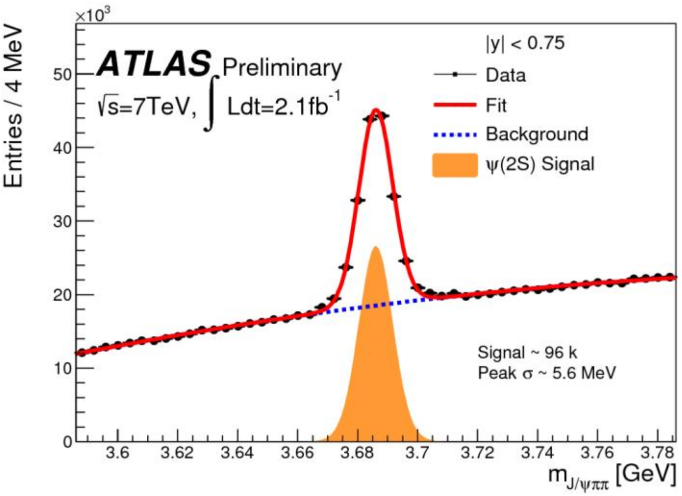
Measured masses with sub-MeV precision

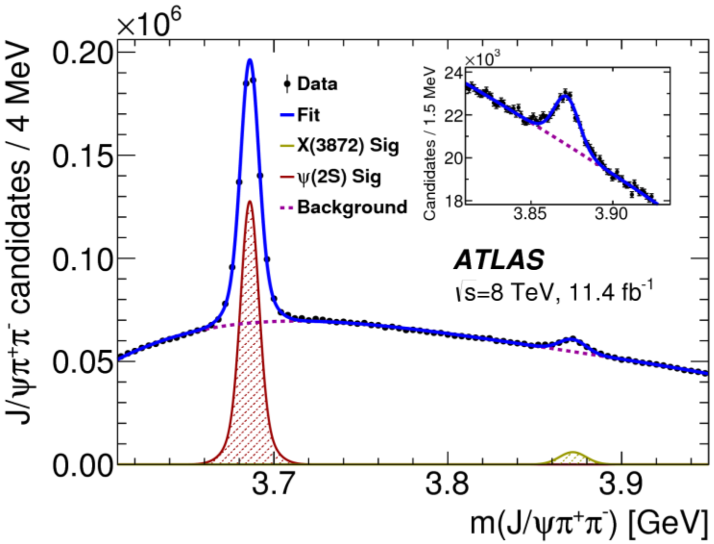
arXiv: 1805.11192

$J/\psi(\to\mu^+\mu^-)\pi^+\pi^-$ mass resolution

Resolution in $\mu^+\mu^-\pi^+\pi^-$ mass is greatly improved by a kinematic fit constraining $\mu^+\mu^-$ to J/ψ mass and all four tracks to the same vertex







Surprisingly enough, LHC detectors (even a general-purpose detector like ATLAS) are capable of studying hadron spectroscopy

Example: J/ψ ($\mu\mu$) final state analysis by ATLAS, arXiv: 1610.09303

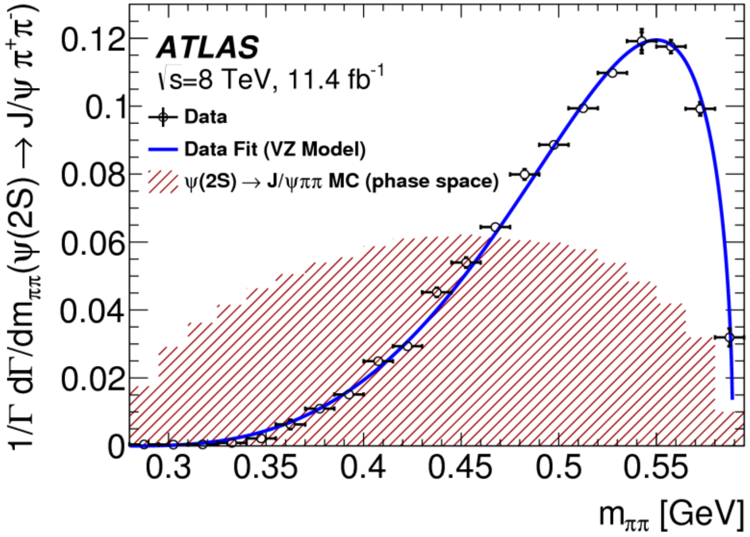
Di-pion mass distributions: results

In ψ(2S) to J/ψπ⁺π⁻ decays

- dipion mass distribution peaks at high masses
- fit to Voloshin-Zakharov function

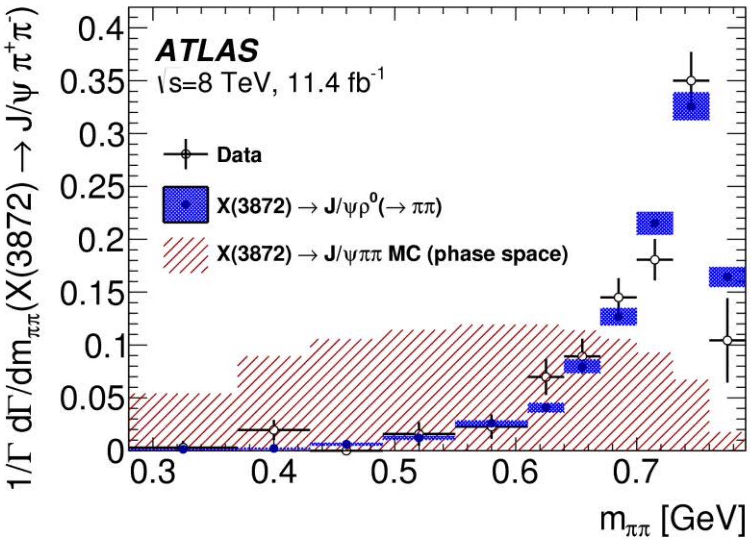
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

- found $\lambda = 4.16 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$
- in agreement with previous measurements



In X(3872) to J/ψπ⁺π⁻ decays

- dipion mass distribution has an even sharper peak at high masses
- in agreement with simulation where the di-pion system is produced via ρ^0 meson decay
- also in agreement with previous observations



Peaks in X→J/ψ+J/ψ/[ψ(2S)]→4μ

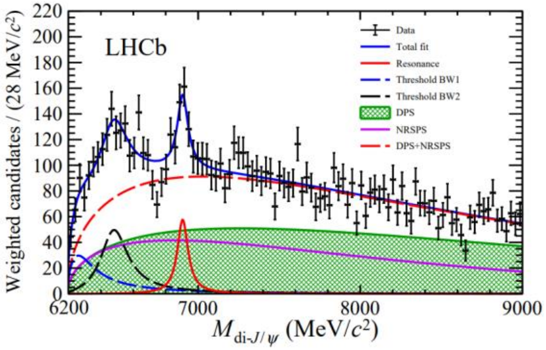
- **Di-J/ψ final states is a well-motivated search channel for low-mass resonances.**
- **LHCb observed narrow structure at 6.9 GeV: can be interpreted as four-charm tetraquark.**

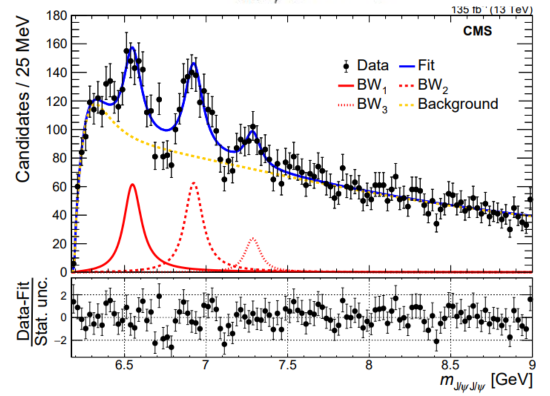
LHCb arXiv:2006.16957, Sci.Bull.65,1983(2020)

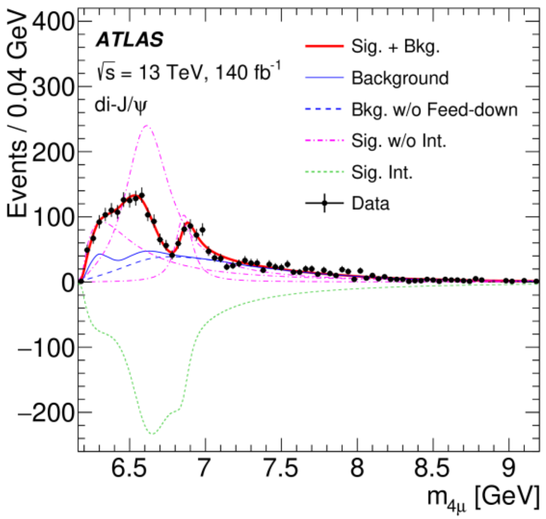
- **CMS and ATLAS are seeing similar pictures**

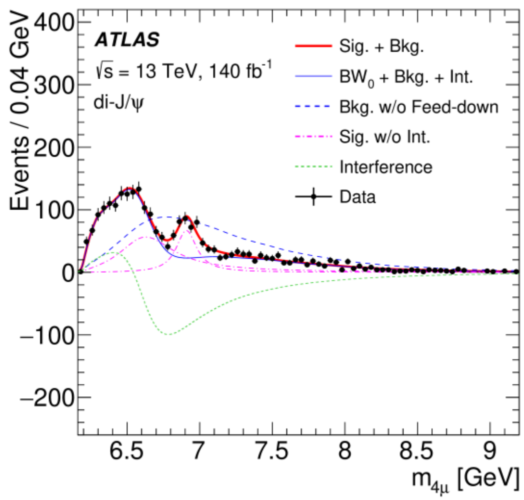
CMS arXiv:2306.07164   ATLAS PRL 131 (2023) 15, 151902

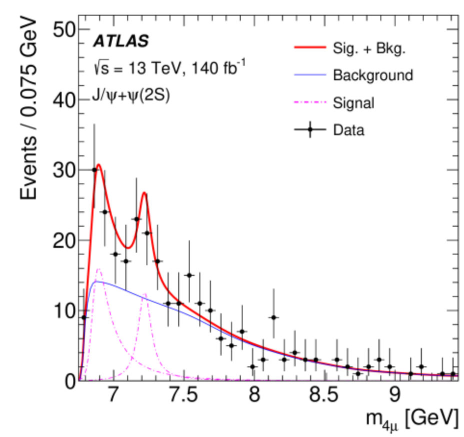
Looks hard to disentangle several closeby resonances of various widths





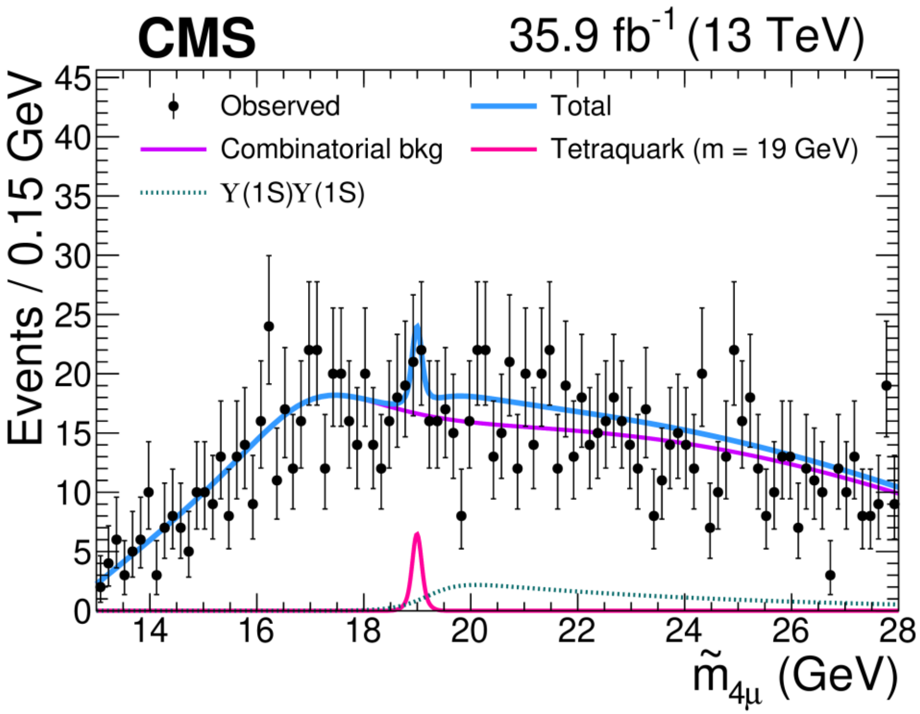


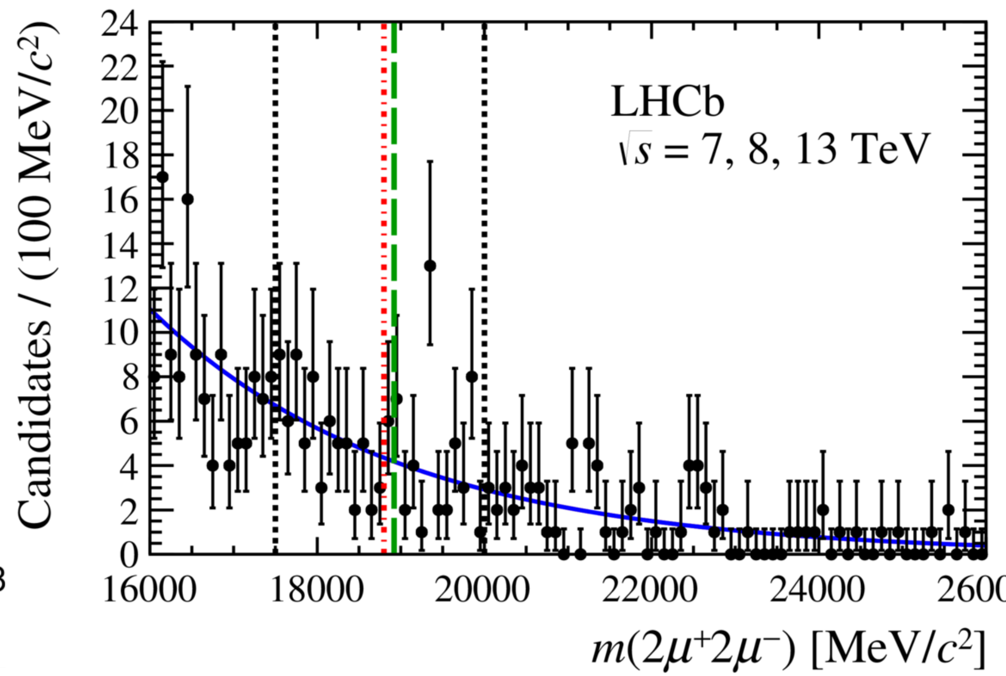




Searches in X→μμ+Υ(1S)→4μ channel

Four-lepton final states with on- or offshell vector mesons such as Υ(1S) give wide coverage for searches for fundamental scalars at low mass, or doubly-hidden beauty tetraquarks.





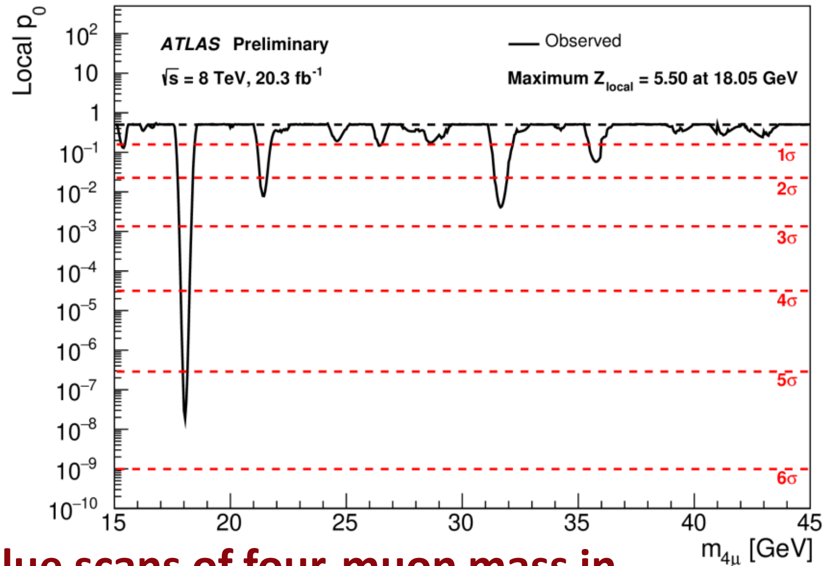
No obvious signal seen in CMS and LHCb

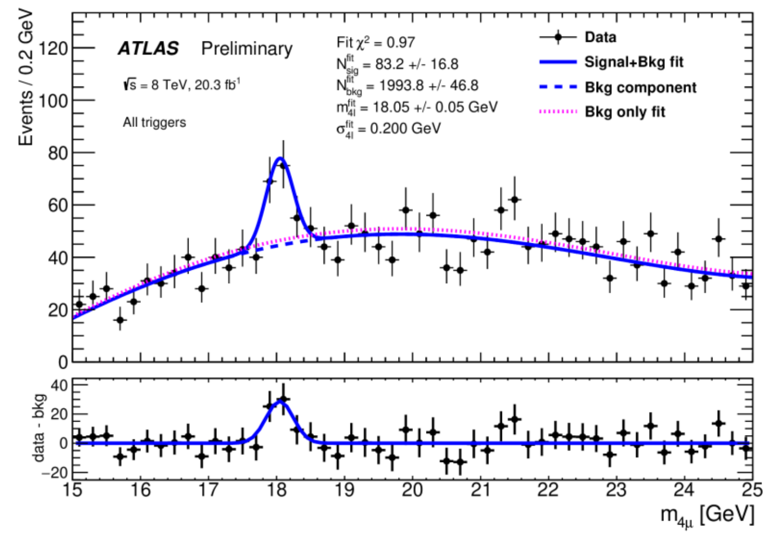
LHCb: arXiv: 1806.09707 **CMS: arXiv: 2002.06393**

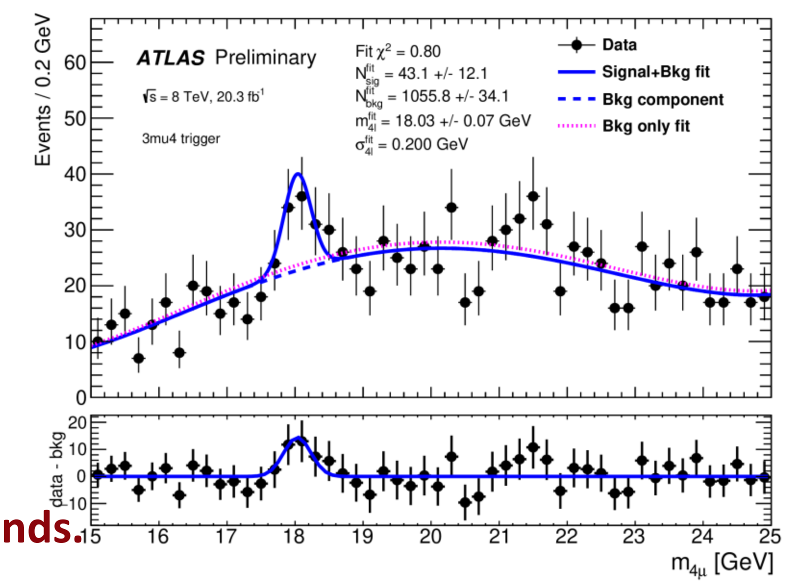
ATLAS preliminary: 8 TeV

ATLAS-CONF-2023-041

- **Structure observed in both di-muon and tri-muon triggered data.**
- **Width fixed to expected det. resolution of 200 MeV**
- **Background-only fit and p-value scan for chosen baseline selection yields significant excess at ~18 GeV.**







p-value scans of four-muon mass in
- Υ(1S)+same-sign muon pair
- Left/right Υ(1S) mass sidebands

find no significant structures.
No indications of artificially created structures from triggers/selections in simulated SPS and DPS backgrounds.

ATLAS preliminary: 13 TeV

Unbiased statistical test of the excess in 13 TeV data

At 13 TeV background rate three or more times 8 TeV levels, different trigger menu:

- No more 2mu4, only 3mu4 in 2015-17
- 3mu4 also gone in 2018
- A new “3mu4bUpsi” available for 2018

EARLY 13 TEV DATA (2015 -17, 51.5 /fb)

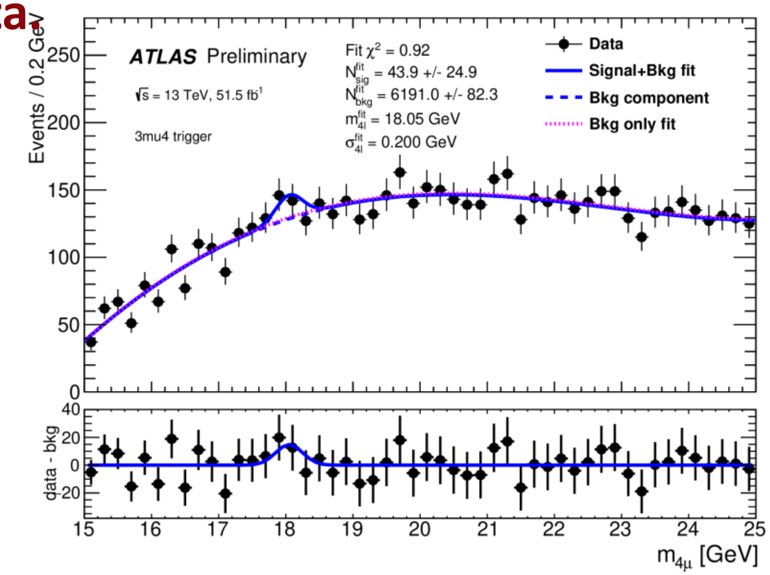
13 TeV data collected with similar tri-muon triggers finds 1.9σ excess for signal fit fixed to 18.05 GeV.

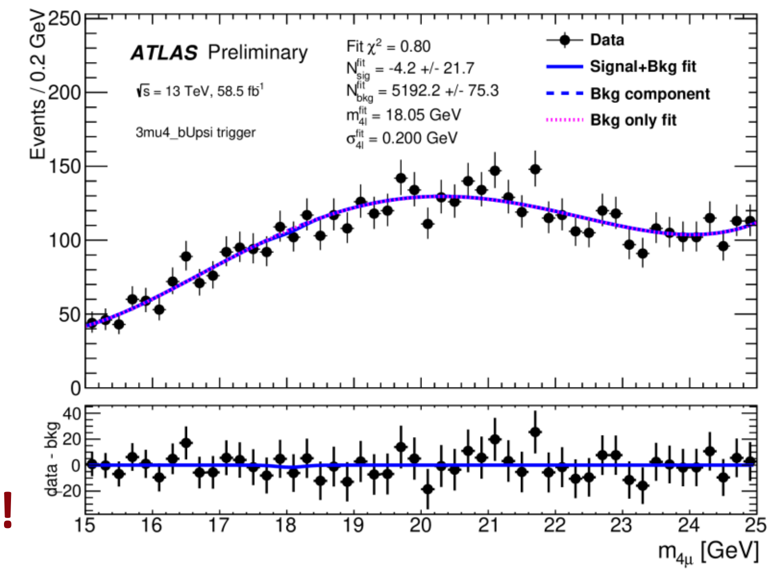
LATE 13 TEV DATA (2018, 58.5 /fb)

No evidence for a signal in 2018 data (new trigger).

Any conclusion/limit strongly model-dependent. Hard, but not impossible to imagine a model for which all data are consistent with each other.

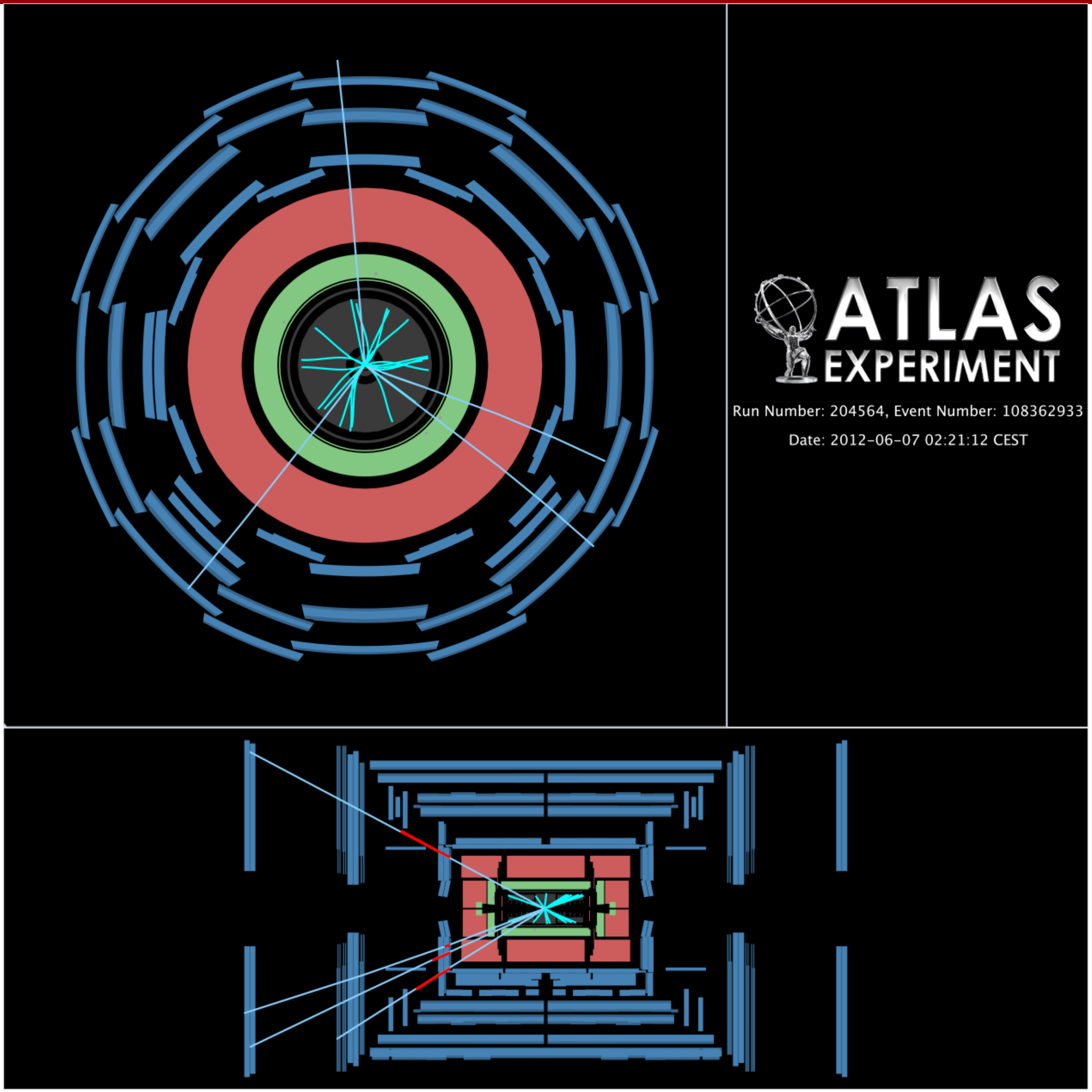
Need good theoretical models for further progress!





NEW OBSERVABLES, QUARKONIA AS TOOLS

Z + J/ψ event candidate



“New observables” in quarkonium production

Clearly, despite 40+ years’ history, we still have no clear picture of quarkonium production in hadronic – and other -- collisions

New energy frontier and higher luminosities allow exploration of other reactions that may help understand better quarkonium production dynamics

Simply speaking, more equations may help determine unknowns better, even if some new unknowns are introduced

Examples of these “new observables”: associated production of quarkonium with other objects, such as:

other quarkonium (LHCb, CMS, now ATLAS)

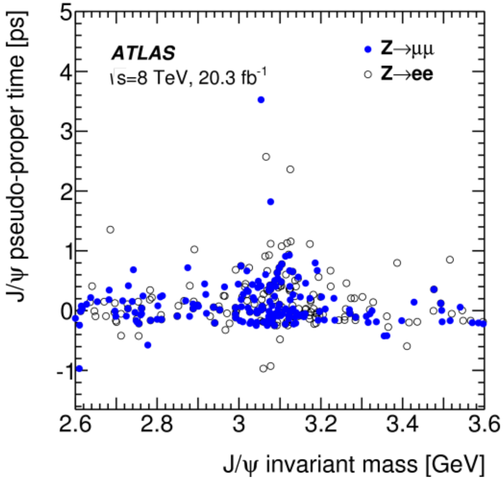
W and Z bosons (ATLAS)

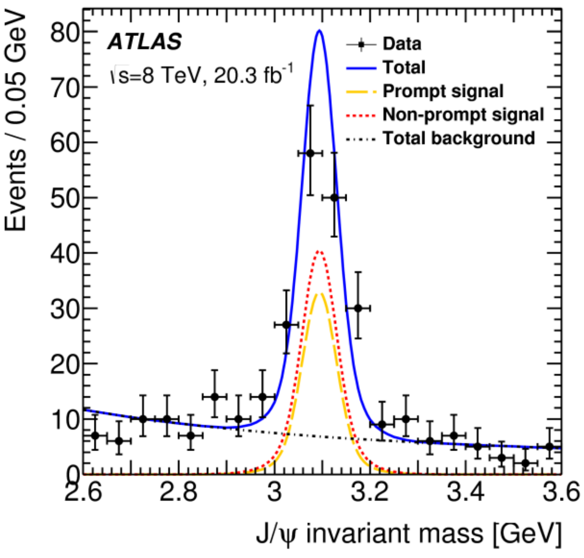
top quark pairs?

photons?

Associated production of J/ψ and Z boson

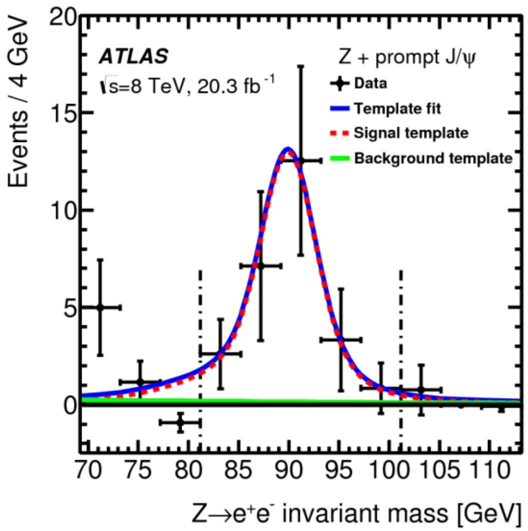
Identify events with a Z boson (decaying into electrons or muons) AND another pair of muons around the J/ψ mass range

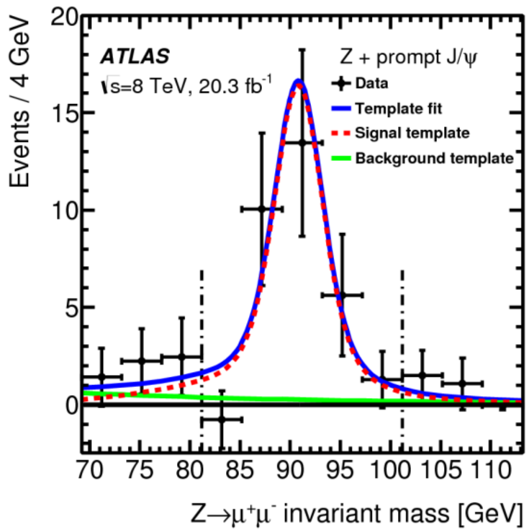


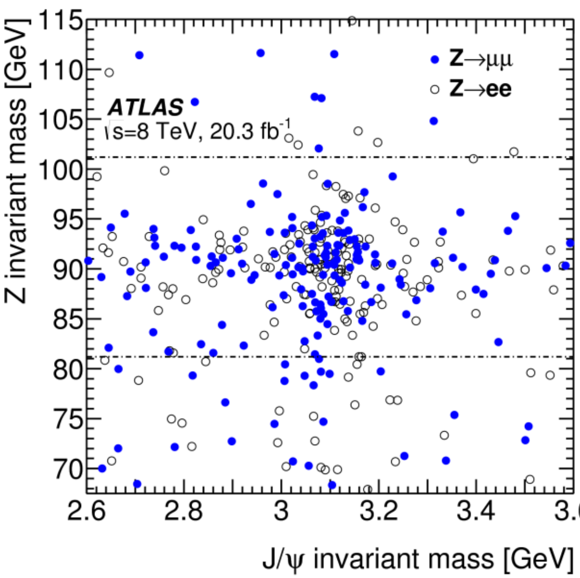


Some J/ψ are prompt, some are non-prompt

ATLAS: arXiv: 1412.6428



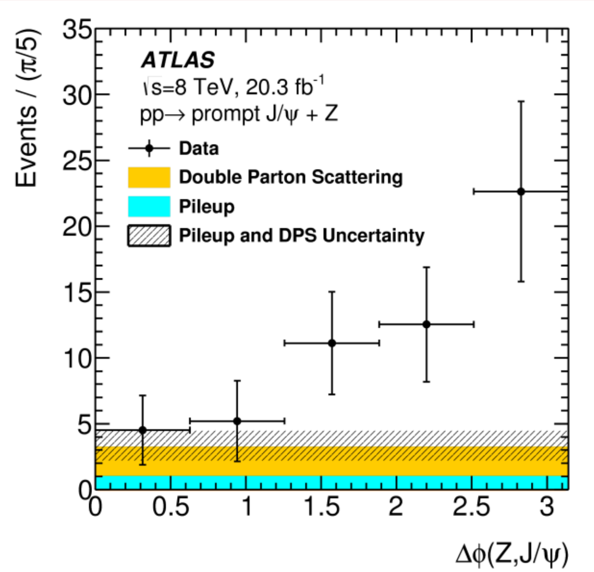




Results

Z and J/ψ can be produced in:

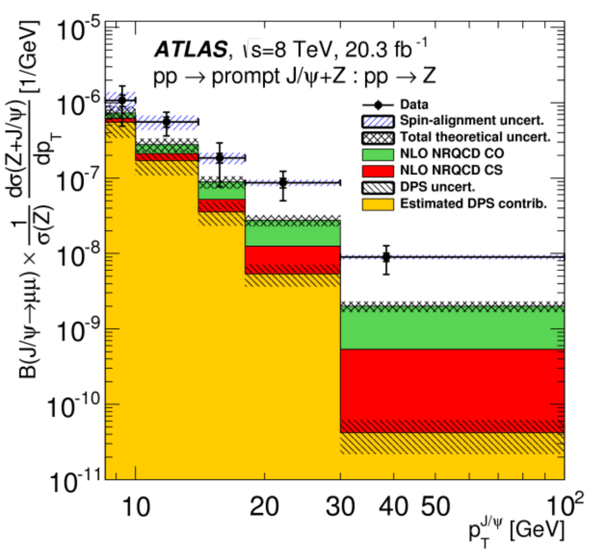
separate hard collisions within the same pp event
(Double Parton Scattering --- DPS) -> isotropic in delta-phi
or in the same hard parton scattering
(Single Parton Scattering --- SPS) -> peaking at back-to-back



$p_T^{J/\psi}$ [GeV]	Inclusive prompt ratio [$\times 10^{-7}$/ GeV] value ± (stat) ±	(syst) ±	(spin)	Estimated DPS [$\times 10^{-7}$/ GeV] assuming $\sigma_{\rm eff} = 15$ mb
(8.5, 10)	10.8 ± 5.6	± 1.9	± 3.1	5.5 ± 2.1
(10, 14)	5.6 ± 1.9	± 0.8	± 1.2	1.7 ± 0.6
(14, 18)	1.9 ± 1.1	± 0.1	± 0.3	0.4 ± 0.1
(18, 30)	0.87 ± 0.37	± 0.12	± 0.09	0.05 ± 0.02
(30, 100)	0.090 ± 0.037	± 0.012	± 0.006	0.0004 ± 0.0002

$p_T^{J/\psi}$ [GeV]	Inclusive non-prompt ratio [$\times 10^{-7}$/ GeV] value ± (stat) ±	(syst) ±	(spin)	Estimated DPS [$\times 10^{-7}$/ GeV] assuming $\sigma_{\rm eff} = 15$ mb
(8.5, 10)	5.1 ± 4.2	± 0.9	± 0.3	2.07 ± 0.77
(10, 14)	9.2 ± 2.5	± 1.2	± 0.3	0.85 ± 0.30
(14, 18)	3.3 ± 1.2	± 0.4	± 0.1	0.26 ± 0.09
(18, 30)	3.04 ± 0.59	± 0.04	± 0.04	0.05 ± 0.02
(30, 100)	0.115 ± 0.039	± 0.002	± 0.001	0.0015 ± 0.0005

Theory predictions well below measurement, especially at high P_T

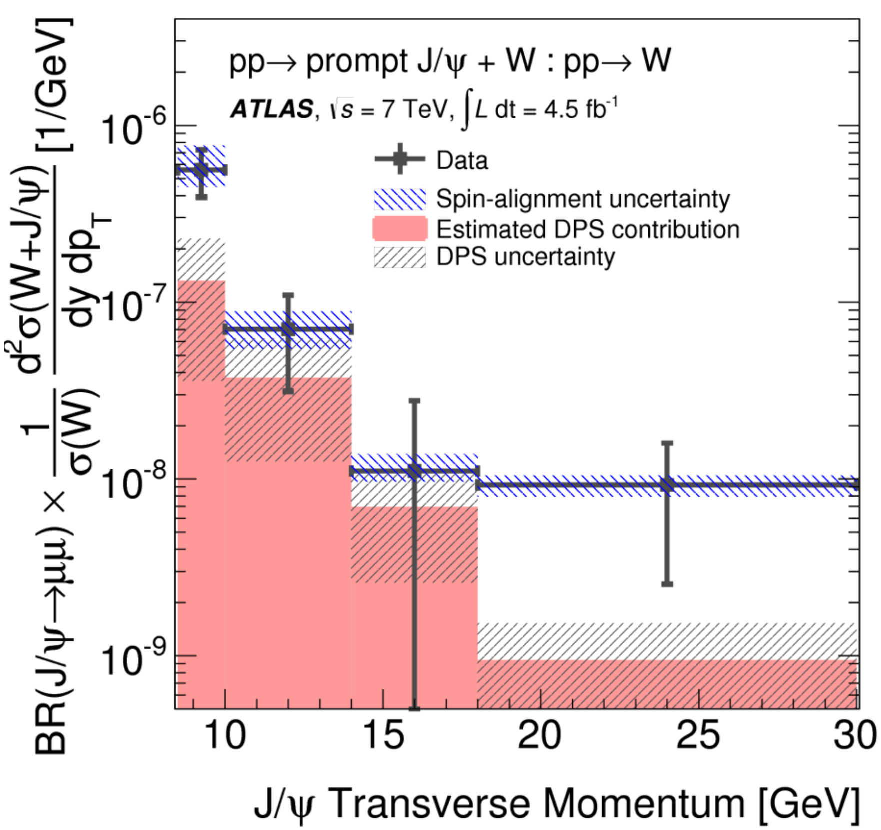


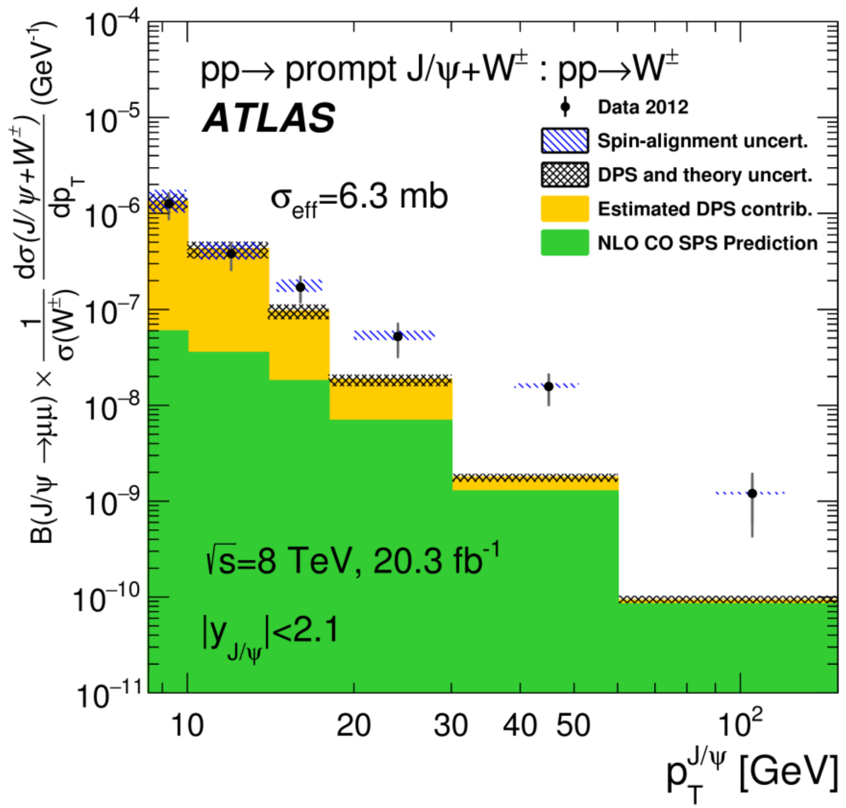
Measured cross section ratio (Z+ J/ψ) / Z differentially in P_T(J/ψ) separately for prompt and non-prompt J/ψ

Will hopefully stimulate further calculations

ATLAS: J/psi + W at 7 and 8 TeV

Lancaster University



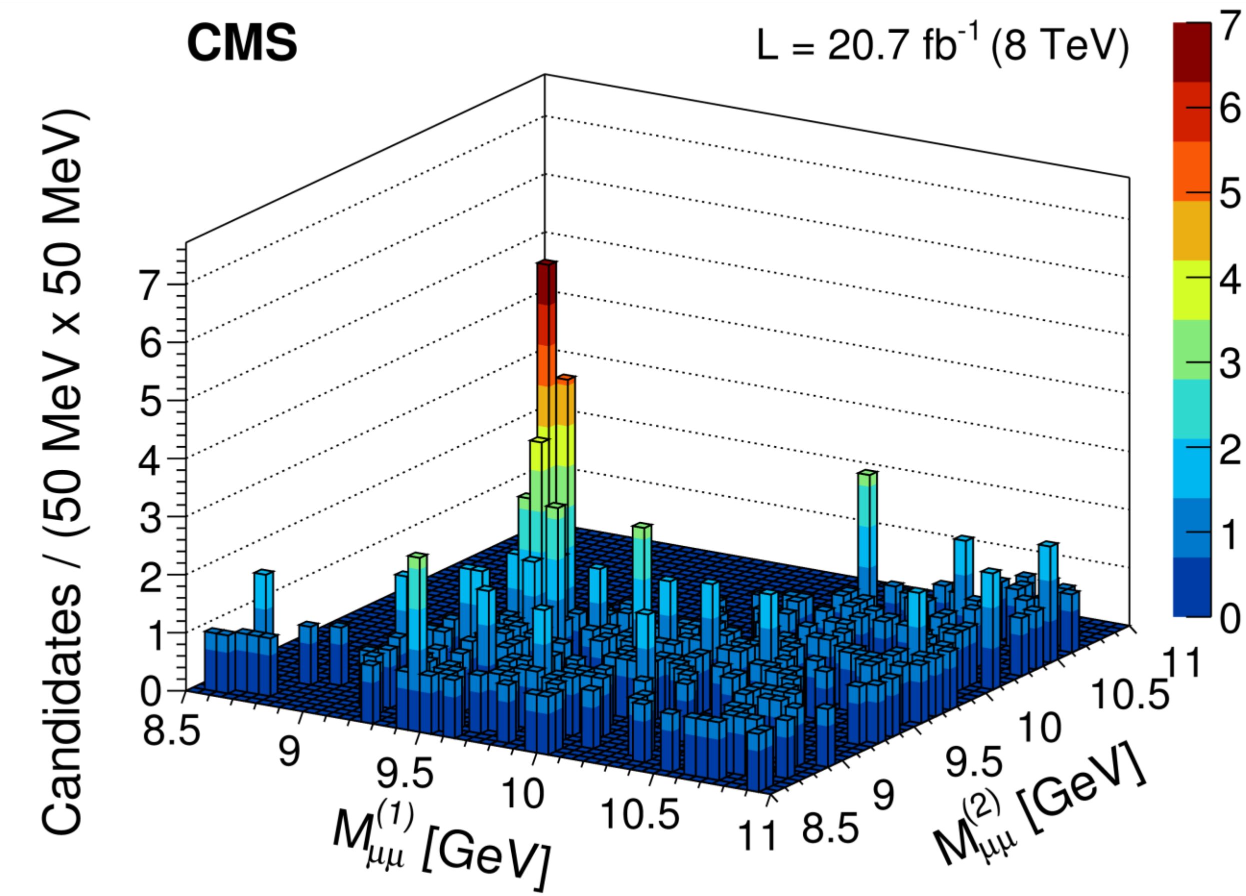


Adding a J/psi to a W or Z production costs ~6 orders of magnitude
pT spectra of such J/psi typically (much) harder than inclusive
Sigma-effective in DPS production tends to be smaller than for VV etc.

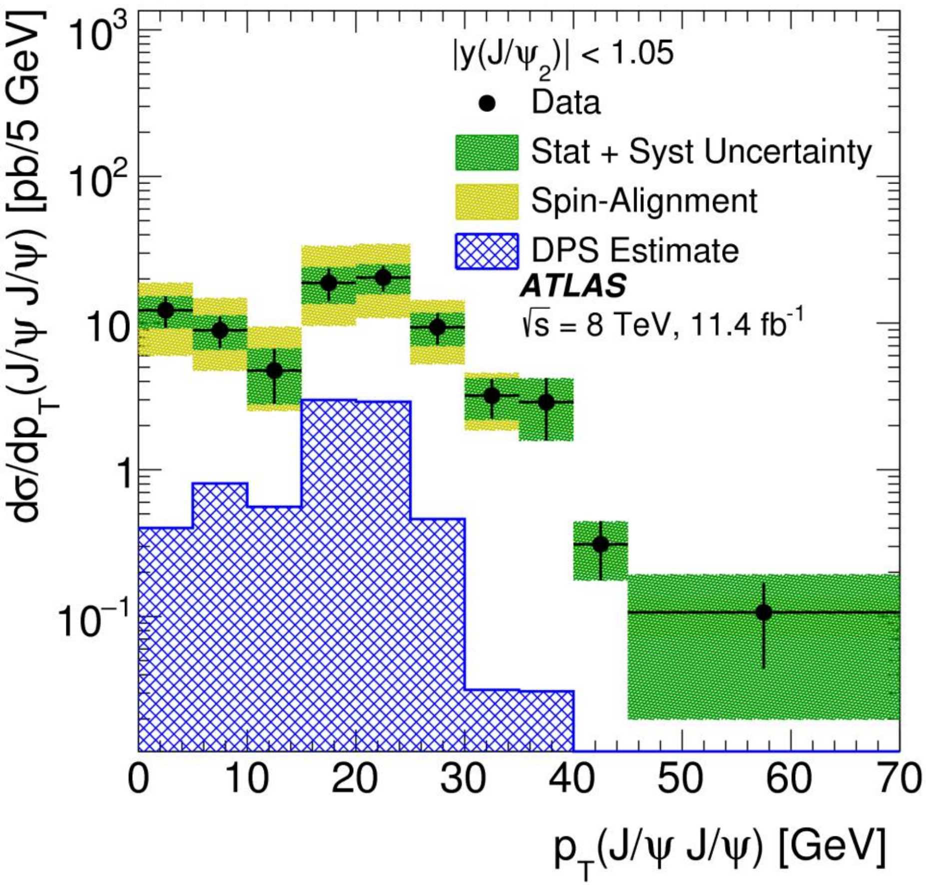
ATLAS 7 TeV arXiv: 1401.2831

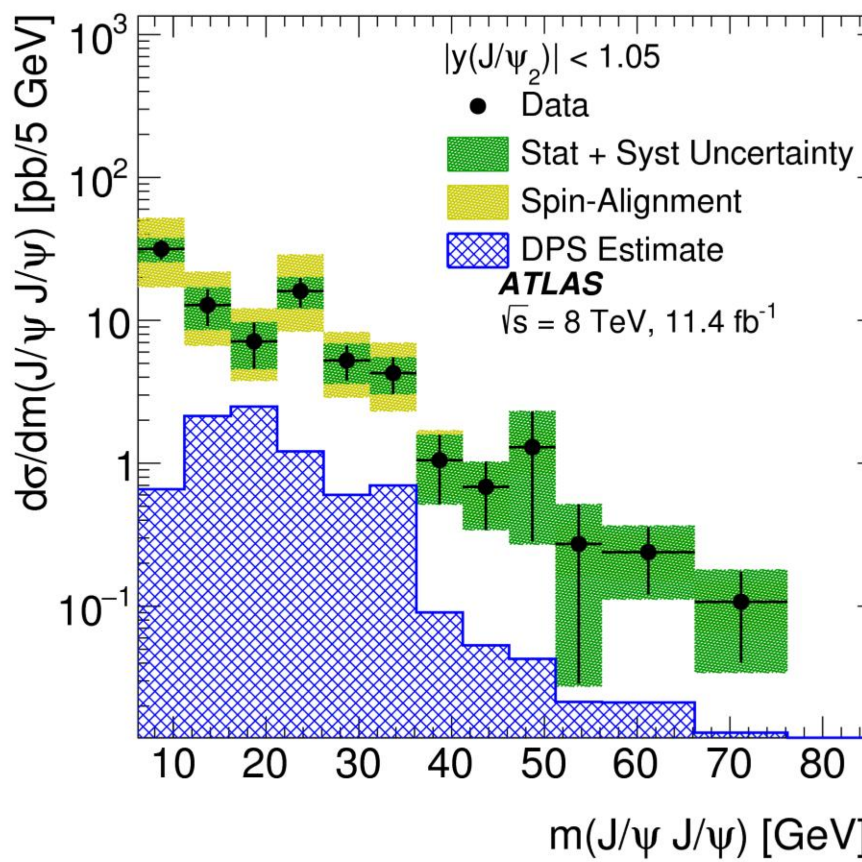
ATLAS 8 TeV arXiv: 1909.13626

CMS: di-Υ production



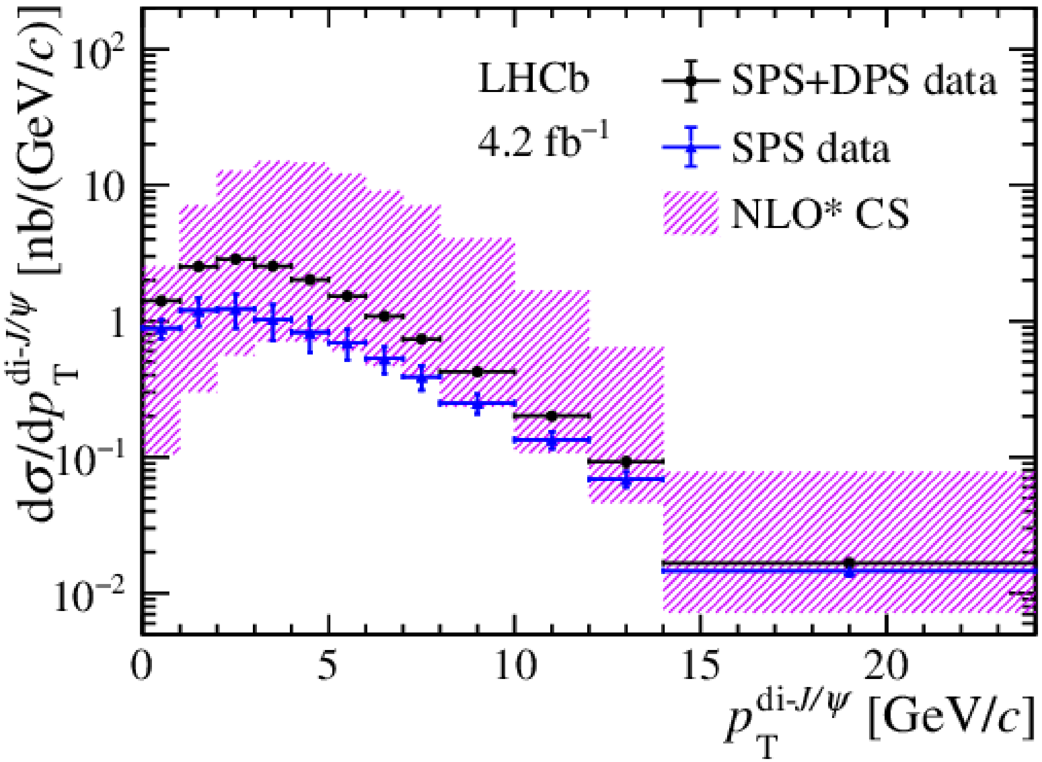
ATLAS: Di-Jpsi at high mass & high pT

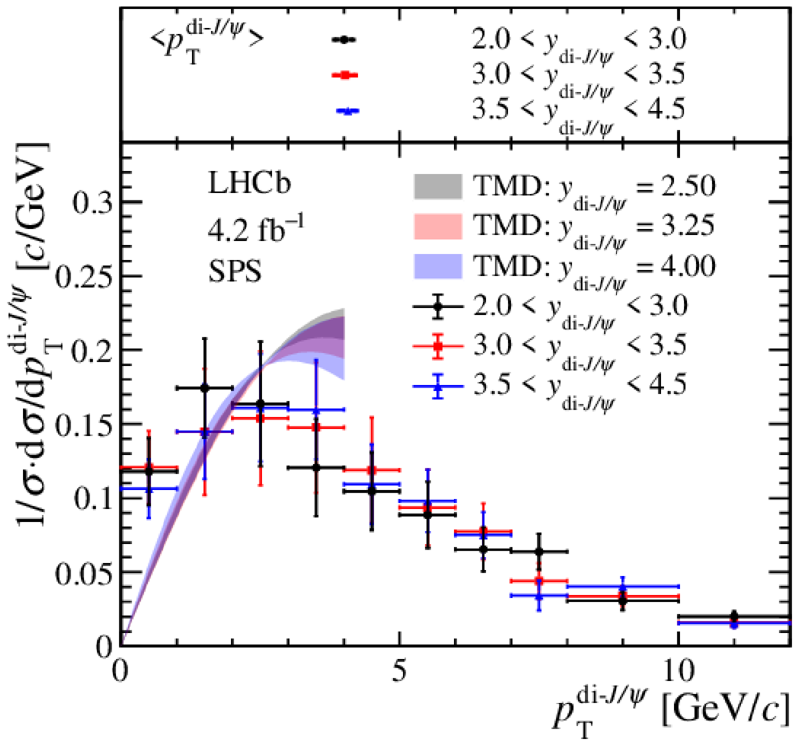




Data suggests large SPS contributions
Strong distortions to distributions by fiducial cuts
Significant effort needed for any downstream analysis

ATLAS 7 TeV arXiv: 1612.02952





LHCb kinematics offers much more favourable fiducial cuts for low pT
Hence much smoother distributions, downstream analysis possible
Will be presented in more detail later in the workshop

LHCb arXiv: 2311.14085

SUMMARY

Tried to cover a HUGE amount of data and a large number of interesting (and sometimes brilliant) results on:

- Quarkonium production
- Quarkonium polarisation
- Quarkonium and/or related spectroscopy
- New observables and quarkonium as a tool

The enormity of the task only became obvious while working on the talk

Apologies again for any omissions, and also for an ATLAS bias

Hope this overview was useful – and sets a right tone for the workshop

THANK YOU!

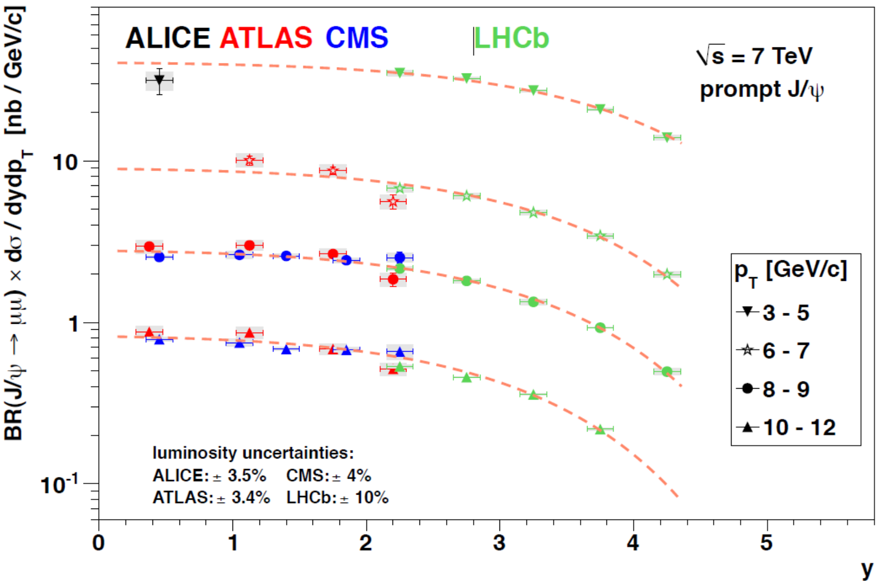
Backup slides

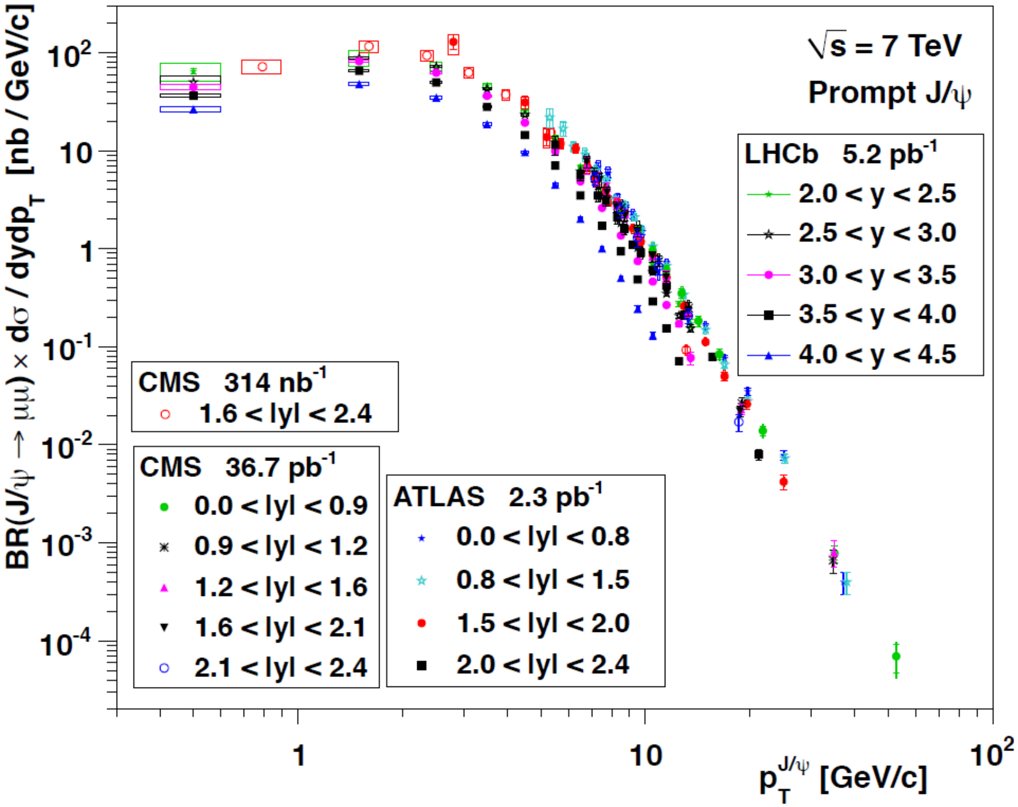
Prompt J/ψ production: LHC 7 TeV

Compilations by Hermine K. Woehri

(a couple of years old by now)

Nice synergy between the LHC experiments





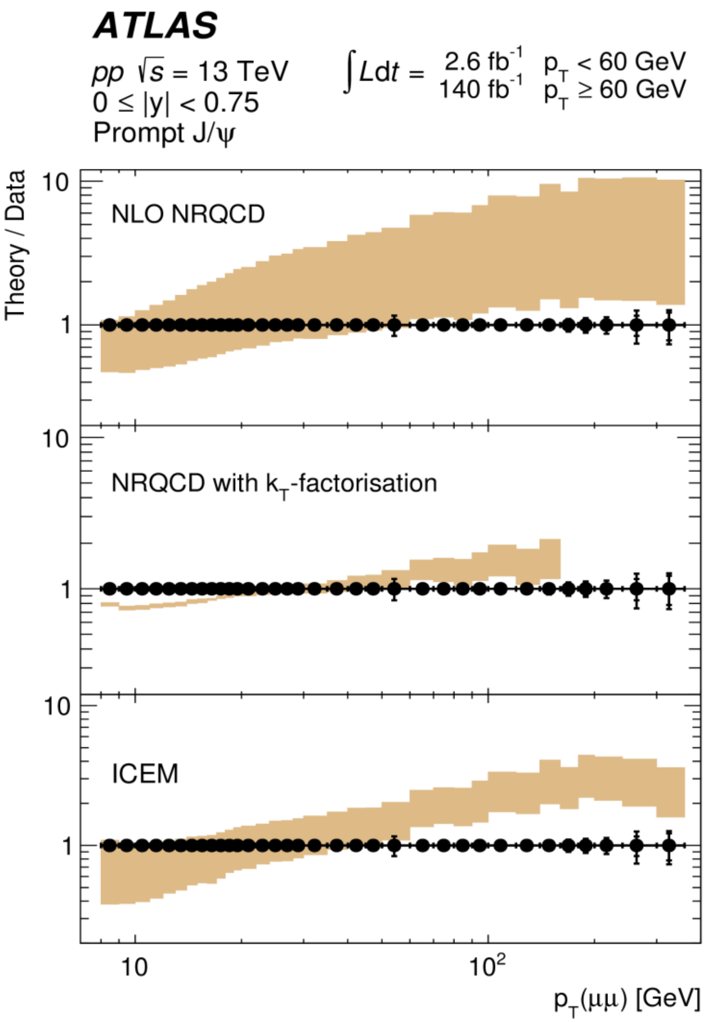
Between the experiments, a huge kinematic range is covered: $|y| < 4.5$, $0 < p_T < 100$ GeV

Over 6 orders of magnitude in p_T

Given the diversity of experiments and conditions, consistency of measurements is really remarkable

Theory comparison: prompt J/ψ and ψ(2S)

Lancaster University



ATLAS

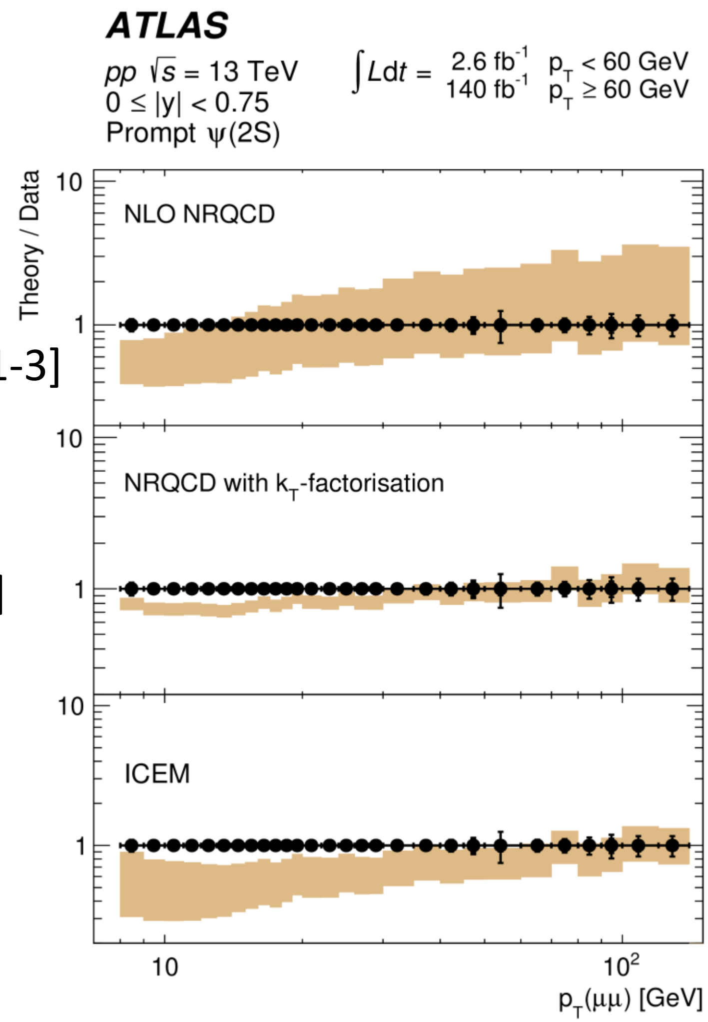
EPJC84(2024)169

arXiv:2309:17177

Butenschön,Kniehl [1-3]

Baranov et al [4-7]

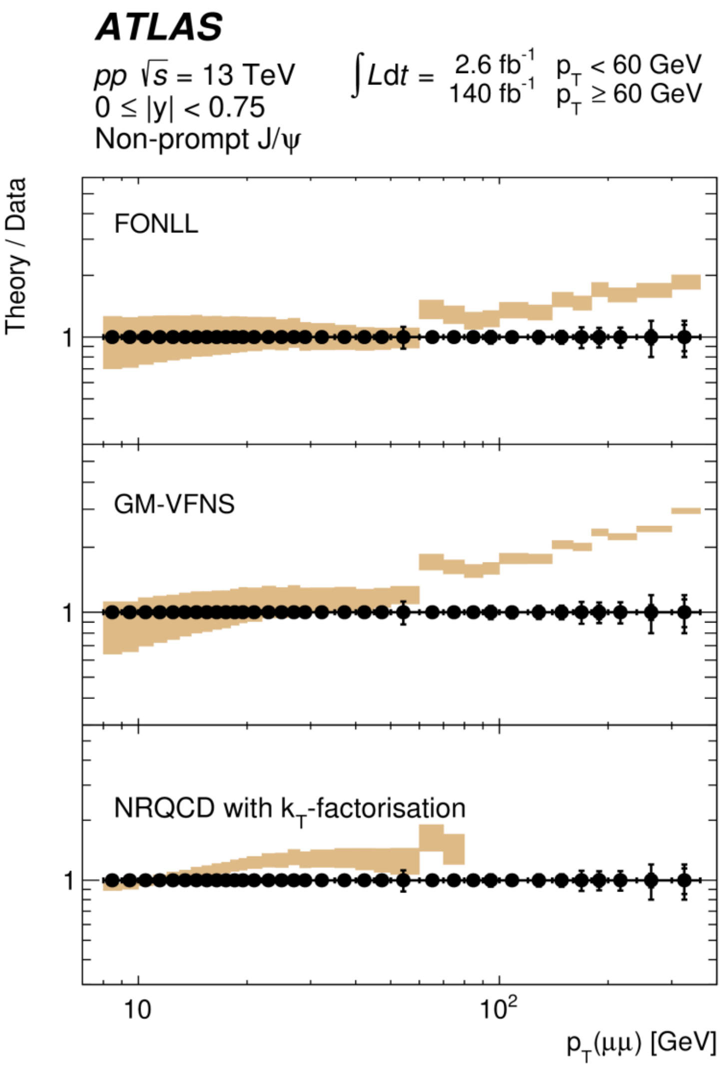
Cheung,Vogt [8]



9 orders of magnitude described within a factor of ~3

There is room for improvement for all models shown

Theory comparison: non-prompt J/ψ and ψ(2S)

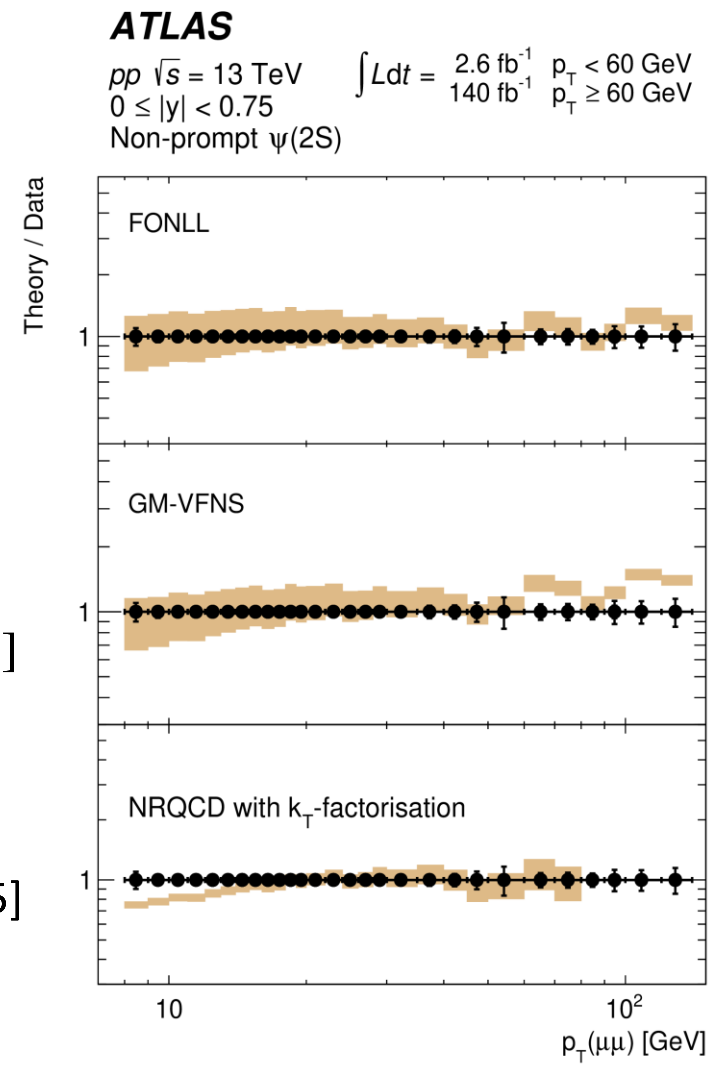


ATLAS
EPJC84(2024)169
arXiv:2309:17177

Cacciari et al [9-11]

Kniehl et al [12-14]

Baranov et al [6,15]



Generally better agreement for non-prompt, still tend to overestimate at high pT

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Searches in X→μμ+Υ(1S)→4μ channel

Lancaster University

ATLAS-CONF-2023-041

Motivation:

Four-lepton final states with on- or offshell vector mesons such as Υ(1S) give wide coverage for searches for fundamental scalars at low mass, or doubly-hidden beauty tetraquarks.

Datasets:

Events (events per /fb)

Dataset	8 TeV		13 TeV	
Luminosity (fb^{-1})	20.3		51.5	58.5
Trigger	All triggers	3μ only	3μ only	3μ_bUpsi only
Four muons, ≥ 3 LowPt, $p_T > (4, 4, 3, 3)$ GeV	261,893	170,467	1,152,307	231,318
	2012		**2015-17**	**2018**
One $\Upsilon(1S)$ and $10 < m_{4\mu} < 50$ GeV	6,467	3,641 (179)	20,887 (406)	19,125 (327)
$\Upsilon(1S) + \mu^+\mu^-$	3,849	2,218 (109)	13,657 (265)	10,862 (186)
$\Upsilon(1S) + \mu^\pm\mu^\pm$	2,618	1,423 (70)	7,230 (140)	8,263 (141)

Mass spectra: 8 TeV sample

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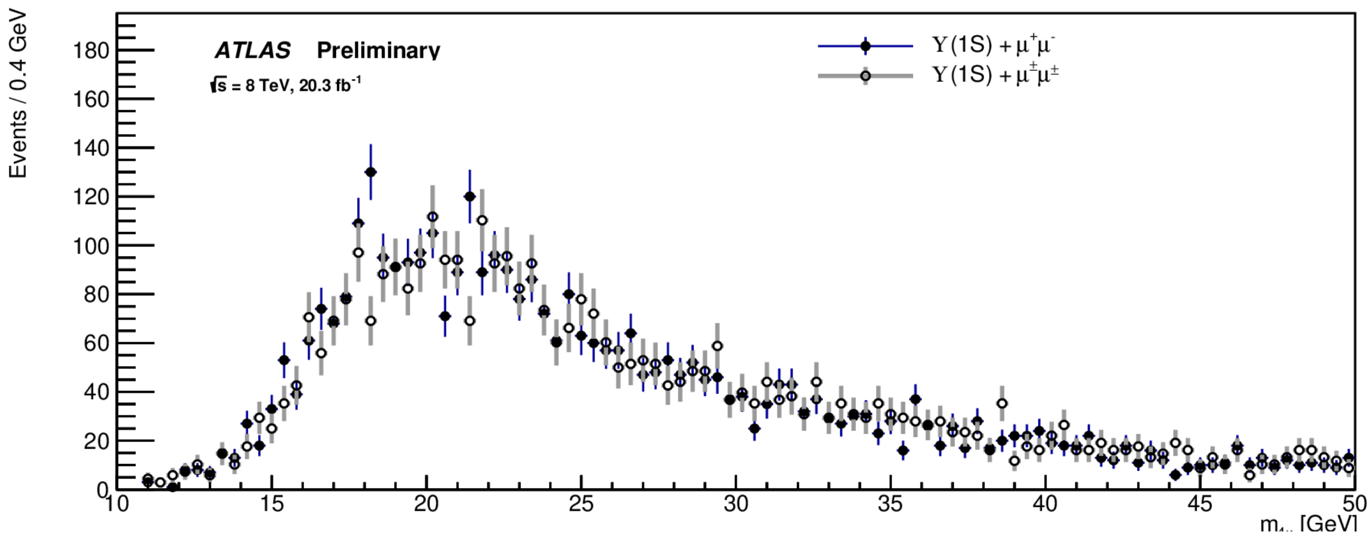
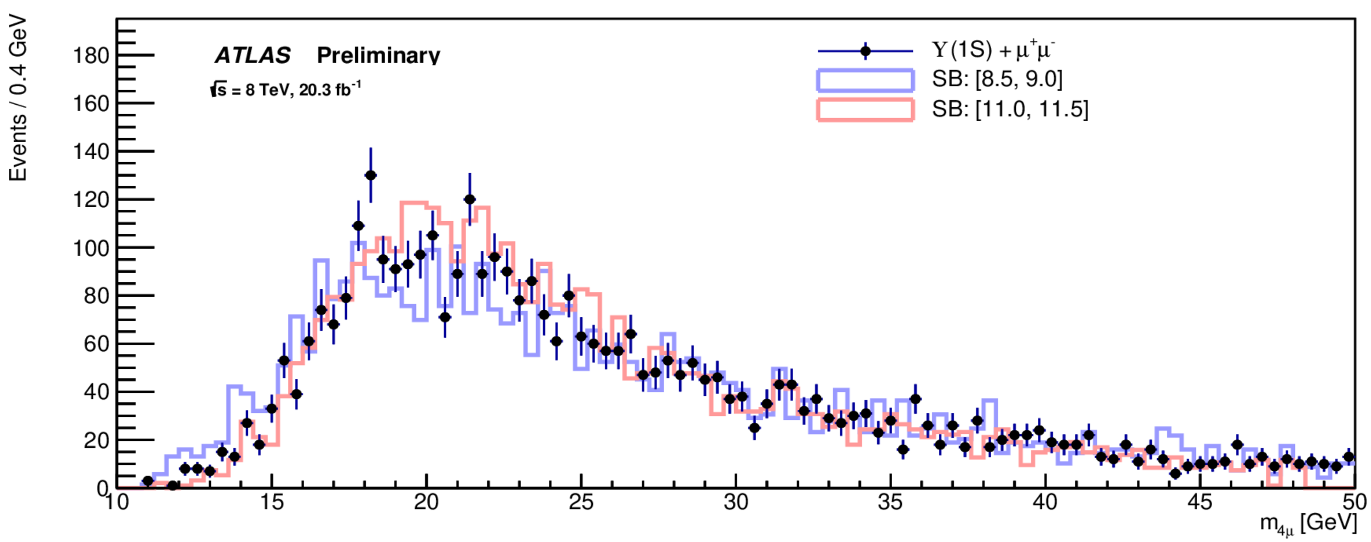
Background shapes compared to

- Y+SS dimuons
- Y sidebands with OS dimuons

Indications of an excess of events in narrow region around 18 GeV in Y(1S) + opposite-sign muon data.





Cross-checks and variations

Since analysis not blind, robustness of 18 GeV excess studied with alternative selections:

Selection criteria	N_B	Mass (GeV)	N_S	Significance (σ)
Baseline	1994 ± 47	18.05 ± 0.05	83 ± 17	5.5
Selection variations from the baseline				
≥ 2 LowPt muons	3124 ± 59	18.09 ± 0.06	94 ± 20	5.0
$= 4$ LowPt muons	689 ± 28	18.03 ± 0.07	37 ± 10	4.1
$m_{\mu^+\mu^-}^{\text{non-res}} > 0$ GeV	2515 ± 53	18.00 ± 0.06	81 ± 19	4.7
$m_{\mu^+\mu^-}^{\text{non-res}} > 0.5$ GeV	2306 ± 51	18.00 ± 0.05	87 ± 18	5.3
$m_{\mu^+\mu^-}^{\text{non-res}} > 2$ GeV	1696 ± 43	18.05 ± 0.07	58 ± 15	4.3
Vertex fit $\chi^2/N_{\text{d.o.f}} \leq 4$	1705 ± 43	18.03 ± 0.05	69 ± 15	5.0
Vertex fit $\chi^2/N_{\text{d.o.f}} \leq 20$	2077 ± 48	18.04 ± 0.05	81 ± 17	5.0
$m_{\Upsilon(1S)} \pm 2\sigma_m$ window	3705 ± 64	18.09 ± 0.06	90 ± 22	4.5
$\Upsilon(1S)$ mass correction	1998 ± 47	18.02 ± 0.08	64 ± 17	4.1
$m_{\mu^+\mu^-}^{\text{non-res}} < m_{\Upsilon(1S)}$	1418 ± 40	18.06 ± 0.05	94 ± 17	6.3
$p_T > 2.5$ GeV non-res. muons	2741 ± 55	18.05 ± 0.05	70 ± 19	4.1
$p_T > 4$ GeV non-res. muons	982 ± 33	18.06 ± 0.08	35 ± 11	3.6
Tight IP cuts	1469 ± 40	18.01 ± 0.05	71 ± 15	5.5
Lifetime $\lvert\tau/\sigma_\tau\rvert < 3$	1873 ± 45	18.04 ± 0.05	86 ± 17	5.6
MBS < 3	1749 ± 44	18.05 ± 0.04	83 ± 16	5.8

Global significance over mass range 15-50 GeV varies between 1.9 – 5.4 σ.

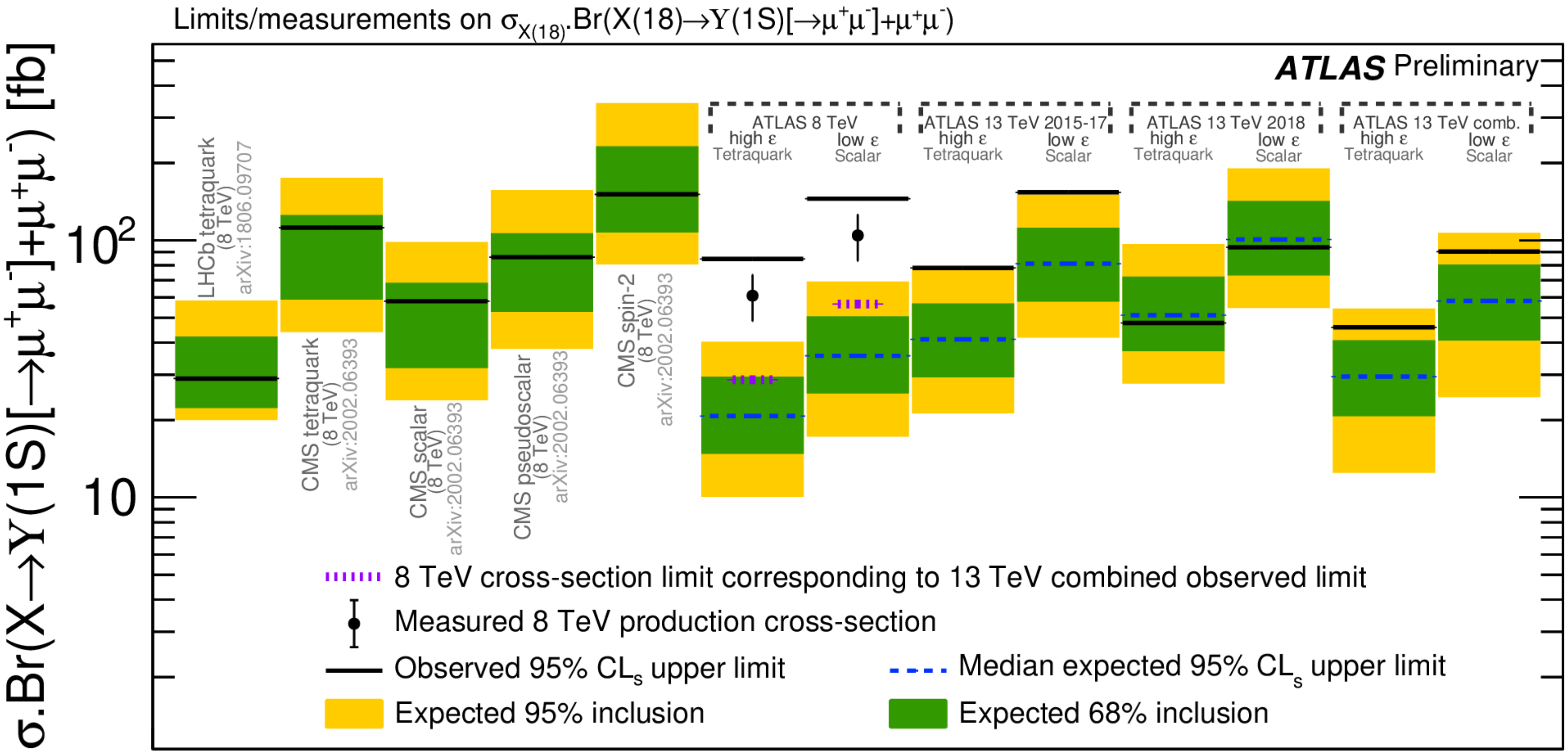
Expected/observed cross-section limits

Limits depend on physics model used in calculations, other factors (<u>very</u> preliminary)

Two models considered: tetraquark (higher efficiency) or scalar (lower efficiency)

8 TeV results compatible with tetraquark (scalar) with 60 fb (100 fb) cross section.

13 TeV results exclude the observed excess at 8 TeV at more than 95% CL for both models.



Outline of the Analysis

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Analysis performed for |y| < 0.75 of the $J/\psi\pi^+\pi^-$ system, for optimal tracking resolution

p_T bin boundaries: [10, 12, 16, 22, 40, 70] GeV

Effective pseudo-proper lifetime $\tau = \frac{L_{xy}\, m}{p_T}$ with $L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{p_T}$

bin boundaries: [-0.3, 0.025, 0.3, 1.5, 15.0] ps

Each $J/\psi\pi^+\pi^-$ candidate weighted to correct for trigger/reco/acceptance losses (next slide)

For each p_T and lifetime bin, binned minimum χ^2 fit in the $J/\psi\pi^+\pi^-$ invariant mass to determine ψ(2S) and X(3872) signal yields

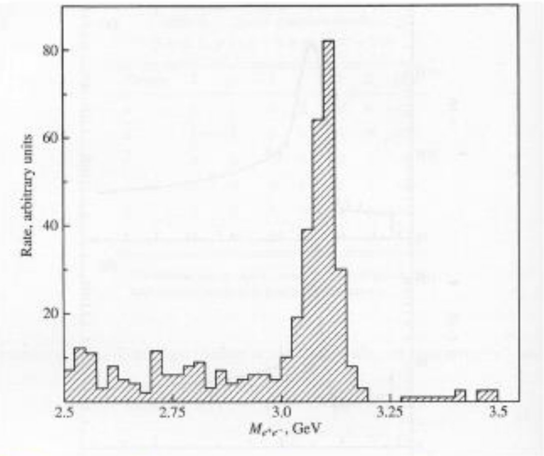
For each p_T bin, the yields in individual lifetime windows are subsequently fitted:

to determine lifetime dependence and hence

separate the signal into prompt and non-prompt components

The lifetime fits are performed separately for ψ(2S) and X(3872)

The Beginning: J/ψ



$\Leftarrow$ **Discovery 1:** Ting's group

$$pN \to e^+e^-X$$

at $P_{\text{lab}} = 30$ GeV/c

[Aubert et al., PRL, 6/11/1974]

Found a peak in e^+e^- inv.mass at 3.1 GeV, called it J.

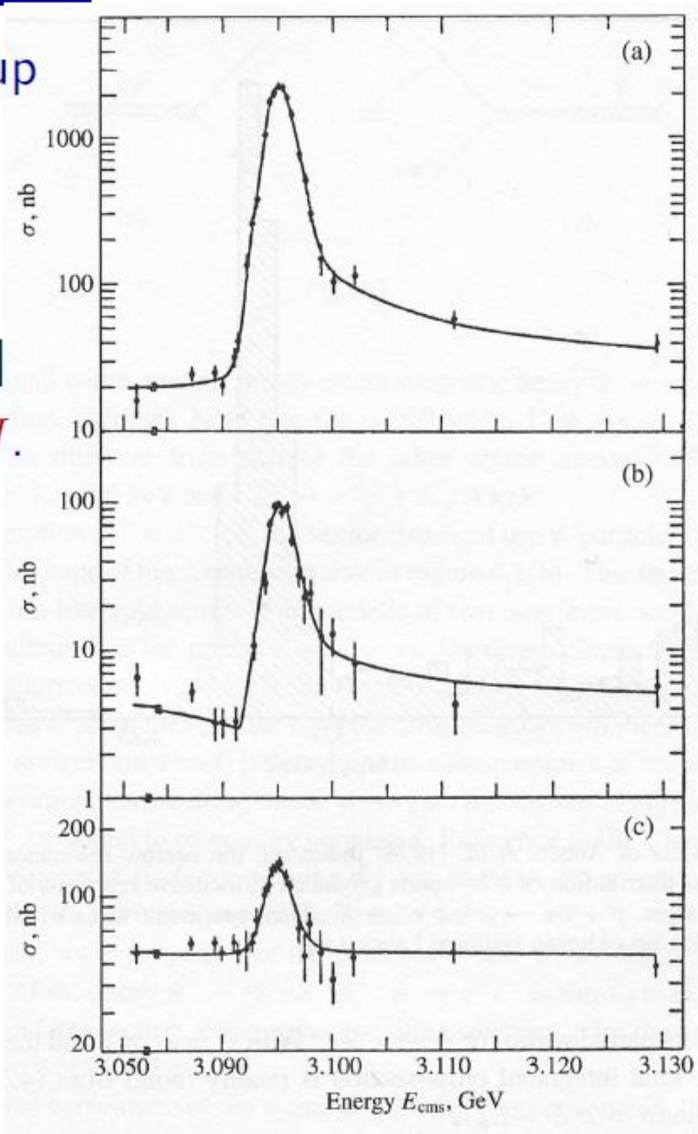
Discovery 2: Richter's group $\Rightarrow$

$$(a)\quad e^+e^- \to \text{hadrons}$$
$$(b)\quad e^+e^- \to \mu^+\mu^-$$
$$(c)\quad e^+e^- \to e^+e^-$$

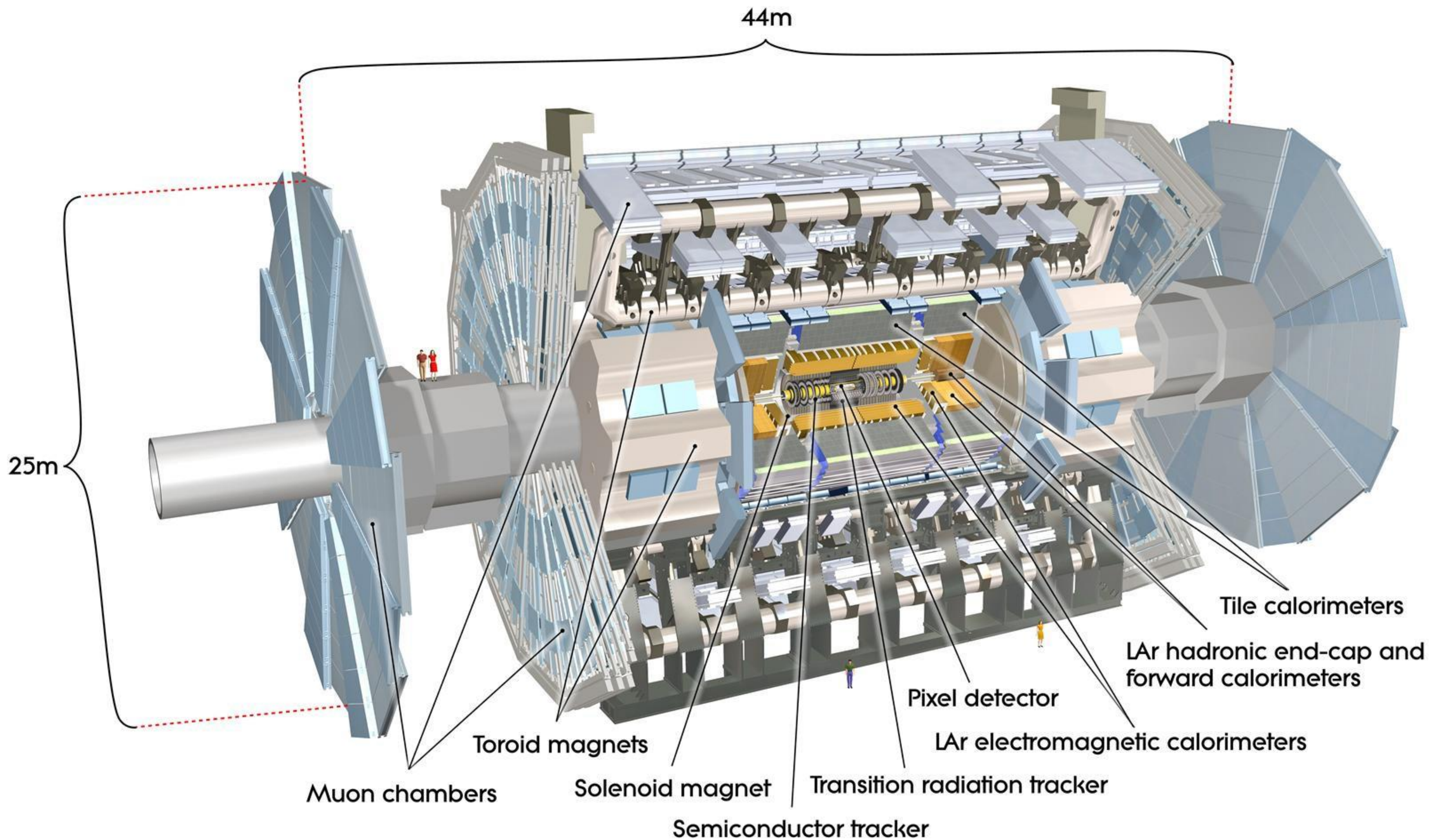
[Augustin et al., PRL, 7/11/1974]

Found a peak in all these three cross-sections,

at the c.m.s. energy 3.1 GeV; called it ψ.



The ATLAS detector at LHC



Observation of the $\chi_{bJ}(3P)$ state (media)

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22 December 2011 Last updated at 10:59

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LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

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Large Hadron Collider has first confirmed sighting of new particle (but it's not the Higgs)

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SCIENCE

Large Hadron Collider discovers a new particle: the Chi-b(3P)

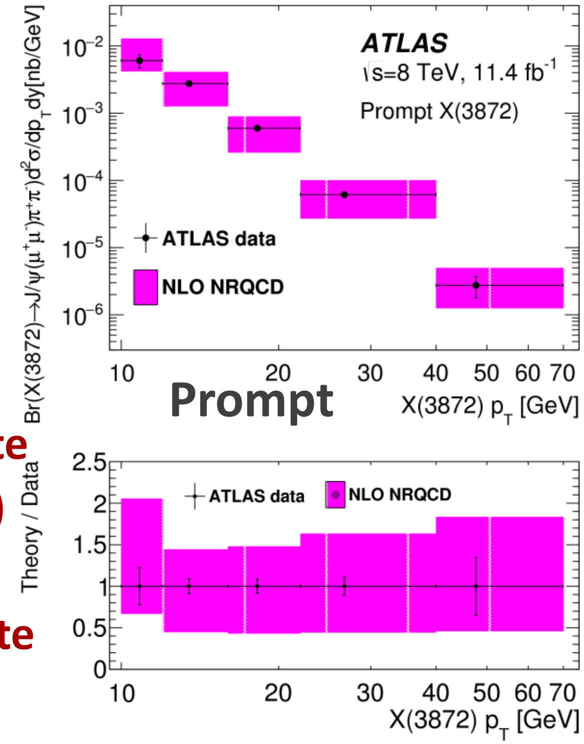
By Mark Brown | 22 December 11

Phys.Rev.Lett. 108 (2012) 152001

X(3872) cross sections

Prompt: **Described well by NLO NRQCD**

- assumes X(3872) is a mix $\chi_{c1}(2P)$ - $(D^0 D^{0*})$
- $\chi_{c1}(2P)$ coupling assumed responsible for production
- parameters fitted to CMS data
- **not surprising, CMS and ATLAS consistent**



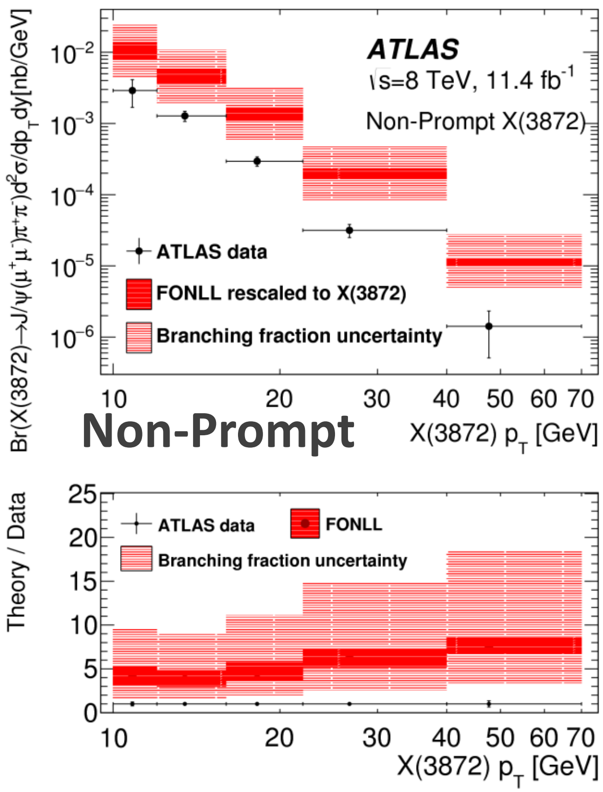
Non prompt:

use the same kinematic template to recalculate FONLL from ψ(2S)

BR not measured – used estimate
from Artoisenet, Braaten
based on Tevatron data [hep-ph:0911.2016]

$$R_B = \frac{Br(B \to X(3872))Br(X(3872) \to J/\psi\pi^+\pi^-)}{Br(B \to \psi(2S))Br(\psi(2S) \to J/\psi\pi^+\pi^-)}$$ **= 18±8 %**

Clearly overshoots the data:
factor of 4 to 8, increasing with pT



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