Measurements of Heavy Flavour Production @ ATLAS & CMS

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(on behalf of ATLAS & CMS collaborations)

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Motivation to study Heavy Flavour @ LHC

With LHC Run-I data : great impact of LHC experiments in the heavy flavour sector !

- Besides LHCb which is a dedicated experiment, **CMS & ATLAS are giving significant contributions to beauty and quarkonium sectors**, mainly using final states containing muon pairs (trigger constraints). This is possibile thanks to excellent **tracking** and **muon identification** performances, combined to a flexible trigger system essential to collect data @ increasing luminosity (and pile-up).
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  - Production xsection and polarization measurements of *S*- & *P*-wave states of conventional quarkonium allow to study the hadron formation within the NRQCD framework.
  - Perturbative & non-perturbative QCD models for B hadrons production/fragmentation are tested. Dynamics of heavy quarks inside hadrons, decay models and spectroscopy are studied.
  - Quarkonium-like exotic states can be searched for; if established their nature can be explored.
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  - Quarkonium-like exotic states can be searched for; if established their nature can be explored.
- The large production cross-sections for heavy flavoured particles in *pp* collisions at LHC energies provides opportunities for **testing the Standard Model picture of flavour dynamics**.
  - Precision measurements of rare decays & CP violation are sensitive to effects of particles beyond the SM, thus allowing to look for indirect evidence or constraints to NP [through *B* meson decays mediated by FCNC transitions].

OUTLINE

- Quarkonium production rates @ LHC are rather high ⇨ LHC is a "quarkonium factory"

This contribution will only focus on a **few selected topics** with **recent results by ATLAS/CMS** mainly related to **quarkonium promptly produced alone or in association with another quarkonium or a vector boson**:

PART-I

- $J/\psi,\ \psi(2S)$ — CMS, PRL 114 (2015) 191802; ATLAS, JHEP 09 (2014) 079 & NPB 850 (2011) 387
- $\Upsilon(nS)\ ,\ n=1,2,3$ — CMS, arXiv:1501:07750
- $\frac{\sigma(\chi_{b2}(1P))}{\sigma(\chi_{b1}(1P))}$ — CMS, PLB 743 (2015) 383
- χ_{c1}, χ_{c2} — ATLAS, JHEP 07 (2014) 154

PART-II

- $J/\psi + J/\psi$ — CMS, JHEP 09 (2014) 094
- $J/\psi + Z$ — ATLAS, arXiv:1412:6428; accepted by EPJC ($J/\psi + W$ — ATLAS, JHEP 04 (2014) 172)

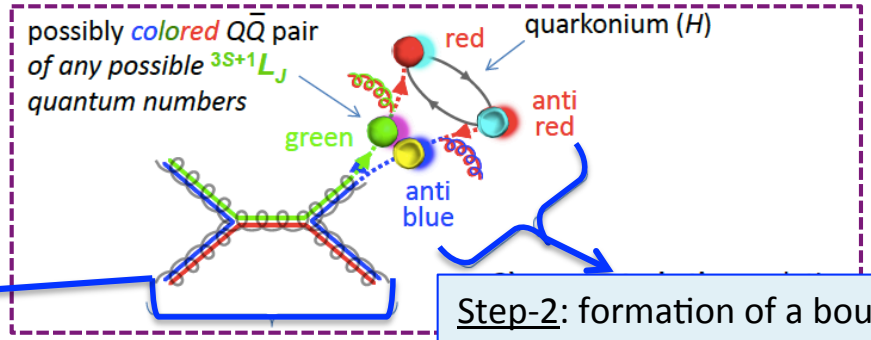
- Search for X_b — ATLAS, JHEP 740 (2015) 199; CMS, PLB 727 (2013) 57

- More results can be found at:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
  - CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

PART-I

Reference theory of production (& polarization) of quarkonia

NRQCD : effective field theory that treats heavy quarkonia ($c\bar{c}$, $b\bar{b}$) as non-relativistic systems.
Inclusive quarkonium production can be factorized in two distinct phases:



Step-1: $Q\bar{Q}$ production in the regime of perturbative QCD

Step-2: formation of a bound state driven by non-pert. QCD

Inclusive xsection for producing quarkonium (***H***) with enough large momentum transfer p_T :

$$\sigma\left(A+B\to H+X\right)=\sum_n \sigma\left(A+B\to\left[Q\bar{Q}\right]_n+X\right)\cdot P\left(\left[Q\bar{Q}\right]_n\to H\right) \quad , \quad n=^{2S+1}L_J^{[C]}$$

Short-distance coefficients (SDCs)

calculated by perturbative QCD (expansions in α_S)

Long-distance matrix elements (LDMEs)

determined from fits to experimental data

relative relevance given by $v=v/c<<1$ **(scaling rules)**

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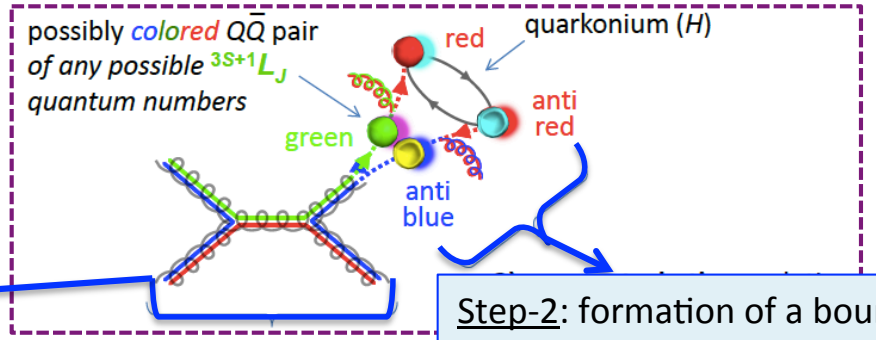

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Theoretical predictions are organized as double expansions in α_S and v.
Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
- Color Singlet (CS) term
- 3 Color Octet (CO) terms

NRQCD predicts the existence of intermediate CO states in nature, that subsequently evolve into physical color-singlet quarkonia by non-perturbative emission of soft gluons.

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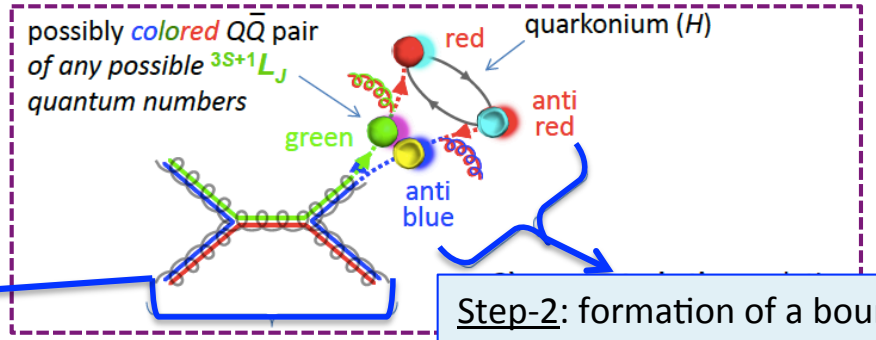

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Recent developments to explain production Xsections **& polarizations** get reasonable agreement with data excluding data at low p_T : **unpolarized CO contribution dominates the production (more in backup)**
[**FKLSW, PLB 736 (2014) 98** (data-driven approach)][**PRL 113 (2014) 022001** (leading-power fragm. formalism)]

Prompt & non prompt quarkonium production

- Quarkonium production occurs through :
  - **a)** **Prompt** production: **direct** QCD process or **feed-down** from higher quarkonium states
  - **b)** **Non-prompt** production : from decays of long-lived b-hadrons (**charmonia only**)

  - The study of quarkonium **prompt production** is suited to understand how quarks combine into a bound state (hadron) [not easy: it is part of the non-perturbative QCD sector].
    The related measurements include **production cross sections & polarizations .**
    Needed precise knowledge of **efficiencies**: data-driven & accounted on an event-by-event basis.

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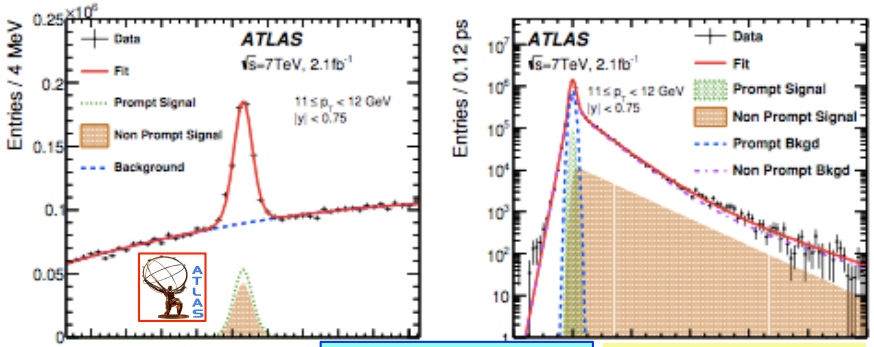
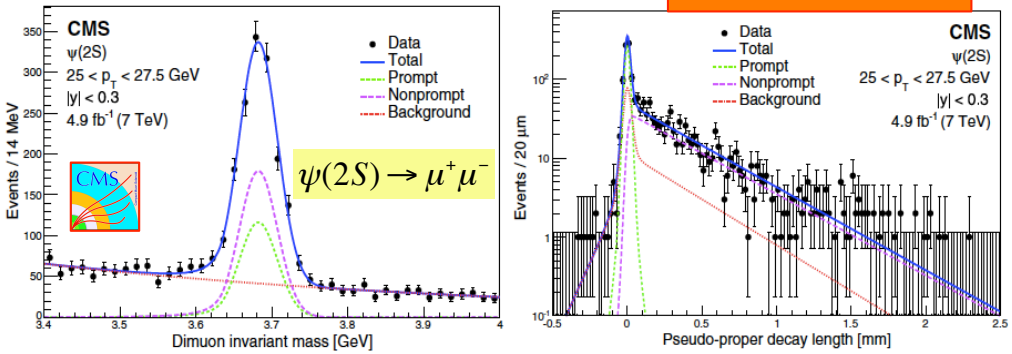
- **Both ATLAS & CMS use a *2D mass+pseudo-proper time fit* to measure prompt & non-prompt yields simultaneously and disentangle the two contributions :**



JHEP 09 (2014) 079 $\psi(2S) \to J/\psi\,\pi^+\pi^-$



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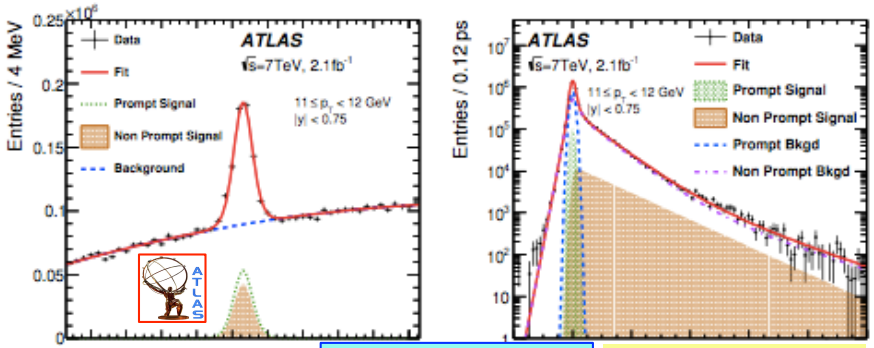

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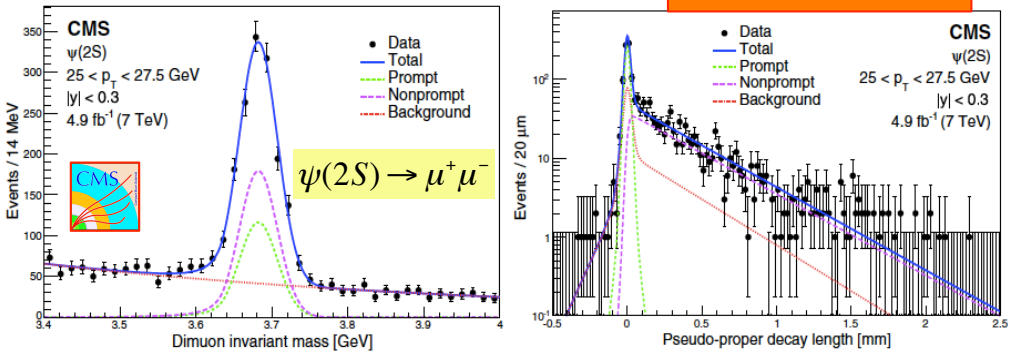

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- **Feed-down can be relevant** [only *ψ(2S)* is free]: for instance, **P-wave radiative decays to S-wave states**: χ_{cJ} for J/ψ and χ_{bJ} for Υ(nS); LHCb recently found for Υ(3S) ~40% feed-down by $\chi_{bJ}(3P)$!
  It would be very useful - for future measurements - to **separate feed-down contributions from direct ones** (photons & pions with low energy are difficult to be reconstructed).

Prompt production Xsections for S-wave quarkonia

$$J/\psi,\ \psi(2S),\ \Upsilon(nS)_{n=1,2,3}$$

CMS, PRL 114 (2015) 191802

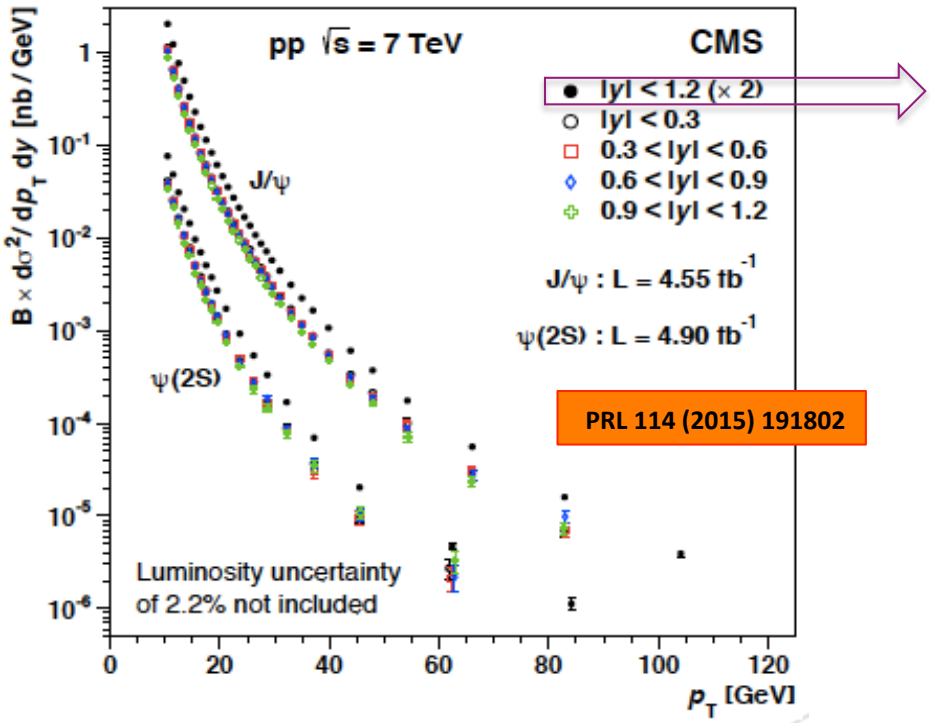
CMS, arXiv:1501:07750

ATLAS, JHEP 09 (2014) 079 & NPB 850 (2011) 387

ATLAS has "older" measurement (with only part of 2011 dataset): PRD87 (2013) 052004

Prompt production Xsections of charmonium S-wave states

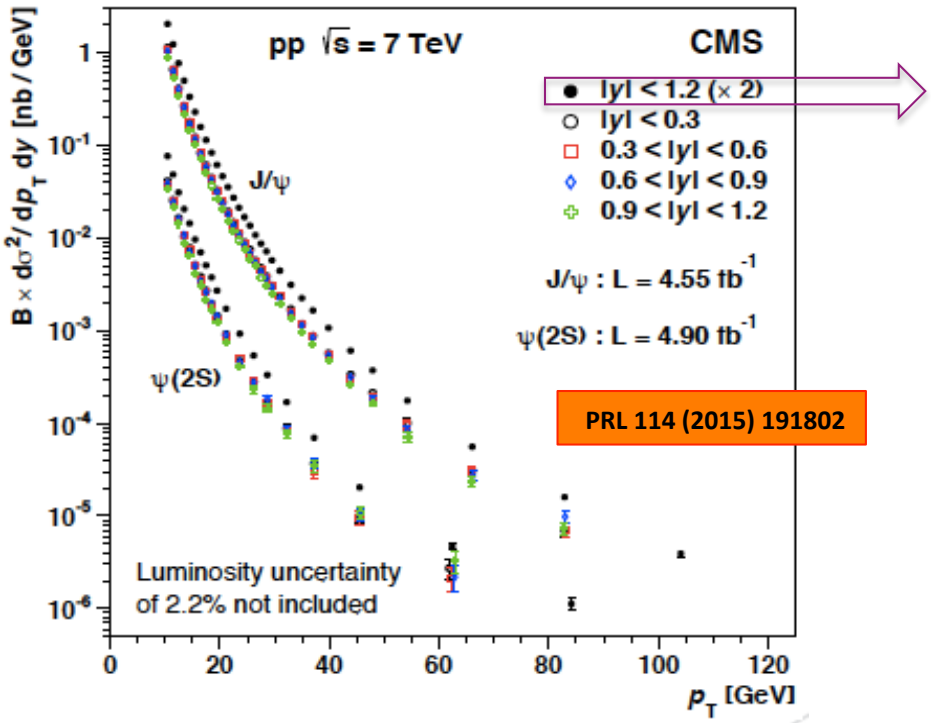
- **Double differential prompt prod. Xsections times the dimuon branching fractions for $J/\psi,\ \psi(2S)$ as a function of p_T in 4 rapidity bins &** **(assuming unpolarized scenario)**
  [uncertainties from int. luminosity and branching fractions not included**]:**

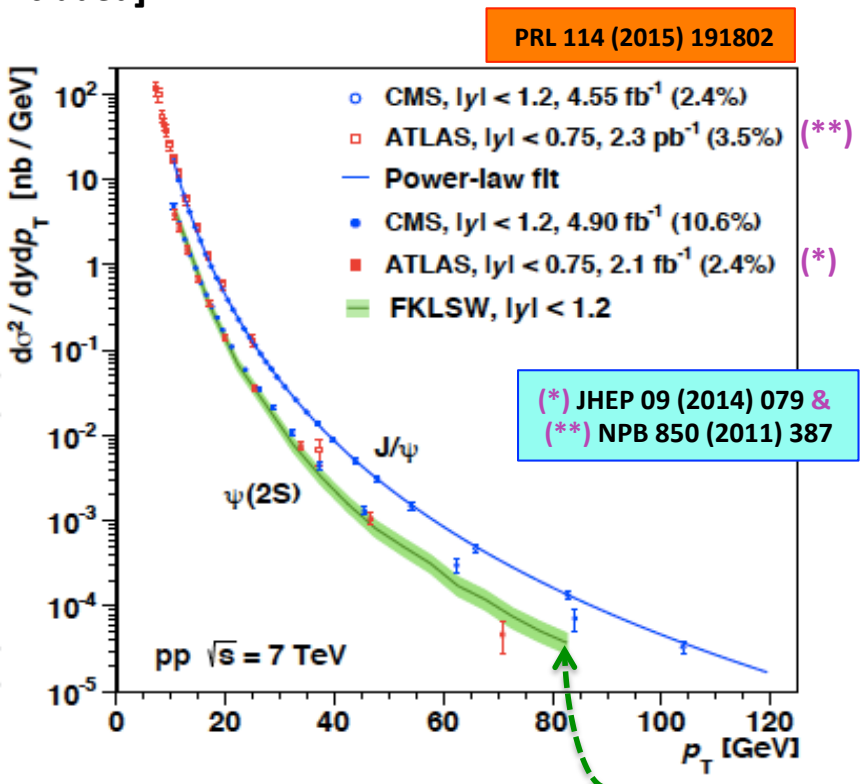


- Significant improvement in terms of precision and p_T reach ($p_T \approx 100 GeV$)

Prompt production Xsections of charmonium S-wave states

- **Double differential prompt prod. Xsections times the dimuon branching fractions for J/ψ, $\psi(2S)$ as a function of p_T in 4 rapidity bins & integrated over the range $|y|<1.2$ (assuming unpolarized scenario)** [uncertainties from int. luminosity and branching fractions not included]:

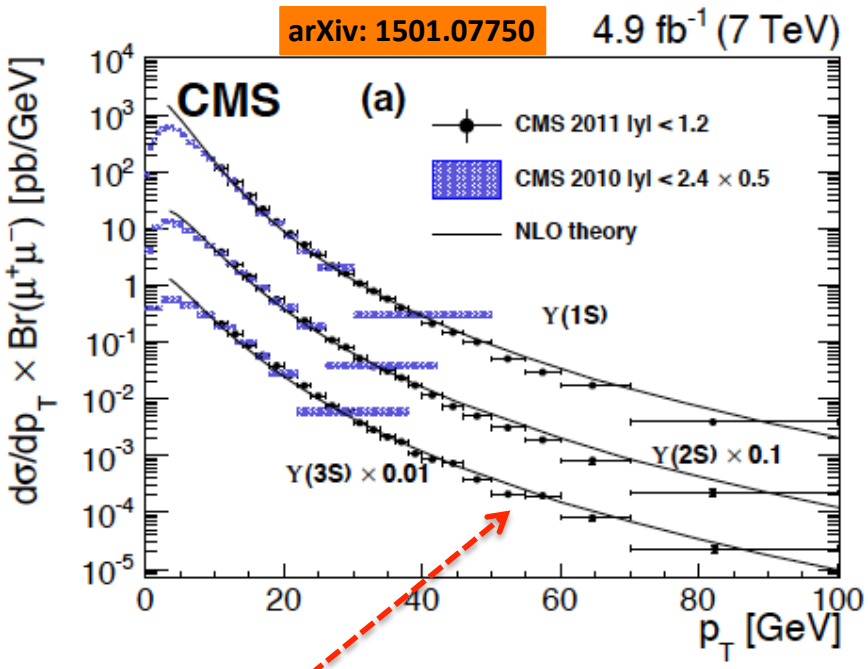


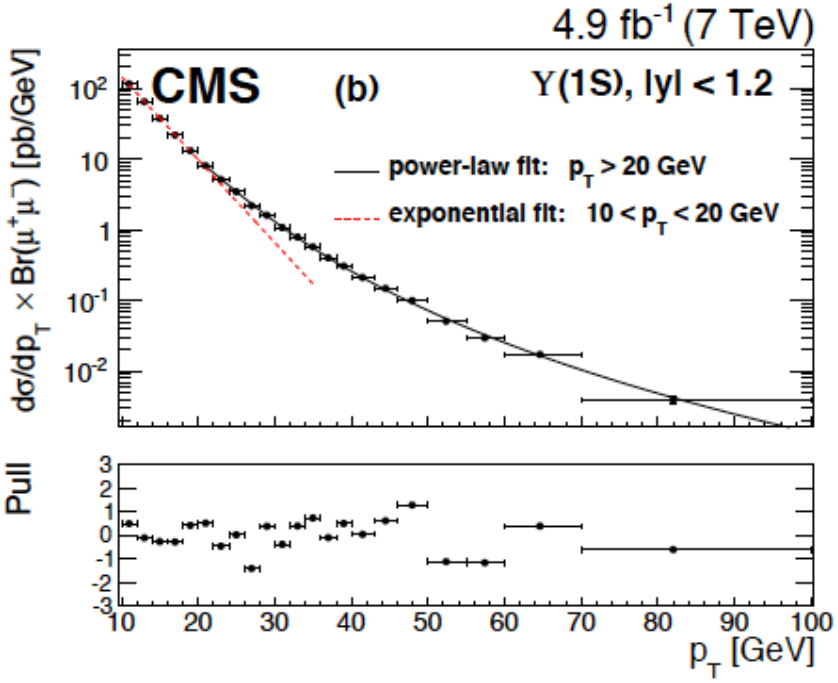


- Significant improvement in terms of precision and p_T reach ($p_T \approx 100 GeV$)
- Blue curve shows a **power-law fit** to J/ψ xsection
- **Green band - labelled FKLSW - represents a calculation of the $\psi(2S)$ xsection using LDMEs determined in a global fit of Xsections and polarizations** [PLB 736 (2014) 98]; Note: according to that fit $\psi(2S)$ mesons are **produced predominantly unpolarized**.

Prompt production Xsections of bottomonium S-wave states

- **Differential prompt prod. Xsections times the dimuon branching fractions for $\Upsilon(nS)$ as a function of p_T over the range $|y| < 1.2$ [uncertainty from int. luminosity not included]**





- All 3 Υ(*n*S) states show similar trends

- **NLO calculations** from [Gong *et al.*, PRL 112, 032001 , for $p_T < 50$ *GeV*] have been extended to cover the range **p_T < 100 GeV** and describe data trend for all 3 Υ(nS) states!

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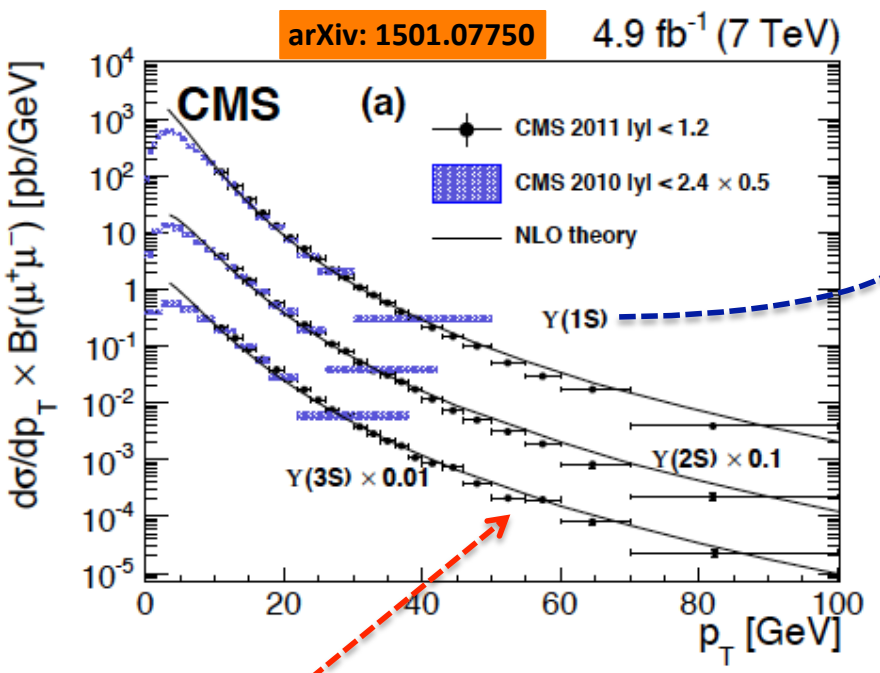

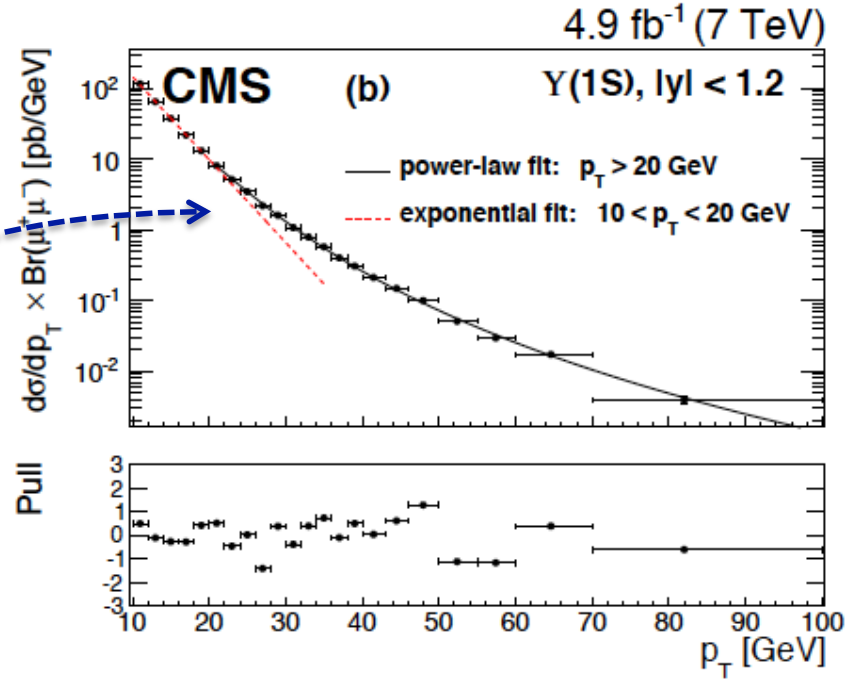

- All 3 Υ(*n*S) states show similar trends
- Measured Xsections show a transition from exponential to power-law behaviour at $p_T \sim 20$ GeV (fit holds for all the 3 states)

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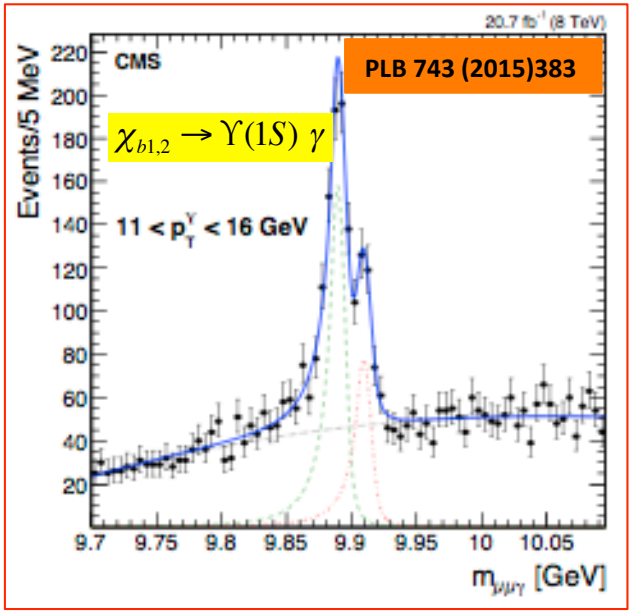
CMS, PLB 743 (2015) 383

χ_{c1}, χ_{c2}

ATLAS, JHEP 07 (2014) 154

Relative production rate of $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$

- P-wave states measurements are crucial to understand quarkonium production. They also help to …
  - … study feed-down effects into S-wave states
  - … constrain CO LDMEs of the χ_c and χ_b states in NRQCD fits to S-wave production/polarization data
- Reconstruction of photons by conversions into e^-e^+ pairs provides enough mass resolution to resolve the two peaks (with 19*MeV* separation)



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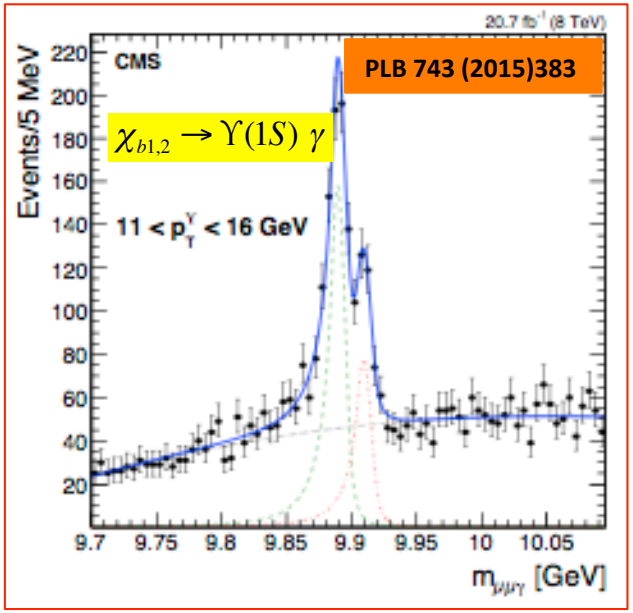

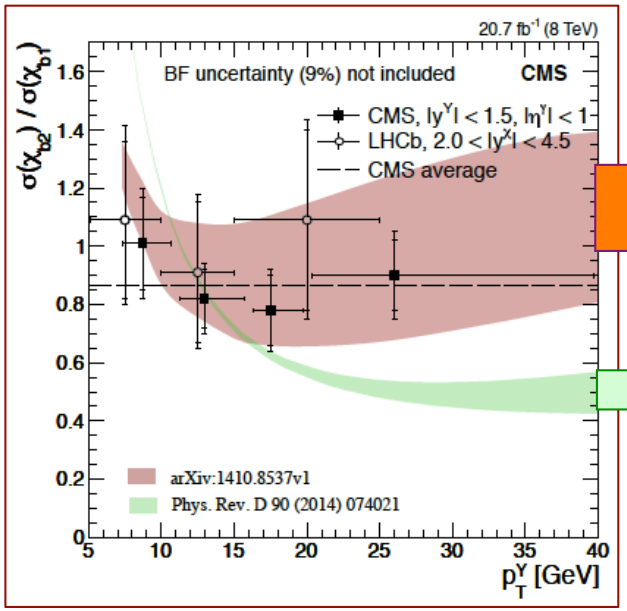

CMS & LHCb data consistent & compared with two different NLO NRQCD calculations (and fits based on different experimental data)

Improve p_T reach & accuracy with Run-II data !

Measurement @ hadron colliders with **smaller uncertainties** for this production cross section ratio (corrected for the ratio of the BFs):

$$< R > \equiv \left\langle \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} \right\rangle = 0.85 \pm 0.07(\text{stat+syst}) \pm 0.08\left(BF(\chi_{b1,2} \to Y(1S) + \gamma)\right)$$

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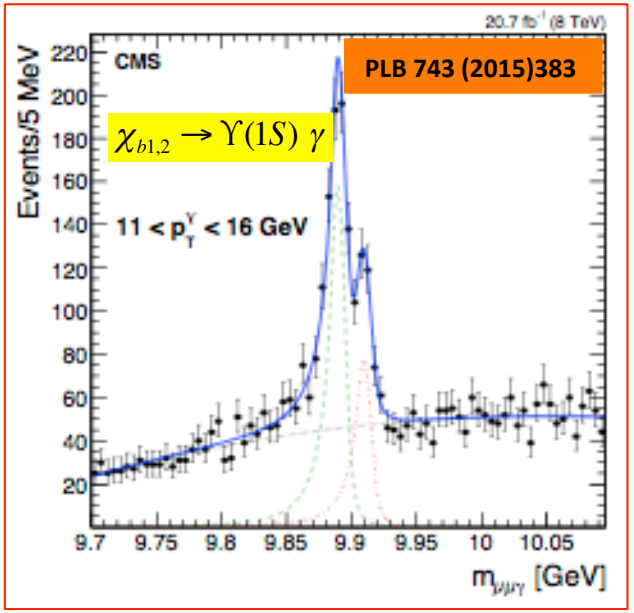

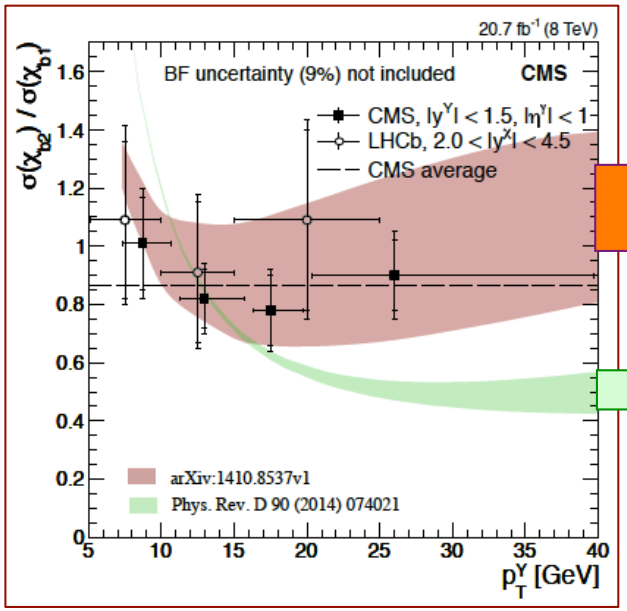

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- Before $\frac{\sigma(\chi_{b2}(1P))}{\sigma(\chi_{b1}(1P))}$, CMS (and ATLAS) already measured $\frac{\sigma(\chi_{c2}(1P))}{\sigma(\chi_{c1}(1P))}$ with same technique

EPJ C72 (2012) 2251

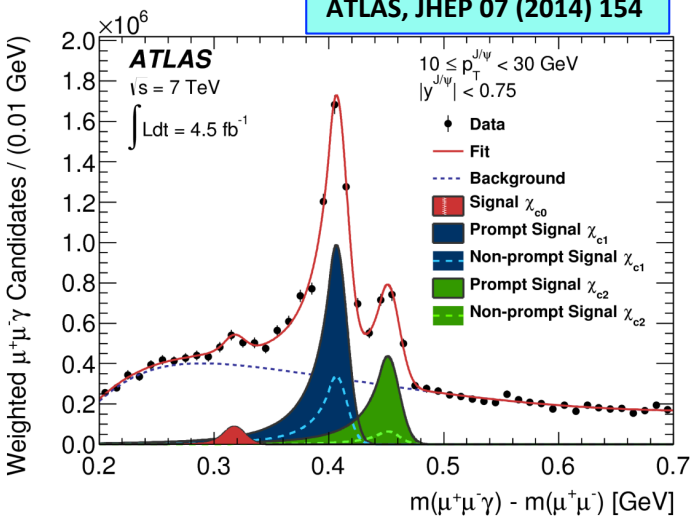
JHEP 07 (2014) 154

Prompt production Xsections of charmonium P-wave states

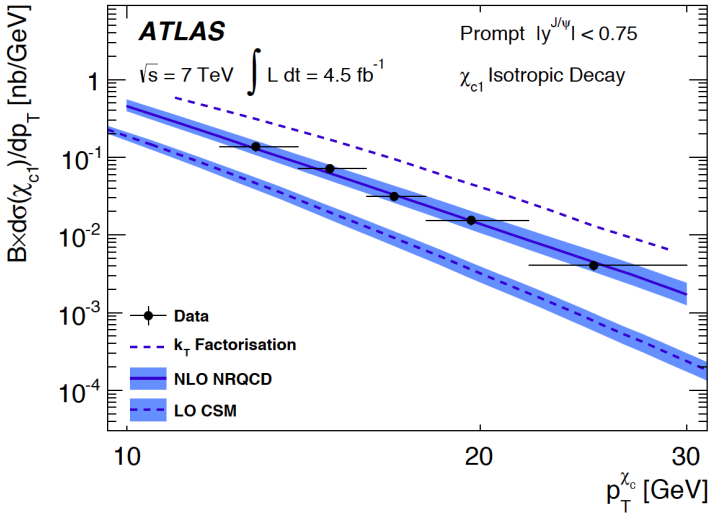
- **By measuring the differential xsection for the prompt production of χ_{c1} & χ_{c2} (reconstructed in their decays $\chi_{c1,2} \to J/\psi\gamma$)**
  ATLAS is the first LHC experiment to provide an absolute production xsection for a P-wave quarlonium state.

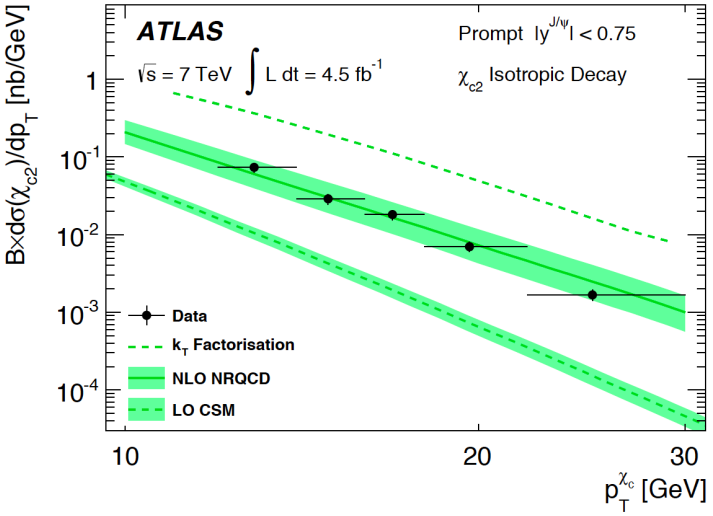
This is a challenging result given very low photon conversion and reconstruction efficiencies. ATLAS has slightly worse $\chi_{c1,2}$ mass resolution & bkg fraction but higher detection efficiency than CMS.

ATLAS, JHEP 07 (2014) 154



Differential xsection are provided in bins of either $p_T^{J/\psi}$ & $p_T^{\chi_c}$:





- **Data are well described by NLO NRQCD predictions [PRD 83 (2011) 111503]**

PART-II

Single/Double Parton Scattering & associated production

- **High flux of incoming partons @ LHC energy ⇨ more than one parton pair may scatter in a pp collision**

  The general assumption is that single parton scattering (SPS) is the dominant process
  [the dominant J/ψ production process in pp collisions @LHC is gluon-gluon fusion]

  Multiparton scattering contributions difficult to be addressed within perturbative QCD framework :
  new measurements can help the creation of more realistic particle production models !

- Two possible production modes of quarkonia produced in association with additional objects (other quarkonia, vector bosons, jets, top, …) :
  - Single Parton Scattering (SPS) : objects from same diagram, resonant or non-resonant
  - Double Parton Scattering (DPS): objects from a separate parton-parton collision (from the same p-p interaction)

While DPS processes are not distinguishable event-by-event from SPS interactions, azimuthal angular correlations between the two objects are expected to be different!

Single/Double Parton Scattering & associated production

- **High flux of incoming partons @ LHC energy ⇨ more than one parton pair may scatter in a pp collision**

  The general assumption is that single parton scattering (SPS) is the dominant process
  [the dominant J/ψ production process in pp collisions @LHC is gluon-gluon fusion]

  Multiparton scattering contributions difficult to be addressed within perturbative QCD framework :
  new measurements can help the creation of more realistic particle production models !

- Two possible production modes of quarkonia produced in association with additional objects (other quarkonia, vector bosons, jets, top, …) :
  - Single Parton Scattering (SPS) : objects from same diagram, resonant or non-resonant
  - Double Parton Scattering (DPS): objects from a separate parton-parton collision (from the same p-p interaction)

  While DPS processes are not distinguishable event-by-event from SPS interactions, angular correlations between the two objects are expected to be different!

- Further motivation for great interest into associated production:
  - Additional observables & final states provide further constraints on CS & CO contributions
  - Searches in new final states: exotic tetraquarks, supersymmetric Higgs, …
    Study of Higgs boson charm couplings; background studies for Higgs decays,…
  - For additional vector bosons (Z,W) : no need of dedicated quarkonia triggers

Prompt double J/ψ production

CMS, JHEP 09 (2014) 094

Prompt double J/ψ production - I

- **It probes specific mechanisms of $c\bar{c}c\bar{c}$ system production and transformation to two mesons that can be potentially sensitive to DPS.**

  At the parton level the two J/ψ mesons are either produced as CS states or CO states that turn into color-singlets after emitting soft gluons. **CO contributions should play a greater role as p_T increases.**

  The strong correlation of the two J/ψ mesons produced via SPS interaction should result in small values of the absolute rapidity difference $|\Delta y|$: large $|\Delta y|$ values are possible for DPS production.

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  Moreover, **resonant states can be searched in a wider J/ψ pair invariant-mass range, i.e. :**

  - $\eta_b \to J/\psi J/\psi$ [in analogy with $\eta_c \to \phi\phi$] predicted to be highly suppressed by NRQCD calculations
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- **LHCb** [**PLB 707 (2012) 52**] xsection for J/ψ pair production in pp collisions @ $\sqrt{s} = 7TeV$: $\sigma = (5.1 \pm 1.0 \pm 1.1)nb$
  Theoretical calculations (SPS, based on LO production of CS states) predict $\sigma_{th} \cong 4nb$ (with a ~30% uncert.) in the LHCb phase-space region: $2 < y^{J/\psi} < 4.5$ & $p_T^{J/\psi} < 10\,GeV/c$, **consistent with measured value**.

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CMS J/ψ production phase space (higher $p_T^{J/\psi}$, more central rapidity) is complementary to that of LHCb and **provides access to the $p_T^{pair} > 15GeV/c$ region for which no theoretical calculations are available !**

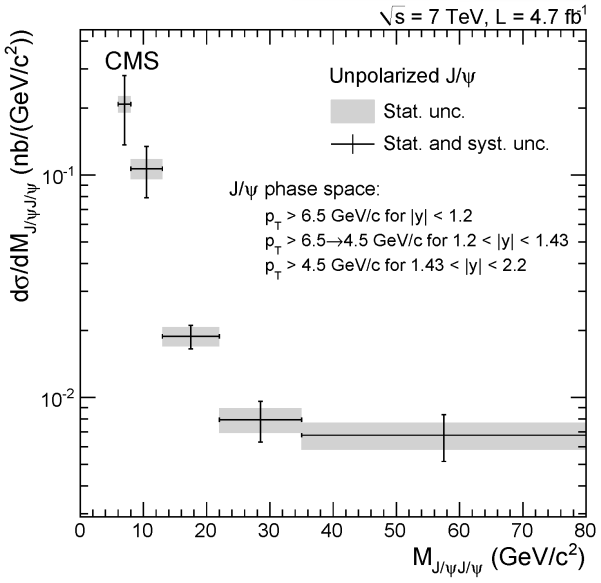
CMS can provide new information useful to the development of production models that include CO contributions, higher-order corrections & DPS.

Prompt double J/ψ production - II

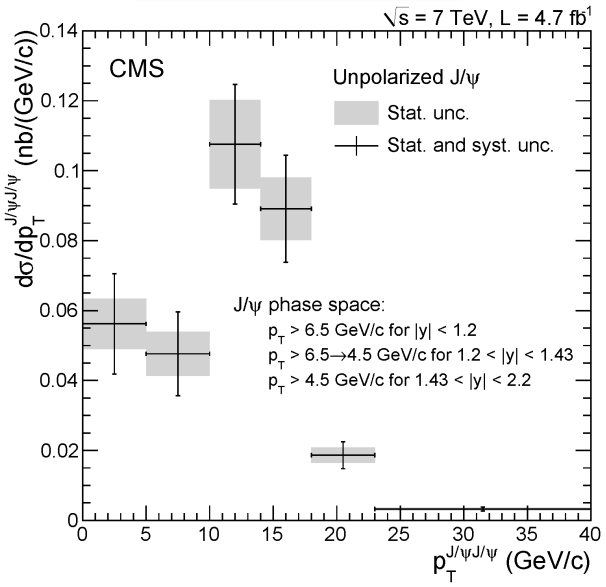
- A signal yield of 446 ± 23 events for the production of prompt J/ψ pairs observed by CMS [see backup]

Differential xsections in bins of :

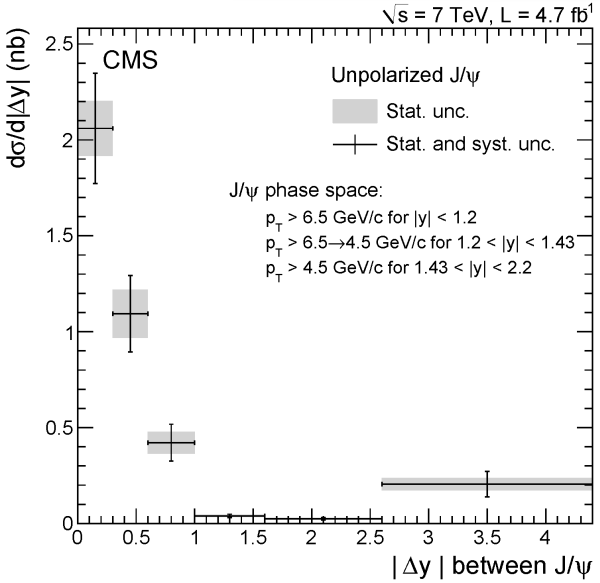
1) J/ψ pair invariant-mass



2) p_T of the J/ψ pair



3) the absolute rapidity difference $|\Delta y|$



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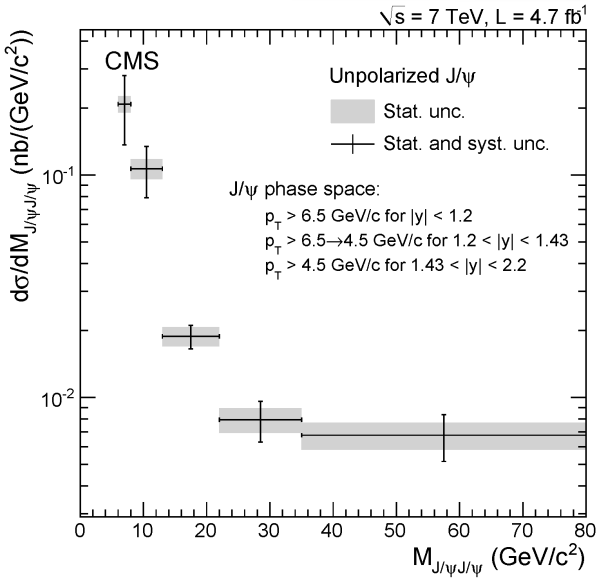

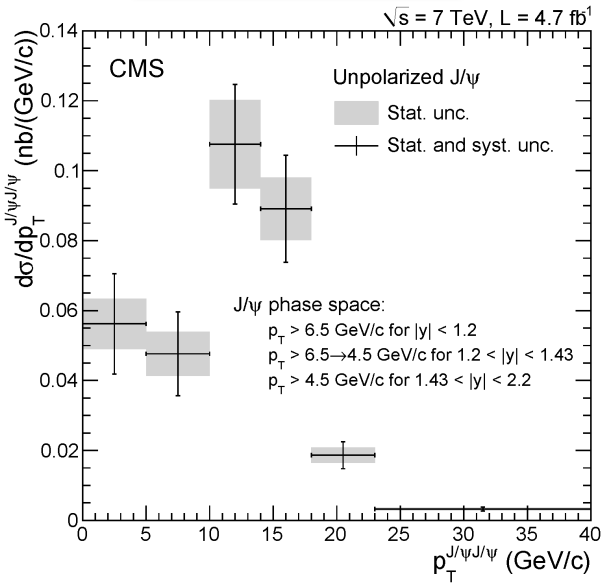

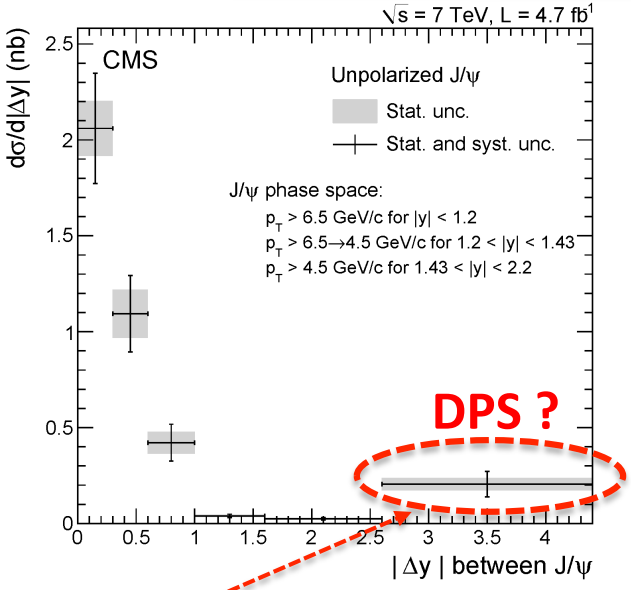

The differential xsections decreases rapidly as a function of $|\Delta y|$, but a non-zero value is measured in the last bin ($2.6 < |\Delta y| < 4.4$) where the DPS contribution is expected to dominate populating the bin !

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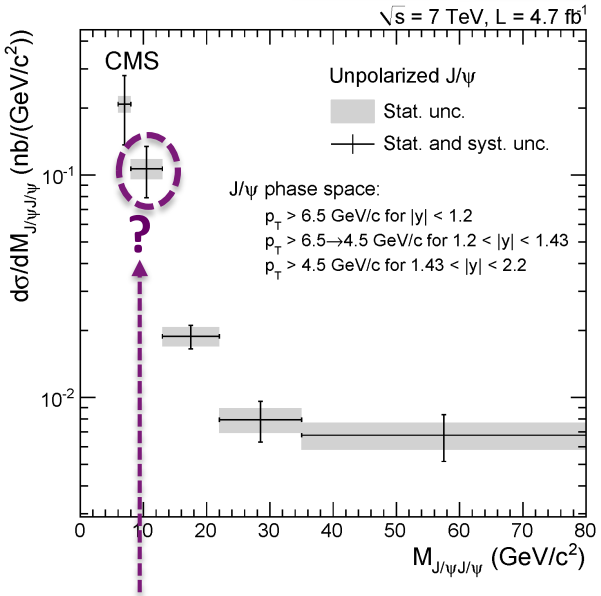

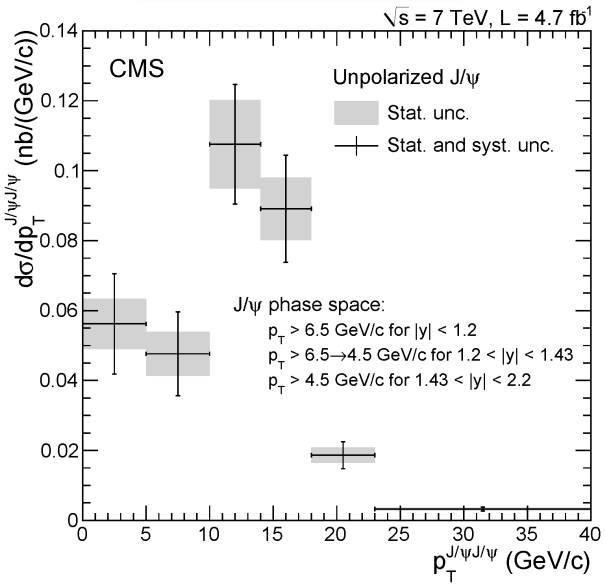

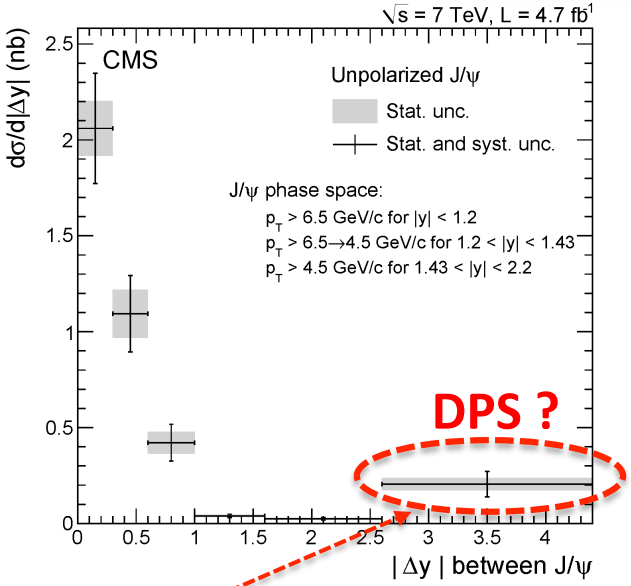

There is **no evidence** for the η_b resonance in the J/ψ pair invariant mass distribution: the yield in the η_b 3σ-signal window [$(9.16 \div 9.64) GeV/c^2$] is $\cong 15$, agreeing with the 15 ± 4 expectations derived from the J/ψ sideband regions.

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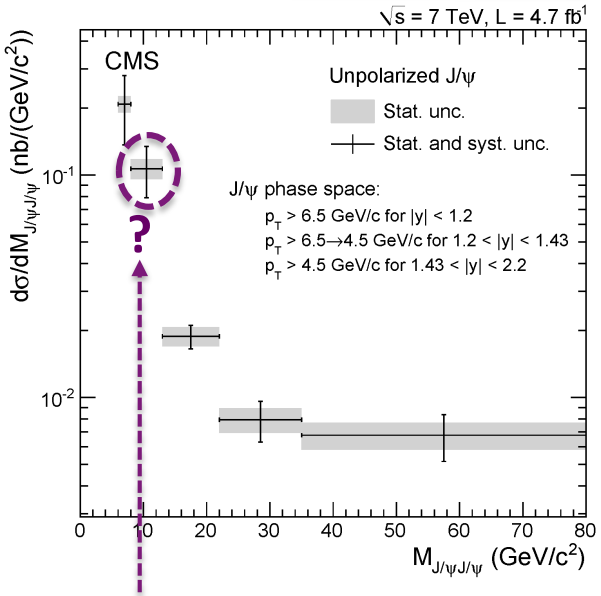

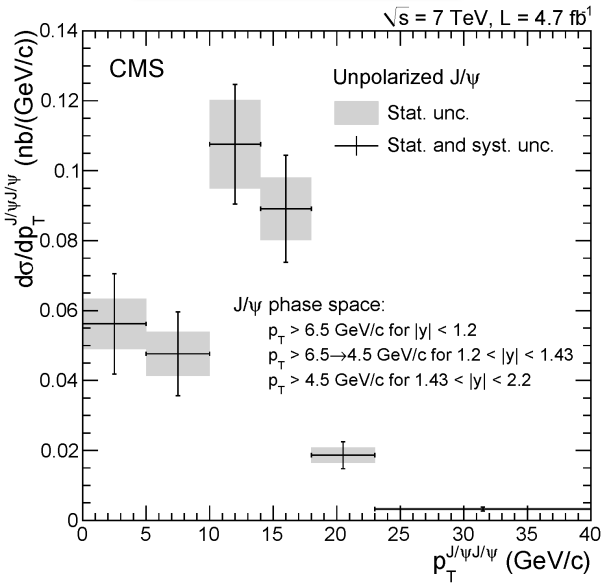

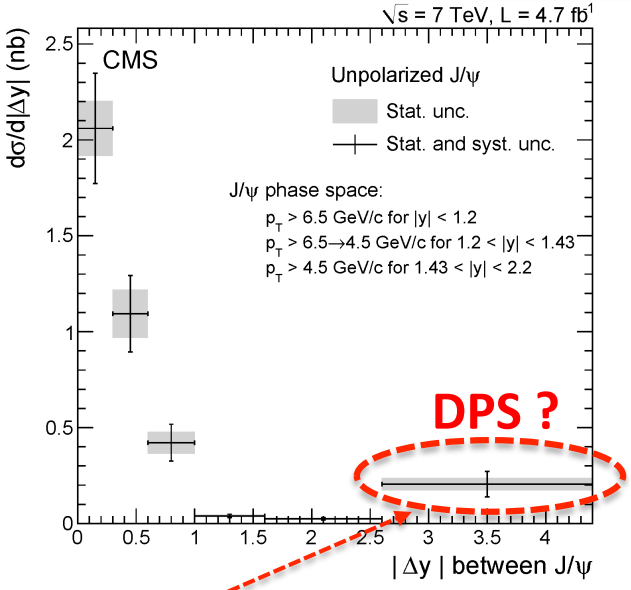

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- **Total prompt double** production xsection (assumed unpolarized): $\sigma(pp \to J/\psi J/\psi + X) = (1.49 \pm 0.07 \pm 0.13) nb$
- **To be redone with 8TeV Run-I data and Run-II data**

Prompt & non-prompt J/ψ production in association with a Z boson

$J/\psi + Z \ @\sqrt{s} = 8TeV$ ATLAS, arXiv:1412:6428; accepted by EPJC

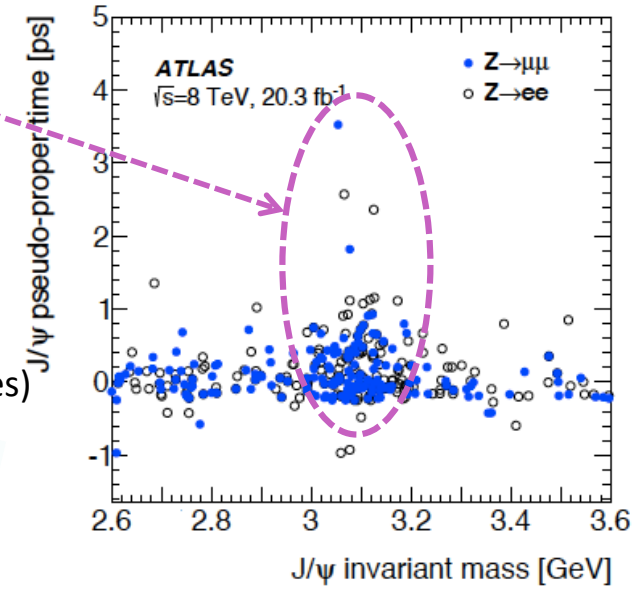
[The production of a prompt J/ψ in association with a W ($J/\psi + W^{\pm} \ @\sqrt{s} = 7TeV$) was previously observed by ATLAS, JHEP 04 (2014) 172 (see backup)]

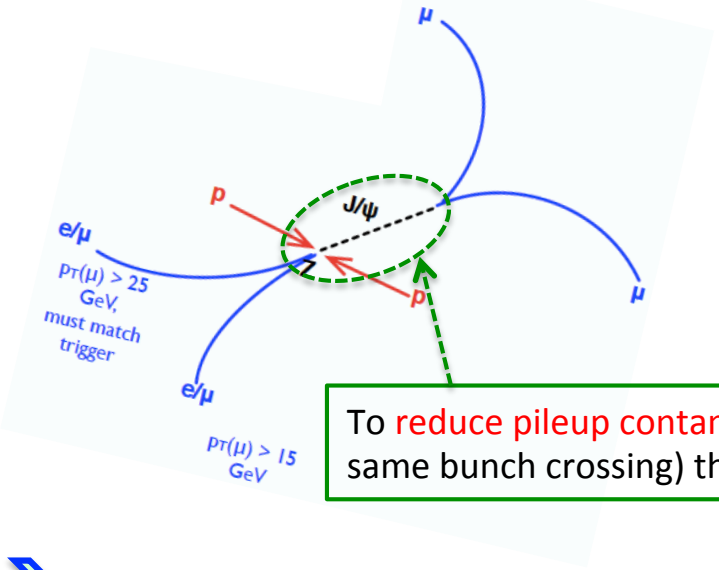
J/ψ production in association with a Z boson - I

Final states: $\mu\mu\mu\mu$, $\mu\mu ee$
(prompt/non-prompt $J/\psi \to \mu\mu$ **)**

Triggers: single high-p_T **μ /e**
$[p_T > 24GeV]$

Same-flavour, opposite-sign lepton pairs are fitted to a dilepton common vertex (with inv.-masses close to Z and J/ψ masses)





To reduce pileup contamination (where Z & J/ψ produced from two separate pp collisions in the same bunch crossing) the two vertices must not be separated by more than 10*mm* in the z-direction

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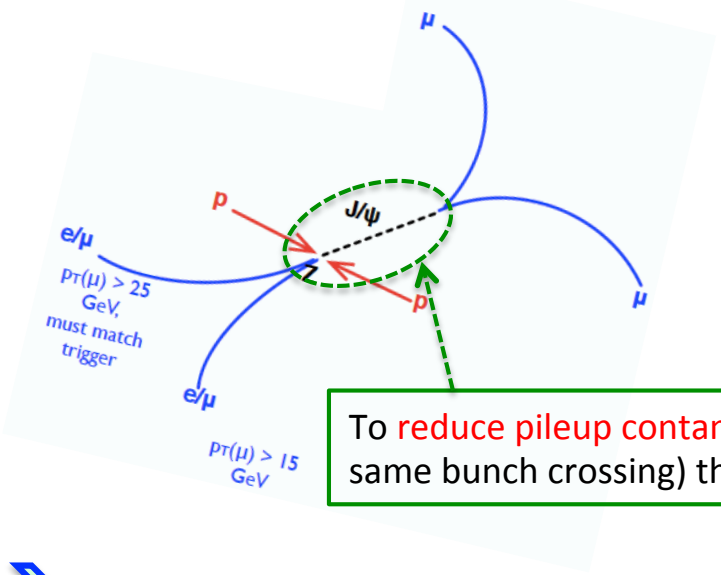
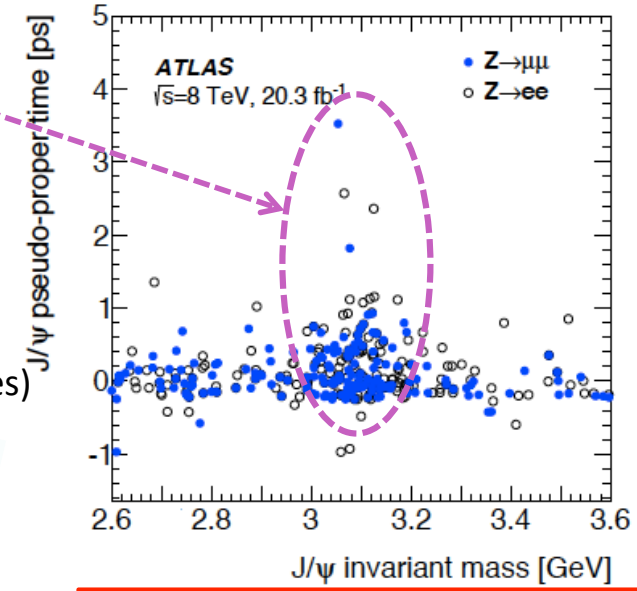
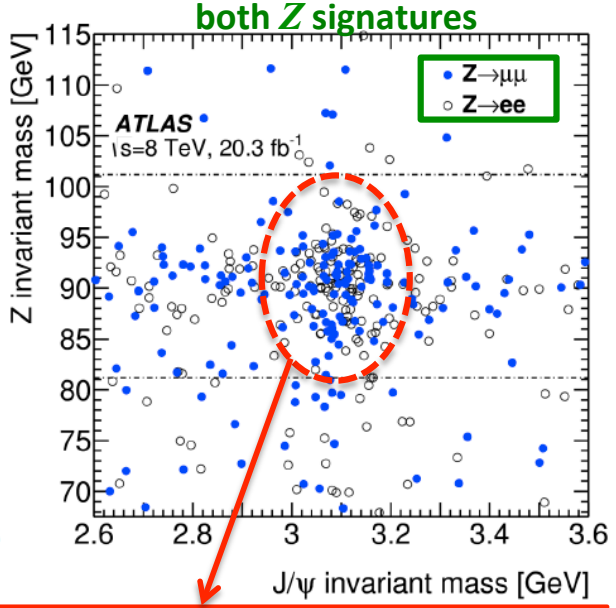


both Z signatures





Established the (first) observation of both *associated* Z+(prompt J/ψ) & Z+(non-prompt J/ψ) *production*, with the bkg-only hypothesis being excluded at 5σ & 9σ respectively!

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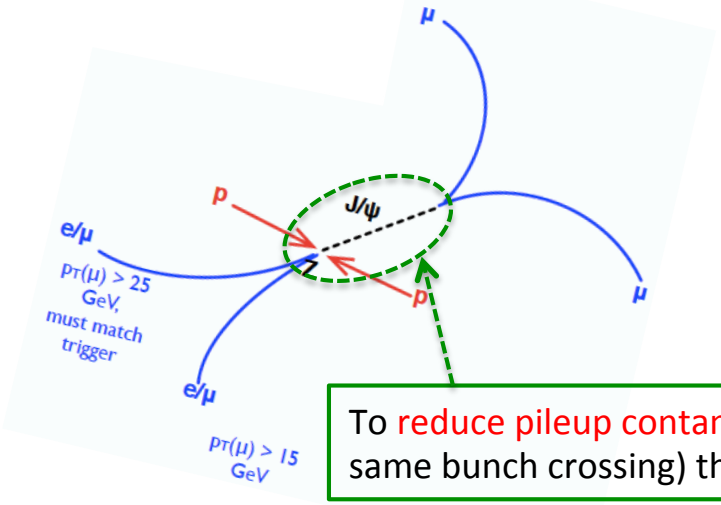

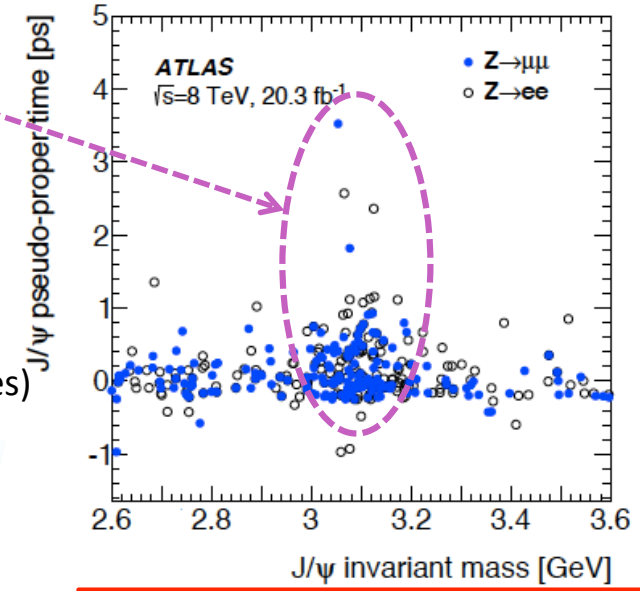

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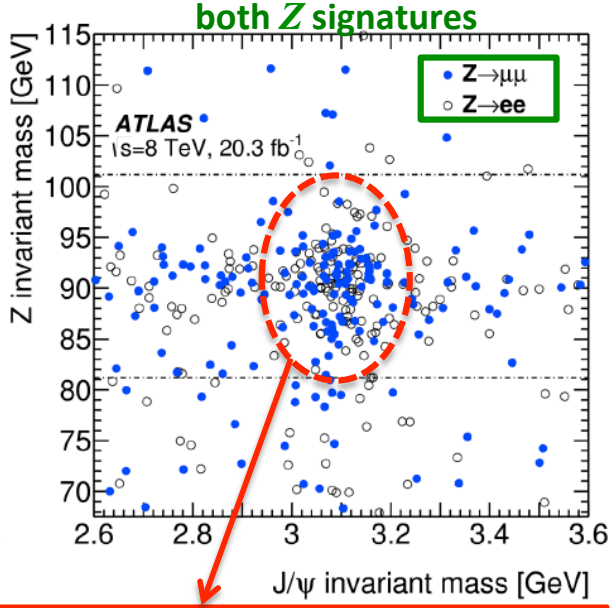

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- **Prompt & non-prompt J/ψ separated by 2D UML fit to dimuon mass & pseudo-proper time distributions.**
  After the fit, for each event, **signal & (2μ-combinatorial) background** disentangled by **`sPlot`** technique.

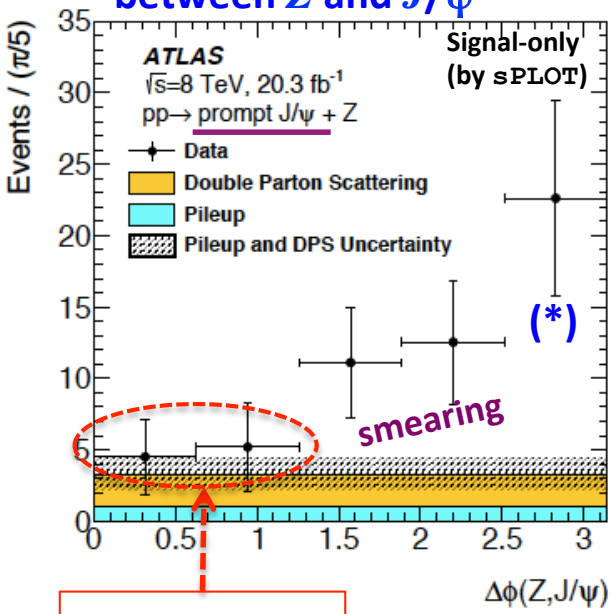
Few details into backup

Fake-Z bkg is found to be **negligible** (by MC studies)

Pile-up bkg (real Z & J/ψ) estimated (MC procedure) through the # of pile-up vertices lying within 10*mm* of a random PV

J/ψ production in association with a Z boson - II

Azimuthal opening angle between Z and J/ψ

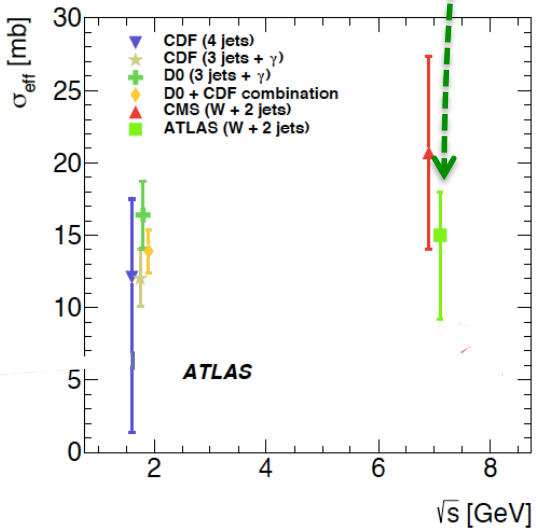


DPS dominates

DPS contribution to the Z+J/ψ sample counted as a part of signal.
DPS yellow band is estimated by using the *effective xsection* σ_{eff} *for double parton interactions rate* as measured by ATLAS in W+2jets events (assumed process independent). [**New J. Phys. 15 (2013) 033038**]

DPS is expected to be flat if the two processes are uncorrelated, whereas **SPS events are expected to show back-to-back correlation**. This behaviour would be **smeared** by the presence of: 1) additional gluons, 2) radiation from leptons & 3) reconstruction effects.

This distribution - interpreted as a combination of a smeared $\Delta\phi=\pi$ peak (*) and a flat DPS contribution - suggests that both SPS and DPS contributions are present !



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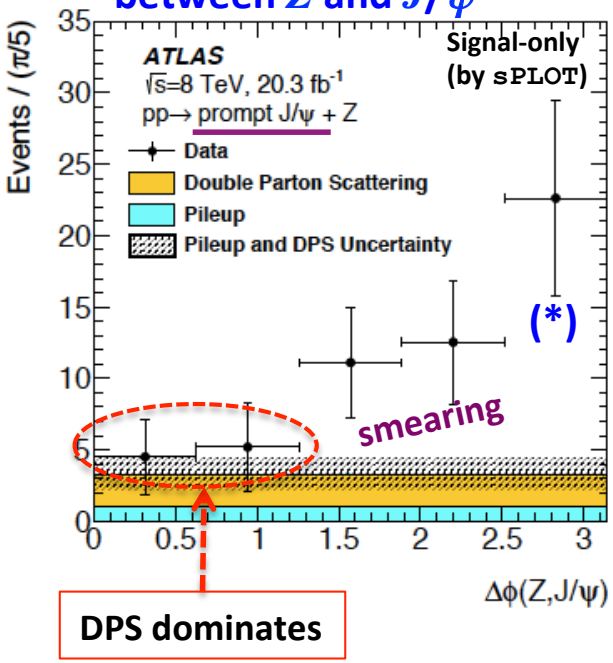

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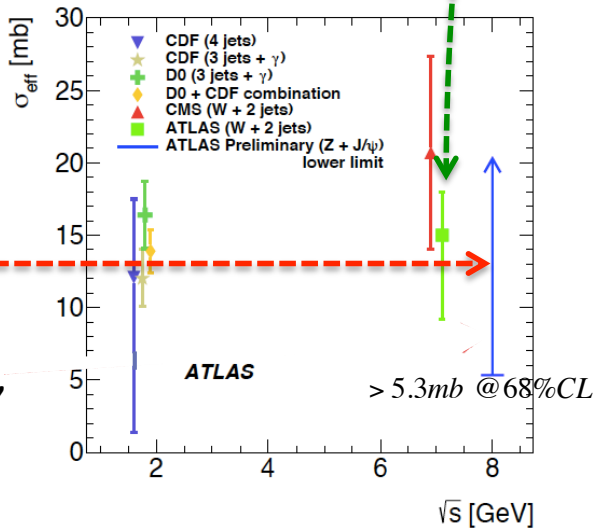
Viceversa, … **by assuming that the first bin is due to DPS** …, it is **possible to set** an upper limit on level of DPS contributing to the observed signal, corresponding to **a lower limit on** σ_{eff} which is **in agreement** with other measurements.



It would be useful to have models for the SPS contribution to Z(W)+J/ψ, particularly as a funtion of $\Delta\phi$, to allow better estimate of DPS & σ_{eff} :
significant SPS contribution is possible at low angles due to high-order processes.

J/ψ production in association with a Z boson - III

- Xsections for the associated production $J/\psi + Z$ *relative* to inclusive Z production are presented separately for prompt & non-prompt J/ψ.

  The normalization sample of inclusively produced Z bosons allows some systematic uncertainties' cancellation by measuring xsection ratios.

- ***Fiducial* xsection ratios (*)** are defined in a restricted phase-space of the muons (no correction applied)

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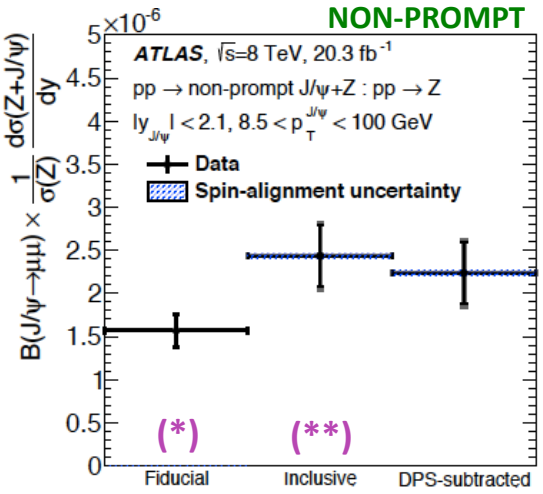

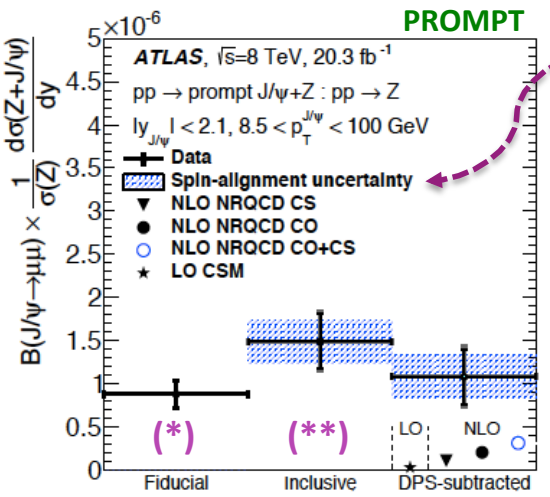

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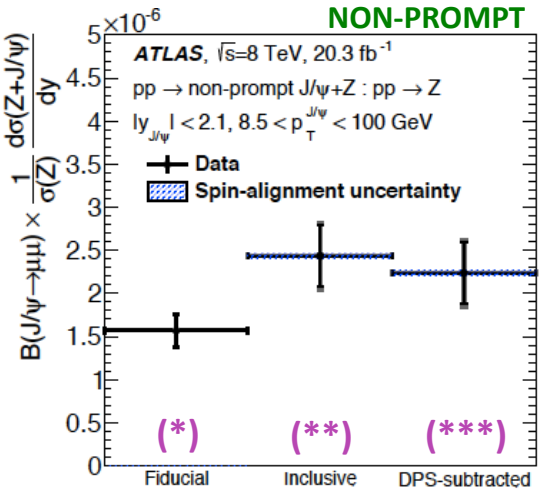
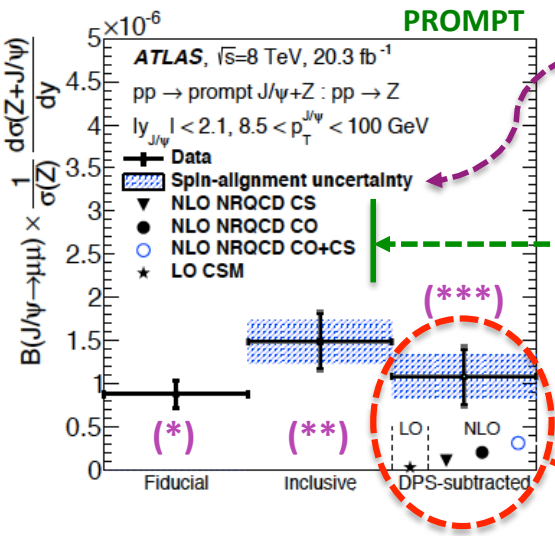
  ***SPS xsection ratios* (***)** are obtained by subtracting the estimated DPS contribution (uncert. into syst.)

  [its fraction is $29 \pm 9\%$ $(8 \pm 2\%)$ for prompt (non-prompt) signal].





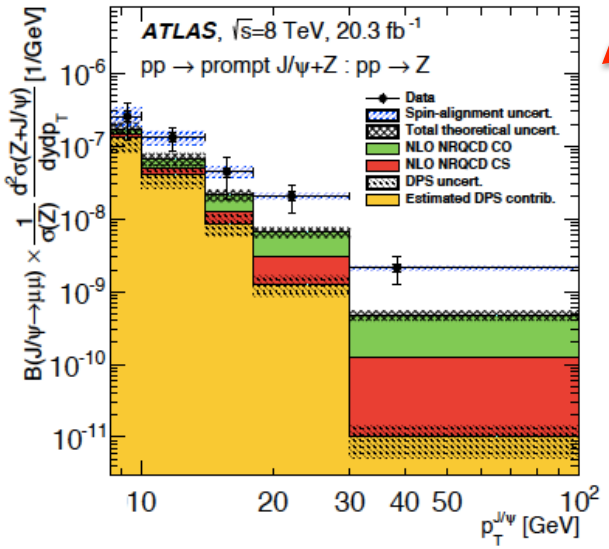
Polarization of J/ψ produced in J/ψ+Z Events may differ from the polarization observed in inclusive J/ψ production.

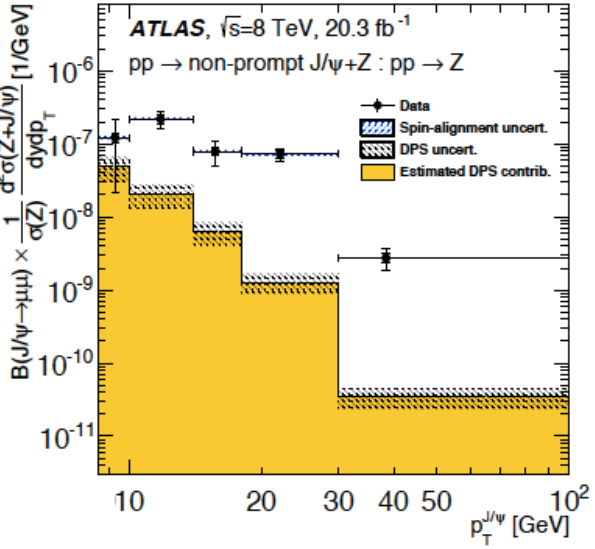
In theoretical calculations, i.e. for **NRQCD** [**Mao et al., JHEP 1102 (2011) 071**], the J/ψ mesons are assumed directly produced: no feed-down from excited charmonia !

Expected NLO(CS+CO) NRQCD rate underestimates SPS production data

J/ψ production in association with a Z boson - IV

- Differential xsection for the associated production $J/\psi + Z$ relative to inclusive Z production, as a function of $p_T^{J/\psi}$, presented separately for prompt & non-prompt J/ψ :





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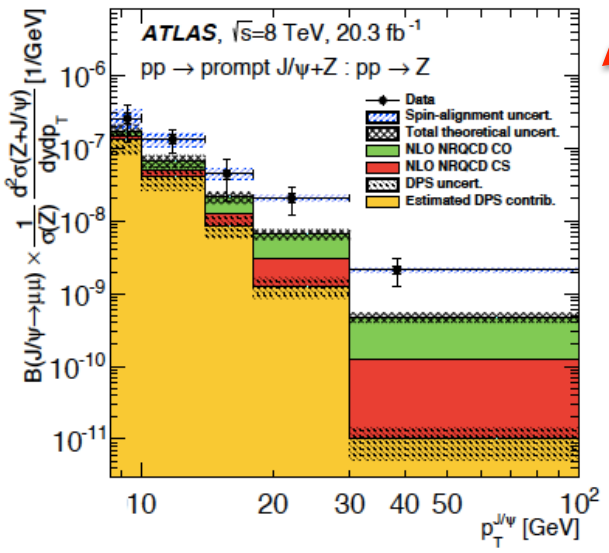

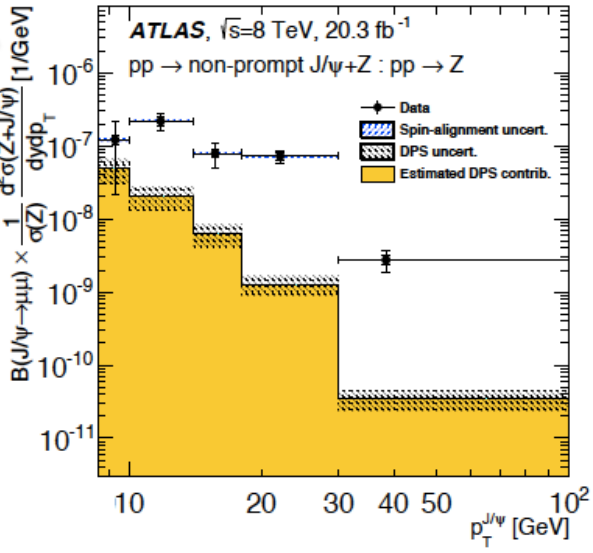

- For the **prompt** $J/\psi + Z$: diff. xsection are compared to NLO, CS & CO, predictions; these are for SPS rates & the estimated DPS contribution is added to theoretical predictions to allow theory-data comparison!

  - The combination of NLO NRQCD & DPS contributions tends to **underestimate** the production rate observed in data; discrepancy increases with $p_T^{J/\psi}$ reaching a factor 4-5!

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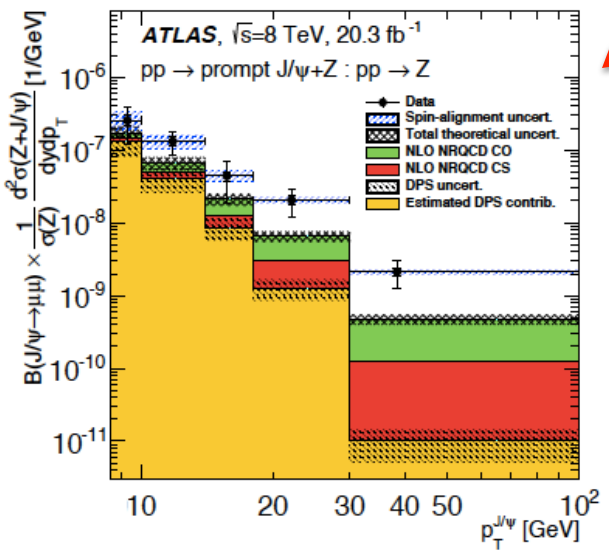

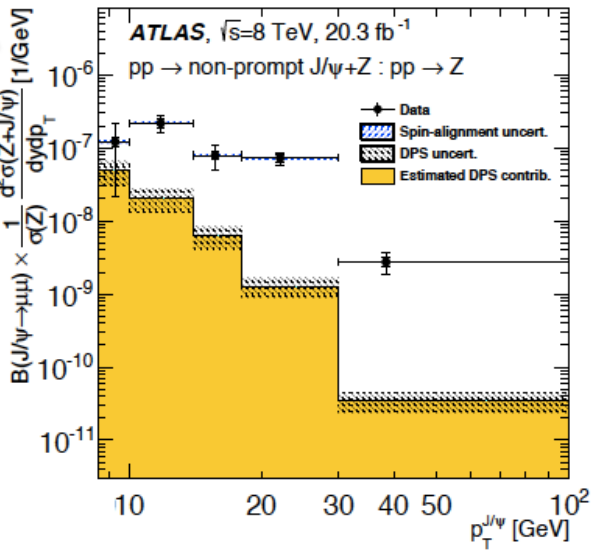

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- For the non-**prompt** $J/\psi + Z$: **no theoretical calculations are available**: the significant contribution to the rate from Z+(*b-jet*) [the jet containing a J/ψ] has not been evaluated.

Search for X_b

ATLAS, PLB 740 (2015) 199

CMS, PLB 727 (2013) 57

Search for X_b [beauty partner of the $X(3872)$]

- **HQ symmetry suggests an X_b analog of X_c.**
  Molecular model suggests to search it close to $B\bar{B}^*$ threshold (e.g. $m \cong 10.561 GeV$; Swanson, 2004)

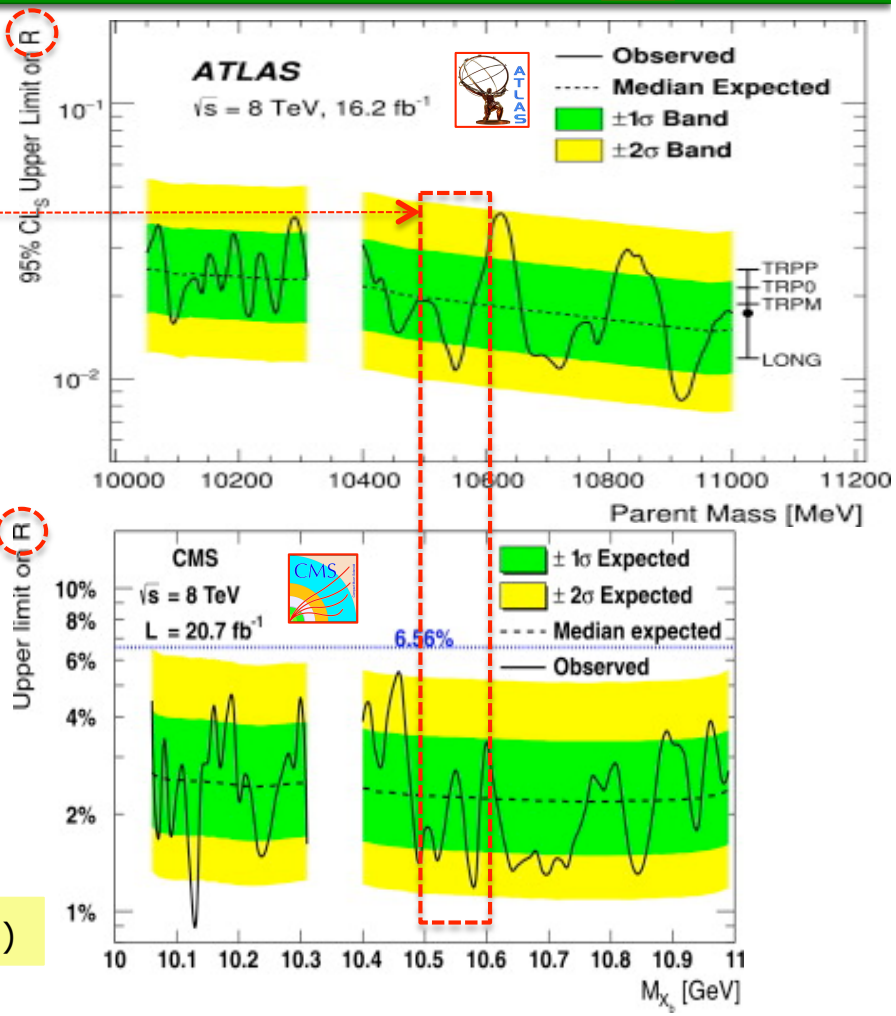
- ATLAS/CMS looked for $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ decay **seemingly analogous** to $X(3872) \to J/\psi\,\pi^+\pi^-$

Analysis strategy: search for a peak other than known Υ(2S) & Υ(3S) in the $\Upsilon(1S)\pi\pi$ spectrum within 10-11GeV

They set 95% CL set upper limits on the ratio *R* of the inclusive production xsections times BFs to $\Upsilon(1S)\pi\pi$ (the one for Xb is unknown):

$$R = \frac{\sigma\left(pp \to X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{\sigma\left(pp \to \Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$

Observed UL range: 0.8(0.9)% to 4.0(5.4)% for ATLAS(CMS)



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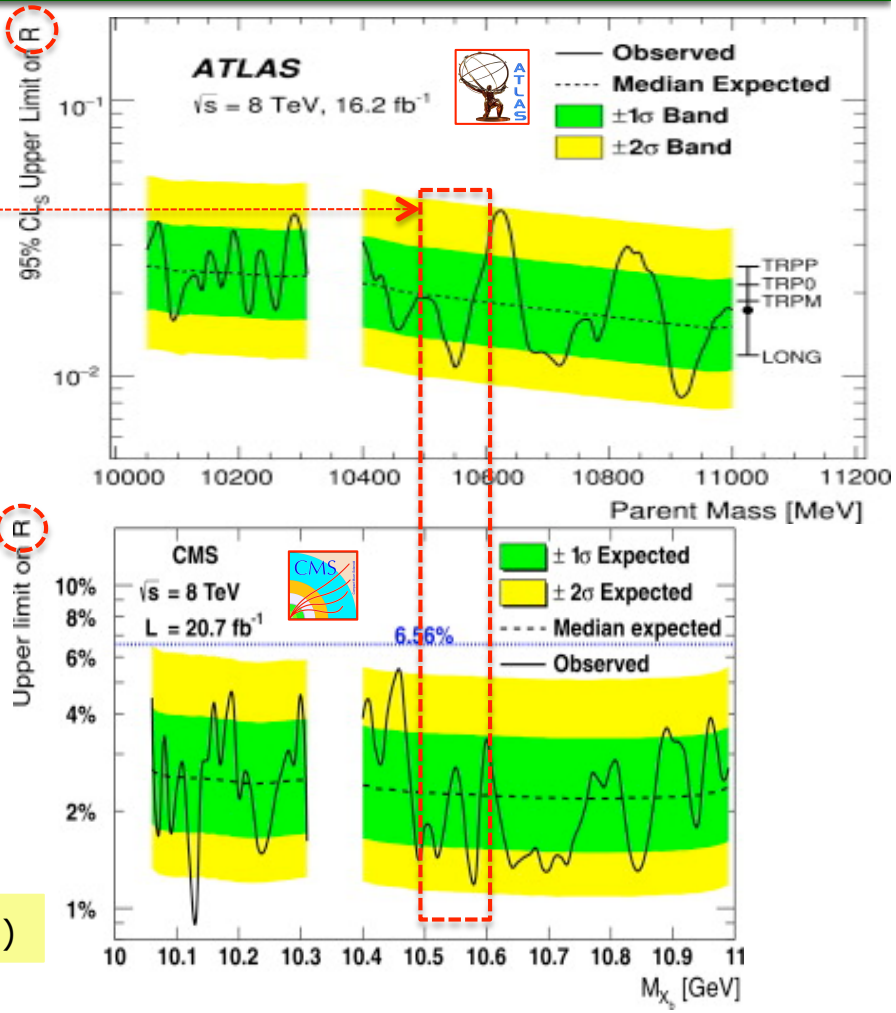

- According to Karliner & Rosner **[PRD91 (2015) 014014], this search decay should be forbidden by G-parity conservation (**in the bottom sector isospin should be well conserved while in charm sector X(3872) maximally breaks isospin**).** The strategy for X_b observation should include search of $X_b \to \Upsilon(1S)\,\omega(\to \pi^+\pi^-\pi^0)$, $X_b \to \chi_{b1}(1P)\pi^+\pi^-$, $X_b \to \Upsilon(3S)\gamma$ [not easy: for Run-2 !]

- ATLAS search for production of the $\Upsilon(1^3D_j)$, $\Upsilon(10860)$ and $\Upsilon(11020)$ states also reveals **no** signals.

Summary & outlook

- Although designed for high-p_T physics …
  … ATLAS/CMS are exceptional apparatuses for dealing with flavour & quarkonia physics!

- Strong theoretical preference for NRQCD @ NLO or higher corrections.
  Xsections measurements @ LHC (& Tevatron) are **dominated by color-octet production**.
  The $Q\bar{Q}$ bound states are preferably formed by two heavy quarks of …
  - different colors (rather than in an already color neutral configuration)
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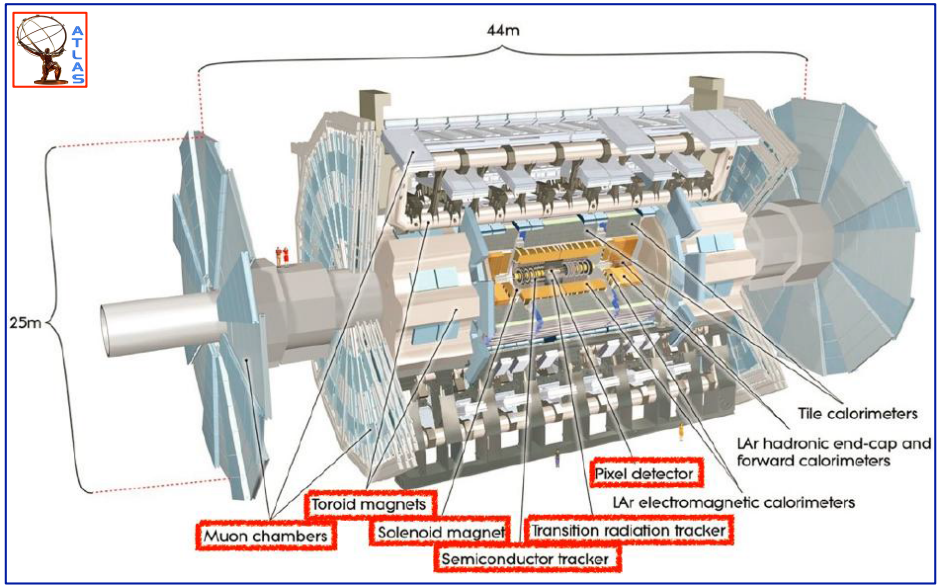
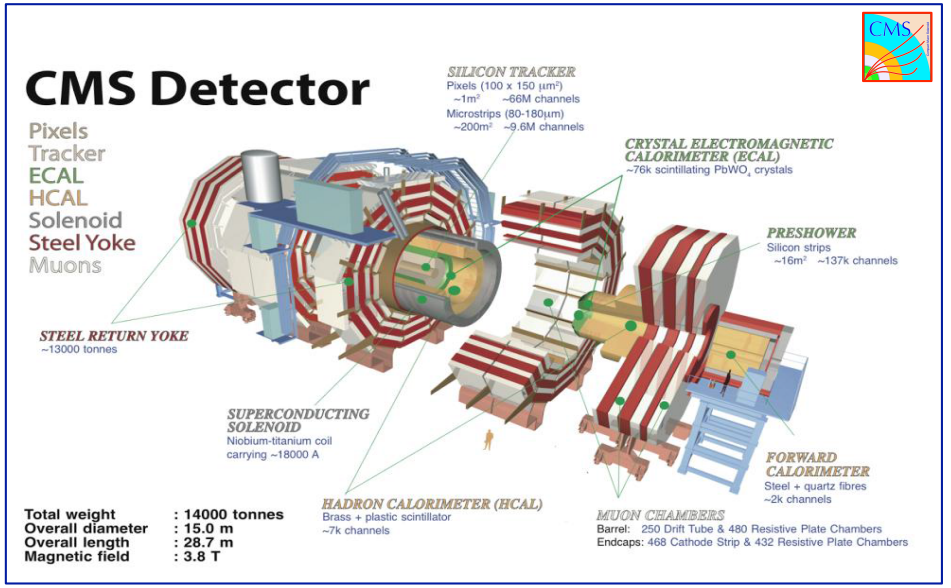
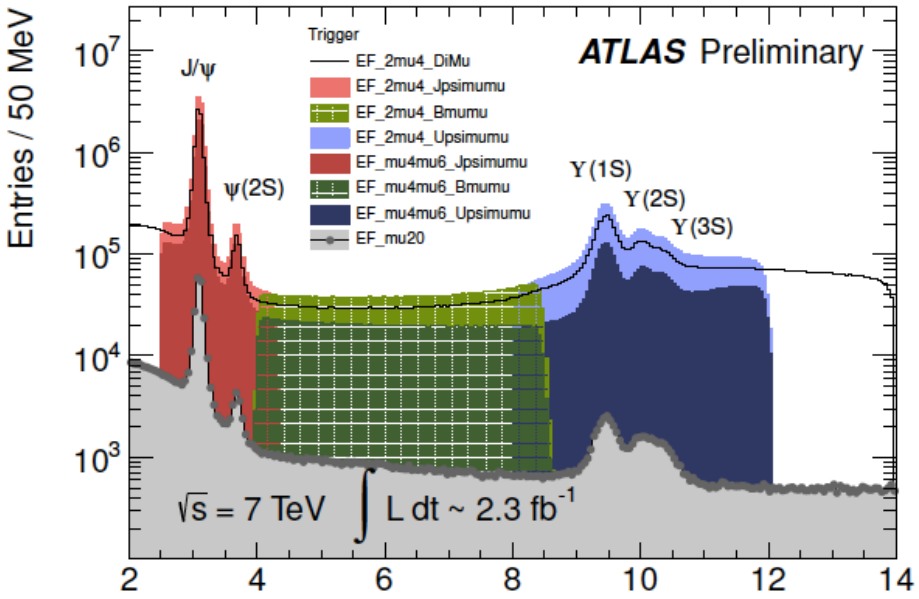
- Production models in the NRQCD framework **need either to be developed** (double J/ψ) **or refined** (production in association with a vector boson). This will constrain the SPS models allowing better estimate of DPS contribution.
  ATLAS/CMS can provide further experimental information exploting Run-2 data.
  Associated production is also suitable to search for exotic or supersymmetric states.

Backup slides/Additional material

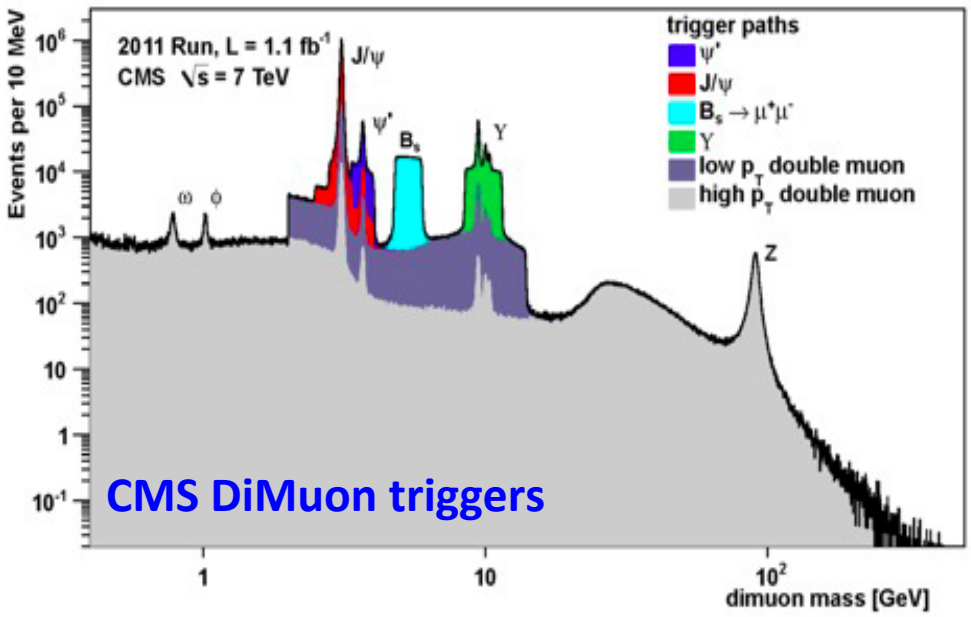
ATLAS & CMS





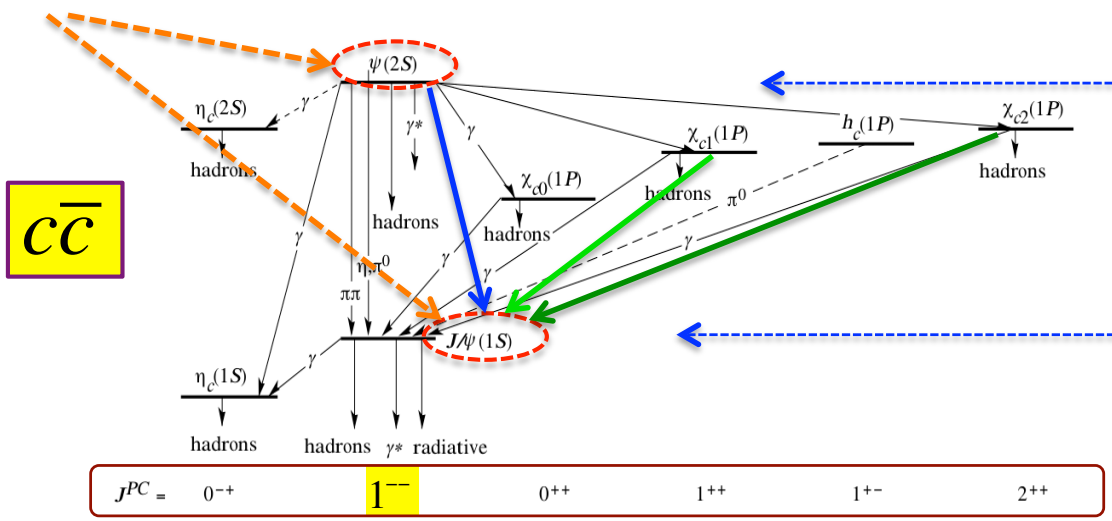


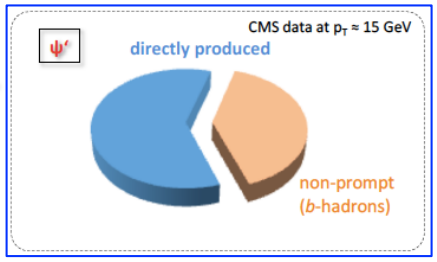
ATLAS DiMuon triggers x quarkonia

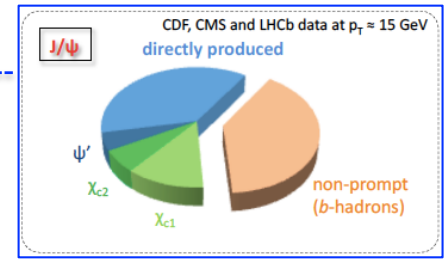


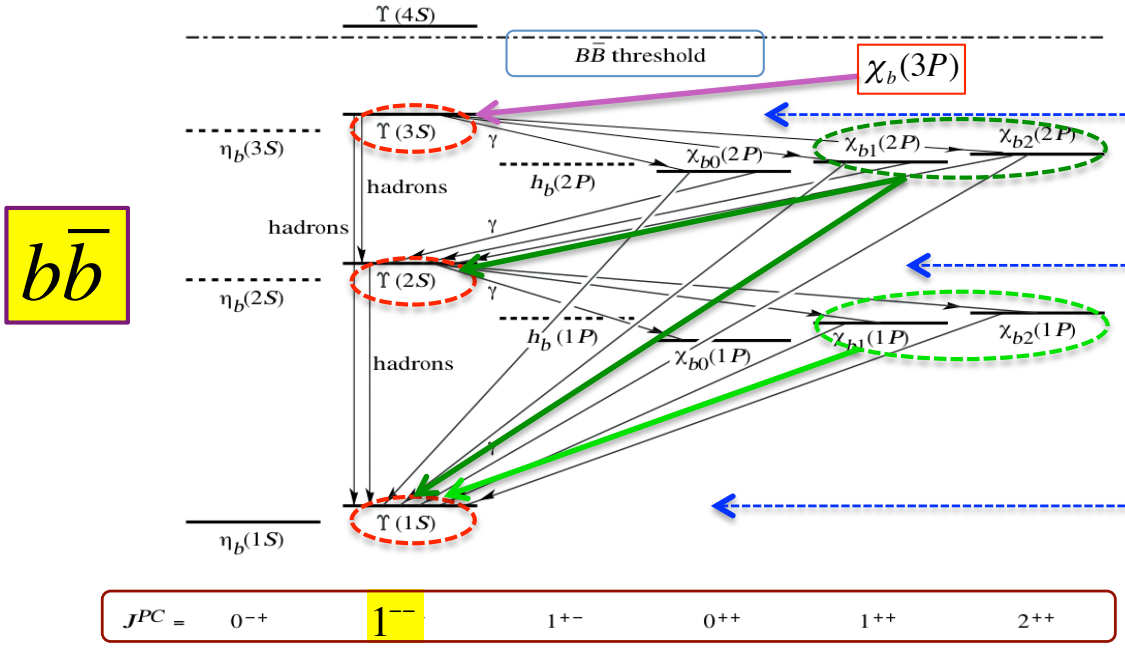
CMS DiMuon triggers

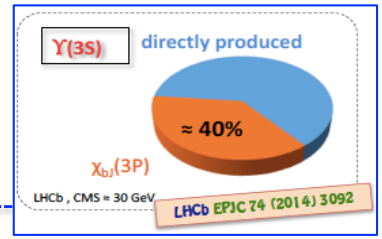
Quarkonium spectra & overview of feed-down into *spin-triplet S-wave* states

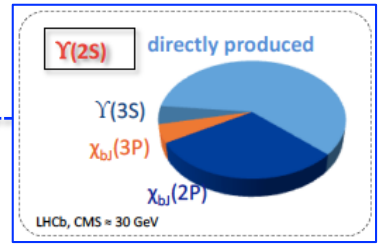


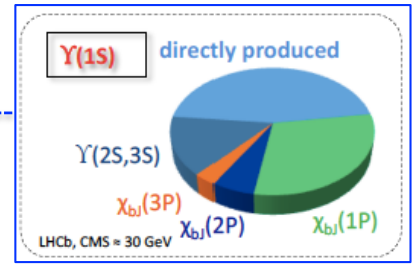












NRQCD : color-singlet & color-octet terms

Inclusive Xsection for producing quarkonium (***H***) with enough large momentum transfer p_T :

$$\sigma\left(A+B\to H+X\right)=\sum_n \sigma\left(A+B\to\left[Q\bar{Q}\right]_n+X\right)\cdot P\left(\left[Q\bar{Q}\right]_n\to H\right)$$

, $n={}^{2S+1}L_J^{[C]}$

$Q\bar{Q}$ can be, at short distances, produced in a state ***n*** with definite: spin ***S***, angular momentum ***L***, and color ***C*** = 1,..,8.

Short-distance coefficients (SDCs)	**Long-distance matrix elements** (LDMEs)
Inclusive pQCD Xsection of partonic processes to form $Q\bar{Q}$ in state n (convoluted with PDFs)	Probability of $Q\bar{Q}$ in state n to evolve into the quarkonium final state *H*
process-dependent **functions** of kinematics	universal **constants** (independent of kinematics)
calculated perturbatively as expansions in α_S	**determined by fits** to exp. data
	relative relevance given by ***v* - scaling rules**

- Theoretical predictions are organized as double expansions in α_S and v.
  Truncation of v-expansion for *S-wave* states in NRQCD includes 4 terms:
  - the Color Singlet (CS) term: ${}^3S_1^{[1]}$ (CS assumption: initial $Q\bar{Q}$ & final ***H*** (${}^3S_1$) have same quantum numbers!
  - 3 Color Octet (CO) terms: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, ${}^3P_{J=0,1,2}^{[8]}$ (of relative order $O(v^4)$ w.r.t. CS)

The CS term is characterized by a suppression of powers of α_S thus making important the CO channels despite of their suppression by powers of v!

Prompt production Xsections of S-wave states

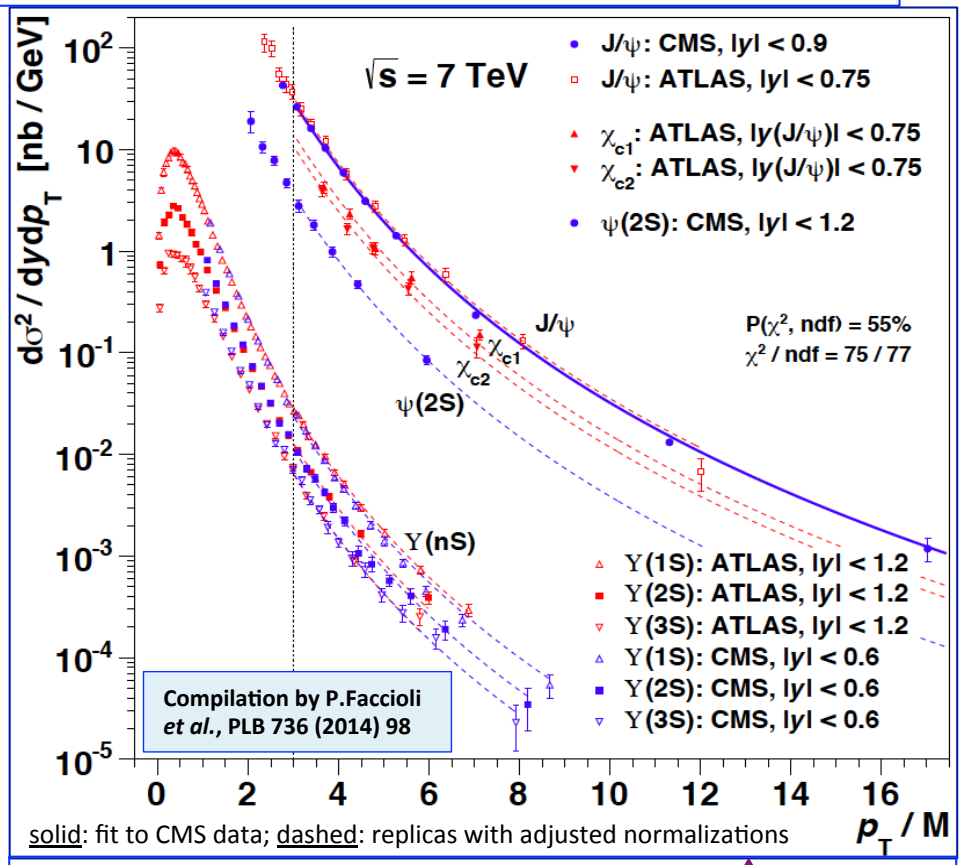
Mid-rapidity double differential prod. xsections for 7 different quarkonia as a function of p_T/M (*):

Shapes are well described by a single empirical power-law for $p_T/M > 3$.
This p_T/M **scaling behaviour** …
… common to 5 *S-wave* & 2 *P-wave* states with different feed-down contaminations ,
suggests a simple composition of processes dominated by 1 single mechanism.

CS processes must be negligible!
A single CO term dominates production!
It could be $^1S_0^{[8]}$ **IF** the NRQCD fit would start @ 10-15*GeV* **[Faccioli et al.,PLB 736 (2014) 98]**

Scaling behaviour must be confirmed with:
- more accurate data up to higher p_T
- polarization data

Indeed the $^3S_1^{[8]}$ term may become dominant at higher values of p_T/M than currently covered !



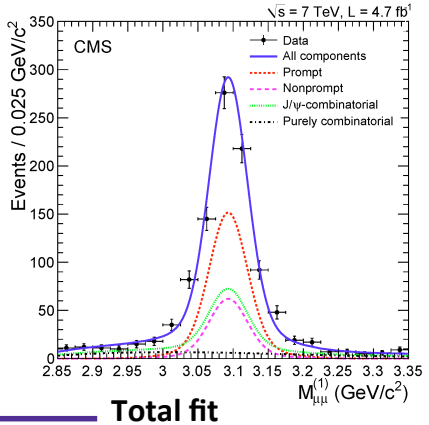
(*) p_T is mass-rescaled to equalize the kinematics effects of different average parton momenta and phase spaces

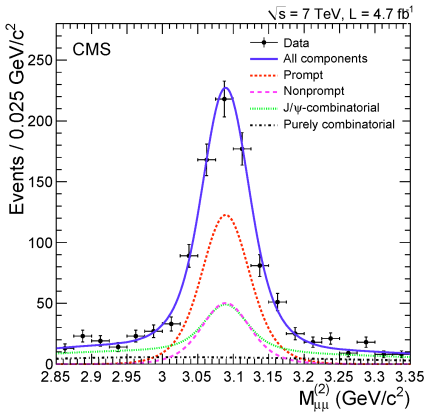
ATLAS, CONF-2013-095; arXiv:1404.7035 (submitted to JHEP)
ATLAS, NPB 850, 387 (2011)
ATLAS, PRD 87, 052004 (2013)
CMS, PLB 727, 101 (2013)
CMS, JHEP 02, 011 (2012)

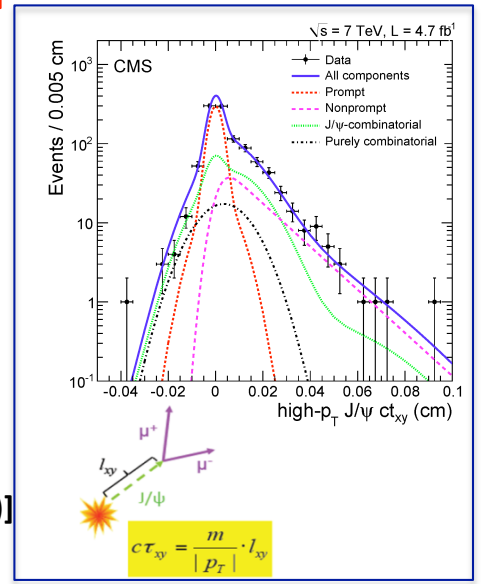
Prompt double J/ψ production

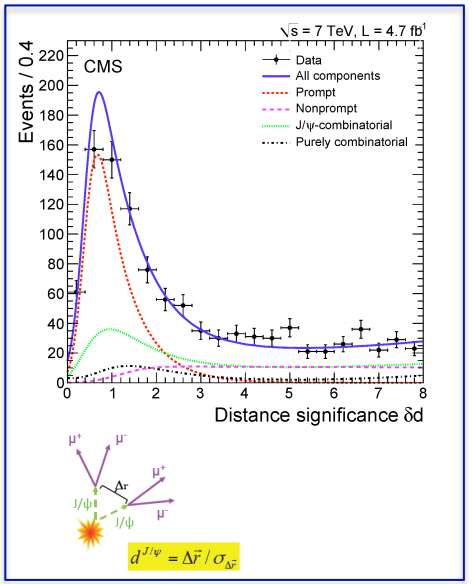
Projections from the ML fit results :

CMS, JHEP 09 (2014) 094









- **Total fit**
- **Signal (real prompt pair)**
- **BKG[at least one non-prompt J/ψ (from B-meson decays)]**
- **BKG[prompt J/ψ + 2 unassociated muons]**
- **Fully combinatorial BKG (4 unassociated muons)**

signal weight for the signal component (in the **4D extML fit)** [by **sPlot**]

The differential cross section of J/ψ pair production is calculated as

$$\frac{d\sigma(pp \to J/\psi\, J/\psi + X)}{dx} = \sum_i \frac{s_i}{a_i \cdot \epsilon_i \cdot (BF)^2 \cdot \Delta x \cdot \mathcal{L}}$$

Sum over events in an interval Δx

$\Delta x = m^{J/\psi J/\psi}, p_T^{J/\psi J/\psi}, \left|\Delta y^{J/\psi - J/\psi}\right|$

luminosity

$BF(J/\psi \to \mu^+\mu^-)$ **[PDG]**

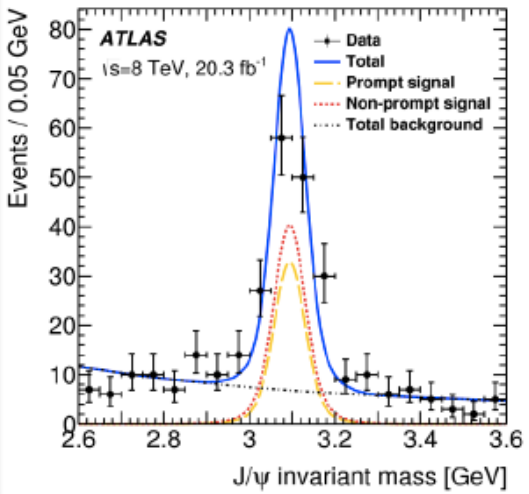
a_i : acceptance (probability that muons from J/ψ decays pass the muon acceptance) [from MC]

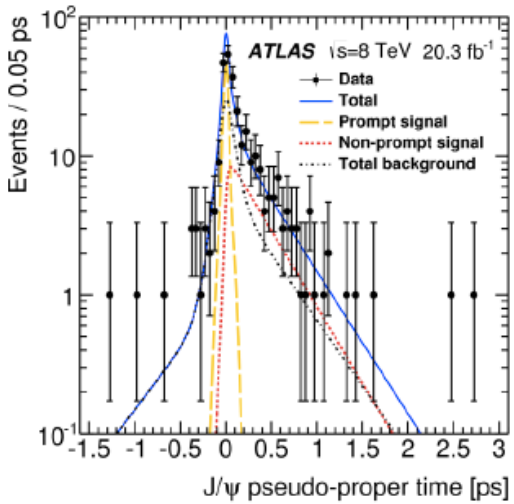
ε_i : detection efficiency (probability for the 4 muons to be detected and pass trigger & reco requirements [by using MC samples for SPS (**PYTHIA 6**) and DPS events (**PYTHIA 8**)].

$J/\psi + Z$ associated production

Projections from the 2D UML fit results :

ATLAS, arXiv:1412:6428





Separation of prompt & non-prompt J/ψ candidates is obtained by a simultaneous fit to the dimuon invariant-mass & pseudo-proper time distributions with a 4-components model (P & NP x Signal & P & NP x Bkg).

J/ψ sidebands are used to constrain **combinatorial bkg** (both **prompt & non-prompt** components).

$$\tau = \frac{L_{xy}^{J/\psi} \cdot m_{PDG}^{J/\psi}}{p_T^{J/\psi}}$$

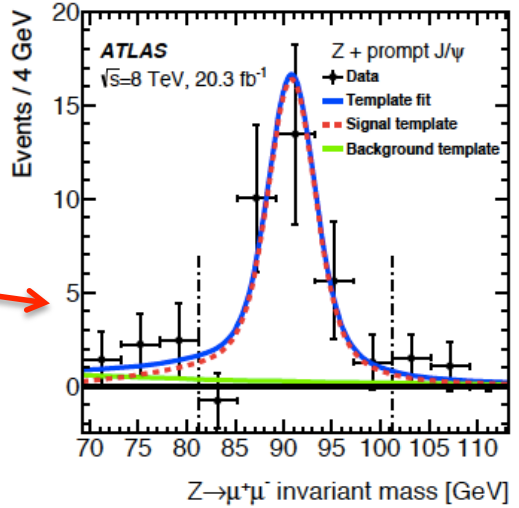
Prompt (non-prompt) samples:

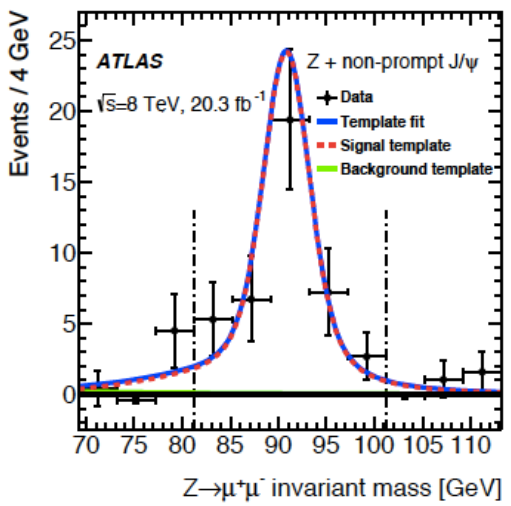
$56 \pm 10 \ \ (95 \pm 12)$

- # of pile-up vertices (lying within 10*mm* of a random PV): $[N_{extra} \cong 2.3 \pm 0.2]$

- After the simultaneous fit is performed, the **sPlot** technique is used **to assign a weight to each event** for each of the **4 components** included in the fit model (discriminating variables are those used in the fit) : **prompt & non-prompt signal & bkg.**
  Yields are extracted by fitting weighted distributions.

- Normalization sample of inclusively produced Z bosons formed by selecting all the events that satisfy the Z-part of the $J/\psi + Z$ selection (trigger included) allows systematic uncertainties cancellation (efficiency & acceptance for the Z boson).





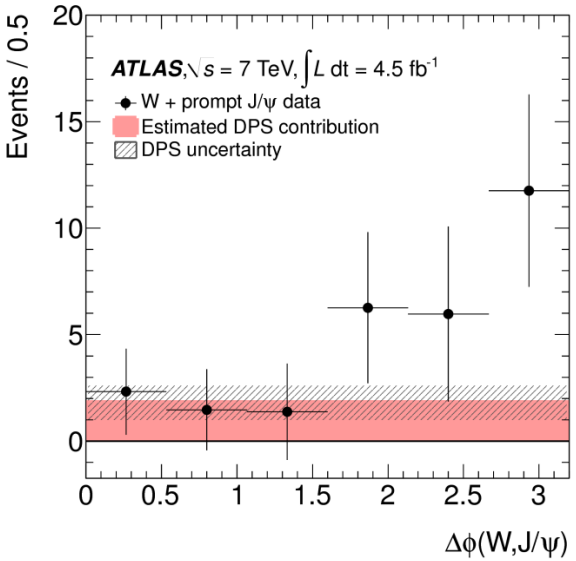
[Template fits for SIG/BKG components are derived from MC/data]

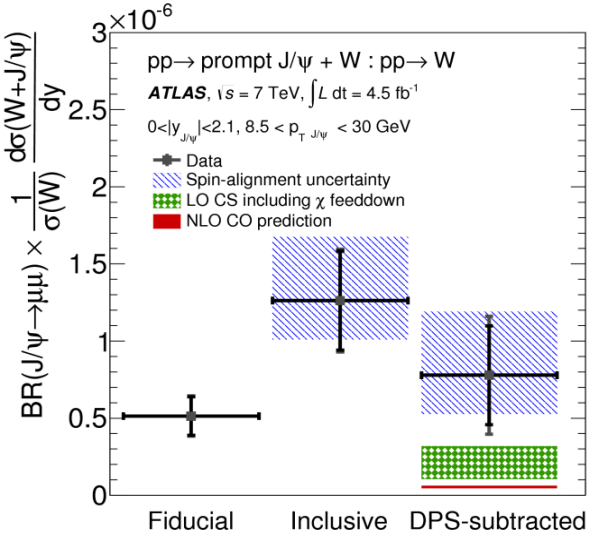
Prompt J/ψ production in association with a W boson

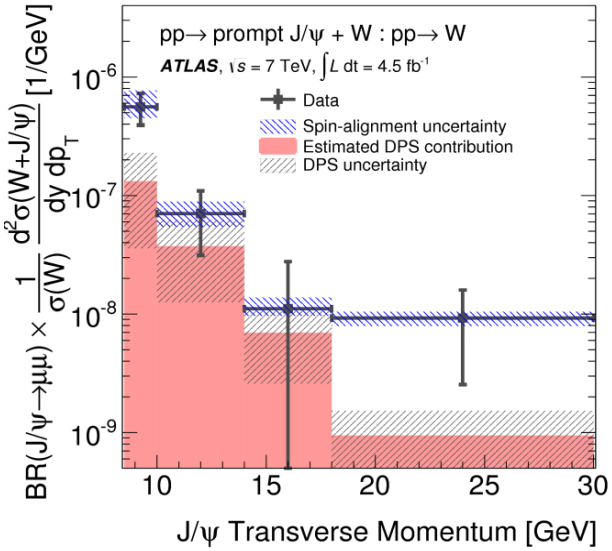
- ATLAS provided first observation of prompt J/ψ production in association with a $W^{\pm}$ boson
  (CDF searches had null results for associated production with W or Z)
  - **Final states:** $\mu\mu\mu + MET$
  - **Separation of prompt & non-prompt J/ψ candidates by a 2D UML fit to diμ inv.-mass & pseudo-proper time**
  - **Analysis strategy analogous to that used later for $Z+J/\psi$.**

- **Results similar** (with lower statistics) to those found later for $Z+J/\psi$:

ATLAS, JHEP 04 (2014) 172



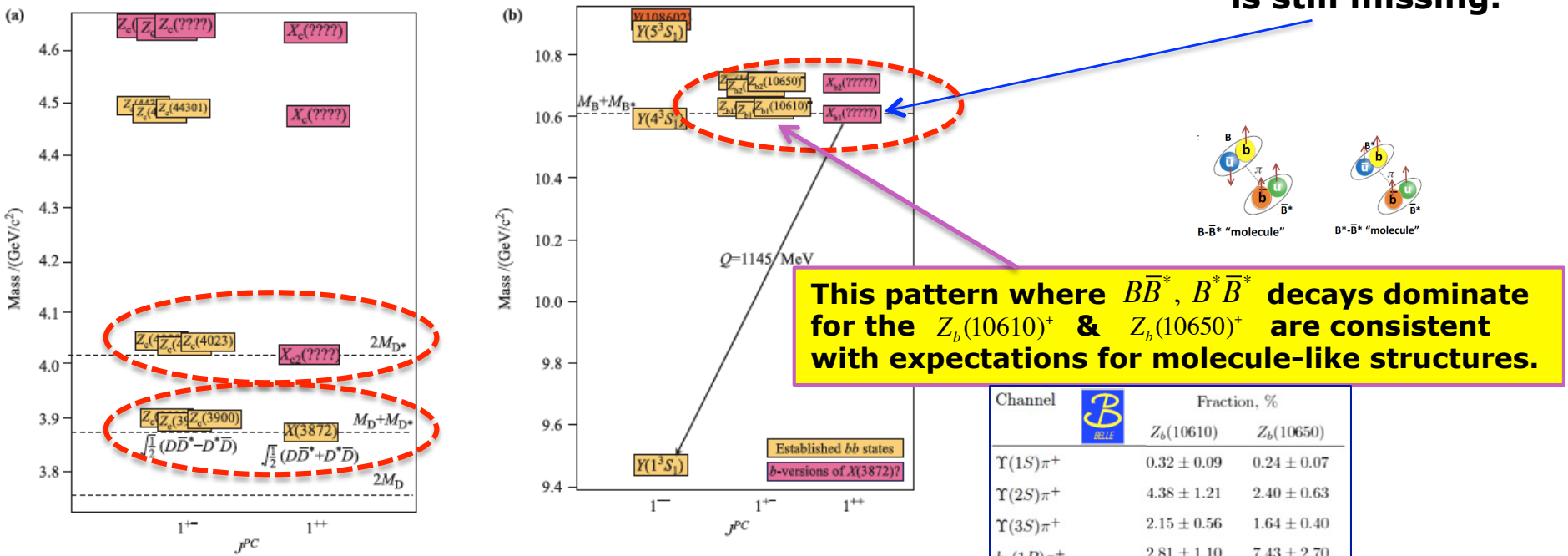




Search for X_b as a molecule

- **A partial picture of many XYZ states establishes:**
  1) a concentration of charmonium-like states crowding the $D\bar{D}^*, D^*\bar{D}^*$ threshold regions
  2) bottomonium isospin triplets near the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds
  These circumstances suggest molecule-like structures.

- **For istance for the charmonium states there can be introduced two isotriplets, while for isotopic triplet in the bottomonium sector the X(3872) counterpart is still missing.**



This pattern where $B\bar{B}^*$, $B^*\bar{B}^*$ decays dominate for the $Z_b(10610)^+$ & $Z_b(10650)^+$ are consistent with expectations for molecule-like structures.

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	4.34 ± 2.07	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

$"Y(5S)" \to B^{(*)}\bar{B}^{(*)}\pi$

Fig. 22 **(a)** Level diagram for the $X(3872)$, the recently discovered $Z_c(3900)$ & $Z_c(4020)$ isotopic triplets, and the $Z(4430)$ isospin triplet. The salmon-colored boxes indicate other states that are suggested by the molecule picture. **(b)** Level diagram for the recently discovered Z_b states, a conjectured b-sector equivalent of the $X(3872)$ at the $m_B + m_{B^*}$ threshold and an additional isoscalar partner of the $Z_b(10650)$ at the $2m_{B^*}$ theshold. The transition between a $m_B + m_{B^*}$ threshold state to the $\Upsilon(1S)$ would have a Q-value of $\simeq 1145$ MeV, well above the mass of the ρ and ω mesons.

Searching for the X_b in the $Y(1S)\pi\pi$ mass spectrum

- $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ **motivated by** $X(3872) \to J/\psi\,\pi^+\pi^-$

  According to Karliner & Rosner [PRD91 (2015) 014014], this analogy is misguided for this particular decay channel. In the bottom sector isospin should be well conserved, while in charm sector X(3872) maximally breaks isospin conservation:

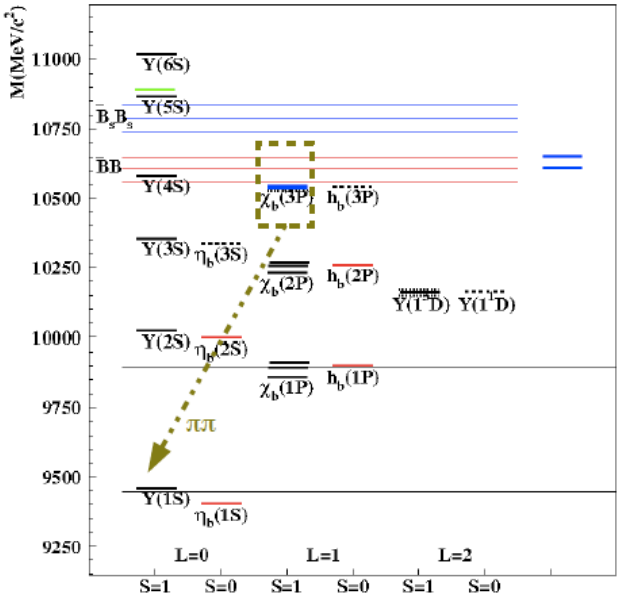
$$\frac{B(X \to J/\psi\,\pi^+\pi^-\pi^0)}{B(X \to J/\psi\,(\pi^+\pi^-)_{\rho^0})} = 1.0 \pm 0.4 \pm 0.3$$

  ω^0 and ρ^0

  Thus for X_b, isoscalar with $J^{PC}=1^{++}$, this decay should be forbidden by G-parity conservation!

- **However, so far no significant signal was found (by Belle in Y(5S) decays [PRD91, 014014 (2015)]) for** $X_b \to \Upsilon(1S)\,\omega(\to \pi^+\pi^-\pi^0)$

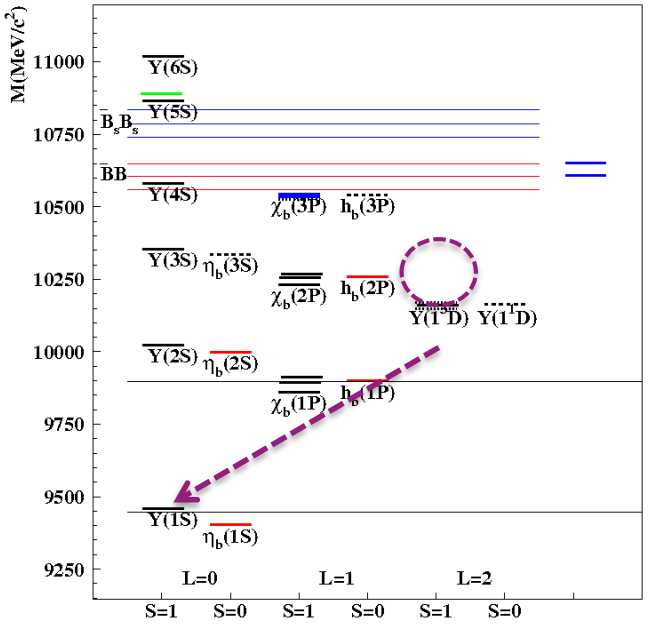
- **Moreover Karliner & Rosner suggest that the X_b may be close in mass to the $\chi_{b1}(3P)$, mixing with it and sharing its decay channels [just as X(3872) may be a mixture of a $D^0\bar{D}^{*0}$ molecule and $\chi_{c1}(2P)$]. Thus the experiments (ATLAS, D0, LHCb both with non-converted & converted photons) that reported observing $\chi_{b1}(3P) \to \Upsilon(1S,2S)\gamma$ might have actually discovered the X_b or a mixture of the two states! It would be worthwhile to examine the $\Upsilon(1S,2S)\gamma$ mass spectra for any departure from single BW behaviour.**



Additional searches in the $Y(1S)\pi\pi$ mass spectrum - I

- $\Upsilon(1^3D_2)$ **seen by CLEO & BaBar in radiative transitions!**

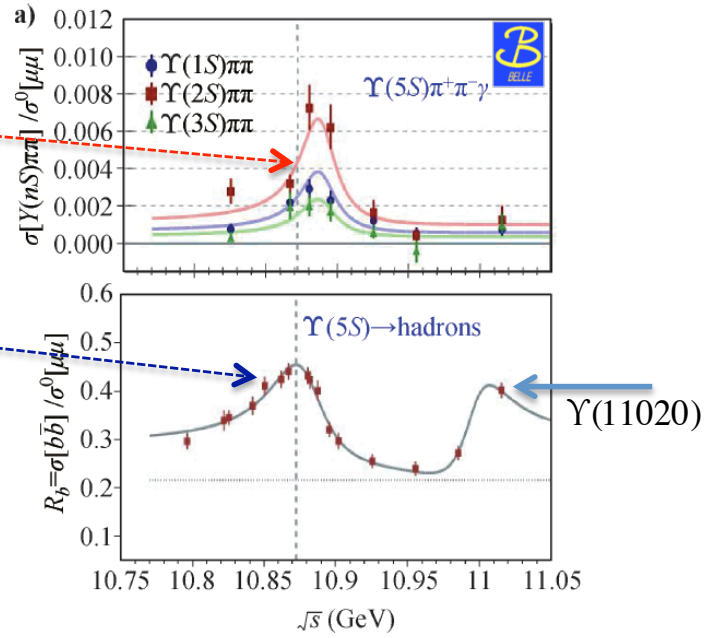
  $\Upsilon(1^3D_j) \to \Upsilon(1S)\,\pi^+\pi^-$ **searched by ATLAS**
  (not seen @ Tevatron)



Additional searches in the $Y(1S)\pi\pi$ mass spectrum - II

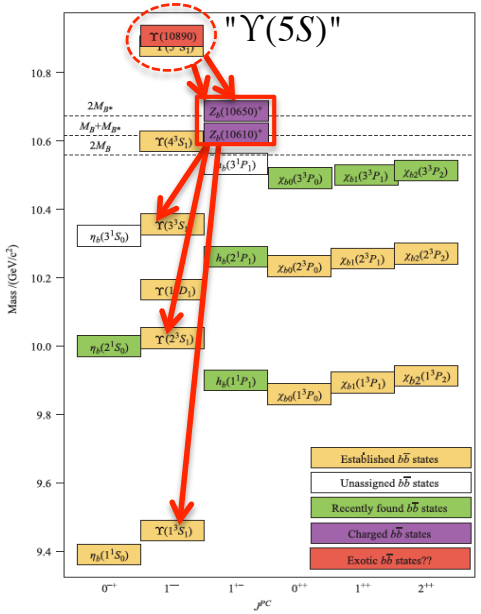
In 2010 Belle uncovers an anomalously large production rate of $\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$ peaking @ $\sqrt{s}\approx 10.89 GeV$:

This peak energy is $\approx 2\sigma$ higher than that of the peak in the $e^+e^-\to hadrons$ xsection @ $\sqrt{s}\cong 10.87 GeV$ that is usually associated with the conventional $\Upsilon(5^3S_1)$ meson



If the "shifted" peak were to be attributed to $\Upsilon(5S)$ decays it would imply partial widths for $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$ hundred of times larger than theoretical predictions ! It would also be incompatible with the production rates measured for the $\Upsilon(4S)$!

This signal, called $\Upsilon(10890)$, should be a $non-b\bar{b}$ state, equivalent of the $\Upsilon(4260)$ in the b-quark sector !



A subsequent study, with the same data (near the $\Upsilon(5S)$ peak) and with fully reconstructed decays $"\Upsilon(5S)"\to\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$, finds peaks @ two mass values ($m\approx 10.61,\ 10.65 GeV$) of the *maximum* inv. mass $\Upsilon(nS)\pi^\pm[n=1,2,3]$: $"\Upsilon(5S)"\to Z_{b(1,2)}\pi^-\to\Upsilon(nS)\pi^+\pi^-\ [n=1,2,3]$