Prospects for future heavy-flavour and quarkonium studies on LHC

(personal view)

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"Physics at AFTER", ECT Trento, 5 February 2013*

Scope and purpose

The organisers offered me a humble task:

"an educated review (of heavy flavour and quarkonium production) of what has been measured, what will be measured and what won't be measured by ATLAS, CMS, LHCb, and ALICE in pp collisions"

I merrily accepted, never mind that

- this definition covers work by thousands of people, tens if publications over several years
- according to A.Einstein: " It's difficult to predict. Especially the future."
- I can only reliably speak about plans within ATLAS – and even that to a limited extent
- I was originally given 40 mins to present this, which was subsequently reduced to 30 mins

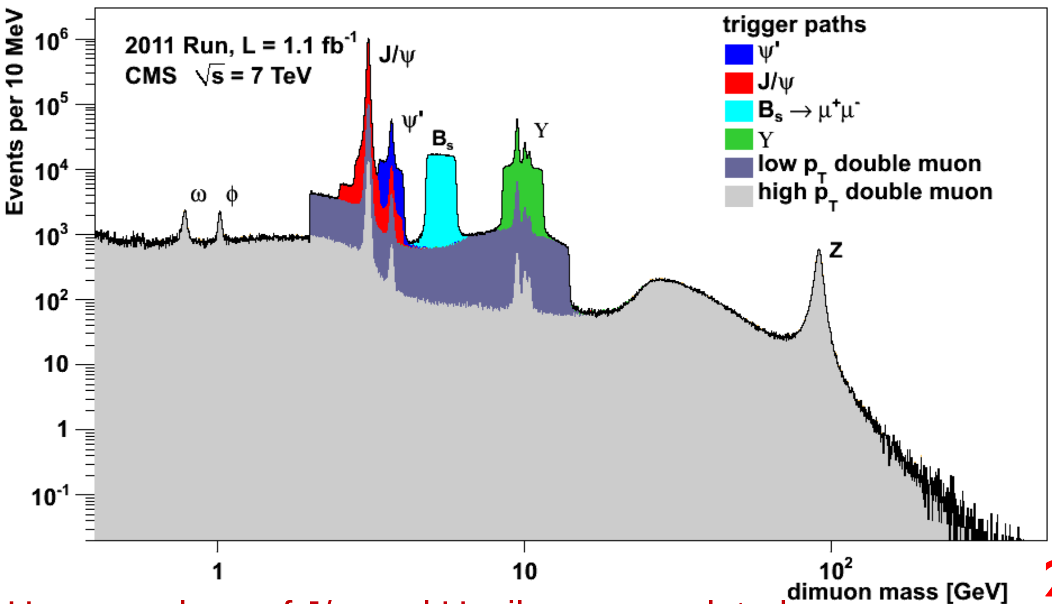
So, I am very curious myself, just how "educated" and useful my review will be...

Outline

The topics I will cover include:

- Overview of triggers
- Measurements so far:
  - Exclusive open beauty production
  - Inclusive open beauty production
  - B_c production
  - Prompt/non-prompt J/ψ production
  - Prompt/non-prompt ψ(2S) production
  - Υ(1,2,3S) production
  - χ_c and χ_b production
  - Polarisation measurement
  - Other observables
- "Immediate" plans
- Limitations and potential future bottlenecks

Dimuons: basis of many HF analyses

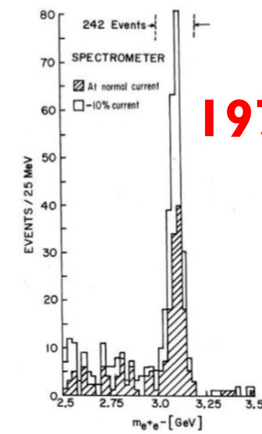


"Some" progress since J/ψ dicovery in 1974

Can see the features of triggers used by ATLAS, CMS

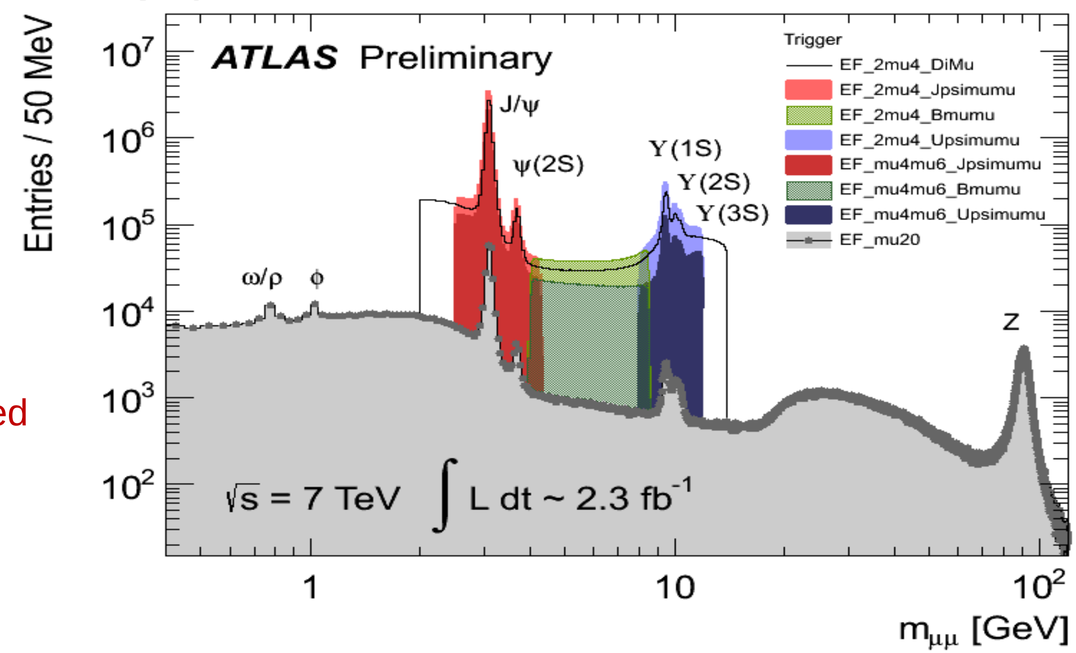
Bandwidth limitations are a major concern:

Need to prescale low-pT triggers



1974

2012



Huge numbers of J/ψ and Upsilon accumulated

Proven (at least in ATLAS) to be useful at any luminosity for checking data quality, measuring efficiencies etc.

Should keep Onia/HF physics alive for the foreseeable future

Many "basic" analyses already systematics-limited

Much more sophisticated analyses may become possible

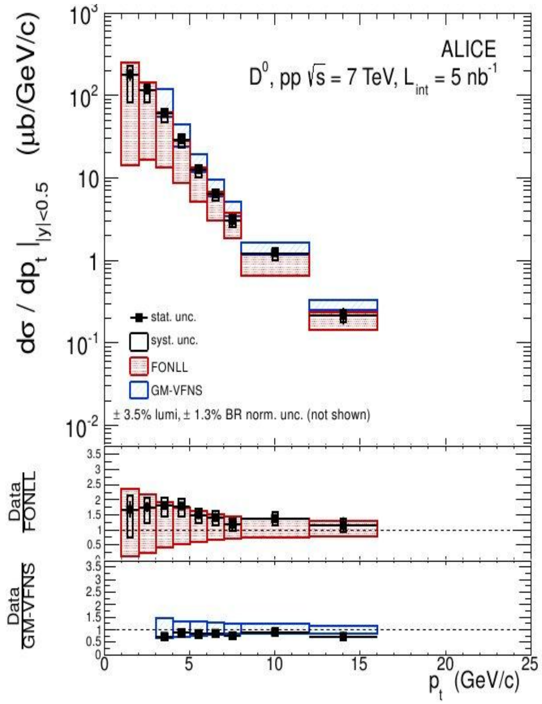
Open charm production

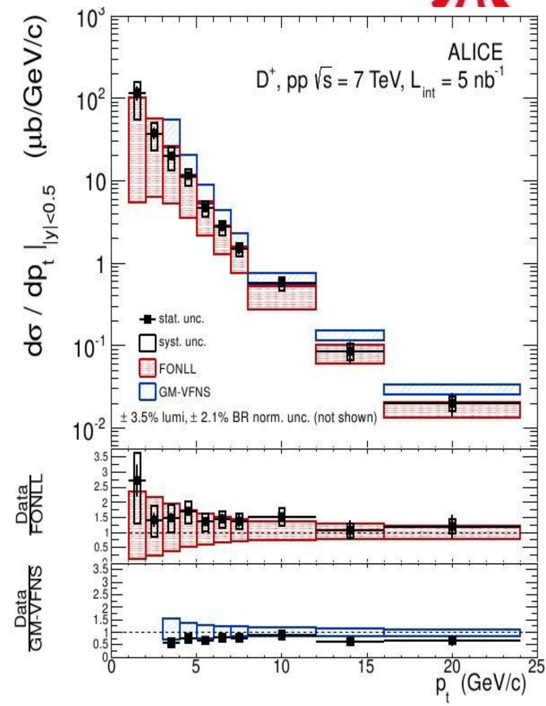
ALICE: JHEP07 (2012) 191
ALICE: JHEP 01 (2012) 128
ATLAS-CONF-2011-017

ALICE: Fully reconstructed charm decays
$s^{1/2}$ = 7 TeV, L_{int} = 5 nb^{-1}, $|y_D|<0.5$

Also, very similar analysis at 2.76 TeV

$$D^0 \to K^-\pi^+,\ D^+ \to K^-\pi^+\pi^+,\ D^{*+} \to D^0\pi^+$$

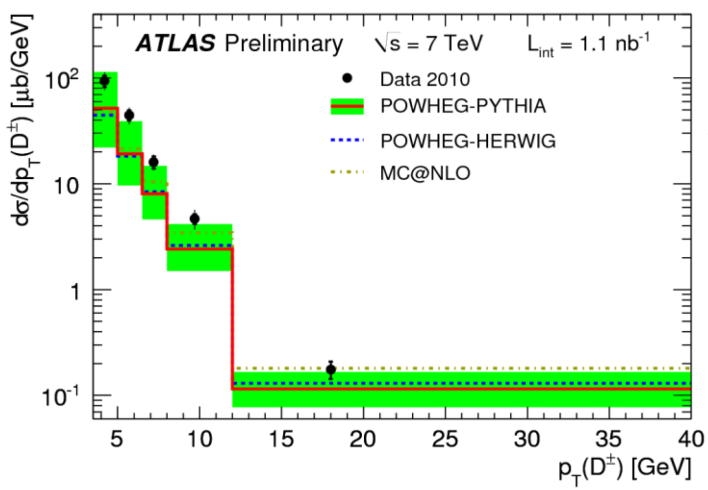


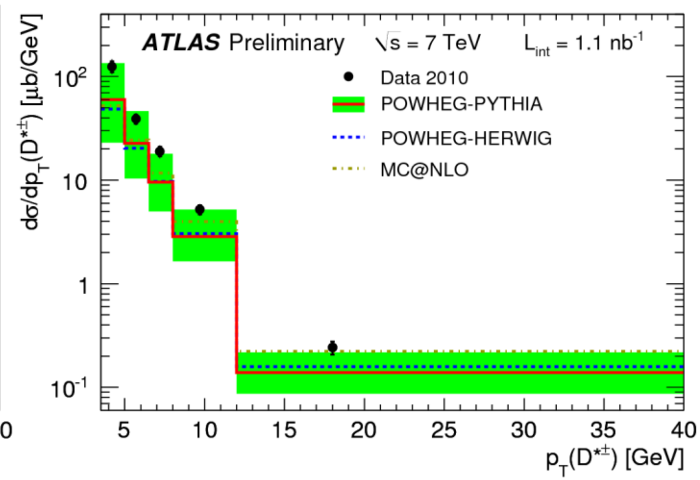


ATLAS: Fully reconstructed decays of $D^{\pm}$ and $D^{*\pm}$

$s^{1/2}$ = 7 TeV, L_{int} = 1.1 nb^{-1}
$|y_D|<2.1$

All described within uncertainties by models based on perturbative QCD





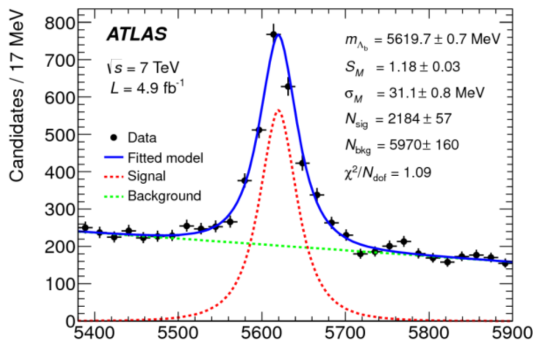
Λ_b production

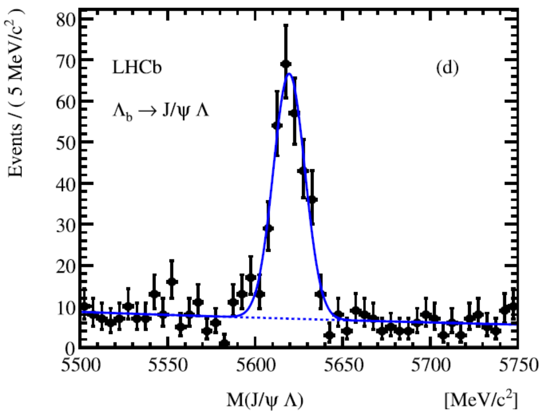
Λ_b : prominent peak in J/ψ+Λ decay mode, competitive measurements of properties by LHC experiments

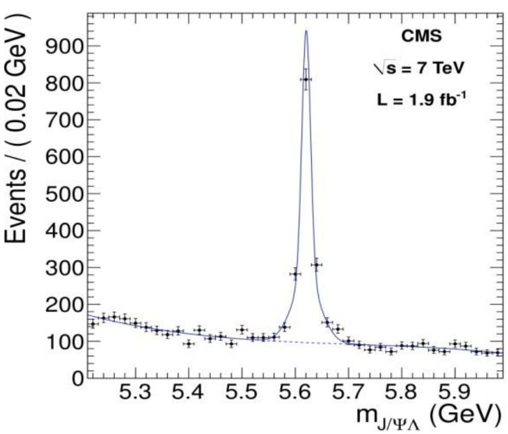
Differential cross section measured by CMS

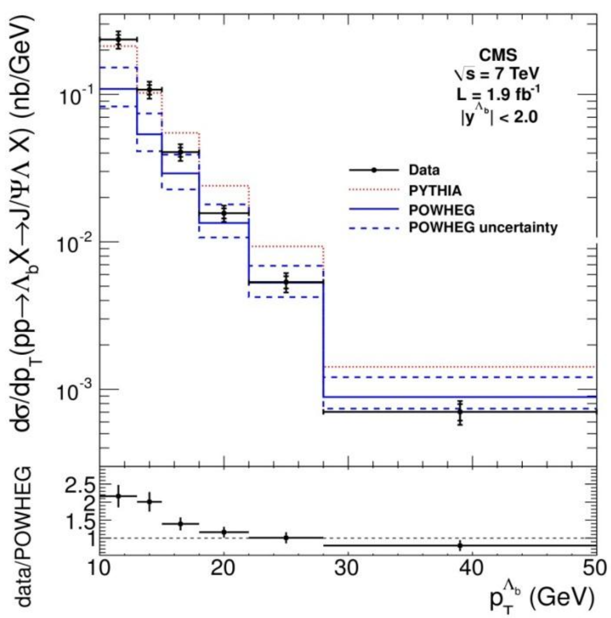
Description of p_T spectrum by theory not perfect, but reasonable

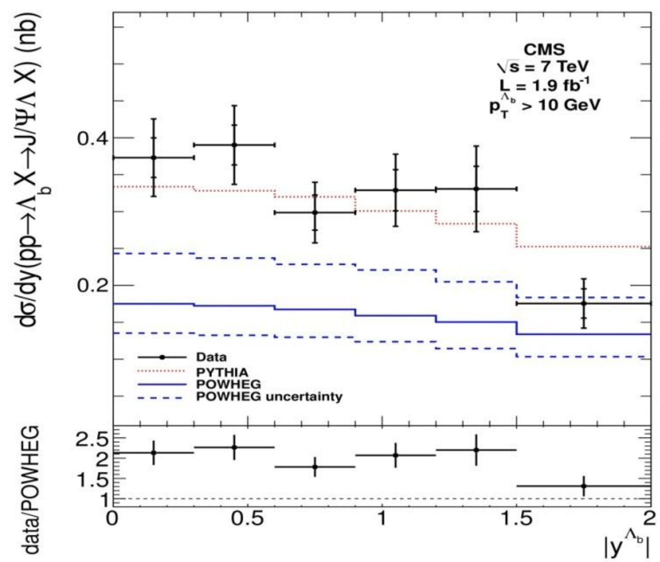
Shape of rapidity dependence reproduced well







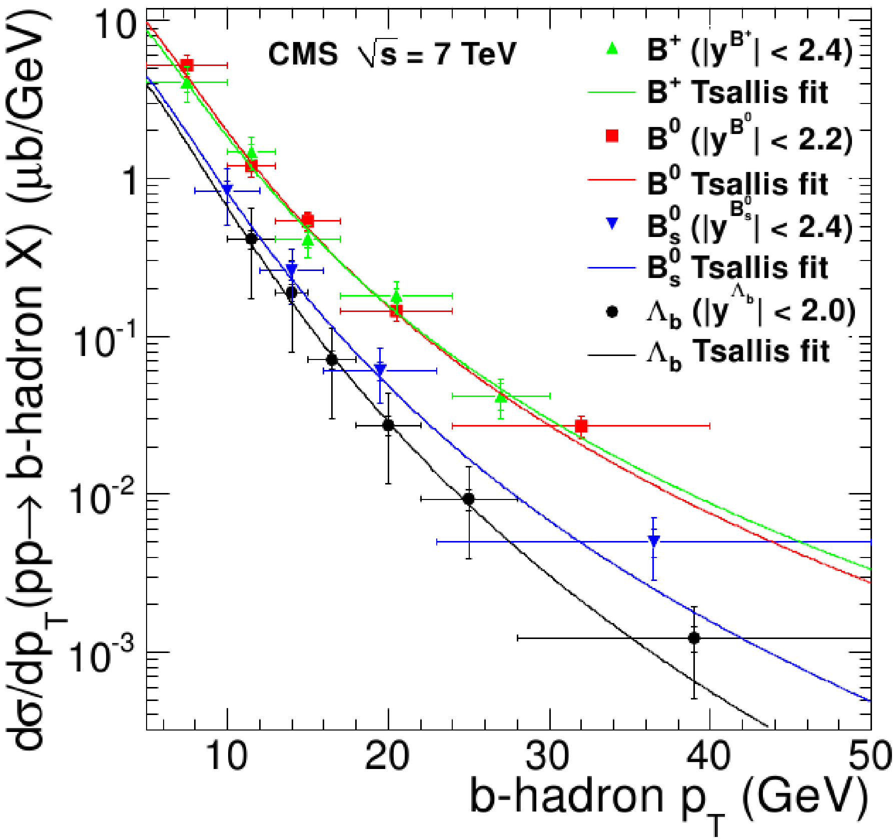


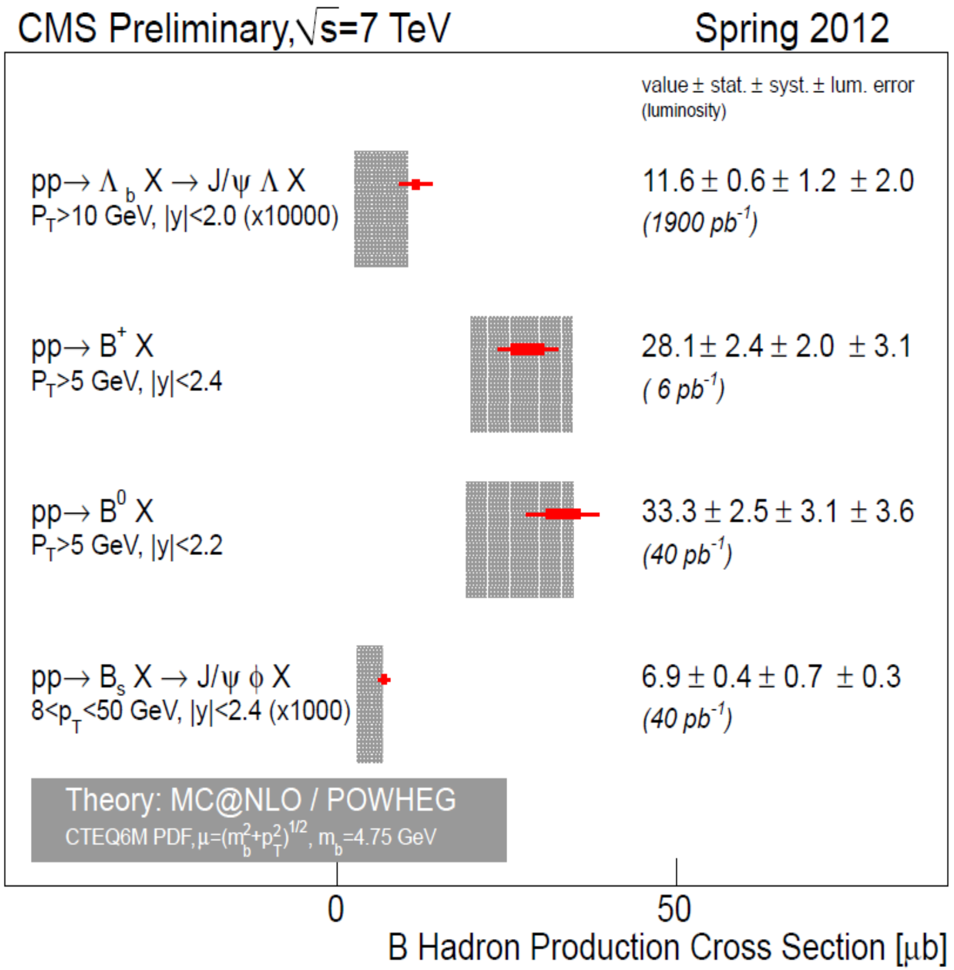


CMS: PLB 714 (2012) 136
LHCb: PLB 708 (212) 241
ATLAS: arXiv: 1207.2284

B hadron production

Compilation of CMS results on specific B hadron production:
The heavier the hardon, the steeper the pT spectrum...
Theory describes data well, but tends to be on the low side



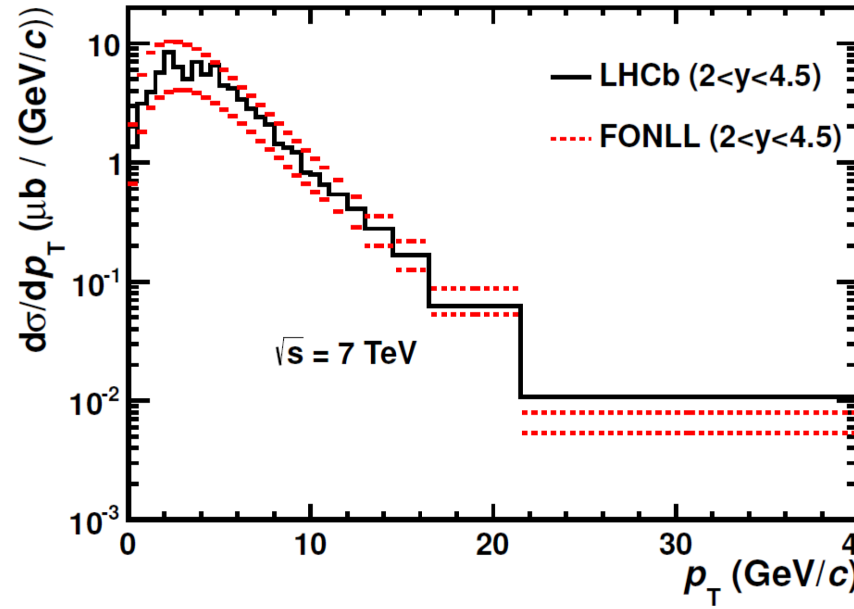


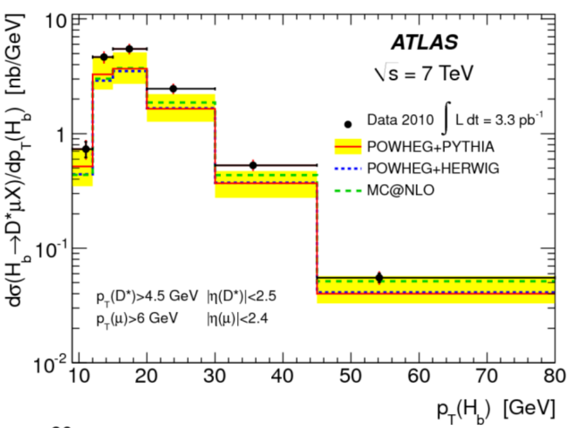
twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

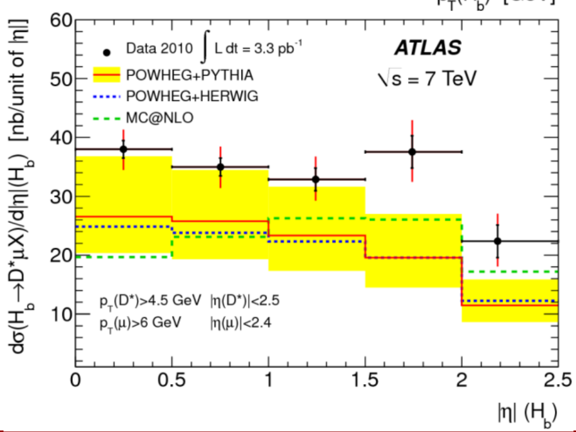
B hadron production (cont)

LHCb: fully reconstructed charged B meson production at 7 TeV

Agreement with models generally good
Theoretical errors larger than experimental







ATLAS: B hadron cross section from partially reconstructed final states, $D^{*+}\ \mu\ X$

7 TeV, $|y| < 2.5$ $10 < p_T < 80$ GeV

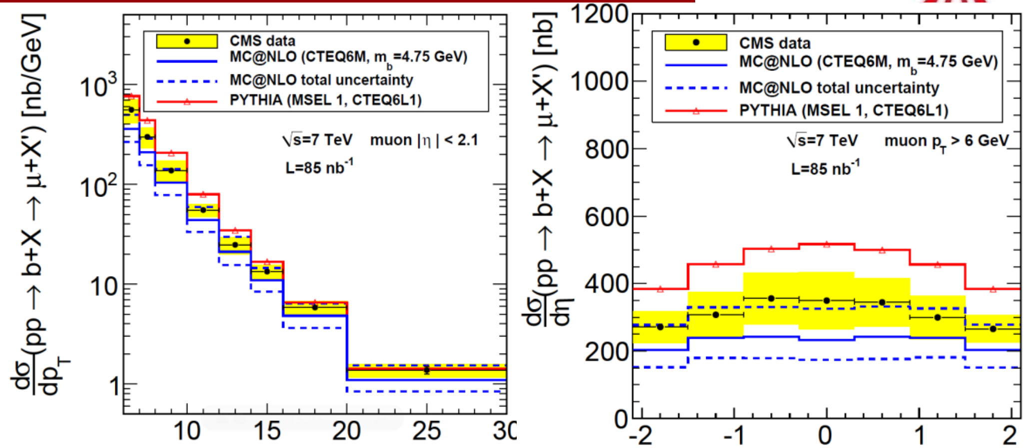
Shapes of both pT and eta distributions reproduced by several MC models reasonably well

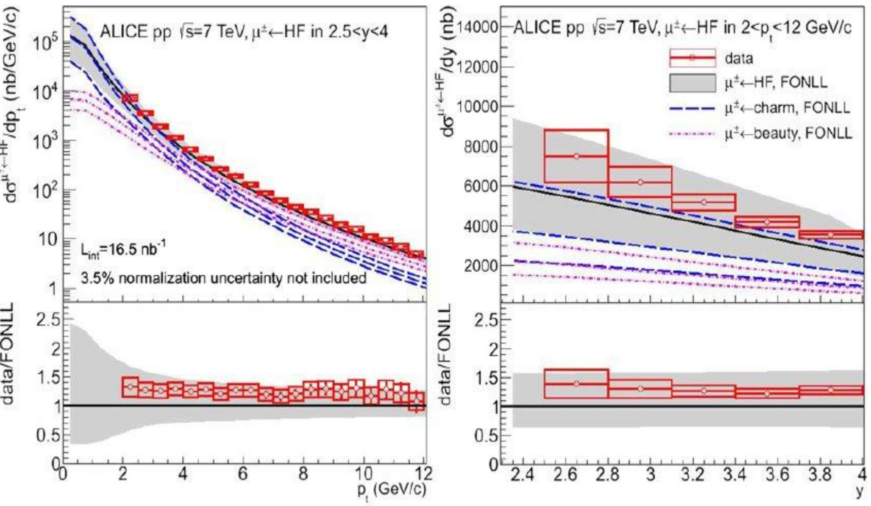
Normalisation somewhat lower than observed

LHCb: JHEP 04 (2012) 093
ATLAS: NPB 864 (2012) 341

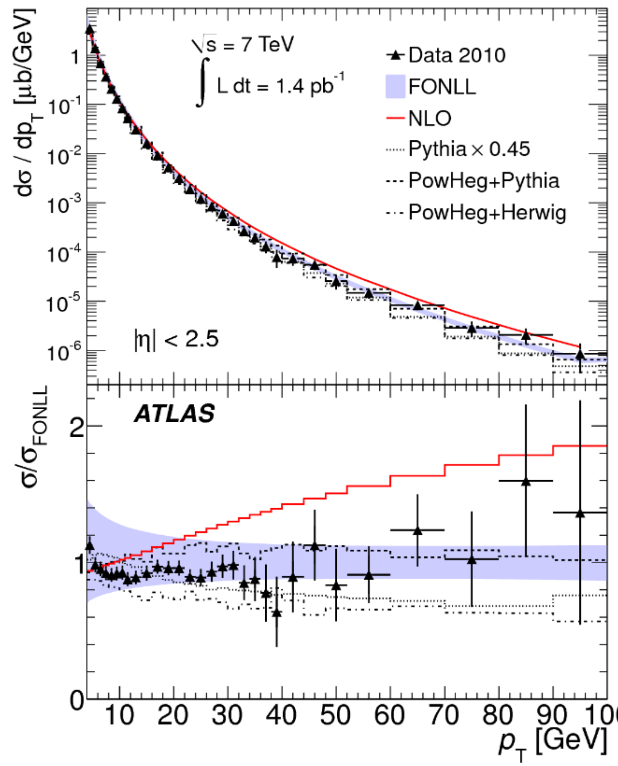
Inclusive muons from heavy flavours

CMS: | η| < 2.1, 4 < $p_T(\mu)$ < 30 GeV
Described well by NLO perturbative calculations





ALICE: PLB 708 (2012) 265
CMS: JHEP 06 (2012) 110
ATLAS: PLB 707 (2012) 438



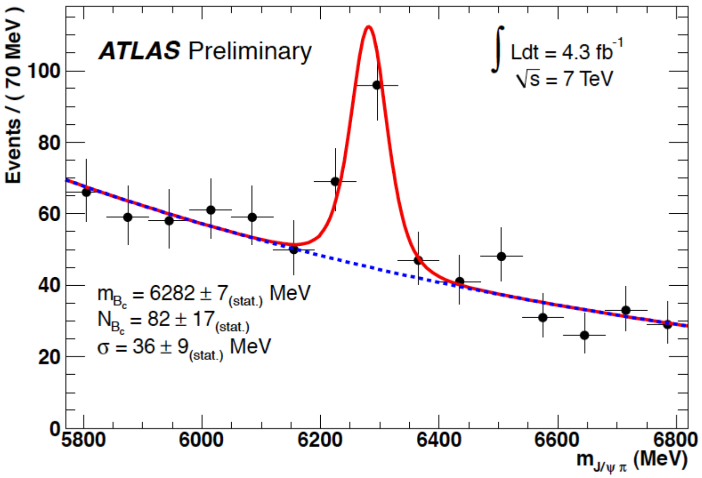
Similar conclusions by ALICE: 2.5 < |y| < 4, 2 < p_T < 12 GeV

ATLAS: |η| < 2.5, 4 < $p_T(\mu)$ < 100 GeV

Again, perturbative calculations doing a good job at low p_T but deviate at higher p_T

FONLL doing a better in the full range covered

B_c production

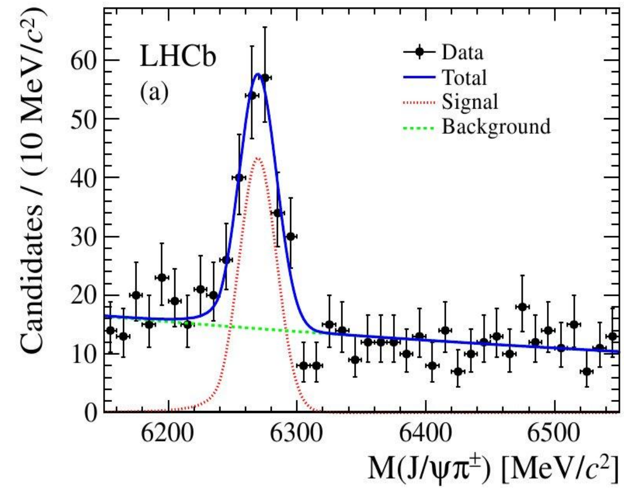


B_c: asymmetric, charged, weakly decaying heavy quarkonium

Now seen by ATLAS, CMS, LHCb

CMS observed it in $J/\psi\ \pi$ and $J/\psi\ 3\pi$

LHCb measured its production rate relative to B+



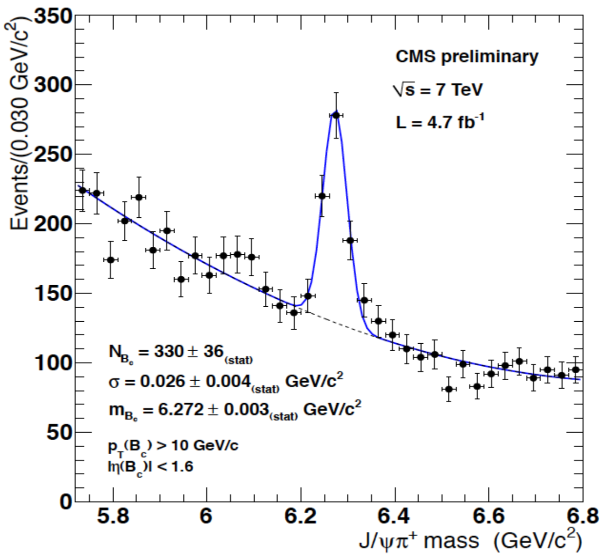
LHCb result at 7 TeV, 0.37 fb^{-1}

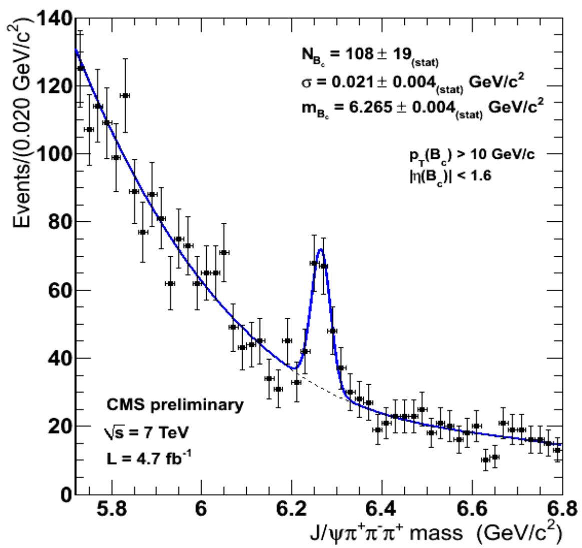
$$R_{c/u} = \frac{\sigma(B_c^+)\,\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\,\mathcal{B}(B^+ \to J/\psi K^+)}$$

= 0.68 % $\pm$0.10 % (stat)
$\pm$0.03 % (syst)
$\pm$0.05 % (lifetime)

for $p_T > 4$ GeV, $2.5<\eta<4.5$

Measurement provides valuable input for theory





LHCb: arXiv:1209.5634
CMS: PAS BPH-11-003
ATLAS:CONF-2012-028

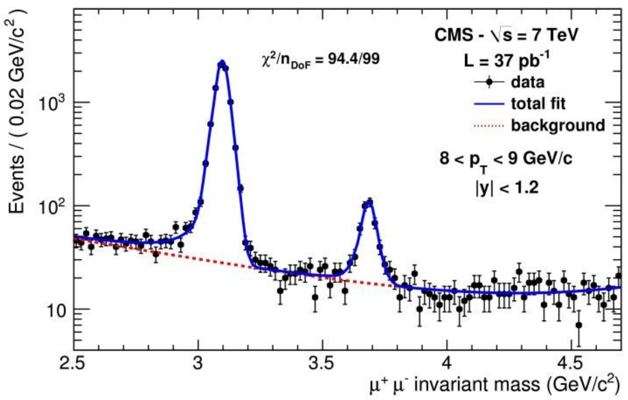
Separating prompt and non-prompt J/ψ and ψ(2S)

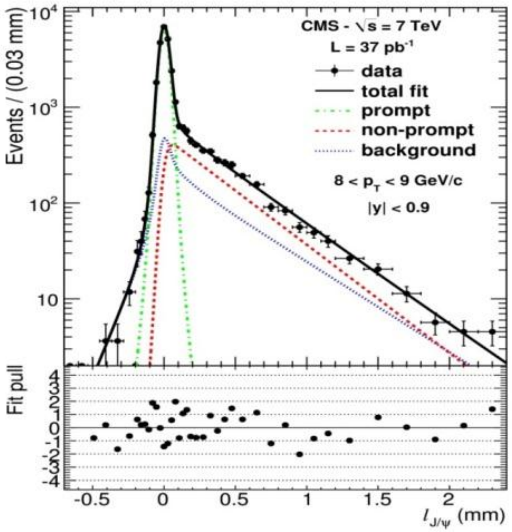
Prompt J/ψ: those produced from short-lived (QCD) sources

- Includes feeddown from **ψ(2S)** and C-even charmonia, if these are produced from short-lived sources

Non-prompt J/ψ: produced from Long-lived sources such as B decays

- May also Include feeddown from **ψ(2S)** and C-even charmonia, if these are produced from B decays

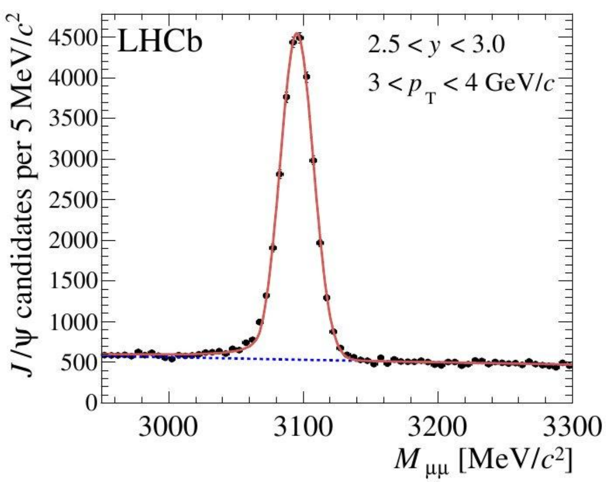


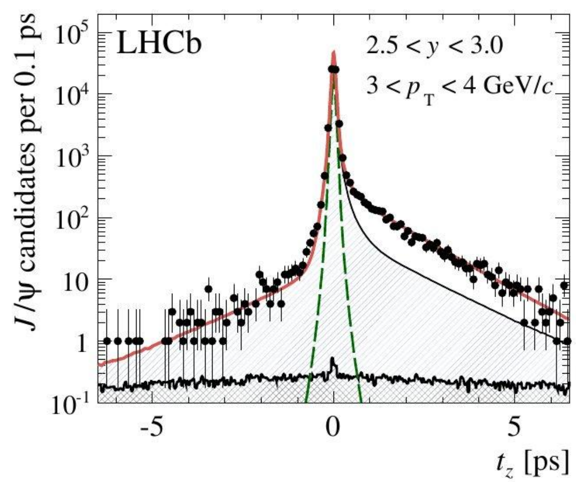


All LHC experiments use (pseudo) proper time to separate prompt and non-prompt production

CMS and ATLAS use **transverse** decay length, while LHCb works with **longitudinal**

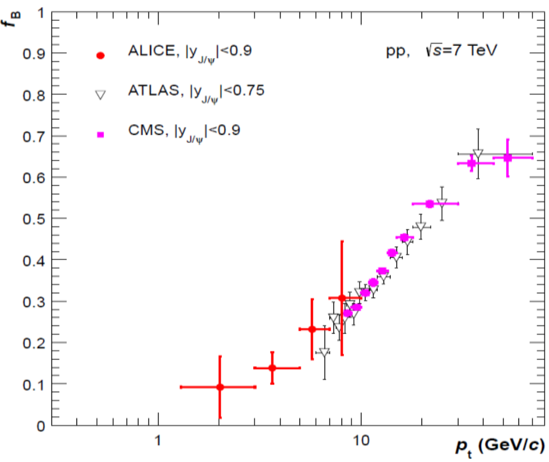
- Similarly for **ψ(2S)**, but there is no feeddown from higher charmonium states here

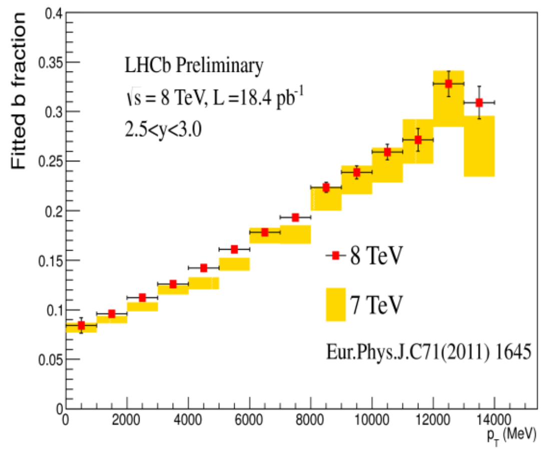


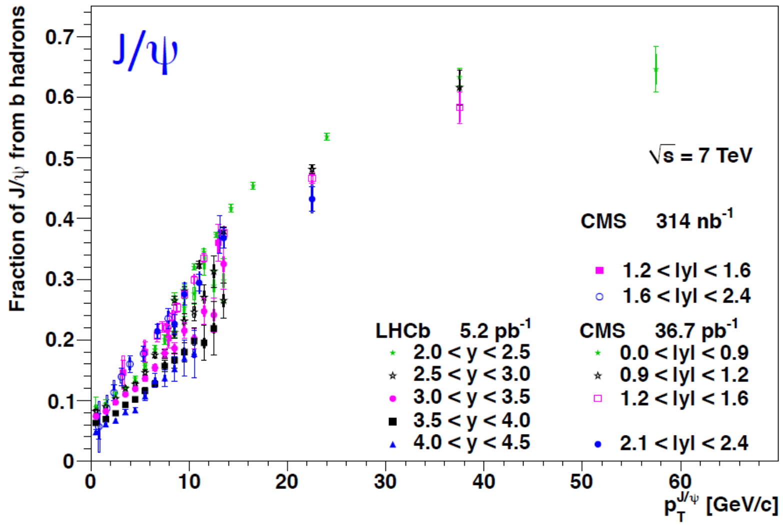


Fraction of J/ψ and ψ(2S) from B decays

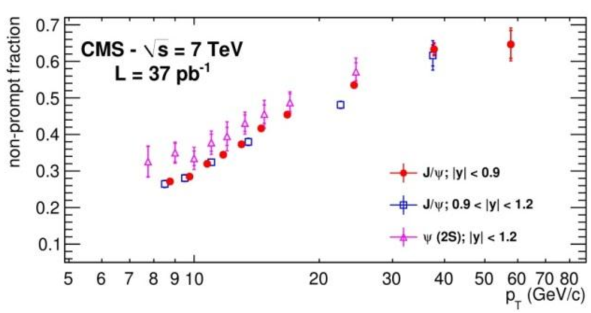
J/ψ: now measured by CDF and all four LHC experiments
Below 10% at low p_T, central rapidity, increasing with p_T to ~70%
This increase slows down at forward rapidities
Weak energy dependence (if any at all)

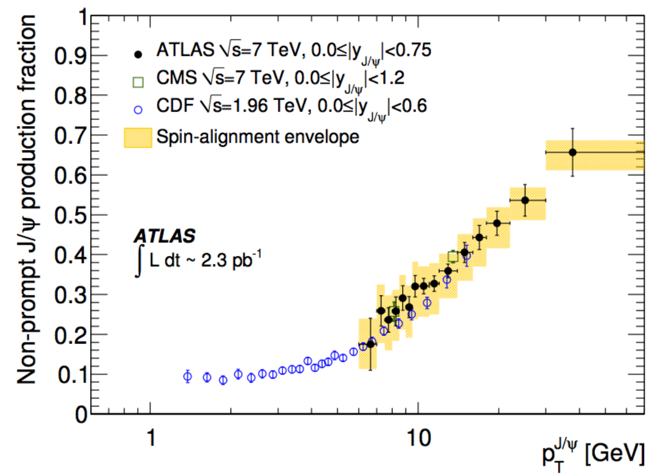






Similarly for **ψ(2S)**, but possibly higher at low p_T
At high p_T, approaches plateau of ~60%



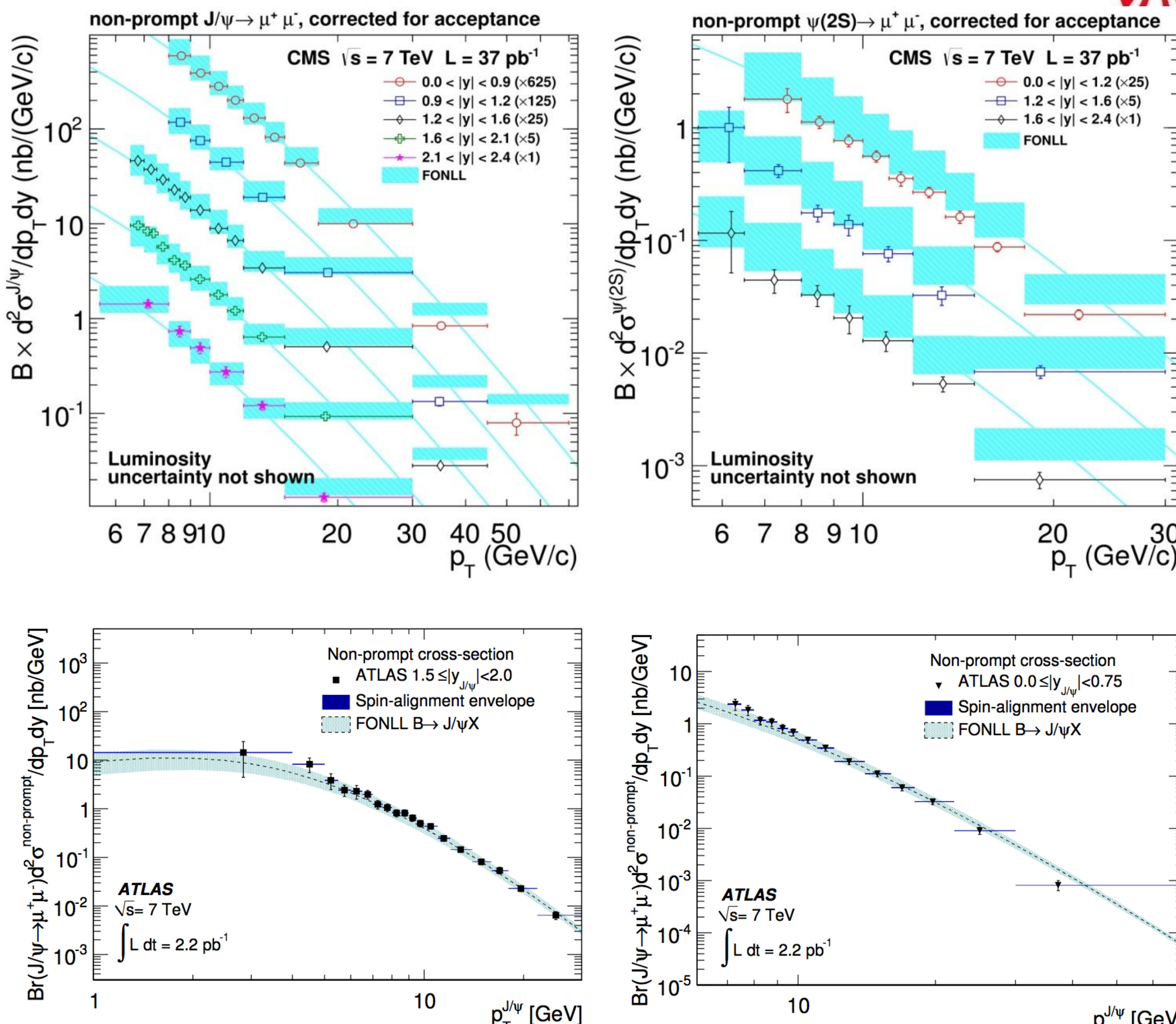


ALICE: arXiv:1205.5880
CMS: EPJ C71 (2011) 1575
ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
CDF: PRD 71 (2005) 032001
CDF: PRD 80 (2009) 031103
LHCb: EPJ C71 (2011) 1645
LHCb: arXiv:1204.1258

Non-prompt J/ψ and ψ(2S) are produced in B hadron decays

Perturbative QCD calculations describe these contributions reasonably well, with no free parameters

ATLAS and CMS results shown here as examples



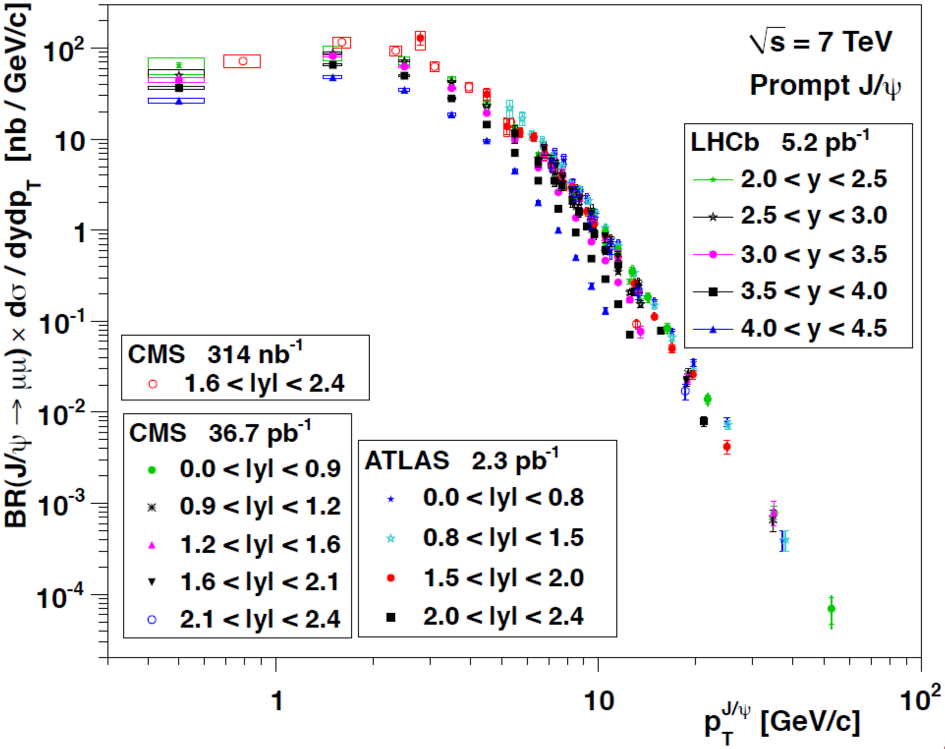
ATLAS: NPB 850, 387 (2011) 387
CMS: JHEP 02 (2012) 011

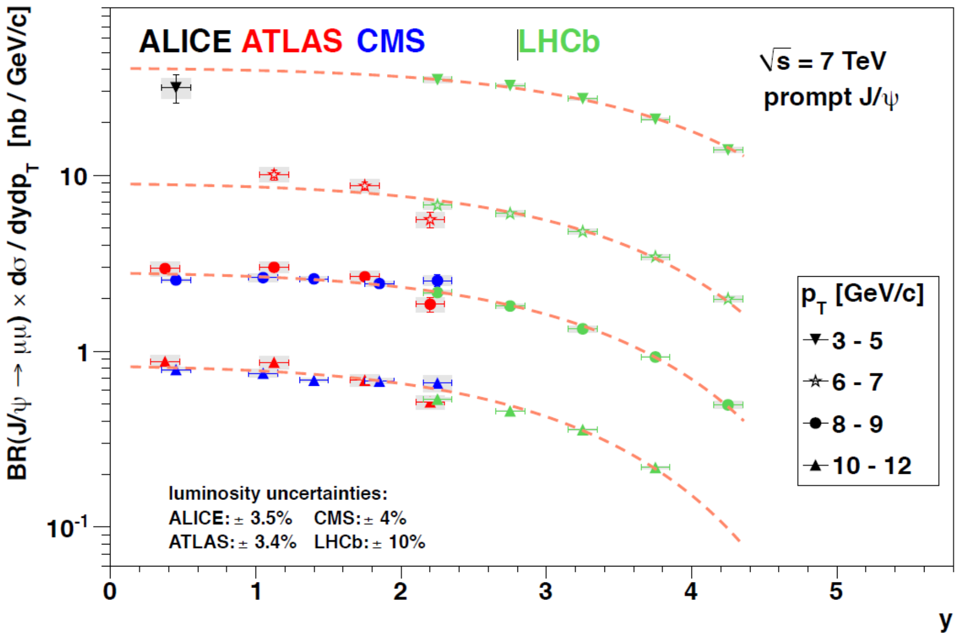
Prompt J/ψ

Between the experiments, a huge kinematic range is covered: $|y| < 4.5$, $0<p_T<70$ GeV

Over 6 orders of magnitude in p_T

Measurements mostly consistent when overlap, some differences in rapidity shapes





Compiled by Hermine K. Woehri

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645

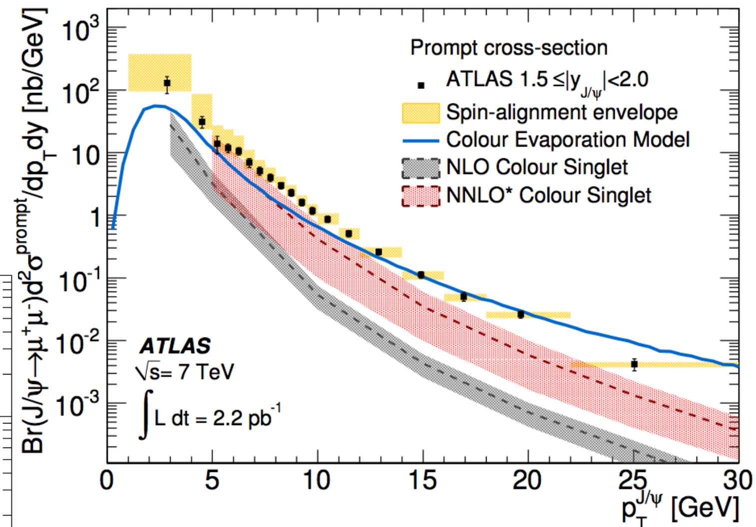
Prompt J/ψ vs theory

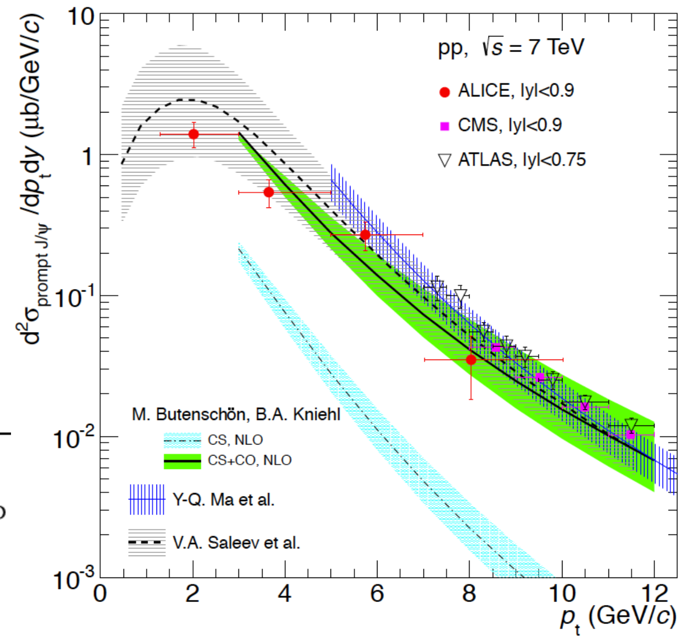
Multitude of models (CSM, CEM, COM) in various incarnations all do a reasonable job, but neither is perfect

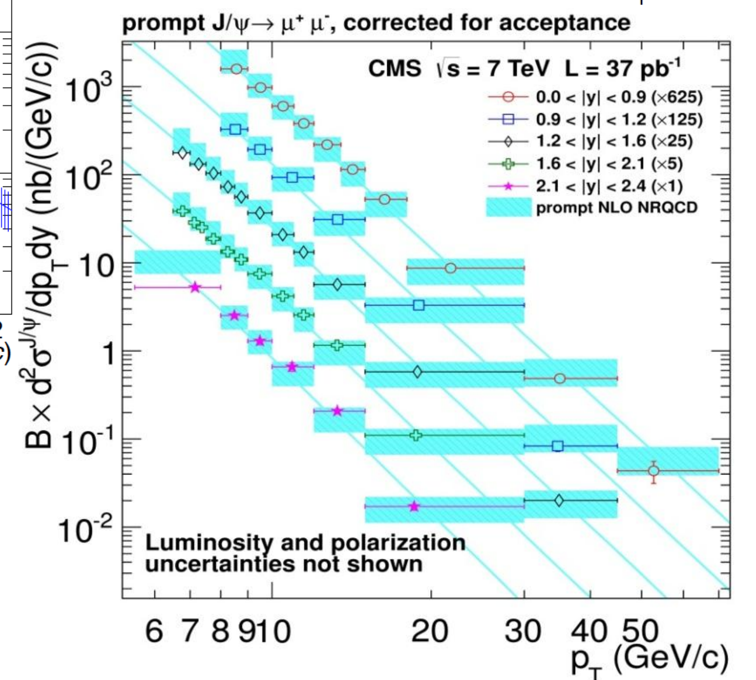
Some have virtually no parameters (CSM, CEM)

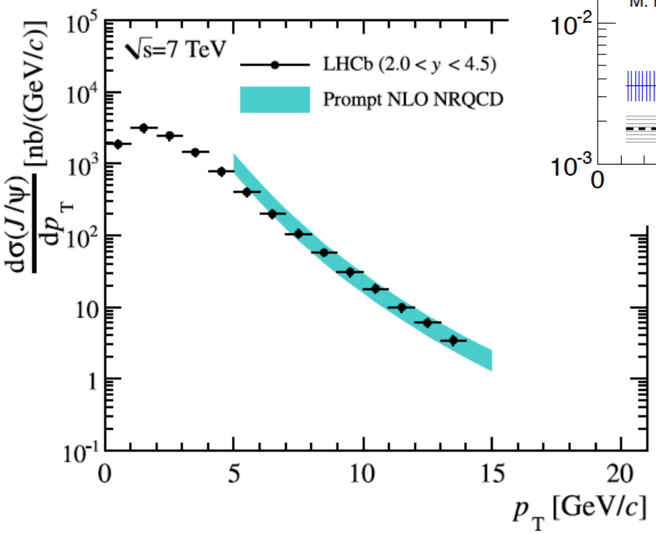
Others (NRQCD-based) have quite a few

p_T spectra alone not enough to make a judgement



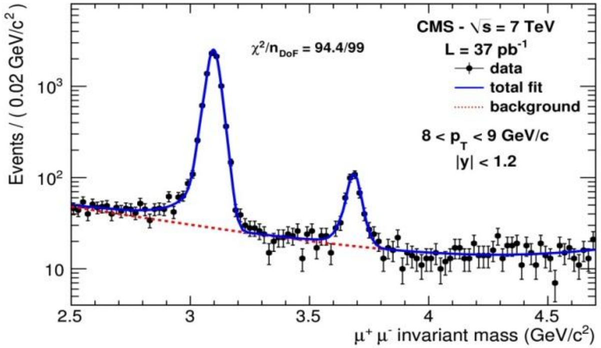






ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645

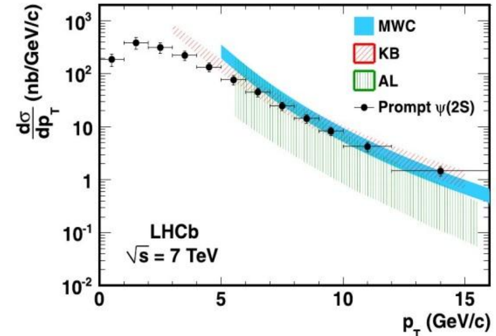
ψ(2S): unique case

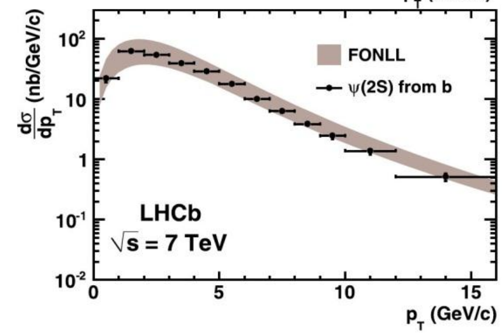


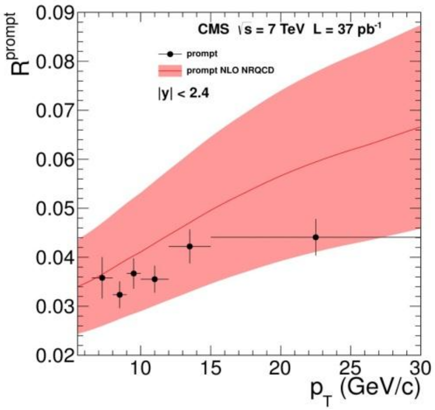
Dimuons from ψ(2S):
~30 times fewer than J/ψ

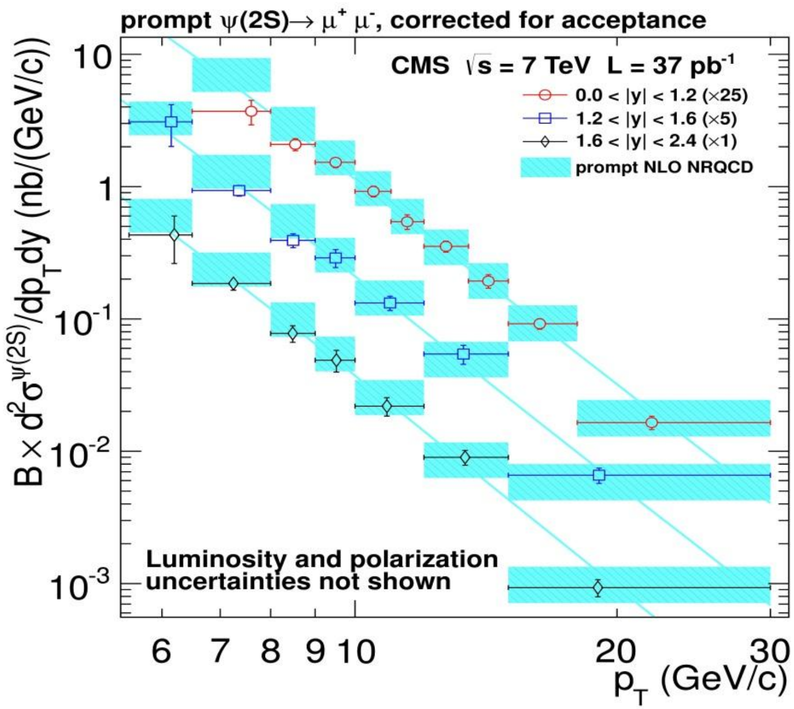
Some ψ(2S) are **non-prompt**, but there is **no** feeddown from heavier states

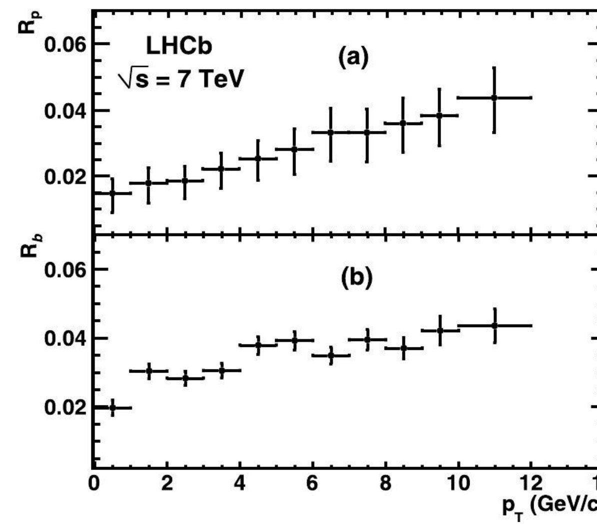
ψ(2S) to J/ψ ratio R (corrected for BR(μμ)) is measured separately for prompt and non-prompt -- a good testbed for production models

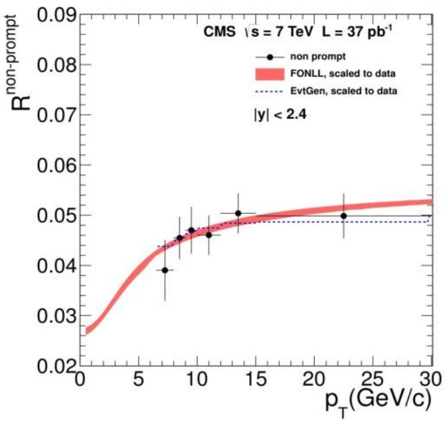




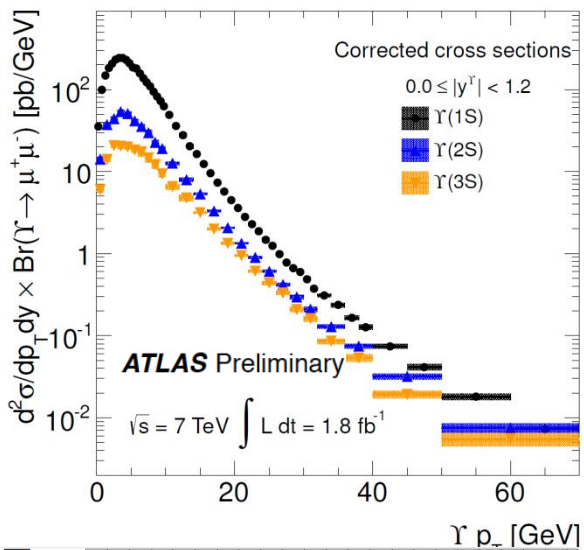








Production of Y(1S), Y(2S), Y(3S)

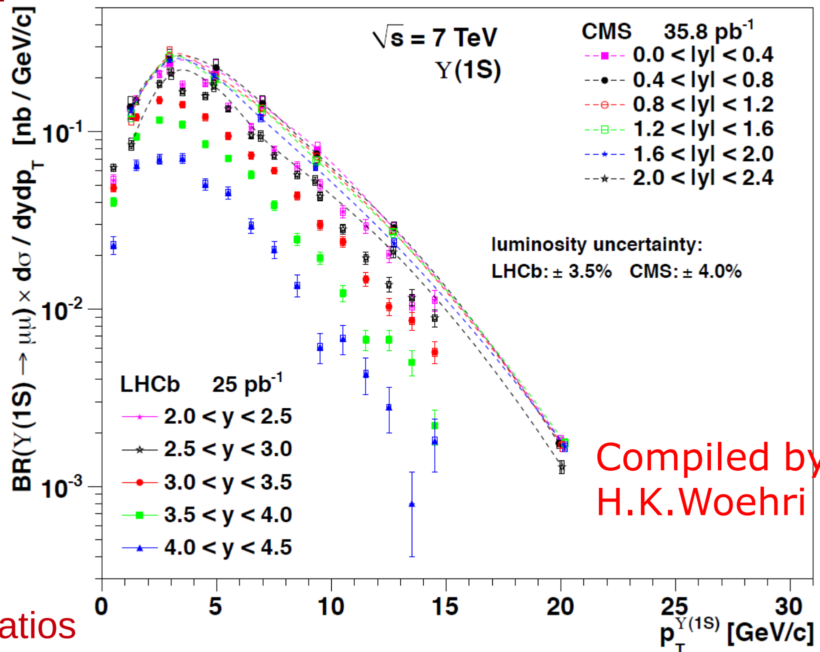


ATLAS: imminent -- double-differential cross section of Y(1,2,3S) with 1.8 fb^{-1}

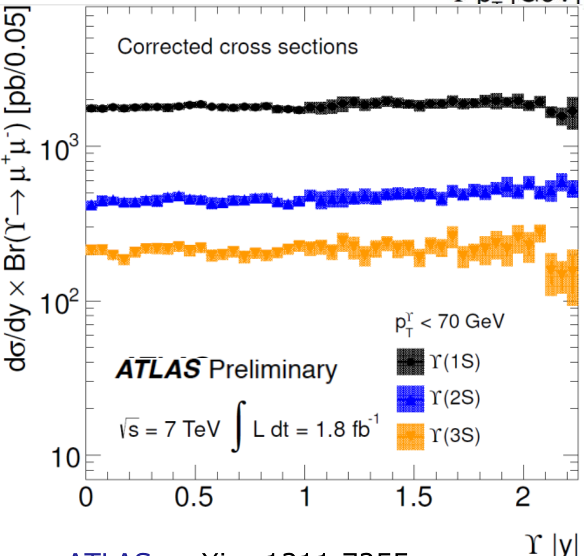
Extended p_T range, finer binning

Agrees well with existing data from CMS and LHCb, wide space covered overall

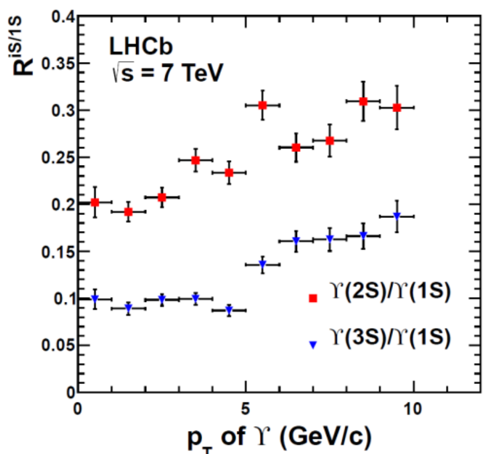
p_T: 0 to 70 GeV, |y| : < 4.5

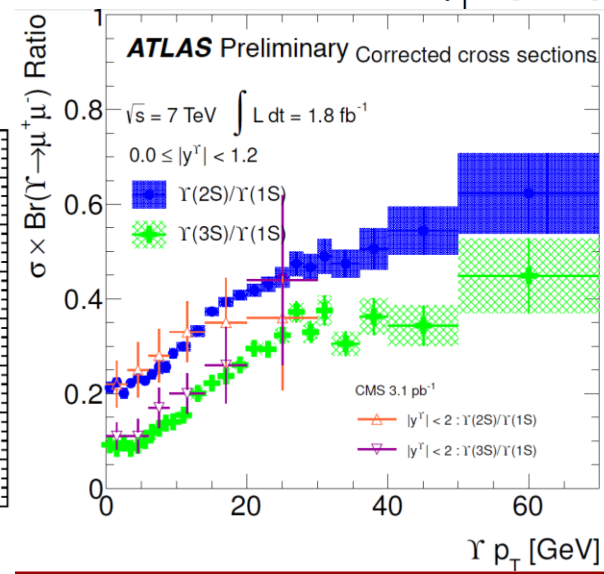


Compiled by H.K.Woehri



Intriguing: p_T dependence of ratios Y(2S)/Y(1S), Y(3S)/Y(1S) confirms existence of multiple mechanisms, hints on their p_T evolution





ATLAS: arXiv: 1211.7255
CMS: PRD 83 (2011) 112004
LHCb: EPJC 72 (2012) 2025

Production of Υ: theory comparison

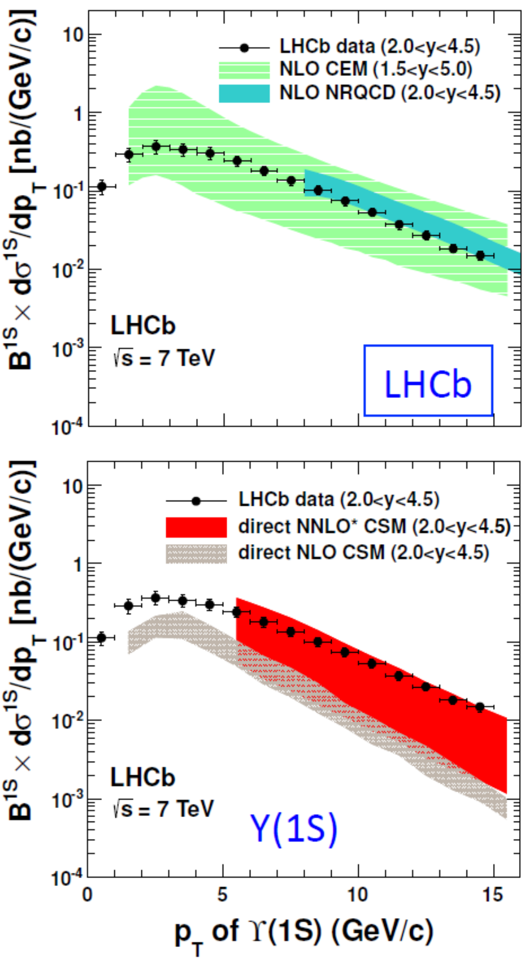
Again, all the usual models – CSM, COM, CEM, etc -- doing a reasonable job, but neither can reproduce the full range

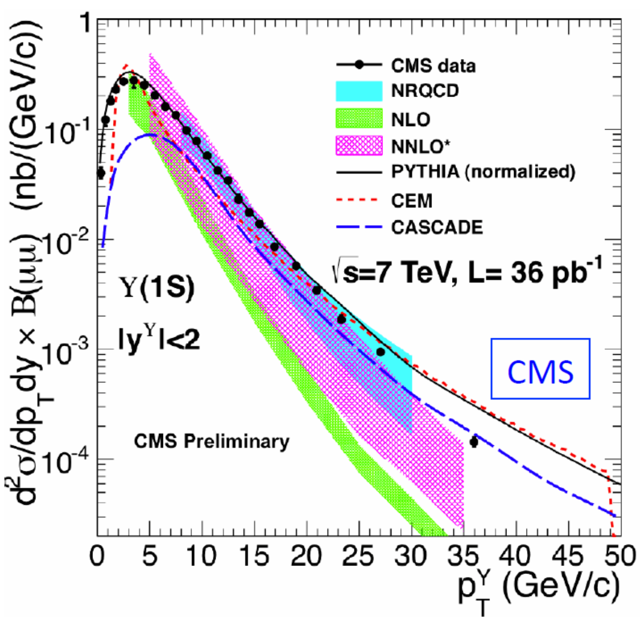
ATLAS: arXiv: 1211.7255
CMS: PRD 83 (2011) 112004
LHCb: EPJC 72 (2012) 2025

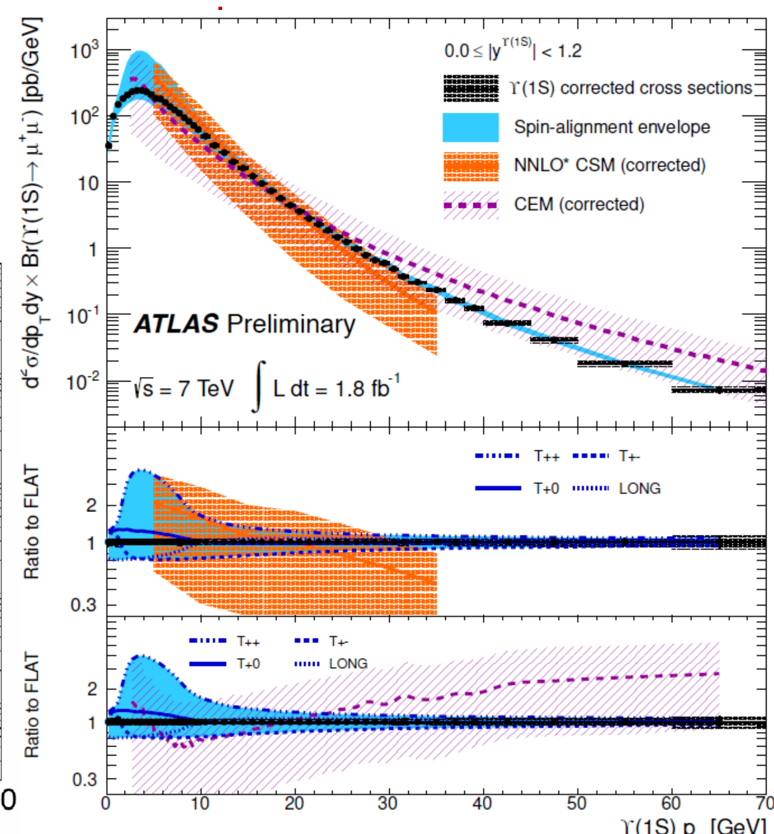
NNLO* CSM doing better than in case of J/ψ

Again, p_T, y spectra alone not enough to make a judgement

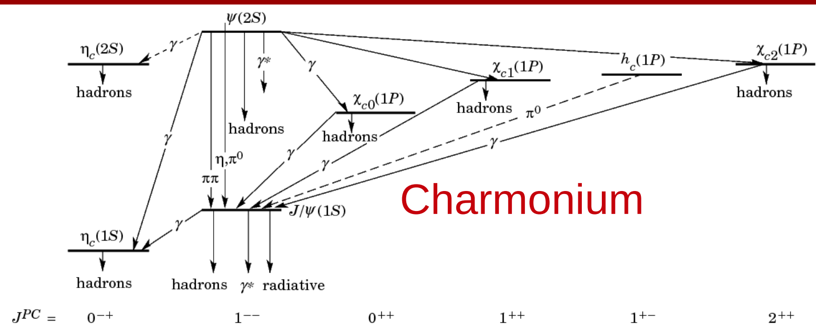
Tough times for theorists!





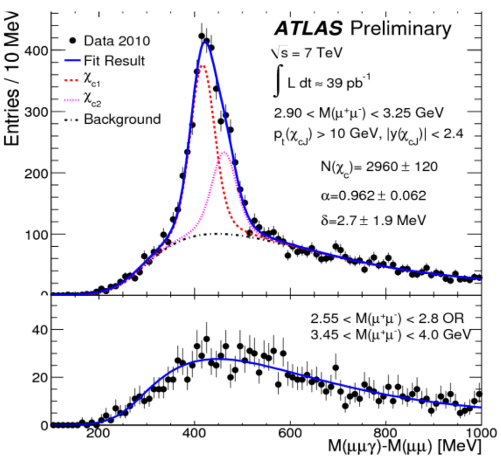


Quarkonium spectroscopy and χ feeddown

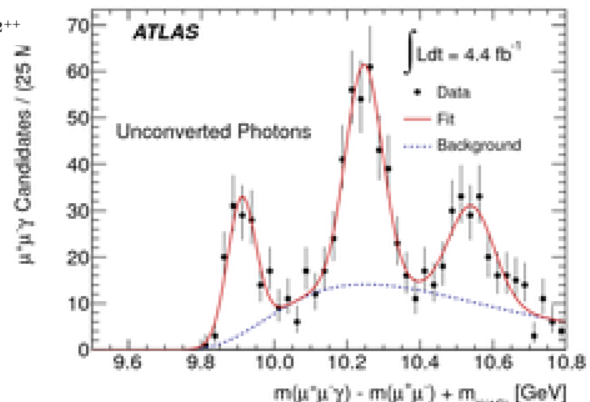


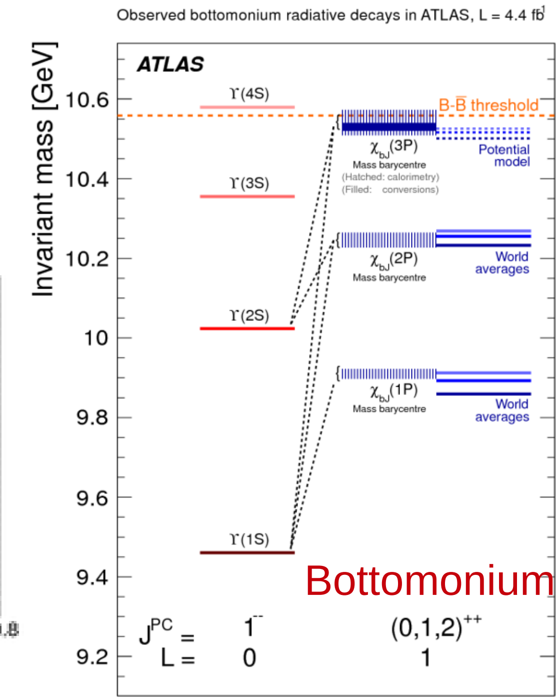
Charmonium

ATLAS: $\chi_b(3P)$ – first discovery of LHC, now confirmed by D0, LHCb



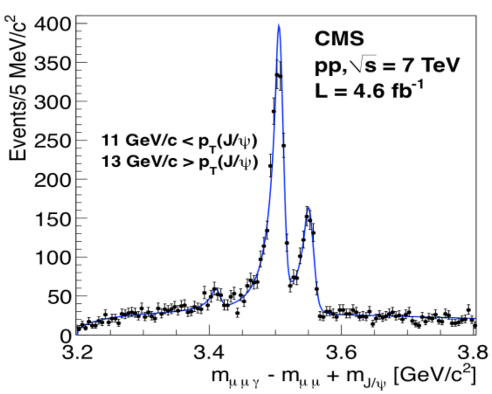
Unconverted photons



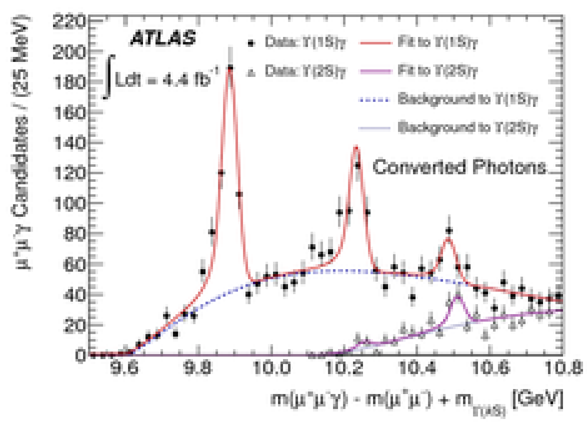


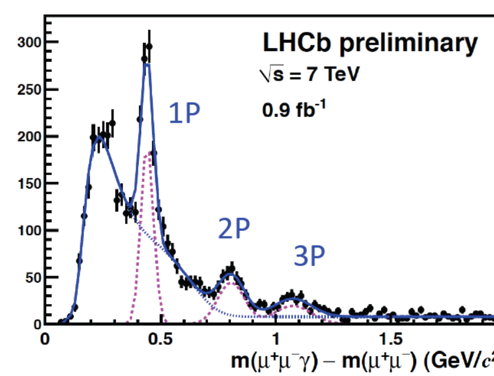
Bottomonium

ATLAS: PRL 108 (2012) 152001
CMS: arXiv:1210.0875
LHCb: CONF-2012-020

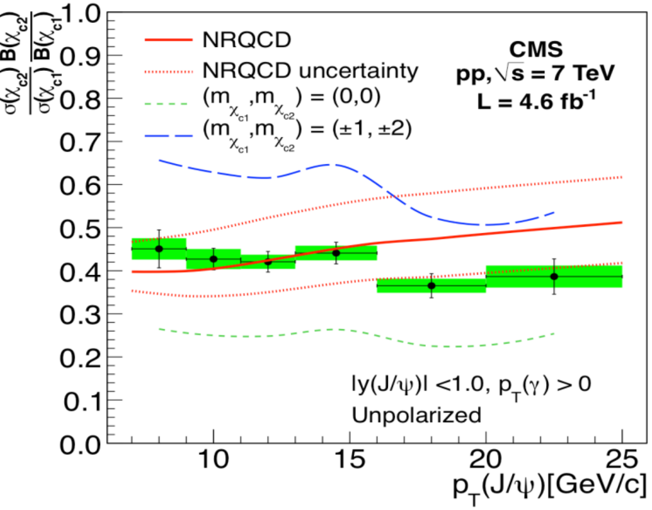


Converted photons





Ratio of prompt χ_c production

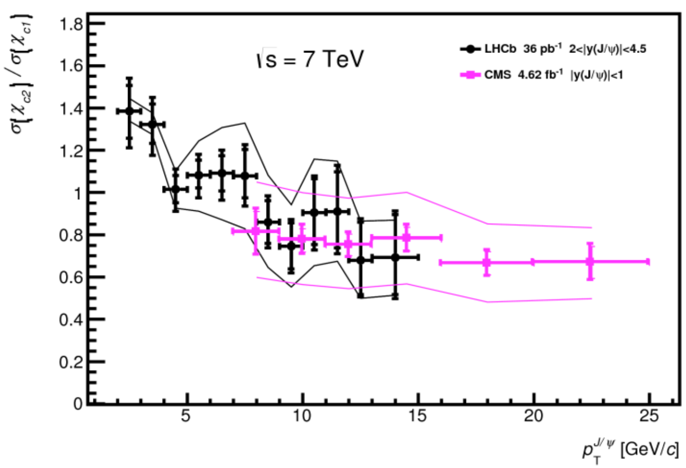


Relative production of prompt χ_{c2} to χ_{c1} in their J/ψ+γ decays

Various theoretical models predict different polarisation of χ_c

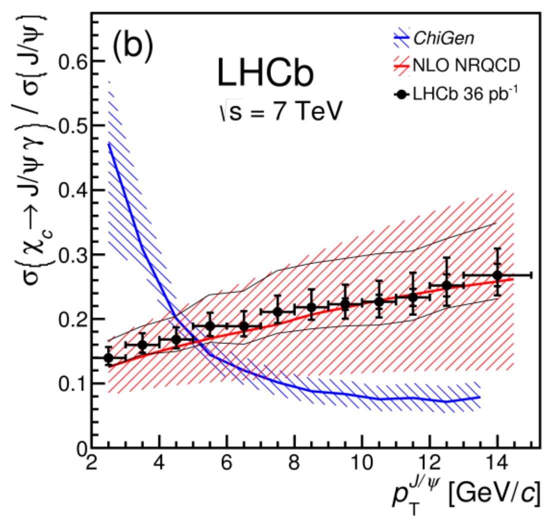
Acceptance corrections depend on assumed polarisation

- Smooth transition from low p_T, high y region studied by LHCb to higher p_T, low y range studied in CMS
- Thin lines show the range with extreme polarisation assumptions
- p_T dependence trend follows qualitative expectations from naive perturbative QCD



LHCb have measured the fraction of J/ψ produced from χ_c radiative decays

COM describes data well, but perturbative CSM-style calculations are in contrast with both



CMS: arXiv:1209.2922
LHCb: arXiv: 1204.1452
LHCb: PLB 714 (2012) 215

Υ production: fraction of feeddown

Feeddown pattern in Υ much more complicated.

LHCb singled out $\chi_b(1P)$ contribution to Υ(1S)

LHCb: $(20.7 \pm 5.7(\text{stat}) \pm 2.1(\text{syst})\ ^{+2.7}_{-5.4}(\text{pol}))\%$ at forward rapidity and pT range shown above, with no significant pT dependence

In agreement with CDF measurements at 1.8 TeV

CDF: $(27.1 \pm 6.9 \pm 4.4)\%$ at central rapidity

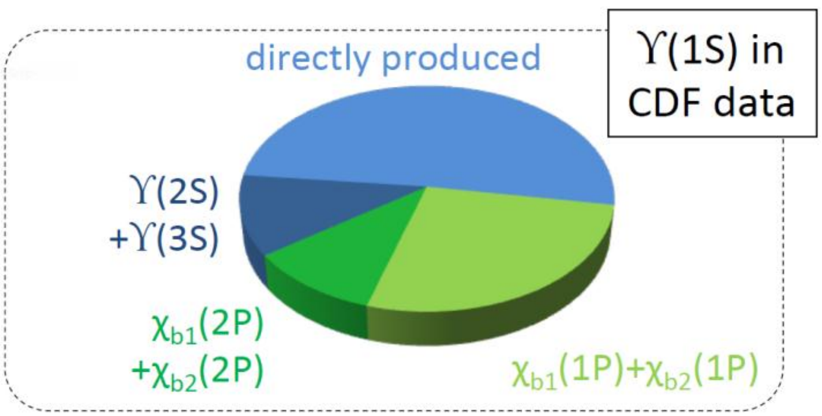
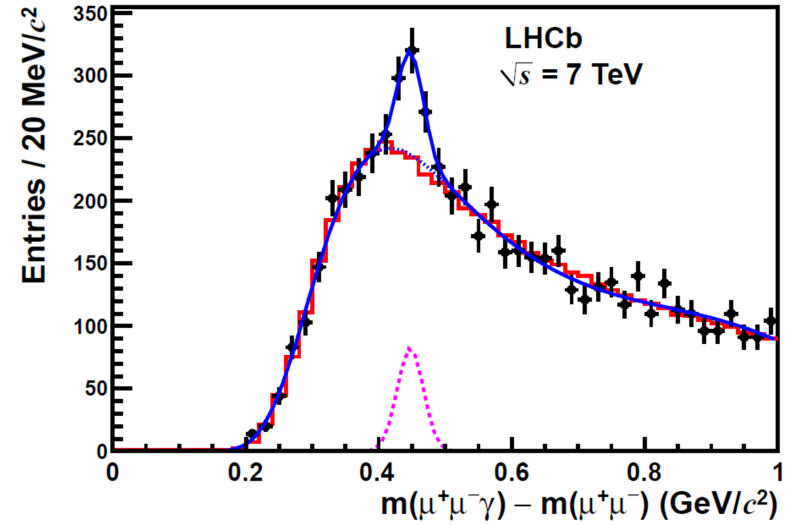
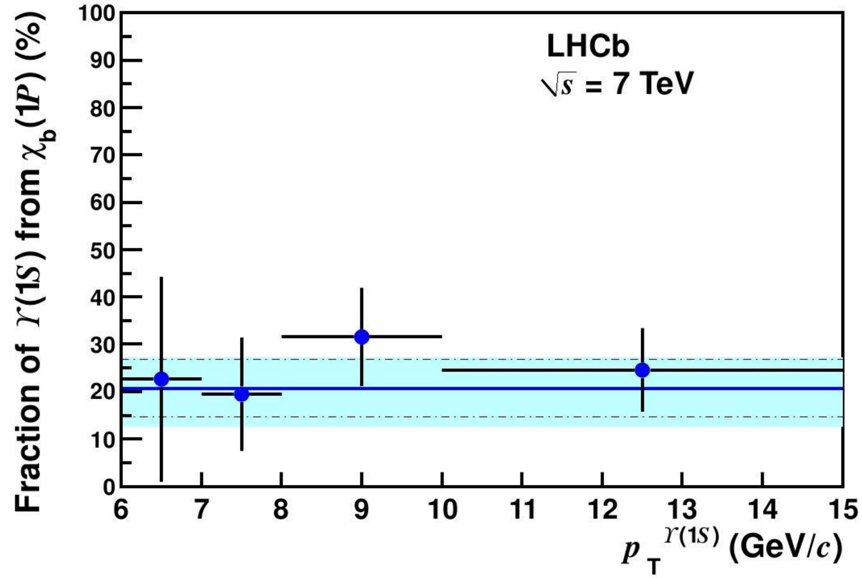


Diagram from P. Faccioli



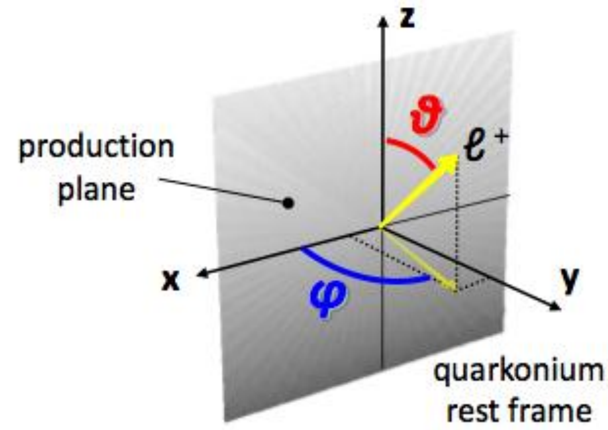


LHCb: arXiv:1209.0282
CDF: PRL 84 (2000) 2094

Spin alignment: two-angle formalism

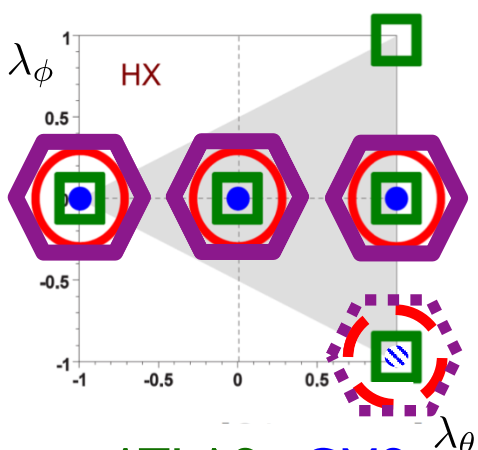
A vector state $|\psi\rangle = a_{-1}\,|1,-1\rangle + a_0\,|1,0\rangle + a_{+1}\,|1,+1\rangle$

produced in a single exclusive process, and decaying into a pair of fermions, has the general angular distribution:



$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star}\cos^2\theta^\star + \lambda_{\phi^\star}\sin^2\theta^\star\cos 2\phi^\star + \lambda_{\theta^\star\phi^\star}\sin 2\theta^\star\cos\phi^\star$$

$$\lambda_{\theta^\star} = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_{\phi^\star} = \frac{2Re\,a^*_{+1}a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta^\star\phi^\star} = \frac{\sqrt{2}Re\,[a_0^*(a_{+1}-a_{-1})]}{1+|a_0|^2}$$



In **cross section measurements**, detector acceptance depends on polarisation, and if the polarisation is unknown, the acceptance-corrected cross section varies with the polarisation hypothesis used

Different experiments use slightly different range of hypotheses

In **polarisation measurements**, it is not safe to integrate over φ*, because fiducial cuts can (and do!) introduce non-trivial and sometimes strong φ*-dependence, thus affecting θ* dependence and hence the extracted value of λ_θ

In the two-angle treatment, a move from helicity frame (above) to e.g. Collins-Soper frame is accoplished by a simple rotation

ALICE: J/ψ polarisation

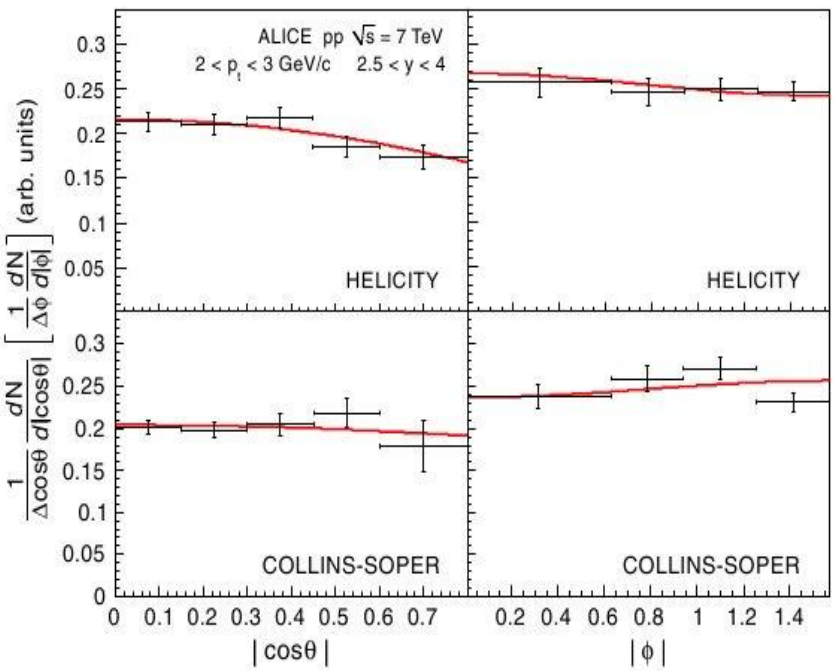
Due to limited statistics, ALICE decided to integrate over the two polarisation angles separately, and thus determined two (of the three) coefficients, one at a time, in both helicity and Collins-Soper reference frames.

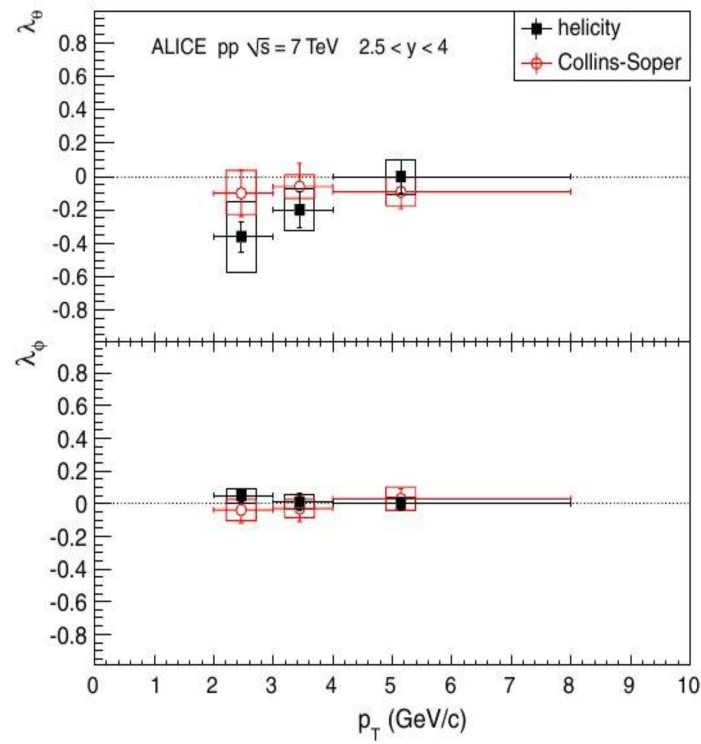
$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta),$$

$$W(\phi) \propto 1 + \frac{2\lambda_\phi}{3+\lambda_\theta}\cos 2\phi,$$

In such analysis, the general warning about acceptance affecting the measurement still holds

Rotation between the frames can (to some extent) be used for a consistency check



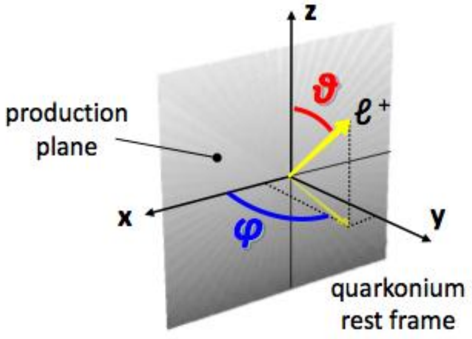


ALICE: PRL 108 (2012) 082001

General angular dependence of decay muons in Υ rest frame:

$$1 + \lambda_{\theta^\star} \cos^2\theta^\star + \lambda_{\phi^\star} \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta^\star\phi^\star} \sin 2\theta^\star \cos\phi^\star$$

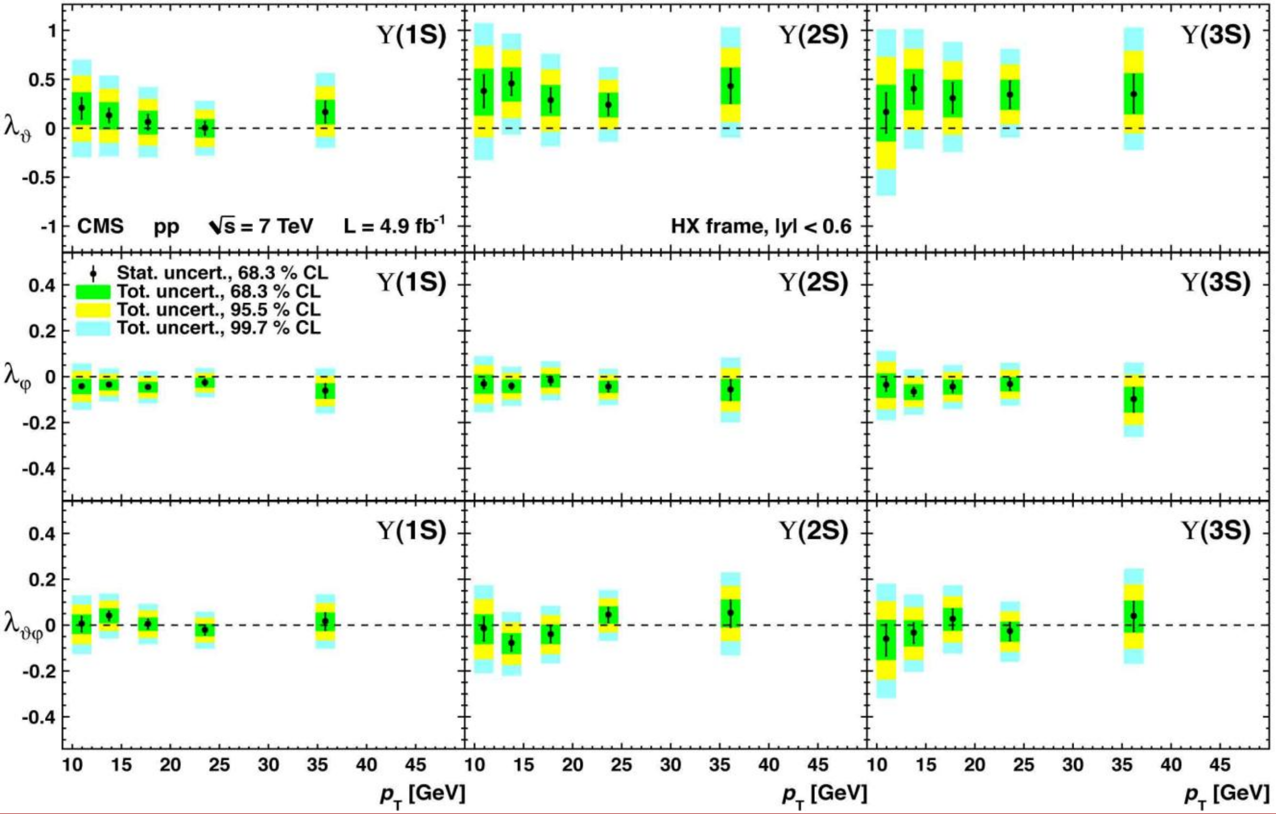
Helicity frame: z axis along the Υ momentum in the lab frame



CMS have made a full 2-angle measurement of the polarisation of all three Υ states, in two rapidity bins, and three different frames, as a function of Υ transverse momentum

Only helicity frame results are shown here, results in others are similar: spin alignment for Υ(1S) is not strong, if any at all

Possible hints of slightly increasing transverse polarisation when moving from Υ(1S) to Υ(2S) to Υ(3S)



CMS: arXiv:1209.2922

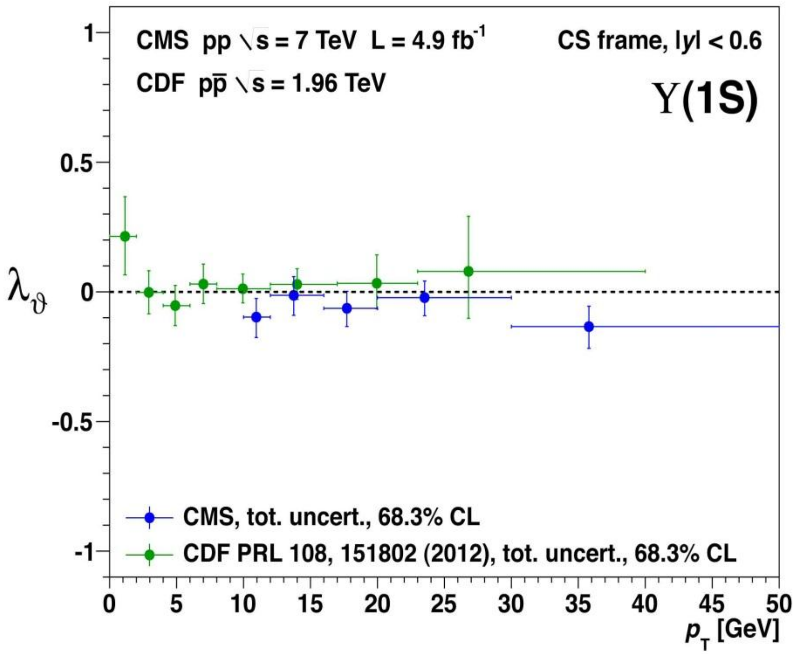
Υ polarisation vs energy, and theory comparison

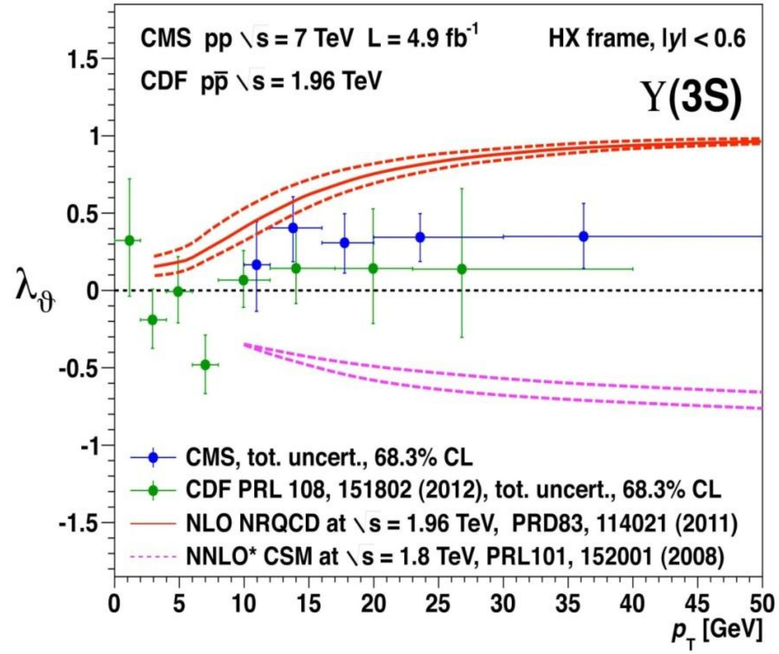
CMS results in good agreement with recent results from CDF

Theoretical predictions are notoriously difficult to make, partly due to feeddown

Model curves below made under assumption that Υ(3S) is direct, however after the observation of $\chi_b(3P)$ we know that's not true!

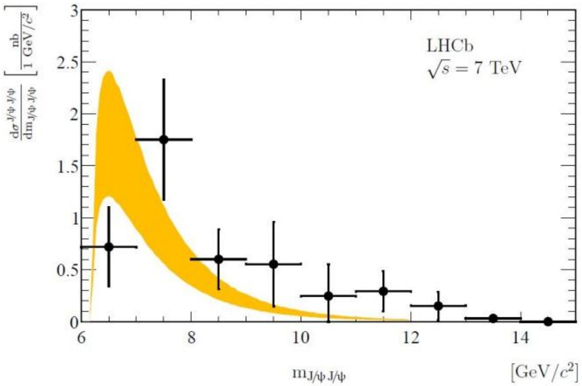
In any case, measured polarisation levels are not as large as those predicted by the theoretical models shown





LHCb: J/ψ + J/ψ, J/ψ + charm

Clearly, p_T and y spectra, or even polarisation measurements, are not enough to discriminate between models



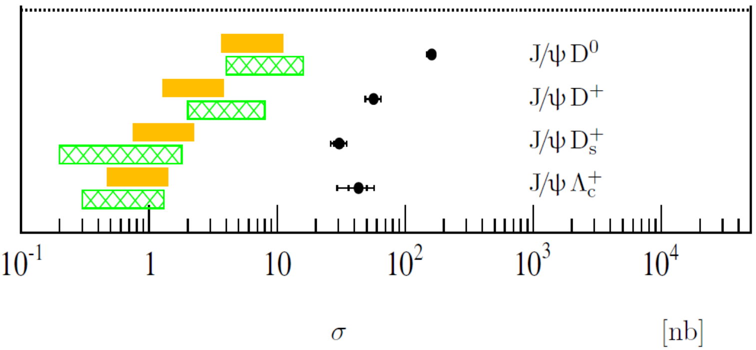
Some mechanisms contain predictions about particle associations, and/or underlying event properties. Experimental setup may suggest new opportunities

An early example:
double J/ψ production in LHCb

Another example of "new observables":
J/ψ + charm compared to charm + (anti) charm

Double charm fewer than charm-anticharm, but still copious

Theoretical predictions hard to make, QCD models clearly underestimate cross section

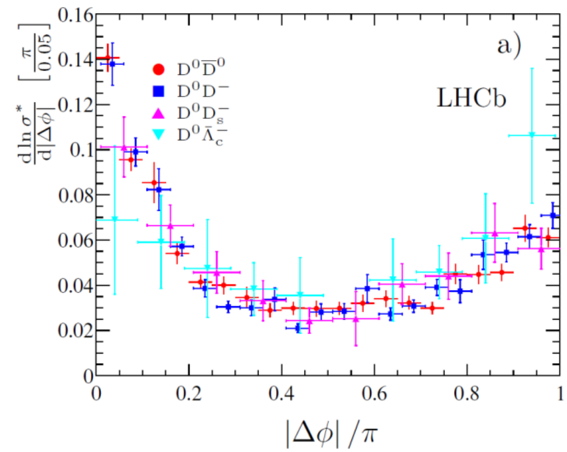


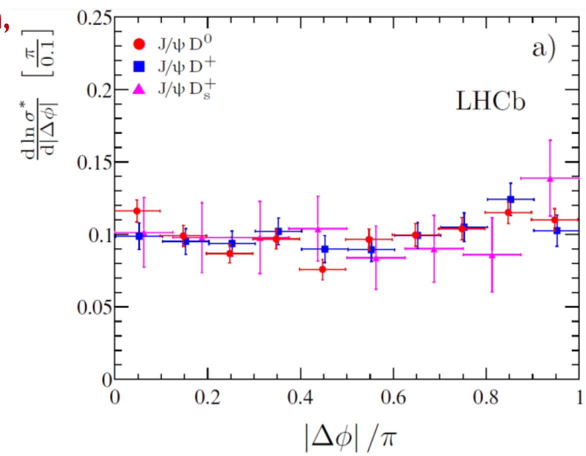
Random uncorrelated: flat in Δφ – Double-Parton Scattering?

Coherent production:
small Δφ : -- gluon-splitting?
large Δφ : -- back-to-back

As opposed to charm-anticharm, majority of J/ψ seem to be uncorrelated with charm

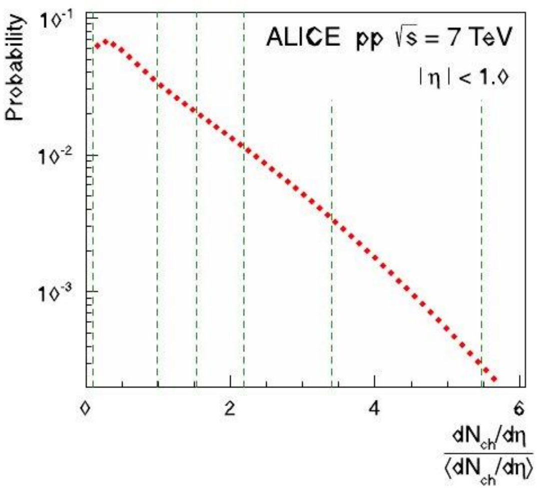
Detailed comprehensive analysis needed

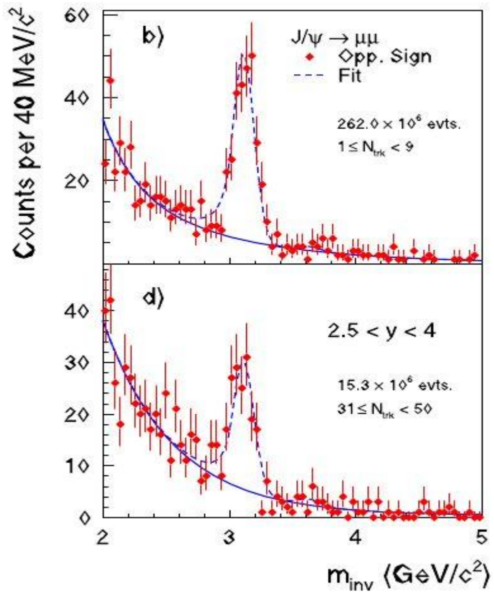


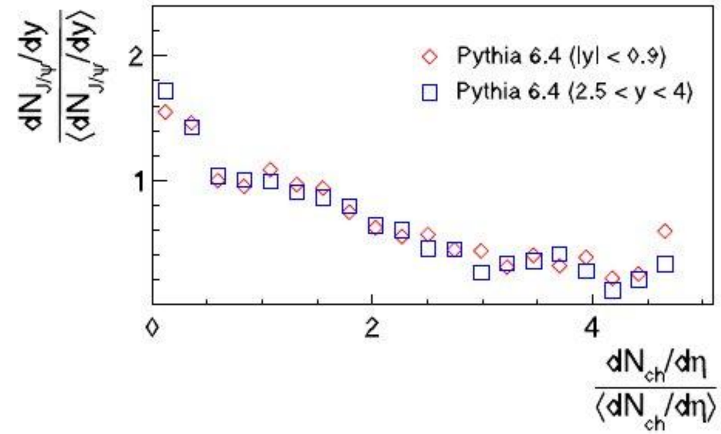


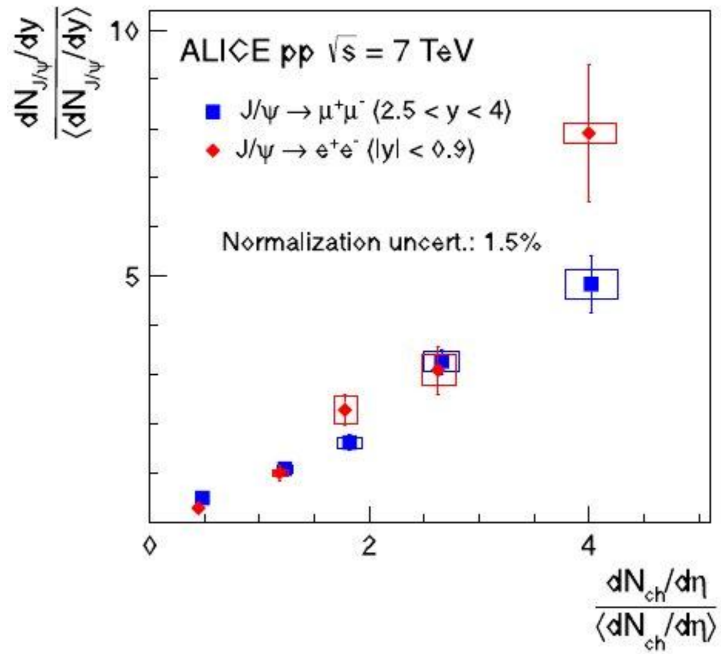
LHCb: PLB 707 (2012) 52
LHCb: JHEP 06 (2012) 141

ALICE: J/ψ production vs $<n_{ch}>$ at η=0









Beyond "just dimuons":

J/ψ production multiplicity as a function of charged particle multiplicity density at central pseudorapidity

A clear, stronger than linear dependence, both at central and forward y of J/ψ

Pythia's tune used by ALICE is clearly unable to reproduce this

ALICE: PLB712 (2012) 165-175

Summary of existing measurements

- Large numbers of various measurements on **open heavy flavour production** have become available from all LHC experiments. All of these are so far described reasonably well by models based on perturbative QCD
- **B_c – "open-charm-open-beauty heavy quarkonium"** -- is now appearing in numbers large enough to study its production characteristics, may help understand some aspects of J/ψ and Υ production
- Production of **prompt J/ψ, $\psi(2S)$, χ_{cJ}** is being studied in detail, with a huge range of p_T and y covered, and the LHC experiments nicely complementing each other.
- These measurements provide lots of input for theorists, and plenty of questions, but no clear answers yet
- Same is true about the **three families of Υ** states, with a possible hint that perturbative QCD may be doing a slightly better job here
- First **"two-angle" measurements of vector quarkonium spin alignment** show no signs of strong polarisation, against the expectations of leading models
- First LHC measurements of **"new observables"** -- studies of Onia associations with other Onia, open HF, underlying event characteristics – have become available, providing new challenges to theory

Now about the future

- Exciting times at LHC: Huge amounts of data together with good understanding of the detectors!
- Many new measurements to be presented at Moriond next month, surely some of them will include heavy flavours and quarkonia!
- Further down the line: higher statistics measurements for various B-hadrons at ever higher pT
- Polarisation of prompt J/ψ, $\psi(2S)$, and more of Υ
- χ_c and χ_b production cross sections, although individual χ_{bJ} (NP) may not be resolved (χ_{cJ} will be), more for J/ψ, $\psi(2S)$
- Bc production (and spectroscopy!) in some detail
- Much more on di-onia production: cross sections, resonances?
- Much more on "new observables": Onia + open HF, Onia + tracks, Onia + jets or photons
- Other things...

Potential bottlenecks

Trigger constraints: limited bandwidth, with only a fraction used for HF/Onia

- Increasing luminosity (and energy!) necessitates more and more selective triggers
- One can intoduce prescales, or increase thresholds, or get really creative (cuts on rapidity, lifetime...)

- Low pT area: probably have seen the best of LHC already
  - no J/ψ at near-zero pt, and no more Υ there either, hence B starting at >10 GeV
- Multi-muon triggers may have problems resolving close-by muons, hence suppression at low masses
- Very high pileup makes many complex studies problematic (e.g. dimuons with jets and/or photons)
- Manpower: only a tiny fraction works on HF/onia analyses (as opposed to Higgs, SUSY, black holes...)
- Many others I could not think of, but will inevitably show up...

THANK YOU!