Recent ATLAS results in the field of meson physics

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On behalf of ATLAS collaboration

13th International Workshop on Meson Production, Properties and Interaction

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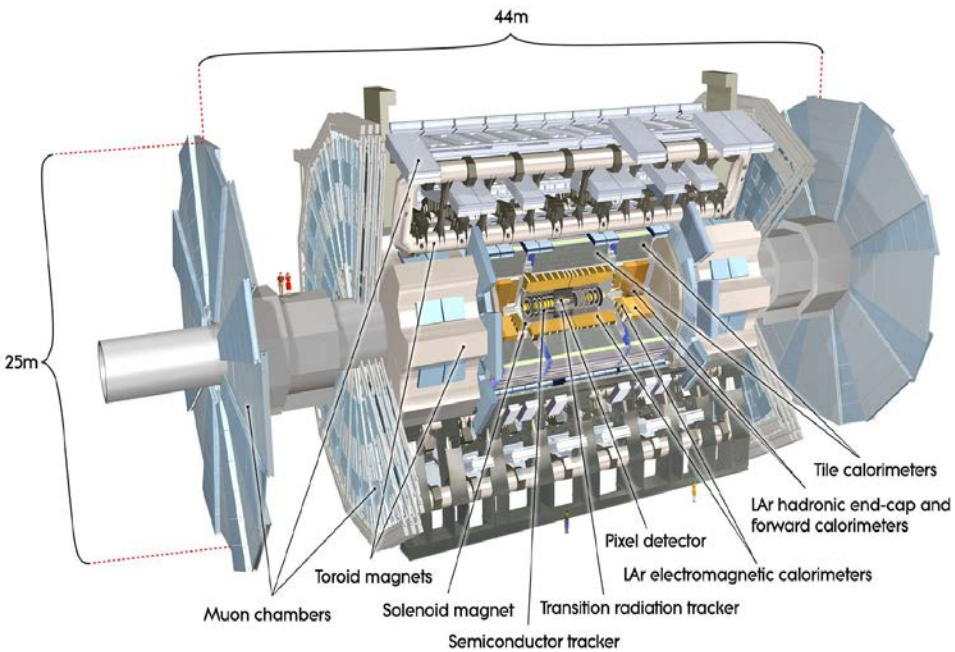
outline

- Introduction of ATLAS
- Recent analysis
  - Light meson production
  - Charmonium and bottomonium
  - Searching for New physics
  - Other results
- Summary and outlook

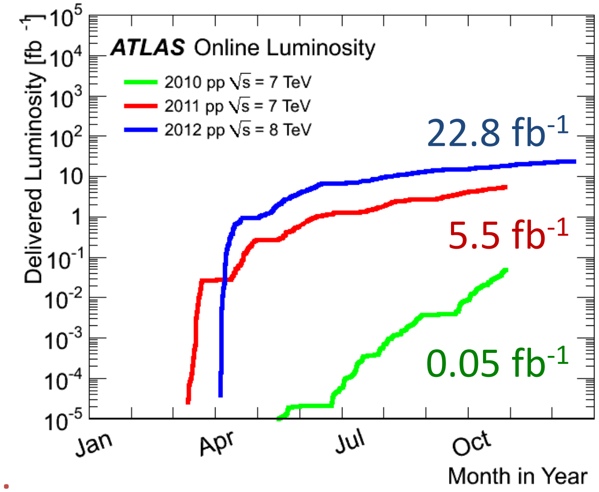
ATLAS detector

Inner Detector (|η|<2.5, 2T Solenoid Magnet)

- PIX, SCT, TRT
- p_T resolution: $\sigma(p_T)/p_T = 3.8 \times 10^{-4} p_T\,(\mathrm{GeV}) \oplus 1.5\%$
- Impact parameter resolution: 15 μm transverse.

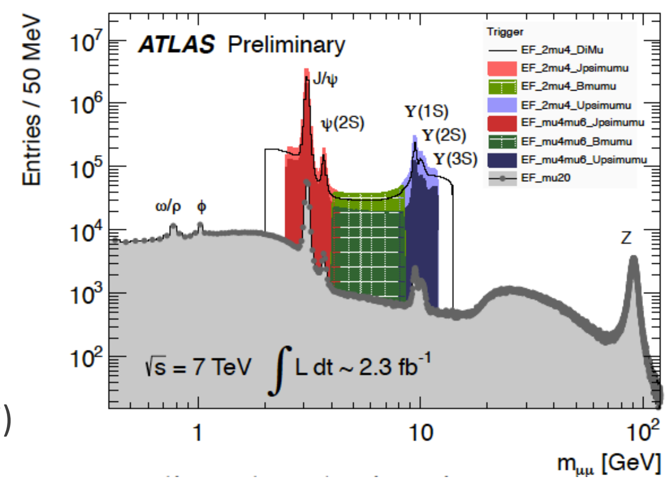


Total 26.4 fb^{-1} recorded



Trigger

- Muon System and Calorimeters.
- Single-muon and di-muon triggers.



Calorimeter

- Lar EM
- Hadronic

Muon Spectrometer

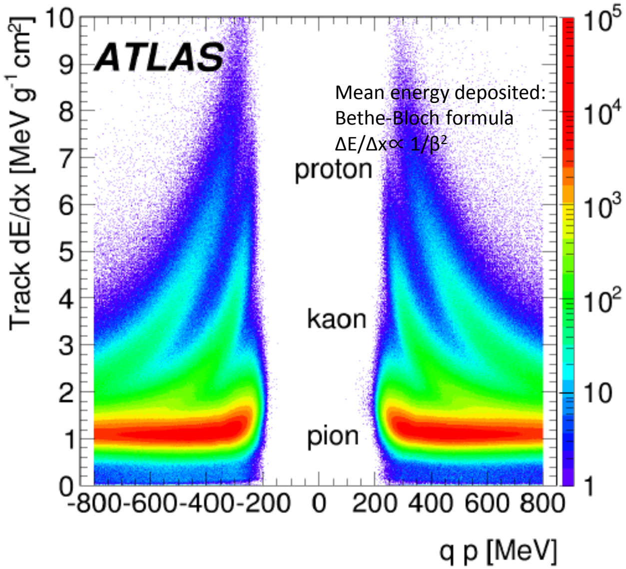
- Toroidal Magnet (~ 0.5 T)
- Triggering (|η|<2.4), presiced tracking (|η|<2.7)

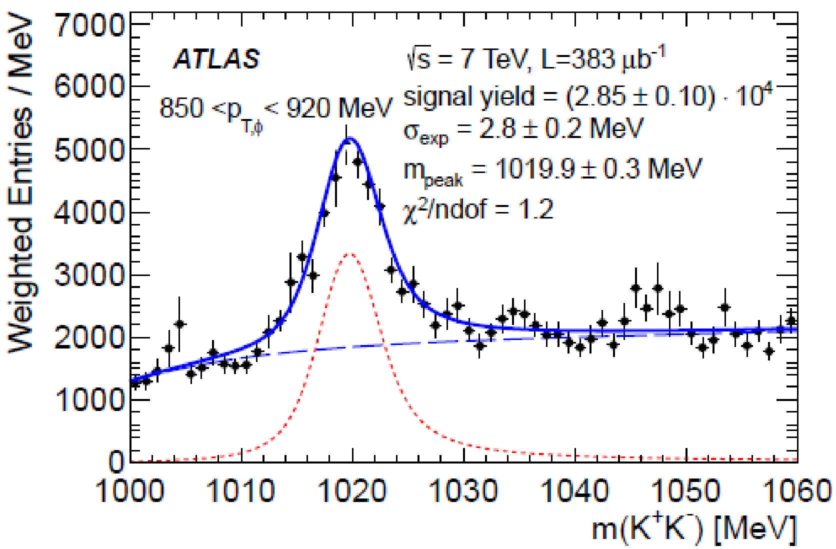
ϕ(1020) production cross section

- pQCD -> physics in high momentum transfer.
- Model? -> soft interactions at lower momentum transfers.

ϕ->KK

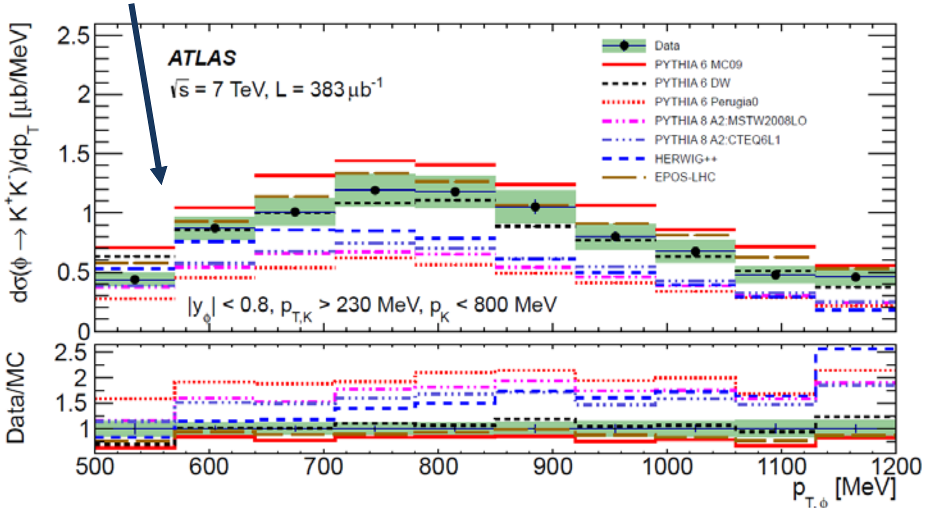
- Measurement at a soft scale Q~1 GeV.
- Produced both in hard scatter of *pp* interaction, as well as in hadronisation -> tune phenomenological fragmentation models.
- Sensitive to s-quark and low-x gluon densities.
- *500MeV < $p_T(\varphi)$ < 1200MeV, $|y(\varphi)|<0.8$*
- 2010 7TeV data, 383 μb^{-1}
- BR = (48.9±0.5)%
- $p_T(K)$ > 230MeV, p(K) < 800MeV



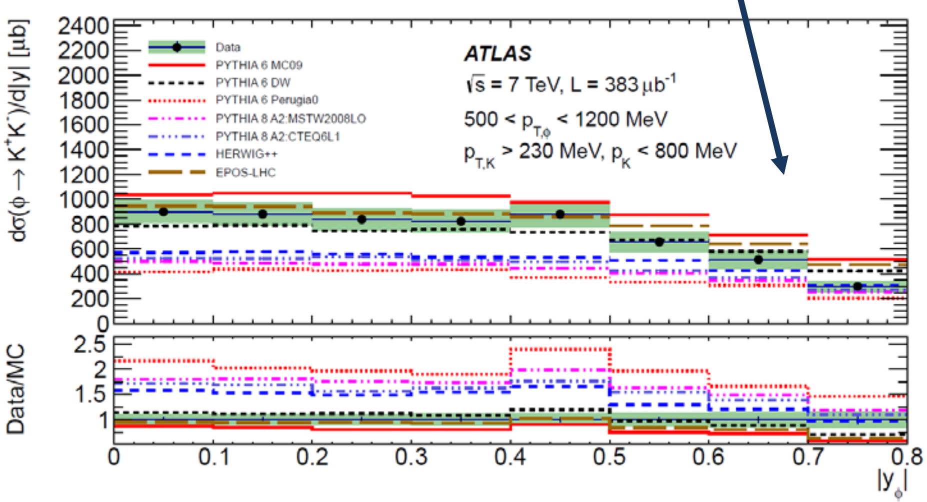


φ(1020) production cross section

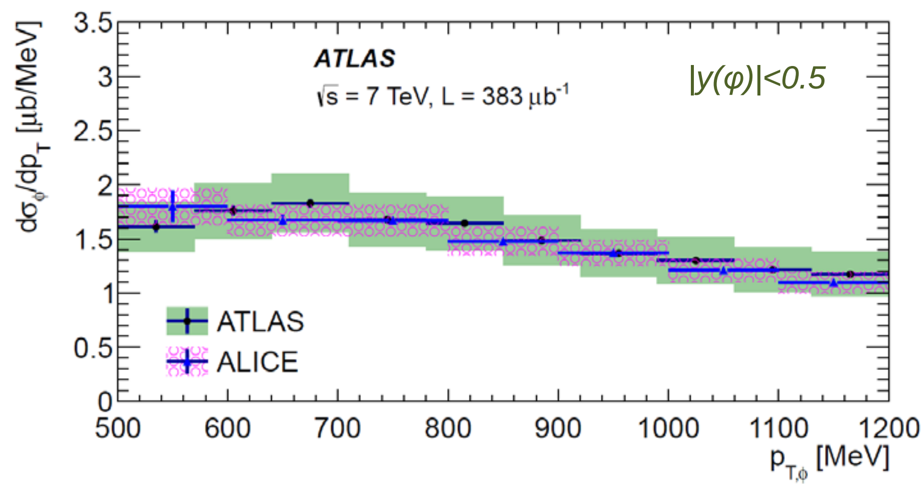
$p_T(K)$>230MeV cut -> increase below 700MeV



p(K)<800MeV cut -> decrease above 0.5

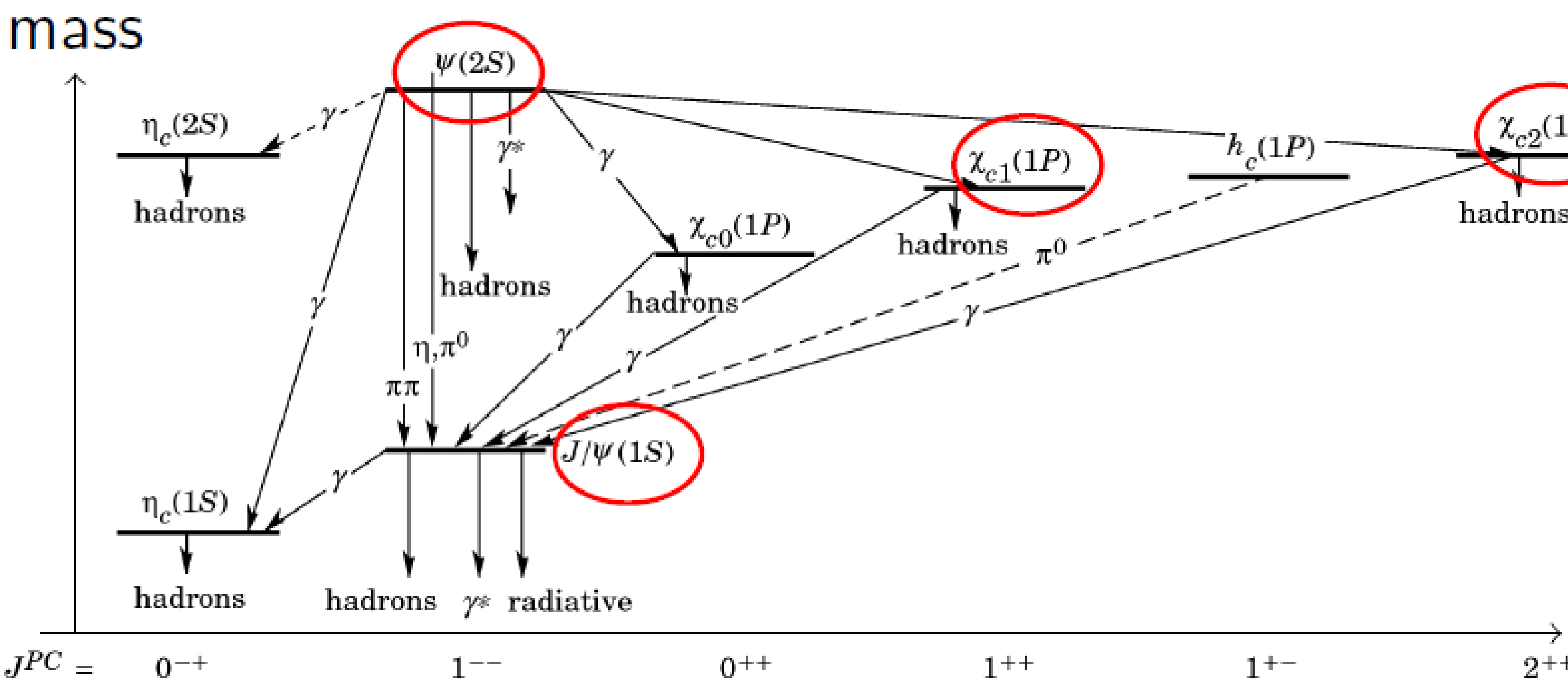


- PYTHIA 6 DW and EPOS-LHC tune-> good
- PYTHIA6 MC09 tune -> slightly overestimate
- Herwig++ -> good for p_T< 700 MeV and |y| > 0.6, underestimated for p_T > 700 MeV and |y| < 0.6.
- PYTHIA6 Perugia0 tune -> underestimates by ~ a factor of 2.
- PYTHIA8 A2 tunes -> different pdf gives similar predictions, underestimates by ~ a factor of 2.



Good agreement with ALICE within the uncertainty.

Charmonium spectrum



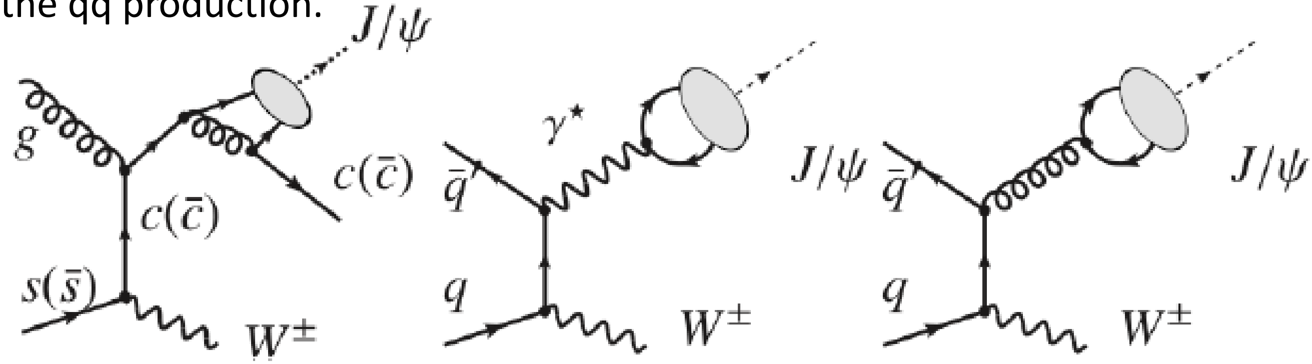
Charmonium Spectrum below $D\bar{D}$ threshold.

- Prompt production: directly from pp collision or from the decay of heavier states.
  - Prompt ψ(2S) only from direct pp collsision.
- Non-prompt production: from b hadron decays.

W + J/ψ associated production

[details in Stefanos Leontsinis's talk]

- Offers new tests at the perturbative / non-perturbative QCD boundary.
- Important test on the relative contribution of color singlet (CS) and color octet (CO) predictions for the $q\bar{q}$ production.

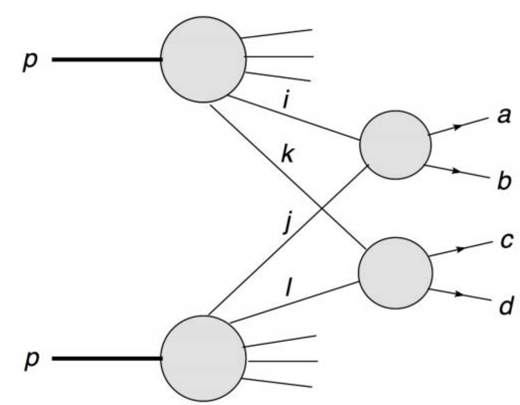


Color singlet

Color octet

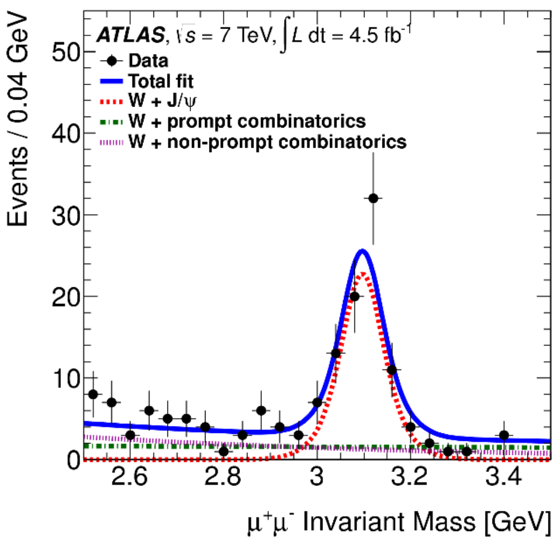
W->μν + prompt J/ψ->μμ

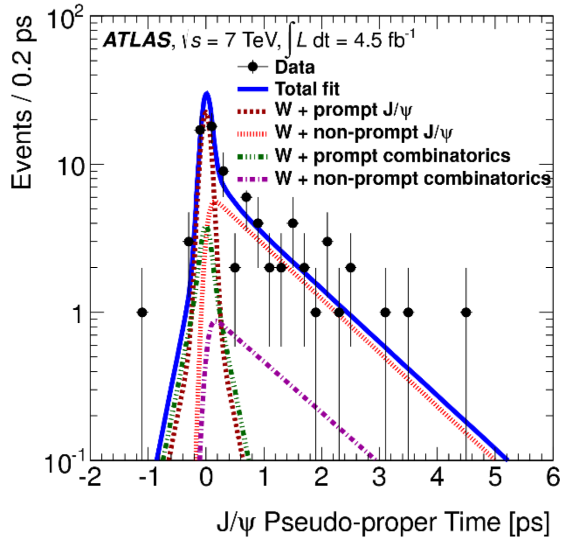
- 2011 7TeV data, 4.5 fb^{-1}
- Single parton scattering (SPS)
- Double parton scattering (DPS)
- Background contributions
  - Pileup, Z+jets, tt, W+b, $B_c \rightarrow J/\psi + \mu\nu + X$, QCD jets.

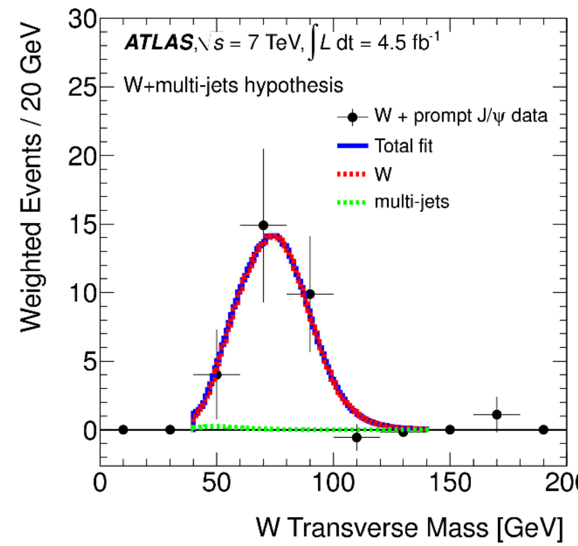


W + J/ψ associated production

- A unbinned simultaneous maximum likelihood fit is used to extract prompt J/ψ events.
- Then $m_T(W)$ is fit to separate the QCD multi-jet background.



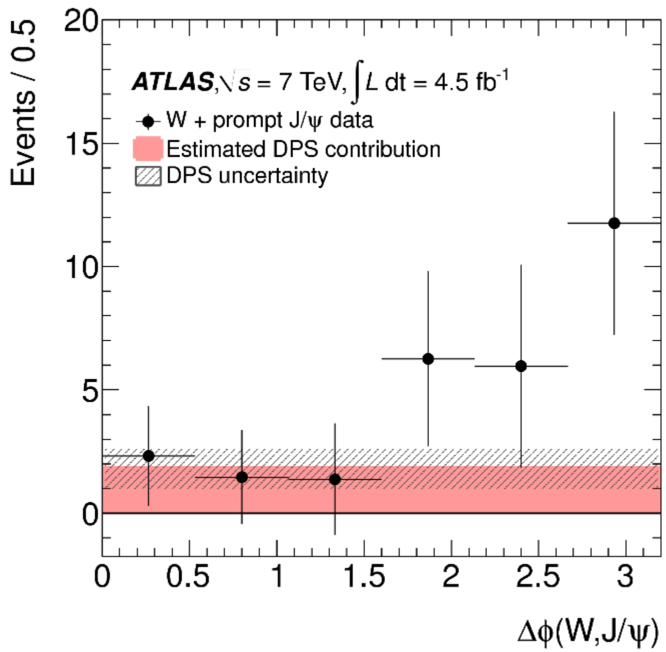


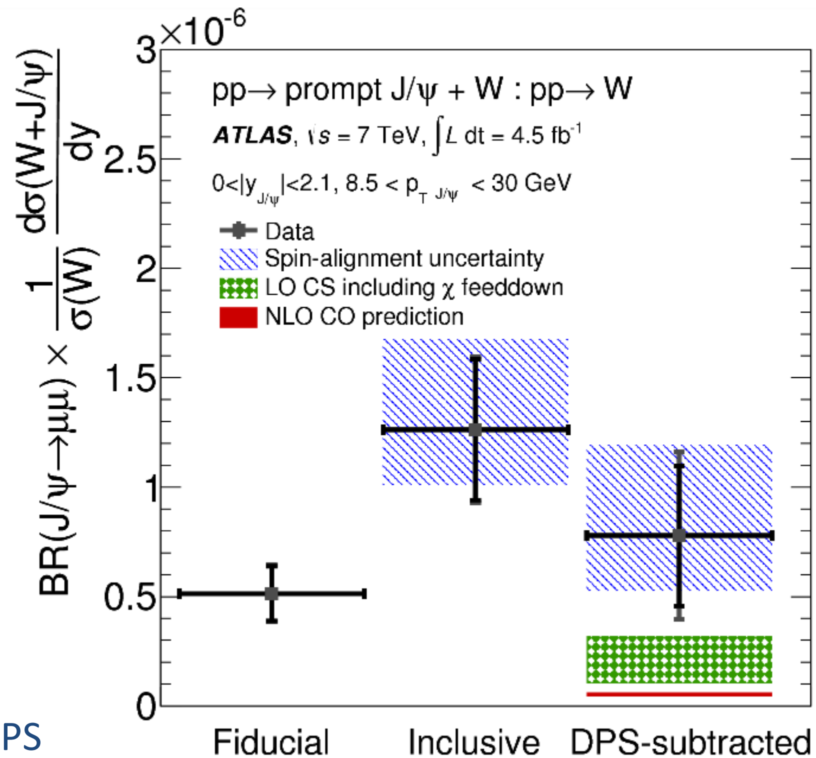


Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

(*) of which 1.8 ± 0.2 originate from pileup

W + J/ψ associated production





- W + prompt J/ψ candidates include both SPS and DPS events.
- The LO CS is ~an order of magnitude larger than the NLO CO.
- This process is dominated by CS production.
- Due to the large uncertainties SPS prediction (LO CS + NLO CO) are compatible with results at the 2σ level.

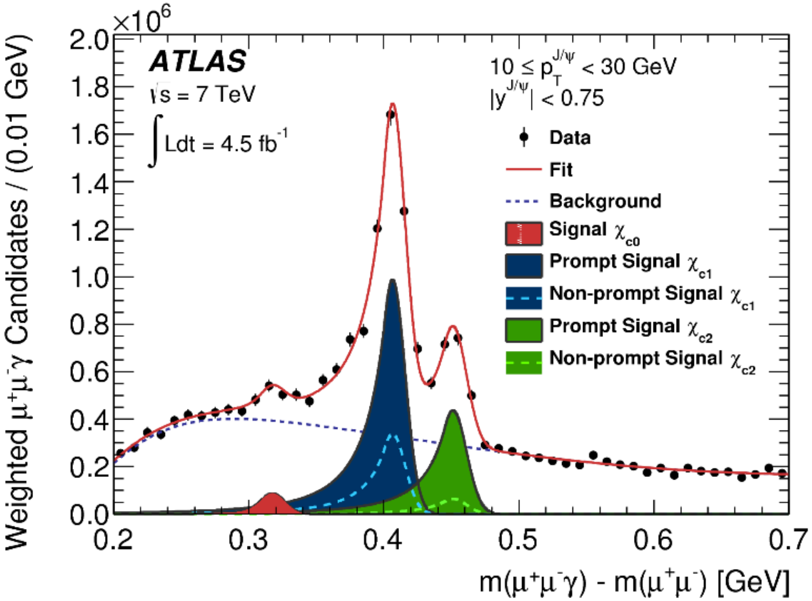
$$R^{\rm fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$$
$$R^{\rm incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$
$$R^{\rm DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$$

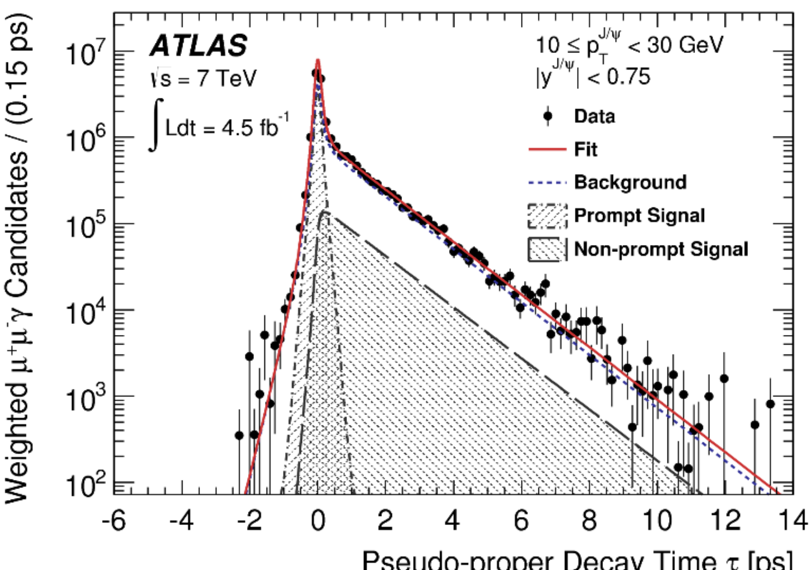
χ_{c1} and χ_{c2} production

$\chi_{cJ} \rightarrow J/\psi(\mu\mu)\gamma(ee)$.

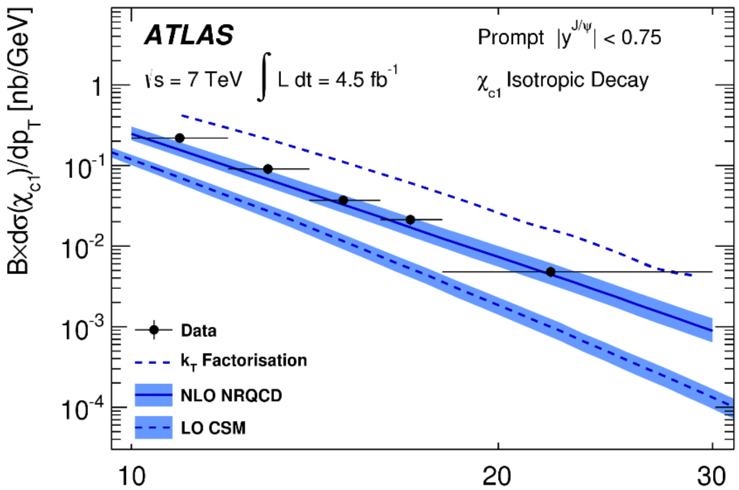
- 2011 7TeV data, 4.5 fb^{-1}.
- $Br(\chi_{c0} \rightarrow J/\psi\gamma) = 1.17\%$,

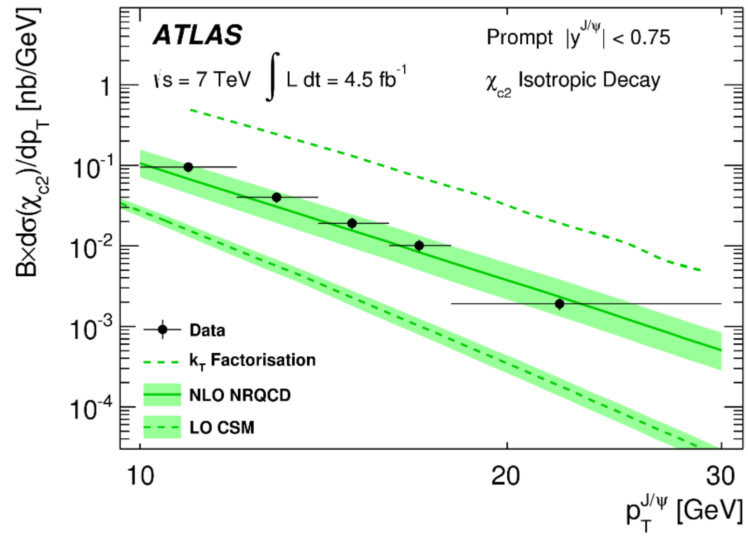
  $Br(\chi_{c1} \rightarrow J/\psi\gamma) = 34.4\%$, $Br(\chi_{c2} \rightarrow J/\psi\gamma) = 19.5\%$
- Reconstruction of the soft γ *(> 1.5GeV).*
- *$10 < p_T(J/\psi) < 30$ GeV, $|y|(J/\psi) < 0.75$*
- $\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$ distribution separates the χ_{cJ} states.

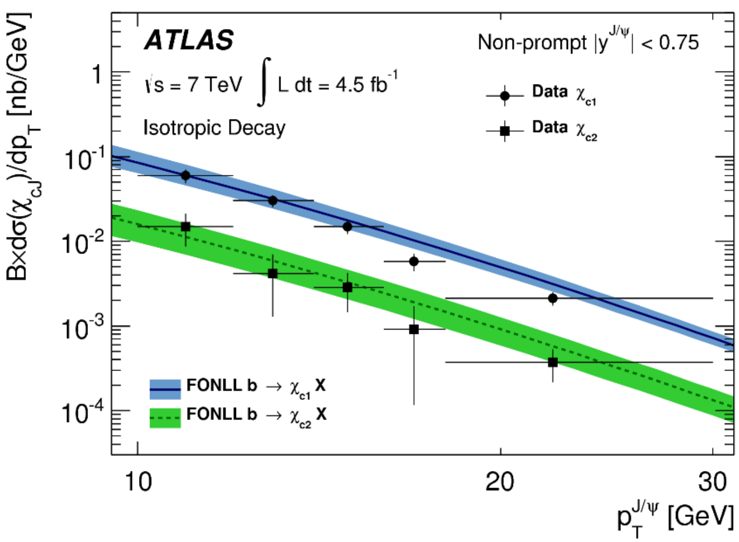




χ_{c1} and χ_{c2} production







Prompt χ_{cJ}

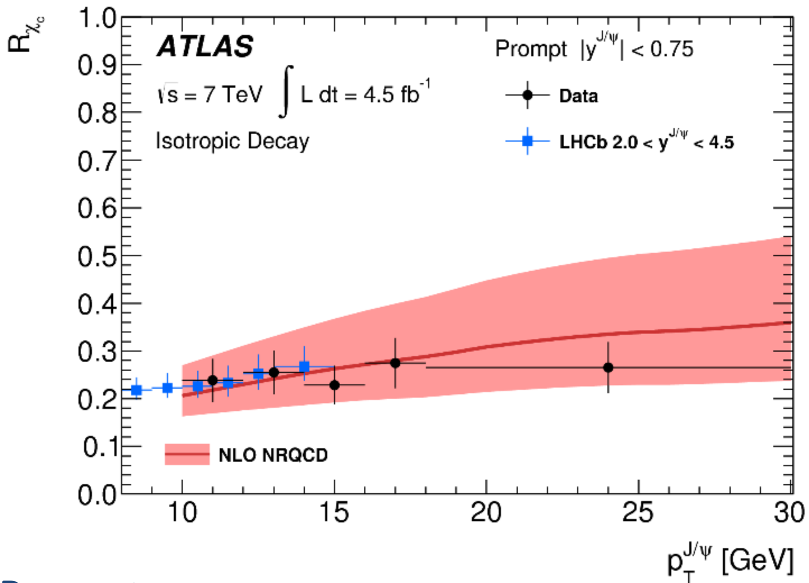
- NRQCD: good
- LO CSM: underestimate.
- The k_T factorization: overestimate.

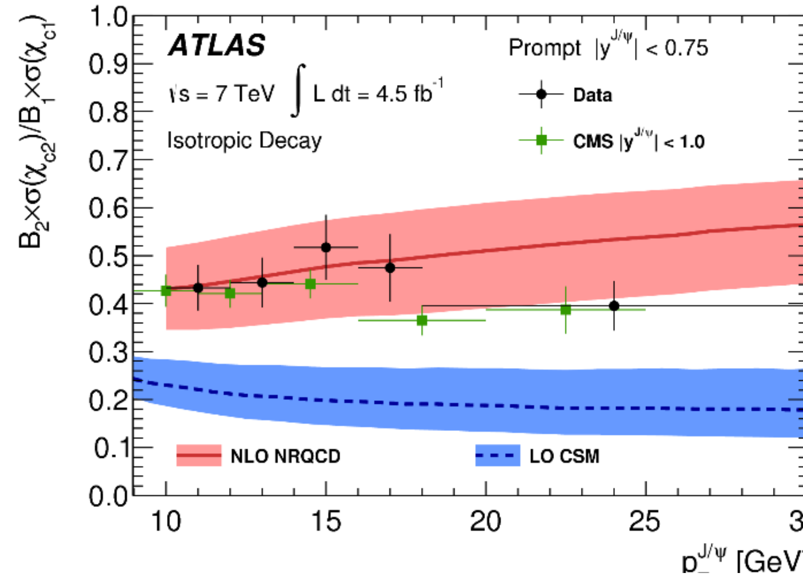
Non-prompt χ_{cJ}

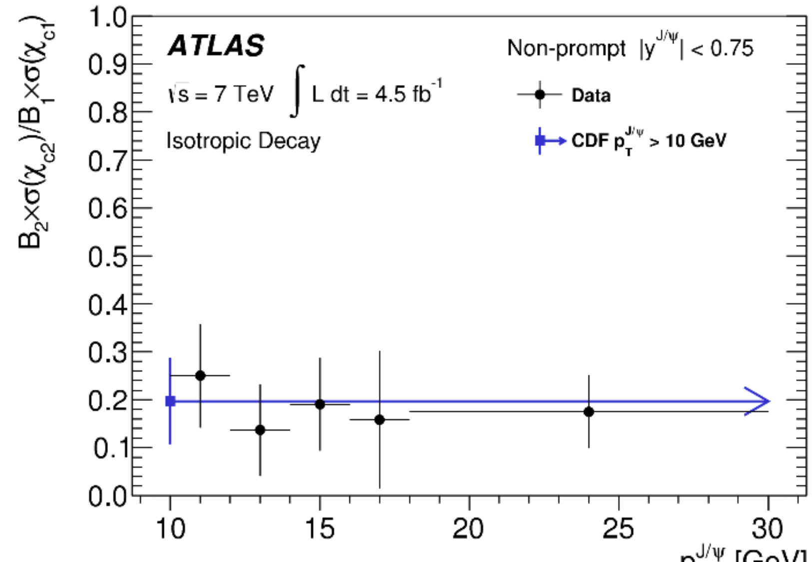
- FONLL: good

NRQCD, tuned to the Tevatron J/ψ and ψ(2S).

χ_{c1} and χ_{c2} production







Prompt χ_{cJ}

- Fraction of prompt J/ψ produced in χ_c feed-down, $R_{\chi c}$
- The ratio of the χ_{c2} cross section to the χ_{c1} cross section

Non-prompt χ_{cJ}

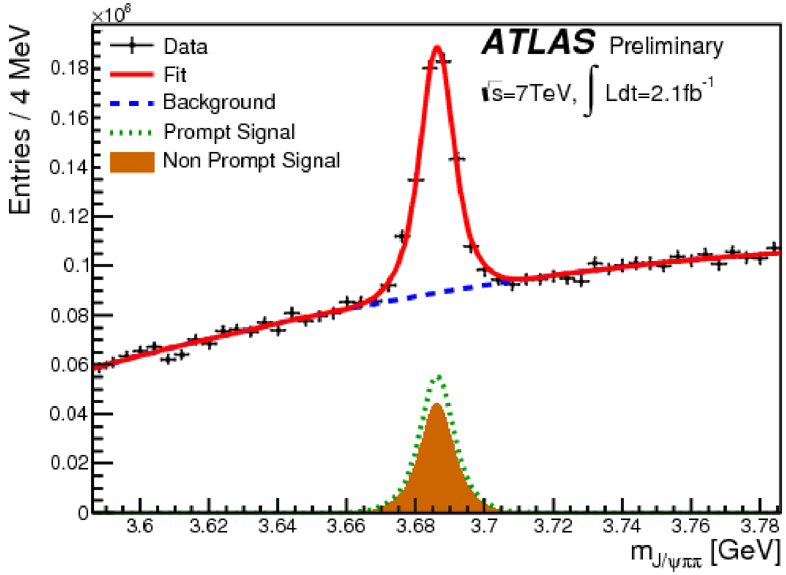
- The ratio of the χ_{c2} cross section to the χ_{c1} cross section

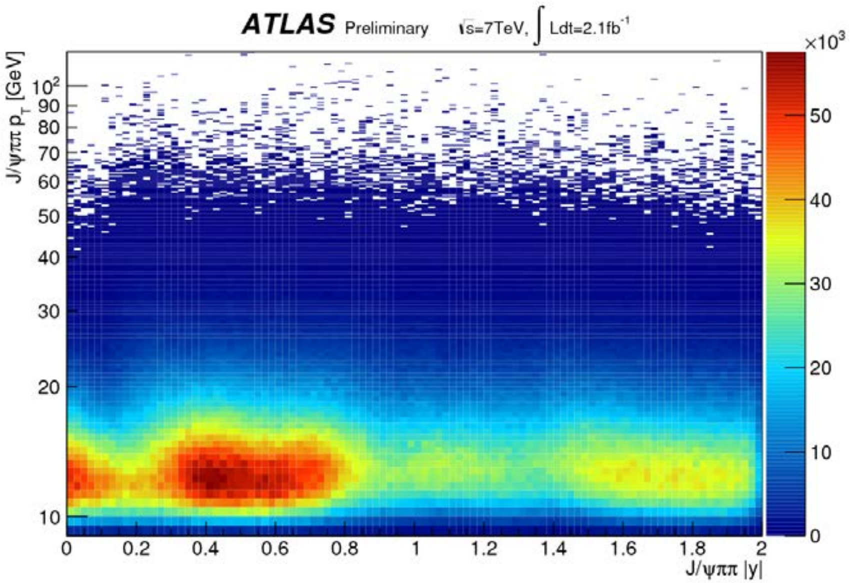
NRQCD, tuned to the Tevatron J/ψ and ψ(2S)

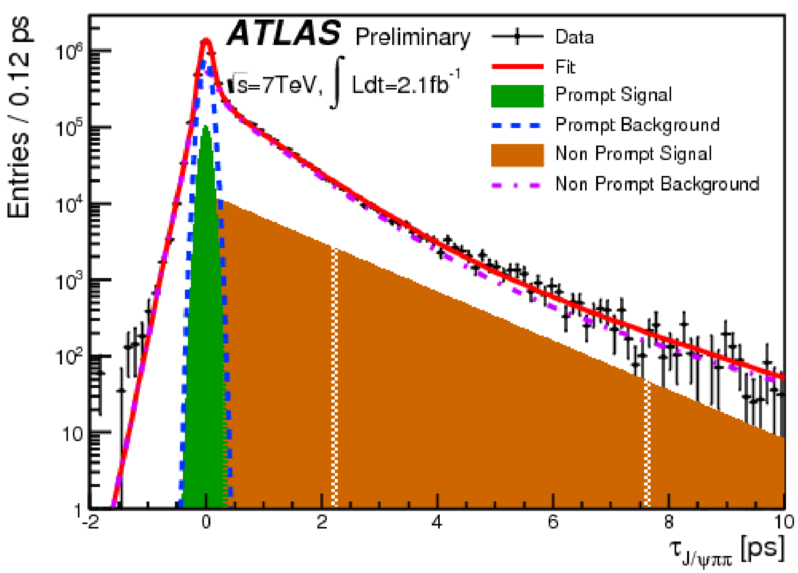
Ψ(2S) production

ψ(2S) → J/ψ(μμ)ππ

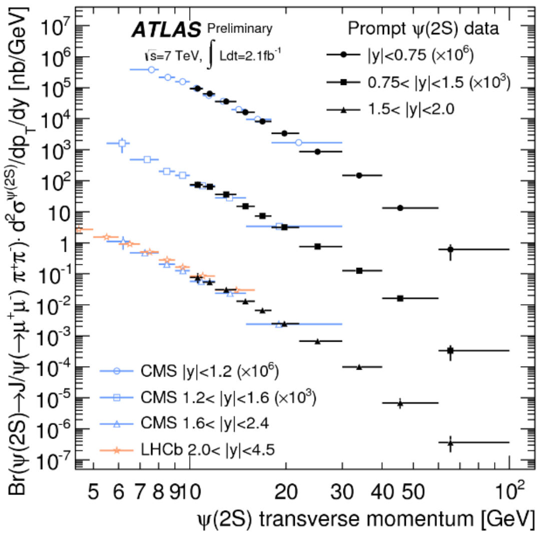
- 2011 7TeV data, 2.1 fb^{-1}
- Br(ψ(2S) → J/ψππ) * Br(J/ψ → μμ) = 2.02%
- *$10<p_T<100$ GeV, $|y| < 2.0$*

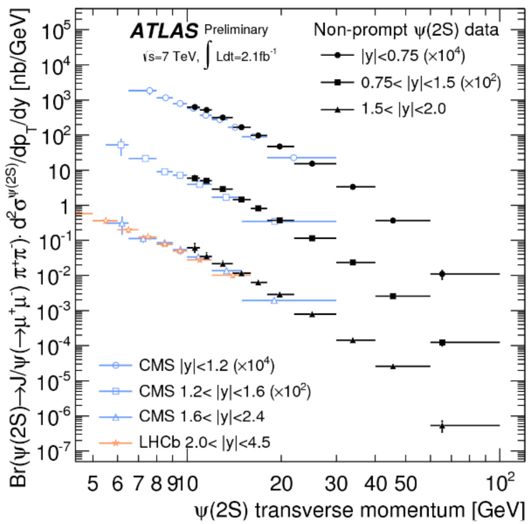






Ψ(2S) production

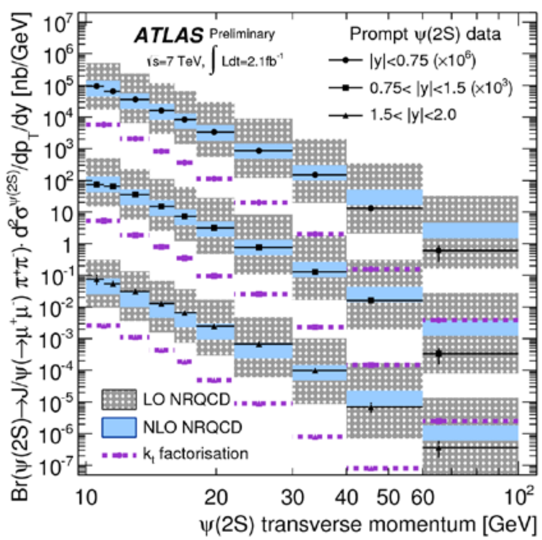


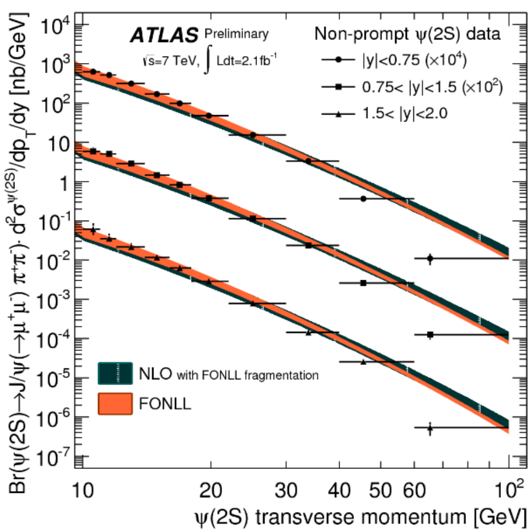


- Compared to LHCb and CMS results in similar y ranges.
- ATLAS benefits at high p_T.
- The common p_T range values are in good agreement.

CMS: arXiv:1111.1557, LHCb: arXiv:1204.1258

- LO: good but with large uncertainties.
- NLO: good until high p_T (overestimates and predicts a harder spectrum).
- k_T factorization: underestimates the data and has a p_T dependent shape <-> overestimates in the production of C-even (χ_c) charmonium states





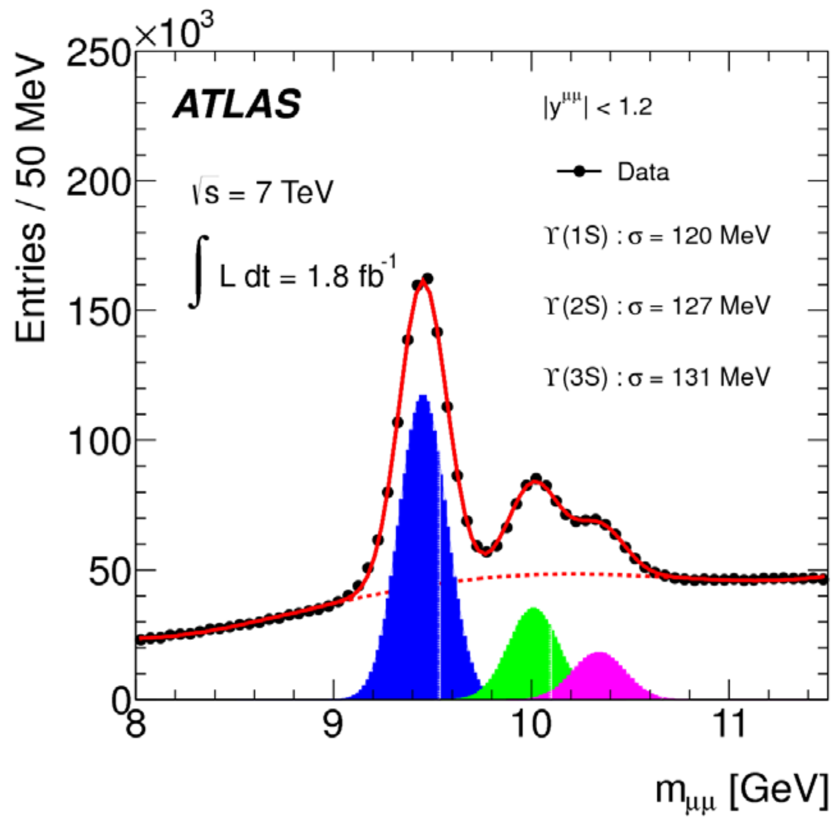
- *FONLL shows better agreement than NLO, but both overestimate at high pT.*

ϒ(nS) production

- Complement of charmonium system studies due to larger mass, allowing more dependable theoretical calculations.
- Improve the theoretical description due to different processes dominated in this regime and the impact of spin-alignment uncertainties are mitigated.
- Direct ϒ*:* produced directly in *pp* collisions or from decay of an excited state (feed-down contribution).

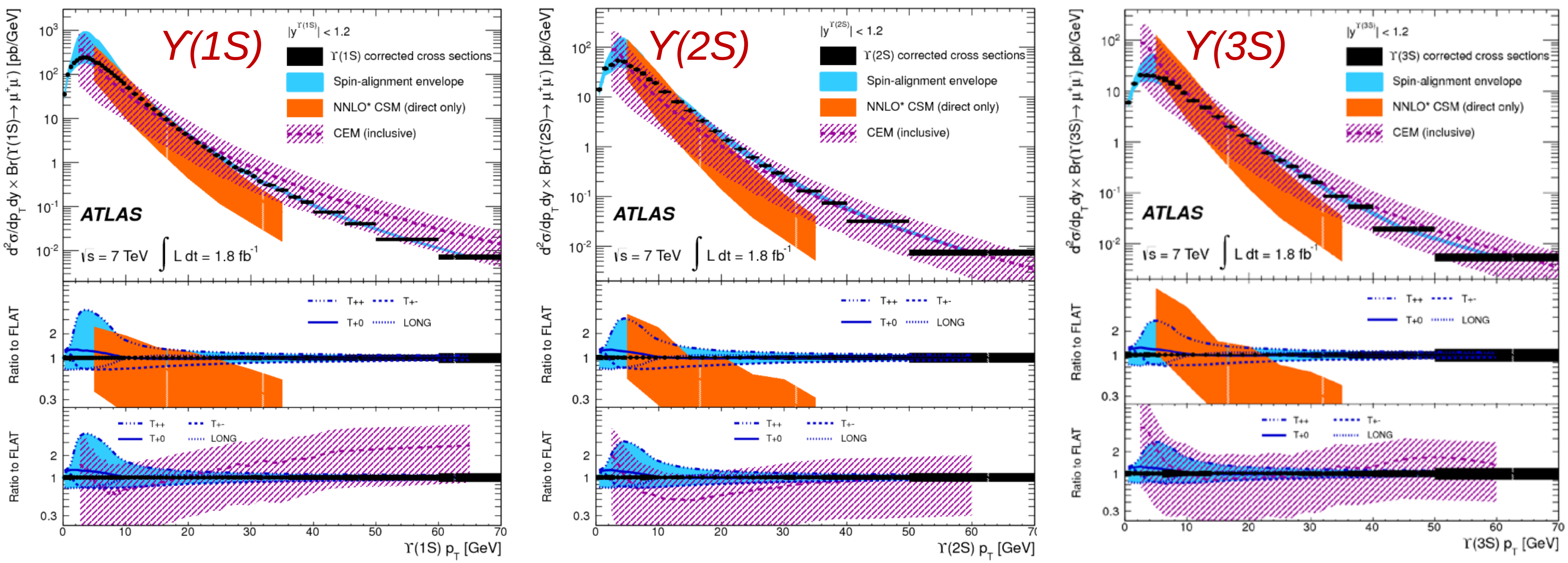
ϒ(nS) → μμ

- 2011 7TeV data, 1.8 fb^{-1}
- p_T<70 GeV, |y| < 2.25
- In high p_T range, contribution from associated ϒ+ bb production may play a more important role than in the low p_T range.
- The impact of the dependence of the production cross section on the spin-alignment of the is relatively small.



Υ(nS) production

NNLO* CSM (no feed-down) fit data well in the moderate p_T region, but underestimate in the high p_T region.

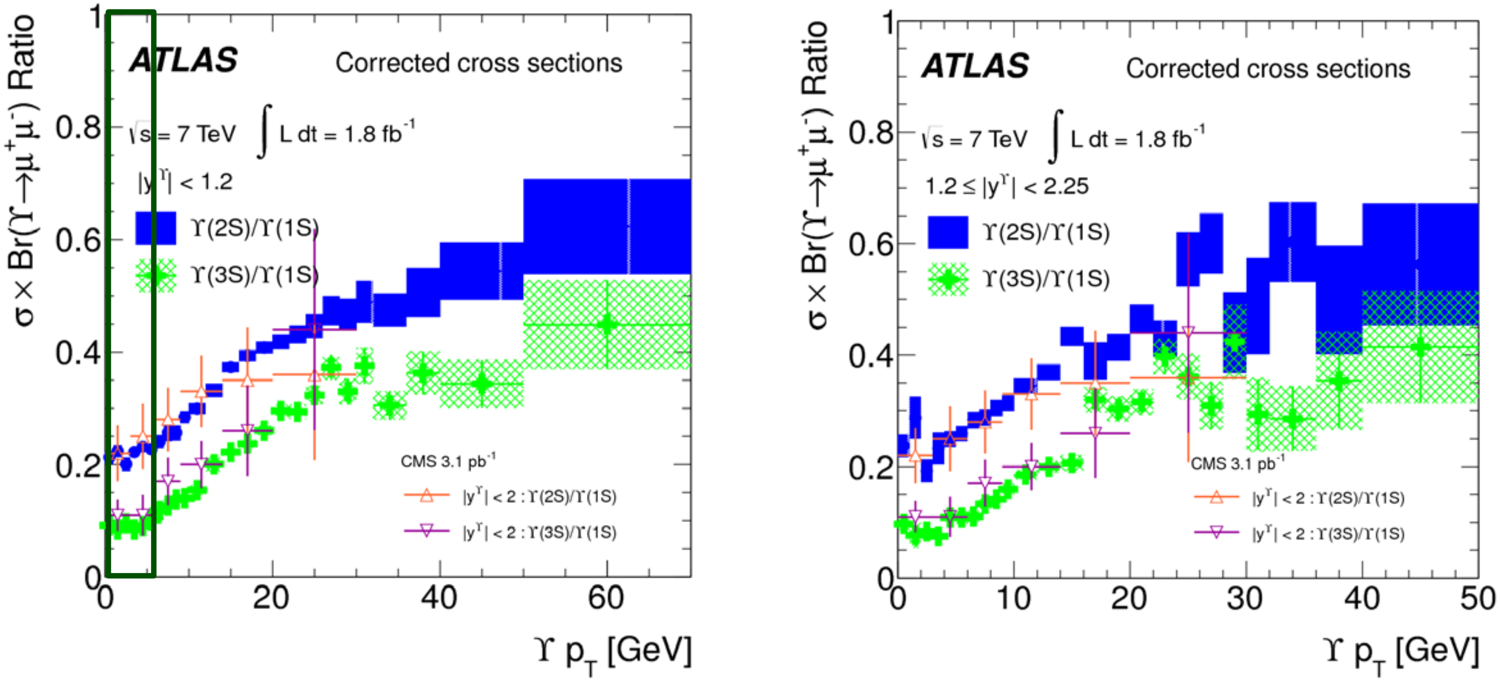


CEM matches data better in the high p_T region.
Underestimate the rate and have problems in modeling the shape of the spectrum, particularly at lower pT.

State	Integrated cross section (nb)
$\Upsilon(1S)$	$8.01 \pm 0.02 \pm 0.36 \pm 0.31$ nb
$\Upsilon(2S)$	$2.05 \pm 0.01 \pm 0.12 \pm 0.08$ nb
$\Upsilon(3S)$	$0.92 \pm 0.01 \pm 0.07 \pm 0.04$ nb

Υ(nS) production

- Contributions from feed-down vary between the 1S, 2S and 3S states
- Changing presence of various kinematically-allowed decays and influence the inclusive production rate.
- Study of the production ratios as a function of kinematic variables provides an indirect but precise measure of these feed-down contributions.



- Constant in the 0 < pT < 5GeV interval at ~20% for the 2S and ~7% for the 3S.
- At higher pT a significant and steady rise due to the feed-down contributions, in agreement with CMS.
- At larger pT (30 - 40GeV), direct production dominates over contributions from the decays of excited states.

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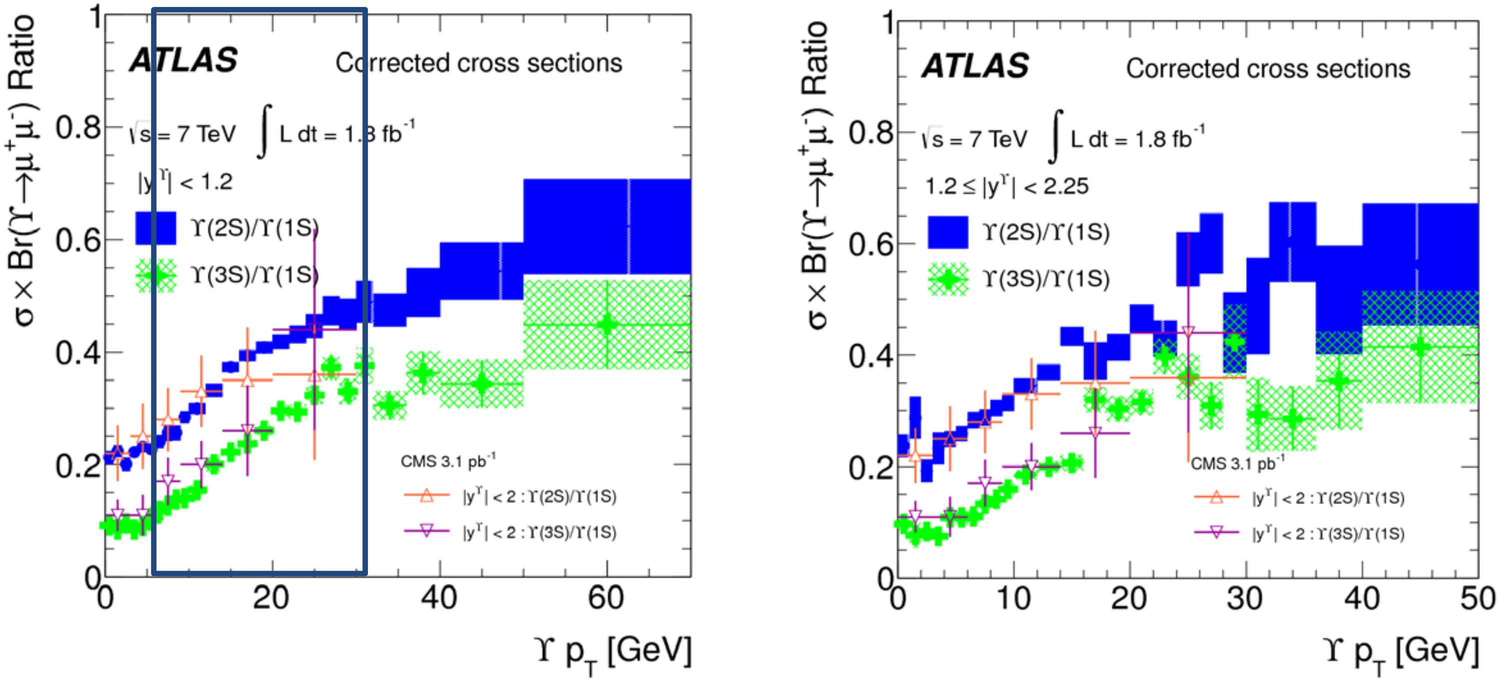

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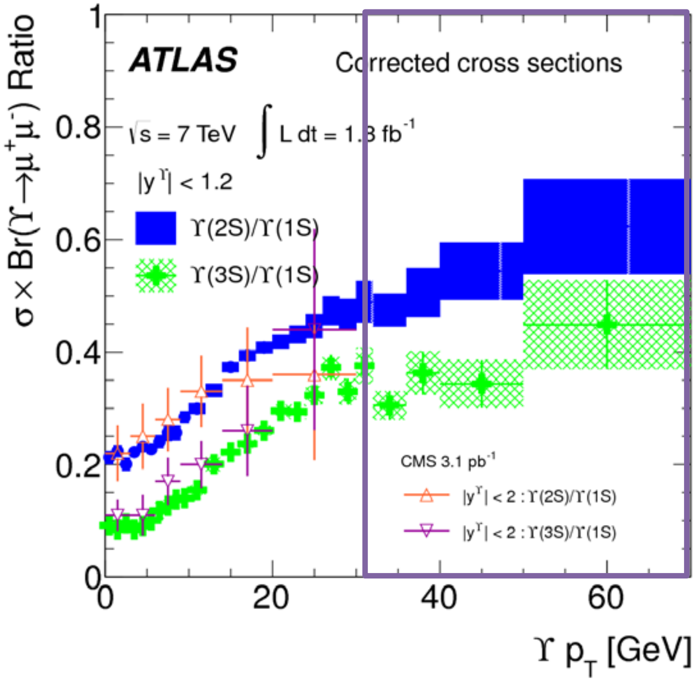

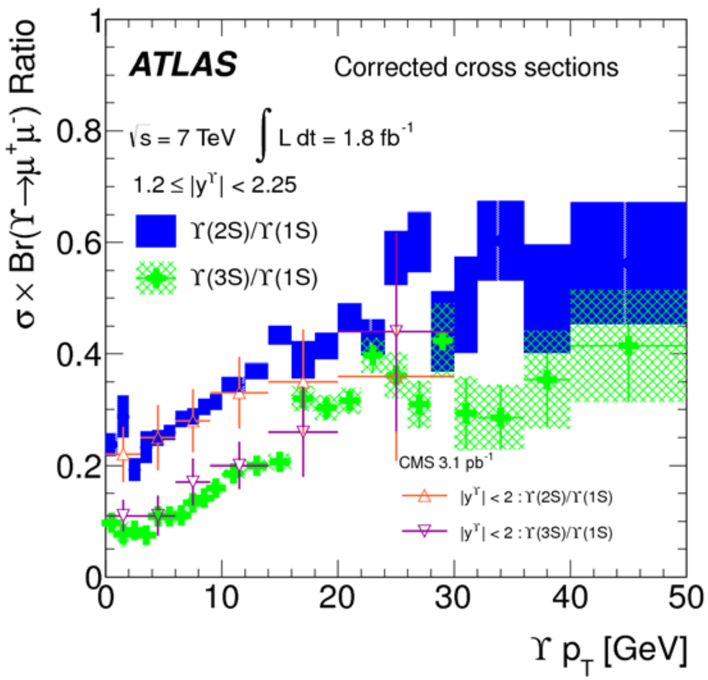

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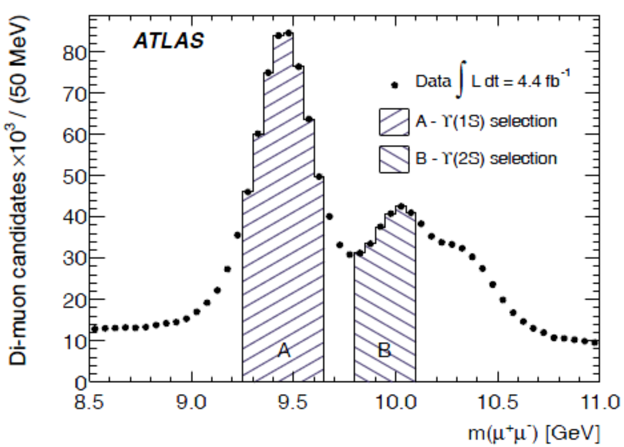
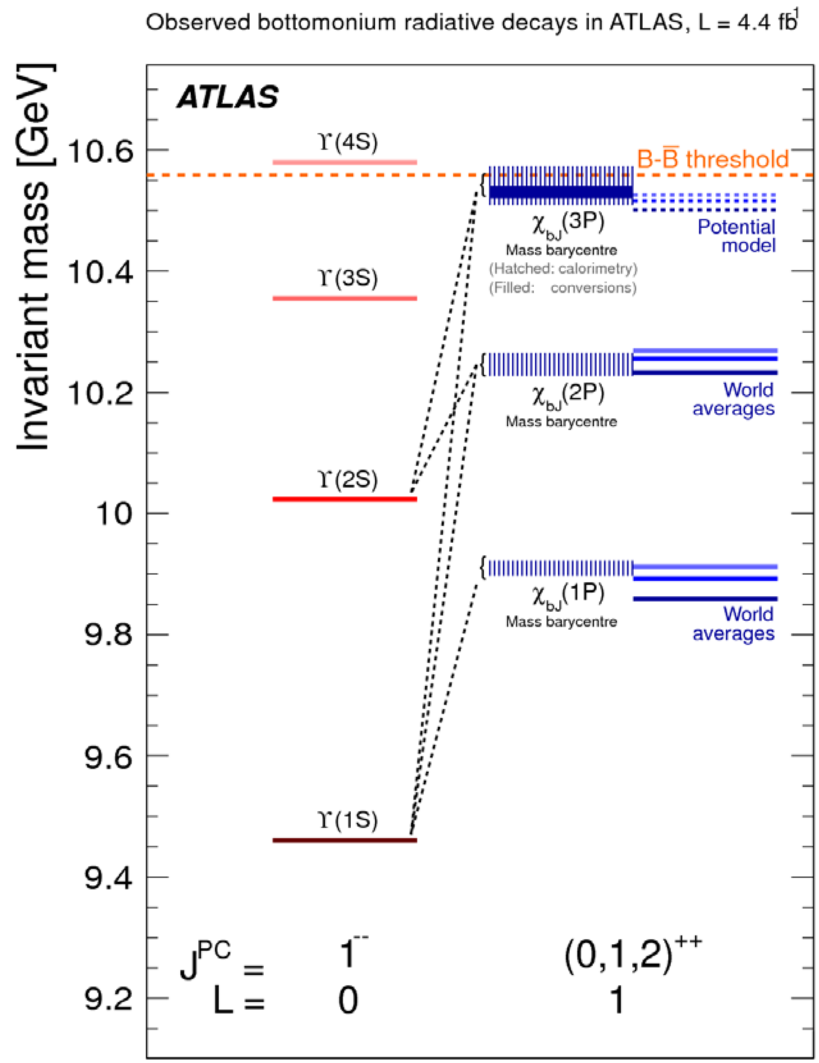
Observation of a New χ_b State

- b quarkonium $\chi_b(1P)$, $\chi_b(2P)$ states have been observed through the radiactive decay modes
- The $\chi_b(3P)$ has not been observed before
  - Predicted mass: ~10.52 GeV
  - Hyperfine splitting: 10-20MeV
  - $\chi_b(3P) \rightarrow Y(1S,2S)\gamma$
- $\chi_b(nP) \rightarrow Y(1S,2S)\gamma$. 2011 7TeV data, 4.4 fb^{-1}.

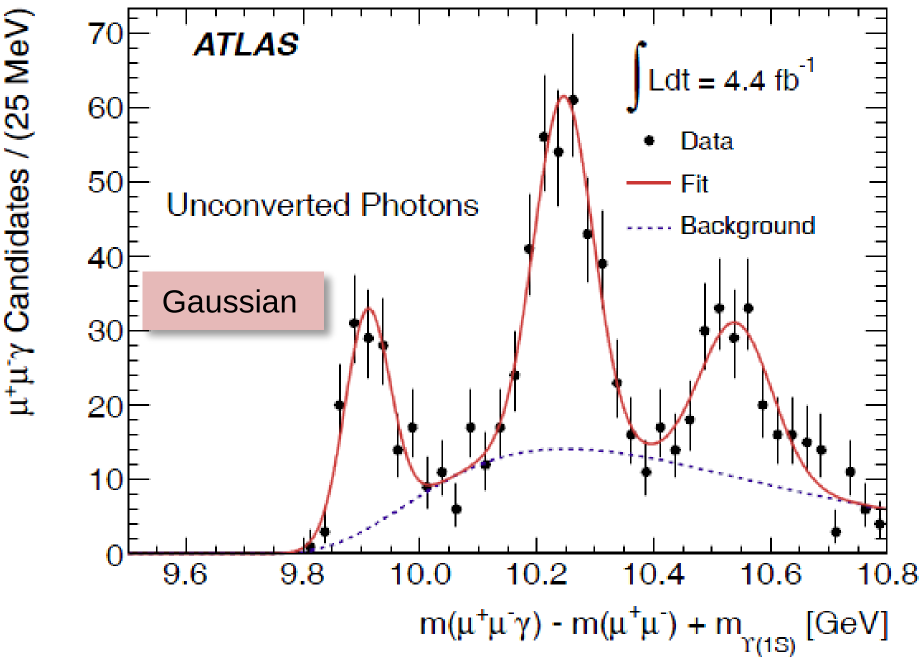


The asymmetric mass window for Y(2S)
-> reduce contamination from the Y(3S) peak and continuum background contributions.

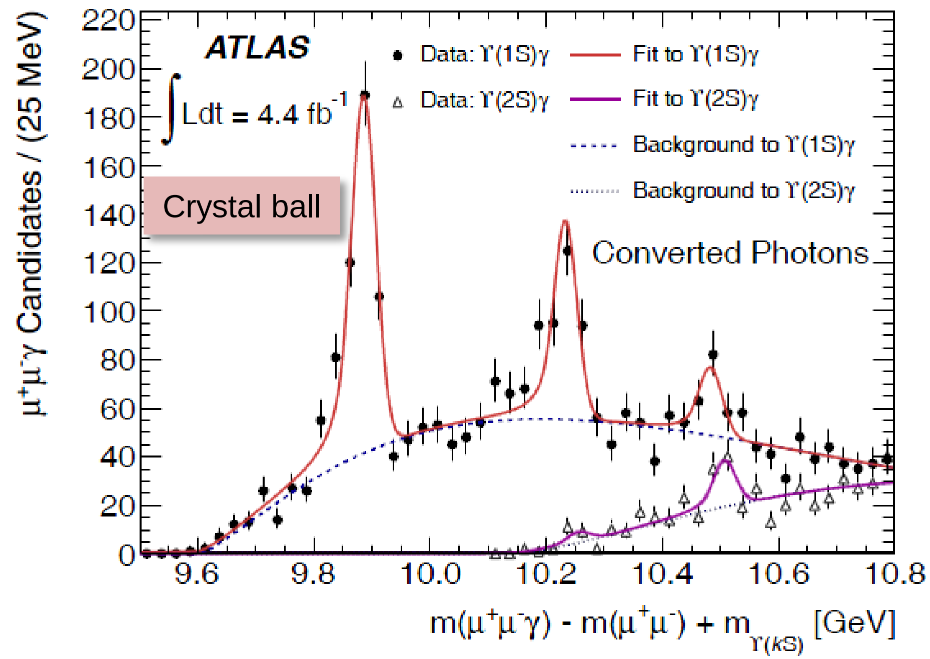


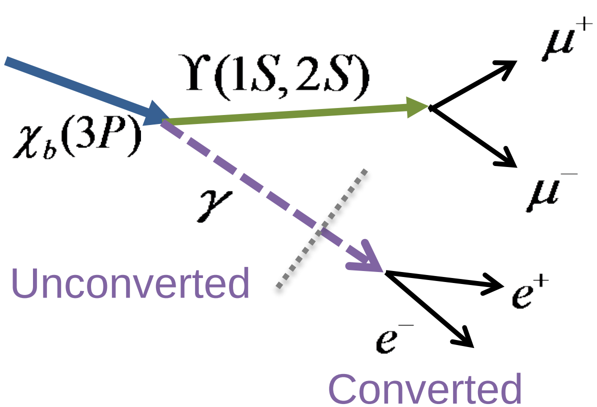
Observation of a New χ_b State

Unconverted photon



Converted photon

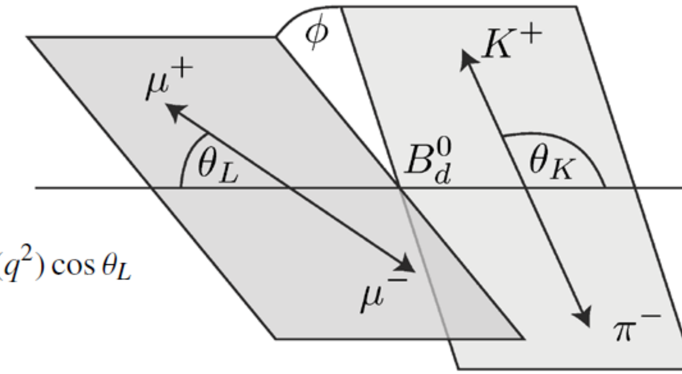




- Search in mass difference $m(\mu^+\mu^-\gamma)-m(\mu^+\mu^-)+m(\Upsilon_{PDG})$ to minimize the muon resolution effects.
- New structure observed at m = 10.530 +/- $0.005_{(stat.)}$ +/- $0.009_{(syst.)}$ GeV
- Significance $\sqrt{-2\log(L/L^0)} > 6\sigma$ in two statistically independent samples.

Angular analysis of $B_d \rightarrow K^{*0}\mu^+\mu^-$

Angular distributions of the 4-particle final state are sensitive to physics beyond the SM.
A_{FB} and F_L are extracted from the two distributions depend on q^2, $\cos\theta_L$ and $\cos\theta_K$.



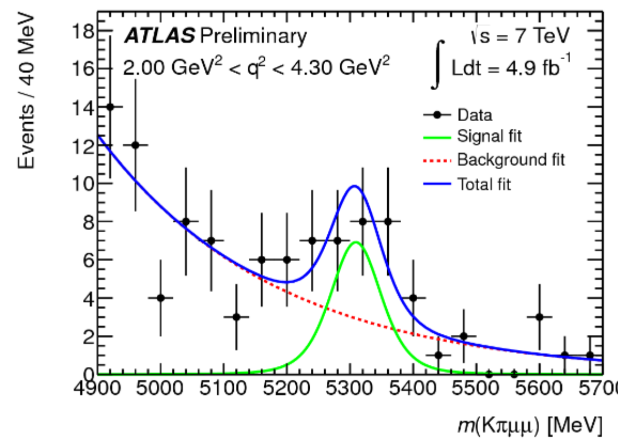
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_L} = \frac{3}{4}F_L(q^2)\left(1-\cos^2\theta_L\right) + \frac{3}{8}\left(1-F_L(q^2)\right)\left(1+\cos^2\theta_L\right) + A_{FB}(q^2)\cos\theta_L$$

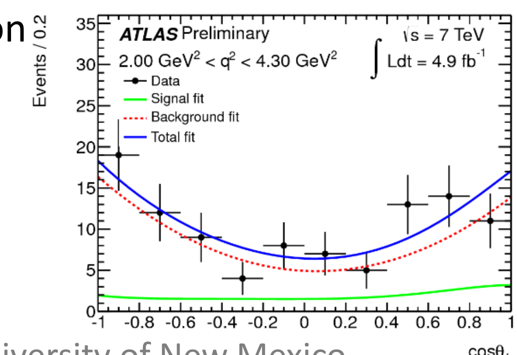
$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}\left(1-F_L(q^2)\right)\left(1-\cos^2\theta_K\right)$$

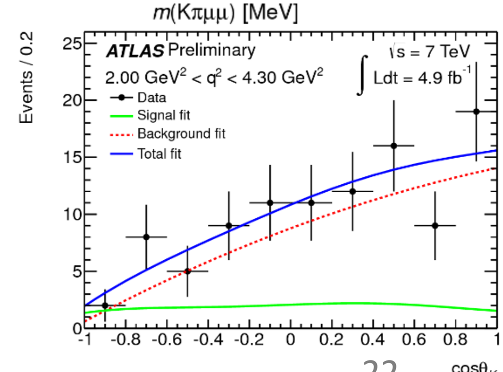
- A_{FB}: muons forward-backward asymmetry.
- F_L: fraction of longitudinal polarization.

$B_d \rightarrow K^{*0}\mu^+\mu^-$

- 2011 7 TeV data, 4.9 fb^{-1}.
- Sequential unbinned maximum likelihood fit.
  - Fit the invariant Kπμμ mass distribution -> fix the signal and background yield.
  - The angular distributions are fitted.
  - No significant bias introduced.

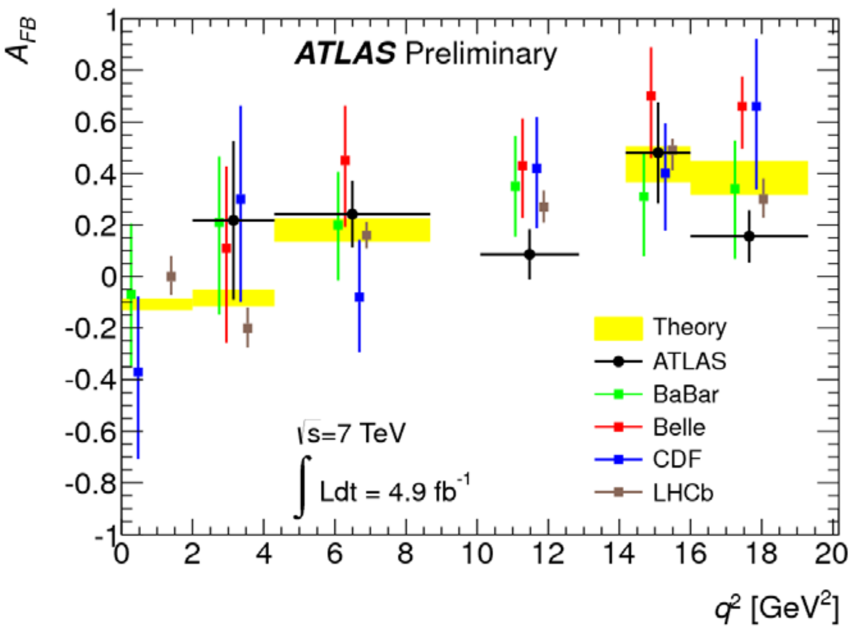


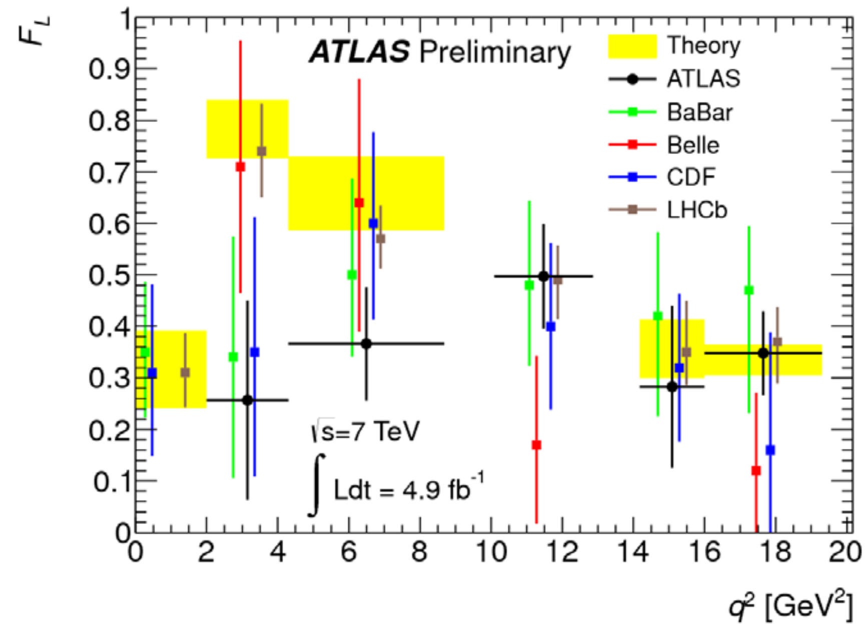




Angular analysis of $B_d \rightarrow K^{*0}\mu^+\mu^-$

The full q^2 range is defined as the three continuous intervals obtained by removing the J/ψ and ψ(2S) regions.



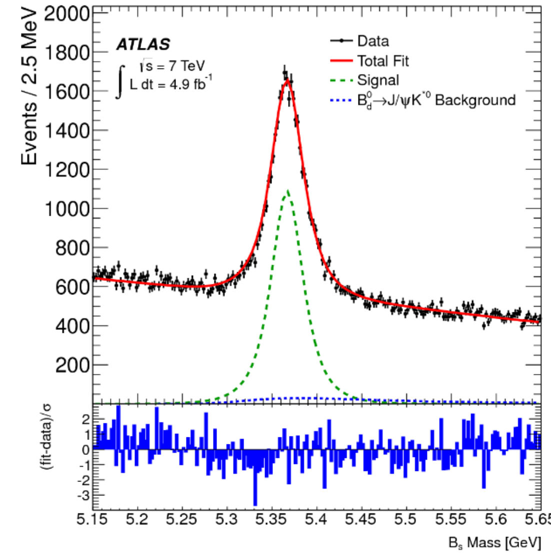


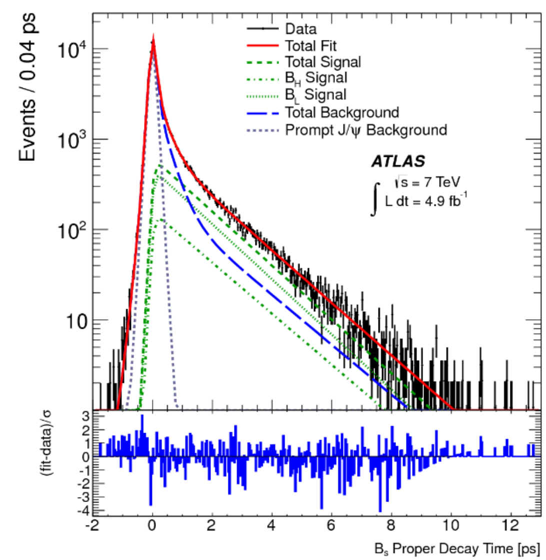
- The SM theoretical predictions calculated for limit of small vector meson energy and for the limit of large vector meson energy, no expectation is given for the central q^2 region.
- ATLAS mainly strength at large q^2.
- A_{FB} and F_L are compatible with SM or other measurements.

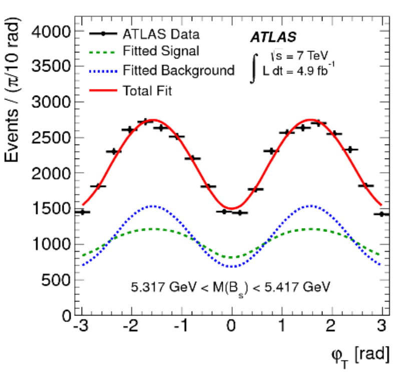
Angular analysis of $B_s \to J/\psi\varphi$

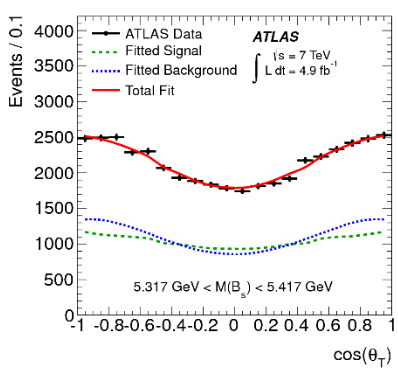
[details in Jaroslav Guenther's talk](#)

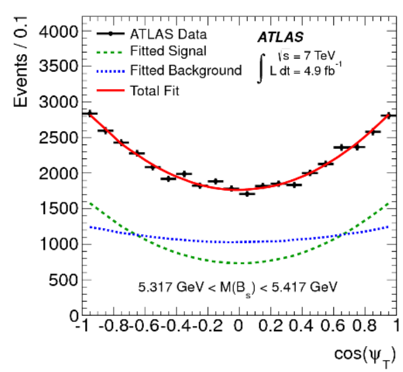
- Sensitive to new physics beyond the SM.
- CP violation occurs due to interference between direct decays and decays occurring through $B^0_s - \overline{B}^0_s$ mixing.
- Flavour tagging (opposite-side tagging OST) was used to reconstruct the initial states.
- The CP states are separated statistically through the time dependence of the decay and angular correlations amongst the final state particles.
- The number of signal B_s^0 meson candidates extracted from the fits was 22670 ± 150.







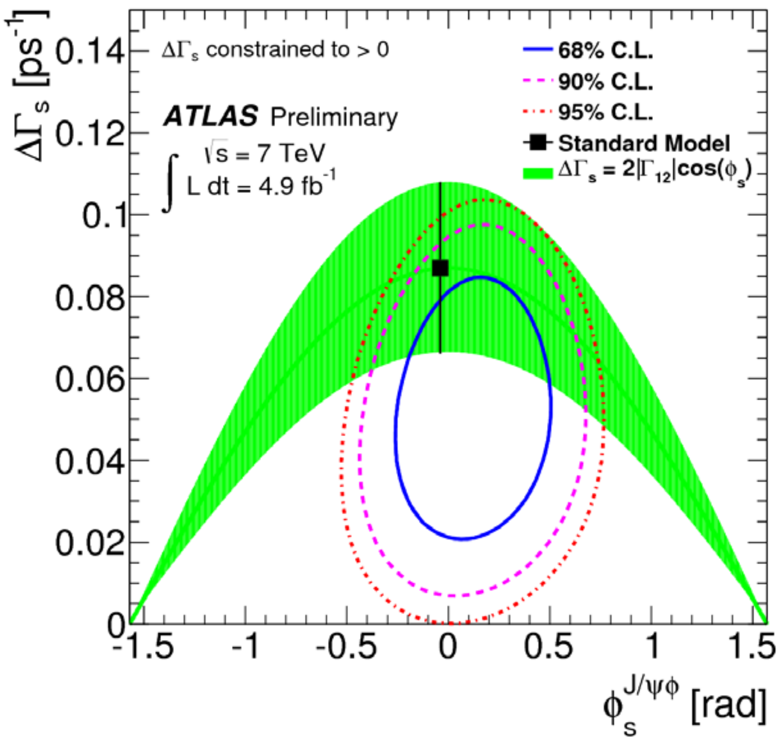




Angular analysis of $B_s \rightarrow J/\psi\varphi$

Likelihood contours (68%, 90% and 95%) in ϕ_s - $\Delta\Gamma_s$ plane compared to SM predictions.

- Results of width difference and CP violating weak phase compatible with SM:
  - $\phi_s^{SM} \approx -2\beta_s = -0.0368 \pm 0.0018$, where $\beta_s = \arg[-(V_{ts} V^*_{tb})/(V_{cs} V^*_{cb})]$
  - $\Delta\Gamma_s^{SM} = \Gamma_L - \Gamma_H = 0.087 \pm 0.021\ ps^{-1}$



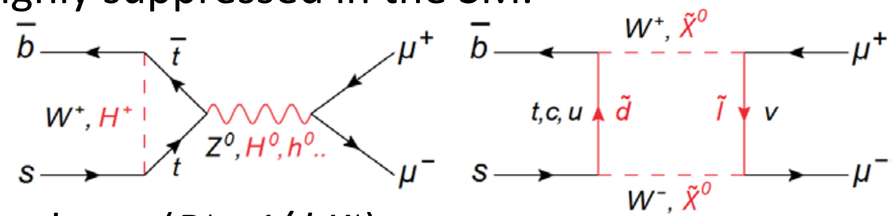
$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.11\ (\text{syst.})\ \text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006 (\text{stat.}) \pm 0.011\ (\text{syst.})$$
$$|A_\parallel(0)|^2 = 0.220 \pm 0.008 (\text{stat.}) \pm 0.009\ (\text{syst.})$$
$$\delta_\perp = 3.89 \pm 0.46\ (\text{stat.}) \pm\ 0.13\ (\text{syst.})\ \text{rad}$$

Search for $B^0_s \to \mu\mu$

[details in Jaroslav Guenther's talk]

Flavour Changing Neutral Currents (FCNC) are highly suppressed in the SM.

- *SM predicted branching fraction: (3.5+/-0.3)*10^{-9}*
- *LHCb result: (2.9 +/- 1.1) * 10^{-9}*
- *CMS result: (3.0 +/- 1.0) * 10^{-9}*

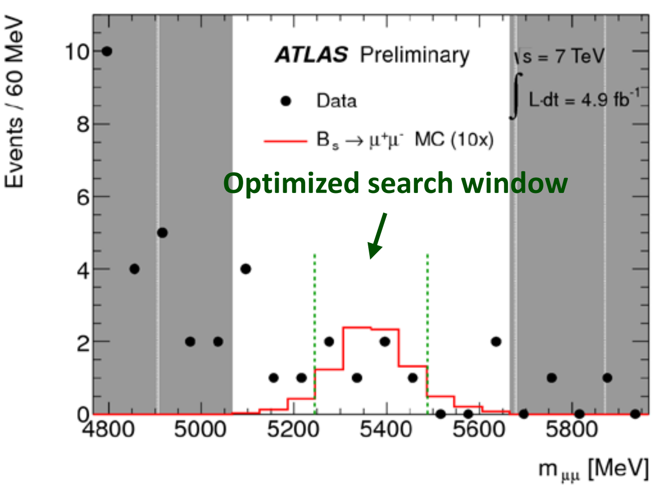


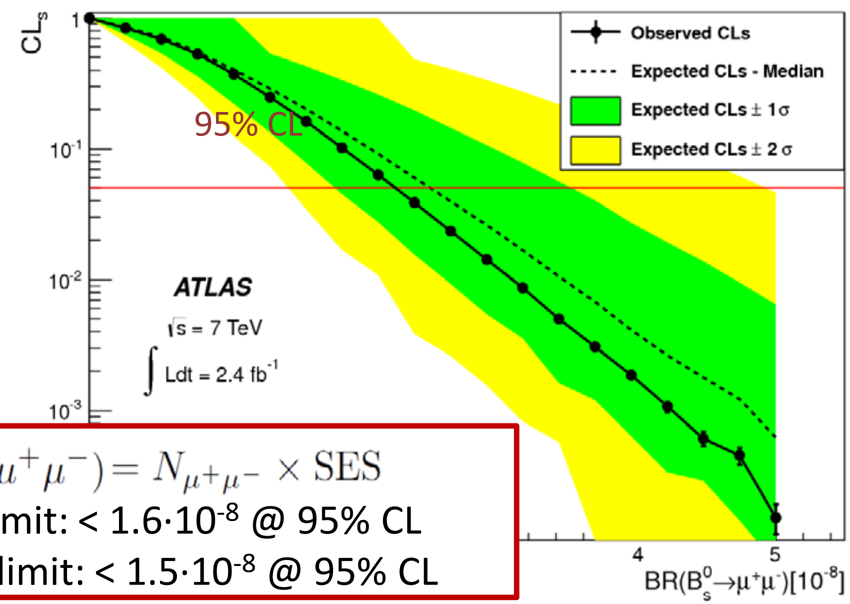
Measured with respect to a prominent reference decay ($B^+ \to J/\psi K^+$).

- Single Event Sensitivity (SES) would yield one observed signal event in the data sample.

$$\mathrm{SES} = \mathrm{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-}} = (2.07 \pm 0.26)\cdot 10^{-9}$$

- *Number of background expected: 6.75*
- *Number of signal observed: 6*





$$\mathrm{BR}(B^0_s \to \mu^+\mu^-) = N_{\mu^+\mu^-} \times \mathrm{SES}$$

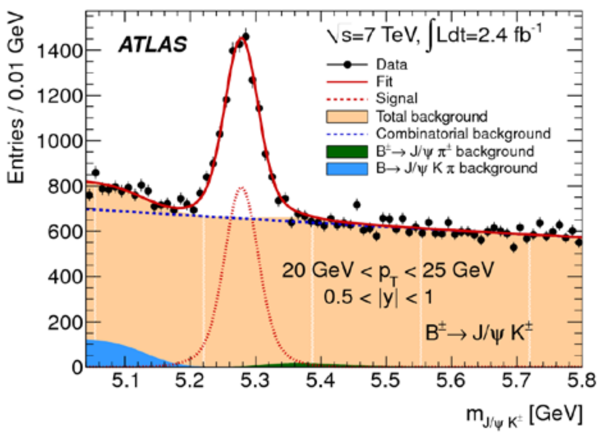
Expected limit: < $1.6\cdot10^{-8}$ @ 95% CL

Measured limit: < $1.5\cdot10^{-8}$ @ 95% CL

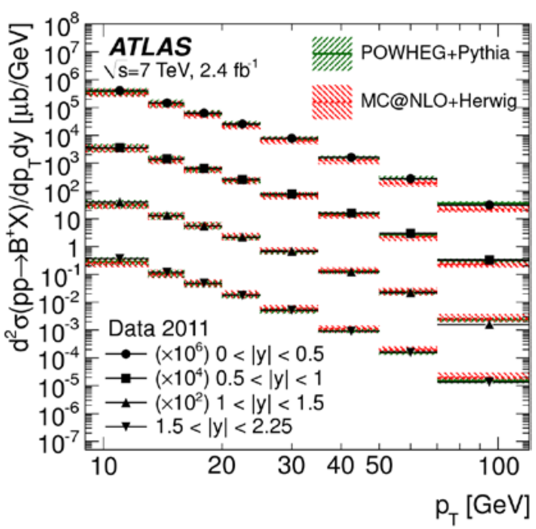
SM: arXiv:1208.0934, LHCb: arXiv:1307.5024v2, CMS: arXiv:1307.5025.

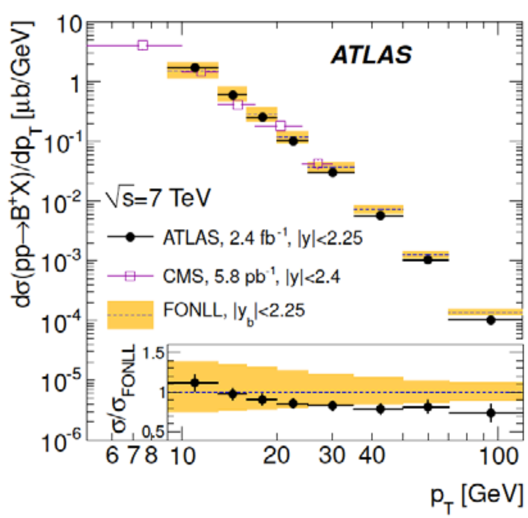
B^+ production cross-section and B_c observation

$B^+ \to J/\psi(\mu^+\mu^-)K^+$

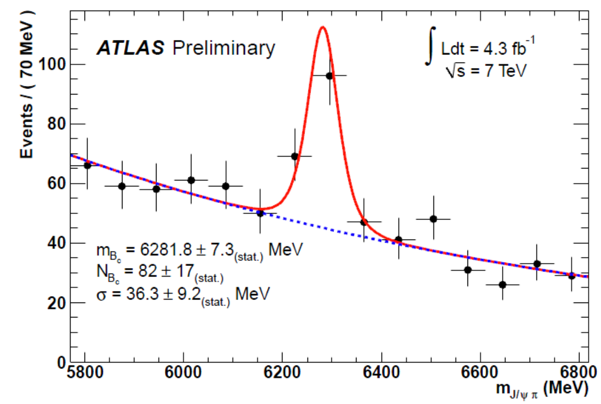


- Early 2011 data, 2.4fb^{-1} at 7TeV.
- 9GeV < $p_T(B^+)$ < 120 GeV, $|y(B^+)|<2.25$
- Compatible to theoretical predictions





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



- 2011 7TeV data, 4.3fb^{-1}.
- PDG(B_c) = 6274.5 ± 1.8 MeV

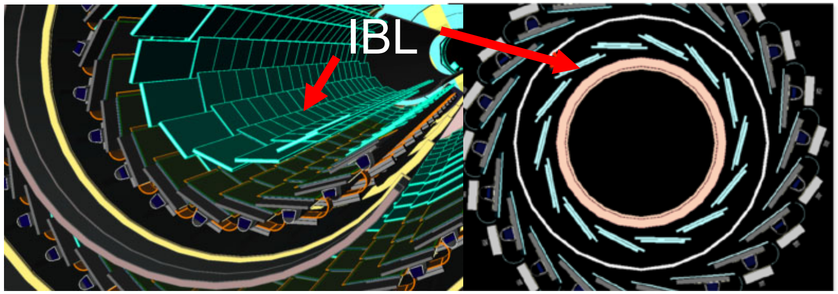
Summary and outlook

Measurements at ATLAS:

- Light meson production ($\phi(1020)$).
- Charmonium and bottonium (W + prompt J/ψ, χ_c, $\psi(2S)$, $\Upsilon(nS)$ production and $\chi_b(3P)$ observation).
- Search for new physics (Angular analysis of $B_d \rightarrow K^{*0}\mu^+\mu^-$ and $B_s \rightarrow J/\psi\phi$, searching for $B_s \rightarrow \mu^+\mu^-$).
- Other measurements (B^+ production, B_c observation).

Outlook

- Many measurement using 8 TeV data are ongoing.
- New Pixel layer installed -> better tracking.
- Improvement in trigger system.
- Increased precision can be expected.



Backup

Reference

- $\phi(1020)$ meson production *(submitted to EPJC, arXiv:1402.6162)*
- $W+J/\psi$ production *(JHEP 04 (2014) 172 arXiv:1401.2831, details in Stefanos Leontsinis's talk)*
- χ_c production *(submitted to JHEP arXiv:1404.7035)*
- $\psi(2S)$ production *(ATLAS-CONF-2013-094)*
- $\Upsilon(nS)$ production x-section and ratios *(Phys. Rev. D 87 (2013) 052004 arXiv:1211.7255)*
- B^+ production *(JHEP 10 (2013) 042 arXiv:1307.0126)*
- $\chi_b(3P)$ observation *(Phys. Rev. Lett. 108 (2012) 152001 arXiv:1112.5154)*
- B_c observation *(ATLAS-CONF-2012-028)*
- Angular analysis of $B_d \rightarrow K^{*0}\mu^+\mu^-$ *(ATLAS-CONF-2013-038)*
- Angular analysis of $B_s \rightarrow J/\psi\phi$ *(Phys. Lett. B713 (2012) 180-196 arXiv:1204.0735, details in Jaroslav Guenther's talk)*
- Searching for $B_s \rightarrow \mu^+\mu^-$ *(ATLAS-CONF-2013-076, details in Jaroslav Guenther's talk)*

B physics triggers

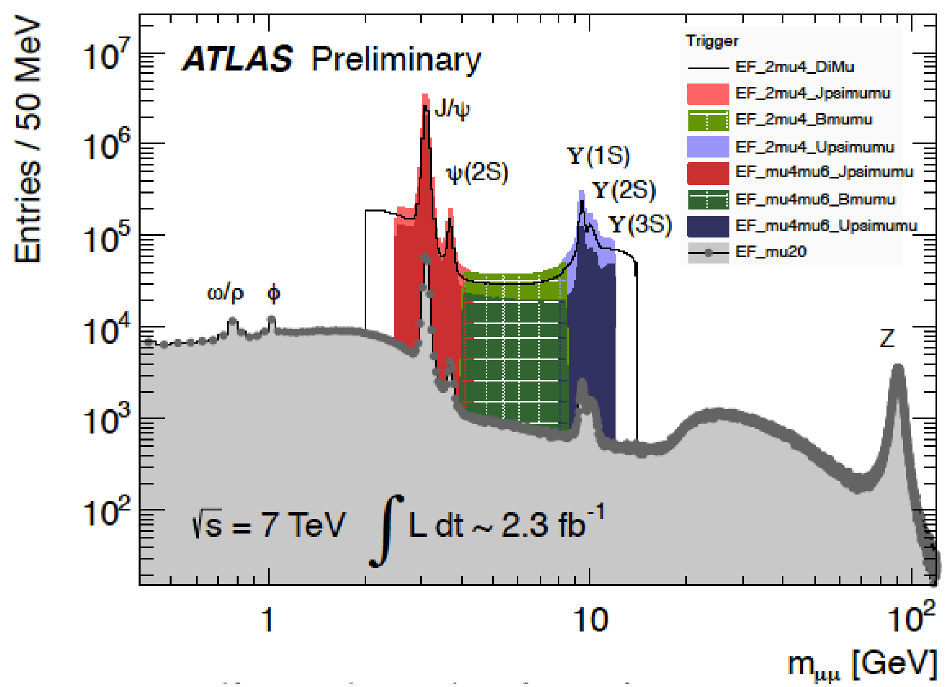
- ATLAS has 3-level trigger system (L1 - hardware, L2 and Event Filter (EF) – High level trigger (HLT))
- Dedicated B-physics triggers are based on both single muons and di-muons with different thresholds and mass ranges.

- Topological triggers process two L1 muon and refine results in the HLT with a good vertex fit and mass cut.

Topology	Mass window
Jpsimumu	2.5-4.3GeV
Upsimumu	8-12 GeV
Bmumu	4-8.3 GeV

- TrigDiMuon triggers require one L1 muon and then search for a second muon in inner detector tracks.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults#Stand_alone_plots



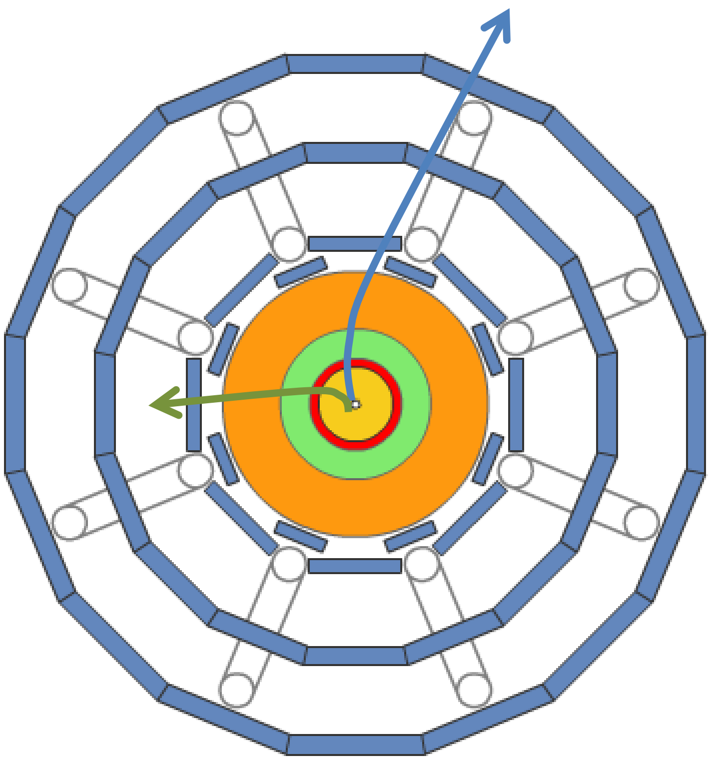
φ(1020) production cross section

- The MC09 and Perugia0 tunes use a p_T-ordered parton shower model with MPI and the initial state shower interleaved in a common sequence of decreasing p_T.
- For the PYTHIA8 A2 tunes, the final-state showers are also interleaved in this way.
- The DW tune utilises the older virtuality-ordered parton shower which is not interleaved with MPI.
- Herwig++ version 2.5.1 is used with the UE7-2 tune. Herwig++ is also a general purpose generator but differs from PYTHIA in that it uses a cluster hadronisation model and an angular ordered parton shower. Herwig++ contains a tunable eikonalised MPI model which assumes independence between separate scatters in the event.
- EPOS 1.99 v2965 is used with the EPOS-LHC tune. EPOS contains a parametrised approximation of the hydrodynamic evolution of initial states using a parton based Gribov-Regge theory which has been tuned to LHC data.

Muon reconstruction

The muon reconstruction in ATLAS makes use of two sub-detectors: the Inner Detector (ID) and the Muon Spectrometer (MS).

- ***Combined muons***: a stand-alone MS track ($|\eta| < 2.5$) matched with an ID track.
- ***Tagged muons***: ID tracks extrapolated to the MS and matched to at least one of MS hits.



ϒ(nS) production