PRODUCTION OF QUARKONIUM STATES AT THE ATLAS EXPERIMENT

PHENO2014

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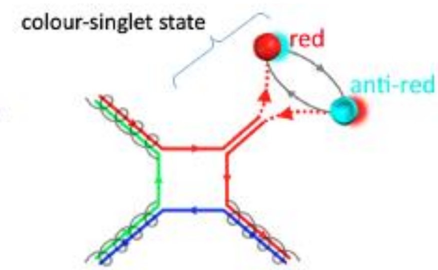
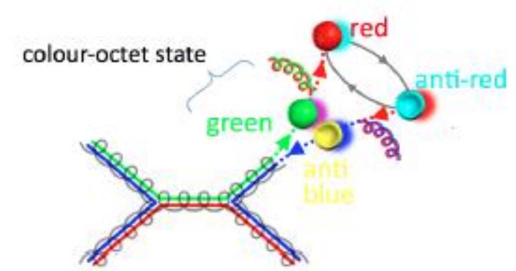
(on behalf of the Atlas Collaboration)

INTEREST IN QUARKONIA PRODUCTION

- Quarkonia are a $q\bar{q}$ bound state.

- A lot to learn from Quarkonium production:
  - Dynamics of strong interaction, and hadron formation.
  - Presence of multiple energy scales (hard scale, soft scale, and ultra soft scale).
  - Higgs decays to quarkonia provide a unique probe to the Higgs Bosons charm couplings.
  - Ideal probe of beyond-the-standard-model (BSM) frameworks.





- Observed in the past large disagreements between experimental results and theoretical production models (Tevatron):
  - Color Singlet Model (CM), Color Octet Model (COM), Color Evaporation Model (CEM),…

RESULTS IN TALK

In this talk I will focus on the three most recent ATLAS Quarkonia results.

- Measurement of W + prompt J/ψ production at $\sqrt{s}$ = 7 TeV: **arXiv:1401.2831 [hep-ex]**, accepted for publication in JHEP.

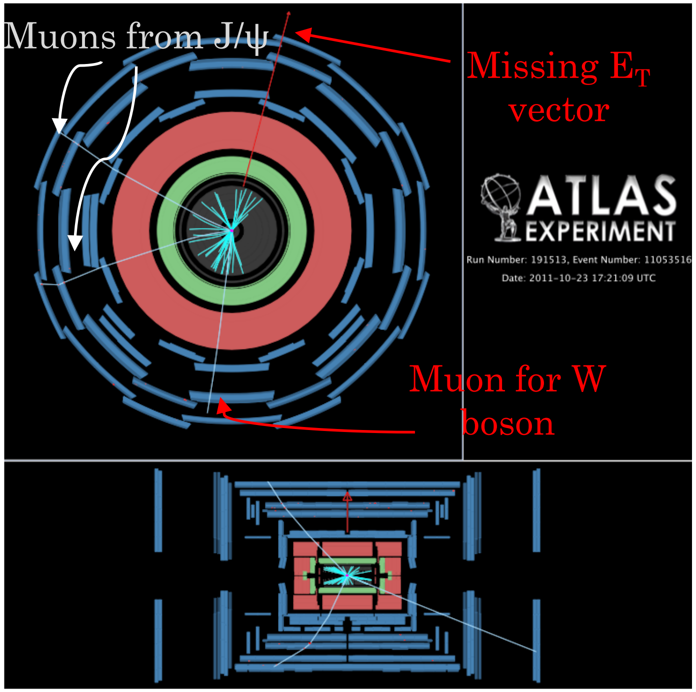
- Measurement of χ_{c1} and χ_{c2} production at $\sqrt{s}$ = 7 TeV: **arXiv:1404.7035 [hep-ex]**, **submitted to JHEP**.

- Cross-Section Measurement of ψ(2S) → J/ψ(→ $\mu^+\mu^-$)$\pi^+\pi^-$ at $\sqrt{s}$ = 7 TeV: ATLAS-CONF-2013-094.

W + PROMPT J/ψ PRODUCTION

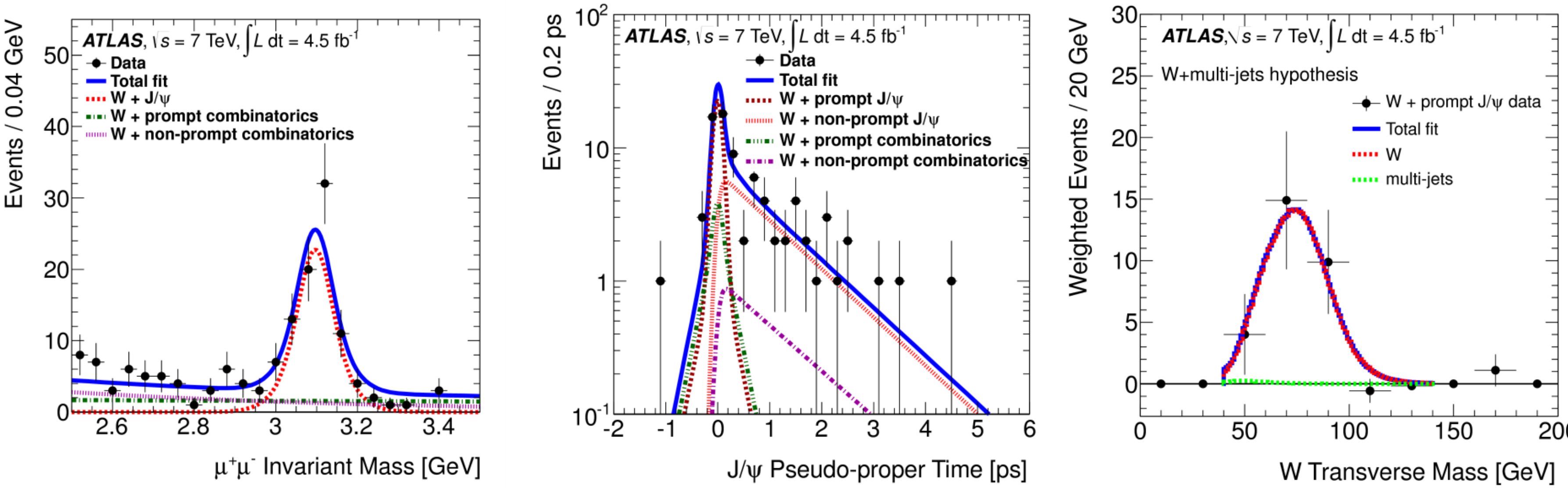
- $4.5\ fb^{-1}$ of 2011 $\sqrt{s}$ = 7 TeV ATLAS data, select W→μν, J/ψ→ μμ.
- Single high p_T muon trigger (p_T > 18 GeV) with:
  - J/ψ: one muon with p_T > 4 GeV, p_T > 3.5 (2.5) GeV for $|\eta|$ < 1.3 (> 1.3), and $|y_{J/\psi}|$<2.1.
  - W Boson: p_T > 25 GeV, $|\eta|$< 2.4, MET > 20 GeV, and $m_T(W)$ > 40 GeV.
- Expected Background:
  - Pileup (multiple pp collisions in a bunch crossing, estimated to be 1.8 ± 0.2 events).
  - W+b-quark.
    - Separated from prompt production with unbinned maximum likelihood fit.
    - **W+b production in itself is of similar magnitude as that of the signal, this is the first such measurement.**
  - Top pair production (predicted to be less than 0.28 events at 95% CL).
  - Z+jets (negligible after vetoing opposite charged muons with invariant mass within 10 GeV of Z mass).
  - Multijet production (found to be smaller than 0.31 events at a 95% CL after fitting m_T(W)).
- Corrected for experimental efficiency and detector acceptance.

ATLAS W + Prompt J/ψ Candidate



EXTRACTING THE SIGNAL

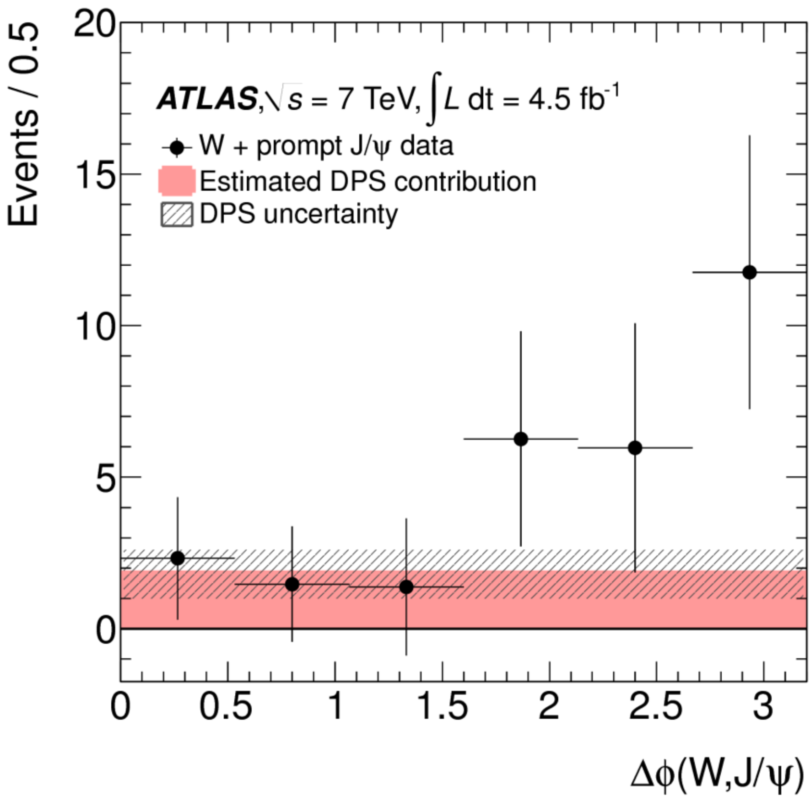
- A Maximum Likelihood fit of the Di-muon invariant mass and J/ψ pseudo-proper time are used to extract prompt J/ψ events. Then $m_T(W)$ is fit to separate the QCD multijet background. **The background-only hypothesis is rejected at 5.1σ**.



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

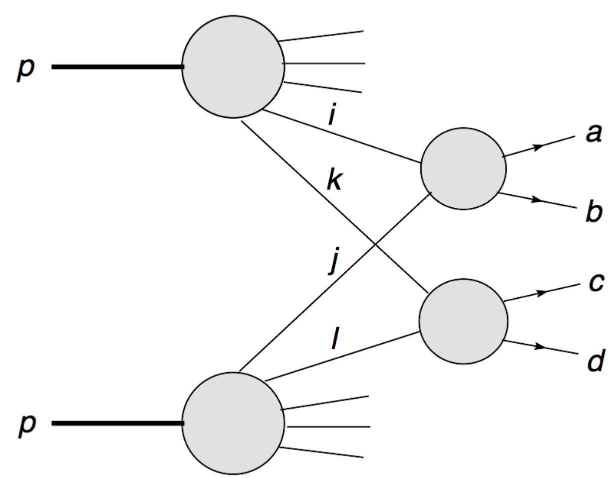
(*) of which 1.8 ± 0.2 originate from pileup

W + PROMPT J/ψ DPS DISTRIBUTION

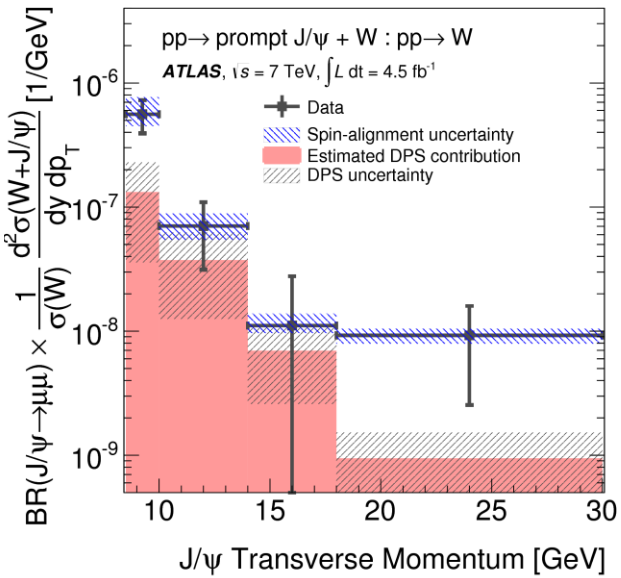


DPS Pythia8: arXiv:0710.3820

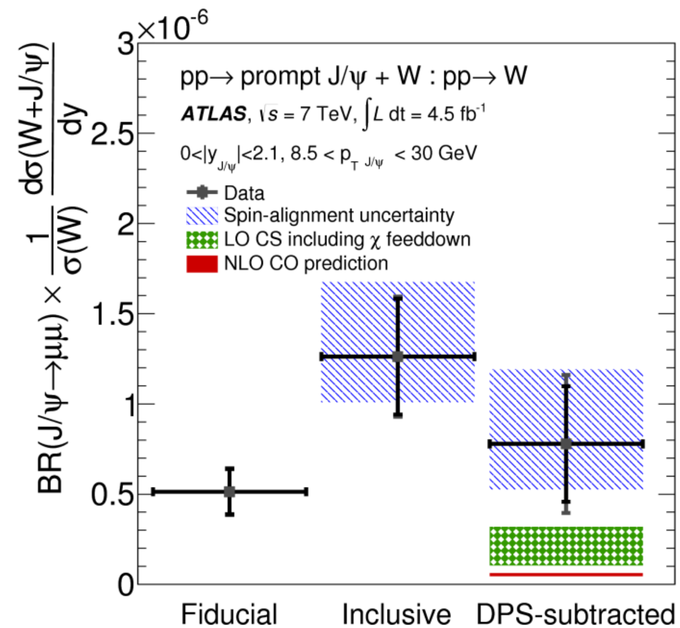
- Double Parton Scattering (DPS): two parton-parton interactions in a single hadron-hadron collision.
- $\sigma_{DPS} = \frac{1}{2}\frac{\sigma_W \sigma_{J/\psi}}{\sigma_{Eff}}$.
- In a DPS event the W boson and J/ψ should be independent of each other which leads to a flat Δϕ distribution.
- The data indicate the presence of both DPS and Single Parton Scattering (SPS).



PRODUCTION CROSS-SECTION FOR W+PROMPT J/Ψ



- The differential cross-section ratio as a function of p_T, $dR^{Incl}_{J/\psi}/dp_T$.
- A DPS estimate is shown and the data suggests DPS is a large fraction of the signal, **$f_{DPS} \sim 37\%$**.



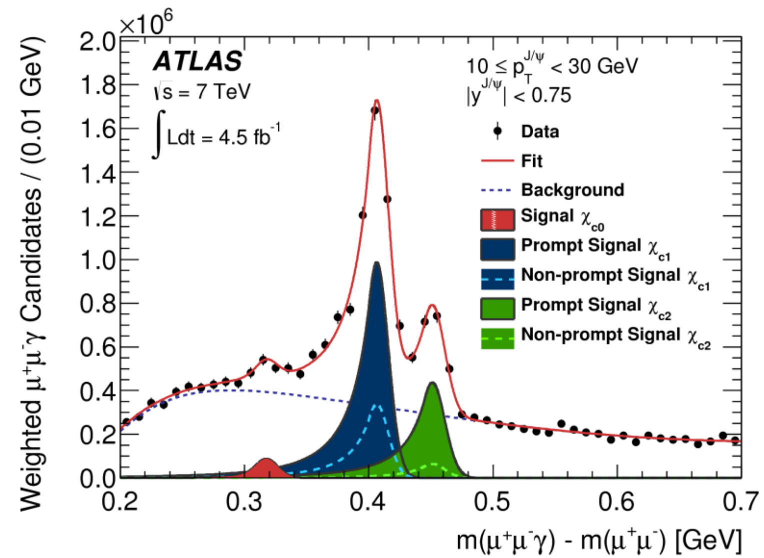
- **NLO Color Octet contributions are an order of magnitude smaller than LO Color Singlet contributions**.
- Color singlet dominance in contradiction to color octet enhancement in other quarkonium production processes. Breakdown of NRQCD universality? Modifications to DPS ansatz?
- Due to the large uncertainties SPS prediction are compatible with results at the 2σ level.

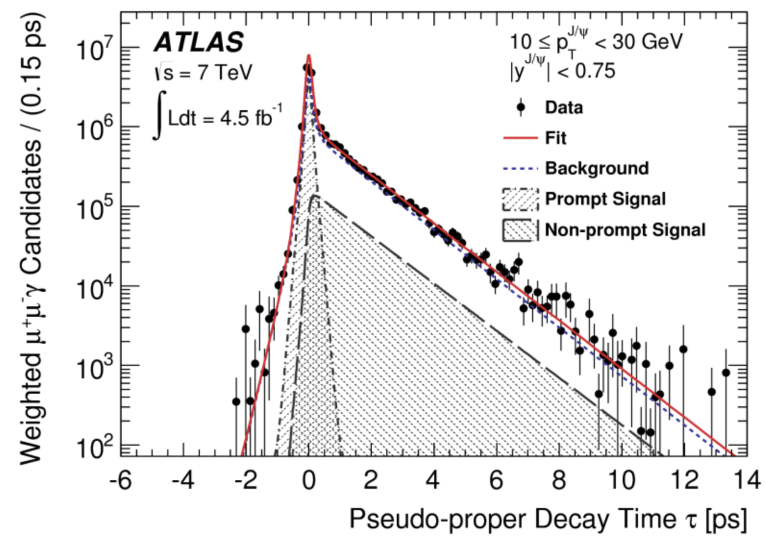
LO: arXiv:1303.5327

NLO: arXiv:1012.3798

χ_{c1} AND χ_{c2} PRODUCTION

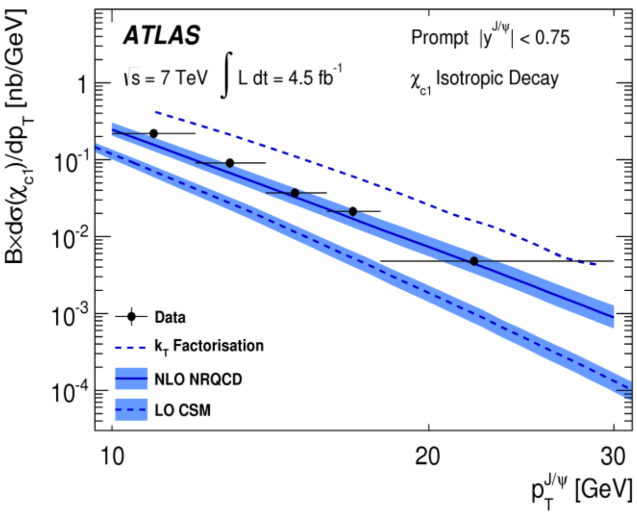
- Prompt J/ψ can be produced directly, or from decays of other states such as χ_c.
- 4.5 fb^{-1} of 2011 $\sqrt{s}$ = 7 TeV ATLAS data, select $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu\mu$.
- Di-muon trigger with p_T>4 GeV.
  - J/ψ: $p_T(\mu) > 4$ GeV, $|\eta| < 2.3$.
  - γ: opp. charged tracks with $p_T > 400$ MeV, $|\eta| < 2.3$. $p_T(\gamma) > 4$ GeV, $|\eta(\gamma)| < 2.3$.
- An unbinned simultaneous Maximum Likelihood fit of $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ and the pseudo-proper lifetime.
  - Corrected for experimental efficiency and detector acceptance.

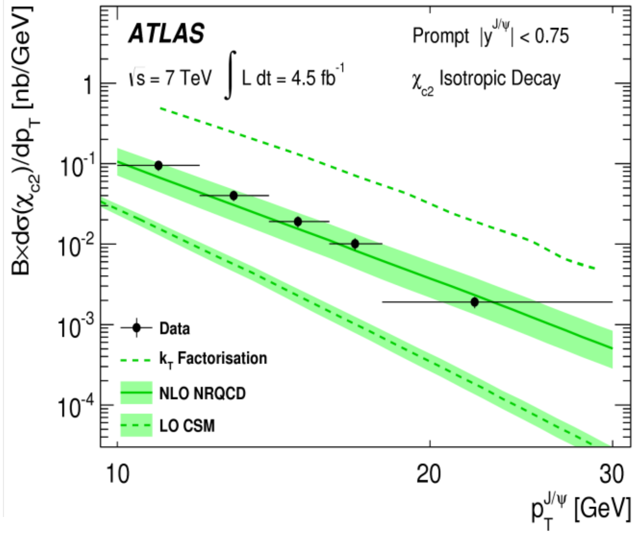




PRODUCTION CROSS-SECTION FOR χ_c VS. $P_T^{J/\psi}$

Prompt

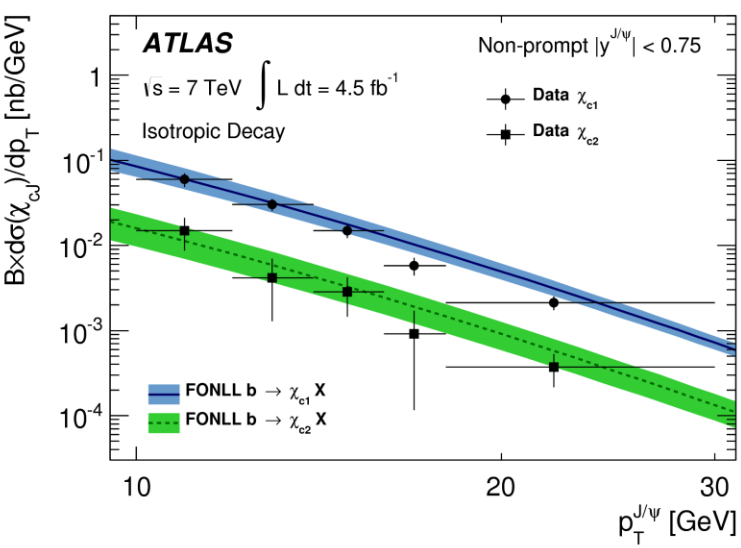




First absolute measurement of differential cross-section of prompt χ_{c1} and χ_{c2}.

- Compared with NLO NRQCD (from the Tevatron), k_T factorization, and LO CSM.
- NRQCD is in good agreement. The k_T factorization approach predicts an excess and LO CSM underestimates the results.

Non-Prompt

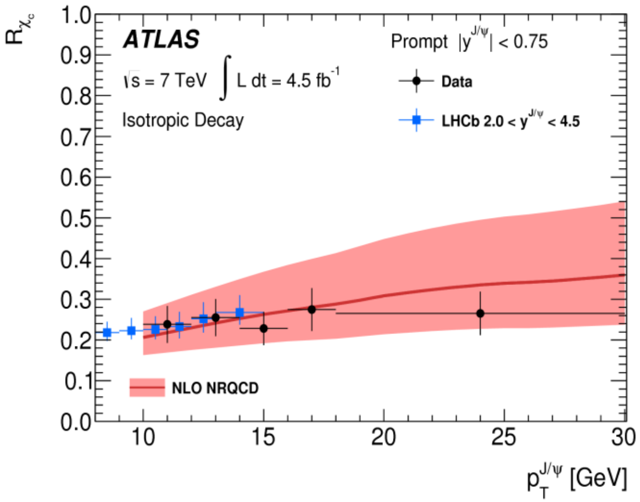


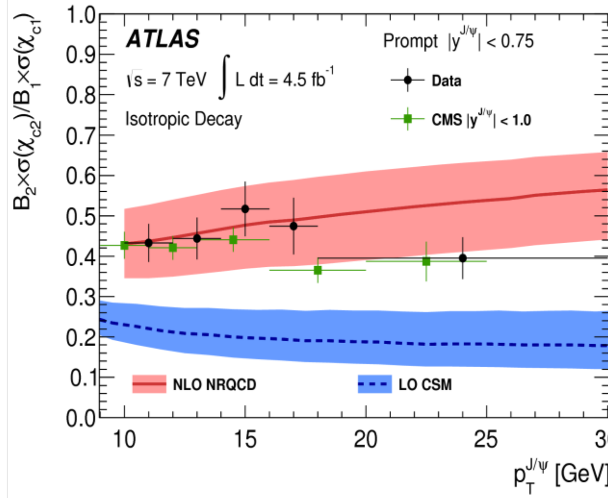
First absolute measurement of differential cross-section of non-prompt χ_{c1} and χ_{c2}.

- The results are compared to FONLL predictions for b-hadron production.
- Measurements found to be in good agreement.

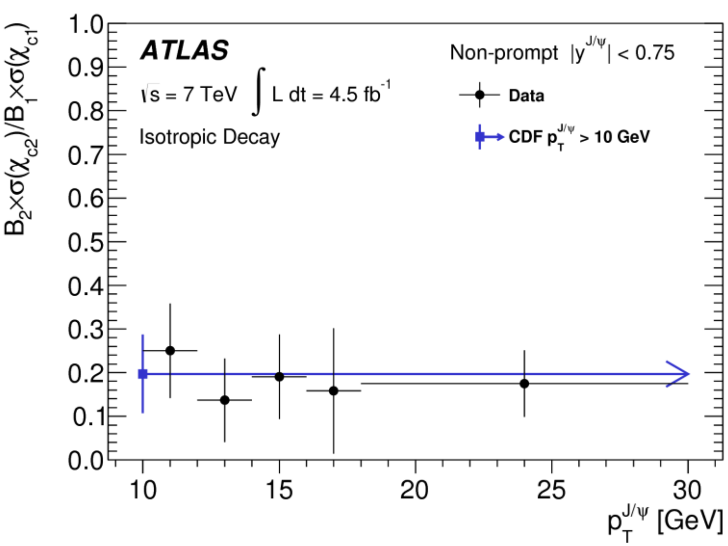
NRQCD:arXiv:1002.3987, arXiv:1212.5293, arXiv:1009.3655
k_T: arXiv:1108.2856
LO CSM: http://superchic.hepforge.org/chigen.html
FONLL: arXiv:1205.6344, hep-ph/9803400

χ_{c1} AND χ_{c2} PRODUCTION RATES





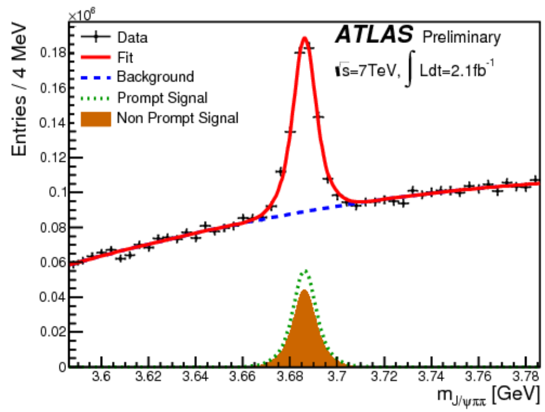
- (Left) **Fraction of prompt J/ψ produced from χ_c decay**.
  - Results compared to LHCb data and NLO NRQCD, and are in good agreement and are between 20-30%.
  - LHCb: arXiv:1204.1462
- (Right) **Ratio of prompt χ_{c2} relative to χ_{c1} as a function of $p_T^{J/\psi}$**.
  - Compared with CMS data and NLO NRQCD predictions. Good agreement especially at low $p_T^{J/\psi}$, but hints of overestimate at high p_T.
  - The LO CSM consistently underestimates the measurements.
  - CMS: arXiv:1210.0875

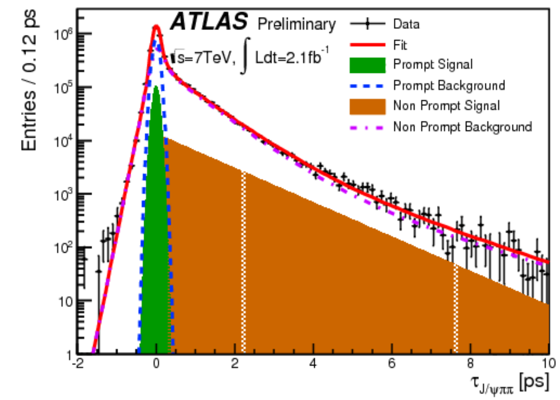


- (Bottom) **Ratio of non-prompt χ_{c2} relative to χ_{c1} as a function of $p_T^{J/\psi}$**.
  - Compared with one data point from CDF. The results are consistent.
  - CDF: hep-ex/0703028
- **The Branching Fraction $\mathcal{B}(B^{\pm} \rightarrow \chi_{c1} K^{\pm})$ is measured. It is found to be : $\mathcal{B}(B^{\pm} \rightarrow \chi_{c1} K^{\pm}) = (4.9 \pm 0.9\ (\text{stat.}) \pm 0.6\ (\text{syst.})) \times 10^{-4}$**. (Details in Backup Slides).

$\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

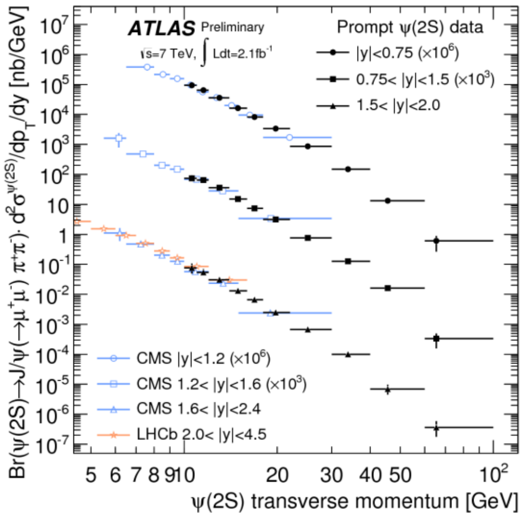
- $\psi(2S)$ has no significant feed down, higher charmonium states decay predominately to $D\bar{D}$. Expands on previous measurements to the range $|y| < 2.0$ and $10 < p_T < 100$ GeV.
- 2.1 fb^{-1} of 2011 $\sqrt{s} = 7$ TeV ATLAS data.

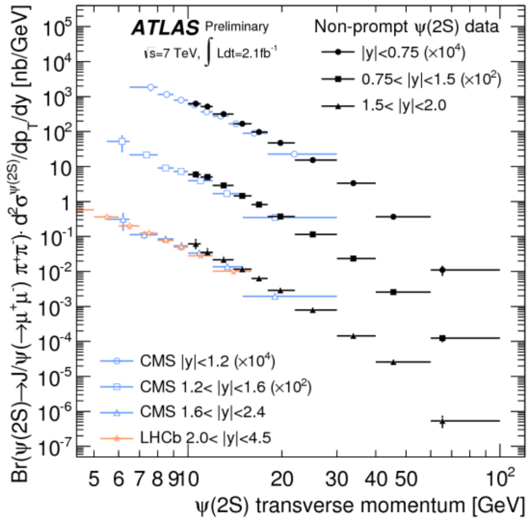




- Di-muon trigger with $p_T > 4$ GeV.
  - J/ψ: $p_T(\mu) > 4$ GeV, $|\eta| < 2.3$. $p_T(J/\psi) > 8$ GeV, $|y(J/\psi)| < 2.0$.
  - π: opp. charged tracks with $p_T > 0.5$ GeV, $|\eta| < 2.5$, and assigning pion mass hypothesis. A four-particle vertex fit is peformed with $M(\mu^+\mu^-)$ constrained to the pdg value for the J/ψ (3096.916 MeV).
- An unbinned simultaneous Maximum Likelihood fit of the $J/\psi\pi\pi$ mass and the pseudo-proper lifetime are in bins of p_T.
  - Split into three rapidity bins: $|y|<0.75$, $0.75<|y|<1.5$, $1.5<|y|<2.0$.
  - Corrected for trigger efficiency, muon reconstruction, pion reconstruction, and detector acceptance.

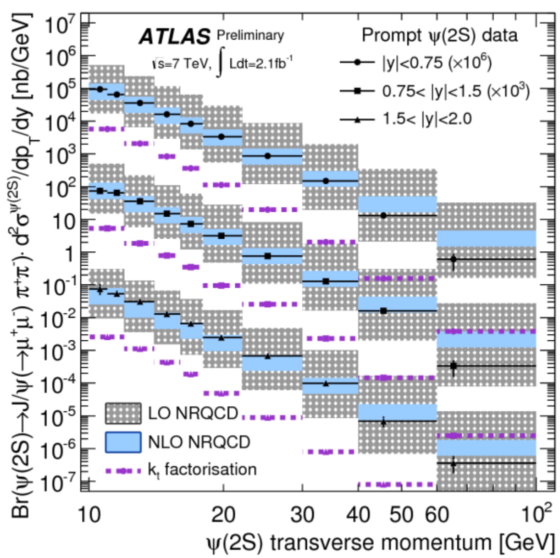
PRODUCTION CROSS-SECTION FOR ψ(2S) → J/ψ(→$\mu^+\mu^-$)$\pi^+\pi^-$

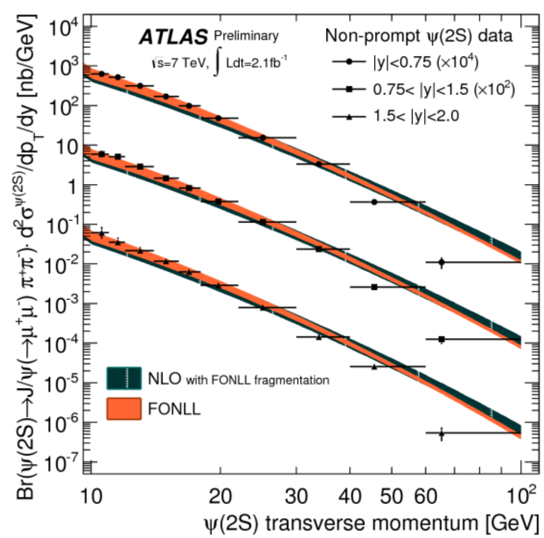




- (Left)Prompt and (Right) non-prompt ψ(2S) cross-section as a function of p_T.
  - Compared to earlier LHCb and CMS results in similar rapidity ranges. The common p_T range values are in good agreement.
  - CMS: arXiv:1111.1557
  - LHCb: arXiv:1204.1258

- (Left) Prompt ψ(2S) cross-section compared with LO and NLO NRQCD, and k_T factorization.
  - LO predictions are in agreement with large uncertainties.
  - NLO are in good agreement until high p_T, where it overestimates and predicts a harder spectrum.
  - k_T factorization underestimates the data and has a p_T dependent shape.
- (Right) Non-Prompt ψ(2S) cross-section compared with FONLL and fixed-order NLO predictions.
  - FONLL shows better agreement than NLO, but both overestimate at high p_T.





CSM: Phys.Rev. D18 (1978) 1501,
NRQCD: arXiv:1009.3655
k_T: arXiv:1108.2856
FONLL: arXiv:hep-ph/0102134

SUMMARY

- W + prompt J/ψ production (**arXiv:1401.2831 [hep-ex]**):
  - **Measured for the first time. Background-only hypothesis rejection at 5.1σ**.
  - **NLO CO contributions are nearly an order of magnitude less than LO CS contributions**.
    - Novel observables with which to test QCD, including DPS contributions, as well as a source of rare/BSM physics.

- χ_{c1} and χ_{c2} production (**arXiv:1404.7035 [hep-ex]**):
  - **χ_c absolute cross-section is measured for the first time**.
    - Prompt production found to be in agreement with NRQCD predictions. kT factorisation approach predicts an excess.
    - Non-prompt production in agreement with FONLL at low p_T, with slight overestimates developing toward high p_T.

- $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ (**ATLAS-CONF-2013-094**):
  - The cross-section for $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ is consistent with previous measurements.
    - For prompt production, NLO NRQCD describes the data well except at high p_T where it overestimates. k_T factorization noticeably undershoots the data, this is correlated with the overestimate in χ_c and can be used to help tune the model.
    - For non-prompt production, both NLO and FONLL describe the data well over a wide range of p_T, but have a **significant overestimation at high p_T**. Possible cause is sharing of energy with B→ ψ(2S)+X? The same overestimate in FONLL is seen in χ_c.

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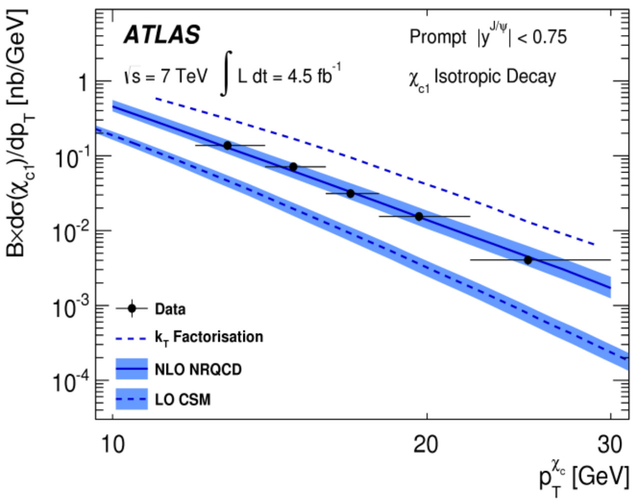
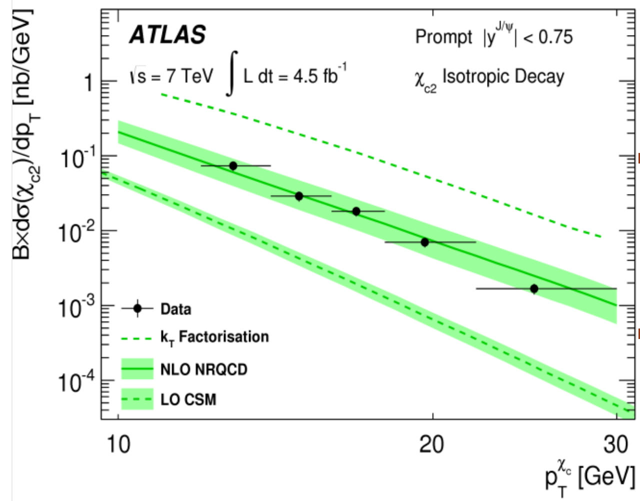
BACKUP SLIDES

DOUBLE PARTON SCATTERING: FEATURES

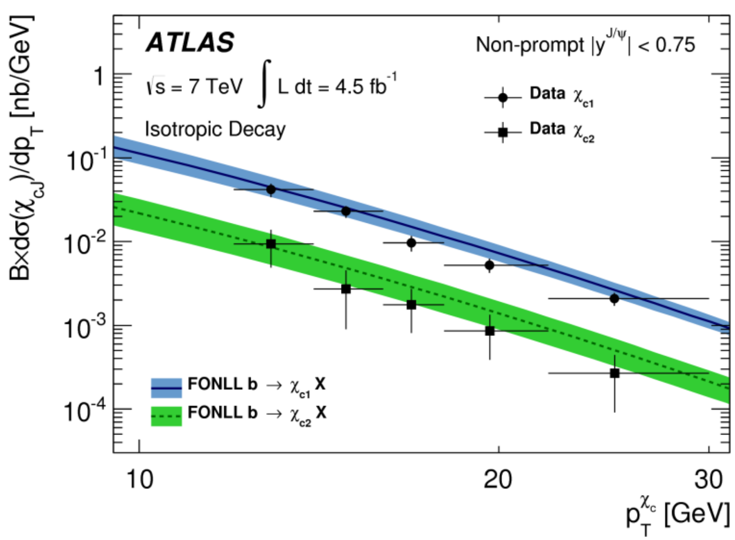
- Double Parton Scattering (DPS) requires large c.m. energies and low values of incoming fractional momenta (x_F). This is possible to achieve at a non-negligible rate at the LHC.
- Because it is dependent on the transverse distance between interactions regions, the DPS cross section decreases quickly as a function of transverse energy.
- Assuming that the two processes (σ_A, σ_B) are independent of each other, DPS cross section can be written as: $\sigma_{DPS}^{(A,B)} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{Eff}}$.
  - $m = 1$ if A and B are distinguishable and $m = 2$ if they are indistinguishable
  - $\sigma_{Eff} = \left[\int\left[\int f(b_1) f(\boldsymbol{b}_1 - \boldsymbol{b})\ d^2 b_1\right]^2 d^2 b\right]^{-1}$ where f(b) parton density in the transverse plane and is assumed to be a universal function, same for both protons.
  - $\frac{\sigma_B}{\sigma_{Eff}}$ is the probability for scattering B to occur given scattering A has already occurred.
  - σ_{Eff} measures the size in impact parameter space of the incident hadron's partonic core.
- $\sigma_{Eff} \sim \frac{1}{4}\ \sigma_{Inel.}$
  - If the effective cross section was equal to the inelastic cross section, it would imply uncorrelated scatterings.
  - This result indicates a correlation ("clumpiness") in the hadron structure.
- A constant value of σ_{Eff} has been able to describe results in different kinematical regions. CDF has also tested the dependence of σ_{Eff} on x_F and had compatible results with being independent of x_F.

PRODUCTION CROSS-SECTION FOR χ_c VS. $P_T^{\chi_c}$



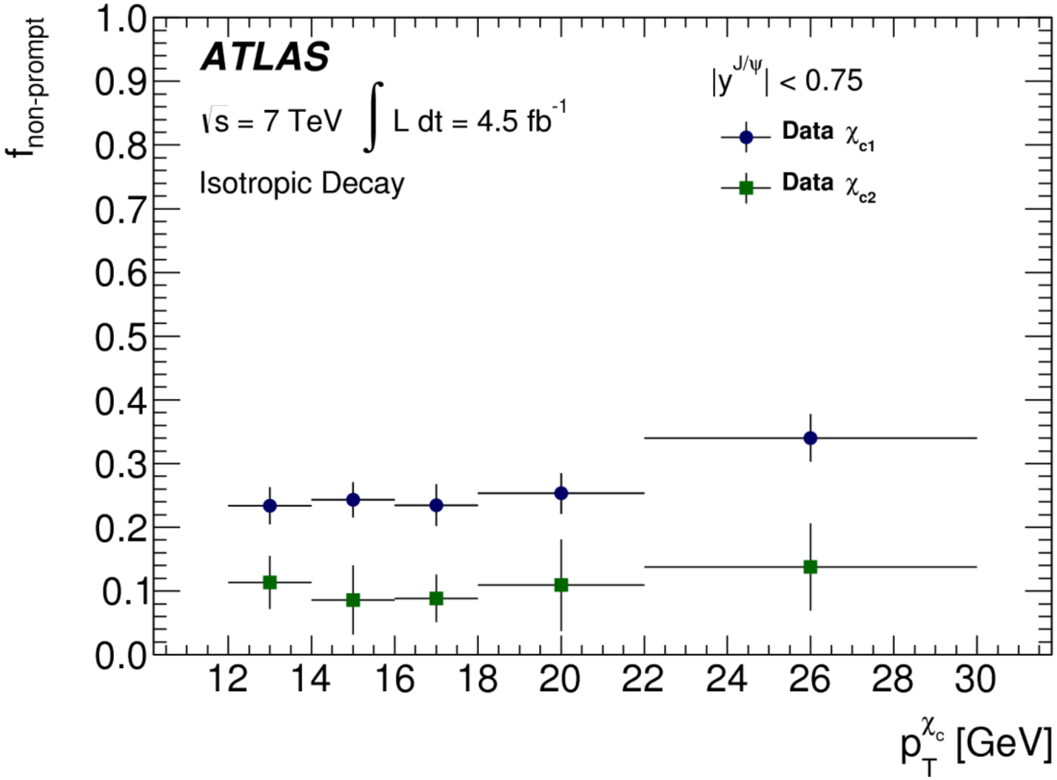


- The differential cross-section of prompt χ_{c1} and χ_{c2} as a function of the χ_c transverse momentum.
- The results are compared with NLO NRQCD (from the Tevatron), k_T factorization, and LO CSM.
- NRQCD is in good agreement with the results. The k_T factorization approach predicts an excess and LO CSM underestimates the results.



- The differential cross-section of non-prompt χ_{c1} and χ_{c2} as a function of the J/ψ transverse momentum.
- The results are compared to FONLL predictions for b-hadron production.
- Measurements found to be in good agreement but discrepancies emerge toward higher p_T.

NON-PROMPT FRACTION IN χ_{c1} AND χ_{c2} PRODUCTION



- The fraction of non-prompt χ_{c1} and χ_{c2} as a function of $p_T^{\chi_c}$. The non-prompt fraction increases with p_T as seen with J/ψ and ψ(2s), but is dominated by prompt production unlike the other two systems.

BRANCHING FRACTION $\mathcal{B}(\mathrm{B}^{\pm} \rightarrow \chi_{c1}\mathrm{K}^{\pm})$

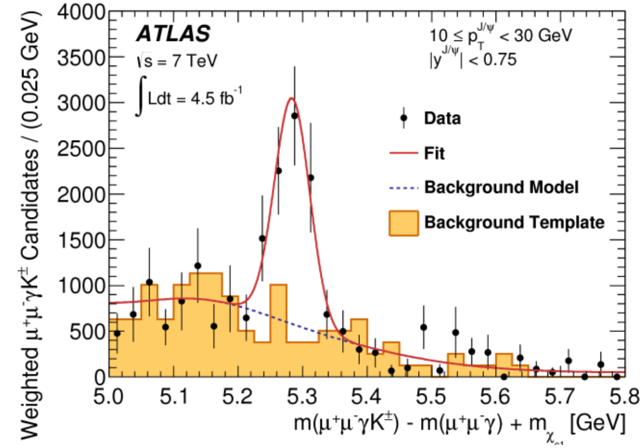
- $B(\mathrm{B}^{\pm} \rightarrow \chi_{c1} K^{\pm}) = A_B \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \frac{B(\mathrm{B}^{\pm} \rightarrow J/\psi K^{\pm})}{B(\chi_{c1} \rightarrow J/\psi \gamma)}$

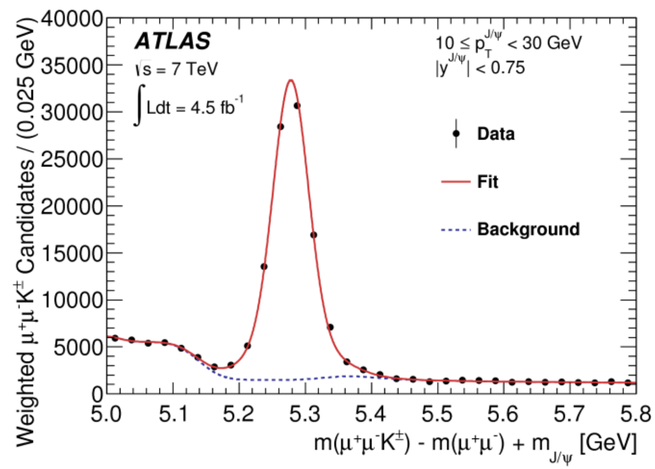
- (Top) Fit of $\mathrm{m}(\mu^+\mu^-\mathrm{K}^{\pm})$-$\mathrm{m}(\mu^+\mu^-\gamma)$ + $\mathrm{m}_{\chi_{c1}}$ used to extract the corrected yields for the χ_{c1} signal.

- (Bottom) Fit of $\mathrm{m}(\mu^+\mu^-\mathrm{K}^{\pm})$-$\mathrm{m}(\mu^+\mu^-\gamma)$ + $\mathrm{m}_{J/\psi}$ used to extract the corrected yields for the J/ψ signal.

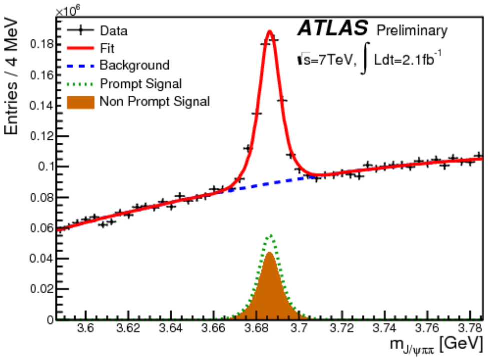
- $B(\mathrm{B}^{\pm} \rightarrow \chi_{c1} K^{\pm}) = (4.9 \pm 0.9\ (\mathrm{stat.}) \pm 0.6\ (\mathrm{syst.})) \times 10^{-4}$.

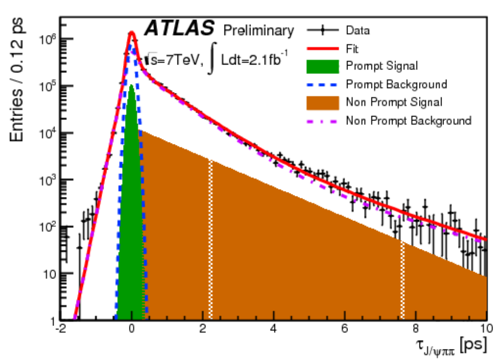
- World average is $(4.79 \pm 0.23) \times 10^{-4}$ and is dominated by Belle and BaBar measurements.





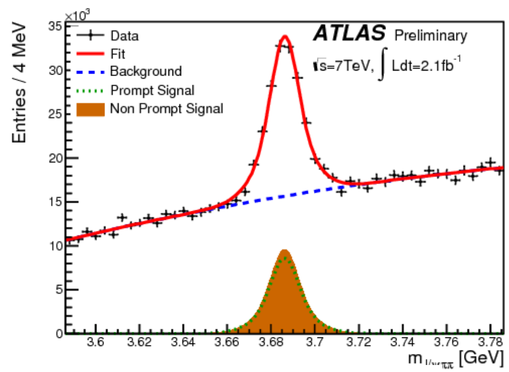
ψ(2S) SIMULTANEOUS FITS

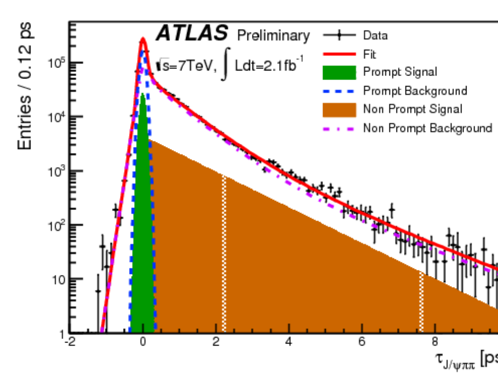


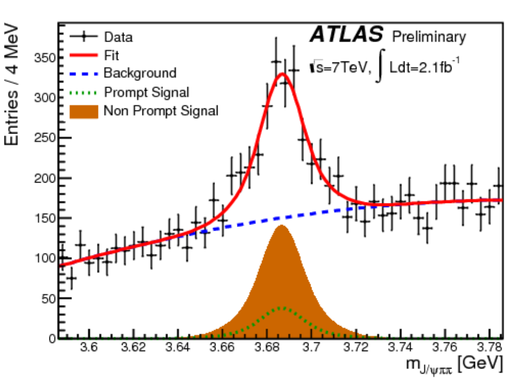


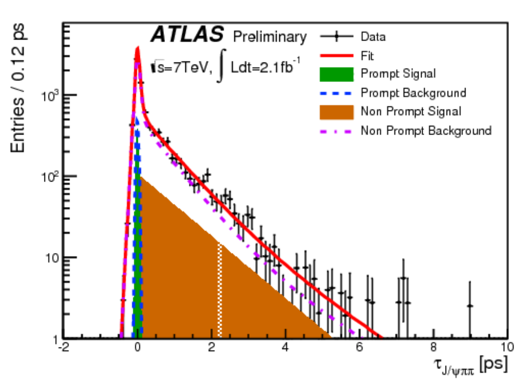
- |y|<0.75

- 0.75 <|y|< 1.5



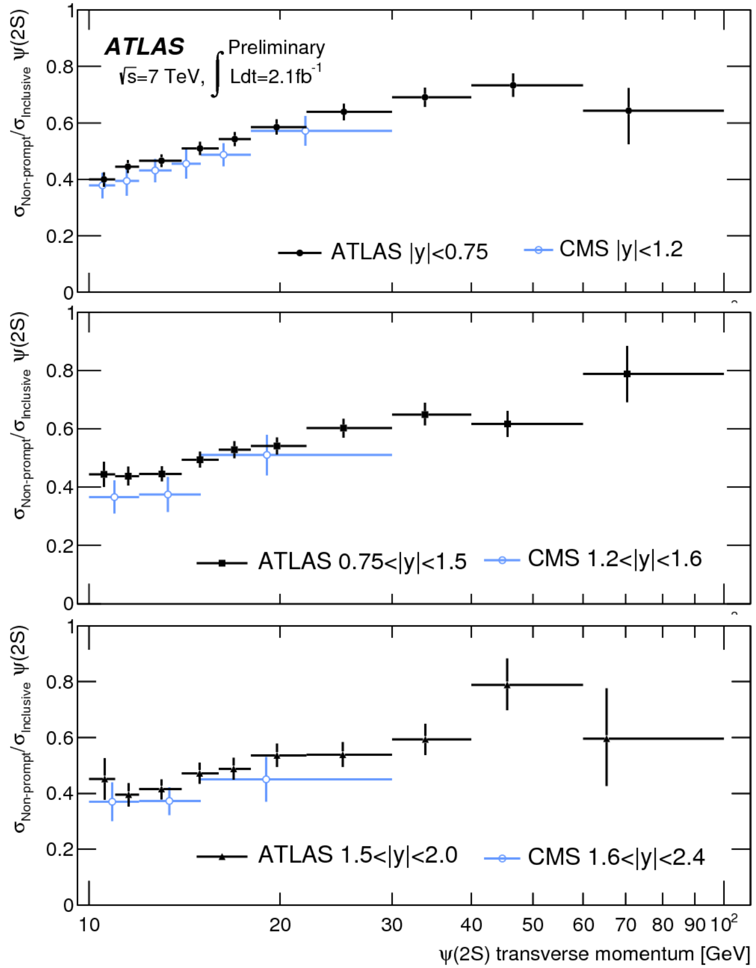






- 1.5 <|y|< 2.0

NON-PROMPT ψ(2S) PRODUCTION FRACTION



MEASURED ψ(2S) DIFFERENTIAL CROSS-SECTION RATIOS