# Measurements of the production of P-wave charmonium states through radiative decays at the ATLAS experiment

Michal Marcisovsky
IoP ASCR Prague

On behalf of the ATLAS Collaboration

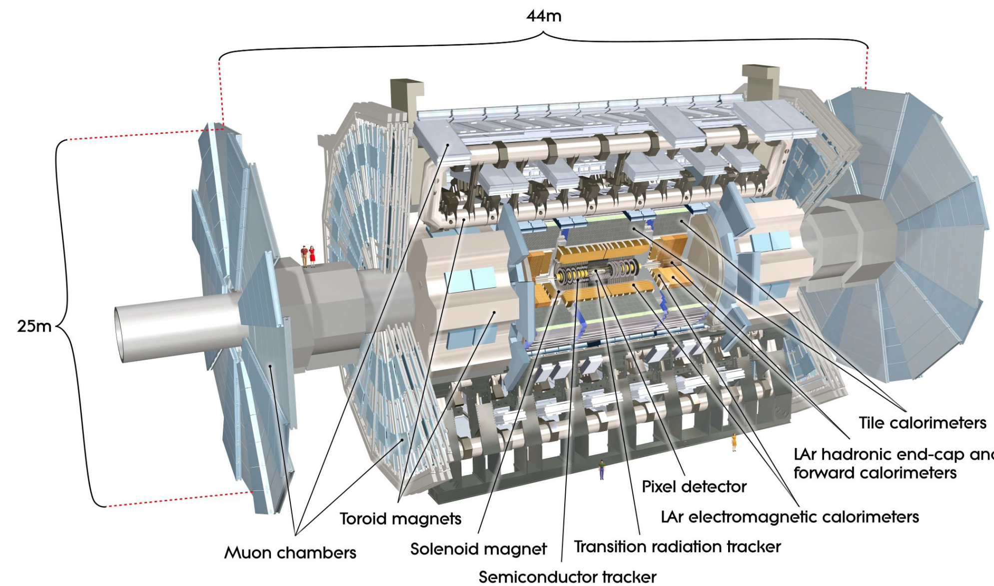
International Conference on New Frontiers in Physics 2013
Κολυμβάρι, Κρήτη

# Outline

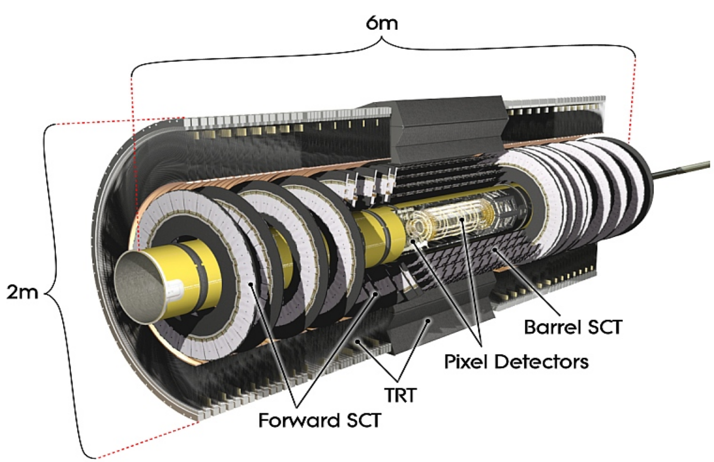
- The ATLAS detector overview
- Measurement of the differential cross section of the prompt and non-prompt $\chi_{c1}$ and $\chi_{c2}$ production as a function of $p_T$
- Ratio of the $\chi_{c1}$ and $\chi_{c2}$ cross sections
- Measurement of the fraction of the prompt $J/\psi$ produced in feed-down from $\chi_c$ decays
- Fractions of $\chi_{c1}$ and $\chi_{c2}$ produced in b-hadron decays
- Measurement $\mathcal{B}(B^{\pm} \rightarrow \chi_{c1} K^{\pm})$

# The ATLAS Detector

- ATLAS is a general purpose detector at the LHC
- Optimized for high $p_T$ physics and instantaneous luminosity up to $10^{34}\,cm^{-2}s^{-1}$

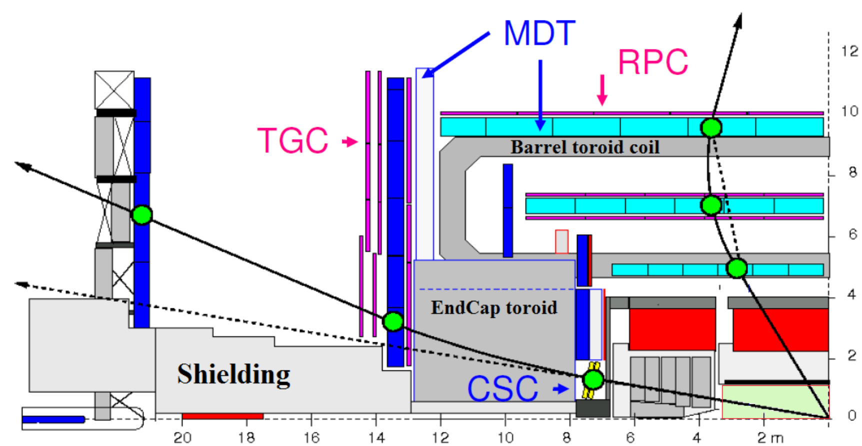



- Muons are reconstructed using the Muon Spectrometer(MS) and Inner Detector (ID)
  - Low momentum muon measurement is dominated by the Inner Detector tracking



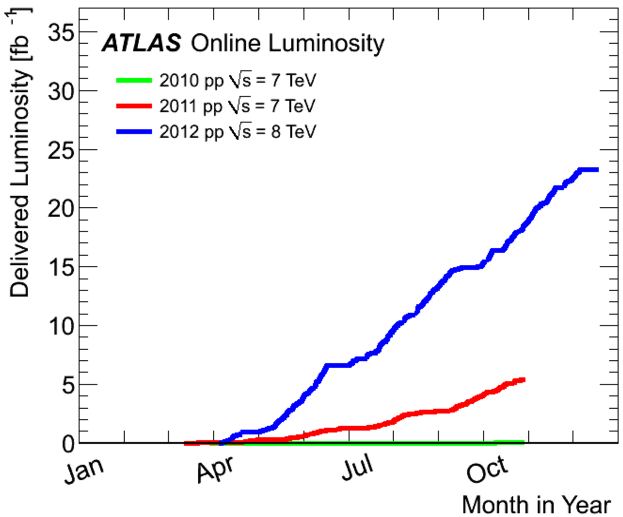

- Covers pseudorapidity region $|\eta| < 2.5$
- Tracks are bent by a 2 T magnetic field
- IP resolution 15 μm in rφ, 100 μm in Z

$\Delta p_T/p_T \sim 0.04\%\ p_T\ [GeV] \otimes 1.5\%$




Superconducting MS magnetic system provides 2.5 Tm bending power in the barrel and 5 Tm in the endcaps.

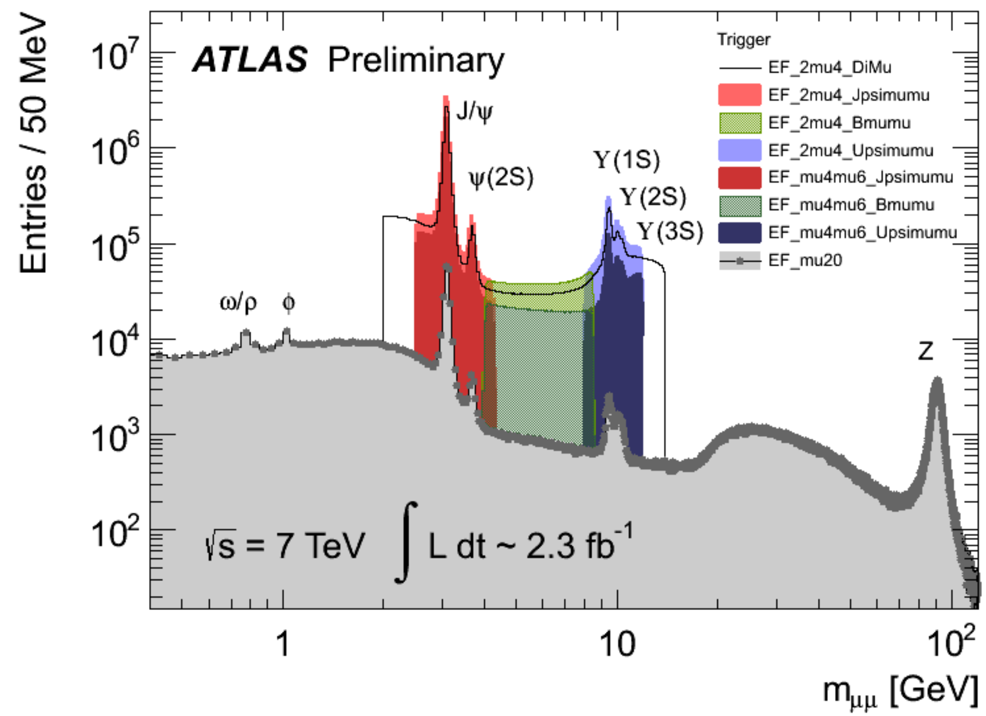
# The ATLAS data sample




- 2011 Peak luminosity $3.7\times10^{33}$ cm$^{-2}$ s$^{-1}$
  - ATLAS recorded 5.2 fb$^{-1}$ at 7 TeV
- 2012 Peak luminosity $7.7\times10^{33}$ cm$^{-2}$ s$^{-1}$
  - ATLAS recorded 21.7 fb$^{-1}$ at 8 TeV

The analysis presented in this talk uses the 4.5 fb$^{-1}$ recorded by the ATLAS detector in 2011.

- Topological triggers process two L1 muon RoIs and refine results in the HLT with a good vertex fit and mass cut
- 2mu4 B-physics triggers run unprescaled in 2011



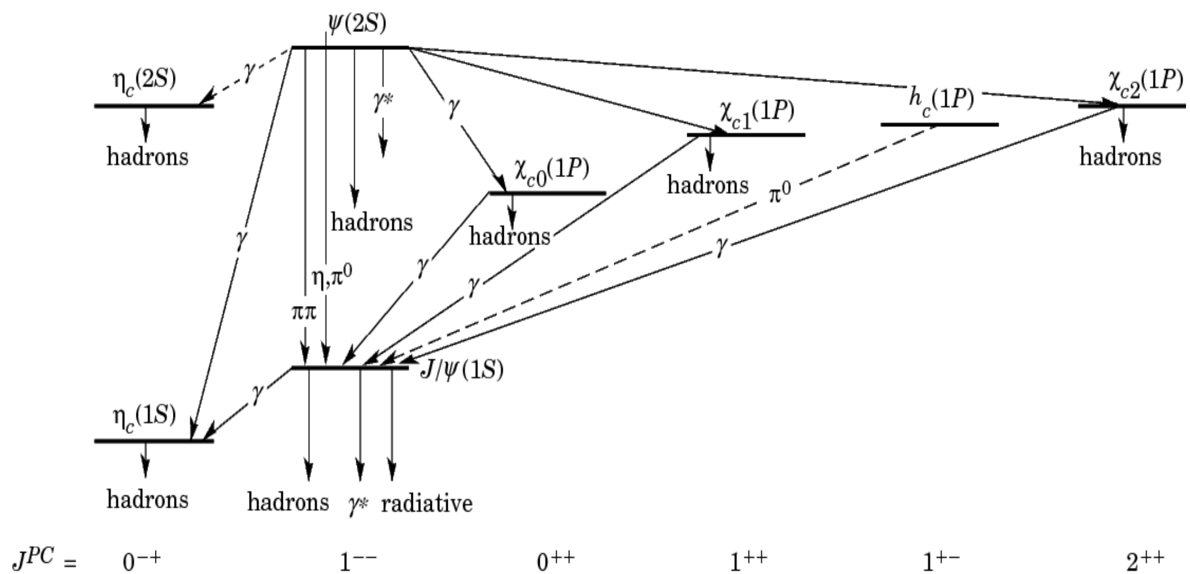

| Trigger name | Mass window | No. of events |
|---|---|---|
| 2mu4_Jpsimumu | 2.5-4.3 GeV | 14M |
| 2mu4_Upsimumu | 8-12 GeV | 9.1M |
| 2mu4_Bmumu | 4-8.3 GeV | 3.7M |

Example with 2.3fb$^{-1}$ data

# Quarkonia

- Quarkonia provide a good testing ground for p-QCD studies and also a natural laboratory for precise tests of lattice QCD
- The high mass of *c* and *b* quarks makes non-relativistic model description possible
- Production still not well understood, Color Singlet (CS) and Color Octet (CO) mechanisms describe $p_T$ spectrum observed at Tevatron and LHC, but polarization predictions disagree with measurements

- Experimental hadron spectroscopy has an essential role in understanding of the QCD
- LHC allows reaching higher $p_T$ and wide rapidity regions




New ATLAS BPhys results

ATLAS-CONF-2013-095

Measurement of $\chi_c$ and $\chi_{c2}$ production with $\sqrt{s}$ = 7TeV pp collisions

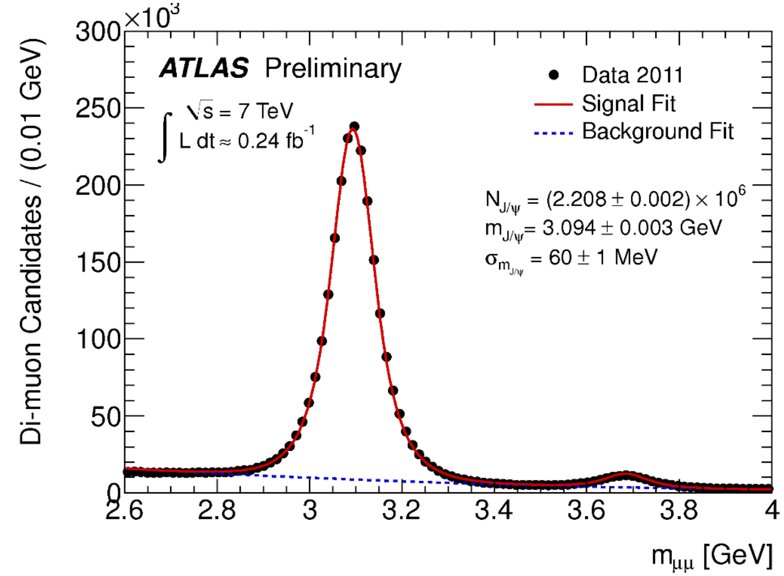
ATLAS-CONF-2013-094

Cross-section measurement of $\psi(2S) \rightarrow J/\psi\ \pi^+ \pi^-$

- QCD testbed (Cornell potential model)
- Mass difference between $0^{-+}$ a $1^{--}$ state is due to the spin-spin hyperfine interaction
- $J^{++}$ triplet mass splitting due to spin – orbit and tensor interaction

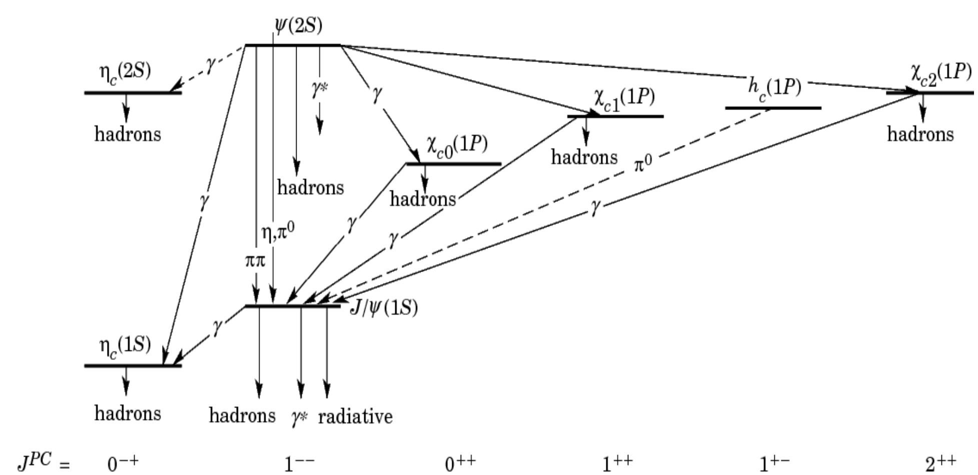
# Charmonium

- J/ψ and its radial excitation ψ(2S) are easily observed in the detector
- Large $\mathcal{B}(J/\Psi \rightarrow \mu^+\mu^-)$ ~ 5.97 %
- Important for B-meson and quarkonia decays studies
- The $\chi_{cJ}$ (1P) states is the only triplet of P-wave states below DD threshold with $J^{PC}=0^{++},1^{++},2^{++}$
- $\mathcal{B}(\chi_{cJ} \rightarrow J/\Psi\gamma)$ = 1.3%, 34.4% and 19.5% for J=0,1 and 2
- The $\chi_{cJ}$ states are reconstructed through radiative decay to $J/\Psi(\mu^+\mu^-)$ and photon, which can detected as a conversion inside of the ID




Nucl. Phys. B850, 387-444 (2011)

- $\chi_{cJ}$ mesons are produced in three ways:
  - Direct production in pp collisions
  - Feed down from heavier charmonium states
    - $\mathcal{B}(\Psi(2S) \rightarrow \chi_{cJ}\gamma)$ ~ 9-10%
  - non-prompt production in decays of B hadrons ($\chi_{c0}$ and $\chi_{c1}$)



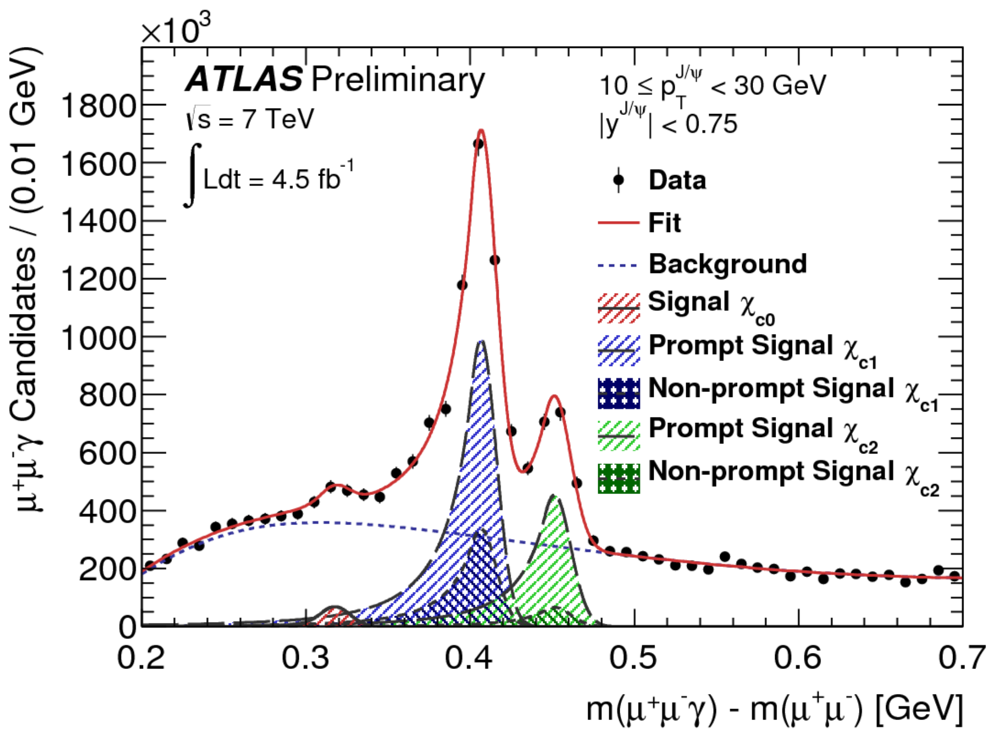
# Event selection

$J/\Psi$:

- Two combined muons with opposite charges
- Must pass di-muon trigger with $p_T$ > 4 GeV
- Primary vertex with at least three tracks
- Requirement on silicon hits (1 pixel and 6 SCT)
- $2.95 < m(\mu^+\mu^-) < 3.25$ GeV
- $|y(\mu^+\mu^-)| < 0.75$

Converted photons:

- Two oppositely charged tracks with at least 6 SCT hits
- $p_T$ > 400 MeV and be reconstructed within $|\eta|<2.3$
- Conversions must have $p_T^{\gamma}$ > 1.5 GeV and $|\eta^{\gamma}|<2$
- vertex must be reconstructed with $\chi^2/N_{dof}$ < 5 and within radius 40< r <150 mm




Requirement of the 3D impact parameter between the conversion and the di-muon vertex, $a_0$ < 5mm.

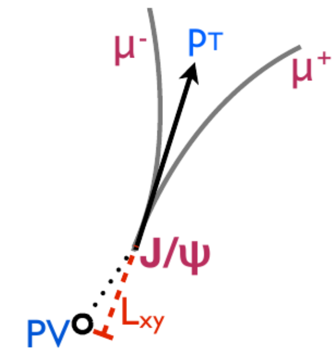
- The $\chi_{c0}$ cross section was not measured due to its small branching fraction to $J/\Psi$ and $\gamma$ and difficult background situation

# Measurement of the $\chi_c$ differential production cross section

$$\frac{d\sigma_i(\chi_{cJ})}{dp_T^{\chi_c}} \cdot \mathcal{B}(\chi_{cJ} \to J/\psi\,\gamma) \cdot \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right) = \frac{N_i^J}{\mathcal{L} \cdot \Delta p_T^{\chi_c}}$$

- Simultaneous $\Delta m$ – lifetime fit is performed
- Pseudo-proper lifetime $\tau$ is the discriminating factor for $\chi_c$ production classes (prompt and B hadron cascade production)

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

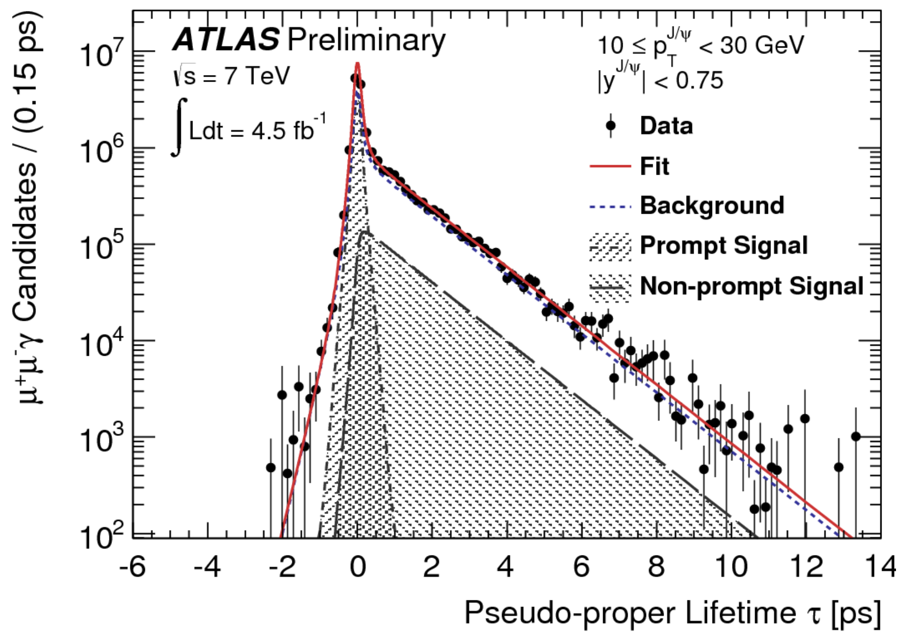



Reconstructed events are weighted by:

$$w^{-1} = \mathcal{A} \cdot \epsilon_{\mathrm{trig}} \cdot \epsilon_{\mathrm{muon}} \cdot \epsilon_{\mathrm{conv}}$$

$\mathcal{A}(p_T, y)$ - Kinematic acceptance

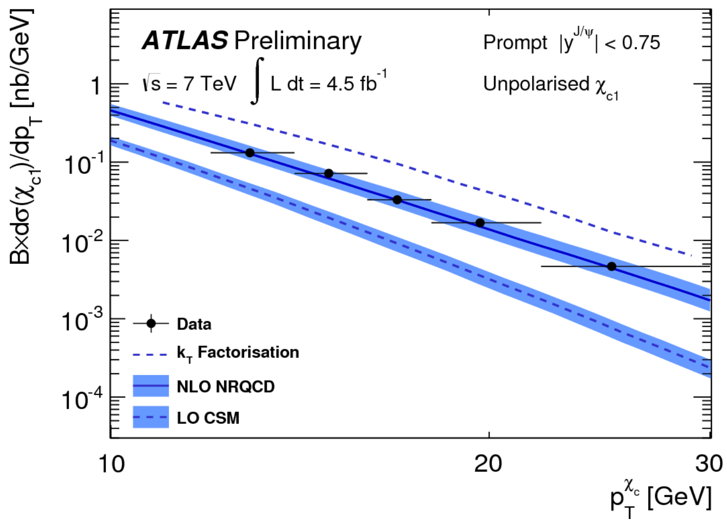
$\mathcal{E}_{trig}$, $\mathcal{E}_{muon}$ and $\mathcal{E}_{conv}$ are efficiencies for triggering, single muon offline tracking efficiency and conversion reconstruction efficiencies.

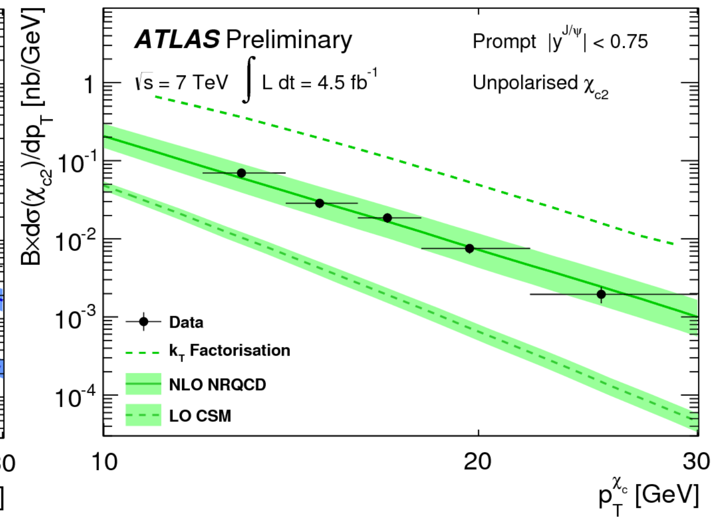



- The polarization of the $\chi_{cJ}$ mesons is unknown. The measurements are corrected for the detector acceptance assuming the $\chi_{cJ}$ states are produced unpolarized.
- Extreme polarization scenarios have been considered to correct cross sections

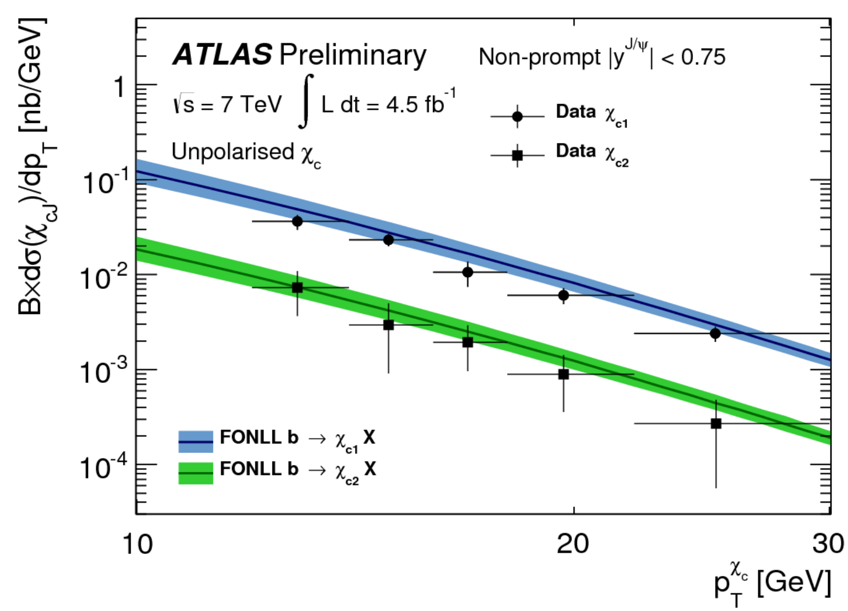
# Differential cross sections for prompt and non-prompt $\chi_{c1,2}$

- Differential cross sections for $\chi_{c1}$, $\chi_{c2}$ prompt (top row) and non-prompt (bottom) production as a function of $\chi_c$ $p_T$ (bottom row)
- First detailed measurement @LHC



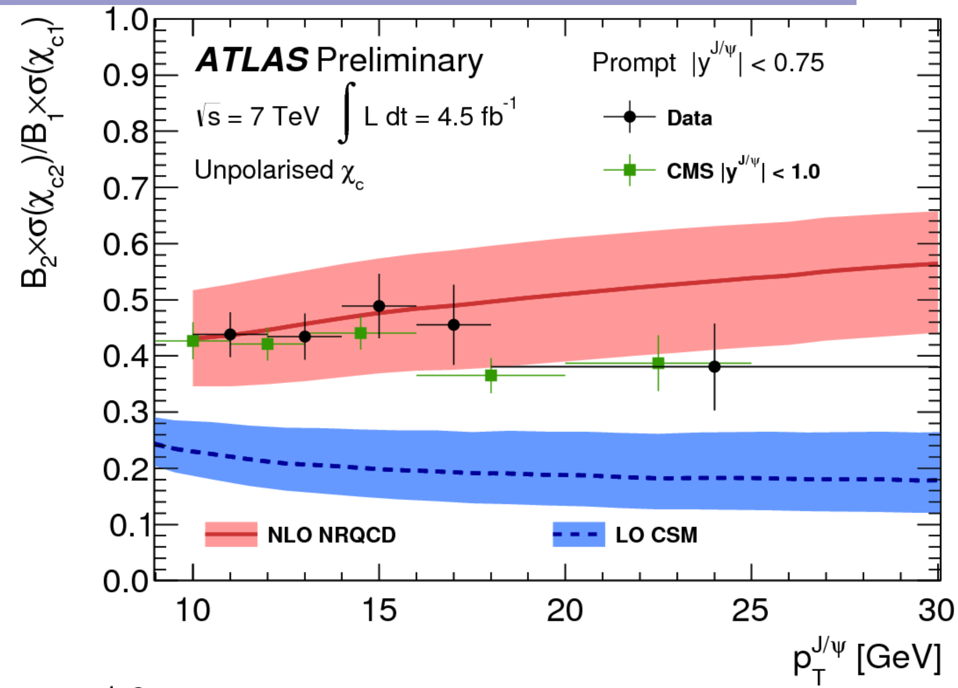

- (prompt) The predictions of NLO NRQCD, the $k_T$ factorization model and the LO CSM are compared to the measurements
- (non-prompt) The predictions of the FONLL are compared to the measurements



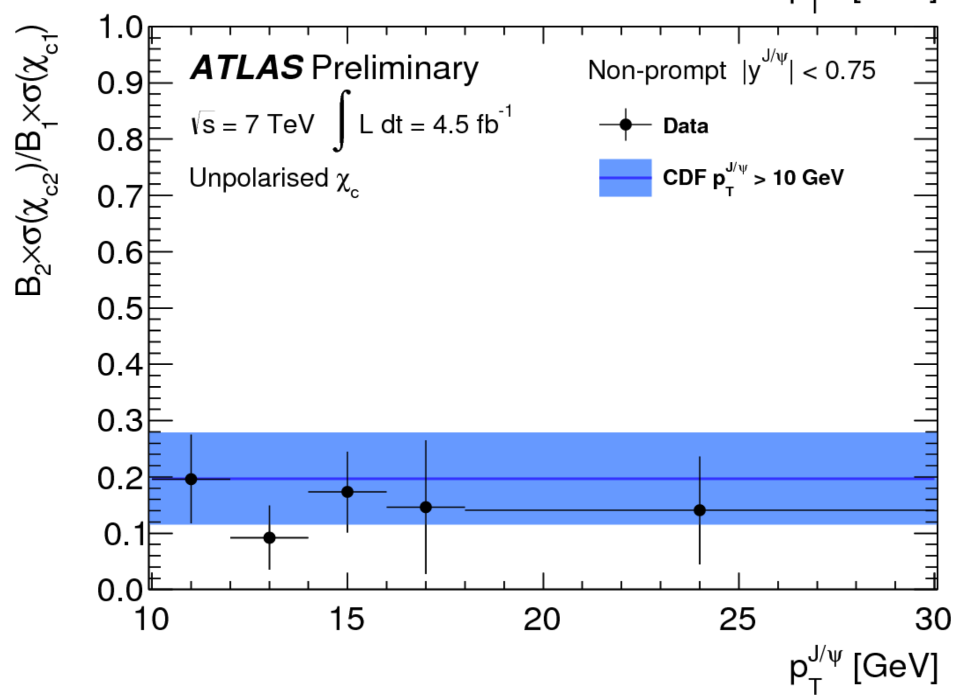

The cross sections are also available in bins of $J/\Psi$ $p_T$.

# Differential cross sections ratios for prompt and non-prompt $\chi_{c1,2}$

- The production cross section of prompt $\chi_{c2}$ relative to prompt $\chi_{c1}$ as a function of $p_T$
- Good agreement with CMS data
- NLO NRQCD in good agreement, while LO CSM underestimates the data

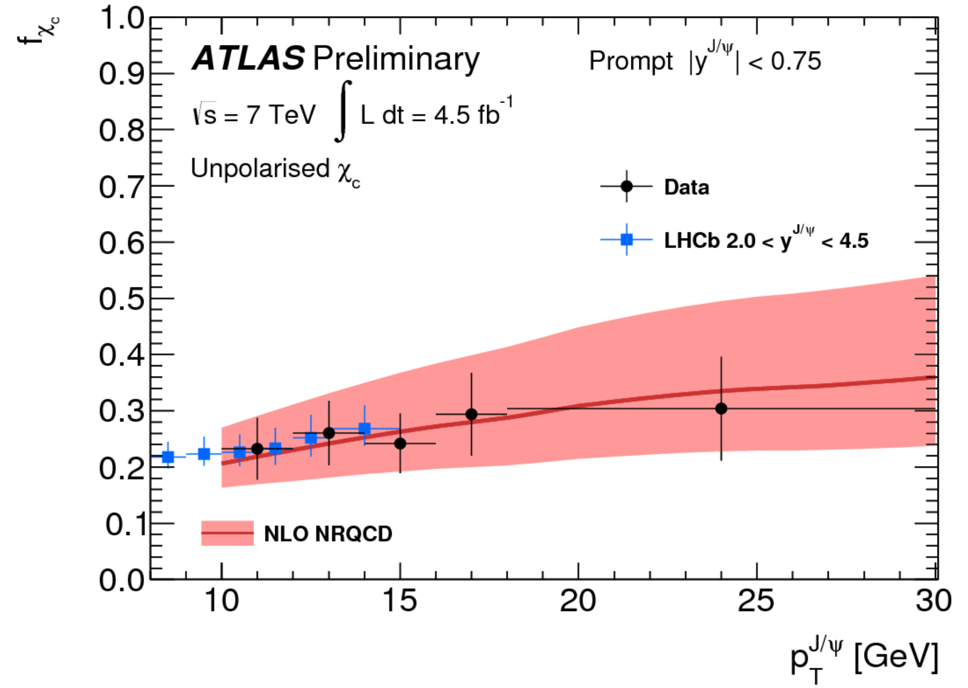



- The production cross section ratio of non-prompt $\chi_{c2}$ to non-prompt $\chi_{c1}$ as a function of $p_T$
- In principle predicted from B branching ratios
- Good agreement with CDF data

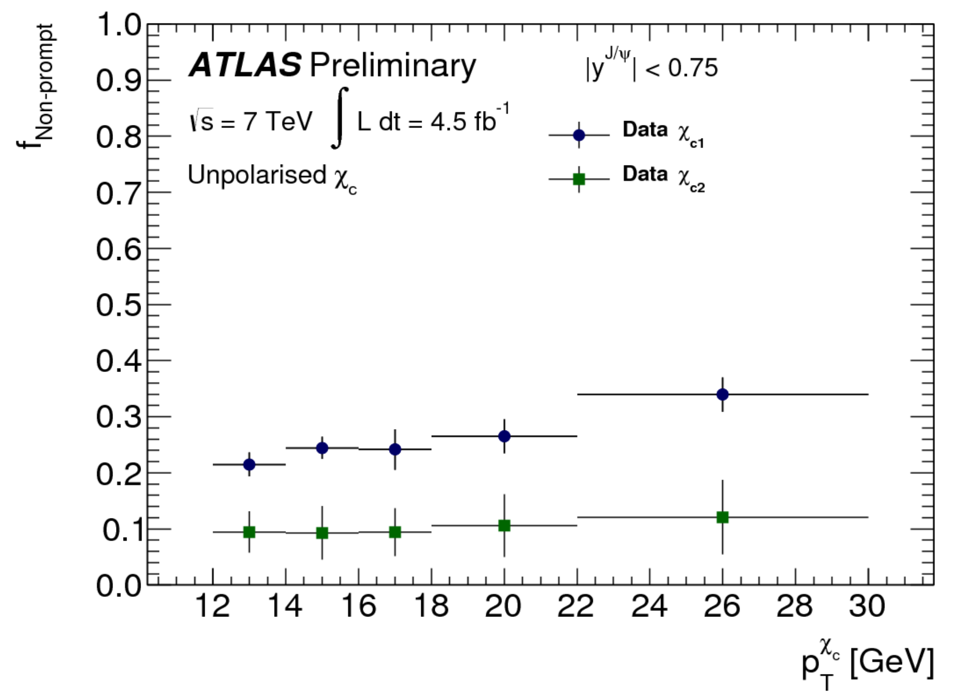


# Fractions of prompt $\chi_c \rightarrow J/\Psi$ feed down and non-prompt $\chi_{c1,2}$

- The fraction of prompt $J/\Psi$ produced by $\chi_{c1,2}$ decays as a function of $J/\Psi$ $p_T$
- Results are normalized to the ATLAS 2010 $J/\Psi$ results
- Good agreement with LHCb measurement
- The measurements are compared to the predictions of NLO NRQCD and the $k_T$ factorization approach
- About 20 – 30% of prompt $J/\Psi$ are produced in feed-down from the $\chi_{c1,2}$




- The fractions of inclusive $\chi_{c1}$ and $\chi_{c2}$ produced in the decays of b-hadrons as a function of $p_T$
- Cross-section of $\chi_{c1}$ and $\chi_{c2}$ is dominated by prompt production (in the $p_T$ range measured)
  - Contrary to the $J/\Psi$ and $\Psi(2S)$ case, where the inclusive sections are dominated by feed-down from b-hadron decays at high transverse momentum



# Measurement of $\mathcal{B}(B^{\pm}\rightarrow \chi_{c1}K^{\pm})$

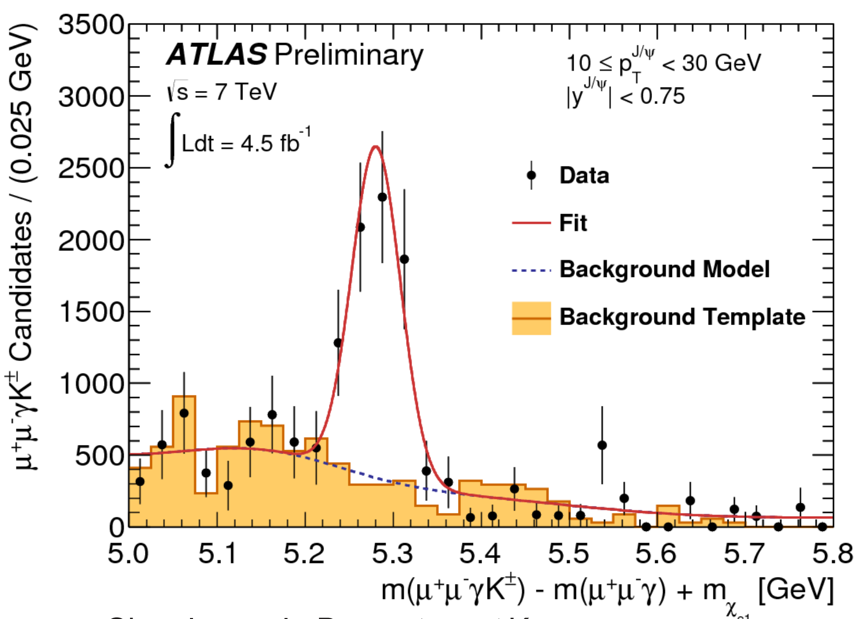
- Several measurements exist from b-factories
- Window $10 < p_T^{J/\Psi} < 30$ GeV and $|y(J/\Psi)| < 0.75$
- Using radiative $\chi_{c1}$ decay
- Branching ratio was calculated as:

$$\mathcal{B}\left(B^{\pm} \rightarrow \chi_{c1} K^{\pm}\right) = \mathcal{A}_B \cdot \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \cdot \frac{\mathcal{B}\left(B^{\pm} \rightarrow J/\psi K^{\pm}\right)}{\mathcal{B}\left(\chi_{c1} \rightarrow J/\psi\, \gamma\right)}$$

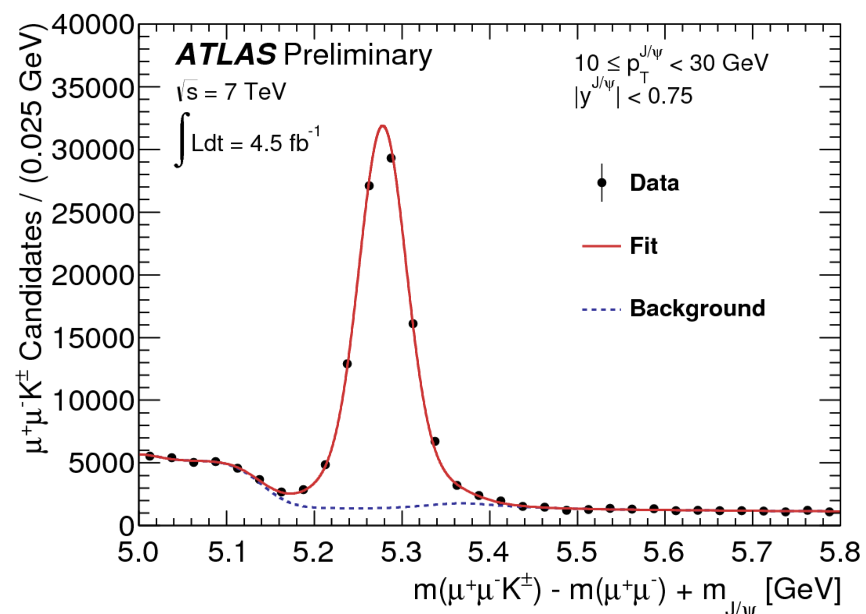
- The final states of both channels are identical except for a photon
- Also a confirmation of photon conversion efficiency

$K^{\pm}$ selection

- 1 pixel and 6 SCT hits
- track $p_T > 3$ GeV and $|\eta|<2.5$
- common vertex with $\chi^2/N_{dof} < 6$
- 1 pixel and 6 SCT hits
- $L_{xy}$ of the $J/\Psi > 0.3$ mm



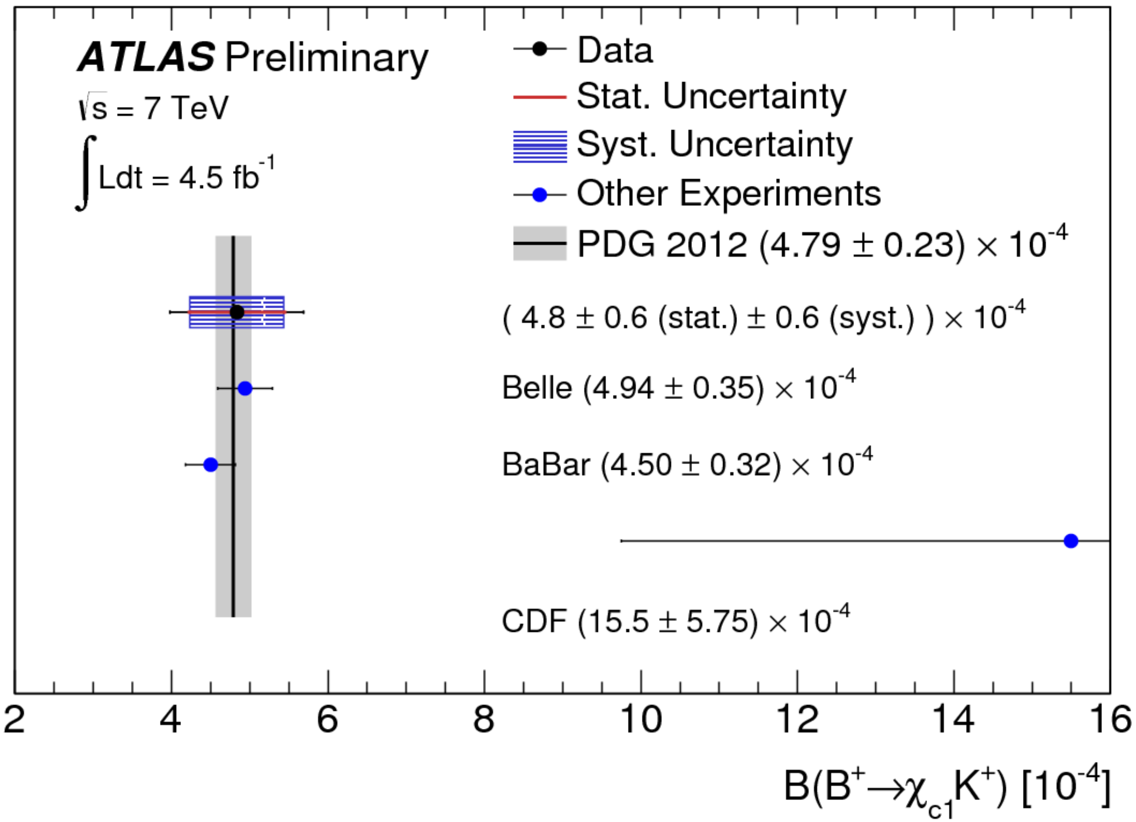

Signal sample $B^{\pm}\rightarrow\chi_{c1}(\mu^+\mu^-\gamma)K^{\pm}$




Control sample $B^{\pm}\rightarrow J/\Psi(\mu^+\mu^-)K^{\pm}$

# Measurement of $\mathcal{B}(B^{\pm} \to \chi_{c1} K^{\pm})$

- Corrected yields extracted from unbinned ML fit
- Obtained value $\mathcal{B}(B^{\pm} \to \chi_{c1} K^{\pm}) = (4.83 \pm 0.6(\text{stat.}) \pm 0.6(\text{syst.})) \times 10^{-4}$
- In good agreement with the world average $(4.79 \pm 0.23) \times 10^{-4}$
- Remarkable measurement performed at a hadron collider




| | $\delta\mathcal{B}$ $[10^{-4}]$ | Fractional uncertainty |
|---|---|---|
| Conversion $\epsilon_{\text{Reco}}$ | 0.5 | 10% |
| Conv. probability | 0.2 | 4% |
| Muon $\epsilon_{\text{Reco}}$ | 0.2 | 4% |
| Trig. fficiency | 0.2 | 4% |
| Acceptance | 0.1 | 2% |
| Fit | 0.2 | 4% |
| Stat. | 0.6 | 13% |
| Syst | 0.6 | 13% |
| Total | 0.8 | 17% |

# Conclusions

After 40 years from its discovery, charmonium spectroscopy is still an interesting and active research field, with challenging theoretical and experimental issues.

Differential cross sections for prompt and non-prompt $\chi_{c1}$ and $\chi_{c2}$ production are presented along with:

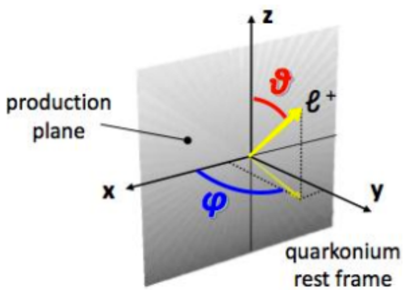
- Prompt and non-prompt cross section ratios ($\chi_{c2}$ relative to $\chi_{c1}$)
- Fraction of prompt $J/\Psi$ produced in decays of $\chi_c$
- Non-prompt fractions of the $\chi_{c1}$ and $\chi_{c2}$
- $\mathcal{B}(B^{\pm} \rightarrow \chi_{c1} K^{\pm})$ was obtained with precision comparable to b-factories
- The NLO NRQCD does a good job in describing the $p_T$ spectrum
- Analyses ongoing, many new results are awaited soon

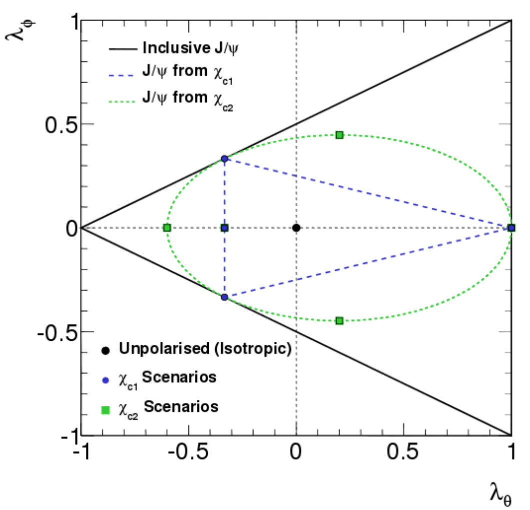
ATLAS-CONF-2013-095

Backup slides

# Uncertainties in $\chi_{cJ}$ cross section measurement

$$\frac{d^2N}{d\cos\theta\, d\varphi} \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos 2\varphi+\lambda_{\theta\varphi}\sin 2\theta\cos\varphi)$$




The allowed $\lambda_\theta$ and $\lambda_\varphi$ parameter space for $\chi_c$ decays.

| | State label | $\lambda_\theta$ | $\lambda_\varphi$ | $\lambda_{\theta\varphi}$ |
|---|---|---|---|---|
| $\chi_{c1}$ | isotropic | 0 | 0 | 0 |
| | Helicity 0 | 1 | 0 | 0 |
| | Helicity±1 | -1/3 | 0 | 0 |
| | AZ+ | -1/3 | +1/3 | 0 |
| | AZ- | -1/3 | -1/3 | 0 |
| $\chi_{c2}$ | isotropic | 0 | 0 | 0 |
| | Helicity 0 | -3/5 | 0 | 0 |
| | Helicity±1 | -1/3 | 0 | 0 |
| | Helicity±2 | 1 | 0 | 0 |
| | AZ+ | 1/5 | 1/√5 | 0 |
| | AZ- | 1/5 | 1/√5 | 0 |

| | Fractional Uncertainty | | | |
|---|---|---|---|---|
| | Prompt $\chi_{c1}$ | Prompt $\chi_{c2}$ | Non-prompt $\chi_{c1}$ | Non-prompt $\chi_{c2}$ |
| Muon Reco. Efficiency | 1% | 1% | 1% | 1% |
| Trigger Efficiency | 3% | 4% | 4% | 4% |
| Conversion Reco. Efficiency | 8% | 10% | 9% | 10% |
| Conversion Probability | 4% | 4% | 4% | 4% |
| Acceptance | 1% | 3% | 1% | 1% |
| Fit Model | 4% | 6% | 11% | 33% |
| Total Systematic | 11% | 14% | 16% | 35% |
| Polarisation Envelope Upper | 30% | 32% | 30% | 32% |
| Polarisation Envelope Lower | 12% | 21% | 12% | 21% |

# Theoretical predictions and other measurements

**Theoretical predictions**

- NLO NRQCD - LDME from Tevatron J/ψ(ψ′ ) measurements
  - QCD radiative corrections to $\chi_{cJ}$ production at hadron colliders, PRD83 111503 (2011)
  - HELAC-Onia
  - J/ψ(ψ′ ) production at the Tevatron and LHC at $O(\alpha^4 v^4)$ s in NRQCD, PRL 106 (2011) 042002; arXiv:1009.3655

- $k_T$ factorization – convolution of CSM partonic Xs with $g(x,k_t^2,\mu^2)$
  - Prompt J/ψ production at LHC: new evidence for the $k_T$-factorization, PRD85 (2012) 014034; arXiv:1108.2856
  - On the $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio in the $k_T$-factorization approach, PRD83 (2011)

- LO CSM - heavy quarks produces in CS state, potential model describes formation of a bound state
  - CHIGEN

- FONLL
  - (re-scaled ψ(2S) prediction) JHEP 1210 (2012) 137

**Existing results**

- CMS Prompt $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio: EPJC 72 (2012) 2251; arXiv:1210.0875
- LHCb Prompt $\sigma(\chi_{c})/\sigma(J/\psi)$ ratio: PLB 718 (2012) 431; arXiv:1204.1462
- CDF non-prompt $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio: PRL 98 (2007) 232001