Production and Decays of Heavy Flavours in ATLAS

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Xth Rencontres du Vietnam – Flavour Physics Conference

ICISE, Quy Nhon,VN, July 27 – August 2, 2014

Outlook

A. Introduction:
   1) General framework
   2) Experimental aspects
B. HF Production:
   1) Quarkonium production
   2) $\psi(2s)$, χ_{cj} and W+J/ψ production
   3) Υ(ns) production
   4) Open states: B^+ production
C. HF Decay:
   1) Observation of $B_c^* \rightarrow B_c^+ \pi^+\pi^-$
   2) Measurement of BR($B^+ \rightarrow \chi_c + K^+$)
   3) Parity violation in $\Lambda_b \rightarrow J/\psi\ \Lambda_0$
   4) Study of the decay $B_d \rightarrow K^{*0}(K\pi)\ \mu^+\mu^-$
D. Conclusions

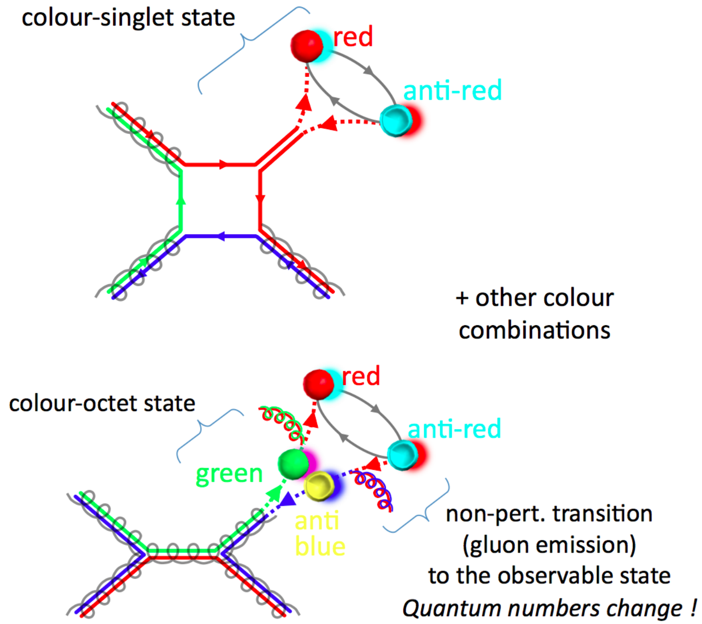
All results available at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

A.1 General framework

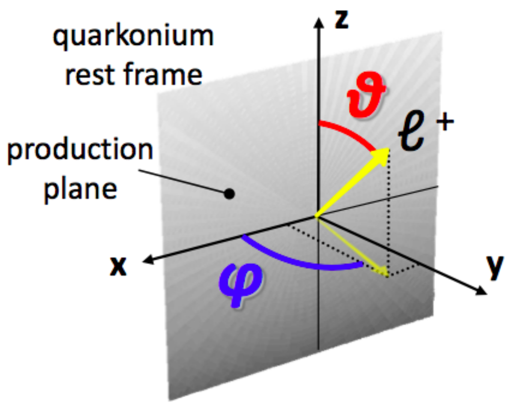
Heavy Quark (HQ) production ⇒ crucial QCD test:

- Color Singlet Model (CSM) improvement with NLO, NNLO* calculations;
- Color Octet Model (NRQCD) with LO, NLO;
- Other models: CEM and k_T Factorization

Theory ⇔ experiments: LHC as high p_T probe



Degree of Polarization (spin alignment)



- divergent theoretical predictions and ambiguous experimental results

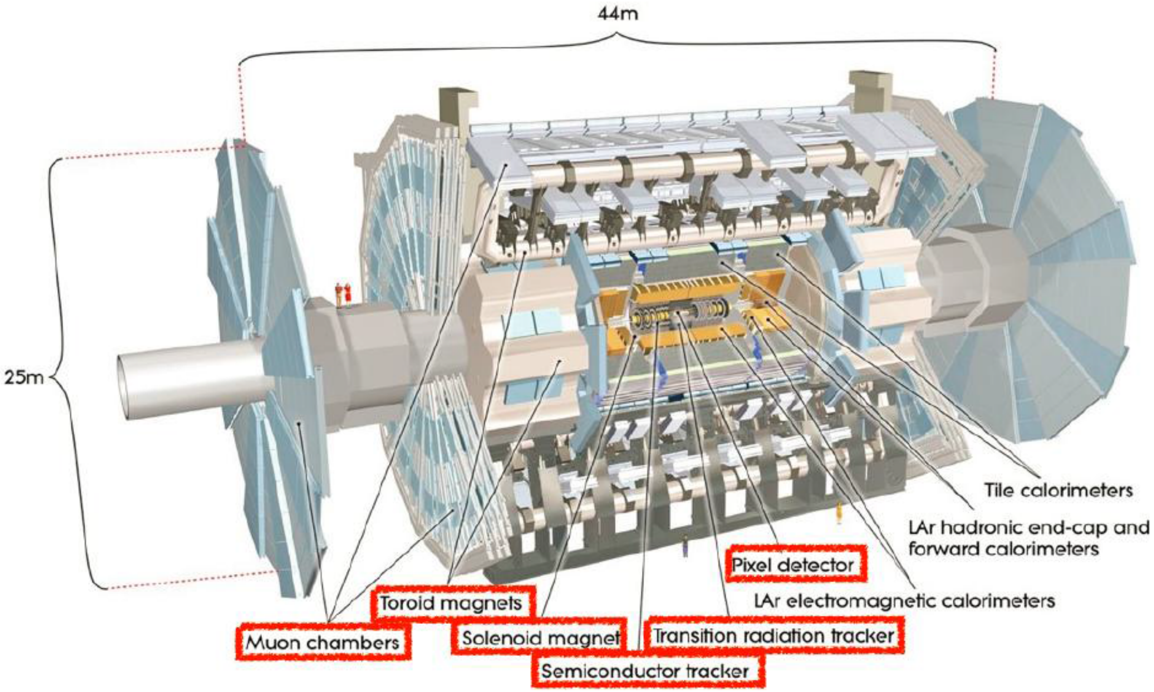
$$\frac{d^2N}{d\cos\theta^* d\phi^*} \propto \left(\frac{1}{3+\lambda_\theta}\right)\left(1+\lambda_\theta \cos^2\theta^* + \right.$$
$$\left. + \lambda_\phi \sin^2\theta^* \cos 2\phi^* + \lambda_{\theta\phi} \sin 2\theta^* \cos\phi^*\right).$$

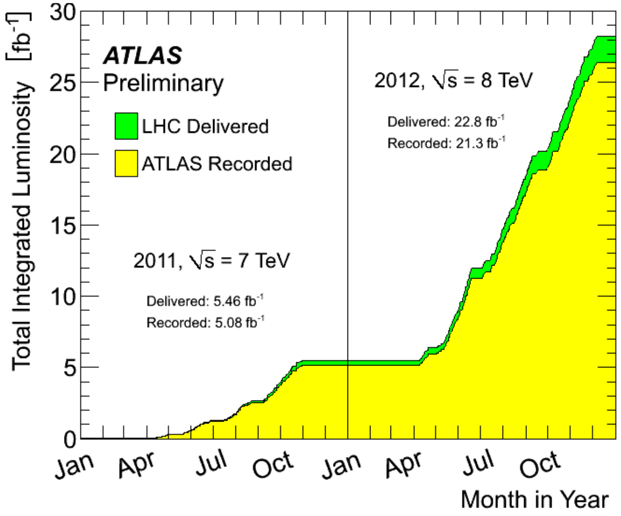
- important for data correction: (25-30)% variation at low p_T

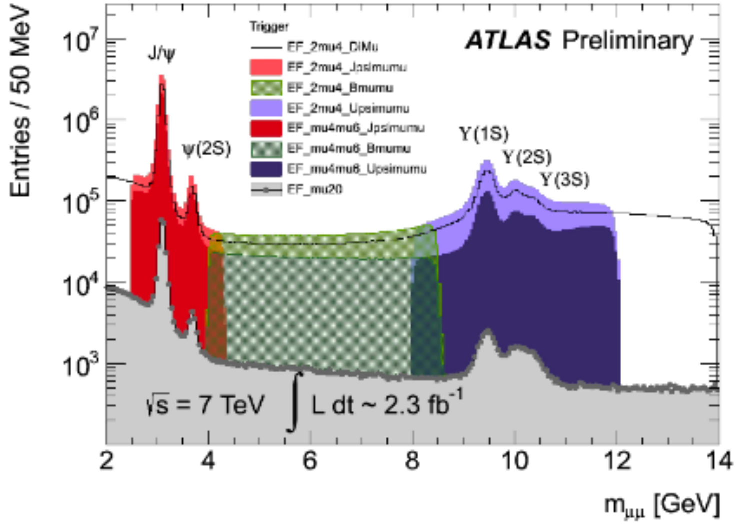
LHC: large b statistics ⇒ new spectroscopy, test of SM, possible evidence for physics BSM (e.g. Rare processes / small amplitudes)

A.2 Experimental aspects

Excellent Run I LHC performance: L~26fb^{-1}







- Muon Spectrometer (MS): triggering |η|<2.4 and precision tracking |η|<2.7
- Inner Detector (ID): Silicon Pixel and Strips (SCT)with Transition Radiation Tracker (TRT), |η|<2.5
- EM calorimeter

Trigger: mainly di-muon p_T^{μ} thresholds (4 – 4) GeV or (4-6) GeV

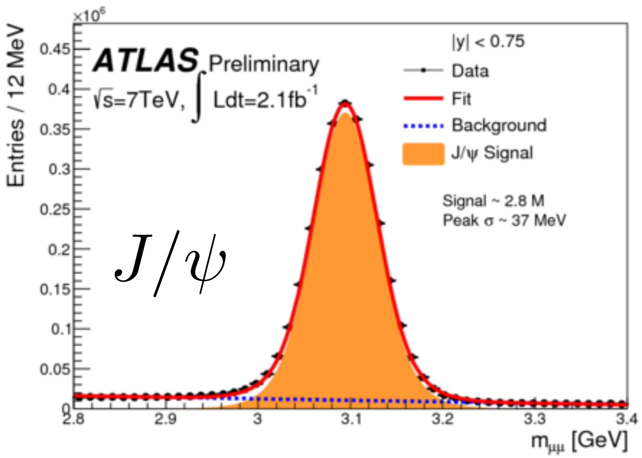
Several results from 2011 data

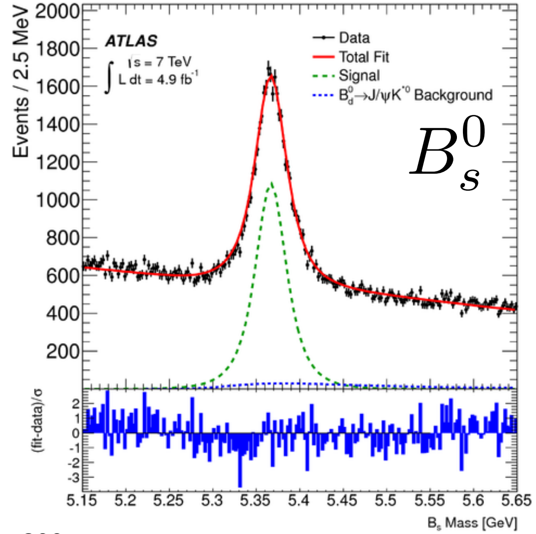
$$\mathcal{L} \approx 4.57 \text{ fb}^{-1}, \quad \sqrt{s} = 7\ TeV$$

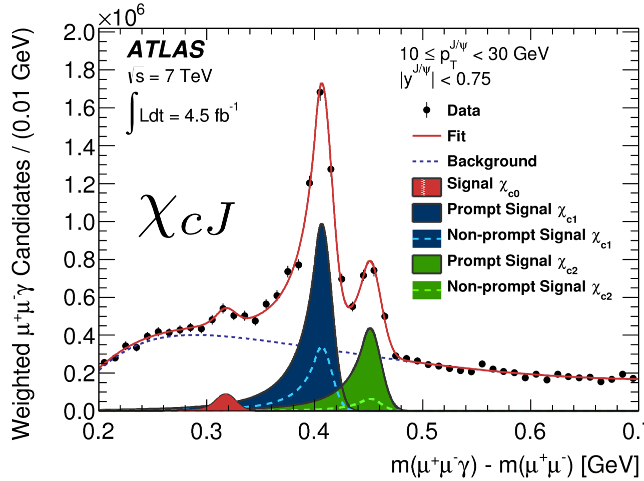
Mass reconstruction ⇒ key tool in HF @ ATLAS:

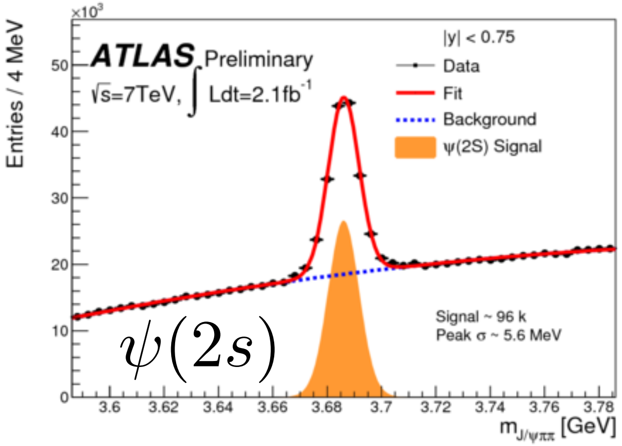
- $(\mu^+\mu^-) \Rightarrow J/\psi$, Υ
- $(J/\psi + \text{trks}) \Rightarrow \Psi$, exclusive B
- $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ "resolution"

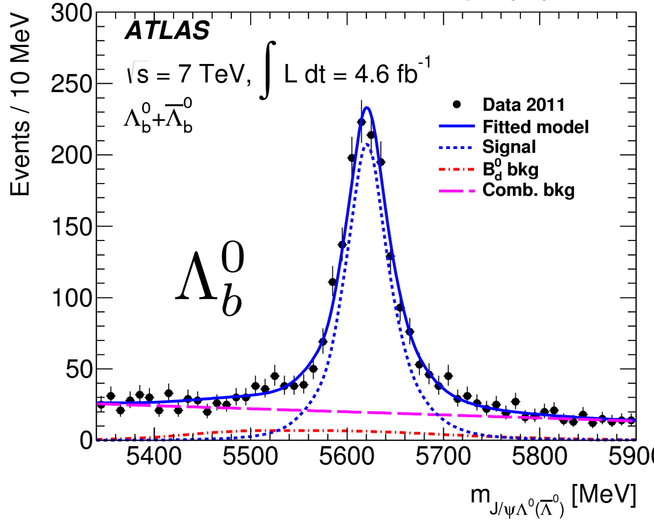
- reconstr. $\varepsilon_{trk} = 99\%$
- $(\sigma_{pT} / p_T) \approx 0.05$ up to 60 GeV
- $\sigma_m \sim (50-100)$MeV
- high S/B

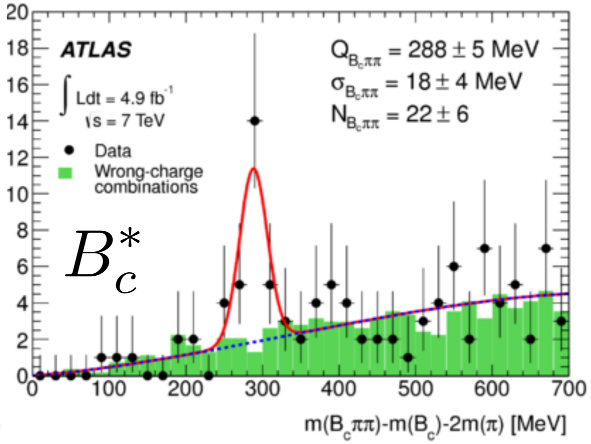






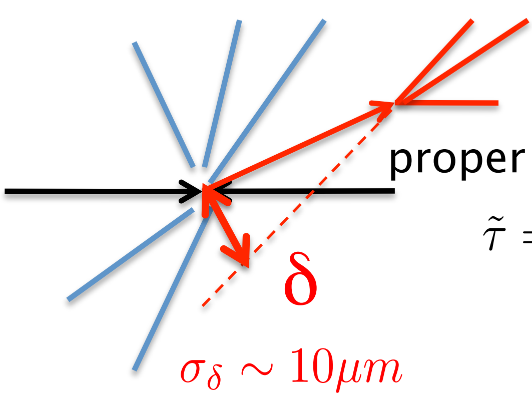






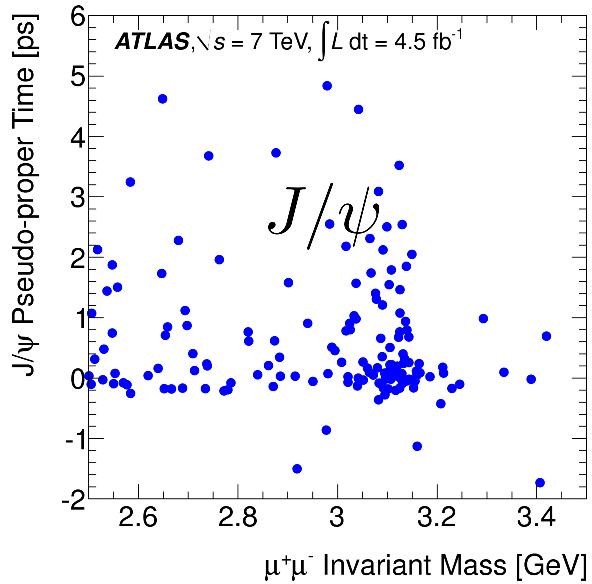
Excellent tracking & vertexing ⇒ primary & secondary vertices

- prompt / non-prompt separation
- background reduction



proper or pseudo-proper time

$$\tilde{\tau} = \left(\vec{L} \cdot \vec{u}_x\right) \frac{m_X}{P_X}$$



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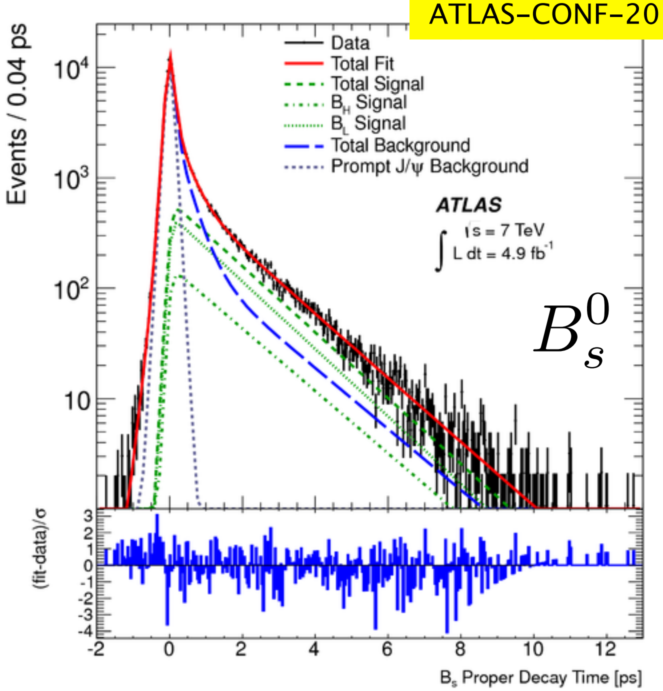

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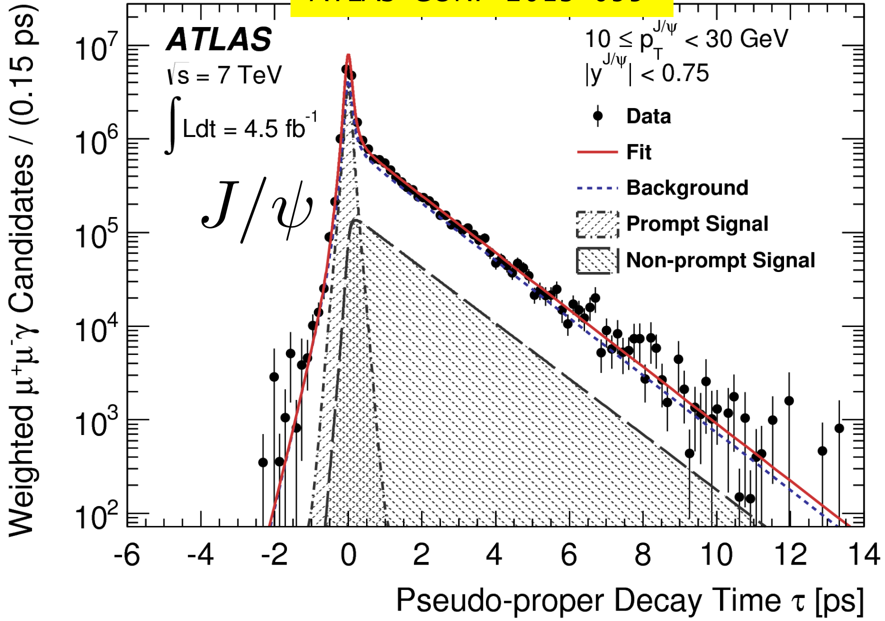
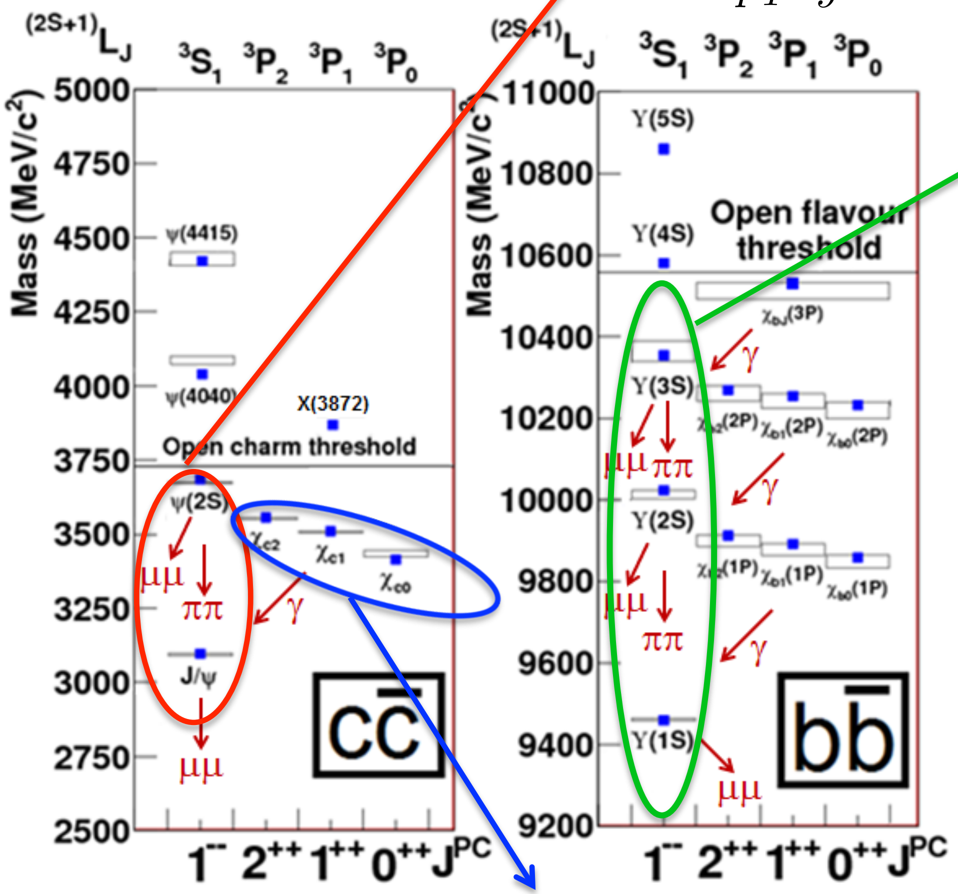


B.1 Quarkonium production

$$\frac{d^2\sigma(\psi(2s)+X)}{dp_T dy} \cdot Br(\psi(2s) \to J/\psi(\to \mu^+\mu^-) + \pi^+\pi^-)$$

$$\frac{d^2\sigma_{\Upsilon_{ns}}}{dydp_T} . Br\left(\Upsilon_{ns} \to \mu^+\mu^-\right)$$



$$\frac{d\sigma(\chi_{cJ}+X)}{dp_T} \cdot Br(\chi_{cJ} \to J/\psi(\to \mu^+\mu^-) + \gamma(\to e^+e^-)$$

Probe:

- high P_T (>40GeV) region
- small spin alignment effects
- feed-down effects
- onia and b-hadron production models

P-states: just below open charm threshold ⇒ reduce feed-down

$$\frac{d^2\sigma(pp \to Q + X)}{dp_T dy} \cdot Br(Q \to \mu\mu) = \frac{N^{Q\to\mu\mu}_{corr}}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}$$

- $N^{Q\to\mu\mu}_{corr}$: signal yield corrected for efficiency and acceptance
- $\mathcal{L}$: integrated luminosity corresponding to the sample
- $\Delta p_T(y)$: interval bin of the differential variable

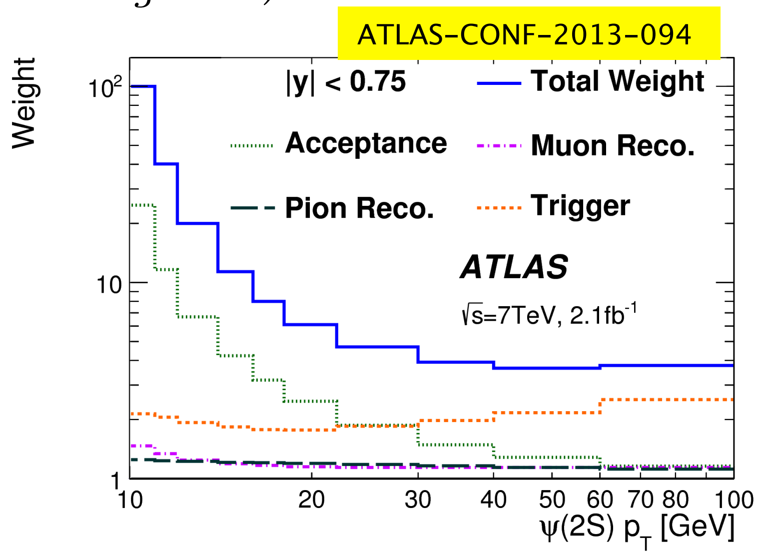
$$\text{correction weight: } w = (\epsilon_{trk} \cdot \epsilon_{\mu} \cdot \epsilon_{trig.} \cdot \mathcal{A})^{-1}$$

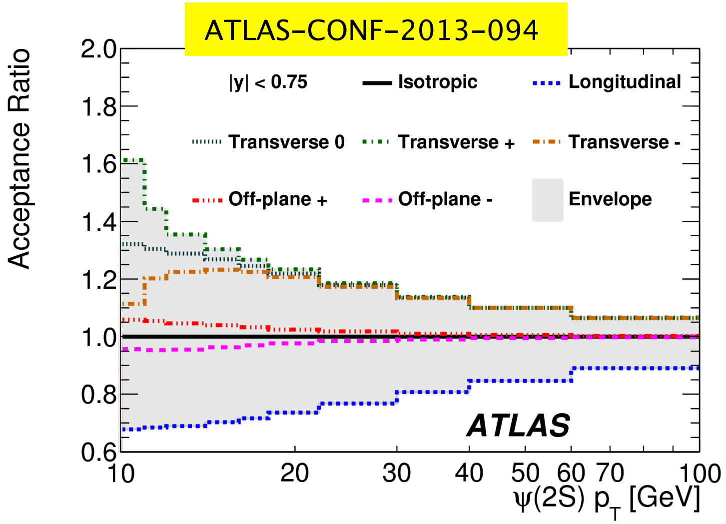
Signal yield: unbinned maximum likelihood fits ⇒ σ_{stat} ~ few %

$\varepsilon(p_T^{(\mu)}, \eta^{(\mu)})$ efficiencies → data driven methods to reduce uncertainties (e.g. tag and probe)

$A(p_T, y)$ acceptance corrections [recover full phase space, esp. @ low P_T] → simulation

Total systematic uncertainty ~(5-10)%





Acceptance ⇔ spin alignment
isotropic case + envelope due to different polarization states

Acceptance variations may reach ~(10-30)%

B.2 $\psi(2s), \chi_{cj}$ production

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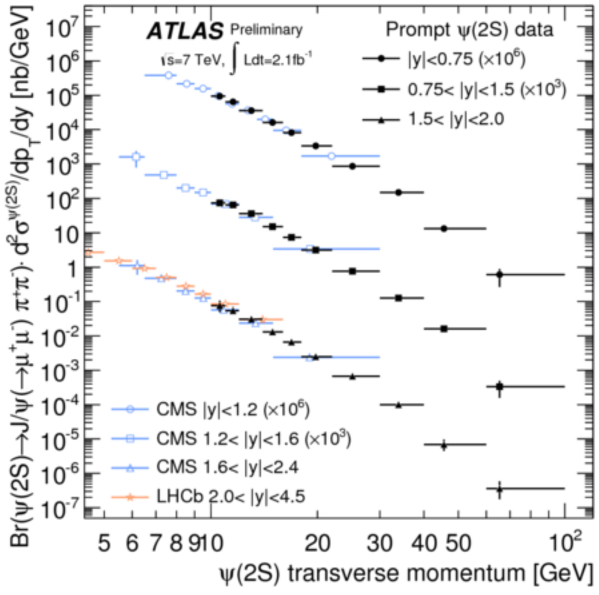
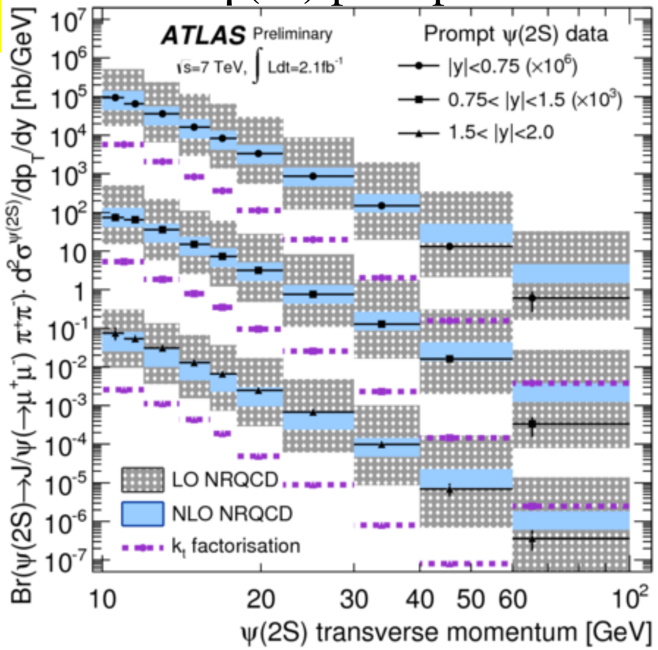


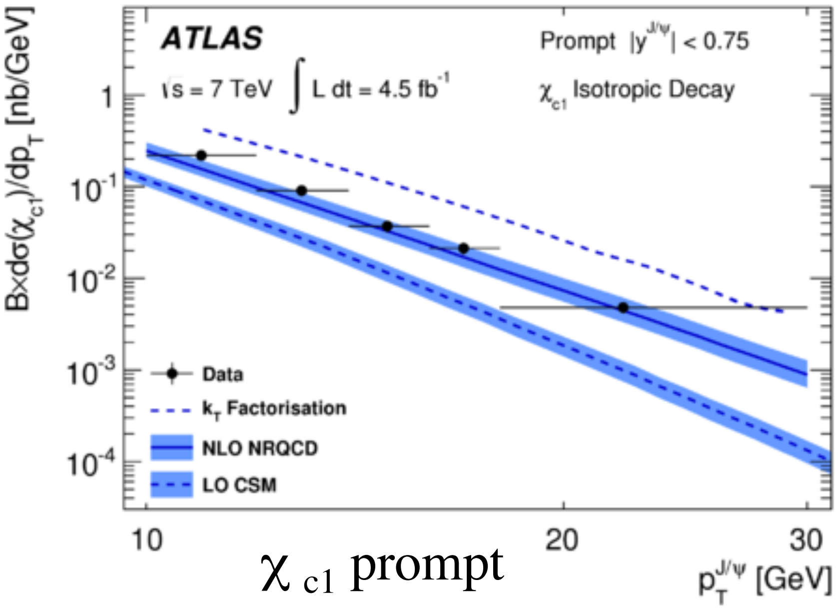
Prompt production:

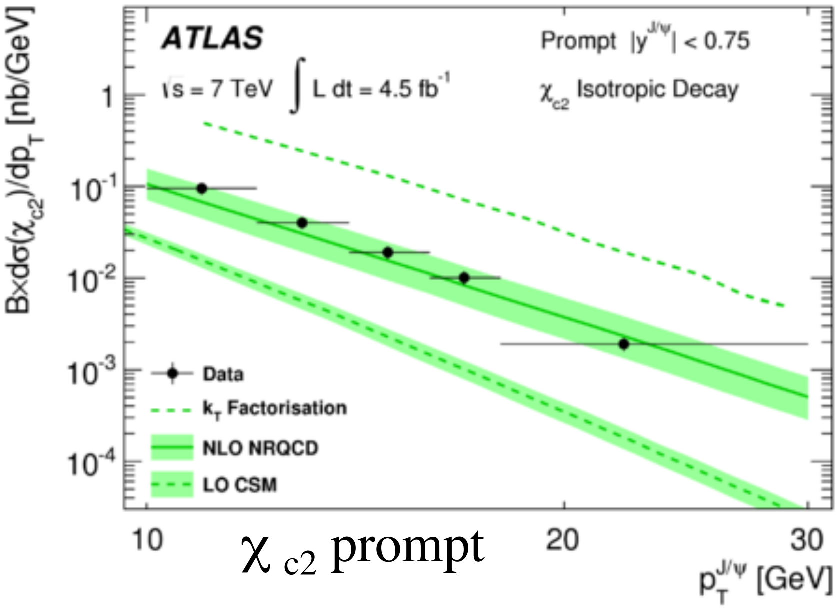
- Good agreement with NRQCD LO and NLO @ low/medium pT
- New high pT territory → deviations
- CSM & k_T models may need higher order contributions

ψ(2s) prompt

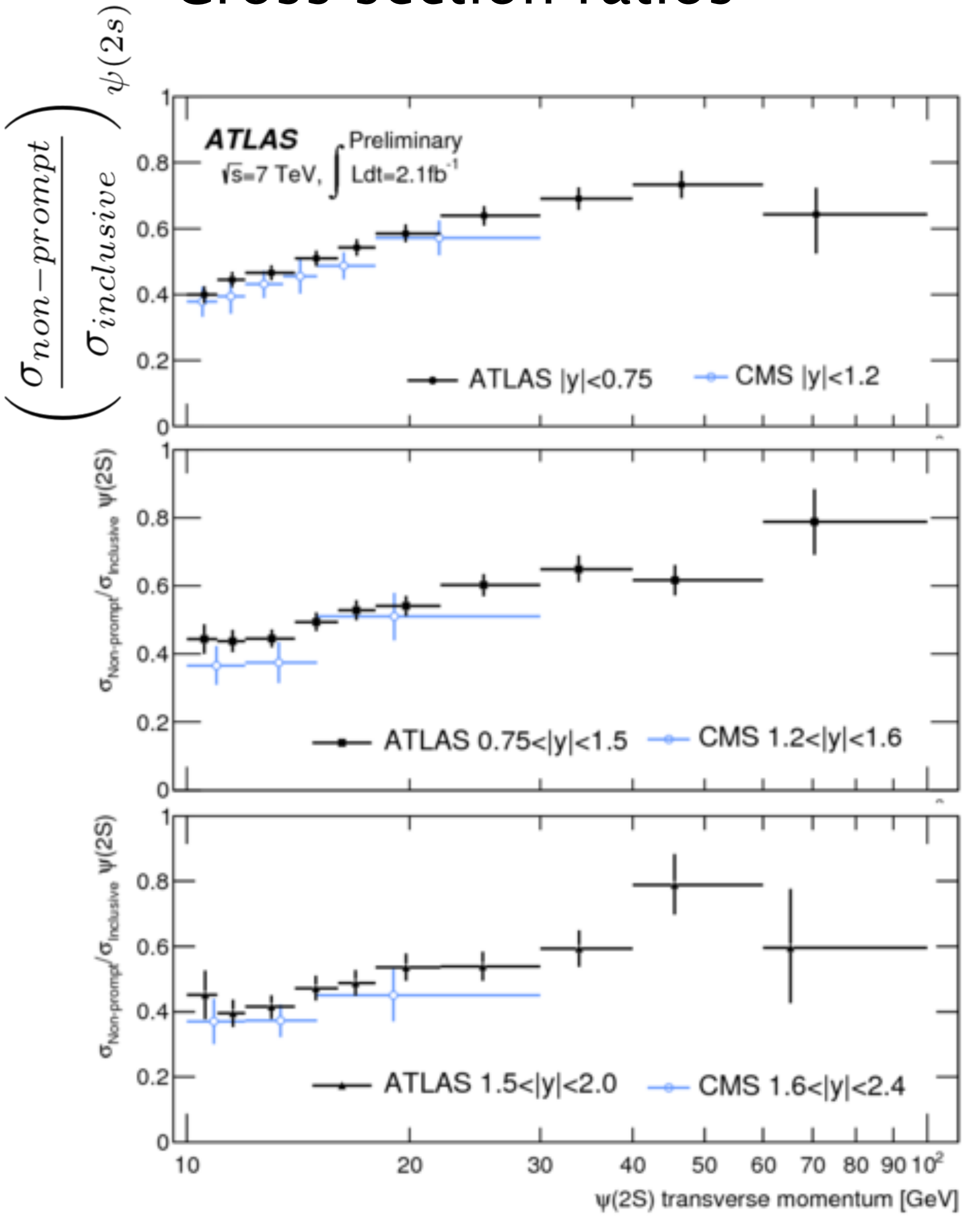


Agreement with CMS & LHCB. ATLAS reaching the "uncharted" high P_T region!





Cross section ratios



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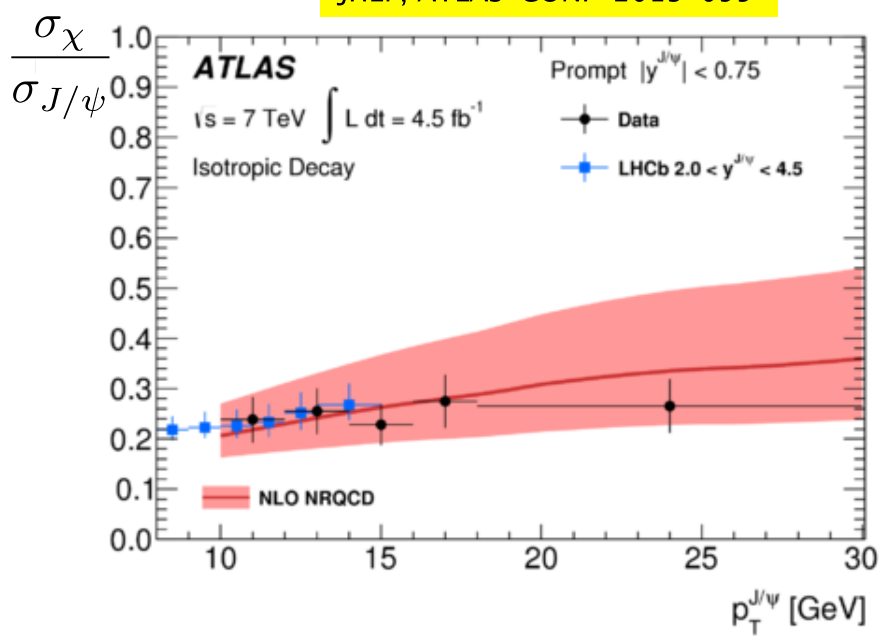
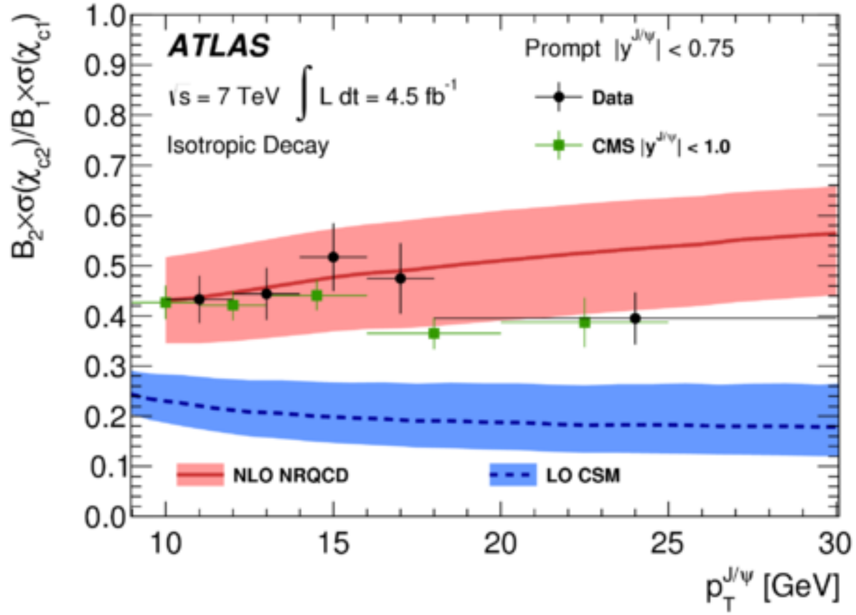
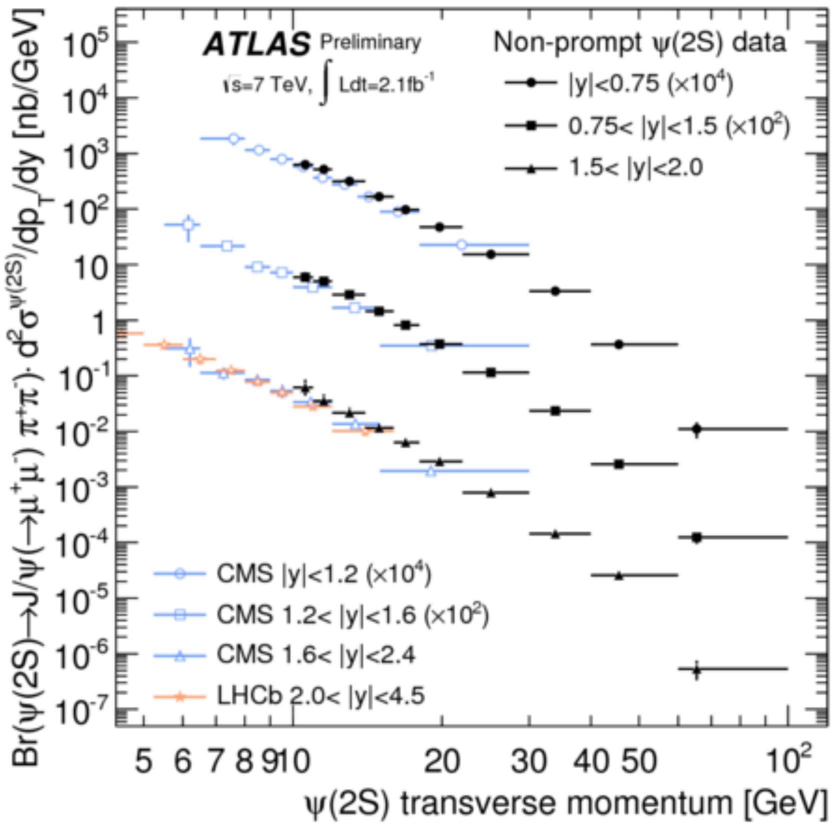
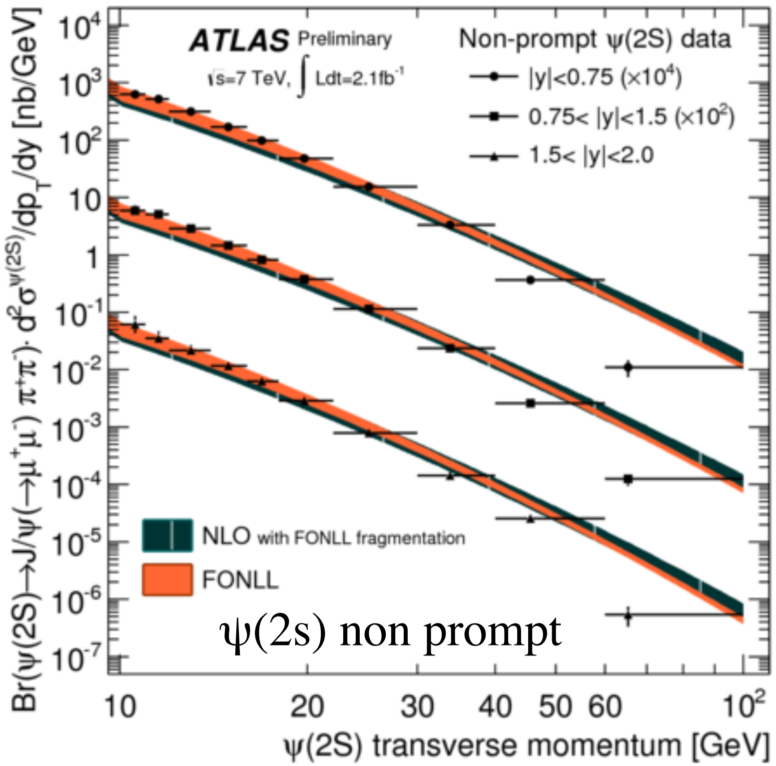


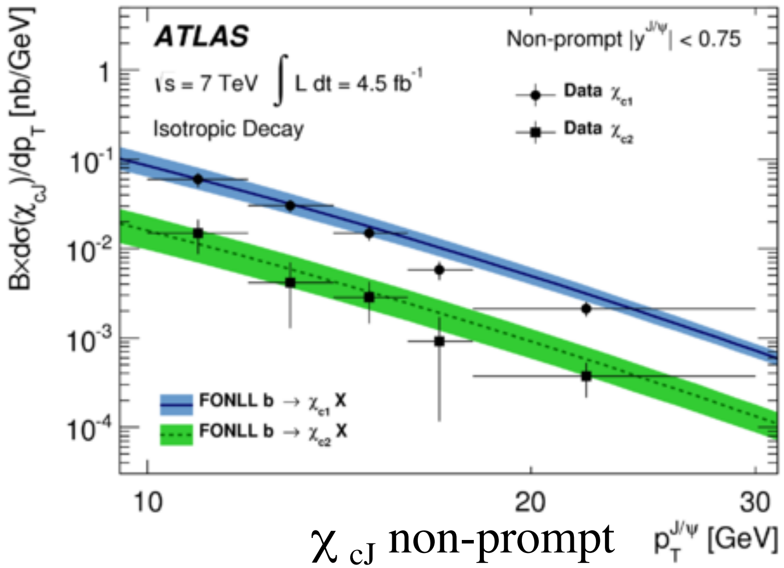






Non-prompt:

- ψ(2s) @ low pT agrees w FONLL & NLO, model improvements needed @ higher pT
- χ_{cJ} generally in good agreement, but limited pT range

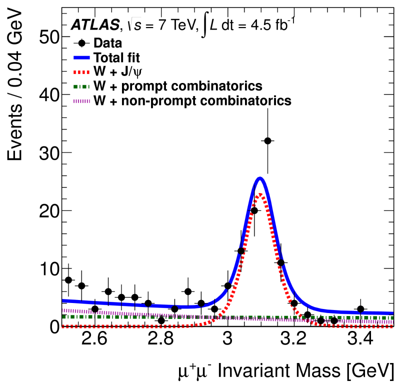


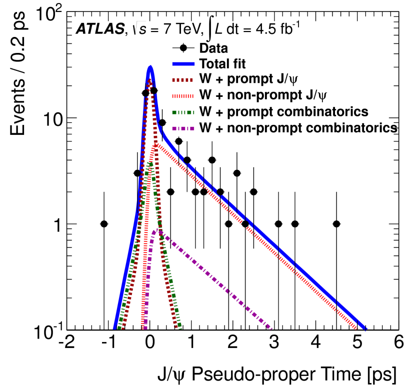
W + J/ψ production

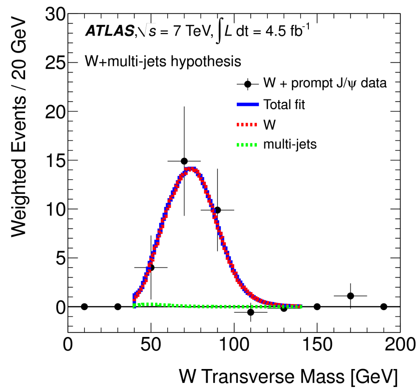
- Test ccbar production modes
- Probe for Higgs/BSM physics

$$\frac{1}{\sigma^{(W)}}\frac{d^2\sigma^{(W+J/\Psi)}}{dp_T dy}\cdot Br(J/\Psi \to \mu\mu)\cdot Br(W\to\mu\nu_\mu)$$

single μ trigger : $p_T^{thr} \geq 18\ GeV$





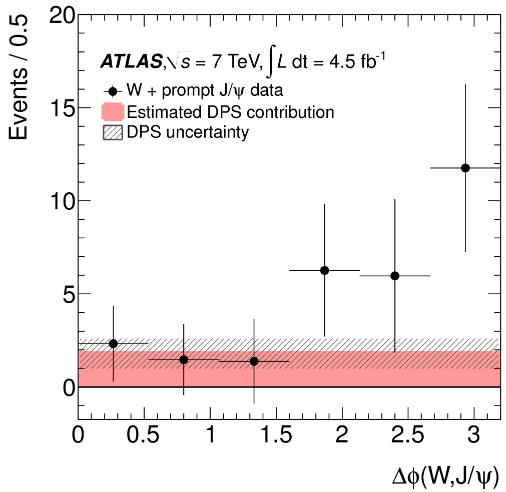


Yields frc	
Process	Total
Prompt J/ψ	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$41.8^{+8.4}_{-7.3}$
Prompt background	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$39.0^{+8.4}_{-7.1}$
p-value	2.1×10^{-7}
Significance (σ)	5.1

(*) of which 1.8 ± 0.2 origina

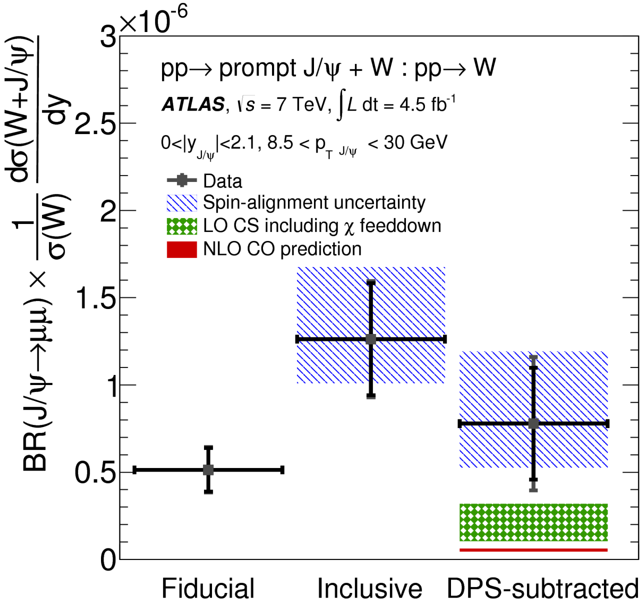
Double Parton Scattering (DPS) contribution

$$d\sigma^{DPS}(W+J/\psi) = d\sigma_W \cdot \underbrace{\frac{d\sigma_{J/\psi}}{\sigma_{eff}}}_{P_{J/\psi|W}}$$



$$\begin{cases}\sigma_{J/\Psi}(ATLAS : J/\Psi\ prompt)\\ \sigma_{eff} = (ATLAS : W+2j)\\ \sigma_W\ \text{(this analysis)}\end{cases}$$

$$\Rightarrow N_{DPS} = 10.8 \pm 4.2 \quad (\sim 35\%)$$



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B.3 Υ(1s,2s,3s) production

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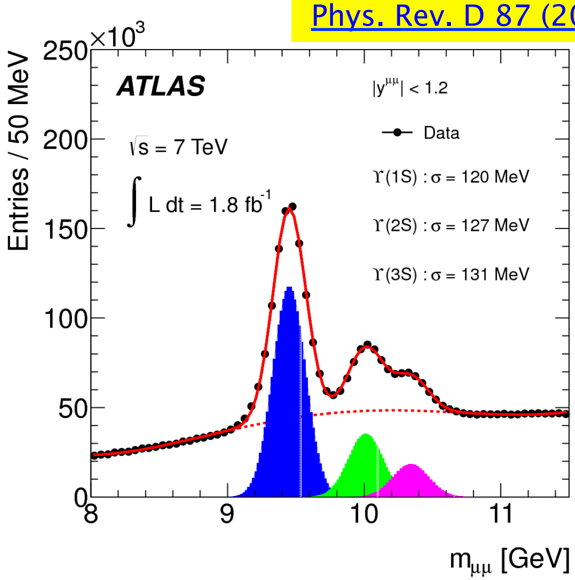
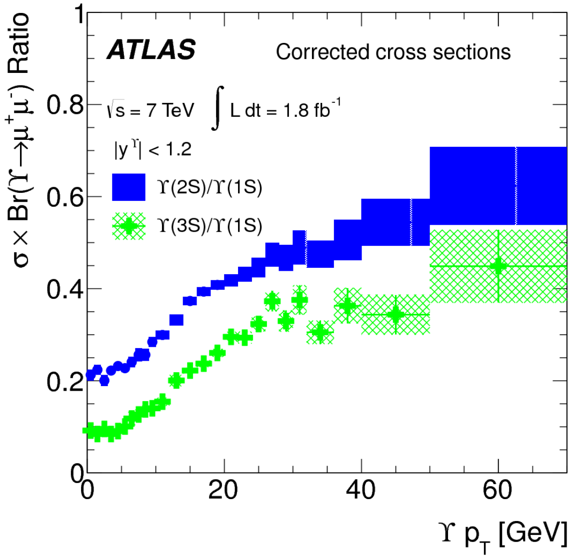
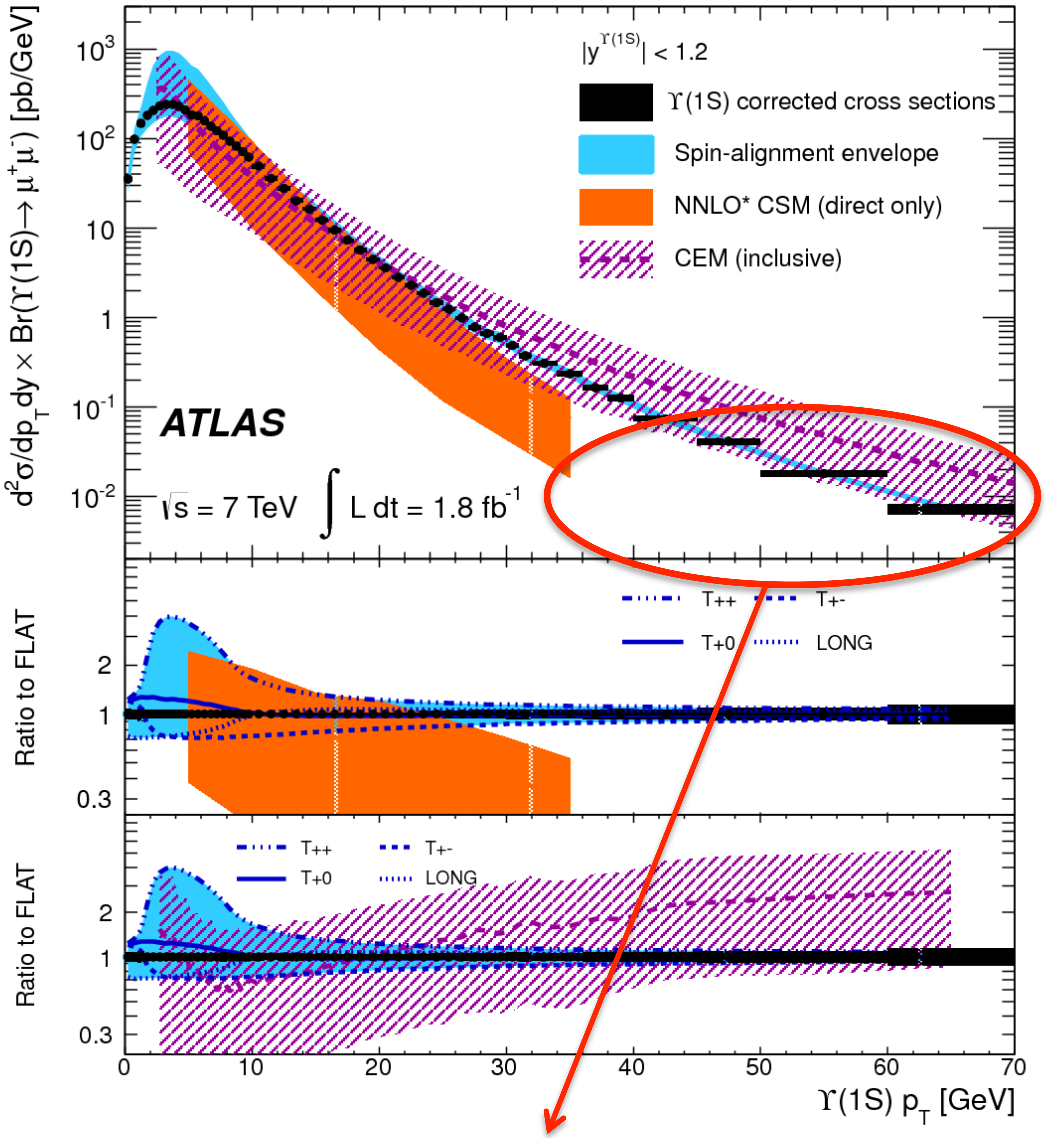






σ ratios ⇒ test predictions

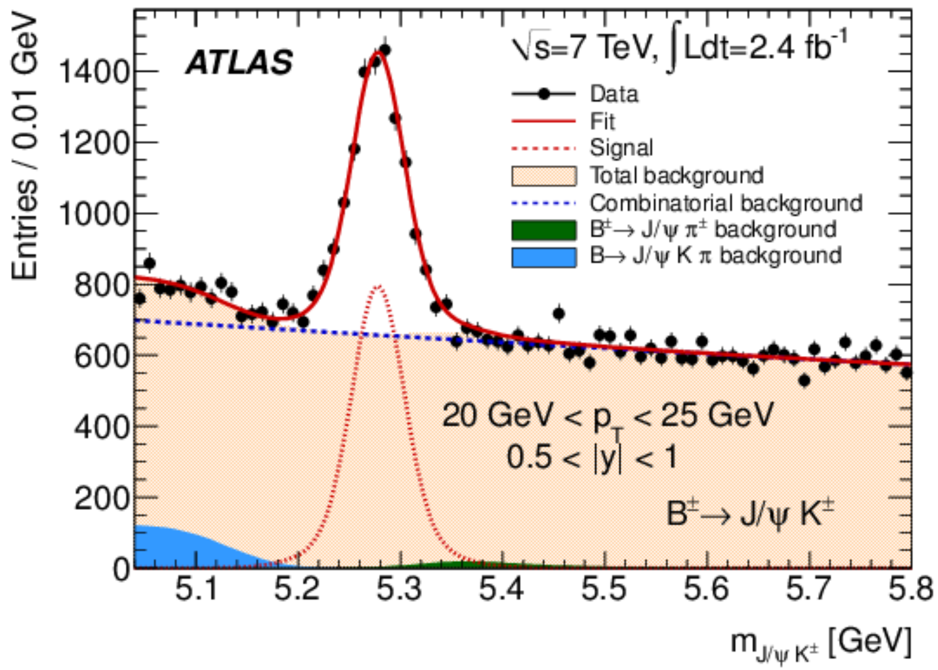
Disagreement w theory (NNLO CSM & CEM) at high P_T (where spin alignment/feed-down are reduced)

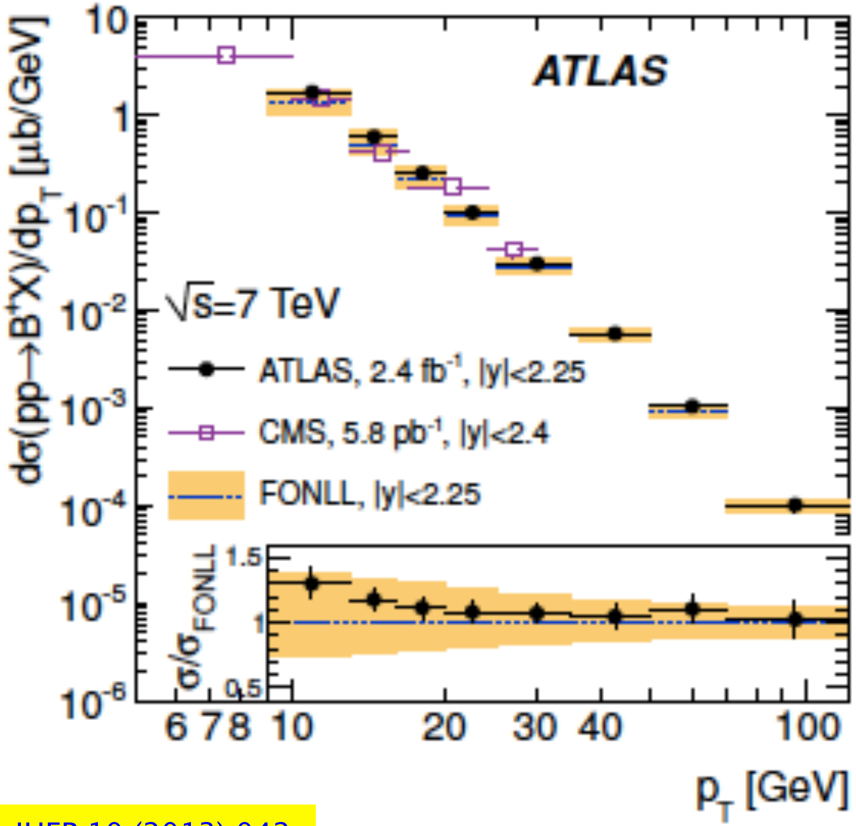
B.4 B⁺ production   Tests b-quark production/fragmentation

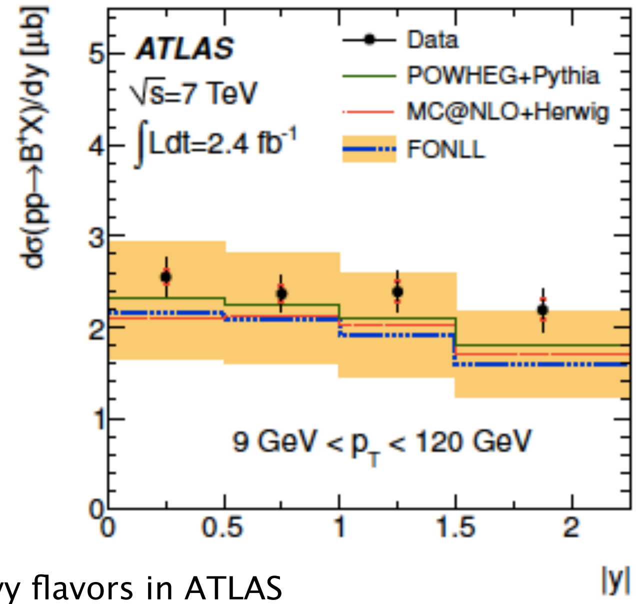
$$\frac{d^2\sigma(B^+ + X)}{dp_T dy} \cdot Br(B^+ \to J/\Psi + K^+)$$

$$p_T^{(B^+)} \geq 9\ GeV, \quad |y^{(B^+)}| \leq 2,25$$

$$5.05\ GeV \leq m_{\mu\mu K} \leq 5.80\ GeV$$







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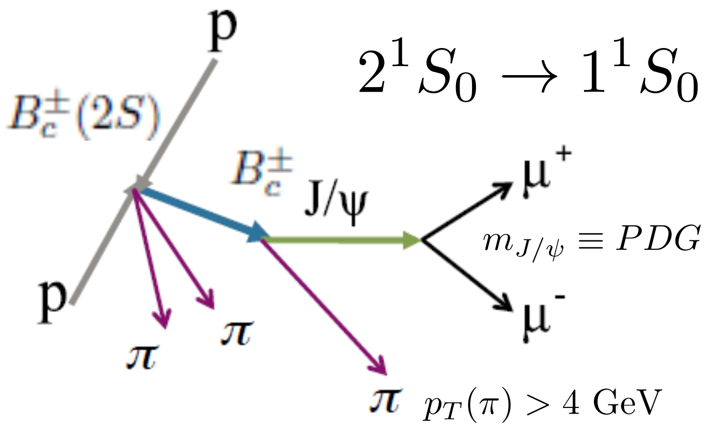
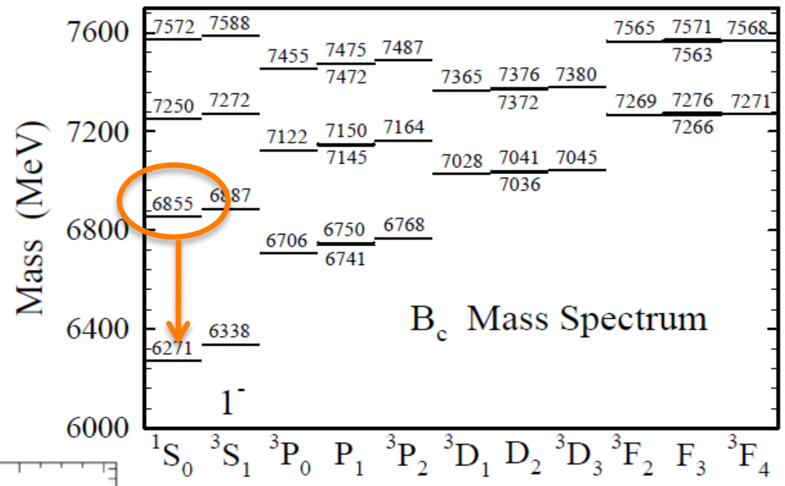
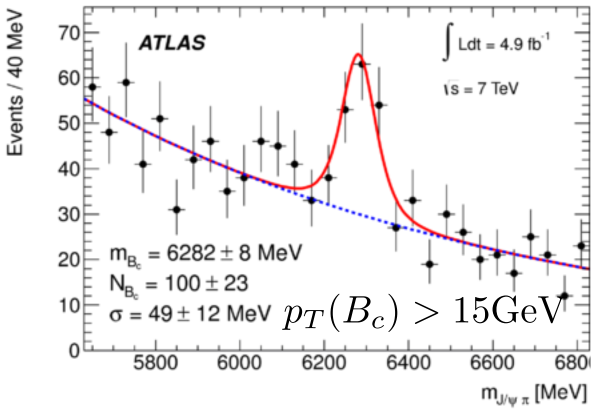
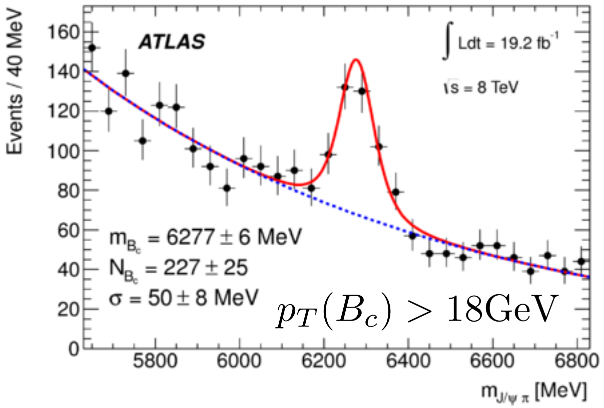
C.1 Observation of the excited $B_c^* \rightarrow B_c^+ \pi^+\pi^-$

$$2^1S_0 \rightarrow 1^1S_0 + \pi\pi$$









$$B_c^+ \rightarrow J/\psi\ K^+$$

Data	Signal events	Peak mean [MeV]
7 TeV	100±23	6282±8
8 TeV	227±25	6277±6

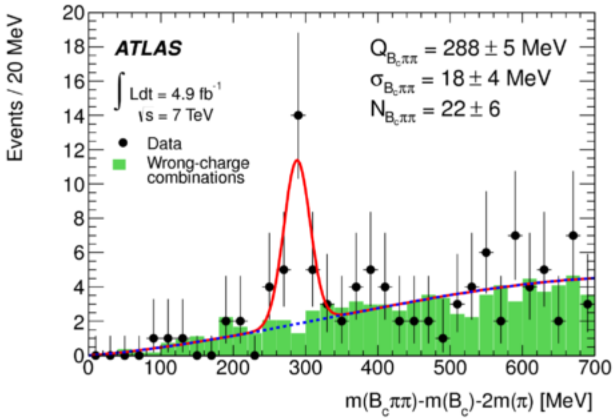
$$\sigma_{B_c}^{peak} \approx (50 \pm 10)\ \text{MeV}$$

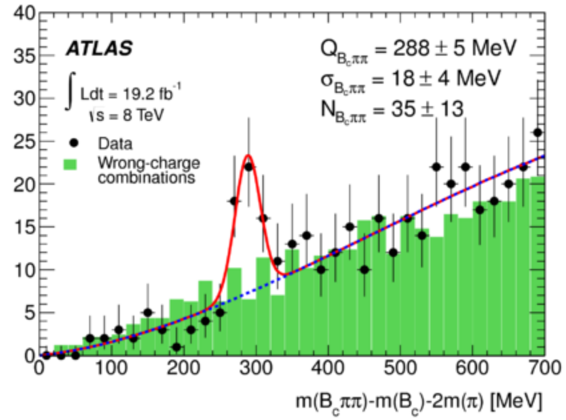
$$\begin{cases} N_{B_c^*} = 22 \pm\ 6 & (\sqrt{s} = 7\ \text{TeV}) \\ N_{B_c^*} = 35 \pm 13 & (\sqrt{s} = 8\ \text{TeV}) \end{cases}$$

$$\sigma_{B_c^*}^{peak} \approx (18 \pm 4)\ \text{MeV}$$

Combined significance: 5.2 σ

- M=(6442±4±5) MeV
- Q=(288.3±3.5±4.1)MeV



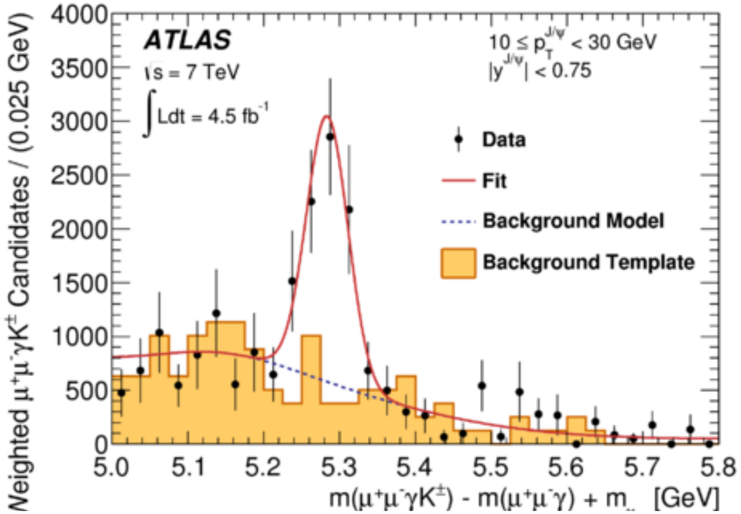


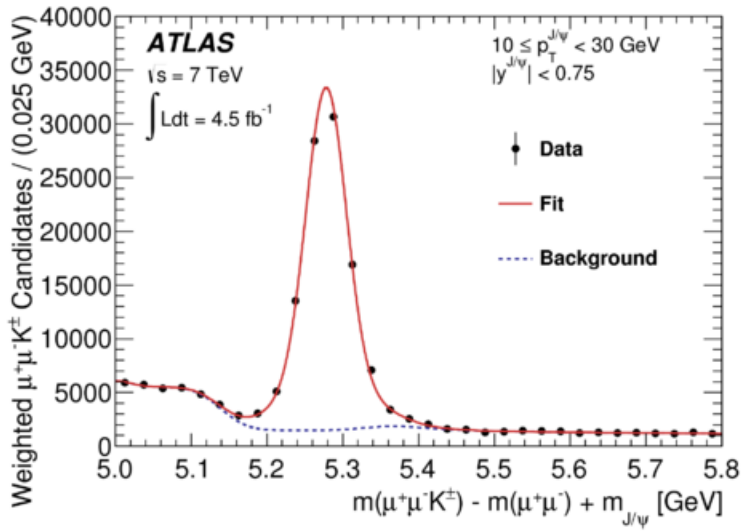
C.2 Measurement of the BR($B^+ \to \chi_c + K^+$)

arXiv:1407.1032

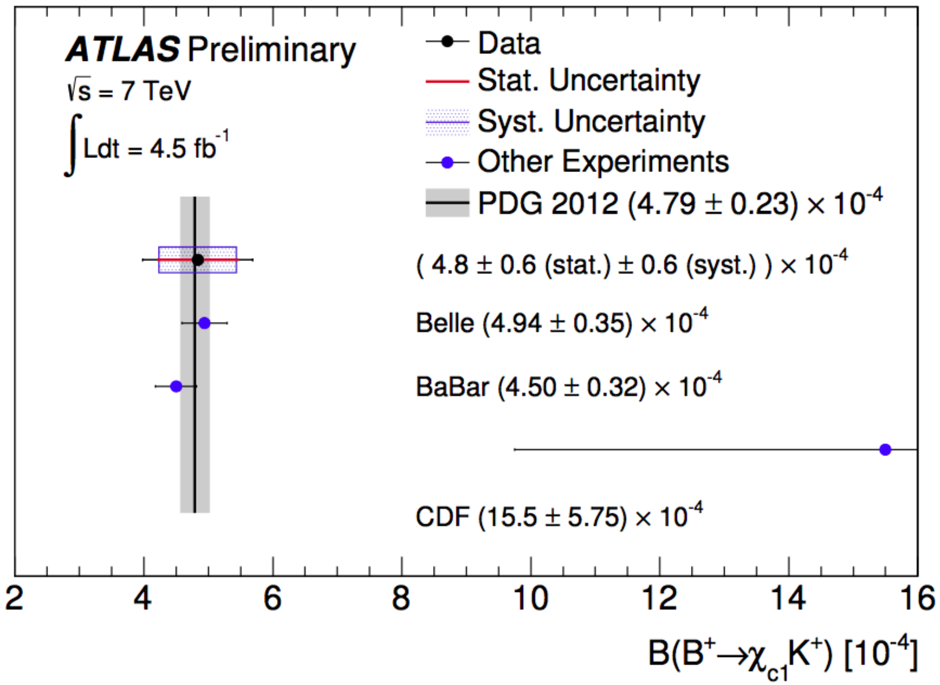
Combine ($\chi_c \to J/\psi + \gamma$) and ($B^+ \to J/\psi\ K^+$) samples to obtain:

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





$$Br\left(B^{\pm} \to \chi_{c1} K^{\pm}\right) =$$
$$(4.8 \pm\ 0.8(stat.)\ \pm 0.6(syst.)) \cdot 10^{-4}$$



Good agreement with B-factories

C.3 Parity violation from $\Lambda_b \to J/\psi\ \Lambda_0$

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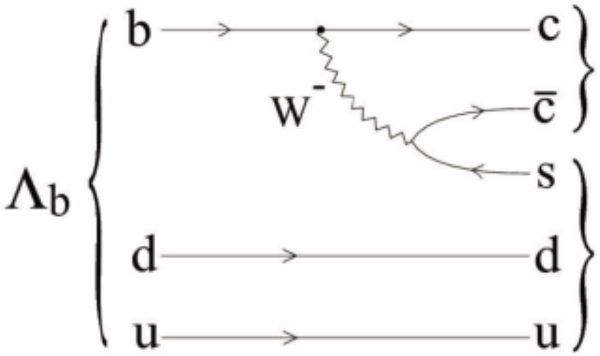
$$w(\cos\theta) = \frac{1}{2}\left(1 + \alpha_b \cdot P \cdot \cos\theta\right)$$

Violation not maximal $\Rightarrow |\alpha|<1$



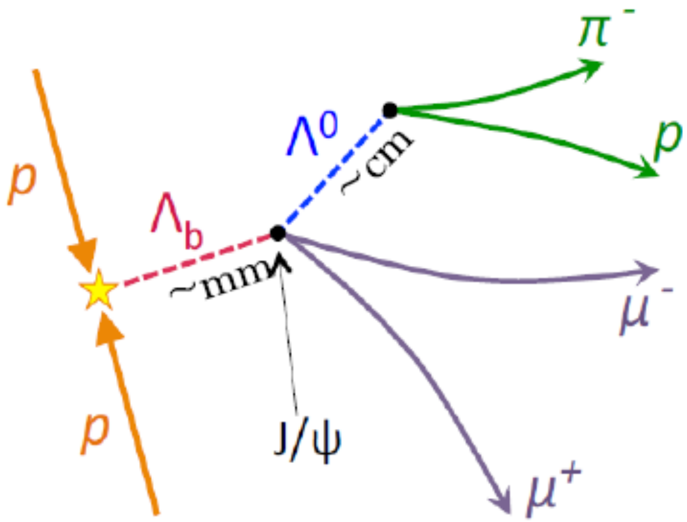
Four possible helicity amplitudes:

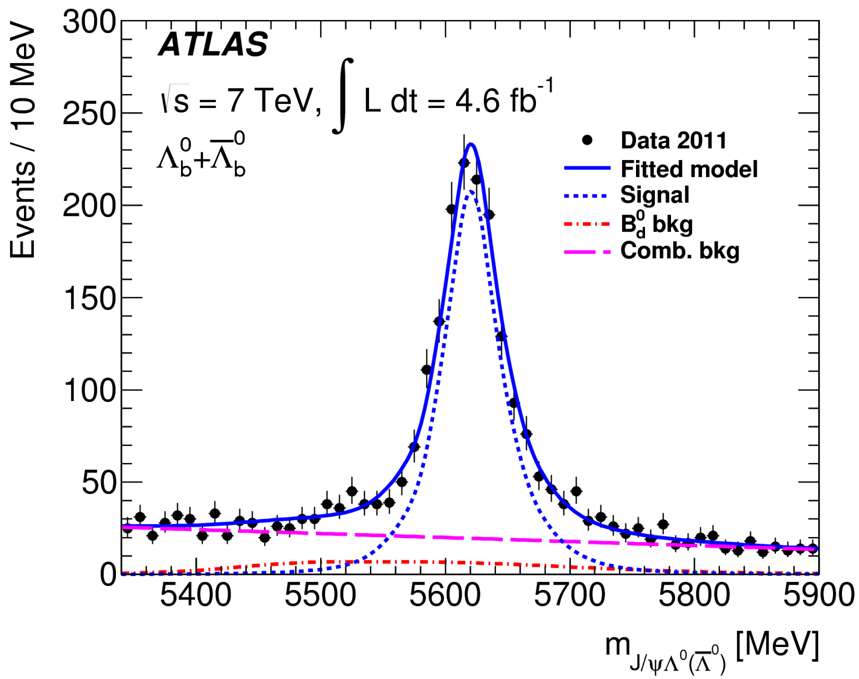
Amplitude	$\lambda_{J/\psi}$	λ_Λ
a_+	0	1/2
a_-	0	-1/2
b_+	-1	-1/2
b_-	1	1/2

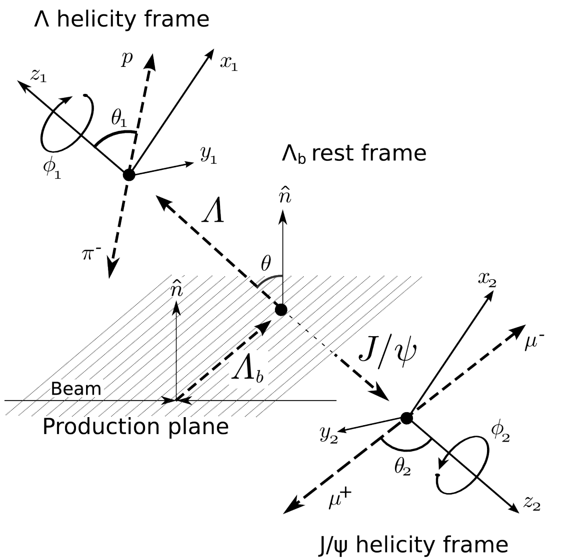
$$|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1.$$

Decay angular distribution $\Rightarrow a_+, a_-, b_+$ and b_-

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$







The full angular probability density function (PDF) of the decay angles $\Omega = (\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$ is [15,17,18]

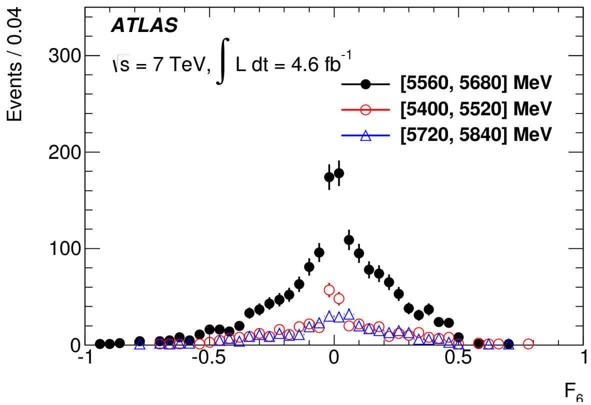
$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega), \qquad (3)$$

$$\langle F_i \rangle = \frac{1}{N^{\text{data}}} \sum_{n=1}^{N^{\text{data}}} F_i(\Omega_n)$$

$$\langle F_i \rangle^{\text{expected}} = \sum_j f_{1j}(\vec{A}) f_{2j}(\alpha_\Lambda) C_{ij},$$

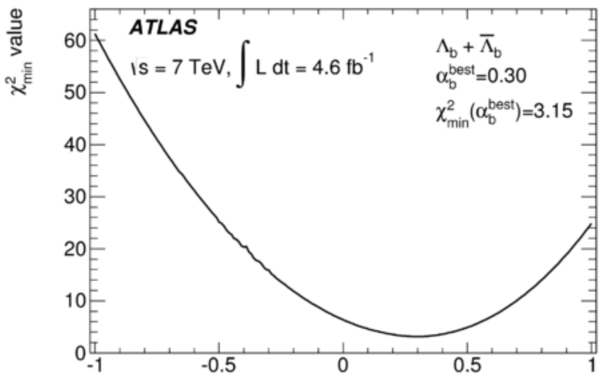
$$\langle F_i \rangle^{\text{expected}} = \langle F_i \rangle,$$

$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\text{expected}} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\text{expected}} - \langle F_j \rangle),$$



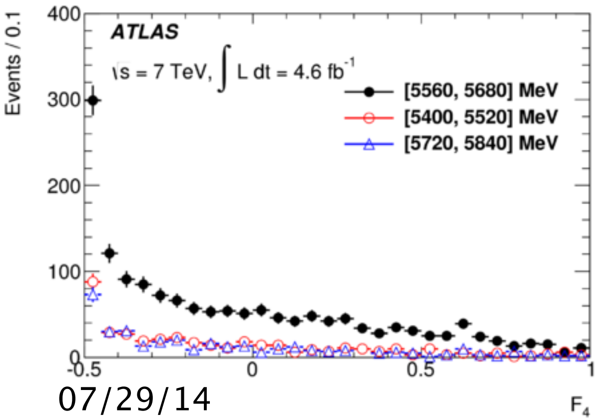
$$\langle F_2 \rangle = -0.282 \pm 0.021,$$
$$\langle F_4 \rangle = -0.044 \pm 0.017,$$
$$\langle F_6 \rangle = 0.001 \pm 0.010,$$
$$\langle F_{18} \rangle = 0.019 \pm 0.009,$$
$$\langle F_{19} \rangle = -0.002 \pm 0.009.$$

$$|a_+| = 0.17^{+0.12}_{-0.17},$$
$$|a_-| = 0.59^{+0.06}_{-0.07},$$
$$|b_+| = 0.79^{+0.04}_{-0.05},$$
$$|b_-| = 0.08^{+0.13}_{-0.08}.$$



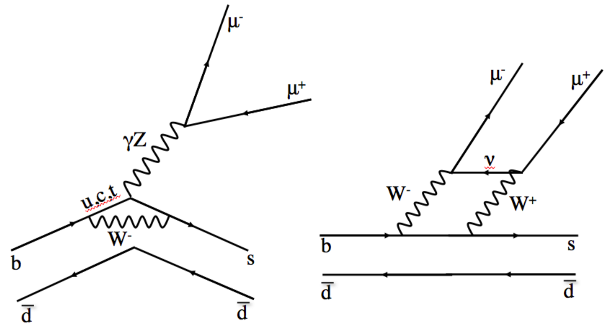
$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

- consistent with α_{LHCB}= 0.05±0.17±0.07
- α_{HQET}=0.78 and α_{pQCD}=−(0.14÷0.17)



C.4 Study of $B_d \to K^{*0}(K\pi)\ \mu^+\mu^-$

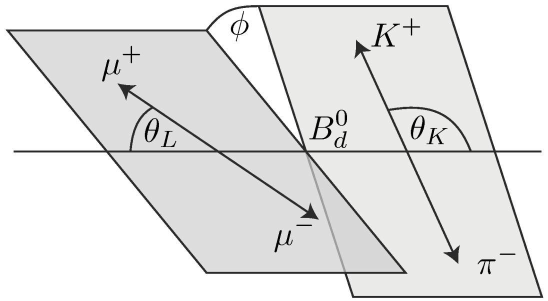
- $b \to s\ l^+\ l^-$ transition
- loop-mediated in SM ⇒ BR≈ 1.1 10^{-6}
- sensitive to BSM contribution



- lepton forward-backward asymmetry A_{FB}
- K^{*0} longitudinal polarisation fraction F_L

3 angles (θ_L, θ_K, φ) and q^2

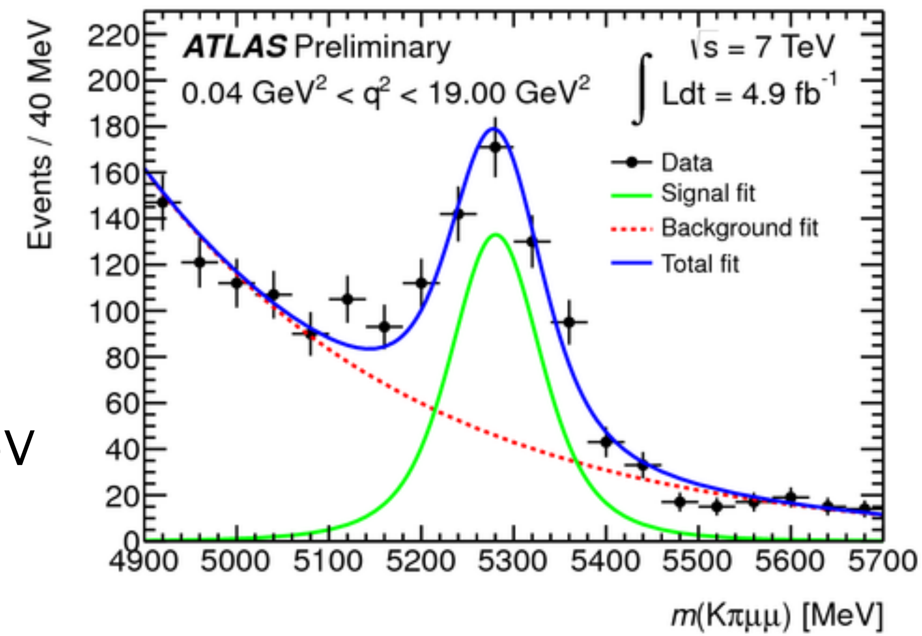
- φ symmetry, then integrate on φ
- alternative integration on θ_L or θ_K



fit to angular distribution ⇒ (A_{FB},F_L) in q^2-intervals

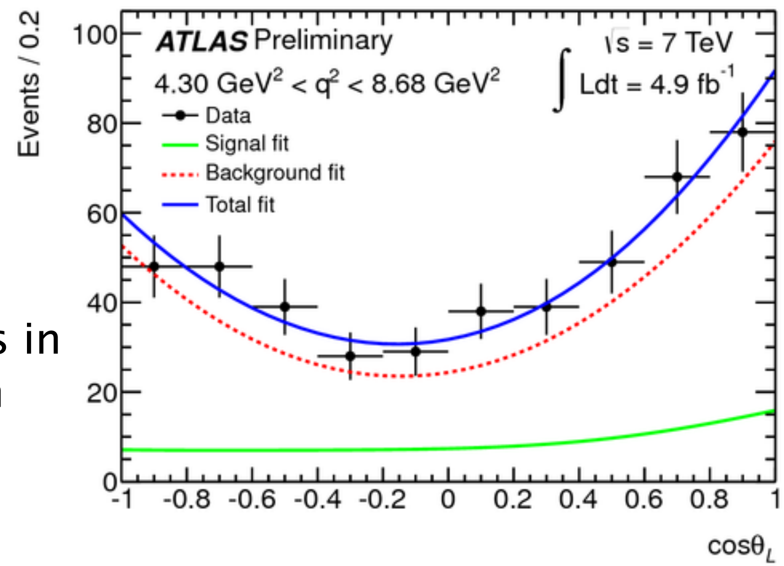
- $q^2 < 2\text{GeV}^2$ limited statistics
- Veto:
  - $q^2=(m^2_{J/\psi},\ m^2_{\psi(2S)})\pm 3\sigma$
  - radiative J/ψ and $\psi(2S)$ decays
  - $K^{*0}(K\pi)$ mass range [846,946] MeV
- maximum likelihood fit

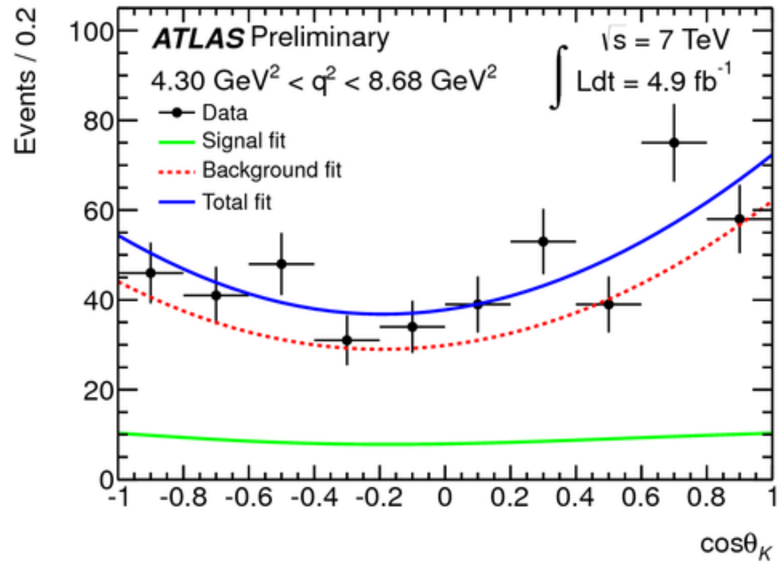
⇒ N_{sig}=466±34 and N_{bkg}=1132±43

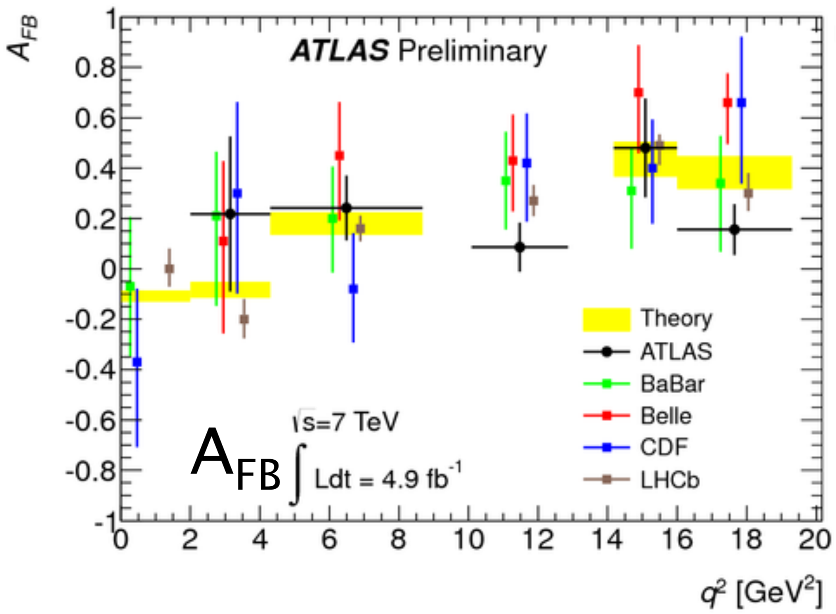


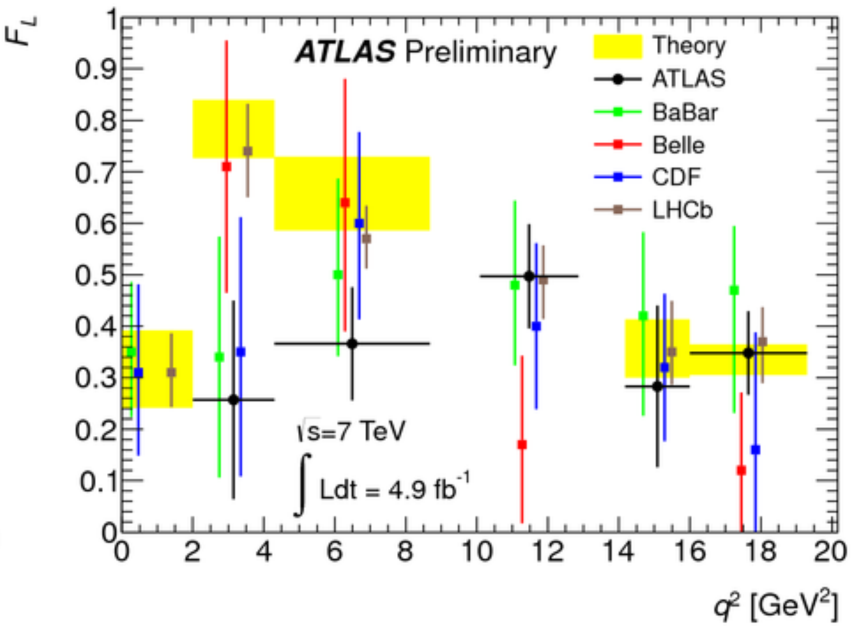
Fit procedure:

1. mass distribution
2. angular distributions in each q^2– bin









F_L

- statistical uncertainty dominates ⇒ improve with $\mathscr{L}$
- agreement with other experiments and SM predictions

Conclusion

- High precision production measurements
  - quarkonium (J/ψ, ψ_{2s}, χ_{cj}, Υ_{ms})
  - open state (B^+)
  - LHC: new kinematical regions (e.g. high p_T) $\Rightarrow$ test predictions of different QCD tools
- ATLAS →
  - → evidence for new states
  - → decay properties of heavy flavour
- Expect to exploit full run-I and future run-II to probe new interesting phenomena in heavy flavour production
  - polarization
  - double quarkonium
  - associated production with W, Z etc…
  - decays to test SM and look for BSM effects (e.g. rare or suppressed decays)