B Physics in ATLAS

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Outline

- Introduction
- Run I Results
  - Production & Decay
  - Spectroscopy
  - Rare Decays
  - CP Violation
- (Some) prospects for Run II

These slide give – for reference - a complete overview: will not discuss everything in detail!

Will not cover (among others):

- The ATLAS detector
- Detector upgrade

Apologies for the neglected areas!

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

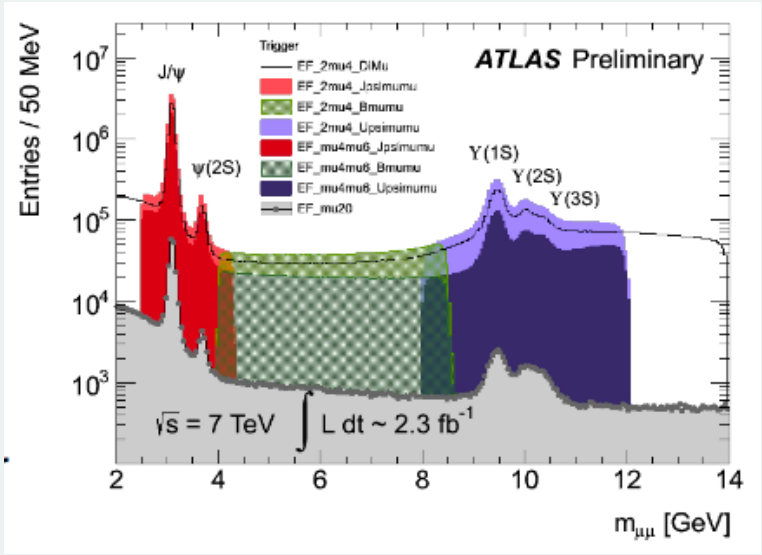
Public ATLAS HF Results

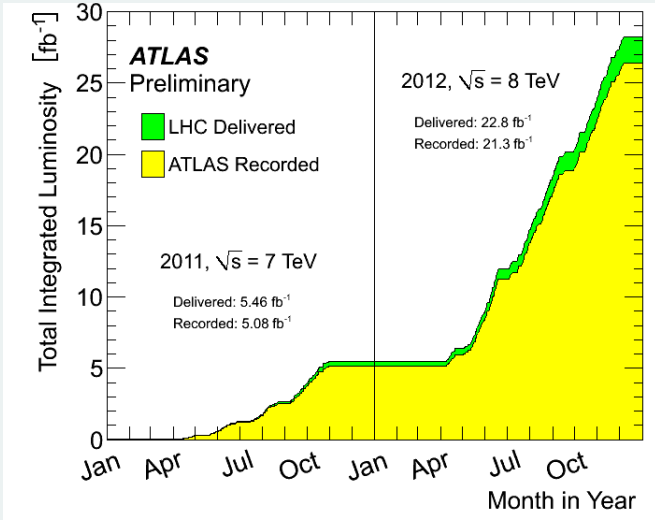
Short Title	Int L	Journal	Preprint	Plots	Preceding CONF-note
NEW Cross-section measurement of $\psi(2S) \to J/\psi (\to \mu^+\mu^-) \pi^+\pi^-$ at $\sqrt{s}$ = 7TeV	2.1 fb^{-1}	JHEP 09 (2014) 079	arXiv:1407.5532	Link	ATLAS-CONF-2013-094
NEW Φ_s and $\Delta\Gamma_s$ from flavour tagged time dependent angular analysis of $B^0_s \to J/\psi\,\phi$	4.9 fb^{-1}	Phys. Rev. D 90 (2014) 052007	arXiv:1407.1796	Link	ATLAS-CONF-2013-039
NEW Observation of an excited $B^{\pm}_c$ meson state with the ATLAS detector	(4.9+19.2) fb^{-1}	Accepted by PRL	arXiv:1407.1032	Link	-
NEW Measurement of χ_{c1} and χ_{c2} production at $\sqrt{s}$ = 7TeV	4.5 fb^{-1}	JHEP 07 (2014) 154	arXiv:1404.7035	Link	ATLAS-CONF-2013-095
NEW Measurement of the parity violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi\,\Lambda^0$	4.6 fb^{-1}	Phys. Rev. D 89 (2014) 092009	arXiv:1404.1071	Link	ATLAS-CONF-2013-071
NEW Associated production of prompt J/ψ mesons and W boson in at $\sqrt{s}$ = 7TeV	4.6 fb^{-1}	JHEP 04 (2014) 172	arXiv:1401.2831	Link	ATLAS-CONF-2013-042
Production cross section of B+ at $\sqrt{s}$ = 7TeV	2.4 fb^{-1}	JHEP 10 (2013) 042	arXiv:1307.0126	Link	ATLAS-CONF-2013-008
Inclusive Υ(nS) differential cross sections and ratios	1.8 fb^{-1}	Phys. Rev. D 87 (2013) 052004	arXiv:1211.7255	Link	-
Φ_s and $\Delta\Gamma_s$ from time dependent angular analysis of $B^0_s \to J/\psi\,\phi$	4.9 fb^{-1}	JHEP 12 (2012) 072	arXiv:1208.0572	Link	-
Measurement of the Λ_b lifetime and mass	4.9 fb^{-1}	Phys. Rev. D 87 (2013) 032002	arXiv:1207.2284	Link	ATLAS-CONF-2012-055
b-hadron production cross-section from D*μX final states	3.3 pb^{-1}	Nucl. Phys. B864 (2012) 341-381	arXiv:1206.3122	Link	
Search for the decay $B^0_s \to \mu\mu$	2.4 fb^{-1}	Phys. Lett. B713 (2012) 180-196	arXiv:1204.0735	Link	ATLAS-CONF-2012-010
Observation of a new χ_b state in radiative transitions to Υ(1S) and Υ(2S)	4.4 fb^{-1}	Phys. Rev. Lett. 108 (2012) 152001	arXiv:1112.5154	Link	
Υ(1S) Fiducial Production Cross-Section	1.1 pb^{-1}	Phys. Lett. B703 (2011) 428-446	arXiv:1106.5325	Link	
Differential cross-sections of inclusive, prompt and non-prompt J/ψ production	2.3 pb^{-1}	Nucl. Phys. B 850 (2011) 387-344	arXiv:1104.3038	Link	
Analyses performed within other ATLAS Physics Groups:					
$D^{*+/-}$ production in jets	0.3 pb^{-1}	Phys. Rev. D 85, 052005 (2012)	arXiv:1112.4432	Link	
Inclusive production of electrons and muons (b/c cross section)	35 pb^{-1}	Phys. Lett. B 707 (2012) 438-458	arXiv:1109.0525	Link	
Centrality dependence of J/ψ production in heavy ions collisions	6.7 μb^{-1}	Phys. Lett. B 697 (2011) 294-312	arXiv:1012.5419	Link	

This is an incomplete list: cannot possibly cover all this in detail… sorry!

HF Data Collected by ATLAS

- Excellent Run I LHC performance: 26 fb^{-1}!
- Trigger: mainly di-muon (4+4) and (4+6) GeV





Several results still based on 2011 data only

$\mathscr{L} \simeq 4.9\ fb^{-1}$ $\sqrt{s}=7$ TeV

Overview

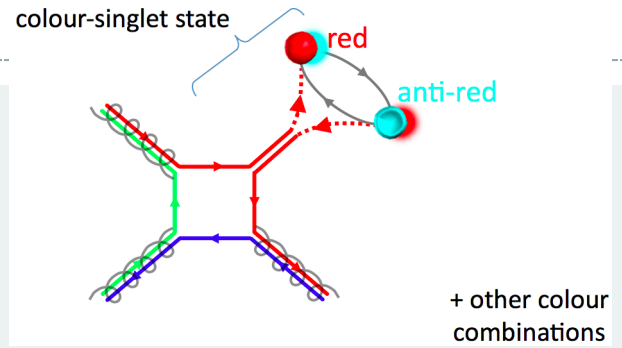
Three (two?) main areas of investigation:

- HF as probe of QCD processes
- Constraining the HF sector in the SM
- HF in searches for new physics

} Closely related: will discuss together!

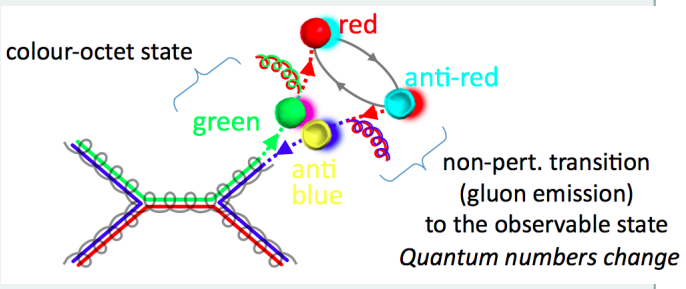
Production & Decay

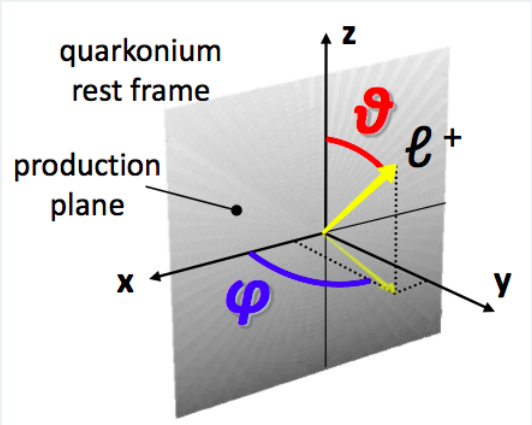
HF Production



- Crucial QCD test
  - CSM with NLO and NNLO* improvements
  - Color Octet Model (NRQCD) with LO and NLO
  - Other models: CEM / k_T factorisation

HF/LHC probes novel (high) p_T regime

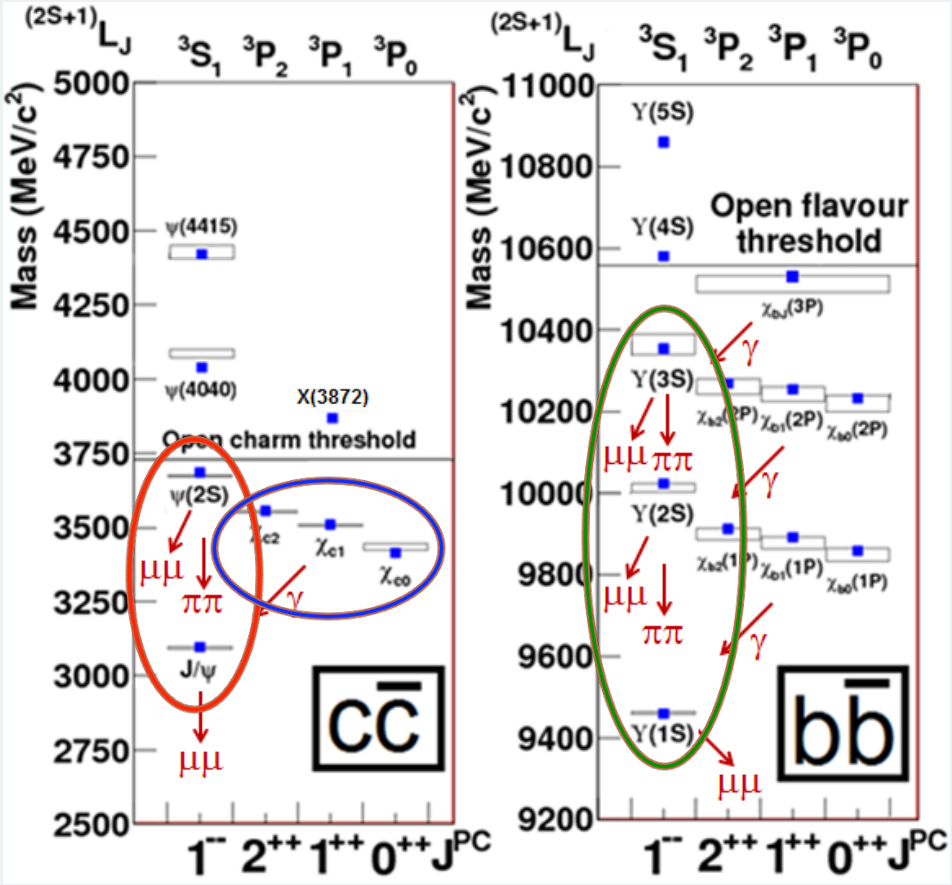




- Polarization
  - Discordant theoretical predictions and ambiguous experimental results
  - Important source of exp. systematics in several production measurements

LHC: high statistic, broader p_T coverage

$q\bar{q}$ Production Measurements



Probe:

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

Binned Differential σ Measurements

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

- $N_{corr}^{Q \to \mu\mu}$: 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

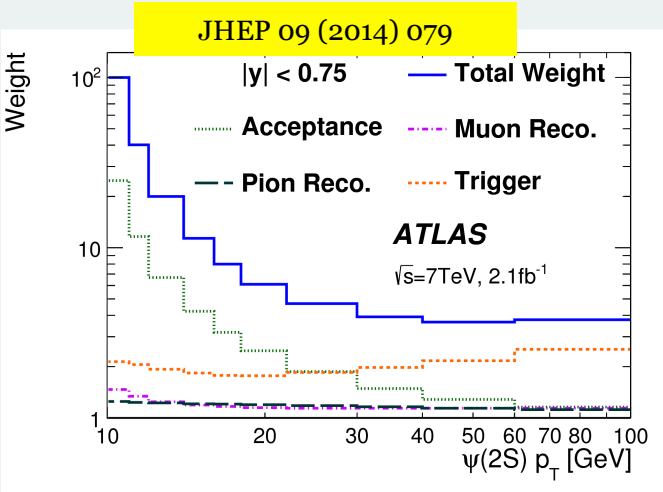
Signal yield: unbinned maximum likelihood fits ⇒ σ_{stat} ~ few %

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

$\varepsilon(p_T^{(\mu)}, \eta^{(\mu)})$ 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)%



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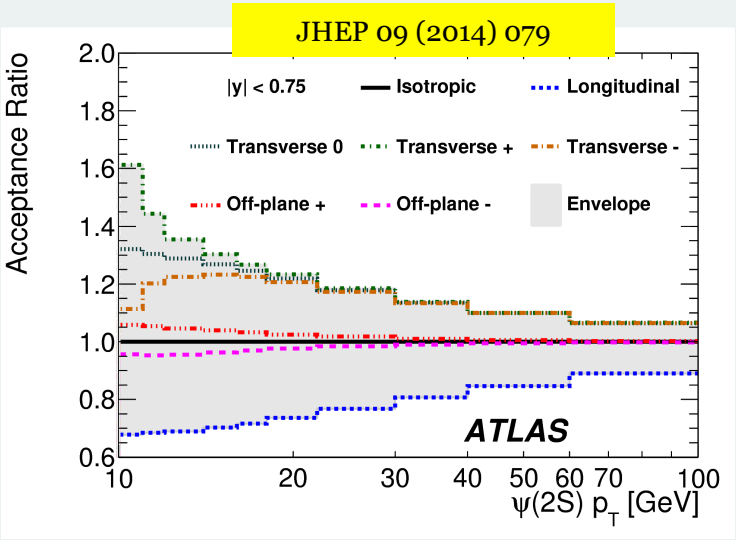
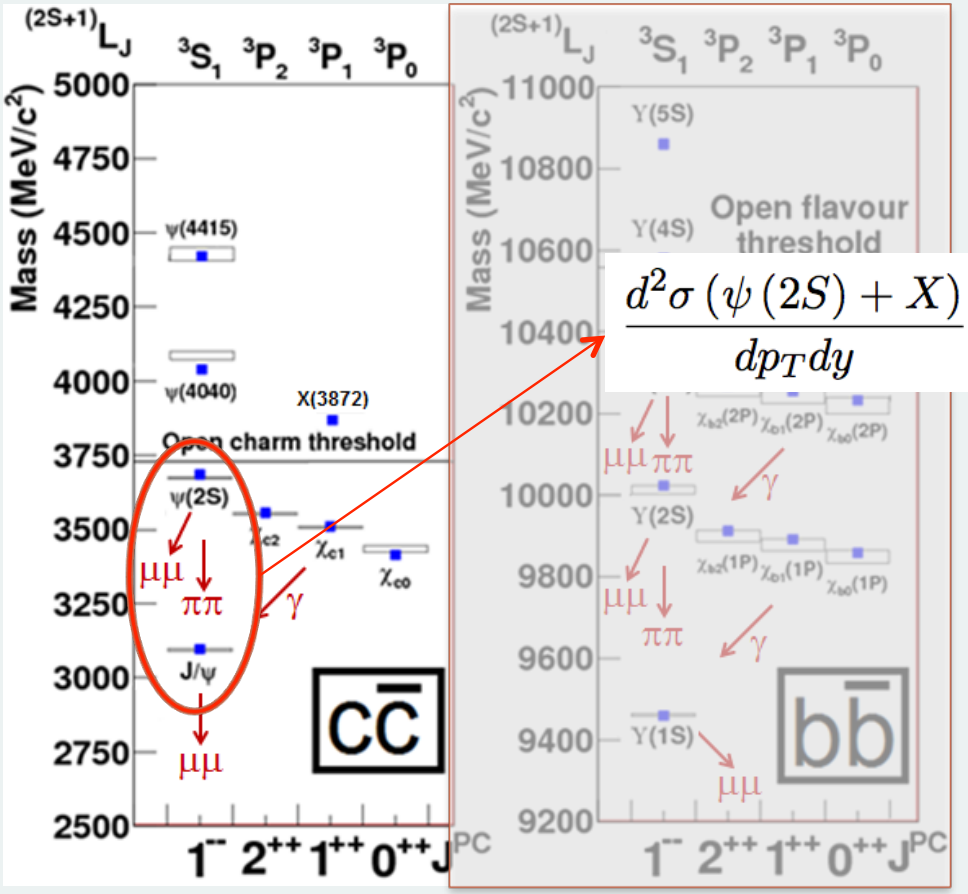
Acceptance ⇔ spin alignment

isotropic case + envelope due to different polarization states



Acceptance variations may reach ~(10-30)%

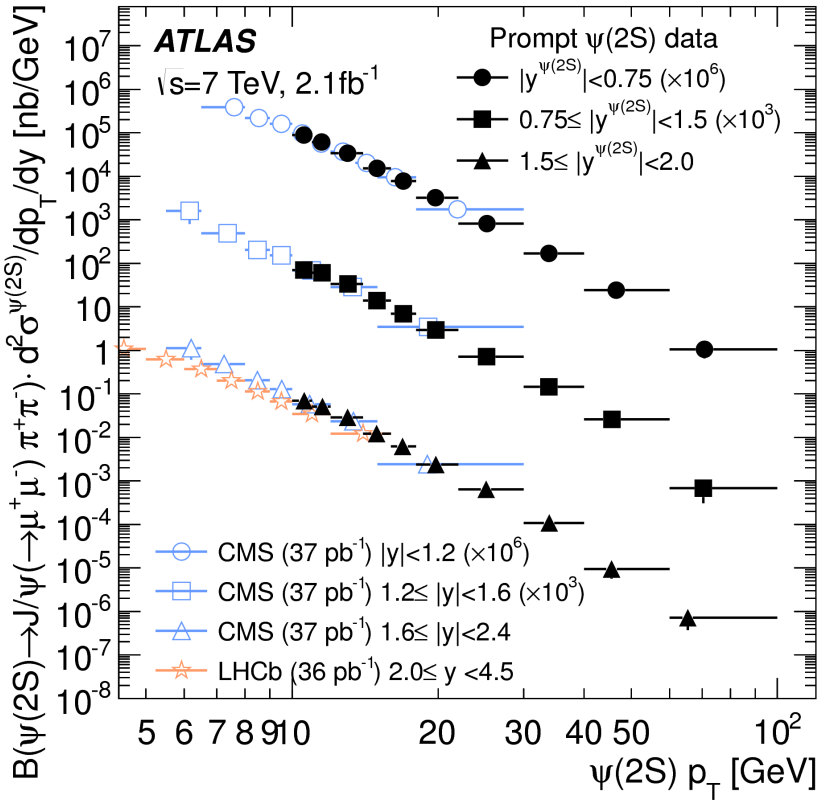
$q\bar{q}$ Production Measurements



$$\frac{d^2\sigma\left(\psi\left(2S\right)+X\right)}{dp_T dy}\cdot Br\left(\psi\left(2S\right)\rightarrow J/\psi\left(\rightarrow\mu^+\mu^-\right)+\pi^+\pi^-\right)$$

Ψ(2s) Production

JHEP 09 (2014) 079

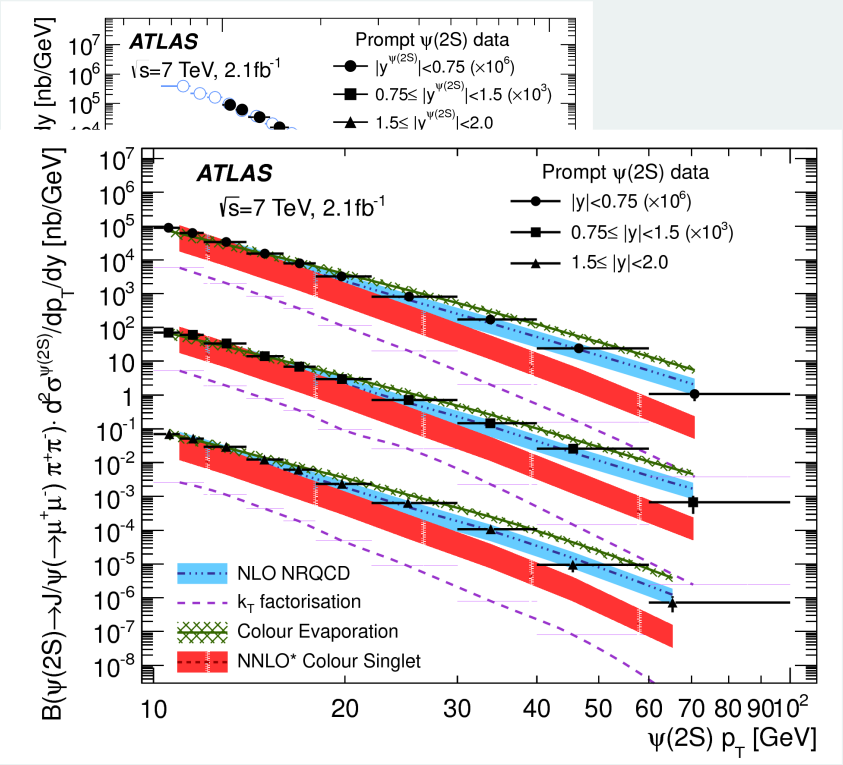


Prompt production:

- Good agreement with CMS and LHCb
- Sensitivity to the new high p_T territory

Ψ(2s) Production

JHEP 09 (2014) 079



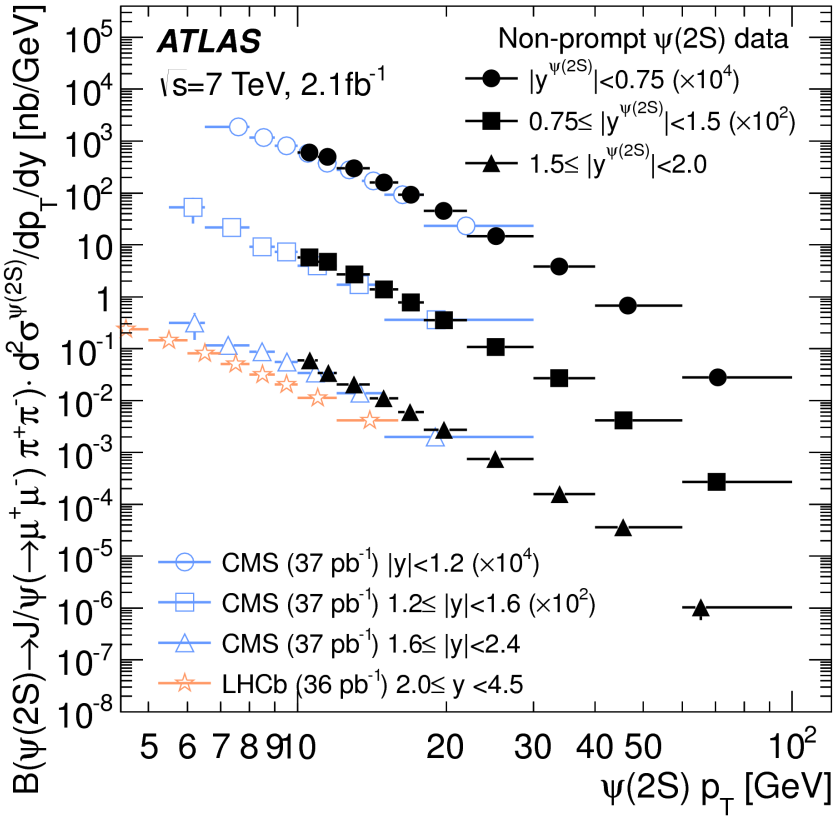
Prompt production:

- Good agreement with CMS and LHCb
- Sensitivity to the new high p_T territory
  - Good agreement with NRQCD LO and NLO @ low/medium p_T
  - Higher p_T: visible deviations

CSM & k_T models may need higher order contributions

Ψ(2s) Production

JHEP 09 (2014) 079

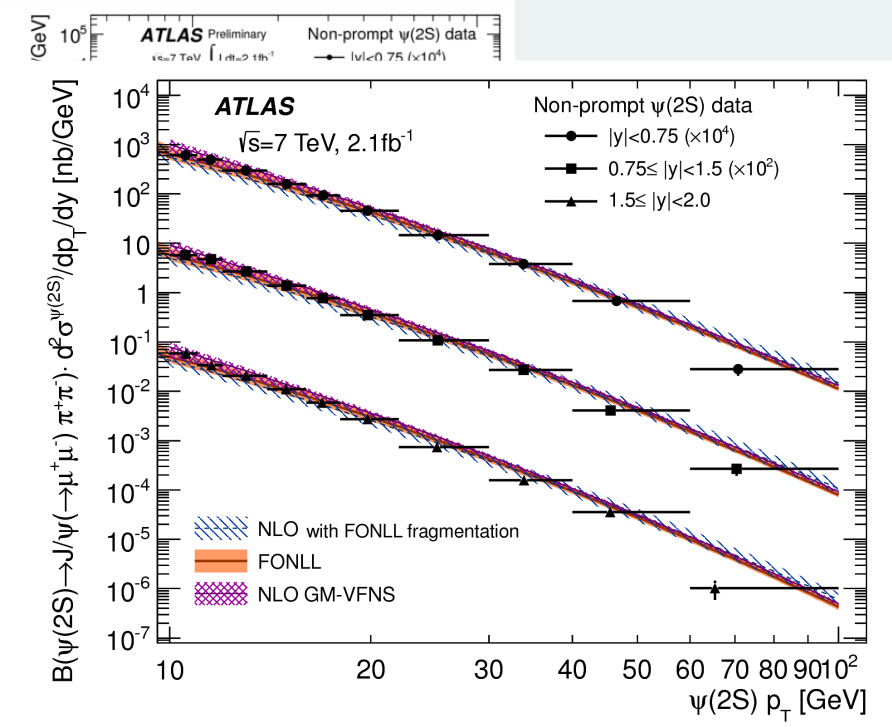


Non Prompt production:

- Good agreement with CMS and LHCb
- Sensitivity to the new high p_T territory

Ψ(2s) Production

JHEP 09 (2014) 079



Non Prompt production:

- Good agreement with CMS and LHCb
- Sensitivity to the new high p_T territory
  - Good agreement with predictions @ ~all p_T

Ψ(2s) Production: non-prompt/inclusive

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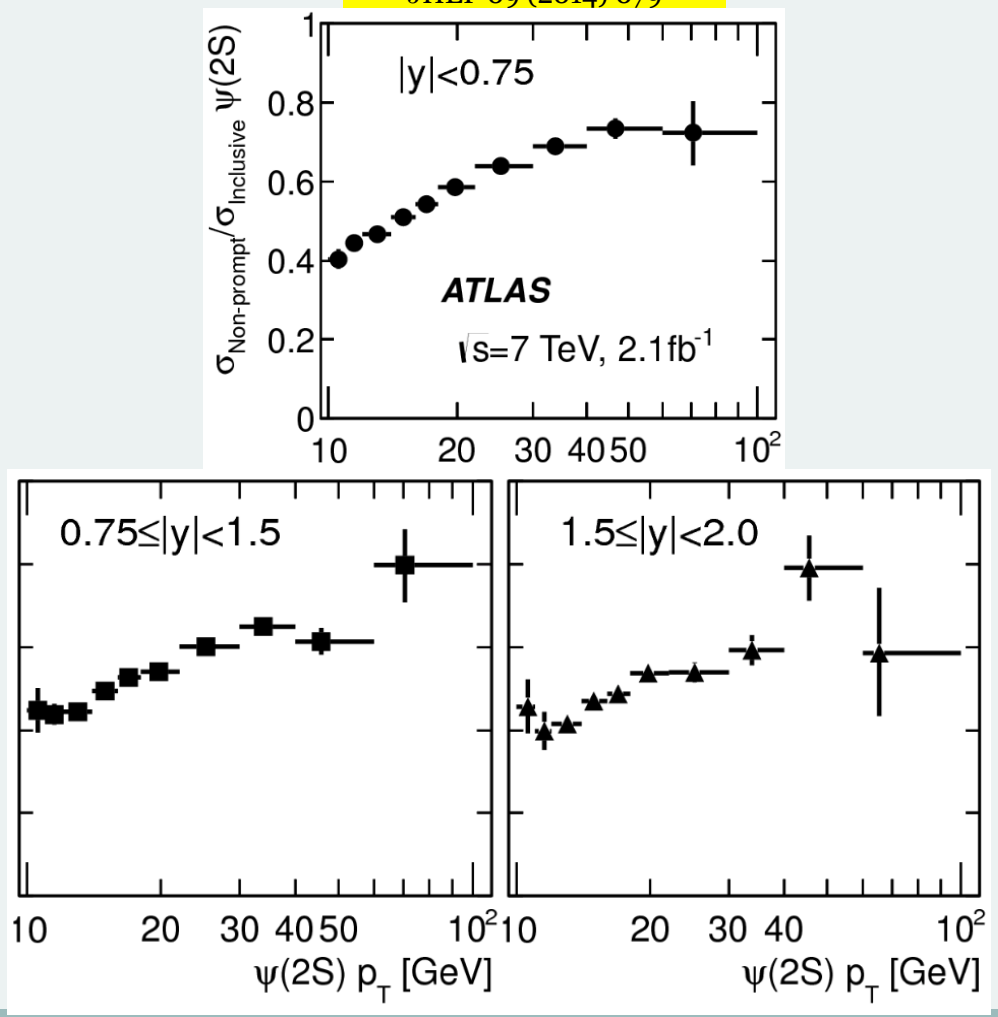


- Better control of systematic uncertainties
- Extended |y| range
- Qualitative agreement with CMS
- Important input to onia production models

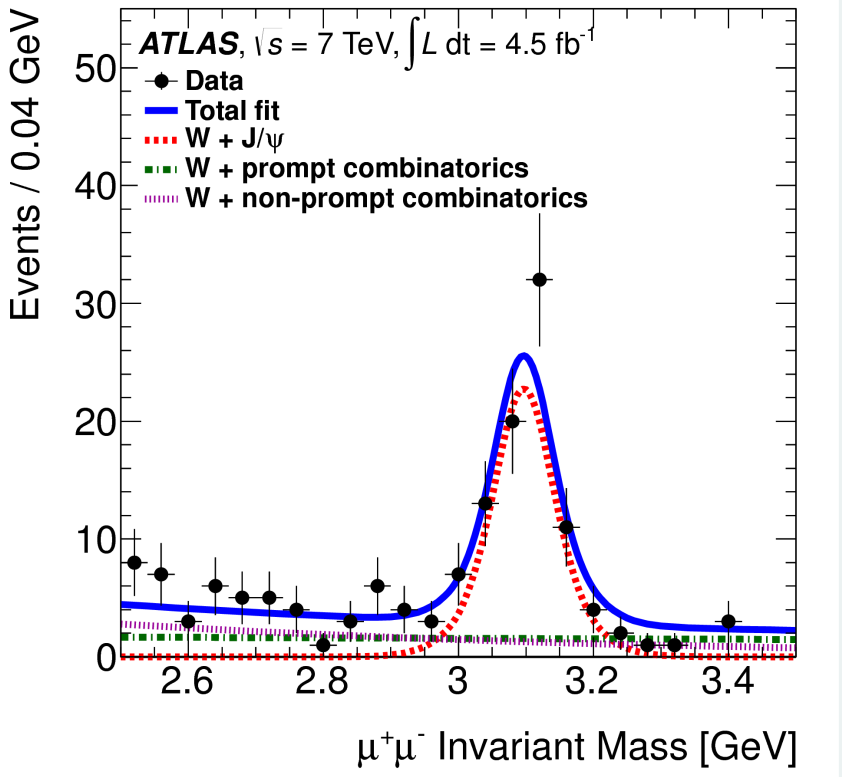
JHEP 04 (2014) 172

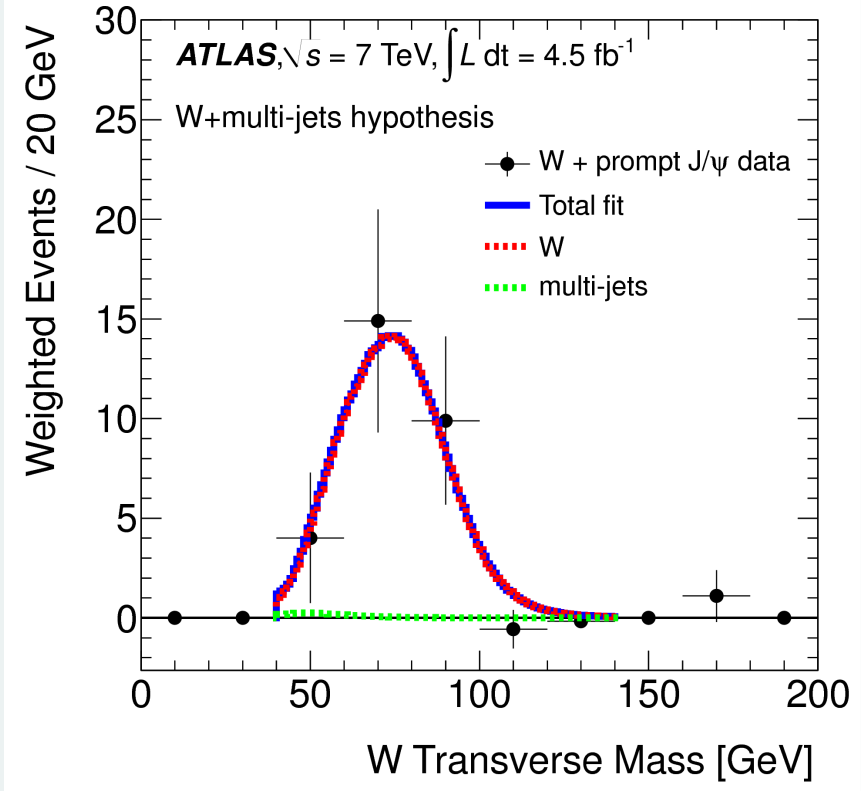
W+J/ψ Production

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

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

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





JHEP 04 (2014) 172

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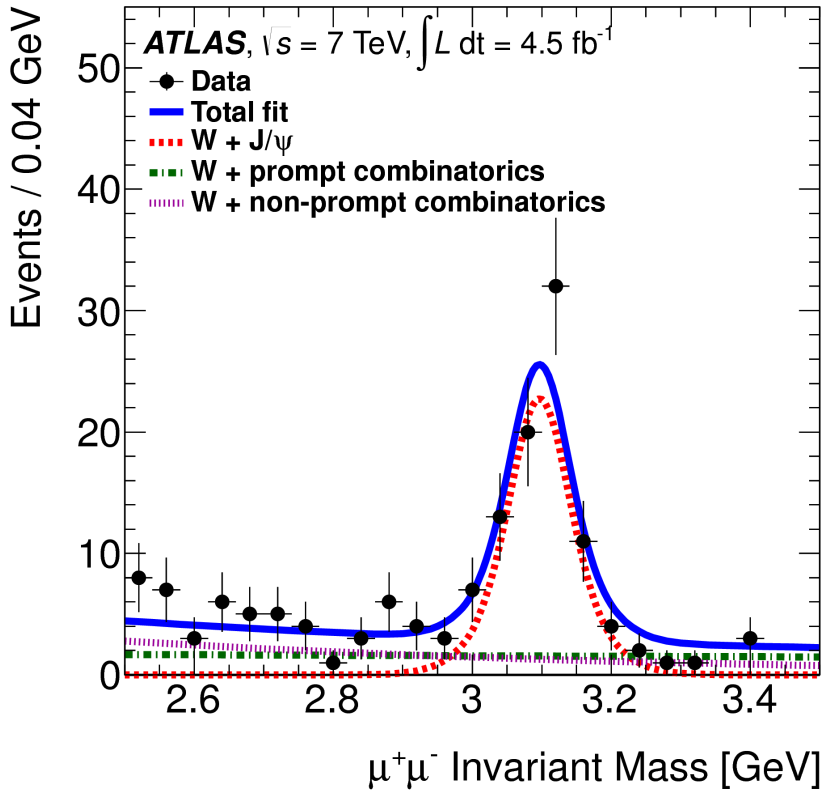

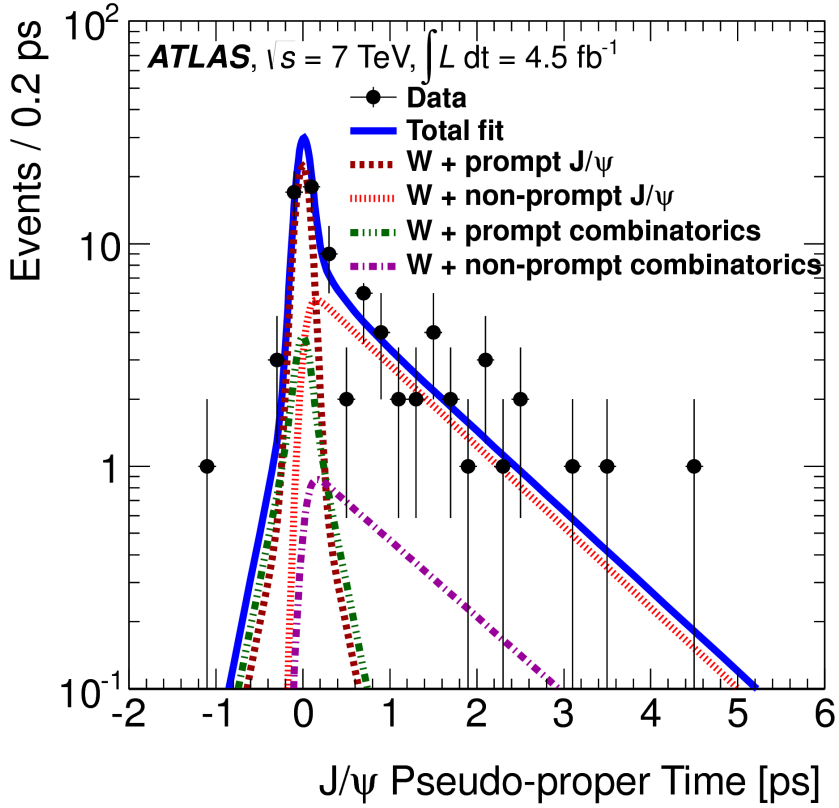

JHEP 04 (2014) 172

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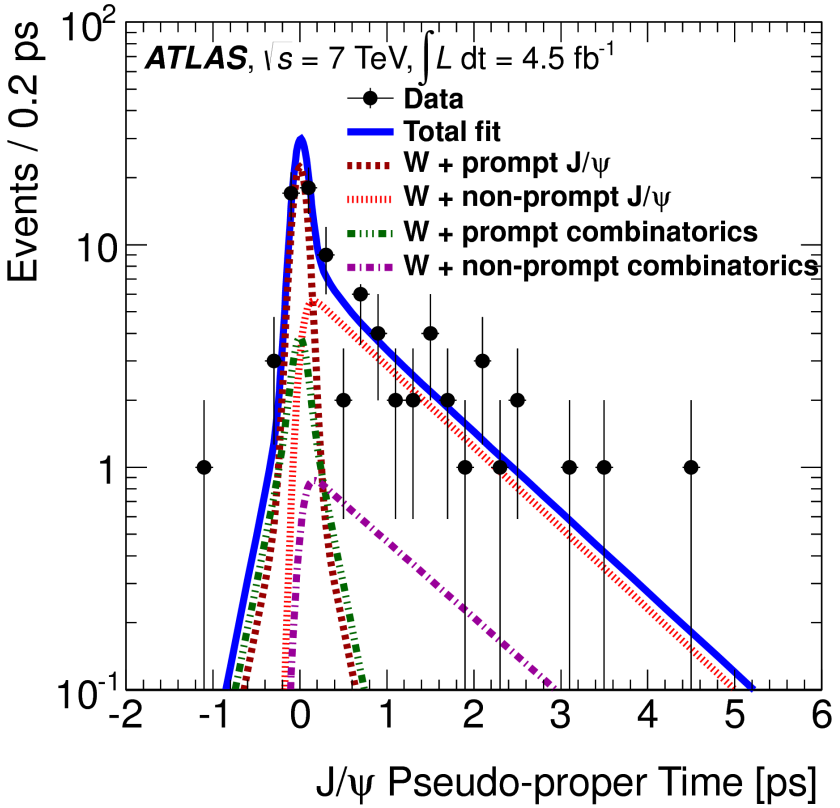
Yields	
Process	Total
Prompt J/ψ	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$41.8^{+8.4}_{-7.3}$
Prompt background	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$39.0^{+8.4}_{-7.1}$
p-value	2.1×10^{-7}
Significance (σ)	5.1

(*) of which 1.8 ± 0.2 originate from pileup



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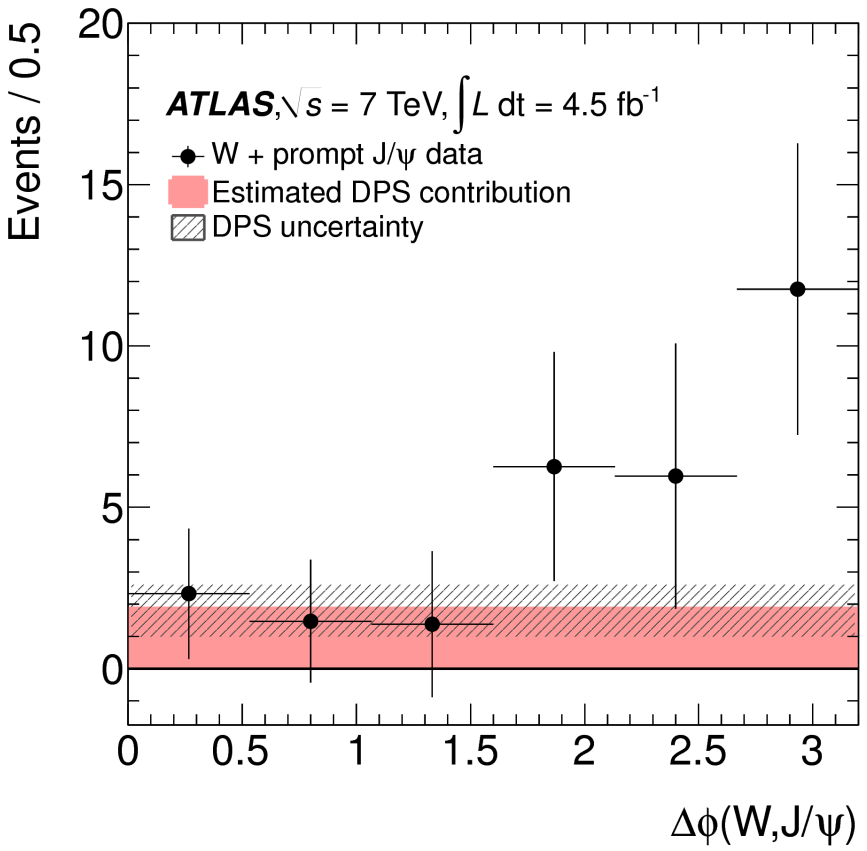


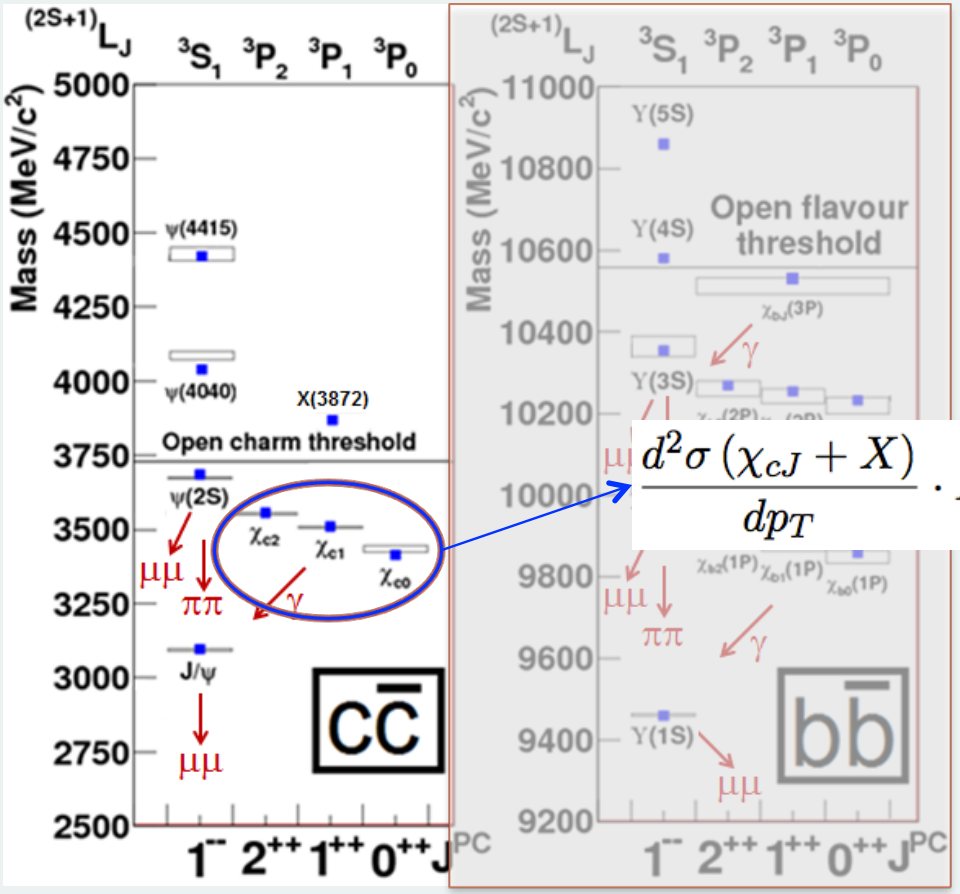
Double Parton Scattering (DPS) contribution

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

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

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

$q\bar{q}$ Production Measurements

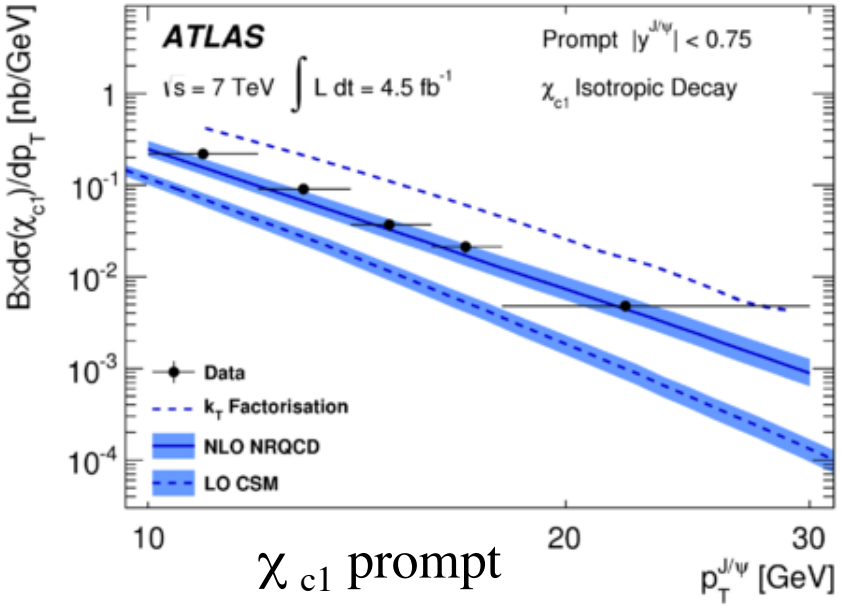


$$\frac{d^2\sigma\left(\chi_{cJ}+X\right)}{dp_T}\cdot Br\left(\chi_{cJ}\rightarrow J/\psi\left(\rightarrow\mu^+\mu^-\right)+\gamma\left(\rightarrow e^+e^-\right)\right)$$

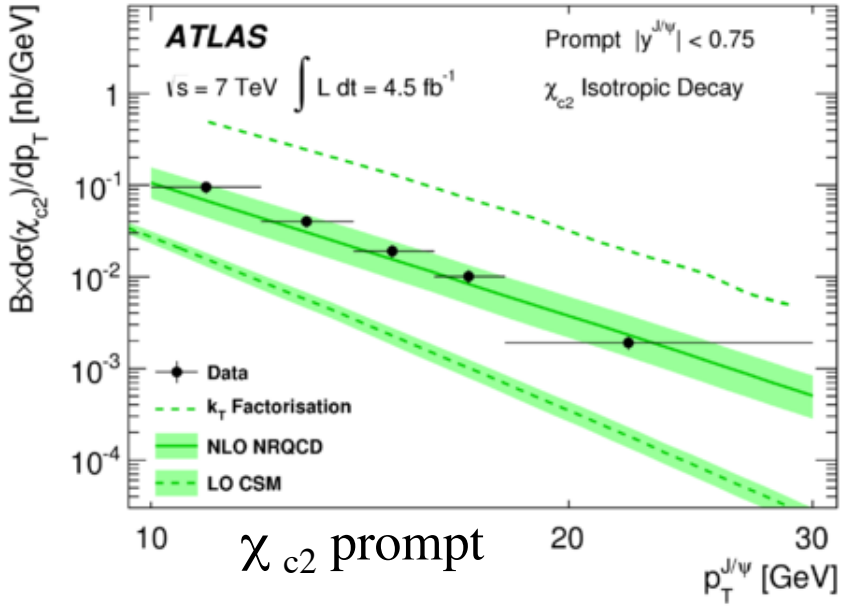
P-states: just below open charm threshold ⇒ reduce feed-down

JHEP 07 (2014) 154

χ_c Production



χ_{c1} prompt

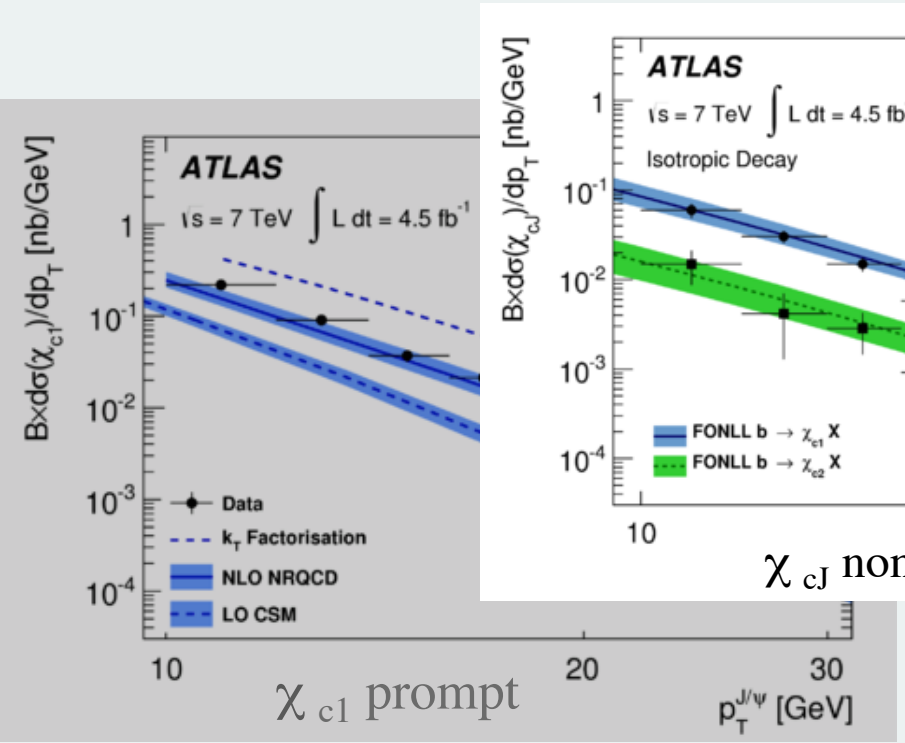


χ_{c2} prompt

More problematic (at all p_T) for current k_T / CSM predictions

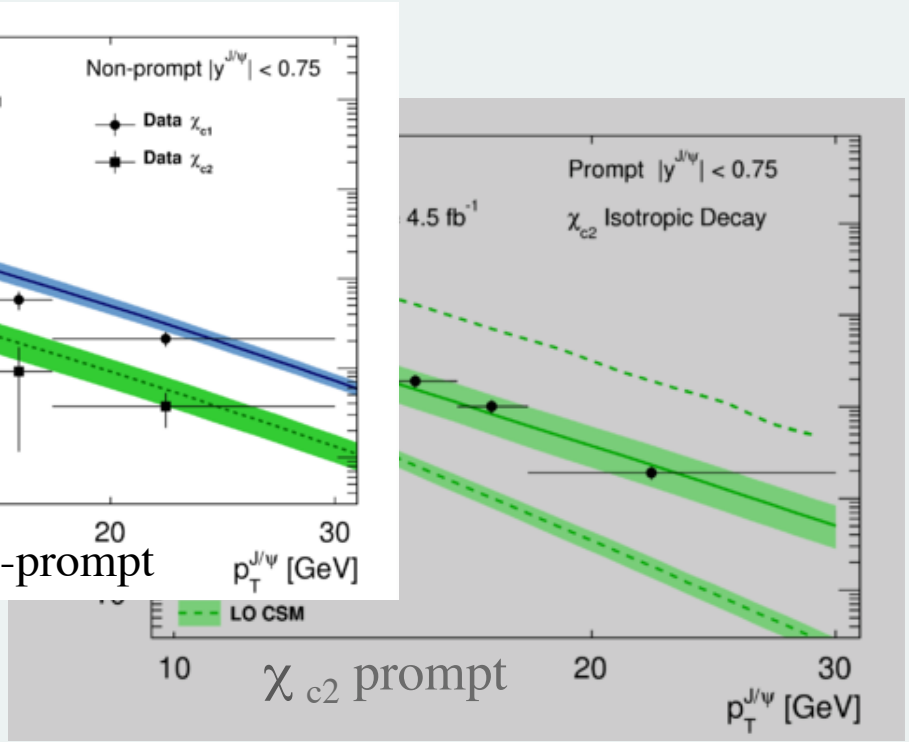
JHEP 07 (2014) 154

χ_c Production



χ_{c1} prompt

χ_{cJ} non-prompt



χ_{c2} prompt

More problematic (at all p_T) for current k_T / CSM predictions

Non-prompt production in agreement (limited p_T/statistics)

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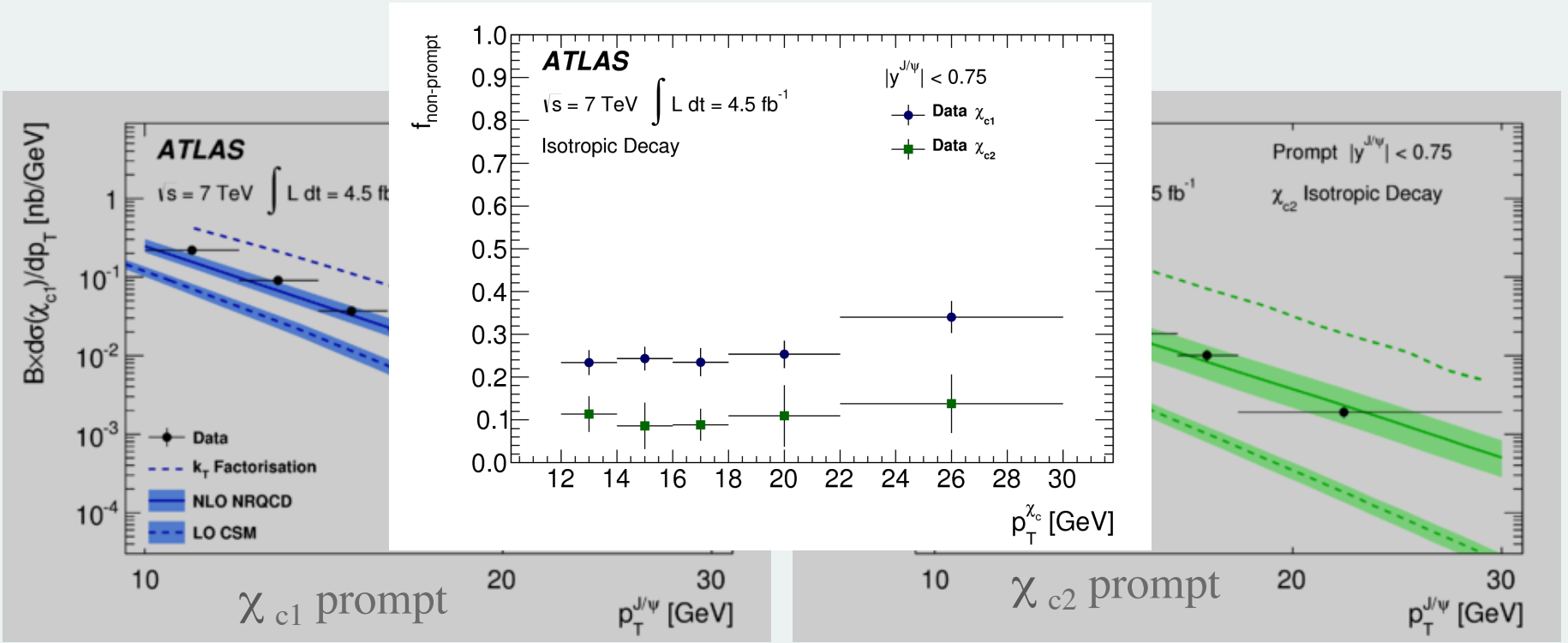
χ_c Production



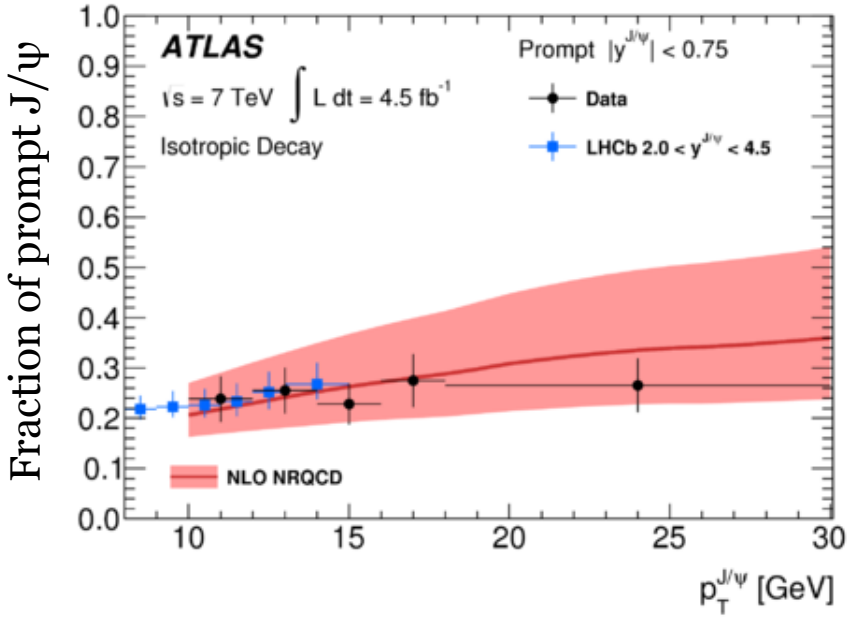
More problematic (at all p_T) for current k_T / CSM predictions

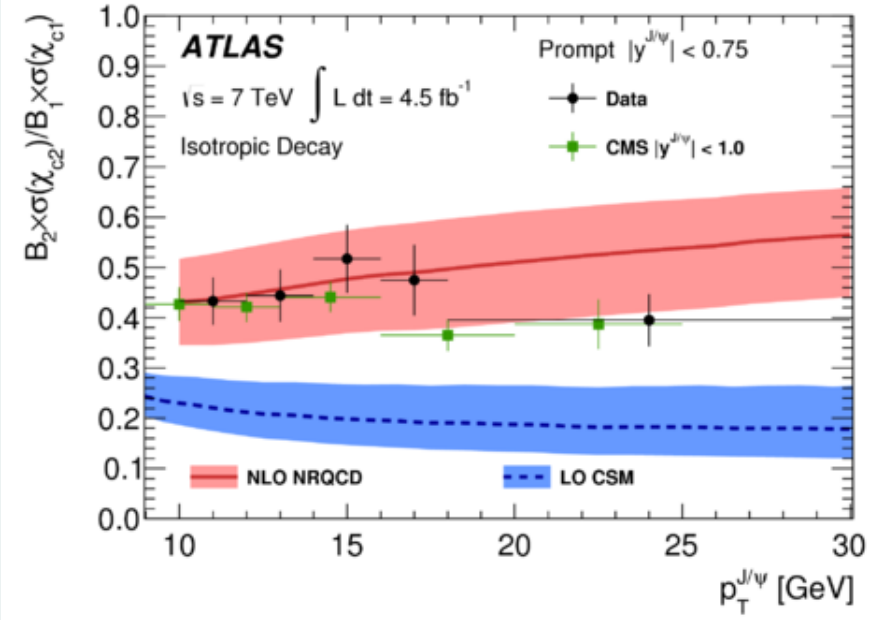
Non-prompt production in agreement (limited p_T/statistics)

Production is mostly prompt (contrary to J/ψ and ψ(2s))

JHEP 07 (2014) 154

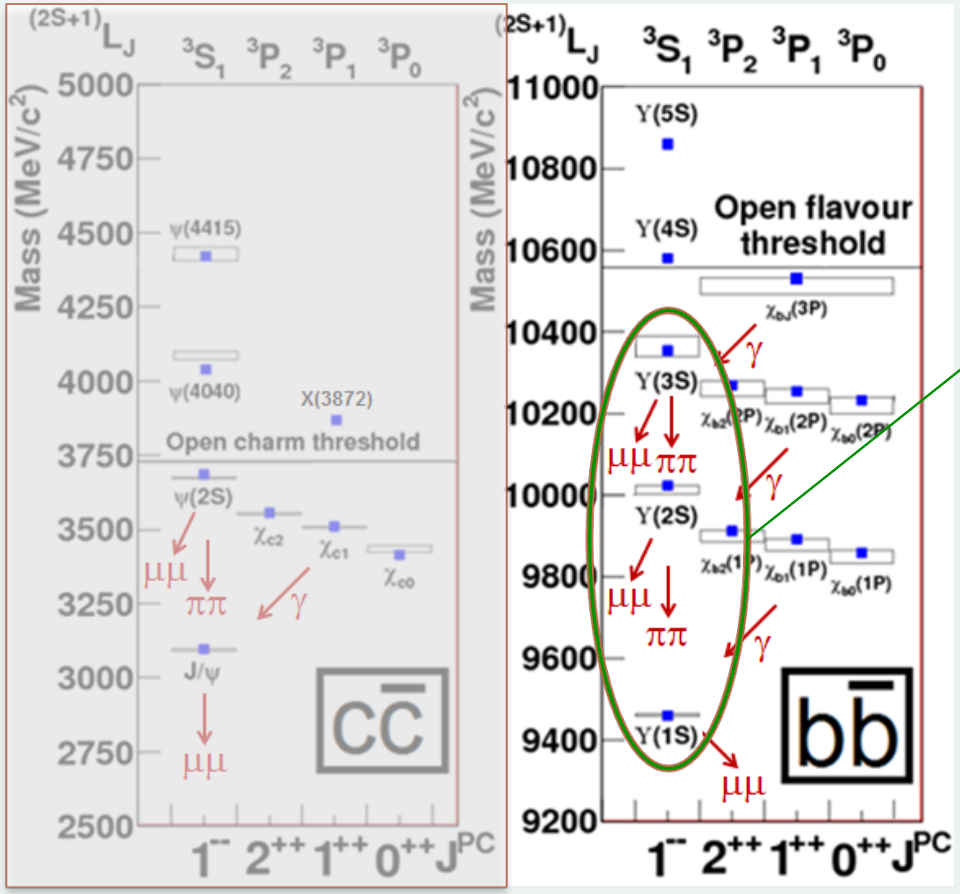
χ_c Production: Relative χ_c/J/ψ and χ_c/χ_c





Similar conclusions on CSM predictions

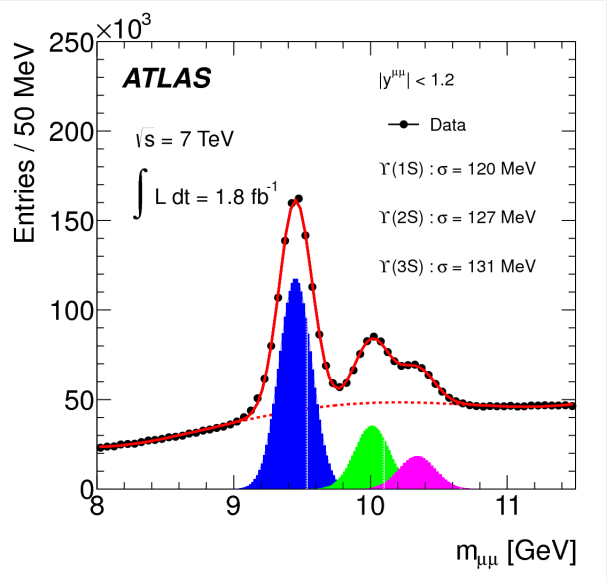
$q\bar{q}$ Production Measurements



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

PRD 87 (2013) 052004

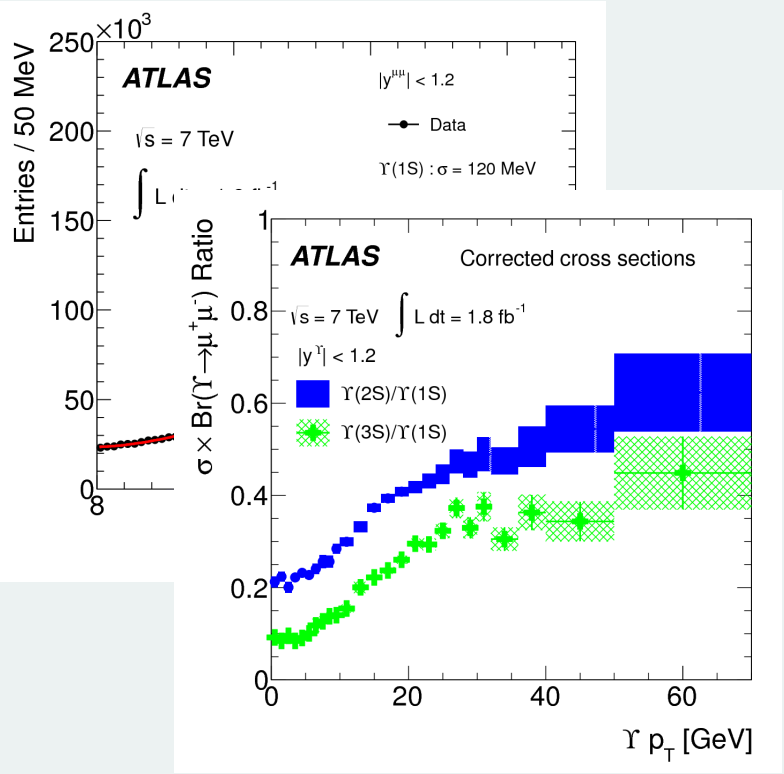
Υ(ns) Production



- Separation of Υ(1s, 2s,3s) in mass

PRD 87 (2013) 052004

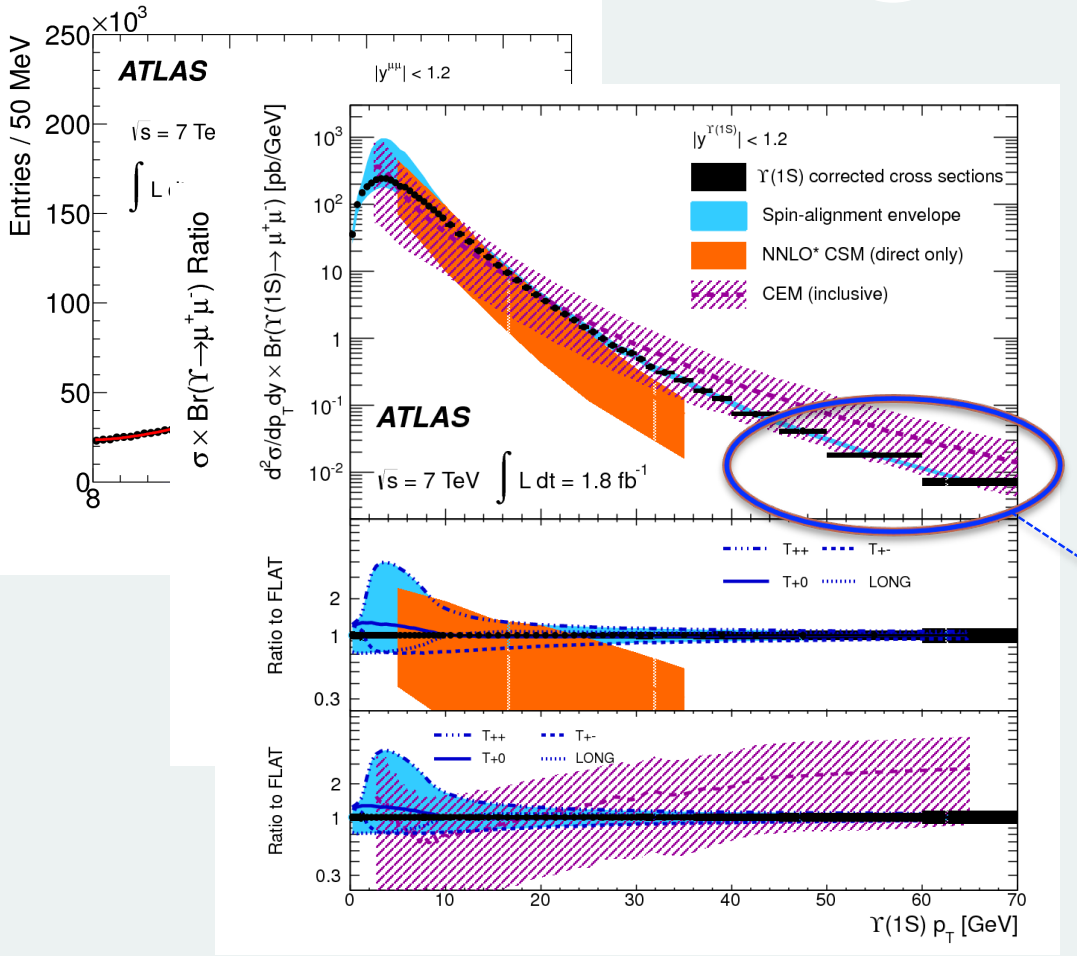
Υ(ns) Production



- Separation of Υ(1s, 2s,3s) in mass
- Cross sections:
  - Absolute Υ(1s)
  - Relative Υ(2s)/Υ(1s) and Υ(3s)/Υ(1s)

PRD 87 (2013) 052004

Υ(ns) Production



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- Cross sections:
  - Absolute Υ(1s)
  - Relative Υ(2s)/Υ(1s) and Υ(3s)/Υ(1s)

Disagreement with theory (NNLO CSM & CEM) at high p_T (where spin-alignment and feed-down effects are less important)

ATLAS-PHYS-PUB-2011-12
PRD 85 (2012) 052005

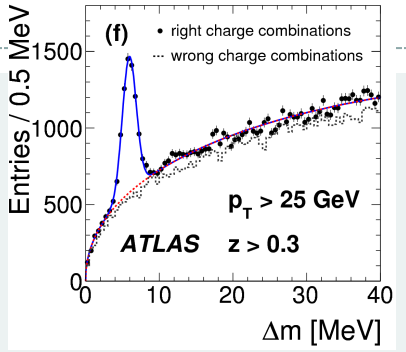
Open Charm

- Charm production
  - In Jets

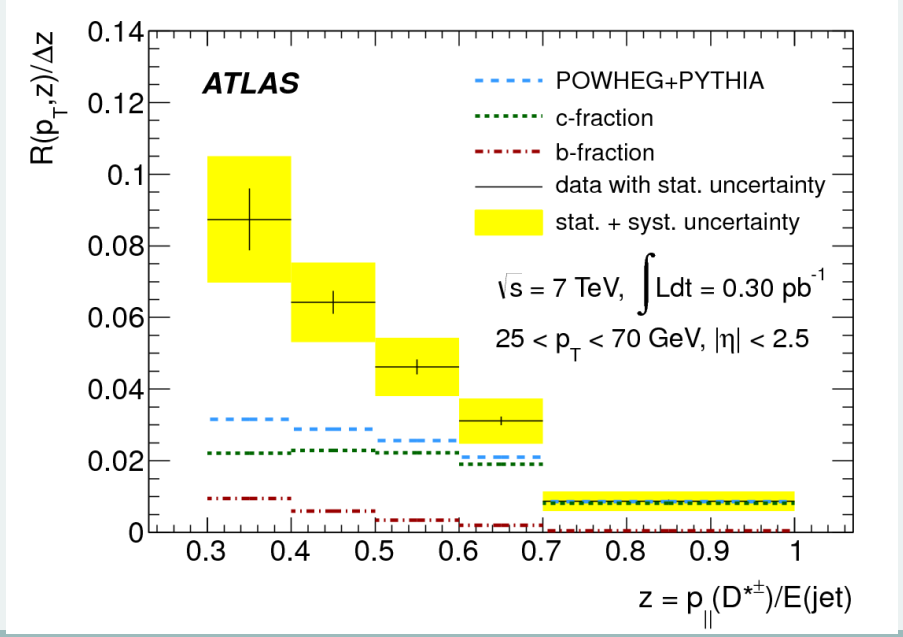
PRD 85 (2011) 052005

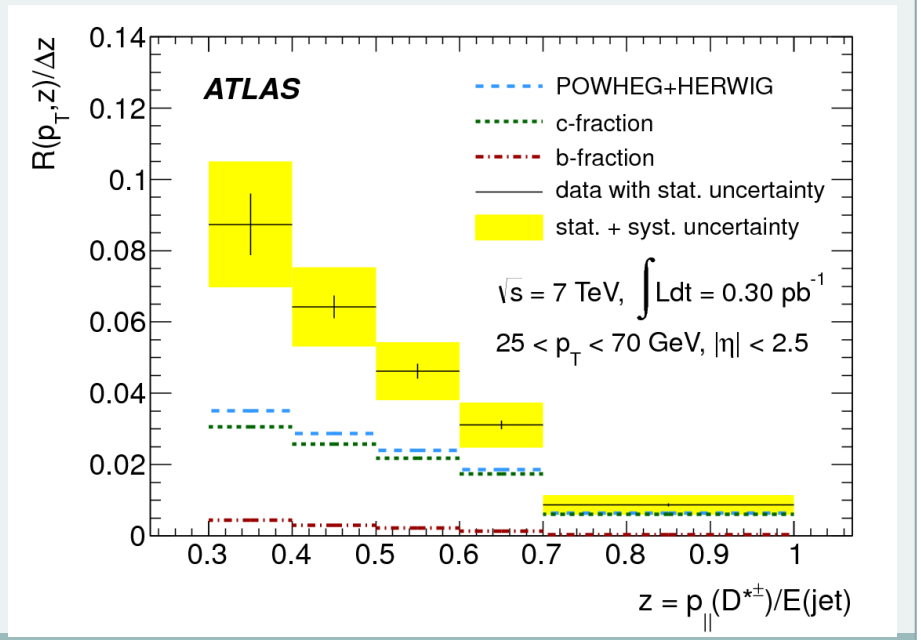
$D^{*\pm} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$

Anti-kT $\Delta R<0.6$ topological cluster



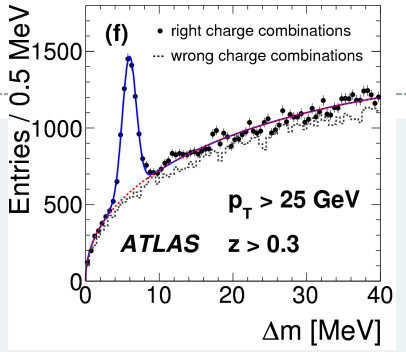
LO+ p_T/angular ordered model inconsistent, esp. at low z





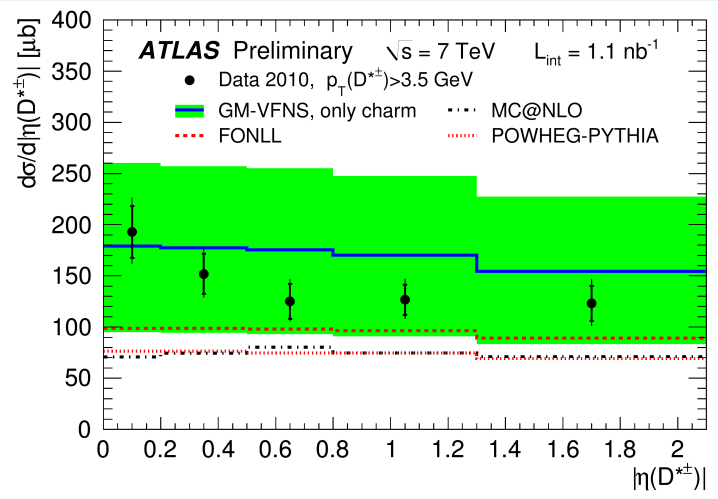
ATLAS-PHYS-PUB-2011-12
PRD 85 (2012) 052005

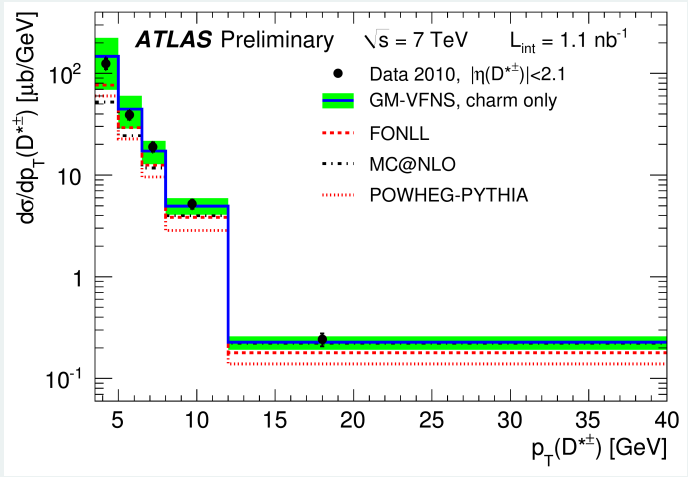
Open Charm



- Charm production
  - In Jets

    LO+ p_T/angular ordered model inconsistent, esp. at low z
  - Inclusive: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$

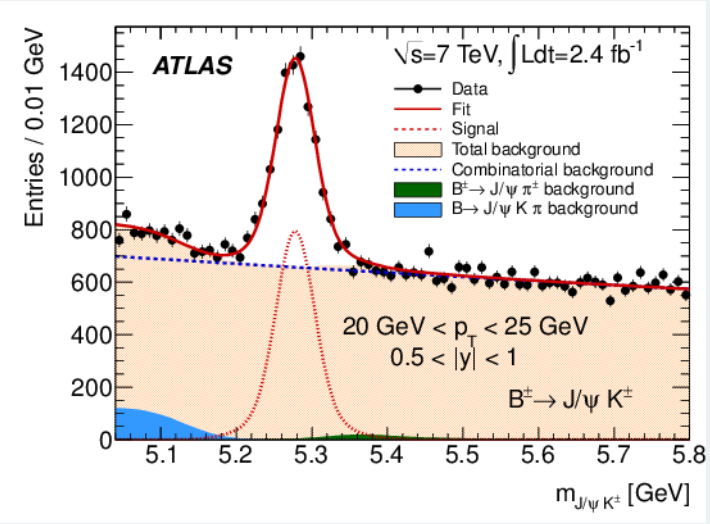




All consistent with models based on perturbative QCD with large theory uncertainties

JHEP 10 (2013) 042

Open Beauty



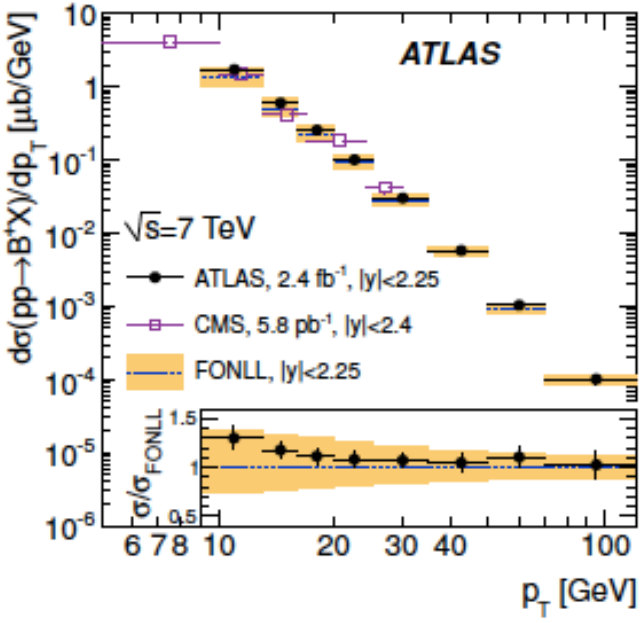
$$\frac{d^2\sigma(B^+ + X)}{dp_T dy} \cdot Br(B^+ \to J/\Psi + K^+)$$

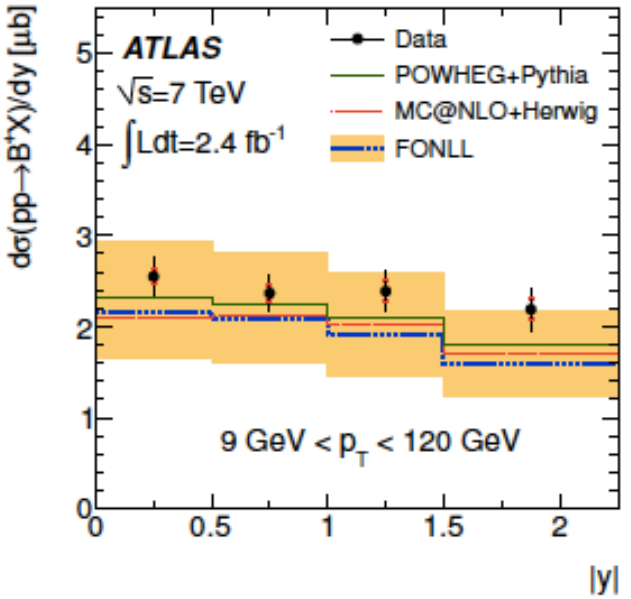
$$p_T^{(B^+)} \geq 9\ GeV, \quad |y^{(B^+)}| \leq 2,25$$

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

Results consistent with available production and fragmentation predictions

...tend to undershoot data?

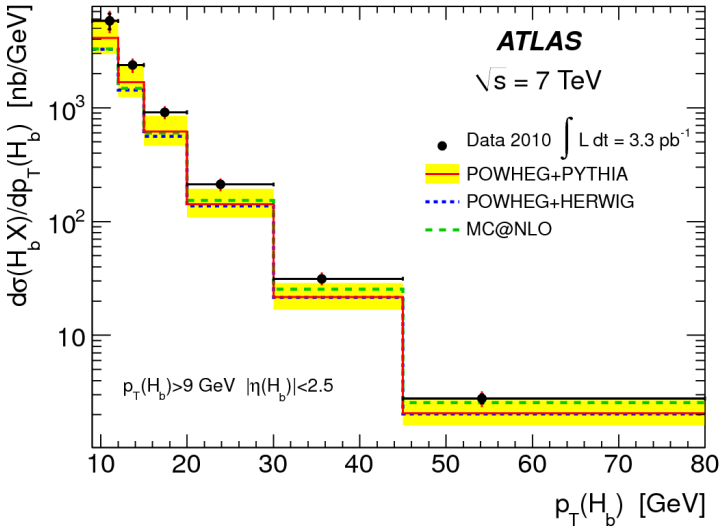


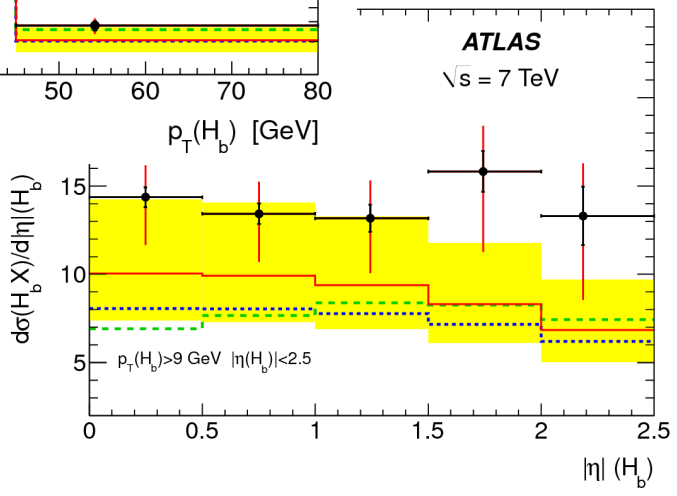


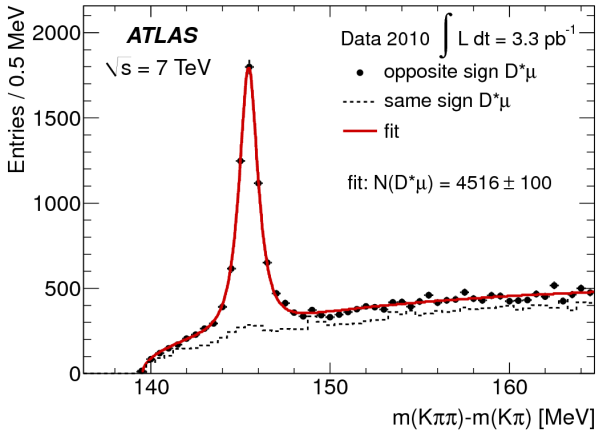
NPB 864 (2012) 341

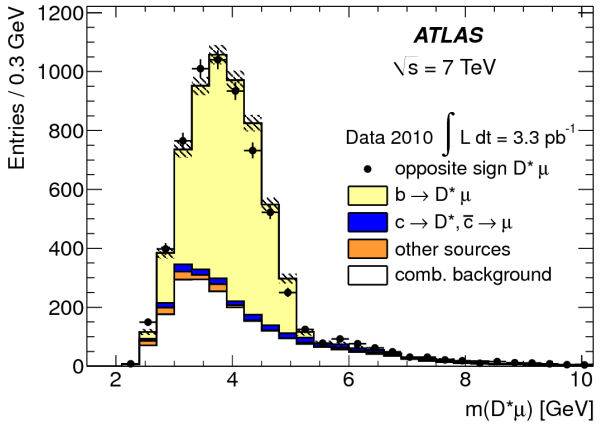
Open Beauty in Jets

$\sqrt{s}$=7 TeV, |y| < 2.5, 10< p_T< 80GeV









NLO models slightly underestimate the observed rates

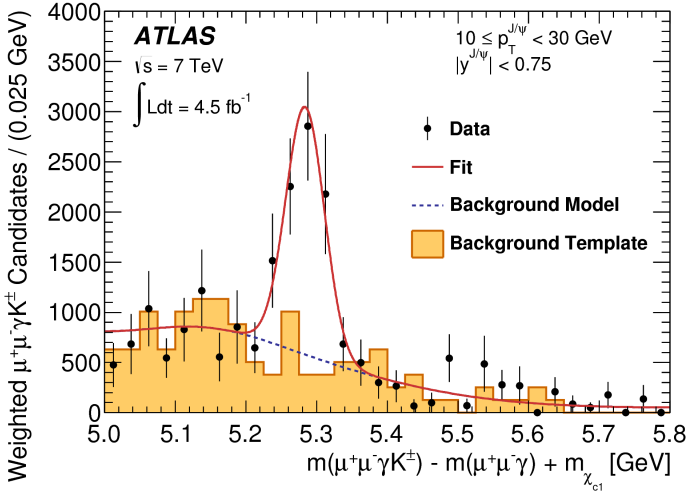
Shapes reasonably reproduced by several MC models

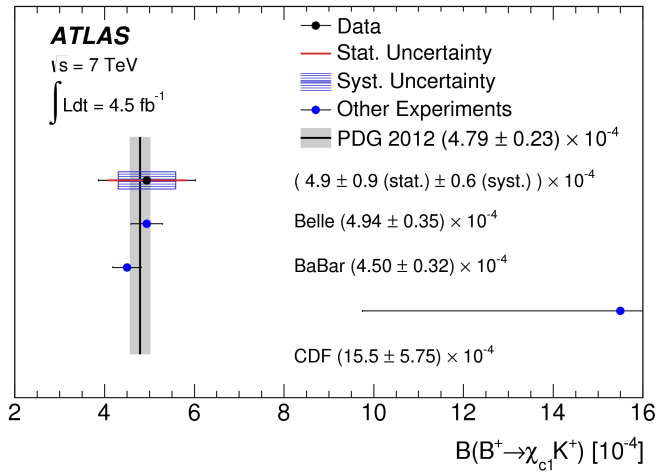
JHEP 07 (2014) 154

$Br(B^+ \rightarrow \chi_{c1} K^+)$

- Sub-set of non-prompt χ_{c1} candidates
  - $J/\psi K^+$ used as control/ reference
- $BR(B^+ \rightarrow \chi_{c1} K^+) =$

  $4.9 \pm 0.9_{stat} \pm 0.6_{sys} \times 10^{-4}$
- Good agreement and big improvement wrt previous hadron collider measurements
- Uncertainties statistical → expect improvements!



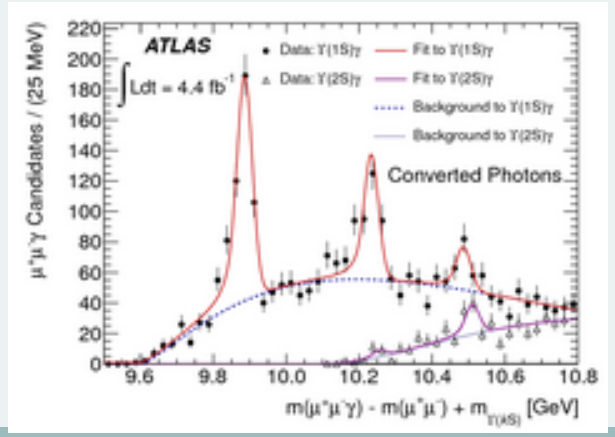


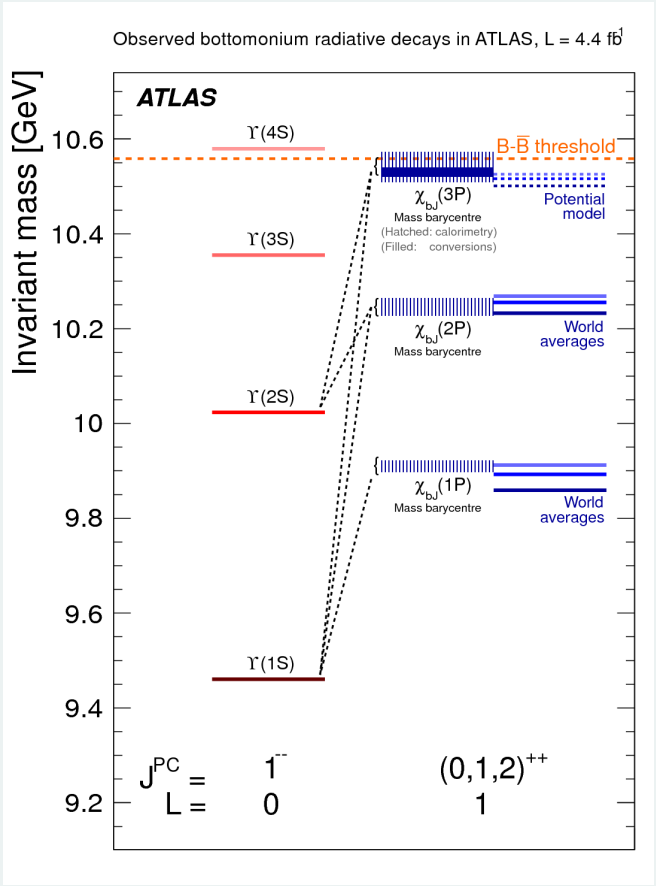
Spectroscopy

PRL 108 (2012) 152001

Bottomonium: $\chi_b(3P)$

- First particle discovered at the LHC!
- ATLAS discovery (end 2011)
- Confirmed (with lower significance) by:
  - LHCb: CONF-2012-020 / PRD 86 (202) 031103(R)
  - Do

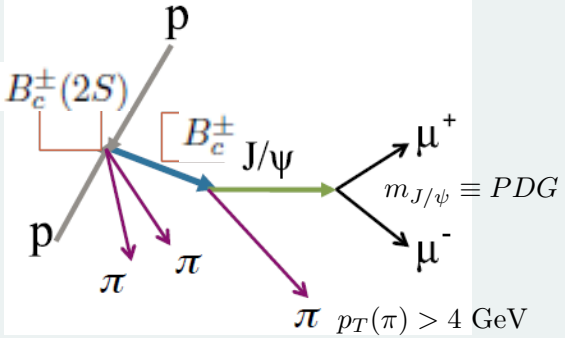


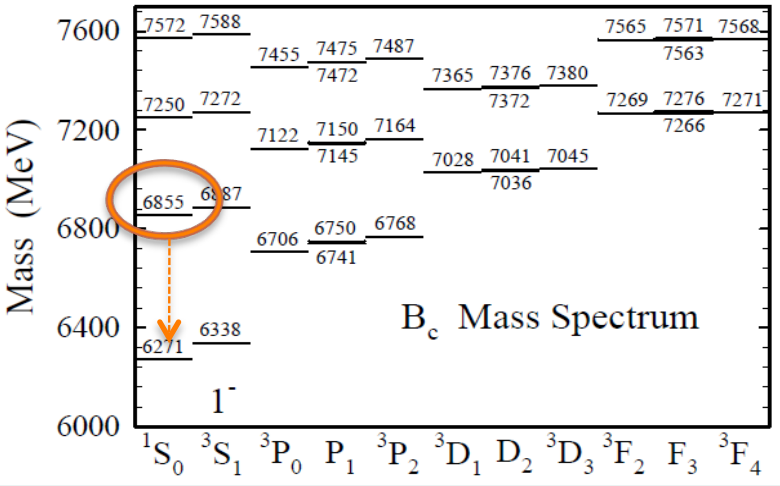


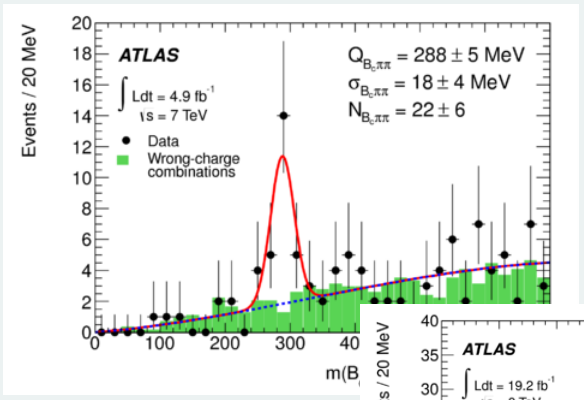
arXiv:1407.1032, Accepted by PRL

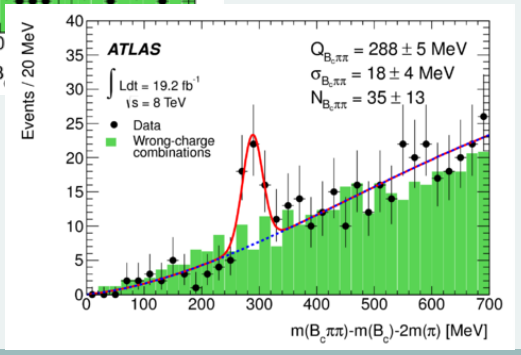
Open Beauty: the observation of the $B_c(2s)$

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









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

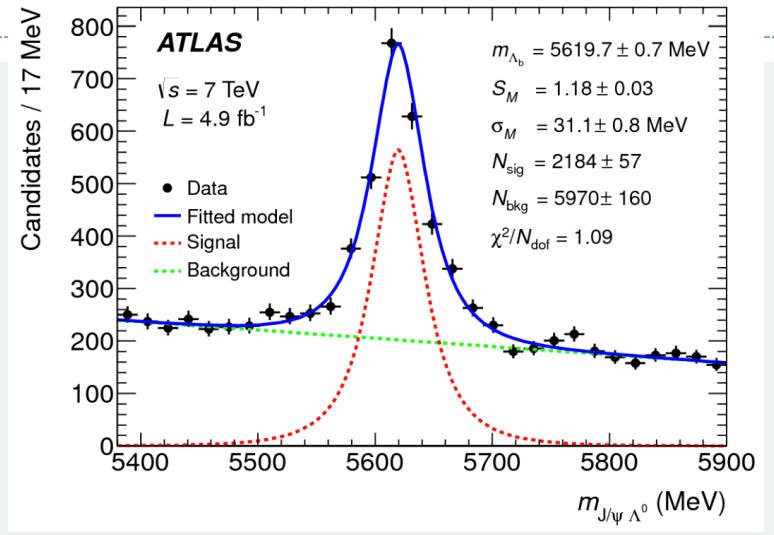
$$\sigma_{B_c^*}^{peak} \approx (18 \pm 4) \text{ MeV}$$

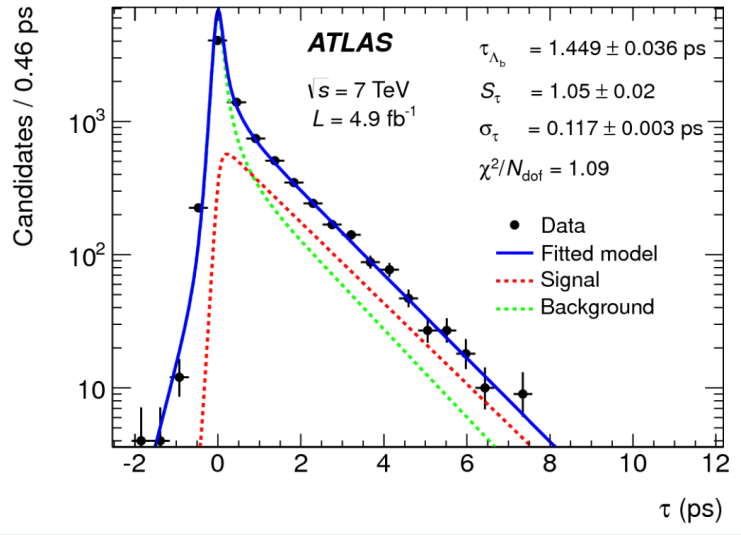
Combined significance: 5.2 σ

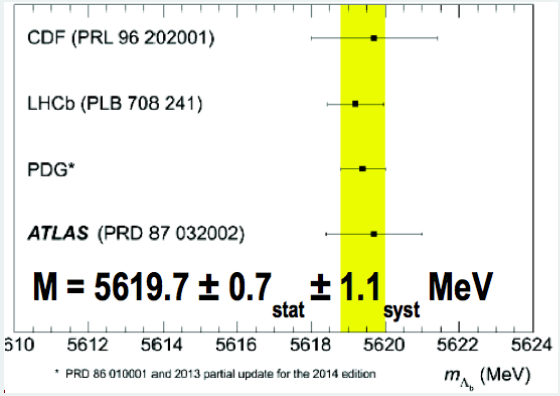
- M=(6442±4±5) MeV
- Q=(288.3±3.5±4.1)MeV

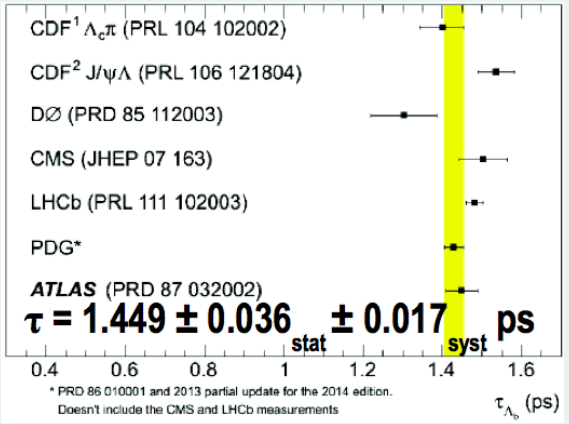
PRD 87 (2013) 032002

Λ_b Mass & Lifetime





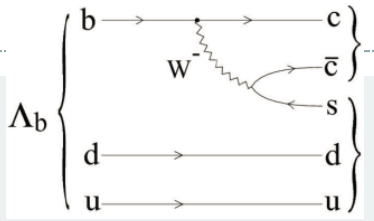




Flavour Observables and Searches For New Physics

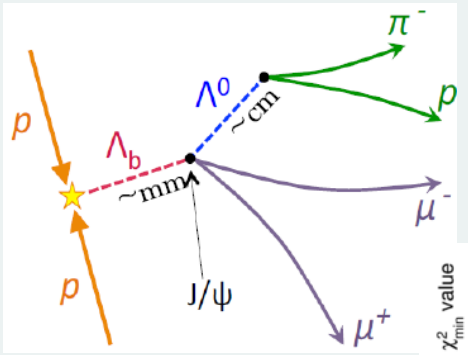
PRD 89 (2014) 092009

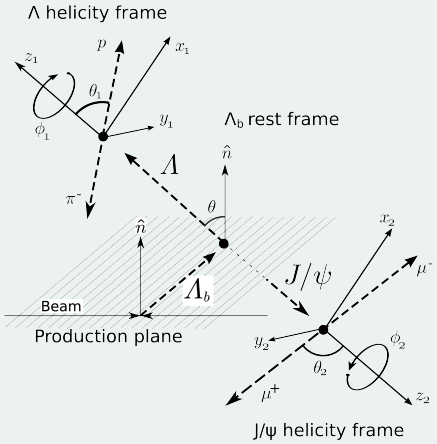
Parity Violation in $\Lambda_b \to J/\psi \Lambda^0$



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

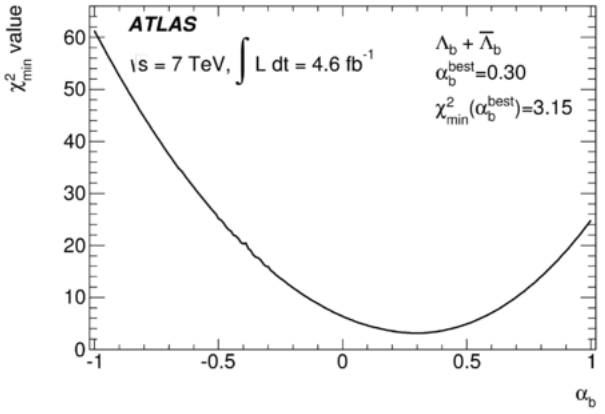
Violation not maximal $\Rightarrow |\alpha| < 1$





- Measure moments (F_i) of the angular distribution
- Minimize:

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



Four possible helicity amplitudes:

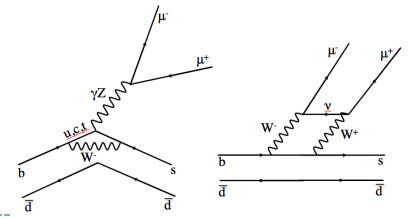
Amplitude	$\lambda_{J/\psi}$	λ_Λ
a_+	0	1/2
a_-	0	-1/2
b_+	-1	-1/2
b_-	1	1/2

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

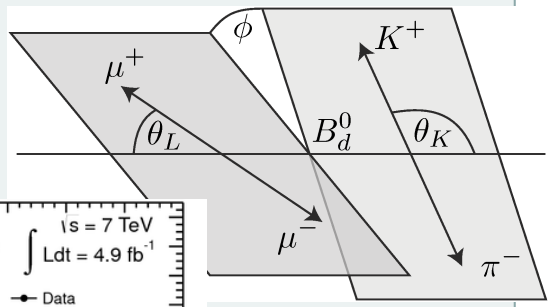
$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

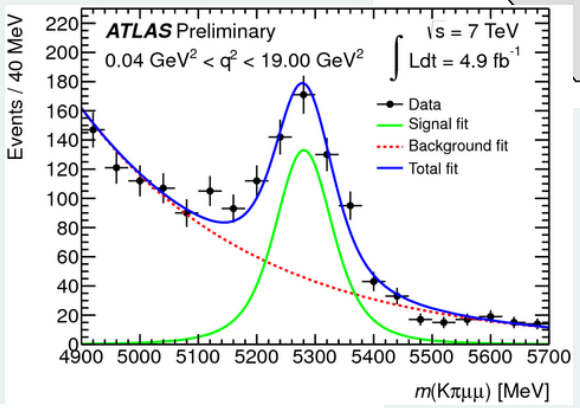
- consistent with $\alpha_{LHCB} = 0.05 \pm 0.17 \pm 0.07$
- $\alpha_{HQET} = 0.78$ and $\alpha_{pQCD} = -(0.14 \div 0.17)$
- Ongoing analyis of 2012 data

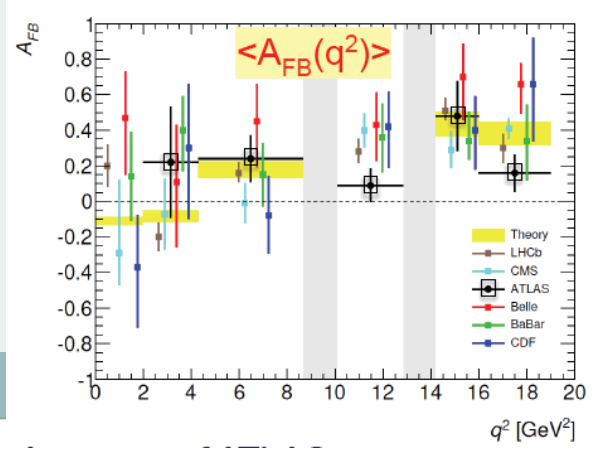
NP in $B_d \to K^{*0}(K^{\pm}\pi^{\mp})\mu^+\mu^-$

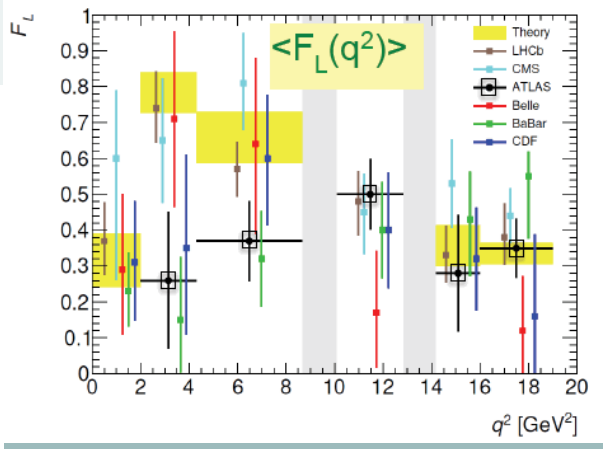


- b→sll transition
  - SM: loop-mediated ⇒BR≈1.1×10^{-6}
- Sensitive to BSM contributions
  - A_{FB}: Lepton forward/backward asym.
  - F_L: K^{*0} longitudinal polariz.
- ML Fit to angular distribution ⇒ (A_{FB},F_L) in q^2-intervals
  - q^2<2 GeV^2 statistically limited
  - Removed ψ(ns)→μμ(γ)
  - N_{sig}=466±34 N_{bck}=1132±43







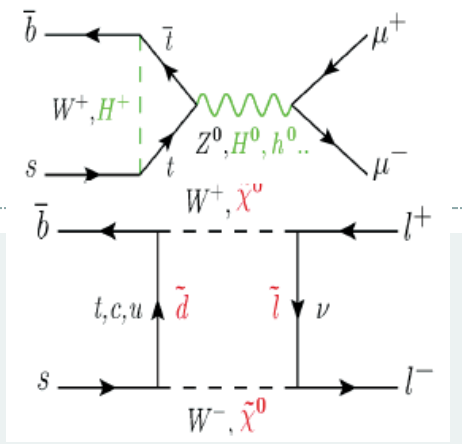


Stat. dominated ⇒ improve with $\mathscr{L}$

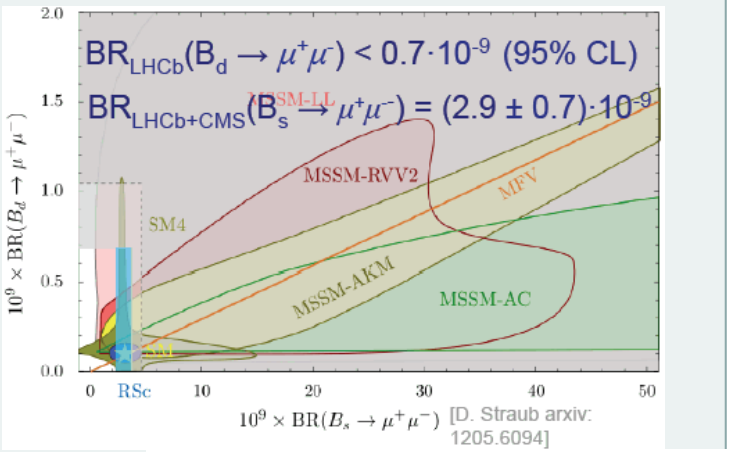
Ongoing analysis of 2012 data (more data, improved fit)

ATLAS-CONF-2013-076

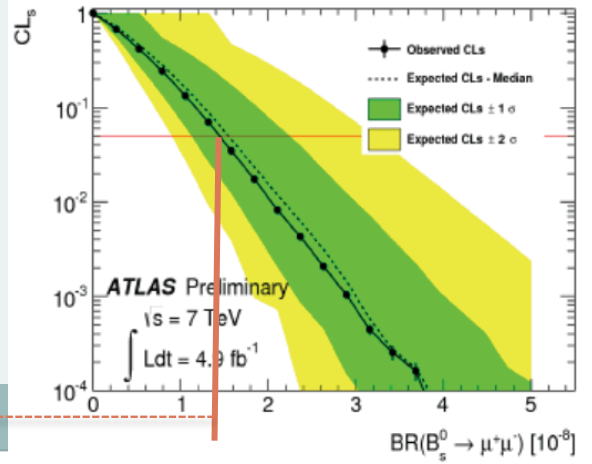
NP in $B_{d/s} \to \mu^+\mu^-$



- Highly suppressed in SM
  - SM $BR(B_s \to \mu\mu) \simeq (3.27 \pm 0.27) \times 10^{-9}$ [Buras et al., EPJC72(2012) 2172]
  - CMS+LHCb measure $BR(B_s \to \mu\mu) \simeq (2.9 \pm 0.7) \times 10^{-9}$ [arXiv 1307.5024, arXiv 1307.5025]
- Sensitive to BSM contributions
  - BR
  - $R = BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu)$
- ATLAS, 5 fb^{-1}:
  - Fully blind analysis
  - $B^+ \to J/\psi K^+$ as reference mode
  - Data-driven BDT training: distinguish $S/B_{nonresonant}$
  - Single Event Sensitivity: $(2.07 \pm 0.26_{STAT}) \times 10^{-9}$
  - Main systematics: BR(B+), f_u/f_s and εA ratio



$BR(B_s \to \mu\mu) < 1.6 \times 10^{-8}$ @ 95% CL

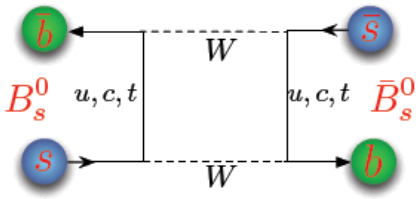


Ongoing analysis of 2012 data:

- 20 fb^{-1} of data, similar acceptances and ε as 2011
- Improved fake μ rejection
- Mass-dependent S and B models in BDT bins

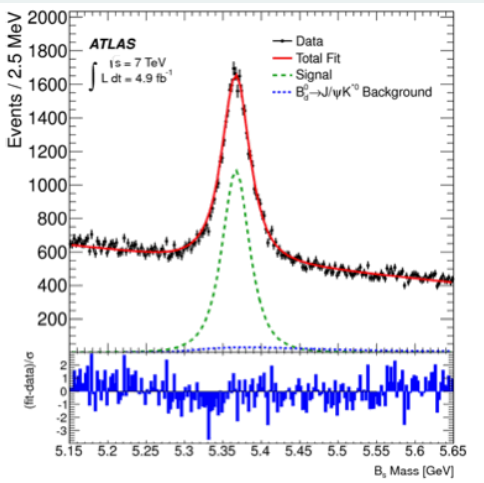
PRD 90 (2014) 052007

NP in $B_s \rightarrow J/\psi\phi$

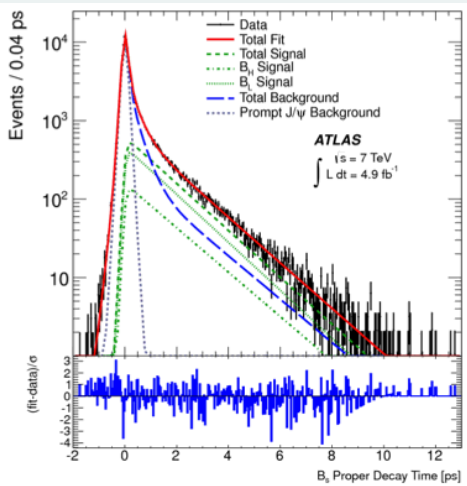


- Sensitive to $\Delta f=2$ (ϕ_s,$\Delta\Gamma_s$)
- arXiv 1407.1796, PRD: 2nd version of 2011 analysis, including flavour tagging
  - Fit: mass+lifetime+angular variables +initial B_s flavour

Tagger	Tagging Power [%]
Combined μ	0.86 ± 0.04
Segment Tagged μ	0.15 ± 0.02
Jet charge	0.45 ± 0.03
Total	1.45±0.05



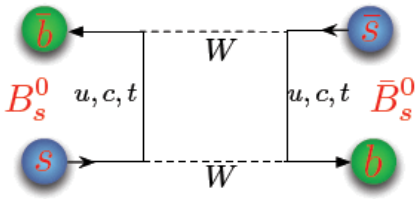
Mass fit projection for $B^0_s \rightarrow J/\psi\,\varphi$



Proper decay time t estimated by

PRD 90 (2014) 052007

NP in $B_s \to J/\psi\phi$



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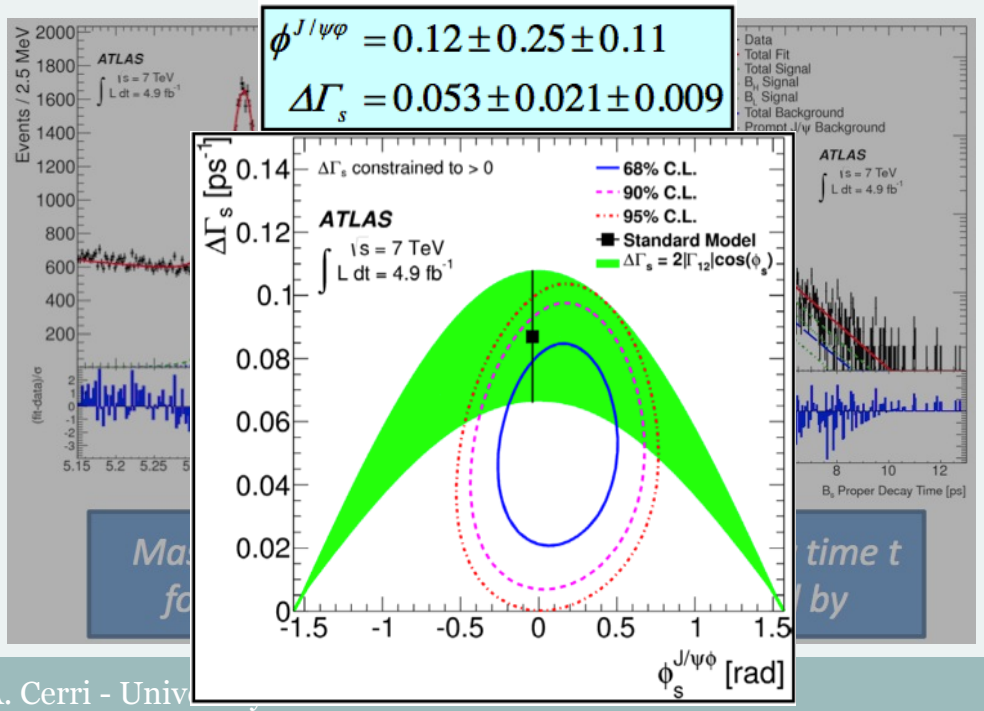
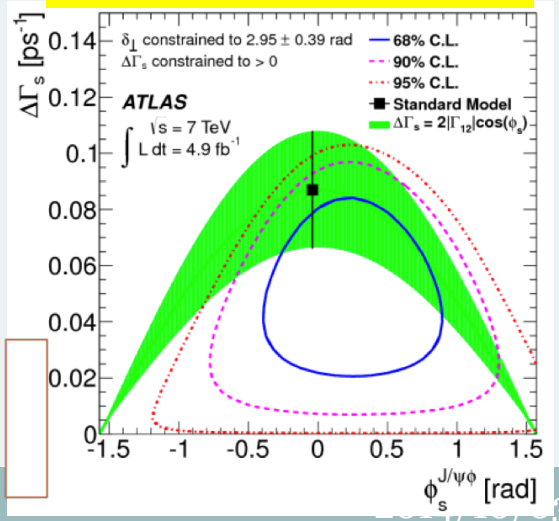
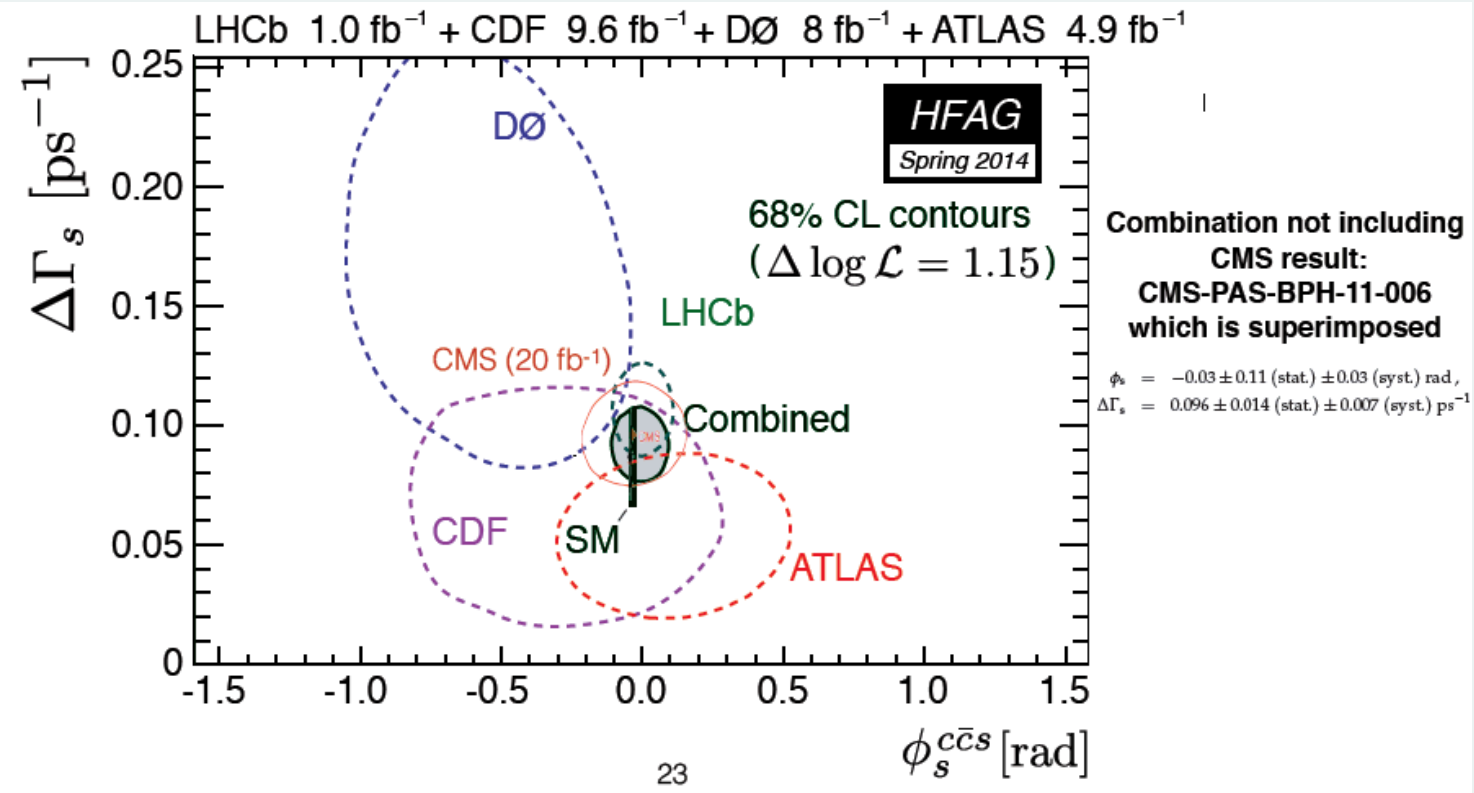


Previous (untagged) Analysis



Combined Results



- CMS result overlaid “by hand” (sorry!)
- Not the final word from ATLAS: 2012+2011 result coming soon!

ATLAS-PHYS-PUB-2013-010

Run II Prospects

- B physics program will continue in Run II
  - Increased statistics
  - Improved detector performance (e.g. cτ resolution)
  - Improved trigger strategies
  - No degradation of performance expected with increased $\mathscr{L}$
- Example → ϕ_s

	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

Conclusions

- Rich and varied HF physics program
  - QCD
  - Flavour
  - New Physics
- Few highlights:
  - Discovery of $\chi_b(3P)$
  - Heavy b-states: B_c, Λ_b
    - Observation of $B_c(2S)$
  - Best (at time of publication) measurement of Λ_b lifetime
  - J/ψ, χ_c, Y, B, D… cross sections up to p_T~70 GeV
  - "Semi-rare" $B \to K^* \mu\mu$
  - Rare decay $B_s \to \mu\mu$
  - CP violation in $B_s \to J/\psi\phi$

2012+2011 combined results coming!

More to come from Run I data, and new exciting results ahead in Run II

Back-up Material

Key Performance Aspects

- Tracking efficiency: ε_{trk} =99%
- Mass Reconstruction
  - $(\mu^+\mu^-) \Rightarrow J/\psi, \Upsilon$
  - $(J/\psi + trks) \Rightarrow \Psi$, exclusive B
  - $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ "resolution"

- $(\sigma_{pT}/p_T) \approx 0.05$ up to 60 GeV
- $\sigma_m \sim (50-100)$MeV
- high S/B