Overview of B Physics Results from the ATLAS Experiment

Tenth Conference in the Symposium on Cosmology and Particle Astrophysics Series

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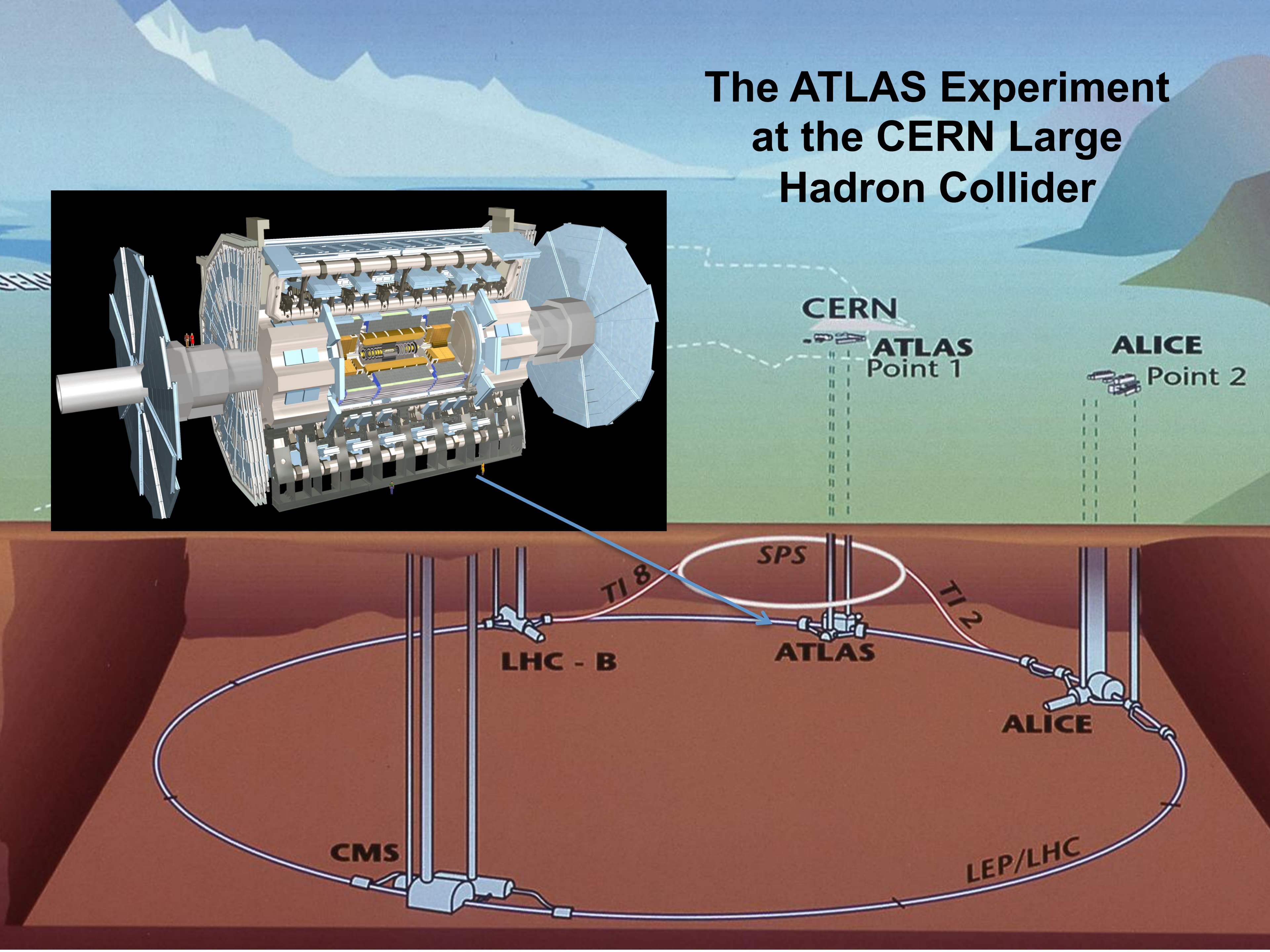
on behalf of the ATLAS Collaboration

The ATLAS Experiment at the CERN Large Hadron Collider



This talk reflects the work of 3000 people from 38 countries.

All of the topics presented here have been announced within the past 14 months.

They are based on data collected in 2011 at 7 TeV center-of-mass energy, and in 2012 at 8 TeV.

These 9 results are a sample of over 100 papers submitted by ATLAS for publication during this period.

Please note the other ATLAS talks by:

Mark Kruse: **ATLAS as a tool for understanding the universe**
Arnaud Lucotte**: Top quark measurements**
Jean-Francois Laporte**: Standard Model studies**
Stefania Xella**: Higgs measurements**
Michele Bianco**: SUSY searches**
James Frost**: Dark matter searches**

Placing a microscope on QCD at the perturbative/non-perturbative boundary:

The Parity-Violating Asymmetry Parameter and Helicity Amplitudes for $\Lambda_b^0 \rightarrow J/\psi\Lambda^0$

J/ψ - $W^{\pm}$ associated production

J/ψ - Z^0 associated production

Prompt and non-prompt $\psi(2S)$ production

χ_{c1} and χ_{c2} production

B^+ production

Discovery of a new particle and its impact on Strong Interaction models:

Observation of an Excited $B_c^{\pm}$ Meson

Search for Hidden Beauty as a way to make sense of Hidden Charm:

Search for the X_b

Search for New Physics:

A measurement of the $B_s^0 \rightarrow J/\psi\phi$ decay parameters

Search for the X_b and other hidden-beauty states in the $\pi^+\pi^-\Upsilon(1S)$ channel

16.2 fb^{-1}@ 8 TeV

$X(3872)$: a narrow resonance, discovered in $B^{\pm} \to K^{\pm}X\left(\to \pi^+\pi^- J/\psi\right)$, existence well-confirmed by several experiments in e^+e^- and $p\bar{p}$, decays strongly to D^0 and J/ψ final states. Interpreted as "hidden charm" (equal amounts c and $\bar{c}$), candidate for tetraquark or $D^0\bar{D}^{*0}$ "molecule."

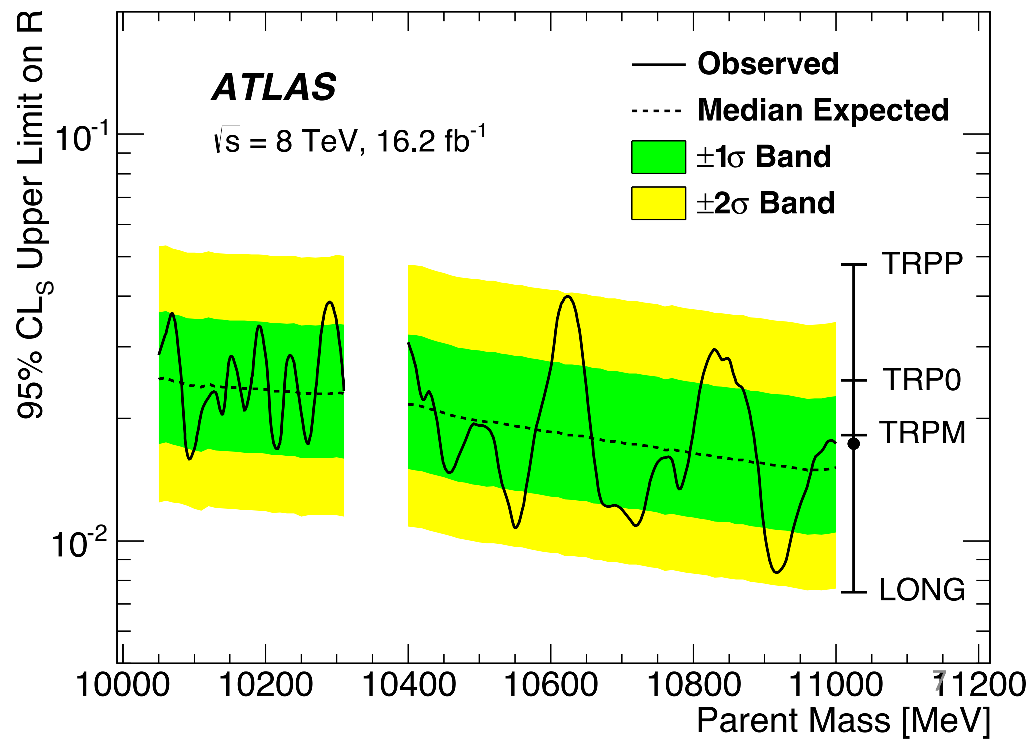
Heavy quark symmetry suggests: an analogous "hidden-beauty" X_b should exist in mass range 10.492 - 10.682 GeV.

Search in channel $X_b \to \pi^+\pi^-\Upsilon(1S)\left(\to \mu^+\mu^-\right)$. Validate search by reconstructing $\Upsilon(2S)$ and $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)\left(\to \mu^+\mu^-\right)$.

arXiv:1410.4409 [hep-ex], to be submitted to PLB

Results of the search :

- $\Upsilon(2S)$ and $\Upsilon(3S)$ observed, yields consistent with expectation.
- Hypothesis test applied for X_b peak for every 10 MeV from 10 GeV to 11 GeV, assuming narrow peak, with three-body phase space decay characteristic and $(|y|, p_T)$ differential cross-section similar to $\Upsilon(2S)$, $\Upsilon(3S)$.
- Search uses 8 bins in y, p_T, and angle between dipion and parent. Apply simultaneous fit to the search region and the nearby $\pi^+\pi^-\Upsilon(1S)$ spectrum.
- No evidence for X_b : upper limits computed assuming production unpolarized, with offsets representing limiting case effects of J/ψ polarization states on acceptance.
- Limits range from 0.8% to 4.0% in ranges [10.05-10.31] and [10.40-11.00] GeV. Above 10.1 GeV these are the most restrictive to date.



Observation of an excited $B_c^{\pm}$ meson state

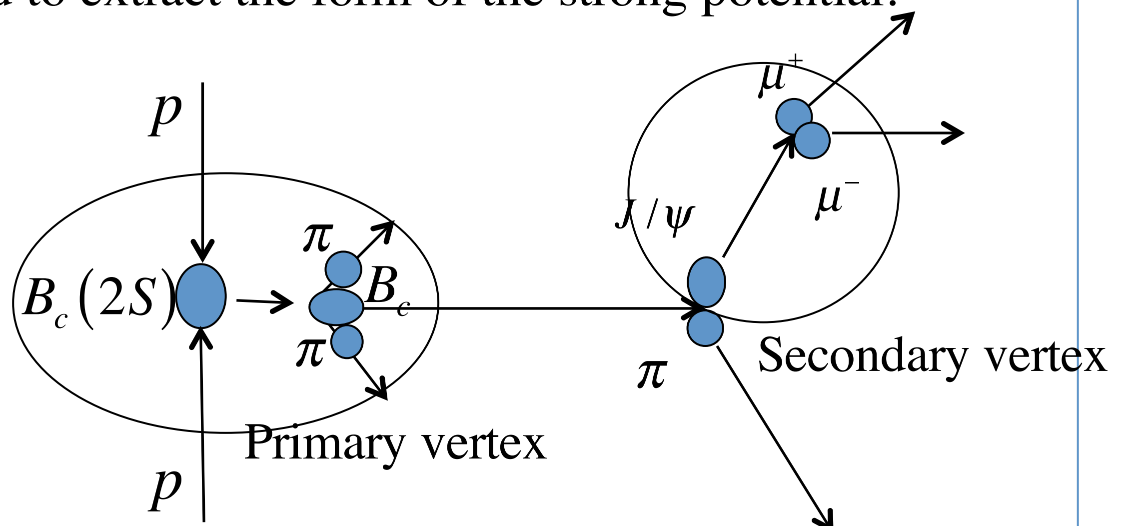
4.9 fb^{-1} @ 7 TeV, 19.2 fb^{-1} @ 8 TeV

Phys. Rev. Lett. 113 (2014) 212004

The B_c is a bound state of (b,c) quarks. No states above ground [$B_c(1S)$, 6.2756 GeV] have been previously observed. B_c is strongly produced and decays weakly.
Its spectrum can be applied to test predictions of non-relativistic potential models, pQCD, and lattice calculations, and to extract the form of the strong potential.

Search for: $B_c(2S) \to B_c(1S)\pi^+\pi^-$;
$B_c(1S) \to J/\psi\pi^{\pm}$; $J/\psi \to \mu^+\mu^-$.

Theoretical predictions span the mass range 6835 - 6917 MeV.

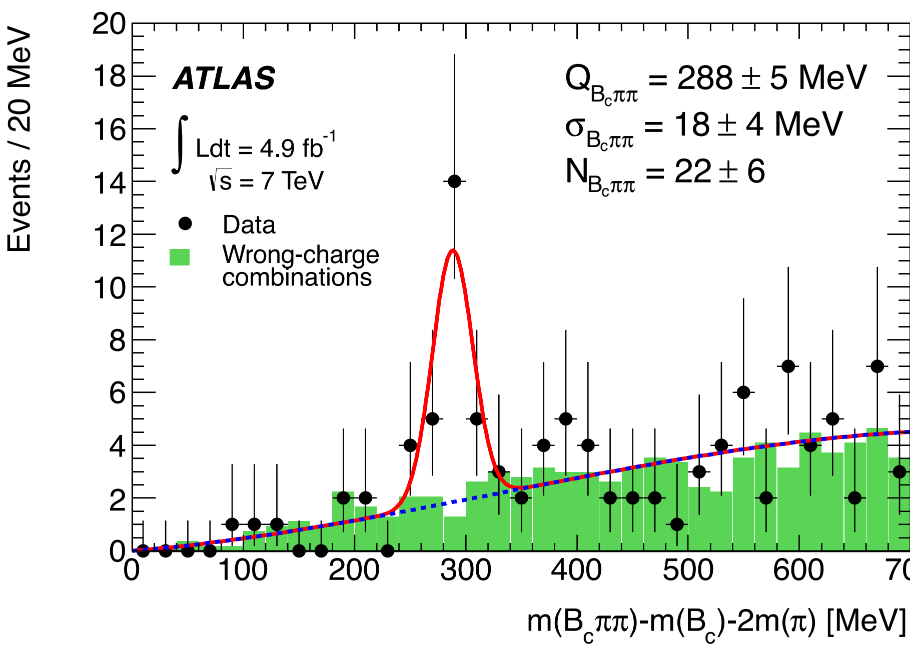


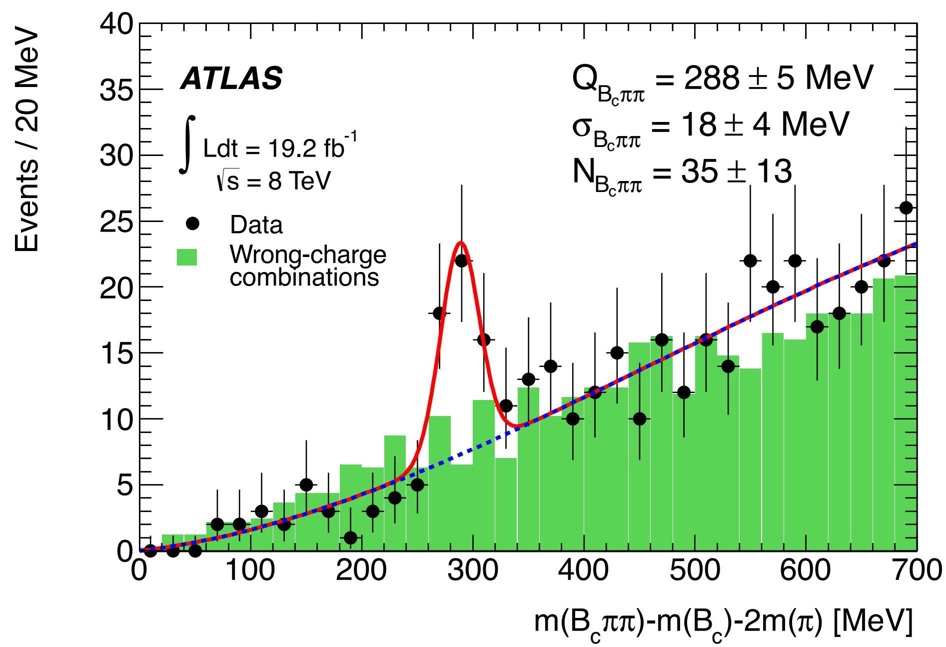
Do not resolve pseudoscalar-vector splitting at the 1S or 2S level.
Take advantage of: a 2-vertex event structure, clean J/ψ dimuon signature.
Cancel some systematics by searching in the mass difference spectrum:

$$Q \equiv m\left(B_c^{\pm}\pi\pi\right) - m\left(B_c^{\pm}\right) - 2m\left(\pi^{\pm}\right).$$

Result of the search :

- Signal observed independently in 2011 and 2012 data at $Q = 288.3 \pm 3.5 \pm 4.1$ MeV.
- Widths are gaussian, consistent with ATLAS resolution.
- Combined significance: 5.2σ.
- This corresponds to a new state of mass $6842 \pm 4 \pm 5$ MeV.





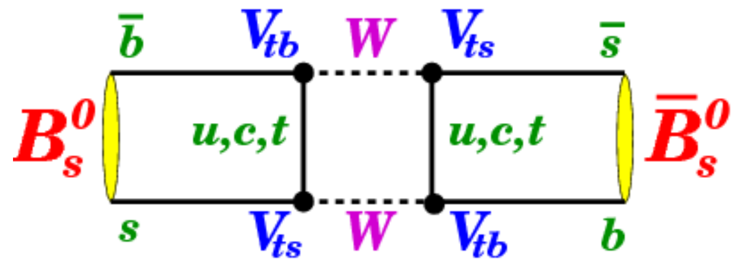
Flavor tagged time dependent angular analysis of the $B_s^0 \to J/\psi\phi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s

4.9 fb^{-1} @ 7 TeV

PRD 90 (2014) 052007.

New physics may alter CP violation in $B_s^0 \to J/\psi\phi$ decays.

CP violation occurs due to interference between direct decays and decays involving $B_s^0 - \bar{B}_s^0$ mixing.



$B_s^0 - \bar{B}_s^0$ oscillation is characterized by a mass difference between mass eigenstates, B_H and B_L.

This analysis measures two CP parameters:

(1) ϕ_s, the weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the Standard Model,

$$\phi_s \simeq -2\arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -0.037 \pm 0.002 \text{ rad}.$$

(2) width difference between the light and heavy eigenstates, $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$.

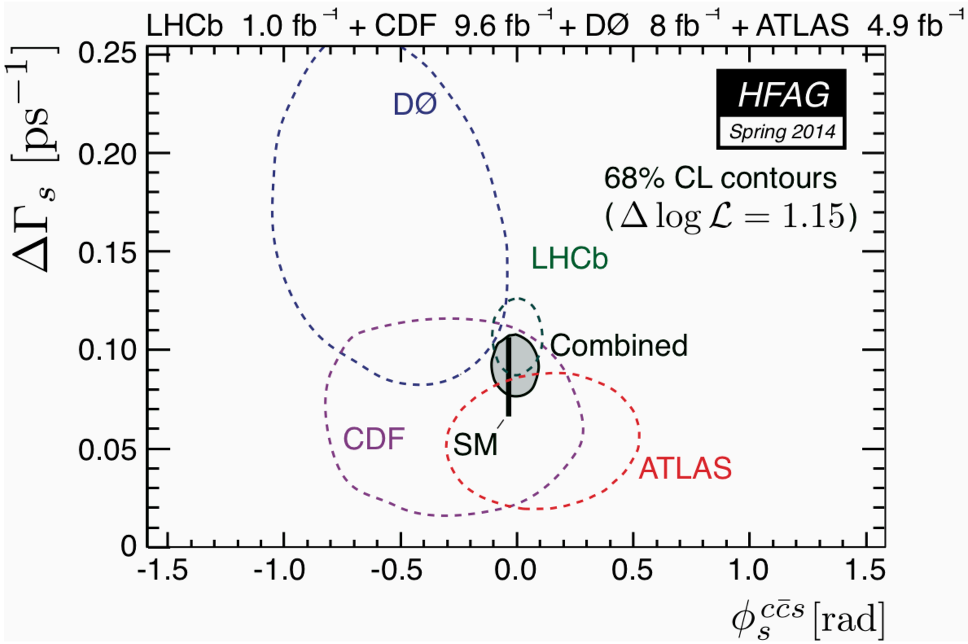
In the Standard Model, $\Delta\Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$.

(Pseudoscalar) $B_s^0 \to$ (vector) J/ψ + (vector) ϕ produces 3 orbital angular momentum states: $L = 0,2$ (CP-even) and $L = 1$ (CP-odd)

To improve precision on ϕ_s, flavor-tagging is used to determine if initial state is B_s^0 or $\overline{B}_s^0$. Time dependent angular analysis of the final states statistically separates them by CP.

A 25-parameter unbinned max likelihood fit is used to extract the parameters of the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi\left(K^+K^-\right)$ decay.

Result : Parameters (now improved in precision) are consistent with the Standard Model and with a previous ATLAS measurement.



Here: Likelihood contours for the measurement; SM prediction; results from other experiments; combined result.

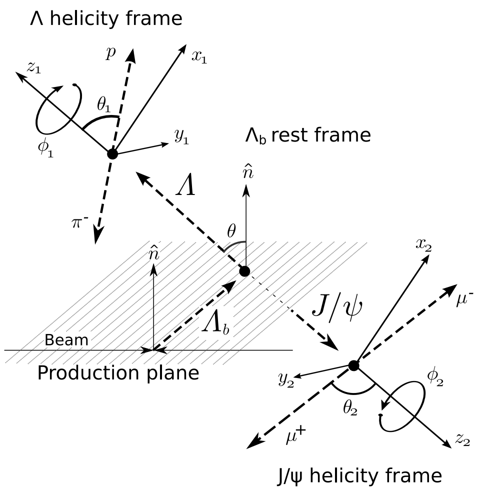
Measurement of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b^0 \to J/\psi\Lambda^0$

4.6 fb^{-1} @ 7 TeV

Parity violation in weak interactions of hadrons depends on the constituents because of the presence of strongly bound spectator quarks. For the decay of a particle with polarization P to two spin-1/2 daughters, the decay asymmetry α enters angular distributions through

$$w(\cos\theta) = \frac{1}{2}(1 + \alpha P \cos\theta).$$

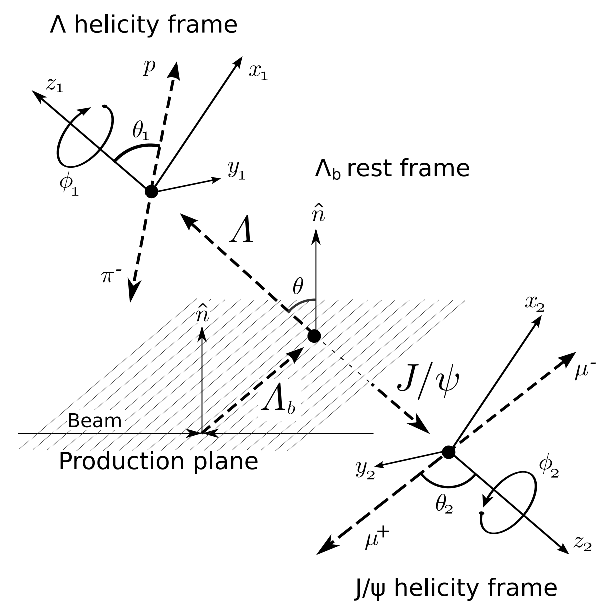
(θ: angle between the polarization vector and the direction of the decay product in the particle's rest frame).



The α is hard to predict for light hadrons, but for heavy baryon Λ_b^0, factorization and pQCD may be justified in calculations of the spectators, making prediction of α_b possible. The decay channel studied is $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$.

Phys. Rev. D 89 (2014) 092009

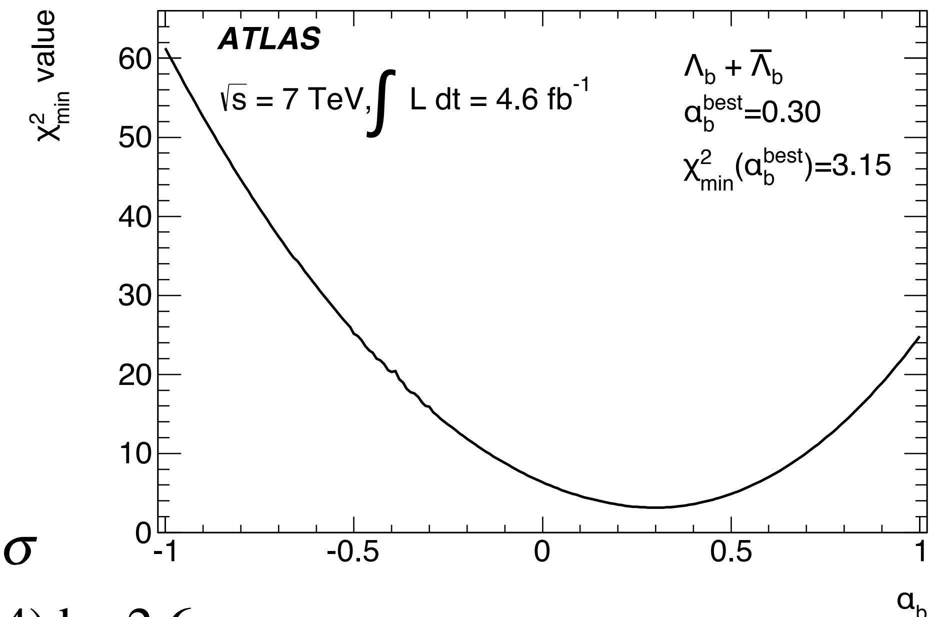
There are 4 possible combinations of the helicity of the Λ ("λ_Λ") and the helicity of the J/ψ ("$\lambda_{J/\psi}$"):



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

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

These a_i, b_i are extracted from the moments of the angular distribution.



Result :

- $\alpha_b = 0.30 \pm 0.16 \pm 0.06.$
- Differs from HQET (prefers 0.78) by 2.8σ
- Differs from pQCD (prefers -0.17 to -0.14) by 2.6σ
- Consistent with LHCb $\left(\alpha_b^{LHCb} = 0.05 \pm 0.17 \pm 0.07\right)$ within 1σ

$4.5\ fb^{-1}$ @ 7 TeV

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Measurement of the production cross section of prompt J/ψ mesons in association with a $W^{\pm}$ boson

Associated W production with prompt (from the same primary vertex) J/ψ tests QCD at the boundary of perturbative processes (heavy quark production) and non-perturbative (formation of the quarkonium).

Perturbative calculations distinguish between production of the J/ψ in the color singlet (CS) or color octet (CO) state.

This measurement also quantifies background to Higgs decays to quarkonia + vector boson, which probe the Higgs-charm coupling and/or can signal charged Higgs.

The analysis includes

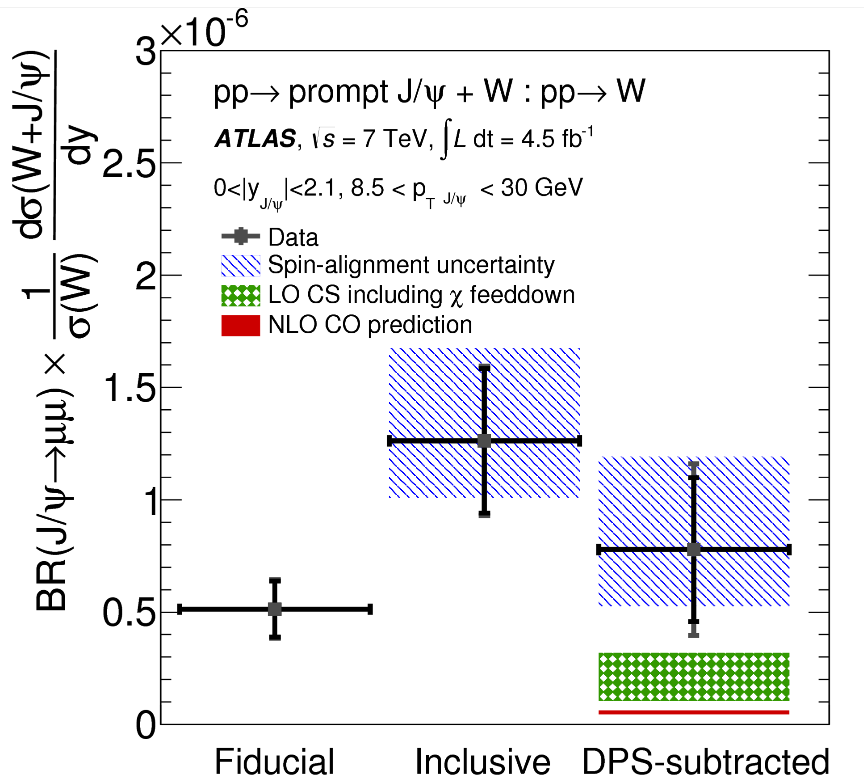
- Single Parton Scatters ("SPS"). Here W and J/ψ are produced together.
- Double Parton Scatters ("DPS"). This W and J/ψ come from different primary vertices.
- W + heavy charmonium produced, then heavy charmonium $\rightarrow J/\psi$.

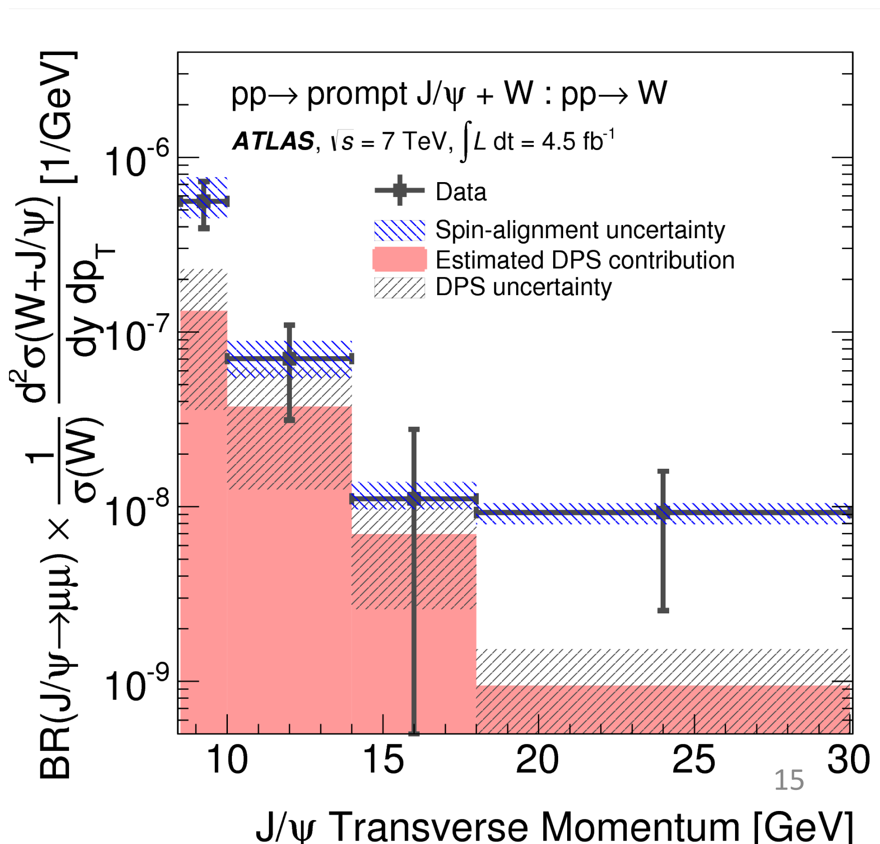
Results of the measurement :

- Associated W + prompt J/ψ observed, at significance 5.1σ.
- Both SPS and DPS contribute.
- Data exceed both CS and CO predictions but are consistent with CS within uncertainty.
- LO CS prediction is nearly 10x higher than NLO CO.

$\rightarrow$ Process seems to be dominated by CS

$\rightarrow$ SPS is the primary contributor to the total rate at low J/ψ p_T.





Measurement of the production cross section of prompt and non-prompt J/ψ mesons in association with a Z^0 boson

20.3 fb^{-1} @ 8 TeV

Again measurement of J/ψ properties tests models for quarkonium production. Requiring the formation of the Z sets a high energy scale for the scattering process that improves the perturbative calculation convergence. While the hadro-production spectrum as a function of p_T is well modeled by NRQCD, other observables (e.g., charmonium spin alignment) are not well modeled simultaneously with it.

$Z+$ non-prompt J/ψ probes b-hadron production models.

$Z+$ prompt J/ψ contributes to understanding of

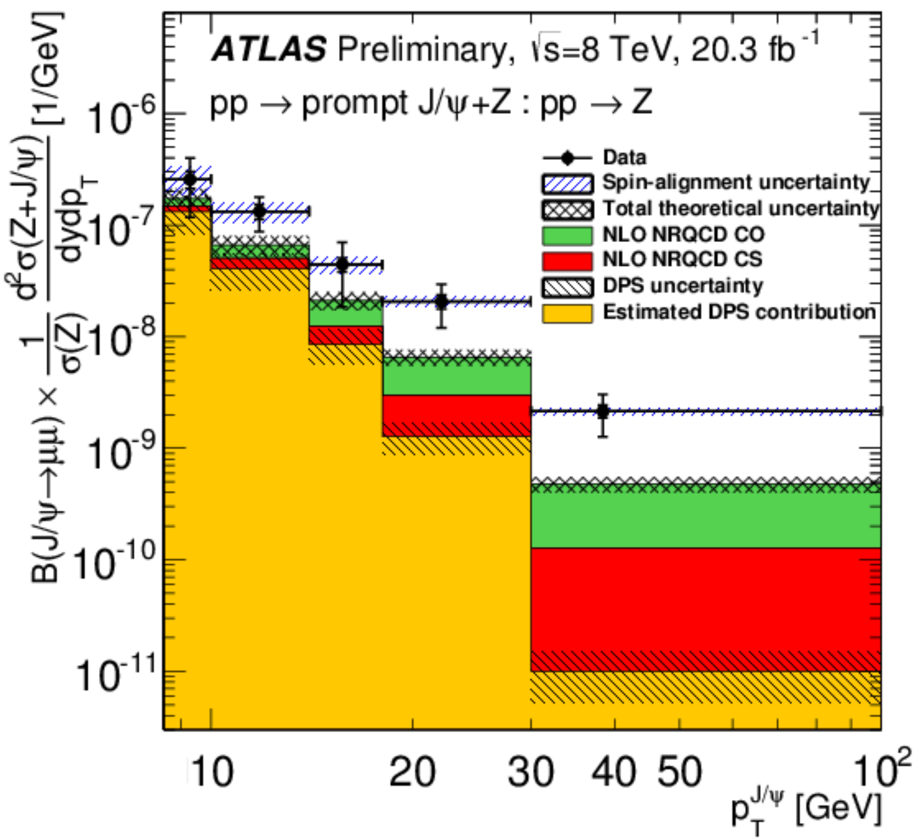
- prompt $\mathrm{ZZ}^*(\to c\bar{c})$ production in a new kinematic regime of pp collisions
- background to the search for rare $\mathrm{Z}\to \ell^+\ell^- J/\psi$ decay
- background to rare decays of Higgs in QQ+V modes (probe Higgs-charm coupling)
- background to $\mathrm{H}\to ZZ^*$
- search mode for new physics

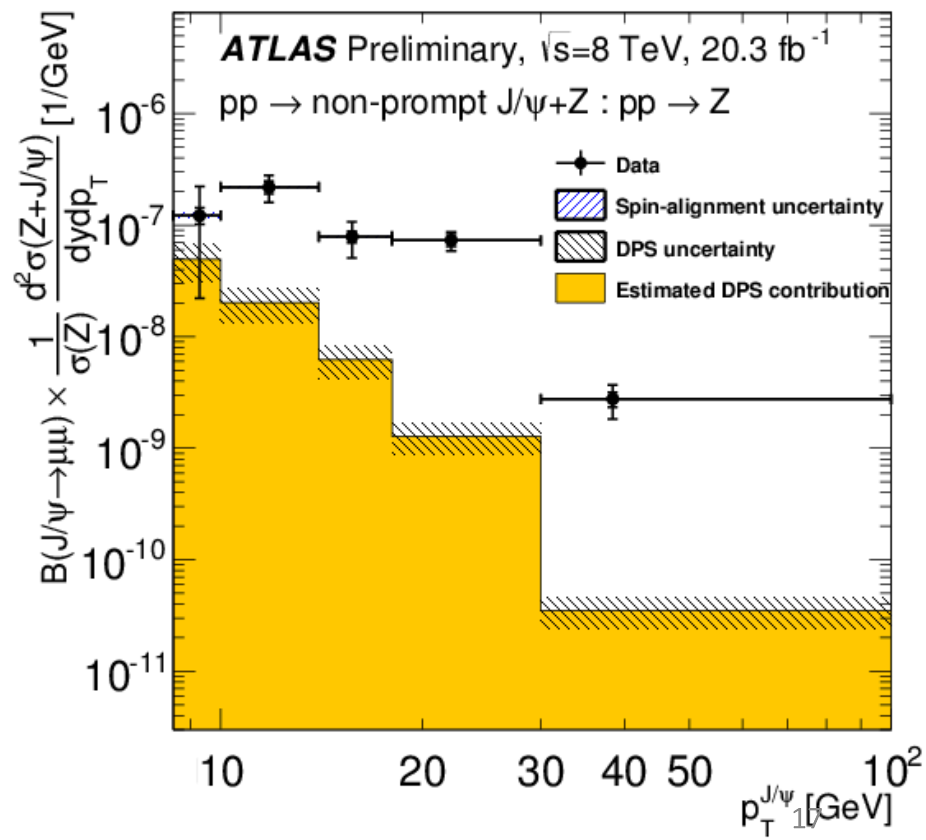
Note: CO prediction = $2\times$ CS prediction

DPS contribution estimated from results of dedicated ATLAS study of DPS in $pp \to W + \ell\nu_\ell + 2$ jets.

Results of this measurement, in 5 intervals of $\mathbf{J/\psi\ p_T}$:

- *First observation*: of $Z+$ prompt J/ψ (signif. 5σ) and $Z+$non-prompt (signif. 9σ).
- Observed production rate exceeds prediction (sum of CO + CS) by a factor of 10.





Measurement of χ_{c1} and χ_{c2} production

4.5 fb^{-1} @ 7 TeV

Now a look at a different heavy quarkonium- - again probes QCD uniquely because its formation involves 2 scales:

- the mass scale of the heavy quark pair produced - perturbative
- the scale at hadronization - non-perturbative

The intermediate mass of the c-quark further challenges theory because simple non-relativistic treatment of the bound state is not obviously applicable. Production can be modeled as color singlet (CS) or color octet (CO).

Triplet of quarkonium P-wave states just below the open-charm threshold: $\chi_{cJ}(1P)$. This analysis studies $\chi_{cJ} \to J/\psi\gamma$ for $J = 1,2$. ($J = 0$ has branching fraction 1.3%, neglected).

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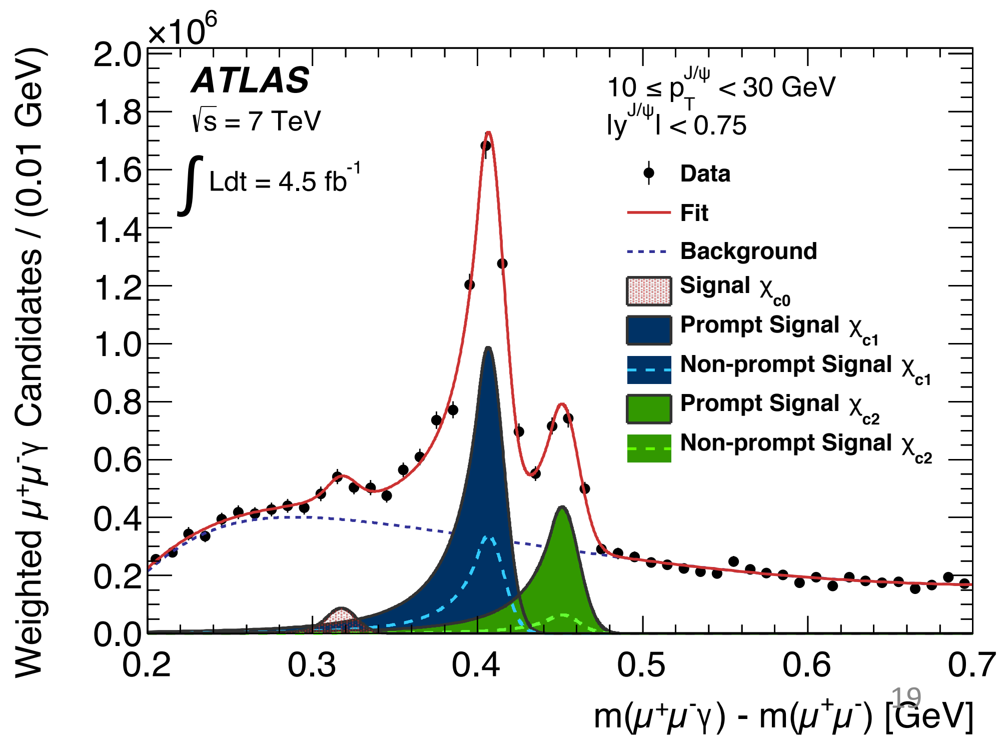
Compare 2 modes of production: *prompt* (pp $\to \chi_{cJ}$ directly OR pp $\to$ heavier quarkonium $\to \chi_{cJ}$) and *non - prompt* (pp $\to$ b-hadron $\to \chi_{cJ}$).

Why study these particular quarkonia, the χ_{cJ}?

(1) χ_{cJ} feed down to J/ψ, so precision measurements of J/ψ depend on understanding *prompt* χ_{cJ}.

(2) b-hadron decays to *non - prompt* charmonium provide an observable for studying b-quark production.

The signals :

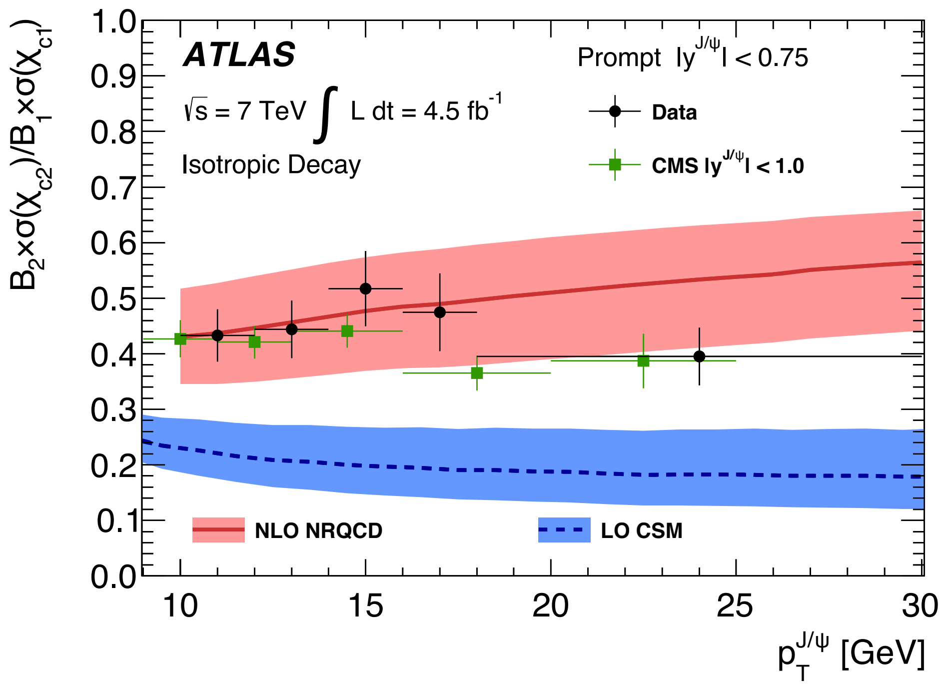


Theoretical models compared to the data:

(1) NLO NRQCD - separates perturbative production of heavy quark (CS or CO) from non-perturbative evolution into quarkonium

(2) k_T factorization - partonic cross-section from CSM convolved with gluon distribution that depends on both longitudinal and transverse momentum.

(3) LO CSM - heavy quarks produced in color singlet state, potential model used to describe bound state.



The conclusions :

- Good agreement between NRQCD and data.
- k_T factorization prediction high; LO CSM prediction low.

$\Rightarrow$ Conclude, higher order corrections or CO contributions may be numerically significant

2.1 fb^{-1} @ 7 TeV

Measurement of the production cross-section of $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$

Again here, a complete theoretical description of quarkonium is difficult due to the multiple energy scales and intermediate mass of the c-quark. This measurement attempts to separate these effects.

Prompt and non-prompt production of $\psi(2S)$ are compared with

- data from LHCb and CMS
- theoretical models for prompt production
- theoretical models for non-prompt production

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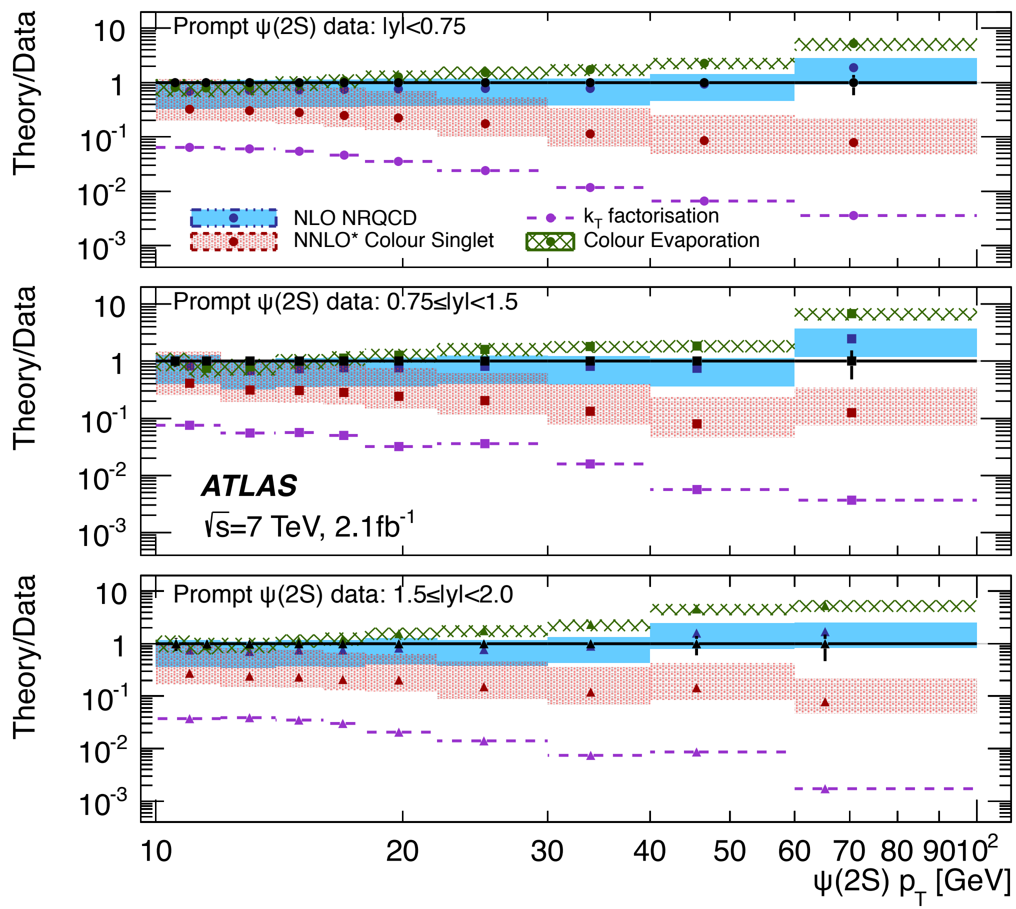
Theoretical models for prompt production :

- color singlet pQCD at partial NNLO ("NNLO*"), using CTEQ6M
- LO and NLO NRQCD (color-octet approach)
- color evaporation model (CEM)
- k_T-factorization

Prompt results :

- CS NNLO* underestimates the data by $\times 5$, beyond attributable to scale; deviation from data increases with p_T.
- NLO agrees well with data over full p_T range.
- CEM similar to NLO but harder at high p_T.
- k_T-factorization underestimates data with p_T-dependent shape.

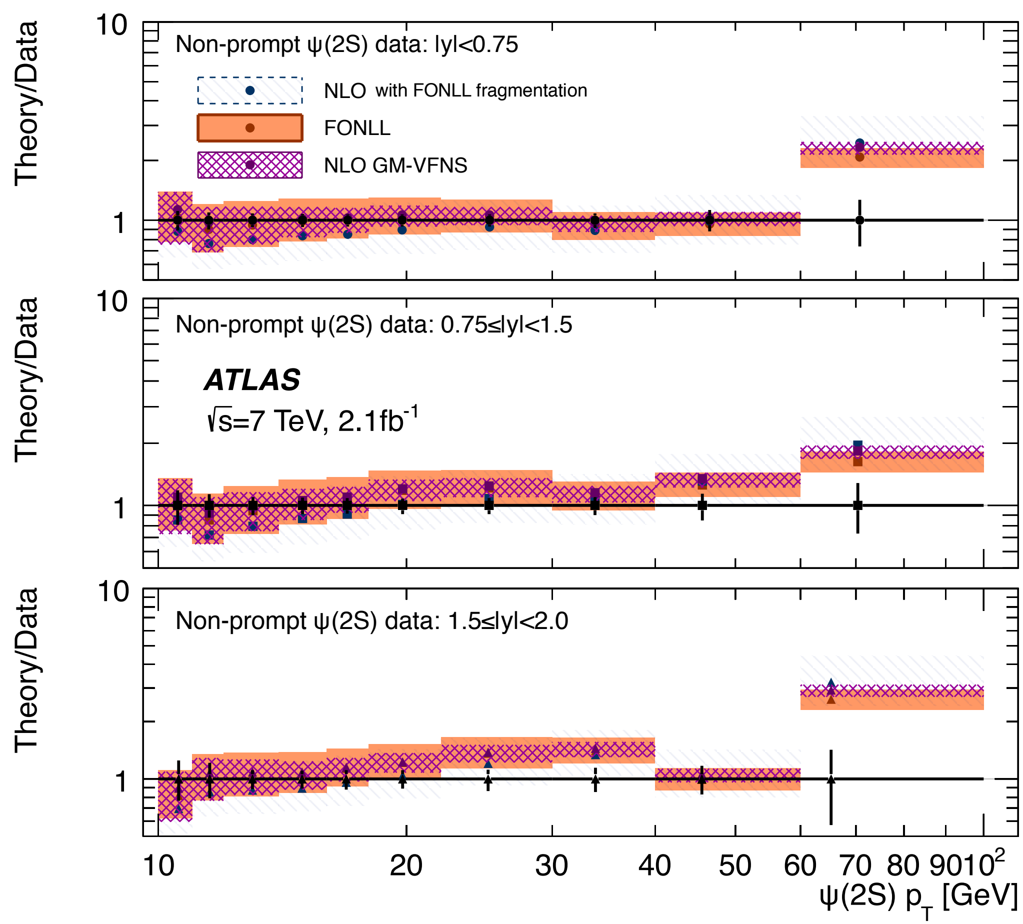


Theoretical models for non - prompt production :

- FONLL (fixed order + next to leading log)
- NLO in the general-mass variable-flavor-number scheme

Non - prompt results :

- FONLL and NLO GM-VFNS match data well but predict slightly harder p_T spectrum.
- similar to trend seen in CMS data; extends comparison to higher p_T.
- Given that FONLL models charged B mesons well at similar p_T, discrepancy may indicate mismodelling of b-hadron composition or decay kinematics rather than b-quark fragmentation.



Differential cross-section of B^+ meson production

2.4 fb^{-1} @ 7 TeV

JHEP 10 (2013) 042

Production cross section measurements are foundational to understanding of heavy quark production in hadronic collisions. Theoretical predictions for b-quark production can have uncertainty up to 40% due to assumptions about factorization and renormalization scales, and b-quark mass.

This measurement:

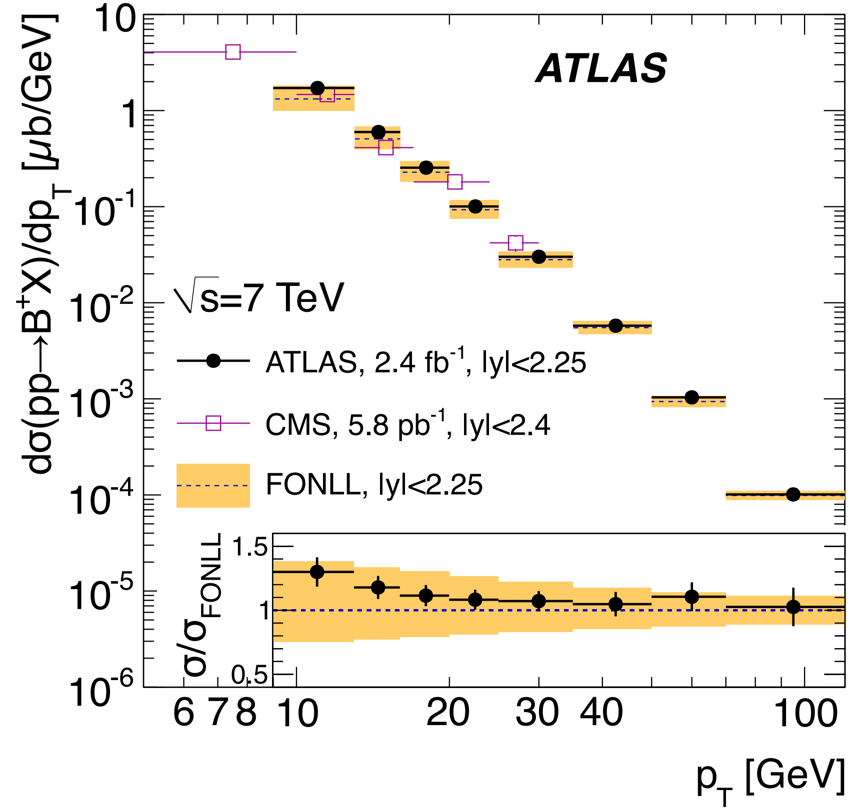
- extends the cross section to $p_T \sim 100$ GeV
- 4 differential measurement ranges in rapidity $|y| < 2.25$

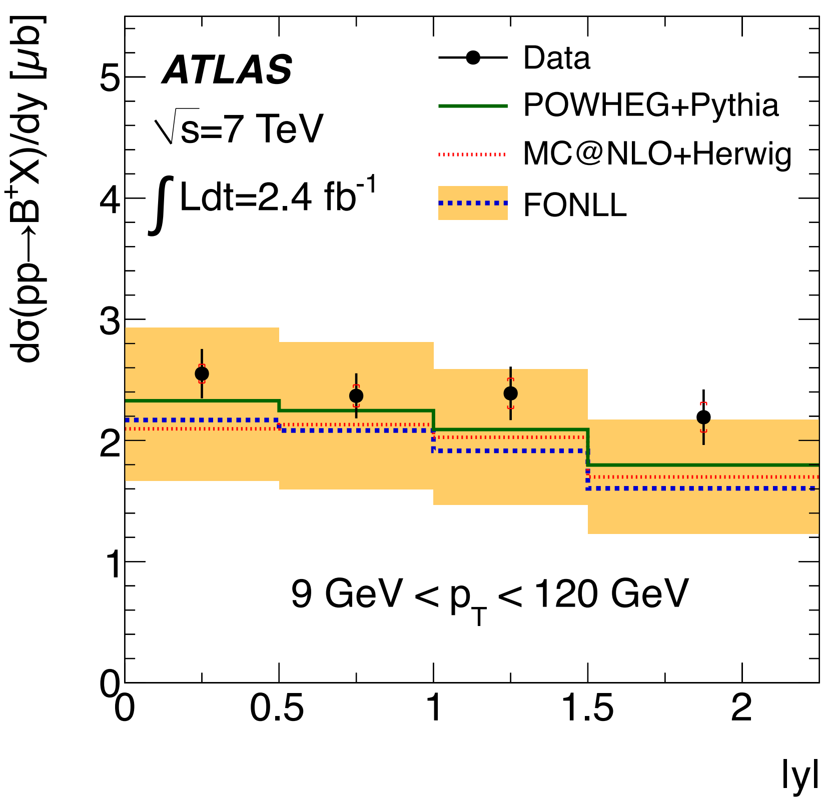
Compare data to:

- POWHEG + PYTHIA using CT10 parameterization for proton pdf
- MC@NLO + HERWIG using CT10 parameterization
- FONLL using CTEQ6.6 parameterization

NLO QCD is compatible with data:

- POWHEG agrees within errors at all p_{T} and y
- MC@NLO predicts p_T spectrum softer than data for low $|y|$ and harder for $|y|>1$.





- FONLL for $\sigma(pp \to bX)$, with PDG world avg. hadronization fraction $f_{b\to B^+} = (40.1 \pm 0.8)\%$, agrees with measured $d\sigma / dp_{\mathrm{T}}$.
- Precision 7% - 30%

Conclusions

Results from 9 ATLAS analyses of heavy flavor processes have been shown:

- Search for hidden beauty states analogous to the still unexplained hidden charm state X(3872).
- Discovery of the first excited B_c meson.
- Search for new physics in $B_s^0 \to J/\psi\phi$ angular characteristics.
- Test of pQCD and HQET-based models through the $\Lambda_b^0 \to J/\psi\Lambda^0$ parameters.
- Production cross sections of the B^+, $\psi(2S)$, χ_{c1} and χ_{c2}, and J/ψ in association with a $W^\pm$ and with a Z^0, all tests of QCD at the perturbative/non-perturbative interface.

The LHC continues to bring light to long-dark corners, ever more stringent tests, discoveries. In Spring 2015 the collider will restart data-taking at 13 TeV, a new window on the unknown.