# Heavy Flavor & Spectroscopy at ATLAS

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# Overview

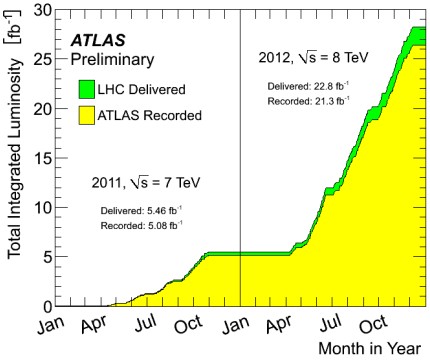


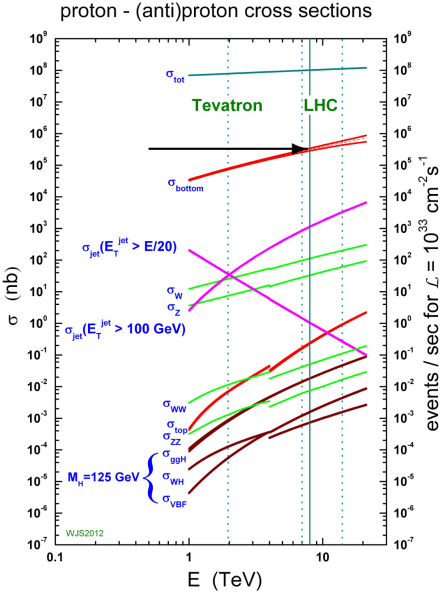
Photo: Victor Franz Hess Cosmic Ray Laboratory, Mt. Hafelekar, Innsbruck, Austria

# B Physics at the LHC

## Motivation

- Heavy Quarkonia: understanding production mechanisms.
- $B$ decays: measurement of new physics models.



# B Physics at ATLAS

Inner Detector:

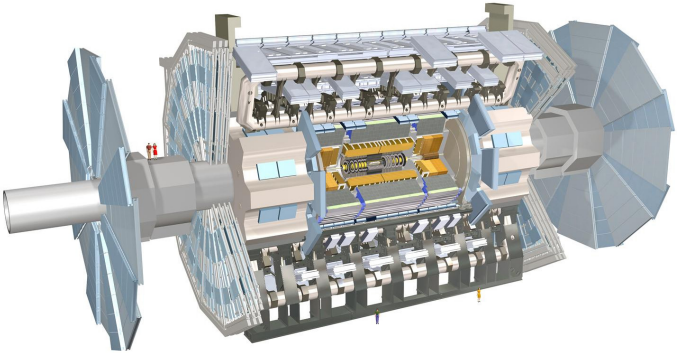
- Pixel, Semiconductor Tracker and Transition Radiation Tracker.
- Coverage $|\eta| < 2.5$.
- ID used for all tracking.

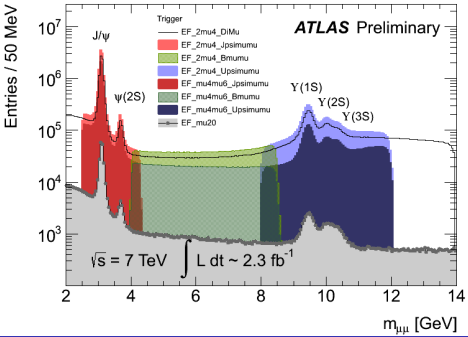
Muon System:

- Muon Tracking Chambers.
- Coverage $|\eta| < 2.7$.
- MS used for triggering.

Trigger:

- B-Physics mainly depends on single-muon and di-muon triggers.





# Latest Charmonium results in ATLAS

Measurement of $J/\psi + W$ production:

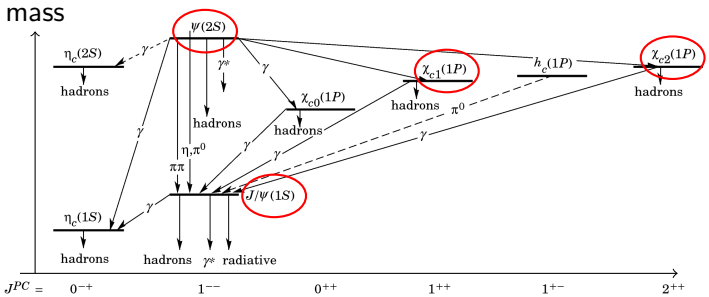
- arXiv:1401:2831[hep-ex]

$\psi(2S) \to J/\psi\pi^+\pi^-$:

- ATLAS-CONF-2013-094

$\chi_{c1}$ and $\chi_{c2}$ production:

- ATLAS-CONF-2013-095



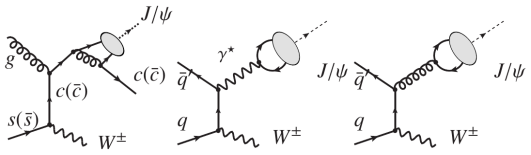

Charmonium Spectrum below $D\bar{D}$ threshold.

## Common to all: Reconstruction of $J/\psi \to \mu^+\mu^-$

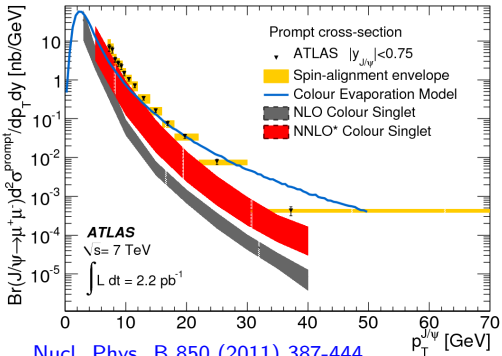
Muon tracks, opposite charge, common $J/\psi$ candidate vertex, kinematics from ID only (but matched to MS track), typically $p_T > 4$ GeV and $|\eta| < 2.3$, min. 1 pixel and 6 SCT hits.

# Prompt $J/\psi + W$ Production

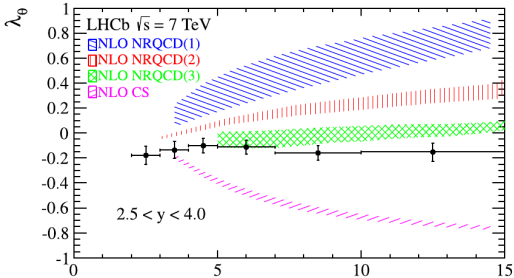
- Heavy quarkonium production models cannot fully predict $p_T$ spectrum and/or polarization (figures right).
- Prompt $J/\psi + W$ production novel approach, possible as single parton (CS or CO) or double parton scattering (DPS).
- Looking for prompt $J/\psi$, distinct from $b \to J/\psi$ BG.
- Interesting channel to study Higgs Charm coupling.




color-singlet color-octet



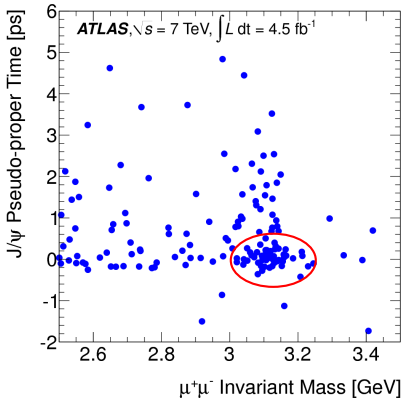

Nucl. Phys. B 850 (2011) 387-444




Eur. Phys. J. C 73 (2013) 2631

# Prompt $J/\psi + W$ Production

- Search for $J/\psi \to \mu^+\mu^-$ + isolated $W^\pm \to \mu^\pm\nu$.
- Discriminate prompt production from $W$ + non-prompt $b \to J/\psi$ background.
- Possible background: pileup, $Z$+jet, $t\bar{t}$, $W + b$, $B_c \to J/\psi + \mu\nu + X$, heavy flavor jets.




arXiv:1401:2831[hep-ex]

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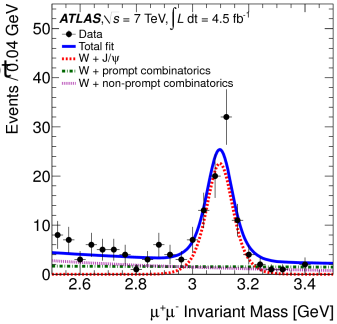
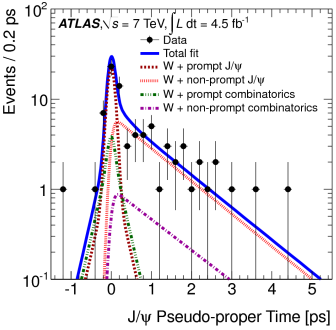
- Possible background: pileup, $Z$+jet, $t\bar{t}$, $W + b$, $B_c \to J/\psi + \mu\nu + X$, heavy flavor jets.
- Unbinned maximum likelihood fit in invariant dimuon mass and pseudo-proper time: $N_{sig} = 27.4^{+7.5}_{-6.5}$.
- Observation at 5.1$\sigma$ in 4.5 fb$^{-1}$.

$$
\begin{aligned}
M_{J/\psi}(m_{\mu^+\mu^-}) &= G(m_{\mu^+\mu^-}; m^{\mathrm{PDG}}_{J/\psi}, \sigma_m) \\
T_{\text{prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left( (1-a)\delta(\tau) + aC_0 \mathrm{e}^{-|\tau|/\tau_0} \right) \\
T_{\text{non-prompt } J/\psi}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left( C_1 \theta(\tau) \mathrm{e}^{-\tau/\tau_1} \right) \\
M_{\text{prompt bkg}}(m_{\mu^+\mu^-}) &= C_2 \mathrm{e}^{-m_{\mu^+\mu^-}/k_0} \\
M_{\text{non-prompt bkg}}(m_{\mu^+\mu^-}) &= C_3 \mathrm{e}^{-m_{\mu^+\mu^-}/k_1} \\
T_{\text{prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left( (1-b)\delta(\tau) + bC_4 \mathrm{e}^{-|\tau|/\tau_0} \right) \\
T_{\text{non-prompt bkg}}(\tau) &= G(\tau; 0, \sigma_\tau) \otimes \left( C_5 \theta(\tau) \mathrm{e}^{-\tau/\tau_2} \right).
\end{aligned}
$$



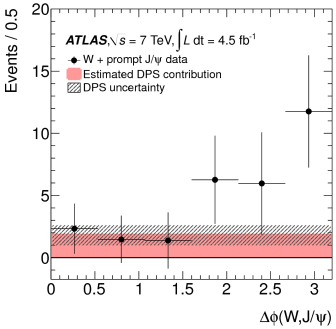

arXiv:1401:2831[hep-ex]

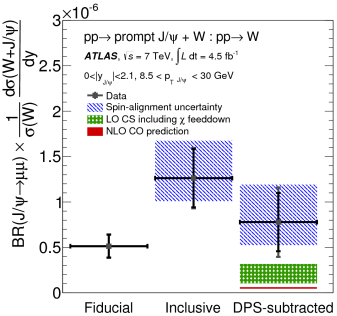
# Prompt $J/\psi + W$ Results

- $\Delta\phi$ between $W^{\pm}$ and $J/\psi$: estimations from $J/\psi$ cross section measurements confirmed estimated DPS contributions flat in $\Delta\phi$.
- Lower plot: ratio of $W + J/\psi$ associated production to the $W^{\pm}$ cross section in fiducial region, inclusive and DPS subtracted.

$$R^{fid}_{J/\psi} = (51 \pm 13 \pm 4) \times 10^{-8}$$
$$R^{incl}_{J/\psi} = (126 \pm 39 \pm 9^{+41}_{-25}) \times 10^{-8}$$
$$R^{DPSsub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$$

- $1^{st}$ err. statistical, $2^{nd}$ err. syst., $3^{rd}$ err. $J/\psi$ spin alignment.
- Comparing predictions of DPS subtracted ratio, color singled mechanism expected to be dominant contribution.

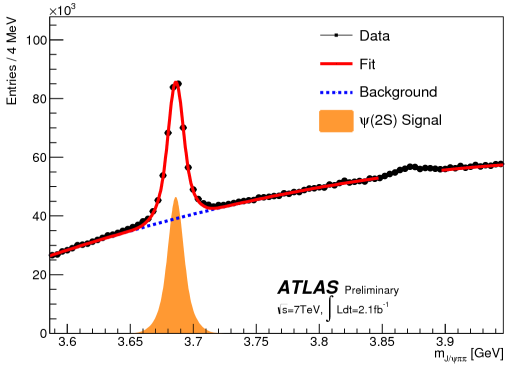


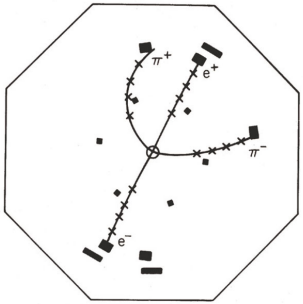

arXiv:1401:2831[hep-ex]

# $\psi(2S)$ Production

- Prompt production via QCD mechanisms.
- Non-prompt production via weak $b$ hadron decays.
- Measurement via mode $\psi(2S) \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$.
- Plot below: uncorrected $\mu^+\mu^-\pi^+\pi^-$ mass spectrum (signal as double Gaussian, BG as 2nd order Chebyshev polynomial).




$\psi'$ discovery, SLAC




- Clear signal near 3.69 GeV.
- Additional structure identified as $X(3872)$.
- Within $|y(\psi(2S))| < 2.0$ around 200k signal events.

ATLAS-CONF-2013-094

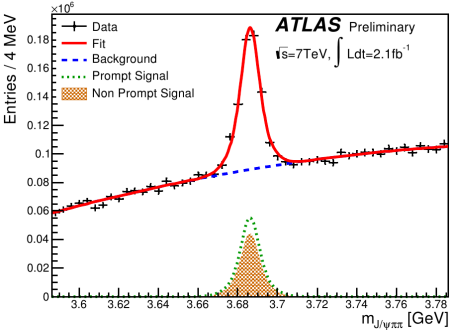
# $\psi(2S)$ Production

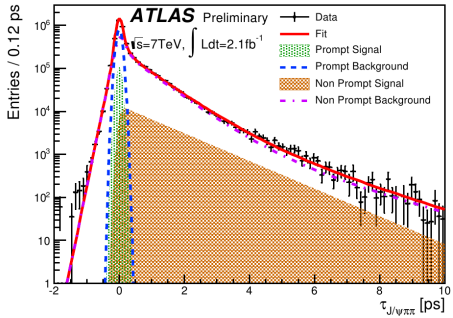
- Weighted two-dimensional unbinned maximum likelihood fit performed in $J/\psi\pi^+\pi^-$ invariant mass and pseudo-proper lifetime:

$$PDF(m,\tau) = \sum_{i=1}^{5} \oplus f_i(m) \cdot h_i(\tau) \otimes G_i(\tau)$$

| i | Type | Source | $f_i(m)$ | $h_i(\tau)$ |
|---|---|---|---|---|
| 1 | Signal | Prompt | $G_1(m) \oplus G_2(m)$ | $\delta(\tau)$ |
| 2 | Signal | Non-prompt | $G_1(m) \oplus G_2(m)$ | $E_1(\tau)$ |
| 3 | Background | Prompt | $C_1(m)$ | $\delta(\tau)$ |
| 4 | Background | Non-prompt | $C_2(m)$ | $E_2(\tau) \oplus E_3(\tau)$ |
| 5 | Background | Non-prompt | $C_3(m)$ | $E_4(\|\tau\|)$ |

$G_i$ Gaussian, $E_i$ exponential, $C_i$ 2nd order Chebyshev polynomials, $\oplus$ normalized sum and $\otimes$ convolution.

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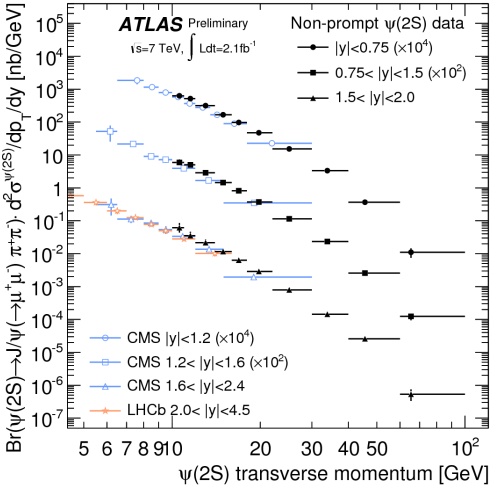
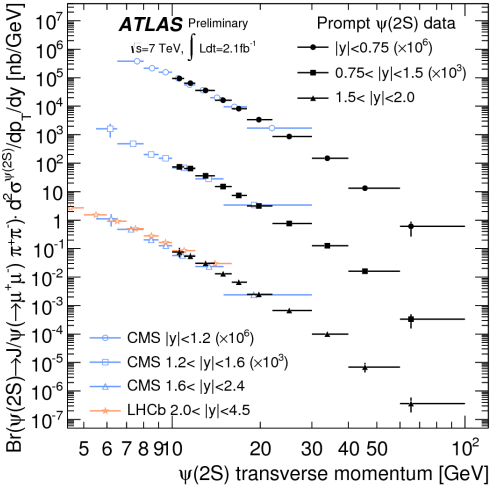
# $\psi(2S)$ Production



- $\psi(2S)$ production, non-prompt (left), prompt (right).
- Comparison with CMS and LHCb results.
- ATLAS measurement increases measurement to large values of $p_T(\psi(2S))$.

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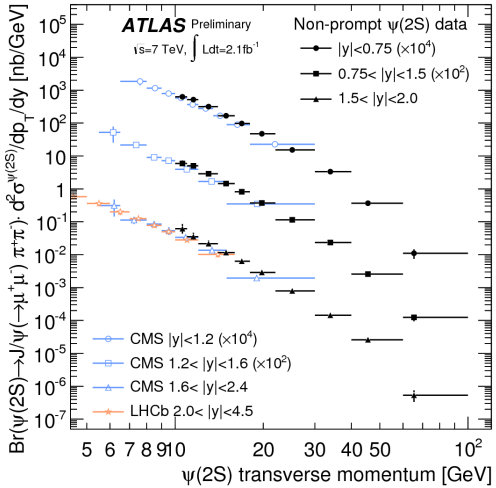
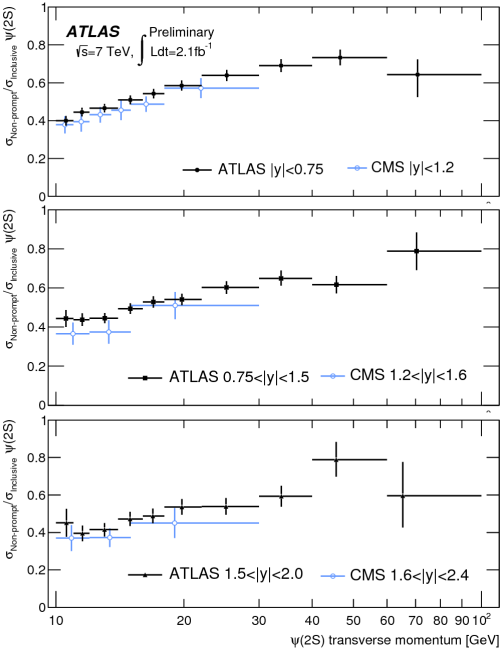
# $\psi(2S)$ Production

- Ratio non-prompt/inclusive (right).
- Comparison with CMS results.

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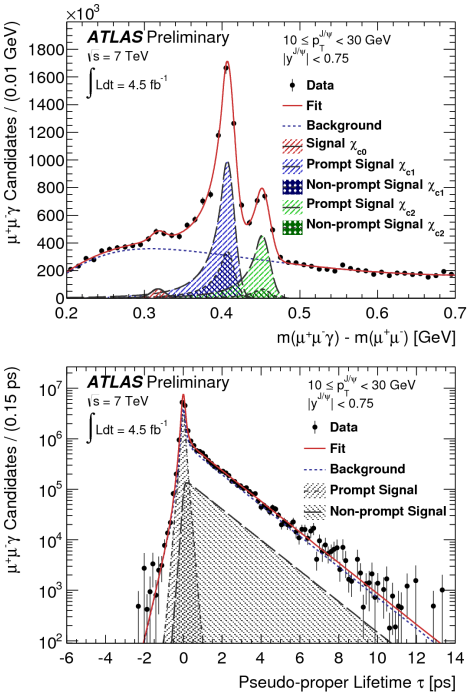
# $\chi_{c1}$ and $\chi_{c2}$ Production

- Similar to $\psi(2S)$, measurement of prompt and non-prompt $\chi_{ci}$ production.
- Measurement via radiative decay $\chi_{ci} \to J/\psi\gamma$.
- $\mathcal{B}(\chi_{c0} \to J/\psi\gamma)$ not measured here.
- Photon via photon conversion $\gamma \to e^+e^-$.
- Weighted two-dimensional unbinned maximum likelihood fit to mass difference $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ and pseudo-proper lifetime $\tau$.

- Comparison with FONLL, NLO NRQCD, $k_T$ factorization and LO CSM.

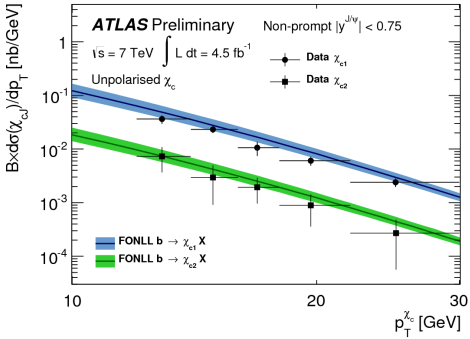


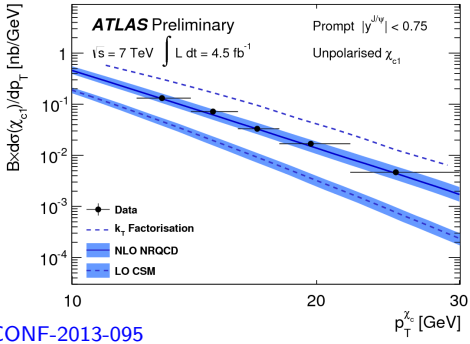

ATLAS-CONF-2013-095

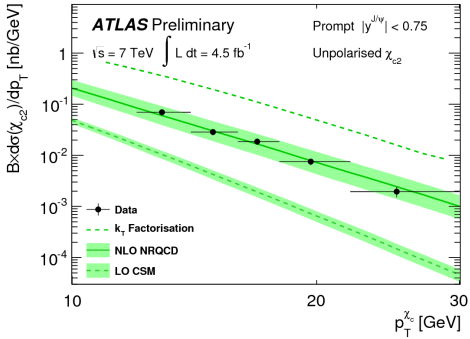
# $\chi_{c1}$ and $\chi_{c2}$ Production

Differential cross section as function of $p_T(\chi_c)$:

- Non-prompt, $\chi_{c1}$ and $\chi_{c2}$, top, compatible with FONLL predictions.
- Prompt $\chi_{c1}$ bottom left, $\chi_{c2}$ bottom right, compatible with NLO NRQCD predictions, not with $k_T$ factorization and LO CSM.

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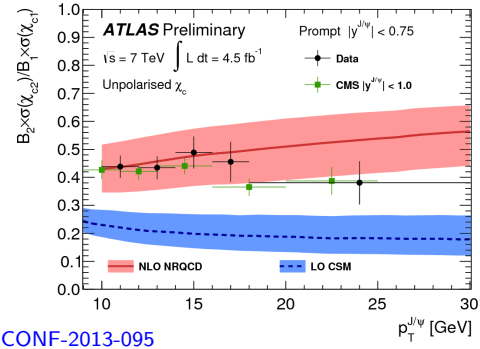
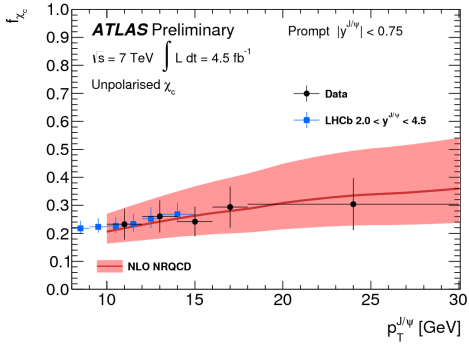
# $\chi_{c1}$ and $\chi_{c2}$ Production

BR ratios as function of $p_T(J/\psi)$:

- Ratio of prompt $\chi_{c2}/\chi_{c1}$ production, compared with CMS results.
- Cross section ratio $\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$, compared with LHCb.
- Results compatible to NLO NRQCD, but discrepancy to LO CSM.

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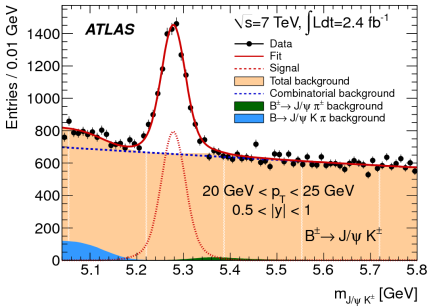
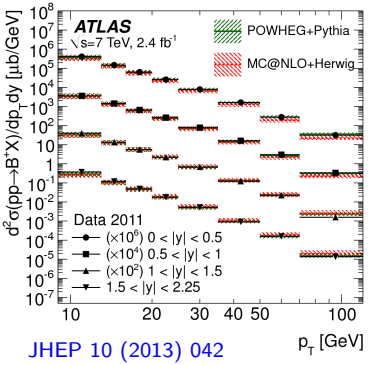
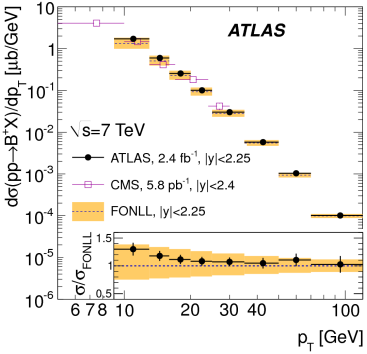
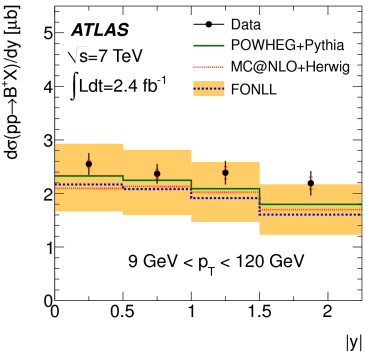
# $B^+$ meson production

- Measurement of $B^{\pm} \to J/\psi K^{\pm}$, see example right top figure.
- Differential cross section as function of $p_T$ in bins of rapidity (left), as function of $p_T$ (middle) and of rapidity (right).
- Compared to:
  - POWHEG + Pythia, agreement.
  - MC@NLO + Herwig, small discrepancies.
  - FONLL in good agreement.



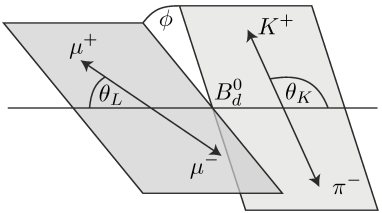



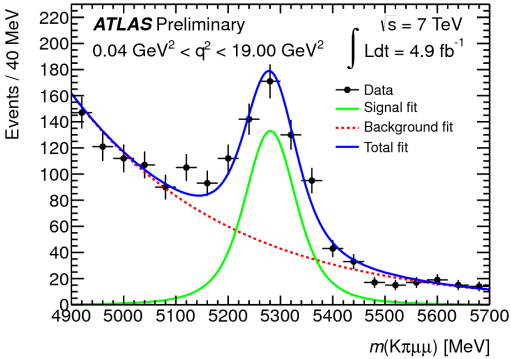




JHEP 10 (2013) 042

# Rare $B$ decays: $B_d \to K^{0*}\mu^+\mu^-$

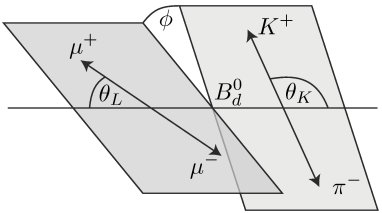


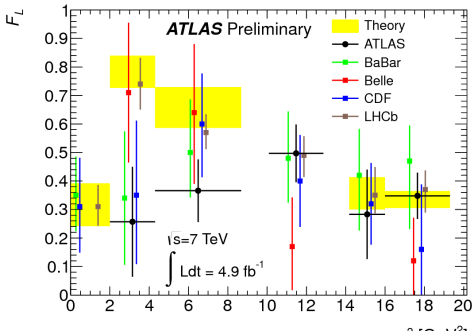

- Transitions $b \to s\ell\ell$ considered as probes to physics BSM in angular distributions.
- Measurement of kaon polarization and muon forward-backward asymmetry by ATLAS in $B_d \to K^{0*}\mu^+\mu^-$ using 4.9 fb$^{-1}$ 2011 data.
- Excluding di-muon invariant mass regions compatible with $J/\psi$ and $\psi(2S)$, $466 \pm 34$ signal $B_d \to K^{0*}\mu^+\mu^-$ found.

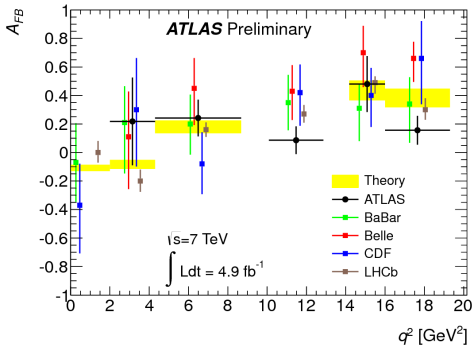
ATLAS-CONF-2013-076

# Rare $B$ decays: $B_d \to K^{0*}\mu^+\mu^-$




- Unbinned maximum likelihood fit on mass $m(K\pi\mu^+\mu^-)$ and angular distributions $\cos\theta_K$ and $\cos\theta_L$ in bins of di-muon mass $q^2$.
- Results of longitudinal $K^*$ polarization $F_L$ (top) and muon forward-backward asymmetry $A_{FB}$ (bottom), ATLAS main strength at large $q^2$.
- 2012 analysis under way, more $b \to s\ell\ell$ measurements under study.

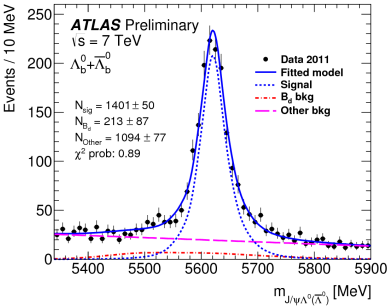



ATLAS-CONF-2013-076

# Parity violation and helicity amplitudes of $\Lambda_b^0 \to J/\psi\Lambda^0$

- Unbinned maximum likelihood fit of $\Lambda_b(\bar{\Lambda}_b) \to J/\psi\Lambda(\bar{\Lambda})$ mass spectrum, signal, $B_d \to J/\psi K_s^0(\pi^+\pi^-)$ and comb. BG.



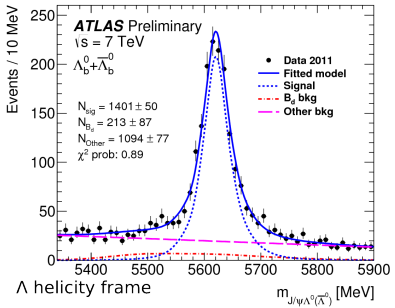

ATLAS-CONF-2013-071

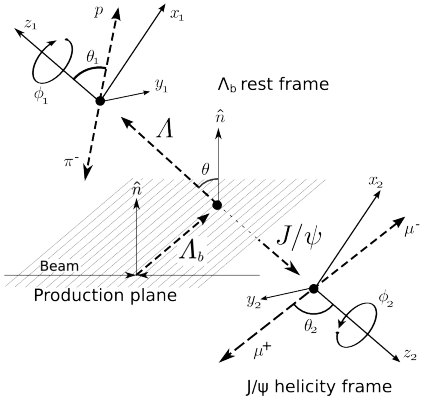
# Parity violation and helicity amplitudes of $\Lambda_b^0 \to J/\psi\Lambda^0$

- Unbinned maximum likelihood fit of $\Lambda_b(\bar{\Lambda}_b) \to J/\psi\Lambda(\bar{\Lambda})$ mass spectrum, signal, $B_d \to J/\psi K_s^0(\pi^+\pi^-)$ and comb. BG.
- Full angular PDF:

$$PDF(\Omega, \vec{A}, P) \propto \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

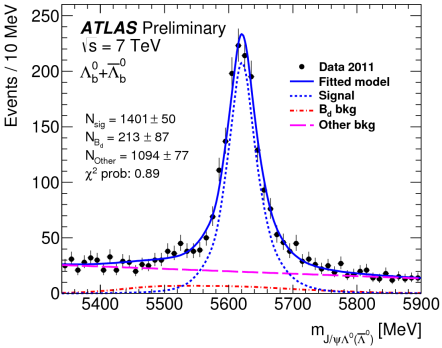
- $pp$ collisions and symmetry in rapidity $\to$ overall polarization $P$ of zero, reducing PDF from 20 to 6 terms.
- Fixed value of $\Lambda^0 \to p\pi^-$ $\alpha_\Lambda = 0.642 \pm 0.013$,
- Method of moments, measured per event: decay angles $\Omega$, results in $\langle F_i \rangle$ terms.
- Comb. BG contribution estimated from the two invariant mass sidebands, peaking BG from MC.
- Helicity amplitudes and decay asymmetry parameter for $\Lambda_b$ extracted by least square fit.

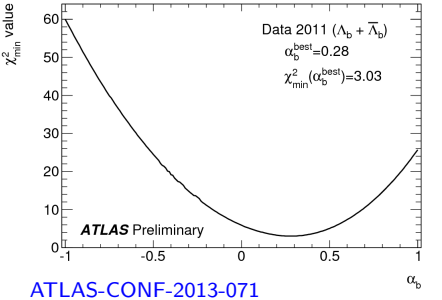



ATLAS-CONF-2013-071

# Parity violation and helicity amplitudes of $\Lambda_b^0 \to J/\psi\Lambda^0$




ATLAS-CONF-2013-071

Helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$:

$$a_+ \equiv A(1/2, 0) \quad \Rightarrow |a_+| = 0.17^{+0.12}_{-0.17}$$
$$a_- \equiv A(-1/2, 0) \quad \Rightarrow |a_-| = 0.59^{+0.06}_{-0.07}$$
$$b_+ \equiv A(-1/2, -1) \quad \Rightarrow |b_+| = 0.78^{+0.04}_{-0.05}$$
$$b_- \equiv A(1/2, 1) \quad \Rightarrow |b_-| = 0.08^{+0.13}_{-0.08}$$

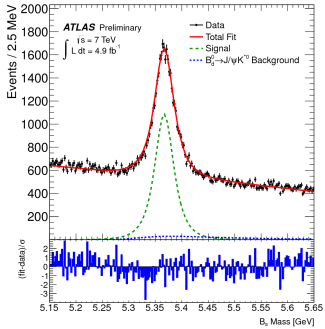
Decay asymmetry parameter:

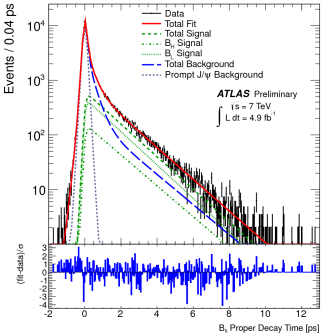
$$|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1$$
$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$
$$\alpha_b = 0.28 \pm 0.16(\text{stat.}) \pm 0.06(\text{syst.})$$

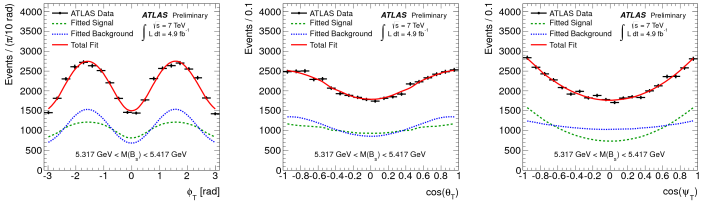
- Compatible with LHCb: $\alpha_b = 0.05 \pm 0.17 \pm 0.07$.
- Discrepancy with pQCD (-21% to -10%) and HQET (77.7%).
- Further measurement (2012 data) planned.

# Angular analsyis of $B_s^0 \to J/\psi\phi$

- Full angular analysis of final state particles $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$.
- Update from last analysis to include flavor tagging:
  - OST muon charge ($\varepsilon D^2 = 0.15\%$ segmented muons, $\varepsilon D^2 = 0.86\%$ combined muons).
  - OST jet charge, highest $p_T$ $b$-tag ($\varepsilon D^2 = 0.45\%$).
  - Total: $\varepsilon = 32\%$, $D = 21\%$, $\varepsilon D^2 = 1.45\%$ .
- Unbinned maximum likelihood fit using $B_s$ mass and proper decay time, their uncertainties, tag probability and transversity angles, measurement of $\Delta\Gamma_s$, $\phi_s$ etc.
- Plots: fit projections on $B_s$ mass, $B_s$ proper decay time and angles (bottom).



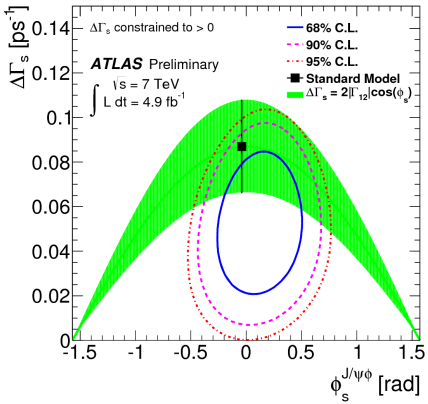




ATLAS-CONF-2013-039

# Angular analsyis of $B_s^0 \to J/\psi\phi$

- Likelihood contours (68%, 90% and 95%) compared to SM predictions, $\phi_s$ precision improved by 40% with flavour tagging:




$$\phi_s = 0.12 \pm 0.25(stat.) \pm 0.11(syst.)\text{rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021(stat.) \pm 0.009(syst.)\text{ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007(stat.) \pm 0.003(syst.)\text{ps}^{-1}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006(stat.) \pm 0.011(syst.)$$
$$|A_{||}(0)|^2 = 0.220 \pm 0.008(stat.) \pm 0.009(syst.)$$
$$\delta_\perp = 3.89 \pm 0.46(stat.) \pm 0.13(syst.)\text{rad}$$

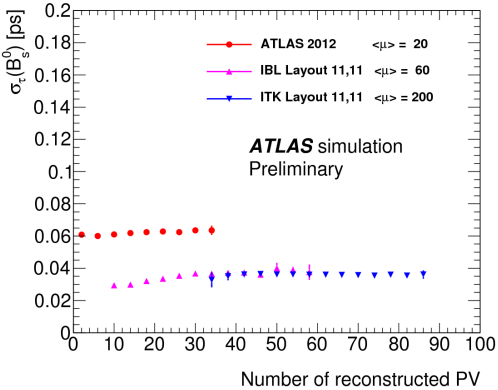
- $\Delta\Gamma_s$ constrained to be positive.
- Measurement of $S$-wave $KK$ or $f_0$ contamination compatible with zero.
- Results of width difference $\Delta\Gamma_s$ and $CP$ violating weak phase $\phi_s$ compatible with SM:

$$\phi_s^{SM} \simeq -2\beta_s = -0.0368 \pm 0.0018$$
$$\Delta\Gamma_s^{SM} = 0.087 \pm 0.021\text{ps}^{-1}$$

ATLAS-CONF-2013-039

# Summary and Outlook

- ATLAS performed a broad spectrum of measurements of charmonium, bottonium, rare decays, *CP* violation, ...
- Further measurements are under preparation, with increasing precision, inclusion of more data, etc.
- For run-2, insertion of upcoming additional *B*-layer promises bright future (e.g. plot of $B_s$ lifetime in 2012, upcoming run-2 and even later in ITK layout, i.e. silicon only ID).



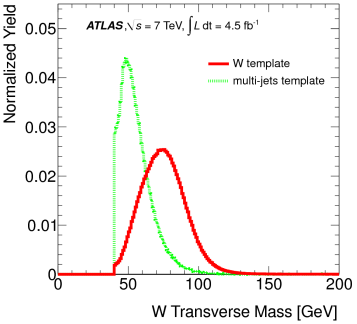

ATL-PHYS-PUB-2013-010

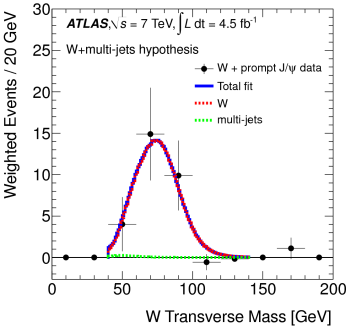
# BACKUP

# $J/\psi + W$ Production

- Using `sPlot` to create transverse mass templates for signal $W$ and multi-jet background.
- Fitted `sPlot` weighted distribution to measure multi-jet background contribution.
- Uncertainties of analysis:

| Source | Barrel | Endcap |
|---|---|---|
| $J/\psi$ muon efficiency | (3–5)% | (3–5)% |
| $W^{\pm}$ boson kinematics | 2% | 5% |
| Fit procedure | $^{+3}_{-2}$% | $^{+2}_{-1}$% |
| Choice of fit nuisance parameters | 1% | 1% |
| Choice of fit functional forms | 4% | 4% |
| Muon momentum scale | negligible | |
| $J/\psi$ spin-alignment | $^{+36}_{-25}$% | $^{+27}_{-13}$% |
| Statistical | $^{+47}_{-40}$% | $^{+30}_{-27}$% |

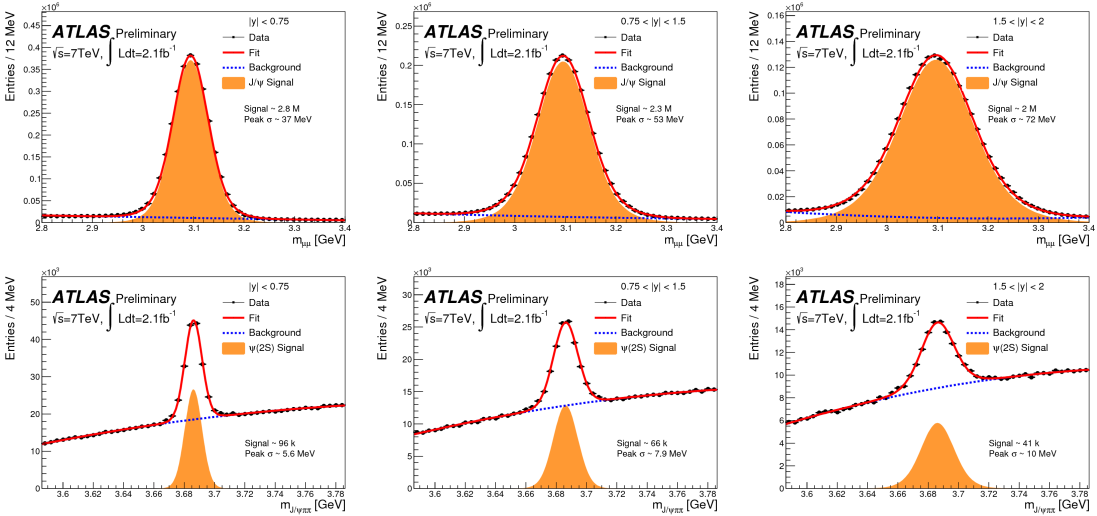



arXiv:1401:2831[hep-ex]

# $\psi(2S)$ Production

- Fit of $J/\psi$ signal peaks in the three different bins of rapidity ($|y| < 0.75$, $0.75 < |y| < 1.5$ and $1.5 < |y| < 2$) in the upper plots.
- Corresponding $\psi(2S)$ fits in the lower plots.



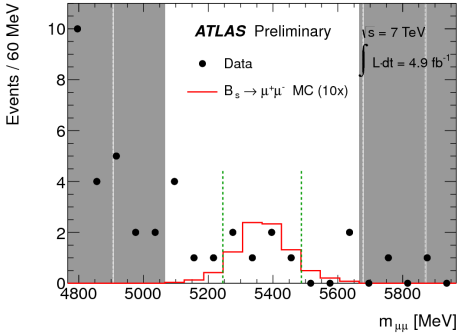

ATLAS-CONF-2013-094

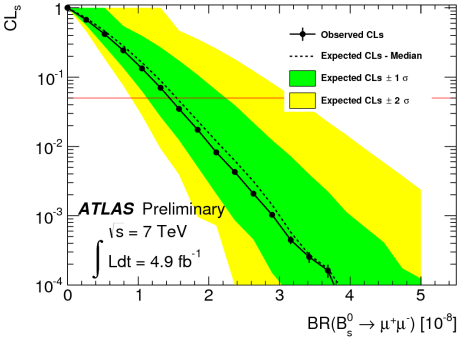
# Rare $B$ decays: $B_s^0 \to \mu^+\mu^-$

- Measurement of BR w.r.t. $B^+ \to J/\psi K^+$, BR defined as:

$$\mathcal{B}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \frac{\varepsilon_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-}}$$

- Signal/Background discrimination via BDT (MC trained only).
- Result: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5(1.2) \times 10^{-8}$ at 95% (90%) CL with $CL_s$ method.
- Measurements from LHCb (CMS) are $2.9^{+1.1}_{-1.0} \times 10^{-9}$ ($3.0^{+1.0}_{-0.9} \times 10^{-9}$) with significance of $4.0\sigma$ ($4.3\sigma$).
- ATLAS currently working on 8 TeV measurement.




ATLAS-CONF-2013-076