



# Latest results on flavour physics from ATLAS

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5th Capri Workshop on Flavour Physics, 23–25 May 2014

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## Overview

Introduction:

- ATLAS Detector
- Trigger for the Flavour Physics

Flavour Production:

- $J/\psi + W$
- ψ(2S)
- $\chi_{_{c1}}$  &  $\chi_{_{c2}}$
- *B*<sup>+</sup> cross section

- @ 4.5 fb<sup>-1</sup>: <u>JHEP 04 (2014) 172</u>
- @ 2.1 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-094</u>
- @ 4.5 fb<sup>-1</sup>: <u>arXiv:1404.7035</u>
- @ 2.4 fb<sup>-1</sup>: <u>JHEP 10 (2013) 042</u>

Heavy flavour decays:

- $\Lambda_b \rightarrow J/\psi \Lambda^0$
- $B_d \rightarrow K^{*0}\mu^+\mu^-$
- $B_{\rm s} \rightarrow J/\psi \varphi$
- $B_s \rightarrow \mu^+ \mu^-$

- @ 4.6 fb<sup>-1</sup>: <u>arXiv:1404.1071</u>
- @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-038</u>
- @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-039</u>
- @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-076</u>

#### Summary



#### Muon Spectrometer

- Muon Tracking Chambers
- Toroidal Magnet (~ 0.5 T)
- $|\eta| < 2.7$  coverage

#### Calorimeters

- LAr EM: |η| < 3.2
- Hadronic

#### Trigger

- Muon System & Calorimeters
- *B*-Physics mainly depends on single-muon & di-muon triggers

### **Trigger for the Flavour Physics**

- In 2011 single muon triggers became prescaled or moved towards high  $p_{\tau}$  threshold. Di-muon triggers dominated in the B-trigger menu.
- $p_{\tau}$  thresholds for muons: 4 GeV & 4(6) GeV for  $J/\psi$ , B & Y



Flavour production: colour-singlet & colour-octet states

Study of the  $J/\psi$  + W production offers new tests at the perturbative / non-perturbative QCD boundary.

Relative contribution of the two processes (colour-singlet (CS) or a colouroctet (CO)) is very important for the understanding of the perturbative calculations of heavy quarkonium production.



#### Prompt $J/\psi$ + associated W

Single parton scattering (SPS): the  $W^{\pm}$  and  $J/\psi$  originate from the same parton interaction.

Double parton scattering (DPS): the  $W^{\pm}$  and  $J/\psi$  originate from two different parton interaction in the same pp-collision.



Prompt *J/ψ* 

**Background contributions:** Pileup, Z+jets, tt production, W+b-quark,  $B_c \rightarrow J/\psi + \mu v + X$ , heavy quark jets

#### $\mu^+\mu^-$ mass spectrum and $J/\psi$ pseudo-proper time

Unbinned maximum likelihood fit to  $J/\psi$  mass and pseudo-proper time.

 $N_{sig} = 27.4^{+7.5}_{-6.5}$  Observation at 5.1 $\sigma$  in 4.5 fb<sup>-1</sup>.



#### Prompt $J/\psi$ + associated *W*: results



The LO CS mechanism makes the dominant contribution to the SPS cross section. Single parton scattering is the dominant contribution to the total rate at low  $J/\psi p_{T}$ .

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#### $\psi(2S)$ production

### $\psi(2S) \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$ decay mode

- Prompt  $\psi(2S)$  only from QCD production.
- Non-prompt  $J/\psi \& \psi(2S)$  production from weak b hadron decays.
- Prompt  $J/\psi$  from QCD or from excited P-wave  $\chi_{c1}$  states with  $J/\psi + X$  f.s.

It is necessary to study both prompt & non-prompt production of  $\psi(2S)$ ,  $\chi_{cJ}(nP) \& J/\psi$ .



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

Measurement performed in three  $\psi(2S)$  rapidity ranges: |y| < 0.75, 0.75<|y| < 1.5, |y| > 1.5

Measured differential cross-sections for prompt & non-prompt  $\psi(2S)$  production.



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

Comparison with CMS & LHCb results.

Measured differential cross-sections for prompt & non-prompt  $\psi(2S)$  production.



Good agreement with CMS & LHCb. ATLAS benefits at high  $p_{T}$ .

# $\chi_{c1} \& \chi_{c2}$ production

- Prompt  $\chi_{c1}$  states are produced directly in pp collisions or from the decay of heavier quarkonium states.
- Non-prompt  $\chi_{c1}$  states are produced from *b*-hadrons decays.
- The  $\chi_{c_1}(1P)$  states (with J = 0,1,2) are the only triplet of P-wave states below the open-charm threshold [J = 0 is beyond the scope of this study].
- Reconstructed  $\chi_c \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\gamma(\rightarrow e^+e^-)$ . Require precise reconstruction of the soft  $\gamma!$
- $\Delta m = m(\mu\mu\gamma) m(\mu\mu)$  distribution distinguishes between  $\chi_c$  candidates.
- Pseudo-proper time distinguishes between prompt & non-prompt contributions.



### Prompt & non-prompt $\chi_{c1}$ & $\chi_{c2}$ production

Differential cross sections for prompt  $\chi_{c1} \& \chi_{c2}$  as a function of  $p_T^{J/\psi}$ .



Differential cross sections for non-prompt  $\chi_{c1} \& \chi_{c2}$  as a function of  $p_T^{J/\psi}$  (left) &  $p_T^{\chi c}$  (right).



Measurement of the  $\chi_{c1}$  &  $\chi_{c2}$  production

Production comparison with CMS, LHCb results and with NLO NRQCD.

Ratio of prompt  $\chi_{c2}/\chi_{c1}$  production as a function of  $p_T^{J/\psi}$ , compared with CMS results.

Cross-section ratio  $\sigma(\chi_c \rightarrow J/\psi\gamma)/\sigma(J/\psi)$ as a function of  $p_T^{J/\psi}$ , compared with LHCb results.



### $B^+$ meson production



*B*<sup>+</sup> meson Reconstructed from *B*<sup>+</sup> → *J/ψ K*<sup>+</sup> decay. The observed invariant mass distribution of *B*<sup>±</sup> candidates (left) with transverse momentum and rapidity in the range 20 GeV <  $p_{T}$  < 25 GeV, 0.5 < |y| < 1 (dots), compared to the binned maximum likelihood fit (solid line).

Double-differential cross-section as a function of  $p_{T}$  & y, averaged over each ( $p_{T}$ , y) interval

> Good agreement with POWHEG+Pythia and with MC@NLO+Herwig



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#### B<sup>+</sup> meson differential cross-sections



Hadronization fraction  $F_{b \rightarrow B^+} = (40.1 \pm 0.8) \%$ 

FONLL in good agreement.

$$\Lambda_b \rightarrow J/\psi \Lambda^0$$

Reconstruction via

 $\Lambda_{\mu} \rightarrow J/\psi (\rightarrow \mu^{+}\mu^{-}) \Lambda^{0} (\rightarrow p^{+}\pi^{-})$  mode.

Motivation:

Lightest baryon containing a *b* quark (*udb*).

Hadron colliders are currently the only place to study *b* baryons.

 $\Lambda_{\mu} \rightarrow J/\psi (\rightarrow \mu^{+}\mu^{-}) \Lambda^{0}(\rightarrow p^{+}\pi^{-})$  mode is perfect for  $\Lambda_{\mu}$  baryon analysis.



Trigger: single muon, di-muon  $J/\psi$ ,  $p_{\tau}(\mu) > 4$  GeV Pre-selection (fit to common vertex):

- Di-muon acc.  $(J/\psi)$ : 2.8 < m $(\mu\mu)$  < 3.4 GeV
- Di-hadron acc. ( $\Lambda^{0}$ ): 1.08 < m(p<sup>+</sup> $\pi^{-}$ ) < 1.15 GeV



The reconstructed mass of  $\Lambda_{h}^{0}$  and  $\Lambda_{h}^{0}$ candidates, fitted with a three-component PDF consisting of signal, combinatorial and  $B_d \rightarrow J/\psi K^0(\to\pi^+\pi^-)$  background.

#### Parity violation and helicity amplitude of $\Lambda_{h} \rightarrow J/\psi \Lambda^{0}$



 $\Lambda_{\rm b}$  can be parametrized by a polar & azimuthal angles in their respective rest frames.

 $\Lambda_{b} \rightarrow J/\psi (\rightarrow \mu^{+}\mu^{-}) \Lambda^{0}(\rightarrow p^{+}\pi^{-})$  decay can be described by:

- 4 helicity amplitudes (a<sub>+</sub>, a<sub>-</sub>, b<sub>+</sub>, b<sub>-</sub>)
- Normalization:  $|a_{+}|^{2} + |a_{-}|^{2} + |b_{+}|^{2} + |b_{-}|^{2} = 1$
- 5 angles sensitive to squared amplitudes
- Parity violating decay asymmetry parameter:  $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$

The full decay angular PDF:

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

Due to *pp* collisions symmetry & ATLAS detector  $\eta$  symmetry overall Polarization = 0, reducing PDF from 20 to 6 terms. 5 independent parameters (3 magnitudes of h.a. + 2 relative phases)

$$\alpha_{b}$$
 measurement of  $\Lambda_{b} \rightarrow J/\psi \Lambda^{0}$ 

Helicity amplitudes are extracted from the  $F^{expected}$  in the PDF.

$$\chi^{2} = \sum_{i} \sum_{j} \left( \langle F_{i} \rangle^{expected} - \langle F_{i} \rangle \right) V_{ij}^{-1} \left( \langle F_{j} \rangle^{expected} - \langle F_{j} \rangle \right)$$
$$\langle F_{i} \rangle^{expected} = \sum_{j} f_{1j}(\vec{A}) f_{2j}(\alpha_{\Lambda}) C_{ij}$$
$$C_{ij} = \frac{1}{(4\pi)^{3}} \int \int F_{i}(\Omega') T(\Omega', \Omega') F_{j}(\Omega) d\Omega' d\Omega$$

$$\begin{aligned} \alpha_{b} &= 0.30 \pm 0.16(\text{stat.}) \pm 0.06(\text{syst.}) \\ a_{+} &= 0.17^{+0.12} \\ {}_{-0.17}(\text{stat.}) \pm 0.09(\text{syst.}) \\ a_{-} &= 0.59^{+0.06} \\ {}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.}) \\ b_{+} &= 0.79^{+0.04} \\ {}_{-0.05}(\text{stat.}) \pm 0.02(\text{syst.}) \\ b_{-} &= 0.08^{+0.13} \\ {}_{-0.08}(\text{stat.}) \pm 0.06(\text{syst.}) \end{aligned}$$



Large  $|a_{-}|$  and  $|b_{+}|$  refer to negative helicity states for  $\Lambda^{o}$  preferred.  $\Lambda^{o}$  and  $J/\psi$  are highly polarized in the direction of their momenta.

 $\alpha_b$  consistent with LHCb:  $\alpha_b = 0.05 \pm 0.17(\text{stat.}) \pm 0.07(\text{syst.})$   $\alpha_b$  differs from pQCD expectation (from -18% to -14%) by ~2.5 $\sigma$  and from HQET expectation (78%) by ~2.5 $\sigma$ 

#### Angular analysis of $B_d \rightarrow K^{*0}\mu^+\mu^-$

Angular distributions of the 4-particle final state are sensitive to physics beyond the SM.

Two integrated 1D distributions to extract  $\cos\theta_{L} \& \cos\theta_{\kappa}$ :

$$\frac{1}{\Gamma} \frac{d^2 \Gamma}{dq^2 d \cos \theta_K} = \frac{3}{2} F_L(q^2) \cos^2 \theta_K + \frac{3}{4} (1 - F_L(q^2)) (1 - \cos^2 \theta_K)$$
$$\frac{1}{\Gamma} \frac{d^2 \Gamma}{dq^2 d \cos \theta_L} = \frac{3}{2} F_L(q^2) (1 - \cos^2 \theta_K) + \frac{3}{8} (1 - F_L(q^2)) (1 + \cos^2 \theta_K) + A_{FB}(q^2) \cos \theta_L$$



Where  $F_L$  — fraction of  $K^{*0}$  longitudinal polarization;  $A_{FB}$  — muons forward-backward asymmetry.

Invariant mass distribution of  $B_d \rightarrow K^{*0} \mu^+ \mu^$ candidates as data points after the full signal selection.

Unbinned maximum likelihood fit was applied for mass and angular fit.

466 ± 34 signal events found (1132 ± 43 background events) for the invariant mass region of 4900 < m( $K\pi\mu\mu$ ) < 5700 MeV.



Angular analysis of  $B_d \rightarrow K^{*0}\mu^+\mu^-$ 

The full  $q^2$  range is defined as the three continuous intervals obtained by removing the  $J/\psi$  and  $\psi(2S)$  regions.

Fraction of longitudinal polarised  $K^{*0}$ mesons  $F_{L}$  as a function of  $q^{2}$  Forward-backward asymmetry  $A_{FB}$  as a function of  $q^2$ 



#### Angular analysis of $B_{s} \rightarrow J/\psi \phi$

Sensitive to NP!

$$B^{0}_{S} \rightarrow J/\psi(\rightarrow \mu^{+}\mu^{-})\phi(\rightarrow K^{+}K^{-})$$
 decay mode

Unbinned maximum likelihood fit using  $B_{s}$  mass, proper decay time & 3 decay angles.

Flavour tagging (opposite-side tagging) was used to distinguish between the initial  $B^{0}$  and  $\overline{B}^{0}$  states. The CP states are separated statistically through the timedependence of the decay and angular correlations amongst the f.s. particles.



### Angular analysis of $B_s \rightarrow J/\psi \varphi$ : results

 $\phi_s = 0.12 \pm 0.25(stat.) \pm 0.11(syst.)$  rad

 $\Delta \Gamma_{s} = 0.053 \pm 0.021(stat.) \pm 0.009(syst.) \text{ ps}^{-1}$ 

 $\Gamma_{s} = 0.677 \pm 0.007(stat.) \pm 0.003(syst.) \text{ ps}^{-1}$ 

 $|A_0(0)|^2 = 0.529 \pm 0.006(stat.) \pm 0.011(syst.)$ 

 $|A_{\parallel}(0)|^2 = 0.220 \pm 0.008(stat.) \pm 0.009(syst.)$ 

 $\delta_{\perp} = 3.89 \pm 0.46(stat.) \pm 0.13(syst.)$  rad

 $\phi_{s}$  statistical error reduced by 40% w.r.t. older untagged analysis.

Likelihood contours in  $\phi_s - \Delta \Gamma_s$  plane compared to SM predictions. Results of width difference and CP violating weak phase compatible with SM:

 $\Delta \Gamma_{s}^{SM} = 0.087 \pm 0.021 \text{ps}^{-1}$ 

 $\phi_{\rm s}^{\rm SM}$  = -0.0368 ± 0.0018

The full simultaneous maximum likelihood fit contains 25 free parameters.

The number of signal  $B_s^0$  meson candidates extracted from the fits was 22670 ± 150.



Search for  $B_s \rightarrow \mu^+ \mu^-$ 

Flavour Changing Neutral Currents (FCNC) are highly suppressed in the SM.



Coupling to non-SM particles may enhance the BR( $B_s \rightarrow \mu^+\mu^-$ )



BR  $B_s \to \mu^+ \mu^-$  SM predictions:  $(3.27 \pm 0.27) \cdot 10^{-9}$  [Buras et al., Eur. Phys. J. C72 (2012) 2172] Evidence from LHCb & CMS. BR( $B_s \to \mu^+ \mu^-$ ):  $(2.9 \pm 0.7) \cdot 10^{-9}$  [LHCb: arXiv: 1307.5024] [CMS: arXiv: 1307.5025]

# $B_s \rightarrow \mu^+ \mu^-$ search results

Signal yield of  $B^+ = 15214 \pm 1.1\%(stat.) \pm 2.4\%(syst.)$  - un-binned maximum lifelihood fit.  $SES = BR(B^+ \rightarrow J/\Psi K^+) \cdot \frac{\epsilon_{J/\Psi K^+} \cdot A_{J/\Psi K^+}}{\epsilon_{\mu\mu} \cdot A_{\mu\mu}} \cdot \frac{f_u}{f_s} \cdot \frac{1}{N_{J/\Psi K^+}} = (2.07 \pm 0.26) \cdot 10^{-9}$ 



### Summary and Outlook

ATLAS has a complex Flavour Physics programme composed of a flavour production including  $J/\psi + W$ ,  $\psi(2S)$ ,  $B^+$ ,  $\chi_{c1} \& \chi_{c2}$  and a decay measurements including:

- $\Lambda_b \rightarrow J/\psi \Lambda_0$
- $B_d \rightarrow K^{*0}\mu^+\mu^-$
- $B^0_s \rightarrow J/\psi \varphi$
- $B_{s} \rightarrow \mu^{+}\mu^{-}$

### Outlook

- One can expect increasing precision of a further measurements based on the analysis of 8 TeV data.
- Recently installed Pixel Insertable B-Layer (IBL) should provide increasing vertexing performance.
- Further Semiconductor Tracker (all silicon ID) and trigger upgrades.

### Backup

### References

Prompt  $J/\psi$  + associated W production @ 4.5 fb<sup>-1</sup>: <u>JHEP 04 (2014) 172</u>

ψ(2S) production @ 2.1 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-094</u>

Prompt and non-prompt  $\chi_{c1} \& \chi_{c2}$  production @ 4.5 fb<sup>-1</sup>: <u>arXiv:1404.7035</u>

*B*<sup>+</sup> production @ 2.4 fb<sup>-1</sup>: <u>JHEP 10 (2013) 042</u>

Measurement of the parity violating asymmetry parameter  $\alpha_{b}$  and the helicity amplitudes for the decay  $\Lambda_{b} \rightarrow J/\psi \Lambda_{0}$  @ 4.6 fb<sup>-1</sup>: <u>arXiv:1404.1071</u>

Angular analysis of  $B_d \rightarrow K^{*0}\mu^+\mu^-$  @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-038</u>

 $\varphi_s$  and  $\Delta \Gamma_s$  from flavor-tagged time-dependent angular analysis of  $B_s \rightarrow J/\psi \varphi$  @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-039</u>

Limit on  $B_s \rightarrow \mu^+\mu^-$  branching fraction @ 4.9 fb<sup>-1</sup>: <u>ATLAS-CONF-2013-076</u>

 $B_s \rightarrow \mu^+ \mu^-$  analysis strategy

Branching fraction measurement  $B_s \rightarrow \mu^+\mu^-$  performed w.r.t. the reference channel  $B^{\pm} \rightarrow J/\psi (\mu^+\mu^-) K^{\pm}$ .

Uncertainties on trigger and pre-selection efficiencies cancel out.

$$BR(B_{s}^{0} \rightarrow \mu^{+}\mu^{-}) = BR(B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow J/\psi \mu^{+}\mu^{-}) \times \frac{f_{u}}{f_{s}} \times \frac{N_{\mu^{+}\mu^{-}}}{N_{J/\psi K^{\pm}}} \times \frac{A_{J/\psi K^{\pm}}}{A_{\mu^{+}\mu^{-}}} \times \frac{\varepsilon_{J/\psi K^{\pm}}}{\varepsilon_{\mu^{+}\mu^{-}}} = N_{\mu^{+}\mu^{-}} \times SES$$

Branching fraction for the reference channel and f<sub>u</sub>/f<sub>s</sub>: from PDG 2012 [*JHEP* 1304 (2013) 001] & LHCb 2011 [arXiv:1301.5286]

Signal events counting in the signal region ( $\pm$  300 MeV from m( $B_s$ ))and background estimation from sidebands.

Acceptances and efficiencies are from MC. Same selection for the  $B_s \rightarrow \mu^+\mu^-$  and for the  $B^{\pm} \rightarrow J/\psi \ (\mu^+\mu^-) K^{\pm}$ .

Single Event Sesitivity (SES) corresponds to the  $B_s = \mu^+\mu^-$  branching fraction which would yield one observed signal event.

### $B_{s} \rightarrow \mu^{+}\mu^{-}$ background discrimination

Background dominated by  $bb \rightarrow \mu^+\mu^- X$ .

Background distinguished from signal using 13 discriminating variables used in a BDT (Boosted Decision Trees) on MC events. The most contribution was from  $I_{0.7} \& \alpha_{20}$ :



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 $B_s \rightarrow \mu^+ \mu^-$  background discrimination

Background distinguished from signal using 13 discriminating variables used in a BDT (Boosted Decision Trees) on MC events.

BDT output for data sidebands and MC signal.

