Latest results on flavour physics from ATLAS

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Overview

Introduction:

- ATLAS Detector
- Trigger for the Flavour Physics

Flavour Production:

- $J/\psi + W$ @ 4.5 fb⁻¹: [arXiv:1401.2831](#)
- $\psi(2S)$ @ 2.1 fb⁻¹: [ATLAS-CONF-2013-094](#)
- χ_{c1} & χ_{c2} @ 4.5 fb⁻¹: [arXiv:1404.7035](#)
- B^+ cross section @ 2.4 fb⁻¹: [JHEP 10 \(2013\) 042](#)

Heavy flavour decays:

- $\Lambda_b \rightarrow J/\psi \Lambda^0$ @ 4.6 fb⁻¹: [ATLAS-CONF-2013-071](#)
- $B_d \rightarrow K^{*0} \mu^+ \mu^-$ @ 4.9 fb⁻¹: [ATLAS-CONF-2013-038](#)
- $B_s \rightarrow J/\psi \varphi$ @ 4.9 fb⁻¹: [ATLAS-CONF-2013-039](#)
- $B_s \rightarrow \mu^+ \mu^-$ @ 4.9 fb⁻¹: [ATLAS-CONF-2013-076](#)

Summary

ATLAS Detector on the LHC

Inner Detector

- Pixel
- Semiconductor Tracker
- Transition Radiation Tracker
- Solenoid Magnet (2T)
- $|\eta| < 2.5$ coverage

Muon Spectrometer

- Muon Tracking Chambers
- Toroidal Magnet ($\sim 0.5 \text{ T}$)
- $|\eta| < 2.7$ coverage

Calorimeters

- LAr EM: $|\eta| < 3.2$
- 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. Di-muon triggers dominated in the B-trigger menu.
- p_T thresholds for muons: 4 GeV & 4(6) GeV for J/ψ , B & Y

Di-muon triggers in 2011 trigger menus.

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 colour-octet (CO)) is very important for the understanding of the perturbative calculations of heavy quarkonium production.

Prompt J/ψ + associated W

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

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

Prompt J/ψ

Background contributions:

Pileup, Z+jets, $t\bar{t}$ production,
W+b-quark, $B_c \rightarrow J/\psi + \mu\nu + X$,
heavy quark jets

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

Unbinned maximum likelihood fit to J/ψ mass and pseudo-proper time.

$$N_{\text{sig}} = 27.4^{+7.5}_{-6.5}$$

Observation at 5.1σ in 4.5 fb^{-1} .

Prompt J/ψ + associated W : results

CS + CO models predict single parton scattering contribution peak at $\Delta\phi = \pi$ (vs. flat $\Delta\phi$ at double parton scattering).

Ratio of J/ψ + W to $W^\pm$ cross-section: J/ψ fiducial region, after J/ψ acceptance correction, after DPS subtraction.

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/ψ p_T .

$\psi(2S)$ production

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

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

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

Uncorrected $|\eta|$ - p_T distribution of $J/\psi \pi^+\pi^-$.

Uncorrected $J/\psi \pi^+\pi^-$ mass spectrum.

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

One can select 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.

Compatible with LO & NLO NRQCD
 k_t factorization undershoots data.

Both NLO & FONLL describe data.
 However both underestimate at high p_T .

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 .

χ_{c1} & χ_{c2} production

- Prompt χ_{c1} states are produced directly in pp collisions or from the decay of heavier quarkonium states.
- Non-prompt χ_{c1} states are produced from b -hadrons decays.
- The $\chi_{cJ}(1P)$ 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 γ !
- $\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$ distribution distinguishes between χ_c candidates.
- Pseudo-proper time distinguishes between prompt & non-prompt contributions.

Prompt & non-prompt χ_{c1} & χ_{c2} production

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

Compatible with
NLO NRQCD,
not with LO CSM
& k_T factorization.

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

Compatible with FONLL.

Measurement of the χ_{c1} & χ_{c2} production

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

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

Compatible with NLO NRQCD.
LO CSM underestimates data.

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.

Compatible with NLO NRQCD.

B^+ meson production

B^+ meson Reconstructed from $B^+ \rightarrow J/\psi K^+$ decay. The observed invariant mass distribution of $B^\pm$ candidates (left) with transverse momentum and rapidity in the range $20 \text{ GeV} < p_T < 25 \text{ GeV}$, $0.5 < |y| < 1$ (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

B^+ meson differential cross-sections

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

FONLL in good agreement.

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

Reconstruction via $\Lambda_b \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) \Lambda^0 (\rightarrow p^+ \pi^-)$ decay mode.

Trigger: single muon, di-muon J/ψ , $p_T(\mu) > 4$ GeV

Pre-selection (fit to common vertex):

- Di-muon acc. (J/ψ): $2.8 < m(\mu\mu) < 3.4$ GeV
- Di-hadron acc. (Λ^0): $1.08 < m(p^+\pi^-) < 1.15$ GeV

The reconstructed mass of Λ_b^0 and $\bar{\Lambda}_b^0$ candidates, fitted with a three-component PDF consisting of signal, combinatorial and $B_d \rightarrow J/\psi K_s^0 (\rightarrow \pi^+ \pi^-)$ background.

Parity violation and helicity amplitude of $\Lambda_b \rightarrow J/\psi \Lambda^0$

Λ_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_+ , a_- , b_+ , b_-)
- 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 η symmetry overall Polarization = 0, reducing PDF from 20 to 6 terms. 5 independent parameters (3 magnitudes of h.a. + 2 relative phases)

α_b measurement of $\Lambda_b \rightarrow J/\psi \Lambda^0$

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

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

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

$$C_{ij} = \frac{1}{(4\pi)^3} \int \int F_i(\Omega') T(\Omega', \Omega) F_j(\Omega) d\Omega' d\Omega$$

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

$$a_+ = 0.17^{+0.12}_{-0.17}(\text{stat.}) \pm 0.09(\text{syst.})$$

$$a_- = 0.59^{+0.06}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.})$$

$$b_+ = 0.79^{+0.04}_{-0.05}(\text{stat.}) \pm 0.02(\text{syst.})$$

$$b_- = 0.08^{+0.13}_{-0.08}(\text{stat.}) \pm 0.06(\text{syst.})$$

Large $|a_-|$ and $|b_+|$ refer to negative helicity states for Λ^0 preferred.
 Λ^0 and J/ψ are highly polarized in the direction of their momenta.

α_b consistent with LHCb:

$$\alpha_b = 0.05 \pm 0.17(\text{stat.}) \pm 0.07(\text{syst.})$$

α_b differs from pQCD expectation (from -18% to -14%) by $\sim 2.5\sigma$ and from HQET expectation (78%) by $\sim 2.5\sigma$

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 $\cos\theta_L$ & $\cos\theta_K$:

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

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

Where F_L — fraction of longitudinal polarisation; 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/ψ 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 $B_s \rightarrow J/\psi \phi$

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

Unbinned maximum likelihood fit using B_s mass and proper decay time.

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

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

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

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 .

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:

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

$$\phi_s^{\text{SM}} = -0.0368 \pm 0.0018$$

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 $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

$\text{BR } B_s \rightarrow \mu^+ \mu^-$ SM predictions: $(3.27 \pm 0.27) \cdot 10^{-9}$ [Buras et al., Eur. Phys. J. C72 (2012) 2172]

Evidence from LHCb и CMS. $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$: $(2.9 \pm 0.7) \cdot 10^{-9}$ [LHCb: arXiv: 1307.5024]
[CMS: arXiv: 1307.5025]

$B_s \rightarrow \mu^+ \mu^-$ 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_u/f_s :
from PDG 2012 [*JHEP* 1304 (2013) 001] & LHCb 2011 [arXiv:1301.5286]

Signal events counting in the signal region (± 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 Sensitivity (SES) corresponds to the $B_s \rightarrow \mu^+ \mu^-$ 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 $I_{0.7}$ и α_{2D} :

$$I_{\Delta R} = \frac{p_T^B}{p_T^B + \sum_{\text{tracks}}^{\Delta R} p_T^{\text{tracks}}}$$

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

Signal yield of $B^+ = 15214 \pm 1.1\%(stat.) \pm 2.4\%(syst.)$ - un-binned maximum likelihood fit.

$$SES = BR(B^+ \rightarrow J/\Psi K^+) \cdot \frac{\epsilon_{J/\Psi K^+} \cdot A_{J/\Psi K^+}}{\epsilon_{\mu\mu} \cdot A_{\mu\mu}} \cdot \frac{f_u}{f_s} \cdot \frac{1}{N_{J/\Psi K^+}} = (2.07 \pm 0.26) \cdot 10^{-9}$$

In the optimised search window:

Expected number of background events: 6.75

Observed number of signal events: 6

$$BR(B_s \rightarrow \mu^+ \mu^-) = SES \cdot N_{\mu\mu}$$

Expected upper limit: $< 1.6 \cdot 10^{-8}$ @ 95% CL
 Measured upper limit: $< 1.5 \cdot 10^{-8}$ @ 95% CL

Summary and Outlook

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

- $\Lambda_b \rightarrow J/\psi \Lambda_0$
- $B_d \rightarrow K^{*0} \mu^+ \mu^-$
- $B_s^0 \rightarrow J/\psi \phi$
- $B_s \rightarrow \mu^+ \mu^-$

Outlook

- One can expect increasing precision of a further measurements based on the analysis of 8 TeV data.
- Upcoming in RUN-2 Pixel Insertable B-Layer (IBL) should provide increasing vertexing performance.
- Further Semiconductor Tracker (all silicon ID) and trigger upgrades.

Backup

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B^+ production @ 2.4 fb⁻¹: [JHEP 10 \(2013\) 042](#)

Measurement of the parity violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b \rightarrow J/\psi \Lambda_0$ @ 4.6 fb⁻¹: [ATLAS-CONF-2013-071](#)

Angular analysis of $B_d \rightarrow K^{*0} \mu^+ \mu^-$ @ 4.9 fb⁻¹: [ATLAS-CONF-2013-038](#)

φ_s and $\Delta\Gamma_s$ from flavor-tagged time-dependent angular analysis of $B_s \rightarrow J/\psi \varphi$ @ 4.9 fb⁻¹: [ATLAS-CONF-2013-039](#)

Limit on $B_s \rightarrow \mu^+ \mu^-$ branching fraction @ 4.9 fb⁻¹: [ATLAS-CONF-2013-076](#)

$B_s \rightarrow \mu^+ \mu^-$ 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.