Heavy flavour studies with the ATLAS detector

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ATLAS detector

Inner Detector: tracking, momentum and vertex measurement

- $|\eta| < 2.5$, d_0 resolution $\sim 10 \mu\text{m}$

Muon Spectrometer: trigger and muon identification

- $|\eta| < 2.7$

Mass resolution $\sigma(m_{J/\psi}) = 60 \pm 1 \text{ MeV}$

Trigger and dataset

B-physics trigger:

- muons, di-muon decays ($J/\psi, \Upsilon$)
- L1: single and di-muon triggers (threshold from $p_T = 4\text{ GeV}$)
- L2 and EF: muons from common vertex, opposite charge
- invariant mass window of J/ψ , B and Υ un-prescaled in 2011
- 2012: added barrel-only triggers to keep a larger fraction of data

Datasets for analyses shown here :

- 2011 dataset at $\sqrt{s} = 7\text{ TeV}$, recorded $\int \mathcal{L} = 5.08\text{ fb}^{-1}$
- 2012 dataset at $\sqrt{s} = 8\text{ TeV}$, recorded $\int \mathcal{L} = 21.3\text{ fb}^{-1}$
- presenting selected recent results only, all results on

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults>

Associated production of prompt and non-prompt J/ψ mesons and Z boson

Associated production of quarkonia with additional objects on LHC:

- single parton scattering (SPS)
- double parton scattering (DPS)

Event selection: $J/\psi \rightarrow \mu^+ \mu^-$, $Z \rightarrow e^+ e^-$ or $\mu^+ \mu^-$

- Z : muons $p_T > 24$ GeV or electrons $p_T > 15$ GeV, isolation requirement on leptons and trigger match for at least 1 lepton
- $m(Z_{cand}) = m(Z_{PDG}) \pm 10$ GeV
- J/ψ : $p_T > 8.5$ GeV, $|\eta| < 2.1$, leading muon $p_T > 4$ GeV,
- dataset 2012, 20.3 fb $^{-1}$

Associated production of J/ψ and Z

Fit J/ψ mass and
pseudo-proper time:

Prompt $J/\psi + Z$:

- $56 \pm 10 \pm 3$ events
- significance $> 5\sigma$

Non-prompt $J/\psi + Z$:

- $95 \pm 12 \pm 8$ events
- significance $> 9\sigma$

Azimuthal angle between J/ψ
and Z :

- DPS expecting flat
- SPS peaking at high $\Delta\phi$

Associated production of J/ψ and Z

- normalised to the inclusive Z cross-section
- fiducial, inclusive (SPS+DPS) and DPS-subtracted cross-section
- compared to theoretical predictions (LO colour-singlet mechanism, NLO colour singlet and colour octet)
- models underestimate the SPS contribution

Associated production of J/ψ and Z

Measured differential production cross-section as a function of p_T
(again normalised to the inclusive Z cross-section)

Associated production of J/ψ and Z

- can set upper limit on DPS contribution (assuming independent hard scattering in DPS)
- that gives lower limit on effective cross-section of DPS

$$\sigma_{\text{eff}} > 5.3 \text{ (3.7) mb at 68 (95)\% C.L.}$$

Parity-violating asymmetry parameter α_b and helicity amplitudes of $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

$$\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-) \Lambda^0(p\pi^-) \text{ helicity}$$

Selection:

- J/ψ : $2.8 \text{ GeV} < m_{\mu\mu} < 3.4 \text{ GeV}$
- Λ^0 : $1.08 \text{ GeV} < m_{hh} < 1.15 \text{ GeV}$
- Λ_b^0 : $5.56 \text{ GeV} < m_{J/\psi\Lambda^0} < 5.68 \text{ GeV}$
- cascade topology: $\chi^2/N_{dof} < 3$,
 $L_{xy} > 10 \text{ mm}$, $\tau_{\Lambda_b} > 0.35 \text{ ps}$
- 1400 Λ_b^0 and $\bar{\Lambda}_b^0$ in 2011 dataset

Analysis:

- decay described by 4 helicity amplitudes
- parity violating asymmetry parameter
 $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$
- full angular PDF
- used method of moments F_i
- lifetime and mass measurement in
 Phys. Rev. D87 (2013) 032002

$$\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-) \Lambda^0(p\pi^-)$$

Check fit: compared F_i for data with weighted signal+background MC

Results:

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

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

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

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

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

- Λ^0 and J/ψ are highly polarized in direction of their momenta
- α_b value consistent with LHCb: $0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$ (Phys. Lett.B724 (2013) 27)
- inconsistent with pQCD $\alpha_b = (-0.17, -0.14)$ and HQET $\alpha_b = 0.78$ at a level of 2.6 and 2.8σ

Study of the $B_c^+ \rightarrow J/\psi D_s^+$ and $B_c^+ \rightarrow J/\psi D_s^{*+}$ decays

$B_c^\pm$ is an interesting object with two different heavy-flavour quarks

- decay $B_c^\pm \rightarrow J/\psi(\mu^+\mu^-)\pi^\pm$ observed in 2011 data (ATLAS-CONF-2012-028)
- process $\bar{b} \rightarrow \bar{c}c\bar{s}$ allows B_c^+ decay to charmonium and $D_s^{(*)+}$
- subsequent $D_s^{*+} \rightarrow D_s^+(\gamma/\pi^0)$ and $D_s^+ \rightarrow \phi(K^+K^-)\pi^+$
- $B_c^+ \rightarrow J/\psi D_s^{*+}$ helicity amplitudes: A_{++} , A_{--} and A_{00}

$B_c^+ \rightarrow J/\psi(\mu^+\mu^-)D_s^+(K^+K^-\pi^+)$ event selection

J/ψ :

- 2 muons $p_T > 3$ GeV
- $\chi^2/\text{n.d.f}(J/\psi) < 15$
- $m(J/\psi)$ in 2800–3400 MeV

D_s^+ :

- 3 tracks fitted to common vertex
- tracks $p_T > 1$ GeV
- $\chi^2/\text{n.d.f} < 8$
- $m(K^+K^-)$ within ± 7 MeV from m_{PDG}
- $m(K^+K^-\pi^+) = 1930\text{--}2010$ MeV
- $0.15 \text{ mm} < L_{xy} < 10 \text{ mm}$
- pion pointing angle: $\cos \theta^* < 0.8$
- $|\cos^3 \theta(K\pi)| > 0.15$ in c.m.s (ϕ)

B_c^+ : fitting cascade decay

- constraining J/ψ and D_s^+ masses to PDG values
- $\chi^2/\text{n.d.f} < 3$
- $p_T > 15$ GeV
- $d_0 < 0.1 \text{ mm}$; $z_0 \cdot \sin \theta < 0.5 \text{ mm}$
- $0.1 \text{ mm} < L_{xy} < 10 \text{ mm}$
- D_s^+ pointing: $\cos \theta^* > -0.8$
- 1547 $J/\psi D_s^+$ candidates selected

$$B_c^+ \rightarrow J/\psi D_s^{(*)+} \text{ fit}$$

2D unbinned maximum likelihood fit of mass and helicity angle $\theta'(\mu^+)$:

- $B_c^+ \rightarrow J/\psi D_s^+$ signal
- $B_c^+ \rightarrow J/\psi D_s^{*+}$ with $A_{\pm\pm}$
- $B_c^+ \rightarrow J/\psi D_s^{*+}$ with A_{00}
- background

Measured transverse polarisation fraction of $B_c^+ \rightarrow J/\psi D_s^{*+}$

$$\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23 \text{ (stat)} {}^{+0.06}_{-0.07} \text{ (syst)}$$

$B_c^+ \rightarrow J/\psi D_s^{(*)+}$ branching fraction ratios

Ratios of branching fractions with $B_c^+ \rightarrow J/\psi \pi^+$ as reference decay:

$$\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 3.8 \pm 1.1 \text{ (stat)} \text{ }^{+0.2}_{-0.6} \text{ (syst)} \pm 0.2 \text{ } (\mathcal{B}_{D_s})$$

$$\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 10.3 \pm 3.1 \text{ (stat)} \text{ }^{+0.8}_{-1.5} \text{ (syst)} \pm 0.6 \text{ } (\mathcal{B}_{D_s})$$

Ratio of $B_c^+ \rightarrow J/\psi D_s^{(*)+}$ branching fractions:

$$\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \rightarrow J/\psi D_s^+)} = 2.7 \text{ }^{+1.1}_{-0.8} \text{ (stat)} \text{ }^{+0.4}_{-0.3} \text{ (syst)}$$

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

Excited states of $B_c^\pm$ are predicted by NRQCD, pQCD and Lattice:

- 1S and 2S states have a mass splitting for 0^+ and 0^- components
- ATLAS not sensitive enough to distinguish them: missing soft gamma, mass resolution

Phys. Rev. D 70 (2004) 054017

$B_c^\pm(1S) \rightarrow J/\psi(\mu^+\mu^-)\pi^\pm$: selection and fit

$B_c^\pm(1S)$ selection optimised separately for 2011 (2012) dataset:

- $p_T(\mu) > 4$ and 6 GeV
- $\chi^2/\text{n.d.f.}(J/\psi) < 15$
- $m(J/\psi)$ 3σ from nominal mass
- $\chi^2/\text{n.d.f.}(B_c) < 2.0$ (1.5)
- $p_T(B_c) > 15$ (18) GeV
- $d_{xy}^0/\sigma(d_{xy}^0)(\pi^+) > 5$ (4.5)

Unbinned fit of mass distribution:

- Gaussian with per-candidate error
- exponential background

$$B_c^\pm(2S) \rightarrow B_c^\pm(2S) \pi^+ \pi^-$$

Candidate selection:

- $B_c^\pm(1S)$ within 3σ from fitted mass
- $p_T(\pi^\pm) > 400$ MeV
- if several candidates per event, select the one with the best cascade fit χ^2

Extended unbinned fit of Q -value:

$$Q_{B_c^\pm \pi \pi} = m(B_c^\pm \pi \pi) - m(B_c^\pm) - 2m(\pi)$$

- Gaussian signal
- 3rd order polynomial for background

Observation of an excited $B_c^\pm$ state

Significance calculated using toy studies to account for "look elsewhere effect"

- 3.7σ in 7 TeV data
- 4.5σ in 8 TeV data
- combined significance is 5.2σ

Observed new state at

$$Q = 288.3 \pm 3.5 \text{ (stat)} \pm 4.1 \text{ (syst)} \text{ MeV}$$

corresponding to a mass

$$m = 6842 \pm 4 \text{ (stat)} \pm 5 \text{ (syst)} \text{ MeV}$$

consistent value of 6835–6917 MeV
predicted by various theories

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

Heavy-quark symmetry suggests existence of X_b analogous to $X(3872)$ observed by Belle in $B^+ \rightarrow K^+ X(3872)$ with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ (Phys. Rev. Lett. 91 (2003) 262001)

- search for X_b in $\Upsilon(nS) \pi^+ \pi^-$
- mass predictions around 10.5 GeV

Data and selection:

- selected by di-muon trigger with $p_T > 4$ GeV, $m(\mu\mu) = 8\text{-}12$ GeV
- 16.2 fb^{-1} at 8 TeV
- reconstructed 6 million $\Upsilon(1S)$ and 0.2 million $\Upsilon(2S)$ candidates

Expected number of X_b events

$$N = N_{2S} \cdot R \cdot \frac{A}{A_{2S}} \cdot \frac{\varepsilon}{2\varepsilon_{2S}}$$

where $R \equiv (\sigma\mathcal{B})/(\sigma\mathcal{B})_{2S}$ is production rate relative to $\Upsilon(2S)$

Search for X_b

- bin data according to S/B in p_T and $\cos(\theta)$
- $\Upsilon(1S)\pi^+\pi^-$ mass distribution for most sensitive bin – $\Upsilon(2S)$ and $\Upsilon(3S)$ peaks
- invariant mass fits for $\Upsilon(2S)$ (barrel, endcap) and $\Upsilon(3S)$:

Search for X_b

- no evidence for X_b found
- considered also different spin alignments for X_b
- upper limits 0.8-4% (depending on mass) - currently the best limits
- no evidence for production of $\Upsilon(1^3D_J)$ triplet, $\Upsilon(10860)$ or $\Upsilon(11020)$

B-physics programme will follow the Run 1 approach:

- precision measurements of rare processes, focus on potential beyond-SM effects
- heavy flavour production at 13 TeV
- searches for new and exotic states and decay modes

Detector upgrades during long shutdowns:

- already installed IBL, additional muon chambers, consolidation
 - improved tracking, impact parameter and decay time resolution
- study potential for CPV measurements, e.g. $B_s^0 \rightarrow J/\psi\phi$

	2011	2012	2015-17	
Detector	current	current	IBL	
Average interactions per BX $\langle\mu\rangle$	6-12	21	60	
Luminosity, fb^{-1}	4.9	20	100	
Di- μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460
Signal events	22 000	86 400	327 900	45 500
Total events in analysis	130 000	550 000	1 874 000	284 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10

Summary

The large amount of Heavy Flavour data collected by ATLAS is potentially sensitive to New Physics. Presented analyses:

- associated production of J/ψ and Z
- asymmetry parameter and helicity amplitudes of $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
- $B_c^+ \rightarrow J/\psi D_s^{*+}$
- $B_c^\pm$ (2S) observation
- search for $X_b \rightarrow \Upsilon(nS)\pi^+\pi^-$

Few more measurements and searches from Run1 dataset to be completed soon and we are collecting first data from Run2.

Thank you for your attention.

Backup slides

Associated production of W and prompt J/ψ

Probes quarkonium production mechanism, sensitive to multiple parton interactions.

Selection:

- prompt J/ψ via mass and pseudo-proper time
- $W^\pm$ muon trigger, identified by μ and missing p_T
- fit $W^\pm$ transverse mass with multijet background
- 29 events with $W^\pm J/\psi$

Associated production of W and prompt J/ψ

- double parton scattering estimate $\sim 40\%$ from

$$d\sigma_{J/\psi|W} = \sigma_W \otimes \sigma_{J/\psi} / \sigma_{\text{eff}}$$

- extract inclusive (SPS+DPS) cross-section ratio
- comparison with theory: measured rate underestimated (but large uncertainties of data)

$B_s^0 \rightarrow J/\psi \phi$ analysis

- tagged analysis using 2011 data (4.9 fb^{-1})
- measured

$$\phi_s = 0.12 \pm 0.25 \text{ (stat)} \pm 0.05 \text{ (syst)} \text{ rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat)} \pm 0.010 \text{ (syst)} \text{ ps}^{-1}$$

- about to release analysis using 2012 data