Heavy Flavour results from ATLAS

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XXXIst Cracow EPHANY Conference on the recent LHC Results

Kraków, Poland
13-17 January 2025
ATLAS heavy-flavour physics studies span numerous topics:
- **Production**: heavy open-flavour hadrons and onia cross-sections
- **Decay**: branching fractions, CP studies, lifetimes
- **Spectroscopy**: exotic and conventional hadrons
- **Strengths**: muon final states, vertexing, extensive kinematic ranges

Latest topics, for Epiphany 2025:

- **Charmonium**: differential $J/\psi$ and $\psi(2S)$ meson production cross-sections
  - [arXiv:2412.15742](https://arxiv.org/abs/2412.15742) (submitted JHEP)
  - Eur. Phys. J. C 84 (2024) 189
  - ATLAS Briefing

- **Open charm**: differential $D^\pm$ and $D_s^\pm$ meson production cross-sections
  - [arXiv:2412.15742](https://arxiv.org/abs/2412.15742) (submitted JHEP)

- **Open beauty**: precision $B^0$ meson effective lifetime measurement
  - [arXiv:2411.09962](https://arxiv.org/abs/2411.09962) (submitted EPJC)
• Muon Spectrometer: reconstruction $p_T > 2.5$ GeV

• Inner Detector tracking systems: $p_T > 0.5$ GeV, $|\eta| < 2.5$

• Multi-level trigger system: L1 (hardware) and High-Level Trigger (software)

• Triggering for heavy flavour, typically
  • di-muon and single-muon triggers
  • Muon $p_T$ thresholds: 4, 6, 11 GeV
  • More info: *B-physics trigger performance*
Motivation and Analysis Approach

- Heavy quarkonia uniquely probe near the boundary between pQCD and non-pQCD

- Quarkonium production occurs via two mechanisms:
  - **Prompt**: short-lived QCD processes, either in $pp$ interactions or feed-down from heavier states
  - **Non-prompt**: $b$-hadron decays

- pQCD much better at describing non-prompt than prompt production

- Kinematic range now pushed to significantly higher regimes, previously unexplored:
  - $J/\psi$: $p_T < 100$ GeV → $p_T < 360$ GeV
  - $\psi(2S)$: $p_T < 100$ GeV → $p_T < 140$ GeV

- Achieved using an **updated trigger strategy**, to overcome insufficient angular resolution at high $p_T$:
  - Low $p_T(\psi) < 60$ GeV: use di-muon triggers
  - High $p_T(\psi) > 60$ GeV: use single-muon trigger (50 GeV muon $p_T$ threshold)

- Distinguish between [$J/\psi$, $\psi(2S)$] and [Prompt, Non-prompt] by 2D fits of **di-muon mass** and **pseudo-proper lifetime**
Charmonium: differential $J/\psi$ and $\psi(2S)$ production cross-sections

- 2D $m_{\mu\mu}$, $\tau$ Fits: 3 rapidity $(y)$ bins $\times$ 34 $p_T$ bins (in interval 8-360 GeV)
  $$= 102 \text{ phase-space bins}$$

- Reconstructed pseudo-proper lifetime:
  $$\tau = \frac{m_{\mu\mu}L_{xy}}{p_T}$$

- Differential cross-sections determined from prompt (P) and non-prompt (NP) $J/\psi$ and $\psi(2S)$ yields:
  $$\frac{d^2\sigma^{P,NP}(pp \to \psi)}{dp_Tdy} \times B(\psi \to \mu^+\mu^-) = \frac{1}{A(\psi)\epsilon_{\text{trg}}\epsilon_{\text{trgSF}}\epsilon_{\text{reco}}\epsilon_{\text{recoSF}}} \frac{N_{J/\psi}^{P,NP}}{\Delta p_T \Delta y \int L \, dt}$$

- Also extracted: fraction of NP production $F_{\psi}^{NP}$ and $R_{P,NP}$, the $\psi(2S)$ to $J/\psi$ production ratios
Charmonium: differential $J/\psi$ and $\psi(2S)$ production cross-sections

**Results (nominal isotropic spin-alignment scenario assumed)**

- 9 [6] orders of magnitude spanned by $J/\psi$ [$\psi(2S)$] cross-sections
- Non-prompt fractions increase at lower $p_T$, plateau at higher $p_T$
- Consistency with other LHC experiments; overlapping kinematic ranges:

ALICE: JHEP (2022) 190
CMS: PLB 780 (2018) 251
Charmonium: differential $J/\psi$ and $\psi(2S)$ production cross-sections

Theory-Comparison Implications

- **Prompt** $J/\psi$ production: predicted spectra harder than those measured; room to improve all models
- **Non-prompt** $J/\psi$ production: predictions better, though still over-estimating at higher $p_T$
- Similar trends for the $\psi(2S)$ analogues
Open Charm: differential $D^\pm$ and $D_s^\pm$ meson cross-sections

- Heavy hadron production in $pp$ collisions is a fundamental process that tests perturbative QCD calculations, which have had persistently large uncertainties:
  - Hard-scatter **energy scales** are comparable to the **heavy quark** masses
  - **Prompt hadronisation** of charm quarks vs. **non-prompt production** via $b$-decays
  - Challenges modelling **non-perturbative effects**, e.g., hadronisation

**This study:**

- **Measure** $D^\pm$ and $D_s^\pm$ production cross-sections simultaneously and differentially using the channels $D^\pm_{(s)} \rightarrow \phi\pi^\pm \rightarrow \mu^+\mu^-\pi^\pm$; less abundant than the analogous $\phi \rightarrow K^+K^-$ process, but can use di-muon triggers and have less background
- **Push** measurement of the $D_s^\pm$ cross-section up to $p_T = 100$ GeV (a first)

**Selection:**
- Di-muon system: triggers, opposite charge, invariant-mass criterion
- Track requirements: total charge, minimum $p_T$, secondary-vertex criteria
- Main observable: invariant mass, $m_{\mu\mu\pi}$

**arXiv:2412.15742 (submitted JHEP)**
Open Charm: differential $D^\pm$ and $D_s^\pm$ meson cross-sections

Invariant mass fitting

- Extended unbinned maximum likelihood fit for signal yields in terms of invariant mass $m_{\mu\mu\pi}$:

$$L(m) = \frac{e^{-(S_{D^+}+S_{D_s^+}+B)}}{n!} \prod \left[ S_{D^+}P_{D^+}(m) + S_{D_s^+}P_{D_s^+}(m) + BP_{\text{Bkg}}(m) \right] \times G(\Delta)$$

$$P_{D^+}(m) = \text{Voigt}(m; m_{D^+}, \gamma_{D^+}, \sigma_{D^+})$$

$$P_{D_s^+}(m) = \text{Voigt}(m; m_{D_s^+}, \gamma_{D_s^+}, \sigma_{D_s^+})$$

$$P_{\text{Bkg}}(m) = A_{\text{norm}} \cdot e^{(c_1 m + c_2 m^2)}$$

$$G(\Delta) = \text{Gauss}(\Delta; \mu_{\Delta}, \sigma_{\Delta})$$

- Voigtian distribution: convolution of Breit-Wigner and Gaussian

- $\Delta \equiv m_{D_s^+} - m_{D^\pm}$ mass difference, required to be close to the world-average value $\mu_{\Delta}$ under a Gaussian constraint

- Fit is designed to be compatible with data in a broad set of kinematic regions while using a small number of parameters
Open Charm: differential $D^\pm$ and $D_s^\pm$ meson cross-sections

**Lifetime fitting**

- **Prompt** ($pp \rightarrow c\bar{c}X \rightarrow D_{(s)}^\pm X'$) and **non-prompt** ($pp \rightarrow b\bar{b}Y \rightarrow cY' \rightarrow D_{(s)}^\pm Y''$) production processes manifest differently in the ATLAS detector; **constrain** their relative contributions using the pseudo-proper lifetime observable $m_{\mu\mu\pi}L_{\chi\mu\pi}^{\mu\mu\pi}/p_T^{\mu\mu\pi}$

- **Lifetime fits**: convolutions of Gaussian and error functions with 1 [2] exponentials for prompt [non-prompt] PDFs
Open Charm: differential $D^\pm$ and $D_s^\pm$ meson cross-sections

Cross-section determination

- **Fiducial volume**: $12 < p_T < 100$ GeV (9 bins)
  
  $|\eta| < 2.5$ (5 bins)

- Extract signal yields from **invariant mass fits** for $D^\pm$ and $D_s^\pm$ simultaneously

- Correct for **reconstruction efficiencies** in each bin, suitably weighted for prompt and non-prompt production fractions (determined from the lifetime fits)

- Account for **branching fractions**:

  \[
  \mathcal{B}(D^\pm \to \phi(\mu\mu)\pi^\pm) = \mathcal{B}(D^\pm \to \phi\pi^\pm) \times \mathcal{B}(\phi \to \mu\mu)
  \]

  \[
  \mathcal{B}(D_s^\pm \to \phi(\mu\mu)\pi^\pm) = \frac{\mathcal{B}(D_s^\pm \to \phi(K^+K^-)\pi^\pm)}{\mathcal{B}(\phi \to K^+K^-)} \times \mathcal{B}(\phi \to \mu\mu)
  \]

  Since this quotient of world averages has smaller uncertainty than the $\mathcal{B}(D_s^\pm \to \phi\pi^\pm)$ world average
Open Charm: differential $D^\pm$ and $D_s^\pm$ meson cross-sections

Cross-section results

\[ \frac{d\sigma}{d|\eta|} = \left. \frac{S^i_{D^\pm/D_s^\pm}}{(D^\pm/D_s^\pm)} \right| \int \mathcal{L} dt \times C^i \times B(D^\pm/D_s^\pm \rightarrow \phi(\mu\mu)\pi^\pm) \times \Delta|\eta| \]

\[ \frac{d\sigma}{dp_T} = \left. \frac{S^i_{D^\pm/D_s^\pm}}{(D^\pm/D_s^\pm)} \right| \int \mathcal{L} dt \times C^i \times B(D^\pm/D_s^\pm \rightarrow \phi(\mu\mu)\pi^\pm) \times \Delta p_T \]

Theory comparisons

- $D^\pm$ production: at low $p_T$ and in all $|\eta|$ bins, both GM-VFNS and FONLL predictions show good agreement; GM-VFNS shows some overestimation at high $p_T$

- $D_s^\pm$ production: only GM-VFNS is available for comparison, showing a similar upward deviation at higher $p_T$

arXiv:2412.15742 (submitted JHEP)
Open Beauty: precision $B^0$ meson lifetime measurement

- Precise $B$-meson lifetimes and their ratios test weak-interaction roles and have potential BSM sensitivity

- **HQE (heavy quark expansion)** theory describes total decay rate $\Gamma = 1/\tau$ as free $b$-quark decay at LO plus sub-leading power-suppressed terms invoking perturbative (Wilson coefficients) and non-perturbative matrix elements

**This study**: Reconstruct weak hadronic spectator-internal colour-suppressed decays

$B^0 \rightarrow J/\psi K^*(892)^0$

and measure their **Effective Lifetime** $\tau_{B^0}$

- $B^0 - \bar{B}^0$ system has light (L) and heavy (H) mass eigenstates with an **average decay width** $\Gamma_d \equiv (\Gamma_L + \Gamma_H)/2$, a **normalized width difference** $y \equiv \Delta \Gamma_d/(2 \Gamma_d) = (\Gamma_L - \Gamma_H)/(2 \Gamma_d)$, and a final-state ($f$) dependent **amplitude asymmetry** $A \equiv (R^f_H - R^f_L)/(R^f_H + R^f_L)$ such that:

$$\tau_{B^0} = \frac{1}{\Gamma_d} \frac{1}{1 - y^2} \left( \frac{1 + 2Ay + y^2}{1 + Ay} \right)$$
Open Beauty: precision $B^0$ meson lifetime measurement

Candidate reconstruction and selection criteria

- $B^0 \rightarrow J/\psi K^{*0}$ candidates:
  - At least one $J/\psi \rightarrow \mu^+\mu^-$ with $\chi^2$/ndof < 10; within mass window retaining 99.7% $J/\psi$ candidates
  - $K^{*0}$: Out of the two $K^+\pi^-/K^-\pi^+$ hypotheses, select that closer to $K^*(892)^0$ PDG mass
  - $J/\psi$ and $K^{*0}$: fit to a common secondary vertex (SV), with di-muon mass constraint to $J/\psi$ PDG mass; $\chi^2$/ndof < 3
  - 10% events have multiple (avg. 2.1) $J/\psi K^{*0}$ candidates; select that with smaller $\chi^2$/ndof

- Primary vertex (PV) selection:
  - Need to choose most likely $B_d^0$ production vertex under pileup conditions (avg. 31)
  - PV positions are recalculated after removing tracks used to reconstruct $B_d^0$ candidate
  - PV candidate with smallest 3D $B_d^0$ impact parameter is chosen

- For each $B_d^0$ candidate, determine pseudo-proper decay time $t$:
  \[
t = \frac{m_B L_{xy}^B}{p_T^B}, \text{ where } L_{xy}^B \text{ is the transverse distance between PV and SV, projected on to } p_T^B\]
Open Beauty: precision $B^0$ meson lifetime measurement

$B^0 \rightarrow J/\psi \ K^*(892)^0$

- **Red lines**: muon candidates
- **Yellow lines**: charged hadrons
- **Pink ellipses**: vertices (PV & SV), separated by ~2 cm
- Energy of 4-track system: **83 GeV**, so highly boosted, jet-like!
Open Beauty: precision $B^0$ meson lifetime measurement

2D unbinned maximum likelihood fit

**Mass PDFs**
- Signal: Johnson $S_U$ - distribution
- Background: linear + sigmoid functions

**Fit projections**

- Based on 2,450,500 ± 2400 $B^0 \rightarrow J/\psi K^{*0}$ candidate signal events
- Measured effective lifetime: $\tau_{B^0} = 1.5053 \pm 0.0012 \text{ (stat.)} \pm 0.0035 \text{ (syst.) \ ps}$

**Pseudo-proper decay time PDFs**
- Signal: exponential convolved with 3-Gaussian resolution function
- Prompt background: 3-Gaussian resolution function
- Combinatorial background: sum of 3 exponentials, each convolved with 3-Gaussian resolution function
**Consistency and stability test**

- Separate $B^0$ lifetime fits for each of 3 data-taking periods
- Black points: subsample lifetimes, stat.-only uncertainties
- $p$-value for consistency, stat.-only: 0.038
- Subsample results are consistent, mutually and with full-sample result

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**ATLAS**

- Run 2 Fitted value
- Run 2 Statistical uncertainty
- Run 2 Total uncertainty
- Fitted value with stat. uncertainty

- $\sqrt{s} = 13$ TeV, 140 fb$^{-1}$

- **Run 2**
  - $1.5053 \pm 0.0012$ (stat.) $\pm 0.0035$ (syst.)

- **2015+2016**
  - $1.5035 \pm 0.0018$ (stat.)

- **2017**
  - $1.5089 \pm 0.0020$ (stat.)

- **2018**
  - $1.5018 \pm 0.0023$ (stat.)
Open Beauty: precision $B^0$ meson lifetime measurement

Results: Determination of the $B^0$ average decay width $\Gamma_d$ and the ratio $\Gamma_d/\Gamma_s$

$\left[ \Gamma_d \right]$

- Use HFLAV (2023) input values of $2y = \Delta \Gamma_d / \Gamma_d = 0.001 \pm 0.010$ and asymmetry $\Lambda = -0.578 \pm 0.136$ with the ATLAS measured effective lifetime $\tau_{B^0}$ to find:

$$\Gamma_d = 0.6639 \pm 0.0005 \text{ (stat.)} \pm 0.0016 \text{ (syst.)} \pm 0.0038 \text{ (ext.) ps}^{-1}$$

where the uncertainty (denoted ‘ext.’) is due to HFLAV inputs and listed separately

- The value of $\Gamma_d$ agrees with HQE theory (Lenz et al., 2023): $0.63^{+0.11}_{-0.07} \text{ ps}^{-1}$

$\left[ \Gamma_d / \Gamma_s \right]$

- Use $\Gamma_s = 0.6703 \pm 0.0014 \text{ (stat.)} \pm 0.0018 \text{ (syst.) ps}^{-1}$ measured by ATLAS (Eur. Phys. J. C 81 (2021) 342) to find:

$$\frac{\Gamma_d}{\Gamma_s} = 0.9905 \pm 0.0022 \text{ (stat.)} \pm 0.0036 \text{ (syst.)} \pm 0.0057 \text{ (ext.)}$$

- The value of $\Gamma_d / \Gamma_s$ agrees with HQE ($1.003 \pm 0.006$) and lattice QCD ($1.00 \pm 0.02$) theory model predictions
Open Beauty: precision $B^0$ meson lifetime measurement

Comparison of ATLAS $B^0$ lifetime with other recent measurements

ATLAS Briefing

New ATLAS result:

- Compatible with most other recent measurements
- PDG 2024 world average: $1.517 \pm 0.004$ ps, differs by $2.1\sigma$ (draws on full history of $B^0$ lifetime measurements)
- First measurement in $pp$ collisions at 13 TeV
- Most precise single measurement to date
• ATLAS heavy-flavour programme is amassing competitive results from LHC Run 2

• **Charmonium**: Differential $J/\psi$ and $\psi(2S)$ production **cross-sections extended** up to $p_T = 360$ and 140 GeV
  • Most comprehensive measurement of charmonium production to date

• **Open charm**: differential $D^\pm$ and $D_s^\pm$ meson production **cross-sections extended** up to $p_T = 100$ GeV
  • First $D_s^\pm$ cross-section measurement to reach transverse momenta of 100 GeV

• None of the consulted **theory predictions** describes charm production well, especially at higher $p_T$

• **Open beauty**: precision $B^0$ meson **effective lifetime** measurement
  • Most precise single measurement to date

• Further results under preparation, including combinations of Run 2 + Run 3 statistics

• ATLAS $B$-physics public results page: [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults)
ATLAS heavy flavour in Run 3

- Increasing instantaneous luminosity, higher $<\mu>$: ~34 (Run 2) $\rightarrow$ ~42 in 2022, ~50 in 2023

- Similar dimuon triggers used, but, early in fills, more aggressive pre-scaling of those with lower di-muon $p_T$

- For high-precision measurements (e.g., lifetimes, $CP$ violation), errors on pseudo-proper lifetimes get reduced with the shift to higher $p_T$ (even with the associated loss of lower-$p_T$ statistics)
ATLAS heavy flavour in Run 4, HL-LHC

- Replacement of entire inner tracking system (ITk upgrade):
  - Refer to talk by Savanna Shaw, Upgrades session
  - Copes with higher instantaneous luminosities, pileup
  - Greater angular acceptance
  - Expect ~21% improvements in pseudo-proper-decay time resolutions

- Reach studies use di-muon triggers with thresholds: $\mu_{10}\mu_{10}, \mu_6\mu_{10}, \mu_6\mu_6$

- $B_{(s)} \rightarrow \mu^+\mu^-$: ATL-PHYS-PUB-2018-005

- $B_s^0 \rightarrow J/\psi\phi$: ATL-PHYS-PUB-2018-041
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**ATLAS**

$pp \sqrt{s} = 13$ TeV

$\int L dt = 2.6$ fb$^{-1}$

$0 \leq |y| < 0.75$

$p_T < 60$ GeV

**Prompt $\psi(2S)$**

Theory / Data

NLO NRQCD

NRQCD with $k_T$-factorisation

ICEM

**ATLAS**

$pp \sqrt{s} = 13$ TeV

$\int L dt = 2.6$ fb$^{-1}$

$0 \leq |y| < 0.75$

$p_T \geq 60$ GeV

**Non-prompt $\psi(2S)$**

Theory / Data

FONLL

GM-VFNS

NRQCD with $k_T$-factorisation

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Open Charm: differential $D^\pm$ and $D_S^\pm$ meson cross-sections

arXiv:2412.15742 (submitted JHEP)
# Open beauty: precision $B^0$ meson lifetime measurement

[arXiv:2411.09962 (submitted EPJC)]

## Table of Systematic Uncertainties

| Source of Uncertainty                               | Systematic Uncertainty [ps] |
|------------------------------------------------------|-----------------------------|
| ID alignment                                         | 0.00108                     |
| Choice of mass window                                | 0.00104                     |
| Time efficiency                                      | 0.00130                     |
| Best-candidate selection                             | 0.00041                     |
| Mass fit model                                       | 0.00152                     |
| Mass-time correlation                                | 0.00229                     |
| Proper decay time fit model                          | 0.00010                     |
| Conditional probability model                        | 0.00070                     |
| Fit model test with pseudo-experiments               | 0.00002                     |
| **Total**                                            | **0.0035**                  |