Heavy quark physics at ATLAS and CMS (excluding top)

Oleg Meshkov (MSU & Lebedev PI)
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On behalf of the ATLAS and CMS Collaborations
b hadron production at the LHC

- b hadrons (and anti-hadrons) are dominantly produced through strong interaction in pp collisions at the LHC
  - Large inclusive $bb$ cross-section ($\sim 0.1 \text{mb}$)
  - All $b$ hadron types including $\Lambda_b$, $B_c$ and $B_s$ are produced

- Unfortunately, it’s hard to efficiently trigger on $b$ hadron decays at the LHC
  - $b$ decay products have relatively low pT, predominantly produced in forward direction

- Exceptions
  - Dedicated displaced vertex triggers (for example, LHCb)
  - Specific final states, e.g. including di-muons
The ATLAS and CMS detectors

- Multipurpose detectors with similar performance designed to study pp collisions at 14 TeV
  - Track momentum resolution and therefore b hadron mass resolution depends critically on magnetic field strength
    - **ATLAS**: 2T; **CMS**: 4T
  - Fake muon rejection critical for background suppression
    - **CMS**: $\pi$ (0.05-0.13)%, $K$ (0.08-0.22)%, $p$ (0.04-0.15)%
    - **ATLAS**: $\pi$ (0.04-0.13)%, $K$ (0.07-0.1)%, $p$ $10^{-5}$
B-physics trigger

- Both experiments have multi-level triggers
  - Level-1 → hardware muon identification
  - High-level → Complete event reconstruction using also ID information
- Trigger is complicated due to low thresholds in muon $P_T$ → Incompatible with bandwidth constraints at high luminosity
- CMS can go lower in muon $P_T$ for the stronger magnetic field
- ATLAS can use topological information ($m(\mu\mu)$, $\Delta R(\mu\mu)$) to reduce the bandwidth acting on kinematic of the di-muon system
B-physics program

• B-physics (and light states):
  ▶ Test of QCD-based prediction: cross section, spectroscopy, etc.
    • Quarkonia production and decay
    • J/ψ + J/ψ, J/ψ W, J/ψ Z associated production (double parton scattering)
    • Spectroscopy (χ_b3P, X_c, X_b searches, B_c excited states), new states
    • Exotic hadrons: Tetraquark (B_Sπ), pentaquark (J/ψp) searches
    • Polarisation, decays asymmetries studies (Λ_b, Λ, bb correlations)
  ▶ Test of EW physics, or search for new physics is areas where the SM predicts rare processes or small effects
    • Rare decay of B_{s,d} → μμ,
    • ϕ_S in B_S → J/ψφ
    • Flavour anomalies (angular correlation in B_d → K^*μμ, R(K^*) )
    • τ → 3μ

Only recently results are presented
Quarkonia production and decay
Quarkonia production in pp and p-Pb collisions at 5 TeV  \textit{ATLAS}  

- Prompt (not from B-decays) and non-prompt (from B-decays) J/ψ and ψ(2S) reconstruction
- Simultaneous fit in mass and pseudo-proper lifetime $\tau_{\mu\mu}$
- Fit data in bins of $P_T$, $y$ and centrality using p.d.f. for $m_{\mu\mu}$ and $\tau_{\mu\mu}$
Charmonia cross-sections in pp collisions at 5 TeV

- Prompt charmonia $J/\psi$ and $\psi(2S)$ cross-sections extracted
- Compared with NRQCD predictions
  - Overall good agreement
Charmonia cross-sections in pp collisions at 5 TeV

- Non-prompt charmonia J/ψ and ψ(2S) cross-sections extracted
- Compared with FONLL predictions
  - Overall good agreement
Y(nS) production in pp collisions at 5 TeV

- Similar analysis for bottomonia Y(nS) (only in $m_{\mu\mu}$)
- Fit data in bins of $P_T$ and $y$ in $m_{\mu\mu}$
- Compared with NRQCD predictions
  - Significant disagreement in the lower part of the PT spectrum
Quarkonia cross-sections in pp collisions at 13 TeV

- Prompt charmonia and Y(nS) cross-sections extracted
- Compared with NRQCD predictions
  - Overall good agreement
  - In low-PT Y(nS) region data below NRQCD prediction (but compatible)
J/ψ production in jets at 8 TeV

• Measurement of J/ψ–jet Association is a test of the role of jet fragmentation in quarkonium production with Run1 data (19.1 fb⁻¹, √s = 8 TeV)

• Theoretically described in Fragmenting-Jet Function (FJF) approach.

• Crucial variables to describe J/ψ kinematics are: E_{jet} and z = E_{J/ψ} / E_{jet}

• Using NRQCD, the theoretical predictions are based on LDMEs with different amplitudes that dominate depending on jet rapidity regions
  ‣ At large rapidities charm fragmentation more prominent
  ‣ At small rapidities gluon fragmentation dominant

• Goal is to measure the double differential cross-section as a function of z and E_{jet} to disentangle the various LDME contribution
J/ψ production in jets at 8 TeV\[ \text{CMS} \]

- $E(J/\psi) > 15 \text{ GeV}, |y| < 1$.
- Anti-\text{kT} jets with $R=0.5$ and $P_T > 25 \text{ GeV}, |\eta| < 1$
- $J/\psi$ associated to a given jet if $\Delta R < 0.5$
- Investigated region: $0.3 < z < 0.8$ where FJF predictions available
- Event with one or two jets are considered

Once $J/\psi$ - jet association is made, compute this:

$$\Xi(E, z) = \frac{1}{N(z)} \frac{N(E, Z)}{0.8} \int_{0.3}^{0.8} N(E, \hat{z}) d\hat{z}$$
**J/ψ production in jets at 8 TeV**

**CMS**

- FJF predictions for gluon jet fragmentation in the central region describe well data

- Jet fragmentation can account for > 80% of J/ψ production
Spectroscopy
New states
B_{c}^{+}(2s) excited state

- CMS measured it with full Run2 data: 143 fb^{-1}

- Final states:
  - B_{c}^{+(2s)} \rightarrow B_{c}^{+} \pi \pi \text{ where } B_{c}^{+} \rightarrow J/\psi \pi
  - B_{c}^{+(2s)} \rightarrow B_{c}^{+(2s)} \gamma \rightarrow B_{c}^{+} \pi \pi \text{ where } B_{c}^{+} \rightarrow J/\psi \pi

- Sensitive to both transition despite the lost soft-photon
  - Theory predicts smaller mass gap w.r.t. $B_{c}^{+(2s)}$ and $B_{c}^{+}$
B_c(2s) excited state

- Higher P_T(B_c^+) threshold at 15 GeV
- \sim 7600 candidates
- Resolution allows to separate both peaks
- \Delta m_{exp} = 29 \pm 1.5 \pm 0.7 \text{ MeV}
- M(B_c^+(2s)) = 6871.0 \pm 1.2 \text{ (stat.)} \pm 1.1 \text{ (syst)} \text{ MeV}
- Two states recently seen also by LHCb
  - Compatible masses and \Delta m with CMS


B_c^*(2s)  B_c(2s)
First observation of the $\Lambda_b \rightarrow J/\psi \Lambda \phi$ CMS

- 60 fb$^{-1}$ at 13 TeV by the CMS
- $\text{Br}(\Lambda_b \rightarrow J/\psi \Lambda \phi)/\text{Br}(\Lambda_b \rightarrow \psi(2S)\Lambda) = (8.26 \pm 0.90 \text{ (stat)} \pm 0.68 \text{ (syst)} \pm 0.11\text{ (Br)}) \times 10^{-2}$
- Calculated by calibration to $\text{Br}(\Lambda_b \rightarrow \psi(2S)\Lambda)$

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)}{\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} = \frac{N(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^- \pi^+) \epsilon(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)}{N(\Lambda_b^0 \rightarrow \psi(2S)\Lambda) \epsilon(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi) \mathcal{B}(\phi \rightarrow K^+K^-)} ,
\]
Rare decays
Measurement of $B_{s}^{0} \rightarrow \mu \mu$ and search $B_{0}^{0} \rightarrow \mu \mu$

- Leptonic B meson decays offer excellent opportunities to perform precision tests of the SM due to minimal uncertainties

- $B_{s}^{0} \rightarrow \mu \mu$ was first observed by CMS and LHCb jointly, but $B_{0}^{0} \rightarrow \mu \mu$ is still not observed yet

- Data sets: 5 and 20 fb$^{-1}$ in 2011 and 2012 at 7 TeV and 8 TeV (Run 1), 36 fb$^{-1}$ in 2016 at 13 TeV (Run 2)
Measurement of $B^0_s \to \mu\mu$ and search $B_0 \to \mu\mu$

- The $B^0_s \to \mu\mu$ decay is observed (expected) with a significance of $5.6\sigma$ ($6.5\sigma$) and the time integrated branching fraction is measured to be $B(B^0_s \to \mu\mu) = [2.9^{+0.7}_{-0.6} \text{ (exp)} \pm 0.2 \text{ (frag)}] \times 10^{-9}$.

- No significant $B^0 \to \mu\mu$ signal is observed and an upper limit $B(B^0 \to \mu\mu) < 3.6 \times 10^{-10}$ is determined at 95% CL.

- $B^0_s$ life time is measured $\tau_{\mu\mu} = 1.70^{+0.61}_{-0.44}$ ps.
**B_{s,d} → μμ BR measurement**

- Rare but clean decay suppressed by FCNC in the SM
  - $\text{BR}(B_s → μμ) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\text{BR}(B_d → μμ) = (1.06 \pm 0.09) \times 10^{-10}$
- Sensitive to New Physics contributions through loops
- Analysis strategy:

\[
B(B_s^0 → μμ) = N(B_s^0 → μμ) \times [B(B^* → J/ψK^*)] \times B(J/ψ → μμ) \times \left( \frac{f_u}{f_{s/d}} \right) \times \left( \frac{1}{D_{\text{norm}}} \right)
\]

- Number of Bs/Bd events from an unbinned ML fit to $m(μμ)$ distribution
- Reference channel: $B^+ → J/ψK^+$
  - Extracted from an unbinned ML fit to $m(μμK^+)$ distribution
- $D_{\text{norm}} = \sum_k N_{J/ψK}^k \alpha_k \left( \frac{ε_{μμ}}{ε_{J/ψK}} \right)_k$
- Acceptance and efficiencies from simulation
- Hadronisation probabilities
- Trigger categories and luminosity prescales
\( \text{B}_{s,d} \rightarrow \mu \mu \) BR measurement

- Results for full Run1+Partial Run2 dataset (25+26 fb\(^{-1}\))
- \( \text{BR(B}_{s} = 2.8 \times 10^{-9} \) (stat. ± syst.)
  - Evidence at 4.6\( \sigma \)
- Upper limit on \( \text{BR(B}_{d} \) placed at 2.1\times 10^{-10}(95\% \text{ CL})
  - Currently the most stringent limit
Angular analysis of $B_d \to K^* \mu \mu$

- The study is using 20.3 fb$^{-1}$ at 8 TeV
- Decay amplitude fully described by the invariant mass $q^2$ of the di-muon system and three angles: $\theta_L$, $\theta_K$ and $\Phi$
- $S_i$-angular coefficients, $F_L$ - fraction of longitudionally polarised $K^*$
- $P'i$ less sensitive to form factor uncertainties at leading order
- LHCb reported a
  - $3.4\sigma$ excess in $P'5$ parameter
  - Similar excess in $B_s \to \phi \mu \mu$ vs $q^2$

\[ P_1 = \frac{2S_3}{1 - F_L} \]
\[ P_2 = \frac{2}{3} \frac{A_{FB}}{1 - F_L} \]
\[ P_3 = \frac{S_9}{1 - F_L} \]
\[ P_{j=4,5,6,8}' = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}. \]
$B_d \rightarrow K^*\mu\mu$: Results

- largest deviation $\sim 2.7\sigma$ from theoretical model for in $P'_4$ and $P'_5$ in $q^2 \in [4,6]$ GeV$^2$ bin
- results consistent with other experiments
  - deviation in $P'5$ coherent with LHCb measurement
Angular analysis of the decay $B^+ \rightarrow K^+\mu\mu$

- The decay $B^+ \rightarrow K^+\mu\mu$ is a manifestation of a flavor changing neutral current process of the type $b \rightarrow s l^+ l^-$

- $A_{FB}$ - forward-backward asymmetry and contribution $F_H$ from the pseudoscalar, scalar, tensor amplitudes to the decay width

- In the SM, $A_{FB}$ is zero up to small corrections, and $F_H$ is also small

- The results are consistent with previous measurements, and are also compatible with different standard model predictions

![Graphs showing $A_{FB}$ and $F_H$ as functions of $q^2$](attachment:image.png)
τ → μμμ BR measurement

- τ from Ds and B decays
- Maximum Likelihood fit in m(μμμ) simultaneously for the six categories (3 mass resolution regions X 2 BDT score regions)
- No excess observed. An upper observed (expected) limit of 8.8(9.9) ×10^-8 is set on the branching fraction BR(τ → 3μ) at 90% CL
τ→μμμ BR measurement

- τ from \( W \to τν \) decays (20.3 fb\(^{-1}\) at 8 TeV)
- \( Br(τ \to 3μ) = \frac{N_s}{(A_s × ε_s) N_{W \to τν}} \)
- \( N_{W \to τν} = (2.41±0.08)×10^{8} \)
- No events are observed in the signal region for the final selection. \( Br(τ \to 3μ) \) upper limit an observed(expected) 3.76(3.94)×10\(^{-7} \)
\( \tau \rightarrow \mu\mu\mu \) BR measurement

- No signal observed
- \( \text{Br}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8} \) Belle
- \( \text{Br}(\tau \rightarrow 3\mu) < 8.8 \times 10^{-8} \) CMS
  - [CMS-PAS-BPH-17-004](https://doi.org/10.4129/learningd.2017.2.1.14)
- \( \text{Br}(\tau \rightarrow 3\mu) < 3.76 \times 10^{-7} \) ATLAS
- \( \text{Br}(\tau \rightarrow 3\mu) < 4.6 \times 10^{-8} \) LHCb
  - [JHEP 02 (2015) 121](https://doi.org/10.1007/JHEP02(2015)121)
CP Violation
CP violation in $B_s \to J/\psi \phi$

- CPV occurs due to interference between a direct decay and a decay with $B_s - \bar{B}_s$ mixing
- Small CPV phase in SM $\to$ Ideal place for New-Physics!
- Essential ingredients at hadron colliders:
  ▶ Good time resolution to measure the oscillation accurately
  ▶ Flavour tagging (i.e. distinguish the “$B_s$ side” of the event )
- The final state $J/\psi (\to \mu\mu) \phi (\to KK)$ is a superposition of CP=+1 and CP=-1 configurations

$$\phi_s \equiv -2\beta_s = -2 \arg \left( \frac{-V_{ts} V_{*tb}^*}{V_{cs} V_{*cb}^*} \right) = -0.04 \text{ rad}$$
Flavour tagging

Opposite side tagging (to identify the flavour of neutral meson is extracted of the other (or opposite) b-hadron from the pair of b and \( \bar{b} \) quarks)

- Use \( b - \bar{b} \) correlation to determine initial signal flavour from the other B-meson in the event
- \( b \rightarrow l \) transition are clean tagging method
- \( b \rightarrow c \rightarrow l \) and neutral B-meson oscillations dilute the tagging
- Provide probability of signal candidate to be \( B^0_s \) or \( \bar{B}^0_s \)
- Tagger types:
  - tight muon, low-\( p_T \) muon, electron, b-tagged jet
- Signal flavour probability derived from charge of \( p_T \) weighted tracks in a cone around the opposite side primary object (e\( \pm \), \( \mu \pm \), b-jet)

\[
Q_x = \frac{\sum_{i}^{N \text{ tracks}} q_i \cdot (p_{T_i})^\kappa}{\sum_{i}^{N \text{ tracks}} (p_{T_i})^\kappa}
\]
CPV in $B_s \rightarrow J/\psi \phi$

- ATLAS result: ATLAS-CONF-2019-009
- Angular analysis with 10 amplitude functions is done
- Simultaneous fit in $B_s$ mass, lifetime, and the three angles
- Extraction of the amplitude parameters and phases with correlations
- Main systematics:
  - Tagging for $\phi_s$
  - Fit models for signal and background for $\Gamma_s$ and $\Delta\Gamma_s$
CPV in $B_s \to J/\psi \phi$

**ATLAS results:**

- $\phi_s = -0.076 \pm 0.034 \text{ (stat.)} \pm 0.019 \text{ (syst.) \, rad}$

- $\Delta \Gamma_s = 0.068 \pm 0.004 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}$

$\phi_s$ (combined) = -0.055$\pm$0.021 rad

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### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
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<tbody>
<tr>
<td>$\phi_s [\text{rad}]$</td>
<td>$-0.076$</td>
<td>$0.034$</td>
<td>$0.019$</td>
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<tr>
<td>$\Delta \Gamma_s [\text{ps}^{-1}]$</td>
<td>$0.068$</td>
<td>$0.004$</td>
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<td>A_0(0)</td>
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<td>$\delta_\perp [\text{rad}]$</td>
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<td>$\delta_\perp - \delta_S [\text{rad}]$</td>
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<td>$0.037$</td>
<td>$0.010$</td>
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Conclusion

• Several measurements in the B-physics and light states areas have been shown
• Both ATLAS and CMS are able to constrain QCD and EW predictions and to give valuable inputs to theoretical models for spectroscopy and quarkonia
• Both experiments can be competitive with LHCb in few areas
• Both experiments are analysing now the full Run2 dataset → new results soon!
Backup
The behaviour of the ground-state yields as a function of centrality is found to match that of Z bosons, while excited states are relatively suppressed in more central collisions.

A stronger cold nuclear matter effect is observed in excited quarkonium states compared to that in ground states.
$B_{s,d} \rightarrow \mu\mu$ BR measurement

- Measurement by CMS and LCHb (combined):
  
  $BR(B_s \rightarrow \mu\mu) = 2.8 \times 10^{-9}$  
  $BR(B_d \rightarrow \mu\mu) = 3.9 \times 10^{-10}$  
  $BR(B_s \rightarrow \mu\mu) = 3.0 \times 10^{-9}$  
  $BR(B_d \rightarrow \mu\mu) < 3.4 \times 10^{-10}$

- CMS last result:
  
  $BR(B_{0s} \rightarrow \mu\mu) = 2.9 \times 10^{-9}$  
  $BR(B_{0d} \rightarrow \mu\mu) < 3.6 \times 10^{-10}$

- ATLAS last result:
  
  $BR(B_{0s} \rightarrow \mu\mu) = 2.8 \times 10^{-9}$  
  $BR(B_{0d} \rightarrow \mu\mu) < 2.1 \times 10^{-10}$
Search for the $X(5568) \rightarrow B^0_s \pi^\pm$ in pp collisions at 8 TeV

- $\rho_X < 1.1\%$ at 95% CL for $p_T(B^0_s) > 10$ GeV
- $\rho_X < 1.0\%$ at 95% CL for $p_T(B^0_s) > 15$ GeV
- $\rho_X^{LHCb} < 2.4 \%$ at 95% CL

CMS