Measurements of heavy flavour properties at ATLAS and CMS

M. Galanti
(Università di Padova & INFN Padova)

On behalf of the ATLAS and CMS Collaborations
Introduction

- This talk will be focused on the measurements of properties of heavy-flavour particles with the ATLAS and CMS detectors at LHC
  - Production measurements covered by A. Barton in the previous talk
- Measuring heavy-flavour properties at ATLAS and CMS has several motivations
  - Helps advancing the b and c hadron spectroscopy
  - Constitutes a powerful test of pQCD and effective theories' predictions
  - Can probe (and give constraints to) a variety of new physics scenarios including Supersymmetry
- Results shown in the next slides include
  - Rare B decays
  - Searches for exotic b and c states and for new particles
  - CP and P violation
  - Lifetime, mass and polarization
ATLAS and CMS

• Most common heavy-flavour physics signatures at ATLAS and CMS are based on muons in the final state

• Heavy flavour programme relying on inner trackers and on muon detectors for trigger and reconstruction

• During LHC Run 1 each of the two detectors has collected $\sim 25 \text{ fb}^{-1}$ of data

$40 \text{ pb}^{-1}(2010) + 5 \text{ fb}^{-1}(2011) + 20 \text{ fb}^{-1}(2012)$

• Results shown in the following are based on data taken in these three years

  • Datasets used depend on the analysis
Measurements of $\mathcal{B}(B_{(S)}^0 \rightarrow \mu^+\mu^-)$

- General strategy: use $B^+ \rightarrow J/\psi(\rightarrow \mu\mu)K^+$ as normalization and $B_s \rightarrow J/\psi(\rightarrow \mu\mu)\phi(\rightarrow K+K^-)$ as control channel

- **ATLAS** (5 fb$^{-1}$ data analyzed):
  - Cut-based approach
    - $\mathcal{B}(B_s \rightarrow \mu\mu) < 1.5(1.2) \times 10^{-8}$ at 95%(90%) CL

- **CMS** (25 fb$^{-1}$ data analyzed):
  - BDT to select signal events from background
  - Categorize the events based on the BDT output for $\mathcal{B}(B_{(S)}^0)$
    - $\mathcal{B}(B_s \rightarrow \mu\mu) = 3.0^{+1.0}_{-0.9} \times 10^{-9}$ (4.3σ significance)
    - $\mathcal{B}(B^0 \rightarrow \mu\mu) = 3.5^{+2.1}_{-1.8} \times 10^{-10}$ (2.0σ significance)
  - or cut on it for the UL on $\mathcal{B}(B^0)$
    - $\mathcal{B}(B^0 \rightarrow \mu\mu) < 1.1 \times 10^{-9}$ at 95% CL
**B(B_{(S)}^{0} \rightarrow \mu^{+}\mu^{-})** combination

- Preliminary CMS+LHCb combination of the B_{(S)}^{0} \rightarrow \mu\mu results with full statistics
- Known correlation between the uncertainties on f_{s}/f_{u} taken into account
- Combined result:

\[
\mathcal{B}(B_{s}^{0} \rightarrow \mu\mu) = (2.9 \pm 0.7) \times 10^{-9} (> 5\sigma)
\]
\[
\mathcal{B}(B^{0} \rightarrow \mu\mu) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} (< 3\sigma)
\]
$B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$ analysis

- Similar strategy for both experiments
- Fit on the $M(K\pi\mu\mu)$, $\cos(\theta_l)$, and $\cos(\theta_K)$ distributions in bins of the di-$\mu$ mass squared $q^2$

- Measured
  - $A_{FB}$: forward-backward asymmetry of the muons
  - $F_L$: fraction of longitudinal polarization of the $K^{*0}$
  - $d\mathcal{B}/dq^2$: differential branching fraction
- CMS results consistent with theory predictions and past measurements, small deviations at low $q^2$ for $F_L$ seen by ATLAS
New states: $\chi_b(3P)$ and $\Xi_b^{*0}$

- **ATLAS** observed for the first time the $\chi_b(3P)$ state looking at the decay modes $\chi_b(3P) \rightarrow Y(1S)\gamma$ and $\chi_b(3P) \rightarrow Y(2S)\gamma$
- Used $Y(nS) \rightarrow \mu\mu$ decays, with converted ($\gamma \rightarrow e^+e^-$) and unconverted photons
- Measured invariant mass of the $\chi_b(3P)$ signal: $M = 10.530 \pm 0.005(\text{stat}) \pm 0.009(\text{syst})$ GeV

- **CMS** observed a new state decaying into $\Xi_b^-\pi^+$, interpreted as the $\Xi_b^{*0}$ baryon
- Reconstructed the long $\Xi_b^-$ decay chain
- Measured the mass difference: $Q = 14.74 \pm 0.74 \pm 0.28$ MeV
Other exotics searches

- **CMS** observed two peaking structures in the $J/\psi\phi$ spectrum in $B^+\to J/\psi\phi K^+$ decays
  - 1$^{\text{st}}$ peak: $M_1 = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst})$ MeV; $\Gamma_1 = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst})$ MeV
  - 2$^{\text{nd}}$ peak: $M_2 = 4313.8 \pm 5.3(\text{stat}) \pm 7.3(\text{syst})$ MeV; $\Gamma_2 = 38^{+30}_{-15}(\text{stat}) \pm 16(\text{syst})$ MeV
  - Nature of these structures still under investigation

- **CMS** also searched for new bottomonium states $X_b$ decaying to $Y(1S)\pi^+\pi^-$
  - No evidence found, set limits to $R$

\[
R = \frac{\sigma(X_b) \times \mathcal{B}(X_b \to Y(1S)\pi^+\pi^-)}{\sigma(Y(2S)) \times \mathcal{B}(Y(2S) \to Y(1S)\pi^+\pi^-)}
\]
**$\phi_s$ and $\Delta \Gamma_s$ in $B_s \rightarrow J/\psi \phi$ decays**

- Fit the differential decay rate vs. invariant mass $M$, proper decay time $t$ and angular distributions $\Theta = \{\theta_T, \psi_T, \varphi_T\}$ in the transversity basis

- **ATLAS** uses a flavour-tagged analysis to measure

  \[
  \phi_s = 0.12 \pm 0.25(\text{stat}) \pm 0.11(\text{syst}) \text{ rad}
  \]

  \[
  \Delta \Gamma_s = 0.053 \pm 0.021(\text{stat}) \pm 0.009(\text{syst}) \text{ ps}^{-1}
  \]

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

- **CMS** does an untagged analysis; $\phi_s$ fixed to 0

  \[
  \tau = 0.04580 \pm 0.00059(\text{stat}) \pm 0.00022(\text{syst}) \text{ cm}
  \]

  \[
  \Delta \Gamma_s = 0.048 \pm 0.024(\text{stat}) \pm 0.003(\text{syst}) \text{ ps}^{-1}
  \]
Measurement of $\alpha_b$ in $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

- ATLAS measured the **parity-violating asymmetry** $\alpha_b$ and the **helicity amplitudes** in $\Lambda_b^0 \rightarrow J/\psi(\rightarrow \mu\mu)\Lambda^0(\rightarrow \rho\pi)$ decays.

- Parameters extracted in a least-squares fit to the moments of the angular distributions $\Omega = \{\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2\}$ under the hypothesis of no CP violation:

  \[
  \alpha_b = 0.28 \pm 0.16 \pm 0.06 \\
  |a_+| = 0.17^{+0.12}_{-0.17} \pm 0.06 \\
  |a_-| = 0.59^{+0.06}_{-0.07} \pm 0.04 \\
  |b_+| = 0.79^{+0.04}_{-0.05} \pm 0.02 \\
  |b_-| = 0.08^{+0.13}_{-0.08} \pm 0.05
  \]

- Result for $\alpha_b$ not compatible with the expectations from pQCD [$\alpha_b = -(0.14 \sim 0.18)$] and HQET ($\alpha_b = 0.78$) at 2.5\sigma and 2.9\sigma level respectively.
**B_{c} \rightarrow J/\psi \pi^{+} and B_{c} \rightarrow J/\psi \pi^{+} \pi^{+} \pi^{-}**

- **ATLAS** observed the $B_{c}$ meson in its decay to $J/\psi(\rightarrow \mu \mu)\pi^{+}$
  - UML fit to mass distribution
  - Yield $= 82 \pm 17$ events
  - $M(B_{c}) = 6282 \pm 7\text{(stat)}$ MeV
  - $\sigma = 36 \pm 9\text{(stat)}$ MeV
- **PDG average**
  - $M(B_{c}) = 6277 \pm 6$ MeV

- **CMS** studied the $B_{c} \rightarrow J/\psi \pi^{+}$ and $B_{c} \rightarrow J/\psi \pi^{+} \pi^{+} \pi^{-}$ decay modes
  - Measured two efficiency-corrected ratios
  - $\frac{\sigma(B_{c}^{\pm}) \times \mathcal{B}(B_{c}^{\pm} \rightarrow J/\psi \pi^{\pm})}{\sigma(B^{\pm}) \times \mathcal{B}(B^{\pm} \rightarrow J/\psi K^{\pm})} = (0.48 \pm 0.05\text{(stat)} \pm 0.04\text{(syst)})^{+0.05}_{-0.03}(\tau_{B_{c}}) \times 10^{-2}$
  - $\frac{\mathcal{B}(B_{c}^{\pm} \rightarrow J/\psi \pi^{\pm} \pi^{\pm} \pi^{\pm})}{\mathcal{B}(B_{c}^{\pm} \rightarrow J/\psi \pi^{\pm})} = 2.43 \pm 0.76\text{(stat)}^{+0.46}_{-0.44}\text{(syst)}$
**Λ_b^0 lifetime and mass**

- Both experiments using \( Λ_b^0 \rightarrow J/ψ(→μ^+μ^-)Λ^0(→pπ^-) \) decay chain
- Simultaneous UML fit on the lifetime \( τ \) and invariant mass \( M \)

- **ATLAS** measures both lifetime and mass

\[
\begin{align*}
τ(Λ_b^0) &= 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst}) \text{ ps} \\
M(Λ_b^0) &= 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst}) \text{ MeV}
\end{align*}
\]

- **CMS** only gives the lifetime measurement

\[
τ(Λ_b^0) = 1.503 \pm 0.052(\text{stat}) \pm 0.031(\text{syst}) \text{ ps}
\]

- Results in agreement with the PDG 2012 averages and latest TeVatron results

\[
\begin{align*}
τ_{\text{PDG}}(Λ_b^0) &= 1.425 \pm 0.032 \text{ ps} \\
M_{\text{PDG}}(Λ_b^0) &= 5619.4 \pm 0.7 \text{ MeV}
\end{align*}
\]
Y(nS) polarizations

- **CMS** measured the polarization parameters $\lambda_\theta$, $\lambda_\varphi$, and $\lambda_{\theta\varphi}$ of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$

- Measurements made in several $\Upsilon(nS)$ $p_T$ and rapidity ranges

- All polarizations found very close to 0, in clear disagreement with the transverse polarizations predicted by fits to (low-$p_T$) cross section data
Prompt J/ψ and ψ(2S) polarizations

- CMS also measured the polarization of prompt J/ψ and ψ(2S)
  - Analysis similar to the Y(nS) case
  - ψ(nS) p_T and rapidity bins
  - Fit also on the pseudo-proper decay time to extract the prompt component
  - Also in this case, all polarizations are very close to 0

- A recent analysis, simultaneously fitting cross-section and polarization data, shows that the ψ(2S) and Y(3S) results are perfectly described by NRQCD NLO calculations for p_T/M > 3, a kinematical domain where NRQCD factorization is seemingly applicable.

P. Faccioli et al., arXiv:1403.3970
Conclusions

- ATLAS and CMS have carried out a rich program of heavy-flavour properties measurements during the Run 1 of LHC
- Recent highlights include
  - The observation of the $B_s \rightarrow \mu \mu$ decay and the best limits so far to $\mathcal{B}(B^0 \rightarrow \mu \mu)$, in agreement with the SM expectations
  - Several searches for new states, marked by the first observation of $\chi_b(3P)$ and $\Xi_b^{*0}$
  - The measurement of the weak CP-violating phase $\phi_s$ and of the P-violating asymmetry $\alpha_b$, respectively sensitive to new physics and pQCD/HFET predictions
  - $Y(nS)$ and $\psi(nS)$ polarization results, in disagreement with the past theoretical predictions, provide crucial inputs for improved global-fit NRQCD analyses
- More results are expected to come in the next future as the last Run 1 analyses are being finalized by the two experiments!
Backup
$B_{(S)}^0 \rightarrow \mu\mu$: extra plots

- **ATLAS:**
  - Invariant mass distribution of selected candidates
  - Exclusion limit

- **CMS:**
  - Top: invariant mass from the significance-weighted combination of the categorized BDT results
  - Bottom: invariant mass from the significance-weighted combination of the 1D-BDT results
ATLAS: $\chi_b(3P)$ – extra plots

- Invariant masses of unconverted and converted $\gamma$ channels
- $\chi_b(nP)$ mass spectrum including the new $\chi_b(3P)$ state
CMS: search for b state in $Y(1S)\pi^+\pi^-$ final state

- Invariant mass, p-value and UL plots

CMS barrel
- $\sqrt{s} = 8$ TeV
- $L = 20.7$ fb$^{-1}$
- $p_T > 13.5$ GeV
- $|y| < 1.2$

CMS endcap
- $\sqrt{s} = 8$ TeV
- $L = 20.7$ fb$^{-1}$
- $p_T > 13.5$ GeV
- $1.2 < |y| < 2.0$
CMS: $\Lambda_b^0$ lifetime and mass fit

- Invariant mass and decay time projections of the fit
CMS: $\Delta \Gamma_s$ in $B_s \to J/\psi \phi$ decays

- Invariant mass and decay time projections of the fit