Heavy flavour
production and properties
at ATLAS and CMS

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on behalf of the
ATLAS and CMS Collaborations
Summary

- ATLAS and CMS detectors
- Data taking summary
- HF physics in ATLAS and CMS
- Recent results
  - Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ NEW!
  - Observation of $B^+ \rightarrow \psi(2S)\phi K^+$
  - Prompt $J/\psi$ pair production cross section
  - $B^+$ cross sections
  - $X(3872)$ and $\psi(2S)$ production cross section
ATLAS and CMS detectors

- General-purpose LHC experiments, conducting a wide range of measurements and searches
- Similar design
  - Inner trackers
  - Calorimeters
  - Muon stations
- Magnetic field
  - ATLAS: solenoidal + toroidal
  - CMS: solenoidal
- Charged particle tracking for $|\eta|<2.5$, calorimetry up to $|\eta|\sim5$
- Highly-configurable multi-level triggers saving to disk $O(500-1000)$Hz of events for offline analysis
Data taking summary

- Taking LHC pp data since 2009
- Integrated luminosity per experiment
  - Run 1:
    - ~6/fb @ 7 TeV
    - ~20/fb @ 8 TeV
  - Run 2:
    - ~45/fb @ 13 TeV

- Heavy flavour analyses are usually complex measurements and take long to complete
  - Still exploiting the full potential of Run 1 data
  - Most of the results that I will show today are based on 8 TeV pp collisions taken in 2012
HF Physics in ATLAS and CMS

- HF physics in ATLAS and CMS is mostly studied through **final states containing muons**

- Several single-, di-, and multi-muon triggers employed to cover a wide range of processes

- Reconstruction of HF processes mainly relying on tracking and muon subdetectors
  - Muon and hadron tracks
  - Secondary decay vertices and IP
  - Transverse decay length \( L_{xy} = \frac{L \cdot p_T}{p_T} \)
  - Pseudo-proper lifetime \( \tau = L_{xy} \cdot m / (c \cdot p_T) \)

- Performance
  - \( \Delta p_T / p_T \sim O(1-5\%) \) for low-momentum tracks
  - Vertex and IP resolution \( O(20-100\mu m) \)
\( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) angular analysis

- \( B^0 \rightarrow K^{*0}(\rightarrow K^-\pi^+)\mu^+\mu^- \) decay proceeding in the Standard Model through FCNC

- The process can be fully described by the three angles \( (\theta_l, \theta_K, \phi) \) and the dimuon invariant mass squared \( q^2 \)

- New physics entering the loop can be detected by looking at the angular distributions of the decay
  - The clean observables \( P_i \) and \( P_i' \) were shown to be sensitive to NP (See JHEP 04 (2012) 104)
  - >3\( \sigma \) deviation from SM seen by LHCb in the \( P5' \) observable at \( q^2<6\text{GeV}^2 \)

- ATLAS and CMS measured the distributions of the \( P_1 \) and \( P_1' \) angular parameters using ~20/fb of 8 TeV pp data taken in 2012
$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

- The two decays $B^0 \to K^{*0}(\to K^\pm \pi^-)\mu^+\mu^-$ and $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$ difficult to disentangle
  - **Mistag fraction**: $\sim 10\%$ from MC simulation (ATLAS); $\sim 14\%$ from data fit (CMS)
- Different $q^2$ ranges probed:
  - **ATLAS**:
    - 3 bins in the range $[0.04, 6]$ GeV$^2$
  - **CMS**:
    - 7 bins in the range $[1, 19]$ GeV$^2$
    - Signal sample obtained from $J/\psi$ and $\psi(2S)$ rejection (then used as control samples)
- Number of signal events: $\sim 340$ (ATLAS), $\sim 1400$ (CMS)
- Both experiments **fold the signal PDF** using its symmetries to reduce the number of free parameters and improve fit convergence (see backup for formulas)
  - **ATLAS**:
    - Four different foldings to extract $P_1$ and $P'_i$ ($i=4,5,6,8$) parameters
    - S-wave component (i.e. non-resonant $K\pi$) neglected in the PDF (included as systematic)
  - **CMS**:
    - Single folding to measure $P_1$ and $P'_5$
    - S-wave component and interference terms included in the PDF
**B^0 → K^{*0}μ^+μ^- angular analysis**

- **ATLAS**: fit signal and background
  - Four different fits, 3 free parameters each
  - $F_L, S_3$ common to each fit
  - $S_4, S_5, S_7, S_8$ fitted parameters
  - $P_1, P_i'$ extracted from fit parameters
  - Main systematic uncertainties: fake $K\pi$, $B\rightarrow D\rightarrow X$, and other backgrounds; S-wave contribution, alignment and calibration

- **CMS**: fit signal, mistag signal, and bkg
  - $F_S, A_S, F_L$ fixed from previous CMS measurement ([PLB 753 (2016) 424](#))
  - $P_1, P_5'$ fitted parameters
  - $A^5_S$ nuisance parameter
  - Main systematic uncertainties: $F_S, A_S, F_L$; fit bias; MC statistical uncertainty

- For both experiments, results are statistically limited
$B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis

- Available theoretical predictions:
  - **DHMV/JC**: QCD factorization, hadronic uncertainties from calculations
  - **HEPfit/CFFMPSV fit**: hadronic charm contributions fitted from LHCb data

- In general, **no significant deviations seen from SM**
  - ATLAS generally in good agreement with SM, except a $2.5(2.7) \sigma$ deviation from DHMV for $P_4'(P_5')$ in the $4 < q^2 < 6 \text{GeV}^2$ bin
  - CMS data compatible with SM predictions in the whole range and favoring DHMV at low $q^2$
Observation of $B^+\rightarrow\psi(2S)\phi K^+$

- CMS observed for the first time the decay $B^+\rightarrow\psi(2S)\phi K^+$ using 9.6/fb of 2012 pp data at 8 TeV
- Final state reconstructed using the $\psi(2S)\rightarrow\mu^+\mu^-$ and $\phi\rightarrow K^+K^-$ decays
- Possible contribution from non-resonant $B^+\rightarrow\psi(2S)K^+K^-K^+$ decays modeled from simulation and found to be negligible in data
  - Upper limit to fraction of non-resonant channel found to be $0.26 \pm 0.01 @ 95\%$ CL
  - More statistics needed to look for $\psi(2S)\phi$ resonances
- $N_{\text{sig}} = 140\pm15$ of signal events observed over the background
- Branching fraction measured with respect to the normalization channel $B^+\rightarrow\psi(2S)K^+$

\[
BF(B^+\rightarrow\psi(2S)\phi K^+) = (4.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.2(\text{BF}_{\text{norm}})) \times 10^{-6}
\]
Prompt J/ψ pair production

- Production of pairs of J/ψ mesons studied by ATLAS on 11.4 fb of 2012 data at 8 TeV
- Main goals: measure the differential $\sigma(J/\psi J/\psi)$, $f_{DPS}$, and $\sigma_{eff}$
- Summary of selection criteria
  - Events triggered by one $J/\psi \rightarrow \mu\mu$
  - Kinematical cuts: $p_T(\mu) > 2.5$ GeV, $|\eta(\mu)| < 2.3$, $p_T(J/\psi) > 8.5$ GeV, and $|y(J/\psi)| < 2.3$
  - Both J/ψ mesons from the same pp collision: $|d_z(J/\psi,J/\psi)| < 1.2$ mm
  - Prompt/non-prompt production separated through the transverse decay length $L_{xy}$
- Analysis performed in two rapidity bins of the sub-leading J/ψ
- Uncertainties
  - Larger uncertainties coming from statistics
  - Cross section: systematic uncertainties dominated by trigger
  - DPS fraction: most systematics canceling out, main contribution from DPS model

| Source                              | $|y(J/\psi_2)| < 1.05$ | $1.05 \leq |y(J/\psi_2)| < 2.1$ |
|-------------------------------------|-------------------------|-----------------------------|
| Trigger                            | ±7.5                    | ±8.3                        |
| Muon reconstruction                | ±1.1                    | ±1.3                        |
| Kinematic acceptance               | ±0.4                    | ±1.1                        |
| Mass model                         | ±0.1                    | ±0.1                        |
| Mass bias                          | ±0.2                    | ±0.2                        |
| Prompt–prompt model                | ±0.2                    | ±0.01                       |
| Differential $f_{PP}$ corr.        | ±0.6                    | ±0.3                        |
| Pile-up                            | ±0.03                   | ±0.4                        |
| Total                              | ± 7.7                   | ± 8.5                       |
| Branching fraction                 | ±1.1                    |                             |
| Luminosity                         | ±1.9                    |                             |
Prompt J/ψ pair production

- Cross sections are measured as a function of the (J/ψ,J/ψ) Δy, Δφ, mass, and p_T, both corrected for muon acceptance and in the fiducial volume
  - Peaks in p_T distribution corresponding to away (p_T~0) and towards (high p_T) topologies
    - In the latter, J/ψ pair produced against a recoiling gluon
- DPS fraction estimated with a template fit on data
  - Data-driven DPS templates produced assuming independent J/ψ production
Prompt J/ψ pair production

- The fraction of double-parton scattering $f_{\text{DPS}}$ is taken from the $\Delta y(\text{J/ψ},\text{J/ψ})$ distribution
  
  $$f_{\text{DPS}} = (9.2 \pm 2.1(\text{stat}) \pm 0.5(\text{syst}))\%$$

- The DPS cross-section corrected for the muon acceptance in the full J/ψ $y$ range is
  
  $$\sigma_{\text{DPS}}(\text{J/ψ},\text{J/ψ}) = 14.8 \pm 3.5(\text{stat}) \pm 1.5(\text{syst}) \pm 0.2(\text{BF}) \pm 0.3(\text{lumi}) \text{ pb}$$

- From these inputs one can calculate the effective DPS cross section $\sigma_{\text{eff}}$

  $$\sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma^2_{\text{J/ψ},\text{J/ψ}}}{\sigma_{\text{DPS}}} = \frac{1}{2} \sigma^2_{\text{J/ψ}} \int_{\text{DPS}} \sigma_{\text{J/ψ},\text{J/ψ}}$$

  $$\sigma_{\text{eff}} = 6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{syst}) \pm 0.1(\text{BF}) \pm 0.1(\text{lumi}) \text{ mb}$$

- Comparing results obtained by several experiments suggests that $\sigma_{\text{eff}}$ for prompt J/ψ-J/ψ production might be lower than that measured for other final states
B\(^+\) cross section at 13 TeV

- CMS measured the B\(^+\) cross section in pp collisions at 13 TeV using 49.4 pb of data
- B\(^+\)→J/\(\psi(\to \mu^+\mu^-)K^+\) decay mode
- Considered the fiducial phase space
  
  \[ |y(B^+)| < 1.45 \text{ for } 10 \leq p_T(B^+) < 17 \text{ GeV}, \text{ and } |y(B^+)| < 2.1 \text{ for } 17 \leq p_T(B^+) < 100 \text{ GeV} \]

- Main backgrounds: combinatorial dimuons, B\(^+\)→J/\(\psi\pi^+\), and B\(^+\)→J/\(\psi\) + hadrons decays

### Systematic sources and uncertainties (%)

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainties (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon trigger, identification, and reconstruction</td>
<td>6.0–13.7</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>2.8</td>
</tr>
<tr>
<td>B(^+) vertex reconstruction</td>
<td>1.4</td>
</tr>
<tr>
<td>Size of simulated samples</td>
<td>0.5–3.9</td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>3.9</td>
</tr>
<tr>
<td>B(^+)→J/(\psi(\to \mu^+\mu^-)K^+) branching fraction</td>
<td>3.1</td>
</tr>
<tr>
<td>Model in likelihood fits</td>
<td>1.0–6.4</td>
</tr>
<tr>
<td>Bin-to-bin migration</td>
<td>0.4–3.7</td>
</tr>
<tr>
<td>B(^+) kinematic distributions</td>
<td>0.4–10.6</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>0.1–0.7</td>
</tr>
<tr>
<td>B(^+) lifetime</td>
<td>0.3</td>
</tr>
<tr>
<td>Total (excluding the integrated luminosity)</td>
<td>9.1–15.6</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.7</td>
</tr>
</tbody>
</table>

- Main systematic uncertainties from
  - Muon trigger, identification, and reconstruction
  - Likelihood fit model
  - Kinematic distributions of B\(^+\) events in simulation
- Analysis is not statistically-limited
**B⁺ cross section at 13 TeV**

- Cross section given in bins of \( p_T(B⁺) \) and \(|\gamma(B⁺)|\)

- **13 TeV results** compared to FONLL predictions and with PYTHIA
  - Data compatible with FONLL at high \( p_T \), while they favour higher cross sections at low \( p_T \)
  - Previous CMS (PRL 106 (2011) 112001, shown above) and ATLAS measurements at 7 TeV (JHEP 10 (2013) 042) have a better data-theory agreement at low \( p_T \)

- **Total cross section** in the fiducial region at 13 TeV measured from the sum over all bins

\[
\sigma(pp\to B^+X) = 14.9 \pm 0.4\text{(stat)} \pm 2.0\text{ (syst)} \pm 0.4\text{(lumi)}\text{ pb}
\]
X(3872) and $\psi(2S)$ production

- ATLAS measured the differential production cross section of X(3872) and $\psi(2S)$ in the $J/\psi(\rightarrow\mu^+\mu^-)\pi^+\pi^-$ final state, using 11.4/fb of pp collisions at 8 TeV
  - $|y(J/\psi\pi\pi)| < 0.75$ and $10 < p_T(J/\psi\pi\pi) < 70$ GeV
- Prompt and non-prompt components in each $p_T$ bin separated using 4 bins of $\tau$ and two alternative models
  - Single exponential
  - Double exponential (Short- and Long-Lived)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\psi(2S)$</th>
<th>$X(3872)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Med</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.9</td>
<td>1.4</td>
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<tr>
<td>Trigger eff.</td>
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<td>1.3</td>
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<tr>
<td>Muon tracking</td>
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<td>Muon reconstruction eff.</td>
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<td>Pion reconstruction eff.</td>
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<td>Bkdg suppression req.</td>
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<td>0.8</td>
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<tr>
<td>Mass fit model variation</td>
<td>0.6</td>
<td>0.8</td>
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<tr>
<td>Short-lifetime variation</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Long-lifetime variation</td>
<td>0.6</td>
<td>1.0</td>
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<tr>
<td>Lifetime resolution model</td>
<td>0.4</td>
<td>1.5</td>
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<tr>
<td>Total systematic</td>
<td>3.5</td>
<td>3.6</td>
</tr>
<tr>
<td>(2L-fit – 1L-fit) / 2L-fit (prompt)</td>
<td>−0.1</td>
<td>−0.4</td>
</tr>
<tr>
<td>(2L-fit – 1L-fit) / 2L-fit (non-prompt)</td>
<td>+0.1</td>
<td>+0.4</td>
</tr>
</tbody>
</table>

- Cross sections
  - $\sigma(\psi(2S))$ systematic and statistical uncertainties roughly equivalent
  - $\sigma(X(3872))$ uncertainties mainly statistical
X(3872) and ψ(2S) production

- Cross sections measured in 5 $p_T$ bins, separately for prompt and non-prompt production
- Predictions for X(3872)
  - Prompt production from NRQCD normalized to CMS data
  - Non-prompt production from FONLL with BF estimated from TeVatron data
- Prompt production
  - NLO NRQCD describes well the prompt production of both ψ(2S) and X(3872)
  - NNLO* CSM model underestimates high-$p_T$ production of ψ(2S)
- Non-prompt production
  - ψ(2S) cross section well described by FONLL calculations over the whole $p_T$ range
  - Non-prompt X(3872) production overshot by prediction by a factor 4-8 increasing with $p_T$
Summary and conclusions

- ATLAS and CMS have a rich heavy-flavour physics program going on since the start of LHC data taking and which continues to deliver important results
  - ATLAS and CMS measurement of $P_1$ and $P_1'$ in $B^0 \to K^{*0} \mu \mu$ decays in agreement with the SM expectations
    - ATLAS showing $<3\sigma$ deviations for $P_4'$ and $P_5'$ in one low $q^2$ bin
    - CMS closer to DHMV predictions over the whole range
  - The new decay mode $B^+ \to \psi(2S)\phi K^+$ was observed by CMS, opening a possible new channel for exotic hadron spectroscopy
  - ATLAS results on $J/\psi$ pair production gives important inputs on DPS in hadron collisions
  - The $B^+$ production cross section was measured by CMS, showing differences with respect to predictions at low $p_T$
  - Measurements of $X(3872)$ and $\psi(2S)$ production cross sections by ATLAS hint to shortcomings in the theoretical descriptions of the prompt and non-prompt production of these two mesons
- Analysis of LHC Run II data at 13TeV by the two experiments is ongoing, so expect new results in the next future!
Backup
$B^0 \rightarrow K^{*0} \mu\mu$: CMS signal PDF

- The signal PDF used in the CMS analysis after the simplification allowed by the trigonometric function symmetry around $\phi=0$ and $\theta_l=\pi/2$ is the following:

$$\frac{1}{d\Gamma/dq^2 dq^2 d\cos\theta_l d\cos\theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ F_S + A_S \cos\theta_K \right] \left( 1 - \cos^2\theta_l \right) + A_S^5 \sqrt{1 - \cos^2\theta_K} \right. $$

$$\left. \sqrt{1 - \cos^2\theta_l \cos\phi} \right\} + \left( 1 - F_S \right) \left[ 2 F_L \cos^2\theta_K \left( 1 - \cos^2\theta_l \right) + \frac{1}{2} P_1 \right] (1 - F_L) $$

$$+ \frac{1}{2} (1 - F_L) \left( 1 - \cos^2\theta_K \right) \left( 1 + \cos^2\theta_l \right) + \frac{1}{2} P_5 \left( 1 - \cos^2\theta_K \right) \sqrt{1 - \cos^2\theta_l \cos\phi} \right\}. $$

S-wave and S+P wave interference

P-wave

- $F_S$: S-wave fraction
- $A_S, A_S^5$: interference amplitudes between S-wave and P-wave
- $F_L$: fraction of longitudinally-polarized $K^{*0}$
- $P_1, P_5$: angular observables defined in JHEP 04 (2012) 104
$B^0 \to K^{*0} \mu \mu$: CMS fit model

- The fit model used in the CMS analysis is the following:

$$pdf(m, \theta_K, \theta_l, \phi) = Y_s^C \left[ S^C(m) S^a(\theta_K, \theta_l, \phi) \epsilon^C(\theta_K, \theta_l, \phi) ight. \\
+ \frac{f^M}{1 - f^M} S^M(m) S^a(-\theta_K, -\theta_l, \phi) \epsilon^M(\theta_K, \theta_l, \phi) \\
+ Y_B B^m(m) B^{\theta_K}(\theta_K) B^{\theta_l}(\theta_l) B^\phi(\phi),$$

- $Y_s^C$: yield of correctly-tagged signal events
- $Y_B$: yield of background
- $f^M$: fraction of mistagged signal events
- $S^C(m), S^M(m)$: mass PDF of correct and mistag signal (sum of 2 Gaussians)
- $S^a(\theta_K, \theta_l, \phi)$: angular PDF of signal (see previous slide)
- $B^m(m), B^{\theta_K}(\theta_K), B^{\theta_l}(\theta_l), B^\phi(\phi)$: PDF of background (from sidebands)
- $\epsilon^C(\theta_K, \theta_l, \phi), \epsilon^M(\theta_K, \theta_l, \phi)$: efficiencies for correctly-tagged and mistagged signal events
$B^0 \rightarrow K^{*0}\mu\mu$: CMS invariant mass
$B^0 \rightarrow K^{*0}\mu\mu$: CMS fit in 2$^{\text{nd}}$ $q^2$ bin
# B^0 → K^{*0}\mu\mu: CMS systematics and results

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$P_1(10^{-3})$</th>
<th>$P'_5(10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–33</td>
<td>10–23</td>
</tr>
<tr>
<td>Fit bias</td>
<td>5–78</td>
<td>10–119</td>
</tr>
<tr>
<td>MC statistical uncertainty</td>
<td>29–73</td>
<td>31–112</td>
</tr>
<tr>
<td>Efficiency</td>
<td>17–100</td>
<td>5–65</td>
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<tr>
<td>Kπ mistagging</td>
<td>8–110</td>
<td>6–66</td>
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<tr>
<td>Background distribution</td>
<td>12–70</td>
<td>10–51</td>
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<tr>
<td>Mass distribution</td>
<td>12</td>
<td>19</td>
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<tr>
<td>Feed-through background</td>
<td>4–12</td>
<td>3–24</td>
</tr>
<tr>
<td>$F_L$, $F_S$, $A_S$ uncertainty propagation</td>
<td>0–126</td>
<td>0–200</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2–68</td>
<td>0.1–12</td>
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<tr>
<td>Total systematic uncertainty</td>
<td>60–220</td>
<td>70–230</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>$q^2$ (GeV$^2$)</th>
<th>Signal yield</th>
<th>$P_1$</th>
<th>$P'_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00–2.00</td>
<td>80 ± 12</td>
<td>$+0.12^{+0.46}_{-0.47} ± 0.06$</td>
<td>$+0.10^{+0.32}_{-0.31} ± 0.12$</td>
</tr>
<tr>
<td>2.00–4.30</td>
<td>145 ± 16</td>
<td>$-0.69^{+0.58}_{-0.27} ± 0.09$</td>
<td>$-0.57^{+0.34}_{-0.31} ± 0.15$</td>
</tr>
<tr>
<td>4.30–6.00</td>
<td>119 ± 14</td>
<td>$+0.53^{+0.24}_{-0.33} ± 0.18$</td>
<td>$-0.96^{+0.22}_{-0.21} ± 0.16$</td>
</tr>
<tr>
<td>6.00–8.68</td>
<td>247 ± 21</td>
<td>$-0.47^{+0.27}_{-0.23} ± 0.13$</td>
<td>$-0.64^{+0.15}_{-0.19} ± 0.14$</td>
</tr>
<tr>
<td>10.09–12.86</td>
<td>354 ± 23</td>
<td>$-0.53^{+0.20}_{-0.14} ± 0.14$</td>
<td>$-0.69^{+0.11}_{-0.14} ± 0.23$</td>
</tr>
<tr>
<td>14.18–16.00</td>
<td>213 ± 17</td>
<td>$-0.33^{+0.24}_{-0.23} ± 0.22$</td>
<td>$-0.66^{+0.13}_{-0.20} ± 0.19$</td>
</tr>
<tr>
<td>16.00–19.00</td>
<td>239 ± 19</td>
<td>$-0.53^{+0.19}_{-0.19} ± 0.13$</td>
<td>$-0.56^{+0.12}_{-0.12} ± 0.07$</td>
</tr>
</tbody>
</table>
B^0\to K^{*0}\mu\mu: ATLAS signal PDF

• The signal PDF used in the ATLAS analysis is the following:

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_L d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3(1 - F_L)}{4} \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1 - F_L}{4} \sin^2\theta_K \cos 2\theta_L \right. \\
- F_L \cos^2\theta_K \cos 2\theta_L + S_3 \sin^2\theta_K \sin^2\theta_L \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_5 \sin 2\theta_K \sin \theta_L \cos \phi \\
+ S_6 \sin^2\theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_L \sin \phi + S_9 \sin^2\theta_K \sin^2\theta_L \sin 2\phi \left. \right]. 
\]

(1)

• S-wave component and S-P interference not in the PDF (related systematic uncertainty found with toy MC)

• \(F_L\): fraction of longitudinally-polarized \(K^{*0}\)

• \(S_i\): angular coefficients

• \(A_{FB} = 3S_6/4\) and \(S_9\) cannot be measured due to folding

• \(P_1, P_1':\) from the definitions on the right

\[
\begin{align*}
P_1 &= \frac{2S_3}{1 - F_L} \\
P_2 &= \frac{2}{3} A_{FB} \\
P_3 &= -\frac{S_9}{1 - F_L} \\
P_{i=4,5,6,8}' &= \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}
\end{align*}
\]
# B⁰ → K*⁰μμ: ATLAS yields and systematics

<table>
<thead>
<tr>
<th>q² [GeV²]</th>
<th>n_{signal}</th>
<th>n_{background}</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.04, 2.0]</td>
<td>128 ± 22</td>
<td>122 ± 22</td>
</tr>
<tr>
<td>[2.0, 4.0]</td>
<td>106 ± 23</td>
<td>113 ± 23</td>
</tr>
<tr>
<td>[4.0, 6.0]</td>
<td>114 ± 24</td>
<td>204 ± 26</td>
</tr>
<tr>
<td>[0.04, 4.0]</td>
<td>236 ± 31</td>
<td>233 ± 32</td>
</tr>
<tr>
<td>[1.1, 6.0]</td>
<td>275 ± 35</td>
<td>363 ± 36</td>
</tr>
<tr>
<td>[0.04, 6.0]</td>
<td>342 ± 39</td>
<td>445 ± 40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>F_L</th>
<th>S_3</th>
<th>S_4</th>
<th>S_5</th>
<th>S_7</th>
<th>S_8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combinatoric Kπ (fake K*) background</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
<td>0.06</td>
<td>0.13</td>
</tr>
<tr>
<td>D and B⁺ veto</td>
<td>0.11</td>
<td>0.04</td>
<td>0.05</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Background p.d.f. shape</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Acceptance function</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Partially reconstructed decay background</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Alignment and B field calibration</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Data/MC differences for ( p_T )</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>S-wave</td>
<td>0.01</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Nuisance parameters</td>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>( \Lambda_b ), ( B^+ ) and ( B_s ) background</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Misreconstructed signal</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Dilution</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
$B^0 \rightarrow K^{*0}\mu\mu$: ATLAS $F_L$ and $S_i$ distributions

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
$q^2$ [GeV$^2$] & $F_L$ & $S_3$ & $S_4$ & $S_5$ & $S_7$ & $S_8$ \\
\hline
[0.04, 2.0] & 0.44 ± 0.08 ± 0.07 & -0.02 ± 0.09 ± 0.02 & 0.19 ± 0.25 ± 0.10 & 0.33 ± 0.13 ± 0.06 & -0.09 ± 0.10 ± 0.02 & -0.11 ± 0.19 ± 0.07 \\
[2.0, 4.0] & 0.64 ± 0.11 ± 0.05 & -0.15 ± 0.10 ± 0.07 & -0.47 ± 0.19 ± 0.10 & -0.16 ± 0.15 ± 0.05 & 0.15 ± 0.14 ± 0.09 & 0.41 ± 0.16 ± 0.15 \\
[4.0, 6.0] & 0.42 ± 0.13 ± 0.12 & 0.00 ± 0.12 ± 0.07 & 0.40 ± 0.21 ± 0.09 & 0.13 ± 0.18 ± 0.07 & 0.03 ± 0.13 ± 0.07 & -0.09 ± 0.16 ± 0.04 \\
[6.0, 8.0] & 0.52 ± 0.07 ± 0.06 & -0.05 ± 0.06 ± 0.04 & -0.19 ± 0.16 ± 0.09 & 0.16 ± 0.10 ± 0.04 & 0.01 ± 0.08 ± 0.05 & 0.15 ± 0.13 ± 0.10 \\
[8.0, 10.0] & 0.56 ± 0.07 ± 0.06 & -0.04 ± 0.07 ± 0.03 & 0.03 ± 0.14 ± 0.07 & 0.00 ± 0.10 ± 0.03 & 0.02 ± 0.08 ± 0.06 & 0.09 ± 0.11 ± 0.08 \\
[10.0, 12.0] & 0.50 ± 0.06 ± 0.04 & -0.04 ± 0.06 ± 0.03 & 0.03 ± 0.13 ± 0.07 & 0.14 ± 0.09 ± 0.03 & 0.02 ± 0.07 ± 0.05 & 0.05 ± 0.10 ± 0.07 \\
\hline
\end{tabular}
### $B^0 \rightarrow K^{*0}\mu\mu$: ATLAS $P_1$ and $P_i'$ distributions

**ATLAS:** ATLAS-CONF-2017-023

<table>
<thead>
<tr>
<th>$q^2$ [GeV$^2$]</th>
<th>$P_1$</th>
<th>$P_4'$</th>
<th>$P_5'$</th>
<th>$P_6'$</th>
<th>$P_8'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.04, 2.0]</td>
<td>$-0.06 \pm 0.30 \pm 0.10$</td>
<td>$0.39 \pm 0.51 \pm 0.25$</td>
<td>$0.67 \pm 0.26 \pm 0.16$</td>
<td>$-0.18 \pm 0.21 \pm 0.04$</td>
<td>$-0.22 \pm 0.38 \pm 0.14$</td>
</tr>
<tr>
<td>[2.0, 4.0]</td>
<td>$-0.78 \pm 0.51 \pm 0.42$</td>
<td>$-0.96 \pm 0.39 \pm 0.26$</td>
<td>$-0.33 \pm 0.31 \pm 0.13$</td>
<td>$0.31 \pm 0.28 \pm 0.19$</td>
<td>$0.84 \pm 0.32 \pm 0.31$</td>
</tr>
<tr>
<td>[4.0, 6.0]</td>
<td>$0.00 \pm 0.47 \pm 0.26$</td>
<td>$0.81 \pm 0.42 \pm 0.24$</td>
<td>$0.26 \pm 0.35 \pm 0.17$</td>
<td>$0.06 \pm 0.27 \pm 0.13$</td>
<td>$-0.19 \pm 0.33 \pm 0.07$</td>
</tr>
<tr>
<td>[0.04, 4.0]</td>
<td>$-0.22 \pm 0.26 \pm 0.16$</td>
<td>$-0.38 \pm 0.31 \pm 0.22$</td>
<td>$0.32 \pm 0.21 \pm 0.10$</td>
<td>$0.01 \pm 0.17 \pm 0.10$</td>
<td>$0.30 \pm 0.26 \pm 0.19$</td>
</tr>
<tr>
<td>[1.1, 6.0]</td>
<td>$-0.17 \pm 0.31 \pm 0.14$</td>
<td>$0.07 \pm 0.28 \pm 0.18$</td>
<td>$0.01 \pm 0.21 \pm 0.07$</td>
<td>$0.03 \pm 0.17 \pm 0.11$</td>
<td>$0.18 \pm 0.22 \pm 0.16$</td>
</tr>
<tr>
<td>[0.04, 6.0]</td>
<td>$-0.15 \pm 0.23 \pm 0.10$</td>
<td>$0.07 \pm 0.26 \pm 0.18$</td>
<td>$0.27 \pm 0.19 \pm 0.07$</td>
<td>$0.03 \pm 0.15 \pm 0.10$</td>
<td>$0.11 \pm 0.21 \pm 0.14$</td>
</tr>
</tbody>
</table>
LHCb results for $B^0 \to K^{*0}\mu^+\mu^-$

A global analysis of the $CP$-averaged angular observables determined from the maximum likelihood fit indicates differences with the presently-available SM predictions at the level of 3.4 standard deviations. These differences could be explained by an unexpectedly large hadronic effect that changes the SM predictions [15, 19]. The differences could also be explained by contributions to the decay from non-SM particles [9–12, 14–21].
X(3872) and $\psi(2S)$ production

- Non-prompt fractions for $\psi(2S)$ and X(3872) measured in the central region
  - Most systematic uncertainties canceling out in the ratio
- Results consistent within uncertainties with older CMS measurements performed at 7 TeV and in a slightly wider $y$ range
- $\psi(2S)$ non-prompt fraction increasing with $p_T$
- No sizeable $p_T$ dependence for non-prompt fraction of X(3872)