Giacomo Fedi$^a$, on behalf of the CMS collaboration

March 3, 2015
- Dimuon mass resolution: 32 MeV (barrel) and 75 MeV (endcap)
- Impact parameter resolution: 10 $\mu$m @ 100 GeV and 20 $\mu$m @ 10 GeV
Heavy flavour physics triggers

Trigger selection
- Muon kinematics
- Dimuon kinematics and vertex probability
- Flight length significance and pointing angle
Recent results on physics of beauty and charm quarks in proton-proton collisions at CMS:

- Search for physics beyond the standard model (by the mean of indirect evidence)
  * Search for $B_{s,d} \rightarrow \mu \mu$ decays at CMS
  * CP-violating phase $\phi_s$ using $B_s \rightarrow J/\psi \phi(1020)$ channel
- Study of standard model of particle physics, test of QCD and particle properties
  * $B^+ \rightarrow \psi(2S)\phi K^+$ rare decay
  * $B_c$ decays
  * $\mathcal{B}(B_s \rightarrow J/\psi f_0(980))/\mathcal{B}(B_s \rightarrow J/\psi \phi(1020))$ ratio
  * $J/\psi$, $\psi(2S)$, $\Upsilon(nS)$, and $\chi_{bn}$ production
Search for $B_{s,d} \rightarrow \mu \mu$ decays at CMS
$B_{s,d} \rightarrow \mu\mu$ search history

![Graph showing the search history for $B_{s,d} \rightarrow \mu\mu$ with data points from various experiments including Belle, L3, CDF, UA1, CLEO, ARGUS, ATLAS, CMS, D0, BABAR, and SM predictions for $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$. The graph spans from 1985 to 2015 with BR UL (95% CL) or measurement on the y-axis and Year on the x-axis.]
$B_{s,d} \rightarrow \mu\mu$ motivation

- Highly suppressed decay in SM
  - Forbidden at tree level $\rightarrow$ FCNC transitions only possible through penguin or box diagram
  - Cabibbo $|V_{td}| < |V_{ts}|$ and helicity suppressed
- SM predictions
  - $B(B_s \rightarrow \mu\mu) = (3.66 \pm 0.23) \cdot 10^{-9}$ (PRL112, 101801, 2014)
  - $B(B_d \rightarrow \mu\mu) = (1.06 \pm 0.10) \cdot 10^{-10}$ (PRL112, 101801, 2014)
- Sensitivity to NP
  - 2HDM and $m(H^+)$
  - MSSM $\tan \beta$
  - Leptoquarks
  - $4^{th}$ generation top
**BS, d → μμ CMS measurement** [PRL 111 (2013) 101804]

- **Selections:**
  - BDT muon selection → low muon fake rate
  - Selection done using a BDT with 12 input variables for B candidates
  - Trained with MC signals sample and with data sidebands
  - Same BDT for $B^\pm \rightarrow J/\psi K^\pm$ normalisation and $B_s \rightarrow J/\psi(1020)$ control channels
  - No pile-dependence, no $B_s$ mass dependence

- **BDT categories:**
  - BDT response divided in multiple bins depending on data period 2012(4) or 2011(2)
  - Two further categories: barrel and endcap regions (different mass resolution)

- **Unbinned ML fit with per-event resolution:**
  - Signal: fit of both $B_s$ and $B^0$ shapes
  - Peaking backgrounds ($B^0 \rightarrow K\pi$, $B_s \rightarrow KK$)
  - Combinatorial and semileptonic BG

$\mathcal{B}(B_s \rightarrow \mu\mu) = (3.0^{+0.9}_{-0.8}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})) \times 10^{-9}$  $S = 4.3\sigma$ (Exp. 4.8)

$\mathcal{B}(B_d \rightarrow \mu\mu) < 1.1 \times 10^{-9}$ (95% C.L.)
$B_{s,d} \rightarrow \mu\mu$ Event display

CMS Experiment at the LHC, CERN
Data recorded: 2012-Nov-30 07:19:44 547430 GMT (08:19:44 CEST)
Run / Event: 208307 / 997510994
$B_{s,d} \to \mu\mu$ CMS + LHCb meas. [arXiv:1411.4413 Sub. to Nature]

- Data: 25 fb$^{-1}$ (CMS) and 3 fb$^{-1}$ (LHCb)
- Selection: BDT with 20 categories, 12 CMS categories which depend on $\sqrt{s}$, detector region, and BDT ranges + 8 LHCb categories which depend on BDT ranges
- Common parameters: hadronisation fraction $f_d/f_s$, $B(B^\pm \to J/\psi K^\pm)$
- Improvement of the CMS analysis: $\Lambda_b \to p\mu\nu$ branching ratio updated to the last prediction

$B(B_s \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$ \hspace{1cm} S=6.2\sigma$ (Exp: 7.4\sigma)
$B(B_d \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$ \hspace{1cm} S=3.0\sigma$ (Exp: 0.8\sigma)
CP-violating phase $\phi_s$ using $B_s \rightarrow J/\psi \phi(1020)$ channel
The $B_s$ meson decays into a final state $J/\psi\phi(1020)$, which is a mixture of two CP eigenstates (odd/even);

- Interference between direct $B_s \to J/\psi\phi(1020)$ decay and decay via mixing gives rise to a CP violation phase $\phi_s \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015} \text{ rad (SM)}$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$;

- If the $\phi_s$ differs w.r.t. the SM prediction, then New Physics might contribute in the mixing box diagram.

We measure the weak phase $\phi_s$ and the decay width difference $\Delta\Gamma_s$ by disentangling the two CP final states of the $B_s$ with a tagged angular analysis;

- Opposite side lepton tagging is used to define the flavour at production time.
\[ \frac{d^4 \Gamma(B_s(t))}{d \Theta dt} = X(\Theta, \alpha, t) = \sum_{i=1}^{10} O_i(\alpha, t) g_i(\Theta), \]

\[ O_i(\alpha, t) = N_i e^{-\Gamma_s t} \left[ a_i \cosh \left( \frac{1}{2} \Delta \Gamma_s t \right) + b_i \sinh \left( \frac{1}{2} \Delta \Gamma_s t \right) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t) \right] \]

- \( b_i \) and \( d_i \) depend on \( \sin \phi_s \) and \( \cos \phi_s \)
- \( \Delta \Gamma_s > 0 \): we use previous LHCb results
- \( \alpha \) physics parameters (\( \Delta \Gamma_s, \phi_s, c \tau, |A_0|^2, |A_S|^2, |A^2_{\perp}|, \delta_\parallel, \delta_\perp, \delta_{\perp} \))
- Averaged performance of the combined (\( \mu \) and \( e \)) tagger: \( \omega = 32.2 \pm 0.3\% \),
  \( \epsilon_{\text{tag}} = 7.67 \pm 0.04\% \), \( P_{\text{tag}} = 0.97 \pm 0.04\% \)
Fit of the tagged model on the 2012 data, with a gaussian constraint of $\Delta m_s$ to the PDG value

$$17.69 \pm 0.08 \text{ } h/\text{ps}$$

Extended maximum-likelihood fit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit results</th>
</tr>
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<tr>
<td>$</td>
<td>A_0</td>
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<tr>
<td>$</td>
<td>A_s</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$\Delta \Gamma_s \text{ [ps}^{-1}]$</td>
<td>$0.096 \pm 0.014$</td>
</tr>
<tr>
<td>$\delta_{\parallel} \text{ [rad]}$</td>
<td>$3.48 \pm 0.09$</td>
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<tr>
<td>$\delta_{S\perp} \text{ [rad]}$</td>
<td>$0.34 \pm 0.24$</td>
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<tr>
<td>$\delta_\perp \text{ [rad]}$</td>
<td>$2.73 \pm 0.36$</td>
</tr>
<tr>
<td>$\phi_s \text{ [rad]}$</td>
<td>$-0.03 \pm 0.11$</td>
</tr>
<tr>
<td>$c\tau \text{ [\mu m]}$</td>
<td>$447 \pm 3$</td>
</tr>
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</table>
B_s \rightarrow J/\psi\phi(1020) \phi_s summary

- Analysing the 2012 CMS data (20.0 \text{ fb}^{-1}), we selected 49k B_s signal events. We obtain:

\[ \phi_s = -0.03 \pm 0.11 \ (\text{stat.}) \pm 0.03 \ (\text{syst.}) \ \text{rad} \]
\[ \Delta \Gamma_s = 0.096 \pm 0.014 \ (\text{stat.}) \pm 0.007 \ (\text{syst.}) \ \text{ps}^{-1} \]

- Contour plot (stat. only), constraining \( \Delta \Gamma_s > 0 \):
$B^+ \rightarrow \psi(2S)\phi K^+$ rare decay
Resonant peak due to $B^+ \rightarrow \psi(2S)\phi K^+$ decay has been found. About 144 events identify as signal. Next step: branching fraction measurement.
$B_c$ decays
The $B_c^\pm \to J/\psi \pi^\pm$ and $B_c^\pm \to J/\psi \pi^\pm \pi^\pm \pi^\mp$ decay modes are studied in CMS in the kinematic region where the transverse momentum of the $B_c^\pm$ meson is greater than 15 GeV/c and within the central rapidity region $|y| < 1.6$.

$$R_{B_c} = \frac{B(B_c^\pm \to J/\psi \pi^\pm \pi^\pm \pi^\mp)}{B(B_c^\pm \to J/\psi \pi^\pm)} = 2.55 \pm 0.80\,(\text{stat}) \pm 0.33\,(\text{syst}) \pm 0.04\,(\tau_{B_c})$$

$$R_{c/u} = \frac{\sigma(B_c^\pm) \times B(B_c^\pm \to J/\psi \pi^\pm)}{\sigma(B^\pm) \times B(B^\pm \to J/\psi K^\pm)} = (0.48 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.05\,(\tau_{B_c})) \times 10^{-2}$$
\[ \frac{\mathcal{B}(B_s \rightarrow J/\psi f_0(980))}{\mathcal{B}(B_s \rightarrow J/\psi \phi(1020))} \text{ ratio} \]
\[ \frac{\mathcal{B}(B_s \rightarrow J/\psi f_0(980))}{\mathcal{B}(B_s \rightarrow J/\psi \phi(1020))} \]

\[ \frac{B_{f_0/\phi}}{B(B_s \rightarrow J/\psi f_0)B(f_0 \rightarrow \pi \pi)} = \frac{N_{f_0}^\text{obs}}{N_{\phi}^\text{obs}} \times \epsilon_{f_0/\phi} = 0.140 \pm 0.013(\text{stat}) \pm 0.018(\text{syst}) \]

- \( N_{f_0}^\text{obs} = 873 \) and \( N_{\phi}^\text{obs} = 8377 \)
- Consistent with predictions (PRD 79 (2009) 074024)
- Consistent with previous measurements

### Systematics

<table>
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<td>Fit model</td>
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<td>( f_0 ) mass window width</td>
<td>6.4%</td>
</tr>
<tr>
<td>MC simulation (( f_0 ) natural width)</td>
<td>8.6%</td>
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<td>Decay model in MC generation</td>
<td>6.2%</td>
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$J/\psi$, $\psi(2S)$, $\Upsilon(nS)$, and $\chi_{bn}$ production
Double differential prompt $J/\psi$ and $\psi(2S)$ cross section and rapidity integrated ($|y| < 1.2$) differential cross section (assuming unpolarised scenario)

- 2011 data with extended $p_T$ range up to 120 GeV ($J/\psi$) and 100 GeV ($\psi(2S)$)
- Acceptance measured for different polarisation scenario

![Graph of $J/\psi$ and $\psi(2S)$ cross section vs. $p_T$](image)

- CMS, $|y| < 1.2$, $4.55 \text{ fb}^{-1}$ (2.4%)
- ATLAS, $|y| < 0.75$, $2.3 \text{ pb}^{-1}$ (3.5%)
- Power-law fits
- CMS, $|y| < 1.2$, $4.90 \text{ fb}^{-1}$ (10.6%)
- ATLAS, $|y| < 0.75$, $2.1 \text{ fb}^{-1}$ (2.4%)
- FKLSW, $|y| < 1.2$

G. Fedi (INFN sezione di Pisa)

Heavy quark physics at CMS
Differential prompt $\Upsilon(1S,2S,3S) \rightarrow \mu\mu$ production as function of $p_T$ in the rapidity range $|y| < 1.2$

NLO calculations from [Gong, et al.] extended by the authors to cover the range $p_T < 100$ GeV

The measurements show a transition from an exponential to a power-law behavior at $p_T \approx 20$ GeV for the three $\Upsilon$ states
Use of converted photons to reconstruct $\Upsilon(1S) + \gamma$ final states in four bins

Cross section ratio $\sigma(\chi_{b2})/\sigma(\chi_{b1})$ shows no evident $p_T$ dependence

Not completely in agreement with the NRQCD model predictions
CMS take advantage of its performance in the reconstruction of high $p_T$ muon to measure the cross section of charmonion and bottomium states at unprecedented $p_T$ range.

Good muon reconstruction permits CMS to be competitive in the search for $B_S \to \mu\mu$ first observation.

Rare decays of $B_c$ and $B^+$ mesons are reconstructed and can be used in next analyses (e.g. cross section and lifetime measurement).

CP-violating phase $\phi_s$ measurement can take advantage of $B_S \to J/\psi f_0(980)$ reconstruction.
Additional slides
$B_{s,d} \rightarrow \mu\mu$ rare backgrounds

\[ \mathcal{B}(B_s \rightarrow \mu\mu) = \frac{N_{B_s}}{N_{\text{norm}}} \frac{f_d}{f_u} \frac{\epsilon_{\text{norm}}}{\epsilon_{B_s}} B_{\text{norm}} \] (1)
\[
\frac{B(B_s \to J/\psi f_0(980))}{B(B_s \to J/\psi \phi(1020))} \text{ ratio non-resonant BG}
\]

- \( f_0 \to \pi\pi \) invariant mass restricted to 50 MeV
- Assumption that \( \pi\pi \) non-resonant component negligible component
- Assumption confirmed by PRD 89 029006
- Dedicated systematics:
  - varying the assumed width of the \( f_0 \) (50 MeV) in the MC simulation by \( \pm 20\% \), which is within the 90\% CL of our measured \( f_0 \) mass model
  - varying the \( f_0(890) \) mass window up to \( \pm 100 \text{ MeV} \) to account for possible backgrounds (basically \( f_0(1500) \) and \( f_2(1270) \))
**B_S → J/ψ φ(1020) φ_S** signal model

We use the same notations as LHCb [arXiv:1304.2600]:

\[
\frac{d^4 \Gamma(B_s(t))}{d\Theta dt} = X(\Theta, \alpha, t) = \sum_{i=1}^{10} O_i(\alpha, t) \cdot g_i(\Theta),
\]

\[
O_i(\alpha, t) = N_i e^{-\Gamma s t} \left[ a_i \cosh(\frac{1}{2} \Delta \Gamma_s t) + b_i \sinh(\frac{1}{2} \Delta \Gamma_s t) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t) \right]
\]

<table>
<thead>
<tr>
<th>(i)</th>
<th>(g_i(\theta_T, \psi_T, \phi_T))</th>
<th>(N_i)</th>
<th>(a_i)</th>
<th>(b_i)</th>
<th>(c_i)</th>
<th>(d_i)</th>
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<td>1</td>
<td>(2 \cos^2 \psi_T (1 - \sin^2 \theta_T \cos^2 \phi_T))</td>
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<td>^2)</td>
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<td>(D)</td>
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<tr>
<td>2</td>
<td>(\sin^2 \psi_T (1 - \sin^2 \theta_T \sin^2 \phi_T))</td>
<td>(</td>
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<td>^2)</td>
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<td>(D)</td>
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<tr>
<td>3</td>
<td>(\sin^2 \psi_T \sin^2 \theta_T)</td>
<td>(</td>
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<td>^2)</td>
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<td>(-D)</td>
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<tr>
<td>4</td>
<td>(- \sin^2 \psi_T \sin 2 \theta_T \sin \phi_T)</td>
<td>(</td>
<td>A_{II}(0)A_{II}(0)</td>
<td>)</td>
<td>(C \sin(\delta_{</td>
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<tr>
<td>5</td>
<td>(\frac{1}{\sqrt{2}} \sin 2 \psi_T \sin^2 \theta_T \sin \phi_T)</td>
<td>(</td>
<td>A_0(0)A_{II}(0)</td>
<td>)</td>
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</tr>
<tr>
<td>6</td>
<td>(\frac{1}{\sqrt{2}} \sin 2 \psi_T \sin \phi_T)</td>
<td>(</td>
<td>A_0(0)A_{II}(0)</td>
<td>)</td>
<td>(C \sin(\delta_{\perp} - \delta_0))</td>
<td>(S \cos(\delta_{\perp} - \delta_0))</td>
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<tr>
<td>7</td>
<td>(\frac{2}{3} (1 - \sin^2 \theta_T \cos^2 \phi_T))</td>
<td>(</td>
<td>A_S(0)</td>
<td>^2)</td>
<td>1</td>
<td>(-D)</td>
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<tr>
<td>8</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi_T \sin^2 \theta_T \sin \phi_T)</td>
<td>(</td>
<td>A_S(0)A_{II}(0)</td>
<td>)</td>
<td>(C \cos(\delta_{</td>
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<tr>
<td>9</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi_T \sin \theta_T \cos \phi_T)</td>
<td>(</td>
<td>A_S(0)A_{II}(0)</td>
<td>)</td>
<td>(\sin(\delta_{\perp} - \delta_S))</td>
<td>(-D \sin(\delta_{\perp} - \delta_S))</td>
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<td>10</td>
<td>(\frac{4}{3} \sqrt{3} \cos \psi_T (1 - \sin^2 \theta_T \cos^2 \phi_T))</td>
<td>(</td>
<td>A_S(0)A_0(0)</td>
<td>)</td>
<td>(C \cos(\delta_0 - \delta_S))</td>
<td>(S \sin(\delta_0 - \delta_S))</td>
</tr>
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</table>

\[C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}, \quad S = -\frac{2|\lambda| \sin \phi_S}{1 + |\lambda|^2}, \quad D = -\frac{2|\lambda| \cos \phi_S}{1 + |\lambda|^2}\]

|\(\lambda|\) includes possible contribution from CP violation in direct decay, we assume |\(\lambda| = 1 and we assign a systematic. 

\(\Delta \Gamma_S > 0\): we use previous LHCb results. |\(\alpha| physics parameters (\(\Delta \Gamma_S, \phi_S, c_T, |A_0|^2, |A_S|^2, |A_{II}|, \delta_{||}, \delta_{\perp}, \delta_S, \delta_T\)).
### $B_s \rightarrow J/\psi \phi(1020) \phi_s$ systematics table

| Source of uncertainty     | $|A_0|^2$ | $|A_s|^2$ | $|A_\perp|^2$ | $\Delta \Gamma_s$ ps$^{-1}$ | $\delta_\parallel$ rad | $\delta_\perp$ rad | $c \tau \mu$m |
|---------------------------|----------|----------|--------------|-----------------|-----------------|-----------------|-----------|
| Statistical uncertainty   | 0.0058   | 0.016    | 0.0077       | 0.0138          | 0.092           | 0.24            | 0.36      |
| Proper time efficiency    | 0.0015   | -        | 0.0023       | 0.0057          | -               | -               | 0.002    |
| Angular efficiency        | 0.0060   | 0.008    | 0.0104       | 0.0021          | 0.674           | 0.14            | 0.66      |
| Model bias                | 0.0008   | -        | -            | 0.0012          | 0.025           | 0.03            | -         |
| Proper decay resolution   | 0.0009   | -        | 0.0008       | 0.0021          | 0.004           | -               | 0.02      |
| BG mistag modelling       | 0.0021   | -        | 0.0013       | 0.0018          | 0.074           | 1.10            | 0.02      |
| Flavour tagging           | -        | -        | -            | -               | -               | -               | -         |
| PDF modelling assumpt.    | 0.0016   | 0.002    | 0.0021       | 0.0021          | 0.010           | 0.03            | 0.04      |
| $|\lambda|$ as a free parameter | 0.0001   | 0.005    | 0.0001       | 0.0003          | 0.002           | 0.01            | 0.03      |
| Kaon $p_T$ re-weighting   | 0.0094   | 0.020    | 0.0041       | 0.0015          | 0.085           | 0.11            | 0.02      |
| Total systematic          | 0.0116   | 0.022    | 0.0117       | 0.0073          | 0.685           | 1.12            | 0.032     |

- The systematic uncertainties from the proper decay time efficiency and the kaon $p_T$ distribution originate from residual differences between data and simulation;
  - For the proper decay time efficiency, the statistical uncertainty of the efficiency model is propagated to the results;
  - For the kaon $p_T$, the discrepancy between the data and the simulation is taken into account as a systematic uncertainty;

- The model bias systematic comes from the biases of the observables obtained with toy pseudo-experiments of the fitted model;
- We left $|\lambda|$ as a free parameter to evaluate the effect of possible other contributions in the weak phase.