B physics and Quarkonia in CMS
Flavor physics @CMS

- The CMS experiment at the LHC has a rich and competitive heavy flavor program

- CMS flavour physics objectives:
  - understand the underlying QCD processes:
    - measuring the spectrum of heavy flavour production (x-sections and polarizations of quarkonia and other states)
    - looking for new exotic quarkonia states and new mesons/baryons
  - test the Standard Model predictions with high precision measurements:
    - studying decay rates, lifetimes, CPV and other b hadron properties
  - look for New Physics indications in the rare decays

- Only selected recent results are presented in this talk
  - measurements based on 8 and 13 TeV data collected during 2012, 2015 and 2016
CMS B-physics triggers

- Flavor physics analyses rely on dimuon triggers
  - displaced/non-displaced quarkonia ($\phi$, $J/\psi$, $\psi(2S)$, $Y$)

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![Graphs showing dimuon invariant mass distributions for different states.](https://cds.cern.ch/record/2160343)

https://cds.cern.ch/record/2161025
https://cds.cern.ch/record/2160343
Flavor physics analyses rely on dimuon triggers

- displaced/non displaced quarkonia (\(\phi\), J/\(\psi\), \(\psi(2S)\), \(\Upsilon\))
- non resonant dimuon
- dimuon + track triggers

**CMS B-physics triggers**

**Trigger paths**

- low mass double muon + track
- double muon inclusive

**PDF shape:**

- Signal: double Gaussian
- Combinatorial background: exponential

**Quality cuts:**

- \(\cos \alpha > 0.99\)
- \(\frac{l_{xy}}{\sigma(l_{xy})} > 3.0\)
- Vertex probability > 10%
- \(p_T(J/\psi) > 8\) GeV
- \(p_T(K) > 1.6\) GeV

**Mass:**

- \(B^0(J/\psi K^0)\) \(\rightarrow J/\psi K^0\): 5.278 \(\pm 0.001\) (stat) GeV
- \(B^0(J/\psi \phi)\) \(\rightarrow J/\psi \phi\): 5.367 \(\pm 0.001\) (stat) GeV

**Events / 20 MeV**

- \(10^0\) to \(10^2\) GeV

**CMS**

- Preliminary

**https://cds.cern.ch/record/2160343**

**https://cds.cern.ch/record/2160343**
B⁺ production cross section at 13 TeV

- Measurement at 13 TeV complements the cross section measurements already pursued during Run I
- Provides new important tests of theoretical calculations at higher energy

- First 13 TeV B⁺ production cross section measurement
  - exploiting the exclusive decay channel $B^+ \rightarrow J/\psi K^+$, with $J/\psi \rightarrow \mu^+ \mu^-$
  - differential cross section as a function of B transverse momentum and rapidity
  - based on 50.8 pb⁻¹ at 13 TeV from 2015 dataset with 50 ns bunch spacing
    - collected with displaced dimuon trigger
    - phase space region $10 < p_B^T < 100$ GeV and $|y^B| < 2.4$
The signal yield is extracted with an extended unbinned maximum likelihood fit to the invariant mass distribution of the $B^+$ candidates, in $p_T$ or $|y|$ bins.

- Signal model: sum of two gaussians
- Combinatorial background: exponential function
- Mis-reconstructed $B \rightarrow J/\psi + \text{track} + X$ decays: error function

![Graphs showing data and fits for different bins of $M_{J/\psi K^*}$ and $|y|$.]
Cross section measurement

- Differential cross sections as a function of $p_T$ for $|y^B| < 2.4$ and as a function of absolute rapidity for $10 < p_T^B < 100$ GeV are measured

\[
\frac{d\sigma(pp \rightarrow B^+ X)}{dp_T^B} = \frac{n_{\text{sig}}(p_T^B)}{2A \cdot \epsilon(p_T^B) \cdot B \cdot \mathcal{L} \cdot \Delta p_T^B}
\]

- Systematic uncertainties related to signal and background models, $p_T$ and $y$ resolution, generator distributions, $B^+$ lifetime, trigger and muon/track reconstruction, size of the simulation and luminosity have been evaluated
**B⁺ cross section results**

- Differential measurements are compared to FONLL and PYTHIA calculations
  - reasonable agreement, both in terms of shape and of normalization, with FONNL calculations and PYTHIA simulation
- 7 TeV measurements are also shown for completeness
Quarkonia cross section at 13 TeV

- Run I experiments at the LHC provided precise measurements of cross sections and polarizations for five quarkonium states: J/ψ, ψ(2S), and Υ(nS) (n= 1, 2, 3)
- Comparison of the 13 TeV to 7 TeV results offers a good opportunity to test NRQCD factorization hypotheses
- Also, the extended p_T reach at 13 TeV and the improved statistical precision can provide further comparisons with theoretical calculations
- Quarkonium states reconstructed in the dimuon decay channel, for dimuon rapidity |y| < 1.2
  - based on 2.4 (2.7) fb⁻¹ from 2015 dataset for J/ψ (other mesons)

\[
BR(qq \rightarrow \mu^+ \mu^-) \times \frac{d^2\sigma^{qq}}{dp_Tdy} = \frac{N^{qq}(p_T,y)}{\mathcal{L} \Delta y \Delta p_T} \cdot \langle \frac{1}{e(p_T,y)A(p_T,y)} \rangle
\]

Bin width

Acceptance
as evaluated on a particle gun MC

Efficiencies
measured through data-driven methods vs p_T and y
Bottomonium signal extraction

- For Y(nS) states, yields are extracted through maximum likelihood fits to the invariant mass spectra
  - three signal peaks modeled with Crystal Ball functions
  - background described by an exponential function
Charmonium signal extraction

- Additional non-prompt component originating from the decay of $b$-hadrons is taken into account for charmonium states

- Prompt and non-prompt yields measured by simultaneous fits to the mass and pseudo-proper decay length distributions
Charmonium results

- The 13 TeV cross sections are factors of 2 to 3 larger than the corresponding 7 TeV cross sections, changing slowly as a function of dimuon $p_T$.

- An increase of this order is expected from the evolution of parton distribution functions, as verified using Pythia 8.
Also for bottomonium the 13 TeV cross sections are factors of 2 to 3 larger than the corresponding 7 TeV cross sections, with slow changes as a function of dimuon $p_T$. 

Bottomonium results
First observation of the simultaneous production of Y(1S) pairs

- measurements of quarkonia pair production are first step in the search for tetra-quark states
- previous measurements from NA3, LHCb, D0 and CMS on J/ψ pairs and J/ψ/Y pairs
- important tests of QCD predictions, complementary to single quarkonia production measurements
  - high statistics measurements could provide information about the production mechanism (Single or Double Parton Scattering)
- analysis is based on 20.7 fb⁻¹ of data at 8 TeV from 2012 dataset
• Events selected requiring four muons with zero total charge and muon \( p_T > 3.5 \) GeV

• Two kinematic variables defined: higher dimuon invariant mass \( M^{1\mu\mu} \) and lower dimuon invariant mass \( M^{2\mu\mu} \)

• Yields are extracted through a 2D likelihood fit
  
  • each muon pair is modeled as signal + background contribution
  
  • signal model: sum of two Crystal Ball functions, parameters are extracted from signal MC samples and fixed
  
  • background: first order Chebyshev Polynomial

\[ N_{\text{sig}} = 38 \pm 7 \text{ events} \]

local significance = 9.6\( \sigma \)
Cross section measurement

- Inclusive cross section is measured in the region $|y(Y)| < 2.0$ and $p_T(Y) < 50$ GeV

$$
\sigma_T = \frac{N_{sig}}{B(Y(1S) \rightarrow \mu^+\mu^-)^2 \cdot \mathcal{L} \cdot < \frac{1}{\varepsilon(p_T, |y|)A(p_T, |y|)>}}
$$

<table>
<thead>
<tr>
<th>Component</th>
<th>Systematic Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF Shape</td>
<td>7.9%</td>
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<tr>
<td>Simulation</td>
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<tr>
<td>Efficiency</td>
<td>3.7%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>2.8%</td>
</tr>
<tr>
<td>Integrated Luminosity</td>
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</tr>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td><strong>10.7%</strong></td>
</tr>
</tbody>
</table>

Efficiency and acceptance corrections on event-by-event basis using data-embedding method to minimize model dependence of correction factors

- both corrections have been validated using signal MC SPS and DPS models

- Assuming unpolarized production of $Y(1S)$ mesons, the cross-section at $\sqrt{s} = 8$ TeV is measured to be

$$
\sigma_T = 68.8 \pm 12.7 \text{ (stat.)} \pm 7.4 \text{ (syst.)} \pm 2.8 \text{ (BR) pb}
$$

- Expected to change by up to +36% (longitudinal) or -38% (transverse) in case of extreme polarization scenarios
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

- FCNC decay that gives access to large number of observables: branching fractions, CP asymmetries and angular observable
  - SM branching fraction is about $4.5 \cdot 10^{-7}$
  - sensitive to new vector or axial-vector currents and virtual photon polarization
  - the decay is fully described by three angles ($\theta_l$, $\theta_K$, $\phi$) and the dimuon invariant mass squared ($q^2$)
  - the observables depend on form-factors for the $B \rightarrow K^*$ transition plus the underlying short distance physics (Wilson coefficients)

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

CMS analysis measures $A_{FB}$, $F_L$ and differential branching fraction ($dB/dq^2$) in bins of $q^2$
Analysis details

- Analysis is performed on a 20.5 fb$^{-1}$ data sample from 8 TeV collisions
- Control channels: $B^0 \rightarrow J/\psi K^{*0}$ (also used as normalization) & $B^0 \rightarrow \psi(2S) K^{*0}$
- 1430 $B^0 \rightarrow K^{*0}\mu^+\mu^-$ signal events divided in 7 $q^2$ bins (excluding $J/\psi$ & $\psi'$ regions)
- Unbinned extended maximum likelihood fits to $m(K\pi\mu\mu)$ and angular variables $\theta_K$ and $\theta_l$ in each $q^2$ bin
Results

- Measurements are compared to two SM predictions, which differ in the calculator of the form factors.
  - Results are consistent with the predictions.
- Measurement of $A_{FB}$ and $F_L$ with good precision at high $q^2$.
- Analysis with more angular variables (P’5, etc) is in preparation.
Measurement of $\varphi_s$ and $\Delta \Gamma_s$

- Very precise predictions of the CP violating phase $\varphi_s$ are available from the SM
  - any measured deviation would be an indication of New Physics contributions
- $\varphi_s$ measured together with decay-width difference $\Delta \Gamma_s$ between light and heavy $B_s$ mass eigenstates using the decay $B_s \to J/\psi \phi(1020) \to \mu^+\mu^-K^+K^-$
  - time-dependent and flavor-tagged angular analysis to disentangle the two CP final states
- three angles $\theta_T$, $\psi_T$, and $\phi_T$ used to describe the decay topology
- OS lepton tagging implemented to determine the $B_s$ flavor at production time
- UML fit to data performed using information on $m_B$, decay angles, tagging, $c_t$ and its uncertainty
**φ_s and ΔΓ_s results**

- Analysis exploits the 8 TeV data sample (19.7 fb⁻¹) collected in 2012
- Measured values for the weak phase φ_s and the decay width difference ΔΓ_s are:

  \[
  \phi_s = -0.075 \pm 0.097 \text{ (stat)} \pm 0.031 \text{ (syst) rad}
  \]

  \[
  \Delta \Gamma_s = 0.095 \pm 0.013 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}
  \]

- Results are consistent with SM predictions for φ_s and confirm non-zero values for ΔΓ_s
- Statistically limited measurement → significant improvement expected from analysis of Run II data
- Analysis of the B_s→J/ψ f_0 decay mode (BR already measured in CMS PLB 756 (2016) 84) could further contribute to the determination of φ_s

![Diagram](https://example.com/diagram.png)
Summary and outlook

- The Run II of the LHC will provide a lot of interesting heavy flavor events
  - analyses of 13 TeV data are promising and first results are appearing
  - differential cross section for $B^+$ production at 13 TeV has been measured up to 100 GeV in $p_T$
  - double differential production cross sections at 13 TeV for $J/\psi, \psi(2S), \Upsilon(nS)$ have been measured
  - improvements in precision are expected for analyses already pursued in Run I, eg. $B_{s(d)} \rightarrow \mu\mu$

<table>
<thead>
<tr>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$N(B^0_s)$</th>
<th>$N(B^0)$</th>
<th>$\delta B(B^0_s \rightarrow \mu^+\mu^-)$</th>
<th>$\delta B(B^0 \rightarrow \mu^+\mu^-)$</th>
<th>$B^0$ sign.</th>
<th>$\delta \frac{B(B^0 \rightarrow \mu^+\mu^-)}{B(B_{s(d)} \rightarrow \mu^+\mu^-)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>18.2</td>
<td>2.2</td>
<td>35%</td>
<td>&gt; 100%</td>
<td>0.0 − 1.5 $\sigma$</td>
<td>&gt; 100%</td>
</tr>
<tr>
<td>100</td>
<td>159</td>
<td>19</td>
<td>14%</td>
<td>63%</td>
<td>0.6 − 2.5 $\sigma$</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>478</td>
<td>57</td>
<td>12%</td>
<td>41%</td>
<td>1.5 − 3.5 $\sigma$</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>346</td>
<td>42</td>
<td>13%</td>
<td>48%</td>
<td>1.2 − 3.3 $\sigma$</td>
<td>50%</td>
</tr>
</tbody>
</table>

- Interesting measurements still being carried out on Run I data
  - the most recent result on Run I has been shown today and is a first observation!

All CMS BPH results are available at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
backup
Angular analysis results

- CMS measurement at 8 TeV is combined with previous measurement at 7 TeV
- Results are compared to measurements from other experiments, showing comparable or higher precision