Rare B-decays at CMS

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Introduction

Flavor production and study of its properties is one of the most interesting areas in particle physics.

There are many unsolved questions in this sector (listing here only few):

- What are the principles for the observed pattern of fermion mass and mixing angles?
- Are there any new sources of flavor symmetry breaking apart from SM Yukawa couplings at TeV scale?
- Are there new sources of CP violation to explain the observed matter-antimatter asymmetry of universe?

LHC era is very important to pin down some of the flavor questions.

Two ways to probe the New Physics (NP):

- **Direct Search:**
  produce the new heavy particles beyond the standard model (SM). The production cross-section are usually very small.

- **Indirect Search:**
  measure observables of SM processes (mainly rare decay processes). any significant deviation from SM prediction would be a hint of NP.
LHC and CMS performance
Why we can do better at higher energy?

- because of large production rate
- B production cross-section goes up by almost one order of magnitude higher compared to Tevatron [ in LHC ~ $O(100\mu b)$ ]
- not only the production, but also the final state is important.
A clean $B^+ \rightarrow J/\psi K^+$ candidate with visible secondary vertex

$p_T = 2.25$ GeV

$K^+$

$p_T = 17.09$ GeV

$\mu^+$

$\mu^-$ $p_T = 6.69$ GeV

$M(\mu^+\mu^-) = 3.11$ GeV

$l_{xy} = 0.41$ cm
Many flavor physics analyses depend upon the prompt and displaced quarkonium triggers. The trigger requirements are tightened due to increased luminosity. ~10% bandwidth is given to flavor physics.
Provides important information to understand particle interactions.

B\(^+\) differential production cross-section presented as a function of B\(^+\) transverse momentum and rapidity

Uses exclusive decay mode B\(^+\) → J/ψK\(^+\) (J/ψ→μμ) [pp → B\(^+\)X → J/ψX]

both muons must be within |\(\eta\)| < 1.6 or one of the muons must have p\(_T\) > 11 GeV

J/ψ candidates must have p\(_T\) > 8GeV and minimum \(\chi^2\) probability for vertex fit.

J/ψ candidate is combined with charged track (considered to be kaon) with p\(_T\) > 1 GeV

The decay length significance cut is applied in transverse plane (distance between secondary vertex and beam spot in transverse plane divided by its uncertainty)

The signal is obtained by extended likelihood fit to the B\(^+\) invariant mass distribution in bins of B\(^+\) p\(_T\) and |\(\eta\)|

The differential cross-section is calculated to be

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

Result shown is based on 49.4 pb\(^{-1}\) data collected @ 13 TeV
- B invariant mass distribution for different $p_T$ and $\eta$ regions.
- Signal: two gaussians
- The mean of the two gaussians fixed while the width and normalization are free (except for some $p_T$ bins where it’s fixed from MC)
B⁺ production cross-section from CMS

(a) CMS data compared to theoretical predictions (FONLL, PYTHIA)

(b) Comparison of CMS data to theoretical predictions (FONLL, PYTHIA) for different rapidity bins

Ratios to FONLL

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Rare B-decays at CMS
Facts about $B_{s/d} \rightarrow \mu^+\mu^-$

- These FCNC decays are highly suppressed in SM
  - Helicity suppressed, by a factor of $(m_\mu/m_B)^2$
  - Forbidden at the tree level in SM, only can proceed through higher order loop diagrams
  - Cabibbo suppressed $|V_{tb(ts)}|^2$

- Possible new particles in the loops
  - May enhance or suppress the decay rates!

- Probably the cleanest rare decay both experimentally and theoretically

**SM Predictions:**

$$\text{BR}(B_s \rightarrow \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\text{BR}(B_d \rightarrow \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al, PRL 112, 101801 (2014)
History of $B_{s/d} \to \mu^+\mu^-$ search
**Analysis Methodology**

- **Full LHC Run 1 datasets**
  - 5 fb\(^{-1}\) (\(\sqrt{s} = 7\) TeV, 2011) and 20 fb\(^{-1}\) (\(\sqrt{s} = 8\) TeV, 2012)
  - Blind signal region until selection is fixed
  - Multivariate candidate selection (BDT)

- **Unbinned maximum likelihood fit to dimuon invariant mass**
  - Fit simultaneously both \(B_s \rightarrow \mu\mu\) and \(B_d \rightarrow \mu\mu\)

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \frac{N_{obs}^{B_s^0}}{N_{B_s^0}^0} \frac{N_{obs}^{B_s^0}}{e_{B_s^0} e_{B_s^0} \mathcal{L}(pp \rightarrow B_s^0)} = \frac{N_{obs}}{N_{B_s^0} f_b} \frac{e^{B_s^0}}{e_{tot}} \mathcal{B}(B^+)
\]

- **Normalization Sample:** \(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm\)
  - Measure \(B_s \rightarrow \mu\mu\) relative to the normalization channel (minimize uncertainty due to b production cross section and integrated luminosity)
  - Nearly identical selection cuts to reduce systematic uncertainties

- **Control Sample:** \(B_s \rightarrow J/\psi \phi \rightarrow \mu^+\mu^- K^+ K^-\)
  - Calibrate and validate MC

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**Region definitions**

| Region definitions            | Invariant mass (GeV) |
|-------------------------------|----------------------|
| overall window                | 4.90 < \(m_{\mu\mu}\) < 5.90 |
| blinding window              | 5.20 < \(m_{\mu\mu}\) < 5.45 |
| \(B^0 \rightarrow \mu^+\mu^-\) window | 5.20 < \(m_{\mu\mu}\) < 5.30 |
| \(B_s \rightarrow \mu^+\mu^-\) window | 5.30 < \(m_{\mu\mu}\) < 5.45 |

**Data split in two categories:**

- **Barrel:** 2 \(\mu\) in barrel \(|\eta|<1.4\)
  - Better sensitivity, \(\sigma_M \sim 40\) MeV
- **Endcap:** \(\geq 1\) \(\mu\) in endcap \(|\eta|>1.4\)
  - More events, \(\sigma_M \sim 60\) MeV
Analysis Strategy

• **Signal**: $B_{s(d)} \rightarrow \mu\mu$
  - two muons from a decay vertex
  - well reconstructed secondary vertex
  - momentum aligned with flight direction
  - invariant mass around $m(B_{s(d)})$
  - blind analysis

• **Backgrounds:**
  - **combinatorial** (from sideband of $B_{s(d)}$ mass)
    - two semi-leptonic $B$ decays
    - one semi-leptonic and one hadronic $B$ decay
  - **rare single $B$ decays** (from MC simulations)
    - peaking background, e.g., $B_s \rightarrow K^+K^-$
    - non peaking background, e.g., $B_s \rightarrow K^-\mu^+\nu$, $\Lambda_b \rightarrow p\mu^+\nu$

![Diagram of signal and background processes](image-url)
Backgrounds for $B_{s/d} \rightarrow \mu^+\mu^-$

- Understanding the background is very important to this kind of rare decay mode
- Plots below show the peaking and non-peaking backgrounds for this channel
**Invariant $\mu^+\mu^-$ mass**

- The dimuon mass is further sub-divided into (apart from barrel and end cap in 7 and 8 TeV) in bins of BDT (boosted decision tree) discriminant. Uses 5 fb$^{-1}$ with 7 TeV and 20 fb$^{-1}$ with 8 TeV data.
The CMS results for $B_s/d \rightarrow \mu^+ \mu^-$

**Experimental Result:**

$BR(B_s \rightarrow \mu \mu) = \left(3.0^{+0.9}_{-0.8} (\text{stat})^{+0.6}_{-0.4} (\text{syst})\right) \times 10^{-9}$

$BR(B_d \rightarrow \mu \mu) = \left(3.5^{+2.1}_{-1.8} (\text{stat}+\text{syst})\right) \times 10^{-10}$

**Theoretical Prediction:**

$BR(B_s \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

$BR(B_d \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

- $B_s \rightarrow \mu \mu$ significance: $4.3 \sigma$
- $B_d \rightarrow \mu \mu$ significance: $2 \sigma$

The results are compatible with SM expectations.
CMS and LHCb combination for $B_{s/d} \to \mu^+\mu^-$

- both CMS and LHCb data are simultaneously fitted with BFs as common free parameters
- an unbinned maximum likelihood fit to the dimuon invariant mass is done over all BDT bins (12 bins for CMS and 8 bins for LHCb)

**observed branching fraction:**

$$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

6.2$\sigma$ observed

3.0$\sigma$ evidence

**SM compatibility:** 1.2$\sigma$ for $B_s$ and 2.2$\sigma$ for $B_d$
CMS future prediction

Expectation assuming SM branching fraction and planned detector upgrade

- Large pile up will affect detection efficiency, tightening selection criteria, reduce background, better determination of peaking background.
Measurement of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ in CMS

- forbidden at tree level, but allowed via loop diagrams (as shown on the right)
- sensitive to NP through BSM particle in the loop
- small branching fraction ($\sim 10^{-6}$)
- observable to be compared to SM predictions: differential BF, $A_{FB}$, $F_L$, $A_{CP}$, $P_5'$, Isospin asymmetry...

$$\frac{1}{\Gamma} \frac{d^3 \Gamma}{d \cos \theta_K d \cos \theta_l d q^2} = \frac{9}{16} \left\{ \frac{2}{3} F_S + A_S \cos \theta_K \right\} (1 - \cos^2 \theta_l)$$

$+ (1 - F_S) \left[ 2 F_L \cos^2 \theta_K (1 - \cos^2 \theta_l) \right]$

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

$+ \frac{4}{3} A_{FB} \left[ (1 - \cos^2 \theta_K) \cos \theta_l \right].$
Measurement of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ in CMS (cont.)

- Unbinned maximum likelihood fit to three variables: $m(K^+\pi^-\mu^+\mu^-)$, and two angular variables $\theta_K, \theta_L$ in each $q^2$ bin.
- **Signal** (correctly tagged)
- **Signal** (wrongly tagged)
- **Combinatorial background**
- we are interested in p-wave components
CMS results are consistent with theory predictions as well as with experimental results.
Summary

- CMS and LHCb reported a first observation of $B_s \rightarrow \mu^+\mu^-$ ($6.2\sigma$ from combined data). The measured BF is compatible with SM predictions (within $1.2\sigma$).
- Both experiments reported the first evidence of $B_d \rightarrow \mu^+\mu^-$. The measurement is compatible with SM within $2.2\sigma$.
- CMS + LHCb provides the most precise BF measurement for these decay modes.
- However, we look forward for the new (13 and 14 TeV) data to give us $B_d \rightarrow \mu^+\mu^-$ observation soon.
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ results are consistent with theory prediction as well as other experiments.
- The next few years would be very crucial for LHC to look for something beyond SM.
