Heavy flavor rare decays from CMS

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Outline

- Motivation
- CMS rare B-decay analyses:

  Analysis of the decay: $B_s^0 \rightarrow \mu^+ \mu^-$ & $B^0 \rightarrow \mu^+ \mu^-$

  CMS-PAS-BPH-16-004

  Angular analysis of the decay: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

  Phys.Lett. B781 (2018) 517-541

  Angular analysis of the decay: $B^+ \rightarrow K^+ \mu^+ \mu^-$

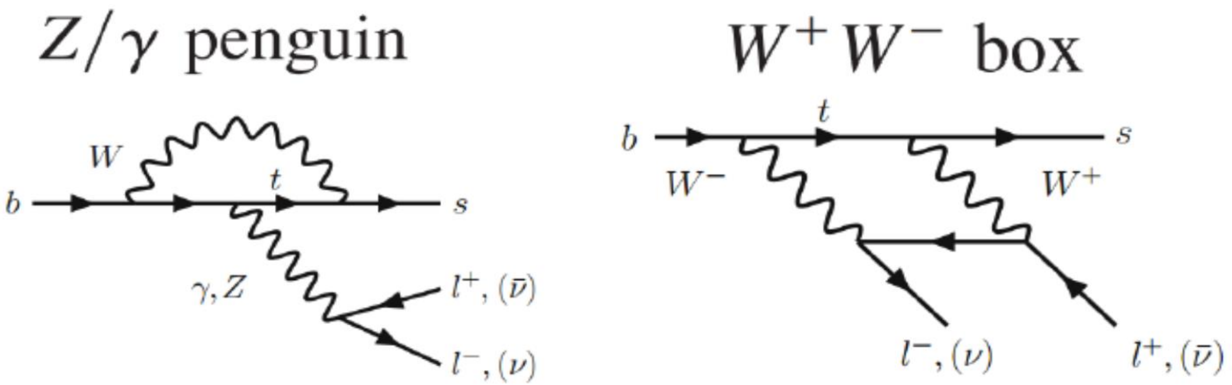
  Phys.Rev. D98 (2018) no.11, 112011

- Summary

Motivation

- ❖ Phenomena beyond the SM can become manifest indirectly, by modifying the production and decay properties of SM particles.
- ❖ In SM, flavor-changing neutral current (FCNC) is forbidden at tree level and occurs through higher-order processes.

- $b \to s\, l^+ l^-$ FCNC process diagram:

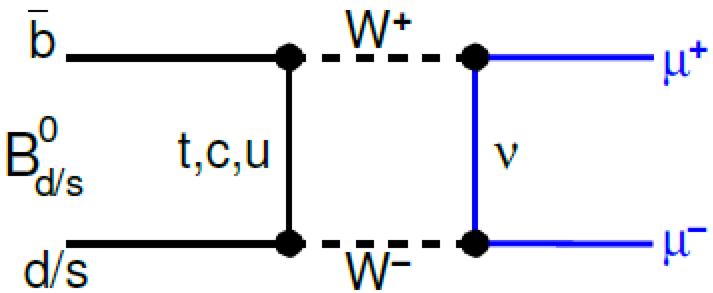


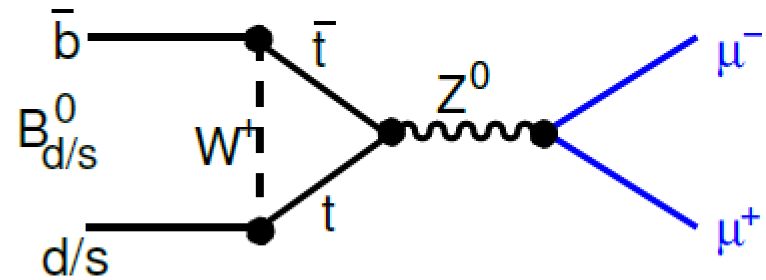
  - The amplitudes may interfere with non-SM particle contributions.
  - The transition can probe NEW particles and processes.

- ❖ Sensitive to possible physics phenomena beyond the SM(BSM).

Analysis of the decay: $B_s^0 \to \mu^+ \mu^-$ & $B^0 \to \mu^+ \mu^-$

- Leptonic B meson decays offer excellent opportunities to perform precise tests of the standard model. The decays proceed only via loop diagrams and are also helicity suppressed.





- Measuring $B_s^0 \to \mu^+ \mu^-$ effective lifetime, $B(B_s^0 \to \mu^+ \mu^-)$ and $B(B^0 \to \mu^+ \mu^-)$
- SM prediction values:

$$\bar{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}$$

$$\tau_{\rm B_s^0} = 1.509 \pm 0.004\,{\rm ps}$$

SM expectation: 4-5% theoretical uncertainty!
$\bar{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)$: decay time-integrated $\mathcal{B}$

Analysis overview

❖ using a data sample of proton-proton collisions accumulated by the CMS experiment in 2011, 2012, and 2016.

❖ Analysis strategy:

1) strict muon identification with boosted decision tree

2) tight candidate selection with (another) boosted decision tree

3) unbinned (extended) maximum likelihood fits to selected events and get values of interests

❖ Reconstructed decays for this analysis:

- $B \to \mu^+ \mu^-$: signal channel
- $B \to J/\psi K^+$: normalization channel
- $B_s^0 \to J/\psi \phi$: control channel

❖ Separation of data into two 'channels'. Central channel & forward channel:

Year	central	forward
2011	$0 < \lvert\eta_\mu^f\rvert < 1.4$	$1.4 < \lvert\eta_\mu^f\rvert < 2.1$
2012	$0 < \lvert\eta_\mu^f\rvert < 1.4$	$1.4 < \lvert\eta_\mu^f\rvert < 2.1$
2016	$0 < \lvert\eta_\mu^f\rvert < 0.7$	$0.7 < \lvert\eta_\mu^f\rvert < 1.4$

Measuring of BFs and $\tau_{\mu+\mu-}$

❖ Branching fractions

- 3D fit for $B(B_s^0 \to \mu^+\mu^-)$ & $B(B^0 \to \mu^+\mu^-)$:
  $$P(m_{\mu\mu};\sigma(m_{\mu\mu})) \times P(\sigma(m_{\mu\mu})/m_{\mu\mu}) \times P(\mathcal{C}) \quad (1)$$
- dimuon mass $m_{\mu\mu}$
- per-event dimuon mass resolution $\sigma(m_{\mu\mu})$
- *C*: binary distribution for dimuon bending configuration
  $C(\pm 1)$: the two muons bending towards (away from) each other
- Measurement of $B(B_s^0 \to \mu^+\mu^-)$ relative to normalization channel:

$$\bar{\mathcal{B}}(B_s^0 \to \mu^+\mu^-) = \frac{n^{\rm obs}_{B_s^0}}{N(B^+ \to J/\psi K^+)} \frac{\varepsilon^{tot}_{B^+}}{\varepsilon^{tot}_{B_s^0}} \frac{f_u}{f_s} \mathcal{B}(B^+ \to J/\psi[\mu^+\mu^-]K) \quad (2)$$

❖ Effective lifetime

- $$\begin{aligned} P(m_{\mu^+\mu^-}, t;\sigma_t) = {} & N_{\rm sig}P_{\rm sig}(m_{\mu^+\mu^-})T_{\rm sig}(t;\sigma_t)\varepsilon_{\rm sig}(t) + N_{\rm comb}P_{\rm comb}(m_{\mu^+\mu^-})T_{\rm comb}(t;\sigma_t) \\ & + N_{\rm peak}P_{\rm peak}(m_{\mu^+\mu^-})T_{\rm peak}(t;\sigma_t)\varepsilon_{\rm peak}(t) + N_{\rm semi}P_{\rm semi}(m_{\mu^+\mu^-})T_{\rm semi}(t;\sigma_t)\varepsilon_{\rm semi}(t), \end{aligned} \quad (3)$$
- Two methods: (1) 2-D UML fit; (2) 1-D ML fit

Results of branching fractions

- Branching fractions from 3D UML fit:

$$\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-) = [2.9^{+0.7}_{-0.6}(\text{exp}) \pm 0.2(f_s/f_u)] \times 10^{-9}$$

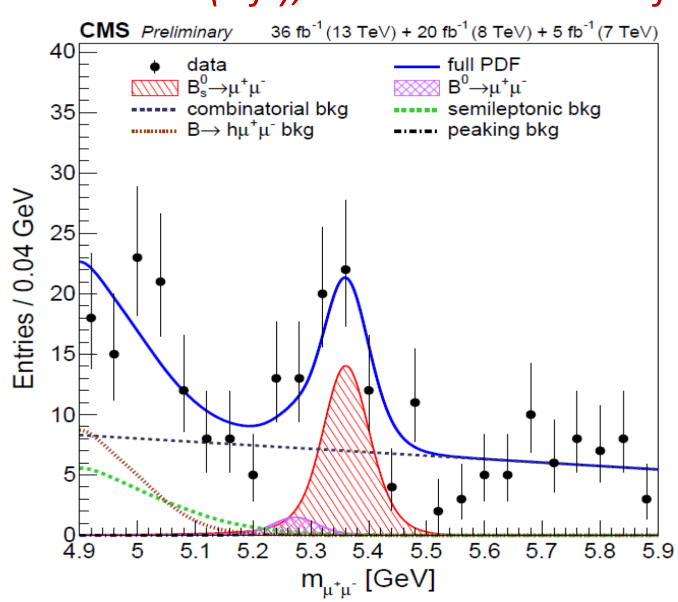
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.8^{+1.4}_{-1.3}) \times 10^{-10}$$

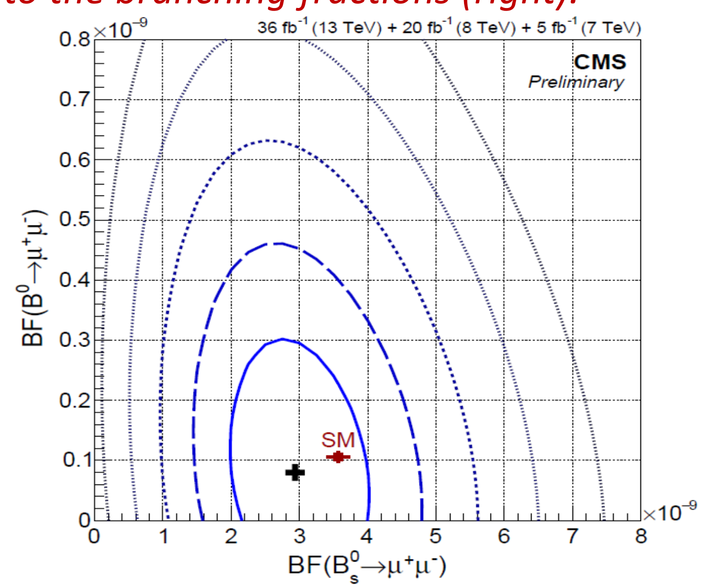
- $B(B^0 \to \mu^+\mu^-)$ upper limit

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10} \quad (95\%\ \text{CL})$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.1 \times 10^{-10} \quad (90\%\ \text{CL})$$

- *Figures: Invariant mass distributions with the fit projection overlays for the branching fraction results (left); Likelihood contours for the fit to the branching fractions (right).*



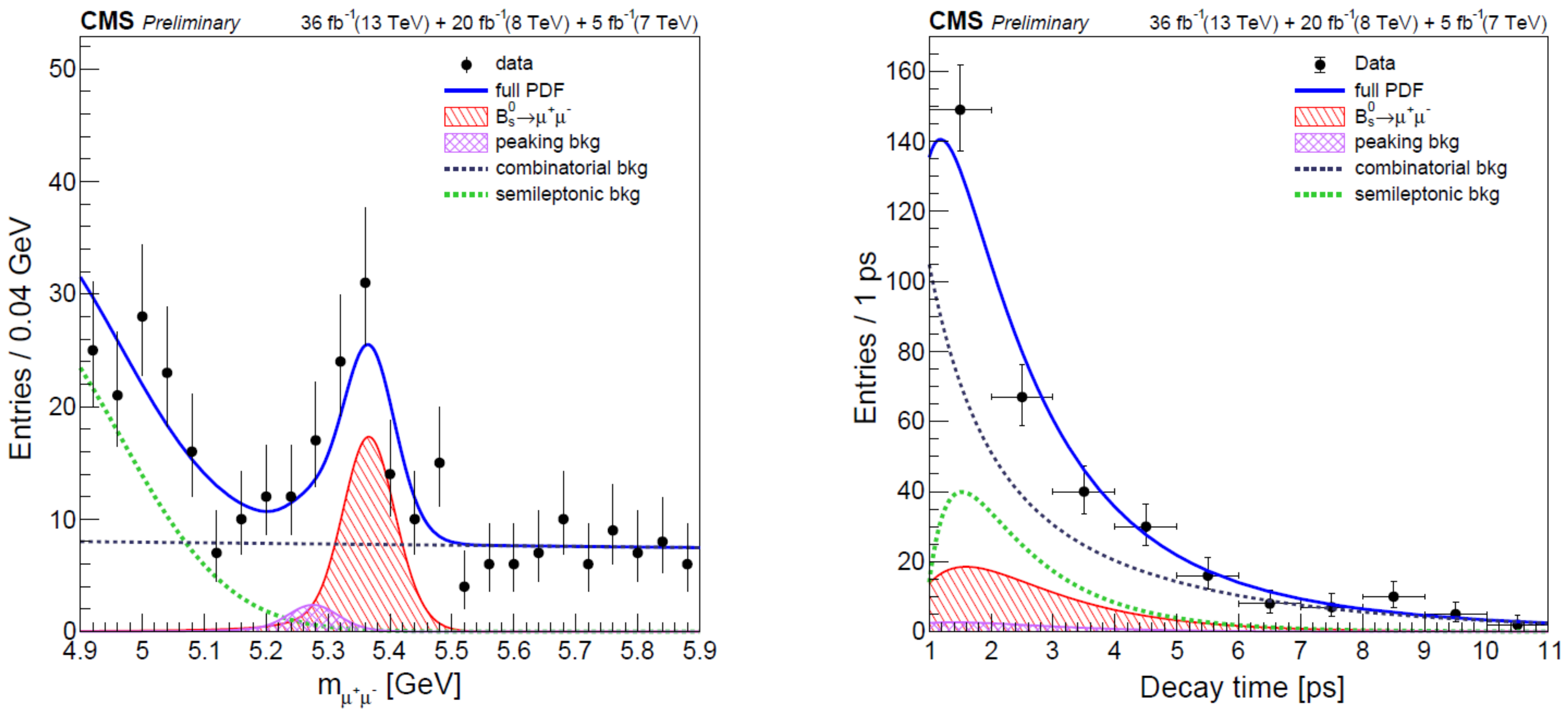


Result of effective lifetime

- Effective lifetime $\tau_{\mu+\mu-}$

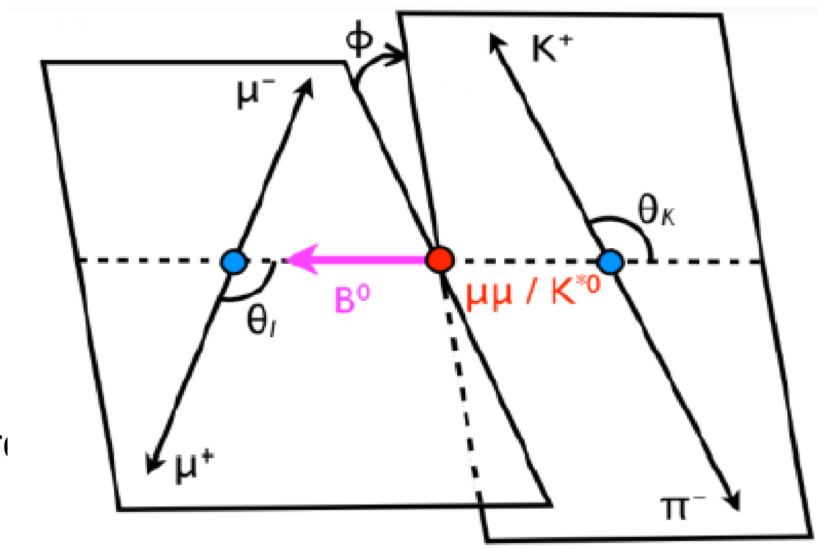
$$\tau(B_s^0 \to \mu^+\mu^-) \quad = \quad 1.70^{+0.61}_{-0.44}\,\text{ps}$$

- *Figures: Invariant mass (left) and proper decay time (right) distributions*



Angular analysis of the decay: $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- Using 20.5 fb^{-1} of 8 TeV pp data taken in 2012
- The process can be fully described by the three angles (θ_ℓ, θ_K, φ) and the dimuon invariant mass squared q^2.
- Robust SM calculation of several angular parameters, A_{FB}, F_L, P_1 and P_5', are available for much of the phase space.
- LHCb reported a discrepancy larger than 3 standard deviations with respect to the SM for P_5'.



- The differential decay formula:

S-wave and S&P-wave interference

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\,d\cos\theta_l\,d\cos\theta_K\,d\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right] + (1-F_S)\left[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

P-wave

A_S^5: nuisance parameter

P_1, P_5': measured parameters

F_L, F_S, A_S: fixed from previous CMS measurement

Fit PDF

- Probability density function

$$\text{p.d.f.}(m,\theta_K,\theta_l,\Phi) = Y_S^C \left[S^C(m)\, S^a(\theta_K,\theta_l,\phi)\, \epsilon^C(\theta_K,\theta_l,\phi) \right.$$ Correctly tagged events

Mistag fraction → f^M

$$\left. + \frac{f^M}{1-f^M} S^M(m)\, S^a(-\theta_K,-\theta_l,\phi)\, \epsilon^M(\theta_K,\theta_l,\phi) \right]$$ Mistagged events

$$+ Y_B\, B^m(m)\, B^{\theta_K}(\theta_K)\, B^{\theta_l}(\theta_l)\, B^{\phi}(\phi),$$ Background

Signal contribution: mass shape (double gaussian), decay rate, and 3D efficiency function

Background contribution: mass shape (exponential) and different degrees polynomial functions for each angular variable.

Analysis overview

❖ Fitting strategy:

- Parameters are extracted from un-binned extended maximum likelihood fit in each bin: $m(K^+\pi^-\mu^+\mu^-)$, $\cos\theta_l$, $\cos\theta_K$, ϕ
- Fit performed in two steps:
  1. Fit sidebands to determine angular background shape, fixed in the next step;
  2. Fit whole mass spectrum, 5 free parameters, A_S^5, P_1, P_5', yields.

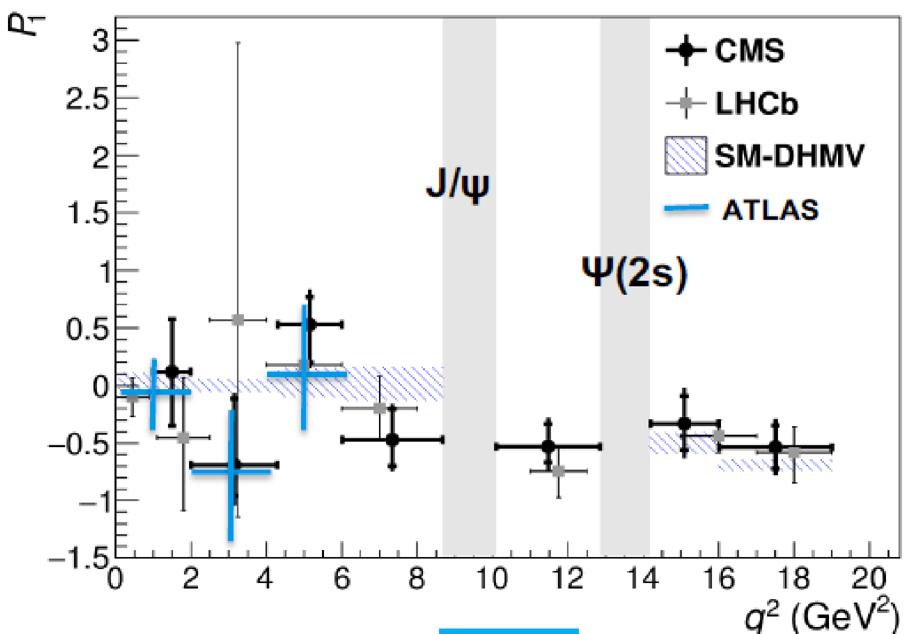
❖ Validation with data control channels:

- Control channels: $B^0 \rightarrow K^{*0} J/\psi(\mu^+ \mu^-)$, $B^0 \rightarrow K^{*0} \psi'(\mu^+ \mu^-)$
- To check efficiency determination;
  - ✓ Fit performed with F_L free to float. F_L measured agrees with PDG value.

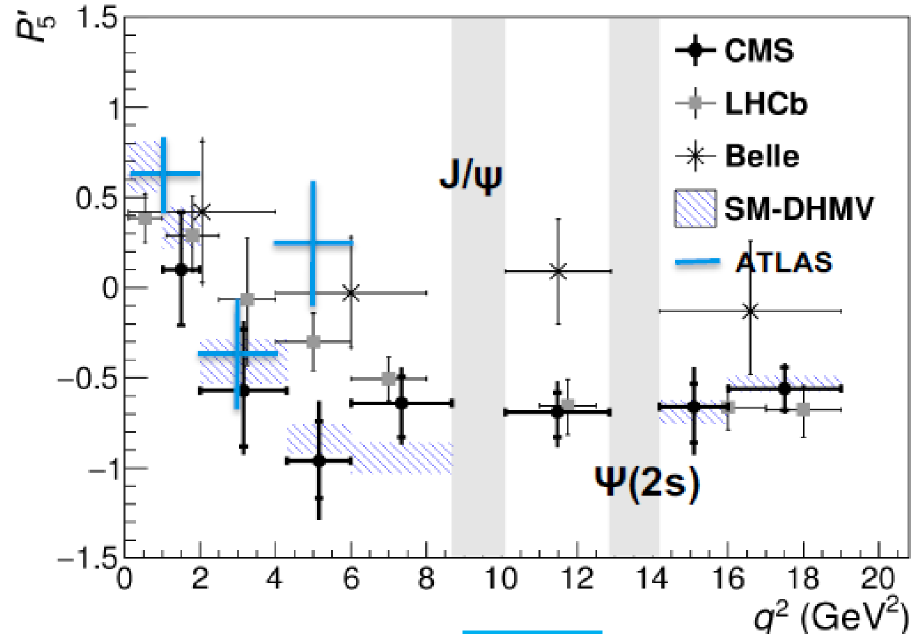
Systematic uncertainty

Systematic uncertainty	$P_1(10^{-3})$	$P_5'(10^{-3})$
Simulation mismodeling	$1-33$	$10-23$
Fit bias	$5-78$	$10-119$
MC statistical uncertainty	$29-73$	$31-112$
Efficiency	$17-100$	$5-65$
$K\pi$ mistagging	$8-110$	$6-66$
Background distribution	$12-70$	$10-51$
Mass distribution	12	19
Feed-through background	$4-12$	$3-24$
F_L, F_S, A_s uncertainty propagation	$0-126$	$0-200$
Angular resolution	$2-68$	$0.1-12$
Total	$60-220$	$70-230$

Results: P_1 and P_5'



P_1



P_5'

The events are fit in seven q^2 bins from 1 to 19 GeV^2, yielding 1397 signal events in total.

The measured P_1 and P_5' are consistent with the SM predictions and previous measurements within the uncertainties.

Angular analysis of the decay: $B^+ \to K^+ \mu^+ \mu^-$

- Using 20.5 fb^{-1} of 8 TeV pp data taken in 2012

Control channels: $B^+ \to K^+ J/\psi(\mu^+ \mu^-)$, $B^+ \to K^+ \psi'(\mu^+ \mu^-)$

- The decay for the process $B^+ \to K^+ \mu^+ \mu^-$ can be described by $\cos\theta_l$ and $q^2=(m_{\mu+\mu-})^2$
- The differential decay formula:

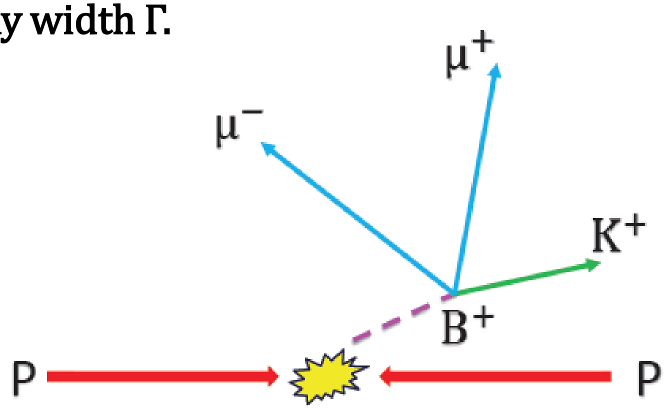
$$\frac{1}{\Gamma}\frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$

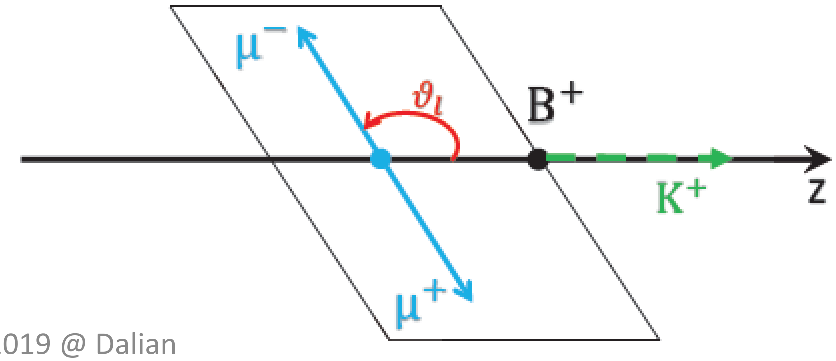
$$0 \le F_H \le 3, A_{FB} \le \min(1, F_H/2)$$

θ_l: $l = \mu$, the angle between the μ^+ (μ^-) and the K^-(K^+) in the rest frame of the dimuon system.

A_{FB}: $\mu^+ \mu^-$ forward-backward asymmetry.

F_H: is a measure of the contribution from pseudoscalar, scalar and tensor amplitudes to the decay width Γ.





Fit PDF

$PDF(m, \cos\theta_l) = Y_S \cdot S(m) \cdot S(\cos\theta_l) \cdot \varepsilon(\cos\theta_l) + Y_B \cdot B(m) \cdot B(\cos\theta_l)$

Signal contribution: mass shape (double Gaussian), decay rate, and efficiency function (6th order polynomial).

Background contribution: mass shape (exponential) and different degrees polynomial plus a Gaussian function for each angular variable.

Analysis overview

Fitting strategy:

- Parameters are Extracted from un-binned extended maximum likelihood fit in each q^2 bin: $M(K^+\mu^+\mu^-)$, $\cos\theta_l$

Validation:

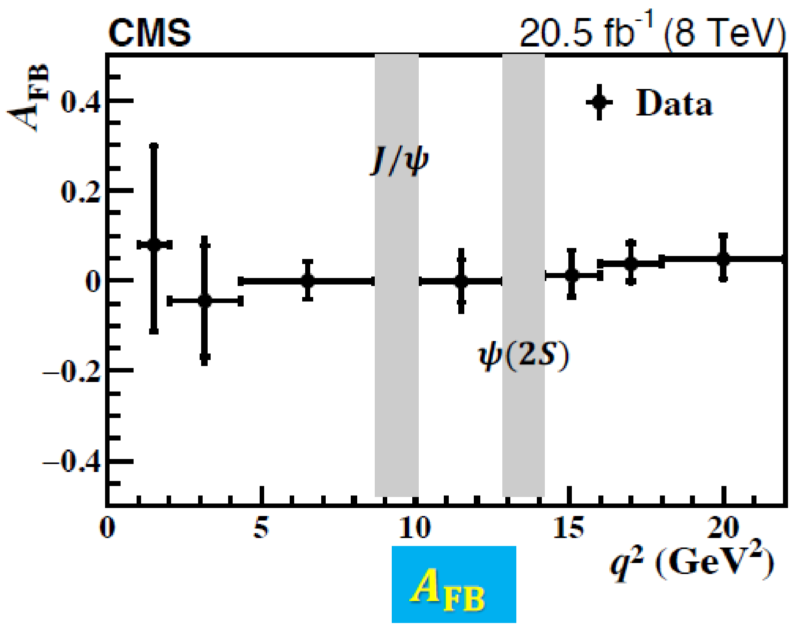
- with resonant control regions
- with MC samples

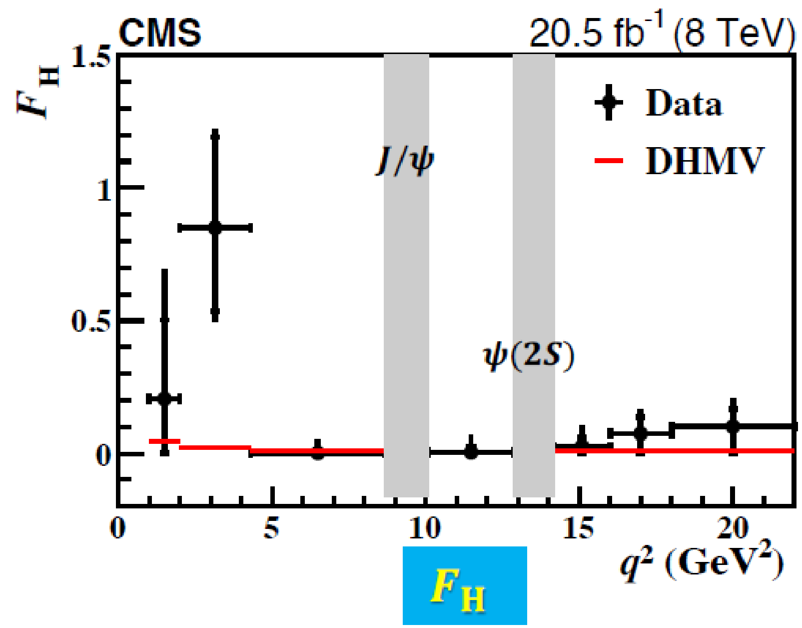
Systematic uncertainty

Systematic uncertainty	A_{FB} ($\times 10^{-2}$)	F_{H} ($\times 10^{-2}$)
Finite size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Simulation mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting procedure	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39

Results: A_{FB} and F_H

- The events are fit in seven q^2 bins from 1 to 22 GeV^2, yielding 2286 signal events in total.
- The measured A_{FB} and F_H show good agreement with the SM predictions within the uncertainties. No clear indication of new physics beyond the SM could be drawn from present results.





Summary

- FCNC rare decays are good probes of physics beyond standard model.

- CMS is a good environment to study rare B-decays.

- The three measurements: $B_s^0 \to \mu^+ \mu^-$ & $B^0 \to \mu^+ \mu^-$; $B^0 \to K^{*0} \mu^+ \mu^-$; $B^+ \to K^+ \mu^+ \mu^-$, which are introduced above showed results that agree with standard model within the uncertainties.

- Further researches will be made by analysing Run2 data.

The End

Thank you!

Backup

Uncertainties of the decay: $B_s^0 \to \mu^+ \mu^-$ & $B^0 \to \mu^+ \mu^-$

- Uncertainties dominated by small signal sample size

▷ relative errors for $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$, absolute for $\tau_{\mu^+\mu^-}$

Source	$\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)$ [%]	$\tau_{\mu^+\mu^-}$ [ps]	
		2D UML	*sPlot*
Kaon tracking	2.3 — 4	—	—
Normalization yield	4	—	—
Background yields	1	0.03	(*)
Production process	3	—	—
Muon identification	3	—	—
Trigger	3	—	—
Efficiency (data/MC simulation)	5 — 10	—	(*)
Efficiency (functional form)	—	0.01	0.04
Efficiency lifetime dependence	1 — 3	(*)	(*)
Era dependence	5 — 6	0.07	0.07
BDT discriminator threshold	—	0.02	0.02
Silicon tracker alignment	—	0.02	—
Finite size of MC sample	—	0.03	—
Fit bias	—	—	0.09
$\mathcal{C}$-correction	—	0.01	0.01
Total systematic uncertainty	$(^{+0.3}_{-0.2}) \times 10^{-9}$	0.09	0.12
Total uncertainty	$(^{+0.7}_{-0.6}) \times 10^{-9}$	$^{+0.61}_{-0.44}$	$^{+0.52}_{-0.33}$

(*) included in other item

Data and MC samples for angular analysis of the decay: $B^+ \rightarrow K^+ \mu^+ \mu^-$

❖ **Datasets-2012 (~20.5 fb^{-1})**

- /DoubleMuParked/Run2012A-22Jan2013-v1/AOD
- /MuOniaParked/Run2012B-22Jan2013-v1/AOD
- /MuOniaParked/Run2012C-22Jan2013-v1/AOD
- /MuOniaParked/Run2012D-22Jan2013-v1/AOD

❖ **Signal MC-8TeV (~3296.8 fb^{-1})**

- /Bu2MuMuK_TuneZ2star_8TeV_Pythia6/Summer12_DR53X-PU_RD2_START53_V19F-v1/AODSIM

❖ **Normalization MC-8TeV**

- $\psi(2S)K^+$ (~212.5 fb^{-1}) /BuToPsiK_KFilter_TuneZ2star_SVS_8TeV-pythia6-evtgen/Summer12_DR53XPU_RD2_START53_V19F-v1/AODSIM
- $J/\psi(2S)K^+$ (~18.6 fb^{-1}) /BuJpsiK_TuneZ2star_8TeV_Pythia6/Summer12_DR53X-PU_RD2_START53_V19F-v1/AODSIM

❖ **Background MC-8TeV**

- $\psi(\mu^+ \mu^-)X$ (~9.8 fb^{-1}) /BpToPsiMuMu_2MuPtEtaFilter_8TeV-pythia6-evtgen/Summer12_DR53XPU_S10_START53_V7Av1/AODSIM
- $K^{*0}\mu^+\mu^-$ (~5951.1 fb^{-1}) /BdToKstarMuMu_EtaPtFilter_8TeV-pythia6-evtgen/Summer12_DR53XPU_RD2_START53_V19F-v1/AODSIM

Systematic uncertainty of the decay: $B^+ \rightarrow K^+ \mu^+ \mu^-$

- **Finite size of MC samples:**

Generating 200 sets of efficiency with parameters varied in multi-Gaussian phase space.

- **Efficiency description:**
- **Simulation mismodeling:**
- **Background parametrization model:**
- **Angular resolution:**

Propagation of efficiency difference from reco'd or gen'd value($\cos\theta_\ell$) with signal MC.

- **Dimuon mass resolution:**

Propagation of efficiency difference from reco'd or gen'd dimuon mass with signal MC.

- **Fitting procedure:**

Fluctuations (RMS) from signal MC subsamples fitting results.
Generate pseudo-experiments with signal from MC and background from data, fit with data fitting procedure.

- **Background distribution:**

Use the pseudo-experiments above, change the background angular p.d.f. to one of the two data side bands, chose the larger deviation as systematic uncertainty.

- **Total systematic uncertainty:**

All added in quadrature.