Indirect Searches for New Physics with Heavy Flavour Decays at CMS

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Motivation

One way to search for New Physics (NP) at the LHC is to directly produce heavier beyond Standard Model (**BSM**) particles.

The complementary way is to **search indirectly** for NP through the **SM rare processes** via precision measurements.

This offers a way to search for NP by probing indirect effects of new interactions in higher order processes. Specifically, the **loop induced couplings** can test detailed SM structure at the level of **radiative corrections**.

Semi-leptonic decays of B-meson ($b \rightarrow s l^+ l^-$) are a good place to determine decay constant, **angular observables** and search for NP effects.

Purely leptonic and **semi-leptonic** decays offer a rich programme through measurement of branching fraction, effective lifetime and search for new effects

$B^+ \rightarrow K^*(892)^+ \mu^+\mu^-$

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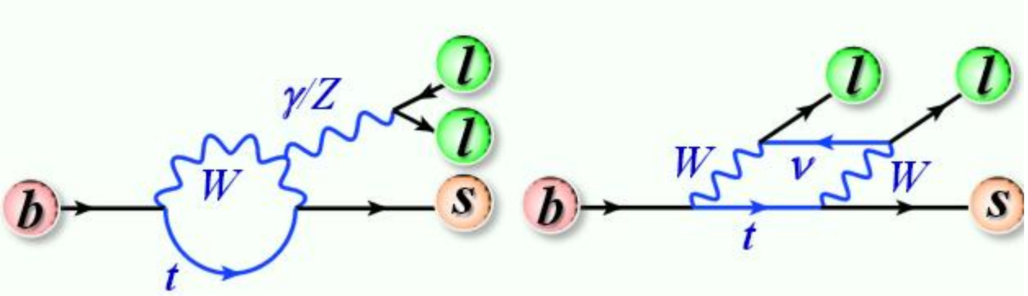
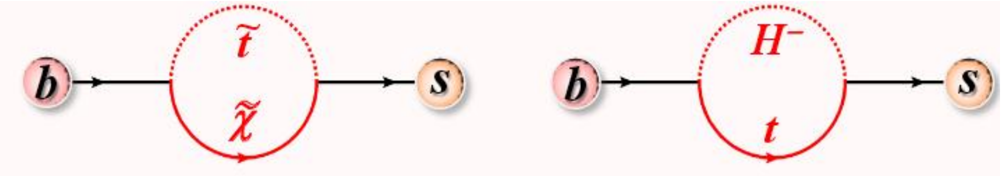
- Use decay modes such as, $B^0 \to K^{*0}\mu^+\mu^-$ $B^+ \to K^{(*)+}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and many more

- Forbidden at the tree level, but allowed via loop diagrams in SM



- Sensitive to NP through BSM particles in the loop



- Small branching fraction

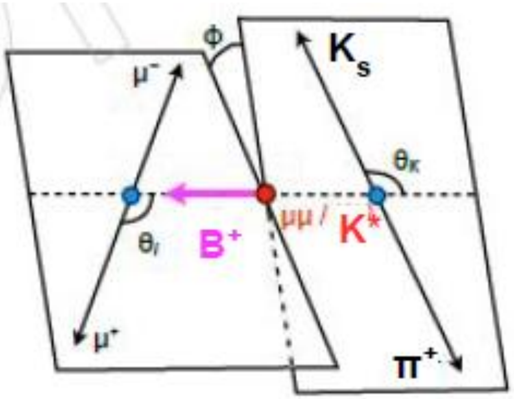
- List of observables to compare with SM predictions (as function of square of dilepton mass): Branching fractions, differential BFs, ratio of BFs between different flavors, CP asymmetry, Isospin asymmetry, Forward-backward asymmetry of leptons, etc

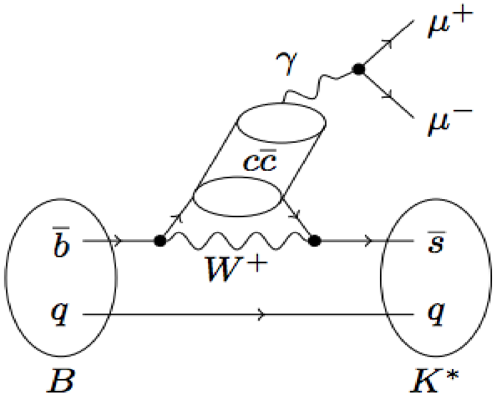
Angular Analysis

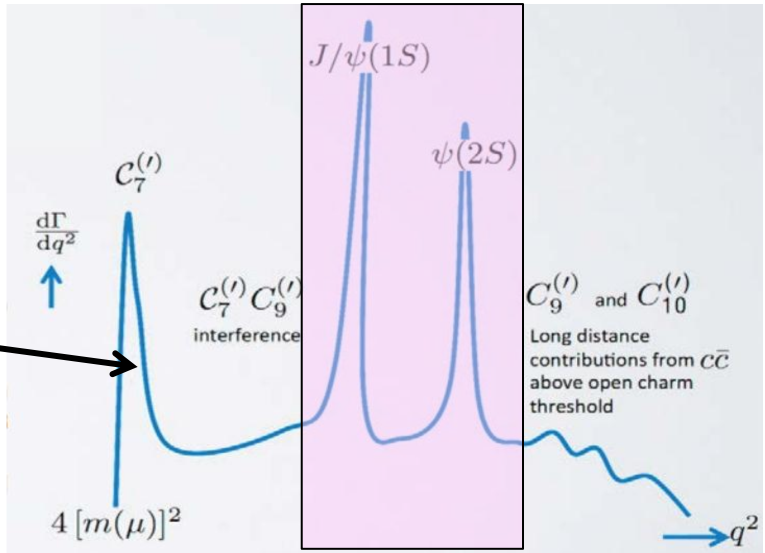
- The decay can be fully described by angular variables (θ_K, θ_l and ϕ):

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} =$$

$$\frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell-1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big].$$







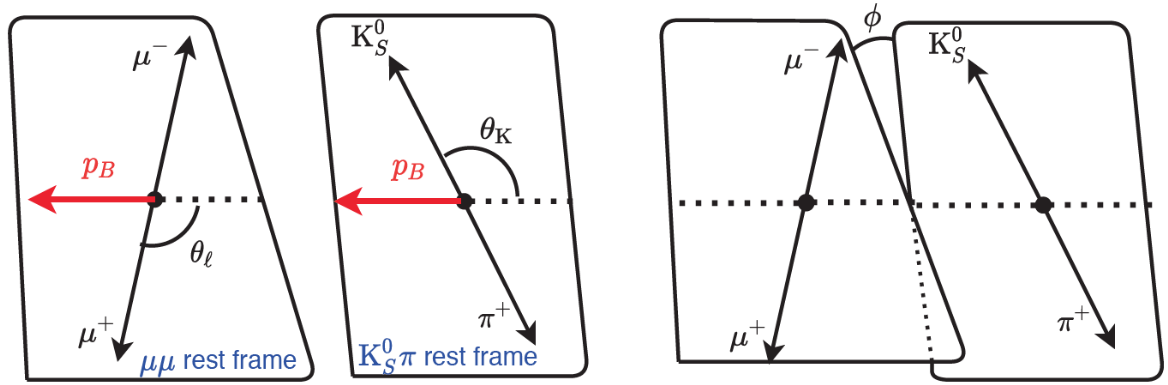
- Large-recoil region (low q^2):
  Dominant effect of Photon Pole
- Charmonium region:
  Dominated by long distance (hadronic) effect
- Low-recoil region (high q^2):
  Dominated by semi-leptonic operators

Angular Analysis

- The final state decay products: $\mathbf{B^+ \rightarrow K^{*+}\mu^+\mu^-}$ where $K^{*+} \rightarrow K^0_s\,\pi^+$
- Data collected with CMS detector at pp collision energy of 8TeV
- Integrated luminosity of about 20 fb^{-1}
- The decay is fully described by three angles: θ_K, θ_l and ϕ
- Integrating out ϕ, the decay rate is given by:

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_K\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}q^2}$$

$$= \frac{9}{16}\left\{\frac{2}{3}\left[F_S + 2A_S\cos\theta_K\right]\left(1-\cos^2\theta_\ell\right) + (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_\ell\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_\ell\right) + \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_\ell\right]\right\}.$$



- The aim is to measure the **longitudinal polarization of K^{*+} meson (F_L)** and the **forward-backward asymmetry of muons (A_{FB})**
- To be measured for different ranges of square of dimuon mass ($q^2 = m_{\mu\mu}^2$)

PDF in 3D Angular Fit

- The observables (**A_{FB}** and **F_L**) are obtained by the fit to the data in three dimensions [**$K^{*+}\mu^+\mu^-$ invariant mass (m)** , **$\cos\theta_K$** , **$\cos\theta_l$**]

- The total PDF is of the form

$$\begin{aligned}
&\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l) \\
&= Y_S \cdot S^m(m) \cdot S^a(\cos\theta_K, \cos\theta_l) \cdot \epsilon(\cos\theta_K, \cos\theta_l) \\
&+ Y_B \cdot B^m(m) \cdot B^{\theta_l}(\cos\theta_l) \cdot B^{\theta_K}(\cos\theta_K)
\end{aligned}$$

- Y_s, Y_B => signal and background yields

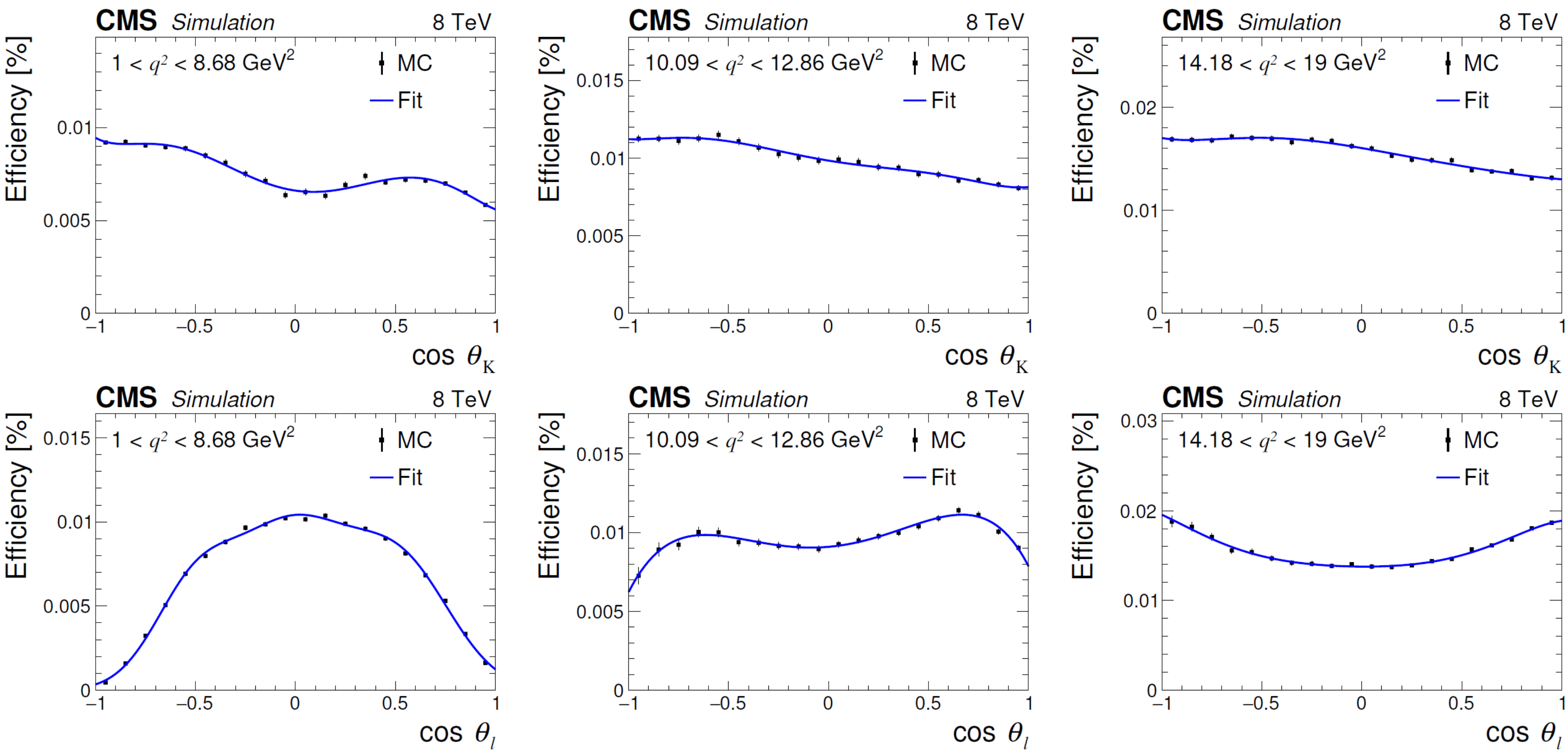
S^m => signal mass shape S^a => signal shape in ($\cos\theta_K$, $\cos\theta_l$)

ε => efficiency in two angular space

B^m => background mass shape (exponential function)

B ($\cos\theta_K$), B($\cos\theta_l$) => background shapes in corresponding angular spaces (analytic functions from sideband data)

PDF in 3D Angular Fit



Fit Projections to Data

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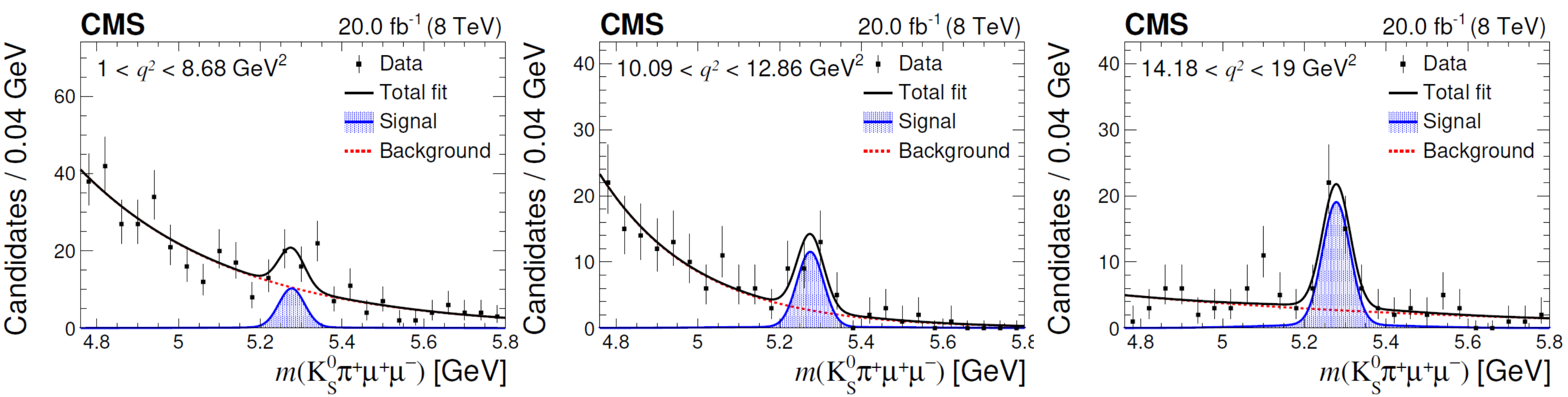
- Projections of each variables from 3D unbinned maximum likelihood fit
- Done in **q^2 ranges**: 1 - 8.68 GeV^2, 10.09 - 12.86 GeV^2, 14.18 - 19 GeV^2
- **B mass (m) fit range: [4.76, 5.8] GeV cosq$_K$, cosq$_l$: [-1.0, +1.0]**



Fit Projections to Data

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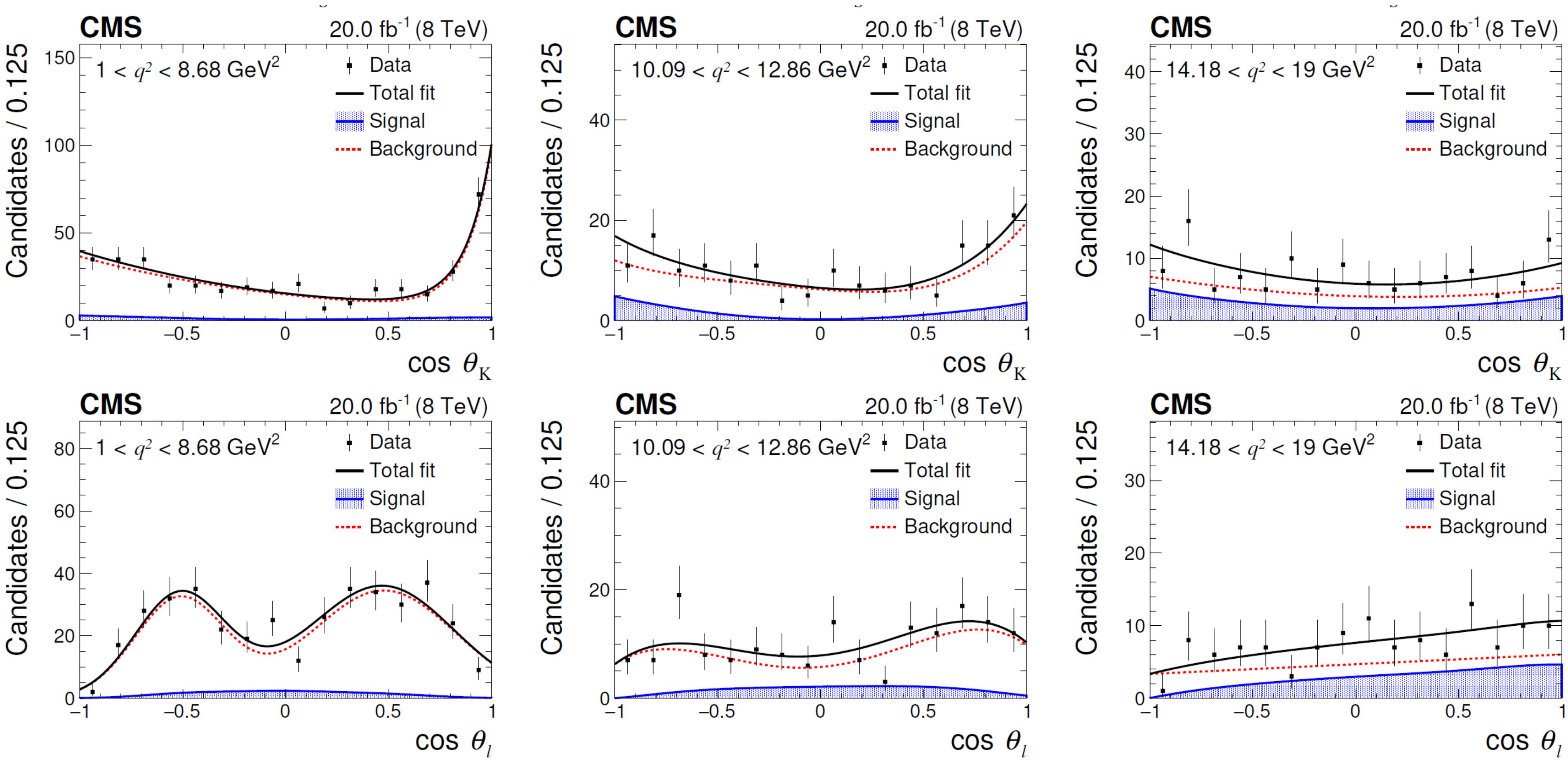
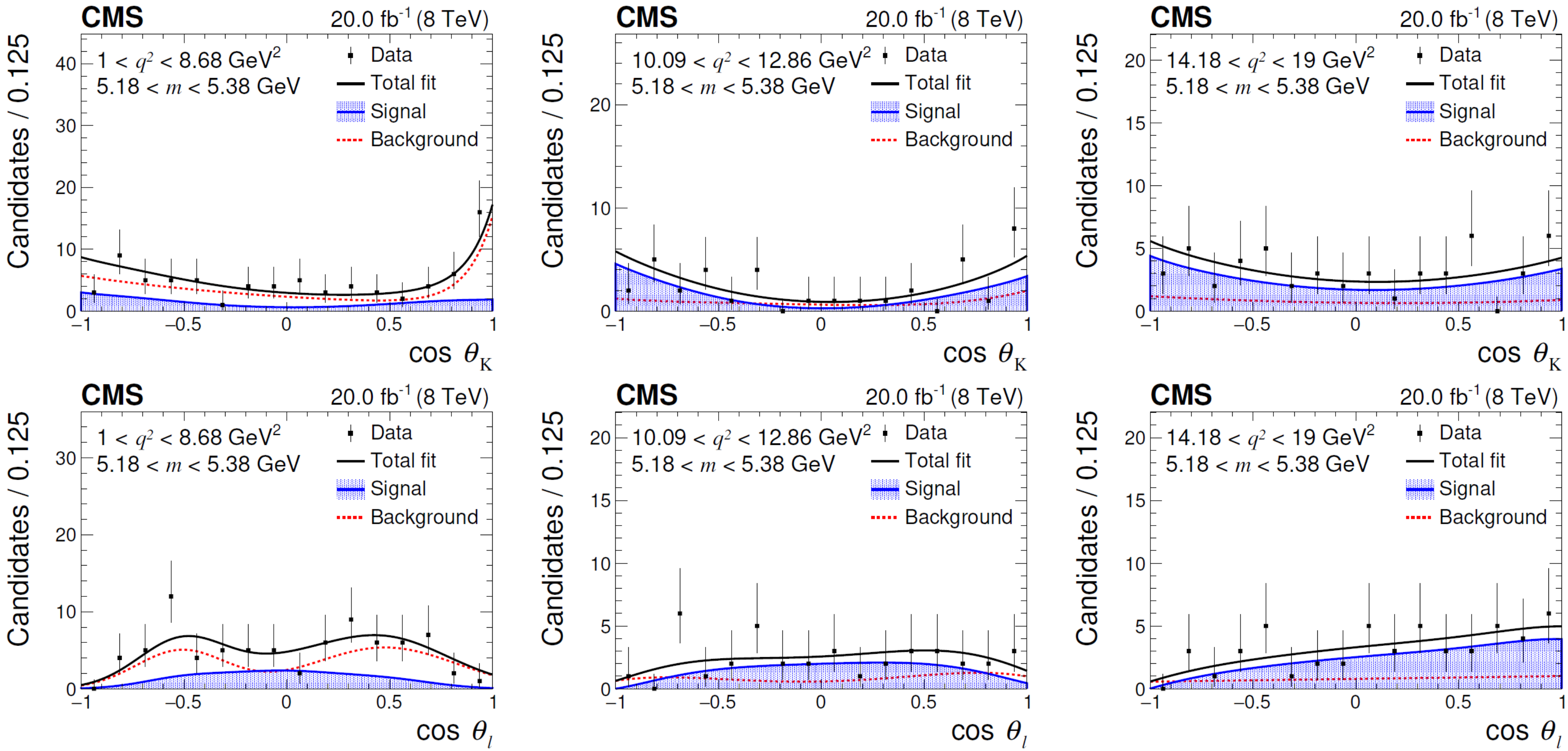
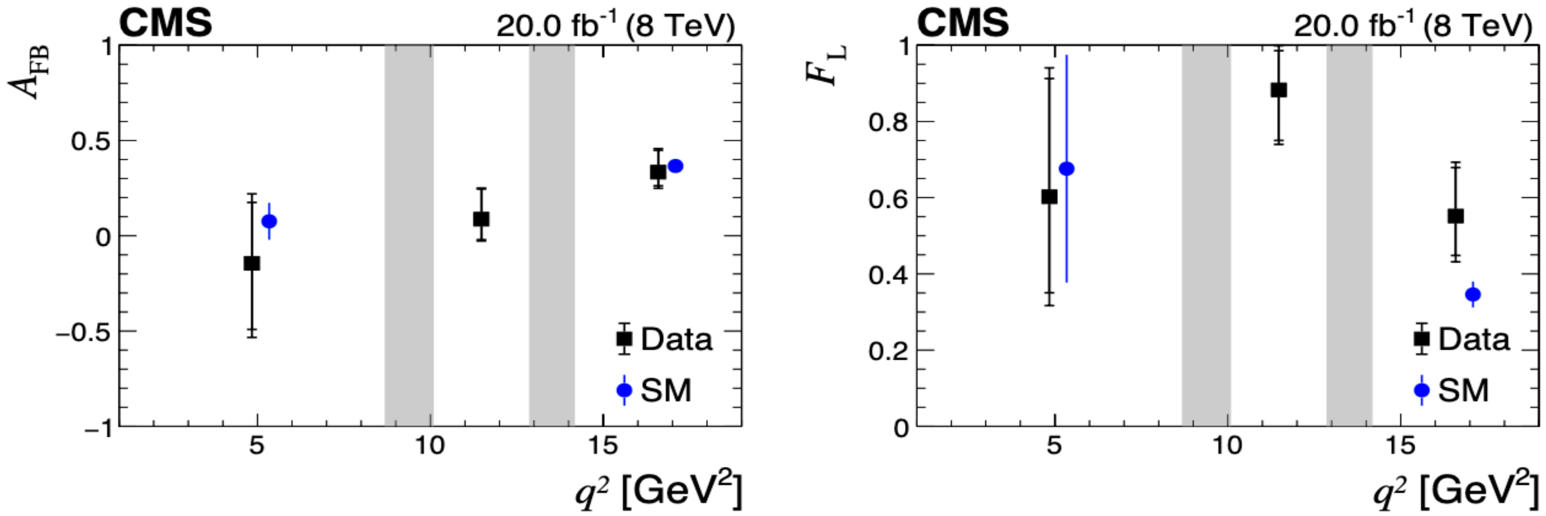


Fit Validation

- Validation of angular PDFs ($\cos\theta_K$, $\cos\theta_l$) from final fit with signal region events.
  => **B mass** (m) : **5.18 - 5.38 GeV**
- Angular distributions for events in the B mass range overlaid with final fit PDF.
- Good description of the signal and background angular PDFs in signal region





Source	A_{FB} (10^{-3})	F_L (10^{-3})
MC statistical uncertainty	12 – 29	18 – 38
Efficiency model	3 – 25	4 – 12
Background shape	34 – 170	46 – 121
S-wave contamination	4 – 22	5 – 12
Total systematic uncertainty	42 – 174	55 – 127

Dominant syst. uncertainty is from background description and effect:

(1) Background functional form
(2) Effect of alternate sideband definition
(3) Sideband statistics uncertainty

q^2 (GeV^2)	Signal yield	A_{FB}	F_L
1.00 – 8.68	22.1 ± 8.1	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09 – 12.86	25.9 ± 6.3	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18 – 19.00	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$

SM prediction uses the method described in: **JHEP** 12 (2014) 125
Result consistent with SM

$B^0_s \to \mu^+\mu^-$

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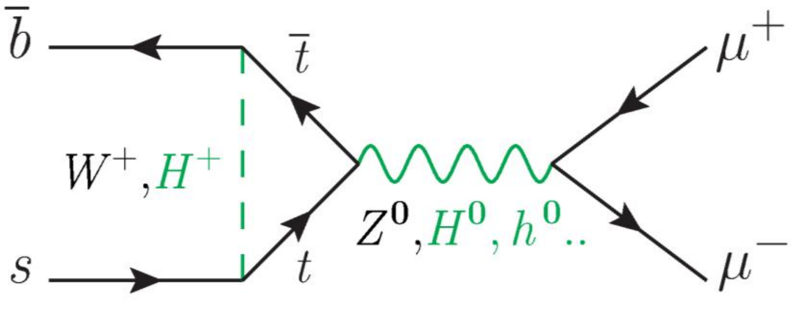
Motivation

In the standard model (SM) this decay is suppressed:



- The process is allowed via loop diagrams in SM

- The precision of the prediction of branching fractions for muonic B^0_s decays provides a good opportunity to observe deviations from the SM and contributions of new physics

- $\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \cdot 10^{-9}$
- $\mathscr{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.005) \cdot 10^{-10}$

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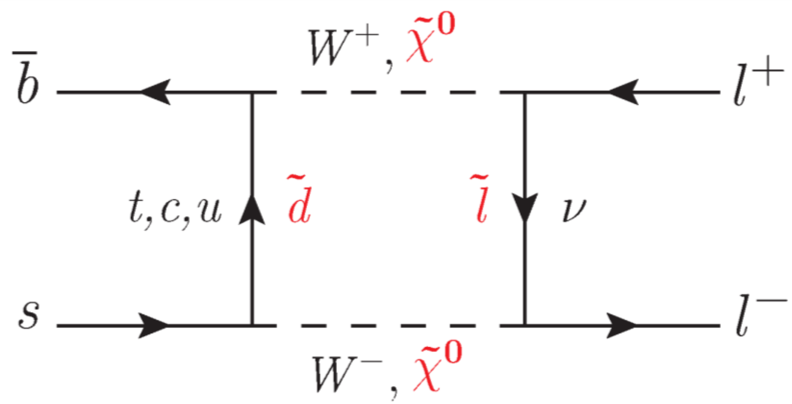

- Experimentally clean signature provides high sensitivity to new physics scenarios

- Significant deviations could arise in models involving non-SM heavy particles (Two higgs doublet Model, Minimal Flavour Violation, SUSY..)

$B^+ \rightarrow J/\psi K^+$ is used as reference channel since abundant and with a well measured branching fraction

$$\mathcal{B}(\mathrm{B}^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{N_{B^+\to J/\psi K^+}} \frac{\epsilon_{B^+\to J/\psi K^+}}{\epsilon_{d(s)}} \frac{f_u}{f_{d(s)}} [\mathcal{B}(\mathrm{B}^+ \to J/\psi \mathrm{K}^+)\mathcal{B}(J/\psi \to \mu^+\mu^-)]$$

N are the yields

ϵ the acceptance times efficiency

ratio of the hadronization probabilities of b-quarks to B^+ or $\mathrm{B}^0_{(s)}$

Selection:

- Starting from dimuon triggered data, pairs of well identified opposite charged muons are combined to form a displaced vertex;
- Additional criteria on isolation, kinematics and geometrical requirements
- Multivariate discriminators to distinguish signal from background events
- Analysis kept blind, i.e. signal mass window is concealed, while selection optimization and signal extraction procedure are defined

CMS: $m_{\mu^+\mu^-}$ in [5.200,5.450] GeV

Background Composition

Peaking background hh' decays with both hadrons misidentified as muons

- Partially reconstructed decays: one or more of the final-state particles (X) in a b-hadron decay are not reconstructed
- ✓ contribution in low dimuon mass region

- Continuum background - dominant
  - ✓ Combinatorial component: muons originated from uncorrelated hadron decay
  - ✓ from the mass sideband in data

- BDT discriminator to distinguish background form signal
  - ✓ 12 variables related to: B meson decay, muon quality and the rest of the event (isolation, number of tracks)

The control samples $\mathbf{B^+}$ yield for the normalization channel is extracted with an unbinned maximum-likelihood fit to the $\mathbf{J/\psi\ K^+}$ invariant mass distribution

Signal Extraction

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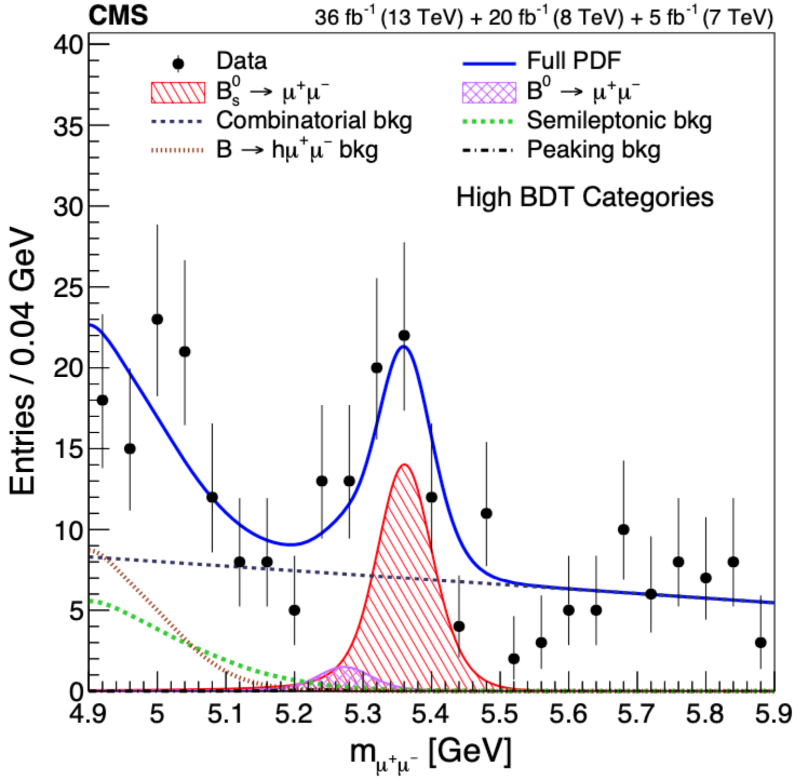
The B^0_s yield is extracted with an unbinned maximum-likelihood fit to the $\mu^+\mu^-$ invariant mass distribution

Fit includes:
- Peaking background and semileptonic decays
- Partially reconstructed decays
- Continuum combinatorial background

The dimuon candidates are classified according to the BDT output
The yield is determined from each BDT bin and data subset category (14- split by year and detector regions)
- In agreement with SM expectations
- Uncertainty is statistically dominated

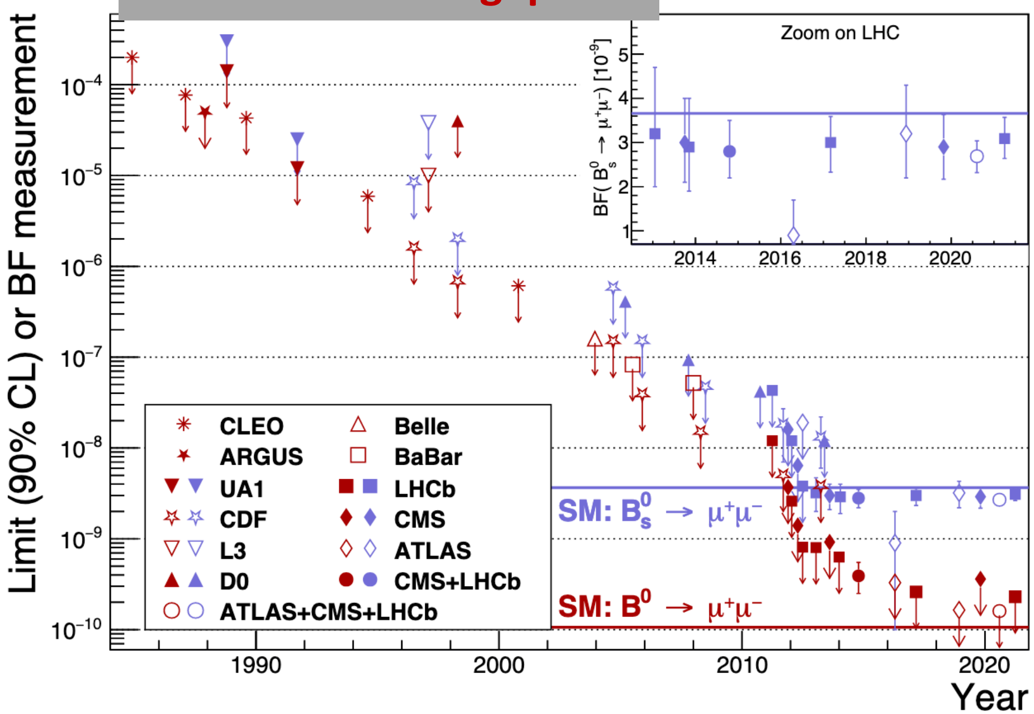


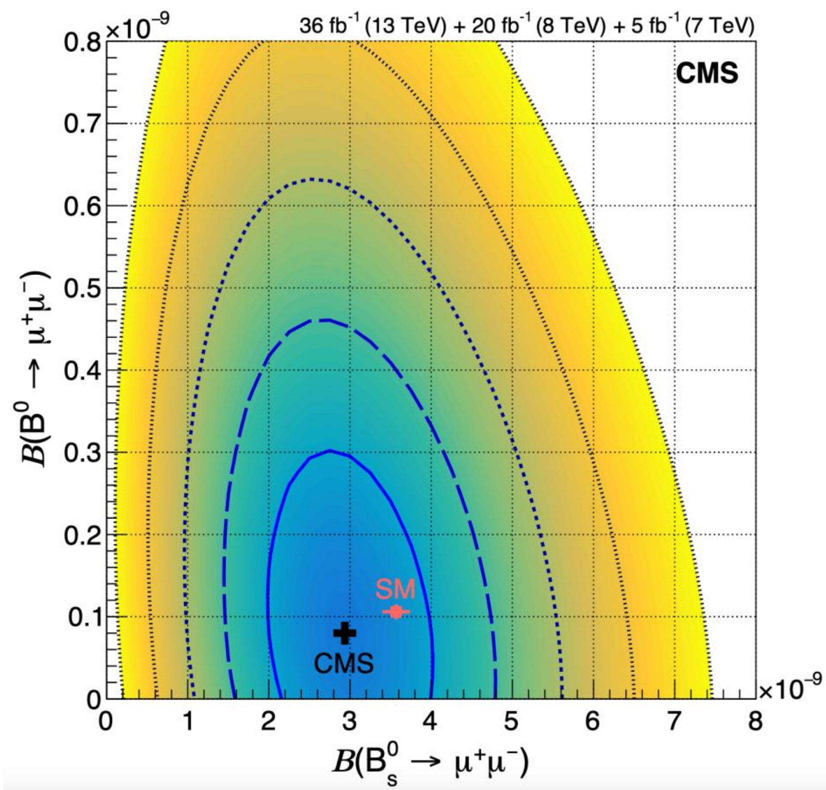
$B^0_s \to \mu^+\mu^-$ Branching Fraction

The branching fraction measured for $\mathbf{B^0_s \to \mu^+\mu^-}$ and $\mathbf{B^0 \to \mu^+\mu^-}$ are found compatible with SM

$\mathscr{B}(B^0_s \to \mu^+\mu^-)$	$[2.9^{+0.7}_{-0.6}(\text{exp}) \pm 0.2(\text{frag})] \cdot 10^{-9}$
$\mathscr{B}(B^0 \to \mu^+\mu^-)$	$(0.8^{+1.4}_{-1.3}) \cdot 10^{-10}$

Three decade long quest





A 2D unbinned maximum likelihood fit to the dimuon invariant mass and the decay time is implemented for extracting the effective lifetime, including the signal and each of the background component

$$\tau_{B^0_s \to \mu^+\mu^-} = (1.7^{+0.6}_{-0.43} \pm 0.09)$$

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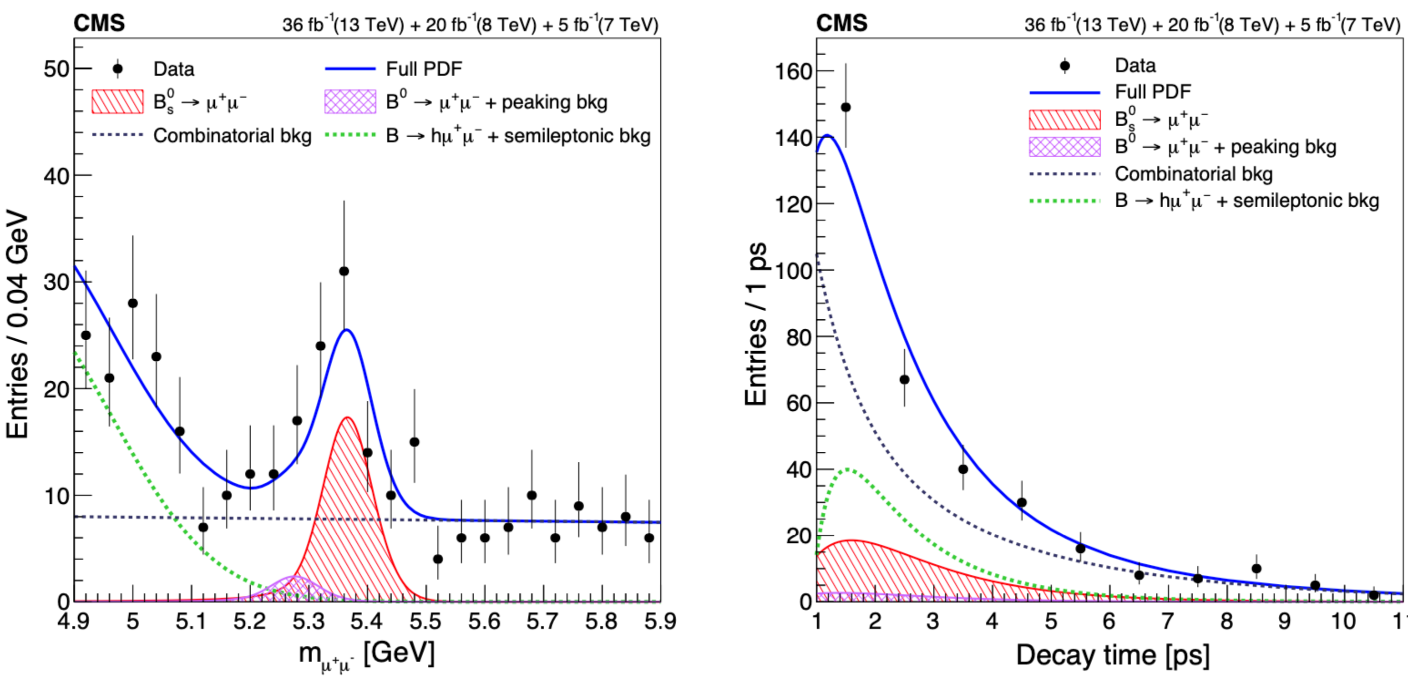

Summary

Rare quark decays play an important role in search for New Physics

Purely-leptonic and semi-leptonic B decays offer a rich lab to search for NP effects

- ❑ **CMS angular analysis of $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decay found compatible with SM**
- ✓ Some tension with SM predictions reported from LHCb in this decay mode
- ✓ Angular analysis with 13 TeV collision data at CMS will shed further light

- ❑ **A three decades long quest achieved through measurement of $B^0_s \rightarrow \mu^+\mu^-$**
- ✓ Branching fraction measured for $\mathbf{B^0_s \rightarrow \mu^+\mu^-}$ compatible with SM
- ✓ Measured lifetime from $\mathbf{B^0_s \rightarrow \mu^+\mu^-}$ is compatible with SM predictions
- ✓ More statistics needed to distinguish between the B^0_s eigen-states

No conclusive hint for New Physics and results are consistent with SM

Need more work from theory as well as experimental side in the future