OZLEM OZCELIK

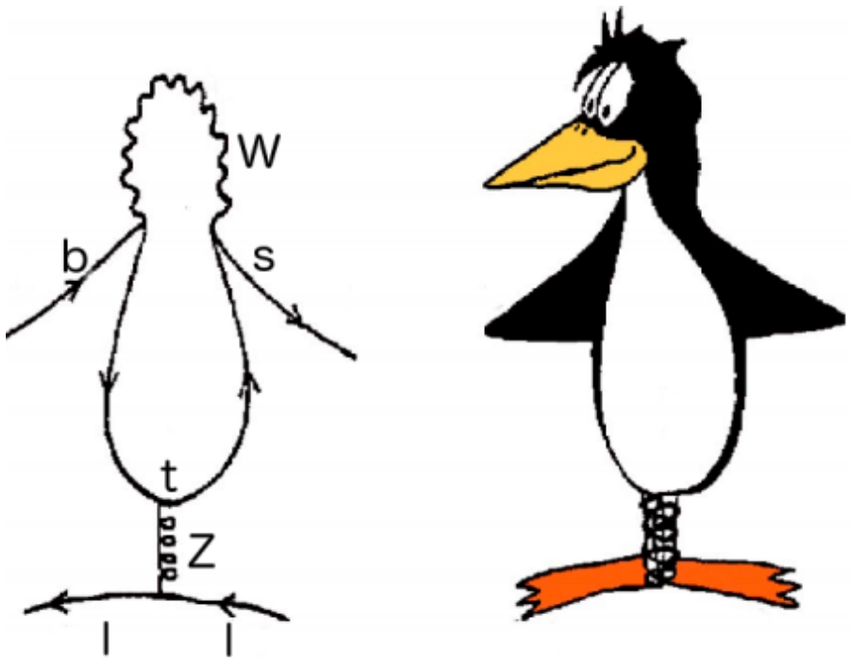
(ON BEHALF OF CMS COLLABORATION)

SEARCH FOR NEW PHYSICS WITH RARE DECAYS AT CMS

ICHEP JULY 28, 2020

$B_{s(d)} \rightarrow \mu^+\mu^-$

$\tau \rightarrow 3\mu$



PAS: CMS-PAS-BPH-16-004

Paper: JHEP 04 (2020) 188

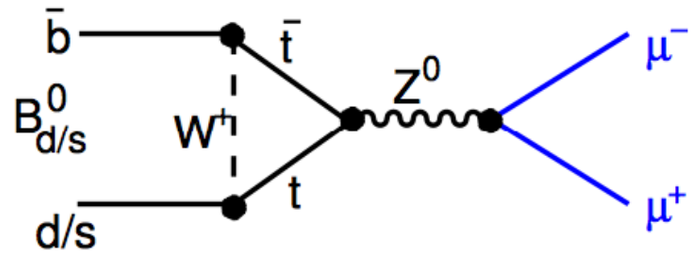
SEARCH FOR B → $\mu\mu$

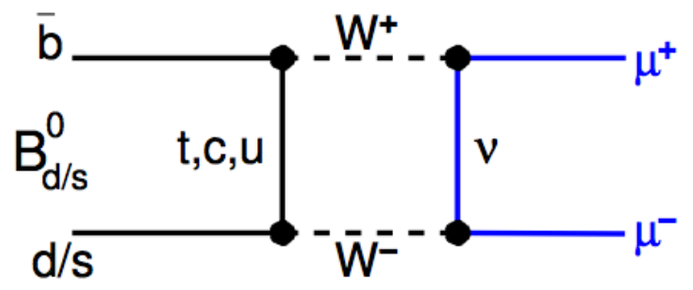
- 5 fb^{-1} of $\sqrt{s}$ = 7 TeV (2011)
- 20 fb^{-1} of $\sqrt{s}$ = 8 TeV (2012)
- 36 fb^{-1} of $\sqrt{s}$ = 13 TeV (2016)

- Analysis is performed in central and forward regions of the detector for all running periods

Introduction

- $B \rightarrow \mu^+\mu^-$ decays are sensitive probes to search **physics beyond the SM**.
  - effective FCNC: only Z penguin & box diagrams
  - suppressed in SM





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

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

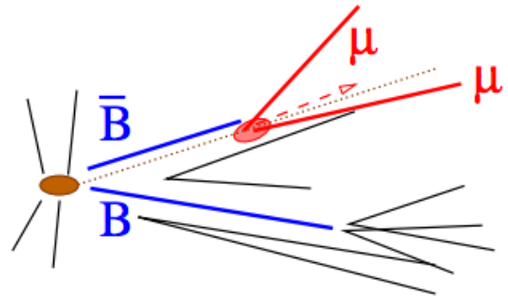
Beneke et al., JHEP 10 (2019) 232

- Two observables to measure :
  - **Branching fractions** : can be enhanced by effects beyond SM.
  - **Effective lifetime** : In **SM,** only the heavy mass eigenstate of B_s decays to dimuons.
    - ➡ $\tau_{\mu^+\mu^-} = 1.615$ ps in SM but may have different contributions from NP effects.

Phys. Rev. D **98**, 030001

Analysis Aspects

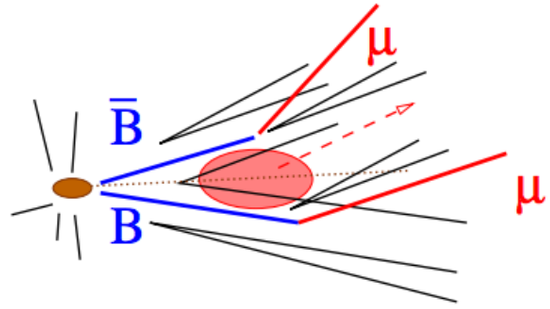
- Signal $B_{s,d} \to \mu^+\mu^-$
  - Two muons fit to a displaced vertex.



- Background
  - Combinatorial (from sidebands)

    Two (uncorrelated) semileptonic B decays.

    one semileptonic B decay + a misidentified hadron



  - Rare single B decays

    e.g., **B→hμυ** non-peaking;

    B→Kπ/KK peaking ;

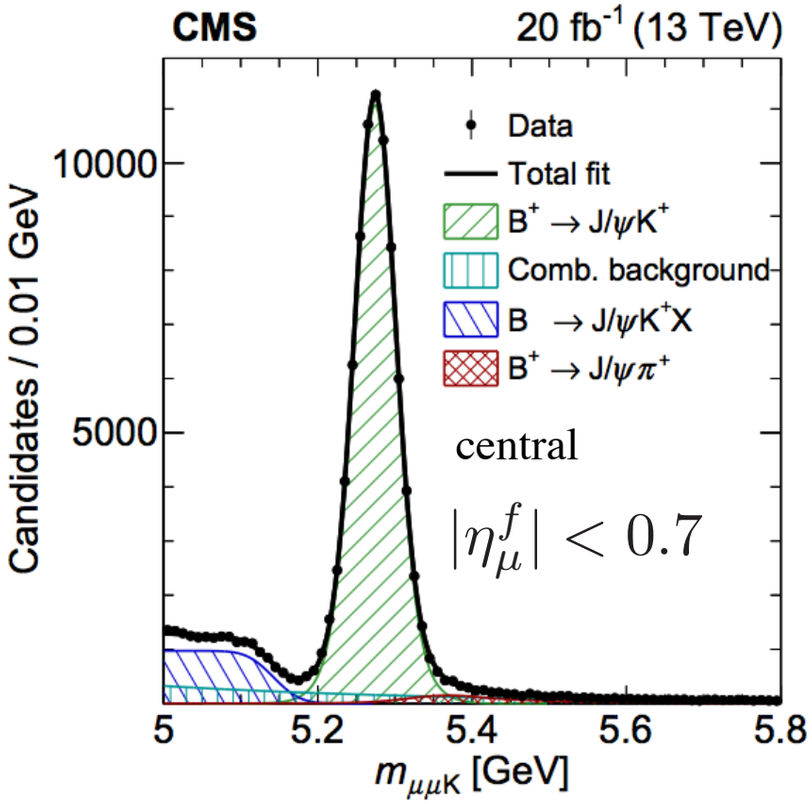
    ◉ $B(B^+ \to J/\psi K^+) = (1.01 \pm 0.03) \times 10^{-3}$

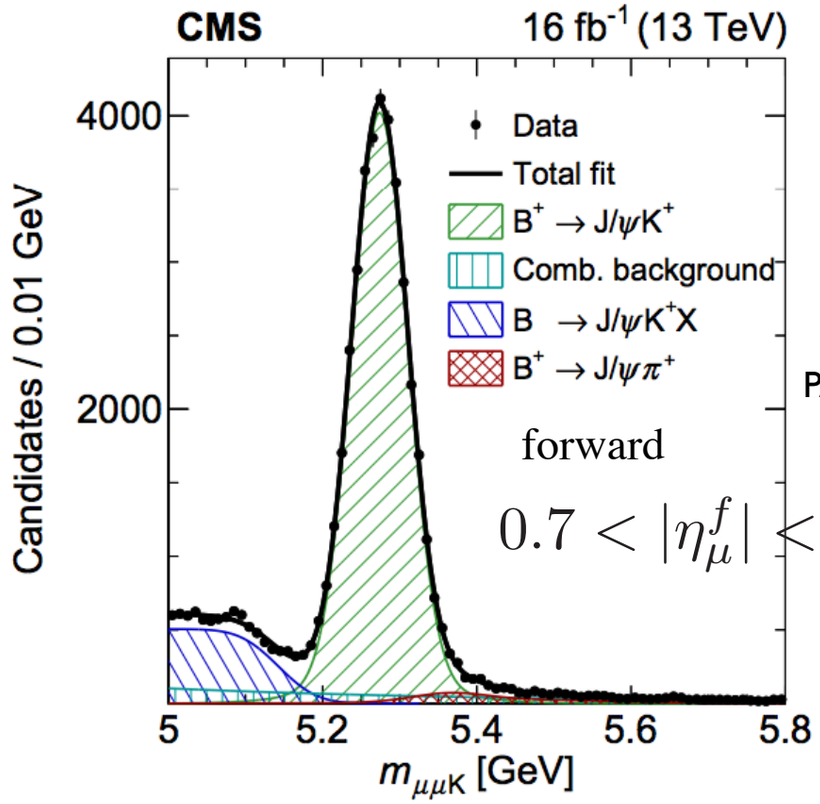
$$\mathcal{B}(B_s \to \mu^+\mu^-) = \frac{N_S}{N(B^\pm \to J/\psi K^\pm)} \times \mathcal{B}(B^\pm \to J/\psi K^\pm) \times \frac{\varepsilon^{tot}(B^\pm)}{\varepsilon^{tot}(B_s)} \times \frac{f_u}{f_s}$$

- Blind analysis, validations with $B_s \to J/\psi\phi$
- BDT training (MVA)
  - signal: **simulated signal events**
  - background**:** **data sidebands**.

Yield Extraction of $B^+ \rightarrow J/\psi K^+$

- Binned ML fit to $J/\psi K^+$ invariant mass distribution
  - Signal: Double Gaussians with common mean
  - Background of $B^+ \rightarrow J/\psi\, K^+$:
    - combinatorial: exponential
    - partially reconstructed: error function
    - $B^+ \rightarrow J/\psi\, \pi^+$: double-Gaussian, constrained to 4% of signal yield
- The total $B^+ \rightarrow J/\psi K^+$ yield is $1.43 \pm 0.06 \times 10^6$

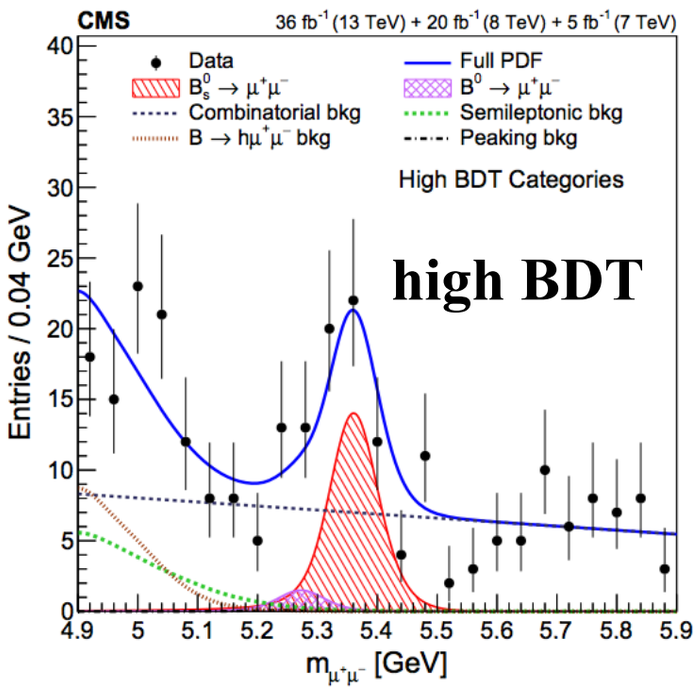


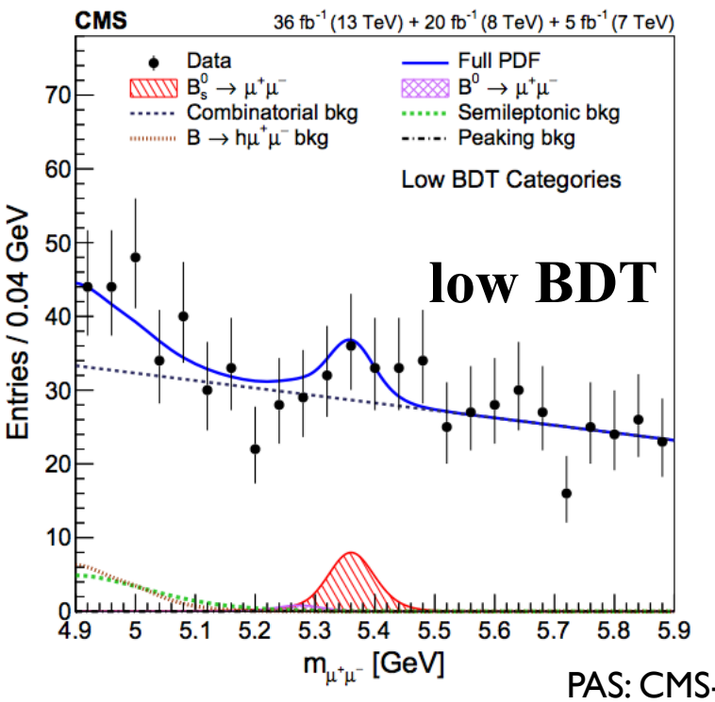


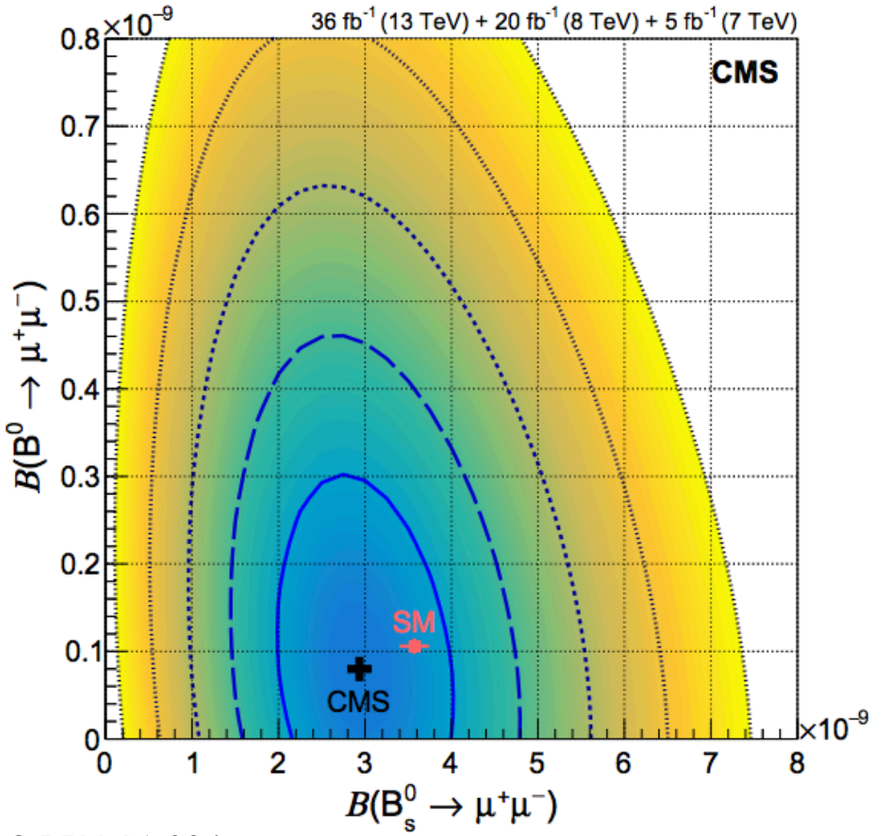
PAS: CMS-PAS-BPH-16-004

Results: Branching Fractions

Combined mass projections for low/high BDT categories *







PAS: CMS-PAS-BPH-16-004

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

observed (expected) significance 5.6σ (6.5σ)

dominated by statistical uncertainties

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

Consistent with SM!

*see backup slide for the categorization

Results: Effective Lifetime

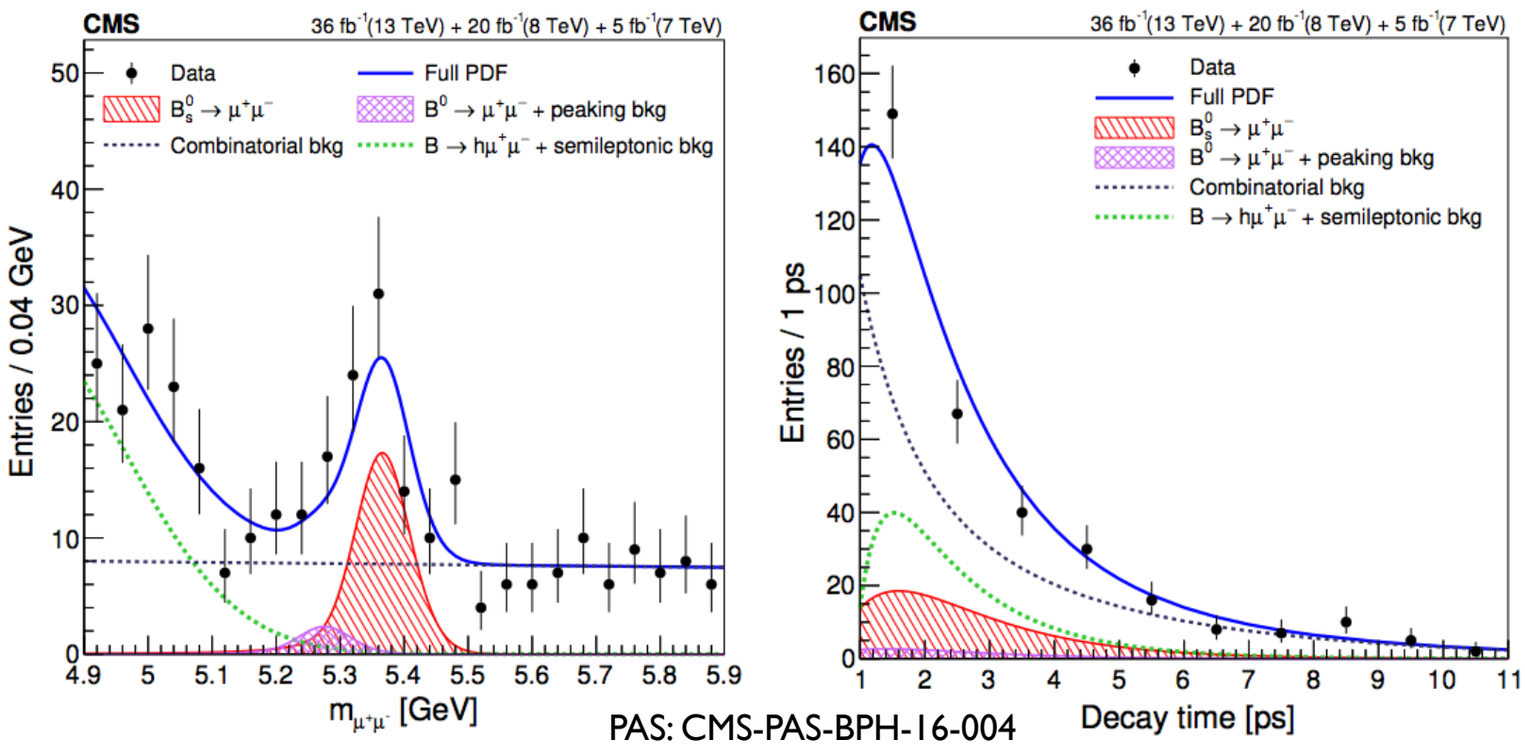
- 2D unbinned extended maximum likelihood fit
  - dimuon invariant mass $m_{\mu^+\mu^-}$ and decay time t (1<t<11 ps)
- The combined mass and proper decay time distributions from all channels

$$\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44}\,\text{ps}$$

➡ **Consistent with SM!**

Systematic uncertainty : 0.09ps

- SM prediction* is $\tau_{\mu^+\mu^-} = 1.615 \pm 0.009$ ps



PAS: CMS-PAS-BPH-16-004

* Phys. Rev. D **98**, 030001

Image: Symmetry magazine

PAS: CMS-PAS-BPH-17-004

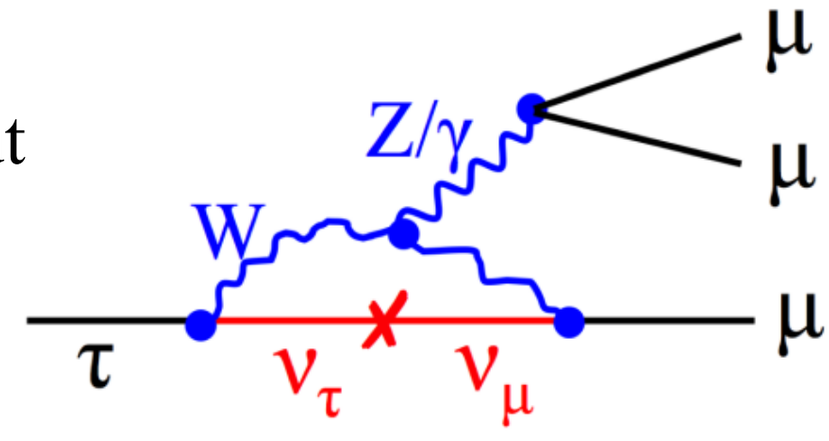
arXiv:2007.05658

SEARCH FOR $\tau \to 3\mu$

- Combination of two sources:
  - W channel
  - Heavy-flavor channel.
- 33 fb^{-1} of $\sqrt{s}$ = 13 TeV (2016)

Introduction

- A charged lepton flavor violation (cLFV) decay $\tau \to 3\mu$ can be induced by neutrino oscillations, but extraordinarily small BFs. (Eur. Phys. J. C 8 (1999) 513)



- The rate can be strongly enhanced by the **new physics scenarios**. (Phys. Rev. D 73 (2006) 055003)

- Searches performed by many experiments LHCb (heavy-flavor decays) & ATLAS (W decays). The best limit set by Belle:

  $\mathcal{B}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% CL.

  (Phys. Lett. B 687 (2010) 139)

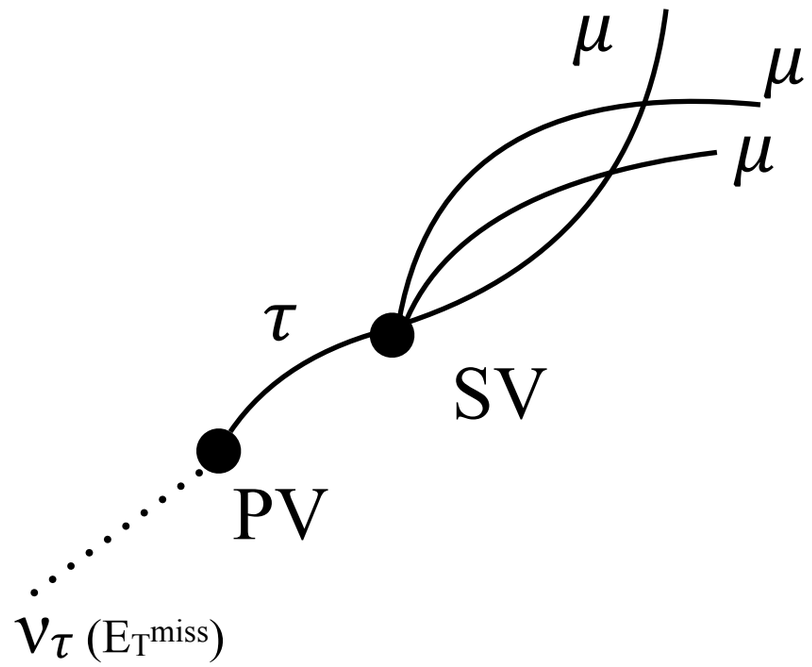
- CMS provides the **first** search for the LFV decay from a combination of two independent channels (from W decays and heavy-flavor decays)!

Analysis Strategy: W Channel

- The search of the $\tau \to 3\mu$ from $W \to \tau\nu$ decays - tau-neutrino is the large transverse missing energy (E_T^{miss}).
- Three muons are fit to a common vertex to make a τ candidate.
- Master formula:

$$\mathcal{B}(\tau \to 3\mu) = \frac{N_{sig}}{\mathcal{L}\sigma(pp \to W+X)\mathcal{B}(W \to \tau\nu)\mathcal{A}_{3\mu}\epsilon_{3\mu}}$$

$A_{3\mu}$ is the acceptance, $\epsilon_{3\mu}$ the combined reconstruction, selection, and trigger efficiency.

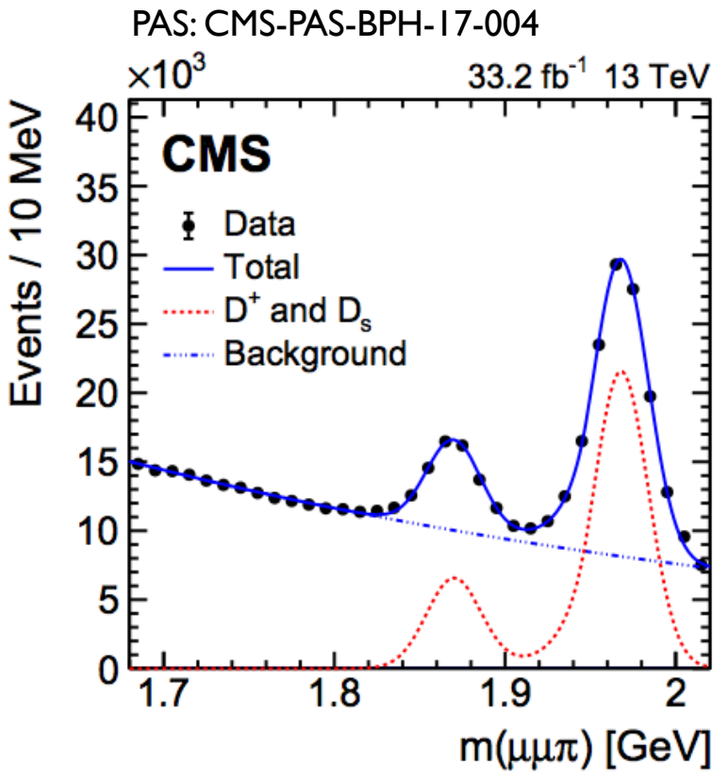


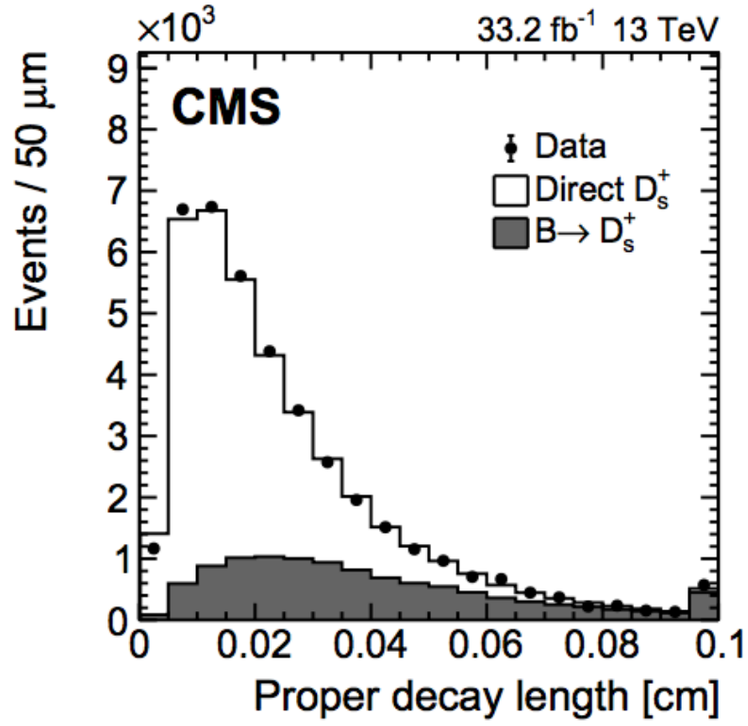
- BDT to reduce the backgrounds: **simulated signal events** and **data sideband**.
- Event categorization based on mass resolution: **two categories**, barrel (trimuon $|\eta| < 1.6$) and endcap ($|\eta| \geq 1.6$)

Analysis Strategy: Heavy Flavor

- The search of the $\tau \to 3\mu$ from B and D meson decays. Three major sources of τ leptons:
  - prompt D meson decays: 65%
  - directly from B meson decays: 25%
  - non-prompt D meson decays (from B): 10%
- Trigger two muons plus a track, with vertex and mass requirement.
- **Normalization channel $D_s \to \phi\pi \to \mu\mu\pi$** : for branching fraction measurement.
- The fraction of (non-)prompt D_s from a fit to the proper decay length distribution.
- Events are categorized based on
  - **trimuon mass resolution :** Divided into 3 bins: <0.7%, 0.7–1%, >1% (**A, B, C**)
  - **BDT score :** 2 bins (“**1**” and “**2**”).

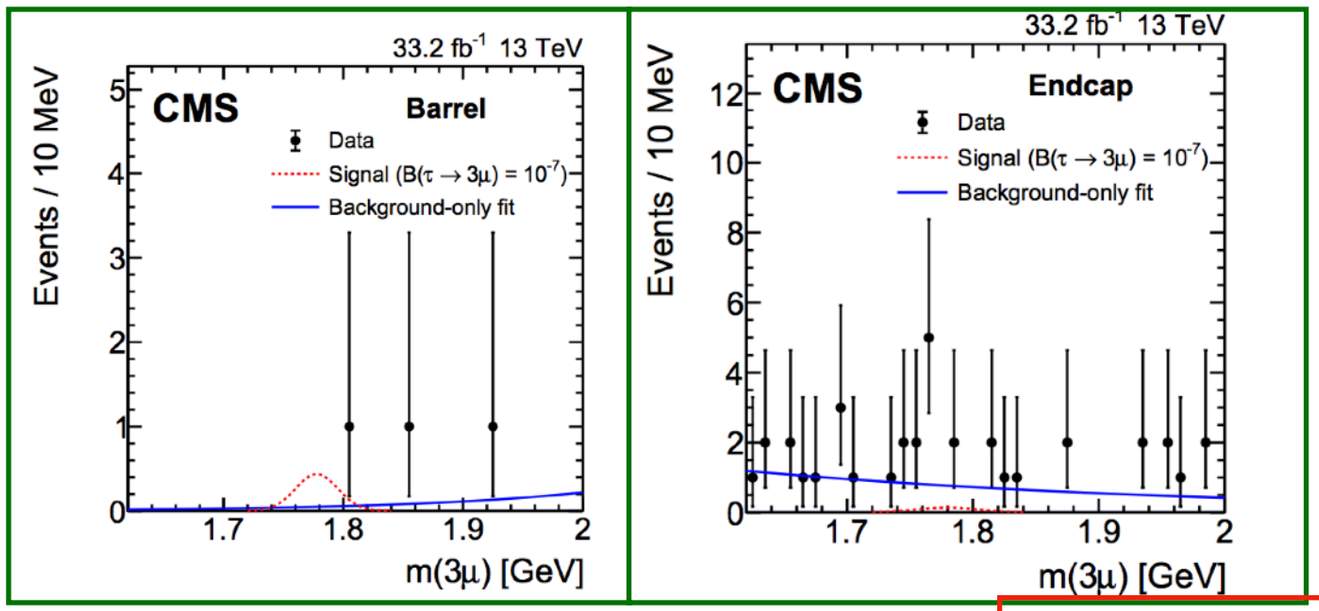
➡ **six categories in total!**



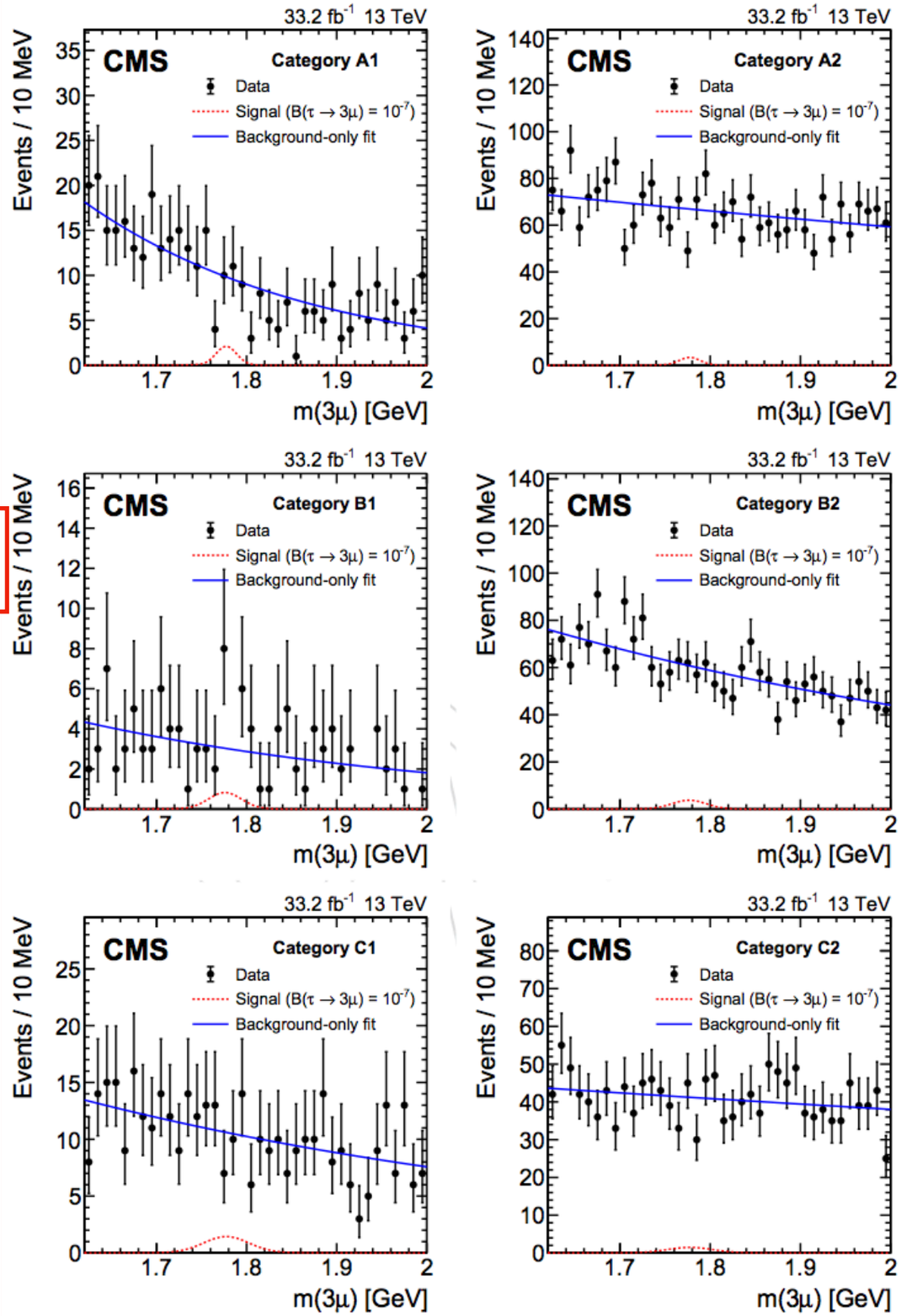


Results

arXiv:2007.05658



expected signal if $\mathcal{B}(\tau \to 3\mu) = 10^{-7}$



- Simultaneous ML fit to trimuon invariant mass
  - **two categories** of the W boson analysis
  - **six categories** of the heavy-flavor analysis
- **No signal is found**, observed (expected) upper limit on branching fraction :

$$\mathcal{B}(\tau \to 3\mu) < 8.0\ (6.9) \times 10^{-8}\ (@\ 90\%\ \mathrm{CL})$$

- Individual results:
  - W channel: $\mathcal{B}(\tau \to 3\mu) < 2.0 \times 10^{-7}$ @ 90% CL
  - HF channel: $\mathcal{B}(\tau \to 3\mu) < 9.2 \times 10^{-8}$ @ 90% CL

Summary

- The rare $B_s \rightarrow \mu^+\mu^-$ decay is observed with a significance of 5.6 standard deviations.

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

- The measurement of $B_s \rightarrow \mu^+\mu^-$ **effective lifetime** is performed **for the first time** at CMS.

$\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44}\text{ps}$

- No significant $B^0 \rightarrow \mu^+\mu^-$ signal is observed and an upper limit is determined.

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

- **The first search** of LFV decay $\tau \rightarrow 3\mu$ from a combination of W and heavy flavor channels is conducted at CMS.

arXiv:2007.05658

$\mathcal{B}(\tau \rightarrow 3\mu) < 8.0\ (6.9) \times 10^{-8}$ (@ 90% CL)

More results are on the way!

- **See backup slides for a quick comparison of the CMS results with other experiments.**

BACKUP

Event Categorization

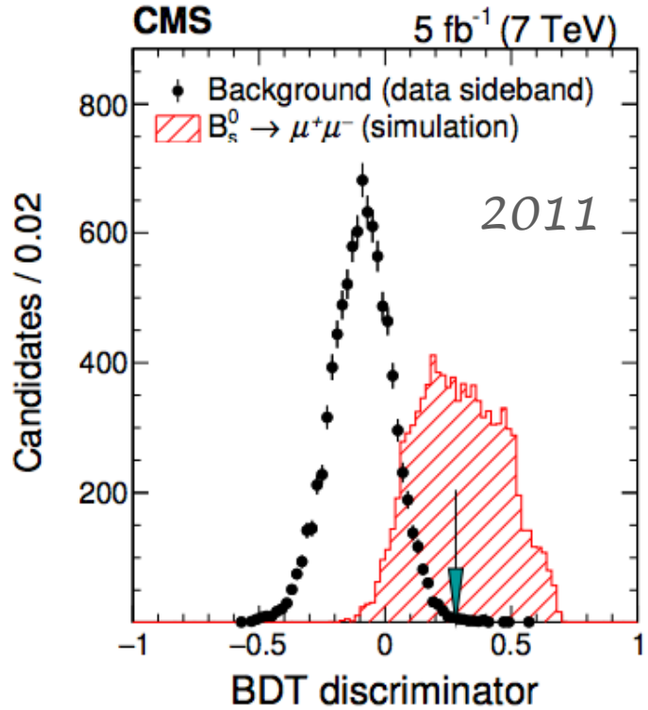
- Events are further divided into exclusive categories as high- and low-BDT categories in the ranges of the BDT discriminator distributions.
- Categorization optimized by maximizing the expected sensitivity
  - The **best significance** for branching fraction measurement
  - The **smallest uncertainty** for lifetime analysis.

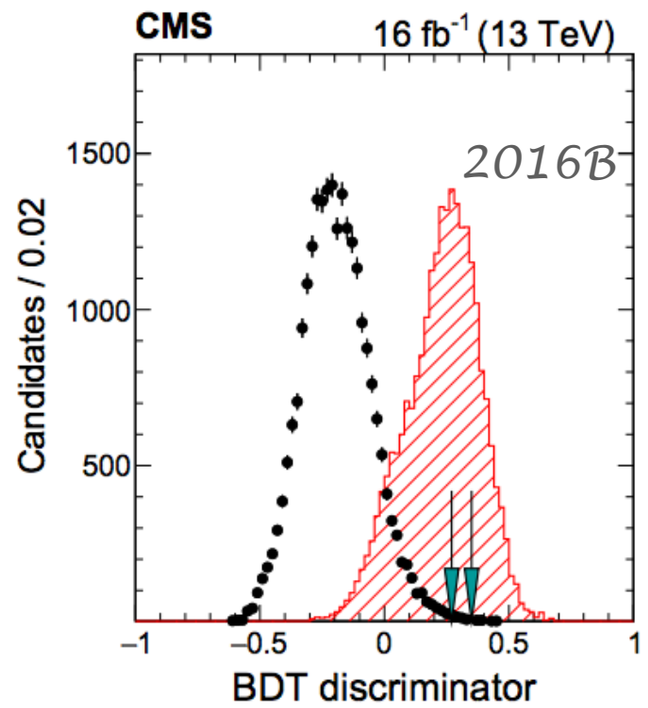
➡ 14 categories for branching fraction measurements

➡ 8 categories for effective lifetime measurements

	branching fraction measurement		effective lifetime measurement	
	central	forward	central	forward
2011	{0.28, 1}	{0.21, 1}	{0.22, 1}	{0.19, 1}
2012	{0.27, 0.35, 1}	{0.23, 0.32, 1}	{0.32, 1}	{0.32, 1}
* 2016A	{0.19, 0.30, 1}	{0.19, 0.30, 1}	{0.22, 1}	{0.30, 1}
* 2016B	{0.18, 0.31, 1}	{0.23, 0.38, 1}	{0.22, 1}	{0.29, 1}

PAS: CMS-PAS-BPH-16-004





Arrows to illustrate the BDT boundaries

*2016 data are divided into two periods **2016A** and **2016B** due to operational instabilities

f_s/f_u

- The ratio of the fragmentation fractions is **an external input** in the BR and the experimental status is **unclear**.
  - LHCb sees pT dependence (ref. PRD 100, 031102).
  - ATLAS (ref. PRL 115, 262001) and CMS do NOT (internal study, not get published).
- In this analysis a different method is used :
  - Take the pt independent value of PDG (*average of LHCb +ATLAS results for 7 TeV)* $f_s/f_u = 0.252 \pm 0.012$
  - additional ad-hoc error estimated from LHCb 13 TeV pT-dependent results

➡ **$f_s/f_u = 0.252 \pm 0.012$ (PDG)**
± 0.015 (pT-dependence)

Comparison among LHC

	CMS(61 fb^{-1})	ATLAS (51.3 fb^{-1})	LHCb (4.4 fb^{-1})
$\mathcal{B}(B_s \to \mu^+\mu^-)$	[2.9 ± 0.7(exp) ± 0.2(frag)]x10^{-9}	$2.8^{+0.8}_{-0.7} \times 10^{-9}$	$[3.0 \pm 0.6^{+0.3}_{-0.2}] \times 10^{-9}$
$\mathcal{B}(B^0 \to \mu^+\mu^-)$ (UL@95% CL)	3.6×10^{-10}	2.1x10^{-10}	3.4×10^{-10}
$\tau_{\mu+\mu-}$	$1.70^{+0.61}_{-0.44}$ps	-	2.04 ± 0.44 ± 0.05ps

CMS: JHEP 04 (2020) 188
ATLAS: JHEP 04 (2019) 098
LHCb: Phys. Rev. Lett. 118 (2017), 191801

	CMS(33 fb^{-1})	ATLAS (20.3 fb^{-1})	LHCb (3.0 fb^{-1})
$\mathcal{B}(\tau \to 3\mu)$ (UL@90CL)	8.0×10^{-8}	3.76×10^{-7}	4.6×10^{-8}

CMS: arXiv:2007.05658
ATLAS: Eur. Phys. J. C 76 (2016) 232
LHCb: JHEP 02 (2015) 121