19th International Conference on B-Physics at Frontier Machines, BEAUTY 2020

Study of rare b and τ decays

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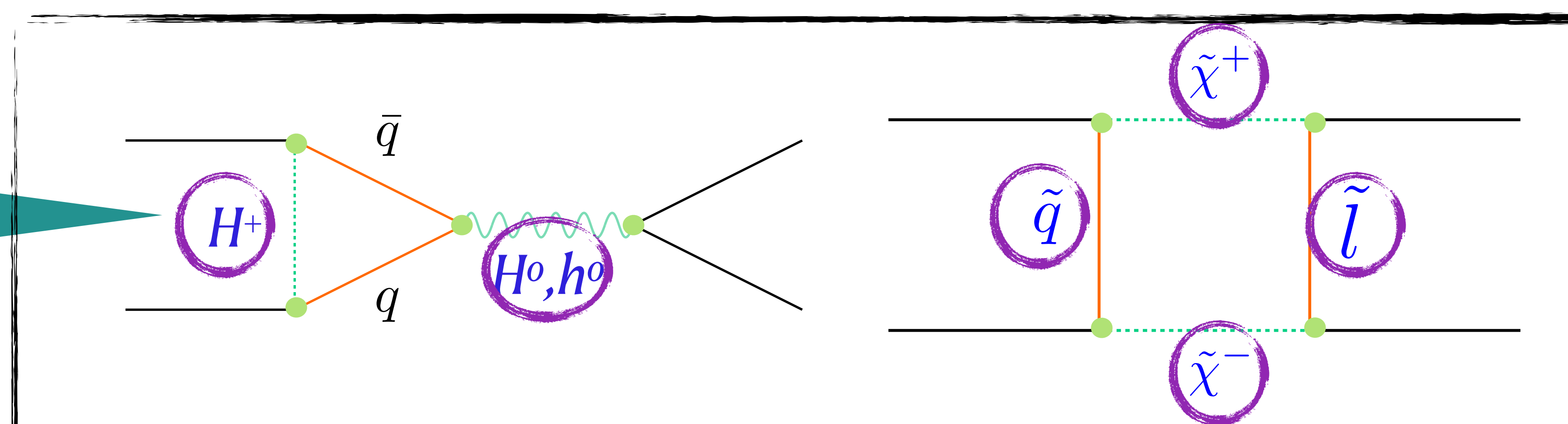
22nd Sept. 2020 - Virtual conference session

Why look for rare decays?

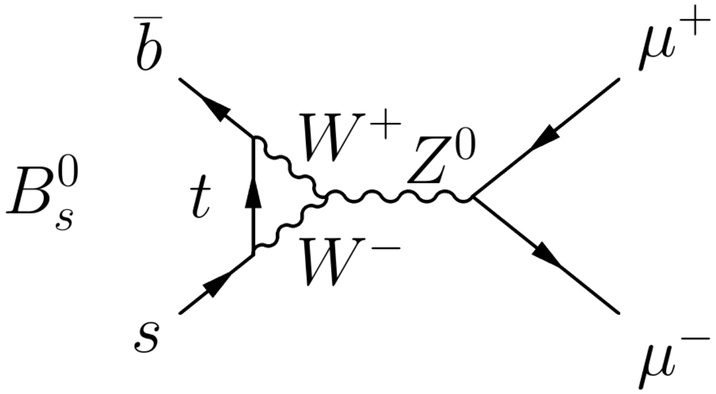
- ✓ Small Standard Model(SM) branching fraction and potential large new physics(NP) contributions
- ✓ Often Flavour Changing Neutral Current(FCNC), which are not possible at tree level in SM
- ✓ Sensitive to higher energy than direct searches due to virtual contributions
- ✓ NP can change rates or properties
- ✓ SM forbidden decays → hint for new physics

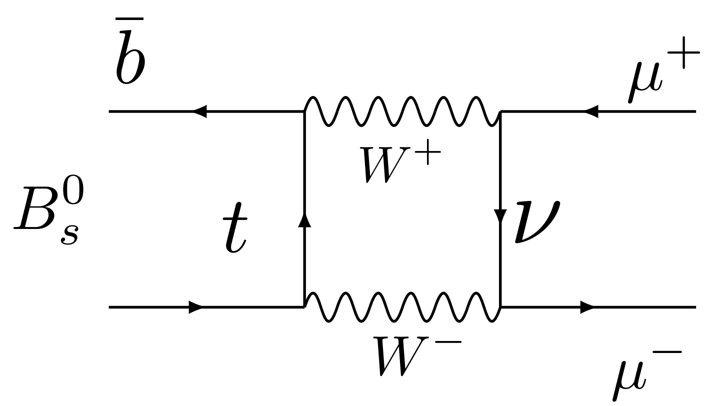
Indirect searches
to look for new particles !



Measurement of $B^0_{(s)} \to \mu^+\mu^-$

- ✓ $B \to \mu\mu$ is the flagship of rare b decays.
- ✓ $B \to \mu\mu$ are heavily suppressed in SM:
  - FCNC processes, only proceed through EW penguin, box diagrams(suppressed by $[m_W/m_t]^2$).
  - Cabibbo suppressed: $|V_{tq}|^2$
  - Helicity suppressed: $[m_\mu/m_B]^2$



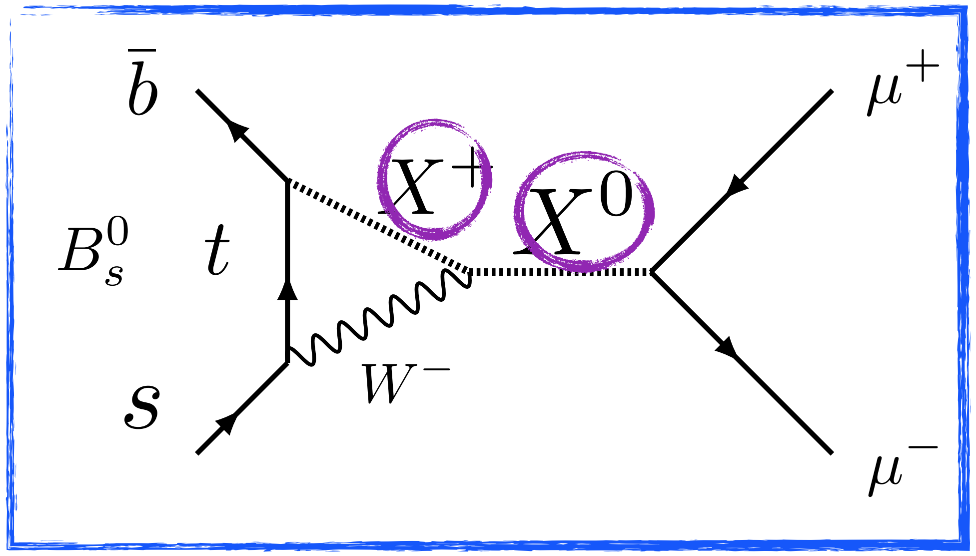


- ✓ SM predictions:
  - SM branching fractions are small
  - theoretical uncertainty: 4-5 %

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Ref:
M. Beneke et al JHEP 10 (2019)232

Measurement of $B^0_{(s)} \to \mu^+\mu^-$



- ✓ New particles in loops
- ✓ Sensitive to (pseudo)scalars : no helicity suppression
- ✓ Some of the new physics scenarios may boost the decay rates
  - 2HDM: $\mathcal{B} \propto tan^4\beta$, *M(H+)*
  - MSSM: $\mathcal{B} \propto tan^6\beta$
- ✓ What we measure:
  - Branching fractions: Precision measurement of $B^0_s \to \mu^+\mu^-$ and look for first evidence of $B^0 \to \mu^+\mu^-$
  - Effective lifetime: the heavier of two B^0_s mass eigenstates can decay to dimuon in SM; NP scenario may alter the prediction

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\Gamma(B_s(t) \to \mu^+\mu^-)dt}{\int_0^\infty \Gamma(B_s(t) \to \mu^+\mu^-)dt} = \frac{\tau_{B^0_s}}{(1-y_s^2)}\left(\frac{1+2\mathcal{A}^{\mu^+\mu^-}_{\Delta\Gamma}y_s + y_s^2}{1+\mathcal{A}^{\mu^+\mu^-}_{\Delta\Gamma}}\right)$$

$$\mathcal{A}^{\mu^+\mu^-}_{\Delta\Gamma} \equiv -\mathcal{R}(\lambda)/(1+|\lambda|^2)$$

$$y_s \equiv \tau_{B^0_s}\Delta\Gamma_s/2$$

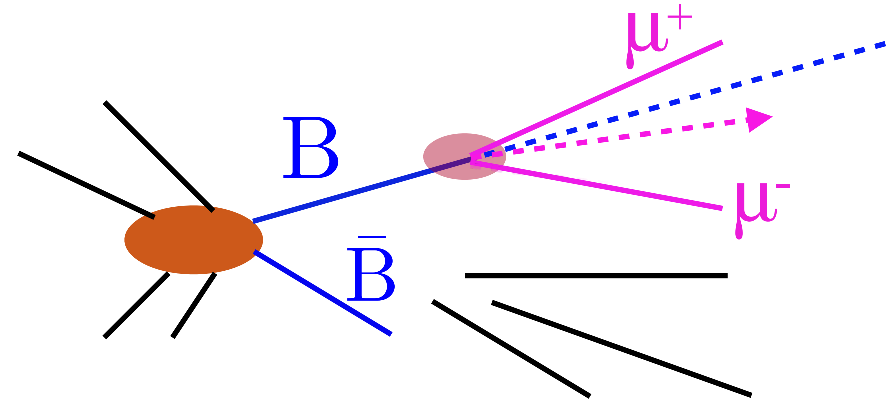
SM → $\mathcal{A}^{\mu^+\mu^-}_{\Delta\Gamma} = +1 \to \tau_{B_s\to\mu^+\mu^-} = (1.609 \pm 0.010)$ ps

Ref: HFLAV, Y.Amhis et al., Eur.Phys.J.C 77(2017)895

Analysis aspects

✓ Signal $B^0_{(s)} \to \mu\mu$:

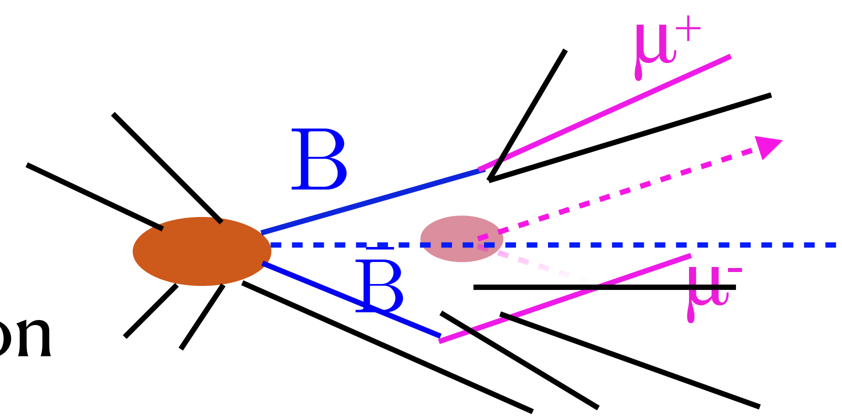
- two muons from same displaced vertex
- mass around $m(B^0_{(s)})$
- momentum aligned with flight direction

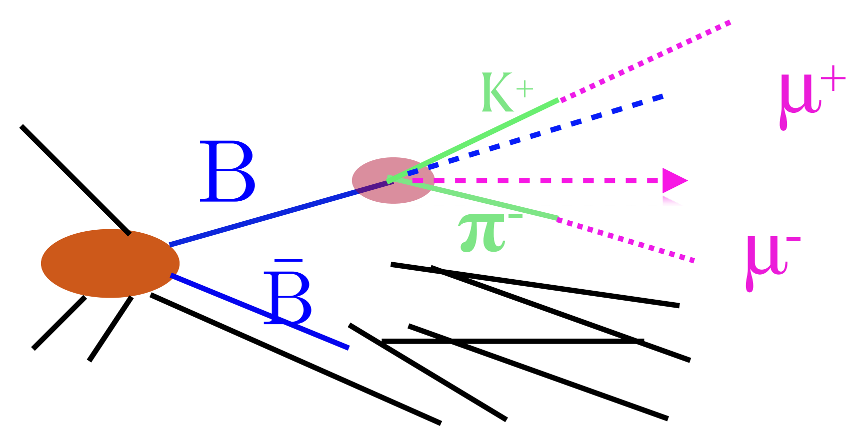


✓ Background:

- two semileptonic B decays
- one semileptonic B and one misidentified hadron
- rare background from single B meson decays:
  - peaking $B \to KK/K\pi$,
  - non peaking $B^0_s \to K^+\mu^-\nu$, $\Lambda_b \to p^+\mu^-\nu$

Flat shape





✓ The goal: high signal efficiency, strong background rejection !

Methodology

✓ Measurement of $B^0_s \to \mu^+\mu^-$ relative to normalization channel ($B^+ \to J/\psi(\mu^+\mu^-)K^+$):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{n^{\text{obs}}_{B_s^0}}{N(B^+ \to J/\psi\, K^+)} \frac{A_{B^+}}{A_{B_s^0}} \frac{\varepsilon^{ana}_{B^+}}{\varepsilon^{ana}_{B_s^0}} \frac{\varepsilon^{\mu}_{B^+}}{\varepsilon^{\mu}_{B_s^0}} \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B_s^0}} \frac{f_u}{f_s} \mathcal{B}(B^+ \to J/\psi\,[\mu^+\mu^-]K)$$

- Acceptance efficiency → $A_{B^+}/A_{B_s^0}$
- Selection efficiency → $\varepsilon^{ana}_{B^+}/\varepsilon^{ana}_{B_s^0}$
- Muon identification efficiency → $\varepsilon^{\mu}_{B^+}/\varepsilon^{\mu}_{B_s^0}$
- Trigger efficiency → $\varepsilon^{trig}_{B^+}/\varepsilon^{trig}_{B_s^0}$
- B-hadronization composition, for B_s only (PDG average : $f_s/f_u = 0.252 \pm 0.012$) → f_u/f_s

Similar trigger and selection to reduce systematics

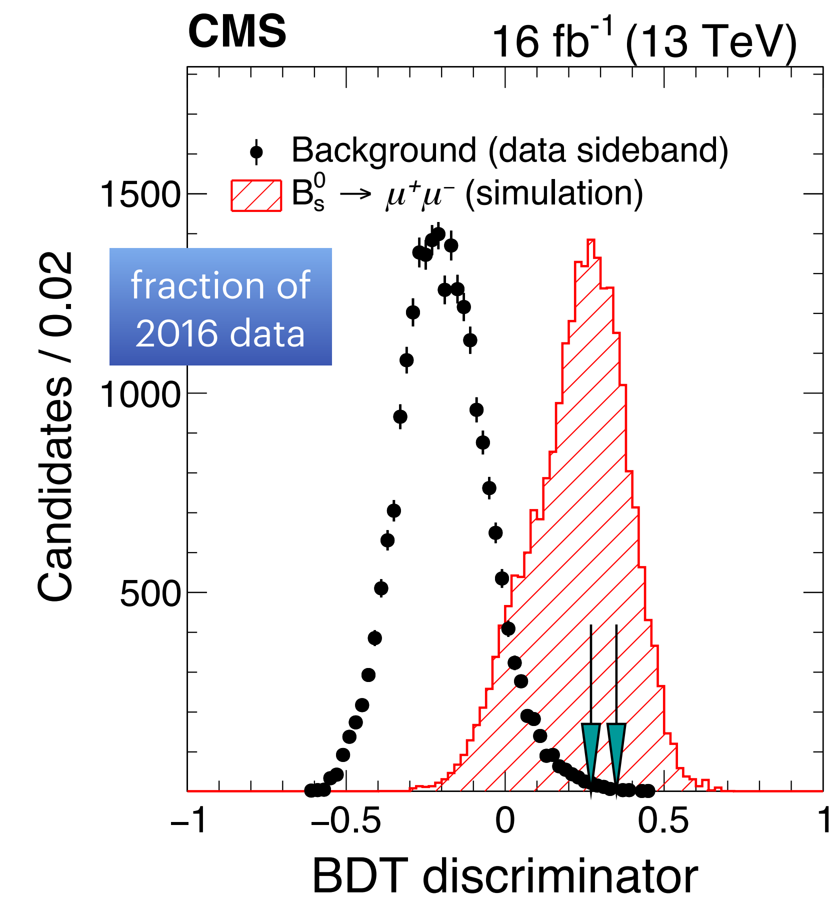
✓ Analysis steps

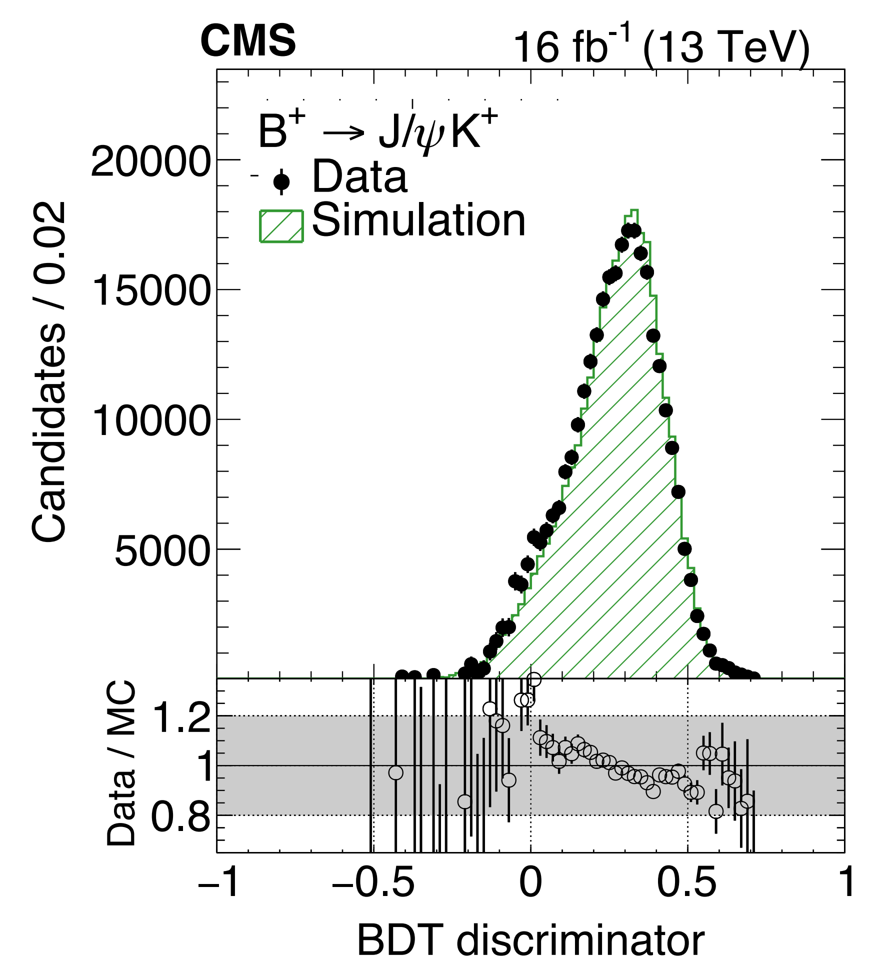
- event classification with boosted decision tree(BDT)
- unbinned (extended) maximum likelihood fits to selected events
    - branching fraction $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$
    - effective lifetime $\tau_{\mu^+\mu^-}$

Ref: CMS JHEP 04 (2020) 188

Multi-variate analysis

- ✓ Combined (re-)analysis of Run 1(25 fb^{-1}) and 2016(36fb^{-1}) datasets
  - separations of data into 'channels' (central and forward)
- ✓ Boosted decision tree
  - discriminating variables: isolation, well-reconstructed secondary vertex, pointing angle, track d_{ca}
- ✓ BDT training
  - signal: $B_s \rightarrow \mu^+\mu^-$ MC simulation
  - background : data dimuon sidebands
  - avoid selection bias
    - split data randomly into three subsets(0,1,2)
    - train on 0, test on 1, apply on 2 etc.
    - each channel have 3 BDTs
- ✓ Optimal BDT discriminator binning
  - Asimov data for significance estimation
  - 14 categories for BF and 8 categories for effective lifetime

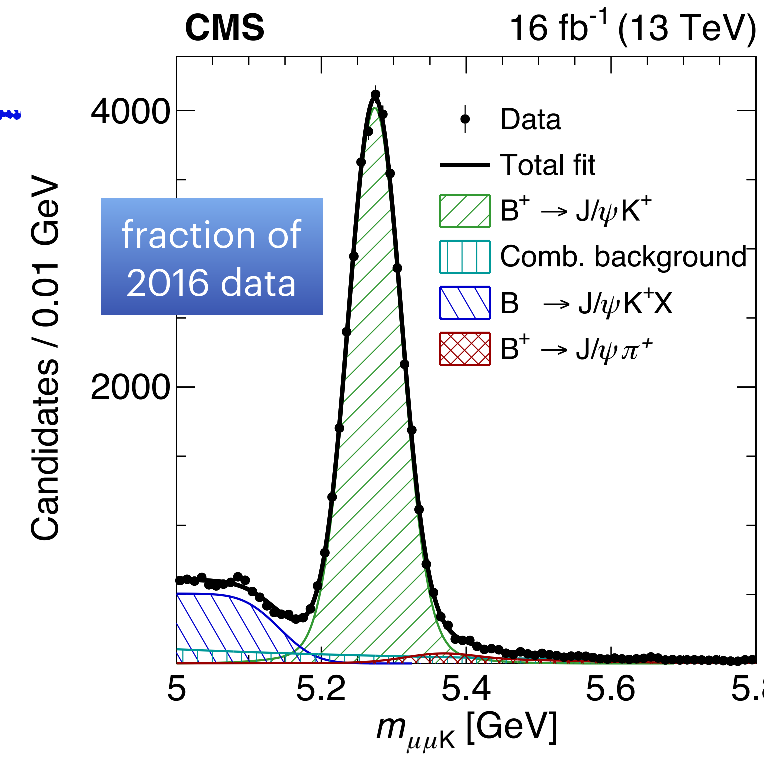




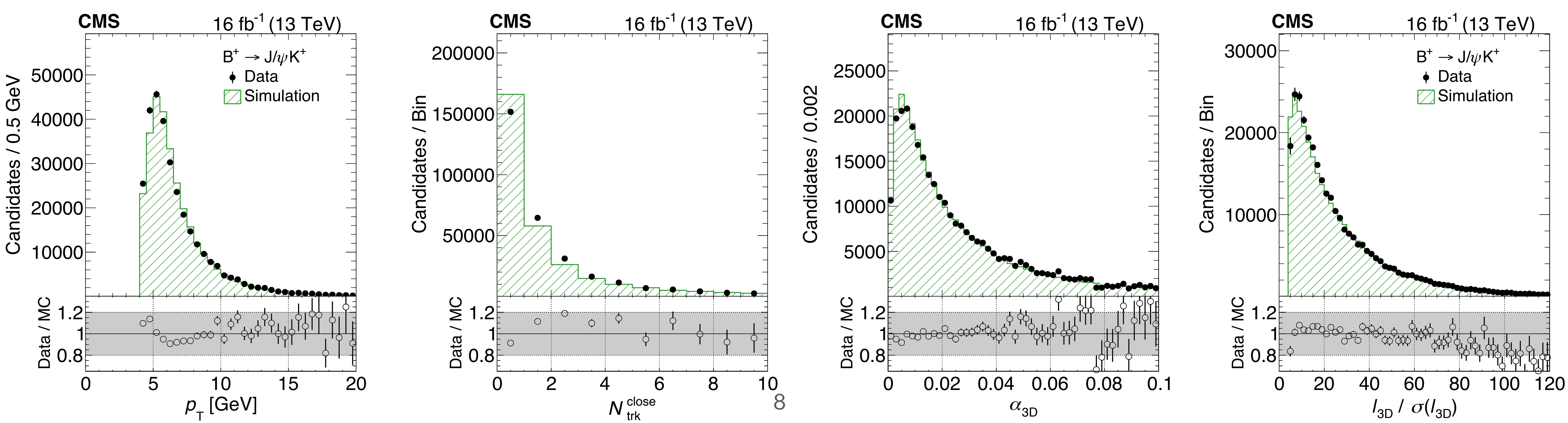
Ref: CMS JHEP 04 (2020) 188

Simulation Vs reality

- Fits to invariant mass
  - Signal: double Gaussian with common mean
  - background:
    - combinatorial: exponential function
    - partial reco'ed bg: error function
    - $B^+ \to J/\psi \pi^+$: triple Gaussian, fixed to 4% of signal shape from MC



- Comparison of normalization samples in sideband subtracted data and MC
  - Difference accounted for in systematics



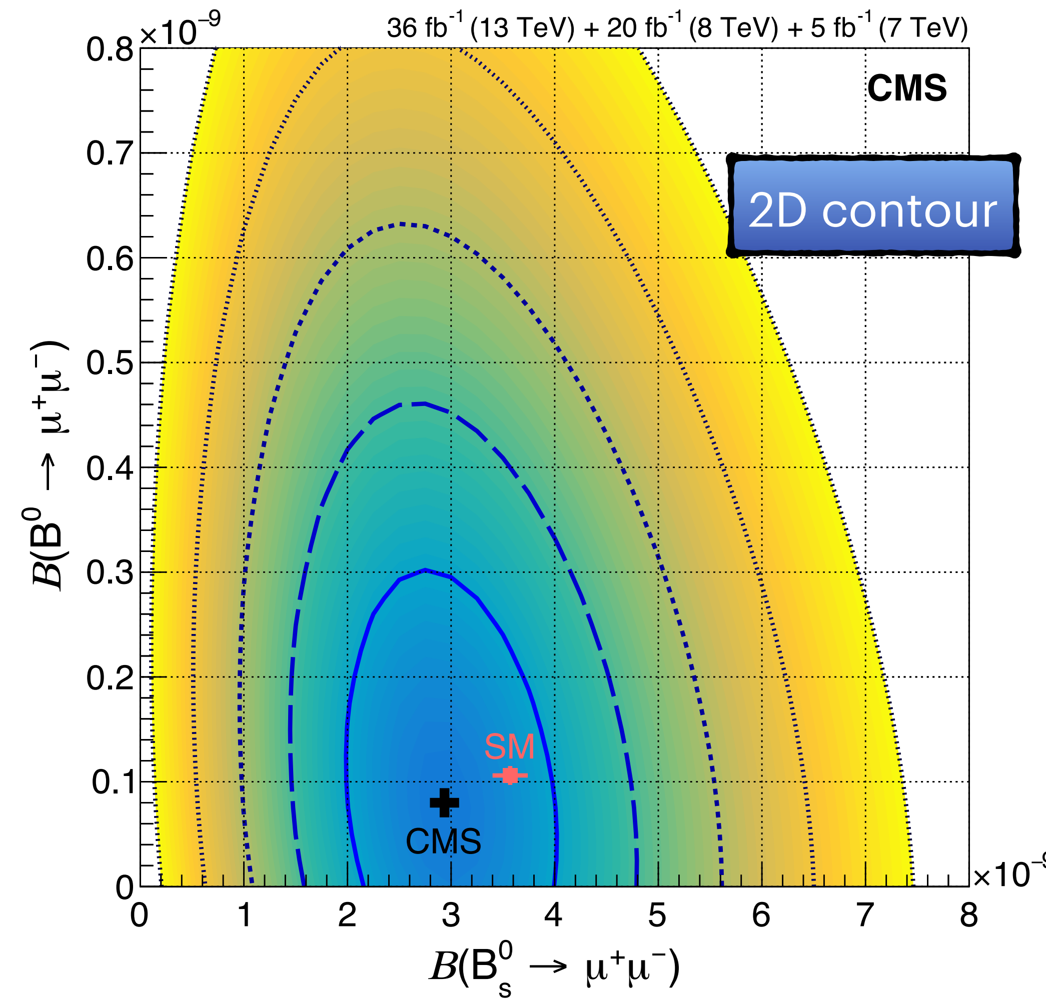
Ref: CMS JHEP 04 (2020) 188

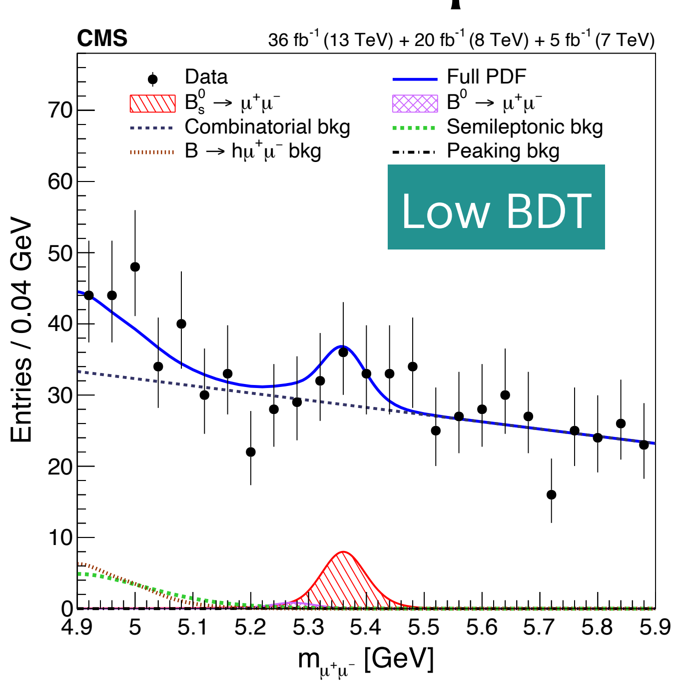
CMS results

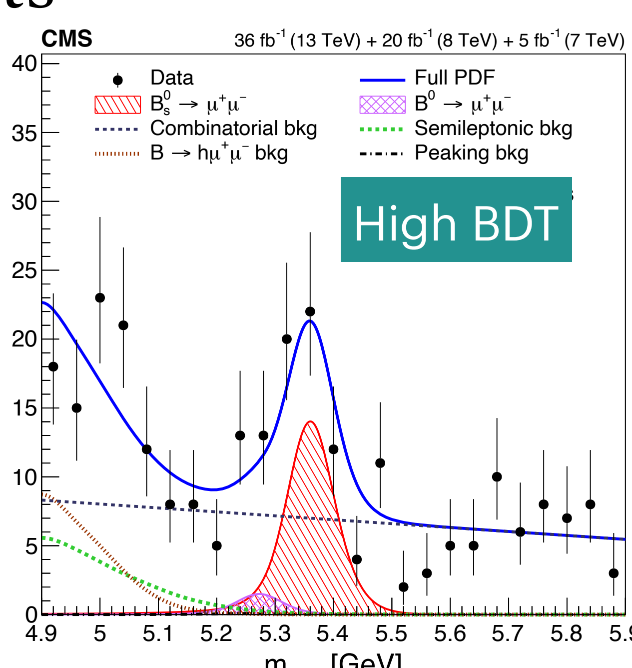
- ✓UML fit to invariant mass (M(μμ)) in the 14 BDT categories

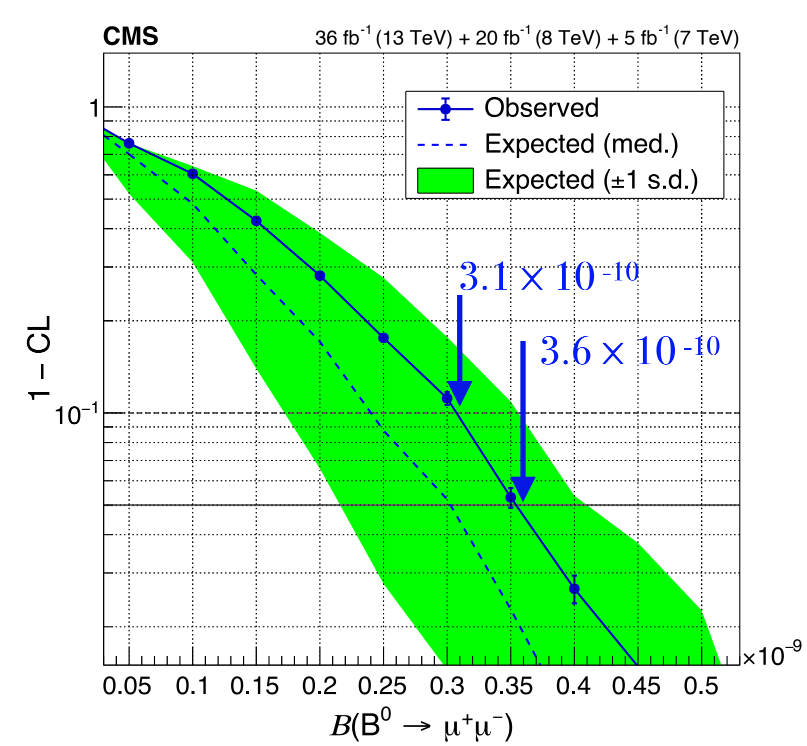
Channel	Branching fraction	Sign. (Obs)
$B^0_s \to \mu^+\mu^-$	$(2.9^{+0.7}_{-0.6}(\mathrm{exp}) \pm 0.2(f_s/f_u)) \times 10^{-9}$	5.6 σ
$B^0 \to \mu^+\mu^-$	$(0.8^{+1.4}_{-1.3}) \times 10^{-10}$	0.6 σ

- ✓ Frequentist CLs method for upper limit
- ✓ $\mathcal{B}(B^0 \to \mu\mu) < 3.6 \times 10^{-10}$ @ 95% C.L
- ✓ Results are consistent with SM as well as with other experiments









Ref: CMS JHEP 04 (2020) 188

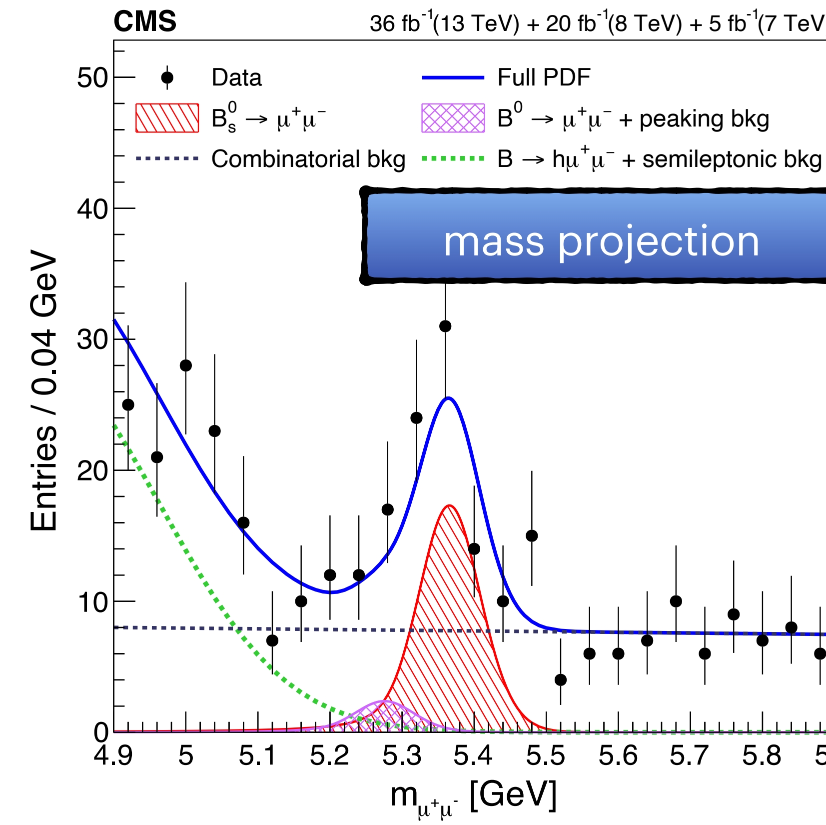
CMS results

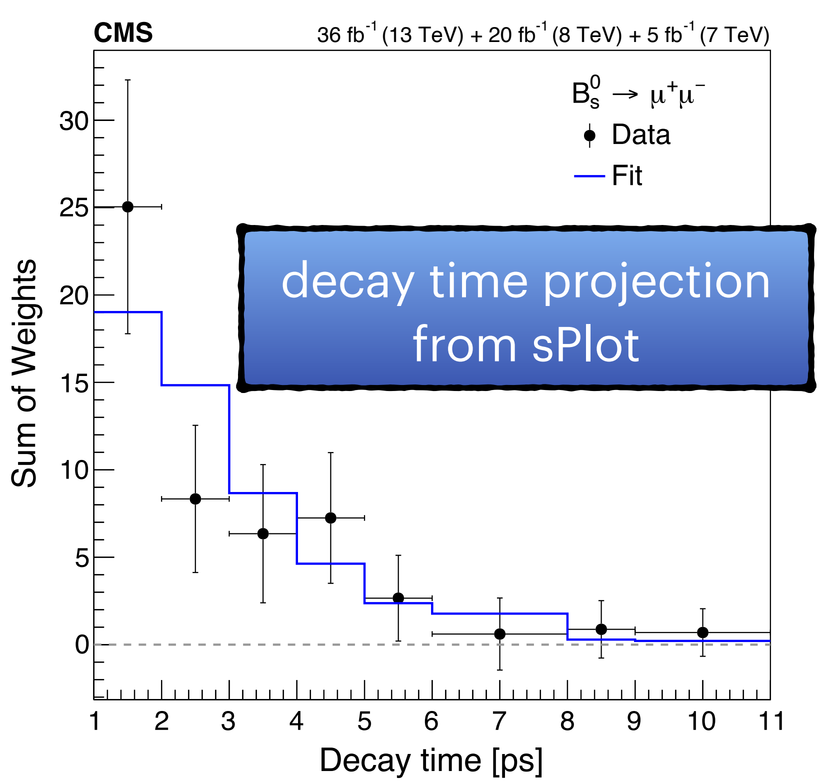
✓ Method 1: 2D UML fit to invariant mass (M(μμ)) and decay time: Simultaneous fit to 8 categories.(primary method)

✓ Method 2: And sPlot weight from the BF; binned likelihood fit with efficiency and resolution

✓ Consistent with SM as well as with previous measurements

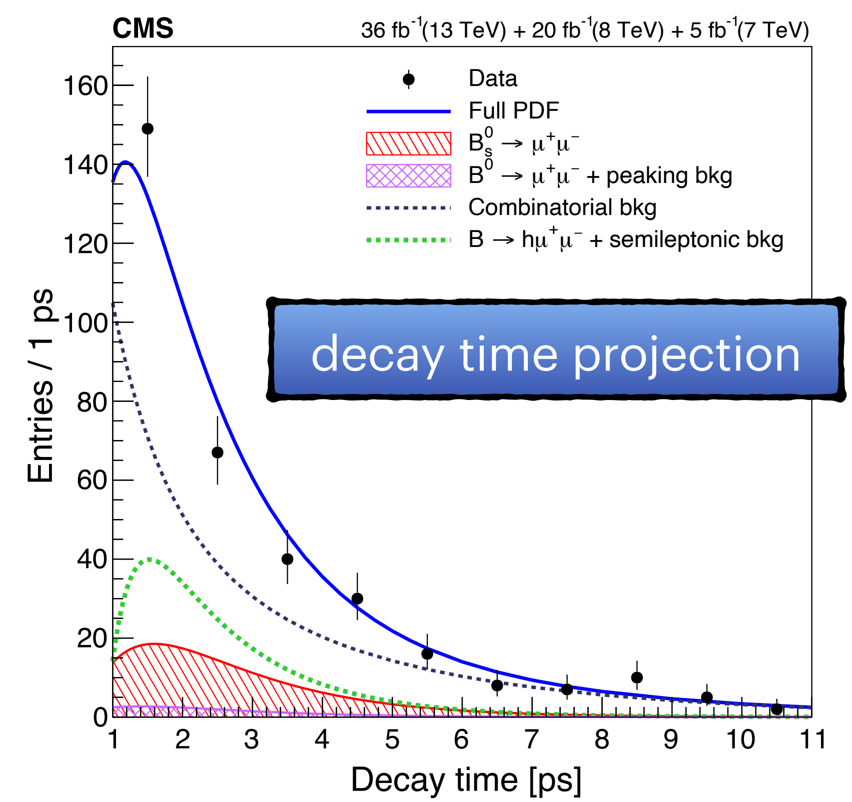
	$\tau_{\mu^+\mu^-}$ (ps)
2D UML	$1.70 + 0.61/-0.44$
sPlot	$1.55 + 0.52/-0.33$





SM

$$\mathcal{A}_{\Delta\Gamma}^{\mu^+\mu^-} = +1 \rightarrow$$
$$\tau_{B_s \rightarrow \mu^+\mu^-} = (1.609 \pm 0.010)\ \text{ps}$$



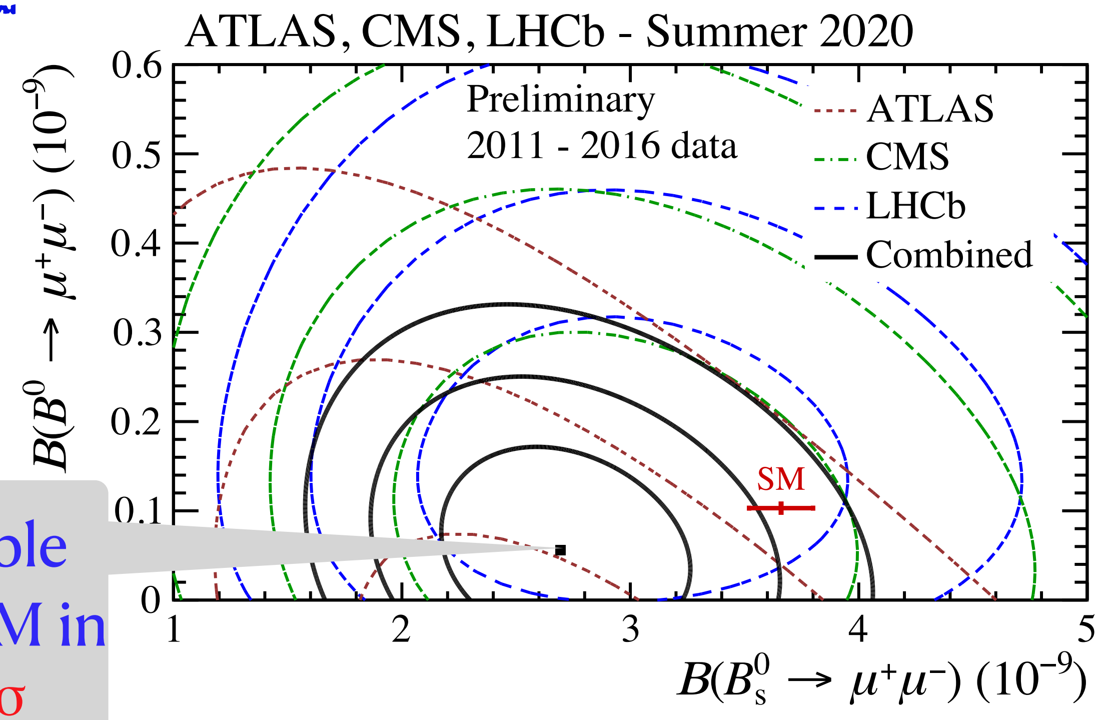
ATLAS + CMS +LHCb results

CMS-PAS-BPH-20-003
LHCb-CONF-2020-002
ATLAS-CONF-2020-049

- ✓ Based on binned 2D profile likelihoods,
- ✓ Apply the analytic model on the **combined 2D likelihood histogram** to obtain the combined branching fractions

Channel	Branching fraction
$B^0_s \to \mu^+\mu^-$	$(\mathbf{2.69^{+0.37}_{-0.35}}) \times \mathbf{10^{-9}}$
$B^0 \to \mu^+\mu^-$	$(\mathbf{0.6 \pm 0.7}) \times \mathbf{10^{-10}}$

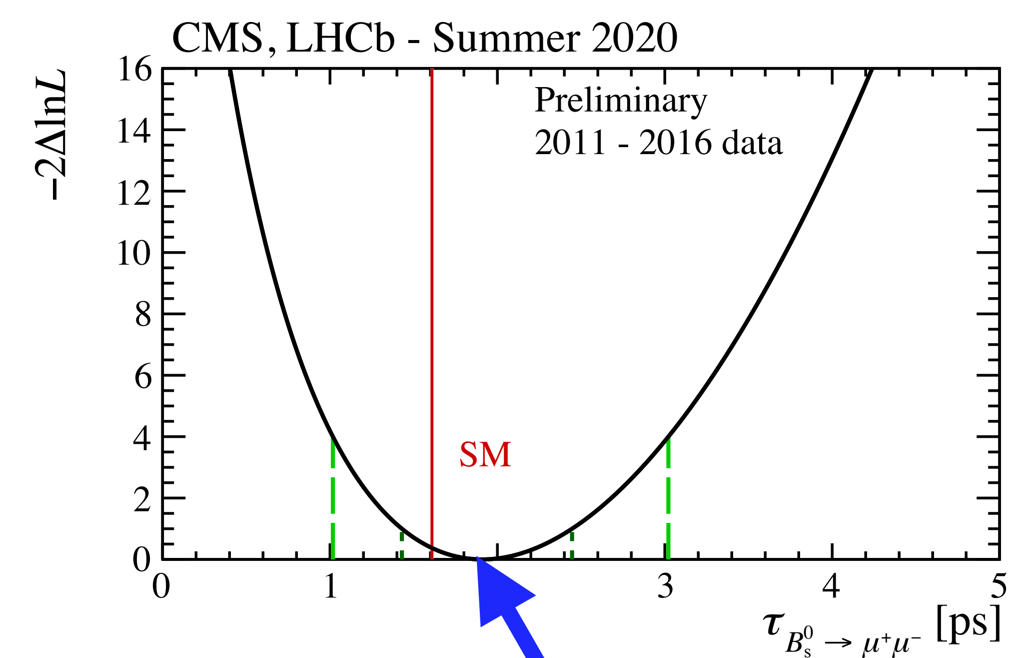
Compatible with the SM in 2D; 2.1 σ



- ✓ Upper limit for B^0 and ratio of BF

	Upper Limit @90(95)% CL
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	$< \mathbf{1.6(1.9) \times 10^{-10}}$
$R = \mathcal{B}(B^0)/\mathcal{B}(B^0_s)$	$< \mathbf{0.052(0.060)}$

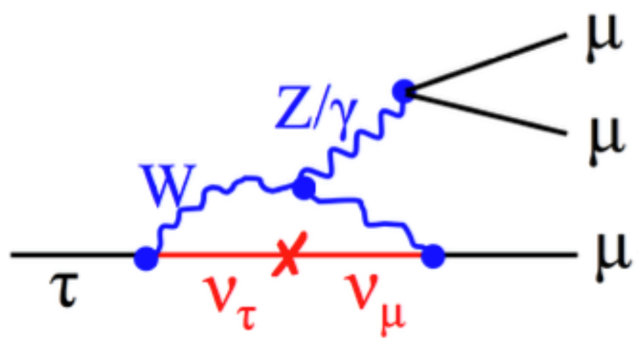
- ✓ Effective lifetime, obtain from the sum of1D log-likelihood curves,
  - Compatible with SM



Exp.	$\tau_{\mu^+\mu^-}$ (ps)
CMS+LHCb	$\mathbf{1.91 + 0.37 / - 0.35}$

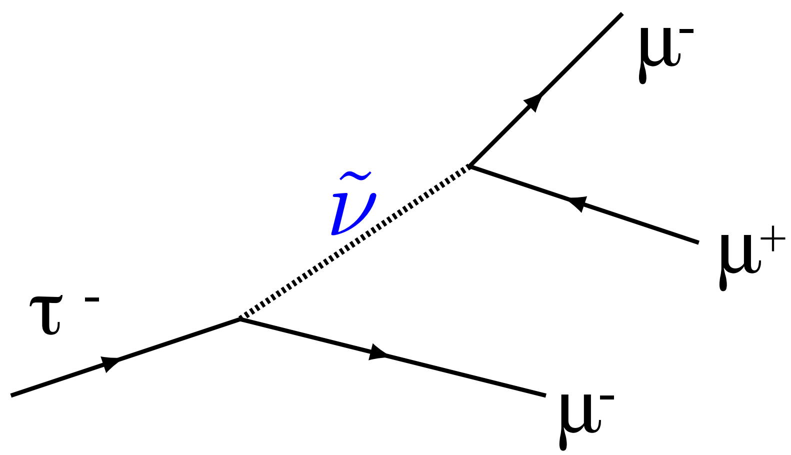
Search for $\tau \to 3\mu$ decay

- ✓ $\tau \to 3\mu$ transition
  - doesn't conserve lepton family number
  - doesn't involve neutrinos in the final state
  - allowed by neutrino oscillation



- ✓ Suppressed in the Standard Model.
  - Branching ratio $\tau \to 3\mu(\mathrm{SM}) \sim O(10^{-14})$
  - Enhanced BR by SUSY, 2HDM

    $\tau \to 3\mu(\mathrm{BSM}) \sim O(10^{-8})$

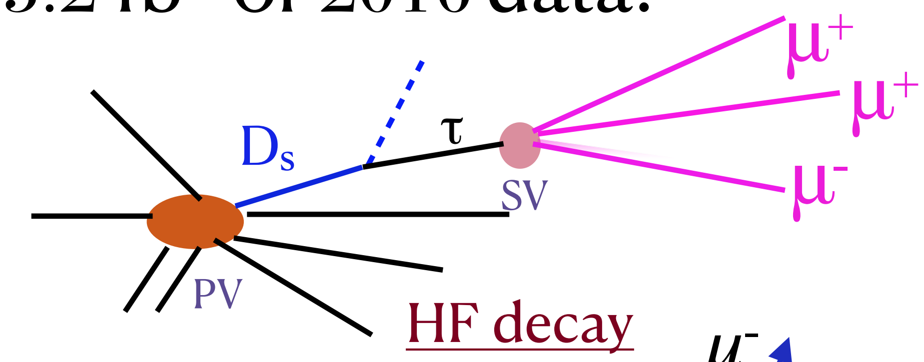


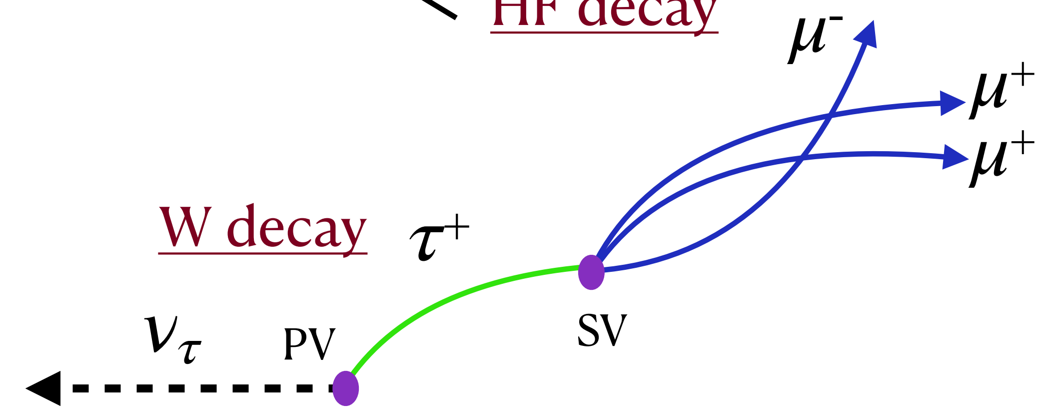
- ✓ Stringent limit by lepton collider;
  - Belle: BF $\tau \to 3\mu(\mathrm{SM}) < 2.1 \times 10^{-8}$ @ 90% CL — Ref: Phys. Lett.B687 (2010)139143
  - Babar: BF $\tau \to 3\mu(\mathrm{SM}) < 3.3 \times 10^{-8}$ @ 90% CL — Ref: Phys. Rev. D81 (2010)111101
- ✓ limit by hadron collider;
  - LHCb(LHC): BF $\tau \to 3\mu(\mathrm{SM}) < 4.6 \times 10^{-8}$ @ 90% CL — Ref: JHEP 02(2015)121
  - ATLAS(LHC): BF $\tau \to 3\mu(\mathrm{SM}) < 3.8 \times 10^{-7}$ @ 90% CL — Ref: Eur. Phys. J. C(2016) 76:232

Selection and normalization

BPH-17-004

- First search for $\tau \to 3\mu$ transition in CMS using 33.2 fb^{-1} of 2016 data.
- Sources of τ
  - Heavy flavor(HF) decay(D, B): large cross section; low p_T, high η; high background
  - W decay: small cross section; high p_T; low background; large missing energy



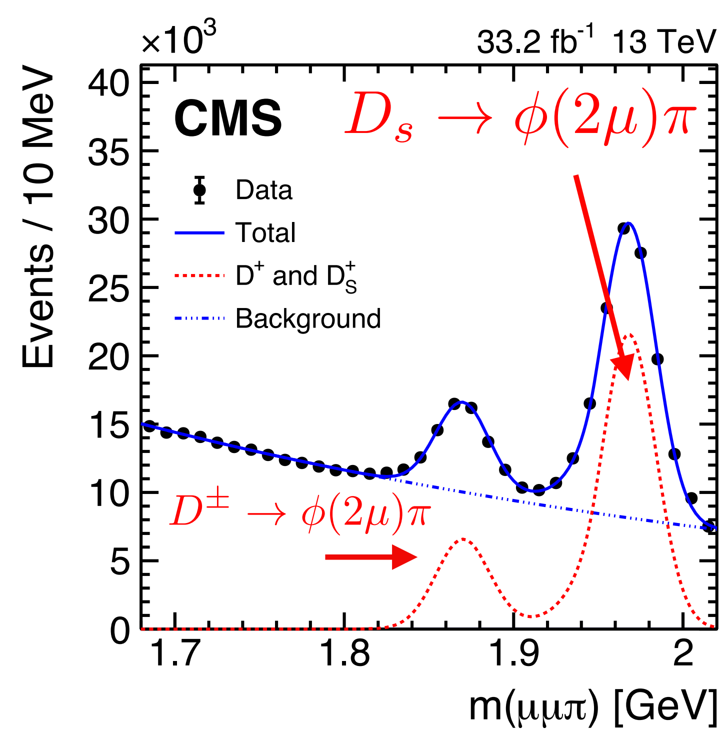


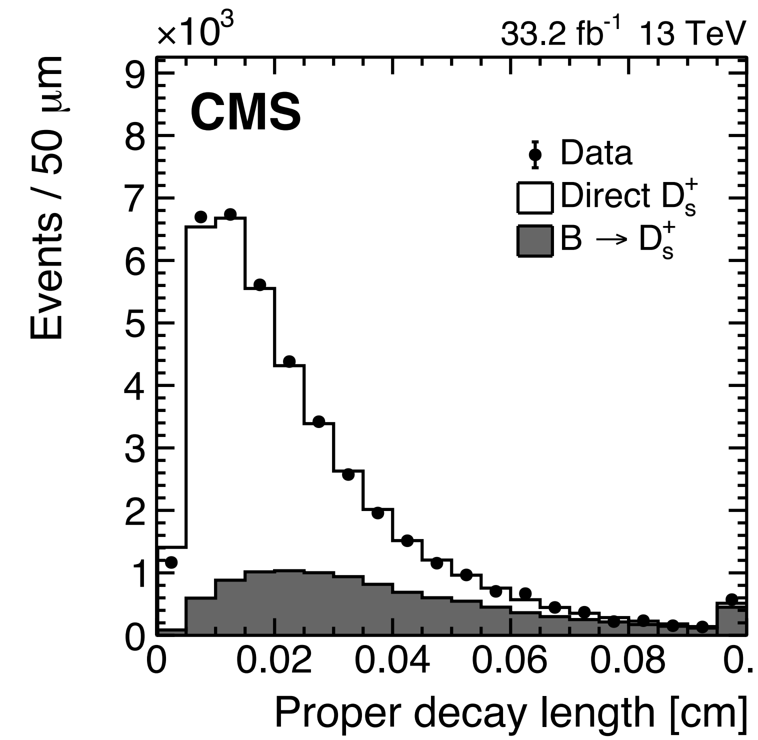
- τ selection
  - Trigger: two muons and a track with mass and vertex requirements,(two muon $p_T > 3$ GeV, track $p_T > 1.2$ GeV)
  - vertex displaced from beam spot $>2\sigma$
  - mass in 1.62 -2.00 GeV

- Normalization:(HF decay)

$$D_s^{\pm} \to \phi\pi^{\pm} \to \mu^{+}\mu^{-}\pi^{\pm}$$

  - Selected with signal trigger
  - Template fit to proper decay length in data to evaluate the fraction of D_s candidates from B meson decay





Analysis strategy

BPH-17-004

- To suppress the background the BDT is trained on sideband data and signal MC sample
- Six categories for HF decay; based on BDT score and mass resolution
- Signal from D_s

$$N_{sig(D)} = N \frac{\mathcal{B}(D_s \to \tau\nu)}{\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{2\mu\pi}} \frac{\epsilon^{3\mu}_{reco}}{\epsilon^{2\mu\pi}_{reco}} \frac{\epsilon^{2\mu}_{trig.sig}}{\epsilon^{2\mu}_{trig(\mu\mu\pi)}} \mathcal{B}(\tau \to 3\mu)$$

Normalization channel yield

Acceptance and efficiency correction

Fraction from decay length fit

Signal from direct B meson decay

$$N_{sig(B)} = f \frac{\mathcal{B}(B \to \tau + ...)}{\mathcal{B}(B \to D_s + ...)\mathcal{B}(D_s \to \tau\nu)} \frac{\mathcal{A}_{3\mu(B)}}{\mathcal{A}_{3\mu(D)}} N_{sig(D)}$$

- Signal from W

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

Acceptance efficiency

combined efficiency

Integrated luminosity

Ref: Phys. Lett. B 759 (2016) 601,Phys. Rev. D 98 (2018) 030001

- Two categories for W decay; based on pseudo-rapidity(barrel and endcap)

Result

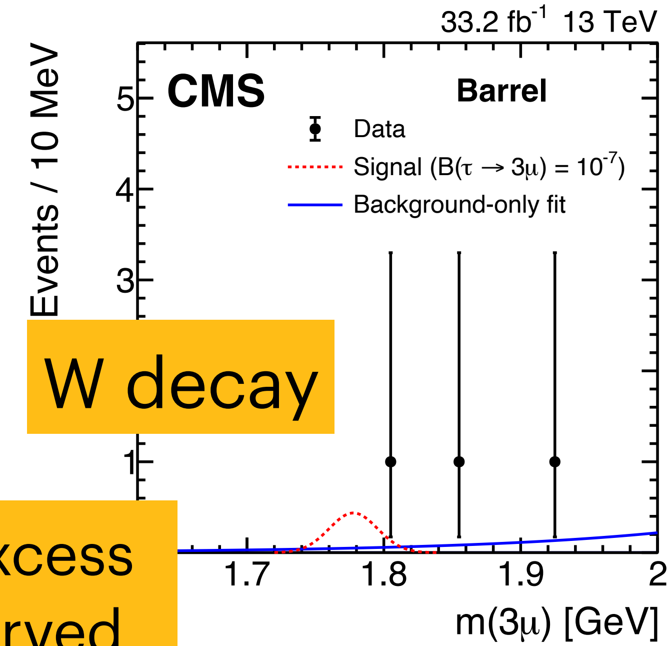
BPH-17-004

- ✓ Simultaneous unbinned maximum likelihood fit performed over eight categories(6+2)
- ✓ Upper limit using modified frequentist CLs method

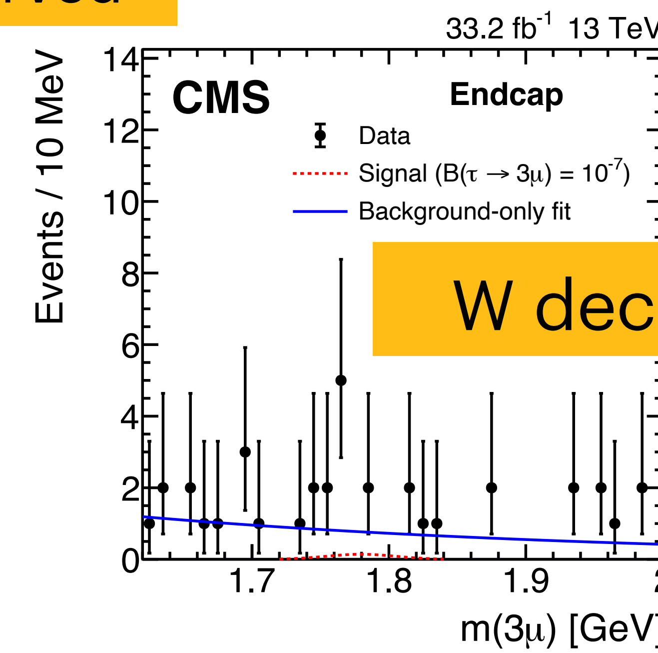
CL(90%)	Expected BR($\tau\to3\mu$)	Observed BR($\tau\to3\mu$)
HF decay	10.0×10^{-8}	9.2×10^{-8}
W decay	13×10^{-8}	20×10^{-8}
Combined	6.9×10^{-8}	8.0×10^{-8}

- ✓ Similar sensitivity to LHCb and Babar
- ✓ 4 times away from current most restrictive one(Belle)

W decay

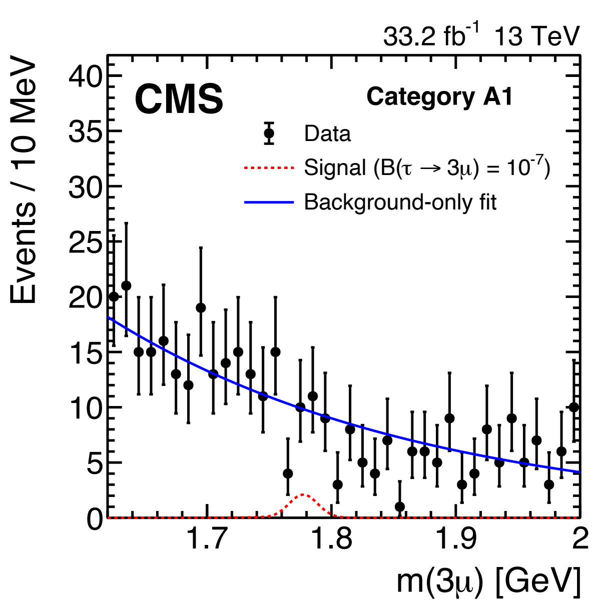


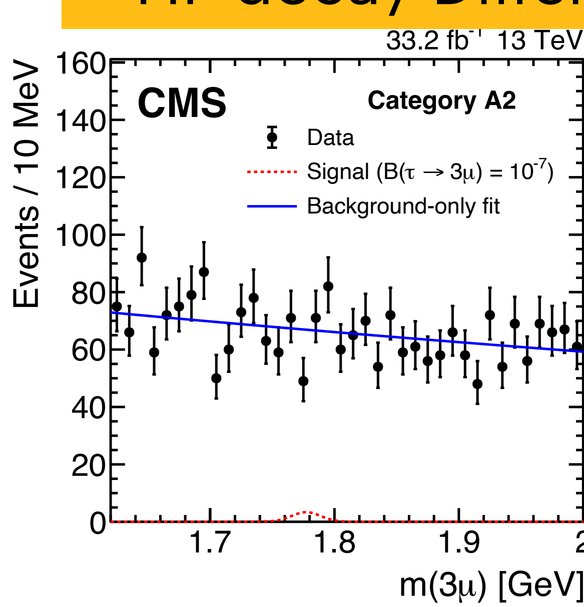
No excess observed

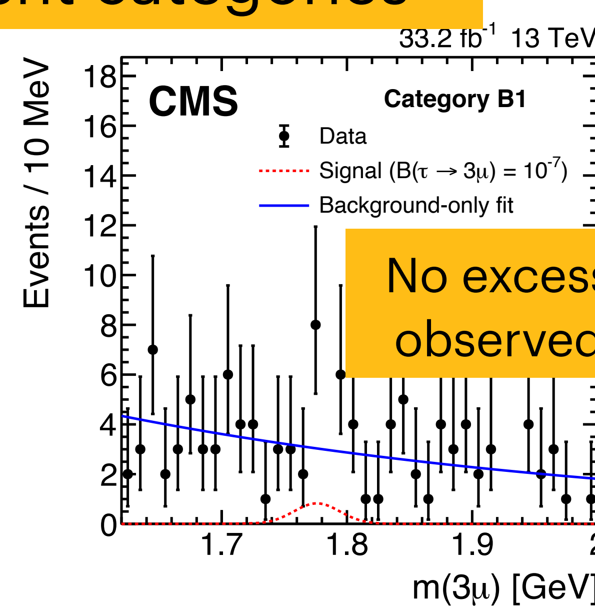


W decay

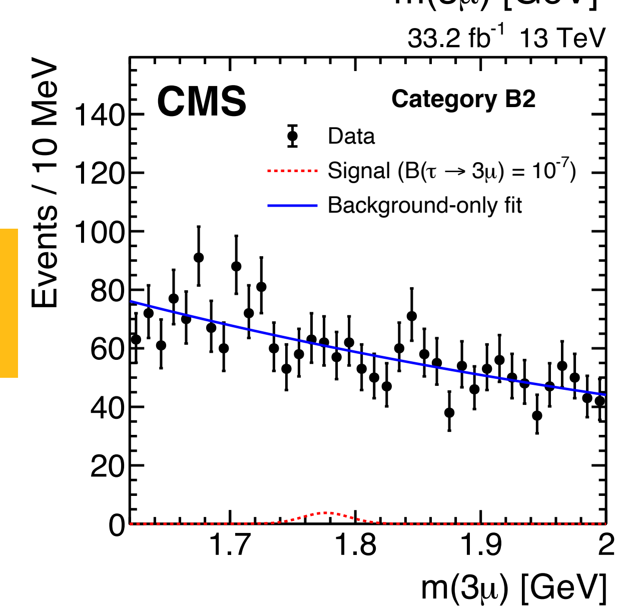
HF decay Different categories







No excess observed



CMS-PAS-BPH-20-003
LHCb-CONF-2020-002
ATLAS-CONF-2020-049

Summary

Two main topics were discussed today:

✓ $B^0_{(s)} \to \mu^+\mu^-$:

- The very rare decay $B^0_s \to \mu^+\mu^-$ has been clearly observed. More data are required to precisely measure the properties of B^0_s mesons and to observe $B^0 \to \mu^+\mu^-$ decay in the near future.

Ref: CMS JHEP 04 (2020) 188

✓ $\tau \to 3\mu$:

- Three-muon mass fit performed in eight categories(HF and W production mode)
- No excess observed
- Upper limit set at 90% CL : $BF(\tau \to 3\mu) < 8.0 \times 10^{-8}$

Ref:BPH-17-004

Thank you !

Backup

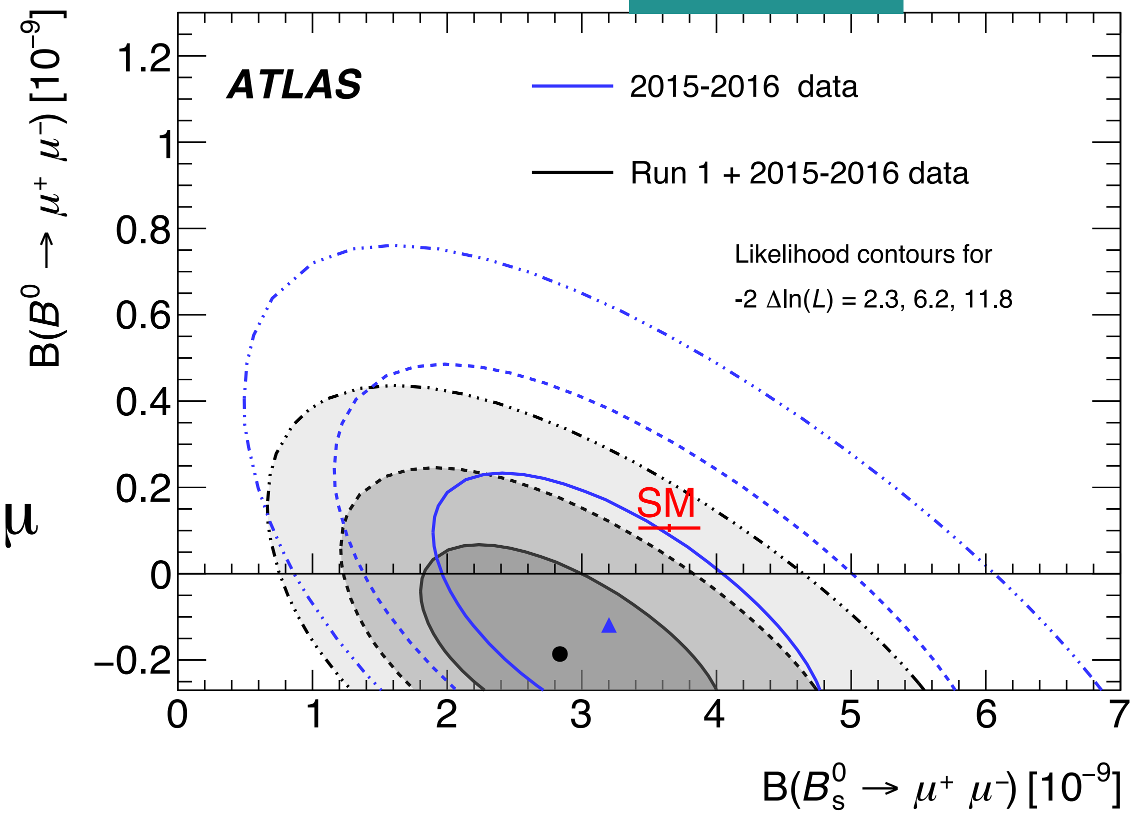
ATLAS results

Ref: ATLAS JHEP 04(2019)098

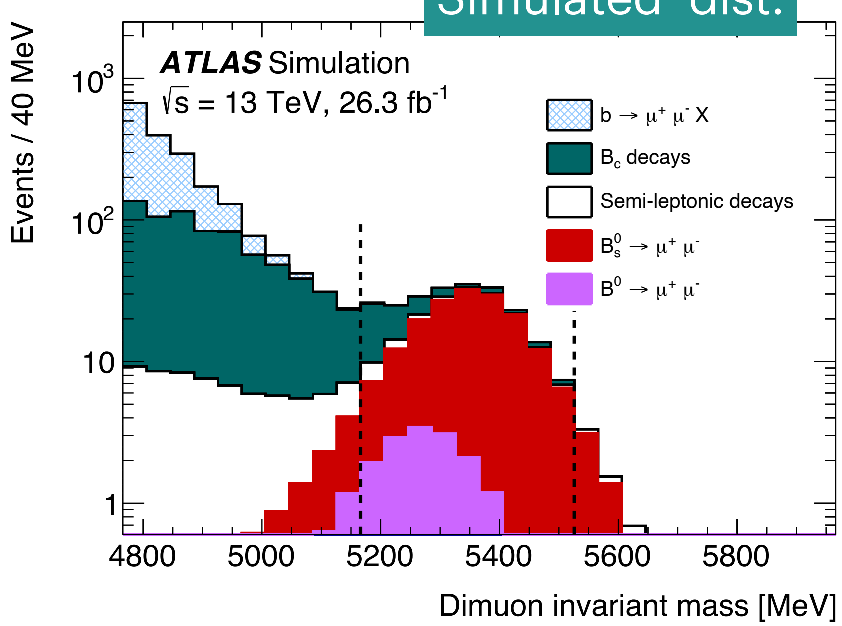
Channel	Branching fraction
$B_s \to \mu^+\mu^-$	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$
$B_d \to \mu^+\mu^-$	$< 2.1 \times 10^{-10}$

✓ Combined significance(Run 1+Run2) for $B_s \to \mu\mu$ 4.6 σ.

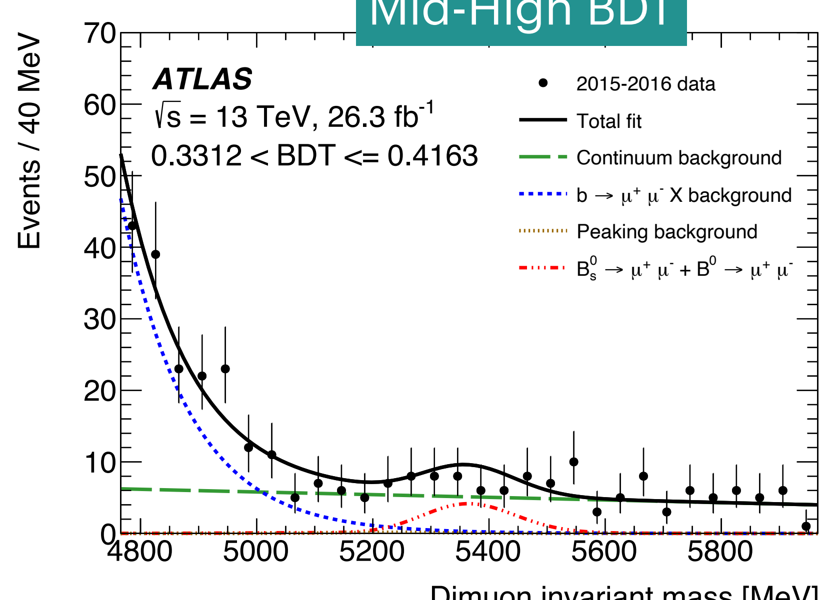
2D contour



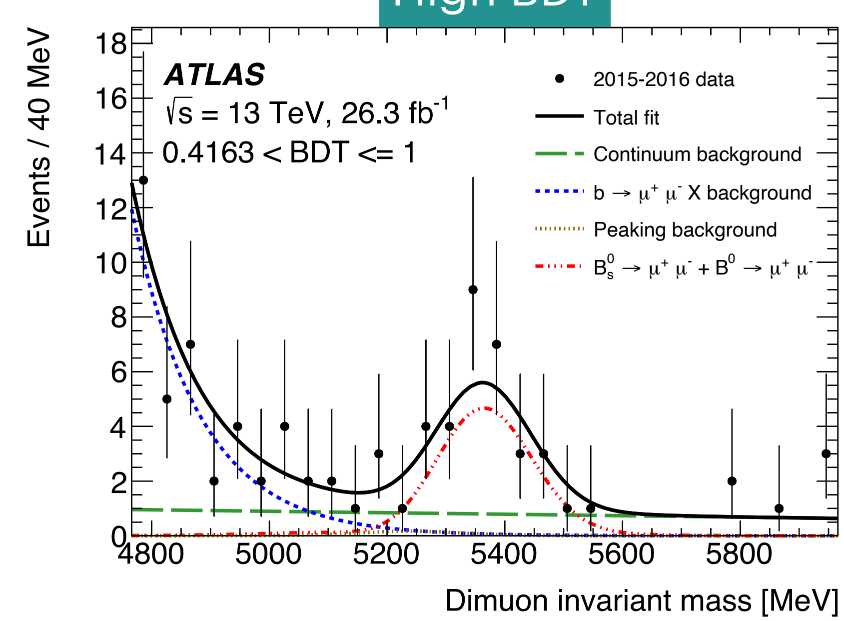
Simulated dist.



Mid-High BDT



High BDT

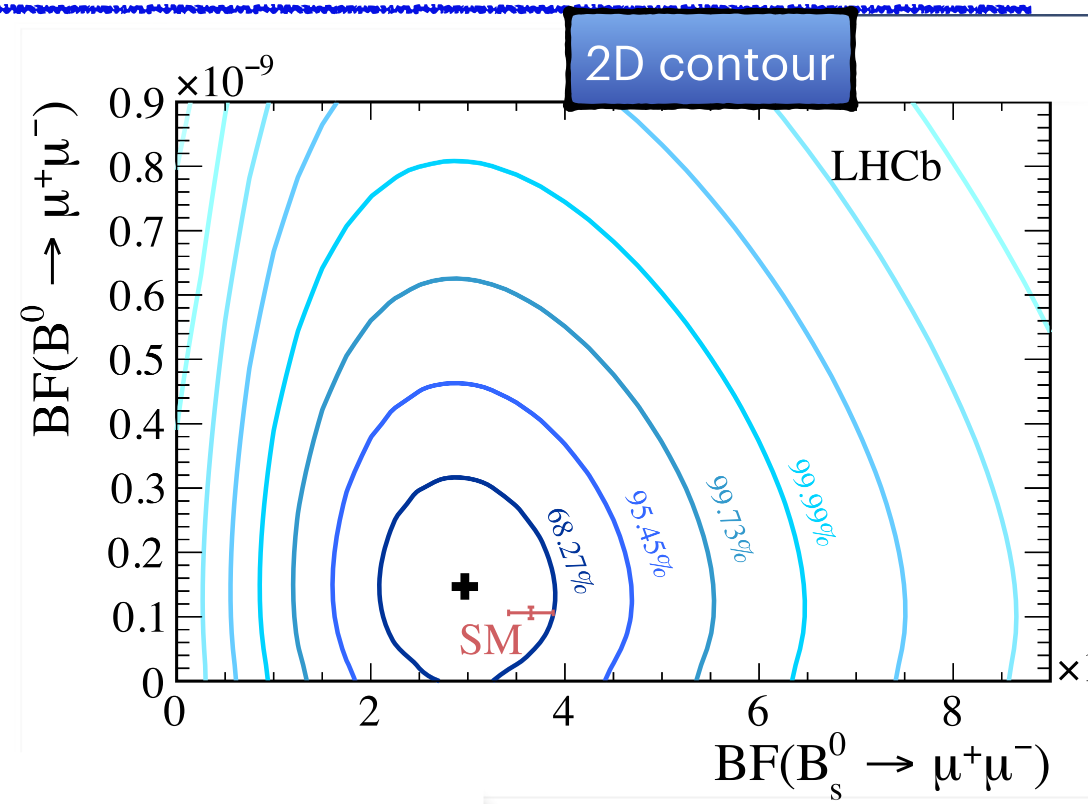


LHCb results

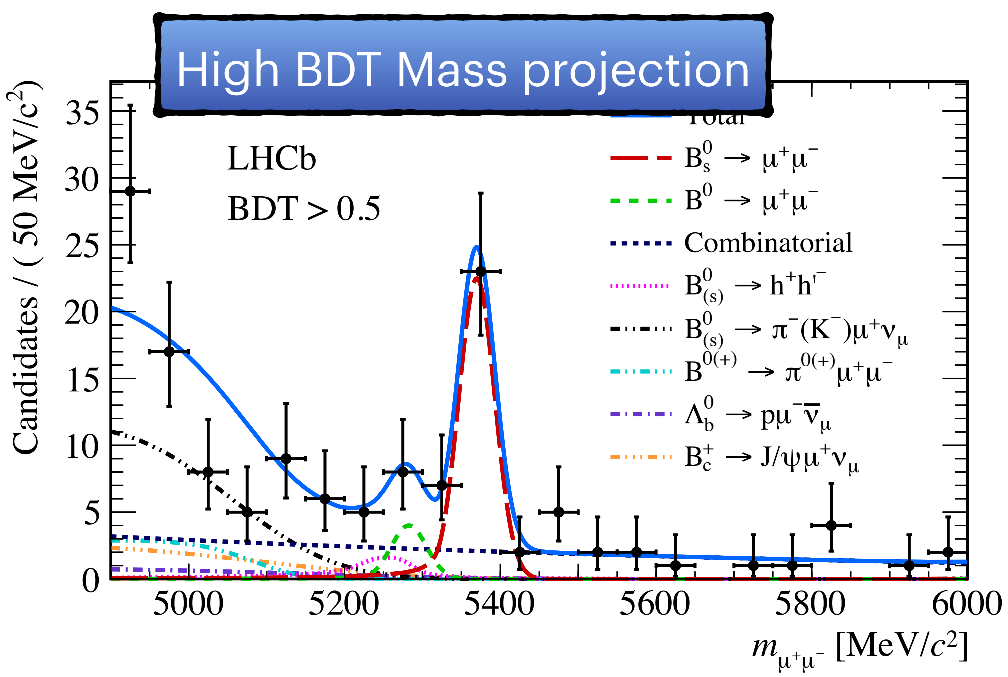
Ref: LHCb PRL 118, 191801 (2017)

- ✓ Compatible with SM.

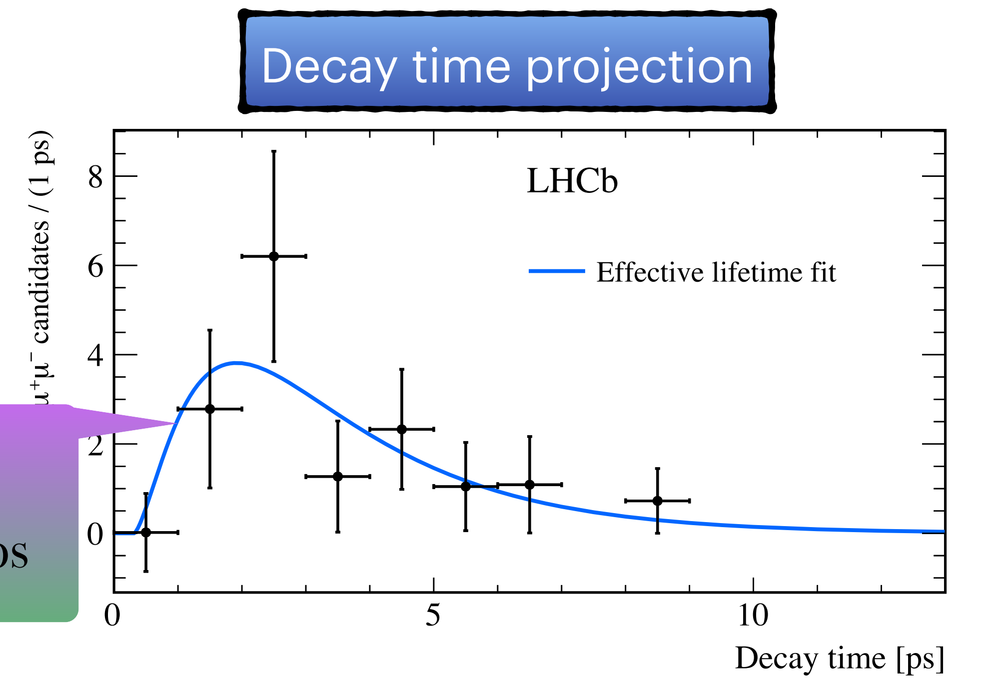
Channel	Branching fraction	Sign.(Obs)
$B_s \to \mu^+\mu^-$	$(3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$	7.8 σ
$B_d \to \mu^+\mu^-$	$(1.5^{+1.2}_{-1.0}) \times 10^{-10}$	1.6 σ



- ✓ $\mathcal{B}(B_d \to \mu\mu) < 3.4 \times 10^{-10}$ @ 95% C.L.
- ✓ sPlot method to evaluate effective lifetime



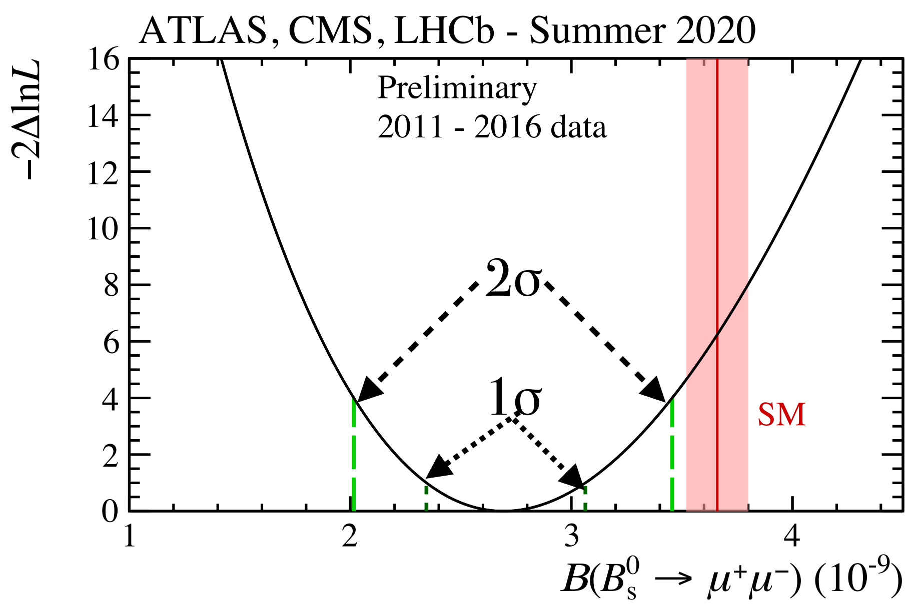
$\tau(\mu\mu)$ =
$2.04 \pm 0.44 \pm 0.05$ps

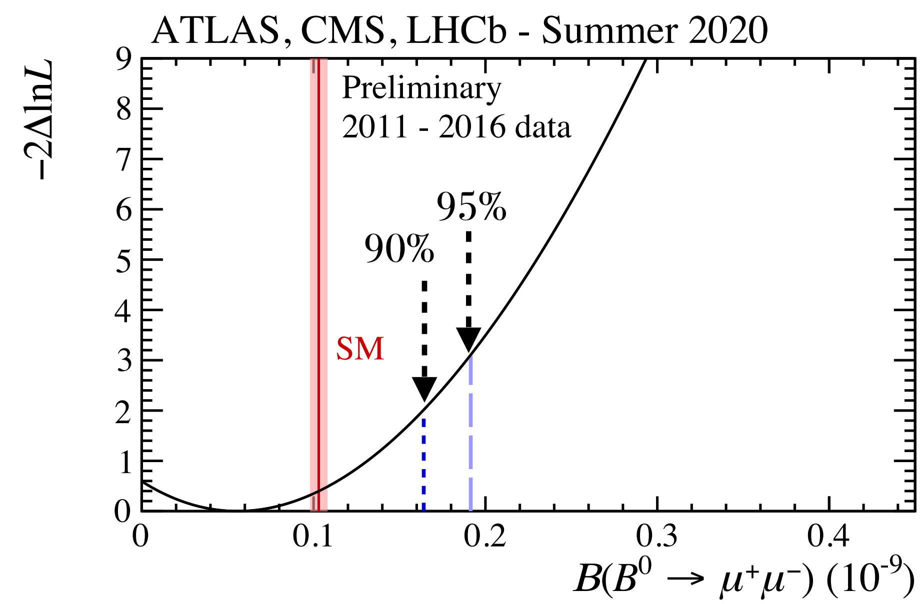


Combined 1D likelihood curve

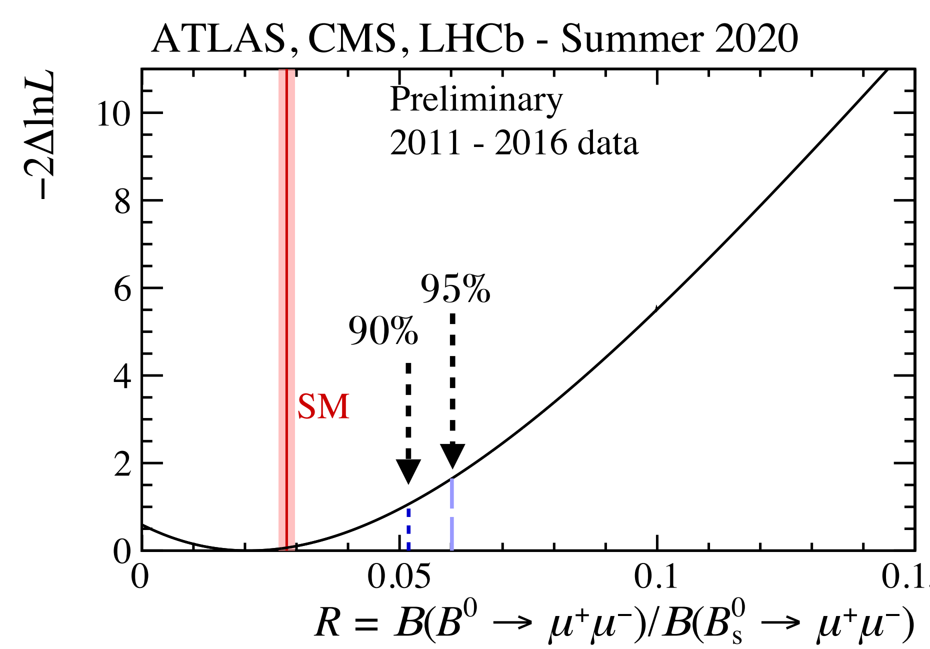
CMS-PAS-BPH-20-003
LHCb-CONF-2020-002
ATLAS-CONF-2020-049

✓ Profile 1D likelihood for one of the branching fraction and ratio
$R = \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$





✓ Compatible with SM at 2.4 σ and 0.6 σ for $\mathcal{B}(B_s)$ and $\mathcal{B}(B^0)$



	Upper Limit @90(95)% CL
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	$< \mathbf{1.6(1.9) \times 10^{-10}}$
$R = \mathcal{B}(B^0)/\mathcal{B}(B_s)$	$< \mathbf{0.052(0.060)}$