Beauty 2023:
21st International Conference on B-Physics at Frontier Machines

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Rare decays at CMS

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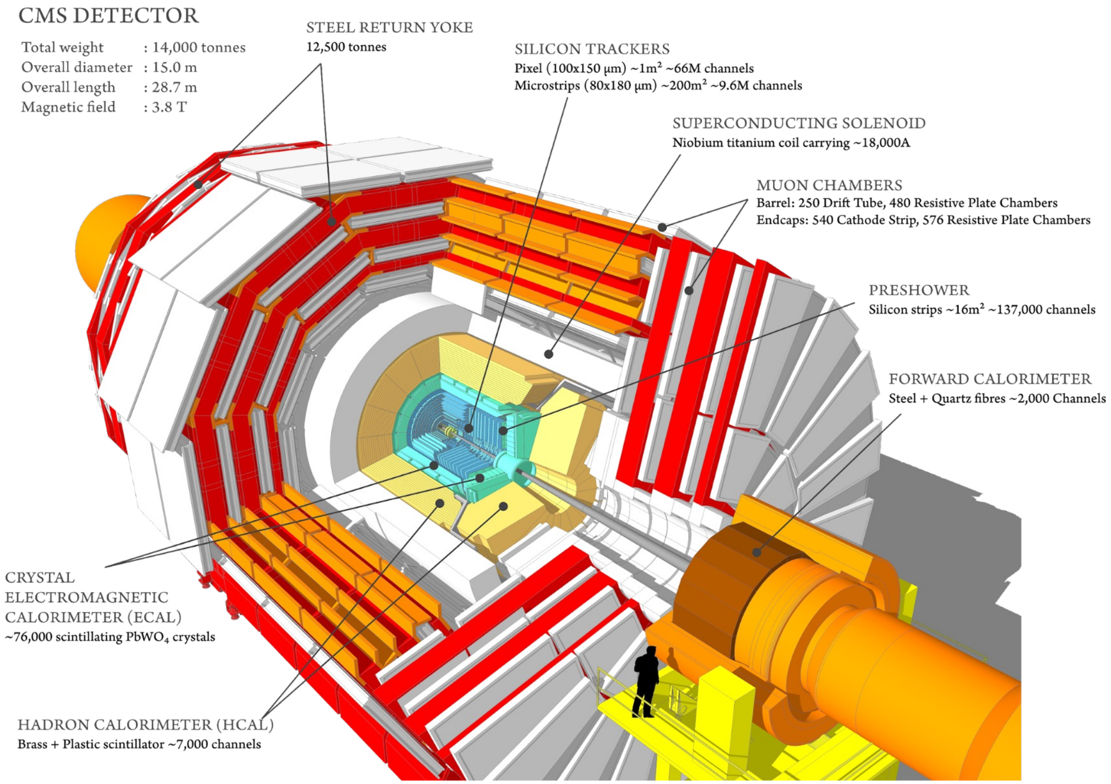
Overview

Results from rare decays and flavour anomalies searched in B-physics at CMS

- search for the LFV $\tau \to 3\mu$ decay in CMS in Run-2 data
- observation of the rare $\eta \to 4\mu$ decay at CMS in Run-2 scouting data
- search for the $B^0_{(s)} \to \mu^+\mu^-$ decay and effective lifetime mesurement in CMS Run-2 data

The CMS detector



collected luminosity:

- Run1: 25 /fb pp @ 7 and 8 TeV
- Run2: 140 /fb pp @ 13 TeV
- Run3 ongoing, 37 /fb collected in 2022

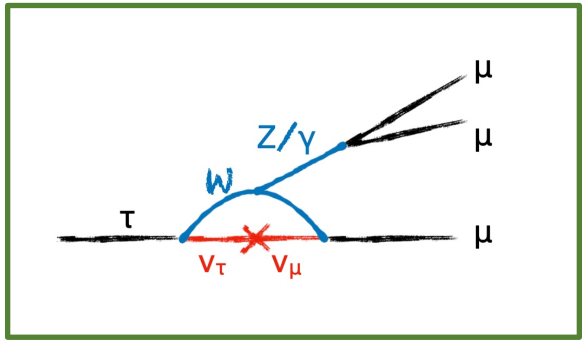
- cylindric compact (15m x 21m) detector
- high granularity **pixel + strip silicon tracker** for excellent track, PV and SV measurements
- **$PbWO_4$ crystal ECAL and brass+plastic HCAL** to achieve hermeticity and jet+EG shower measurement
- **3.8T solenoid** for pT measurement
- **external muon chambers** outside steel return yoke for a clean muon detection and pT measurement
- **two level trigger system** (hardware + software)

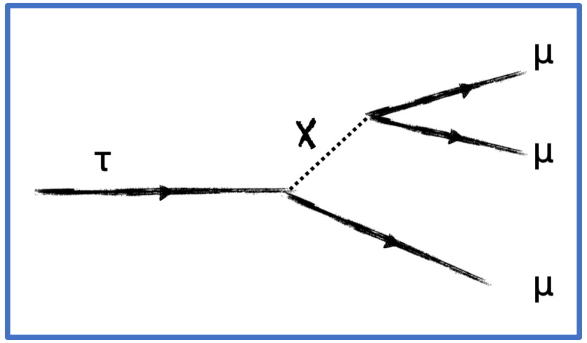
$\tau^+ \longrightarrow \mu^+\mu^+\mu^-$

τ⟶3μ
the physics case

Lepton Flavour Violating (LFV) decays are strongly suppressed in the Standard Model (SM)

- allowed by neutrino oscillations at lowest Branching Ratios (BR) 10.1140/epjc/s10052-020-8059-7
  - *SM BR* ($\tau \longrightarrow 3\mu$) ~ 10^{-55}
- LFV decays are a good field for New Physics (NP) searches
  - predicted by some NP model at BR ~ 10^{-9}
    10.1393/ncr/i2018-10144-0
    10.1007/JHEP10(2018)148

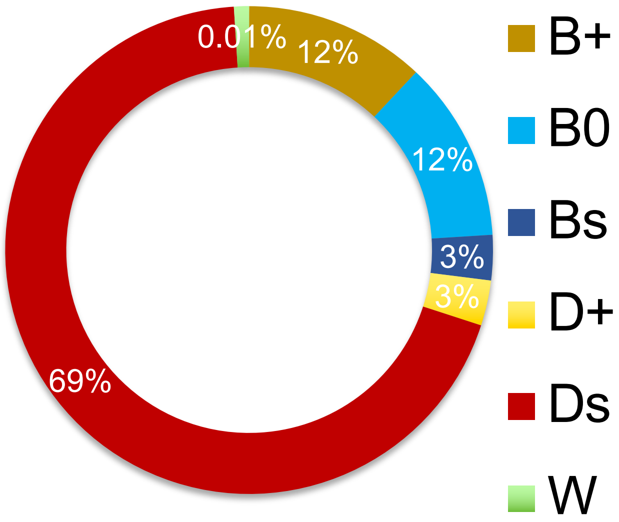




$\tau \longrightarrow 3\mu$

sources of τ leptons

Two sources of τ leptons used for the Run-2 analysis: heavy flavours and W



- **heavy flavour (HF)** mesons are the most abundant source of tau leptons in pp collisions (~10^{11} taus per /fb)
    - low-pT and high |η| → less efficient trigger selection
    - more sensitive to fake signal muons from π's and K's
- production in the **W channel** less abundant (~10^{7} taus per /fb)
    - harder spectra and more central decay → more efficient trigger selection
    - properties of W → τν bring additional handles for background suppression (large missing pT, low hadron activity, larger signal pT)

State of the art and 2016 CMS result

Observed upper limits (x10^{-8} @90% CL)

• **Belle** 782 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 2.1$	$e^+e^- \rightarrow \tau^+\tau^-$	10.1016/j.physletb.2010.03.037
• **BaBar** 468 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 3.3$	$e^+e^- \rightarrow \tau^+\tau^-$	10.1103/PhysRevD.81.111101
• **LHCb** 2 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 4.6$	HF$\rightarrow \tau$	10.1007/JHEP02(2015)121
• **ATLAS** 20.3 fb^{-1}	$\mathcal{B}(\tau \longrightarrow 3\mu) < 38$	W$\rightarrow \tau$	10.1140/epjc/s10052-016-4041-9
• **CMS** 33.2 fb^{-1} (partial Run-2)	$\mathcal{B}(\tau \longrightarrow 3\mu) < 8.0$	HF+W$\rightarrow \tau$	10.1007/JHEP01(2021)163

CMS 2016 (partial Run-2) result has proven that the experiment can investigate both the HF and W production channels with a good sensitivity → analysis extended to Run-2 (this presentation)

cds.cern.ch/record/2860087

$\tau \longrightarrow 3\mu$

overview

pp collision @13 TeV 131 /fb

- 2016 data analysis already public doi.org/10.1007/JHEP01(2021)163
- extend to full Run2 era

event selection

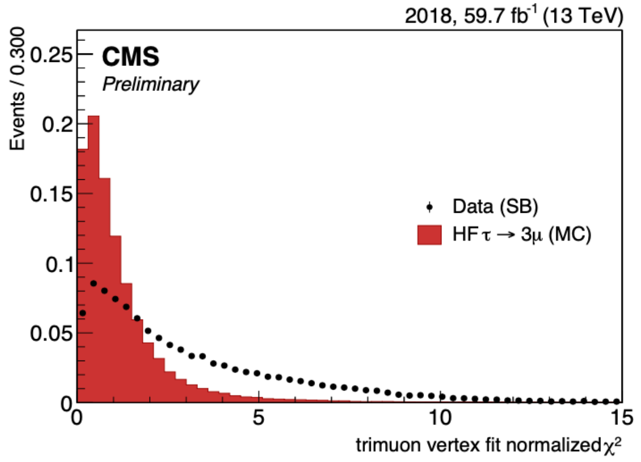
- **dedicated HLT paths** selects signal events
  - W: three isolated muons
  - HF: two muons and one track (2017) or three muons (2018)
- signal candidate composed of charge-one **three muons events** selected by the analysis trigger
- **categorize** events based on their invariant mass resolution
  - three categories per year per production channel
- figure of merit: **three-muon invariant mass** distribution → simulataneous fit the signal strength on each category

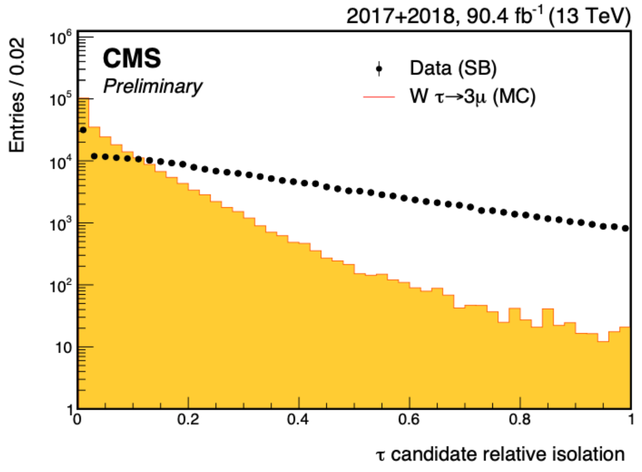
background rejection

- kinematically closed decays of **D mesons**
  - veto $\phi \to \mu\mu$ and $\omega \to \mu\mu$ resonances
  - muon ID by track quality to suppress pion and kaon fakes (ad-hoc MVA ID for HF channel)
- **semileptonic decays** of D mesons
  - involves non-reconstructed particles ⟶ mass below signal region
  - further suppression by an MVA discriminator
- **combinatorial** ⟶ suppressed by MVA discriminator
- **electroweak $W \to \mu\nu$+FSR decays**: 3μ+large MET prompt background survives the MVA selection, removed by cutting on the displacement significance from the interaction point

τ→3μ
multivariate analysis

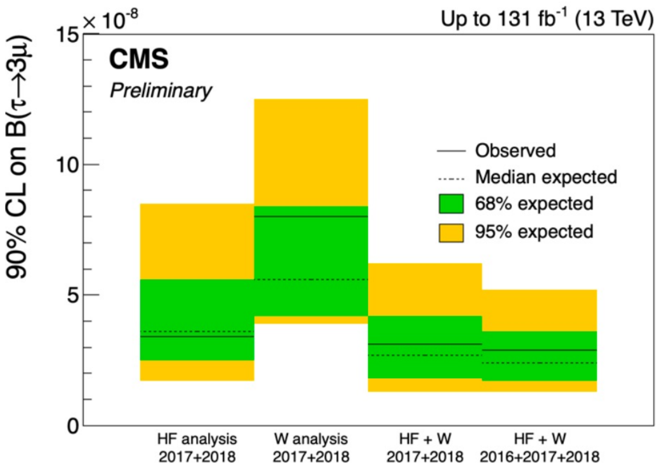
- using **Boosted Decision Tree** (BDT) discriminators to separate signal from background
  - **background**: data events from signal sidebands
  - **signal**: MC τ→3μ signal samples
- scale factors applied to the MC signal to match the data efficiencies and spectra
- training information includes kinematic (momenta, missing energy) and topological (SV properties, isolation properties) of the decay, specific of each channel
- BDT score thresholds are defined to tag signal candidates

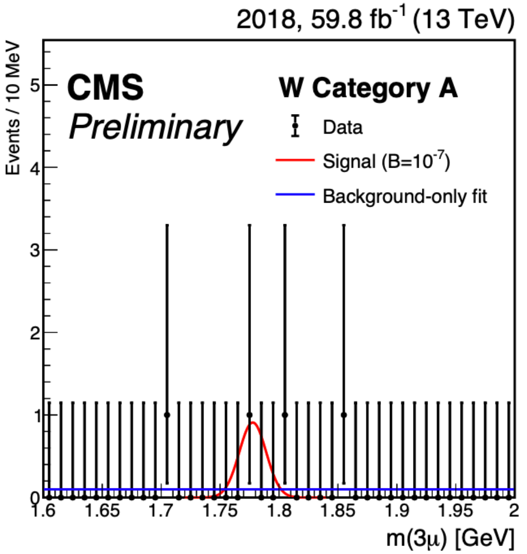




τ⟶3μ
results

- Signal strength extracted with **UML fit to the three-muon invariant mass** distribution
  - HF: gaussian+crystalball + exponential
  - W: gaussian + flat polynomial
  - **mass resolution categories combined via simultaneous fit** of the signal strength
  - no signal evidence in data ⟶ upper limit set on the τ⟶3μ branching fraction
- extend the analysis with the 2016 analysis (doi.org/10.1007/JHEP01(2021)163) to the full Run2 dataset





observed (expected) upper limit @ 90% of CL

B(τ→3μ) < 2.9 (2.4) x 10^{-8}

observed (expected) upper limit @ 95% of CL

B(τ→3μ) < 3.6 (3.0) x 10^{-8}

$\eta \rightarrow 4\mu$

doi.org/10.48550/arXiv.2305.04904

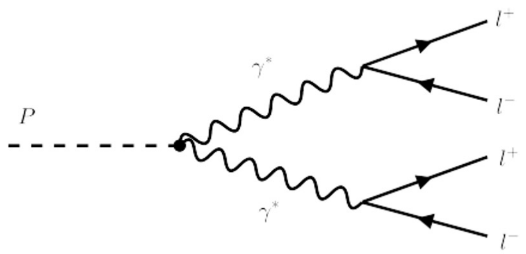
$\eta \to 4\mu$
introduction

motivation

- $\eta \to 4\mu$ decay predicted with a very low branching fraction (3.9×10^{-9})
  - never observed so far: precision test of the Standard Model (SM)
  - sensitive to new physics scenarios doi.org/10.1016/j.physrep.2021.11.001

result

- first observation of the rare $\eta \to 4\mu$ decay



data scouting

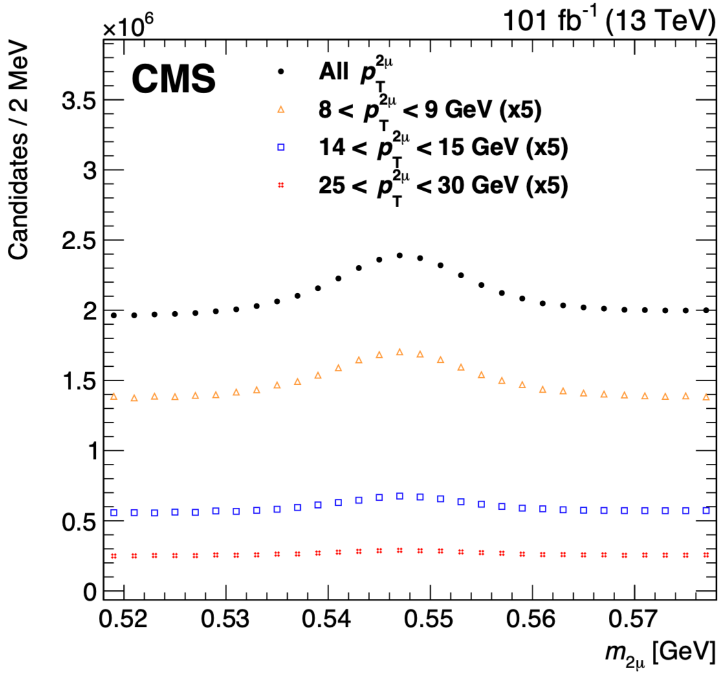
- trigger thresholds limited by the computing power and bandwidth of the experiment
- reduce event size and fasten data acquisition
  - limit the amount of information to muon tracks
  - save HLT reconstruction and skip *prompt* event processing
  - event size reduced to ~kB (from ~MB)

→ can use looser muon thresholds → allow for low transverse momentum (pT) rare decays searches

$\eta \to 4\mu$

event selection

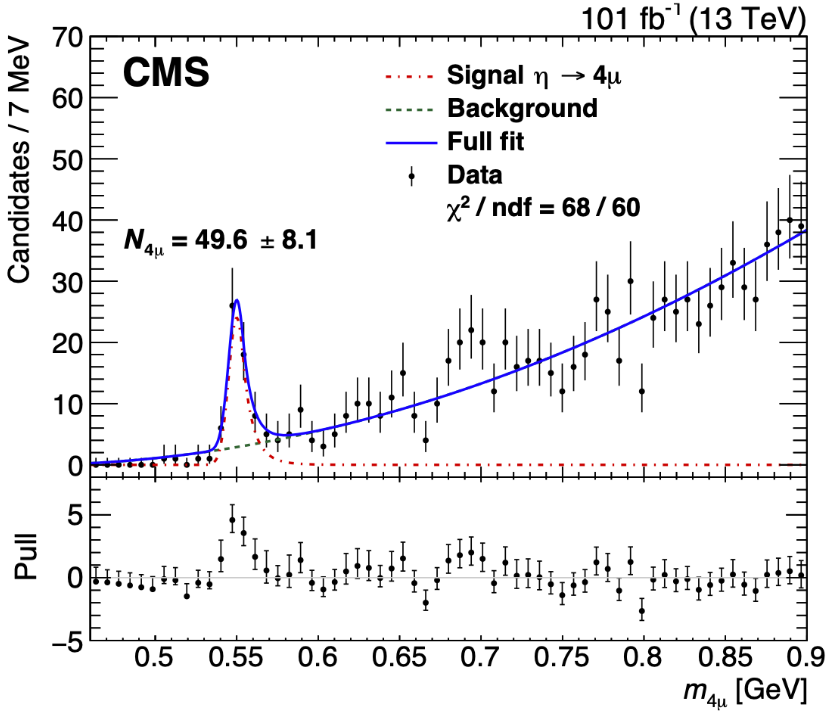
- pp collisions @ 13 TeV 101 /fb collected in 2017 and 2018
- CMS trigger system
  - L1 trigger: di-muon patterns select low-pT collimated muons (pT>~4 GeV)
  - HLT trigger: di-muon pattern with mild pT selection (pT>3 GeV)
  - di-muon triggers select both 4μ (signal) and 2μ (control channel) η decays
- trigger scouting for low pT analysis
  - higher trigger rate possible (2 kHz vs. 30 Hz of standard di-muon triggers)
  - size reduction: 4 (8) kB per event in 2017 (2018)
  - 4.5 M of $\eta \to 2\mu$ events recorded → several billions η mesons produced in the CMS acceptance
- further signal skimming: charge-zero 4μ events with common vertex



invariant mass of di-muon events in the eta range, collected by 2017 and 2018 CMS parking triggers

η→4μ
results

- η→4μ yield is normalized to the η→2μ yield
  - relatively precise normalization strategy (13.8% uncertainty)
- efficiency and acceptance corrections from MC samples
  - MC correction for 2μ-4μ differences
- η→4μ yield fit with CB function + polynomial
  - ~50 η→4μ events observed: 5 sigma excess from background (estimated with LLR)
  - resonant backgrounds faking 4μ in the signal region excluded by MC studies (see backup)



$$\mathcal{B}(\eta \to 4\mu) = 5.0 \pm 0.8(stat) \pm 0.7(syst) \pm 0.7(\mathcal{B}) \times 10^{-9}$$

- in agreement with SM prediction $3.98 \pm 0.15 \times 10^{-9}$

$B^0_{(s)} \longrightarrow \mu^+\mu^-$

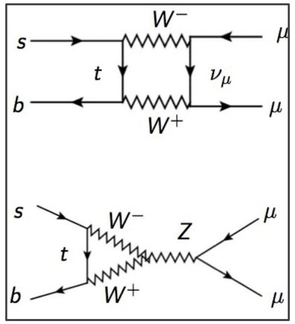
doi.org/10.1016/j.physletb.2023.137955

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

the physics case

motivations

- $B^0_{(s)} \to \mu^+\mu^-$ strongly suppressed in the SM (FCNC and helicity)
- connected to $b \to s l^+ l^-$ transitions via the EFT operators can help understand $b \to s$ anomalies doi.org/10.1140/epjc/s10052-021-09725-1
- probe SM though lifetime measurements
- clear final state and experimental signature at CMS



result

- pp @ 13 TeV Run2 data (2016-2018) 140 /fb
  - updates the published result on 2016 data (30 /fb)
- 12.5 sigma observation of the $B^0_{(s)} \to \mu^+\mu^-$ decay, upper limit on the $B(B^0 \to \mu^+\mu^-)$ and life time measurement of $B^0_{(s)} \to \mu^+\mu^-$

$B^0_{(s)} \to \mu^+\mu^-$ event selection

Data collection

- trigger selection: di-muon triggers with tight quality tracks and a valid secondary vertex (SV)
- similar selection for the control channels $B \to J/\Psi K^+$ and $B \to J/\Psi\phi$

signal selection

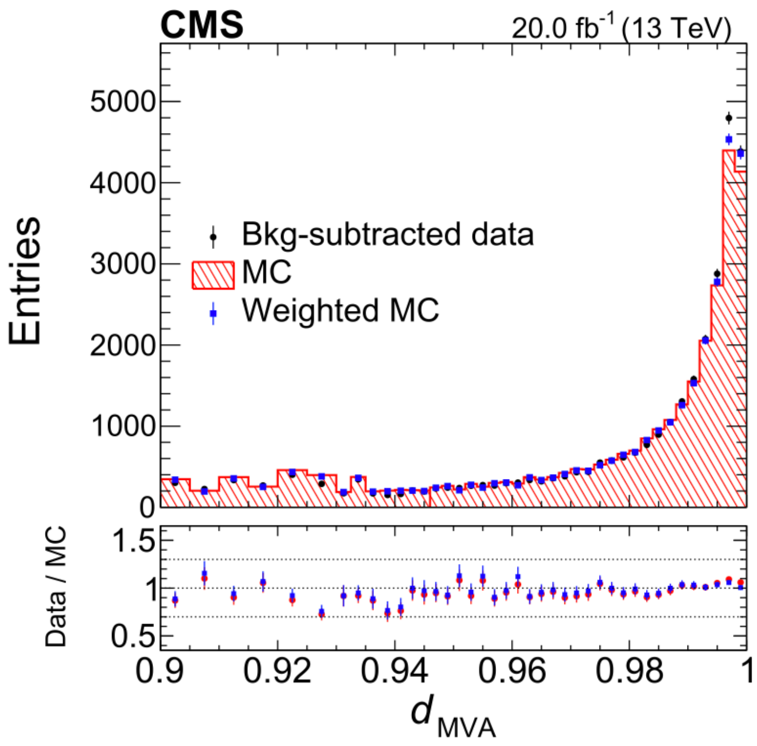
- two opposite-sign muons with pT > 4 GeV and $|\eta| < 1.4$
- decay vertex of B meson→ kinematic re-fit of the muon tracks with additional SV constraint
- 16 categories: 4 years x 2 BDT bins x 2 detector $|\eta|$ regions

Background contamination

- combinatorial from $b\bar{b}$ events → MVA reduction
- partially reconstructed semi-leptonic $b \to h\mu\nu$ and $b \to hhX$ decays → MVA reduction
- charmless hadronic two-body decays $B \to hh$ → negligible after tight muon track selection

$B^0_{(s)} \to \mu^+\mu^-$
MVA analysis

- exploit several weak discrimination variables with a BDT (XGBoost)
  - features: pointing angles (2D and 3D) → effective vs. all non-two-body backgrounds
  - features: SV (quality and displacement) → effective vs. combinatorial
  - features: isolation (sum of pT surrounding the signal) → effective vs. semi-leptonic decays
- trained on data from the signal mass sidebands and MC signal samples
  - validate on $B^+ \to J/\Psi K^+$ events



MVA score distribution for data (black dots), MC (bars) and re-weighted MC (blue dots) for 2016a $B^+ \to J/\Psi K^+$ events

$B^0_{(s)} \to \mu^+\mu^-$ signal extraction

- 2D UML fit to the μμ mass x mass-resolution to extract the B→μμ signal yields. Two strategies for B^0_s normalization:
  - $B^+ \to J/\Psi(\to\mu^+\mu^-)\,K^+$ normalization → rely on the knowledge of fs / fu
  - $B^0_s \to J/\Psi(\to\mu^+\mu^-)\,\phi(\to K^+K^-)$ normalization → higher systematic (additional kaon)

$$\mathcal{B}(B^0_s \to \mu\mu) = \mathcal{B}(B^+ \to J/\Psi K^+) \cdot \frac{N_{B^0_s\to\mu\mu}}{N_{B^+\to J/\Psi K^+}} \cdot \frac{\epsilon_{B^+\to J/\Psi K^+}}{\epsilon_{B^0_s\to\mu\mu}} \cdot \frac{f_u}{f_s}$$

derived from LHCb measurement: 0.231 ± 0.008

doi.org/10.1103/PhysRevD.104.032005

$$\mathcal{B}(B^0_s \to \mu\mu) = \mathcal{B}(B^0_s \to J/\Psi\Phi) \cdot \frac{N_{B^0_s\to\mu\mu}}{N_{B^0_s\to J/\Psi\Phi}} \cdot \frac{\epsilon_{B^0_s\to J/\Psi\Phi}}{\epsilon_{B^0_s\to\mu\mu}}$$

$$\mathcal{B}(B^0 \to \mu\mu) = \mathcal{B}(B^+ \to J/\Psi K^+) \cdot \frac{N_{B^0\to\mu\mu}}{N_{B^+\to J/\Psi K^+}} \cdot \frac{\epsilon_{B^+\to J/\Psi K^+}}{\epsilon_{B^0_s\to\mu\mu}} \cdot \frac{f_u}{f_d}$$

- UML fit to the decay time to extract τ (3D fit: decay time, its uncertainty and μμ mass)

$B^0_{(s)} \rightarrow \mu^+\mu^-$ results

$\mathcal{B}(\mathbf{B^0_s} \rightarrow \mu^+\mu^-) = 3.83^{+0.38}_{-0.36}(stat)^{+0.19}_{-0.16}(syst)\ ^{+0.14}_{-0.13}(fs/fu) \times 10^{-9}$ (from $J/\Psi K^+$)

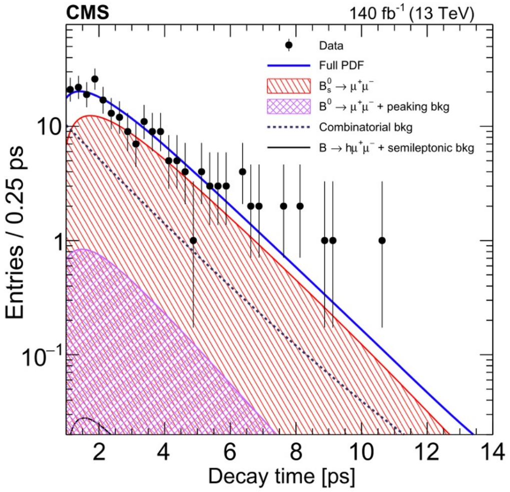
$\mathcal{B}(\mathbf{B^0_s} \rightarrow \mu^+\mu^-) = 4.02^{+0.40}_{-0.38}(stat)^{+0.28}_{-0.23}(syst)\ ^{+0.18}_{-0.15}(BF) \times 10^{-9}$ (from $J/\Psi\phi$)

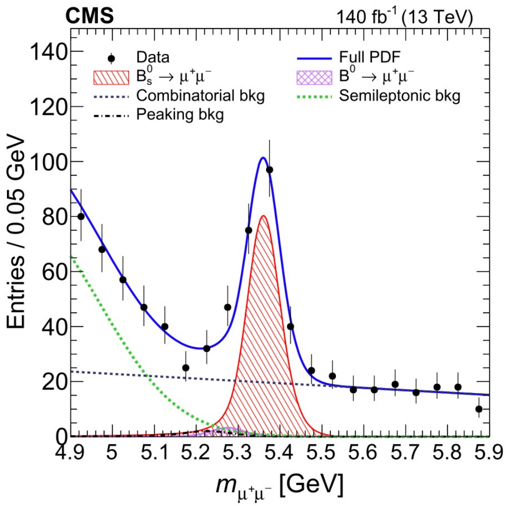
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-10}$ @ 90% CL

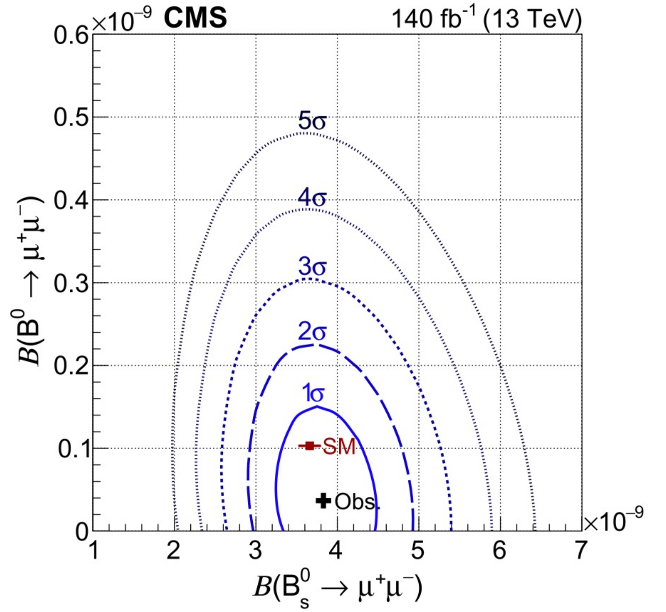
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.9 \times 10^{-10}$ @ 95% CL

$\tau(\mathbf{B^0_s}) = 1.83^{+0.23}_{-0.20}(stat)^{+0.04}_{-0.04}(syst)$ ps

- All UML fit results are compatible with the SM prediction within 1 sigma
- most precise measurement of $B^0_s \rightarrow \mu^+\mu^-$ branching fraction and lifetime to date







Summary

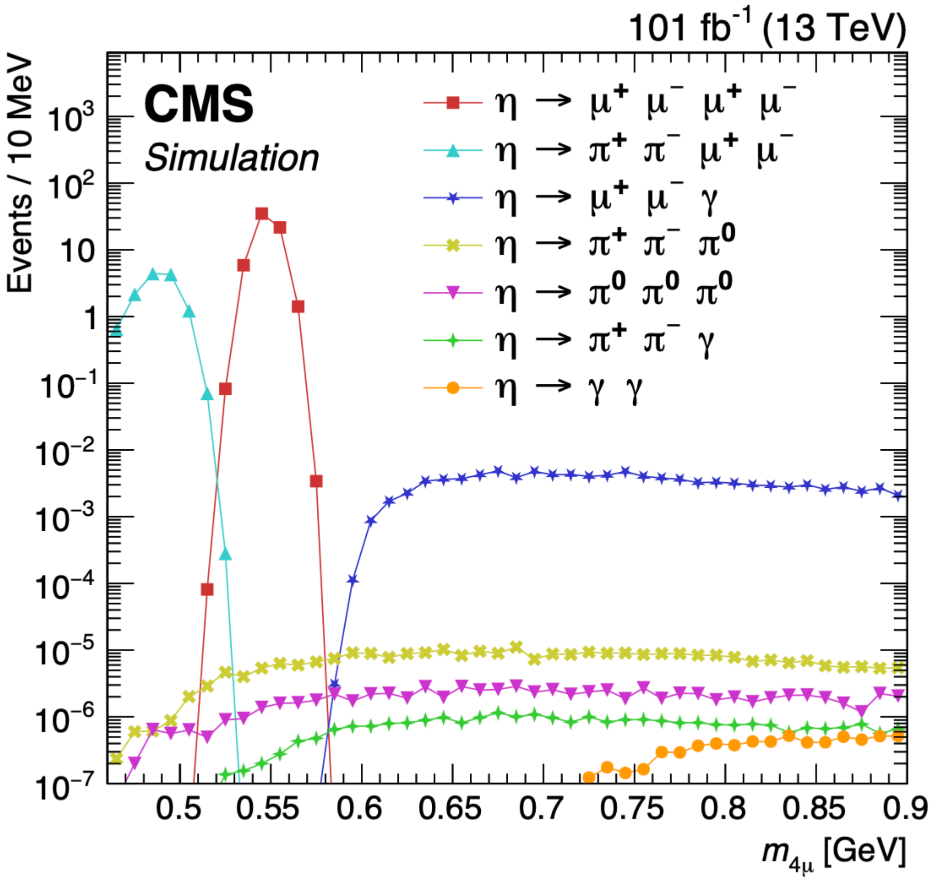
Summary of the talk

- **$\tau \to 3\mu$ (W and D/B channels) at CMS in pp collisions @ 13 TeV (131 /fb)**
  - observed (expected) $B(\tau \to 3\mu) < 2.9\ (2.4) \times 10^{-8}$ @ 90% CL
- **First $\eta \to 4\mu$ observation in CMS Run2 scouting data @ 13 TeV (101 /fb)**
  - $B(\eta \to 4\mu) = 5.0 \pm 0.8\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 0.7\ (B) \cdot 10^{-9}$
- **$B^0_{(s)} \to \mu^+\mu^-$ at CMS on pp collisions @ 13 TeV (140 /fb)**
  - $B(B^0_s \to K^{0*}\mu^+\mu^-) = 3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (\text{fs/fu}) \cdot 10^{-9}$ (*)
  - $B(B^0 \to \mu^+\mu^-) < 1.5\ (1.9) \cdot 10^{-10}$ @ 90% (95%) CL
  - $\tau(B^0_s) = 1.83^{+0.23}_{-0.20}(\text{stat})^{+0.04}_{-0.04}$ ps (*)

(*) most precise up to date

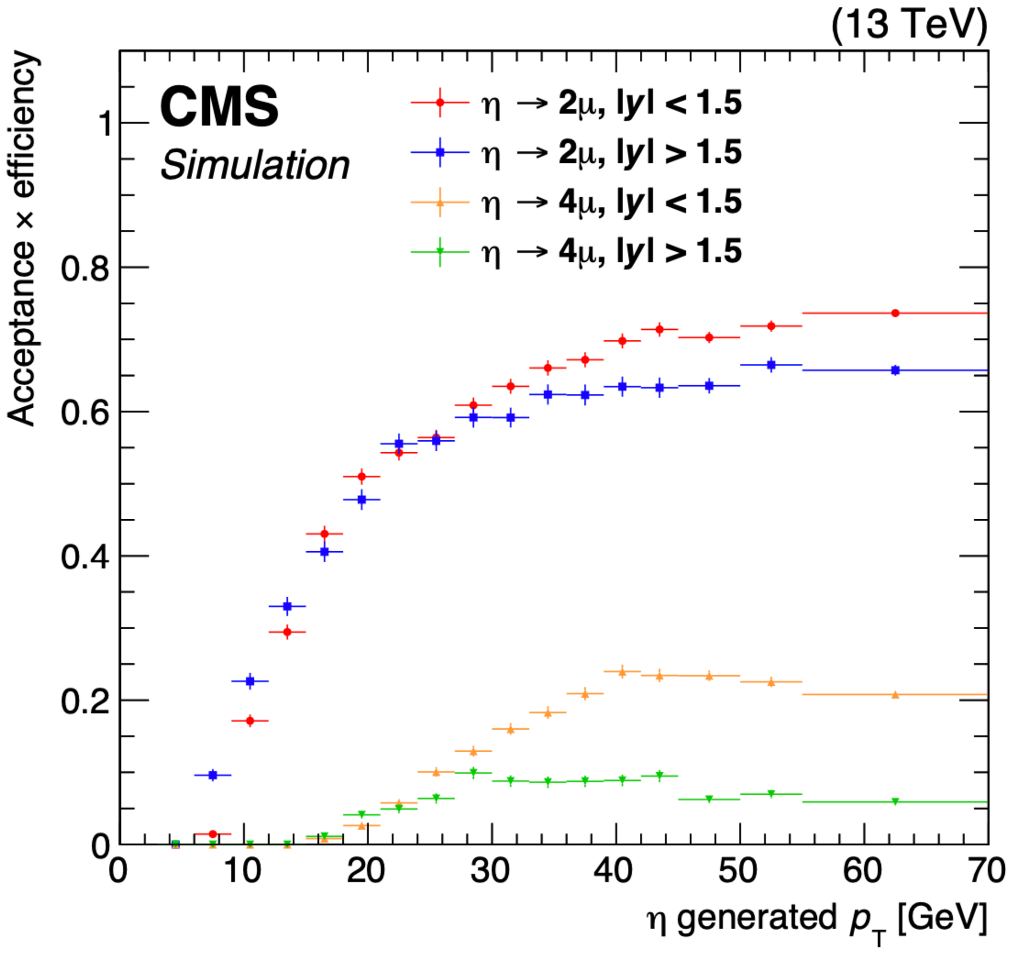
Backup

η→4μ
resonsnat background contamination



- no peaking decay under the η peak
- note: unobserved decays are normalized to their upper limit

η→4μ
acceptance correction



- 4μ and 2μ efficiencies in bins of pT and rapidity

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}},$$

i, j = pT and rapidity bins

$\eta \to 4\mu$
systematic uncertainties

- **track pT threshold uncertainty [9%]:** imperfect modeling of turn-on behaviour of single-muon reconstruction efficiency in simulated data
- **trigger pT threshold uncertainty [8.4%]**: imperfect modeling of turn-on behaviour of single-muon reconstruction efficiency at HLT in simulated data
- **plateau efficiency uncertainty [3.2%]:** mismodeling of trigger efficiency plateau
- **fit bias:** subdominant
- **$\eta \to 2\mu$ branching fraction [13.8%]**

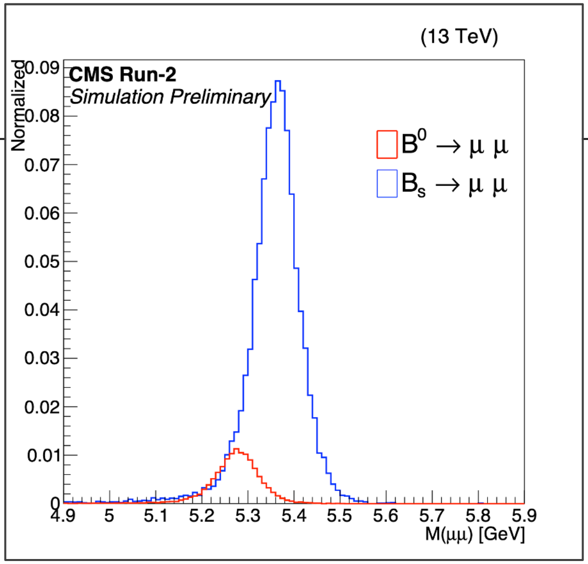
cds.cern.ch/record/2650545

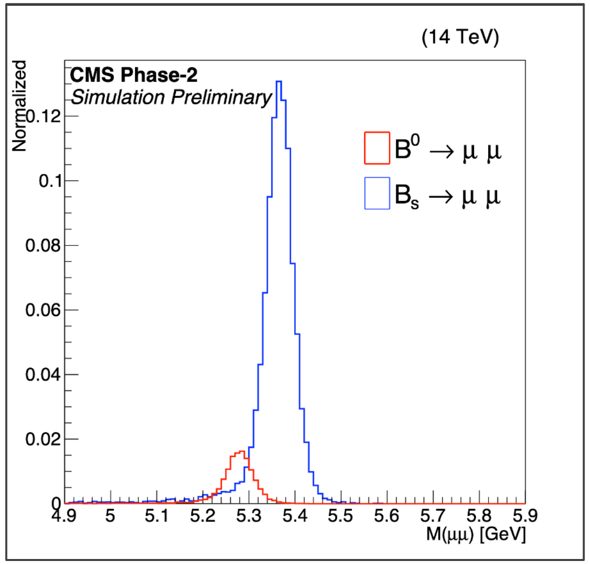
$B^0_{(s)} \to \mu^+\mu^-$ perspectives at the HL-LHC

- CMS prediction for HL-LHC (Phase 2) starting in 2029
  - 14 TeV pp collision → ~ same b production
  - x5 collision rate (200 PU) → no large impact from 200PU is expected
  - 3 /ab of luminosity → x20 Run-2
- extrapolation via MC simulation (full Phase2 detector) + toys from Run-1 results
  - reasonable projection of most of the systematic uncertainties (x0.5)
- much better mass resolution following tracker upgrade
  - less contamination from semi-leptonic fakes
  - better B^0_s - B^0 hypothesis separation

➢ Time resolution on lifetime: 0.05 ps

➢ observation of $B^0 \to \mu\mu$ at more than 5 sigmas





CMS: $B^0_{(s)} \to \mu^+\mu^-$

SYSTEMATIC UNCERTAINTIES

Table 3
Summary of the systematic uncertainties for the $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fraction measurements.

Effect	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
f_s/f_u ratio of the B meson production fractions	3.5%	–
d_{MVA} correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
Trigger efficiency	2.4–3.7%	
Fit bias	2.2%	4.5%
Pileup	1%	
Vertex quality requirement	1%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
$B^+ \to J/\psi K^+$ branching fraction	1.9%	

Table 4
Summary of the systematic uncertainties in the $B^0_s \to \mu^+\mu^-$ effective lifetime measurement (in ps) in four data-taking periods.

Effect	2016a	2016b	2017	2018
Lifetime fit bias	0.04	0.04	0.05	0.04
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Total	0.11	0.07	0.05	0.04

- **trigger:** data-MC comparison of control channels
- **pileup:** by means of reweighing
- **vertex:** the control channel triggers require a tighter selection. Evaluated the difference of the two selections.
- **MVA:** difference between data and MC efficiencies evaluated after an MVA reweight of the control channel
- **tracking:** comparing $D^0 \to K\pi$ and $D^0 \to K\pi\pi\pi$ ratio with world average
- **B→J/ΨK shape:** evaluating different shapes
- **fit bias:** with pseudo-experiments
- **fs/fu:** from external measurement
- **lifetime fit bias:** correlation of the BDT to the life-time. Measured by comparing the B→J/ΨK fit to the SM prediction after the BDT cut
- **decay time distribution mismodeling:** the lifetime distribution of simulated signal events is corrected using scale factors from B→J/ΨK events taken after BDT>.9 over BDT>.99. The fit difference introduced by data- or MC-derived corrections is taken as uncertainty.
- **efficiency modelling:** evaluated using different efficiency functions
- **lifetime fit bias:** measured with pseudo-experiments with different lifetimes

$\tau \to 3\mu$ at the HL-LHC

- luminosity-scaled projections based on the HF results place CMS sensitivity at 3.7×10^{-9} @ 90% CL

  arXiv:1812.07638