

FPCP 2023:

21st Conference on Flavour Physics and CP Violation

**Lyon - June 30<sup>th</sup>, 2023**

# Rare decays at CMS

# Overview

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## results from rare decays searches in B-physics at CMS

- search for the LFV  $\tau \rightarrow 3\mu$  decays in CMS in Run2 data
- observation of the rare  $\eta \rightarrow 4\mu$  decay at CMS in Run2 scouting data
- search for  $B^0_{(s)} \rightarrow \mu^+\mu^-$  events at CMS and  $B^0_s$  life-time measurement in Run2 data
- angular analysis  $B^0 \rightarrow K^{0*}\mu^+\mu^-$  at CMS in Run1 data

# The CMS detector

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

SILICON TRACKERS  
Pixel ( $100 \times 150 \mu\text{m}$ )  $\sim 1\text{m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80 \times 180 \mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

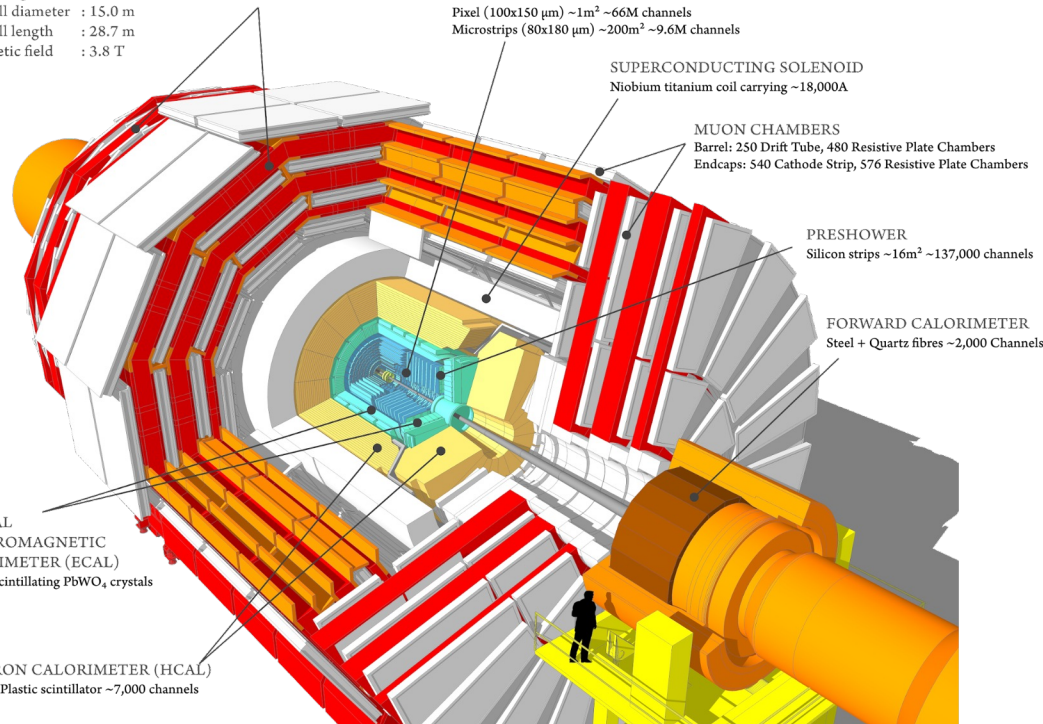
MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels



collected luminosity:

- Run1: 25 /fb pp @ 7 and 8 TeV
- Run2: 140 /fb pp @ 13 TeV
- Run3 ongoing, 37 /fb collected in 2022 @ 13.6 TeV

- cylindric compact (15m x 21m) detector
- high granularity pixel + strip silicon tracker for excellent track, PV and SV measurements
- $\text{PbWO}_4$  crystal ECAL and brass+plastic HCAL to achieve hermeticity and for 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)

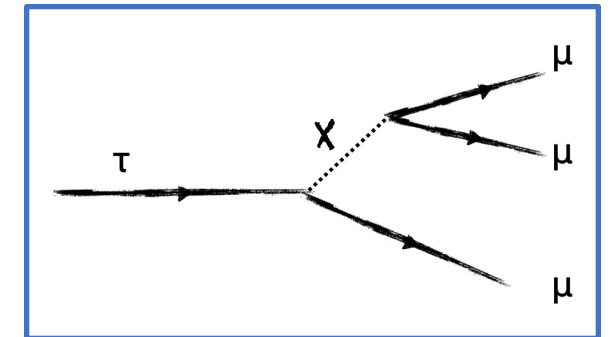
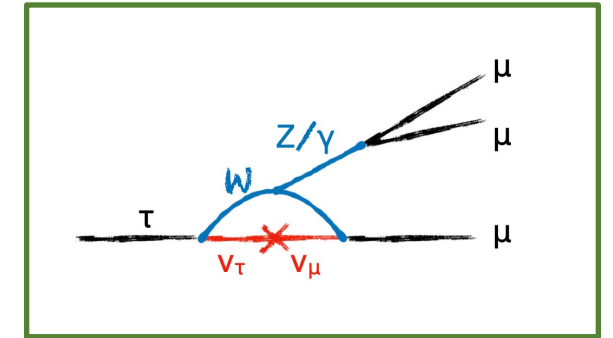
$$\tau^+ \rightarrow \mu^+ \mu^+ \mu^-$$

# $\tau \rightarrow 3\mu$

## the physics case

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

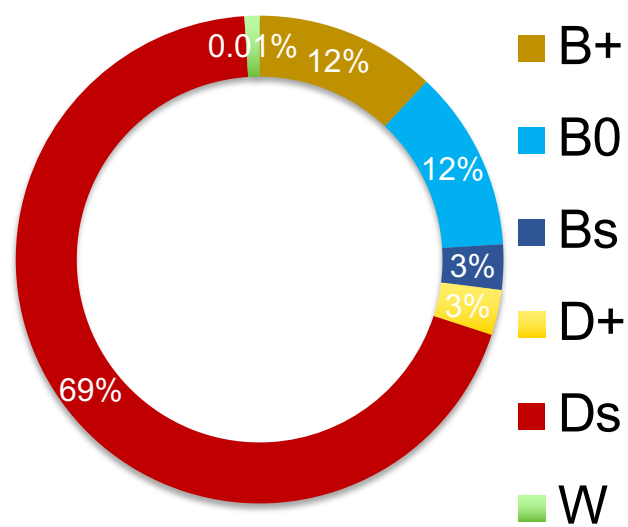
- allowed by **neutrino oscillations** at lowest Branching Ratios (BR) [10.1140/epjc/s10052-020-8059-7](https://arxiv.org/abs/10.1140/epjc/s10052-020-8059-7)
  - SM BR ( $\tau \rightarrow 3\mu$ )  $\sim 10^{-55}$
- LFV decays are a good field for **New Physics** (NP) searches
  - predicted by some NP model at BR  $\sim 10^{-9}$



# $\tau \rightarrow 3\mu$

## sources of $\tau$ leptons

Two sources of  $\tau$  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 ( $\sim 10^{11}$  taus per /fb)
  - low- $p_T$  and high  $|\eta| \rightarrow$  less efficient trigger selection
  - more sensitive to fake signal muons from  $\pi$ 's and K's
- production in the **W channel** less abundant ( $\sim 10^7$  taus per /fb)
  - harder spectra and more central decay  $\rightarrow$  more efficient trigger selection
  - properties of  $W \rightarrow \tau\nu$  bring additional handles for background suppression (large missing  $p_T$ , low hadron activity, larger signal  $p_T$ )

# $\tau \rightarrow 3\mu$

## overview

### pp collision @13 TeV 131 /fb

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

### event selection

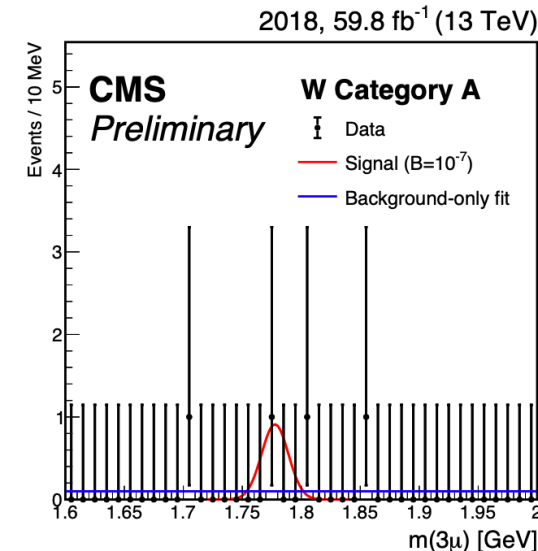
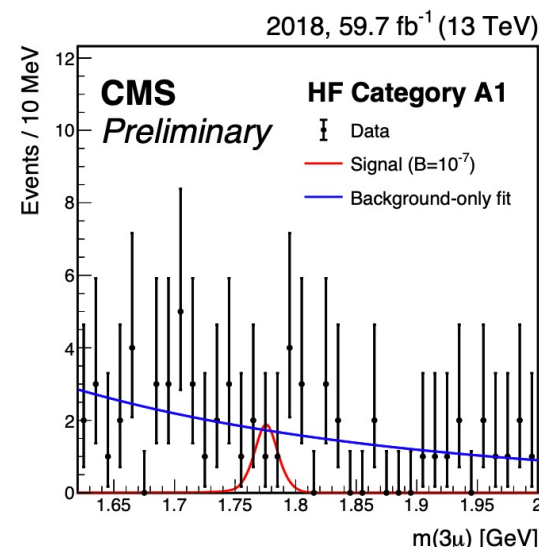
- **dedicated HLT paths** selects signal events
  - W: three isolated muons
  - HF: two muons and one track (2017) or three muons (2018)
- signal candidate composed of charge-one **three muons events** selected by the analysis trigger
- **categorize** events based on their invariant mass resolution
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

### background rejection

- kinematically closed decays of **D mesons**
  - veto  $\phi \rightarrow \mu\mu$  and  $\omega \rightarrow \mu\mu$  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  $\rightarrow$  mass below signal region
  - further suppression by an MVA discriminator
- **combinatorial**  $\rightarrow$  suppressed by MVA discriminator
- **electroweak  $W \rightarrow \mu\nu + \text{FSR decays}$** :  $3\mu$ +large MET prompt background survives the MVA selection, removed by cutting on the displacement significance from the interaction point

# $\tau \rightarrow 3\mu$ 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  $\rightarrow$  upper limit set on the  $\tau \rightarrow 3\mu$  branching fraction
- extend the analysis with the 2016 analysis ([doi.org/10.1007/JHEP01\(2021\)163](https://doi.org/10.1007/JHEP01(2021)163)) to the full Run2 dataset



observed (expected) upper limit @ 90% of CL

$$B(\tau \rightarrow 3\mu) < 2.9 \text{ (2.4)} \times 10^{-8}$$

observed (expected) upper limit @ 95% of CL

$$B(\tau \rightarrow 3\mu) < 3.6 \text{ (3.0)} \times 10^{-8}$$



$$\eta \rightarrow 4\mu$$

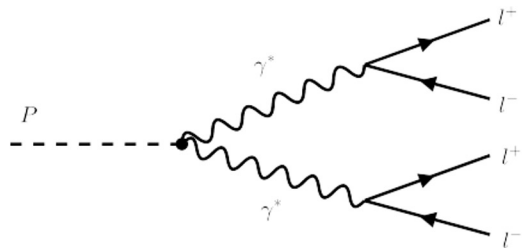
# $\eta \rightarrow 4\mu$ introduction

## motivation

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

## result on pp collisions @ 13 TeV (101 /fb)

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

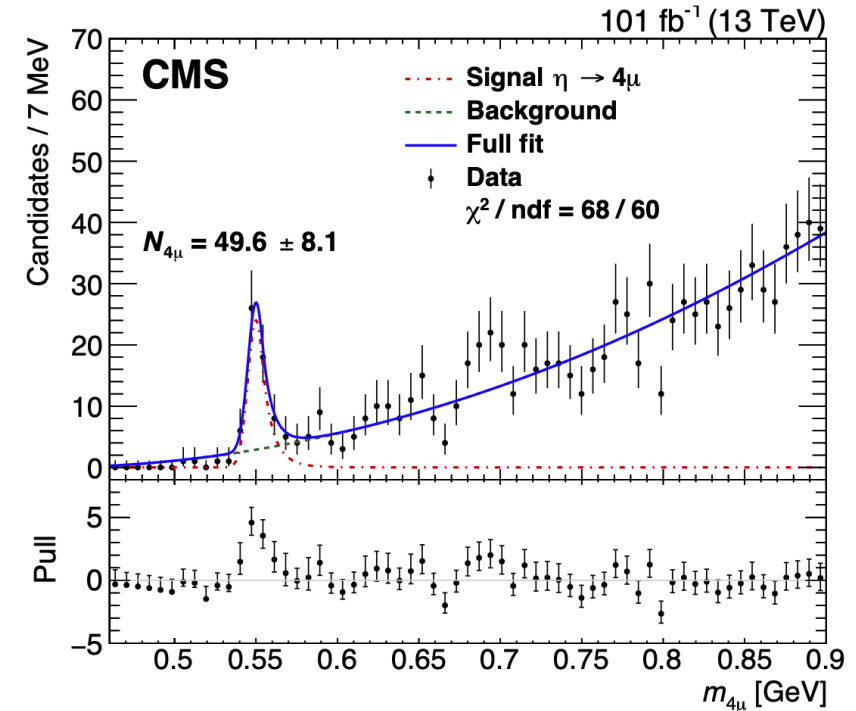


## analysis overview and data scouting

- 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**
    - **run analysis on 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
- further skimming of signal candidates to isolate 4-muons zero-charge events

# $\eta \rightarrow 4\mu$ results

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



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

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

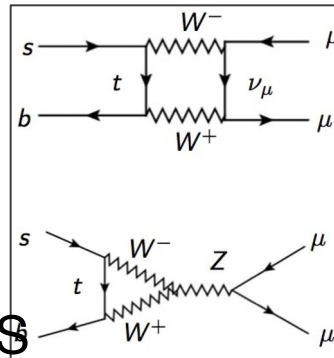
$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

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

## the physics case

### motivations

- $B^0_{(s)} \rightarrow \mu^+ \mu^-$  strongly suppressed in the SM (FCNC and helicity)
- connected to  $b \rightarrow s l^+ l^-$  transitions via the EFT operators can help understand  $b \rightarrow s$  anomalies [doi.org/10.1140/epjc/s10052-021-09725-1](https://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  $B^0_{(s)} \rightarrow \mu^+ \mu^-$  decay, upper limit on the  $B(B^0_{(s)} \rightarrow \mu^+ \mu^-)$  and life time measurement of  $B^0_{(s)} \rightarrow \mu^+ \mu^-$

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

## 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  $B \rightarrow J/\psi K^+$  and  $B \rightarrow J/\psi \phi$

### signal selection

- two opposite-sign muons with  $p_T > 4 \text{ GeV}$  and  $|\eta| < 1.4$
- decay vertex of B meson  $\rightarrow$  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  $\rightarrow$  MVA reduction
- partially reconstructed semi-leptonic  $b \rightarrow h\mu\nu$  and  $b \rightarrow hhX$  decays  $\rightarrow$  MVA reduction
- charmless hadronic two-body decays  $B \rightarrow hh \rightarrow$  negligible after tight muon track selection

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

- Extract branching fraction with UML fit to the mass distribution x its uncertainty
- Normalize wrt to the  $B^+ \rightarrow J/\psi K^+$  or  $B^0 \rightarrow J/\psi \phi$  control channels
- Extract lifetime with UML fit to decay time x its uncertainty x  $\mu\mu$  invariant mass

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = 3.83^{+0.38}_{-0.36}(\text{stat})^{+0.14}_{-0.13}(\text{syst})^{+0.14}_{-0.13}(fs/fu)$$

x  $10^{-9}$  (from  $J/\psi K^+$ )

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = 3.95^{+0.39}_{-0.37}(\text{stat})^{+0.27}_{-0.22}(\text{syst})^{+0.21}_{-0.19}(BF)$$

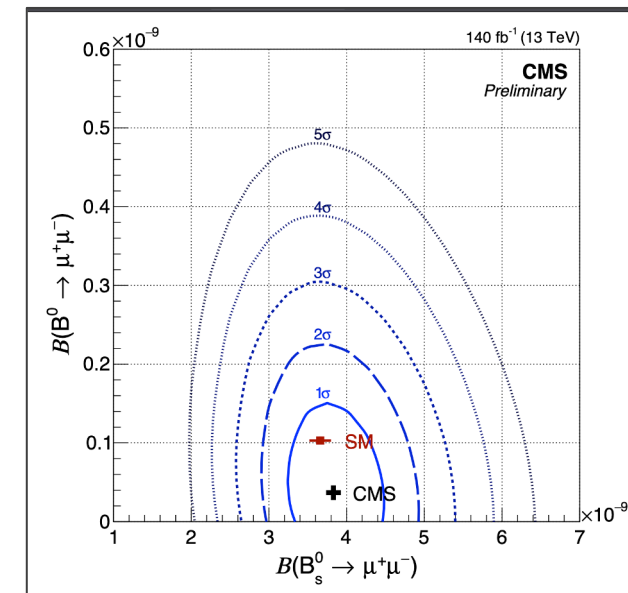
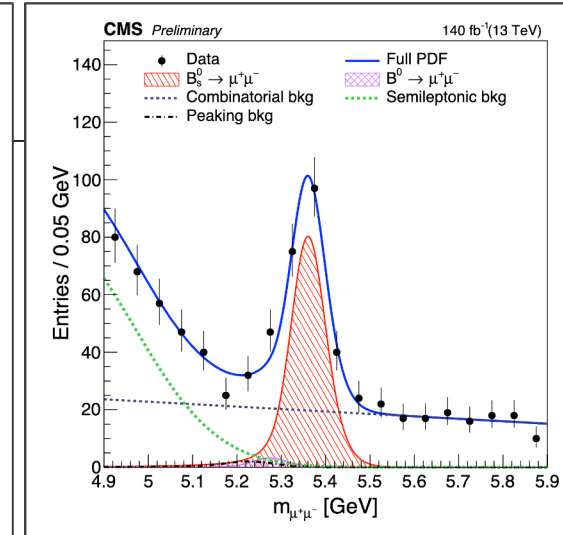
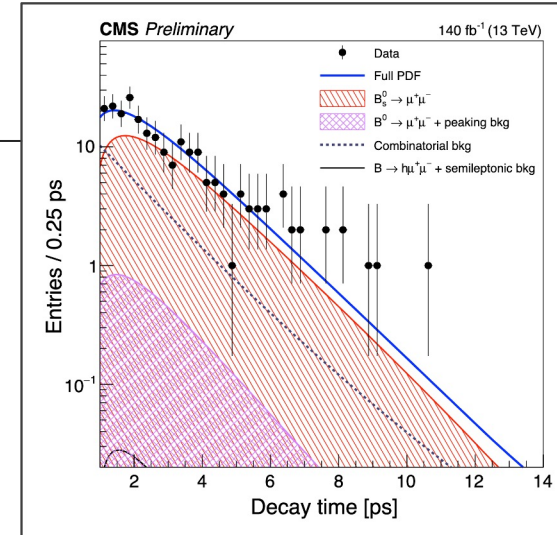
x  $10^{-9}$  (from  $J/\psi \phi$ )

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

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

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

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

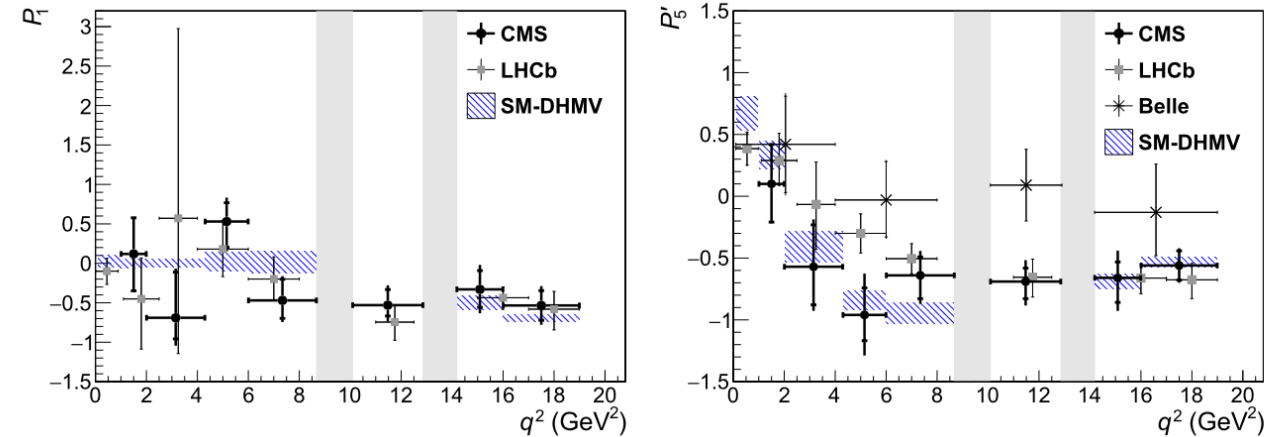


$$B^0 \rightarrow K^{0*} \mu^+ \mu^-$$



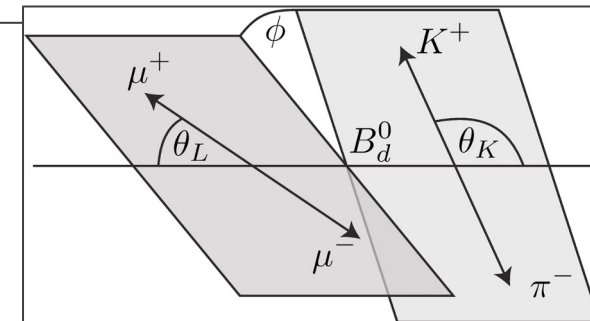
# $B^0 \rightarrow K^{0*} \mu^+ \mu^-$

- FCNC strongly suppressed in the SM
- new physics might manifest as distortions of the SM angular distribution (defined by the  $P_1$  and  $P_5'$  parameters)
  - $P_5'$  most interesting following 2–3 sigmas deviation from SM observed by LHCb in the  $4 < q^2 < 6$  and  $6 < q^2 < 8$   $\text{GeV}^2$  bins in Run1



- **Run1 data @8 TeV (20.5 /fb)**
- signal selected in the  $\mu\mu K\pi$  final state from the same vertex
  - resolve PID ambiguity by selecting the  $K\pi$  hypothesis closest to the  $K^*$  mass (misid: 12-14%)
- angular analysis: **fit the three-angular distribution x mass distribution** to extract the parameters

- **no significant deviation from the SM observed**
- results compatible with LHCb



# Summary

# Summary of the talk

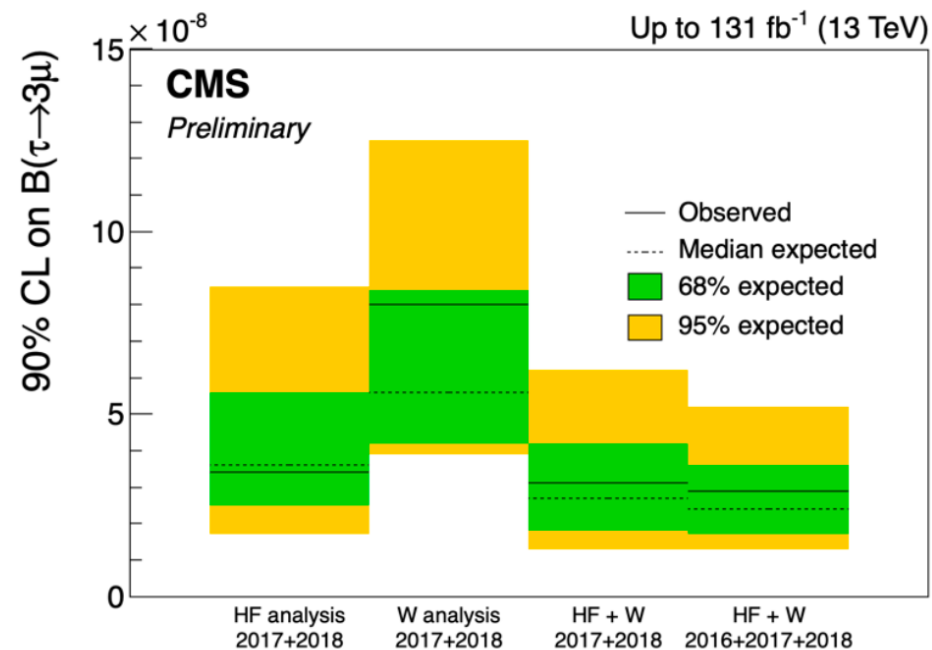
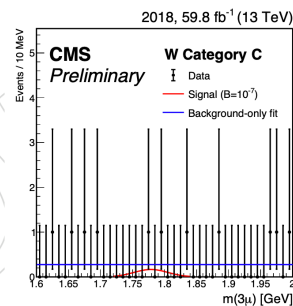
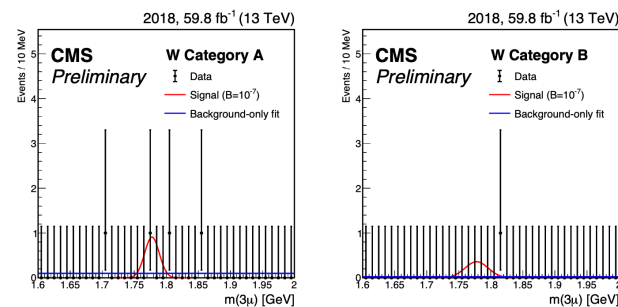
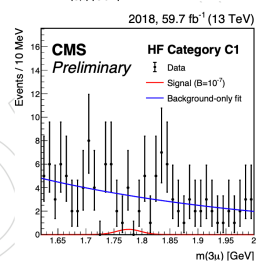
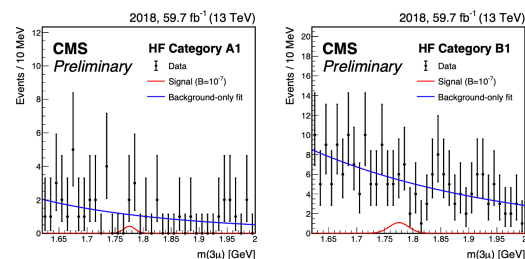
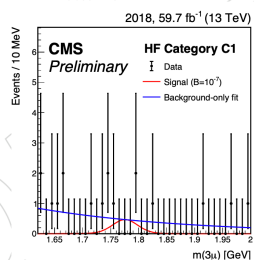
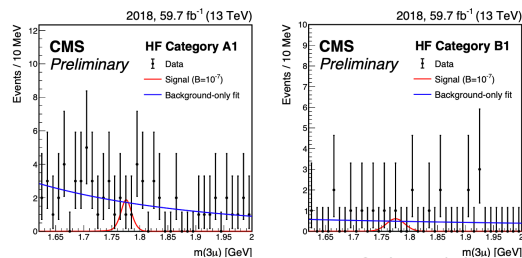
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- **$\tau \rightarrow 3\mu$  (W and D/B channels) at CMS in pp collisions @ 13 TeV (131 /fb)**
  - observed (expected)  $B(\tau \rightarrow 3\mu) < 2.9 (2.4) \times 10^{-8}$  @ 90% CL
- **First  $\eta \rightarrow 4\mu$  observation in CMS Run2 scouting data @ 13 TeV (101 /fb)**
  - $B(\eta \rightarrow 4\mu) = 5.0 \pm 0.8 \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.7 \text{ (B)} \cdot 10^{-9}$
- **$B^0_{(s)} \rightarrow \mu^+ \mu^-$  at CMS on pp collisions @ 13 TeV (140 /fb)**
  - $B(B^0_s \rightarrow \mu^+ \mu^-) = 3.83^{+0.38}_{-0.36} \text{ (stat)}^{+0.14}_{-0.13} \text{ (syst)}^{+0.14}_{-0.13} \text{ (fs/fu)} \cdot 10^{-9} \text{ (*)}$
  - $B(B^0 \rightarrow \mu^+ \mu^-) < 1.5 (1.9) \cdot 10^{-10}$  @ 90% (95%) CL
  - $\tau(B^0_s) = 1.83^{+0.23}_{-0.20} \text{ (stat)}^{+0.04}_{-0.04} \text{ ps (*)}$
- **$B^0 \rightarrow K^{0*} \mu^+ \mu^-$  at CMS in pp collisions @ 8 TeV (20.5 /fb)**
  - angular analysis: all angular parameters compatible with the SM, no deviation observed in the  $P5'$  parameter

(\*) most precise up to date

Backup

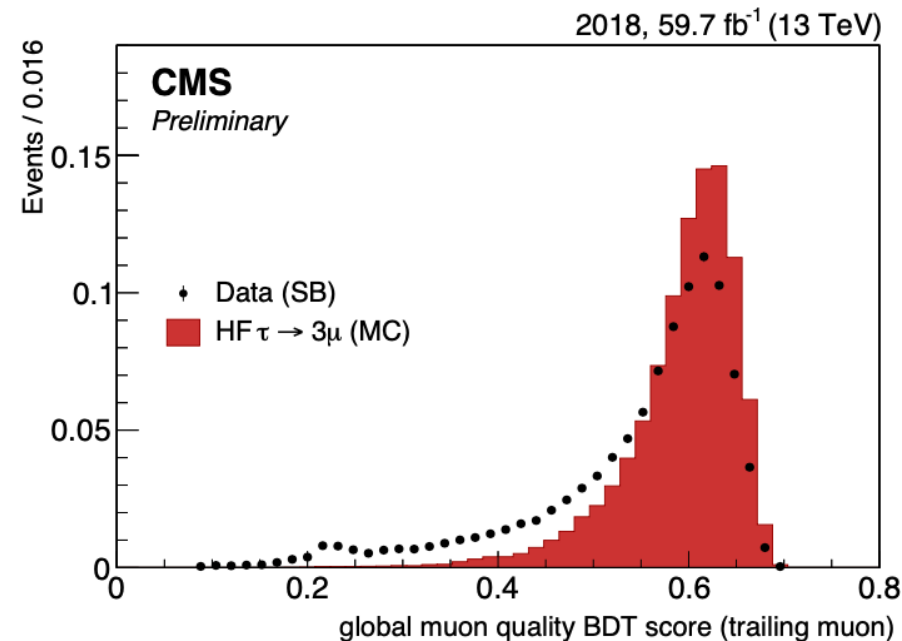
# $\tau \rightarrow 3\mu$ mass plots



# $\tau \rightarrow 3\mu$

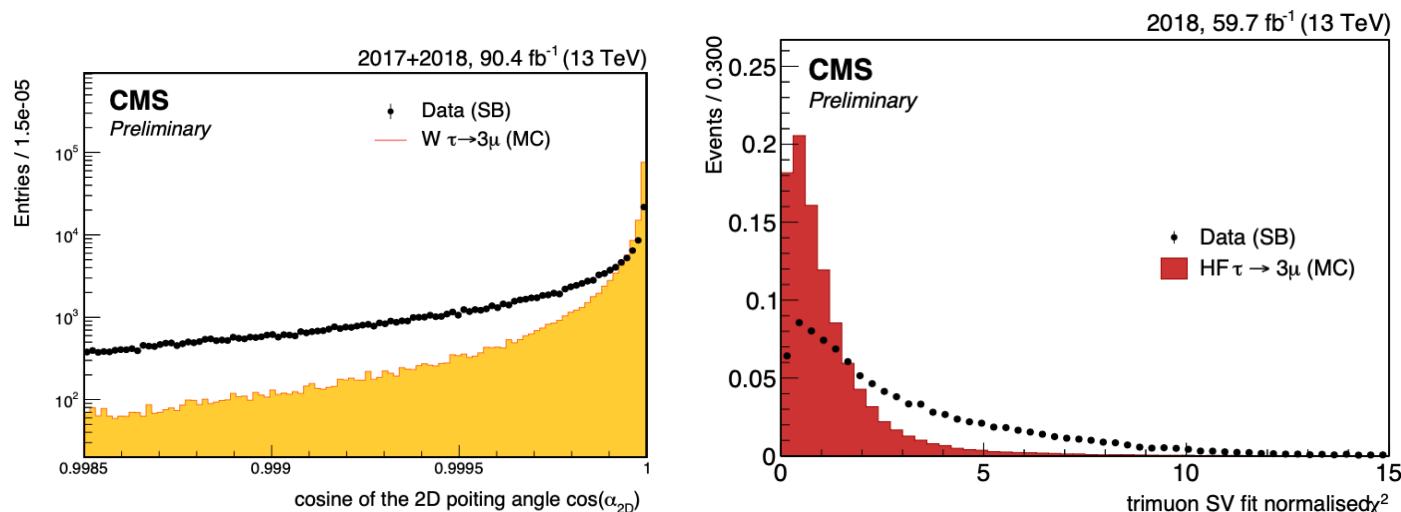
## MVA muon ID

- suppress fake contamination from pions and kaons
- trained on MC events of  $B \rightarrow hh$  decays (fakes) and  $\tau \rightarrow 3\mu$  decays (true muons)
- training information from silicon and muon tracks and their compatibility



# $\tau \rightarrow 3\mu$ multivariate analysis

- reject background events via **Boosted Decision Tree (BDT)**
- **signal**: MC  $\tau \rightarrow 3\mu$  simulation passing the pre-selection
- **background**: data events passing the preselection, taken from the signal side-bands
- HF and W topologically and kinematically different: different training for the two channels
- **input features** from decay **kinematics** and **topology** and **SV** properties



## W channel features

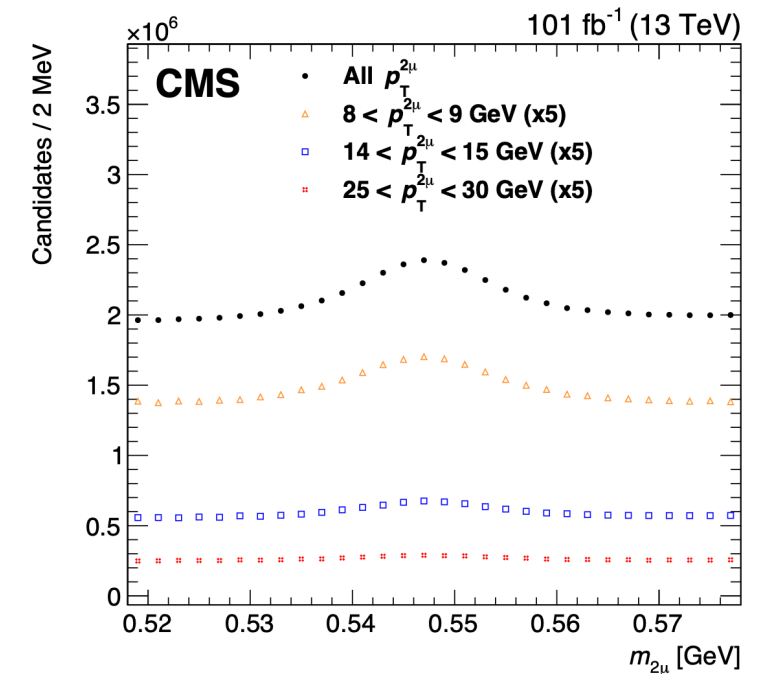
- W and muons transverse momenta
- transverse missing momentum and transverse mass  $m_T = \sqrt{2p_T^\tau p_T^{\text{miss}}(1 - \cos \Delta\phi(\tau, \vec{p}_T^{\text{miss}}))}$
- muon tight quality flag
- missing longitudinal momentum
- SV fit probability, displacement uncertainty, pointing angle cosine
- isolation

## HF features

- tau candidate transverse momentum
- muon MVA and hardware quality score
- SV fit  $\chi^2$ , displacement significance and pointing angle
- isolation

# $\eta \rightarrow 4\mu$ 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 ( $p_T > \sim 4$  GeV)
  - HLT trigger: di-muon pattern with mild  $p_T$  selection ( $p_T > 3$  GeV)
  - di-muon triggers select both  $4\mu$  (signal) and  $2\mu$  (control channel)  $\eta$  decays
- trigger scouting for low  $p_T$  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  $\eta \rightarrow 2\mu$  events recorded  $\rightarrow$  several billions  $\eta$  mesons produced in the CMS acceptance
- further signal skimming: charge-zero  $4\mu$  events with common vertex



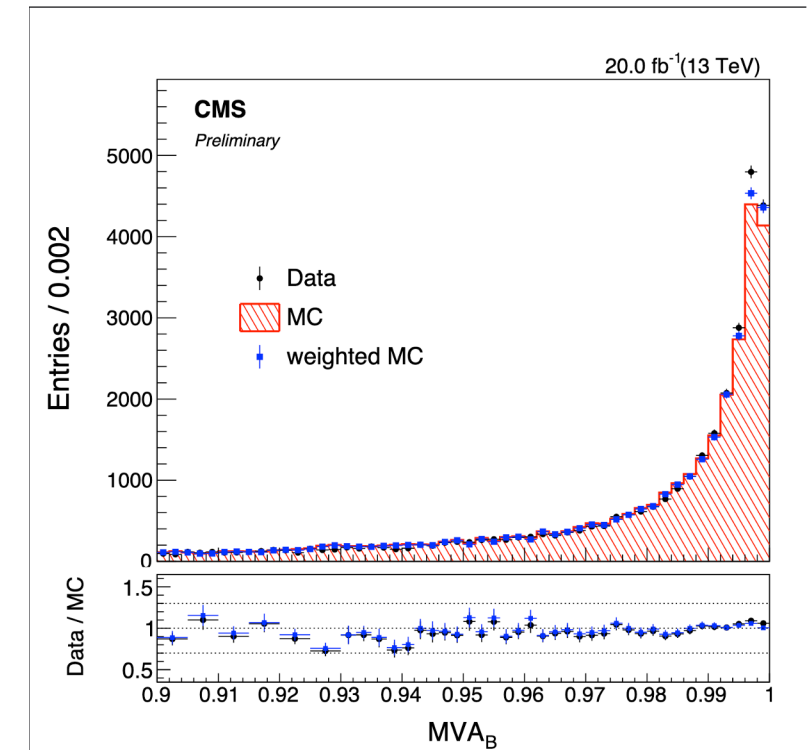
invariant mass of di-muon events in the eta range, collected by 2017 and 2018 CMS parking triggers



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

## MVA analysis

- exploit several weak discrimination variables with a BDT
  - 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  $B^+ \rightarrow J/\psi K^+$  events



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

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

## signal extraction

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

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

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

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

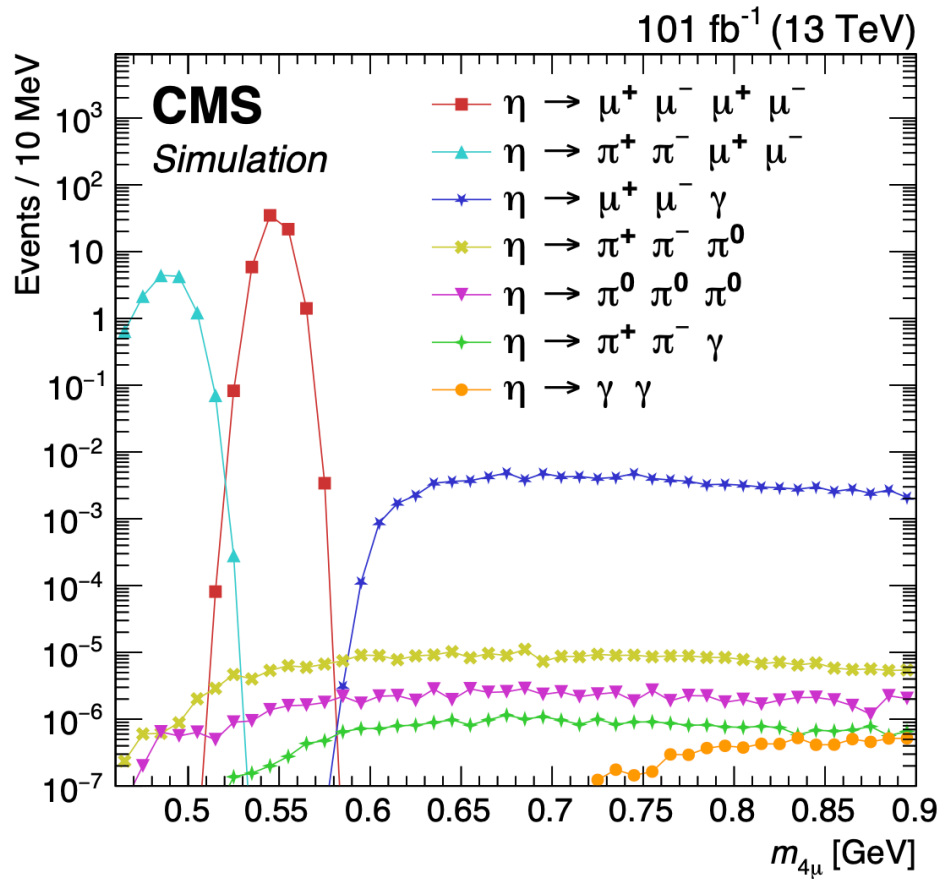
derived from  
LHCb  
measurement:  
 $0.231 \pm 0.008$

[doi.org/10.1103/PhysRevD.104.032005](https://doi.org/10.1103/PhysRevD.104.032005)

- UML fit to the decay time to extract  $\tau$  (3D fit: decay time, its uncertainty and  $\mu\mu$  mass)

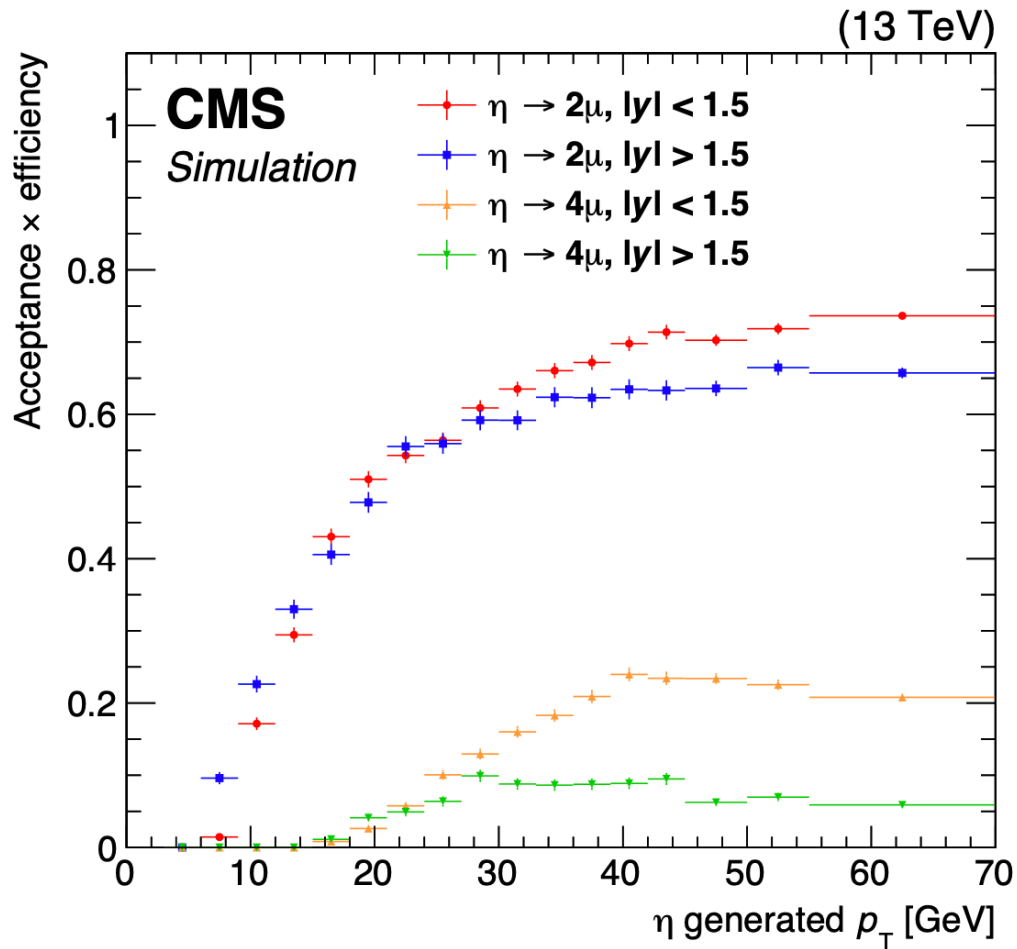
# $\eta \rightarrow 4\mu$

## resonant background contamination



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

# $\eta \rightarrow 4\mu$ acceptance correction



- $4\mu$  and  $2\mu$  efficiencies in bins of  $p_T$  and rapidity

# $\eta \rightarrow 4\mu$ systematic uncertainties

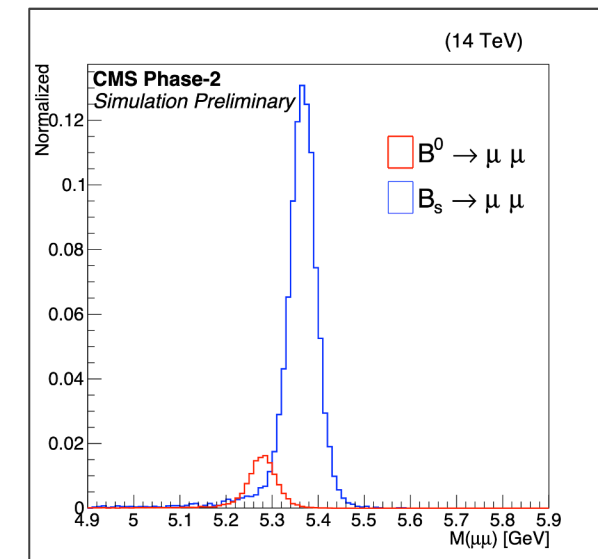
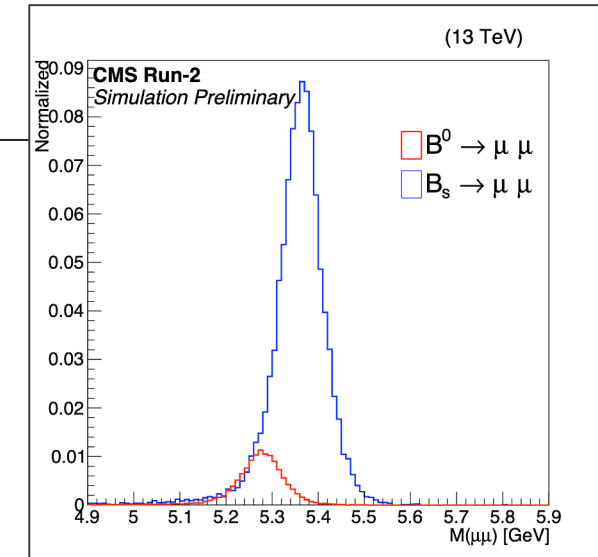
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- **track pT threshold uncertainty [9%]:** imperfect modeling of turn-on behaviour of single-muon reconstruction efficiency in simulated data
- **trigger pT threshold uncertainty [8.4%]:** imperfect modeling of turn-on behaviour of single-muon reconstruction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

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

## perspectives at the HL-LHC

- CMS prediction for HL-LHC (Phase 2) starting in 2029
  - 14 TeV pp collision  $\rightarrow$   $\sim$  same b production
  - x5 collision rate (200 PU)  $\rightarrow$  no large impact from 200PU is expected
  - 3 /ab of luminosity  $\rightarrow$  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  $B_s^0$  -  $B^0$  hypothesis separation
- Time resolution on lifetime: 0.05 ps
- observation of  $B^0 \rightarrow \mu\mu$  at more than 5 sigmas



# CMS: $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

## SYSTEMATIC UNCERTAINTIES

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

Effect	$B_s^0 \rightarrow \mu^+ \mu^-$	$B^0 \rightarrow \mu^+ \mu^-$
Trigger efficiency	2 – 4%	
Pileup	1%	
Vertex quality requirement	1%	
MVA <sub>B</sub> correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
$B^+ \rightarrow J/\psi K^+$ shape uncertainty	1%	
Fit bias	2.2%	4.5%
$f_s/f_u$ - ratio of the B meson production fractions	3.5%	-

Table 4: Summary of the systematic uncertainties in the  $B_s^0 \rightarrow \mu^+ \mu^-$  effective lifetime measurement (ps).

Effect	2016a	2016b	2017	2018
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Lifetime fit bias	0.04	0.04	0.05	0.04
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  $D^0 \rightarrow K\pi$  and  $D^0 \rightarrow K\pi\pi\pi$  ratio with world average
- **$B \rightarrow J/\psi K$  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  $B \rightarrow J/\psi K$  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  $B \rightarrow J/\psi K$  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

# $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ systematic uncertainties

Source	$P_1 (\times 10^{-3})$	$P'_5 (\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
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	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

- **simulation mismodeling:** fit a simulated signal sample with 400x data and see the fit difference wrt to the input
- **fit bias:** use 200 simulated signal samples + simulated data (~data size) to estimate the fit bias
- **finite size of simulated samples:** due to the finite size of the MC used to derive the efficiency shape. Generate 100 numerator and denominator shapes from the original ones and refit them to estimate the difference due to the statistical uncertainty.
- **efficiency:** fit the control channels to extrapolate fixed parameters (FL) and cross check with PDG
- **$K\pi$  mistagging:** fit the mistag rate on the control channel  $B \rightarrow J/\psi K^*$  and take the difference wrt the simulation as systematics
- **background shape:** fit the data 200 times varying the shape of the background distributions within their error (fixed in these test fits) and evaluating the POIs distribution RMS
- **signal mass shape:** fit the control channels letting their width vary alternately and see the effect on the POIs
- **background feed-through:** see the difference in the POIs after counting for an additional systematic uncertainty describing the feed-through from  $B \rightarrow J/\psi / \psi' K^*$  events
- **$F_L, F_S, A_S$  uncertainties propagation:** fit pseudo-experiments allowing these parameters to change and compare the POIs values with the nominal procedure
- **angular resolution:** fit a simulated sample using generated or reconstructed values of the angular parameters and see the difference

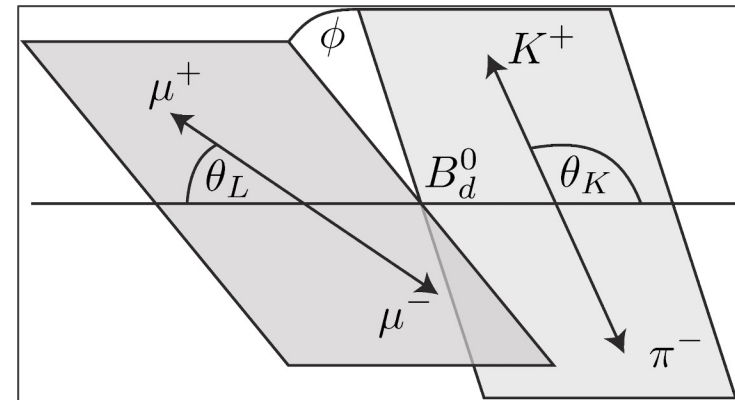


# $B^0 \rightarrow K^{0*} \mu^+ \mu^-$

## fit strategy

- simplify the angular pdf by considering symmetries in the  $\phi=0$  and  $\theta_l=\pi/2$  angles
  - reduce the POIs that can be extracted to  $P_1$  and  $P_5$
- UML fit to the mass and angular distributions
  - signal mass shape: double-gaussian different for correct- and wrong-tagged events, with parameters obtained from simulated samples
  - angular pdf for background: polynomials (factorizing)
  - mass pdf for background: exponential
  - angular efficiencies: obtained from kernel-density estimators, different for correct- and wrong-tagged events
- Fit run in two steps:
  1. fit the sidebands and fix the background shapes
  2. fit the full distribution and obtain the POIs

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



# $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ results

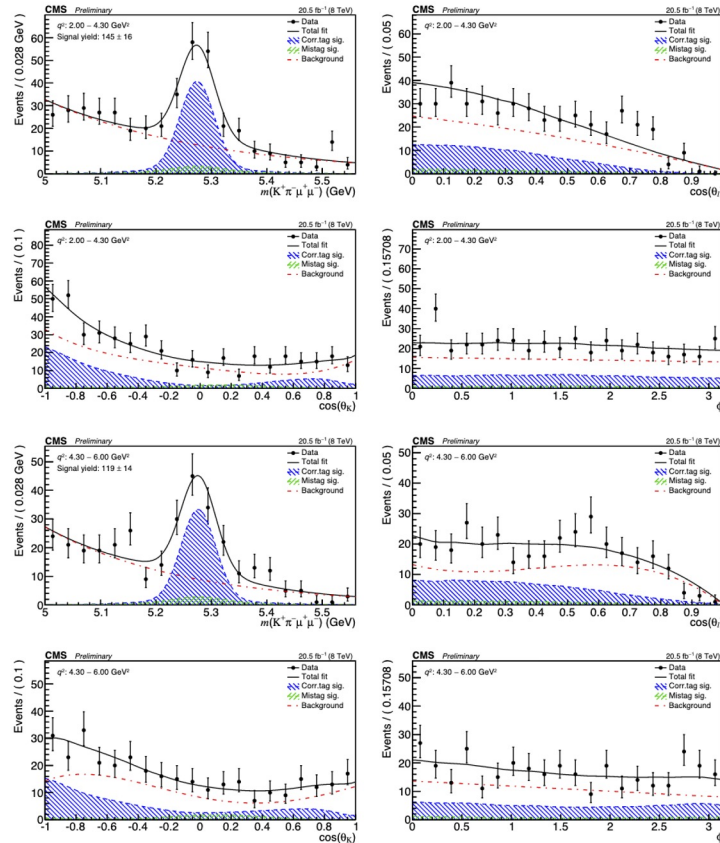
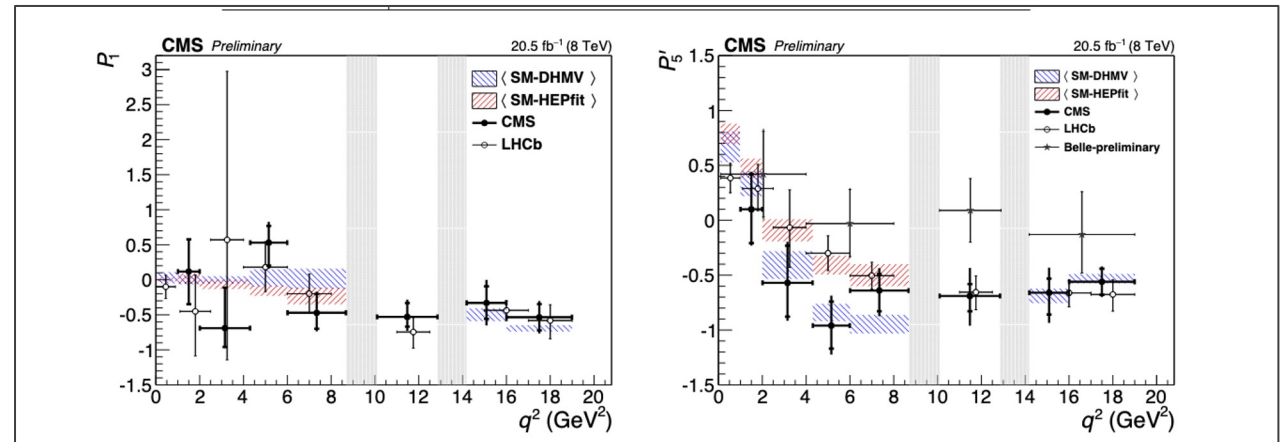
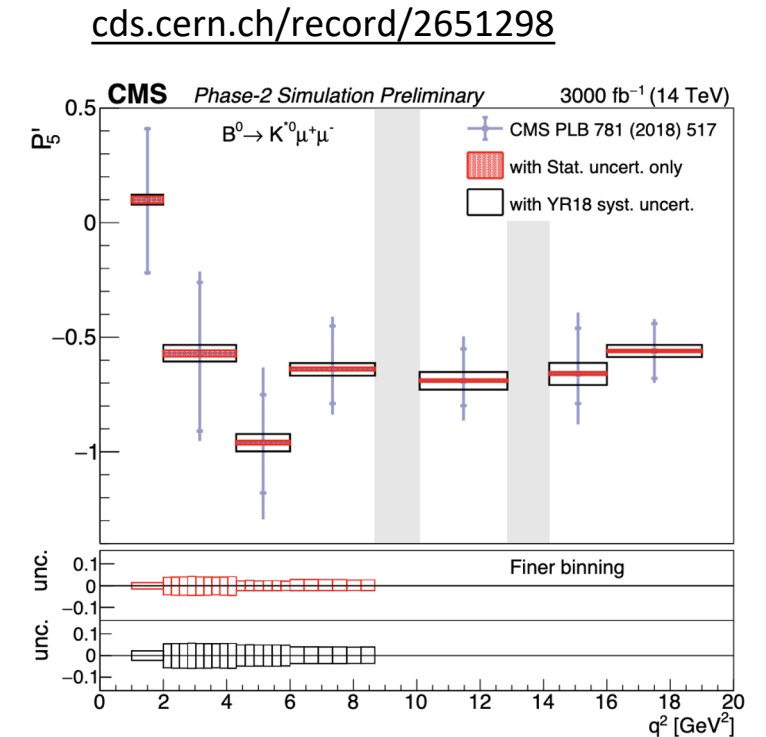


Figure 2:  $K^+ \pi^- \mu^+ \mu^-$  invariant mass and angular distributions for the second and third  $q^2$  bin (top four plots)  $2.00 < q^2 < 4.30 \text{ GeV}^2$ , and (bottom four plots)  $4.30 < q^2 < 6.00 \text{ GeV}^2$ . Overlaid on each plot is the projection of the results for the total fit, as well as for the three components: correctly tagged signal, mistagged signal, and background. The vertical bars indicate the statistical uncertainties.



# $B^0 \rightarrow K^{0*} \mu^+ \mu^-$ at the HL-LHC

- MC study to address the precision reached by ATLAS at the HL-LHC (3 /ab)
- analysis strategy same as Run1
  - reduce fit-related systematics by  $1/\sqrt{L}$
  - reduce most of uncertainties (signal shape, efficiency shape, mis-tag, detector-related) by a factor 2
- precision increase up to x15 better → also explore possibilities of finer binning



# $\tau \rightarrow 3\mu$ at the HL-LHC

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- luminosity-scaled projections based on the HF results place CMS sensitivity at  $3.7 \times 10^{-9}$  @ 90% CL  
[arXiv:1812.07638](https://arxiv.org/abs/1812.07638)