Search for new physics in rare heavy flavor decays at CMS

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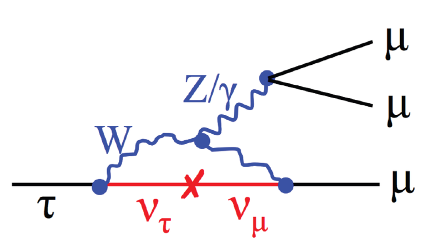
ICHEP 2022 : International Conference on High Energy Physics, 6-13 July 2022, Bologna

Introduction

In the Standard Model(SM) there is **NO symmetry** that enforces the **conservation of the lepton flavor.**

- the observation of neutrino oscillations is an evidence of the lepton flavor violation (LFV) in *neutral* lepton sector
- *Charged* LFV decays are possible in SM through neutrino oscillations:



$\mathcal{B}(\tau \to 3\mu) \sim \mathbf{10^{-54}}$ *too rare to be observed*

- BSM theories predict: $\mathcal{B}(\tau \to 3\mu) \sim \mathbf{10^{-8}} \text{–} \mathbf{10^{-9}}$ *at reach with the next-to-come data*

State of the art and channels used for this search

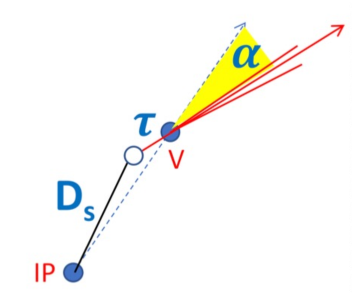
- Two main channels for **τ** production at LHC:
  - **Heavy Flavor (HF) channel**: **τ** from D, B mesons
  - W channel: **τ** from W bosons

Process	number of τ leptons (L=33 fb^{-1})
$pp \to c\,\bar{c} + ...$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^\pm$)
$pp \to b\,\bar{b} + ...$	
$B \to \tau\nu + ...$	1.5×10^{12} (44% $B^\pm$, 45% B^0, 11% B^0_s, 0% $B^\pm_c$)
$B \to D(\tau\nu) + ...$	6.3×10^{11} (98% D_s, 2% $D^\pm$)
$pp \to W + ... \to \tau\nu + ...$	6.7×10^8
$pp \to Z + ... \to \tau\tau + ...$	$1.3 \times 10^8 (60 < m(\tau\tau) < 120\ GeV)$

The $\tau \to 3\mu$ decay has **never** been observed so far

- The best experimental upper limit was set by **Belle** $\mathcal{B}(\tau \to 3\mu) < \mathbf{2.1 \cdot 10^{-8}}$ at 90% C.L. [1]
- At LHC:
  - **LHCb:** $\mathcal{B}(\tau \to 3\mu) < \mathbf{4.6 \cdot 10^{-8}}$ at 90% C.L. [2] — HF channel
  - **ATLAS:** $\mathcal{B}(\tau \to 3\mu) < \mathbf{3.8 \cdot 10^{-7}}$ at 90% C.L. [3] — W channel

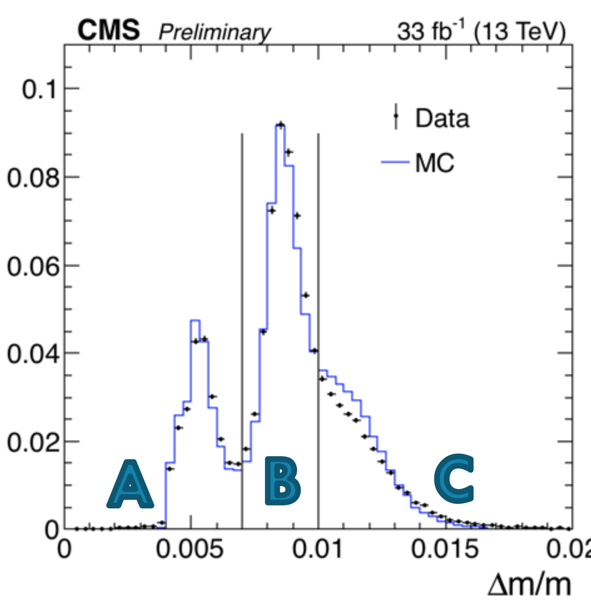
Analysis strategy – HF channel

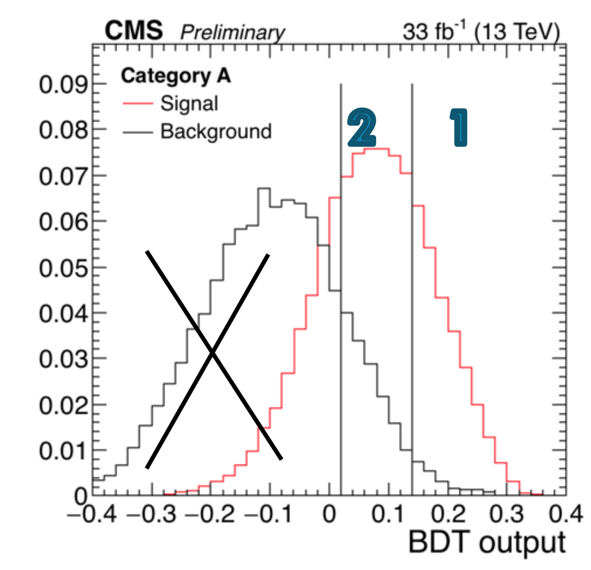


Trigger

- 2 muons with p_T>3 GeV + track with p_T>1.2 GeV
- invariant mass of triplet in [1.62 - 2.00] GeV
- distance of 3μ from beam spot $>2\sigma$

1. **Selection of events with D and B mesons decaying into τ**
   - characterized by **low pT muons**
   - background events ~10^7 **signal** events
   - **background composition:**
     - semi-leptonic decays of B mesons, with1-2 pions and/or kaons reconstructed as muons
     - decays in flight
2. **Events classification into 3 exclusive categories**
   - to increase the analysis sensitivity
   - based on **resolution of 3 mu mass**

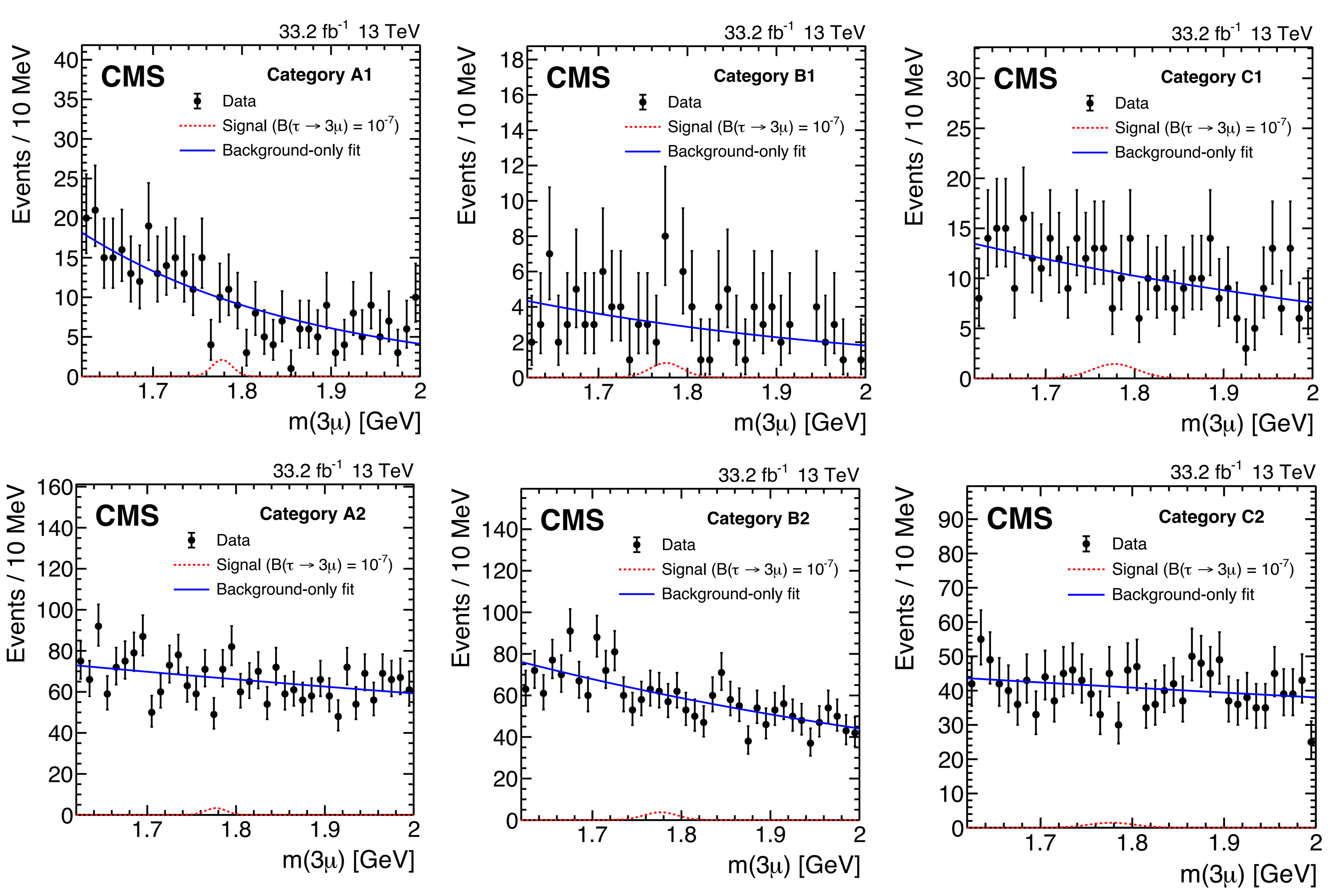




3. **Multivariate analysis with Boosted Decision Tree**
   - each category is split into **3 subcategories** based on the BDT output and the **worst** one is **discarded**
   - in the end: 3x2 = **6 categories**

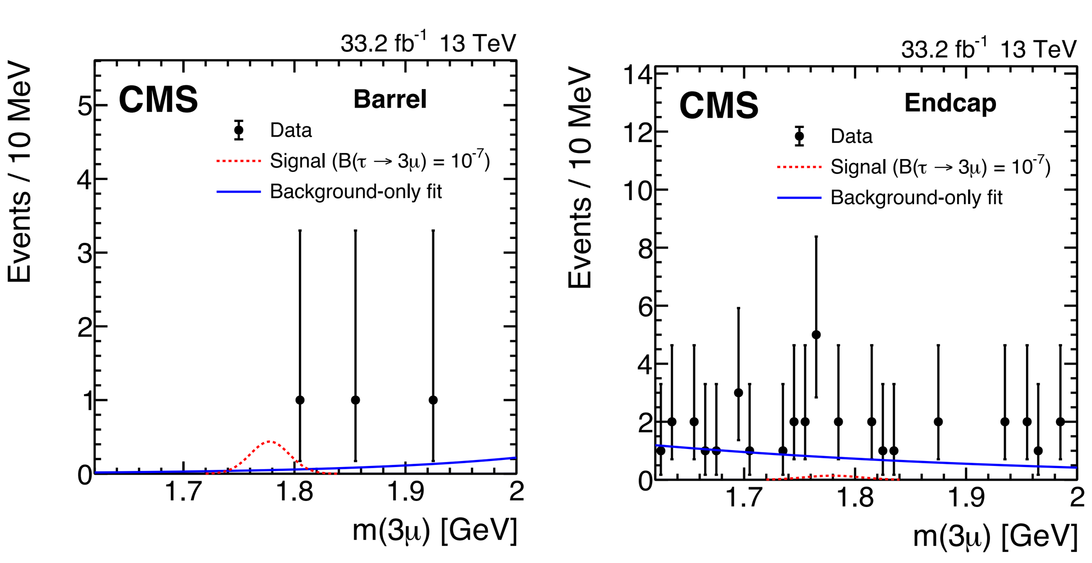
Signal extraction and conclusions

- **Maximum likelihood fit** of the 3 muons inv. mass in the **6+2 categories**
  - **signal MC fit** with **Gaussian + Crystal Ball** functions
  - **background fit** with an **exponential** function



HF: Upper limit observed (expected) at 90% C.L.

$\mathcal{B}(\tau \to 3\mu) < 9.2\ (10.0) \cdot 10^{-8}$



W: Upper limit observed (expected) at 90% C.L.

$\mathcal{B}(\tau \to 3\mu) < 2.0\ (1.3) \cdot 10^{-7}$

Combination of the 2 channels

Upper limit observed (expected) at 90% C.L. [4]

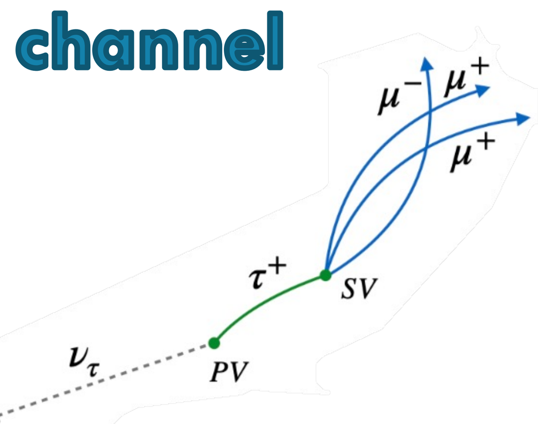
$\mathcal{B}(\tau \to 3\mu) < 8.0\ (6.9) \cdot 10^{-8}$

- **Events** (data & MC) **in common** between the two channels are **removed from the HF** one in the combination
- **Systematics** considered **not correlated** among the two channels

Analysis with 2017 and 2018 data in both channels is being finalized

Analysis strategy – W channel

1. Selection of events with W bosons decaying into τ
2. Multivariate analysis with Boosted Decision Tree
3. Event classification in 2 categories
   - barrel and endcap



- **VETO** to suppress events from decays of **hadronic resonances in 2 muons:** η, ω(783), ρ(770), φ(1020), J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S), Z
- **Jets** used are clustered with **anti-kT** algorithm (with tracks assigned to the candidate vertices as input) and the **relative missing transverse momentum** (opposite of the vectorial sum of the jets p_T)

Systematics

HF channel

Source of uncertainty	Uncertainty (%)	Yield (%)
D^+_s normalization	10	10
$\mathcal{B}(D^+_s \to \tau^+\nu)$	4	3
$\mathcal{B}(D^+_s \to \phi\pi^+ \to \mu^+\mu^-\pi^+)$	8	8
$\mathcal{B}(B \to D^+_s + X)$	16	5
$\mathcal{B}(B \to \tau + X)$	11	3
B/D ratio f	11	3
Number of events from L1 trimuon trigger	12	3
Acceptance ratio $\mathcal{A}_{3\mu}/\mathcal{A}_{\mu\mu\pi}$	1	1
Muon reconstruction efficiency	1	1
BDT requirement efficiency	5	5
Total		16

W channel

Source	Uncertainty (%) Barrel	Uncertainty (%) Endcap
Signal efficiency	7.9	32
Limited size of simulated samples	4.3	6.2
Integrated luminosity	2.5	2.5
$pp \to W$ cross section	2.9	2.9
$\mathcal{B}(W \to \mu\nu)$	0.2	0.2
$\mathcal{B}(W \to \tau\nu)$	0.2	0.2
Total	9.8	33

Systematics are used as *nuisance* parameters in the fit

References

[1] Belle Collaboration, *Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced Tau+Tau- Pairs*, Phys. Lett B 687 (2010) 139, doi:10.1016/j.physletb.2010.03.037, arXiv:1001.3221.

[2] LHCb Collaboration, *Search for the lepton flavour violating decay $\tau \to \mu^+\mu^-\mu^+$*, JHEP 02 (2015) 121, doi:10.1007/JHEP02(2015)121, arXiv:1409.8548.

[3] ATLAS Collaboration, *Probing lepton flavour violation via neutrinoless $\tau \to 3\mu$ decays with the ATLAS detector*, arXiv:1601.03567.

[4] CMS Collaboration, *Search for the lepton flavor violating decay $\tau \to 3\mu$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, JHEP 01 (2021) 163, https://doi.org/10.1007/JHEP01(2021)163.