The $\tau \rightarrow 3\mu$ search at CMS in future LHC runs: preparation for Run 3 and optimization studies toward HL-LHC

Research program proposal of Caterina Aruta

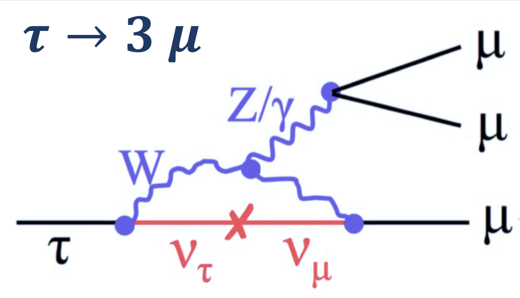
PhD school in Physics - XXXV cycle

Introduction

In the Standard Model there is **NO symmetry** than enforces the conservation of the **lepton flavor**.

- The observation of neutrino oscillations is an evidence of the lepton flavor violation in the *neutral* lepton sector.
- *Charged* lepton flavor violating decays are possible in Standard Model with neutrino oscillations.

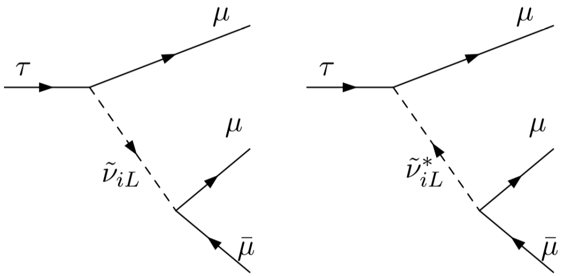
In particular, the decay $\tau \rightarrow 3\mu$ is predicted with branching fraction $\sim 10^{-14}$. *too rare to be observed at present-day experiments*



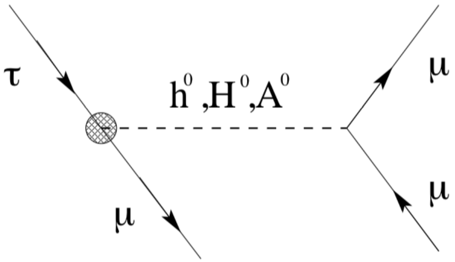
However, there exist several **extensions of the SM** predicting this decay with bigger branching fractions.

$\sim 10^{-8}$- 10^{-9}

(observable at present-day experiments)



MSSM with R-parity violation



MSSM with See-Saw mechanism

Status of the art for the $\tau \to 3\mu$ search

The $\boldsymbol{\tau} \to$ ***3μ*** *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.

At LHC

LHCb : $\mathcal{B}(\tau \to 3\mu) < \mathbf{4.6 \cdot 10^{-8}}$,

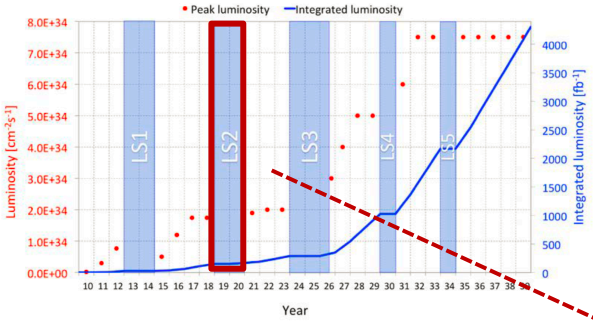
ATLAS : $\mathcal{B}(\tau \to 3\mu) < \mathbf{3.8 \cdot 10^{-7}}$

CMS : $\mathcal{B}(\tau \to 3\mu) < \mathbf{8.8 \cdot 10^{-8}}$

with **2016** data ($\mathcal{L} = 33\ fb^{-1}$)

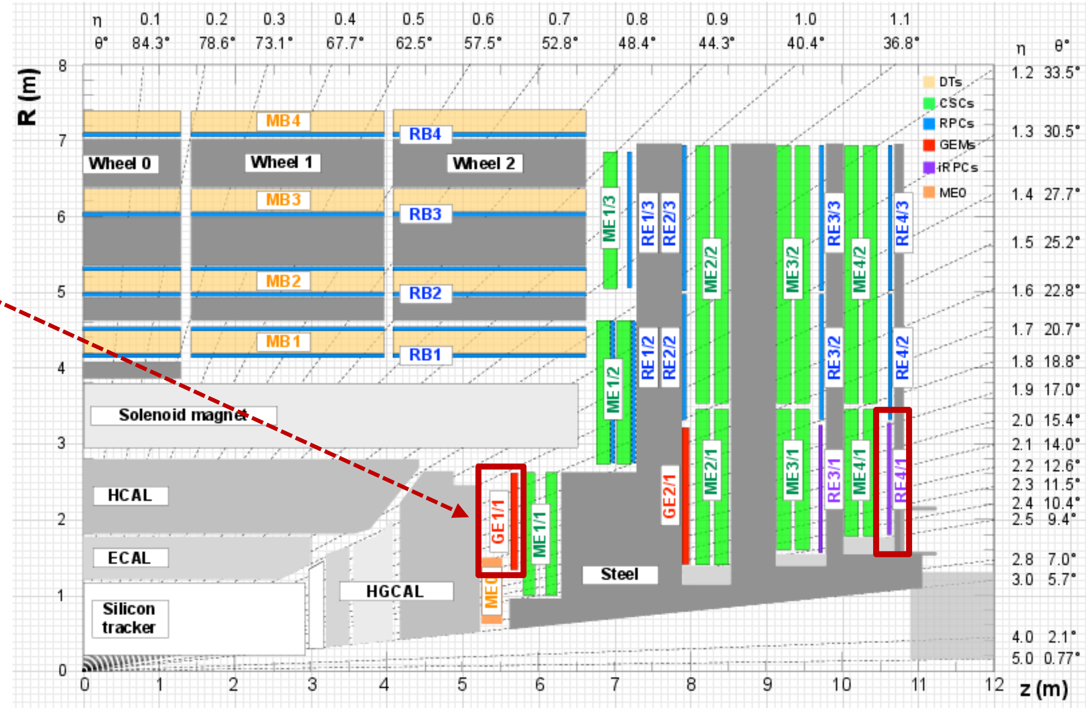
During the work of my master thesis, I have searched this decay using **2017** CMS data ($\mathcal{L} = 38\ fb^{-1}$) and an *expected* upper limit of $\mathcal{B}(\tau \to 3\mu) < 1.1 \cdot 10^{-7}$ at 90% C.L. was estimated, which is compatible with the one obtained in 2016: $\mathcal{B}(\tau \to 3\mu) < 9.9 \cdot 10^{-8}$ at 90% C.L

CMS upgrade during the second Long Shutdown

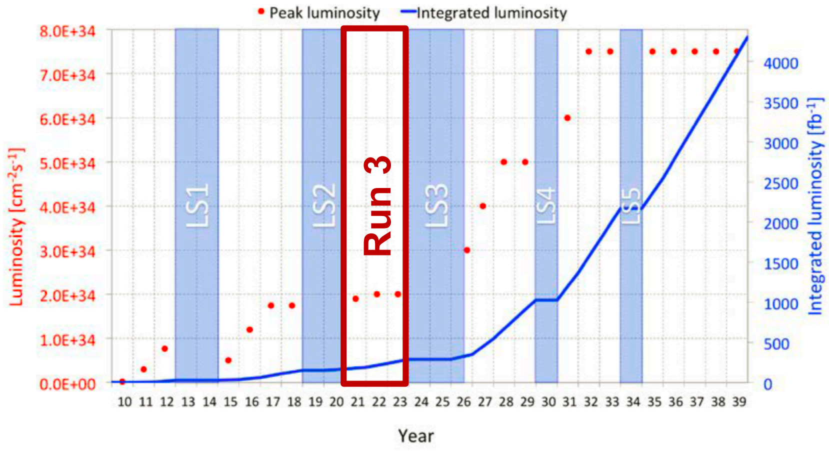


CMS muon system upgrade

- GE1/1 station will add redundancy to the system in a region characterized by high background
- this new station of detectors will improve the L1 trigger and the muon momentum resolution



Future perspectives for τ → 3μ search // Run 3



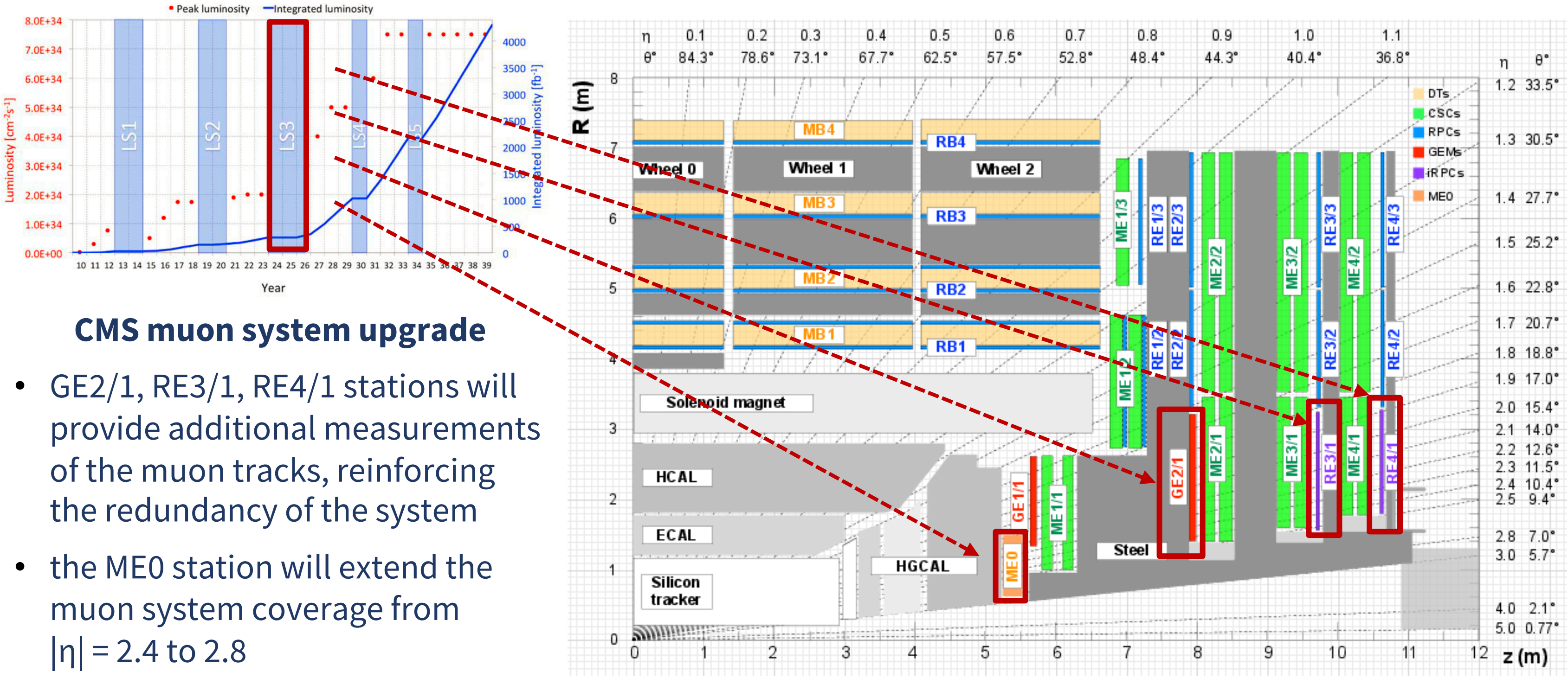
Run 3

- 300 fb^{-1} expected to be collected during Run 3 data taking
- By increasing the sensitivity of the $\tau \rightarrow 3\mu$ analysis of at least a factor two, the estimated upper limit for Run 3 can be competitive with the one obtained in 2023 by LHCb.

Research activity proposal

- ❑ improvement of the $\tau \rightarrow 3\mu$ analysis sensitivity by studying a new strategy for the multivariate analysis in order to increase the background rejection. Search for $\tau \rightarrow 3\mu$ using first data of Run 3.
- ❑ development of a new High Level Trigger path for Run 3 data taking, which can exploit new tools available in CMS in the next run (e.g. GEM-CSC trigger in $1.6 < \eta < 2.1$) to tag the muons at Level 1.

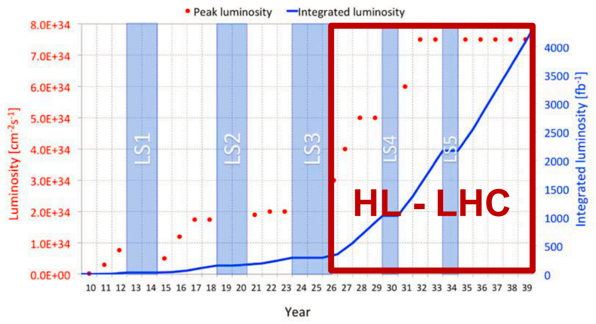
CMS upgrade during the third Long Shutdown



CMS muon system upgrade

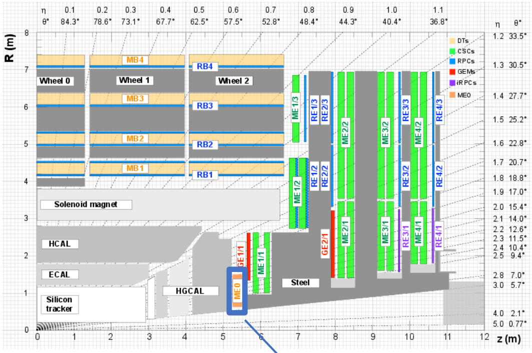
- GE2/1, RE3/1, RE4/1 stations will provide additional measurements of the muon tracks, reinforcing the redundancy of the system
- the ME0 station will extend the muon system coverage from $|\eta| = 2.4$ to 2.8

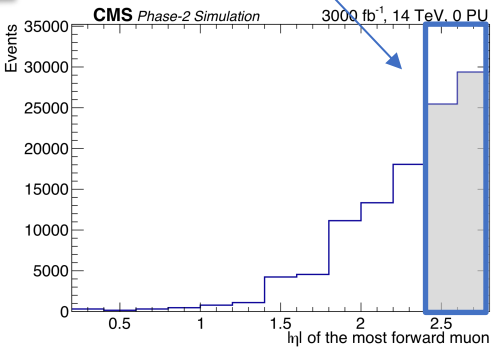
Future perspectives for τ → 3μ search // HL-LHC



HL – HLC

- During HL-LHC era 4000 fb^{-1} are expected to be collected and the sensitivity of the analysis improves with the increasing of the luminosity ($\mathcal{L}$), as it depends on $\sqrt{1/\mathcal{L}}$.
- the $\tau \rightarrow 3\mu$ analysis will benefit from the extended acceptance provided by the ME0 station





Research activity proposal

- ❑ optimization of the muon reconstruction and identification algorithms to include information coming from the new muon stations.
- ❑ The background rejection in the expected 200 pile up can be improved by exploiting machine learning techniques
- ❑ full analysis implementation in HL-LHC scenario with simulated datasets

Research activity program

First year program

- improvement of the $\tau \to 3\mu$ analysis sensitivity in order to make it compatible with Belle, by studying a new strategy for the multivariate analysis
- development of a new High Level Trigger path for Run 3 data taking, by exploiting the GEM-CSC trigger in $1.6 < \eta < 2.1$

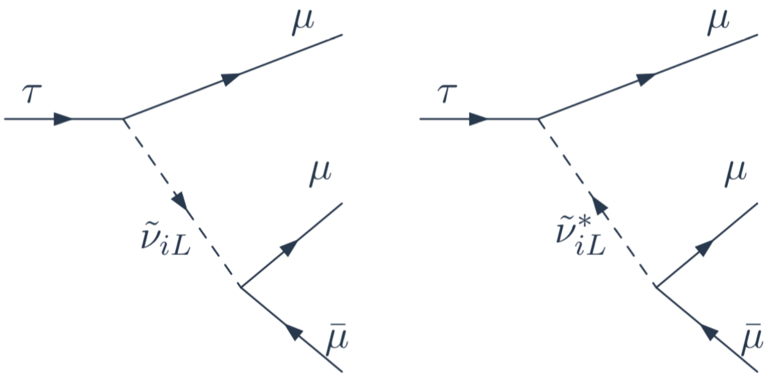
Second and third year program

- optimization of the muon reconstruction and identification algorithms to include information coming from the new muon stations
- study of a background rejection strategy by exploiting machine learning techniques
- full analysis implementation in HL-LHC scenario with simulated datasets
- $\tau \to 3\mu$ search using data collected in the first part of Run 3 data taking

Backup slides

LFV in Beyond the Standard Model theories

MSSM with R-parity violation



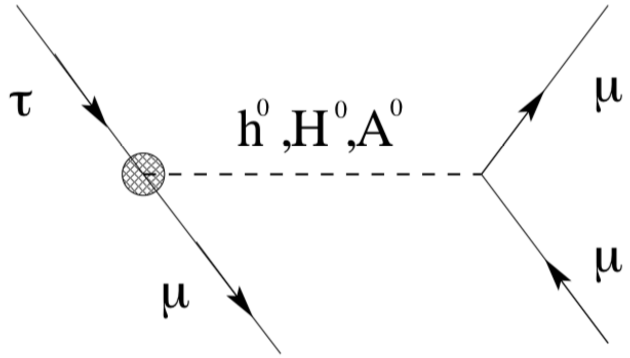
$$R_p = (-1)^R = \begin{cases} +1 & \text{for SM particles } (R - even) \\ -1 & \text{for SUSY particles } (R - odd) \end{cases}$$

$$R = 3B + L + 2S$$

Feynman diagram representing the $\tau \to 3\mu$ decay in a MSSM with R-parity violation ($\tilde{v}_{iL}$ and $\tilde{v}^*{}_{iL}$ are sneutrinos).
The upper limit to the branching ratio of this process is $\mathcal{B}(\tau \to 3\mu) < 2.2 \cdot 10{-}3\ \ m(\tilde{v}^2{}_{iL})$.

LFV in Beyond the Standard Model theories

MSSM with See-Saw mechanism



Feynman diagram contributing to the $\tau \rightarrow 3\mu$ decay in a MSSM model with See-Saw mechanism (h_0, H_0 and A_0 are neutral Higgs bosons)

CMS upper limit extrapolations with Run 2 and Run 3 statistics

$$\mathrm{UL}_{CMS}^{Run2} = \sqrt{\frac{\mathcal{L}_{CMS}^{2016}}{\mathcal{L}_{CMS}^{Run2}}} \cdot \mathrm{UL}_{CMS}^{2016} = 0.4 \cdot 10^{-7} \text{ at 90\% C.L.}$$

However, if the upper limit sensitivity is increased by at least a factor two, it is possible to obtain a final limit for the whole Run 2 equal to:

$$\boxed{\mathrm{UL}_{CMS}^{Run2} = 0.2 \cdot 10^{-7} \text{ at 90\% C.L.}}$$

and, consequently, for Run 3:

$$\mathrm{UL}_{CMS}^{Run3} = \sqrt{\frac{\mathcal{L}_{CMS}^{Run2}}{\mathcal{L}_{CMS}^{Run3}}} \cdot \mathrm{UL}_{CMS}^{Run2} \Longrightarrow \boxed{\mathrm{UL}_{CMS}^{Run3} = 0.1 \cdot 10^{-7} \text{ at 90\% C.L.}}$$

Upper limit extrapolations @ 2023

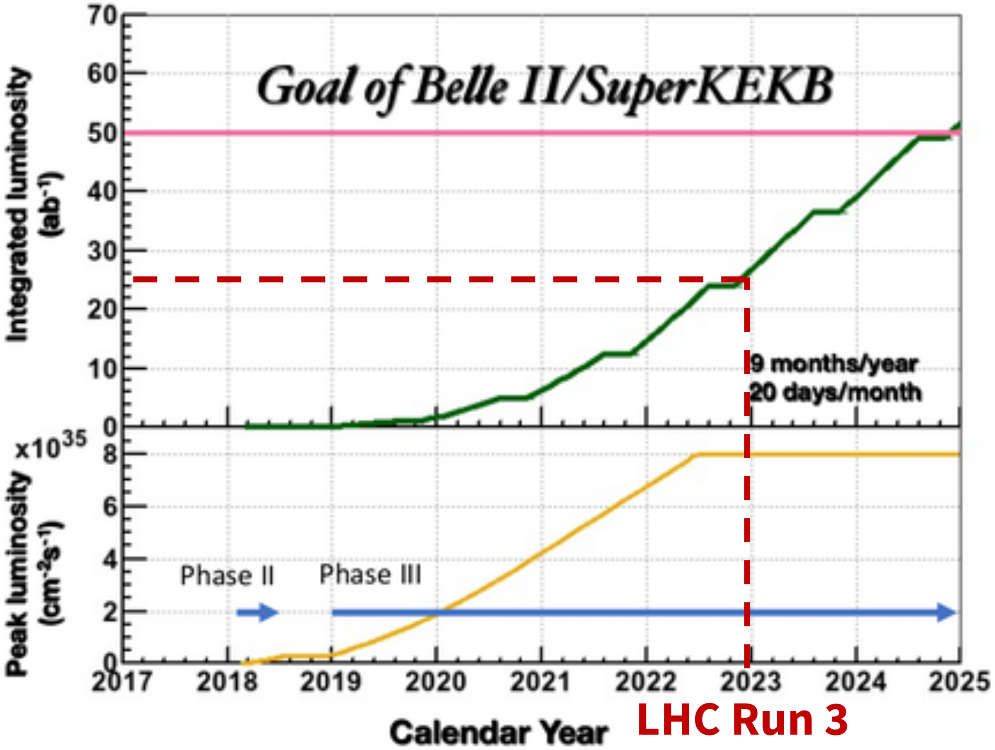
LHCb

$$\mathrm{UL}_{LHCb}^{Run3} = \sqrt{\frac{\mathcal{L}_{LHCb}^{Run1}}{\mathcal{L}_{LHCb}^{Run2+3}}} \cdot \mathrm{UL}_{LHCb}^{Run1} = 0.1 \cdot 10^{-7} \text{at 90\% C.L.}$$

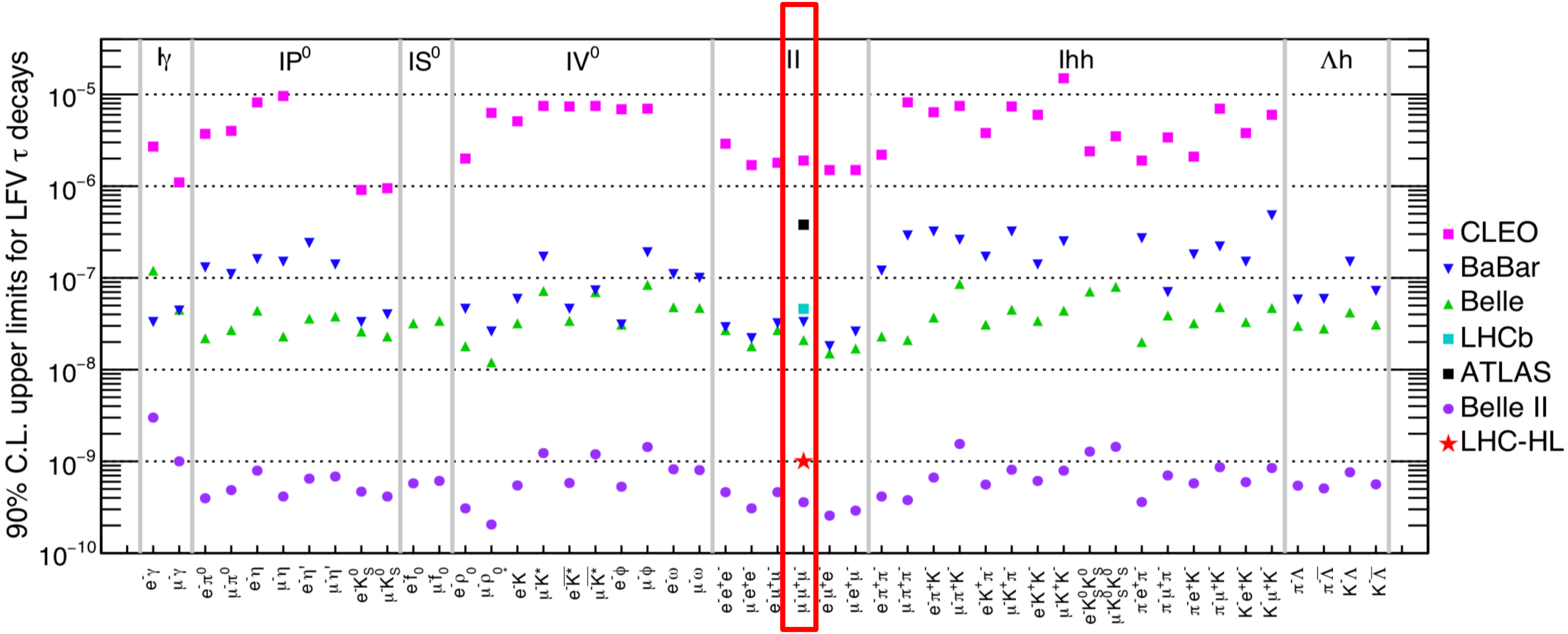
BelleII

$$\mathrm{UL}_{BelleII}^{2023} = \sqrt{\frac{\mathcal{L}_{Belle}}{\mathcal{L}_{BelleII}^{2023}}} \cdot \mathrm{UL}_{Belle} = 0.05 \cdot 10^{-7} \text{at 90\% C.L.}$$

The Belle II schedule



Future perspectives for LFV search in τ decays



Bounds on Tau Lepton Flavour Data from the existing experiments are compiled by HFLAV; projections of the Belle-II bounds were performed by the Belle-II collaboration assuming 50 ab^{-1} of integrated luminosity.

arXiv:1812.07638

Search for τ → 3μ at HL-LHC

	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4580	3640
Trimuon mass resolution	18 MeV	31 MeV
$\mathcal{B}(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$\mathcal{B}(\tau \to 3\mu)$ 90% C.L. limit	3.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 3-σ evidence	6.7×10^{-9}	
$\mathcal{B}(\tau \to 3\mu)$ for 5-σ observation	1.1×10^{-8}	

(Top) The expected numbers of signal and background events in the mass window 1.55 -2.0 GeV for CMS. An integrated luminosity of **3000 fb^{-1}** and a signal $B(\tau \to 3\mu) = 2 \times 10^{-8}$ is assumed.

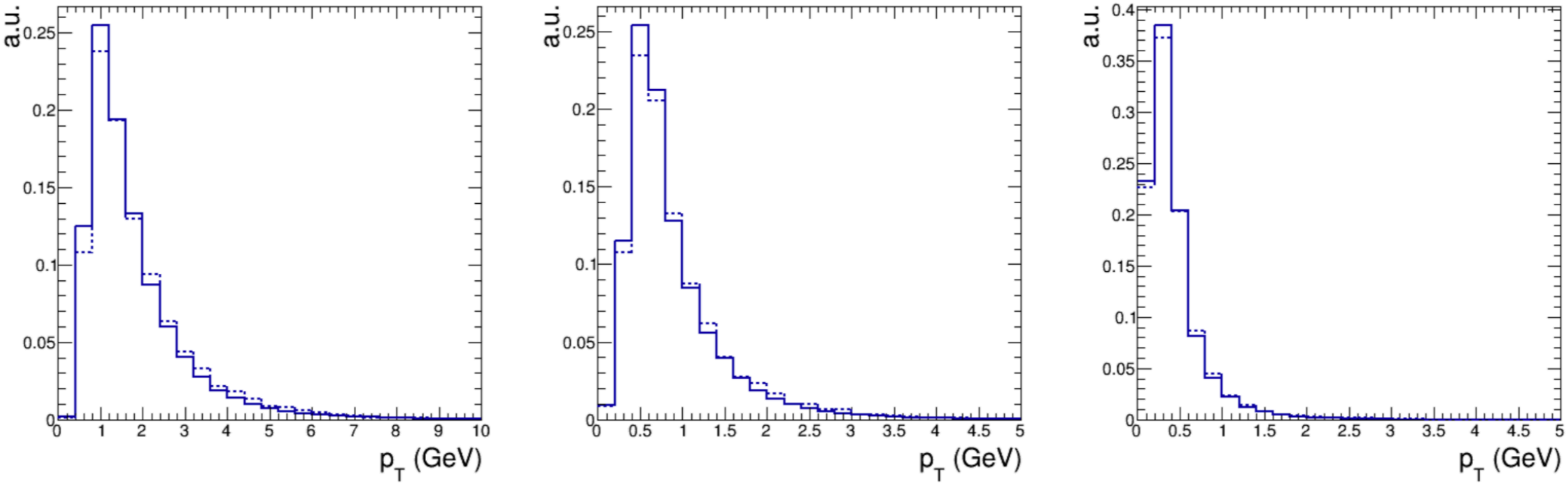
(Bottom) The search sensitivities for the combined categories.

Category 1 for events with all three muons reconstructed only with the Phase-1 detectors, and Category 2 for events with at least one muon reconstructed by the new triple Gas Electron Multiplier (GEM) detectors.

D and B meson decay branching fractions

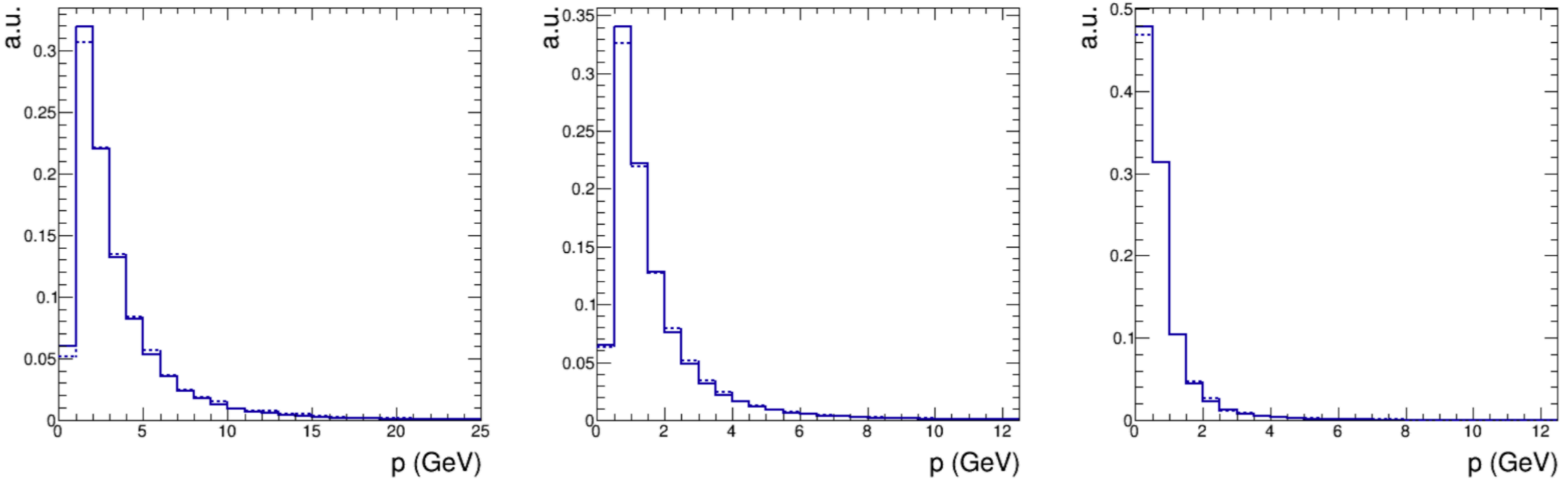
Process	Branching ratio (BR)	Reference
$D_s \to \tau\nu_\tau$	$(5.48 \pm 0.23) \cdot 10^{-2}$	PDG
$B^+ \to \tau\nu_\tau D_0^*$	$(2.7 \pm 0.3) \cdot 10^{-2}$	PDG
other $B^+ \to \tau\nu_\tau X$	$0.7 \cdot 10^{-2}$	PYTHIA
$B^0 \to \tau\nu_\tau D^{+*}$	$(2.7 \pm 0.3) \cdot 10^{-2}$	PDG
other $B^0 \to \tau\nu_\tau X$	$0.7 \cdot 10^{-2}$	PYTHIA
$B^+ \to D_s X$	$(9.0 \pm 1.5) \cdot 10^{-2}$	PDG
$B^0 \to D_s X$	$(10.3 \pm 2.1) \cdot 10^{-2}$	PDG
$D_s \to \phi\pi \to \mu\mu\pi$	$(1.3 \pm 0.1) \cdot 10^{-5}$	PDG

Signal acceptance at generator level



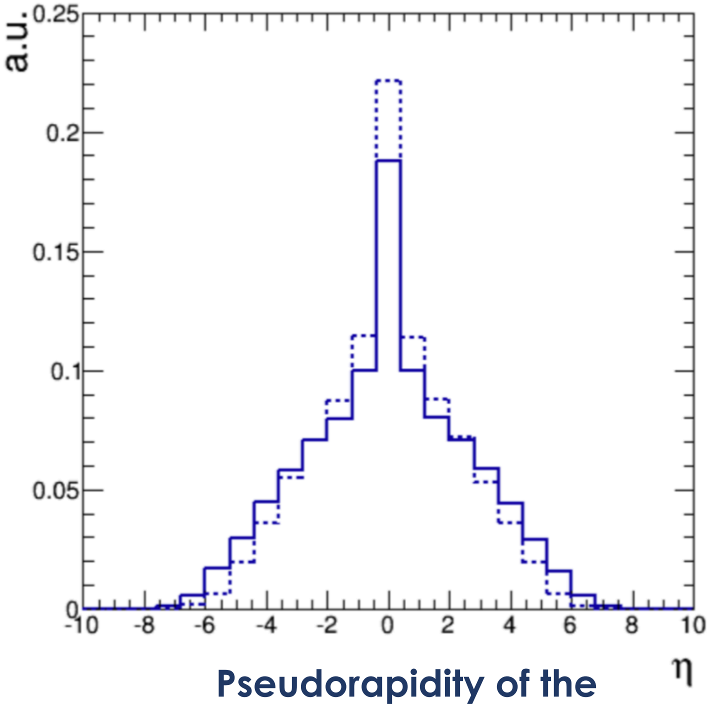
Transverse momentum of each muon from τ produced by D mesons (solid histogram) and B mesons (dashed histogram) in events with all three muons having |η|< 2.4

Signal acceptance at generator level

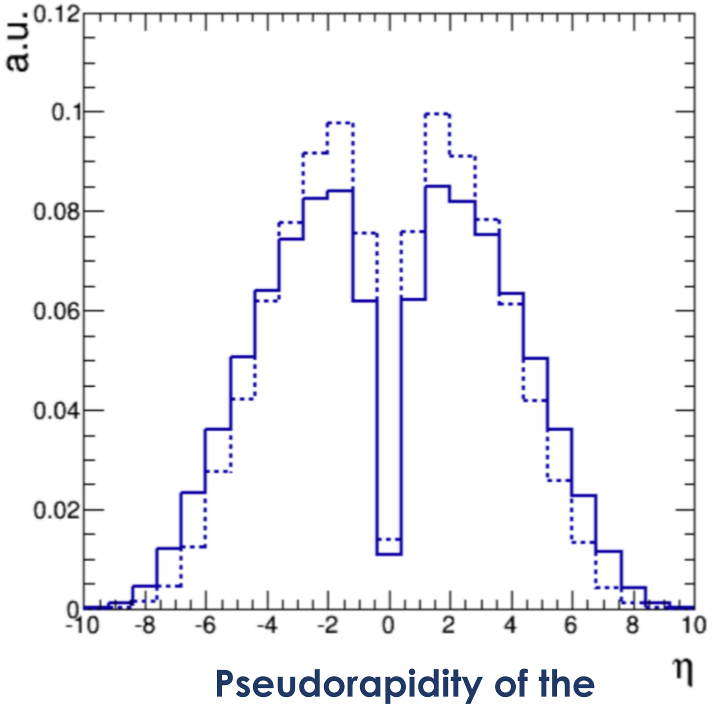


Momentum of each muon from τ produced by D mesons (solid histogram) and B mesons (dashed histogram) in events with all three muons having |η|< 2.4

Signal acceptance at generator level

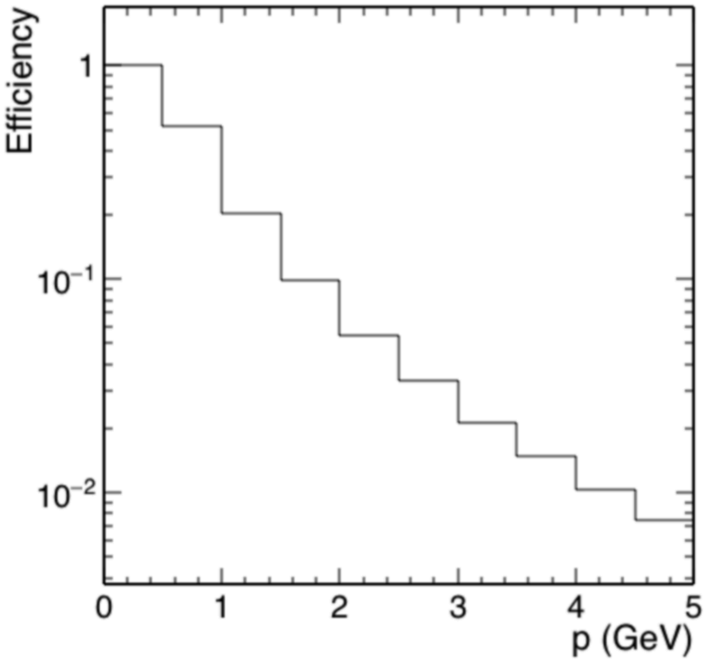


Pseudorapidity of the most central muon



Pseudorapidity of the most forward muon

Signal acceptance at generator level



Efficiency for 3 muons with $|\eta| < 2.4$

CMS fiducial volume:

$|\eta| < 2.4$

$p > 2.5$ GeV

Only ~ 2 % of generator level events are within the CMS acceptance

Level 1 trigger paths - $\tau \rightarrow 3\mu$

- *L1_DoubleMu0er1p5_SQ_OS_dR_Max1p4*

this L1 trigger requires 2 muons with opposite sign and with $|\eta|<1.5$ and ΔR in [0, 1.961].

No p_T thresholds are applied.

- *L1_TripleMu_5_3_0_DoubleMu_5_3_OS_Mass_Max17*

it requires three muons and the two muons with the highest p_T must have opposite sign and their invariant mass has to be in [0, 144.5] GeV.

Furthermore, the highest p_T muon must have a p_T > 5 GeV and the second one a p_T >3GeV.

- *L1_TripleMu_5SQ_3SQ_0_DoubleMu_5_3_SQ_OS_Mass_Max9*

it requires 3 muons and the two muons with the highest p_T must have opposite sign and their invariant mass has to be in [0, 40.5] GeV.

Furthermore, the highest p_T muon must have a p_T > 5GeV and the second one a p_T > 3GeV.

High Level Trigger path - τ → 3μ

- *HLT_DoubleMu3_Trk_Tau3mu v**

it requires two muons with $p_T > 3$ GeV and a track with $p_T > 1.2$ GeV.

In addition the invariant mass of the track + 2 muons must be in [1.60 - 2.02] GeV and the vertex of this triplet has to be displaced from beam-spot by more than two sigma.