TAU2021: 16th International Workshop on Tau Lepton Physics

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SEARCH FOR $\tau \rightarrow 3\mu$ DECAYS WITH CMS EXPERIMENT AT LHC

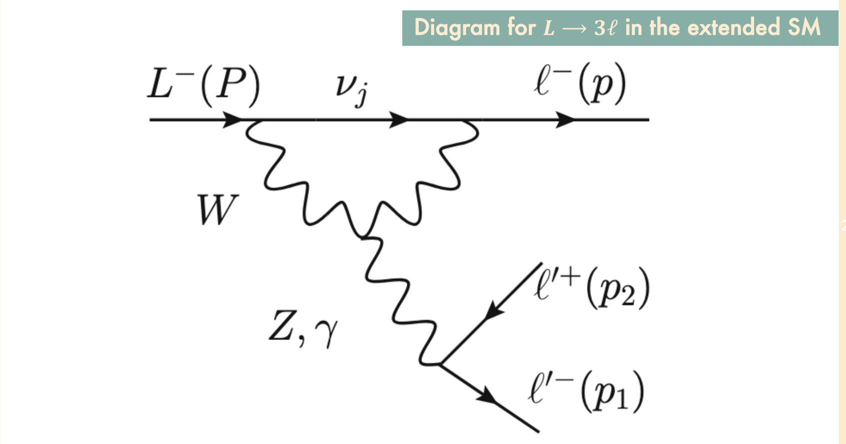
MOTIVATIONS AND STATE OF THE ART

CHARGED LEPTON FLAVOUR VIOLATION

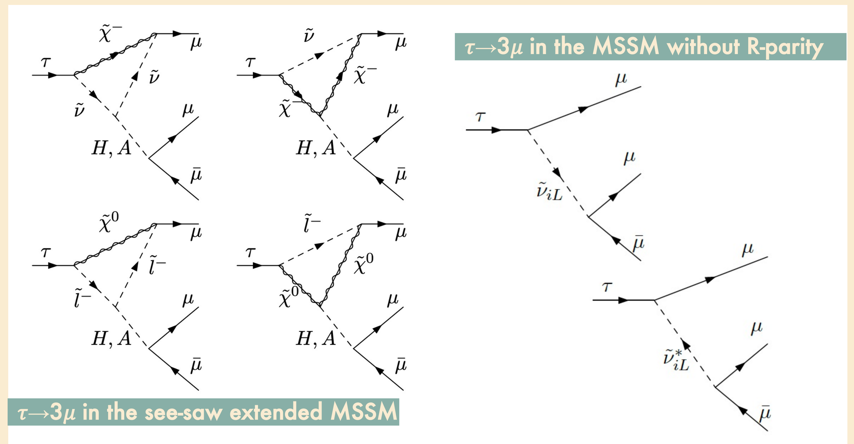
Lepton Flavour Violation (LFV) is allowed in the Standard Model extended to include neutrino mass.
LFV for charged leptons has never been observed:

- Suppressed in the Standard Model:
Branching Ratio $\tau\rightarrow3\mu$ (SM) ~ $\mathcal{O}(10^{-54})$ [1]

Diagram for $L \rightarrow 3\ell$ in the extended SM



- Enhanced BR in SUSY, 2HDM
Branching Ratio $\tau\rightarrow3\mu$ (BSM) ~ $\mathcal{O}(10^{-7} \div 10^{-9})$ [2][3]



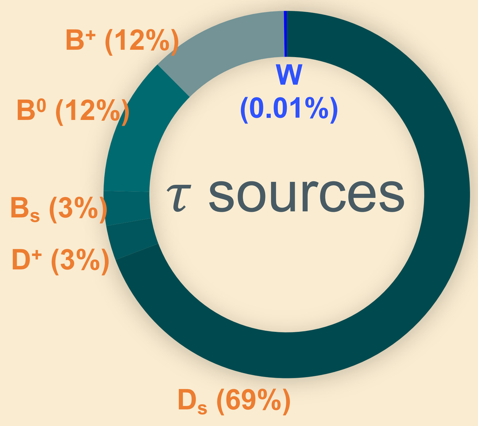
$\tau\rightarrow3\mu$ in the MSSM without R-parity

$\tau\rightarrow3\mu$ in the see-saw extended MSSM

SEARCH FOR $\tau\rightarrow3\mu$ AT COLLIDERS

Date	Experiment	Exp. [*]	Obs [*]	[*] x 10^{-8} at 90% CL	
2010	**Belle**	-	**2.1**	$ee \rightarrow \tau\tau$	[4]
2010	BaBar	4.0	3.3	$ee \rightarrow \tau\tau$	[5]
2014	LHCb	5.0	4.6	*HF channel - Run I*	[6]
2016	ATLAS	39	38	*W channel - Run I*	[7]
2020	**CMS**	**6.9**	**8.0**	***HF + W - 2016***	[8]

SOURCES OF τ LEPTONS



at LHC: $\sigma(10^{11})$/fb^{-1} τ leptons

Heavy Flavour (**HF**)
(D ⟶ τν, B ⟶ τν..., B ⟶ D(τν)...)
large cross section; low p_T; high η; high bkg

Heavy Flavour (**W**)
relatively small cross section; high p_T; low bkg

CMS is capable of exploring both!
Search for $\tau\rightarrow3\mu$ in 2016 Run II data [8]

ANALYSIS: HEAVY FLAVOUR CHANNEL

01. ANALYSIS STRATEGY

D/B⟶τ⟶3μ signal MC → **Data**

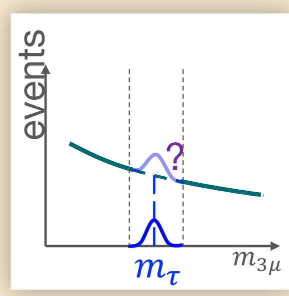
Online: dedicated trigger
low-p_T $\mu\mu$ pairs + 1 track
forming displaced common vertex

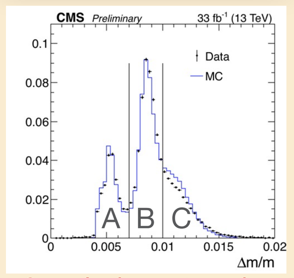
Offline selections:
- Cuts reproducing HLT requirements (vertexing, displacement, collimation)
- Reconstruction of final-state muons

Train Boosted Decision Tree for signal-background separation
- Signal: MC - Bkg: data in mass sidebands

Event categories based on mass resolution m(3μ)

Limit on $\mathcal{B}(\tau \rightarrow 3\mu)$ from maximum likelihood fit on m(3μ) shapes



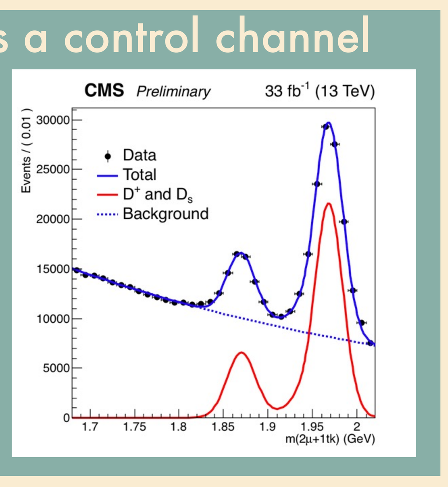


3 exclusive categories

- Signal from MC simulation
- No assumption on background composition: modelled from data in mass sidebands
- Multivariate analysis (BDT) for background rejection
- Limit extraction in different mass resolution categories

$D_s \rightarrow \phi(\mu\mu)\pi$ as a control channel

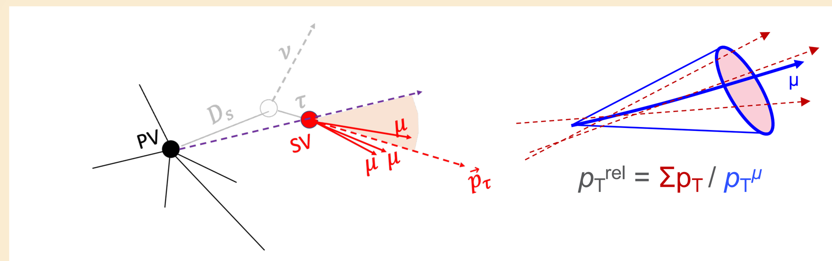
Signal channel and $D_s \rightarrow \phi(\mu\mu)\pi$ share same final-state topology.
Events are corrected using the same trigger.
The $D_s \rightarrow \phi(\mu\mu)\pi$ is therefore used as a control and normalization channel.

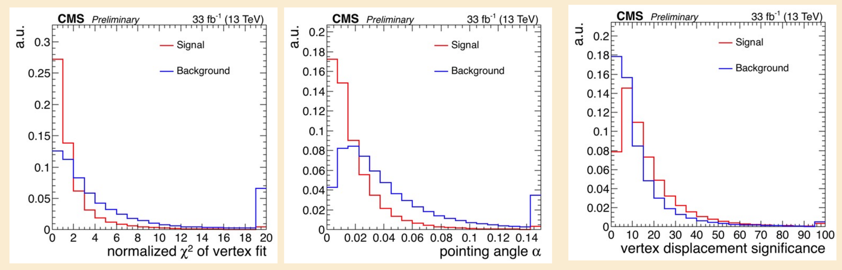


02. BOOSTED DECISION TREE

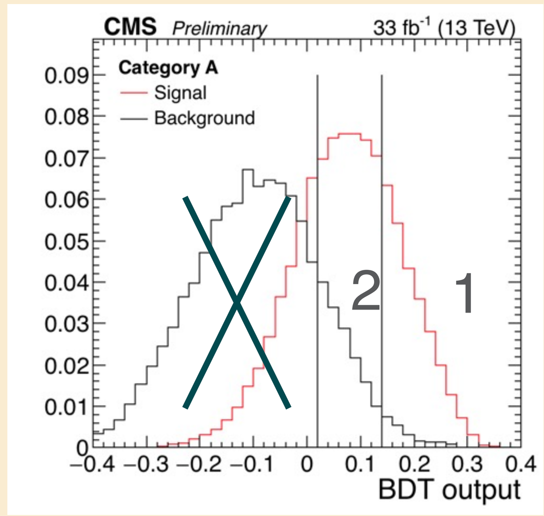
By QCD MC study, we know the dominant background is B→D cascade muonic decays, combined with a π/K

- Data sidebands used as bkg in BDT analysis
- Vertexing variables the most discriminating
  - 3μ vertex chi2, 3μ vertex displacement
  - angle between the PV-SV direction and the 3μ direction





Sub-categories 1 and 2 are chosen for each mass category, background-like events are discarded



ANALYSIS: W CHANNEL

01.ANALYSIS STRATEGY

W→τν→3μ signal MC → **Data**

Online: dedicated trigger
$\mu\mu$ pairs + 1 track
forming isolated tau candidate

Efficiency corrections (trigger, μID) applied to MC

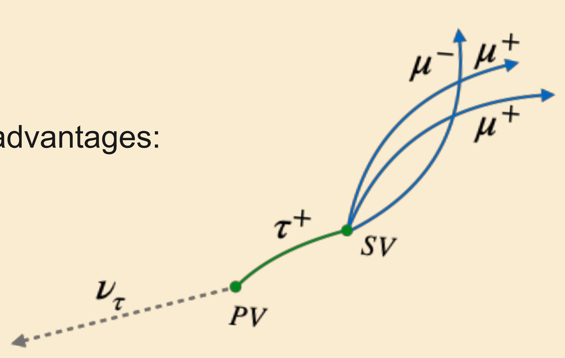
Train Boosted Decision Tree for signal-background separation
- Signal: MC - Bkg: data in mass sidebands

Event categories: barrel - endcap

Limit on $\mathcal{B}(\tau \rightarrow 3\mu)$ from maximum likelihood fit on m(3μ) shapes

W channel: small contribution to τ production LHC (~ 0.01%), but significant advantages:

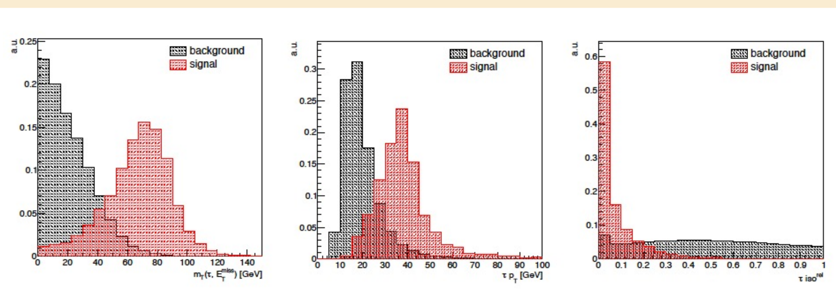
- Fewer background sources
- Isolated high momentum muons
- Higher trigger and offline selection efficiency
- W→lν like signature, where l indicates a narrow, isolated 3μ 'jet'
- Presence of large MET in the final state



02.BOOSTED DECISION TREE

BDT training:

- Isolation, missing energy, transverse mass, muon reconstruction quality as input variables
- Using a 10-fold cross-validation to exploit the limited statistics in BDT training



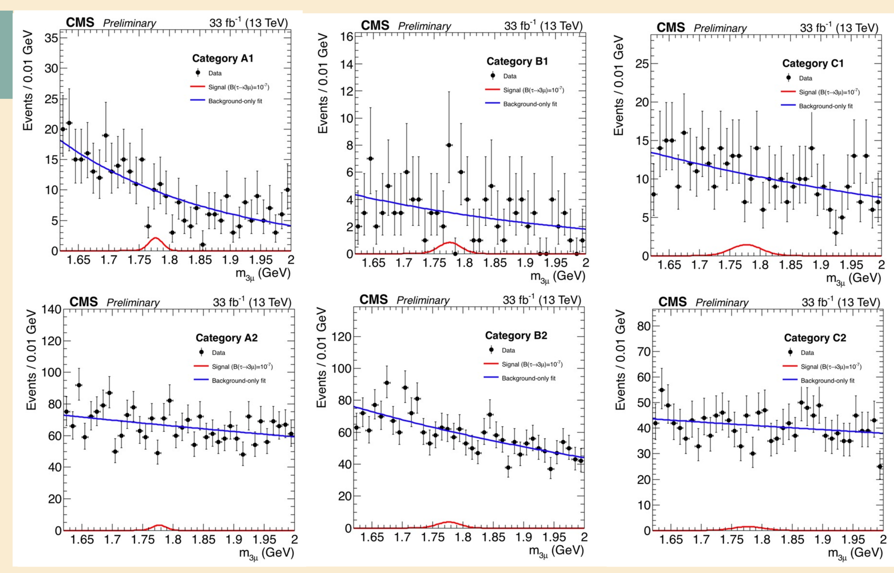
RESULTS – 2016 DATA

HEAVY FLAVOUR

Signal is extracted from a maximum likelihood fit to the 3μ system invariant mass, in each of the six event categories.
– MC signal is parametrized with Crystal Ball functions
– exponential plus a polynomial to model the background.
• Systematics uncertainties are treated as nuisance parameters in the fit.

- No significant event excess observed
- Upper limits on the branching fraction BR(τ → 3μ) are set using the modified frequentist CLs criterion

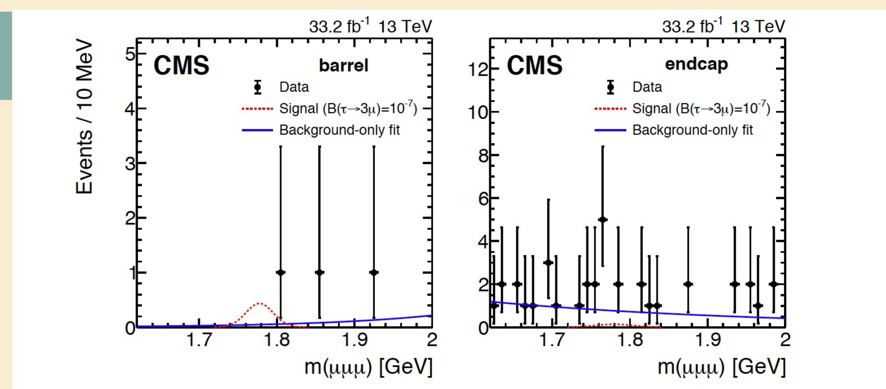
Observed (expected) BR(τ → 3μ) =
9.2 (10.0) 10^{-8} at 90% C.L.



W CHANNEL

- Two event categories: barrel-endcap
- No significant event excess observed

Observed (expected) BR(τ → 3μ) =
19.5x10^{-8} (12.9x10^{-8}) 10^{-8} at 90% C.L.



Combining the two channels, the upper limit on BR(τ → 3μ) set by the CMS experiment using the 2016 Run 2 data is:
Observed (expected) BR(τ → 3μ) = **8.0x10^{-8} (6.9x10^{-8}) 10^{-8} at 90% C.L**

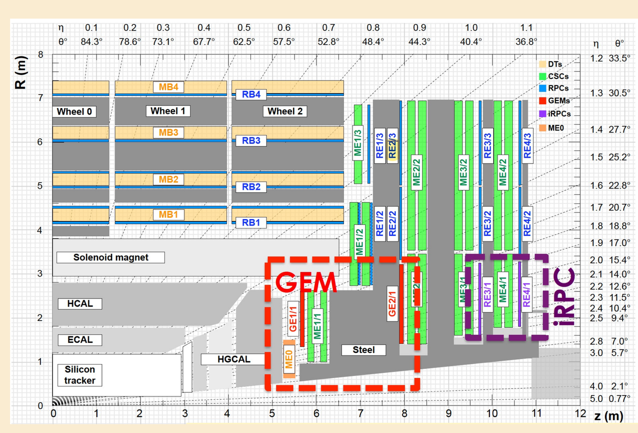
PERSPECTIVES

Run II, pp @ 13 TeV: Analysis at final stages
2017: 38 fb^{-1} **2018:** 59.7 fb^{-1}

- Higher statistics → Higher sensitivity and larger statistics to train Multi-Variate discriminators
- CMS detector in 2017 and 2018: improved pixel detector → improved vertex reconstruction and track momentum resolution

The $\tau\rightarrow3\mu$ search in Run 3: $\mathcal{L}_{CMS}^{Run3} \sim 200\ fb^{-1}$
Dedicated trigger path under development:
- Goal: lowering the p_T threshold to enhance the signal acceptance while keeping similar rates as 2018. Enlarge eta acceptance

New tools in Run 3:
- Level-1 trigger: implementation of a 3-μ invariant mass object
- CSC-GEM segment (1.6 < |eta|< 2.1)
  - improved momentum resolution at L1 trigger
  - Extended eta coverage



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[6] J. High Energ. Phys 02-2015, 121, (2015)
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[8] J. High Energ. Phys. 2021, 163 (2021)

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