Test of Lepton Flavor (Universality) Violation at CMS

Through Heavy Mesons and Leptons decays

Federica Riti, on behalf of the CMS Collaboration

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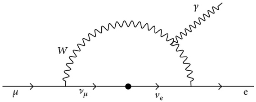
Lepton Flavor (Universality) Violation

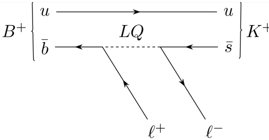
Lepton Flavor Violation (LFV)

- Charged lepton flavor is conserved in the SM through accidental symmetry
- Neutrino oscillations exist [arXiv:hep-ex/0701049]: evidence of neutral LFV
- Charged LFV happens in loop diagrams with ν mixing, but strongly suppressed in the SM (rate $\sim 10^{-55}$)
- SM extensions predict a larger BR up to $10^{-10} - 10^{-8}$ EPJC57(2008)13-182



Lepton Flavor Universality Violation (LFUV)

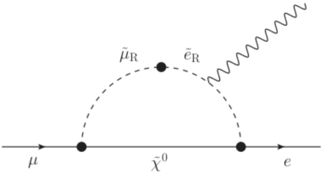
- In SM EW couplings are the same for the three lepton flavours



Lepton Flavour measurements $\rightarrow$ strategic sector to look for new Physics

Why look for LF(U)V?

- **If we find the violations**: proof of New Physics!
- **If we don't find the violations**: constraints to Beyond the Standard Model theories.



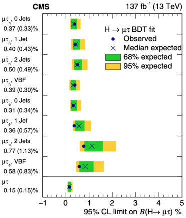
In this talk $\rightarrow$ overview of LF(U)V measurements and prospects in CMS with heavy mesons and leptons.

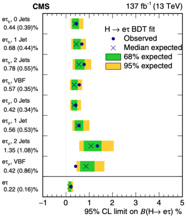
- **LFV**: $\tau \rightarrow 3\mu$ measurement in CMS JHEP01(2021)163;
- **LFUV in B Physics**: prospects and possibilities in CMS.

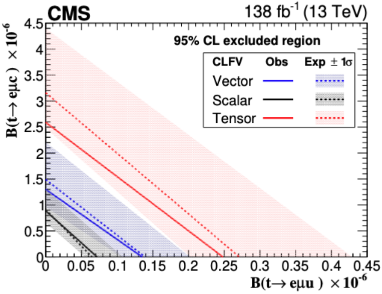
Lepton Flavor Violation

Direct LFV search can be done in different sectors:

- Higgs sector, with $H(e/\mu\tau)$ decays PRD104(2021)032013
- Top quark decays ($t \to e\mu q$) JHEP06(2022)082
- Drell-Yann/ Z decays ($Z \to (e/\mu\tau), Z(e\mu)$) arXiv:2204.10783
- B decays LHCb-TALK-2022-040







LFV Overview - Few Experimental Examples

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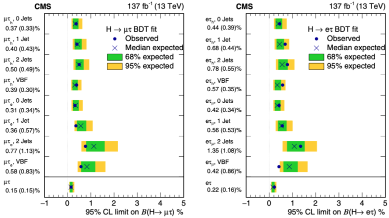

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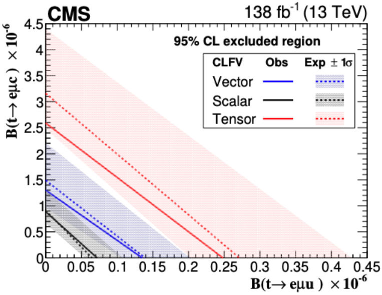
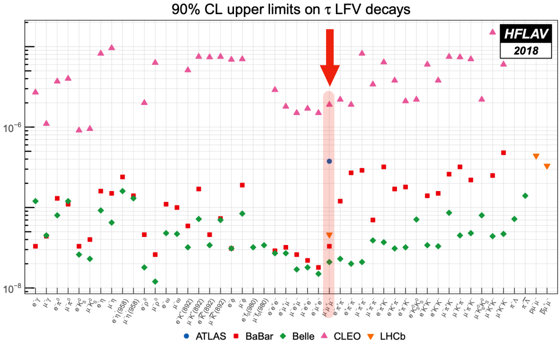
- **Leptonic decays ($\tau \to 3\mu$)**



LFV $\tau \to 3\mu$ in CMS - Experimental Scenario

- With $\tau \to 3\mu$ analysis the LFV is tested in CMS JHEP01(2021)163.
- The best limit was set from Belle collaboration to $\mathcal{B}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$ at 90% confidence level PLB687(2010)139-143.
- On this topic, also check Caterina's poster

arXiv:1909.12524

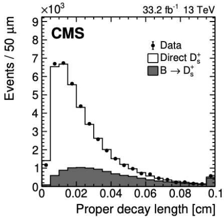


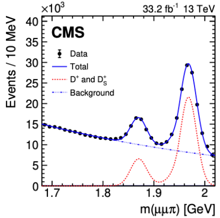
LFV $\tau \to 3\mu$ in CMS - Heavy Flavours (HF) channel

Two channels for this search, depending on the production of the τ:

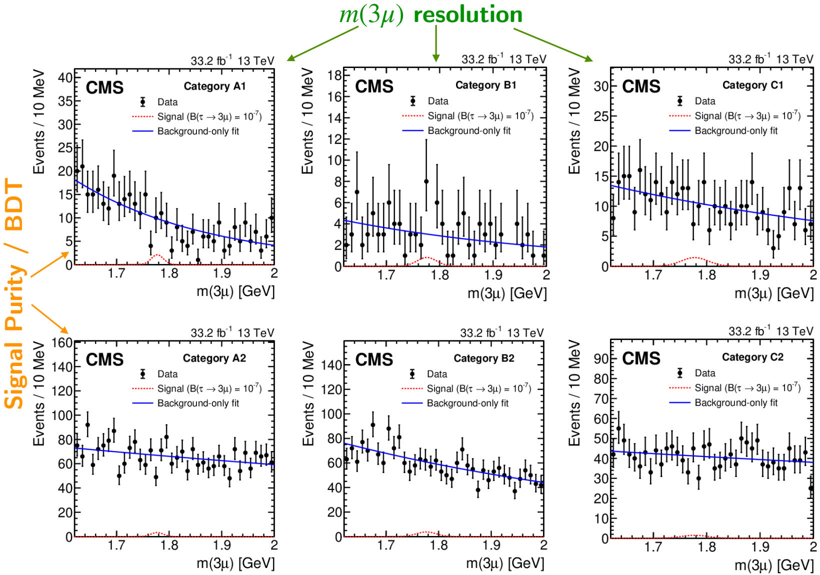
Heavy Flavours (HF) channel

- $D_s^+ \to \tau^+\nu$, $B \to \tau + X$
- Abundant, but challenging for very low p_T forward muons
- Veto on dimuon decays from hadronic resonances to suppress bkg
- To reduce uncertainties, $D_s^+ \to \phi\pi^+ \to \mu + \mu^-\pi^+$ is used to normalize the signal yield
- BDT trained to improve the signal to bkg ratio with 10 variables: muons kinematics and their iso; trimuon vertex properties and its iso.



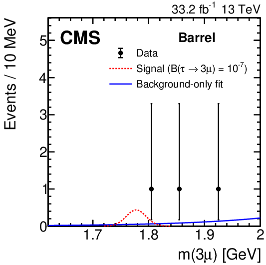


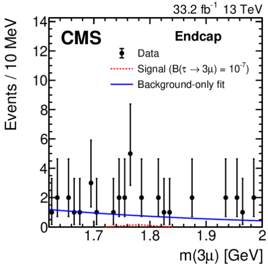
LFV $\tau \to 3\mu$ in CMS - 6 categories for HF



$W \to \tau\nu$ channel

- $\sim 10^4$ less yield, but more clear signature: higher p_T, isolation, MET and transverse mass $\sqrt{2p_T^{3\mu}p_T^{miss}(1-cos\Delta\phi)}$
- Veto on dimuon decays from hadronic resonances to suppress bkg
- BDT trained to separate signal from bkg with 18 variables: muons quality; τ kinematics and iso; trimuon vertex properties.



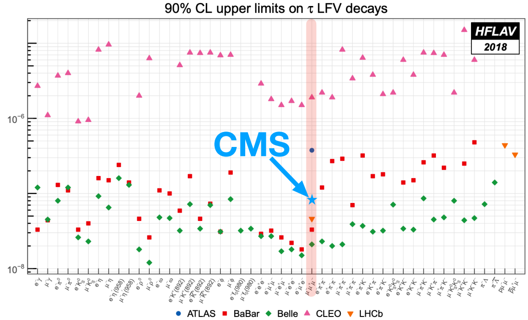


LFV $\tau \to 3\mu$ in CMS - Results and Interpretation

No evidence of LFV found [1]

- **HF channel**: $9.2 \cdot 10^{-8}(10.0 \cdot 10^{-8})$ with 90% CL
- ***W* channel**: $20 \cdot 10^{-8}(13 \cdot 10^{-8})$ with 90% CL

with a combined limit of $8.0 \cdot 10^{-8}(6.9 \cdot 10^{-8})$ with 90% CL.



The analysis includes only **2016 data**, and an updated analysis with the complete Run II dataset is on-going.

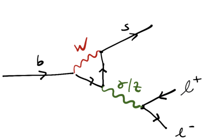
[1] Observed (Expected)

Lepton Flavor Universality Violation

LFUV in the B Sector

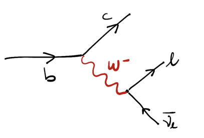
$$R_{H_s} = \frac{\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to H_s e^+ e^-)}$$

- $b \to s l^+ l^-$
- loop level $\to$ smaller BR;
- ν-less $\to$ fully reconstructed;
- precise predictions.



$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu_\tau})}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu_\mu})}$$

- $b \to c l^- \bar{\nu}_l$
- tree level $\to$ large BR; sensitive to syst uncert;
- ν's $\to$ missing mass; template fits.
- sensitive to QCD calculations.

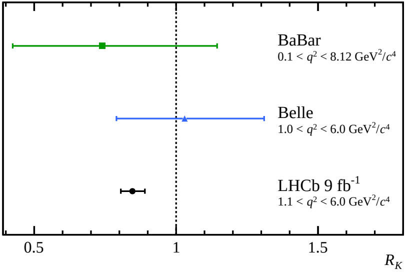


- LFUVs can be detected also from angular analyses of B mesons (Alessio's talk) and measurements of rare B decays (Dmytro's talk)

LFU Anomalies

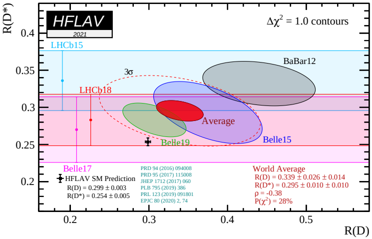
- There are several experiments that suggest deviations from the SM predictions (several talks on this topic)

$b \to s l^+ l^-$



LHCb Nature Phys. 18 (2022) 277;

$b \to c l \nu$



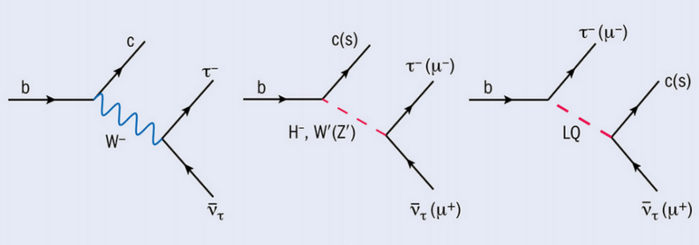
HFLAV 2021 Update

Theoretical Interpretation of anomalies

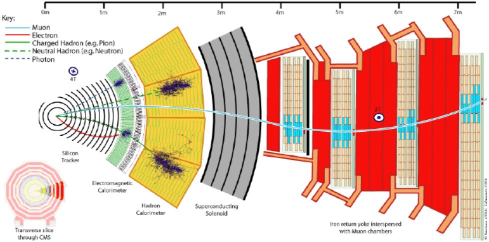
What are the proposed explanations for a deviation from the SM predictions?

Extensions of the SM, with enhanced weak couplings to third-generation leptons and quarks, such as interactions involving

- a charged Higgs boson [1][2][3][4][5];
- leptoquarks (LQ) EXOtica;
- new vector bosons (Summary plots EXO).



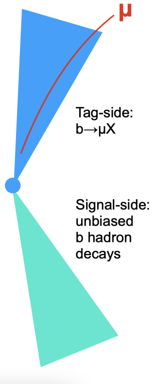
What can CMS do?



- General purpose detector with magnetic field for charged particles measurements;
- CMS has high instantaneous luminosity for high-p_T physics program and central acceptance: it can be complementary to other experiments like LHCb, with forward acceptance
- A huge effort has been done in CMS in the past years to make LFUV measurements in B physics possible
- The challenge for B-ph is trigger on soft objects other than μs $\rightarrow$ CMS Bparking campaign

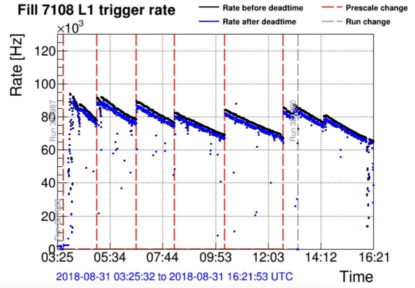
CMS parked data

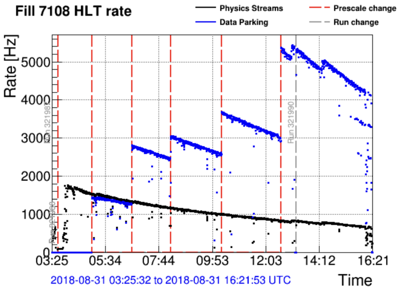
- CMS has implemented for 2018 a new trigger for soft muons from B-meson decays CMS-DP-2019/043
- Events recorded with a trigger logic that requires the presence of a single displaced muon
- $b\bar{b}$ events with high purity
- The μ candidate responsible for the trigger comes from the "tag-side" b hadron that undergoes a $b \to \mu + X$ decay.
- The "signal-side" b hadron decays naturally as it is not biased by the trigger requirements.



CMS parked data

- The trigger threshold depends on the instantaneous luminosity: when it decreases, together with the other physics triggers, the B-park trigger requirements are loosened to exploit spare bandwidth.

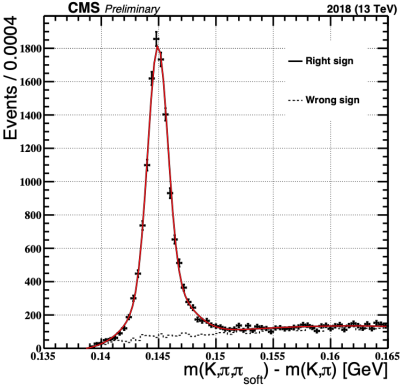




B-hadron purity

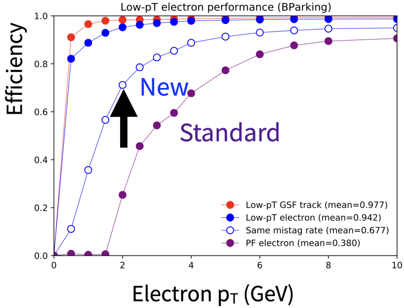
- 12 Billion events recorded in 2018 with $b\bar{b}$ purity of 75 %

- The purity determination relies on the decay $B^0 \to D^{*+}\mu\nu \to (D^0\pi_{soft})\mu\nu \to (K\pi\pi_{soft})\mu\nu$
- In the plot the difference for D^{*+} and D^0 is shown
- The product of K and μ is required to be $+1$ (right sign), or -1 (wrong sign)

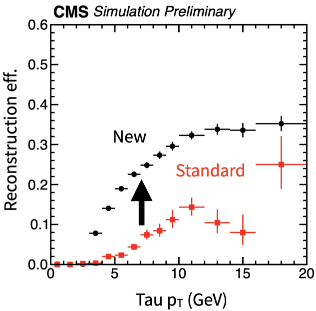


Low-p_T lepton reconstruction

- The lepton p_T distributions are very soft
- This imply challenges related to e and τ reco efficiency



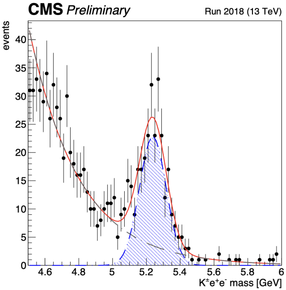
New low-p_T electron reconstruction scheme CMS-DP-2019-043

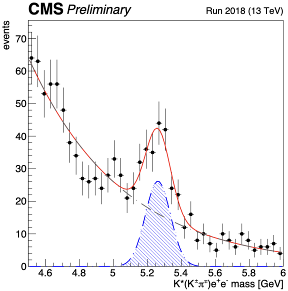


New low-p_T tau reconstruction algorithm dedicated to hadronic $\tau \to \pi\pi\pi\nu$ decay CMS-DP-2020-039

Standard Candles

- using a fraction of the B Parking dataset, invariant mass distributions are computed for some B decays





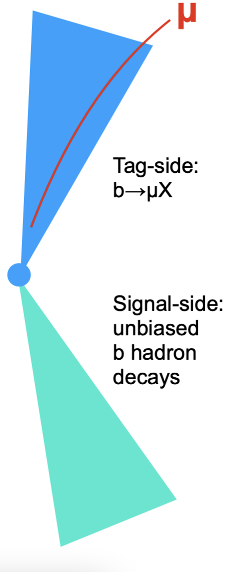
CMS-DP-2019-043

- R(K) and R(K*) normalisation channels
- Useful also to test the low-p_T reconstruction algorithm

Considerations on BParking potential

The possible measurements that can be done with the BParking dataset

- **Single μ analyses**: B-Parking makes them possible for the first time; the B single-muon dataset is the largest ever collected.
- **B unbiased**: Measurements of hadronic decays that were precluded before the B-Parking dataset $\rightarrow$ fragmentation fraction.



Conclusions

- LF(U)V is a very exciting field to look for new physics
- In CMS a big effort is put into LFV and LFUV analyses
- The $\tau \to 3\mu$ LFV measurement with only 2016 data is published and an analysis with all Run II data is ongoing
- The B-parked dataset has been collected in 2018 to allow CMS to enter the test of LFUV measurements, with the B-single muon dataset the largest ever collected
- **Many analyses on going with this dataset and new results coming!**