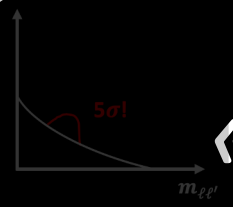
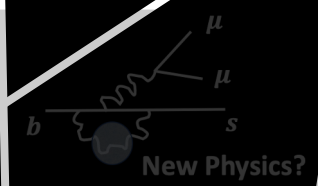




«Searches and tests for lepton-flavour-violating processes at CMS»

Lepton Decays

Higgs

B-Physics

Exotics

Top

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} O_a^{(6)} + \dots$$

Luigi Marchese,

on behalf of the CMS collaboration

17-23 July 2023, Melbourne

«Lepton Photon Interactions at High Energies» 2023

CMS

ETH zürich

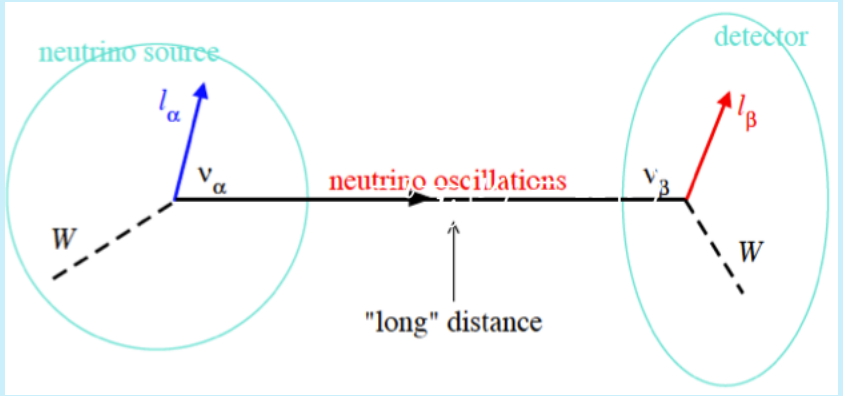
OUTLINE

- Introduction to Lepton Flavour Violation
- Motivation
  - Experimental Motivation
  - Theoretical Motivation
- The CMS LFU Program
  - Higgs sector
  - Top sector
  - Lepton sector
  - Exotics sector
  - *B* Physics sector
- Conclusions

INTRODUCTION

➢ In the Standard Model (SM) *Lepton Flavour Universality (LFU) is not a* formal symmetry

- *Neutral Lepton Flavour Universality (NLFU)* broken by the evidence of neutrino oscillations: *Phys. Rev. Lett. 81:1562-1567, 1998*
  ☑ Proportional to neutrino masses

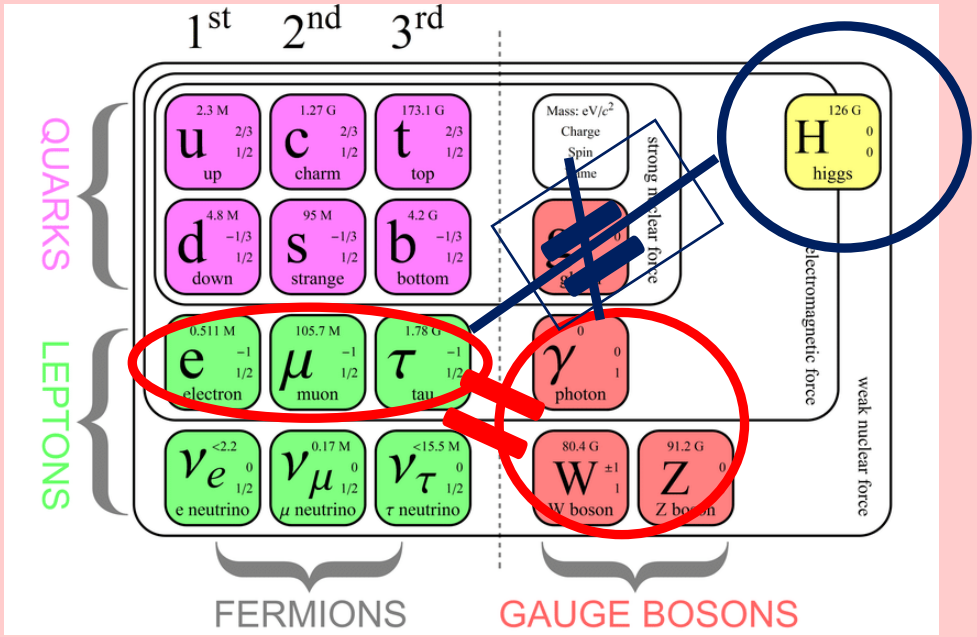


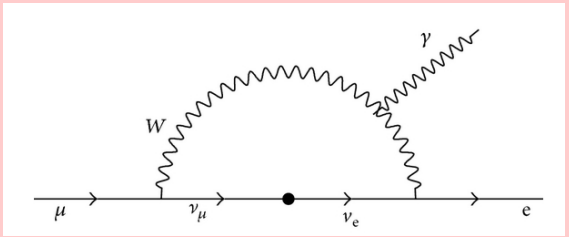
INTRODUCTION

➢ In the Standard Model (SM) *Lepton Flavour Universality (LFU) is not a* formal symmetry

- Charged *Lepton Flavour Universality (CLFU)*
  - ☑ Expected in the electroweak (EW) sector
  - ☑ Broken by Yukawa interactions of the Higgs boson with the three leptons
  - ☑ Violation *possible* only via neutrino mixing.
    Very Rare event:

$$\mathcal{B}(\mu^+ \to W^+\nu(\nu_\mu \to \nu_e) \to e^+\gamma < \mathbf{10^{-55}}$$





Observation of LFU violation implies physics beyond the SM!

OUTLINE

- Introduction to Lepton Flavour Violation
- Motivation
  - Experimental Motivation
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  - Higgs sector
  - Top sector
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  - B Physics sector
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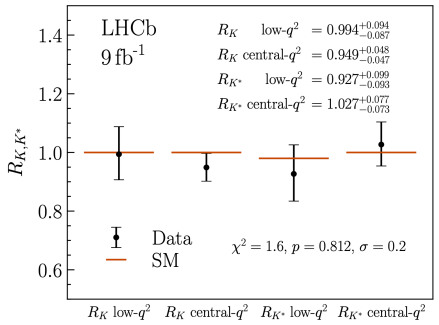
EXPERIMENTAL MOTIVATION

- Semi-leptonic decays of *B* mesons have proved to be an additional lever-arm to test LFU

$b \to s$ quark transition

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

- Some excitement in 2021 with a 3.1σ-deviation from the SM for $\mathcal{R}(K^{(*)})$ by LHCb: *Nature Physics* **volume 18**, pages 277–282 (2022)
- Updated result (Dec 2022):
- arXiv:2212.09152 and arXiv:2212.09153



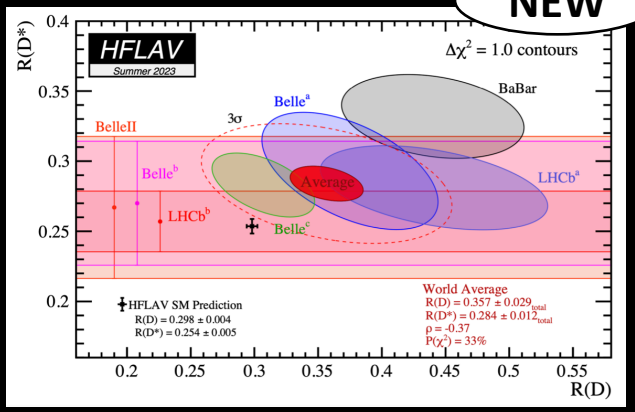
SM Consistent!

$b \to c$ quark transition

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

- Since 2012, three experiments reporting on $\mathcal{R}(D^{(*)})$: BaBar, Belle and LHCb
- Including the latest LHCb result (Feb 2023): arXiv:2302.02886

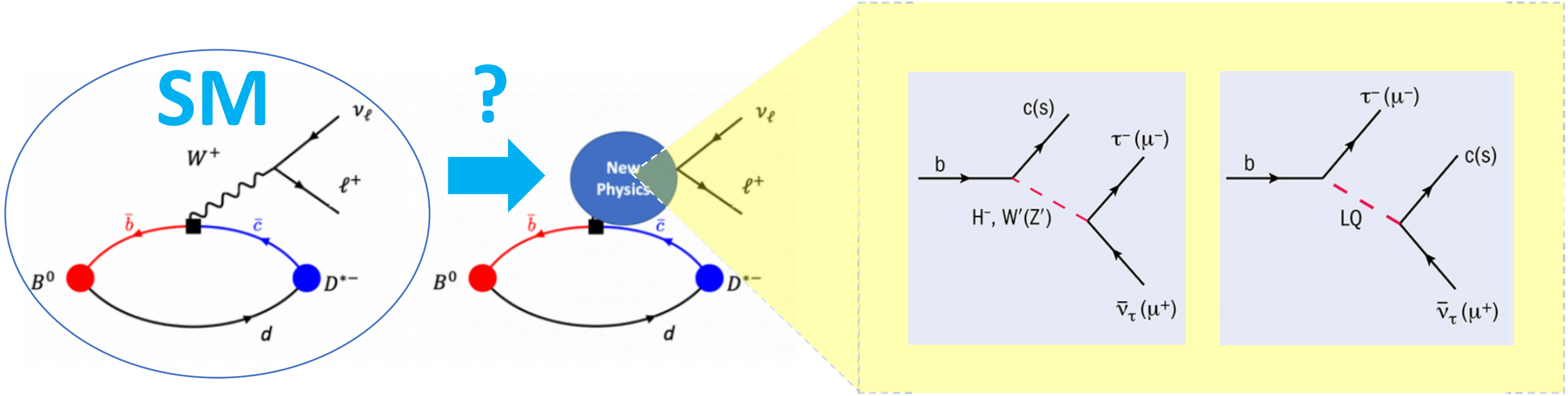
NEW



3.3σ-deviation from the SM!

THEORETICAL MOTIVATION

- Possible LFU violation will be clear indication of new Beyond-the-SM (BSM) physics:
  - **Extended Higgs** or **Gauge sector** or **LeptoQuarks** (LQ at CMS in Ben's talk)



- **Impact**: to give the idea
  - Last *Flavour Anomaly Workshop* attended by >550 scientists at CERN
  - If one searches for "LFU violation" in iNSPIRE >1500 contributions appear

OUTLINE

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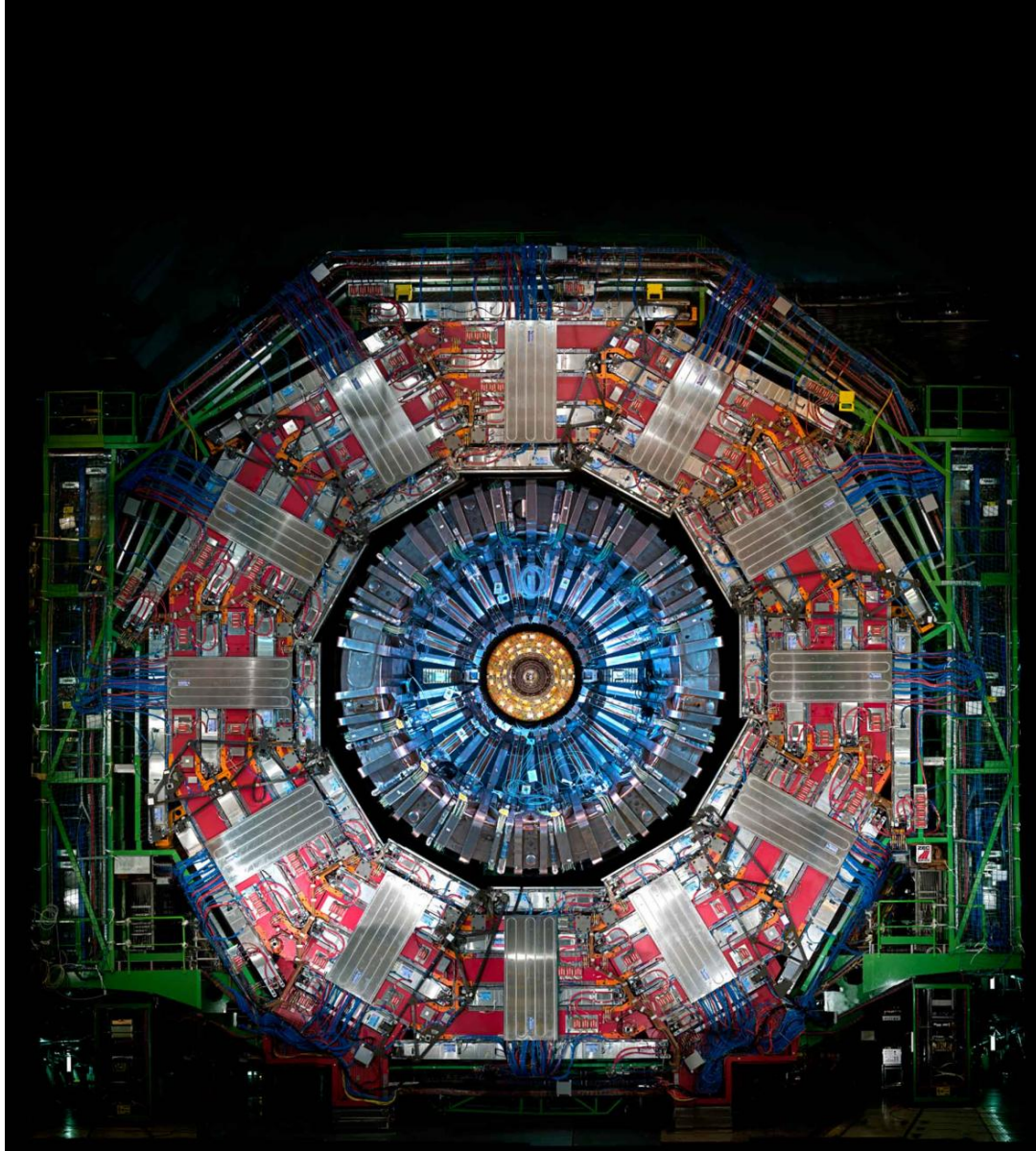
THE CMS EXPERIMENT

- One of the four proton-proton interaction points of the LHC ring
- Multi-purpose detector with a broad physics programme
- We are currently in the Run 3 data-taking operations
- Most of the results shown in this talk are based on 138 fb^{-1}, full Run-2 statistics, at $\sqrt{s} = 13$ TeV
- Special *B Physics Trigger* since Run 2
  - aimed at maximizing the CMS physics potential also for LFU studies



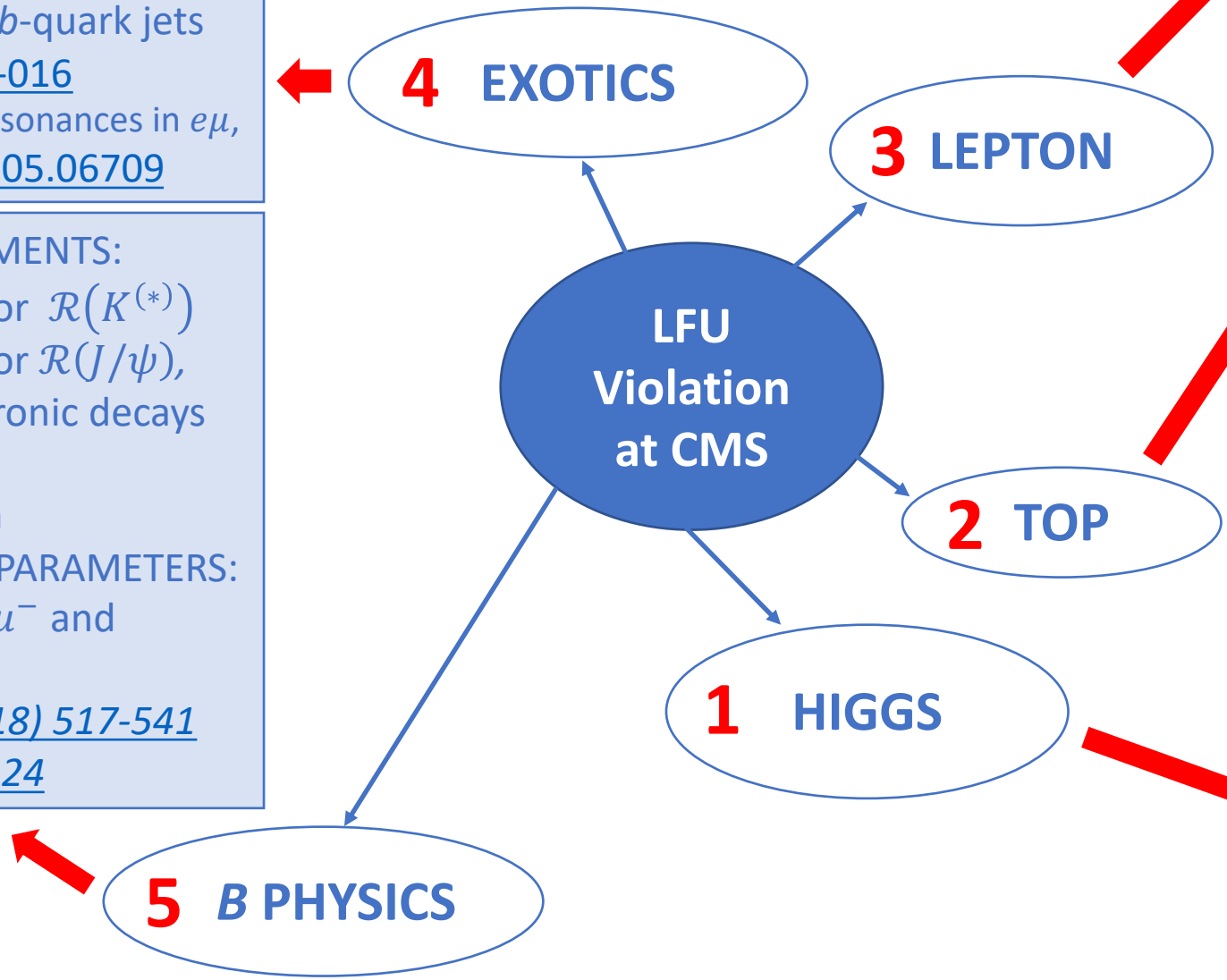
THE CMS LFU PROGRAM

TWO DIRECT SEARCHES:
1. Search for Z' with b-quark jets CMS-PAS-EXO-22-016
2. Search for Heavy resonances in $e\mu$, $\mu\tau$ and eτ arXiv:2205.06709

TWO R(X) MEASUREMENTS:
1. Ongoing efforts for $\mathcal{R}(K^{(*)})$
2. Ongoing efforts for $\mathcal{R}(J/\psi)$, leptonic and hadronic decays of τ-leptons
   - ➢ Results soon

TESTS ON ANGULAR PARAMETERS:
1. For $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$

Phys. Lett. B 781 (2018) 517-541 and *JHEP 04 (2021) 124*



ONE DIRECT SEARCH:
1. Search for $\tau \to 3\mu$ CMS-PAS-BPH-21-005

ONE DIRECT SEARCH:
1. Search for t→ $e\mu u$, t→ $e\mu c$ fopr tensor, vector and scalar interactions CMS-PAS-TOP-22-005

TWO DIRECT SEARCHES:
1. Search for $H \to e\mu$ arXiv:2305.18106
2. Search for $H \to e\tau$ and $H \to \mu\tau$ *Phys. Rev. D 104, 032013*

HUNTING FOR LFUV

Where?

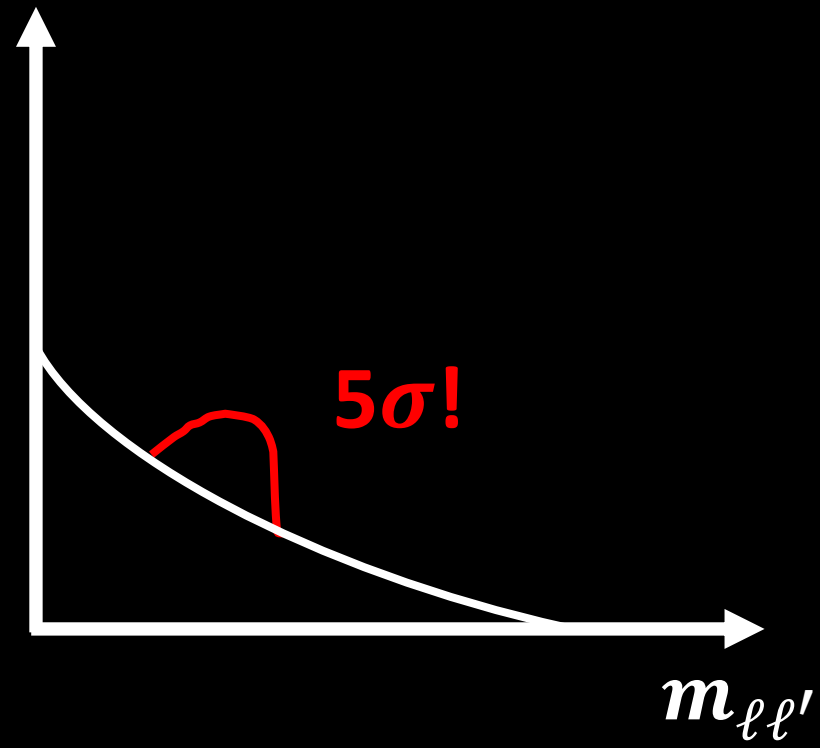
- From low-p_T to high-p_T …

  Huge phase-space!

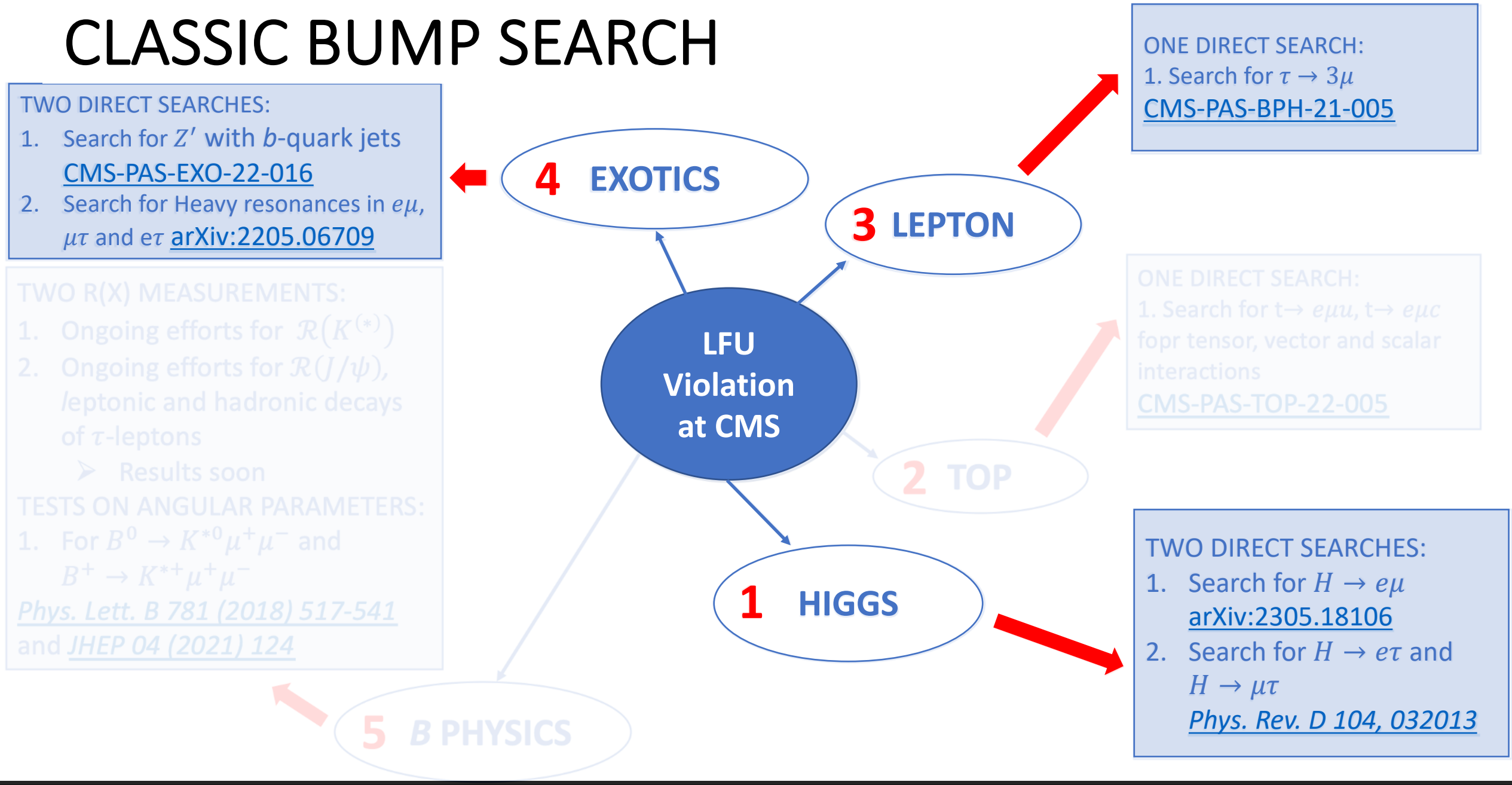
HUNTING FOR LFUV

How?

- Different approaches:
  - **Classic bump search**



CLASSIC BUMP SEARCH



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2. Search for $H \to e\tau$ and $H \to \mu\tau$ *Phys. Rev. D 104, 032013*

HUNTING FOR LFUV

How?

- Different approaches:
  - **Infer the impact of additional contributions due to LFU violation**

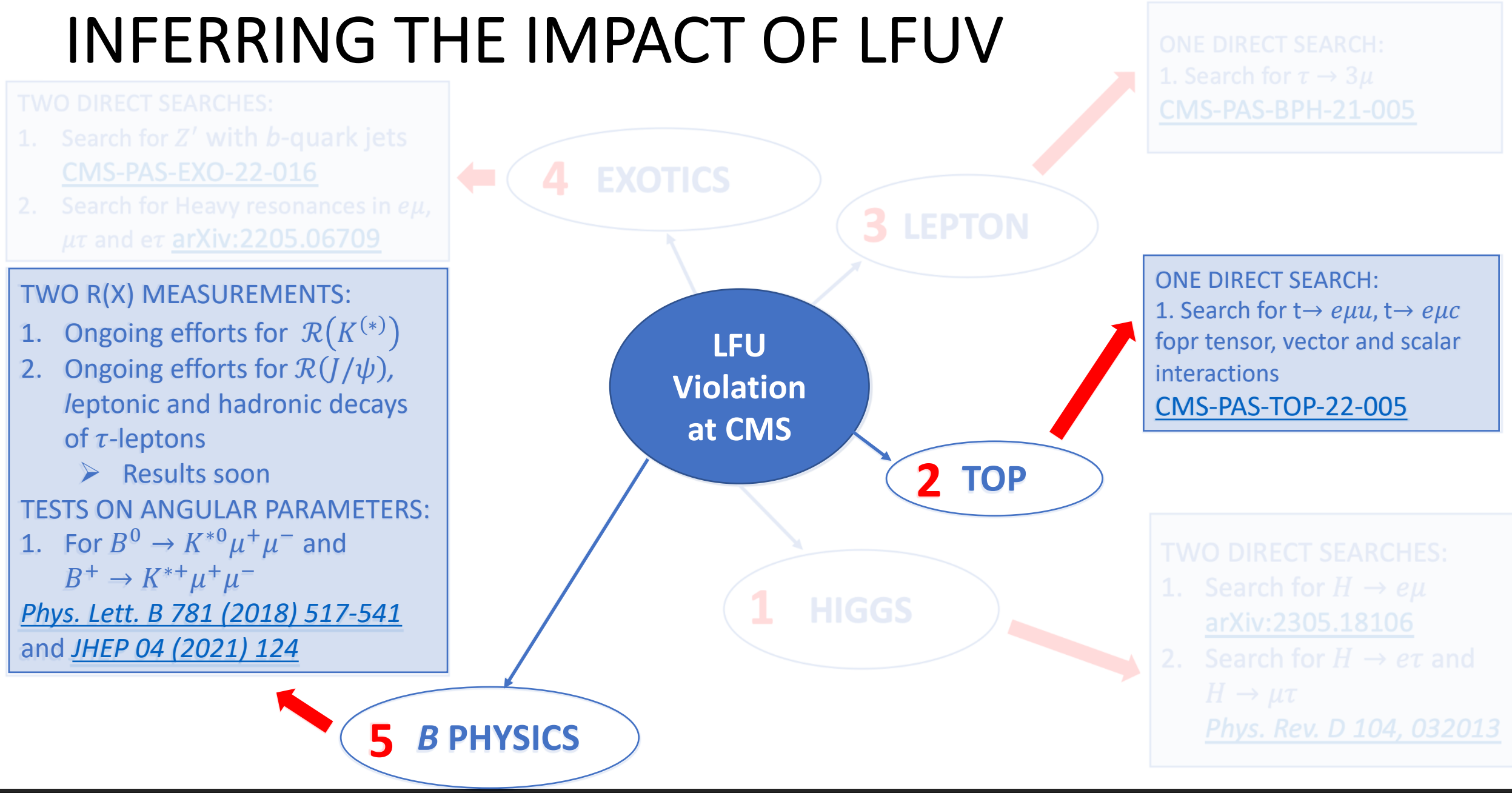
- **Additional EFT LFUV Operators:**

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} O_a^{(6)} + \dots$$

- **Deviation of SM processes looking at clear observables**

New Physics?

INFERRING THE IMPACT OF LFUV



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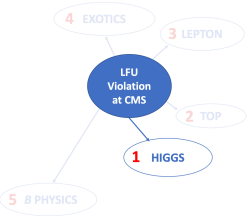
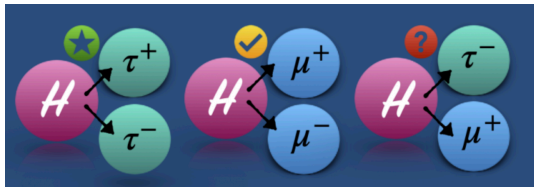
2. Search for $H \to e\tau$ and $H \to \mu\tau$ *Phys. Rev. D 104, 032013*

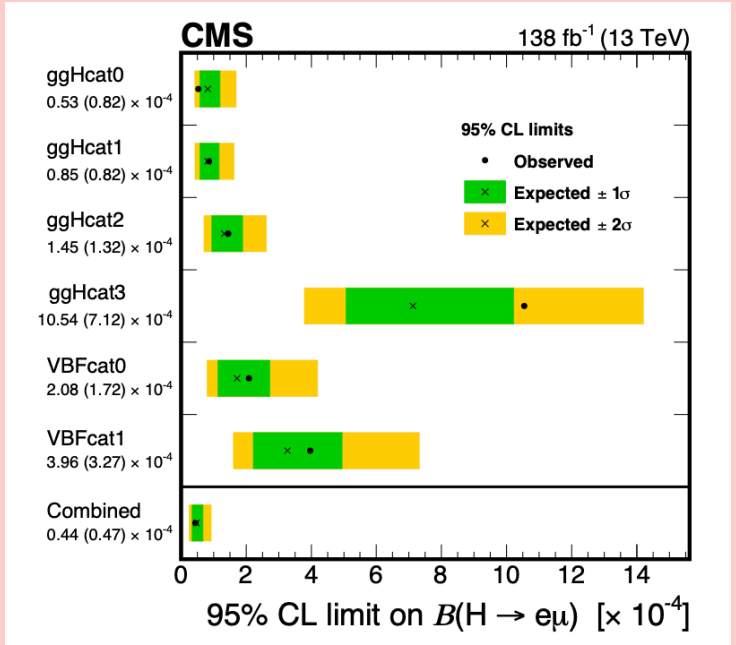
1 LFU VIOLATION IN HIGGS PHYSICS

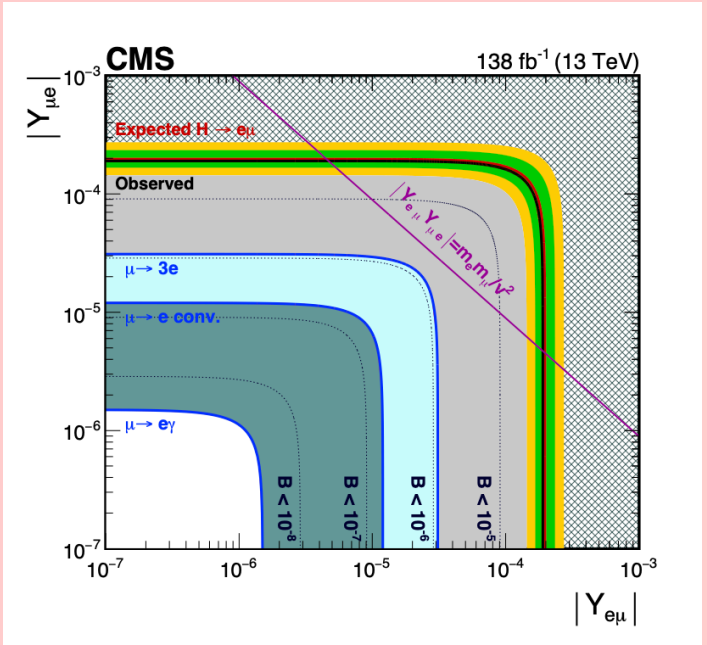




$H \to e\mu$ arXiv:2305.18106

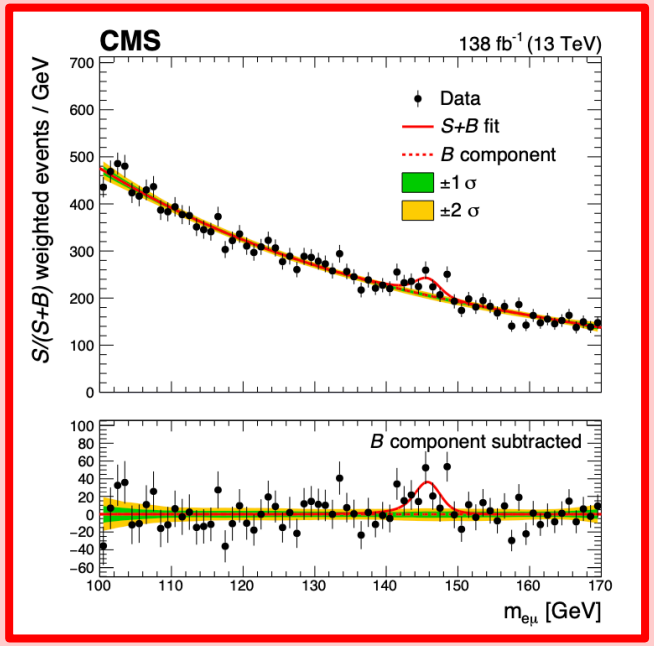
- Search for new resonance with mass of 110 -160 GeV in the $e\mu$-final state with 138 fb^{-1}
  - ggF and VBF productions with separate BDTs to separate signals from main backgrounds ($t\bar{t}$ and WW)





Observed(expected) most stringent limit:

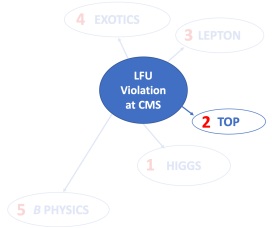
$\mathcal{B}(H \to e\mu) < 4.4(4.7) \cdot 10^{-5} at\ 95\%\ CL$



No excess observed for H(125)!

Excess observed with local(global) sign. of $3.8(2.8)\sigma$ at $m_{e\mu} \sim 146\ GeV$

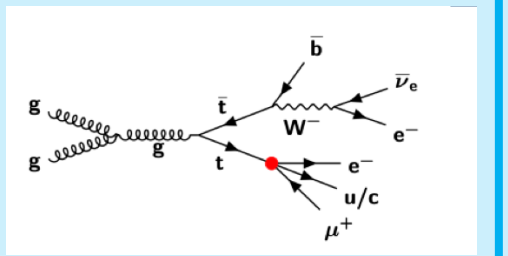
2 LFU VIOLATION IN TOP PHYSICS



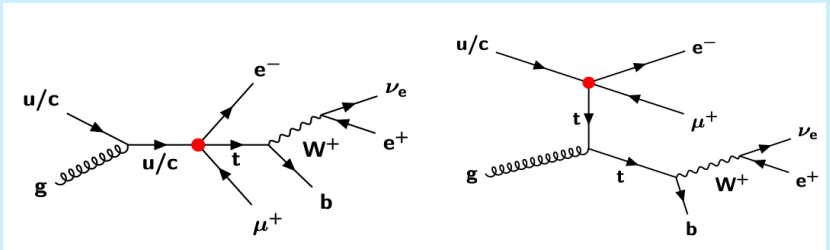
Top Decays and Production

arXiv:2305.18106

- Search in both top decay and production, looking at the trilepton final state with 138 fb^{-1}
- LFU violation is parametrized via a dim-6 EFT Operator
- SM Background: prompt (from EW bosons producing 3 leptons) and non-prompt(Drell-Yan) separated via BDT



LFUV from top decays



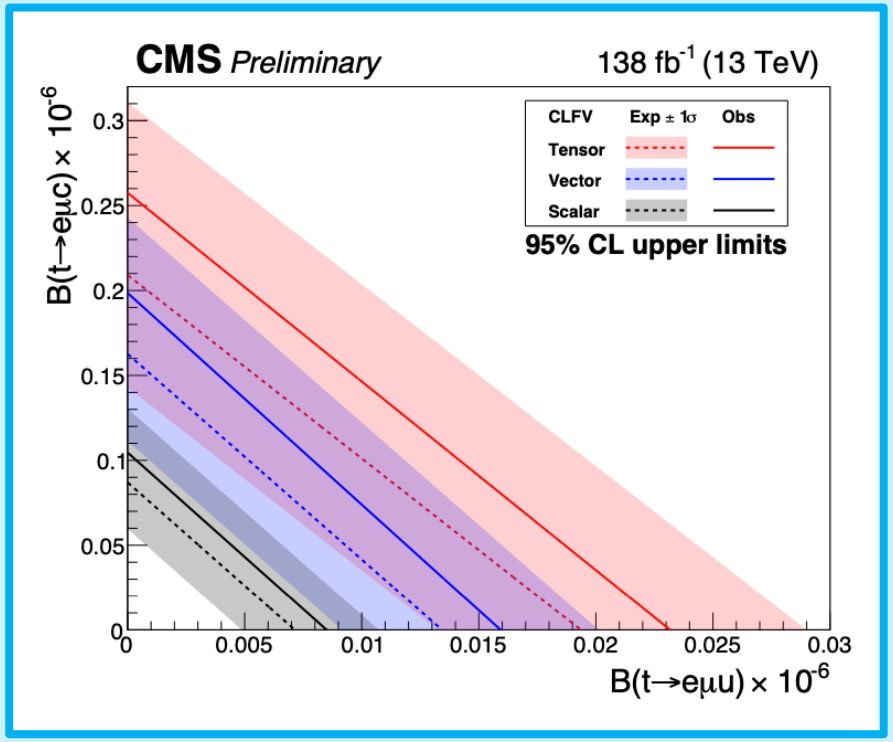
LFUV from top production

Observed most stringent limits at 95% CL :

$\mathcal{B}(t \to e\mu u) < 0.023\ or\ 0.016\ or\ 0.09\ \cdot 10^{-6}$

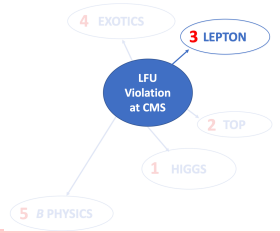
$\mathcal{B}(t \to e\mu c) < 0.0258\ or\ 0.199\ or\ 0.105\ \cdot 10^{-6}$

$for\ tensor, vector\ and\ scalar\ interactions$



No excess observed w.r.t. the SM!

3 LFU VIOLATION WITH LEPTON DECAYS



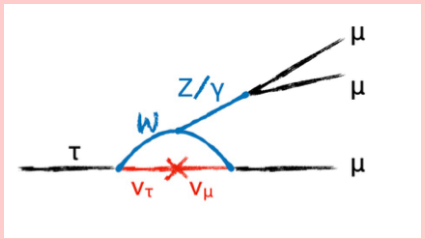
NEW

Search for $\tau \to 3\mu$ Decay

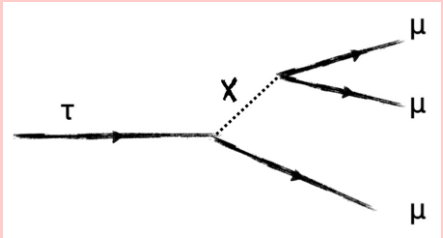
CMS-PAS-BPH-21-005

- Strongly suppressed process in the SM
  - Allowed via neutrino oscillations with $\mathcal{B}(\tau \to 3\mu) \sim 10^{-55}$
  - BSM models predict $\mathcal{B}(\tau \to 3\mu) \sim 10^{-9}$

10.1007/JHEP10(2018)148

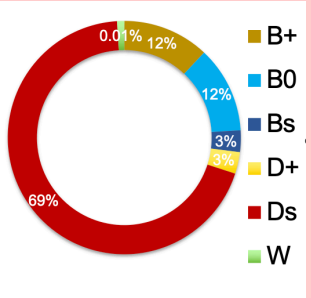


LFUV via ν-oscillations

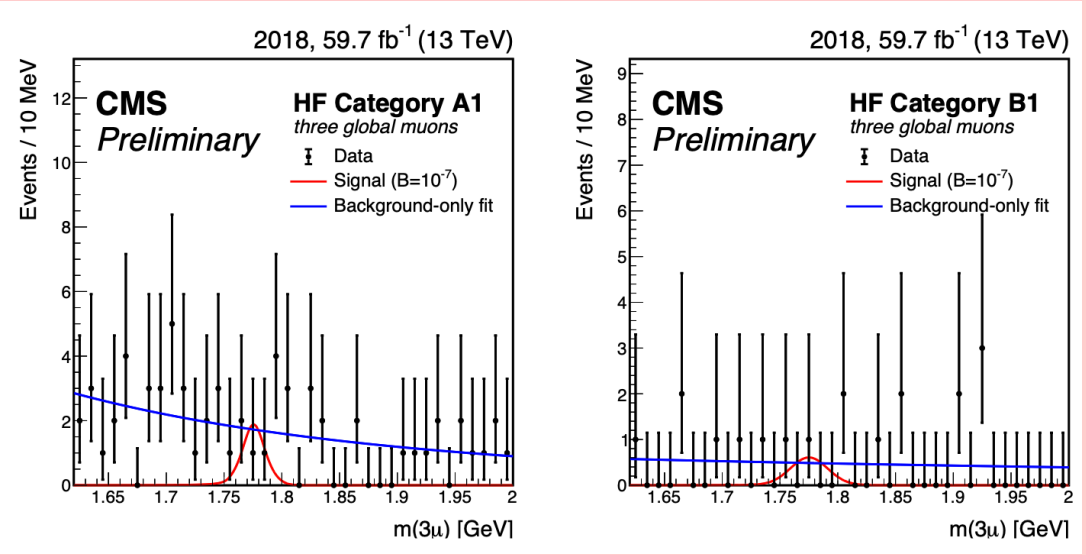


LFUV in BSM theories

- Search with 131 fb^{-1} focused on two production categories: τ-leptons from *W* and heavy flavour (HF) mesons

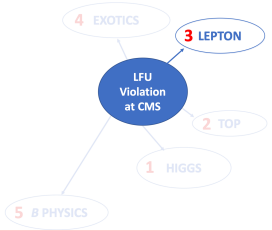


- BDT to separate signal from SM backgrounds (main: *D*-meson decays, EW and combinatorics)



$m(3\mu)$ mass-resolution in differet BDT categories for HF: different signal purtiy!

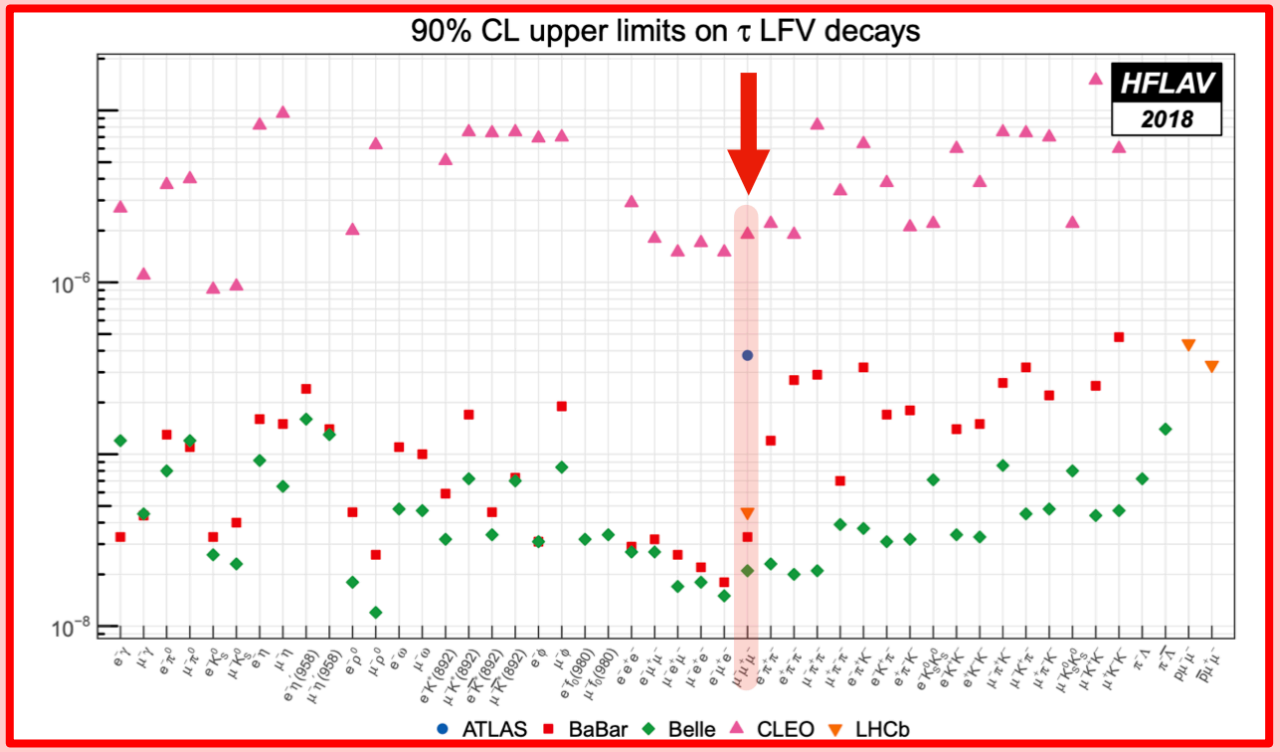
3 LFU VIOLATION WITH LEPTON DECAYS

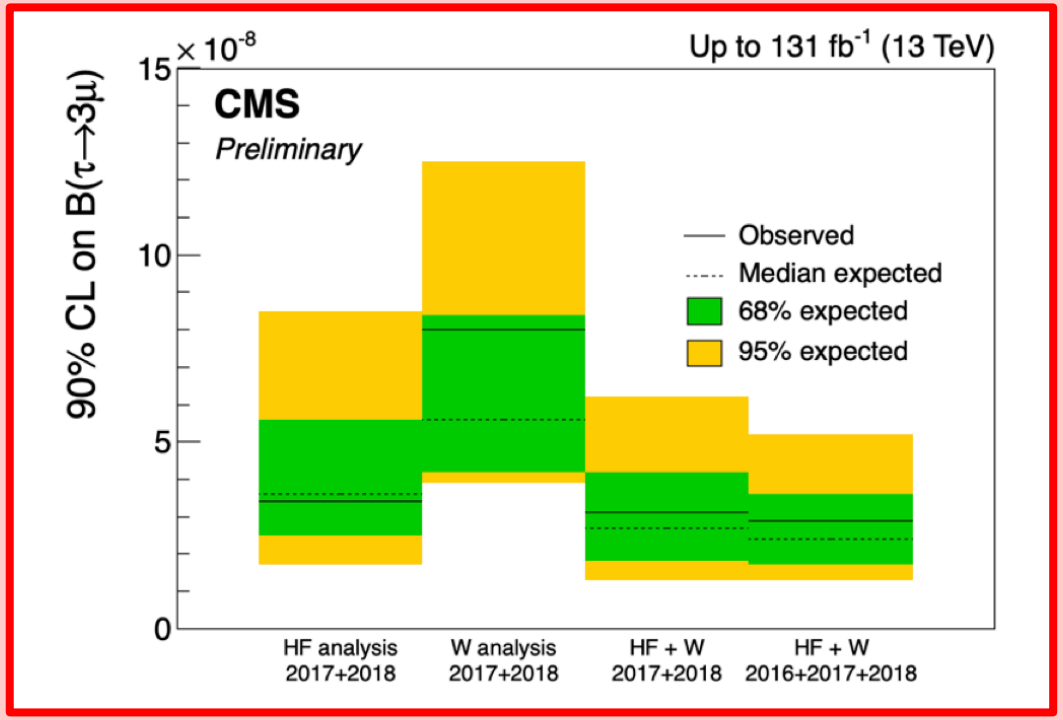


NEW

Search for $\tau \to 3\mu$ Decay

CMS-PAS-BPH-21-005





No excess observed w.r.t. the SM!

Observed(expected) limits at 95% CL :

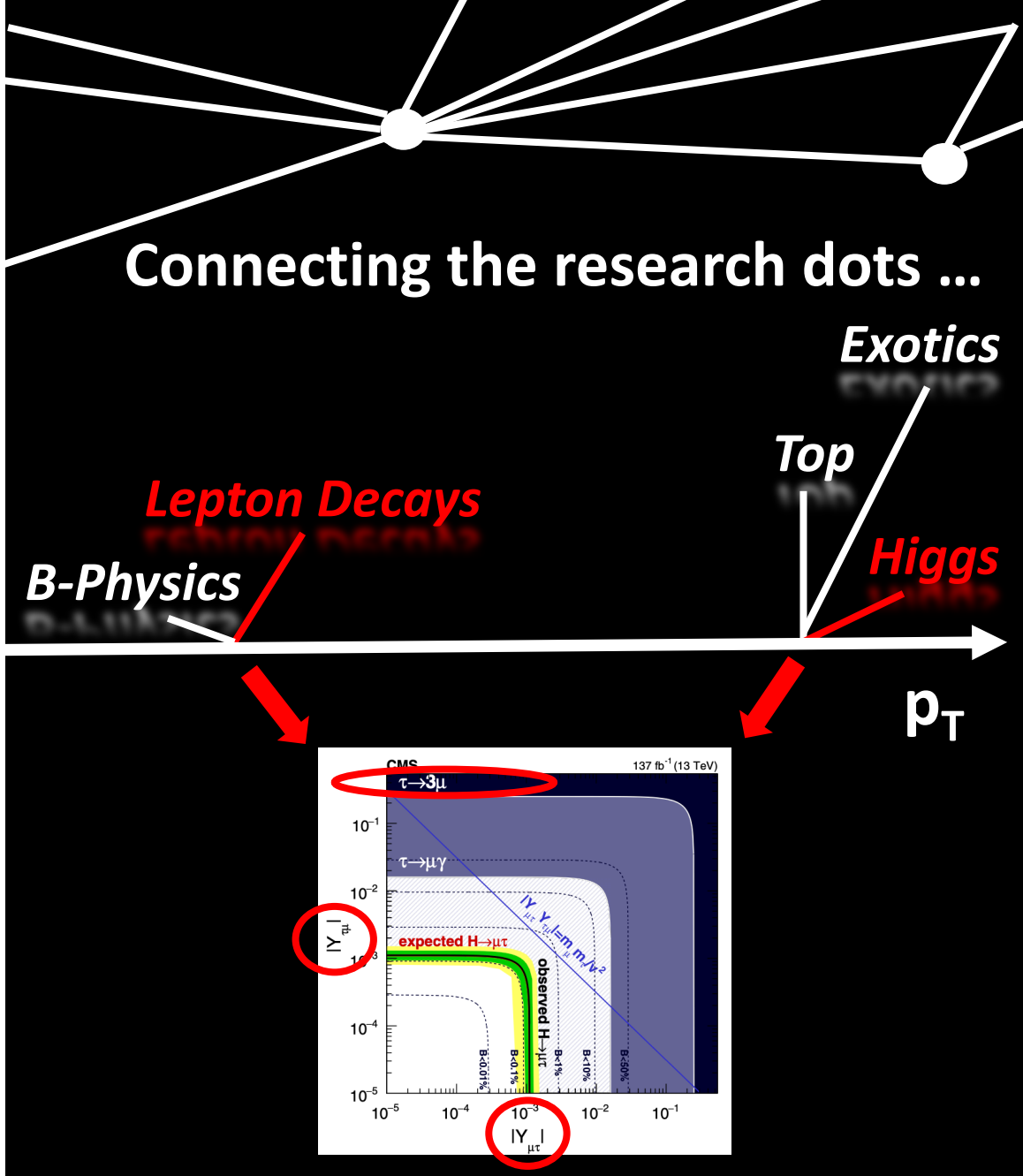
$$\mathcal{B}(\tau \to 3\mu) < 3.6\ (3.0)\ 10^{-8}$$

HUNTING FOR LFUV

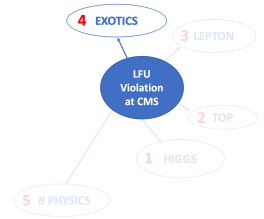
Often you move from

- low-p_T to high-p_T
- one approach to another

… in a complementary mode!

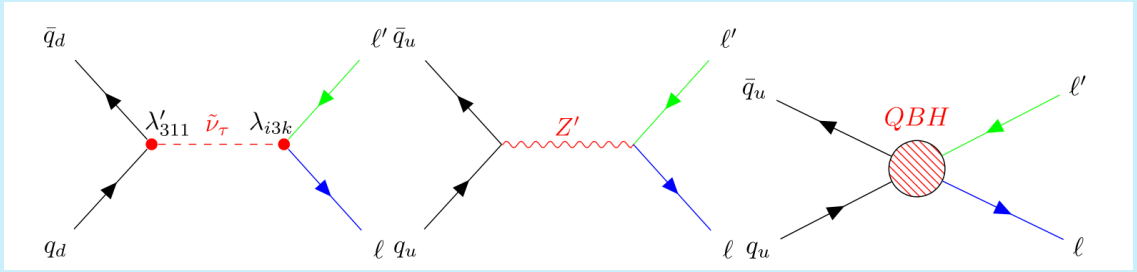


4 LFU VIOLATION IN EXOTICS SEARCHES



Heavy Resonances/Black Holes in $e\mu, e\tau, \mu\tau$

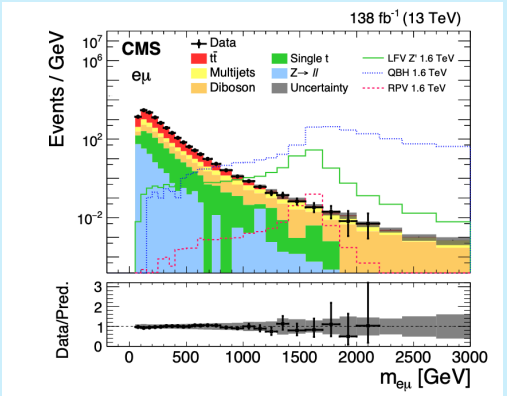
- Model- dependent search with 138 fb^{-1}
- Three benchmark signals arXiv:2205.06709
  - Resonant τ sneutrino for *R parity* violating SUSY
  - Heavy Z' with LFUV decays
  - Quantum black holes (QBH) with extra dimensions
- SM Background: $t\bar{t}$, diboson and multijets

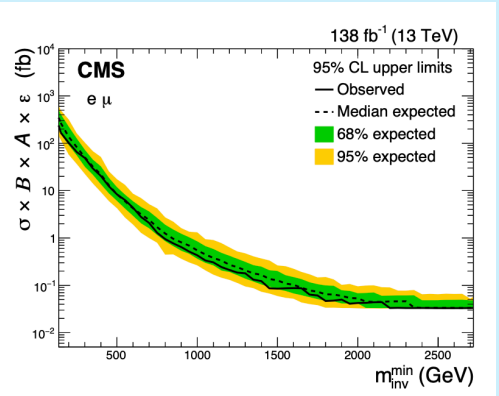


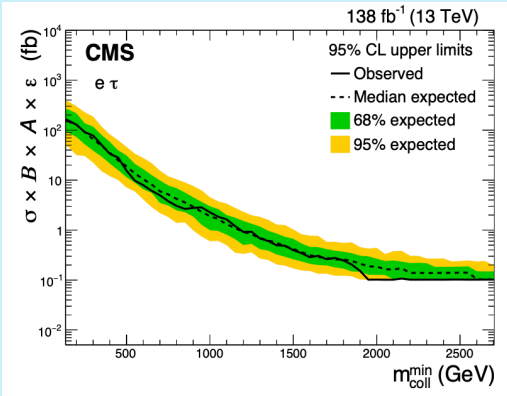
Benchmark Signals

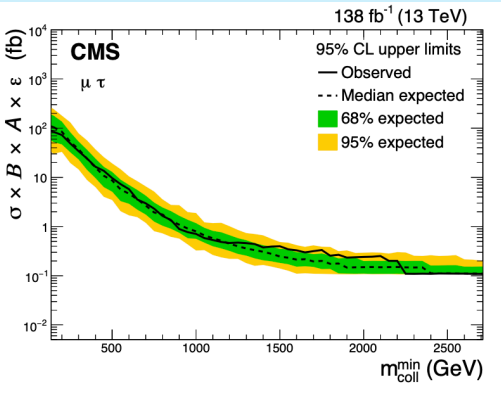
Observed limits at 95% CL :

τ sneutrino $excluded\ up\ to\ 4.2\ TeV\ (e\mu), 3.7(e\tau), 3.6(\mu\tau)\ TeV$
$Z'\ excluded\ up\ to\ 5.0(e\mu), 4.3(e\tau), 4.1(\mu\tau)\ TeV$
$QBH\ excluded\ up\ to\ 5.6(e\mu), 5.2(e\tau), 5.0(\mu\tau)\ TeV$



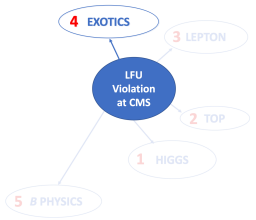






No excess observed w.r.t. the SM!

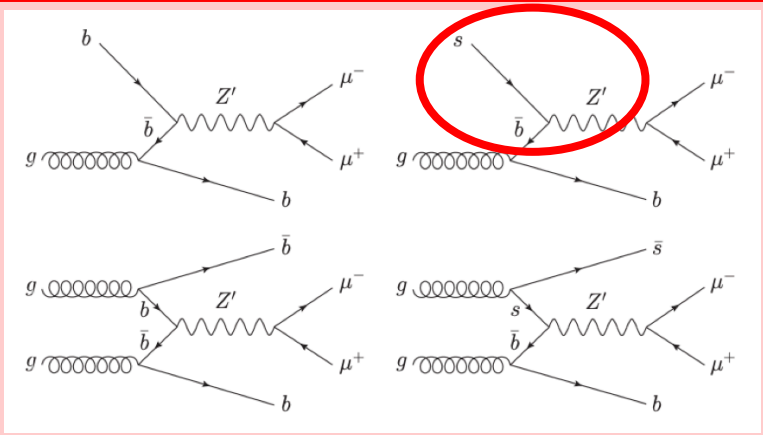
4 LFU VIOLATION IN EXOTICS SEARCHES



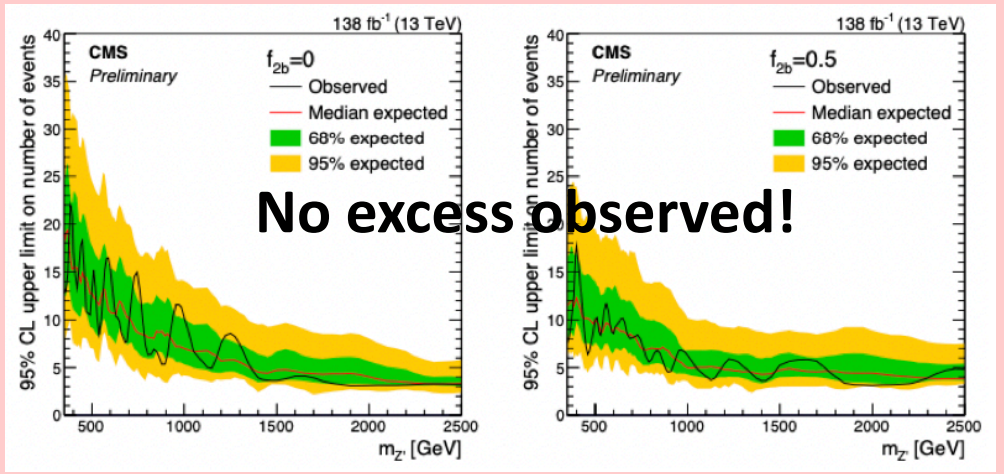
NEW

Search for $Z' \to \mu\mu$ boson with b-quark jets

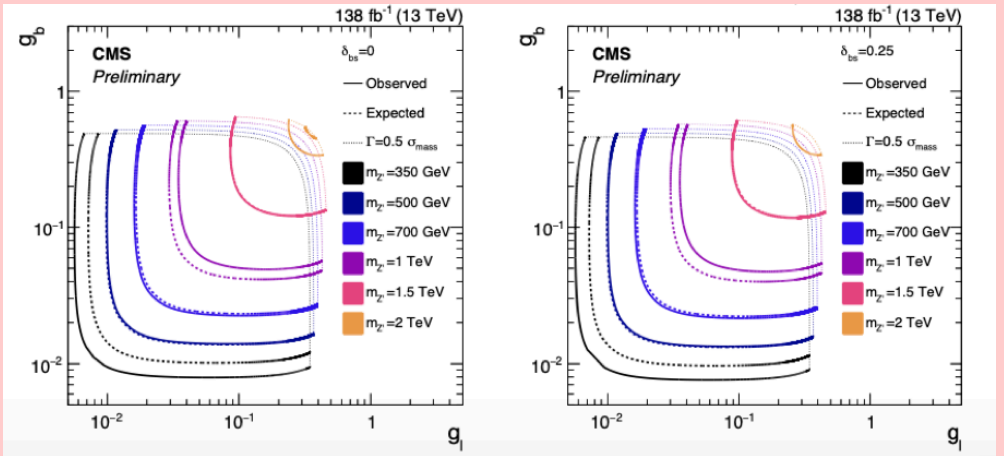
- Model independent search with 138 fb^{-1}
  - First search at LHC sensitive to Z' couplings to 2nd, 3rd generation of quarks ($Z'sb$) CMS-PAS-EXO-22-016
  - Z' with $m_{Z'} > 350$ GeV + at least 1 b-quark jet
  - Leading background: Drell-Yan and $t\bar{t}$ significantly reduced w.r.t. previous searches
  - Dimuon-mass fit to analytical functions



Benchmark Signals

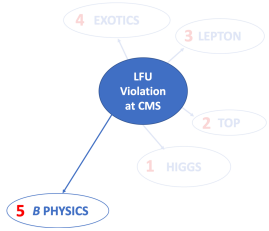


No excess observed!



Constraints in the $g_b - g_\ell$ plane for LFU model

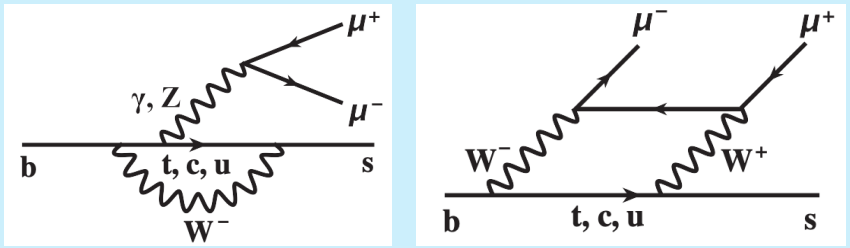
5 LFU VIOLATION IN *B* PHYSICS



Angular Analyses

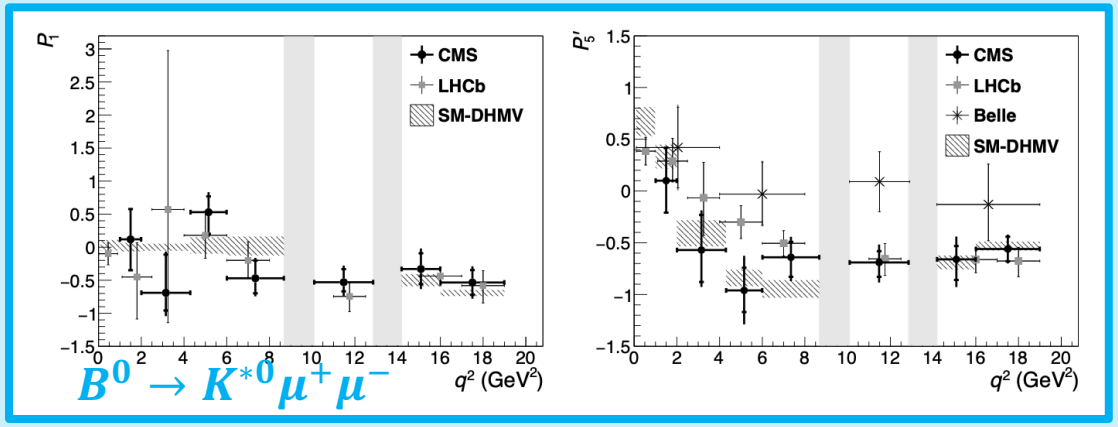
Phys. Lett. B 781 (2018) 517-541 and *JHEP 04 (2021) 124*

- Analyses of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$ with 20.5 fb^{-1}
- $b \to s\ell\ell$ are neutral flavour changing processes
  - Not possible in the SM at tree level
  - Can happen via higher-order diagrams
  - Deviations from SM => BSM effects

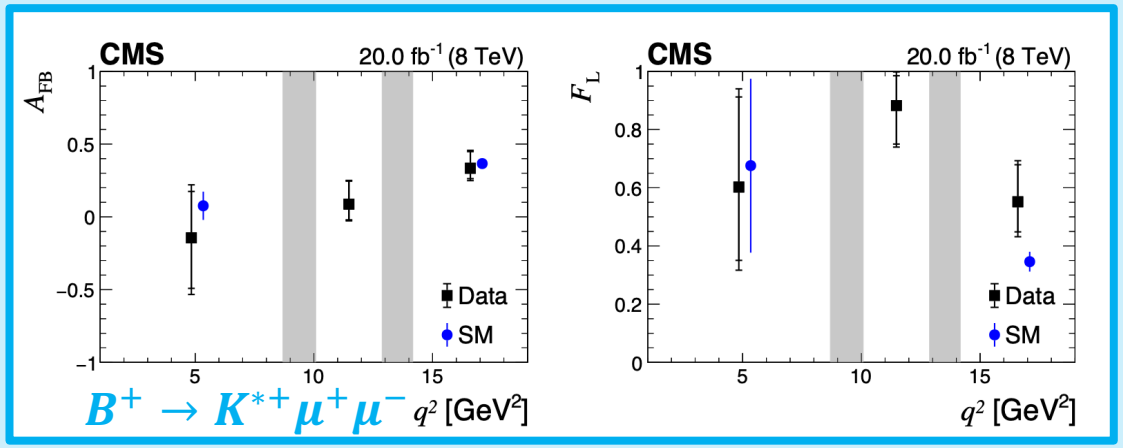


$\mathbf{B^+ \to K^{*+}\mu^+\mu^-}$ **in the SM**

- Differential rate fully described by three angles and $q^2 = (m^2_{\mu\mu})$
- Previous LHCb results with some deviations from SM: *Phys. Rev. Lett. 125, 011802*



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



$B^+ \to K^{*+}\mu^+\mu^-$

CMS results compatible with SM!

OUTLINE

- Introduction to Lepton Flavour Violation
- Motivation
  - Experimental Motivation
  - Theoretical Motivation
- The CMS LFU Program
  - Higgs sector
  - Top sector
  - Lepton sector
  - Exotics sector
  - *B* Physics sector
- Conclusions

Introduction

Motivation

The CMS LFU Program

Conclusions

CONCLUSIONS

- Lepton Flavour Universality Violation is an interesting research area where to look for new physics
- Some experimental indications are puzzling the scientific community
- Dedicated Trigger Campaign in CMS aimed also at maximizing the potential for LFU measurements
- The CMS LFU Program is ramping up with searches and tests in many different sectors:
  - Higgs sector
  - Top sector
  - Lepton sector
  - Exotics sector
  - *B* Physics sector
- Three different R(X) measurements to be released soon ...

... STAY TUNED!

BACK-UP

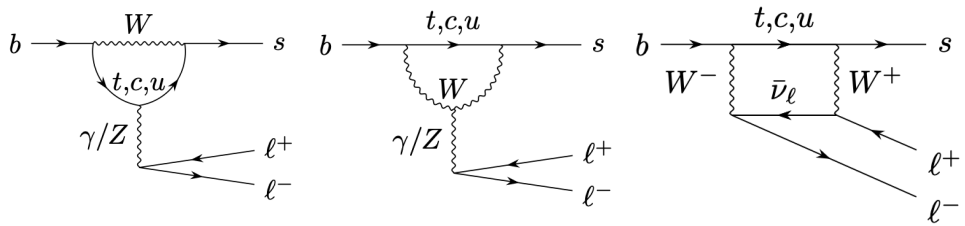
EXPERIMENTAL MOTIVATION I

- Semi-leptonic decays of *B* mesons have proved to be an additional lever-arm to test LFU

$b \to s$ quark transition

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

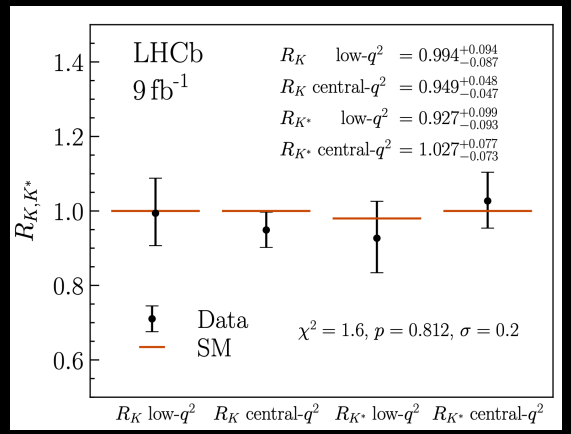
- Loop-level process: leading-order Feynman diagrams



- Experimentally, full reconstruction
- Theoretically, good precision

Experimental results

- Some excitement in 2021 with LHCb reporting on a 3.1σ-deviation with the SM for $\mathcal{R}(K^{(*)})$:
  Nature Physics **volume 18**, pages 277–282 (2022)
- Updated result (Dec 2022):
  arXiv:2212.09152 and arXiv:2212.09153



Consistent with the SM!

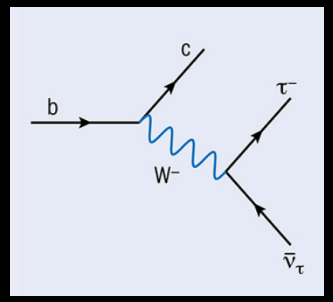
EXPERIMENTAL MOTIVATION II

- Semi-leptonic decays of *B* mesons have proved to be an additional lever-arm to test LFU

$b \to c$ quark transition

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu^+ \nu_\mu)}$$

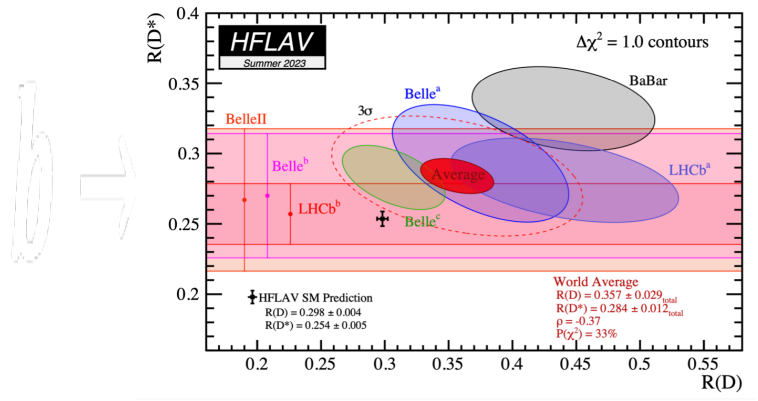
- Tree-level process:



- Experimentally, no full reconstruction
- Sensitive to QCD calculations
- Motivation regardless of $b \to s$

Experimental results

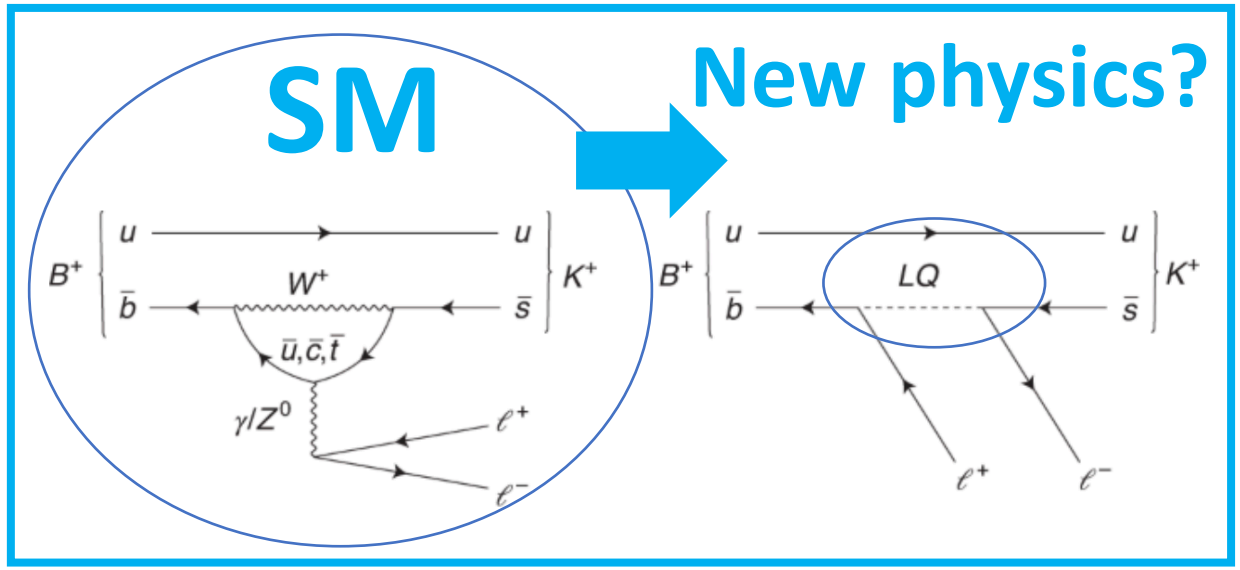
- Since 2012, three experiments reporting on $\mathcal{R}(D^{(*)})$: BaBar, Belle and LHCb
- Including the latest LHCb result (Feb 2023): arXiv:2302.02886



3.3σ-deviation with the SM!

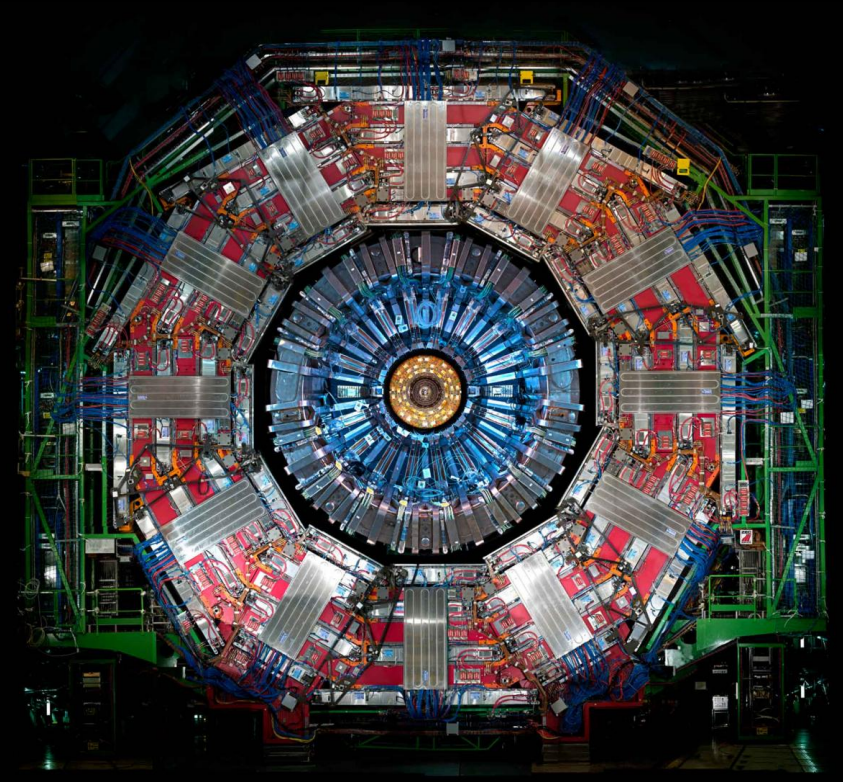
$b \to s$ and $b \to c$ MOTIVATION

- **In 2021** some excitement as the LHCb collaboration reported on a 3.1σ-discrepancy (single-experiment evidence) with the SM also in the $b \to s\mu\mu$ quark transition
- **Theoretically, less motivated.** BSM effects are mostly expected for the heavier τ − lepton
- **In 2022** new result from LHCb showing there was an error in one background estimate: results consistent with the SM!
- **The theoretical motivation for BSM physics in the proposed project is disconnected from this and more grounded!**

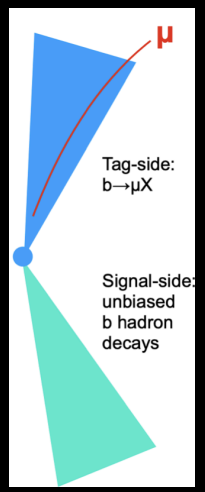


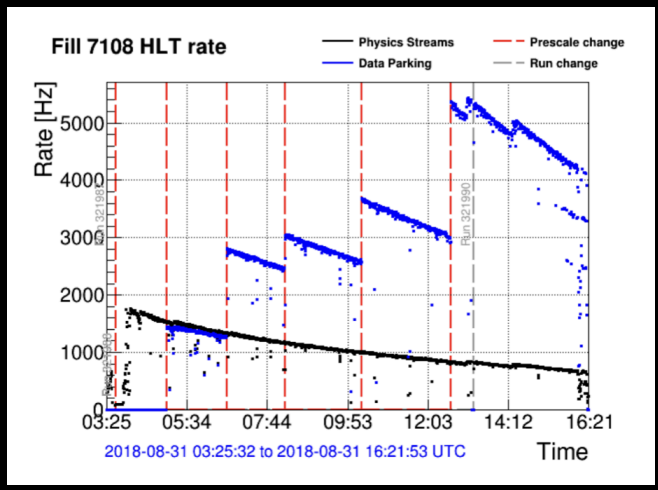
THE CMS EXPERIMENT

- One of the four proton-proton interaction points of the LHC ring
- Multi-purpose detector with a broad physics programme
- We are currently in the Run 3 data-taking operations
- Special *B Physics Trigger* since Run 2
  - aimed at maximizing the physics potential also for LFU studies
  - selection of 12 billion events with 75% $b\bar{b}$ -purity based on a logic requiring a single displaced muon
  - To not affect the CMS core-physics program, trigger thresholds loosened when the instantaneous luminosity drops

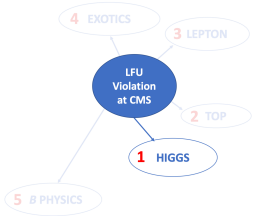


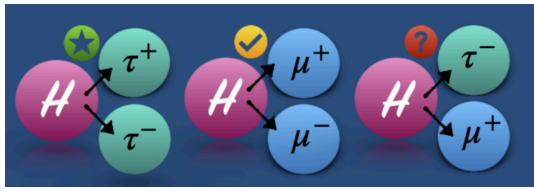
BParking **at CMS**





1 LFU VIOLATION IN HIGGS PHYSICS





$H \to e\mu$ arXiv:2305.18106

- So far, good consistency with SM, with little space for for BSM Higgs
  $\mathcal{B}(H \to invisible) < 0.16$ *at 95% CL*
- LFU violation of Yukawa couplings expected in BSM theories with more than one Higgs doublet, the Randall-Sundrum model or composite Higgs models
- Indirect limit of $\mathcal{B}(H \to e\mu) < 10^{-8}$ *at 95% CL* only from $\mu \to e\gamma$ **with strong assumption on the almost exclusive contribution of Higgs in FCNC and on $\Upsilon_{\mu\mu}$ and Υ_{ee}**

SIGNALS produced at NLO QCD

- ggF and VBF SM H(125)
- ggF and VBF for $X \to e\mu$ with $m_X = [110, 120, 130, 140, 150, 160]\ GeV$

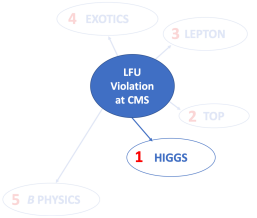
Backgrounds

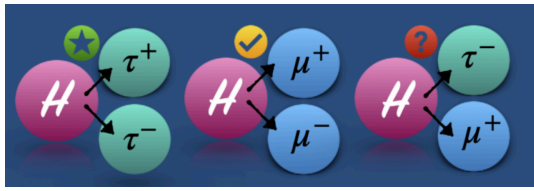
- $H \to \tau\tau$ and $H \to WW^*$– leptonic decays

Strategy:

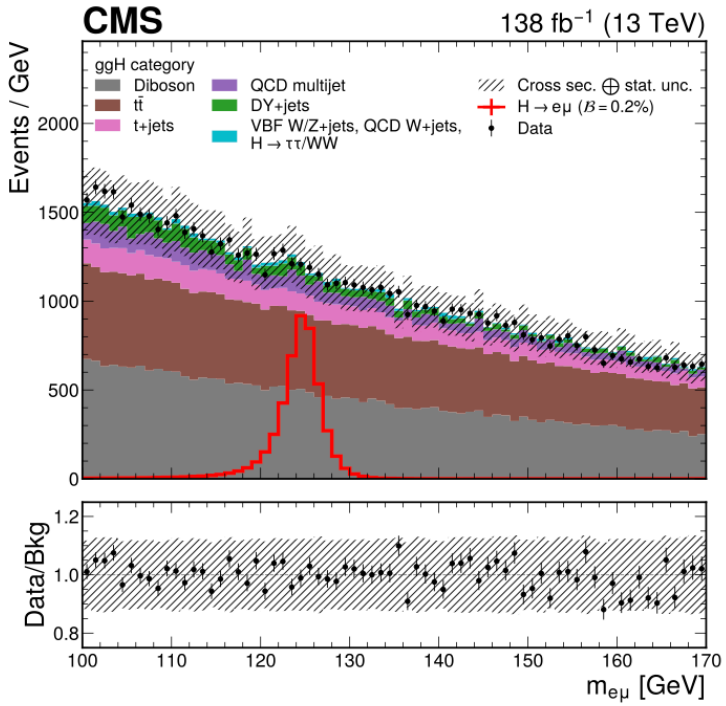
- Events classified using BDT in each VBF and ggF category (6 categories)
- BDT input variables chosen to avoid correlation with the $m_{e\mu}$ variable
- Simultaneous fit to of signal (sum of Gaussians) and backgrounds (Bernstein polynomials) in each category

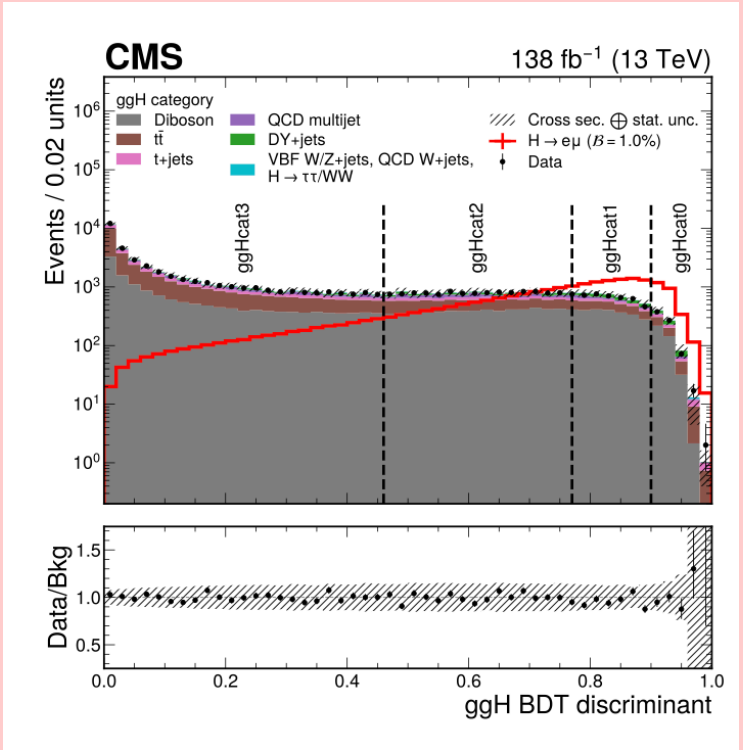
1 LFU VIOLATION IN HIGGS PHYSICS

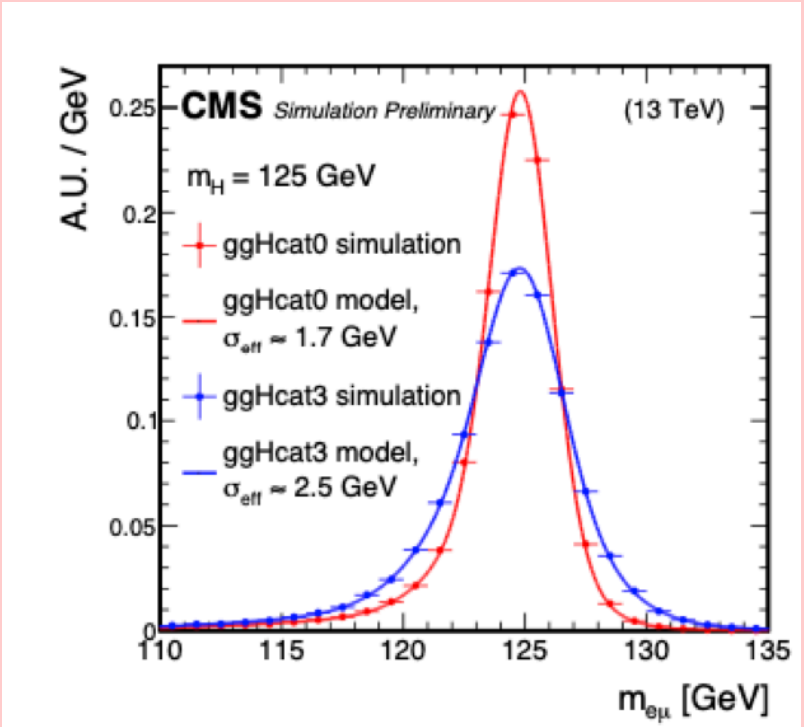




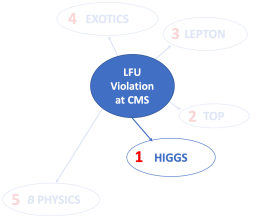
ggF

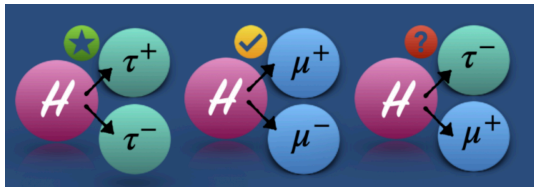






1 LFU VIOLATION IN HIGGS PHYSICS





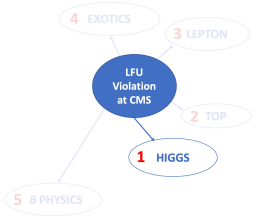
Systematic uncertainties	ggH mode (%)	VBF mode (%)
Muon identification, isolation, and trigger	0.2–0.4	0.3–0.4
Electron identification, isolation, and trigger	1.8–2.6	2.0–2.5
b-tagging veto efficiency	0.1–0.4	0.1–0.3
Jet energy scale	0.6–18.6	4.0–10.0
Unclustered energy scale	0.1–9.3	0.1–9.9
Trigger timing inefficiency	0.1–0.4	0.2–0.5
Integrated luminosity	1.6	1.6
Pileup	0.1–1.6	0.1–1.6
Parton shower	—	1.9–11.4
Renormalization and factorization scales	3.9–8.0	0.2–0.5
PDF+α_S	3.0–3.2	1.9–2.1
Effect of the ren. and fact. scales on the acceptance	0.2–11.2	0.2–1.3
Effect of the PDF+α_S on the acceptance	0.1–0.6	0.1

$$\Gamma(\mathrm{H} \to \mathrm{e}\mu) = \frac{m_{\mathrm{H}}}{8\pi}(|Y_{\mathrm{e}\mu}|^2 + |Y_{\mu\mathrm{e}}|^2).$$

$$\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu) = \frac{\Gamma(\mathrm{H} \to \mathrm{e}\mu)}{\Gamma(\mathrm{H} \to \mathrm{e}\mu) + \Gamma_{\mathrm{SM}}}.$$

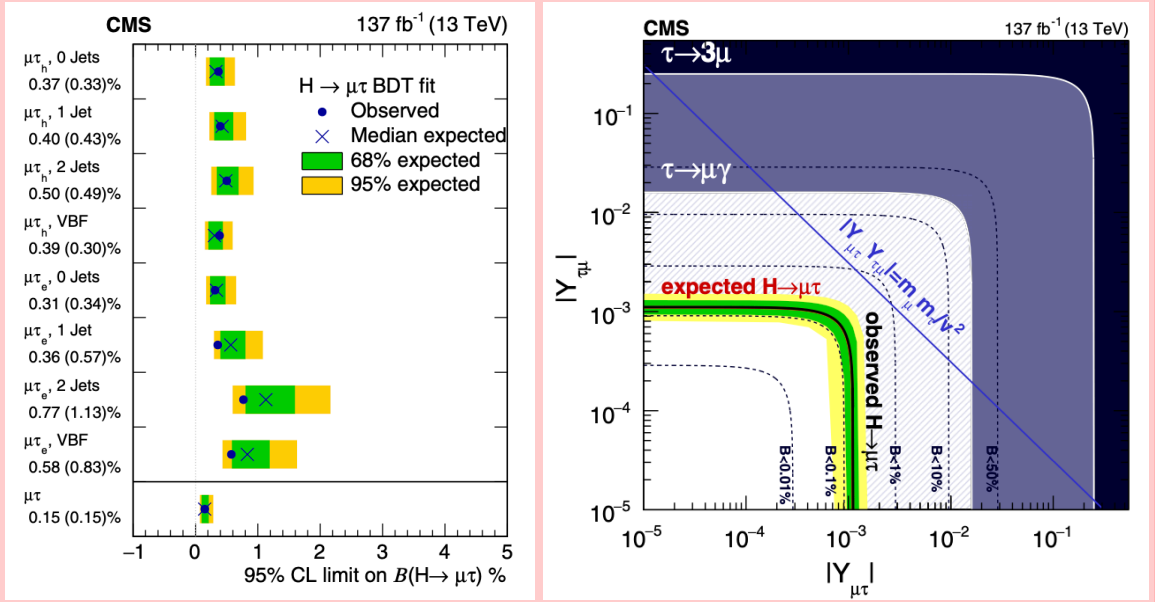
$$\sqrt{|Y_{\mathrm{e}\mu}|^2 + |Y_{\mu\mathrm{e}}|^2}$$

1 LFU VIOLATION IN HIGGS PHYSICS

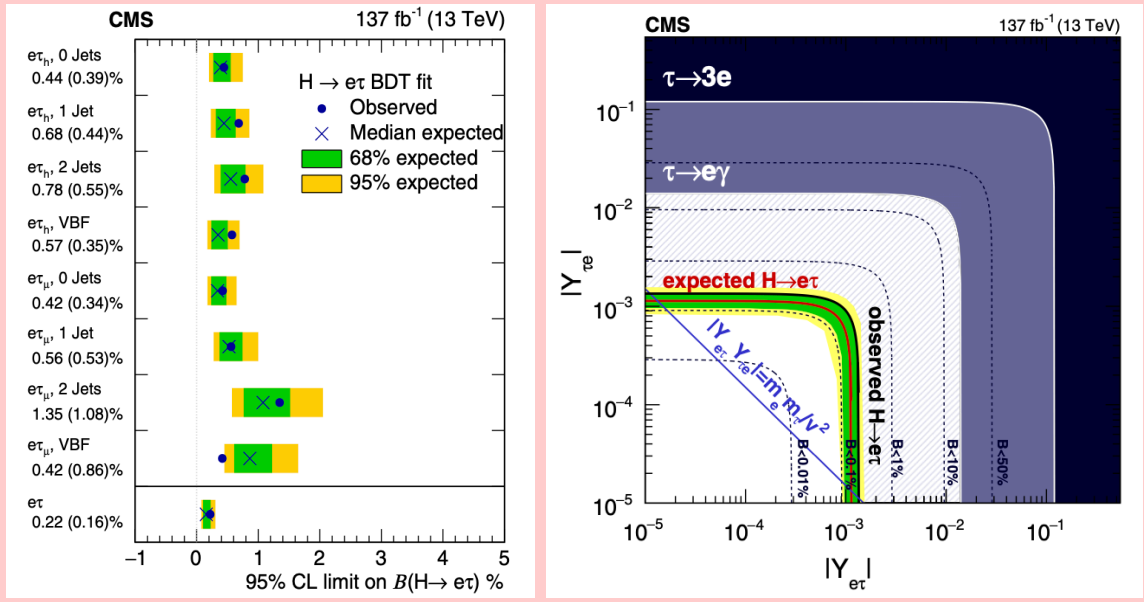


$H \to \mu\tau$ and $H \to e\tau$ *Phys. Rev. D 104, 032013*

- Search for SM Higgs boson in the $\mu\tau$- and eτ-final states with 137 fb^{-1}
- Hadronic and leptonic channels of τ-leptons studied

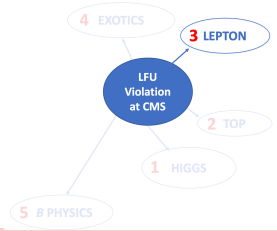


Observed(expected) limit:
$\mathcal{B}(H \to \mu\tau) < 1.5(1.5) \cdot 10^{-2} at\ 95\%\ CL$



Observed(expected) limit:
$\mathcal{B}(H \to e\tau) < 2.2(1.6) \cdot 10^{-2} at\ 95\%\ CL$

3 LFU VIOLATION WITH LEPTON DECAYS

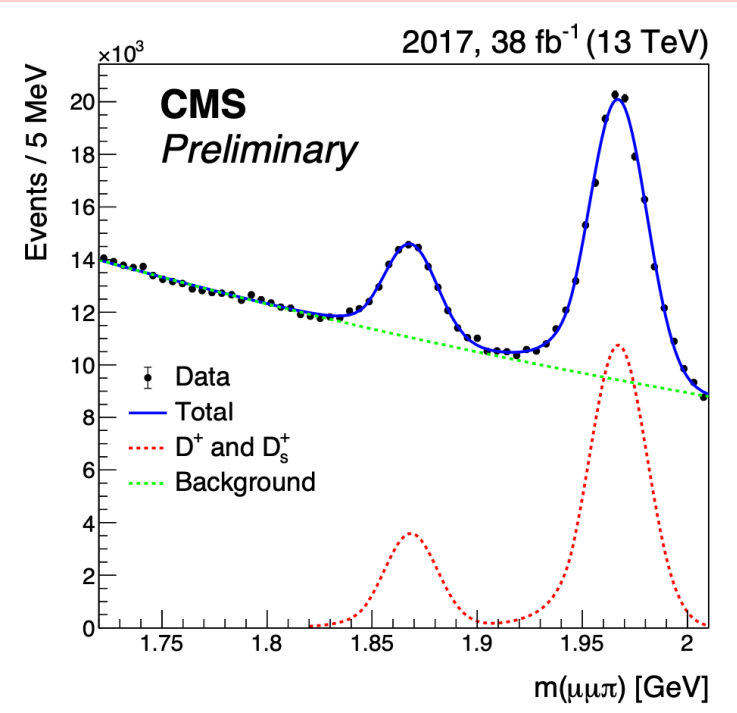


NEW

Search for $\tau \to 3\mu$ Decay

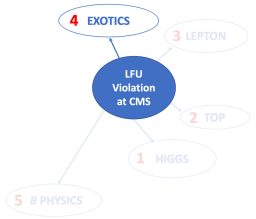
CMS-PAS-BPH-21-005

$$N_{3\mu(\mathrm{D})} = N_{\mu\mu\pi} \frac{\mathcal{B}(\mathrm{D}_s^+ \to \tau^+\nu)}{\mathcal{B}(\mathrm{D}_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu),$$



- Chain of BDTs to separate signal from background at:
  - Mass-resolution level
  - Misidentified-muon level (global - tracker muons)
- In total 36 categories for each year

4 LFU VIOLATION IN EXOTICS SEARCHES



Search for $Z' \to \mu\mu$ boson with *b*-quark jets

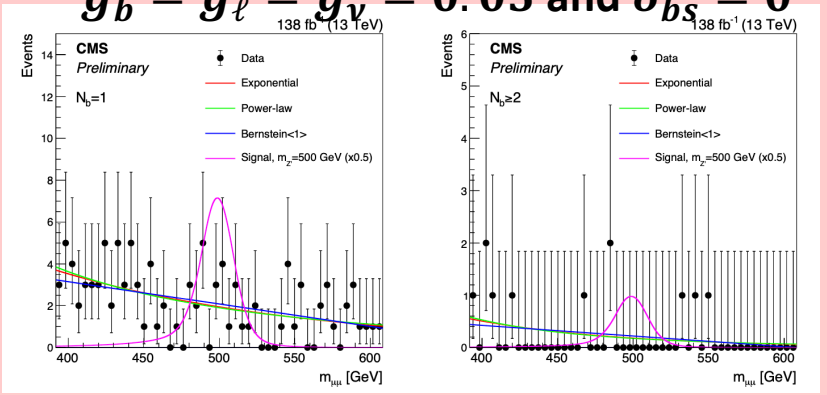
$$\mathcal{L}_{BSM} = Z'_\eta \left\{ g_\ell \sum_{f=e,\mu,\tau} \bar{f}\gamma^\eta P_L f + g_\nu \sum_{f=\nu_e,\nu_\mu,\nu_\tau} \bar{f}\gamma^\eta P_L f + g_b \left[\bar{b}\gamma^\eta P_L b + \delta_{bs} (\bar{s}\gamma^\eta P_L b + \text{h.c.}) \right] \right\}.$$

- **Background rejection**:
  - Drell-Yan via the request of at least a *b*-jet
  - $t\bar{t}$ via the request of $m_{\mu b} > 175$ GeV
  - Other bkg ($tZ + X, WZ$ etc.) via vetoing additional leptons or isolated charged hadrons

Systematic uncertainties

Source	Normalization $N_b = 1$	Normalization $N_b \geq 2$	Shape
Luminosity	1.6%		—
Trigger	1–5%		—
Jet energy scale	1–1.5%	2–5%	—
b-tagging	1%	5%	—
μ reconstruction	2.5%		—
μ identification	5%		—
Fit window size	$\lesssim 5\%$		—
MC sample size	$< 1\%$	$< 5\%$	—
μ momentum scale in $\overline{m}_{\mu\mu}$	—		$\lesssim 0.1\%\ m^2_{Z'}/(1\,\text{TeV})$
μ momentum resolution in $\overline{\sigma}_{\text{mass}}$	—		$\lesssim 10\%\ \sigma_{\text{mass}}$

$g_b = g_\ell = g_\nu = 0.05$ and $\delta_{bs} = 0$



Model-dependent (B_3-L_2) interpretation