Lepton flavor (universality) violation studies at CMS

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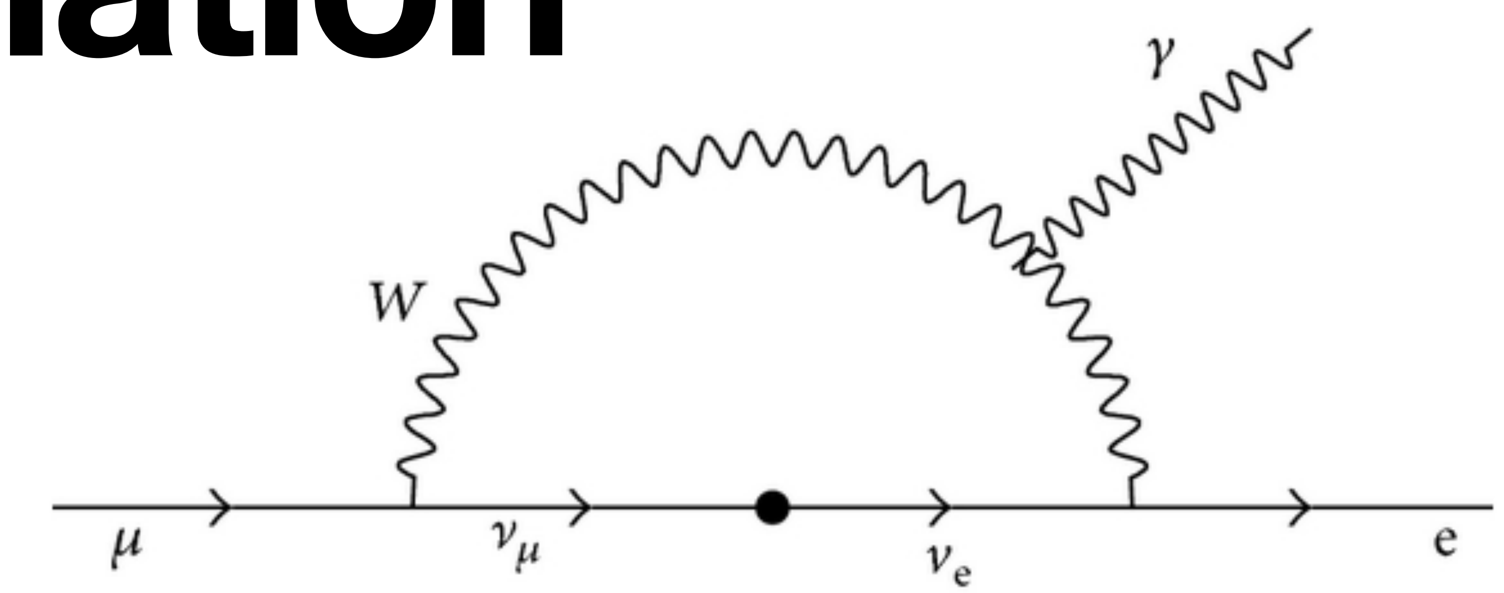
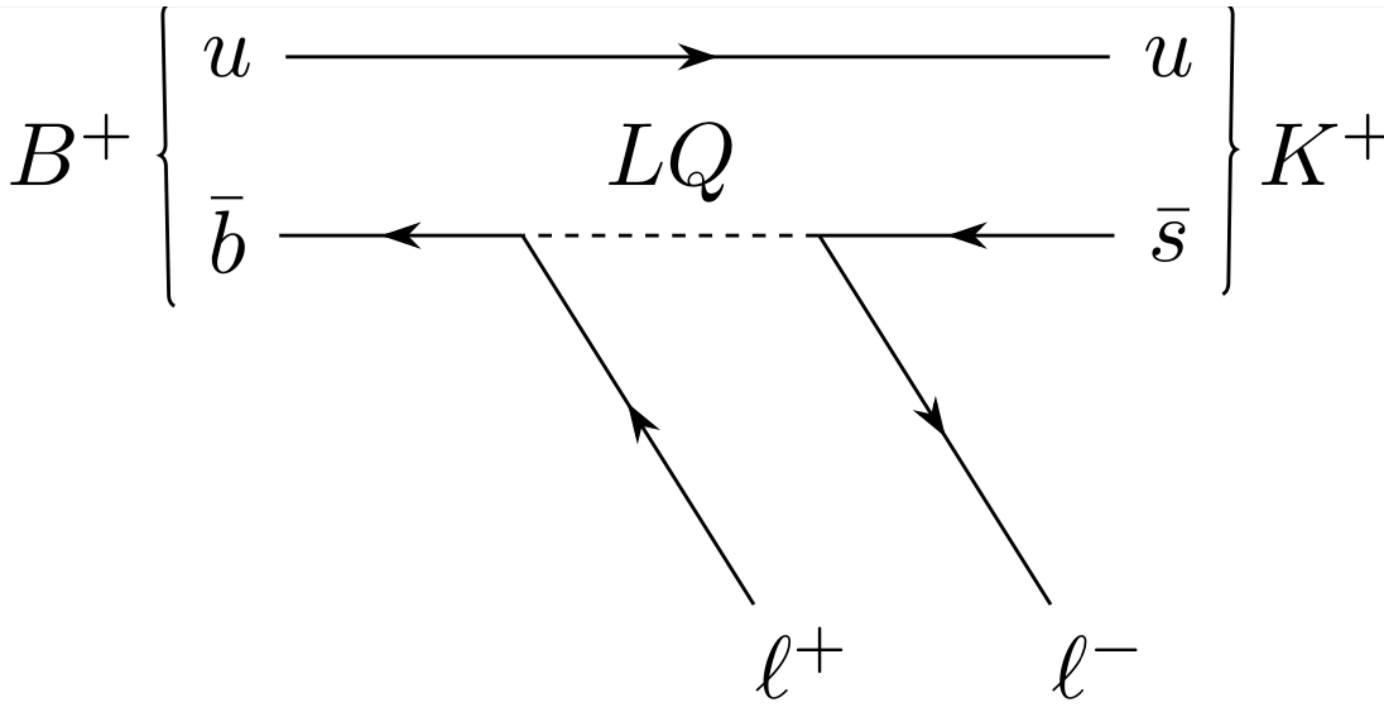
Beauty 2023 @ Clermont-Ferrand

3-7 July 2023

Lepton Flavour (Universality) Violation



- **Lepton Flavour Violation (LFV)**
  - There is evidence of neutral LFV through neutrino oscillations
    NuclPhysB(2007)02.014
  - Charged LFV happens in loop diagrams with ν mixing, but strongly suppressed in the SM (rate $\sim 10^{-55}$)
    - SM extensions predict larger BR up to $10^{-10} - 10^{-8}$
      EPJC57(2008)13-182

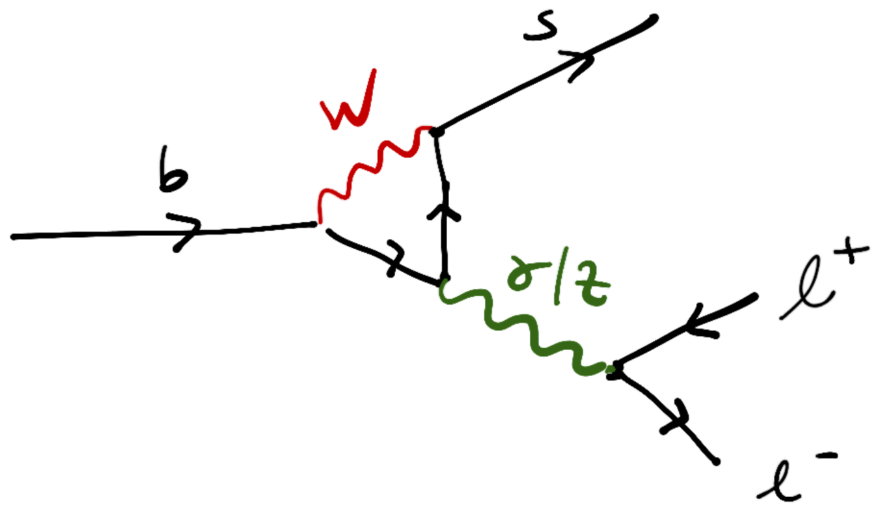


- **Lepton Flavour Universality Violation**
  - In SM EW couplings are the same for the three lepton flavours
    - SM extensions predict different couplings

Lepton Flavour measurements are a strategic sector to look for new Physics!

Anomalies

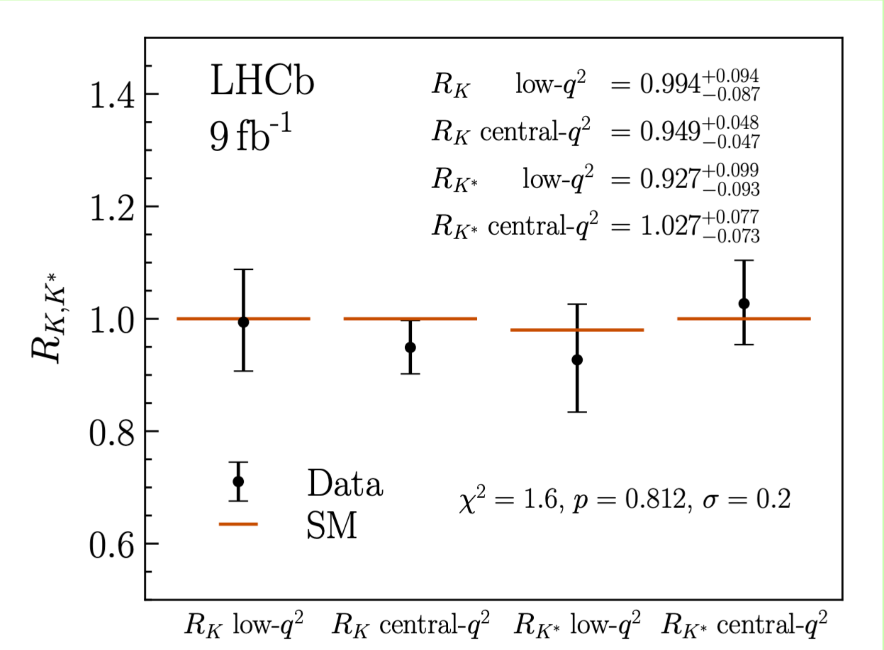
- Several experiments suggest deviations from the SM predictions:
- Most recent deviations in indirect LFUV searches in B-sector by LHCb



No tension with SM prediction

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

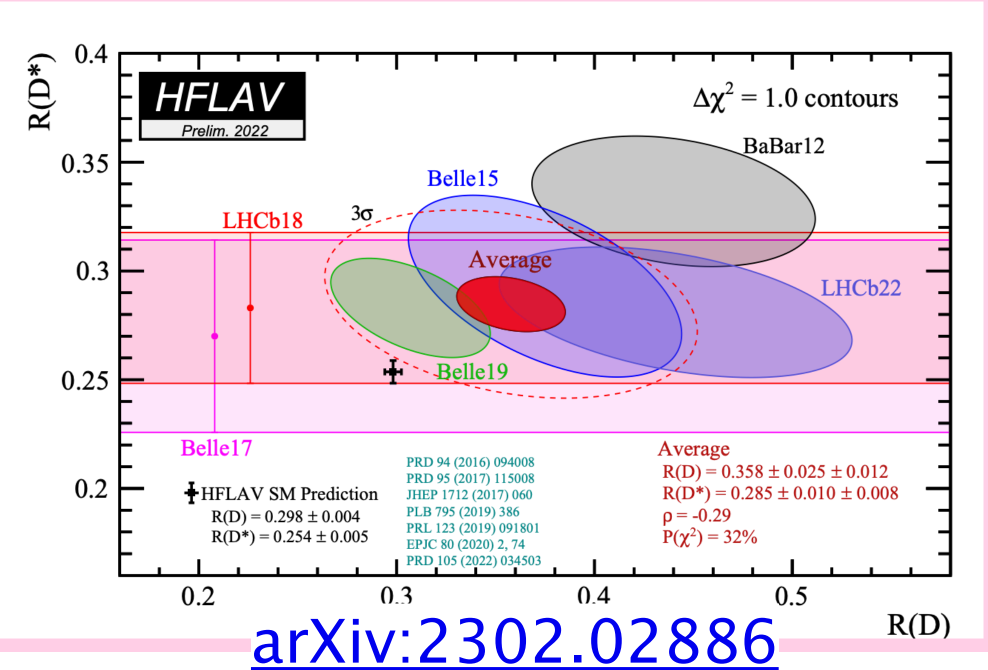
- $$R_{H_s} = \frac{\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to H_s e^+ e^-)}$$
- Loop-level → smaller BR
- ν-less
- Precise predictions



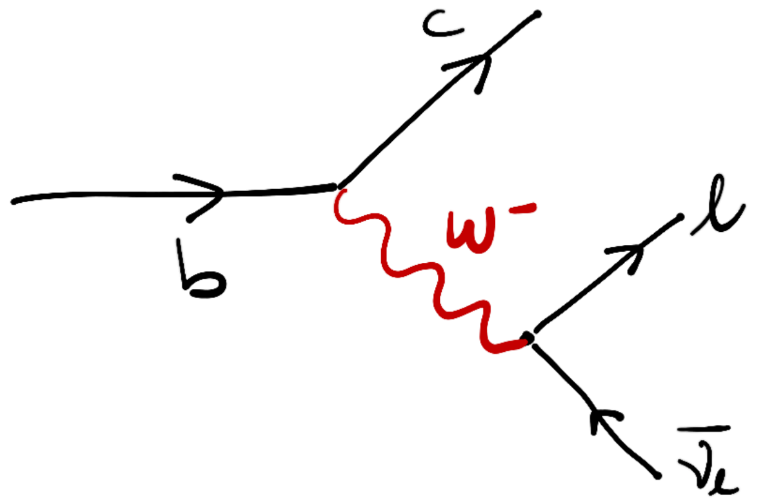
arXiv:2212.09153 arXiv:2212.09152

$b \to c l^- \bar{\nu}_l$

- $$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu^- \bar{\nu}_\mu)}$$
- tree-level → large BR; sensitive to syst unc
- νs in the final state
- Sensitive to QCD calculations



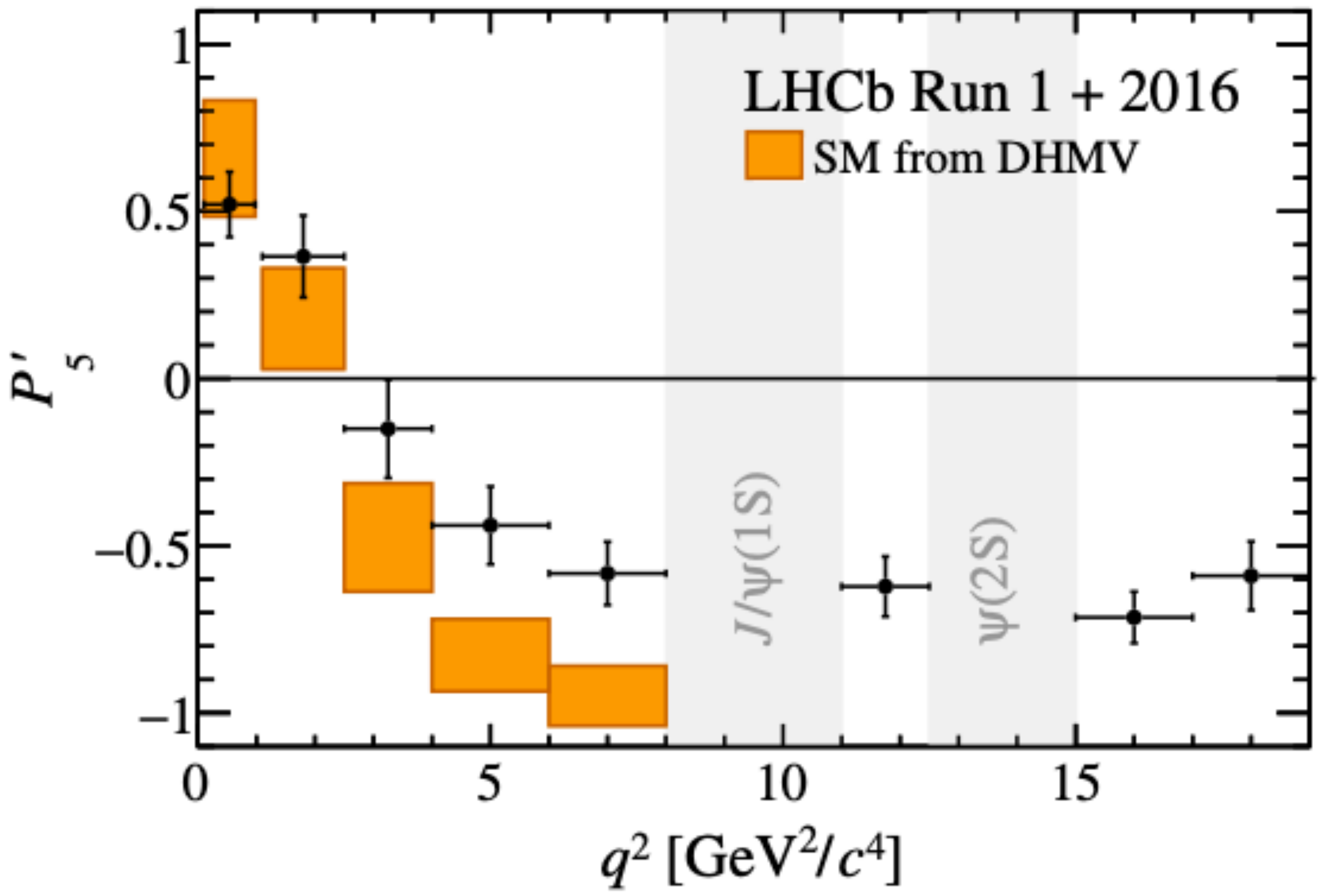
arXiv:2302.02886



3σ tension with the SM prediction

Anomalies

- Several experiments suggest deviations from the SM predictions:
- Deviations in $B^0 \to K^{*0}\mu^+\mu^-$ angular distributions

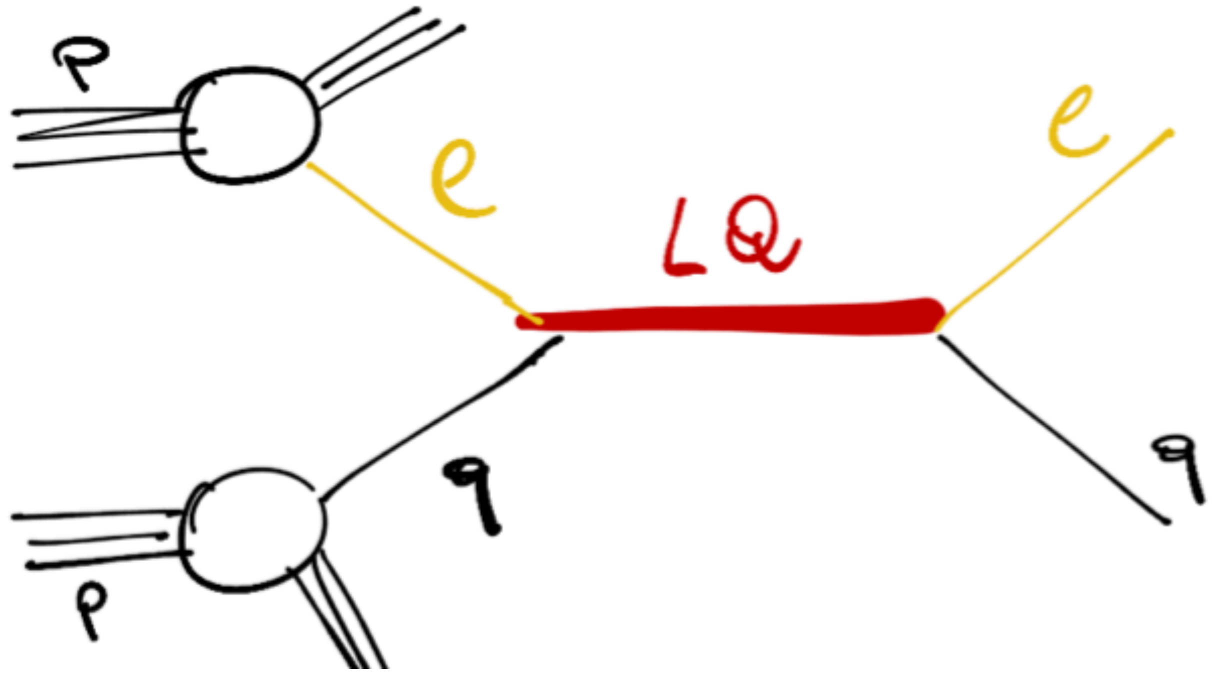


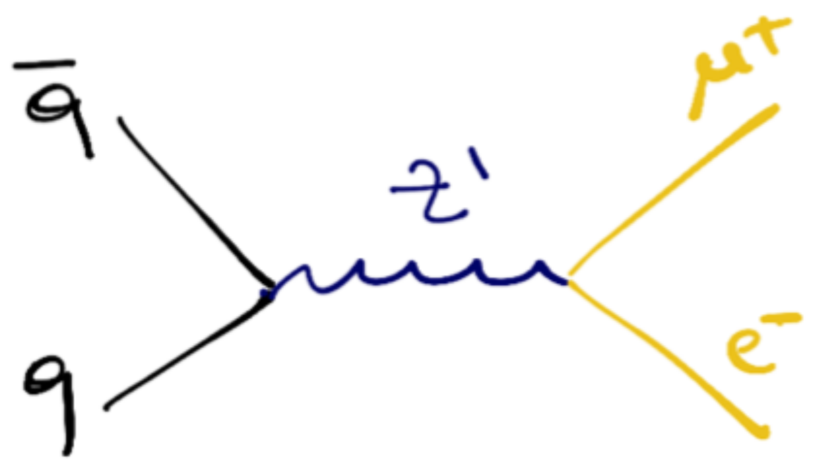
Phys. Rev. Lett. 125, 011802

Angular observable P'_5 shows **tension with the SM prediction > 2.5 σ** from Run 1+ Run 2 (2016) data collected by LHCb

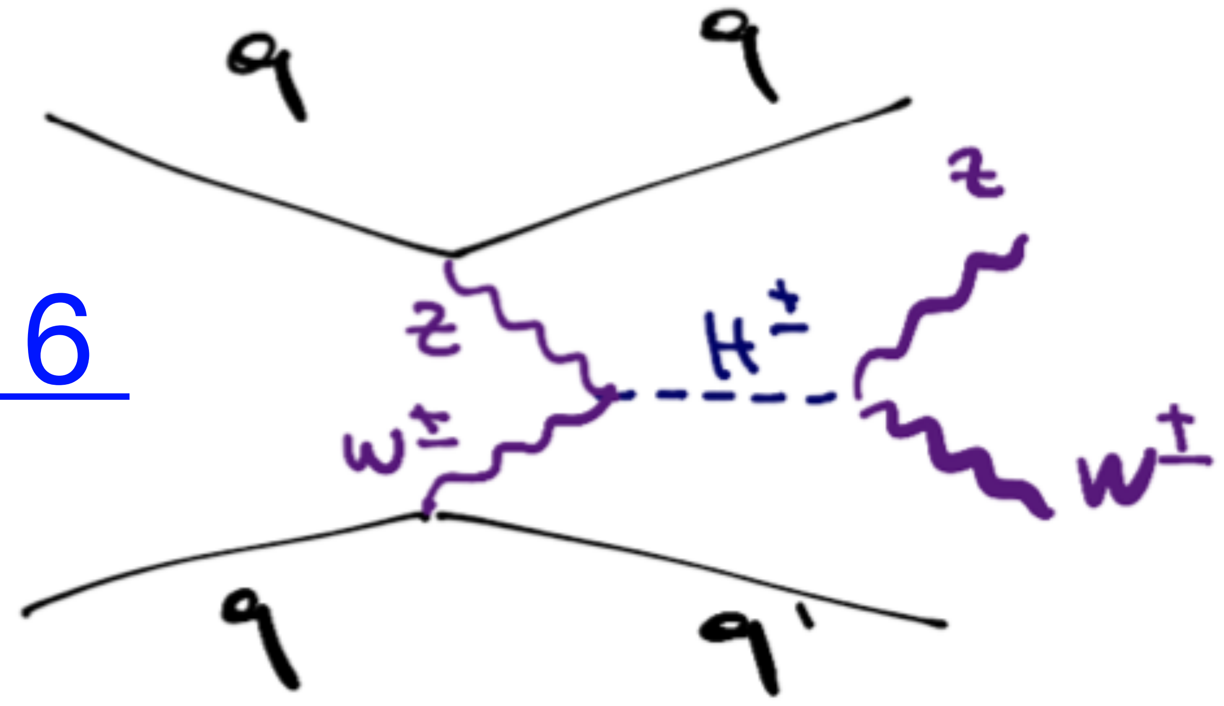
Proposed Explanations

- If LF(U)V exist and are confirmed, what are the proposed explanations for these deviations from the SM?





- **Extensions of the SM** such as:
  - Charged Higgs bosons [1] [2] [3]
  - New vector bosons EXO summary
  - Leptoquarks CMS-PAS-EXO-22-018 CMS-PAS-EXO-19-016



Many analyses on going to search for these particles

What do we do at CMS?

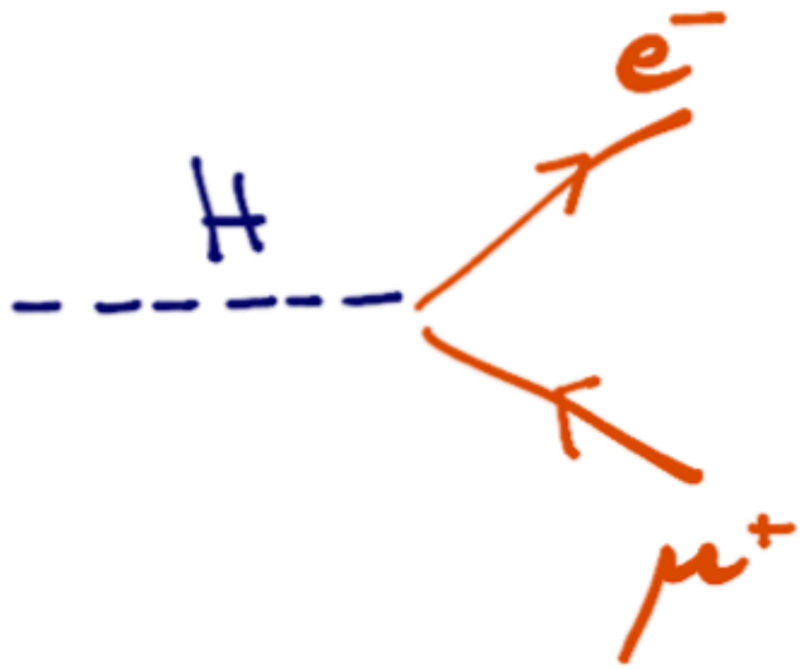
- A huge effort has been done in CMS in the past years to make LF(U)V measurements possible
  - ***Single and double μ and high rate double e triggers campaign in 2018 and Run III to provide datasets for LF(U)V***
  - **R(X) LF(U)V measurements**
    - Still under review in CMS
  - **Angular Analyses** $\rightarrow B^0 \rightarrow K^{*0}\mu^+\mu^-$; $B^+ \rightarrow K^{(*)+}\mu^+\mu^-$ (Chandiprasad's talk this morning)
  - **LF(U)V searches** in many sectors
    - Higgs sector $\rightarrow$ **Search for** $H \rightarrow e\mu$ arXiv:2305.18106 In this talk

      $\rightarrow$ **Search for** $H \rightarrow e\tau$ **and** $H \rightarrow \mu\tau$ Phys. Rev. D 104, 032013
    - Leptonic decays $\rightarrow$ **Search for LFV** $\tau \rightarrow 3\mu$ **decays** (Luca's talk on Thursday) CMS-PAS-BPH-21-005
    - Top quark decays $\rightarrow$ **Search for LFV in top quark sector** CMS-PAS-TOP-22-005 In this talk
    - Exotic sector $\rightarrow$ **High mass LFV decays** arXiv:2205.06709 In this talk

      $\rightarrow$ **Search for LFUV Z'** CMS-PAS-EXO-22-016 In this talk

arXiv:2305.18106
(submitted to Phys. Rev. D)

Search for $H \to e\mu$



Introduction

- H boson LFV decays are forbidden in the SM but are present in BSM theories
  - If $H \to e\mu$ decay is found → **New Physics!**
  - ATLAS search, Run II data, B($H \to e\mu$) < 6.2 (5.9) 10^{-5} @95% CL

At CMS:

- *Search for LFV decay of a H boson or other exotic resonances with a mass from 110 – 160 GeV to an $e^{\pm}\mu^{\mp}$ pair.*
- Run II data $\mathscr{L} = 138\ fb^{-1}$

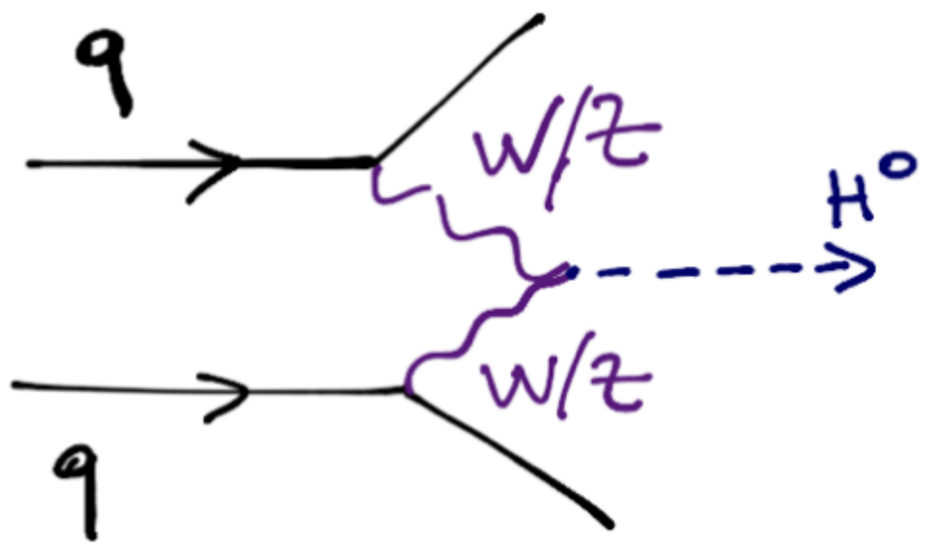
[arXiv:2305.18106
(submitted to Phys. Rev. D)]

Search for $H \rightarrow e\mu$

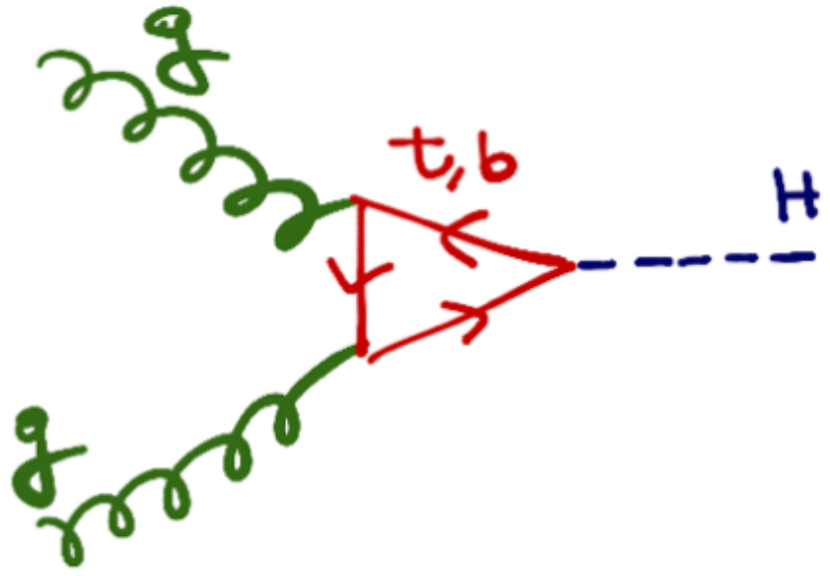
Signal and Background

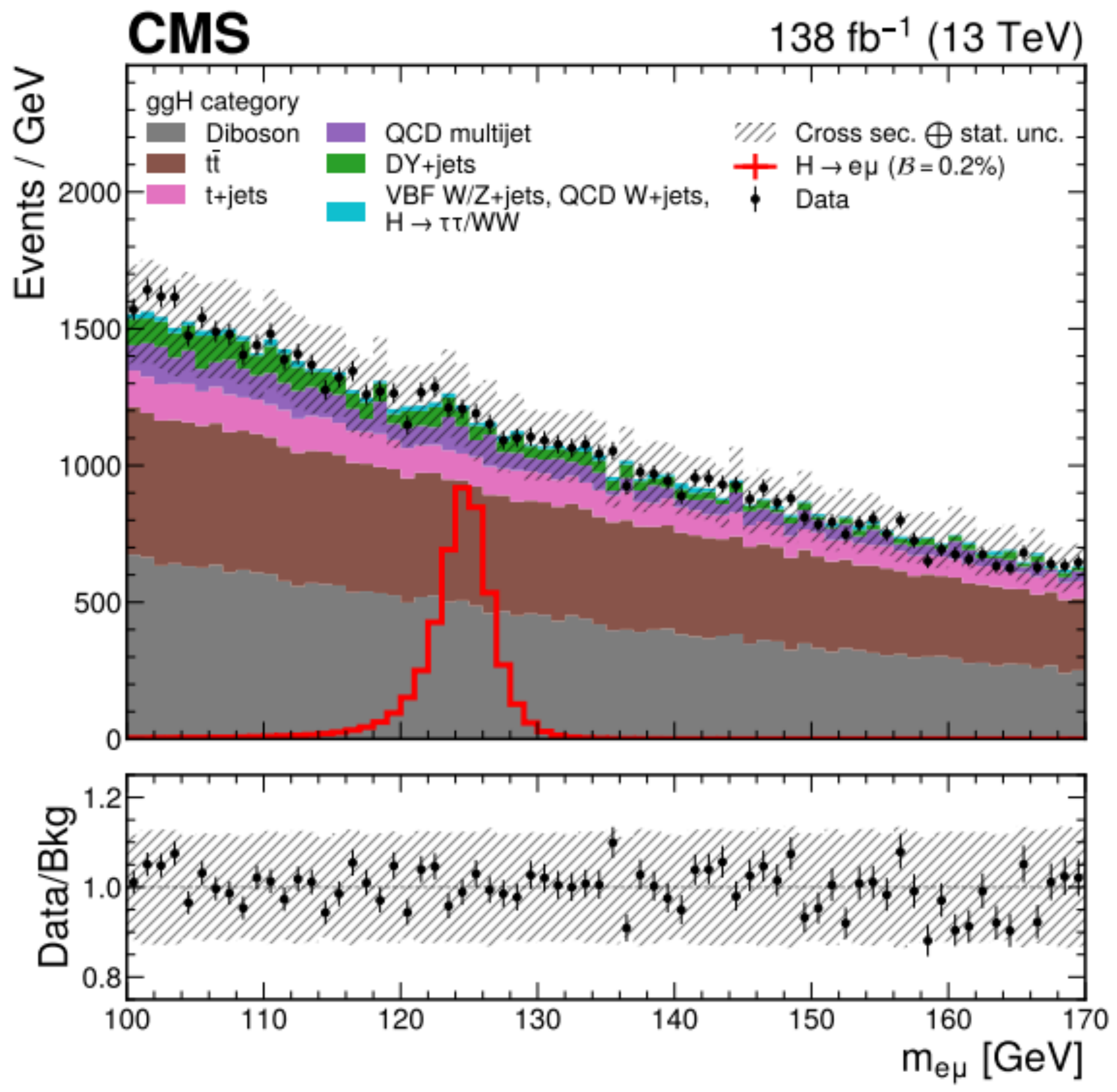
- H production modes:
  - Vector boson fusion (**VBF**)
  - Gluon fusion (**ggH**)

VBF



ggH





- Backgrounds:

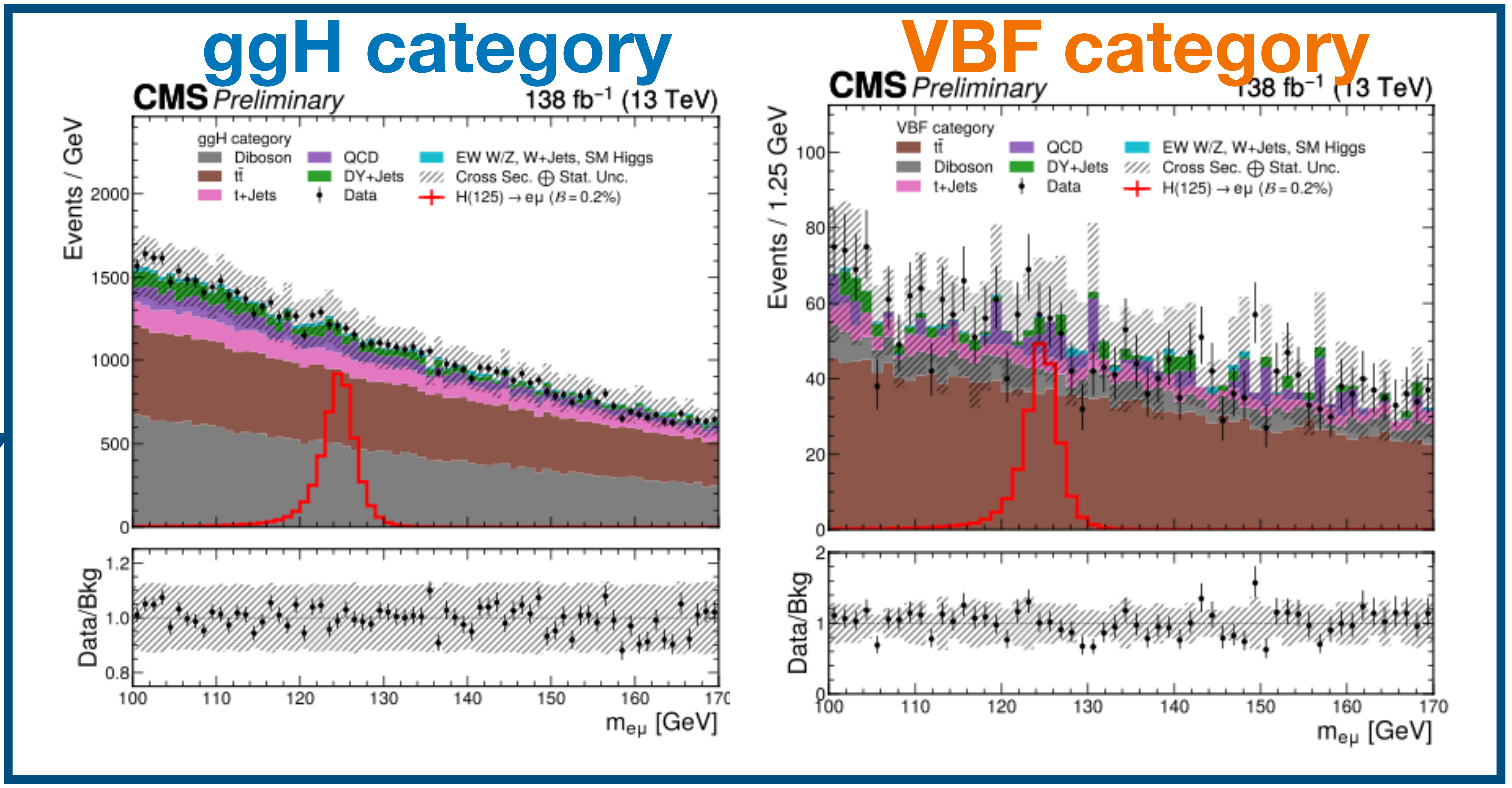
Dominant bkg
  - Leptonic decays of $t\bar{t}$ and WW events
  - DY events with misidentified lepton

Smaller bkg
  - leptonic decays of top
  - EW decays of W with misidentified jet
  - Decay of H to τ, diboson, EW Z

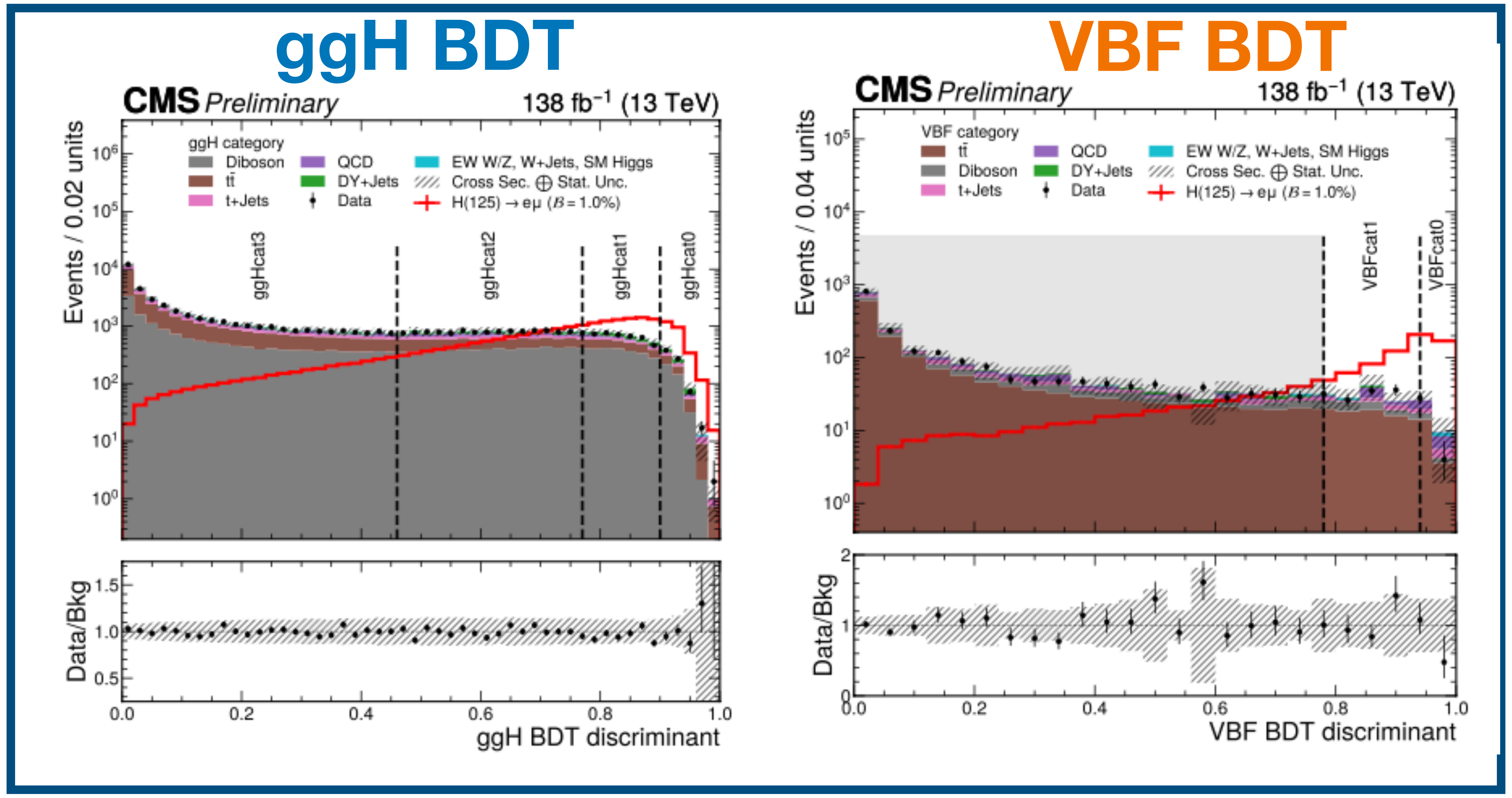
[arXiv:2305.18106](https://arxiv.org/abs/2305.18106)

Search for $H \rightarrow e\mu$

Categorisation and MVA



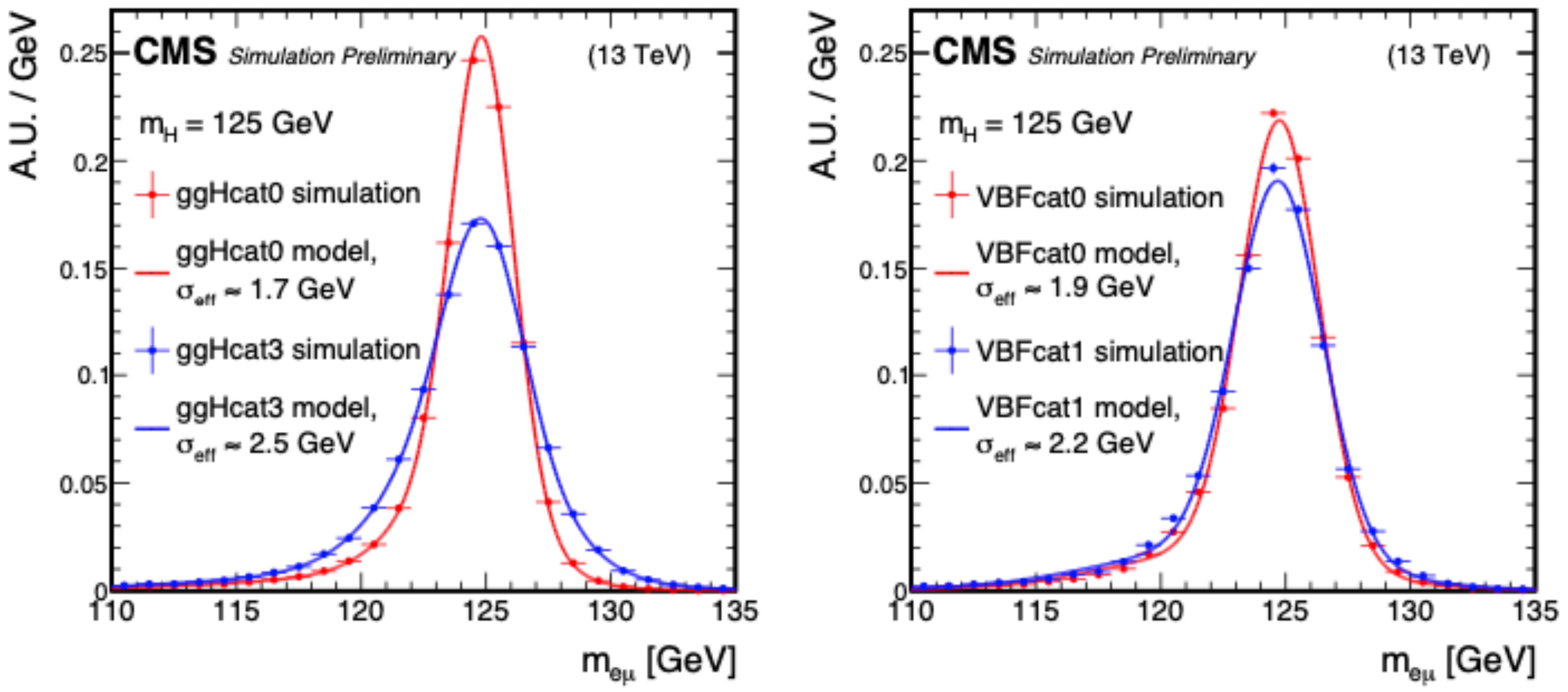
- <u>Sensitivity optimisation:</u>
  1. Events categorisation for each prod mode
  2. Events categorisation to distinguish between signal and background using boosted decision trees (BDT) score
     - BDTs trained separately for ggH and VBF
     - Mixture of simulated events used in training (m_X= 110, 120, 125, 130, 140, 150, 160 GeV)
     - Dominant bkg sources used in training
     - Input variables not correlated with $m_{e\mu}$



[arXiv:2305.18106](https://arxiv.org/abs/2305.18106)
[(submitted to Phys. Rev. D)](https://arxiv.org/abs/2305.18106)

Search for $H \to e\mu$

Simultaneous Fit



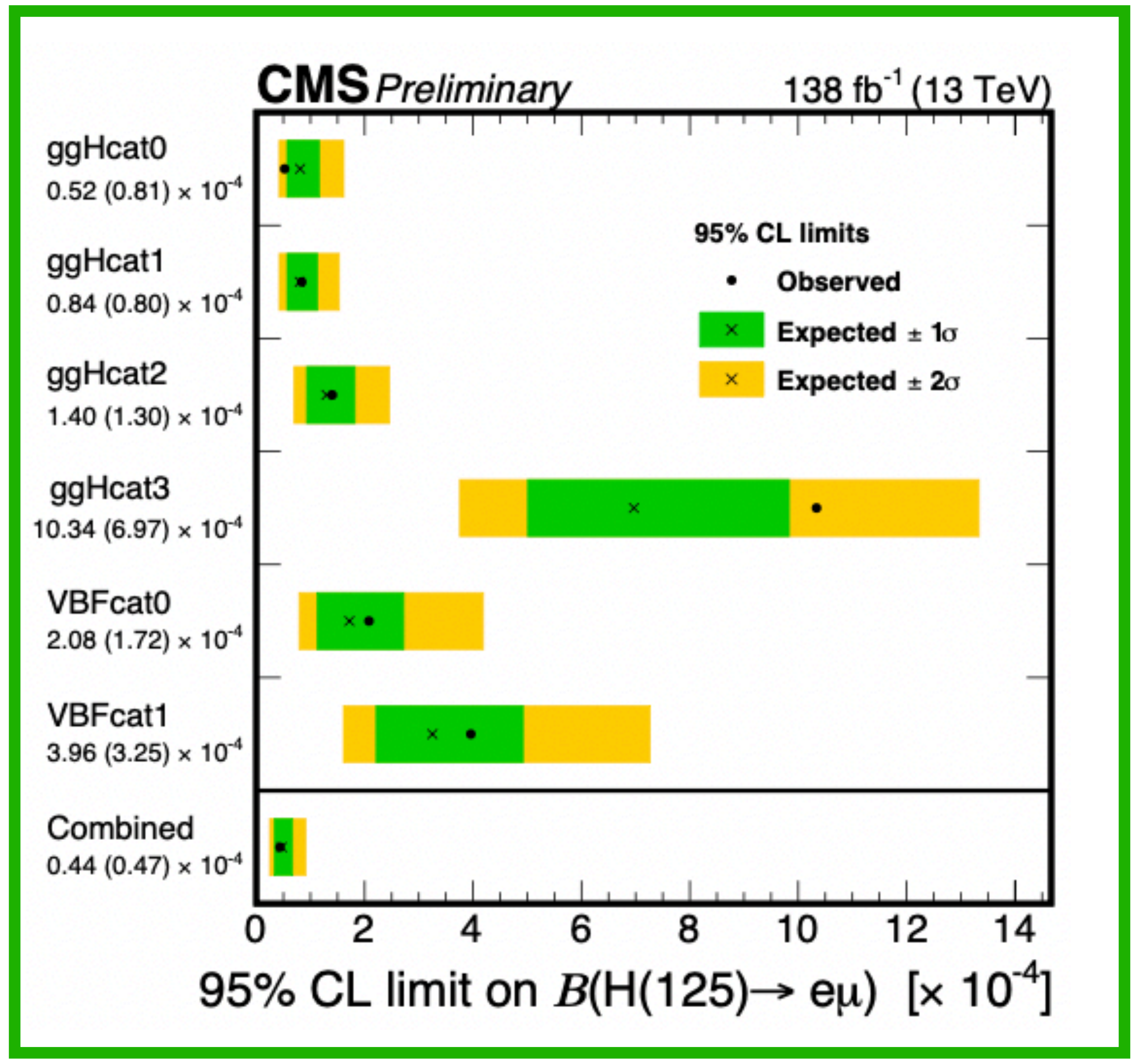
- <u>Simultaneous fit of signal and bkg:</u>
  - $m_{e\mu}$ distributions
  - 8 categories
  - Signal peaks modelled with sum of Gaussians for each category and m_H
    - For m_H between the simulated ones, $m_{e\mu}$ distributions are interpolated
  - Total background modelled with Bernstein polynomials

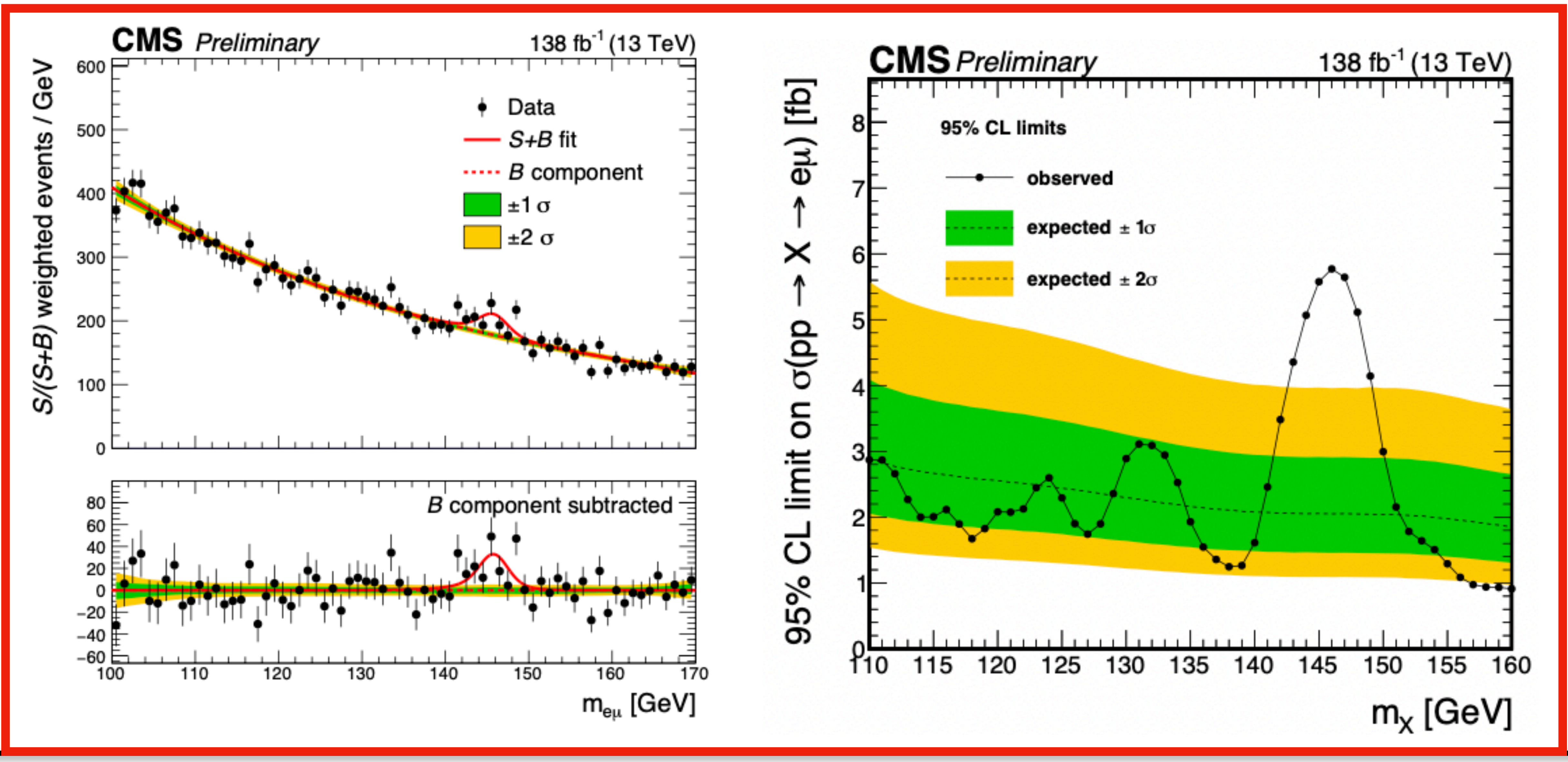
[arXiv:2305.18106 (submitted to Phys. Rev. D)](arXiv:2305.18106)

Search for $H \to e\mu$

Results

- $\underline{H(125) \to e\mu}$: **no significant eccess** observed for SM H
  - Observed (expected) upper limit on $\mathscr{B}(H(125) \to e\mu)$ is 4.4 (4.7) × 10^{-5} at 95% CL
  - **Best limit from direct searches**





- $\underline{H(X) \to e\mu}$: **an excess of events** over the expected bkg is observed at $m_X \sim 146$ GeV with a global (local) combined significance of 2.8 (3.8) σ

Search for LFV in top quark sector

Introduction

- LFV involving top quarks is within the LHC sensitivity for some BSM models
- At CMS:
  - Search for LFV processes involving top quark production and decay
  - Run II data $\mathscr{L} = 138\ fb^{-1}$

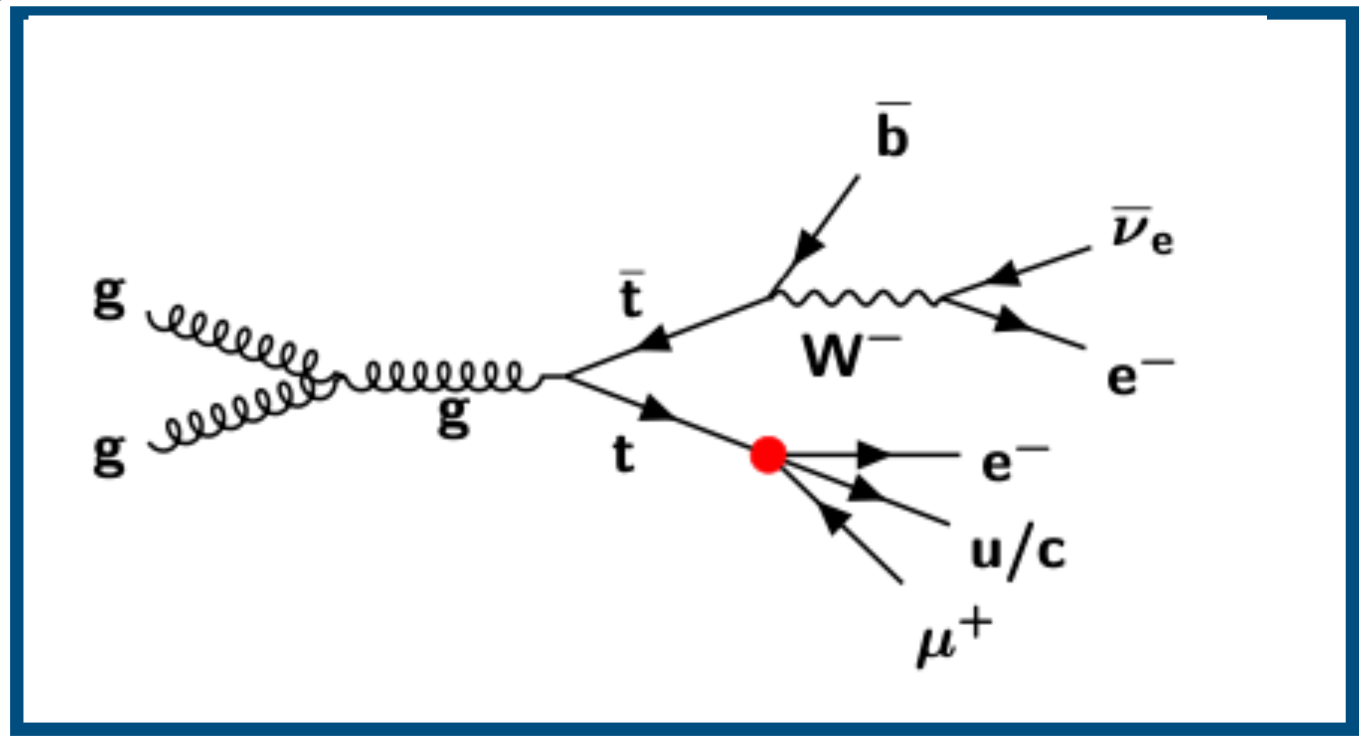
Search for LFV in top quark sector

Signal and Backgrounds

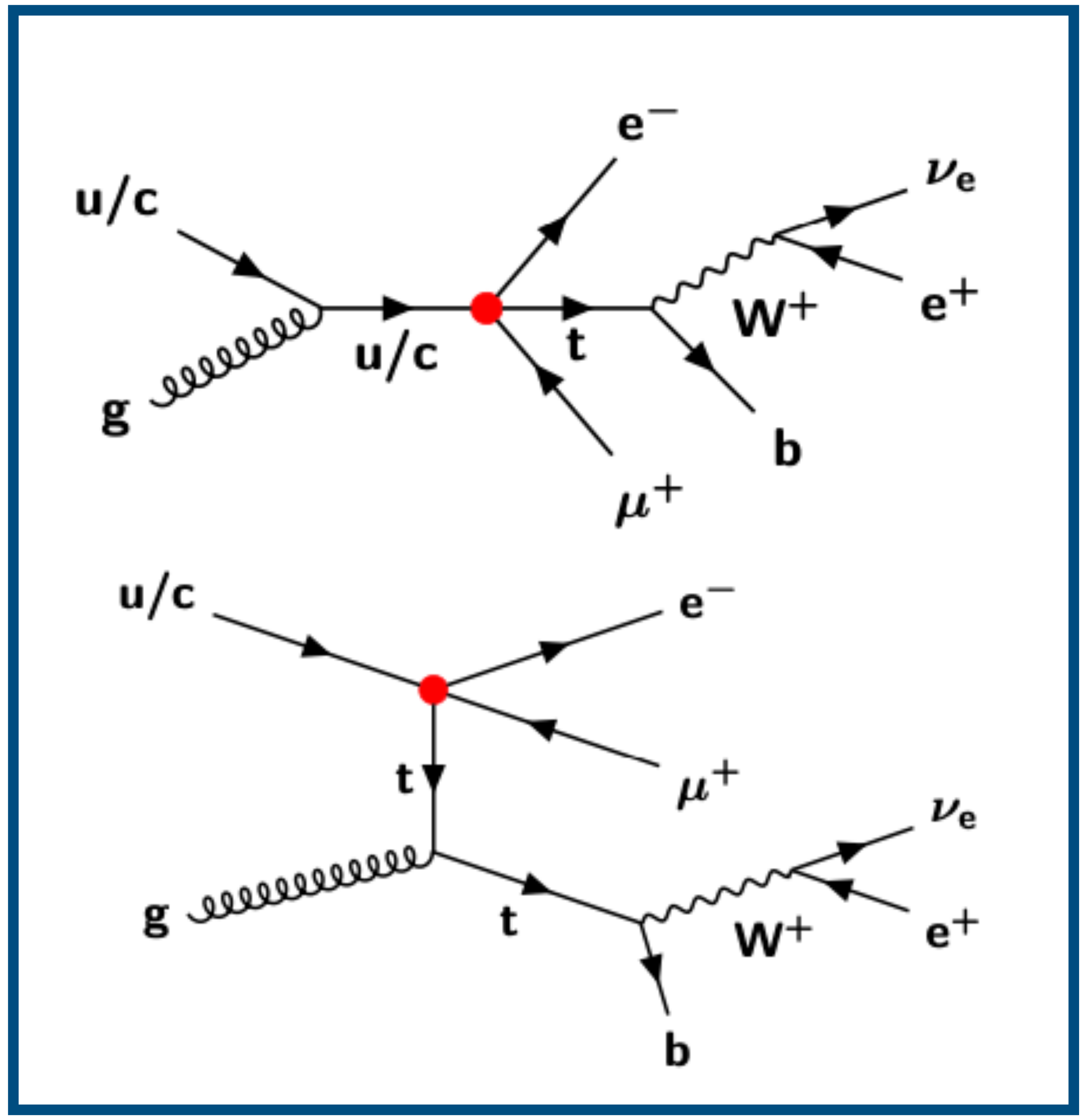
- **Signal processes: decay and production**
  - LFV Parametrised with dim-6 EFT operators

- SM Background processes:
  - **Prompt background:** from SM processes that produce at least 3 leptons via decays of EW bosons
    - MC simulation
  - **Non-prompt backgrounds:** fail the above criterion
    - Data-driven

Top Decay LFV signal



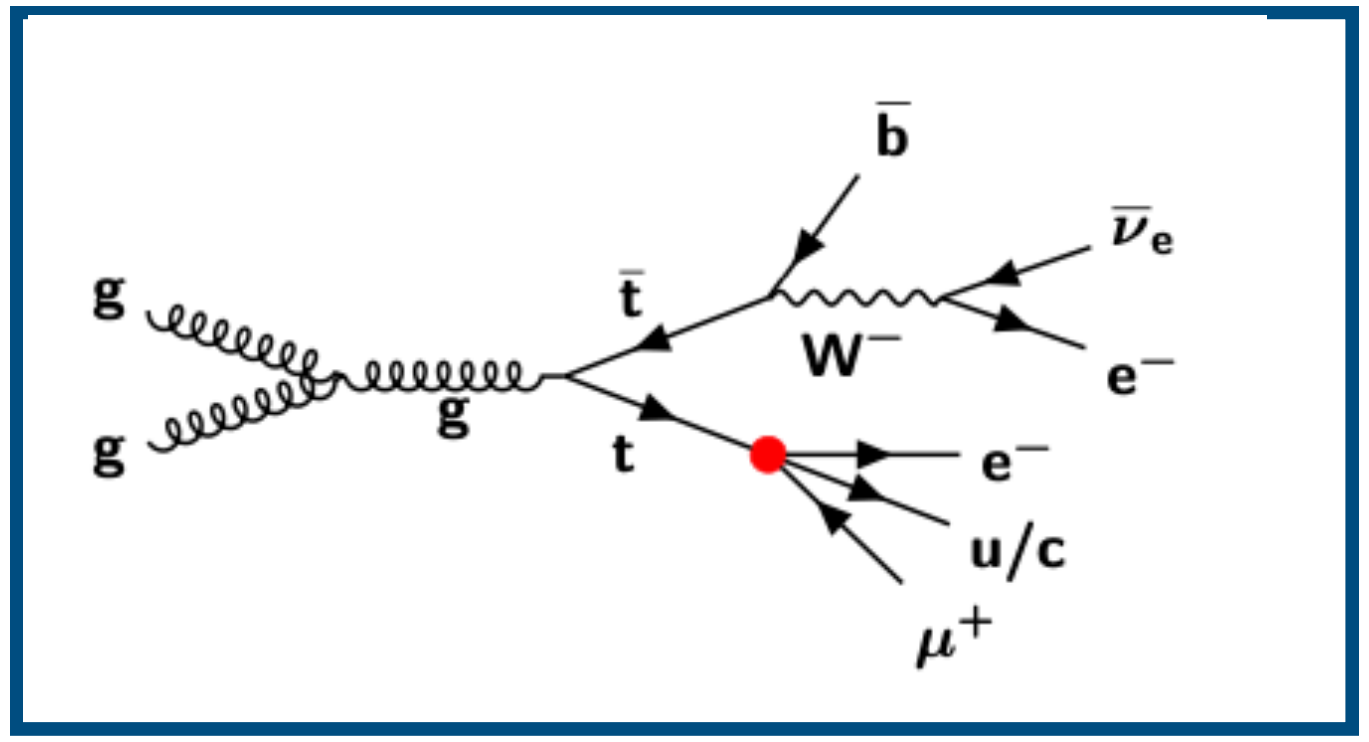
Top Production LFV signals

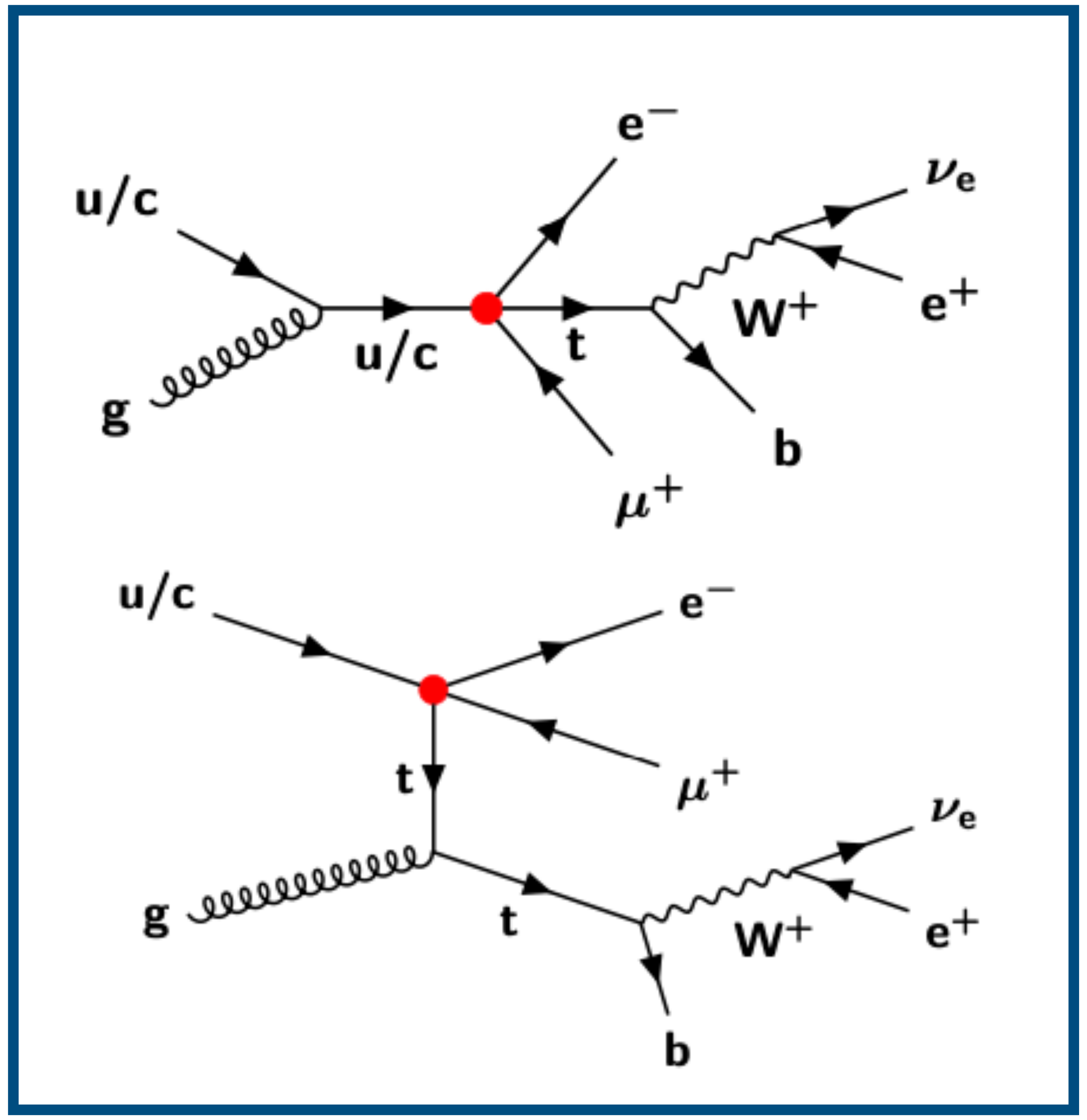


Search for LFV in top quark sector

Event selection

- Selection:
  - Exactly **3 charged leptons**
    - 1 l from SM decay of other top quark
    - 2 l from LFV interaction (opposite charge opposite flavour OCOF)
  - At least 1 jet and at most 1 jet associated with b-quark
- Kinematic Reconstruction:
  - SM top quark: b-jet, SM lepton and p_T^{miss}
  - BSM top quark: OCOF leptons, non b-like jet



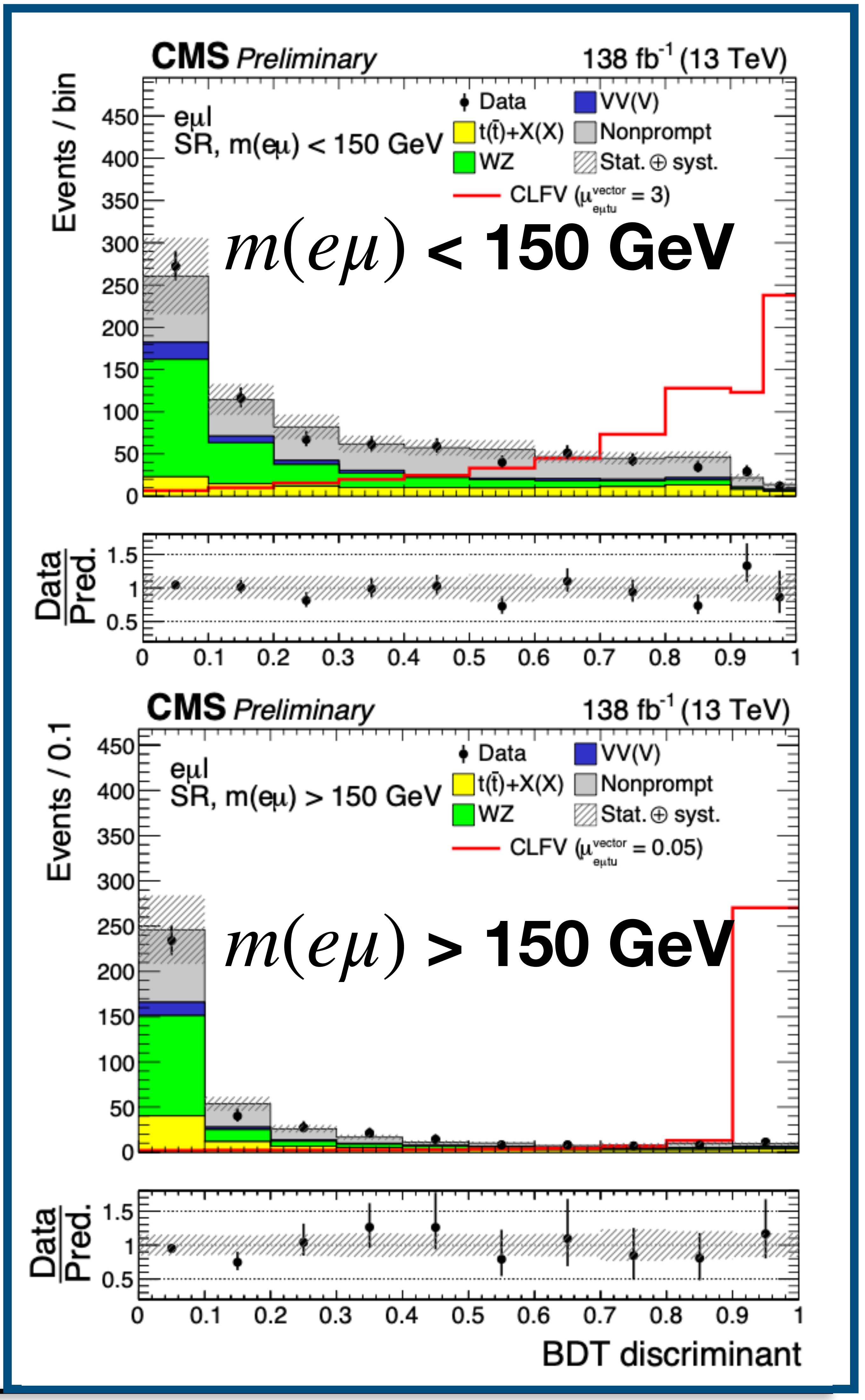


Search for LFV in top quark sector

Categories and Fit

- Two signal regions are defined:
  - SR + $m(e\mu) < 150$ GeV: top quark decay enriched
  - SR + $m(e\mu) > 150$ GeV: top quark production enriched
- Simultaneous fit to a total of 6 regions (3 years x 2 SRs)
- Binned likelihood function constructed using the BDT discriminators
  - Kin distribution of final particles is different in the two SRs → two BDTs trained

BDT discriminants

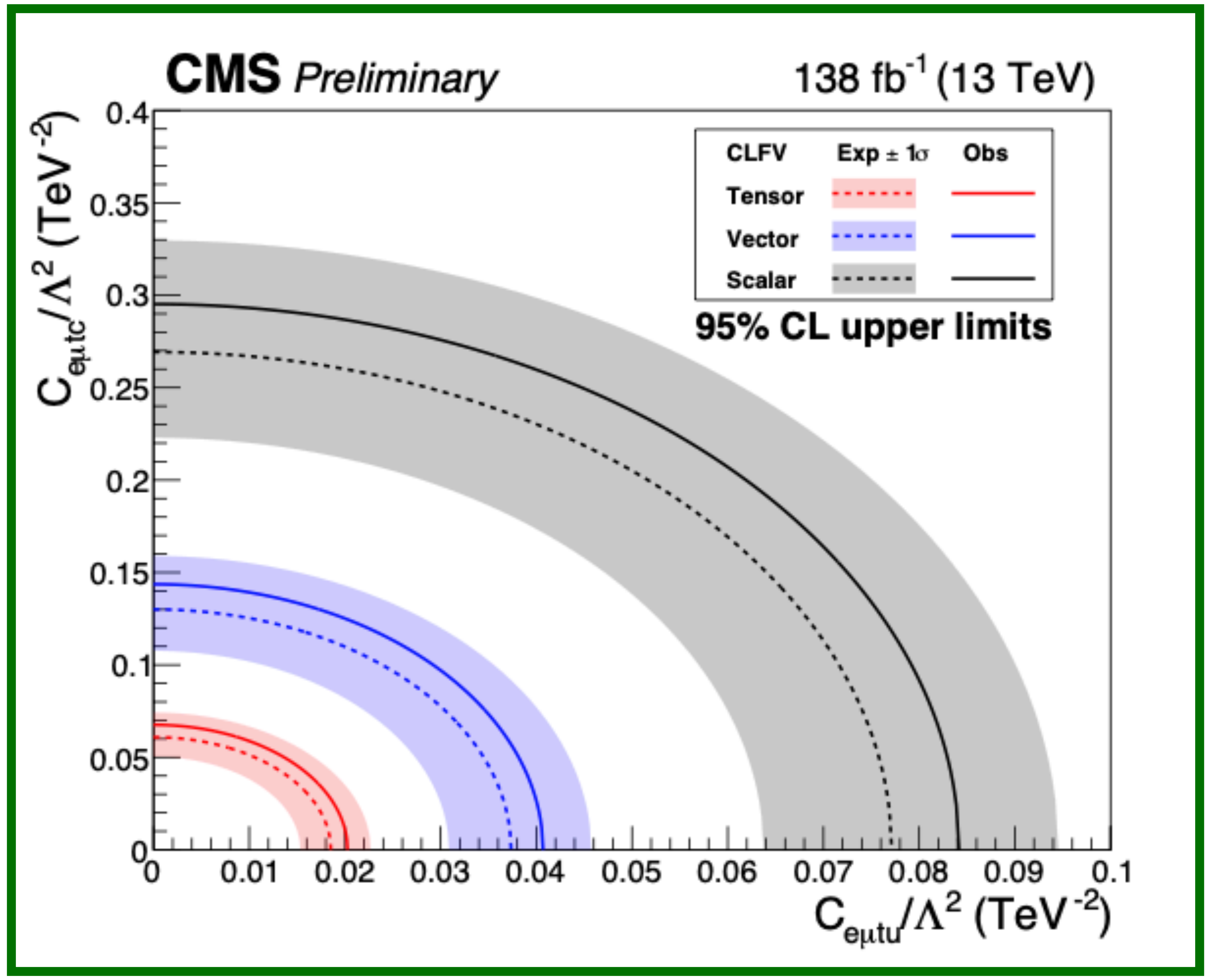


Search for LFV in top quark sector

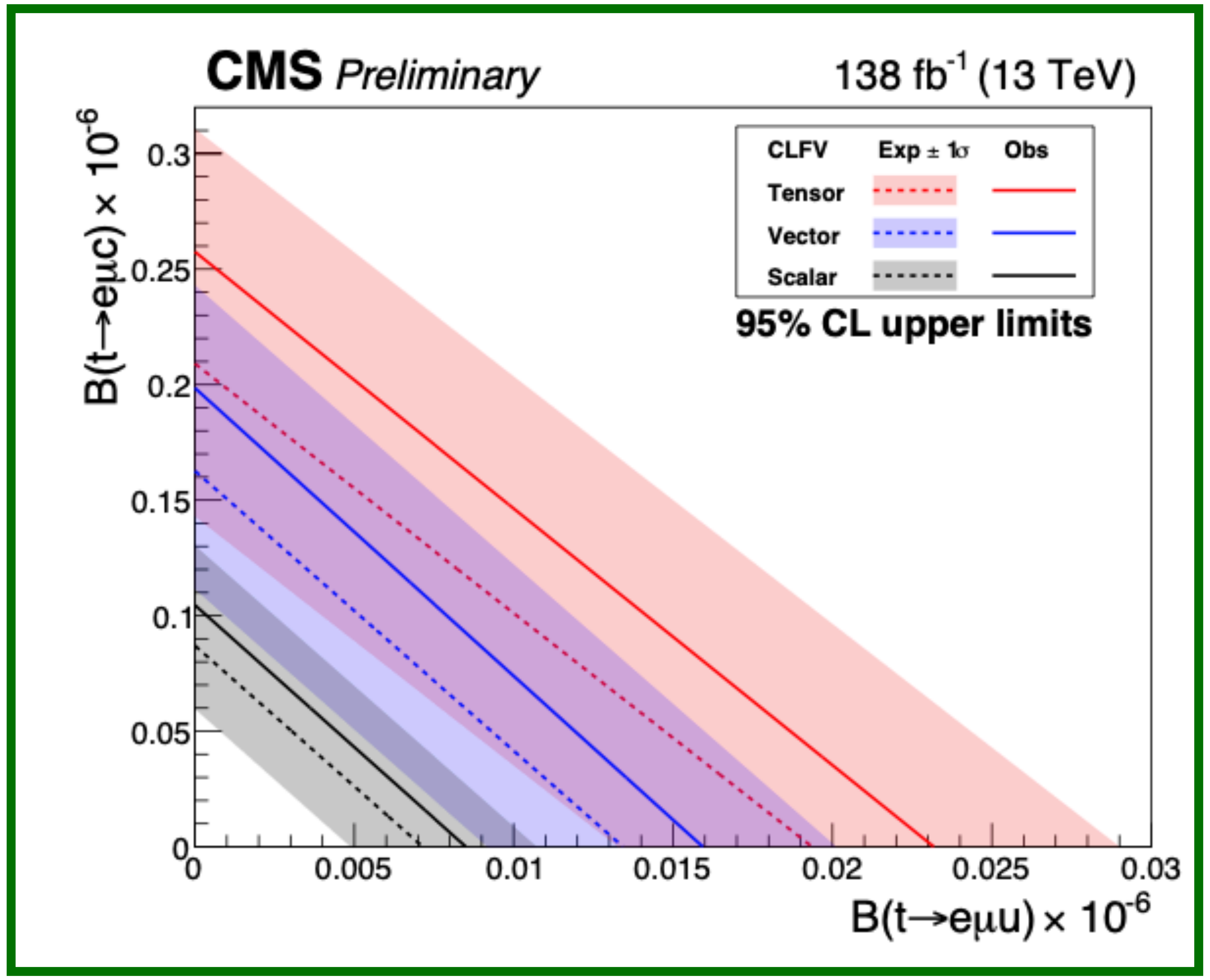
Results

- **No excess over the SM prediction**
- **Most stringent limits**

Limits on Wilson coefficients



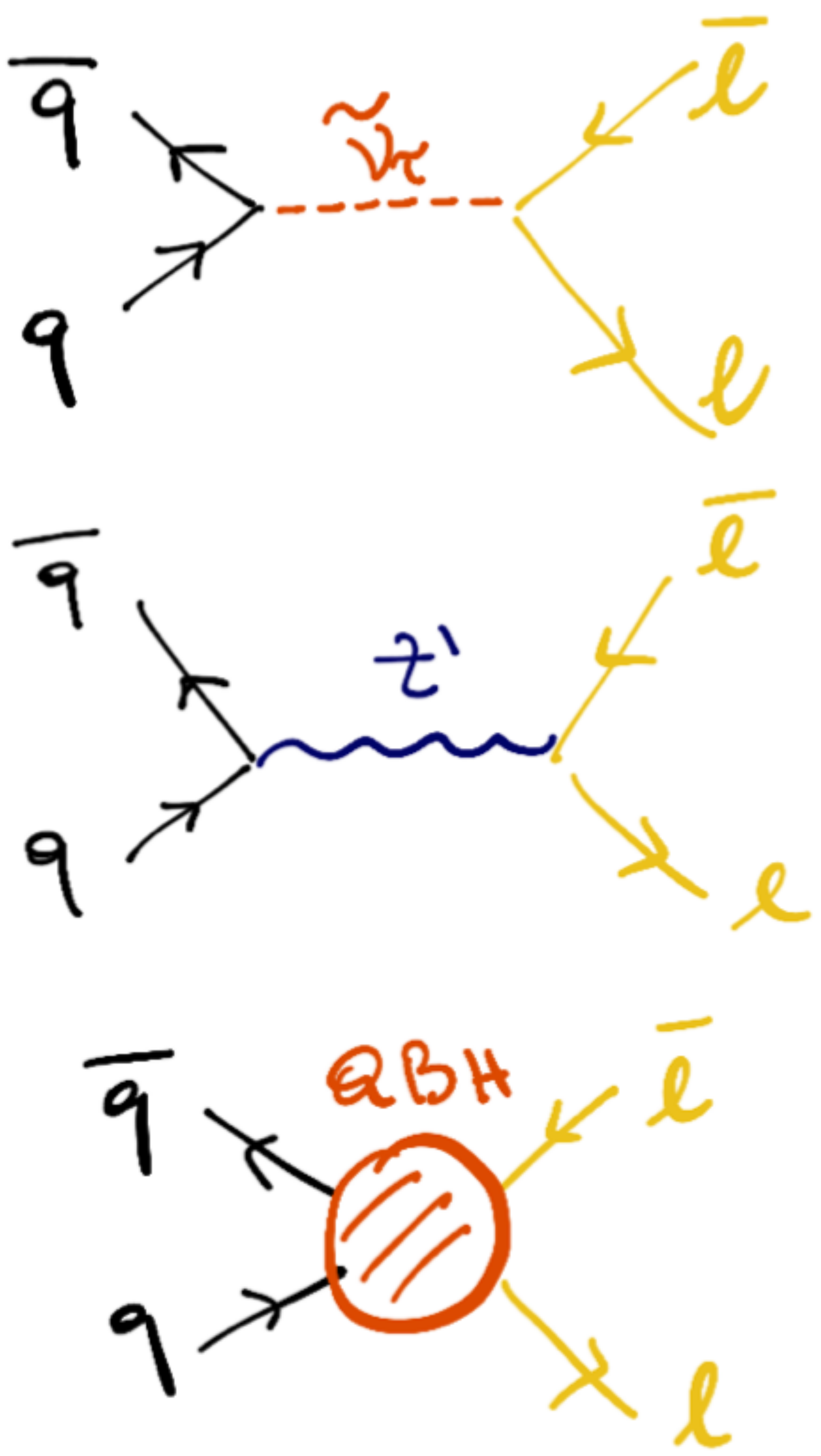
Limits on BR



Heavy resonances

Introduction

- **Search for heavy resonances and quantum black holes in $e\mu, e\tau, \mu\tau$ final states**
- CMS Run II data
- Analysis designed to be as model-independent as possible
- Results interpreted as
  - τ sneutrino → R parity violating SUSY models
  - Heavy Z' gauge boson → LFV models
  - QBHs



arXiv:2205.06709

Heavy resonances

Selection

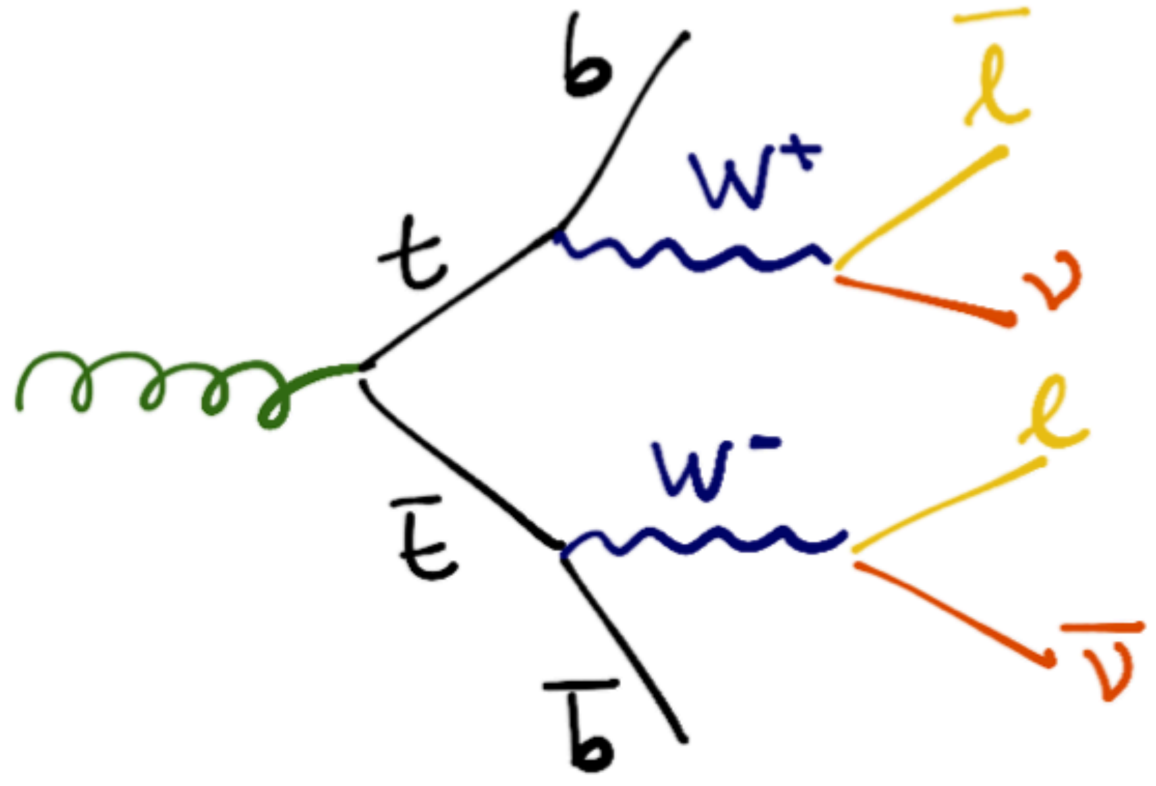
<table>
<tr><th>$e\mu$ events</th><th>$e\tau$ events</th><th>$\mu\tau$ events</th></tr>
<tr><td rowspan="2">• At least 1 prompt & isolated μ and e
• No opposite charge required → prevent loss due to misidentification of the sign of l at high p_T</td><td>• Single-e triggers & single EM cluster triggers
• Muon veto</td><td>• high p_T triggers
• Electron veto</td></tr>
<tr><td colspan="2">• τ with $p_T > 50$ GeV
• τ pass the DEEPTAU discriminator
• Transverse mass $m_T > 120$ GeV, to reject misidentified τ bkg</td></tr>
</table>

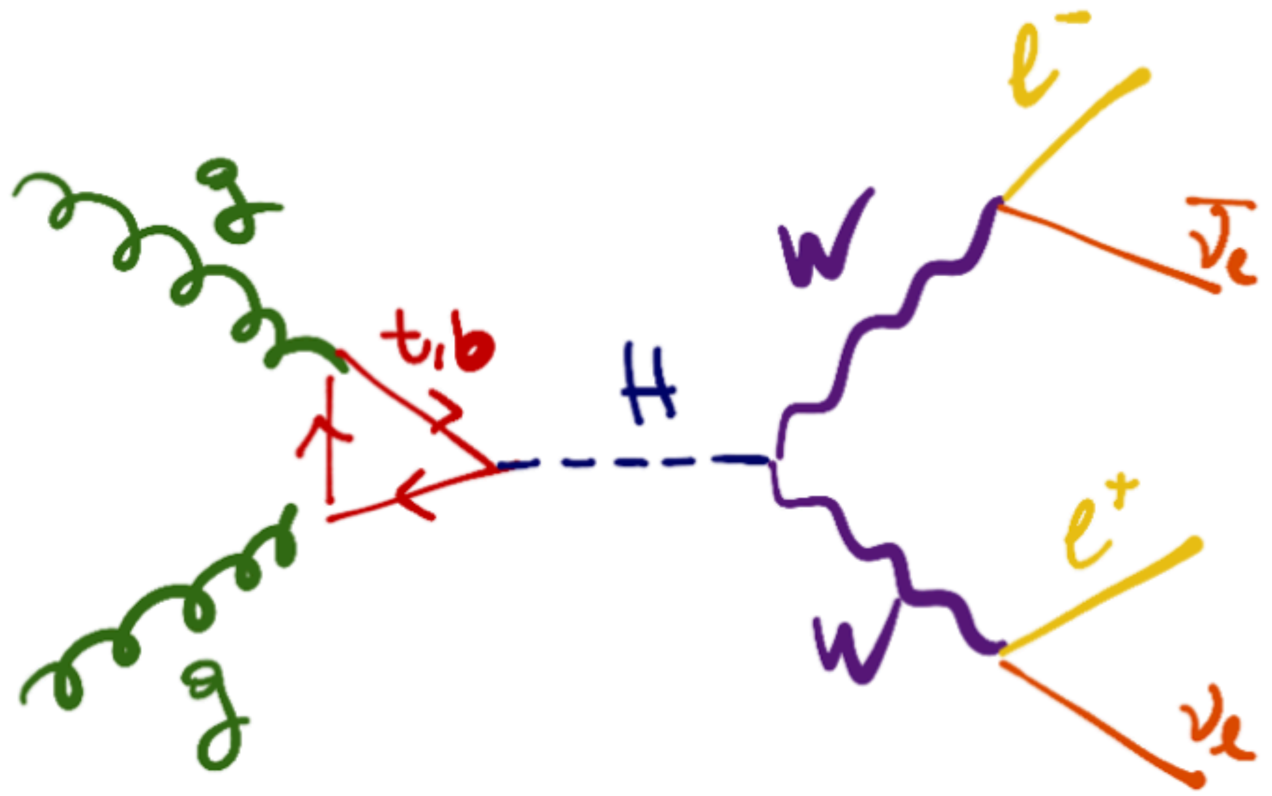
If more than one $e\mu$, $e\tau$ or $\mu\tau$ in the event, the pair with highest invariant mass chosen

Heavy resonances

Background

- **Processes that produce final states with leptons of different flavour**
    - Dominant bkg: $t\bar{t} \rightarrow$ MC
    - Other bkgs:
        - diboson, Wγ, $Z \rightarrow ll$, single top quark production → MC
        - Multijet and W+jets → data-driven



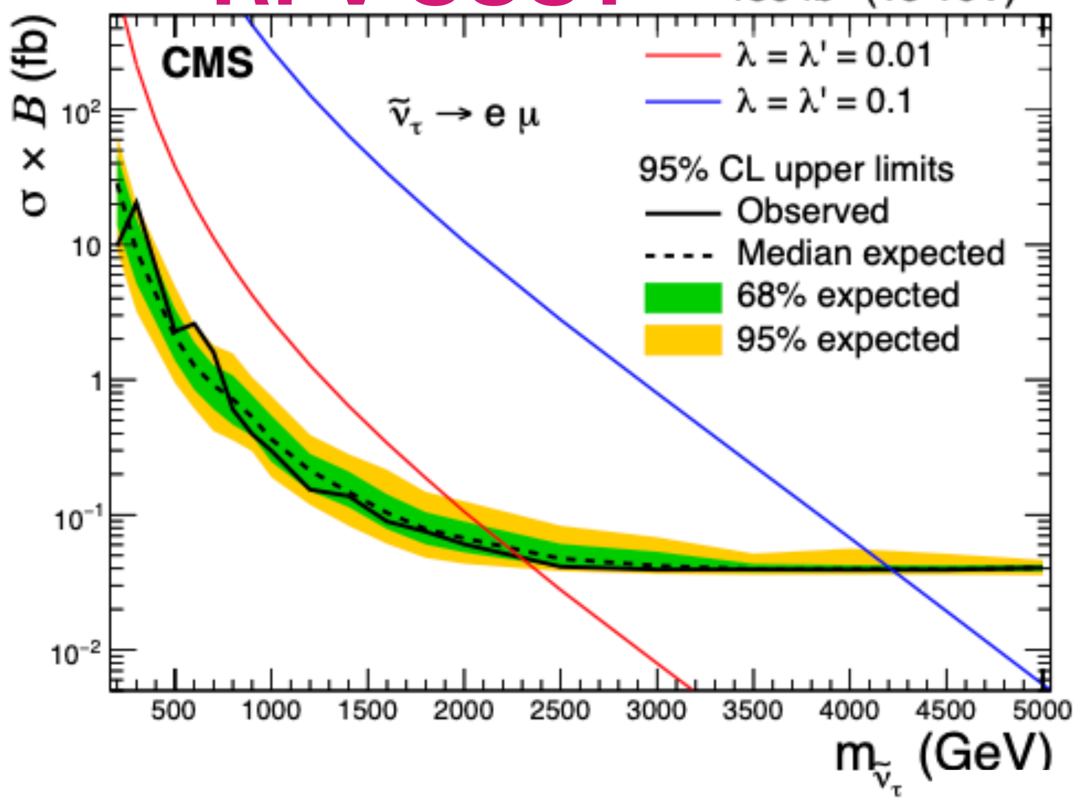


Heavy resonances

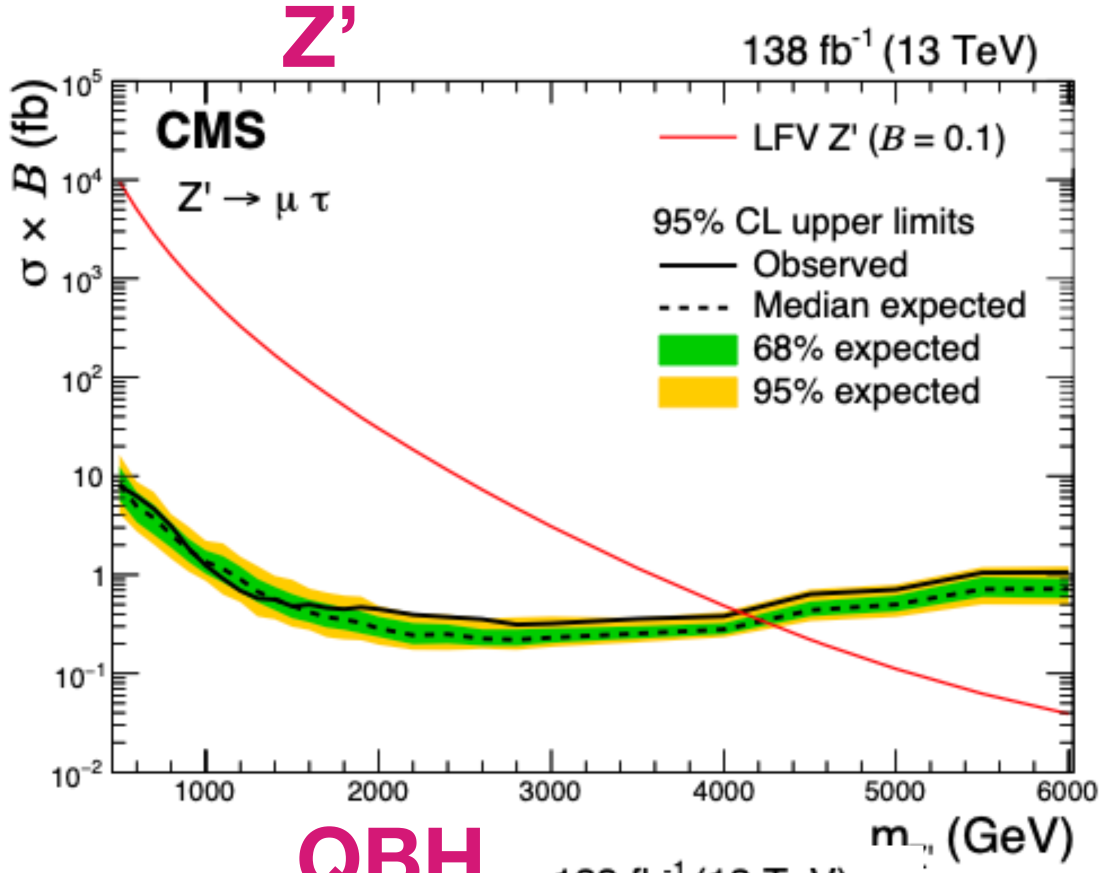
Results

Model-specific limits

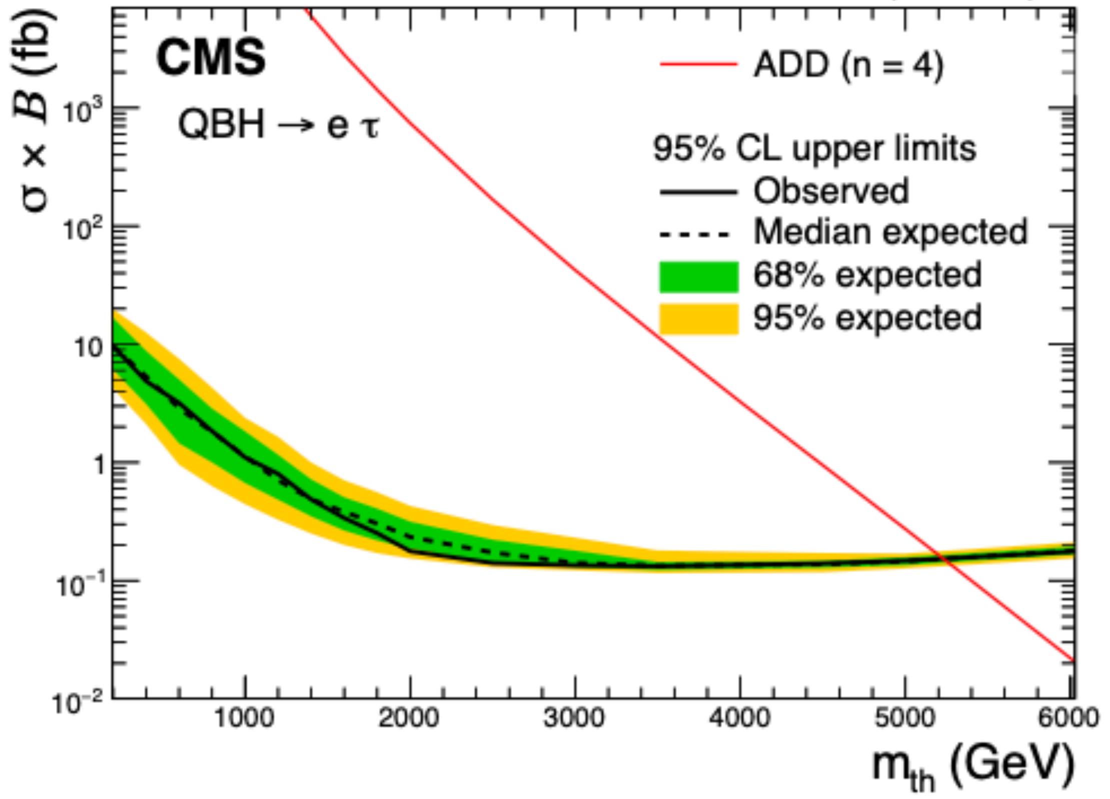
RPV SUSY



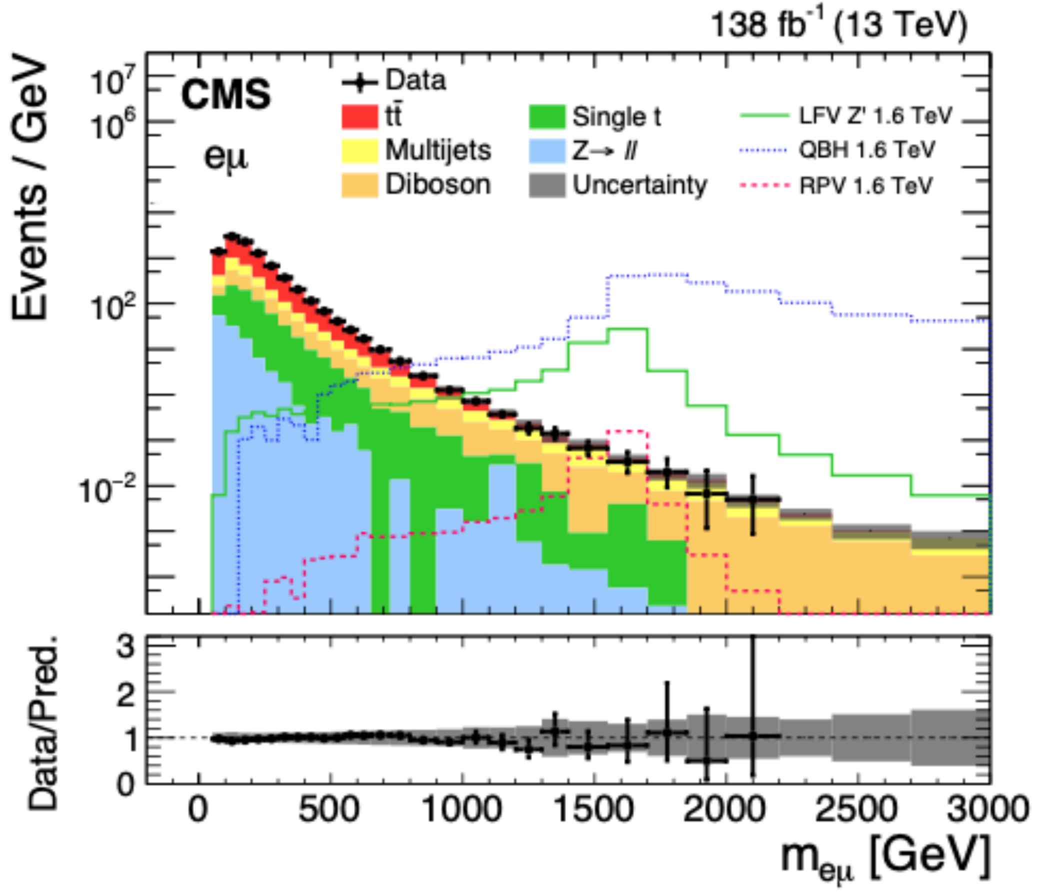
Z'

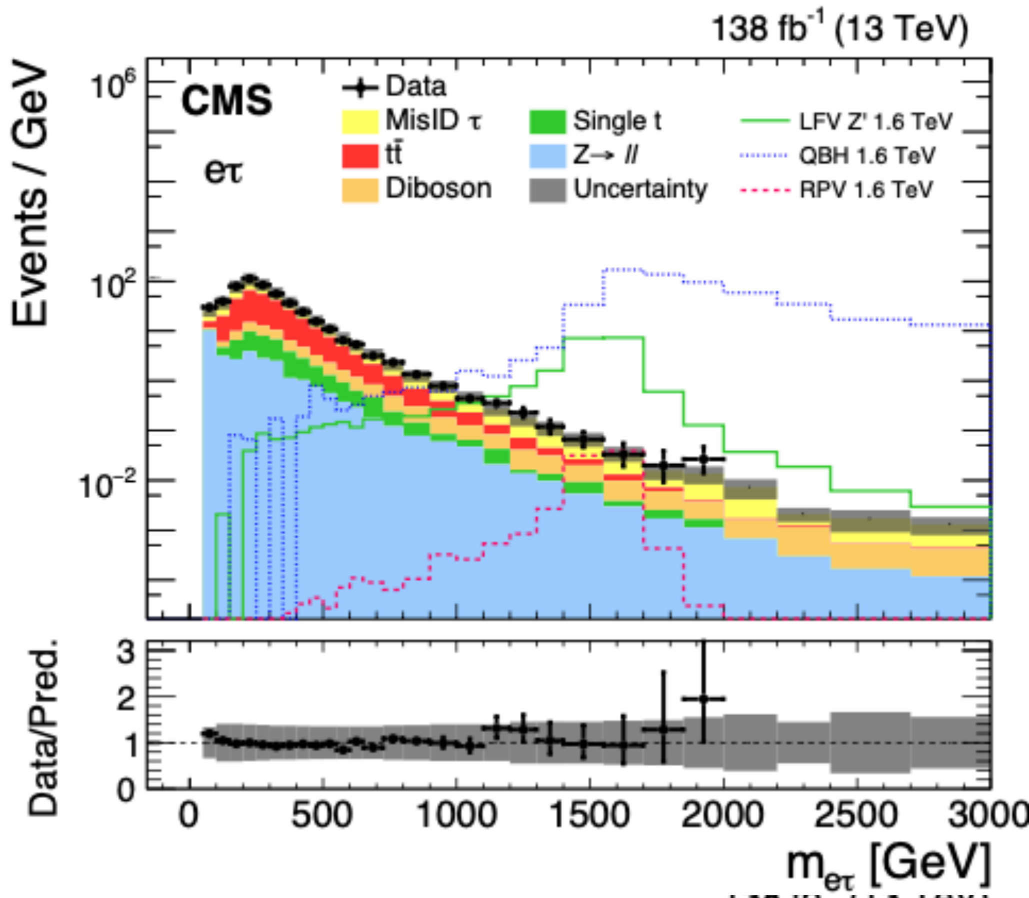


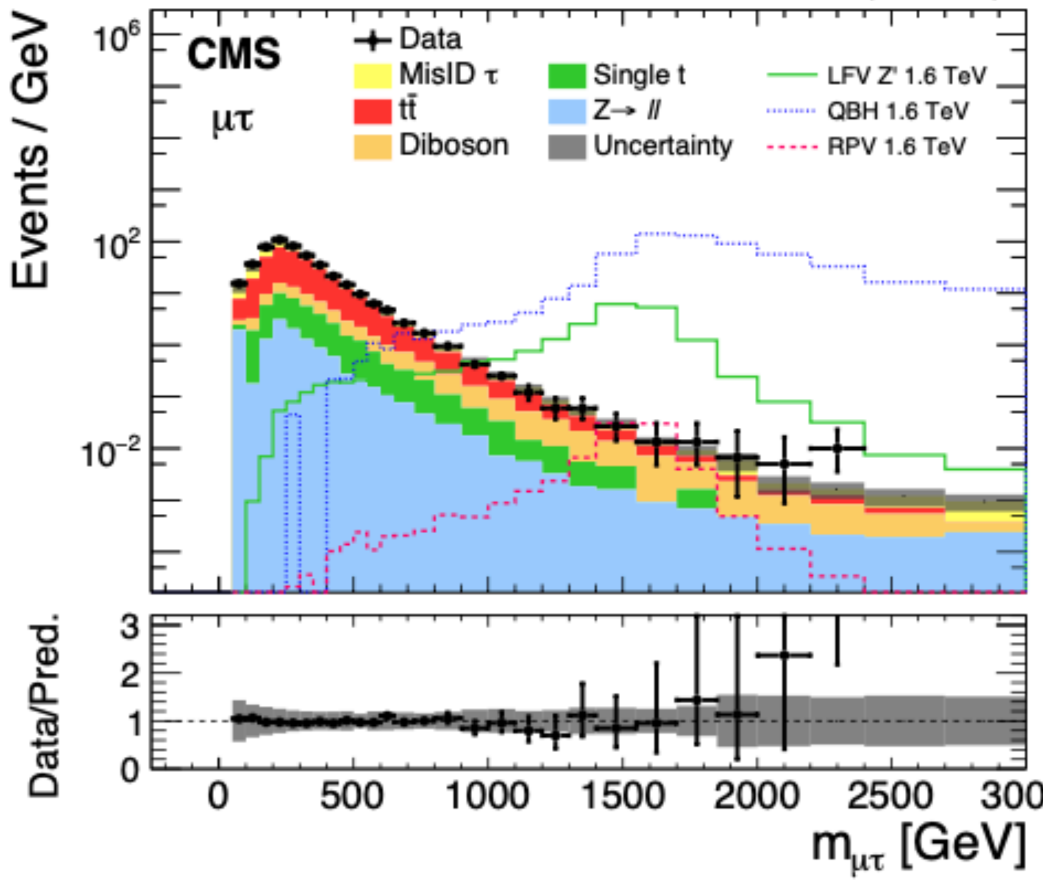
QBH



Most stringent limits available from collider experiments for heavy particles that undergo LFV decays.

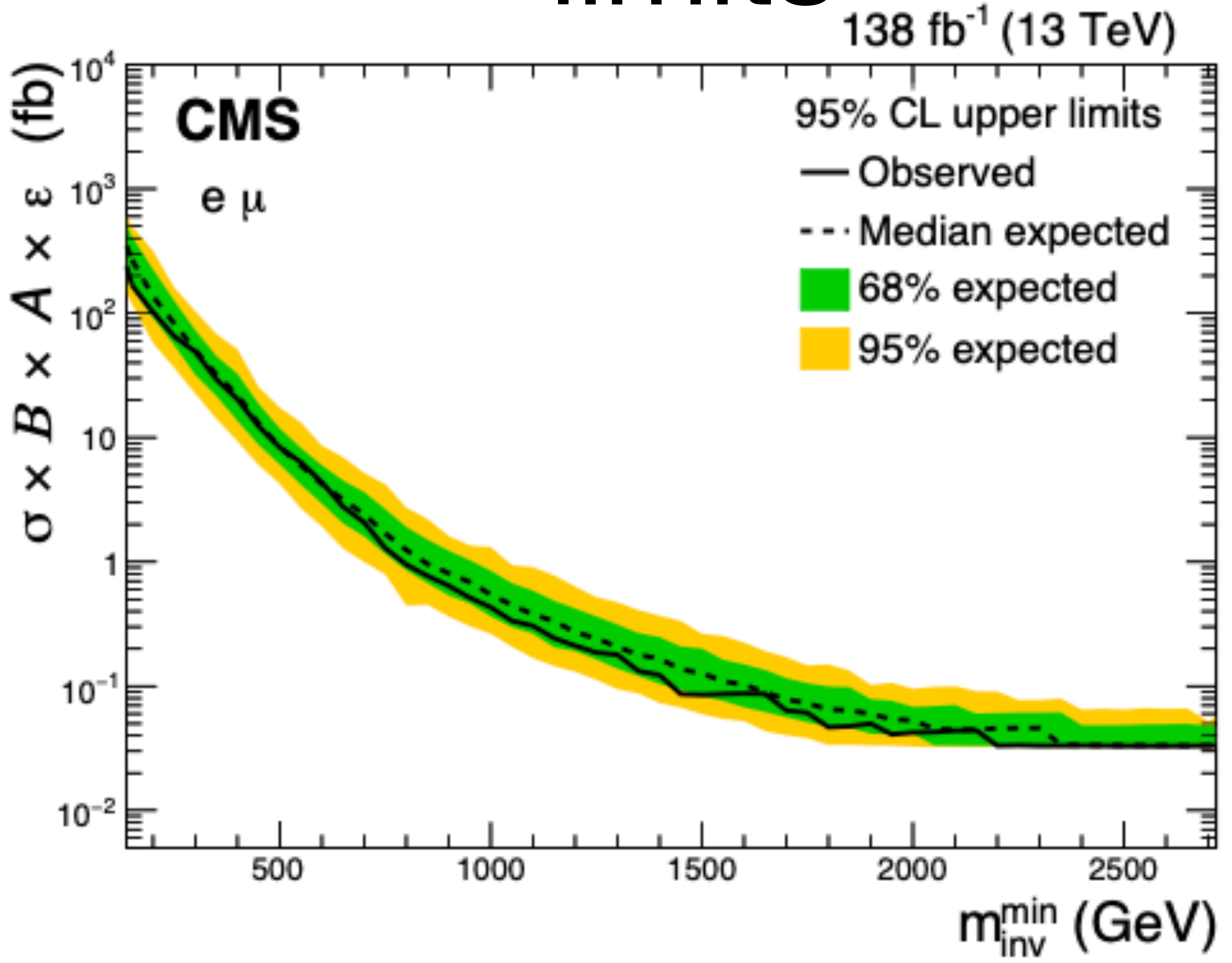






Invariant mass fit

Model-independent limits



Consistent with SM predictions

[CMS-PAS-EXO-22-016](CMS-PAS-EXO-22-016)

Run II $\mathscr{L} = 138\ fb^{-1}$

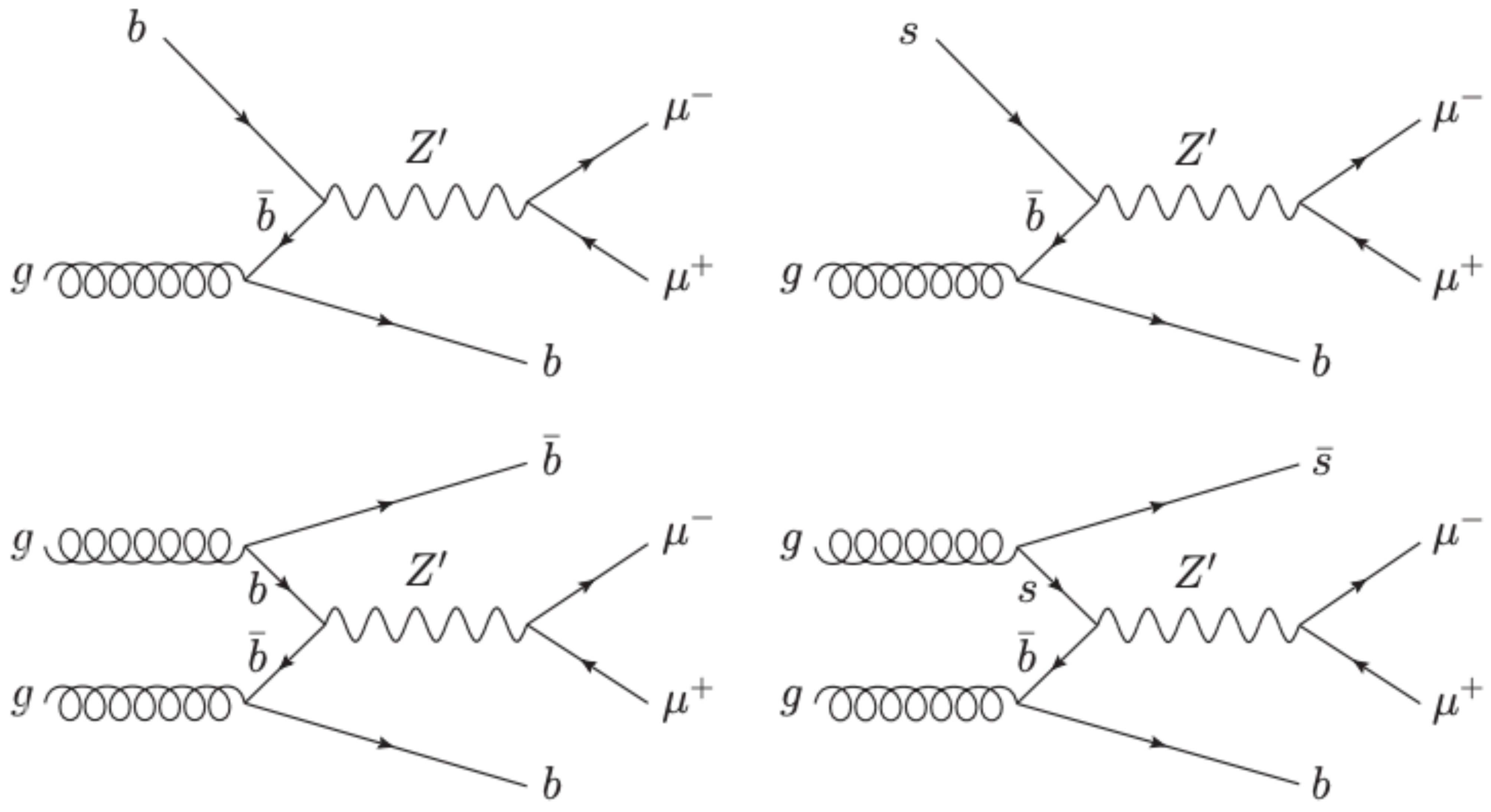
Search for Z'

Introduction

- **Search for $Z' \to \mu\mu$ resonance with b quark jets**
  - Previous searches at LHC not sensitive to Z' coupling to 2nd or 3rd generation of quarks
  - LFU interpretations with 4 coupling parameters: $g_l, g_\nu, g_b, \delta_{bs}$

- Signal:
  - $Z' \to \mu\mu$ resonance with $m_{Z'} > 350$ GeV and with at least 1 b quark jet
- Background sources
  1. DY
  2. $t\bar{t}$ production
  3. tZ+X, tW+X and $t\bar{t}$V, diboson production

} Dominant bkg (1. and 2.)



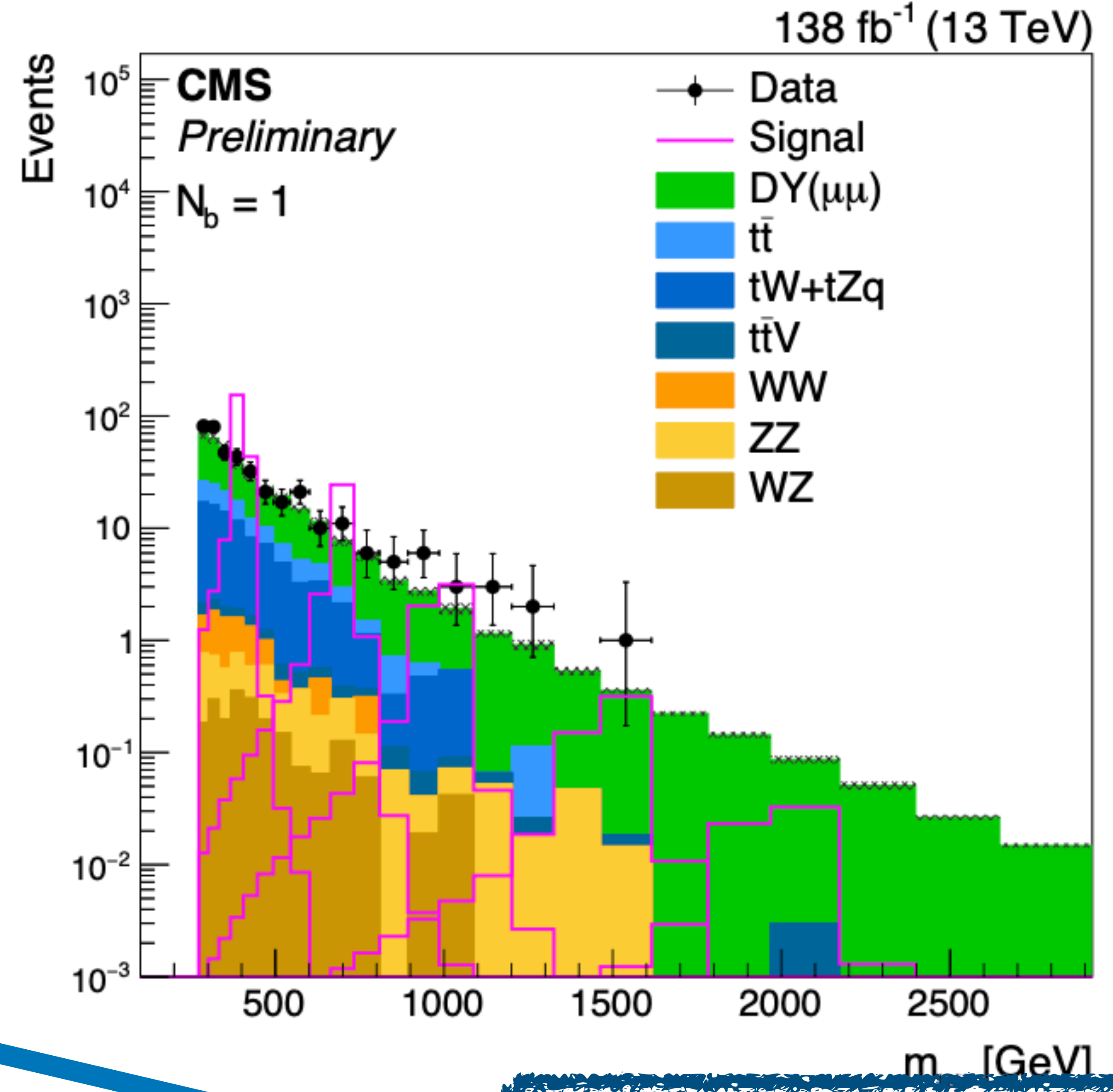
Bkg sources substantially reduced with respect to previous dilepton+b quark searches

Search for Z'

Selection

-PAS-EXO-22-016

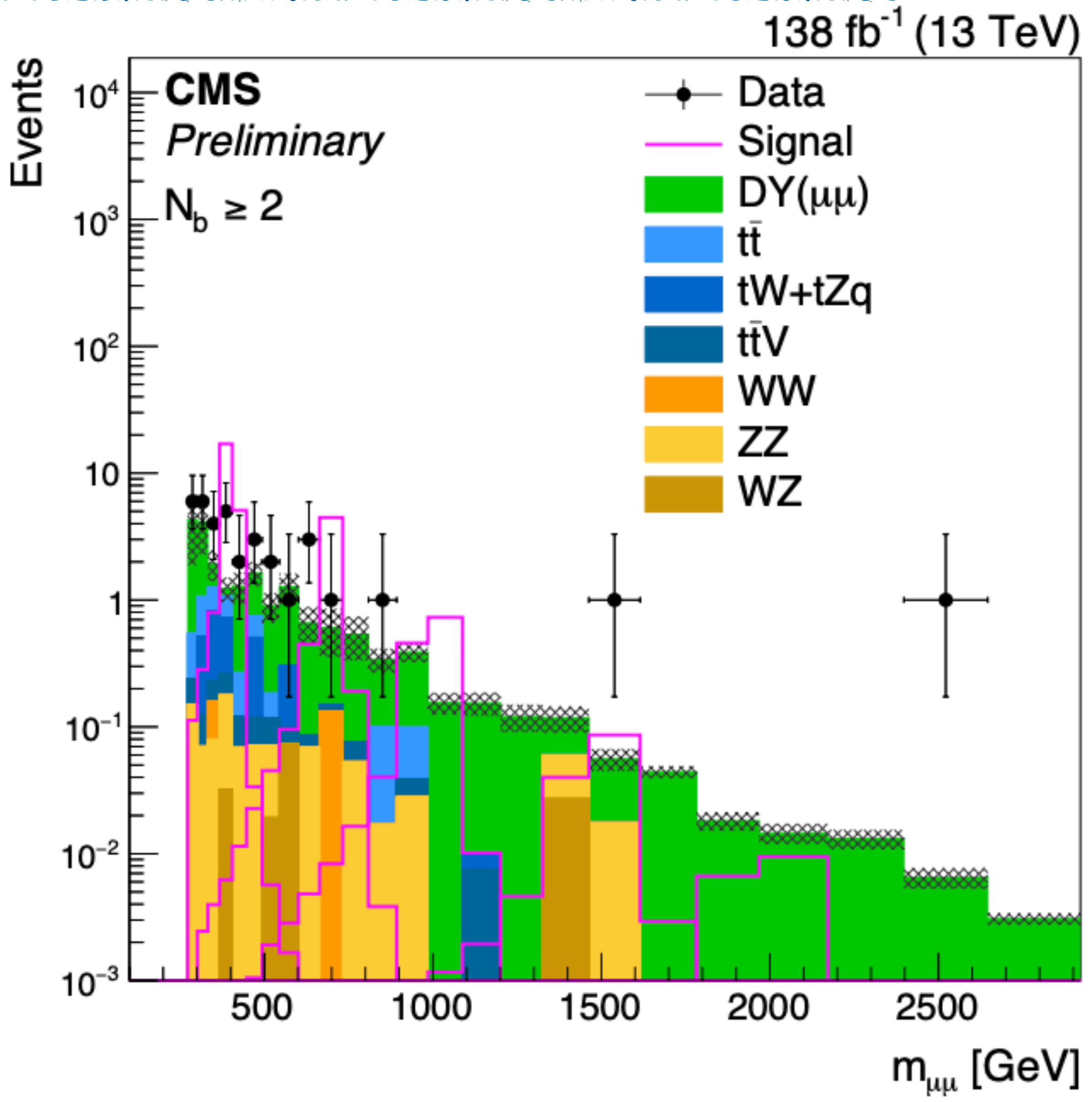
- Selection:
    - High p_T isolated muons $p_T > 53$ GeV
    - Veto to events with extra isolated leptons and charged hadrons coming from the PV
    - Jets $p_T > 20$ GeV
    - At least 1 b jet
        - $m(\mu, b) > 175$ GeV
    - Anomalous high-p_T^{miss} events are rejected
- Categorisation with multiplicity of b quark jets $N_b = 1$ and $N_b > 1$



Reduce tZ+X, tW+X, $t\bar{t}V$ bkg

Reduce Drell-Yan bkg

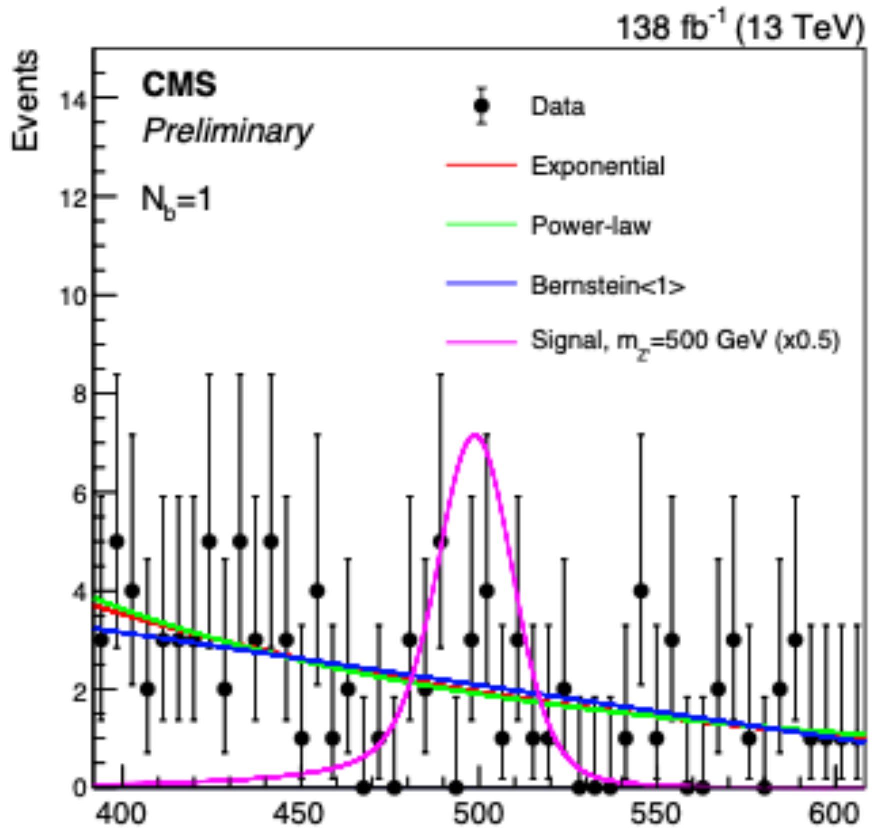
Reduce $t\bar{t}$ bkg

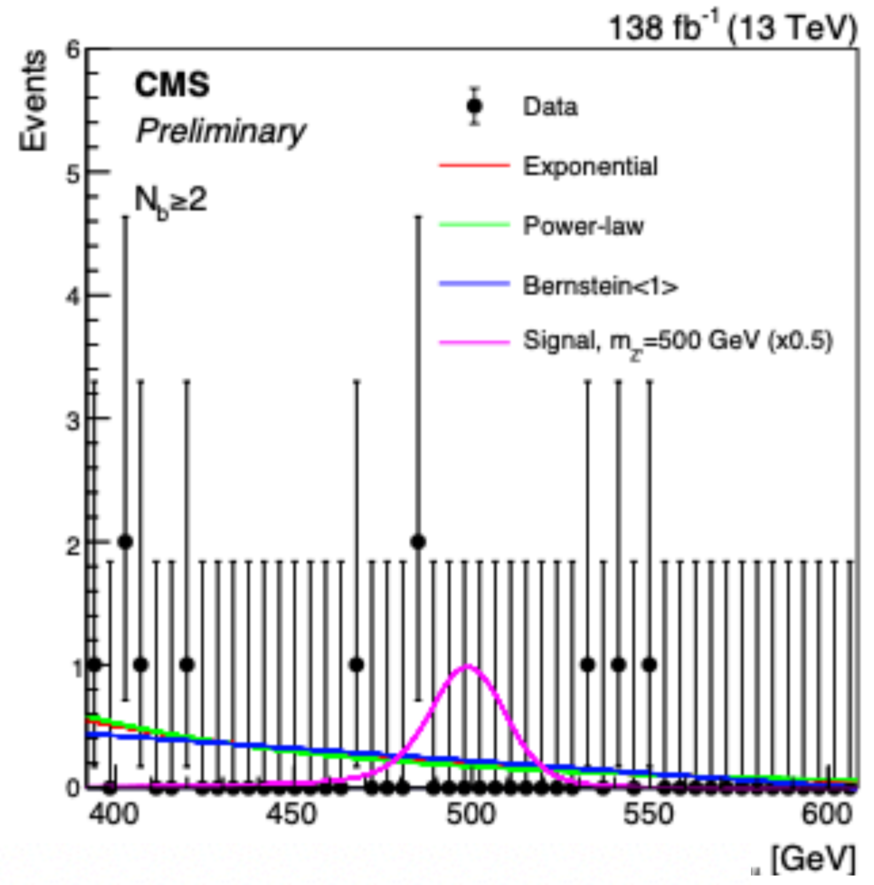


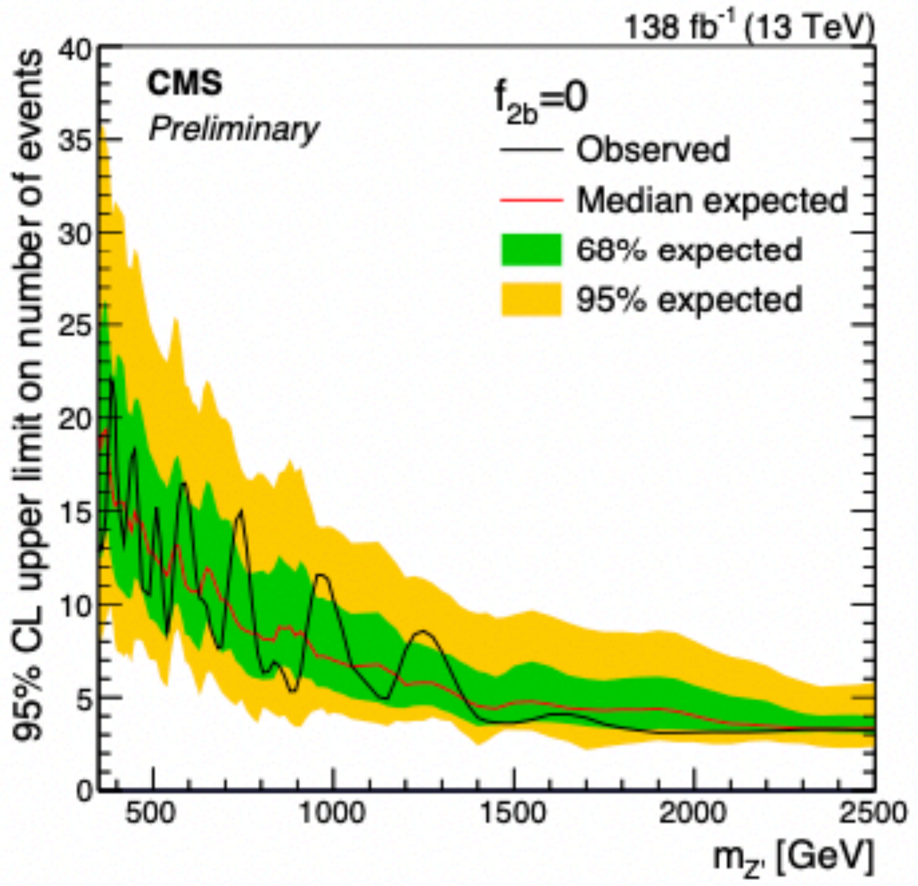
Search for Z’

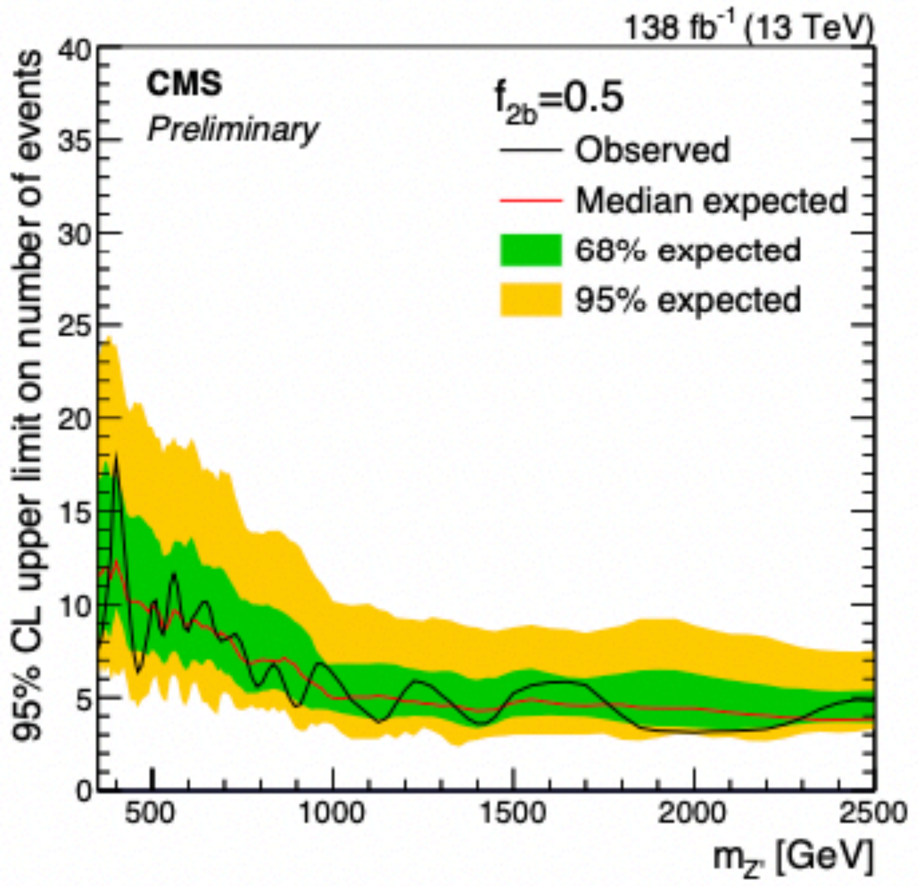
Results

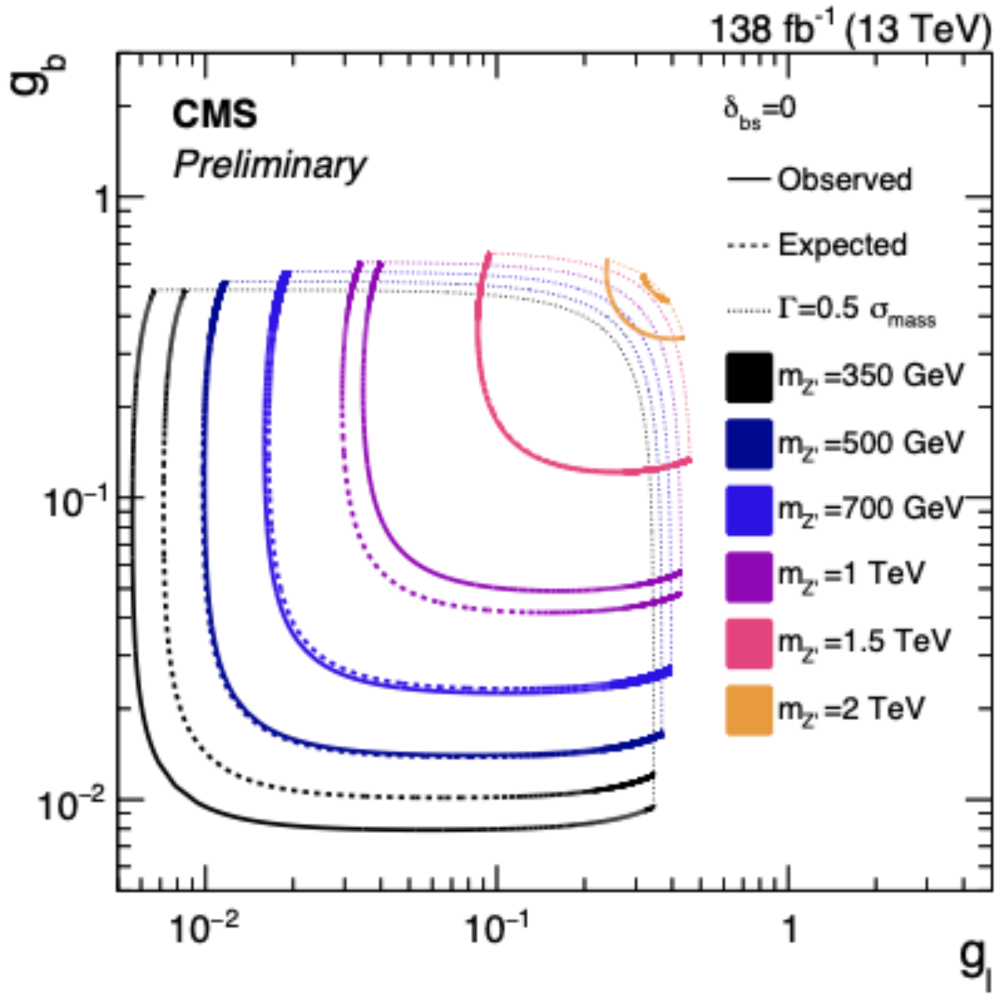
- Fit with analytical functions
- **No significant excess observed**
  - Model-independent limits
  - Coupling parameters limits

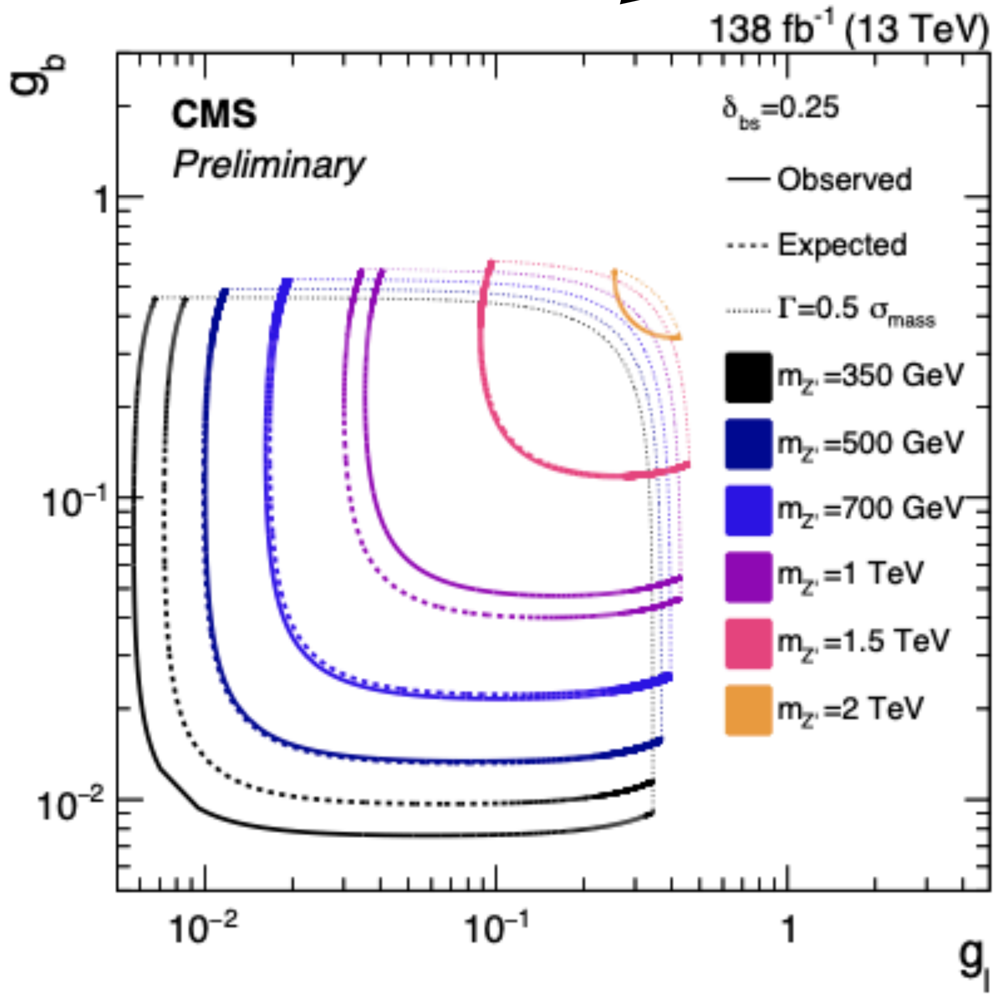


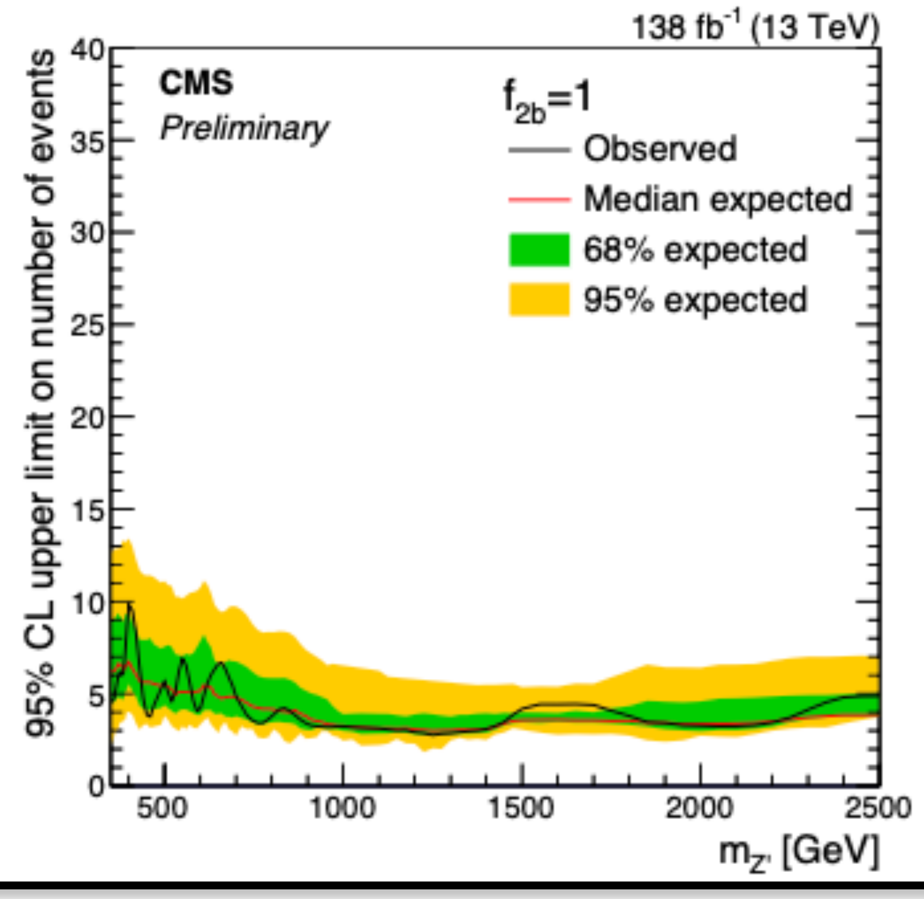












Conclusions

- LF(U)V is a **very exciting field** to look for new physics
- In CMS a **big effort is put into indirect and direct LF(U)V analyses**
- Recent analyses have been shown in this presentation
  - Search for $H \rightarrow e\mu$
  - Search for LFV in top quark sector
  - Search for the high mass LFV decays
  - Search for Z' bosons

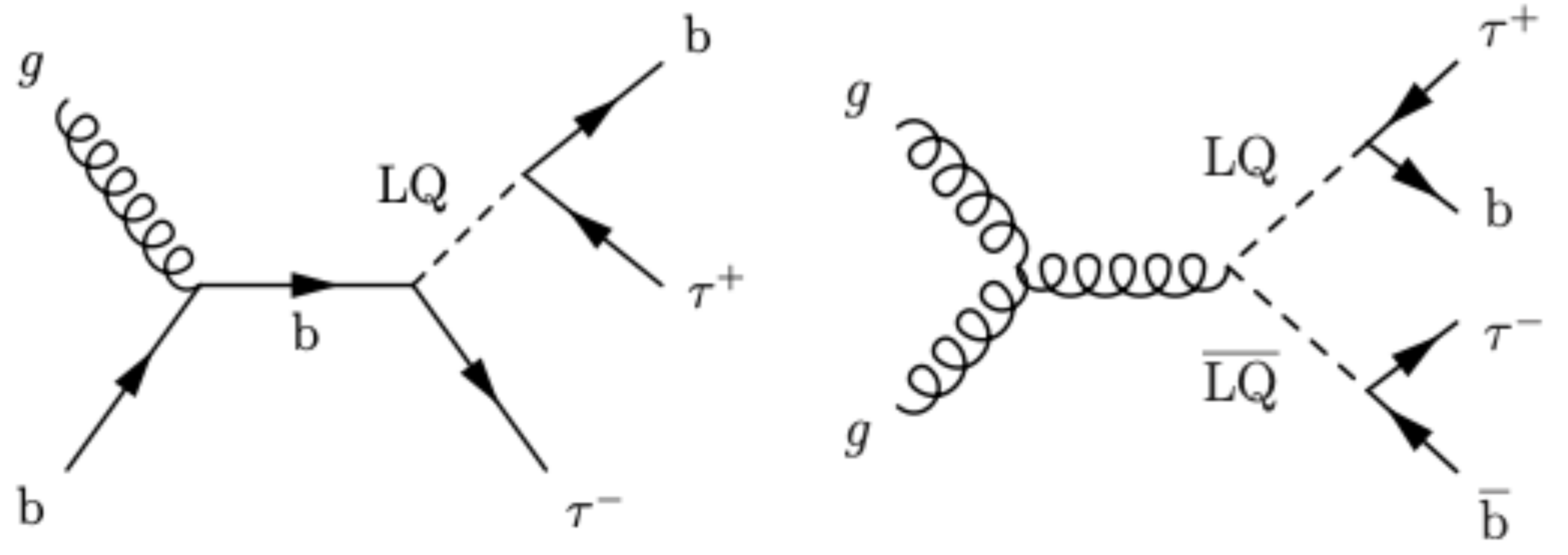
Many analyses still ongoing and hopefully new interesting results very soon!

Additional material

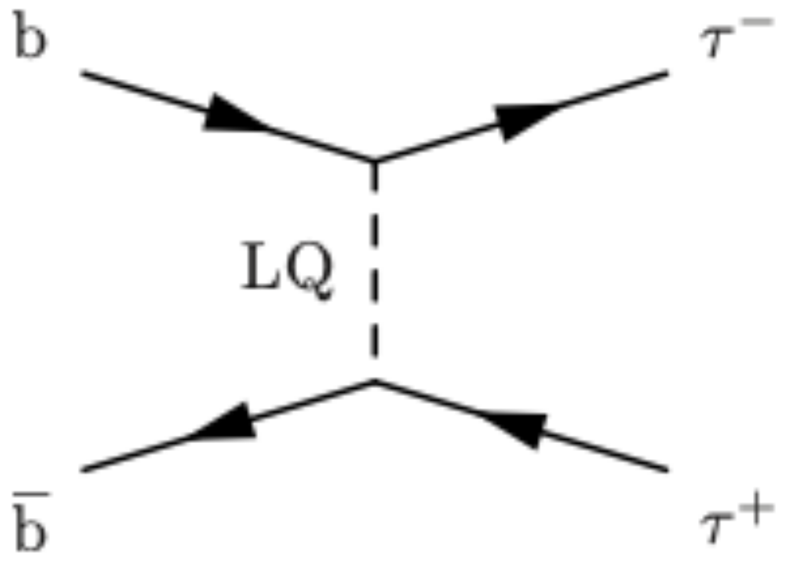
Run II $\mathscr{L} = 138\ fb^{-1}$

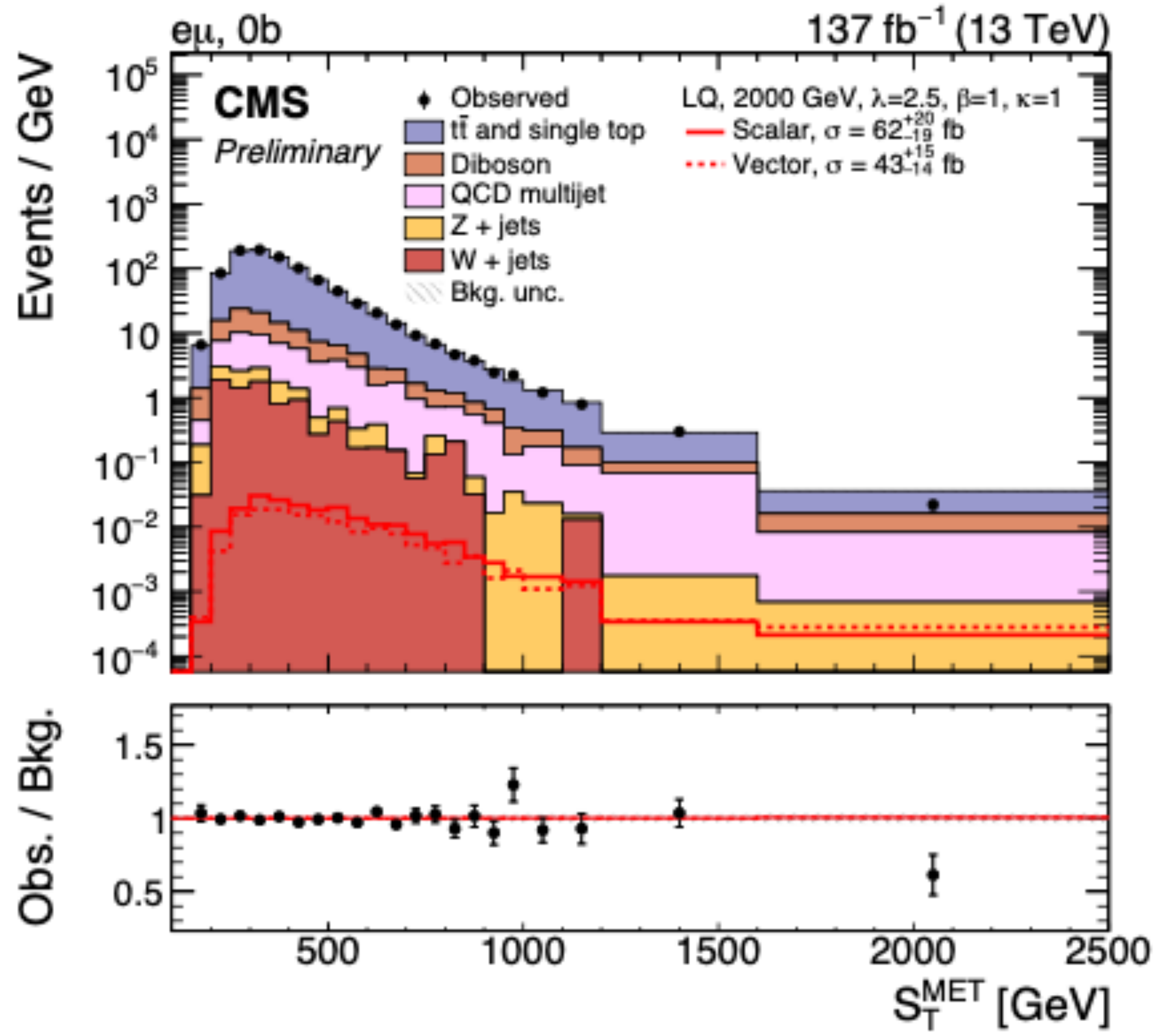
Search for LQ coupling with τ and b

- LQs possible explanations of LF(U)V
- Single and pair production of scalar and vector LQs that decay exclusively to a τ lepton and a b quark
- + Novel search for the nonresonant production of a τ lepton pair
- Signature: 2 τ + *(possible) extra jets*



$$S_T^{\text{MET}} \equiv p_T^1 + p_T^2 + p_T^j + p_T^{\text{miss}}$$

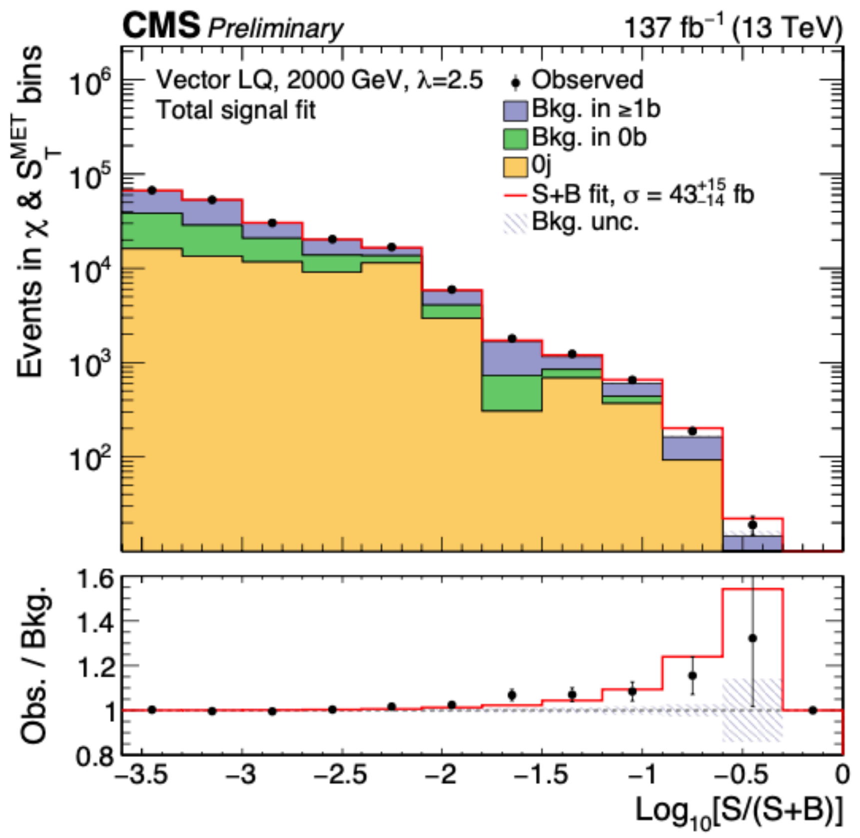


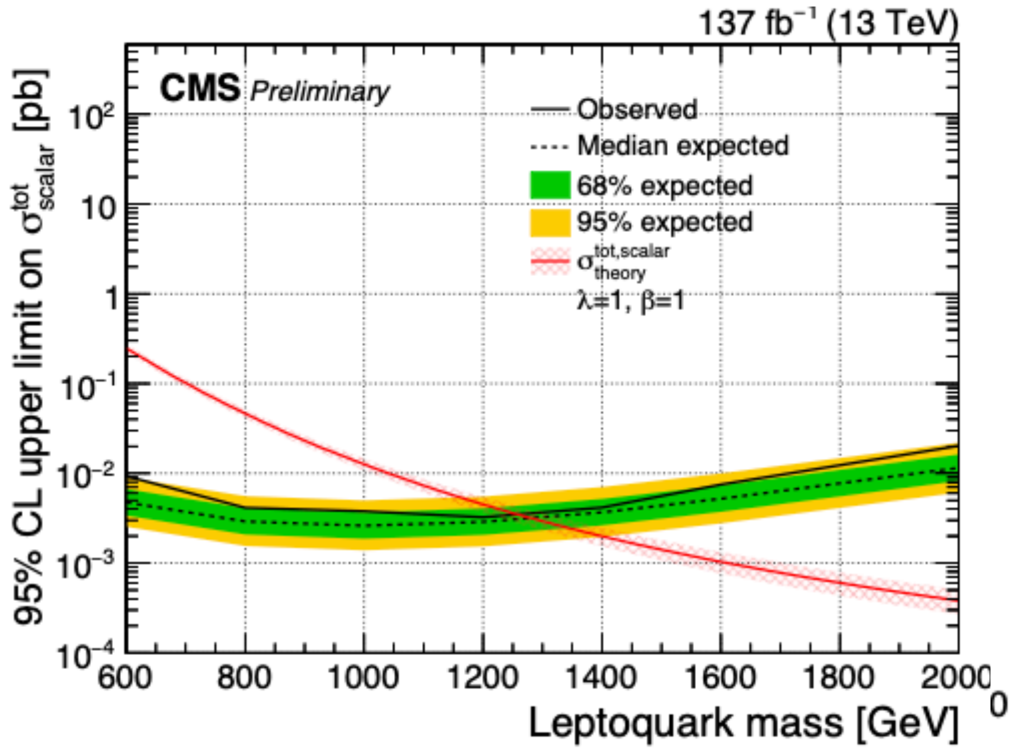


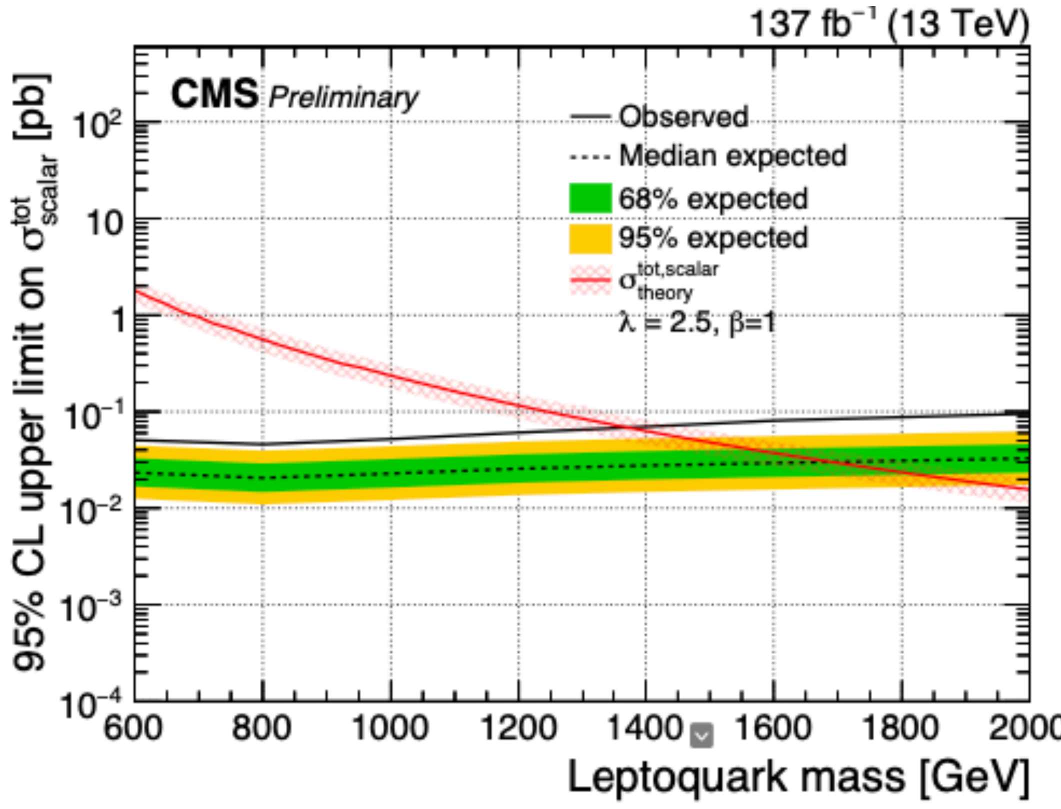
Run II $\mathscr{L} = 138\ fb^{-1}$

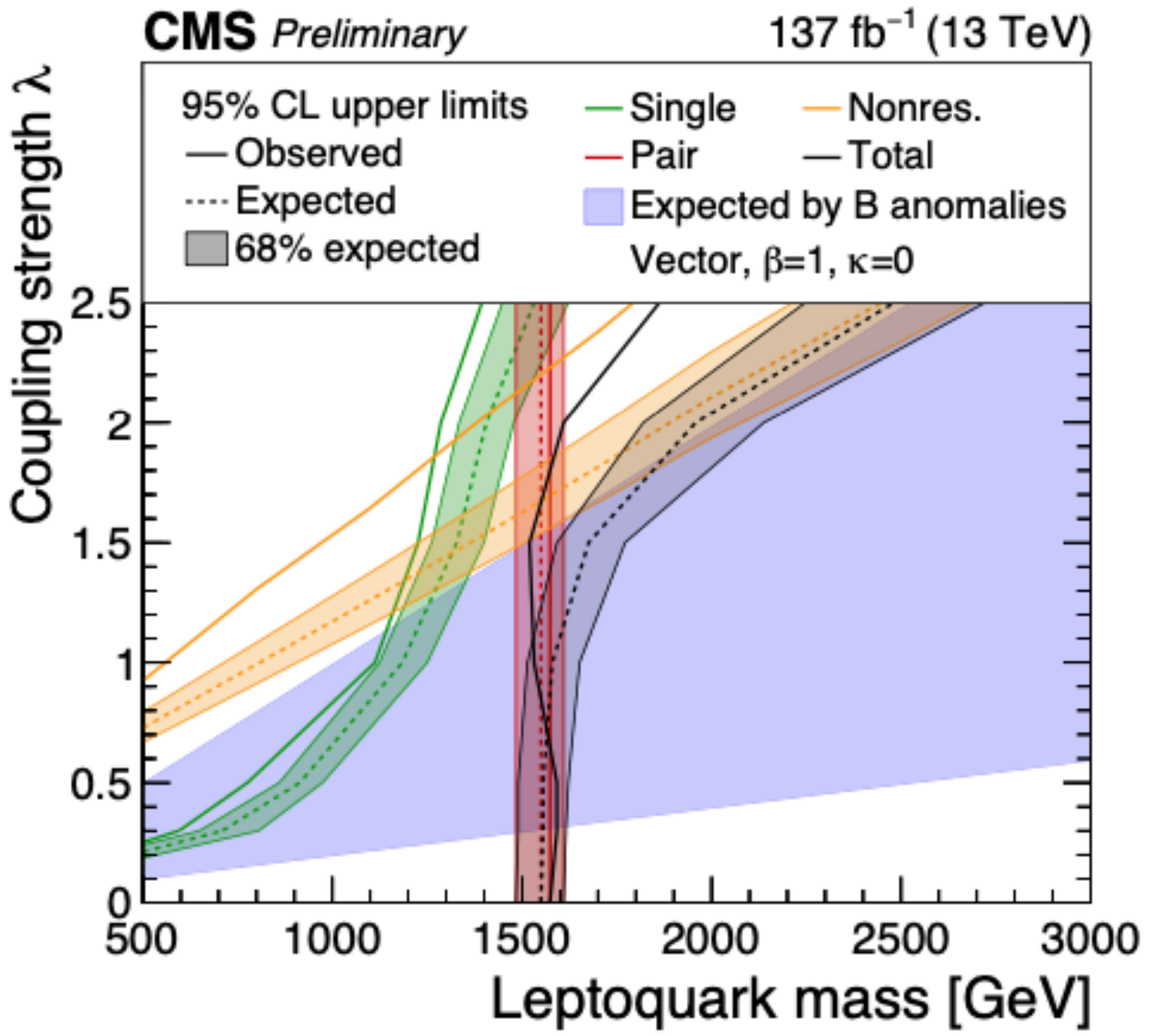
Search for LQ coupling with τ and b

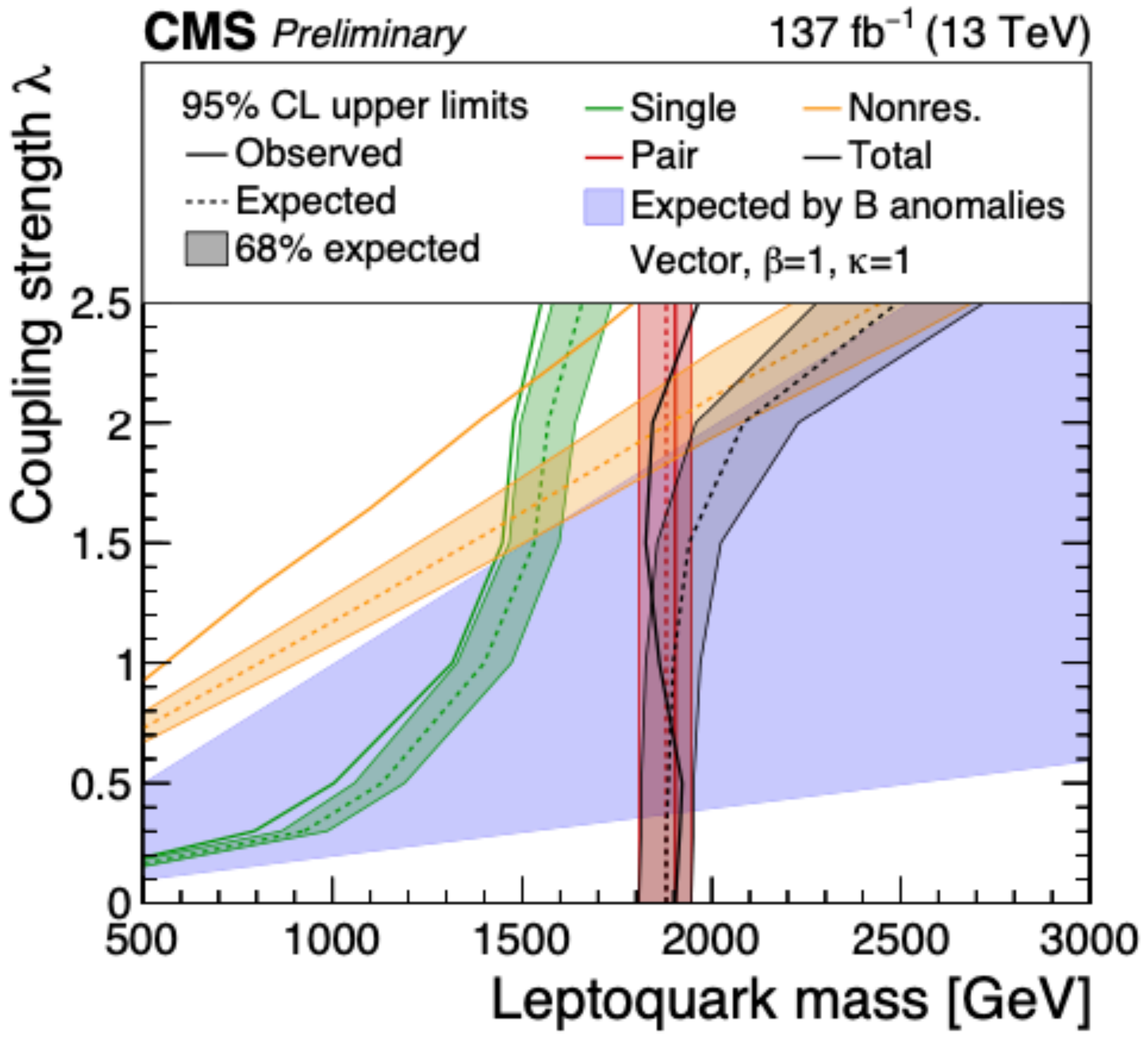
- Interesting variables:
  - χ = angular separation between two τs
  - $S_T^{MET} \equiv p_T^1 + p_T^2 + p_T^j + p_T^{miss}$
  - Invariant mass of the visible τ-decay m_{vis}
  - λ coupling strength
- **For lower masses and λ, observed data agrees with SM**
- **At higher masses and λ, excess with significance up to 3.4 σ above SM bkg**









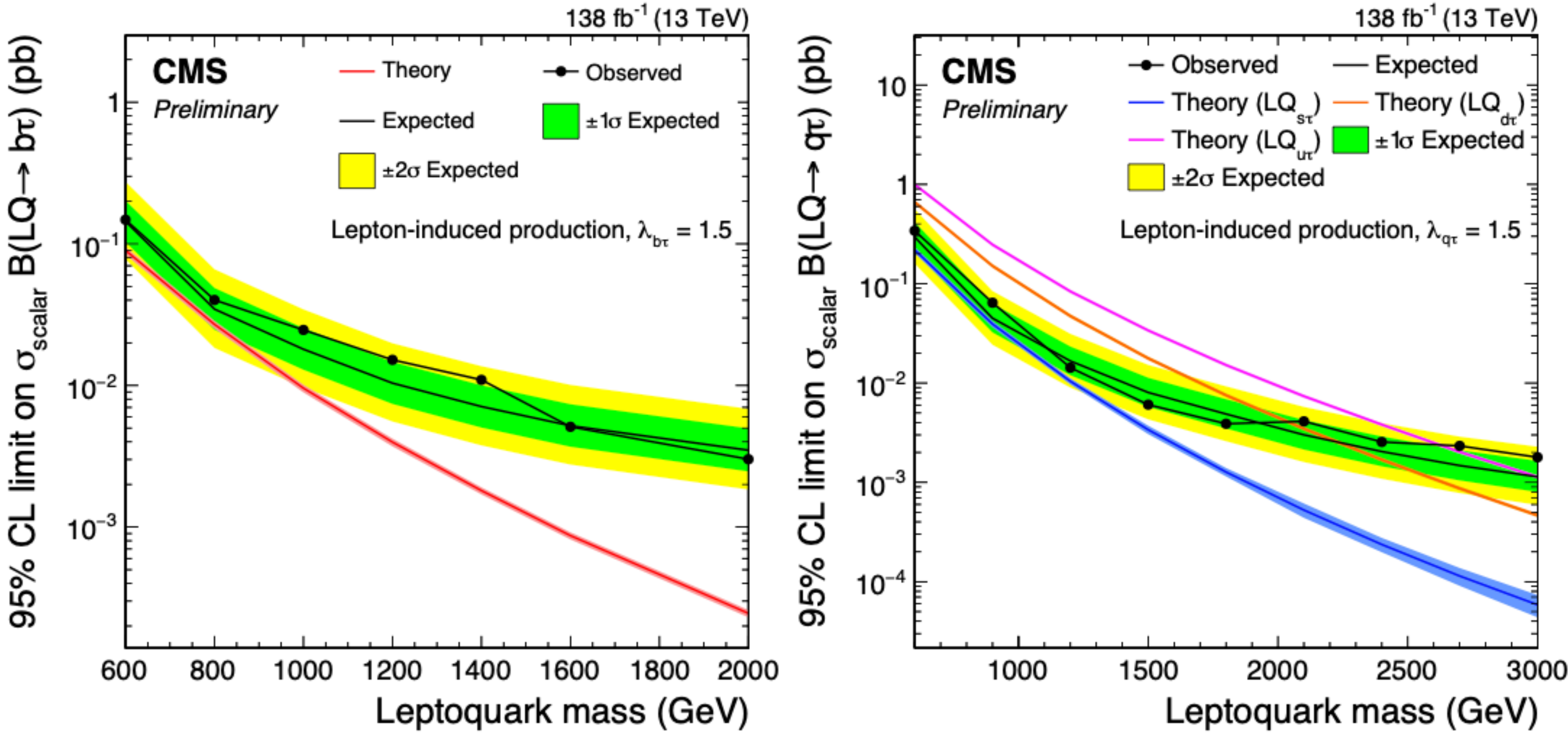


Search for LQ produced in l-q collisions and coupling to τ

CMS-PAS-EXO-22-018

Run II $\mathscr{L} = 138\ fb^{-1}$

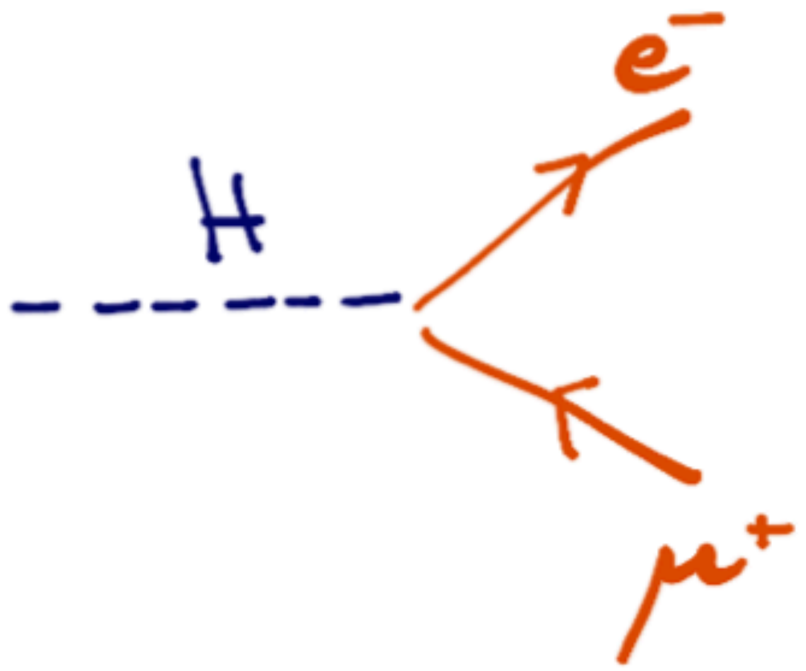
- Final state: jet; p_T^{miss}; τ (either lep. or had.)
- **No excess over SM bkg**
- These results complement the constraints on the leptoquark-τ-b couplings set by previous searches in other production modes, while they are the first limits for leptoquark-τ-u, leptoquark-τ-d, and leptoquark-τ-s couplings.



Backup

Search for $H \to e\mu$

Reasoning



arXiv:2305.18106
(submitted to Phys. Rev. D)

- Combined CMS results from the CMS constrained potential BSM decays of the Higgs boson to be B(H → BSM) < 0.16 at 95% CL (s41586-022-04892-x)
- LFV H decays in BSM theories such as : H doublets; flavor symmetries; Randall-Sandrum model; composite H models; SUSY models…
- Off-diagonal LFV Yukawa couplings $Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$ which couple the Higgs boson with leptons of different flavor
  - Enhances processes such as $\mu \to 3e$, $\mu \to e$ conversion, and $\mu \to e\gamma$ that could proceed via a virtual Higgs boson exchange
  - Most stringent limit on B($H(125) \to e\mu$) is obtained indirectly from the limit on $\mu \to e\gamma$ to be < 10^{-8}
  - BUT indirect limit on $H(125) \to e\mu$ assumes the SM values for the not yet tightly constrained Yukawa couplings $Y_{\mu\mu}$, Y_{ee}

Direct search for $H \to e\mu$ remain important

arXiv:2305.18106
(submitted to Phys. Rev. D)

Search for $H \to e\mu$
Systematic Uncertainties

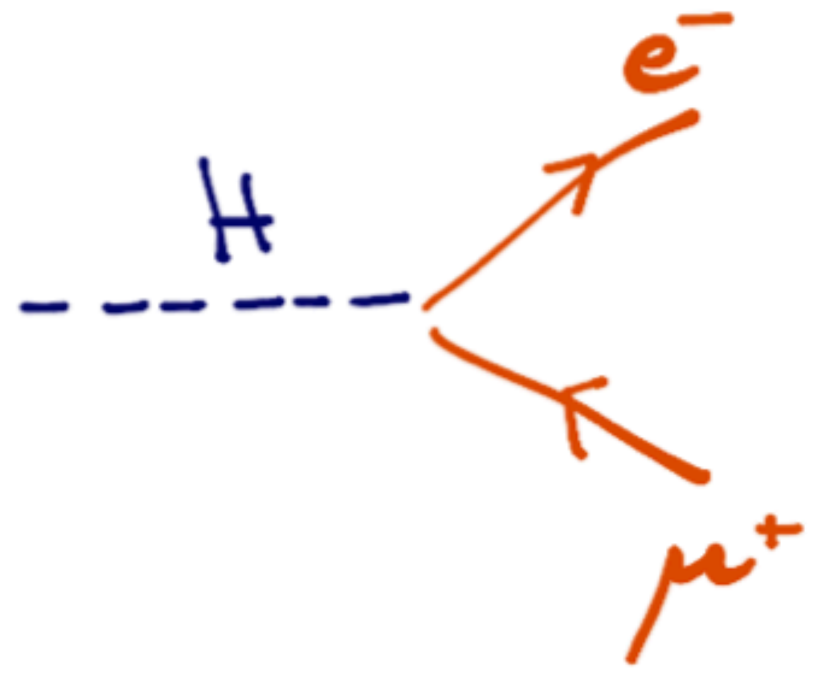


Table 2: Systematic uncertainties in the expected signal yields from different sources for the ggH and VBF production modes. All the uncertainties are treated as correlated among categories.

Systematic uncertainties	ggH mode (%)	VBF mode (%)
Muon identification, isolation, and trigger	< 1	< 1
Electron identification, isolation, and trigger	2	2
b tagging efficiency	< 1	< 1
Jet energy scale	1–8	1–3
Unclustered energy scale	2–6	1–6
Trigger timing inefficiency	< 1	< 1
Integrated luminosity	< 2	< 2
Pileup	< 2	< 2
Parton shower	-	3–11
Ren. and fact. scales	4	1
PDF + α_S	3	2
Effect of the ren. and fact. scales on the acceptance	1–10	< 2
Effect of the PDF + α_S on the acceptance	< 1	< 1

Search for LFV in top quark sector

Theory

Table 1: Summary of relevant dimension-6 operators considered in this analysis. The indices i and j are lepton flavor indices that run from 1 to 2 with $i \neq j$; k and l are quark flavor indices with the condition that one of them is 3 and the other one runs from 1 to 2.

vector	$O_{lq}^{(1)ijkl}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{lu}^{ijkl}	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l)$
	O_{eq}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l)$
	O_{eu}^{ijkl}	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l)$
scalar	$O_{lequ}^{(1)ijkl}$	$(\bar{l}_i e_j)\ \varepsilon\ (\bar{q}_k u_l)$
tensor	$O_{lequ}^{(3)ijkl}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\ \varepsilon\ (\bar{q}_k\sigma_{\mu\nu} u_l)$

- Parametrise CLFV signals with dim-6 EFT operators

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

- O_a are dim-6 non-renormalizable operators, and C_a are the corresponding Wilson coefficients

- Assuming the CLFV coupling involves exactly one e, one mu, one top, and one u/c quark at tree level, the complete list of dimension-6 operators can be shortened

Search for LFV in top quark sector

Channels and Bkg

- $e\mu l$ channel: SR
- eee and $\mu\mu\mu$ channels: study the bkg composition

Table 2: Summary of the selection criteria used to define different event regions.

Channel	Region	OnZ	OffZ	$p_T^{miss} > 20$ GeV	# jets ≥ 1	# b jets ≤ 1
eee/$\mu\mu\mu$	VR	-	-	-	-	-
	WZ CR	✓	-	✓	✓	✓
$e\mu l$	SR	-	✓	✓	✓	✓
	VR	✓	-	-	-	-
	WZ CR	✓	-	✓	✓	✓

Expected bkg contributions

Table 3: Expected background contributions and the number of events observed in data collected during 2016–2018. The systematic and statistical uncertainties are added in quadrature. The CLFV signal, generated with $C^{\text{vector}}_{e\mu tu}/\Lambda^2 = 1\,\text{TeV}^{-2}$, is also listed for reference.

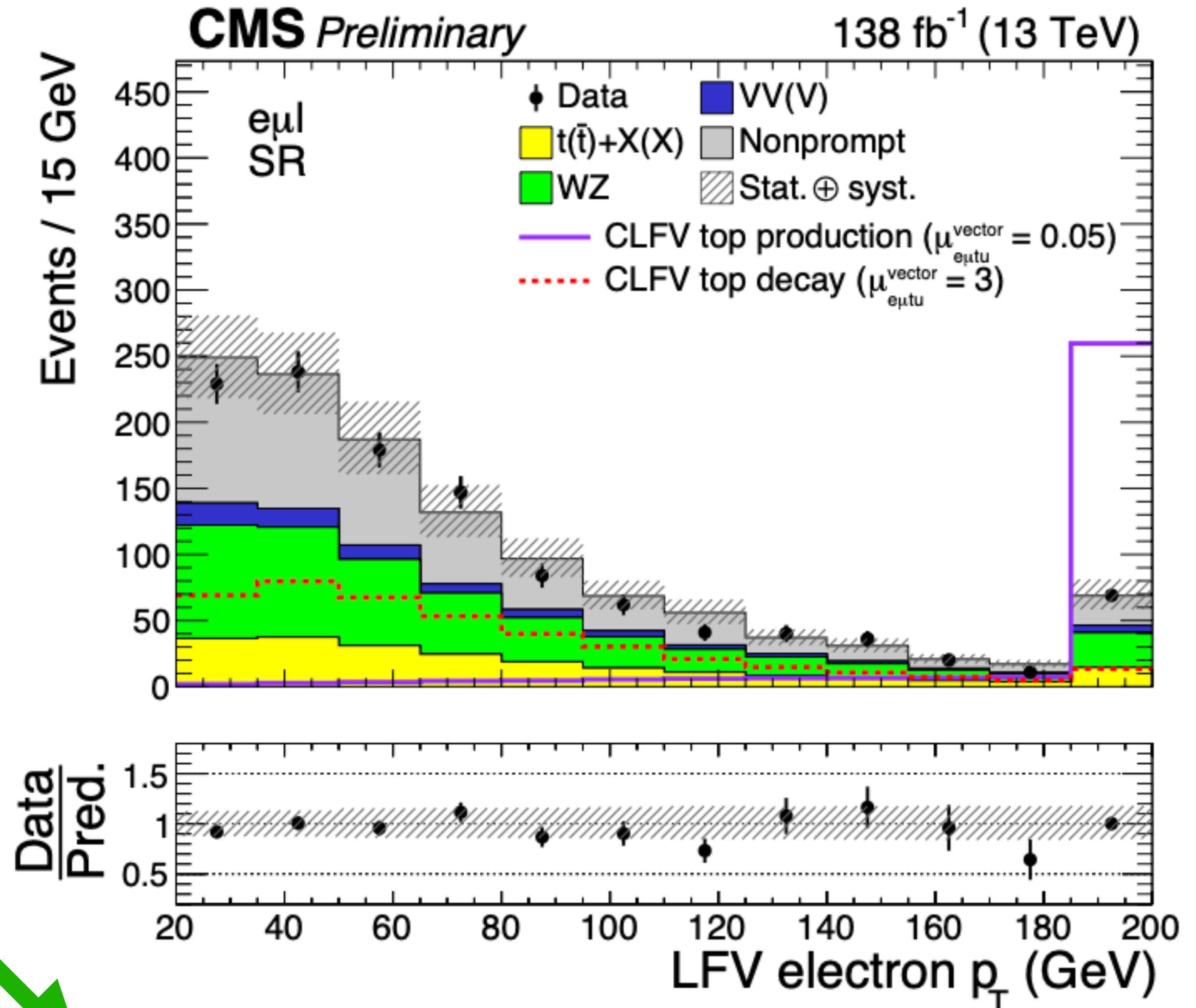
Process	$m(e\mu) < 150$ GeV	$m(e\mu) > 150$ GeV
Nonprompt	351 ± 92	146 ± 38
WZ	275 ± 64	145 ± 35
ZZ	33.2 ± 6.5	13.1 ± 2.6
VVV	17.0 ± 8.5	12.0 ± 6.0
$t\bar{t}W$	47.6 ± 10.0	40.0 ± 9.1
$t\bar{t}Z$	39.1 ± 7.9	25.8 ± 5.4
$t\bar{t}H$	28.2 ± 4.5	10.0 ± 1.6
tZq	5.5 ± 1.1	2.5 ± 0.5
Other backgrounds	7.3 ± 3.7	4.5 ± 2.3
Total expected background	805 ± 123	398 ± 57
Data	783	378
CLFV	239 ± 14	6195 ± 305

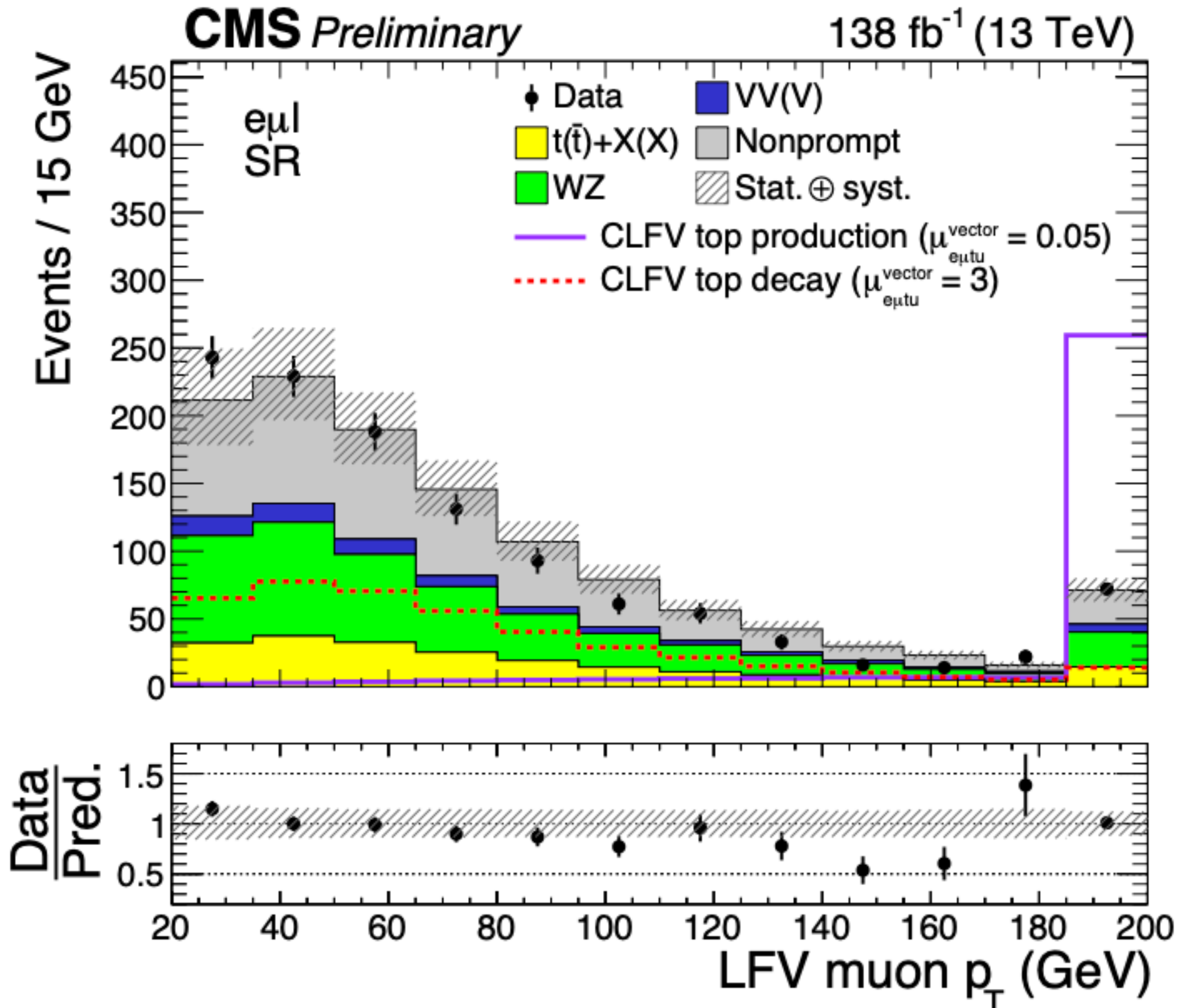
[CMS-PAS-TOP-22-005]

Search for LFV in top quark sector

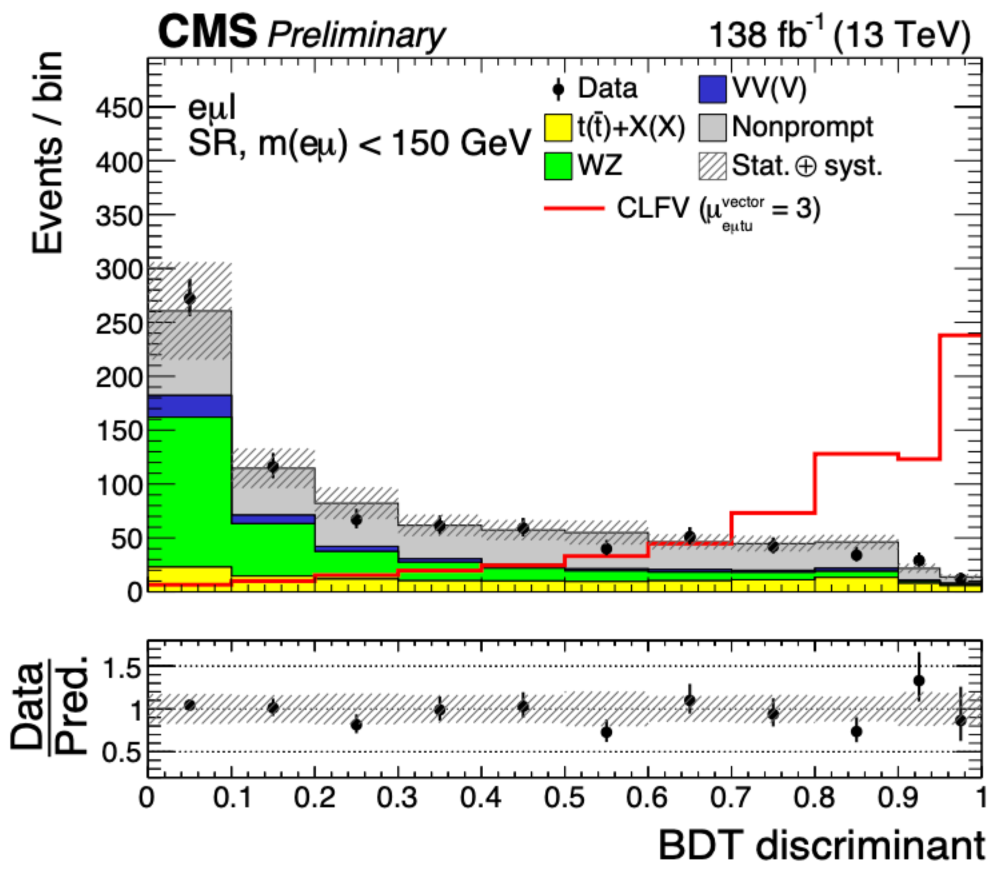
Some plots in SR

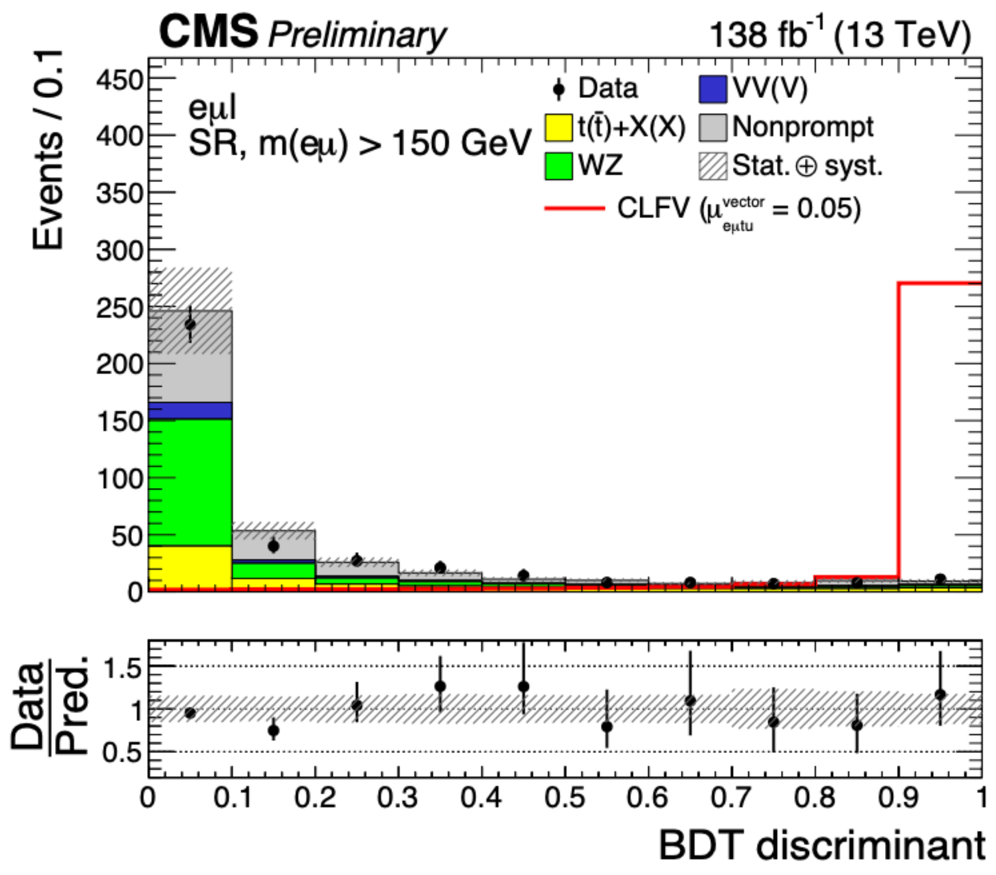
Two of the most important variables in the BDT training

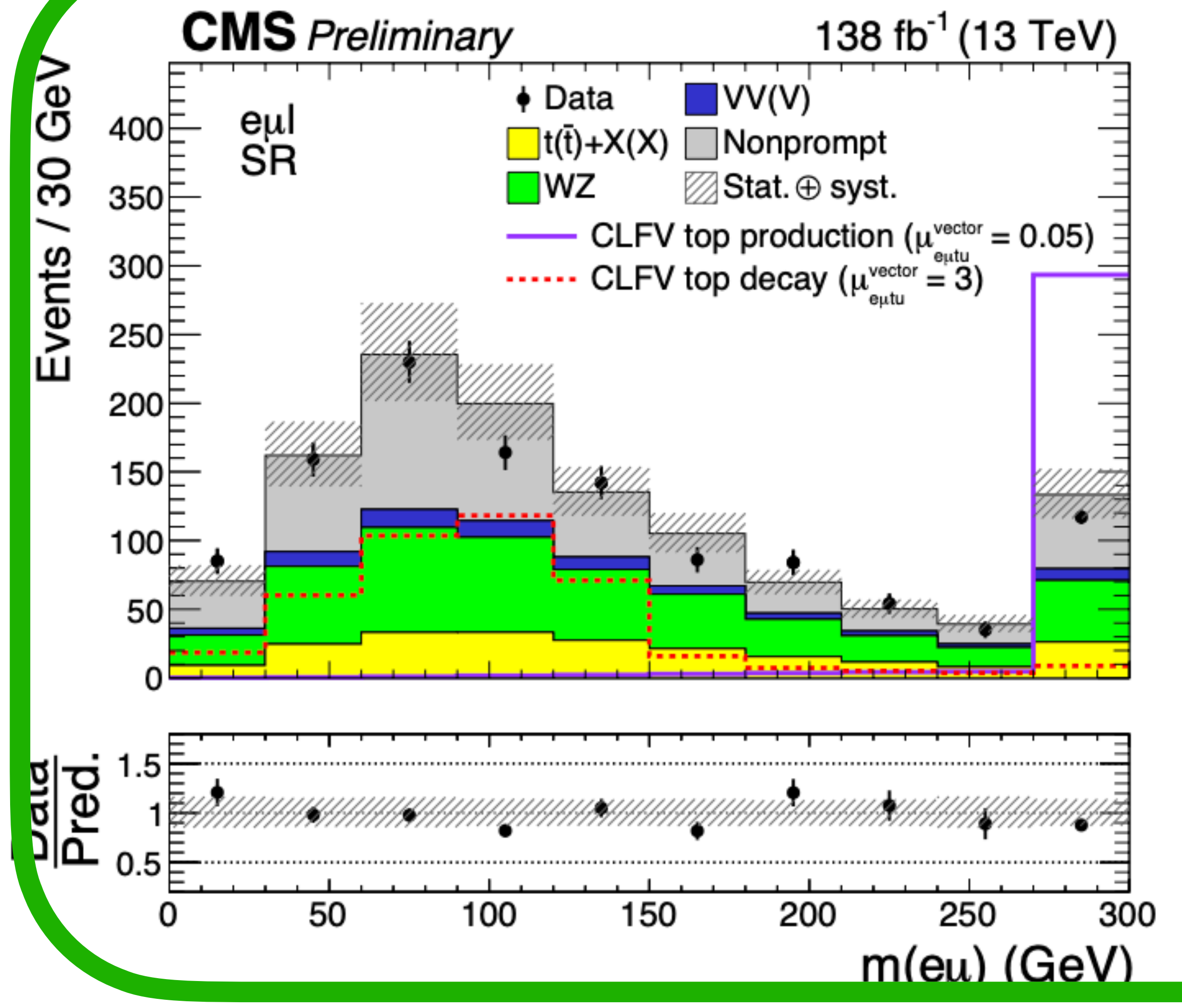


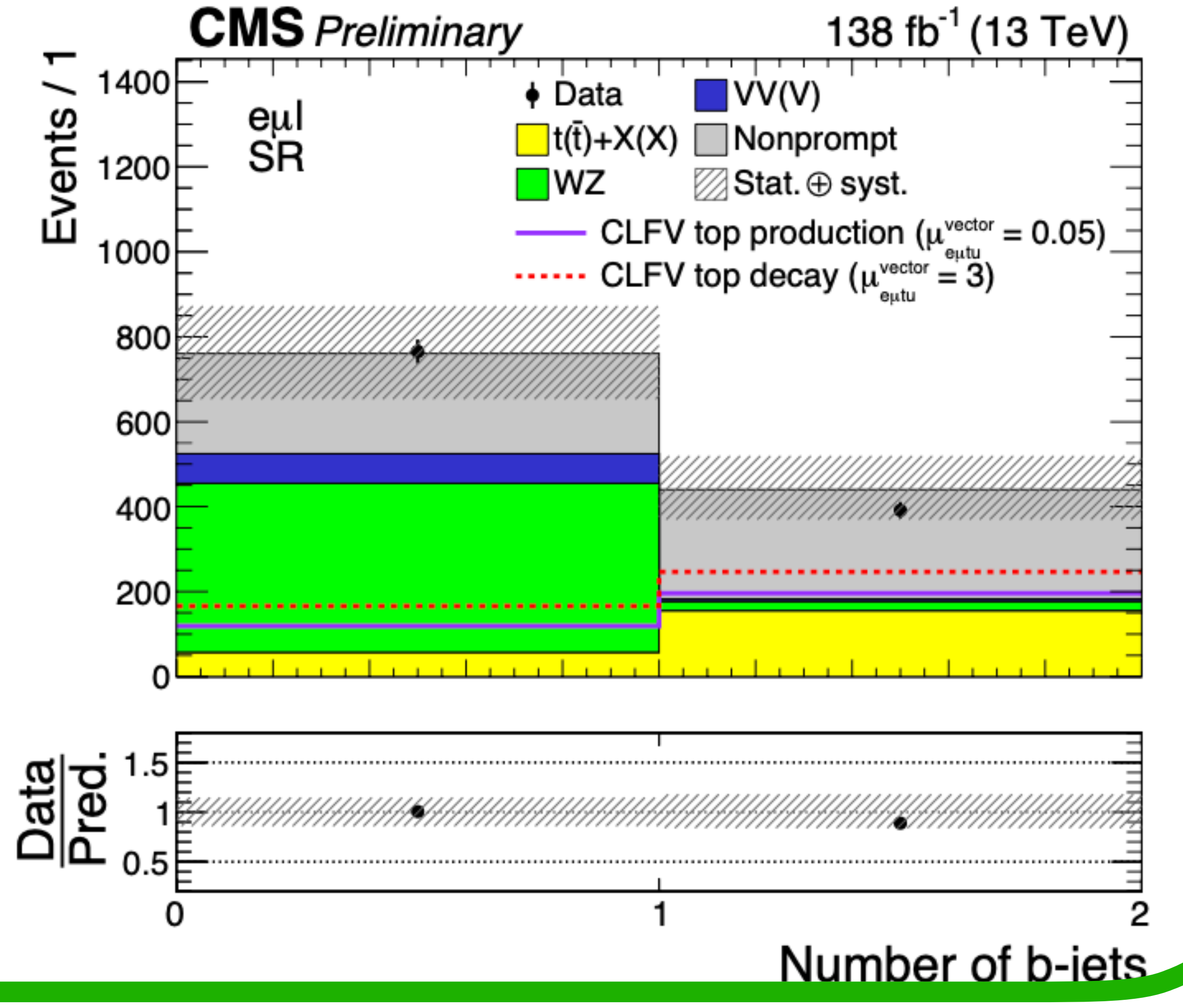


BDT discriminant









CMS-PAS-TOP-22-005

Search for LFV in top quark sector

Systematics

- Lumi: ~2%
- Unc on the diboson CR to cover msmodeling effects: 10–20%, affecting the WZ and ZZ bkgs
- Trigger eff uncertainty 2%
- Reco, ID, ISO efficiencies of e and μ
- Jet energy scans (JES) and jet energy resolution (JER)
- B-tag efficiency
- Uncertainties on the data-driven non-prompt bkg estimation
- Theory-related

Search for LFV in top quark sector

Final Limits

Table 4: Upper limits at the 95% CL on the different CLFV signals obtained from the 2016–2018 data set. The observed and expected upper limits are shown in boldface and standard style, respectively. The intervals that contain 68% of the distribution of the expected upper limits are shown in parentheses.

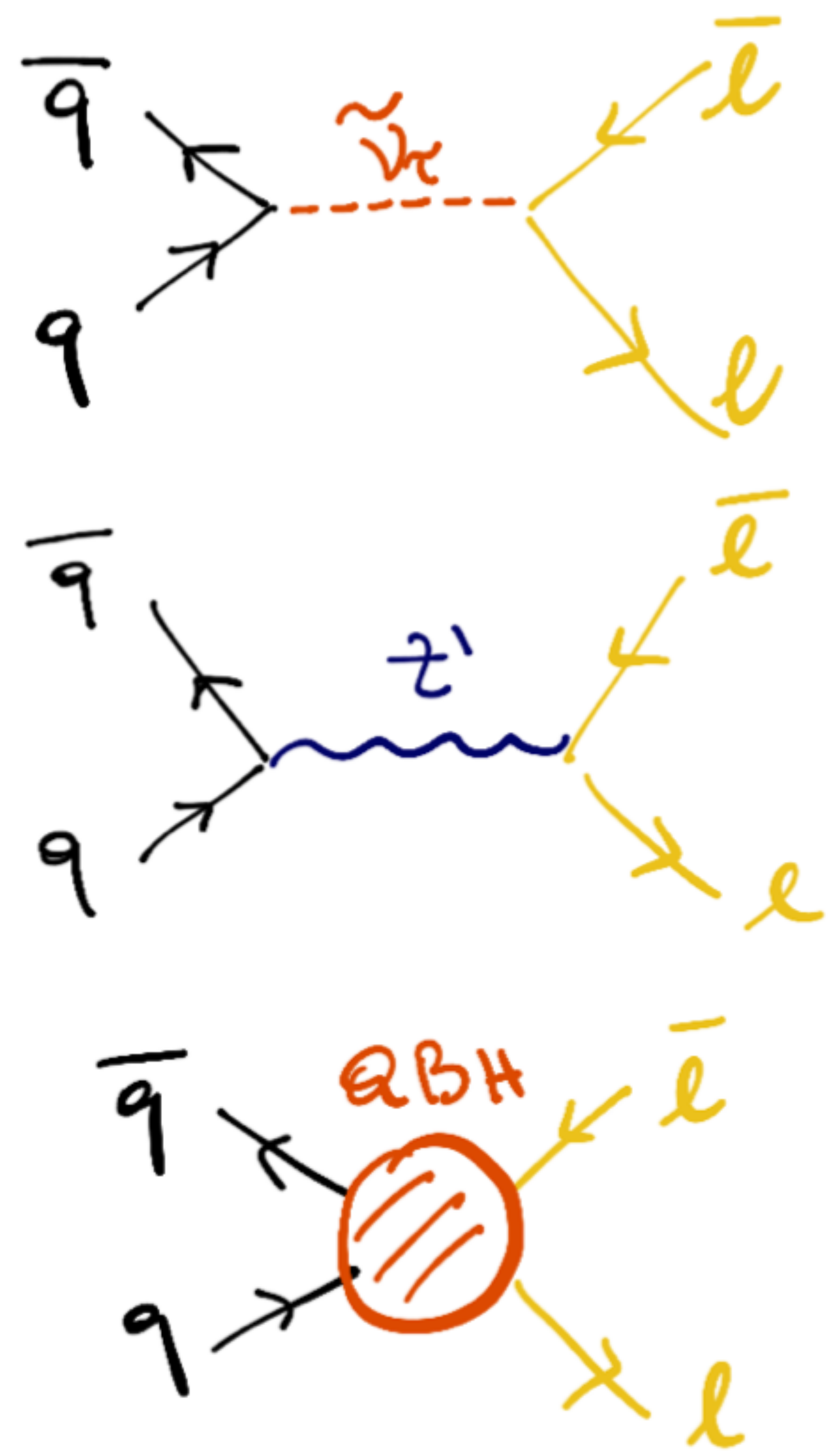
CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) exp $(-\sigma, +\sigma)$	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ exp $(-\sigma, +\sigma)$	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ obs
$e\mu tu$	tensor	0.019 (0.015, 0.023)	**0.020**	0.019 (0.013, 0.029)	**0.023**
	vector	0.037 (0.031, 0.046)	**0.041**	0.013 (0.009, 0.020)	**0.016**
	scalar	0.077 (0.064, 0.095)	**0.084**	0.007 (0.005, 0.011)	**0.009**
$e\mu tc$	tensor	0.061 (0.050, 0.074)	**0.068**	0.209 (0.143, 0.311)	**0.258**
	vector	0.130 (0.108, 0.159)	**0.144**	0.163 (0.111, 0.243)	**0.199**
	scalar	0.269 (0.223, 0.330)	**0.295**	0.087 (0.060, 0.130)	**0.105**

This analysis constitutes the most stringent limits on these processes to date

arXiv:2205.06709

Heavy resonances

Previous searches



- Similar searches in LFV dilepton mass spectra have been carried out by the CDF and D0 experiments at the Fermilab Tevatron in proton-antiproton collisions and by the ATLAS and CMS experiments at the LHC in pp collisions

Heavy resonances

Systematics

- Dominant: on bkgs WW and tt
- Muon pt scale and eff
- Hadronic tau identification and energy scale
- E pt scale and resolution
- Jet energy scale
- Lumi
- Cross sections

Heavy resonances

Results for SUSY sneutrinos

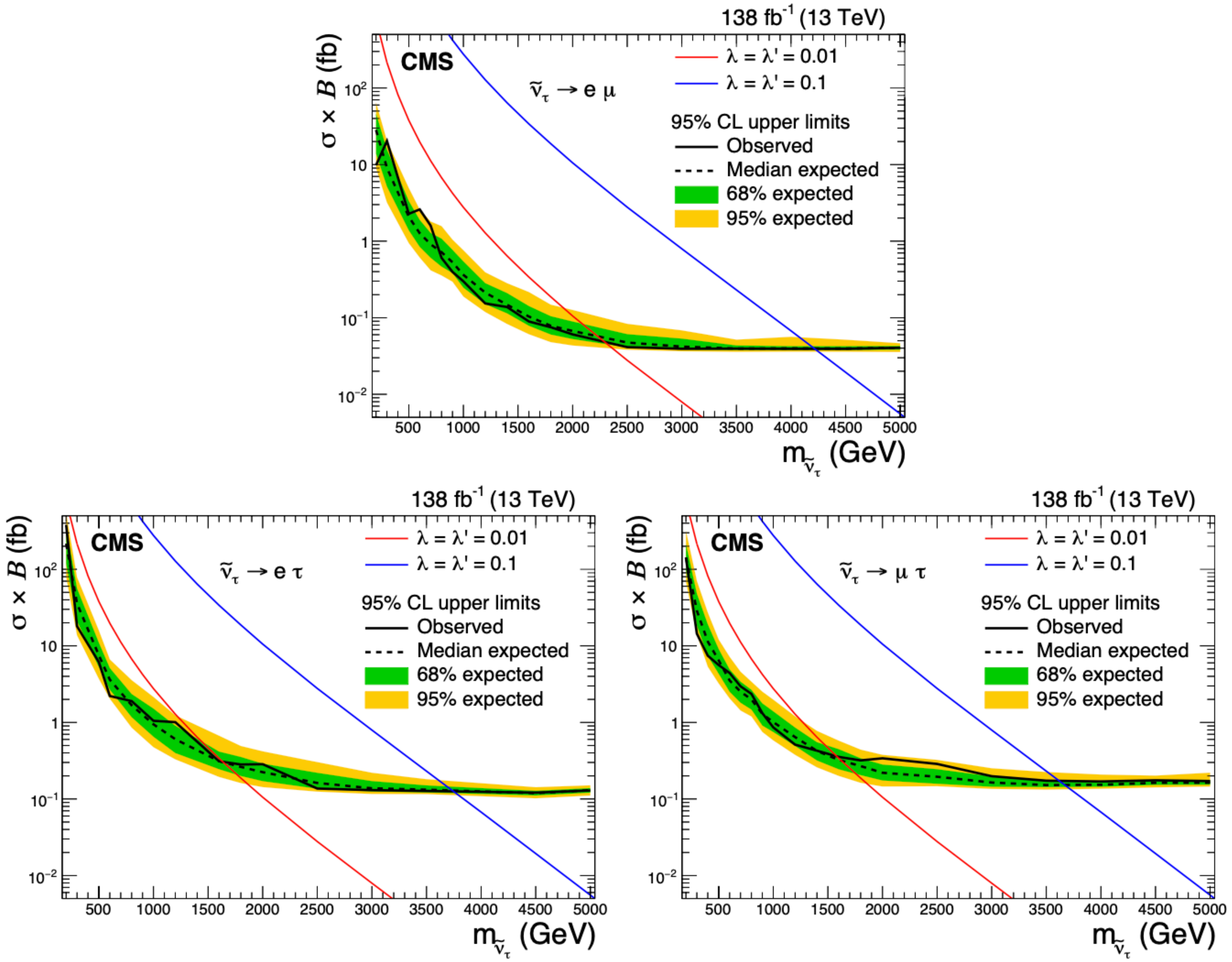


Figure 3: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the product of the cross section and the branching fraction as a function of the τ sneutrino mass in an RPV SUSY model for the eμ (upper), eτ (lower left), and $\mu\tau$ (lower right) channels. The shaded bands represent 68% and 95% uncertainties in the expected limits. The red and blue solid lines show the predicted product of the cross section and the branching fraction as a function of the tau sneutrino mass for two different values of the couplings.

Heavy resonances

Results for Z’

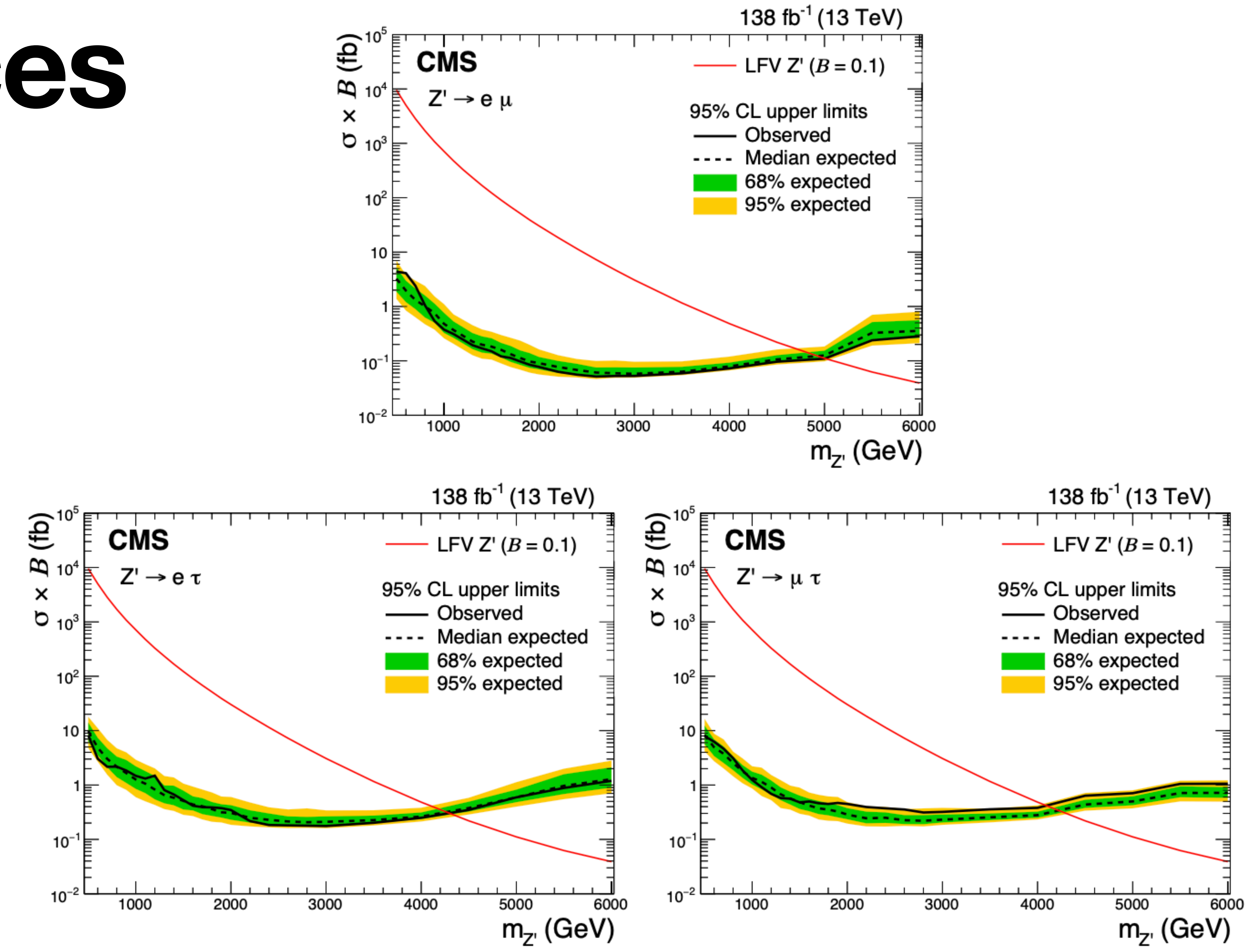


Figure 4: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the product of the cross section and the branching fraction for a Z' boson with LFV decays, in the $e\mu$ (upper), $e\tau$ (lower left), and $\mu\tau$ (lower right) channels. The shaded bands represent 68% and 95% uncertainties in the expected limits. The red solid lines show the predicted product of the cross section and the branching fraction as a function of the Z' mass assuming $\mathcal{B} = 0.1$.

arXiv:2205.06709

Heavy resonances

Results for QBH

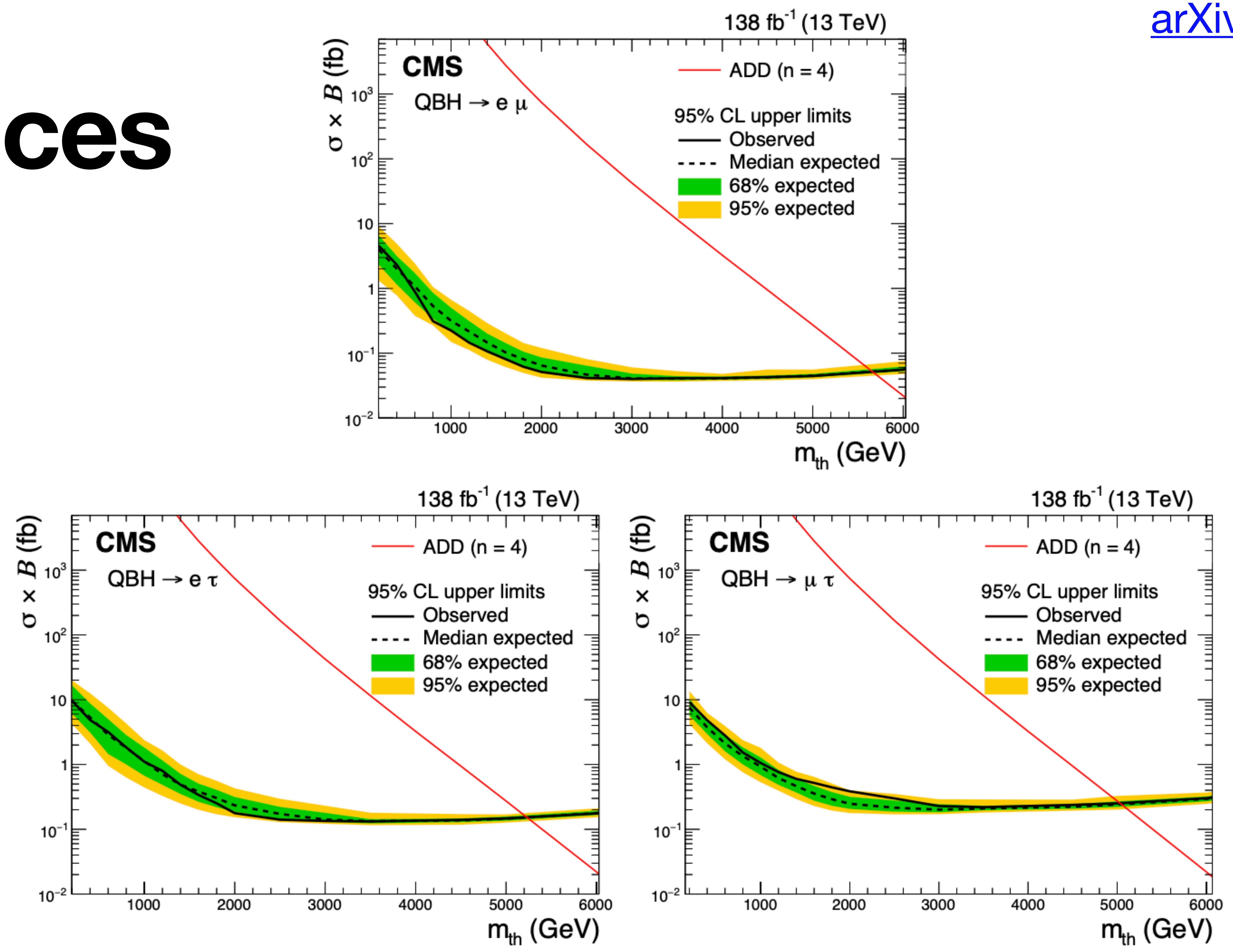


Figure 5: Expected (black dashed line) and observed (black solid line) 95% CL upper limits on the product of the cross section and the branching fraction for quantum black hole production in an ADD model with $n = 4$ extra dimensions, in the $e\mu$ (upper), $e\tau$ (lower left), and $\mu\tau$ (lower right) channels. The shaded bands represent 68% and 95% uncertainties in the expected limits. The red solid lines show the predicted product of the cross section and the branching fraction as a function of the QBH threshold mass.

Heavy resonances

Limits

Table 1: The observed and expected (in parentheses) 95% CL lower mass limits on the RPV SUSY, Z′, and QBH signals for the eμ, eτ, and $\mu\tau$ channels.

Channel	RPV SUSY $\tilde{\nu}_\tau$ (TeV)		LFV Z′ (TeV)	QBH m_{th} (TeV)
	$\lambda = \lambda' = 0.01$	$\lambda = \lambda' = 0.1$	$\mathcal{B} = 0.1$	$n = 4$
eμ	2.2 (2.2)	4.2 (4.2)	5.0 (4.9)	5.6 (5.6)
eτ	1.6 (1.6)	3.7 (3.7)	4.3 (4.3)	5.2 (5.2)
$\mu\tau$	1.6 (1.6)	3.6 (3.7)	4.1 (4.2)	5.0 (5.0)

- These are the first results of a high-mass lepton flavor violation search using the full Run 2 data set, and they are currently the most stringent limits from any collider experiment.

Search for Z’

Systematics

Table 1: Summary of signal uncertainties relevant in this analysis. The uncertainties are grouped based on whether they affect the normalization or the shape of the signal. The fit parameter $\overline{m}_{\mu\mu}$ corresponds to the position of the maximum of the $m_{\mu\mu}$ distribution after detector effects, and $\overline{\sigma}_{\text{mass}}$ is the resolution parameter used in the fit, distinguished from the values of σ_{mass} extracted from simulation.

Source	Normalization		Shape
	$N_b = 1$	$N_b \geq 2$	
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 $\overline{\sigma}_{\text{mass}}$	—		$\lesssim 10\%\ \sigma_{\text{mass}}$