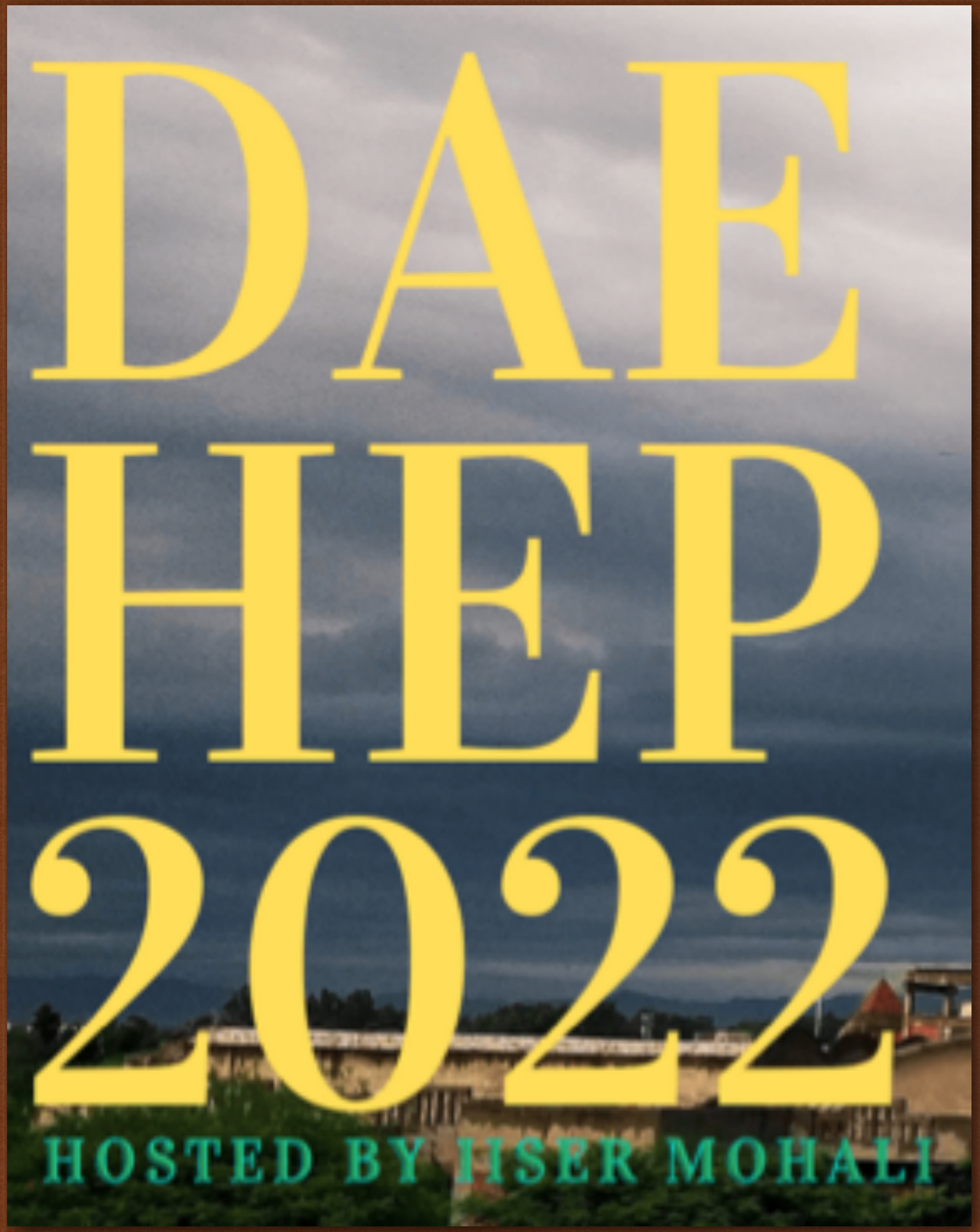

Search for Lepton Flavor Violating Decays of Heavy Resonances and Quantum Black Holes in Dilepton Final States With Full Run2 CMS Data

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for CMS Collaboration

Punjab Agricultural University, Ludhiana

Diamond Jubilee
1962-2022
PAU, LUDHIANA, INDIA

CMS
Compact Muon Solenoid

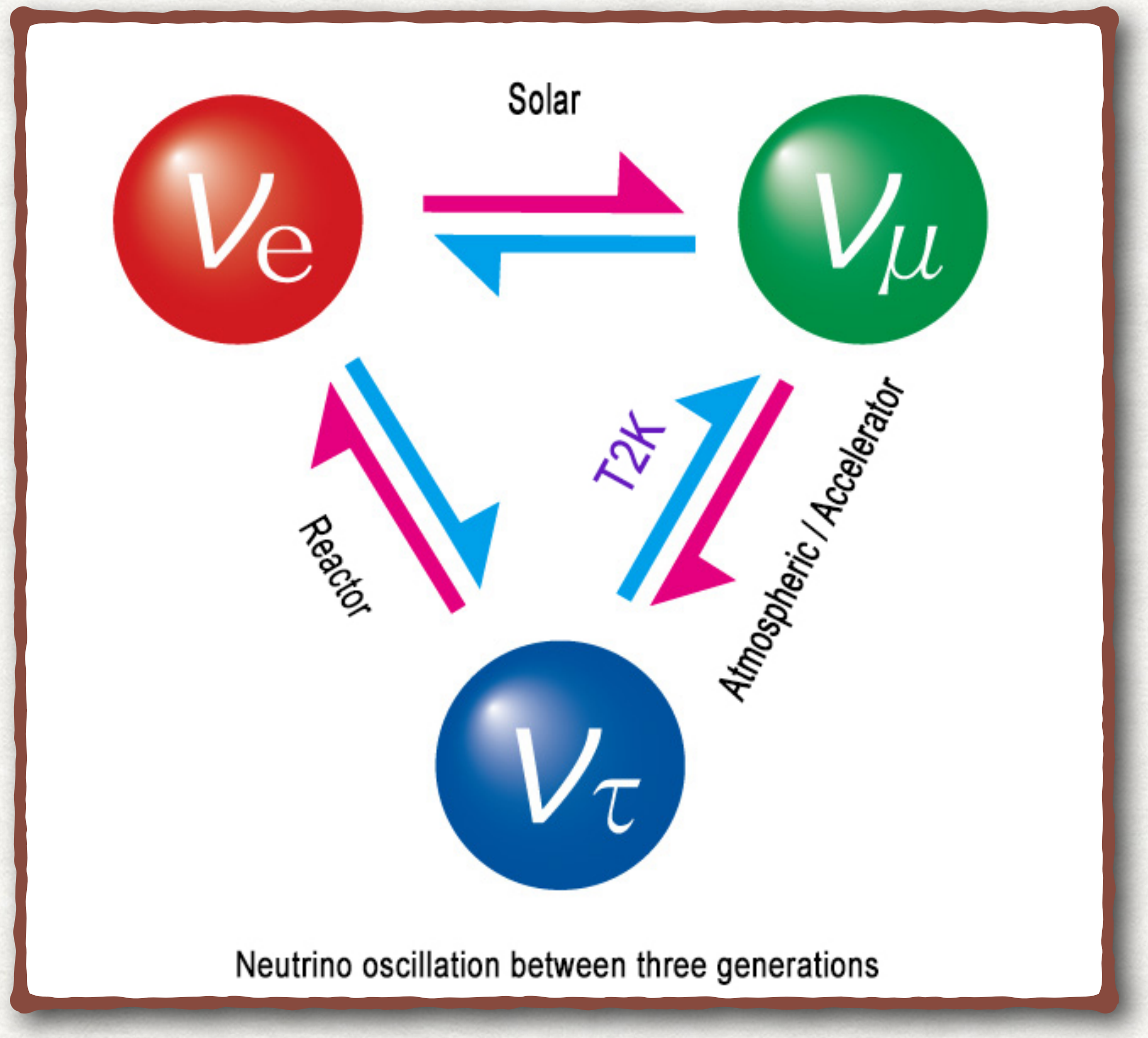
Introduction

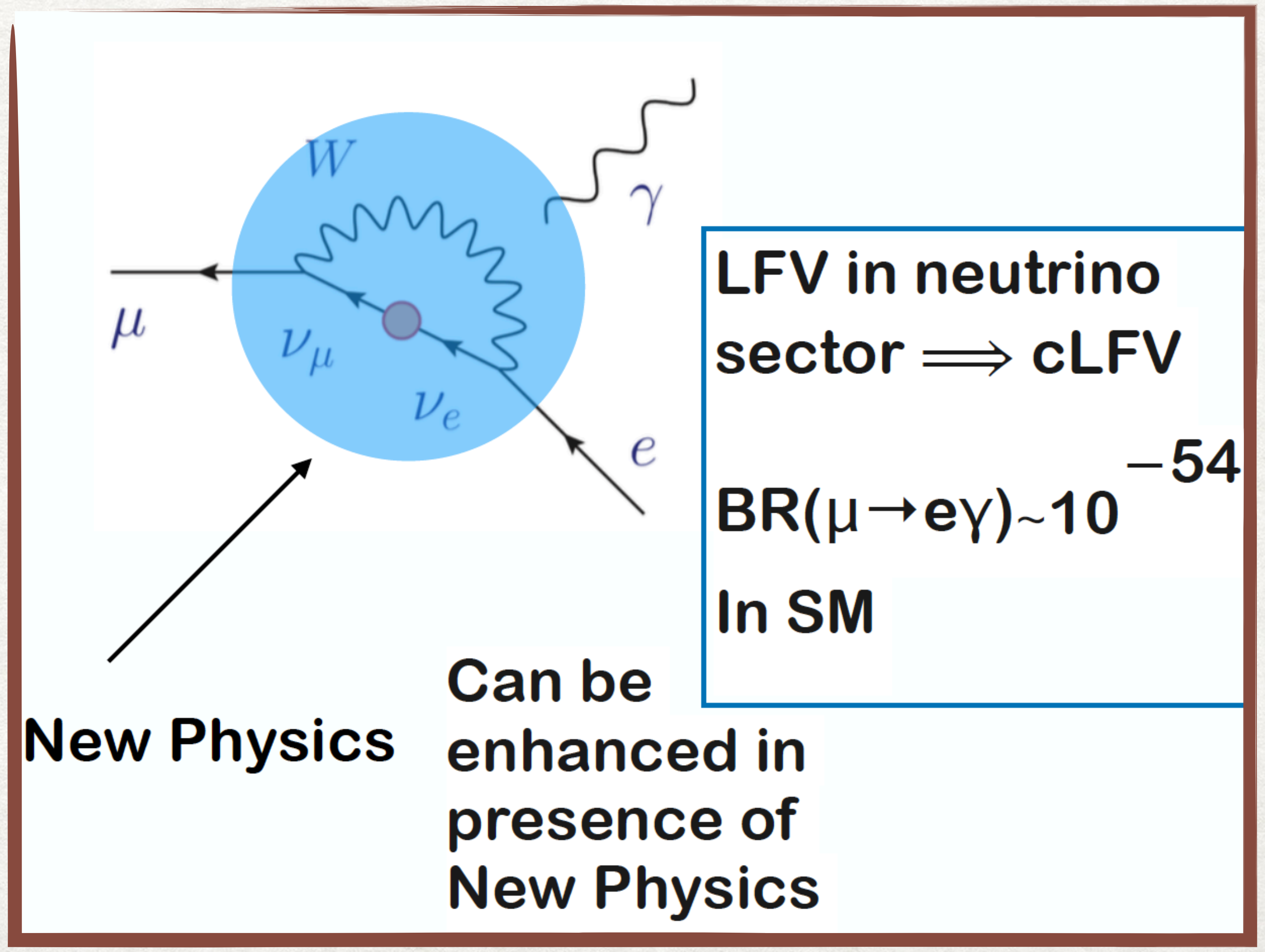
Flavour conservation is not a fundamental symmetry in the SM

Fermions do change flavour:
- Quarks: CKM matrix →quark mixing observed
- Leptons: PMNS matrix →neutrino mixing observed

How about charged leptons?
- →(charged) Lepton Flavour Violation (cLFV)
- Not observed yet

In the SM
- Loop with neutrino oscillations
- Vanishingly small branching ratios





“

Discovery of Charged Lepton Flavor Violation is New Physics!

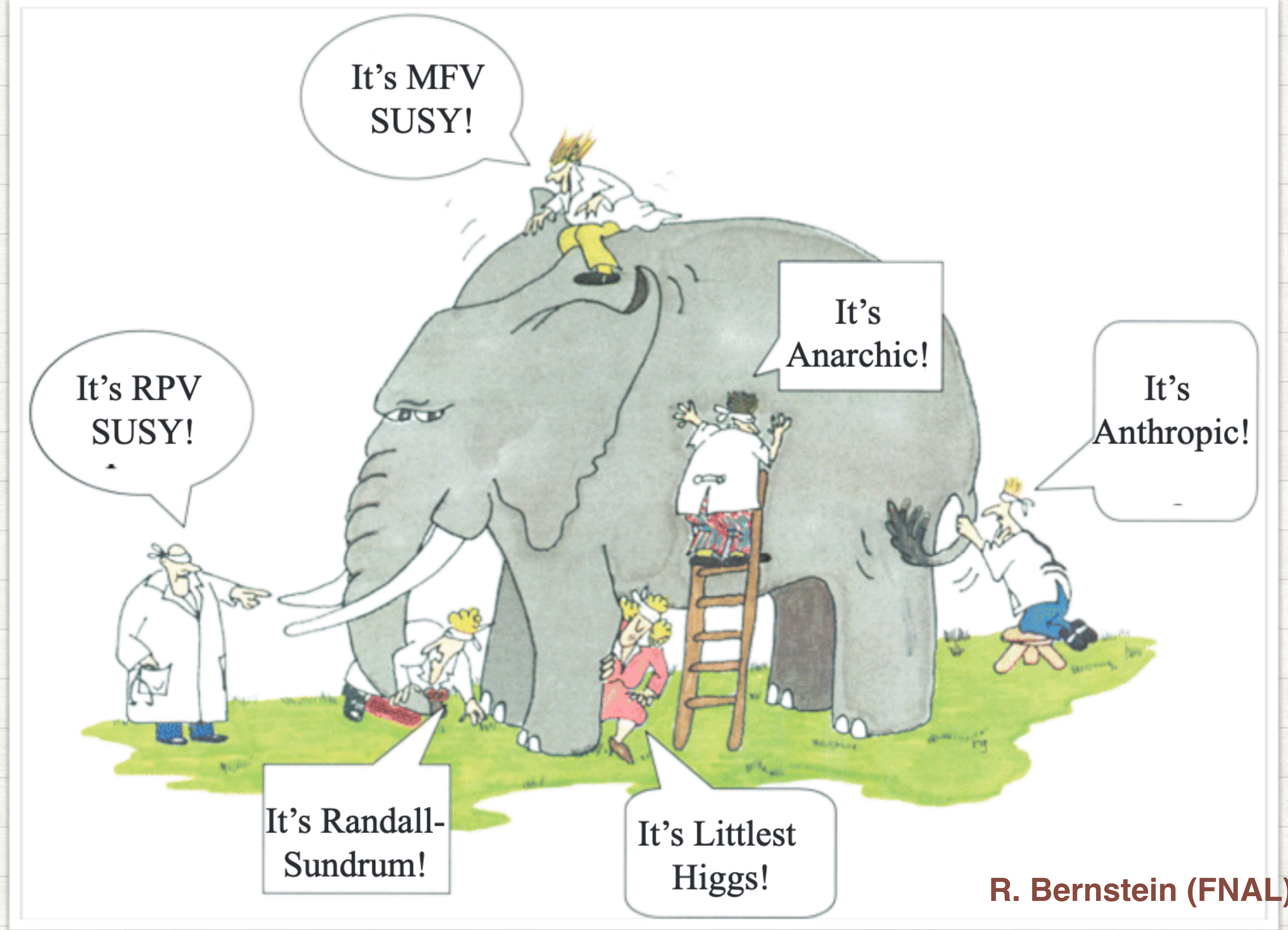
violation of a (so-far) conservation law

”

- Various **BSM** models: Supersymmetry, extended gauge models, heavy neutrinos, etc.
- Predict LFV couplings to be tested at the LHC

Low Energy Results Provide Indirect Constraints (Often With Assumptions)

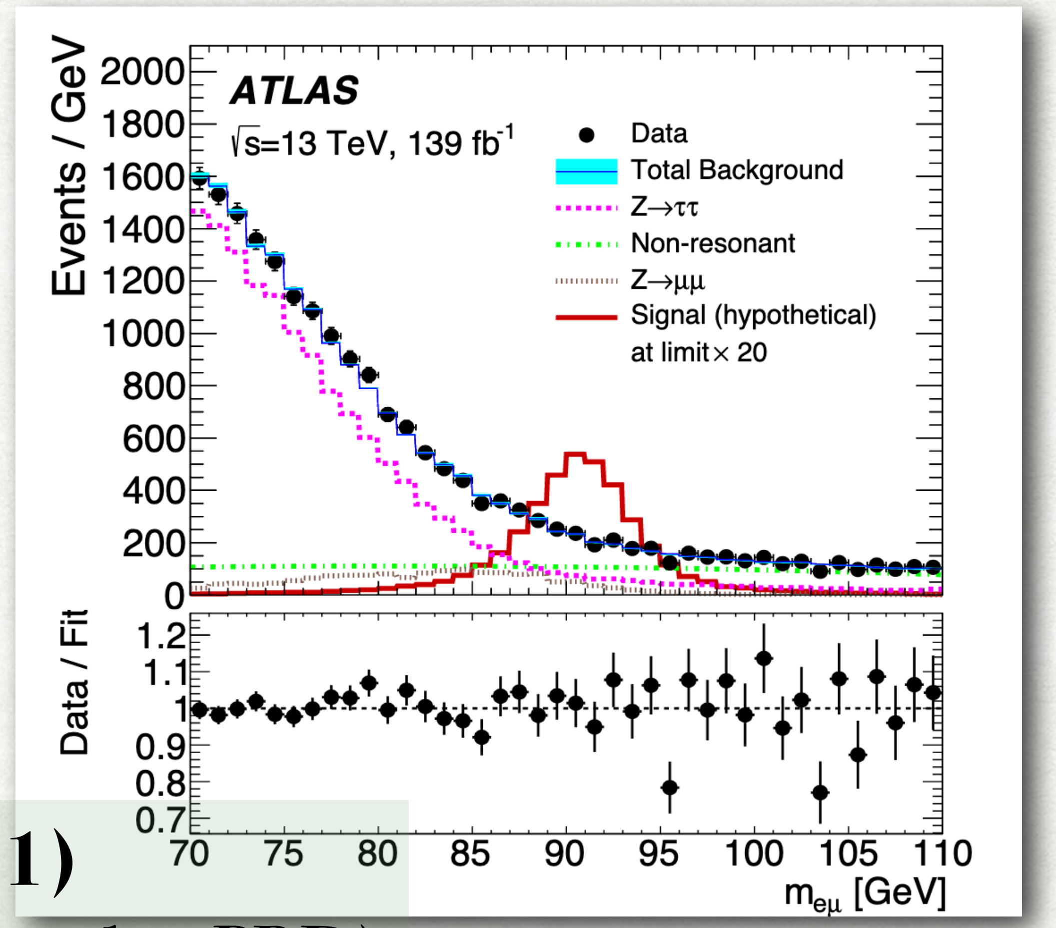
- lepton-flavor violating processes
  - $\mu \to e\gamma$, $\tau \to e\gamma$, etc.
  - $\mu \to eee$, $\tau \to \mu ee$, etc.
  - $\mu^+ e^- \to e^- \mu^+$
  - $Z^0 \to \mu e$, τe, etc.
  - $H \to \mu e$, τe, etc.
  - K^0 (B^0, D^0, ...) $\to \mu e$, τe, etc.
  - K^+ (B^+, D^+, ...) $\to \pi^+ \mu e$, $\pi^+ \tau e$, etc.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$



Need Multiple Measurements To Understand the Full Picture

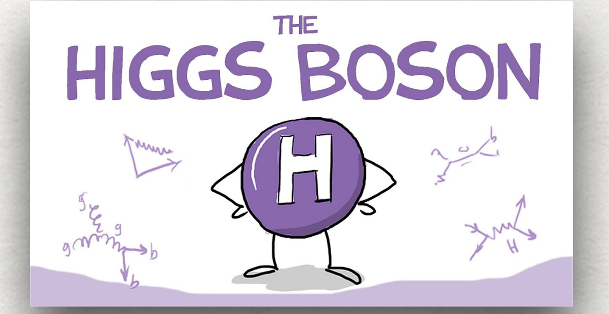
LFV Searches @LHC : Overview

LFV Z→ ll'



PRL 127, 271801 (2021)
arXiv:2204.10783 (submitted to PRD)
Nature Phys. 17 (2021) 819

CMS (8 TeV data)	B(Z→eμ)	< 7.3 x 10^{-7}
ATLAS 139 fb^{-1} (Run 1 + Run2)	B(Z→eμ) B(Z→μτ) B(Z→eτ)	< 2.62 x 10^{-7} < 6.5 x 10^{-6} < 5.0 x 10^{-6}
LEP	B(Z→eμ) B(Z→μτ) B(Z→eτ)	< 1.7 x 10^{-6} < 1.2 x 10^{-5} < 9.8 x 10^{-6}

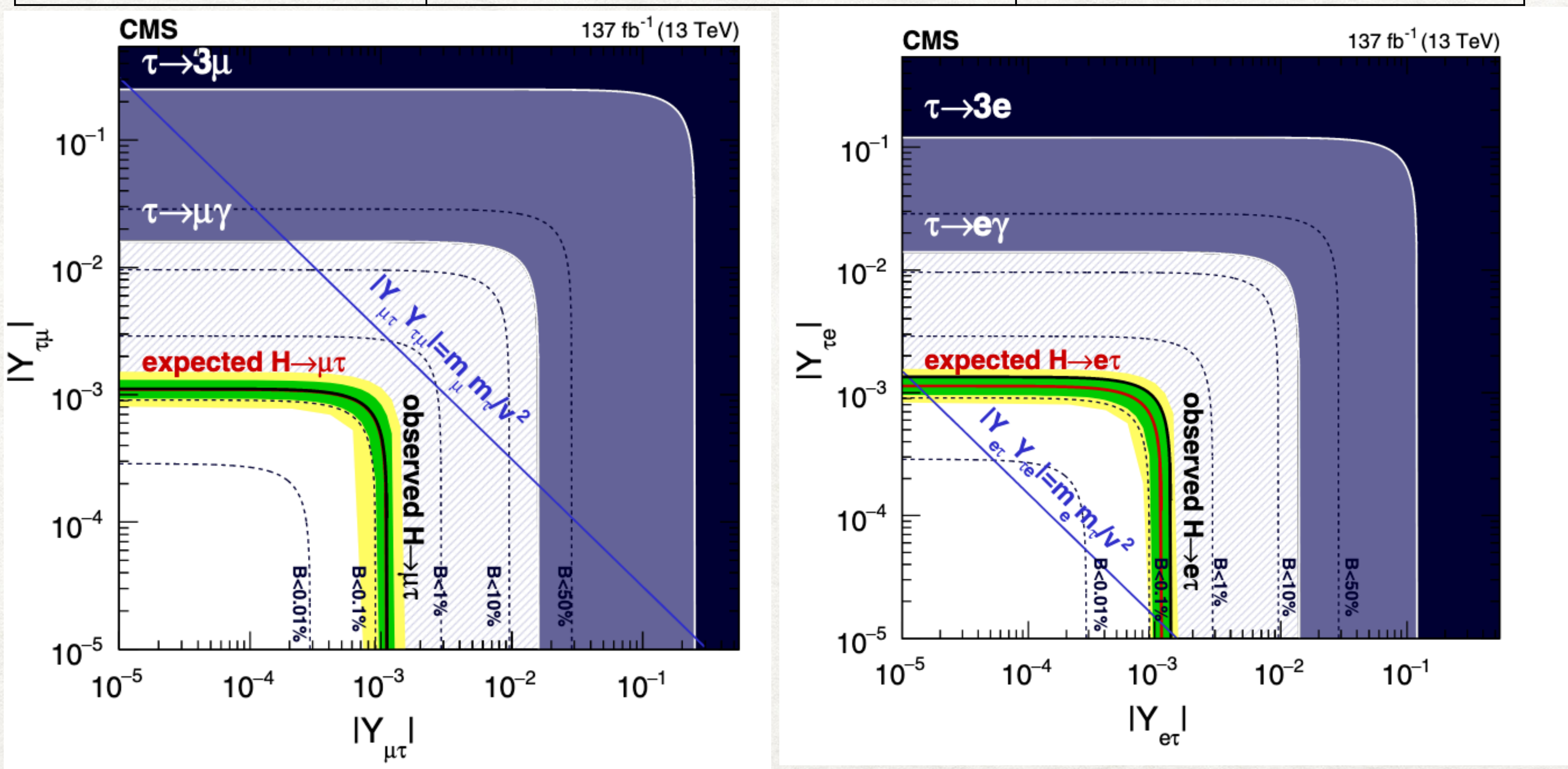


LFV H(125) →ll' decays

Phys Rev D.104.032013

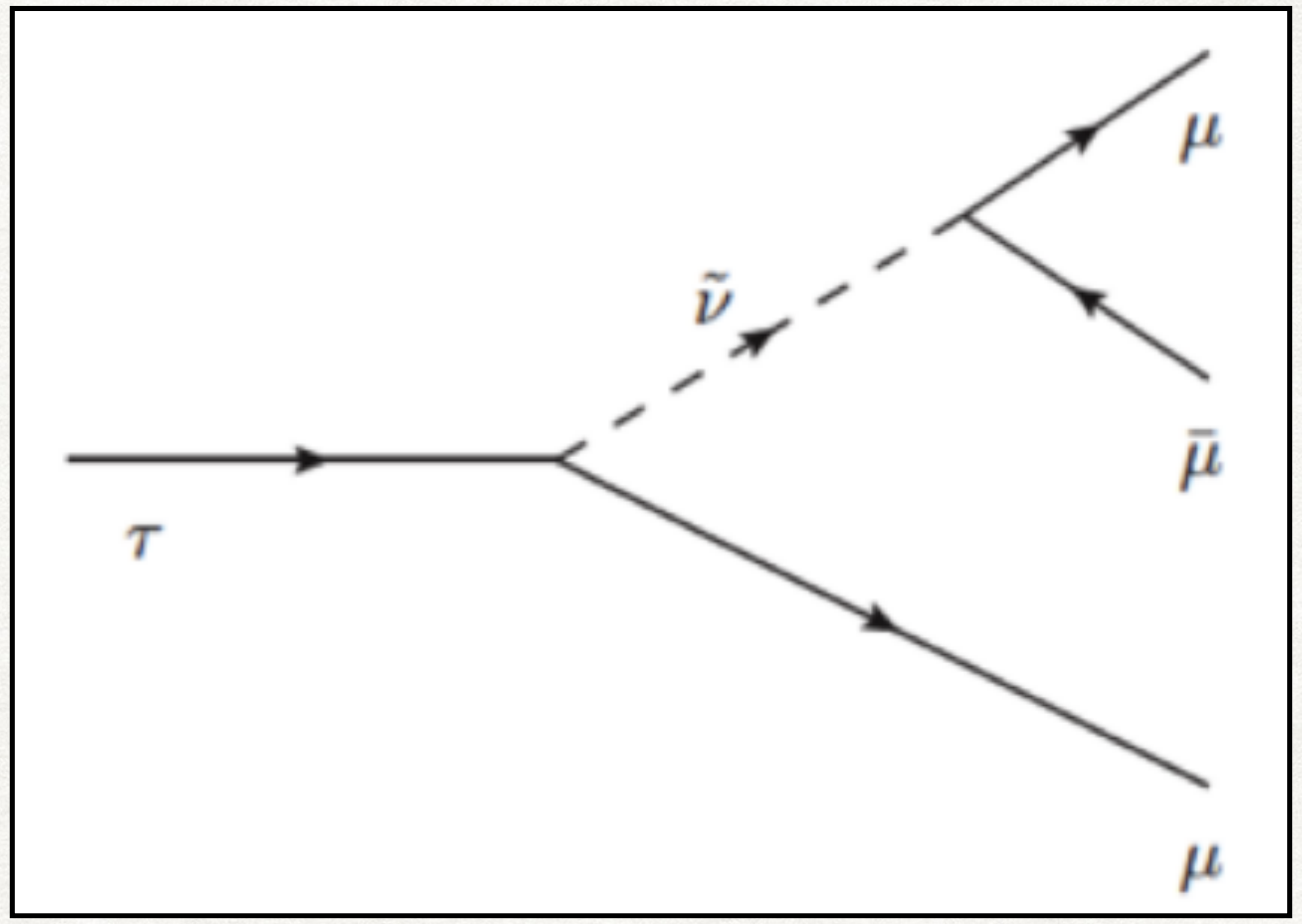
Null result for μ→eγ strongly constrains B(H →eμ) to < 10^{-8} while τ→μγ/ τ→eγ and other measurements constrain B(H →eτ) and B(H→μτ) ≈10%

	CMS (Run2)	ATLAS (2016)
B(H→μτ)	< 0.15 %	< 0.28 %
B(H→eτ)	< 0.22 %	< 0.47 %

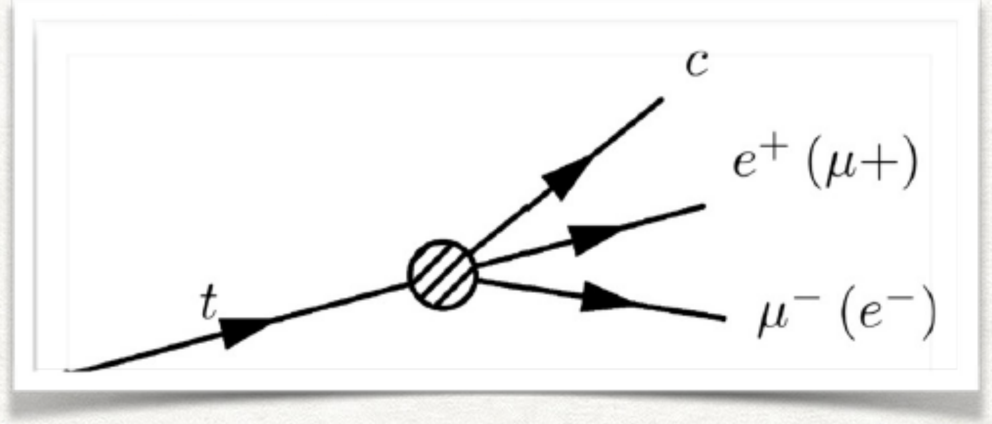


& many more…..

$\tau \rightarrow 3\mu$



ATLAS (8 TeV, 90% CL) W decays	< 3.76×10^{-7} Eur. Phys. J. C (2016) 76:232
CMS (13 TeV, 33.2 fb^{-1}, 90%CL) B/D and W decays	< 8.0×10^{-8} JHEP01(2021)163
BELLE BABAR LHCb	< 2.1×10^{-8} < 5.3×10^{-8} < 4.6×10^{-8}



JHEP 06 (2022) 082
CMS

Vertex	Int. type	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
	Vector	0.12	0.12	0.14	0.13
$e\mu tu$	Scalar	0.23	0.24	0.06	0.07
	Tensor	0.07	0.06	0.27	0.25
	Vector	0.39	0.37	1.49	1.31
$e\mu tc$	Scalar	0.87	0.86	0.91	0.89
	Tensor	0.24	0.21	3.16	2.59

LFV Heavy Higgs (200-900 GeV)
35.9 fb^{-1}

JHEP 03 (2020) 103

	CMS
$\sigma(gg \rightarrow H) \times B(H \rightarrow \mu\tau)$	51.9 fb - 1.6 fb
$\sigma(gg \rightarrow H) \times B(H \rightarrow e\tau)$	97.4 fb- 2.3 fb

What about heavier states? Can we find them @ LHC

History of LFV heavy mass X→ ll' searches

Heavy state	CMS (2016, eμ) JHEP 04 (2018) 073	ATLAS 2016 eμ, eτ, μτ Phys. Rev. D 98 (2018) 092008
Z'	4.4 TeV	4.5, 3.7, 3.5 TeV
RPV	4.2 TeV (λ=0.1) 3.8 TeV (λ=0.01)	3.4, 2.9, 2.6 TeV λ_{311} = 0.11, λ_{313} = 0.07
QBH	5.3 TeV	5.5, 4.9, 4.5 TeV (ADD n=6) 3.4, 2.9, 2.6 TeV (RS)

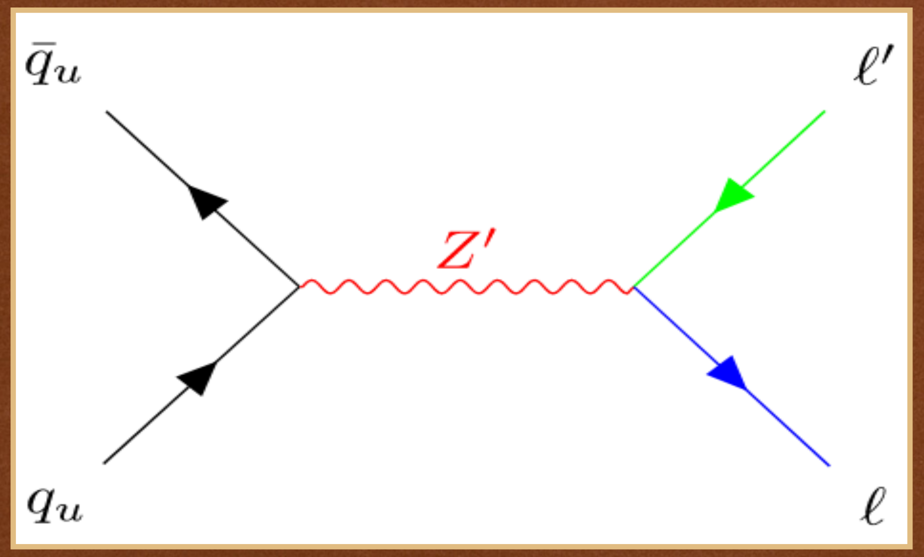
No results from CMS in tau final states till then..

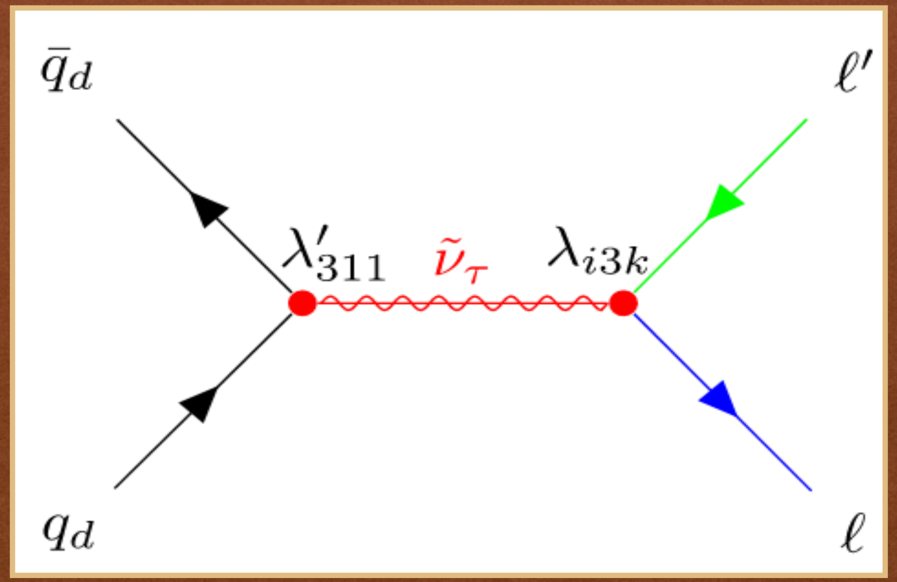
CMS-EXO-19-014

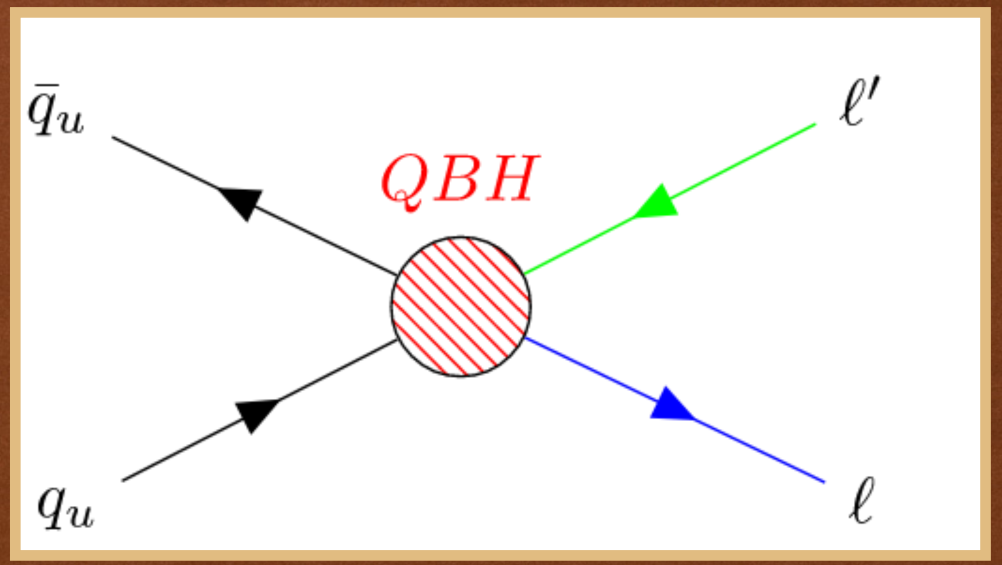
arXiv: 2205.06709v1
Submitted to JHEP

- Search for heavy resonances and quantum black holes in eμ, eτ, and μτ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV (138 fb^{-1})
- Model-independent, inclusive, signature-based search
- Interpretation in three models
  +model independent limits

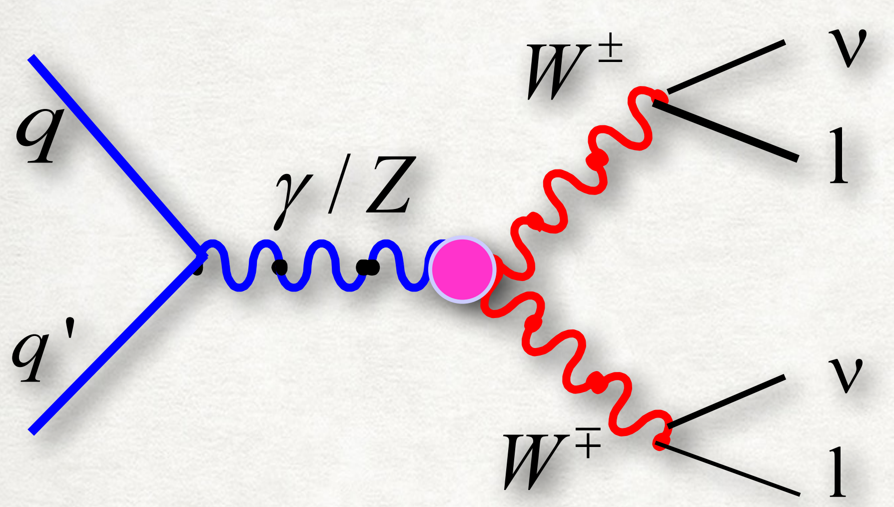
SSM like New gauge boson Z'	Tau neutrino in R-parity violating (RPV) SUSY	Quantum Black Holes QBH
Z-like couplings in quark sector LFV decays in lepton sector	ν_τ resonance: lightest SUSY particle All RPV couplings = 0 except those allowing $q\bar{q} \rightarrow \nu_\tau$ and LFV decay to a specific final state	Extra dimensions ➜ TeV scale QBH: Spin 0, colorless, neutral n=4 extra dimensions (ADD)

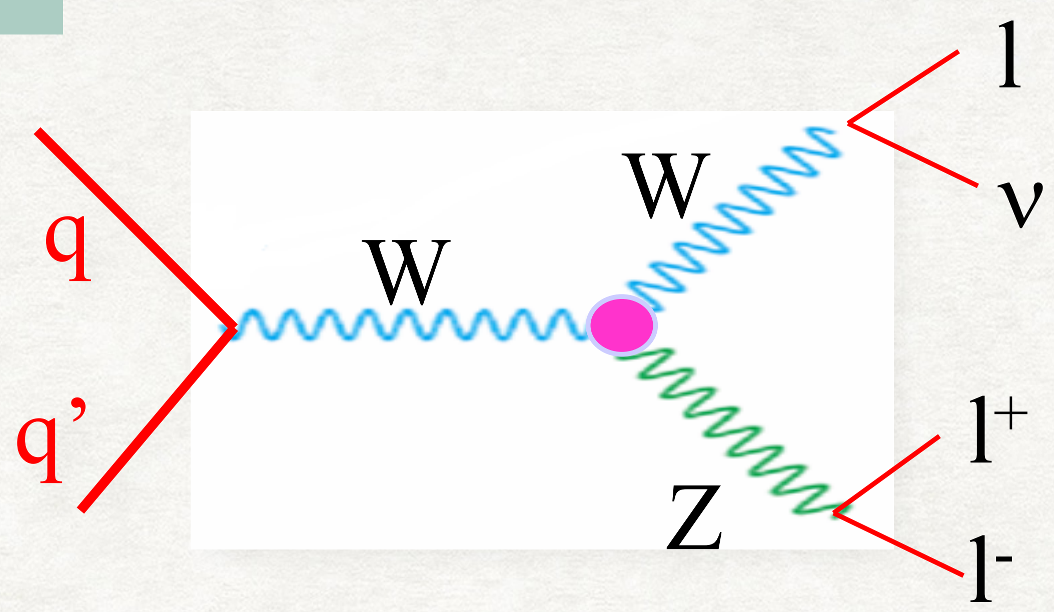


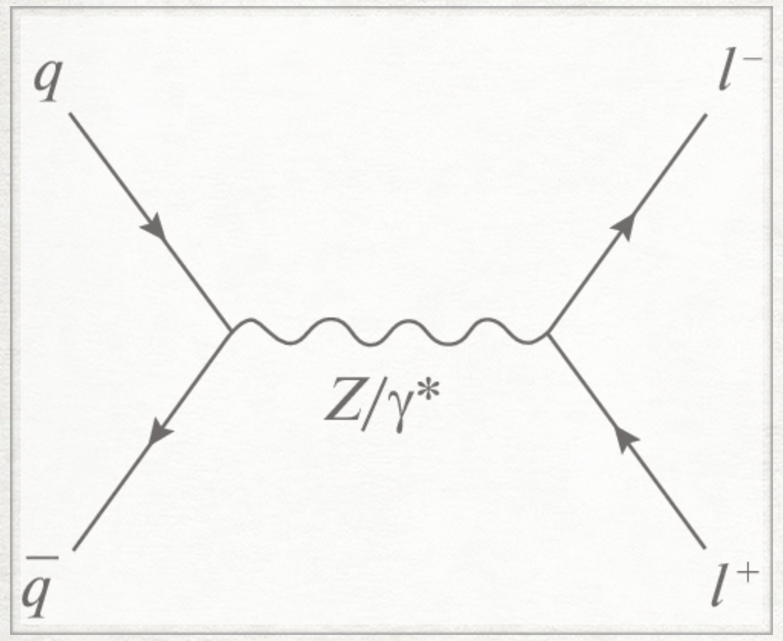


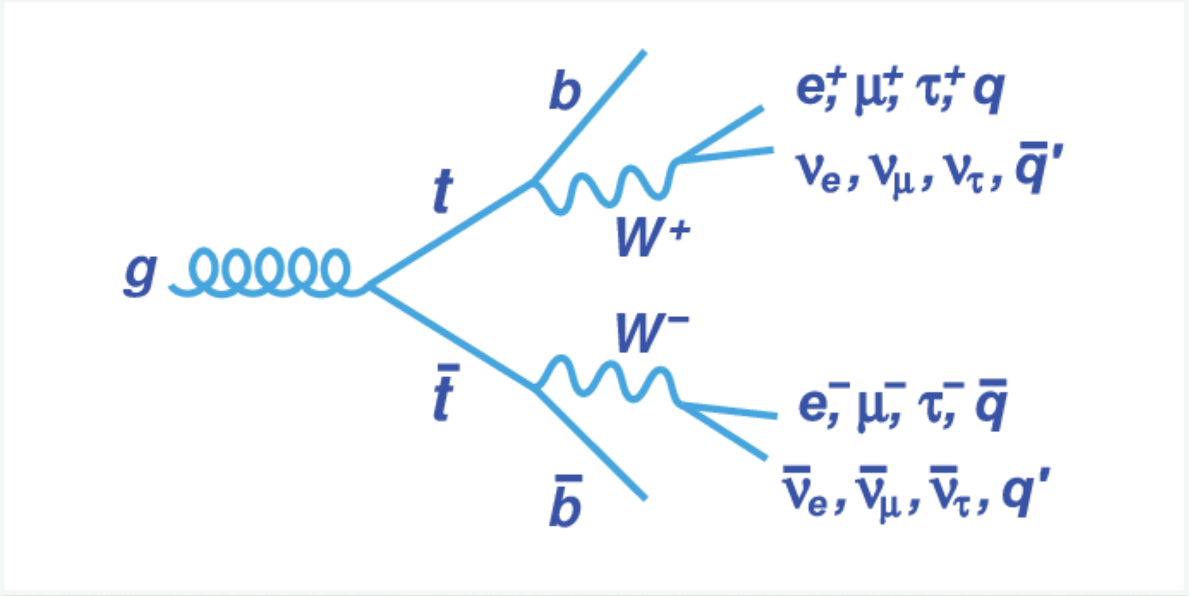


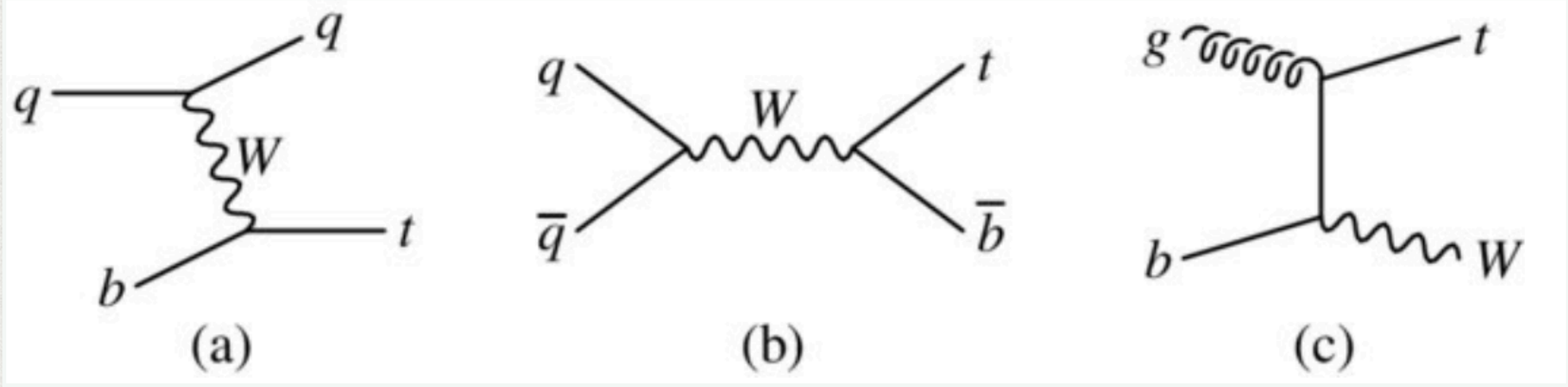
Background processes

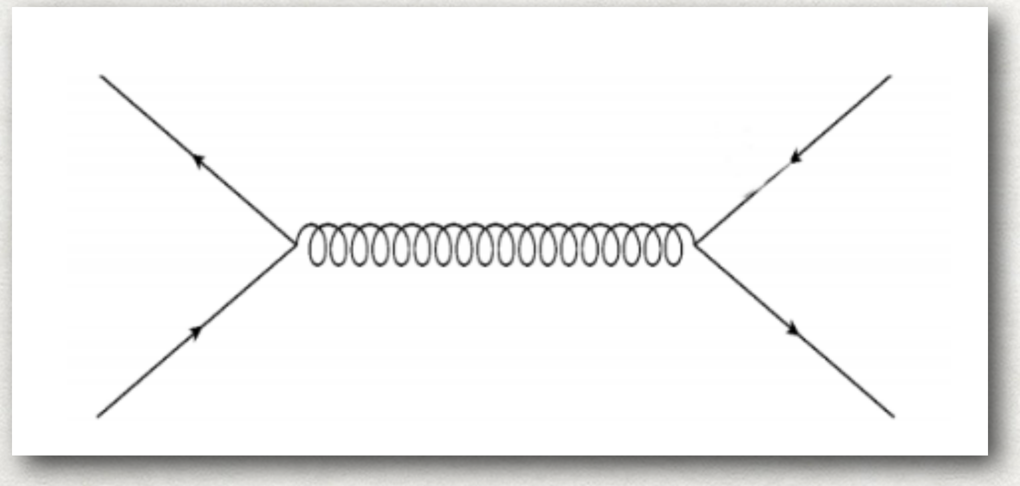


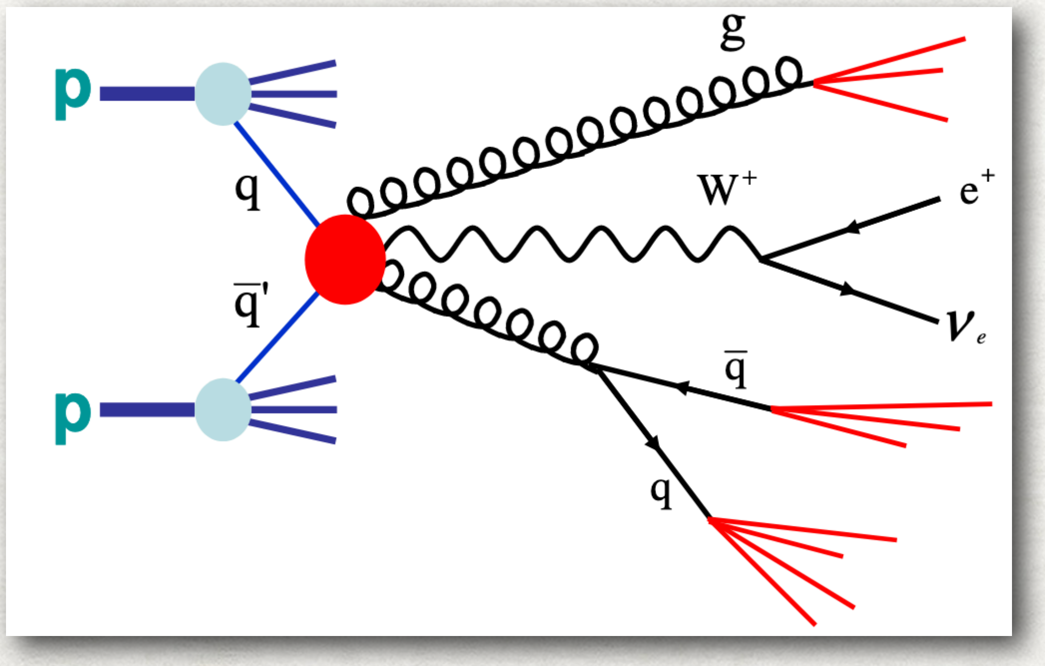










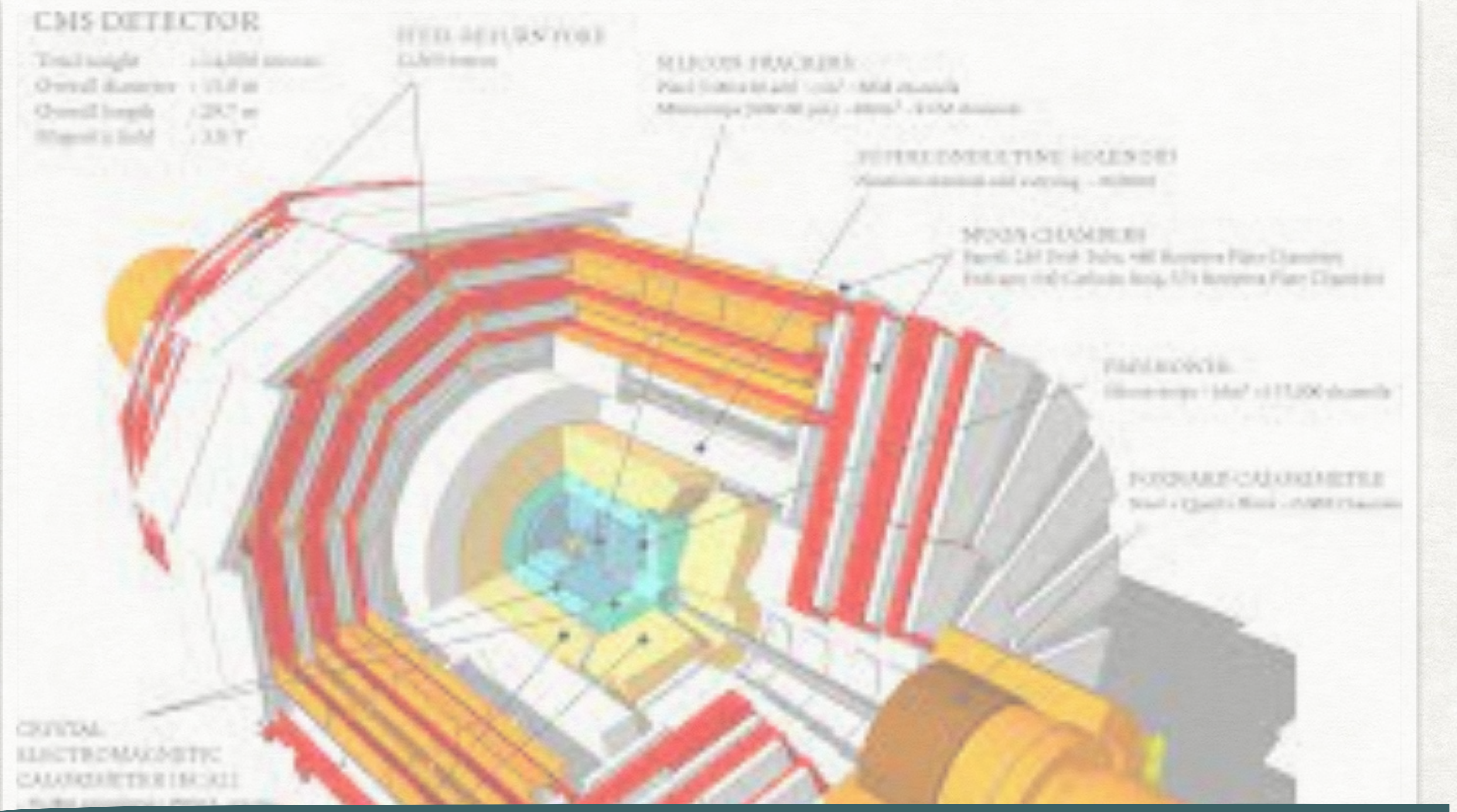


Signal processes generation

RPV : CalcHEP simulation (LO, cross-section scaled to NLO)

QBH : Dedicated QBH generator v3.0 (LO)

Z′ : PYTHIA8 (LO) CUETP8M1/CP5 tunes



Use of 2016, 2017, and 2018 pp collision data collected by CMS detector at a center-of-mass energy of 13 TeV (138 fb^{-1})

Analysis Strategy

Model independent selection criteria

eμ	eτ	μτ
Events selected by single muon and electromagnetic cluster triggers	Events selected by single electron and electromagnetic cluster triggers	Events selected by single muon triggers
μ: p_T>53 GeV, $\|\eta\|$<2.4, passing high-p_T muon identification criteria, tracker iso < 10% of muon p_T E :p_T > 35 GeV passing high energy electron ID criteria.	e : p_T > 50 GeV, passing high energy electron ID criteria τ: p_T > 50 GeV, $\|\eta\|$ < 2.3 passing DEEP TAU tight anti-jet, loose anti-e and tight anti-μ discriminators	μ: p_T>53 GeV, $\|\eta\|$ < 2.4, high-p_T muon identification criteria , tracker iso < 10% of muon p_T τ: p_T>50 GeV, $\|\eta\|$<2.3 passing DEEPTAU tight anti-jet, loose anti-e and tight anti-μ discriminators
At least an eμ pair	At least one eτ pair $m_T(e, E_T^{miss})$ > 120 GeV No extra electron or muon in an event	At least one μτ pair $m_T(\mu, E_T^{miss})$ > 120 GeV No extra electron or muon in an event

No requirement on charge of lepton pairs

$$m_T = \sqrt{2p_T^l \cdot p_T^{miss}(1 - \cos\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss}))},$$

eμ final state

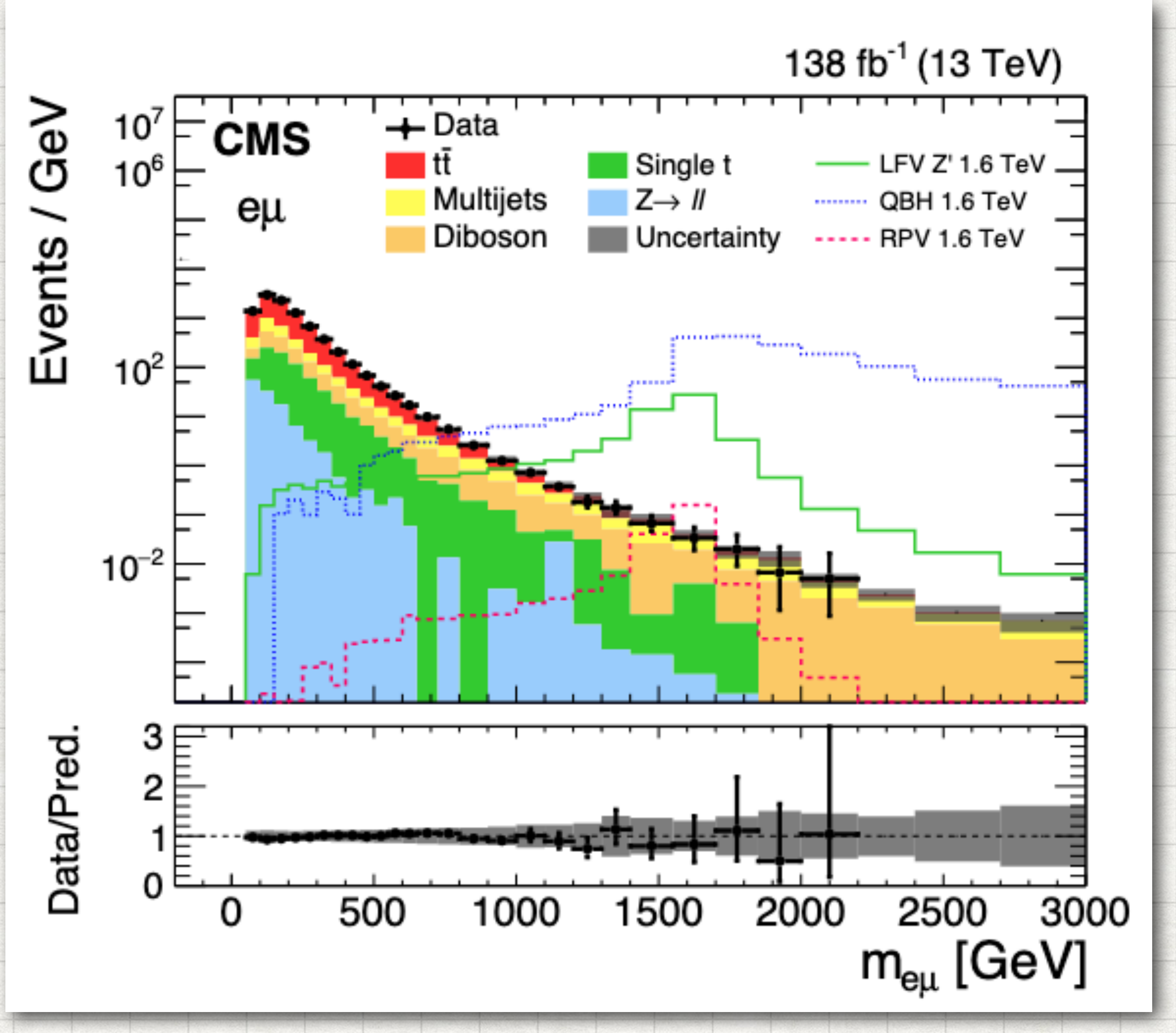
No other signal specific cut in order to stay model independent

Main backgrounds:

- Top and Diboson events: estimated from simulation
- W+jets and multijet events using fake rate method from data

Fake rate method:

- Derived a jet dominated control region to calculate probability of a jet passing pre-selection cuts to also pass lepton ID cuts
- Fake rate parametrized as function of pt and eta of lepton



Key variable: invariant mass of eμ pair

Tau final states (eτ, μτ)

Backgrounds with
- Prompt taus from simulation
- Misidentified taus are estimated from data

Main backgrounds:
- Top and Diboson events
- W+jets and multijet events determined from data using Fake factors obtained in jet enriched region.

Fake rate method:

- Invert $m_T(e/\mu, E_T^{miss})$ cut i.e. < 120 GeV
- Calculate the probability for an accompanying jet to be misidentified as a τ_h candidate in bins of tau candidate pt, its pt ratio with parent jet and pseudorapadity

Collinear mass Approximation

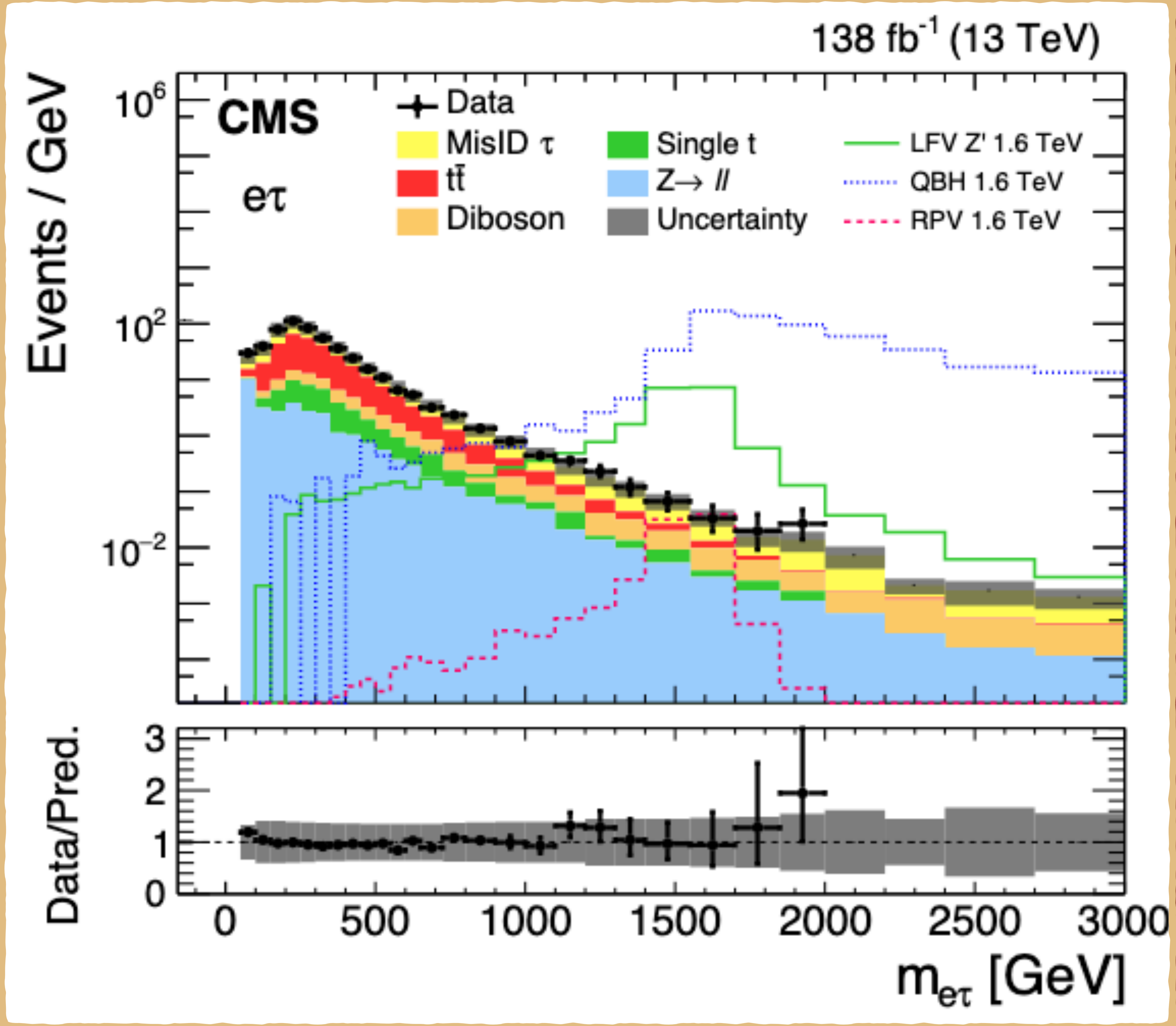
- Tau is boosted and tau-decay products are produced collinearly
- Missing transverse energy is only coming from tau-neutrinos

$$x_\tau^{vis} = \frac{p_T^{vis}}{(p_T^{vis} + p_{T,coll}^{miss})}$$

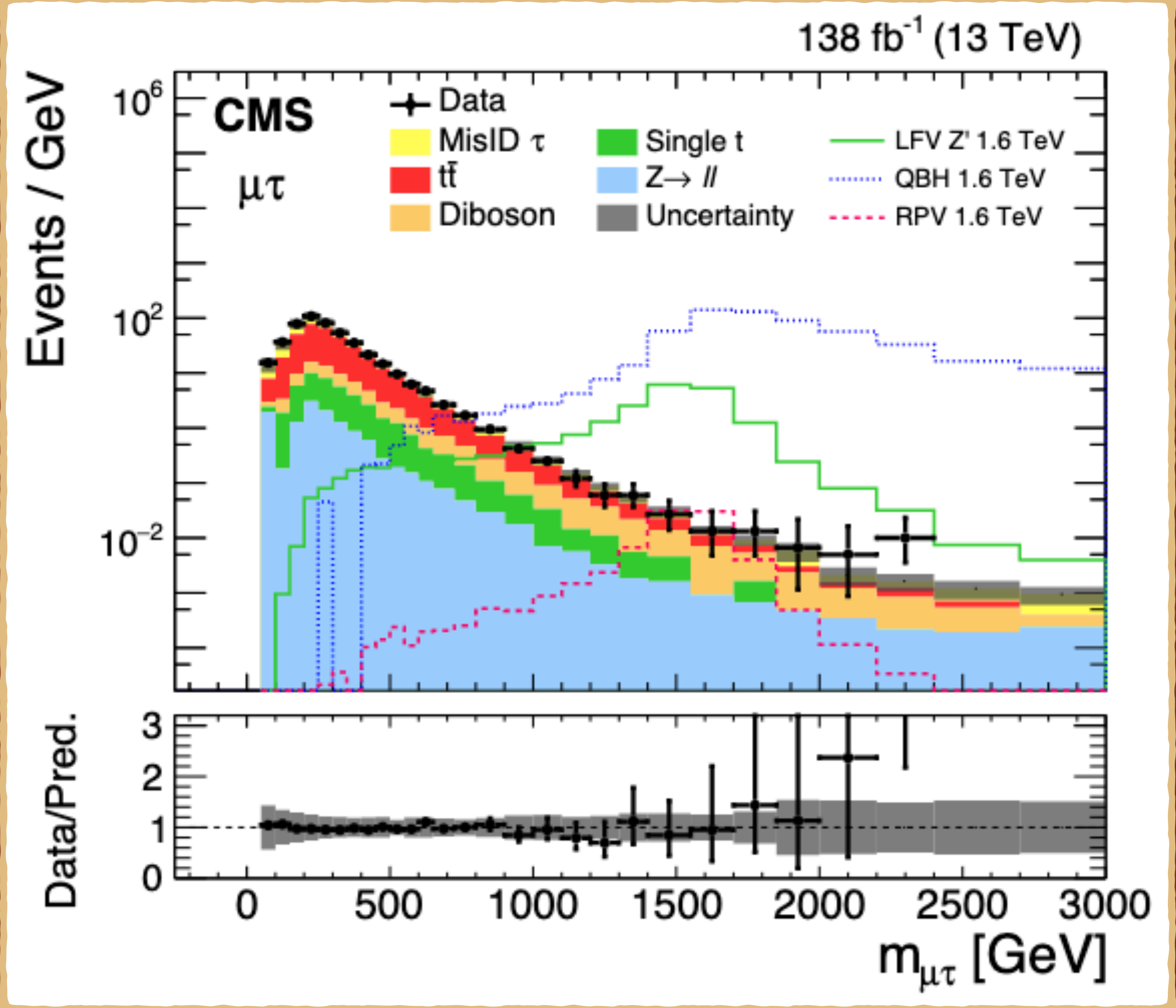
$$m_{coll} = \frac{m_{vis}}{\sqrt{x_\tau^{vis}}}$$

Key variable: collinear mass (m_{coll})

eτ final state



μτ final state



No significant excess observed over SM prediction

Systematic Uncertainties

Systematics affecting shape and normalization of mass distributions

- Uncertainty in estimation of WW/tt background with variations in PDF, renormalisation and factorisation scales.
- Uncertainty in muon momentum scale and resolution, muon efficiency
- Uncertainty in electron efficiency, momentum scale and resolution
- Tau identification and energy scale
- Pile up reweighing
- PDF
- Trigger Efficiencies
- Jet energy scale, jet energy resolution
- Energy scale of unclustered particles

Systematics affecting normalization of mass distributions

- Uncertainty related to integrated luminosity (1.6%)
- Uncertainties related to cross sections of simulated processes: WW(3%), DY (2%), single top (5%), WZ and ZZ (4%)
- Uncertainty related to data-driven estimation of background consisting of mis-identified jets : 50%

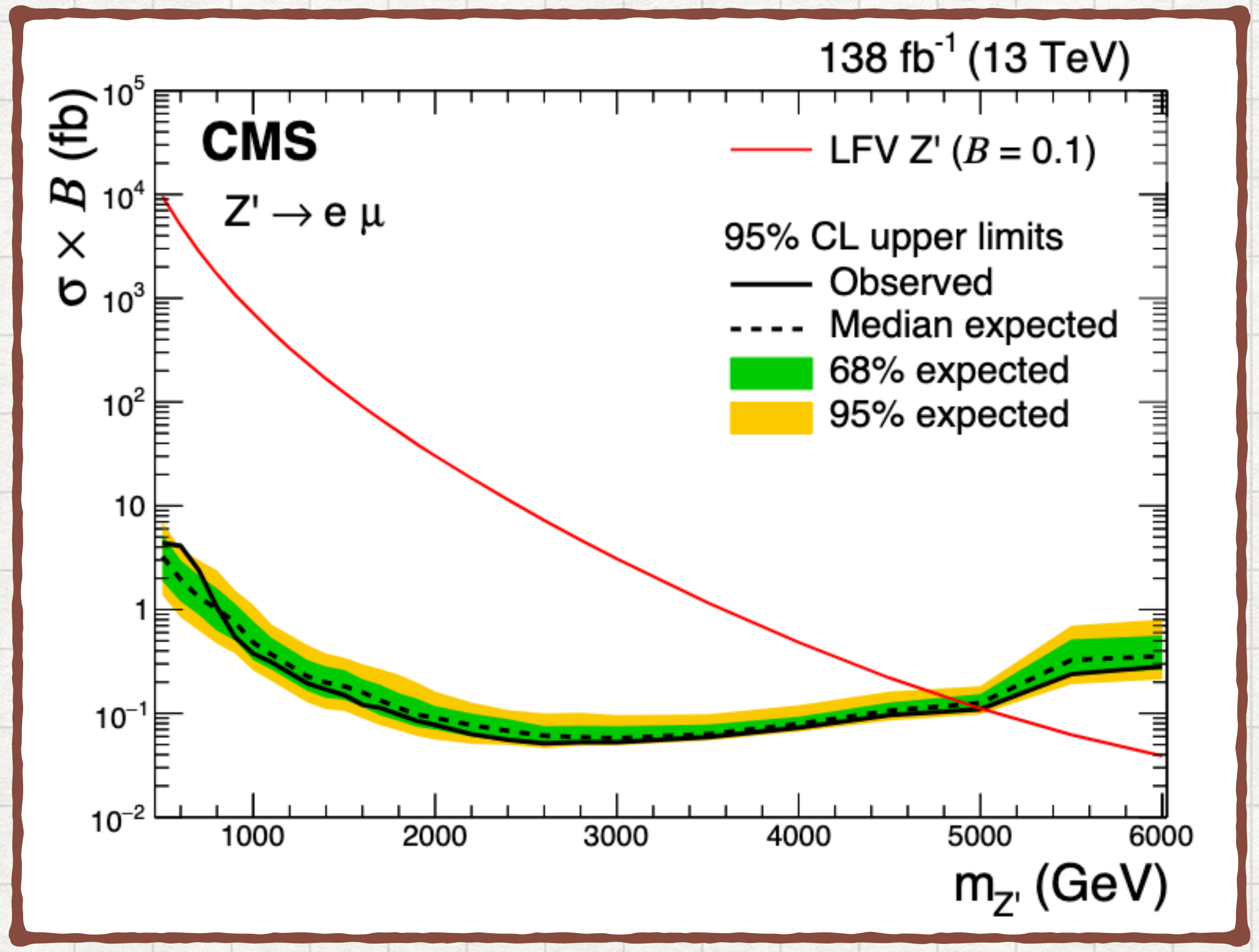
☑ Uncertainties associated with limited sizes of event samples in MC signal and background processes.

Correlation of uncertainties across different data-taking periods with exceptions of uncertainties related to taus and unclustered energy ➜ derived from statistically independent sources.

Heavy gauge boson (Z′) interpretation

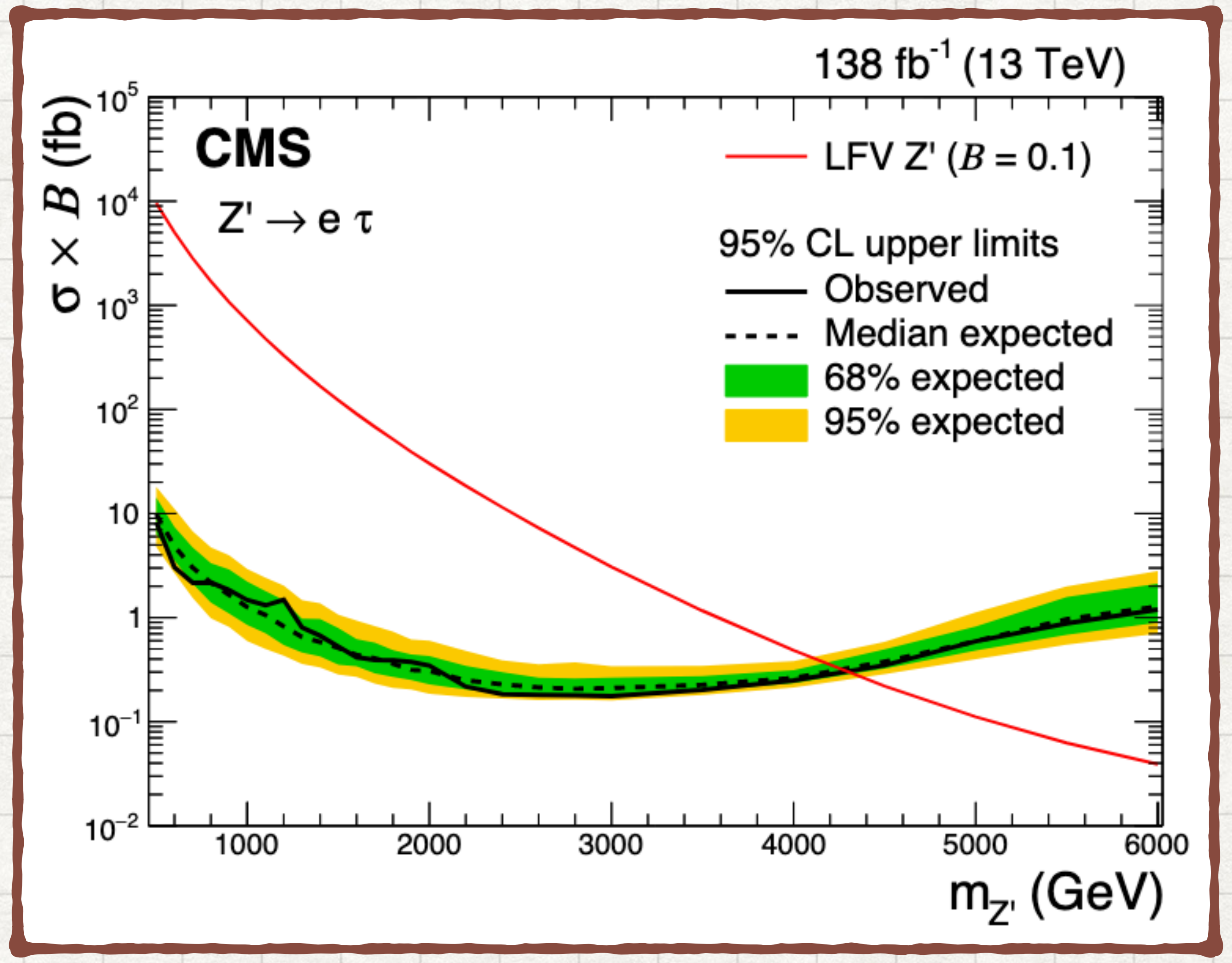
- Z' in a model similar to sequential standard model
- Only one LFV coupling non-zero at a time
- Z' width 3% of its mass

eμ



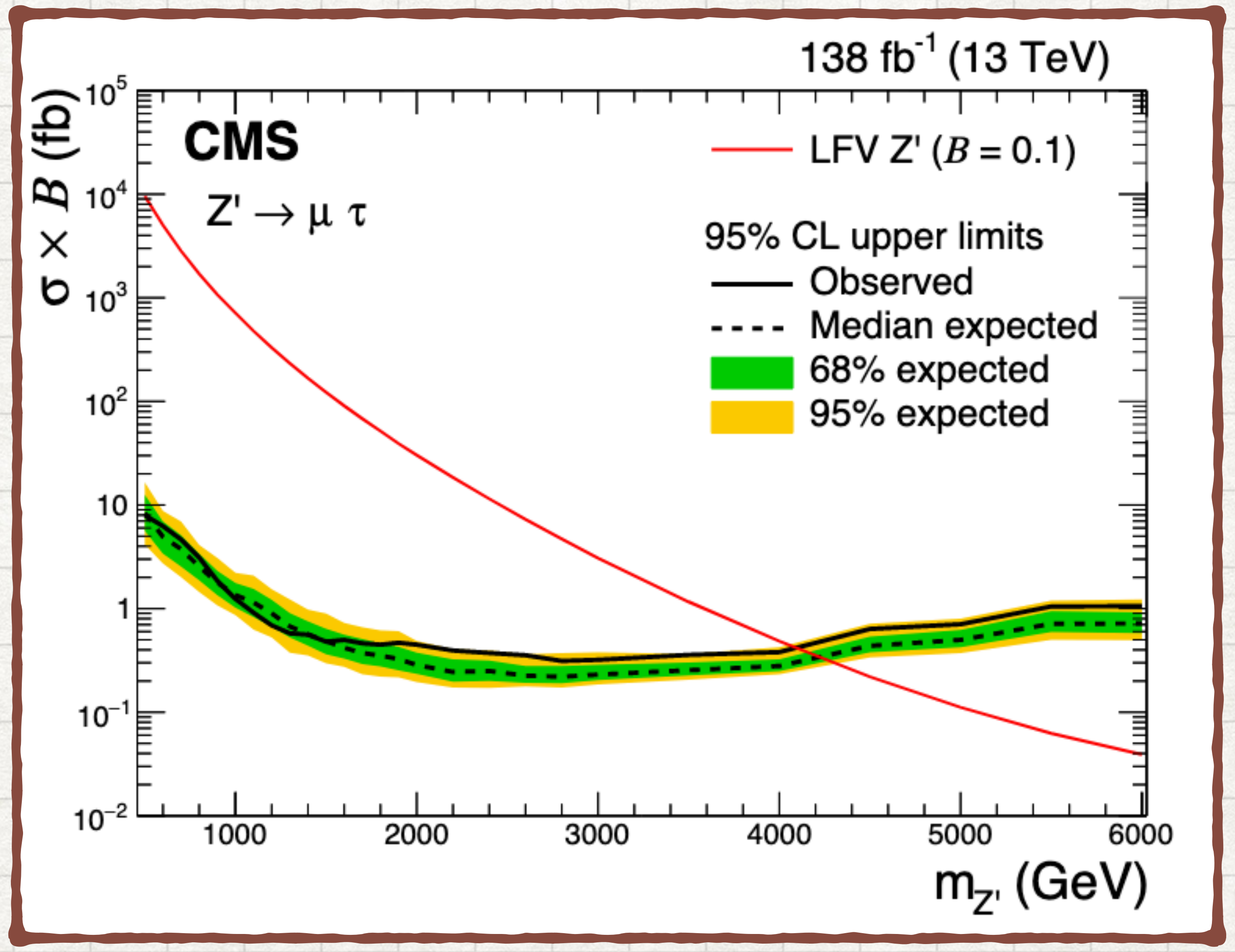
Mass Limit: 5.0 (4.9) TeV

eτ



Mass Limit: 4.3 (4.3) TeV

μτ

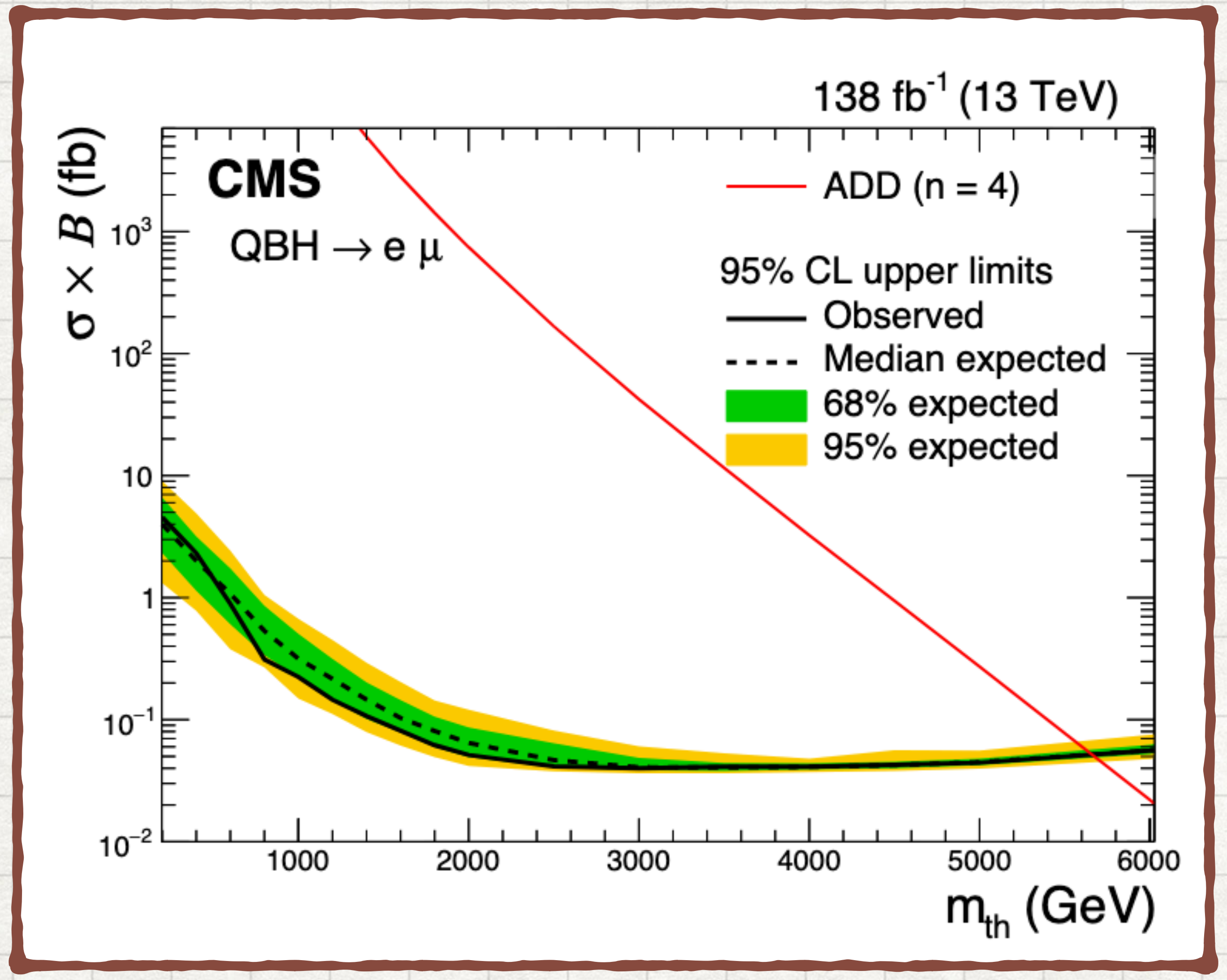


Mass Limit: 4.1(4.2) TeV

QBH interpretation

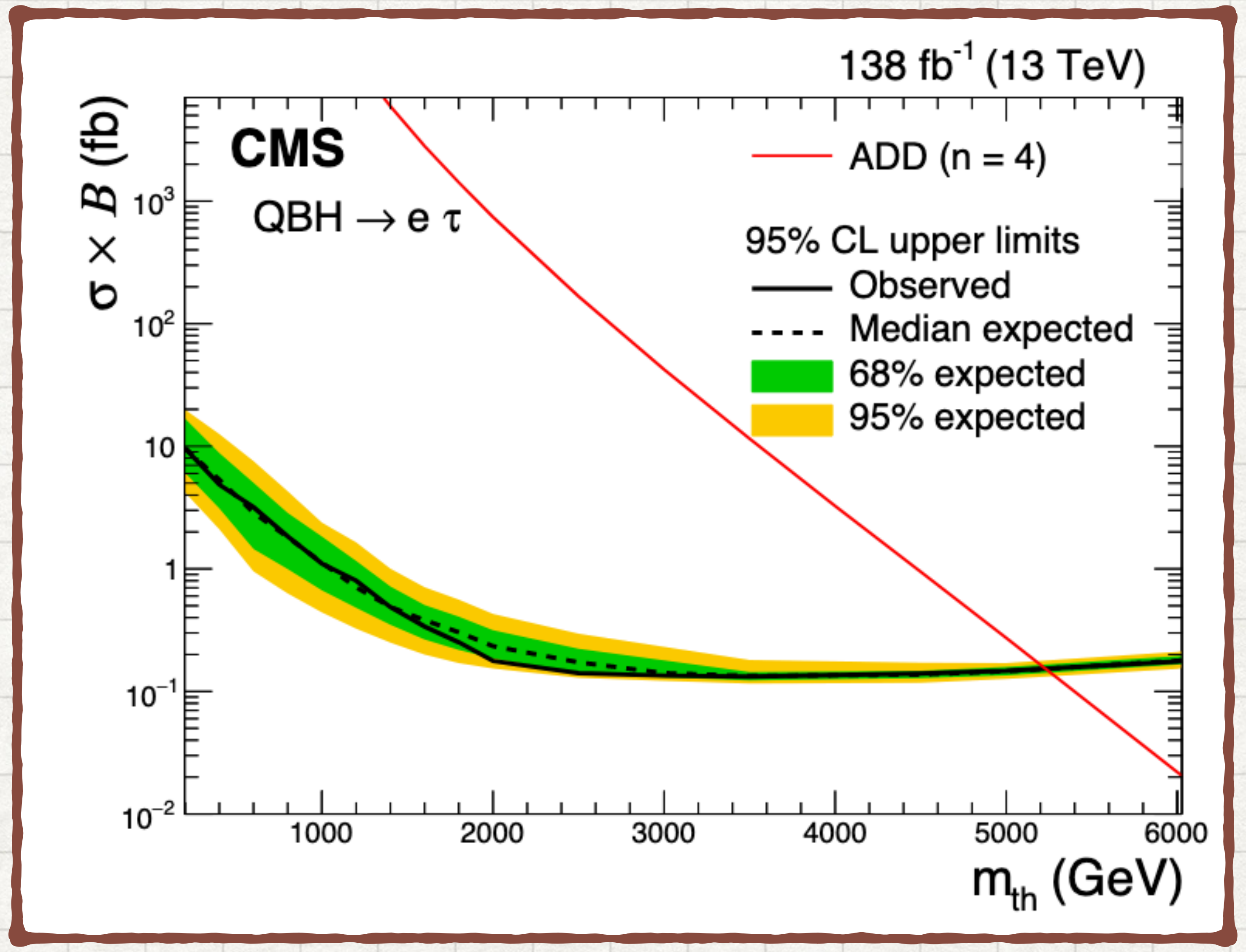
- Extra dimension(s)⟶ Fundamental Planck scale lowered to TeV region
- QBH produced if $\sqrt{s} > M_P$
- Spin-0, colorless, charge-neutral QBH
- Cross section depends on threshold mass for QBH production ($M_{th}=M_P$) and number of extra dimensions (n)

eμ



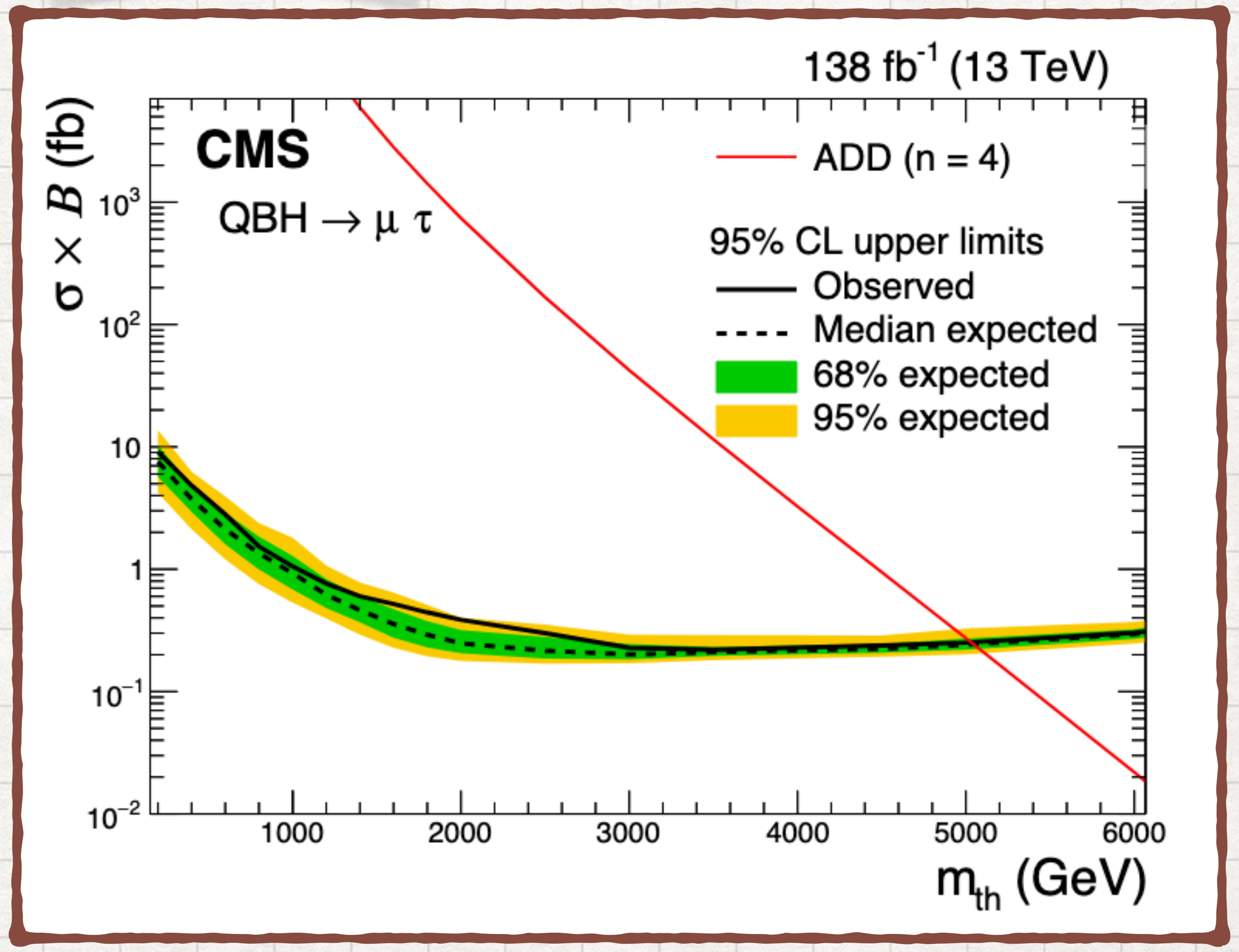
Mass Limit: 5.6 (5.6) TeV

eτ



Mass Limit: 5.2 (5.2) TeV

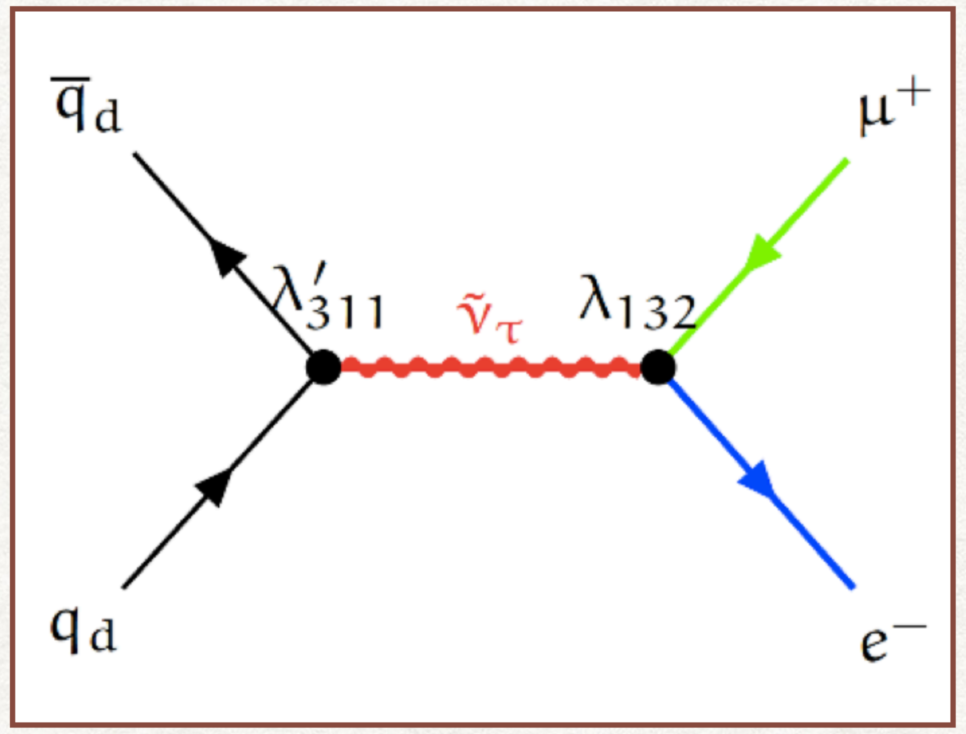
μτ



Mass Limit: 5.0(5.0) TeV

RPV SUSY interpretation

- R-parity (R) = $(-1)^{3B+L+2s}$
- Resonant production of **τ** sneutrino LSP
- Decay to leptons of different flavours
- Assume all RPV couplings vanish, except λ'_{311}, λ_{i3j}, λ_{j3i}

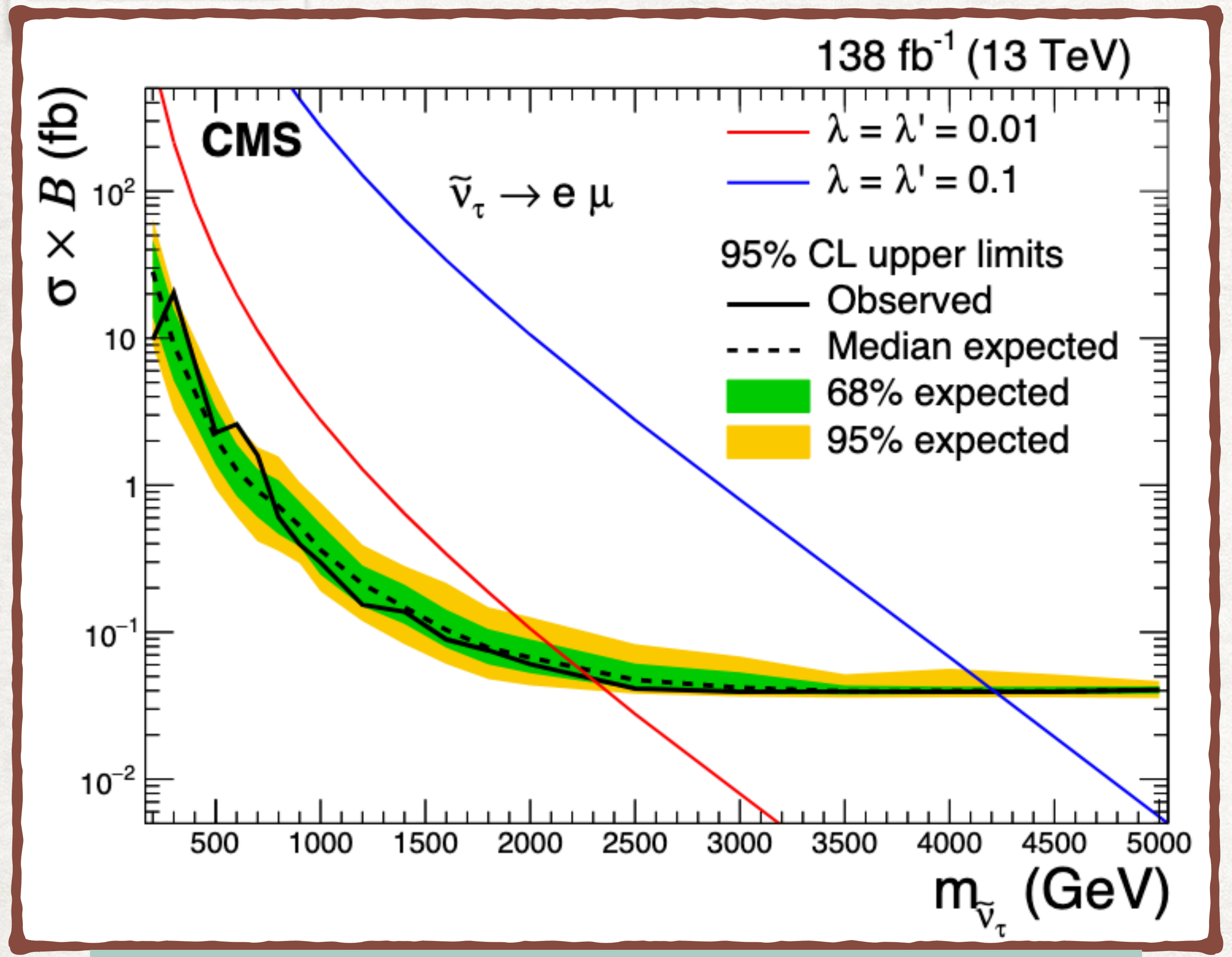


$$W_{\Delta L=1} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{e}_k + \lambda'_{ijk}L_iQ_j\bar{d}_k + \mu'_iL_iH_u + \ldots\ldots$$

LLE LQD

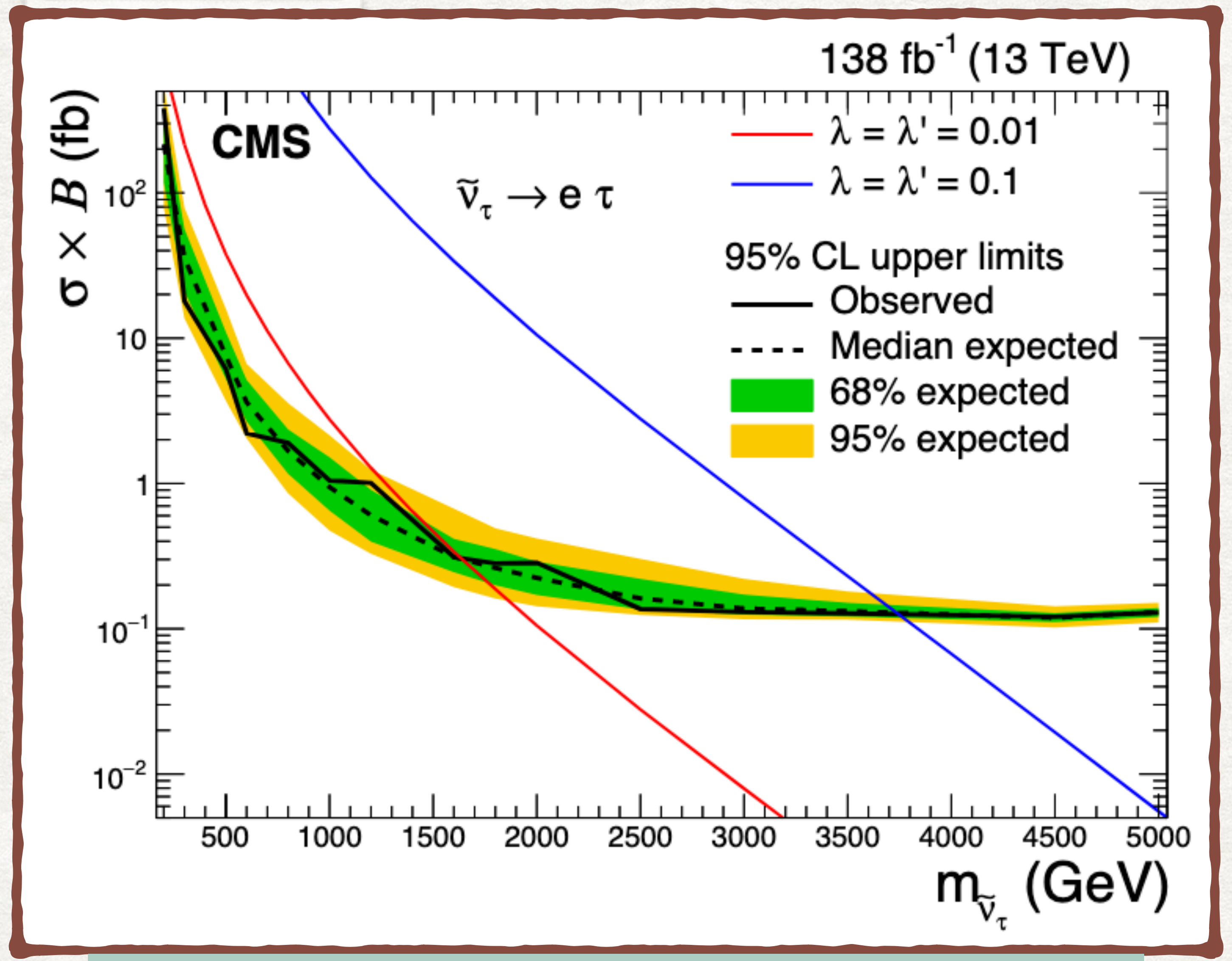
λ and λ' terms violate lepton number (and also lepton flavor)

eμ



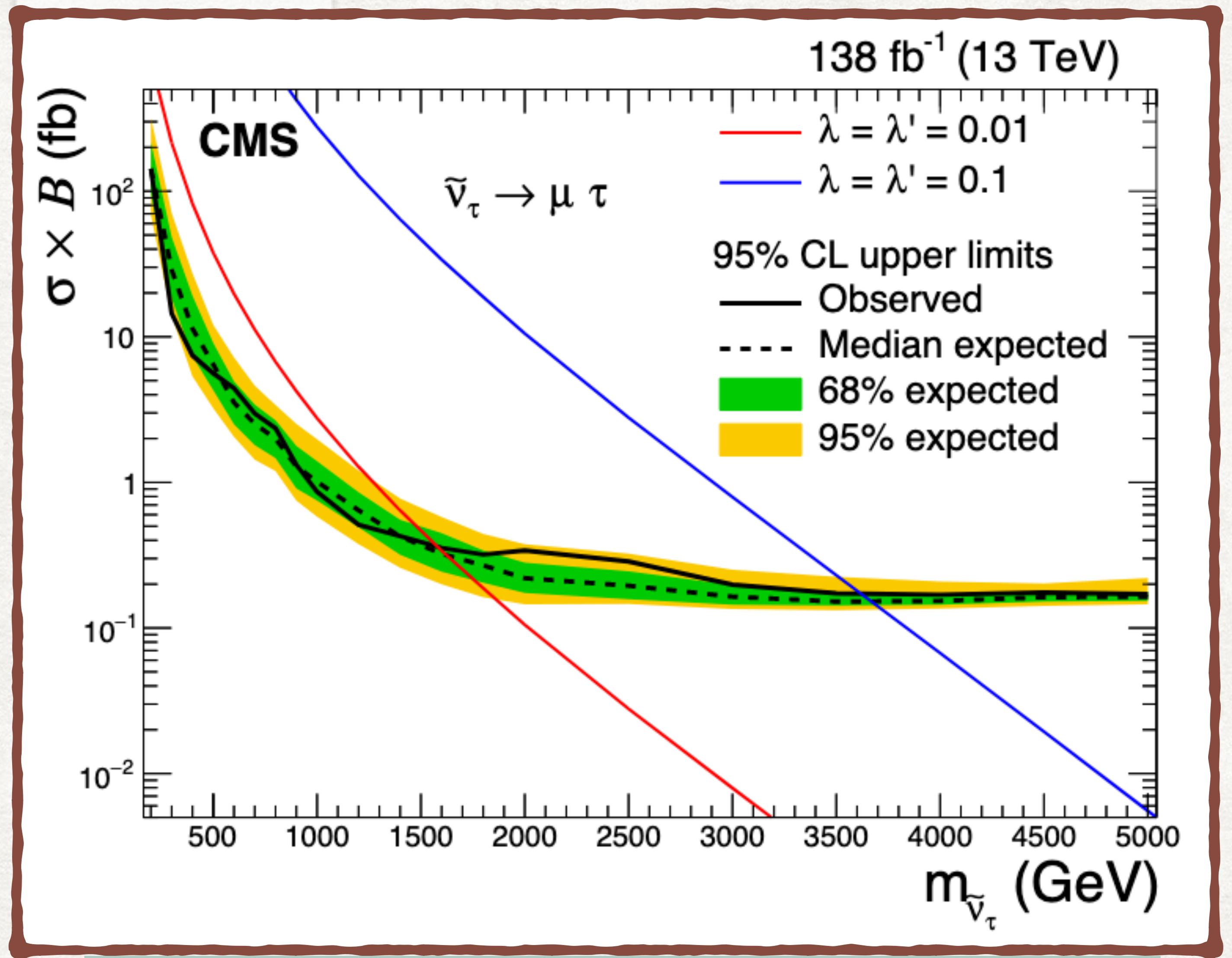
Mass Limit: 4.2 (4.2) TeV
2.2 (2.2) TeV

eτ



Mass Limit: 3.7 (3.7) TeV
1.6 (1.6) TeV

μτ



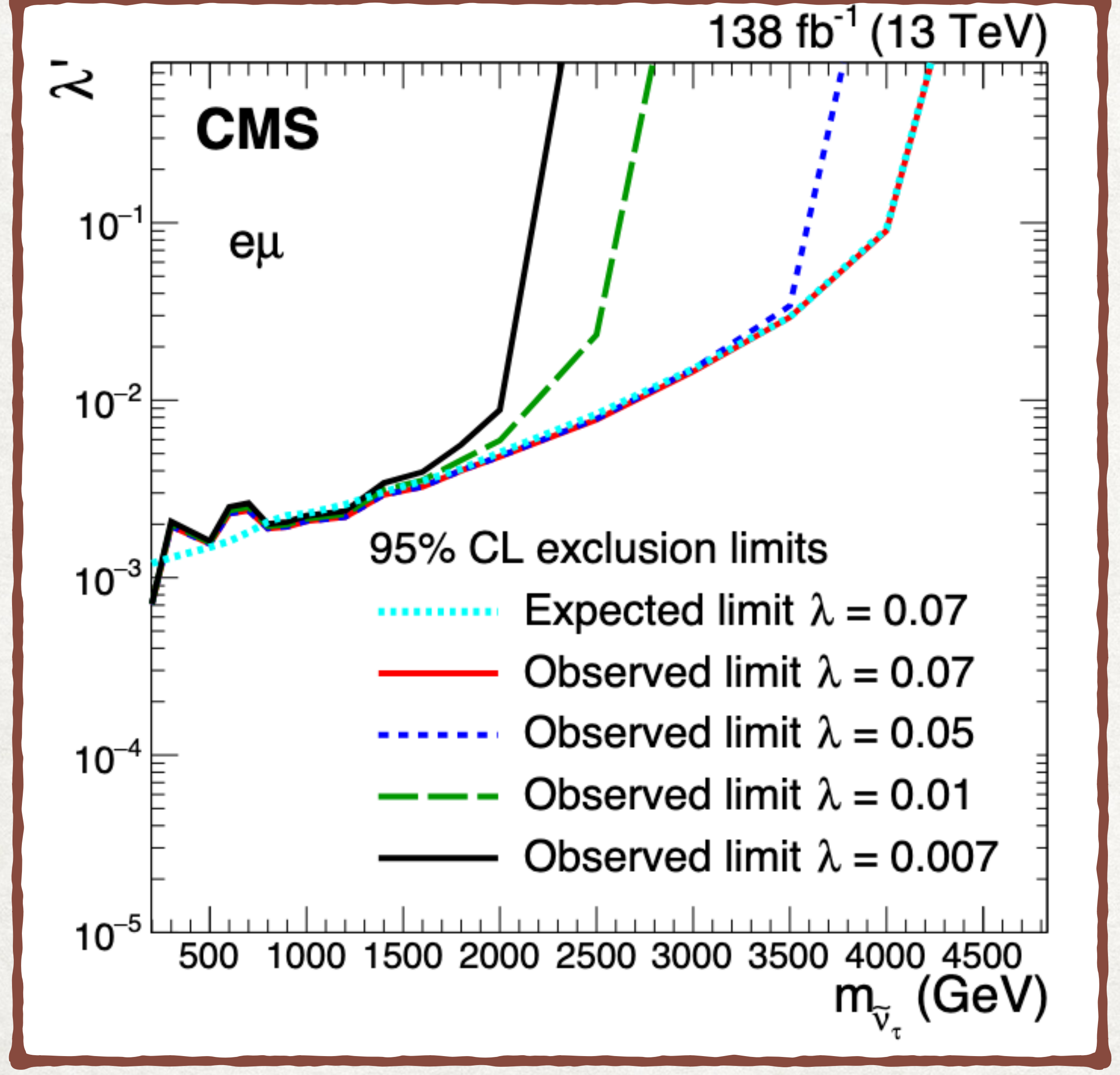
Mass Limit: 3.7 (3.7) TeV
1.6 (1.6) TeV

In narrow width approximation

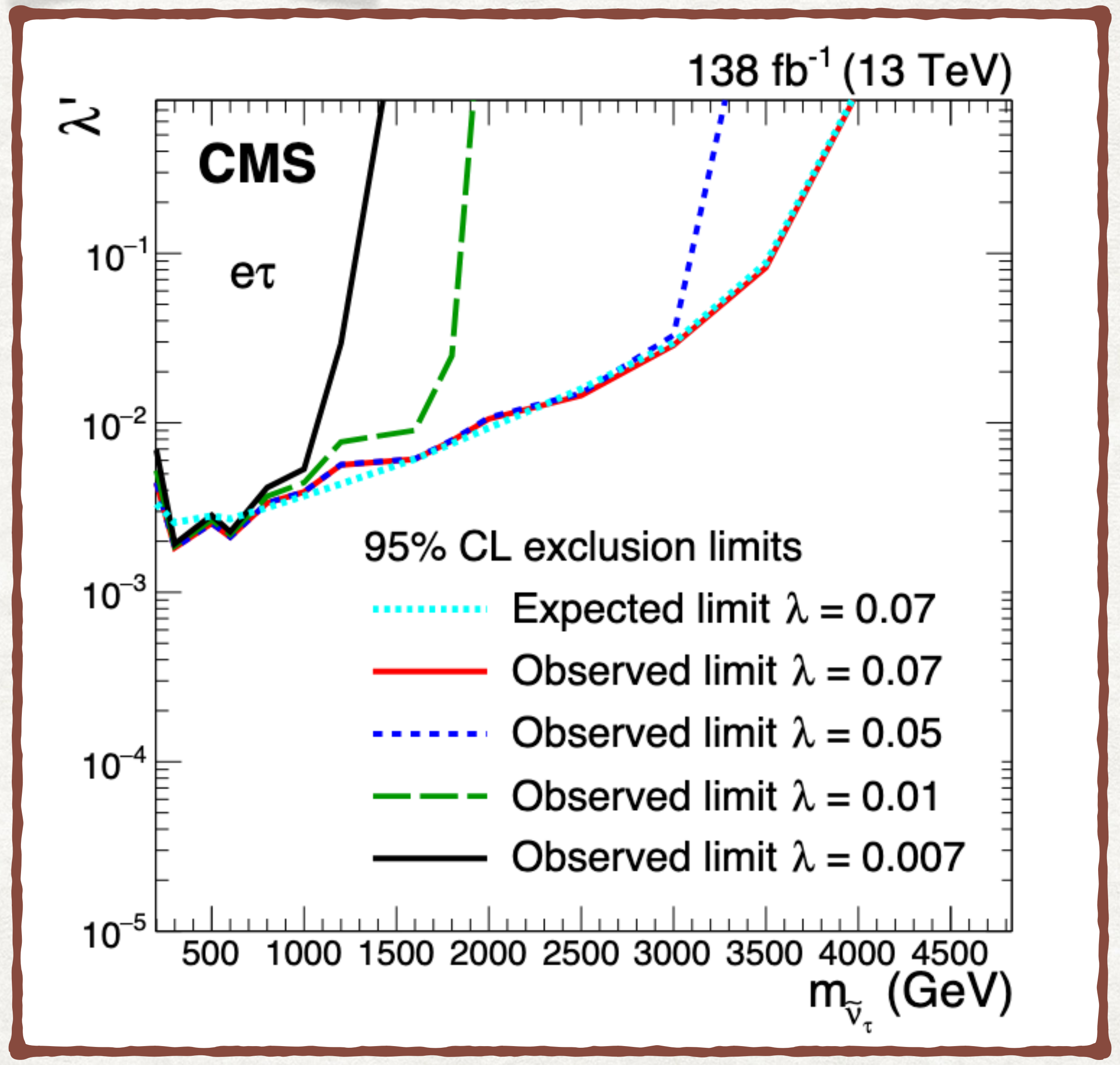
$$\sigma B \approx (\lambda'_{311})^2[(\lambda_{132})^2 + (\lambda_{231})^2]/(3(\lambda'_{311})^2 + [(\lambda_{132})^2 + (\lambda_{231})^2]).$$

Derived limit contours in the plane of mass and coupling of the parameter space of the RPV SUSY model for fixed values of the λ.

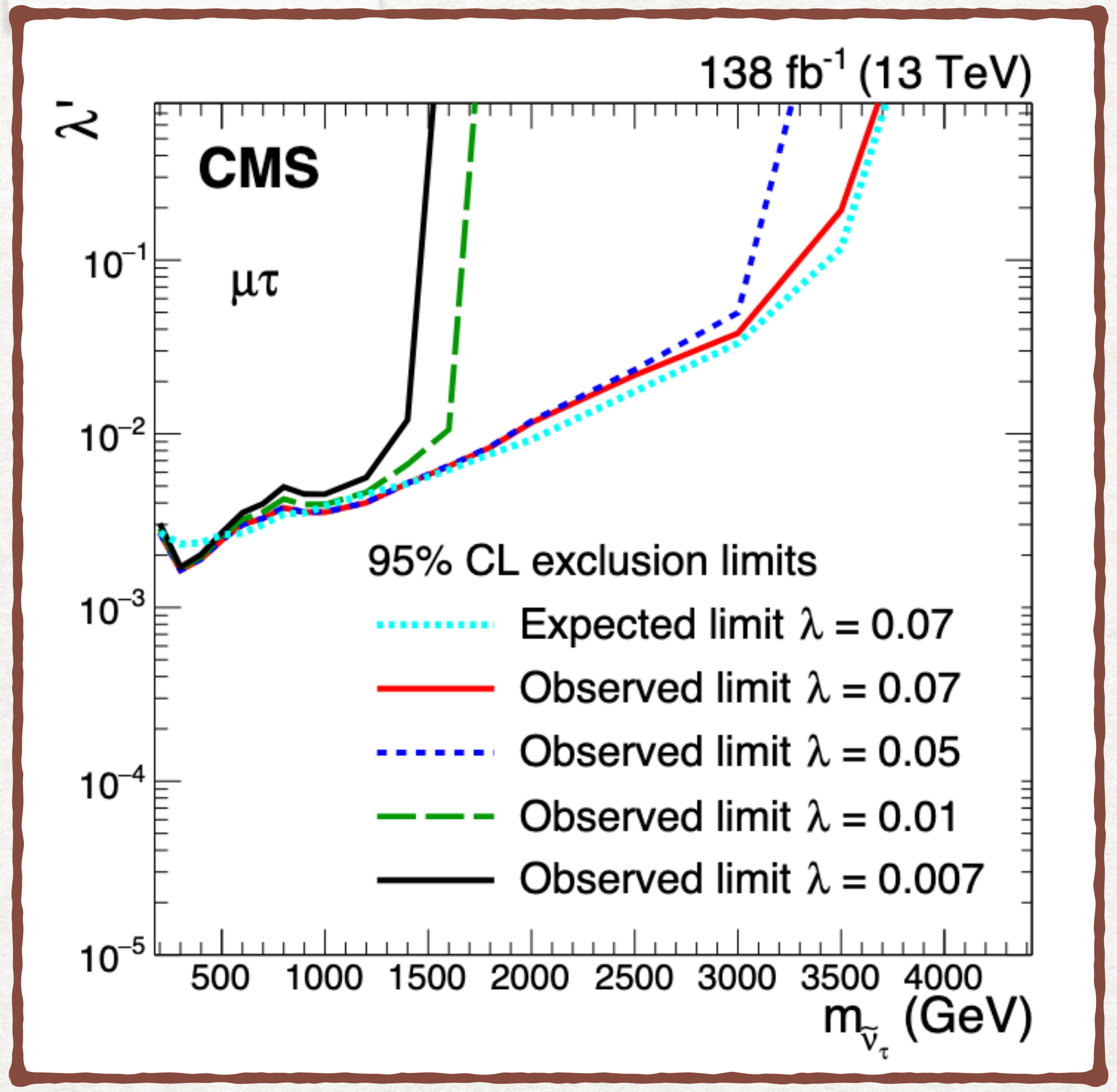
eμ



eτ



μτ

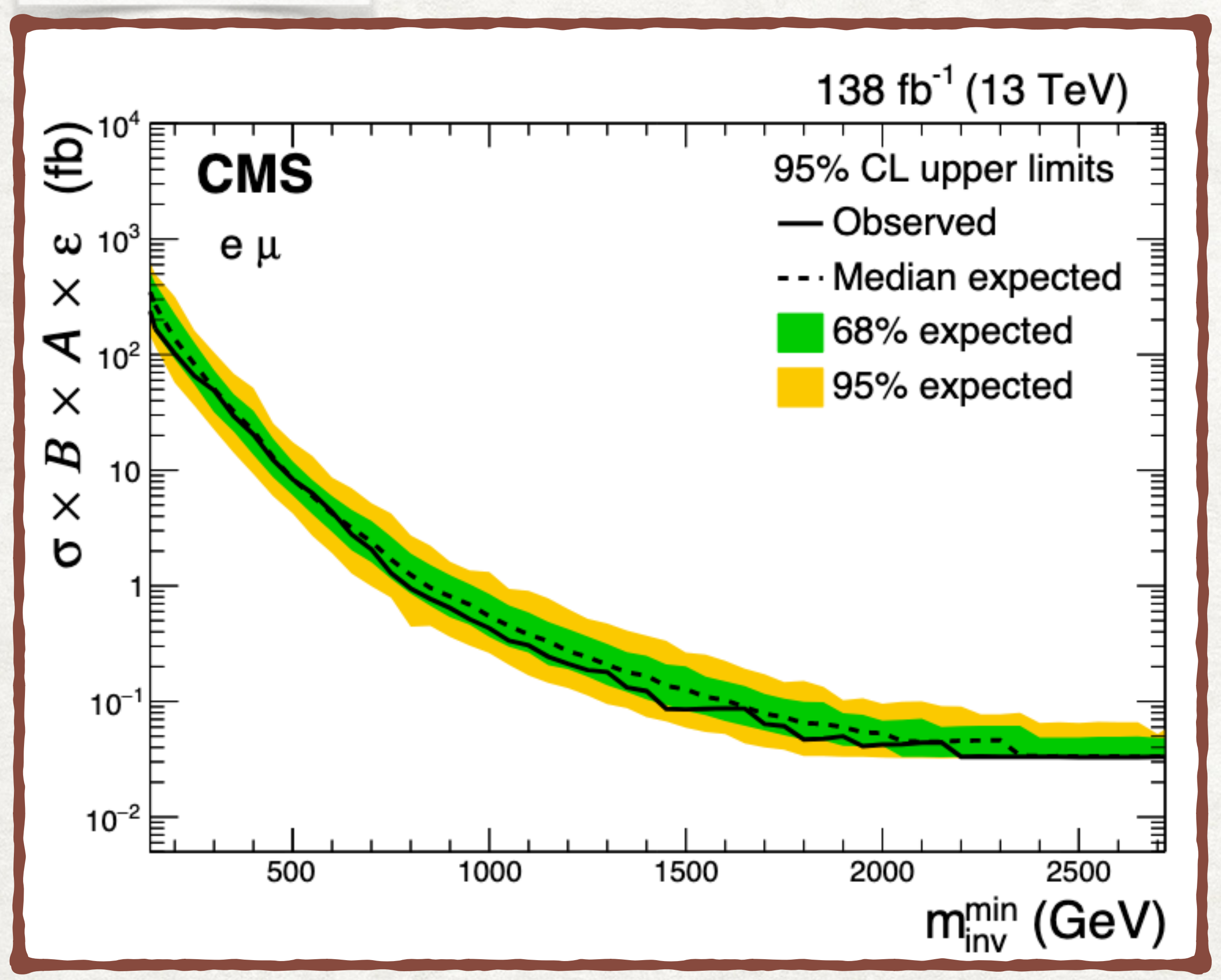


Model Independent Limits

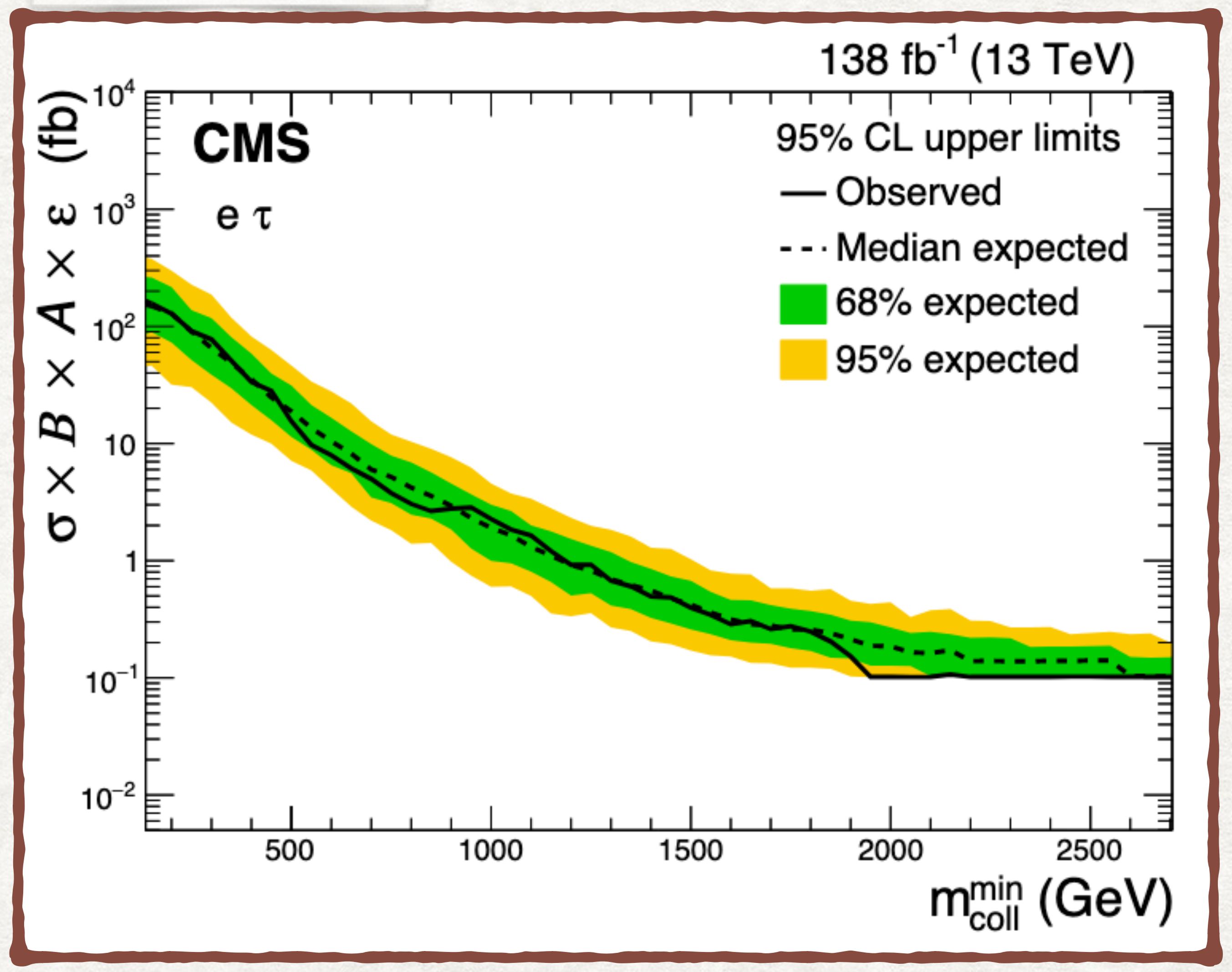
$$(\sigma \mathcal{B} A\varepsilon)_{\text{excl}}(\text{total}) = \frac{(\sigma \mathcal{B} A\varepsilon)_{\text{MI}}(m^{\text{min}})}{f_m(m^{\text{min}})}$$

- Event counting above a mass threshold
- No assumptions on the signal shape other than a flat product of acceptance times efficiency as a function of the mass
- To derive limit for a specific model from the MI limit, the model-dependent part of the acceptance &efficiency needs to be applied
- f_m is obtained by calculating events over m^{min} over number of generated MC events

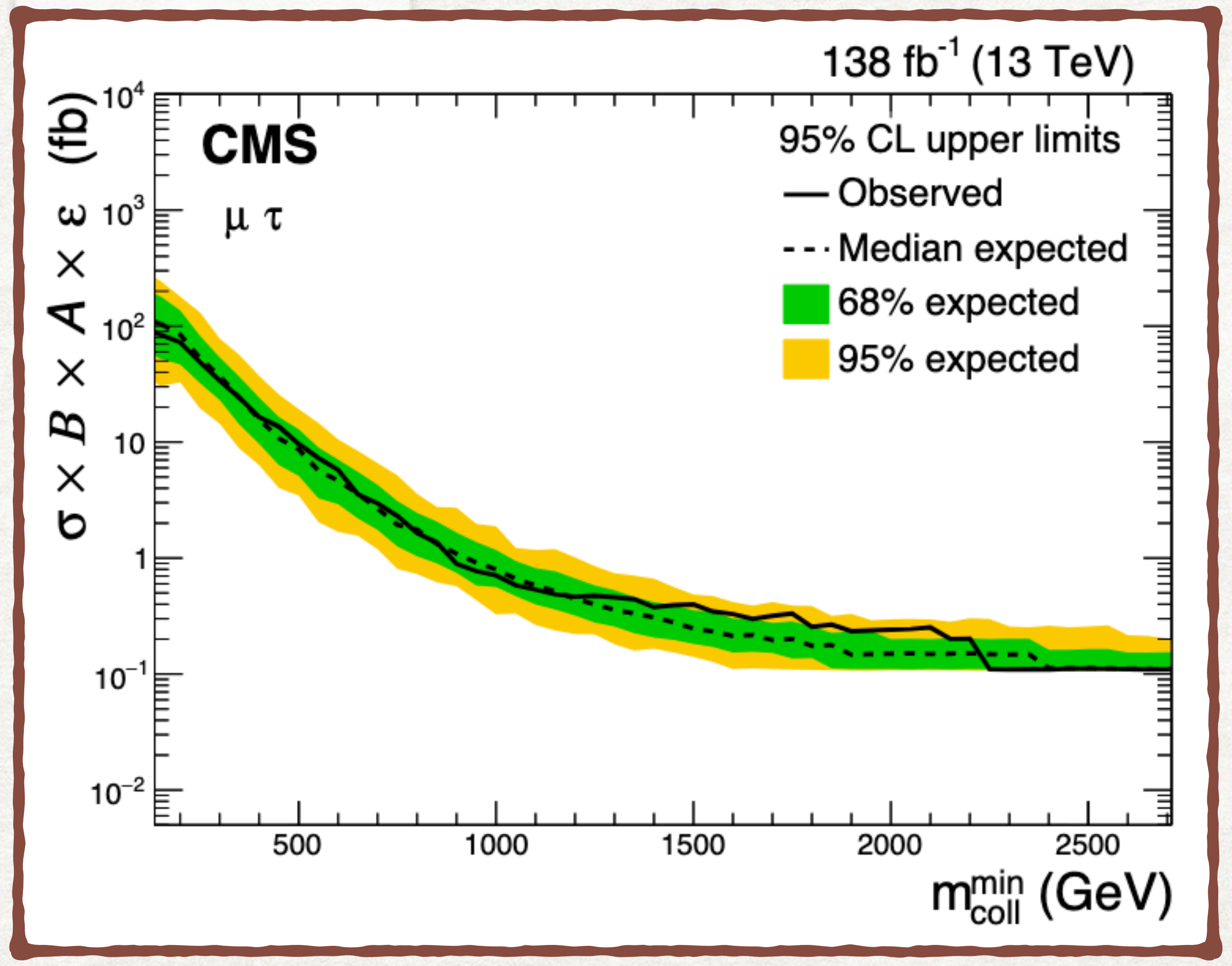
eμ



eτ



μτ



Summary

- *A brief overview of LFV searches @ LHC*
- *Search for high mass new physics in three LFV final states (eμ, eτ, μτ), with full Run2 data*
- *First CMS analysis with high mass LFV tau channels*
- *Data is consistent with the SM expectation*
- *Upper limits are set on three different LFV models (Z', RPV SUSY and QBH)*
- *Model independent limits are reported using counting method*
- *Results of this search are currently the best limits from the LHC in the considered models.*

Channel	RPV SUSY $\tilde{\nu}_\tau$ (TeV)		LFV Z' (TeV)	QBH m_{th} (TeV)
	$\lambda = \lambda' = 0.01$	$\lambda = \lambda' = 0.1$	$\mathcal{B} = 0.1$	$n = 4$
$e\mu$	2.2 (2.2)	4.2 (4.2)	5.0 (4.9)	5.6 (5.6)
$e\tau$	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)