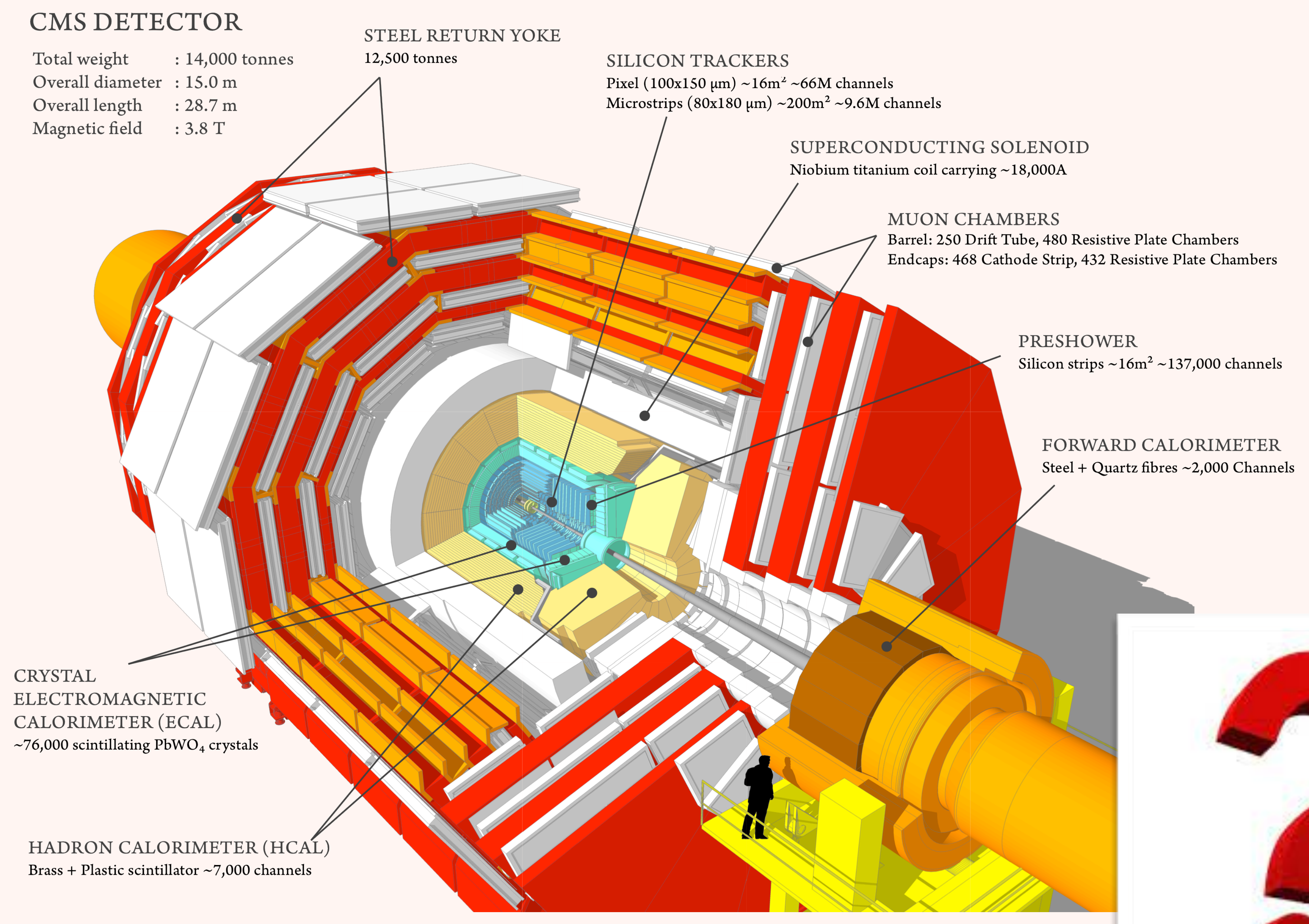
CHARGED LEPTON VIOLATION IN CMS

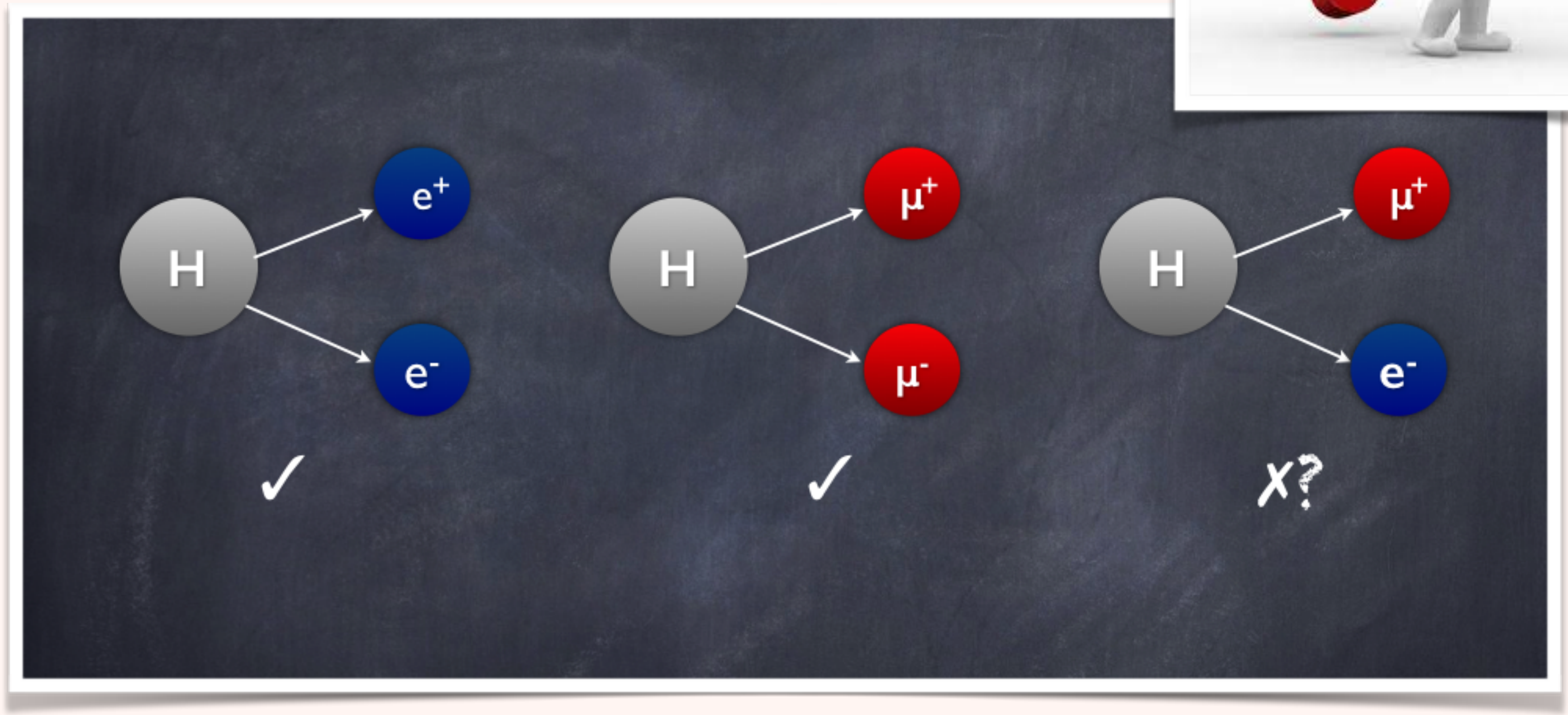
Amandeep Kaur Kalsi[1,2], Diego Beghin[1],

Barbara Clerbaux[1]

IIHE-ULB[1]

Punjab Agri. University, India[2]





Lepton Flavor Violation

Flavor conservation is not a fundamental symmetry in the SM

Fermions do change flavour:

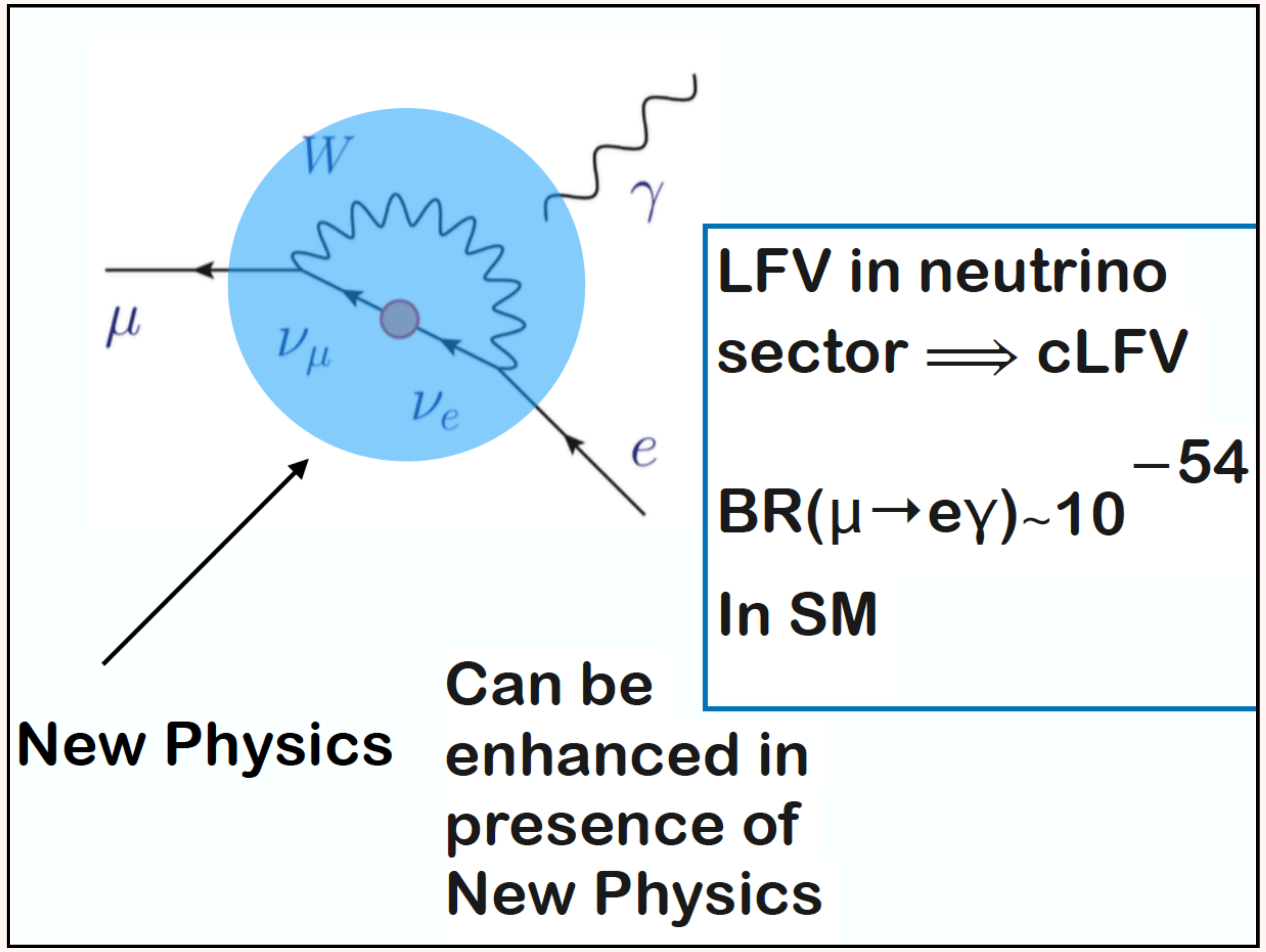
- Quarks: CKM matrix →quark mixing observed
- Leptons: PMNS matrix →neutrino mixing observed

How about charged leptons?

- →(charged) Lepton Flavour Violation (cLFV)
- Not observed yet

In the SM

- Loop with neutrino oscillations
- Vanishingly small branching ratios

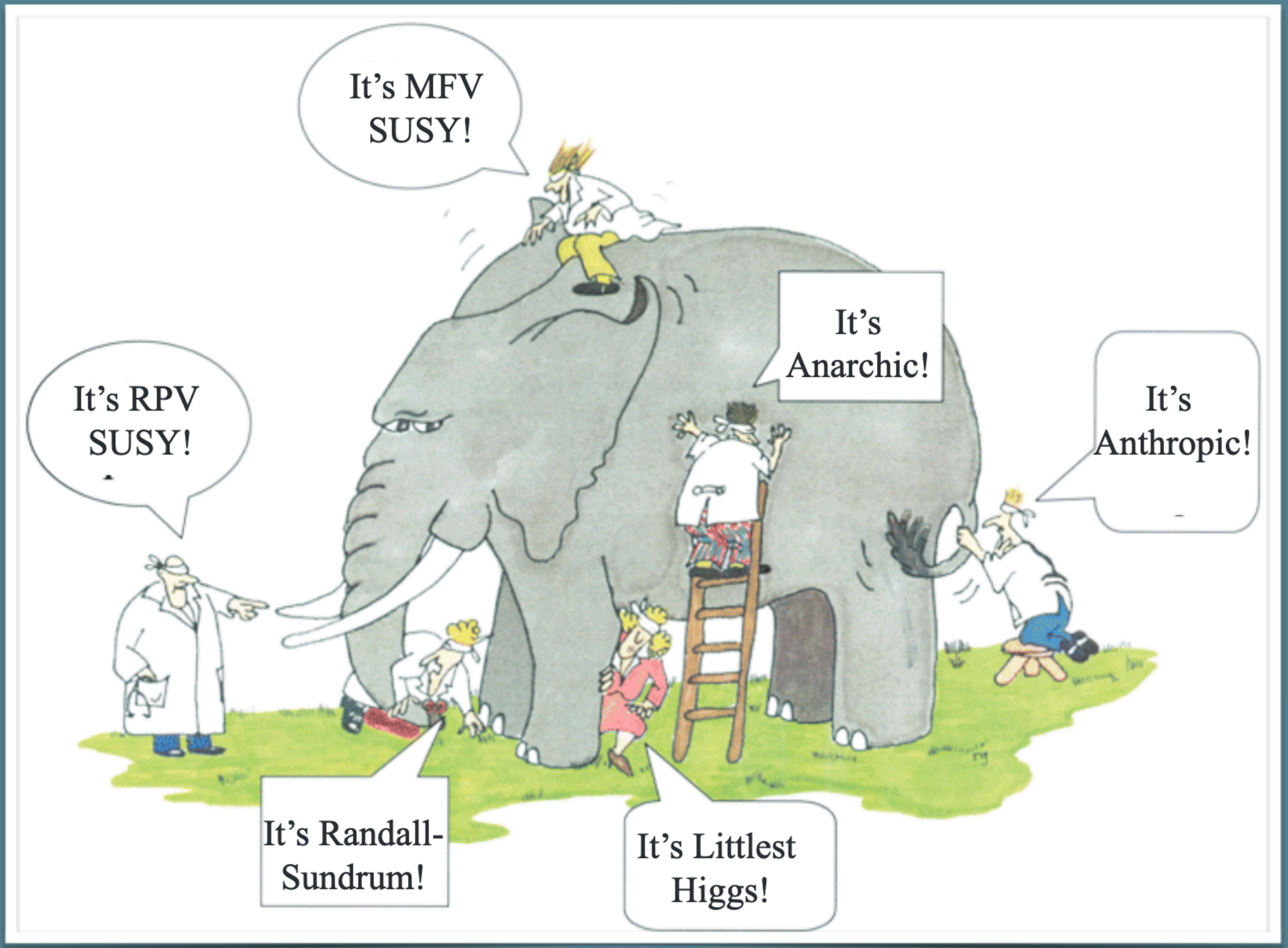


Various **BSM** models: Supersymmetry, extended gauge models, heavy neutrinos, etc.

Predict LFV couplings to be tested at the LHC

- 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.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$

Low energy results provide constraints (often with assumptions)



R. Bernstein (FNAL)

Need multiple measurements to understand the full picture

LFV Z→ll′ decays

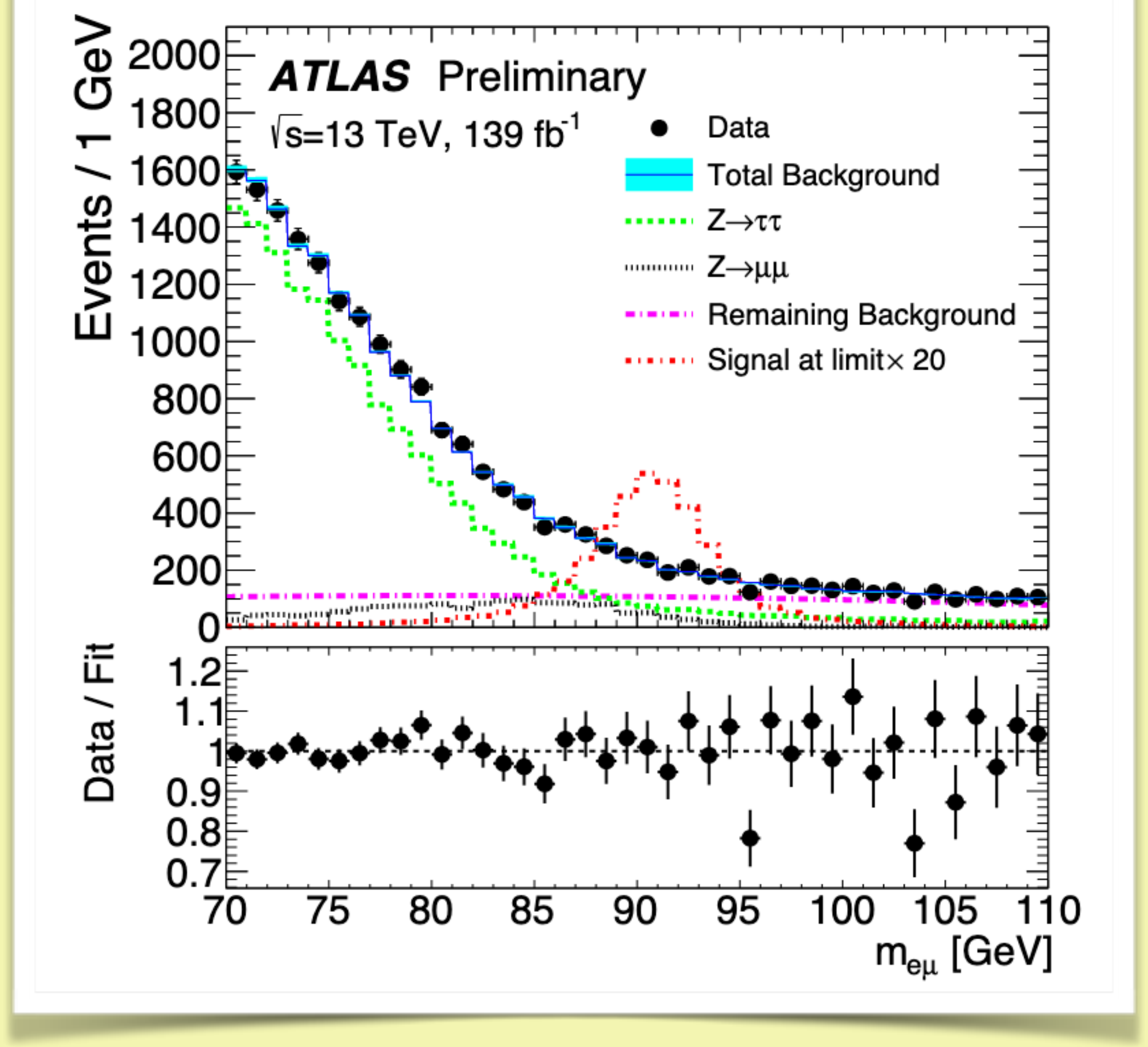
Selections: Two tight leptons with opposite sign in Z mass region [70,110] GeV

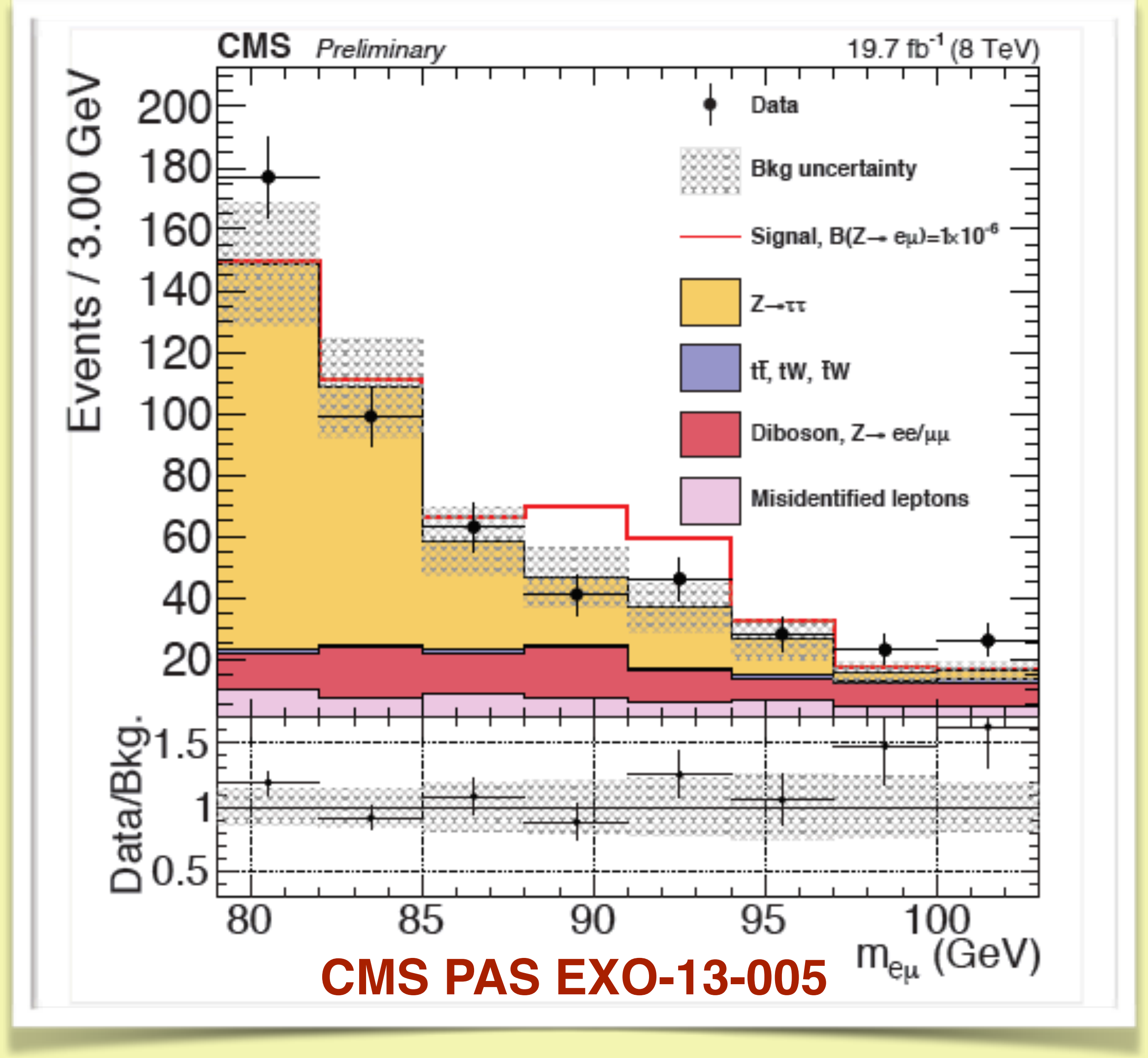
- B-Jet-Veto: suppresses ttbar
- Low transverse Mass or Missing transverse momenta

Use of BDT cut/neural network classifiers to discriminate signal from background processes for tau final states

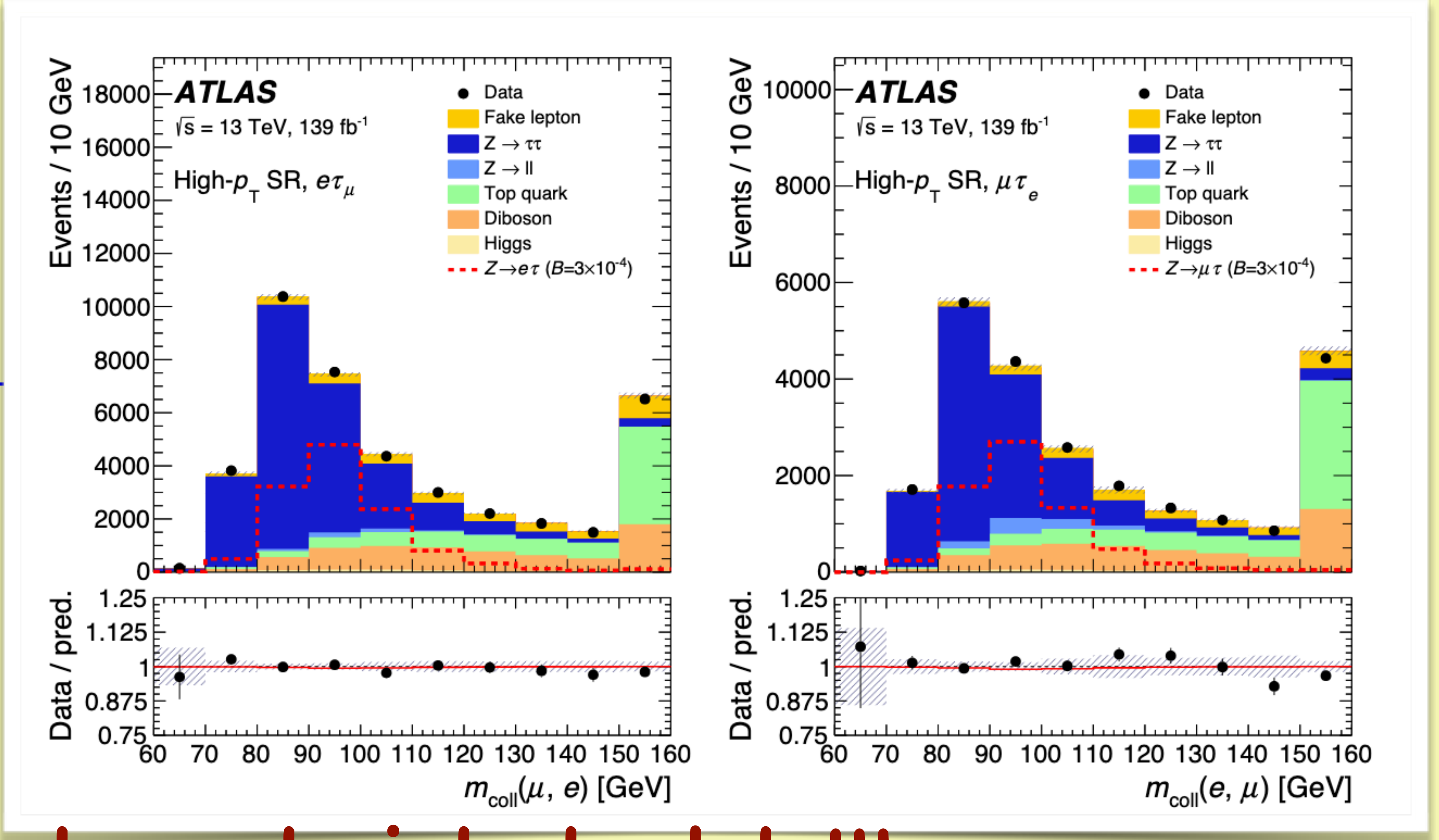
CMS	B(Z→eμ)	< 7.3 x 10^{-7}
ATLAS 139 fb^{-1} (Run 1 + Run2)	B(Z→eμ) B(Z→μτ) B(Z→eτ)	< 3.04 x 10^{-7} < 6.5 x 10^{-6} < 5.0 x 10^{-6}
LEP	B(Z→eμ) B(Z→μτ) B(Z→eτ)	< 1.7 x 10^{-6} < 1.2 x 10^{-5} < 9.8 x 10^{-6}

ATLAS-CONF-2021-042





arXiv:2105.12491

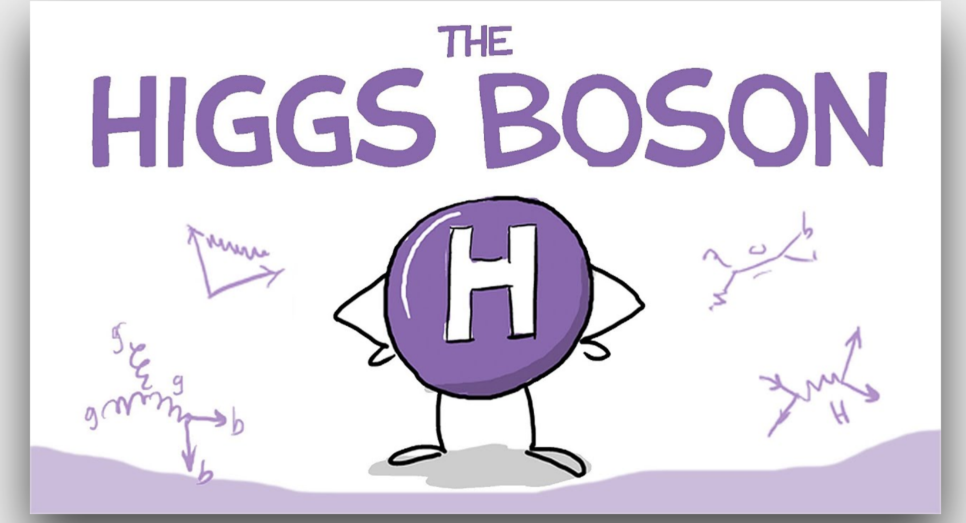


Most stringent constraints to date!!!

LFV H(125) $\rightarrow ll'$ decays

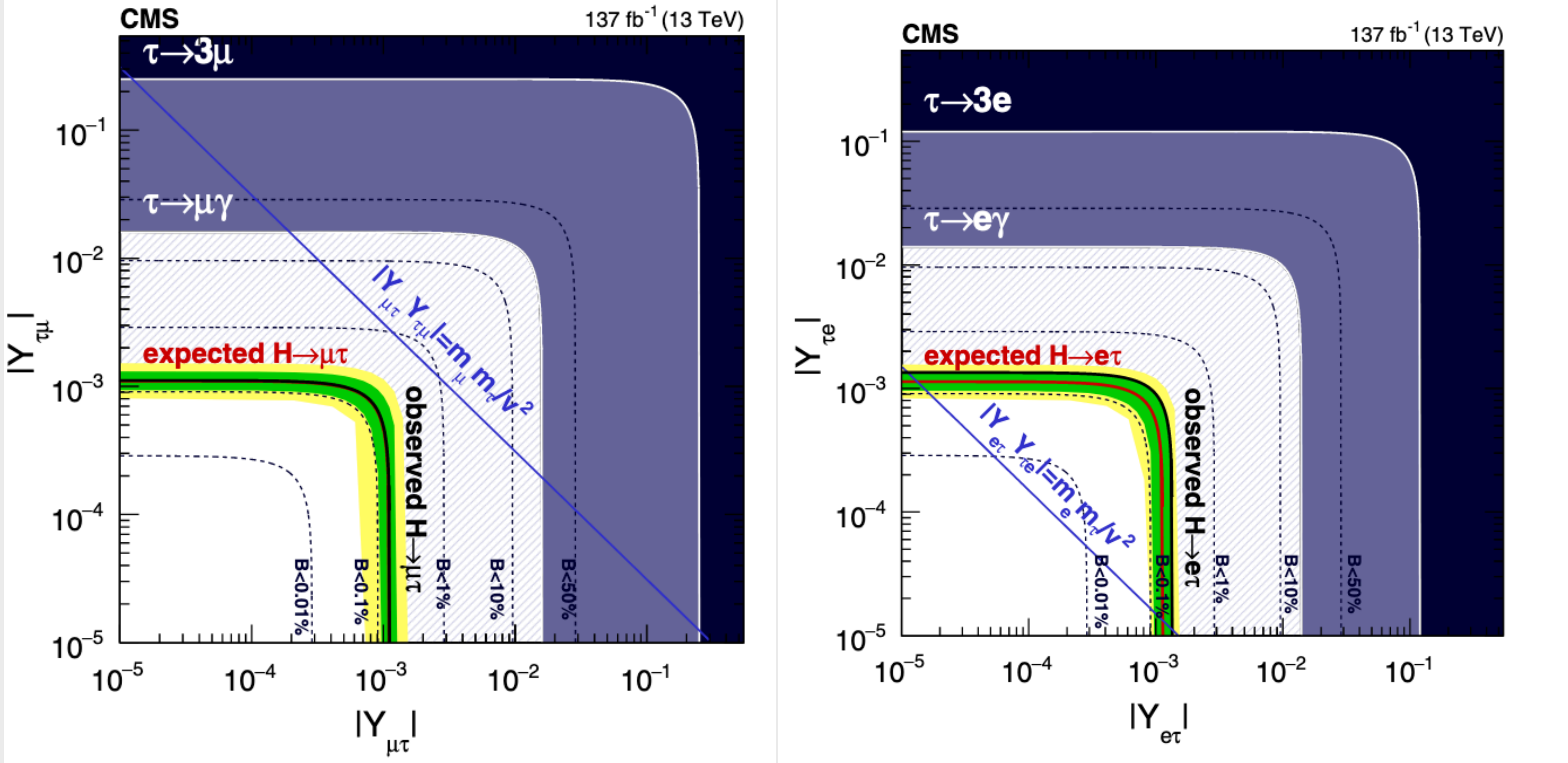
PhysRevD.104.032013

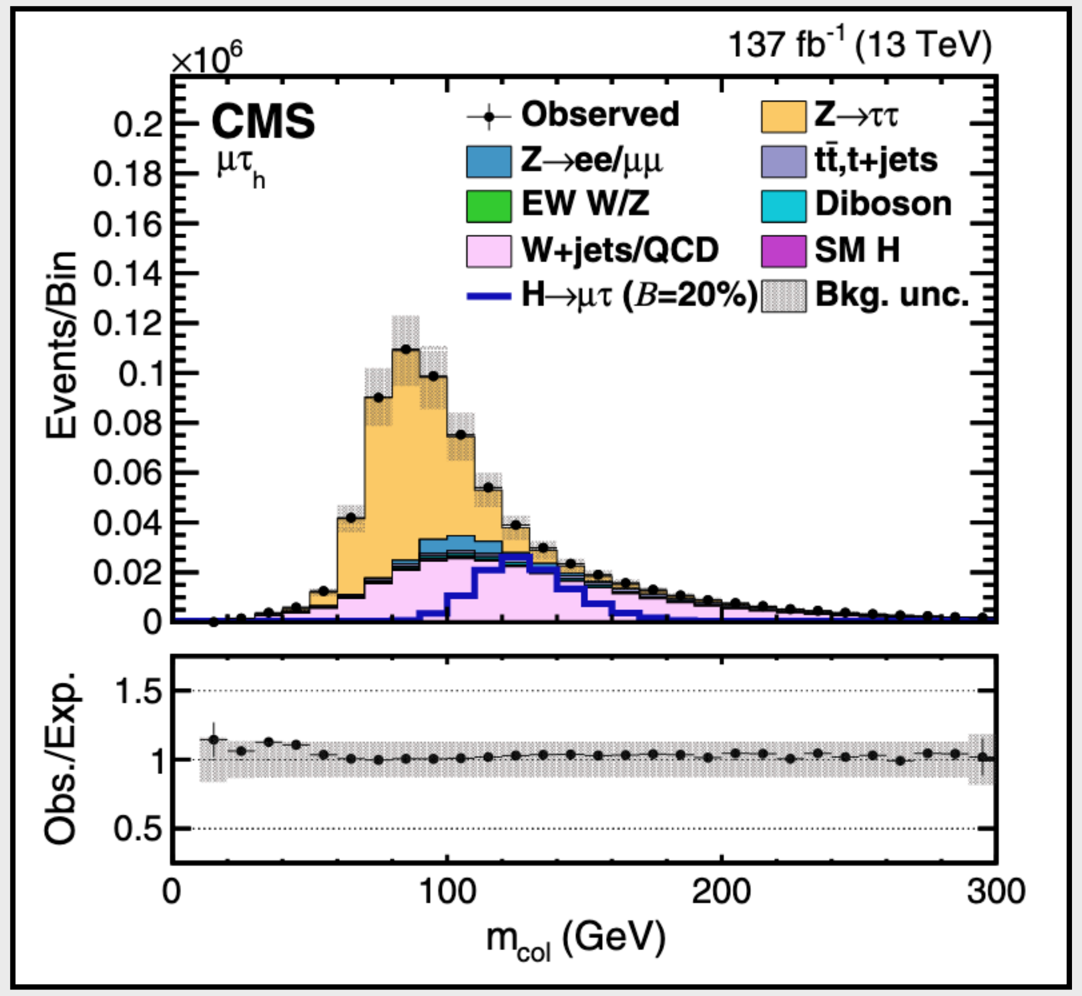
Null result for $\mu\rightarrow e\gamma$ strongly constrains B(H $\rightarrow e\mu$) to < 10^{-8} while $\tau\rightarrow\mu\gamma$/ $\tau\rightarrow e\gamma$ and other measurements constrain B(H $\rightarrow e\tau$) and B(H$\rightarrow\mu\tau$) ≈10%

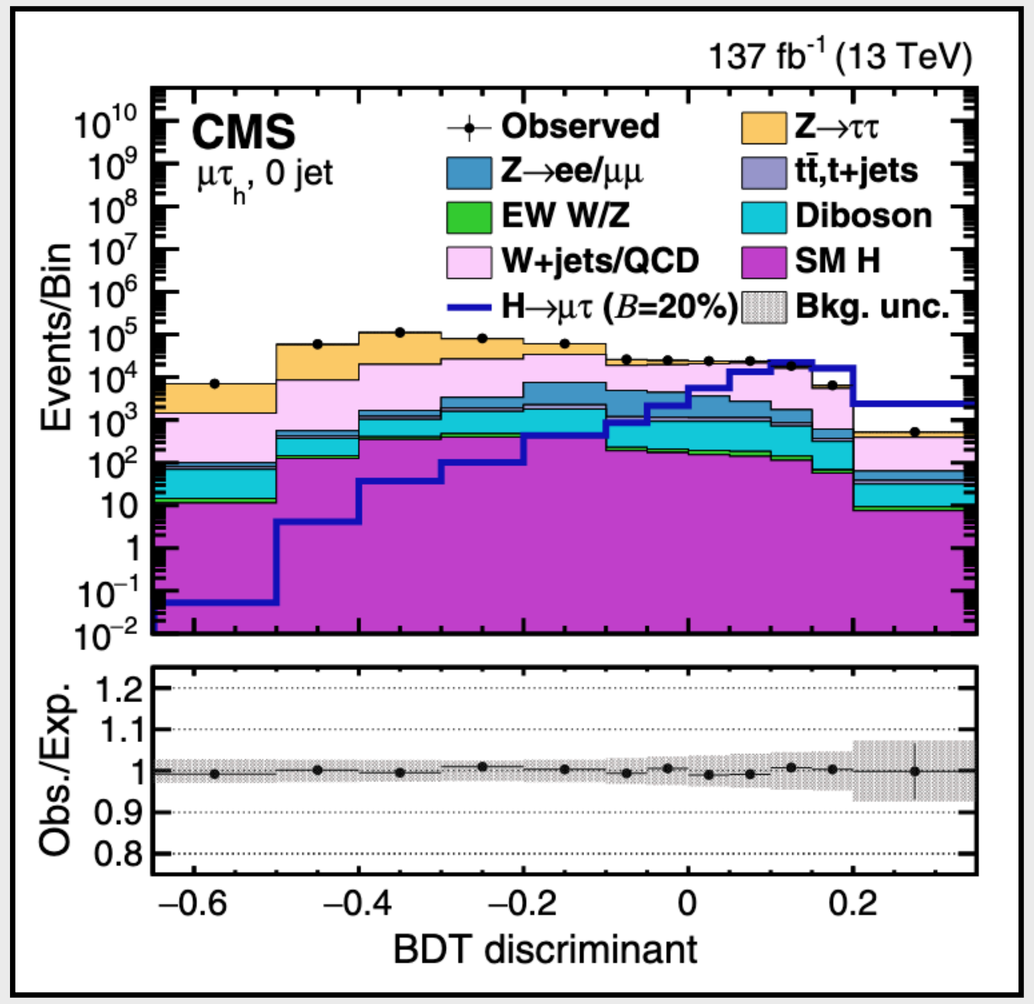


Strategy:

- Main backgrounds are the Z $\rightarrow\tau\tau$, W+jets, ttbar and QCD production.
- Analysis employs categorization in VBF and non-VBF categories
  - CMS: subcategorisation of non-VBF in 0-jet, 1-jet and 2 jet final states
- Fit BDT distribution to obtain final results



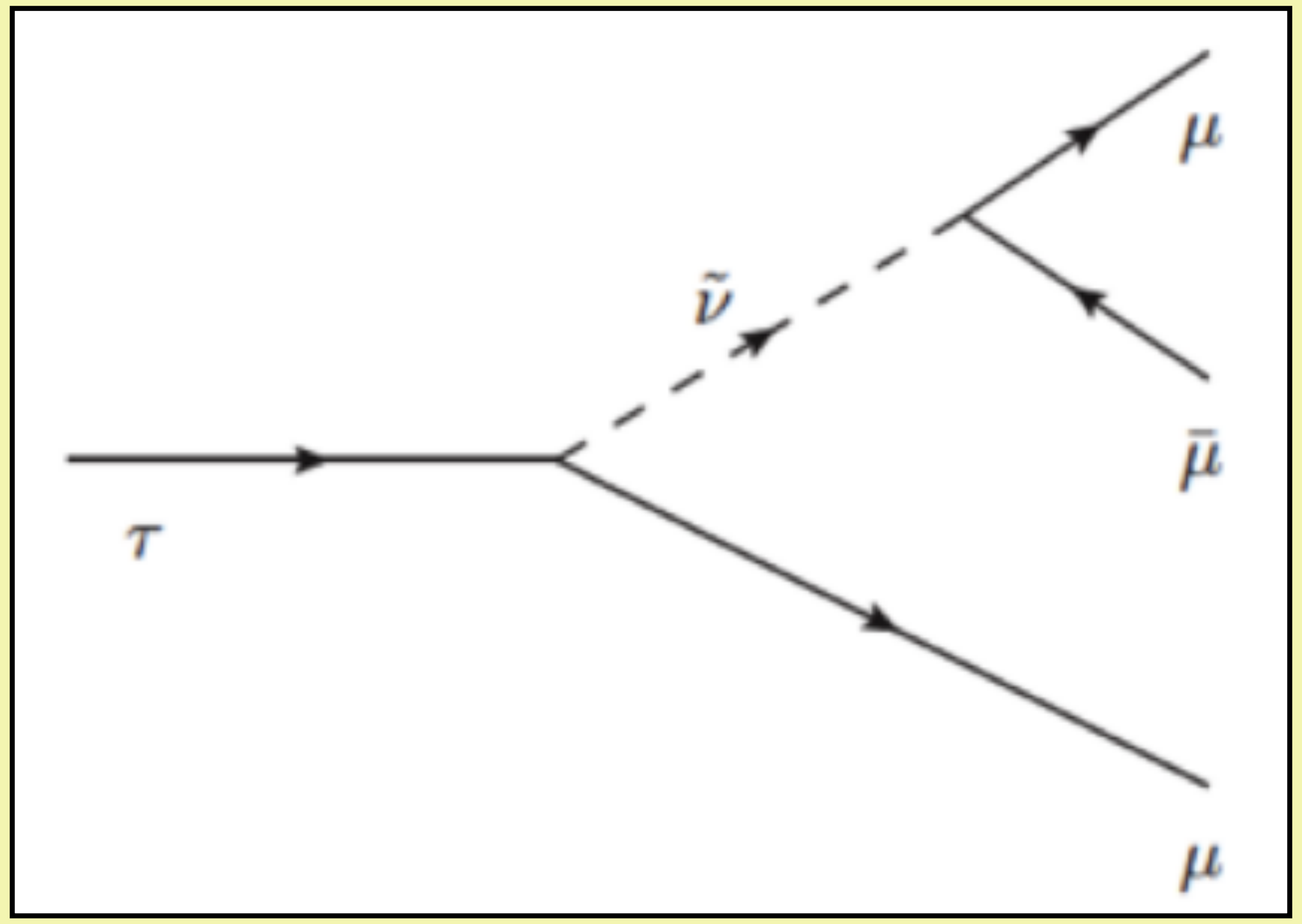




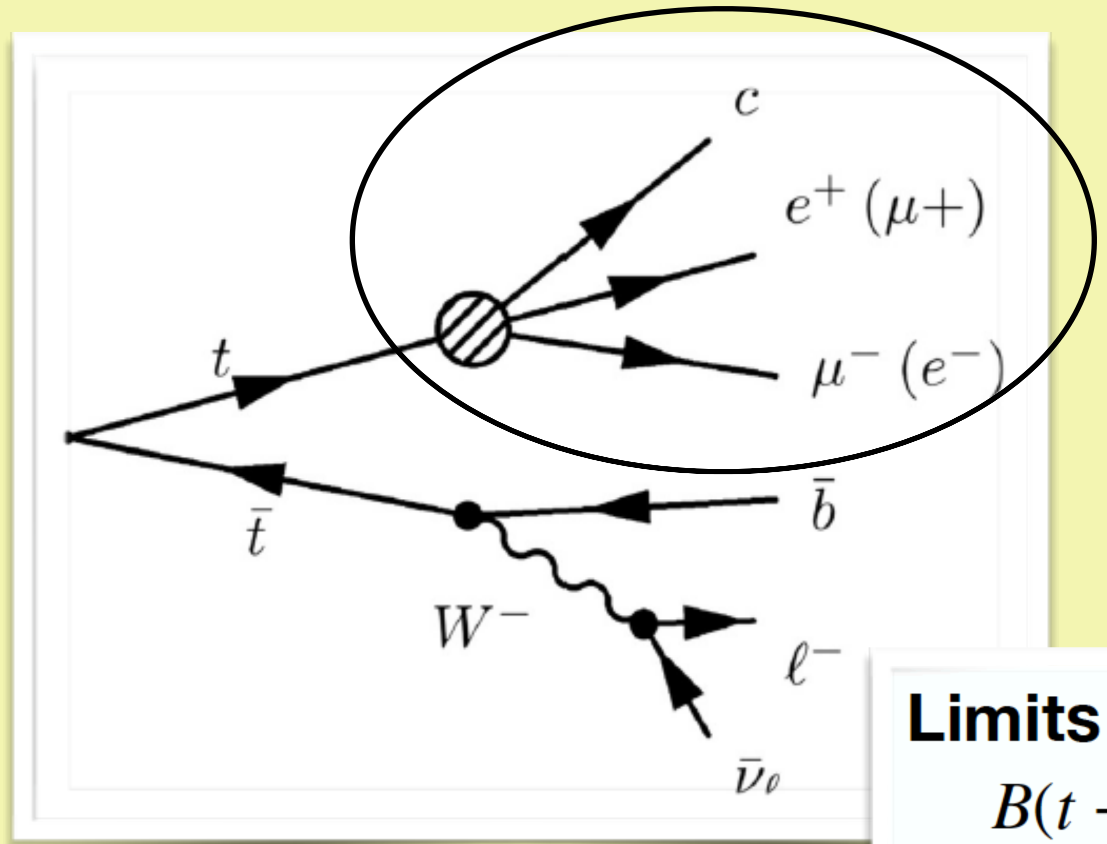
	CMS (Run2)	ATLAS (2016)
B(H→μτ)	< 0.15 %	< 0.28 %
B(H→eτ)	< 0.22 %	< 0.47 %

& many more…..

τ→ 3μ



ATLAS (8 TeV, 90% CL) W decays	< 3.76 x 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 x 10^{-8} **JHEP01(2021)163**
BELLE BABAR LHCb	< 2.1 x 10^{-8} < 5.3 x 10^{-8} < 4.6 x 10^{-8}



ATLAS-CONF-2018-044

Limits at 95% CL

$B(t \to ll'q) < 1.36^{+0.61}_{-0.37} \times 10^{-5}$ exp.

$B(t \to ll'q) < 1.86 \times 10^{-5}$ Obs.

$B(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6}$ exp.

$B(t \to e\mu q) < 6.6 \times 10^{-6}$ Obs.

No τ in cLFV

LFV Heavy Higgs (200-900 GeV)

JHEP 03 (2020) 103	CMS
σ(gg->H) x B(H →$\mu\tau$)	51.9 fb - 1.6 fb
σ(gg->H) x B(H →$e\tau$)	97.4 fb- 2.3 fb

What about more Heavy states? Can we find them @ LHC

History of LFV heavy X -> ll searches

Heavy state	CMS (2016, $e\mu$) JHEP 04 (2018) 073	ATLAS 2016 $e\mu$, $e\tau$, $\mu\tau$ 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)

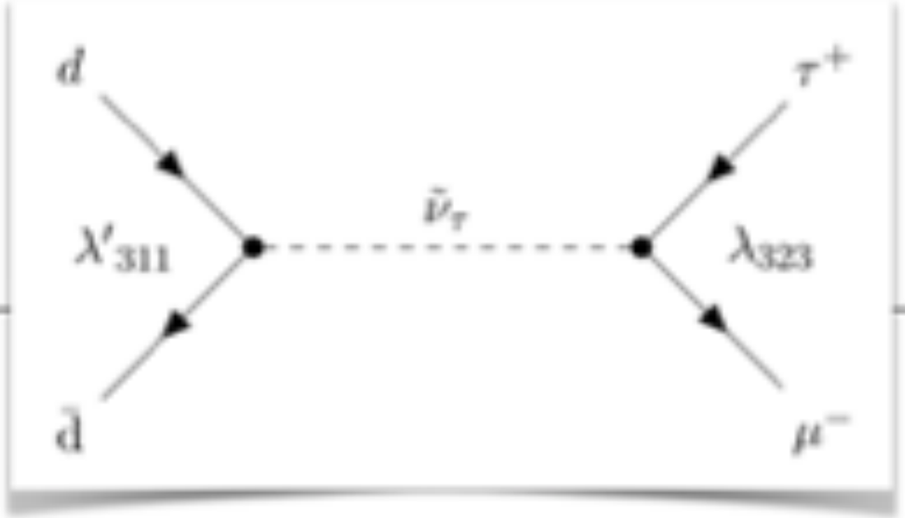
- ☑ Search for heavy resonances and quantum black holes in $e\mu$, $e\tau$, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV (137 fb^{-1})
- ☑ Model-independent, inclusive, signature-based search
- ☑ Interpretation in three models
  +model independent limits

Analysis Team

Diego Beghin	Reza Goldouzian
Amandeep Kaur Kalsi	Sebastian Weidenbeck
Xuyang Gao	Swagata Mukherjee
Barbara Clerbaux	Arnd Meyer

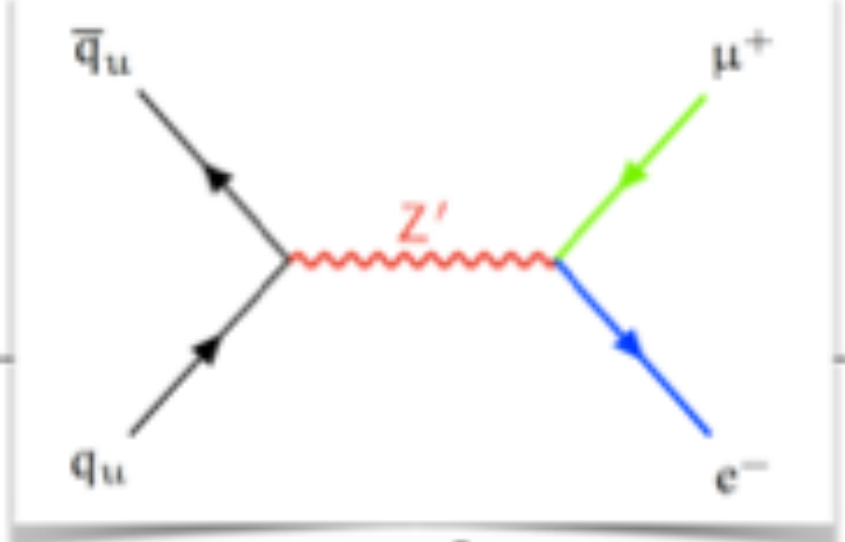
Tau sneutrino in R-parity violating (RPV) SUSY

- ν_τ resonance: lightest SUSY particle
- All RPV couplings = 0 except those allowing for $q\bar{q} \to \tilde{\nu}_\tau$ and LFV decay to a specific final state



SSM-like New gauge boson Z'

- Z-like couplings in quark sector
- LFV-only decays in lepton sector



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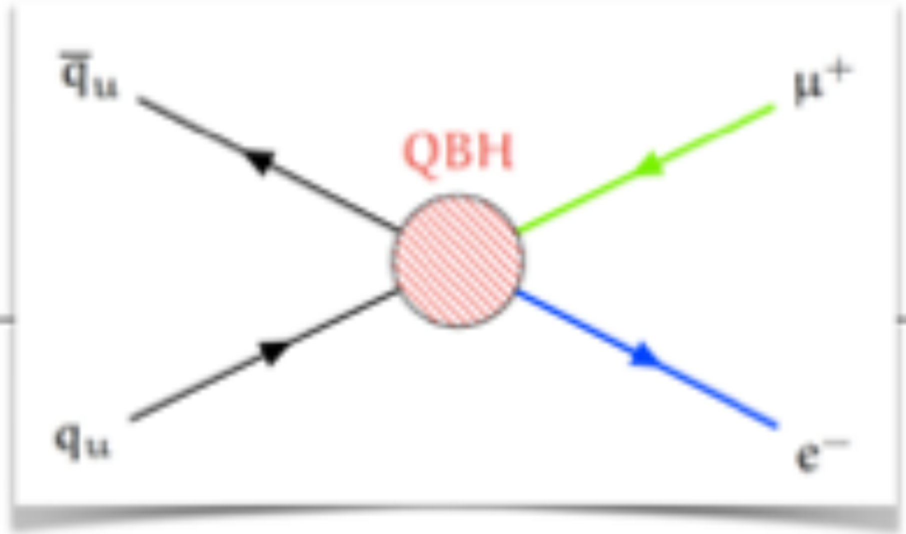
Quantum black holes (QBH)

- Extra dimensions → TeV scale
- QBH: Spin 0, colorless, neutral
- n=4 extra dimensions (ADD)



Analysis Strategy

Used 2016, 2017, and 2018 pp collisions at a center-of-mass energy of 13 TeV (137.1 fb^{-1})

Background samples:

$t\bar{t} \rightarrow 2l2\nu$: POWHEG binned in Mll, NNLO QCD + NLO EW

$WW \rightarrow 2l2\nu$: POWHEG binned in Mll, NNLO

WZ, ZZ : POWHEG and amc@NLO binned in decay mode, WZ: NLO, ZZ: NNLO

$DY \rightarrow ll$: amc@NLO binned in Mll, NLO

Single Top : POWHEG

Signal samples

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

QBH : Dedicated QBH generator v3.0 (LO)

Z′ : PYTHIA8 (LO) CUETP8M1/CP5 tunes

eμ	eτ	μτ
Events selected by single muon and photon triggers	Events selected by single electron and photon triggers	Events selected by single muon triggers
μ: p_T>53 GeV, $\lvert\eta\rvert$<2.4, HighPtID, tracker iso < 0.1, **Electron** :p_T > 35 GeV, HEEP ID	τ: p_T > 50 GeV, $\lvert\eta\rvert$ < 2.3, Deep Tau tight anti-jet, loose anti-e and tight anti-μ **Electron** : p_T > 50 GeV, HEEP ID	τ: p_T>50 GeV,$\lvert\eta\rvert$<2.3, DeepTau tight anti-jet, loose anti-e and tight anti-μ μ: p_T>53 GeV, $\lvert\eta\rvert$ < 2.4, HighPtID, tracker iso < 0.1
At least an $e\mu$ pair	At least an $e\tau$ pair $m_T(e,E_T^{miss})$ > 120 GeV No extra electron or muon	At least an $\mu\tau$ pair $m_T(\mu,E_T^{miss})$ > 120 GeV No extra electron or muon

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

- No requirement on charge of lepton pairs

eμ final state

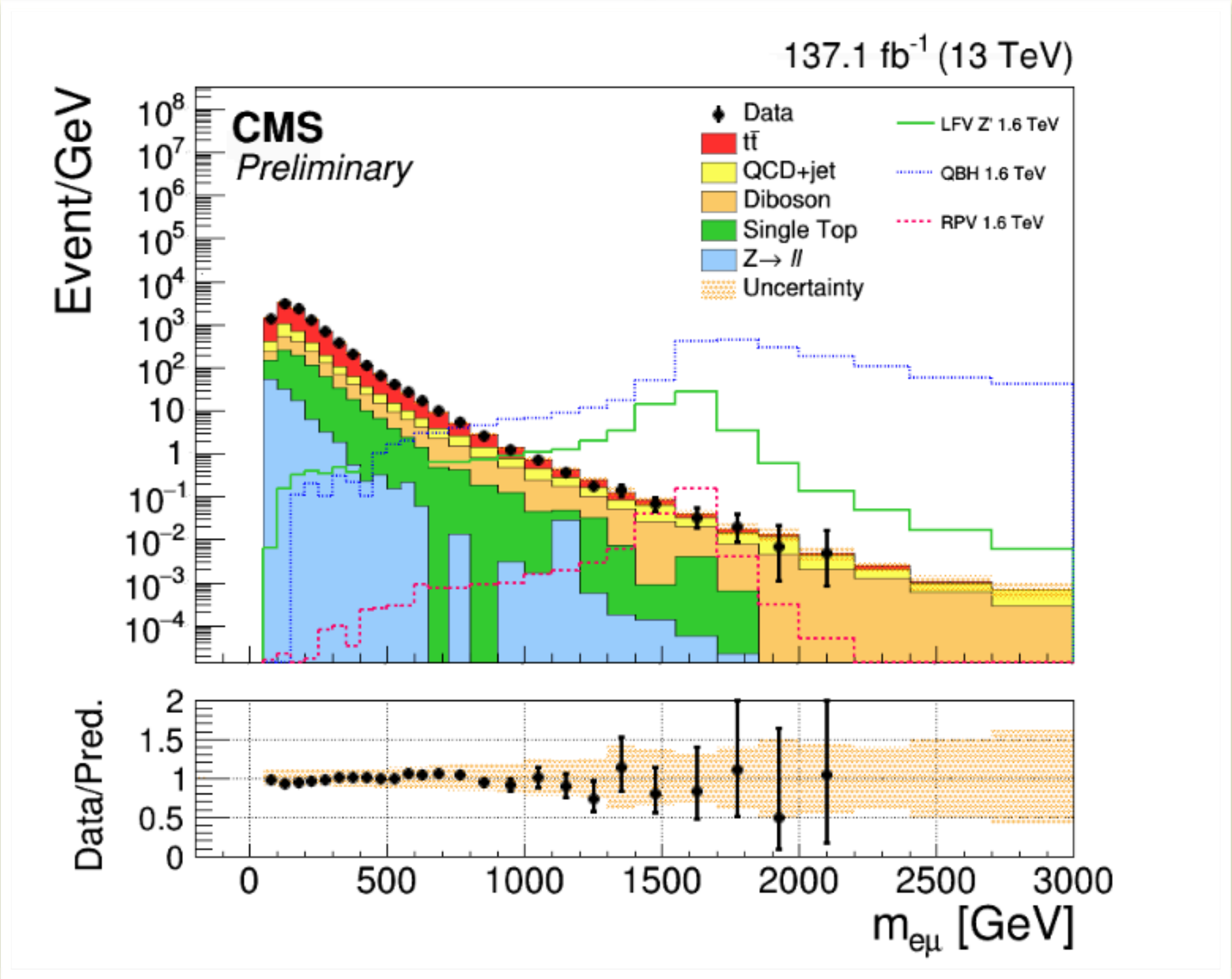
No other signal specific cut in order to stay model independent

Main backgrounds:

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

Fake rate method:

- Probability of a jet passing pre-selection cuts to also pass lepton selection
- Derived a jet dominated control sample in data using relaxed lepton identification criteria (e.g. electron isolation or shower shape variables and so on..) to evaluate the contribution of jets passing the full lepton selection
- Fake rate parametrized as function of pt and eta of lepton



Key variable: invariant mass of eμ pair

Tau final states ($e\tau$, $\mu\tau$)

Main backgrounds:

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

Fake factor estimation:

- Probability of a jet to be misidentified as a τ_h
- 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 pseudorapidity

Collinear mass Approximation

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

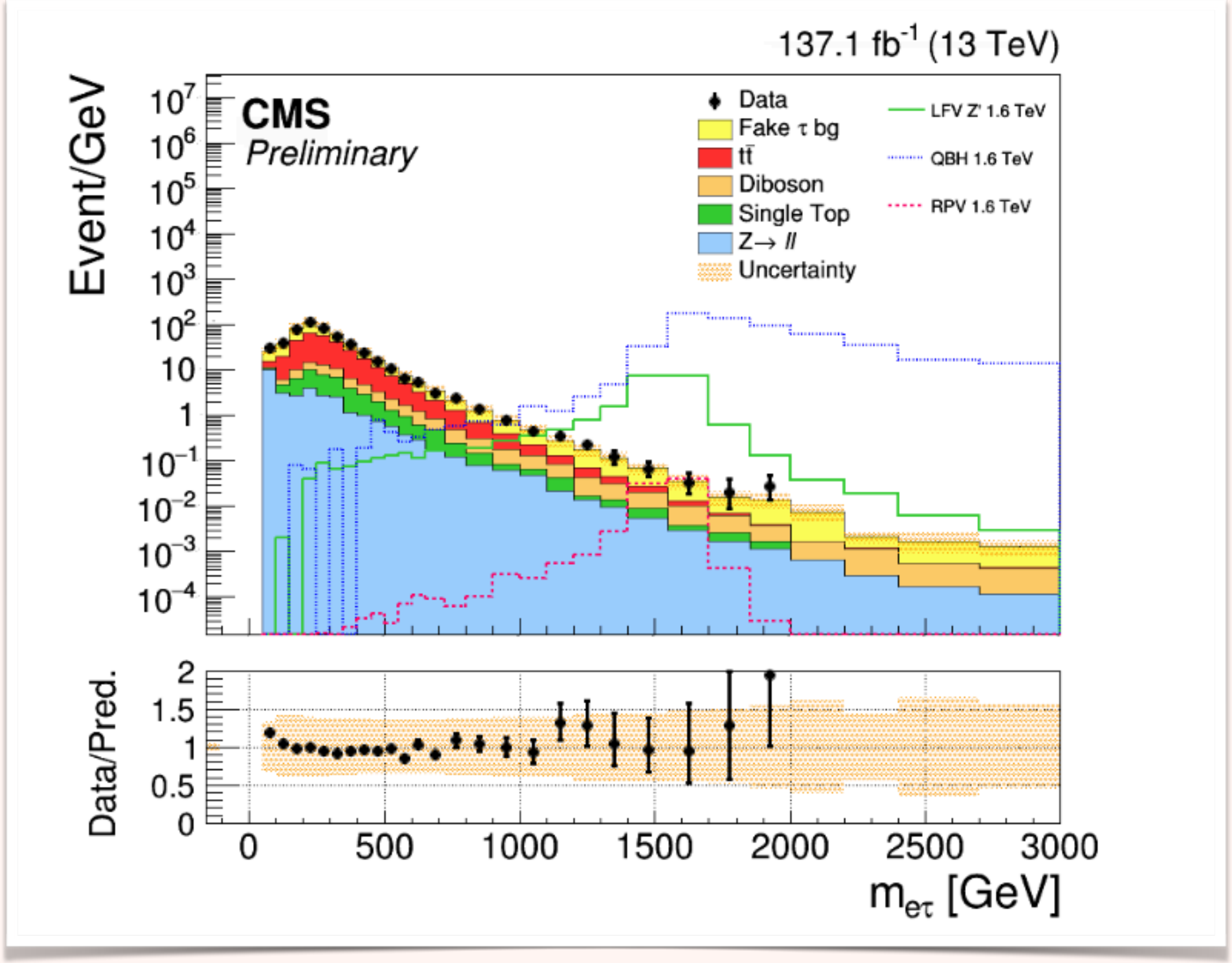
$$m_{col} = \frac{m_{vis}}{\sqrt{x_{vis}}}$$

$$x_{vis} = \frac{p_T(\tau_h)}{p_T(\tau_h) + \not{p}_{T\,col}}$$

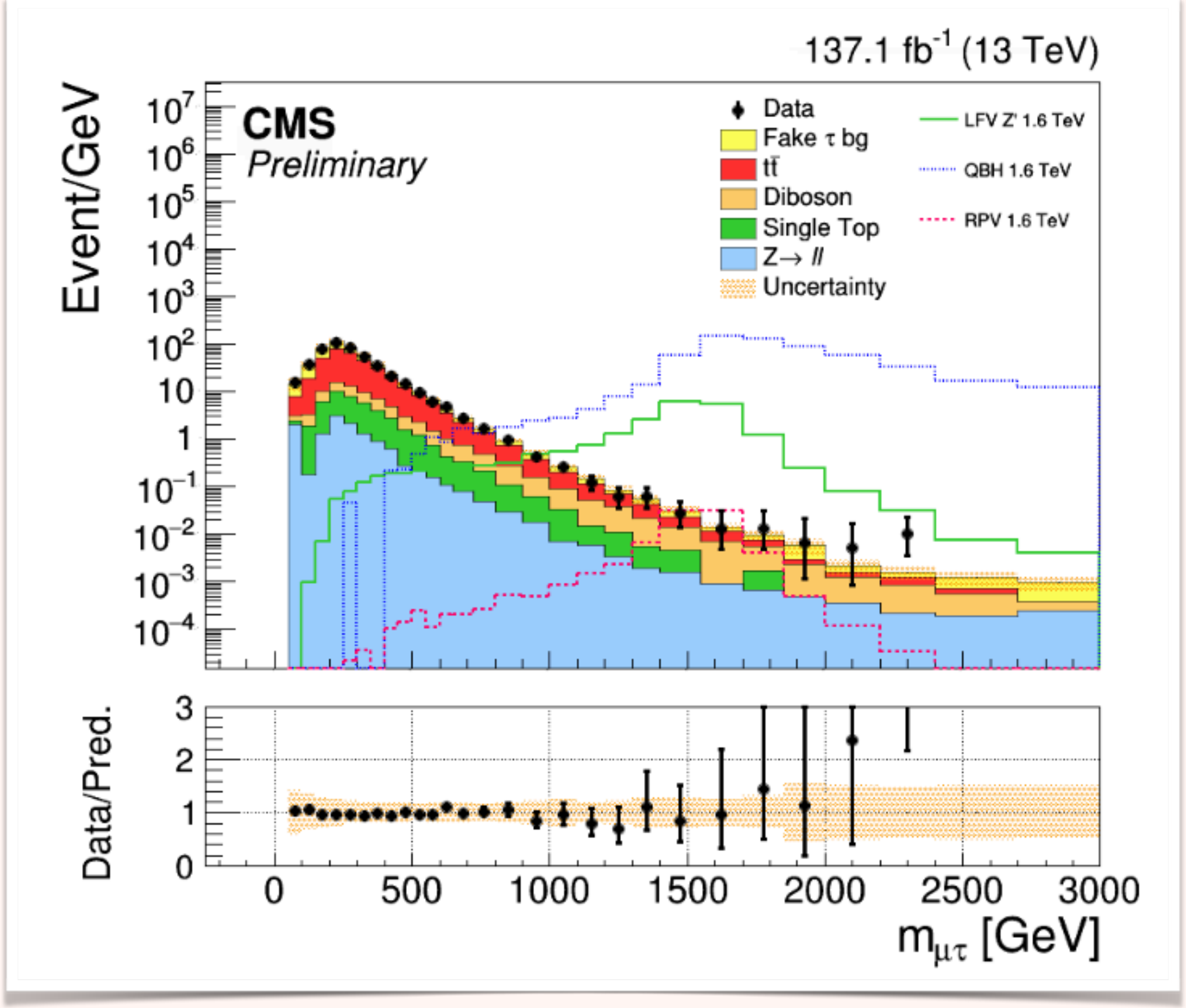
$$\not{p}_{T\,col} = \max\left(\frac{\vec{\not{p}}_T \cdot \vec{p}_T(\tau_h)}{p_T(\tau_h)}, 0\right)$$

Collinear mass distribution in Tau final states ($e\tau$, $\mu\tau$)

$e\tau$ final state



$\mu\tau$ final state

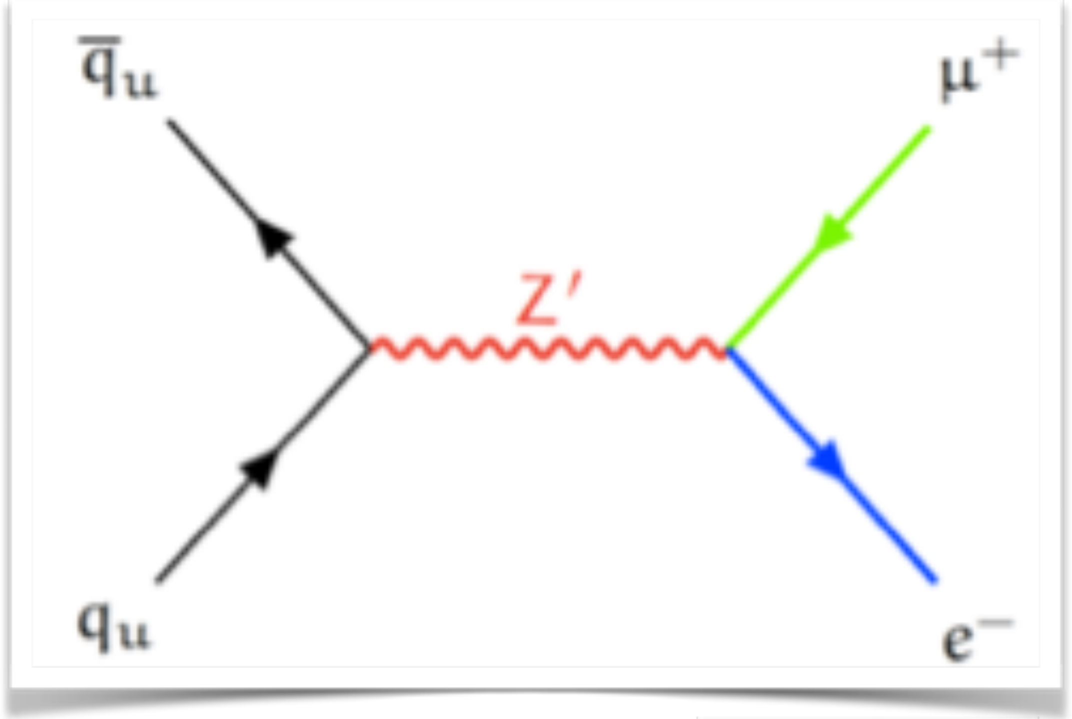


No significant excess observed over SM prediction

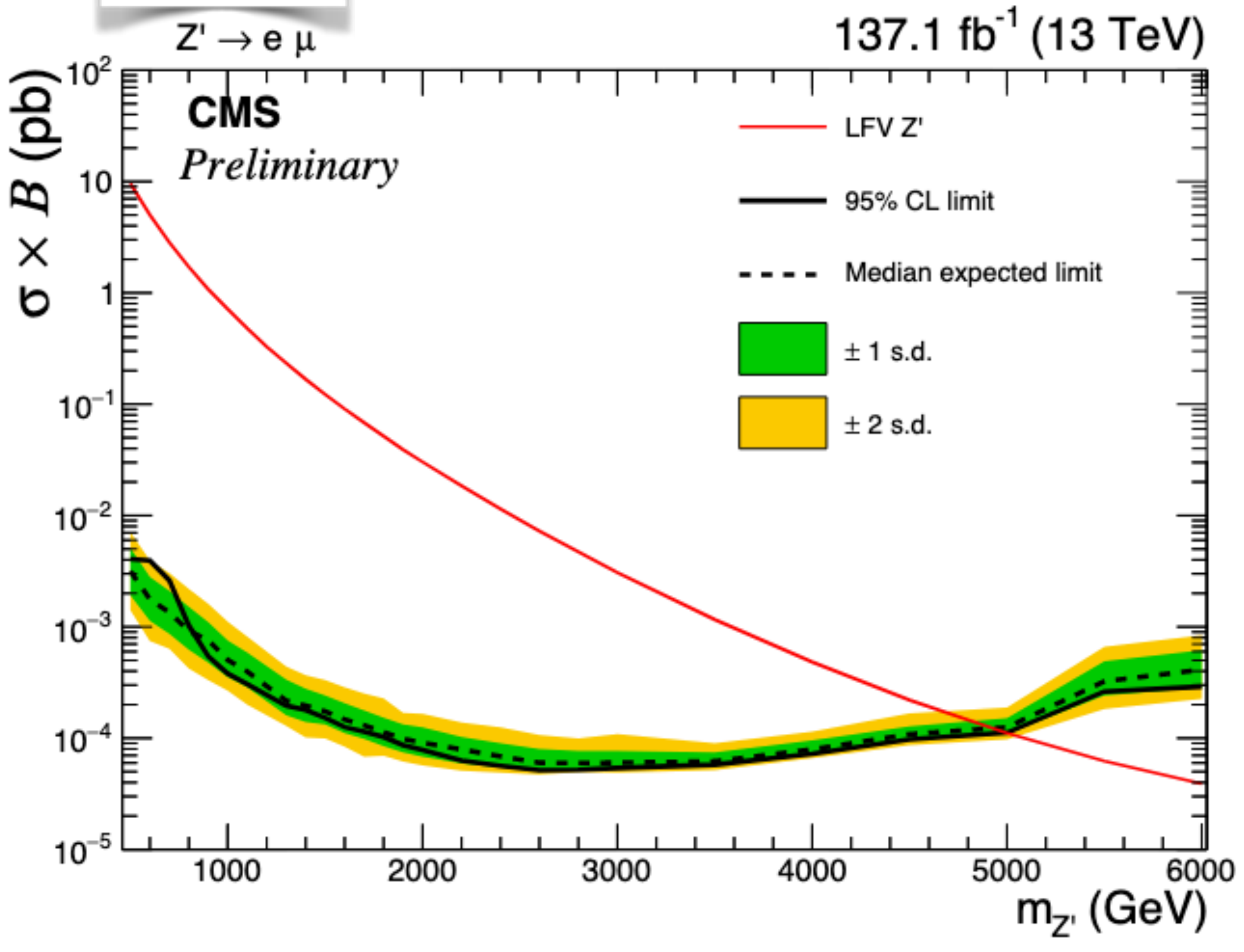
Dominant systematic uncertainty from Fake-τ estimation

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

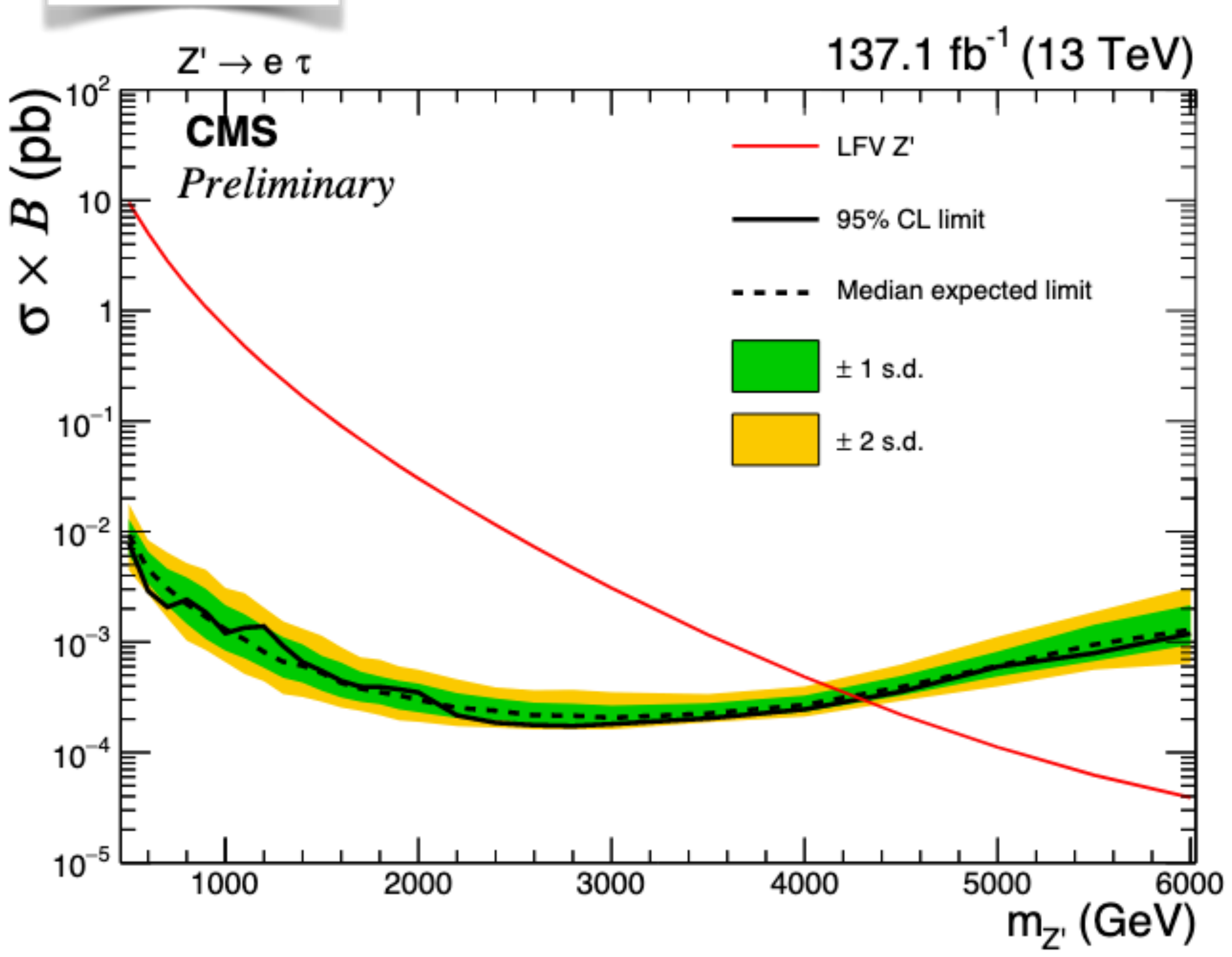


eμ



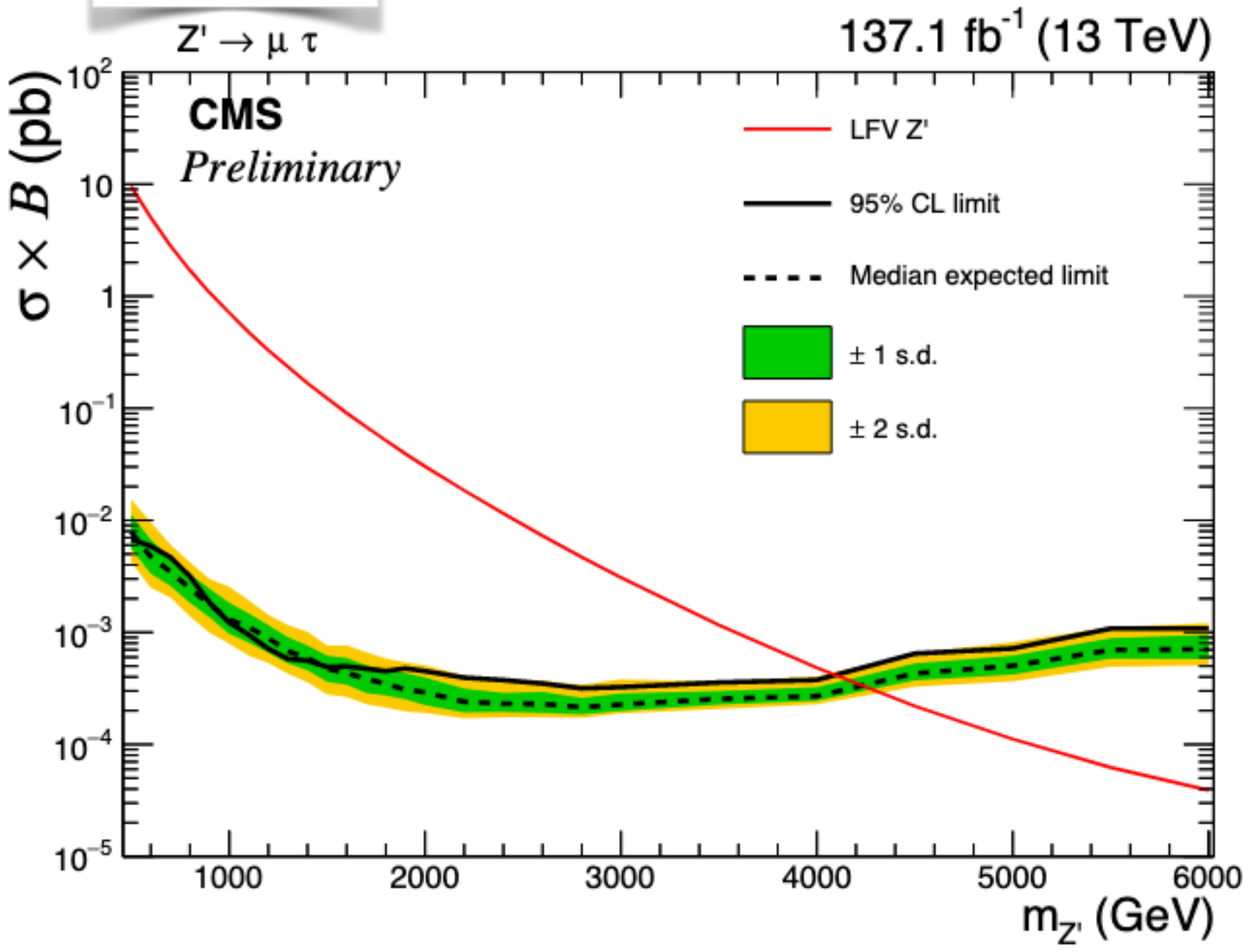
Mass limit: 5.0 (4.9) TeV

eτ



Mass limit: 4.3 (4.3) TeV

μτ



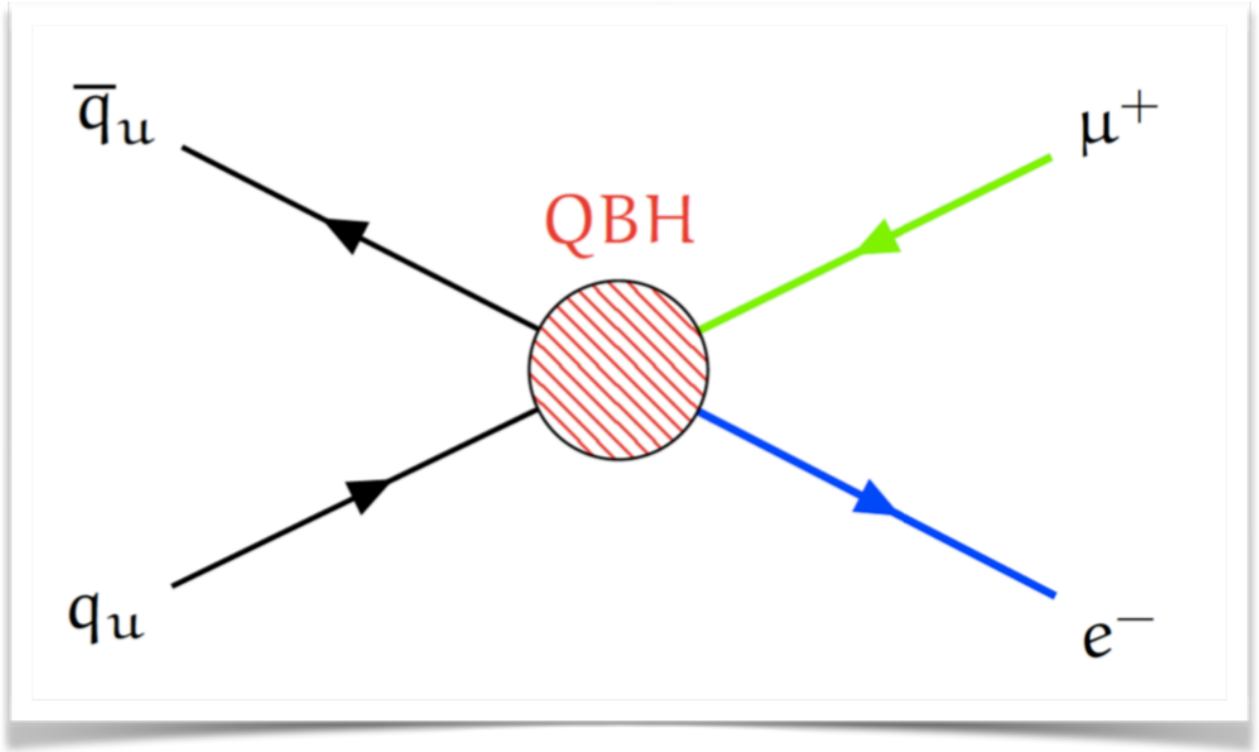
Mass limit: 4.1 (4.2) TeV

Results of this search are currently the best limits from the LHC in the considered models.

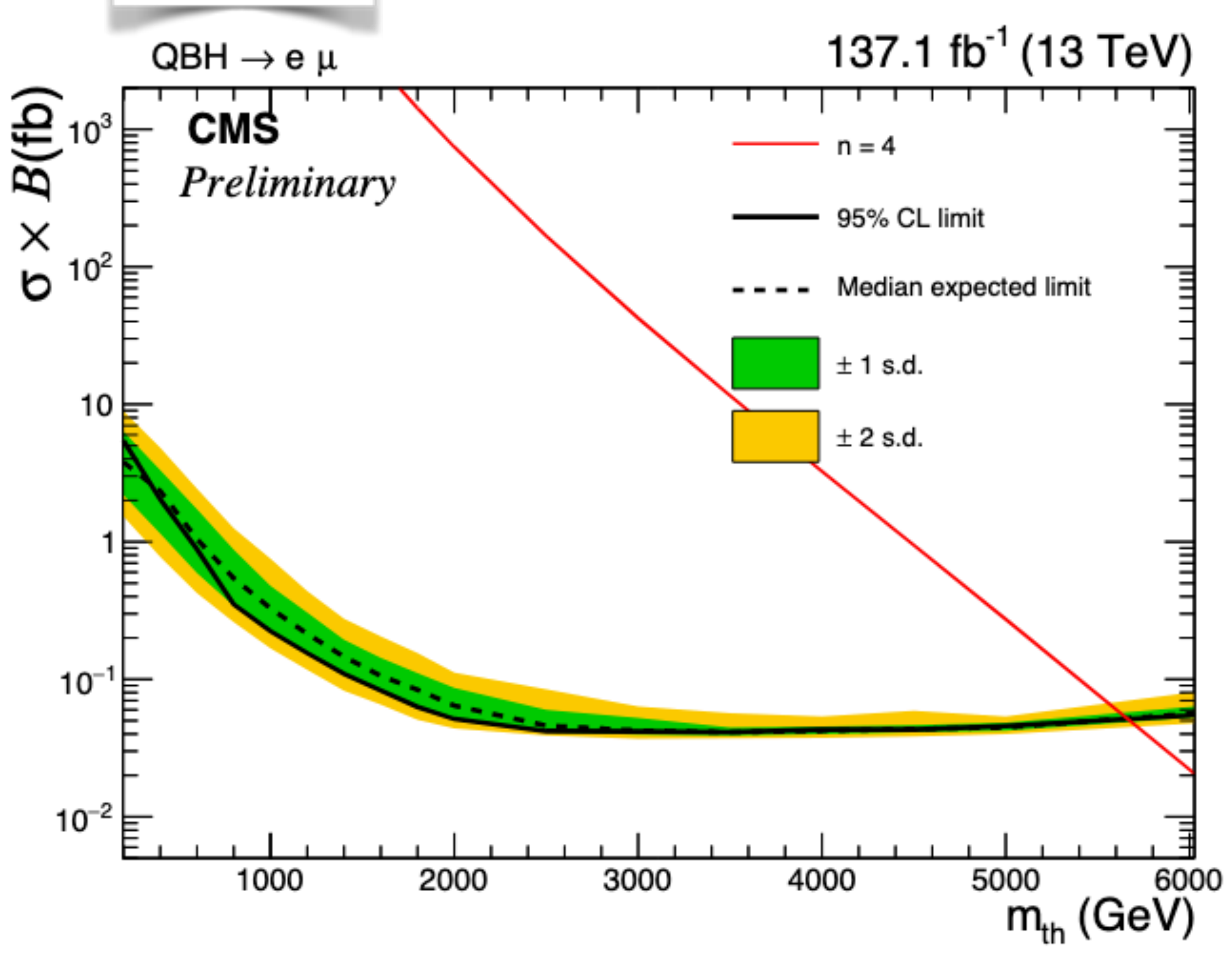
QBH interpretation

Extra dimension(s)→ Fundamental Planck scale lowered to TeV region

- QBH produced if $\sqrt{s}$ > MP
- Spin-0, colorless, charge-neutral QBH
- Cross section depends on threshold mass for QBH production (M_{th}=MP) and number of extra dimensions (n)

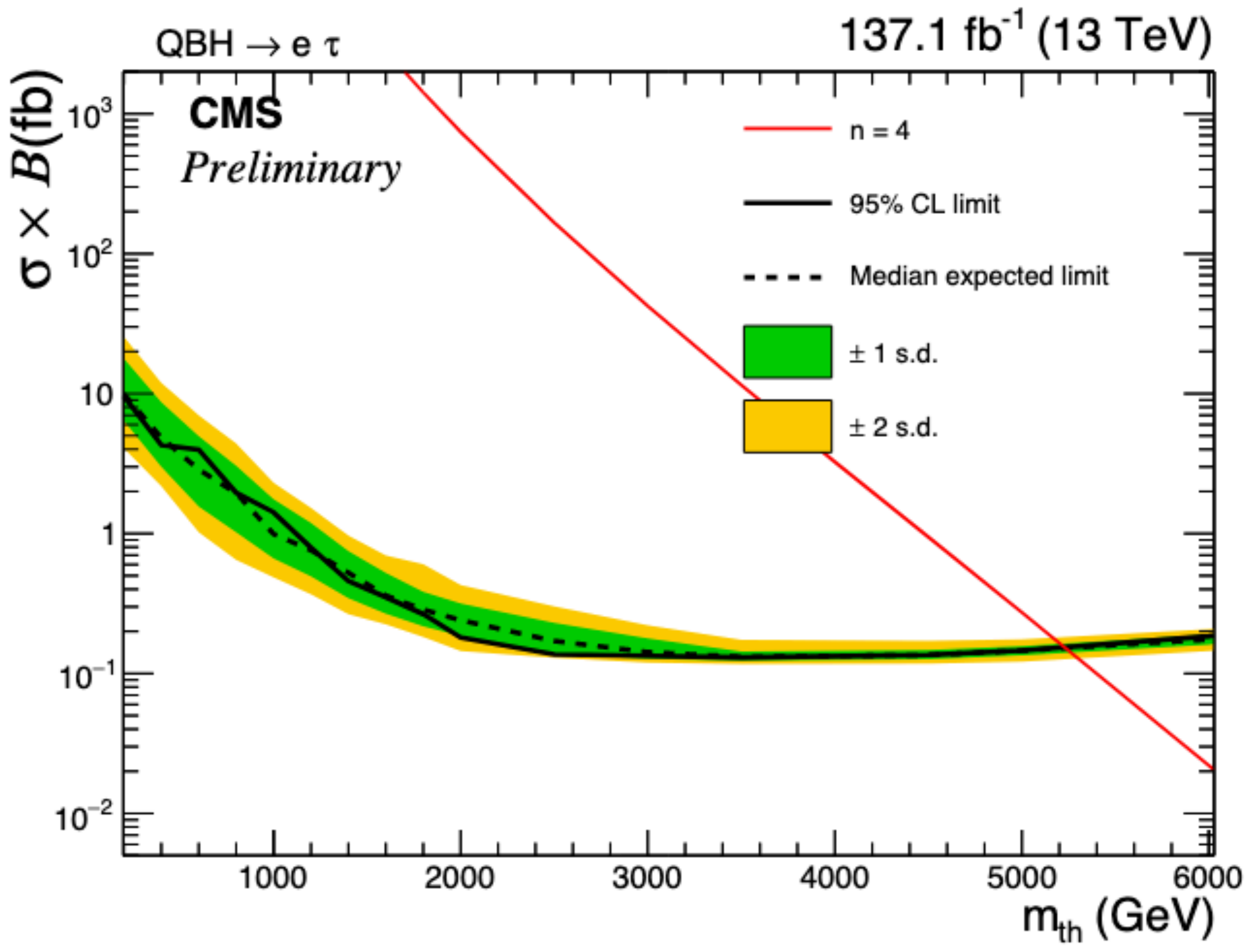


eμ



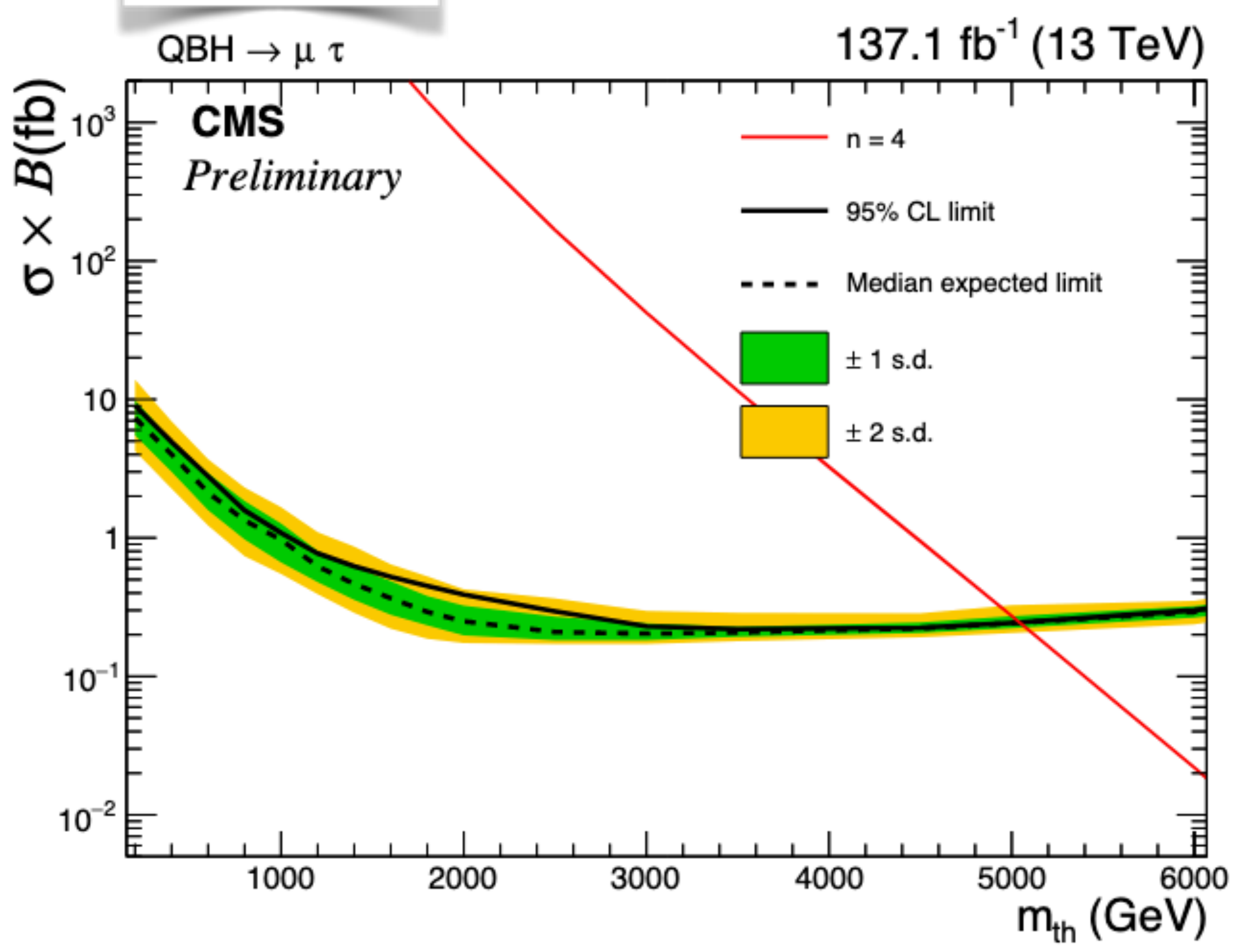
Mass limit: 5.6 (5.6) TeV

eτ



Mass limit: 5.2 (5.2) TeV

μτ



Mass limit: 5.0 (5.0) TeV

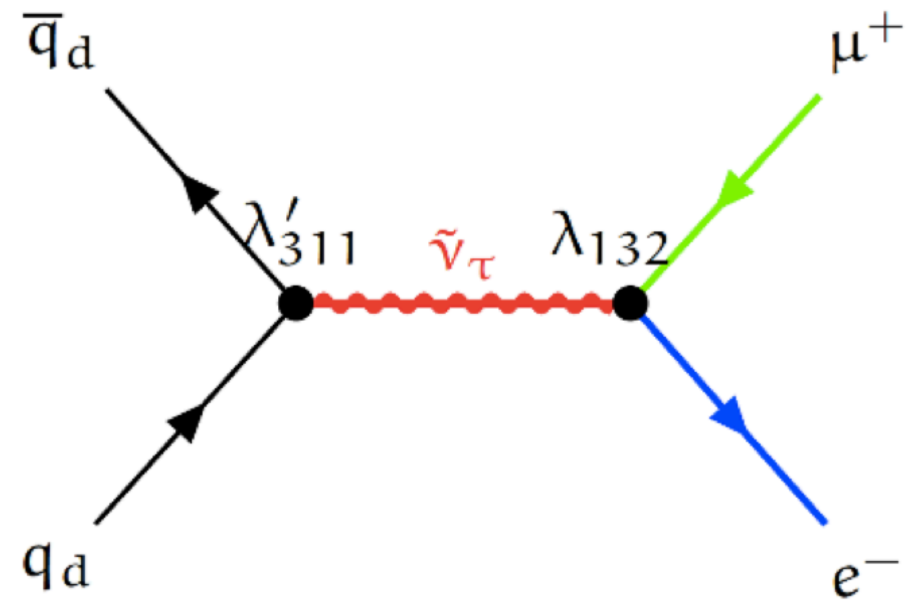
Results of this search are currently the best limits from the LHC in the considered models.

RPV SUSY interpretation

R-parity (R) = $(-1)^{3B+L+2s}$

- Resonant production of τ sneutrino LSP
- Decay to leptons of different flavours

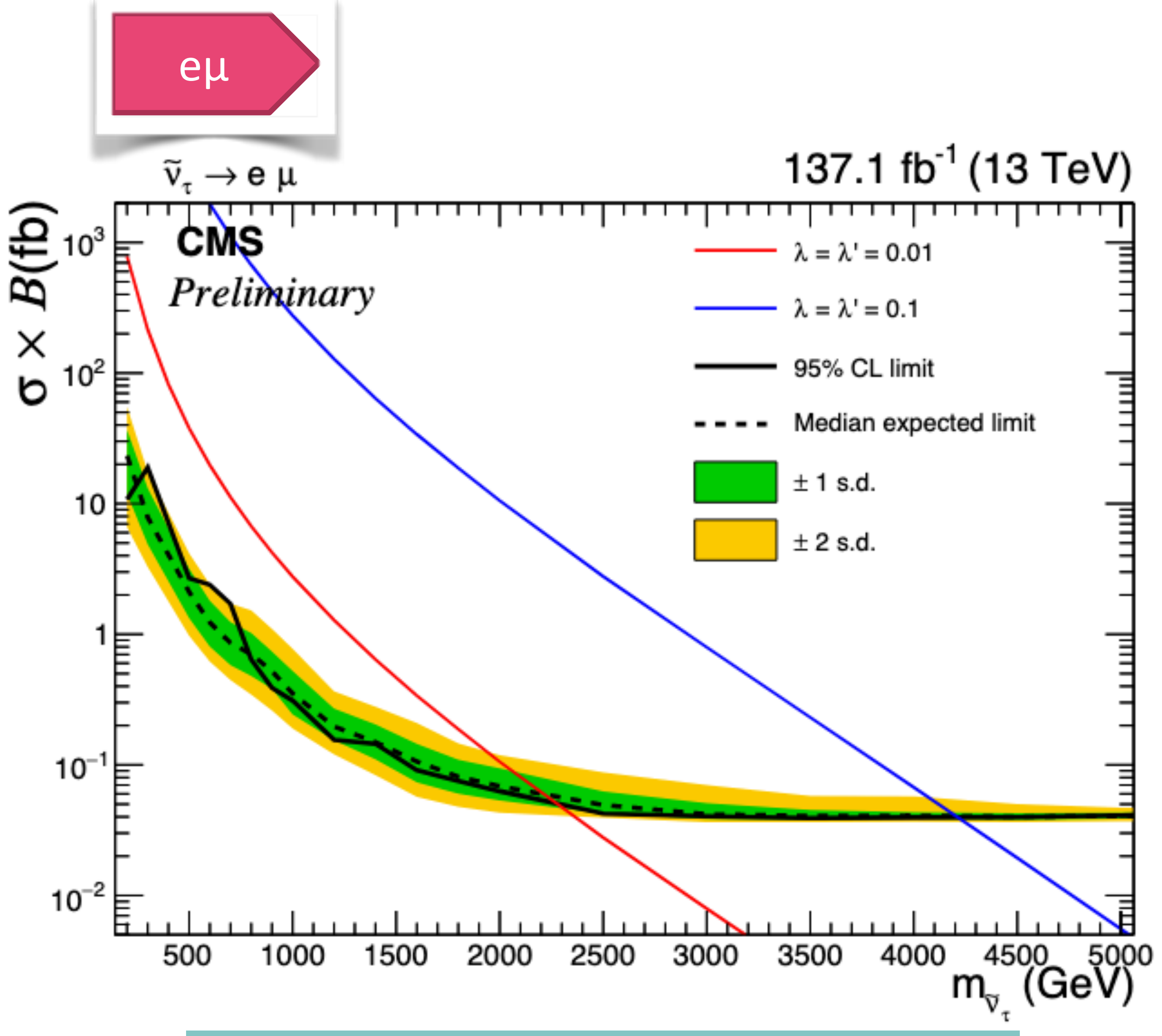
Assume all RPV couplings vanish, except λ'_{311}, λ_{i3j}, λ_{j3i}



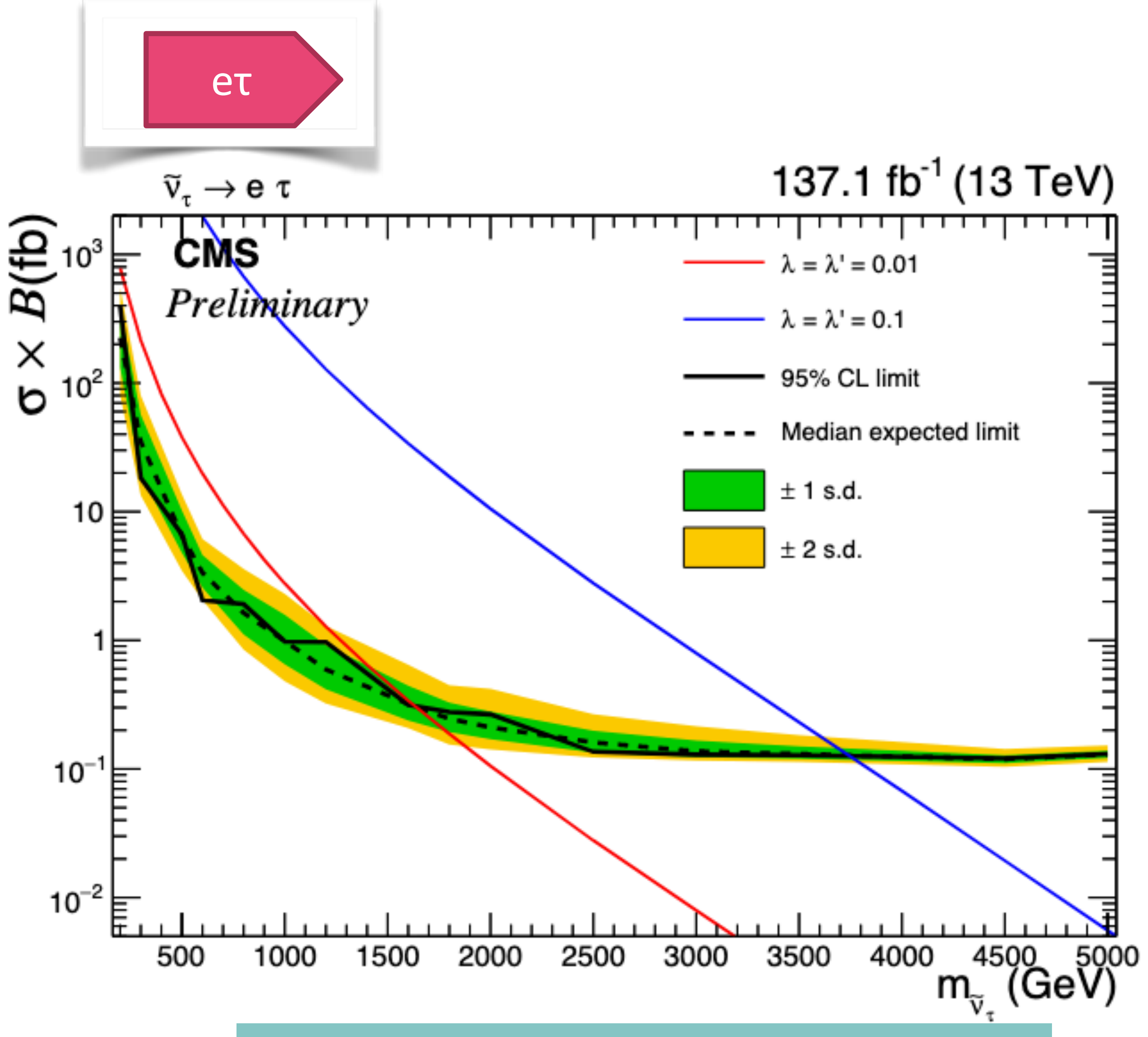
$$W_{RPV} = \frac{1}{2}\lambda_{ijk}L_iL_j\overline{E}_k + \lambda'_{ijk}L_iQ_j\overline{D}_k,$$

LLE LQD

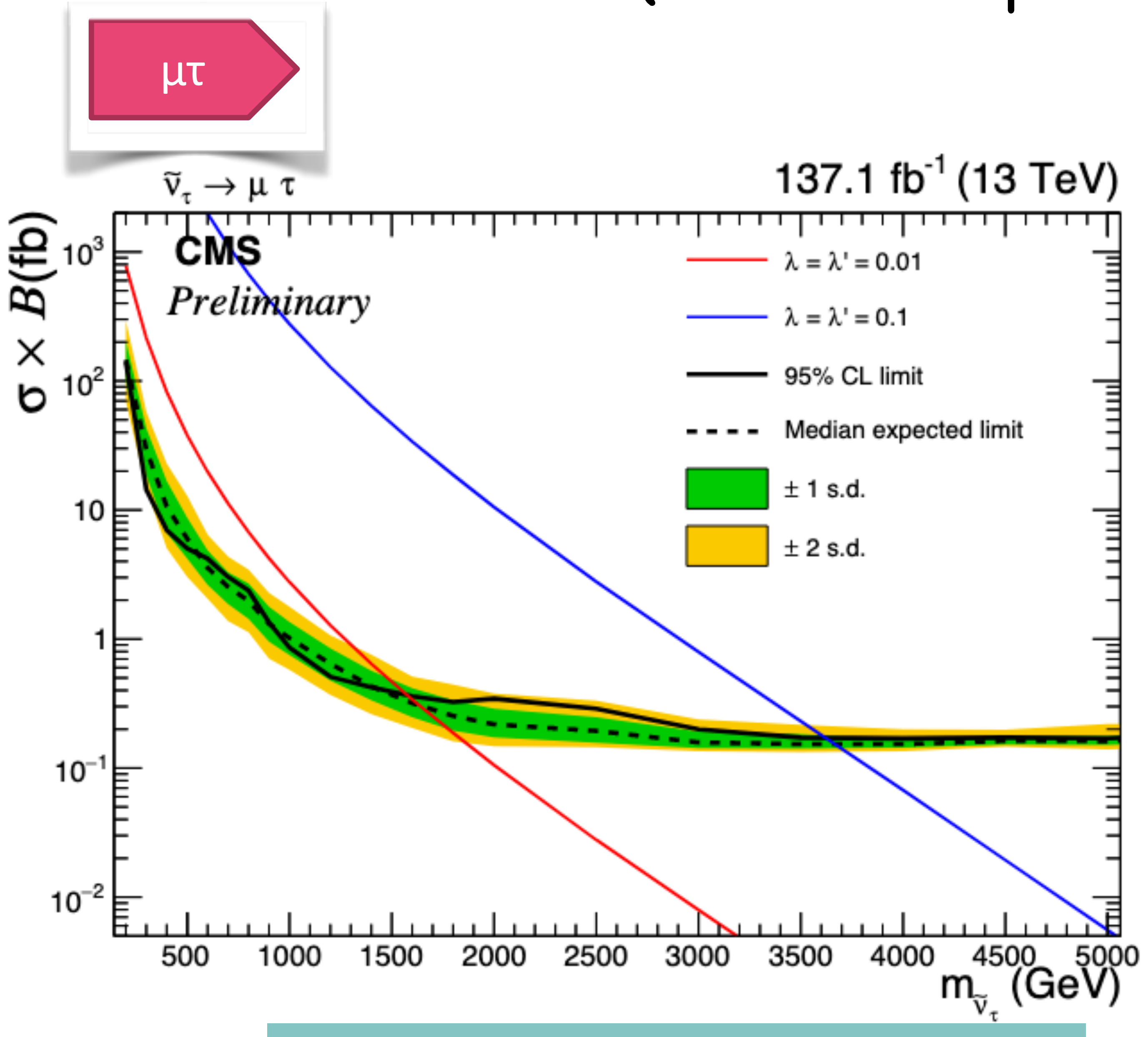
λ and λ′ terms violate lepton number (and also lepton flavor)



Mass limit: 4.2 (4.2) TeV
2.2 (2.2) TeV



Mass limit: 3.7 (3.7) TeV
1.6 (1.6) TeV



Mass limit: 3.6 (3.7) TeV
1.6 (1.6) TeV

Results of this search are currently the best limits from the LHC in the considered models.

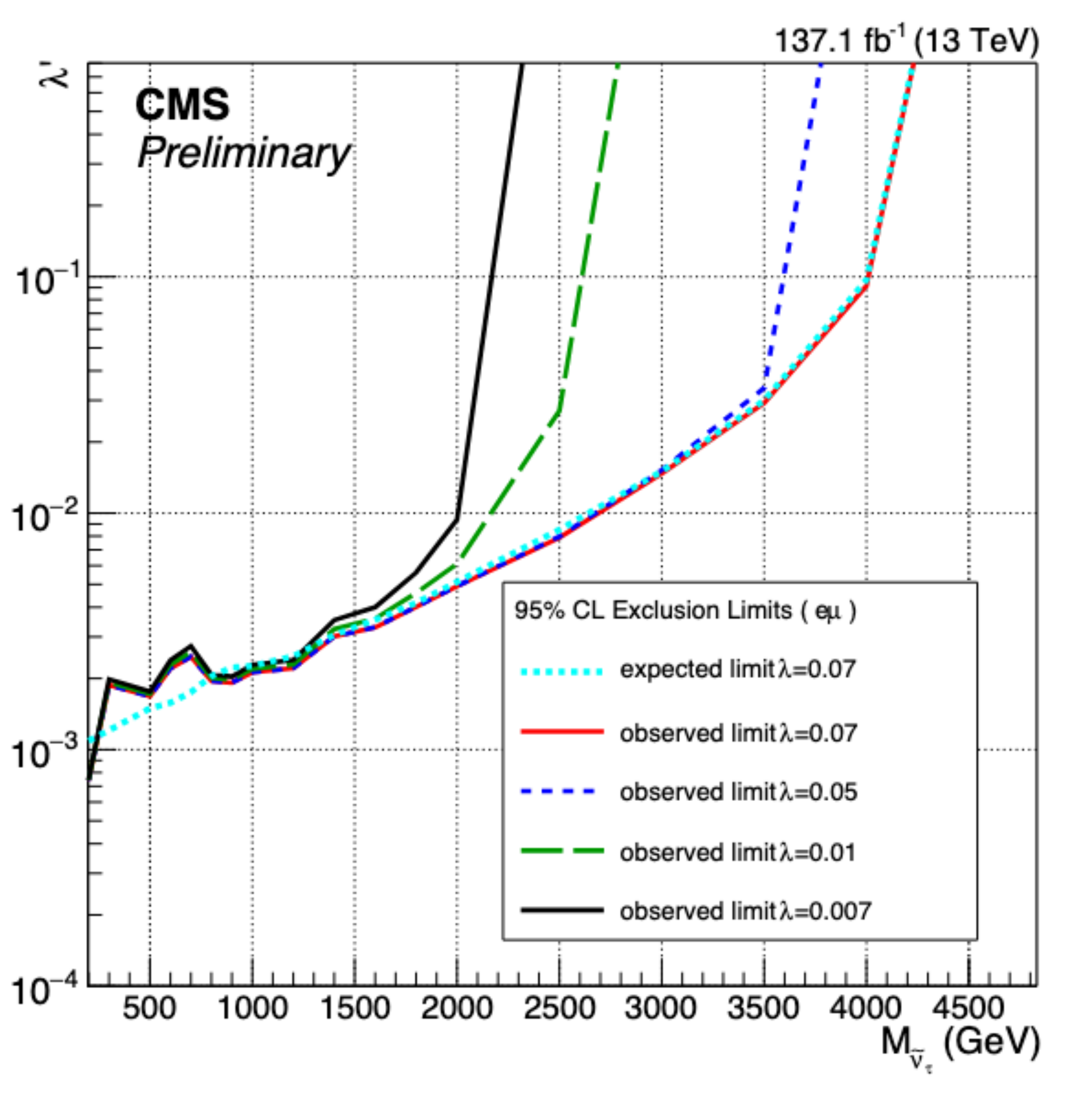
2D Limit Contour plots

In narrow width approximation

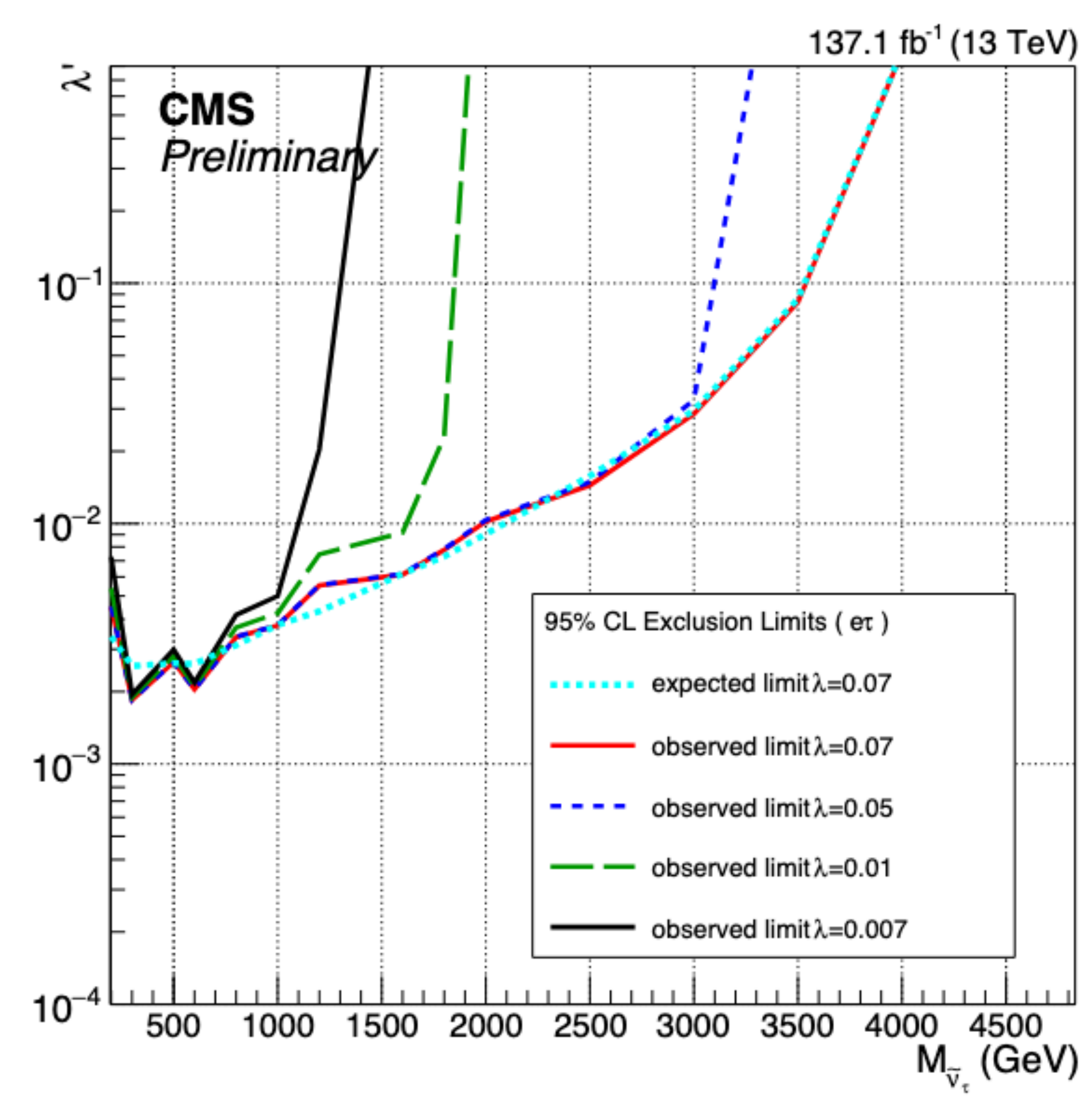
$$\sigma B \approx (\lambda'_{311})^2[(\lambda_{132})^2 + (\lambda_{231})^2]/(3(\lambda'_{311})^2 + [(\lambda_{132})^2 + (\lambda_{231})^2]).$$

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.

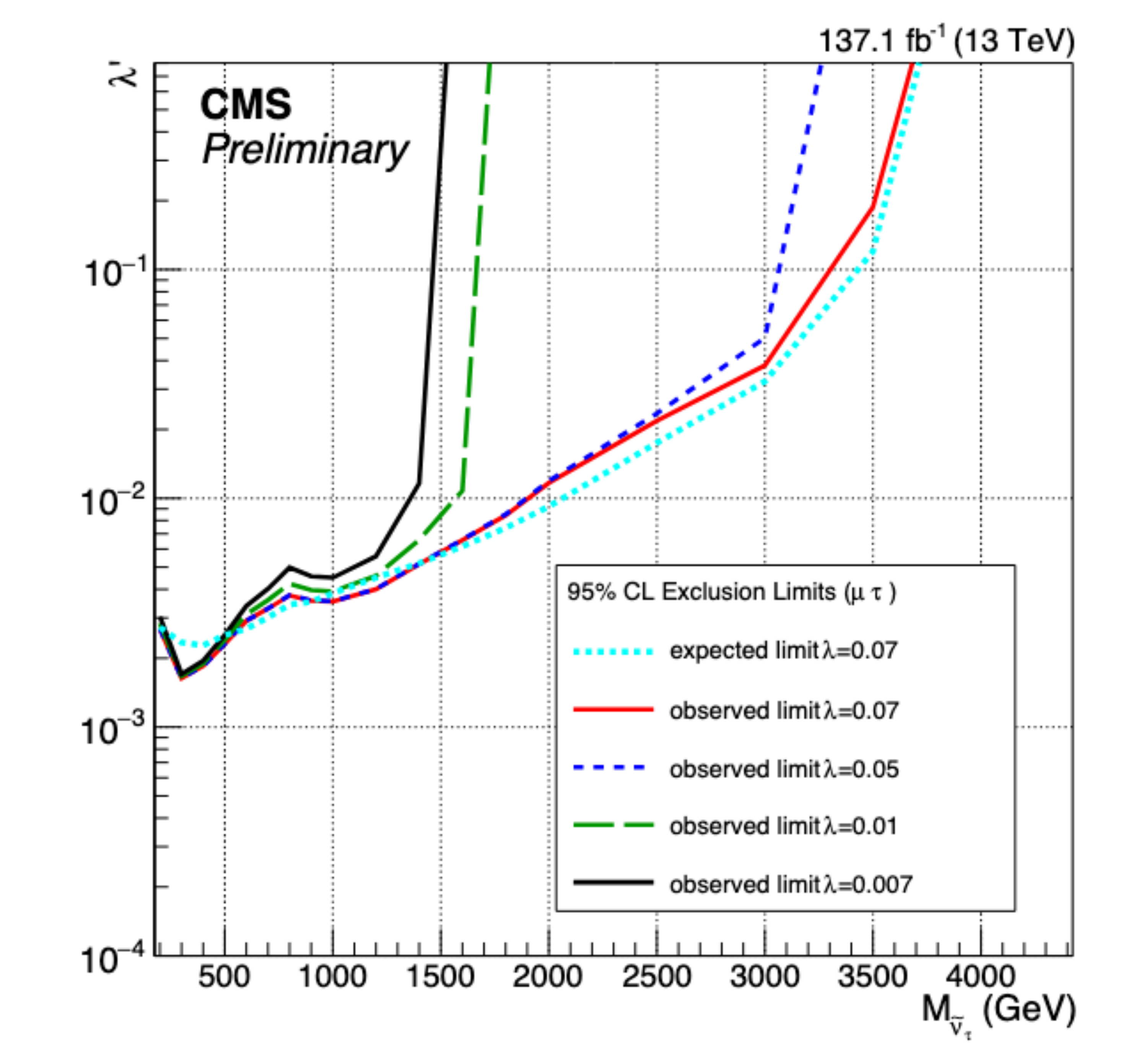
eμ



eτ



μτ

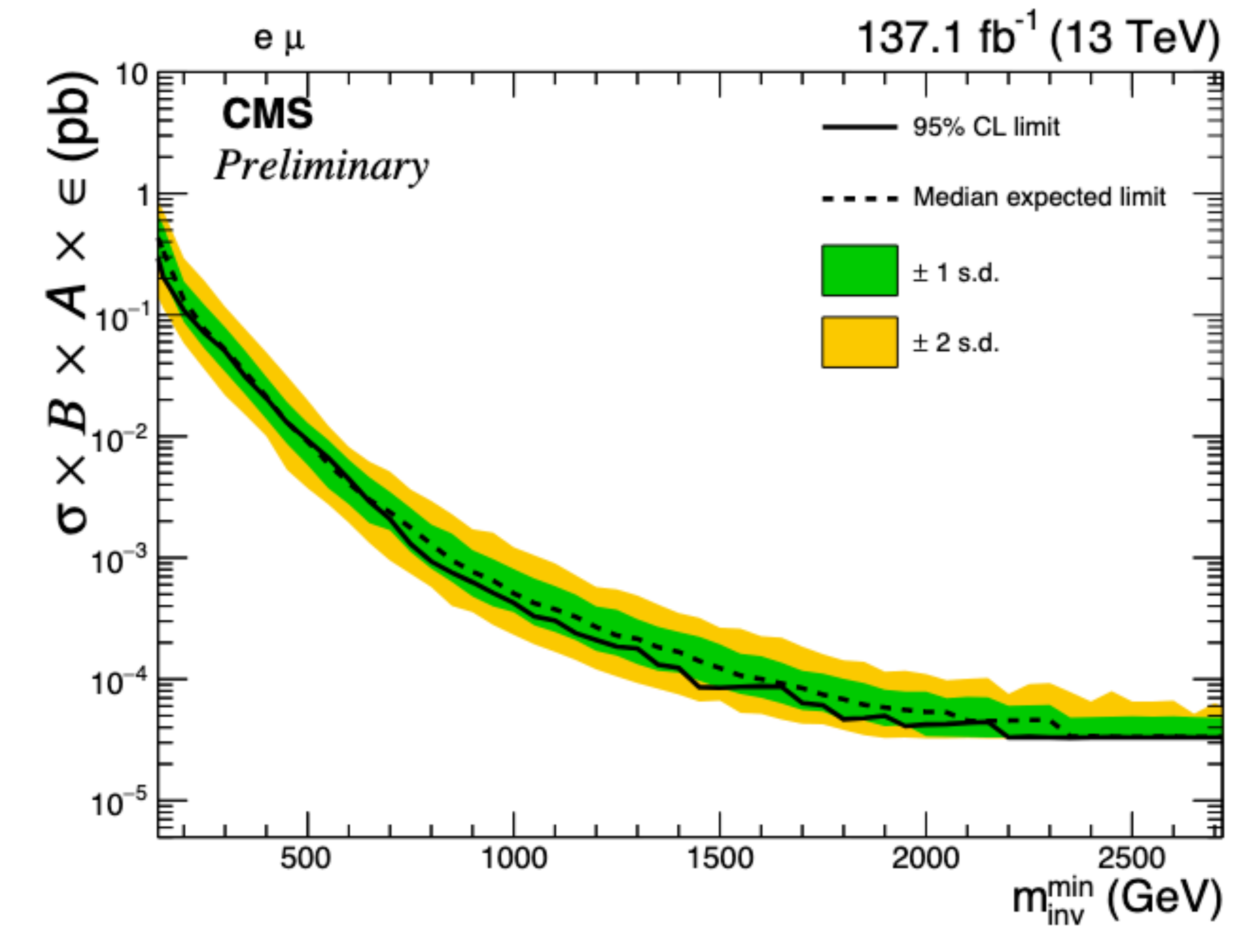


Model Independent Limits

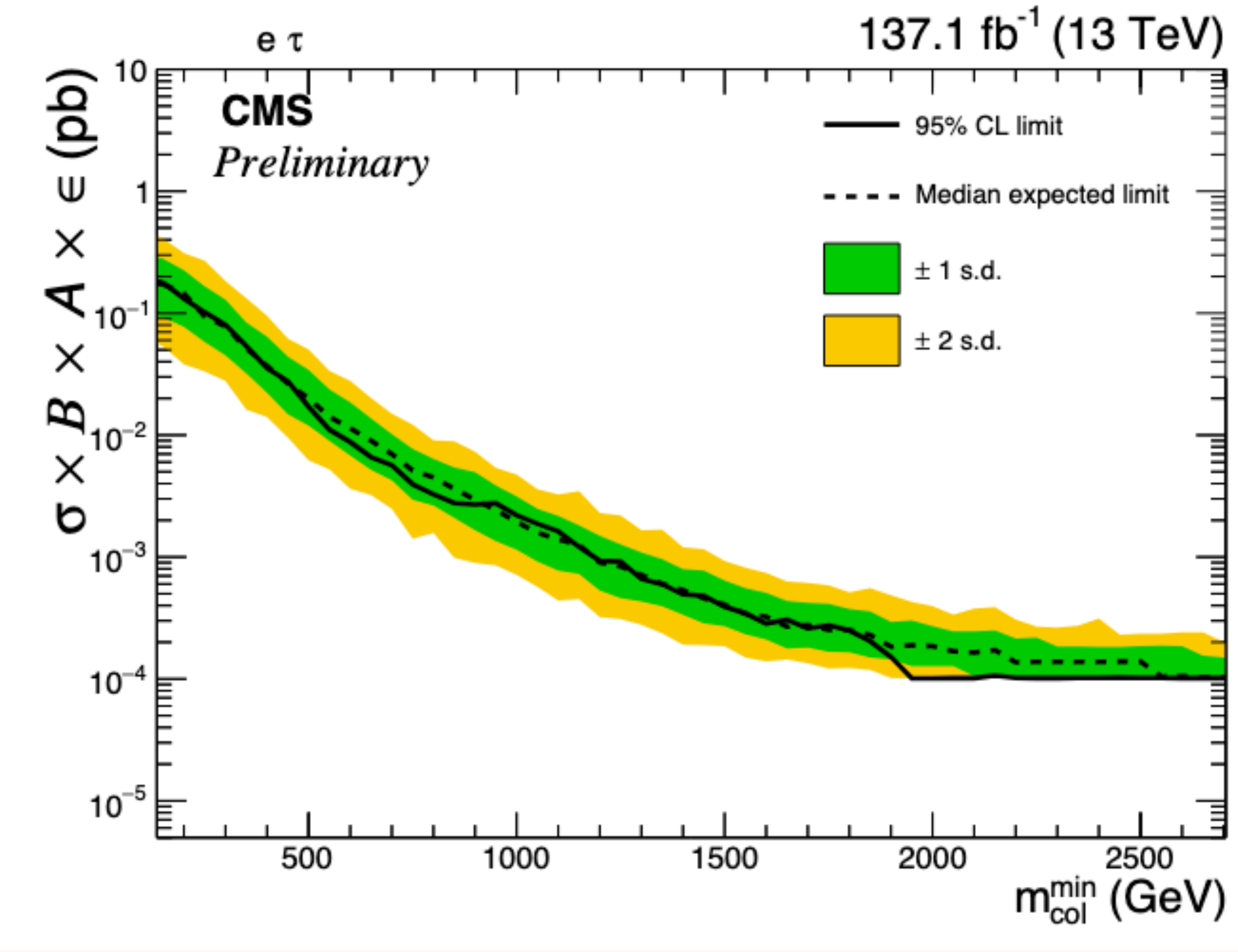
- Event counting above a mass threshold
- No assumptions on the signal shape other than a flat product of acceptance times efficiency as a function of the mass
- To derive limit for a specific model from the MI limit, the model-dependent part of the efficiency needs to be applied
- f_m is obtained by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

$$(\sigma \mathrm{BA}\epsilon)_{\mathrm{excl}} = \frac{(\sigma BA\epsilon)_{MI} m^{\mathrm{min}}}{f_m(m^{\mathrm{min}})}.$$

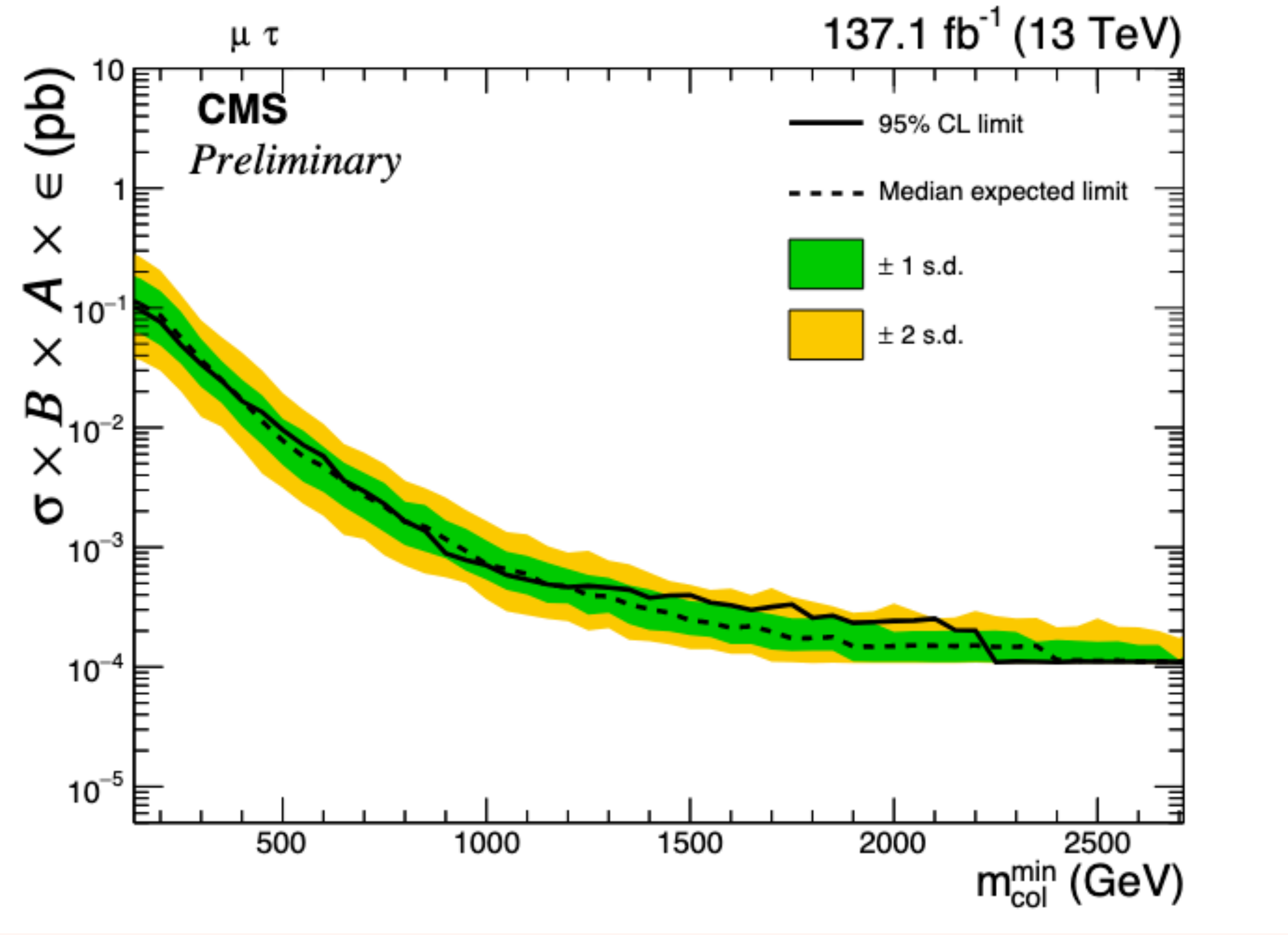
eμ



eτ



μτ



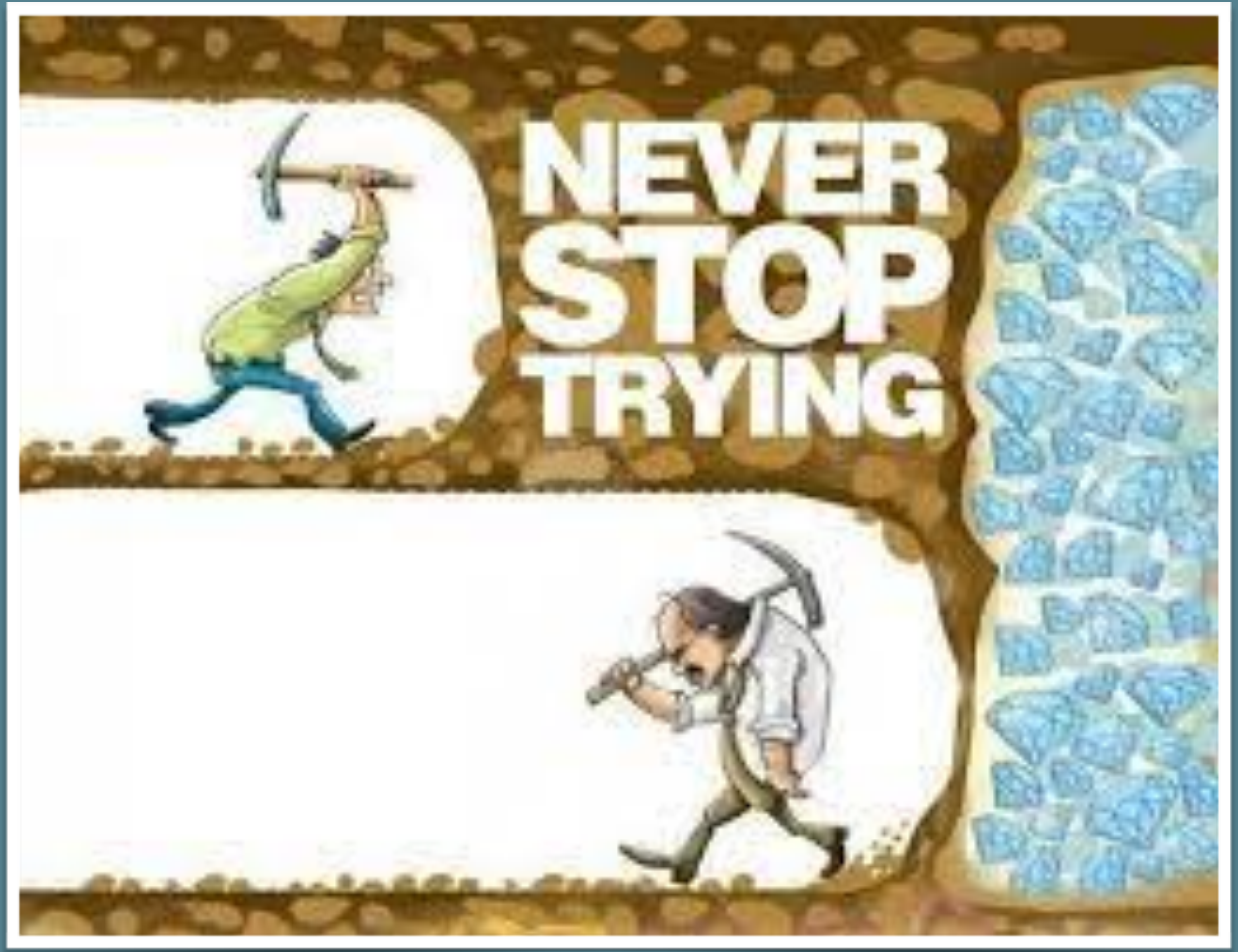
Summary

✓Charged LFV is an extremely clean and sensitive probe for physics beyond the Standard Model

✓Strong portfolio of charged LFV searches in CMS and ATLAS

✓ Presented some searches

✓ Unfortunately no sign of new physics yet
But these searches sets the strongest constraints to date



Stay tuned…. more to come

BACKUP

Systematic Uncertainties

- PU reweighting: minimum bias σ=69.2 mb, with 5% uncertainty
- Prefiring uncertainty (2016-2017)
- Luminosity: 2.5% uncertainty
- Electron uncertainties: energy scale and related to high energy electron id
- Muon uncertainties: energy scale , high pt ID and isolation
- Tau uncertainties: energy scale + Tau ID
- Trigger scale factor uncertainty
- Jet Energy Scale and Resolution
- MET uncertainty: unclustered MET
- Normalization uncertainties:
  tt(5%), WW(3%), DY (2%), single top (5%), WZ and ZZ (4%)
- Data driven BGs (50%)
- tt uncertainties: PDF + Qscale (arxiv: 1705.04105)
- WW uncertainties: PDF + Qscale (arxiv:1705.00598)

CMS LFV : EXO-19-014

Channel	RPV (TeV)		Z' (TeV)	QBH (TeV)
	$\lambda = \lambda' = 0.01$	$\lambda = \lambda' = 0.1$		
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)