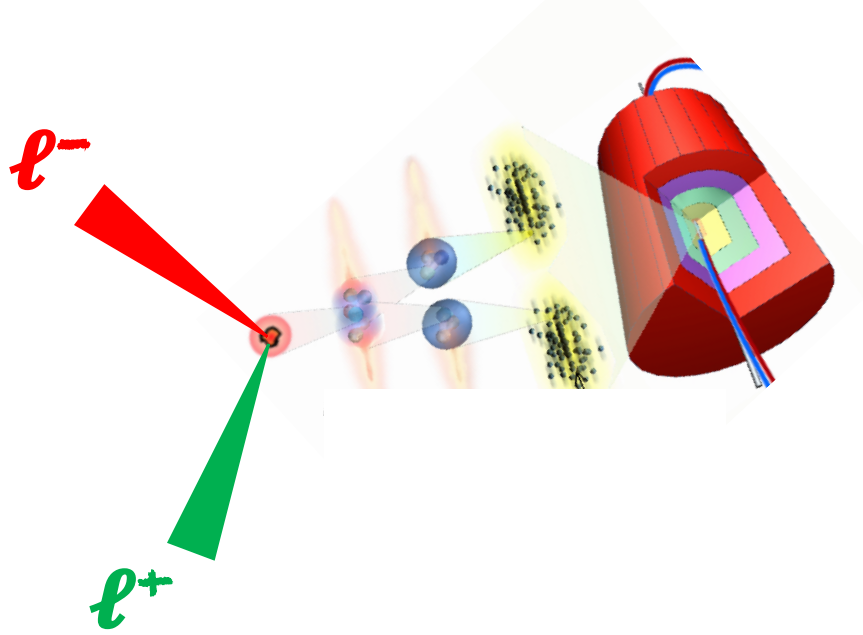
Searches with Lepton Flavor Violation at the CMS experiment



Varun sharma

University of Wisconsin – Madison, USA

on behalf of the CMS Collaboration

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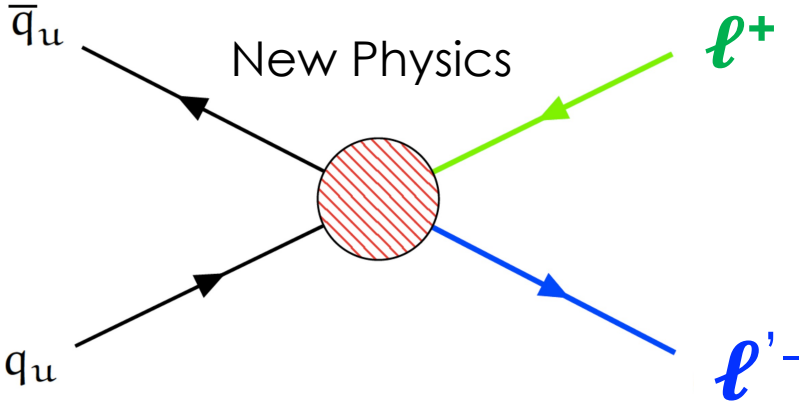
IBS, Center for Theoretical Physics of the Universe

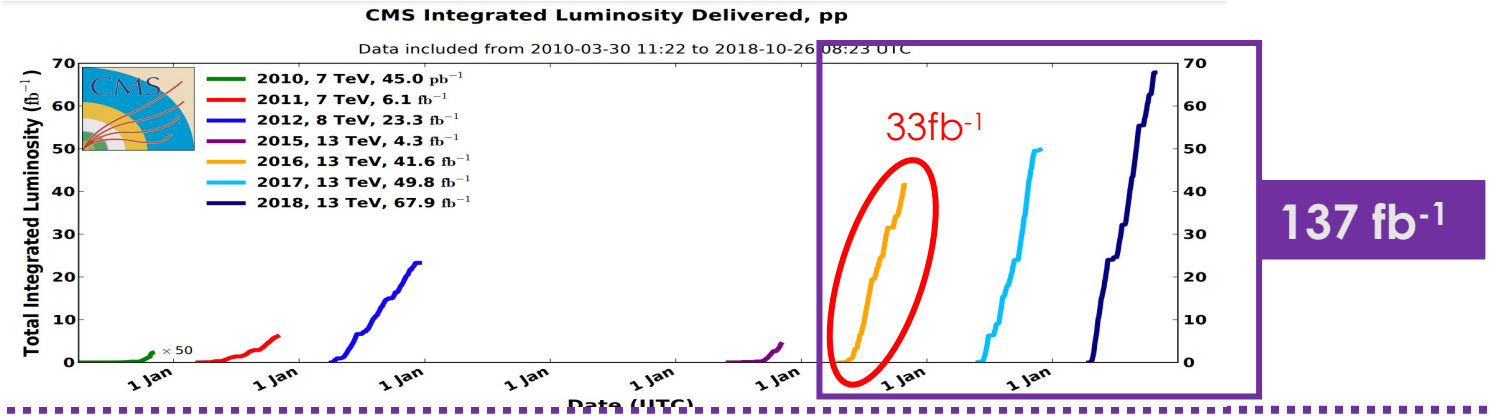
PASCOS 2021

26th International Symposium on Particles, Strings & Cosmology

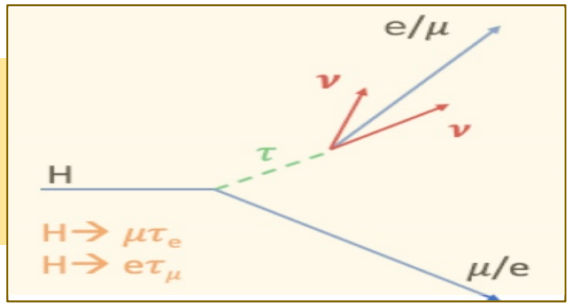
Introduction

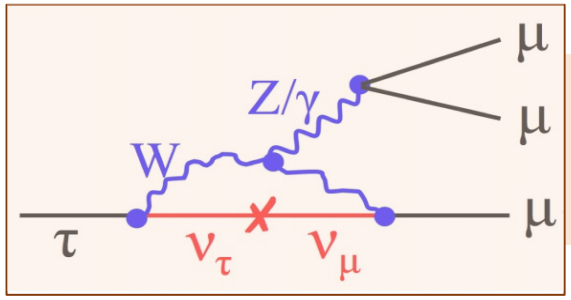
- Three generations of quarks, leptons: quarks change generations, so do neutrinos
- Non-zero Neutrino masses => Flavor exchange
- Though Particle Physics deal with symmetries but No fundamental law to forbid Charge Lepton Flavor Violation
- Will present different searches probing **Lepton Flavor/Number violation** using proton-proton collision data collected by the CMS experiment at $\sqrt{s}$ = 13 TeV





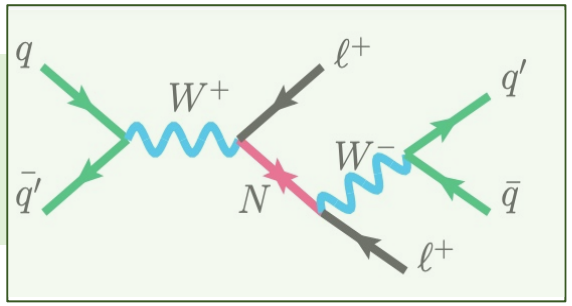
SM Higgs $\rightarrow e\tau$ & $\mu\tau$

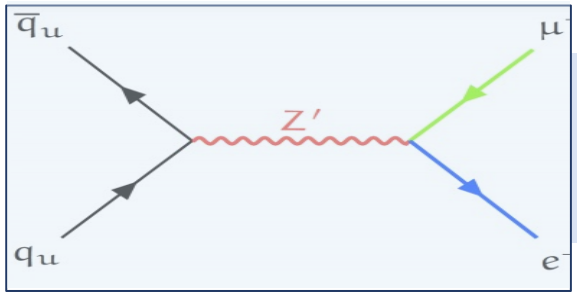




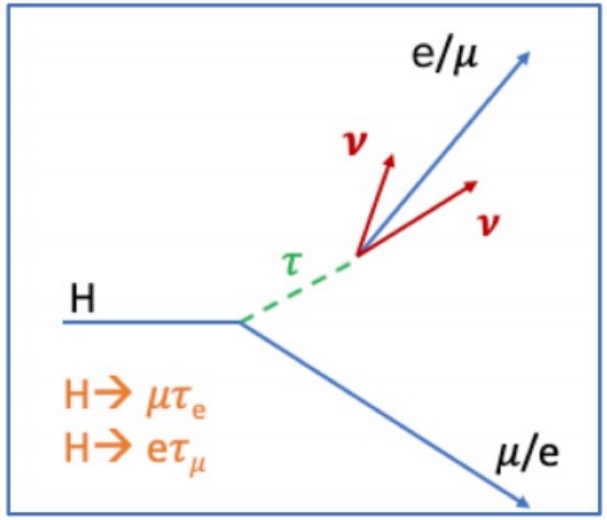
$\tau \rightarrow \mu\mu\mu$

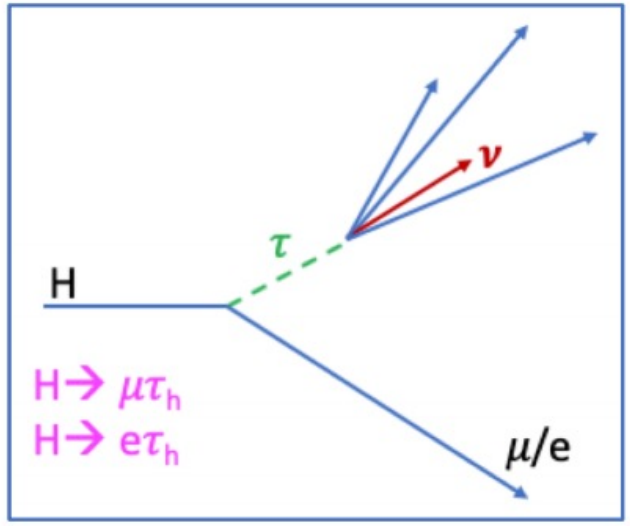
Heavy Majorana Neutrinos





Heavy Resonances to e-μ





LFV: SM Higgs → $e\tau$ & $\mu\tau$

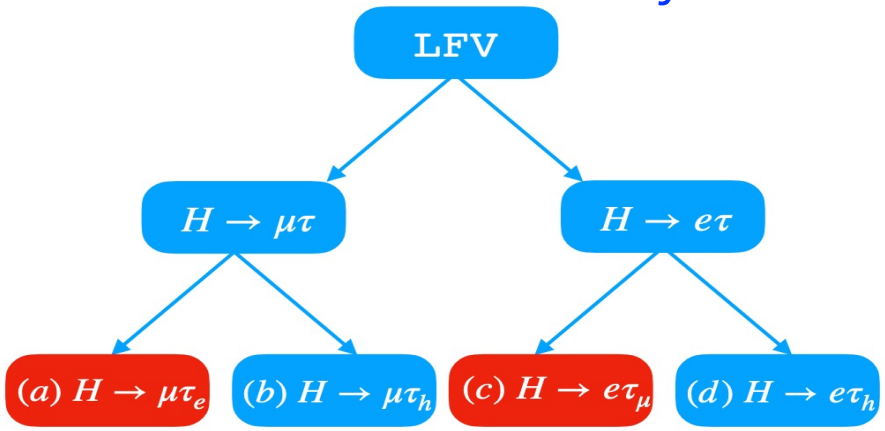
CMS-PAS-HIG-20-009 arXiv:2105.03007 (Submitted to PRD)

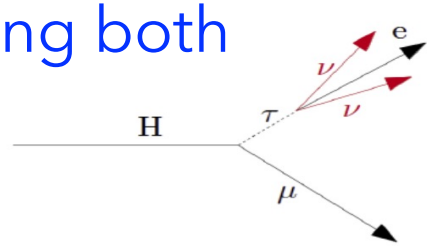
LFV: H $\rightarrow e/\mu + \tau$

arXiv:2105.03007
CMS-PAS-HIG-20-009

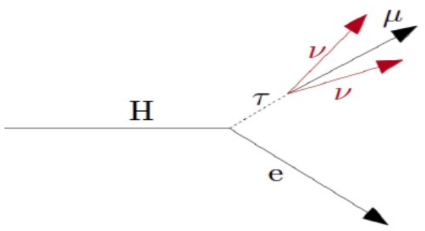
- Fermion mass in SM $\propto$ VEV while couplings to Higgs is given by Yukawa coupling
  - SM has only diagonal terms in Yukawa matrix while several BSM theories allow for off-diagonal terms ($Y_{e\mu}$, $Y_{e\tau}$, $Y_{\mu\tau}$)
- LFV decay of Higgs boson serves as a good probe for physics BSM

Search for H$\rightarrow\mu\tau$ & H$\rightarrow e\tau$ decays considering both leptonic and hadronic decays of τ

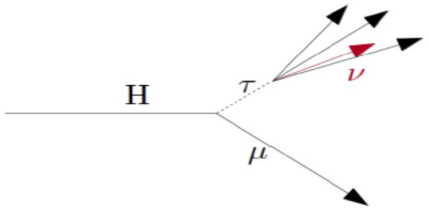




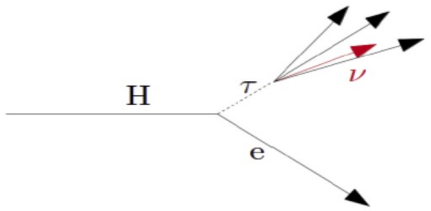
(a) leptonic: H $\rightarrow \mu\tau_e$



(c) leptonic: H $\rightarrow e\tau_\mu$



(b) hadronic: H $\rightarrow \mu\tau_h$



(d) hadronic: H $\rightarrow e\tau_h$

LFV: H $\rightarrow e/\mu + \tau$ | Strategy

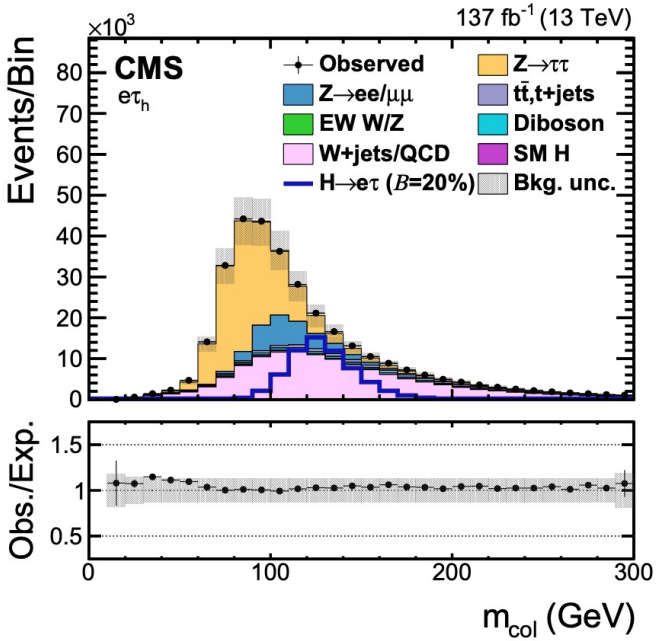
arXiv:2105.03007
CMS-PAS-HIG-20-009

Data set: 137 fb^{-1} of pp collision data (2016-2018)

Signal: ggH and VBF Higgs

Backgrounds

- Z+jets
- Mis-identified leptons (W+jets/QCD)
- ttbar and Single top
- Dibosons
- SM Higgs



Events categorization : 0 jets, 1 jet, 2 jets (ggH & VBF)

Signal extraction:

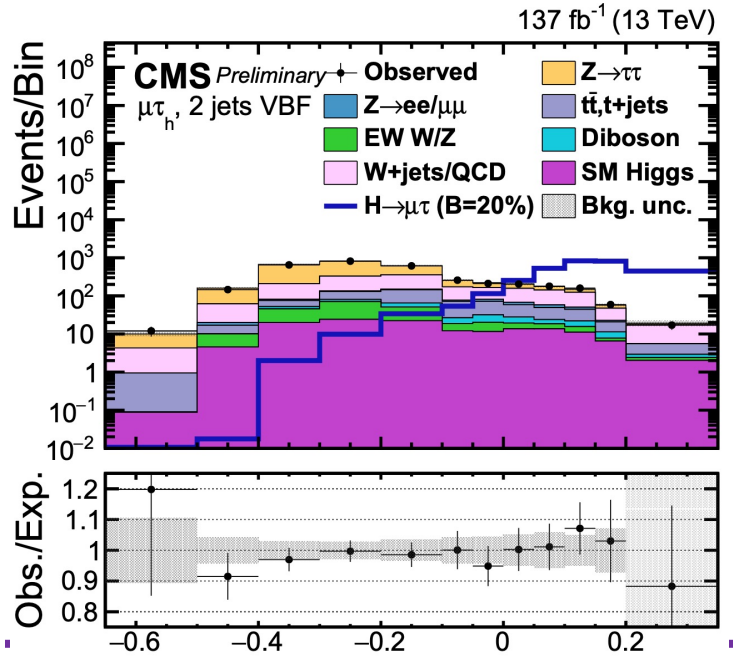
- BDT trained with adaptive boosting in TMVA to discriminate signal from background
- Max. likelihood fit of BDT discriminator distributions

Variables of Interest:

- Transverse Mass of Lepton & MET
- Collinear mass

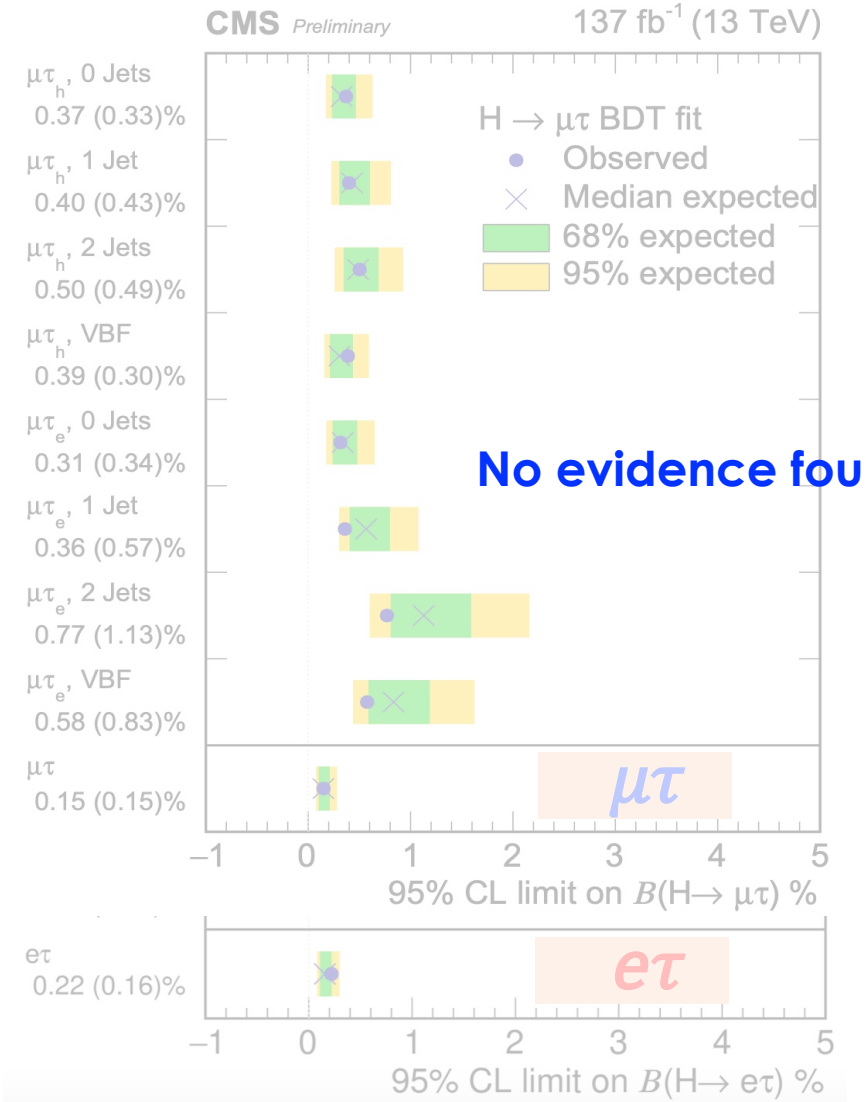
BDT Inputs

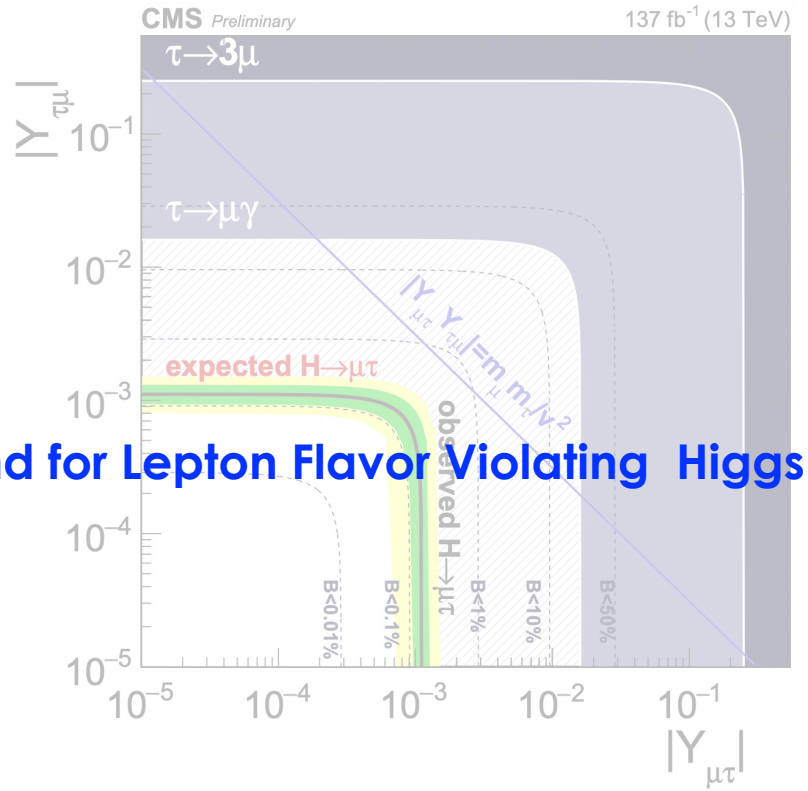
$H \rightarrow \mu\tau_h$	$H \rightarrow \mu\tau_e$	$H \rightarrow e\tau_h$	$H \rightarrow e\tau_\mu$
$M_{col}(\mu,\tau)$	$M_{col}(\mu,e)$	$M_{vis}(e,\tau)$	$M_{vis}(e,\mu)$
p_T^{μ}	p_T^{μ}	$\Delta\phi(\tau, MET)$	$M_{col}(e,\mu)$
$\Delta\phi(\tau, MET)$	$\Delta\phi(e, MET)$	$\Delta\eta(e,\tau)$	p_T^{e}
$E_T^{\vec{mis}}$	$\Delta\phi(\mu, MET)$	$\Delta\phi(e,\tau)$	$\Delta\phi(\mu, MET)$
$\Delta\phi(\mu,\tau)$	$\Delta\phi(\mu,e)$	$M_{col}(e,\tau)$	$\Delta\phi(e, MET)$
$\Delta\eta(\mu,\tau)$	$M_T(e, MET)$	p_T^{e}	$\Delta\phi(e,\mu)$
p_T^{τ}	$M_T(\mu, MET)$	$M_T(\tau, MET)$	p_T^{μ}
$M_T(\tau, MET)$	p_T^{e}	p_T^{τ}	$M_T(\mu, MET)$

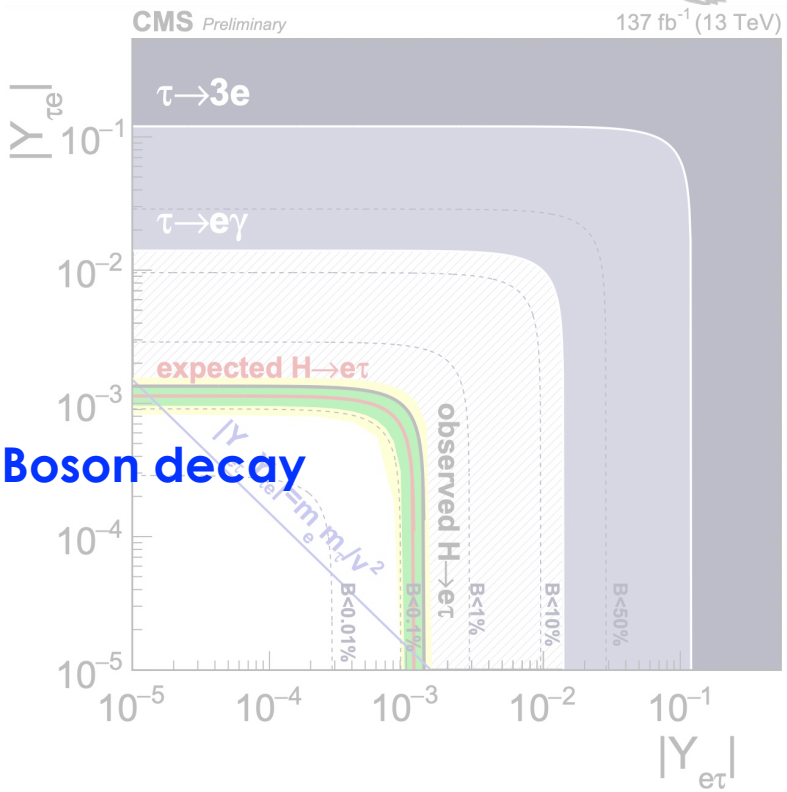


LFV: H $\rightarrow e/\mu + \tau$ | Results

arXiv:2105.03007
CMS-PAS-HIG-20-009







No evidence found for Lepton Flavor Violating Higgs Boson decay

Expected (red line) and observed (black solid line) 95% CL upper limits on the LFV Yukawa couplings

$$\mathrm{H} \rightarrow \mu\tau \;\; < 1.11\,(1.10) \times 10^{-3}$$
$$\mathrm{H} \rightarrow e\tau \;\; < 1.35\,(1.14) \times 10^{-3}$$

LFV: H $\rightarrow e/\mu + \tau$ | Results

arXiv:2105.03007
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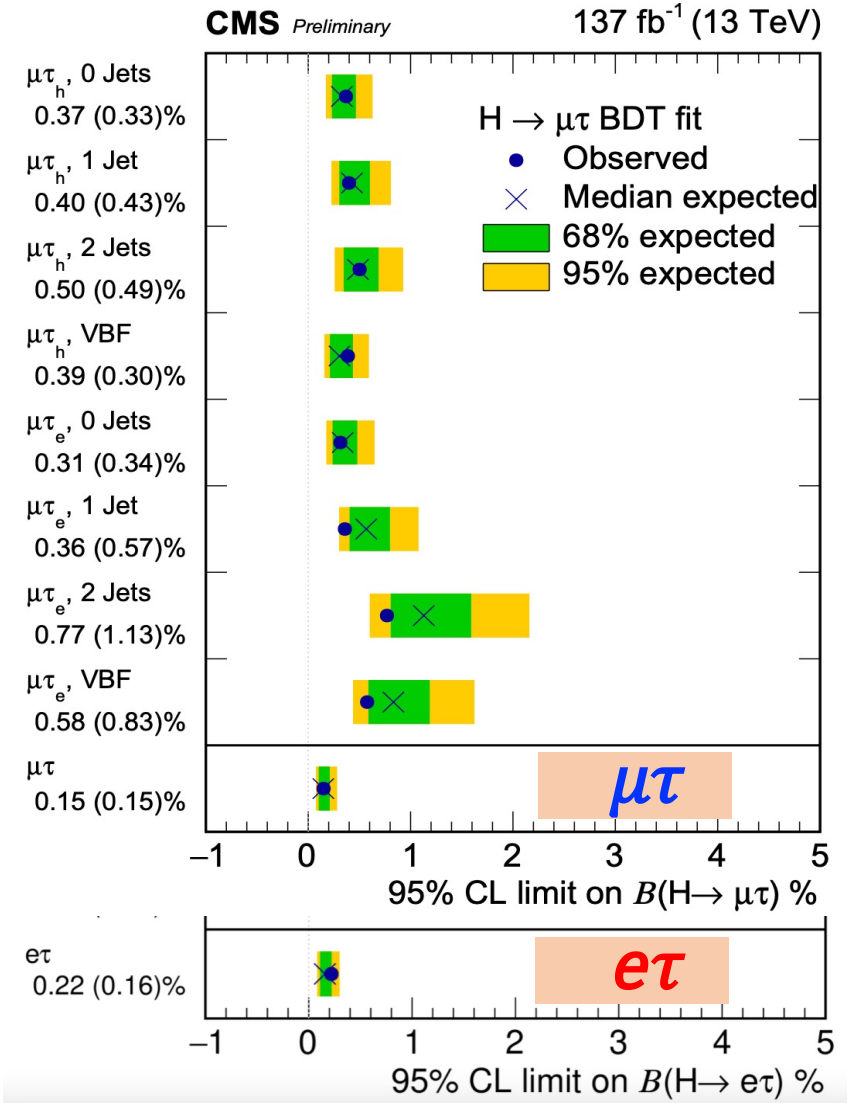

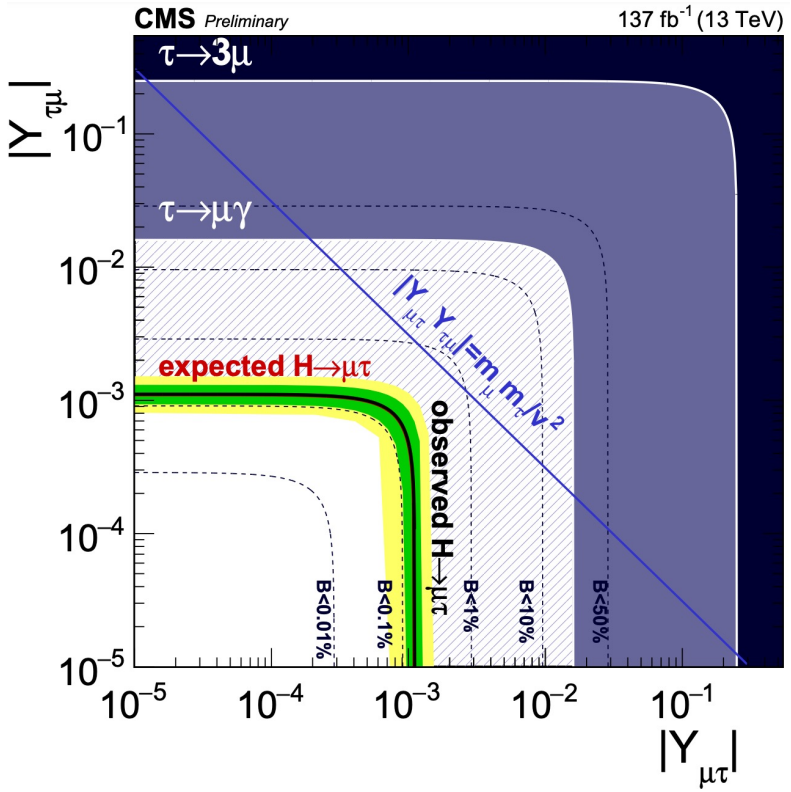

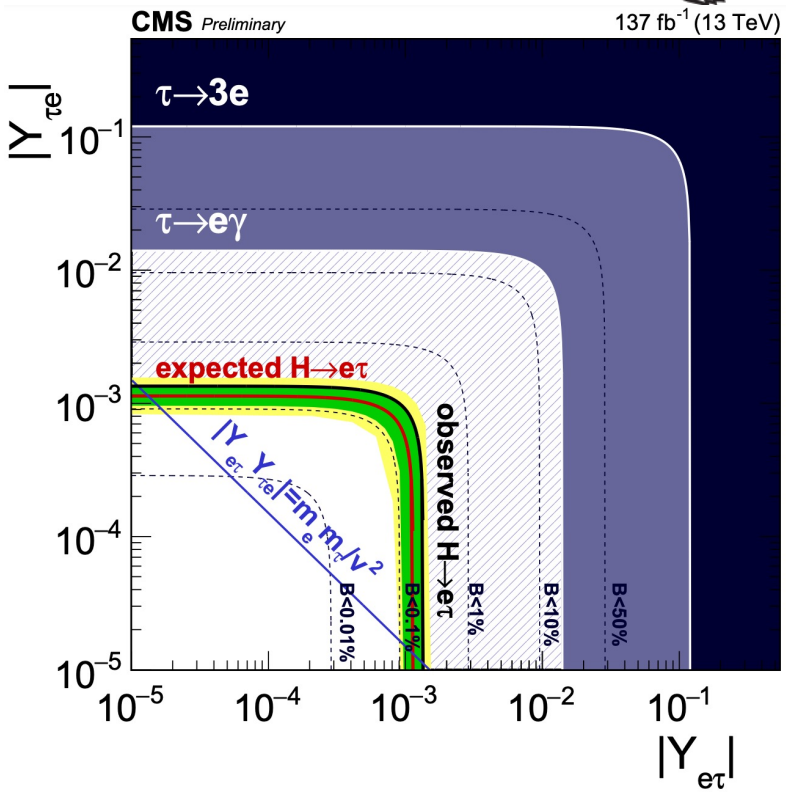

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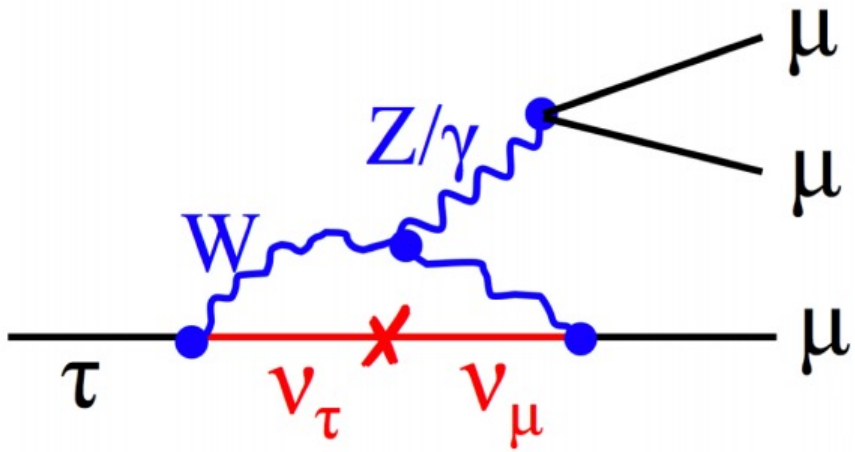

LFV: $\tau \rightarrow \mu\mu\mu$

BPH-17-004 JHEP 01 (2021) 163

LFV: $\tau \rightarrow 3\mu$

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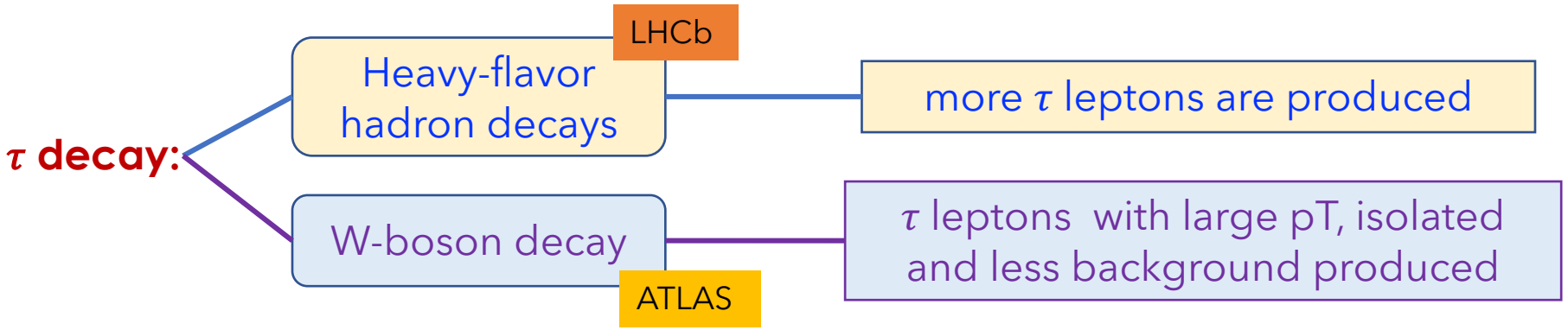
BPH-17-004

- Neutrino Oscillations ⇒ Lepton Flavor is not conserved
- Provides mechanism, through neutrino loops, for LFV decays (extra ordinarily small branching fraction)



33 fb^{-1} of pp collision data triggered with at least 3 muons

Signal region
3-μ invariant mass:1.75-1.80 GeV

Select 3- μ candidate events
Train BDT to separate signal from background in muon mass sidebands

Event categorization (Heavy flavor):
- 3 categories – based on per-event trimuon mass resolution
- Further into 2-categories based on BDT score
- Total of 6 categories

LFV: $\tau \rightarrow 3\mu$

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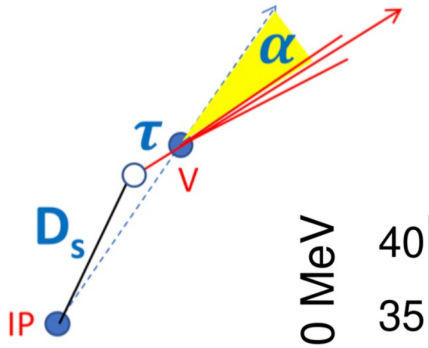
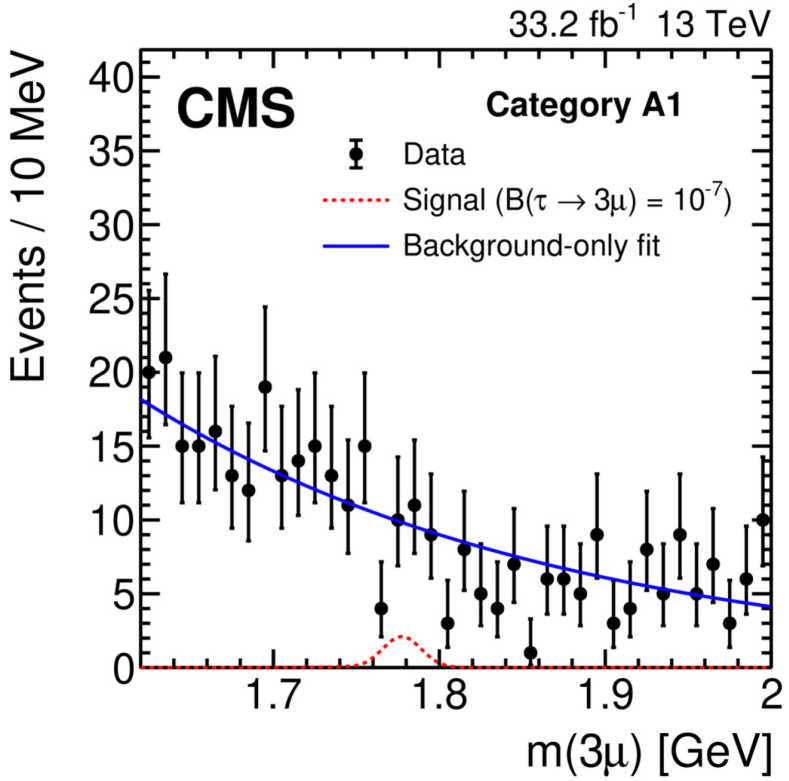
Important inputs to BDT:

- χ^2 of the trimuon vertex fit,
- Angle b/w the trimuon momentum vector and the vector connecting the primary and trimuon vertices
- PV divided by the uncertainty in that distance
- Smallest transverse impact parameter of the muons w.r.t the PV
- Isolation variables



Tri-muon invariant mass for Heavy Flavor decay



Results from simulation indicate that the τ leptons in the data sample overwhelmingly come from:

- 75% from D decays (mostly D_S)
- 25% from direct B decays

LFV: $\tau \rightarrow 3\mu$ | Results

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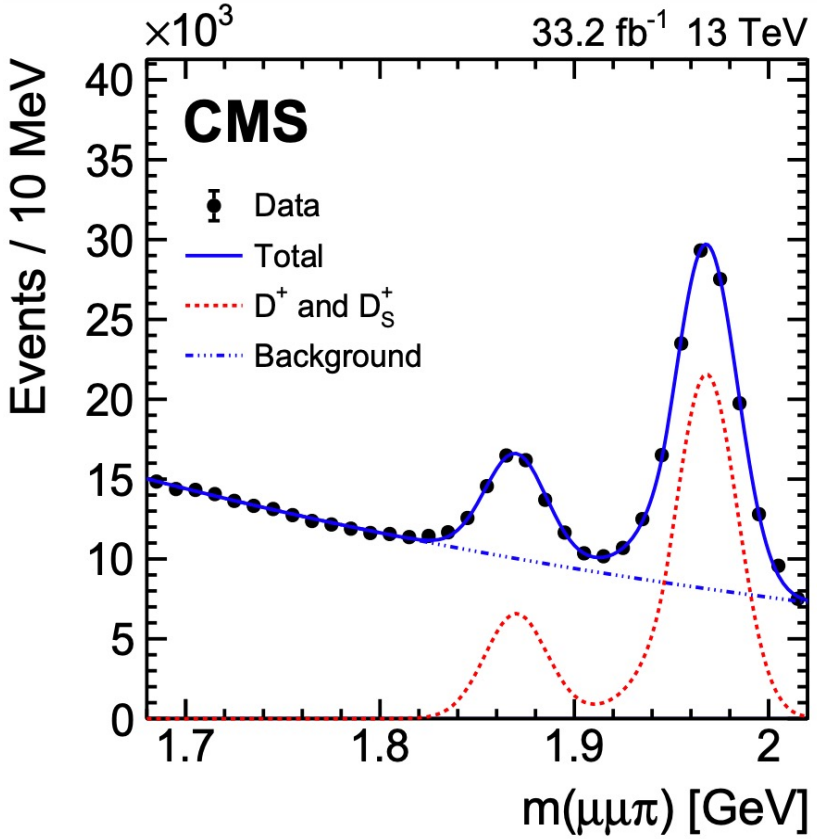
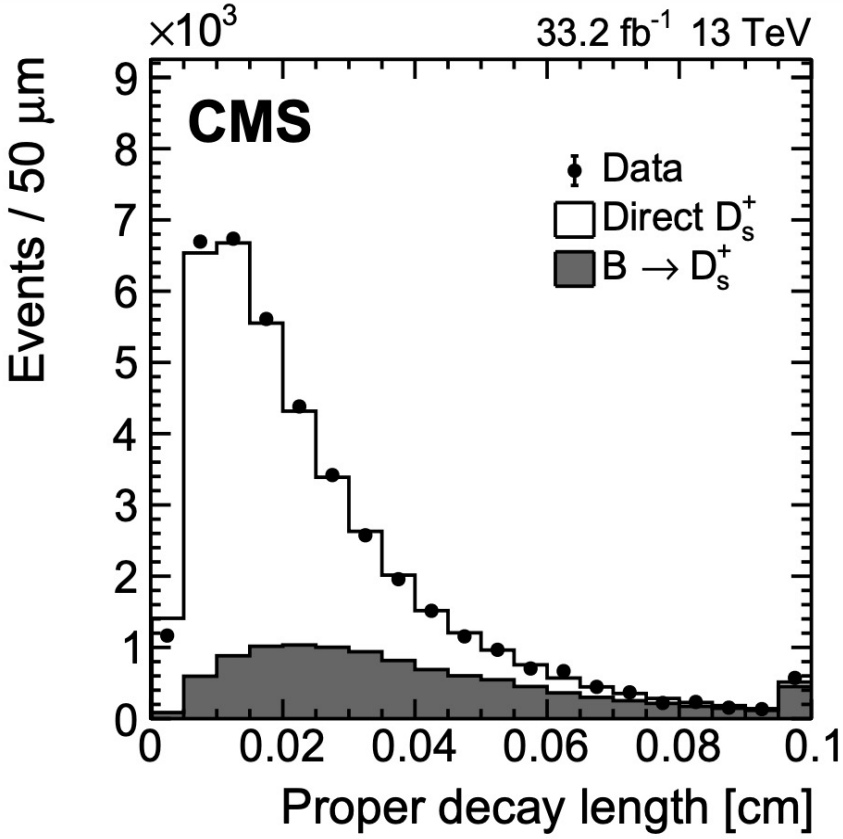
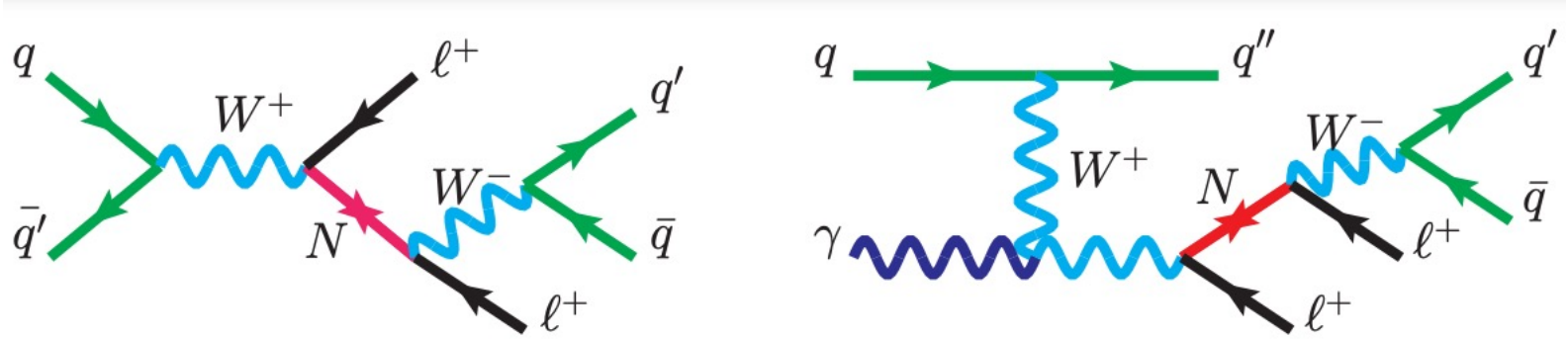




Combining two channels gives

- An observed upper limit on the B($\tau \rightarrow 3\mu$) of **8 x 10^{-8}** at 90% CL with an expected upper limit of **6.9 x 10^{-8}**
- Sensitivity comparable to BaBar and LHCb but still a factor of four away from current best by Belle experiment



Heavy Majorana Neutrinos

EXO-17-028 JHEP 01 (2019) 122

Majorana Neutrino

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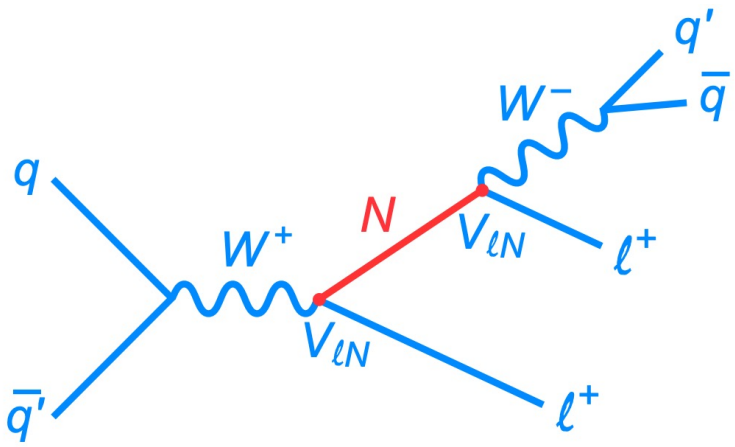
EXO-17-028

- ν^{mass} != 0 ⇒ Physics BSM
  - Explanation: Type-I "Seesaw" mechanism
  - Heavy Majorana 'N' neutrino (Model probed: νMSM)

→ New heavy-neutrino states w/o additional vector bosons



$$m_\nu \sim y_\nu^2 v^2 / m_N.$$

Limit on $|V_{\ell N}|^2$ using cut & count method

Majorana neutrino ⇒ Same-sign lepton pair possible

Lepton number violation

Majorana ν | Selection

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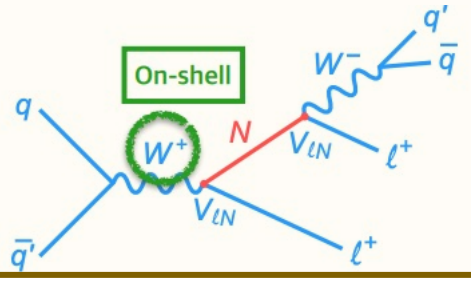
EXO-17-028

Preselection

- SS2ℓ (ee : |m(ee)-m(Z)| > 10 GeV)
- m($\ell\ell$) > 10 GeV
- Veto additional leptons
- Require at least one jet

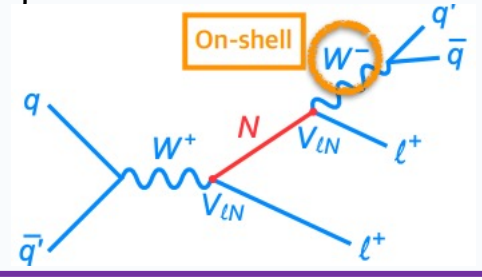
Low Mass Region: m(N) < m(W)

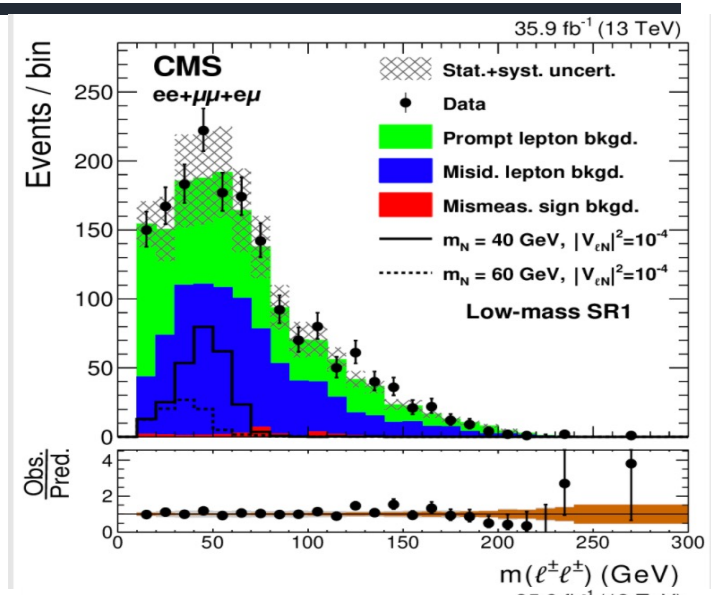
- W_{jet}
  - (SR1) AK4 jet ≧ 2 m($\ell\ell$jj) closest to m(W) are picked
  - (SR2) AK4 jet = 1: proxy of W_{jet}
- m($\ell\ell$Wjet) < 300 GeV
- MET < 80 GeV
- b-jet veto

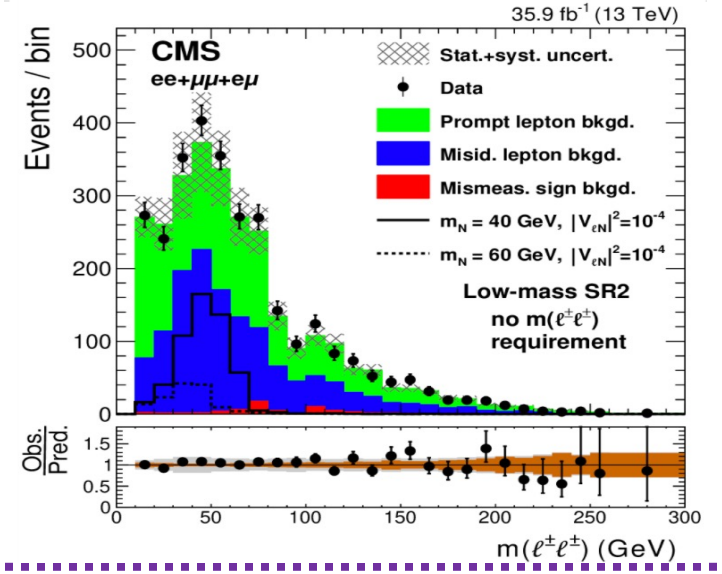


High Mass Region: m(N) > m(W)

- W_{jet}
  - (SR1) AK4 jet ≧ 2 m($\ell\ell$jj) closest to m(W) are picked
  - (SR2) AK8 jet ≧ 1: m(J) closest to m(W) are picked
- m(Wjet) < 150 GeV
- MET^2/S_T < 15 GeV
- b-jet veto







Majorana ν | Results

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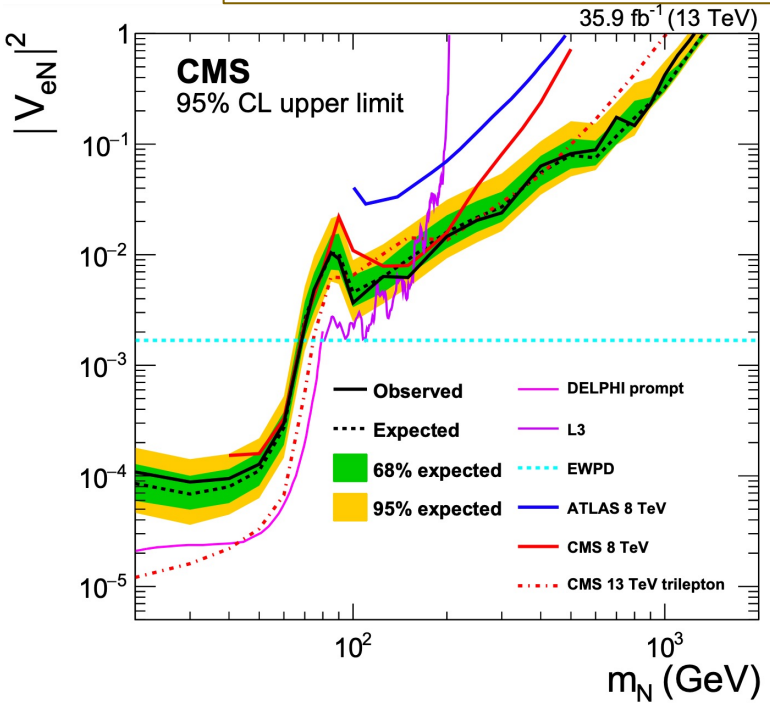
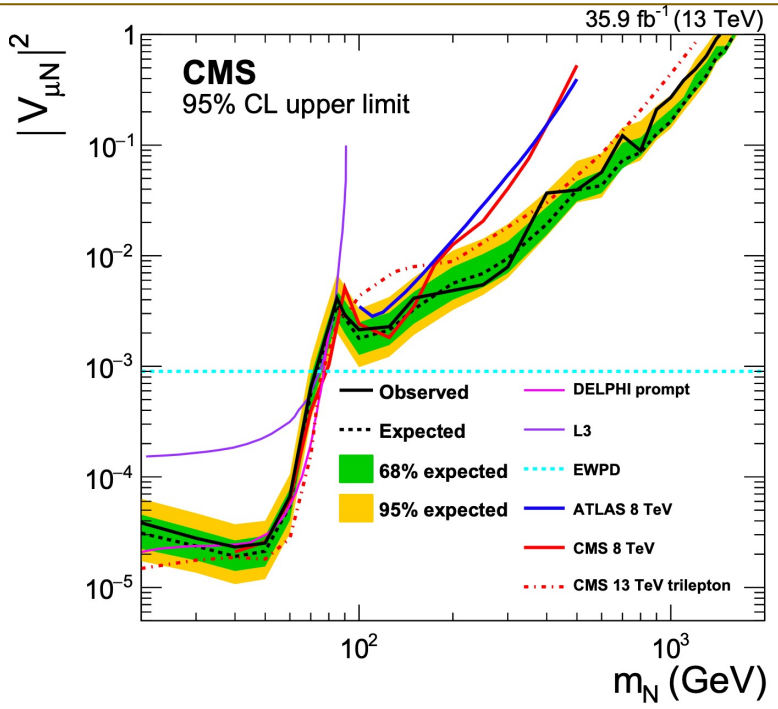
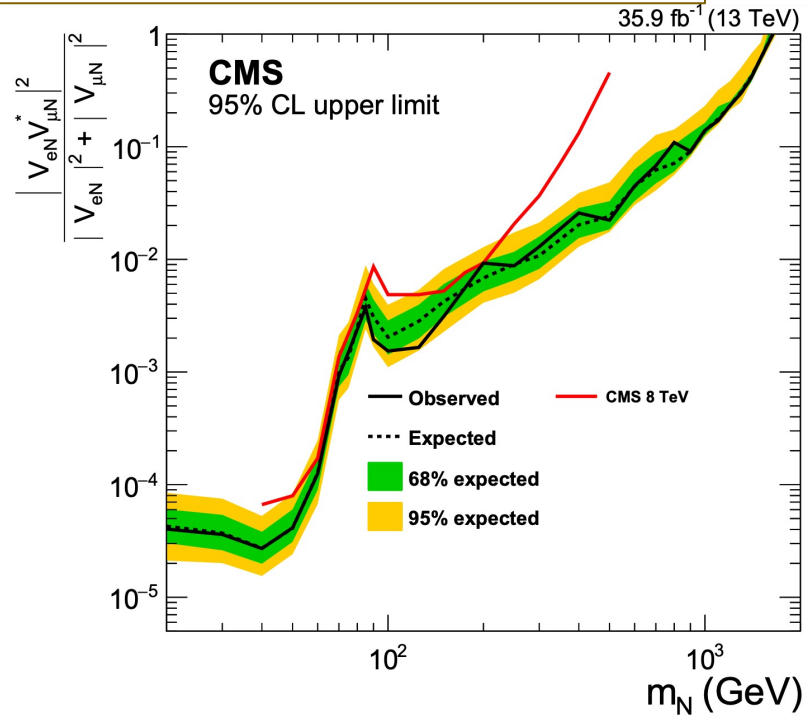
EXO-17-028

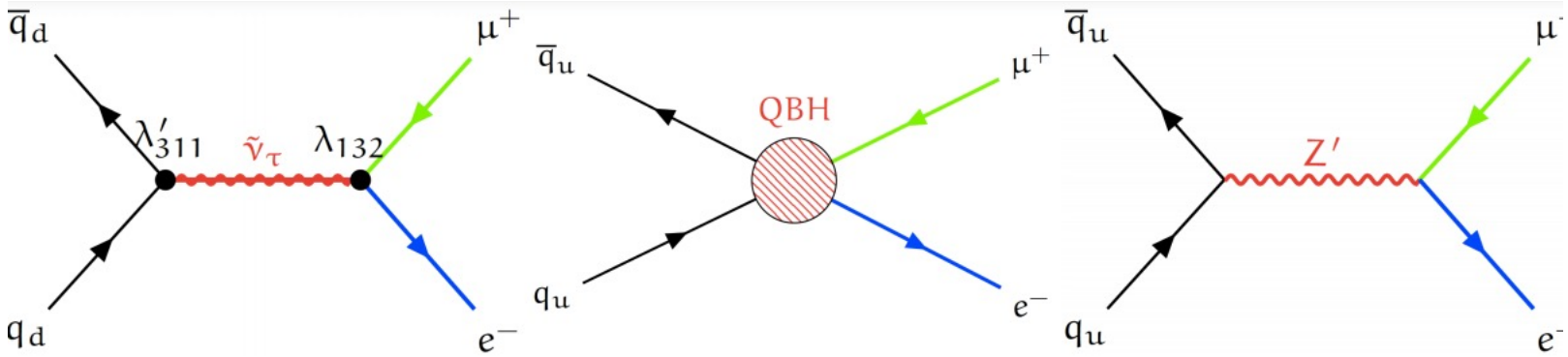
Upper limits at 95% CL are set on the mixing matrix element between SM ν and N ($|V_{\ell N}|$) in the context of a Type-I seesaw model, as a function of N mass.







The search is sensitive to masses of N from 20 to 1600 GeV with 36fb^{-1} of proton-proton collision data



Heavy Resonances to e-μ

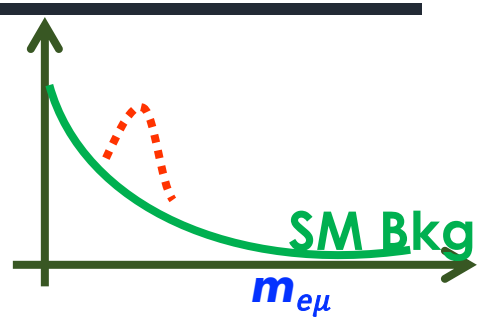
EXO-16-058

JHEP 04 (2018) 073

$X \rightarrow e\mu$

JHEP 04 (2018) 073
EXO-16-058

- Model In-dependent search for existence of heavy particles that undergo LFV decays at 13 TeV with 36 fb^{-1} of pp data
- Results are interpreted using RPV SUSY models, QBH, Z'



RPV SUSY

- Lepton flavor & number are violated at the lowest Born level in interactions between fermions and their super-partners
- Assume that all RPV couplings vanish, except for λ_{123}, λ_{231} & λ'_{311}
- Neutralino decays to $e\mu$ promptly and not long lived

QBH

- Theories provide possibilities to produce microscopic blackholes at LHC
- QBHs are nonthermal objects, expected to decay predominantly to pairs of particles
- Spin-0, colorless, neutral QBHs in a model with LFV

Z'

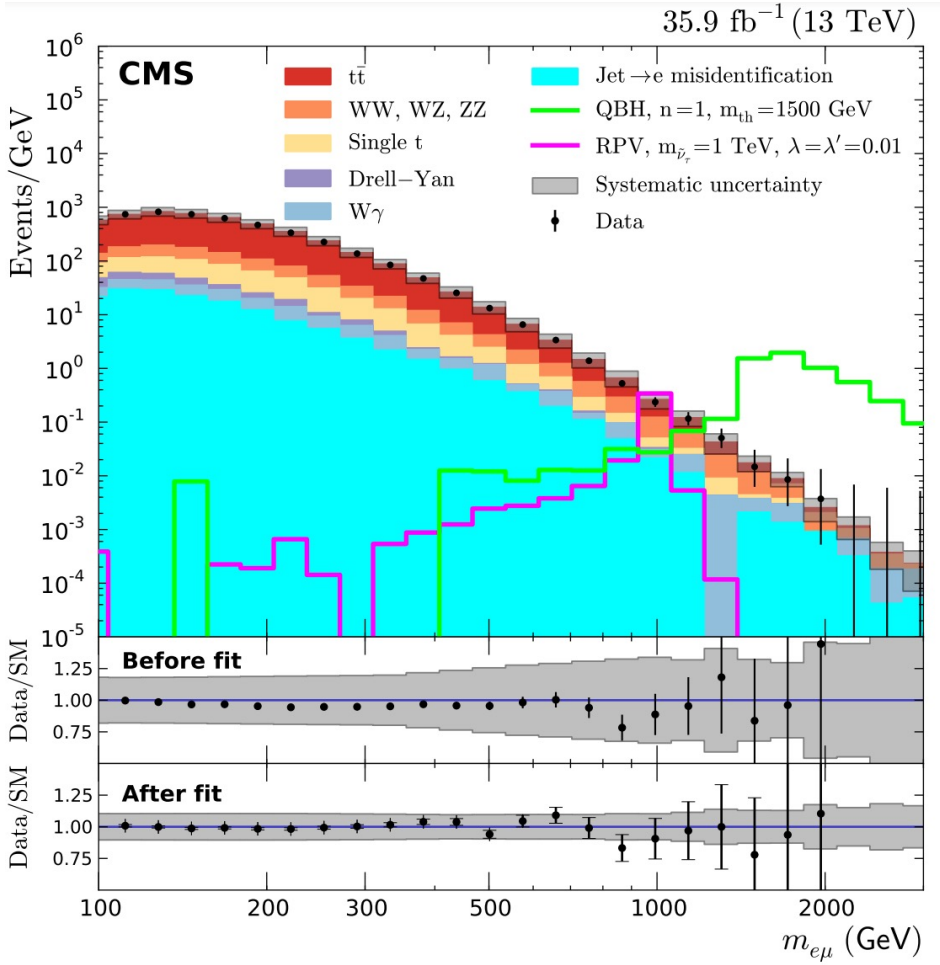
- Extension of the SM through the addition of an extra U(1) gauge symmetry
- Massive Z' vector boson
- Coupling similar to SM Z boson but also decay to the LFV eμ final state with a branching fraction of 10%
- Z' width ~3% for m > tt

$X \rightarrow e\mu$ | Selection

JHEP 04 (2018) 073
EXO-16-058

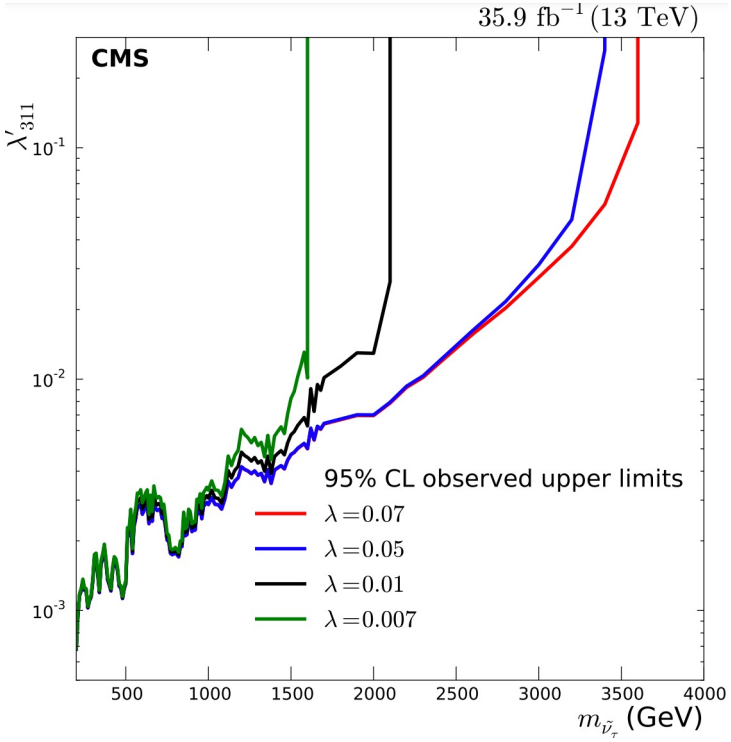
- Muons pT > 53 GeV & $|\eta| < 2.4$
- ΔR(Ele, mu) > 0.1

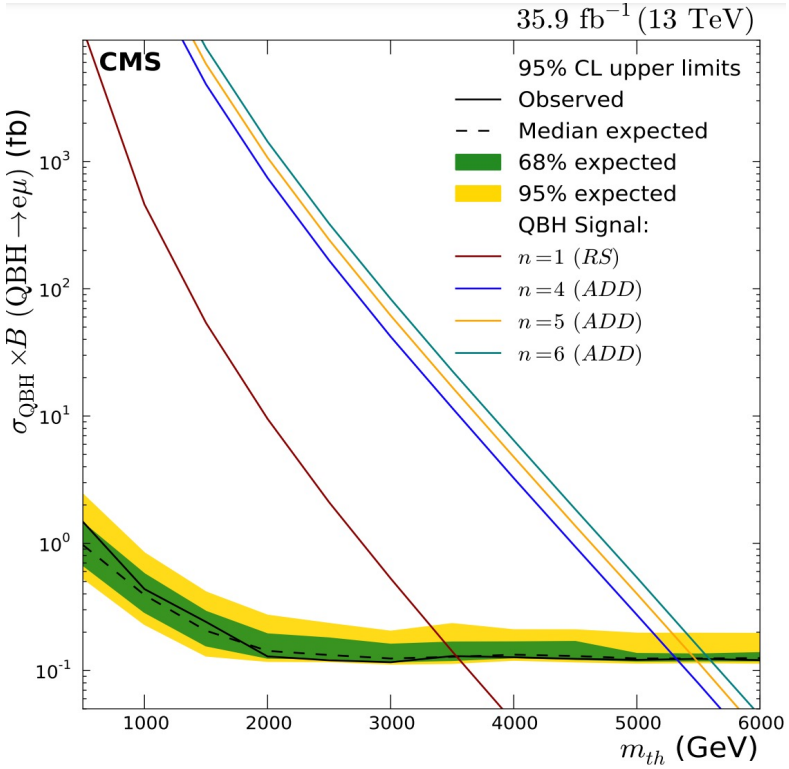
Mass range (GeV)	$m_{e\mu} < 500$	$500 < m_{e\mu} < 1000$	$1000 < m_{e\mu} < 1500$	$m_{e\mu} > 1500$
Jet→e misidentification	3601	82.8	2.92	0.849
Wγ	2462	56.2	2.76	0.562
Drell–Yan	2638	5.31	0.343	0.0145
Single t	9930	141	2.81	0.178
WW, WZ, ZZ	11126	239	13.0	2.03
$t\bar{t}$	96754	971	18.5	1.01
Total background	126513	1495	40.3	4.64
Systematic uncertainty	23495	420	13.5	1.28
Data	123150	1426	41	4

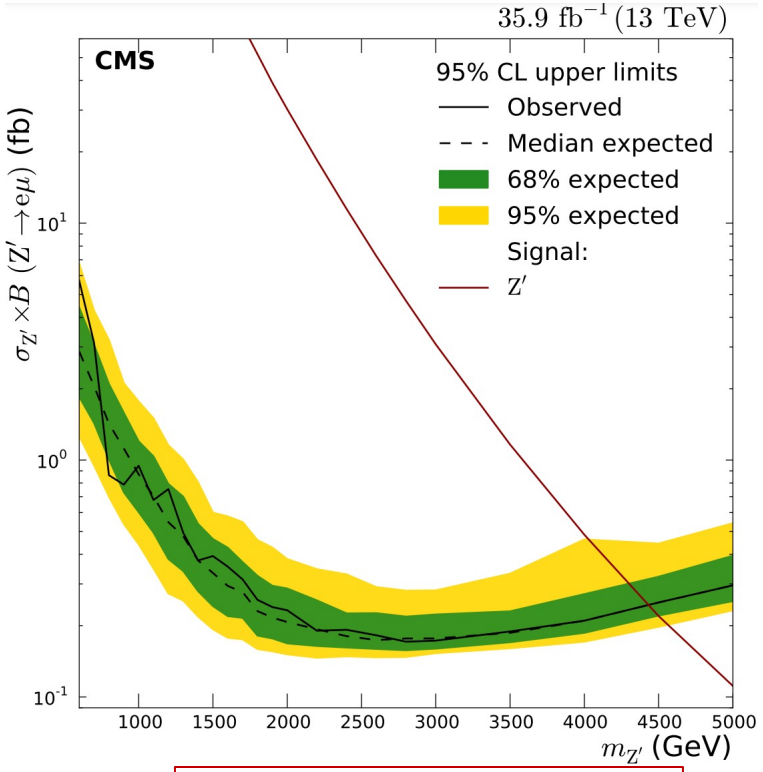


$X \rightarrow e\mu$ | Results

JHEP 04 (2018) 073
EXO-16-058







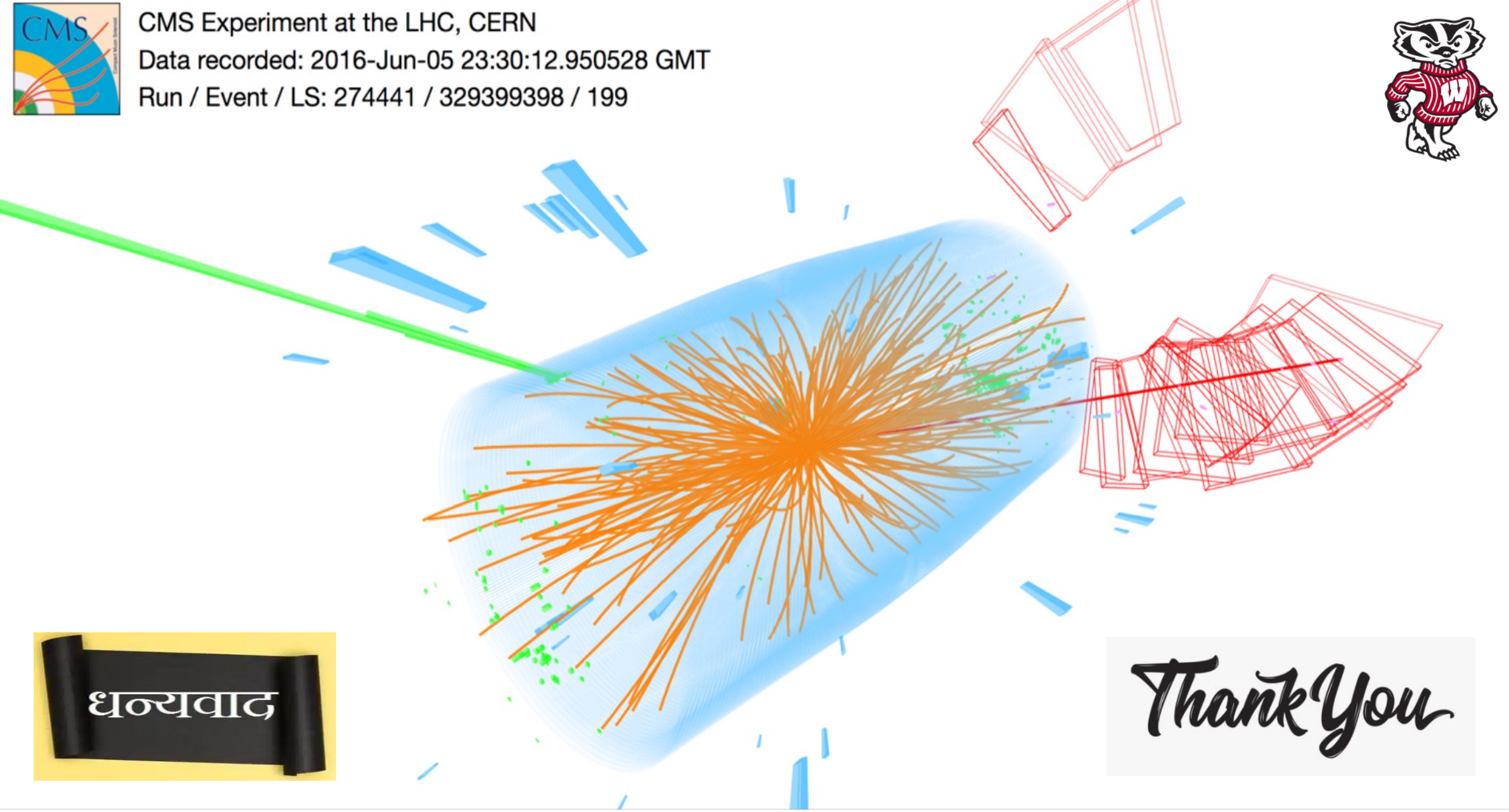
Lower limits of 5.3, 5.5, and 5.6 TeV are set on the threshold mass of QBH in a model with 4, 5, and 6 LEDs

Z′ boson with a 10% branching fraction to the eμ channel is excluded for masses below 4.4 TeV

Summary

arXiv:2105.03007
CMS-PAS-HIG-20-009

- CMS performed several searches for Lepton Flavor Violation in different channel
- No evidence has been found yet and thus stringent bounds has been placed on different models
- Stay tuned for upcoming results with full Run-2 data!



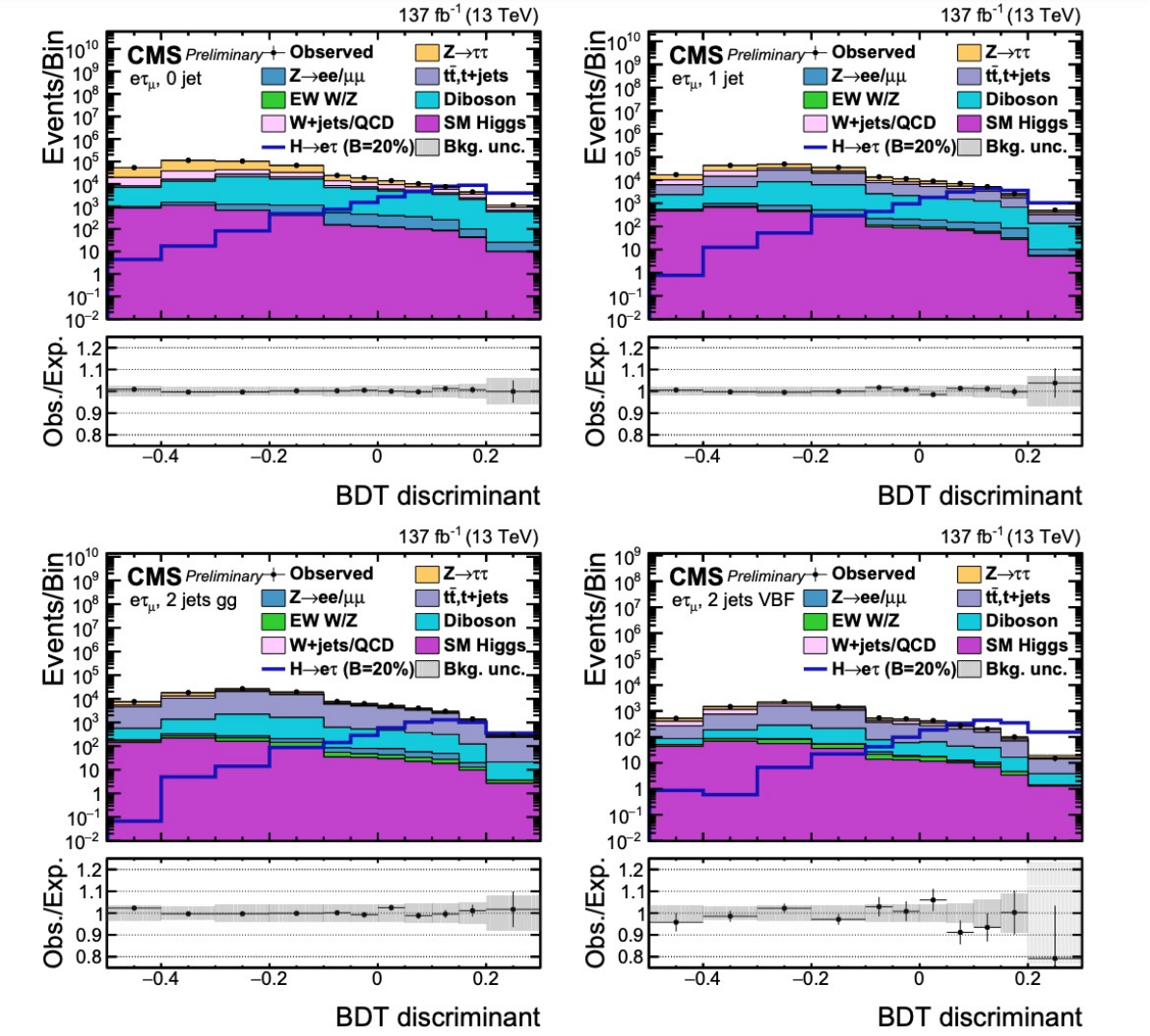
धन्यवाद

Thank You

Additional Material

Higgs LFV

arXiv:2105.03007
CMS-PAS-HIG-20-009



BDT discriminant distributions for the data and background processes in the H→eτ channel. A B(H→eτ) of 20% is assumed for the signal. The channel categories are 0 jets (upper row left), 1 jet (upper row right), 2 jets ggH (lower row left), and 2 jets VBF (lower row right). The lower panel in each plot shows the ratio of data and estimated background. The uncertainty band corresponds to the post-fit statistical and systematic uncertainties added in quadrature.

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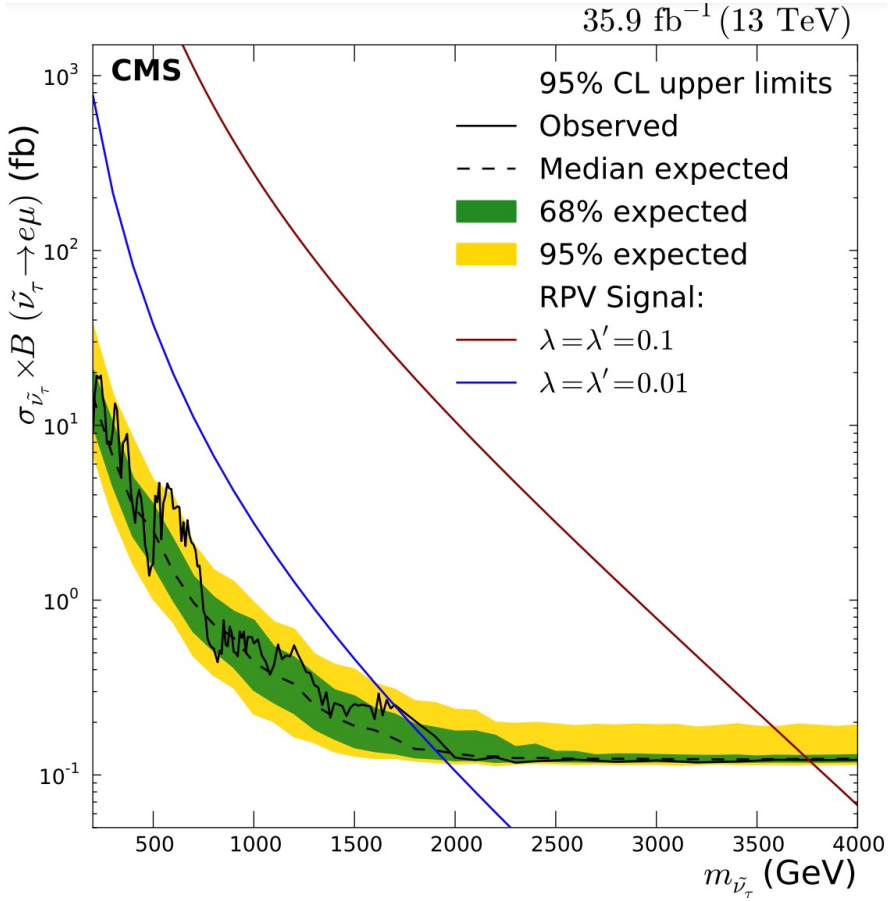

- For couplings $\lambda_{123} = \lambda_{231} = \lambda'_{311}$ = 0.01 and 0.1, a Neutralino is excluded for masses below 1.7 and 3.8 TeV respectively, assuming it is the lightest supersymmetric particle