Universität Hamburg
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Search for Charged Lepton Flavor Violation at CMS

Daniel Troendle

On behalf of the CMS Collaboration

University of Hamburg

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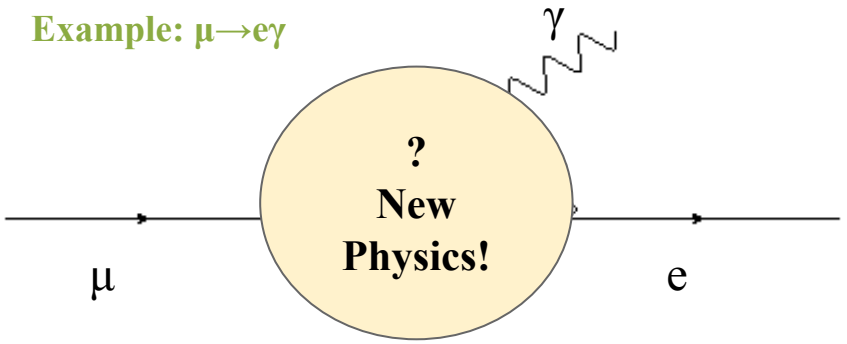
Motivation: CFLV at LHC (CMS)

- **Lepton Flavor Number (L) is not conserved** →Neutrino Oscillation!
- Charged-Lepton-Flavor violation (CLFV): no SM contribution, hence clear signature for **New Physics**!



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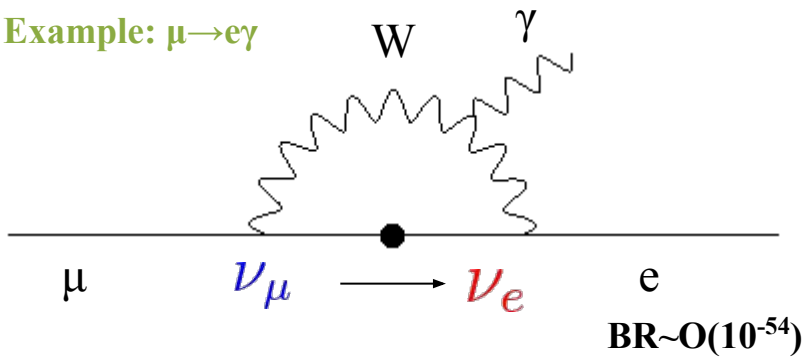

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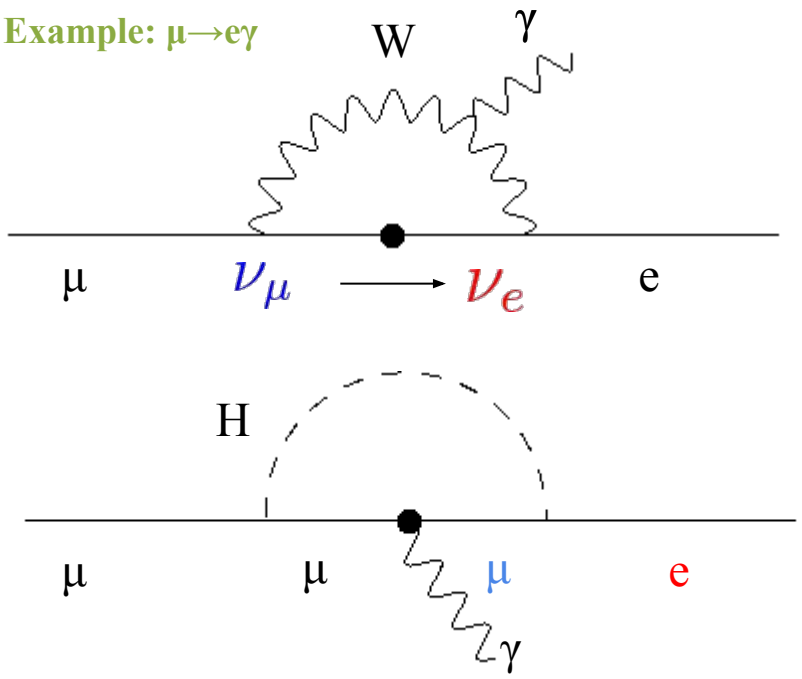

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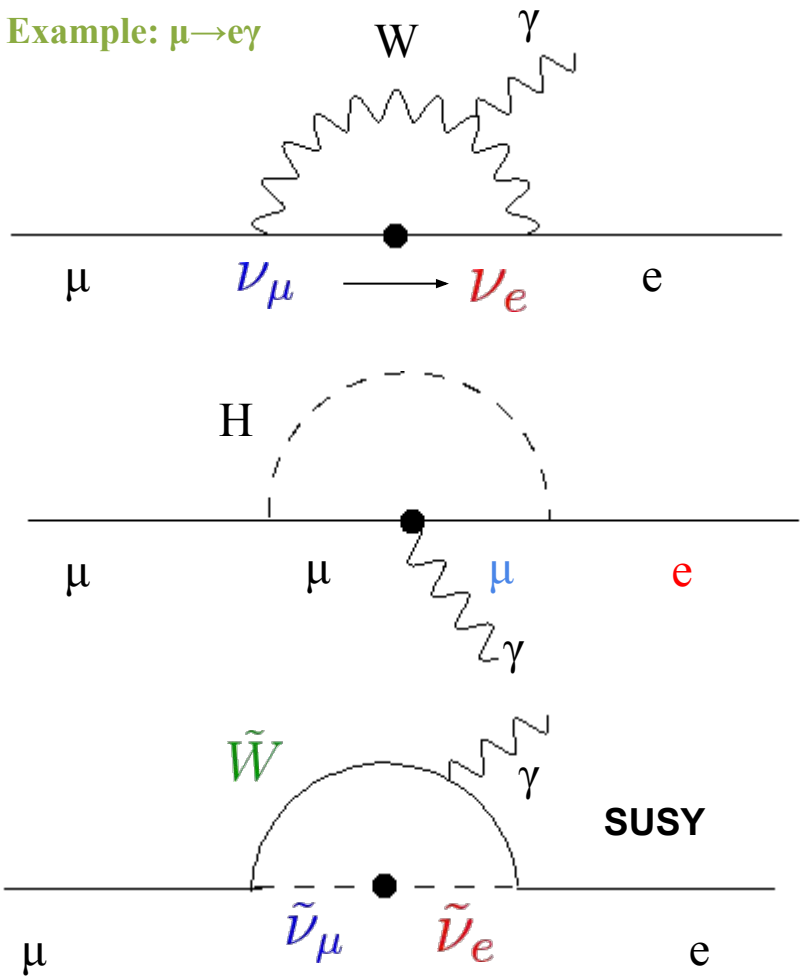

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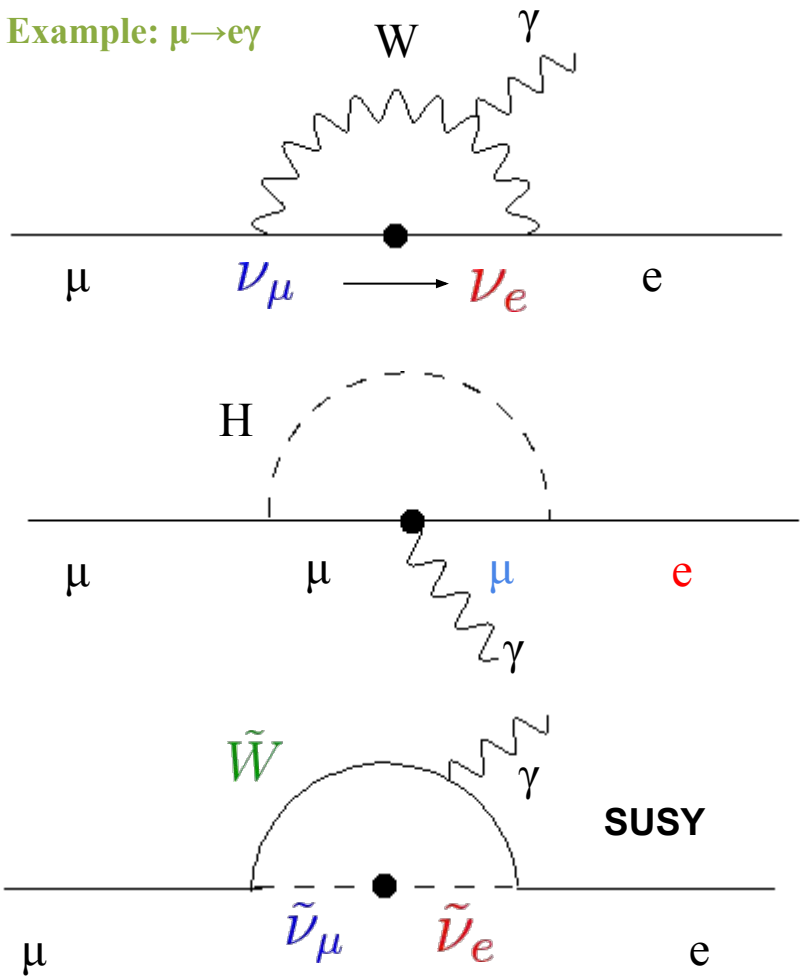
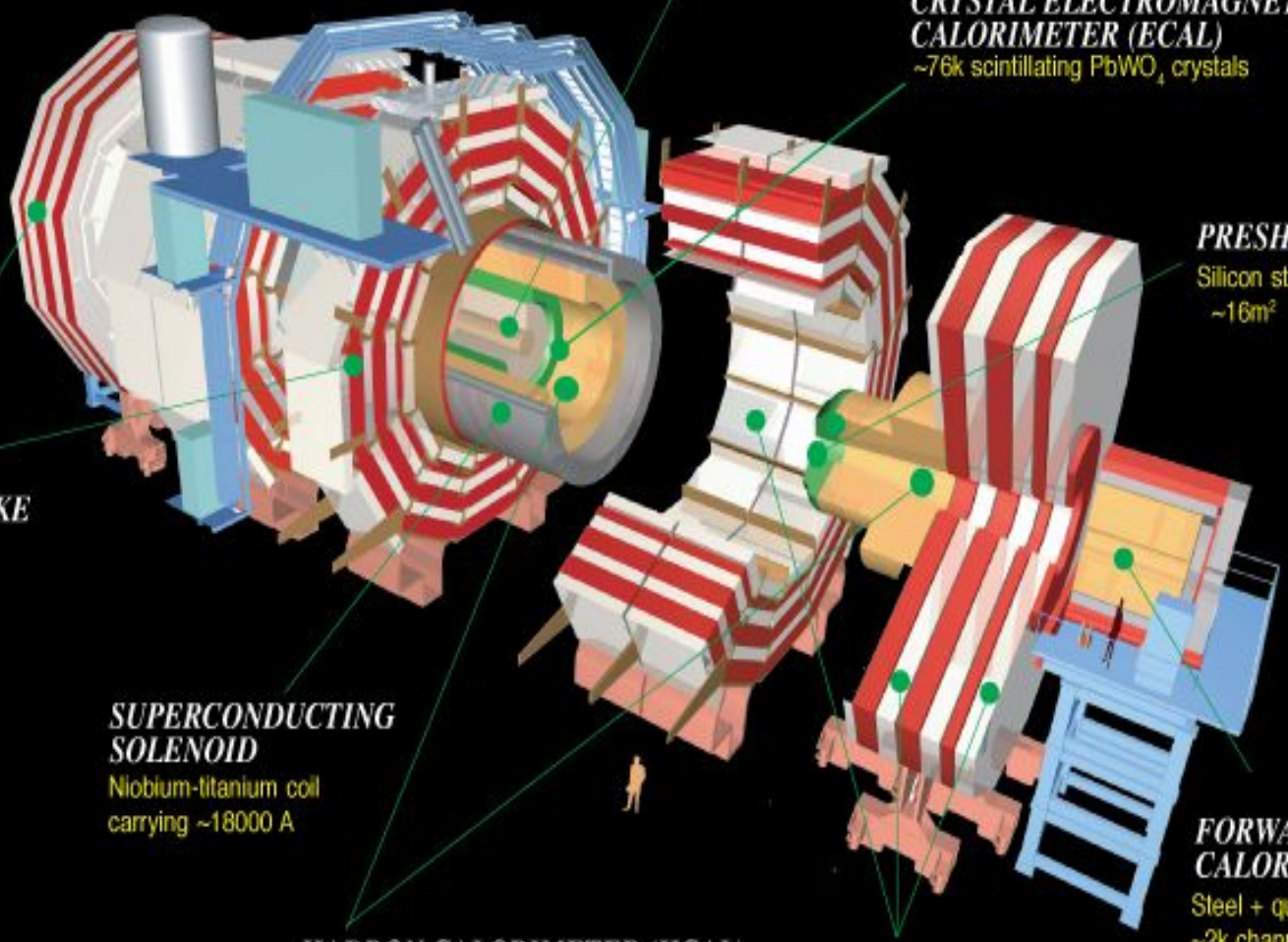
- Examples for NP contribution: Higgs , SUSY, Heavy Neutrinos, Leptoquarks, Z', ...



CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

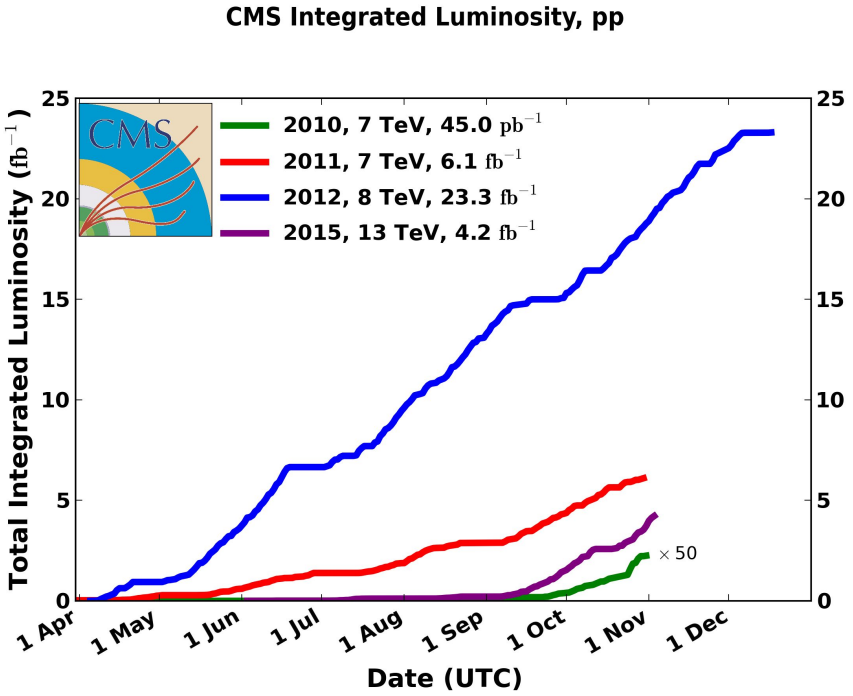
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

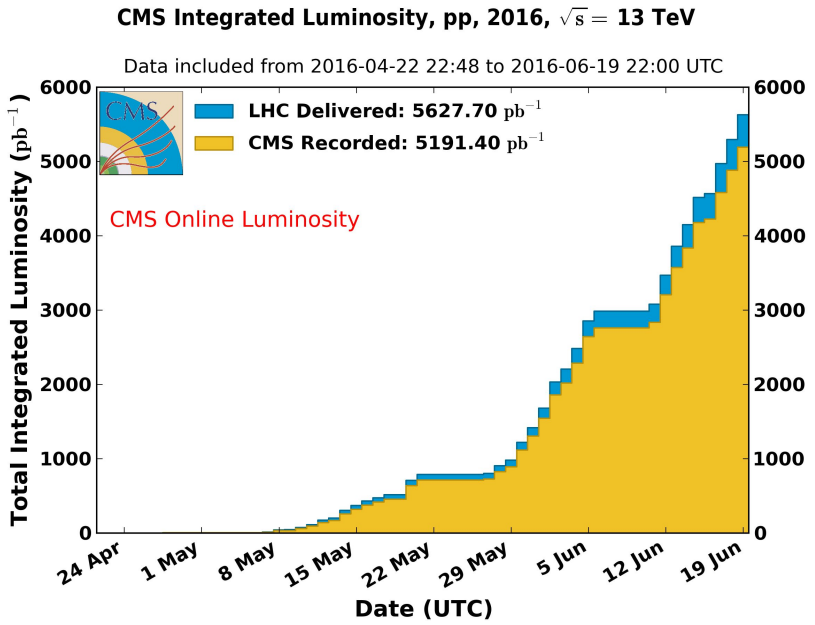
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

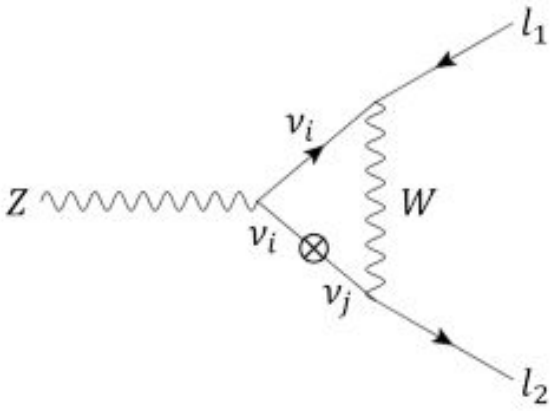
Recorded Data





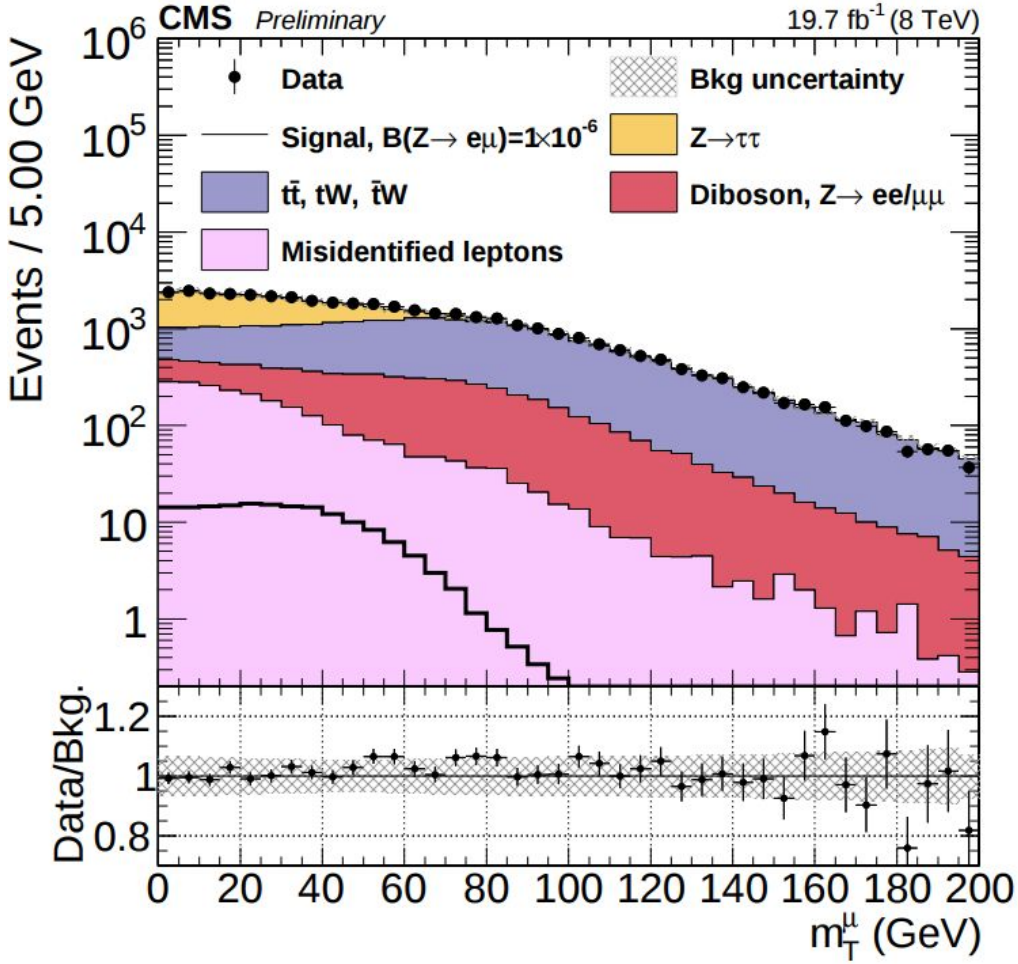
Results shown in the following are based on the data taking at 7, 8 and 13 TeV center-of-mass energy!

Search for Z→μe decays

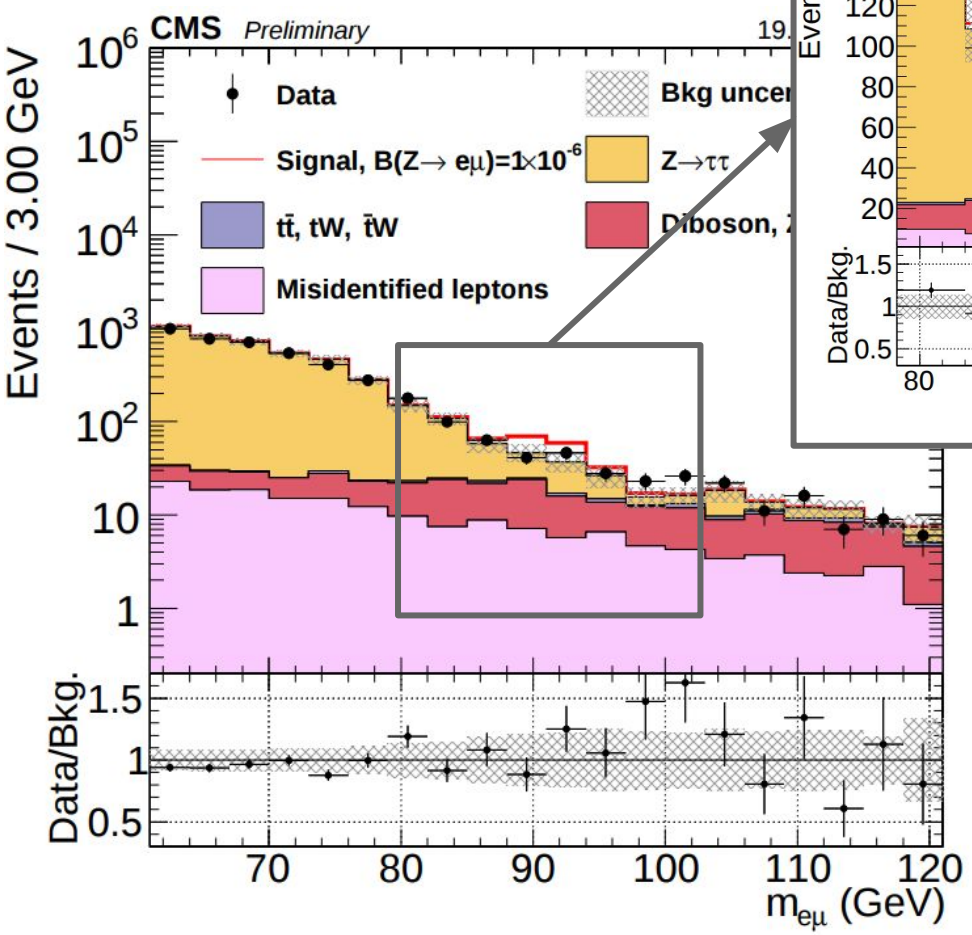


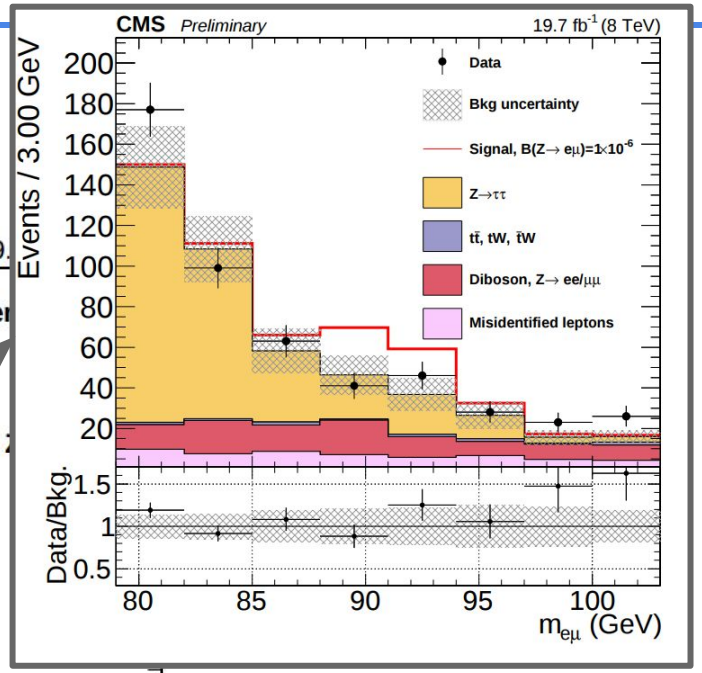
Event Selection:

- Two tight leptons (e,μ) with opposite sign
- Jet-Veto: suppresses ttbar
- Low transverse Mass: suppresses WW
- Misidentified leptons estimated from data



Z→μe: Results





No significant excess has been observed.

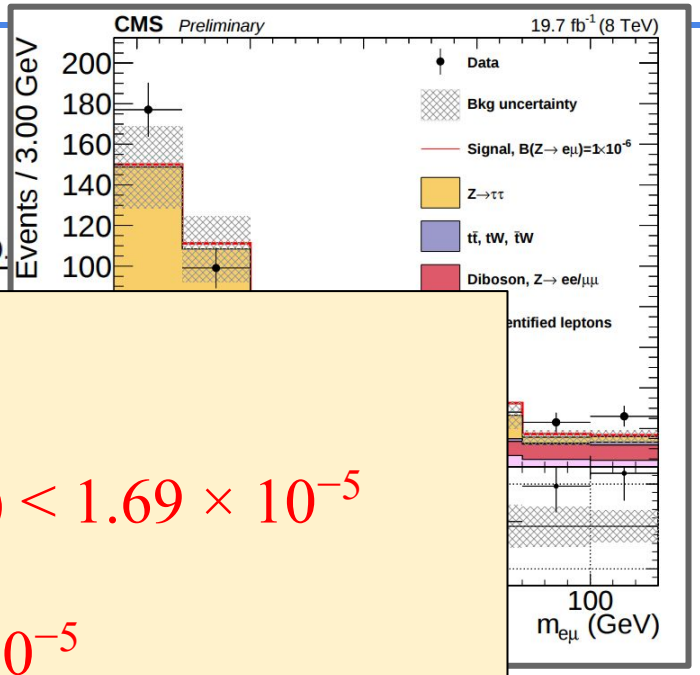
Limit:

Expected: $B(Z\rightarrow\mu e) < 6.7 \cdot 10^{-7}$

Observed: $B(Z\rightarrow\mu e) < 7.3 \cdot 10^{-7}$

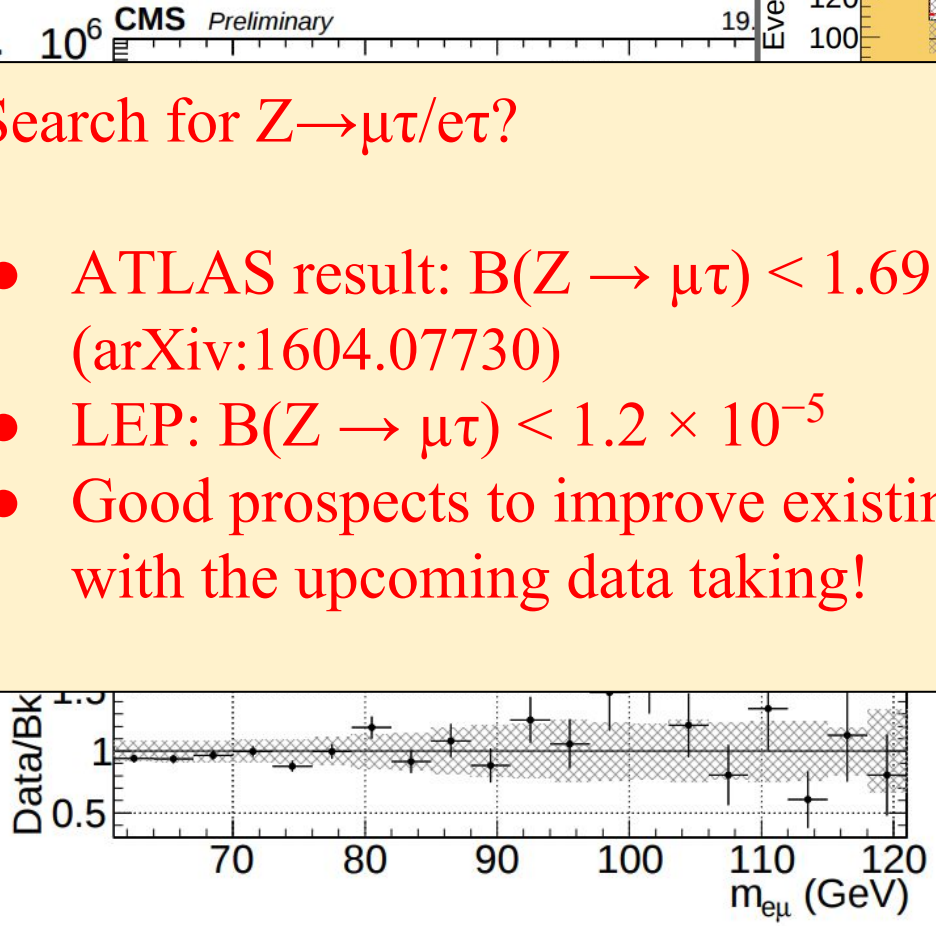
LEP: $B(Z\rightarrow\mu e) < 7.5 \cdot 10^{-7}$

Z→μe: Results



Search for Z→μτ/eτ?

- ATLAS result: $B(Z \rightarrow \mu\tau) < 1.69 \times 10^{-5}$ (arXiv:1604.07730)
- LEP: $B(Z \rightarrow \mu\tau) < 1.2 \times 10^{-5}$
- Good prospects to improve existing limits with the upcoming data taking!



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Search for CLFV Higgs decays

In general two Higgs-Doublet models (2HDMs):

- ***CFLV Higgs coupling are possible!***
- Typically one need to introduce an additional symmetry to suppress flavor changing neutral currents (FCNC)...
- **LHC-RunII: exploit the full yukawa-matrix, not "only" the diagonal entries!**

SM values

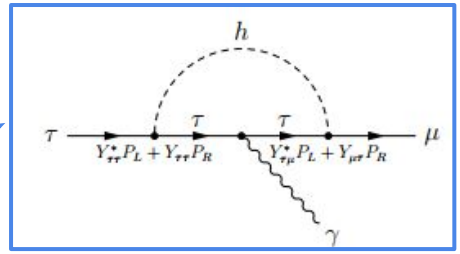
$$Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

Harnik, Kopp, Zupan, arXiv:1209.1397

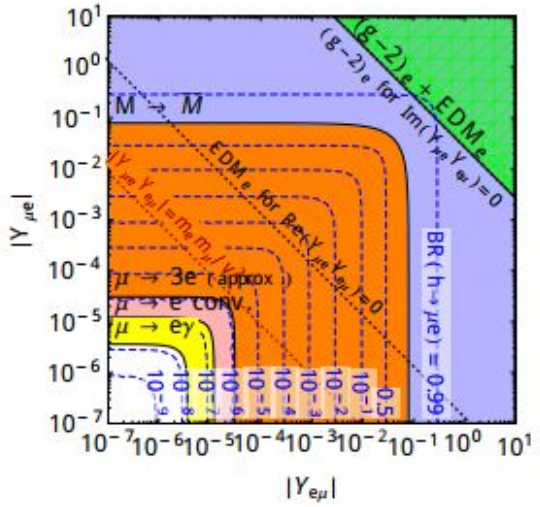
Search for CLFV Higgs decays

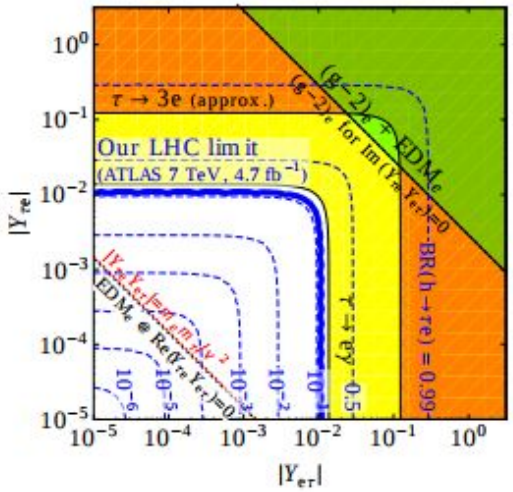
Pre-LFC bounds on LFV Higgs couplings

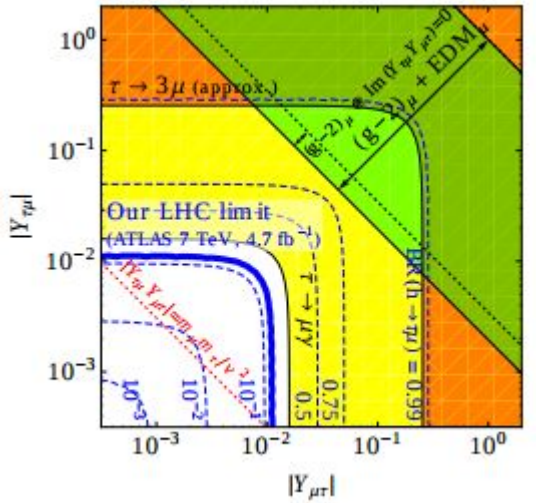
Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu}Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu}Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau}Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau}Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau}Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau}Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$(\lvert Y_{\tau\mu}Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau}Y_{\tau e}\rvert^2)^{1/4}$	$< 3.4 \times 10^{-4}$

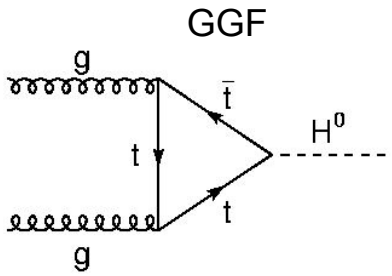


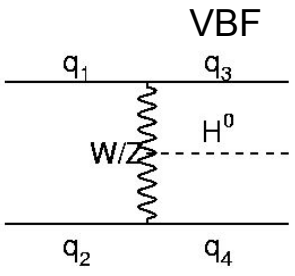
Pre-LHC constraints: B (H→μτ/eτ)~O(10%) are still allowed!





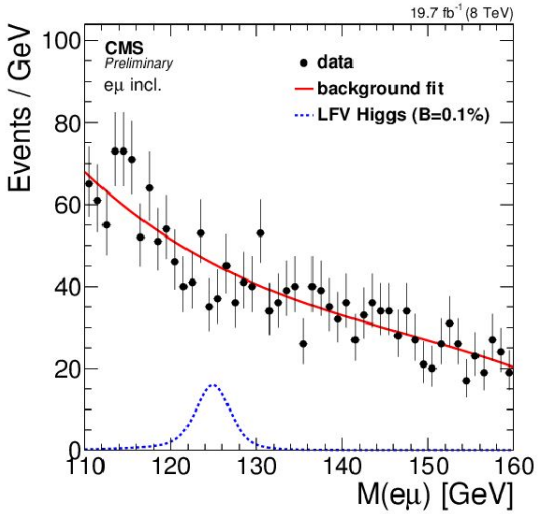


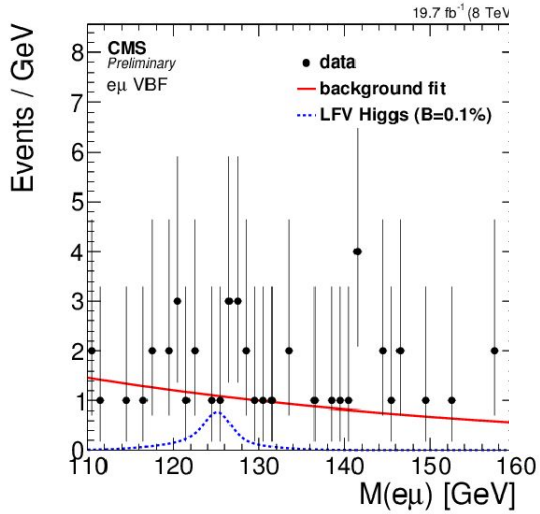


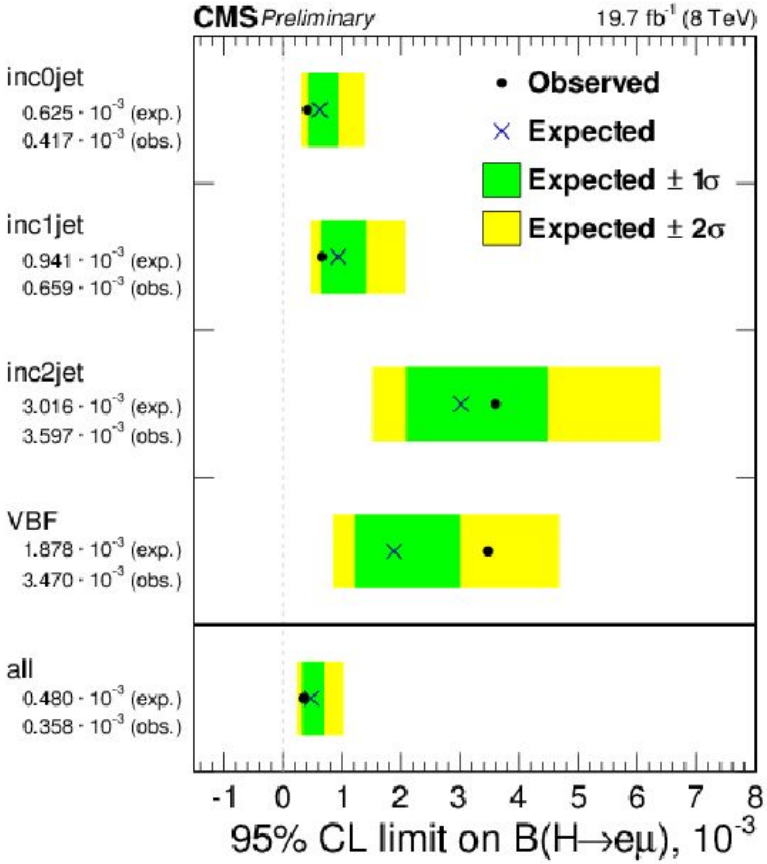


Search for H→eμ

- Dilepton: e+μ with opposite sign
- GGF and VBF production: 0,1 and 2 Jet category
- Low MET in the events is required
- Background: 'simple' fit of the dilepton invariant mass distribution $m_{e\mu}$ = [110,160]



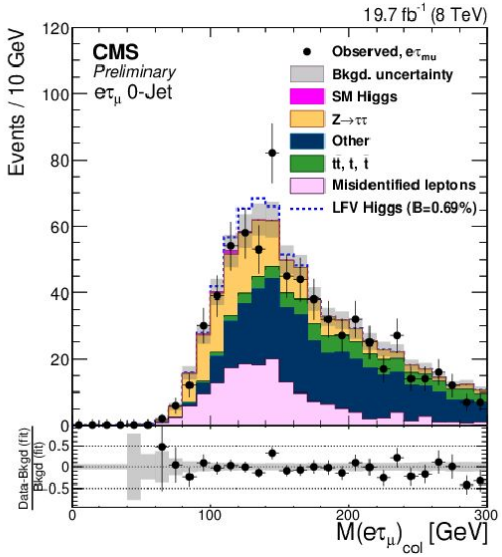


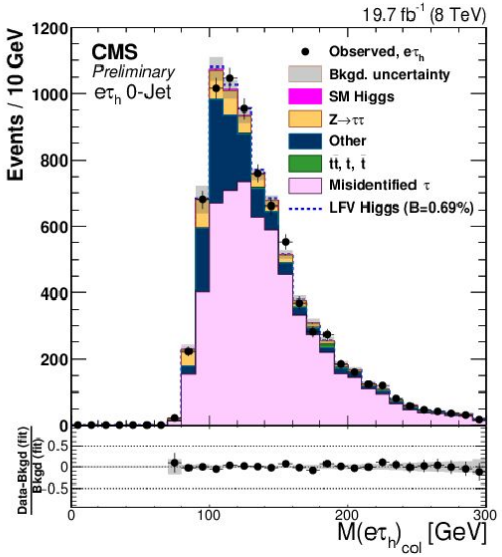


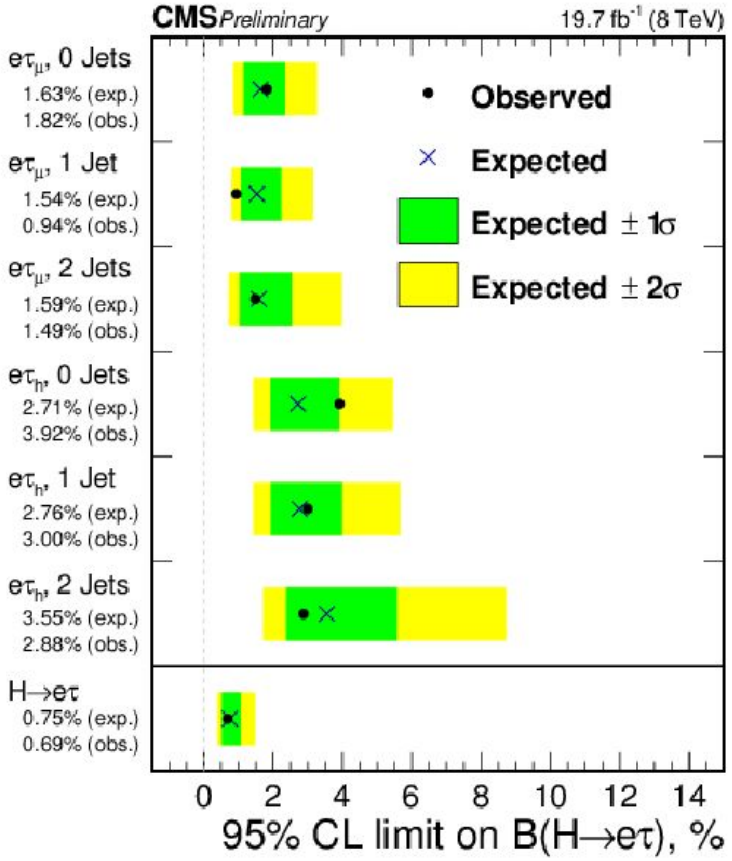
CMS-PAS-HIG-14-040

Search for H→eτ

- 2 channels: leptonic tau (μ) and hadronic tau decays
- GGF and VBF production channels: 0, 1 and 2-Jet categories
- Kinematic cuts to enhance S/B ratio







Search for H→μτ

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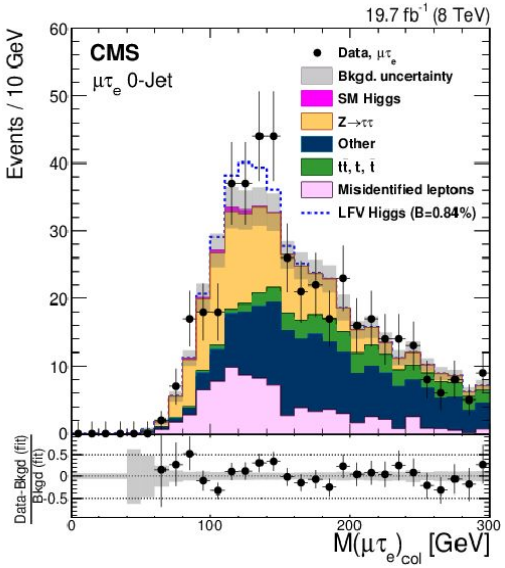
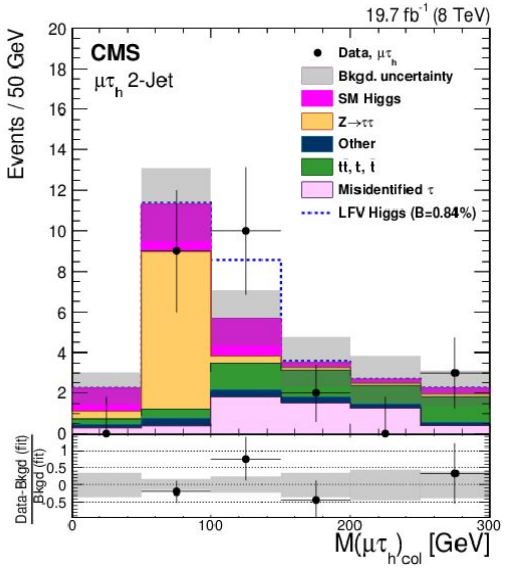
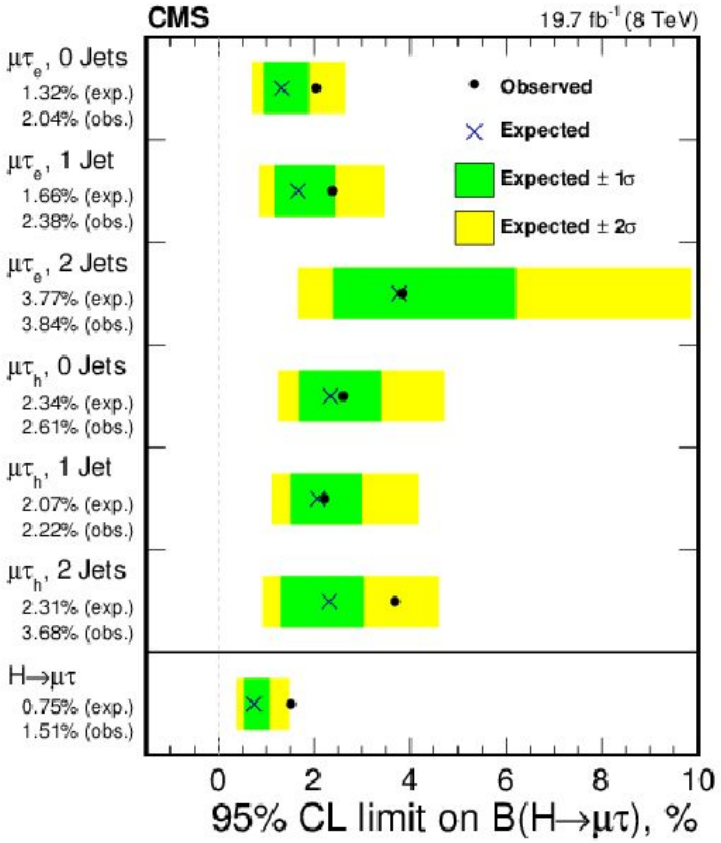
- GGF and VBF production considered: 0,1 and 2-Jet categories
- Kinematic cuts to enhance S/B ratio



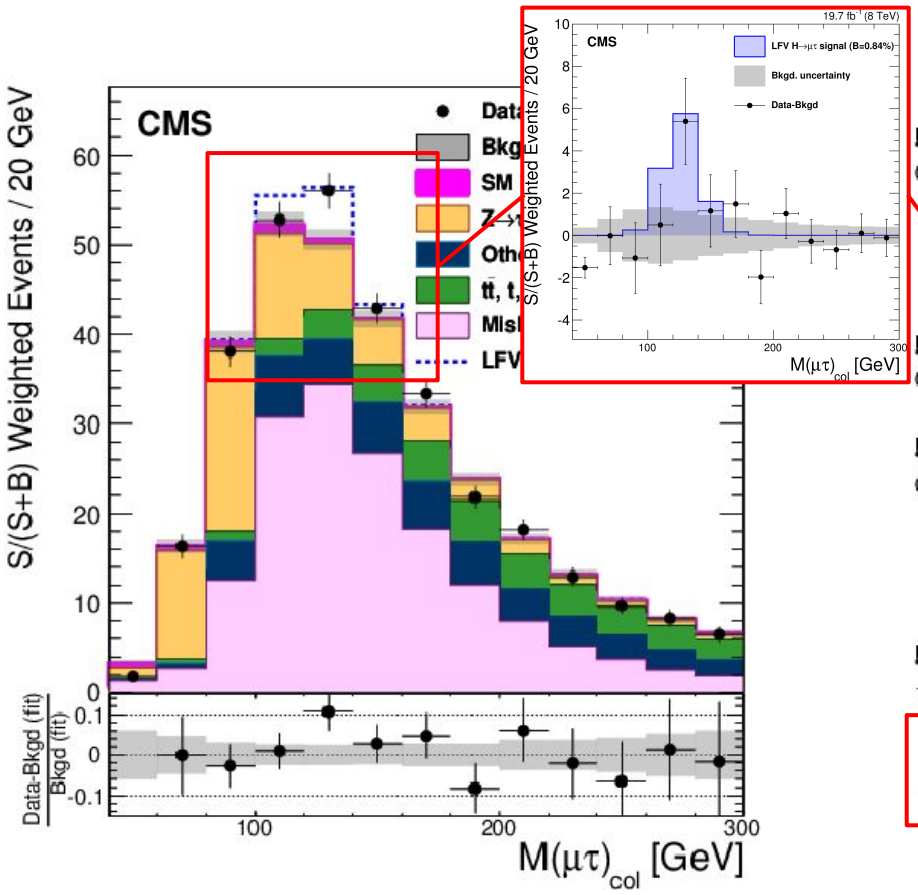


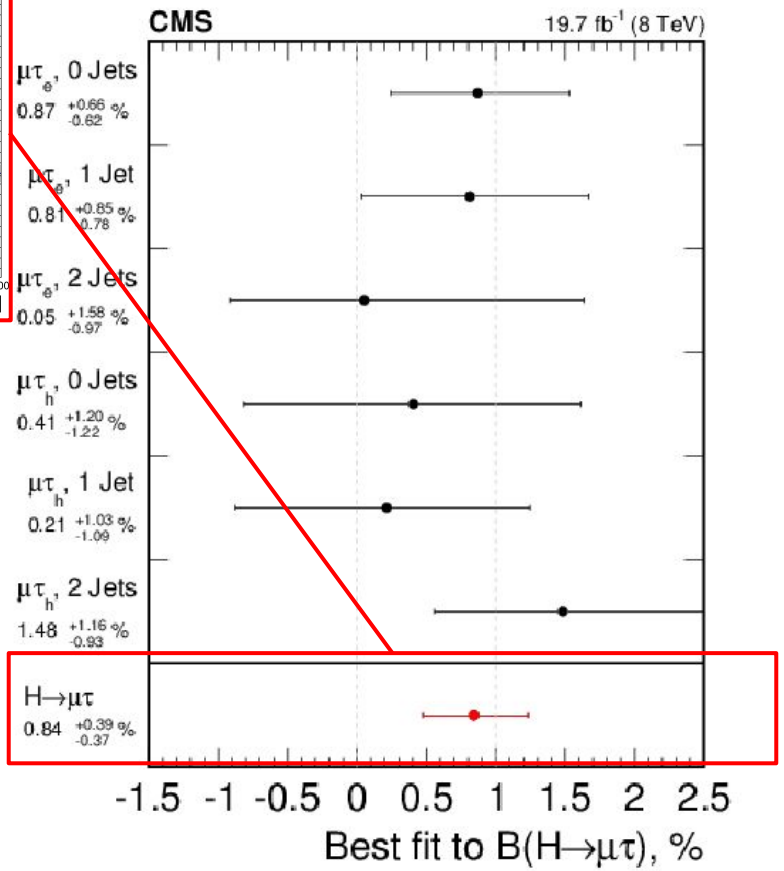


Phys. Lett. B 749 (2015) 337

Search for H→μτ

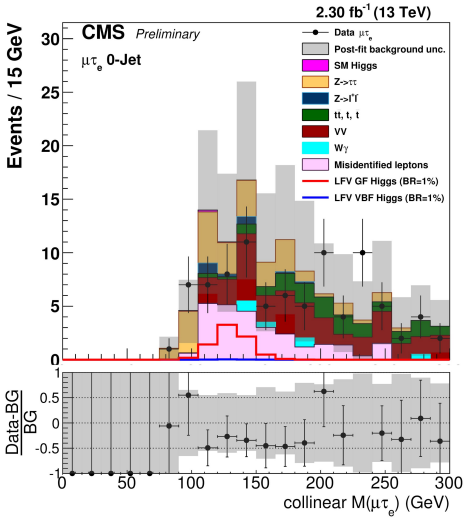
Excess: ~2.4σ excess
Best Fit B(H→μτ)=0.84±0.39%

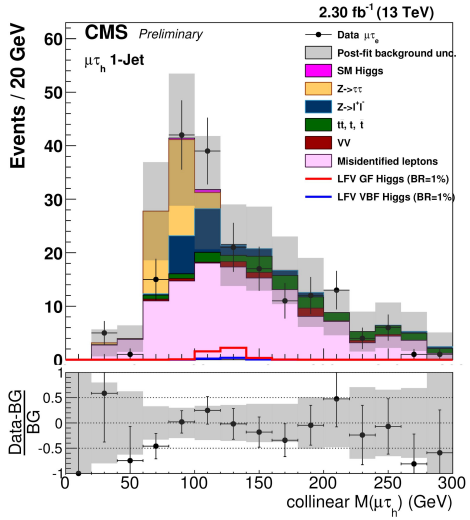


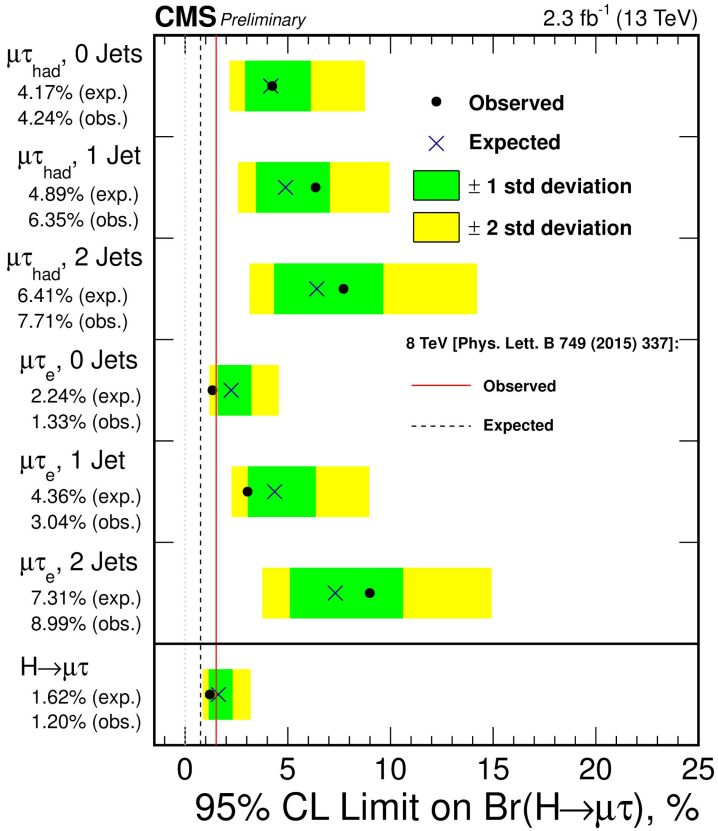


Search for H→μτ @ 13TeV!

- Repetition of 8TeV H→μτ analysis: no change of strategy and kinematic cuts
- **Slight excess of 8TeV analysis could not be confirmed so far, but also not excluded!**
- Updated B(H→μτ) Limit: B(H→μτ)<1.2% observed (1.62% expected)

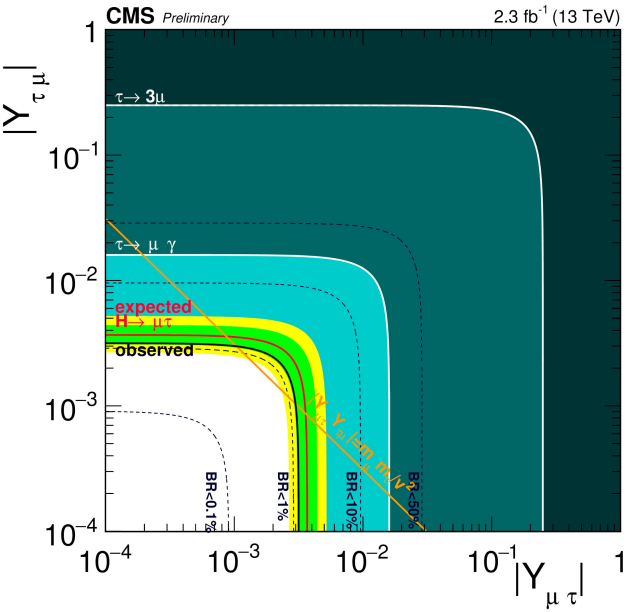


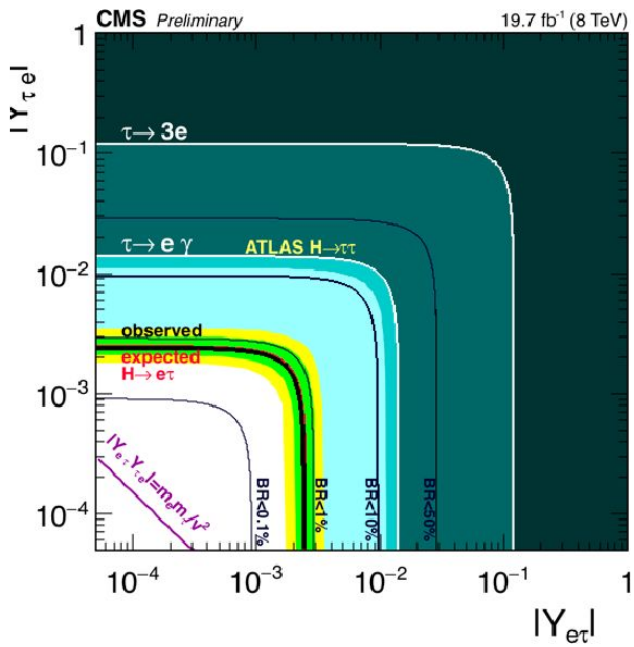


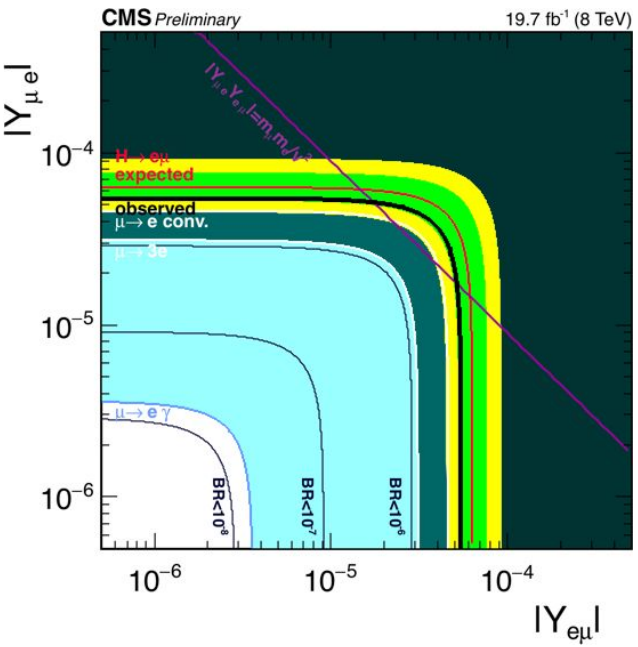


CMS-PAS-HIG-16-005

LFV Higgs Summary







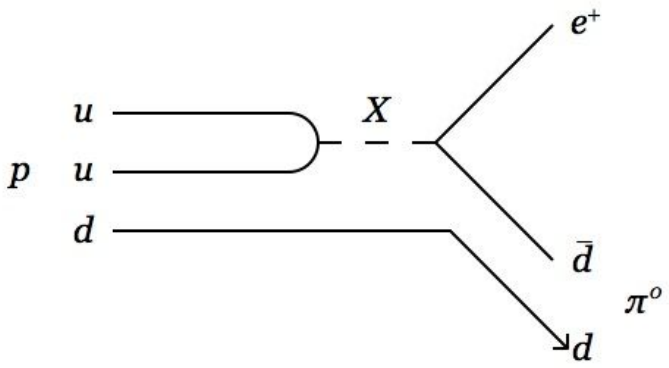
Expect major update by end of the year!

Extension to higher masses (H,A→μτ,eτ) is on the list to do!

(L)RPV-SUSY
Heavy Resonances,
Heavy neutrinos,...

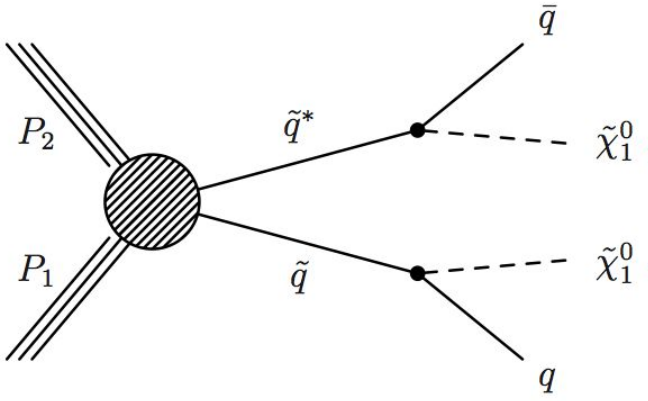
R Parity Violating (RPV) SUSY

R-Parity: $R = (-1)^{3B+L+2S}$



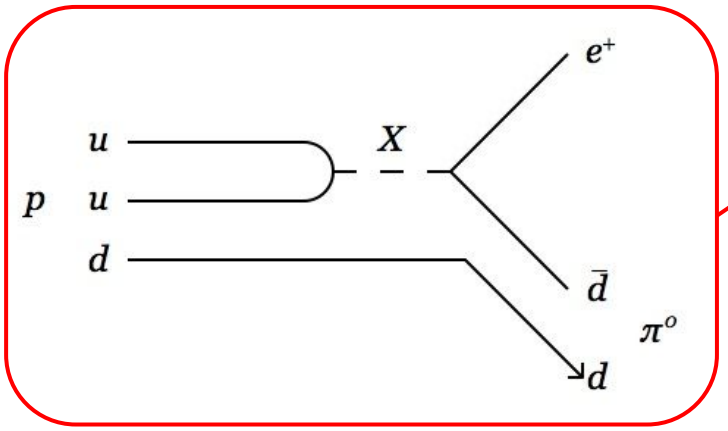
Conversation of R-Parity:

- R_{SM}=+1 and R_{SUSY}=-1
- **Proton stable**
- Lightest SUSY Particle is stable
- ...



Search for RPV SUSY

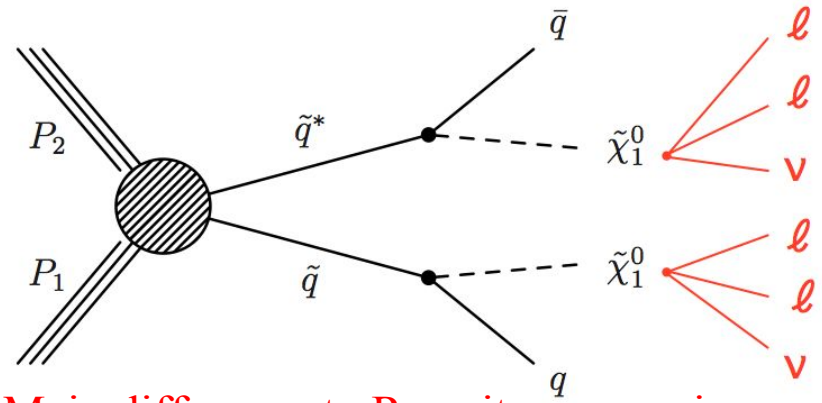
R-Parity: $R = (-1)^{3B+L+2S}$



Baryon-Number (B) and Lepton-Number (L) are violated!
If only L or B is violated, then the proton would be still stable!

Conversation of R-Parity:

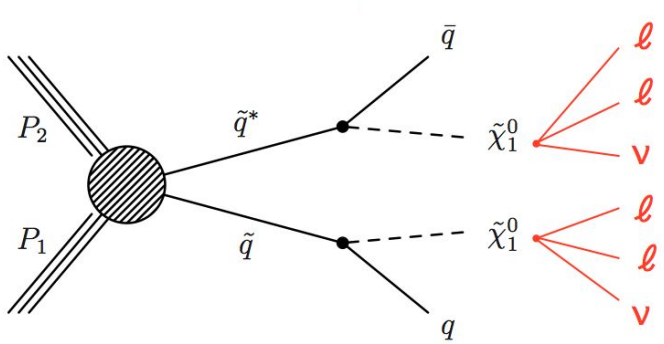
- R_{SM}=+1 and R_{SUSY}=-1
- **Proton stable!**
- Lightest SUSY Particle is stable
- ....



Main difference to R-parity conserving SUSY: lower MET expectation!

Focus on L-RPV in the following:. For others, please check http://cms-results.web.cern.ch/cms-results/public-results/

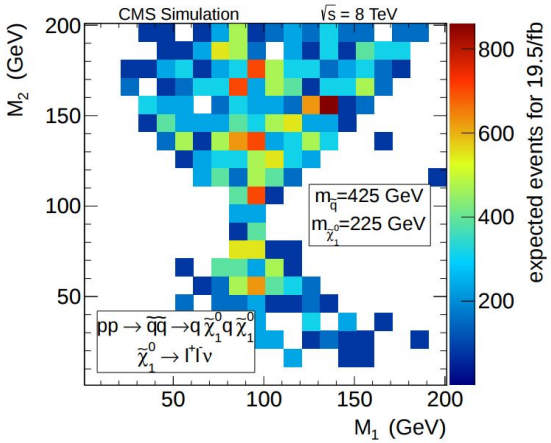
Search for RPV SUSY in 4l final state

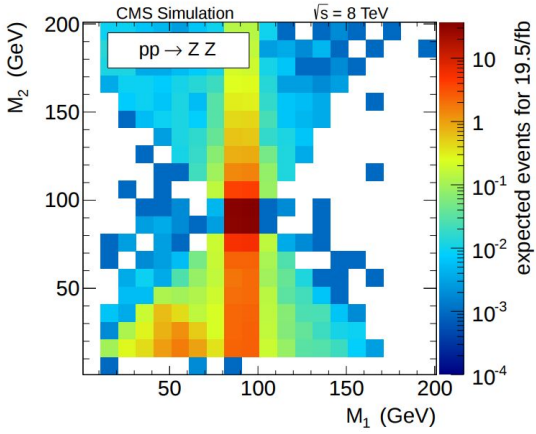


λ-term	neutralino LSP decay mode
$\lambda_{121} = -\lambda_{211}$	$e\mu\nu_e + ee\nu_\mu$
$\lambda_{122} = -\lambda_{212}$	$\mu\mu\nu_e + \mu e\nu_\mu$
$\lambda_{123} = -\lambda_{231}$	$\tau\mu\nu_e + \tau e\nu_\mu$
$\lambda_{131} = -\lambda_{311}$	$e\tau\nu_e + ee\nu_\tau$
$\lambda_{132} = -\lambda_{312}$	$\mu\tau\nu_e + \mu e\nu_\tau$
$\lambda_{133} = -\lambda_{331}$	$\tau\tau\nu_e + \tau e\nu_\tau$
$\lambda_{231} = -\lambda_{321}$	$e\tau\nu_\mu + e\mu\nu_\tau$
$\lambda_{232} = -\lambda_{322}$	$\mu\tau\nu_\mu + \mu\mu\nu_\tau$
$\lambda_{233} = -\lambda_{323}$	$\tau\tau\nu_\mu + \tau\mu\nu_\tau$

Search Strategy:

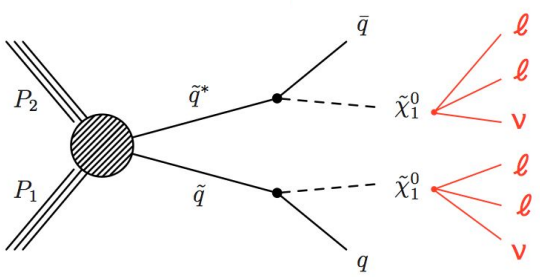
- 4 tight leptons (e,μ)
- Split M_1 and M_2 in on-Z and off-Z regions
  ($M_{1(2)}$: invariant mass of first (second) opposite sign same flavor pair)

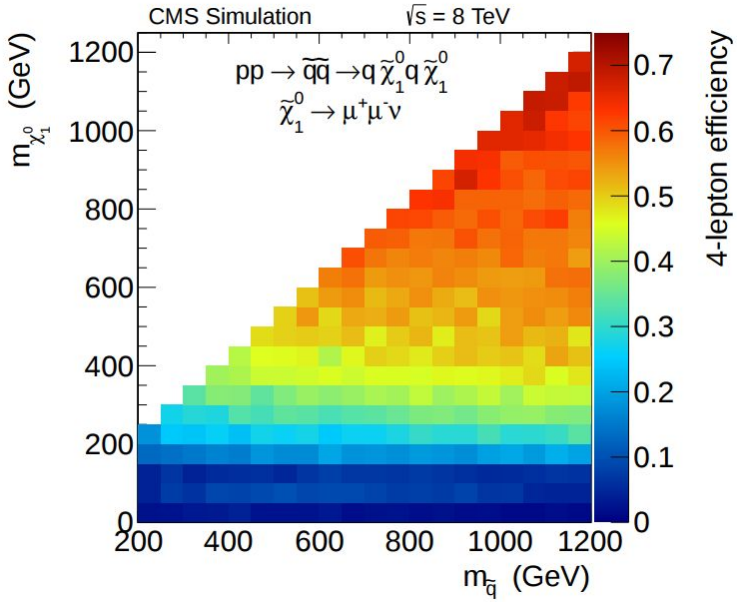


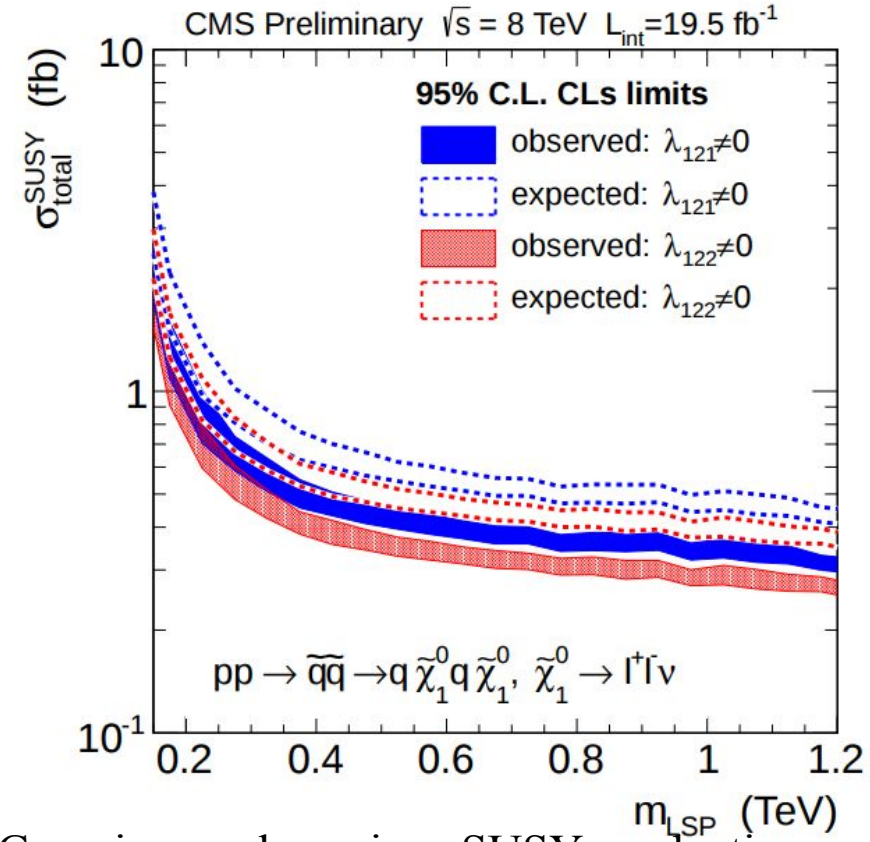


CMS-PAS-SUS-13-010

Search for RPV SUSY in 4l final state



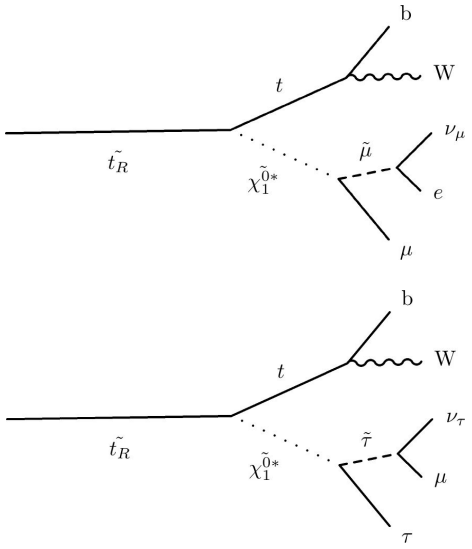




Generic search: various SUSY production modes can be extended for 4 lepton RPV final states. Check the documentation for other interpretations!

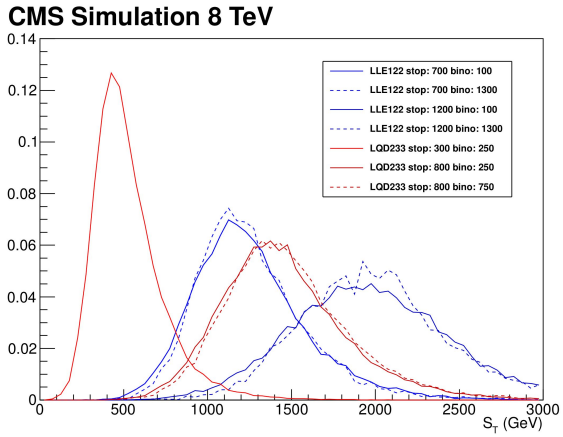
CMS-PAS-SUS-13-010

Search for RPV stop quarks



Search Strategy:

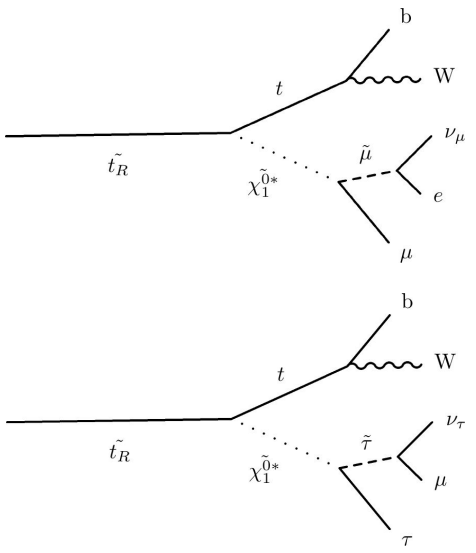
- 3+ tight leptons (e,μ,τ_{had})
- S_T:scalar sum of all transverse momenta
- Signal regions 1-4:at least one b-tagged jets and no Z-candidate
- Signal regions 5-8: a Z-Candidate or no b-tagged jet

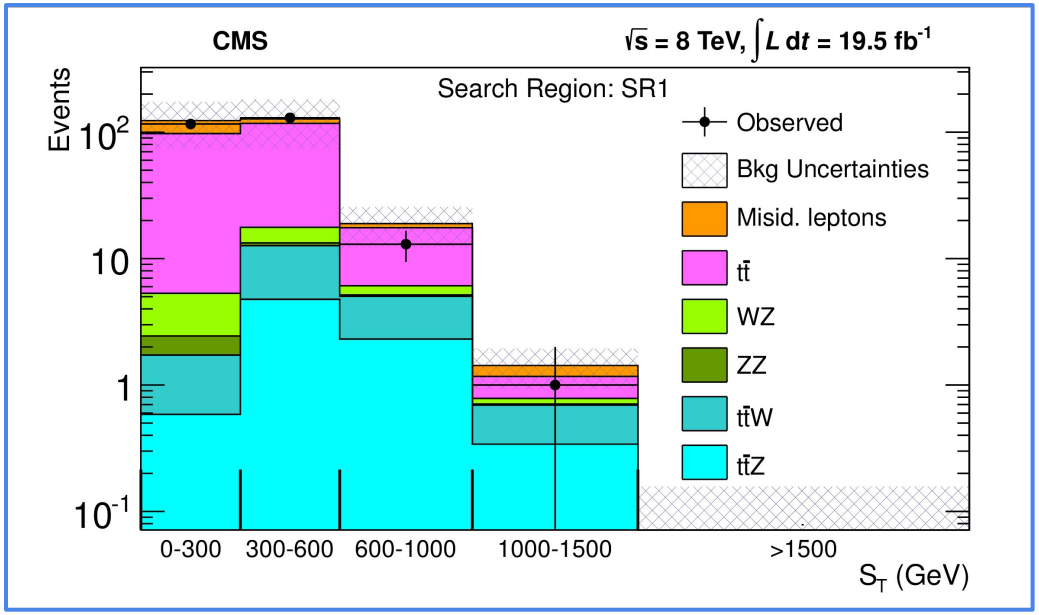


SR	N_L	N_τ	$0 < S_T < 300$		$300 < S_T < 600$		$600 < S_T < 1000$		$1000 < S_T < 1500$		$S_T > 1500$	
			obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
SR1	3	0	116	123 ± 50	130	127 ± 54	13	18.9 ± 6.7	1	1.43 ± 0.51	0	0.208 ± 0.096
SR2	3	≥ 1	710	698 ± 287	746	837 ± 423	83	97 ± 48	3	6.9 ± 3.9	0	0.73 ± 0.49
SR3	4	0	0	0.186 ± 0.074	1	0.43 ± 0.22	0	0.19 ± 0.12	0	0.037 ± 0.039	0	0.000 ± 0.021
SR4	4	≥ 1	1	0.89 ± 0.42	0	1.31 ± 0.48	0	0.39 ± 0.19	0	0.019 ± 0.026	0	0.000 ± 0.021
SR5	3	0	—	—	—	—	165	174 ± 53	16	21.4 ± 8.4	5	2.18 ± 0.99
SR6	3	≥ 1	—	—	—	—	276	249 ± 80	17	19.9 ± 6.8	0	1.84 ± 0.83
SR7	4	0	—	—	—	—	5	8.2 ± 2.6	2	0.96 ± 0.37	0	0.113 ± 0.056
SR8	4	≥ 1	—	—	—	—	2	3.8 ± 1.3	0	0.34 ± 0.16	0	0.040 ± 0.033

Phys. Rev. Lett. 111 (2013) 221801

Search for RPV stop quarks





SR	N_L	N_T	$0 < S_T < 300$		$300 < S_T < 600$		$600 < S_T < 1000$		$1000 < S_T < 1500$		$S_T > 1500$	
			obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
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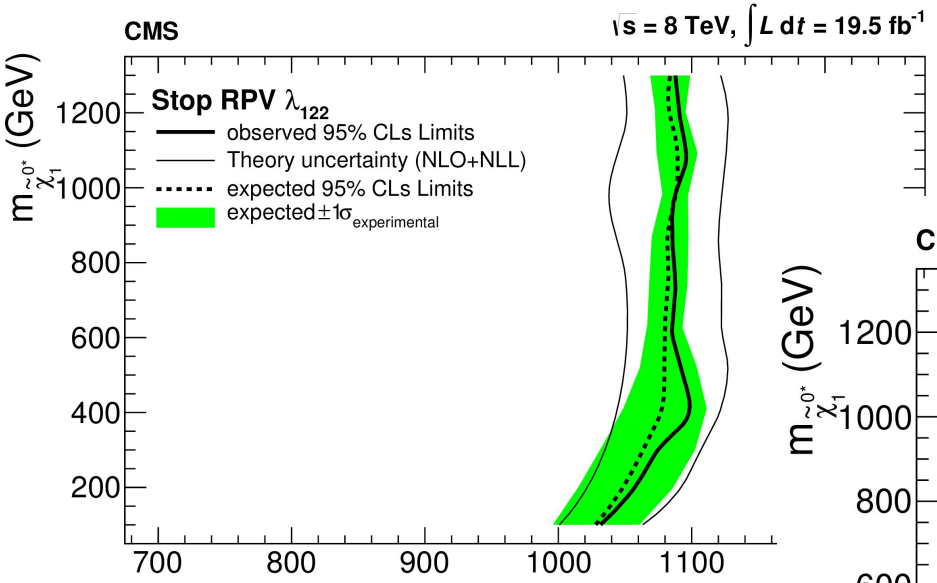
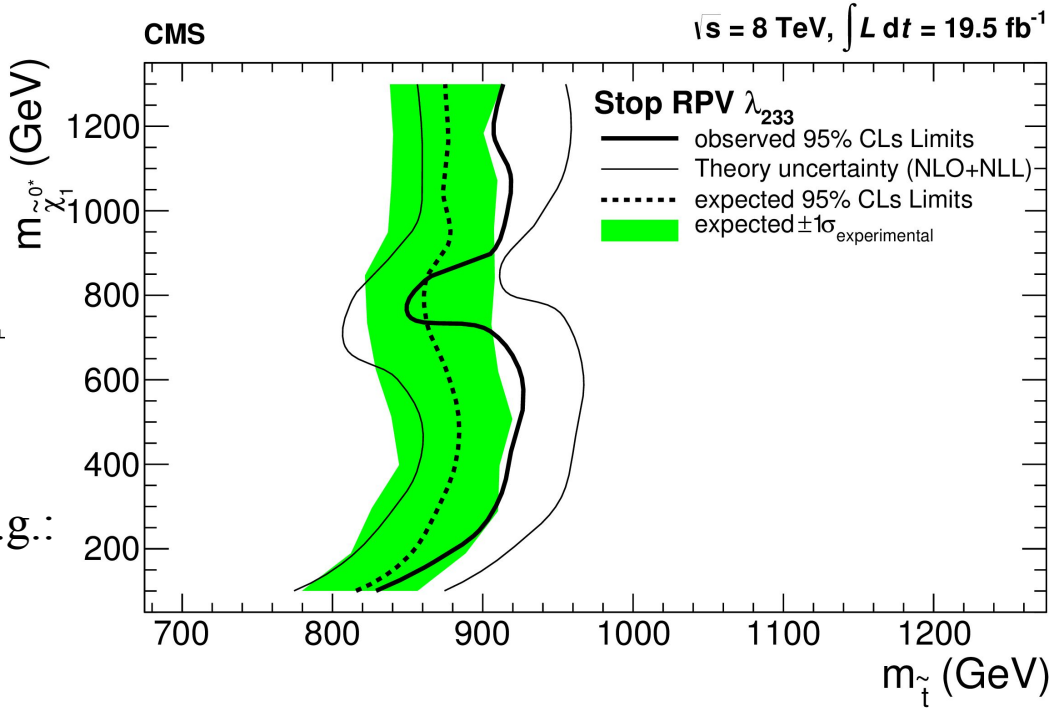
Phys. Rev. Lett. 111 (2013) 221801

Search for RPV stop quarks



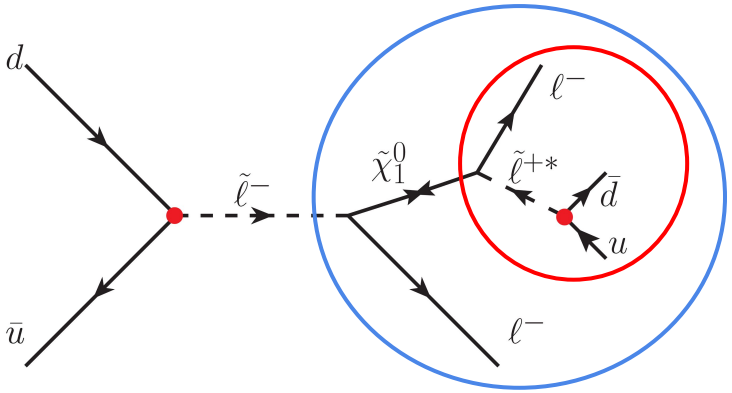


No significant excess observed…
Limits on various RPV couplings, e.g.:

- λ_{122} and M_{Bino}=200GeV:
  M_{stop} < 1020 GeV excluded
- λ_{233} and M_{Bino}=200GeV:
  M_{stop} < 820 GeV excluded

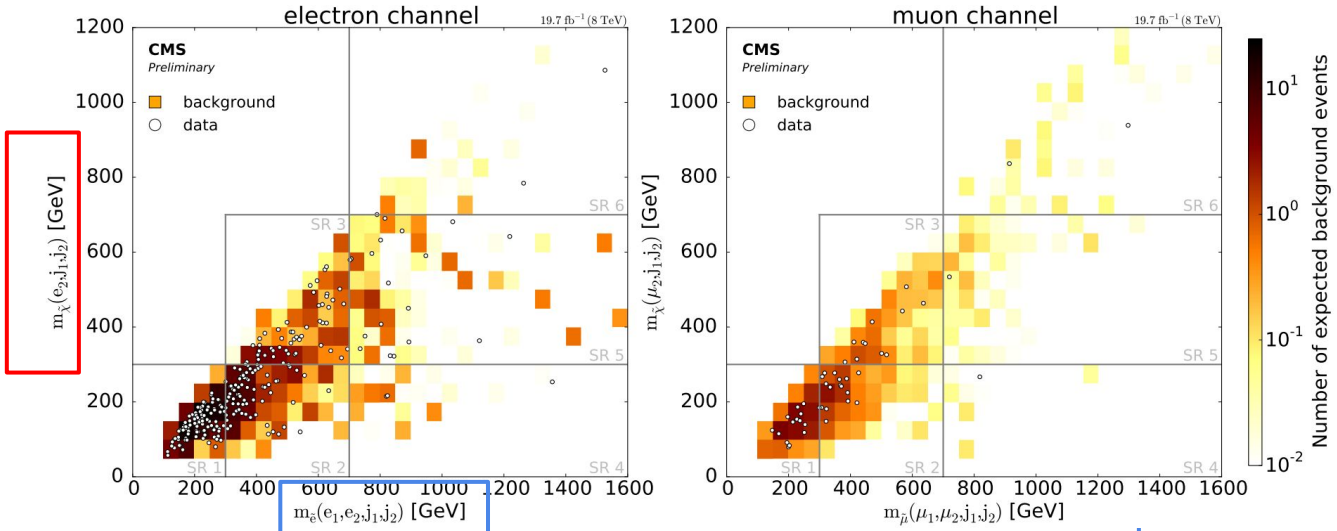
Phys. Rev. Lett. 111 (2013) 221801

Search for RPV SUSY in dilepton channels

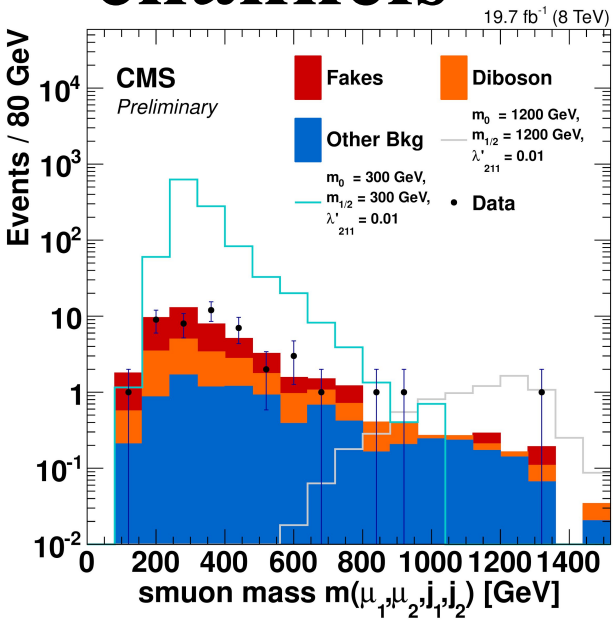


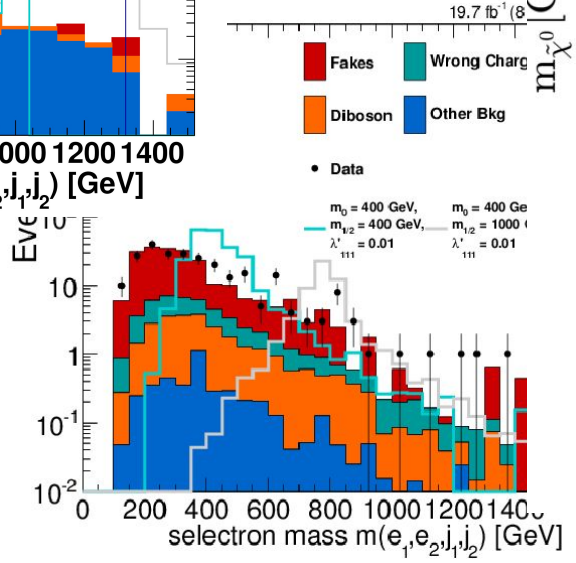
Search Strategy:

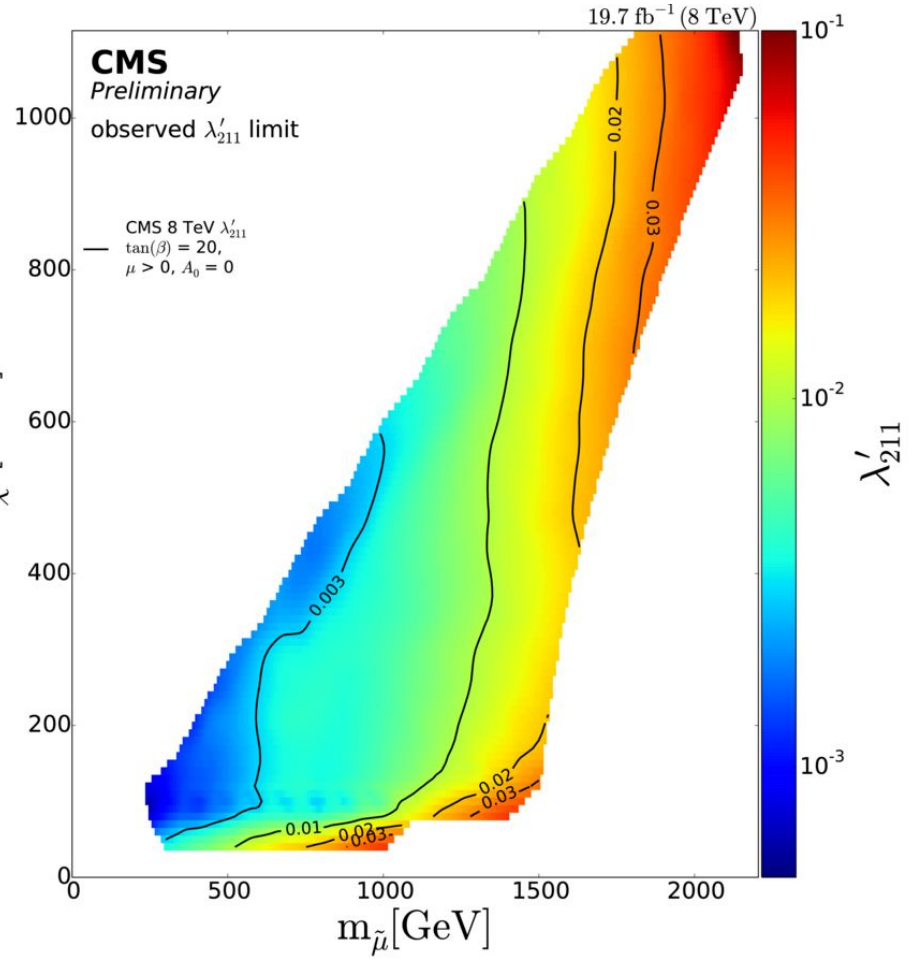
- 2 tight leptons (e,μ)
- 2 Jets (not b-tagged)
- Split event according to $M_{slepton}$ (lljj) and $M_{neutralino}$(ljj)



Search for RPV SUSY in dilepton channels





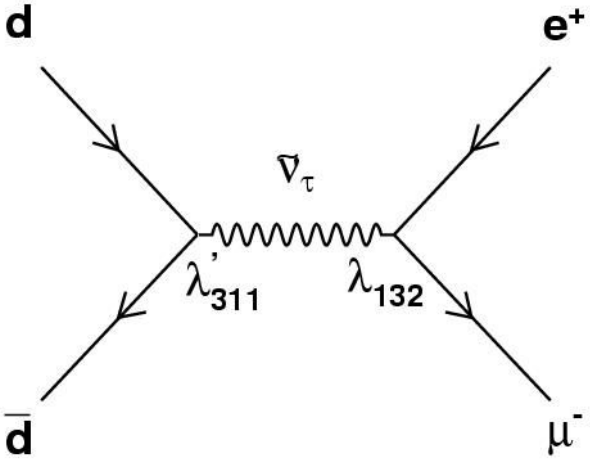


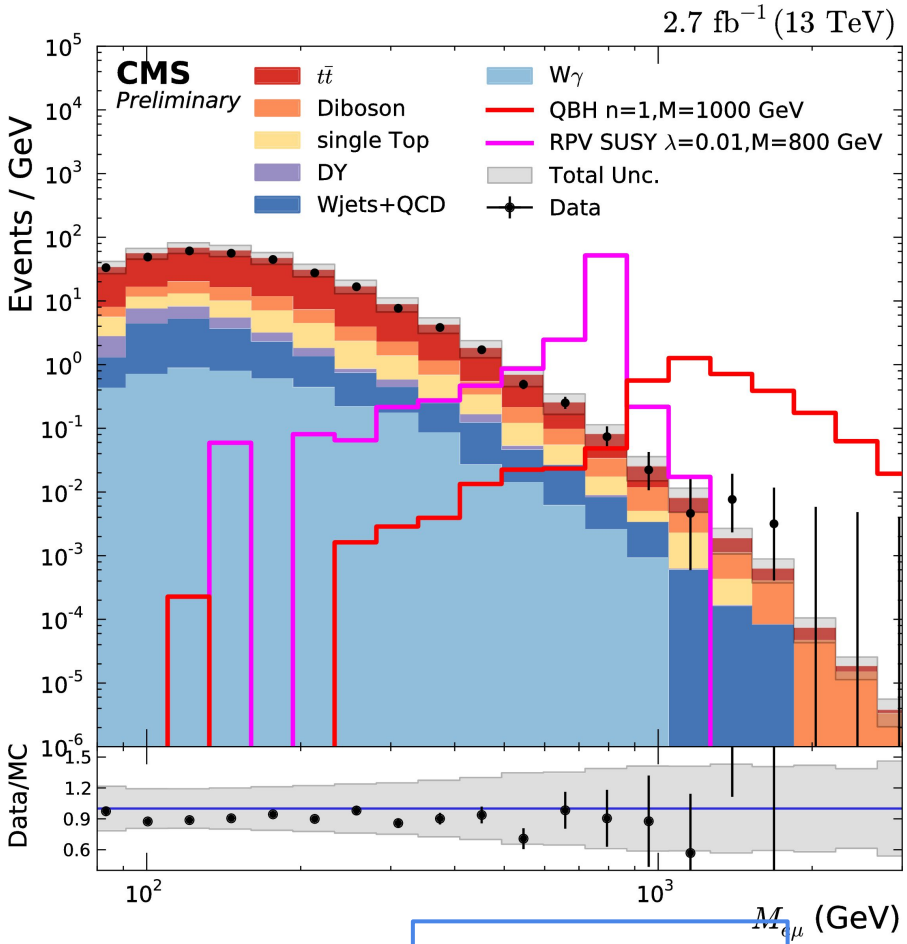
No significant excess observed...

CMS-PAS-SUS-14-018

Search for high mass resonances in the eμ final states at 13 TeV

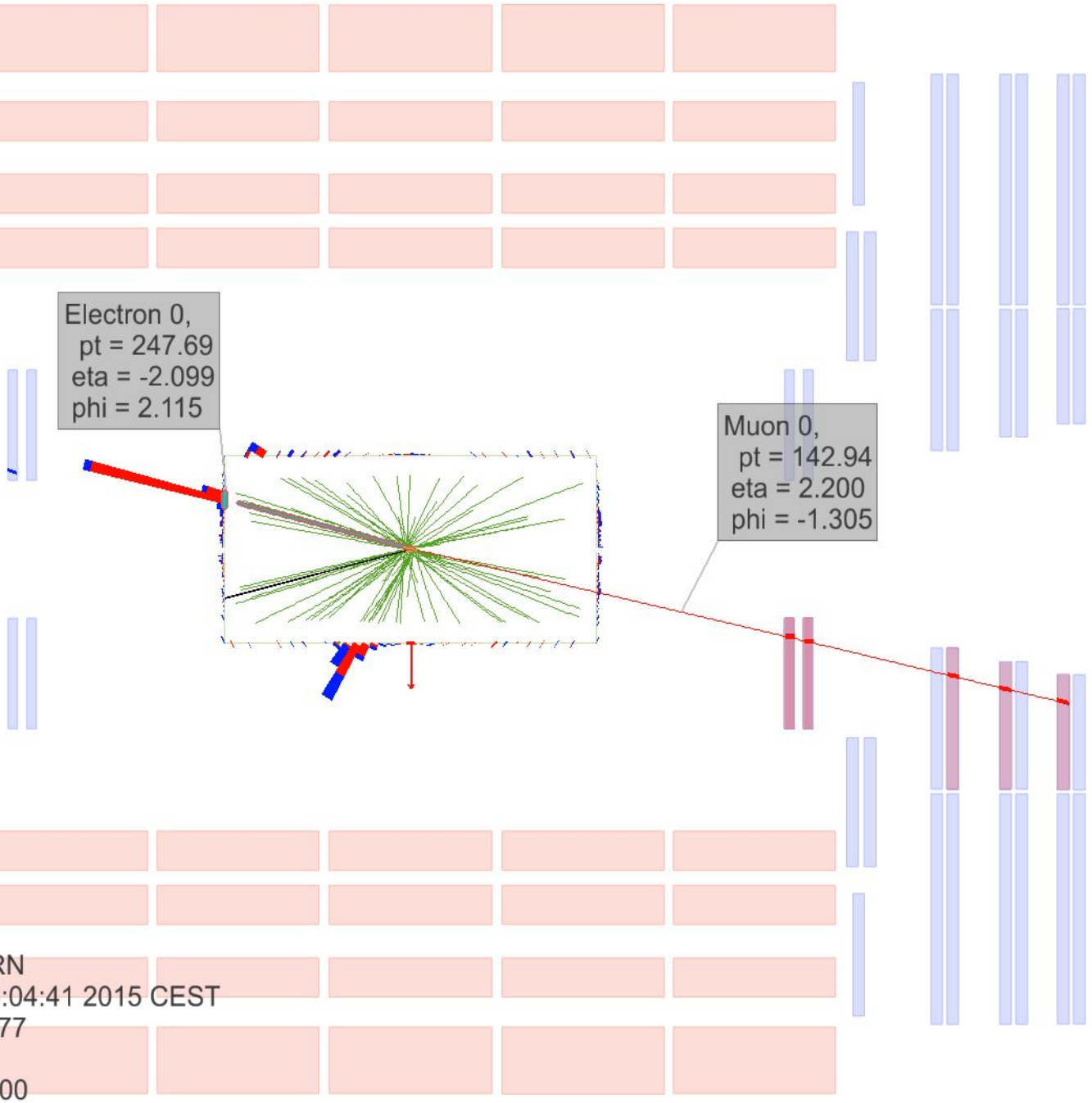
Resonant sneutrino decays (RPV-SUSY) or non-resonant Quantum-Black-Holes (QBH) could decay into eμ pairs (+others models).





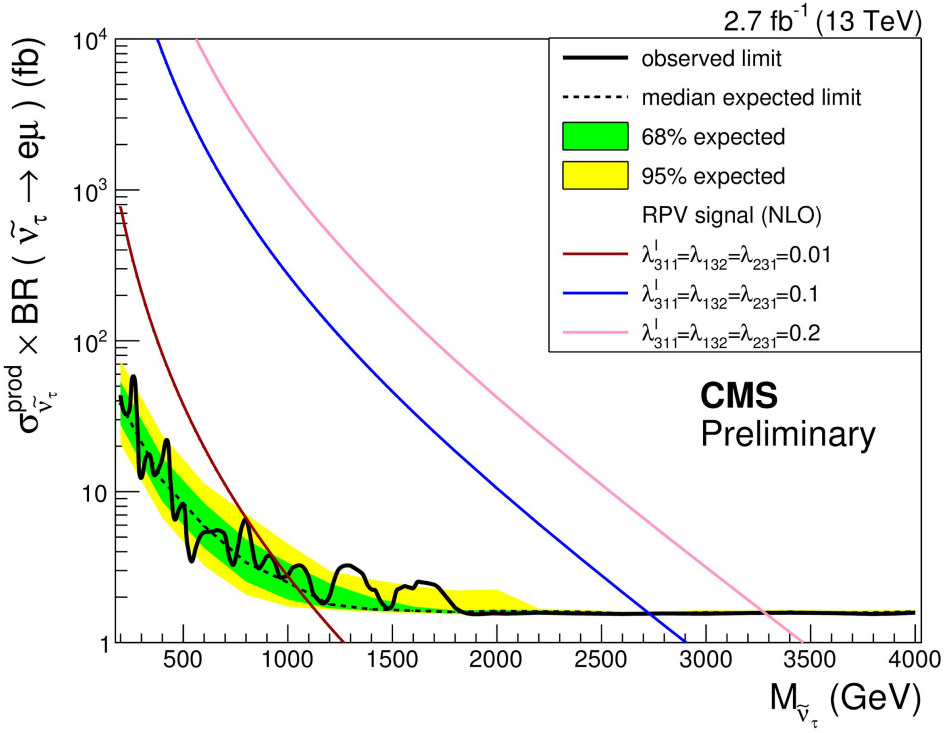
CMS-PAS-EXO-16-001

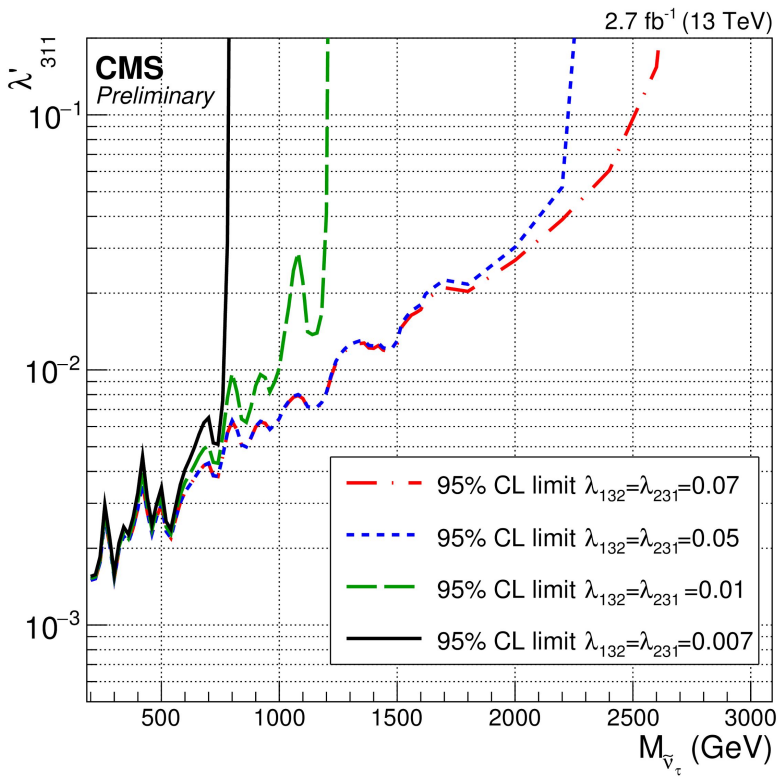
Highest Mass e-μ pair: M=1635 GeV (13TeV)



CMS Experiment at LHC, CERN
Data recorded: Thu Sep 17 14:04:41 2015 CEST
Run/Event: 256677 / 330567777
Lumi section: 324
Orbit/Crossing: 84785800 / 3000

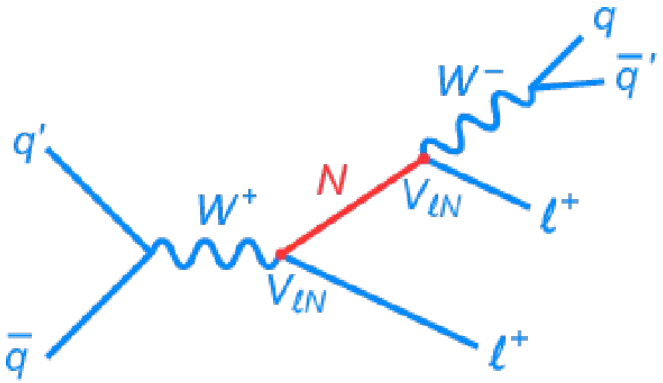
Search for high mass resonances in the eμ final states at 13 TeV





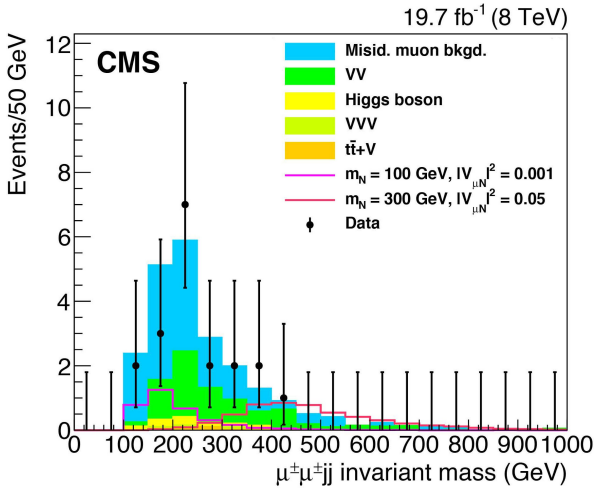
CMS-PAS-EXO-16-001

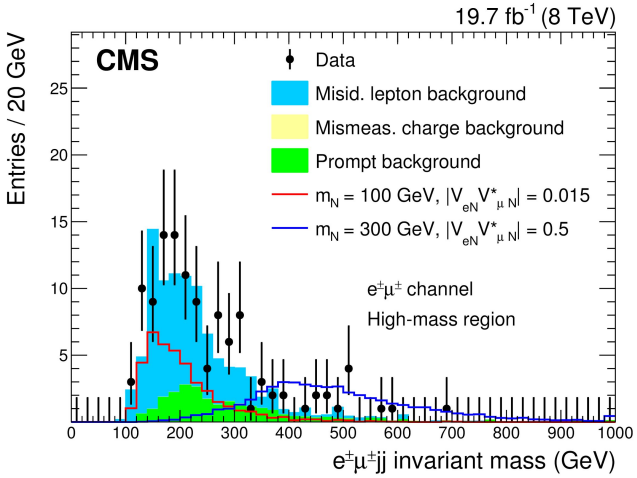
Search for Heavy Majorana Neutrinos

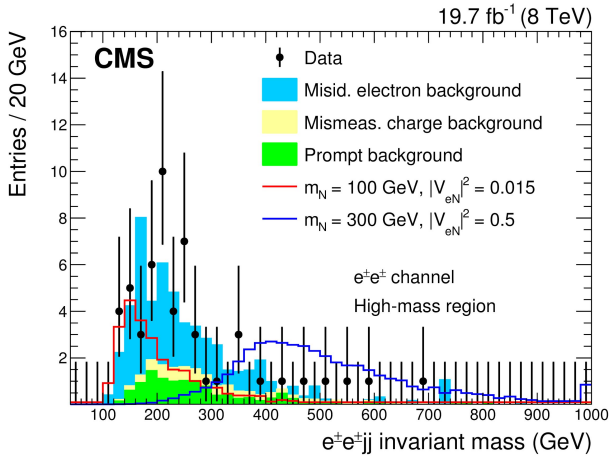


Search Strategy:

- Two tight leptons with same sign($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$)
- Mass dependent cust:
  - Low mass m_N < 90 GeV: MET<30 GeV , m (lljj)<200 GeV, m(jj)<120 GeV
  - High mass m_N> 90 GeV: MET<35 GeV, m (jj)=m_W ± 30 GeV

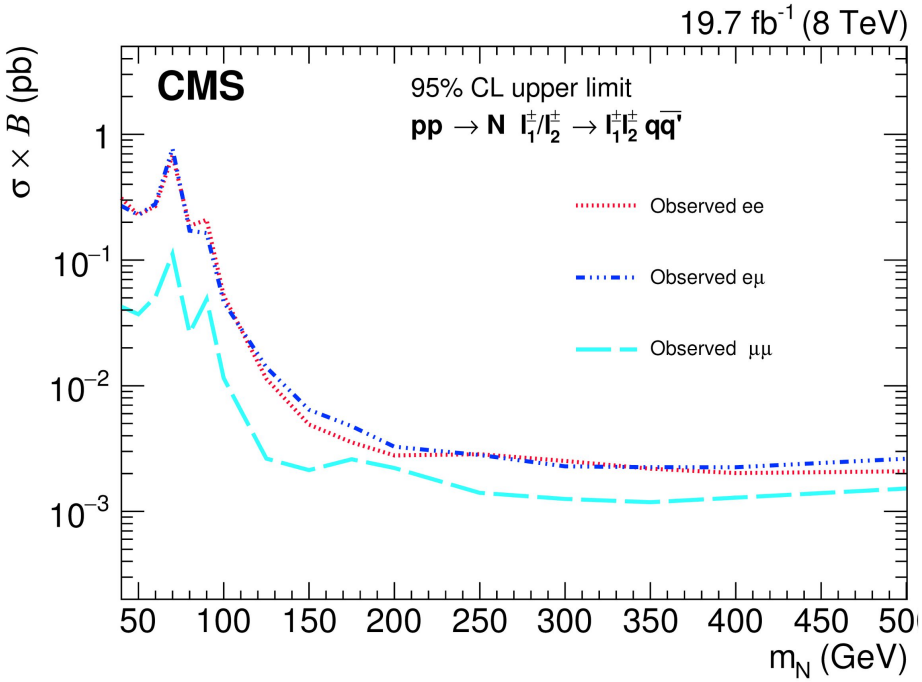


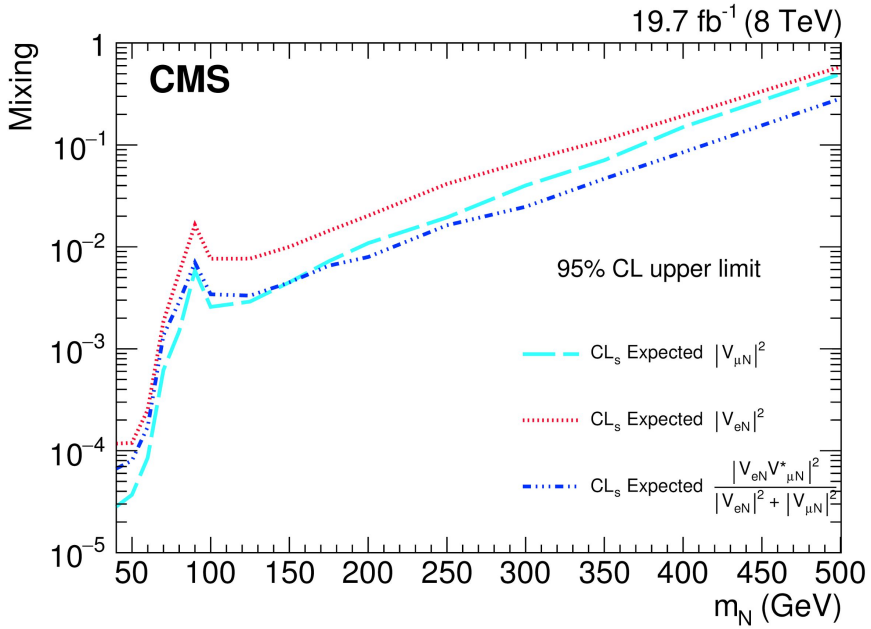




JHEP 04 (2016) 169
Phys. Lett. B 748 (2015) 144

Search for Heavy Majorana Neutrinos





JHEP 04 (2016) 169
Phys. Lett. B 748 (2015) 144

Conclusion

- Strong portfolio of CLFV searches in CMS
- New Physics models on CLFV tested up to multi-TeV scale already
- LHC Run-II: expect more interesting updates by the end of the year!

http://cms-results.web.cern.ch/cms-results/public-results/publications/