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Europe/Stockholm timezone

Search for charged lepton flavour violation processes & heavy neutrinos at CMS

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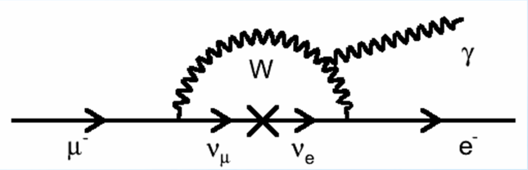
Introduction

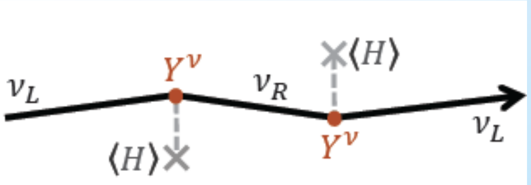
In SM : Lepton Number/Lepton Flavor are not related to a gauge symmetry

- **In 1998 : Observation of flavor neutrino oscillations** → prove neutral LFV
  Massive neutrinos → go beyond the minimal SM (BSM physics)
  however: neutrinos masses << other (charged) fermion masses
- **Key questions :**
  → **What is the mechanism at the origin of the neutrino mass ?**
  - What about charged LFV ?
  - Do heavy right-handed neutrinos exist ?



Neutrino-induced lepton flavor violation for charged leptons is expected to be very small [e.g., Br($\mu \to e\gamma$) ~ 10^{-50}]

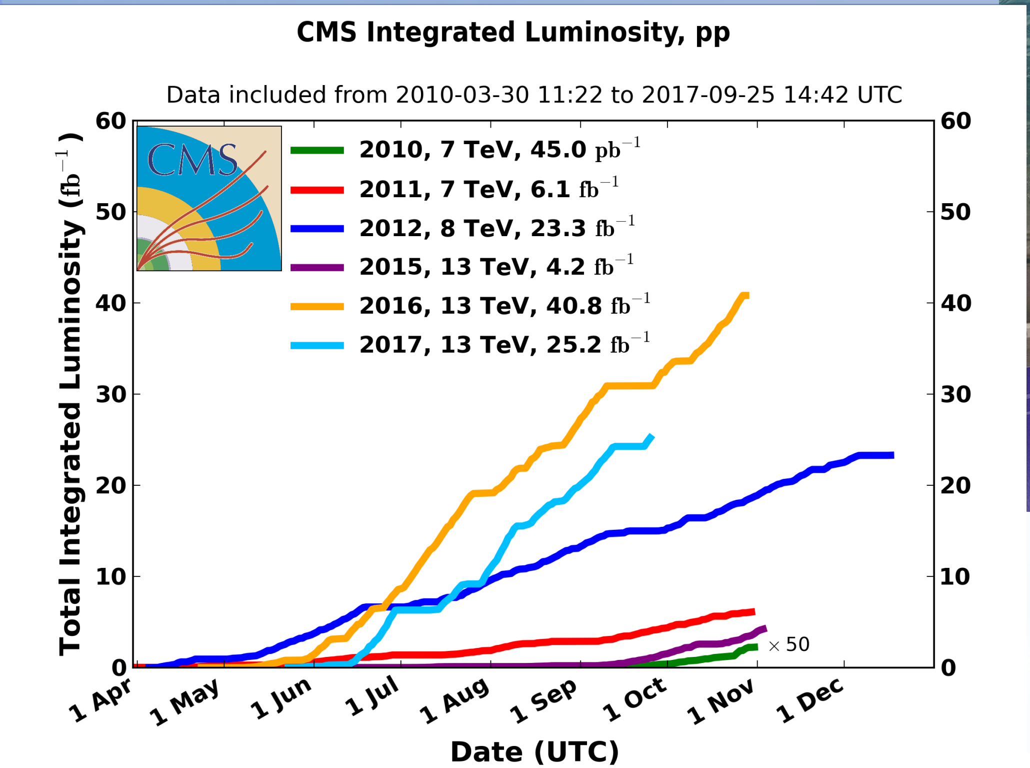
Many news physics models can enhance this decay
Example : RPV SUSY, Extra-dim, GUT, models with Majorana N etc
→ good probe for new physics

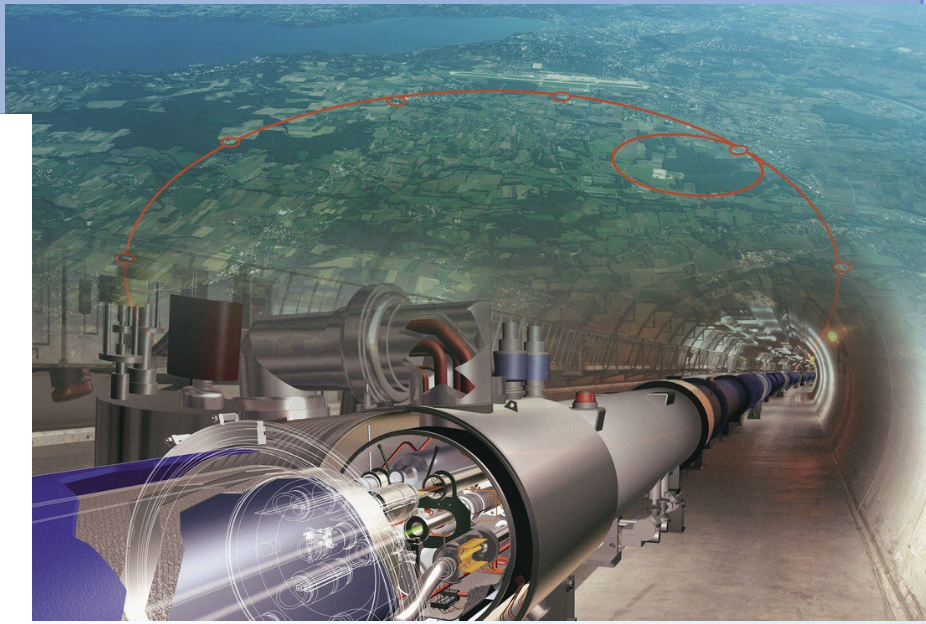


A natural way to generate LNV and neutrino mass :
- Seesaw Mechanism (type I, II, III)
- Left-Right Symmetry model offers the Seesaw scale and heavy neutrinos

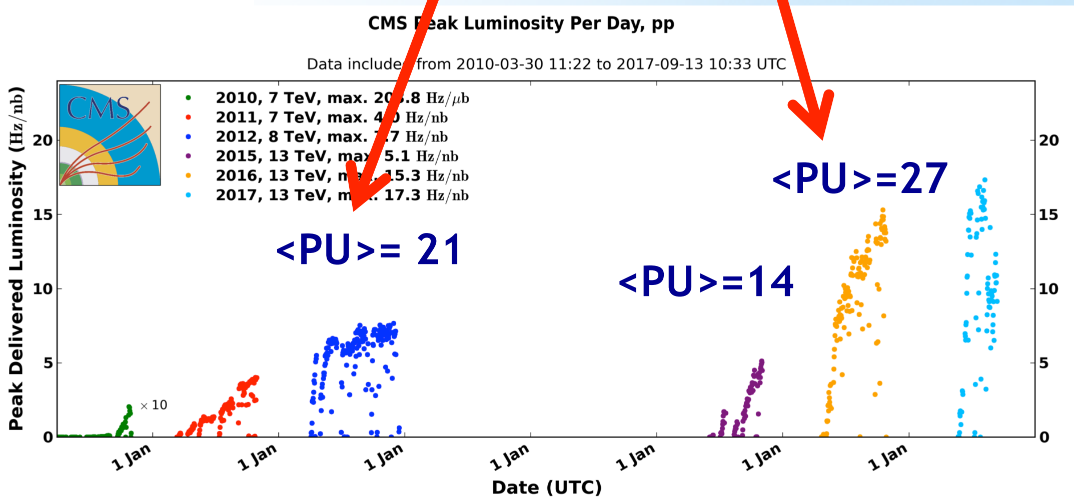
$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ $\quad M_{W_R} \gg M_{W_L}$

The LHC





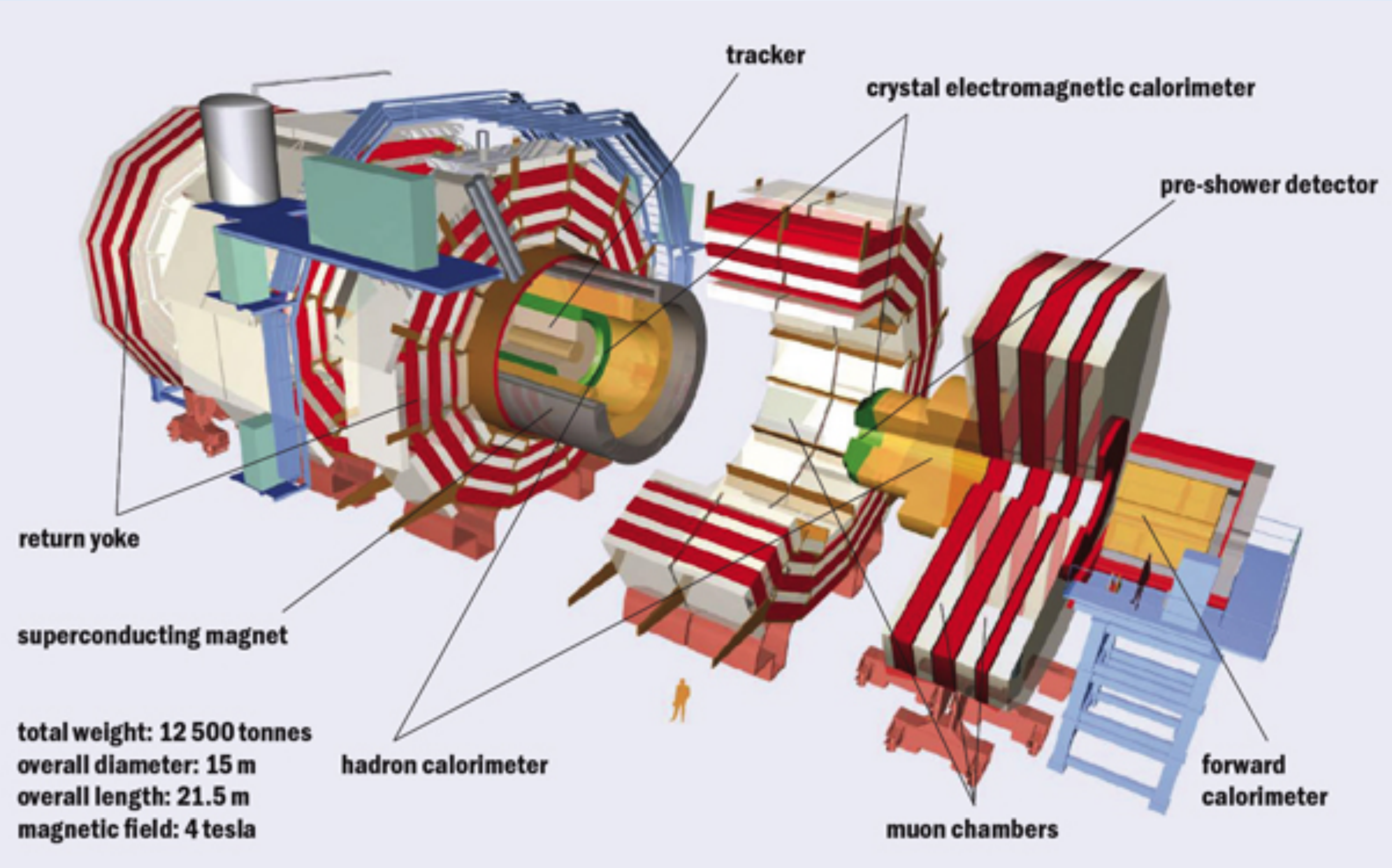
run1 & run2



Analyses presented in this talk use :

2012 : 8 TeV, 23 fb^{-1}
2015 : 13 TeV, 4 fb^{-1}
2016 : 13 TeV, 40 fb^{-1}
(LHC delivered luminosity)

The CMS detector



High precision multipurpose detectors

Particle identification: electrons, muons, photons, charged hadrons, neutral hadrons

LFV searches @CMS : outline

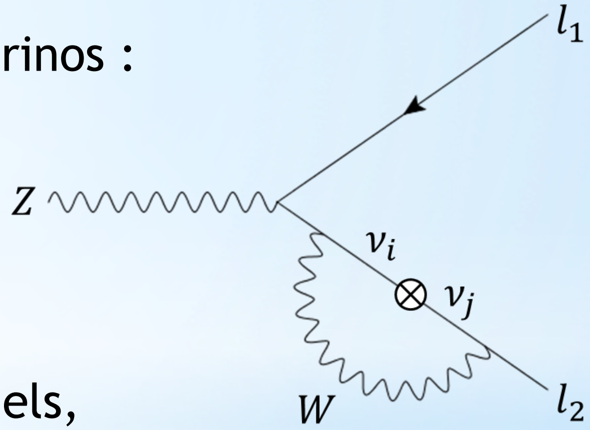
- Lepton flavour violation in Z decays
- Lepton flavour violation in H decays
- LFV of heavy state $X \to e\mu$
- Search for heavy neutrinos :
  - Type I seesaw and Left-Right SM
  - Type III seesaw

Low energy results (e.g., $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, etc.) provide constraints (but often with assumptions)

LFV in Z decays

LFV in Z decays : Z→eμ

- From one-loop decay with flavor-oscillating neutrinos :
  Predicts LFV in Z decay, Br(Z→eμ)<10^{-60}



- In BSM scenarios :
  Br(Z→eμ) can be enhanced to 10^{-8} or 10^{-9}
  ex : Models with massive Dirac
  or Majorana neutrinos, extended gauge models,
  or RPV SUSY arXiv:hep-ph/0010193

- Indirect constraint from low energy experiment :
  μ→3e: Br(Z→eμ) < 5×10^{-13}
  worth to check if this hold at high energy

- Limit from LEP : Br(Z→eμ) < 1.7×10^{-6} @95% CL

LFV in Z decays : Z→eμ

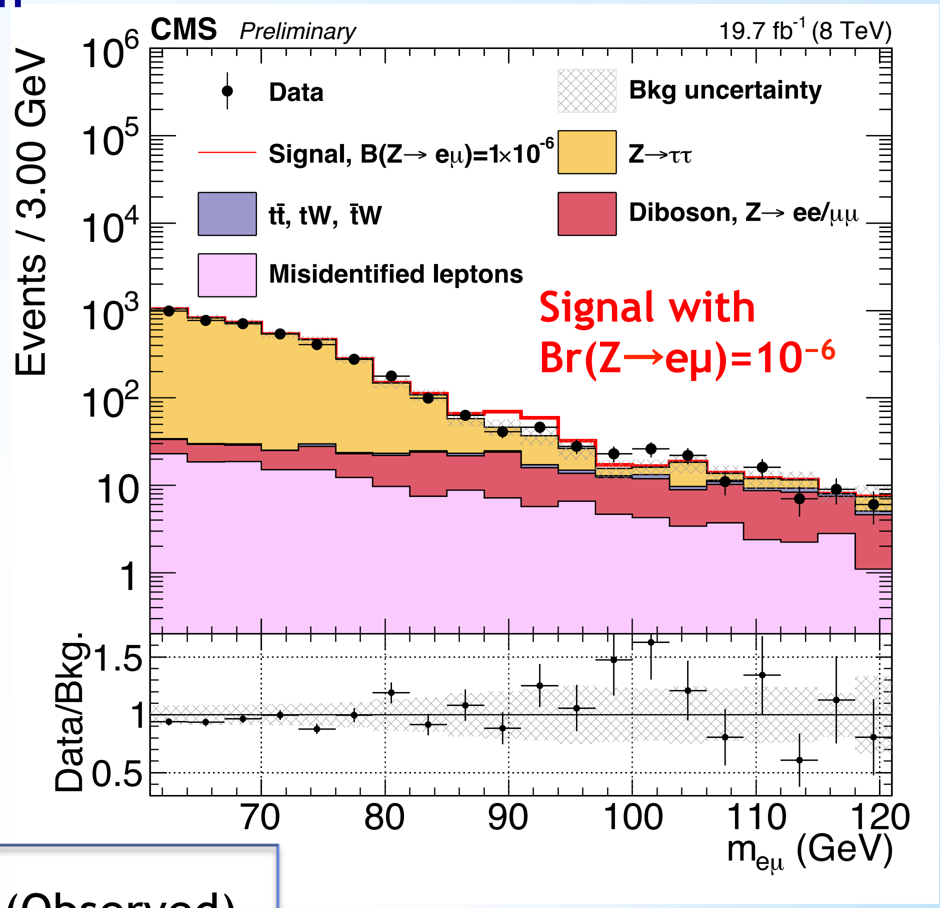
CMS-PAS-EXO-13-005

2012 data analysis (8 TeV, 19.7 fb^{-1})

Search for a bump around the Z mass in the invariant e-μ mass spectrum

Main backgrounds: $Z\to\tau\tau$, W+W-, top-quark pair production, tW, WZ, ZZ, Z+jets and W+jets

Strong event selection to reduce the backgrounds : isolated e and μ, opposite charge, third lepton veto, jet veto, transverse mass (muon) veto, $p_T(Z)$< 10 GeV



Count events in window around the Z

- Background prediction of 83 ± 9
- Events found in data: 87
- Use CLS method to determine limit

Limits @95% CL : Br(Z→eμ) < 7.3 10^{-7} (Observed)
6.7 10^{-7} (Expected)

Better limit than LEP

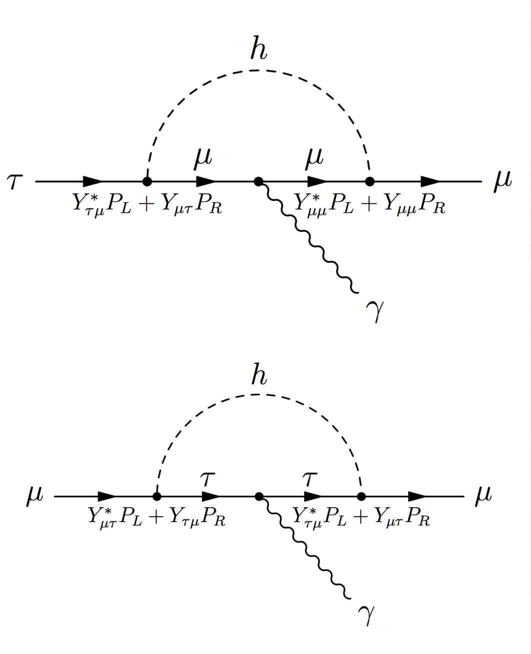
LFV in Higgs decays

LFV in Higgs decays

- LFV couplings to the Higgs possible, e.g., if SM only valid to finite scale
  For example in 2 Higgs Doublet models (2HDM), extra-dimension models, compositness models.

  arXiv:1209.1397

  LFV Higgs couplings would allow processes like :
  μ→e, τ→μ and τ→e via a virtual Higgs boson



- Strong constraint:
  from searches for μ→eγ
  Br(H→eμ) < O(10^{-8}) @ 95% CL

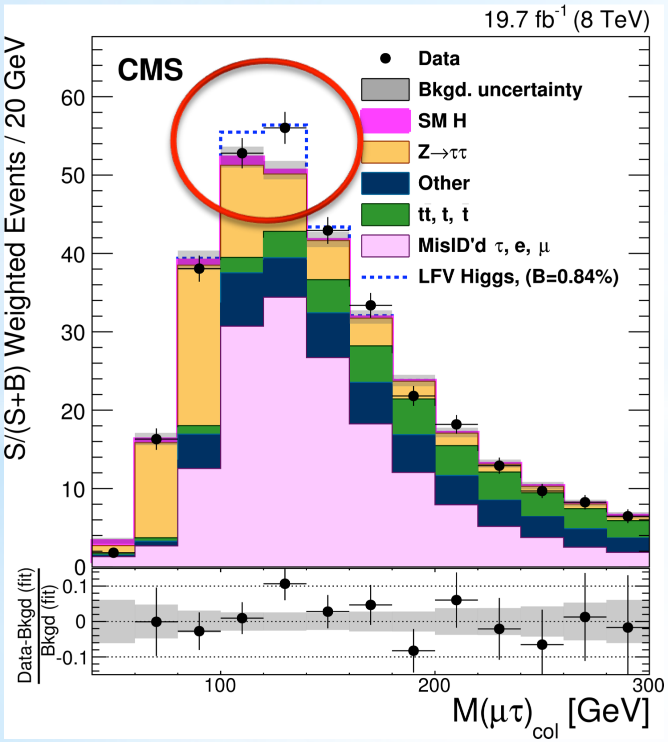
  Weaker limits on
  Br(H→e/μτ) < O(10%) @ 95% CL
  from searches for τ→e/μγ and
  μ/e g-2 measurements

→ direct search for H→eτ and H→μτ: promising

History of H→μτ channel @CMS

Search for H→μτ, 2 channels: μ τ(e) and μ τ(h), and 3 categories: 0,1,2 jets

2012 data analysis (8 TeV, 19.7 fb^{-1})

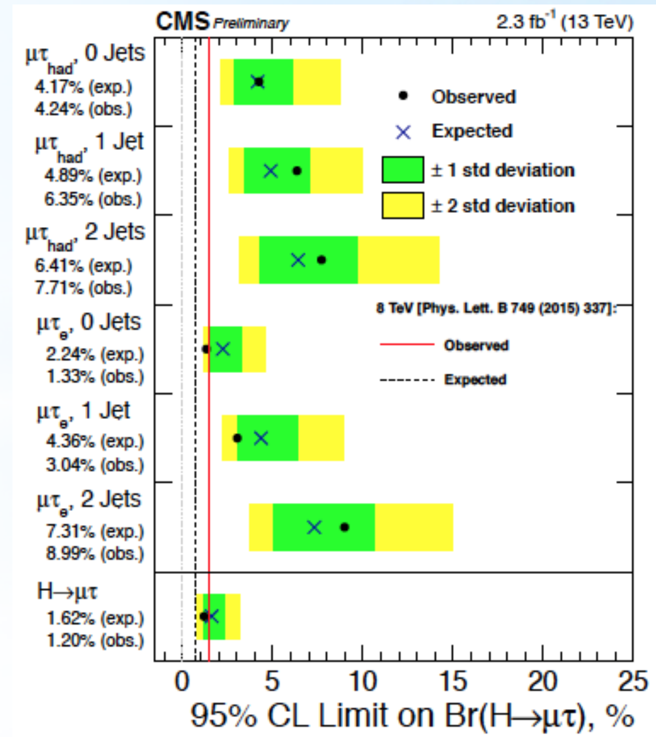


PLB 749 (2015) 337
CMS-HIG-14-005

A small (2.4 sigmas) excess

Br(H→μτ) <1.51% (0.75% expected)

2015 data analysis (13 TeV, 2.3 fb^{-1})



CMS-PAS-HIG-16-005

Br(H→μτ)<1.20% (1.62% expected): not yet at the Run1 sensitivity

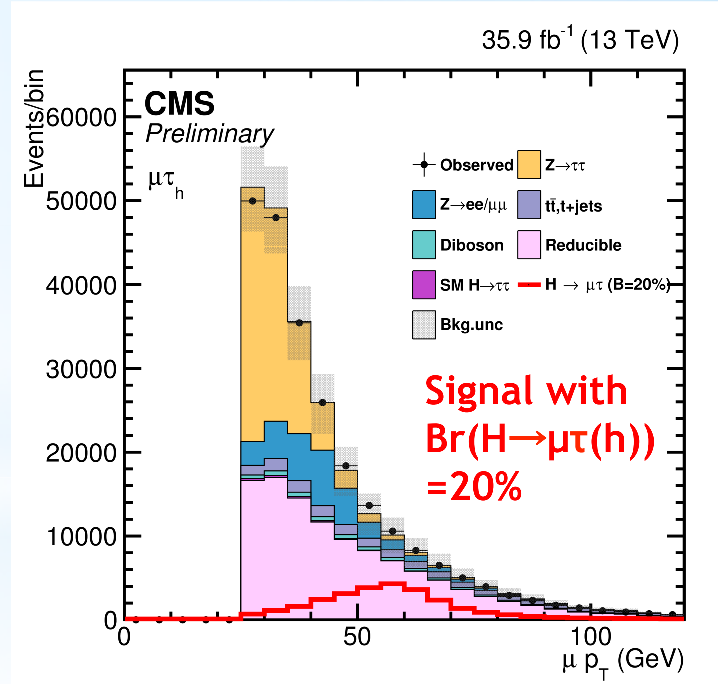
Br(H→eτ) <0.69%
Br(H→eμ) <0.035%

PLB763C (2016) 472

H→μτ & H→eτ channels

UPDATE : 2016 dataset (13 TeV, 35.9 fb^{-1})
Number of channels : μ τ(e) & μ τ(h) and e τ(μ) & e τ(h)
Number of categories : 0, 1, 2 & VBF

CMS PAS HIG-17-001
To be submitted to JHEP



Very similar signatures as the SM H→ττ but with significant kinematic differences
The e(μ) in the LFV H→e(μ)τ decay produced promptly
→ larger momentum than in the SM H→τ(e/μ) τ(h)

Analysis strategy :
-Loose selection+BDT analysis-fit: a set of 8 kinematics variables is combined into a Boost Decision Tree (BDT) (p_{T1},p_{T2},Mcol,Et(miss),M_T(τ(h)), Δη(l_1, l_2), and 2 ΔΦ cuts)
-Mcol-fit analysis as cross check (cut based analysis)

Background estimation : using data driven technique (control regions)
Z→ττ, Z→μμ, Z→ee , also W+jets, multijet bg from QCD (fake leptons)
tt+jet, H→ττ, diboson (using simulations)

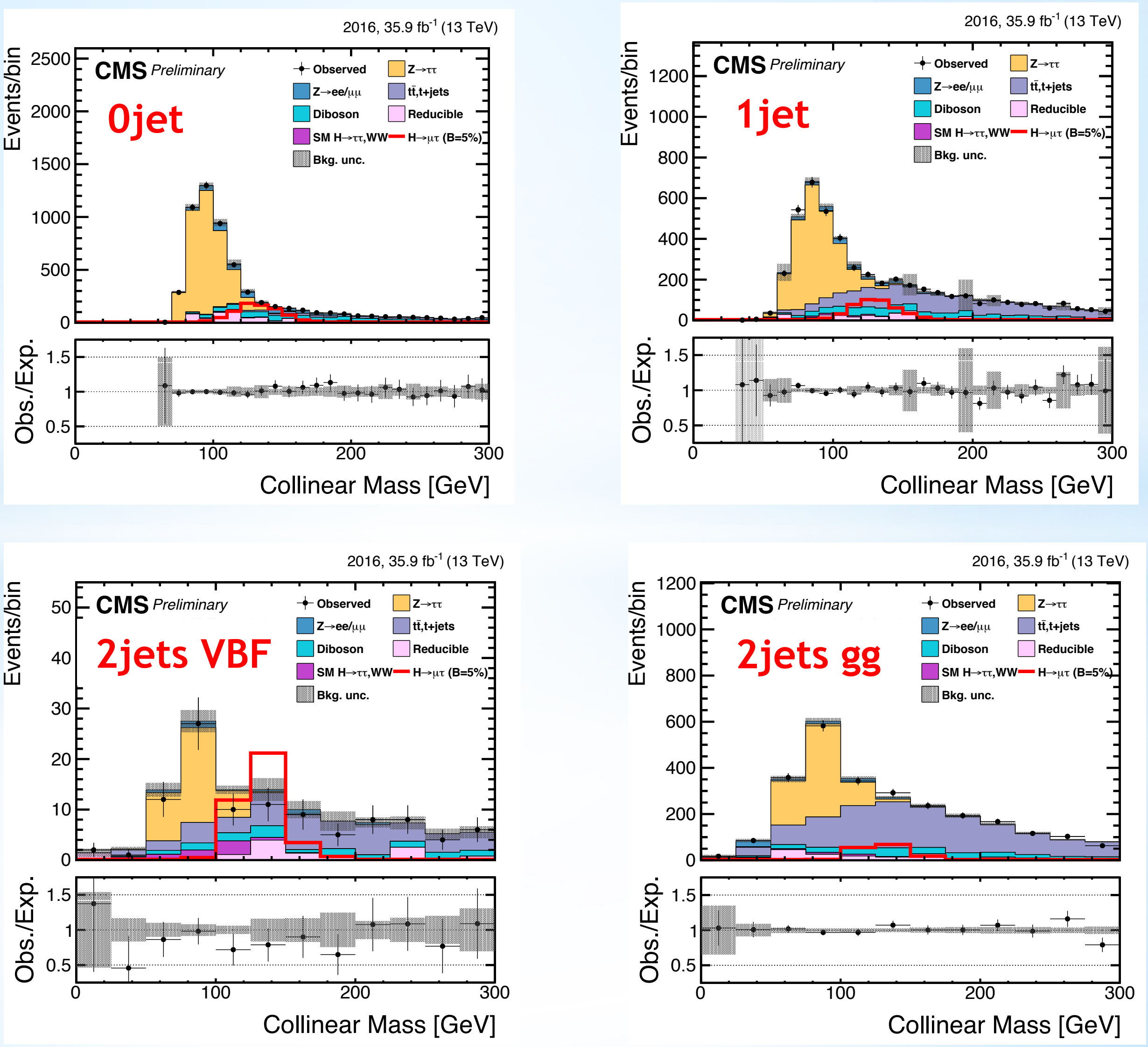
Collinear mass : estimate of Higgs mass using the observed decay of H
+ collinear approximation (M_H>>Mτ) → τ are boosted
→ suppose neutrinos direction = visible decay products of the τ

Collinear mass distribution

NEW

Collinear mass
H→μτ(e) channel :

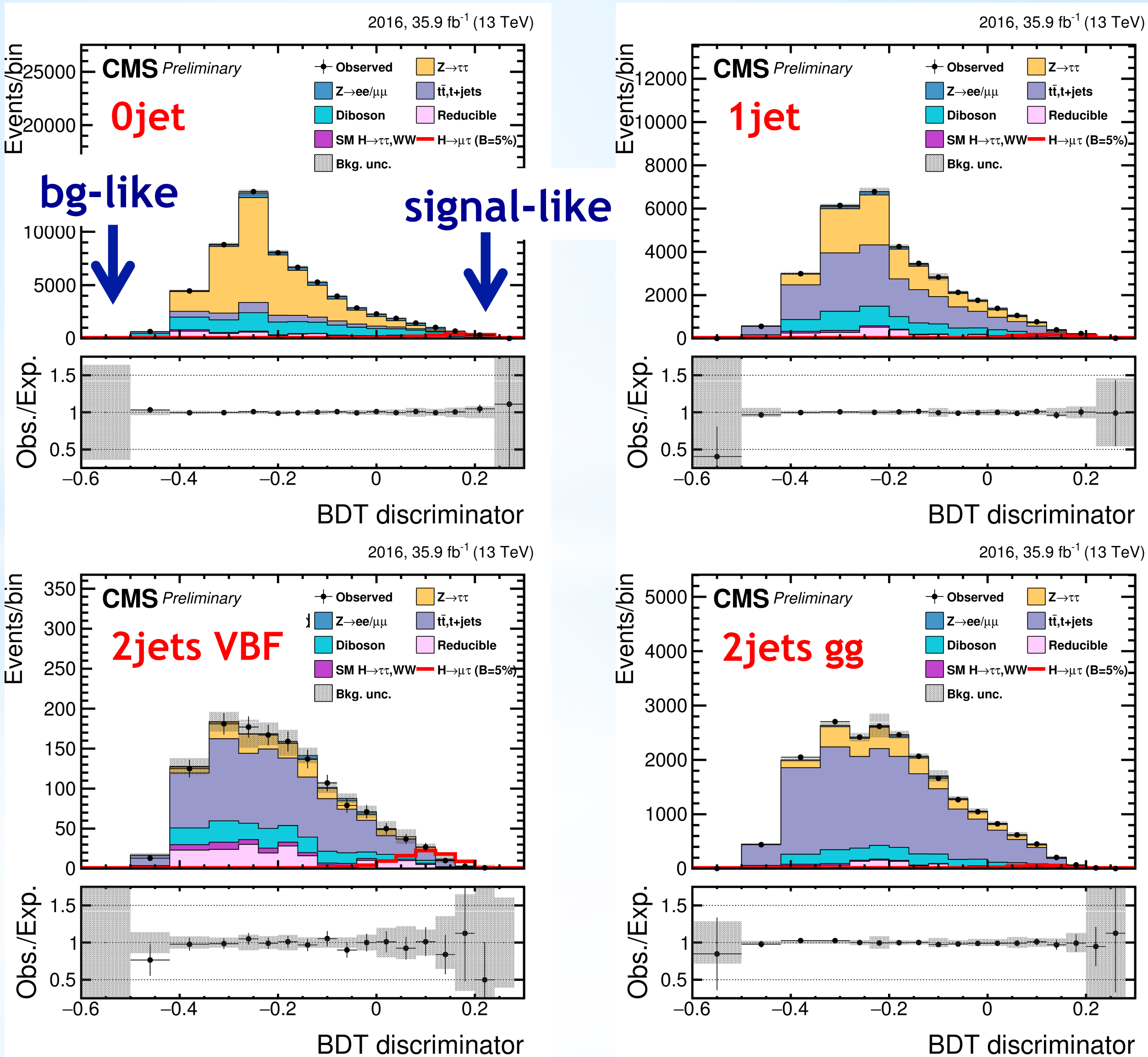
Signal with Br(H→μτ(e)) =5%



BDT output disctribution

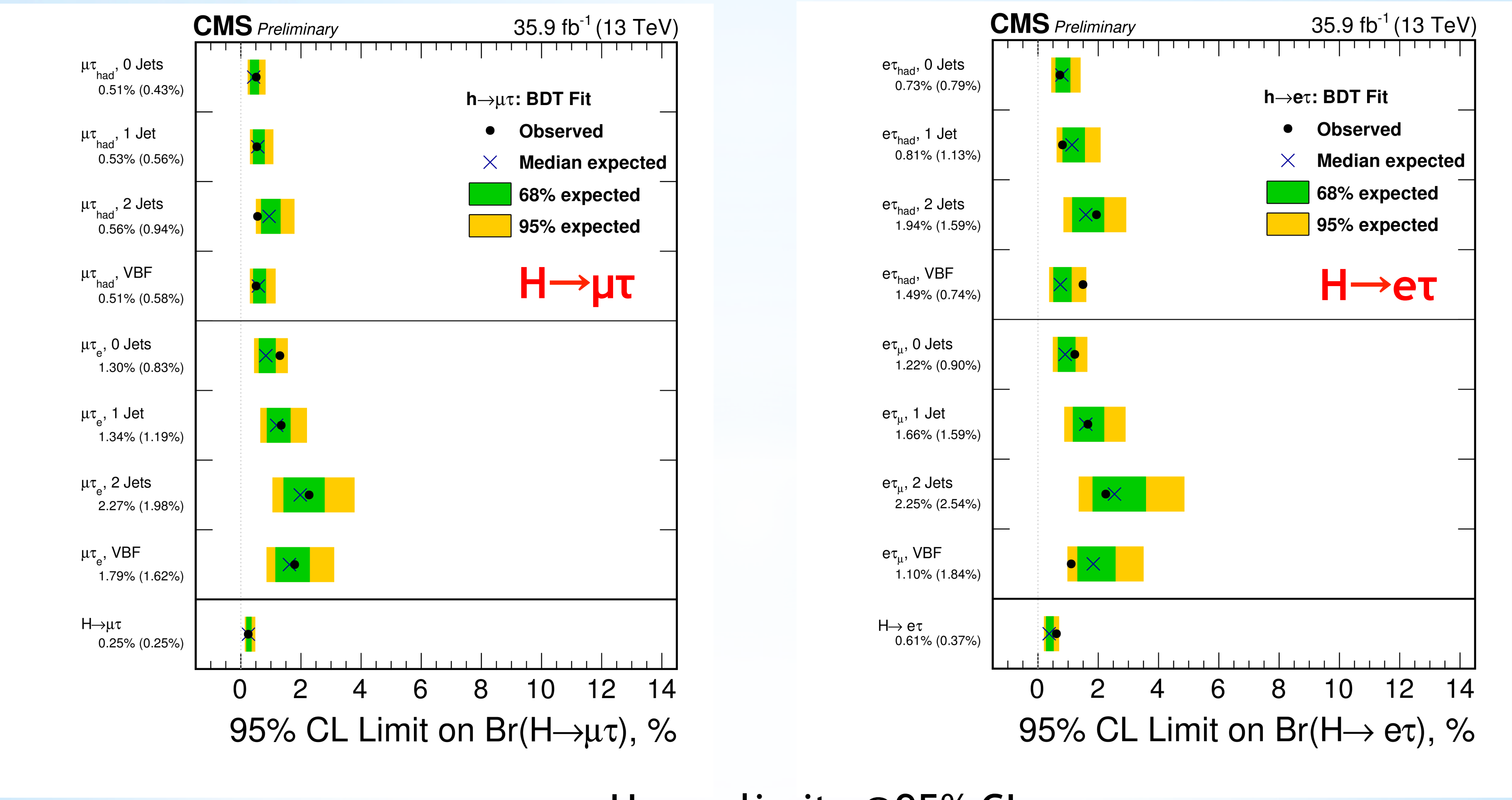
BDT output for the H→μτ(e) channel :

Signal with Br(H→μτ(e)) =5%



Results : H→μτ & H→eτ

BDT-fit analysis results for the 8 categories :



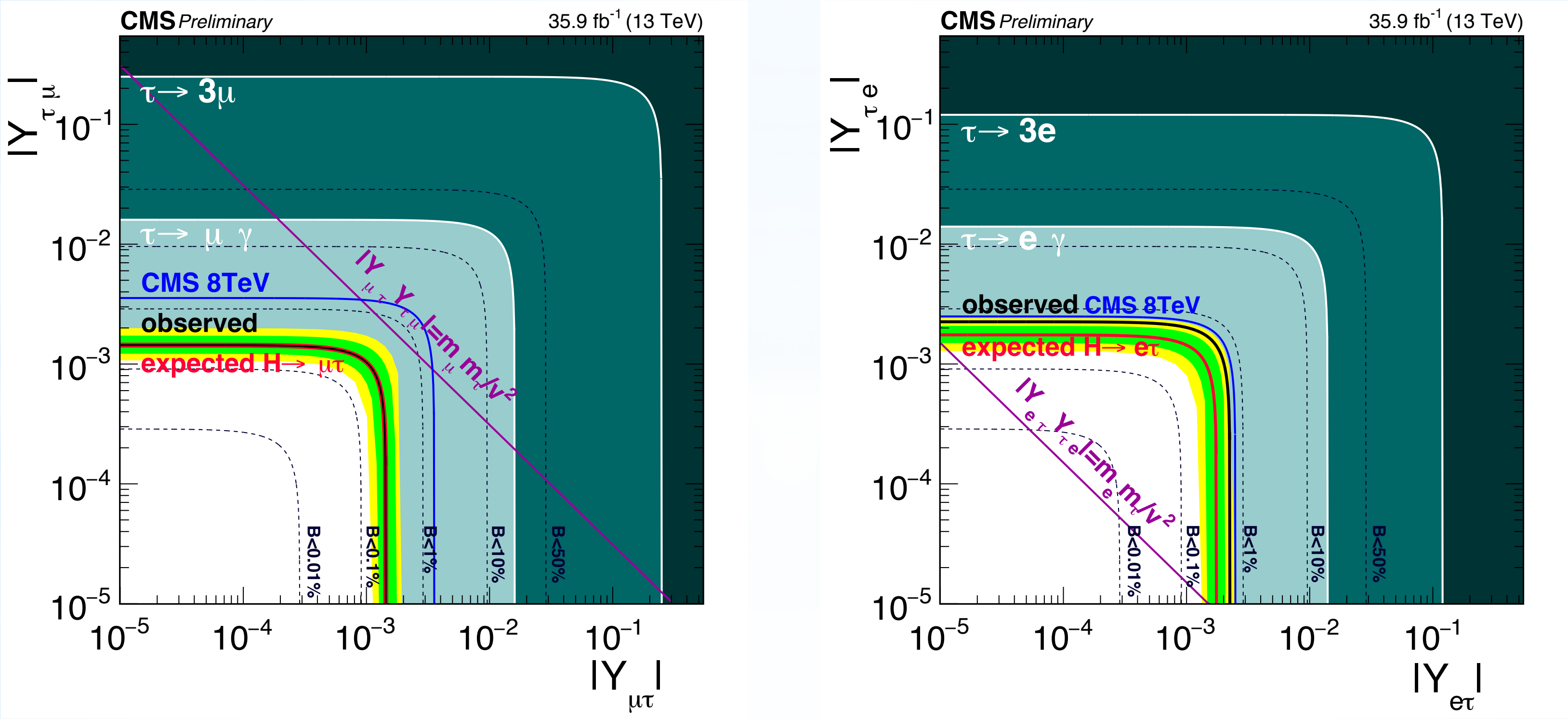
Upper limits @95% CL :

Br(H→μτ) <0.25% (0.25% exp.)   Br(H→eτ) <0.61% (0.37% exp.)

→ Clear improvements compared to results from 2012 and 2015 data analyses
The 2.4 sigmas excess (Run1) is now excluded by the 2016 data analyses

Results : H→μτ & H→eτ

Upper limits on the off-diagonal μτ and eτ Yukawa couplings:
From BDT method :

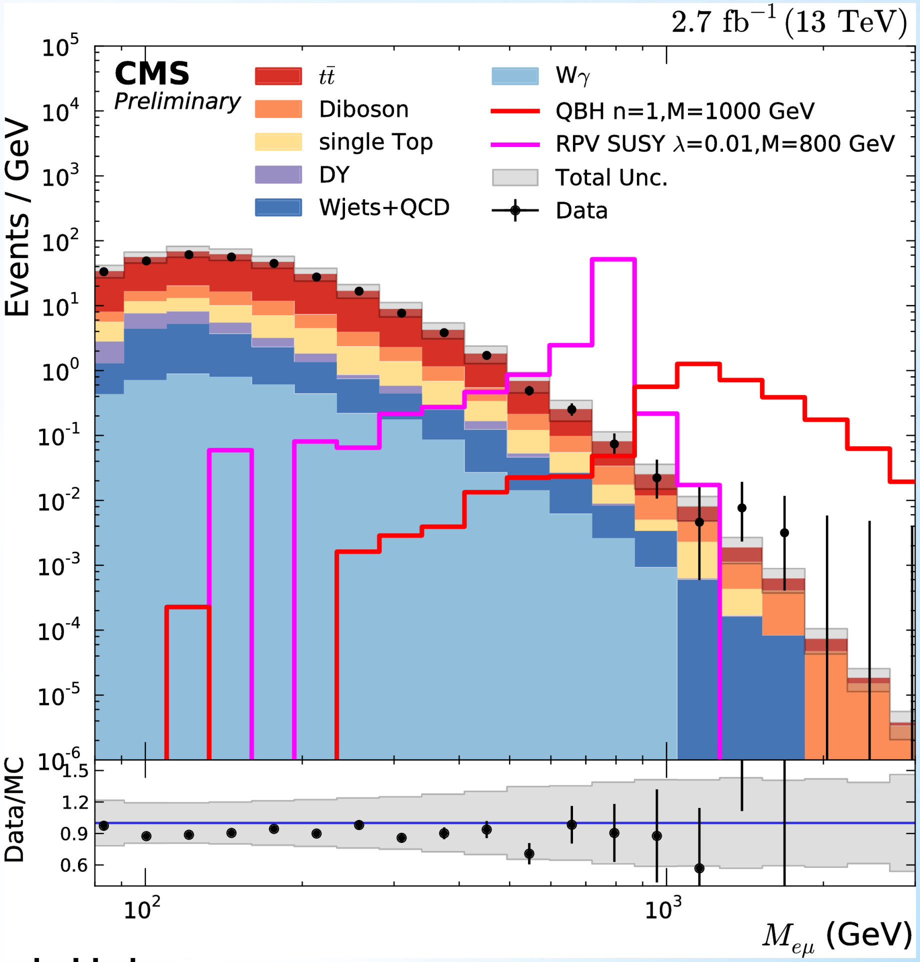


	M_{col}-fit	BDT-fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 2.05 \times 10^{-3}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.45 \times 10^{-3}$	$< 2.26 \times 10^{-3}$

LFV decay of heavy states $X \to e\mu$

Selection cuts and background

2012 data analysis (8 TeV, 19.7 fb^{-1}) → EPJC 76 (2016) 317
2015 data analysis (13 TeV, 2.7 fb^{-1}) → CMS-PAS-EXO-16-001
2016 data analysis → in preparation



Analysis strategy : inclusive search

Single-μ trigger

e : p_T > 53 GeV, |η|<2.4

μ : p_T > 35 GeV, |η|<2.5

→ eμ invariant mass spectrum:

- No further criteria to remain model independent
- Main backgrounds: top-quark pairs and W^+W^-
- Interpretation in 2 BSM models :
  - R-parity violating SUSY
  - Extra-dimension model - Quantum Black Hole

Interpretation in RPV SUSY

- **SUSY allows superpotential :**

Violate R-parity, R = $(-1)^{3(B-L)+2S}$
λ and λ' terms violate lepton N and F
λ'' terms violate baryon number
Limits on proton decay mean either λ and λ' are 0 or λ'' terms are 0

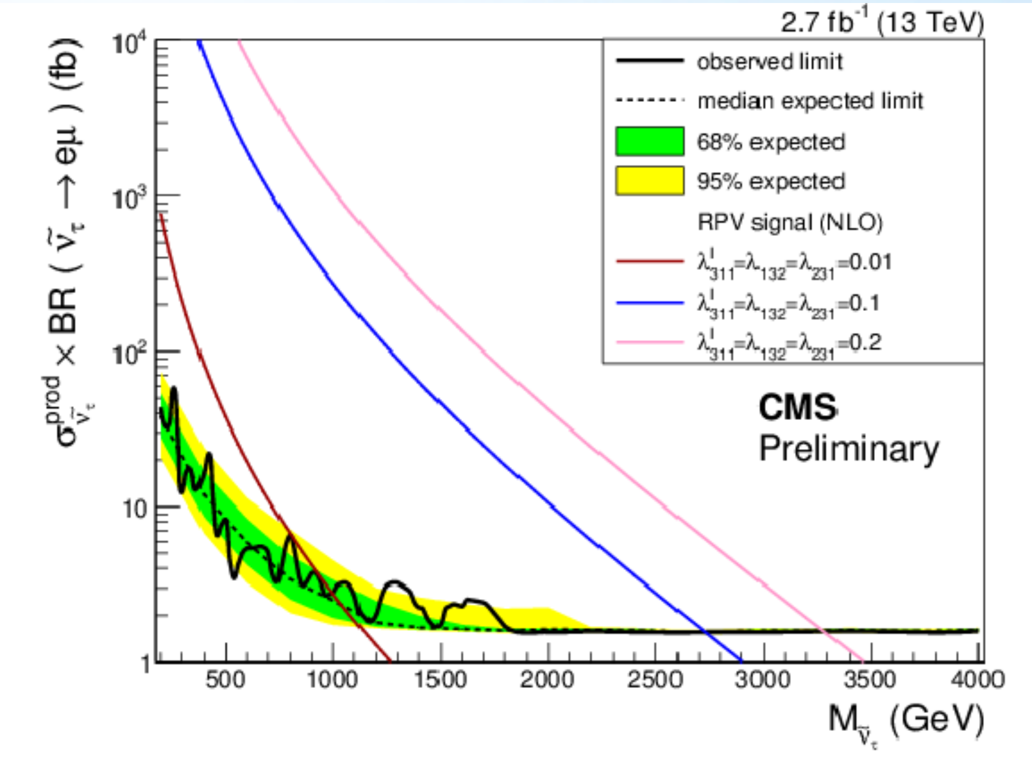
$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_j\overline{D}_k + \frac{1}{2}\lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k + \epsilon_iL_iH_2$$

- **R-parity violating SUSY with τ sneutrino as LSP:**

- LSP can decay into eμ or dd via couplings λ_{132} , λ_{231} or λ'_{311}
  Suppose $\lambda_{132} = \lambda_{231}$
- from μ→e conversion experiments:
  $|\lambda_{132}\,\lambda'_{311}| < 4.1\ 10^{-9} \cdot (M/100\ \text{GeV})^2$

CMS limits @95% CL :
2015 : M < 1.0 (3.3) TeV
for $\lambda_{132} = \lambda'_{311} = 0.01$ (0.2)

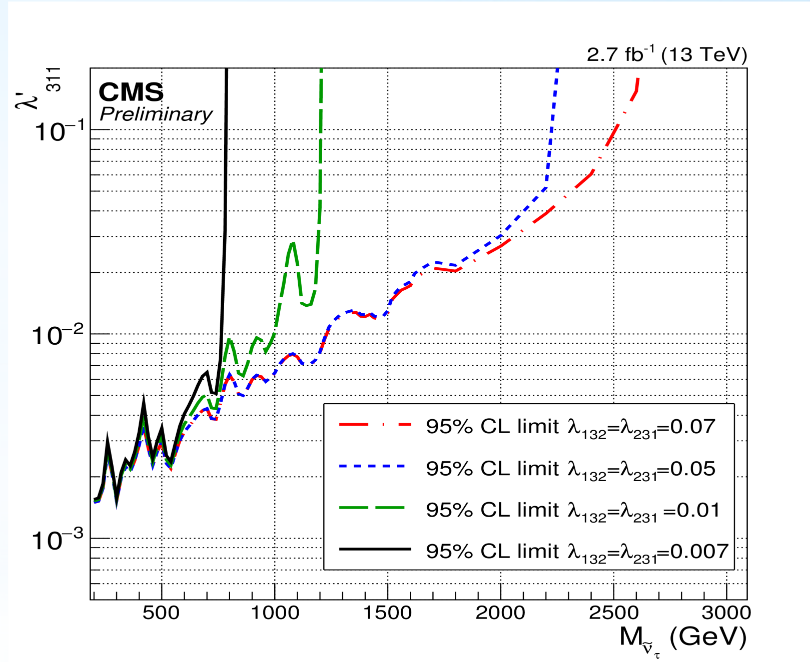
2012 : M < 1.28 (2.30) TeV @ 95% CL
for $\lambda_{132} = \lambda'_{311} = 0.01$
($\lambda_{132} = 0.07$, $\lambda'_{311} = 0.11$)



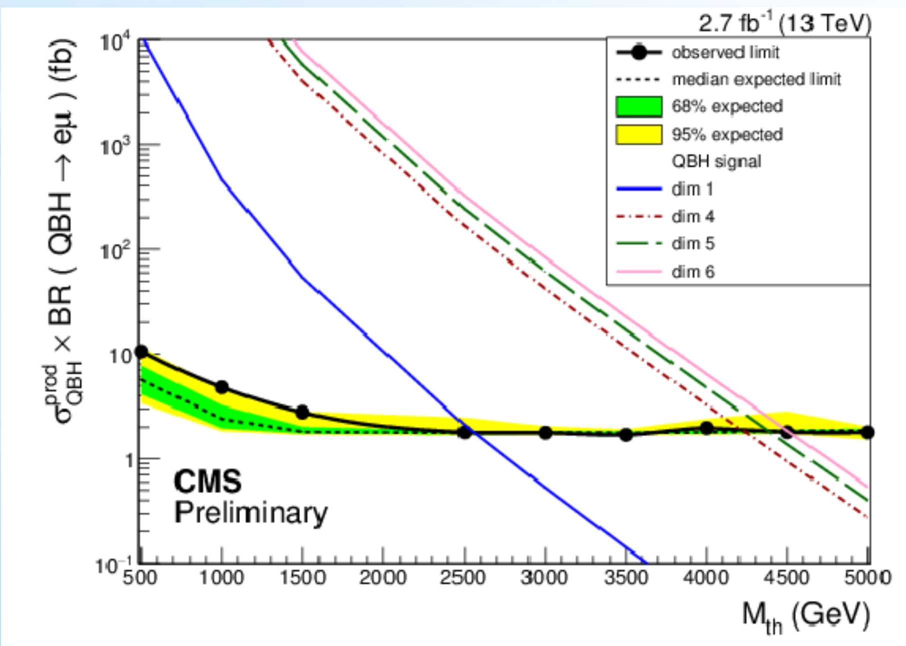
Upper limits & model interpretation

- R-parity violating SUSY with τ sneutrino as LSP :

  Limit in the plane (λ'_{311},M) →



- Quantum black holes :



- Spin-0, colorless & neutral QBH with LFV considered
- Cross section depends on threshold mass and number of extra dimensions n

CMS limits @95% CL :
2015 : M < 2.50 – 4.50 TeV for n=1–6

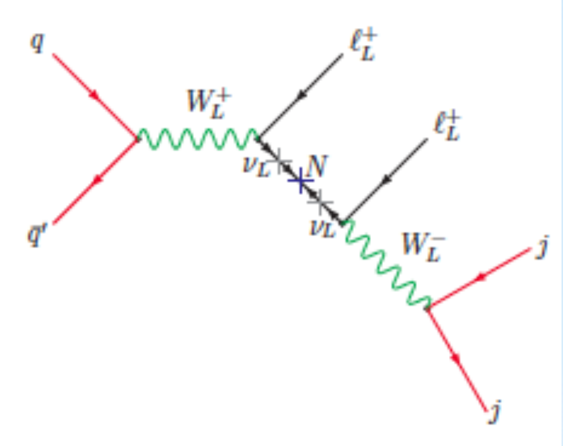
2012 : M < 2.36 - 3.63 TeV for n=1–6

Search for heavy neutrinos and right-handed W

Search for heavy N @CMS

- **Search for the "Type I Seesaw" mechanism :**

Resonant production via s-channel W* or W(real) probe light-heavy mixing
Majorana neutrino: 50% same-sign
Cross section depends on $|V_{lN}|2$ and m_N
Signal : 2 SS leptons (e or μ) + 2jets + no MET
SS = same sign

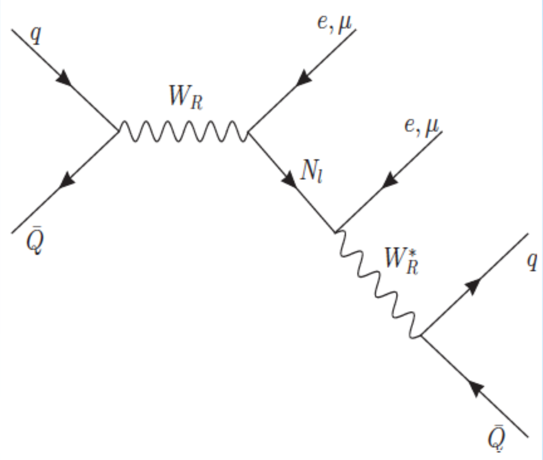


Two jets from W decay :
m(jj) = m(W)

- **Search for Left-Right SM (LRSM):**

Search for a resonance W_R production
Signal : 2 leptons (e or μ) + 2jets + no MET
(no sign requirement)

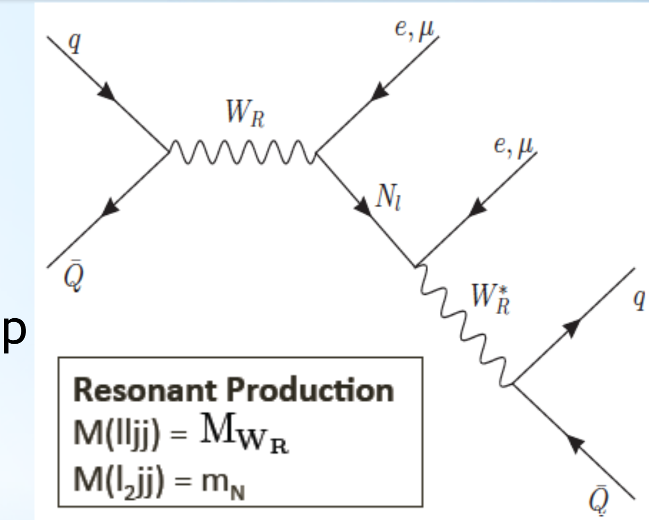
→ Same final state as type I
But different kinematics



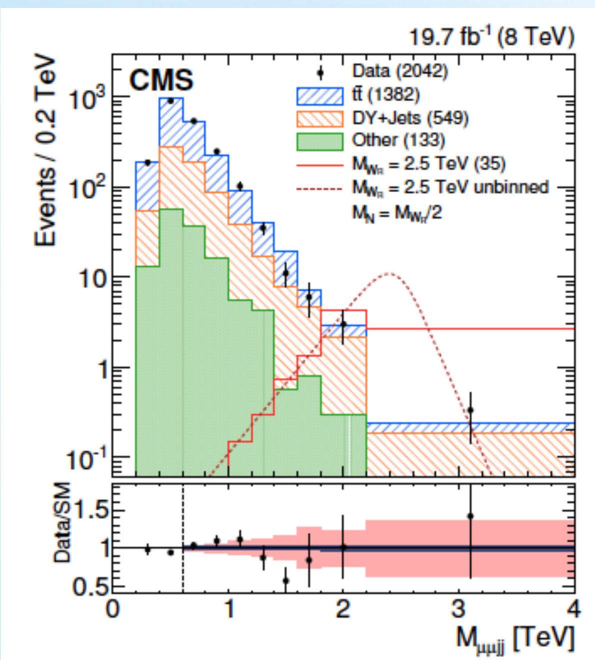
LRSM searches @8 TeV

Selection :
2 isolated leptons (no charge requirement)
Lepton p_T > 60, 40 GeV, M(ll) > 200 GeV
N jets ≥ 2, M(lljj) > 600 GeV

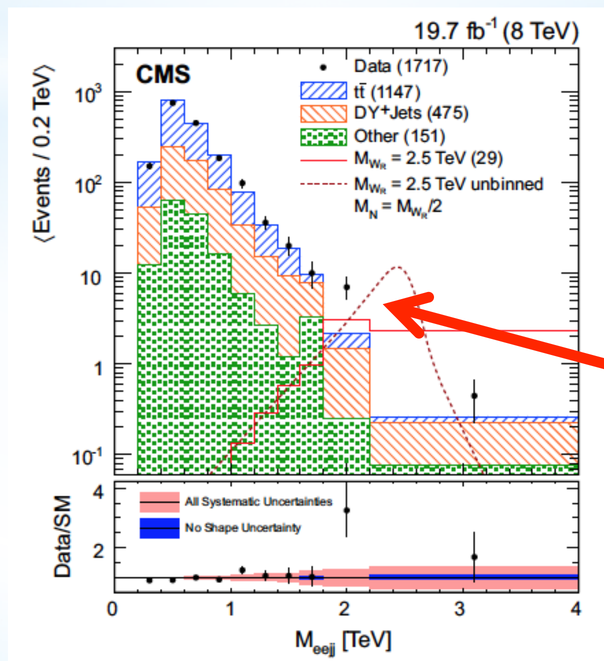
For m(N) << m(W_R), jets and lepton from N decay overlap
→ Need dedicated isolation criteria



Di-muon channel



Di-electron channel



Main backgrounds:
tt and DY+jets

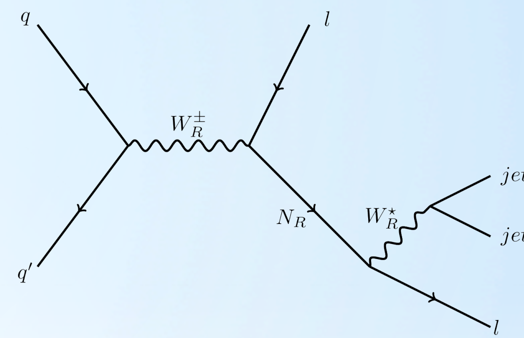
A 2.8σ effect
(local significance)
In the eejj channel only

Update - Searches at 13 TeV

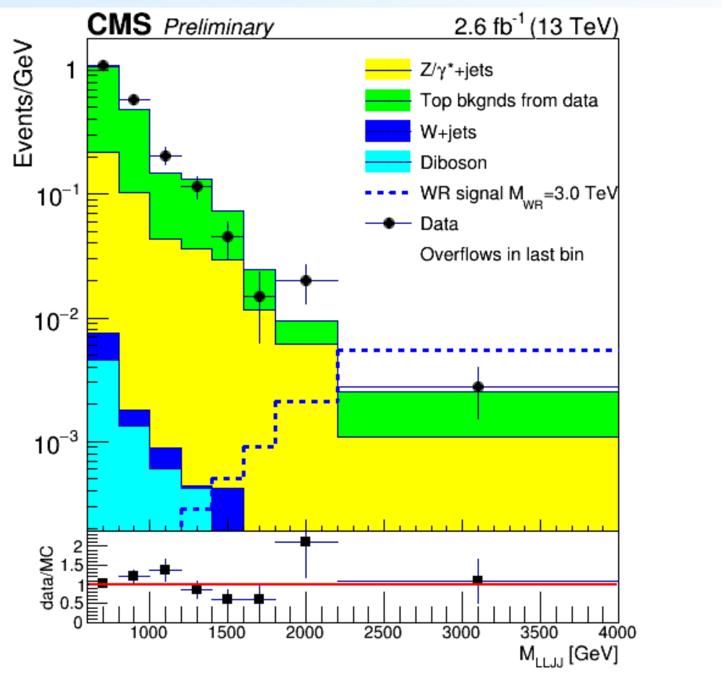
CMS PAS EXO-16-045

2015 data analysis (13 TeV, 2.7 fb^{-1})
Search for a heavy right-handed N_l and a heavy W_R
In the LRSM model

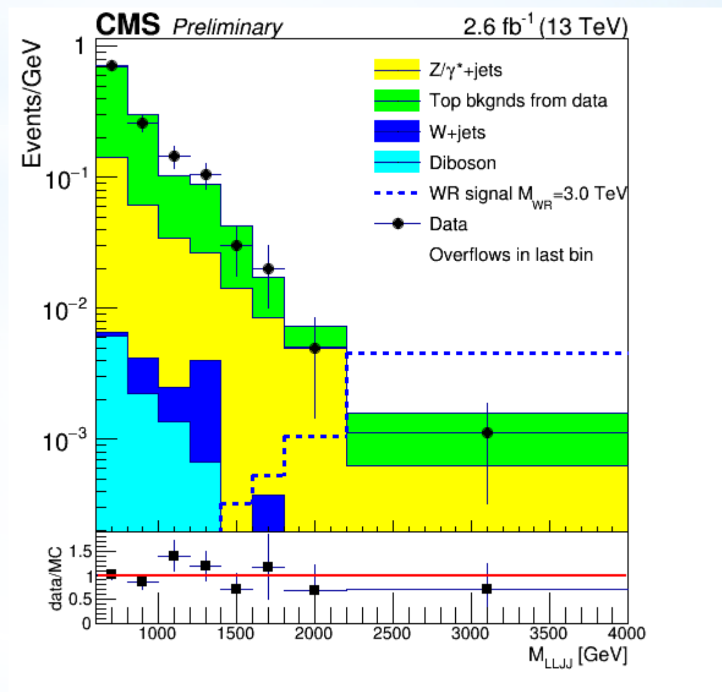
2 isolated leptons (no charge requirement)
Lepton p_T > 60, 53 GeV, M(ll) > 200 GeV
N jets ≥ 2, p_T > 40 GeV, M(lljj) > 600 GeV



Di-muon channel



Di-electron channel



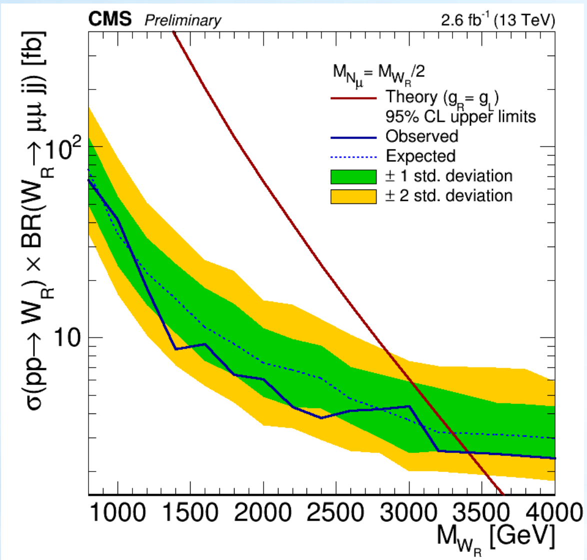
For the signal shown :
$M(W_R)$=3 TeV
$M(N_l)$ = ½$M(W_R)$

Main backgrounds:
tt and DY+jets

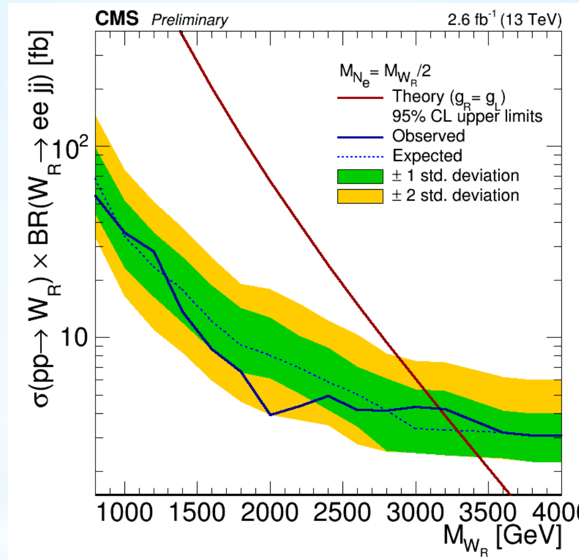
Update - Searches at 13 TeV

CMS PAS EXO-16-045

Di-muon channel

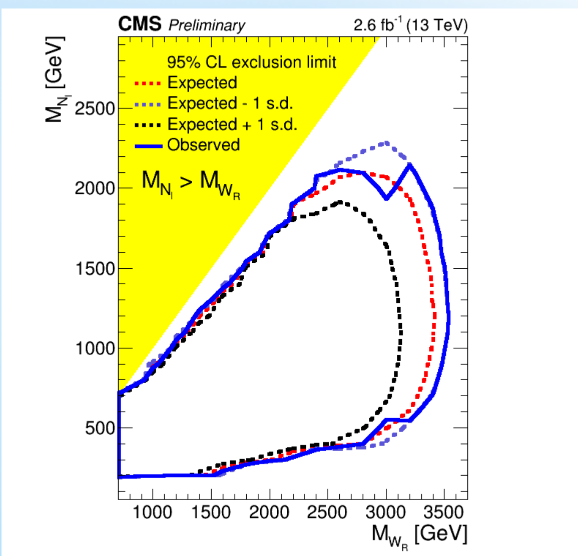


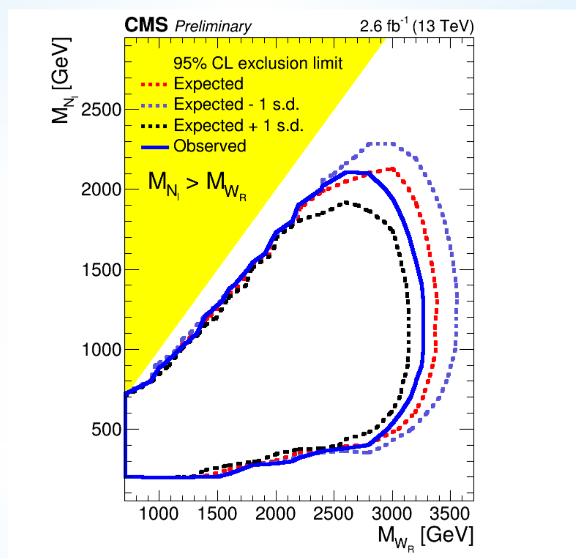
Di-electron channel



Upper limits on cross section as a function of the W_R mass
For $M(N_l) = ½M(W_R)$

$M(W_R)$ > 3.5(3.3) TeV in the μμjj (eejj) channel



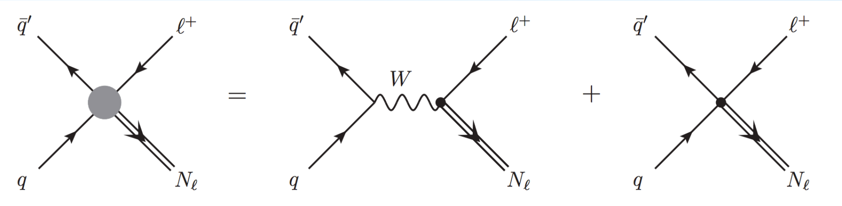


2D mass exclusion limits in the $M(W_R)$, $M(N_l)$ plane

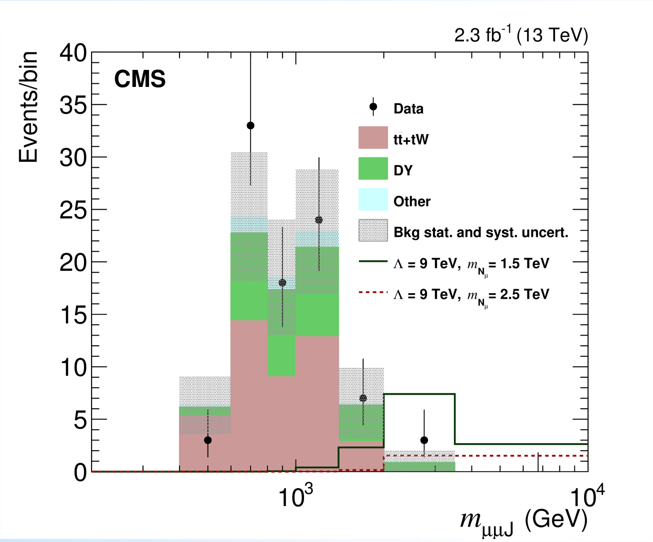
Searches at 13 TeV

Submitted to PLB
CMS PAS EXO-16-026

- Test a recently proposed model :
- Heavy composite Majorana neutrino (HCMN)
  Final state : llqq'
  2 same flavor leptons and 2 jets



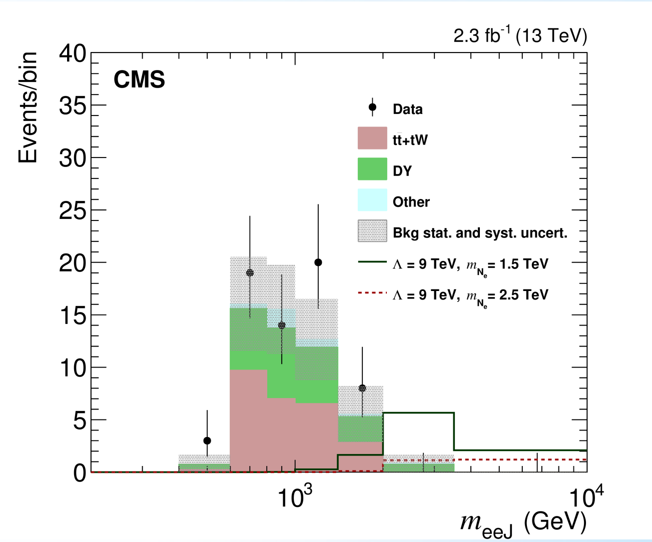
Di-muon channel
$p_T(\mu)$>53, 30 GeV



m(ee or μμ) >300 GeV,

≥1 fat jet with p_T(jet) > 190 GeV

Di-electron channel
p_T(e): 110, 35 GeV



Upper limits at 95% CL on the cross section*Br
Exclude A Composite Majorana Neutrino of mass up to 4.50 (μ), 4.35 (e) TeV

Searches in the ττ channel

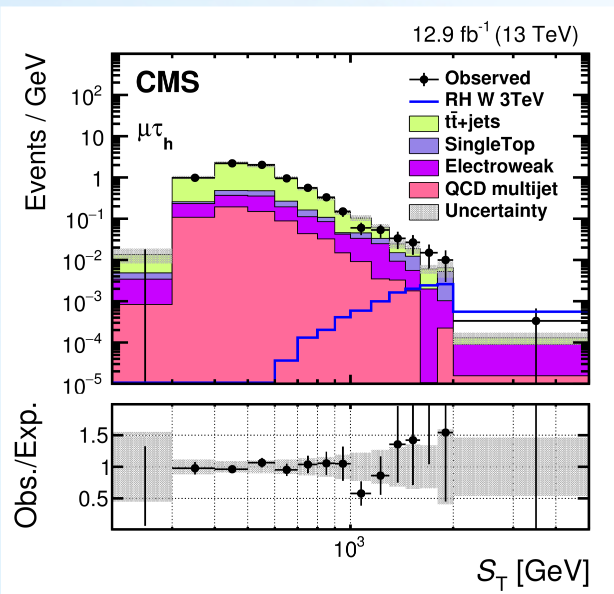
CMS PAS EXO-16-023

JHEP 07 (2017) 121

A 2.8σ excess in eejj channel but no excess in dimuon channel

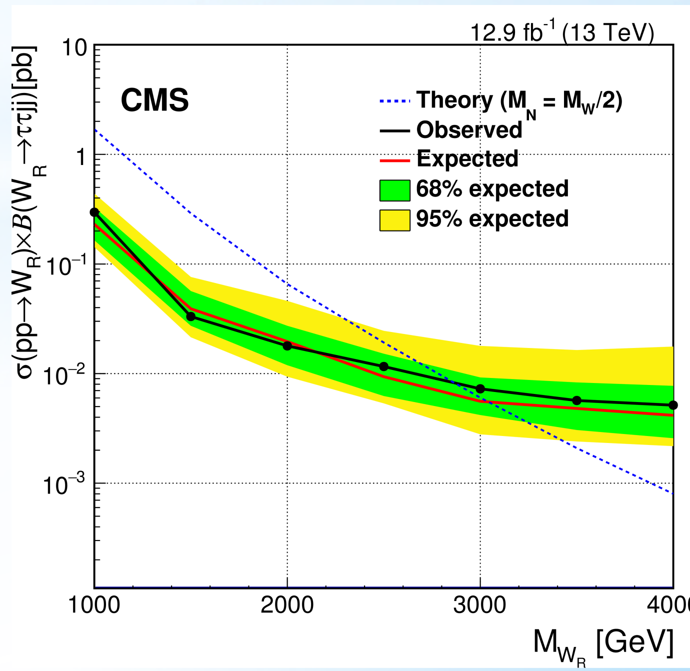
→ **Searches in ττ :**

- **All hadronic channel:** $\tau_h\tau_h$, using 2.1 fb^{-1} at 13 TeV
  The largest branching ratio, but large QCD bg from fake taus
- **Lepton+hadronic channel: $\tau(e)\tau_h$, $\tau(\mu)\tau_h$, use 2016 data: 12.9 fb^{-1}**
  Clean events, but with a small branching ratio



$$S_T = p_T(\ell) + p_T(\tau_h) + p_T(jet_1) + p_T(jet_2) + E_T^{miss}$$

p_T(e or μ) > 50 GeV,
$p_T(\tau_h)$ > 60 GeV,
MET> 50 GeV
2 jets with p_T>50 GeV
M($e\tau_h$ or $\mu\tau_h$)>150 GeV
M($j\tau_h$) > 250 GeV



No excess in data, exclude W_R up to 2.9 TeV

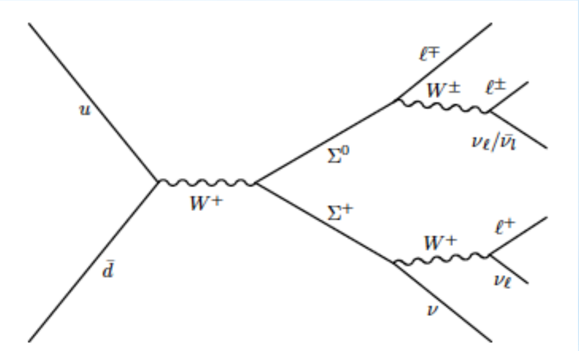
Type III seesaw mechanism

NEW

CMS PAS EXO-17-006
Submitted to PRL

2016 data analysis (13 TeV, 35.9 fb^{-1})
Search for type-III seesaw heavy fermions signal in multilepton final states : 3 or 4 electrons or muons

Different production and decay of $\Sigma^0\Sigma^\pm$ and $\Sigma^+\Sigma^-$ are considered via s-channel W*
Suppose Σ^0 and $\Sigma^\pm$ degenerate in mass



6 event categories :

N_{leptons}	OSSF & mass	Variable	p_T^{miss} requirement
3	OSSF1, on-Z	M_T	$p_T^{\text{miss}} > 100\,\text{GeV}$
3	OSSF1, above-Z	$L_T + p_T^{\text{miss}}$	—
	OSSF1, below-Z	$L_T + p_T^{\text{miss}}$	$p_T^{\text{miss}} > 50\,\text{GeV}$
	OSSF0	$L_T + p_T^{\text{miss}}$	—
≥ 4	OSSF1	$L_T + p_T^{\text{miss}}$	—
	OSSF2	$L_T + p_T^{\text{miss}}$	$p_T^{\text{miss}} > 50\,\text{GeV}$ if on-Z

Discriminant variable : scalar sum of charged pt + Missing pt
→ L_T + MET

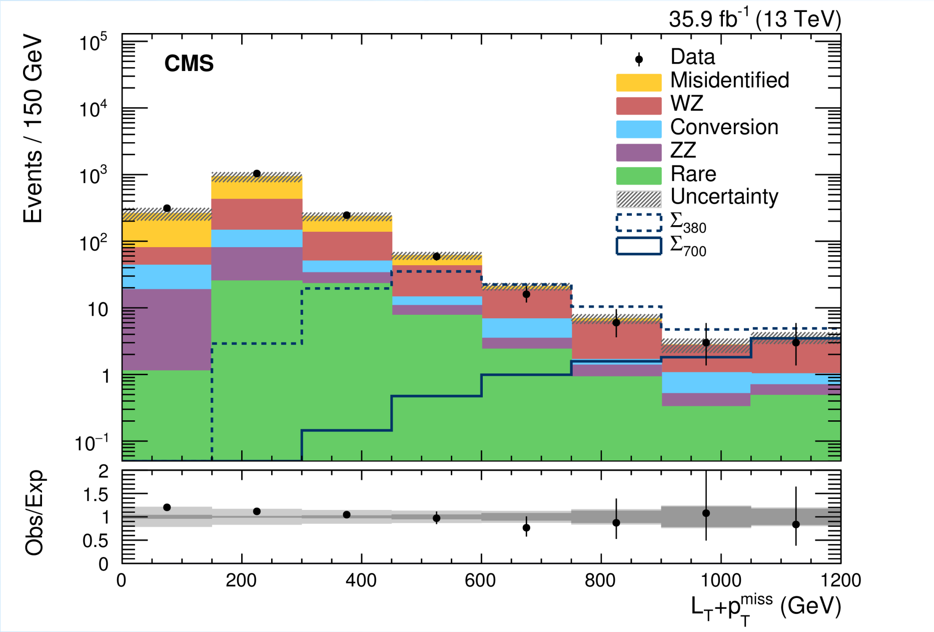
Type III seesaw mechanism

NEW

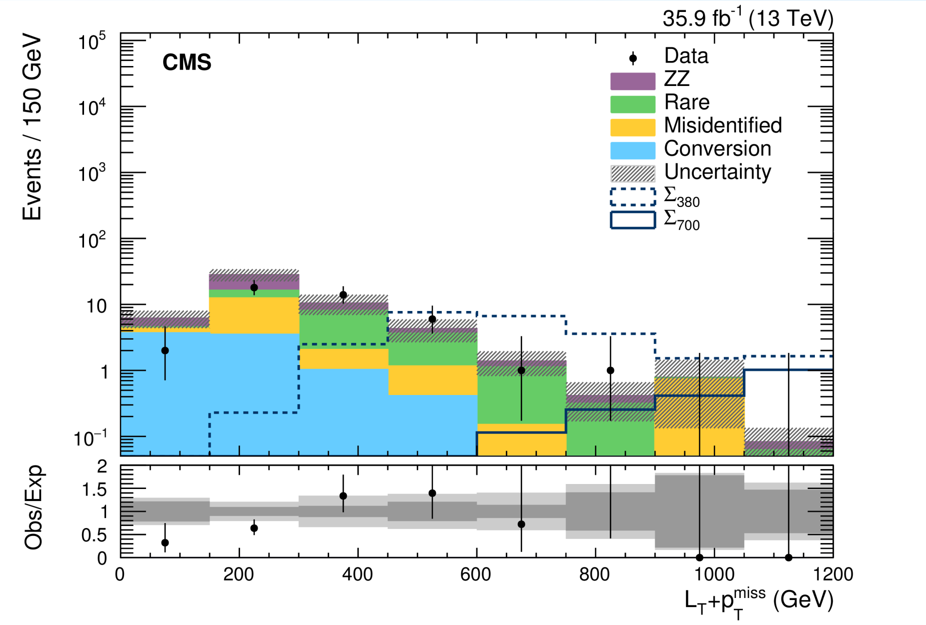
CMS PAS EXO-17-006
Submitted to PRL

L_T+MET distributions for two signal regions :

N(l)=3, OSSF1, above-Z



N(l)>=4, OSSF1



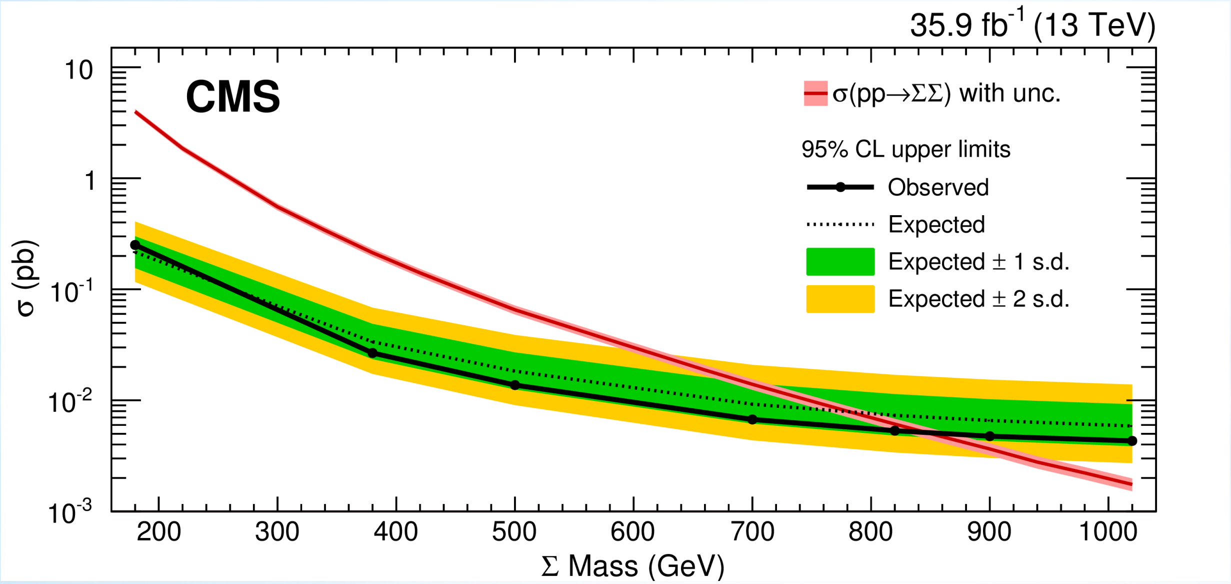
Irreducible bg from WZ and ZZ processes
Reducible bg from Z+jets, tt+jets (fake-leptons)

Type III seesaw mechanism

NEW

CMS PAS EXO-17-006
Submitted to PRL

The 95% CL upper limits on the cross section for production of heavy fermion pairs:



Theo. prediction :
in the flavor-democratic scenario

Limits :

- In the lepton-flavor democratic scenario (Be=Bμ=Bτ):
  heavy fermion pair production is excluded for masses below 840 GeV (780 GeV expected)
- In the ττ-phobic case (Bτ=0,Be+Bμ=1) the mass limits range from 900 to 930 GeV

Summary

- **Neutrinos oscillations provide interest for various BSM searches @LHC : searches for charged LFV and searches for heavy neutrinos**
- **Test various models that try to explain the small ν mass**
- **Previous excess in H decay and LRSM searches : not confirmed with new data**

Results Reported on: (highlights on updates using the 2016 dataset)

- **Search for LFV in the decays :**
  Z→eμ, X→eμ, and H→eτ and H→μτ
  Br(H→μτ) < 0.25% (0.25% exp.)
  Br(H→eτ) < 0.61% (0.37% exp.)

	M_{col}-fit	BDT-fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2+\lvert Y_{\tau\mu}\rvert^2}$	$< 2.05\times10^{-3}$	$< 1.43\times10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2+\lvert Y_{\tau e}\rvert^2}$	$< 2.45\times10^{-3}$	$< 2.26\times10^{-3}$

- **Search for a heavy neutrinos:**
  - LRSM scenario right-handed N_l and a heavy W_R
  For the μμjj channels : $M(W_R)$ > 3.5 TeV
  For the eejj channels : $M(W_R)$ > 3.3 TeV
  - Heavy composite Majorana neutrino (HCMN): M>4.5 TeV
  - Type III seewsaw mechanism
  Multilepton final state : M(Σ) > 840 GeV (Be=Bμ=Bτ)

- **Prospects:**
  - Some of the analysis of the 2016 dataset: to be released soon
  - more data to come to perform precision measurements
    Run2 (2015-2018) and Run3 (2021-2023): about 120 and 300 fb^{-1} expected
    HL-LHC (2026-2036): about 3000 fb^{-1} expected
    Challenge : higher pileup (tracking, isolation, …)