Recent Results on Lepton Flavor Violation from CMS

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Outline

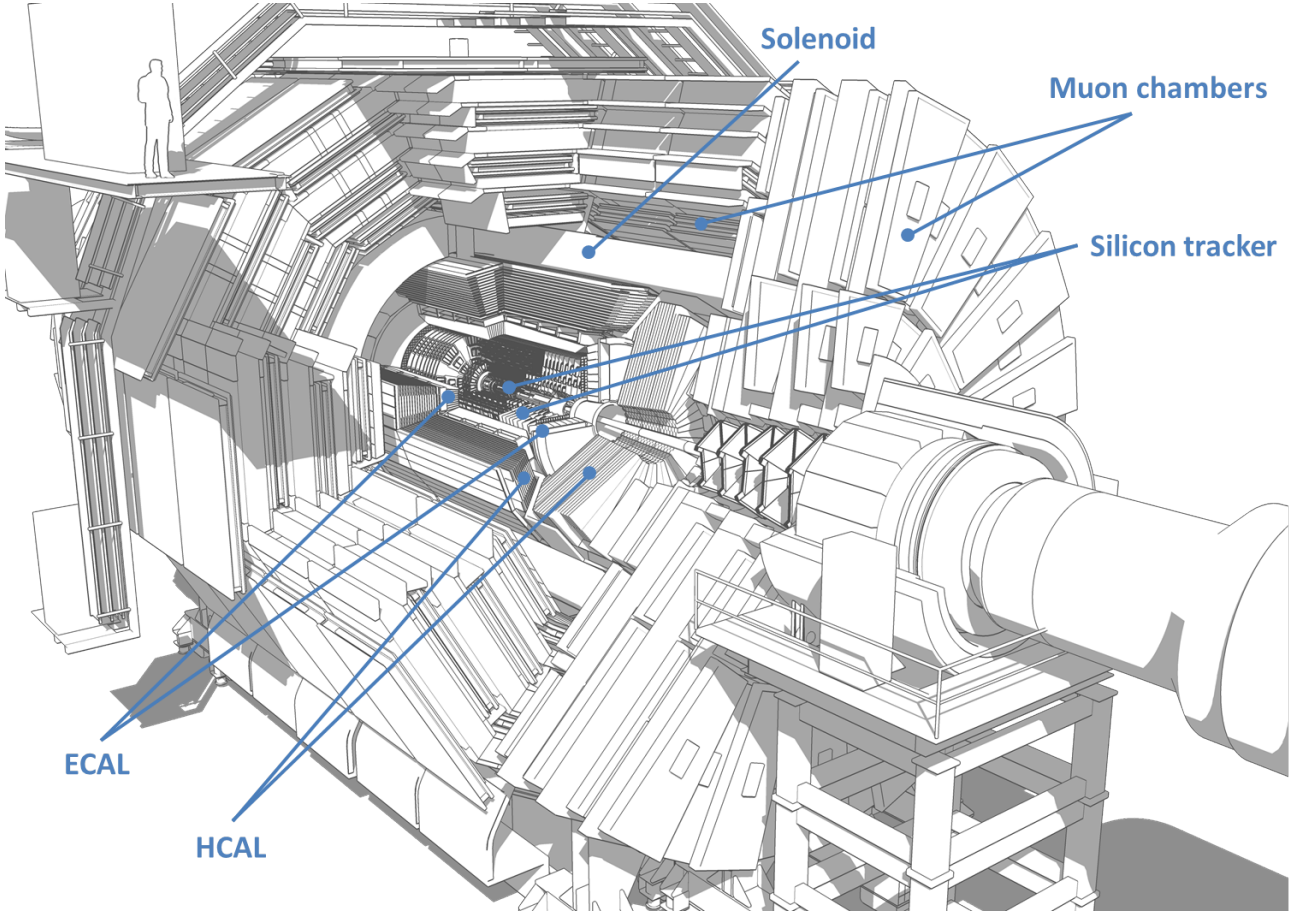
- Introduction
- Lepton flavor violation (LFV) in …
  - … decays of the Higgs boson
  - … decays of heavy states to eμ pairs
  - … decays of the Z boson
- Summary & Outloook

Lepton Flavor Violation

- Lepton flavor is conserved in particle interactions in the standard model (SM)
  - Reason for this is not an underlying symmetry but the lack of observed LFV
- An analysis of the atmospheric neutrino flux in 1998 resulted in the first evidence of neutrino oscillations (doi:10.1103/PhysRevLett.81.1562)
- Flavor oscillations of neutrinos prove neutral LFV, so what about charged LFV?
  - Many searches carried out by low and high energy experiments without success
    - e.g., $\mu \to e\gamma$, $\mu \to 3e$, $\tau \to \mu\gamma$, $Z \to \mu\tau$, …
  - cLFV enhanced in a lot of BSM theories → good probe for new physics

➡ Let's look for it also in LHC data …

The CMS Detector



LFV in Higgs Decays

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LFV in Higgs decays

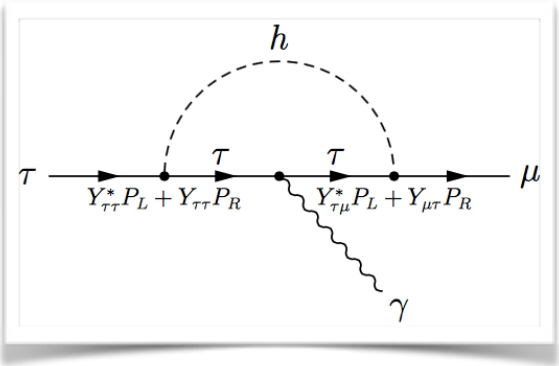
Introduction

arXiv:1209.1397

- LFV couplings to the Higgs possible, e.g., if SM only valid to finite scale Λ

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

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



- $\mathcal{B}$(H→eμ) < O(10^{-8}) @ 95% CL from searches for μ→eγ
- $\mathcal{B}$(H→e/μτ) < O(10%) @ 95% CL from searches for τ→e/μγ and μ/e g-2 measurements
- $\mathcal{B}$(H→e/μτ) < 13% @ 95% CL from theoretical reinterpretation of H→$\tau\tau$ search results from ATLAS

→ direct search very promising

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LFV in Higgs decays

arXiv:1502:07400

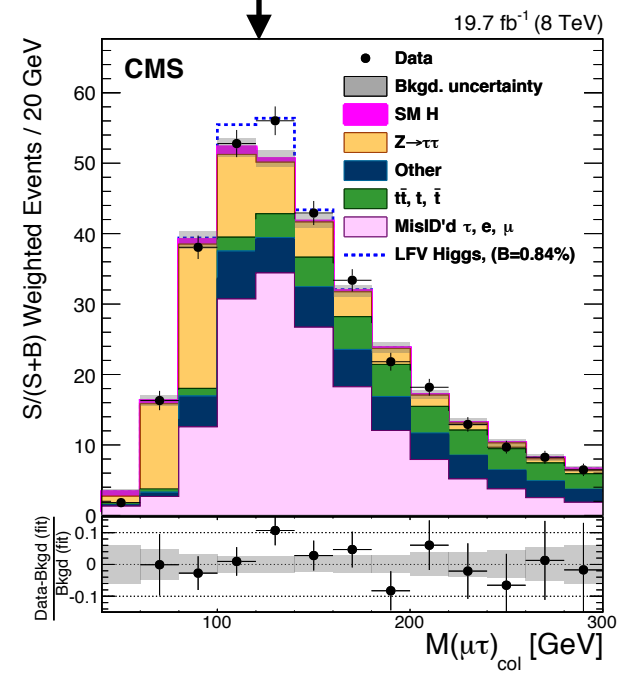
Search Strategy for H→μτ_e and H→μτ_h

Select different production mechanisms

Use collinear approximation

Use kinematic variables

Lepton selection → Categorize: n_{jet}= 0, 1 or 2 → Calculate $m_{\mu\tau}$ → Background suppression



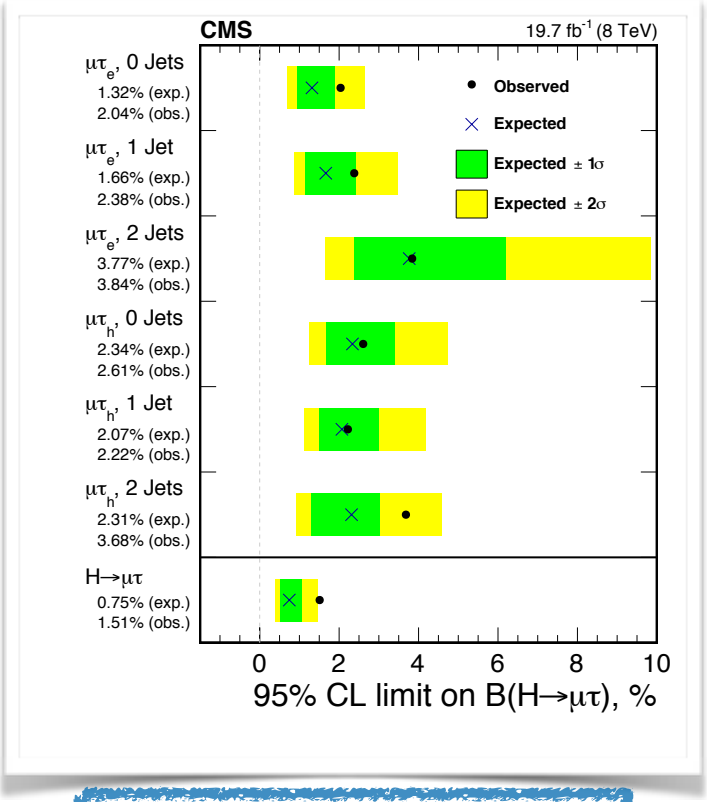
Determine $\mathcal{B}$(H→μτ) → $\mathcal{B}(H \to \mu\tau)_{\text{best fit}} = (0.84^{+0.39}_{-0.37})\%$

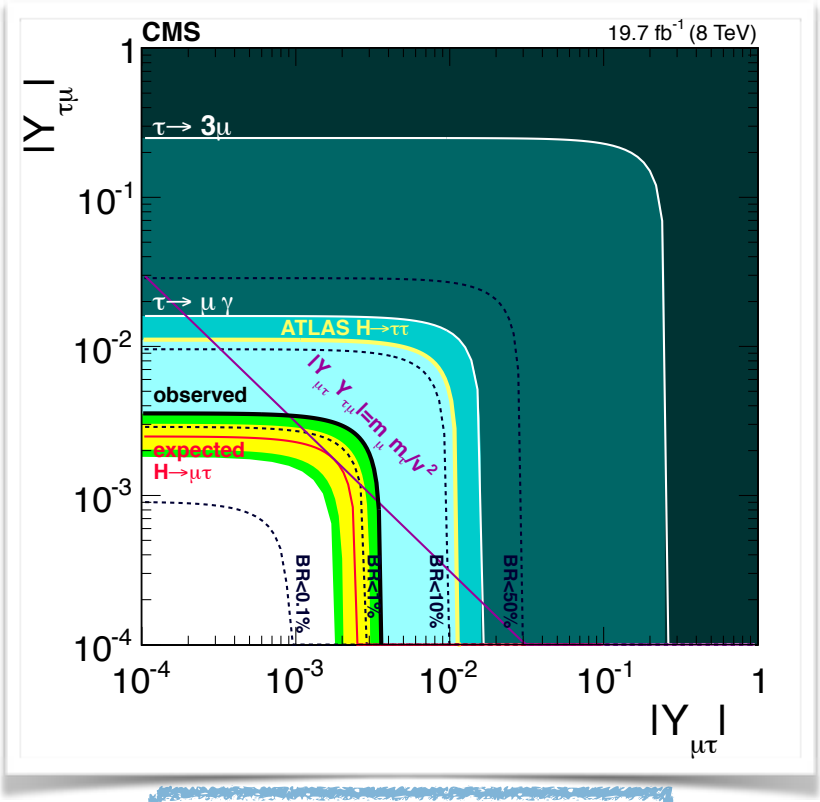
Determine limit on $\mathcal{B}$(H→μτ)

LFV in Higgs decays

Results

arXiv:1502:07400





$$\mathcal{B}(H \to \mu\tau) < 1.51\% \text{ @ } 95\% \text{ CL}$$

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \cdot 10^{-3}$$

LFV Decays of Heavy States to eμ Pairs

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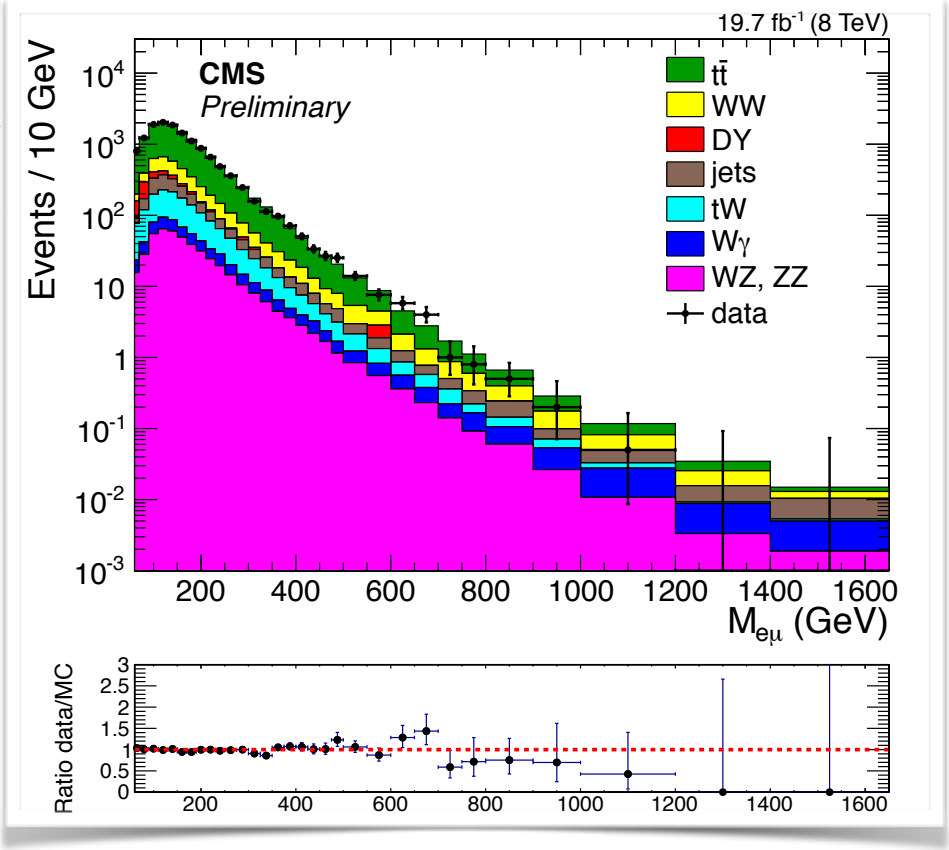
LFV Decays of Heavy States to eμ Pairs

CMS-EXO-13-002

Analysis Strategy

Lepton selection → Calculate $m_{e\mu}$ →

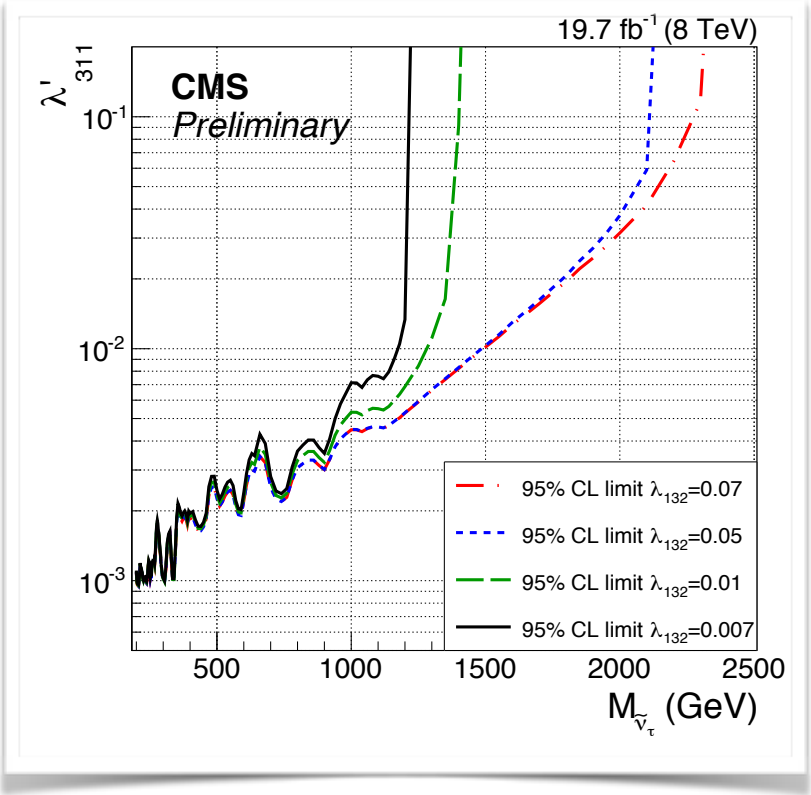
- No further criteria to remain model-independent!
- Main backgrounds: top-pairs (69%) and W^+W^- (11%)
- m ≥ 200 GeV considered for shape-based significance search & limit setting



LFV Decays of Heavy States to eμ Pairs

Results

CMS-EXO-13-002



R-parity violating SUSY with τ sneutrino as LSP

- LSP can decay into an eμ or a down-antidown pair via couplings λ_{132} & λ'_{311}
- Limit from ATLAS m < 2.00 TeV @ 95% CL
- from μ→e conversion experiments:

$$|\lambda_{132}\lambda'_{311}| < 4.1 \cdot 10^{-9} \cdot (\mathrm{m}/100\,\mathrm{GeV})^2$$

CMS limits:

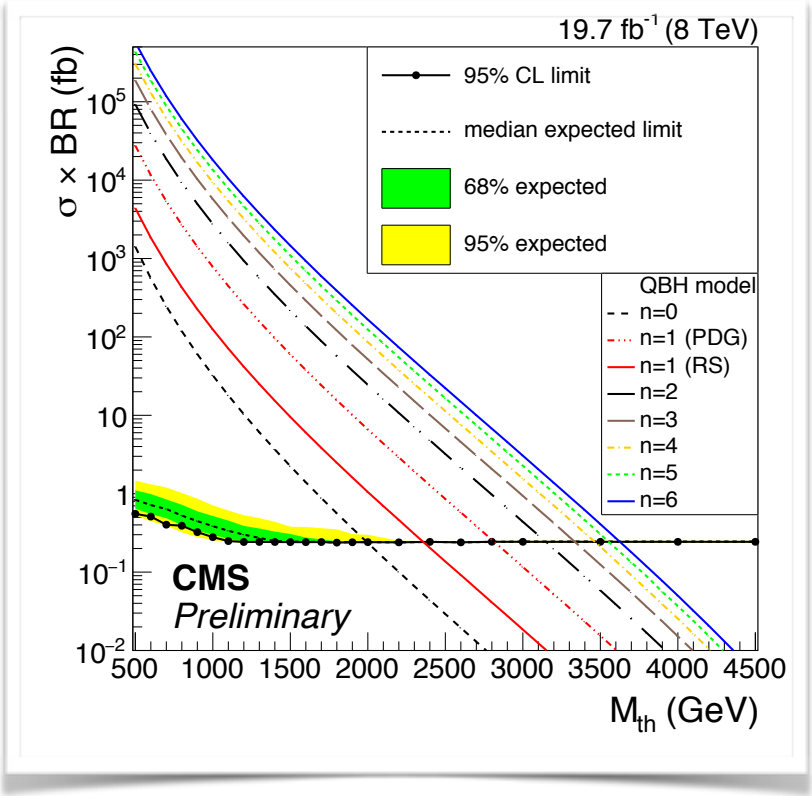
m < 1.21 (2.11) TeV @ 95% CL for

$\lambda_{132} = \lambda'_{311} = 0.01$ ($\lambda_{132} = 0.05$, $\lambda'_{311} = 0.1$)

LFV Decays of Heavy States to eμ Pairs

Results

CMS-EXO-13-002



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:

m < 1.99 - 3.63 TeV for n = 0 - 6

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LFV in Z Decays

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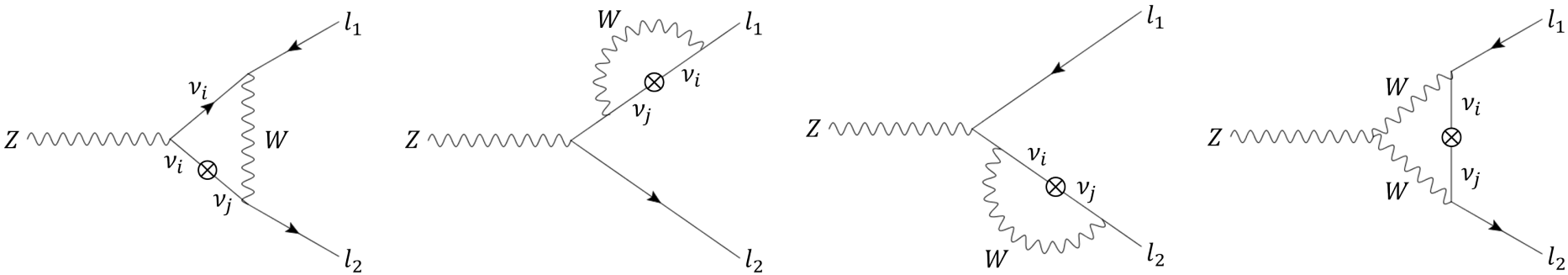
LFV in Z Decays

Introduction

arXiv:hep-ph/0010193

- Neutrino osciallation predicts LFV in Z decays, but $\mathcal{B}(Z \to e\mu) < 10^{-60}$

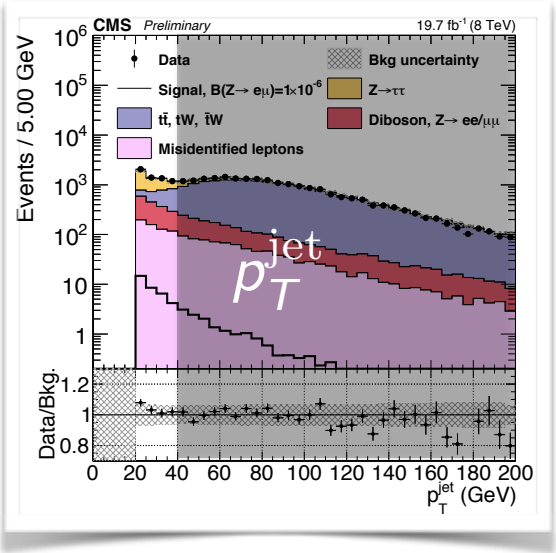


- Good probe for new physics!
- Current constraints:
  - Indirect from μ→3e: $\mathcal{B}(Z \to e\mu) < 5 \cdot 10^{-13}$
  - Direct from ATLAS: $\mathcal{B}(Z \to e\mu) < 7.5 \cdot 10^{-7}$

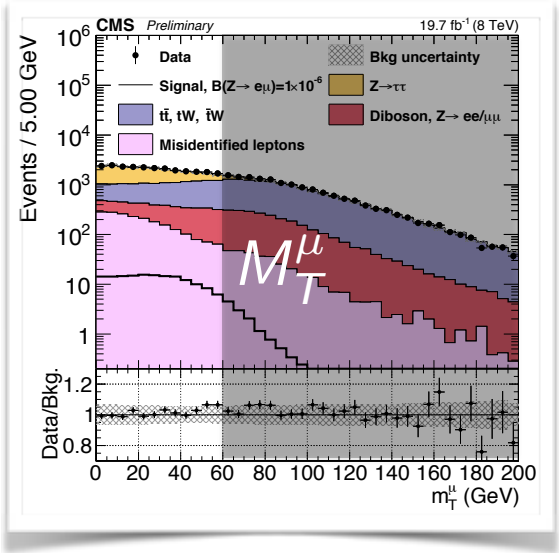
Analysis Strategy

CMS-EXO-13-005

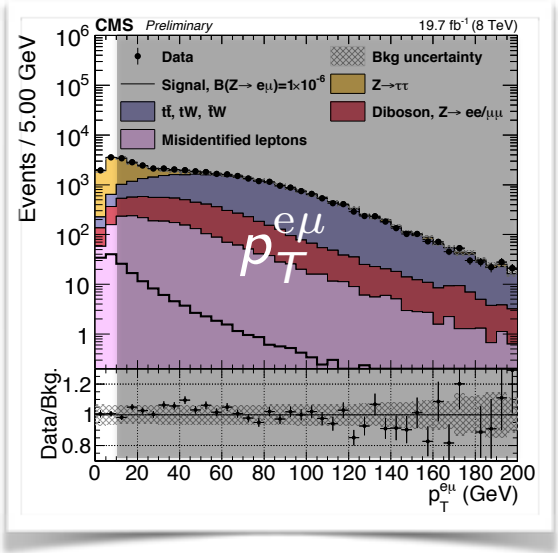
- Search for a bump around the Z mass in the invariant e-μ mass spectrum
- Major backgrounds: top-pair production, W^+W^- and $Z \to \tau\tau$ ☛ apply selection



Reduce top-pair contribution



Reduce top-pair & W^+W^- contribution



Reduce top-pair, W^+W^- & fake lepton contribution

LFV in Z Decays

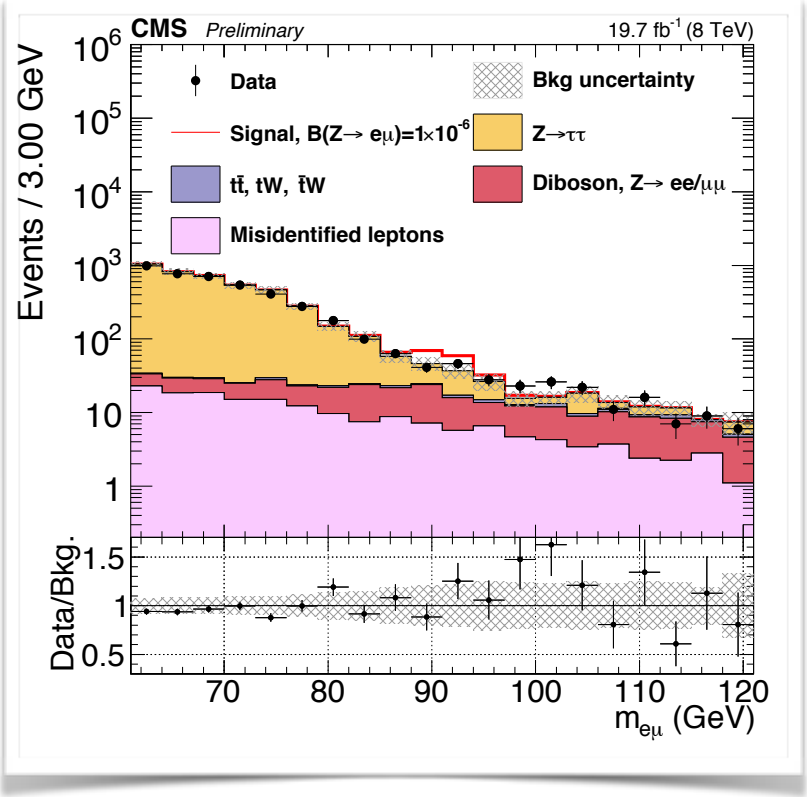
Results

CMS-EXO-13-005

- Count events in window around Z mass: (91 ± 3) GeV
- Background prediction of 83 ± 9
- Events found in data: 87
- Use CL_S method to determine limit:

$$\mathcal{B}(Z \to e\mu)_{\text{expected}} < (6.7^{+2.8}_{-2.0}) \cdot 10^{-7}$$

$$\boxed{\mathcal{B}(Z \to e\mu)_{\text{observed}} < 7.3 \cdot 10^{-7}}$$



Outlook

Prospects for Run 2

- Where we can gain …
  - Including more channels
    - final states with τ's in searches for LFV in decays of Z boson and heavy states
  - Increase of cross sections with higher center-of-mass energy
    - interesting for QBH and Higgs searches
  - Significantly more data available → lower uncertainties in data-driven methods (e.g., estimation of multijet and W+jet background)
- The challenges …
  - Higher pileup → more difficult tracking, worse isolation of prompt leptons, …
  - Top-pair production cross section more than triples
    - Impact on eμ final states in low to medium mass range

Summary

- H→μτ:
  - 2.4σ deviation from SM observed
  - Limits on branching fraction & LFV Yukawa couplings set:

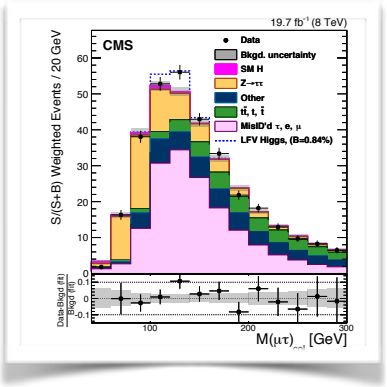
$$\mathcal{B}(H \to \mu\tau) < 1.51\%$$

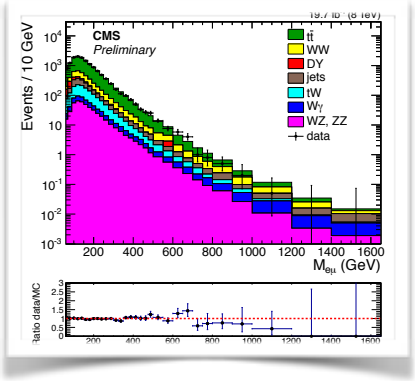
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \cdot 10^{-3}$$

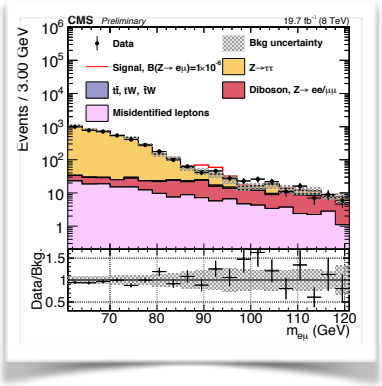
- Heavy states:
  - Model-independent analysis
    - τ sneutrino: m < 1.28 (2.11) TeV for $\lambda_{132} = \lambda_{311} = 0.01$ ($\lambda_{132} = 0.05$, $\lambda_{311} = 0.1$)
    - QBHs: m < 1.99 - 3.63 TeV for $n_{\text{extra dim.}} = 0 - 6$
    - Z'/a': no sensitivity, yet

- Z→eμ:
  - Obtained most stringent direct limit on branching fraction:

$$\mathcal{B}(Z \to e\mu) < 7.3 \cdot 10^{-7}$$







Backup

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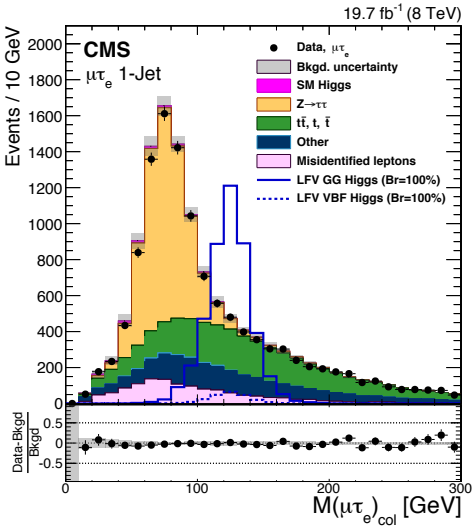
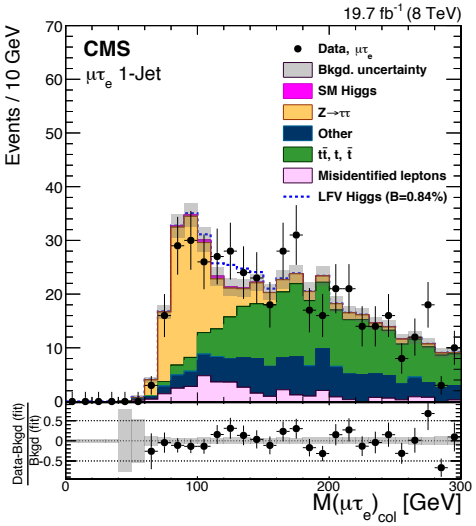
LFV in Higgs decays

Background Suppression

Variable	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^{\mu} >$	50	45	25	45	35	30
$p_T^{e} >$	10	10	10	—	—	—
$p_T^{\tau} >$	—	—	—	35	40	40
$M_T^{e} <$	65	65	25	—	—	—
$M_T^{\mu} >$	50	40	15	—	—	—
$M_T^{\tau} <$	—	—	—	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^{\mu}-\vec{p}_T^{\tau_h}} >$	—	—	—	2.7	—	—
$\Delta\phi_{\vec{p}_T^{e}-\vec{E}_T^{miss}} <$	0.5	0.5	0.3	—	—	—
$\Delta\phi_{\vec{p}_T^{e}-\vec{p}_T^{\mu}} >$	2.7	1.0	—	—	—	—





* not correlated between categories

Systematic Uncertainties

Experimental Uncertainties

Systematic uncertainty	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
electron trigger/ID/isolation	3	3	3	—	—	—
muon trigger/ID/isolation	2	2	2	2	2	2
hadronic tau efficiency	—	—	—	9	9	9
luminosity	2.6	2.6	2.6	2.6	2.6	2.6
$Z \to \tau\tau$ background	3+3*	3+5*	3+10*	3+5*	3+5*	3+10*
$Z \to \mu\mu$, ee background	30	30	30	30	30	30
misidentified μ, e background	40	40	40	—	—	—
misidentified τ_h background	—	—	—	30+10*	30	30
WW, ZZ+jets background	15	15	15	15	15	65
$t\bar{t}$ background	10	10	10+10*	10	10	10+33*
$W + \gamma$ background	100	100	100	—	—	—
b-tagging veto	3	3	3	—	—	—
single top production background	10	10	10	10	10	10

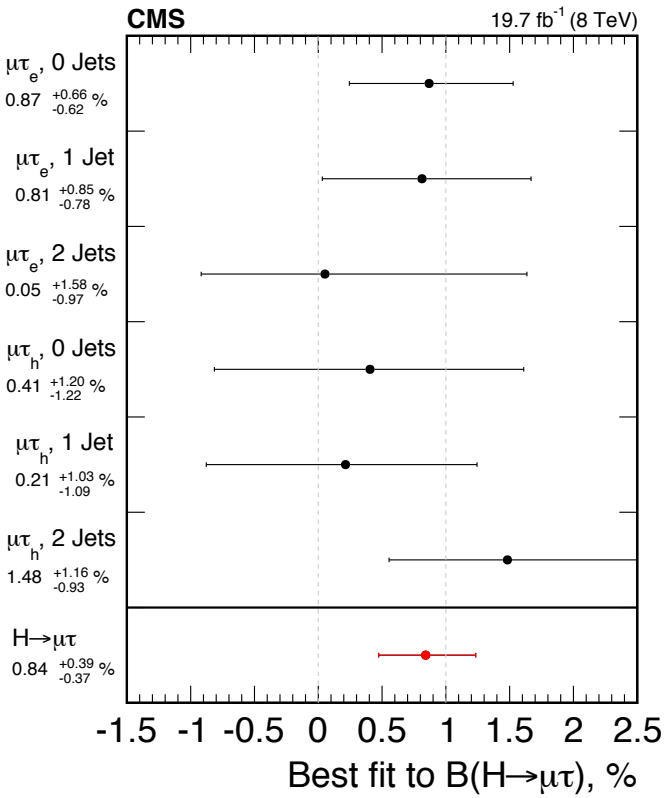
Shape uncertainties of templates

Systematic uncertainty	$H \to \mu\tau_e$	$H \to \mu\tau_h$
hadronic tau energy scale	—	3
jet energy scale	3–7	3–7
unclustered energy scale	10	10
$Z \to \tau\tau$ bias	100	—

Theoretical Uncertainties

Systematic uncertainty	Gluon-Gluon Fusion			Vector Boson Fusion		
	0-Jets	1-Jets	2-Jets	0-Jet	1-Jet	2-Jets
parton density function	+9.7	+9.7	+9.7	+3.6	+3.6	+3.6
renormalization/factorization scale	+8	+10	−30	+4	+1.5	+2
underlying event/parton shower	+4	−5	−10	+10	<1	−1

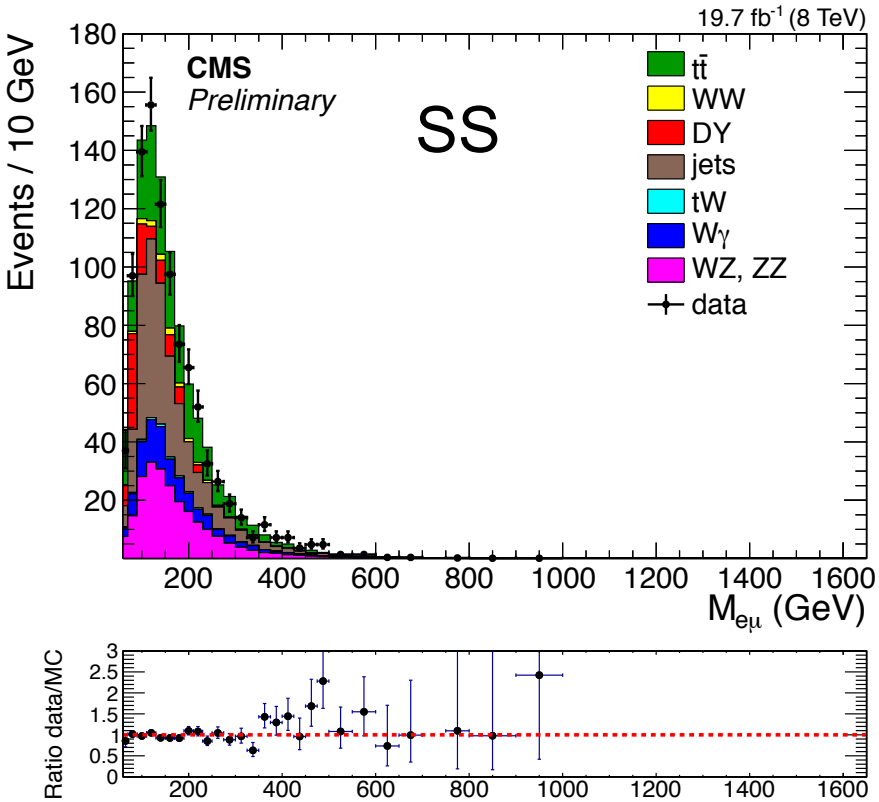
Best Fit & Limits

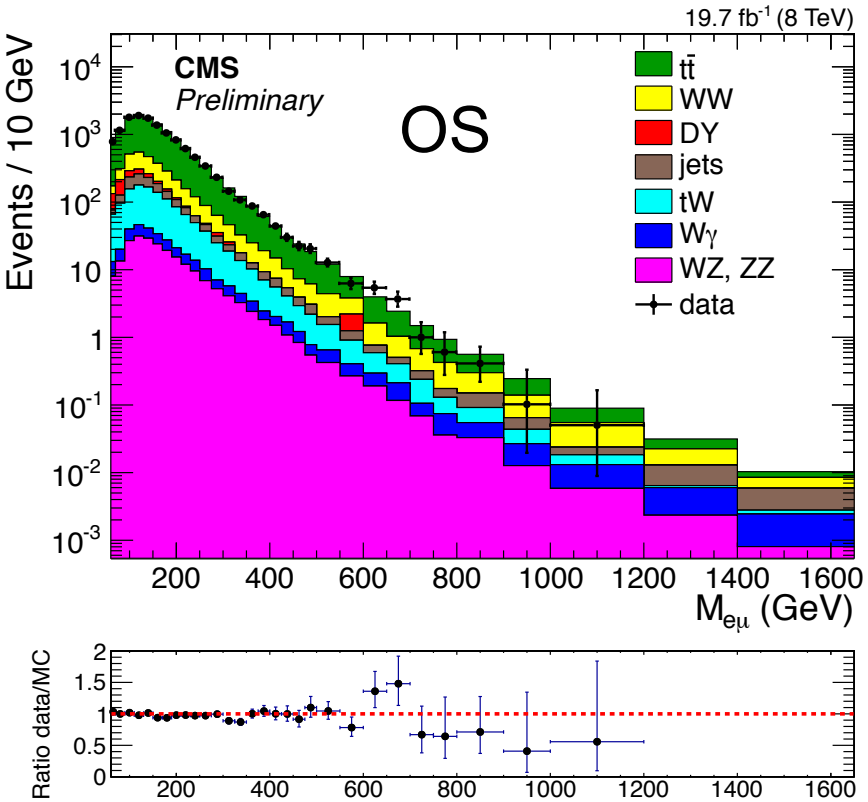


	0-Jet (%)	1-Jet (%)	2-Jets (%)
Expected Limits			
$\mu\tau_e$	<1.32 (±0.67)	<1.66 (±0.85)	<3.77 (±1.92)
$\mu\tau_h$	<2.34 (±1.19)	<2.07 (±1.06)	<2.31 (±1.18)
$\mu\tau$	<0.75 (±0.38)		
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

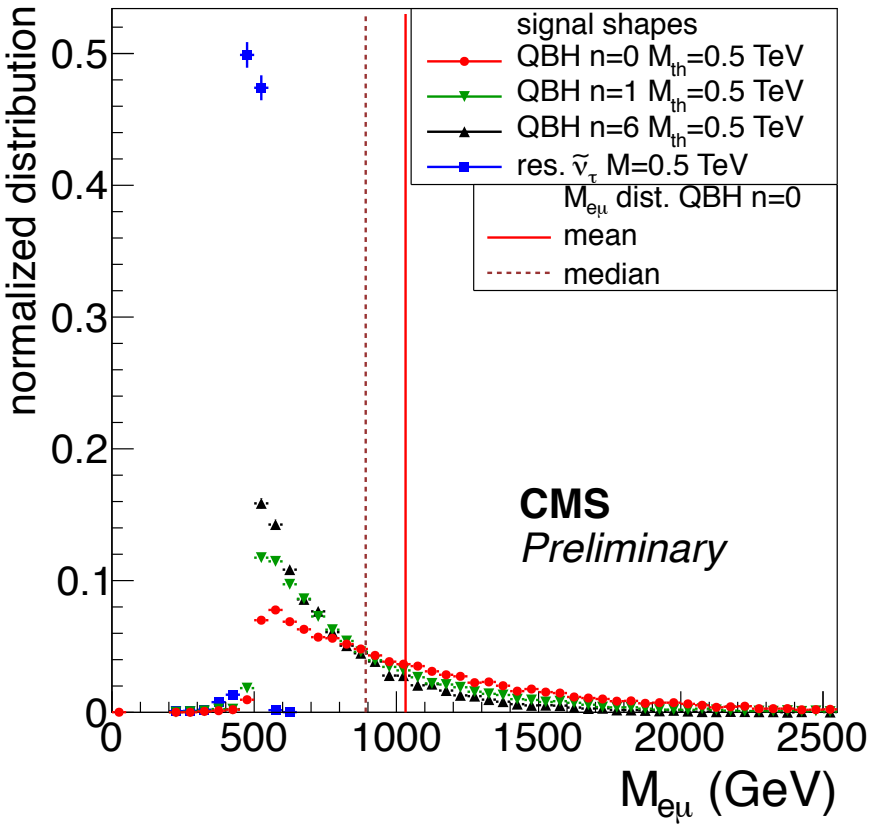
LFV Decays of Heavy States to eμ Pairs

Same Sign vs. Opposite Sign Charge





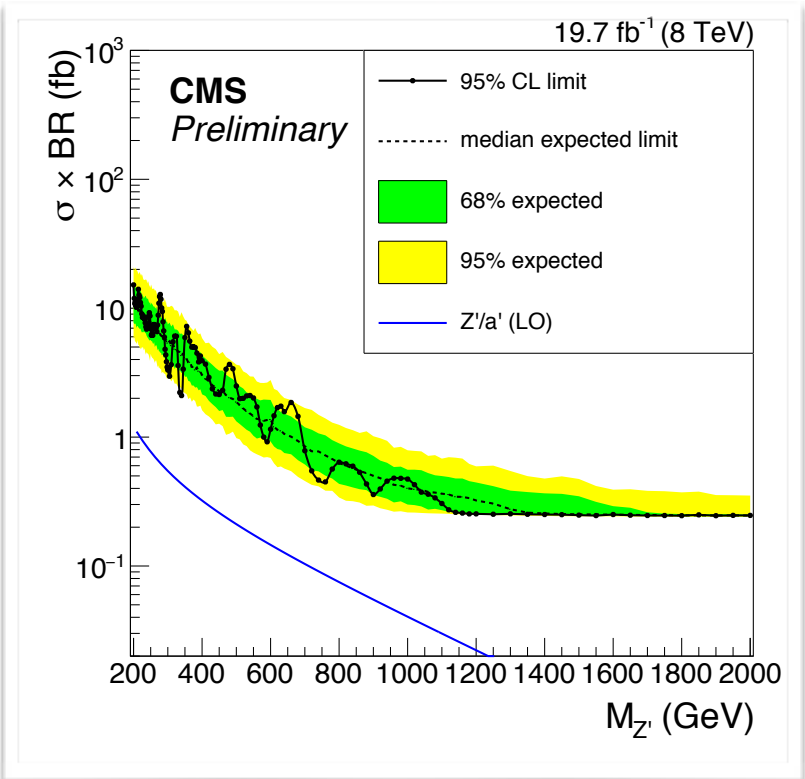
Signal Shapes and Limits



Theoretical Model	Mass Limit (TeV)
RPV $\tilde{\nu}_\tau$ ($\lambda_{132} = \lambda'_{311} = 0.01$)	1.28
RPV $\tilde{\nu}_\tau$ ($\lambda_{132} = 0.05$, $\lambda'_{311} = 0.1$)	2.11
QBH n=0	1.99
QBH n=1 (RS)	2.36
QBH n=1 (PDG)	2.81
QBH n=2	3.15
QBH n=3	3.34
QBH n=4	3.46
QBH n=5	3.55
QBH n=6	3.63

LFV Decays of Heavy States to eμ Pairs

Z'/a' Limits



Z'/a'

- Mass degeneracy assumed
- Decays into eμ and μτ possible
- Coupling fixed to mass-dependent limits from $K_L \rightarrow e\mu$

Event Yields and Systematic Uncertainties

Process	Events
$Z \to \tau\tau$	41 ± 9
WW	17 ± 1
Misidentified leptons	12.8 ± 0.5
$Z \to ee/\mu\mu$	10 ± 2
$t\bar{t}$	1.3 ± 0.5
$tW/\bar{t}W$	0.6 ± 0.6
WZ	0.3 ± 0.1
ZZ	< 0.1
Total background	83 ± 9
Data	87

Source	Uncertainty Background	Uncertainty Signal
Luminosity	2.6%	2.6%
Pileup	3.3%	0.8%
Trigger	0.3%	0.5%
Muon Id	0.5%	0.8%
Muon p_T scale	2.9%	0.2%
Muon p_T resolution	0.4%	0.1%
Electron Id	0.5%	0.8%
Electron energy scale	3.1%	1.1%
Electron energy resolution	0.3%	0.4%
Jet energy scale	0.2%	$< 0.1\%$
Jet energy resolution	$< 0.1\%$	$< 0.1\%$
E_T^{miss}	0.6%	2.2%
Dilepton p_T	0.4%	1.1%
PDF	1.0%	1.0%
Limited number of simulated events	10.6%	1.2%
Normalization (Tab. 1)	6.8%	3.3%

Invariant Mass after Selection