BNL forum, Oct 8, 2015

Contributions of Vectorlike Leptons to Diboson-like signals

- Heavy Higgs cascade decays contributing to WW-like signal

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R. Dermisek, J.P. Hall, E. Lunghi, S. Shin, JHEP1412, 013 (2014)

R. Dermisek, A. Raval, S. Shin, PRD90, 034023 (2014)

R. Dermisek, E. Lunghi, S. Shin, JHEP 1508, 126 (2015)

R. Dermisek, E. Lunghi, S. Shin, arXiv:1509.04292

Contents

- BSM searches in weak gauge boson production
  introduce vectorlike lepton that mix with a SM lepton
- Drell-Yan production of vectorlike leptons (EW gauge interaction)
- In cascade decays of a Higgs boson (Yukawa interaction)
  - SM Higgs exotic decays (VV*-like signals)
  - Heavy BSM Higgs decays
- Recent $\sigma(pp \to WW)$ measurements and contributions of heavy Higgs cascade decays mediated by a neutral vectorlike lepton
- An explicit example : a VLL extension of THDM (type-II)
- Conclusions

BSM searches in gauge boson production

SM weak gauge boson production at the LHC

- Focus on leptonic final states : clean signal
- LHC sensitivity strong enough to measure SM diboson signals (including $h \to VV^*$)
- New Physics searches, producing on-shell gauge boson, can be promising

We consider contributions to diboson-like signals generated by vectorlike leptons produced in

- Drell-Yan processes (EW gauge interactions)
- Cascade decays of a Higgs boson (Yukawa interactions)

NP signal could be hidden in the current Run1 data (7, 8 TeV) : non-optimal cuts

Why Vectorlike Leptons?

- Unification of gauge couplings in non-SUSY model

  Dermisek PLB713, 469 (2012), PRD87, 055008 (2013)

- A simple framework explaining various anomalies

  - muon g-2 Dermisek, Raval, PRD88, 013017 (2013)
  - $h \to \gamma\,\gamma$ Carena, Low, Wagner JHEP 1208, 060

- Acquire masses independently of their Yukawa couplings:

  - Weakly constrained in the absence of mixing with SM leptons

    Direct bounds are only from LEPII

- Decay products are SM leptons : clean signal (diboson-like)

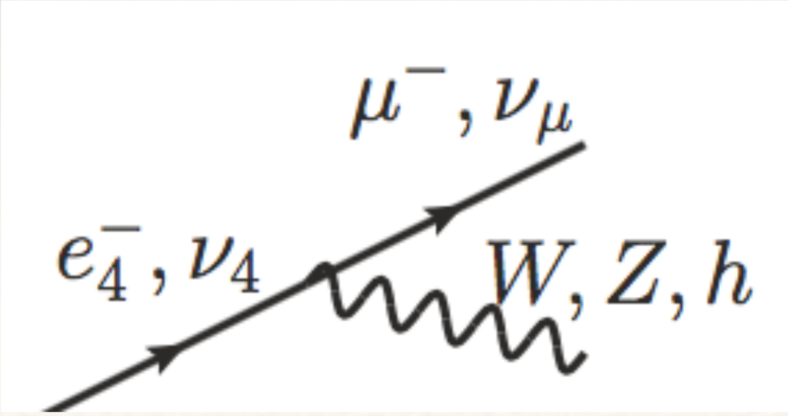
- Phenomenological results are easily convertible to different NP scenarios : electroweakinos (SUSY), triplet fermions (Seesaw)

Vectorlike Leptons

Basic structure of our scenario :

- Mixing with the SM muon : inspired from the muon g-2 Dermisek, Raval, PRD88, 013017 (2013)
- No mixing with other generations of the SM lepton : to avoid LFV
- Mass eigenstates after mixing (after EW breaking) : e_4 , e_5 & ν_4, ν_5

Flavor changing interactions (SM lepton and VLL) :



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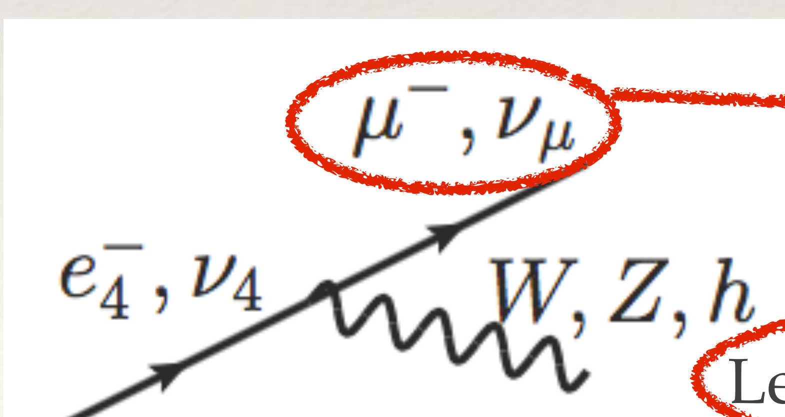
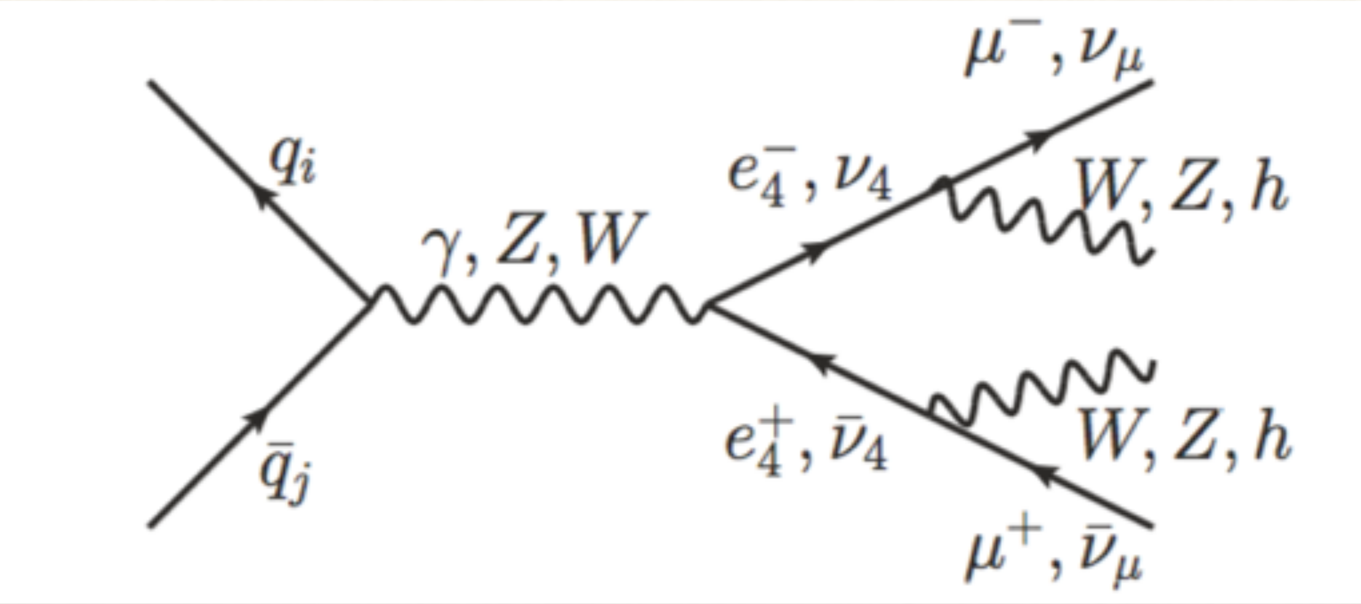


Diboson-like signals (+ ℓ's)

Leptons from a gauge boson decay

Drell-Yan production of vectorlike leptons

Production of vectorlike leptons in DY processes (gauge interactions)



Multilepton (3+ charged SM leptons) + missing E_T : Dermisek, Hall, Lunghi, Shin JHEP 1404, 140

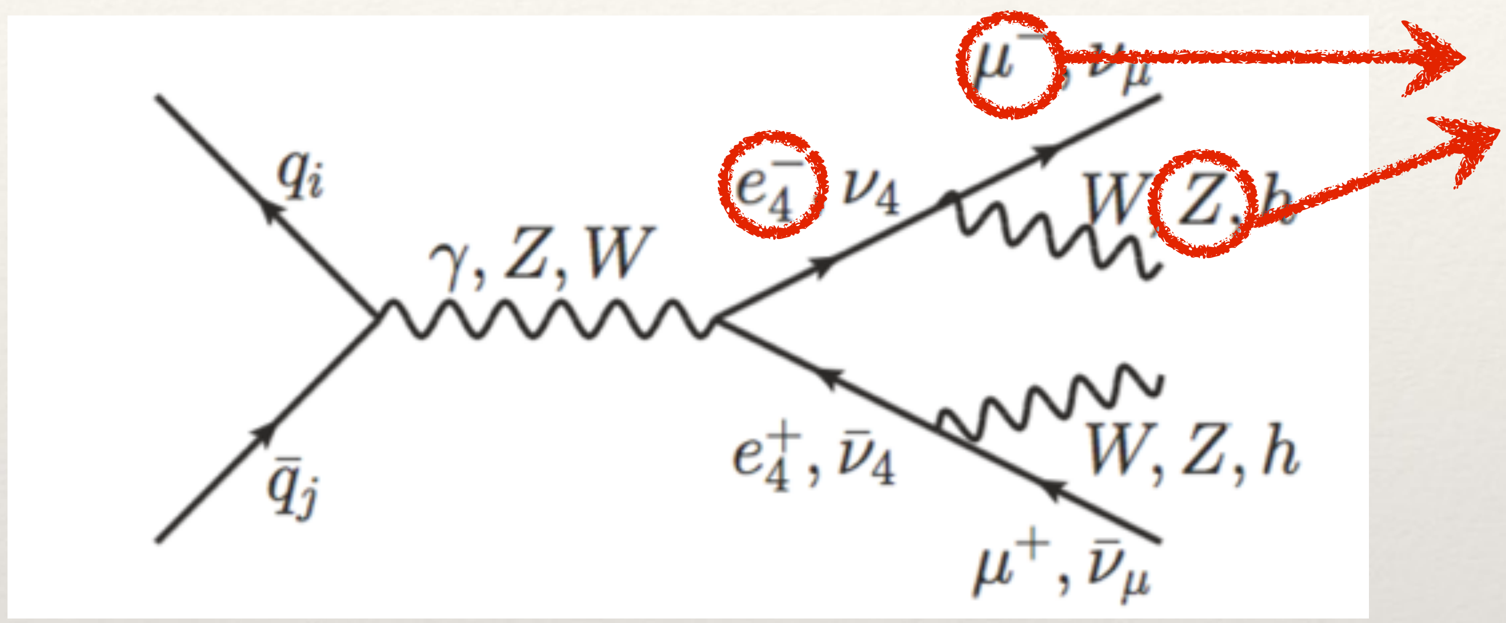
ATLAS-CONF-2013-070

for simplicity

- Express the results in terms of $\sigma\times$BRs : assume $m_{e4} = m_{\nu 4}$ & e_4 is either doublet or singlet
  ν_4 is only doublet
- Mixing with e : expect to give similar results
- Mixing with τ : about an order of magnitude weaker except ~ 105 GeV

Drell-Yan production of vectorlike leptons

Production of vectorlike leptons in DY processes (gauge interactions)

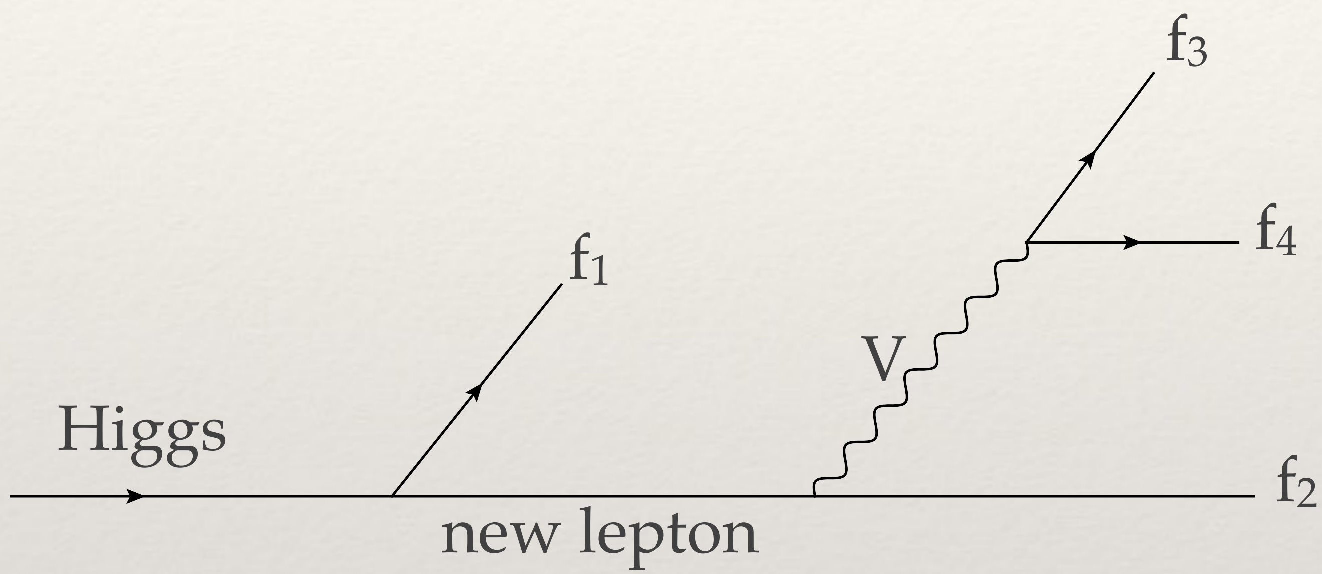


3ℓ from e_4

There is one current LHC search on the three leptons resonance : ATLAS arXiv:1506.01291

Single gauge boson production in a Higgs cascade decay

NP contribution to the SM diboson-like signals through Yukawa interactions



$f_{1,2}$: SM leptons

- SM Higgs exotic decay producing VV* final states : inv. mass is (or m_T smaller than) 125 GeV

  $h_{SM} \to e_4 \mu \to Z\mu\mu \to 4\ell$ Dermisek, Raval, Shin, PRD90, 034023 (2014)

  $h_{SM} \to e_4 \mu \to W\mu\, \nu_\mu \to 2\ell 2\nu$

- ✓ Heavy BSM Higgs decays result in diboson-like signals

  For pp→WW ($\to \ell \nu_\ell \ell' \nu_{\ell'}$) Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015) & arXiv:1509.04292

Measurements of σ(pp→WW)

Current situation in observing pp→WW ($\to \ell \nu_\ell \ell' \nu_{\ell'}$)

- ATLAS at 8 TeV $\mathscr{L}$ ~ 20.3 fb^{-1} : 2σ deviation - NLO level SM expectations

$$[\sigma(pp \to WW) + \sigma(gg \to h \to WW^*)]_{\rm exp} = 71.4^{+1.2}_{-1.2}({\rm stat})^{+5.0}_{-4.4}({\rm syst})^{+2.2}_{-2.1}({\rm lumi})\ {\rm pb}$$

$$[\sigma(pp \to WW) + \sigma(gg \to h \to WW^*)]_{\rm th,NLO} = 58.7^{+3.0}_{-2.7}\ {\rm pb}$$

$$\boxed{\Delta\sigma_{\rm ATLAS} \simeq (13 \pm 6)\ {\rm pb}}$$

ATLAS-CONF-2014-033, ATLAS-COM-CONF-2014-045

- Similar deviation in the CMS at 8 TeV $\mathscr{L}$ ~ 3.5 fb^{-1} CMS, Phys. Lett. B 721, 190 (2013)

- Signal events are generated at the NLO + parton shower using the MC tools

Measurements of σ(pp→WW)

Current situation in observing pp→WW (→$\ell\nu_\ell\ell'\nu_{\ell'}$)

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reweight with resummed p_T^{WW} distribution

- CMS preliminary at 8 TeV $\mathscr{L}$ ~ 19.4 fb^{-1} CMS PAS SMP-14-016

$$\sigma(pp \to WW)_{\rm exp} = 60.1 \pm 0.9({\rm stat}) \pm 3.2({\rm exp}) \pm 3.1({\rm th}) \pm 1.6({\rm lumi})\ {\rm pb}$$

claim its consistency with the recent $\sigma(pp \to WW)_{\rm th,NNLO} = 59.84^{+2.2\%}_{-1.9\%}\ {\rm pb}$ without H→WW

Gehrmann et al., PRL 113, 212001 (2014)

$\boxed{\Delta\sigma_{\rm CMS} \simeq (0 \pm 5)\ {\rm pb}}$ still large uncertainty

Measurements of $\sigma(pp \to WW)$

Extraction of the cross section $\sigma(pp \to WW)$

- Cross section $\sigma(pp \to WW) = (N_{data} - N_{bkg}) / (\mathscr{L} \cdot A \cdot \epsilon \cdot BR)$ (data : $\ell \nu_{\ell} \ell' \nu_{\ell'}$)
- What the detector measures : $\sigma^{fid} = \sigma(pp \to WW \to \ell \nu_{\ell} \ell' \nu_{\ell'}) \cdot A$

observations $\Leftrightarrow$ theoretical expectations (MC : NLO + shower)

$$[\sigma^{fid}]_{exp} = (N_{data} - N_{bkg}) / (\mathscr{L} \cdot \epsilon) \quad \Leftrightarrow \quad [\sigma^{fid}]_{th.} = \underbrace{\sigma(pp \to WW \to \ell \nu_{\ell} \ell' \nu_{\ell'})}_{\text{purely theoretical calculations}} \cdot A_{MC:NLO+shower}$$

fixed by the observation

In terms of $\sigma(pp \to WW)$

$$\sigma(pp \to WW)_{exp} = \underbrace{[\sigma^{fid}]_{exp}}_{\text{fixed by the observation}} / (A_{MC:NLO+shower} \cdot BR) \quad \Leftrightarrow \quad \underbrace{\sigma(pp \to WW)_{th}}_{\text{purely theoretical calculations}}$$

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fixed by the observation

purely theoretical calculations

Explanations of the excess

- New Physics : EW production of NP particles with gauge couplings

Curtin, Jaiswal, Meade, PRD 87, 031701 (2013), Jaiswal, Kopp, Okui, PRD 87, 115017 (2013)
Curtin, Jaiswal, Meade, Tien, JHEP 1308, 068 (2013), Curtin, Meade, Tien, PRD 90, 115012 (2014)
Rolbiecki, Sakurai, JHEP 1309, 004 (2013), Kim, Rolbiecki, Sakurai, Tattersall, JHEP 1412, 010 (2014), …

- Jet-veto efficiency : jets vetoed to suppress the top quark backgrounds (main)

$\varepsilon_{j\text{-}veto} = \sigma_{jet\text{-}vetoed}/\sigma \;\; \Rightarrow \;\;$ change $[\sigma^{fid}]_{th}$

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Explanations of the excess

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Talk by Jaiswal

- Jet-veto efficiency : jets vetoed to suppress the top quark backgrounds (main)

$\varepsilon_{j\text{-veto}} = \sigma_{jet\text{-vetoed}}/\sigma \;\Rightarrow\;$ change $[\sigma^{fid}]_{th}$

Still allow some deviations

- NNLL level p_T resummation of WW or jet-veto

  Meade, Ramani, Zeng, PRD 90, 114006 (2014), Jaiswal, Okui, PRD 90, 073009 (2014)

- Parton level NLO enhances $\varepsilon_{j\text{-veto}}$ but NNL contributions to $\sigma \cdot A$ cancels (NLO is enough)

  Monni, Zanderighi, 1410.4745

Measurements of $\sigma(pp \to WW)$

Our brief summary of pp→WW

$$\Delta\sigma_{\text{ATLAS}} \simeq (13 \pm 6)\ \text{pb} \quad \text{or} \quad \Delta\sigma_{\text{CMS}} \simeq (0 \pm 5)\ \text{pb}$$

- NNLO level MC generators are on their way : better situation in the future
- At face value we take NLO prediction to compare with the ATLAS result
- Experimental uncertainties are at the 5pb level

We can take the current result as being compatible with O(10)pb NP contribution either as an explanation of the excess or a 2σ upper limit

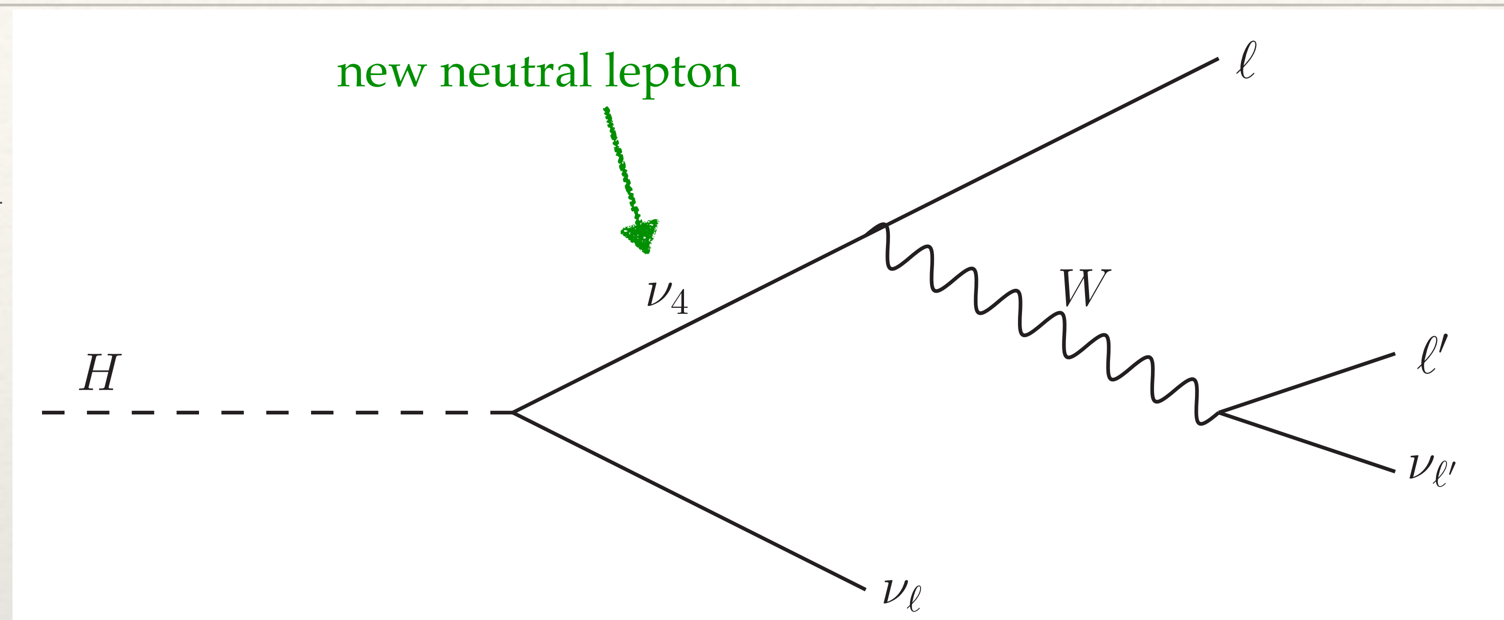
Heavy BSM Higgs decay to WW-like signal

Simplified model

H-ν_4- ν_μ

W-ν_4 -ν_μ

~~H-W-W~~



Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015)

Large contribution to WW-like signal pp→$\ell \nu_\ell \ell' \nu_{\ell'}$

- pp→H cross section is O(10)pb

Not too heavy H

~~H-V-V~~
- The new decay mode of H can be large when $m_H < 2m_t$ (practically $m_H < 2\, m_h$)
- Only one W decaying leptonically : avoiding an extra BR(W→$\ell \nu_\ell$) suppression

Heavy BSM Higgs decay to WW-like signal

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H-ν_4-ν_μ

W-ν_4-ν_μ

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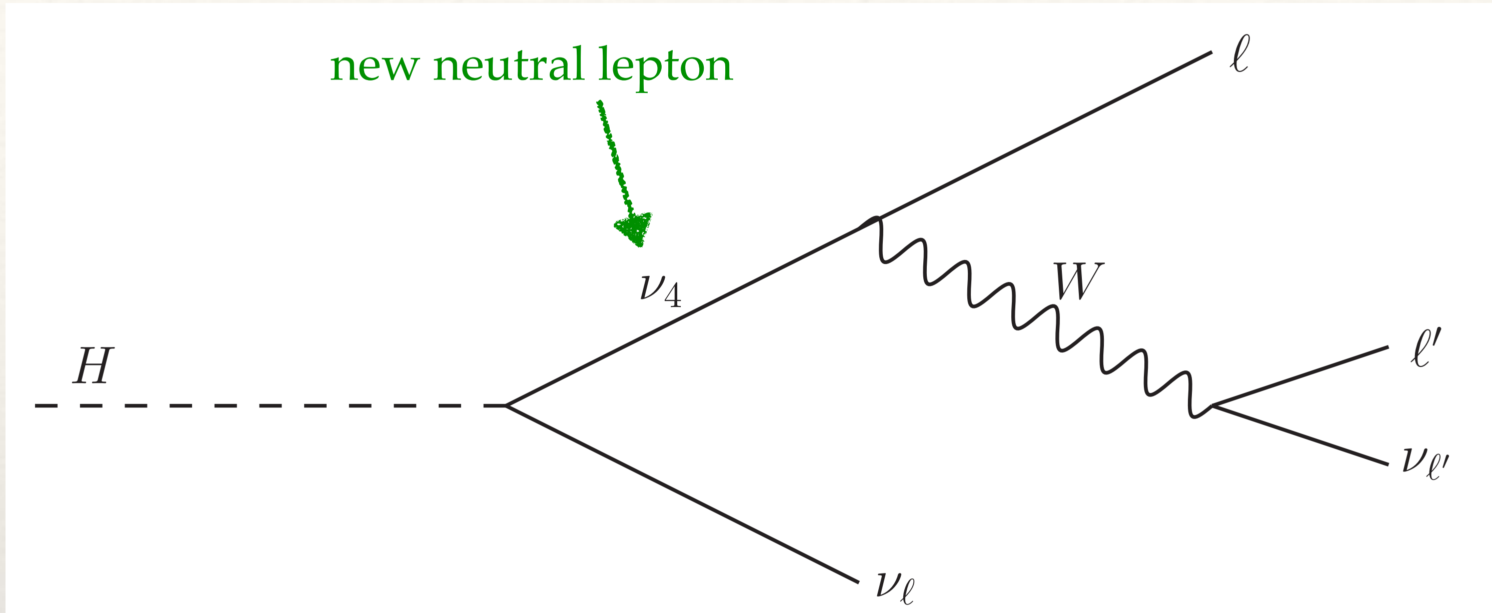

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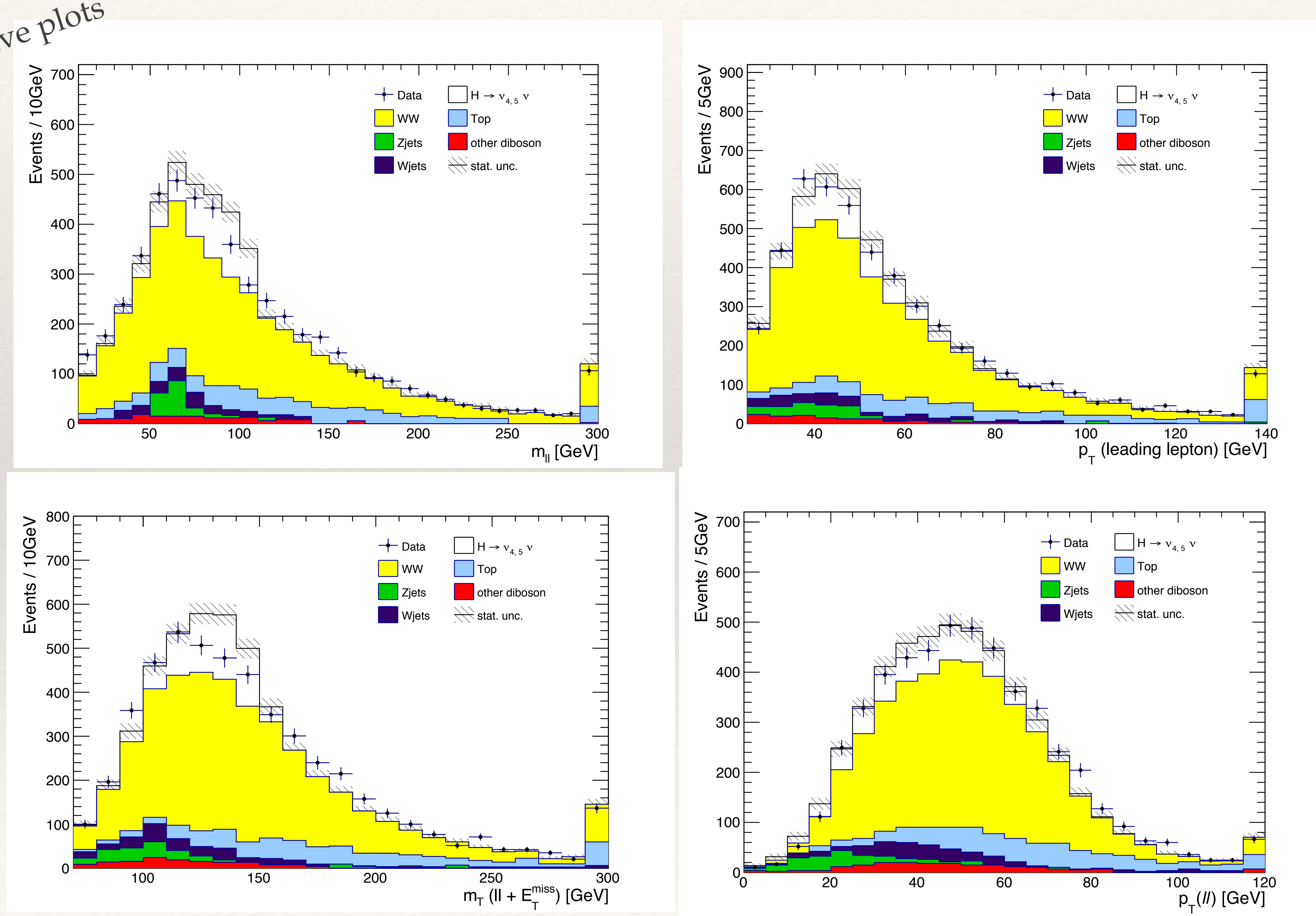
We are in an excellent position to explain a significant excess or to place strong constraints in large range of (m's, BR's)

Kinematic distributions

Taking the recent $\sigma(pp \to WW)$ by ATLAS at face value

Representative plots



Reference : $m_H = 155$ GeV, $m_{\nu 4} = 135$ GeV, BR($H \to W\ell\nu_\ell$) = 0.16 ($e\mu$), possibly with additional lepton for ee

THDM with VLL extension

A complete model : VLL extension in type-II THDM

Dermisek, Lunghi, Shin, arXiv:1509.04292

	μ_L	μ_R	$L_{L,R}$	$E_{L,R}$	$N_{L,R}$	H_d	H_u
$\mathrm{SU(2)_L}$	**2**	**1**	**2**	**1**	**1**	**2**	**2**
$\mathrm{U(1)_Y}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{Z_2}$	+	−	+	−	+	−	+

$$\begin{aligned}\mathcal{L} \supset & -y_\mu \bar{\mu}_L \mu_R H_d - \lambda_E \bar{\mu}_L E_R H_d - \lambda_L \bar{L}_L \mu_R H_d - \lambda \bar{L}_L E_R H_d - \bar{\lambda} H_d^\dagger \bar{E}_L L_R \\ & - \kappa_N \bar{\mu}_L N_R H_u - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H_u^\dagger \bar{N}_L L_R \\ & - M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - M_N \bar{N}_L N_R + \text{h.c.} \,,\end{aligned}$$

H : heavy CP even Higgs (we require that h has 100% SM gauge interaction)

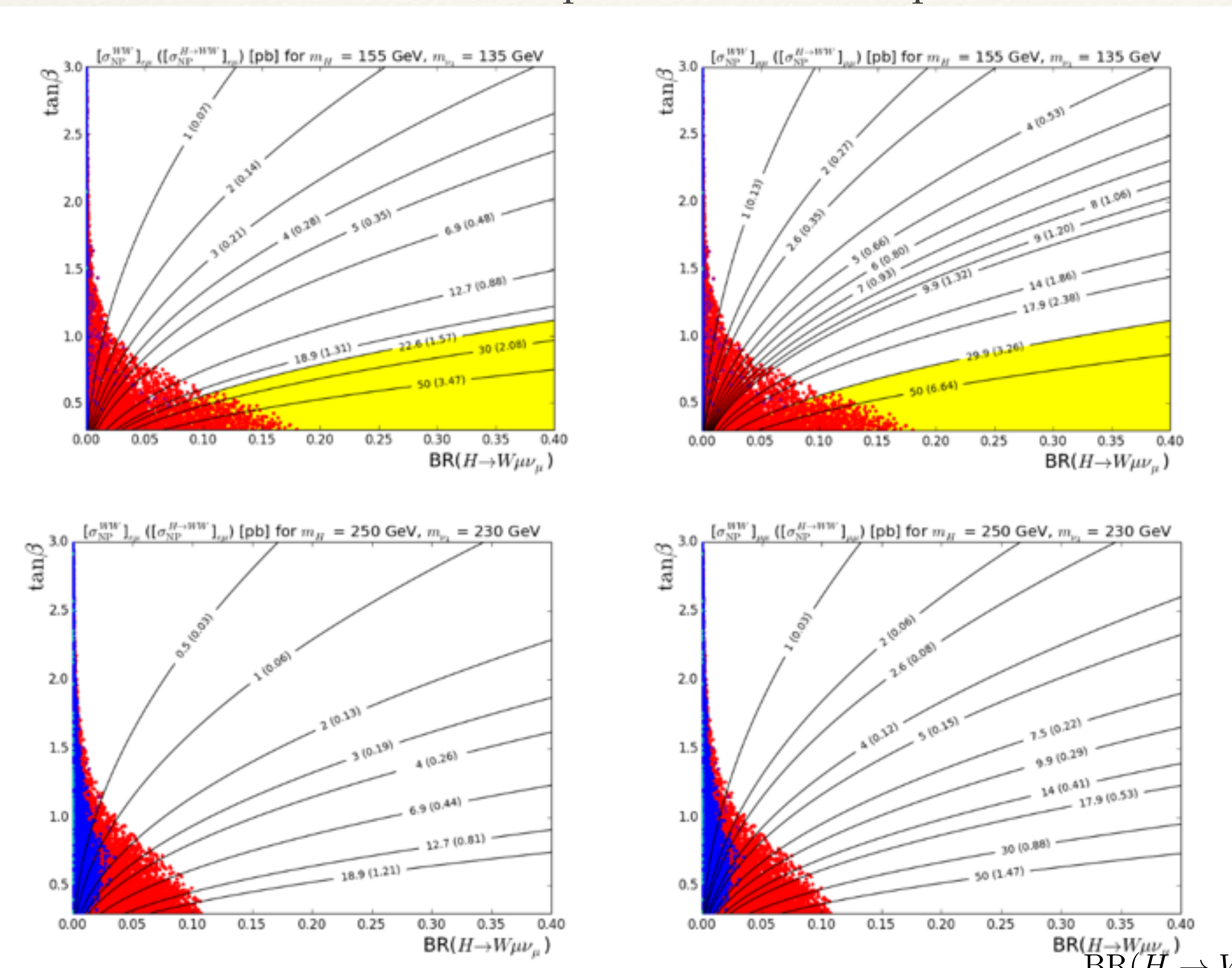
i) Parameter region allowed by

- EW precision data : Z-pole observables (including inv. Z-width), muon lifetime, W partial width, oblique corrections, neutral current parameters
- Constraints from DY pair or single production of vectorlike leptons (multi ℓ + $\not{E}_T$)
  Dermisek, Hall, Lunghi, Shin JHEP 1404, 140

ii) All other VLL processes that contribute to the WW-like signal (pp→$\ell\nu_\ell\ell'\nu_{\ell'}$) ~ 1 pb

THDM with VLL extension

All EW precision + multilepton search constraints



- Red : SM singlet-like
- Blue : SU(2) doublet-like
- Yellow : constrained by H → WW search
- Contours : effective contributions to pp→WW and pp → H → WW
- LHC 13 with 100 fb^{-1} can test most of the allowed parameter space

both $\nu_4\bar{\nu}_\mu + \bar{\nu}_4\nu_\mu$

$$\mathrm{BR}(H \to W\mu\nu_\mu) = \mathrm{BR}(H \to \nu_4\nu_\mu)\mathrm{BR}(\nu_4 \to W\mu)$$

THDM with VLL extension

After imposing all EW precision + multilepton search constraints

- Large BR(H → $\nu_4\nu_\mu$) ≲ 35% is possible (depending on the choice of masses $m_H < 2m_h$)
- Effects on SM gauge couplings $g_L^{W\nu_\mu\mu}$, $g_L^{Z\nu_\mu\nu_\mu}$ < 0.1%
- New flavor changing gauge couplings $g_{L,R}^{W\nu_4\mu}$, $g_L^{Z\nu_4\nu_\mu}$ < $\boldsymbol{O}(10^{-2})$
- New flavor changing Yukawa couplings < 0.04 ($\lambda_h^{\nu_4\nu_\mu}$) and 0.13 ($\lambda_H^{\nu_4\nu_\mu}$)
- Constraints from single production of vectorlike leptons (multi ℓ + $\not{E}_T$) are negligible
  (also applied in TeV scale seesaw models with very small LFV)

All other VLL processes that contribute to the WW-like signal (pp→$\ell\nu_\ell\ell'\nu_{\ell'}$) ~ 1 pb

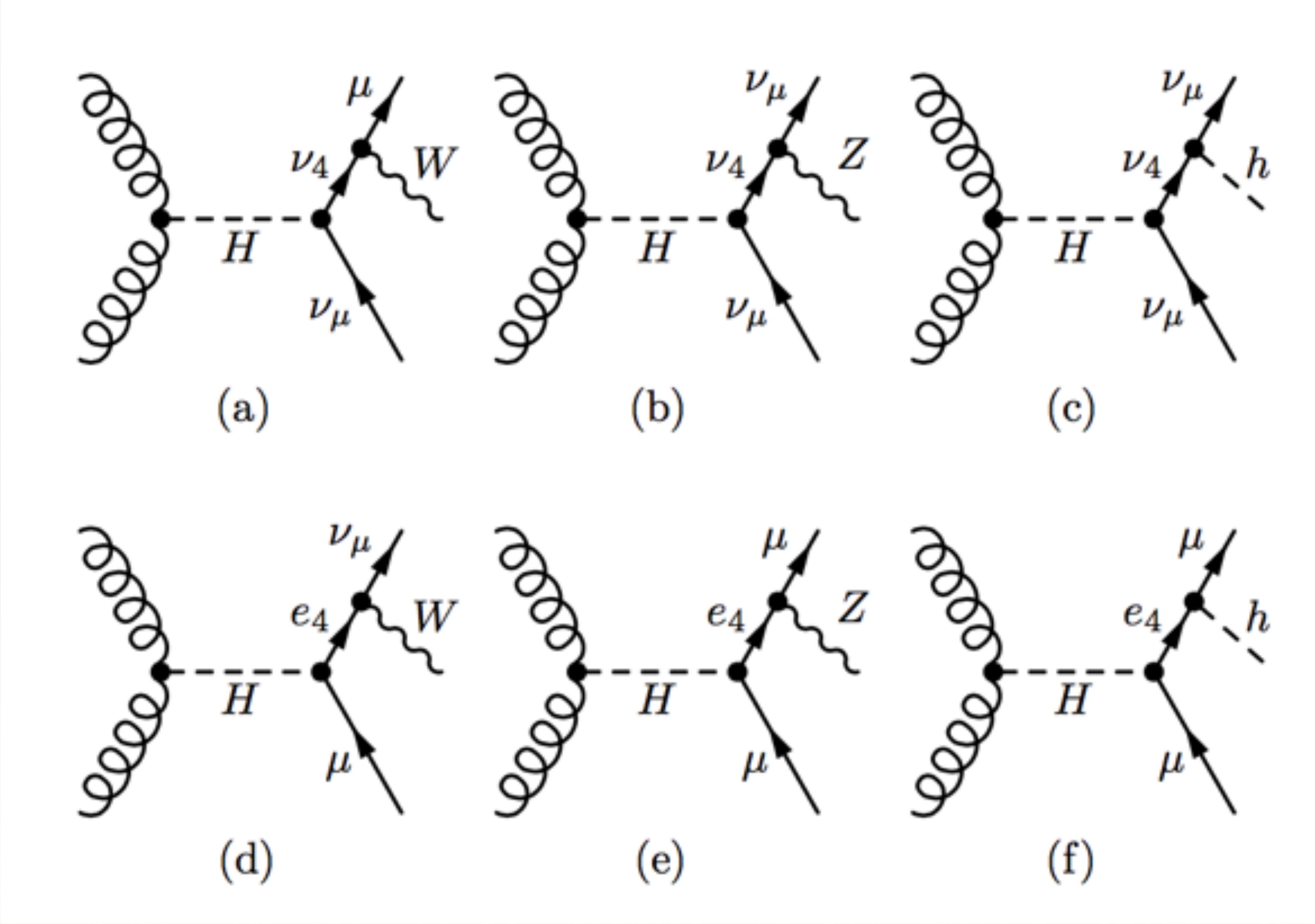
- H → $e_4\mu$ → Wμ ν_μ → $\ell\nu_\ell\ell'\nu_{\ell'}$ (few pb)
- h_{SM} → $\nu_4\nu_\mu$ or $e_4\mu$ → Wμ ν_μ
- DY productions (including single ν_4 production)

$$pp \to (\gamma, Z) \to e_4^\pm e_4^\mp \to W^\pm W^\mp \nu_\mu \bar{\nu}_\mu \to 2\ell 4\nu \ ,$$
$$pp \to Z \to \nu_4 \nu_\mu \to W \mu \nu_\mu \to \ell \mu 2\nu \ .$$

More search on Higgs cascade decays

Additional heavy Higgs cascade decays are possible : WW, ZZ, Zh like signals (correlated)

Dermisek, Lunghi, Shin, Work in progress



Several interesting signals

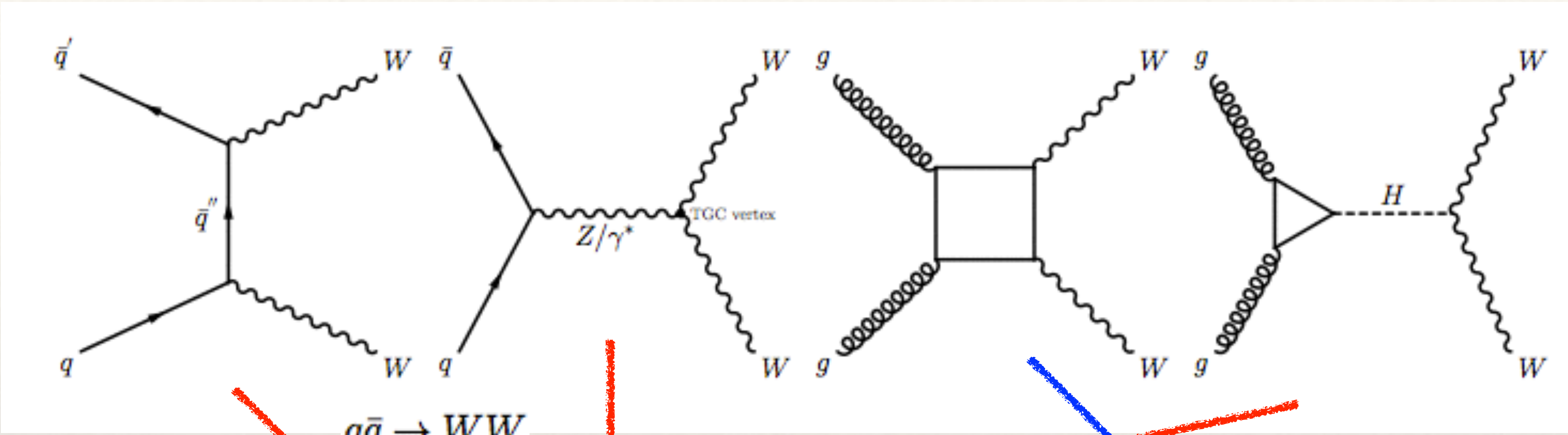
- High multiplicity lepton : 6
- $\not{E}_T$ + $\gamma\gamma$ or monojet
- $\not{E}_T$ + bb
- etc…..

Apparently unrelated experimental searches can be connected

Conclusions

- BSM searches in diboson production to leptonic final states are promising (clean signals).
- Example : Extra vectorlike leptons that mix with a SM lepton (with flavor violating Yukawa and gauge couplings).
- Possibly large contributions to diboson-like signals in DY production of VLL with flavor changing gauge interactions or in cascade decays of a Higgs boson with flavor changing Yukawa interactions.
- The cascade decay of a heavy BSM Higgs H $\to \nu_4 \nu_\mu \to W \mu \, \nu_\mu$ can contribute to the measurement of $\sigma(pp \to WW)$; it nicely fits the nominal excess claimed by ATLAS.
- Explicit model : a VLL extension of type-II THDM
  - Constraints from EW precision & multilepton + E_T (DY production)
    Large effective contribution to pp $\to$WW or pp $\to$H $\to$WW with small $\tan\beta$
- Additional cascade decays produce signals like WW, ZZ, Zh (now under study)

Back-up



POWHEG : NLO + Pythia : shower GG2WW

ATLAS

Process	Cross section [pb]	Scale [pb]	PDF+α_s [pb]	Branching fraction [pb]	Calculation	Total [pb]
$q\bar{q} \to WW$	53.2	$^{+2.3}_{-1.9}$	$^{+1.0}_{-1.1}$	-	NLO MCFM [1]	$^{+2.5}_{-2.2}$
$gg \to WW$	1.4	$^{+0.3}_{-0.2}$	$^{+0.1}_{-0.1}$	-	LO MCFM [1]	$^{+0.3}_{-0.2}$
$gg \to H \to WW$	4.1	$\pm$ 0.3	$\pm$0.3	$\pm$0.2	NNLO+NNLL QCD, NLO EW [3]	$\pm$0.5

Back-up

$$\sigma^{\rm fid}_{\rm SM} = \sigma^{\rm SM}_{pp\to WW}\ {\rm BR}(W\to \ell\nu_\ell)\ {\rm BR}(W\to \ell'\nu_{\ell'})\ A_{\rm SM}$$
$$\sigma^{\rm fid}_{\rm NP} = \sigma^{\rm NP}_{pp\to H}\ {\rm BR}(H\to W\ell\nu_\ell)\ {\rm BR}(W\to \ell'\nu_{\ell'})\ A_{\rm NP}$$

$$\sigma^{WW}_{\rm NP} = \frac{\sigma^{\rm fid}_{\rm NP}}{\sigma^{\rm fid}_{\rm SM}}\sigma^{WW}_{\rm SM} = \begin{cases} \dfrac{\left[\sigma^{\rm fid}_{\rm NP}\right]_{e\mu}}{2\,{\rm BR}(W\to\ell\nu)^2\ A^{e\mu}_{\rm SM}} \\ \dfrac{\left[\sigma^{\rm fid}_{\rm NP}\right]_{\mu\mu}}{{\rm BR}(W\to\ell\nu)^2\ A^{\mu\mu}_{\rm SM}} \end{cases}$$

	$\sigma^{\rm fid}_{\rm exp}$ [fb]	$\sigma^{\rm fid}_{\rm SM}$ [fb]	$\sigma^{\rm fid}_{\rm NP}$ [fb]	$\sigma^{\rm WW}_{\rm NP}$ [pb]
$e\mu$	$377.8^{+28.4}_{-25.6}$	$310.6^{+15.9}_{-14.3}$	67.2^{+30}_{-32}	$12.7^{+6.2}_{-5.8}$
ee	$68.5^{+9.0}_{-8.0}$	$58.6^{+3.0}_{-2.7}$	$9.9^{+9.4}_{-8.5}$	$9.9^{+9.5}_{-8.6}$
$\mu\mu$	$74.4^{+8.1}_{-7.1}$	$63.7^{+3.3}_{-2.9}$	$10.7^{+8.6}_{-7.8}$	$9.9^{+8.0}_{-7.3}$

- Event generation : MG5 + Pythia6 (parton shower) from our model (FeynRules)
- The resulting StdHEP file ⇒ ROOT format by Delphes
- Jet clustering : handled by FastJet (ΔR = 0.4 for our signal)

Back-up

The dominant constraint on $\sigma_{\rm NP}^{\rm fid}$ comes from the $H \to WW$ CMS search presented in refs. [25, 26] where a number of different cuts, each optimized to be sensitive to a SM–like heavy Higgs of a given mass, are considered. For each cut (that we label $\mathcal{H}$) CMS, effectively, places a 95% C.L. upper limit on a fiducial cross section:

$$\sigma_{\mathcal{H}}^{\rm fid} = A_{\rm NP}^{\mathcal{H}}\, \sigma^{\rm NP} < \beta_{95}^{\mathcal{H}}\,, \tag{3.1}$$

where $\sigma^{\rm NP}$ is the same total cross section (including branching ratios) that appears in eq. (2.3) and $A_{\rm NP}^{\mathcal{H}}$ is the acceptance for the cut selection $\mathcal{H}$. Since CMS does not present the results of the analysis in terms of fiducial cross sections, the extraction of these upper limits is not straightforward. We list in table 2 the $\beta_{95}^{\mathcal{H}}$ that we obtain and relegate the technical details to appendix A. In the table we consider six CMS analyses (labelled by the value $\hat{m}_H$ of the Higgs mass for which each analysis is optimized) and present separately the $e\mu$ and $\mu\mu$ channels. The implied upper limit on the fiducial cross section (2.3) is then

$$\sigma_{\rm NP}^{\rm fid} < A_{\rm NP} \min_{\mathcal{H}} \left[\frac{\beta_{95}^{\mathcal{H}}}{A_{\rm NP}^{\mathcal{H}}}\right] . \tag{3.2}$$

$\hat{m}_H$ [GeV]	120	125	130	160	200	400
$e\mu$	5.1 fb	4.8 fb	4.9 fb	3.3 fb	9.7 fb	3.7 fb
$\mu\mu$	5.6 fb	5.8 fb	4.5 fb	3.6 fb	6.3 fb	4.0 fb

Table 2. The quantities $\beta_{95}^{\mathcal{H}}$ for the $e\mu$, ee and $\mu\mu$ channels and for each of the six CMS analyses that we consider (labelled by their $\hat{m}_H$ value).

$m_{\nu_4} \in [120, 250]$ GeV and $m_H \in [130, 250]$ GeV

$A_{\rm NP}^{\mathcal{H}}$ for both $e\mu$ and $\mu\mu$ final states

$[0.01, 4]\%$

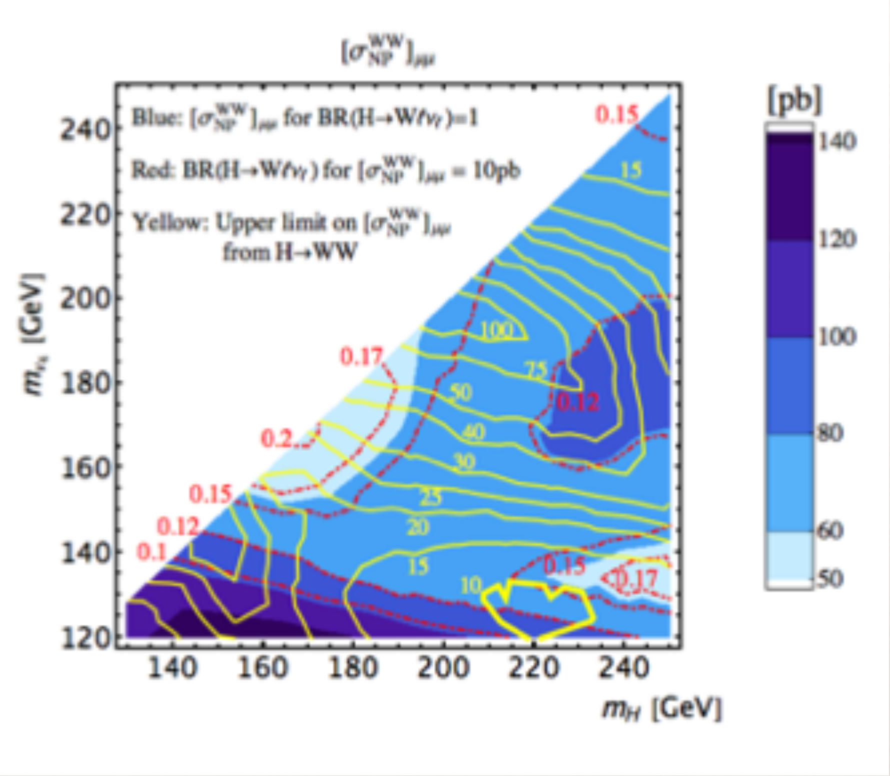
$[A_{\rm NP}]_{e\mu} \in [24, 29]\%$

$[A_{\rm NP}]_{\mu\mu} \in [5, 15]\%$

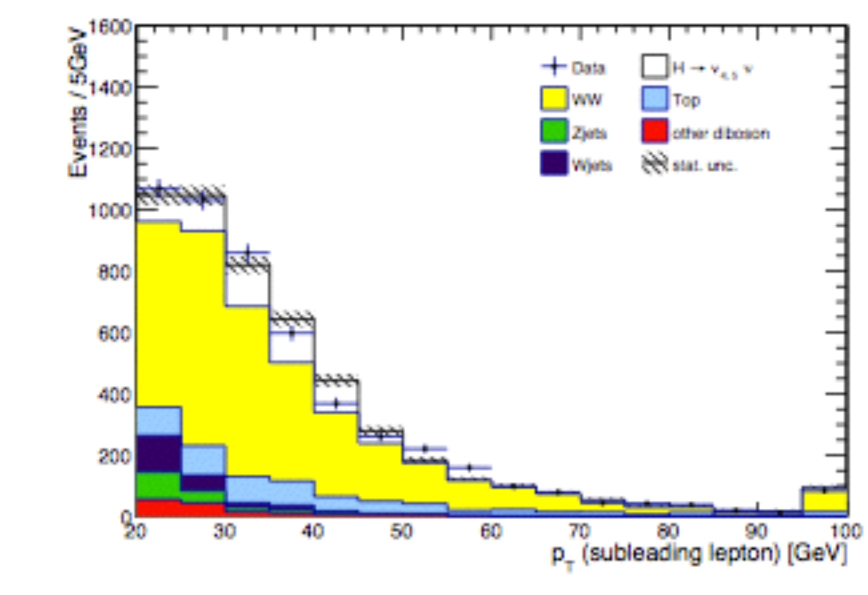
$A_{\rm NP}/A_{\rm NP}^{\mathcal{H}}$ suppressed

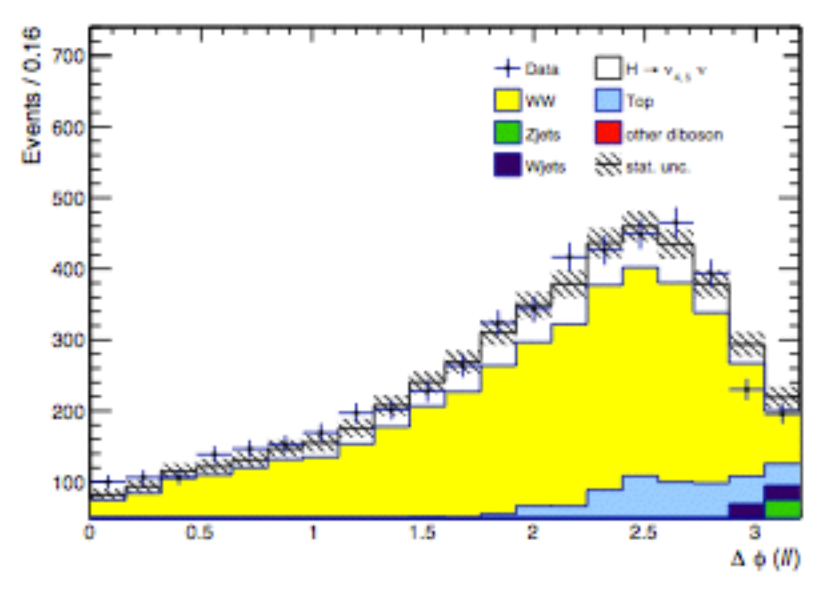
Back-up

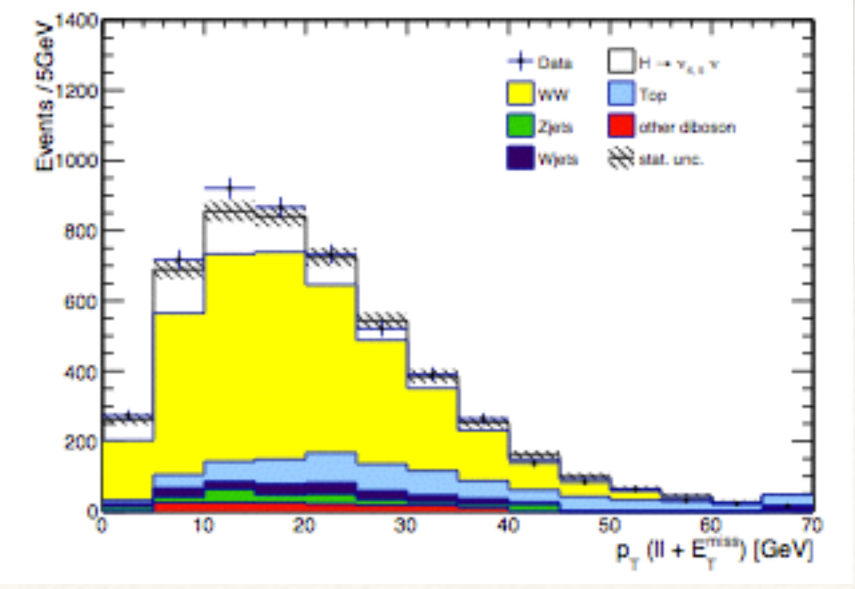
$$pp \to H \to \nu_4 \nu_\mu \to W \mu \nu_\mu \to \ell \nu_\ell \mu \nu_\mu$$
$$pp \to H \to \nu_5 \nu_e \to W e \nu_e \quad \to \ell \nu_\ell e \nu_e$$



$$\mathrm{BR}(H \to W\ell\nu_\ell) \equiv \mathrm{BR}(H \to \nu_4\nu_\mu)\,\mathrm{BR}(\nu_4 \to W\mu) + \mathrm{BR}(H \to \nu_5\nu_e)\,\mathrm{BR}(\nu_5 \to We)$$



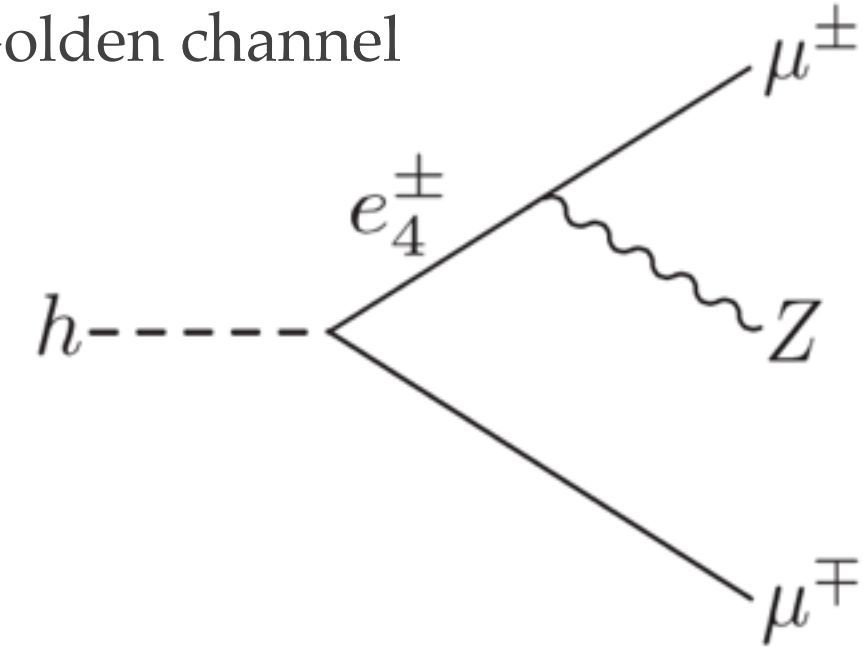




SM exotic decay to a charged vectorlike lepton

Dermisek, Raval, Shin, PRD90, 034023 (2014)

Golden channel



e_4 : lightest charged vectorlike lepton

$Z \to \mu$ or e pair

Contribute to 4μ or 2e2μ final states of

$\boxed{h_{SM} \to ZZ^* \to 4\ell}$

- The EW precision data : Z-pole observables, τ_μ, $\Gamma_{W\to\mu\nu}$, oblique corrections
- h $\to \mu\mu$ from the CMS : CMS-PAS-HIG-13-007
- Also show the parameters explaining the muon g-2 anomaly

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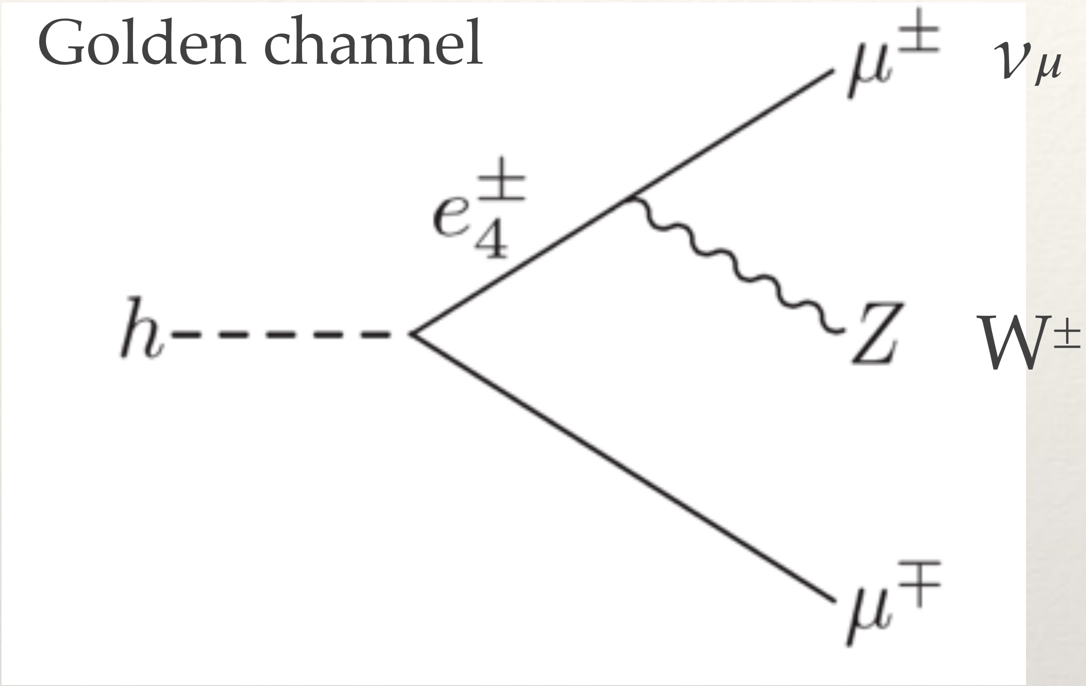

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Contribute to 4μ or 2e2μ final states of

$$\boxed{h_{SM} \to ZZ^* \to 4\ell}$$

2μ2ν or μe2ν final states of

$$\boxed{h_{SM} \to WW^* \to 2\ell 2\nu}$$

- The EW precision data : Z-pole observables, τ_μ, $\Gamma_{W\to\mu\nu}$, oblique corrections
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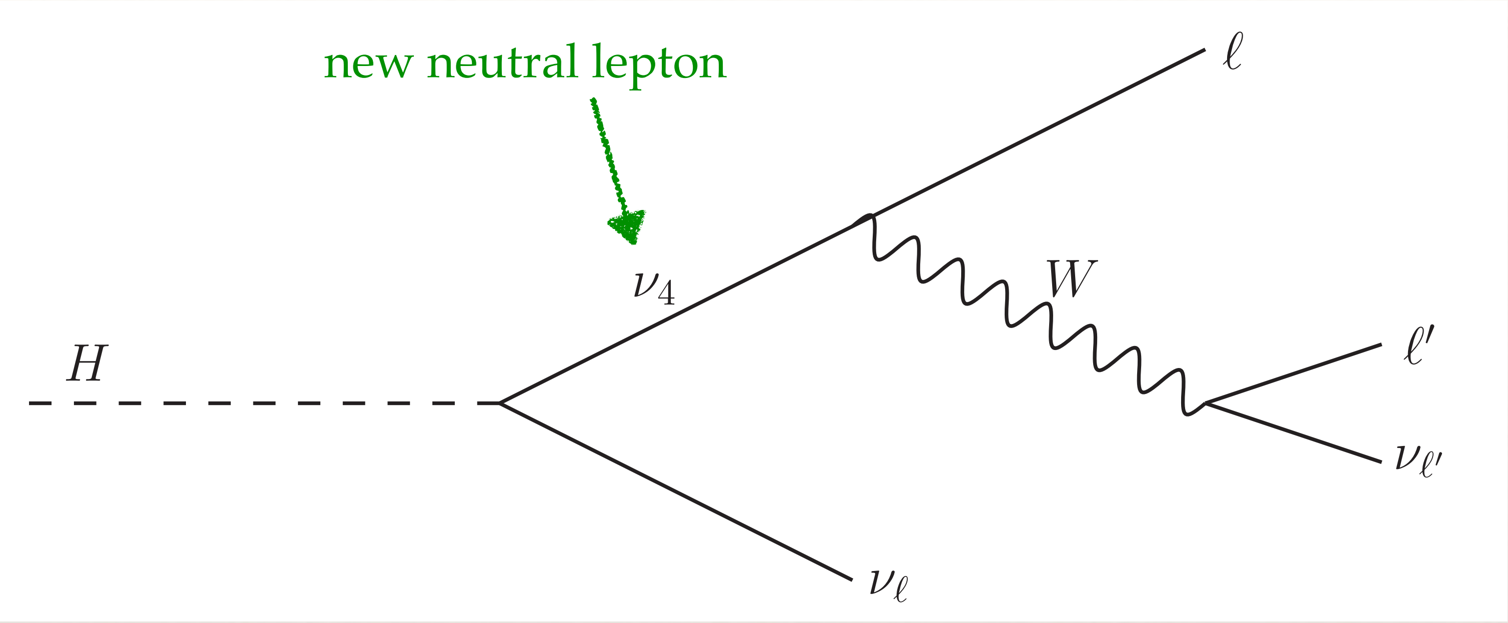
Back-up



- We first set $\ell=\mu$ contributing to e$\mu\nu_e\nu_\mu$ and $\mu\mu\nu_\mu\nu_\mu$ final states
  - NP mostly affect the statistically dominant eμ channel
  - In order to contribute to ee mode as well, if desirable, additional neutral lepton
- This scenario can arises, e.g., 2HDM with vectorlike leptons

  Dermisek, Lunghi, Shin, arXiv:1509.04292
- Simplified model $\Rightarrow$ present the results simply with m_H, m_{ν_4}, BR($H \to W\ell\nu_\ell$)

$$\mathrm{BR}(H \to W\ell\nu_\ell) \equiv \mathrm{BR}(H \to \nu_4\nu_\mu)\,\mathrm{BR}(\nu_4 \to W\mu)$$

Allowed parameter space & constraints from H searches

- ATLAS results are presented in terms of $\sigma^{\rm fid}$
  - Our analysis done in terms of $\sigma^{\rm fid}$ without detailed detector simulation

- For an easy understanding of NP contribution
  - Define an alternative quantity corresponding to $\Delta\sigma(pp\to WW)$: O(10)pb
    (Our process $H\to W\ell\nu_\ell$ has only one W)

$$\sigma_{\rm NP}^{WW} = \frac{\sigma_{\rm NP}^{\rm fid}}{\sigma_{\rm SM}^{\rm fid}}\sigma_{\rm SM}^{WW} = \begin{cases} \dfrac{\left[\sigma_{\rm NP}^{\rm fid}\right]_{e\mu}}{2\,{\rm BR}(W\to\ell\nu)^2\,A_{\rm SM}^{e\mu}} \\ \dfrac{\left[\sigma_{\rm NP}^{\rm fid}\right]_{\mu\mu}}{{\rm BR}(W\to\ell\nu)^2\,A_{\rm SM}^{\mu\mu}} \end{cases}$$

- Even without direct coupling H - WW, constraints from $H\to WW$, $\gamma\gamma$ should be considered (due to the Yukawa couplings of H in our simplified model)

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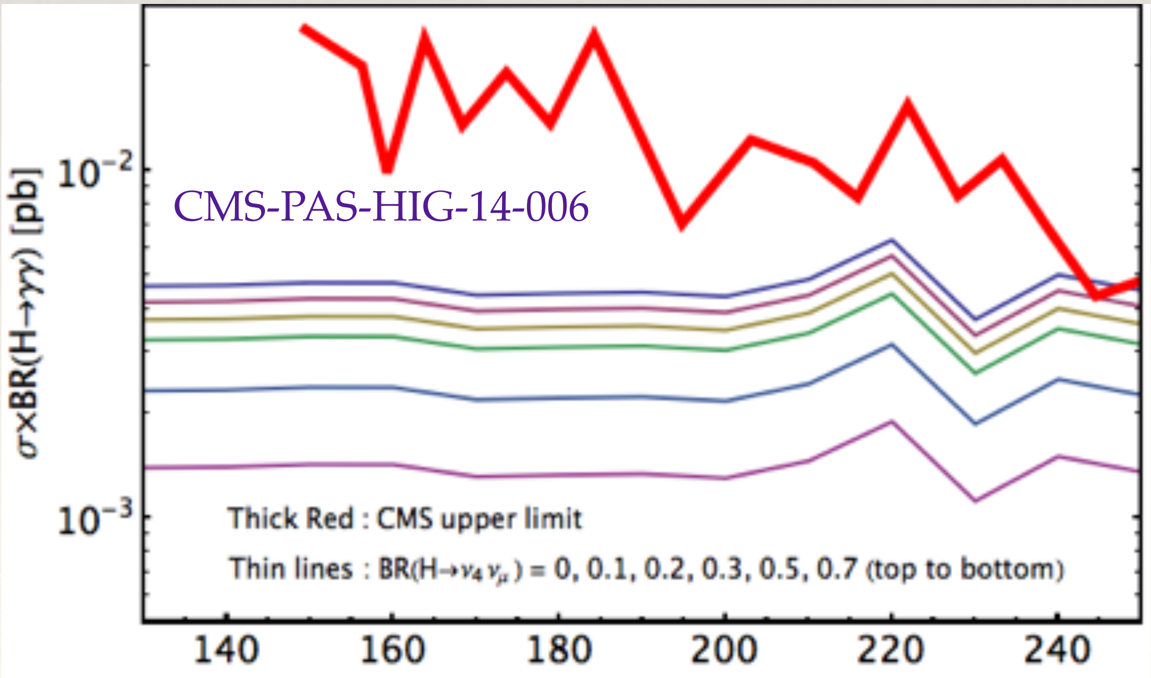
- Even without direct coupling H - WW, constraints from $H\to WW, \gamma\gamma$ should be considered (due to the Yukawa couplings of H in our simplified model)

$H\to\gamma\gamma$ only through top Yukawa

Suppressed compared to the SM-like Higgs
(dominated by WW loop + interference with t)



Allowed parameter space & constraints from H searches

- Constraints from H→WW are controlled by the acceptance$^{H\to WW}$ of our process
- Contributions of our process to pp→$\ell\nu_\ell\ell'\nu_{\ell'}$ (WW search) are by the acceptance^{WW}

The bound by H→WW on H→W$\ell\nu_\ell$→$\ell\nu_\ell\ell'\nu_{\ell'}$ weakened : A^{WW} / $A^{H\to WW}$

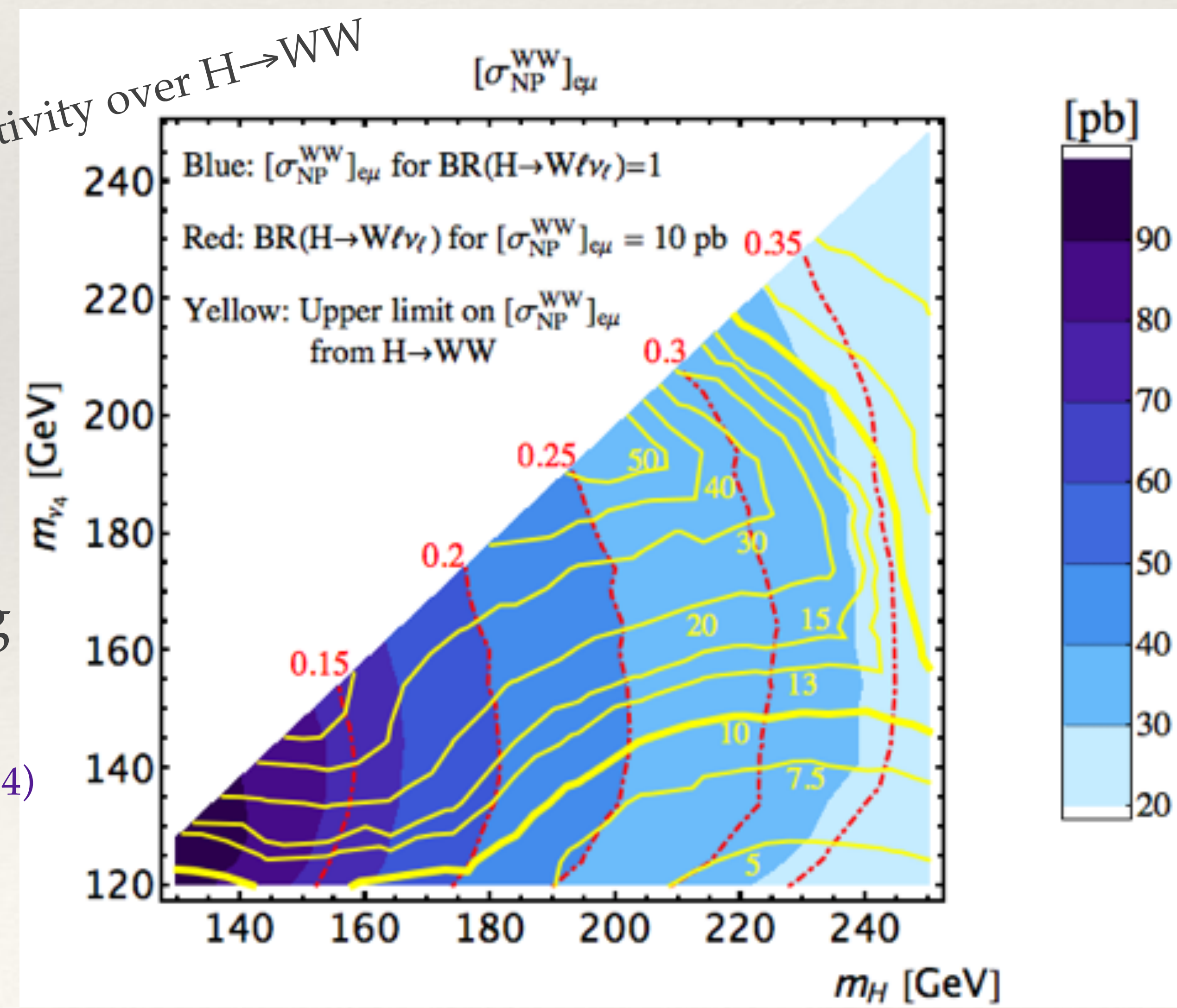
- Show the allowed contributions of H→W$\ell\nu_\ell$→$\ell\nu_\ell\ell'\nu_{\ell'}$ (possibly excess in the future) in terms of $\sigma_{\rm NP}^{WW}$ e.g., eμ channel

- To obtain H→WW bound (95% C.L.) we proceed the cut-based analysis considering the cuts in each Higgs mass hypothesis given in the CMS search CMS, JHEP 1401, 096 (2014)

$$\mathrm{BR}(H\to W\ell\nu_\ell)\equiv\mathrm{BR}(H\to\nu_4\nu_\mu)\,\mathrm{BR}(\nu_4\to W\mu)$$

general BR : simple rescaling

sensitivity over H→WW

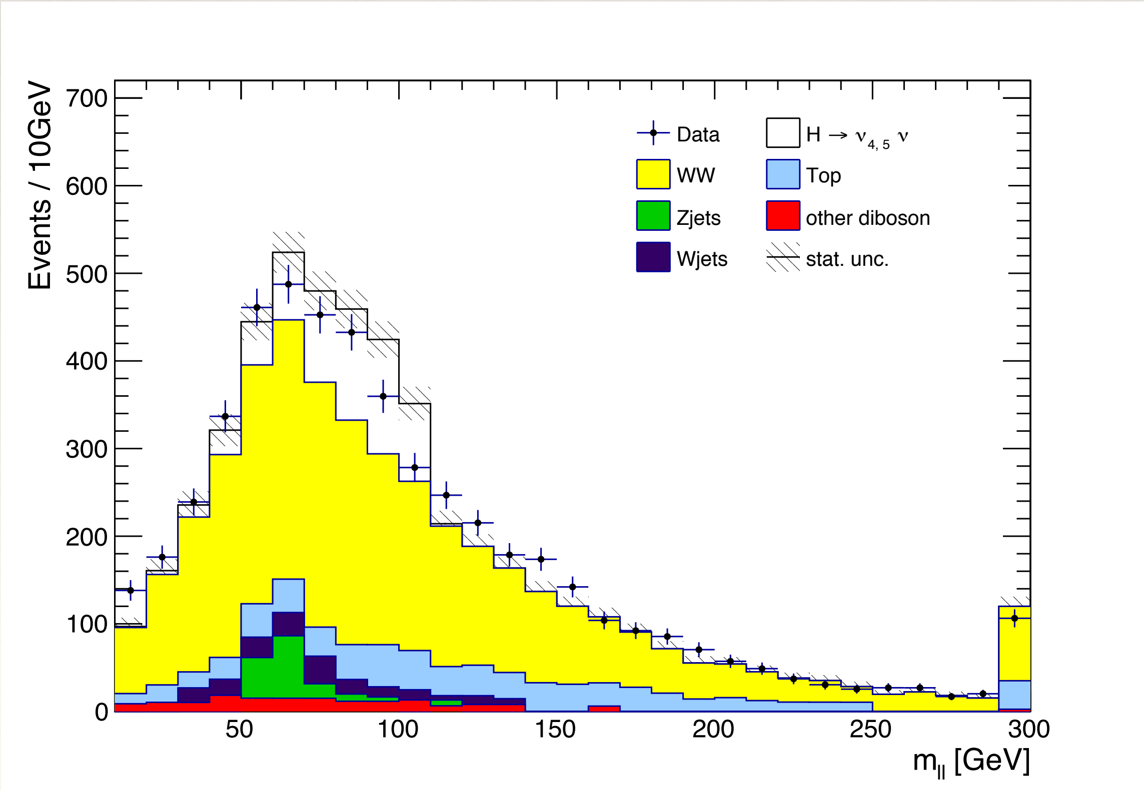


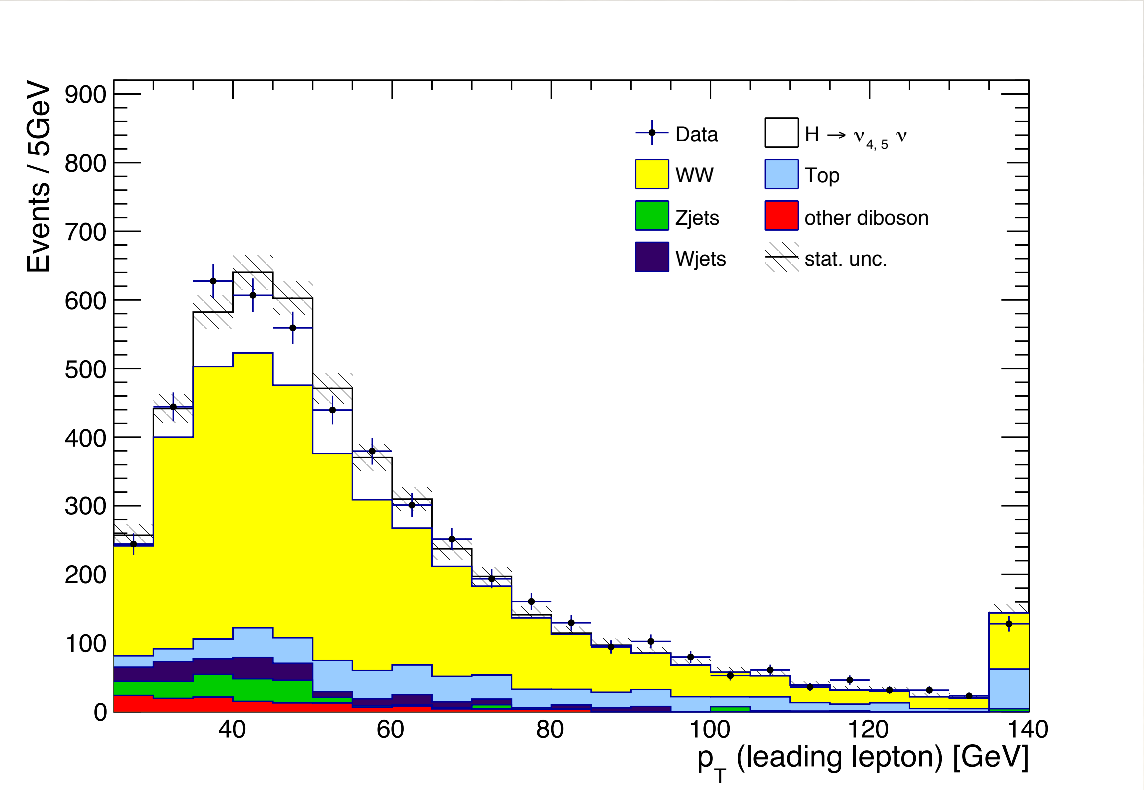
Back-up

- Check the contributions of our process $H \to W\ell\nu_\ell \to \ell\nu_\ell\ell'\nu_{\ell'}$ to the kinematic variables (following the ATLAS result)
  - p_T of leading and subleading leptons
  - p_T, azimuthal angle, invariant mass of $\ell\ell$
  - p_T, m_T of $\ell\ell' + \nu_\ell\nu_{\ell'}$ (WW)

- Reference parameter : $m_H = 155$ GeV, $m_{\nu_4} = 135$ GeV, $BR(H \to W\ell\nu_\ell) = 0.16$ ($e\mu$)
  - N_{events} ~ 90% of the central excess observed by the ATLAS

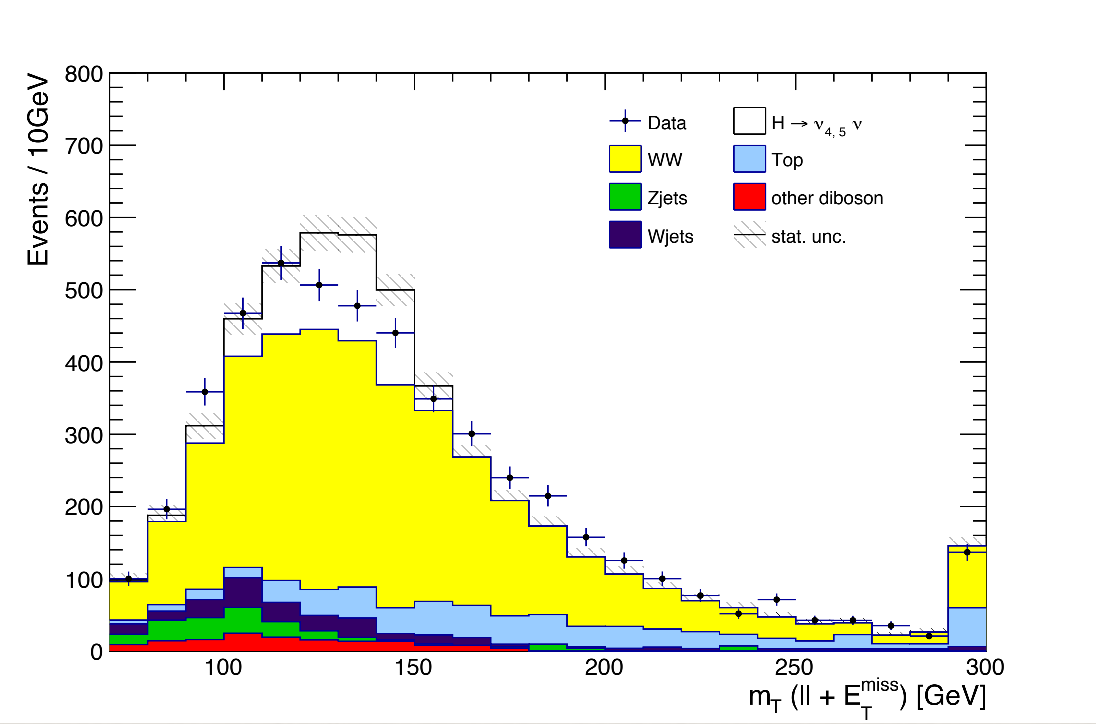
Representative plots

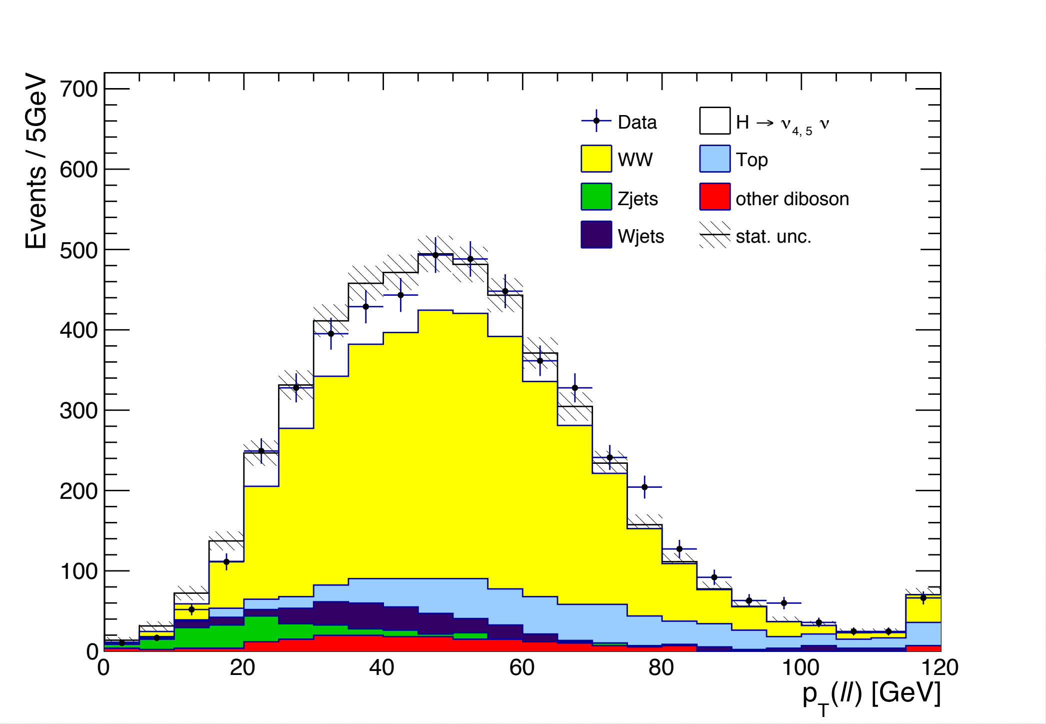




Back-up

Representative plots (crucial for the choice of our reference parameter)





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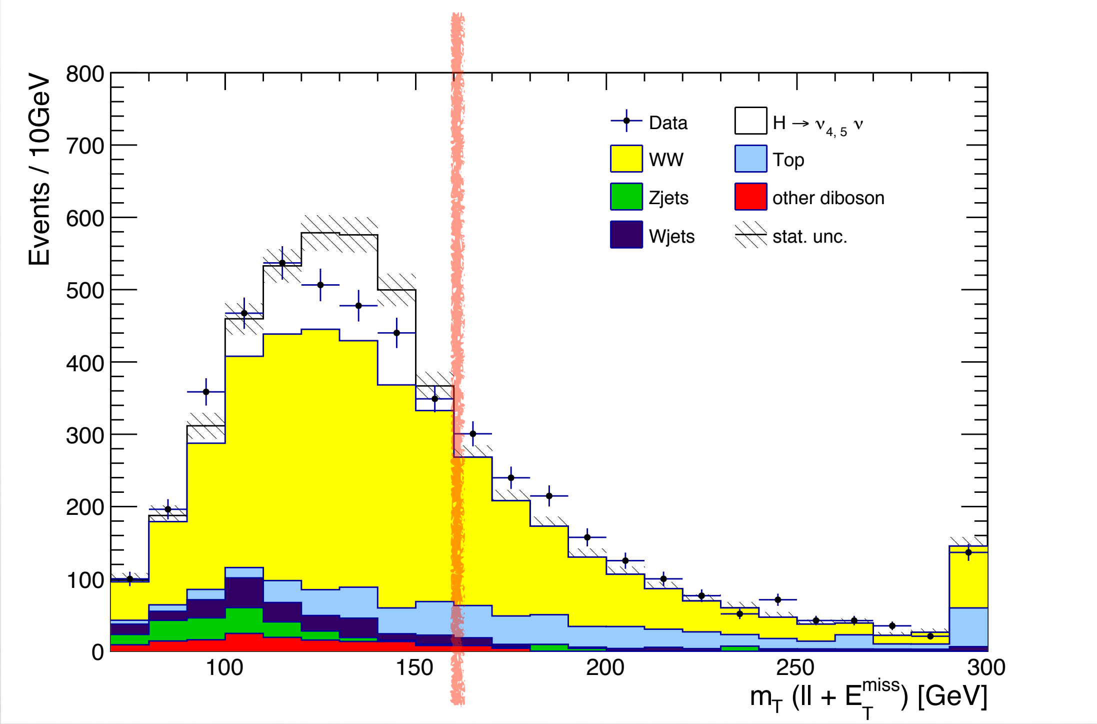

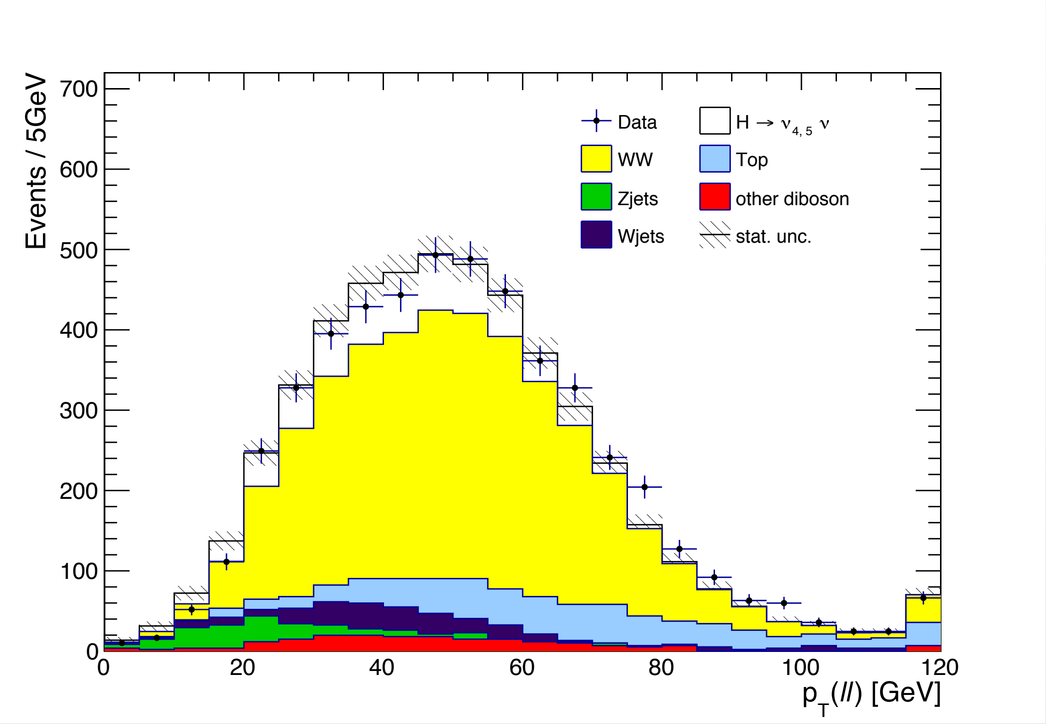

parent particle mass m_H

$\ell\ell$ come from ν_4 : m_{ν_4}

Back-up

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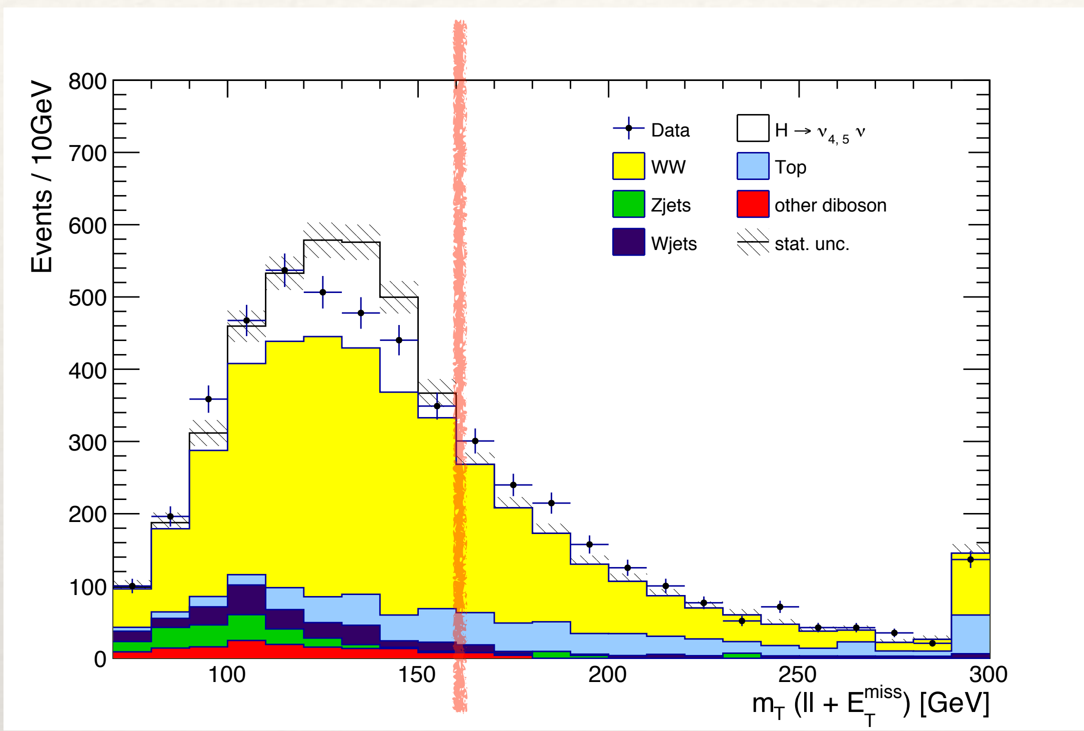

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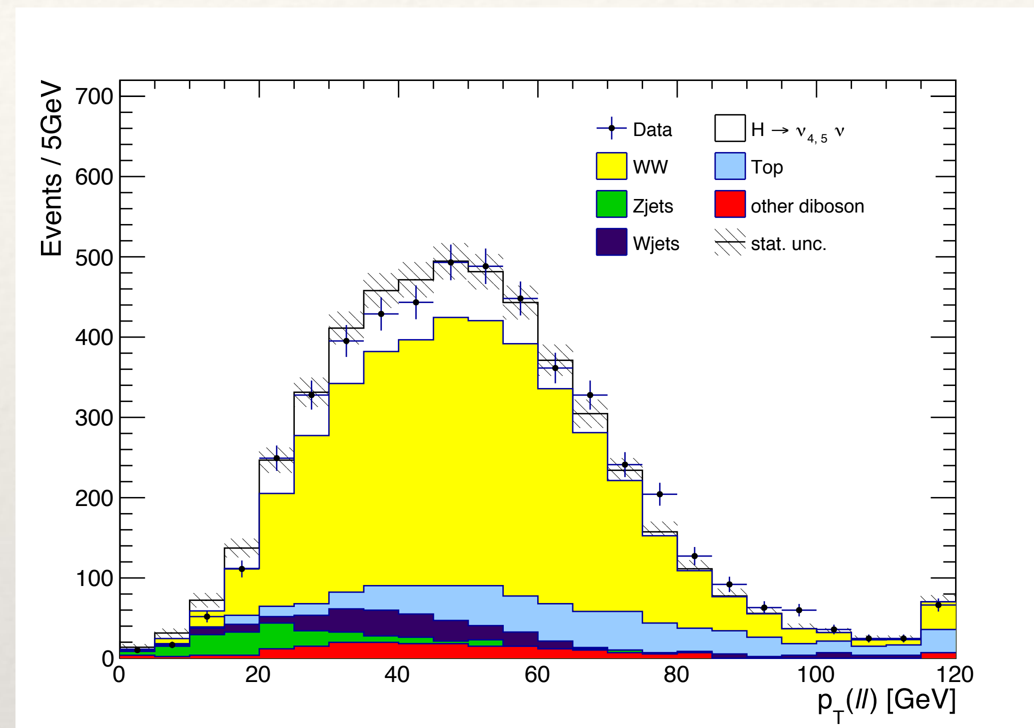


$\ell\ell$ come from ν_4 : m_{ν_4}

The rest of the results are in the paper

- The contributions by $H \to W\ell\nu_\ell \to \ell\nu_\ell\ell'\nu_{\ell'}$ agree well with the data (with proper parameter)
- Better fitting in m_T : more complex scenarios, e.g., $h_{SM} \to W\ell\nu_\ell$ with larger m_H

Back-up

Alternative contributions (small) in pp→$\ell \nu_\ell \ell' \nu_{\ell'}$

~ 5 time suppression in $\sigma^{\rm fid}$

- pp→H→$\nu_4 \nu_\tau$→W$\tau\nu_\tau$→$\ell \nu_\ell \mu \nu_\mu$ with leptonic decay of $\tau \to \ell \nu_\ell \nu_\tau$

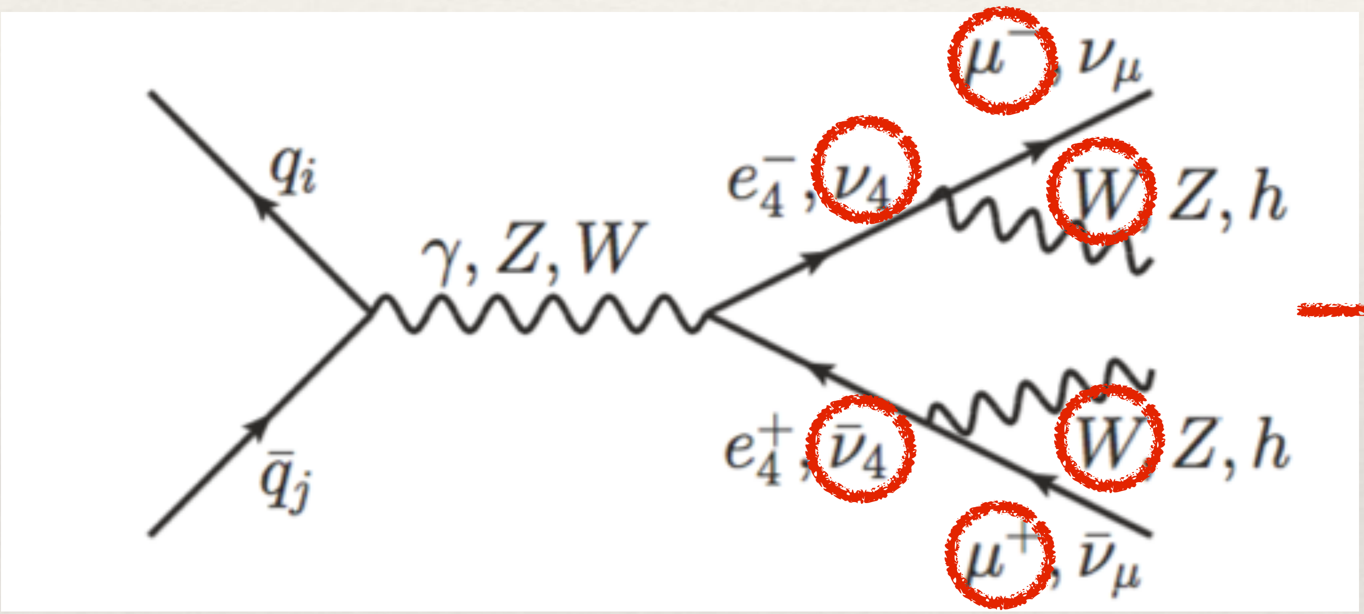
additional missing E : lower p_T of ℓ
lowers A

Our scenarios can be also connected with the neutrino mass generations

e.g., TeV seesaw models Bhupal Dev, Franceschini, Mohapatra, PRD 86, 093010 (2012)

Back-up

Practical parameter scan : allow mixing only in the neutral lepton sector



$pp \to \nu_4\nu_4 \to WW\mu\mu$

m_{ν_4} [GeV]	105	125	150	200	300
$[R_{\nu_4\nu_4}\times \mathrm{BR}^2(\nu_4 \to W\mu)]_{max}$	0.090	0.141	0.141	0.164	0.582
$[R_{e_4\nu_4}\times \mathrm{BR}(\nu_4 \to W\mu)]_{max}$	0.109	0.203	0.267	0.355	1

Back-up

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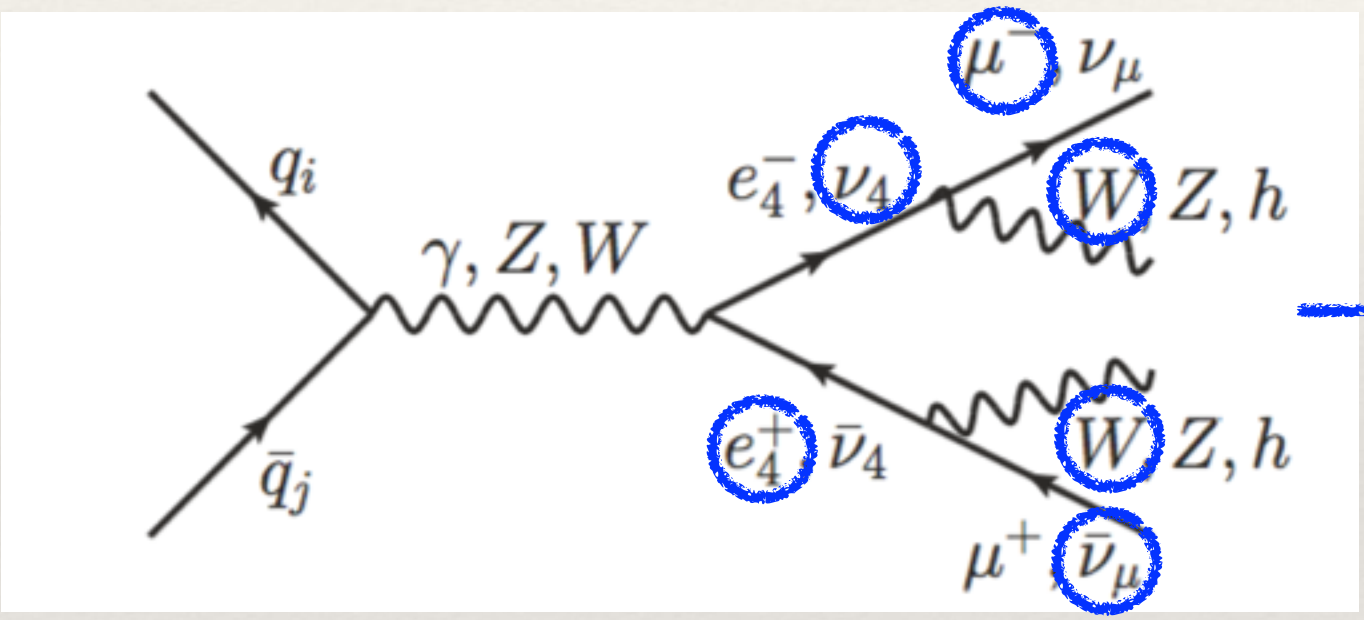

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Back-up

Singlet production of a neutral VLL

$$pp \to W^* \to \nu_4\mu \to W\mu\mu\ ,\ Z\nu_\mu\mu\ ,\ h\nu_\mu\mu$$

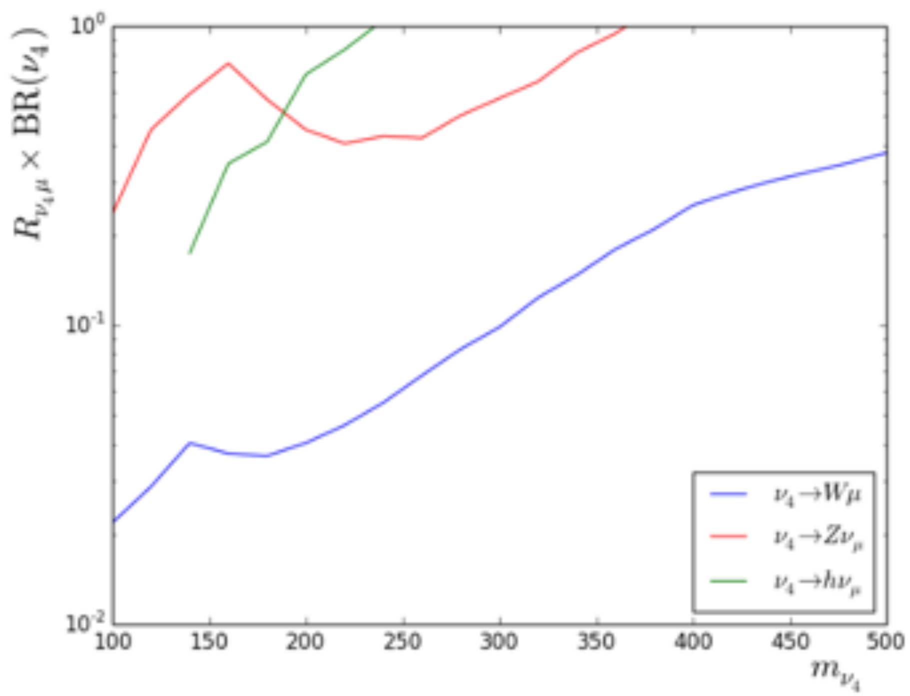

Figure 2. Upper bounds on $R_{\nu_4\mu} \times \mathrm{BR}(\nu_4 \to W\mu, Z\nu_\mu, h\nu_\mu)$ as functions of m_{ν_4}.

$$R_{\nu_4\mu} \equiv \left[(V_L^\dagger)_{42}(U_L)_{22} + (V_L^\dagger)_{44}(U_L)_{42}\right]^2 + \left[(V_R^\dagger)_{44}(U_R)_{42}\right]^2$$

combination of branching ratios the constraint on $R_{\nu_4\mu}$ is at most of $\mathcal{O}(10^{-2})$. This limit is much weaker than those obtained from precision EW data; in fact, for the surviving points in figure 1 the maximum value of $R_{\nu_4\mu}$ is of $\mathcal{O}(10^{-3})$.

$$pp \to Z \to e_4^{\pm} e_4^{\mp} \to W^{\pm} W^{\mp} \nu_\mu \bar{\nu}_\mu \to 2\ell 4\nu$$

$$pp \to Z \to \nu_4 \nu_\mu \to W \mu \nu_\mu \to \ell \mu 2\nu$$

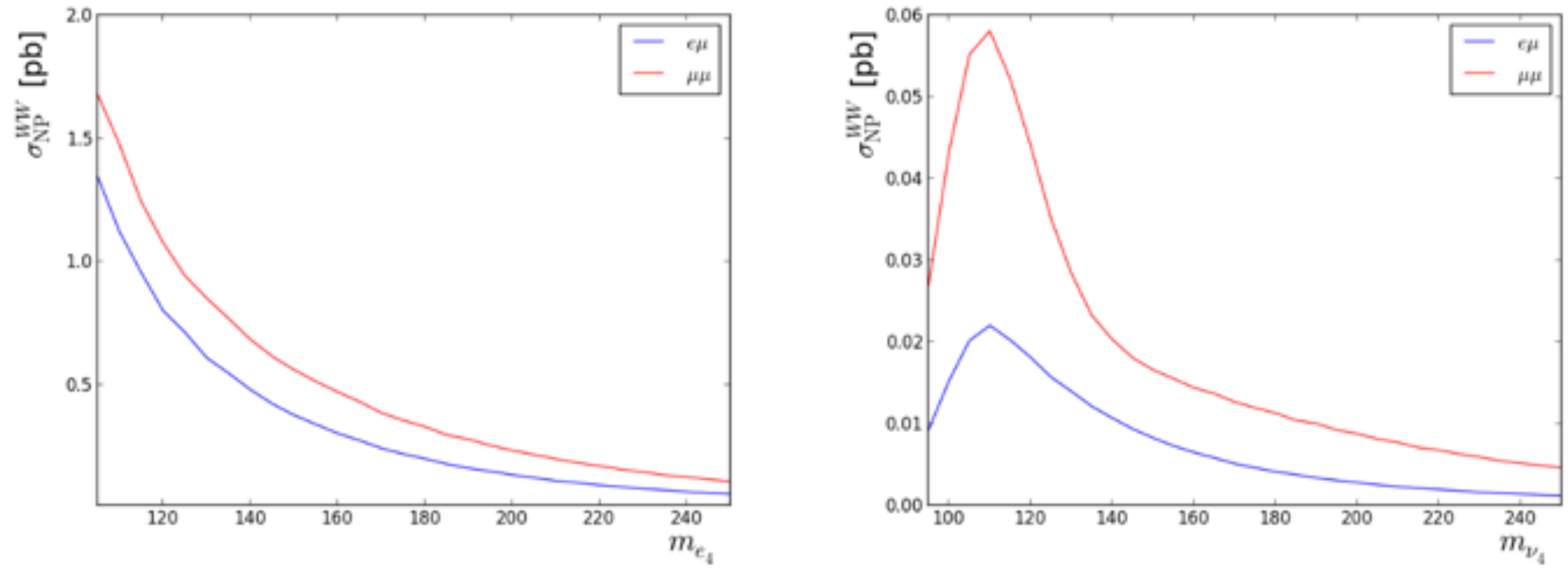

Figure 13. The effective cross section $\sigma_{\rm NP}^{WW}$ [pb] for Drell-Yan processes. In the left panel we consider the channel $pp \to (\gamma, Z) \to e_4^{\pm} e_4^{\mp} \to W^{\pm} W^{\mp} \nu_\mu \bar{\nu}_\mu \to 2\ell 4\nu$ assuming SM-like strength of the $Z - e_4 - e_4$ vertex, $\mathrm{BR}(e_4 \to W \nu_\mu) = 1$ and $m_{e_4} = 105 - 250$ GeV. In the right panel we show $pp \to Z \to \nu_4 \nu_\mu \to W \mu \nu_\mu \to \ell \mu 2\nu$ for $R_{\nu_4 \nu_\mu} \cdot \mathrm{BR}(\nu_4 \to W \mu) = 10^{-3}$ and $m_{\nu_4} = 95 - 250$ GeV.

$$R_{e_4 e_4} \equiv \frac{(g_L^{Ze_4e_4})^2 + (g_R^{Ze_4e_4})^2}{2(g/\cos\theta_W)^2(1/2 - \sin^2\theta_W)^2} \, ,$$
$$R_{\nu_4 \nu_\mu} \equiv \frac{(g_L^{Z\nu_4\nu_\mu})^2}{g^2/4\cos^2\theta_W} \, .$$

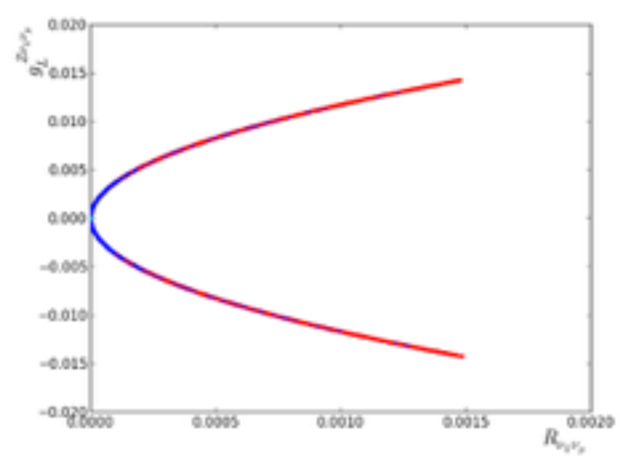

Figure 12. Allowed values of $R_{\nu_4\nu_\mu}$ and $g_L^{Z\nu_4\nu_\mu}$ for $m_{\nu_4} = 110$ GeV. We see that $R_{\nu_4\nu_\mu} \lesssim 1.5 \times 10^{-3}$ and $|g_L^{Z\nu_4\nu_\mu}| \lesssim 0.02$. Similar bounds are found for different ν_4 masses.