PHENO 2015, May 4, 2015

Contributions of flavor violating couplings of a Higgs boson to $pp \to WW$

Seodong Shin

Indiana University

R. Dermisek, E. Lunghi, S. Shin, arXiv:1503.08829

Contents

- BSM in gauge boson production
- Recent measurements on σ(pp→WW) : dileptonic
- Contribution of our simplified model to this : a BSM Higgs H→ $W\ell\nu_\ell$ to pp→$\ell\nu_\ell\ell'\nu_{\ell'}$
- Allowed parameter space & constraints from (SM-like) heavy H searches
- Kinematic distributions
- Conclusions

BSM in gauge boson production

SM weak gauge boson production at the LHC

- Focus on the leptonic final states : clean signal
- LHC sensitivity strong enough to measure pp→VV and pp→h→VV in the SM
- New Physics search can be promising : multilepton signal from V decays

  e.g., multilepton(≥3) + $\not{E}_T$ Dermisek, Hall, Lunghi, Shin, JHEP 1412, 013 (2014)
- NP signal can be hidden already at 8 TeV (because of non-optimal cuts)
  - Squeezed spectrum of the NP particles (e.g., degenerate SUSY particles) : too weak
  - NP process accompanied by on-shell gauge boson production : hard to discriminate

    Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 (2014)

Exotic SM Higgs decays hidden in the same final states of h→VV search

h→ZZ→4ℓ (golden channel), h→WW→$\ell\nu_\ell\ell'\nu_{\ell'}$

Dermisek, Raval, Shin, PRD 90, 034024 (2014)

Falkowski, Vega-Morales, JHEP 1412, 037 (2014)

In this talk; NP contribution hidden in general pp→WW

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Measurements of σ(pp→WW)

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

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

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

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

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

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

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

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

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

reweight with resummed p_T^{WW} distribution

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

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

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

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

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

Measurements of σ(pp→WW)

Extraction of the cross section σ(pp→WW)

- Cross section $\sigma(pp \to WW) = (N_{data} - N_{bkg}) / \mathcal{L} \cdot A \cdot \epsilon \cdot BR$ (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 ⇔ theoretical expectations (MC : NLO + shower)

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

fixed by the observation

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)

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

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

  - 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 $\mathcal{E}_{j\text{-veto}}$ but NNL contributions on $\sigma \cdot A$ are cancelled (NLO is enough)

    Monni, Zanderighi, 1410.4745

Measurements of σ(pp→WW)

Our brief understanding of pp→WW

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

- 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
- The most recent CMS claim still includes large uncertainties ~ 5pb at 1σ

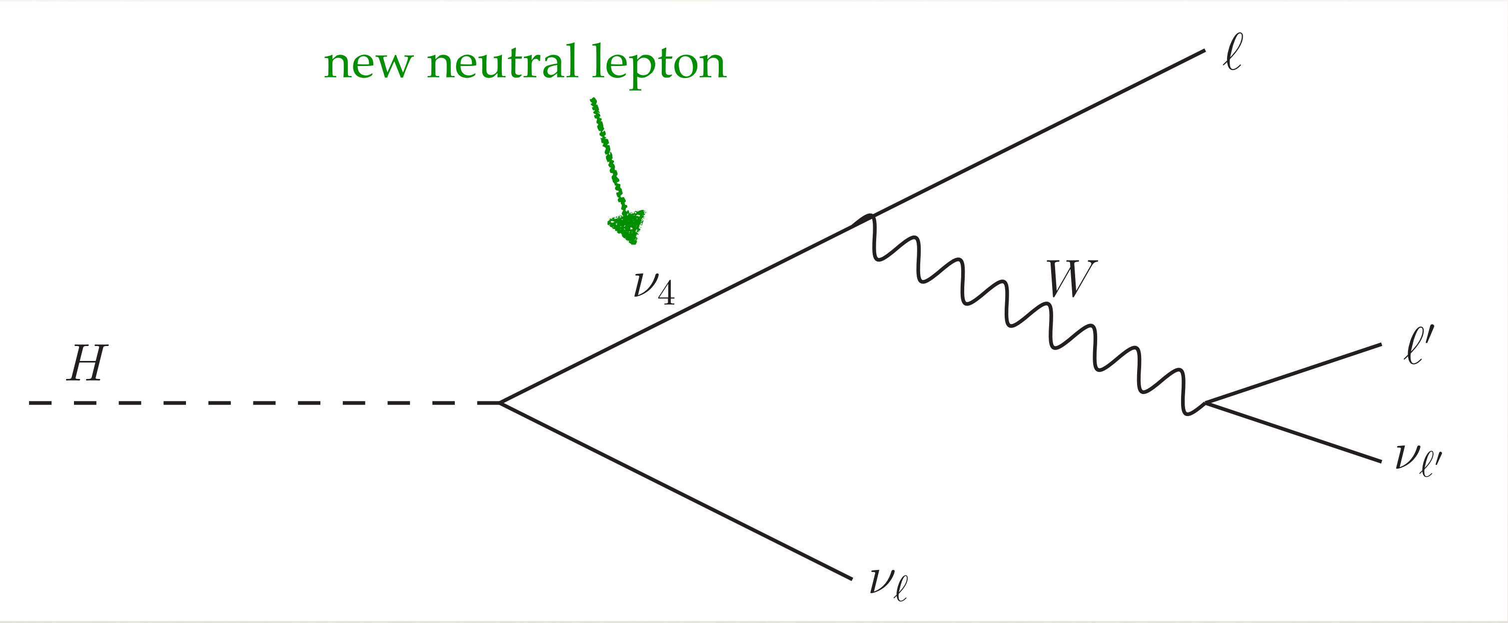
We can take the current result as being compatible with O(10)pb level NP contribution either as an explanation of the excess or a 2σ upper limit

Heavy Higgs decay to $W\ell\nu_\ell$ (through new lepton)

Simplified model

H-ν_4- ν_μ

W-ν_4 -ν_μ



- Assume : H does not couple to WW directly & ν_4 only couples to ℓ (avoid LFV)
- Large contribution to pp→$\ell\nu_\ell\ell'\nu_{\ell'}$
  - i) O(10)pb cross section of pp→H
  - ii) Only one W decaying leptonically : benefit in BR(W→$\ell\nu_\ell$) suppression

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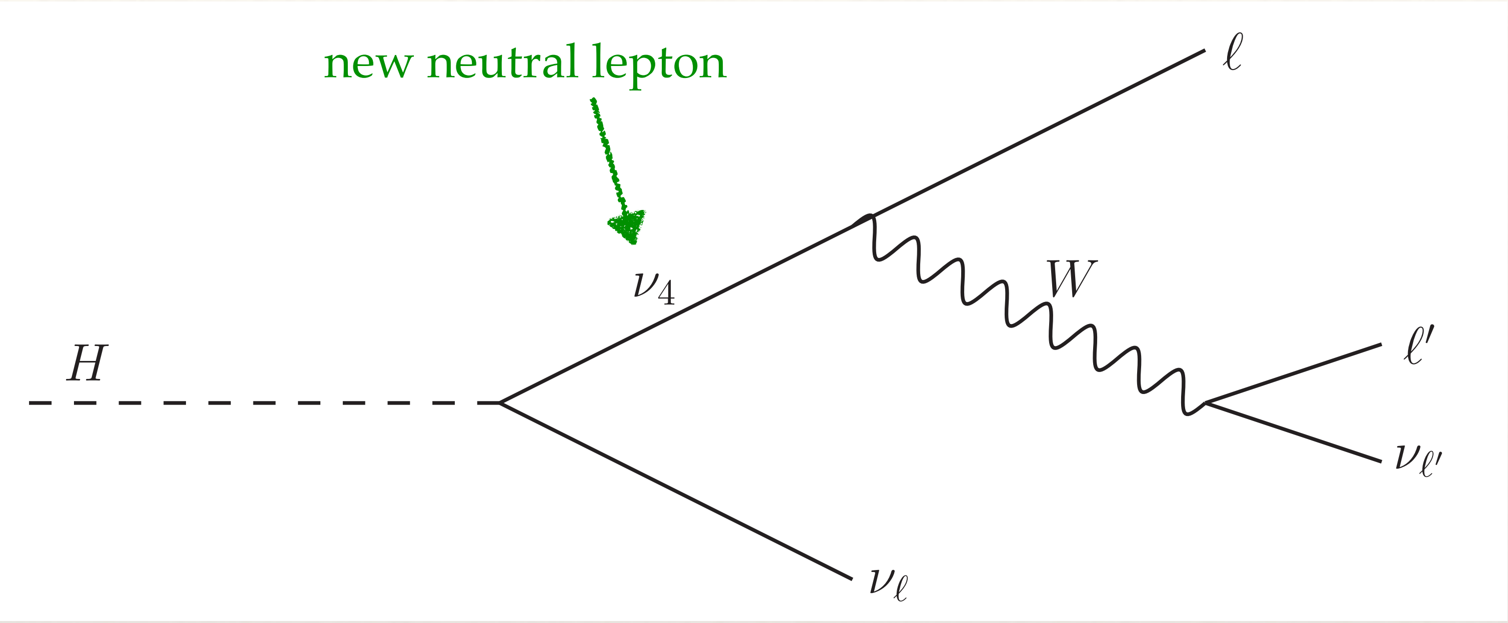

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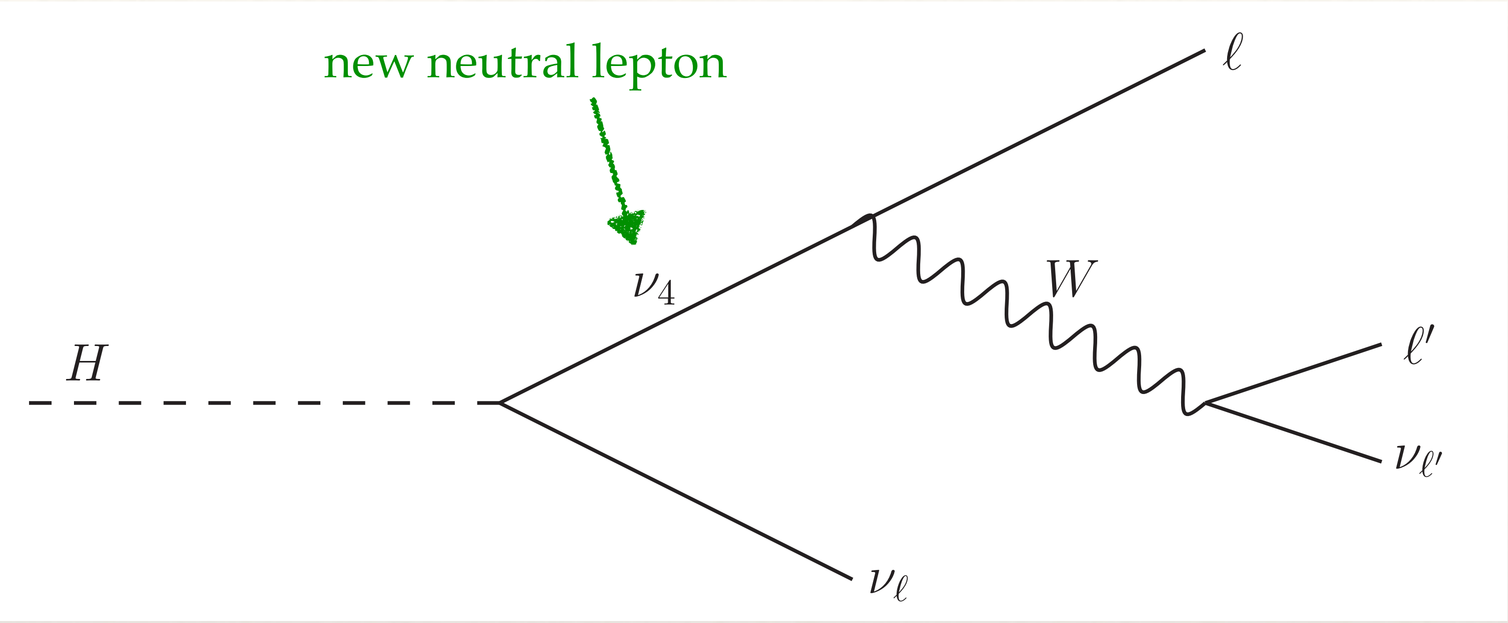
pp→WW→$\ell\nu_\ell\ell'\nu_{\ell'}$ required (or bounded) in the exp. : O(0.1)pb

Our pp→W$\ell\nu_\ell$→$\ell\nu_\ell\ell'\nu_{\ell'}$: up to O(1)pb

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

Heavy Higgs decay to W$\ell\nu_\ell$ (through new lepton)



- 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 $e\mu$ channel
  - In order to contribute to ee mode as well : additional neutral lepton
- This scenario can arises, e.g., 2HDM with vectorlike leptons

Dermisek, Lunghi, Shin, work in progress

- Simplified model ⇒ 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 σ^{fid}
  - Our analysis done in terms of σ^{fid} without detailed detector simulation

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

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

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

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

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  - Define an alternative quantity corresponding to $\Delta\sigma(pp\to WW)$: O(10)pb
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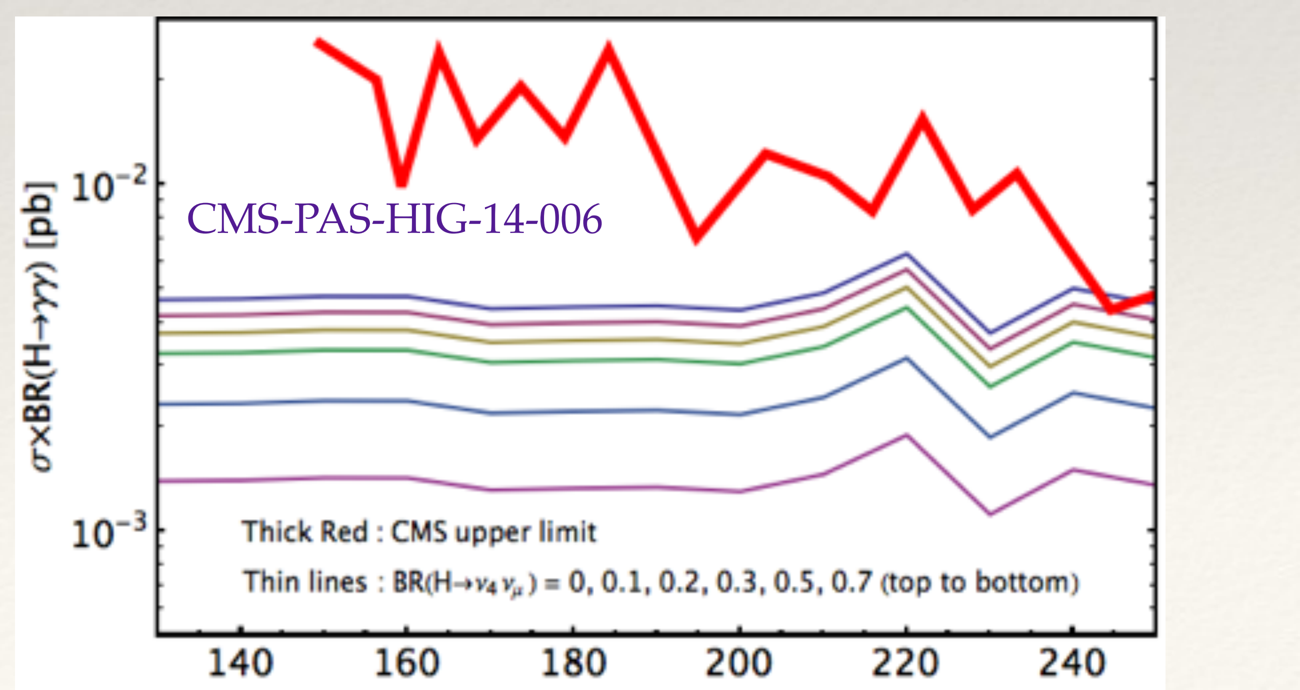
- Even without direct coupling H - WW, constraints from $H\to WW$, $\gamma\gamma$ should be considered (due to the Yukawa couplings of H in our simplified model)

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

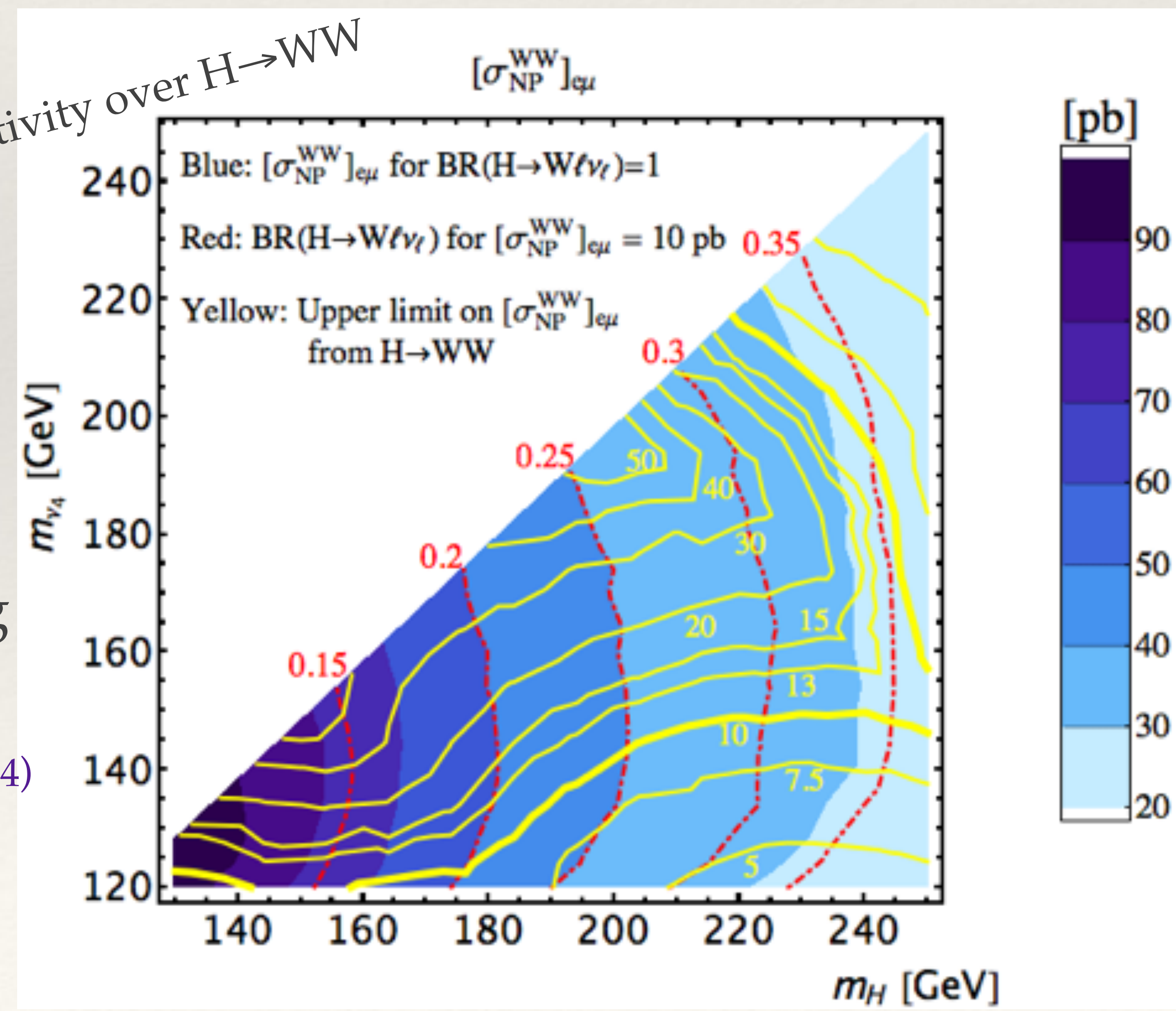
The bound by H→WW on H→W$\ell\nu_\ell$→$\ell\nu_\ell\ell'\nu_{\ell'}$ weakened : $A^{\mathrm{WW}} / A^{\mathrm{H\to WW}}$

- Show the allowed contributions of H→W$\ell\nu_\ell$→$\ell\nu_\ell\ell'\nu_{\ell'}$ (possibly excess in the future) in terms of $\sigma_{\mathrm{NP}}^{WW}$ 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

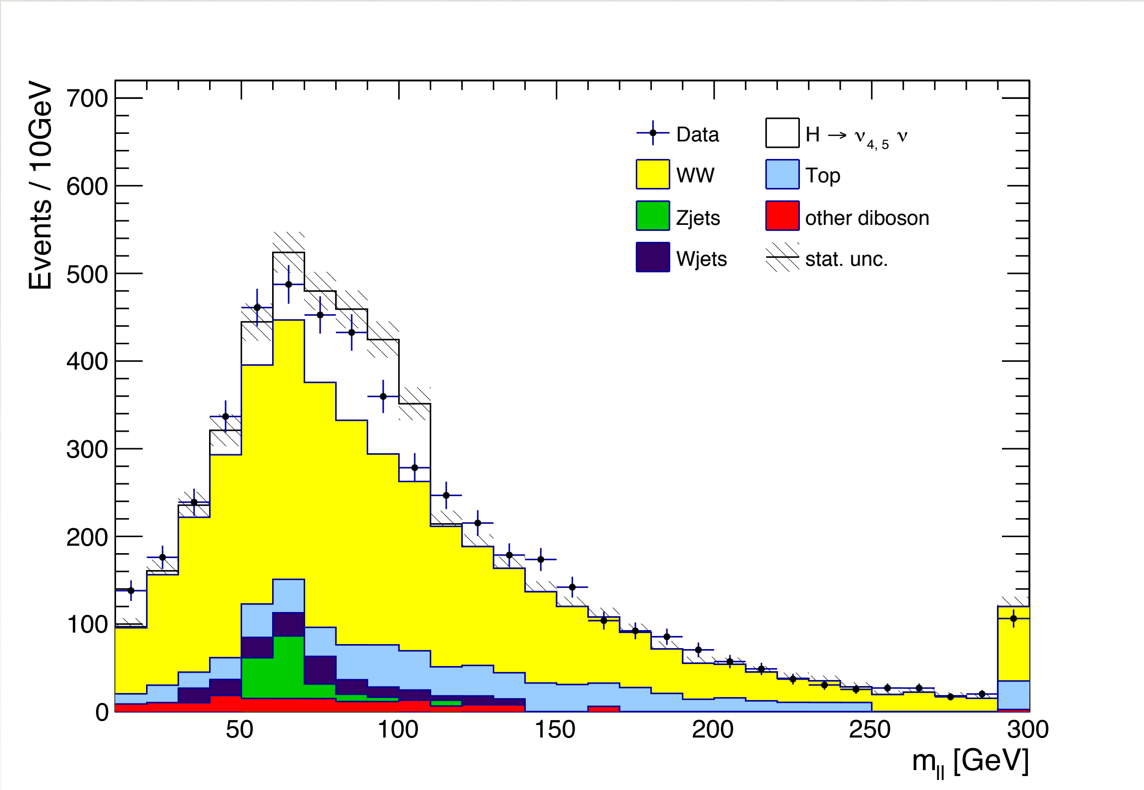


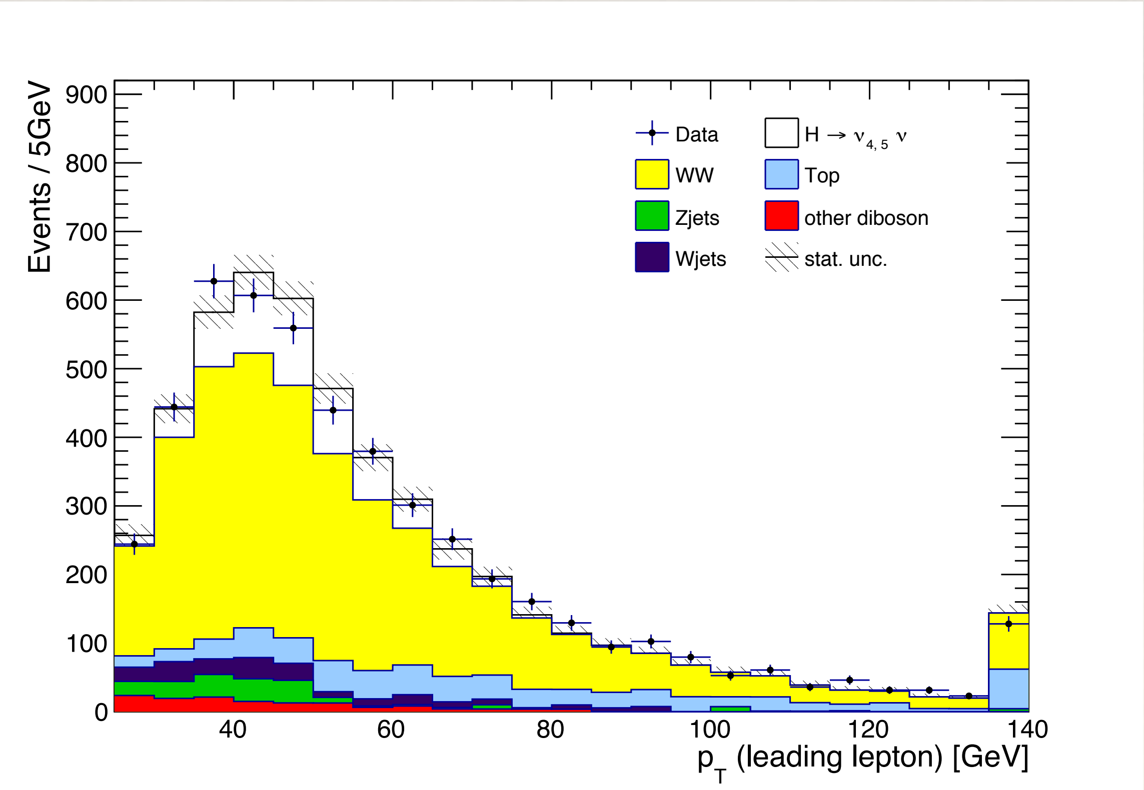
Kinematic distributions

- 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

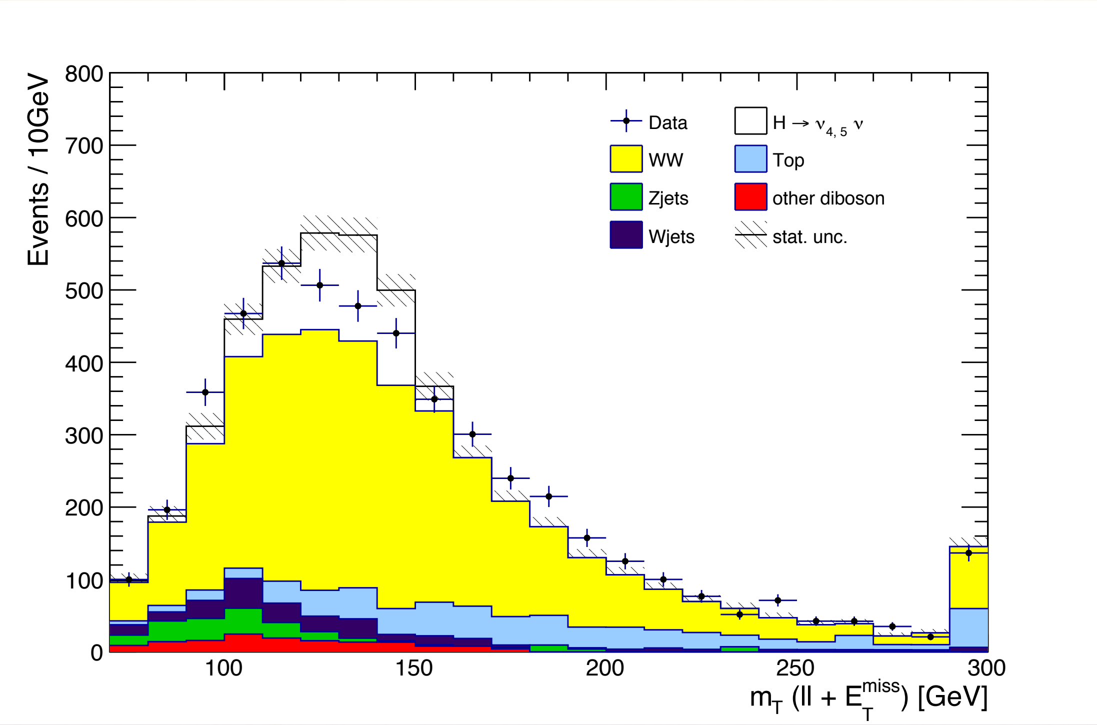
Representative plots

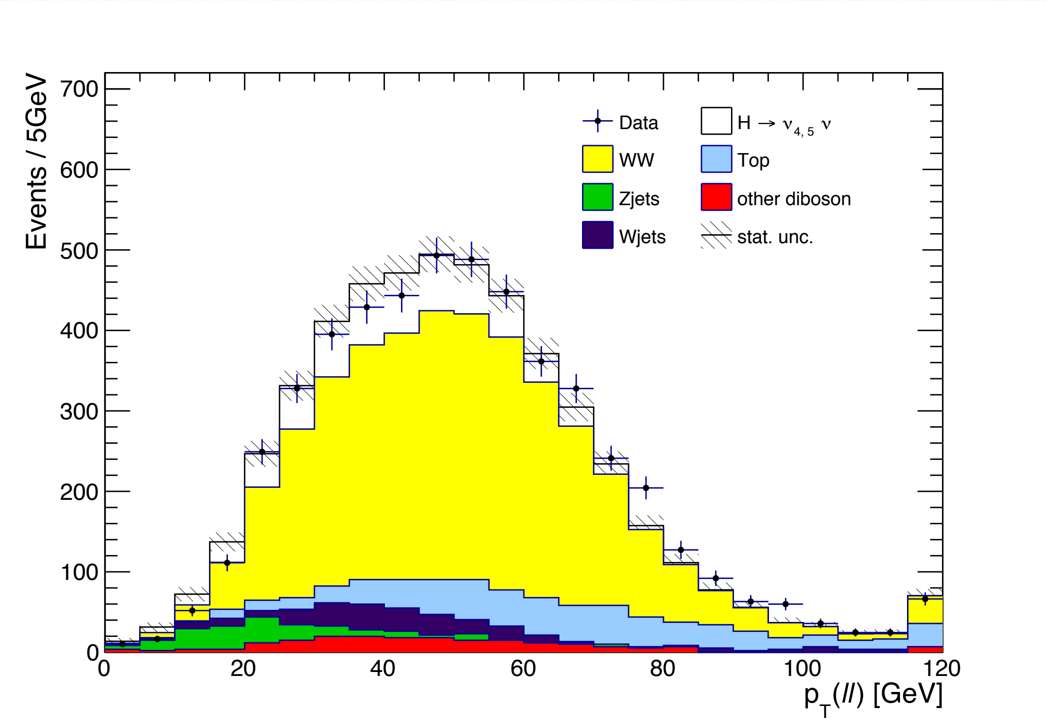




Kinematic distributions

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





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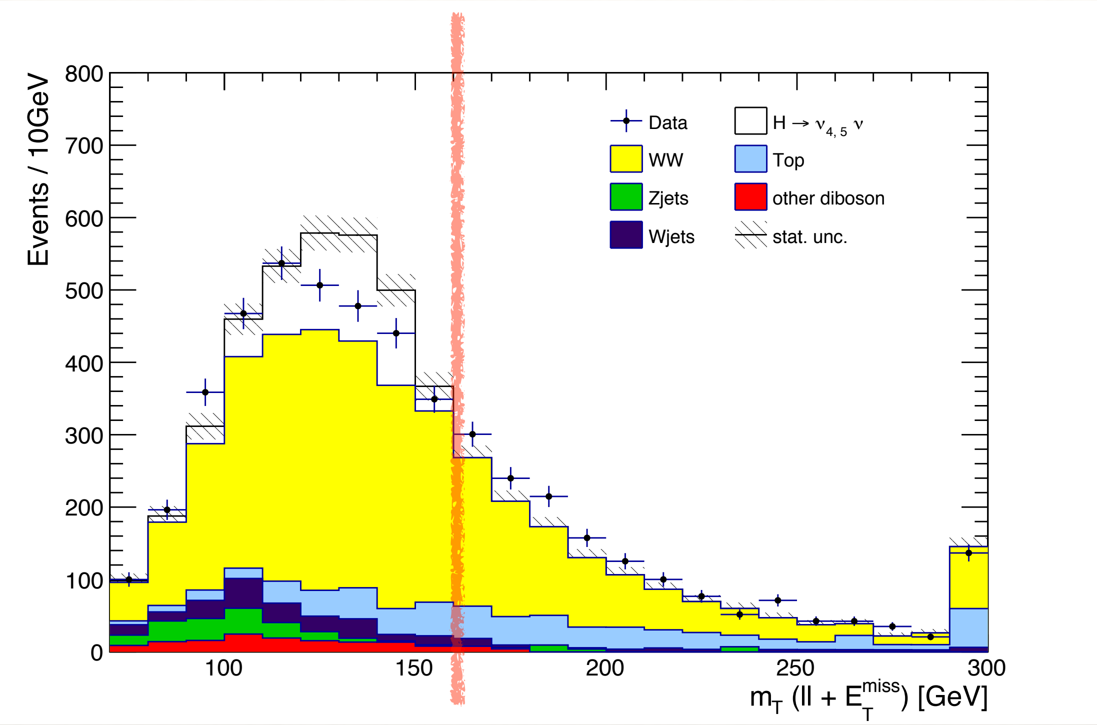
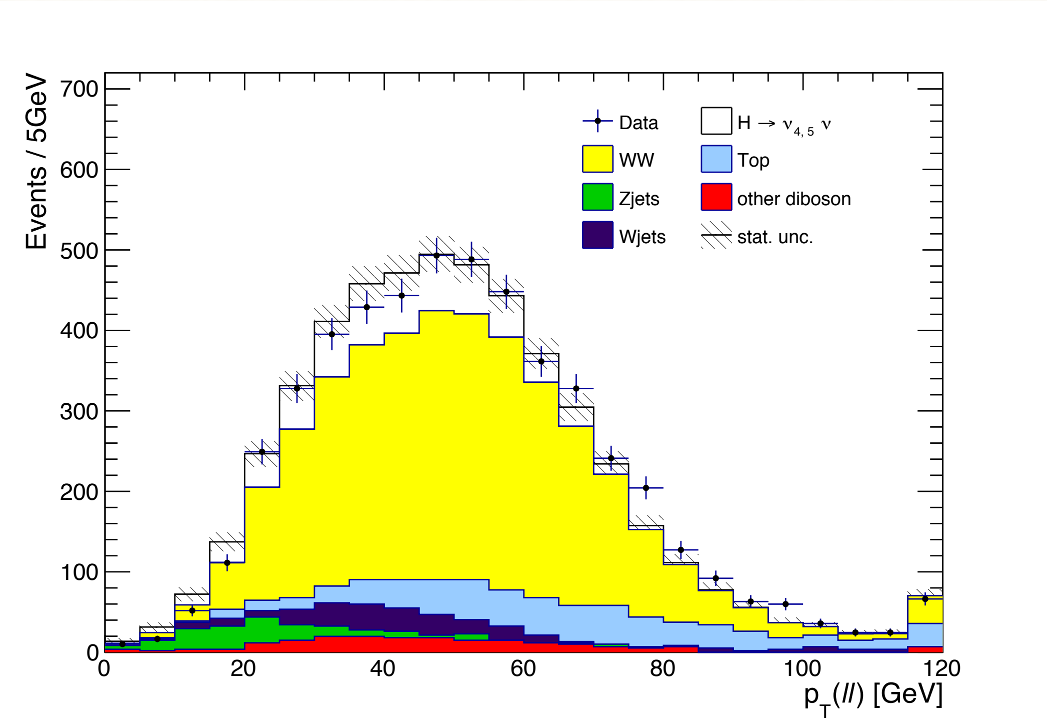


parent particle mass m_H



$\ell\ell$ come from ν_4 : m_{ν_4}

Kinematic distributions

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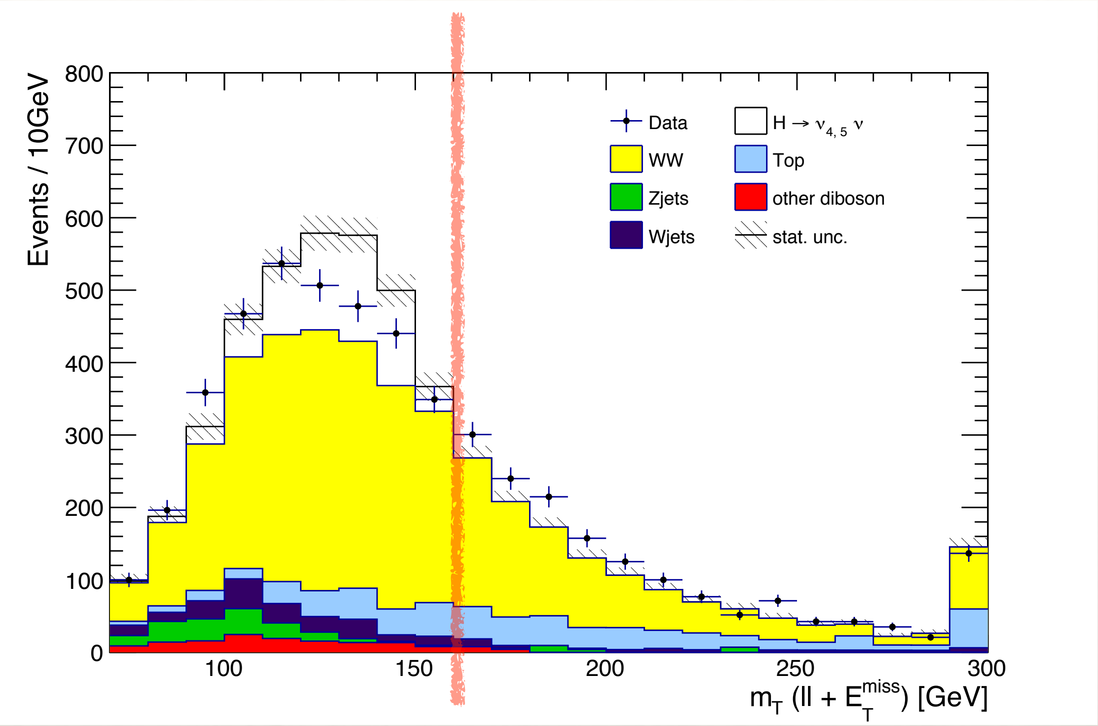

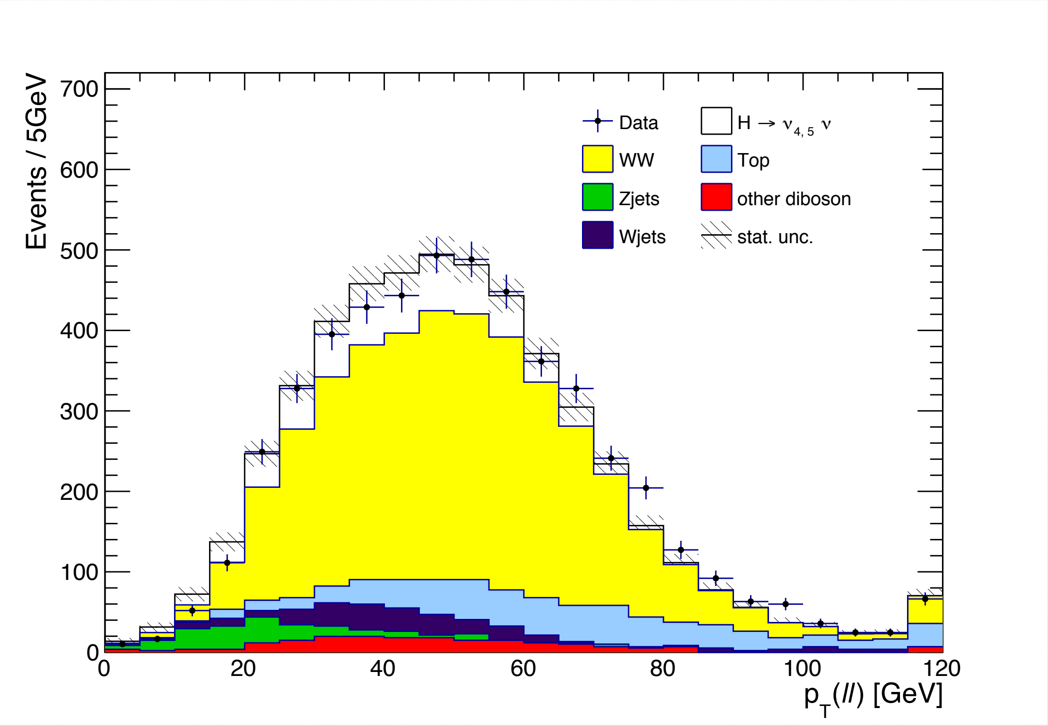

parent particle mass m_H

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The rest of the results are in the paper

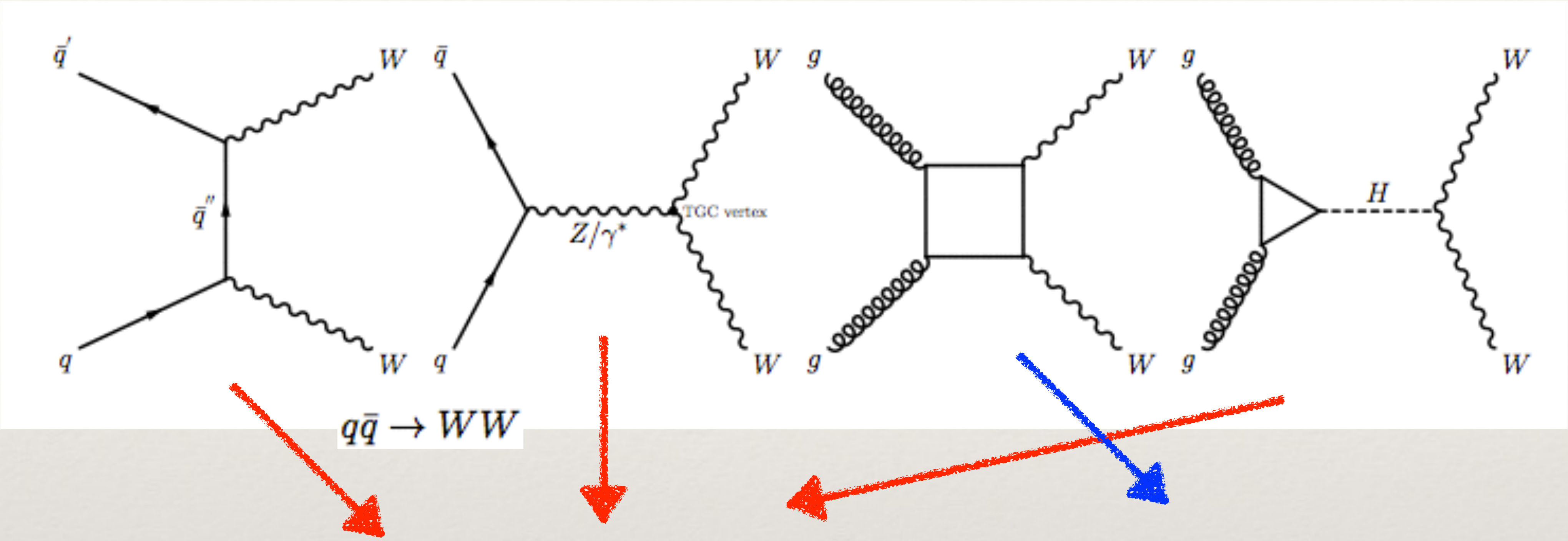
- The contributions by $H \to W\ell\nu_\ell \to \ell\nu_\ell\ell'\nu_{\ell'}$ agree well with the data (with proper parameter)
- Better fitting in m_T : more complex scenarios, e.g., $h_{SM} \to W\ell\nu_\ell$ with larger m_H

Conclusions

- We investigated the contributions to the standard pp→W^+W^-→$\ell\nu_\ell\ell'\nu_{\ell'}$ in models with a new heavy Higgs, H, and a neutral lepton, ν_4 , with the flavor violating Yukawa and gauge couplings : pp→H→$\nu_4\,\nu_\mu$→$W\mu\nu_\mu$→$\ell\nu_\ell\mu\nu_\mu$
- This scenario is able to generate large contributions because of a Higgs production cross section O(10)pb coupled with having only one W (avoid BR suppression)
- In a wide range of parameters the present sensitivity of our process to pp→WW than the direct search of heavy Higgs to WW or $\gamma\gamma$
- We checked several kinematic variables and found that all the observed distributions by the ATLAS can be easily accommodated in our scenario
- Full NNLO simulations will clarify whether there is or not an excess. Accordingly, this scenario can either provide a large enough signal or be severely constrained.
- In specific models additional constraints can be considered ($\supset$ EW precision) : 2HDM + VLL

  Dermisek, Lunghi, Shin, work in progress
- Suggesting decent methods to probe the BSM signal hidden in the SM gauge boson production is required : optimal cuts or kinematic variables (generally applied)

Back-up



POWHEG : NLO + Pythia : shower GG2WW

ATLAS

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

Back-up

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

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

	$\sigma^{\rm fid}_{\rm exp}$ [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 $\sigma^{\rm fid}_{\rm NP}$ 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:

$$\sigma^{\rm fid}_{\mathcal{H}} = A^{\mathcal{H}}_{\rm NP}\, \sigma^{\rm NP} < \beta^{\mathcal{H}}_{95}\,, \tag{3.1}$$

where $\sigma^{\rm NP}$ is the same total cross section (including branching ratios) that appears in eq. (2.3) and $A^{\mathcal{H}}_{\rm NP}$ 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 $\beta^{\mathcal{H}}_{95}$ 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

$$\sigma^{\rm fid}_{\rm NP} < A_{\rm NP}\, \min_{\mathcal{H}} \left[\frac{\beta^{\mathcal{H}}_{95}}{A^{\mathcal{H}}_{\rm NP}}\right]\,. \tag{3.2}$$

$\hat{m}_H$ [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 $\beta^{\mathcal{H}}_{95}$ 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

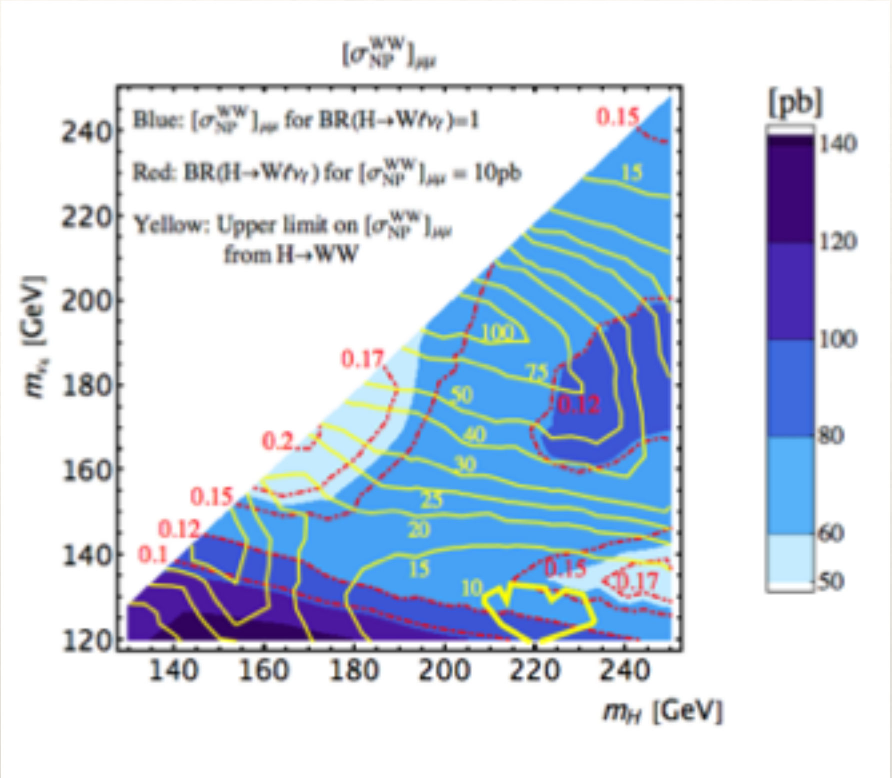
$A^{\mathcal{H}}_{\rm NP}$ for both $e\mu$ and $\mu\mu$ final states $[0.01, 4]\%$

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

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

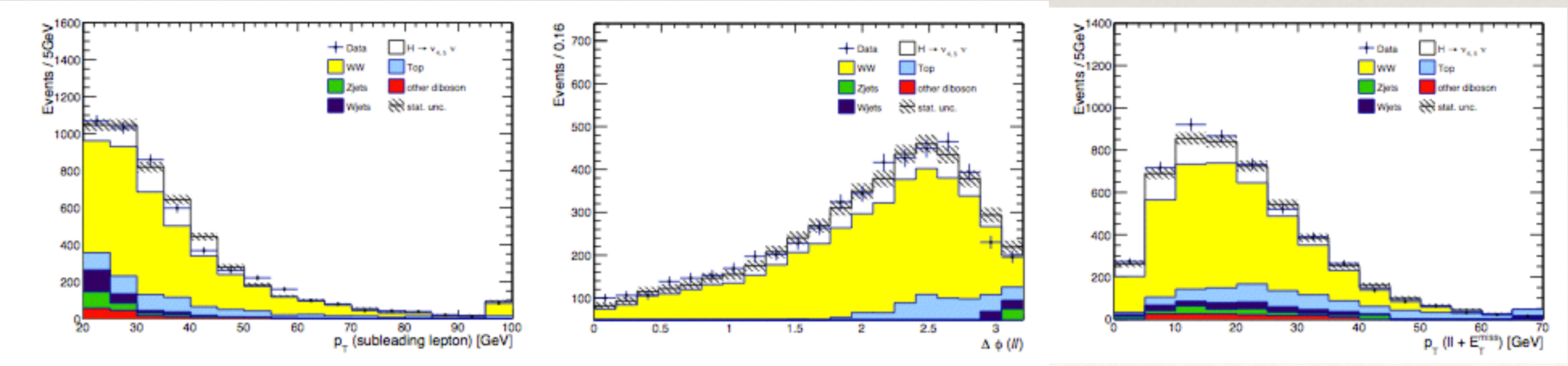
$A_{\rm NP}/A^{\mathcal{H}}_{\rm NP}$ suppressed

Back-up



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

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



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 τ→$\ell\nu_\ell\nu_\tau$

additional missing E : lower p_T of ℓ

lowers A

- DY production pp→W→$\nu_4\,\mu$→W$\mu\nu_\mu$→$\ell\nu_\ell\mu\nu_\mu$ (with minimal FV gauge coupling)

Too small cross section

- Other model dependent choices

Dermisek, Lunghi, Shin, work in progress

Our scenarios can be also connected with the neutrino mass generations

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