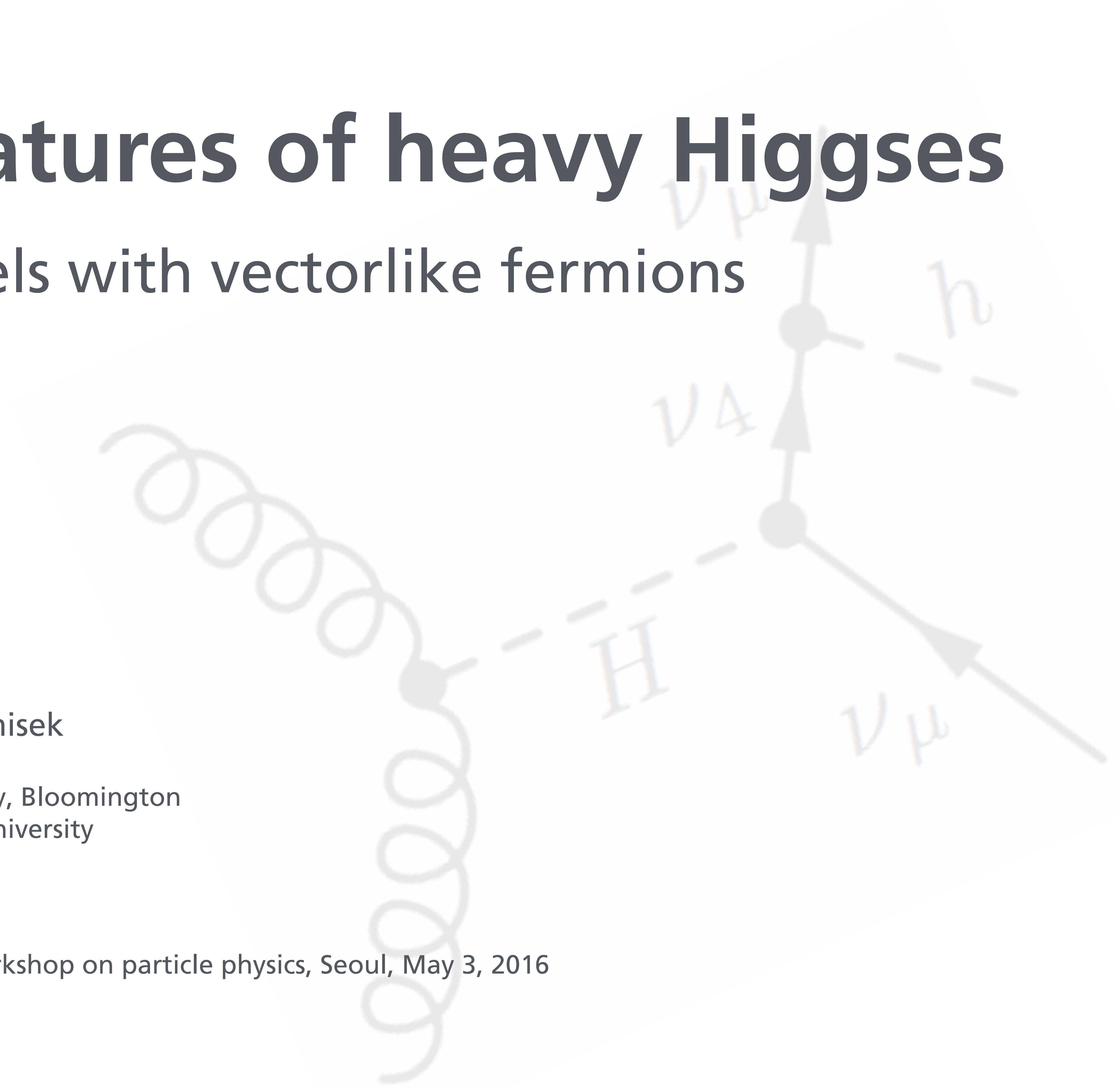
Signatures of heavy Higgses

in models with vectorlike fermions



Radovan Dermisek

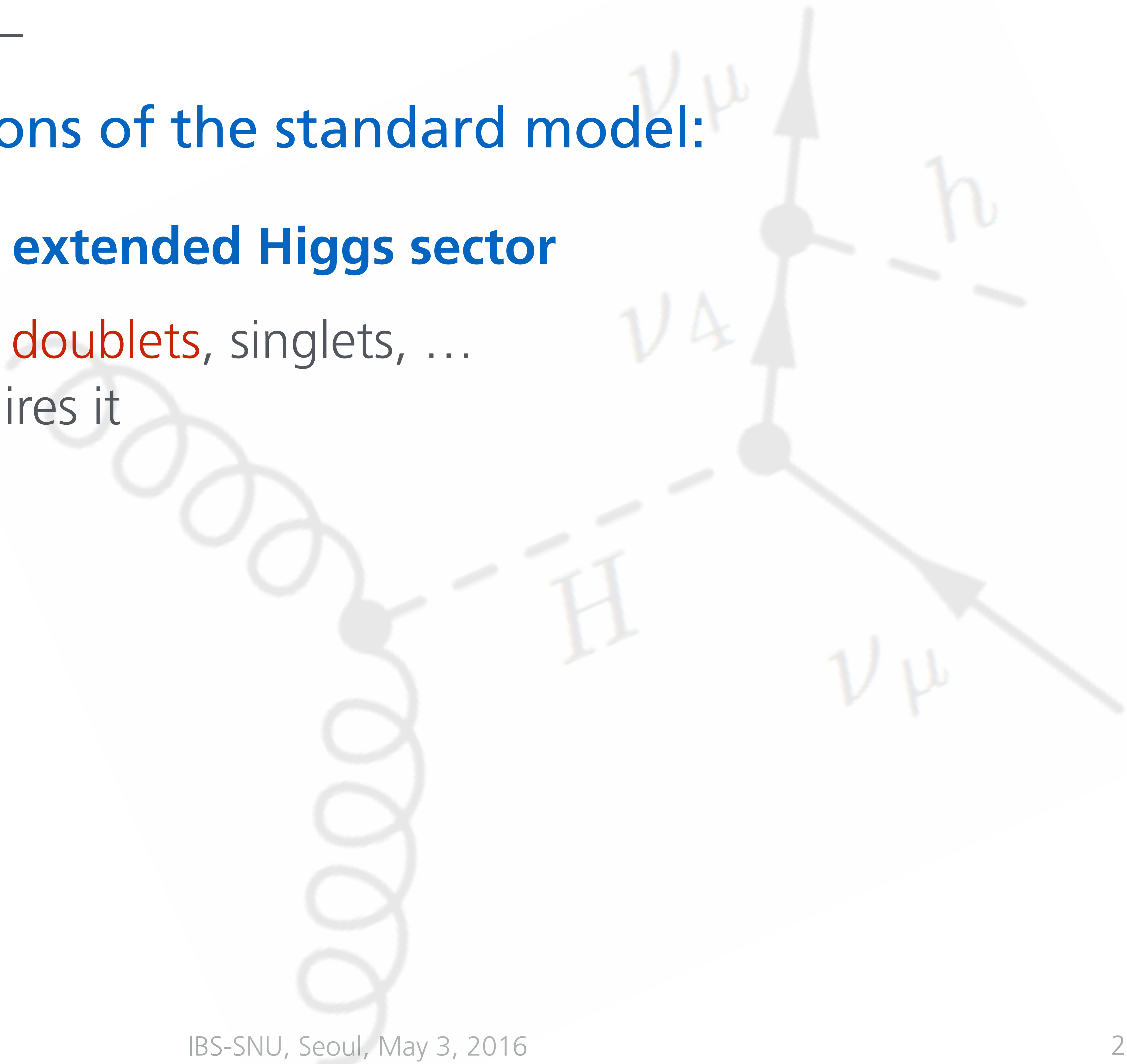
Indiana University, Bloomington
Seoul National University

IBS-SNU joint workshop on particle physics, Seoul, May 3, 2016

Motivation

Simple extensions of the standard model:

- **Models with extended Higgs sector**
  - two Higgs doublets, singlets, …
  - SUSY requires it



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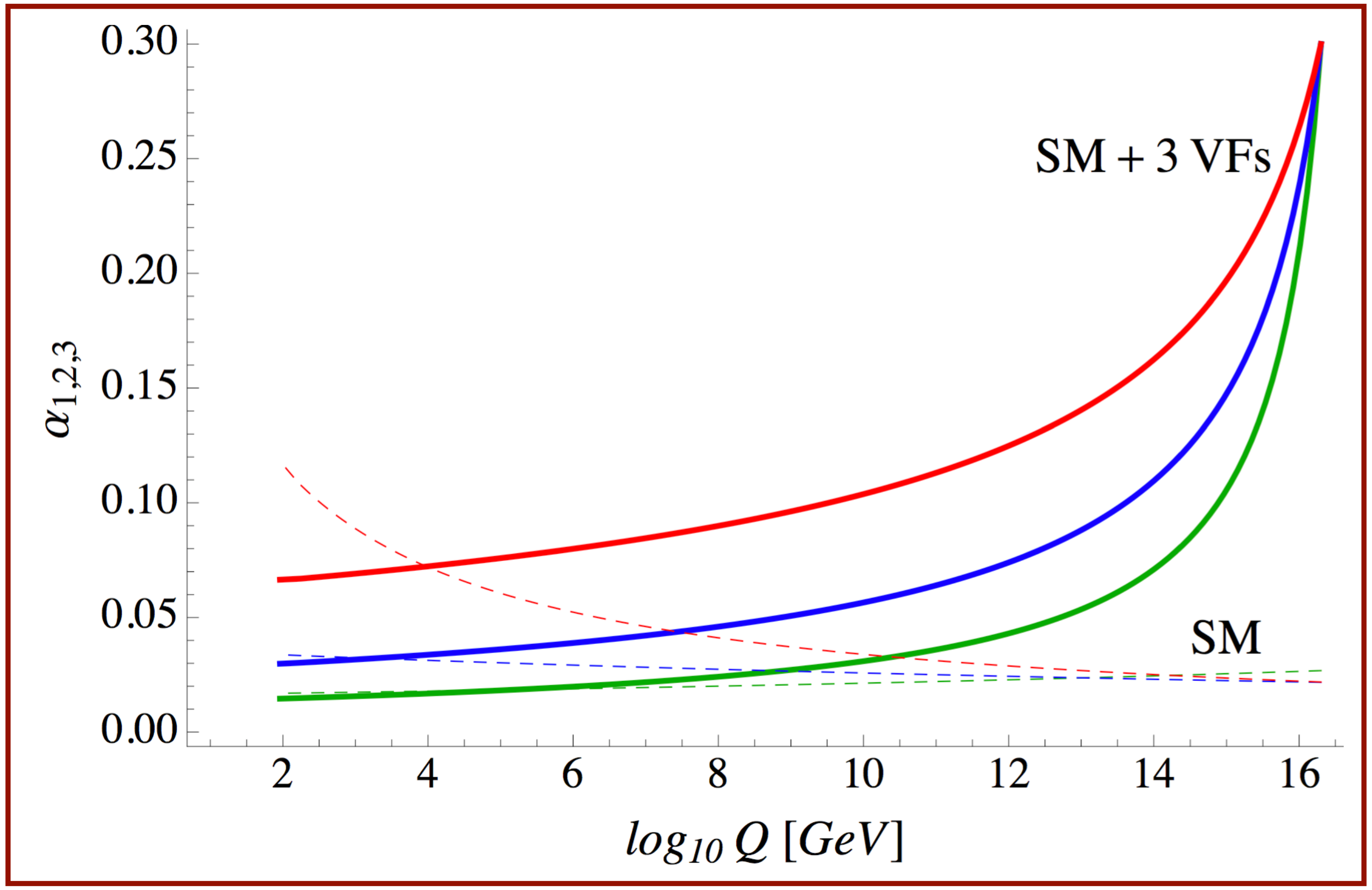
- **Models with more matter fields**
  - vectorlike quarks and leptons, …
  - in complete families easy to add to any GUT

Gauge couplings in the SM + 3VFs

R.D.,1204.6533, 1212.3035



$$\frac{\alpha_i(M_Z)}{\alpha_j(M_Z)} \simeq \frac{b_j}{b_i}$$

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi} \ln \frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

gauge couplings understood from:

- **IR fixed point predictions** **(two parameter free predictions)**

$$\sin^2\theta_W \equiv \frac{\alpha'}{\alpha_2+\alpha'} = \frac{b_2}{b_2+b'} = 0.193$$

Maiani, Parisi, and Petronzio (1978)

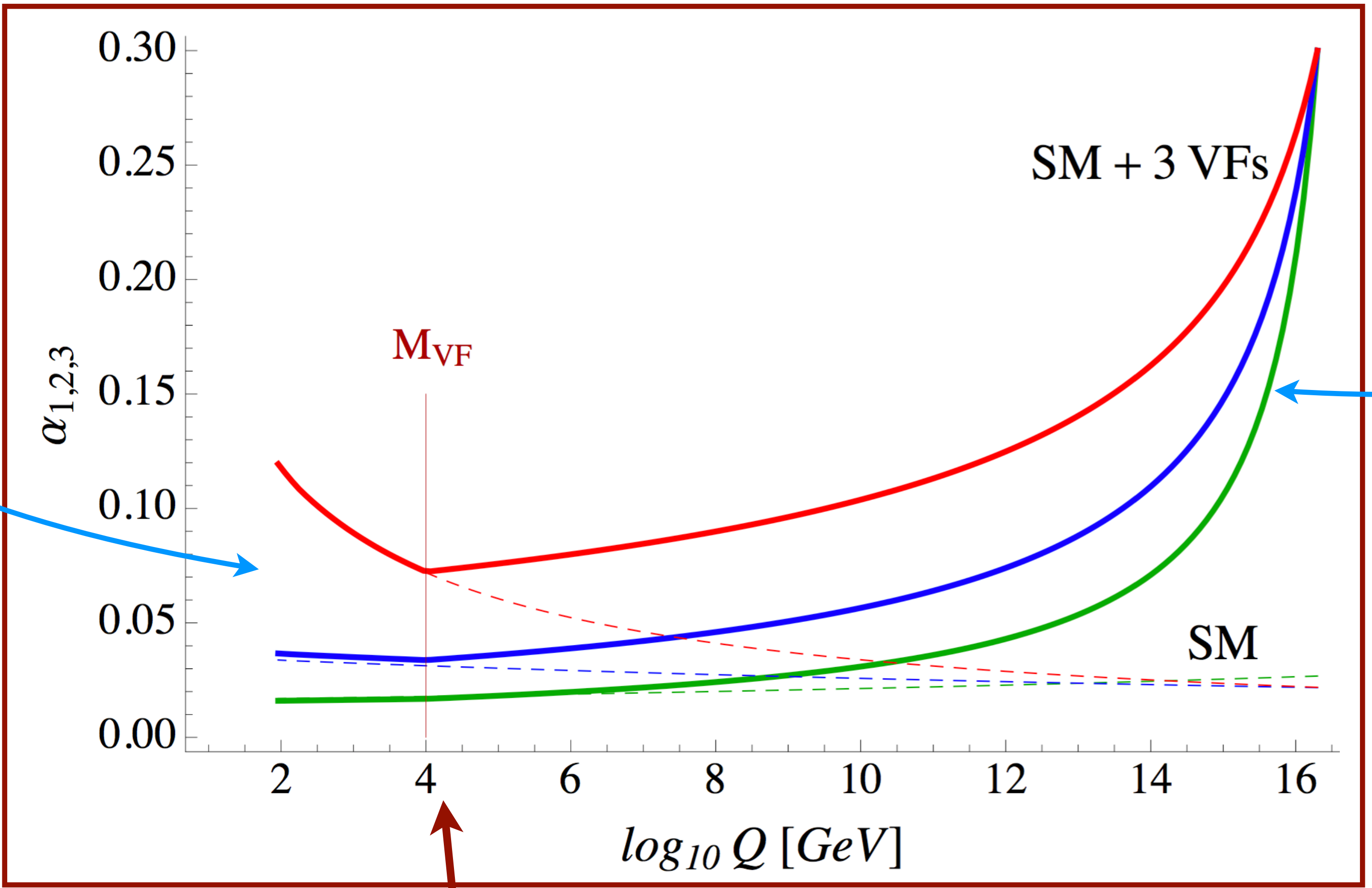
$$\alpha_3\big|_{\alpha_{EM}^{exp}} \simeq 0.072$$

(includes 2-loop)

Gauge couplings in the SM + 3VFs

R.D.,1204.6533, 1212.3035

$b_i = (41/10,\ -19/6,\ -7)$



$b_i = (121/10,\ 29/6,\ +1)$

$$\alpha_i^{-1}(M_Z) = \frac{b_i}{2\pi}\ln\frac{M_G}{M_Z} + \alpha_i^{-1}(M_G)$$

gauge couplings understood from:

- **IR fixed point predictions** **(two parameter free predictions)**
- **threshold effects from masses of VFs**

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Sometimes searching for combined signatures of two extensions is more advantageous than separate searches

Two Higgs doublet model - type II + VL

VL mixing only with 2nd generation of leptons:

R.D., E. Lunghi and S. Shin, 1509.04292, 1512.07837

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

$$\mu_L = \begin{pmatrix} \nu_\mu \\ \mu_L^- \end{pmatrix}, \; L_{L,R} = \begin{pmatrix} L_{L,R}^0 \\ L_{L,R}^- \end{pmatrix}, \; H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}, \; H_u = \begin{pmatrix} H_u^0 \\ H_u^- \end{pmatrix}$$

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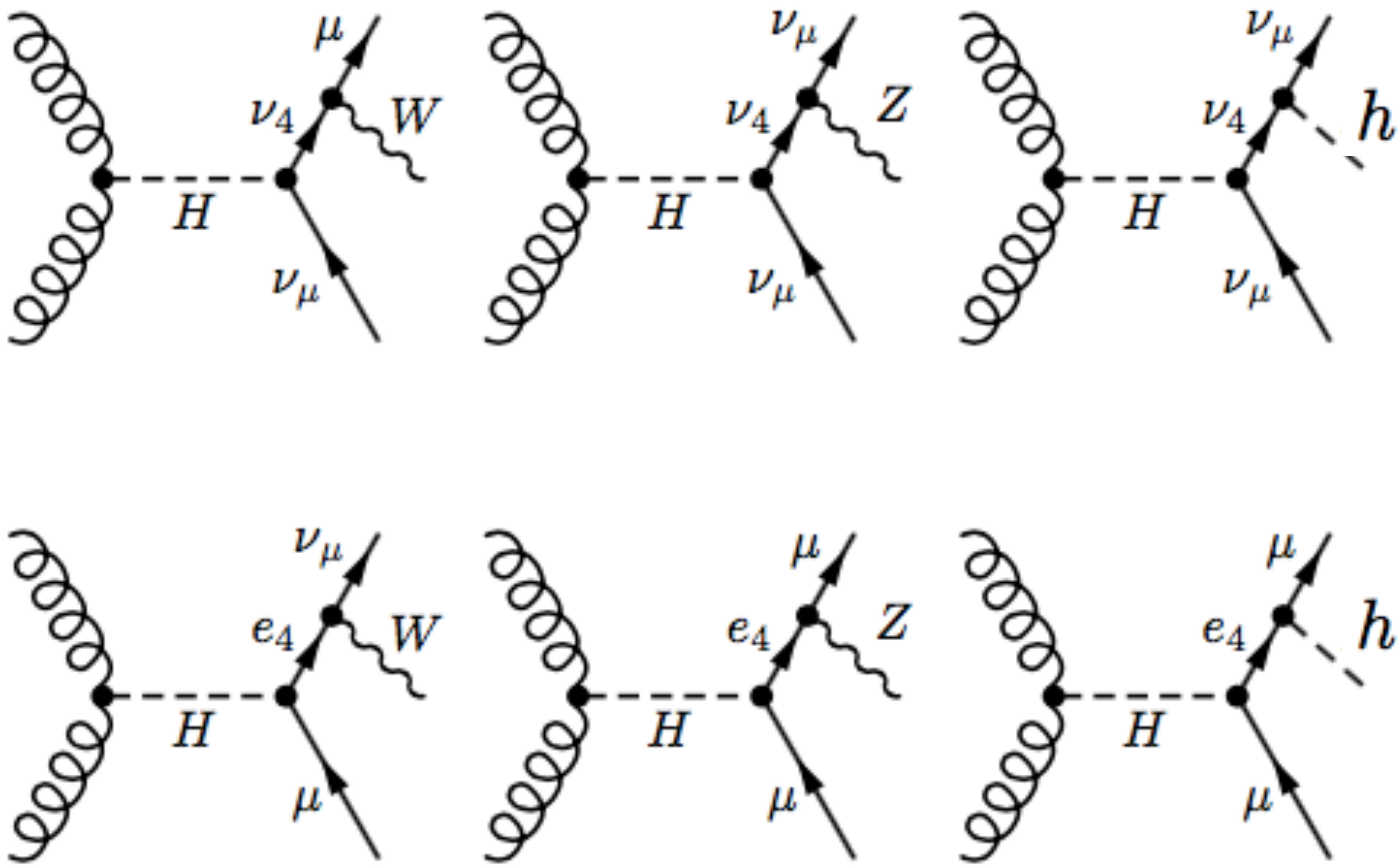
couplings to gauge bosons are modified because SU(2) doublets mix with SU(2) singlets and couplings to Higgs are modified because of explicit vectorlike mass terms:

$$(\bar{\mu}_L, \bar{L}_L^-, \bar{E}_L) \begin{pmatrix} y_\mu v_d & 0 & \lambda^E v_d \\ \lambda^L v_d & M_L & \lambda v_d \\ 0 & \bar{\lambda} v_d & M_E \end{pmatrix} \begin{pmatrix} \mu_R \\ L_R^- \\ E_R \end{pmatrix} \qquad \begin{pmatrix} \bar{\nu}_\mu & \bar{L}_L^0 & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & 0 & \kappa_N v_u \\ 0 & M_L & \kappa v_u \\ 0 & \bar{\kappa} v_u & M_N \end{pmatrix} \begin{pmatrix} \nu_R = 0 \\ L_R^0 \\ N_R \end{pmatrix}$$

and flavor changing couplings are generated: $e_4\mu(Z,h,H),\; \nu_4\nu(Z,h,H),\; (e_4\nu, \nu_4\mu)W$

New (possibly discovery) decay modes

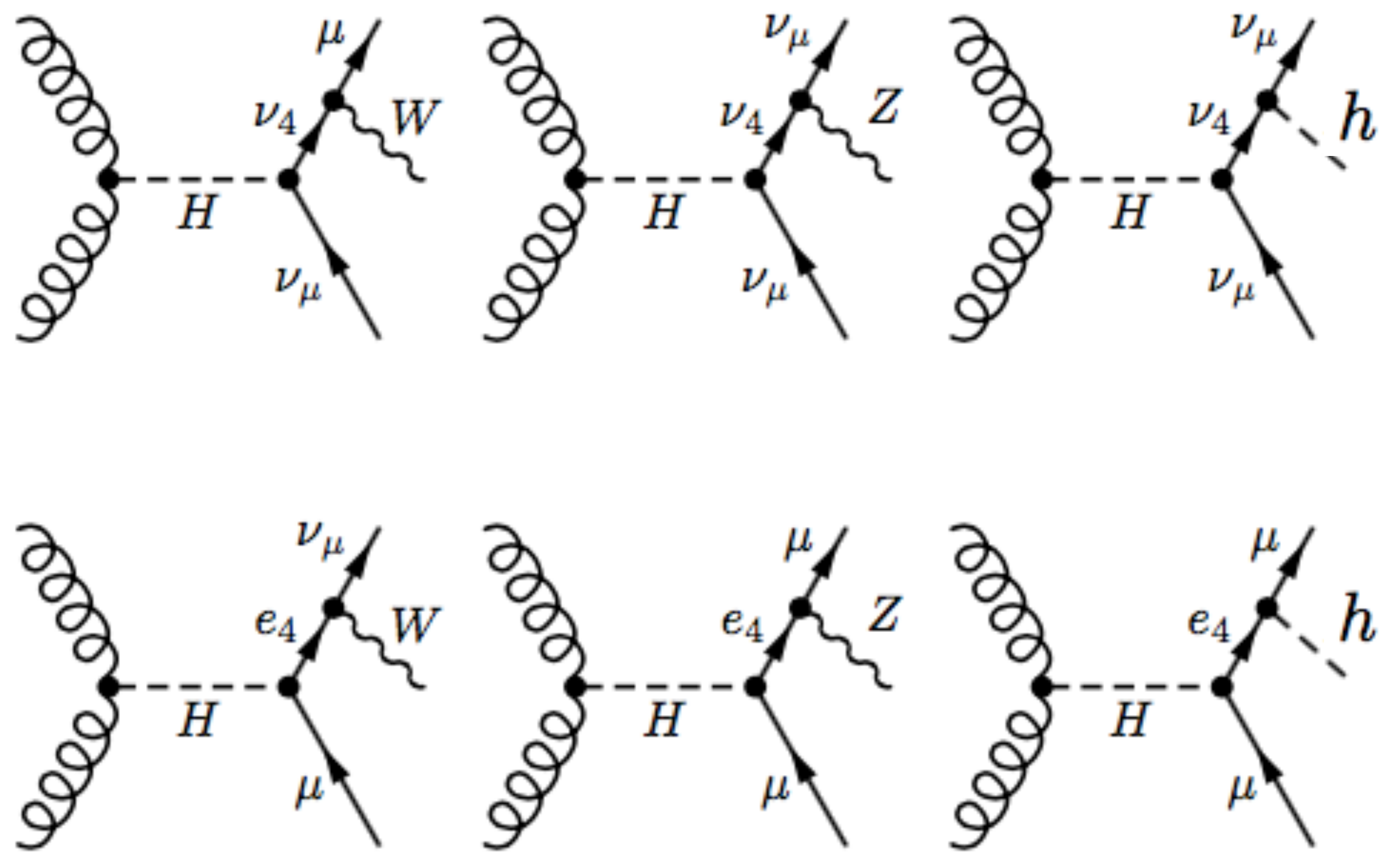
The flavor changing couplings lead to new decay modes of heavy Higgses:



New (possibly discovery) decay modes

$$H \to \cancel{WW},\ \cancel{ZZ},\ \gamma\gamma,\ \cancel{t\bar{t}},\ b\bar{b},\ \tau\bar{\tau},\ \dots$$

if h is SM-like and H (or A) is below ~350 GeV flavor changing decays can be dominant:



decays to pairs of heavy leptons also possible but limited to smaller mass ranges and lead to the same final states as pair-production

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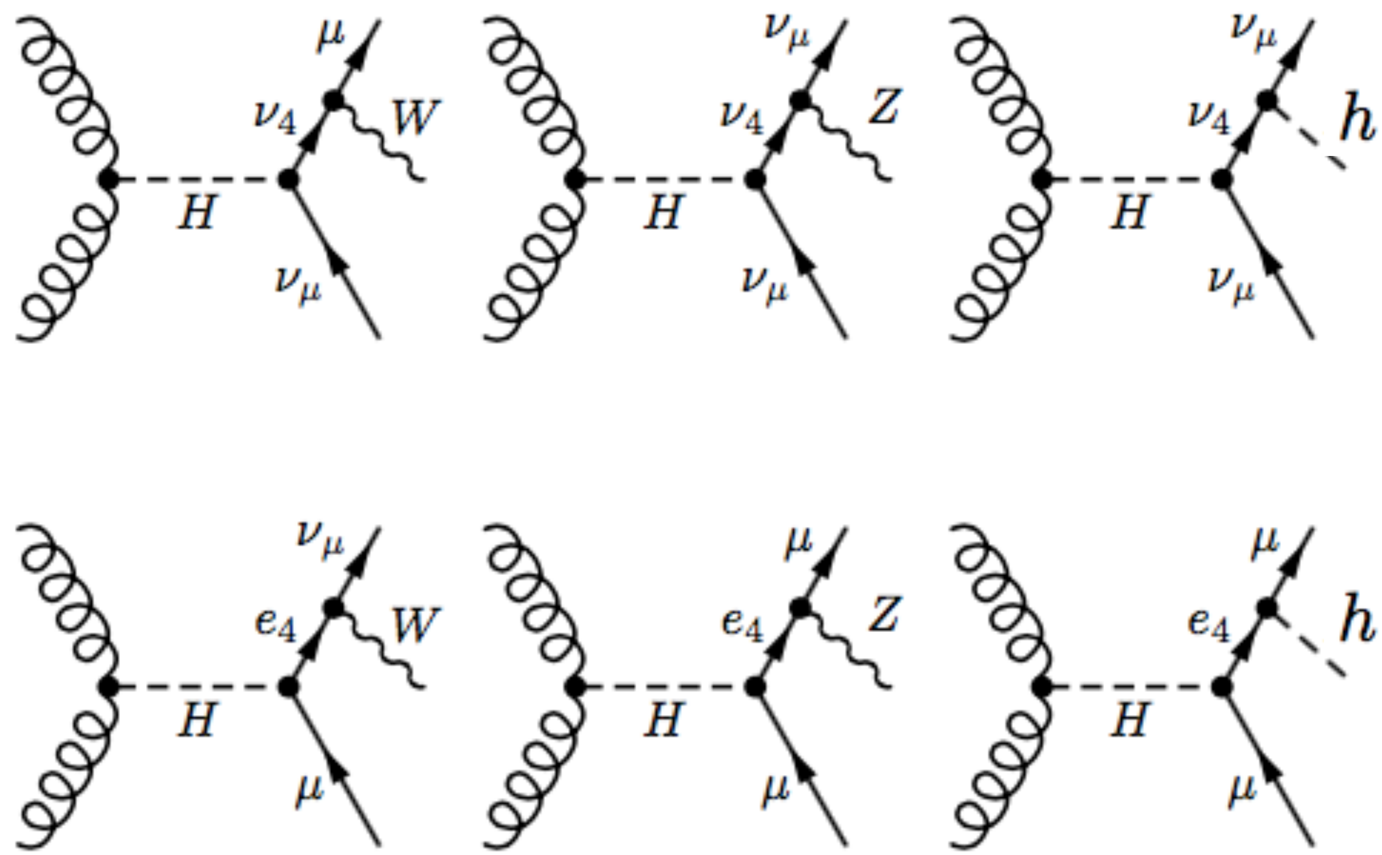


decays to pairs of heavy leptons also possible but limited to smaller mass ranges and lead to the same final states as pair-production

they all look similar to WW, ZZ, hZ decay modes of H or ZZ, WW, Zh production!

Scan over the parameter space

We scan over parameters in the following ranges:

$$m_H \in [130, 340]\ \text{GeV}\ ,$$

$$\tan\beta \in [0.3, 3]\ ,$$

$$\kappa_N, \kappa, \bar{\kappa} \in [-0.5, 0.5] \quad \text{or} \quad \lambda_L, \lambda_E, \lambda, \bar{\lambda} \in [-0.5, 0.5]\ ,$$

$$M_{L,N} \in [100, 500]\ \text{GeV} \quad \text{or} \quad M_{L,E} \in [100, 500]\ \text{GeV}$$

Constraints:

- Precision EW data (muon lifetime, Z-pole obs., S and T, …)
- direct searches for new leptons
- searches for anomalous production of multi-lepton events
  R.D., J. Hall, E. Lunghi and S. Shin, arXiv:1408.3123
- searches for H → γγ and H → WW
  R.D., E. Lunghi and S. Shin,1503.0882, 1509.04292

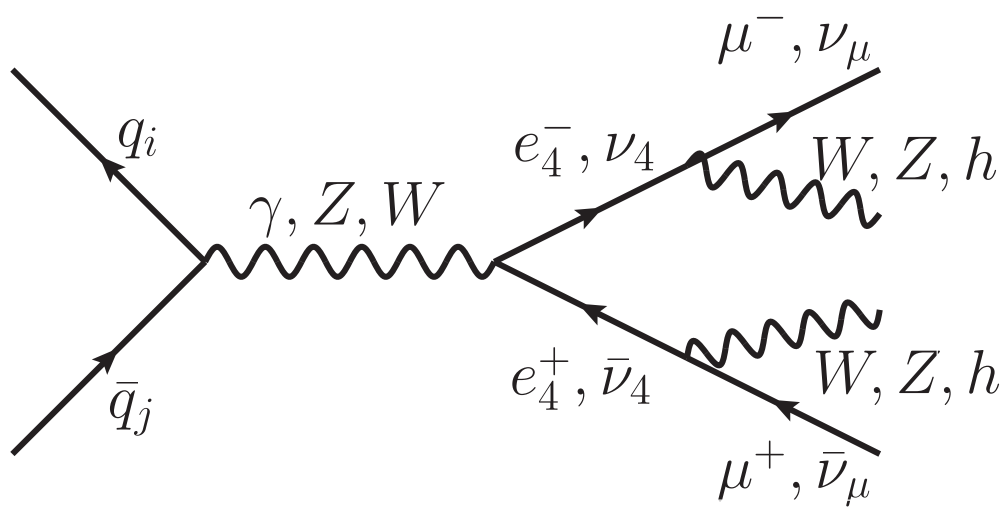
Limits on vectorlike leptons

from searches for anomalous production of multi-lepton events

R.D., J. Hall, E. Lunghi and S. Shin, arXiv:1408.3123

based on ATLAS-CONF-2013-070

We set limits on 20 possible processed with at least 3 SM leptons in the final state (originating from 3 pair production processes, and 3 possible decay modes of each of the final state leptons)



Assumption: The vector like leptons mix with only one SM lepton, namely the muon.

Limits for electron would be similar, and the current analysis is not sensitive to the tau case.

	masses / GeV								
	105	125	150	200	300	400	500	750	1000
	predicted production cross-sections / fb								
$\sigma(e_4^+ e_4^-)$ (singlet)	426	225	114	37.2	6.73	1.75	0.552	0.0481	0.00573
$\sigma(e_4^+ e_4^-)$ (doublet)	1040	538	269	86.6	15.5	3.98	1.24	0.106	0.0124
$\sigma(e_4^\pm \nu_4)$ (doublet)	3870	1970	973	310	55.5	14.4	4.53	0.378	0.0408
$\sigma(\nu_4 \nu_4)$ (doublet)	372	185	88.9	27.4	4.64	1.15	0.35	0.0279	0.00306
	95% C.L. limits / fb and best cuts								
$\sigma(e_4^+ e_4^-)\times$ $\mathrm{BR}(e_4 \to Z\mu)^2$	530 Cb	190 Af	66 Af	21 Af	12 Af	7.5 Ah	4.8 Ah	2.2 Am	1.9 Am
$\sigma(e_4^+ e_4^-)\times$ $\mathrm{BR}(e_4 \to Z\mu)\mathrm{BR}(e_4 \to W\nu)$	520 Cb	260 Cb	140 Cb	65 Cb	43 Cc	29 Cc	23 Cd	5.1 Cr	3.7 Cr
$\sigma(e_4^+ e_4^-)\times$ $\mathrm{BR}(e_4 \to Z\mu)\mathrm{BR}(e_4 \to h\mu)$			100 Aa	19 Ag	8.4 Ag	5.5 Ah	3.1 Ah	1.3 Am	1.1 Am
$\sigma(e_4^+ e_4^-)\times$ $\mathrm{BR}(e_4 \to W\nu)\mathrm{BR}(e_4 \to h\mu)$			370 Ab	130 Ab	67 Ab	41 Ac	28 Ac	11 Am	7.2 Am
$\sigma(e_4^+ e_4^-)\times$ $\mathrm{BR}(e_4 \to h\mu)^2$			220 Aa	64 Ag	17 Ag	14 Ag	7.2 Ah	2.5 Am	2.1 Am
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to Z\mu)\mathrm{BR}(\nu_4 \to Z\nu)$	820 Cb	510 Cb	230 Cb	79 Cb	44 Cb	29 Cc	23 Cd	4.8 Cr	3.4 Cr
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to Z\mu)\mathrm{BR}(\nu_4 \to W\mu)$	190 Aa	83 Aa	45 Ag	13 Ag	7.3 Af	4.7 Ah	2.8 Ah	1.2 Am	1 Am
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to W\nu)\mathrm{BR}(\nu_4 \to Z\nu)$	2700 Cb	1800 Cb	1100 Cb	520 Cb	330 Cb	150 Cc	110 Cd	45 Cd	42 Cd
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to W\nu)\mathrm{BR}(\nu_4 \to W\mu)$	420 Aa	400 Aa	260 Ab	110 Ag	57 Ab	32 Ac	21 Ac	11 Am	7.1 Am
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to Z\mu)\mathrm{BR}(\nu_4 \to h\nu)$			1100 Aa	280 Cb	110 Cb	64 Cc	51 Cr	9.8 Cr	7.7 Cr
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to h\mu)\mathrm{BR}(\nu_4 \to Z\nu)$			1400 Aa	250 Cb	110 Cb	75 Cq	53 Cr	9.3 Cr	7.1 Cr
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to W\nu)\mathrm{BR}(\nu_4 \to h\nu)$			6400 Ab	5000 Ap	1800 Ab	1200 Bc	680 Ac	360 Ac	270 Bc
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to h\mu)\mathrm{BR}(\nu_4 \to W\mu)$			110 Aa	20 Ag	9.2 Ag	6.3 Ah	3.5 Ah	1.5 Am	1.2 Am
$\sigma(e_4^\pm \nu_4)\times$ $\mathrm{BR}(e_4 \to h\mu)\mathrm{BR}(\nu_4 \to h\nu)$			910 Aa	420 Ap	140 Ap	93 Aq	52 An	19 Am	13 Am
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to Z\nu)^2$	5100 Cc	5700 Cf	4000 Cb	850 Cb	450 Cc	200 Cc	150 Cd	87 Cd	73 Cd
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to Z\nu)\mathrm{BR}(\nu_4 \to W\mu)$	570 Ag	450 Ag	290 Ag	82 Cb	47 Cb	33 Cc	22 Cr	4.6 Cr	3.5 Cr
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to W\mu)^2$	67 Aa	52 Aa	25 Ag	9 Ag	5.4 Af	3.1 Ah	1.9 Am	0.82 Am	0.72 Am
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to Z\nu)\mathrm{BR}(\nu_4 \to h\nu)$			2800 Cb	830 Cb	380 Cb	220 Cc	160 Cc	79 Cd	72 Cd
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to W\mu)\mathrm{BR}(\nu_4 \to h\nu)$			320 Ag	120 Ag	61 Ag	40 Ac	27 Ac	11 Am	6.9 Am
$\sigma(\nu_4 \nu_4)\times$ $\mathrm{BR}(\nu_4 \to h\nu)^2$			9400 Aa	6900 Ap	2800 Ab	1700 Bc	930 Bc	460 Bc	380 Bc

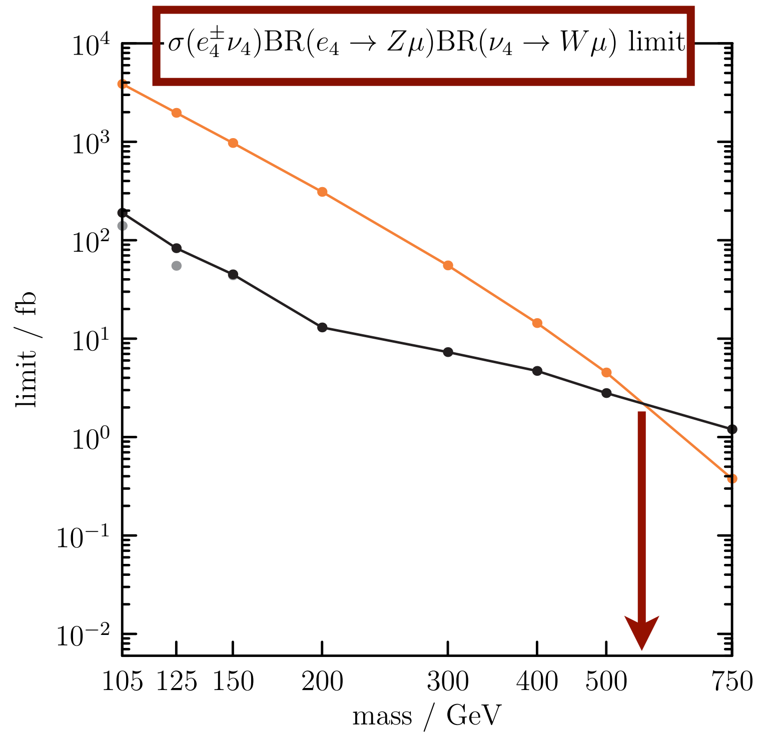
(orange) indicates non-trivial limits assuming doublet production

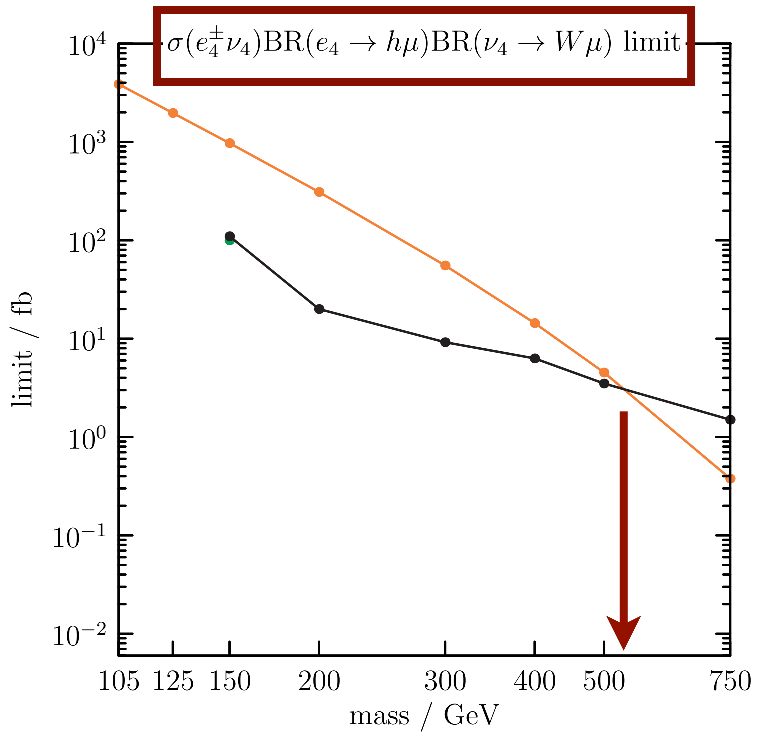
(purple) indicates, additionally, non-trivial limits assuming singlet production

Search categories:

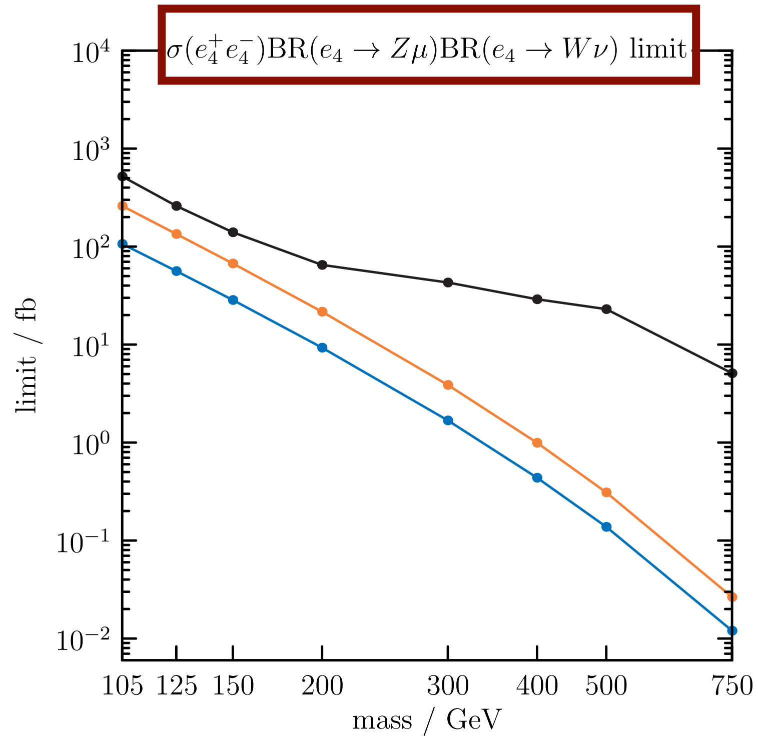
A	$\geq 3e/\mu$ off-Z
B	$2e/\mu + \tau_h$ off-Z
C	$\geq 3e/\mu$ on-Z
D	$2e/\mu + \tau_h$ on-Z
a	$H_T^j < 150$ GeV
b	$H_T^j < 150$ GeV, $\not{E}_T > 100$ GeV
c	$H_T^j < 150$ GeV, $\not{E}_T > 200$ GeV
d	$H_T^j < 150$ GeV, $\not{E}_T > 300$ GeV
f	min $p_T^l > 50$ GeV
g	$H_T^l > 200$ GeV
h	$H_T^l > 500$ GeV
m	$m_{\rm eff} > 1000$ GeV
n	$H_T^j > 150$ GeV, $\not{E}_T > 200$ GeV
p	$\not{E}_T > 100$ GeV
q	$\not{E}_T > 100$ GeV, $m_{\rm eff} > 600$ GeV
r	$\not{E}_T > 100$ GeV, $m_{\rm eff} > 1200$ GeV

Some of the strongest limits:





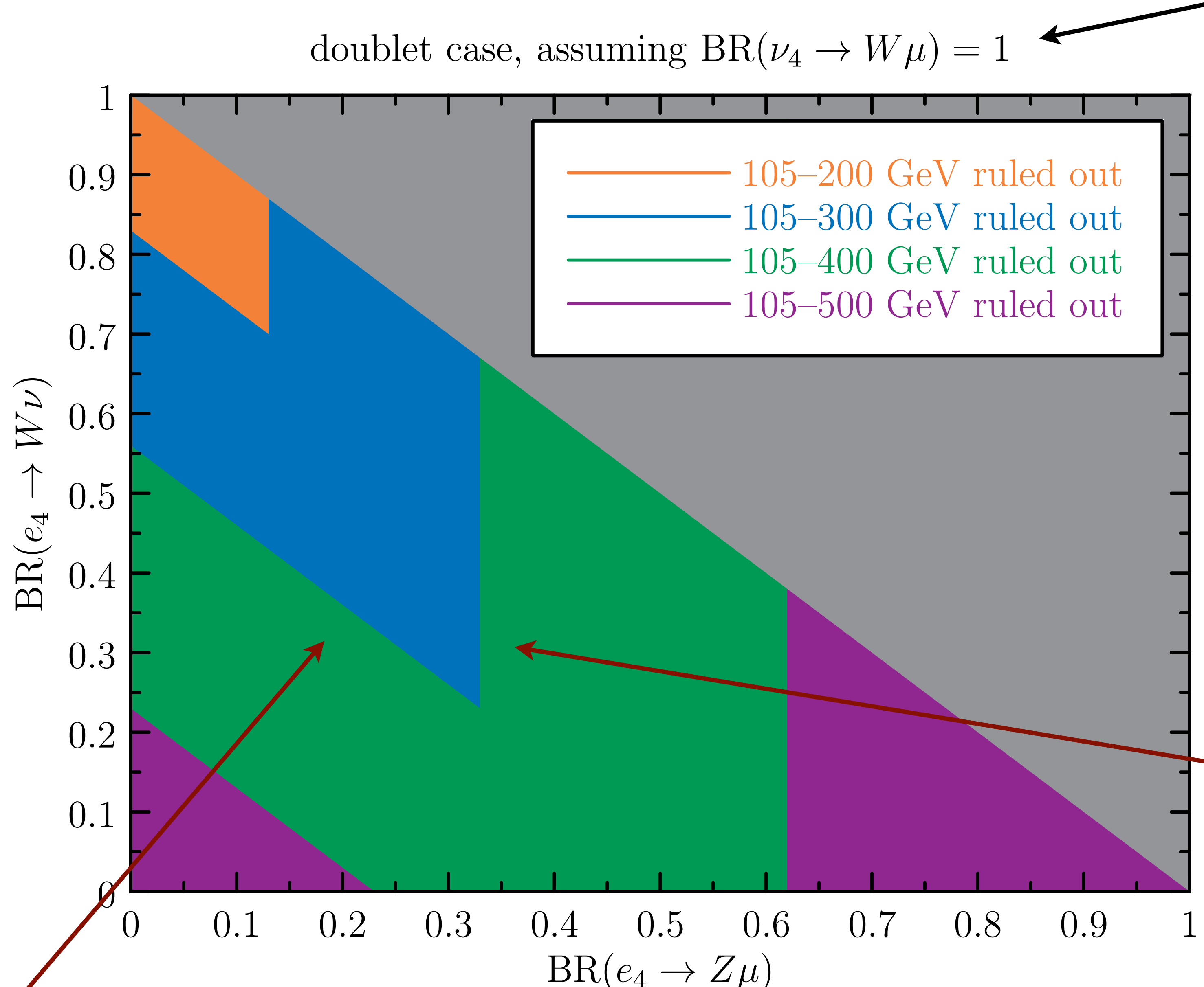
Some of the weakest limits:



no constraints at all if both charged leptons decay through W

Combined limits on simple scenarios

if there are no SM-singlet vectorlike leptons



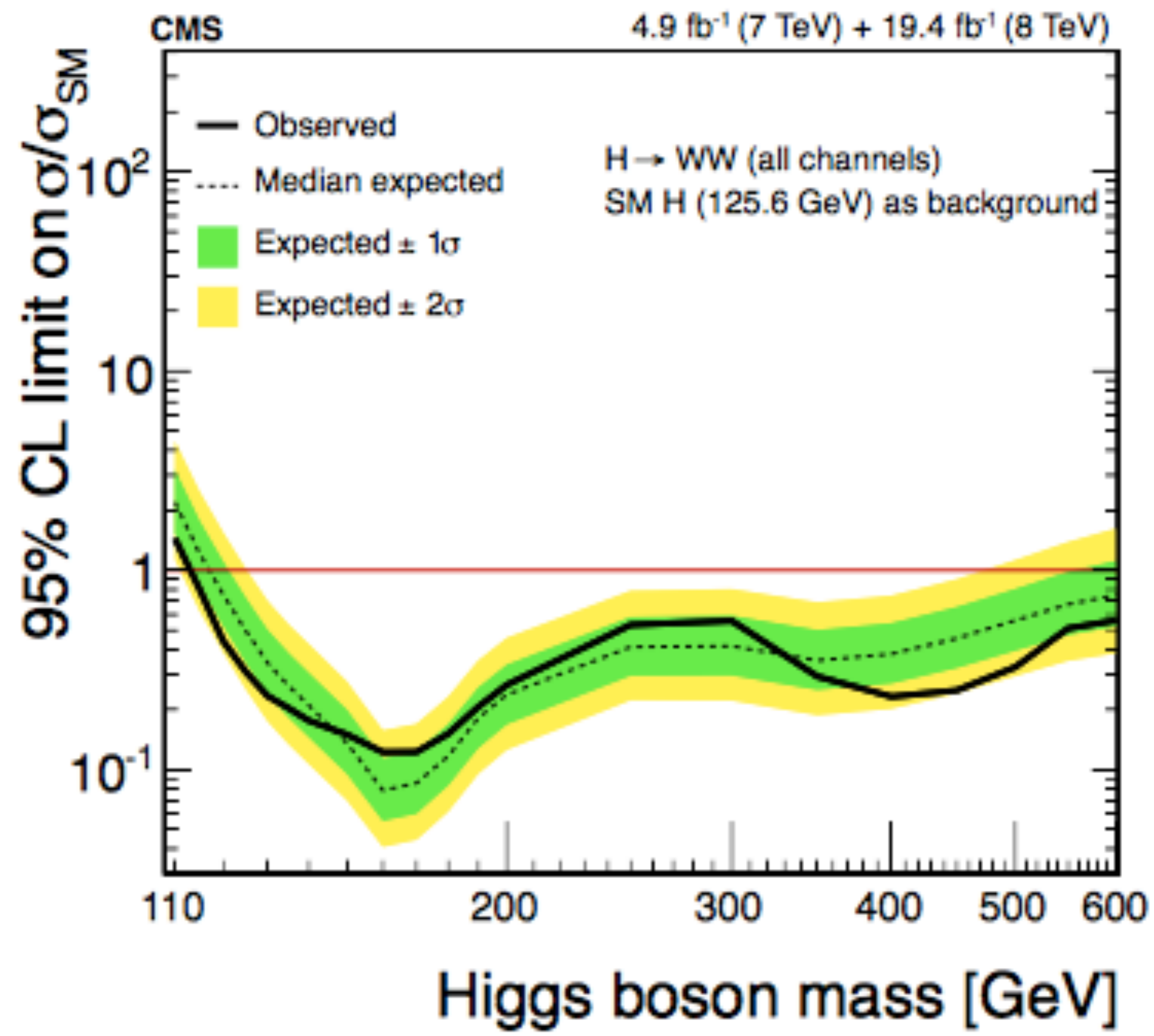
$BR(e_4 \to Z\mu)BR(\nu_4 \to W\mu)$

$BR(e_4 \to h\mu)BR(\nu_4 \to W\mu)$

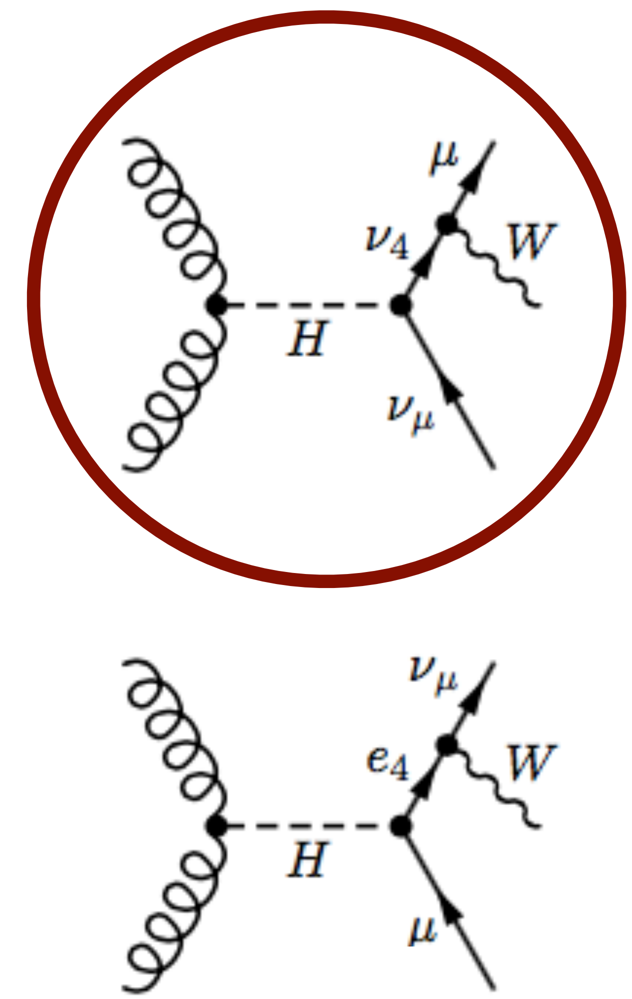
H $\longrightarrow \nu_4 \nu_\mu$ vs. H $\longrightarrow$ WW and pp $\longrightarrow$ WW

constraints from H $\longrightarrow$ WW:

CMS, 1312.1129



contributes more

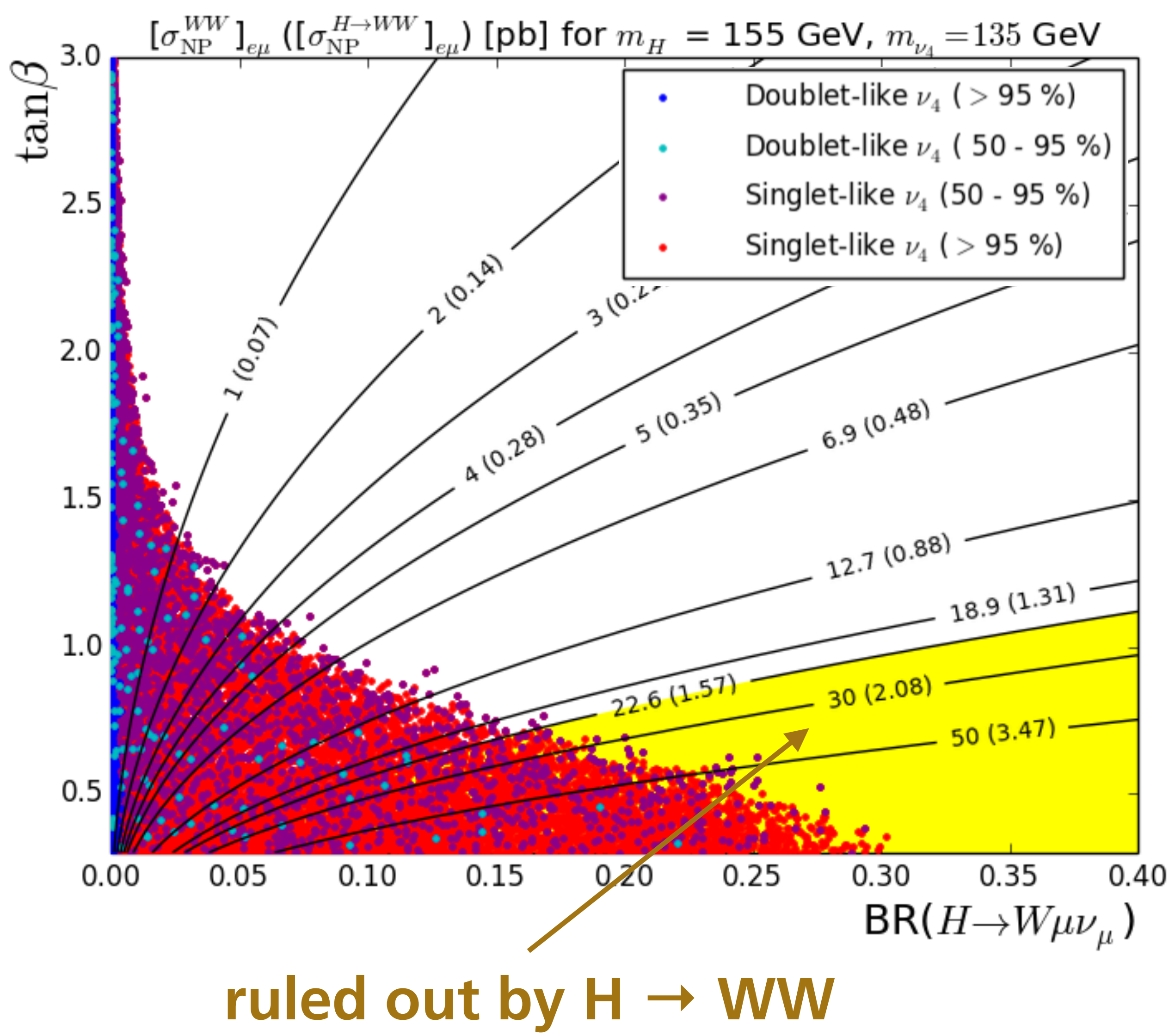


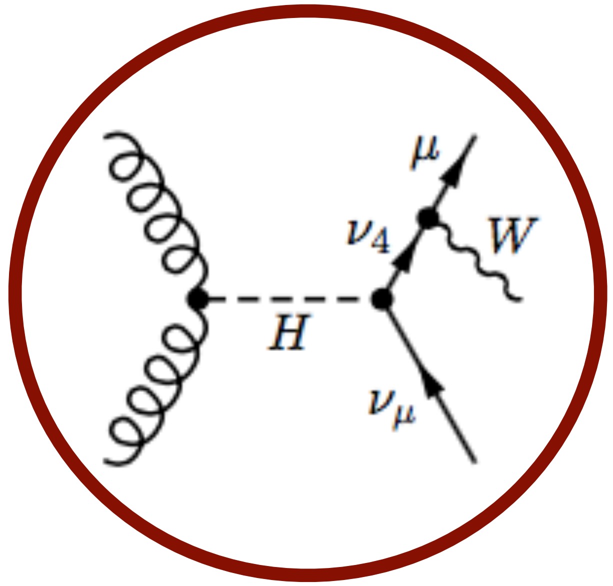
naively SM production cross section for H is ruled out, but different kinematic distribution of final states leads to different acceptances

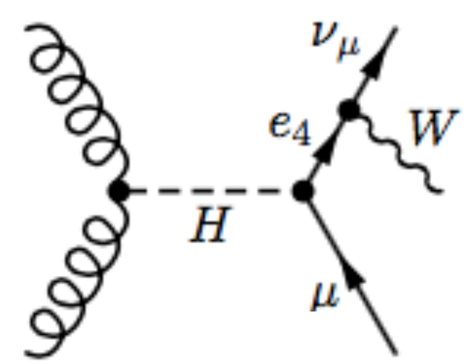
H → $\nu_4 \nu_\mu$ vs. H → WW and pp → WW

contribution to pp → WW consistent with H → WW:

R.D., E. Lunghi and S. Shin, 1503.08829, 1509.04292





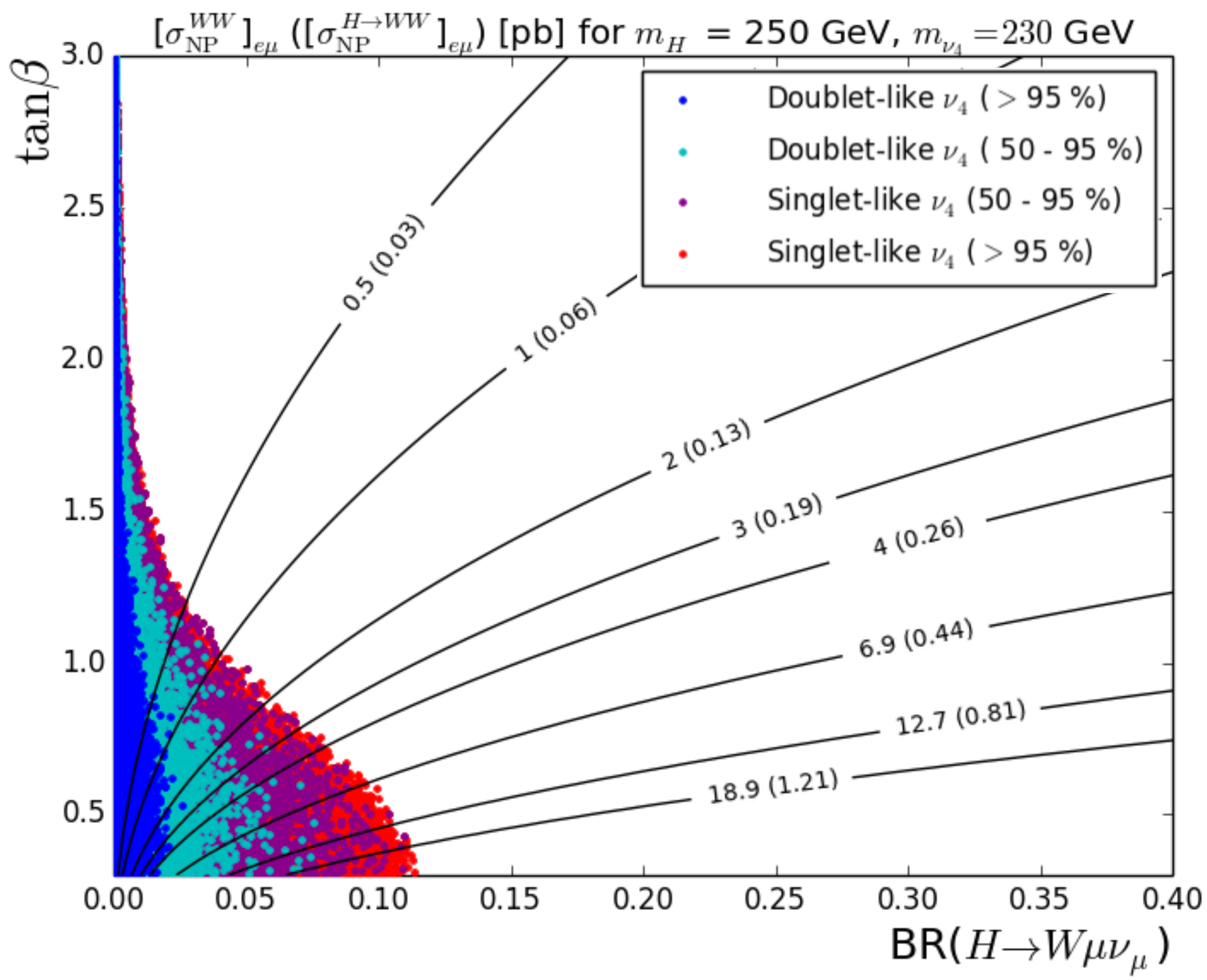


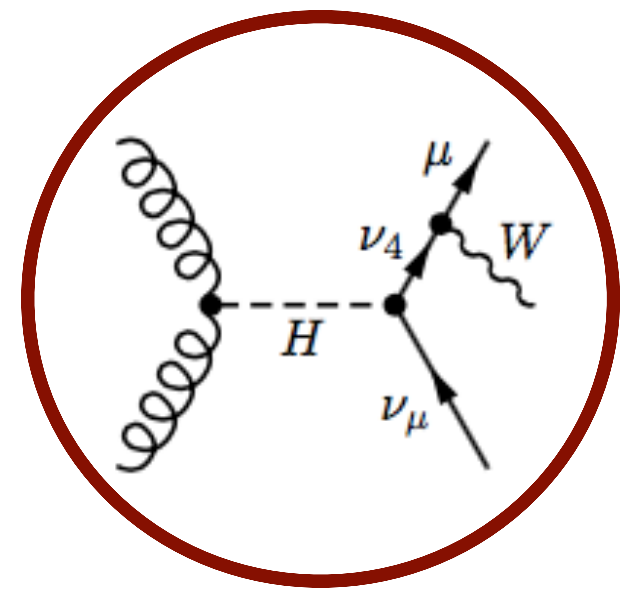
very large (even larger than H production cross section!) contributions to pp → WW are possible and consistent with H → WW constraints

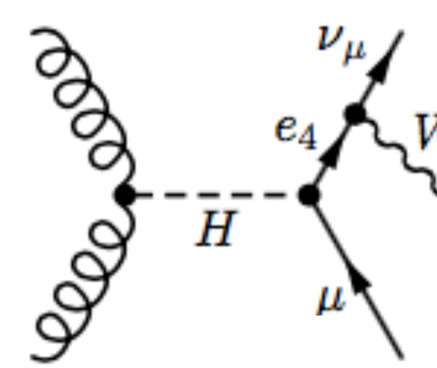
$H \to \nu_4 \nu_\mu$ vs. $H \to WW$ and $pp \to WW$

contribution to $pp \to WW$ consistent with $H \to WW$:

R.D., E. Lunghi and S. Shin, 1503.08829, 1509.04292





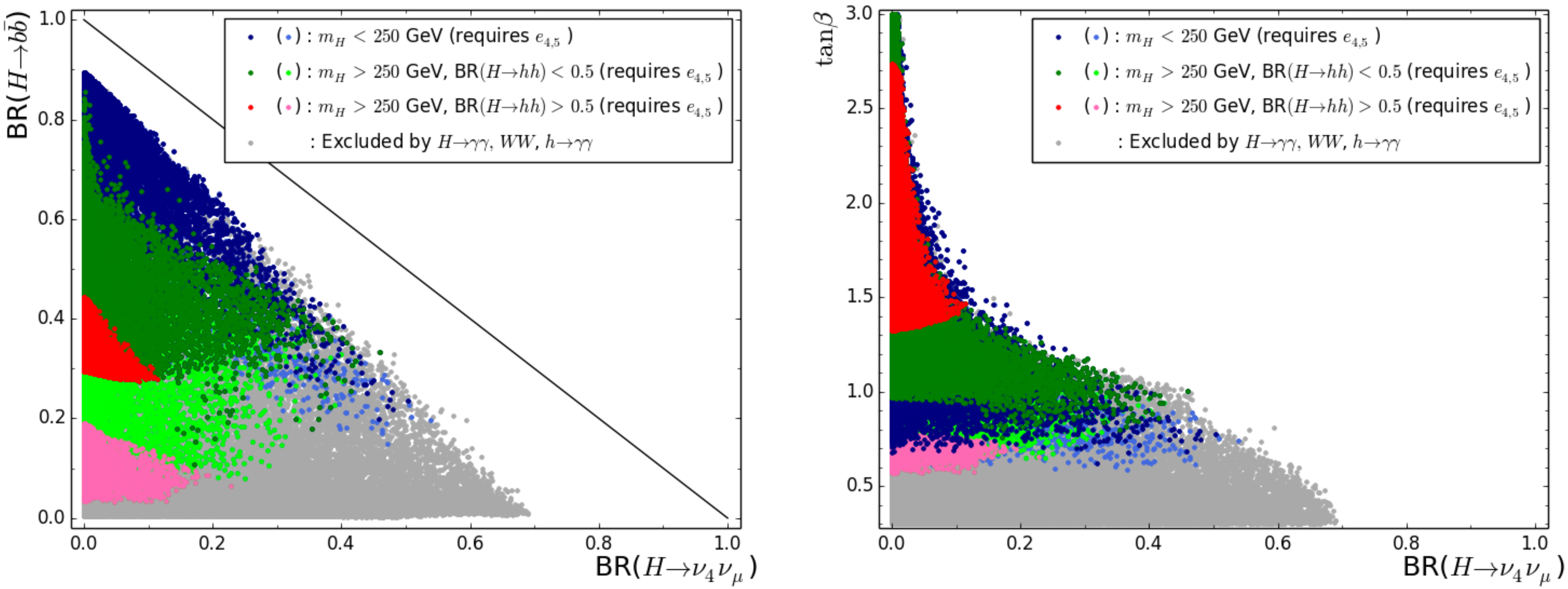


nothing ruled out by $H \to WW$

very large (even larger than H production cross section!) contributions to $pp \to WW$ are possible and consistent with $H \to WW$ constraints

Allowed ranges for H ⟶ $\nu_4\nu_\mu$

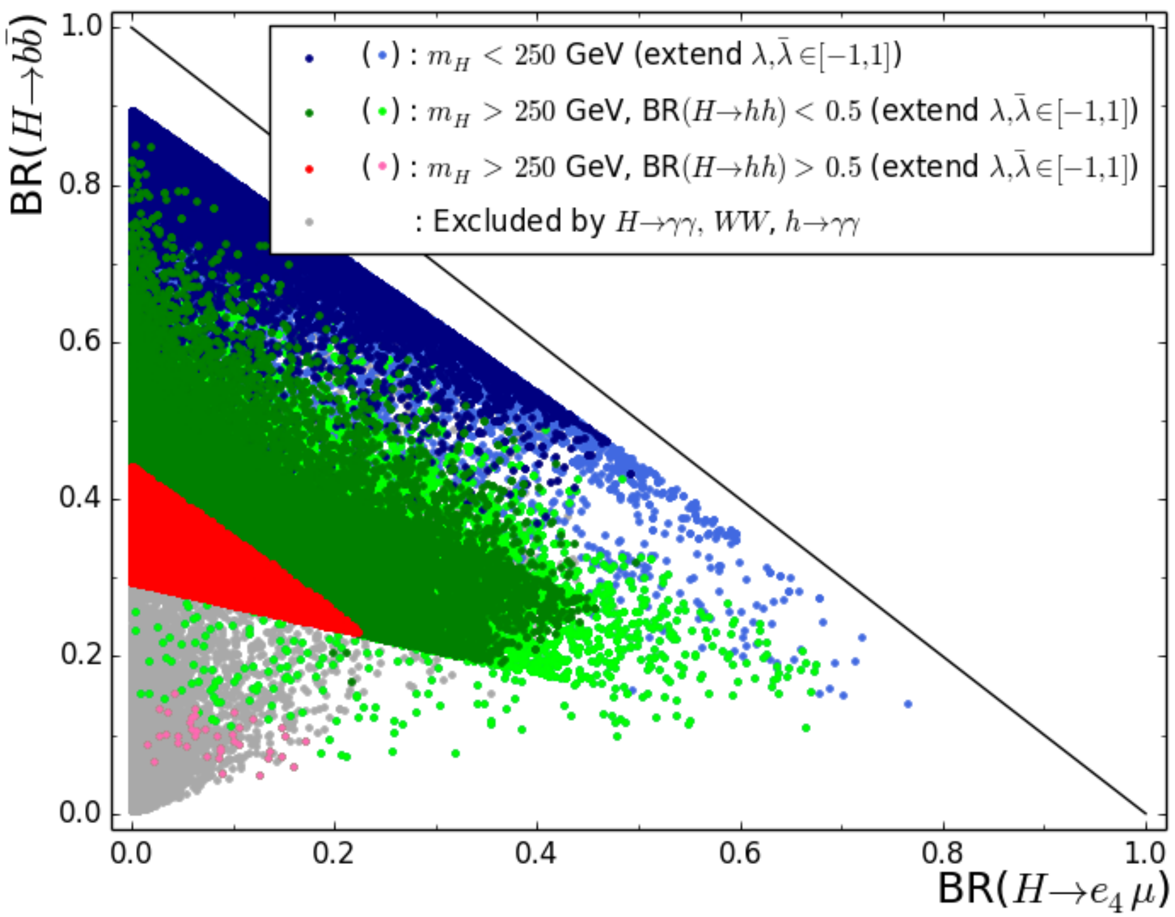
Applying all the constraints:

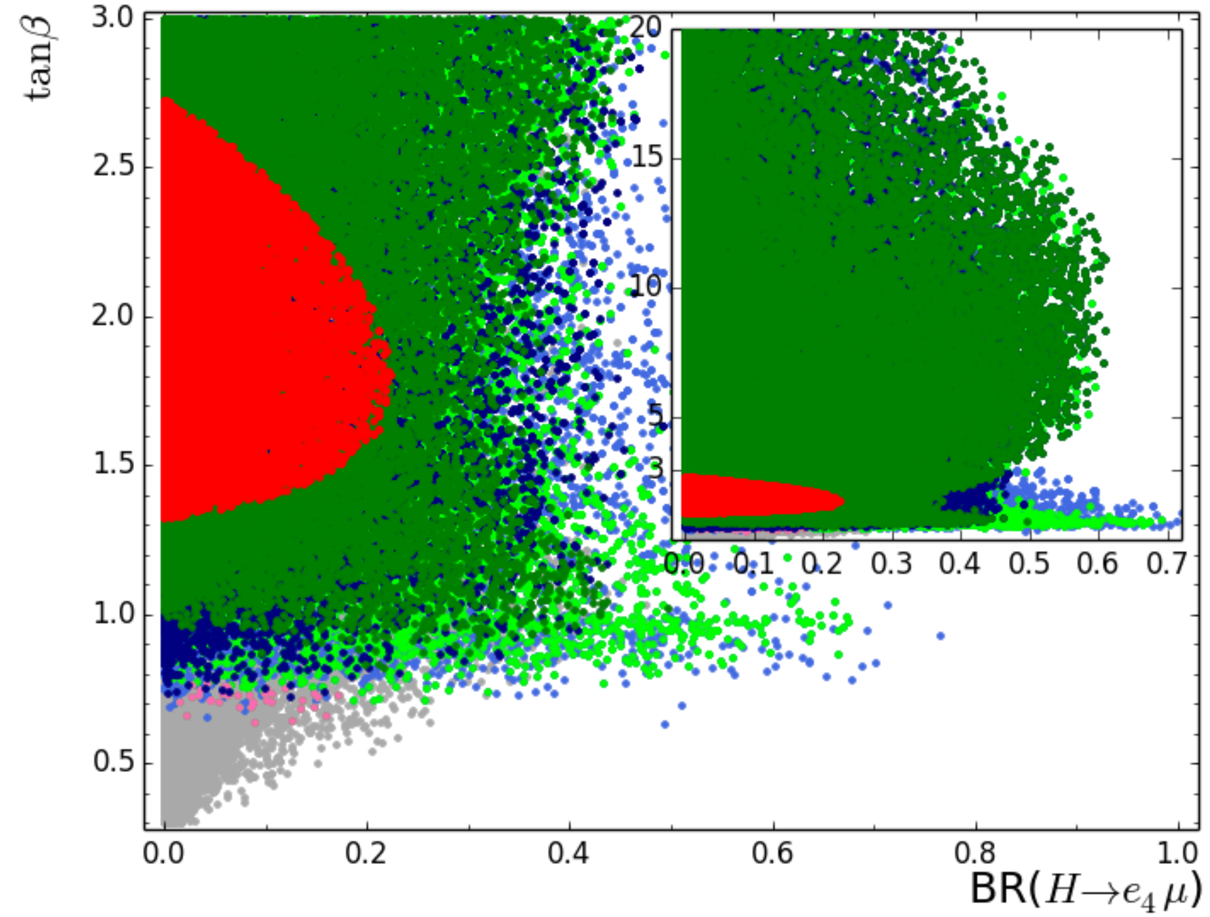


H ⟶ $\nu_4\nu_\mu$ can be as large as 50%

Allowed ranges for H $\longrightarrow e_4\mu$

Applying all the constraints:





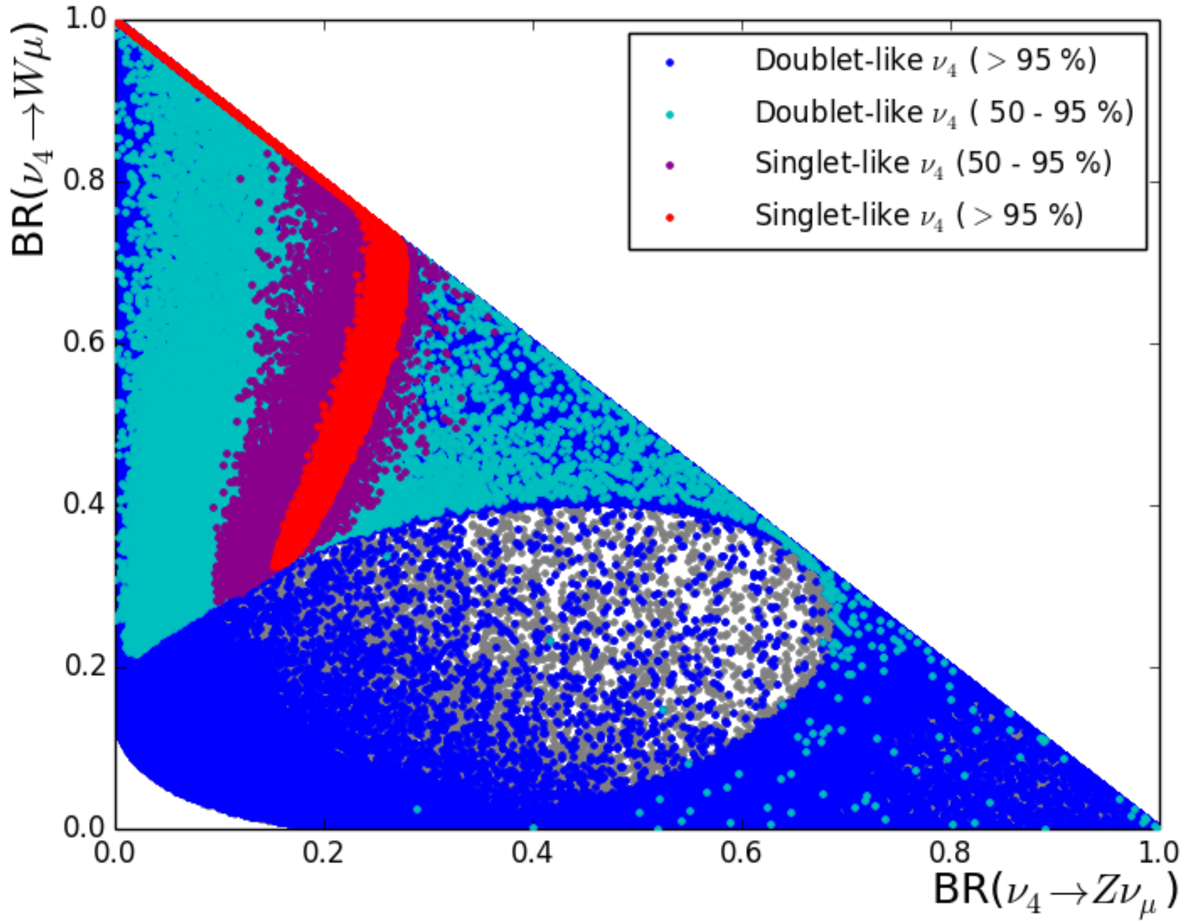
H $\longrightarrow e_4\mu$ can be larger than 50%

Allowed branching ratios of ν_4

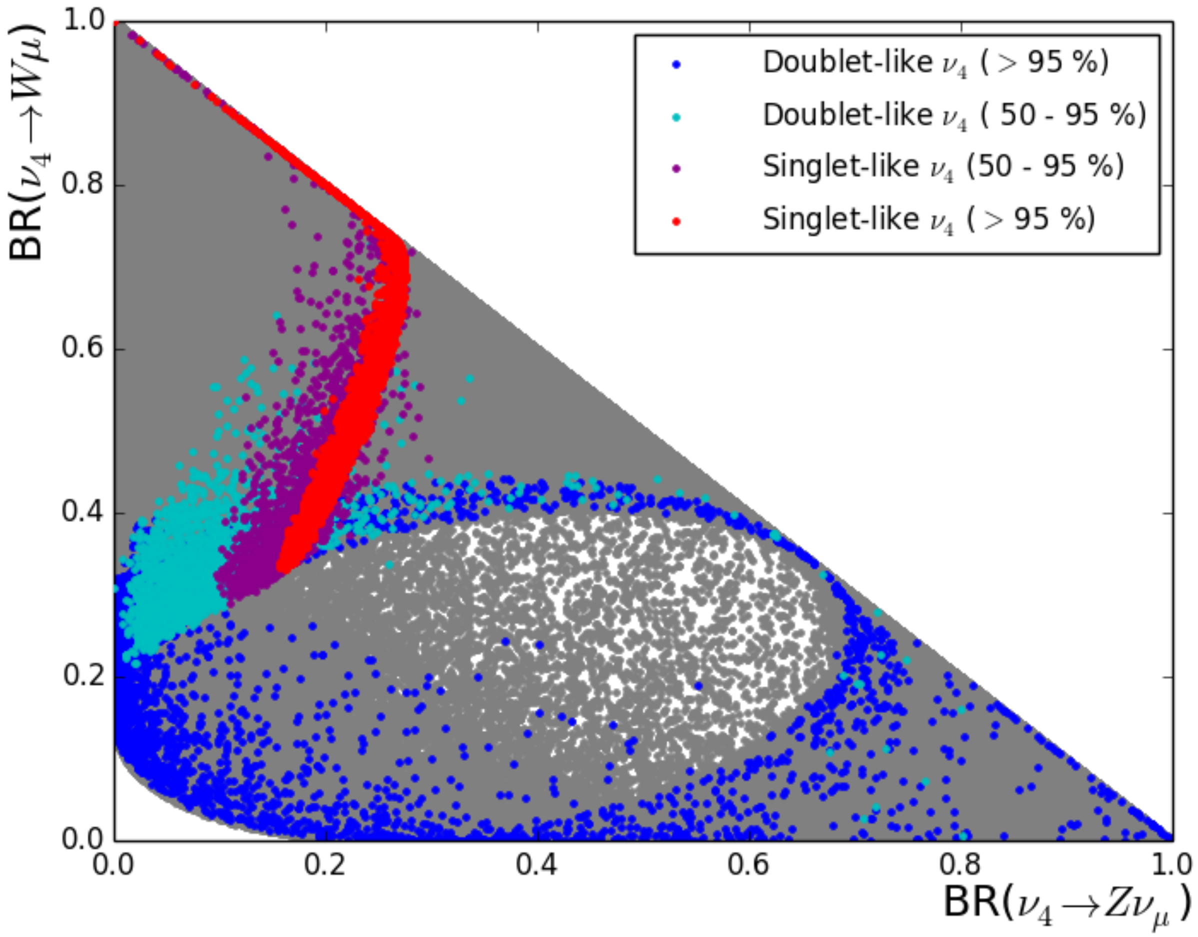
Impact of searches for anomalous production of multi-lepton events:

R.D., J. Hall, E. Lunghi and S. Shin, arXiv:1408.3123

R.D., E. Lunghi and S. Shin, 1512.07837



EW precision



EW precision + multilepton

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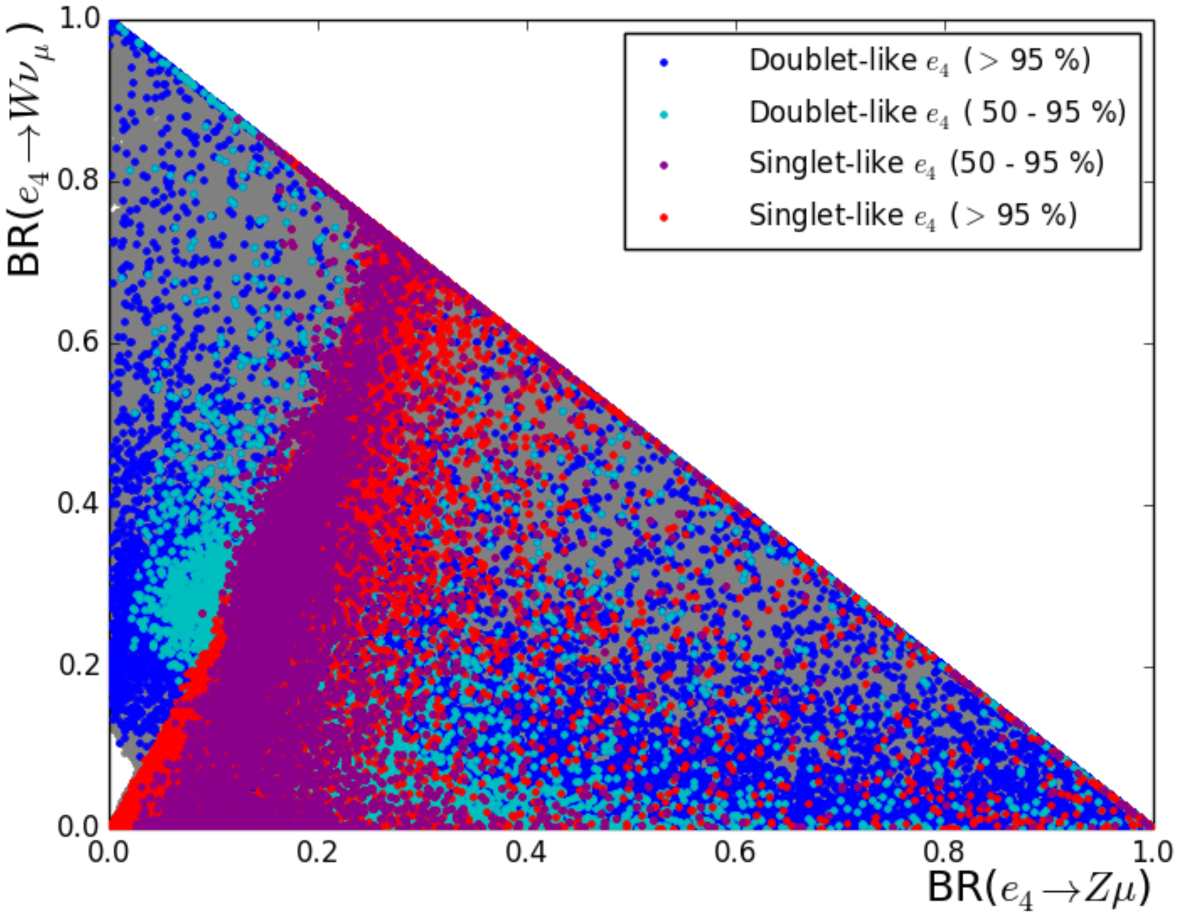

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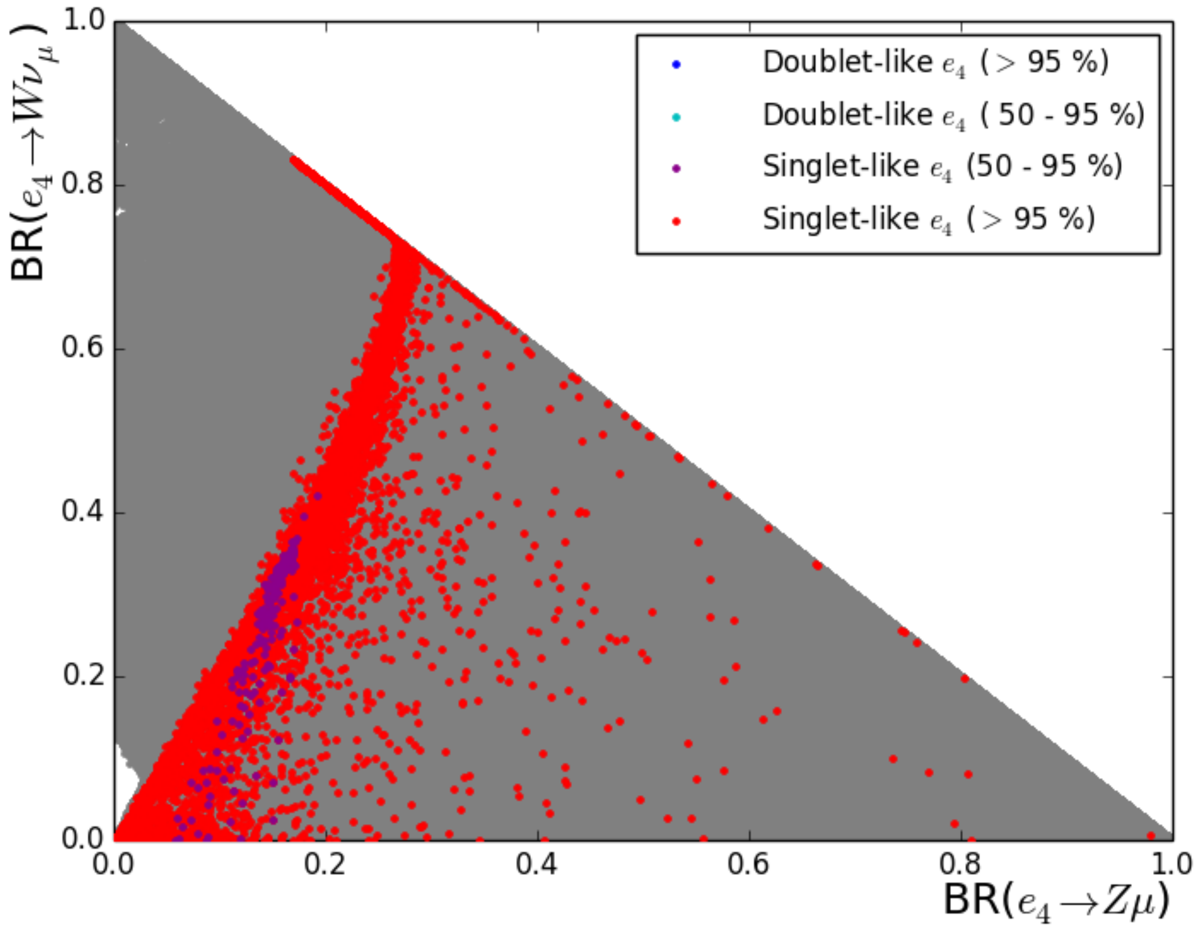


EW precision + multilepton

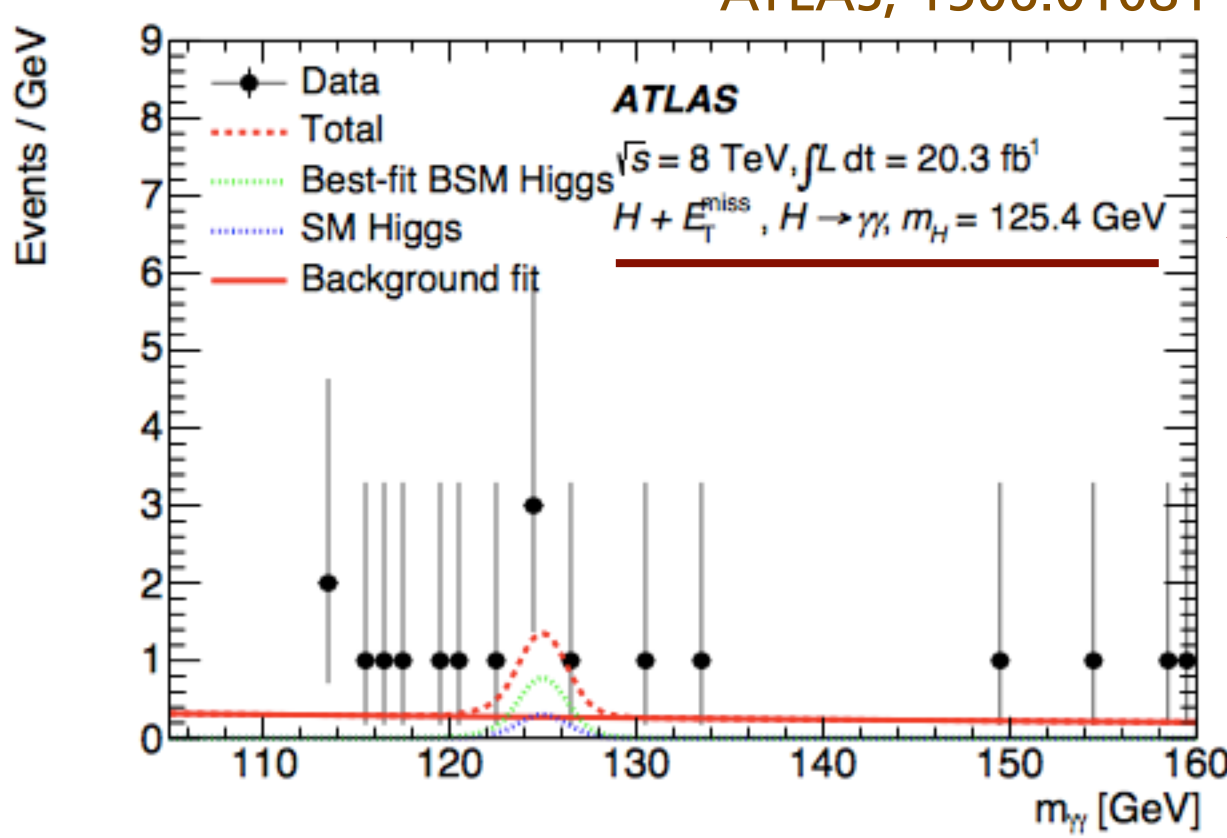
H ⟶ hνν and H ⟶ hμμ

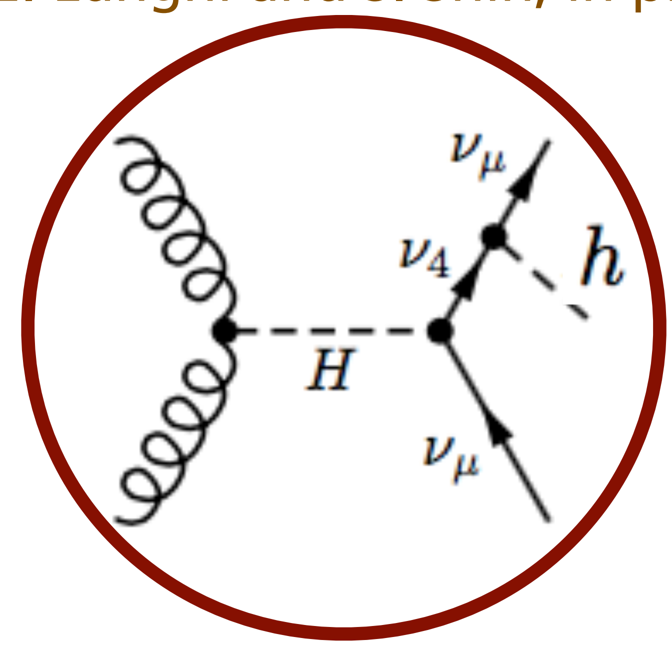
look like Zh production, with potentially much larger cross section, (no Z, but no penalty for 2 leptons)

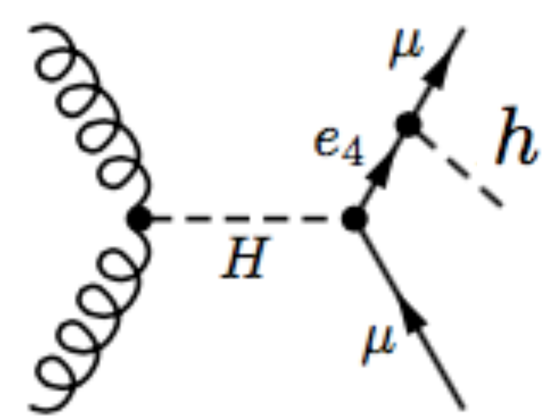
R.D., E. Lunghi and S. Shin, in progress

some decay modes almost background free, e.g. h ⟶ γγ:

ATLAS, 1506.01081



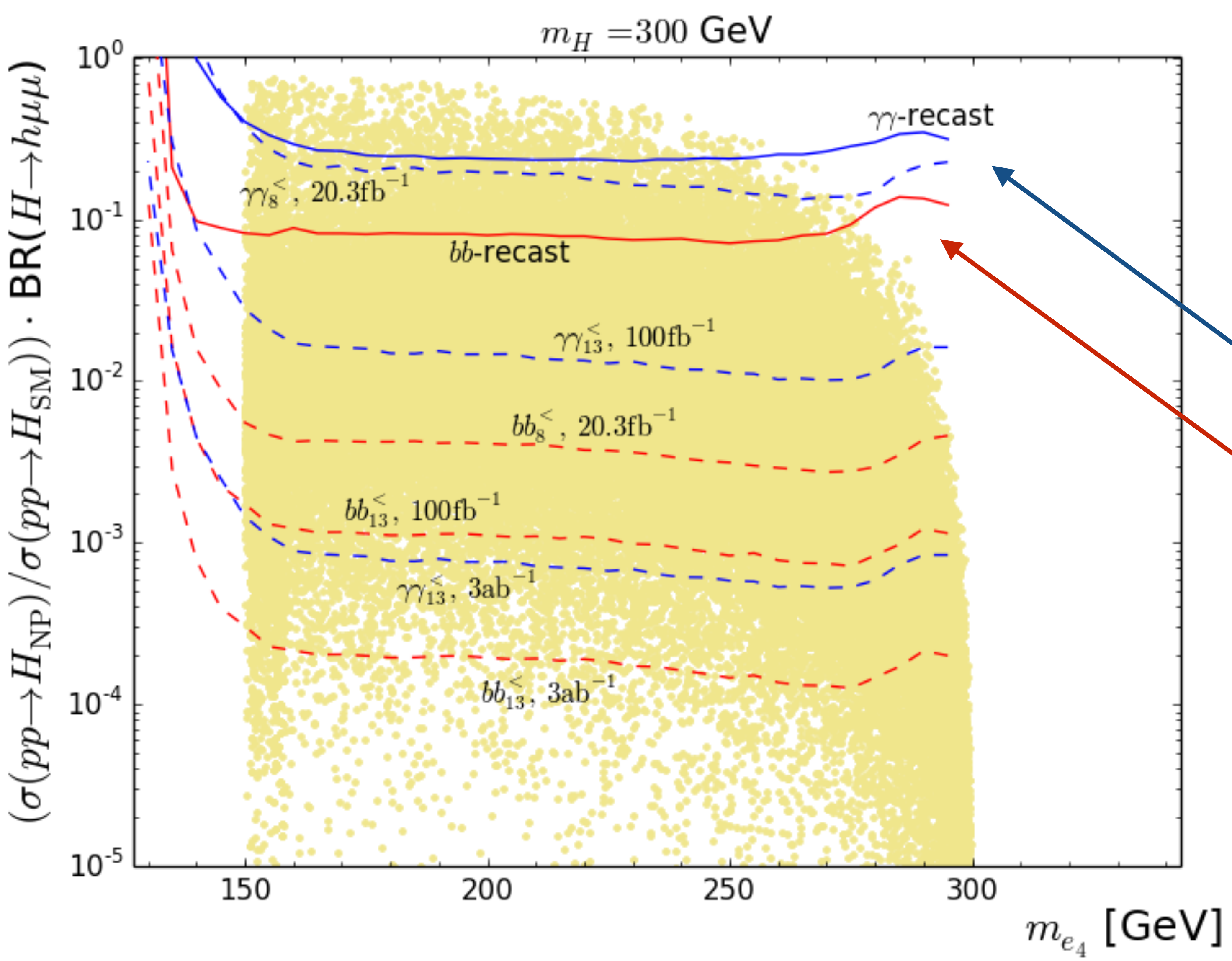


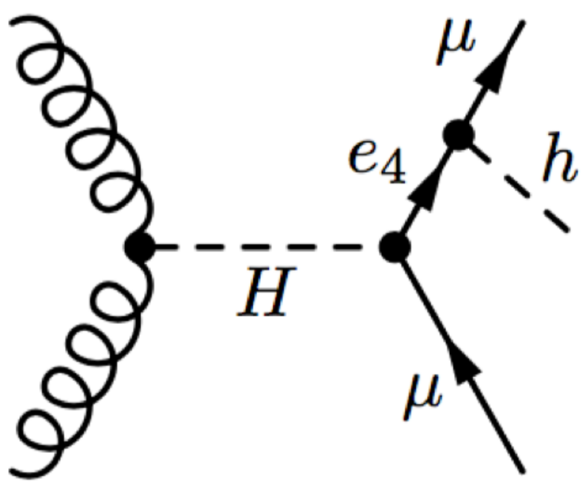


H ⟶ h$\mu\mu$

perhaps the most interesting channel, and no limits

R.D., E. Lunghi and S. Shin, in progress





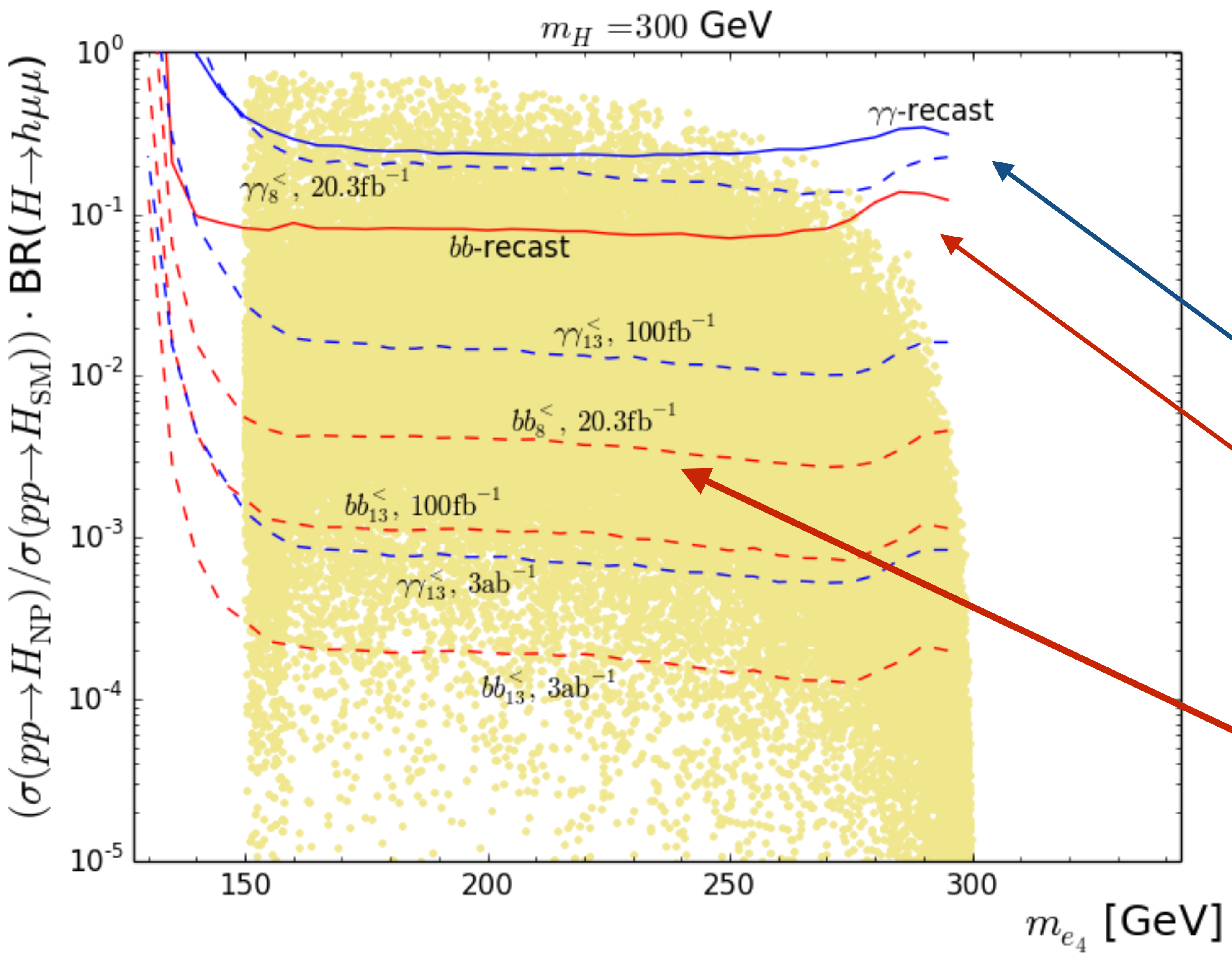
recast of ATLAS, 1407.4222

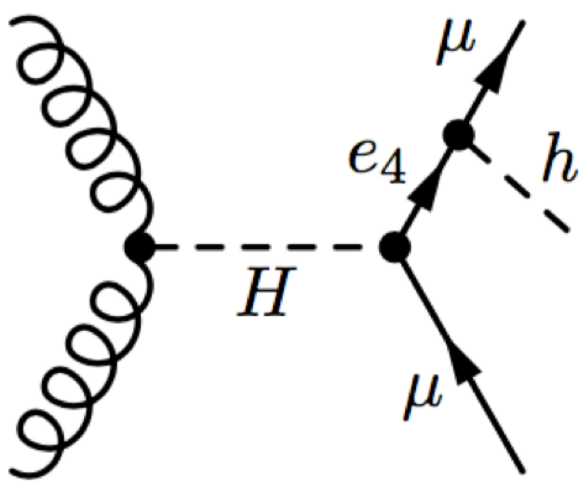
recast of ATLAS, 1409.6212

H → h$\mu\mu$

perhaps the most interesting channel, and no limits

R.D., E. Lunghi and S. Shin, in progress





recast of ATLAS, 1407.4222

recast of ATLAS, 1409.6212

sensitivity of existing analysis with additional off-Z cut

Conclusions

Heavy Higgs decays in models with VL:

- **Both heavy Higgses and VL independently motivated**
- **potentially large production cross section**
- **large branching ratios allowed**
- **Some of the decay modes are almost background free**

Great discovery prospects!