Vectorlike lepton in Higgs cascade decays:

Episode I - The Three Resonances

Seodong Shin

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R. Dermisek, E. Lunghi, S. Shin, arXiv:1512.07837, Accepted by JHEP

R. Dermisek, E. Lunghi, S. Shin, arXiv:1605.xxxxx

Why Vectorlike Leptons?

- Unification of gauge couplings in non-SUSY models (SM + 3VF)

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

- Simple framework explaining various anomalies
  (Acquire masses independently of their Yukawa couplings)

  - muon g-2 (VLL mixing with μ) Dermisek, Raval, PRD88, 013017 (2013)

  - For charged fermion, h → $\gamma\gamma$ or X → $\gamma\gamma$ (750 GeV ?)

  - Raise Higgs mass in SUSY models Martin, Phys. Rev. D 81, 035004 (2010)

  - Pure bino LSP scenario with right relic without resonance or co-ann.
    (new ann. channel without helicity suppression)

    Abdullah, Feng, Phys. Rev. D 93, 015006 (2016)

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Direct search at the LHC is required!

Direct search at the LHC needed

minimally

	ℓ_L	e_R	$L_{L,R}$	$E_{L,R}$
$SU(3)_C$	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**2**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	-1

Direct search at the LHC needed

	ℓ_L	e_R	$L_{L,R}$	$E_{L,R}$	$N_{L,R}$
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forbid mixing with the SM leptons?

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forbid mixing with the SM leptons?

Direct search classified by the production channels of VLL

- Gauge interaction: Drell-Yan process
- Yukawa interaction: Higgs (or BSM scalar) decay

Direct search at the LHC needed

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~~$\mathbb{Z}_2$?~~	~~1~~	~~1~~	~~-1~~	~~-1~~	~~-1~~

~~forbid mixing with the SM leptons?~~

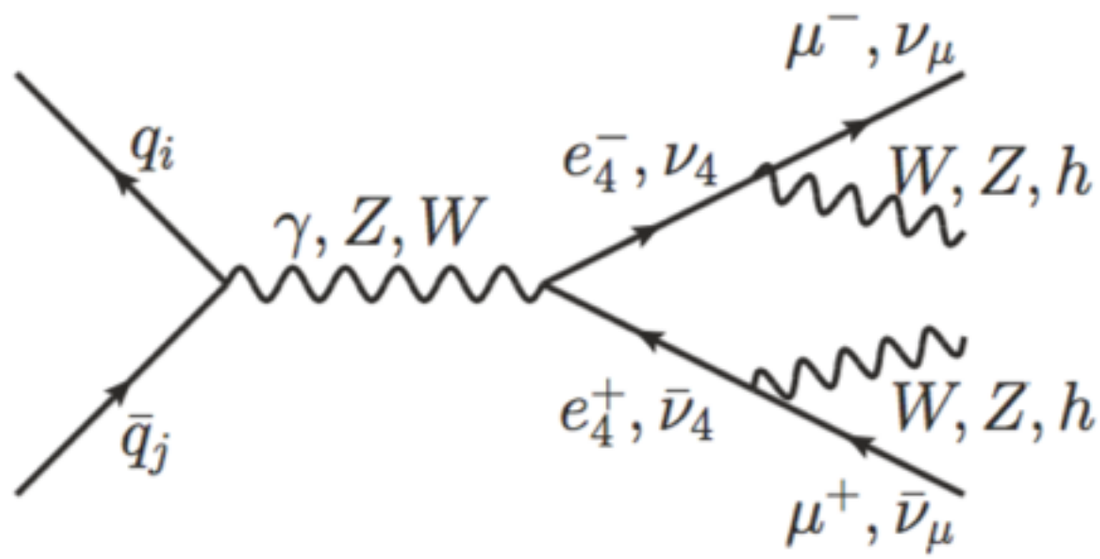
My setup

- Scenario of VLL mixing with SM lepton: here, μ from muon g-2
- μ,ν_μ gauge/Yukawa couplings modified & off-diagonal couplings (μ,ν_μ)-(e_4,ν_4)
- Approximate muon number on VLL: to avoid huge LFV

Productions of VLL: Drell-Yan (pair)

e_4 : charged

ν_4 : neutral



Multilepton (3+ charged SM leptons) + missing E_T

Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 [arXiv:1408.3123]

- 8TeV data already constrain $\sigma\times$BR: particularly $e_4\nu_4$ (up to 500-600 GeV)
- Mixing with τ ? : about an order of magnitude weaker except ~ 105 GeV

See also Kumar and Martin, Phys. Rev. D 92, 115018

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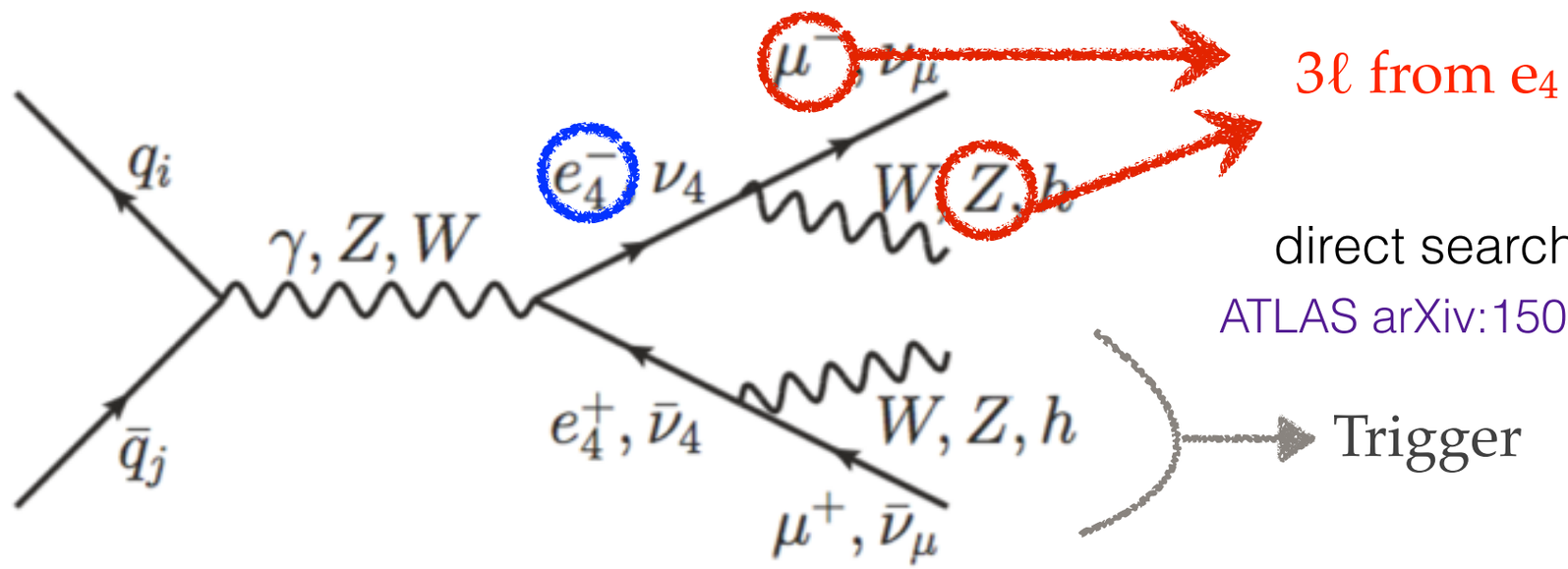

direct search

ATLAS arXiv:1506.01291

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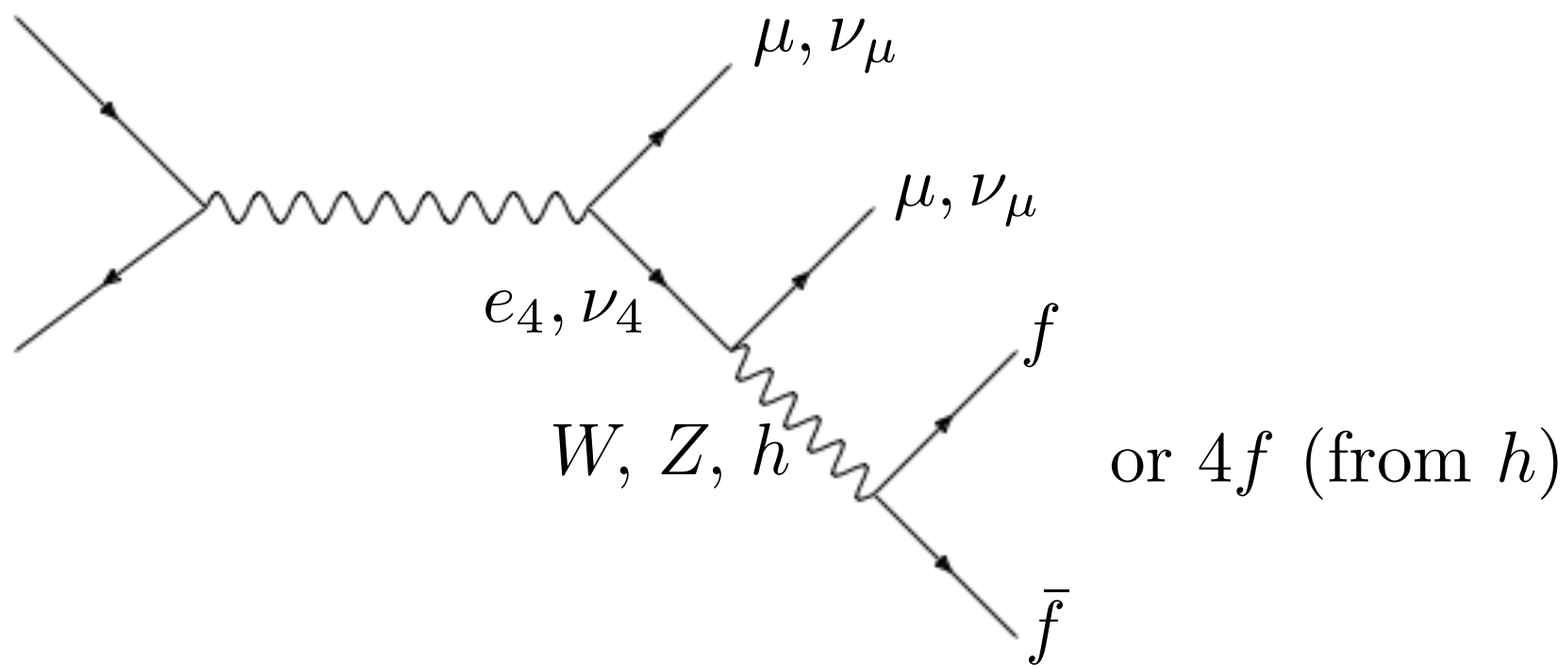
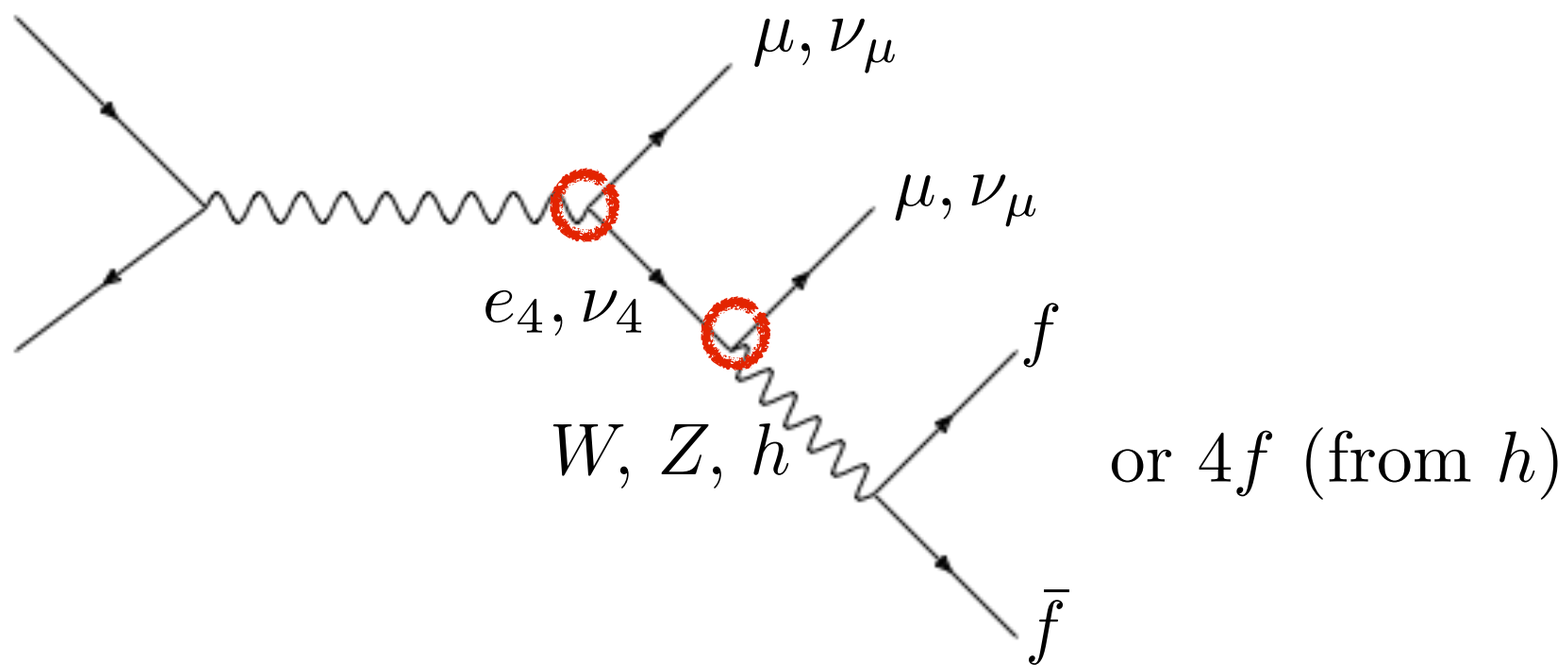


Dermisek, Lunghi, Shin, JHEP1602, 119 [arXiv:1509.04292]

Productions of VLL: Drell-Yan (single)

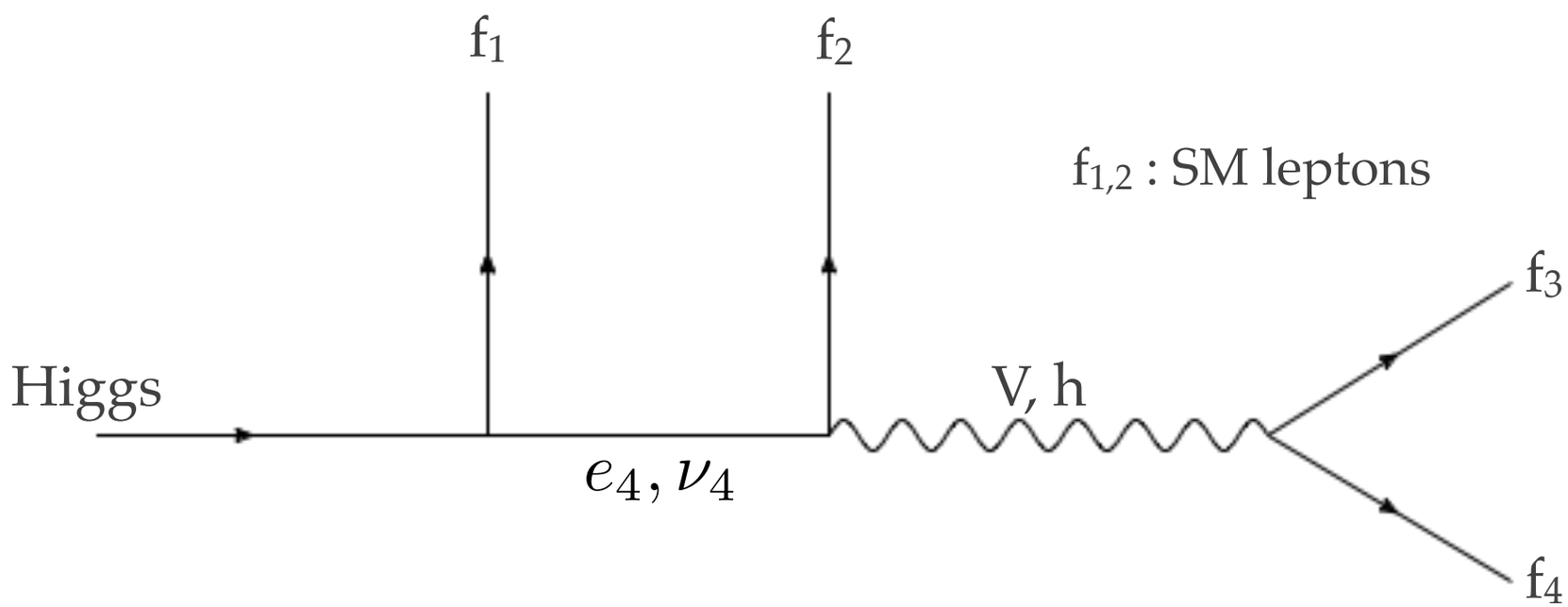
off-diagonal coupling: constrained by EWPT



Dermisek, Lunghi, Shin, JHEP1602, 119 [arXiv:1509.04292]

- 8TeV results: multilepton signal constrain weaker than EWPT
- Sensitive in the future data: HL-LHC, ILC

Productions of VLL: Higgs decay



Production rate is high : ggF + phase space

- SM Higgs exotic decay producing WW* and ZZ* like final states

  Dermisek, Raval, Shin, PRD 90, 034023 (2014) [arXiv:1406.7018]

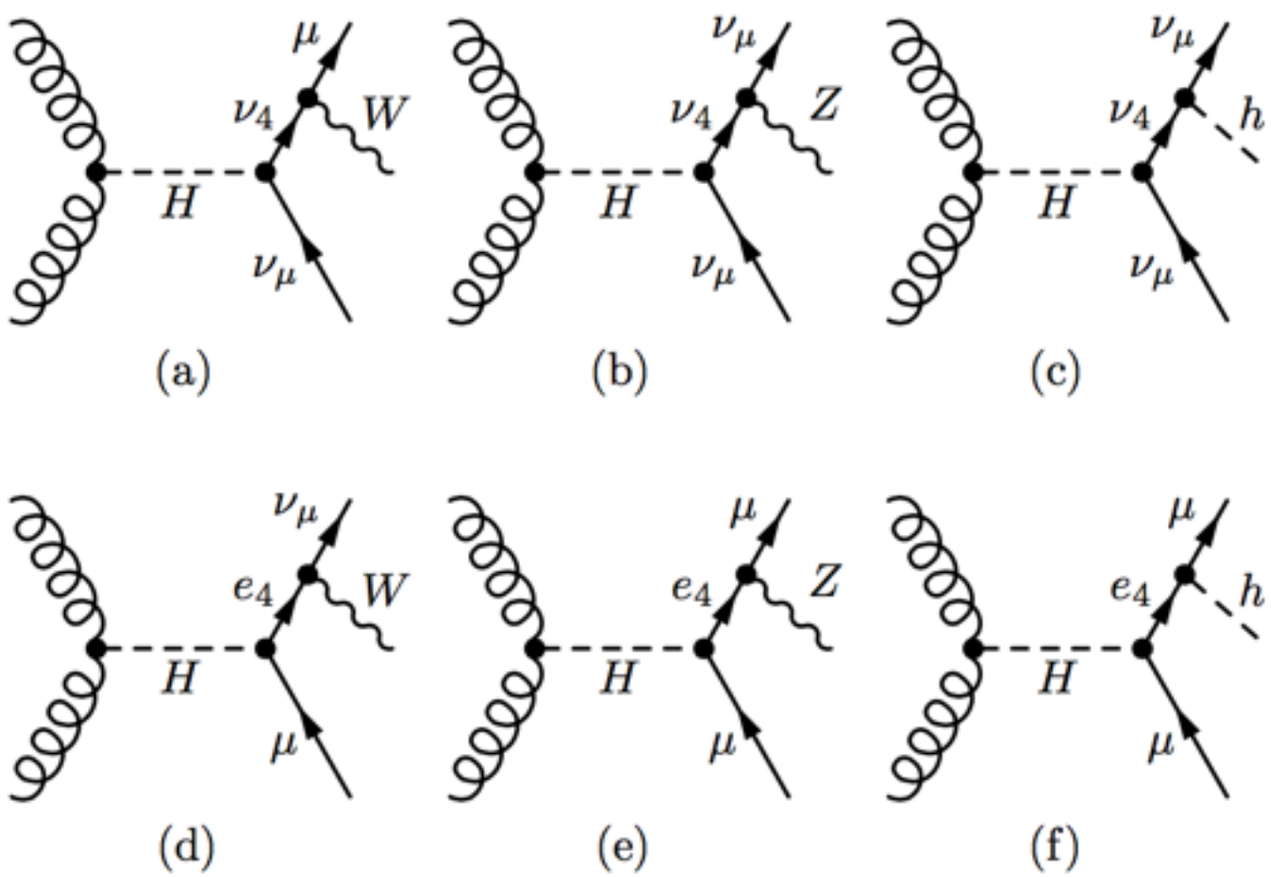
- Heavy BSM Higgs cascade decays

  Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015) [arXiv:1503.08829]
  & JHEP1602, 119 [arXiv:1509.04292]

VLL extended THDM type-II

Heavy Higgs decays: WW, ZZ, Zh like signals

Dermisek, Lunghi, Shin, arXiv:1512.07837



- Alignment limit: H→~~WW,ZZ~~
- Dominant when $m_H \lesssim 340$ GeV

Focus on this region

VLL extended THDM type-II

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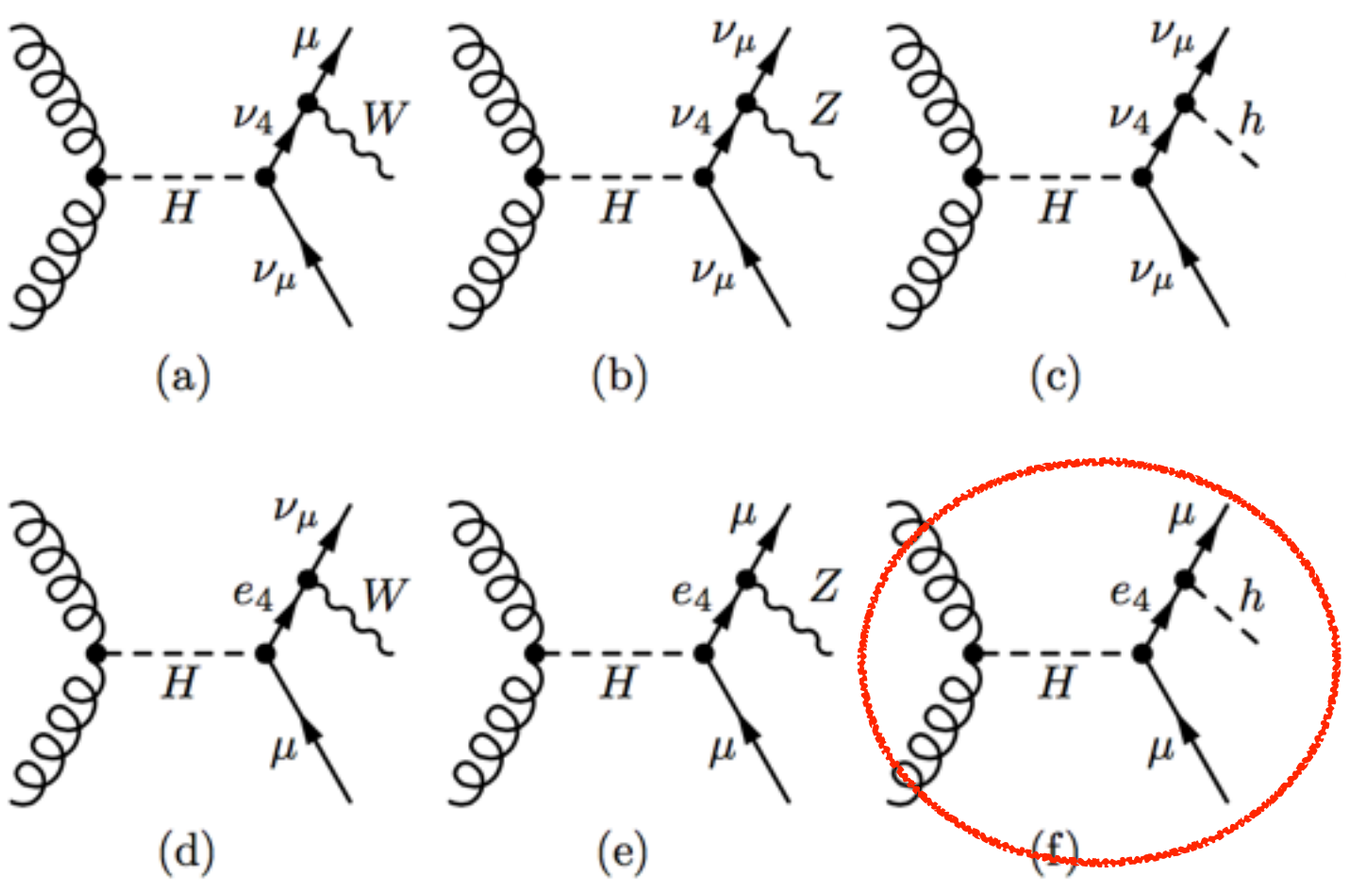


(multi-) Higgs cascade decay

- The three resonances from H, e_4, and h
- Unique signature

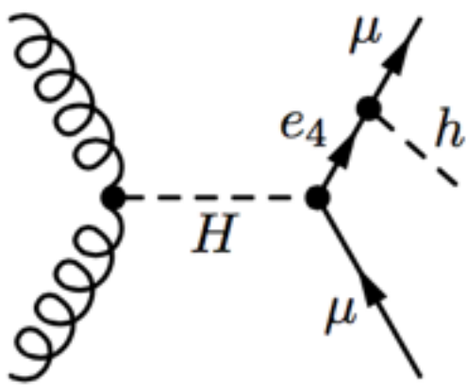
$$\gamma\gamma\mu^+\mu^-$$

$$4\ell + E_T^{\rm miss}$$

$$6\ell$$

VLL extended THDM type-II

Final state categories



$h \to b\bar{b}$

$h \to \tau^+\tau^-$

$h \to WW^* \to 2\ell 2\nu_\ell$

$h \to \gamma\gamma$

$h \to \mu^+\mu^-$

$h \to ZZ^* \to 4\ell$

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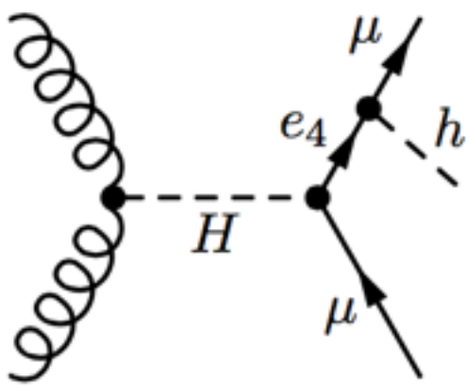


$h \to b\bar{b}$ → $b\bar{b}\mu^+\mu^-$

Many signals & backgrounds

$h \to \tau^+\tau^-$

$h \to WW^* \to 2\ell 2\nu_\ell$

$h \to \gamma\gamma$ → $\gamma\gamma\mu^+\mu^-$

Less signals & almost no backgrounds

$h \to \mu^+\mu^-$

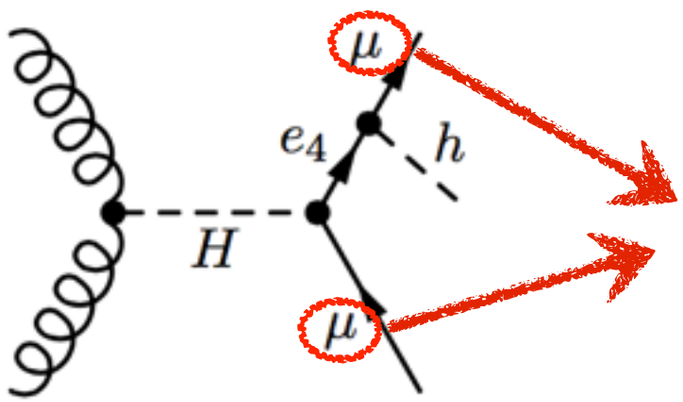
$h \to ZZ^* \to 4\ell$

Experimental sensitivities on the BR of the new decay mode

$$\mathrm{BR}(H \to h\mu\mu) \equiv \mathrm{BR}(H \to e_4^+\mu^-) \times \mathrm{BR}(e_4^+ \to h\mu^+) + \mathrm{BR}(H \to e_4^-\mu^+) \times \mathrm{BR}(e_4^- \to h\mu^-)$$

VLL extended THDM type-II

Crucial selection cuts



In a large range of masses m_H, m_{e_4}

dimuon invariant mass $|m_{\mu\mu} - M_Z| > 15$ GeV

(but still $m_{\mu\mu} > 20$ GeV) off-Z

distinguish from background: Z + jets, ZZ, hZ

VLL extended THDM type-II

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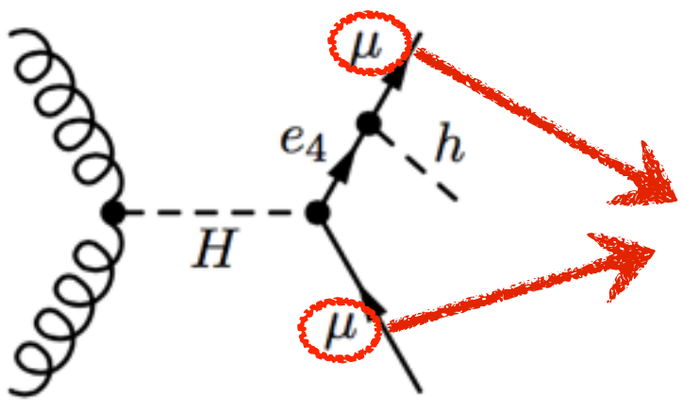

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$b\bar{b}\mu^+\mu^-$

$\gamma\gamma\mu^+\mu^-$

no missing E: distinguish from $t\bar{t}$, $ht\bar{t}$

$\not{E}_T$ cut

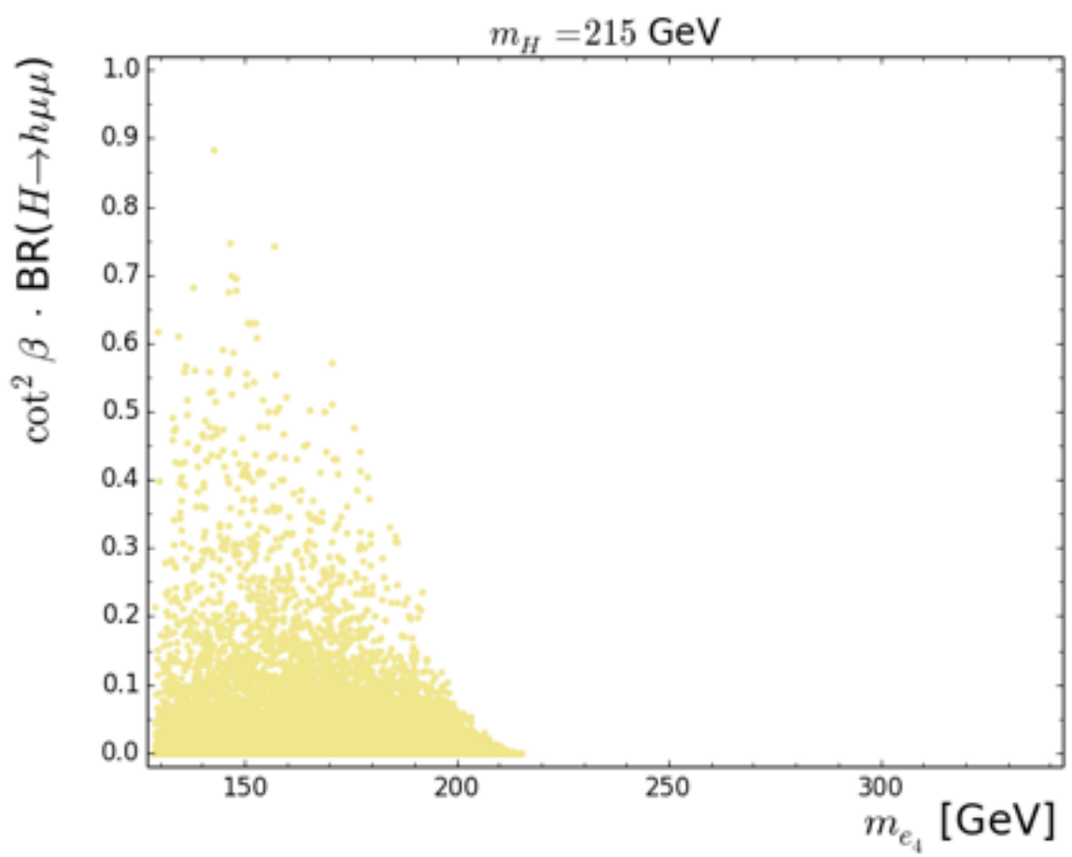
Experimental sensitivities

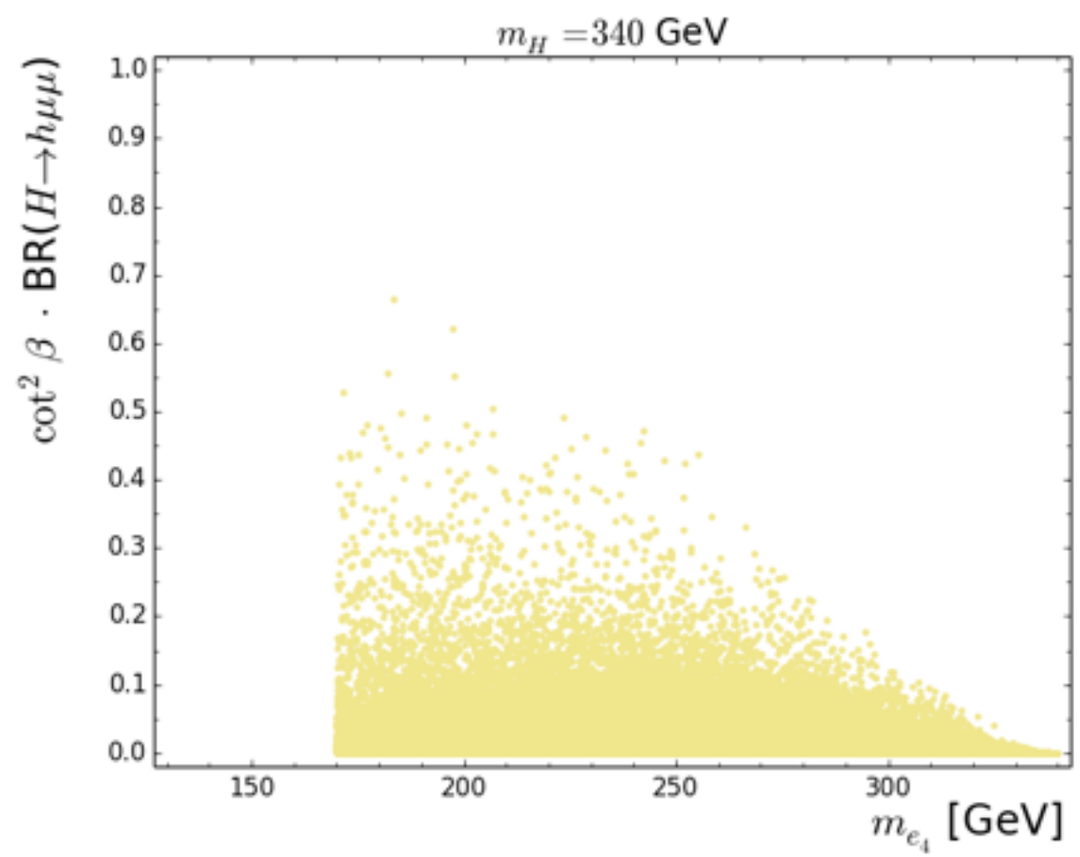
- EW precision data, multilepton + $\not{E}_T$, h→$\gamma\gamma$, H→WW,$\gamma\gamma$

- Recast from the existing searches A→hZ, h→$\gamma\gamma$ + a SM lepton

ATLAS, 1503.08089 ATLAS, 1407.4222

- Expected experimental sensitivities: new cut at 8 TeV & future data





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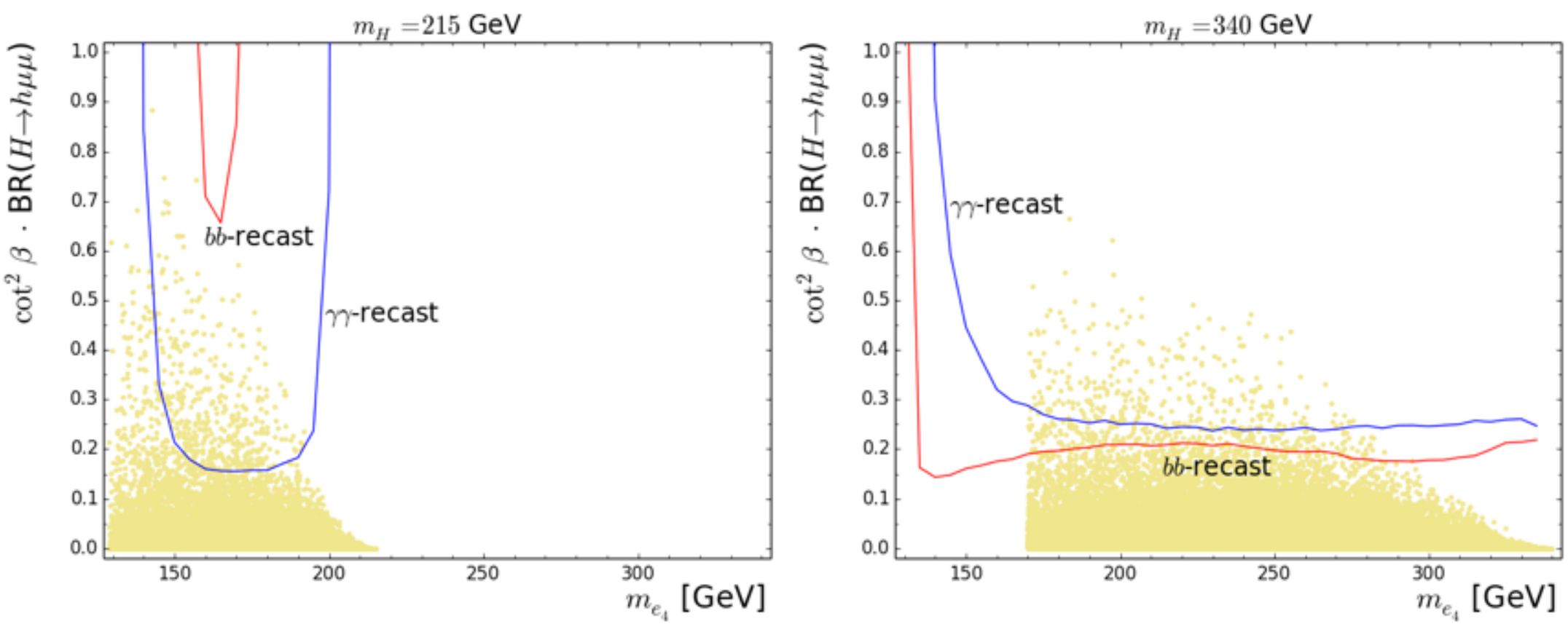

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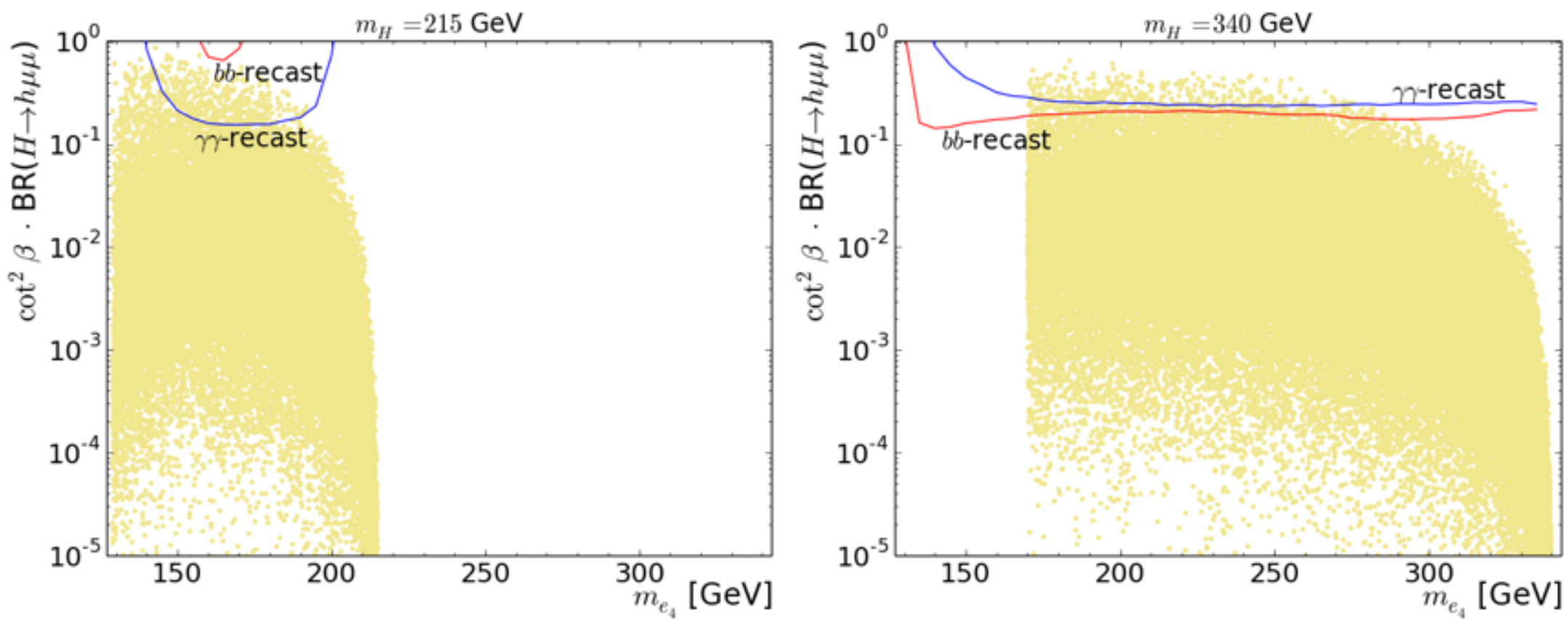

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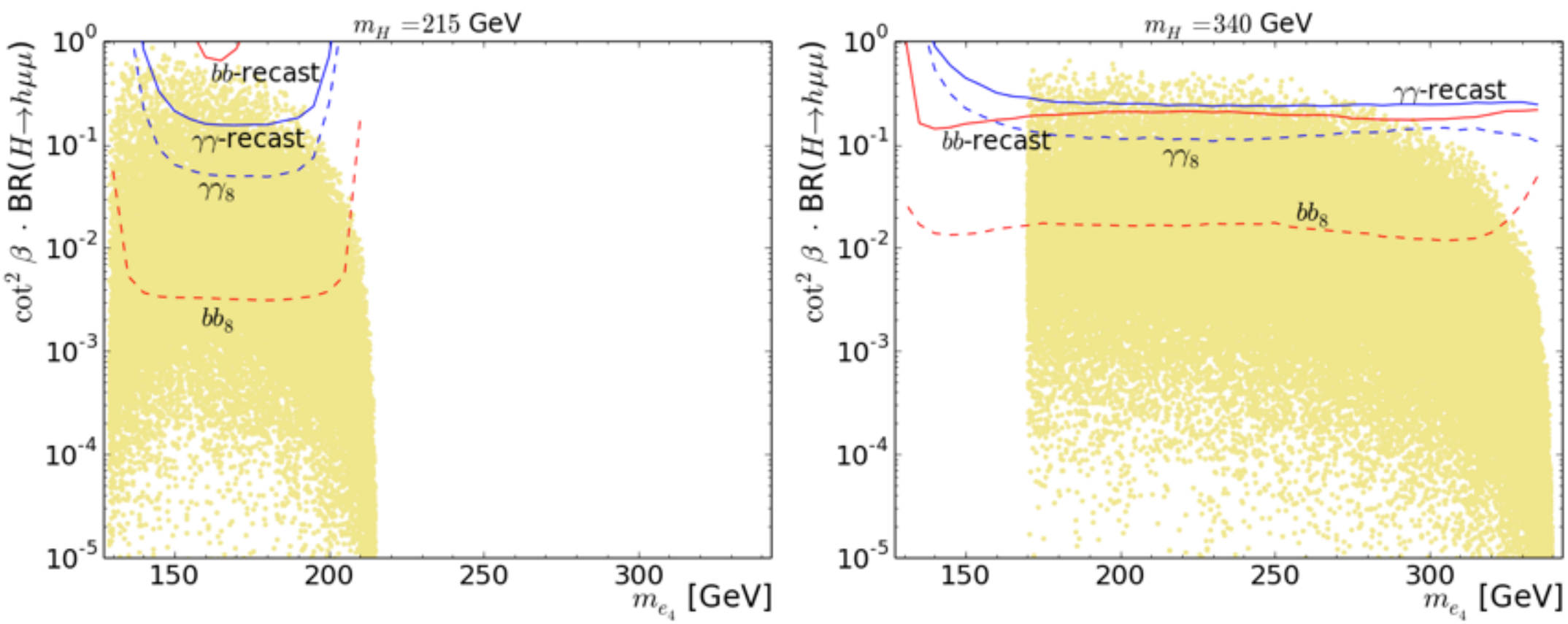
bb$\mu\mu$ is more sensitive!



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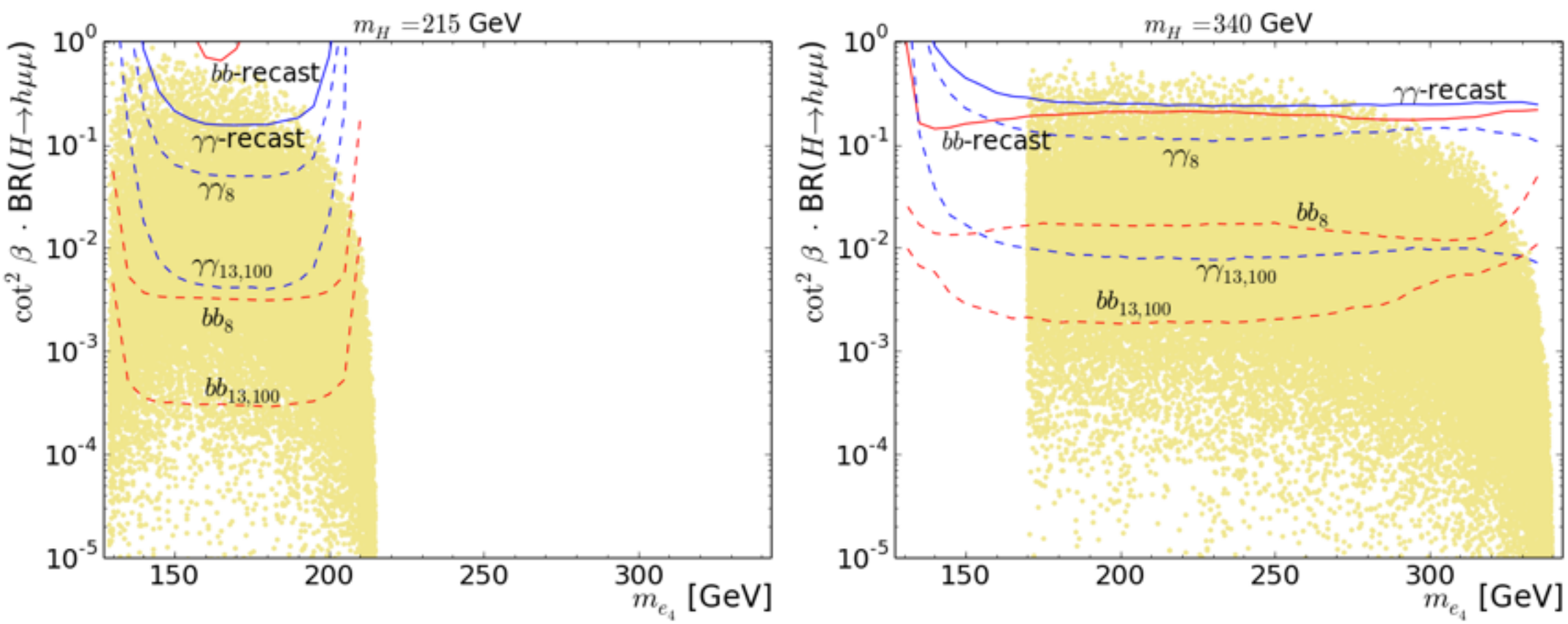

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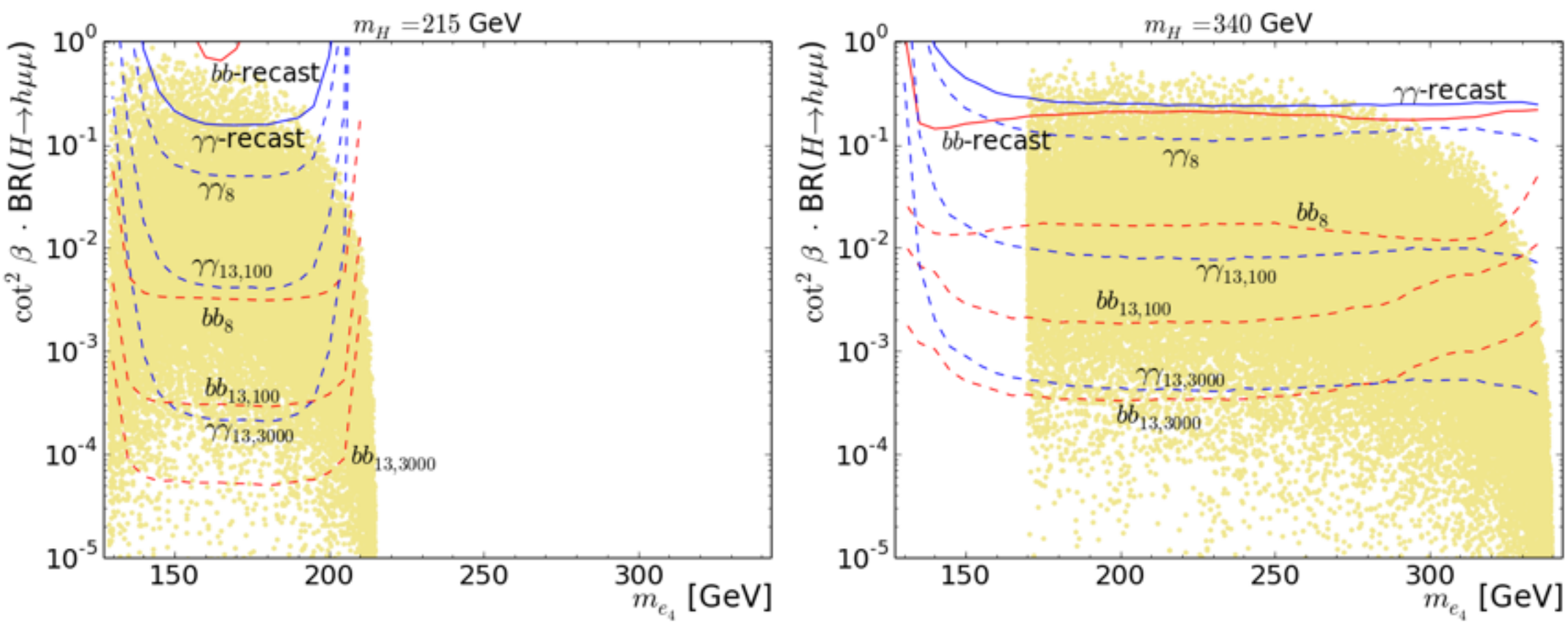
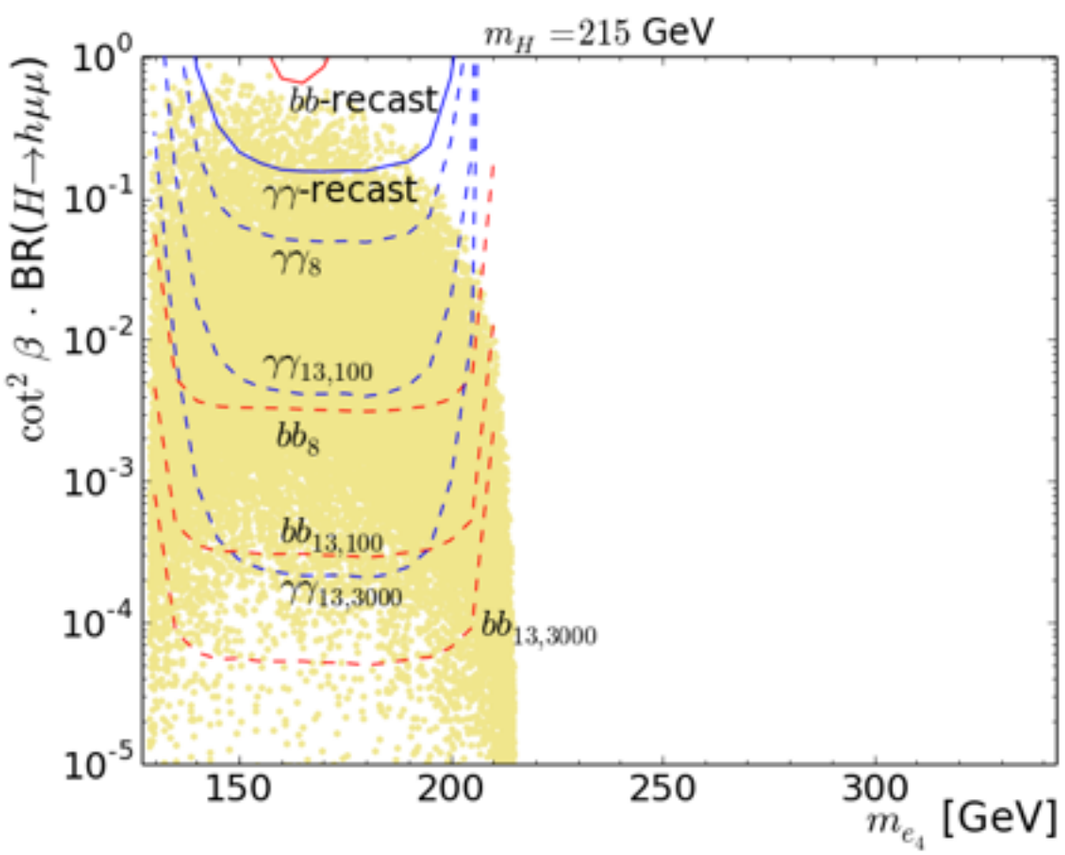
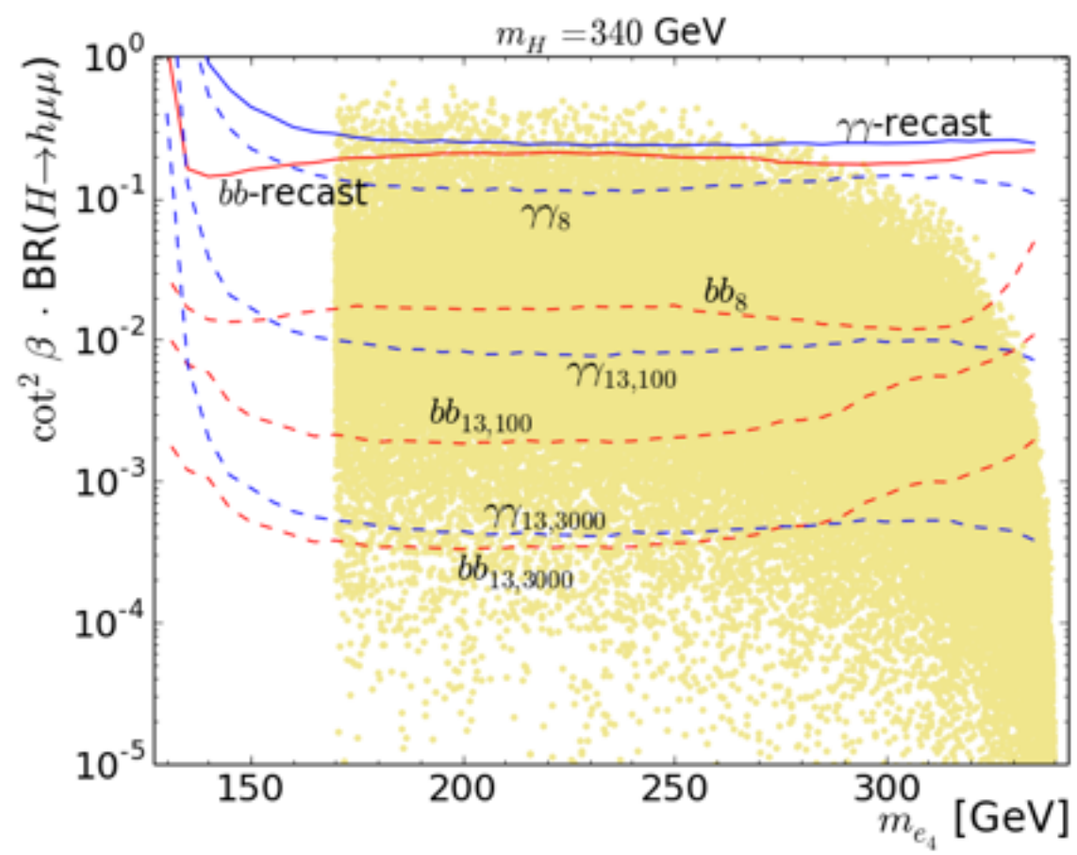


Experimental sensitivities

- bb$\mu\mu$ is more sensitive than $\gamma\gamma\mu\mu$: background subtraction good
- Multi-Variate Analysis: even 5 times better with naive assumptions
- Our results apply for general models with heavy Higgs & VLL





Conclusions

- Charged vectorlike lepton in a Higgs cascade decay:
  3 resonance signals from H, e_4, h

- Expected discovery: bb$\mu\mu$, $\tau\tau\mu\mu$, $4\ell 2\nu$, $\gamma\gamma\mu\mu$, 6ℓ (or 4μ)
  Background subtraction is good enough (off-Z cut)

- Heavier lepton: compete with H→tt (check for large tanβ)

- Pair production from H: doubled final states (antler topologies)
  phase space small

- Similar approaches are possible in searching Vectorlike Quarks

Back up

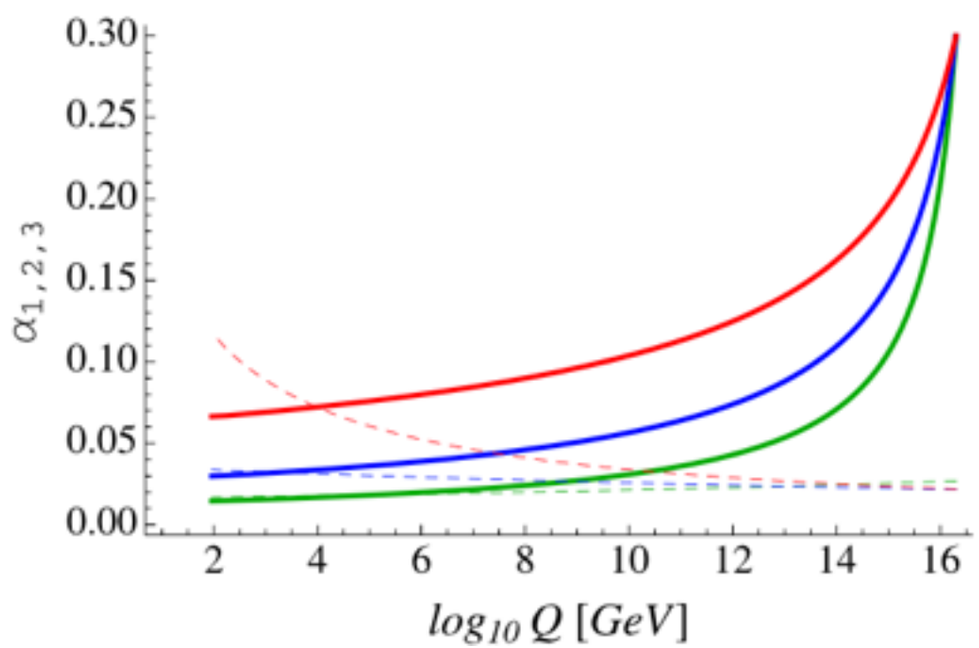
Unification of gauge couplings in a simple non-SUSY model (SM + 3VF)

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

- A unification with large α_G : infrared fixed point behavior
- Threshold corrections from Vectorlike Fermion masses $< O(100\ \text{TeV})$
- Some vectorlike fermions < 1 TeV : investigation at the LHC is possible

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

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



$$\alpha_G = 0.3$$
$$M_G = 2\times 10^{16}\ \text{GeV}$$

$$\frac{d\alpha_i}{dt} = \beta(\alpha_i) = \frac{\alpha_i^2}{2\pi}b_i$$

$$b_i = \left(\frac{1}{10} + \frac{4}{3}n_f, -\frac{43}{6} + \frac{4}{3}n_f, -11 + \frac{4}{3}n_f\right)$$

$$n_f = 3 + 2\times 3 = 9$$

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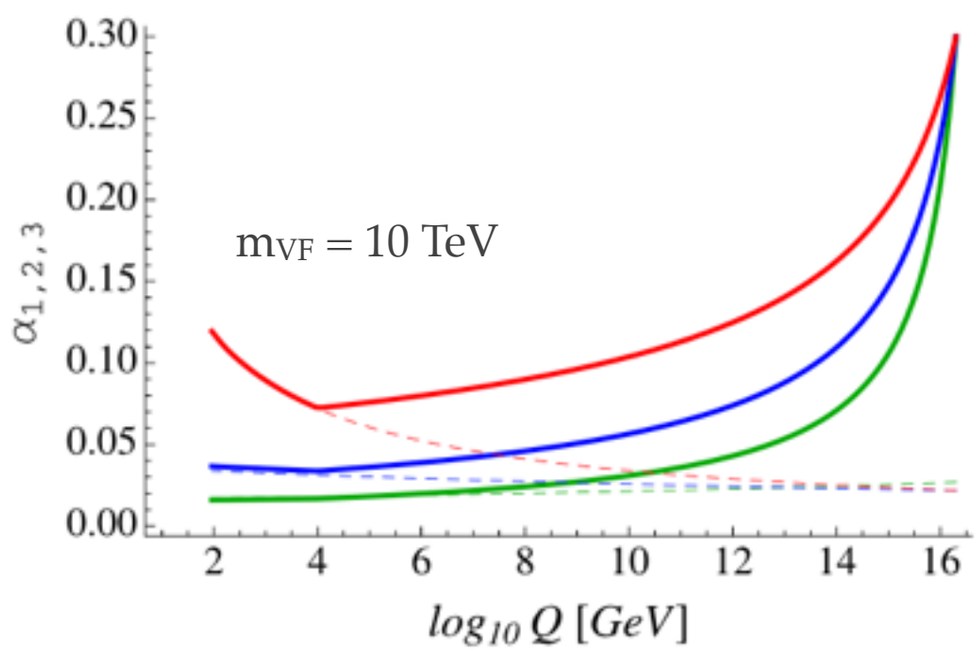
Insensitive unification



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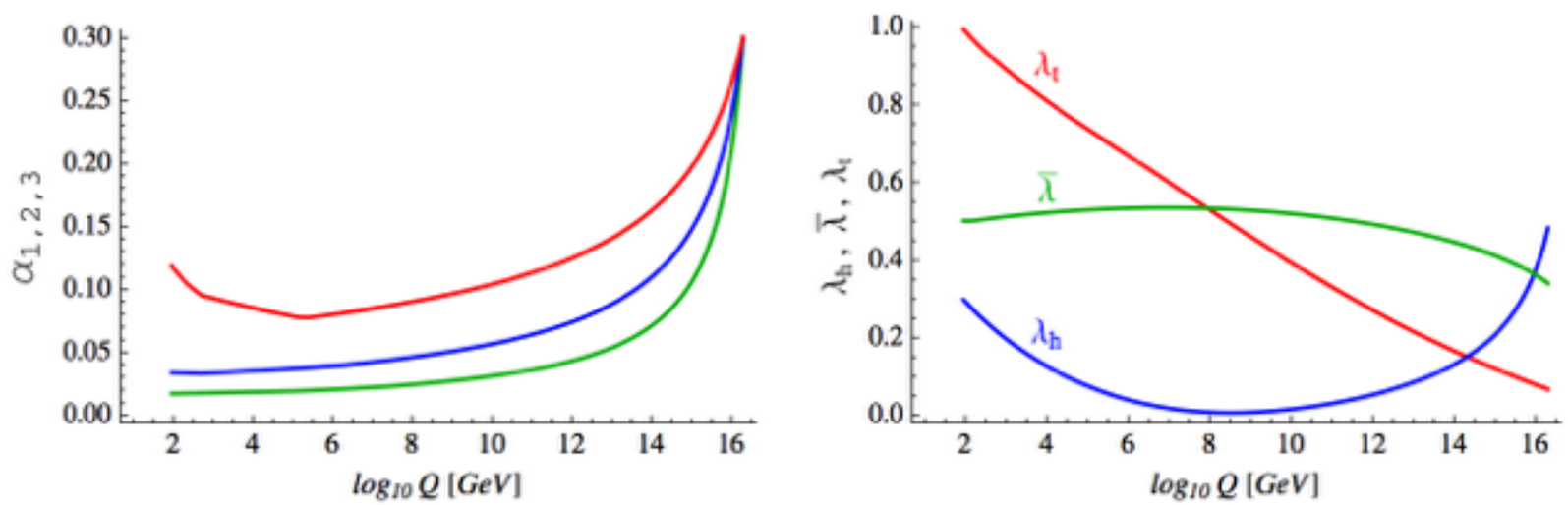
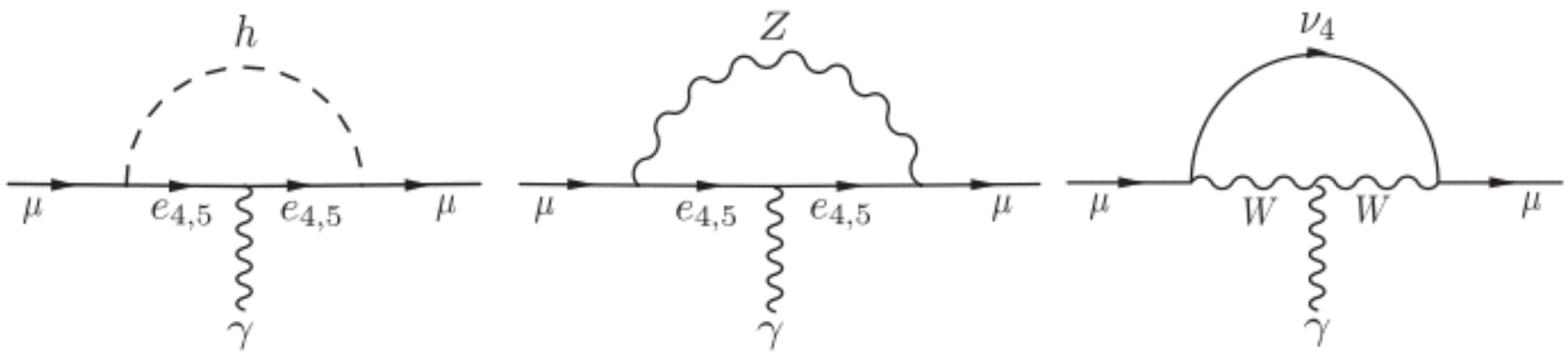


Left: the RG evolution of gauge couplings, α_3 (top), α_2 (middle), and α_1 (bottom), in the SM extended by three vectorlike families for $\alpha_G = 0.3$ at $M_G = 2 \times 10^{16}$ GeV. Right: the RG evolution of the Higgs quartic coupling for $m_h = 126$ GeV, the top Yukawa coupling, and the $\bar{\lambda}$ with the EW scale value of 0.5. The masses of vectorlike fermions are $M_{L_1} = M_{E_1} =$ 150 GeV, $M_{L_{2,3}} = 2.0 \times 10^6$ GeV, $M_{E_{2,3}} = 2.4 \times 10^7$ GeV, $M_Q = 520$ GeV, $M_U = 1.4 \times 10^5$ GeV, and $M_D = 2.5 \times 10^5$ GeV.

Back up

Dermisek, Raval, PRD88, 013017 (2013)



Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)

Back up

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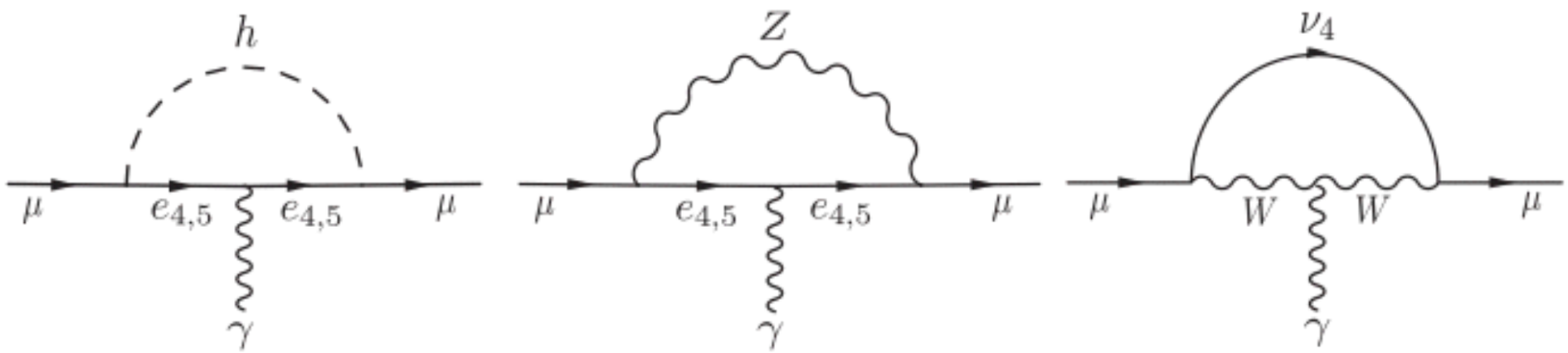


Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)

same chiral structure

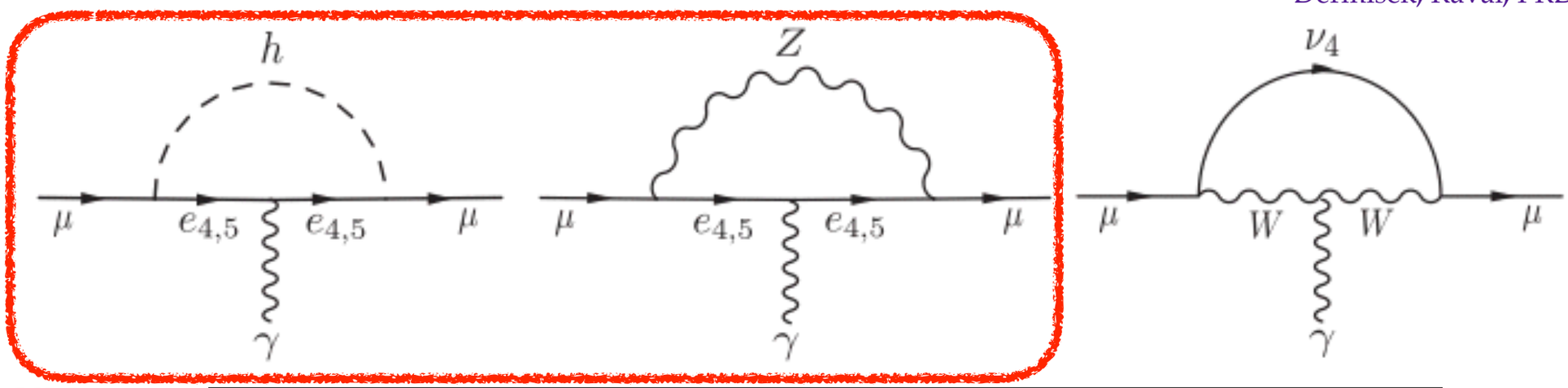
Correlated with the physical <u>muon mass</u>

$$\mathcal{L}_{\rm eff} \supset -\bar{\mu}_L\left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger\right)\mu_R H + \text{H.c.}$$
$$\to -(m_\mu^H + m_\mu^{LE})\bar{\mu}_L \mu_R + \text{H.c.},$$

$$\Delta a_\mu \simeq c\frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85c\frac{m_\mu^{LE}}{m_\mu}\Delta a_\mu^{\rm exp}.$$

Back up

Dermisek, Raval, PRD88, 013017 (2013)



heavy VLL

Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)

same chiral structure

Correlated with the physical muon mass

$\Delta a_\mu^{\rm obs.}$

Effective Yukawa coupling

$$\mathcal{L}_{\rm eff} \supset -\bar{\mu}_L\left(y_\mu + \frac{\lambda^L \bar{\lambda} \lambda^E}{M_L M_E} H H^\dagger\right)\mu_R H + \text{H.c.}$$
$$\to -(m_\mu^H + m_\mu^{LE})\bar{\mu}_L \mu_R + \text{H.c.},$$

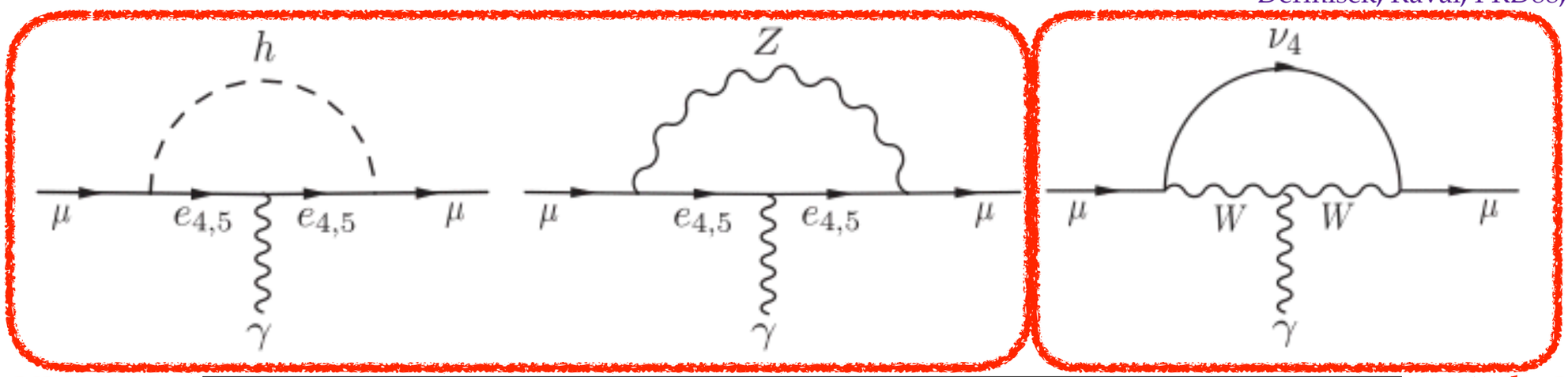
$$m_\mu^{LE}/m_\mu \simeq -1 \quad \text{for } M_L \gg M_Z$$

$$y_\mu = -(y_\mu)^{\rm SM}$$

$$\Delta a_\mu \simeq c\frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85c\frac{m_\mu^{LE}}{m_\mu}\Delta a_\mu^{\rm exp}.$$

Back up

Dermisek, Raval, PRD88, 013017 (2013)



heavy VLL

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Enhanced by the helicity flip on the masses of $e_{4,5}$ & $\nu_{4,5}$

Yukawa between VLL & muon (doublets and singlets)

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Correlated with the physical <u>muon mass</u>

$\Delta a_\mu^{\rm obs.}$

Effective Yukawa coupling

$$\mathcal{L}_{\rm eff} \supset -\bar{\mu}_L\left(y_\mu + \frac{\lambda^L \bar{\lambda}\lambda^E}{M_L M_E} HH^\dagger\right)\mu_R H + \text{H.c.}$$
$$\to -(m_\mu^H + m_\mu^{LE})\bar{\mu}_L\mu_R + \text{H.c.},$$

$$m_\mu^{LE}/m_\mu \simeq -1 \quad \text{for } M_L \gg M_Z \qquad y_\mu = -(y_\mu)^{\rm SM}$$

$$m_\mu^{LE}/m_\mu \simeq 1 \quad \text{for } M_L \simeq M_Z \qquad y_\mu = 3(y_\mu)^{\rm SM}$$

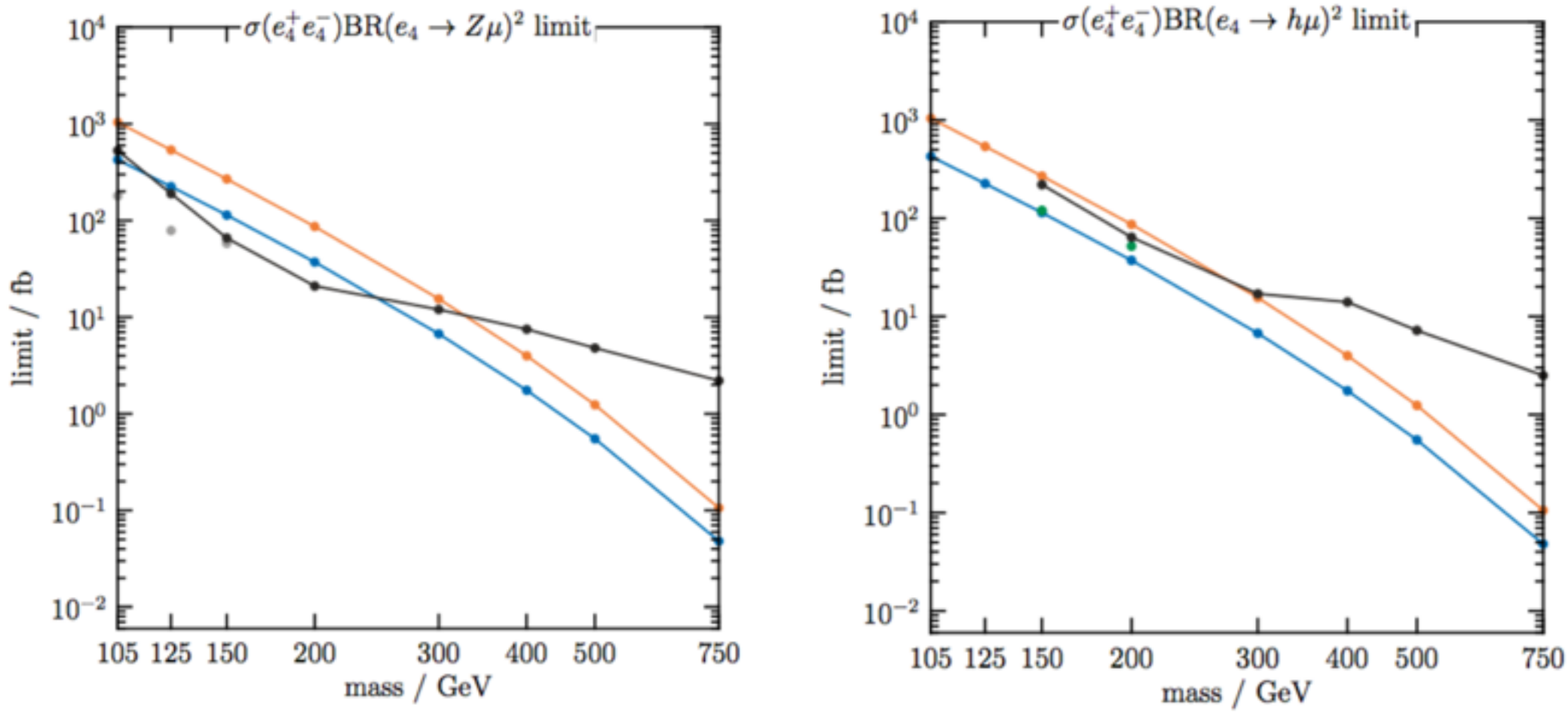
$$\Delta a_\mu \simeq c\frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85c\frac{m_\mu^{LE}}{m_\mu}\Delta a_\mu^{\rm exp}.$$

h→$\mu\mu$ fully from the mixing satisfying (g-2)$_\mu$

$$R_{\mu\mu} \equiv \frac{\Gamma(h\to\mu^+\mu^-)}{\Gamma(h\to\mu^+\mu^-)_{\rm SM}}.$$

Back up

Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 [arXiv:1408.3123]



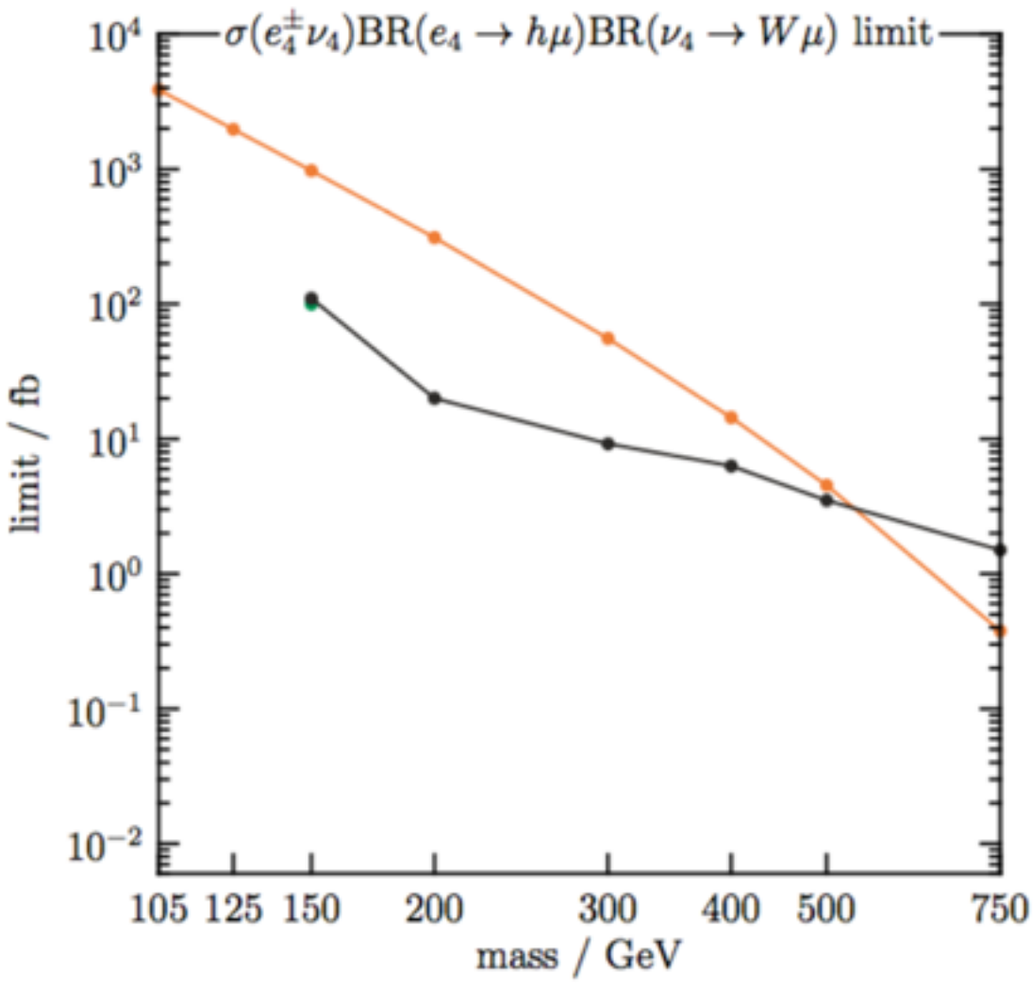
Black : upper bounds

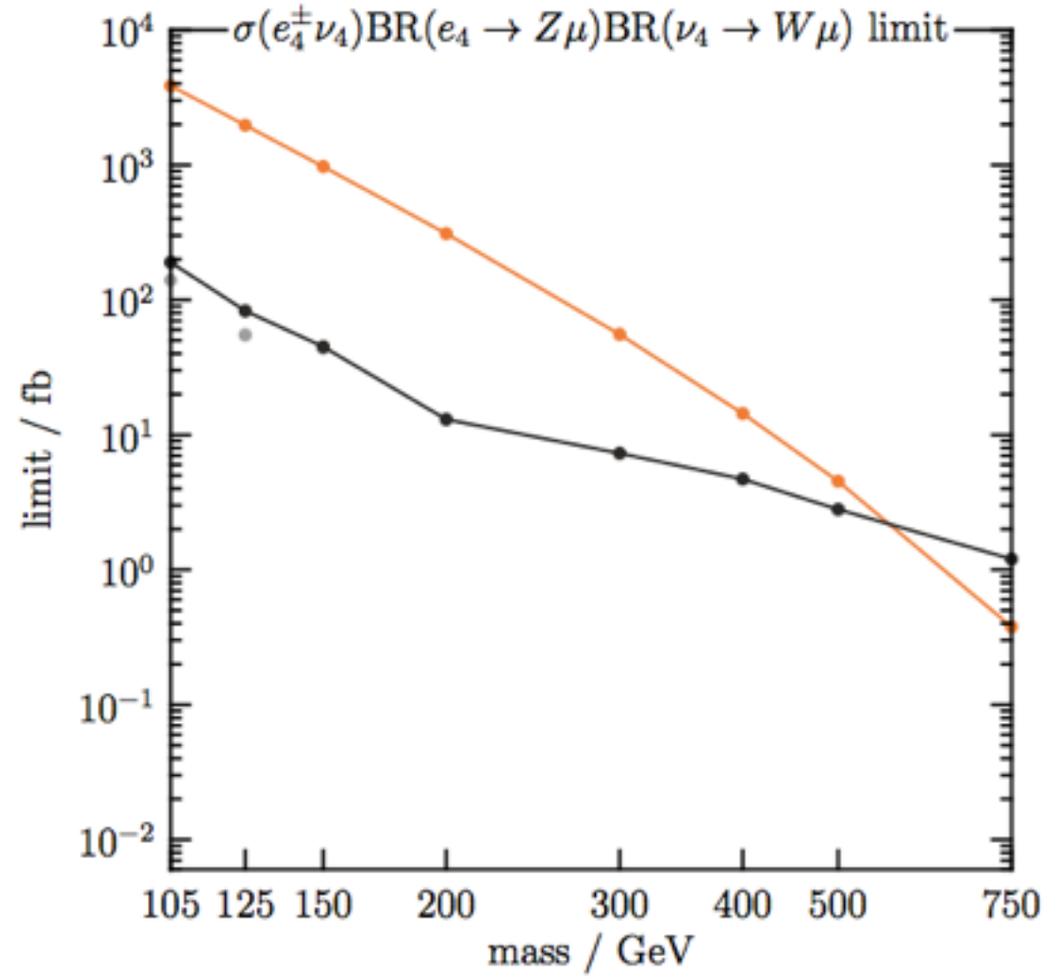
Red : predicted production cross sections of doublets

Blue : predicted production cross sections of singlets

Back up

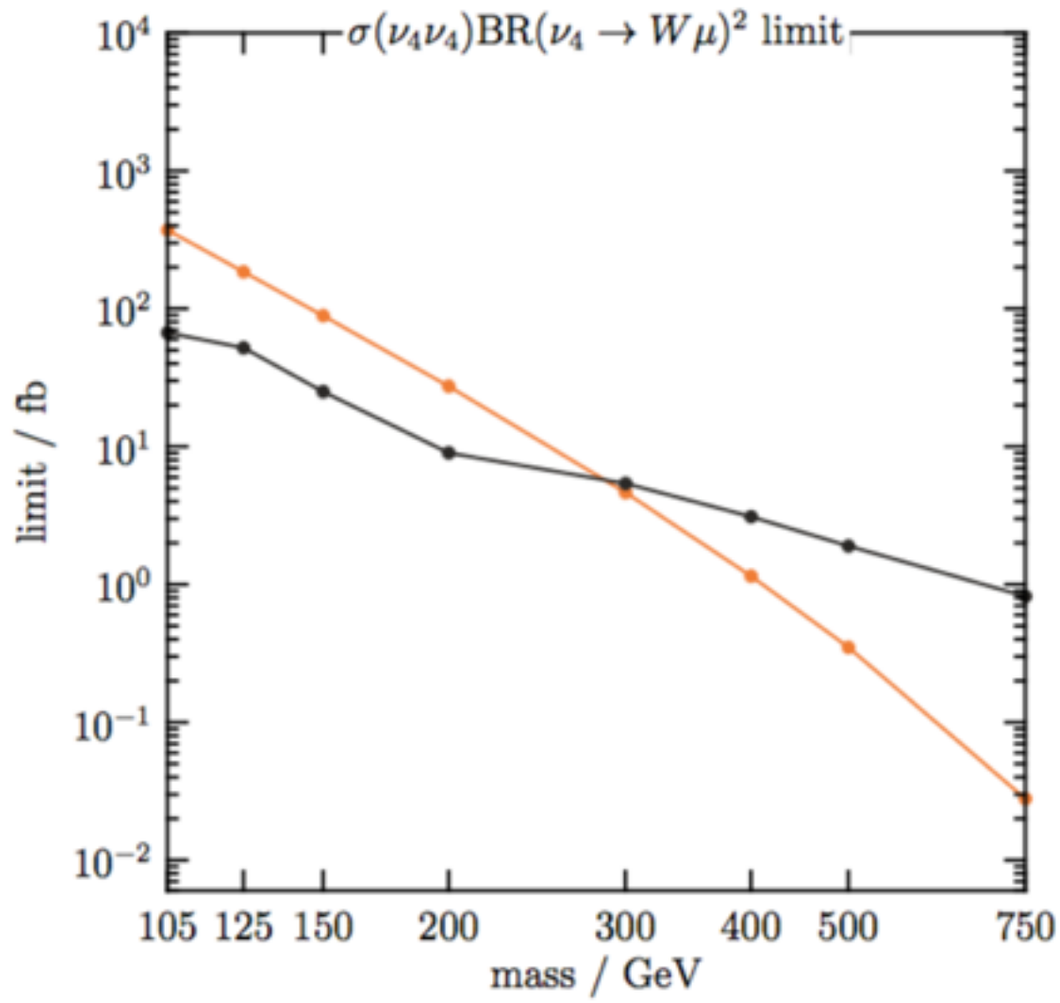
Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 [arXiv:1408.3123]





Back up

Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 [arXiv:1408.3123]



Strong constraints for the decay mode $\nu_4 \to W\mu$

Back up

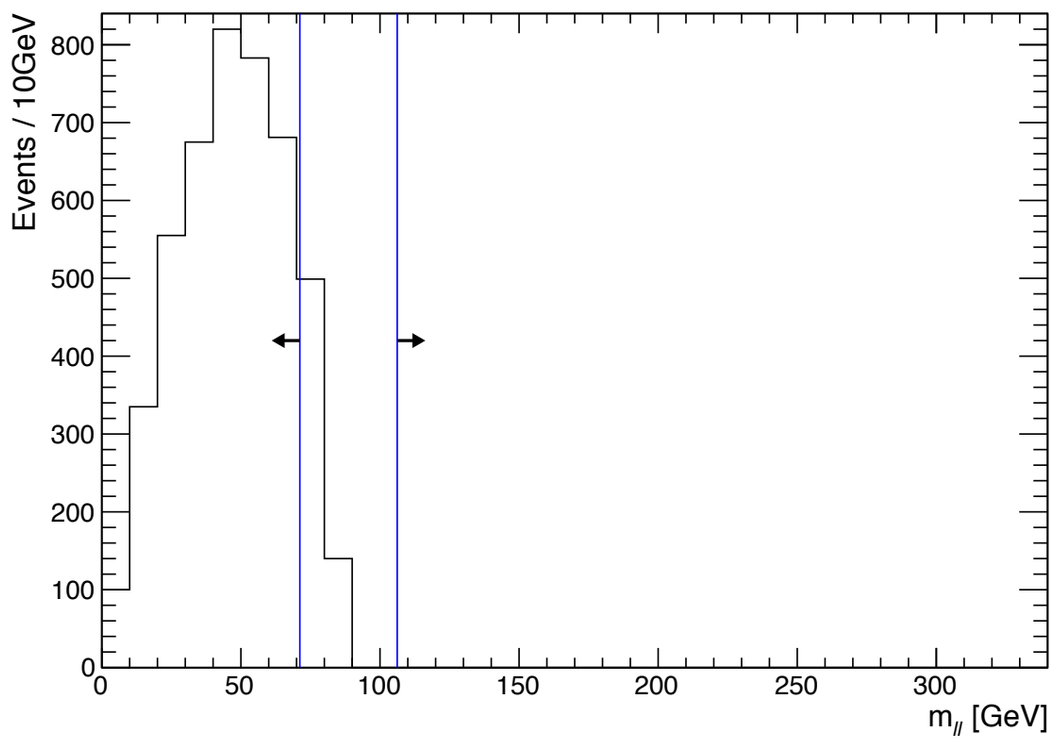
Dermisek, Hall, Lunghi, Shin, JHEP 1404, 140 [arXiv:1408.3123]

	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								
$\sigma(e_4^+e_4^-)\times$ 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
$\sigma(e_4^+e_4^-)\times$ BR$(e_4\to Z\mu)$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
$\sigma(e_4^+e_4^-)\times$ BR$(e_4\to Z\mu)$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
$\sigma(e_4^+e_4^-)\times$ BR$(e_4\to W\nu)$BR$(e_4\to h\mu)$			370 Ab	130 Ab	67 Ab	41 Ac	28 Ac	11 Am	7.2 Am
$\sigma(e_4^+e_4^-)\times$ BR$(e_4\to h\mu)^2$			220 Aa	64 Ag	17 Ag	14 Ag	7.2 Ah	2.5 Am	2.1 Am
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to Z\mu)$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
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to Z\mu)$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
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to W\nu)$BR$(\nu_4\to Z\nu)$	2700 Cb	1800 Cb	1100 Cb	520 Cb	330 Cb	150 Cc	110 Cd	45 Cd	42 Cd
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to W\nu)$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
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to Z\mu)$BR$(\nu_4\to h\nu)$			1100 Aa	280 Cb	110 Cb	64 Cc	51 Cr	9.8 Cr	7.7 Cr
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to h\mu)$BR$(\nu_4\to Z\nu)$			1400 Aa	250 Cb	110 Cb	75 Cq	53 Cr	9.3 Cr	7.1 Cr
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to W\nu)$BR$(\nu_4\to h\nu)$			6400 Ab	5000 Ap	1800 Ab	1200 Bc	680 Ac	360 Ac	270 Bc
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to h\mu)$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
$\sigma(e_4^\pm\nu_4)\times$ BR$(e_4\to h\mu)$BR$(\nu_4\to h\nu)$			910 Aa	420 Ap	140 Ap	93 Aq	52 An	19 Am	13 Am
$\sigma(\nu_4\nu_4)\times$ 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
$\sigma(\nu_4\nu_4)\times$ BR$(\nu_4\to Z\nu)$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
$\sigma(\nu_4\nu_4)\times$ 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
$\sigma(\nu_4\nu_4)\times$ BR$(\nu_4\to Z\nu)$BR$(\nu_4\to h\nu)$			2800 Cb	830 Cb	380 Cb	220 Cc	160 Cc	79 Cd	72 Cd
$\sigma(\nu_4\nu_4)\times$ BR$(\nu_4\to W\mu)$BR$(\nu_4\to h\nu)$			320 Ag	120 Ag	61 Ag	40 Ac	27 Ac	11 Am	6.9 Am
$\sigma(\nu_4\nu_4)\times$ BR$(\nu_4\to h\nu)^2$			9400 Aa	6900 Ap	2800 Ab	1700 Bc	930 Bc	460 Bc	380 Bc

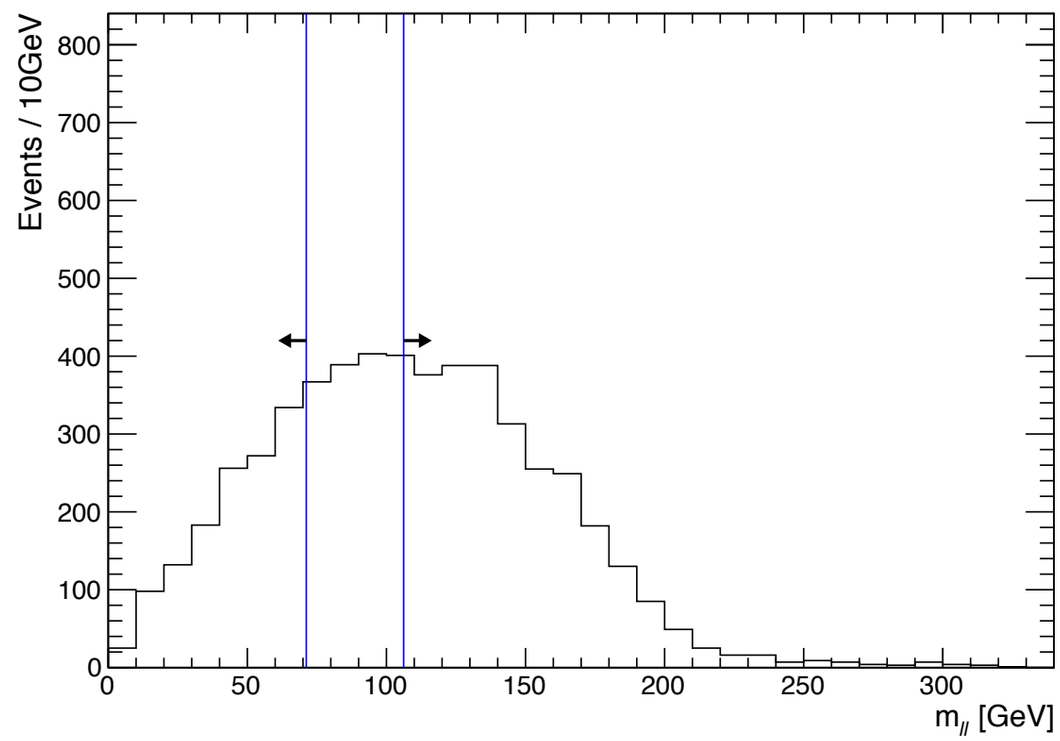
A	$\geq 3e/\mu$ off-Z
B	$2e/\mu + \tau_h$ off-Z
C	$\geq 3e/\mu$ on-Z
D	$2e/\mu + \tau_h$ on-Z
a	$H_T^j < 150\,\text{GeV}$
b	$H_T^j < 150\,\text{GeV}$, $\not{E}_T > 100\,\text{GeV}$
c	$H_T^j < 150\,\text{GeV}$, $\not{E}_T > 200\,\text{GeV}$
d	$H_T^j < 150\,\text{GeV}$, $\not{E}_T > 300\,\text{GeV}$
f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

20 possible processes

Back up



$m_H = 215\,\mathrm{GeV}\ , m_{e_4} = 170\,\mathrm{GeV}$



$m_H = 340\,\mathrm{GeV}\ , m_{e_4} = 170\,\mathrm{GeV}$

Back up: VLL extended THDM type-II

Dermisek, Lunghi, Shin, JHEP 1602, 119 [arXiv:1509.04292]

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

Most general renormalizable Lagrangian

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

Back up: VLL extended THDM type-II

Dermisek, Lunghi, Shin, JHEP 1602, 119 [arXiv:1509.04292]

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

Most general renormalizable Lagrangian

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