CIPANP2018

Heavy Higgs Search in the Models with Vectorlike Fermions

Seodong Shin

THE UNIVERSITY OF CHICAGO

YONSEI UNIVERSITY

Collaborations with R. Dermisek, E. Lunghi

Why Vectorlike Fermions?

SM: 3 generation of fermions

- No symmetric reason why only 3: additional fermions?
- Chiral 4th: strongly constrained by Yukawa & experiments
  - SM4 excluded: EWPT, LEP, Higgs at the LHC   Djouadi, Lenz (2012)
  - Strong dynamics above TeV scale with extra Higgs? enhanced $h \rightarrow \tau\tau$
    Geller, Bar-Shalom, Eilam, Soni (2012)
  - Z_2 parity? constrained by SUSY searches   Lee, Soni (2012)
- Vectorlike fermion: mass and Yukawa independent
  (Heavy fermion easily allowed without gauge anomaly)

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Only vector current exists $J^{\mu(+)} = J^\mu_L + J^\mu_R = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$

Why Vectorlike Fermions?

Expected in various BSM categories

- Composite Higgs models, Little Higgs models
- Invisible axion models
- Z' models (anomaly cancellation)

  Kim, Seo, Shin, PRD83, 036003 (2011), ……..
- Supersymmetric model (little hierarchy problem, pheno reasons)

  Martin, PRD81, 035004 (2010)   Dermisek, PRD95, 015002 (2017)
- Simple SM + VLF

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- Simple SM + VLF

  - Gauge coupling unification (UV insensitive)

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

  - Anomalous muon g-2 (VLL mixing with μ)

    Dermisek, Raval, PRD88, 013017 (2013) Dermisek, Raval, Shin, PRD 90, 034023 (2014)

    Kannike, Raidal, Straub, Strumia, JHEP 1202, 106 (2012)

Direct searches at the LHC

- Single fermion which is pure iso-singlet or doublet (or triplet)
- Production through gauge interaction
- Focus on VLQ

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This talk

- Introduce both iso-singlet and doublet
  (general vectorlike copy of SM fermions)

Novel channel

- Production through Yukawa interaction (BSM heavy Higgs)
- Focus on VLQ + VLL

Model framework

e.g., VLF with THDM type II

	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	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{Z_2}$	$+$	$-$	$+$	$-$	$+$	$-$	$+$

Dermisek, Lunghi, Shin, JHEP 1602, 119

	q_L^i	u_R^i	d_R^i	$Q_{L,R}$	$T_{L,R}$	$B_{L,R}$
$\mathrm{SU(2)_L}$	**2**	**1**	**1**	**2**	**1**	**1**
$\mathrm{U(1)_Y}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$
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Dermisek, Lunghi, Shin, Work in progress

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Z_2	+	−	+	−	+	−	+

Dermisek, Lunghi, Shin, JHEP 1602, 119

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Z_2	+	+	−	+	+	−

Dermisek, Lunghi, Shin, Work in progress

New fermions (SM fermion copies + singlet neutral lepton)

Model framework

Most general renormalizable Lagrangian

VLL

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

example

- VLL mixing with SM lepton: In my papers, μ from muon g-2 (Approximate muon number VLL: to avoid dangerous LFV)
- Mass eigenstates: (e_4, e_5), (ν_4, ν_5)
- μ, ν_μ gauge/Yukawa couplings modified: EWPT

Model framework

Most general renormalizable Lagrangian

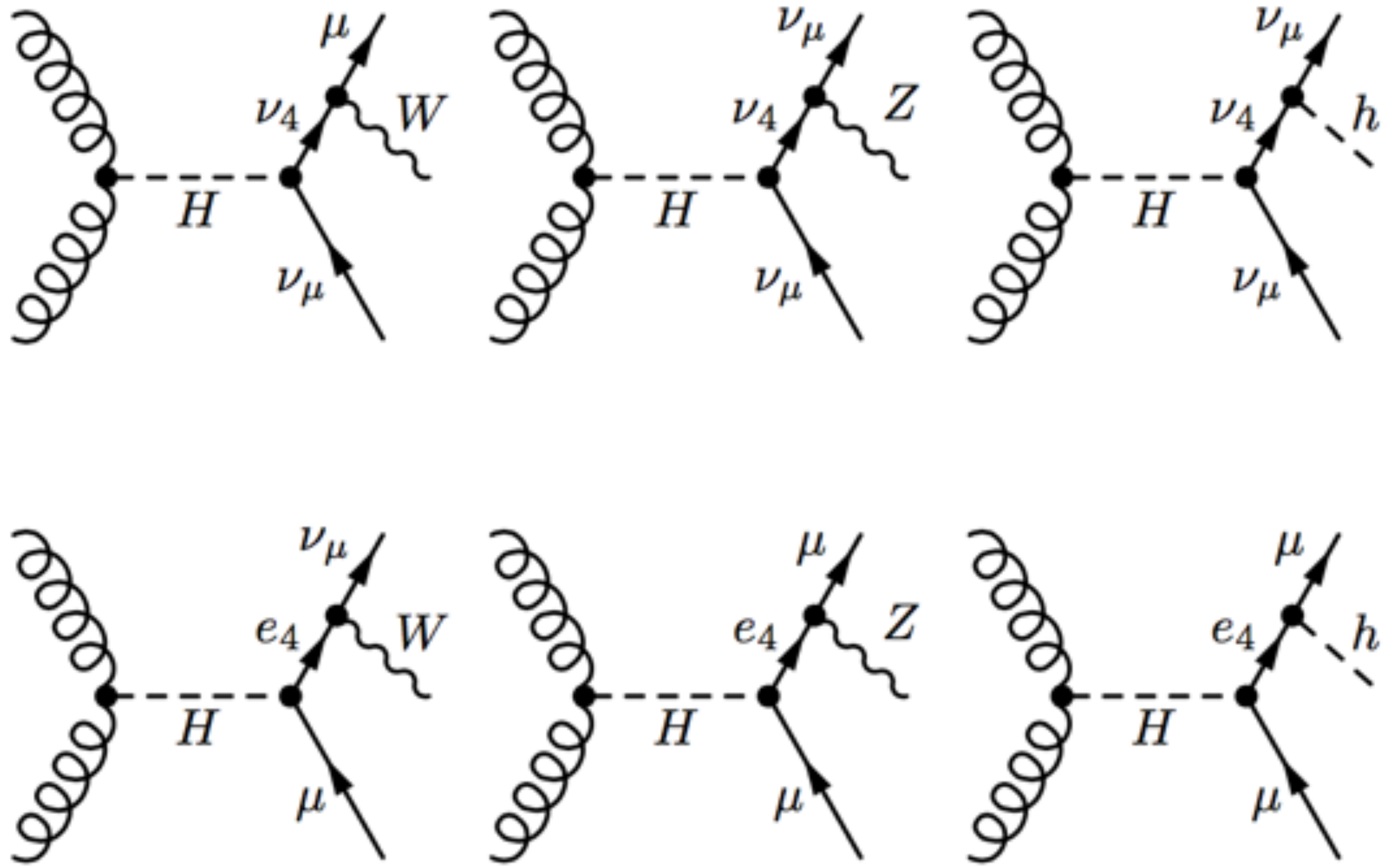
VLQ

$$\mathcal{L} \supset -y_d^{ij}\bar{q}_L^i d_R^j H_d - \lambda_B^i \bar{q}_L^i B_R H_d - \lambda_Q^j \bar{Q}_L d_R^j H_d - \lambda \bar{Q}_L B_R H_d - \bar{\lambda} H_d^\dagger \bar{B}_L Q_R$$
$$- y_u^{ij}\bar{q}_L^i u_R^j H_u - \kappa_T^i \bar{q}_L^i T_R H_u - \kappa_Q^j \bar{Q}_L u_R^j H_u - \kappa \bar{Q}_L T_R H_u - \bar{\kappa} H_u^\dagger \bar{T}_L Q_R$$
$$- M_Q \bar{Q}_L Q_R - M_T \bar{T}_L T_R - M_B \bar{B}_L B_R + \text{h.c.} \ ,$$

- VLQ mixing with SM quark: here, 3rd generation exclusively
- Mass eigenstates: (t_4, t_5), (b_4, b_5)
- EWPT: oblique corrections, R_b

Heavy Higgs cascade decay

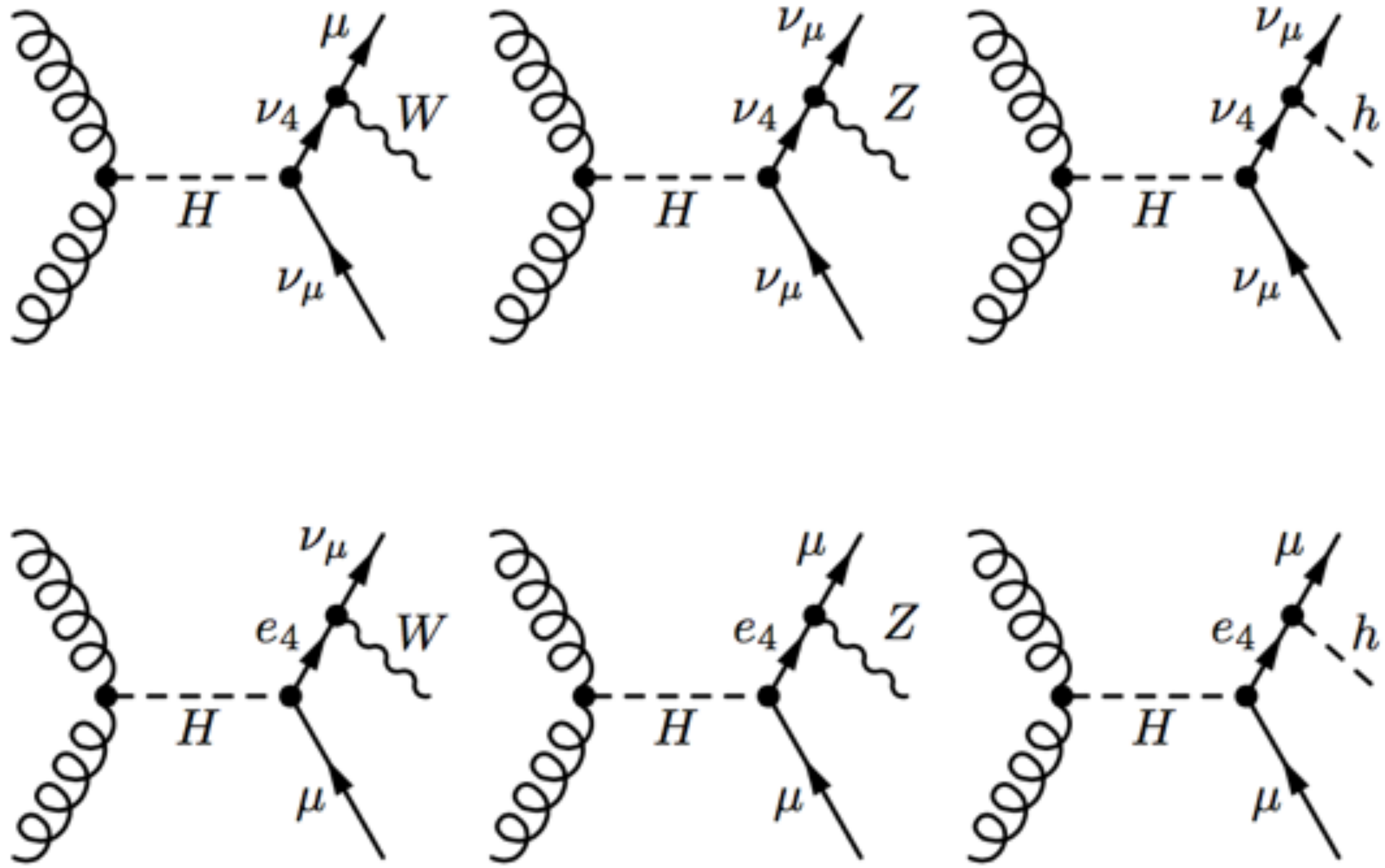
VLL



Promising channel searching for both H and VLF

Heavy Higgs cascade decay

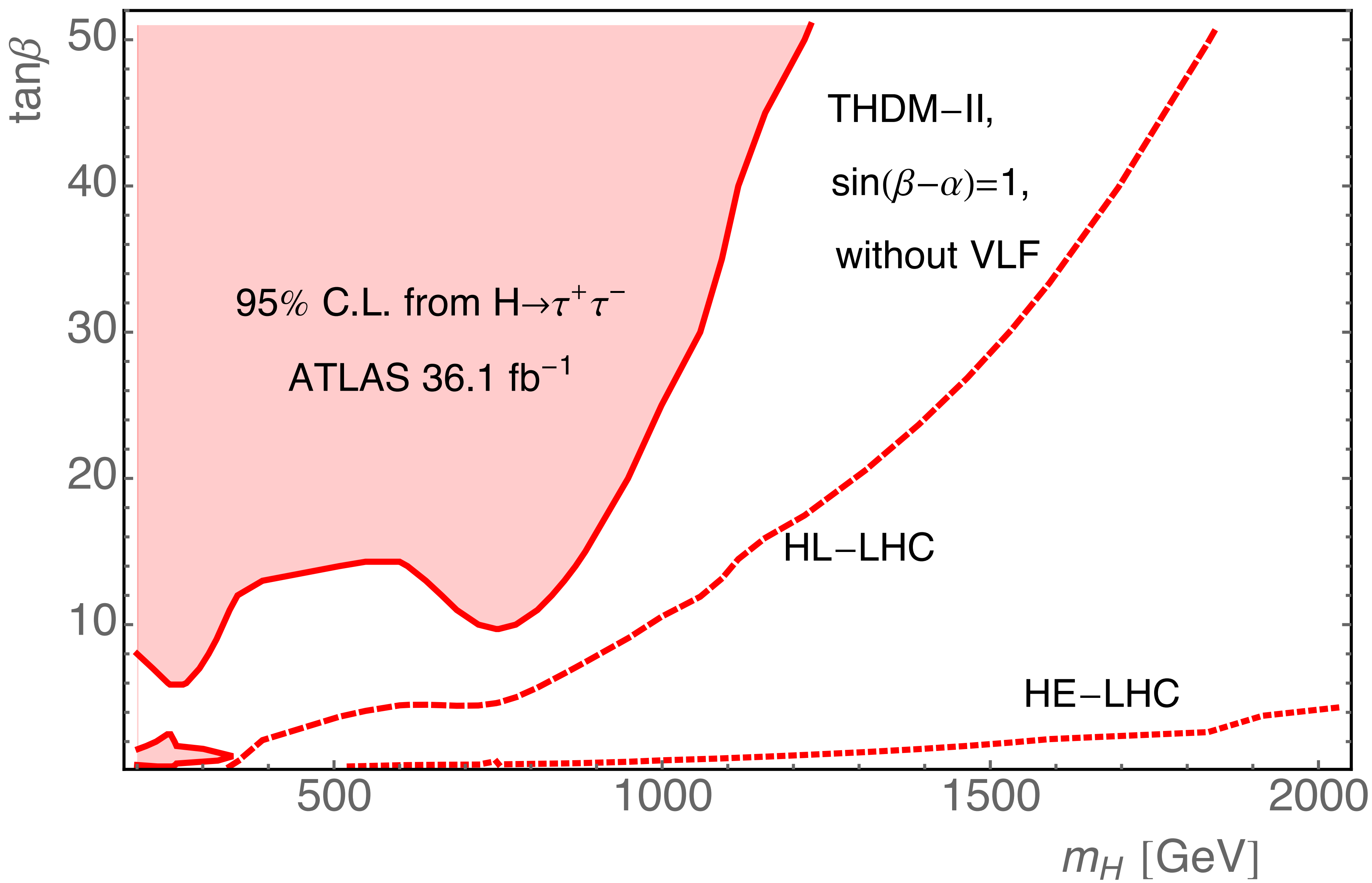
VLL



Promising channel searching for both H and VLF

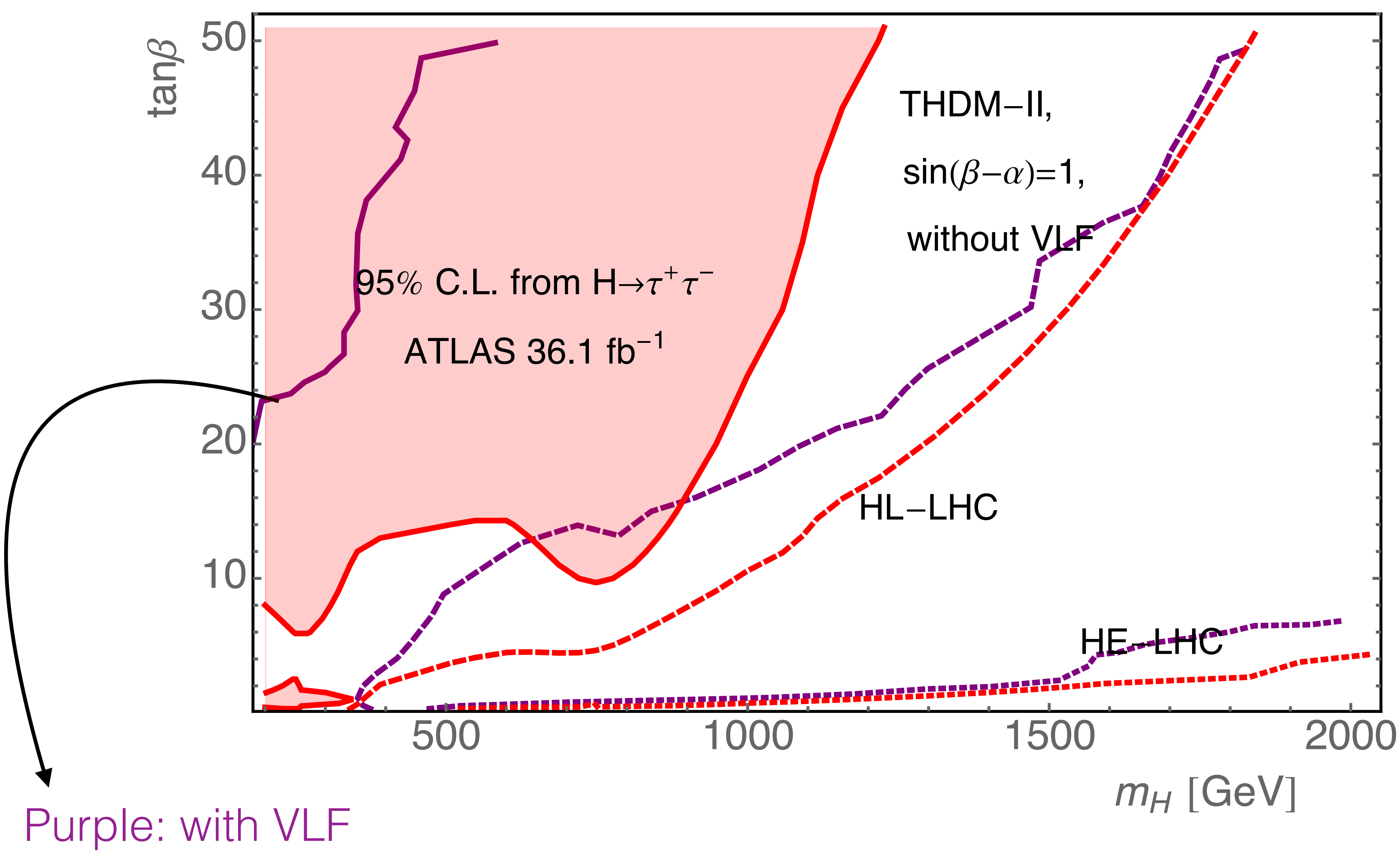
In the alignment limit, H→~~WW,ZZ~~
mostly compete with H→$\tau^+\tau^-$

Comparison with $H \to \tau^+\tau^-$



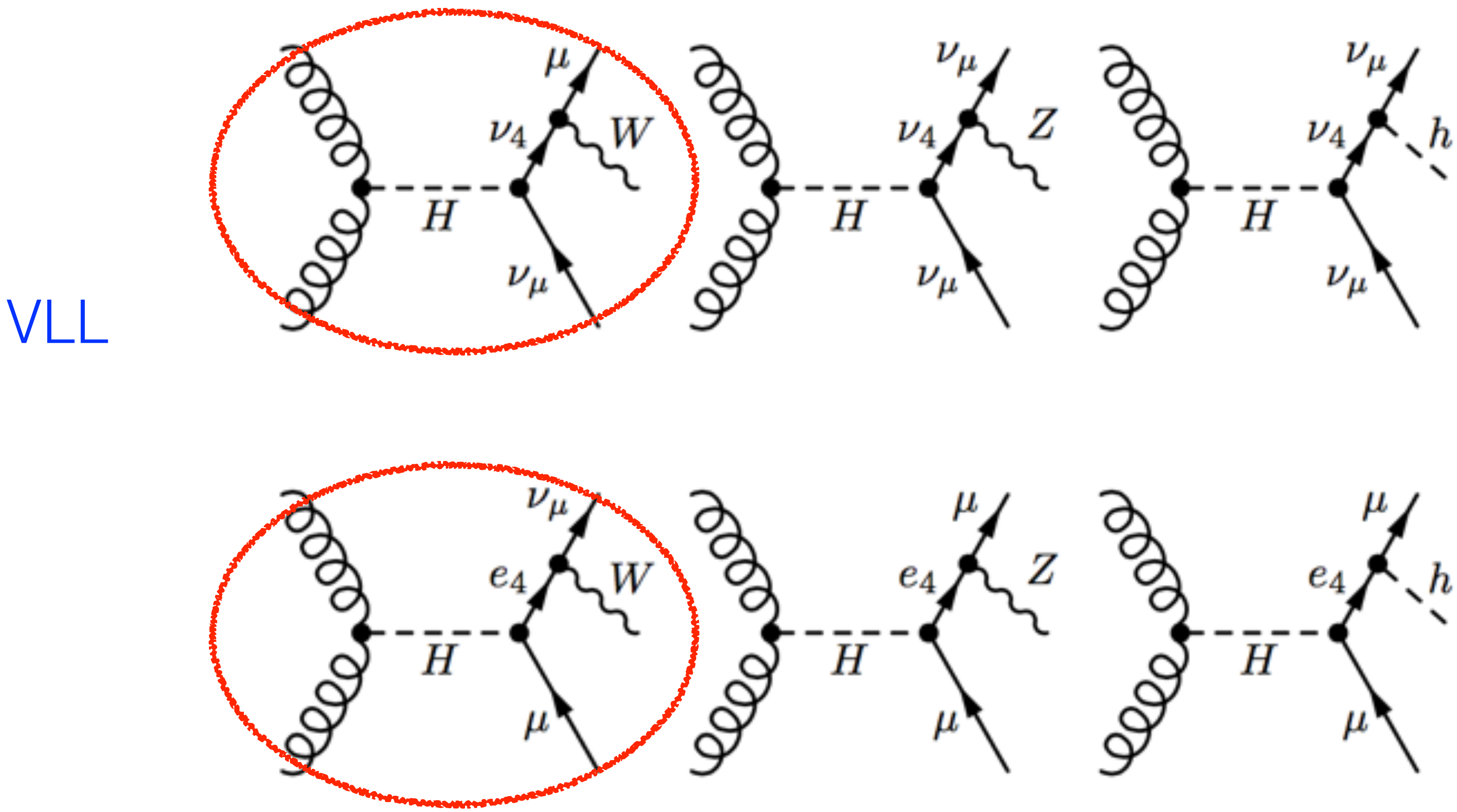
Alignment limit

Comparison with H→$\tau^+\tau^-$



Alignment limit

Heavy Higgs cascade decay



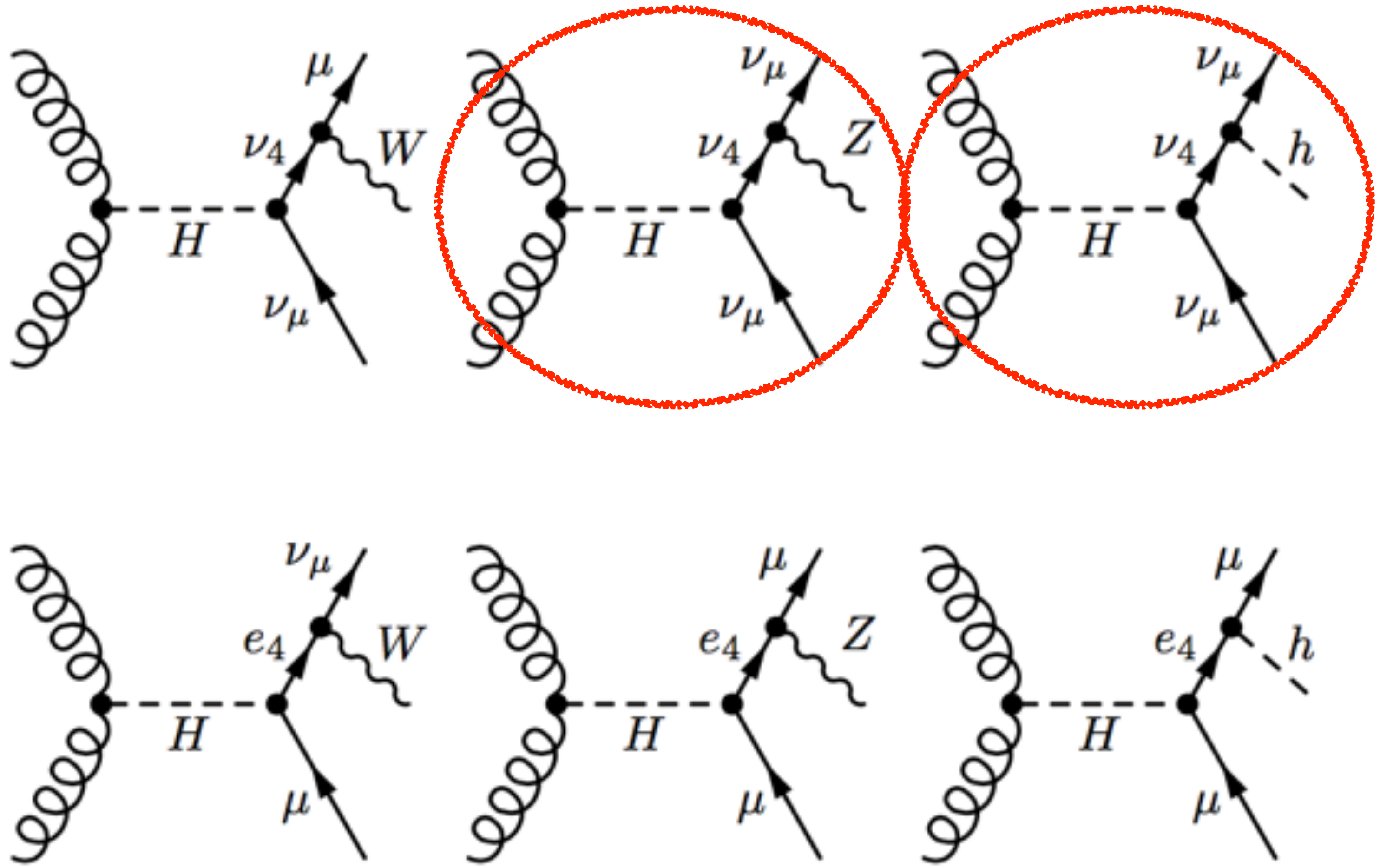
- pp→WW & H→WW
- Semileptonic final states (W→jj): find H & ν_4
- Dileptonic: M_{T2} cut

Dermisek, Lunghi, Shin, JHEP 1508, 126 (2015) & JHEP1602, 119

Dermisek, Raval, Shin, PRD 90, 034023 (2014)

Heavy Higgs cascade decay

VLL



Dermisek, Lunghi, Shin, JHEP1605, 148

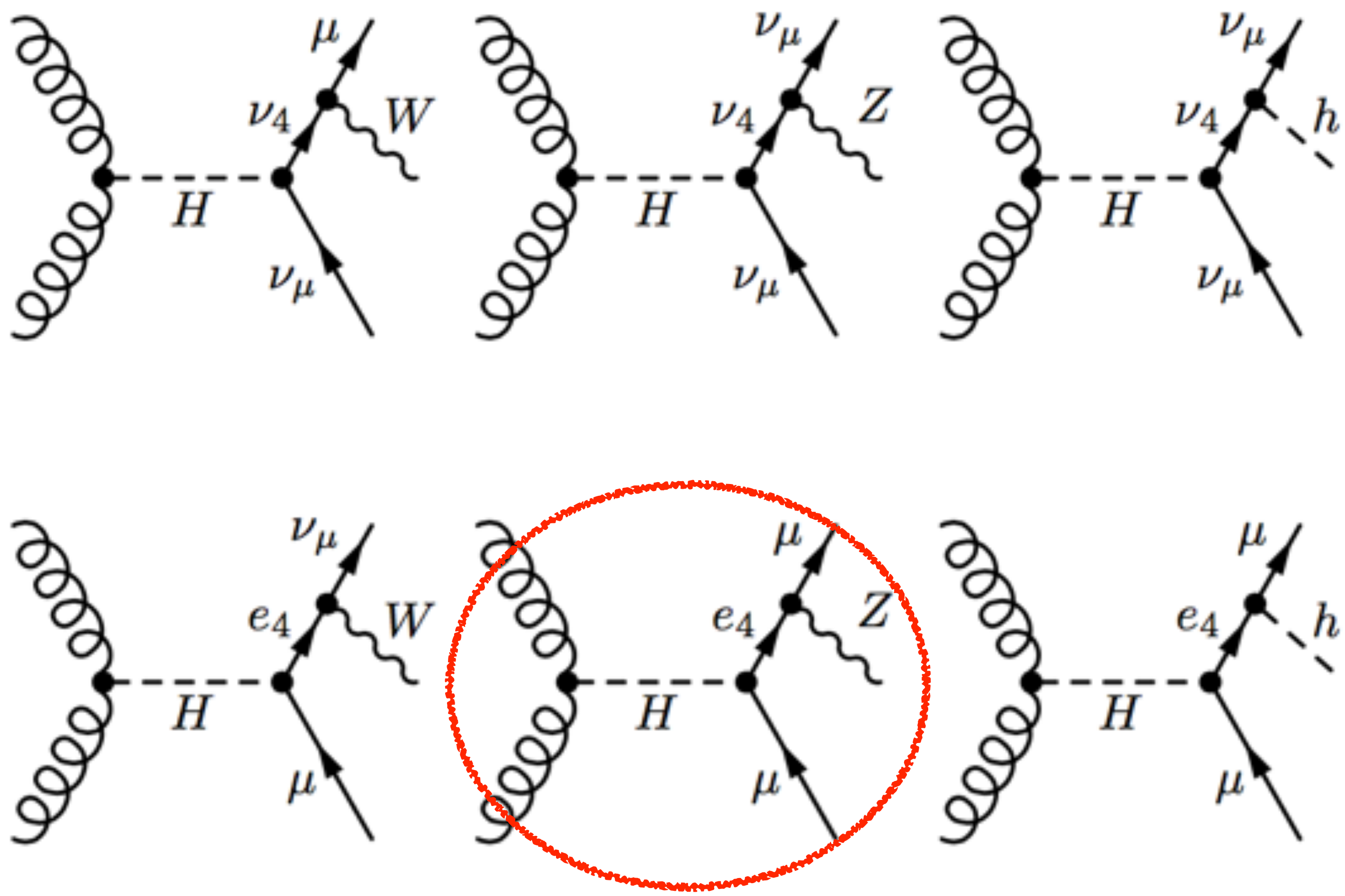
- Constraints from the DM search at the LHC

Future work

- Identifying this separately from DM nontrivial

Heavy Higgs cascade decay

VLL

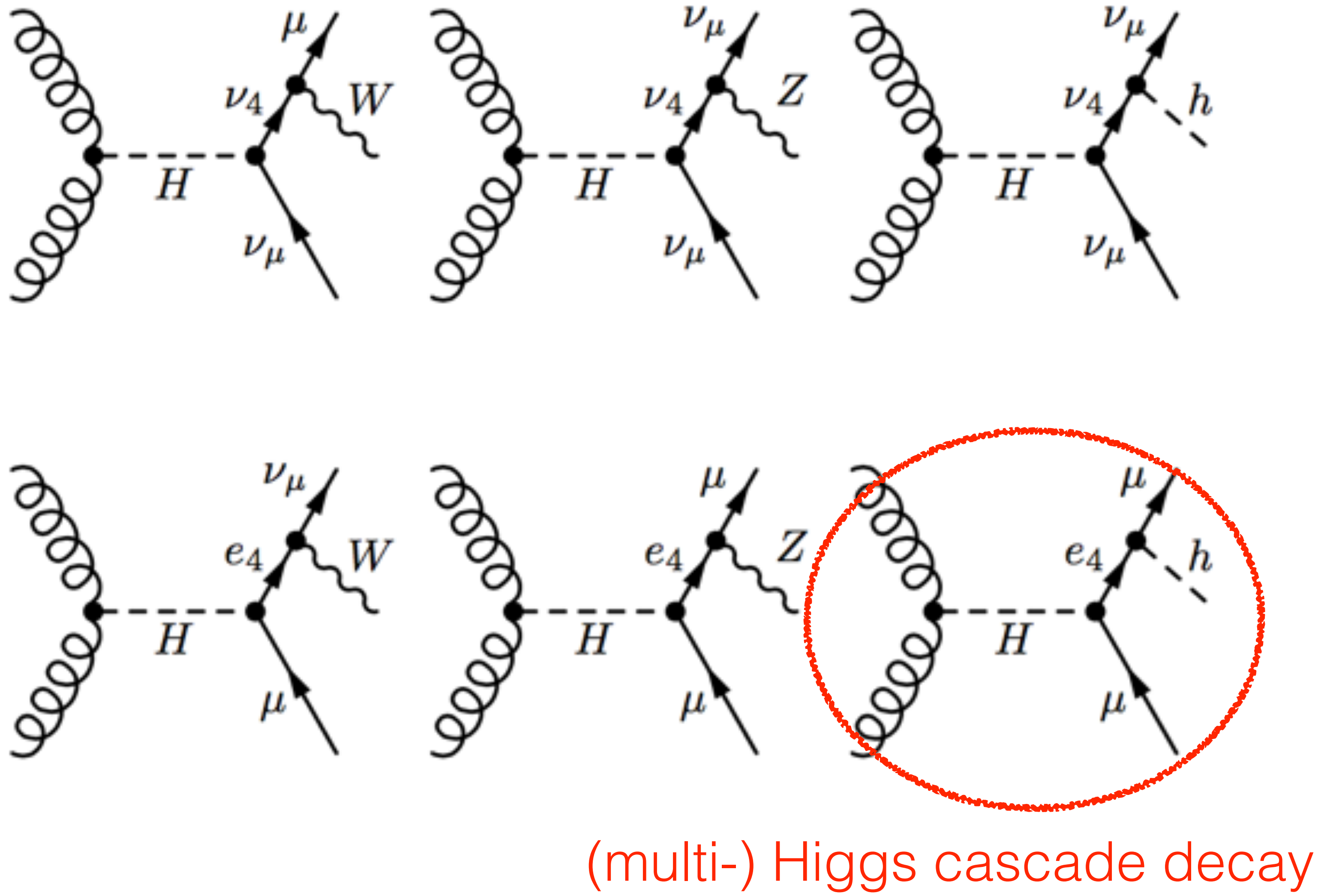


Future work

- Resonance search if Z → visible particles
- Two leptons are not from Z

Heavy Higgs cascade decay

VLL

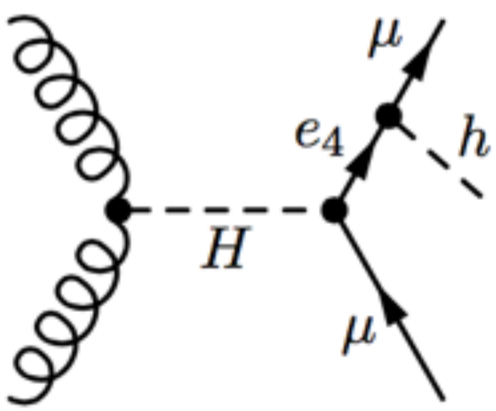


Dermisek, Lunghi, Shin, JHEP1610, 081

- The three resonances from H, e_4, h
- Unique signature $\gamma\gamma\mu^+\mu^-$ $4\ell + E_T^{\text{miss}}$ 6ℓ

multi-Higgs cascade

Final state categories



Dermisek, Lunghi, Shin, JHEP1610, 081

$$h \to b\bar{b}$$

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

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

$$h \to \gamma\gamma$$

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

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

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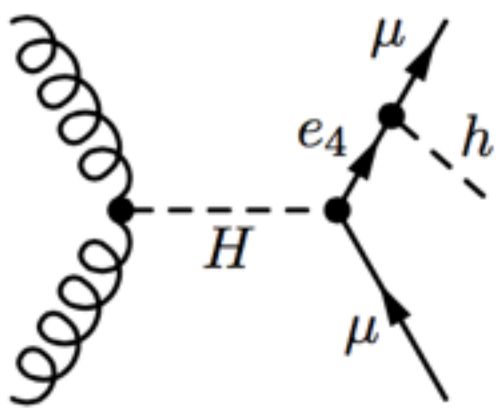


Dermisek, Lunghi, Shin, JHEP1610, 081

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

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

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

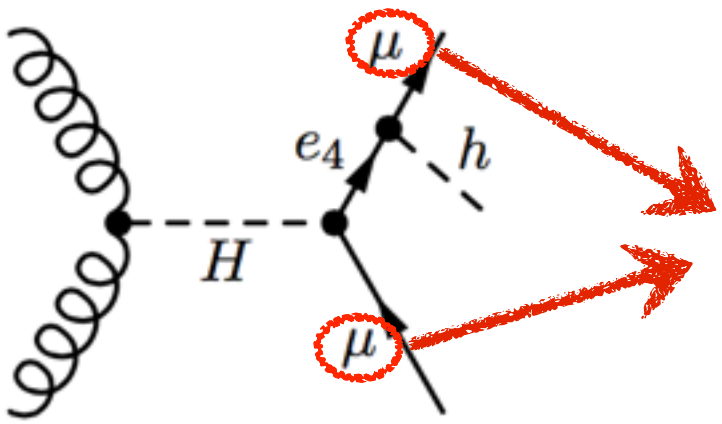
$h \to ZZ^* \to 4\ell$

Experimental sensitivities on the BR of the new decay mode

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

multi-Higgs cascade

Crucial selection cuts



Dermisek, Lunghi, Shin, JHEP1610, 081

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

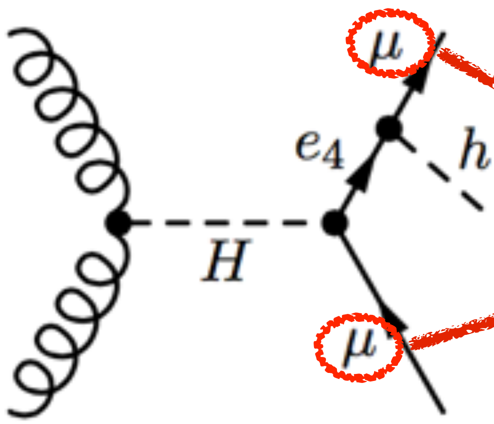
dimuon invariant mass $|m_{\mu\mu} - M_Z| > 15\ \text{GeV}$

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

distinguish from background: Z + jets, ZZ, hZ

multi-Higgs cascade

Crucial selection cuts



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distinguish from background: Z + jets, ZZ, hZ

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

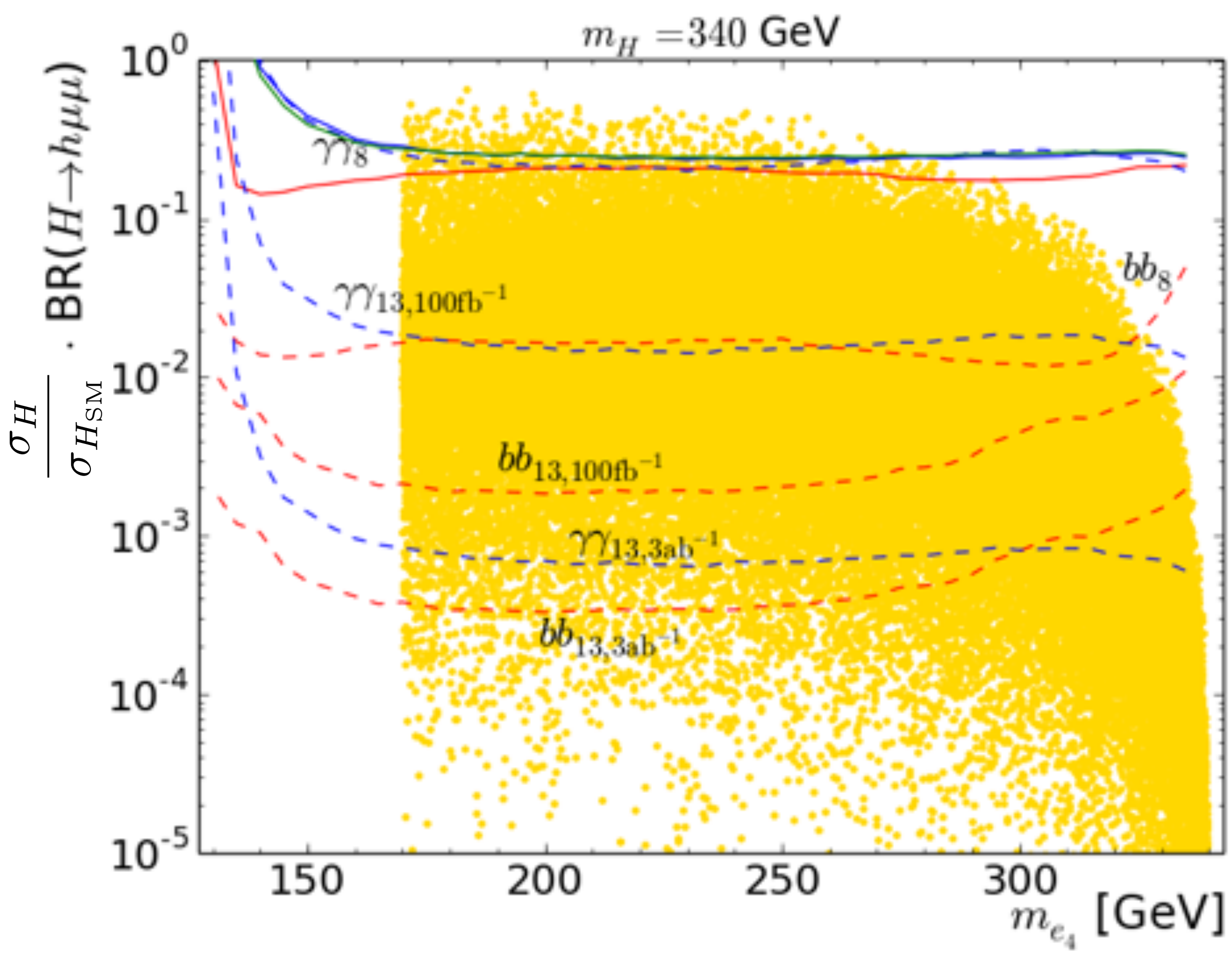
$\gamma\gamma\mu^+\mu^-$

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

$\not{E}_T$ cut

Experimental sensitivities: HL-LHC

- EW precision data, multilepton + $\not{E}_T$, h→$\gamma\gamma$, H→WW,$\gamma\gamma$
- Recast from the 8 TeV searches A→hZ(bbZ), h→$\gamma\gamma$ + a SM lepton, $\gamma\gamma$Z
  ATLAS, 1503.08089 1407.4222 1604.05232
- Expected experimental sensitivities: new cut at 8 TeV & 13 TeV



Disclaimer: Old analysis (2016)

bb$\mu\mu$ is more sensitive!
(off-Z cut powerful)

but $\gamma\gamma\mu\mu$ gets rapidly sensitive
with more date

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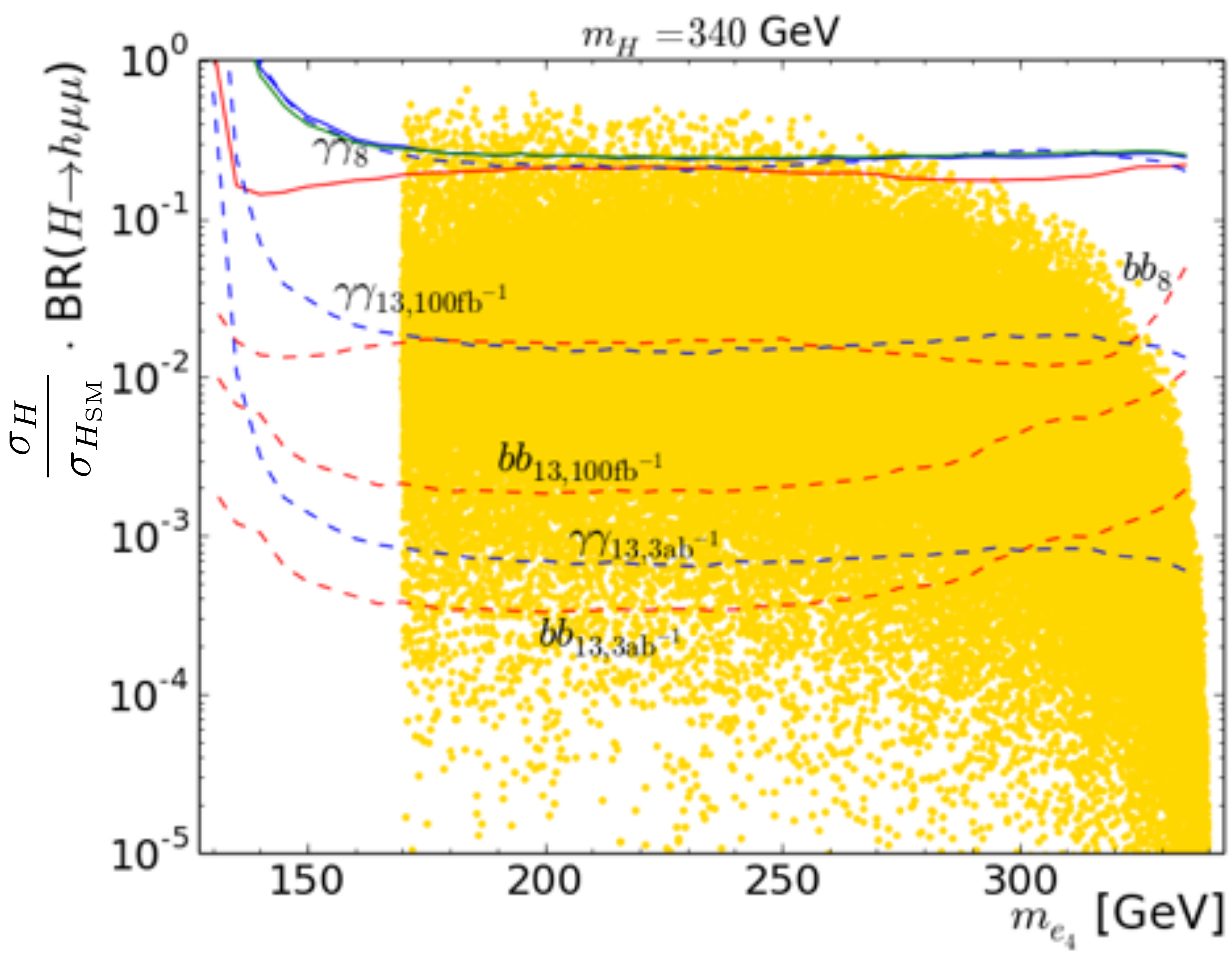

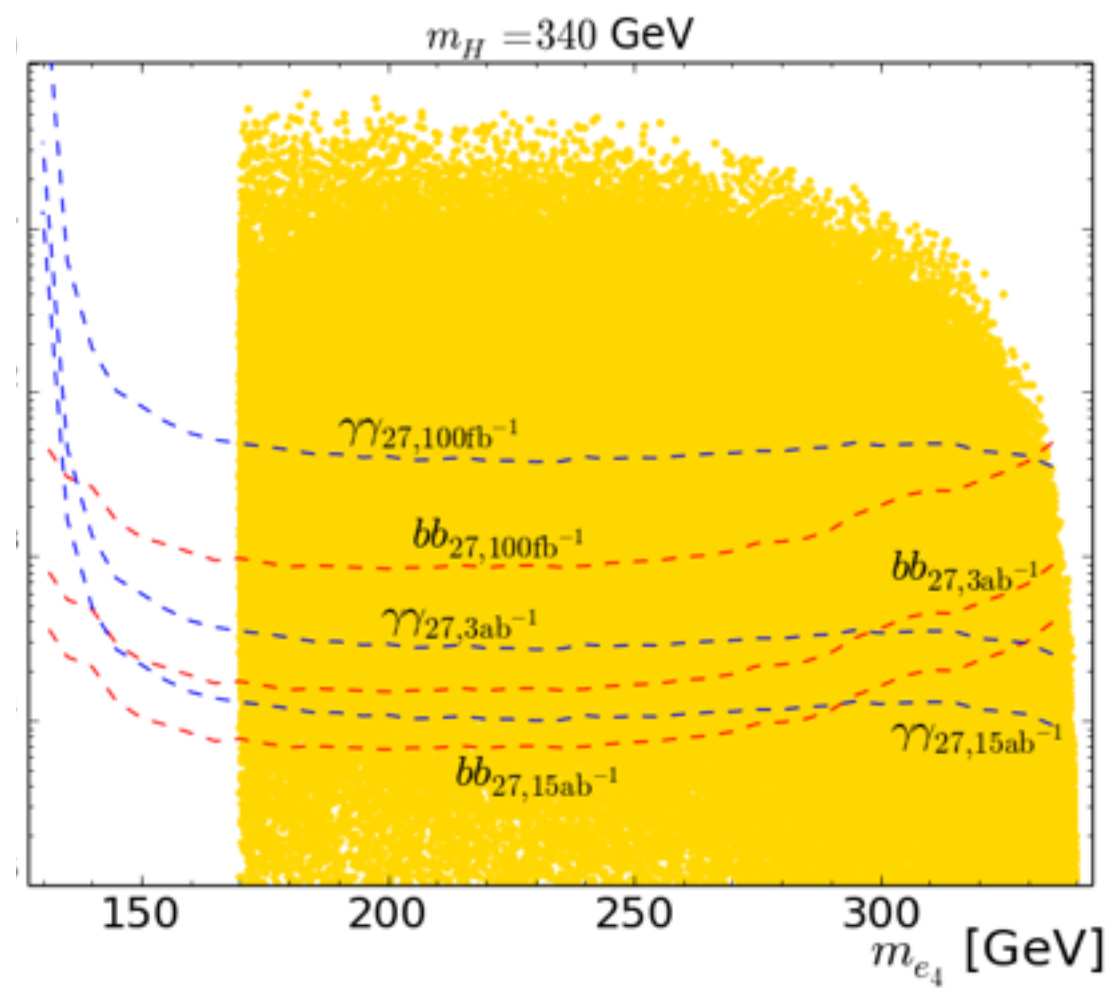

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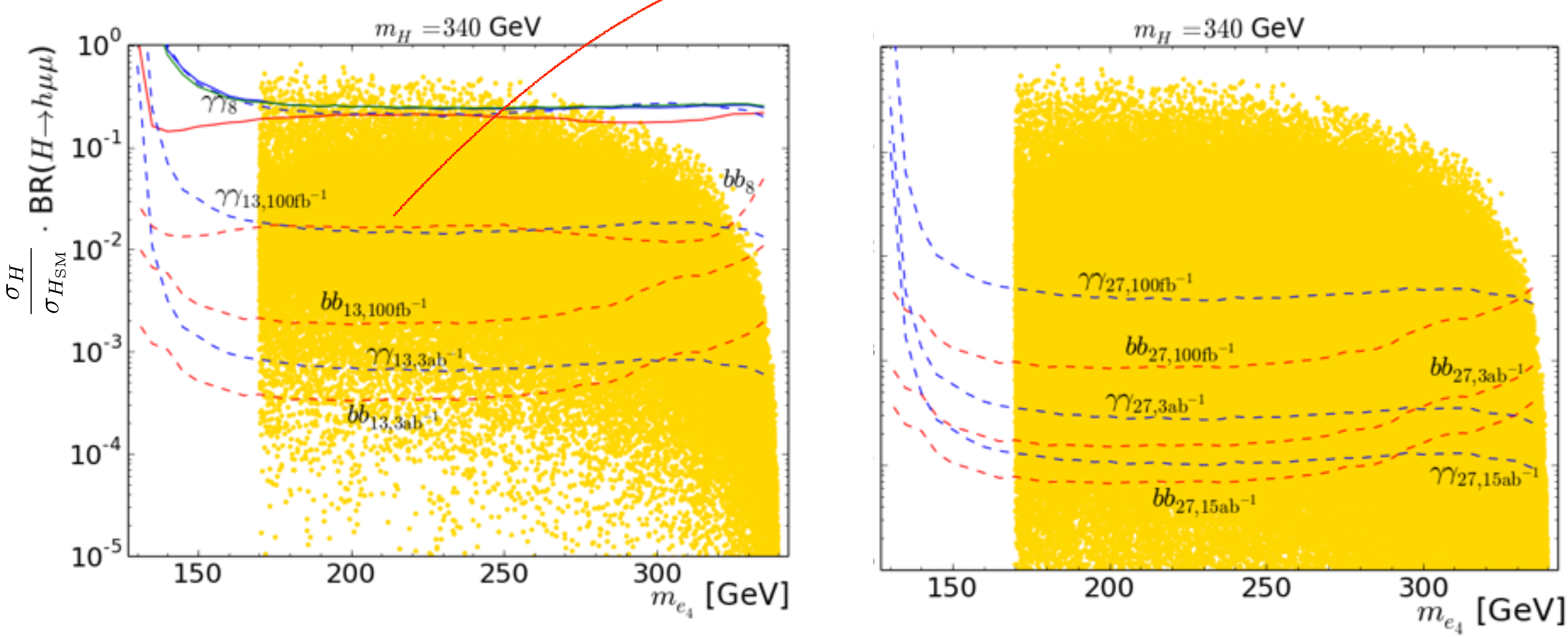
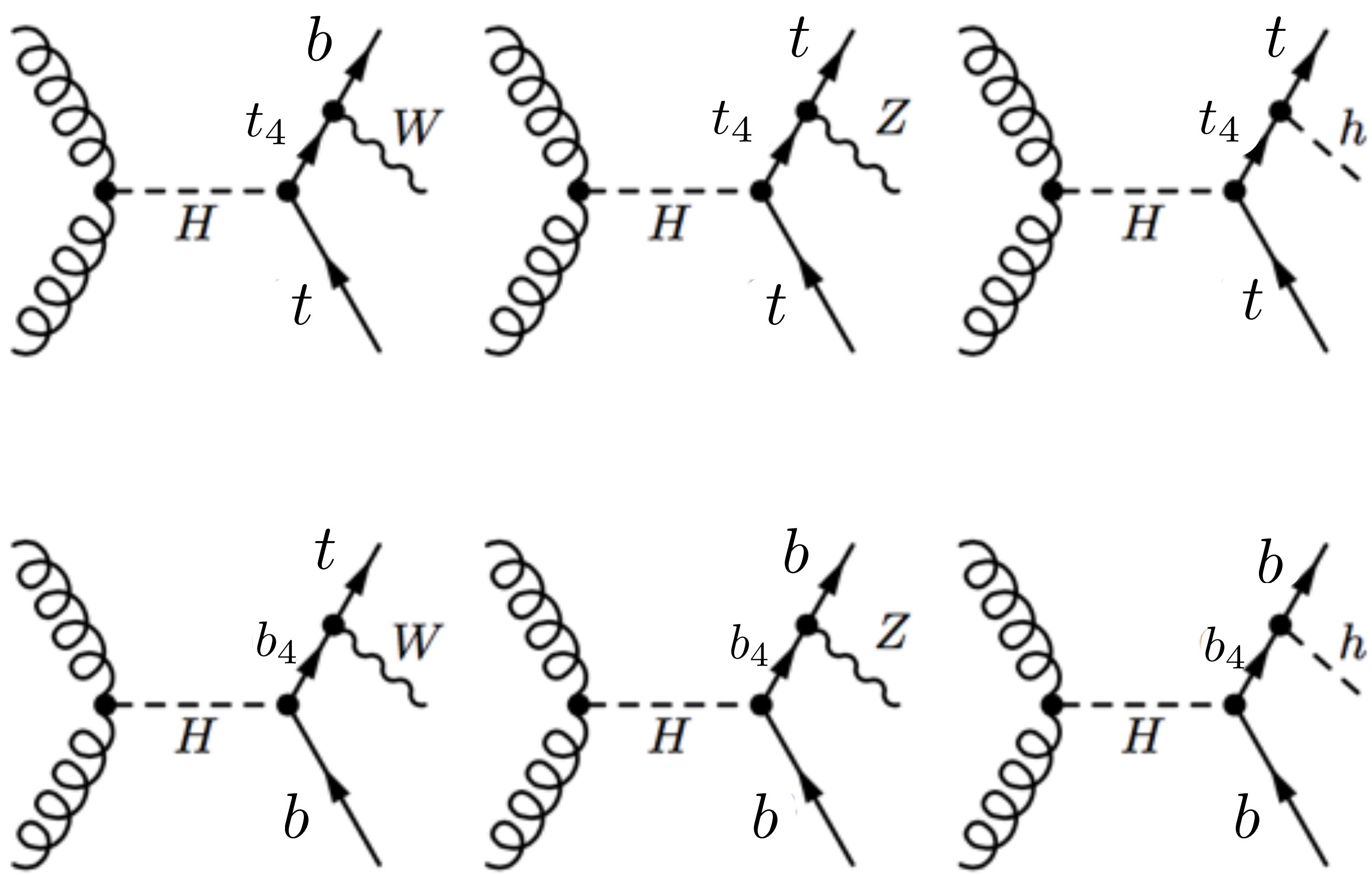
Same level sensitivity for heavier H (> 600 GeV)



Heavy Higgs cascade decay

VLQ



- Boosted objects (VLQ mass ≳ 1 TeV from the constraints)

Heavy Higgs cascade decay

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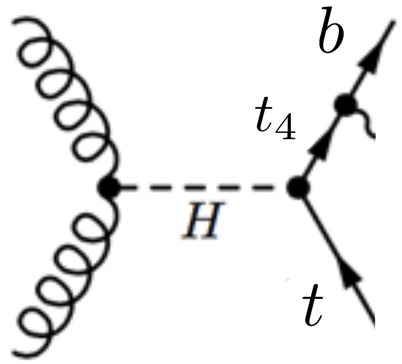
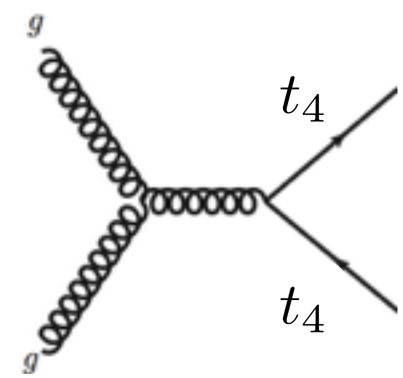
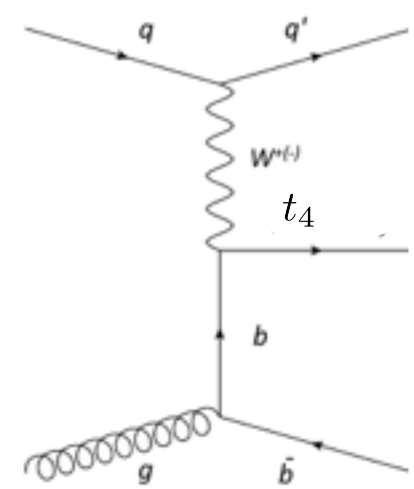


- Production cross section comparable with



- Production cross section smaller than



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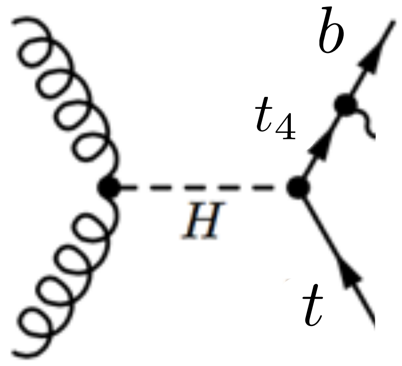

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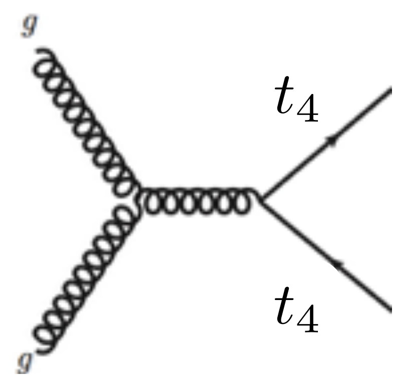

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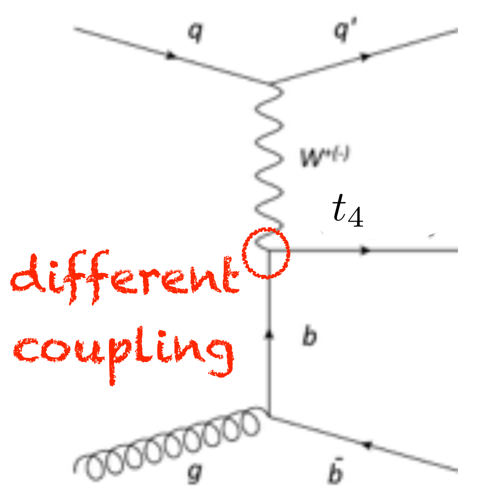
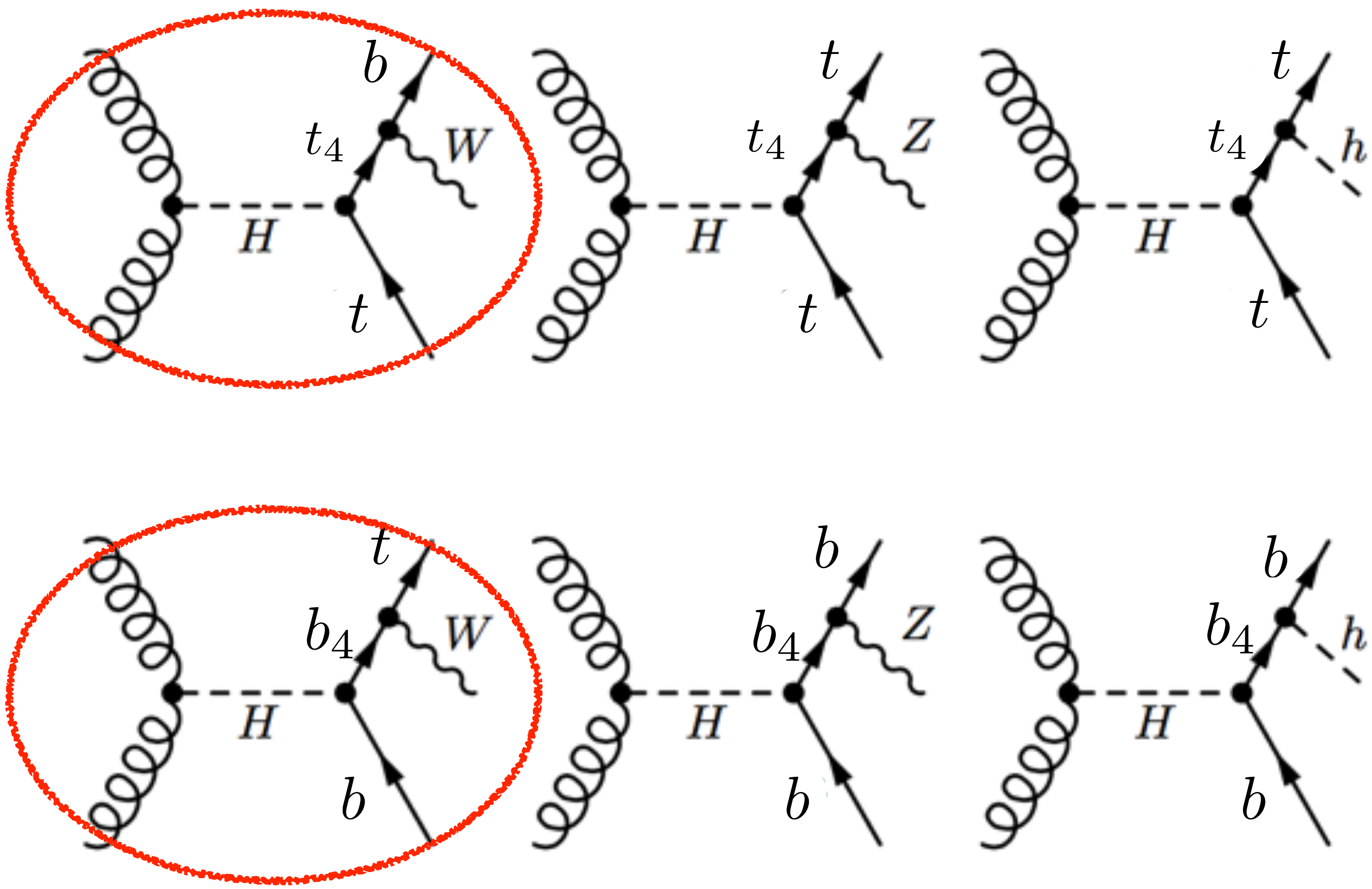


- Uniqueness of signals: kinematic topology, resonances

Heavy Higgs cascade decay

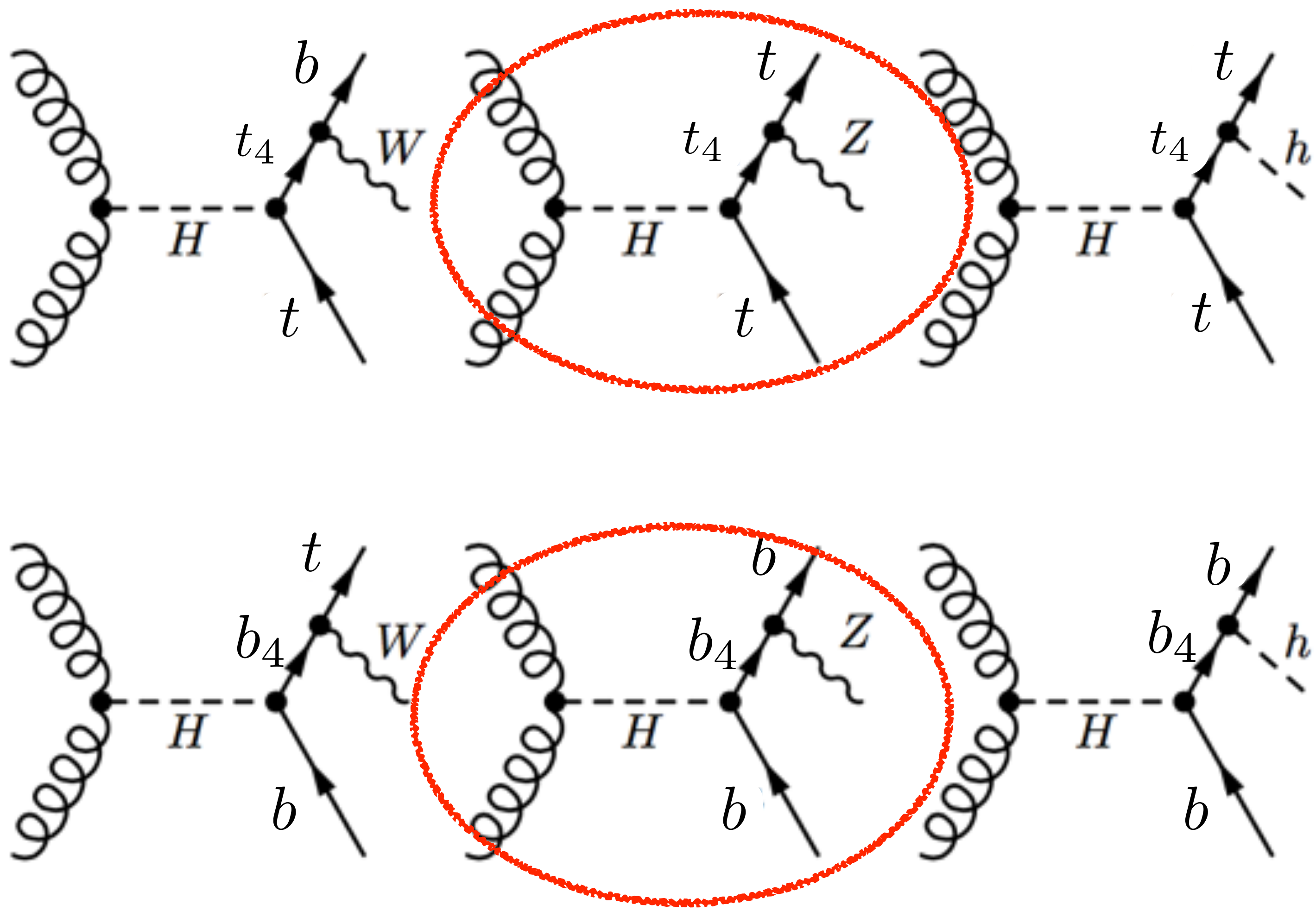
VLQ



- Single top (boosted)
- tbW (kinematically) different from $t\bar{t}$

Heavy Higgs cascade decay

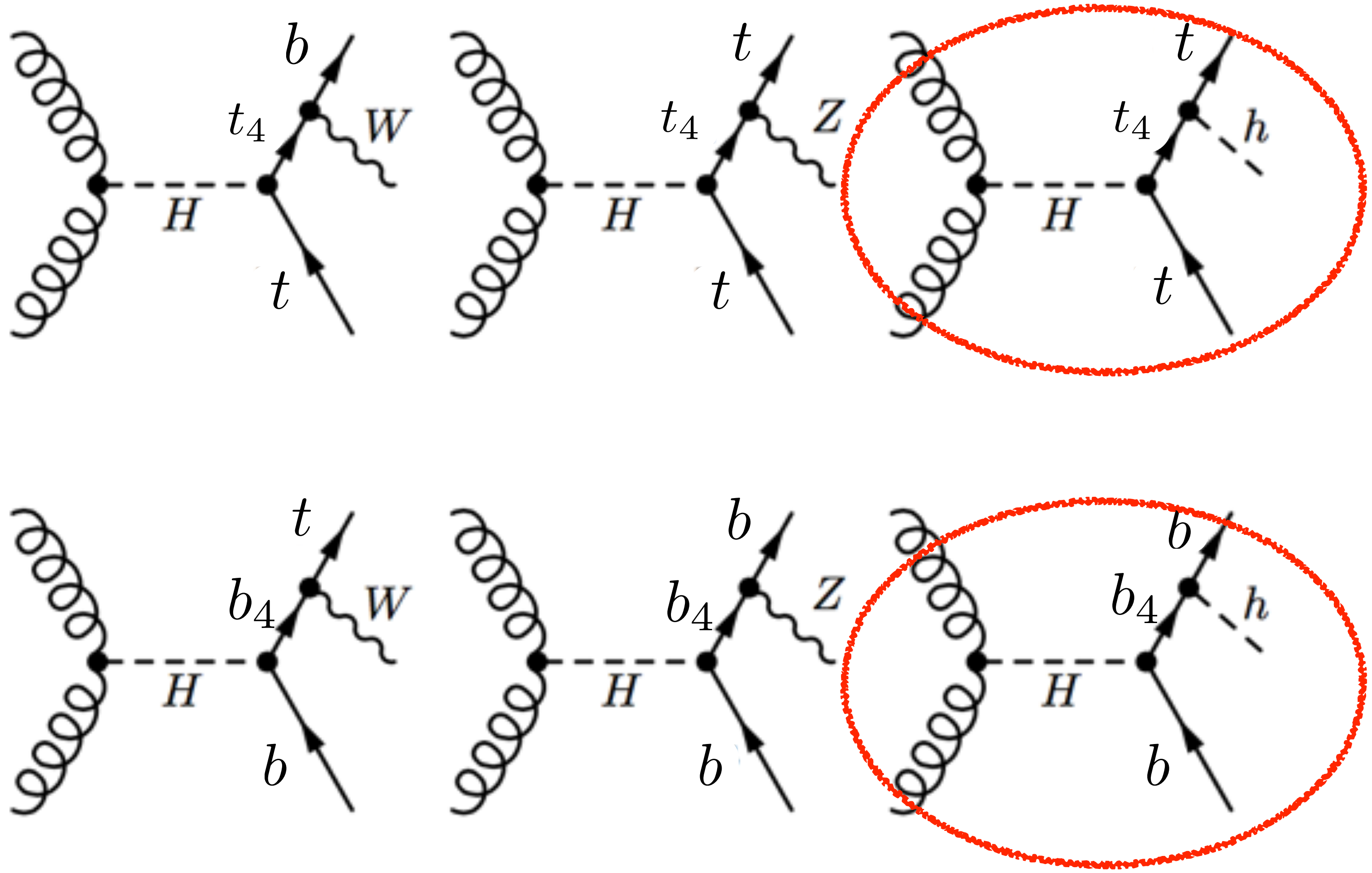
VLQ



- tt or bb out of m_Z resonance

Heavy Higgs cascade decay

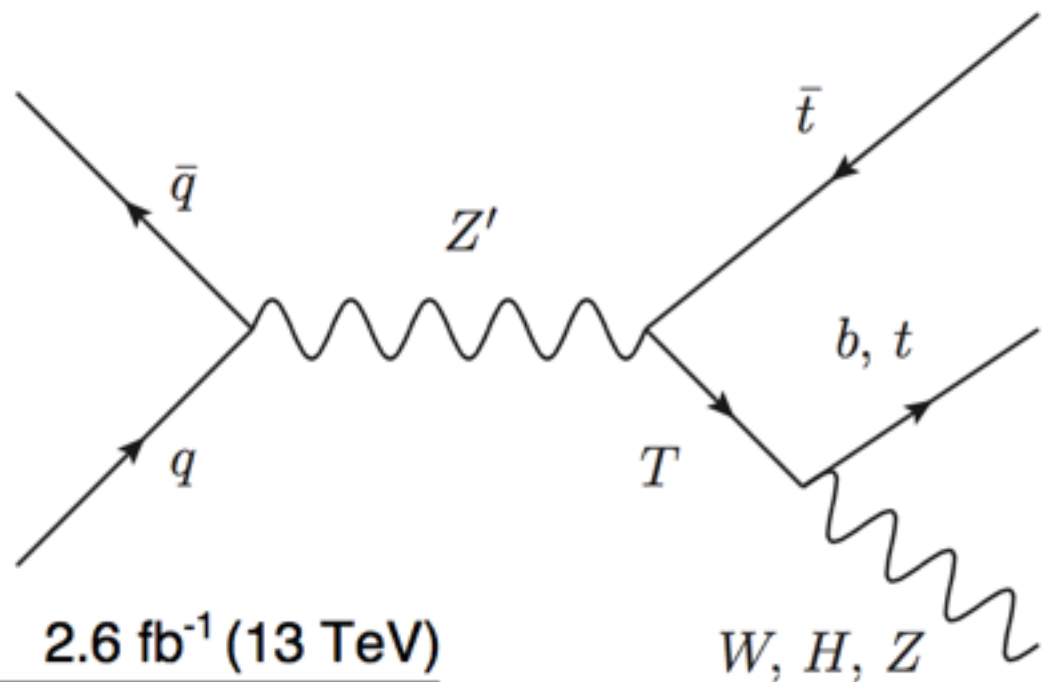
VLQ

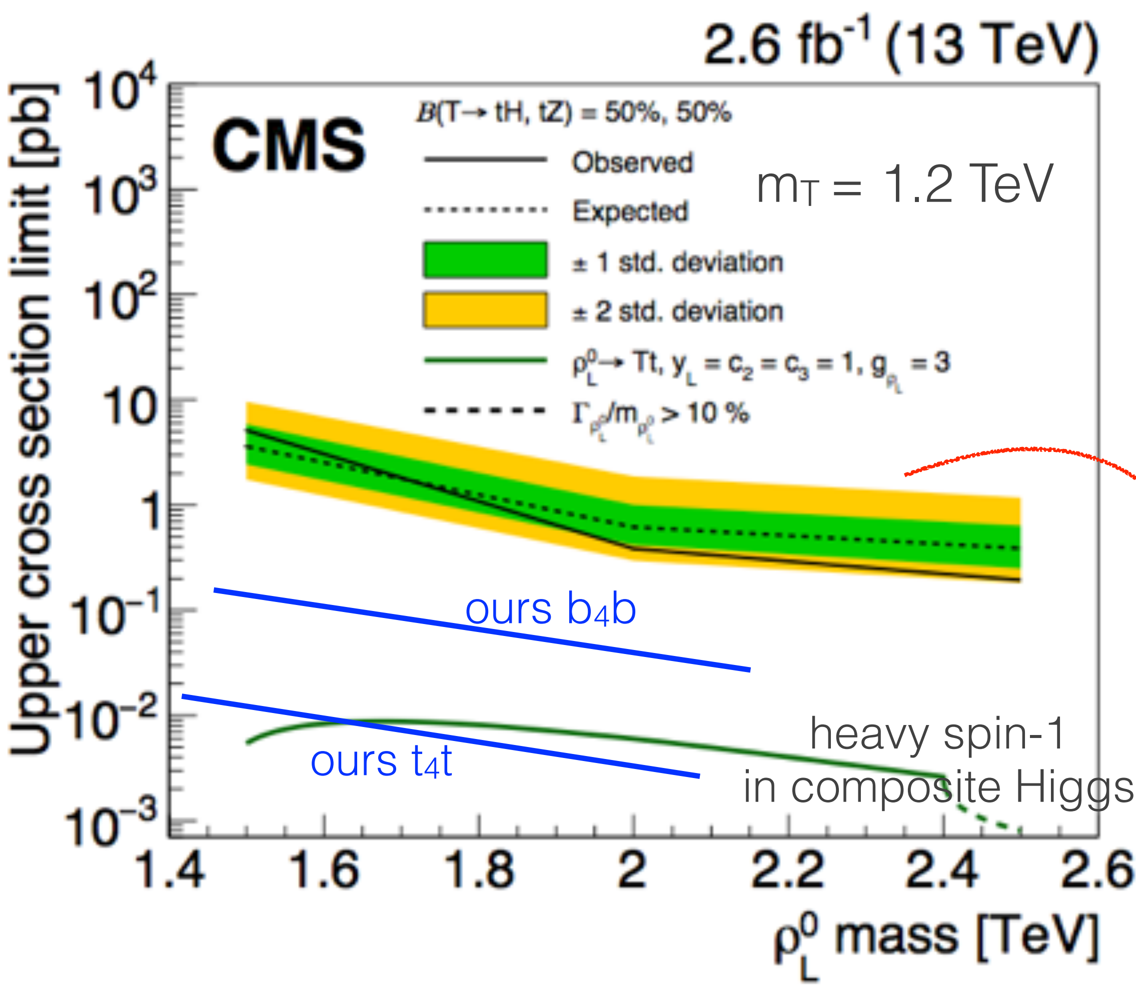


- tth or bbh-like signals

CMS search on the same topology

1703.06352





Further improvement
in HL/HE-LHC

Conclusions

- Search of heavy Higgs & VLF possible by observing the cascade decay channel

- Many resonance signals, e.g., (multi-)Higgs cascade:
  3 resonance signals from H, VLF, h
  Background subtraction is good enough (off-Z cut)

- Promising channel for the search of heavy Higgs even above $t\bar{t}$

- Pair production of VLF from H decay: doubled final states
  (antler topologies)

Back up

- Supersymmetric model
  - Gauge coupling unification restriction: number, mass, type
    Kopp, Lindner, Niro, Underwood, PRD81, 025008 (2010)
    Martin, PRD81, 035004 (2010)
  - Raise lightest Higgs mass
  - Reduce fine tuning in EWSB: $m_{\tilde{t}}$ from mixing with VL squark
    Dermisek, 1606.09031
  - Pure bino scenario without resonance or co-ann.
    (new ann. channel into new lepton, avoiding helicity suppression)
    Abdullah, Feng, PRD93, 015006 (2016)
- Non-supersymmetric model VLL
  - Gauge coupling unification without SUSY: number, mass, type
    Dermisek, PLB713, 469 (2012), PRD87, 055008 (2013)
  - Several exp. anomalies: muon g-2 (VLL mixing with μ), X → $\gamma\,\gamma$
    Dermisek, Raval, PRD88, 013017 (2013)
    Kannike, Raidal, Straub, Strumia, JHEP 1202, 106 (2012)
    Freitas, Lykken, Kell, Westhoff, JHEP1405, 145 (2014)

Back up

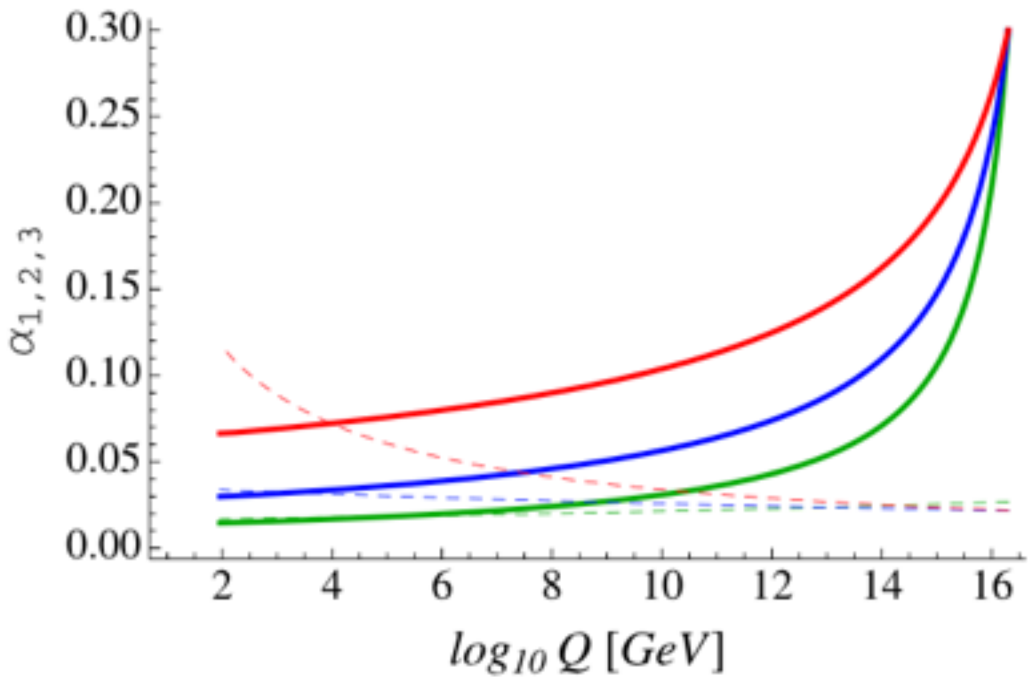
Unification of gauge couplings in a simple non-SUSY model (SM + 3VF)

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 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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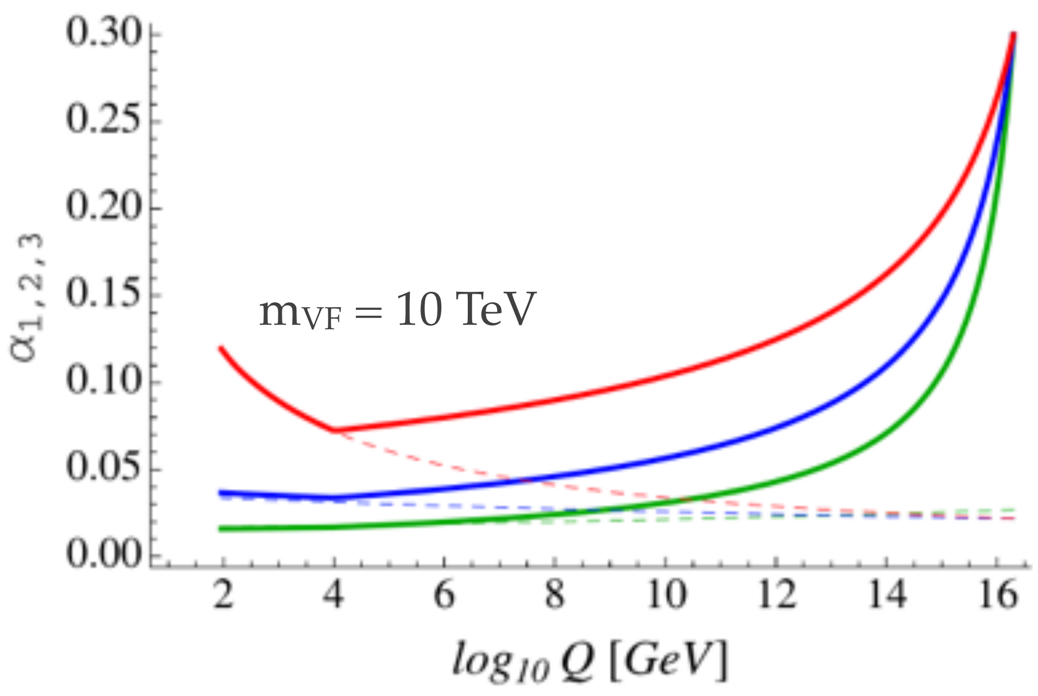
Insensitive unification



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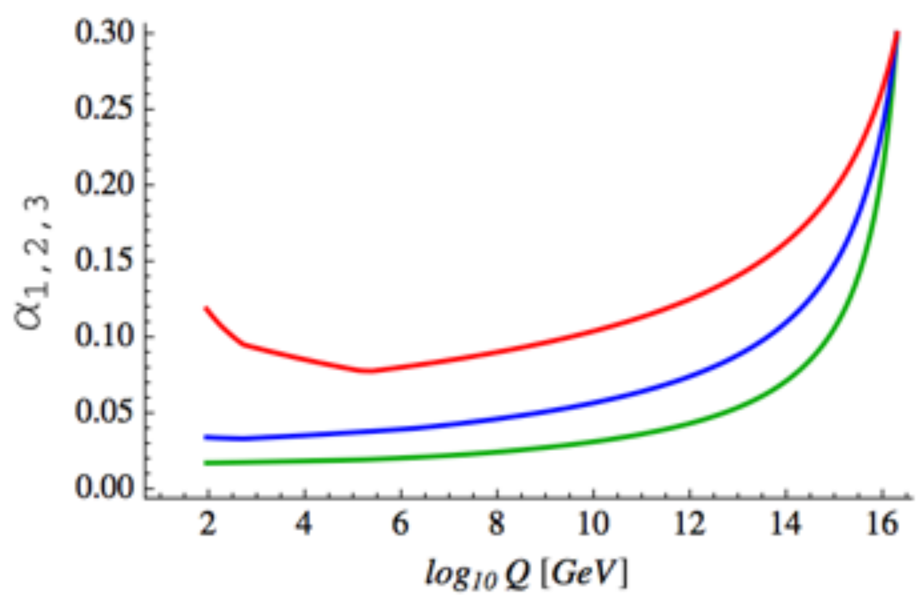
$$n_f = 3 + 2\times 3 = 9$$

Back up

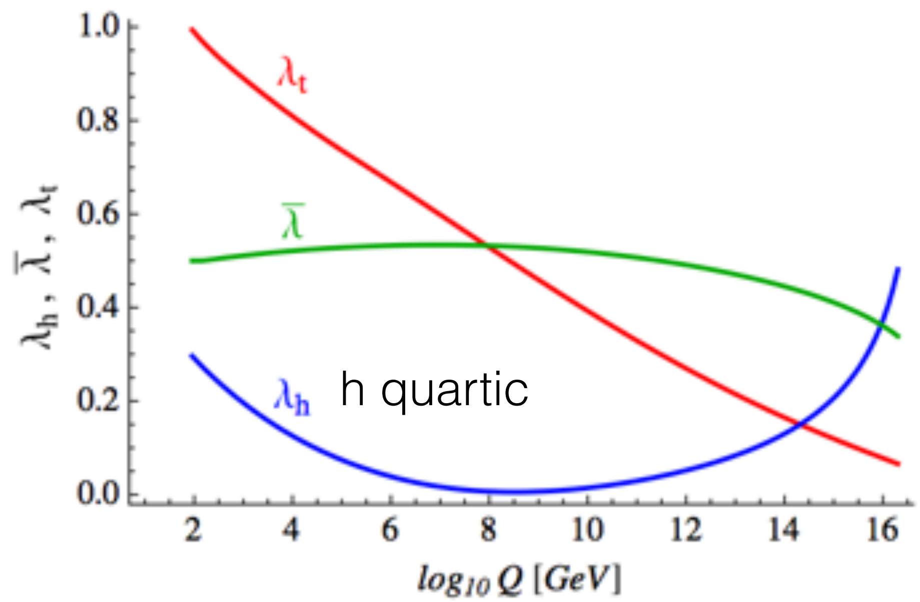
Unification of gauge couplings in a simple non-SUSY model (SM + 3VF)

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 TeV)
- Some vectorlike fermions < 1 TeV: investigation at the LHC is possible



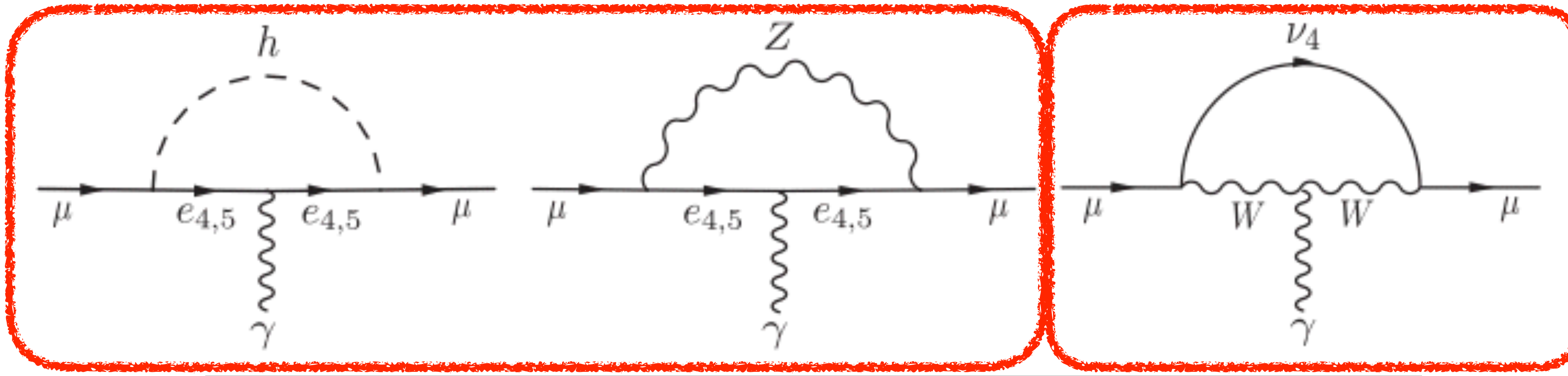
$$\alpha_G = 0.3,\ M_G = 2 \times 10^{16}\,\mathrm{GeV}$$
$$M_{L_1} = M_{E_1} = 150\,\mathrm{GeV},\ M_Q = 520\,\mathrm{GeV}$$



$\bar{\lambda}$: Yukawa (new doublet & singlet)

Back up

Dermisek, Raval, PRD88, 013017 (2013)



heavy VLL (large λ^L,λ^E)

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

light VLL (small λ^L,λ^E)

Yukawa between VLLs $\bar{\lambda}$ & with muon λ_L, λ_E

same chiral structure

Correlated with the physical muon mass

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

Effective Yukawa coupling

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

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

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

$m_\mu^{LE}/m_\mu \simeq 1$ for $M_L \simeq M_Z$
$c \simeq +1$

$y_\mu = 3(y_\mu)^{\rm SM}$

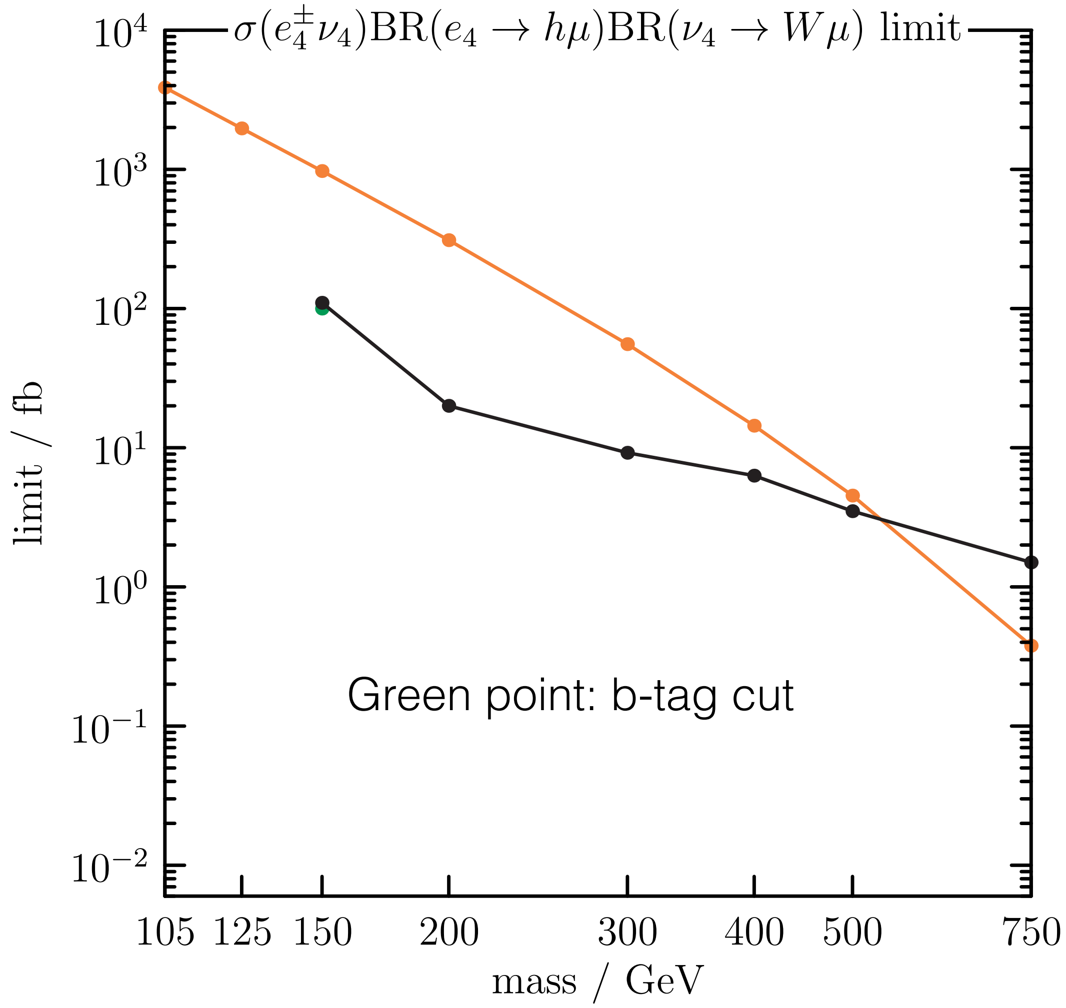
$$\Delta a_\mu \simeq c\frac{m_\mu m_\mu^{LE}}{(4\pi v)^2} \simeq 0.85c\frac{m_\mu^{LE}}{m_\mu}\Delta a_\mu^{\rm exp}.$$

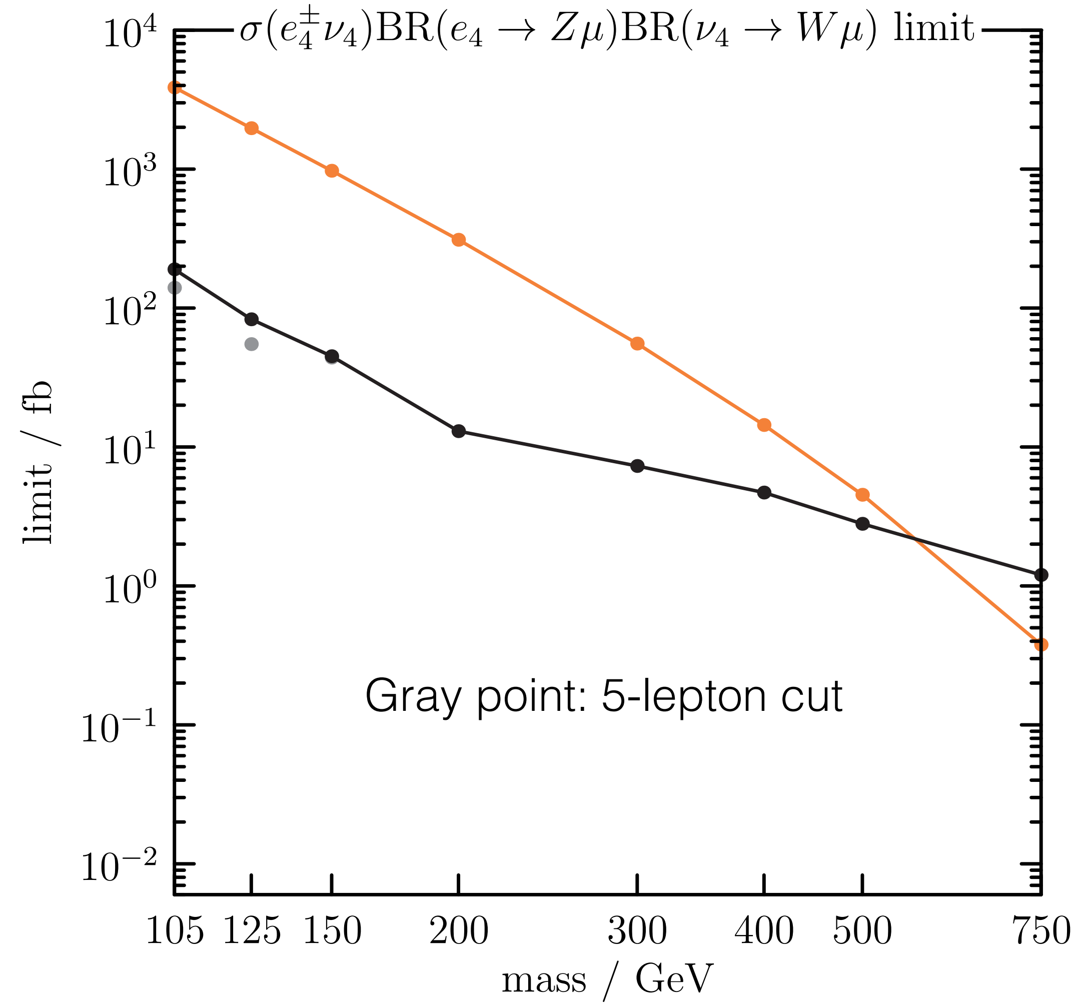
m_μ fully from the mixing with VLL

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

Back up

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

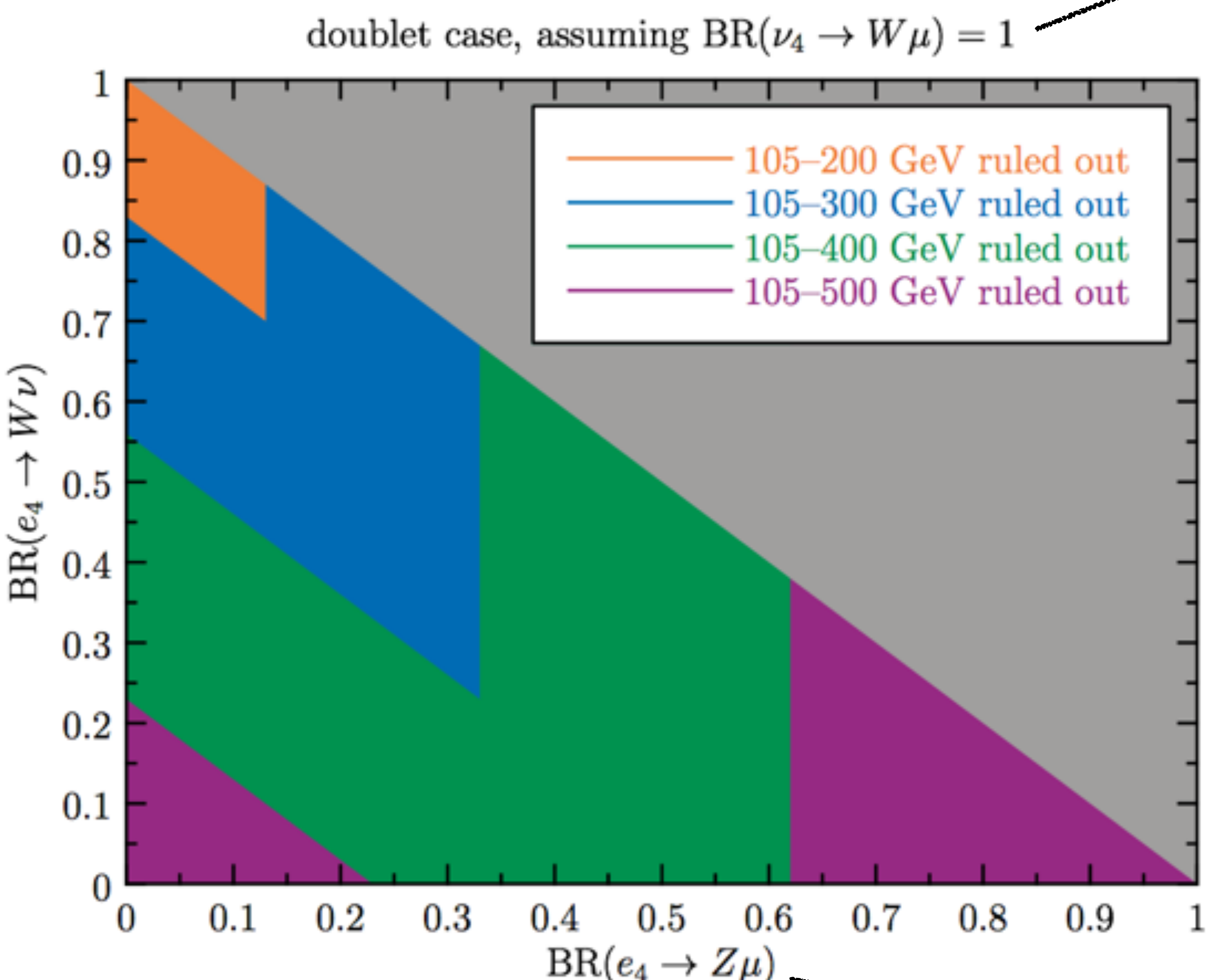




Black: 95%CL upper bounds

Red: predicted production cross sections of doublets

Back up



true without SM singlet N

strongly constrained!

m_{e4} > 200 GeV!!!

- Orange: m_{e4} > 200 GeV
- Blue: m_{e4} > 300 GeV
- Green: m_{e4} > 400 GeV
- Purple: m_{e4} > 500 GeV

Back up

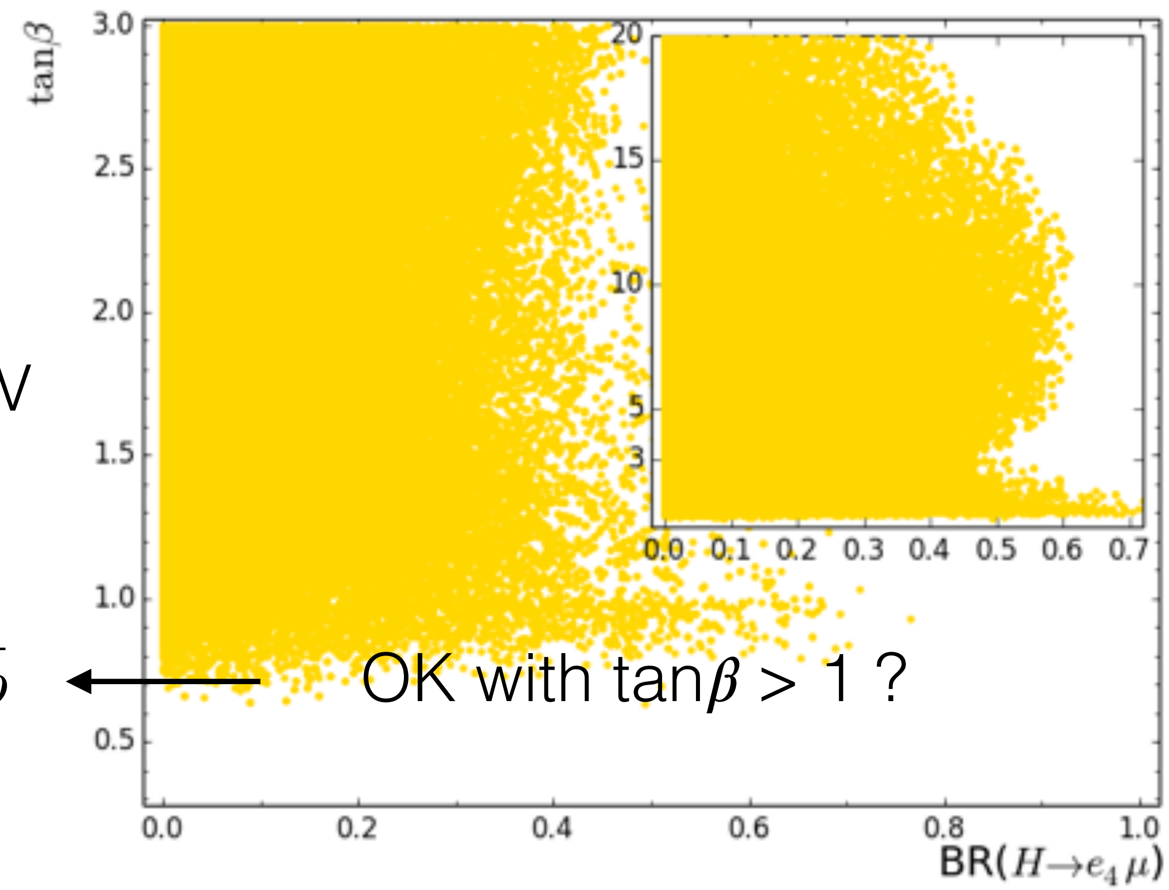
Focused on $m_H \lesssim 340$ GeV to avoid competition with $H \to t\bar{t}$

True: BR(H→$\nu_4 \nu_\mu$) low tanβ but False: BR(H→$e_4 \mu$) when tanβ >1 ?

compete with $H \to t\bar{t}$ compete with $H \to b\bar{b}$

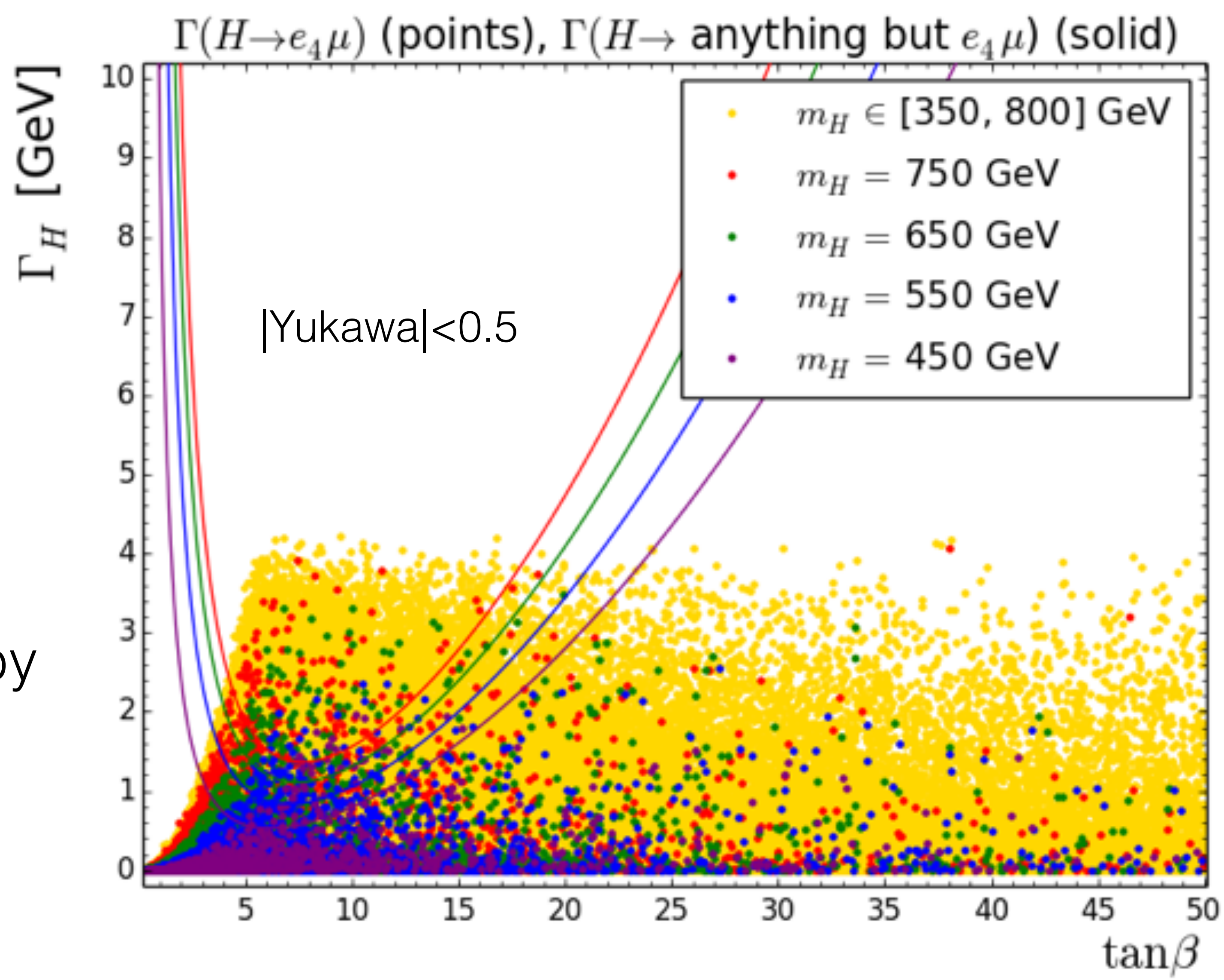
New Yukawa coupling: large

Example below 340 GeV



We may beat $H \to b\bar{b}$ ← OK with tanβ > 1 ?

Back up



Dominated by $H \to t\bar{t}$

Dominated by $H \to b\bar{b}$

For 4 ≲ tanβ ≲17 with |Yukawa|<0.5

For 4 ≲ tanβ ≲32 with |Yukawa|<1.0

We beat both $H \to t\bar{t}$ & $H \to b\bar{b}$

Promising in H discovery: better than H→tt (interference)

Jung et al., 1505.00291

Liu & Carena, 1608.07282

Back up

Constraints from flavor physics (for low tanβ)

- $b \to s\gamma$ → OK for $m_{H^\pm}$: 400 - 500 GeV
- $R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \mathrm{hadrons})}$ → OK for $m_{H^\pm}$: 400 - 500 GeV

  strong for tanβ < 0.8 → OK with a VLQ mixing with b
- ΔM_b weak

Song, Yoon, PRD91, 113012 (2015)