A Higgs Portal to Vectorlike Fermions

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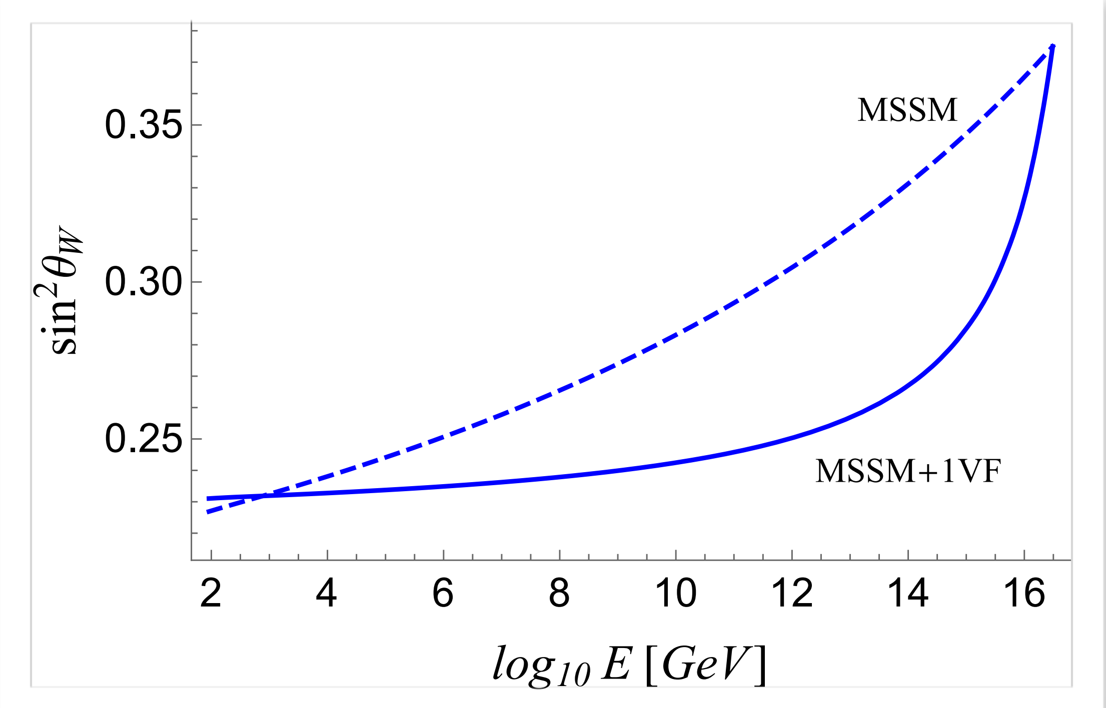
R. Dermisek, E.L. and S. Shin, to appear

Motivations

- From a purely theoretical point of view the most natural extensions of the SM are:
  - A sequential fourth generation (now heavily constrained)
  - A second Higgs doublet
    - The Higgs sector is not constrained by any symmetry apart from custodial SU(2). Note though that one doublet implies the CKM.
    - A second doublet is required in any supersymmetry model.
  - Vectorlike fermions which appear in many extensions of the SM.
    - String theories
    - Little Higgs models (heavy partners of SM fermions)
    - Warped extra dimensions (KK excitations)
    - Composite Higgs models (excited Higgs constituent states)
    - Supersymmetric models (improve the little hierarchy problem, modify the Higgs spectrum without affecting EW precision observables)
    - Top see-saw models
    - …

Motivations

- From a phenomenological point of view, vectorlike fermions have been invoked
  - to explain anomalies in Z-pole observables (VLQ)
  - to resolve the muon g-2 anomaly (VLL which mixes with the muon)
  - to understand values of gauge couplings from IR fixed point behavior
  - as an explanation for the (now defunct) 750 GeV di-gamma resonance
  - ….
- We consider simple scenarios in which a 2HDM is supplemented by a SU(2) singlet or doublet vectorlike lepton (VLL) or quark (VLQ)
  - The main appeal of these models is that it is easy to arrange for large branching ratios of a heavy Higgs into a vectorlike fermion plus SM fermion; thus gaining competitive access to large Higgs and vectorlike fermion masses



[Dermisek, McGinnis]

What are vectorlike fermions?

- Left and Right handed chiral components belong to the same SU(3)xSU(2)xU(1) representation.
  - All anomalies automatically cancel
  - Mass terms do not break gauge invariance, implying that the mass of vectorlike fermions is decoupled from the Higgs sector
- The simplest way to think about vectorlike fermions is to add a pair of left-handed fields transforming under the representations R and $\bar{R}$ (the latter correspond to the right-handed component)
- Models usually considered in the literature consist of
  - Singlets: $T_{L,R}$ and $B_{L,R}$
  - Doublets: $(T\ B)_{L,R}$, $(X\ T)_{L,R}$ and $(B\ Y)_{L,R}$
  - Triplets: $(X\ T\ B)_{L,R}$ and $(T\ B\ Y)_{L,R}$
- The convention is that the field *T* and *B* have charges 2/3 and -1/3, implying that the field X, Y have charges 5/3 and -4/3
- We consider $T_{L,R}$, $B_{L,R}$ and $(T^Q\ B^Q)_{L,R}$ which transform as t_R, b_R and $(t_L\ b_L)$

A simple model with a handful of parameters

- The particle content we consider is:

									VLQ doublet	VLQ singlets		VLL doublet	VLL singlets	
	q_L	u_R	d_R	ℓ_L	ν_R	ℓ_R	H_u	H_d	$Q_{L,R}$	$T_{L,R}$	$B_{L,R}$	$L_{L,R}$	$N_{L,R}$	$E_{L,R}$
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_I$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	0	-1	$-\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	0	-1
Z_2	$+$	$+$	$-$	$+$	$+$	$-$	$+$	$-$	$+$	$+$	$-$	$+$	$+$	$-$

- The Z_2 assignment has been made to guarantee a 2HDM type-II and avoid tree-level flavor changing neutral currents:
  - the *SU(2)* singlets u_R and $T_{L,R}$ couple only to H_u
  - the *SU(2)* singlets d_R and $B_{L,R}$ couple only to H_d

- Note that the $Q = (T^Q \; B^Q)$ and that T^Q and T are different particles!

Vectorlike Quarks

A simple model with a handful of parameters

- The most general Yukawa and Mass terms are:

SM | mixing in Yukawa interactions

$$\mathcal{L}^{\rm VLQ}_{\rm Mass} = \underbrace{-y_d^{ij}\,\bar{q}^i_L d^j_R H_d - y_u^{ij}\,\bar{q}^i_L u^j_R H_u}_{\rm SM} \underbrace{-\lambda^i_B \bar{q}^i_L B_R H_d - \lambda^j_Q \bar{Q}^i_L d^j_R H_d - \kappa^i_T \bar{q}^i_L T_R H_u - \kappa^j_Q \bar{Q}^i_L u^j_R H_u}_{\text{mixing in Yukawa interactions}}$$

VLQ masses

$$-M_Q \bar{Q}_L Q_R - M_T \bar{T}_L T_R - M_B \bar{B}_L B_R$$

VLQ Yukawas

$$-\lambda \bar{Q}_L B_R H_d - \bar{\lambda} H_d^\dagger \bar{B}_L Q_R - \kappa \bar{Q}_L T_R H_u - \bar{\kappa} H_u^\dagger \bar{T}_L Q_R + \text{h.c.}$$

- After EW Symmetry Breaking the mass matrix for the 5 charge 2/3 particles is:

$$\begin{pmatrix} \bar{u}^i_L & \bar{T}^Q_L & \bar{T}_L \end{pmatrix} \begin{pmatrix} y_u^{ij} v_u & 0 & \kappa^i_T v_u \\ \kappa^j_Q v_u & M_Q & \kappa v_u \\ 0 & \bar{\kappa} v_u & M_T \end{pmatrix} \begin{pmatrix} u^j_R \\ T^Q_R \\ T_R \end{pmatrix}$$

A simple model with a handful of parameters

- The vectors κ_T^i and κ_Q^i introduce mixing between the VLQs and the SM fermions
- Strong constraints from atomic parity violation and the R_c measurement at LEP, essentially confines this mixing to the third generation (hence the notation that we adopted)
- The decoupling of the direct contributions to the VLQ masses ($M_{T,B,Q}$) from the corresponding subleading Yukawa terms, $(\lambda_Q, \lambda_B)v_d$ and $(\kappa_Q, \kappa_T)v_u$, allows to evade bounds from Higgs production (that severely constrains a sequential fourth generation)
- The 3x3 mass matrices for up and down type VLQs are:

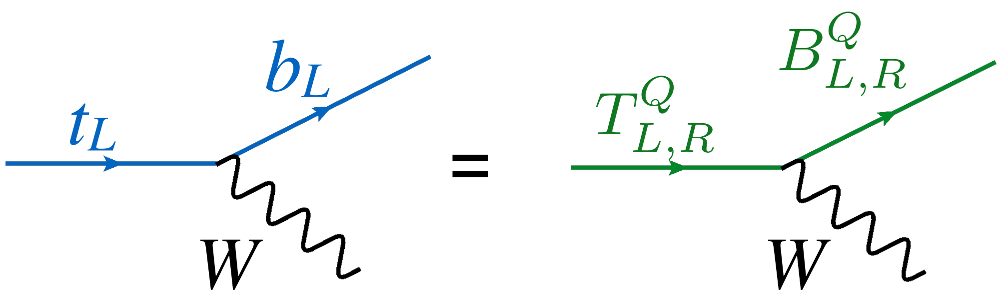
$$M_u = \begin{pmatrix} y_t v_u & 0 & \kappa_T v_u \\ \kappa_Q v_u & M_Q & \kappa v_u \\ 0 & \bar\kappa v_u & M_T \end{pmatrix} \quad M_d = \begin{pmatrix} y_b v_d & 0 & \lambda_B v_d \\ \lambda_Q v_d & M_Q & \lambda v_d \\ 0 & \bar\lambda v_d & M_B \end{pmatrix}$$

parameters:
Q → 3
T/B → 2
Q + T/B → 7
Q+T+B → 11

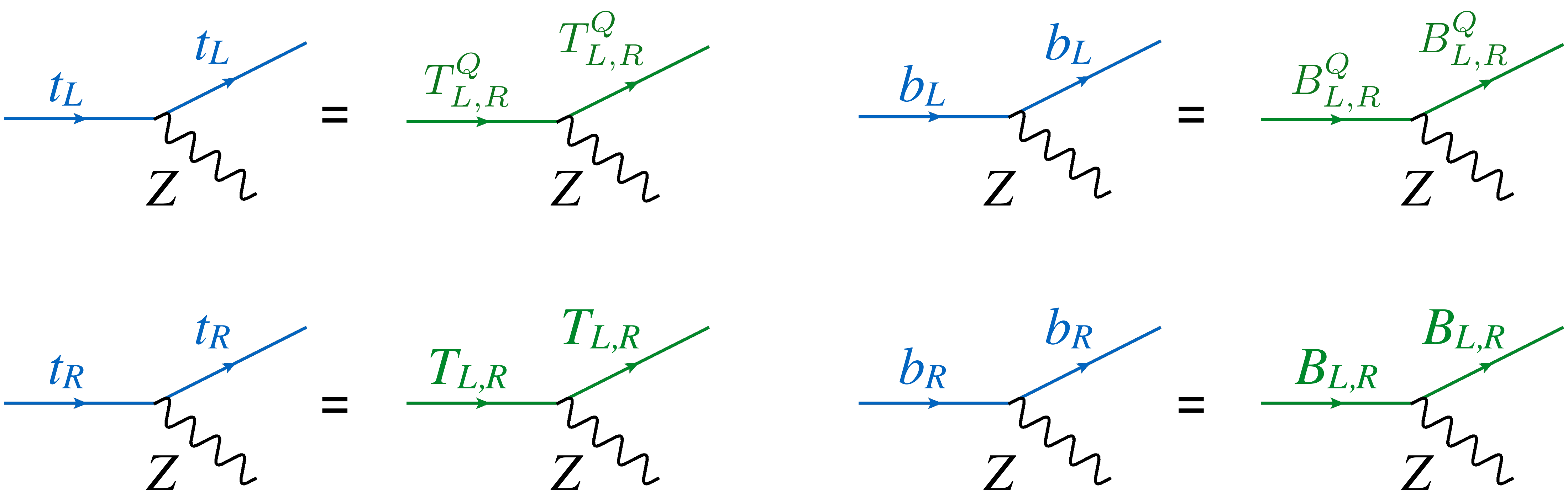
- In our notation the 4 vectorlike mass eigenstates are denoted as $t_{4,5}$ and $b_{4,5}$
- The parameters $\kappa,\ \bar\kappa,\ \lambda, \bar\lambda$ control the mixing between the VLQ doublet and singlets: the doublet fraction of the lightest VLQ (t_4 in our case) is an important quantity because it controls its coupling to the W boson.

Gauge bosons couplings

- Before switching on mixing terms (λ and κ terms) gauge interactions are diagonal and controlled by the fermion representations:



Left and Right VLQ have same couplings to W and Z



Gauge bosons couplings

- The mixed VLQ-SM Yukawa interactions generate the following mixing:

At large VLQ masses doublets (singlets) mix only with right (left) handed quarks

T^Q_L — t_L $= \kappa_Q y_t \frac{v_u^2}{M_Q^2}$

T^Q_R — t_R $= \kappa_Q \frac{v_u}{M_Q}$

B^Q_L — b_L ≈ 0

B^Q_R — b_R $= \lambda_Q \frac{v_d}{M_Q}$

T_L — t_L $= \kappa_T \frac{v_u}{M_T}$

T_R — t_R $= \kappa_T y_T \frac{v_u^2}{M_T^2}$

B_L — b_L $= \lambda_B \frac{v_d}{M_B}$

B_R — b_R ≈ 0

- W-interactions between VLQ and the third generation:

T^Q_L — t_L — b_L, W $= \frac{g}{\sqrt{2}} V_{tb} \kappa_Q y_t \frac{v_u^2}{M_Q^2}$

T^Q_R — B^Q_R — b_R, W $= \frac{g}{\sqrt{2}} \lambda_Q \frac{v_d}{M_Q}$

T_L — t_L — b_L, W + T_L — B_L — b_L, W

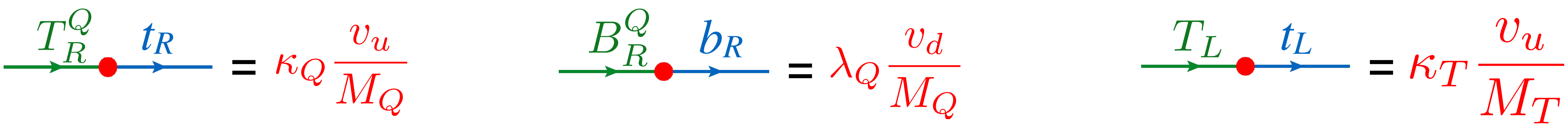
$$= \frac{g}{\sqrt{2}} \left[V_{tb} \kappa_T \frac{v_u}{M_T} + \lambda_B \frac{v_d}{M_B} \right]$$

T_R — B_R — b_R, W ≈ 0

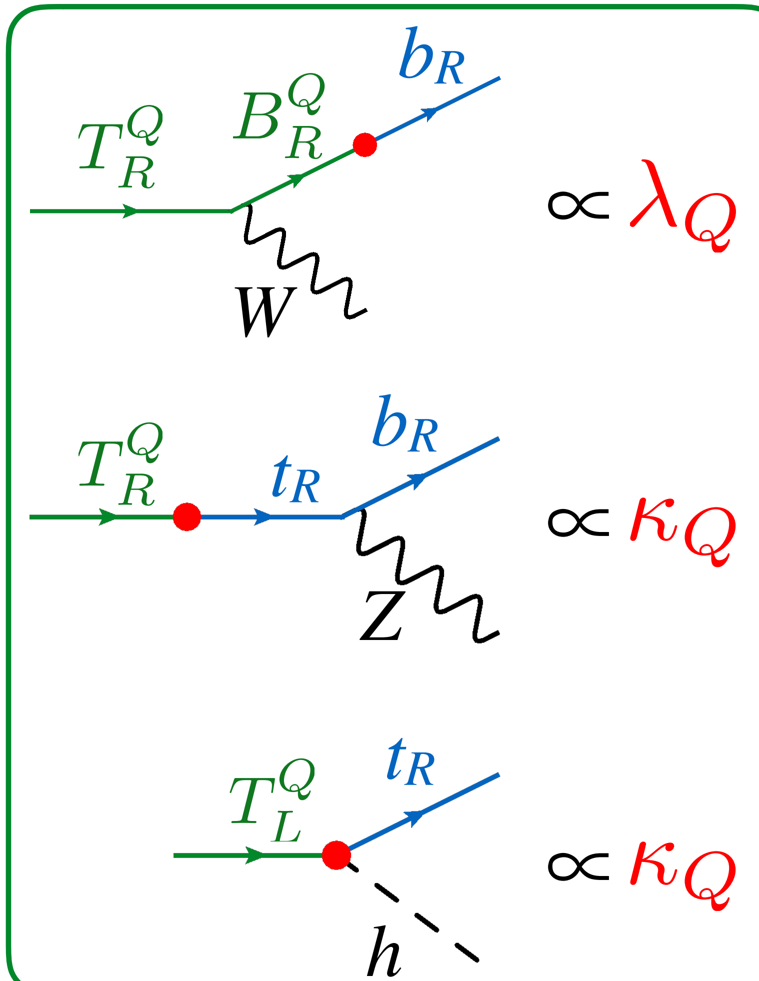
Gauge bosons couplings

- Let's compare the W, Z and h couplings of a doublet/singlet vectorlike top:

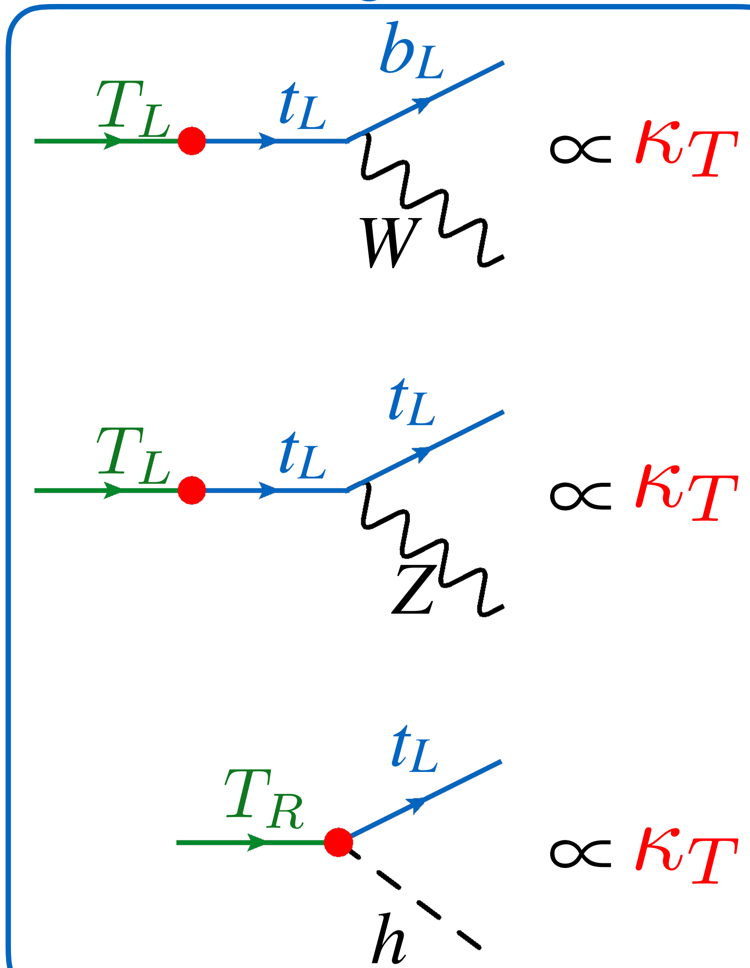
Leading Mixing terms:



Doublet:



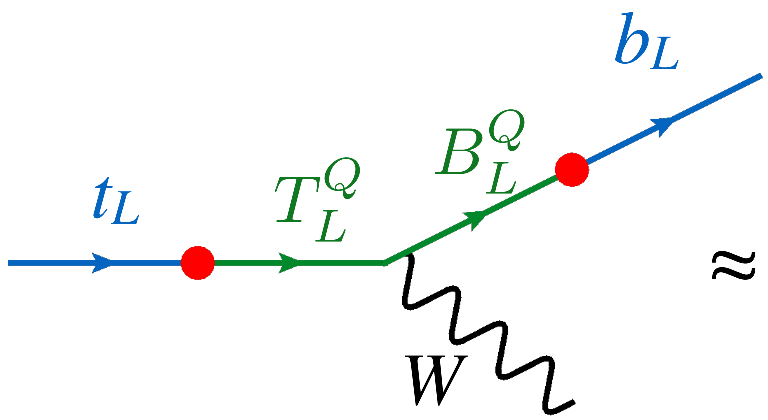
Singlet:



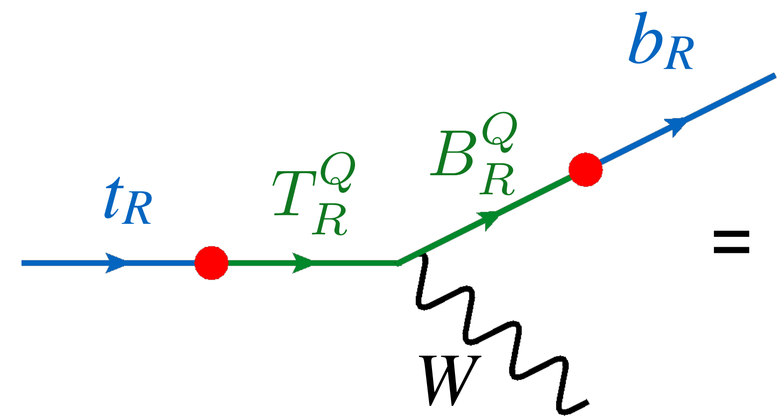
- Doublet partial widths depend on two Yukawa couplings (λ_Q, κ_Q).
  At large m_{t4} with $\lambda_Q=0$ we have:
  $BR(t_4 \to Zt) \sim BR(t_4 \to ht) \sim 50\%$
  At large m_{t4} with $\kappa_Q=0$ we have:
  $BR(t_4 \to Wb) \sim 100\%$
- Singlet partial widths depend on one Yukawa coupling (κ_T).
  At large m_{t4} one expects:
  $BR(t_4 \to Zt) \sim BR(t_4 \to ht)$
  $\sim ½\ BR(t_4 \to Wb) \sim 25\%$

Gauge bosons couplings

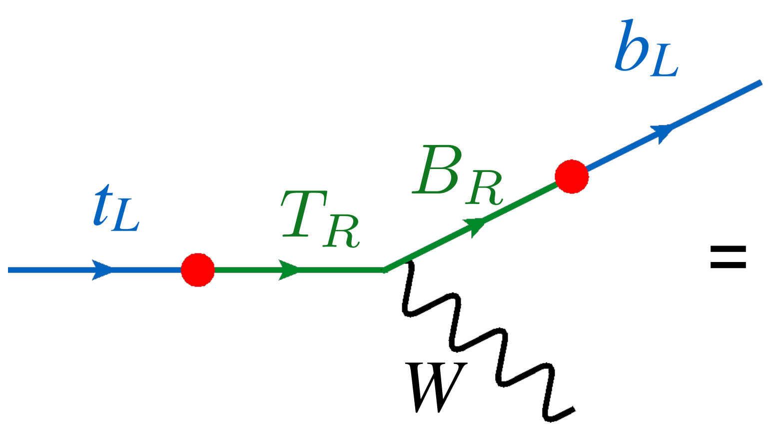
- W and Z interactions are responsible for VLQ decays (e.g. $t_4 \to Wb$ and $t_4 \to Zt$) and EW single production
- Modification of third generation couplings to W and Z. For instance:



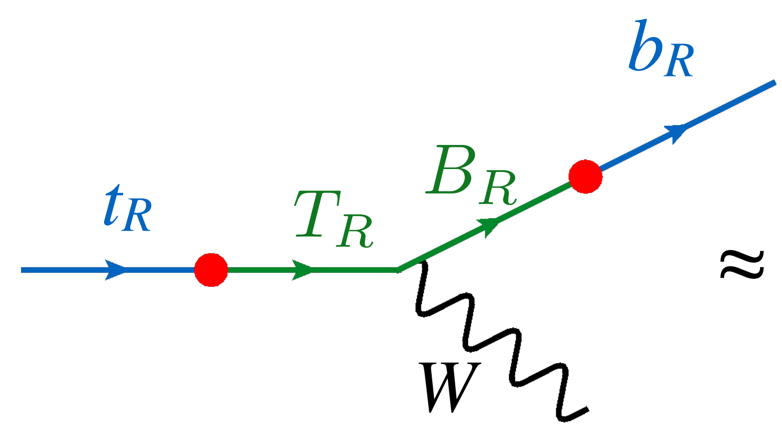
$$\approx 0$$



$$= \frac{g}{\sqrt{2}} \kappa_T \lambda_B \frac{v_u v_d}{M_T M_B}$$



$$= \frac{g}{\sqrt{2}} \kappa_Q \lambda_Q \frac{v_u v_d}{M_Q^2}$$



$$\approx 0$$

Gauge bosons couplings: CKM

- What about flavor changing interactions?
  - As long as the vectorlike fermions couple to the third generation only, there are no induced FCNC (at tree level) amongst the three SM generations
  - The structure of the CKM is modified by mixing with the VLQ quarks:

$$V_{\rm CKM}^{\rm eff} = \begin{pmatrix} V_{ud} & V_{us} & \alpha_b\, V_{ub} \\ V_{cd} & V_{cs} & \alpha_b\, V_{cb} \\ \alpha_t\, V_{td} & \alpha_t\, V_{ts} & \alpha_b \alpha_t\, V_{tb} \end{pmatrix} \quad \text{where} \quad \begin{cases} \alpha_t = 1 - v_u^2 \frac{\kappa_T^2}{2M_T^2} \\ \alpha_b = 1 - v_d^2 \frac{\lambda_B^2}{2M_B^2} \end{cases}$$

$\lesssim 10^{-2}$

- Phenomenological implications:
  - No impact on CKM angles α, β and γ
  - Possible constraints from unitarity
  - Possible enhancements in D mixing and decays:

$$A(c \to u) \sim \alpha_d^2\, V_{cb} V_{ub}^*\, f(\frac{m_b^2}{m_W^2}) + (V_{cs}V_{us}^* + V_{cd}V_{ud}^*)\, f(0) \sim V_{cb}V_{ub}^* \left[\frac{m_b^2}{m_W^2} + (\alpha_d^2 - 1) \right]$$

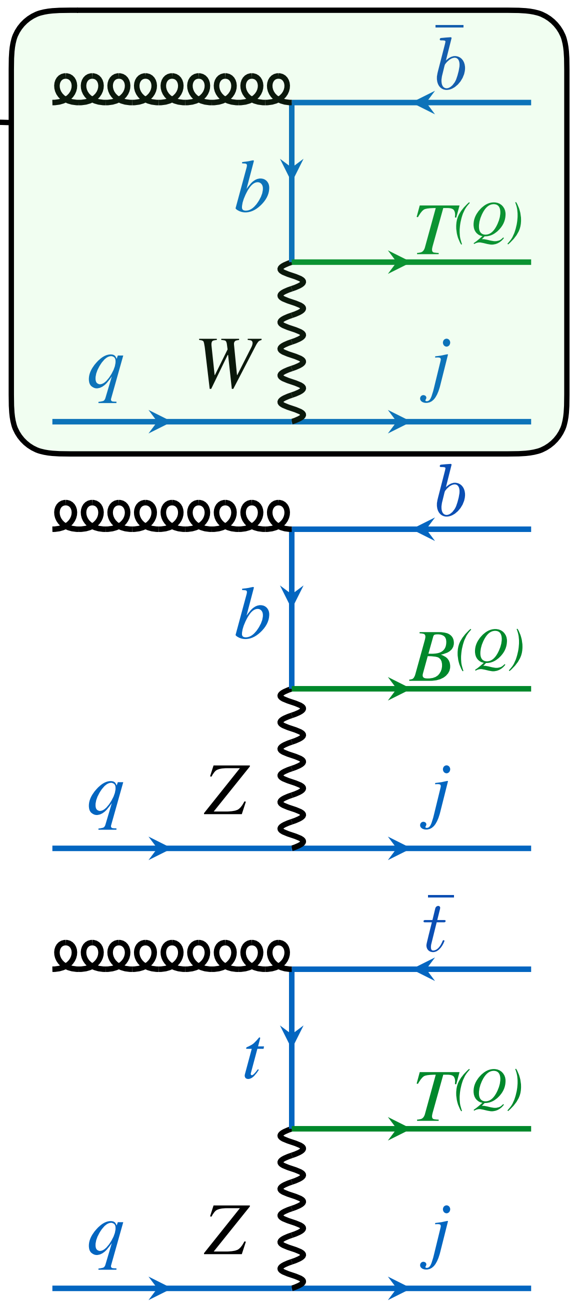
$\sim 4\ 10^{-3}$ $\quad \lesssim 2\ 10^{-2}$

  - Effects in B physics are expected to be small

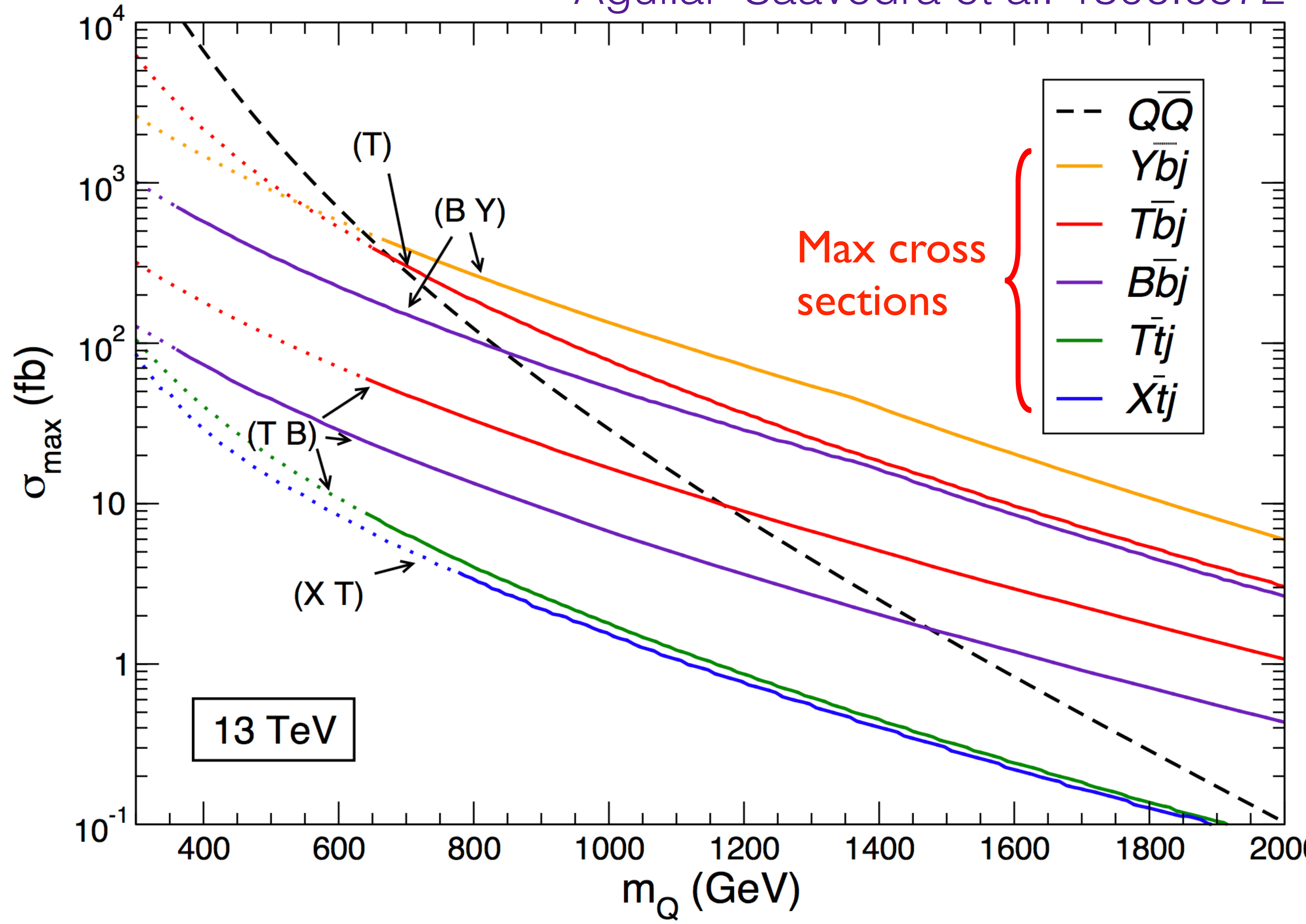
VLQ: Standard production channels

- Pair production: controlled only by the VLQ mass
- Single production: sensitive to mixing with SM fermions. Smaller than pair production but can become dominant (in some scenarios) at large VLQ mass

potentially large but depends on various couplings ($\lambda_Q, \kappa_Q, \kappa_T, \kappa, \bar{\kappa}$)

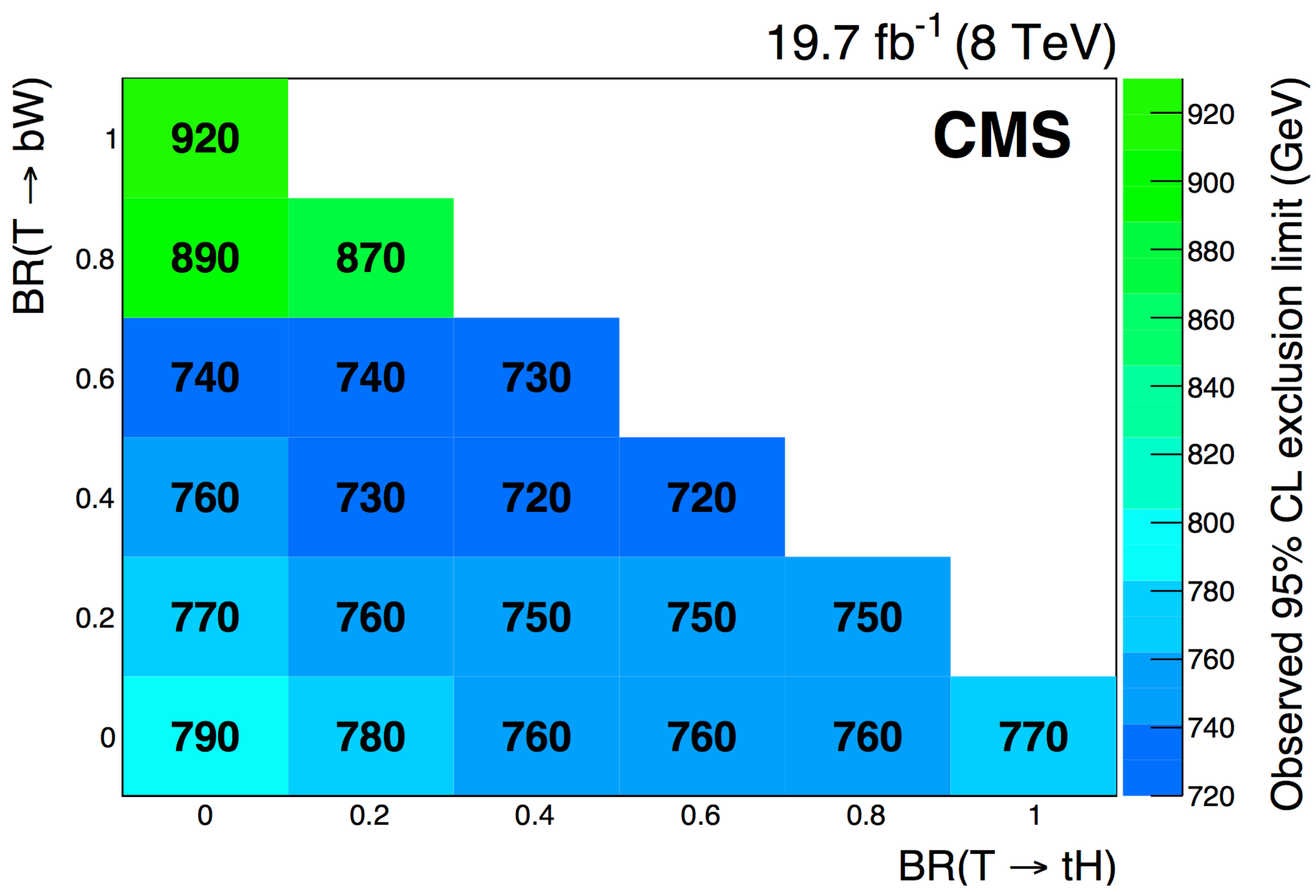


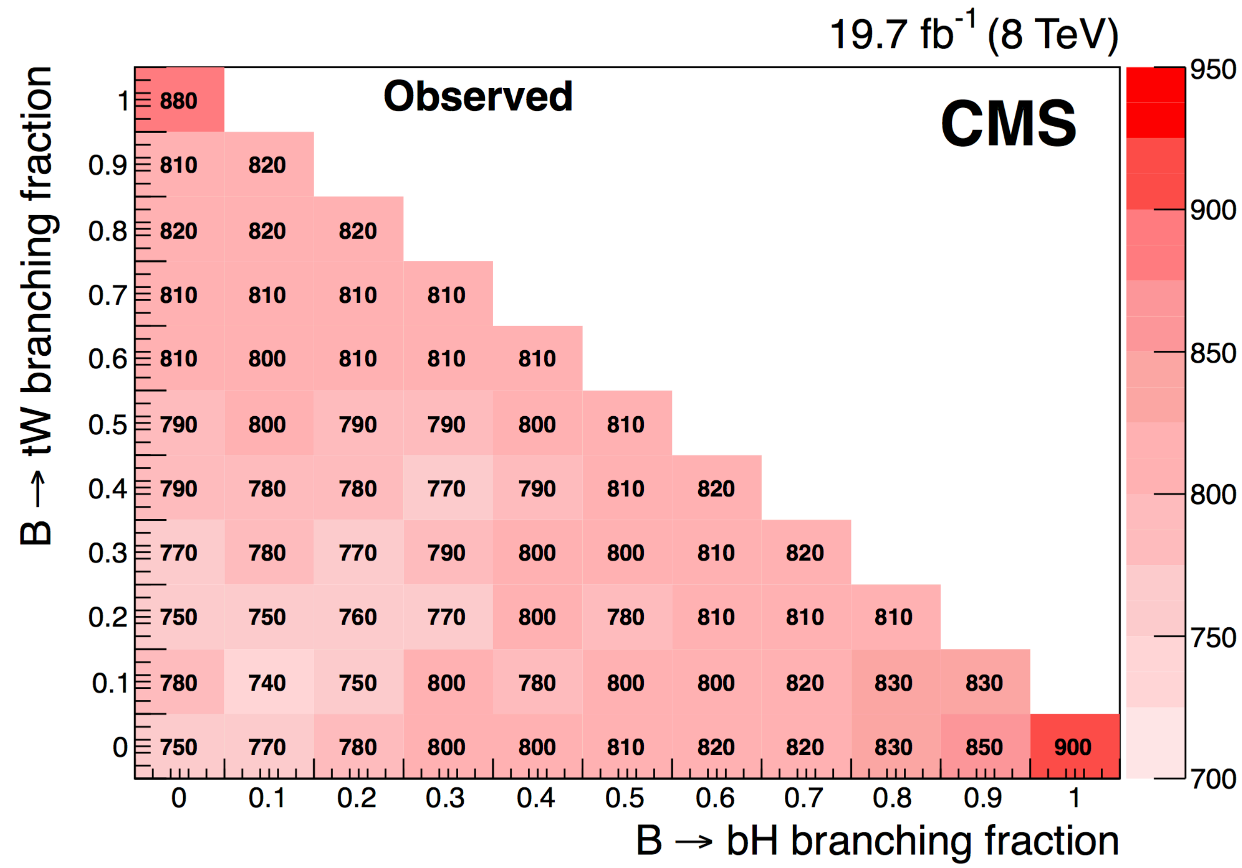
Aguilar–Saavedra et al. 1306.0572



VLQ: Existing constraints

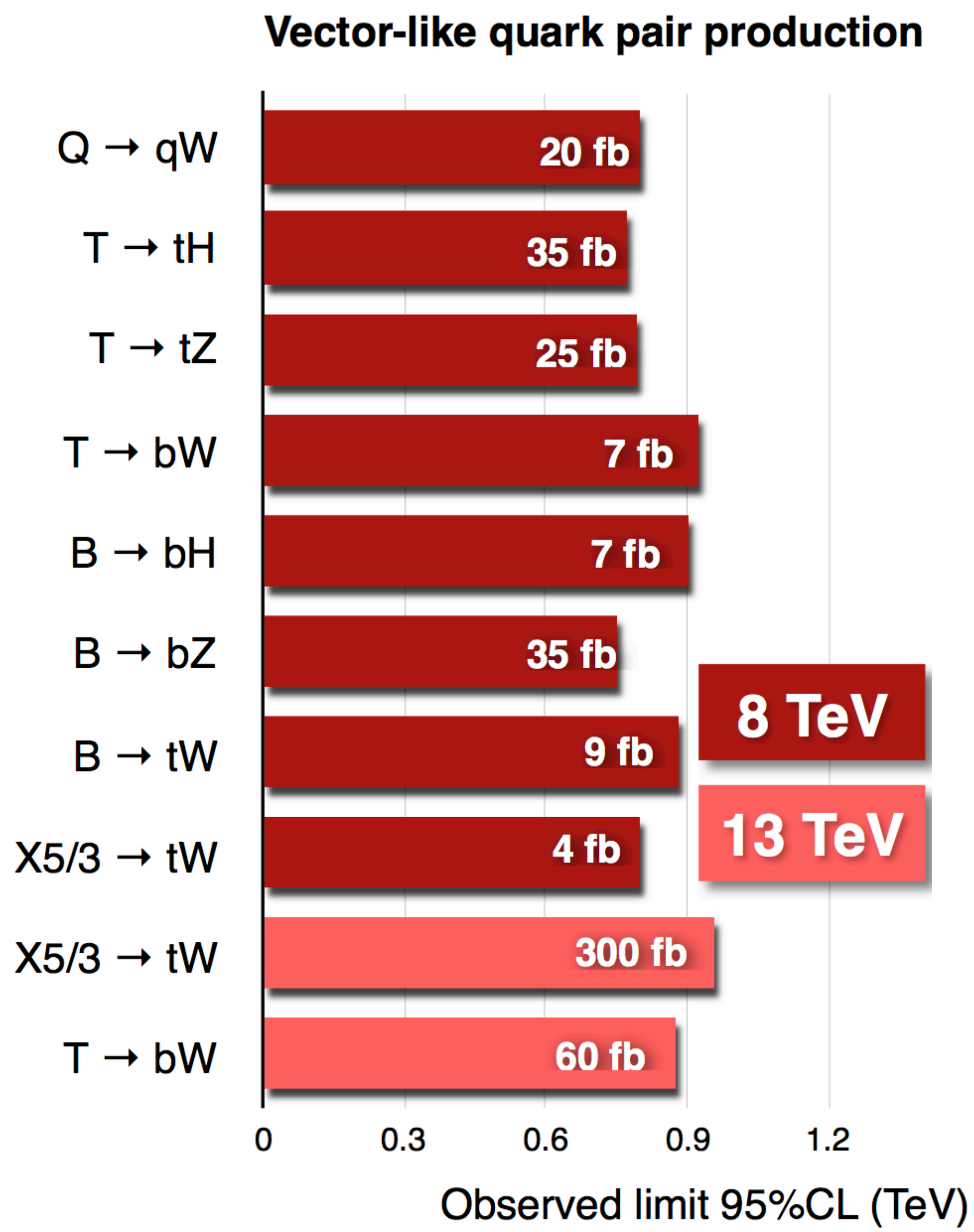
- CMS inclusive constraints from T and B pair production - 8 TeV data
- Independent of any model parameter (as long as there are only three decay modes)!
- Remember that singlet and doublet pair production is identical.

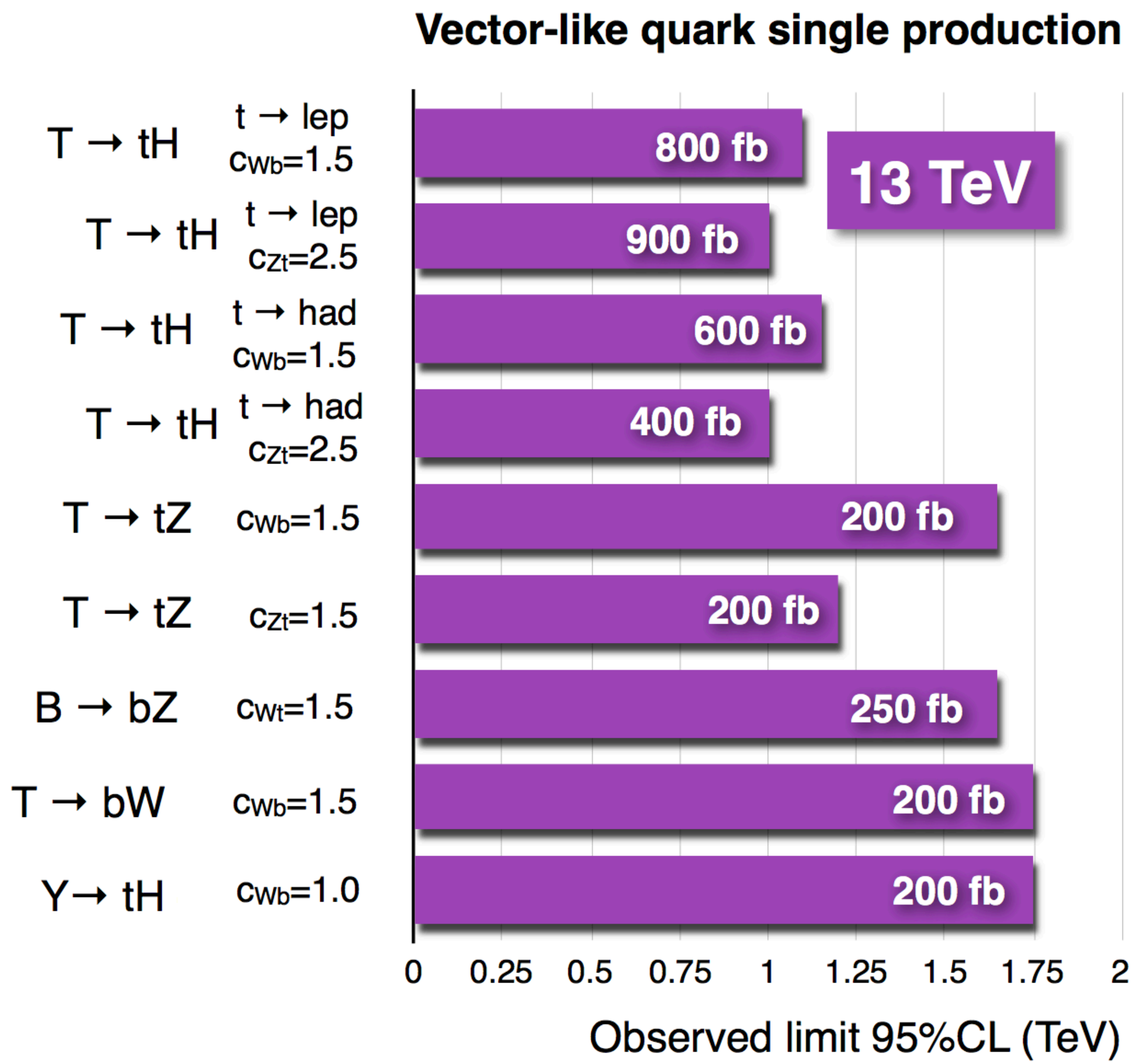




VLQ: Existing constraints

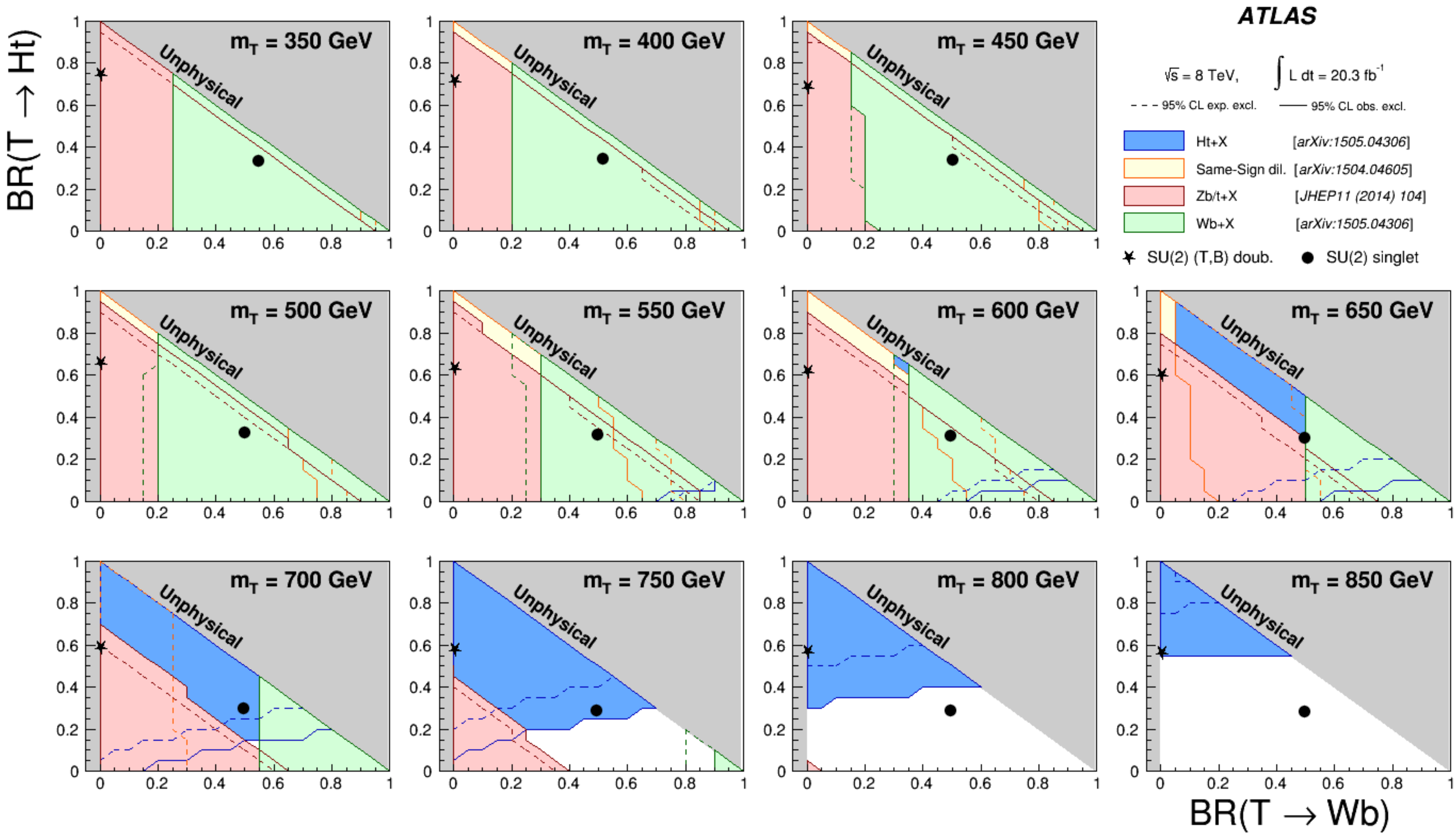
- CMS constraints on single and pair production of VLQs (including 13 TeV data)
- GB equivalence theorem assumptions on BRs and coupling at 0.5.





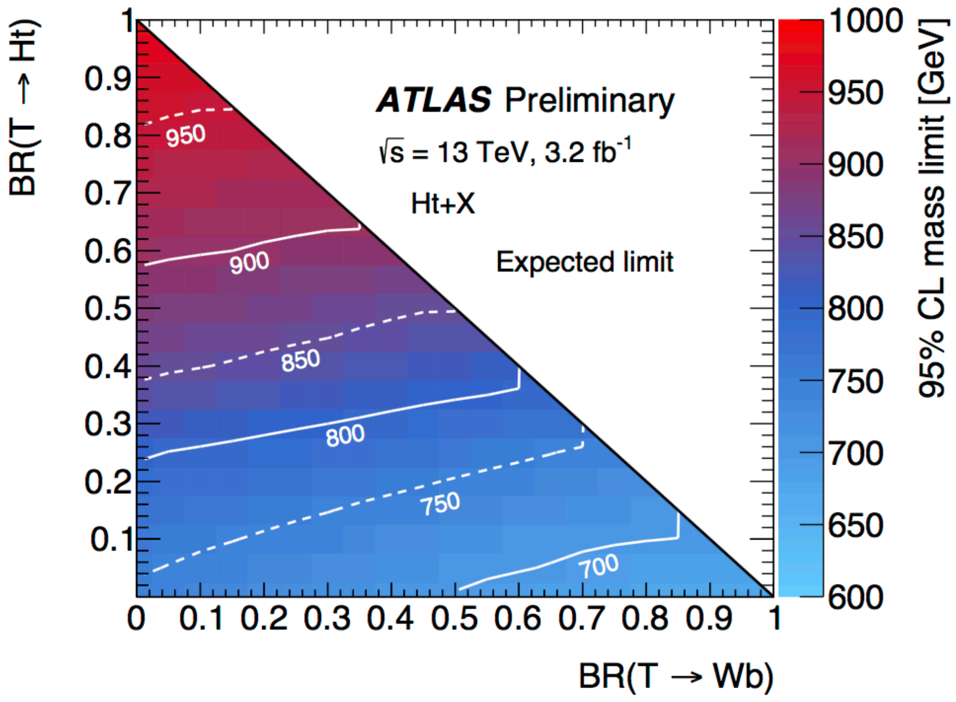
VLQ: Existing constraints

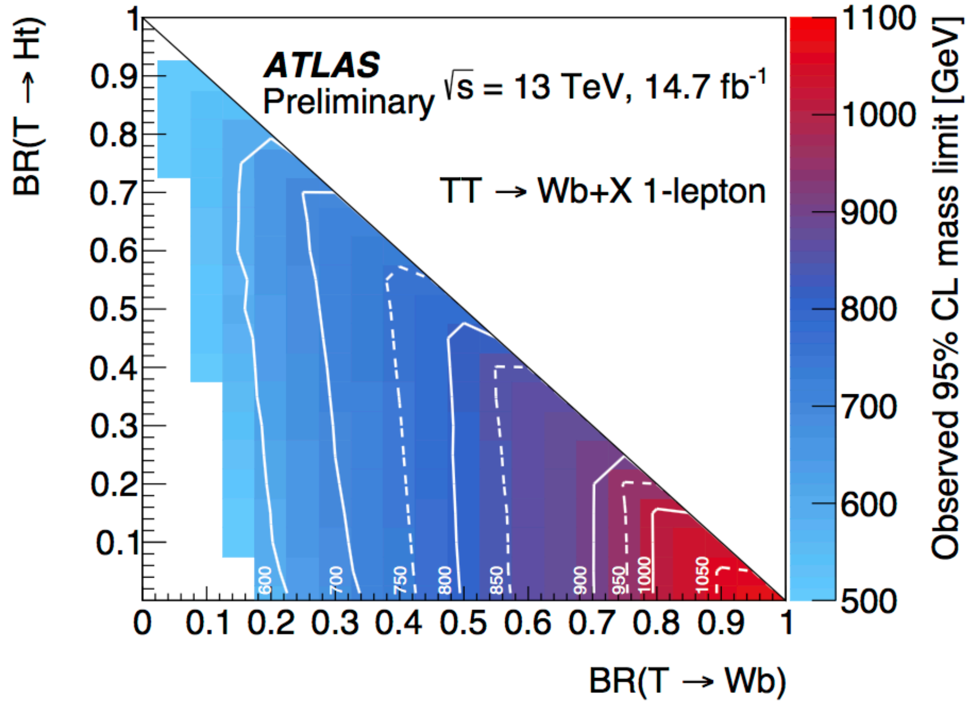
- ATLAS inclusive constraints from T and T^Q pair production - 8 TeV data

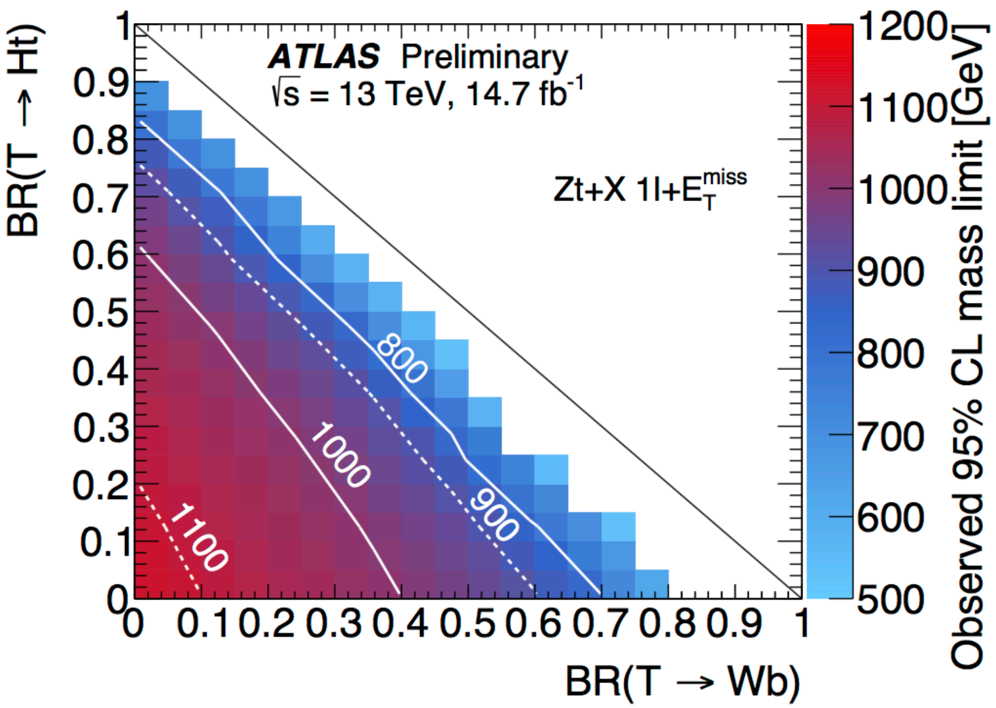


VLQ: Existing constraints

- ATLAS inclusive constraints from T and T^Q pair production - 13 TeV data

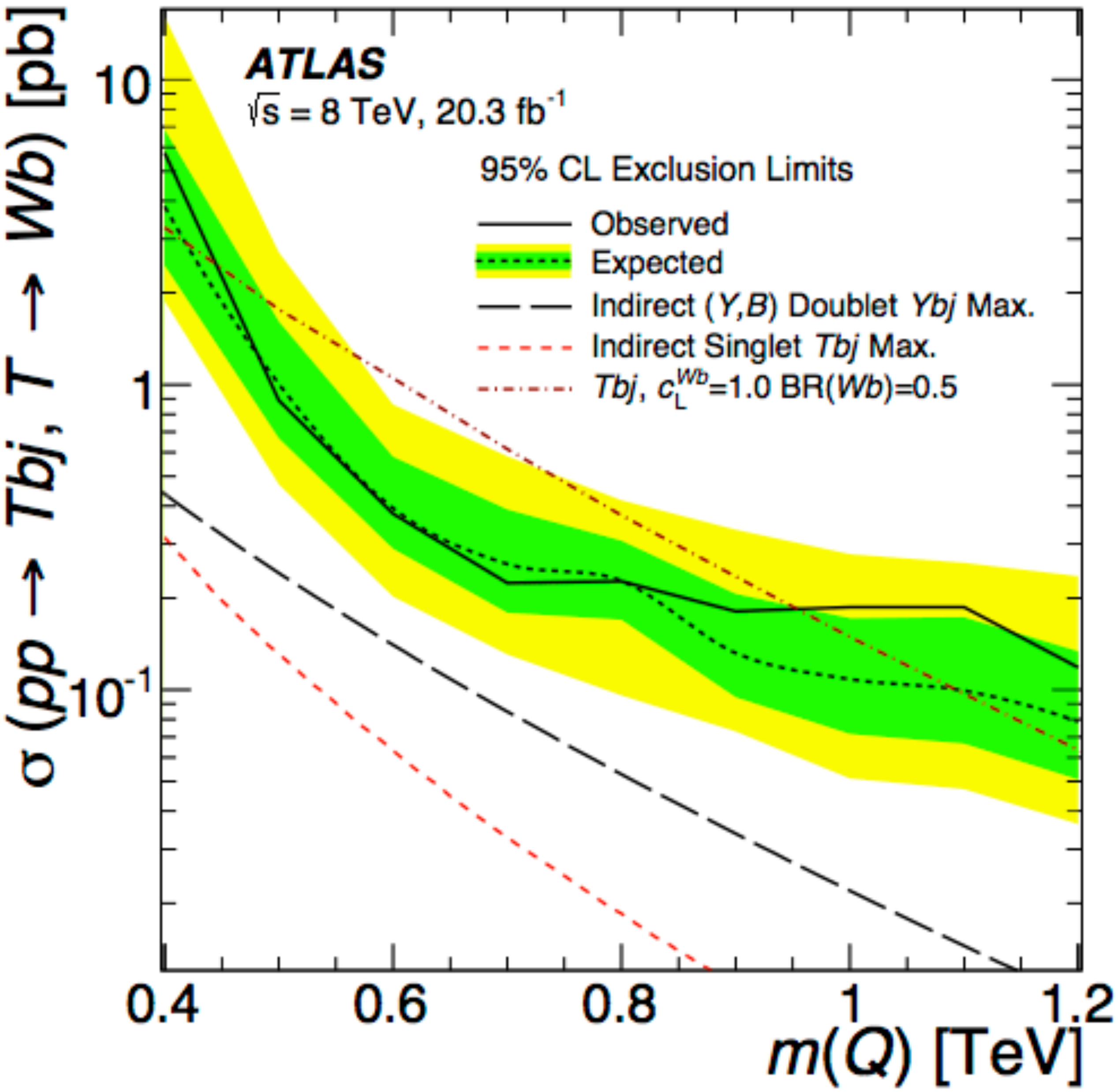


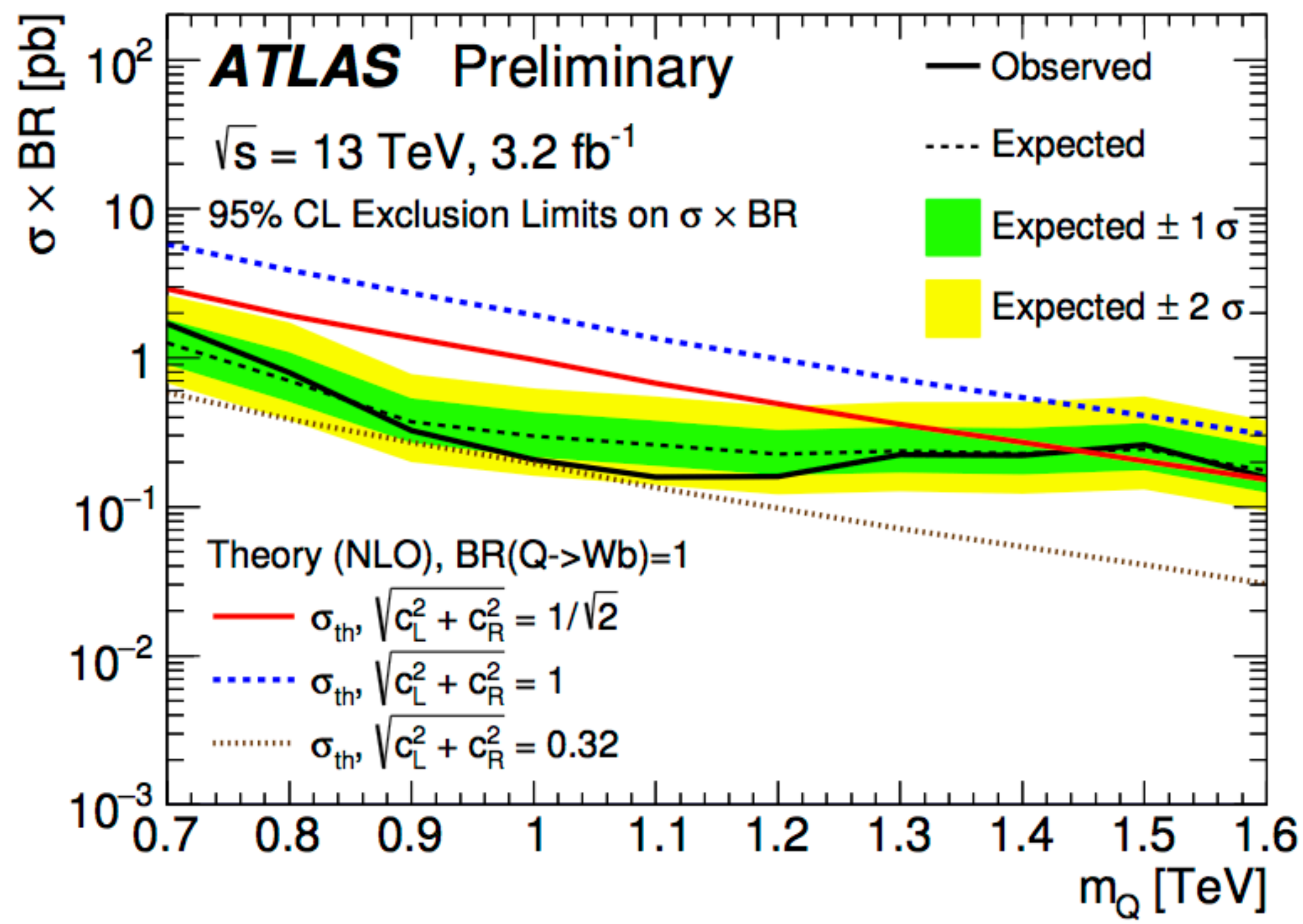




VLQ: Existing constraints

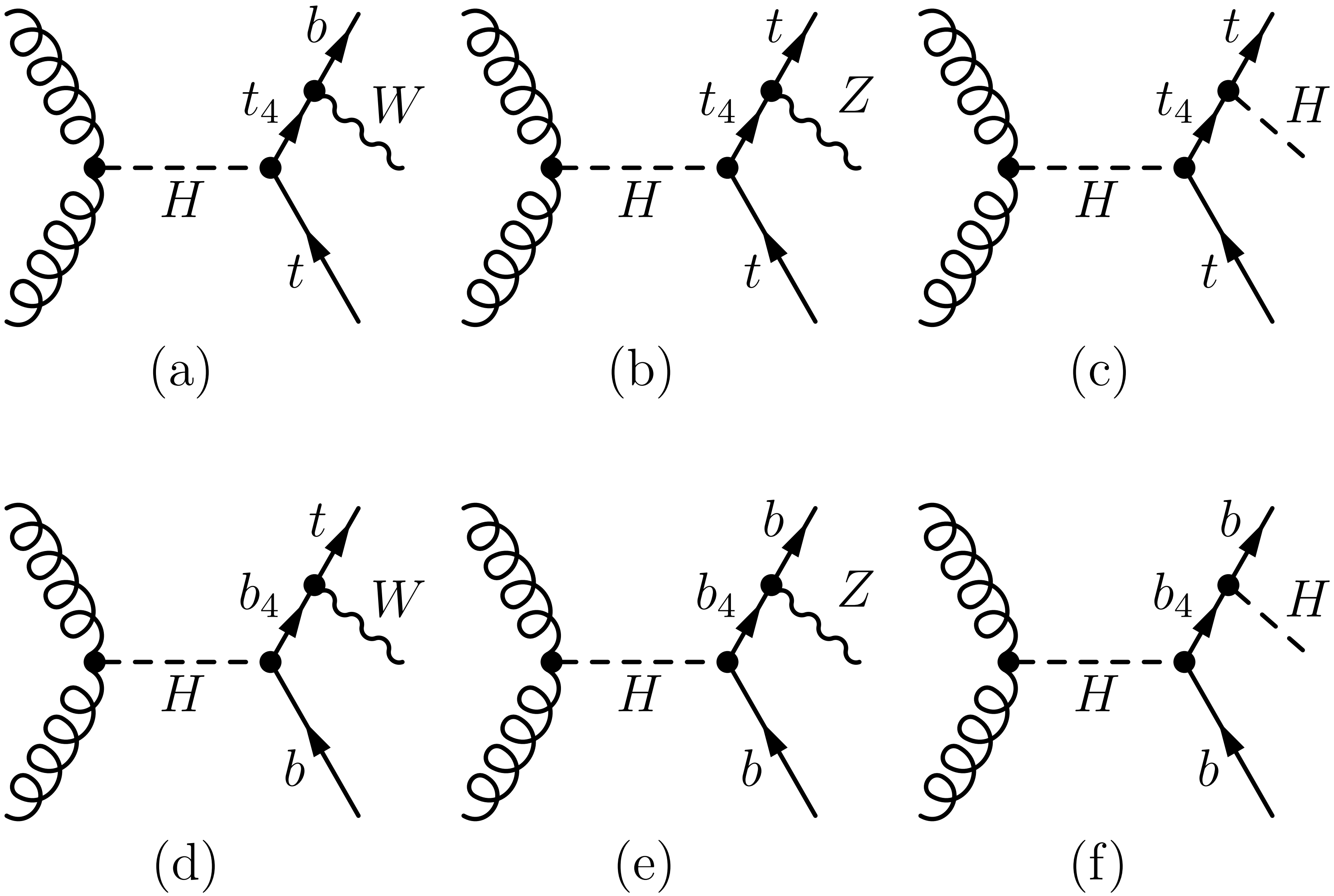
- ATLAS constraints on single T and T^Q production (8 and 13 TeV data)





VLQ: Higgs mediated channel

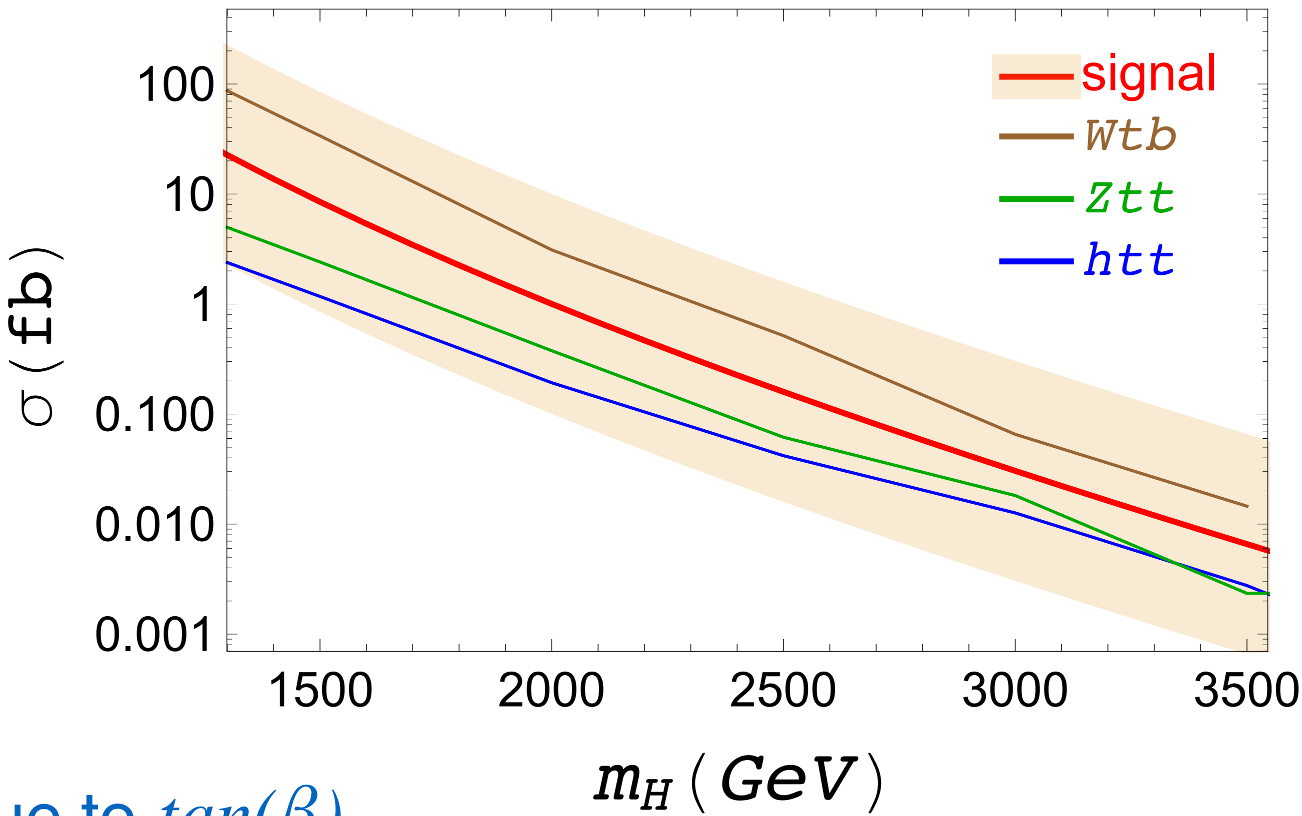
- We consider the following Higgs-mediated single production topologies:



- Details of mixing enter only via the H and t_4 branching ratios
- Dependence of EW and Higgs-mediated single production on the model parameters are different

VLQ: cross sections and backgrounds

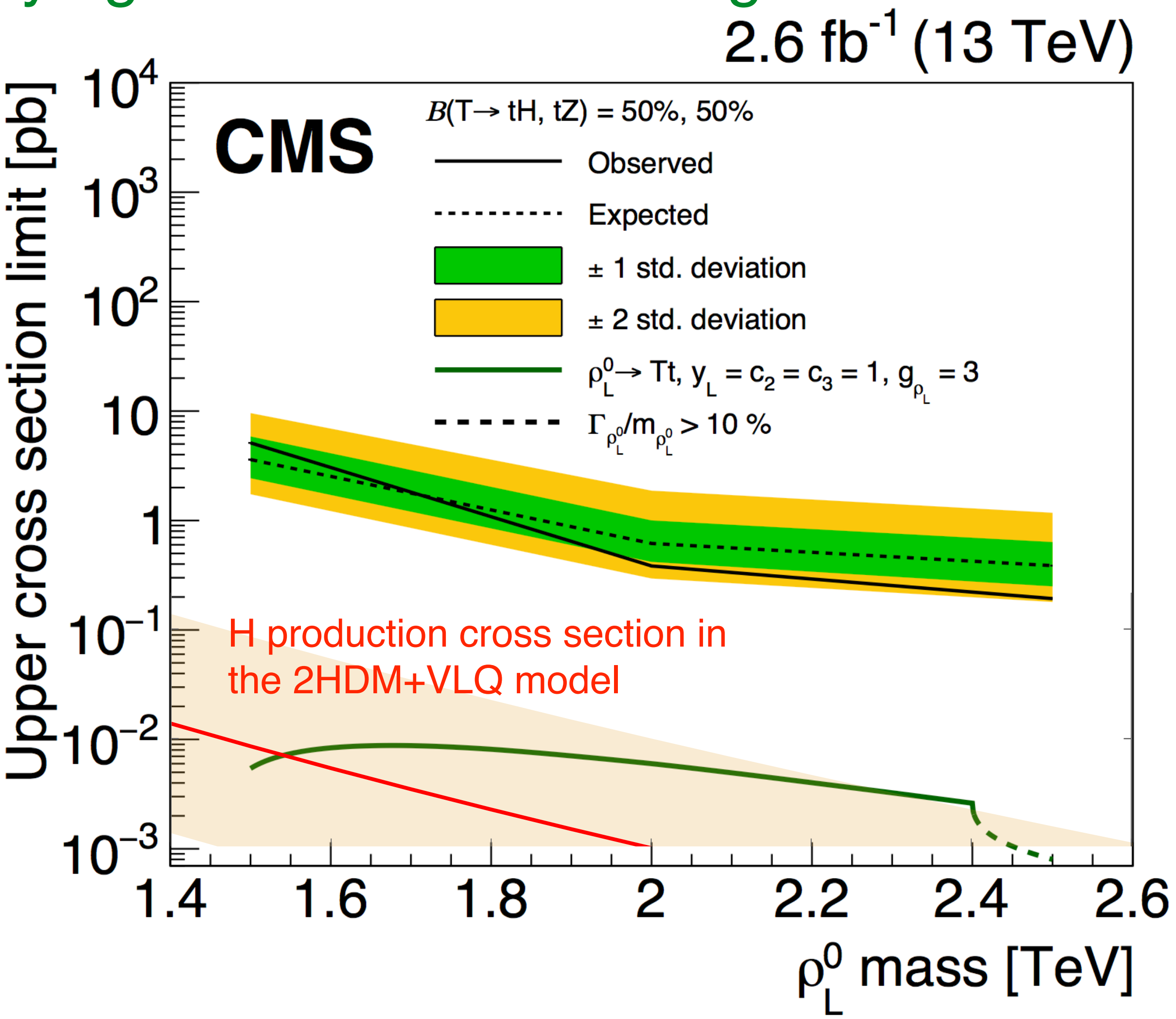
- To avoid constraints from the 125GeV Higgs we impose alignment on the 2HDM: $\sin(\beta-\alpha)=1$
- This implies suppressed H couplings to Gauge bosons
- The signal cross section is simply $(gg,bb)\to H$ (VBF is suppressed) and has been generated with SuShi and HiGlu



- The range of the signal cross section is due to $\tan(\beta)$
- In order to be competitive with pair and EW single production we focus on mass spectra for which the H-t_4 splitting is small
- Backgrounds have been estimated using MadGraph 5
- We require only some rough cuts (with signal acceptance larger than 80%):
  - The decay products of the t_4 are required to have $p_T > m_{t4}/2$
  - The reconstructed Higgs mass is required to lie in a 100 GeV window

VLQ: cross sections and backgrounds

- The topology of our signal is very similar to a heavy Z′: $pp \to Z' \to t_4 t$
- In order to enhance the Z′ branching ratio into the VLQ channel, one needs to assume a model in which the Z′ is leptophilic and restrict the range of masses in such a way to suppress $Z' \to t_4 t_4$
- In the first analysis with 2.3 fb^{-1} the impact of the spin of the intermediate resonance was not found to be large, implying that Z′ search strategies can be trivially extended to $H \to t_4 t$
- Present bounds are [CMS 1703.06352]:



Parameter space scan

- The crucial quantities that we need are: $BR(H \rightarrow t_4\, t)$
  $BR(t_4 \rightarrow W\, b,\, Z\, t,\, h\, t)$

- We perform a scan over our model parameter space:

$$\tan(\beta) \in [0.3, 50]$$
$$M_Q \in [0.9, 6]\ \mathrm{TeV}$$
$$M_T \in [0.9, 6]\ \mathrm{TeV}$$
$$\kappa_Q, \kappa_T, \kappa, \bar{\kappa} \in [-1, 1]$$
$$\sin(\beta - \alpha) = 1$$
$$m_{t_5} > m_H$$

- We impose constraints from
  - Direct searches
  - Oblique Corrections (S,T,U)
  - $h \rightarrow \gamma\gamma$
  - $H \rightarrow \gamma\gamma$
  - Z-pole observables (R_b)
  - $H \rightarrow (WW, ZZ)$

Parameter space scan: H production

- The origin of the large spread in H production cross sections can be simply understood by looking at the top and bottom Higgs couplings:

$$tth \sim 1 + \frac{\xi}{\tan(\beta)}$$

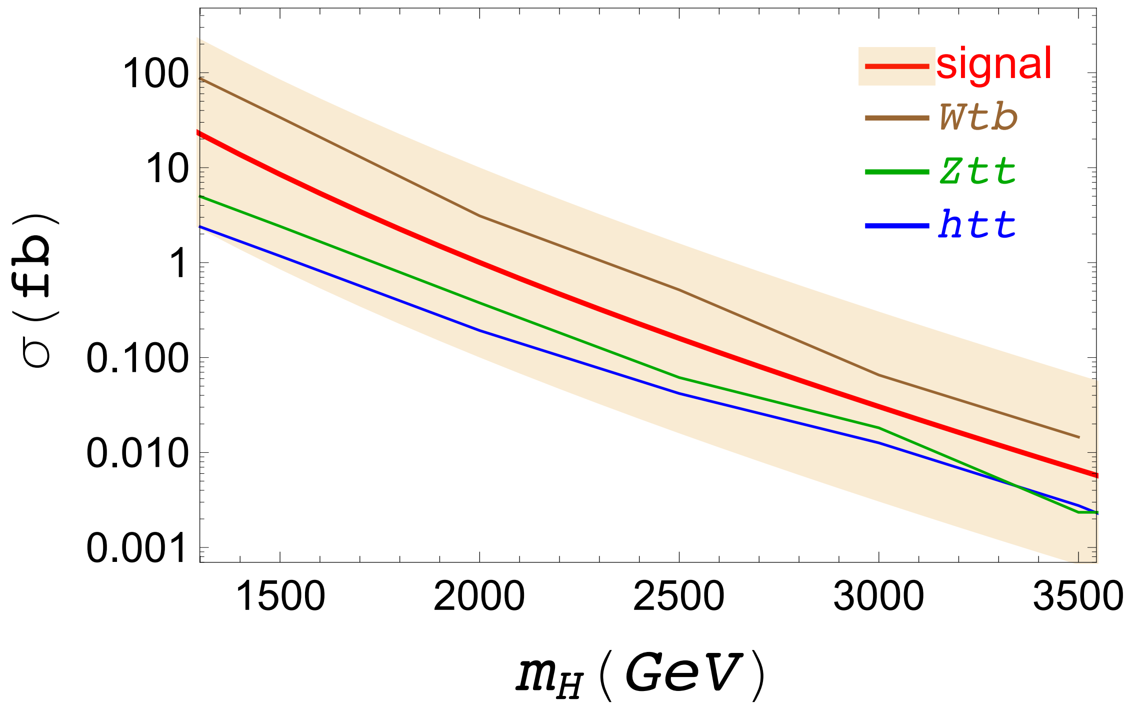
$$bbh \sim 1 - \xi \tan(\beta)$$

$$ttH \sim -\frac{1}{\tan(\beta)} + \xi$$

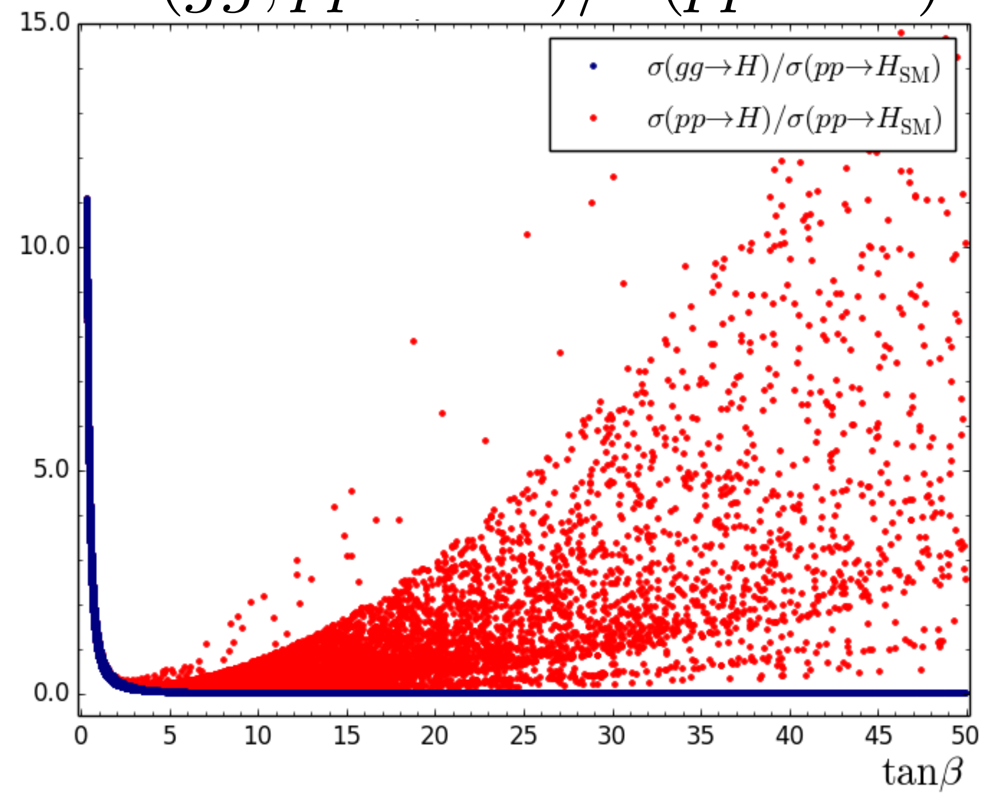
$$bbH \sim \tan(\beta) + \xi$$

where we take

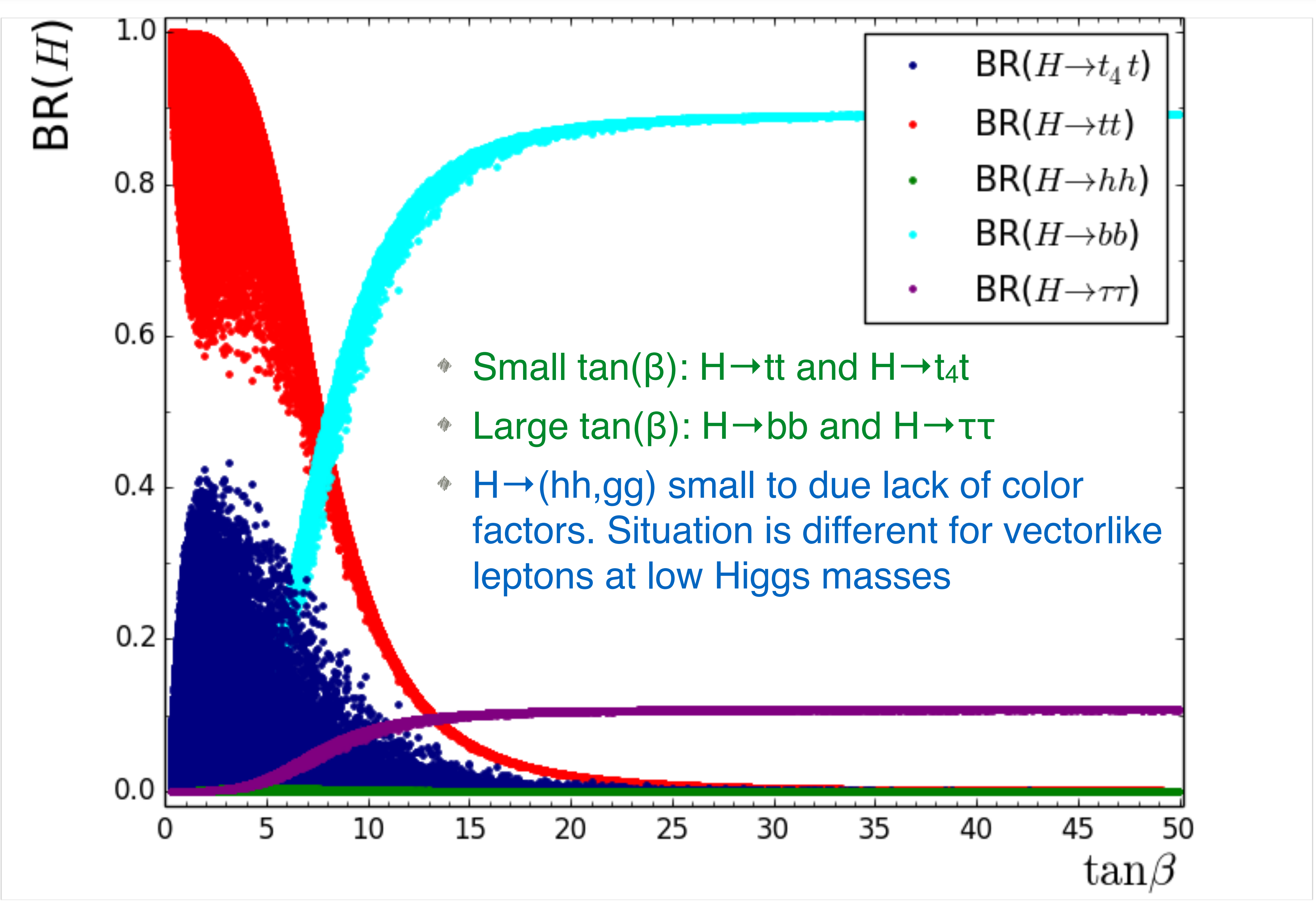
$$\xi = \cos(\beta - \alpha) = 0$$



$$\sigma(gg, pp \to H)/\sigma(pp \to h)$$

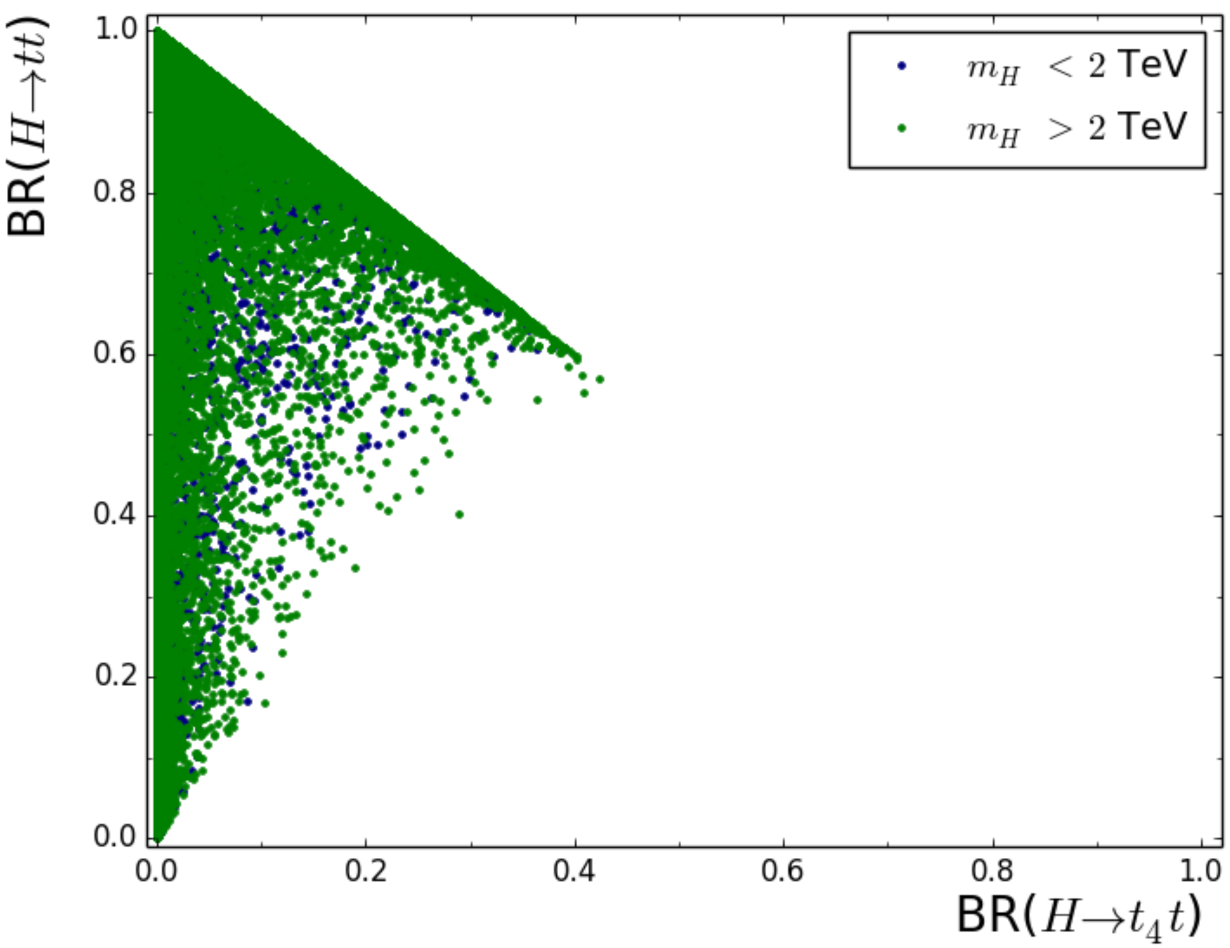


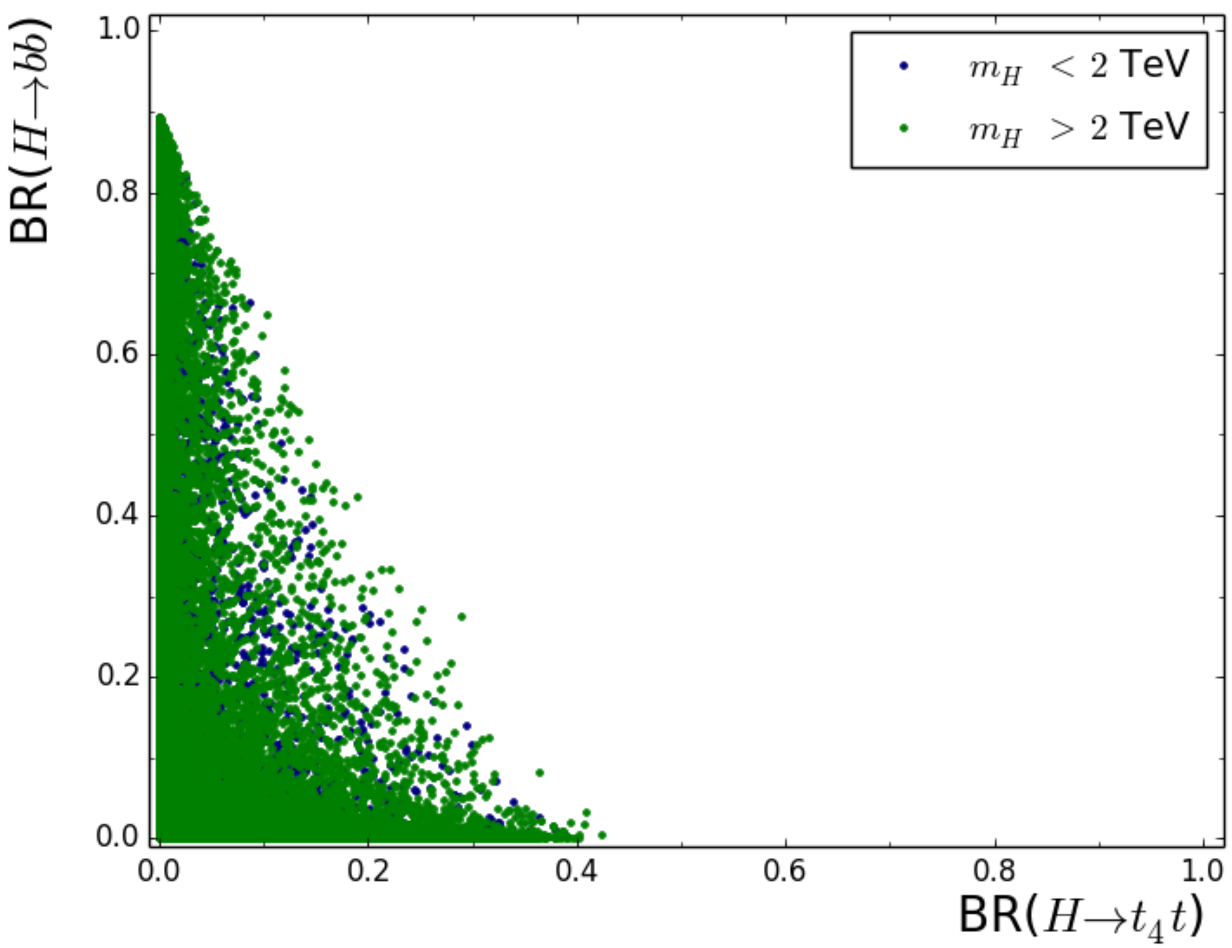
Parameter space scan: H branching ratios



- Small tan(β): H→tt and H→t_4t
- Large tan(β): H→bb and H→ττ
- H→(hh,gg) small to due lack of color factors. Situation is different for vectorlike leptons at low Higgs masses

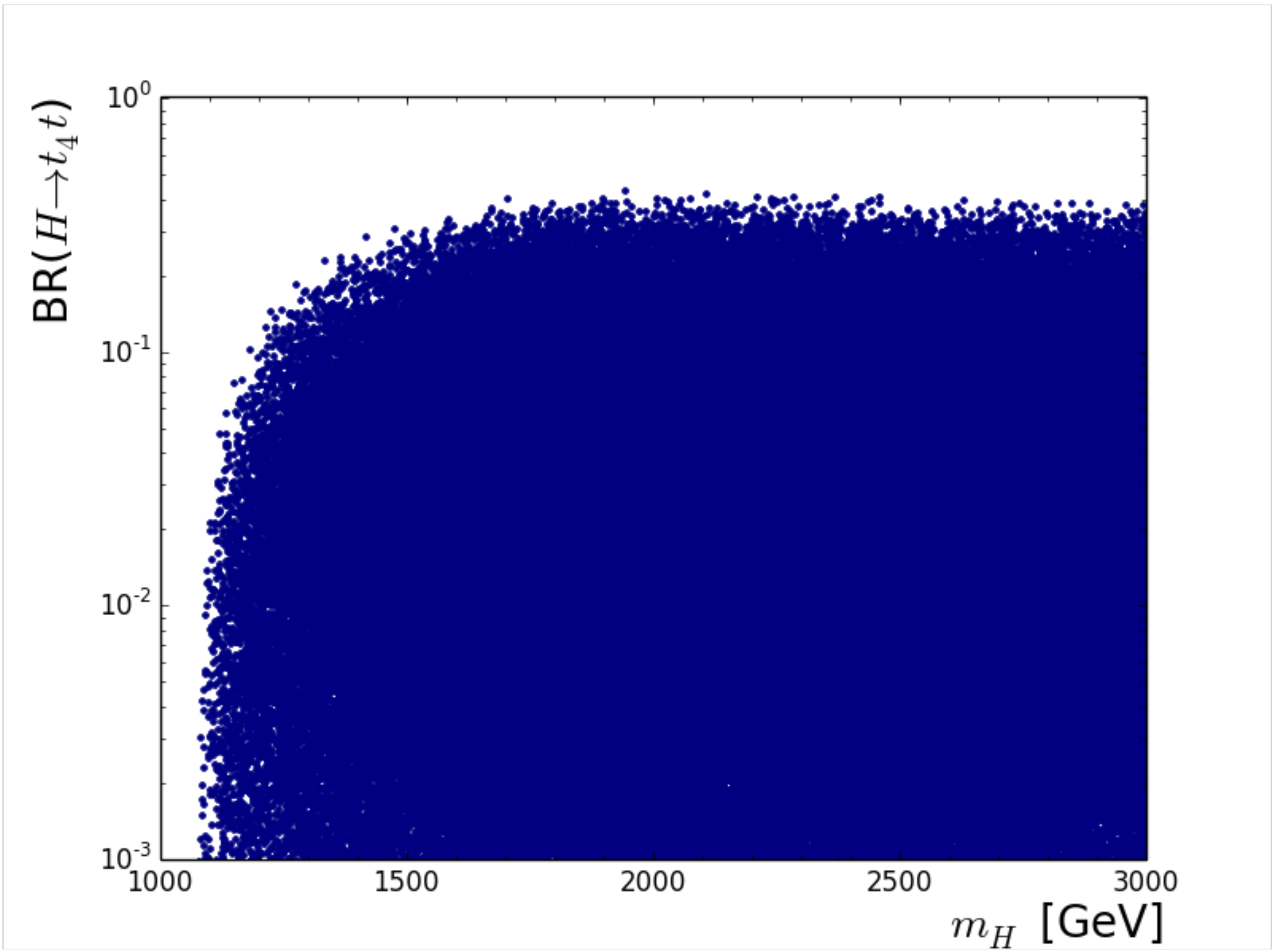
Parameter space scan: H branching ratios





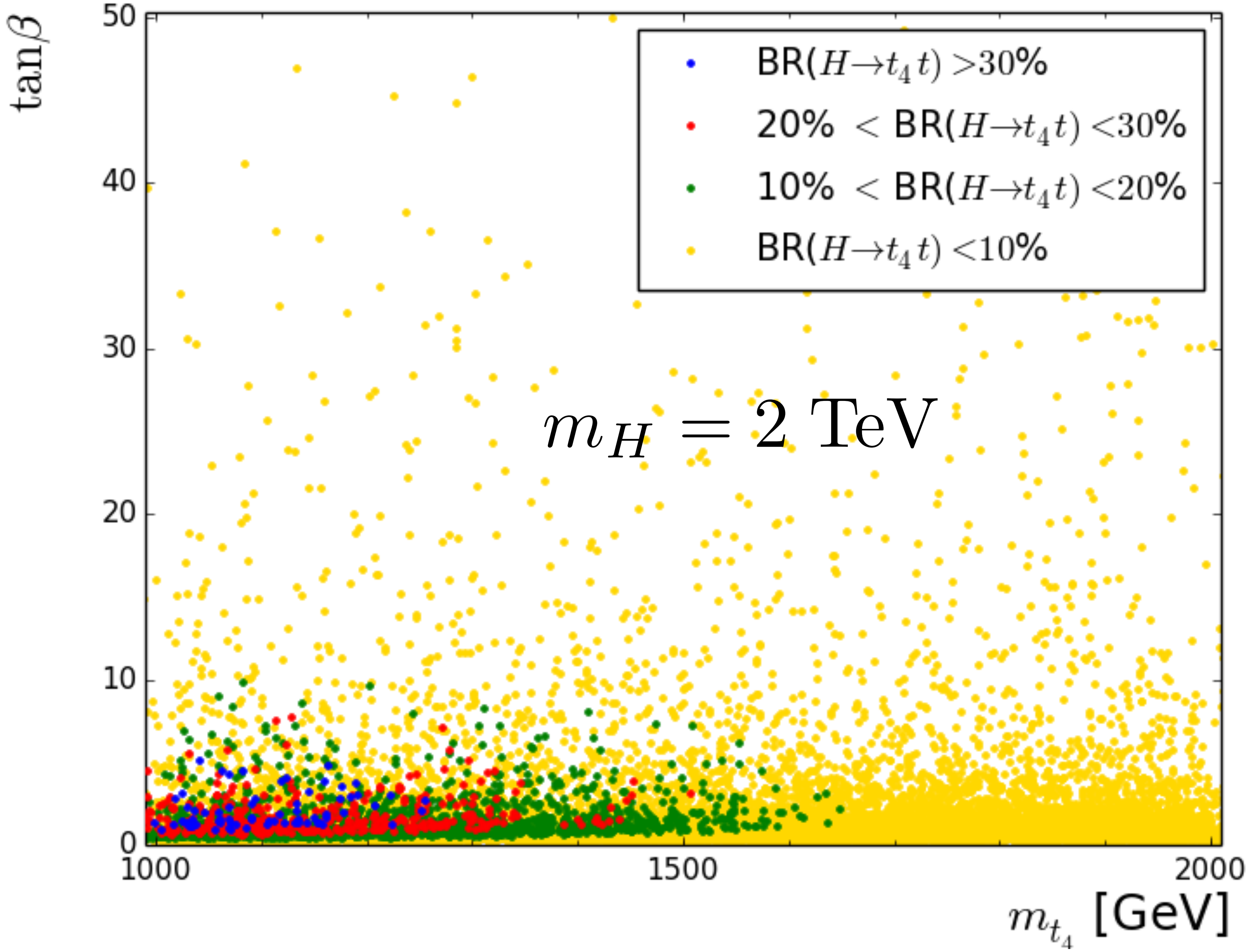
- We find $H \to t_4$ t branching ratios up to 40%
- Branching ratios are essentially independent of the H mass

Parameter space scan: H branching ratios

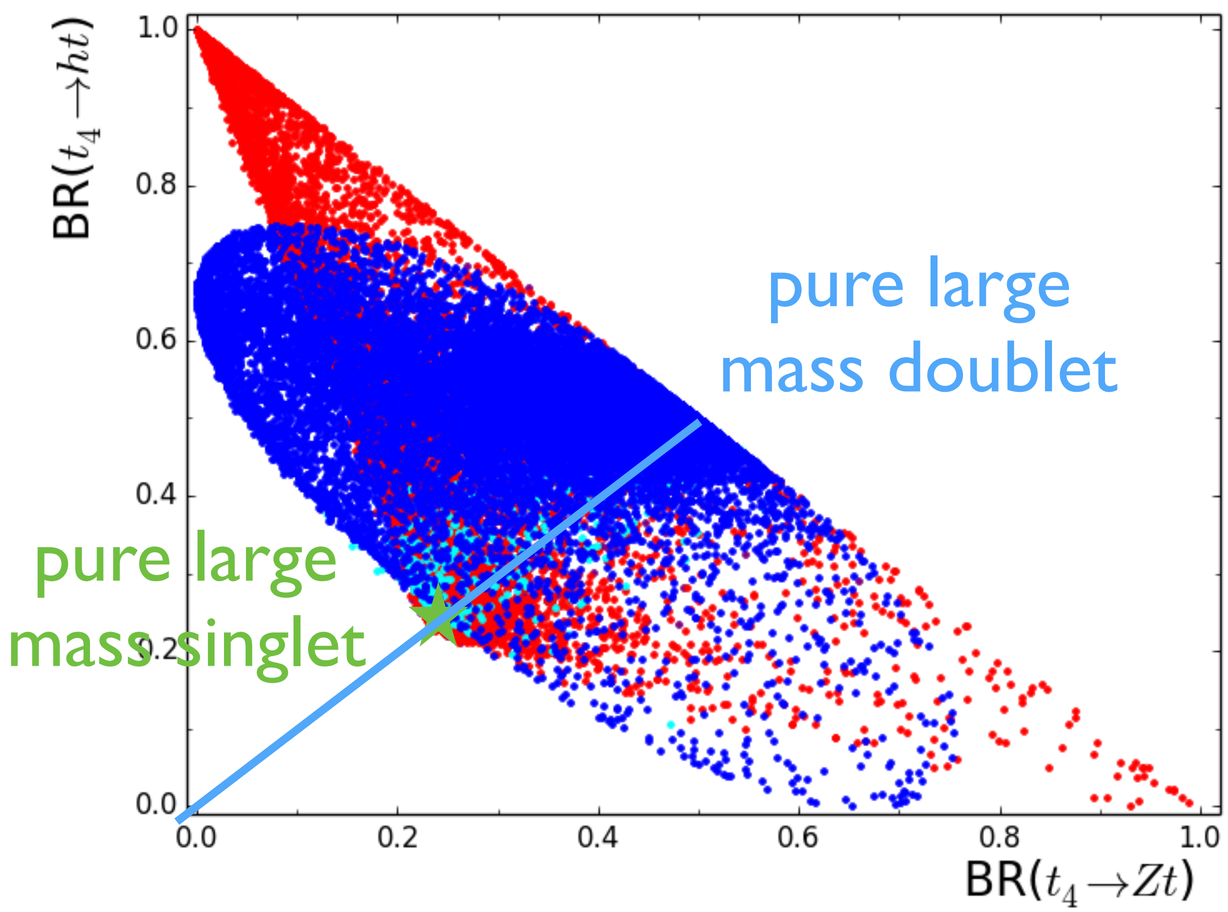


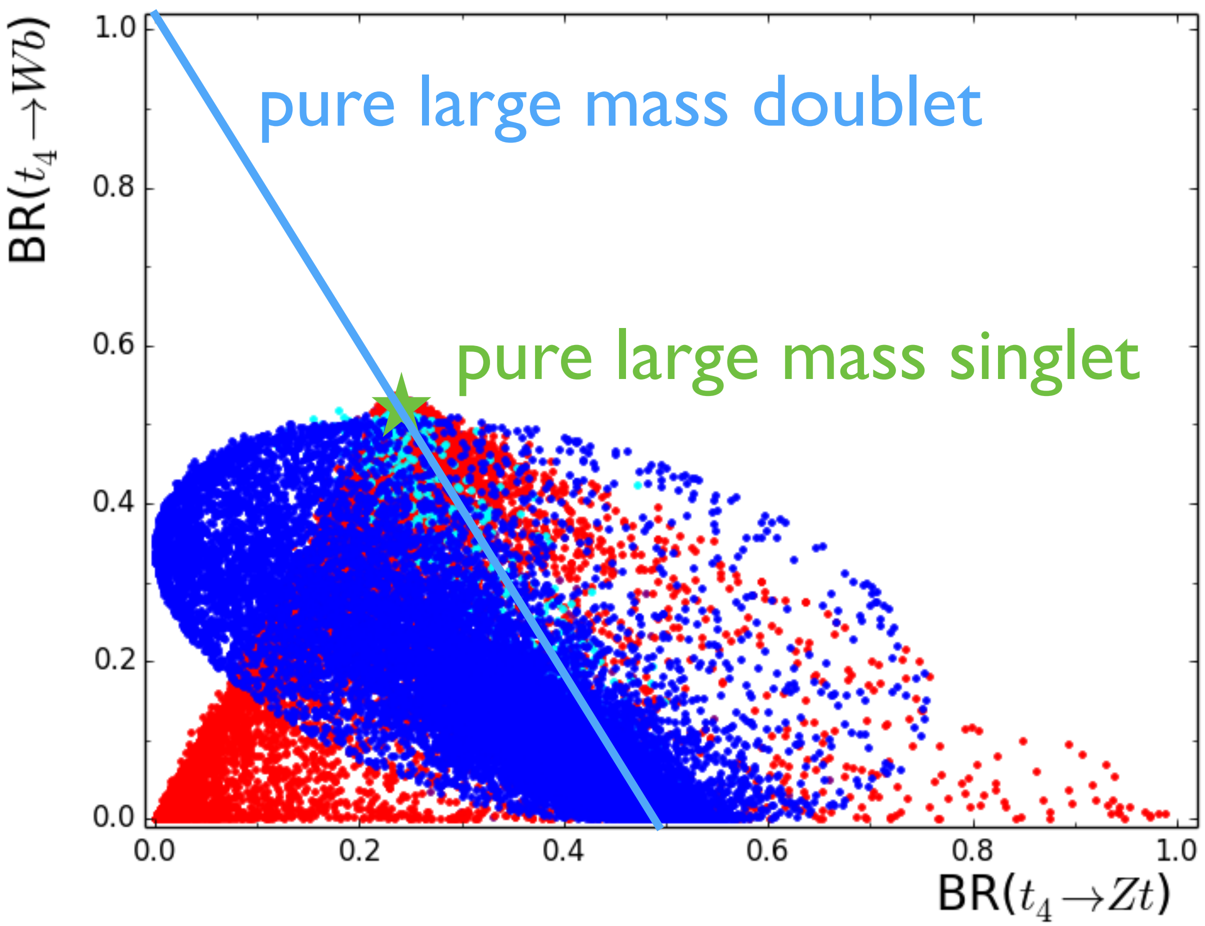
Parameter space scan: H branching ratios

- Dominant parameters are m_{t4} and tan(β)
- Mixing is required (of course) but it is not responsible for setting the highest possible branching ratios



Parameter space scan: t_4 branching ratios

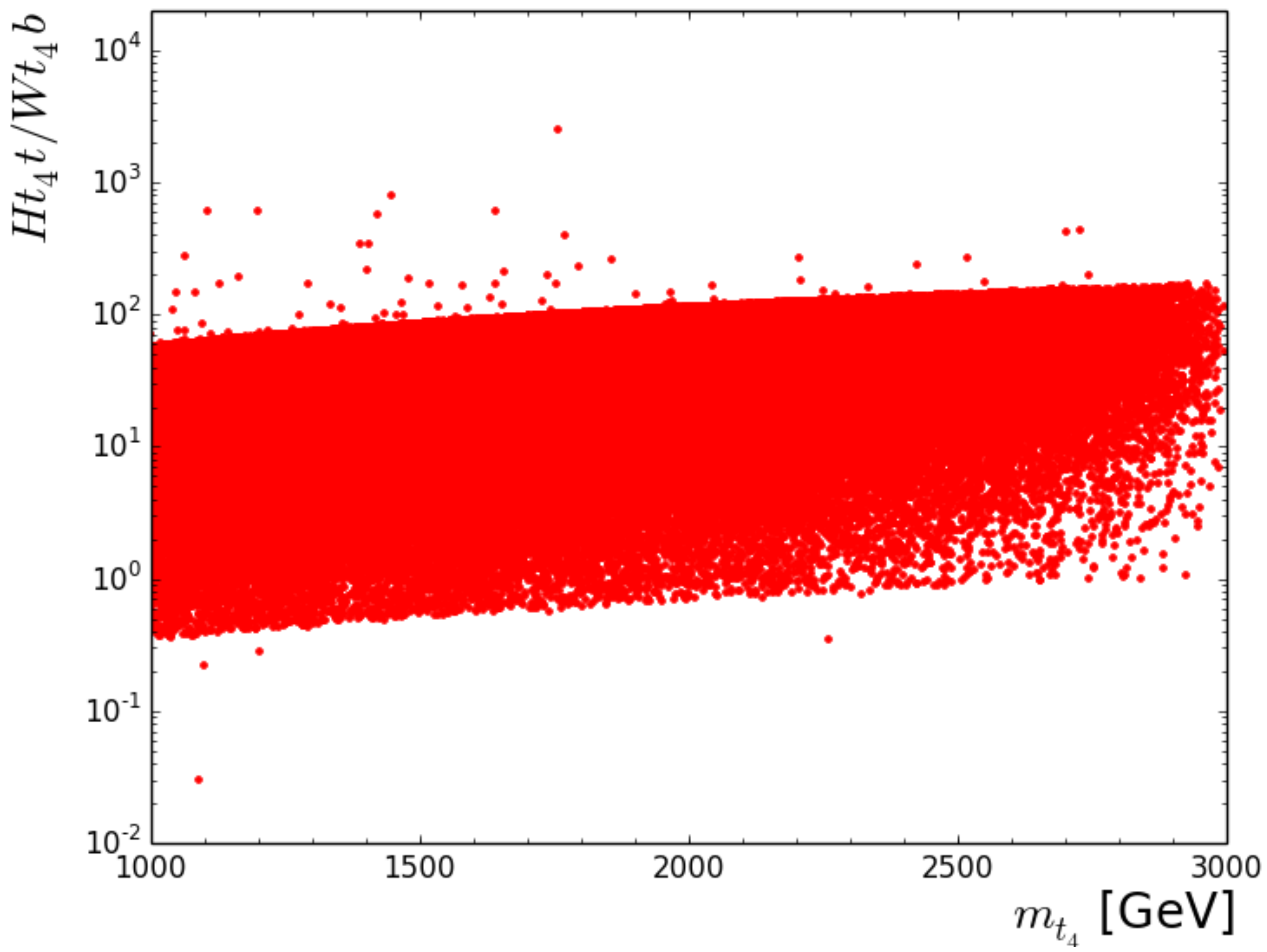




- Ellipsoidal shape caused the presence of simultaneous Yukawa couplings for iso-doublet vectorlike quarks
- Dominant constraint is from oblique corrections

Parameter space scan: EW vs Higgs production

- The ratio of Ht_4t and Wt_4b couplings ranges over more than two orders of magnitude, implying that, depending on the parameters, we expect regions of EW/Higgs dominance
- Numerical study in progress



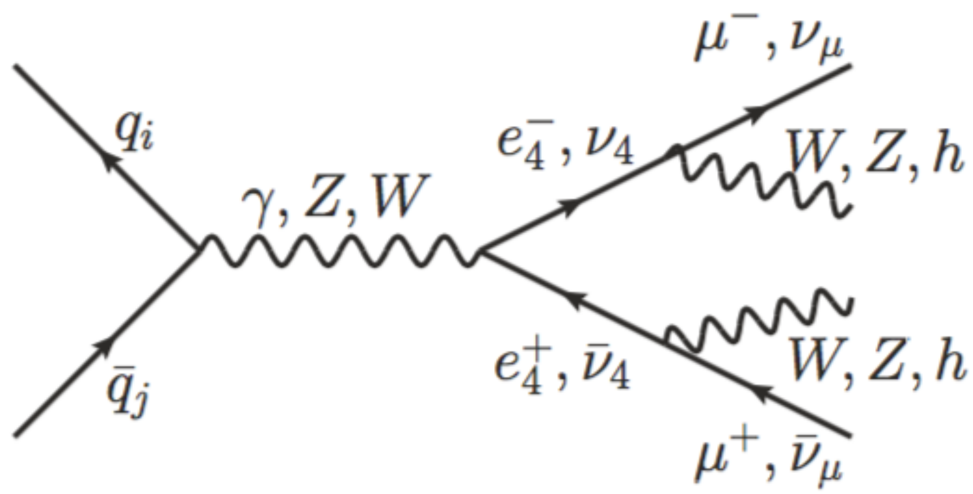
VLQ signatures

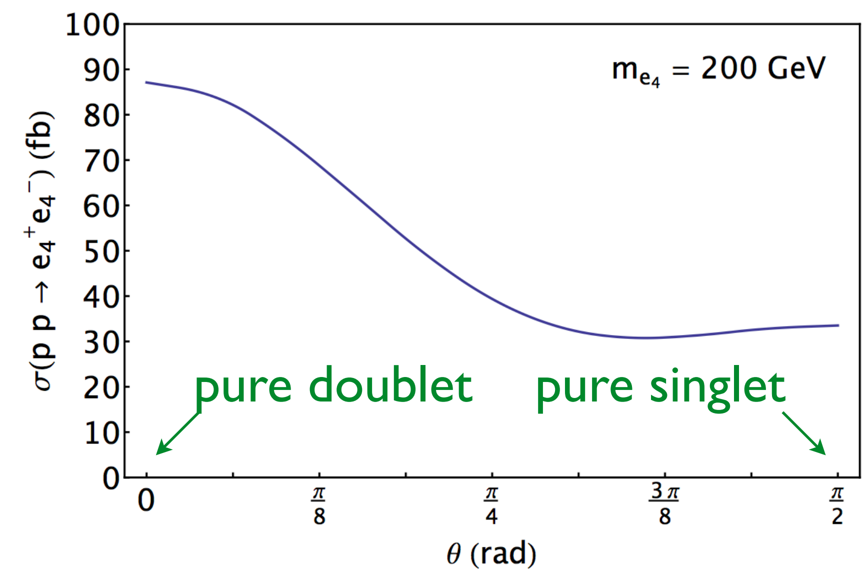
- Given the small cross sections it is necessary to avoid the very clean and suppressed $Z \to ll$ and $h \to \gamma\gamma$ modes, thus focusing on boosted massive jet signatures
- Main properties of the signal are the very large p_T of the vectorlike quark decay products and presence of two resonances.
- The signal that we propose is very similar to production of a single VLQ in the decay of a heavy Z'
- Models with leptophobic Z' which decays dominantly into a VLQ are quite contrived (need to suppress decays to pair of light fermions and need to kinematically forbid decays to VLQ pair).
- Our main points are that
    - the model we propose is well motivated and very reasonable
    - In presence of vectorlike quarks, heavy Higgses might be accessible exclusively via cascade decays

Vectorlike Leptons

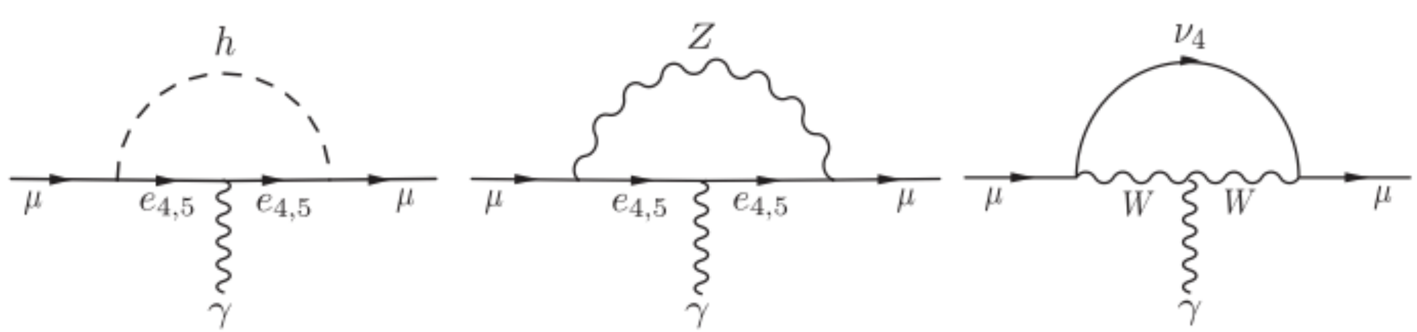
Vectorlike leptons

- Present bounds are very weak (few hundred GeV depending on the decay mode)





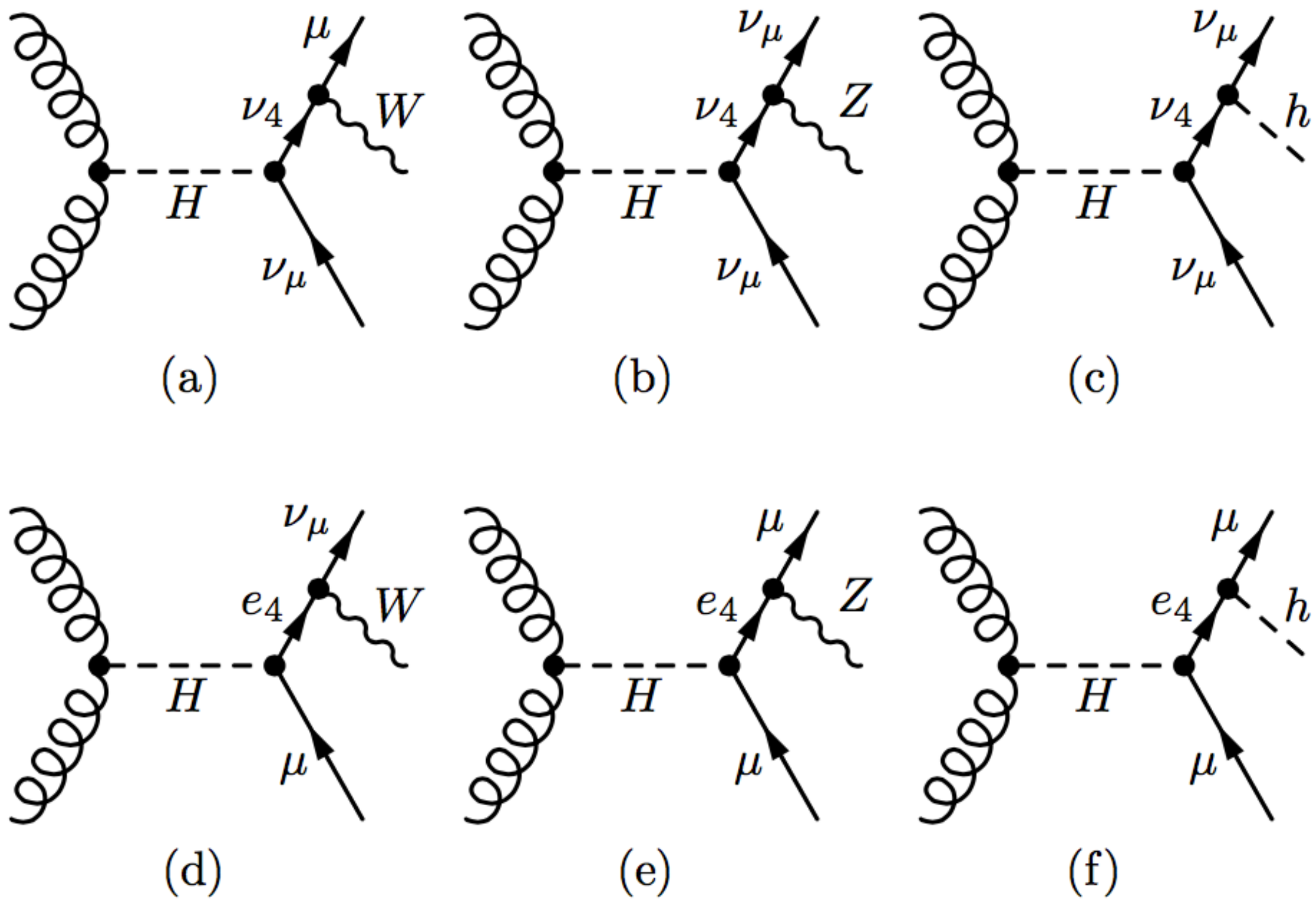
- To avoid enormous lepton flavor violation (e.g. $\mu \to e\gamma$) we need to preserve generalized lepton number by coupling the VLL to one generation only
- Light VLL (< 200 GeV) allow to resolve the muon g-2 anomaly.



- Most recent flavor anomalies ($b \to sll$, $R(K^{(*)})$, $R(D^{(*)})$) point quite decisively to lepton universality violation: VLL mixing with the muon could play a role.

Vectorlike leptons

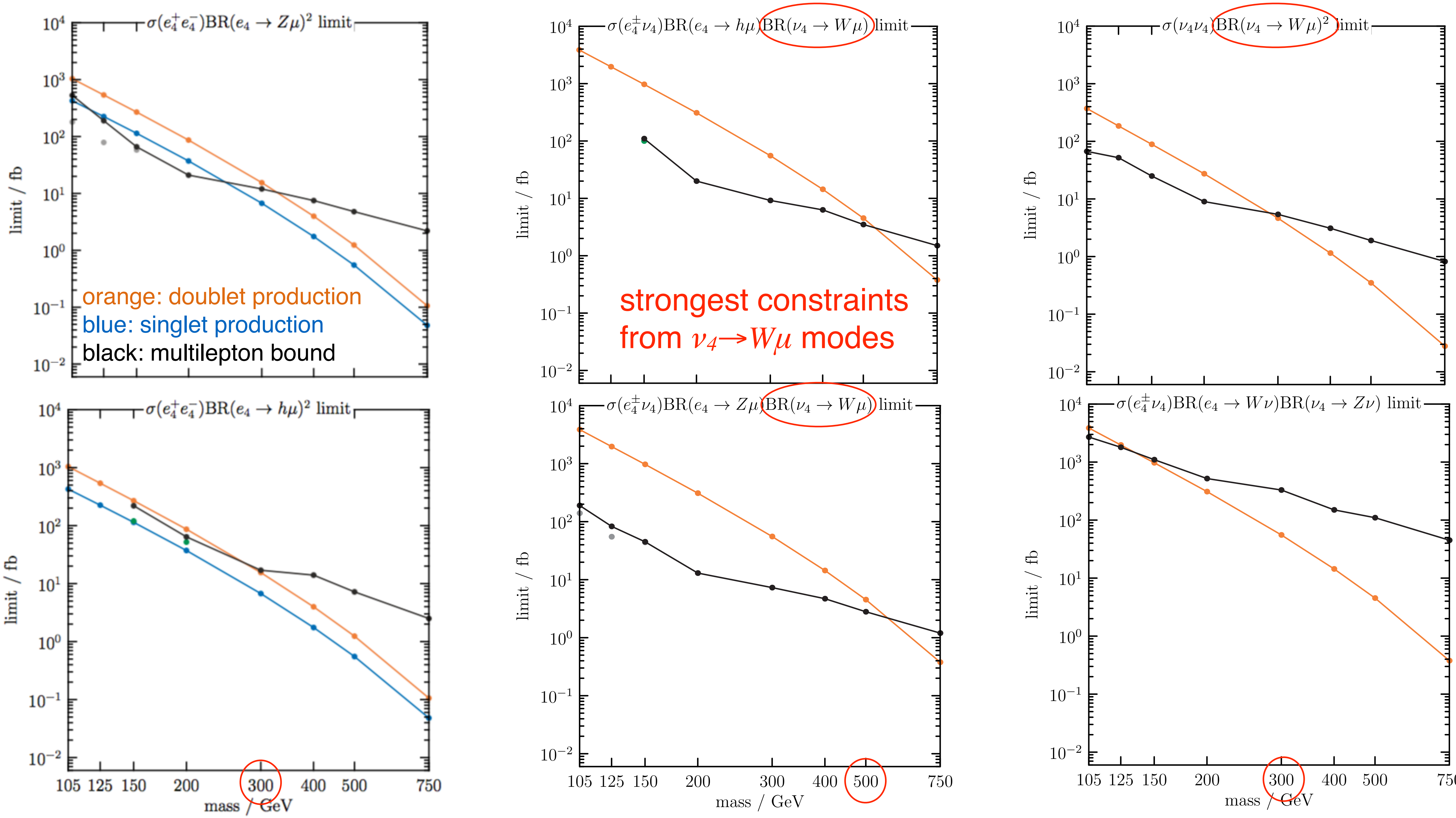
- Collider signatures: VLQ vs VLL
  - Pair production of VLL is much smaller than in the VLQ case (EW suppression)
  - Single EW VLL production is absent
  - Single production in heavy Higgs decays are identical. Weak direct constraints on VLL imply much larger production cross sections which allow for searches based on $h \to \gamma\gamma$ and leptonic Z and W decays.



Vectorlike leptons: constraints

- Recast multi-lepton LHC searches into VLL bounds

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



Vectorlike leptons: the model

- The Lagrangians for VLQ and VLL are identical:

SM | mixing in Yukawa interactions

$$\mathcal{L}^{\rm VLL}_{\rm Mass} = \boxed{-y_\ell^{ij}\,\bar{\ell}^i_L \ell^j_R H_d} \; \boxed{-\lambda^i_E \bar{\ell}^i_L E_R H_d - \lambda^j_L \bar{L}^i_L \ell^j_R H_d - \kappa^i_N \bar{\ell}^i_L N_R H_u}$$

VLL masses

$$-M_L L_L L_R - M_N N_L N_R - M_E E_L E_R$$

VLL Yukawas

$$-\lambda \bar{L}_L E_R H_d - \bar{\lambda} H_d^\dagger \bar{E}_L L_R - \kappa \bar{L}_L N_R H_u - \bar{\kappa} H_u^\dagger \bar{N}_L L_R + \text{h.c.}$$

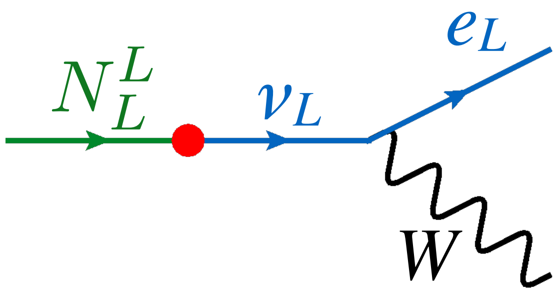
- Mixing patterns in absence of doublet/singlet mixing and right-handed neutrino:

N^L_L — ν_L = 0 N_L — ν_L = $\kappa_N \dfrac{v_u}{M_N}$

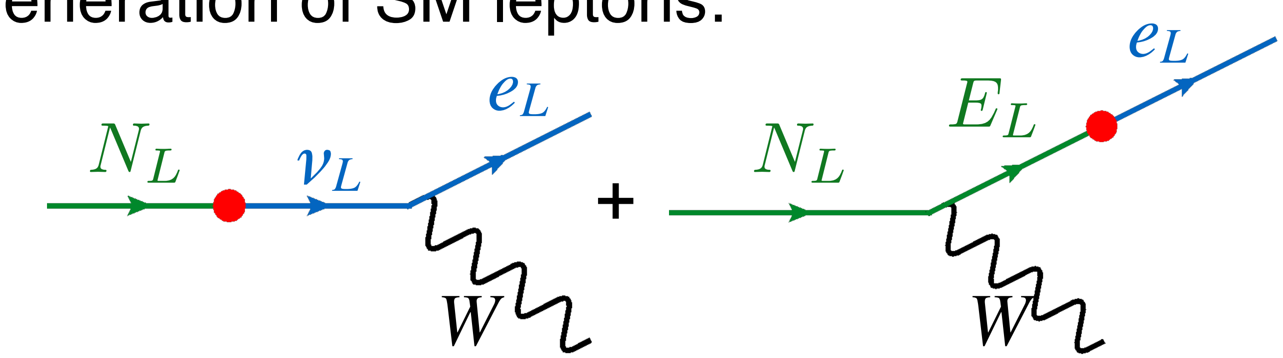
E^L_L — e_L = 0 E_L — e_L = $\lambda_E \dfrac{v_d}{M_E}$

E^R_L — e_R = $\lambda_L \dfrac{v_d}{M_L}$ E_R — e_R = 0

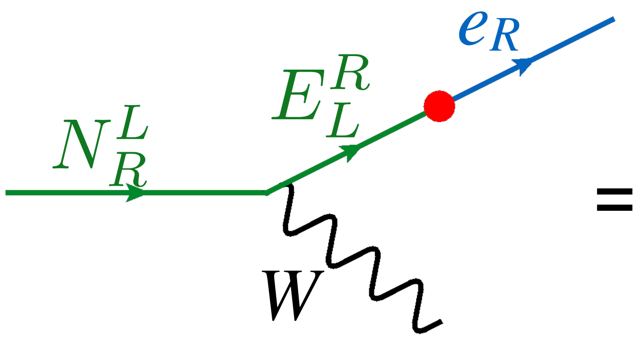
- W interactions between VLL and one generation of SM leptons:



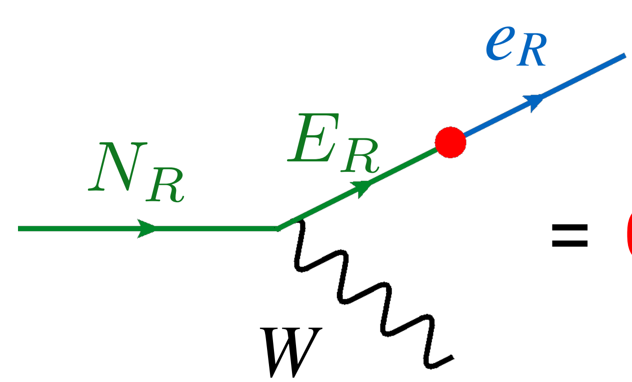
$= 0$



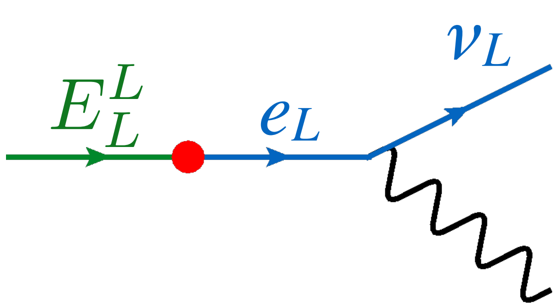
$$= \frac{g}{\sqrt{2}} \left[\kappa_N \frac{v_u}{M_N} + \lambda_E \frac{v_d}{M_E} \right]$$



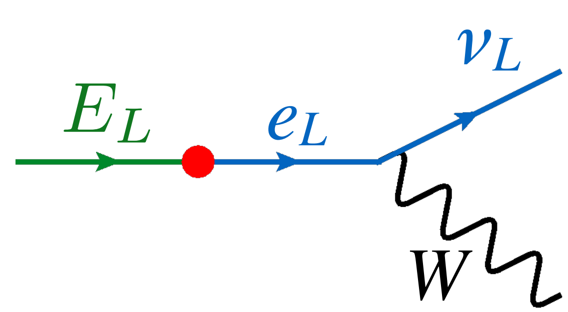
$$= \frac{g}{\sqrt{2}} \lambda_L \frac{v_d}{M_L}$$



$= 0$



$= 0$



$$= \frac{g}{\sqrt{2}} \lambda_E \frac{v_d}{M_E}$$

- $e_4 \to W\nu$ absent for purely doublet VLQ

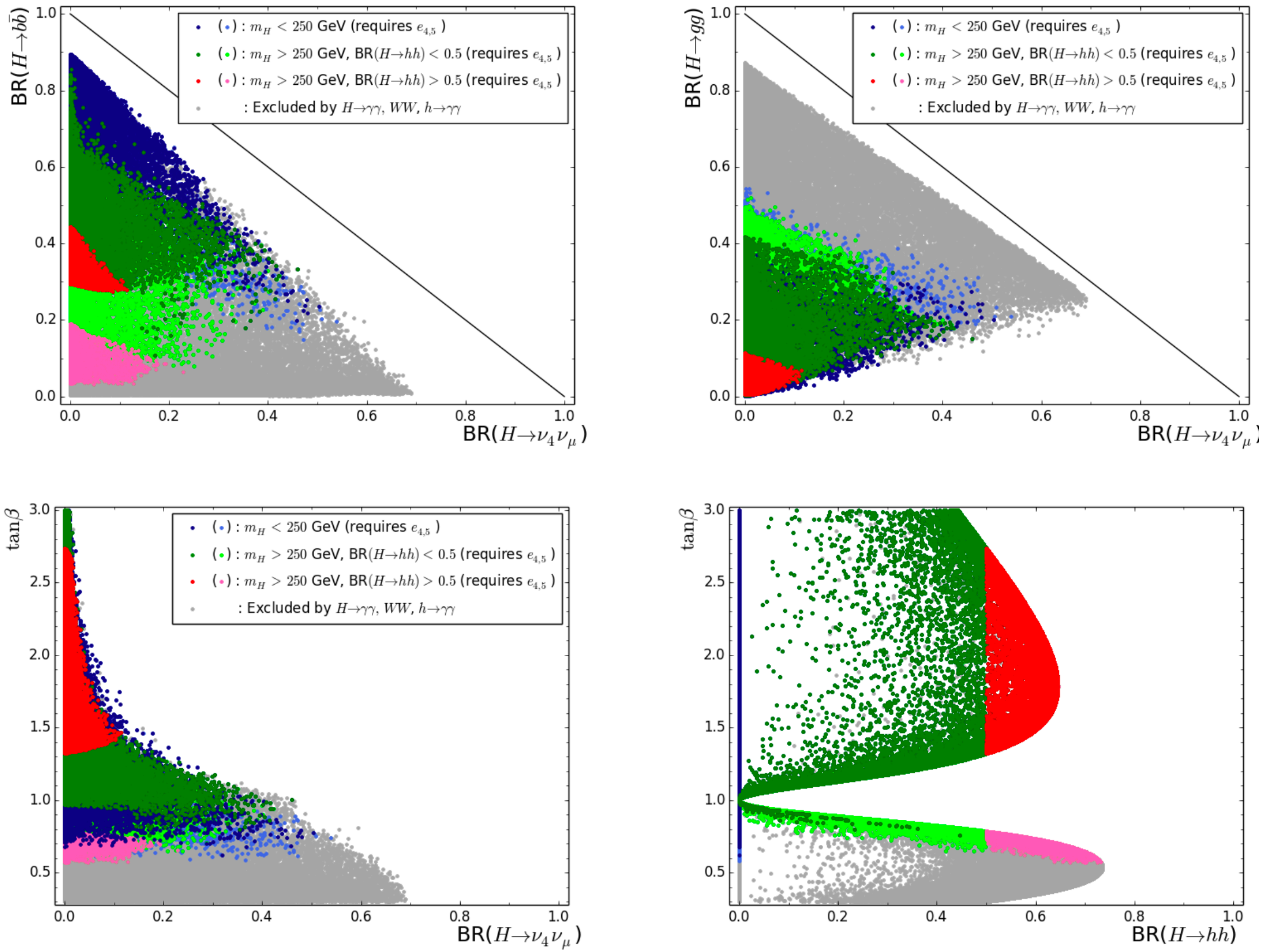
Vectorlike leptons: constraints and parameter scan

- We perform a scan over our model parameter space:

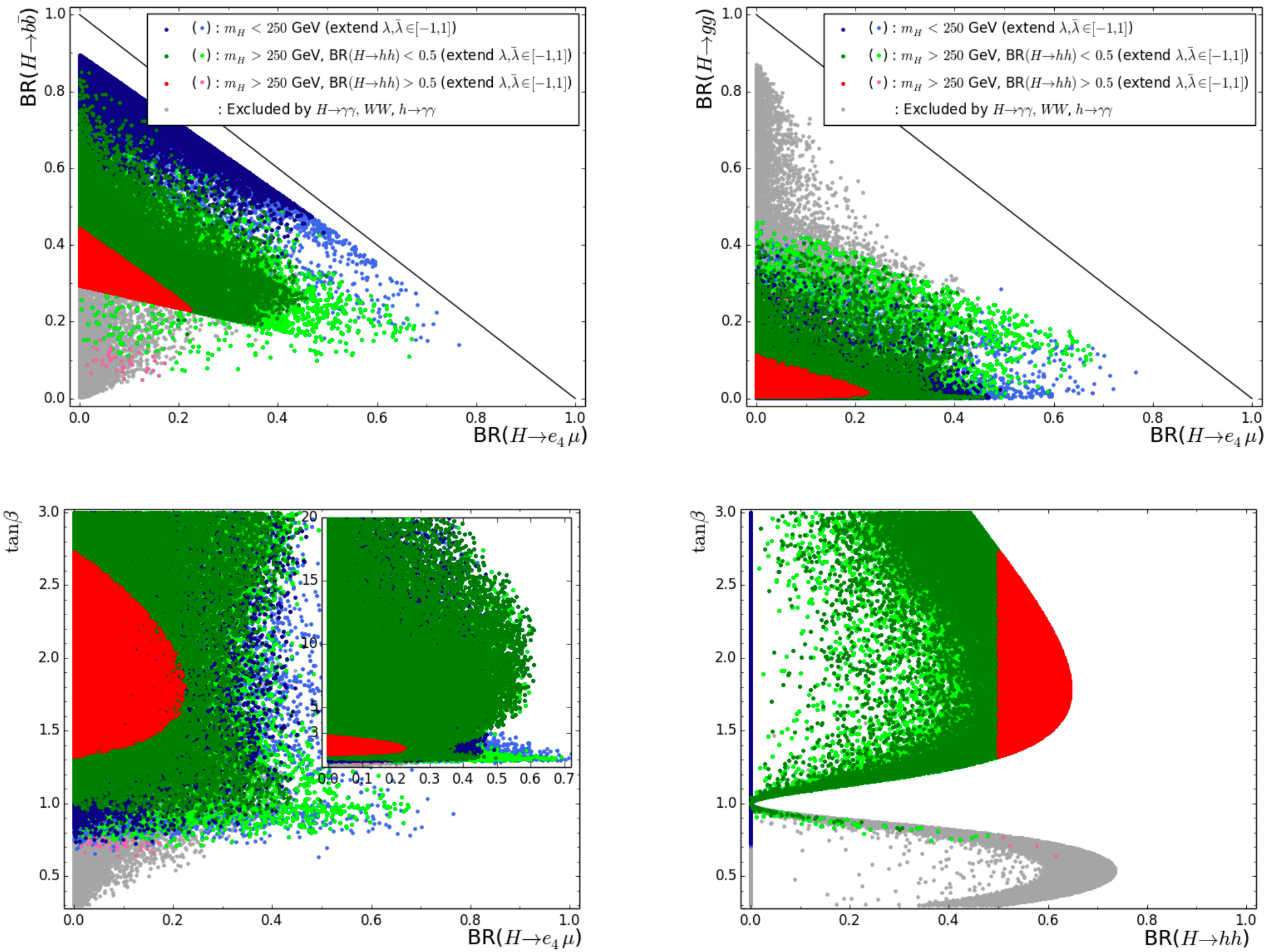
$$\tan(\beta) \in [0.3, 3]$$
$$M_{L,N,E} \in [100, 500]\ \text{GeV}$$
$$\kappa_N, \kappa, \bar{\kappa} \in [-1, 1]$$
$$\lambda_L, \lambda_E, \lambda, \bar{\lambda} \in [-1, 1]$$
$$\sin(\beta - \alpha) = 1$$

- We impose constraints from
  - LEP bound (m_{e4} > 105 GeV)
  - Oblique Corrections (S,T,U)
  - $h \to \gamma\gamma$
  - $H \to \gamma\gamma$
  - $H \to WW$
  - muon lifetime
  - Z-pole observables (partial width to μμ, invisible width, Forward-backward asymmetry, Left-right asymmetry)
  - Constraints from multilepton searches at LHC

Vectorlike leptons: H branching ratios

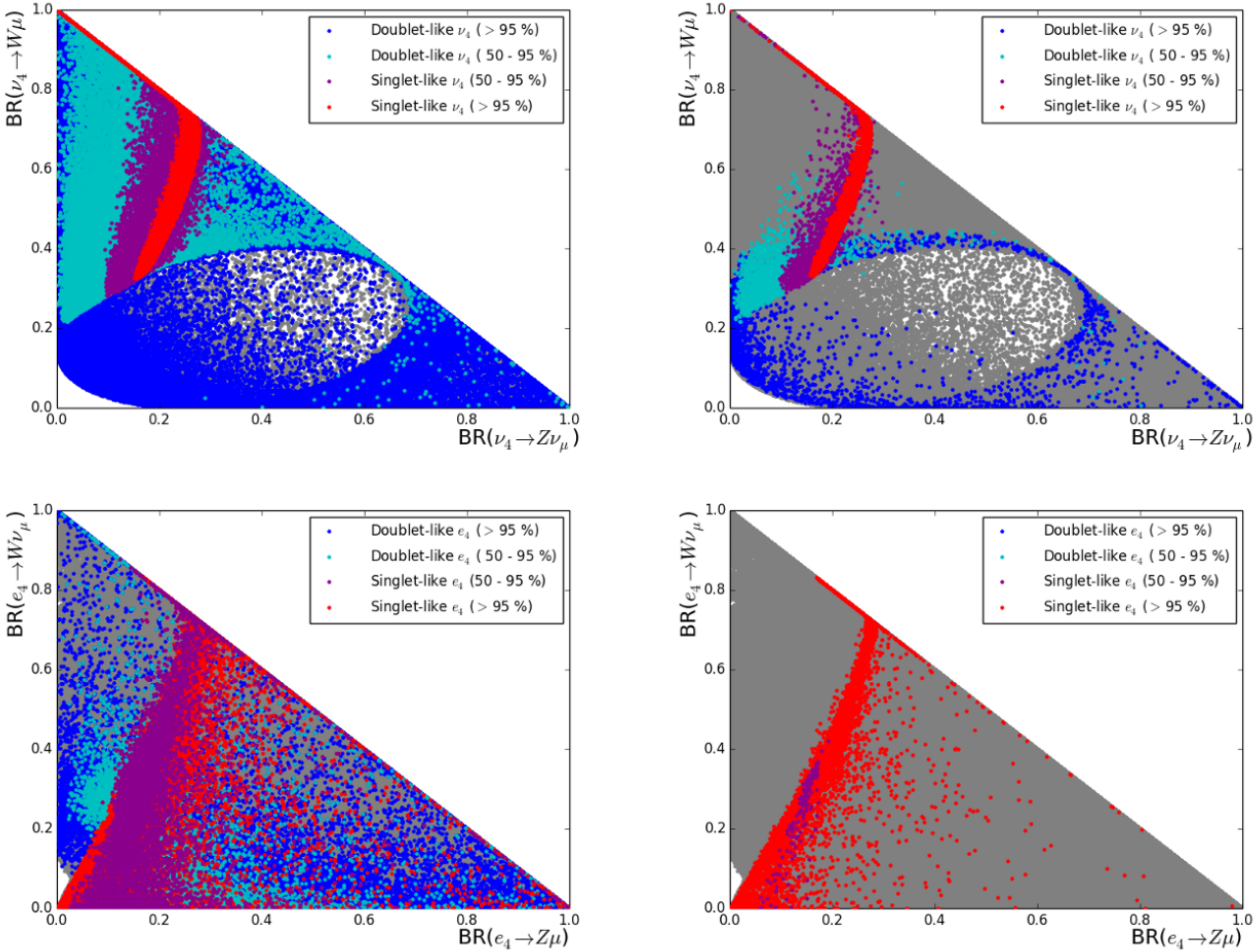


Vectorlike leptons: H branching ratios

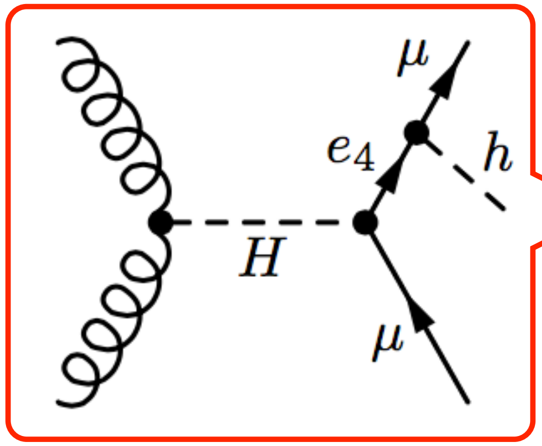


Vectorlike leptons: VLL branching ratios

- Impact of multilepton constraints



A case study: $h\mu\mu \to (\gamma\gamma, bb)\mu\mu$

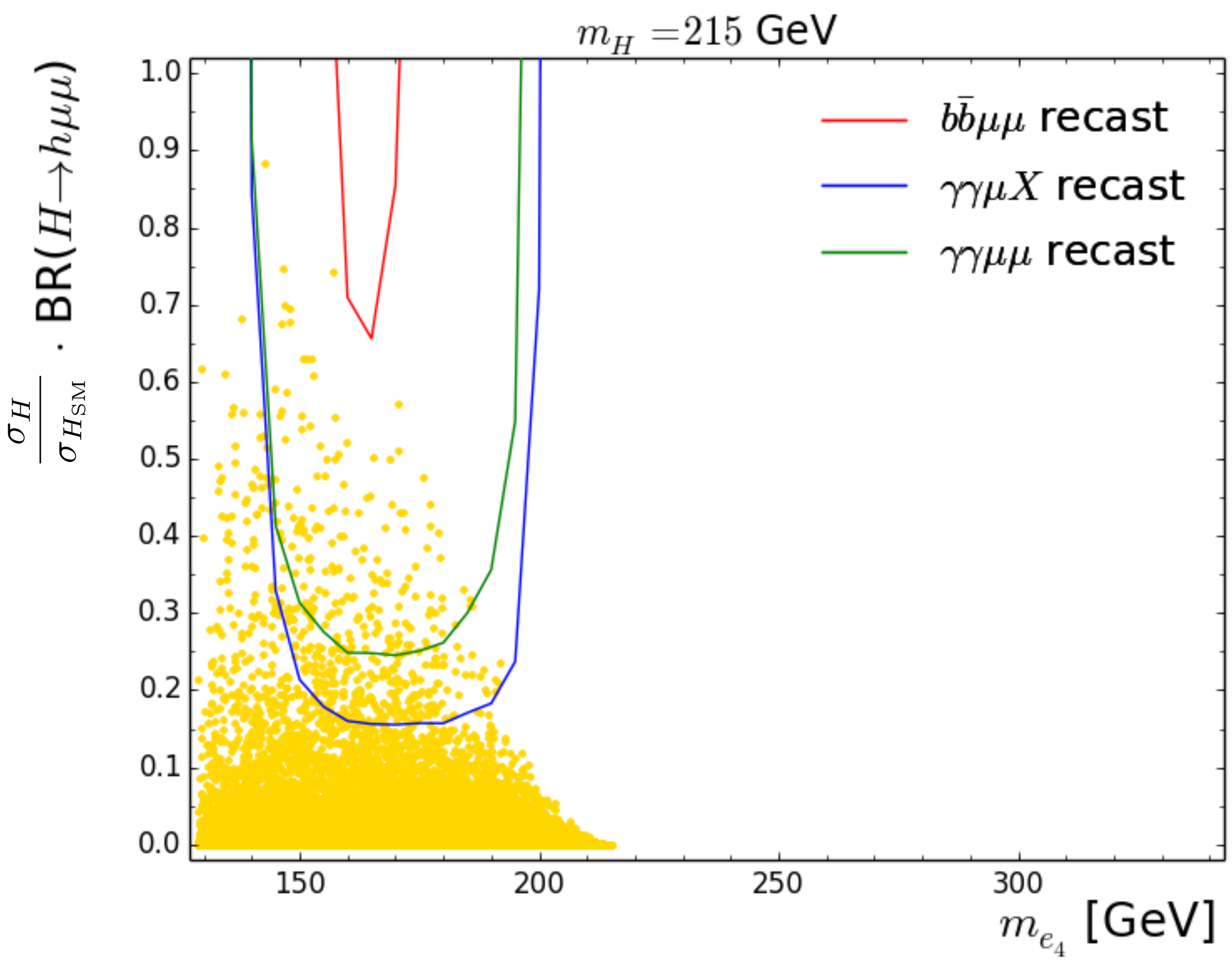


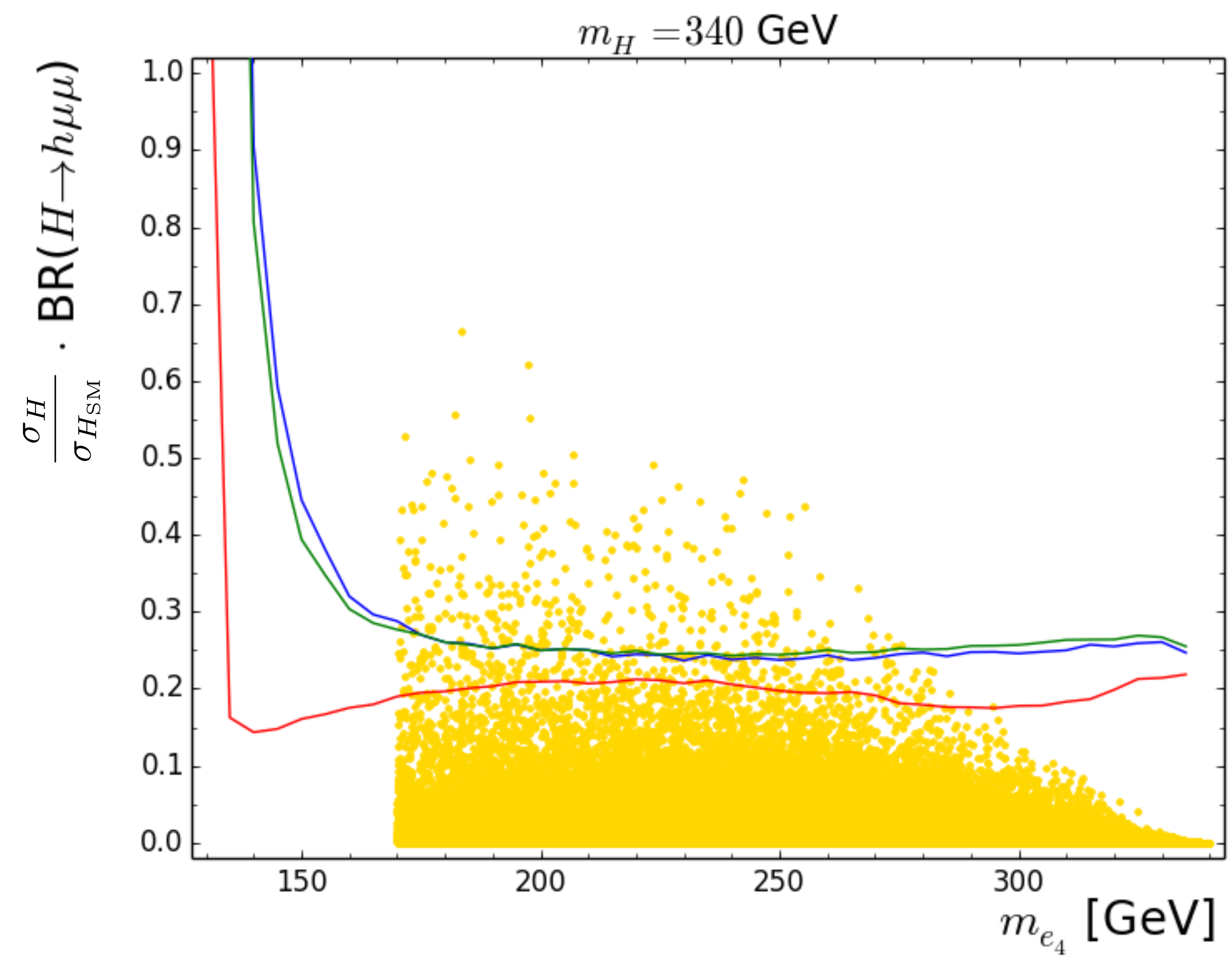
Higgs decay mode	final state	σ
$h \to b\bar{b}$	$b\bar{b}\mu^+\mu^-$	5.3 pb
$h \to \tau^+\tau^-$	$\tau^+\tau^-\mu^+\mu^-$	0.58 pb
$h \to WW^* \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ $(\ell = e,\ \mu)$	$\ell^+\ell^-\mu^+\mu^-\nu_\ell\bar{\nu}_\ell$	97 fb
$h \to \gamma\gamma$	$\gamma\gamma\mu^+\mu^-$	28 fb
$h \to \mu^+\mu^-$	$\mu^+\mu^-\mu^+\mu^-$	2 fb
$h \to ZZ^* \to 2\ell^+2\ell^-$ $(\ell = e,\ \mu)$	$\ell^+\ell^-\ell^+\ell^-\mu^+\mu^-$	1.1 fb

- Cross sections for $m_H = 200$ GeV, $\tan(\beta)=1$, $BR(H\to h\mu\mu) = BR(H\to e_4\mu\to h\mu\mu)=0.5$
- Existing searches require a $Z\to\mu\mu$:
  - $A\to hZ\to bb\mu\mu$ [ATLAS 1503.08089]
  - $hlX\to\gamma\gamma lX$ [ATLAS 1407.4222]
  - $Z\gamma\gamma\to ll\gamma\gamma$ [ATLAS 1604.05232]
- Simple improvements can enhance the sensitivity:
  - off-Z cut, $|m_{\mu\mu} - M_Z| > 15$ GeV, to suppress Z+jets, ZZ, hZ backgrounds
  - missing energy cut to suppress tt and hit backgrounds

A case study: $h\mu\mu \to (\gamma\gamma, bb)\mu\mu$

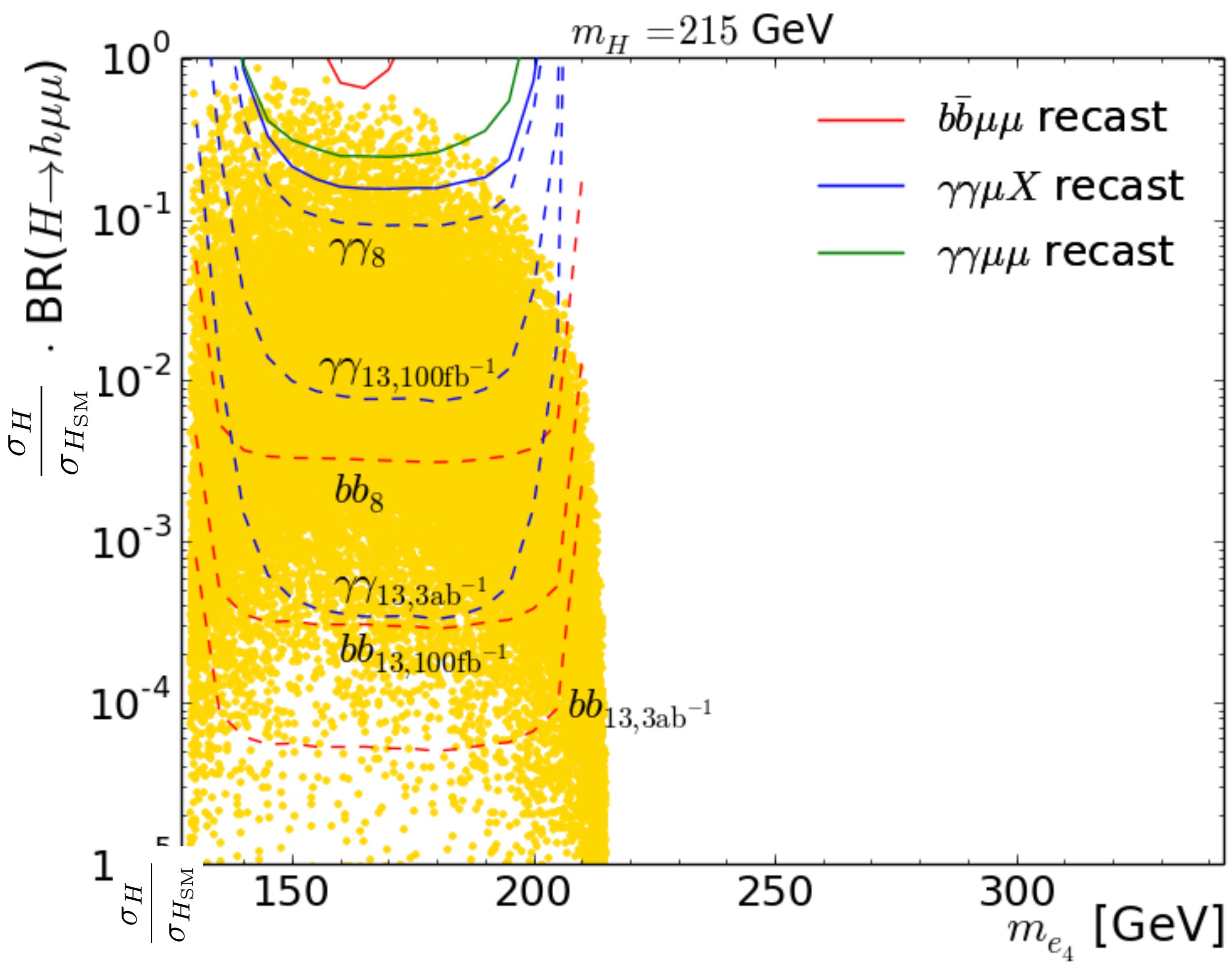
- Present searches (not optimized) already constrain the parameter space!

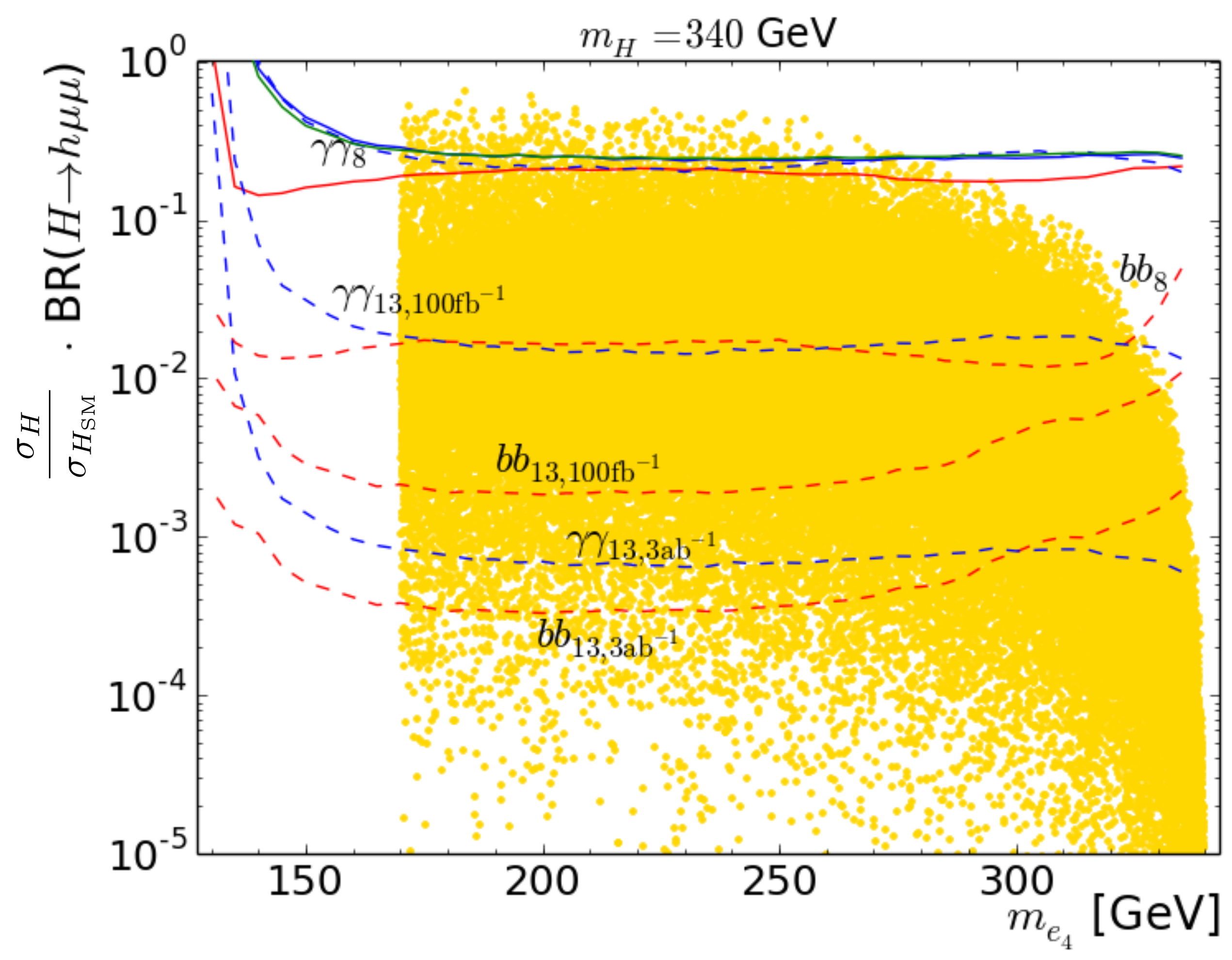




A case study: $h\mu\mu \to (\gamma\gamma, bb)\mu\mu$

- Expected constraints from dedicated reanalysis of existing and future data:

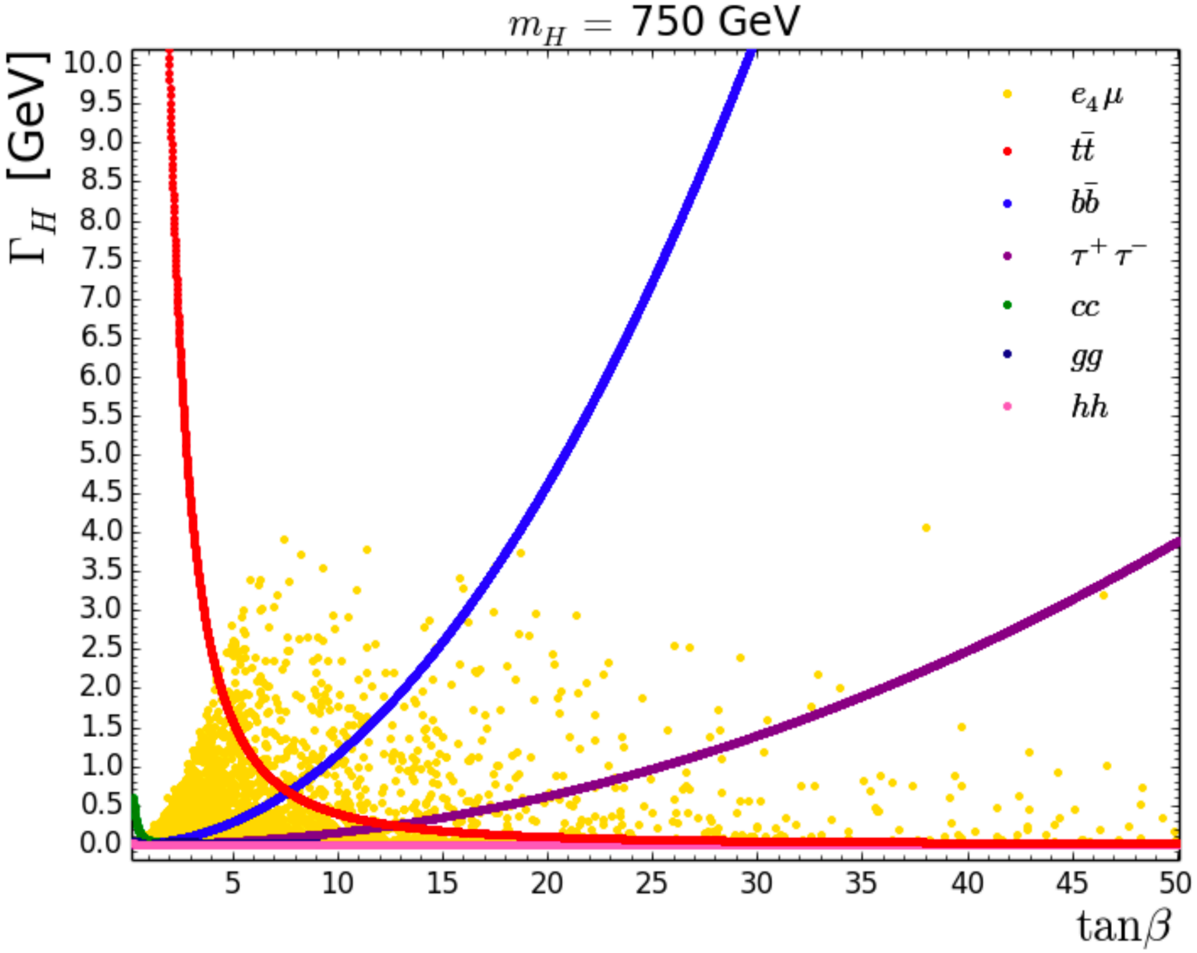




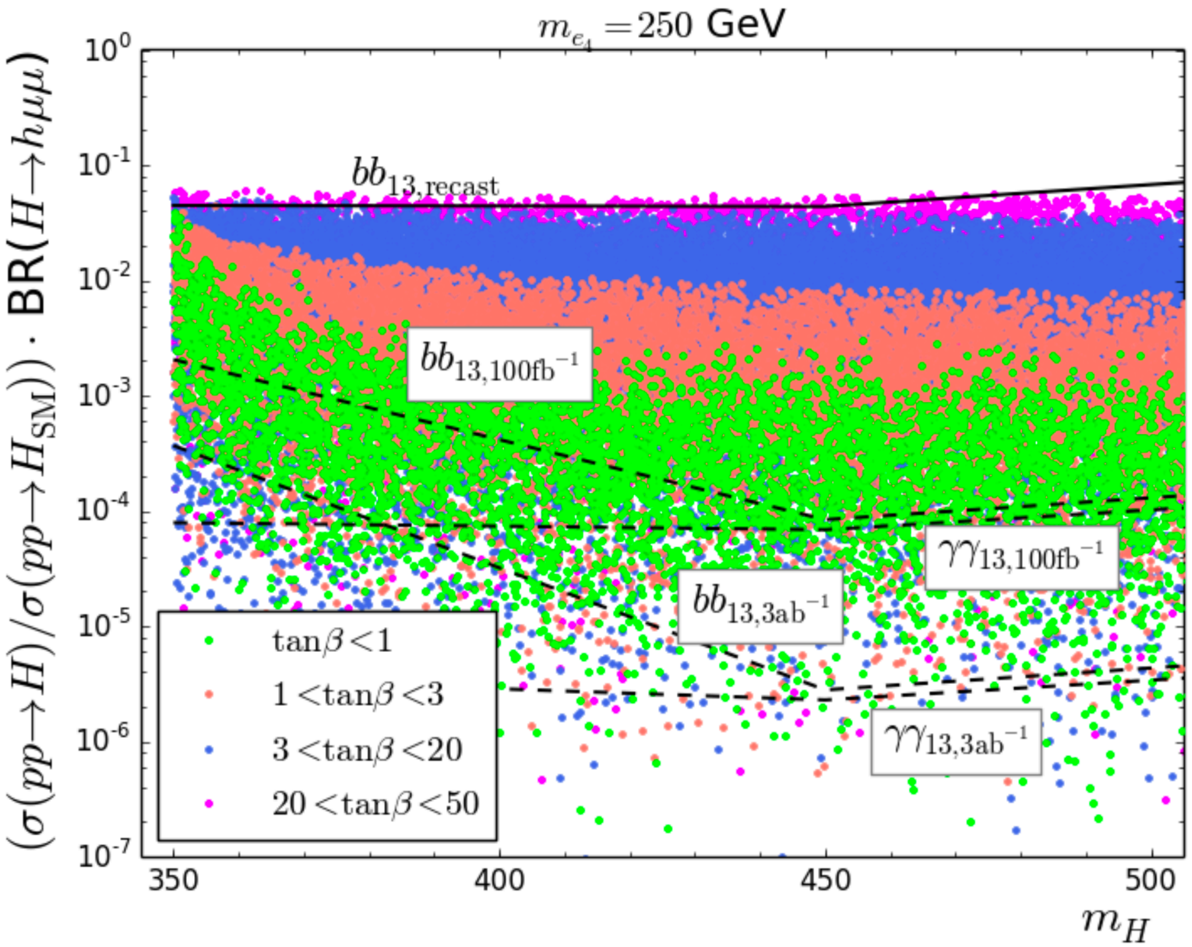
- Due to the extremely low background to the di-photon searches, higher luminosity favors the bb channel.

A case study: $h\mu\mu \to (\gamma\gamma, bb)\mu\mu$ at large m_H

- partial widths at large m_H:

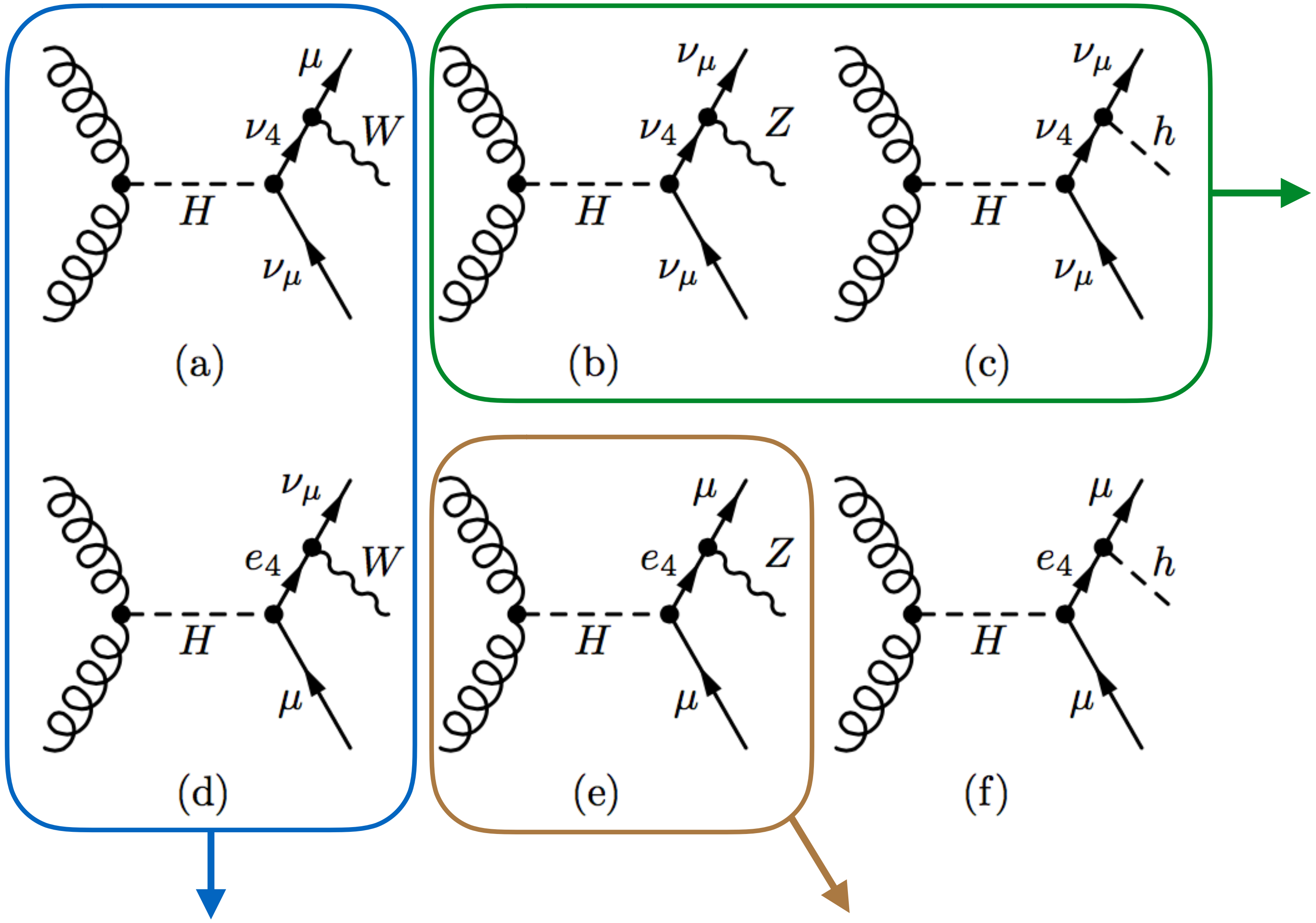


- Prospects:



- $H\to tt$ dominates at small $tan(\beta)$
- $H\to bb$ dominates at large $tan(\beta)$
- $H\to e_4\mu$ can dominate for $4 < tan(\beta) < 17$

Vectorlike leptons: other signatures



- $H \to Z\nu\nu \to \ell\ell\nu\nu$: same signal as ZZ, H→ZZ, mono-Z + MET. Reference point: σ_{sig} = 210 fb
- $H \to h\nu\nu \to (\gamma\gamma)_h\nu\nu$ Reference point: σ_{sig} = 10.5 fb
- …

- Contributions to pp→WW and pp→H→WW

Dermisek, Lunghi, Shin, 1509.04292

- H→Zμμ→llμμ Reference point: σ_{sig} = 210 fb

Conclusions

- A second Higgs doublet (with alignment) and vectorlike fermions are amongst the most straightforward extensions of the SM and appear in many BSM models.
- Vectorlike fermions have been invoked to solve several phenomenological issues (unification, muon g-2, flavor anomalies, …)
- Vectorlike Quarks standard productions mechanisms (QCD pair production and EW single production) are supplemented by production in Higgs decays
- Higgs mediated production cross sections can be large and yields promising channels to discover heavy Higgses and VLQ
- Vectorlike Leptons are allowed to be much lighter, have smaller pair production cross sections and no EW single production: Higgs mediated production is, therefore, extremely advantageous yielding a large number of novel signatures
- For both VLQ and VLL we explored the allowed parameter space and discussed novel signatures