Vectorlike fermions: motivations and phenomenology

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Chiral fermions

- L and R transform differently under $SU(2)_L \times U(1)_Y$
- Get masses mostly from Yukawa coupling to Higgs VEV
- All Standard Model fermions in this category

Vectorlike fermions

- L and R transform same way
- Get masses mostly from bare, electroweak singlet, mass terms
- Can be arbitrarily heavy. So why should we think they are accessible to LHC and other current experiments?

Many BSM models require vectorlike fermions near the weak scale:

- Little Higgs models (“top partners”)
- composite Higgs models
- warped extra dimensions
- realistic string compactifications
- SUSY models

In the case of SUSY, the Higgsinos are nothing but vectorlike doublet fermions with very specific Yukawa couplings to sfermion-fermion and gaugino-Higgs pairs. Extensions of the MSSM also use additional vectorlike fermions to address other issues.

Why not new chiral fermions?

Anomaly cancellation is a non-trivial constraint.

A 4th chiral family added to the Standard Model (SM4) would consist of 2-component L-handed fermions transform under $SU(3)_C \times SU(2)_L \times U(1)_Y$ as:

$$(t'_L,\, b'_L) \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}) \qquad t'^*_R \sim (\overline{\mathbf{3}}, \mathbf{1}, -\tfrac{2}{3}), \qquad b'^*_R \sim (\overline{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}),$$
$$(\nu'_L,\, \tau'_L) \sim (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}), \qquad \tau'^*_R \sim (\mathbf{1}, \mathbf{1}, 1), \qquad \nu'^*_R \sim (\mathbf{1}, \mathbf{1}, 0),$$

Masses are proportional to Higgs VEV $v = 174$ GeV:

$$M_{t'} = y_{t'} v, \qquad M_{b'} = y_{b'} v, \qquad M_{\tau'} = y_{\tau'} v$$

Yukawa couplings must be very large to avoid discovery in previous millenium.

Constraints on SM4 (chiral 4th family)

- Direct searches ($\longrightarrow$ very large Yukawa couplings that will blow up in UV)
- Therefore, requires non-trivial UV completion at relatively low scale
- Flavor mixing observables
- Precision electroweak oblique corrections (S, T, U parameters)

  Kribs, Plehn, Spannowsky, Tait 0706.3718: wasn't then ruled out as previously claimed, but masses were highly constrained
- Higgs production and decay affected by loops

  After Higgs discovery and measurements, SM4 is finally killed. See for example:

  A. Lenz, Adv. High Energy Phys. 2013, 910275 (2013).

  A. Djouadi and A. Lenz, 1204.1252

  O. Eberhardt *et al.*, 1209.1101

  Possible exceptions have epicyclic add-ons.

Constraints on vectorlike fermions

- Anomalies cancel automatically
- Direct searches still powerful
- Flavor mixing constraints still powerful, but can always dial dangerous Yukawa couplings to be arbitrarily small
- Yukawa couplings can be as small as you want: $y \ll M/v$.
- Decouple (for small y^2/M^2) from precision electroweak observables
- Decouple (for small y/M) from Higgs production and decay
- Don't decouple from the Higgs mass, or the hierarchy problem

Vectorlike fermions can be $SU(2)_L$-doublet pairs $F, \overline{F}$, or $SU(2)_L$-singlet pairs $f, \overline{f}$, or both. Possible mass terms:

$$-\mathcal{L} \quad = \quad M_F \overline{F} F + M_f \overline{f} f + y_1 H F \overline{f} + y_2 H^* \overline{F} f$$

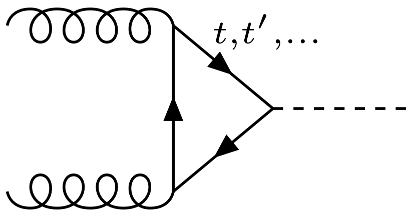
Also, can mix with Standard Model fermions with same quantum numbers, for example:

$$\begin{aligned} -\mathcal{L} \quad = \quad & \lambda_1 H \begin{pmatrix} t \\ b \end{pmatrix} \bar{t}' + \lambda_2 H \begin{pmatrix} T' \\ B' \end{pmatrix} \bar{t} \\ & + \lambda_3 H^* \begin{pmatrix} t \\ b \end{pmatrix} \bar{b}' + \lambda_4 H^* \begin{pmatrix} T' \\ B' \end{pmatrix} \bar{b} \end{aligned}$$

In general, need to diagonalize a mass matrix, leading to mixing angles, but M_F and/or M_f is the main source of mass.

Without the λ-type couplings above, the lightest vectorlike quark would be absolutely stable. But even if they are smaller than 10^{-6}, decays can be prompt on collider detector length scales.

Fermion loop contributions to Higgs production



$$\sigma(gg \to h) = \frac{\alpha_S^2 G_F m_h^3}{36\sqrt{2}\pi^3} \left| \sum_q \frac{y_q v}{m_q} F\left(\frac{m_h^2}{4m_q^2}\right) \right|^2 \delta(\hat{s}/M_h^2 - 1)$$

where

$$F(x) = 1 + 7x/30 + \ldots \qquad \text{(for small } x\text{)}$$

So:

Chiral: $\sigma(gg \to h)_{\text{SM4}} \approx 9\,\sigma(gg \to h)_{\text{SM}} \qquad (q = t, t', b')$

Vectorlike: $\sigma(gg \to h)_{q'} \approx \left[1 + \sum_{q'} y_{q'} \left(\frac{348 \text{ GeV}}{M_{q'}}\right)\right] \sigma(gg \to h)_{\text{SM}}$

In vectorlike case, loop effects on production, decay of Higgs decouple like $y_{f'}/M_{f'}$.

Can still be invoked to explain small or moderate discrepancies. . .

<u>What are the most outstanding accomplishments of the LHC so far?</u>

- Discovered the Higgs boson with $M_h = 125$ GeV.
- Ruled out most non-decoupling theories, notably chiral quarks and leptons. This is highly non-trivial!

Decoupling theories, those that agree better and better with the Standard Model as the masses of new particles are increased, remain alive after LHC. Includes:

- SUSY†
- Vectorlike fermions

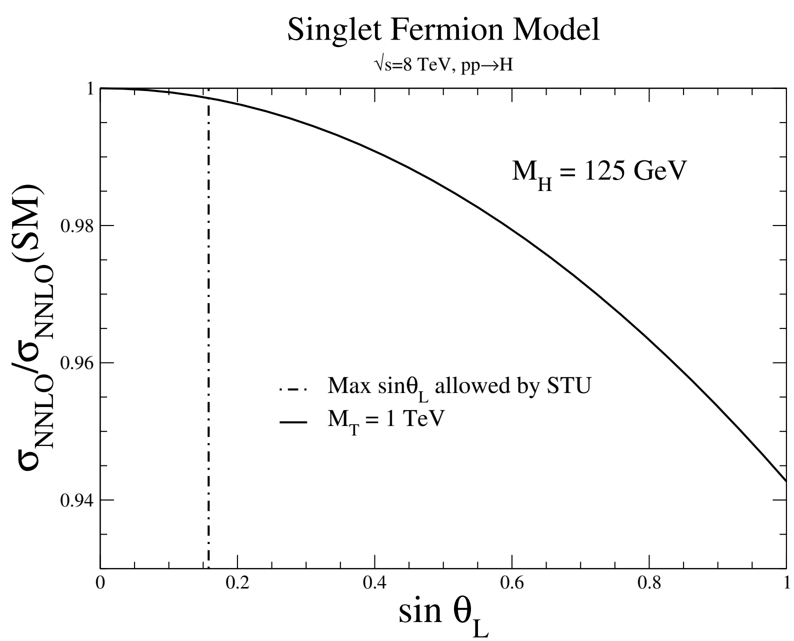
Because these are decoupling theories, they can never be ruled out, just bounded.

† Actually, SUSY is not quite decoupling; it predicted $M_h \lesssim 135$ GeV. But now that we've found that a light Higgs exists with $M_h = 125$ GeV, SUSY effectively has become a decoupling theory; you can't rule it out, you can only put bounds on it. **LHC had a real chance to rule out SUSY, but it failed!**

Precision electroweak observables:

$$\Delta S = \frac{4s_W^2 c_W^2}{\alpha M_Z^2}\left[\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0) - \Pi_{\gamma\gamma}(M_Z^2) - 2\cot(\theta_W)\Pi_{\gamma Z}(M_Z^2)\right]$$
$$\Delta T = \Pi_{WW}(0)/M_W^2 - \Pi_{ZZ}(0)/M_Z^2$$
$$R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$$
$$\ldots$$

can put strong constraints, if vectorlike quarks aren't too heavy. **If** large mixing with SM quarks, these are even stronger than constraints from Higgs observables.

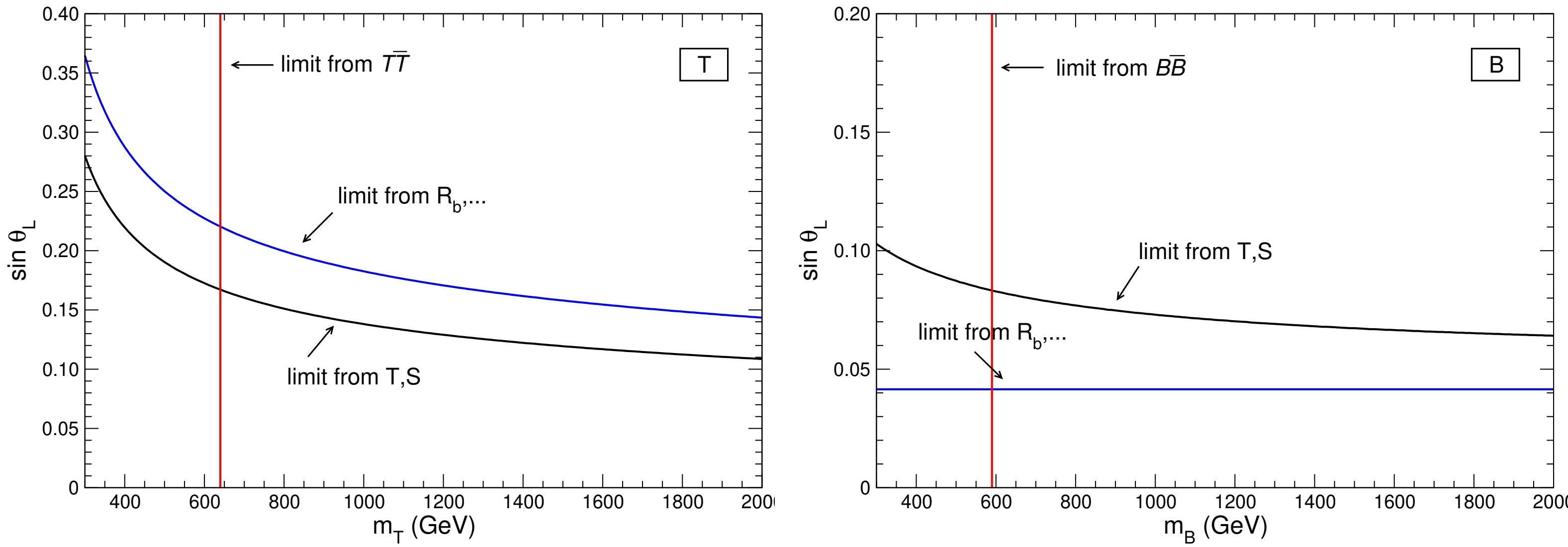


From Dawson and Furlan, 1205.4733.

$\theta_L =$ mixing angle between t, t'.

Once precision electroweak constraints are included, Higgs cross-section must be *very* close to Standard Model in this model.

From Aguilar–Saavedra, Benbrik, Heinemeyer, Pérez-Victoria 1306.0572, limits on mixing angles of (t, t') and of (b, b'), from R_b and S, T.



However, in a general vectorlike fermion model, these mixing angles can be made as small as you want; just need to generate ordinary $t, b, \tau, \ldots$ masses through their own Yukawa couplings.

Top partners t' are the most often considered, because of possible connection to the hierarchy problem in Little Higgs and Composite Higgs models.

Coverage of the vectorlike quark possibilities by the LHC experimental collaborations is now fairly mature.

The same cannot be said for the vectorlike lepton possibility. . .

Vectorlike charged leptons have been proposed to:

- Modify $\sigma(pp \to h \to \gamma\gamma)$

  Kearney, Pierce, Weiner 1207.7062; Batell, Jung, Lee 1211.2449;

  W-Z. Feng, P. Nath 1303.0289; Joglekar, Schwaller, Wagner 1303.2969

- Explain the muon $g-2$ anomaly

  Dermisek, Raval 1305.3522; Dermisek, Raval, Shin 1408.1082; Poh, Raby 1705.07007

- Explain dark matter

  Arina, Mohapatra, Sahu 1211.0435; Schwaller, Tait, Vega-Morales 1305.1108;

  Halverson, Orlofsky, Pierce 1403.1592; Abdullah, Feng, Iwamoto, Lillard 1608,00283;

  Lu, Morrissey, Wijangco 1705.08896; Kawamura, Okawa, Omura, Tang 1812.07004

- Explain baryogenesis

  Fairbairn, Grothaus 1307.8011, Bell et al 1903.11255

- Modify SUSY in various ways while maintaining gauge unification

  T. Moroi, Y. Okada 1992; Babu, Gogoladze, Kolda 9605408; Babu, Gogoladze, Rehman, Shafi 0807.3055; SPM 0910.2732; . . . ; Dermisek, McGinnis 1712.03527 1810.12474 1812.05240 . . .

Below, assume that:

- Vectorlike fermions have non-exotic EM and color charges.
- Mixing with Standard Model fermions is **small**, and mostly with the 3rd family. This is the easiest way to avoid flavor and precision electroweak constraints.

It follows that vectorlike fermions are pair-produced, with decays:

- $t' \to tZ,\ \ th,\ \ bW$
- $b' \to bZ,\ \ bh,\ \ tW$
- $\tau' \to \tau Z,\ \ \tau h,\ \ \nu W$
- $\nu' \to \nu Z,\ \ \nu h,\ \ \tau W$

Vectorlike fermion decays

Simple cases in the high mass limit are governed by Goldstone boson equivalence theorem. Decays to gauge bosons are dominated by the longitudinal mode, equivalent to the corresponding eaten Goldstone boson, with amplitudes correlated to decay to h:

- Pure $SU(2)_L$ doublet:
$$BR(f' \to fZ) = BR(f' \to fh) = 0.5$$
- Pure $SU(2)_L$ singlet:
$$BR(f' \to fZ) = BR(f' \to fh) = 0.25, \;\; BR(f' \to FW) = 0.5$$

However, many other possibilities are allowed; examples below.

Experimentalists should just search for all of them, in all possible combinations!

SUSY already requires a vectorlike fermion mass term:

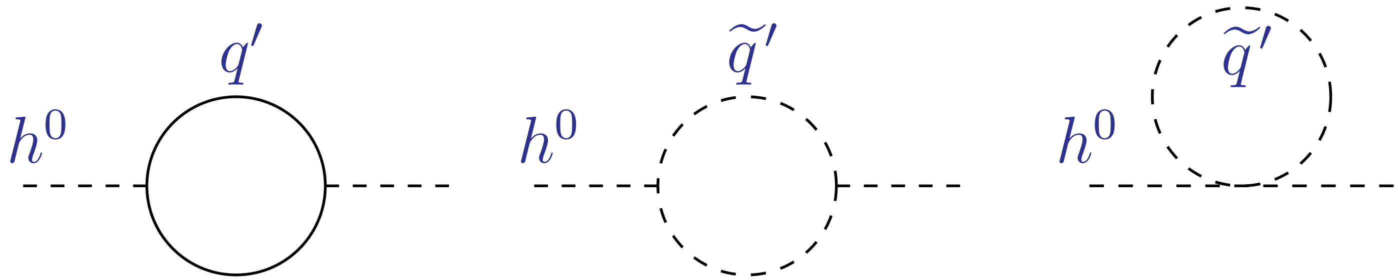
$$-\mathcal{L} = \mu H_u H_d.$$

Whatever mechanism provides for $\mu \sim 1$ TeV can also be invoked to provide for vectorlike fermion masses of the same order.

(Kim-Nilles mechanism, Giudice-Masiero mechanism, NMSSM, ...)

In SUSY, $M_h = 125$ GeV difficult in models accessible to LHC.

Vectorlike supermultiplets can raise M_h^2 through Yukawa couplings:



These contributions do **not** decouple for large $M_{q'}$, as long as there is a significant ratio $M_{\tilde{q}'}/M_{q'} > 1$.

T. Moroi, Y. Okada 1992; Babu, Gogoladze, Kolda 9605408; Babu, Gogoladze, Rehman, Shafi 0807.3055; SPM 0910.2732; ...

- No mixing with 3rd family required.
- Can rescue models that would be otherwise not viable, for example minimal GMSB.

Generic structure of new extra vectorlike matter superfields:

$$F, \overline{F} \quad = \quad SU(2)_L \text{ doublets (vectorlike)}$$
$$f, \overline{f} \quad = \quad SU(2)_L \text{ singlets (vectorlike)}$$

Superpotential, including Yukawa coupling k:

$$W = M_F F \overline{F} + M_f f \overline{f} + k H_u F \overline{f} + \ldots$$

Correction to lightest Higgs boson mass is $\Delta M_h^2 \propto k^4$. To get k as large as possible = IR quasi-fixed point of renormalization group equations.

Want to maintain successes of minimal SUSY:

- Perturbative gauge coupling unification
- No unconfined fractional charges

Building block superfields, under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$
\begin{aligned}
Q, \overline{Q} : &\qquad (\mathbf{3}, \mathbf{2}, \frac{1}{6}),\ (\overline{\mathbf{3}}, \mathbf{2}, -\frac{1}{6}) \\
U, \overline{U} : &\qquad (\mathbf{3}, \mathbf{1}, \frac{2}{3}),\ (\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}) \\
D, \overline{D} : &\qquad (\mathbf{3}, \mathbf{1}, -\frac{1}{3}),\ (\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}) \\
L, \overline{L} : &\qquad (\mathbf{1}, \mathbf{2}, -\frac{1}{2}),\ (\mathbf{1}, \mathbf{2}, \frac{1}{2}) \\
E, \overline{E} : &\qquad (\mathbf{1}, \mathbf{1}, -1),\ (\mathbf{1}, \mathbf{1}, 1) \\
N : &\qquad (\mathbf{1}, \mathbf{1}, 0) \quad \text{(singlet)}
\end{aligned}
$$

Models with gauge coupling unification:

(LND)^n :	$(L, \overline{L}, D, \overline{D}, N, \overline{N}) \times n$	$[\mathbf{5} + \overline{\mathbf{5}}$ of $SU(5),\ \ n = 1, 2, 3]$
QUE :	$Q, \overline{Q}, U, \overline{U}, E, \overline{E}$	$[\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)]$
QDEE :	$Q, \overline{Q}, D, \overline{D}, E, \overline{E}, E, \overline{E}$	
$\mathbf{16} + \overline{\mathbf{16}}$:	$Q, \overline{Q}, U, \overline{U}, E, \overline{E}, L, \overline{L}, D, \overline{D}, N, \overline{N}$	$[\mathbf{16} + \overline{\mathbf{16}}$ of $SO(10)]$
$\ldots$		

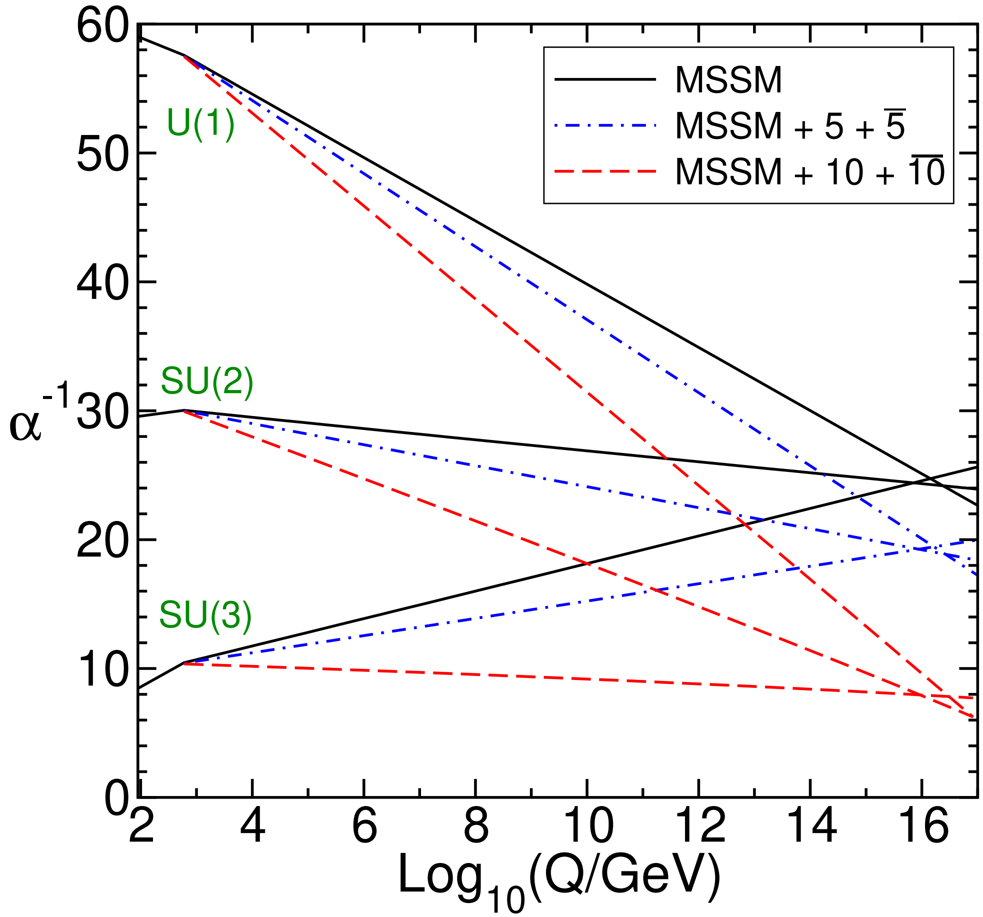
The last may lose perturbativity below $M_{\rm GUT}$; **need** multi-loop beta functions to get things correct.

Note: all combinations have vectorlike leptons as well as quarks.

If you don't care about unification, can have smaller veectorlike supermultiplet content, for example $Q + \overline{Q} + U + \overline{U}$, or just $L + \overline{L}$.

Gauge couplings still unify above 10^{16} GeV, but at stronger coupling.

Three-loop running:



Black = MSSM

Blue = LND Model

Red = QUE Model

(QDEE similar)

Extra fields contribute equally to the three beta functions at 1 loop.

QUE Model:

$$W = M_Q Q\overline{Q} + M_U U\overline{U} + kH_u Q\overline{U} + M_E E\overline{E}$$

The Yukawa coupling k has an IR quasi-fixed point at $k \approx 1.05$.

New fermions: $t', \quad t'', \quad b', \quad \tau'$

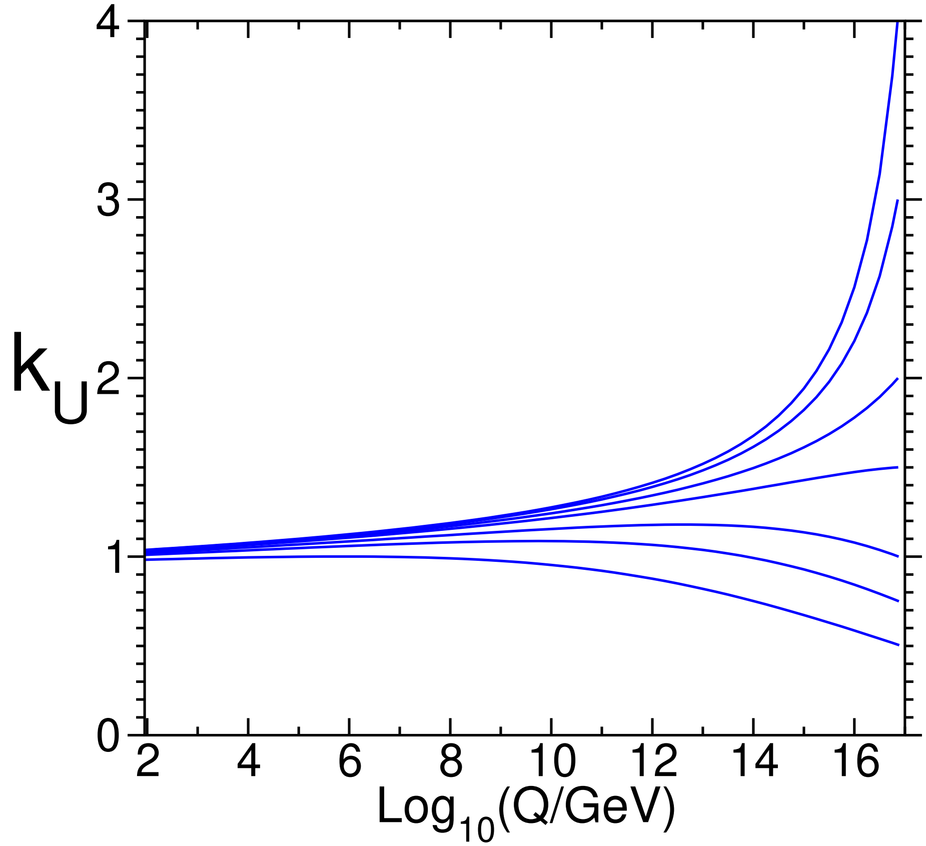
New scalars: $\tilde{t}'_{1,2,3,4}, \quad \tilde{b}'_{1,2}, \quad \tilde{\tau}'_{1,2}$

The first discovered new particle might be t', b', or τ'. May discover one of them before any superpartner.

Assuming for simplicity that the new scalars are degenerate with mass M_S, and the new fermions are degenerate with mass M_F, then (note doesn't decouple!):

$$\Delta M_h^2 \approx \frac{3v^2}{2\pi^2} k^4 \left[\ln(M_S/M_F) - 5/12 + 2M_F^2/M_S^2 \right]$$

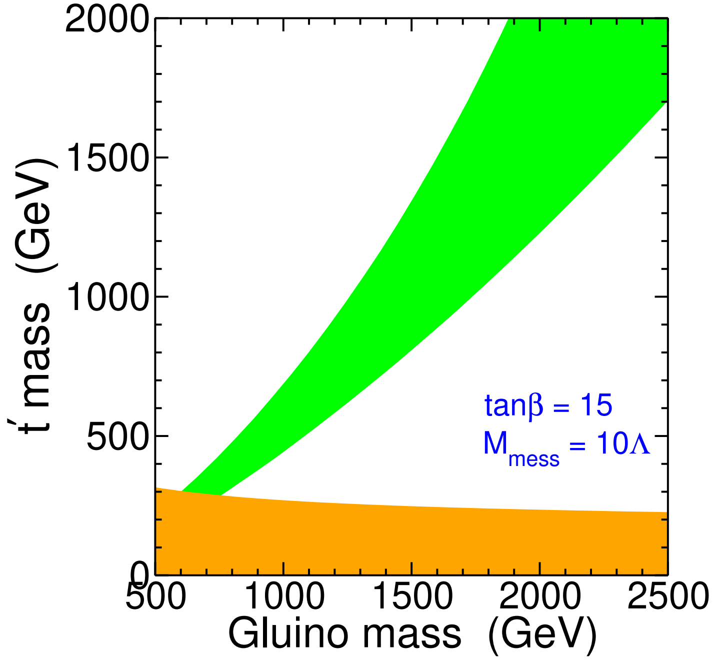
Infrared-stable fixed point at $k = 1.05$ in the QUE model:



This large value is natural in the sense that many inputs at GUT scale end up there. The QDEE model behaves very similarly.

Vectorlike quarks can raise the prediction for the Higgs mass, allowing $M_h = 125$ GeV, if Yukawa coupling is large.

For example, minimal Gauge Mediated SUSY Breaking + vectorlike quarks+leptons with $k = 1.05$ can have gluino, squarks, and t' accessible to LHC:



Green = allowed by $M_h = 125$ GeV.

SPM+Wells, 1206.2956

None of this plane allowed without the vectorlike fermions; M_h would be too small.

Corrections to Peskin-Takeuchi S, T parameters are approximately:

$$\Delta T \approx 0.034\, N_c\, k^4 \left(\frac{400 \text{ GeV}}{M_F}\right)^2$$

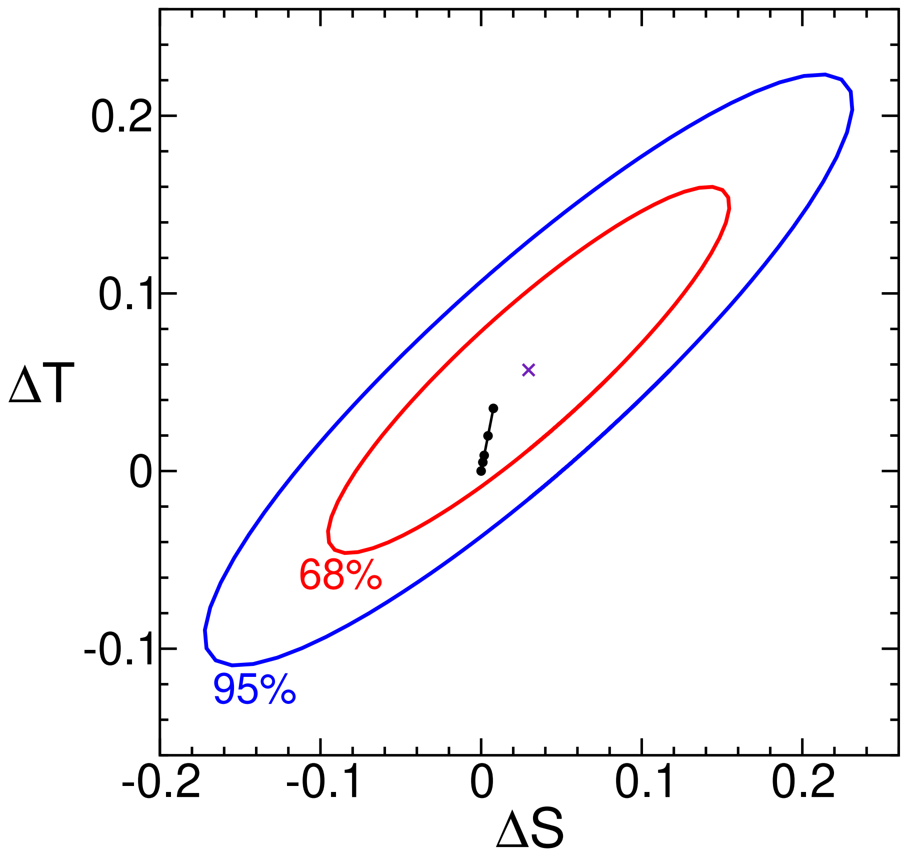
$$\Delta S \approx 0.0081\, N_c\, k^2 \left(\frac{400 \text{ GeV}}{M_F}\right)^2$$

Assumes mixing with Standard Model fermions is small.

The scalar sector contributes a smaller but non-negligible amount.

Note that these corrections do decouple quadratically with M_F, unlike the corrections to the Higgs mass.

ΔS, ΔT for typical QUE model with varying $M_Q = M_U$ and $k = 1.05$:



$\Delta S = \Delta T = 0$ defined here by Standard Model with $m_t = 173.1$ GeV, $M_h = 125$ GeV.

$\times$ $=$ best fit to Z-pole data.

Black dots are (top to bottom): $m_{t_1'} = 750, 1000, 1500$ GeV and ∞.

Agreement with Standard Model gets better, but by a very small amount.

Note: assumed mixing with 3rd family quarks is small. Otherwise, S, T corrections can be much larger.

Example: how does the t' decay in QUE Model?

Depends on the form of the mixing term between the extra quarks and the Standard Model ones (assumed to be t, b). Possible terms are:

- $\mathcal{L} \; = \; \epsilon_1 H_d Q \bar{b}$

  Implies charged-current ("W-philic") decays, with

  $BR(t' \to bW,\, tZ,\, th) = (1,\, 0,\, 0)$.

- $\mathcal{L} \; = \; \epsilon_2 H_u Q \bar{t}$

  Implies dominantly neutral current ("W-phobic") decays, with

  $BR(t' \to bW,\, tZ,\, th) = (0,\, 0.5,\, 0.5)$ in the high mass limit.

- $\mathcal{L} \; = \; \epsilon_3 H_u \begin{pmatrix} t \\ b \end{pmatrix} \overline{U}$

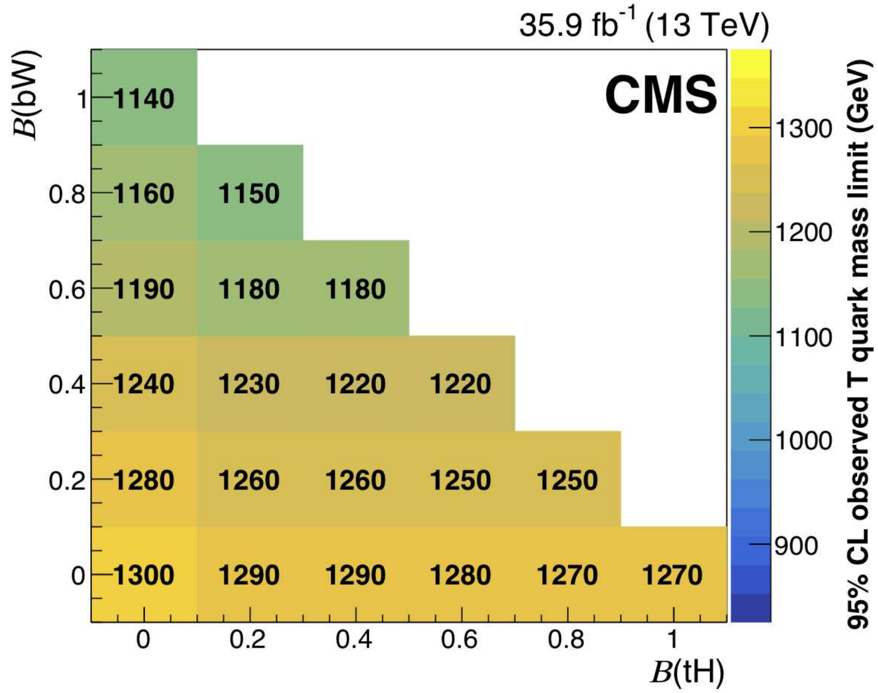
  Implies "democratic" decays, with

  $BR(t' \to bW,\, tZ,\, th) = (0.5,\, 0.25,\, 0.25)$ in the high mass limit.

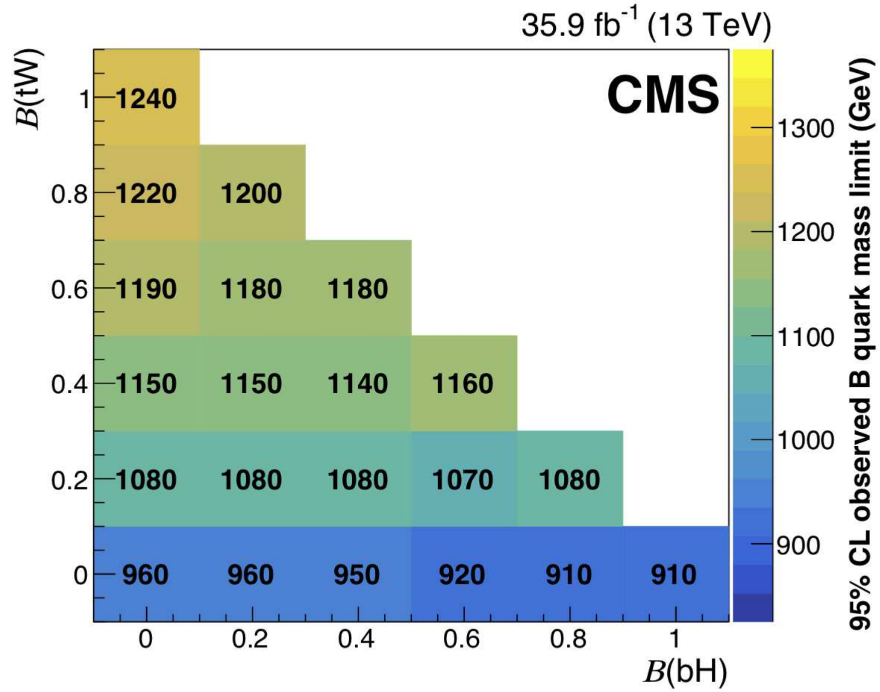
Any linear combinations of these are also possible!

Vectorlike quark mass limits from CMS 1805.04758

t'



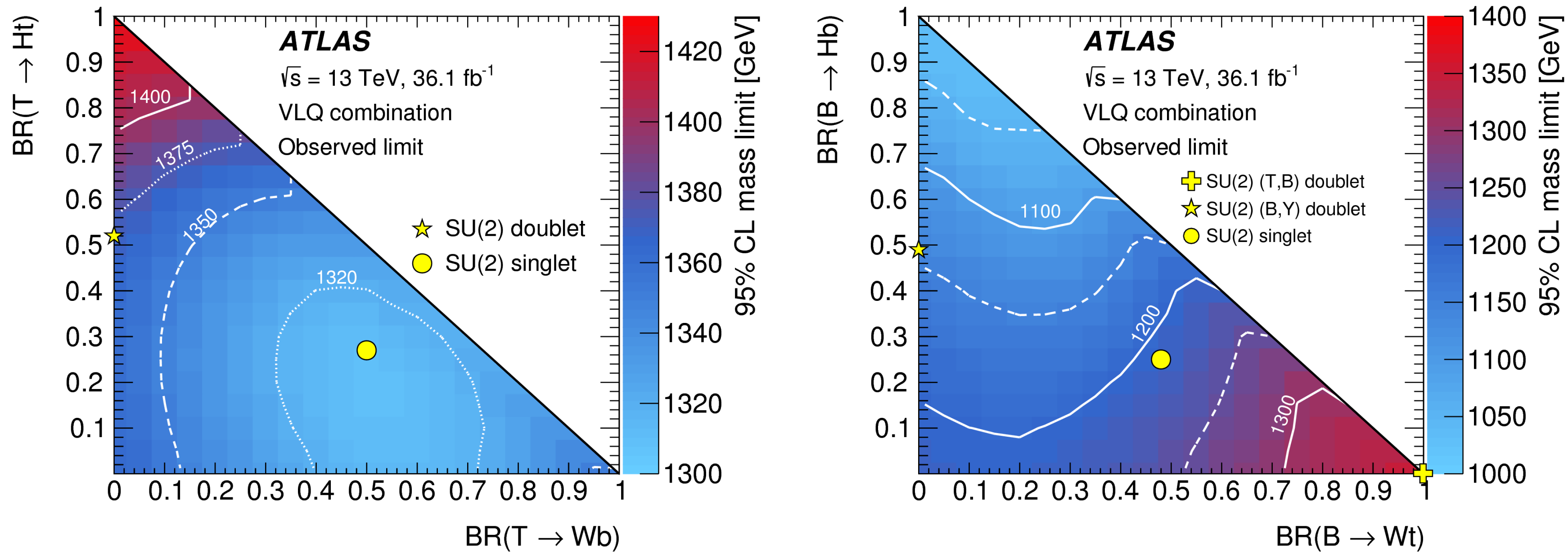
b'



For $BR(b' \to bZ) = 1$, limit is improved to 1130 GeV by 1812.09768.

Vectorlike quark mass limits from ATLAS 1808.02343

t' b'



Appear to be somewhat stronger than CMS, for now.

(Caution: axes are flipped!)

Vectorlike leptons

As 2-component fermions, transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as:

$$L + \overline{L} \quad = \quad (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}) + (\mathbf{1}, \mathbf{2}, +\tfrac{1}{2}) \qquad \textbf{Doublet VLL}$$

or

$$E + \overline{E} \quad = \quad (\mathbf{1}, \mathbf{1}, -1) + (\mathbf{1}, \mathbf{1}, +1) \qquad \textbf{Singlet VLL}$$

In both cases, assume decays to Standard Model states by mixing with the ordinary tau leptons.

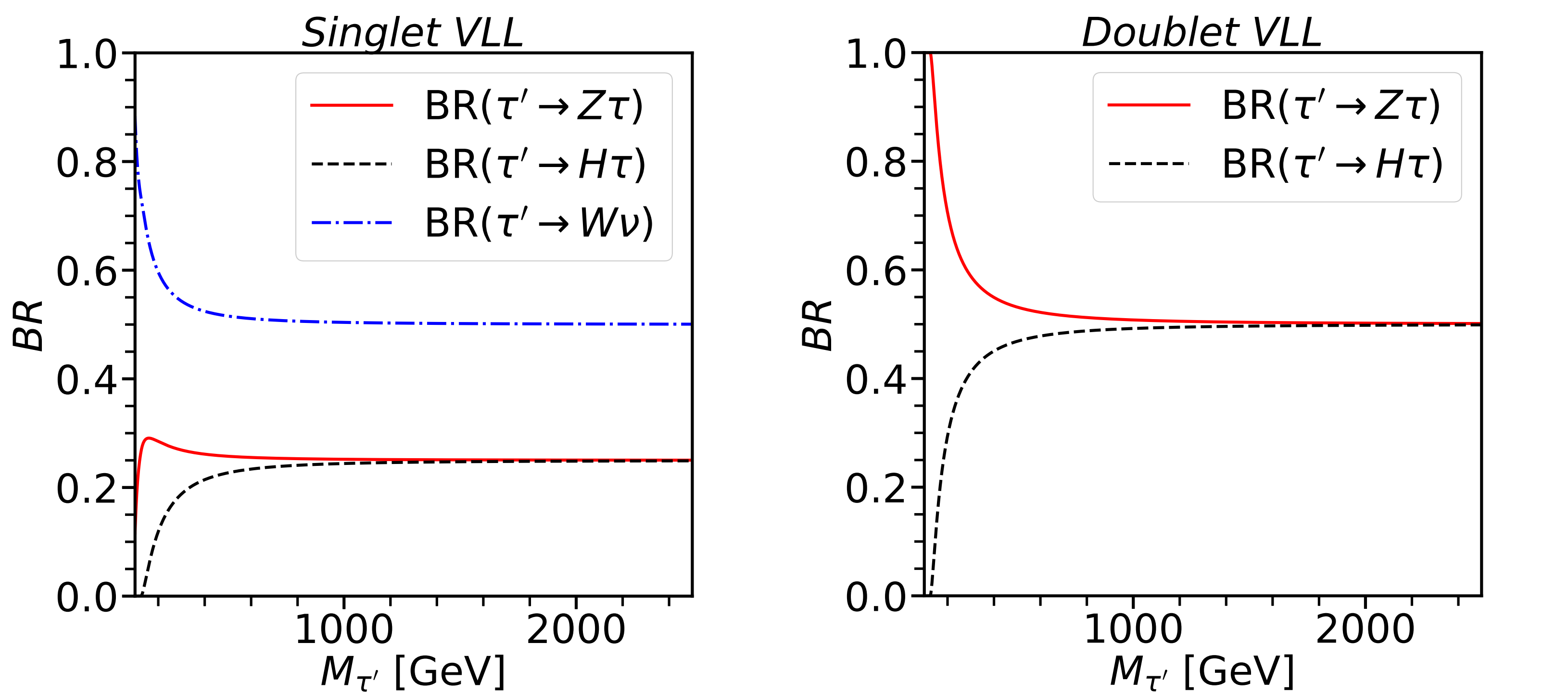
LHC phenomenology: Ishiwata, Wise 1307.1112; Falkowski, Straub, Vicente 1312.5329; Holdom, Ratzlaff 1405.4573; Kumar, SPM 1510.03456; Bhattiprolu, SPM 1905.00498

Easier case of mixing with muons: Dermisek, Hall, Lunghi, Shin 1408.3123, ATLAS 1506.01291 based on 8 TeV; excludes 114 GeV $< M_{\mu'} <$ 176 GeV
Production through heavy Higgs decays: Dermisek, Lunghi, Shin 1608.00662

Mass mixing for τ, τ' in both singlet and doublet cases:

$$\mathcal{M} \;=\; \begin{pmatrix} y_\tau v & 0 \\ \epsilon v & M \end{pmatrix}.$$

Assume ϵ is small; need $\epsilon \gtrsim 10^{-7}$ for prompt τ' decays. Then branching ratios are predicted, and asymptotically obey Goldstone equivalence:



For the Doublet VLL model, also have

$$\mathrm{BR}(\nu' \to \tau W) = 1.$$

At LHC, look for multi-lepton signals including one or two τs.

For Doublet VLL model, the final states are:

$$pp \to \tau'\tau' \to ZZ\tau^+\tau^-, \qquad hh\tau^+\tau^-, \qquad Zh\tau^+\tau^-$$

and

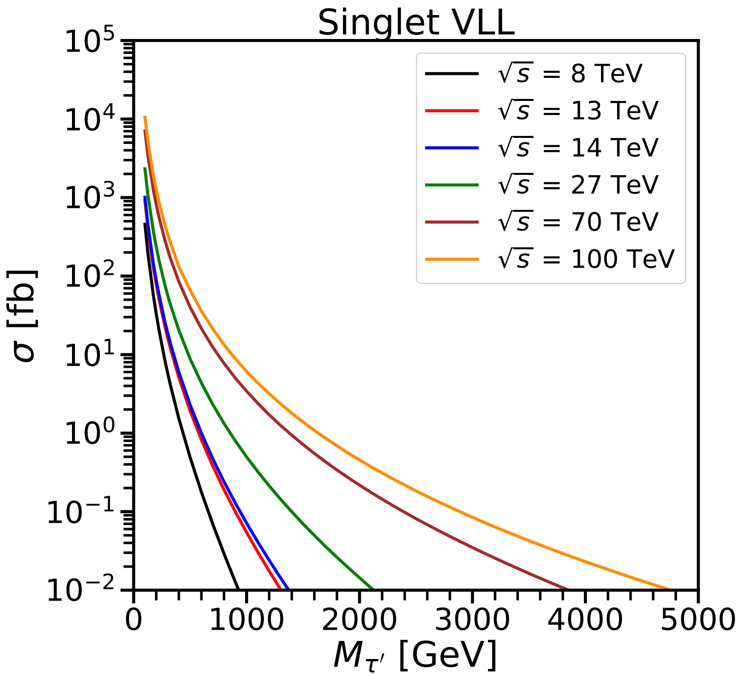
$$pp \to \nu'\nu' \to W^+W^-\tau^+\tau^-$$

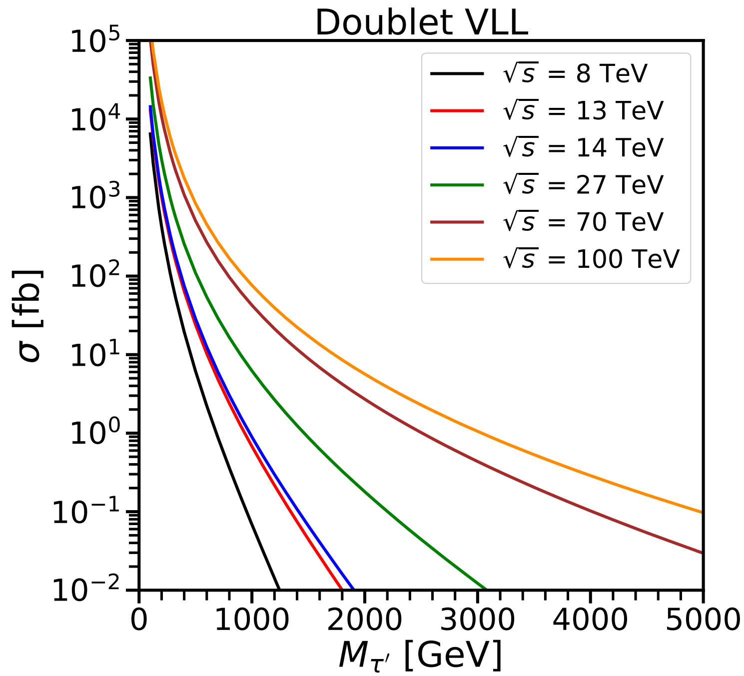
and

$$pp \to \tau'\nu' \to ZW^\pm\tau^+\tau^-, \qquad hW^\pm\tau^+\tau^-.$$

The $\tau'\nu'$ channel has the largest production cross-section, by far.

Production cross sections:





At the $\sqrt{s} = 13$ TeV LHC, there is a significant exclusion/discovery reach for the **Doublet VLL** model, but it is luminosity limited for larger masses.

The minimal **Singlet VLL** model presents much more severe challenges. Cross-section has γ-Z destructive interference.

See talk by Prudhvi Bhattiprolu for projections for High-Luminosity LHC, High-Energy LHC, and 100 TeV pp collider.

Present LHC bounds

Doublet VLL model:

CMS search in CMS-PAS-EXO-18-005 based on 41.4 fb^{-1} at $\sqrt{s} = 13$ TeV excludes

$$130 \text{ GeV} < M_{\tau'} < 690 \text{ GeV}.$$

This was aided by a deficit of events in the search regions, notably

$$2e/\mu + \geq 1\tau.$$

Expected exclusion was only up to 560 GeV.

Singlet VLL model:

No LHC limits! (Yet?)

Non-minimal vectorlike lepton models

Consider combination of $SU(2)_L$ singlet and doublet vectorlike leptons:

$$E + \overline{E} + L + \overline{L} \quad = \quad (\mathbf{1}, -1) + (\mathbf{1}, +1) + (\mathbf{2}, -\tfrac{1}{2}) + (\mathbf{2}, +\tfrac{1}{2})$$

under $SU(2)_L \times U(1)_Y$. The mass matrix that mixes these with the ordinary τ_L and τ_R lepton is:

$$-\mathcal{L} \quad = \quad \begin{pmatrix} \overline{\tau}_R & \overline{E} & \overline{L} \end{pmatrix} \begin{pmatrix} y_\tau v & 0 & \epsilon_2 v \\ \epsilon_1 v & M_1 & x_2 v \\ 0 & x_1 v & M_2 \end{pmatrix} \begin{pmatrix} \tau_L \\ E \\ L \end{pmatrix}$$

where $y_\tau, \epsilon_1, \epsilon_2, x_1, x_2$ are all Yukawa couplings to the Standard Model Higgs field, and M_1, M_2 are bare vectorlike mass terms.

Can get any branching ratios you want! Some special limits. . .

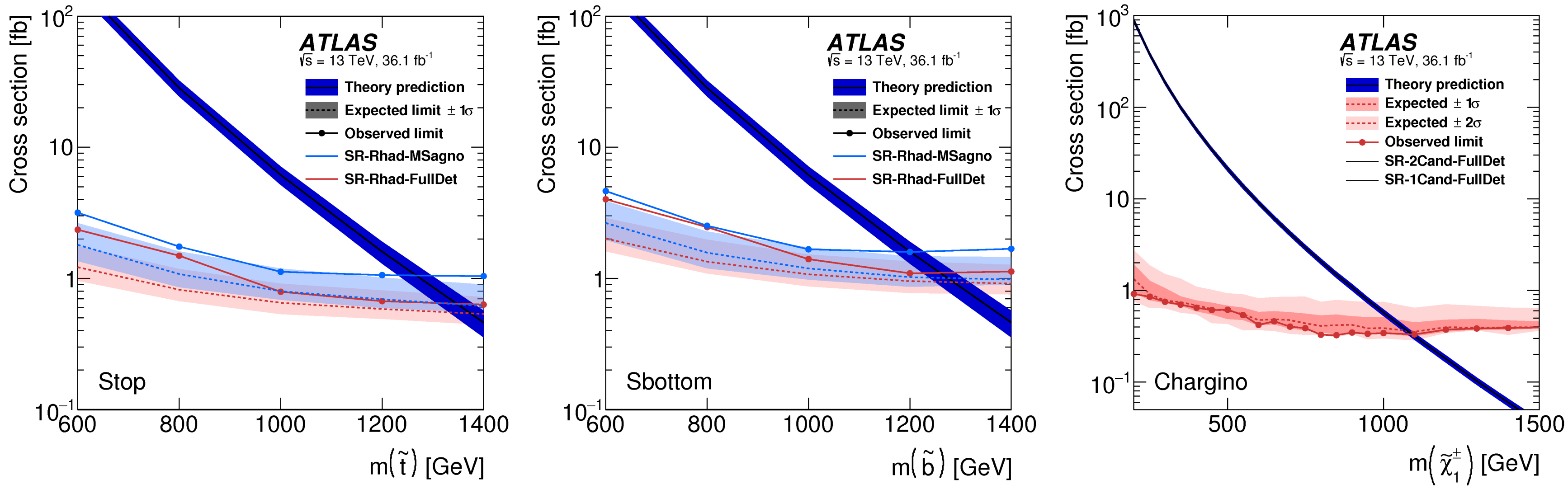
- If $M_2 \ll M_1$ and $\epsilon_1 = 0$, then the singlet decouples, and we have the Doublet VLL model;
  BR$(\tau' \to h\tau) \approx \mathrm{BR}(\tau' \to Z\tau) \approx 0.5.$

- If $M_1 \ll M_2$ and $\epsilon_2 = 0$, then the doublet decouples, and we have the minimal Singlet VLL model;
  BR$(\tau' \to W\nu) \approx 0.5;$ BR$(\tau' \to h\tau) \approx \mathrm{BR}(\tau' \to Z\tau) \approx 0.25.$

- If $M_1 \ll M_2$ and $\epsilon_1 = 0$ but $\epsilon_2 \neq 0$, then the doublet is heavy, but the light singlet τ' can decay in distinct ways by mixing with the much heavier doublet:
  - ⋆ W-phobic Singlet VLL: if $x_1 = 0$, then acts like a doublet,
    BR$(\tau' \to h\tau) \approx \mathrm{BR}(\tau' \to Z\tau) \approx 0.5.$
  - ⋆ Higgs-philic Singlet VLL: if $x_2 = 0$, then
    BR$(\tau' \to h\tau) \approx 1.$
  - ⋆ Z-philic Singlet VLL: if $x_1 \approx -x_2 M_1/2M_2$, then
    $\mathrm{BR}(\tau' \to Z\tau) \approx 1.$

What if vectorlike fermions are quasi-stable on collider detector length scales?

Infer exclusions from ATLAS 1902.01636 cross-section limits on (t', b', τ') from long-lived (top squarks, bottom squarks, and charginos), respectively, using large ionization rate dE/dx and time-of-flight:



My unofficial estimates of mass exclusions for long-lived fermions:

$M_{t'} > 1550$ GeV

$M_{b'} > 1460$ GeV

$M_{\tau'} > 750$ GeV if weak isosinglet (doublet decays too fast to $\nu'\pi$).

Vectorlike quarks and leptons:

- Very common feature of motivated BSM models
- Decoupling properties provide model-independent motivation
- Mass exclusions, assuming prompt decays to 3rd family fermions:
  - t' mass $<$ 1310 to 1420 GeV (BR dependent), from ATLAS
  - b' mass $<$ 1030 to 1370 GeV (BR dependent), from ATLAS
  - doublet τ', ν' mass $<$ 690 GeV from CMS
  - singlet τ' mass only from LEP2 $\lesssim$ 100 GeV
- See talks by: P. Bhattiprolu (Vectorlike leptons at pp colliders, next),

  M. Sullivan and S. Lane (Maverick Top Partners, here, after coffee break),

  L. Li ($t\bar{t}hh$ from top partner production, today 3:45),

  J. Kawamura (Vectorlike 4th family model for muon anomalies, Tuesday 2:30),

  N. McGinnis (IR fixed points in MSSM with a vectorlike family, Tuesday 2:30)