Composite Higgs and LHC phenomenology

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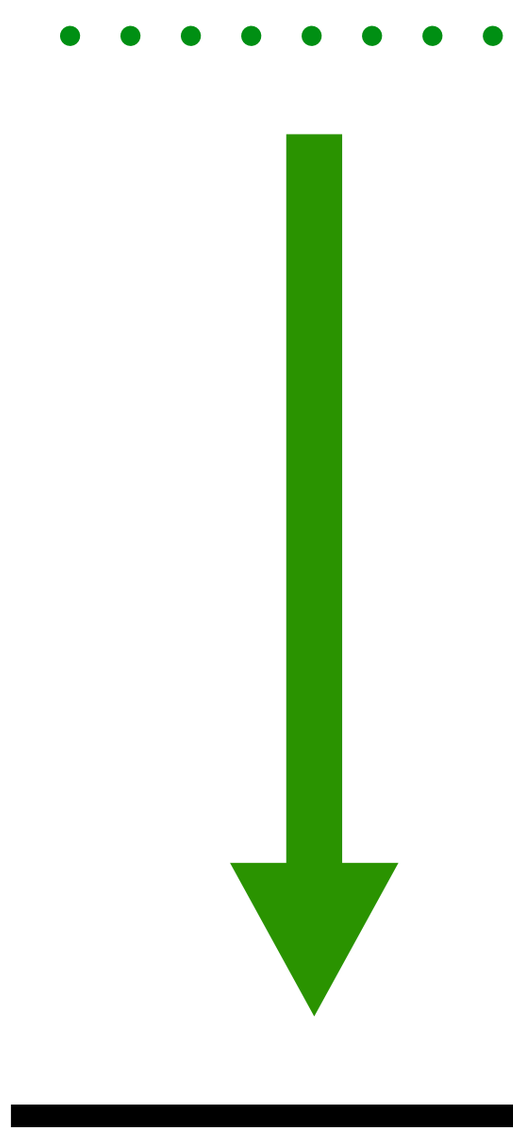
This talk

- Composite Higgs models.
  - Many of them. Will focus on generic feature, not details.
- Will cover LHC phenomenology.
- Beyond LHC (briefly).

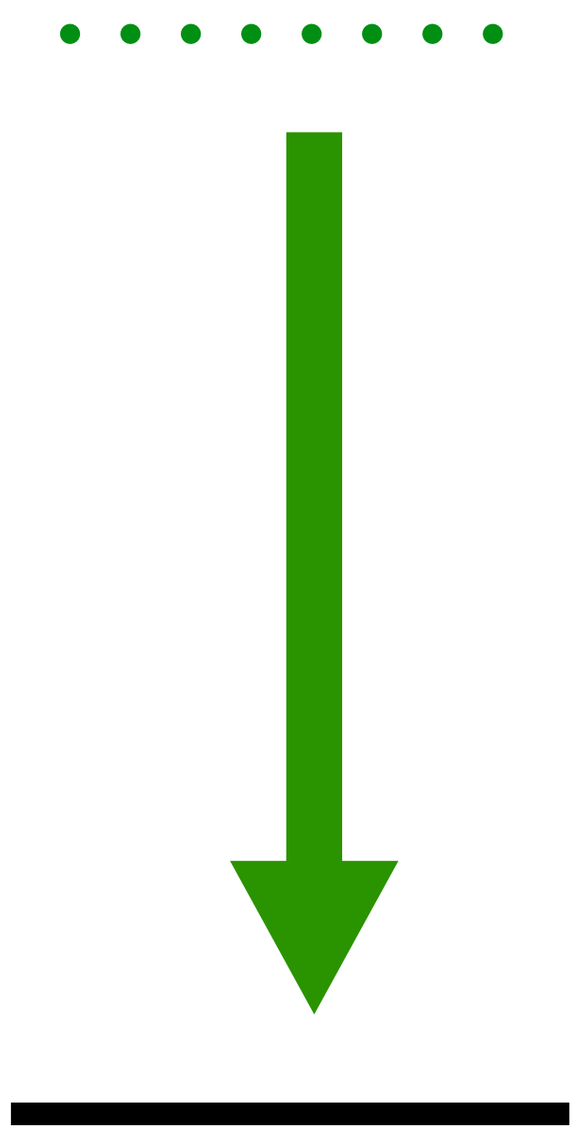
Explaining EWSB: naturalness



Λ: a cut-off.
The energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.
m_h , m_W …

Explaining EWSB: naturalness



Λ: a cut-off.
The energy scale of new physics responsible for EWSB

What is Λ? Can it be very high, such as $M_{Planck} = 10^{19}$ GeV, …?

So different from 100 GeV?

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking

Λ: a cut-off.
The energy scale of new physics
responsible for EWSB

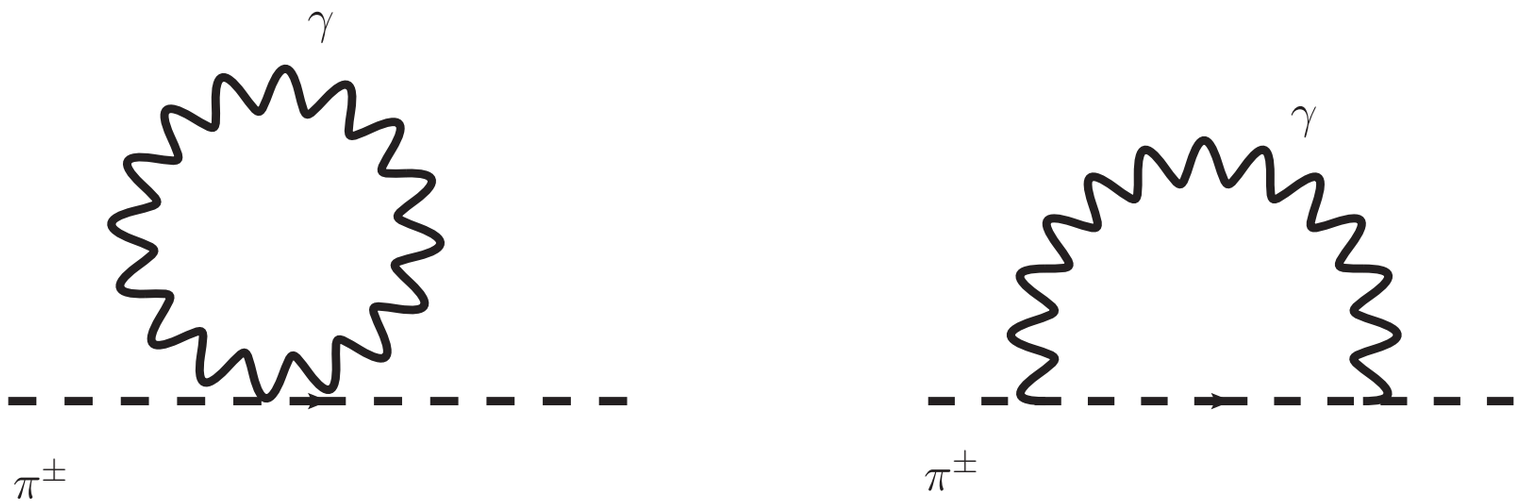
What is Λ? Can it be very high,
such as $M_{Planck} = 10^{19}$ GeV, …?

So different from 100 GeV?

TeV new physics.
Naturalness motivated

Electroweak scale, 100 GeV.
m_h , m_W …

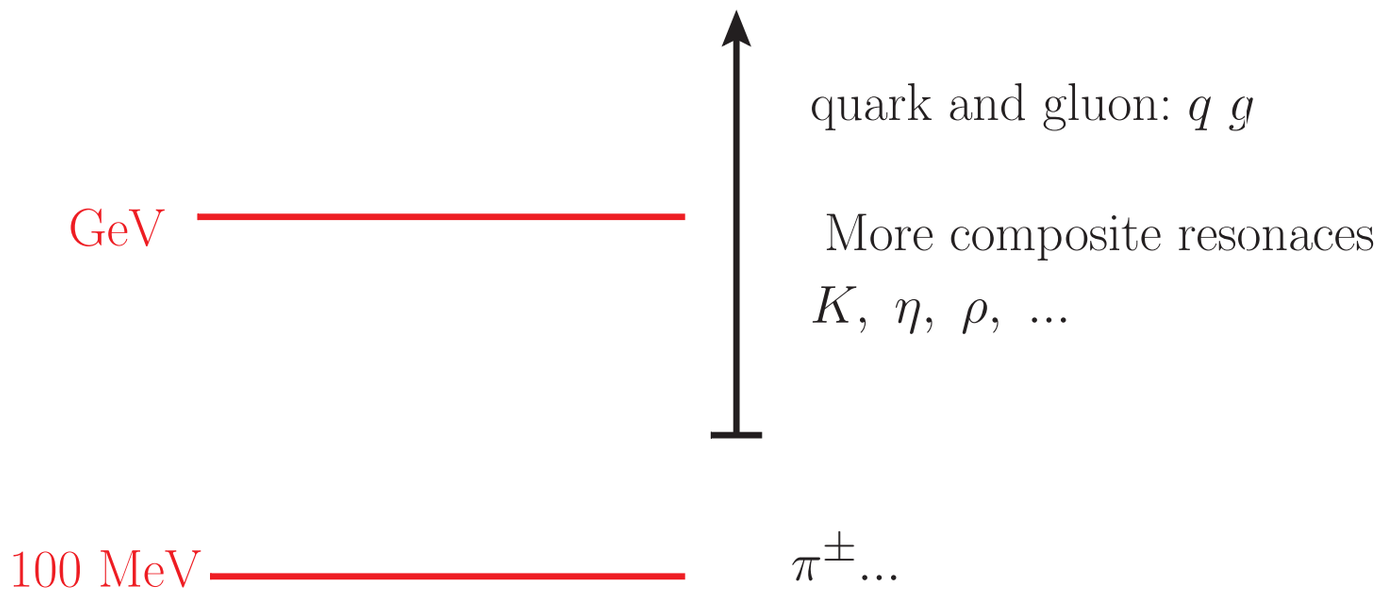
Example of naturalness in nature



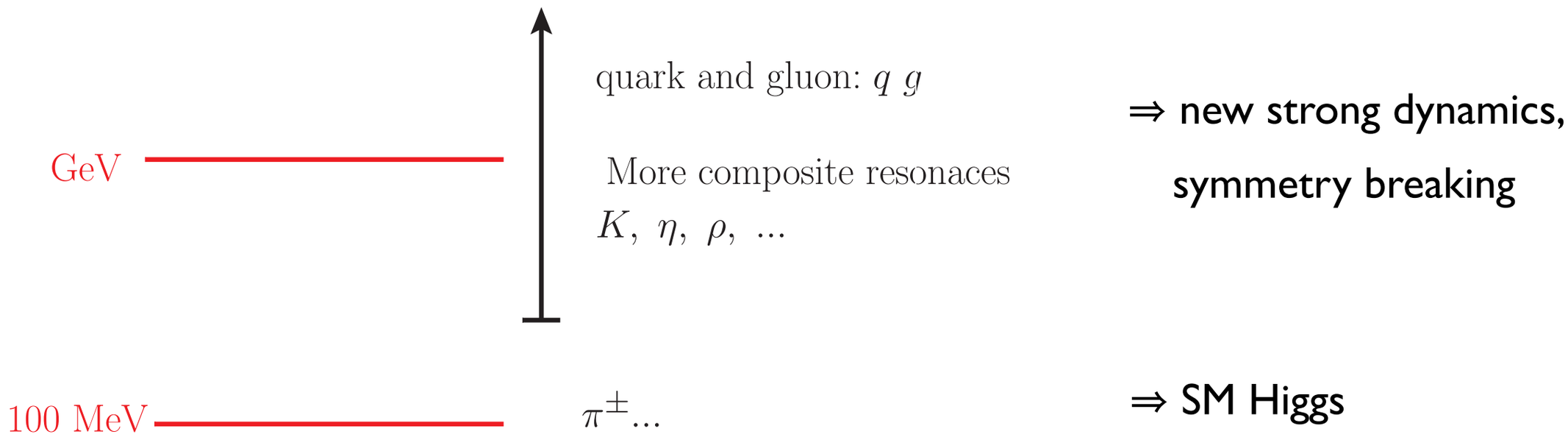
$$\delta m^2_{\pi^\pm} \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

- Example: low energy QCD resonances: pion ....
- $m_\pi \sim$ 100 MeV.
- Naturalness requires $\Lambda \approx$ GeV.
  - Indeed, at GeV, QCD $\Rightarrow$ theory of quark and gluon
  - Pion is natural since it is not elementary.

"Learning" from QCD

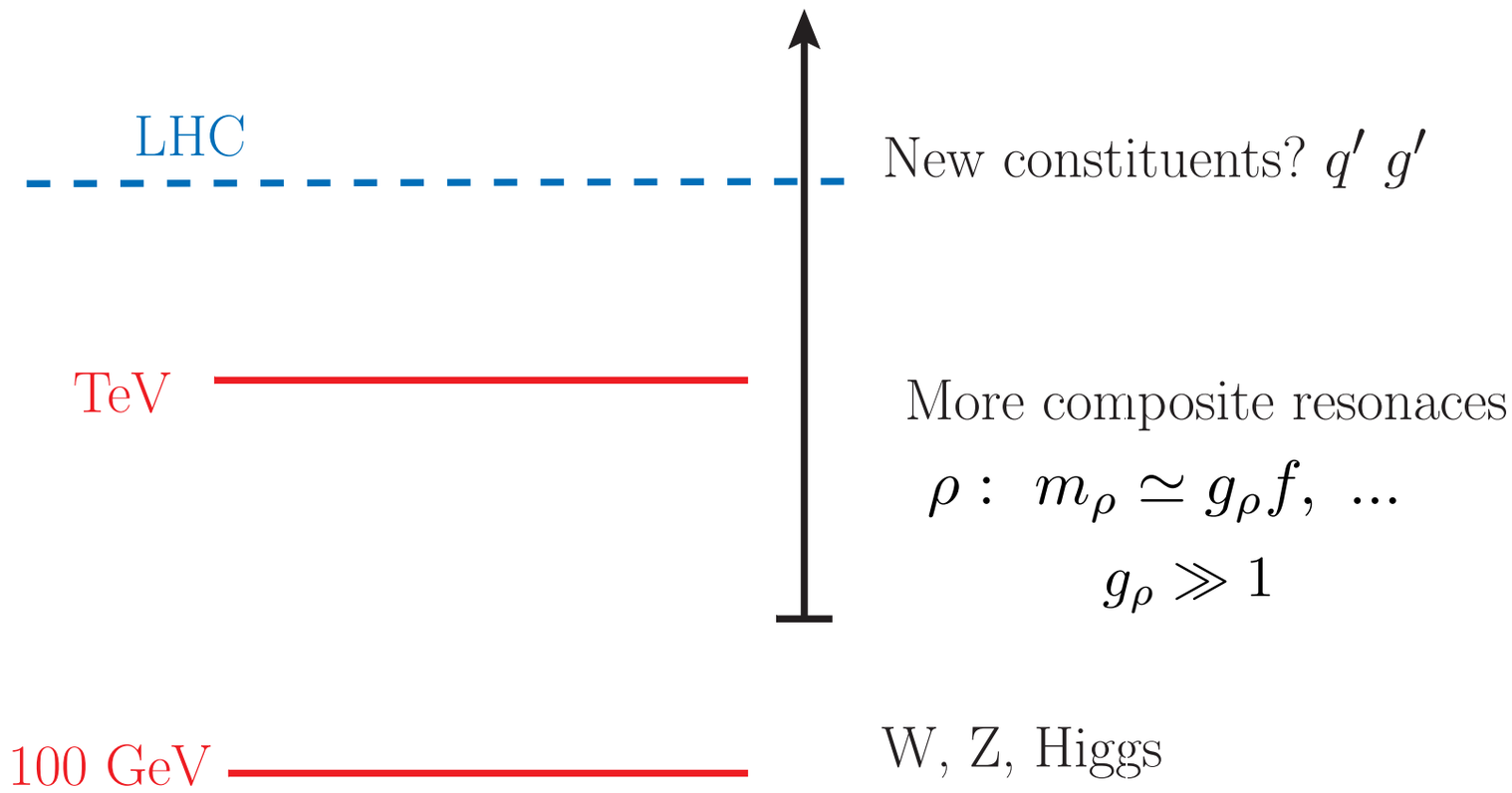


"Learning" from QCD



- New strong dynamics in which the low lying states will be the SM Higgs.
- Composite Higgs models, natural.
- QCD scale is natural. Nature could just repeat itself for the weak scale.

Composite Higgs



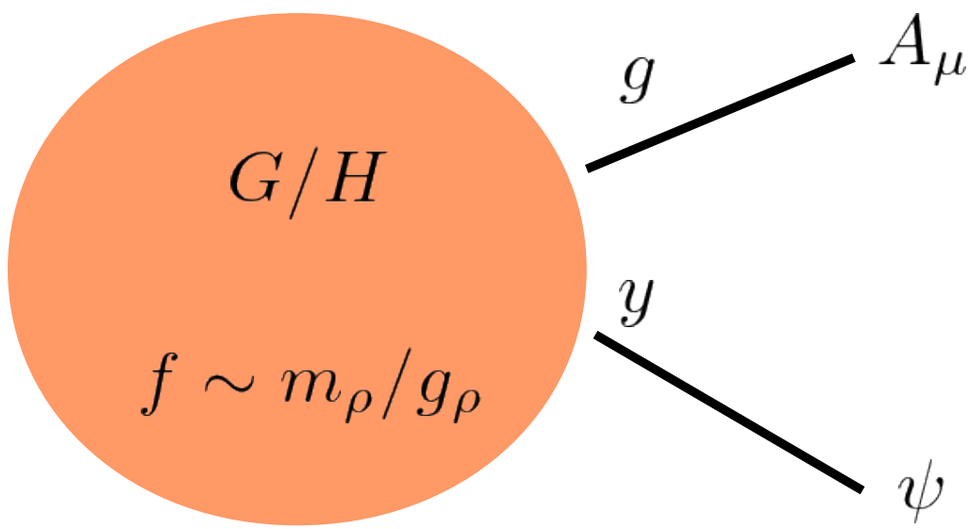
- Many models in this class.

– Similar scenarios: Randall-Sundrum...

Agashe, Sundrum; Contino, Nomura, Pomarol

Composite Higgs EFT

Georgi and Kaplan



Higgs (and W/Z goldstones) are part of the strong sector

The external fields are the SM quarks and (transverse) gauge bosons

- Higgs boson (and W_L Z_L) NGB of symmetry breaking G/H.

- Small explicit symmetry breaking (involving external fields) generates Higgs potential. (NGB ➜ pNGB).

Minimal composite

Agashe, Contino, Pomarol

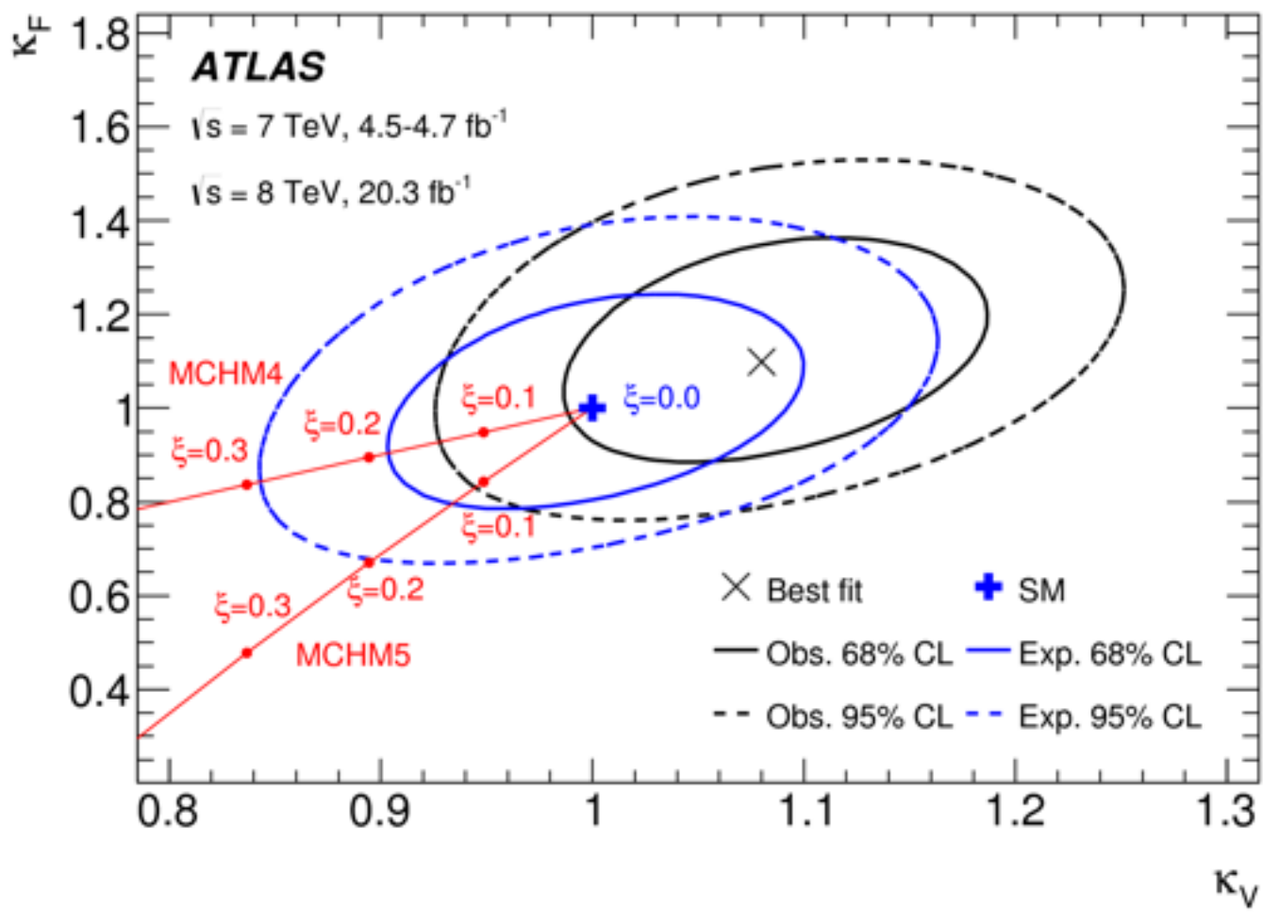
$$SO(5)/SO(4) \to 4\,\mathrm{GBs}$$

$$U = \exp\left(i\sqrt{2}\frac{\pi^a}{f}T^a\right) \quad T^a = \begin{pmatrix} 0 & X_a \\ -X_a & 0 \end{pmatrix} \quad \Sigma_i = U_{i5}$$

$$\frac{1}{2}(D_\mu\Sigma)^2 \supset \frac{1}{2}(\partial h)^2 + \frac{1}{2}m_V^2 V_\mu^2\left(1 + 2\sqrt{1 - \frac{v^2}{f^2}}\frac{h}{v} + \cdots\right)$$

First prediction: deviation in Higgs coupling

Higgs coupling.



$$c_{hVV} = \sqrt{1 - \frac{v^2}{f^2}}\, c_{hVV}^{\rm SM}$$

- Higgs couplings.
  - f > 500-600 GeV > v. Some fine tuning seems unavoidable.

EW precision.

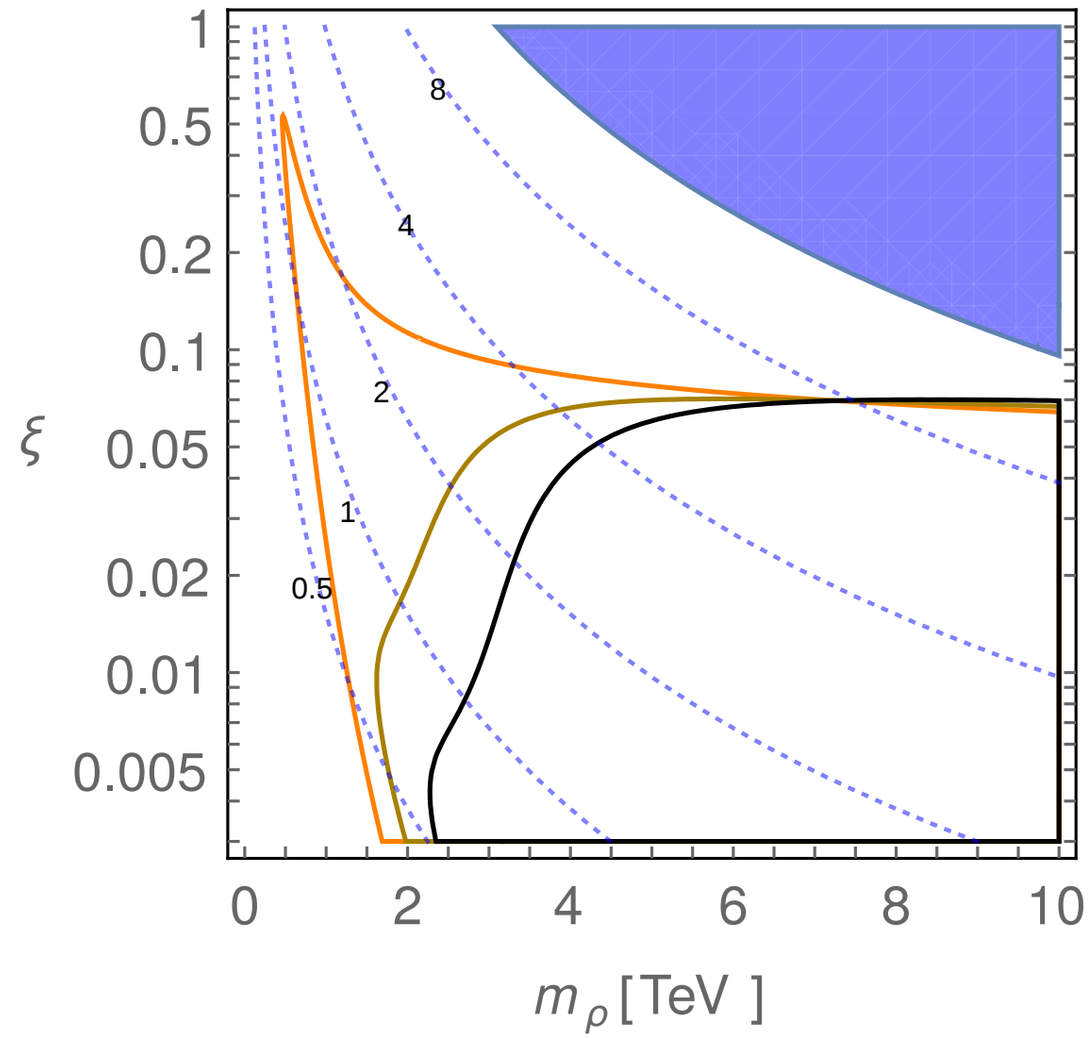
Tree level S-parameter

$$S \sim \frac{4\pi v^2}{m_\rho^2}$$

One loop to S and T

$$\frac{1}{16\pi^2}\frac{v^2}{f^2}\log(m_\rho/m_h)$$

Additional UV contribution parameterized by general CCWZ



Contino, Salvarezza, 2015

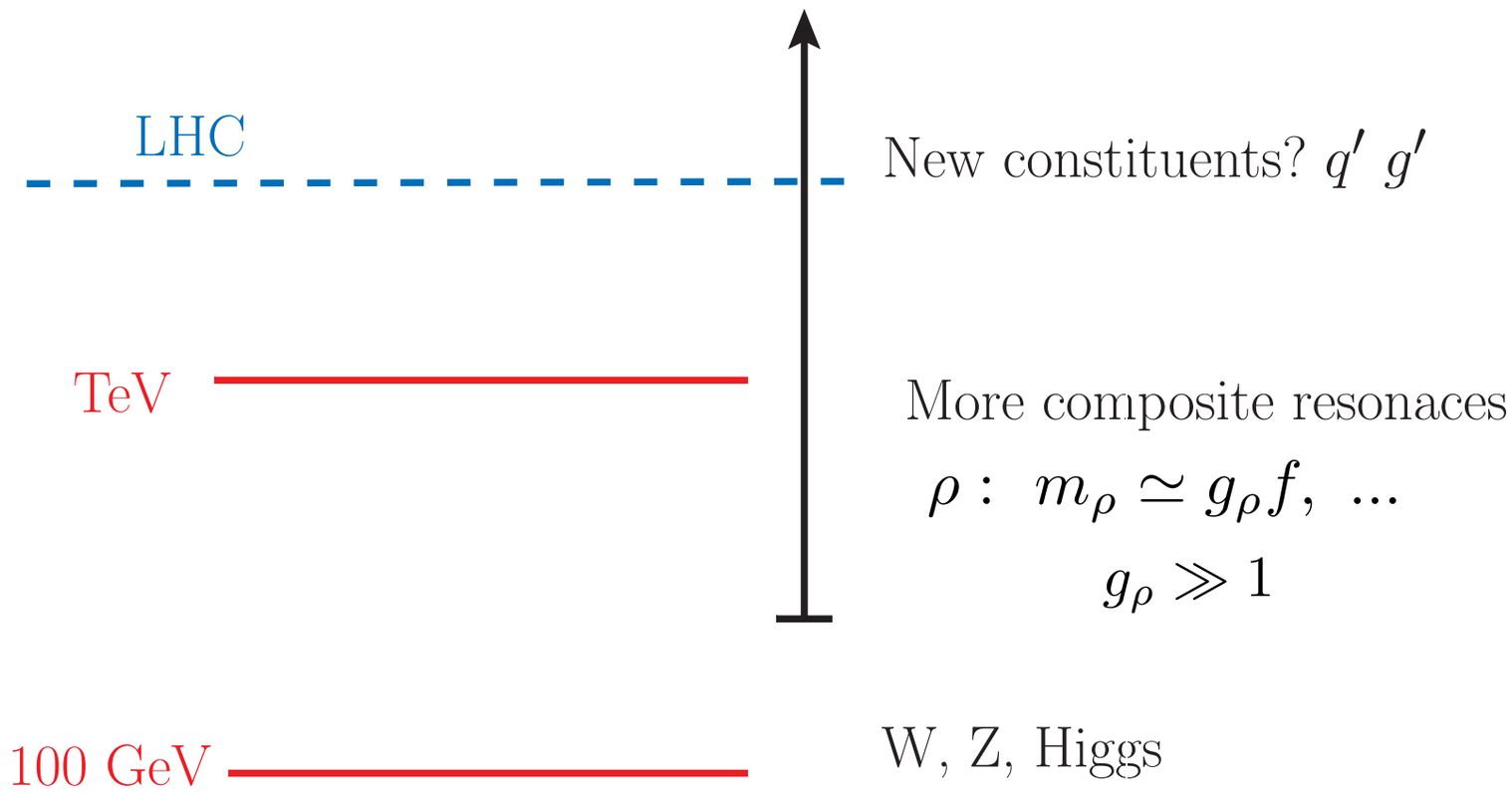
In addition, constraints from Z decay. Relevant for partially composite u_L

$$R_h: \quad \delta g_{u_L} = \frac{1}{4}\frac{v^2}{f^2}s_{L,u}^2 < 0.5\times 10^{-3}$$

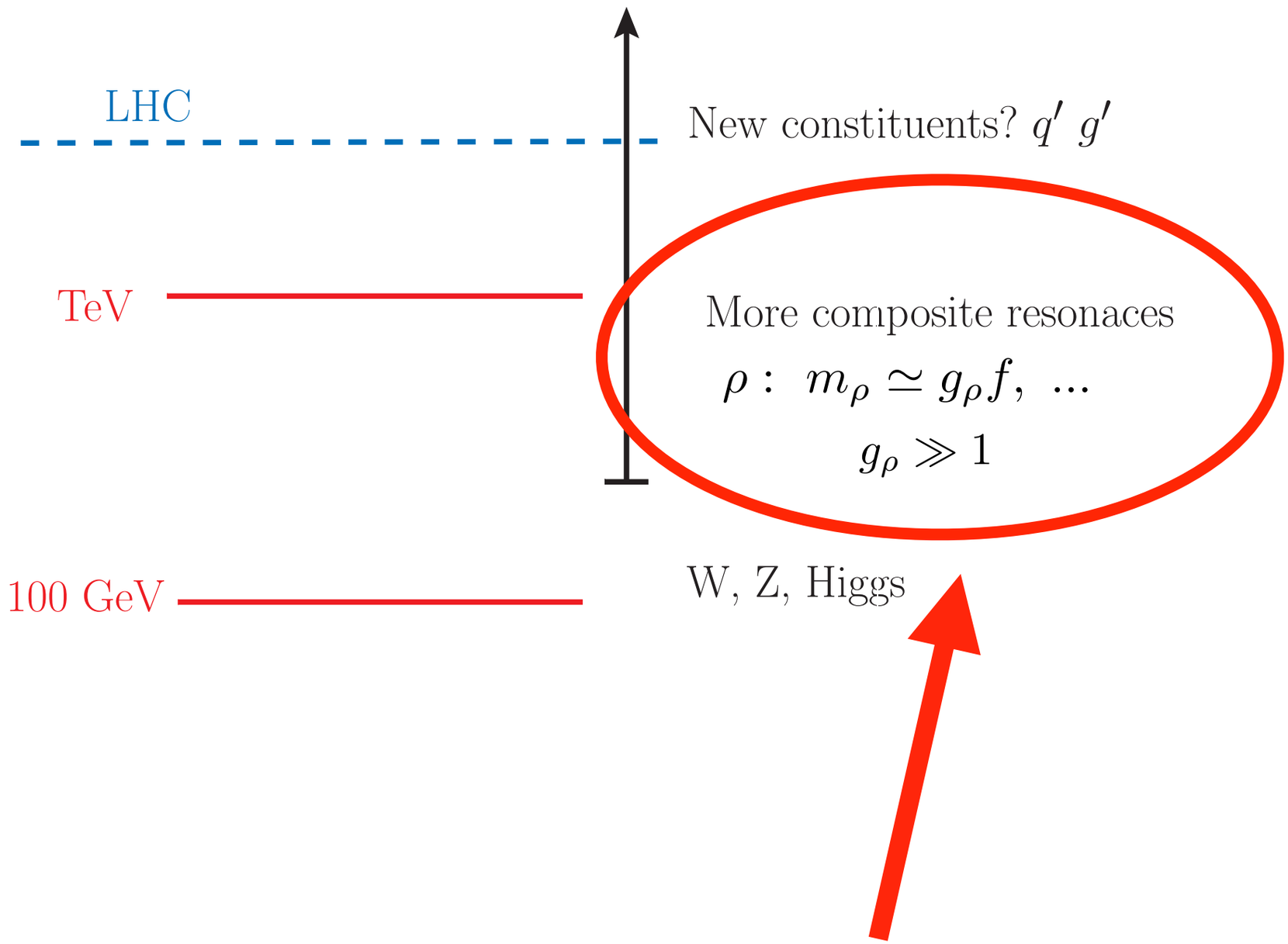
Problem of f > v ?

- Higgs potential "wants" to have f≈v.
- A little bit fine tuned.
- One can invent something to deal with it (such as little Higgs, etc.).
  - A lot of additional structure for a factor of 10-100?
- Or, take the tuning as acceptable. (Will take the view here).

Composite Higgs



Composite Higgs



Phenomenology of the resonances

Spin-1 resonances

$$G/H = SO(5)/SO(4)$$

Spin-1 resonance in 6 of SO(4) $\qquad m_\rho \sim g_\rho f$

$$SO(4) \times U(1)_X = SU(2)_L \times SU(2)_R \times U(1)_X \qquad Y = T_R^3 + X$$

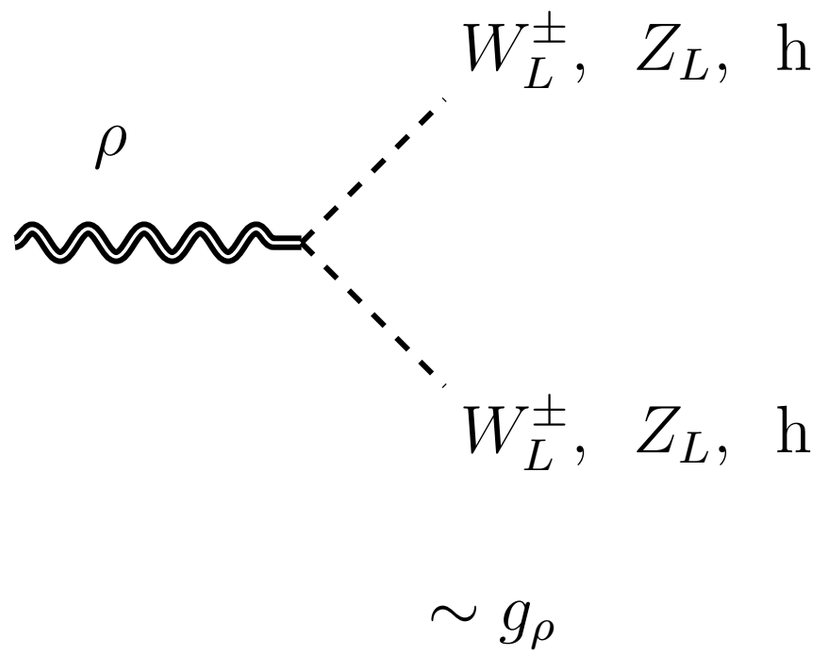
Under this, spin-1 res. decompose as

$$\mathbf{6} \to \mathbf{3}_0 + \mathbf{1}_0 + \mathbf{1}_\pm$$

$\rho_L : \ \rho_0, \ \rho^\pm \qquad \rho_B \qquad \rho_C^\pm$

ρ coupling to h, W_L , Z_L

$$\mathcal{L} \supset i g_\rho c_H \rho^a_\mu (H^\dagger \tau^a D^\mu H - (D^\mu H)^\dagger \tau^a H)$$

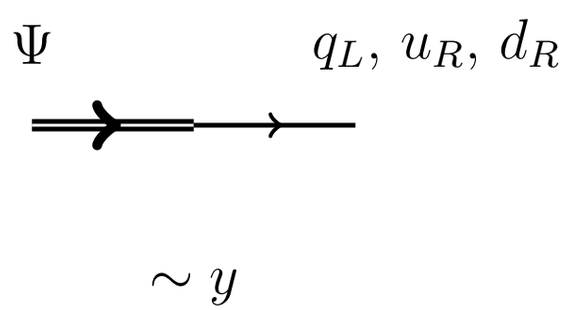


- h, W_L Z_L composite, large coupling to ρ.

Partial compositeness

composite fermion with the same gauge quantum numbers as SM fermion.

$$\mathcal{L}_{\rm pc} = -m_\Psi \bar{\Psi}\Psi - y_L f(\bar{q}_L \Psi + h.c.) - y_R f(\bar{u}_R \Psi + h.c.)$$

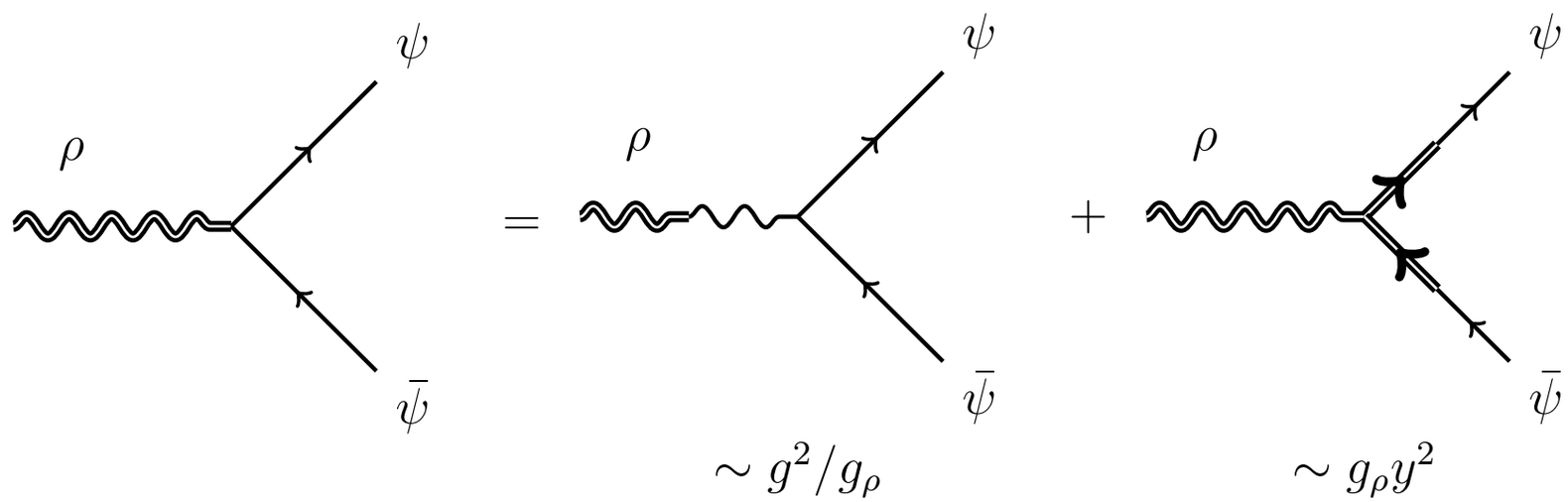


$$y_f = \frac{m_\Psi}{f} \sin\phi_L^f \sin\phi_R^f$$

$$\sin\phi_{L,R} \equiv \frac{y_{L,R}}{\sqrt{(m_\Psi/f)^2 + y_{L,R}^2}}.$$

- Mixing angles not completely fixed.
- For example, for top quark, the mixing should be large, O(1).
  - Top quark heavy because it is composite.

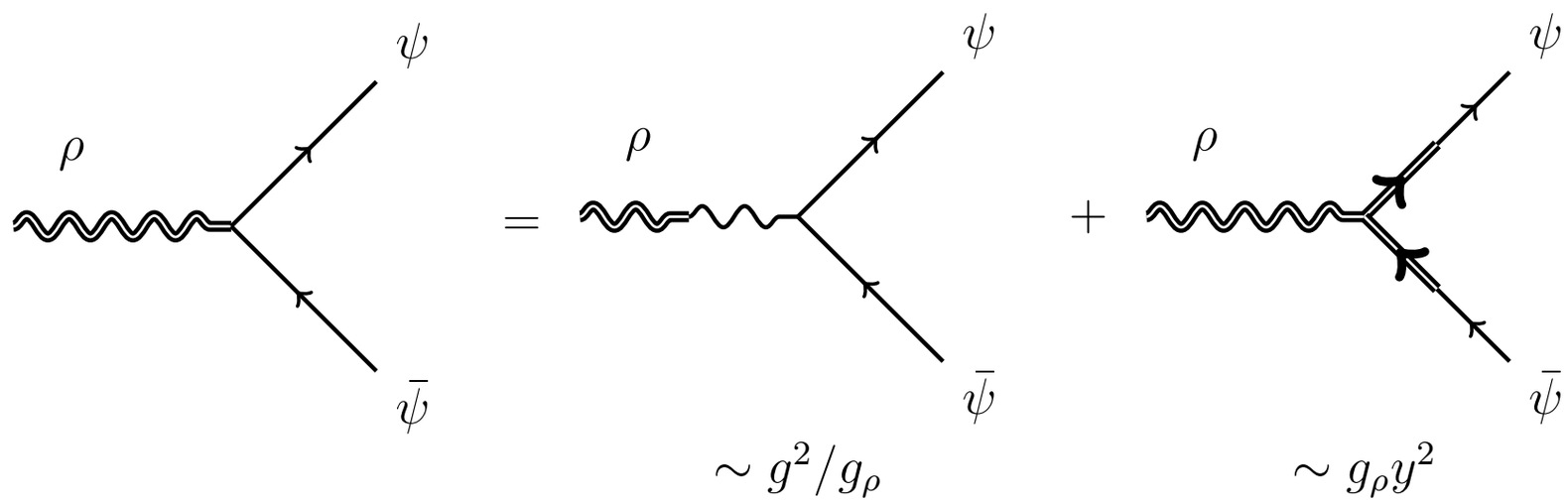
ρ coupling to SM fermion



ρ mixes with W/Z mixing angle: g/g_ρ

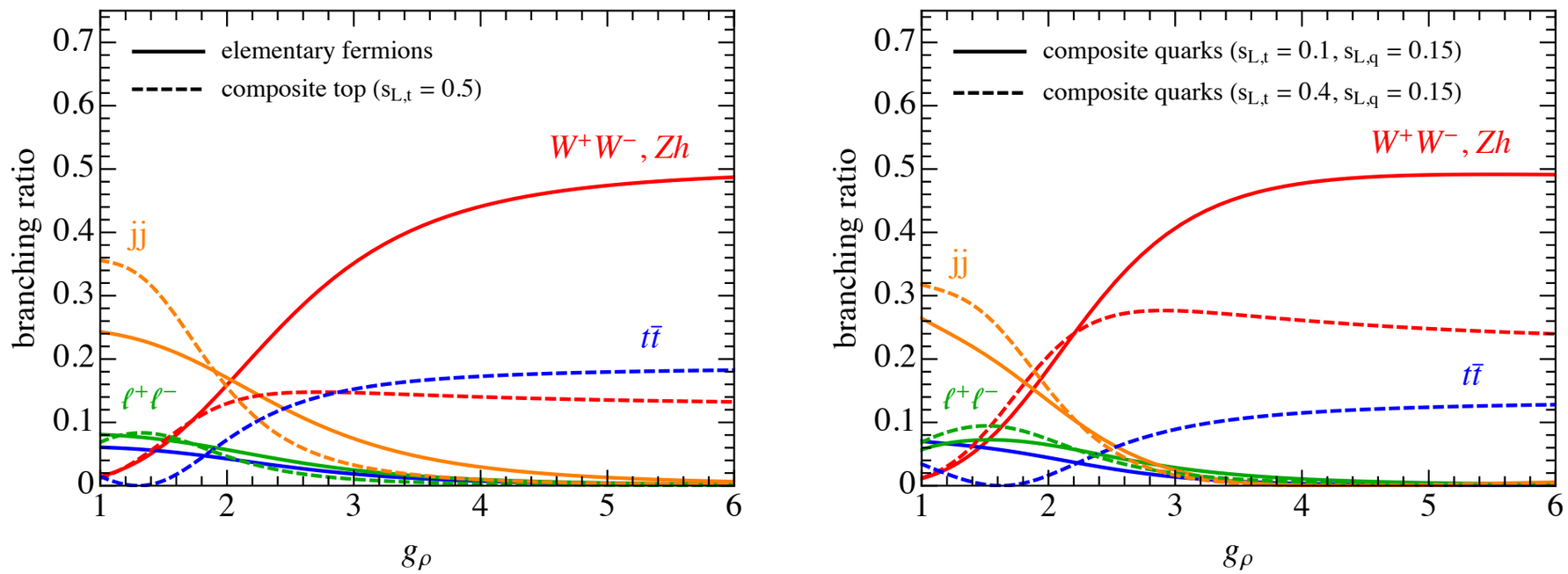
ρ couples to composite fermion first, which mixes with SM fermion.

ρ coupling to SM fermion



	VV, Vh	$\bar{q}_L\gamma^\mu q_L$	$\bar{u}_R\gamma^\mu u_R$	$\bar{d}_R\gamma^\mu d_R$	$\bar{\ell}_L\gamma^\mu \ell_L$	$\bar{e}_R\gamma^\mu e_R$
$\rho^{0,\pm}$	g_ρ	$-\frac{g^2}{g_\rho}(1-a_L\frac{g_\rho^2}{g^2}s_{L,q}^2)\tau^a$	–	–	$-\frac{g^2}{g_\rho}\tau^a$	–
ρ_B^0	g_ρ	$-\frac{1}{6}\frac{g'^2}{g_\rho}(1+3a_L\frac{g_\rho^2}{g'^2}s_{L,q}^2)$	$-\frac{2}{3}\frac{g'^2}{g_\rho}$	$\frac{1}{3}\frac{g'^2}{g_\rho}$	$\frac{1}{2}\frac{g'^2}{g_\rho}$	$\frac{g'^2}{g_\rho}$
$\rho_C^\pm$	g_ρ	–	–	–	–	–

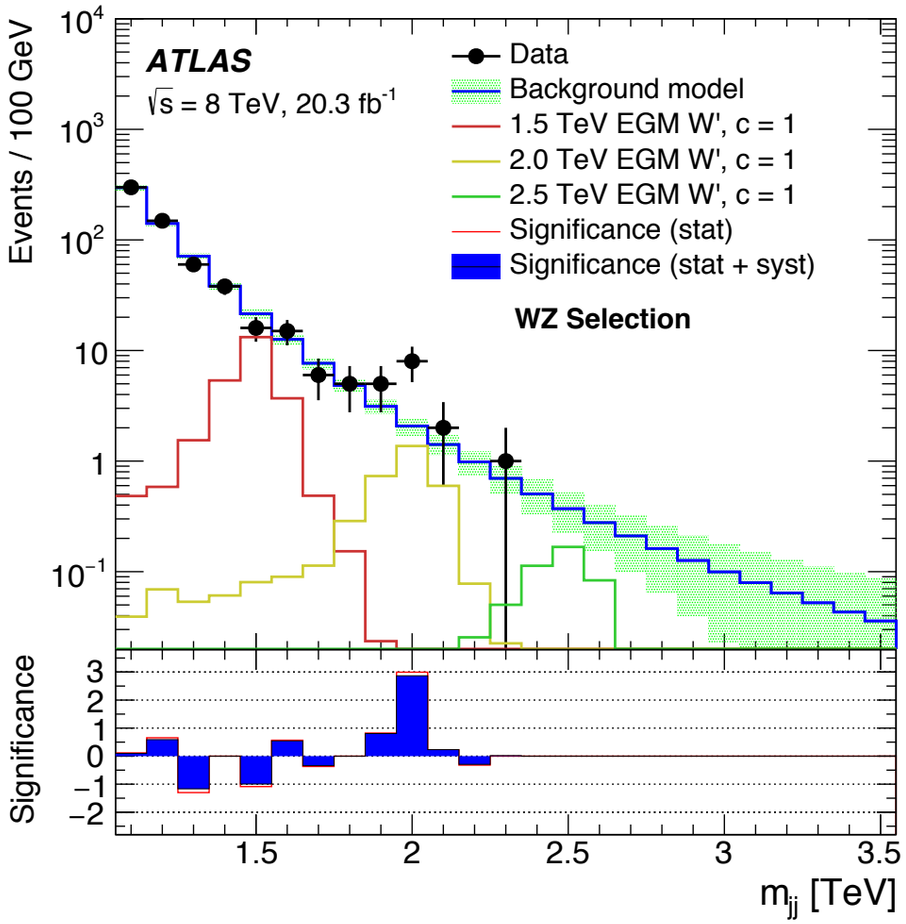
Decay of composite spin-1 res.

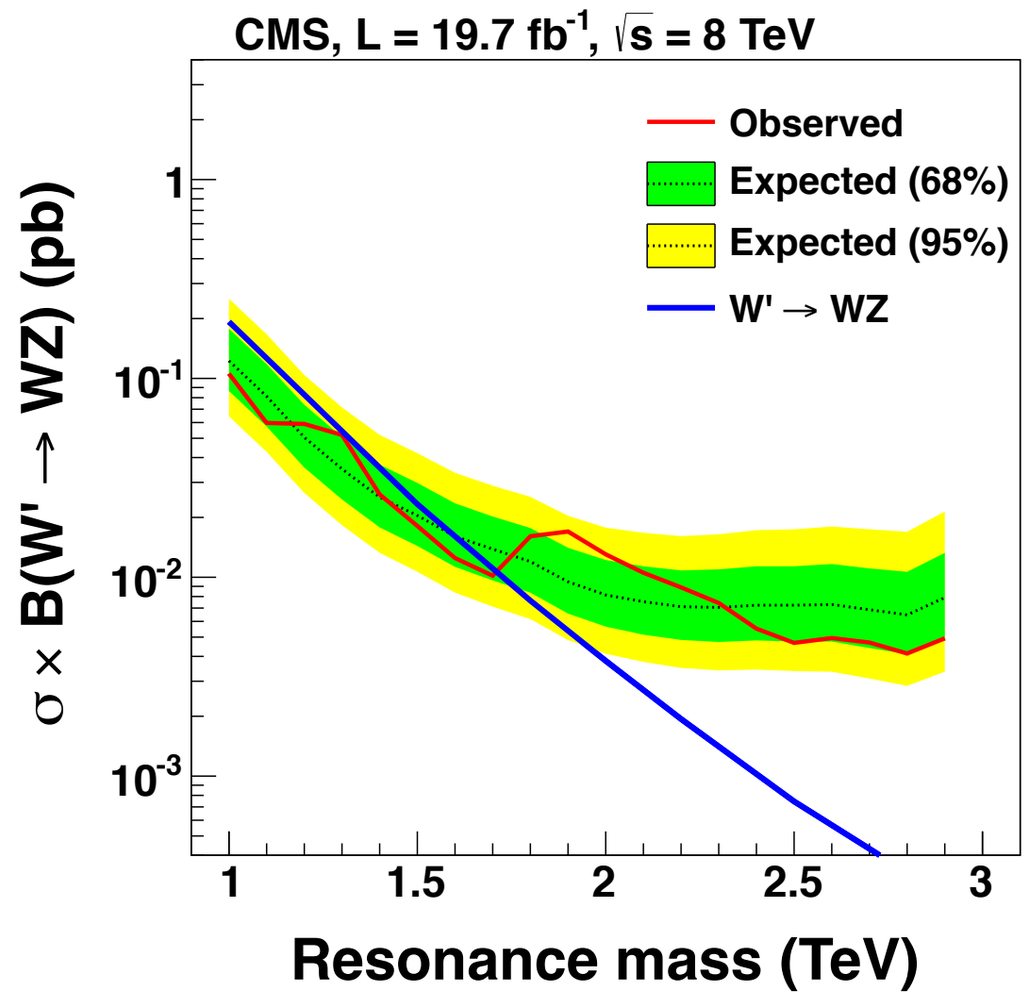


- BR to diboson is large. Suppressed fermion coupling. Could have large rate.
  - c.f., usual gauge boson, small BR to diboson.
- Suppressed fermion coupling ➜ suppress for example di-lepton mode.

$$\frac{\mathrm{BR}(\rho^0 \to \ell^+\ell^-)}{\mathrm{BR}(\rho^0 \to W^+W^-)} = \frac{8}{c_H^2}\frac{g^4}{g_\rho^4}$$

Excess around 2 TeV?



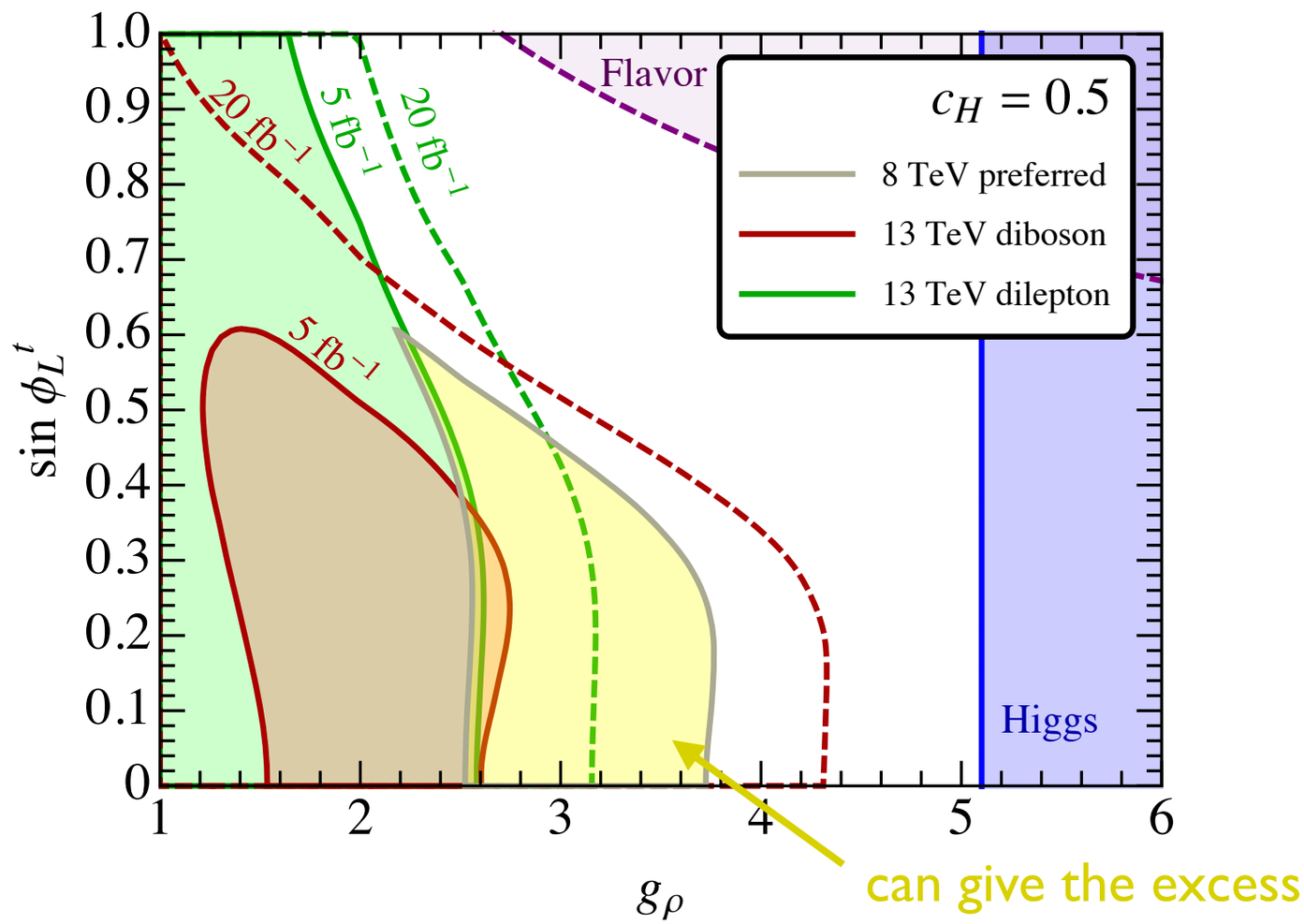


Composite spin-1 vector?

Thamm, Torre, Wulzer
Bian, Liu, Shu
Low, Tesi, LTW
…

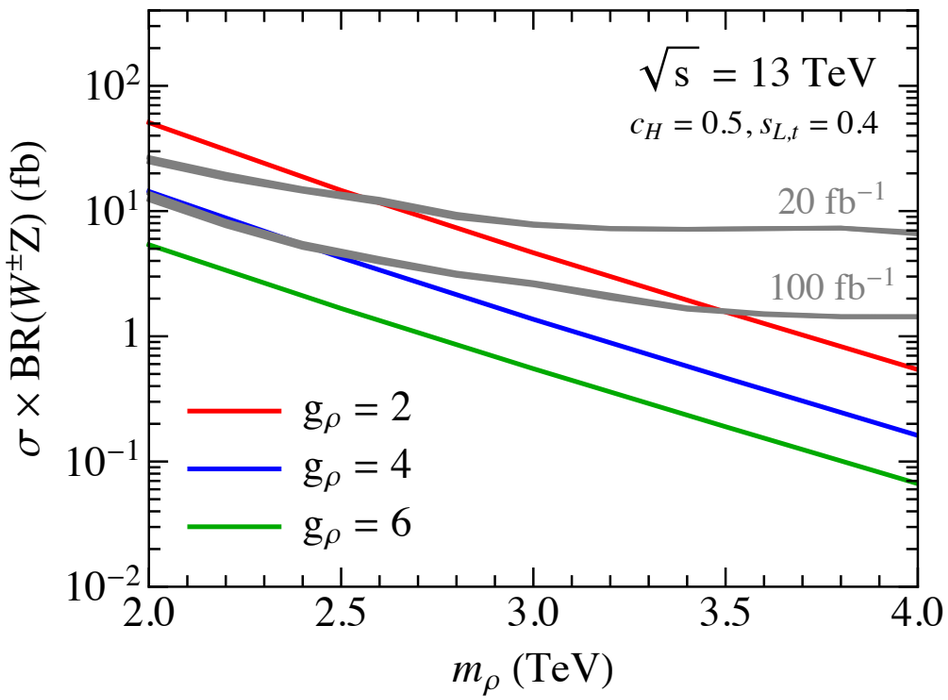
Run 1 data, generated some excitement.
Not confirmed by run 2 (so far).

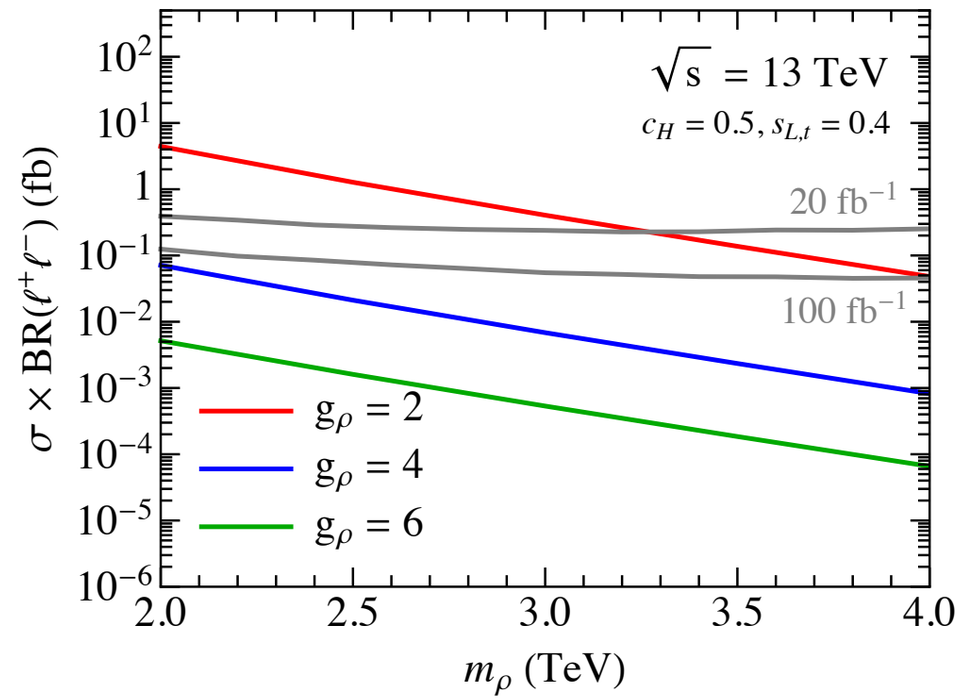
Run 2 projection



- Can confirm or rule out with modest luminosity.

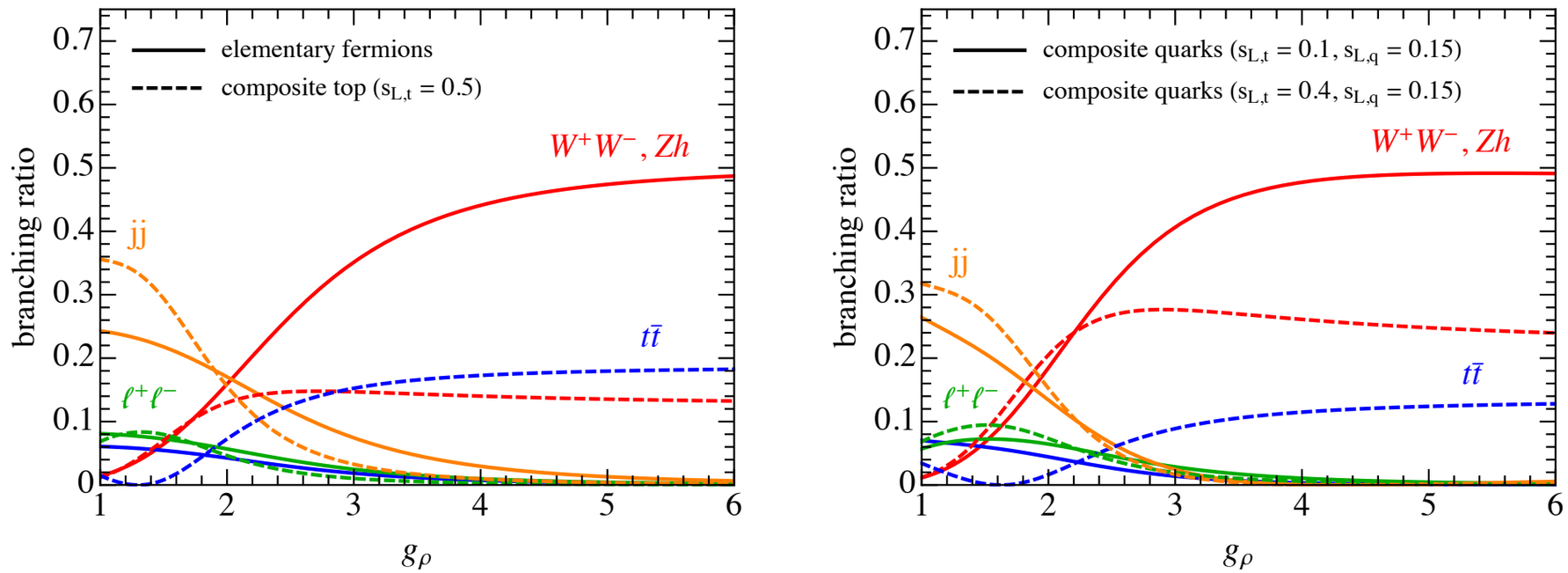
Reach of Run 2, di-boson and di-lepton





- At most 4 TeV.

Additional channels



- If it is there, should be able to see it in
  - Wh, Zh
  - tt, tb

Top partner

Integrating out top partner ➜ Higgs potential

$$V \simeq \frac{N_c}{16\pi^2} m_\Psi^4 \left[a \frac{y_t f}{m_\Psi} F_a + b \left(\frac{y_t f}{m_\Psi}\right)^2 F_b \right]$$

$F_{a,b}$: function of $\frac{h}{f}$

m_Ψ : mass of top partner

$$m_h^2 \simeq b \, \frac{N_c y_t^2 v^2}{2\pi^2} \, \frac{m_\Psi^2}{f^2}$$

Light Higgs ➜ light top partner

Top partner colored.
Can be produced efficiently at the LHC.
Good prospect, and strong constraint.

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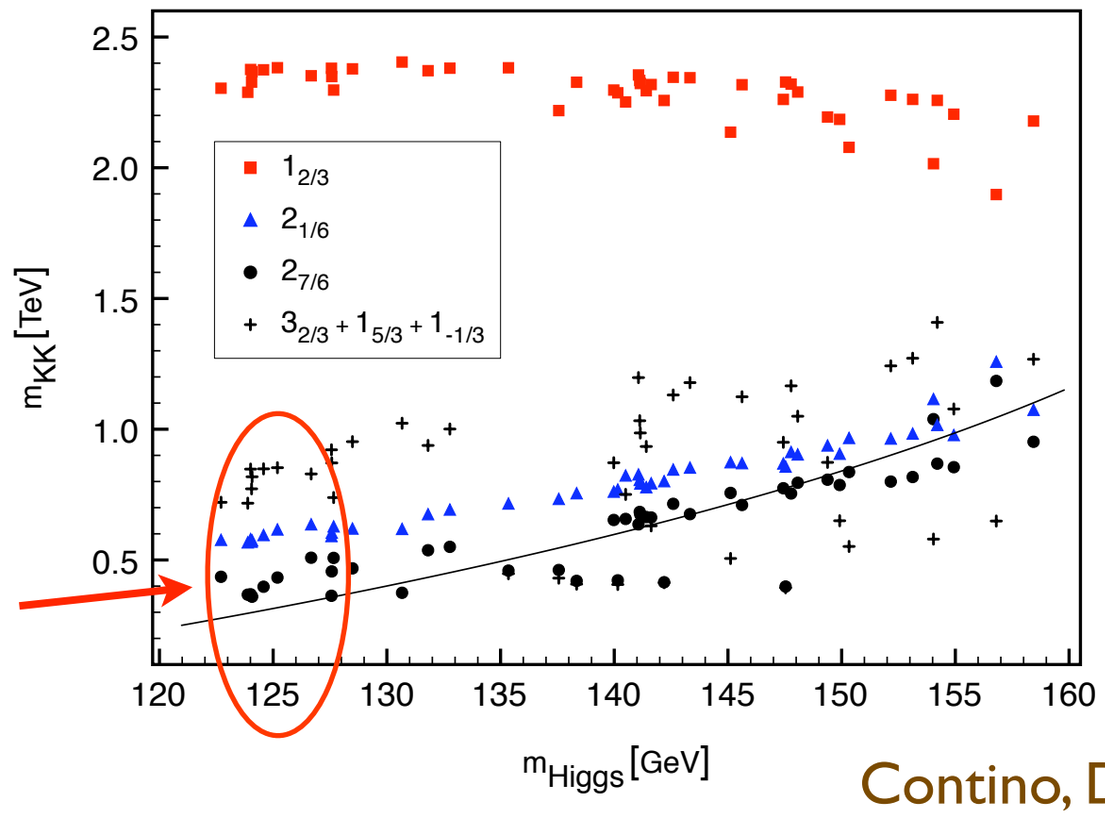
Compositeness and top partner



prefers a light T'

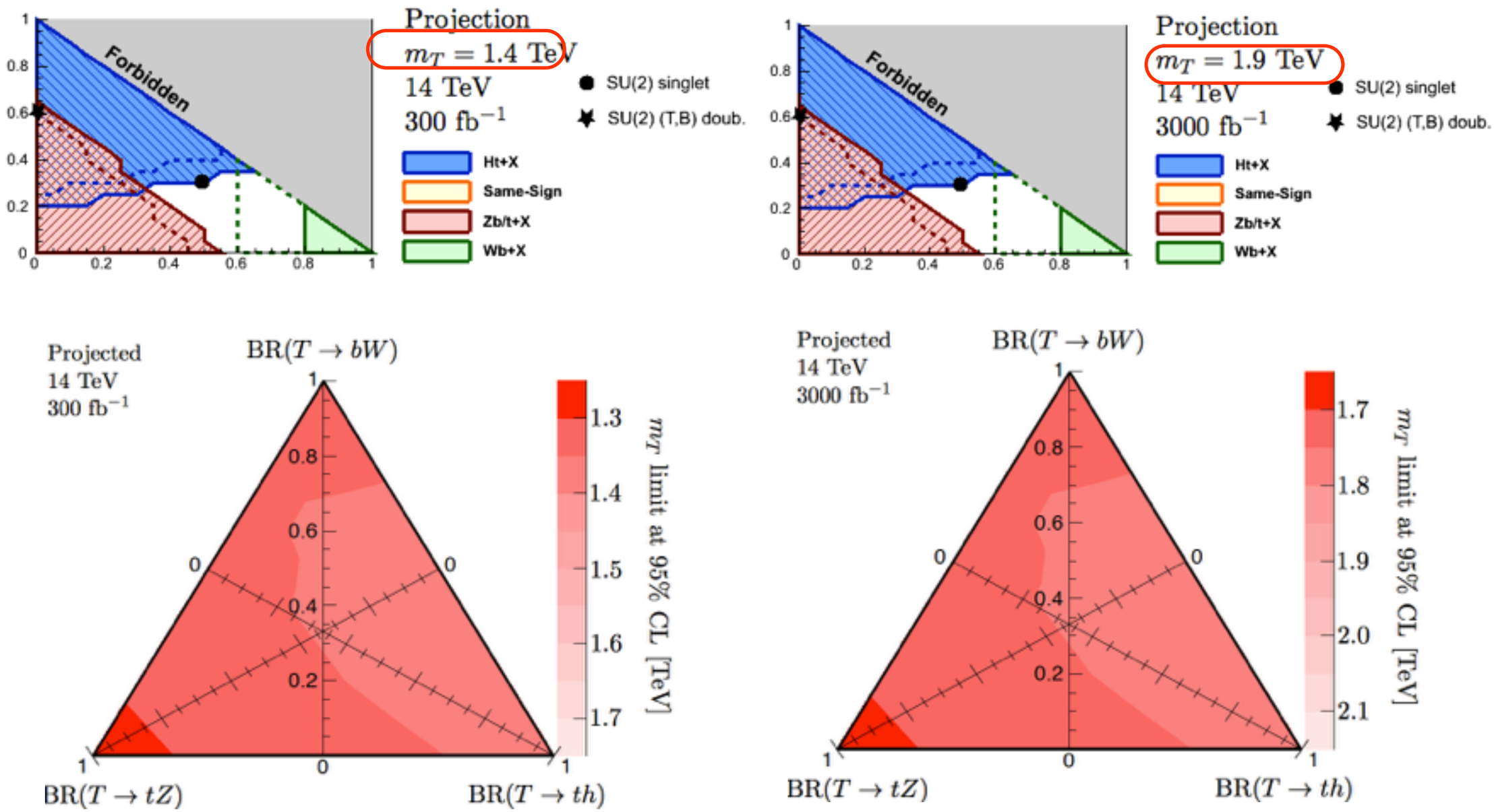
Contino, Da Rold, Pomarol, 2006

For a comprehensive discussion, see
De Simone, Matsedonskyi, Rattazzi, Wulzer, 1211.5663

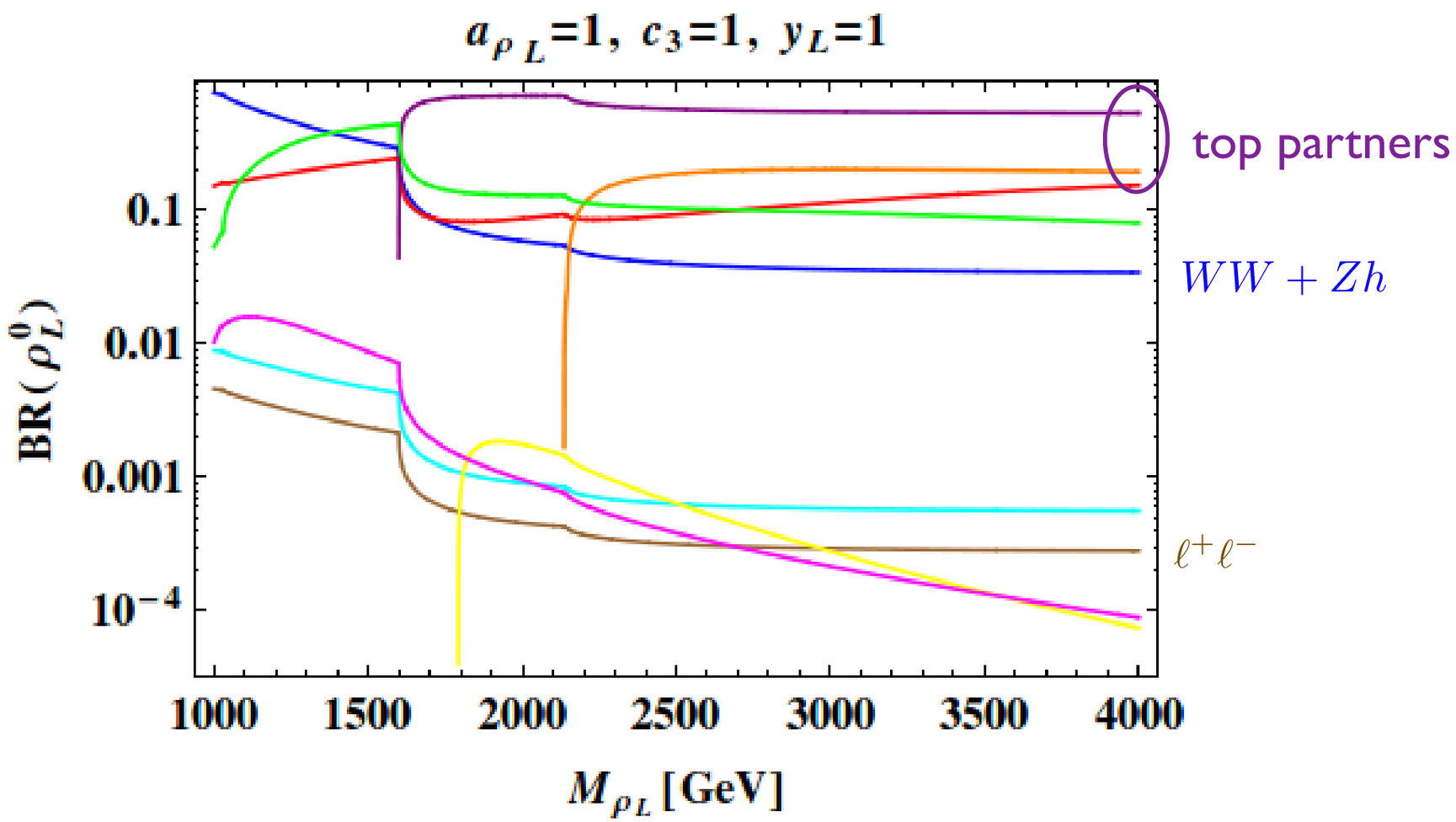
- Light top partner (ψ which mixes with top) could be less than TeV.

- Plays a crucial role in EWSB.

LHC 14 should cover (most of) it.

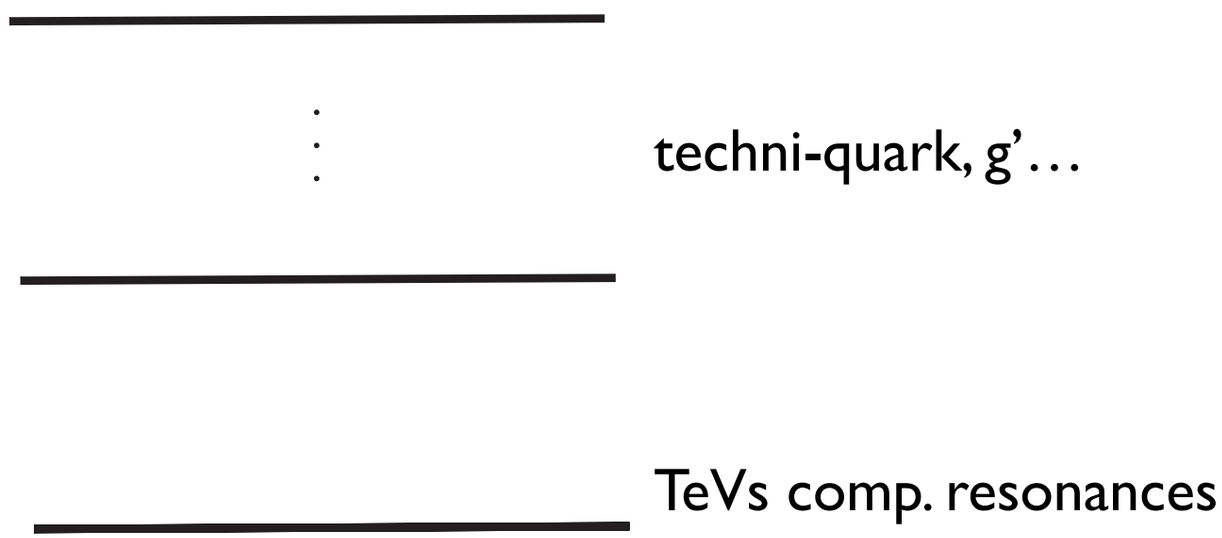


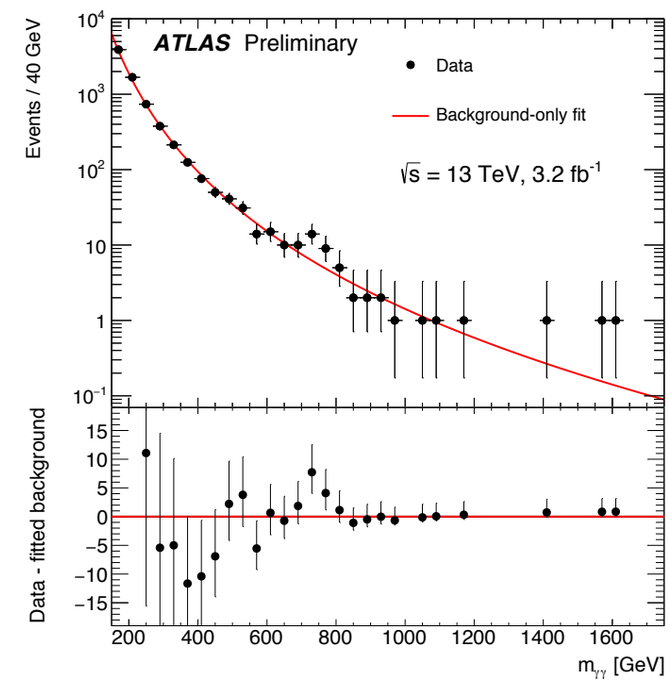
ρ decaying into top partners

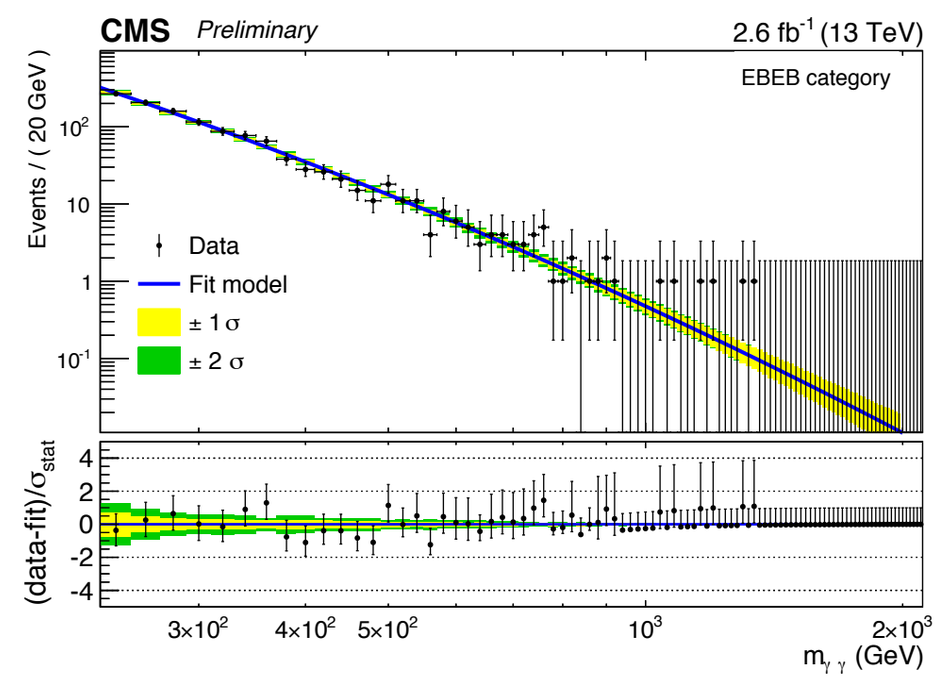


- BR(ρ ➜ ψψ) O(1). Would dominate if allowed.
- Diboson would not be the leading channel.
- Can assume ψ heavy, more fine-tuning.

May show up somewhere else?







Mass 750 is fully natural here.

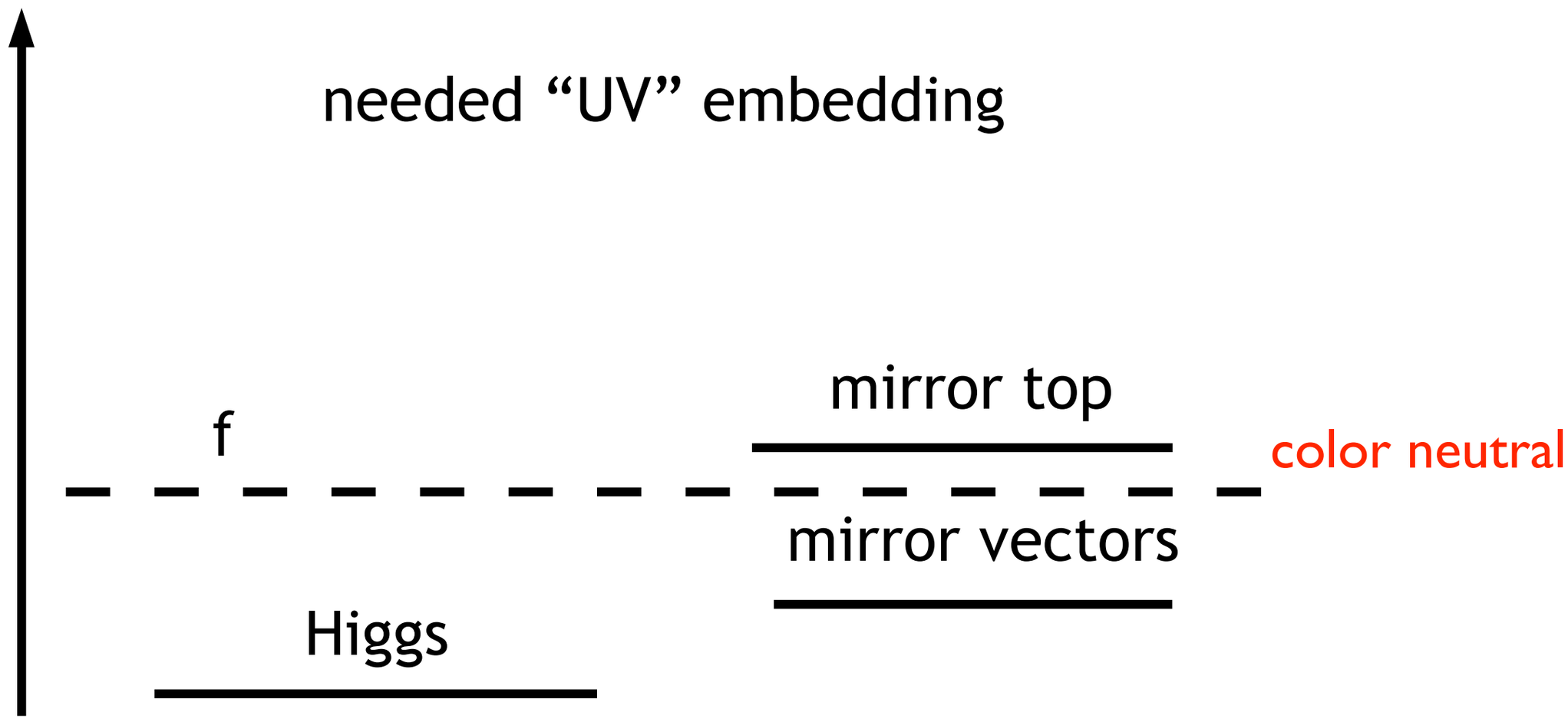
Model complicated, however.

(over?)reaction to null results from new physics search at the LHC, etc.

- Constraints from electroweak precision data, Higgs coupling
- No composite resonances, such as the top partner.
- A bit fine-tuned.
- Perhaps everything is fine, just hidden from us?
- Parallel development on the SUSY side.

Twin Higgs.

Burdman, Chacko, Harnik…

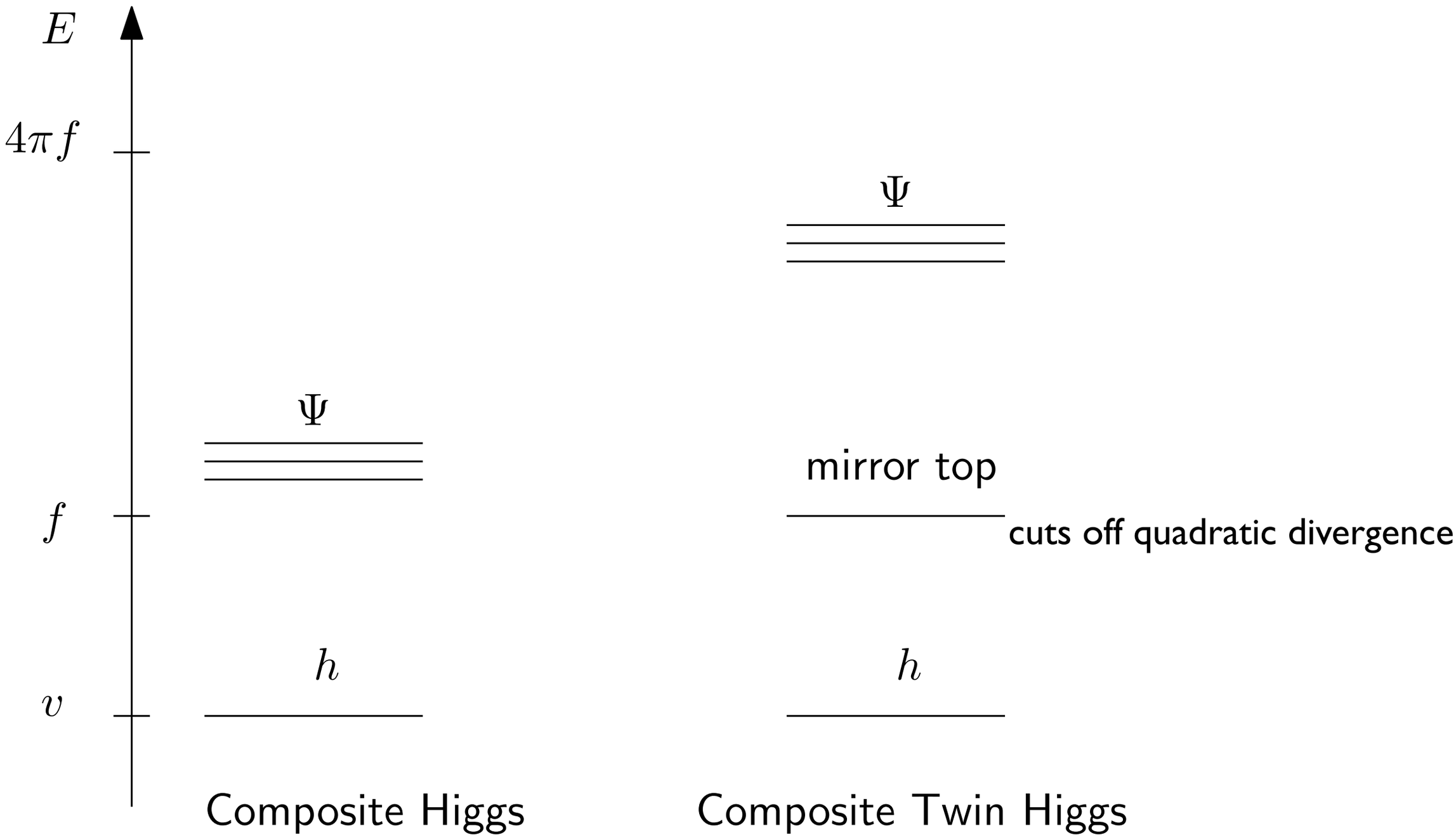


- Additional Z_2 symmetry protects Higgs potential.
- Mirror top cuts off the quadratic divergence.

"Neutral naturalness"

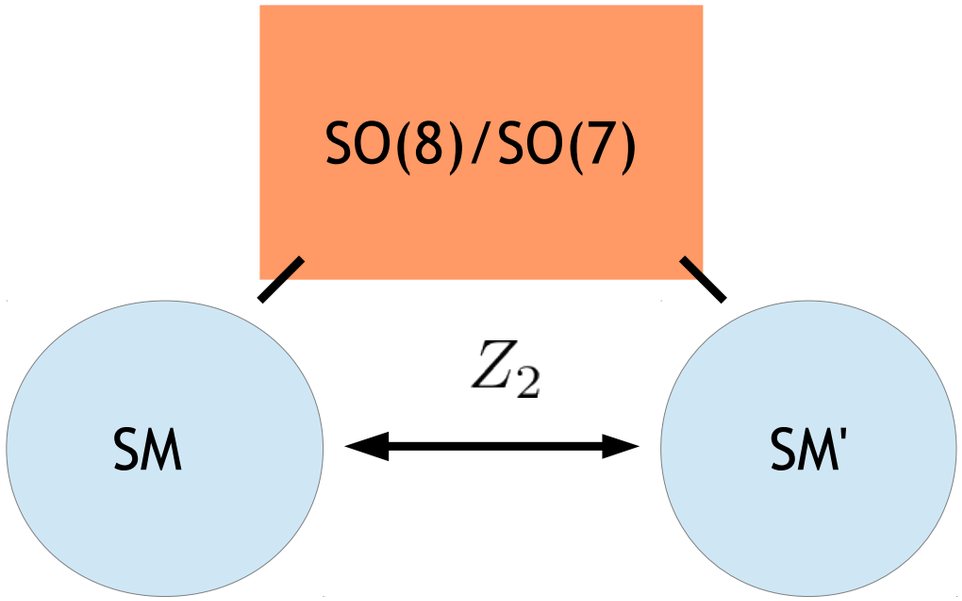
Twin composite Higgs.

Low, Tesi, LTW
Barbieri, Greco, Rattazzi, Wulzer



"Neutral naturalness"

Twin composite Higgs



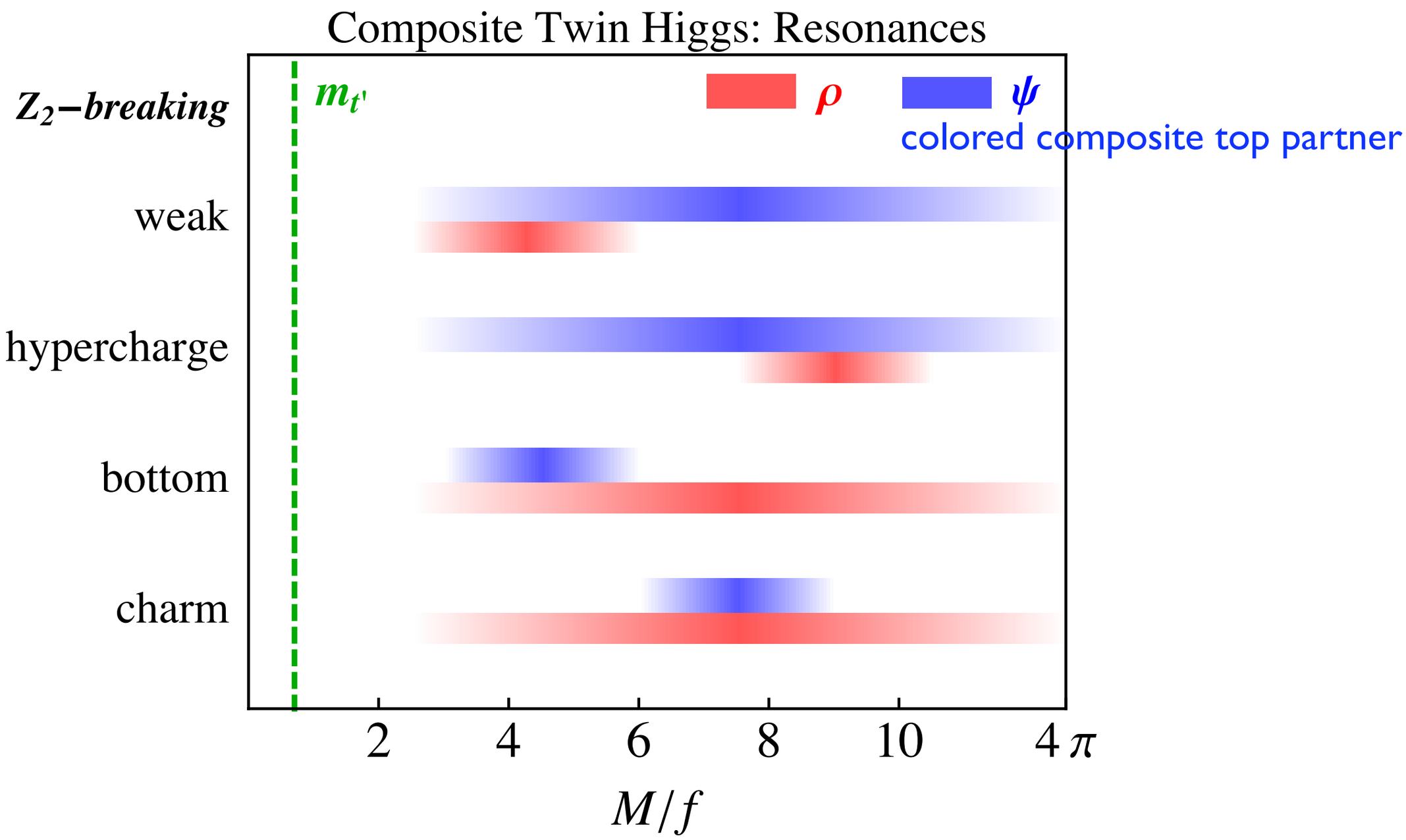
The gauging of the EW part of SM and SM' is given by

$$\left(\begin{array}{c|c} g \cdot SO(4) & 0 \\ \hline 0 & g' \cdot SO(4)' \end{array}\right)$$

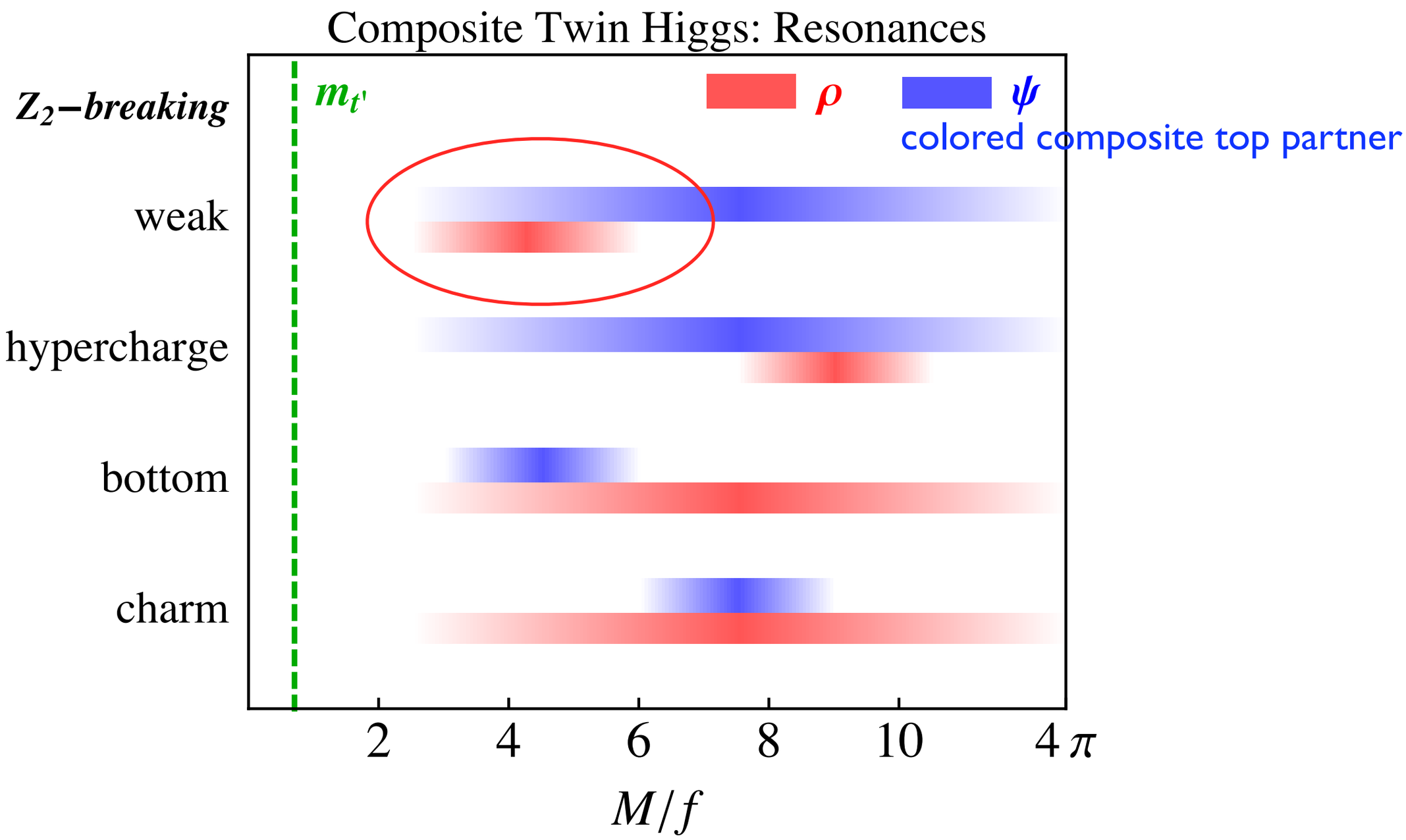
If Z_2 is exact, then SM and SM' has the same scale, v≃f.
Must introduce Z_2 breaking.

Freedom in choosing how to do it:
Difference in gauge or Yuk interaction between SM and SM'

Z_2 breaking and spectrum



Z_2 breaking and spectrum



My take

- Good idea and good exercise to explore this possibility.
- Given our confusion about naturalness, certainly worth trying and searching.
- Models are too complicated and not that convincing.
  - Someone knows we can only build proton colliders?

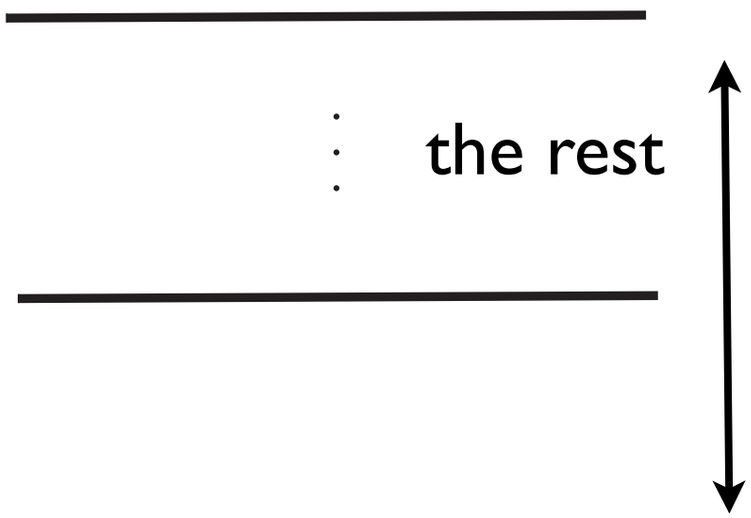
UV completion for composite Higgs.

- Focused on EFT so far.
  - Good for quickly explore the possibilities of low energy spectrum and signal.
- Ultimately, we want to go one step beyond.
  - Some preliminary investigation already.

e.g., Barnard, Gherghetta, Ray; Ferretti, Karateev. 2013

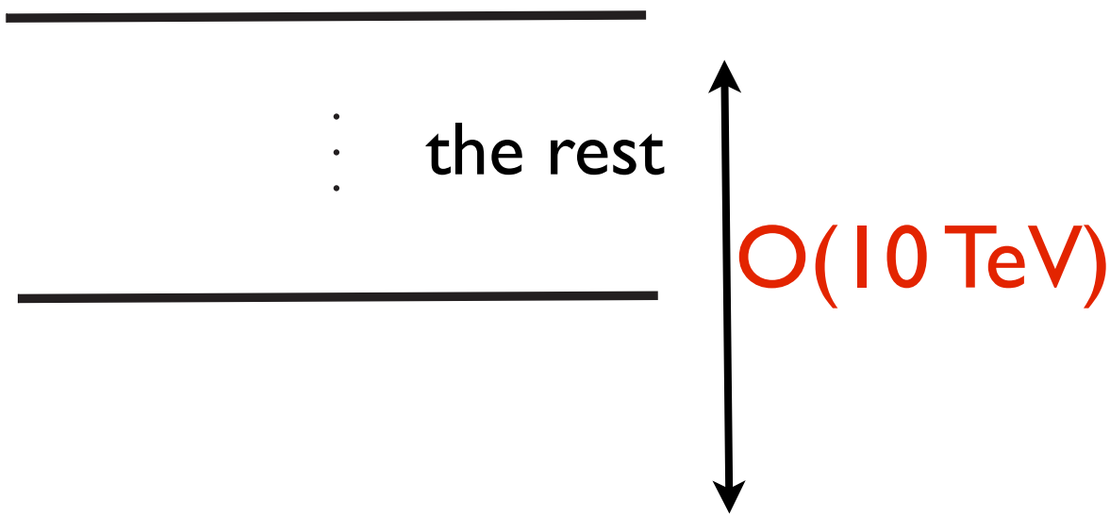
- Another example of a strongly interacting theory.
  - Probably won't be "just another QCD".
  - Leads to new insights.

Going to the UV, experimentally



TeV-ish ρ, T'... Possible discovery at run 2

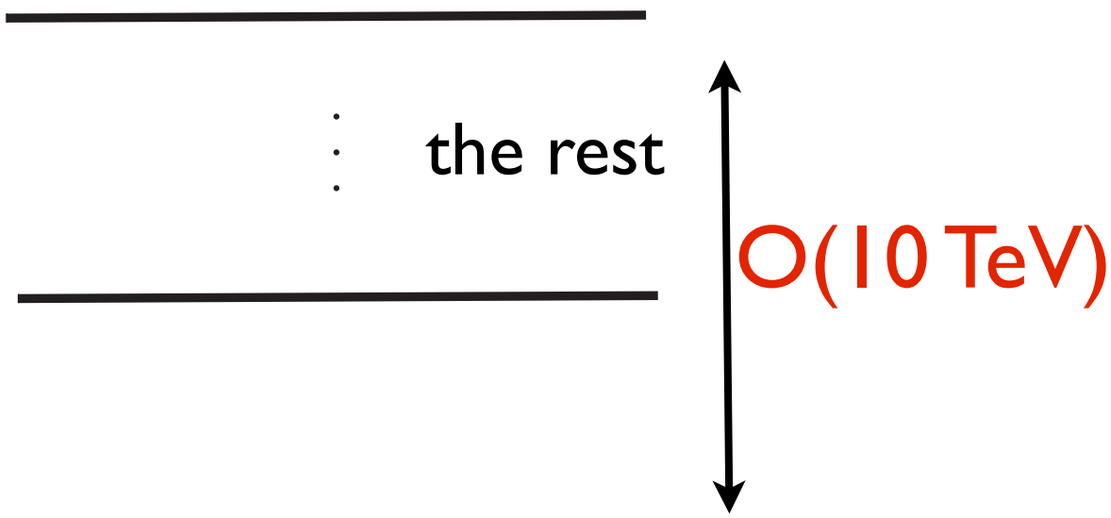
Going to the UV, experimentally



Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

TeV-ish ρ, T'... Possible discovery at run 2

Going to the UV, experimentally



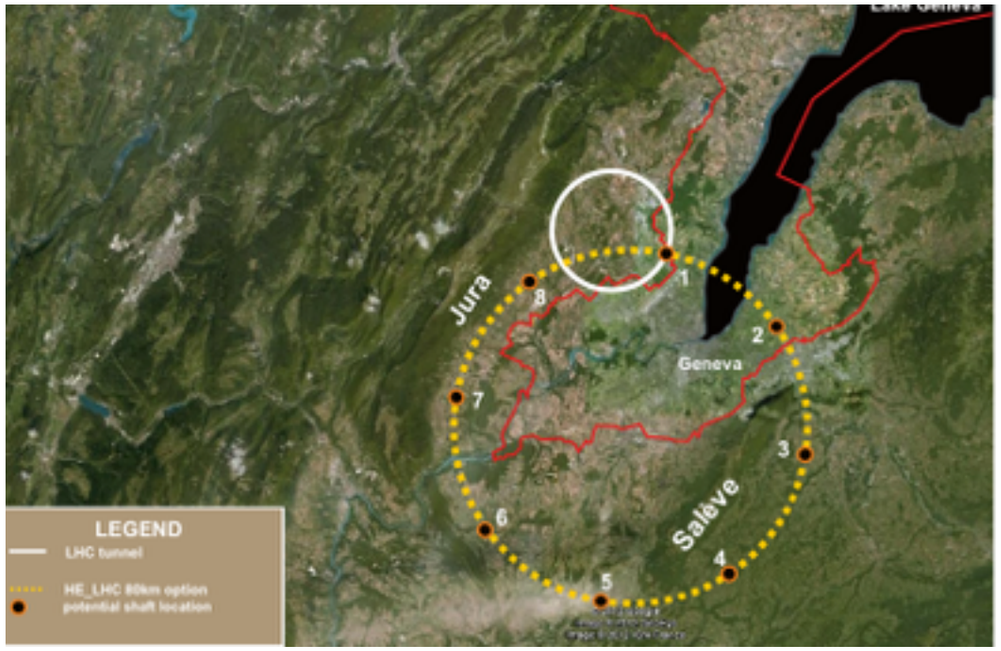
Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

TeV-ish ρ, T'... Possible discovery at run 2

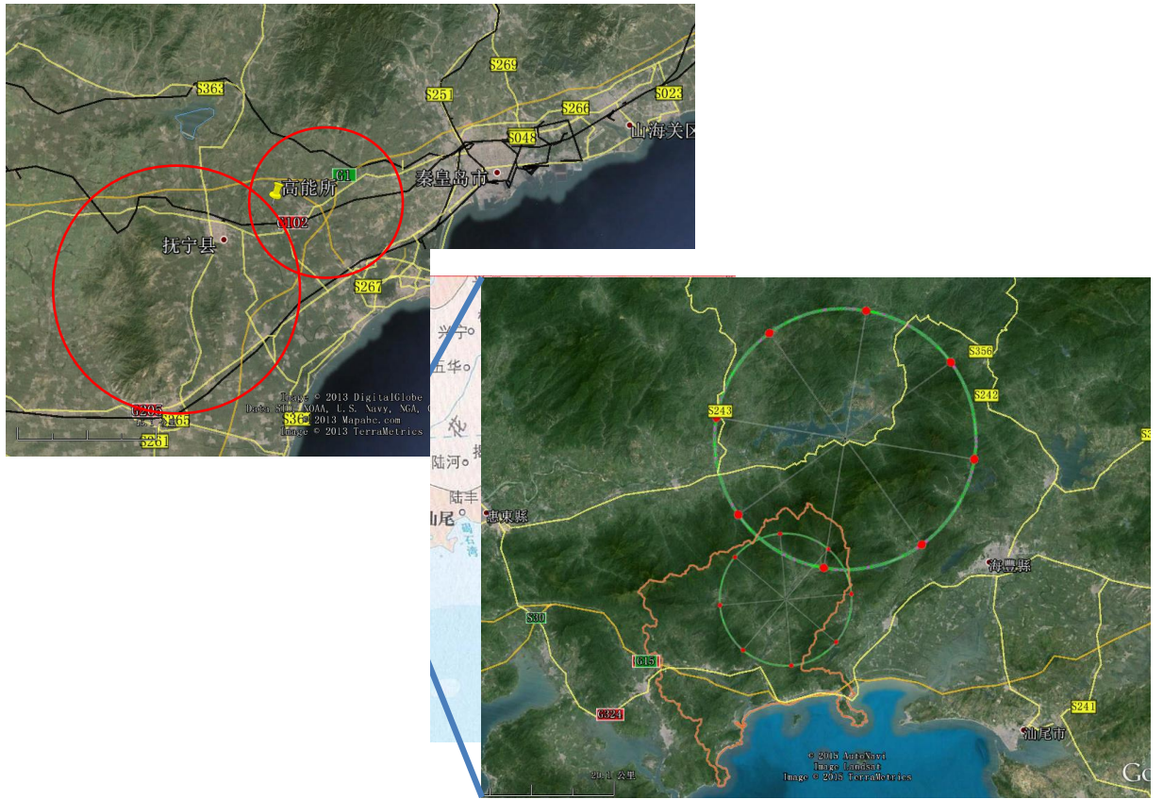
What could be the UV completion?

Need to go beyond LHC!

Future circular colliders

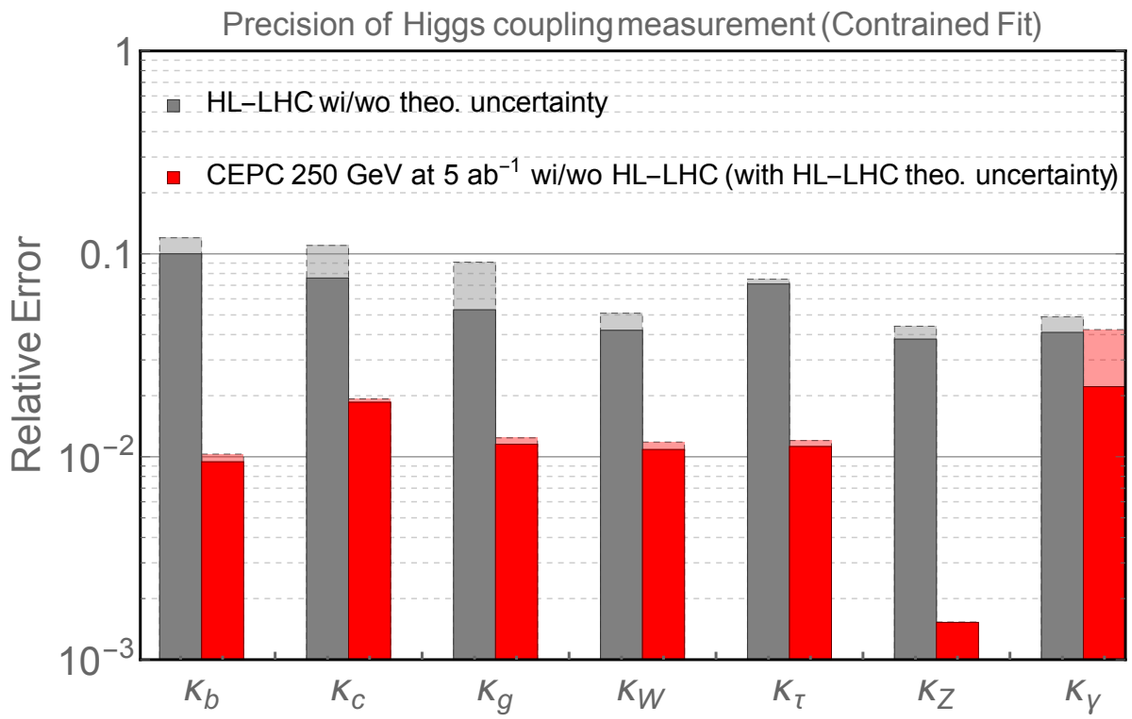


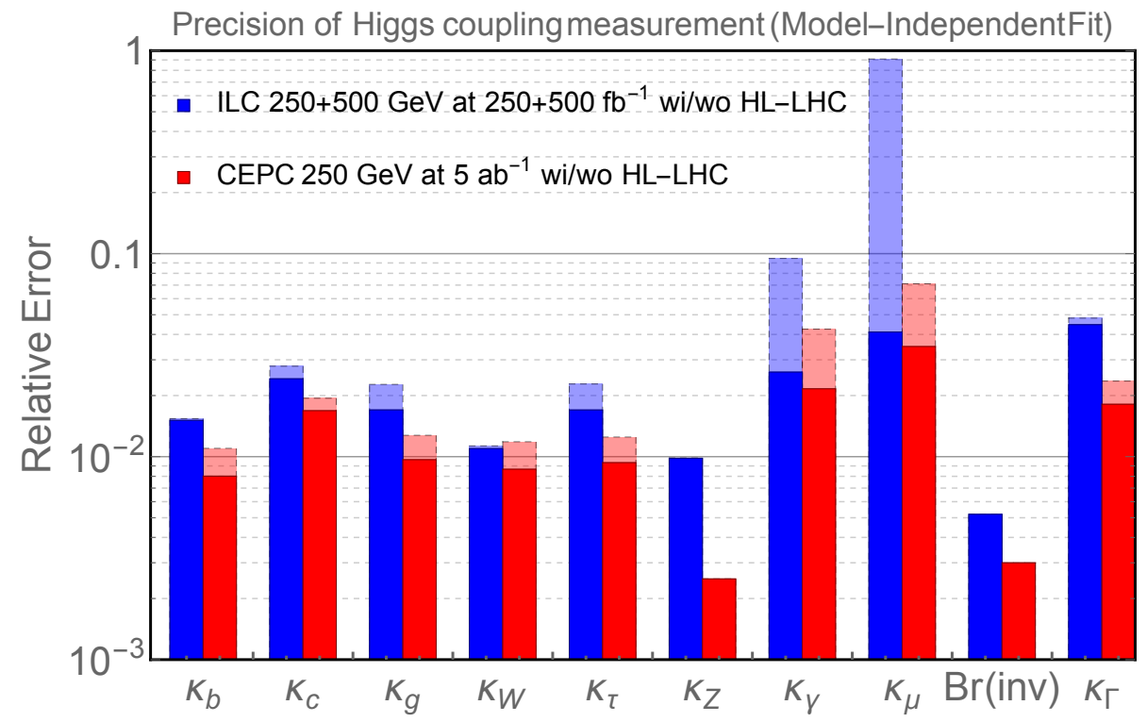
CERN
Higgs/Z factory: FCC-ee
pp Collider: FCC-hh



China.
Higgs/Z factory: CEPC
pp Collider: SppC

Higgs coupling at lepton colliders



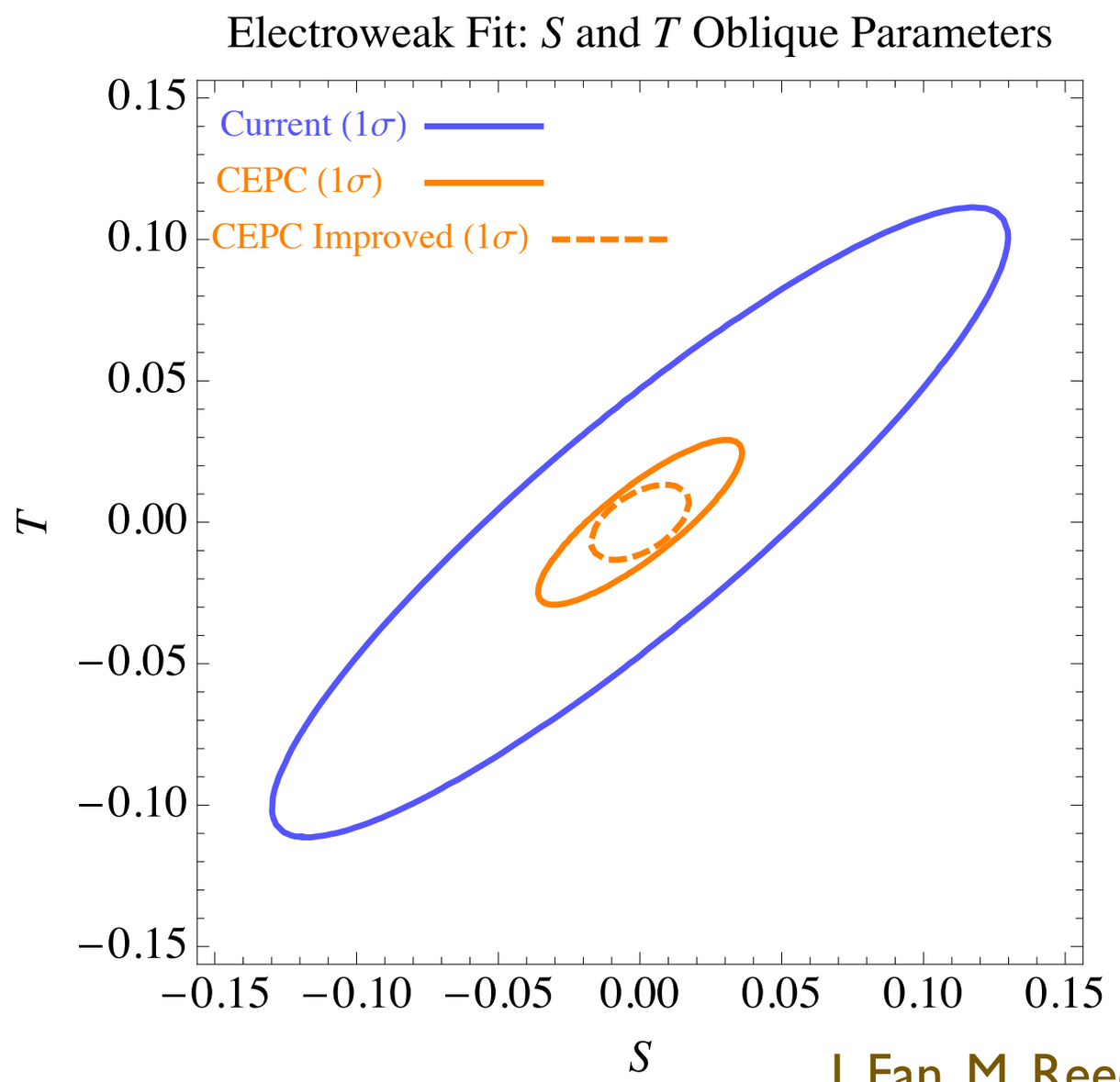


$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Electroweak precision at Z factory



J. Fan, M. Reece, LT Wang, 1411.1054

- A big step beyond the current precision.

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

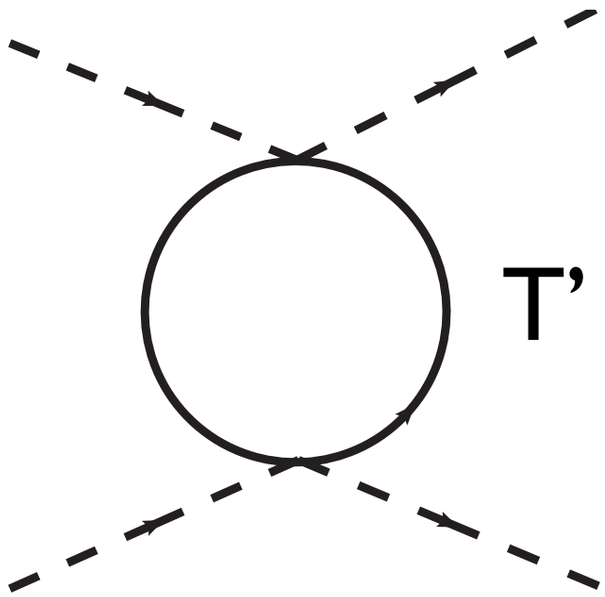
Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

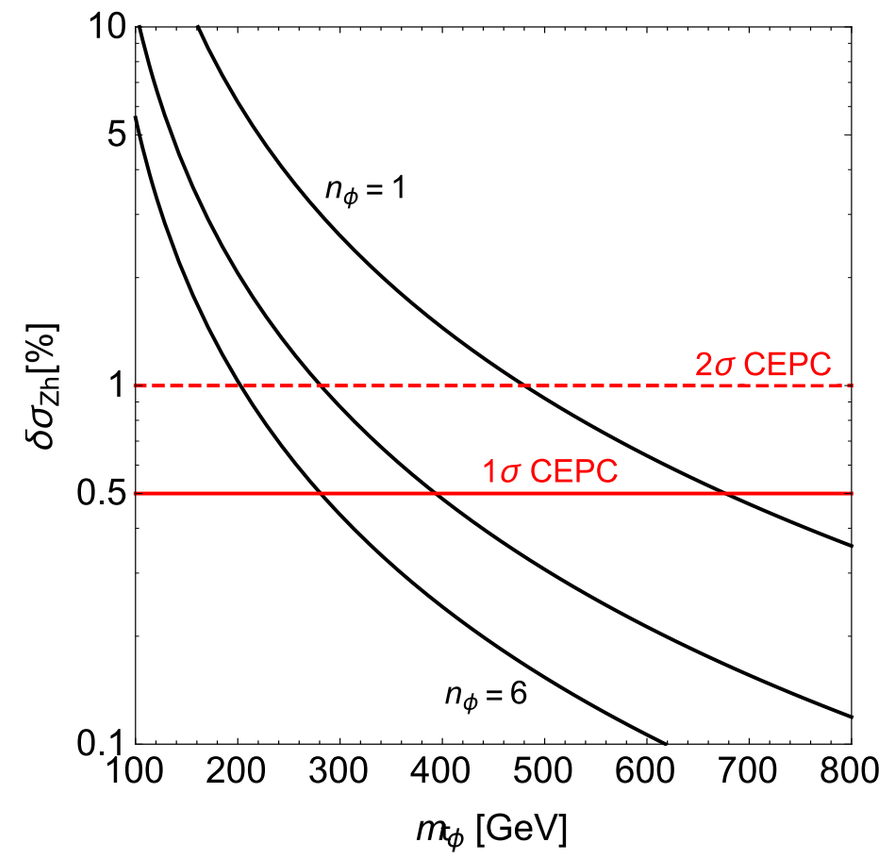
A clear big step above the LHC.

Neutral naturalness

Twin Higgs. Chacko et al.



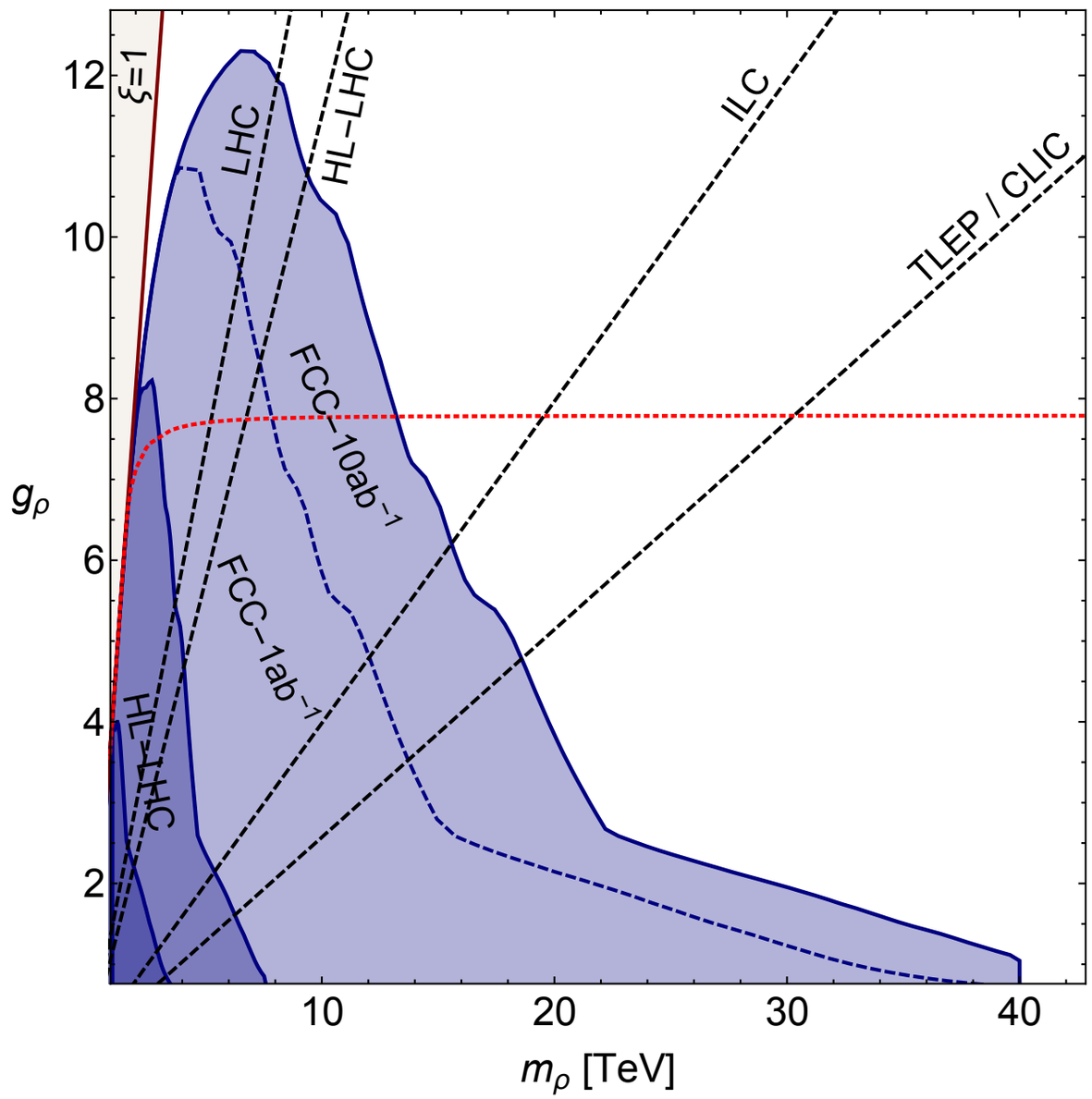
Top partner only couple to Higgs.
Wavefunction renormalization
Induce shift in Higgs coupling.



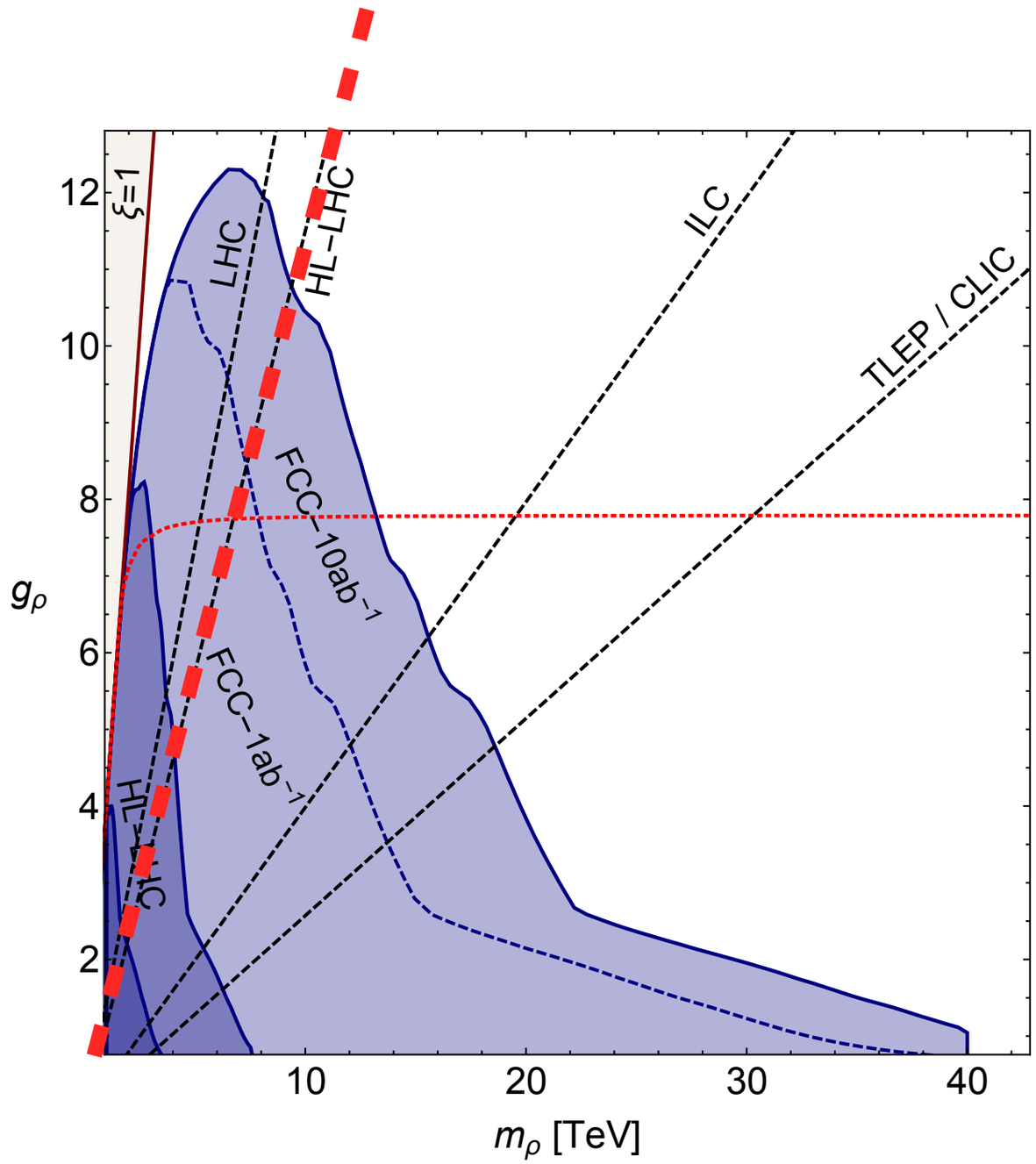
Craig, Englert, McCullough, 2013

- LHC reach poor. Theory can be completely natural.
- Higgs factory can test this.

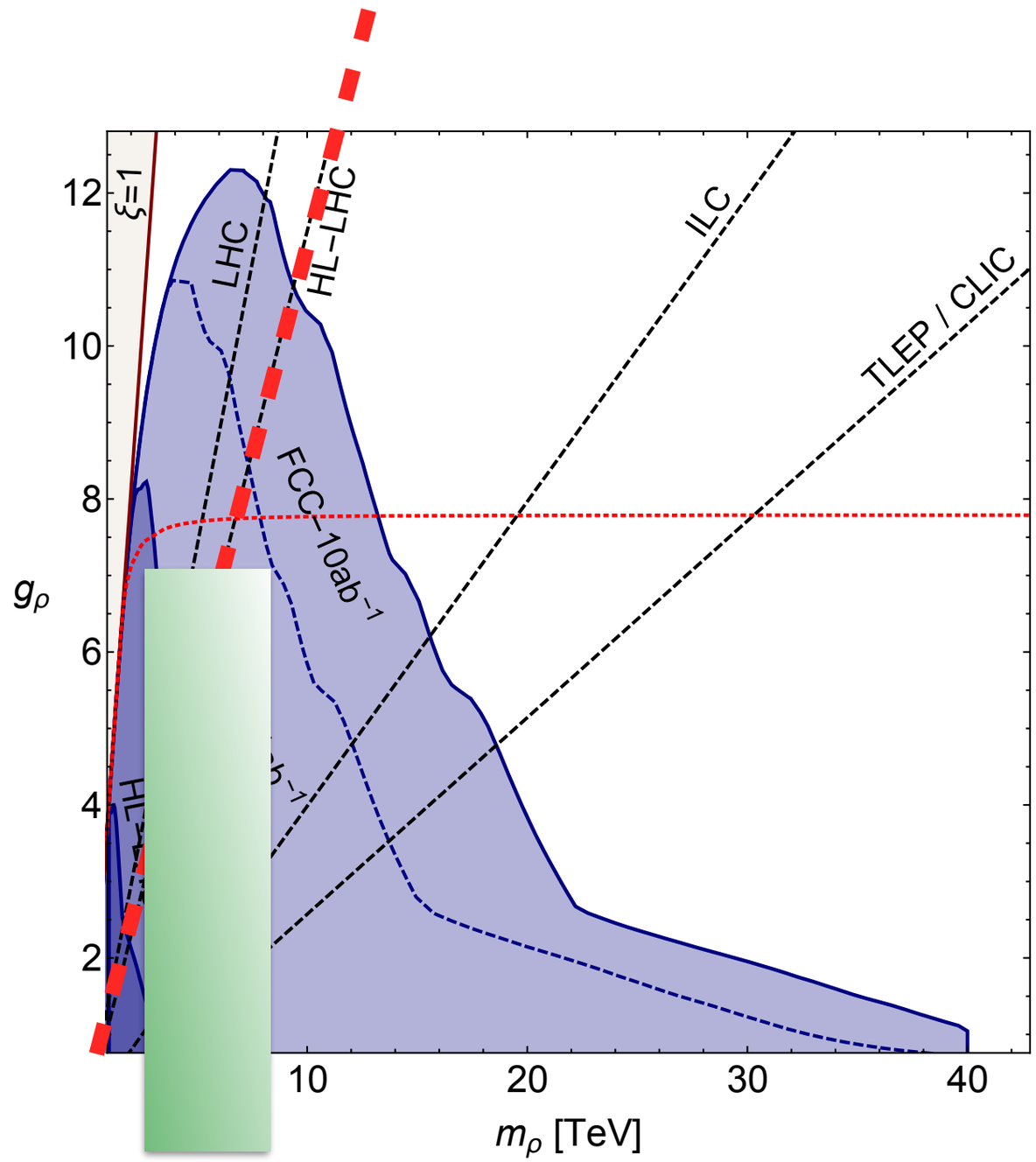
Composite Higgs, full picture



Composite Higgs, full picture

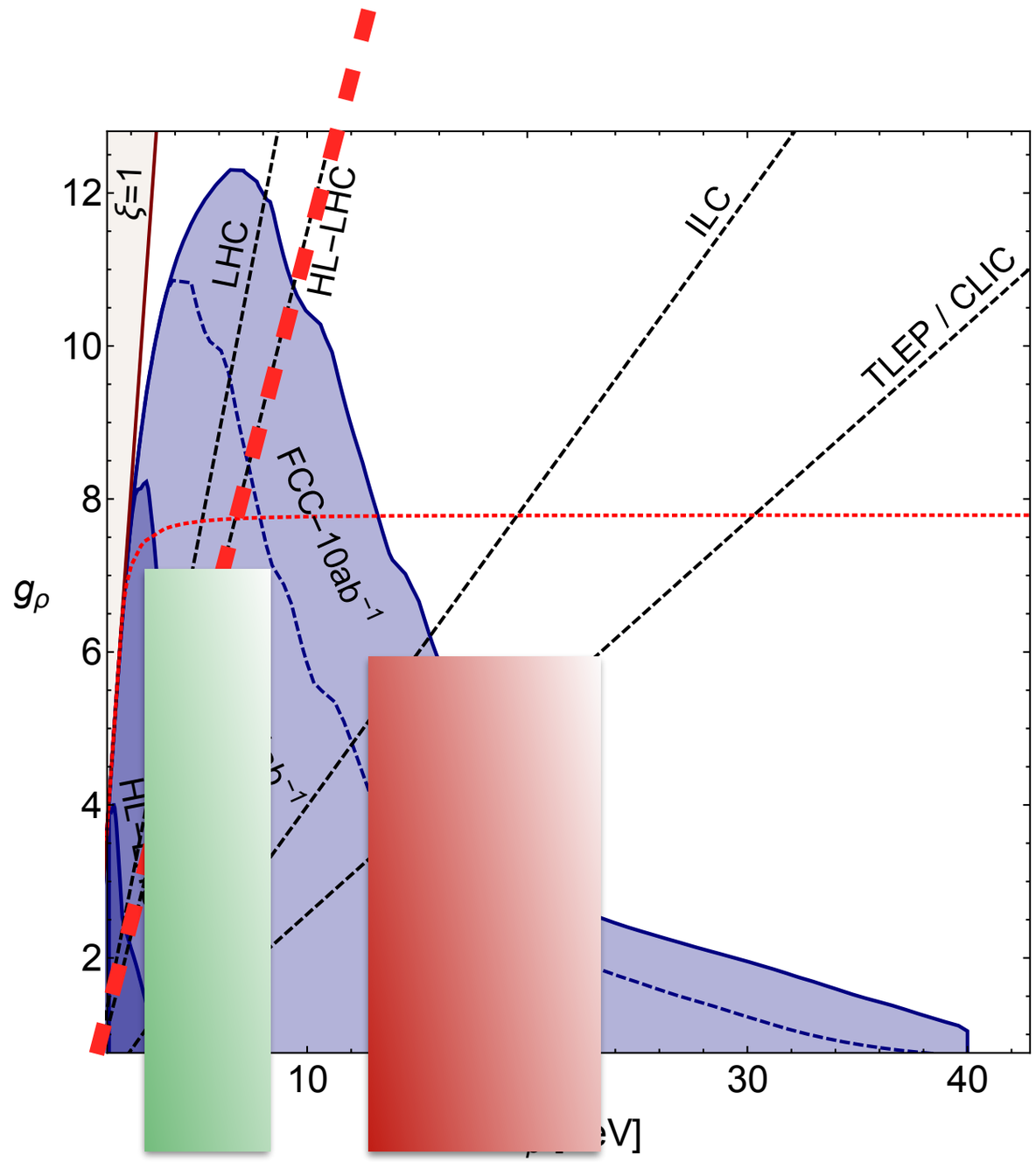


Composite Higgs, full picture



new
resonances

Composite Higgs, full picture



new resonances

new strong integration
new gluon and quarks

Conclusions.

- Composite Higgs is a plausible solution to the naturalness problem.
- Rich phenomenology.
  - Spin-1 resonances: di-boson, ttbar, etc...
  - Top partner.
- If it is there
  - Another triumph of naturalness. (Nature use the same trick).

Conclusions.

- Another example of a strongly interacting theory.

  Need to learn as much as we can.

- LHC would not be able to cover full composite Higgs spectrum, since we have not seen anything yet.

  At most a couple of lower lying states.

- Need to go beyond.
  - Higgs factory + 100 TeV pp collider can do a good job.

Looking forward to exciting discoveries.

extras

Constraints other than di-boson

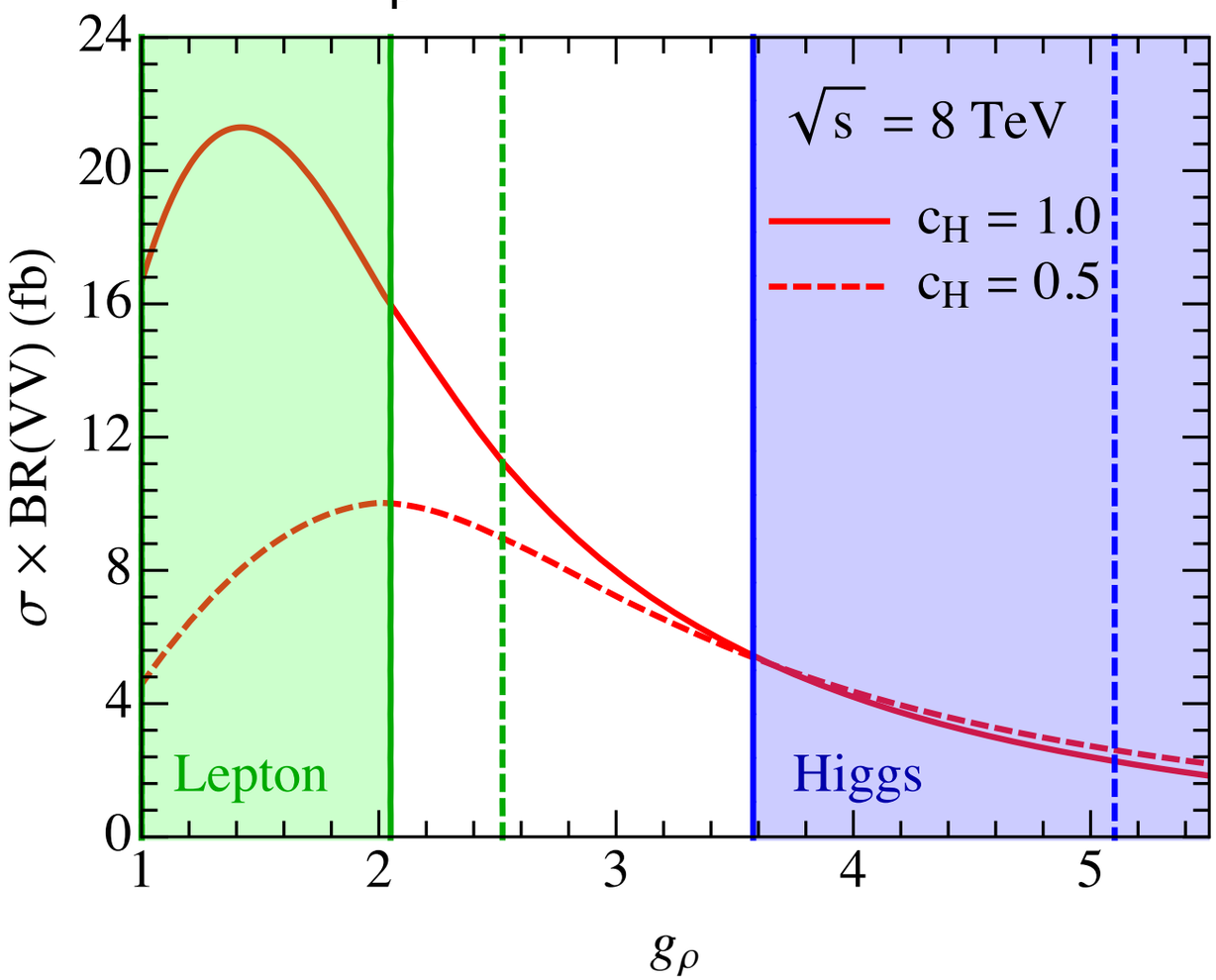
Can still be relevant

Not as strong

final state	ATLAS		CMS	
$\ell^+\ell^-$	0.2 fb	[3]	0.25 fb	[4]
$\ell^\pm \not{E}_T$	0.9 fb	[66]	0.4 fb	[67]
$t\bar{b}$	120 fb	[68]	100 fb	[69]
$t\bar{t}$	50 fb	[70]	20 fb	[71]
jj	130 fb	[72]	100 fb	[73]

(over)simplified model.

m_ρ fixes to be 2 TeV



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jj	130 fb	[72]	100 fb	[73]

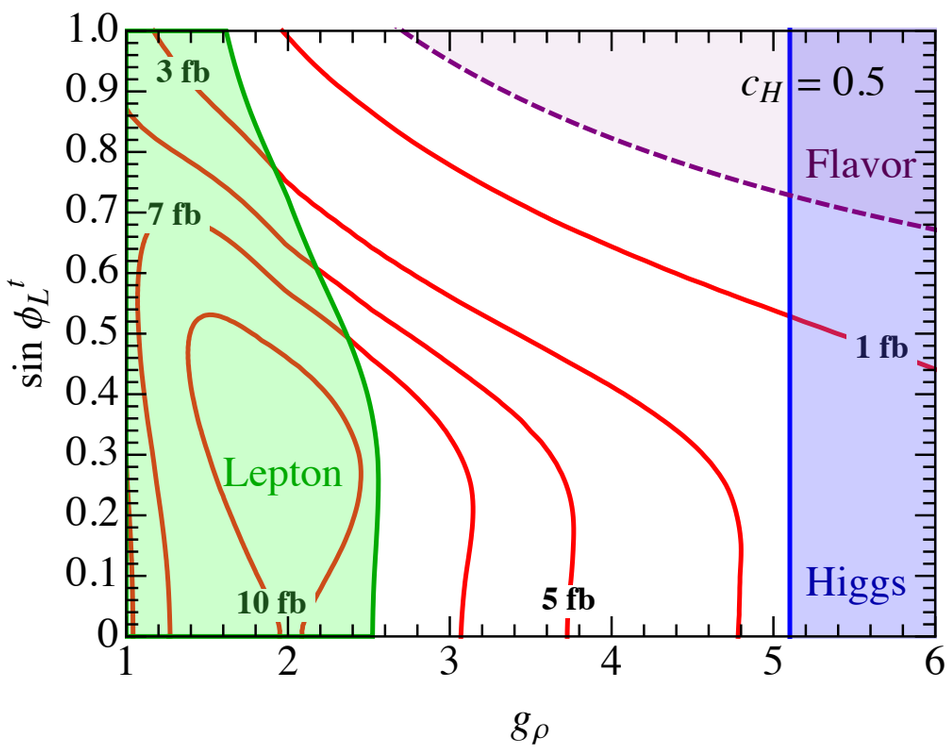
$$\mathcal{L} \supset i g_\rho c_H \rho^a_\mu (H^\dagger \tau^a D^\mu H - (D^\mu H)^\dagger \tau^a H)$$

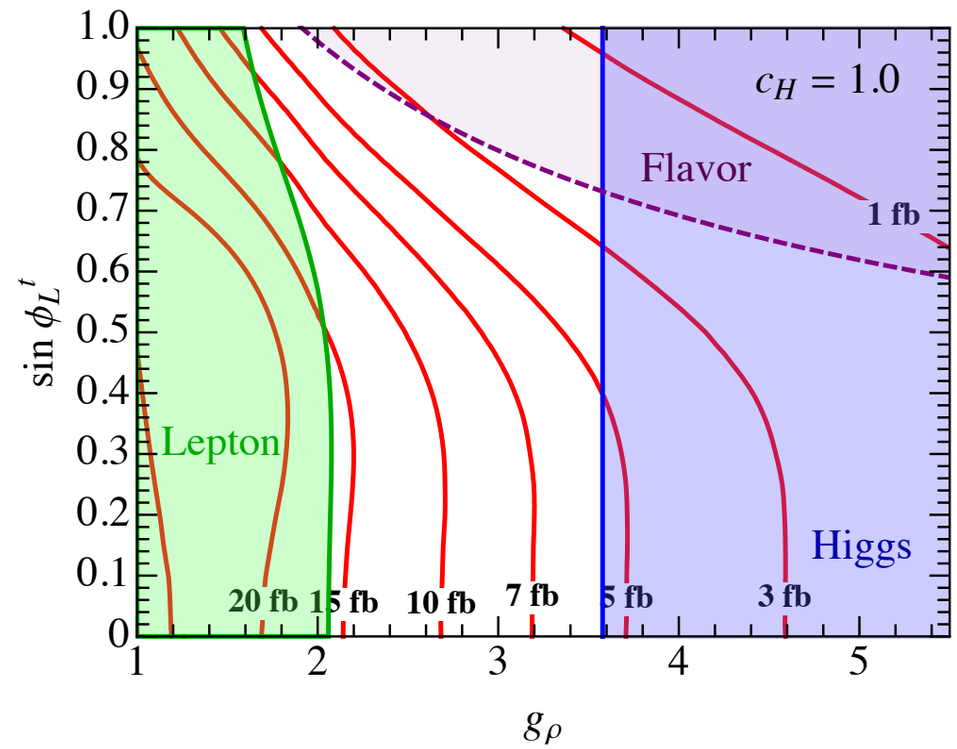
$$m_\rho = \sqrt{c_H}\, g_\rho f$$

- Elementary fermion. Toy model.

Composite top.

m_ρ fixes to be 2 TeV

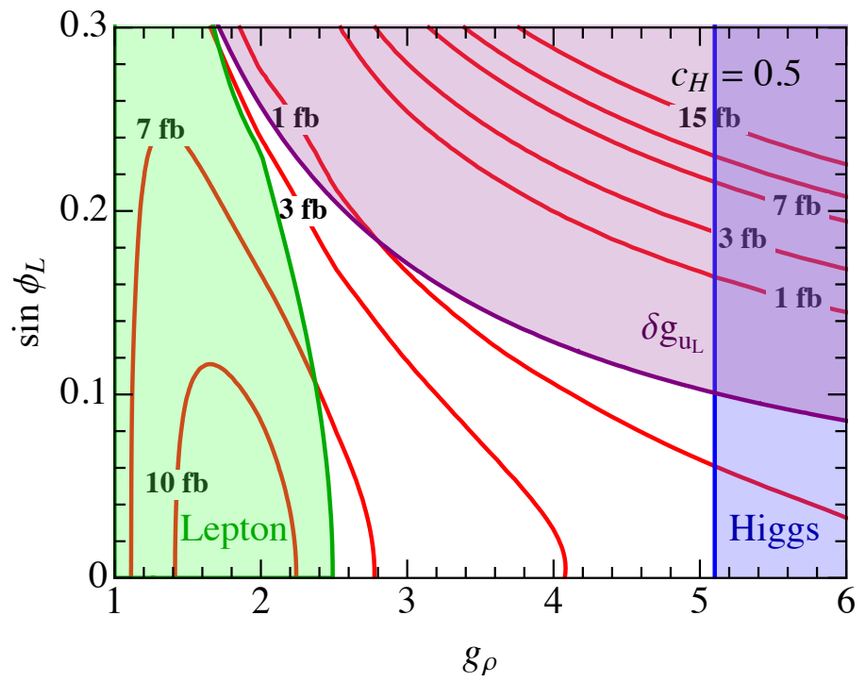


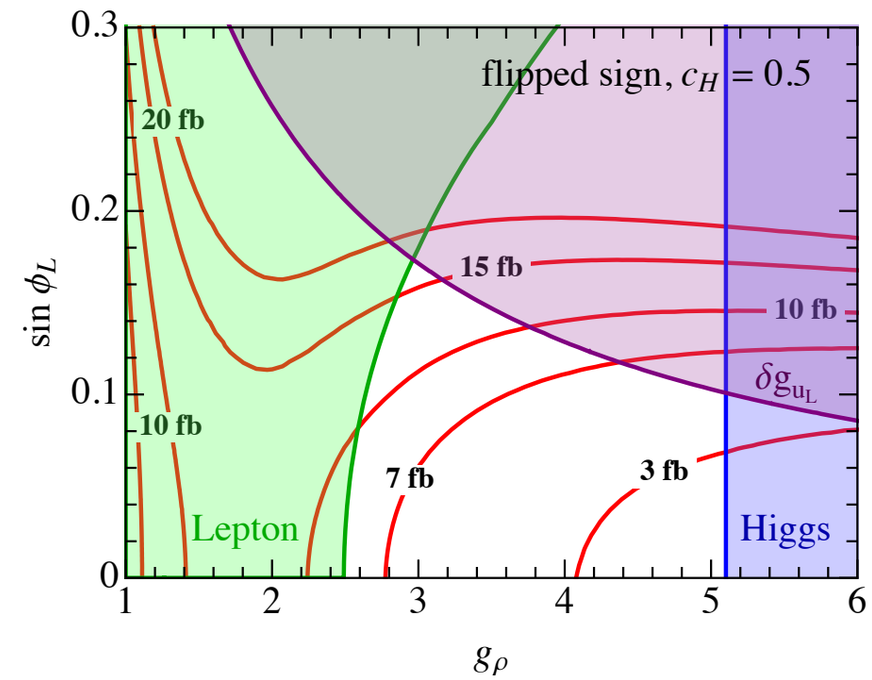


- Vary top compositeness.
- 1st and 2nd generations elementary.

Composite quarks.

m_ρ fixes to be 2 TeV $\sin\phi_L^t = 0.4$





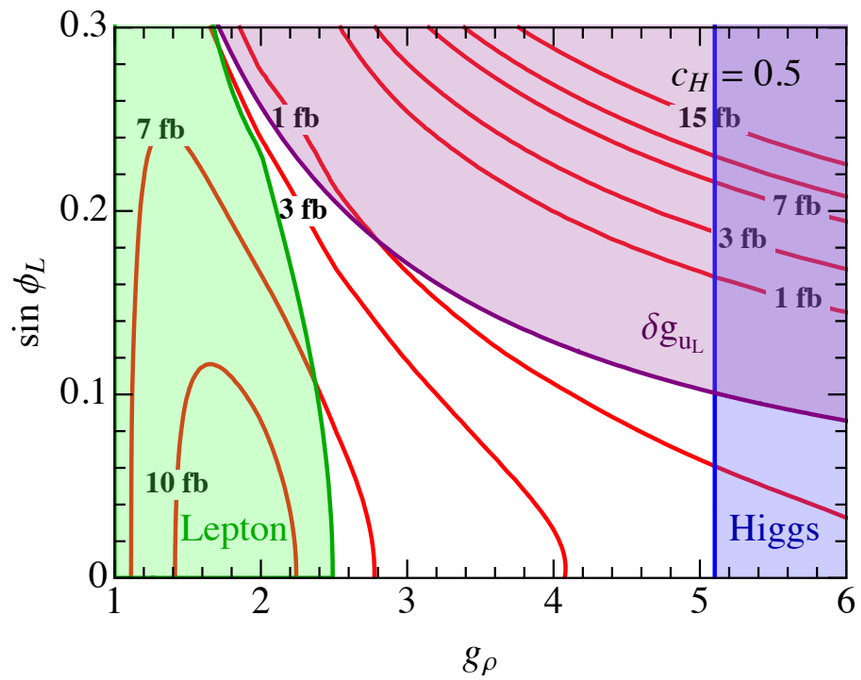
	VV, Vh	$\bar{q}_L\gamma^\mu q_L$
$\rho^{0,\pm}$	g_ρ	$-\frac{g^2}{g_\rho}(1 - a_L\frac{g_\rho^2}{g^2}s_{L,q}^2)\tau^a$

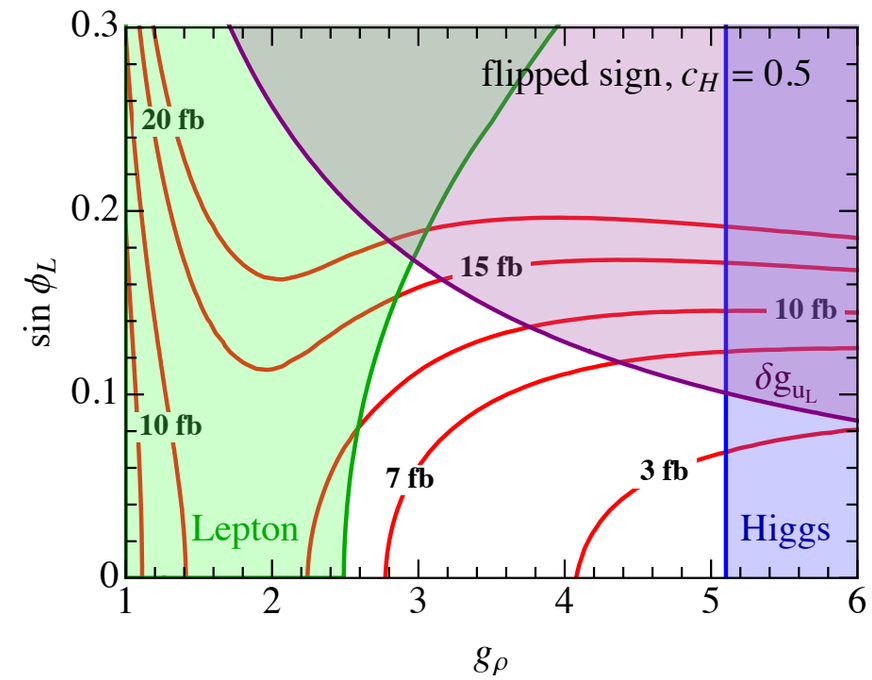
flipped sign: $a_L = -1$

- Vary compositeness of light quarks.

Composite quarks.

m_ρ fixes to be 2 TeV $\sin\phi_L^t = 0.4$





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- Vary compositeness of light quarks.

Bottom line

Composite spin 1 resonance can fit the excess and satisfy all constraints without too much effort.