Composite Spin-1 resonance at the LHC (and beyond)

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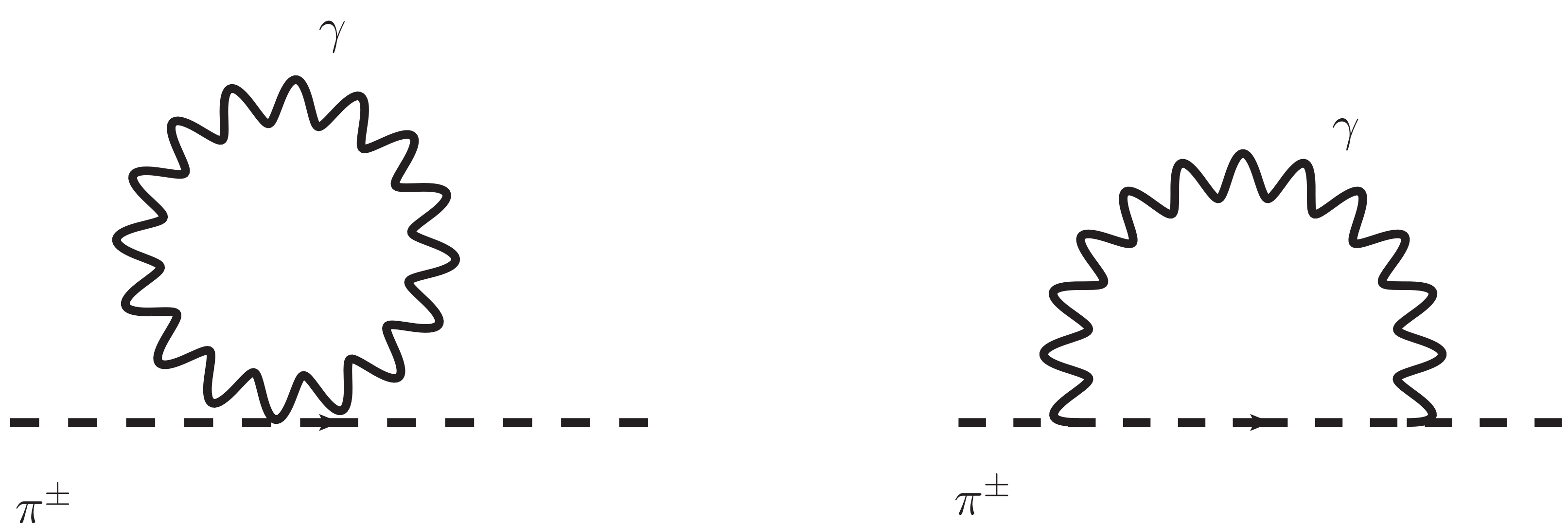
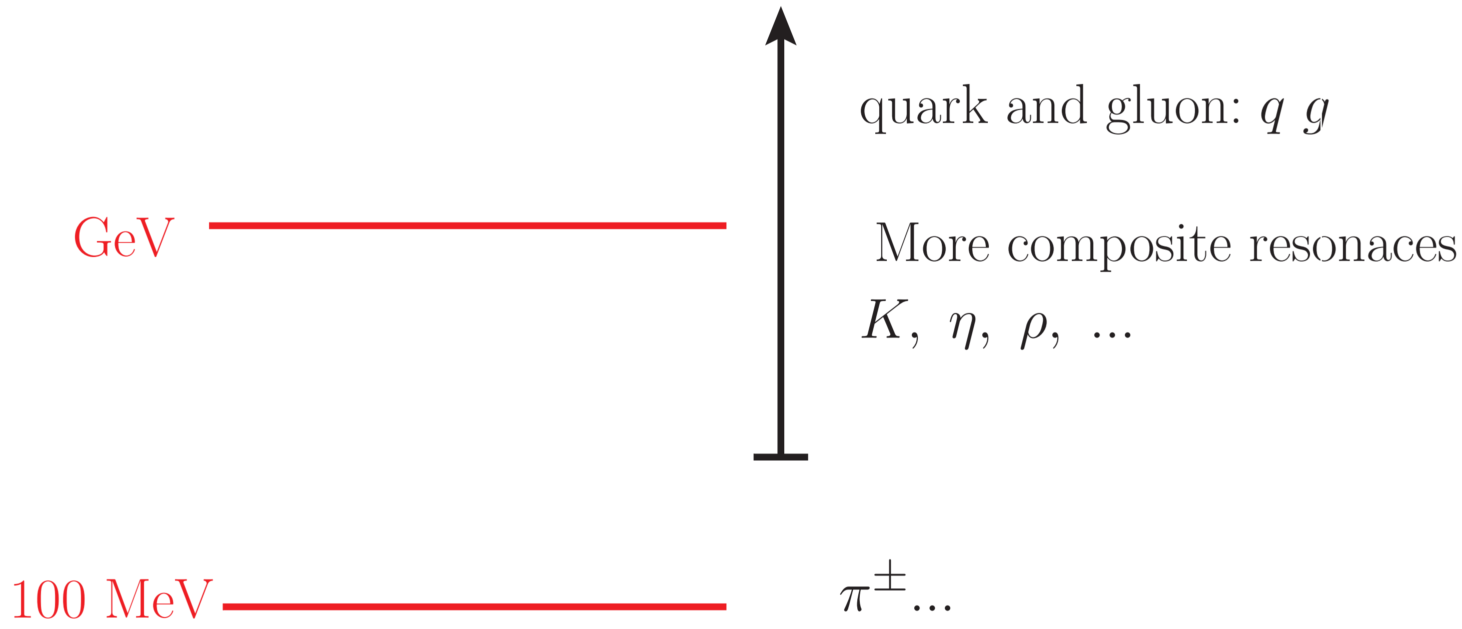
Naturalness in nature?



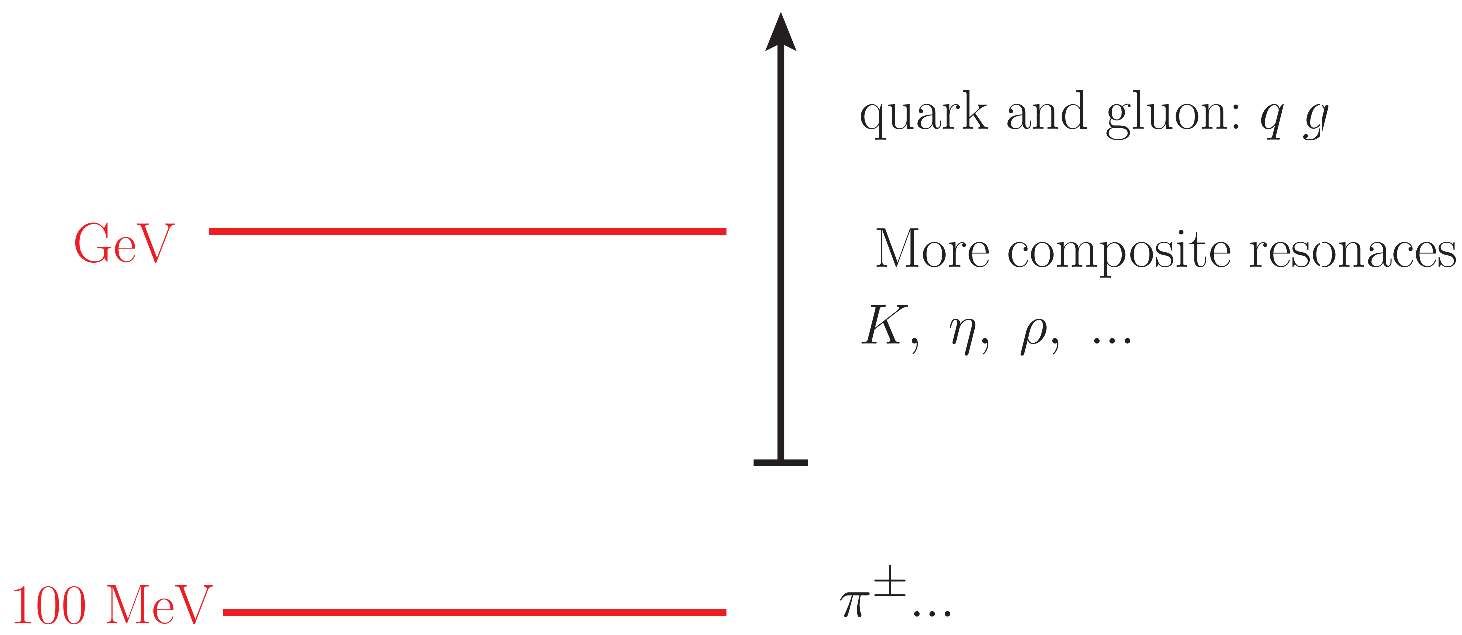
$$\delta m_{\pi^{\pm}}^2 \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

- Example: low energy QCD resonances: pion ....
- m_{π} ~ 100 MeV.
- Naturalness requires $\Lambda \approx$ GeV.
  - Indeed, at GeV, QCD $\Rightarrow$ theory of quark and gluon
  - Pion is not elementary.

"Learning" from QCD



"Learning" from QCD

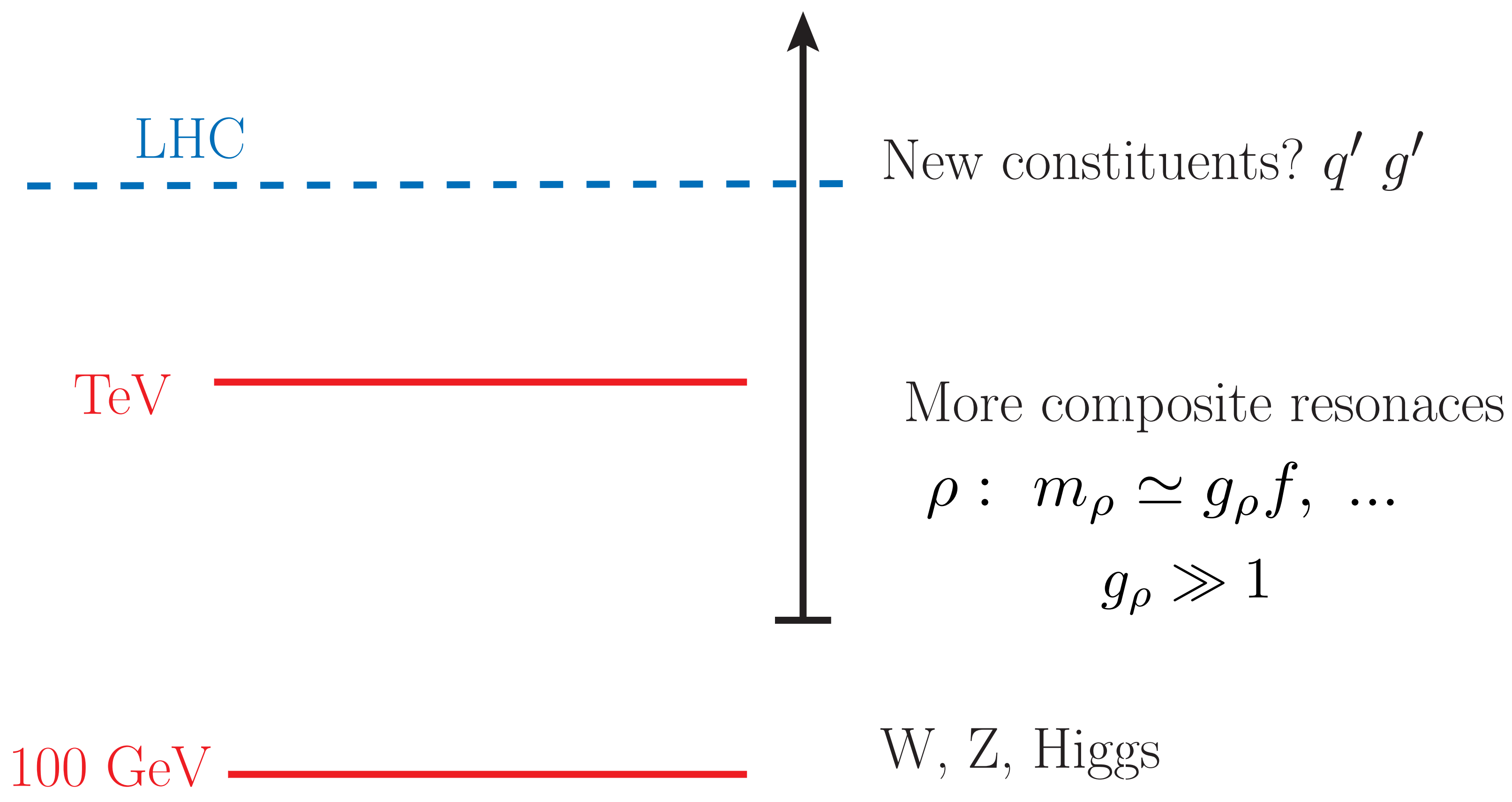


$\Rightarrow$ new strong dynamics, symmetry breaking

$\Rightarrow$ SM Higgs

- Construct a new strong dynamics in which the low lying states will be the SM Higgs.
- Composite Higgs models. Still a natural theory.
- Nature may be more interesting, but it could also just repeat itself.

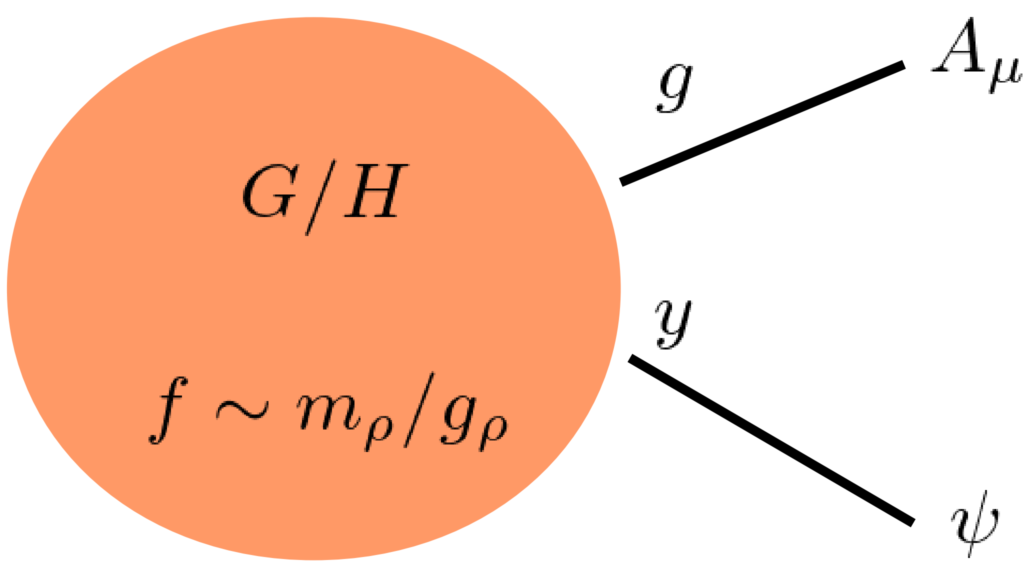
Composite Higgs



- Many models in this class.

– Similar scenarios: Randall-Sundrum...

Composite Higgs



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

Spin-1 resonances

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

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

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

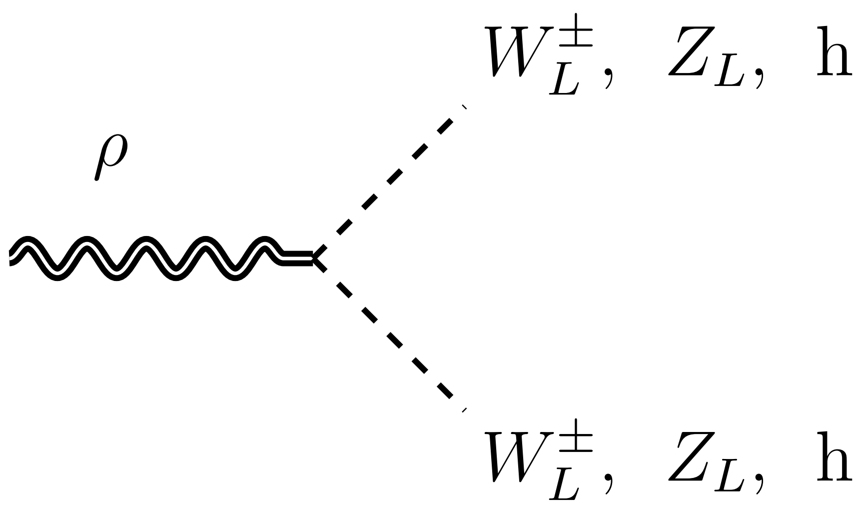
Under this, spin-1 res. decompose as

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

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

ρ coupling to h, W_L , Z_L

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

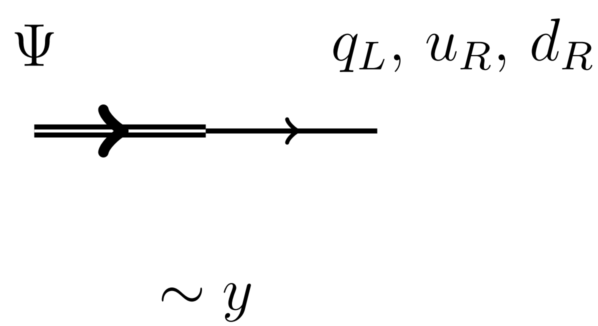


$\sim g_\rho$

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

Partial compositeness

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



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

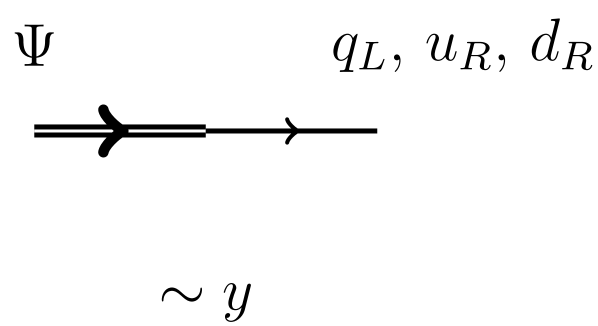
$$\sin\phi_{L,R} \equiv \frac{y_{L,R}}{\sqrt{(m_\Psi/f)^2 + y_{L,R}^2}}.$$

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

Partial compositeness

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

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



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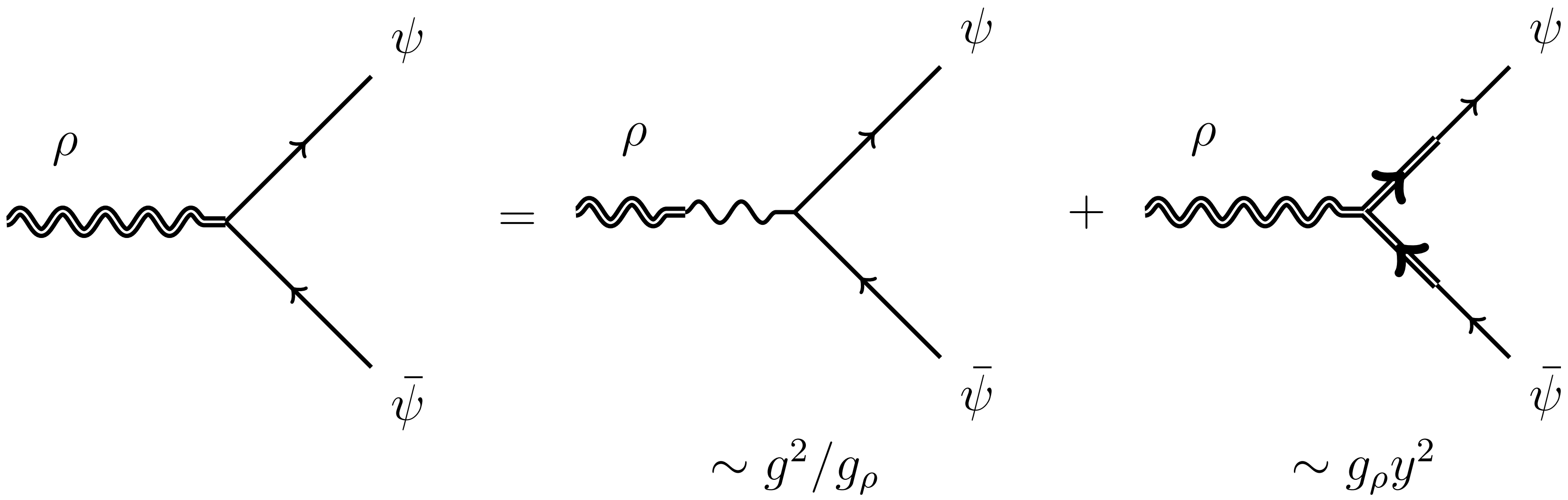
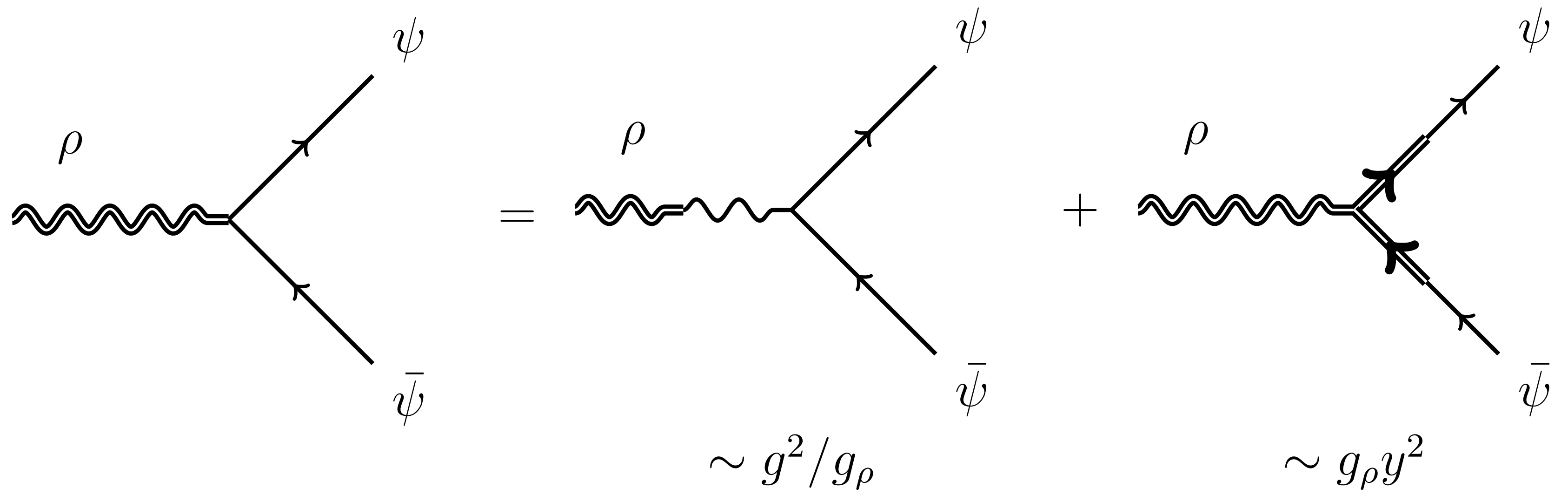
ρ coupling to SM fermion



ρ mixes with W/Z
mixing angle: g/g_ρ

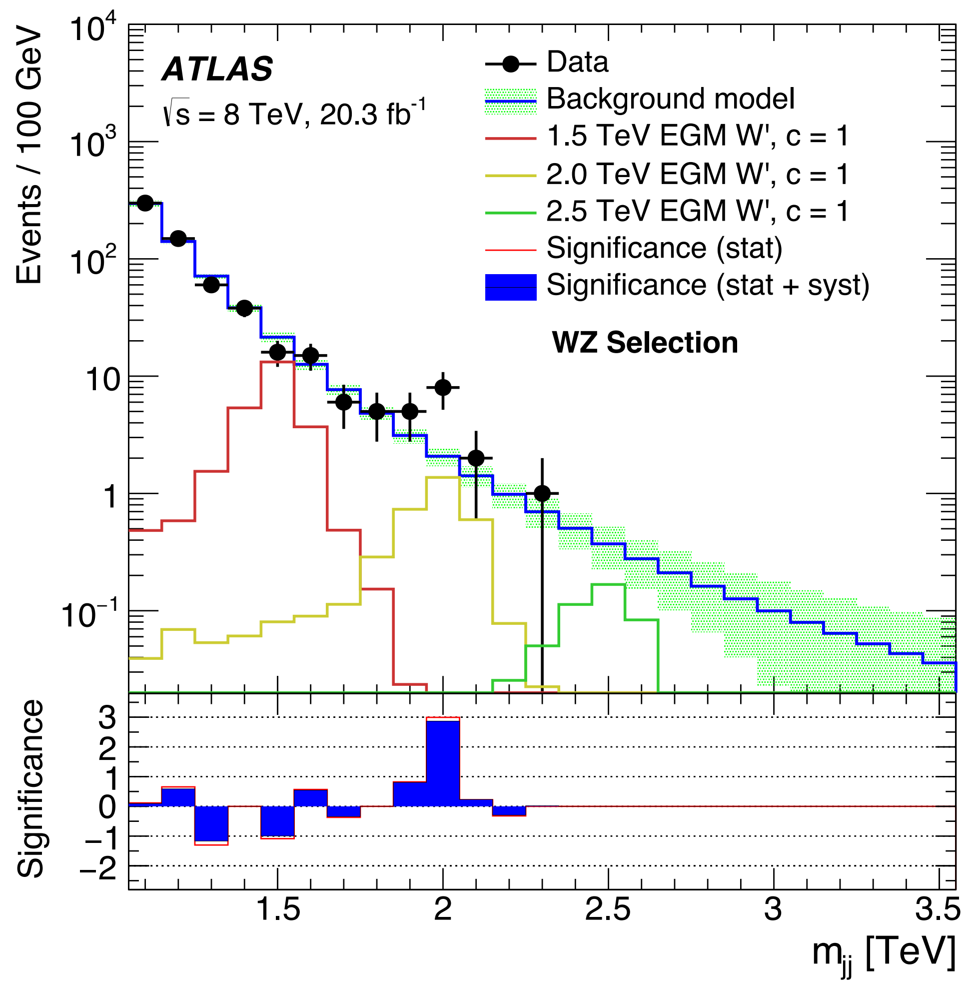
ρ couples to composite fermion first, which mixes with SM fermion.

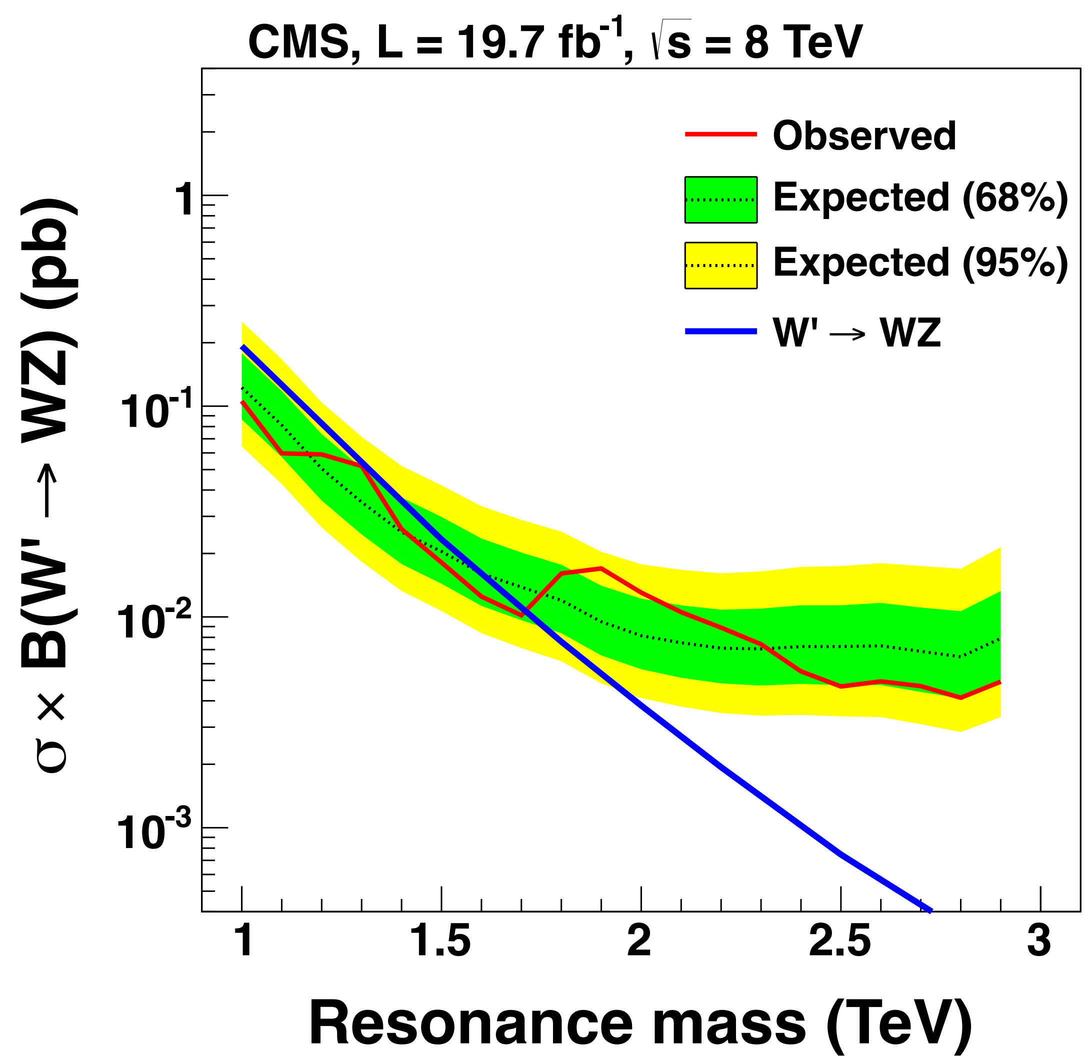
ρ coupling to SM fermion



	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	$-$	$-$	$-$	$-$	$-$

Excess around 2 TeV?





Composite spin-1 vector?

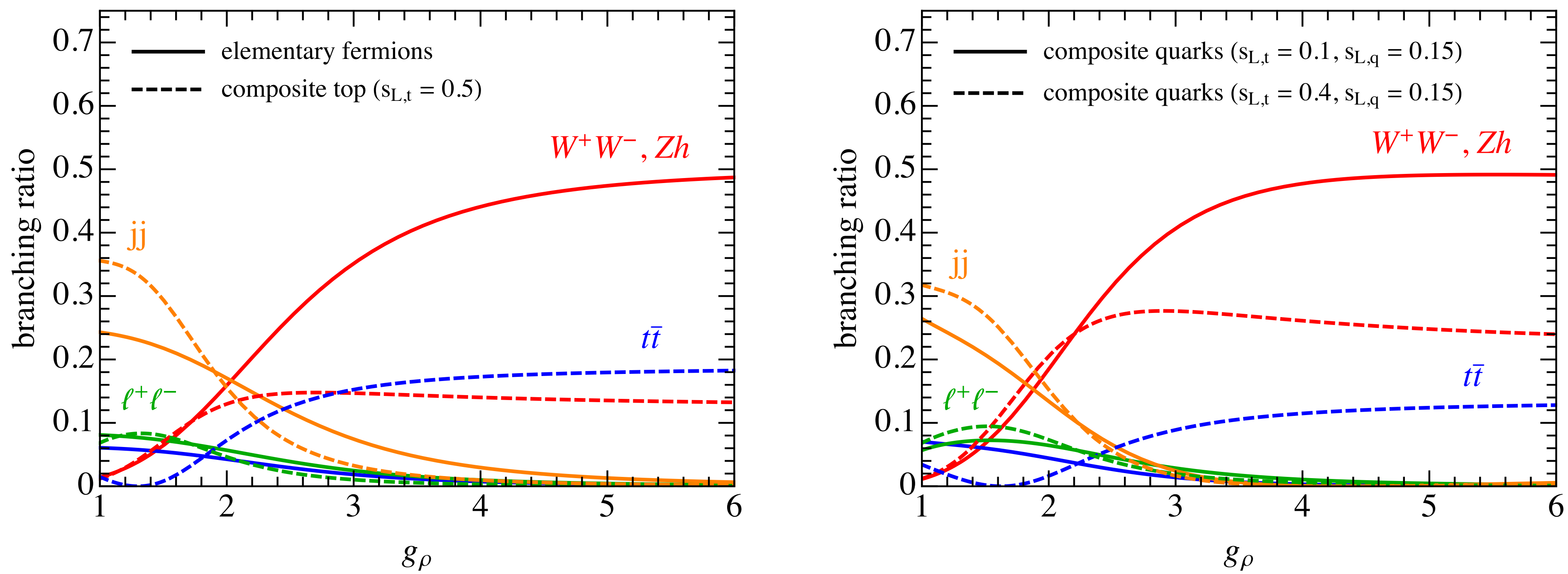
Thamm, Torre, Wulzer
Bian, Liu, Shu
Low, Tesi, LTW
…

Some features of the "excess"

- Data is confusing, no clear picture.
- Large-ish rate. 5-10 fb.
- Not seen else where. Diboson is the leading channel.
- "Usual" gauge boson.
  - Di-lepton and single lepton limits < 1 fb.
  - L-R models.
- Scalar?
  - Rate small. BR to WZ small.

Decay of composite spin-1 res.

m_ρ fixes to be 2 TeV



- 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 di-lepton mode.

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

Constraints other than di-boson

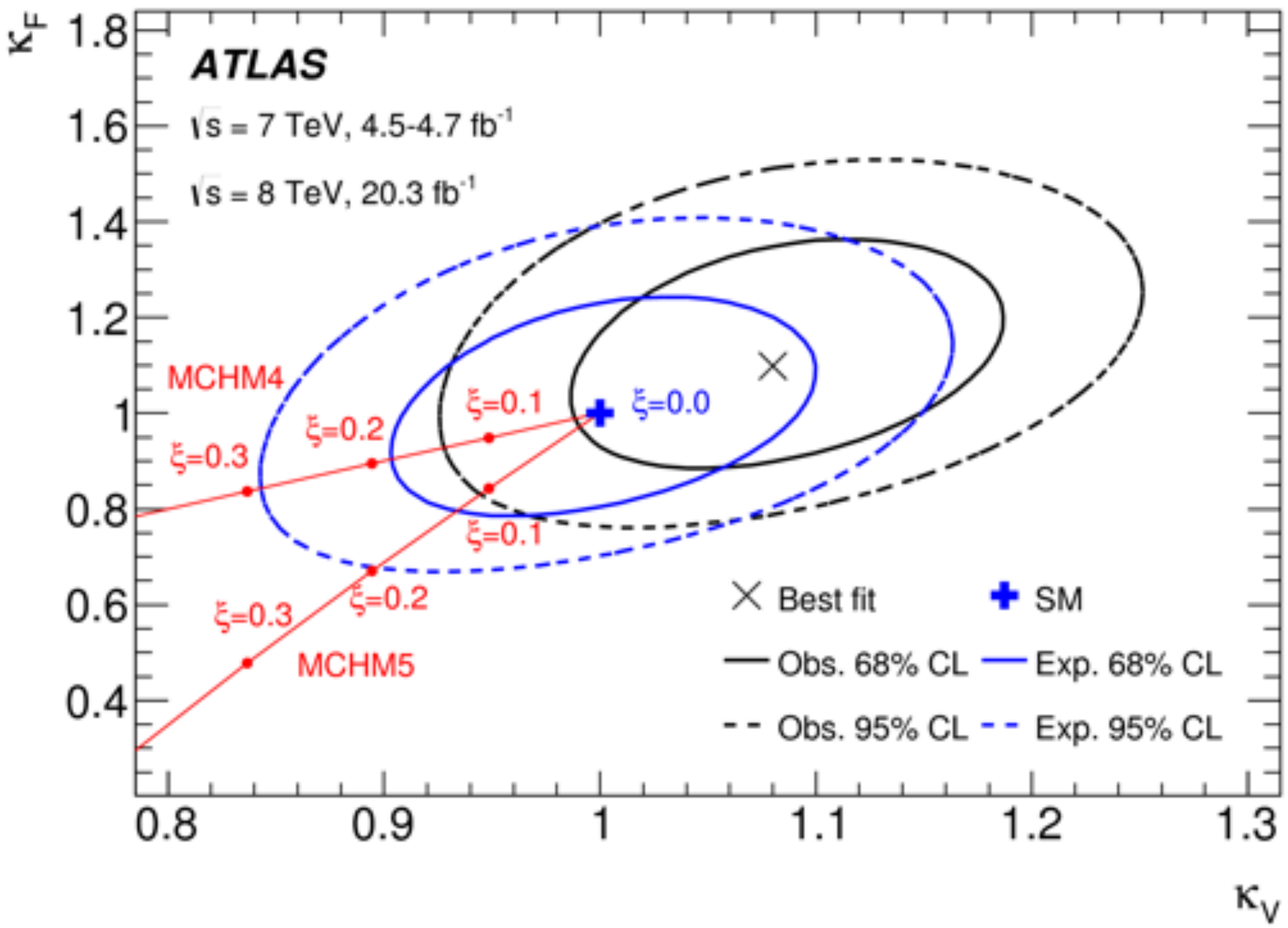
final state	ATLAS	CMS
$\ell^+\ell^-$	0.2 fb [3]	0.25 fb [4]
$\ell^\pm \not{E}_T$	0.9 fb [66]	0.4 fb [67]
$t\bar{b}$	120 fb [68]	100 fb [69]
$t\bar{t}$	50 fb [70]	20 fb [71]
jj	130 fb [72]	100 fb [73]

Can still be relevant

Not as strong

Indirect constraints

Higgs coupling.



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

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

EW precision.

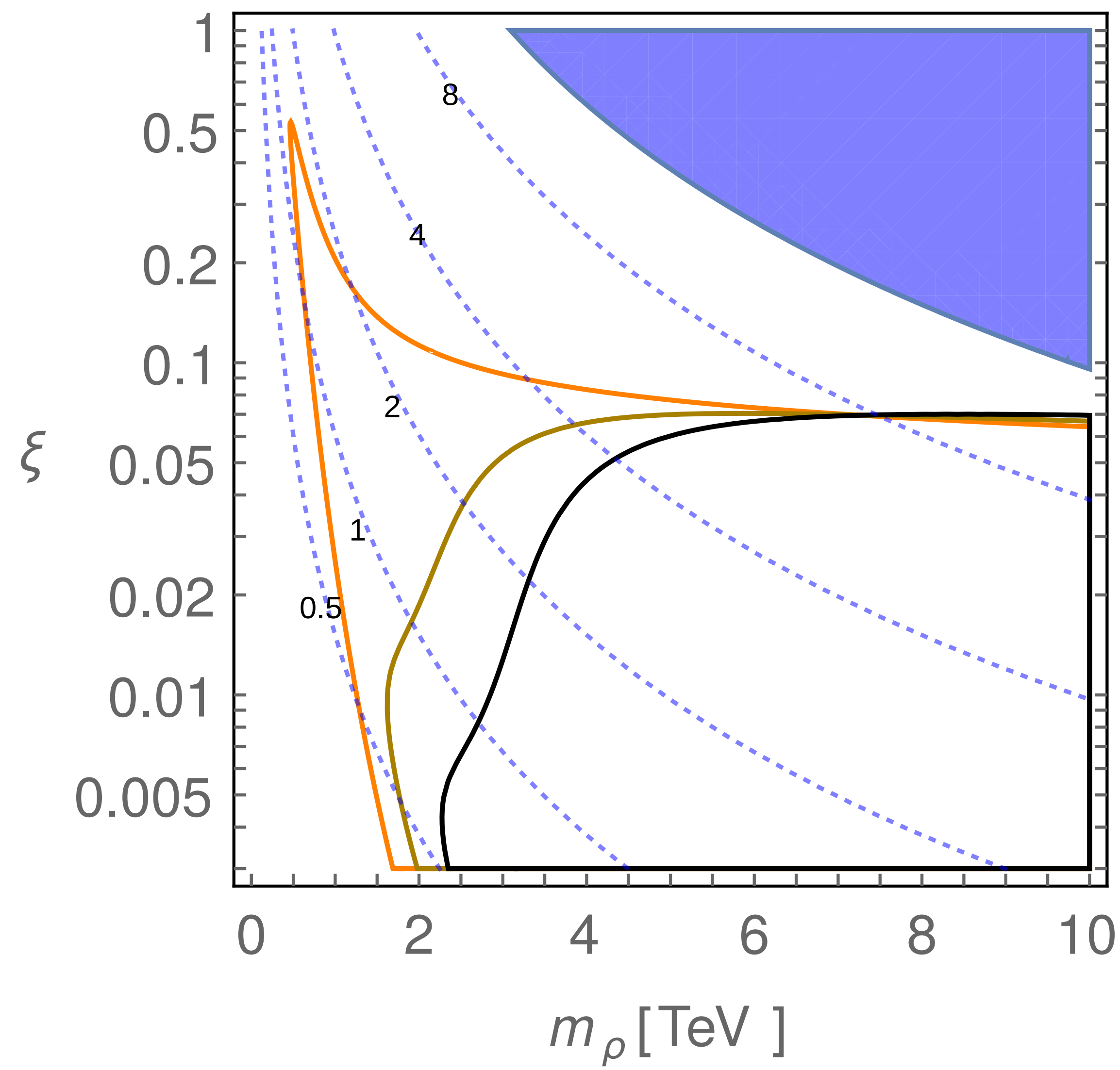
Tree level S-parameter

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

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

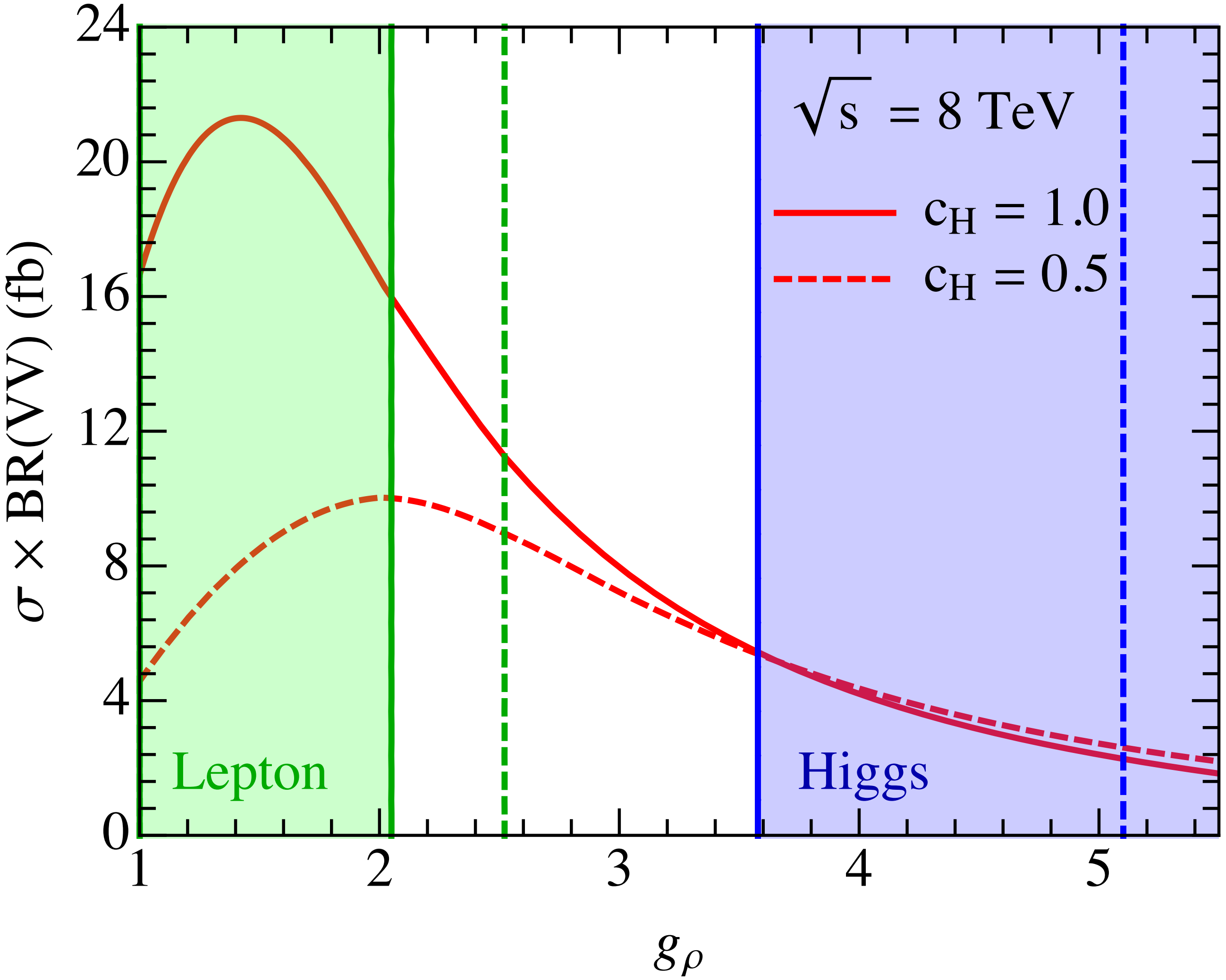
In addition, constraints from Z decay. Relevant for partially composite u_L

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

Parameter space for 2 TeV resonance

(over)simplified model.

m_ρ fixes to be 2 TeV



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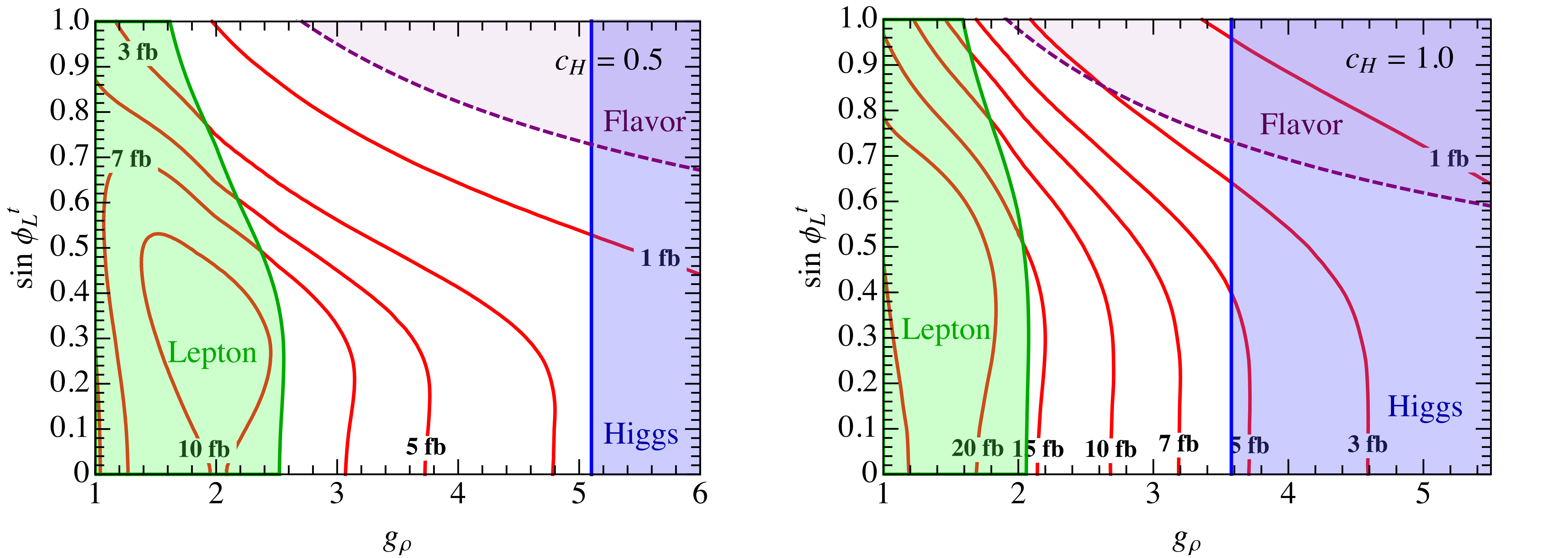
$$\mathcal{L} \supset i g_\rho \underline{c_H} \rho^a_\mu (H^\dagger \tau^a D^\mu H - (D^\mu H)^\dagger \tau^a H)$$

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

- Elementary fermion. Toy model.

Composite top.

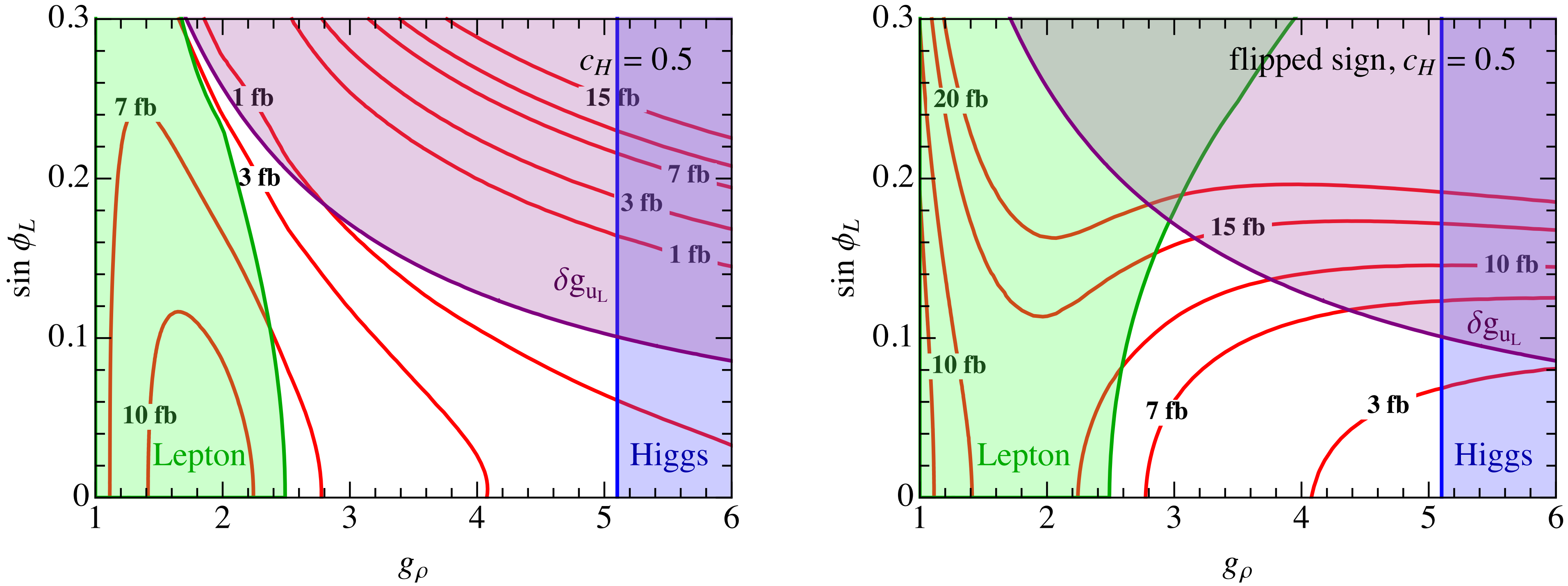
m_ρ fixes to be 2 TeV



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

Composite quarks.

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



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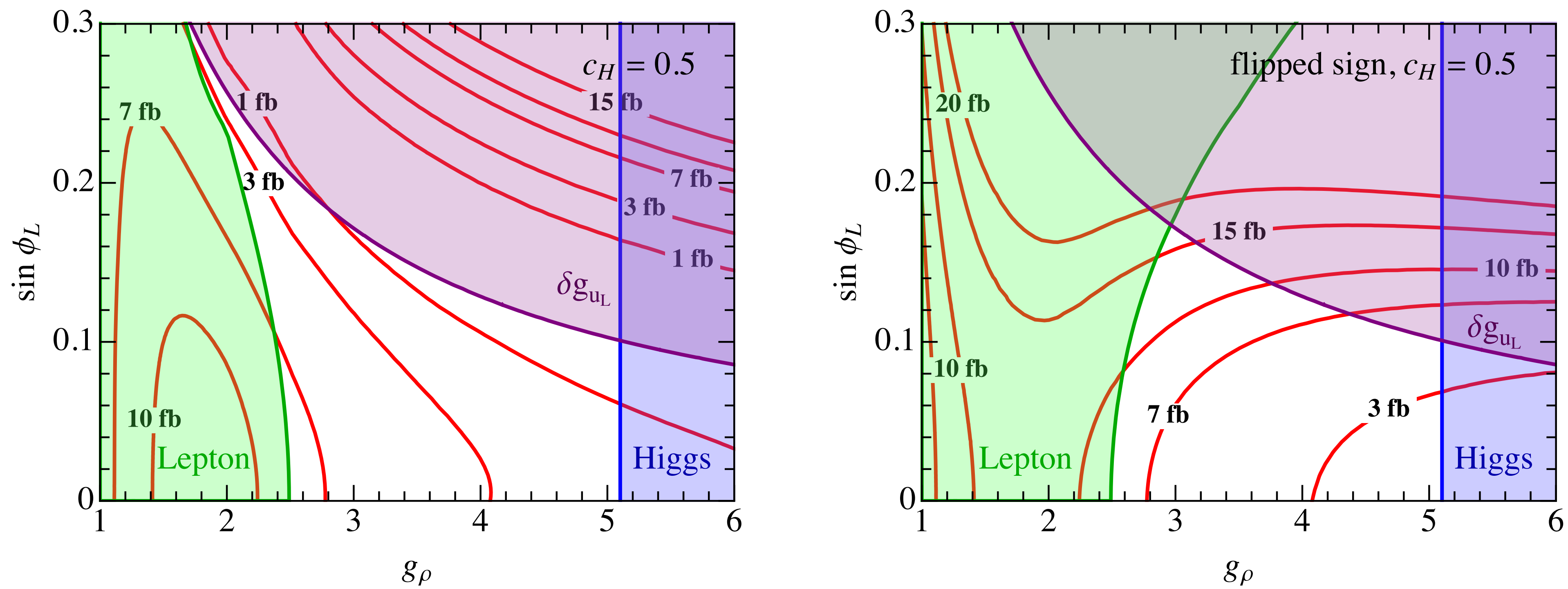
flipped sign: $\quad a_L = -1$

- Vary compositeness of light quarks.

Composite quarks.

m$_\rho$ fixes to be 2 TeV $\qquad \sin\phi_L^t = 0.4$



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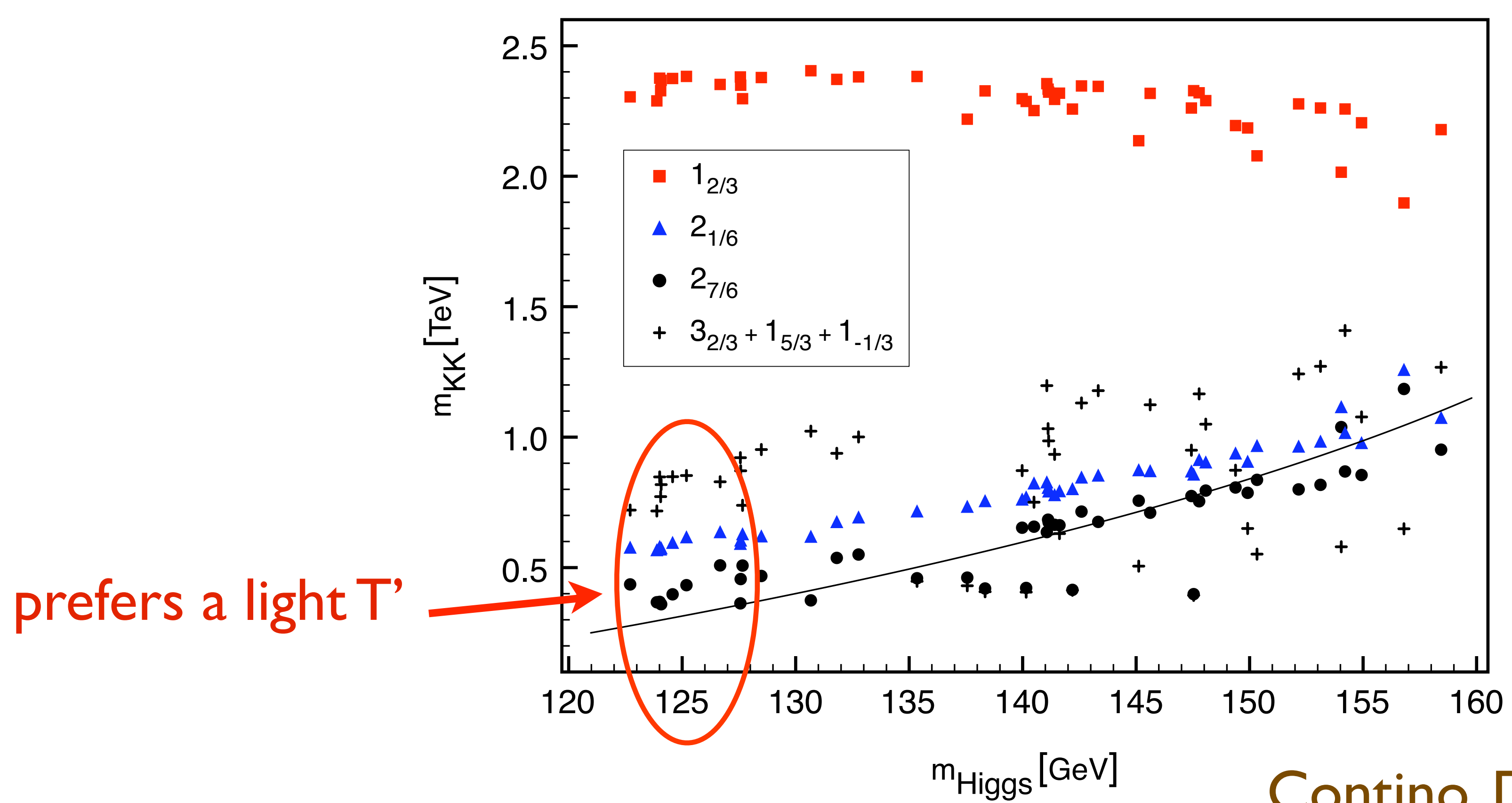
flipped sign: $\quad a_L = -1$

- Vary compositeness of light quarks.

Bottom line

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

Compositeness and top partner

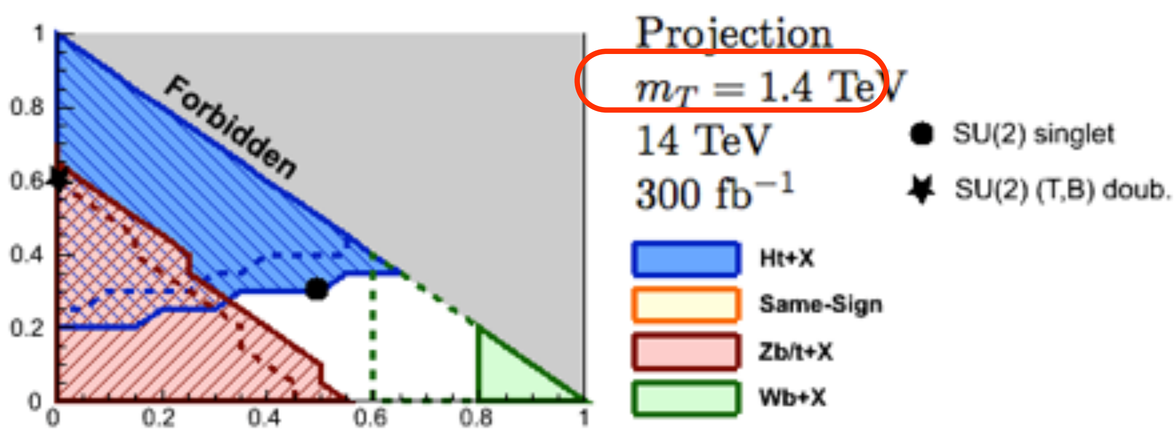


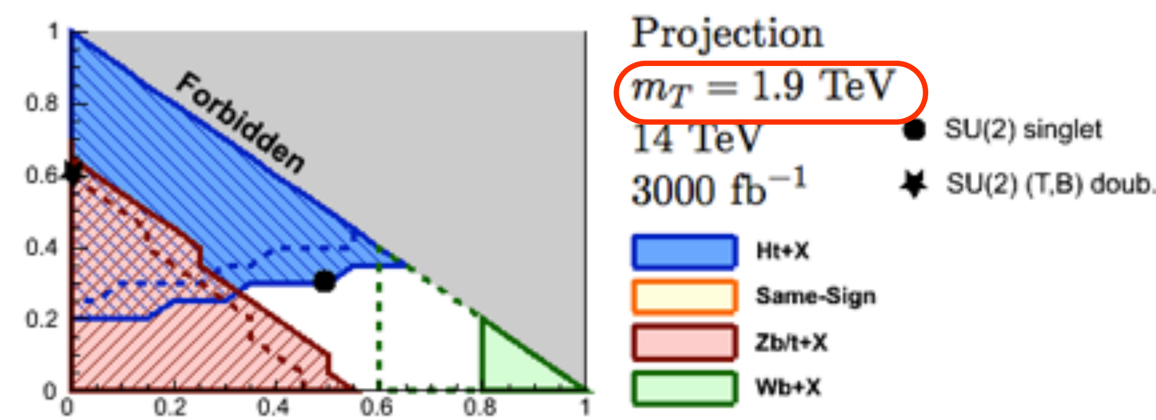
Contino, Da Rold, Pomarol, 2006

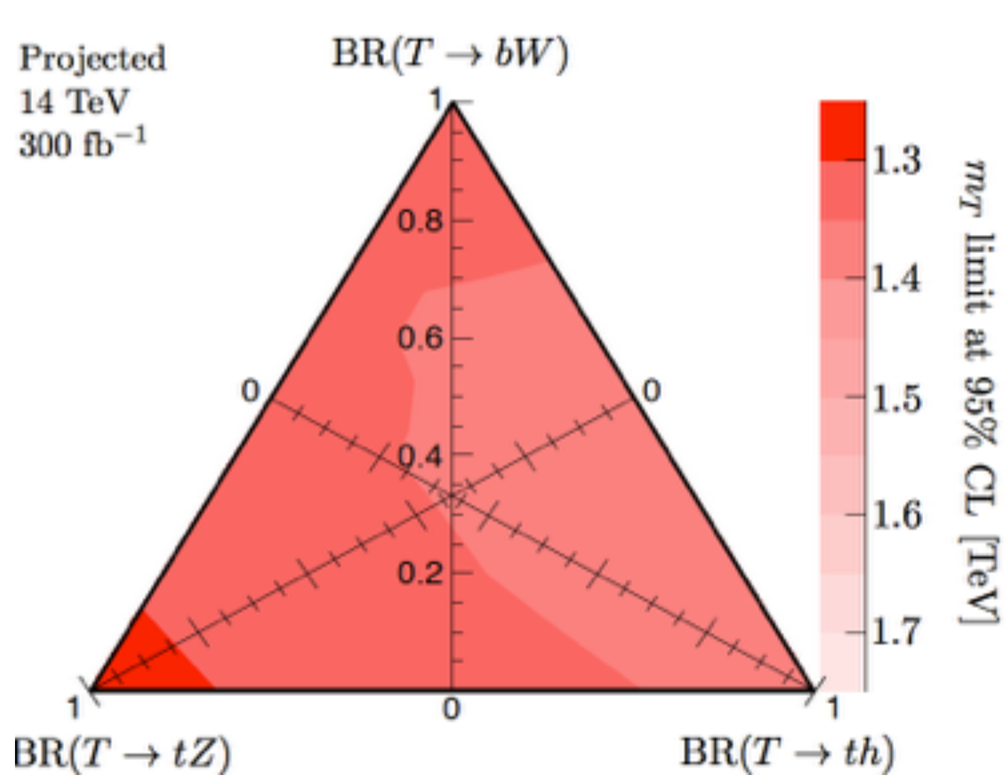
- Light top partner (ψ which mixes with top) could be less than TeV.

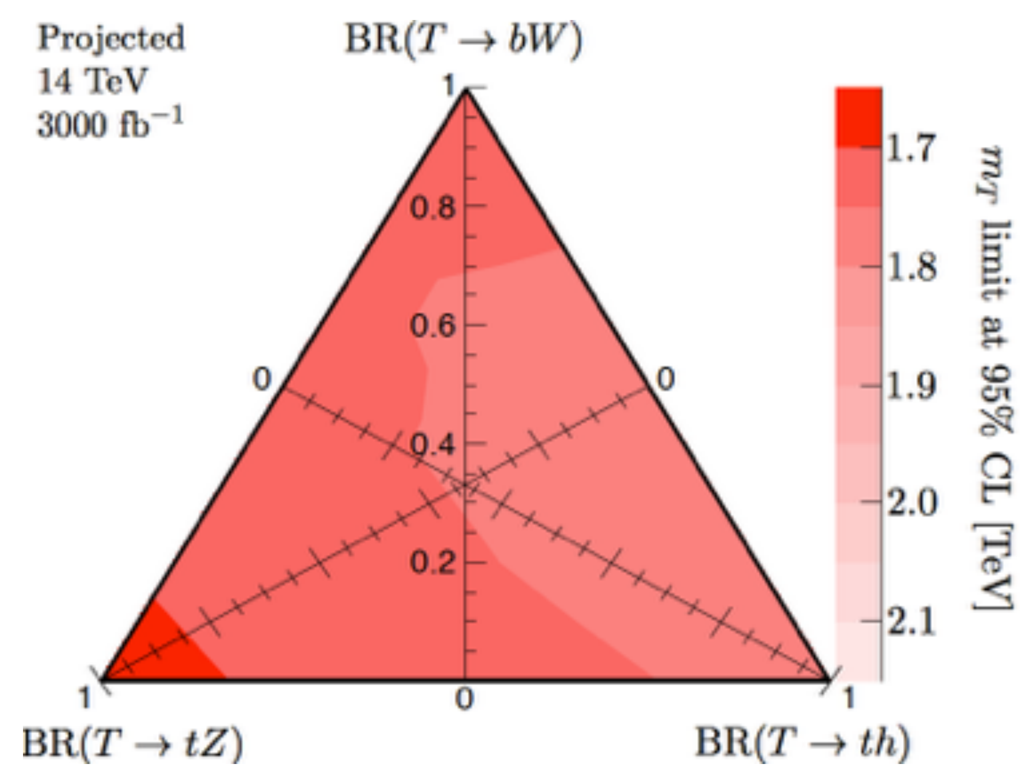
- Plays a crucial role in EWSB.

LHC 14 should cover (most of) it.

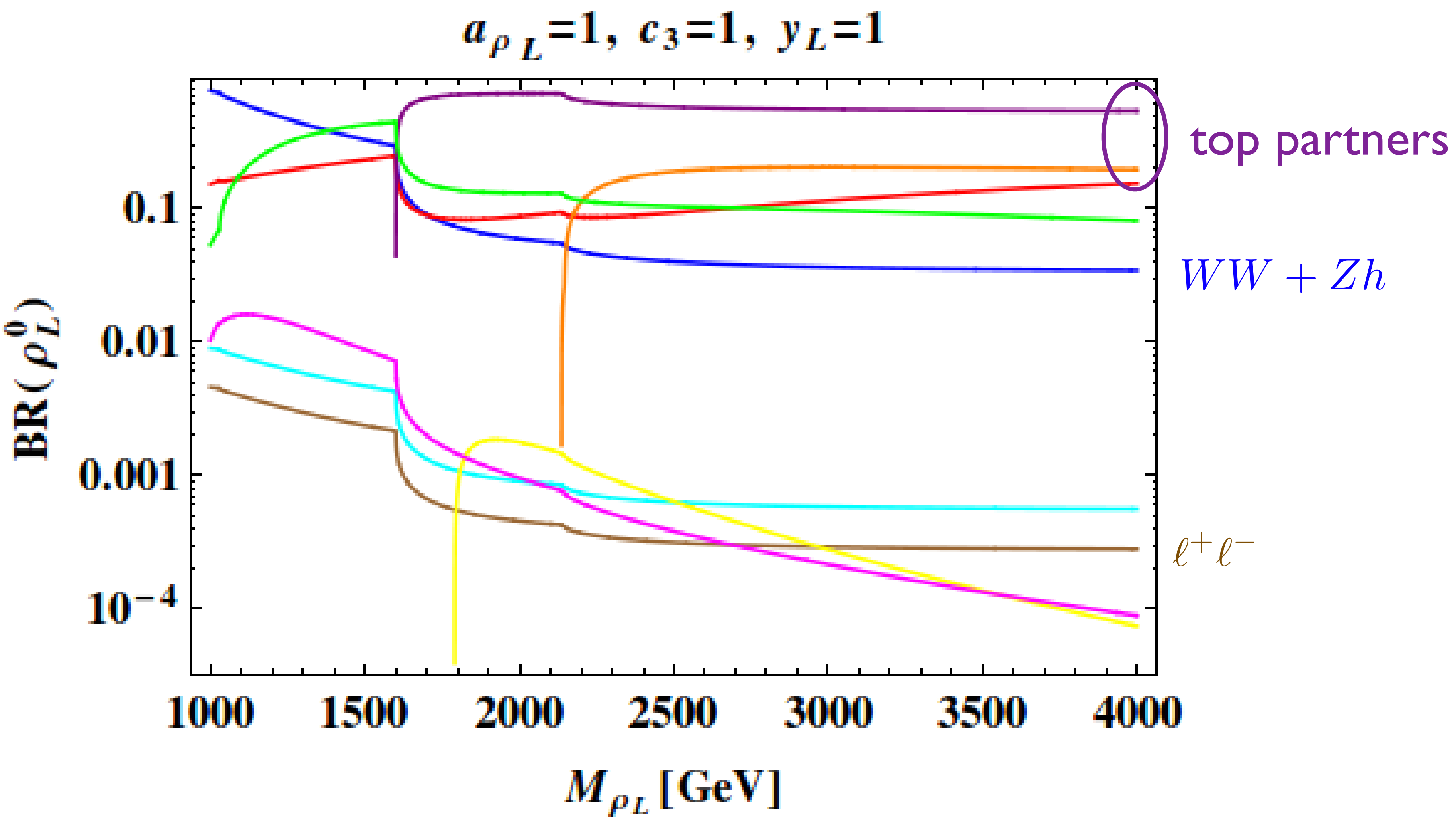








ρ decaying into top partners



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

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

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

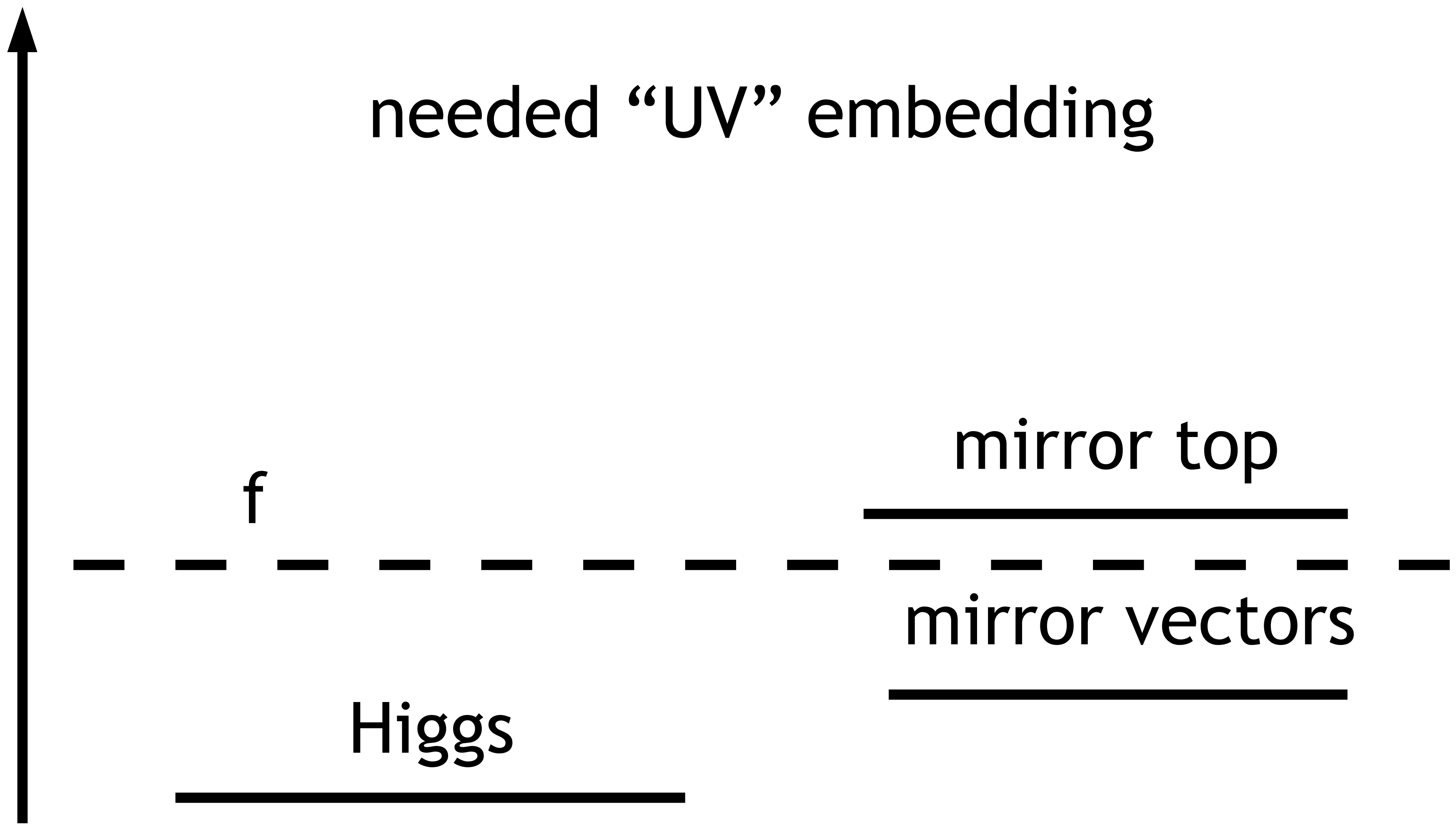
Light Higgs ➜ light top partner

Top partner colored.
LHC searches already constrains top partner mass.
Run 2 will completely cover the simplest cases.

There is an exception: twin Higgs. Singlet top partner.

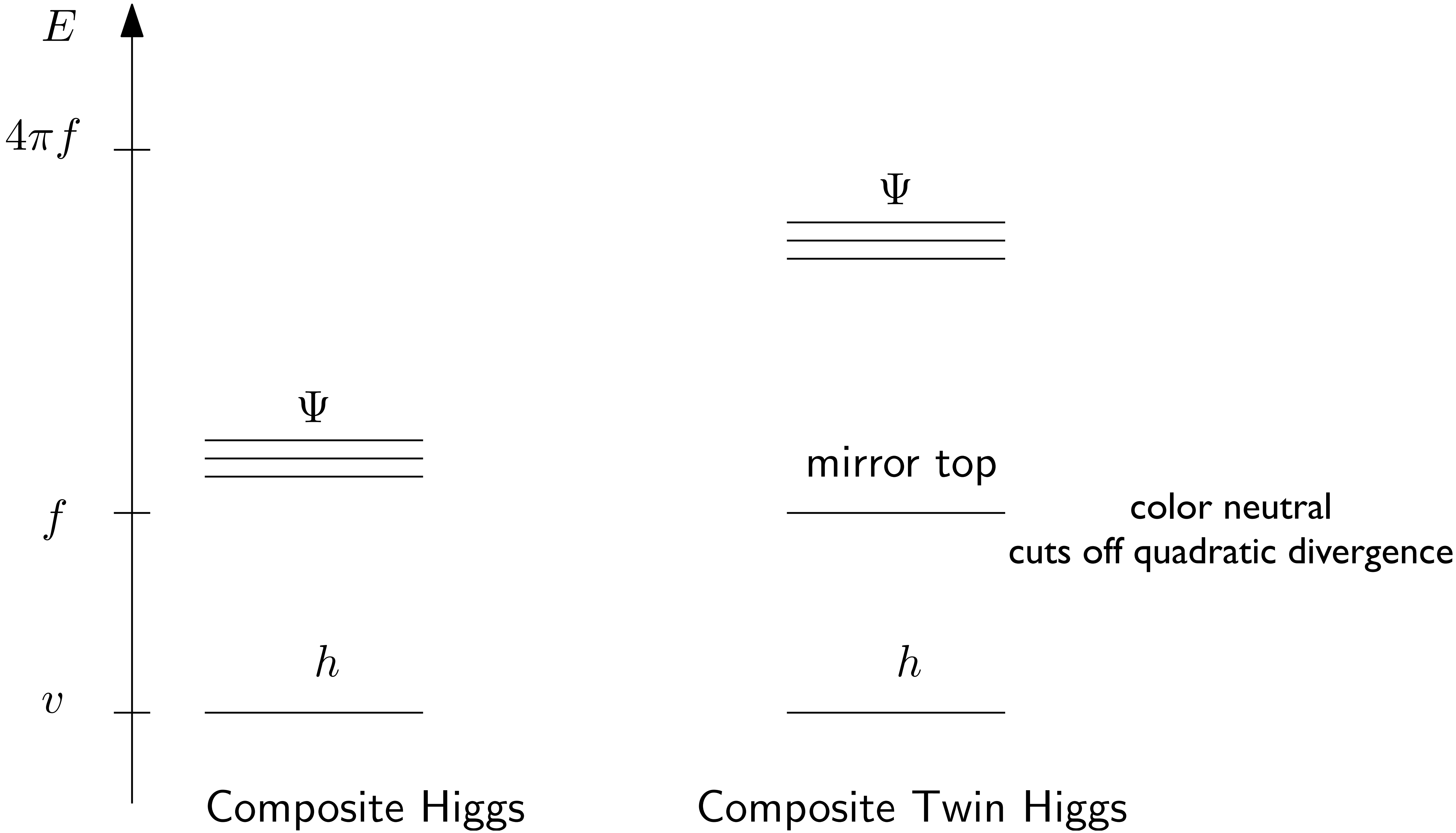
Burdman, Chacko, Harnik

Twin Higgs.



Twin composite Higgs.

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



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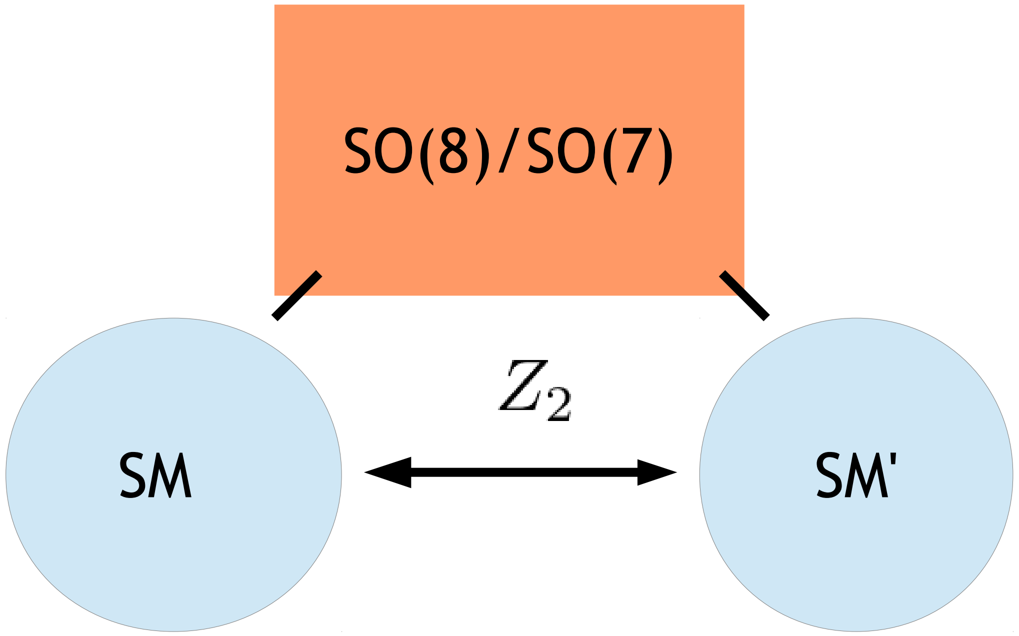


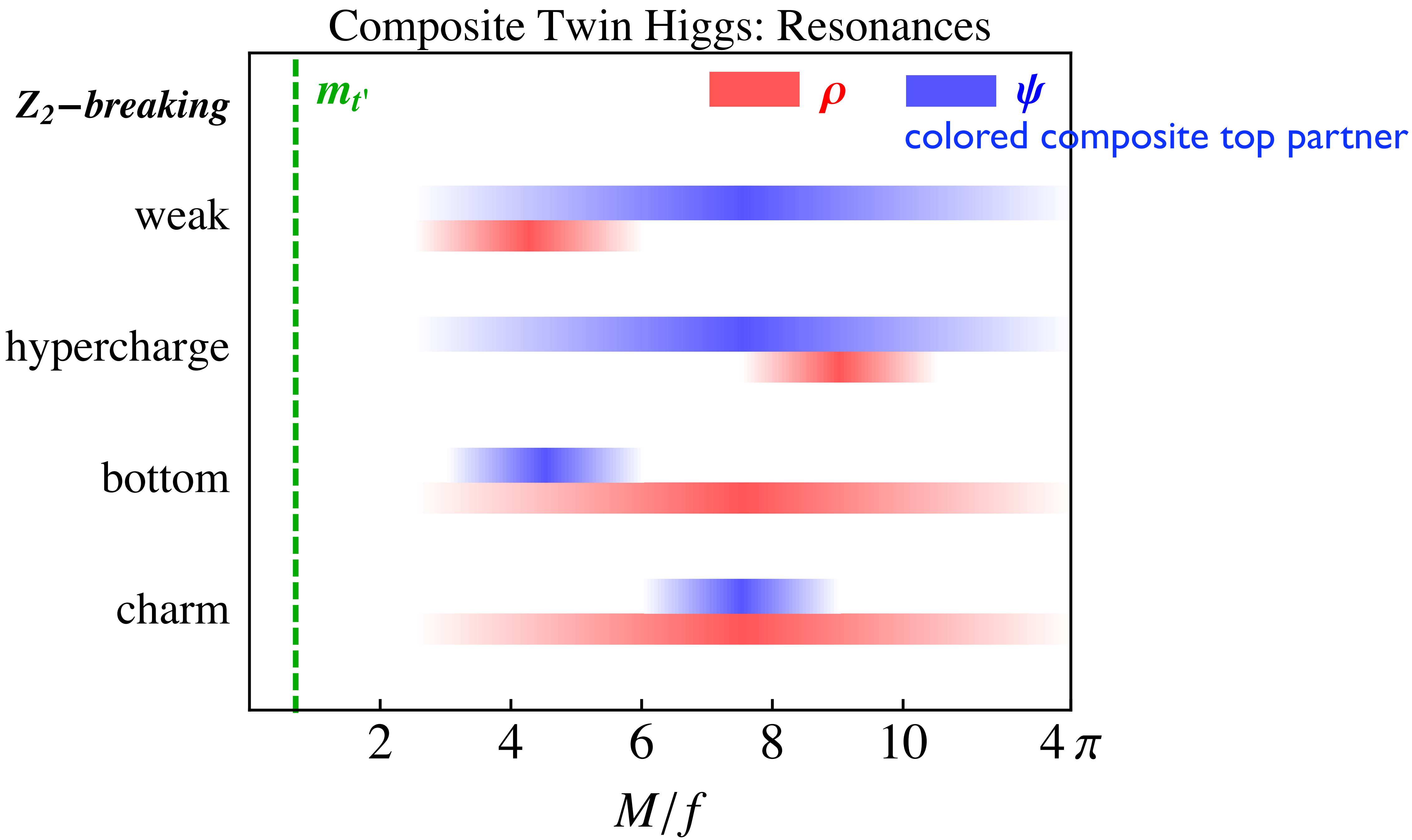
The gauging of the EW part of SM and SM' is given by

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

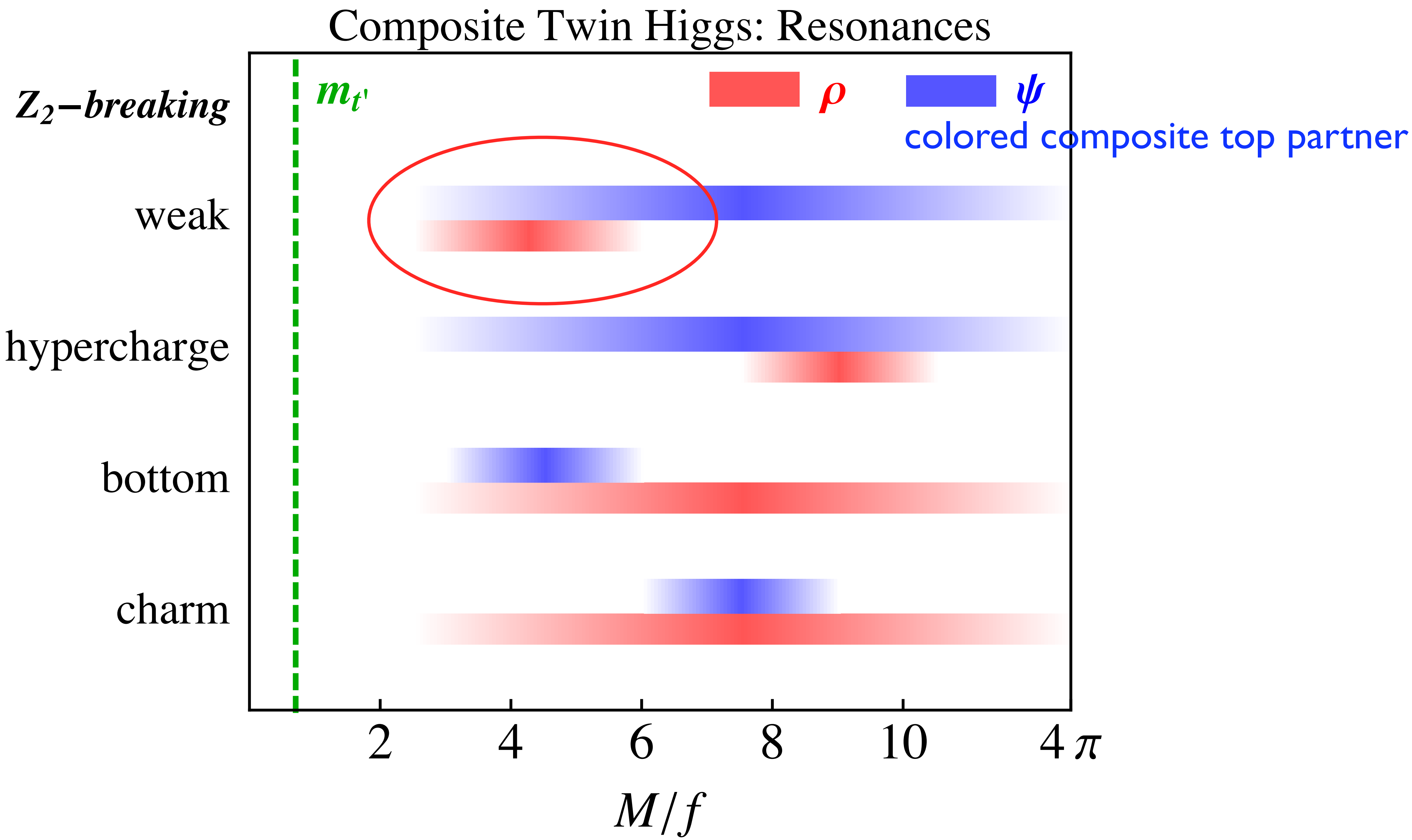
If Z_2 is exact, then SM and SM' has the same scale, v≃f.
Must introduce Z_2 breaking.

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

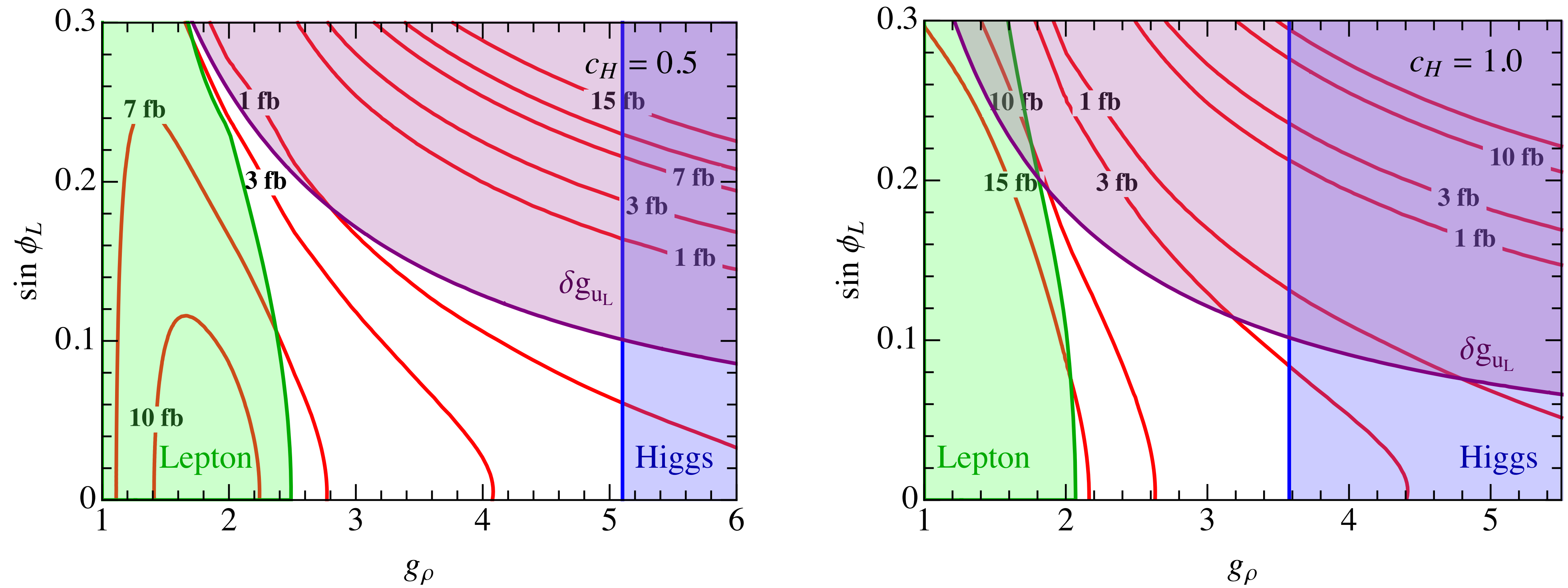
Z_2 breaking and spectrum



Z_2 breaking and spectrum



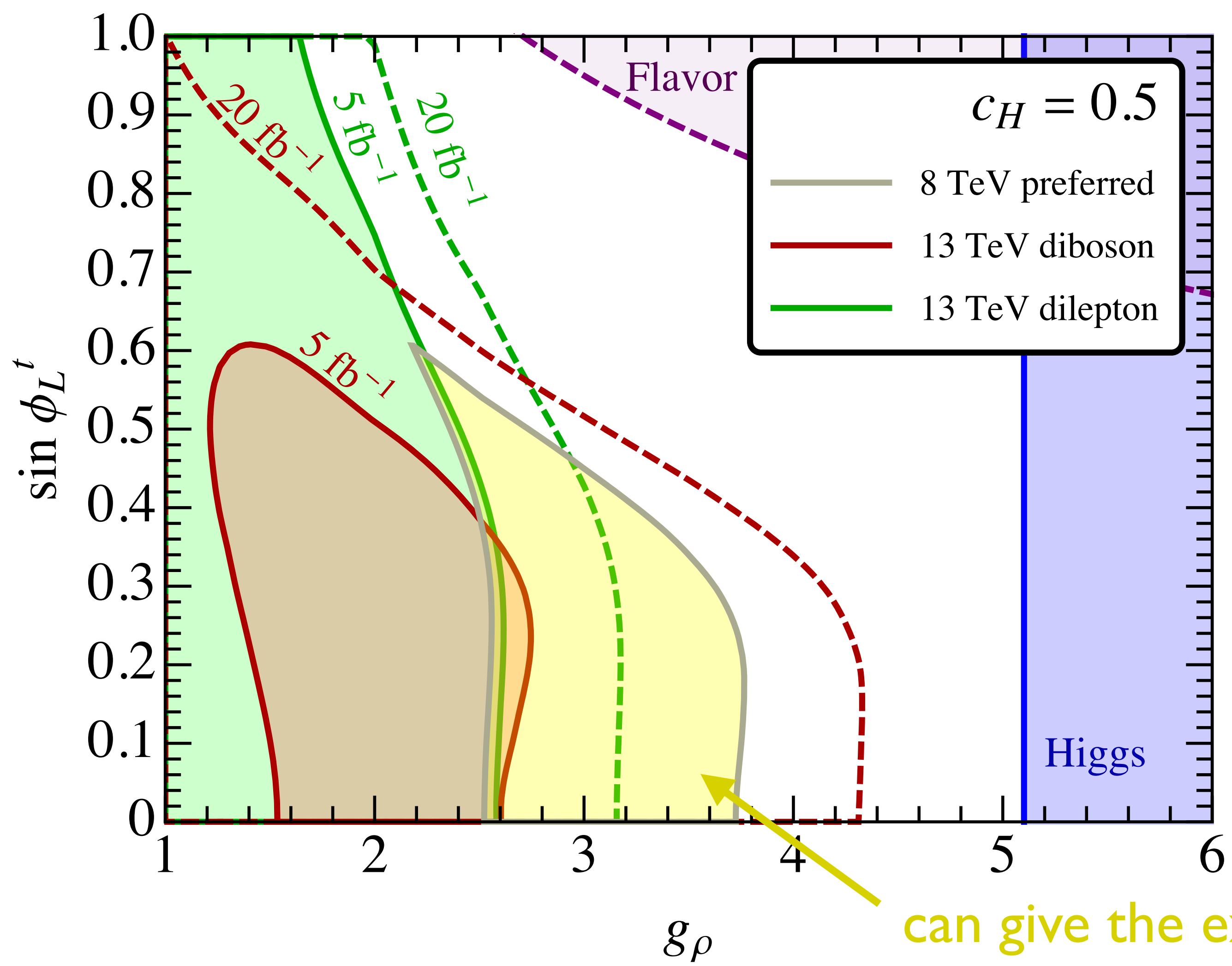
$\sin\phi_L^t = 0.1$



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

- For a twin composite scenarion, composite top can be very heavy.
  - Mixing can be smaller.

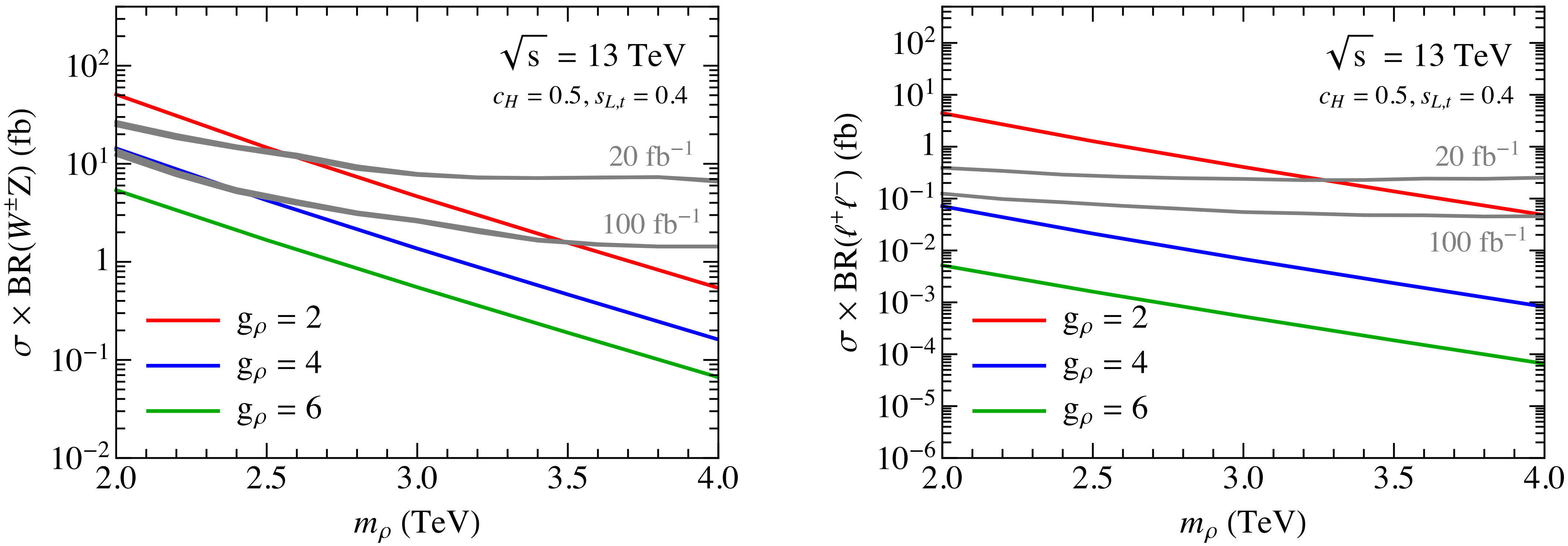
Run 2 projection



can give the excess

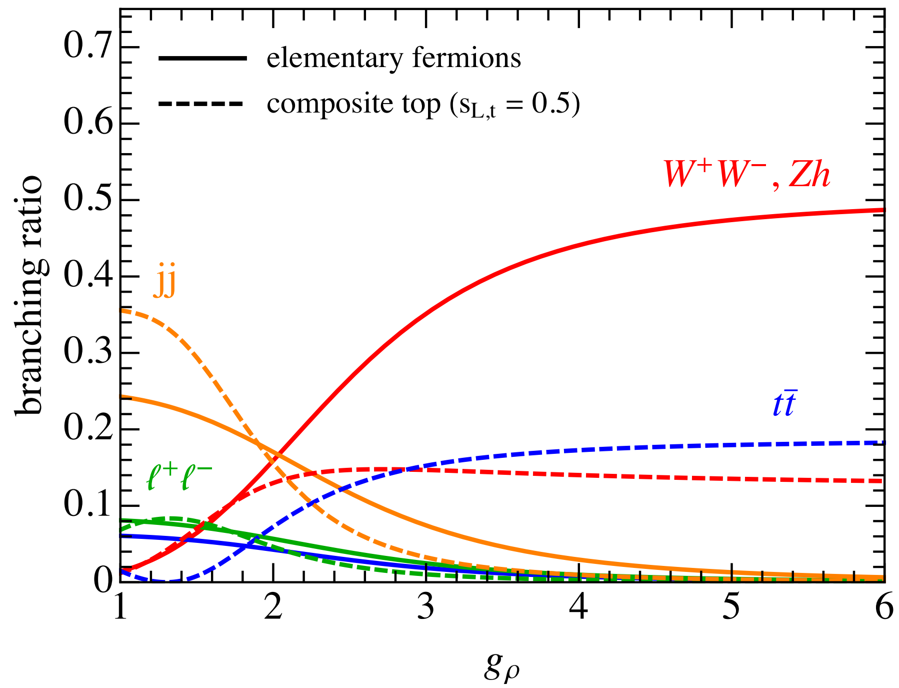
- Can confirm or rule out with modest luminosity.

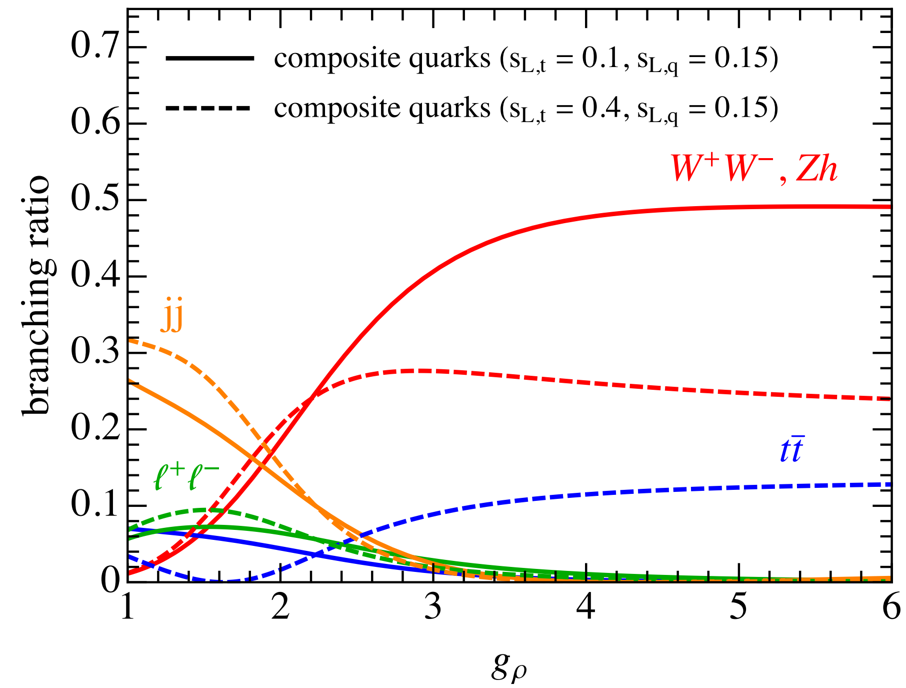
Reach of Run 2, di-boson and di-lepton



- At most 4 TeV.

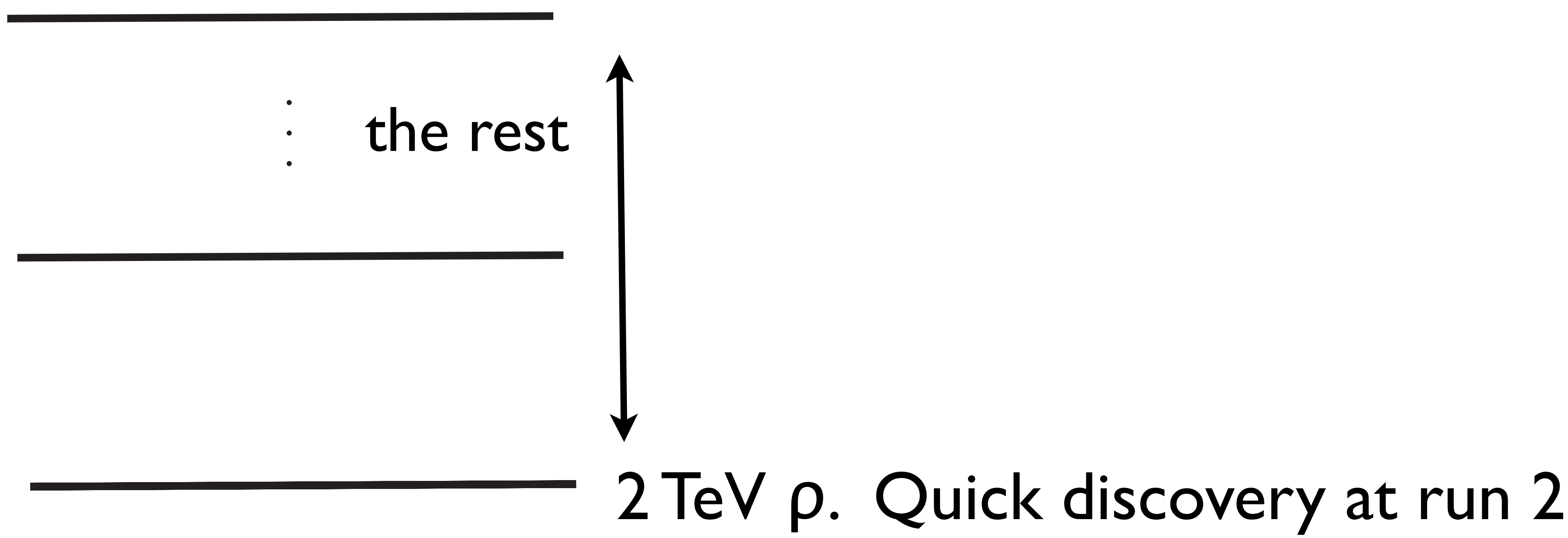
Additional channels



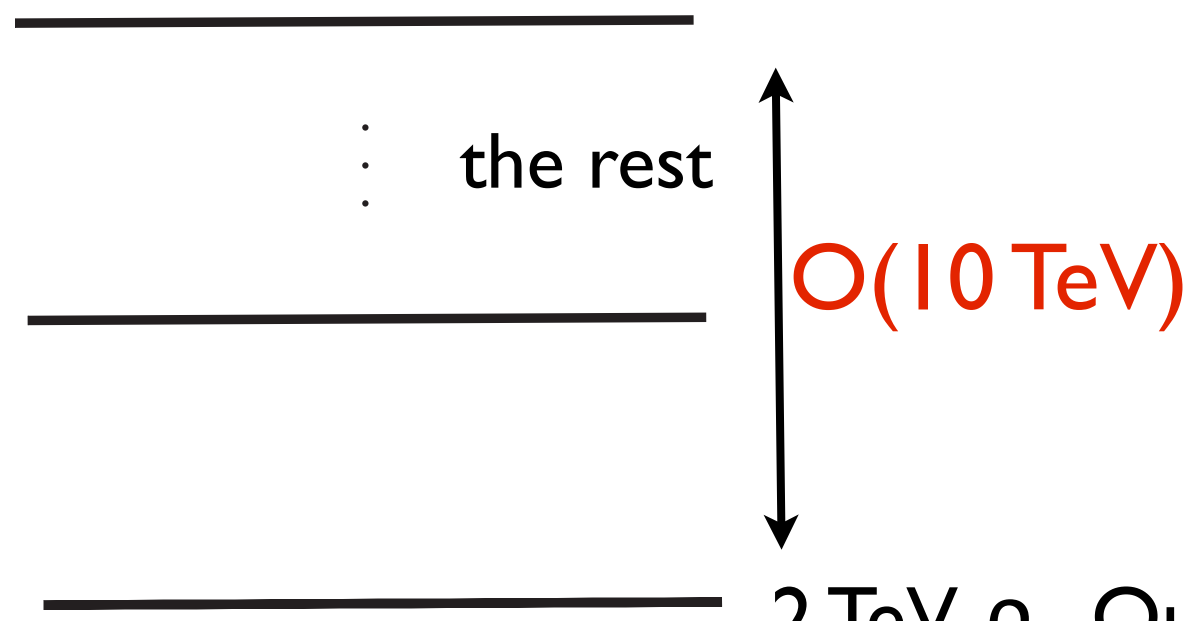


- If it is there, should be able to see it in
  - Wh, Zh
  - tt, tb

Composite Higgs



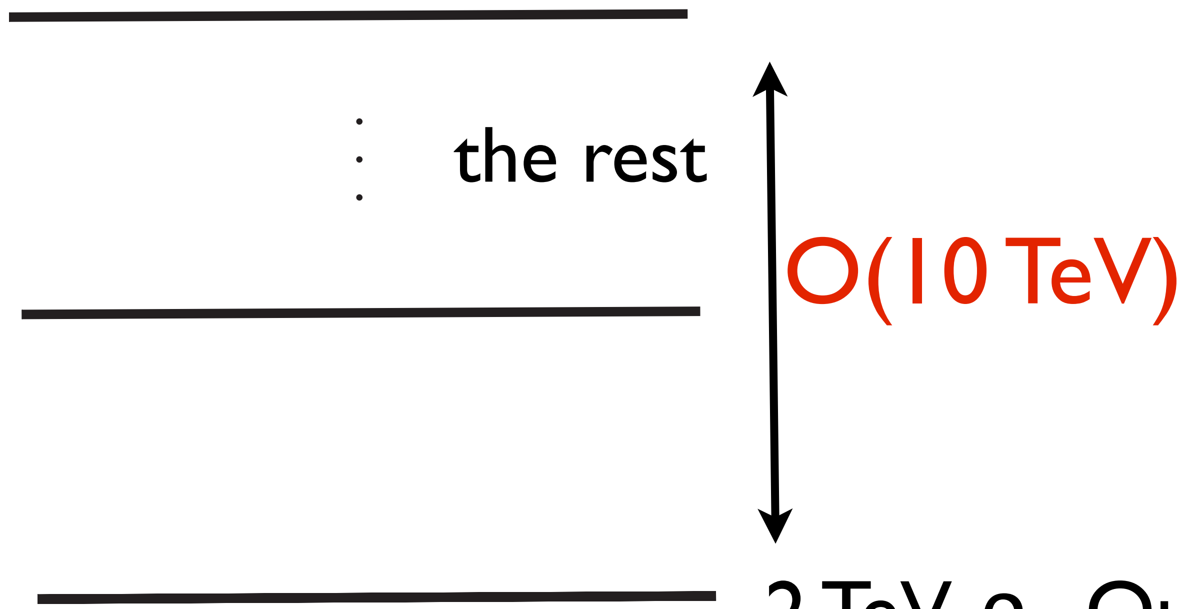
Composite Higgs



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

2 TeV ρ. Quick discovery at run 2

Composite Higgs



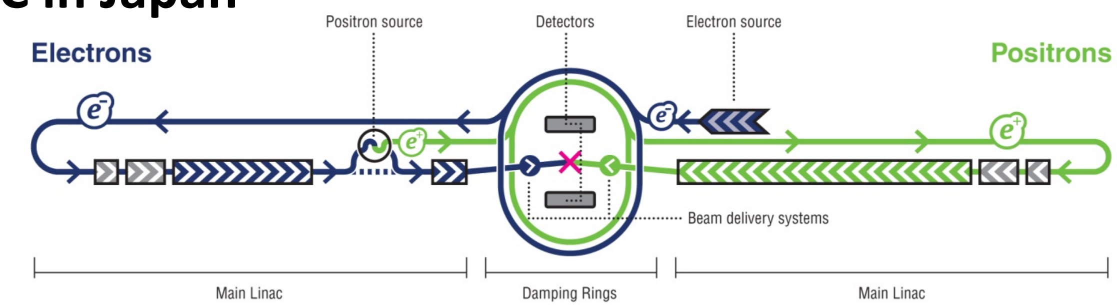
Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

2 TeV ρ. Quick discovery at run 2

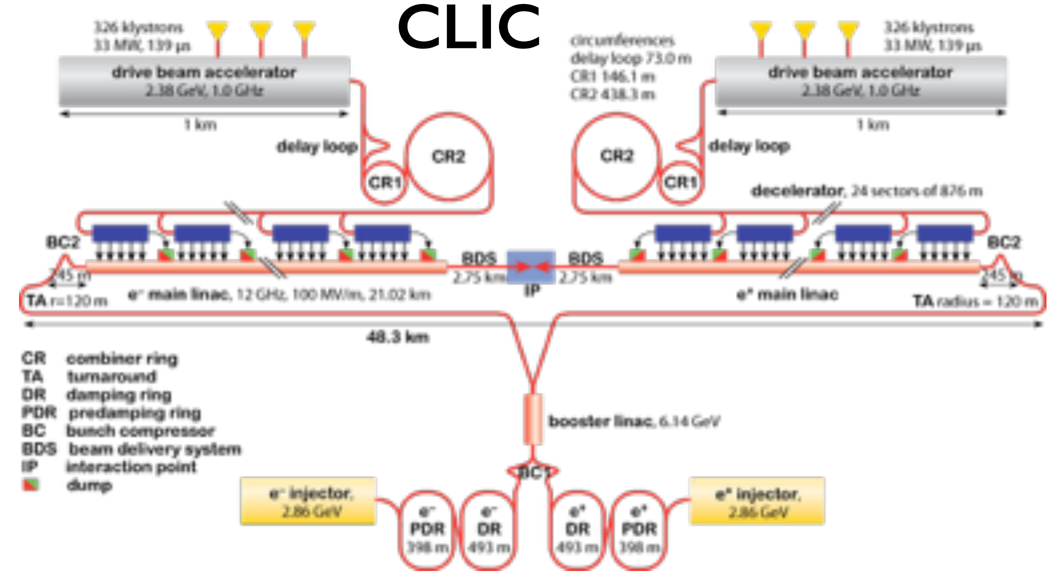
Need to go beyond!

Beyond the LHC, future facilities

ILC in Japan



CLIC

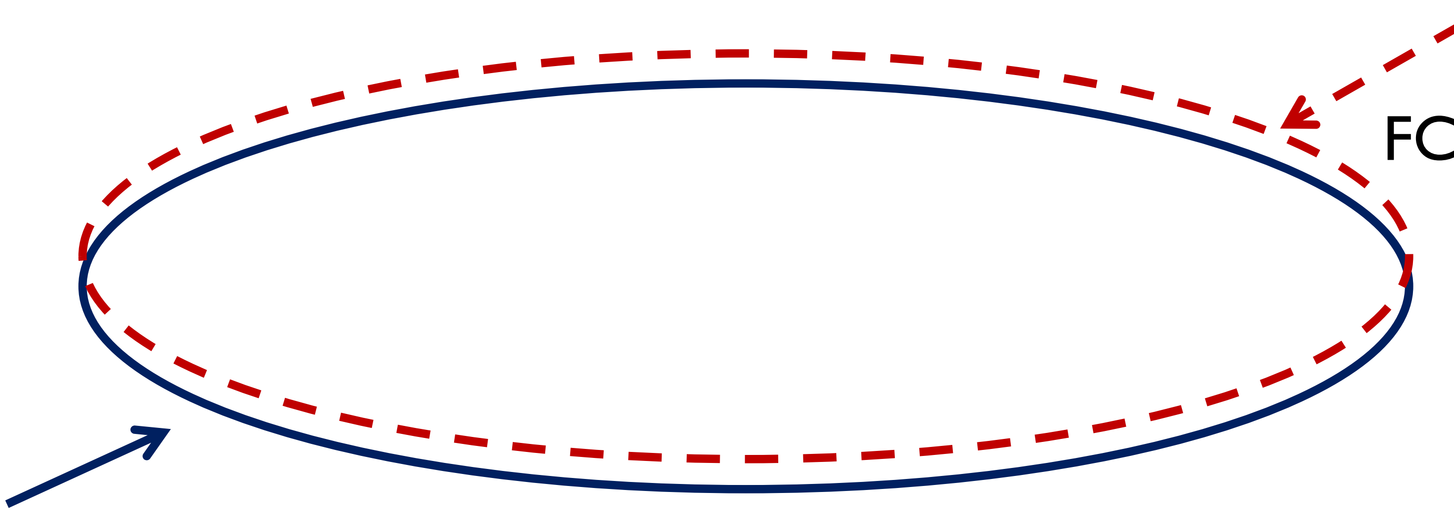


Circular. “Scale up” LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)

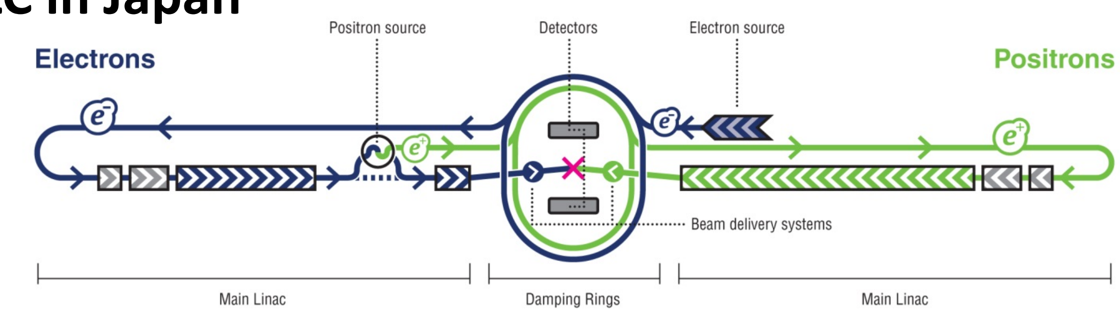


250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Beyond the LHC, future facilities

ILC in Japan



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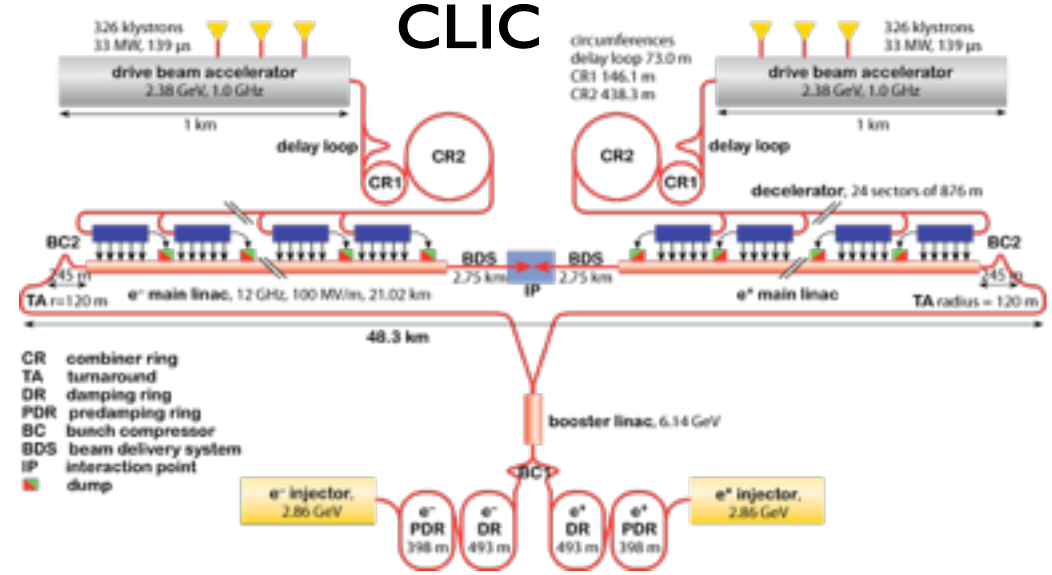

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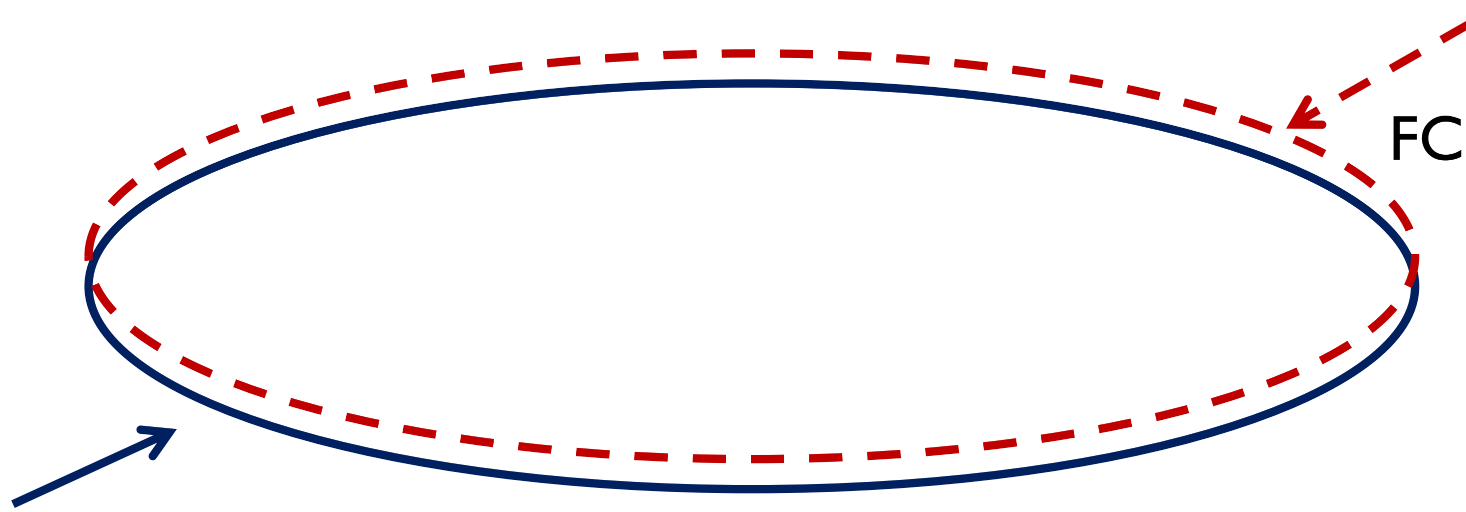
pp collider

FCC-hh (CERN), SppC(China)

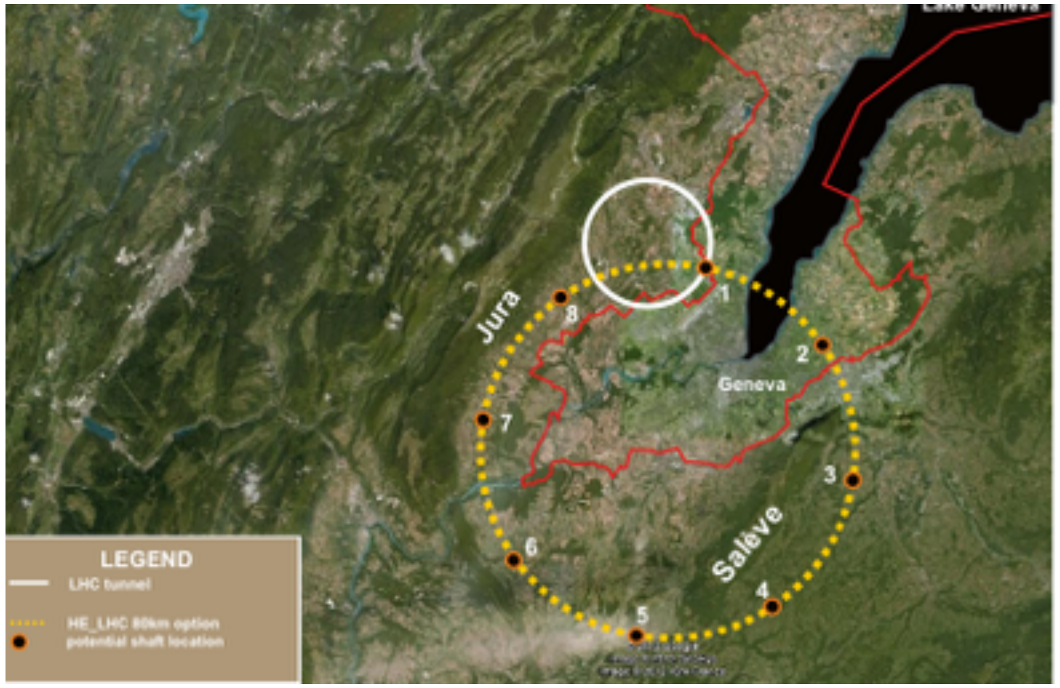


250 GeV **e^-e^+ Higgs Factory**

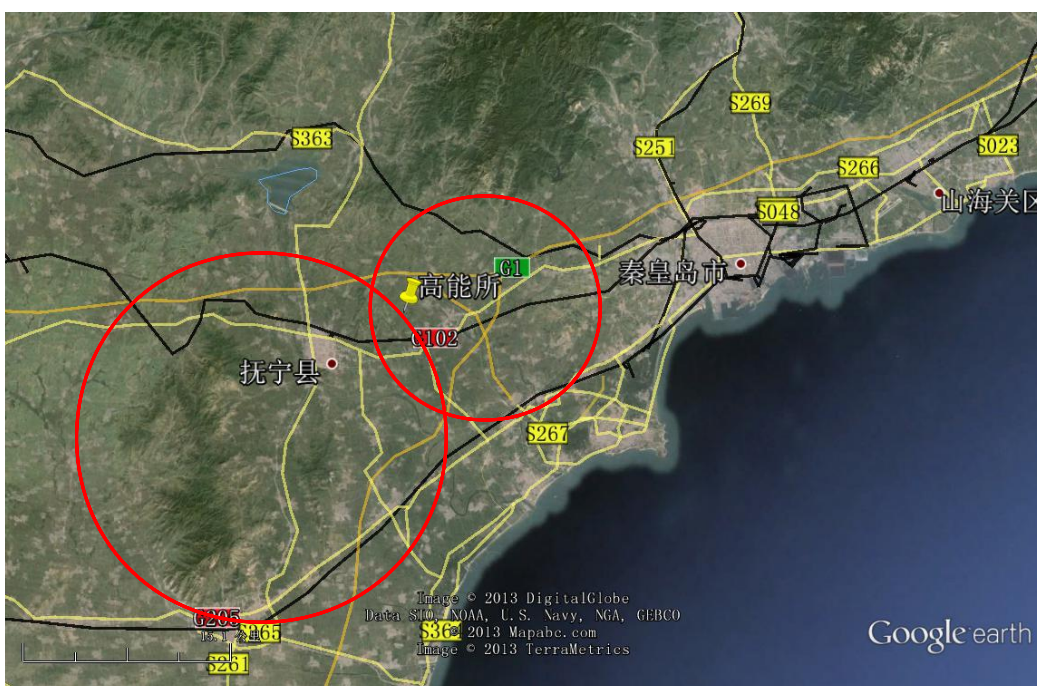
FCC-ee (CERN), CEPC(China)

I will focus on
the circular (hadron) colliders
in this talk

Future circular colliders

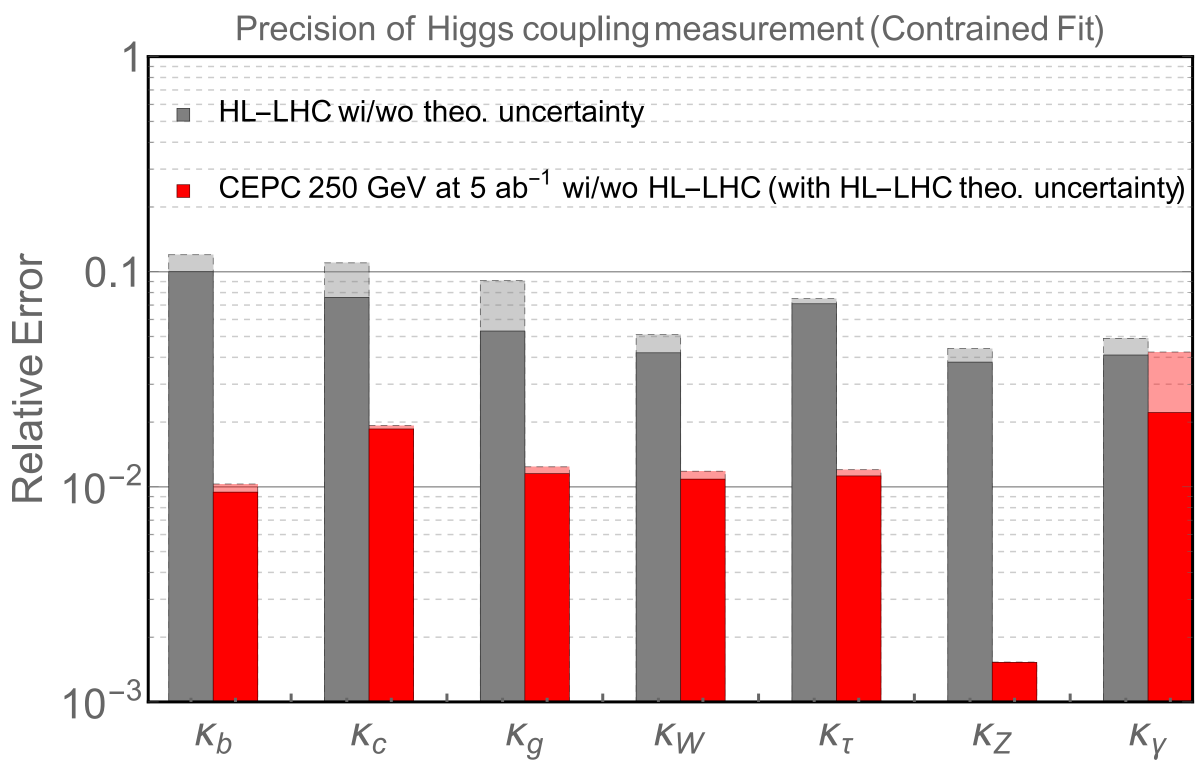


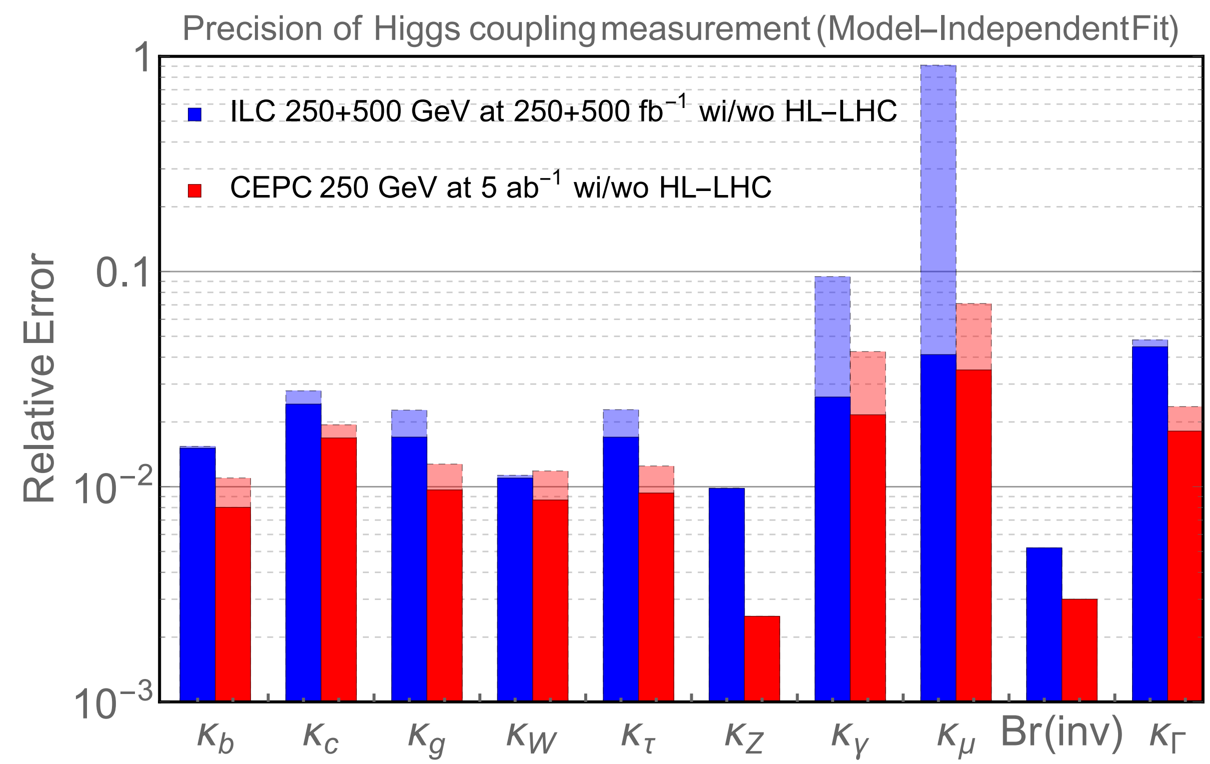
CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh



China.
Higgs factory: CEPC
pp Collider: SppC

Higgs coupling at lepton colliders



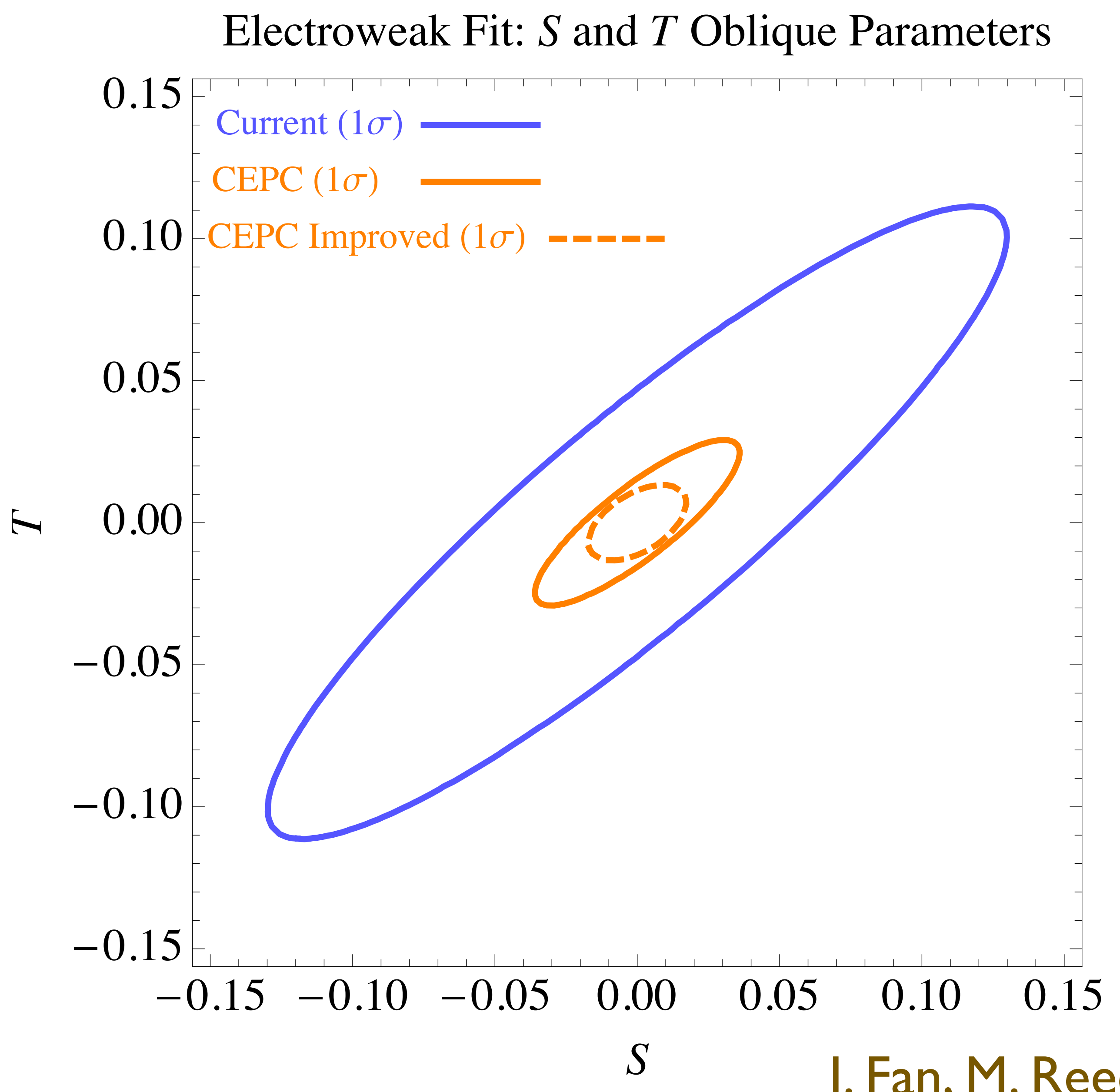


$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

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 CEPC



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	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.

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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
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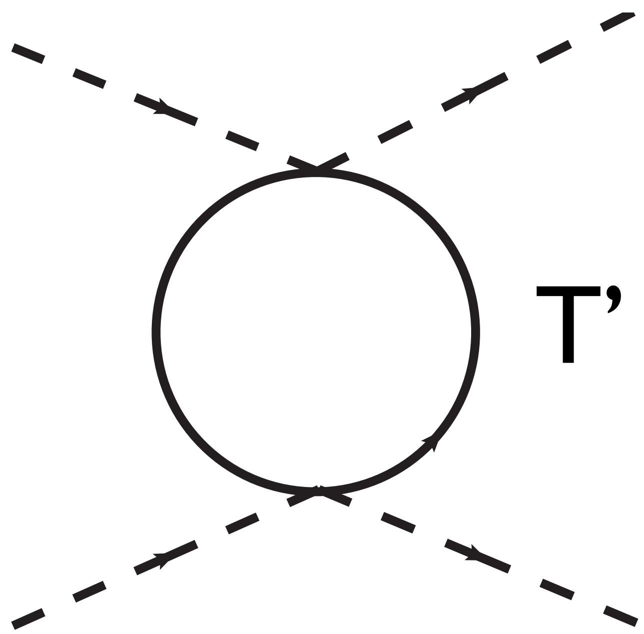
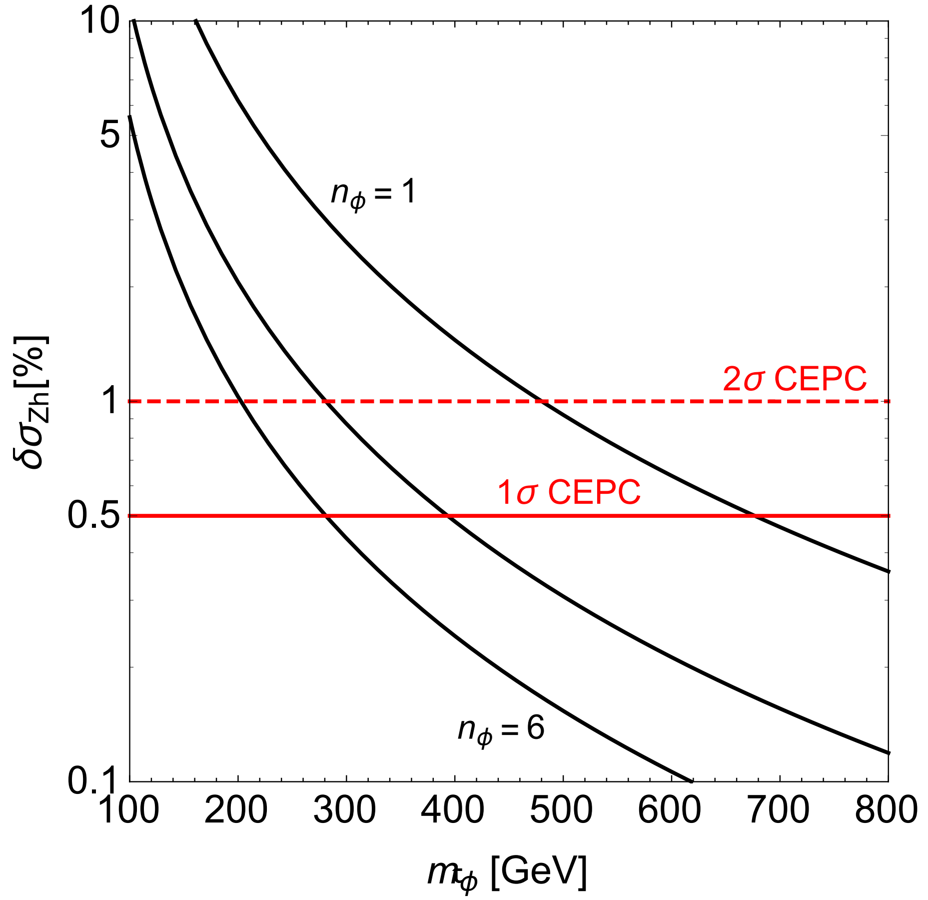
A clear big step above the LHC.

Neutral naturalness

Twin Higgs. Chacko et al. Talk by Craig



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

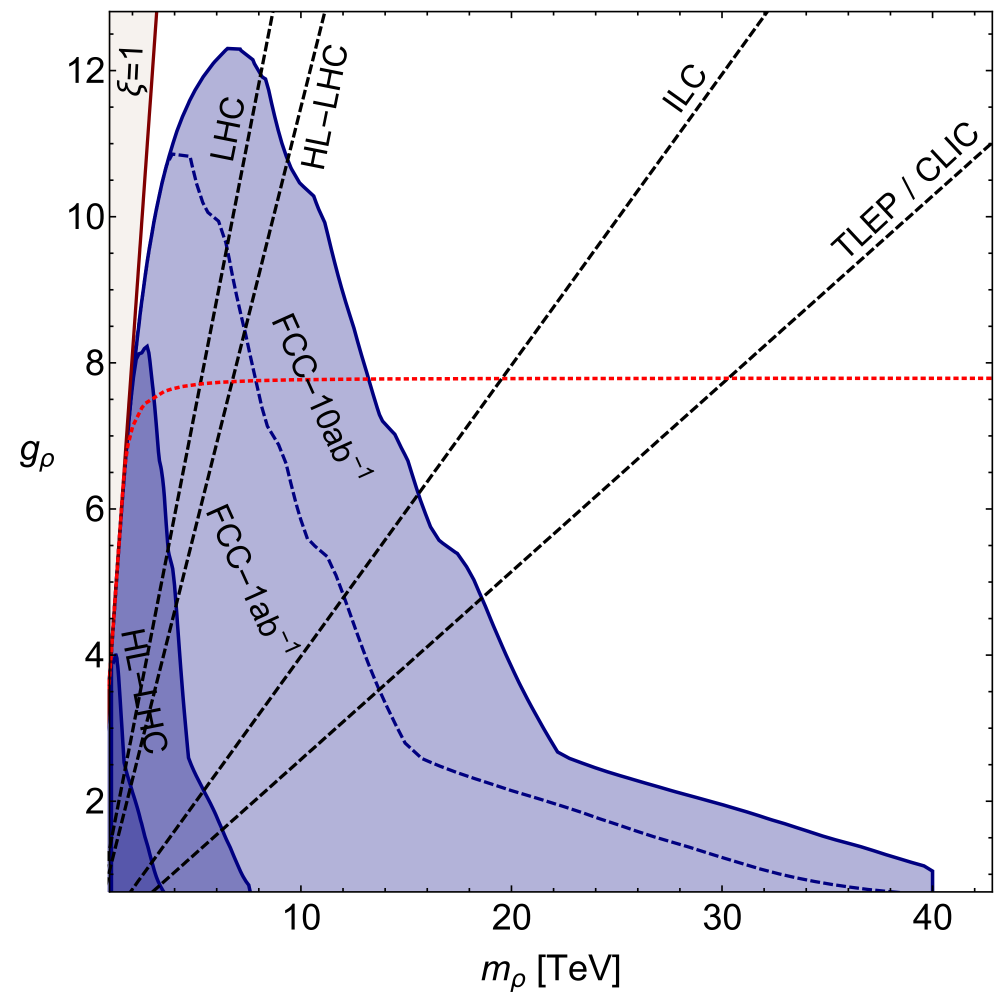


Craig, Englert, McCullough, 2013

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

At 100 TeV collider

Pappadopulo, Thamm, Torre, Wulzer, 2014



- tune proportional to $(m_{NP})^2$.
  - Much better test than LHC, by orders of magnitude!
  - Potential for discovery (would be a victory for naturalness).

Conclusions.

- Composite Higgs is a plausible solution to the naturalness problem.
- Could give rise to the excess near 2 TeV.
    - Will confirm or rule out soon at Run 2.
- Twin version can have large mass of colored top partner.
    - Di-boson will be the leading discovery channel.
- Whether the excess is there or not, spin-1 resonance should be a main target for LHC. searches.

Conclusions.

- 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.

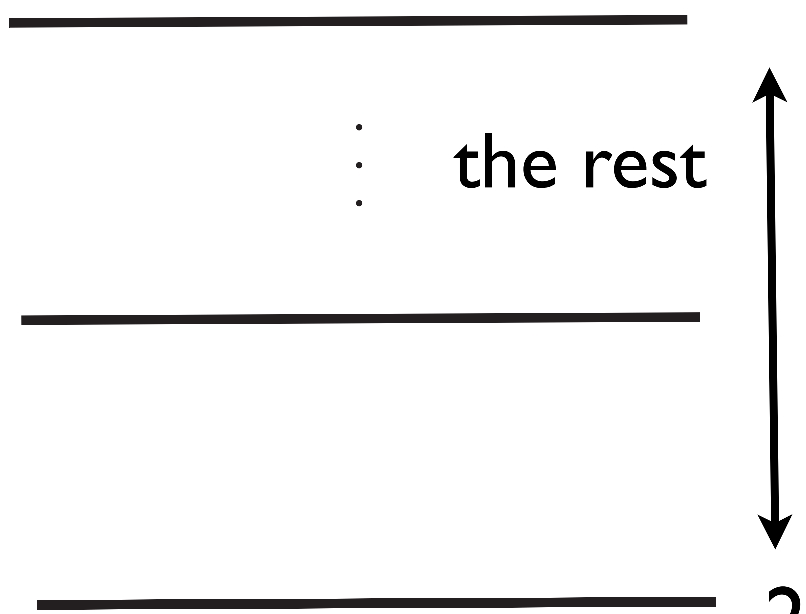
- Need to go beyond.

    - Higgs factory + 100 TeV pp collider can do a good job.

A lot to look forward to!

extras

Composite Higgs



2 TeV ρ. Quick discovery at run 2

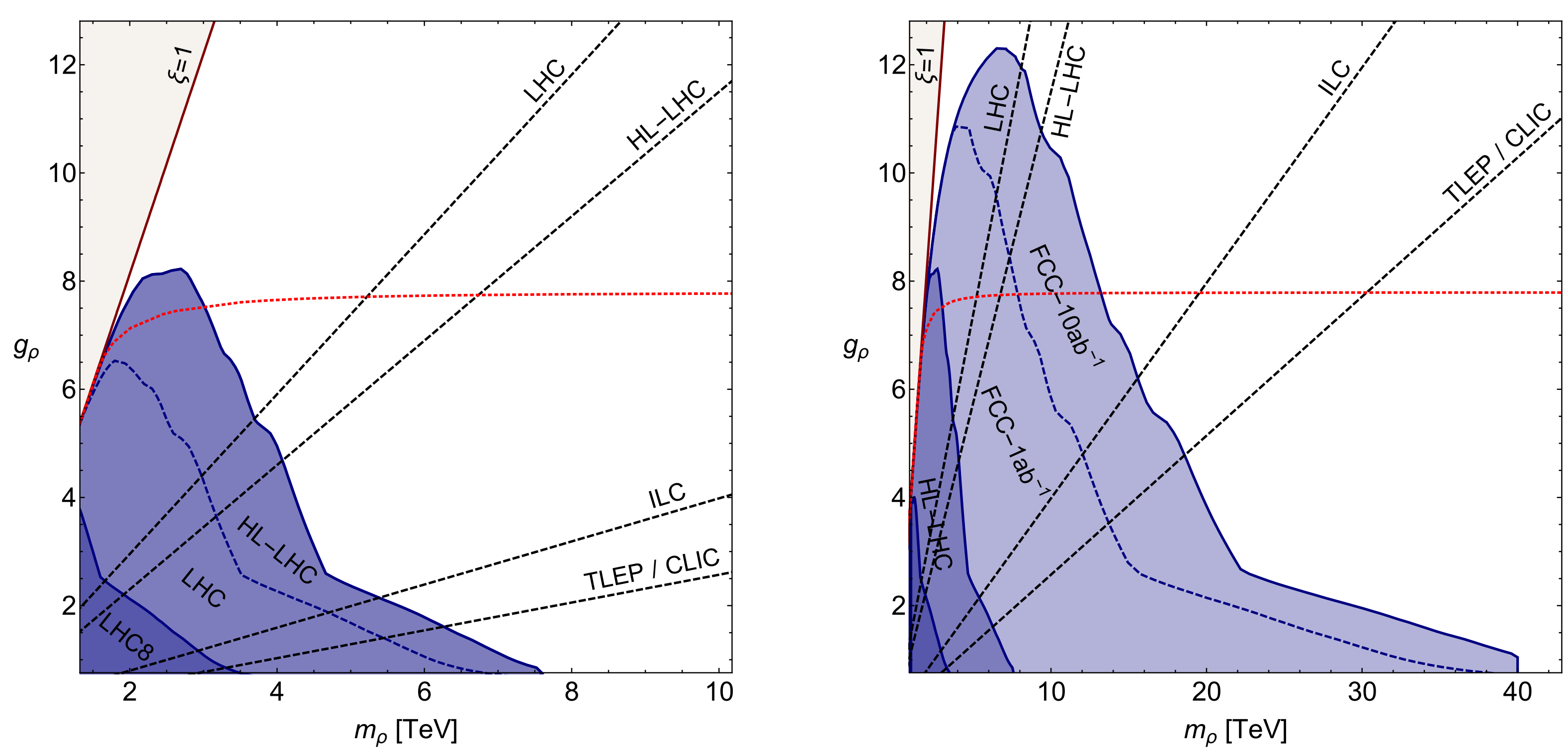
Composite Higgs

the rest

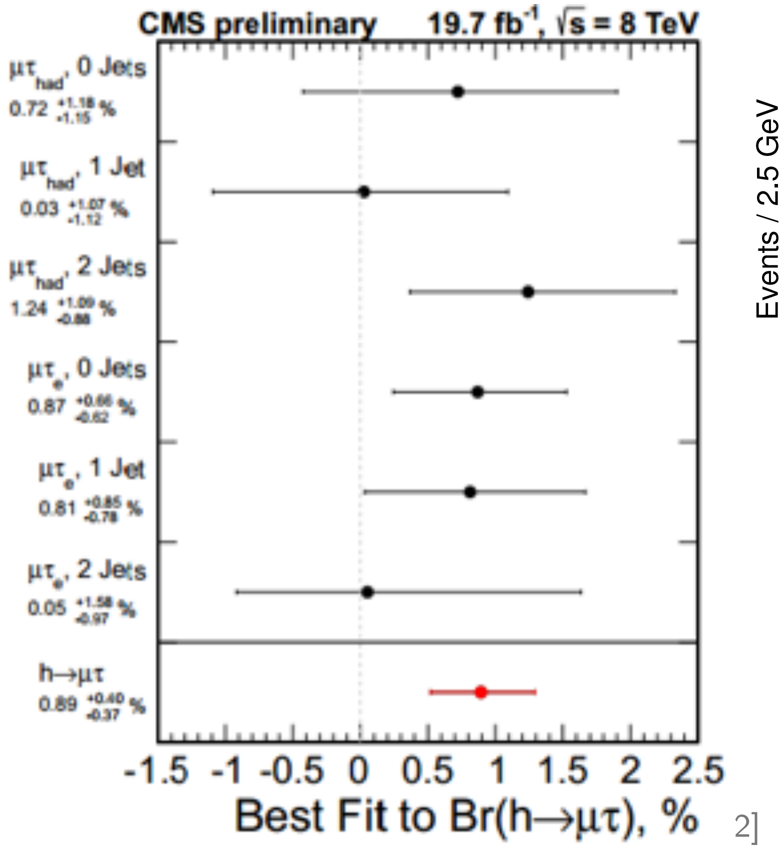
O(10 TeV)

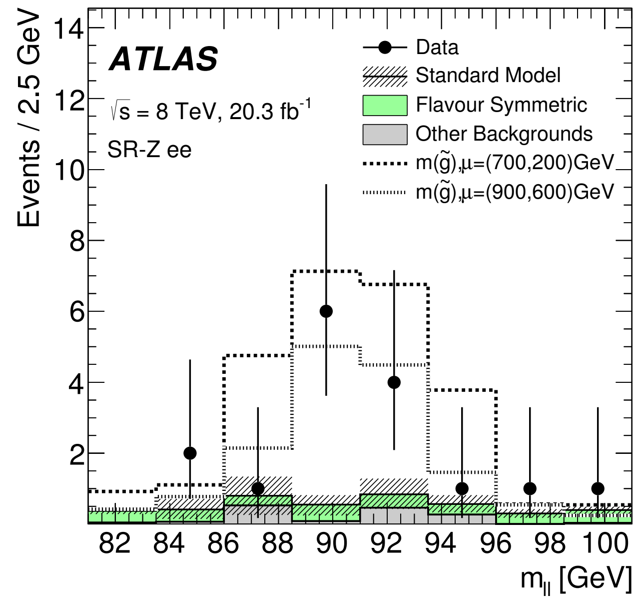
2 TeV ρ. Quick discovery at run 2

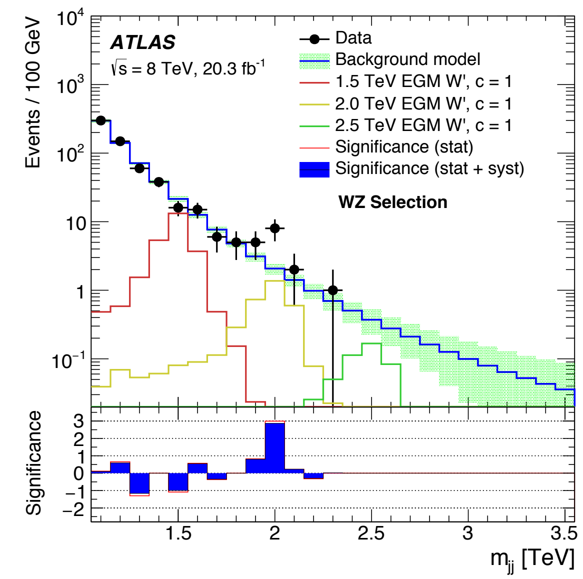
Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

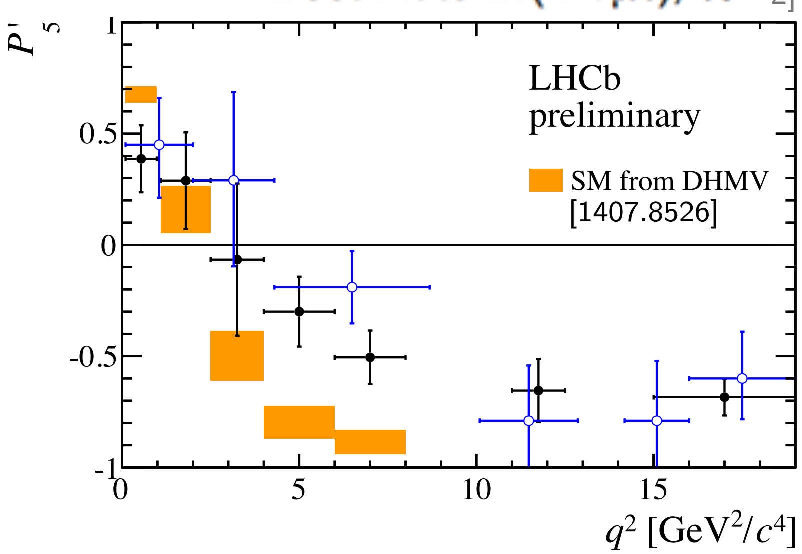


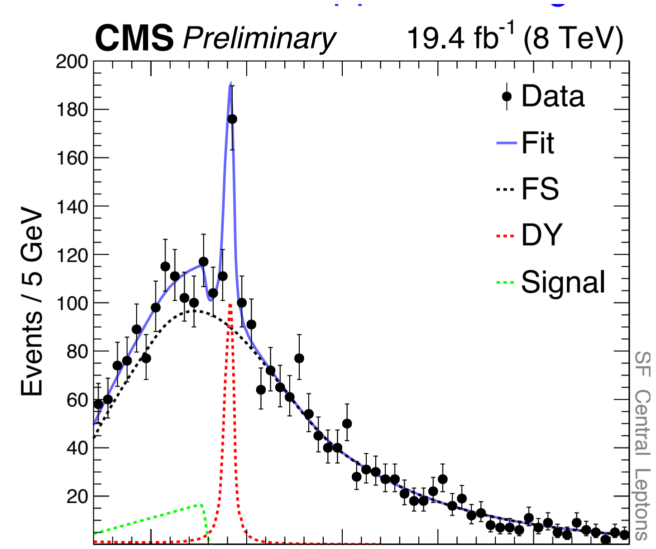
Maybe one of these?

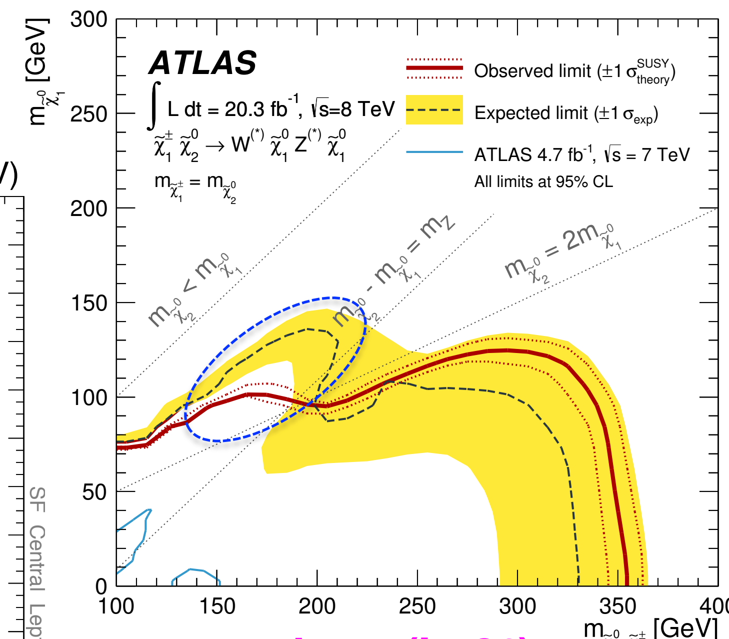










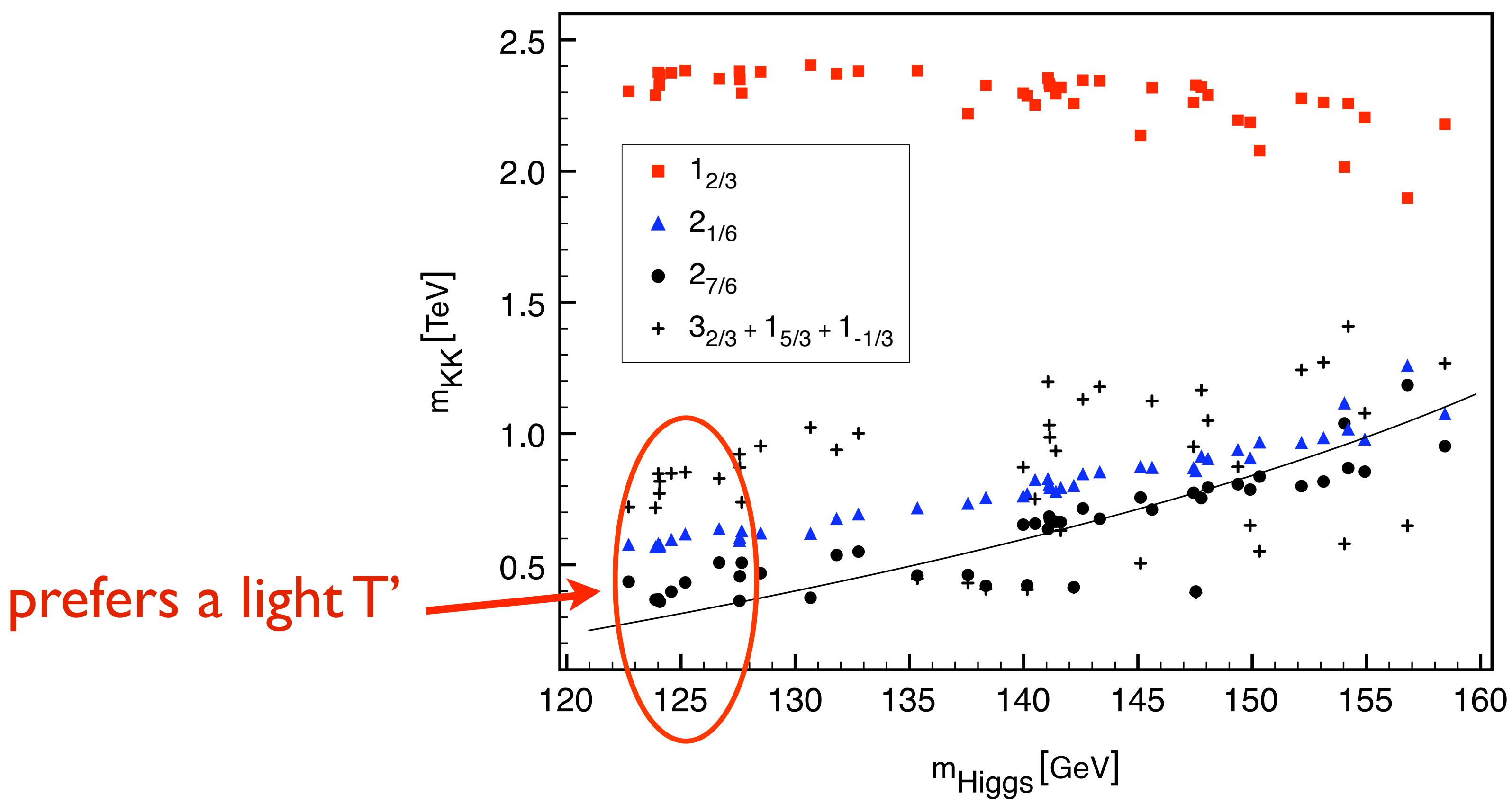


an excess here (in 3ℓ)

Or something else just around the corner?
Spectacular early discovery!

Compositeness and top partner

Wulzer's talk

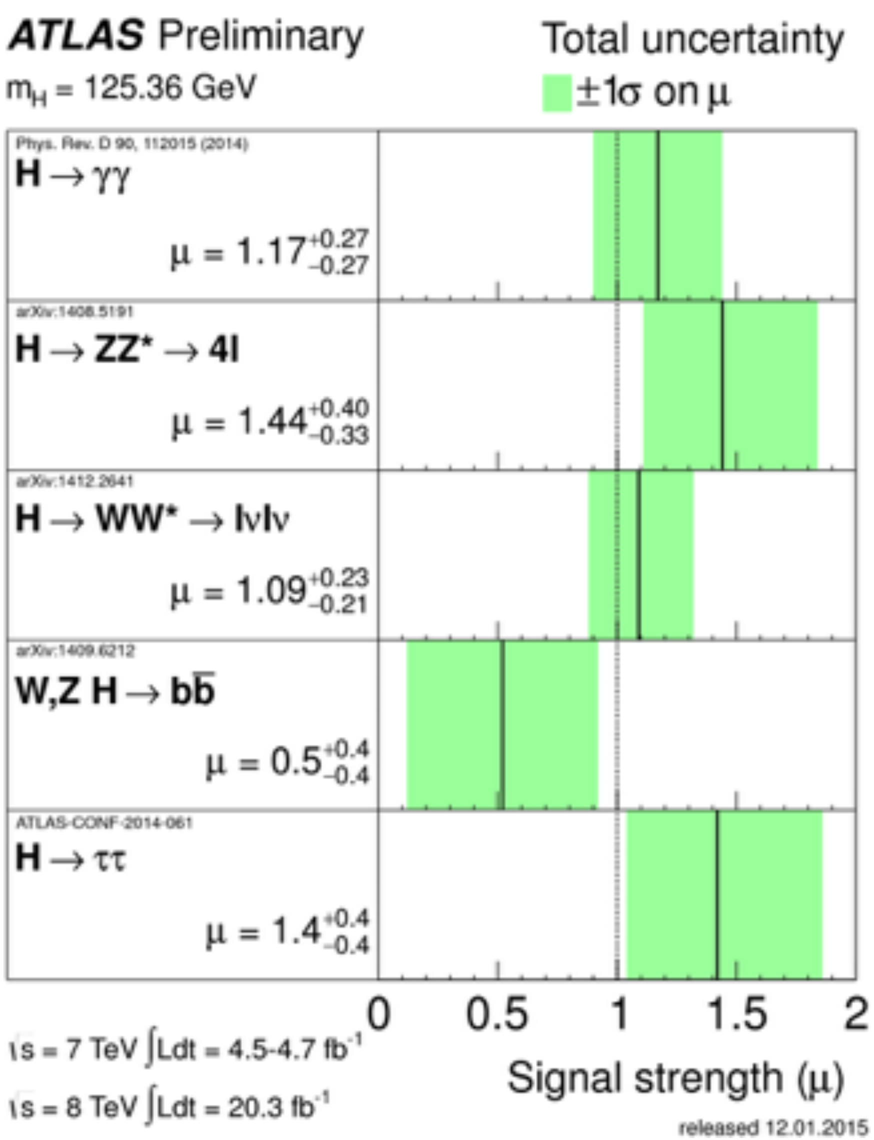


Contino, Da Rold, Pomarol, 2006

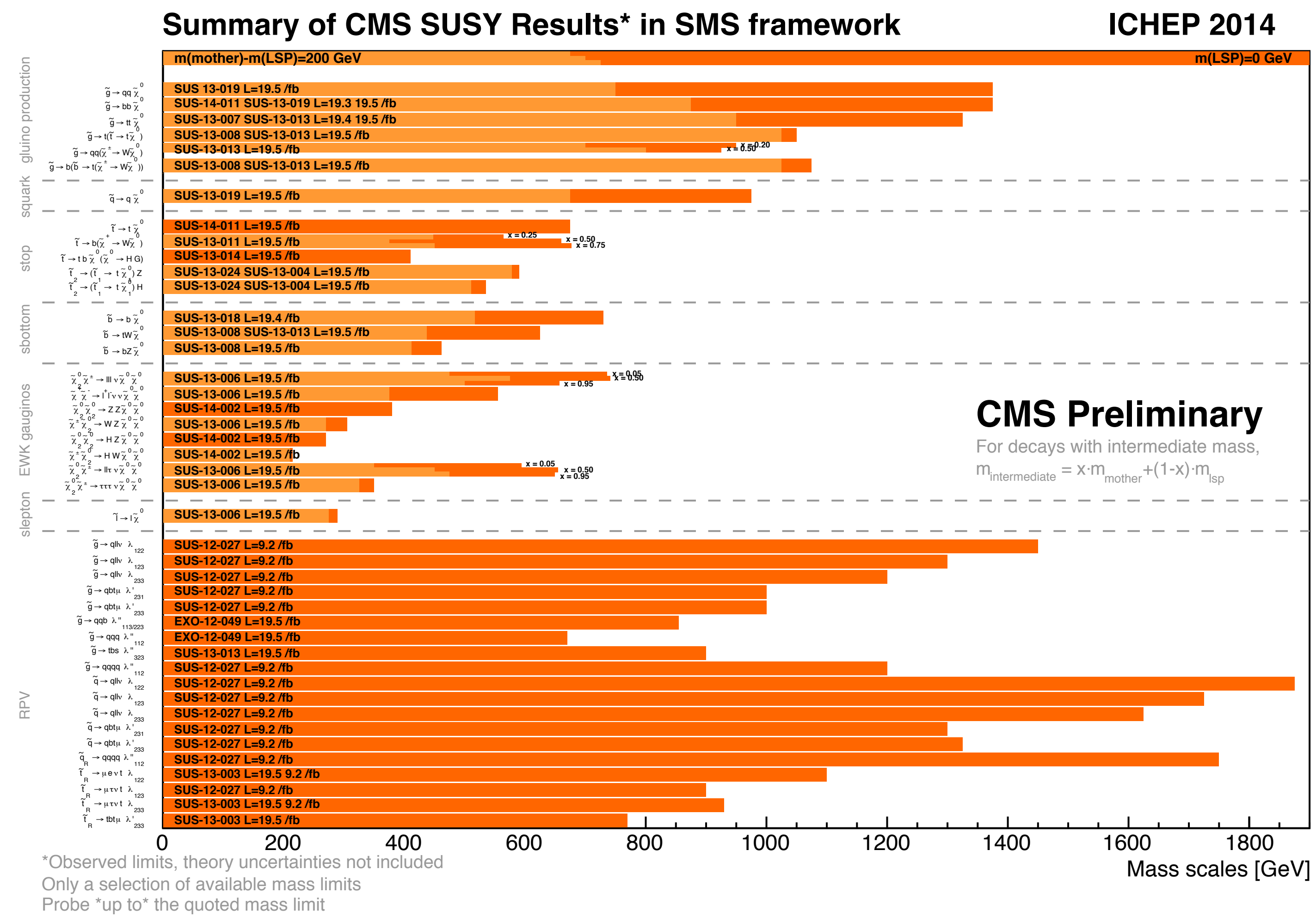
- Plays a crucial role in EWSB.

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

Current status

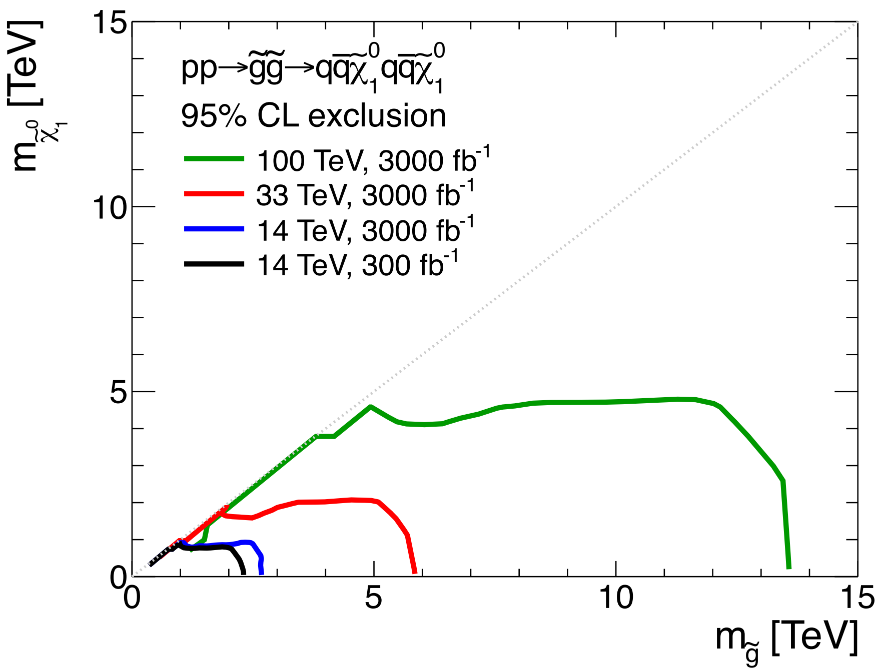


Found Higgs

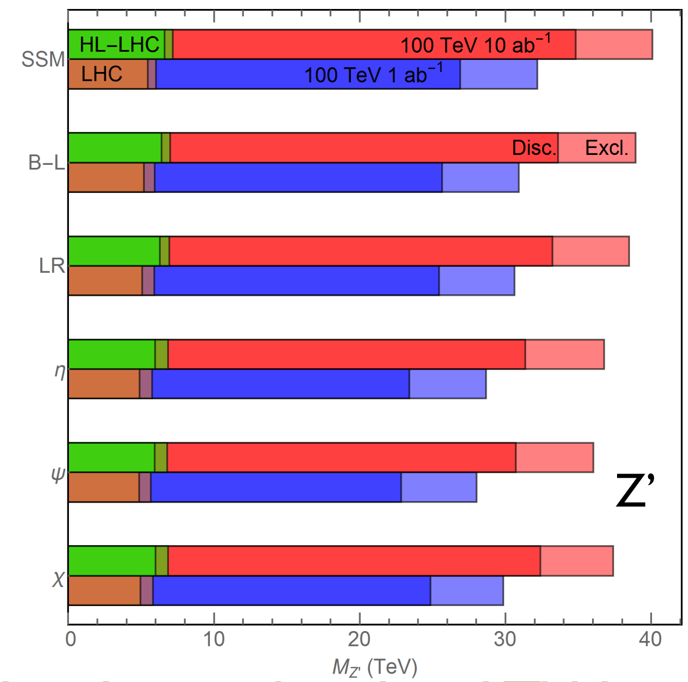


None observation of other new physics

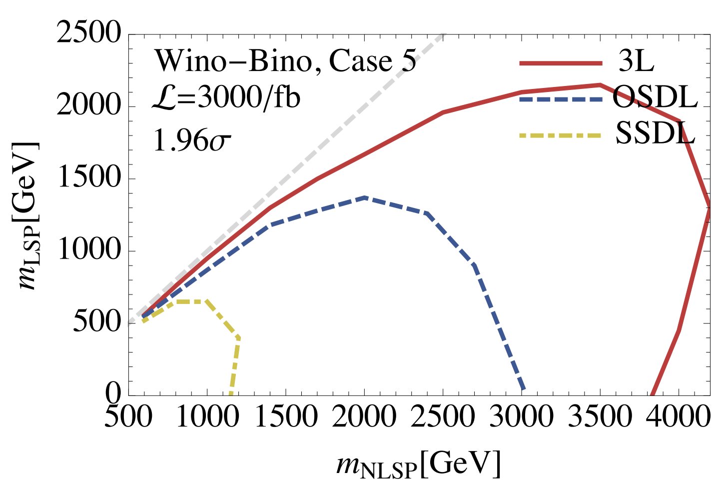
A big step forward in the energy frontier



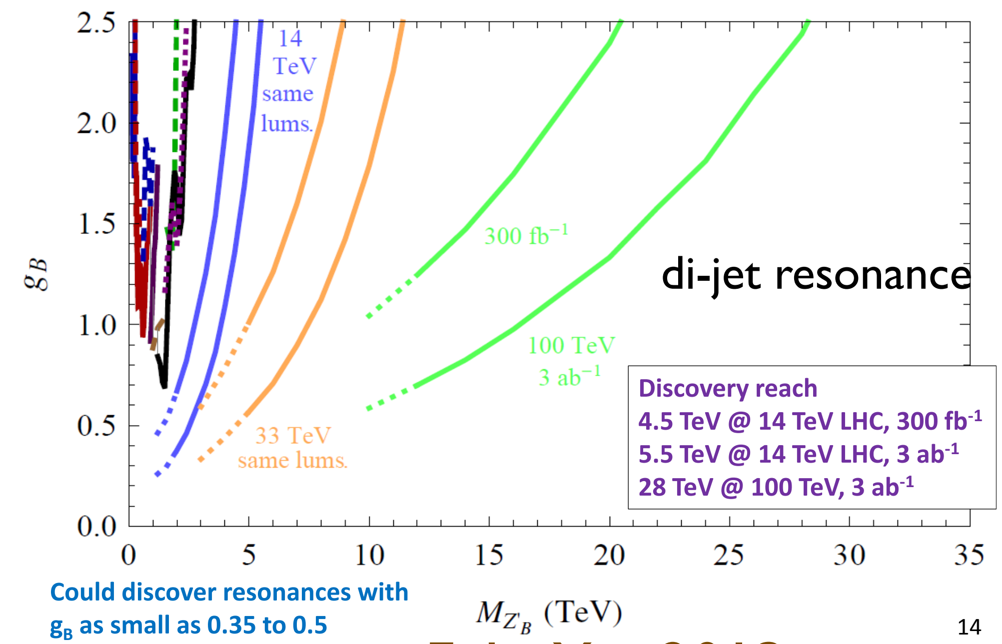
Cohen et al, 2013



Han, Langacker, Liu, LTW, to appear



Gori, Jung, LTW, Wells, 2014



Could discover resonances with g_B as small as 0.35 to 0.5

Felix Yu, 2013

cross the board: x 5(more) improvement, into (10)TeV regime