The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

2400-9

Workshop on Strongly Coupled Physics Beyond the Standard Model

25 - 27 January 2012

A view on strongly coupled EWSB

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A view on strongly coupled EWSB

&

Summary

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Was the hierarchy problem a good problem?


Higgs comin' !!

Was the hierarchy problem a good problem?

If Yes, then:

What is the dynamics of Electroweak Symmetry Breaking ?

Is it weak or is it strong?

What about Flavor?

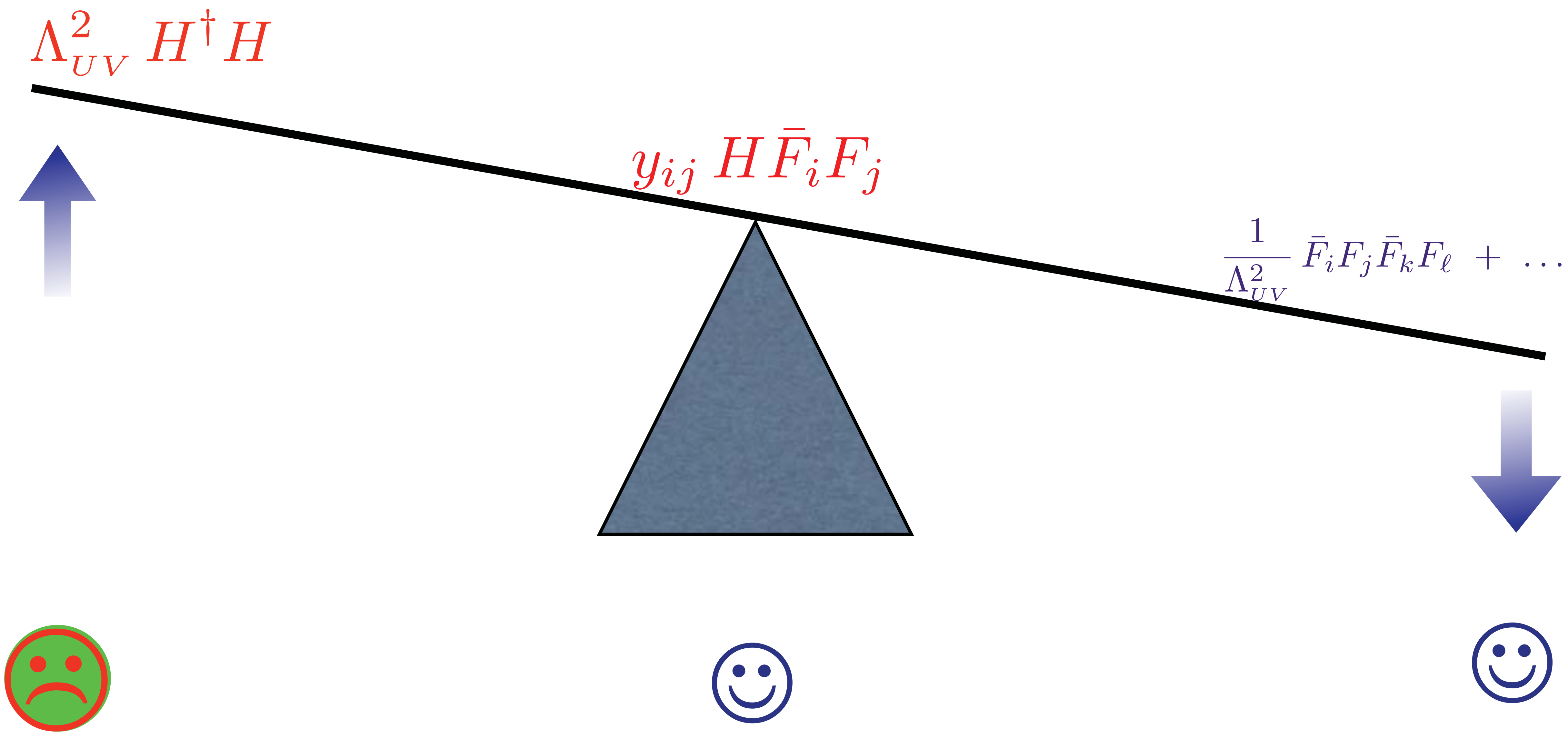
.....

I. Flavor

II. Higgs

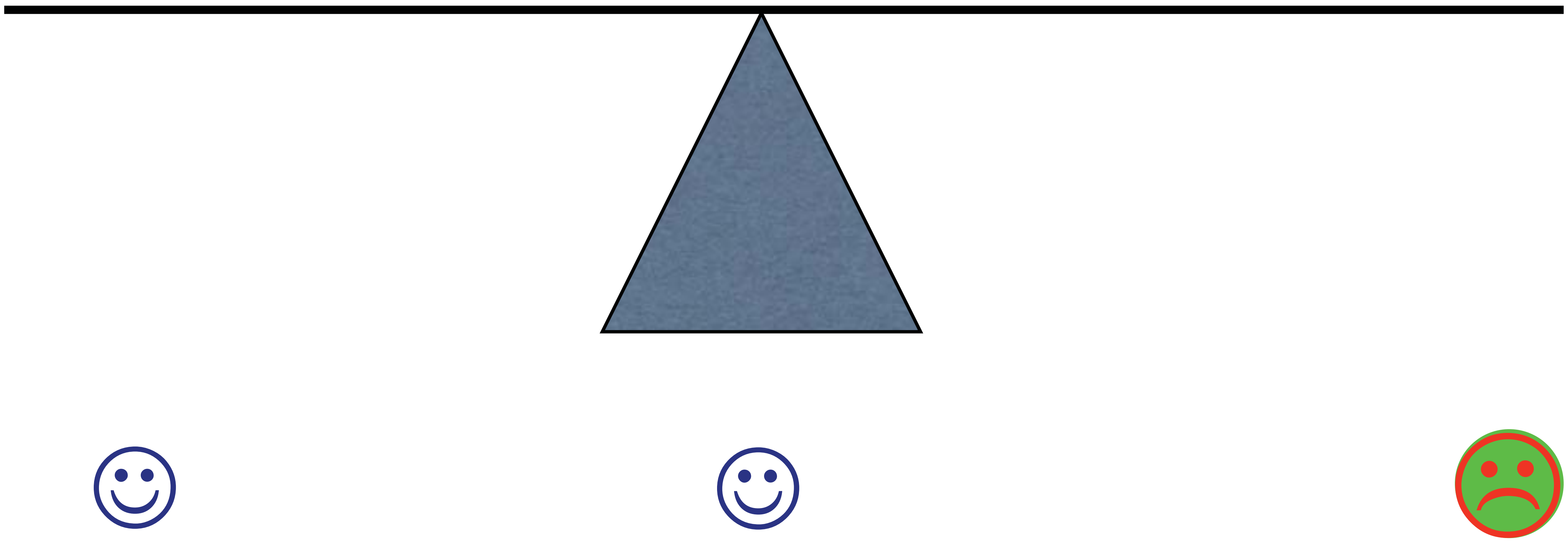
Hierarchy see-saw

Standard Model up to some $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$



Natural SM with $\Lambda_{UV}^2 \lesssim 1\,\mathrm{TeV}$

$\Lambda_{UV}^2\, H^\dagger H$ $\quad$ $y_{ij}\, H \bar{F}_i F_j$ $\quad$ $\frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \ldots$



Strongly coupled EWSB: basic picture

Λ_{UV}^{II}

TeV$\equiv \Lambda_{UV}^{I}$

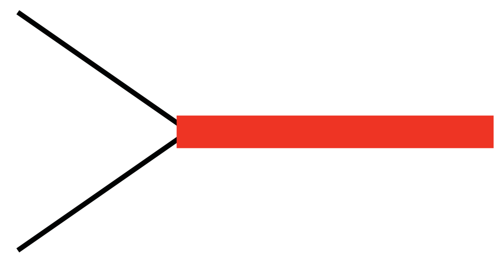
Use $\Lambda_{UV}^{II} \gg$ TeV
to filter out unwanted
effects and produce a
realistic Flavor story

Should one, or should one not,
assume $\sim$ conformal invariance ?
ask J.F. Fortin and M. Luty

Three Ways to Flavor

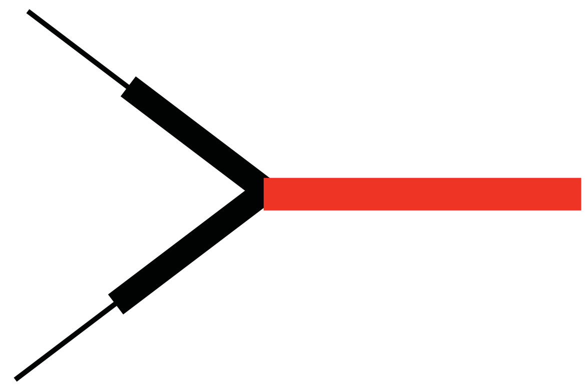
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui



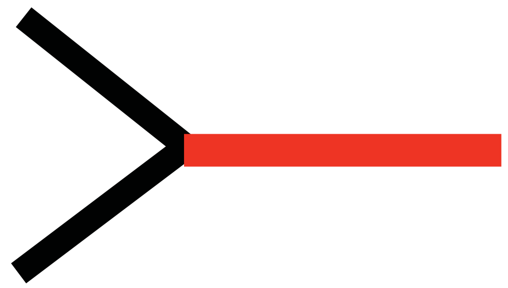
Linear: partial compositeness

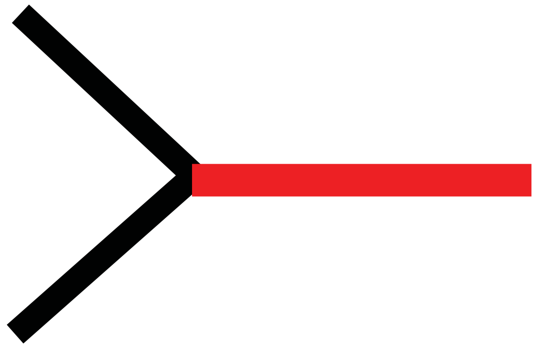
D.B. Kaplan
....
Huber
RS with bulk fermions



Total compositeness

ex: minimal RS
Rattazzi-Zaffaroni





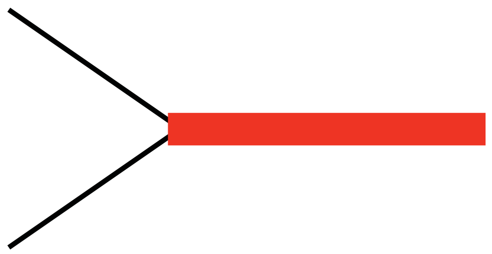
$$\frac{g_\rho^2}{m_\rho^2}\ \bar{\ell}\ell\bar{\ell}\ell$$

$$m_\rho > g_\rho \times 5\,\mathrm{TeV} \sim \frac{50\,\mathrm{TeV}}{\sqrt{N}}$$

$$\frac{g_\rho^2}{m_\rho^2}\ \bar{q}q\bar{q}q$$

$$m_\rho > g_\rho \times 3\,\mathrm{TeV} \sim \frac{30\,\mathrm{TeV}}{\sqrt{N}}$$

...and we haven't even broken flavor yet
let us move on!



Wishes ...

Flavor

$$\frac{1}{\Lambda_{UV}^{d_H-1}} H\bar{F}F \; + \; \frac{c}{\Lambda_{UV}^2}\bar{F}F\bar{F}F$$

wish d_H as close to 1 as possible

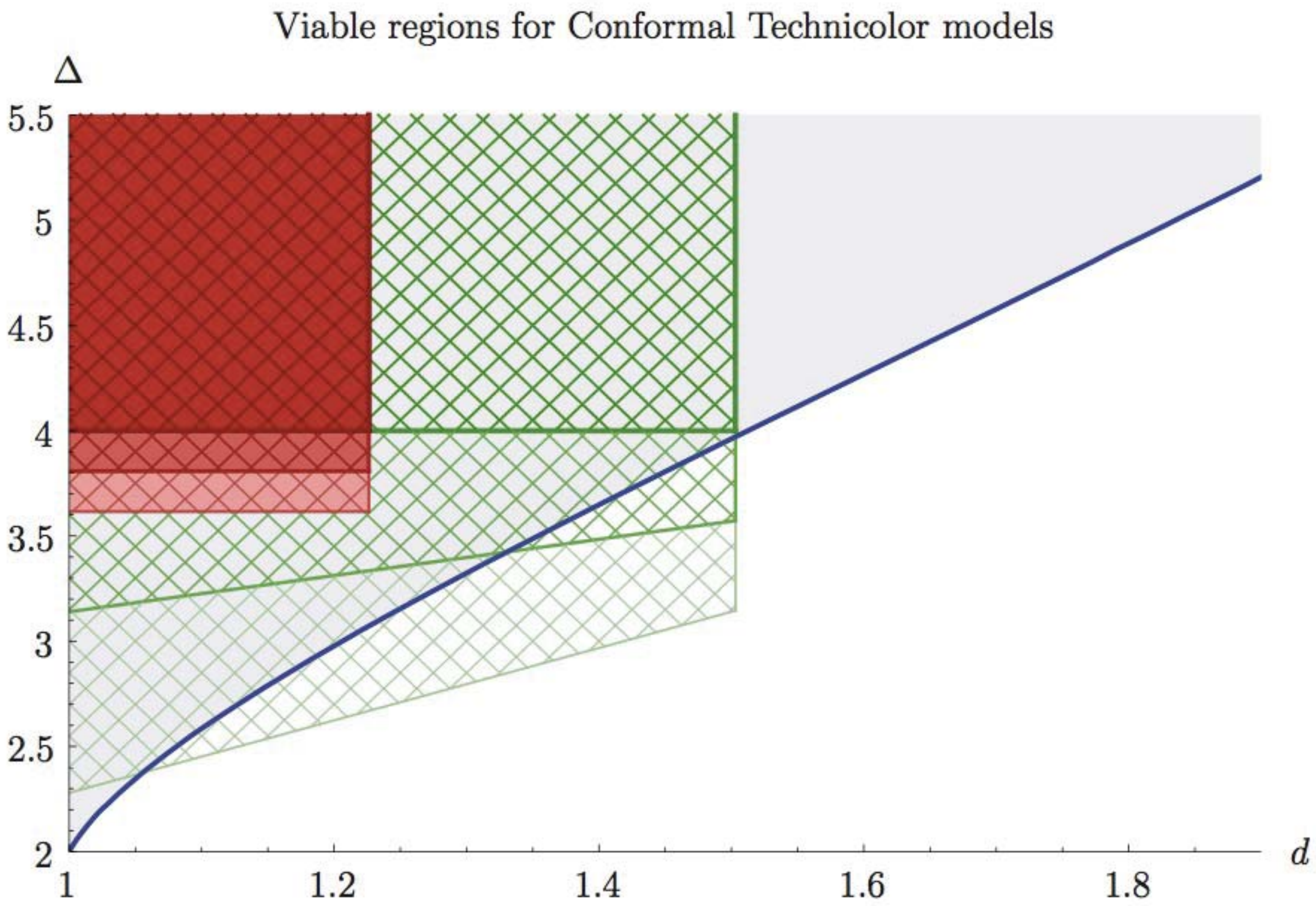
Hierarchy

$$(\Lambda_{UV})^{\Delta-4} \, H^\dagger H \qquad \Delta \equiv \dim(H^\dagger H)$$

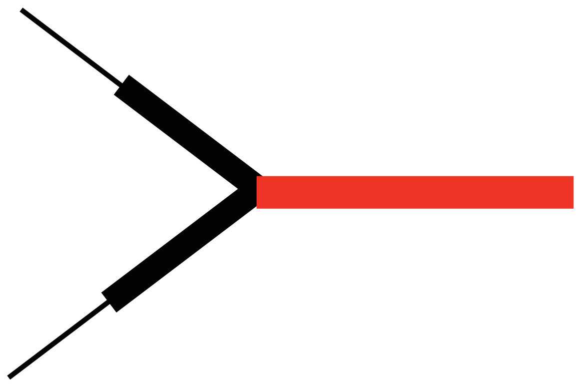
wish $\Delta > 4 - \varepsilon$

Poland's talk

... Constraints



Poland, Simmons-Duffin, Vichi '11



$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \mathcal{O}_q^i + \epsilon_u^i u_L^i \mathcal{O}_u^i + \epsilon_d^i d_L^i \mathcal{O}_d^i$$

Yukawas

$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_\rho$$

$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_\rho$$

ΔF=1

$$\epsilon_q^i \epsilon_u^j g_\rho \times \frac{v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \quad \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$$

ΔF=2

$$\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_\rho^2}{m_\rho^2} \quad (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$$

Bounds & and perhaps an interesting hint

my thanks to Isidori,Perez, Redi,Weiler

ϵ_k $\qquad$ $m_\rho \gtrsim 20\ \text{TeV}$

?

$\epsilon'/\epsilon, \quad b \to s\gamma, \quad d_n$ $\qquad$ $m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (20-40)\ \text{TeV}$

LHCb
CP violation in D decays

$\Delta a_{CP} = a_{KK} - a_{\pi\pi} = -(0.82 \pm 0.21 \pm 0.11)\%$ $\qquad$ $m_\rho \simeq \frac{g_\rho}{4\pi} \times 10\ \text{TeV}$

Curiously `borderline', though connection with weak scale not too good
Obviously need a composite light Higgs to tune VEV

Tuning $\qquad$ $$\frac{v^2}{f^2} = \left(\frac{g_\rho \times 200\ \text{GeV}}{m_\rho}\right)^2 \lesssim 10^{-2}$$

$$\mu \to e\gamma \qquad\qquad \frac{\sqrt{m_\mu m_e}}{m_\rho^2}\,\bar{\mu}\sigma_{\alpha\beta}e\,F^{\alpha\beta}$$

MEG: Br($\mu \to e\,\gamma$) < 2.4 x 10^{-12} $\qquad$ $m_\rho \gtrsim 10^3$ TeV

Partial compositeness clearly cannot be the full story

Must assume strong sector possesses some flavor symmetry

Range of possibilities

$U(1)_e$ x $U(1)_\mu$ x $(1)_\tau$

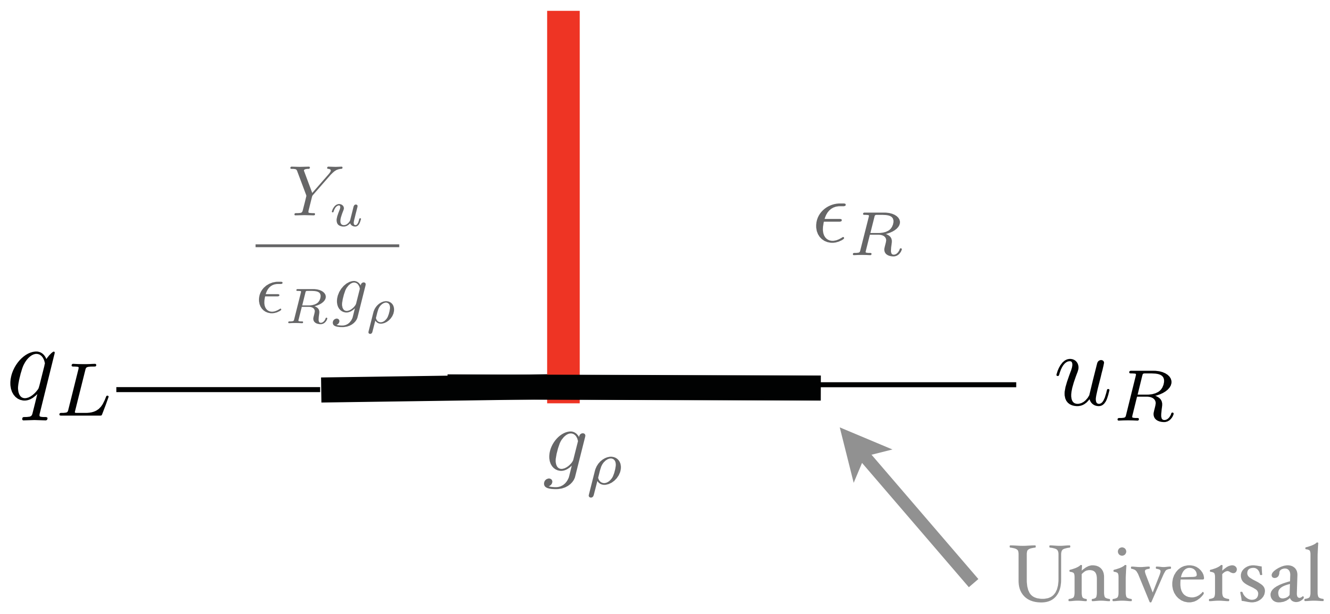
. . . .

SU(3) x SU(3) x ...

Basically the only case where it makes sense to invoke MFV

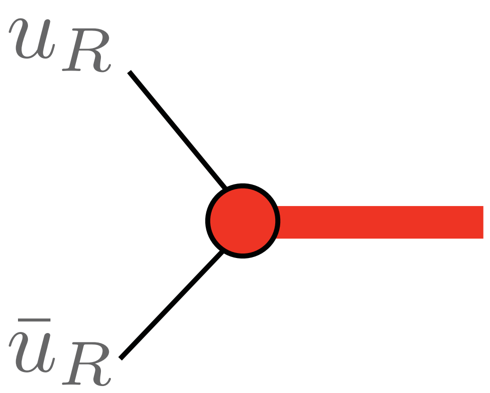
Redi, Weiler '11

Weiler's talk



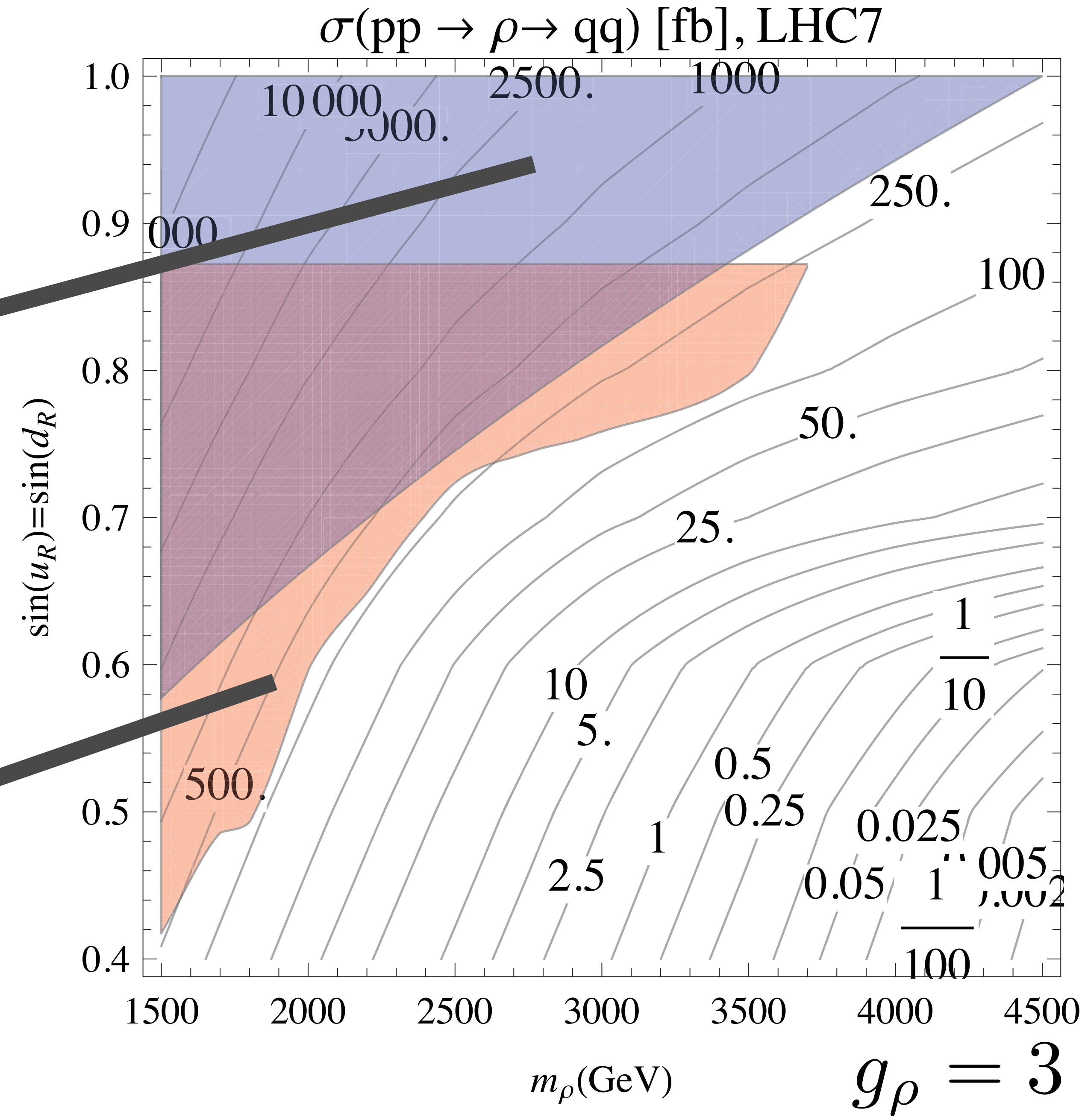
Observed m_t → $\epsilon_R \gtrsim \frac{1}{g_\rho} > 0.1$

Predict sizeable effects in right handed quarks



all possible resonances (Ex. massive gluon)

LHC7 bounds already relevant:



Di-jet bounds 35/pb

CMS-EXO-11-015
1/fb

Expected signals in di-jet.

General properties of 'Strongly Coupled EWSB'

&

LHC Phenomenology

broadly described by

g'

ρ

$m_\rho \qquad g_\rho$

$$m_\rho \sim g_\rho f$$

$$g_\rho \sim \frac{4\pi}{\sqrt{N}}$$

TeV

top partners

lonely weirdo's
(ex. scalar octet, why not?)

Redi's talk

see Dobrescu

100 GeV

$W_L^{\pm}, Z_L^0 \;+$

$q, \ell, \gamma, W_T, Z_T, g$

Composite

Elementary

✦ Technicolor SO(4)/SO(3): ☆ =nothing

Not feeling too well

✦ pseudo-NG Higgs SO(5)/SO(4): ☆ $= h$ $W_L^\pm\,,\, Z_L^0\,, h \to \begin{pmatrix} H^+ \\ H_0 \end{pmatrix}$

extended cosets SO(6)/SO(5), SO(6)/SO(4) x U(1), ... : additional light scalars

✦ pseudo-dilaton: ☆ $= \chi$ does **not** fit in SU(2) doublet

The main advantage of pseudo-NG Higgs

Georgi, Kaplan '84

Manton '79
Hosotani'84

Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04
....

$$\widehat{S} = \widehat{S}_{TC} \times \frac{v^2}{f^2}$$

f = Goldstone decay const

EWPT are OK with mild tuning $\quad \frac{v^2}{f^2} \sim 0.1 - 0.3$

(or maybe by Little Higgs mech)

$$\epsilon_3 = \widehat{S} \sim \frac{m_W^2}{m_\rho^2} \to 10^{-3}$$

Resonances still in the few-TeV-range

Collider Signals of Composite Higgs

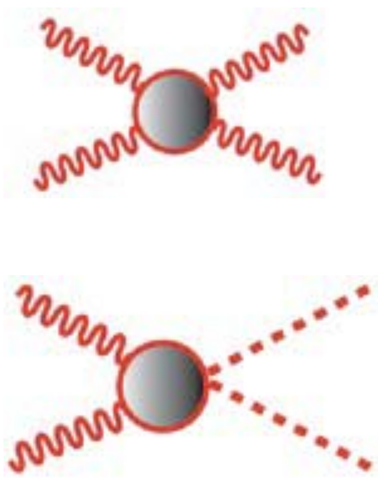
I) Direct

❖ production of resonances

(can be effectively modeled by 5D holographic realizations, or by deconstruction)

❖ strong scattering

Zeppenfeld



LHC with > 100 fb^{-1}

LHC with > 300 fb^{-1}

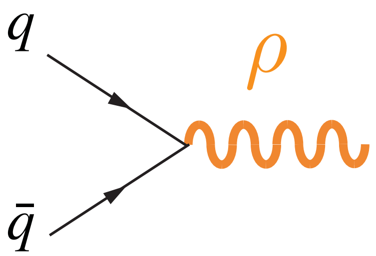
$$\frac{v^2}{f^2} > 0.3$$

CLIC more realistically $\frac{v^2}{f^2} > 0.01$

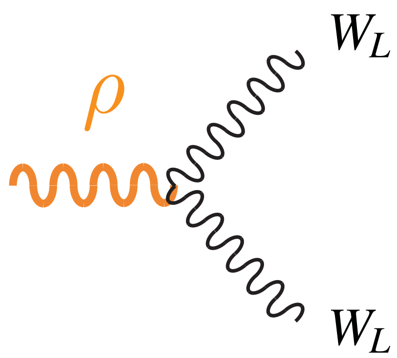
Contino, Grojean, Moretti, Pappadopulo, Piccinini, RR,Thamm '10 + to appear

II) Indirect: $O(v^2/f^2)$deviations from the Standard Model in Higgs production rates and branching ratios

Giudice, Grojean, Pomarol, Rattazzi 07



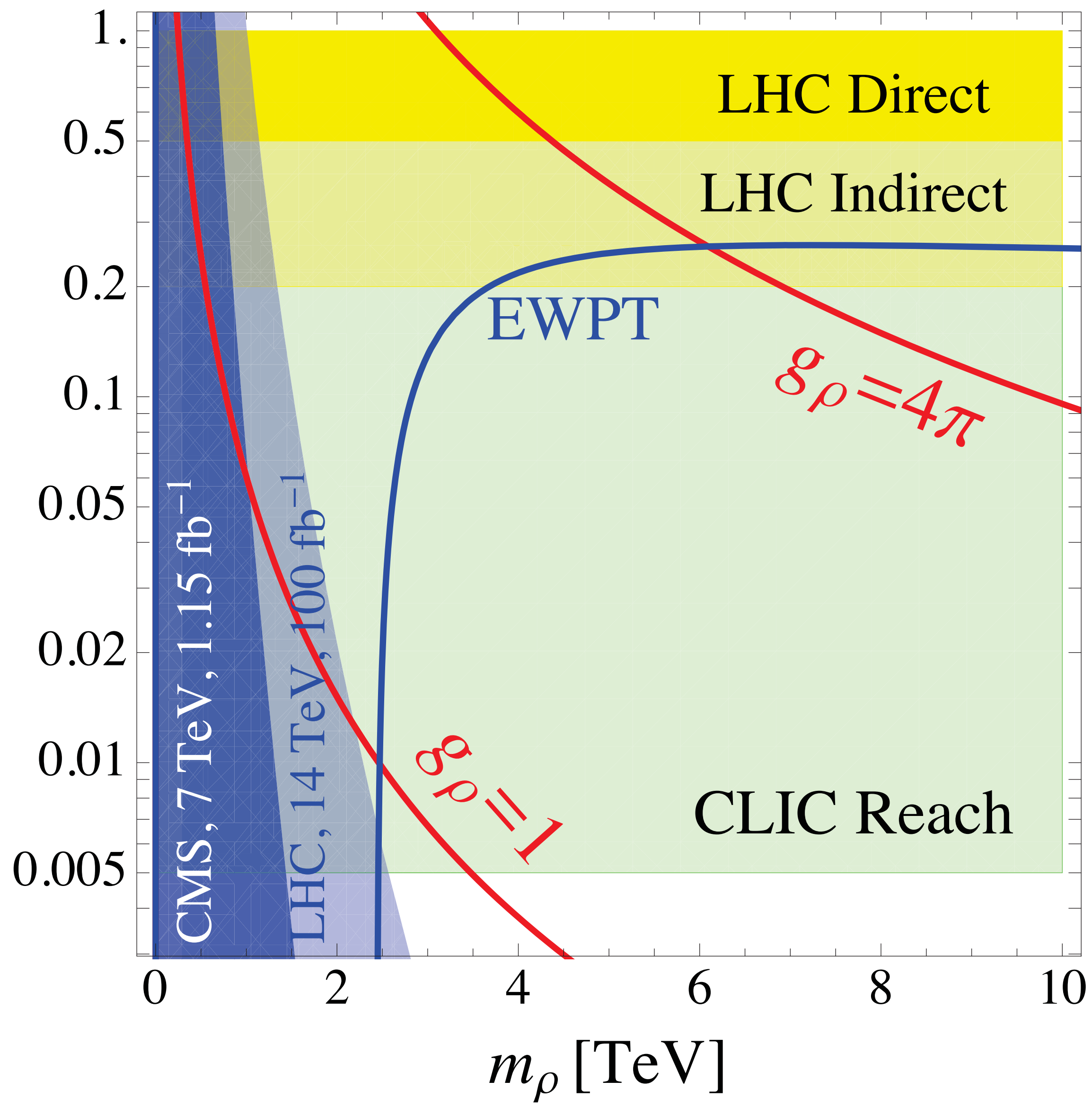
$$= \frac{g_W^2}{g_\rho} \ll g_W$$



$$= g_\rho$$

Weiler's talk

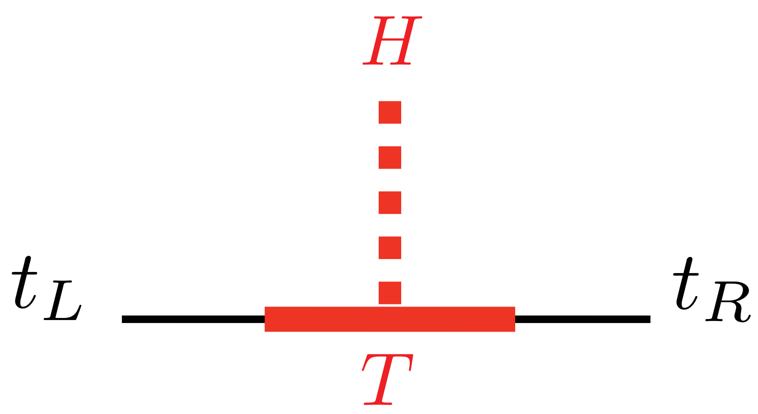
$$\xi \equiv \frac{v^2}{f^2}$$



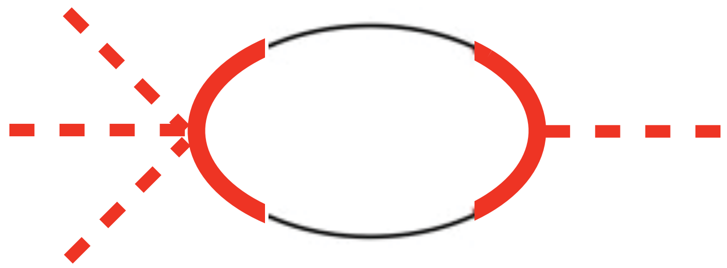
$$m_\rho \sim g_\rho f$$

m_h, m_t and colored resonances

talks by Redi & by Wulzer



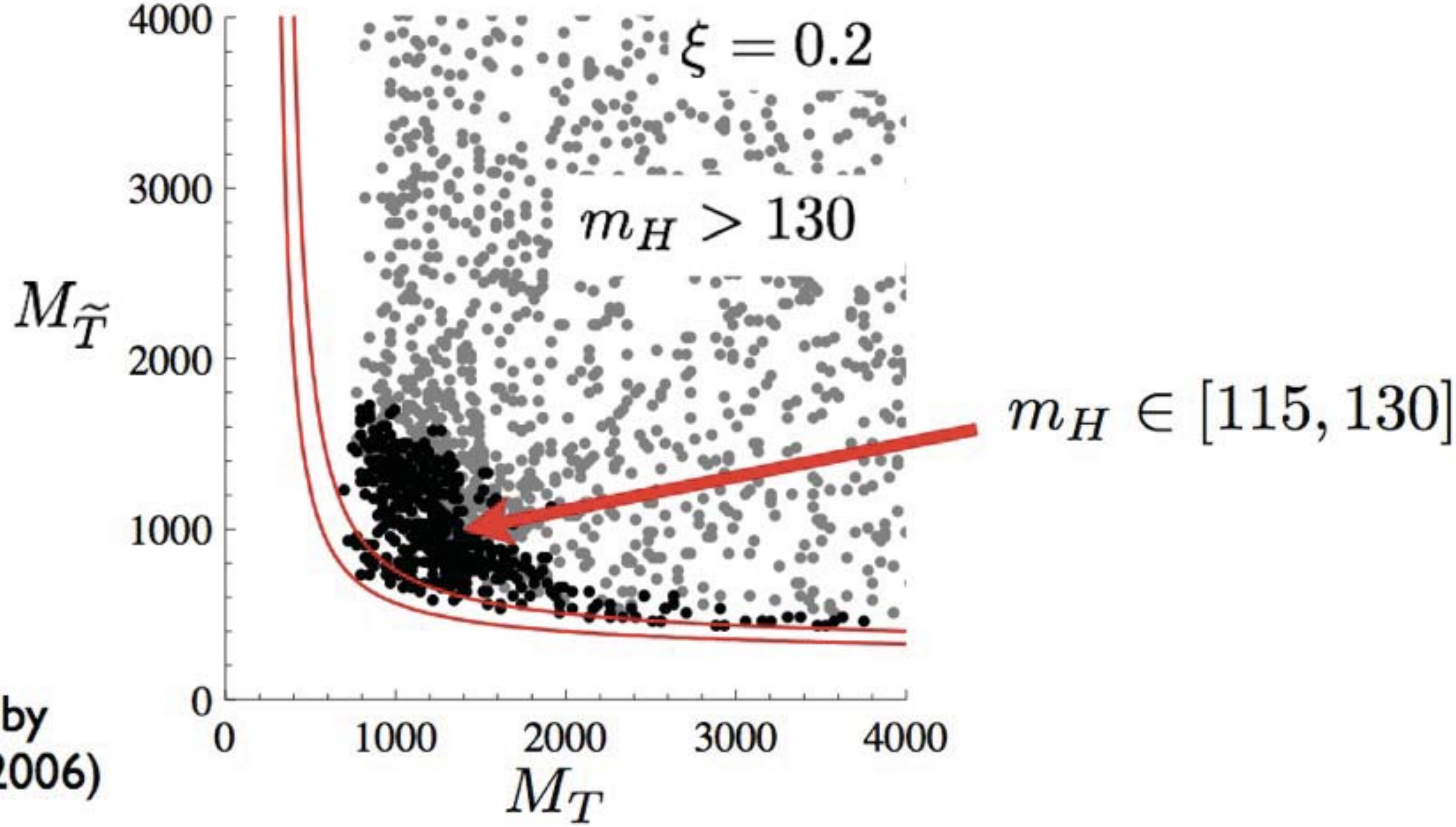
$$y_t \sim \frac{y_L y_R f}{M_T}$$



$$+ \cdots \quad \rightarrow \quad m_h \sim m_t \frac{M_T}{\pi f}$$

$$m_h < 130 \text{ GeV} \quad \rightarrow \quad M_T \lesssim 1 \text{ TeV} \left(\frac{0.5}{\frac{v}{f}} \right)$$

Light Higgs wants **Light Partners** :

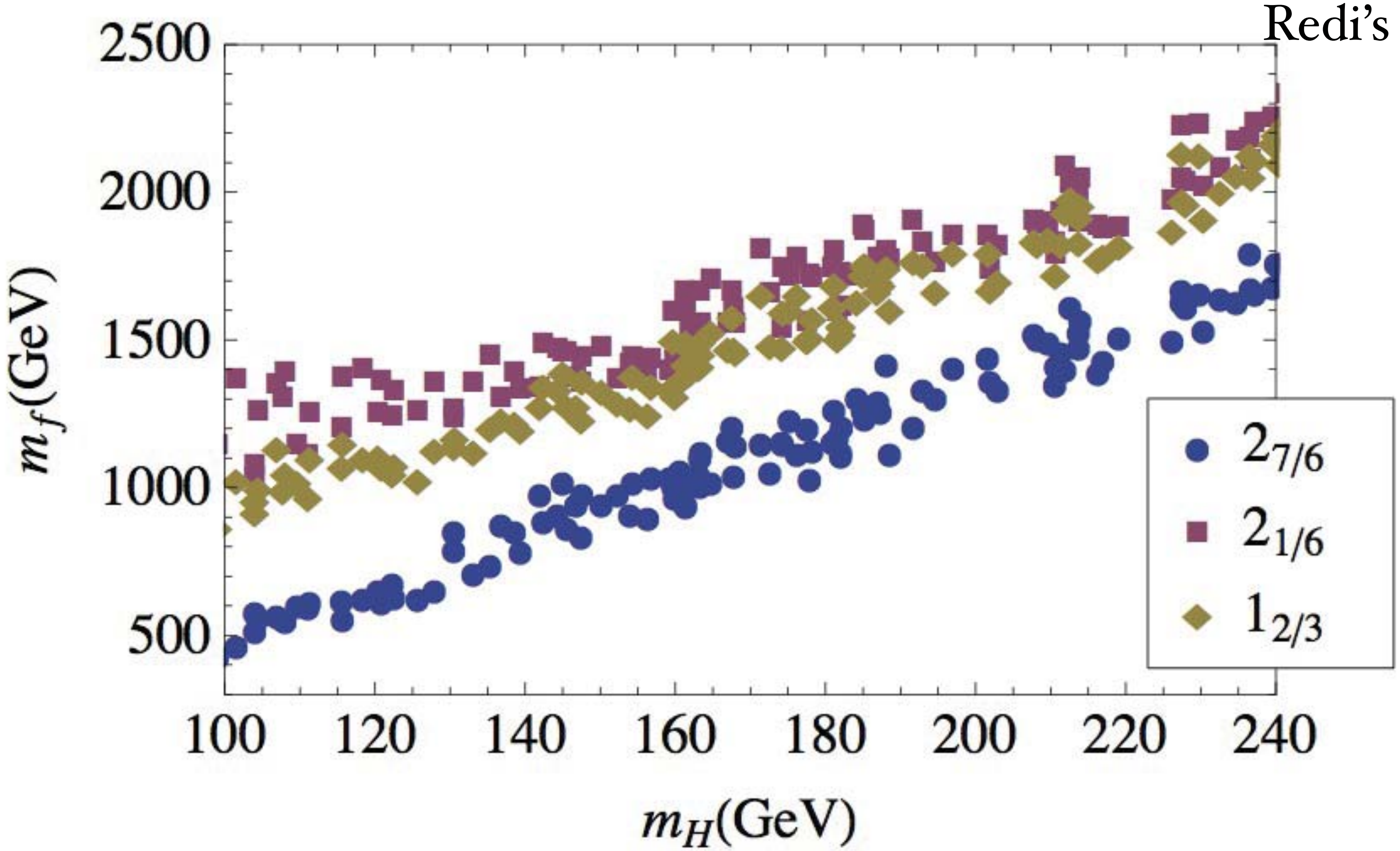


First noticed by
Contino et. al (2006)

Wulzer & Panico

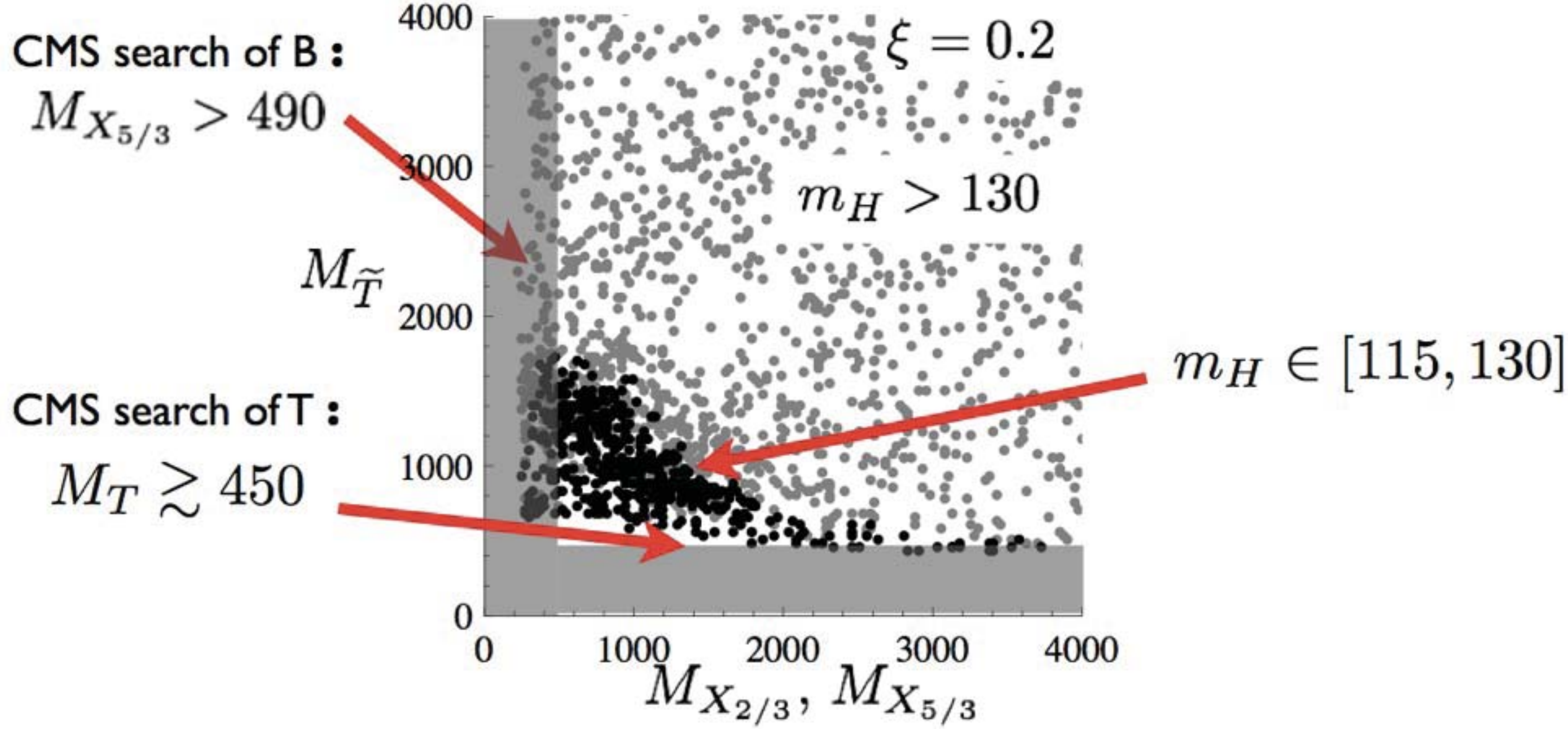
De Curtis, Redi, Tesi '11

Redi's talk

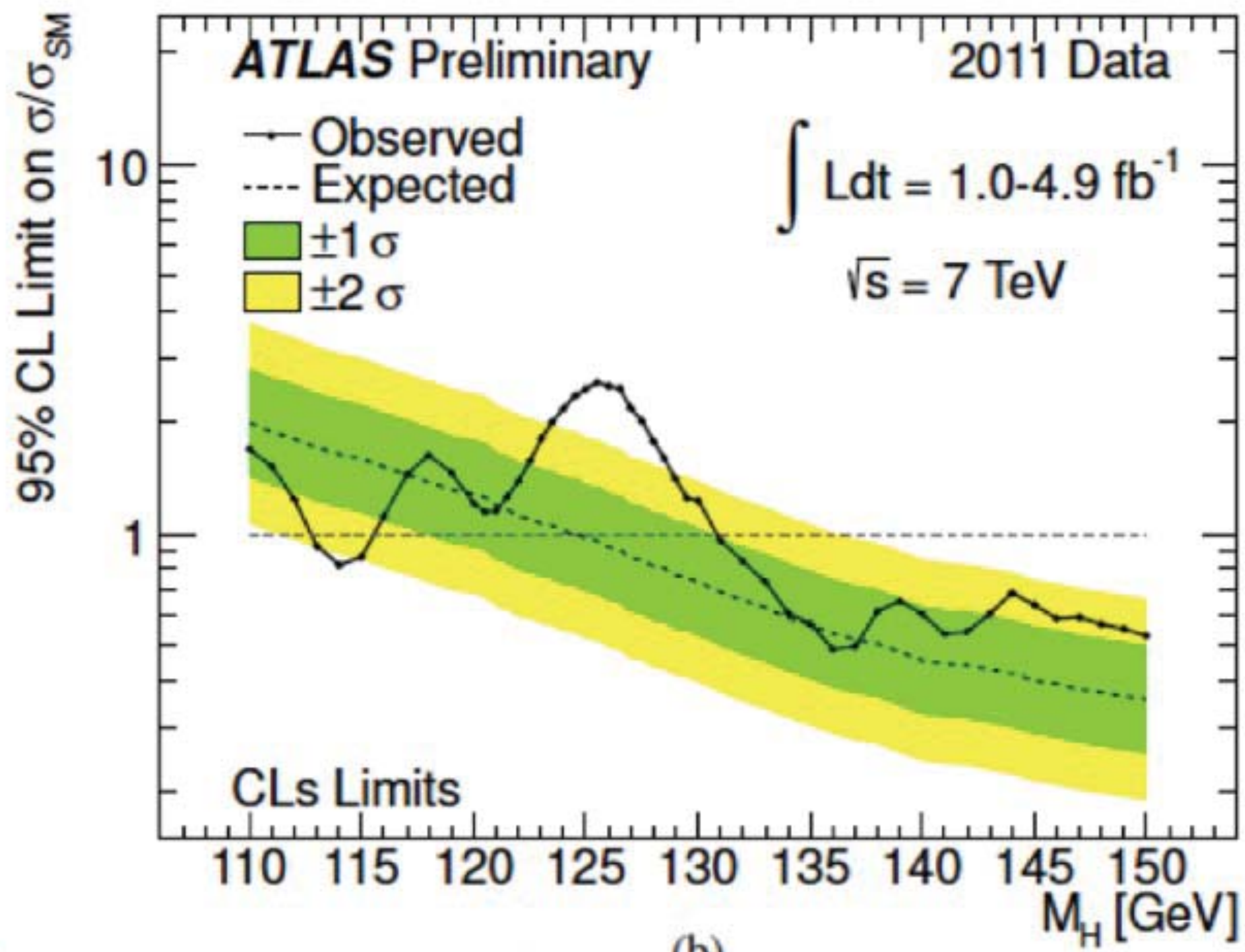


Would be interesting to explore m_h-m_f correlation in 'nicer' models, if they exist

LHC has **already probed** part of this plot :



Contino, Servant '08
Mrazek, Wulzer '09



(b)

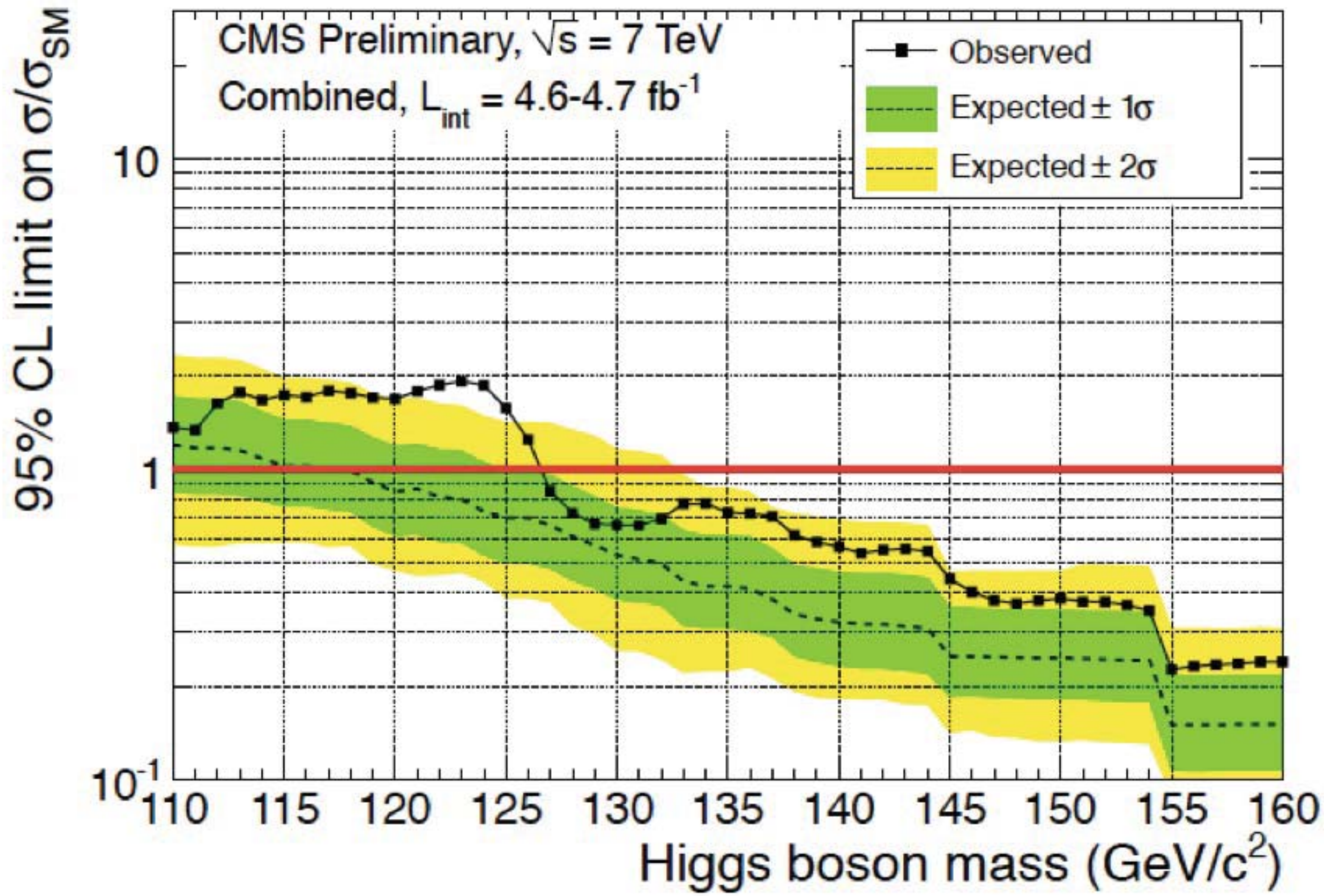
Observed excess over SM for m_H ~ 126 GeV in:

H->γγ (2.8σ), H->ZZ*->4l± (2.1σ), H->WW*-> lνlν (1.4σ).

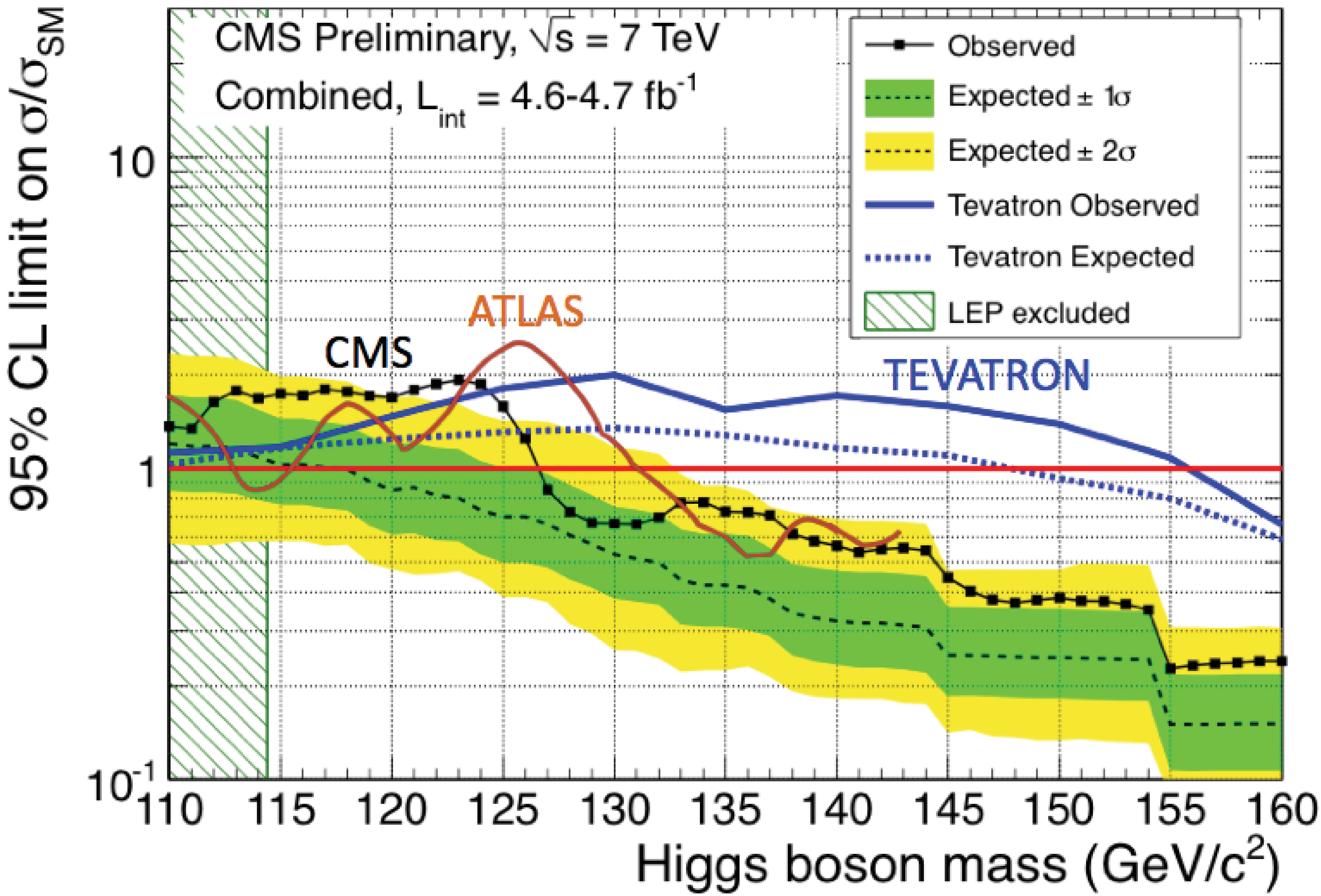
Combined: 3.6σ (but with look-elsewhere-effect 2.3σ)

⊕ The most obvious "elsewhere" is CMS →

Also in CMS there is an excess, but smaller (2.6 σ)



Kilminster



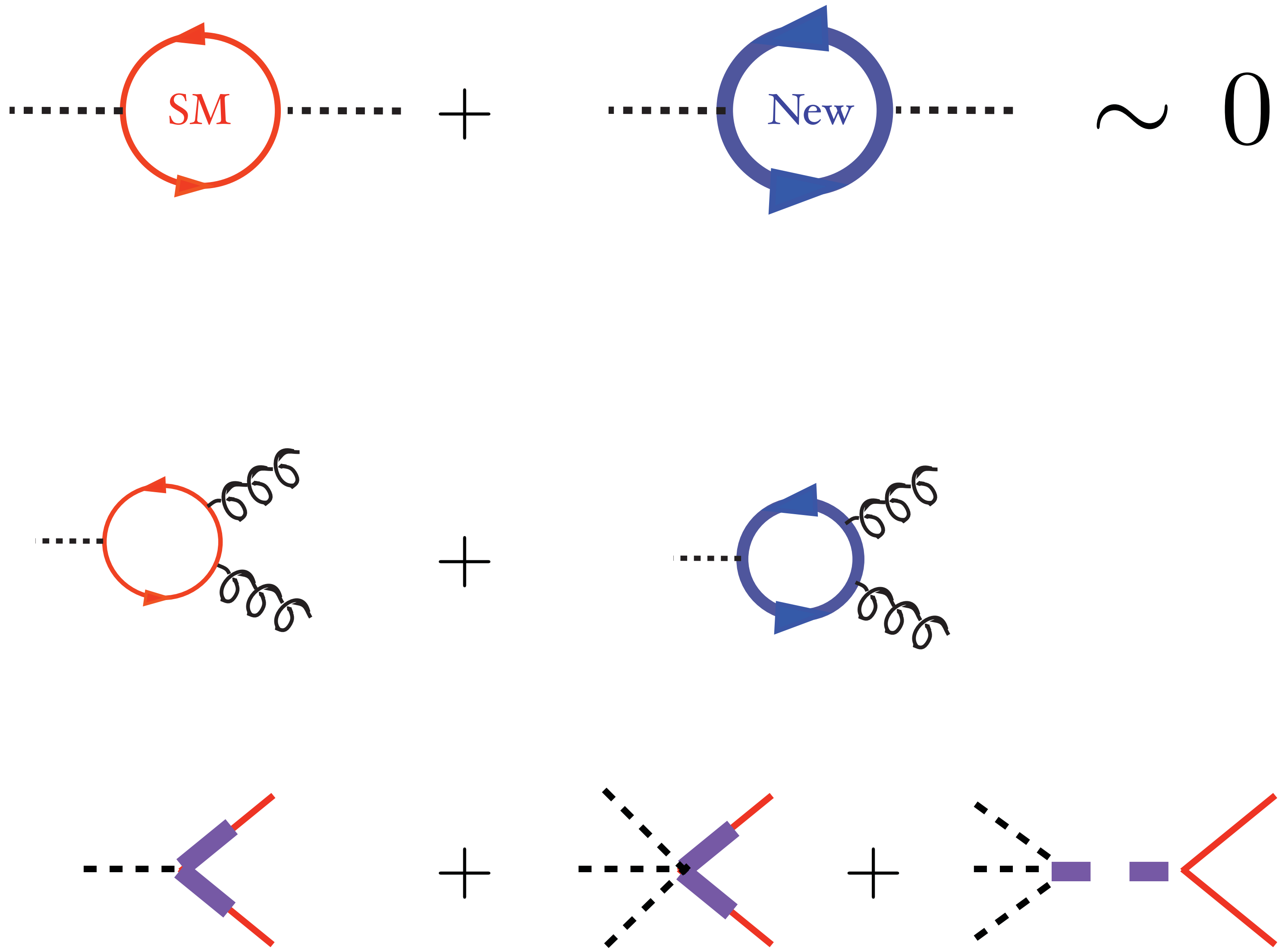
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
Tevatron Observed
Tevatron Expected
LEP excluded
ATLAS
CMS
TEVATRON
95% CL limit on σ/σ_{SM}
Higgs boson mass (GeV/c^2)
10
1
10^{-1}
110
115
120
125
130
135
140
145
150
155
160

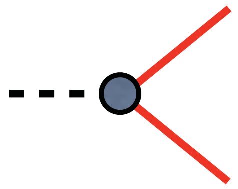
Higgs-mantics

Divination through Higgs

The more natural the theory the more the Higgs rates deviate from SM

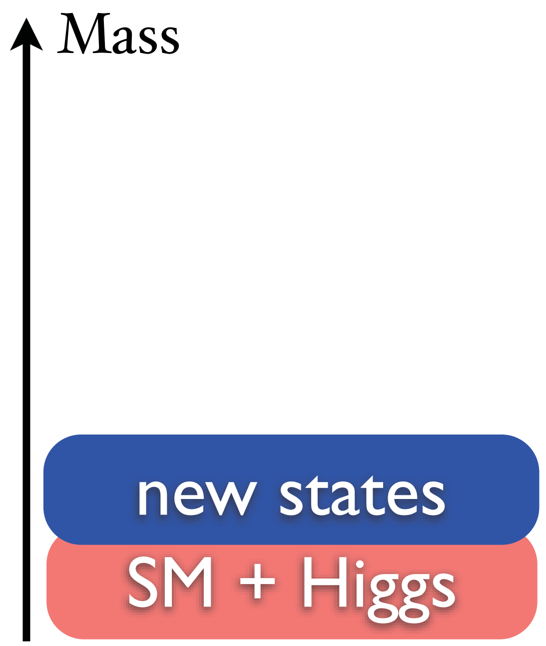
$$\delta m_H^2 = \; [\text{SM loop}] + [\text{New loop}] \sim 0$$



 = first probes into EWSB dynamics and into hierarchy puzzle

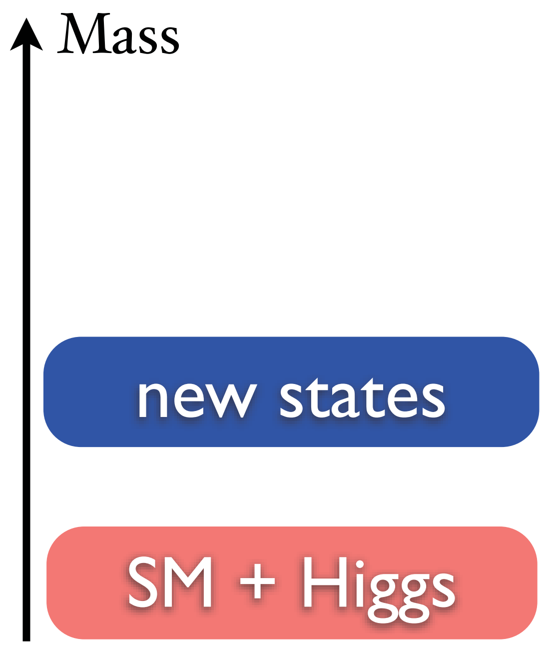
$115\,\mathrm{GeV} \lesssim m_h \lesssim 130\,\mathrm{GeV}$ lucky range to measure all couplings

It would be useful to develop a 'Higgs diagnostic': associate the possible patterns of deviation to broad/specific features of the underlying theory



Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models



Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models

General parametrization of *Higgslike scalar h*

Contino, Grojean, Moretti, Piccinini, RR '10

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\,(V_\mu V^\mu)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right] - m_i \bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \mathrm{h.c.}$$
$$+ \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$
$$+ c_g\frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma\frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}$$

c flavor universal in minimal flavor violating set up

✦ Standard Model: $a = b = c = d_3 = 1$ $c_g = c_\gamma = 0$

✦ h = pseudo-Goldstone implies additional constraints

$SO(5)/SO(4)$ Pseudo-Goldstone Higgs

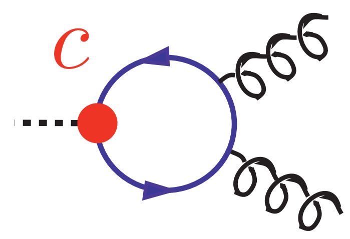
Agashe, Contino, Pomarol '04

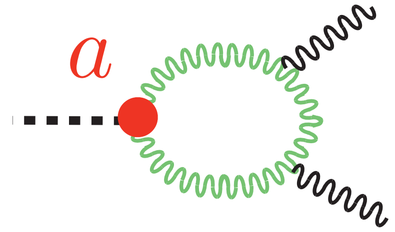
$a = \sqrt{1 - v^2/f^2}$ $\quad b = 1 - 2v^2/f^2$ model independent

$c = d_3 = \sqrt{1 - v^2/f^2}$ fermions in **4**

$c = d_3 = \dfrac{1 - 2v^2/f^2}{\sqrt{1 - v^2/f^2}}$ fermions in **5**

} model dependent





$c_g,\ c_\gamma \sim \dfrac{\alpha_t}{4\pi}$ controlled by small explicit SO(5) breaking

NEGLIGIBLE!

Interesting inequalities

$0 \leq a, |b| \leq 1$ robust

$0 < c < 1$ in range favored by EWPT

In specific models just one free parameter $\xi \equiv \frac{v^2}{f^2}$

In general 4 parameters $a,\ c_t,\ c_b,\ c_\tau$

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to t\bar{t})}{\Gamma(h \to t\bar{t})|_{SM}} = c_t^2$$

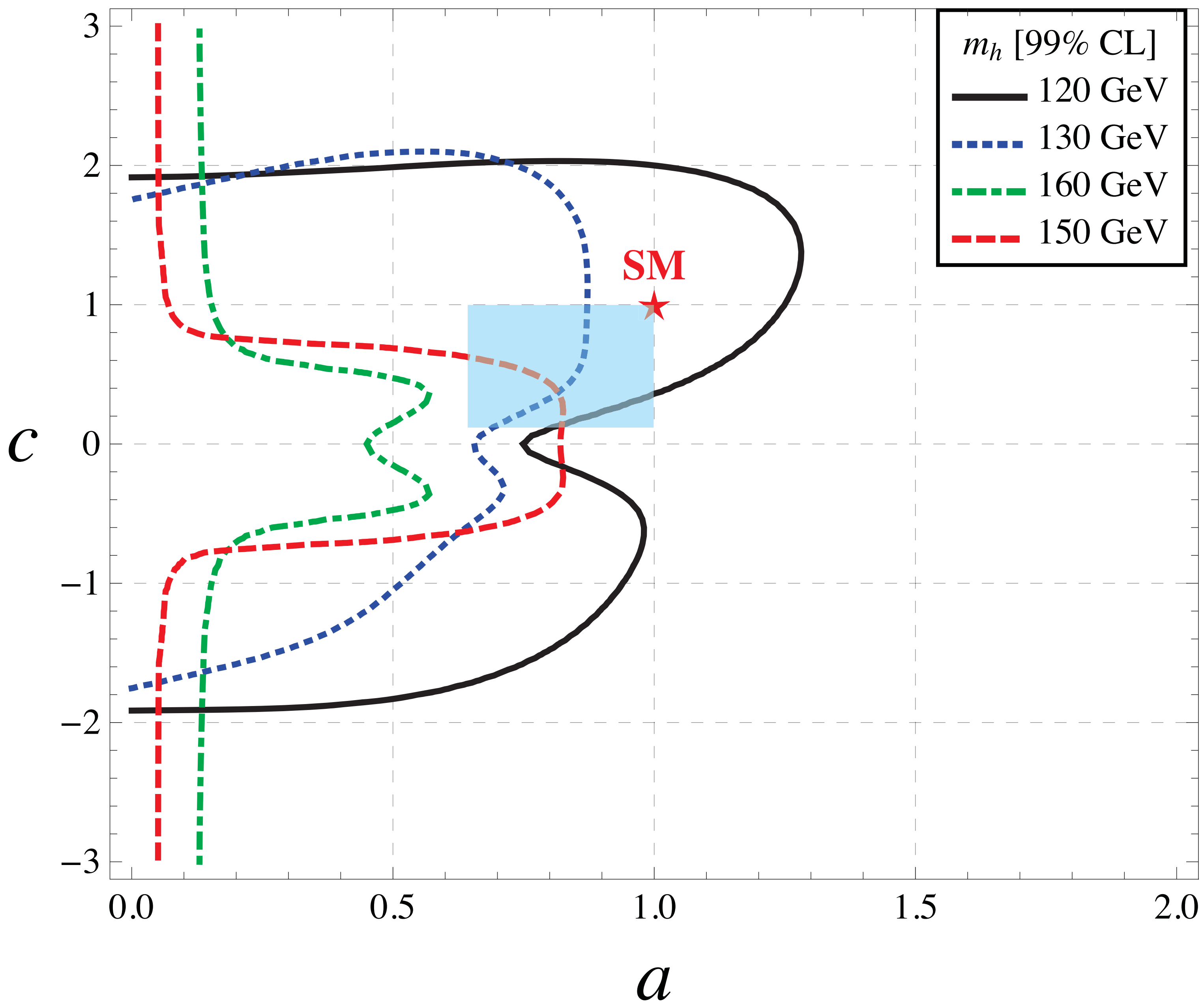
$$\frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c_f^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2\left[1 + 0.28(1 - c_t/a)\right]^2 \sim a^2$$

$$\frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2$$

In the preferred range all rates are reduced

Exclusion using CMS data [≤ 4.7 fb^{-1}]



$$c_t = c_b = c_\tau \equiv c$$

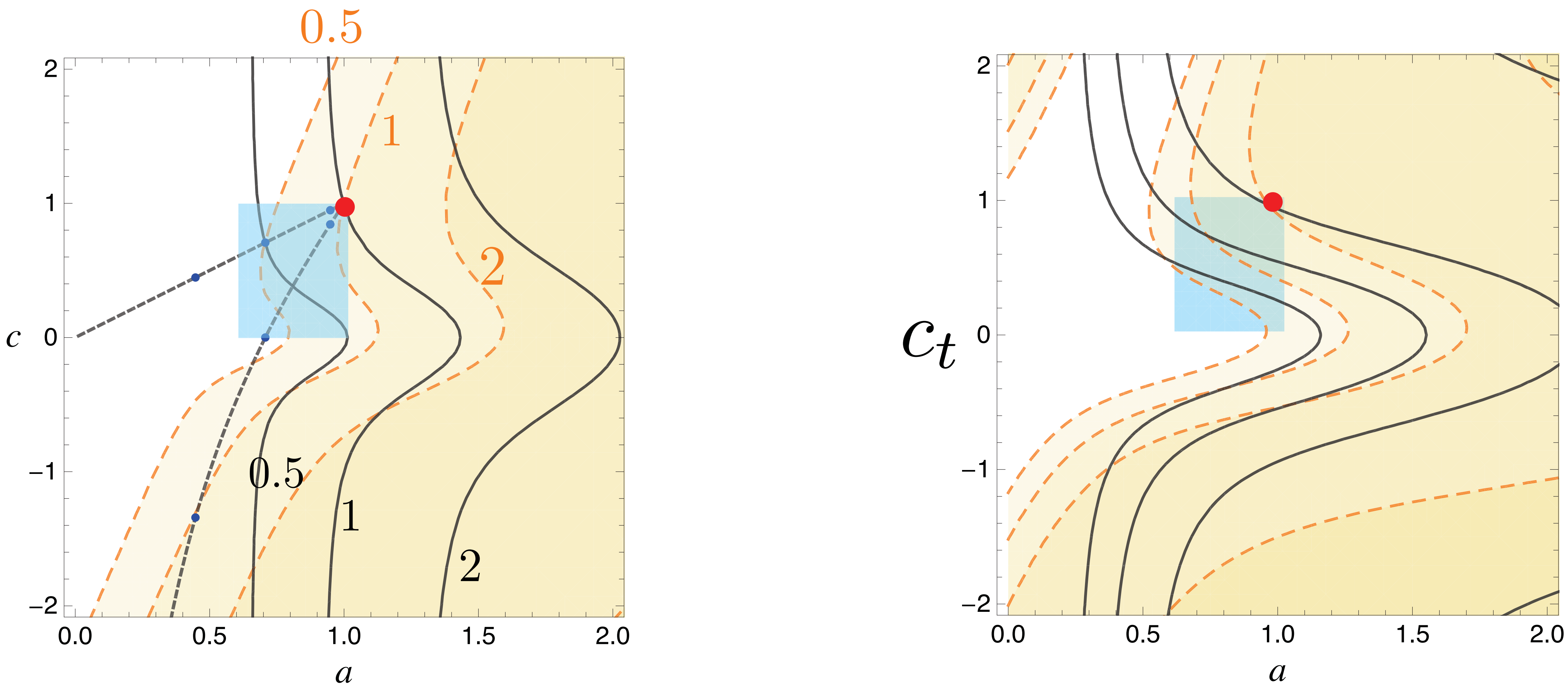
Azatov, Contino, Galloway to appear

R_{ZZ} ———

$R_{\gamma\gamma}$ - - - - -

$m_h = 125$ GeV

Contino's talk



$c_t = c_b = c_\tau \equiv c$

$c_b = c_\tau = 0.4$

Can increase $R_{\gamma\gamma}$, but at the price of R_{bb}

$$\frac{v^2}{f^2} \ll 1$$

SILH effective lagrangian

$$\mathcal{L}_{eff} = \frac{c_H}{2f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) + y_f \frac{c_y}{f^2} H^\dagger H \, \bar{\psi}_L H \psi_R - \frac{c_6 \lambda}{f^2} \left(H^\dagger H\right)^3$$

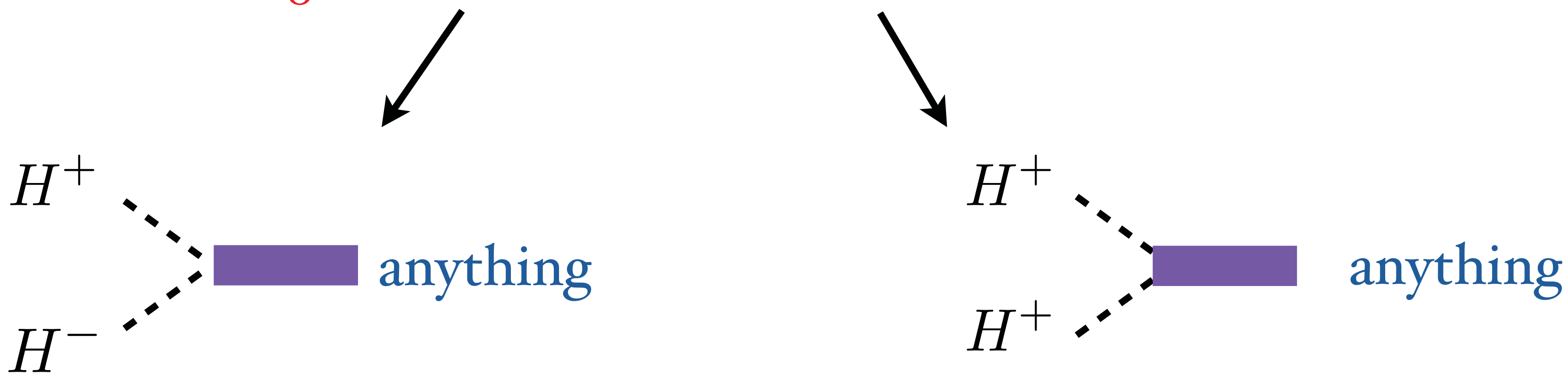
$$0 \leq a, b, c \leq 1 \qquad c_H, c_y > 0$$

true in larger class including Little Higgs

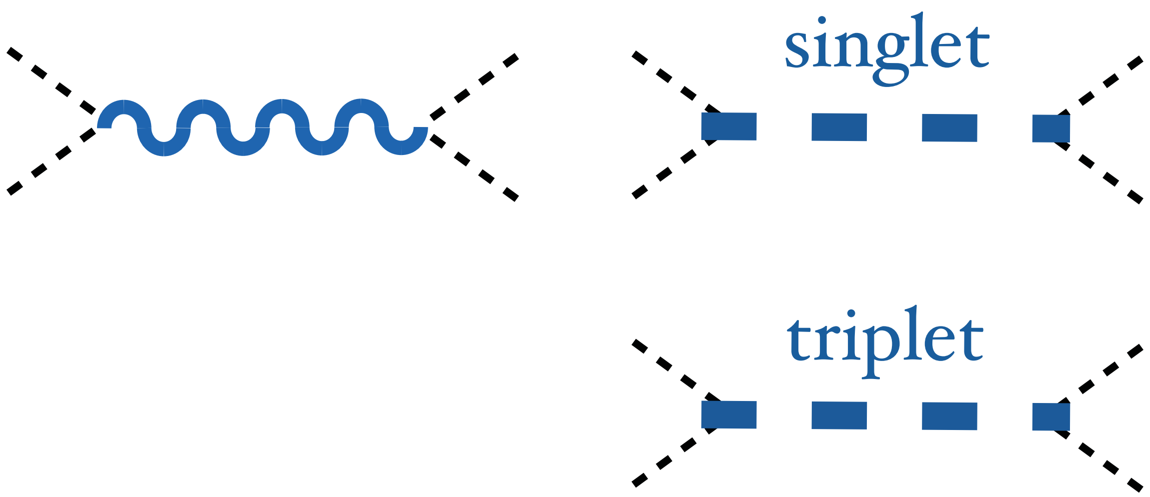
A dispersion relation for c_H

Low, Rattazzi,Vichi '09

$$c_H = \frac{f^2}{\pi}\int_0^\infty \left(\sigma_{+-}(s) - \sigma_{++}(s)\right)\frac{ds}{s}$$



c_H not positive definite, but almost so



$$\Delta c_H > 0$$

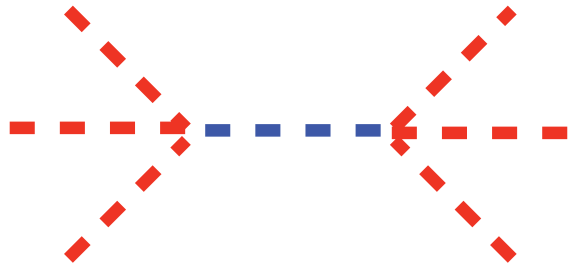
$$\Delta c_H < 0$$

Scalar triplets do not dominate in known models addressing hierarchy

An exercise in Higgs diagnostic

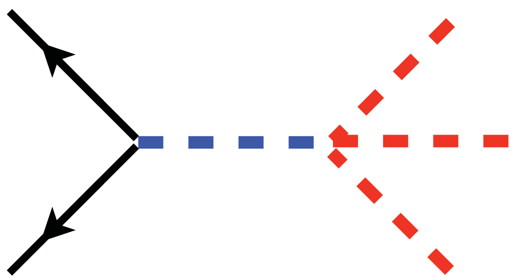
$H' = -\cos\beta H_2 + \sin\beta H_1$

$H = \cos\beta H_1 + \sin\beta H_2$

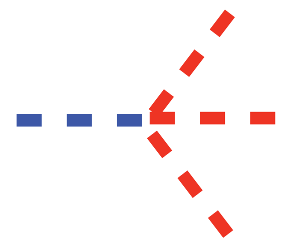


$\Delta c_H = 0$

dim 8 operator: quick decoupling in h $\gamma\,\gamma$ and hWW



sign depends on structure of quartic



MSSM $\quad (H_1^2 - H_2^2)^2$

$c_b > 1$

$c_t < 1$

Hall, Pinner, Ruderman '11

NMSSM $\quad H_1^2 H_2^2$

$c_b < 1$

$c_t > 1$

Other roads to increase Higgs couplings

Dilaton

$$\begin{cases} a = \sqrt{b} = c = \dfrac{v}{f_D} \\ d_3 = \dfrac{5}{3}\dfrac{v}{f_D} + O(\epsilon) \\ c_g,\, c_\gamma = O(v/f_D) \end{cases}$$

$a,\, b,\, c \lessgtr 1$

Yamawaki's talk

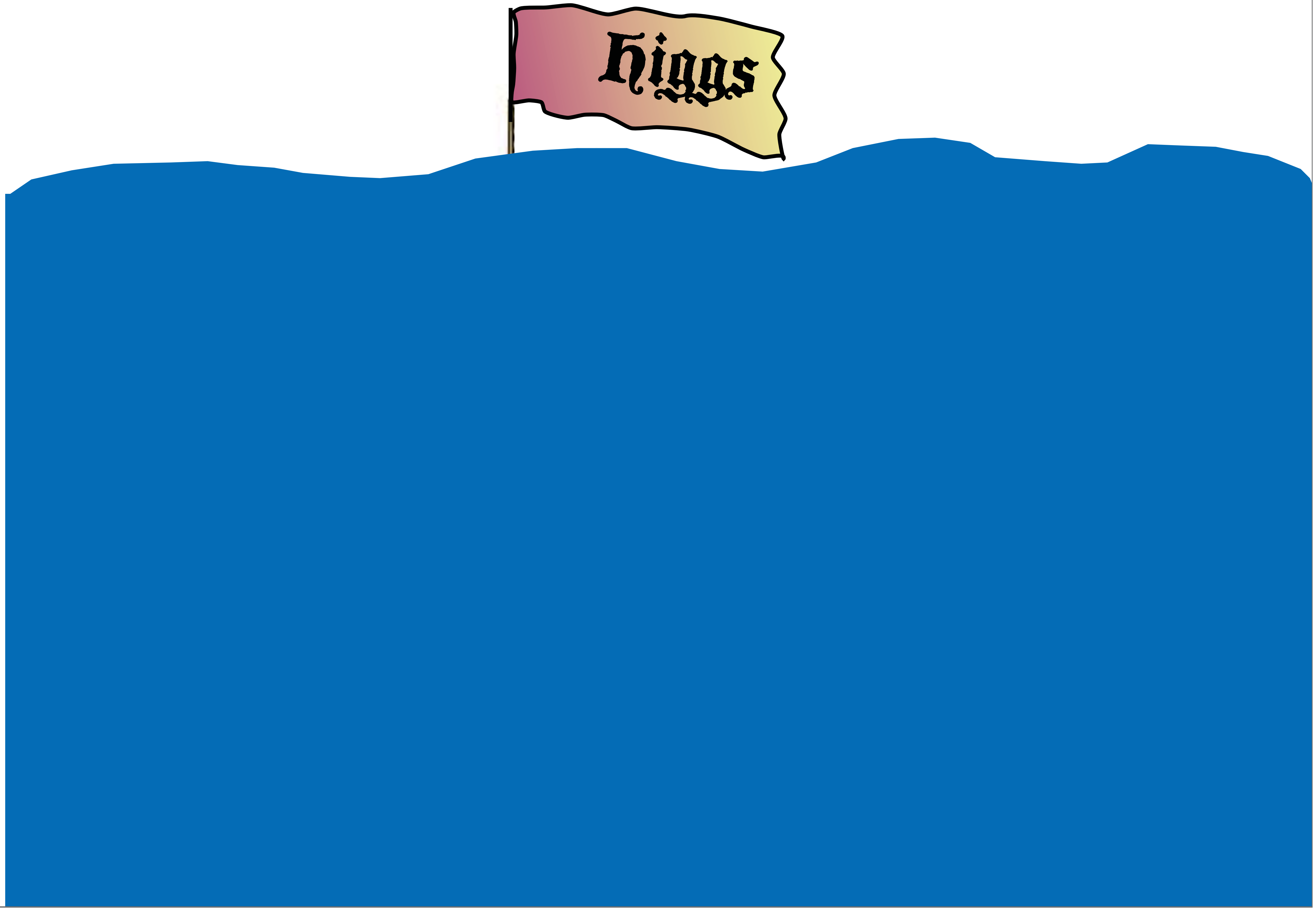
Non-Compact coset space

$H \in SO(4,1)/SO(4)$

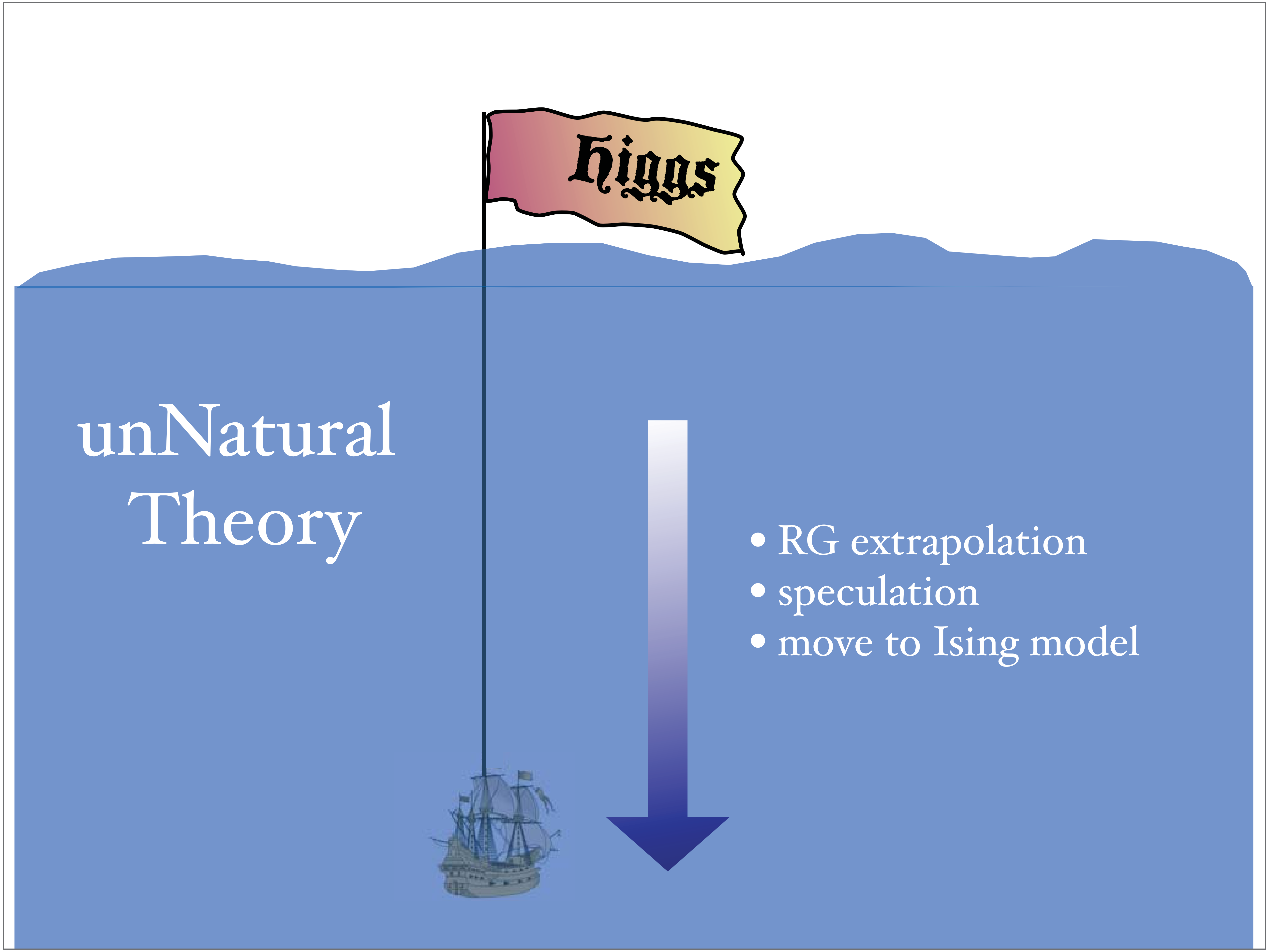
$$\begin{cases} \dfrac{v^2}{f^2} \to -\dfrac{v^2}{f^2} \\ a = \sqrt{1 + v^2/f^2} \qquad b = 1 + 2v^2/f^2 \end{cases}$$

Low's talk

No Unitary QFT as UV completion ➔ TeV scale Quantum Gravity ?


higgs

Natural
Theory


higgs
unNatural Theory
• RG extrapolation
• speculation
• move to Ising model