A (critical) overview of electroweak symmetry breaking

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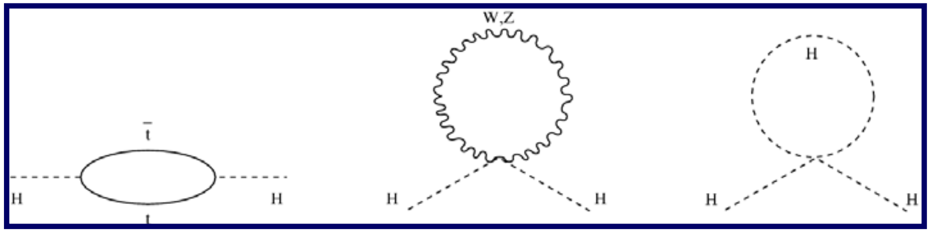
Outline

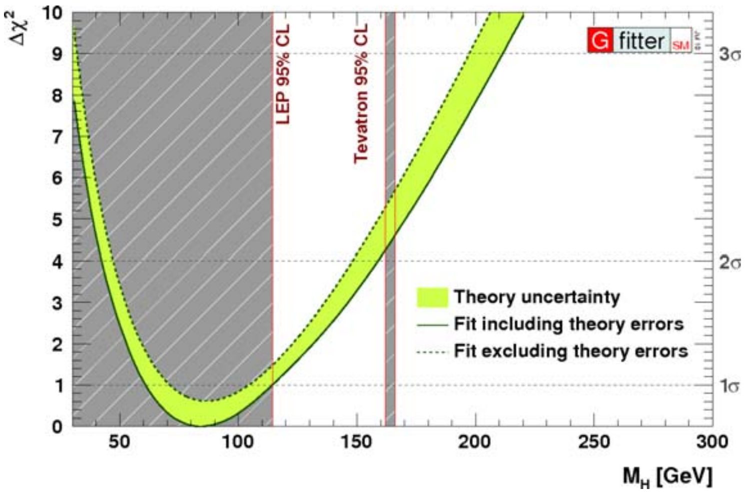
- The standard Higgs, big vs. little hierarchy
- EWSB in supersymmetry & little hierarchy of MSSM
  - Buried Higgs
  - Bigger quartic (D-terms, NMSSM, fat higgs,….)
- Strong dynamics & related models
  - Technicolor
  - Monopole condensate
  - Warped extra dimensions
  - Realistic RS, Higgsless
  - Composite Higgs
  - Little Higgs

The SM, big vs. little hierarchy

- Standard higgs mechanism very successful
- EWP analysis suggests light higgs boson
- Hard to understand how higgs remains light, sensitive to any new physics…

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$





(From GFITTER group at this conference)

•This is usually referred to big hierarchy problem: why is $m_h \ll \Lambda$

•Usual resolution: $\Lambda \sim$ 1 TeV, where new physics shows up that makes higgs insensitive to higher scales (SUSY partners, strong dynamics, …)

•"Little hierarchy": why have we not seen any trace of indirect hint for these new particles?

•In most models EWP forces new particles more like 5-10 TeV, a new tuning of ~ 1 % is emerging

•Called "LEP paradox" Barbieri & Strumia

•Suppression scale of higher dim. op's (~ masses of heavy particles) must be > 1 TeV

Dimensions six operators	$m_h = 115\ GeV$ $c_i = -1$	$c_i = +1$
$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

(Barbieri, Strumia `99)

•SUSY: somewhat special, R-parity protects from tree-level EWP corrections, m_{SUSY} can be lower, BUT...

I. The little hierarchy in the MSSM

- In SUSY: 2 Higgs doublets H_u, H_d

- Only source of quartic is due to "D-terms": the scalar terms needed to supersymmetrize gauge interactions

- Higgs potential:

$$V(H_u, H_d) = (m^2_{H_u} + \mu^2)|H_u|^2 + (m^2_{H_d} + \mu^2)|H_d|^2 - B_\mu(H_u H_d + \text{h.c.}) + \frac{g^2}{2}(H_u^\dagger \vec{\tau} H_u + H_d^\dagger \vec{\tau} H_d)^2 + \frac{g'^2}{2}(H_u^\dagger H_u - H_d^\dagger H_d)^2$$

- Minimizing this:

$$M_Z^2 = 2\left(\frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{\tan^2\beta - 1} - \mu^2\right)$$

- Expression for Higgs mass (at large tan β):

$$m^2_{Higgs} = M_Z^2 + \frac{3 m_t^2 \lambda_t^2}{4\pi^2} \log \frac{m_{\tilde{t}}}{m_t}$$

- Need m_{Higgs} > 114 GeV

- Need large stop-top splitting

- But contribution to m^2_{Hu}:

$$m_{H_u}^2 = m_0^2 - \frac{3\lambda_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}$$

- And for large tan β $M_Z^2 \sim -2m_{H_u}^2$

- Implies <1% tuning generically (large A_t can help a bit)

Possible ways out:

- Higgs is lighter than LEP bound but has weird decays

- Need additional contribution to quartic, eg.
    - Additional D-term from bigger group
    - Bigger NMSSM-like quartic (fat Higgs)

Hiding the Higgs at LEP

**(Dobrescu, Matchev;
Dermisek, Gunion;
Chang, Fox, Weiner;…)**

- Higgs searched for in many channels at LEP

- For SM, MSSM m_h>114 GeV

- If Higgs has unusual decays, then might need dedicated search that was not (fully) done at LEP

- The situation ~ 1 year ago:

LEP Higgs bounds

Decay channel	Limit (GeV)
$h \to b\bar{b}, \tau\bar{\tau}$	115
$h \to jj$	113
$h \to \gamma\gamma$	117
$h \to WW^*, ZZ^*$	110
$h \to$ invisible	115
$h \to \eta\eta \to 4b$	110
$h \to \eta\eta \to 4\tau, 4c, 4g$	86
model indep.	82

This is low enough to remove little hierarchy of SUSY – lots of models that try to use this

- Most popular possibility

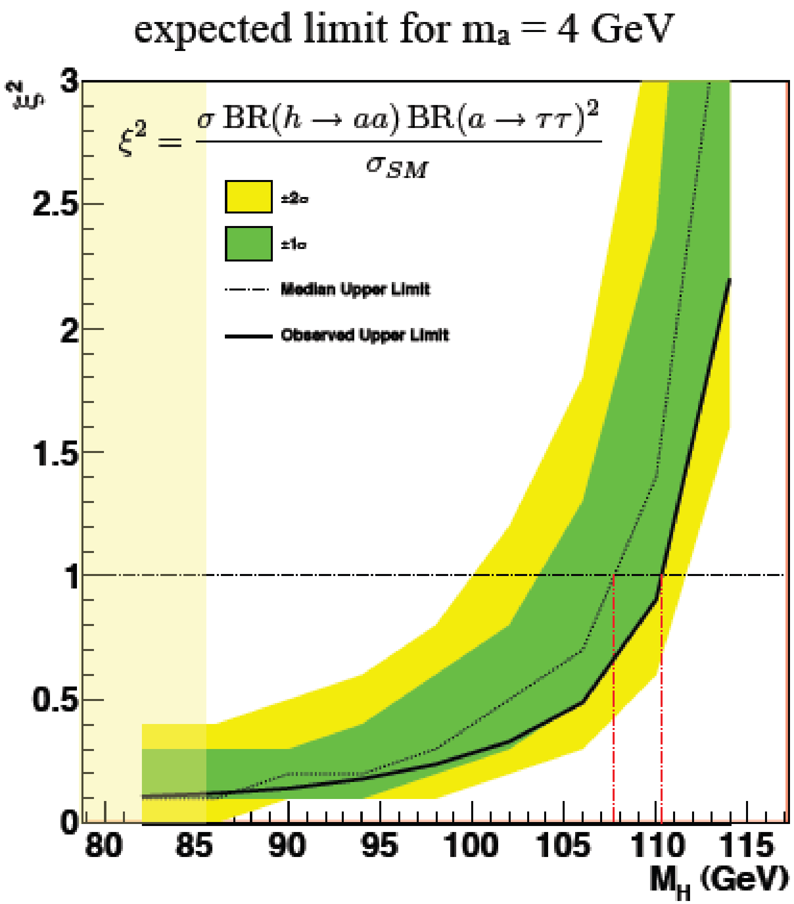
(Dermisek, Gunion; Chang, Fox, Weiner)

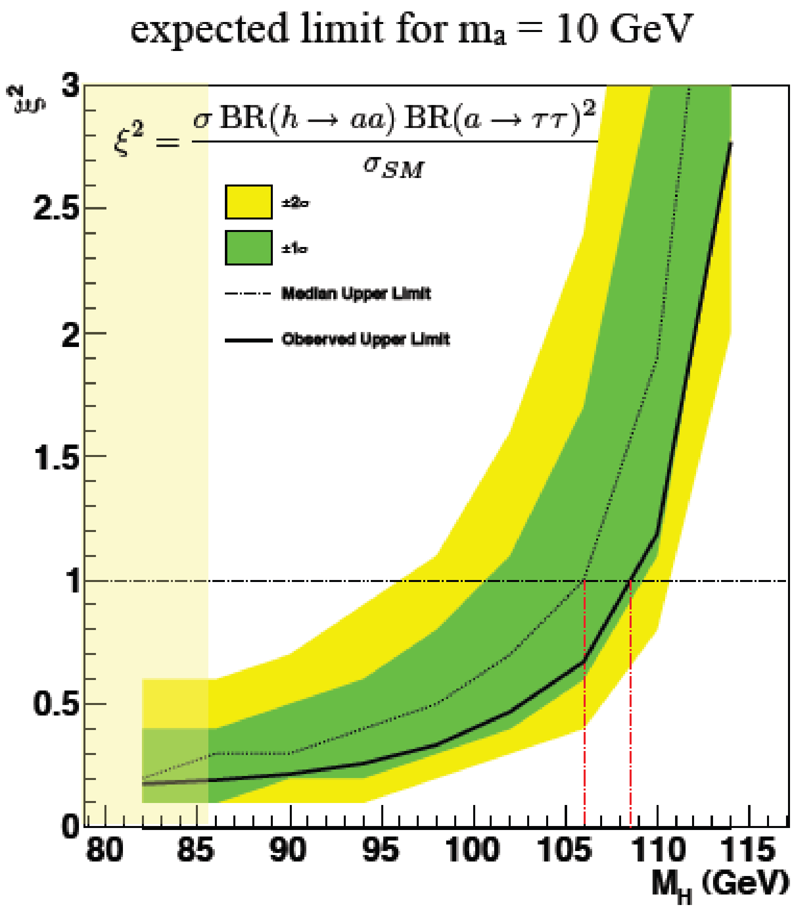
$$h \to 2A \to 4\tau$$

- Can be naturally obtained in NMSSM

- But: new LEP analysis from ALEPH excludes possibility when $h \to 4\tau$ is ~100%

ALEPH bound on h→4τ of order 105-110 GeV!





(Cranmer, Yavin, Beacham, Spagnolo, ALEPH collab. `09, see I. Yavin poster at this conference)

- Still possible: $h \to 4\tau$ around 50%, and the rest to jets **(Dermisek, Gunion `10)**

- Additional analysis of Cranmer et al. Aleph group under way to constrain $h \to 2\tau + 2j$ (and also $h \to 4j$ channels)

- For $h \to 4j$ and $h \to 2\tau + 2j$ jets are merged: need to use jet substructure to distinguish from QCD

The updated bounds

Decay channel	Limit (GeV)
$h \to b\bar{b}, \tau\bar{\tau}$	115
$h \to jj$	113
$h \to \gamma\gamma$	117
$h \to WW^*, ZZ^*$	110
$h \to$ invisible	115
$h \to \eta\eta \to 4b$	110
$h \to \eta\eta \to 4\tau$	105 – 110
$h \to \eta\eta \to 4c, 4g$	86
model indep.	82

Need to use h→4j or more complicated final states if want to hide the higgs at LEP

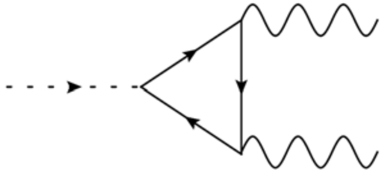
An interesting possibility: $h \to 4j$

•Already mentioned by Chang, Fox, Weiner & D. E. Kaplan et al.

•Simple realistic model "**Buried higgs**" based on SU(3)xU(1) extension of SM with global sym. breaking scale f~350 GeV

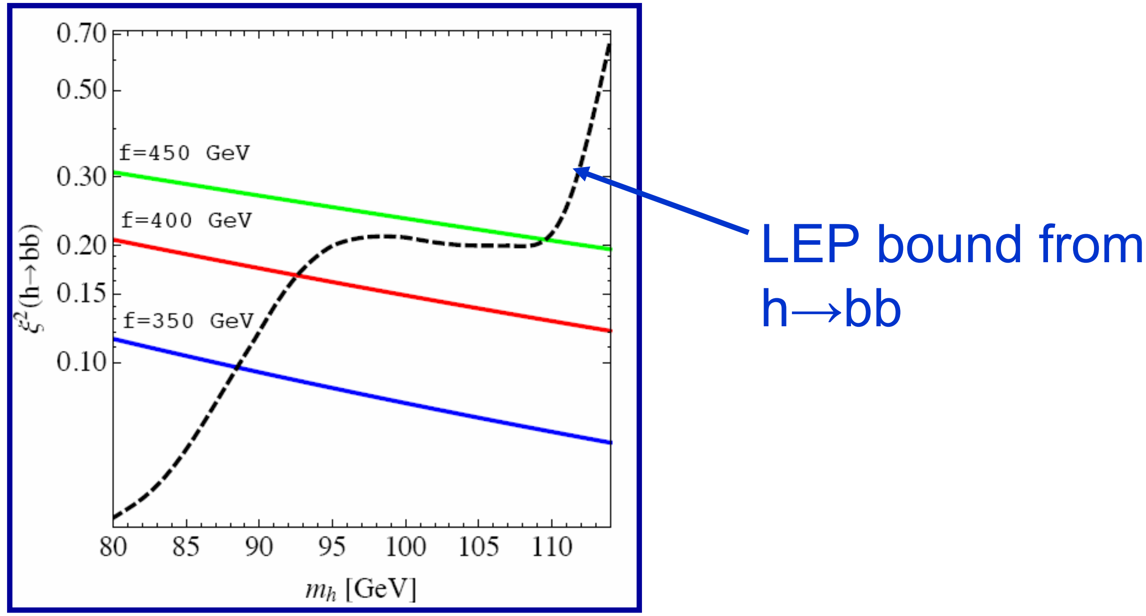
•Leading higgs decay $h \to 2\eta$ where η is an SU(2)xU(1) singlet pGB

•The η decays via triangle diagrams to 2g

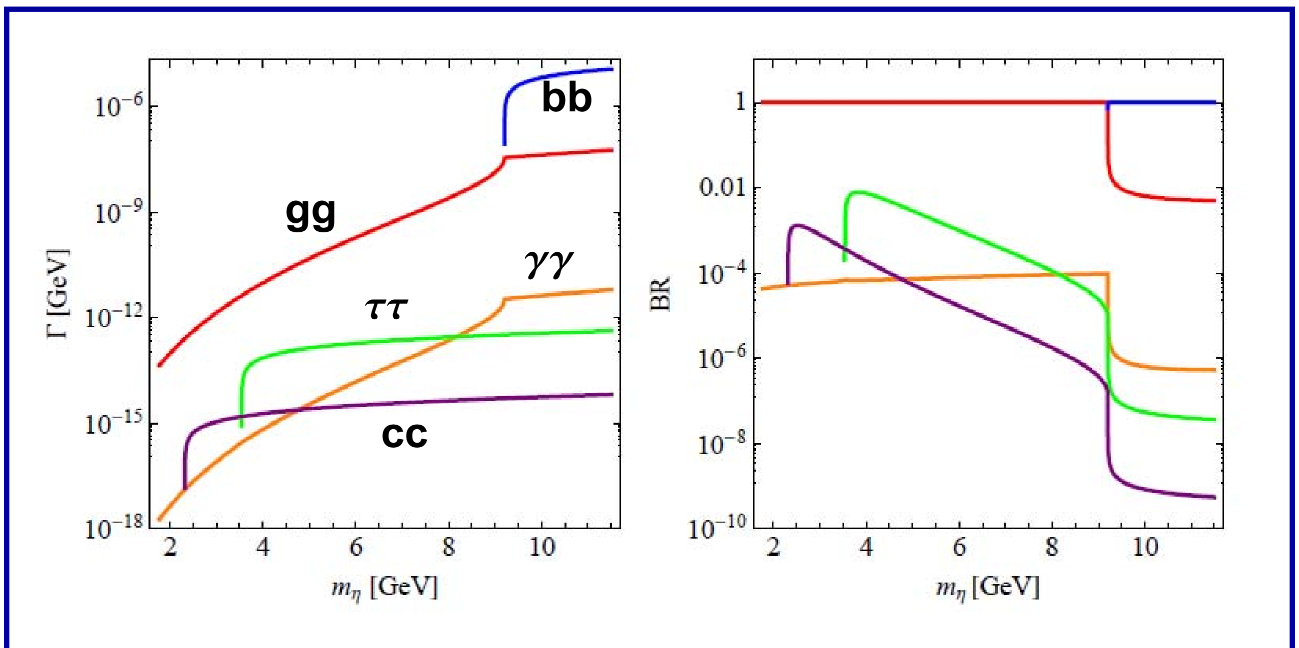


(Bellazzini, C.C., Falkowski, Weiler `09)

•The h decays



•The η decays

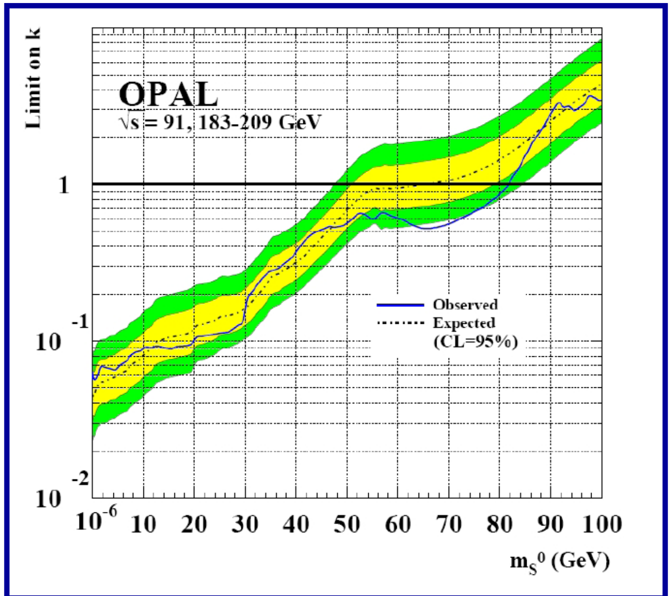


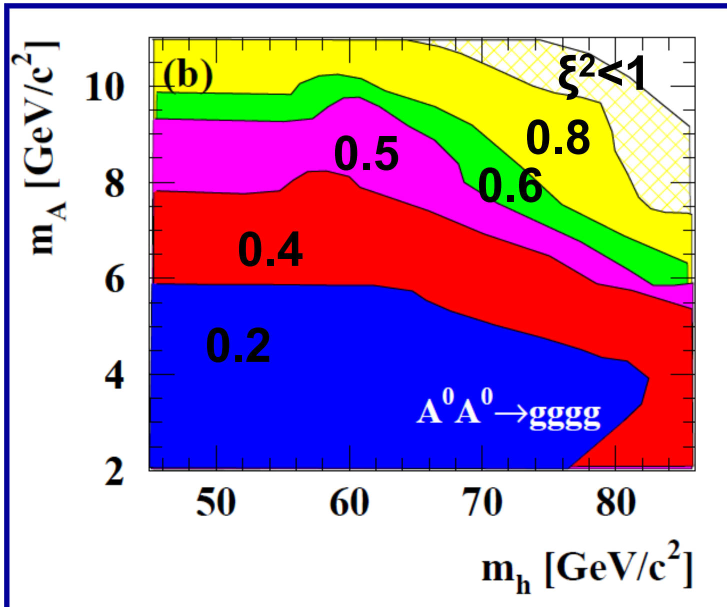
$$f = 350 \text{ GeV},\ \mu_V = 500 \text{ GeV},\ M_c = 400GeV,\ M_\tau = 200 \text{ GeV}$$

- $h \to 4g$ around 80 % (the rest the SM $h \to 2b$)
- $h \to \gamma\gamma gg$ of order 10^{-4}
- $h \to \tau\tau gg$ of order 10^{-3} – 10^{-5}
- $h \to 4\mu$ and $h \to \tau\tau\mu\mu$ very suppressed…

- LEP bound: model indep. $m_h > 78$ GeV

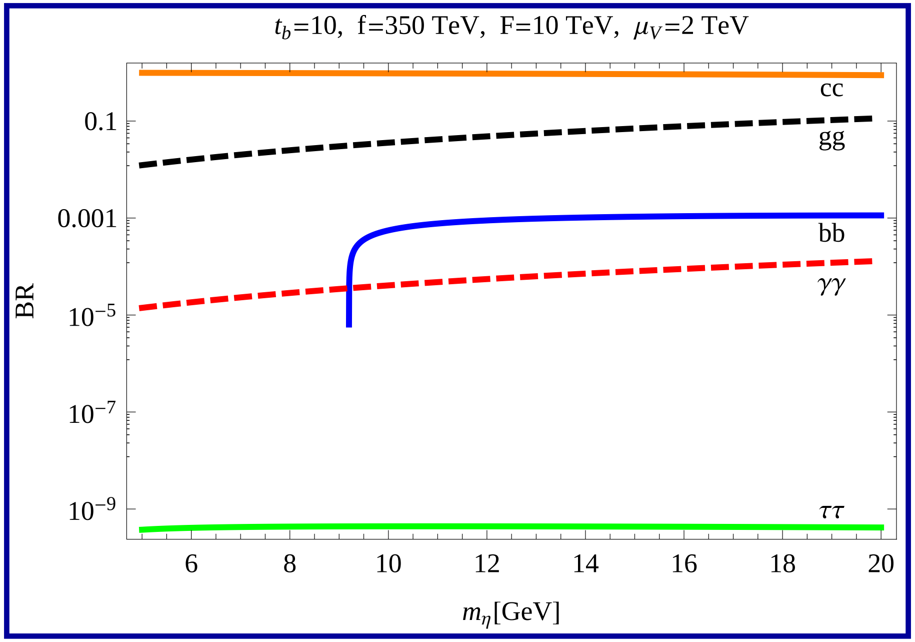
- OPAL $h \to 2\eta \to 4j$ analysis (assuming $m_h < 86$ GeV):





Charming Higgs

- A variation of previous model where $\eta\to 2c$ is dominant



- η does not have to be below 10 GeV

(Bellazzini, C.C., Falkowski, Weiler `09)

•$h \to 4j$ very difficult to discover at the LHC (buried in QCD background)

•Likely need jet substructure analysis or similar techniques to distinguish from background

(Chen, Nojiri, Streethawong `10; Falkowski, Krohn, Shelton, Wang `10)

•Other interesting possibility:

$h \to$ hidden sector $\to$ lepton jets

•Lots of non-isolated leptons – is it really viable at Tevatron?

(Falkowski, Ruderman, Volansky, Zupan `10)

Other SUSY approaches

•**NMSSM**: quartic from $W \supset \lambda S H_u H_d$

•But λ can not be too large either to avoid Landau pole before M_{GUT}. Requires $m_h \lesssim 150$ GeV

•**Fat Higgs**: around Landau pole weakly coupled Seiberg-dual, can have $m_h \sim 400$ GeV (Harnik, Kribs, Larson, Murayama `03)

•**Dine-Seiberg-Thomas**: NMSSM-like effective theory

$$W \supset \frac{1}{M}(H_u H_d)^2$$

type term like when integrating out massive S

- Additional quartic from **extra D-term**

- Usually D-terms decouple if gauge breaking fully supersymmetric

- If m_{soft} ~ VEV for field breaking the additional gauge symmetry D-term does not decouple

- Can raise Higgs mass to ~400 GeV

(Batra, Delgado, Kaplan, Tait `03)

II. Models of strong dynamics

- Don't necessarily need elementary Higgs to break symmetry

- Example: QCD

- Quark-antiquark (or LH and RH quarks) strongly attract, form vacuum condensate:

$$\langle u_L u_R \rangle = \langle d_L d_R \rangle \sim f_\pi^3$$

- This breaks EWS and gives mass to W,Z, just too small contribution

- **Technicolor**: new strong interaction with $f_{TC} \sim v = 246$ GeV. Scaled-up QCD

Issues with technicolor-like theories

•Electroweak precision: S-parameter usually too large (but not calculable). If like scaled-up QCD

$$S \sim 0.28 N_D \frac{N_{TC}}{3}$$

•Fermion masses: usually hard to get large enough top mass without also generating large FCNC's

For m_t need Λ_F< 10 TeV

$$\frac{1}{\Lambda_F^2}\bar{q}q\bar{\psi}\psi$$

To avoid FCNC Λ_F>10^4 TeV

$$\frac{1}{\Lambda_F^2}\bar{q}q\bar{q}q$$

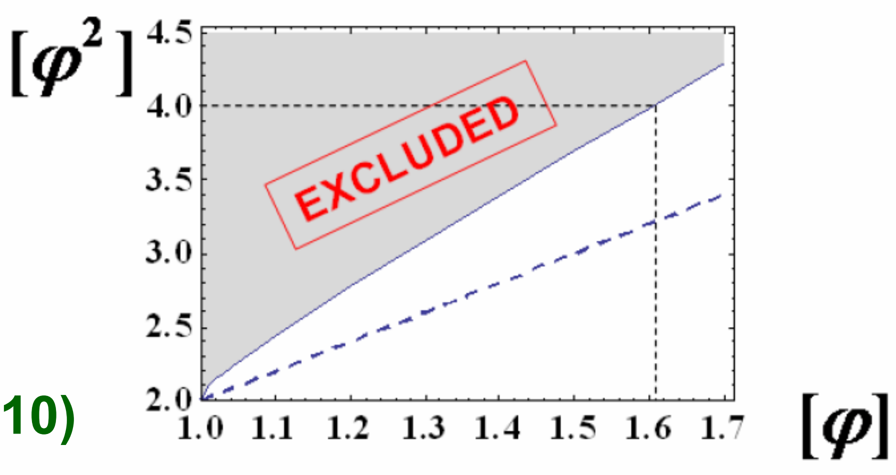
•Walking technicolor: large anomalous dimension for $\bar{\psi}\psi$ relieves some of the tension in Λ_F

•Conformal technicolor: can the anomalous dim. of $\bar{\psi}\psi$ be so large that $\bar{\psi}\psi$ is almost like a free field (d~1+ϵ)? **(Luty, Okui `04)**

•Talk by V. Rychkov: upper bound on anomalous dimension from general principles (crossing)

•Can not sufficiently suppress FCNC's w/o hierarchy hitting back…

(Rattazzi, Rychkov, Tonni, Vichi `08-'10)



EWSB via monopole condensation

(C.C., Shirman, Terning `10)

- An interesting alternative to technicolor, no new gauge group, use strong interaction between monopoles of $U(1)_Y$

- Toy model:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q	$\square$	$\square$	$\frac{1}{6}$	3
L	1	$\square$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\square}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

Possible condensates

- Assume: β-function of $U(1)_Y$ not much modified. Magnetic attraction becomes strong: condensate

- Condensate should not carry magnetic charge

- Have quantum number of Higgs

$$Q\bar{D} \sim (1,2,\frac{1}{2}) \sim H, \quad Q\bar{U} \sim (1,2,-\frac{1}{2}) \sim H^*,$$

$$L\bar{E} \sim (1,2,\frac{1}{2}) \sim H, \quad L\bar{N} \sim (1,2,-\frac{1}{2}) \sim H^*.$$

- Assume some of these condensates generated

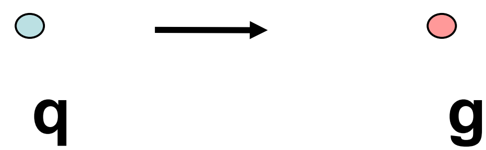
$$\langle U_L\bar{U}\rangle \sim \langle D_L\bar{D}\rangle \sim \langle N_L\bar{N}\rangle \sim \langle E_L\bar{E}\rangle \sim \Lambda_{mag}^d$$

- Λ_{mag} is a dynamical of order few x 100 GeV

The Rubakov-Callan effect

- Angular mom. of EM. field: $$\vec{J} = qg\vec{n}$$
depends on direction from charge to pole

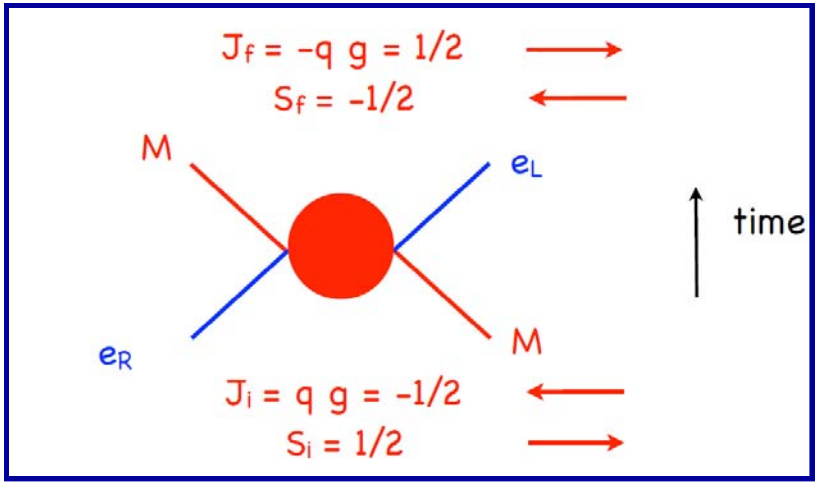
- In head-on scattering this direction changes, even though no force



- Spin of scattered fermion must also flip

- New 4-fermi op's in modified model with $U(1)_{EM}$

$$\lambda_{ij}^{(u)} u_R^i N_L \left(u_L^j N_R\right)^\dagger$$



- After condensation large m_{top}

Phenomenology of Monocolor

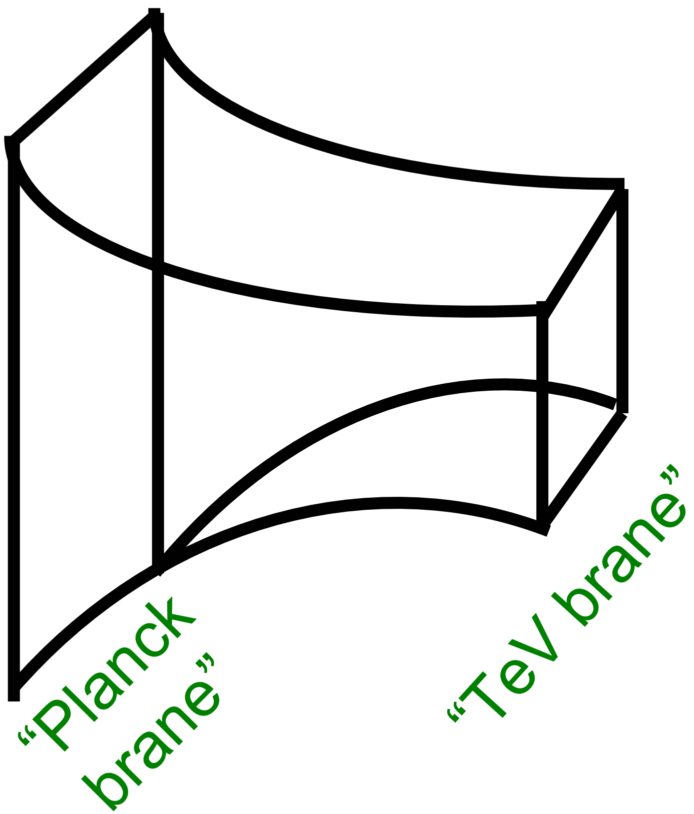
- After EWSB theory vectorlike, expect monopoles to pick up mass of order Λ_{mag}~500 GeV – TeV

- Not confined, behave like "ordinary" QED monopole

- No magnetic coupling to Z; electric coupling is there, expect EWPO (S,T) like a heavy fourth generation but magnetic contr. to γ-γ 2pt function should be small

- **At LHC:** likely pair produced. Due to strong force strong attraction, will always annihilate at LHC. Large radiation, then annihilation. Lots of photons, some of them hard. Cross section ~ pb **(A. Weiler)**

Warped extra dimension



(Randall,Sundrum `99; Maldacena `97;…)

- Metric exponentially falling

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

- Mass scales very different at endpoints
- Graviton peaked at Planck
- SM on IR brane

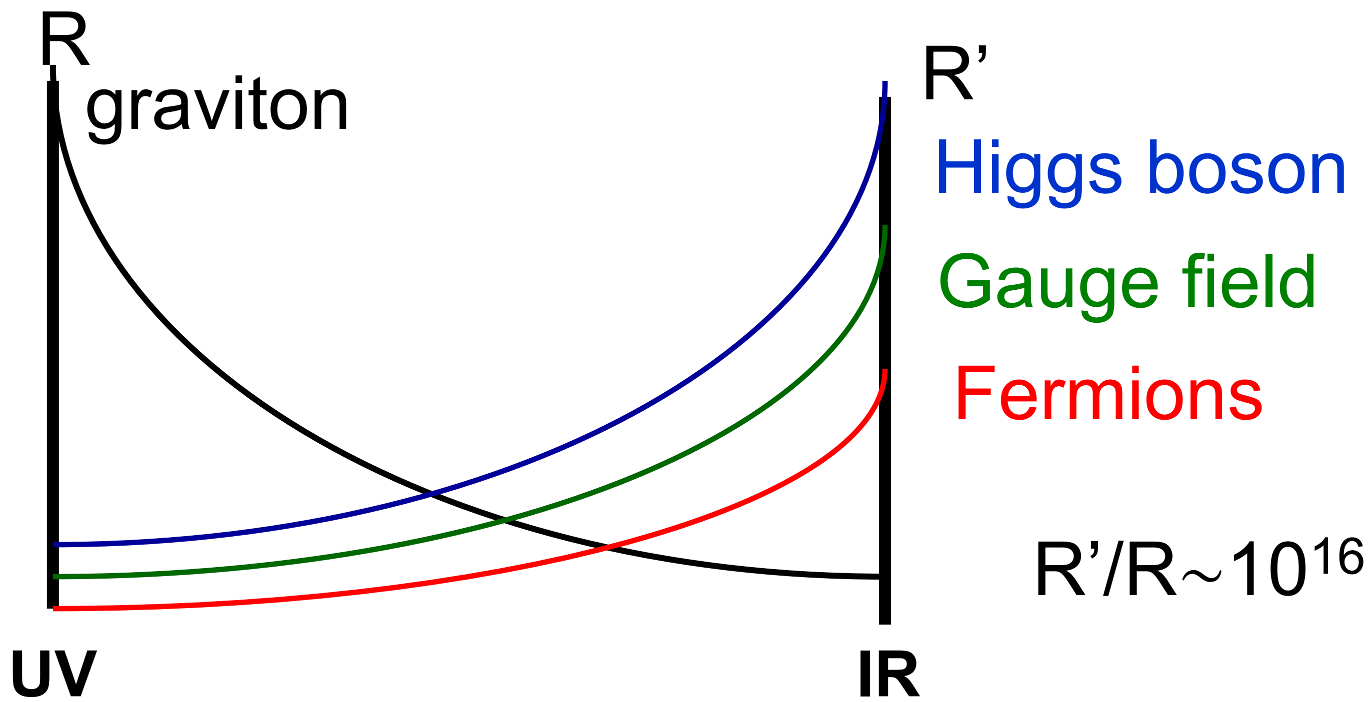
- Related to strong dynamics/technicolor models via AdS/CFT duality

- Fields peaked on UV: elementary (natural mass scale very large)

- Fields peaked on IR: composite of strong dynamics (natural mass scale low)

- If Higgs on IR brane: composite, natural scale TeV

The original RS model

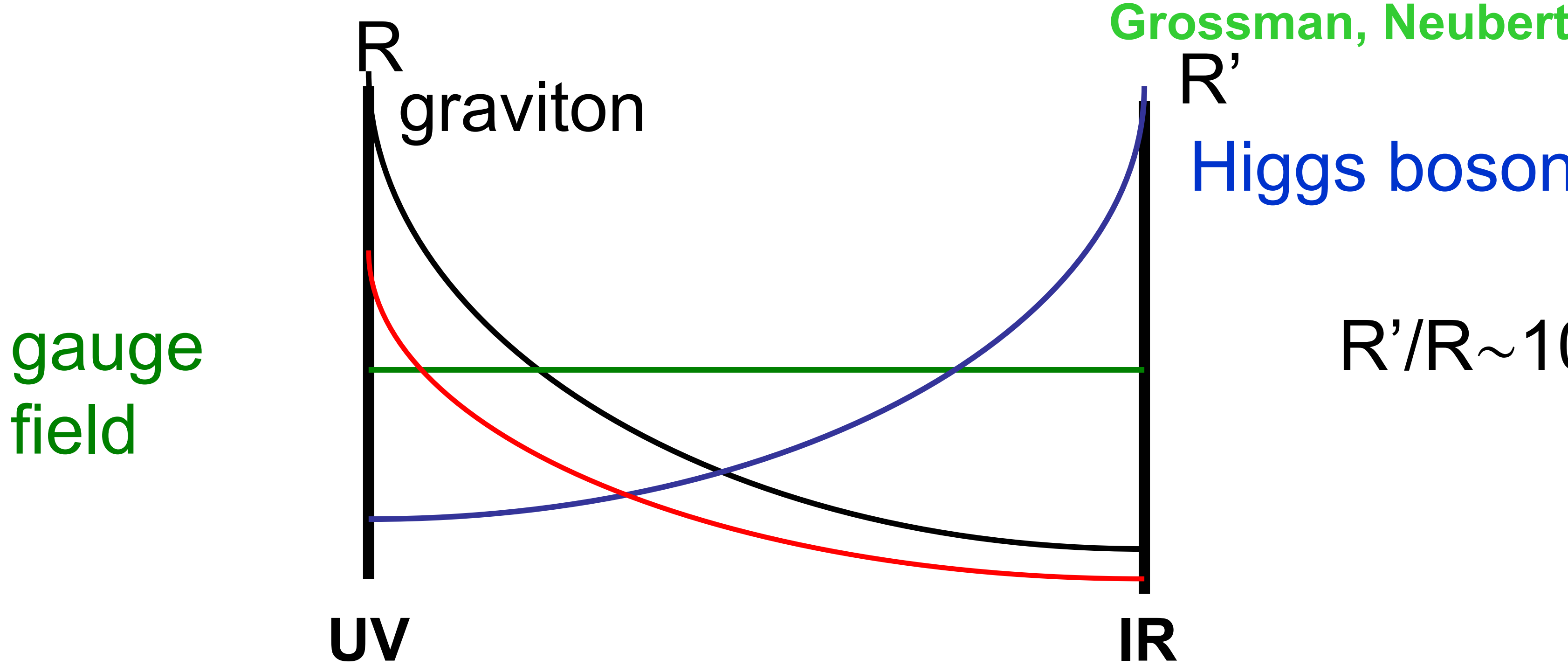


Solves the hierarchy problem.

But: electroweak precision? If all fields on IR brane expect large EWP contributions, large FCNC's

Realistic RS model

(Davoudiasl, Hewett, Rizzo; Gherghetta, Pomarol; Grossman, Neubert;…)



$R'/R \sim 10^{16}$

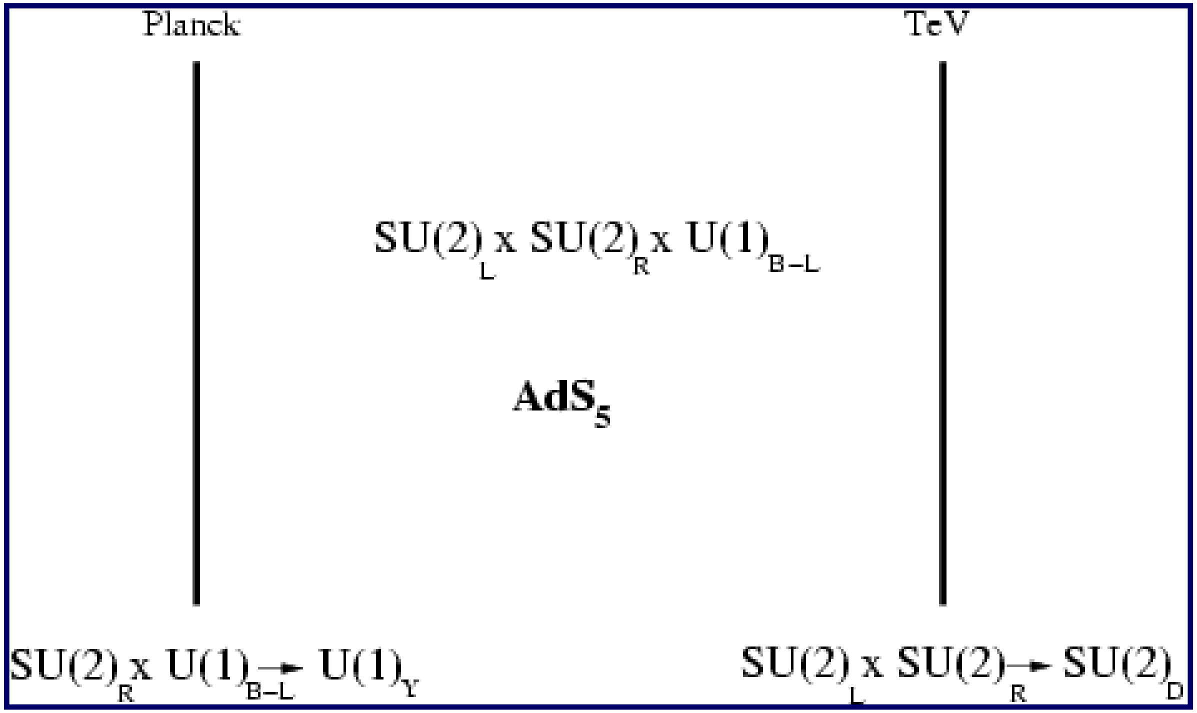
Still solves hierarchy problem since Higgs on IR

FCNC suppressed since fermions on UV

T-parameter can be protected via custodial sym.

The “canonical” realistic RS model

- Need to put fermions away from IR brane for FCNC
- To protect T-parameter need to include $SU(2)_R$ custodial symmetry

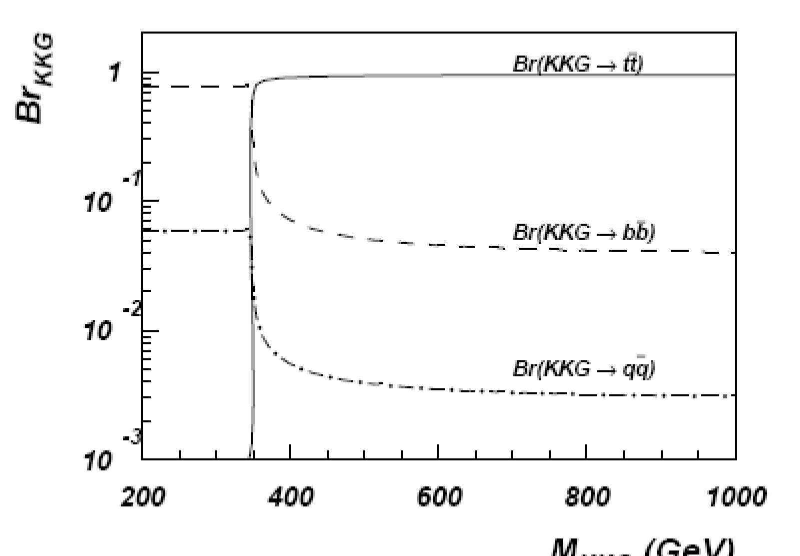


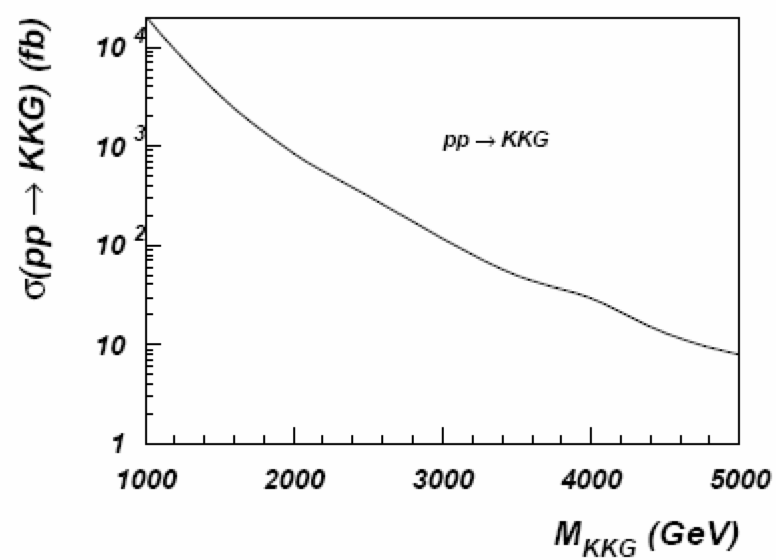
(Agashe, Delgado, May, Sundrum, `03)

- $S \sim 12\pi\, v^2/m_{KK}^2$ Bound $m_{KK} > 3$ TeV
- T parameter at tree level suppressed

(Carena, Delgado, Ponton, Tait, Wagner)

- Signals:
- Light top partners
- 3 TeV KK gluon, but mostly coupled to t_R





(From Agashe, Belyaev, Krupvnickas, Perez, Virzi; see also Davoudiasl, Randall, Wang)

- Little hierarchy: NOT solved here either

- Cutoff scale: $$\Lambda \sim \frac{16\pi^2}{g^2 R' \log \frac{R'}{R}} \sim 10 - 100 \ \text{TeV}$$

- Natural Higgs mass $m_H \sim \Lambda/(4\pi) > 1$ TeV

- Can give theory of flavor (talks by Neubert, Soni)

- To also solve little hierarchy:

  Higgsless (gauge-phobic)

  Pseudo-Goldstone Higgs

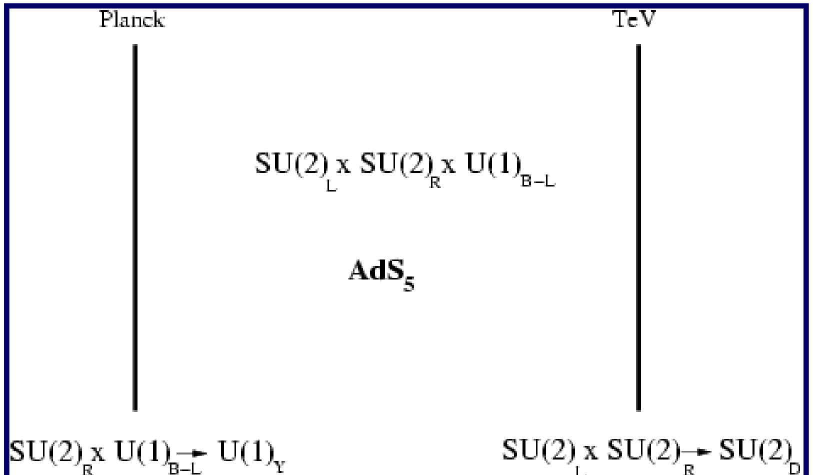
Higgsless models

(C.C., Grojean, Murayama, Pilo, Terning `03)

•Realistic RS: little hierarchy problem

•Simply let Higgs VEV to be big on IR brane

•Higgs VEV will repel gauge boson wave functions, Higgs will simply decouple from theory



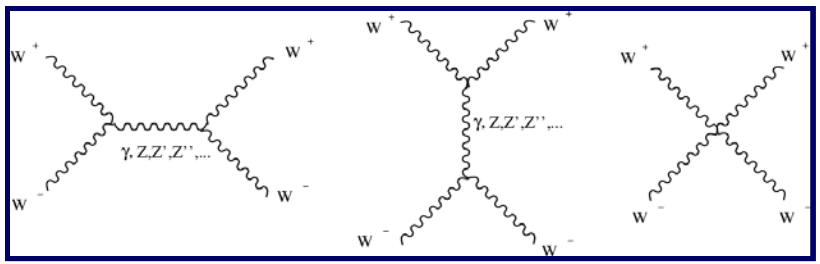
Same as for RS, except Higgs VEV →∞ on IR brane

- In practice, just implies BC's for gauge fields
- Typical mass spectrum:

$$M_W^2 = \frac{1}{R'^2 \log\left(\frac{R'}{R}\right)}$$

- BUT: w/o higgs at $\Lambda = 4\pi M_W/g \sim 1.6 \text{ TeV}$ unitarity would be violated??

- Exchange of KK gauge bosons restores unitarity



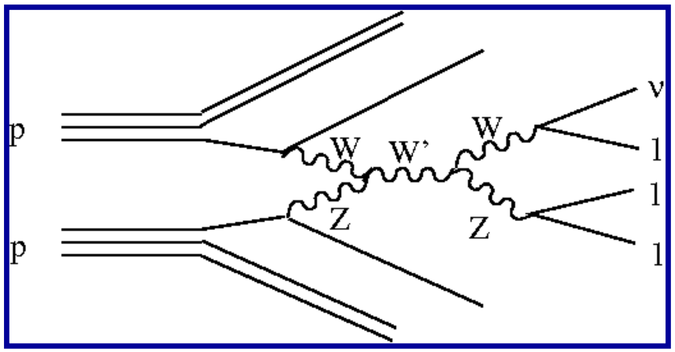
- Implies sum rules among masses and couplings

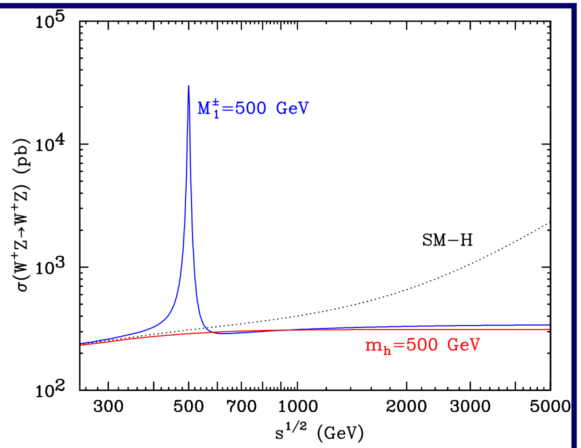
$$\begin{aligned} g_{WWWW} &= g_{WW\gamma}^2 + g_{WWZ}^2 + \sum_i g_{WWZ^i}^2 \\ \frac{4}{3} g_{WWWW} M_W^2 &= g_{WWZ}^2 M_Z^2 + \sum_i g_{WWZ^i}^2 M_{Z^i}^2 \end{aligned}$$

LHC predictions of Higgsless

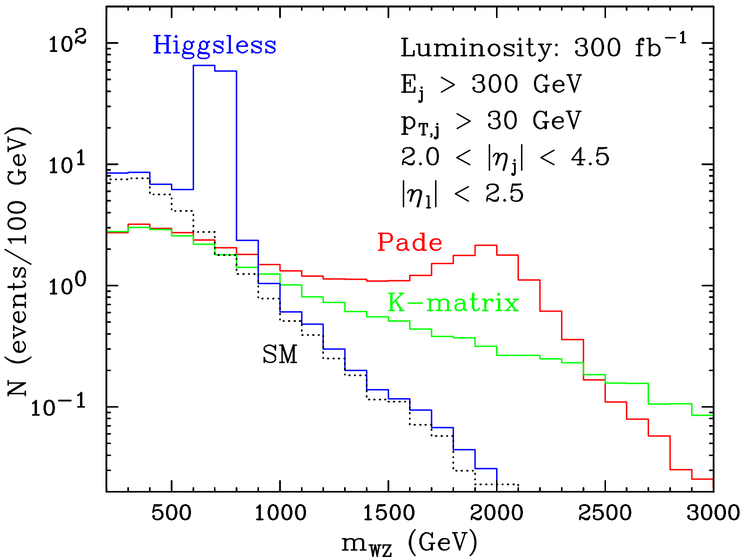
(Birkedal, Matchev, Perelstein `04)

- WW scattering not that different from SM
- WZ scattering is very different (new peak due to W')



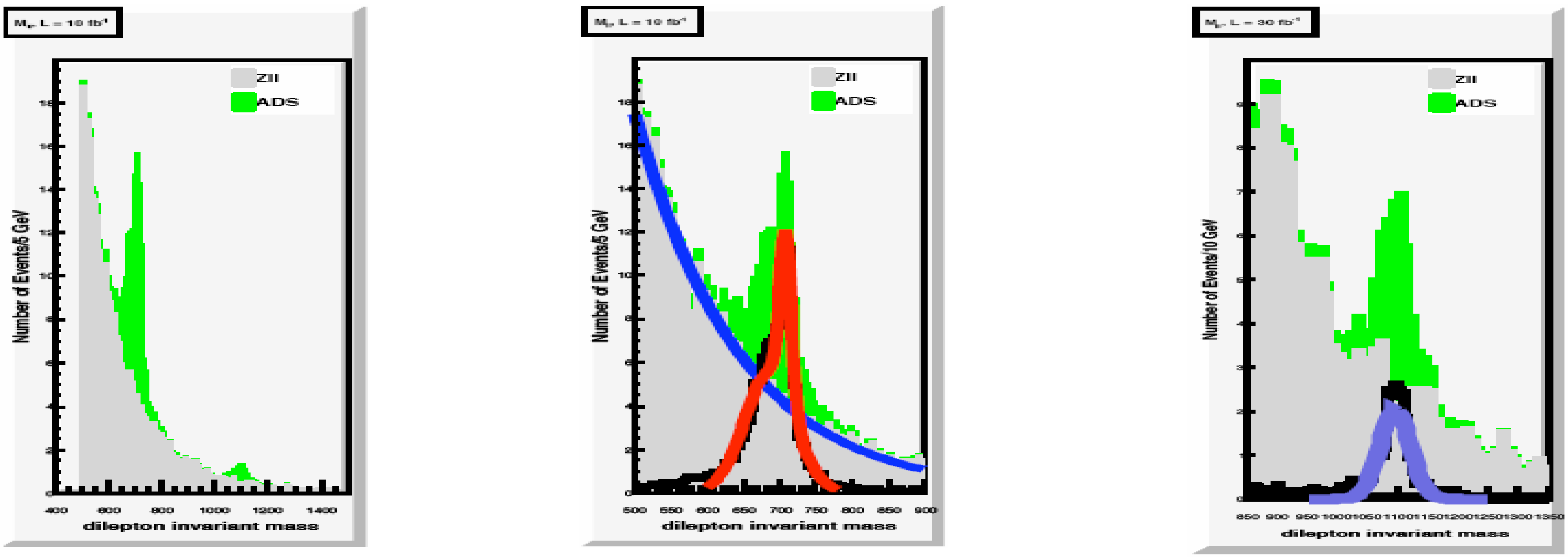


WZ→WZ



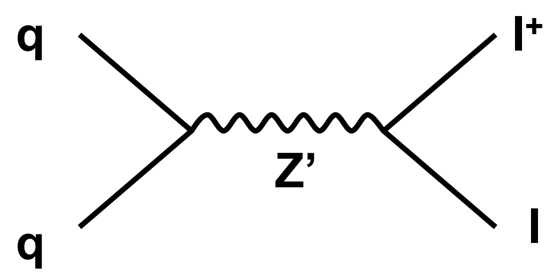
- Coupling to fermions not that small, DY will still be leading channel at LHC

Example Z’→l^+l^- DY at LHC for a sample point



(Martin and Sanz `09)

Process	σ	ϵ	# events
$Z_i \to \ell^+\ell^-$	0.045 pb	0.34	152
$Z \to \ell^+\ell^-$	1.58 pb	0.032	521

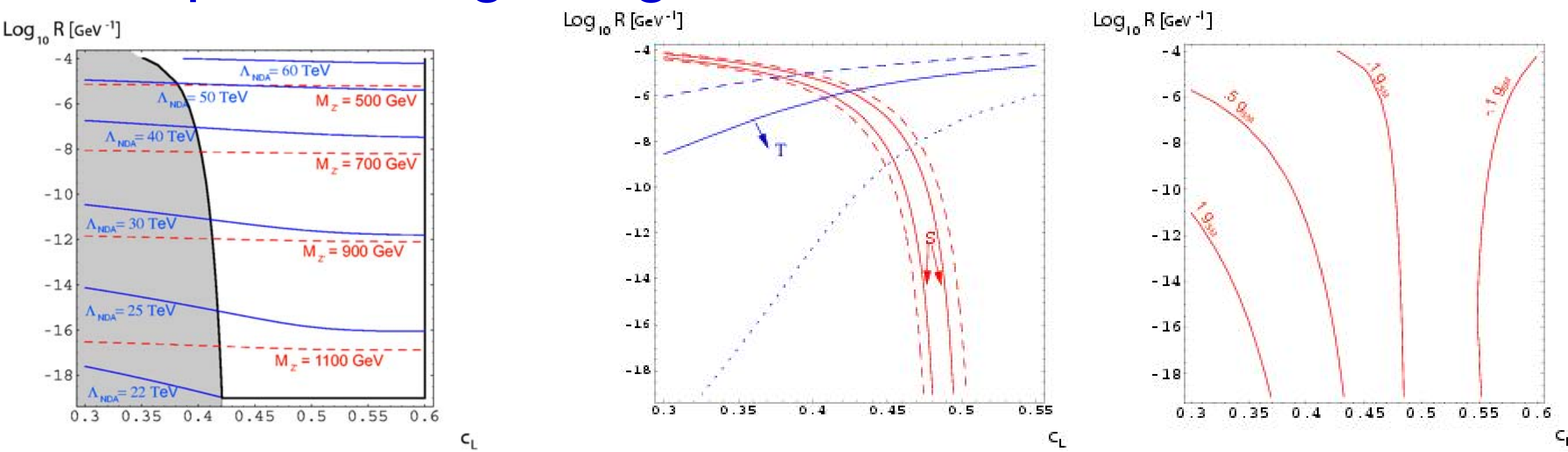


Electroweak precision tests & higgsless

- Dual to technicolor, S usually too large:

$$S \sim \frac{N}{\pi} \sim \frac{12\pi}{g^2}\frac{M_W^2}{m_\rho^2}$$

- S depends on fermions: if elementary too big, if Composite: large negative. Can cancel in between



- S is sufficiently small
- KK modes sufficiently heavy
- Couplings to KK modes small

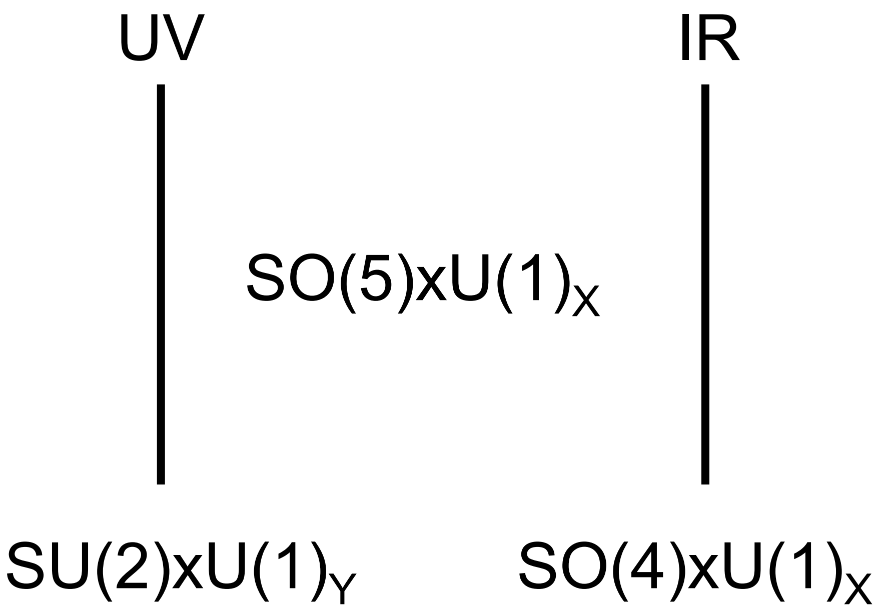
BUT: 1% level tuning in c

(Cacciapaglia, C.C.,Grojean, Terning, `04)

Composite pGB Higgs models

- In technicolor (or Higgsless): S too large: not enough separation between m_W and m_ρ
- Other possibility: still strong dynamics, but scales separated more $m_\rho \gg m_W$
- If strong dynamics produces a composite Higgs
- But then Higgs mass expected at the strong scale
- To lower Higgs mass: make it a Goldstone boson
- Higgs mass due to 1-loop electroweak corrections

The minimal example (MCH)



(Contino, Nomura, Pomarol;
Agashe, Contino, Pomarol;
Carena, Ponton, Santiago, Wagner,…)

- A 5D model (doesn't have to be)
- Sym. breaking pattern:
- $SO(5)xU(1)_X$ global→ $SO(4)xU(1)_X$ global
- SM subgroup gauged

Higgs potential:

$$V(h) = 0 \cdot |h|^2 + 0 \cdot |h|^4 + \frac{g^2}{16\pi^2} f^4 \cos^n(|h|/f)$$

Tree-level vanishes due to PGB nature

Generic PGB pot.

•The main difficulty: in Higgs potential everything radiative, again no natural separation between v, f

Mass:

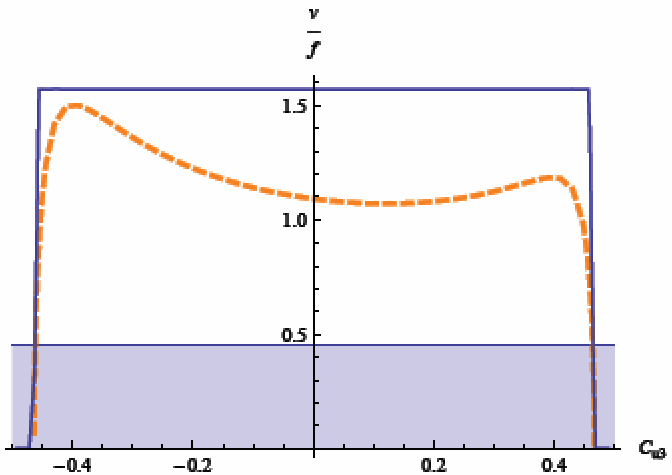
$$m_h^2 \propto \frac{g^2}{16\pi^2} f^2$$

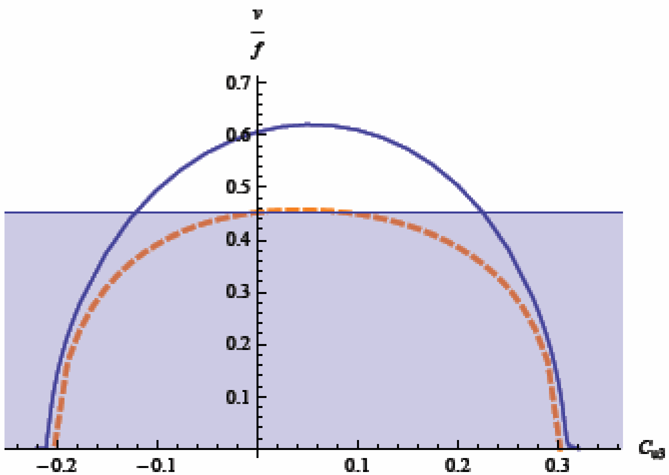
Quartic:

$$\lambda \propto \frac{g^2}{16\pi^2}$$

•Generically would expect v~f. Need some tuning to avoid

(Carena, Ponton, Santiago, Wagner `07; C.C., Falkowski, Weiler `08)



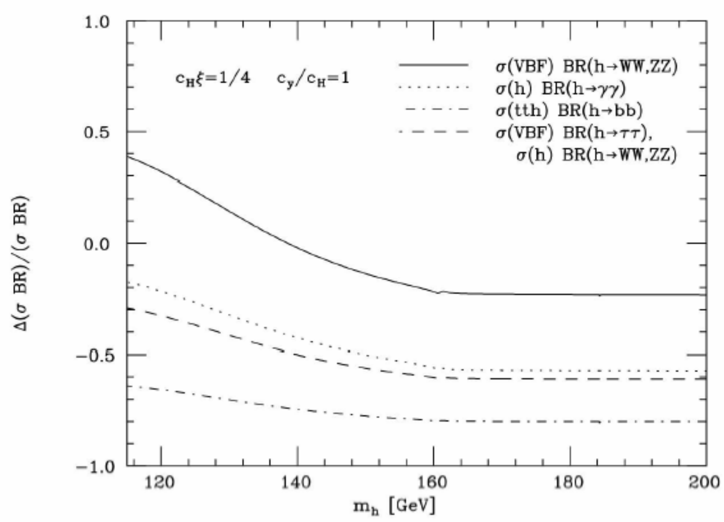


Experimental consequences of pGB MCH

- Try to find states from extra sector: similar to RS searches (m_ρ >3 TeV, KK gluon,…)

- Higgs properties modified due to compositeness (“Higgs form factors”)

(Giudice, Grojean, Pomarol, Rattazzi `07)



Little Higgs models

(Arkani-Hamed, Cohen, Katz, Nelson `02)

- Higgs is Goldstone again

- Added ingredient: "collective breaking": need at least two couplings simultaneously to break symmetry

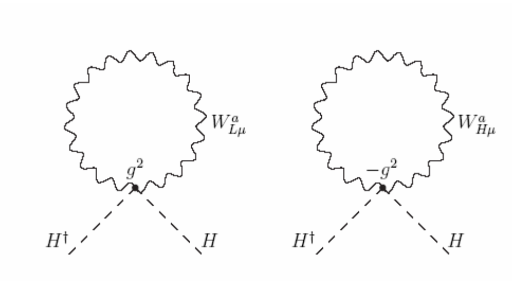
- Mass suppressed, but quartic is large

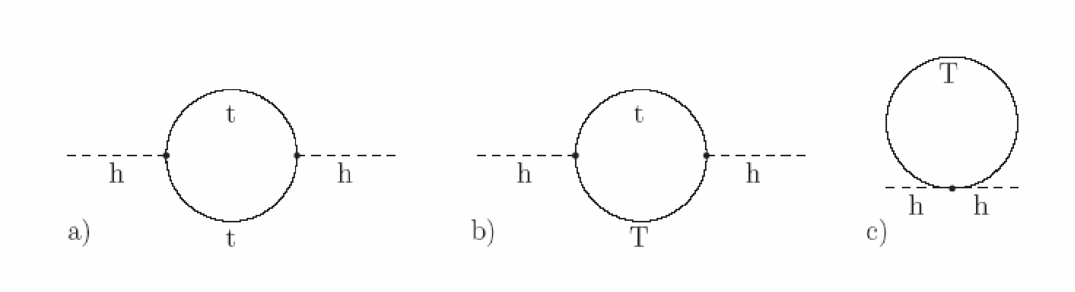
$$m_h^2 \propto \frac{g^2}{16\pi^2} f^2 \qquad\qquad \lambda \propto g^2$$

- Now $\langle h \rangle \sim f/(4\pi)$, really no tuning to get little hierarchy

- But needs lots of additional states to achieve collective breaking, issue with EWP again…

•For collective breaking need new light particles ~ 1 TeV, "little partners"





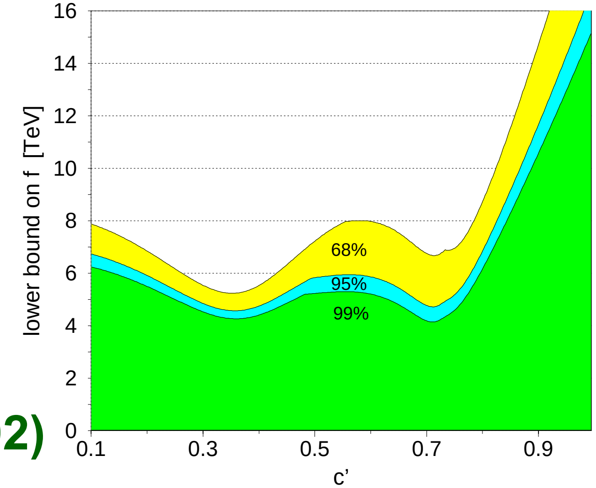
Gauge loops

Top loops

•But new particles themselves will contribute to EWPO's

•Will force generically f>4 TeV

(C.C., Hubisz, Kribs, Meade, Terning `02)



- Way out: ensure no tree-level EWP contribution
- New Z_2 parity needed dubbed T-parity **(Cheng, Low `03)**
- However, full model quite complicated

(C.C., Heinonen, Perelstein, Spethmann `08)

- For example, one generation…

a)	$SU(5)$	$SU(2)_3$	$U(1)_3$	b)	$SU(5)$	$SU(2)_3$	$U(1)_3$	c)	$SU(5)$	$SU(2)_3$	$U(1)_3$
Q_1	$\bar{\Box}$	1	$+2/3$	Q'_1	$\bar{\Box}$	1	$-2/3$	L_1	$\bar{\Box}$	1	0
Q_2	$\Box$	1	$+2/3$	Q'_2	$\Box$	1	$-2/3$	L_2	$\Box$	1	0
q_3	1	$\Box$	$-1/6$	q'_3, q''_3	1	$\Box$	$+1/6$	ℓ_3	1	$\Box$	$+1/2$
q_4	1	$\Box$	$-7/6$	q'_4	1	$\Box$	$+7/6$	ℓ_4	1	$\Box$	$-1/2$
q_5	1	$\Box$	$-7/6$	q'_5	1	$\Box$	$+7/6$	ℓ_5	1	$\Box$	$-1/2$
U_{R1}	1	1	$-2/3$	U'_{R1}	1	1	$+2/3$	E_{R1}	1	1	0
U_{R2}	1	1	$-2/3$	U'_{R2}	1	1	$+2/3$	E_{R2}	1	1	0
u_R	1	1	$-2/3$					e_R	1	1	$+1$
d_R	1	1	$+1/3$					$(\nu_R$	1	1	$0\ )$

Summary

- Don't understand how higgs is light and still no trace of new physics

- In SUSY calls for extension of MSSM
  - Hidden higgs
  - Extra quartic
- Strong dynamics models: EWP usually issue
  - Warped extra dimension (composite Higgs, higgsless)
  - Little higgs
  - Technicolor, monopole condensation,…
- None of them fully convincing

- LHC should settle these by ICHEP 2014 (2012?)