An overview of electroweak symmetry breaking scenarios and their signals

Csaba Csáki (Cornell University)

Kobe Workshop on BSM and Predictable Observables
January 6, 2011
Kobe, Japan

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

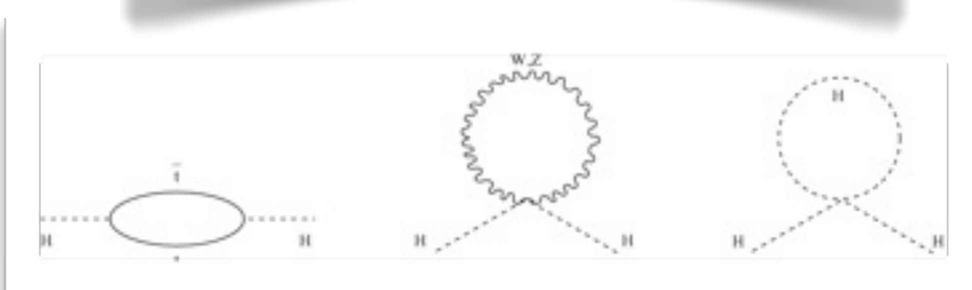
The SM, big vs. little hierarchy

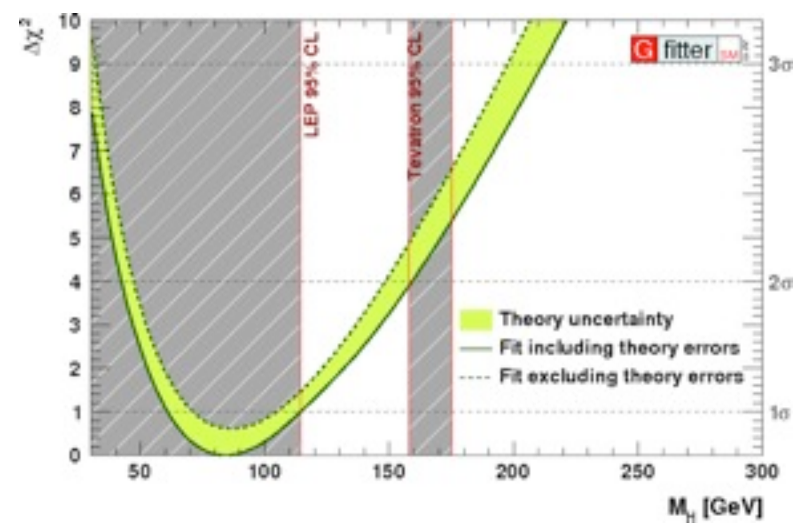
•Standard higgs mechanism very successful

•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)

•This issue is usually referred to as “big hierarchy” problem: why is $m_h << M_{Pl}$

•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
$\|H^\dagger D_\mu H\|^2$	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:

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

- Minimizing this:

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

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

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

- Need m_{Higgs} > 114 GeV

- Need large stop-top splitting

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

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

- And for large tan β

$$M_Z^2 \sim -2m^2_{H_u}$$

- 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 ~ 1.5 years 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

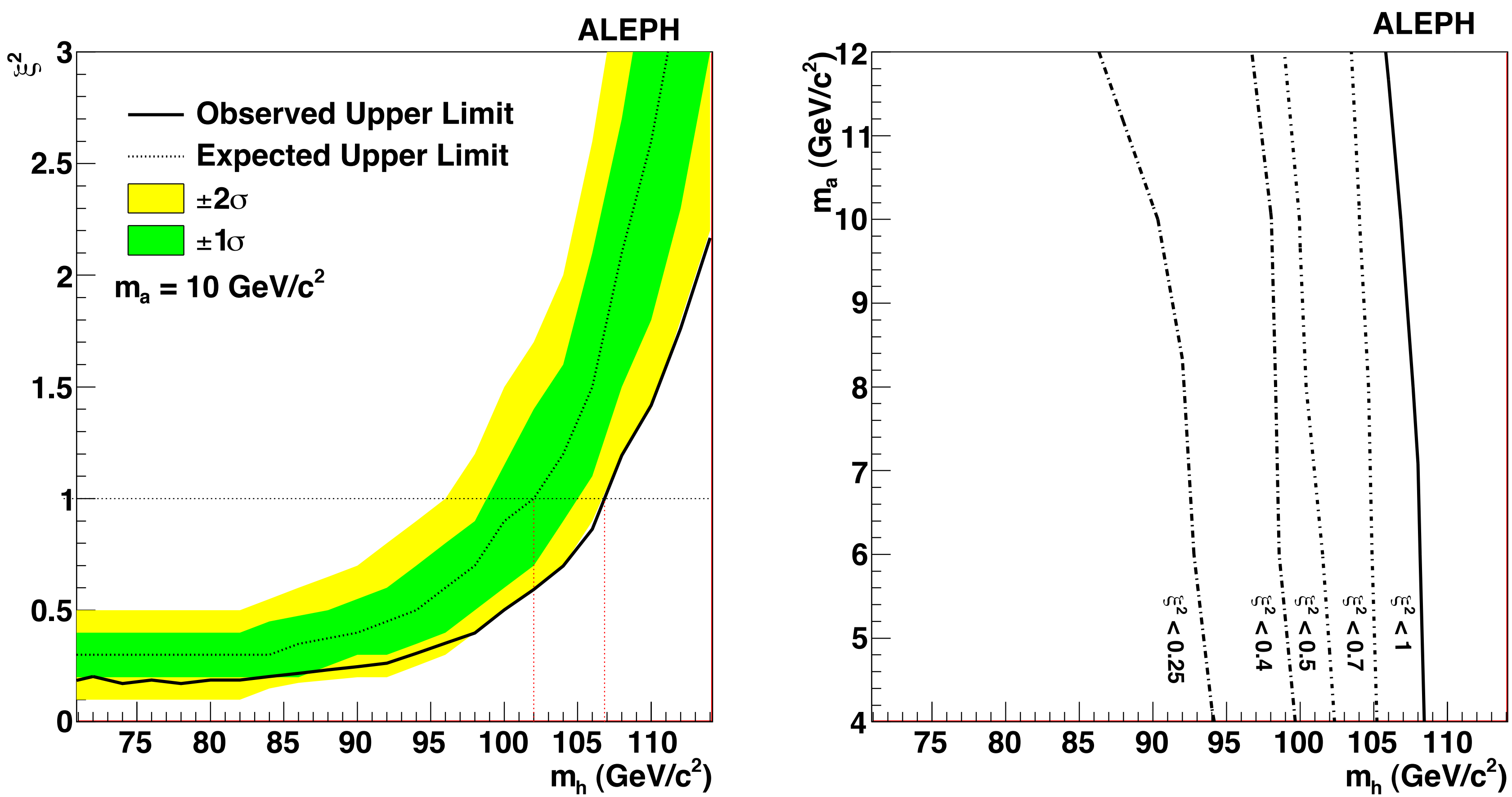
- Most popular possibility

(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)

- 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 $h \to 4j$ or more complicated final states if want to hide the higgs at LEP

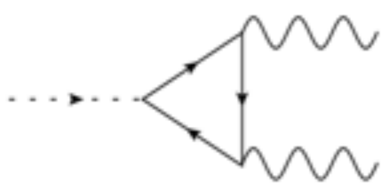
An interesting possibility: $h \to 4j$

•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

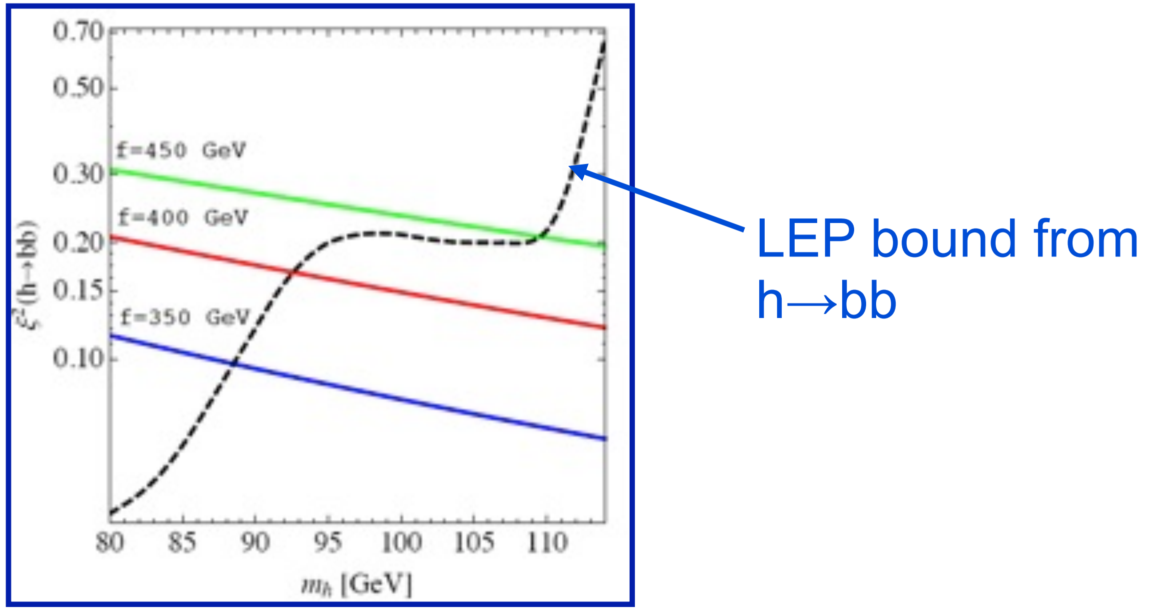
•Leading higgs decay $h \to 2\eta$ where η is an SU(2)xU(1) singlet pGB

•The η decays via triangle diagrams to 2g

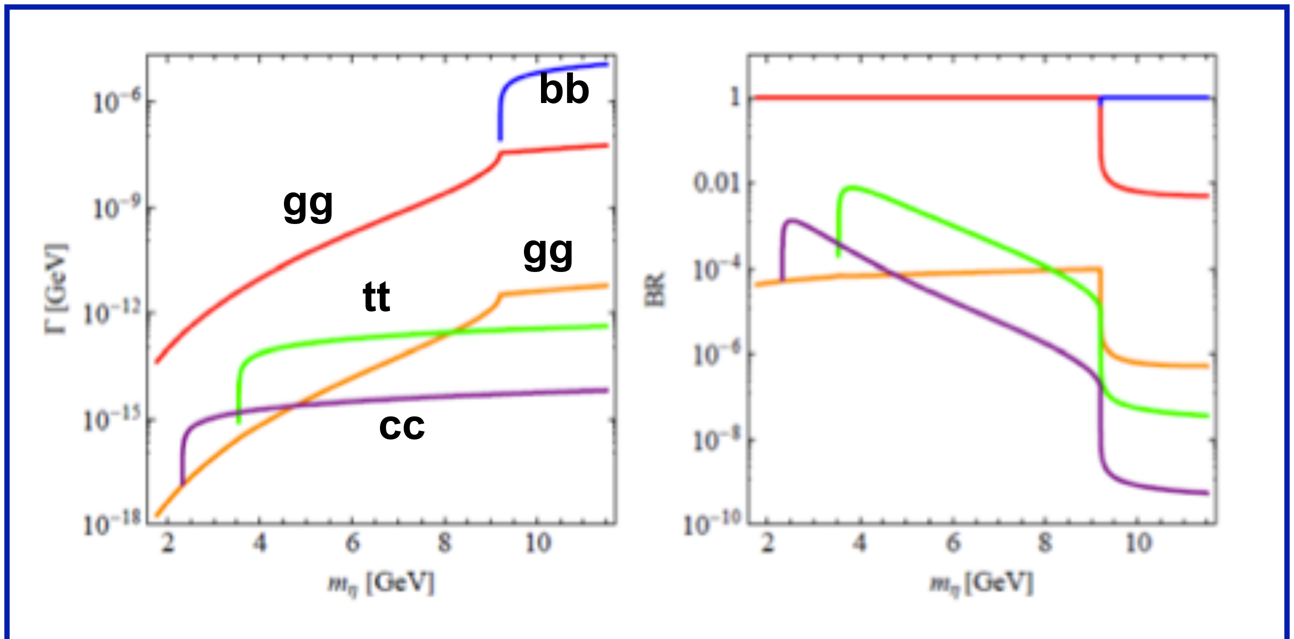


(Bellazzini, C.C., Falkowski, Weiler `09)

• **The h decays**



• **The η decays**

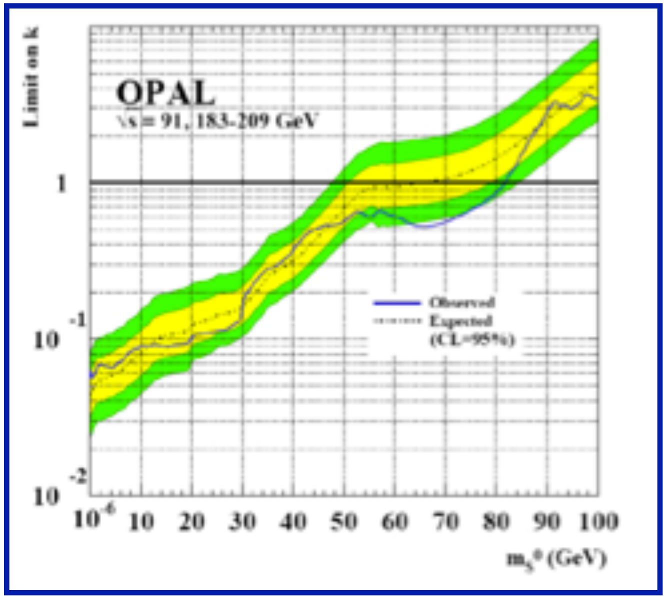


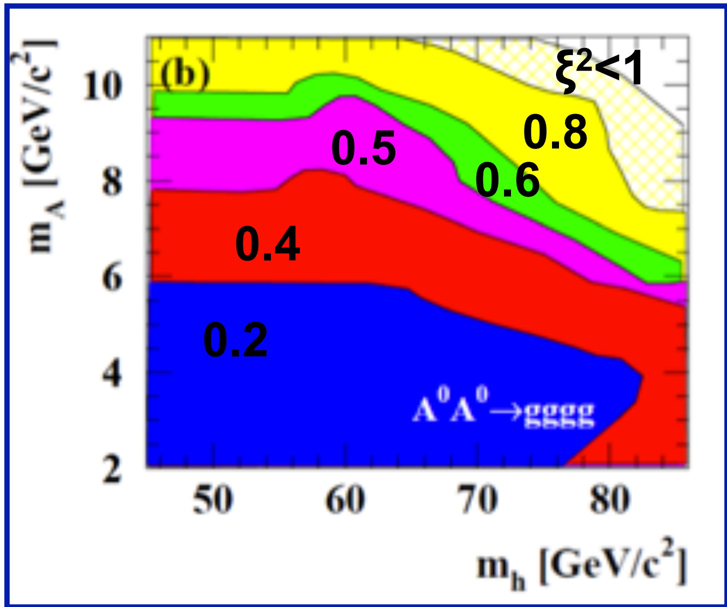
$f = 350$ GeV, $\mu_V = 500$ GeV, $M_c = 400 GeV$, $M_\tau = 200$ GeV

- $h \to 4g$ around 80 % (the rest the SM $h \to 2b$)
- $h \to 4\gamma$ of order 10^{-4}
- $h \to \tau\tau\gamma\gamma$ 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

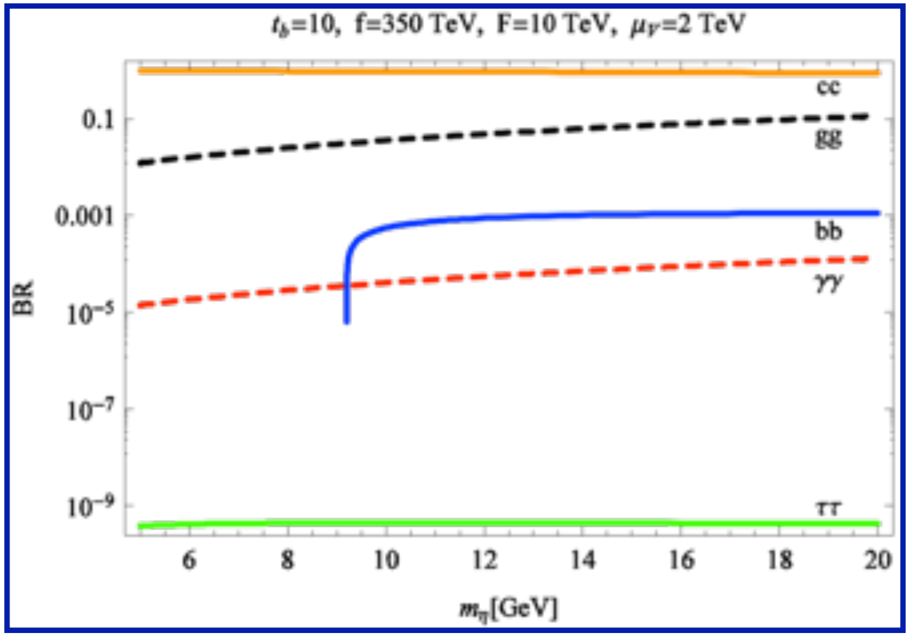
- OPAL $h \to 2h \to 4j$ analysis (assuming $m_h < 86$ GeV):





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)

Searching for a buried higgs

Two options:

1. Look for SM production gg→h→4j

- Need to fight QCD background
- Need a lot of data ~100 fb^{-1}
- Use jet substructure tools to cut QCD background

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

2. Look for higgs in supersymmetric cascades like $\chi_2^0 \to \chi_1^0 + h$

- Use SUSY cuts to get rid of QCD background
- Look for bump in jet mass
- Use jet substructure tools just as in Wang et al. and Nojiri et al. to get rid of SUSY background

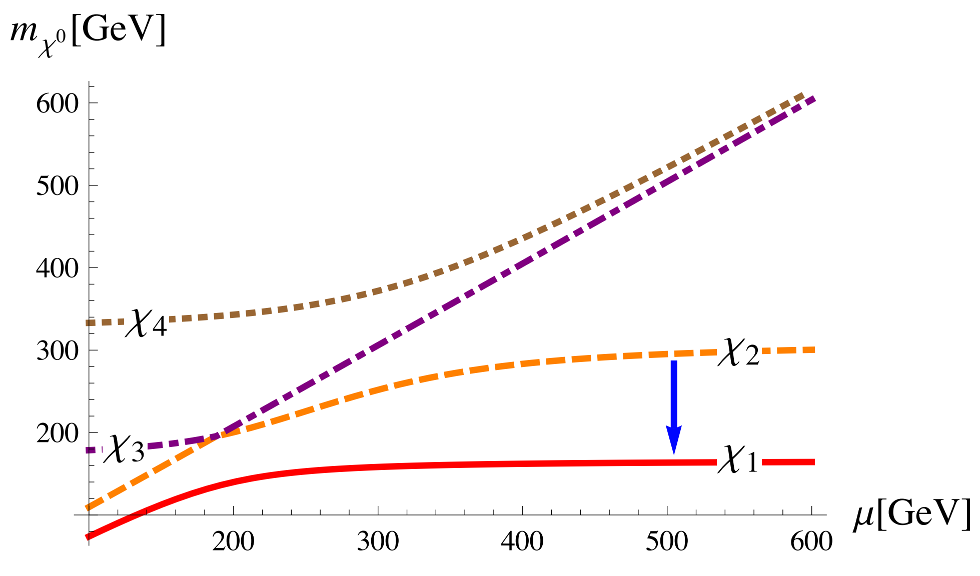
(Bellazzini, C.C., Hubisz, Shao '10)

The SUSY cascade analysis

(Bellazzini, C.C., Hubisz, Shao '10)

Sample SUSY scenarios

Model	1	2
$m_{\tilde{q}_{L,R}}$	940, 910	1000
$m_{\tilde{\ell}}$	1000	1000
$m_{\tilde{g}}$	949	2036
$m_{\chi_1^0}$	163	138
$m_{\chi_2^0}$	306	-158
$m_{\chi_3^0}$	-518	306
$m_{\chi_4^0}$	535	625
$m_{\chi_1^\pm}$	305	148
$m_{\chi_2^\pm}$	534	625
$\tan\beta$	10	10
μ	512	150
$\sigma(\tilde{g}, \tilde{q})$	2.5 pb	0.41 pb
$\mathrm{BR}(\tilde{q}_L \to h)$	30%	22%
$\mathrm{BR}(\tilde{q}_L \to Z)$	3%	25%
$\mathrm{BR}(\tilde{q}_L \to W)$	64%	48%
$\sigma \cdot \mathrm{BR}(h)$	0.29 pb	0.04 pb
$\sigma \cdot \mathrm{BR}(h + W/Z)$	0.47 pb	0.1 pb
$\sigma \cdot \mathrm{BR}(W/Z)$	1.04 pb	0.23 pb



1. Large μ: neutralinos gaugino-like. If sleptons heavy, $\chi_2^0 \to \chi_1^0 + Z$ doubly suppressed by higgsino mixing, $\chi_2^0 \to \chi_1^0 + h$ will dominate

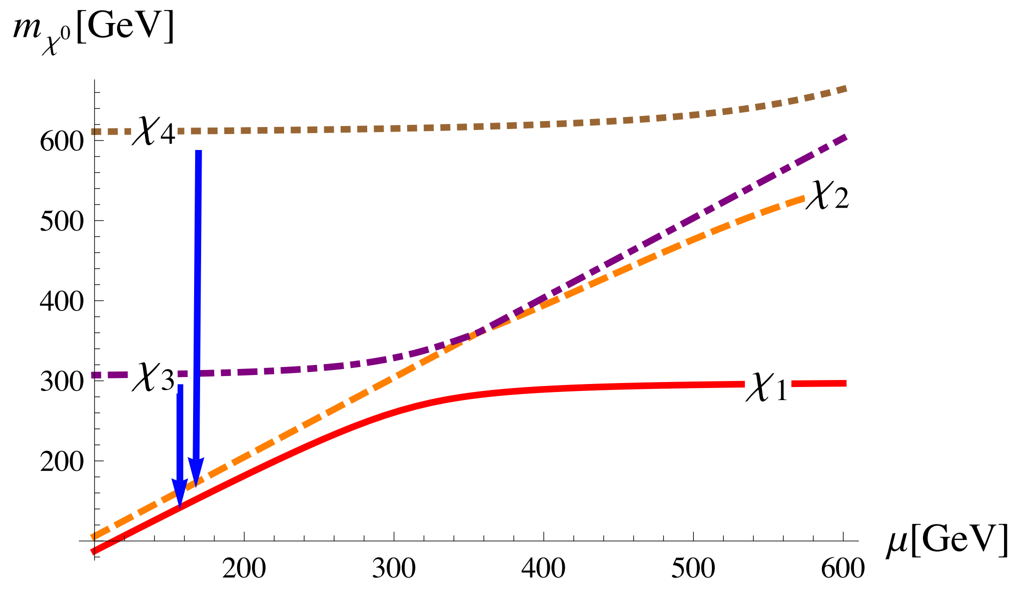
Little cascade

The SUSY cascade analysis

(Bellazzini, C.C., Hubisz, Shao '10)

Sample SUSY scenarios

Model	1	2
$m_{\tilde{q}_{L,R}}$	940, 910	1000
$m_{\tilde{\ell}}$	1000	1000
$m_{\tilde{g}}$	949	2036
$m_{\chi_1^0}$	163	138
$m_{\chi_2^0}$	306	−158
$m_{\chi_3^0}$	−518	306
$m_{\chi_4^0}$	535	625
$m_{\chi_1^\pm}$	305	148
$m_{\chi_2^\pm}$	534	625
$\tan\beta$	10	10
μ	512	150
$\sigma(\tilde{g}, \tilde{q})$	2.5 pb	0.41 pb
$\mathrm{BR}(\tilde{q}_L \to h)$	30%	22%
$\mathrm{BR}(\tilde{q}_L \to Z)$	3%	25%
$\mathrm{BR}(\tilde{q}_L \to W)$	64%	48%
$\sigma \cdot \mathrm{BR}(h)$	0.29 pb	0.04 pb
$\sigma \cdot \mathrm{BR}(h + W/Z)$	0.47 pb	0.1 pb
$\sigma \cdot \mathrm{BR}(W/Z)$	1.04 pb	0.23 pb



2. Small μ<<M1,2 : $\chi^0_{3,4}, \chi^\pm_2$ gaugino-like. Will dominantly decay via $\chi^0_{3,4} \to \chi^0_{1,2} + h$ through gaugino-higgs-higgsino vertex:

Big cascade

The cuts

1. Standard SUSY cuts

cut/sample	1	2
$E_T^{miss} > 200\text{GeV}$	80.64%	80.54%
$N_j \geq 3$	75.32%	78.87%
$p_{T,1} > 180, p_{T,2} > 110$	72.29%	77.72%
$H_T > 500$ GeV	35.54%	54.47%

2. Standard jet-substructure cuts (BDRS algorithm)

(Butterworth, Davison, Rubin, Salam)

1. Form FAT jets by recombining hadronic activity until $\Delta R_{ij} < R \sim 1.2$
2. Uncluster fat jet into $j_{1,2}$ and require
    1. Significant mass drop in jet masses (corresponding to actual subjets)

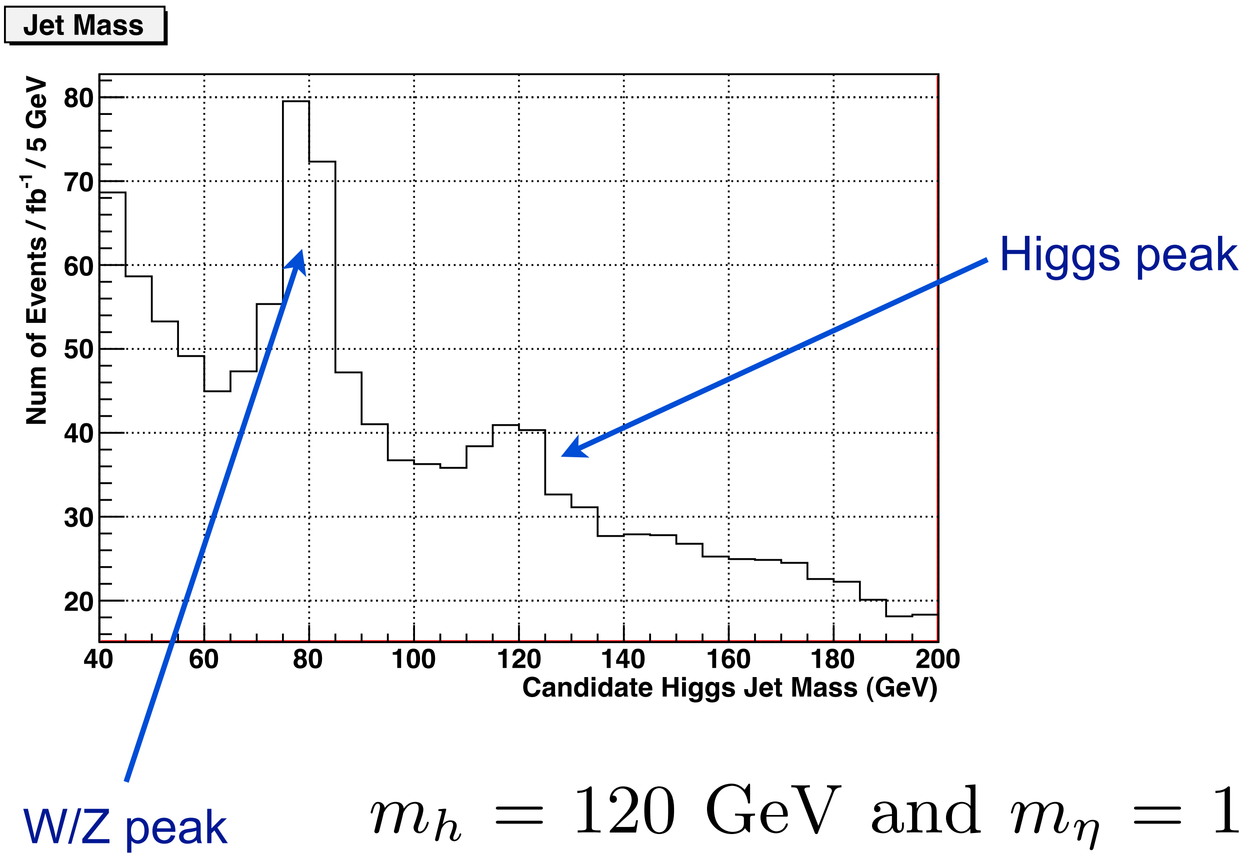
    $$m_{j1} < \mu\, m_j$$

    2. No significant asymmetry in subjets

    $$y \equiv \min(p_{T\,j_1}^2, p_{T\,j_2}^2)/m_j^2\, \Delta R_{j_1,j_2}^2 > y_{cut}$$

3. If subjets do not satisfy 2 uncluster further until no more subjets or $p_T < 50$ GeV

A typical resulting jet mass



$$m_h = 120 \text{ GeV and } m_\eta = 10 \text{ GeV}$$

Want to further clean up distribution using more cuts

Especially important if $m_h \sim m_{W,Z}$

Further cuts

Mass democracy:

$$\alpha_{\rm MD} \equiv \frac{\min(m_{j1}, m_{j2})}{\max(m_{j1}, m_{j2})}$$

Flow variable:

$$\beta_{\rm flow} \equiv \frac{p_{T,j3}}{p_{T,j1} + p_{T,j2}}, \quad \text{if} \quad p_{T,j3} > p_T^{min}.$$

Designed to eliminate QCD background

Works here as well, since $m_\eta \ll m_{W,Z}$

Eliminates part of combinatorics, part of W,Z

(Falkowski, Krohn, Shelton, Thalapillil, Wang)

If η heavy: events more like 4 jets, expect more than 2 subjets

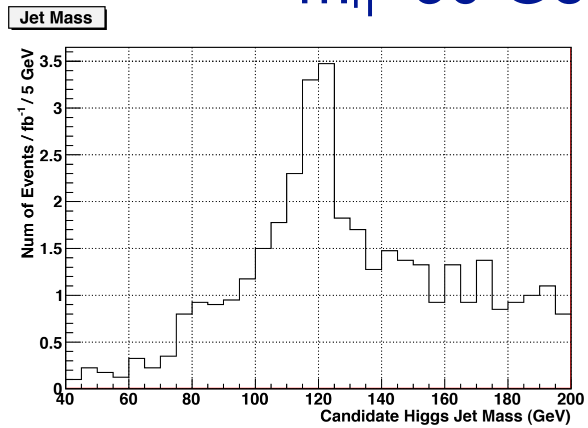
Number of subjets:

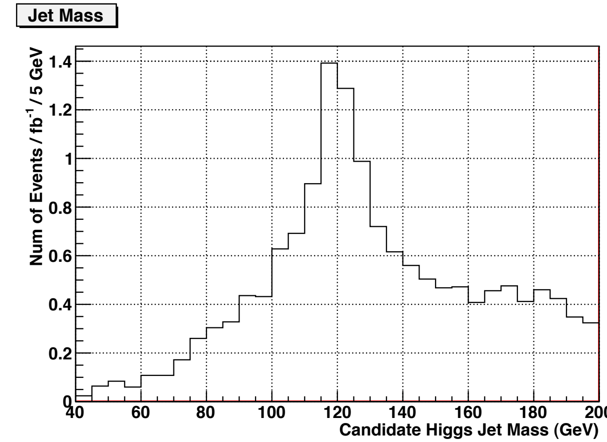
$$n_{\rm subjet} \geq 4 \quad \text{with} \quad p_T > 15 \text{ GeV}.$$

Results: high η mass

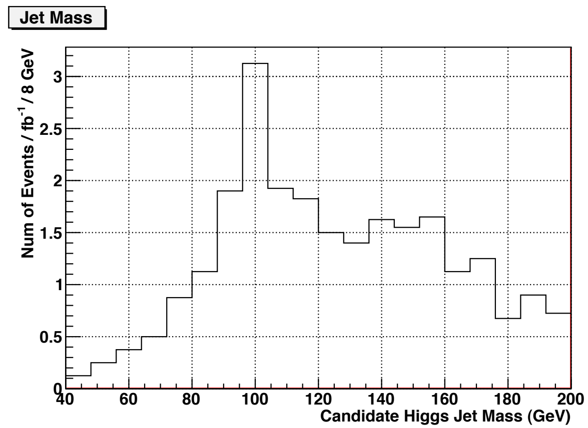
m_η=30 GeV

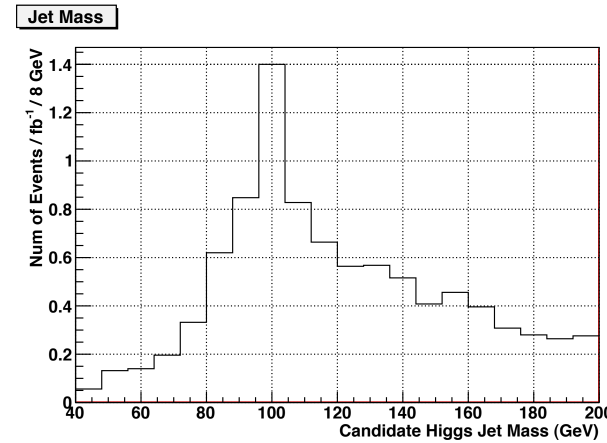
m_{Higgs}=120 GeV





m_{Higgs}=100 GeV





Benchmark 1

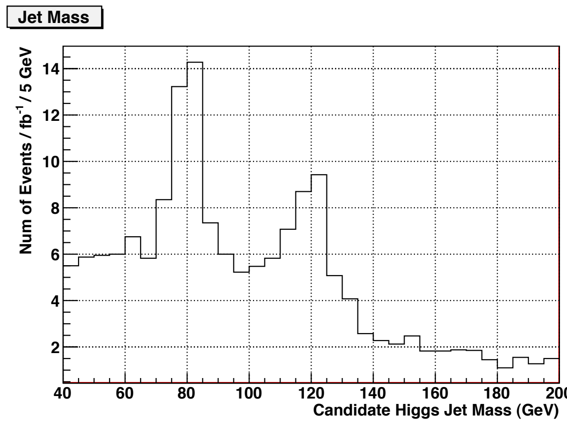
Benchmark 2

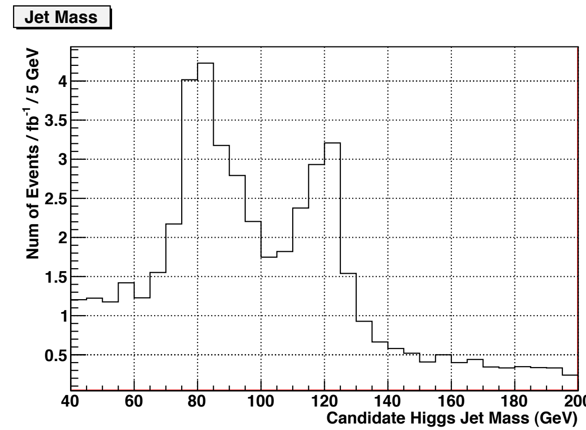
For heavy η n_{subjet} is a very good discriminator, only Higgs peak: can discover with 10 fb^{-1} (m_H=120) or 30 fb^{-1} (m_H=100)

Results: low η mass

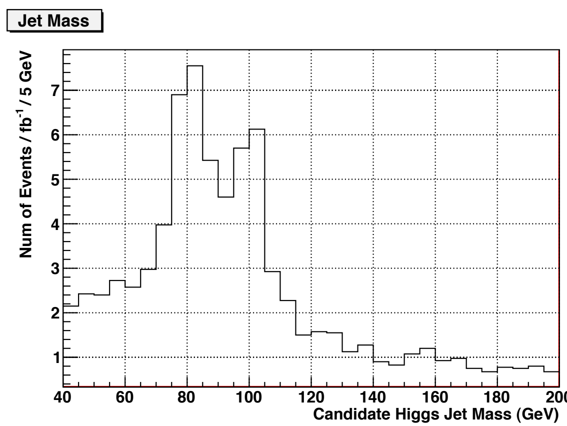
m_η=10 GeV

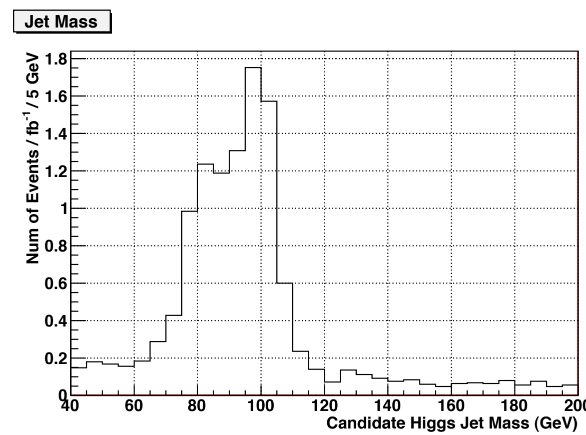
m_{Higgs}=120 GeV





m_{Higgs}=100 GeV





Benchmark 1 Benchmark 2

Hard to eliminate W/Z contamination! For m_H=120 GeV need 10 fb^{-1}. But for m_H=100 no separate peaks, need to subtract W/Z

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 $m_h \leq 150$ 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

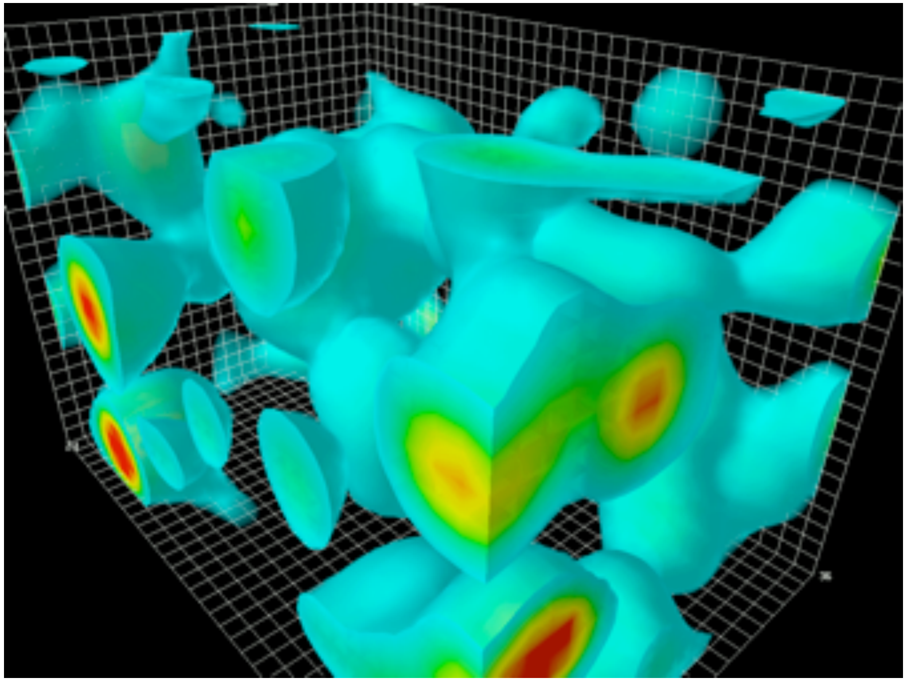
- Don't necessarily need elementary Higgs to break symmetry

- Example: QCD

II. Models of strong dynamics

- Don't necessarily need elementary Higgs to break symmetry

- Example: QCD



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}~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 $\Lambda_F < 10$ TeV

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

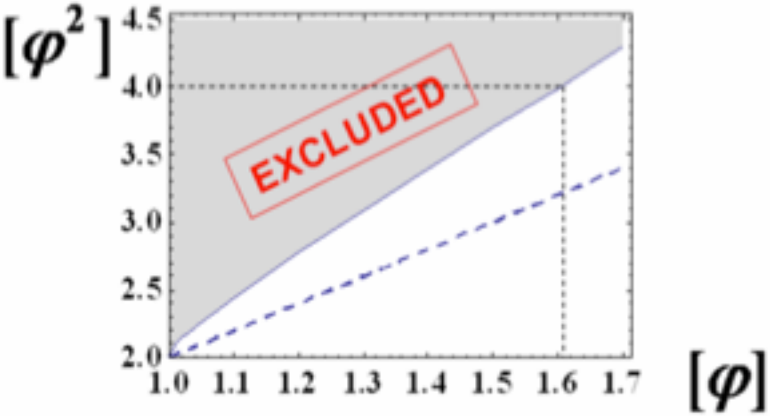
To avoid FCNC $\Lambda_F > 10^4$ TeV

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

•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)**

•But results of Rattazzi et al.: upper bound on anomalous dimension from general principles (crossing)



•Can not sufficiently suppress FCNC's in simplest versions 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

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

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

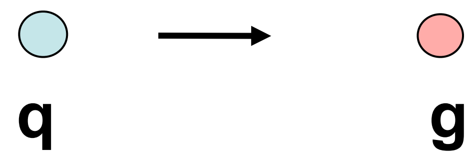
The Rubakov-Callan effect

•Angular mom. of EM. field:

$$\vec{J} = qg\vec{n}$$

depends on direction from charge to pole

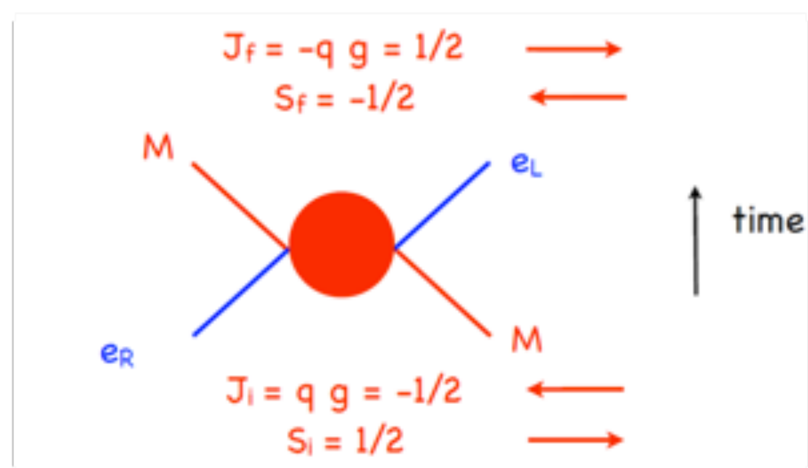
•In head-on scattering this direction changes, even though no force



•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

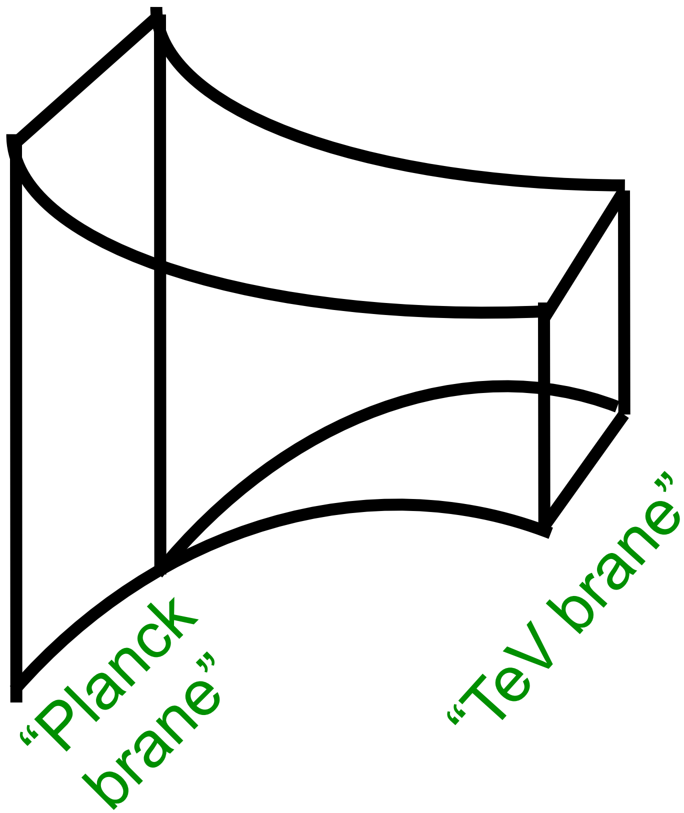
- After EWSB theory vectorlike, expect monopoles to pick up mass of order Λ_{mag}~500 GeV – TeV

- 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 not calculable. Most naive estimate ~ few x 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

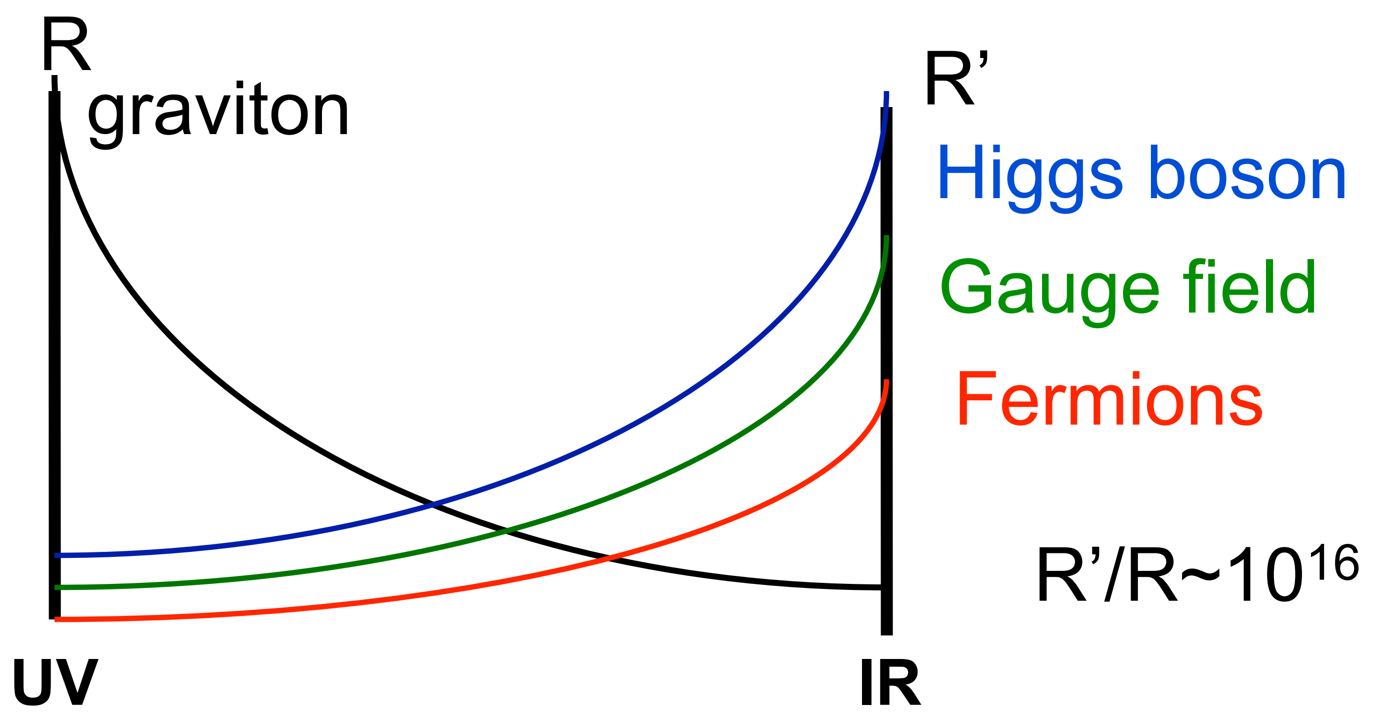
- Related to strong dynamics/technicolor models via AdS/CFT duality

- 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

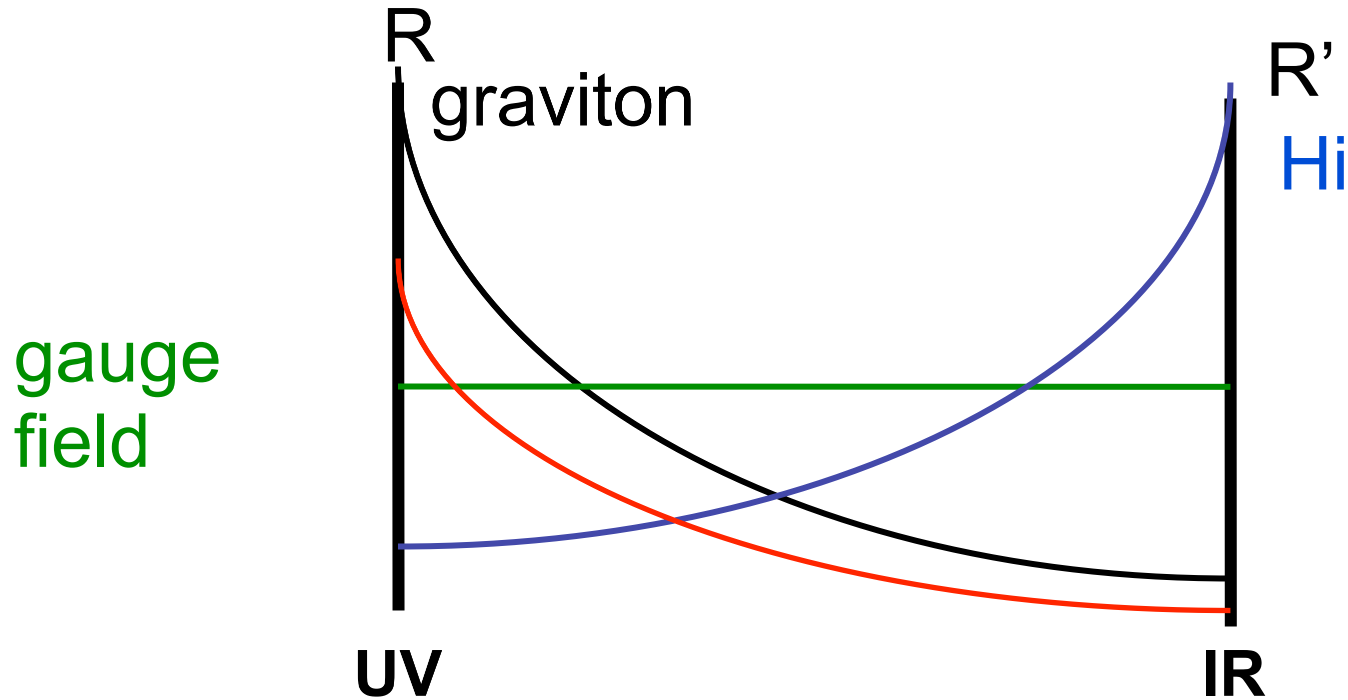
The original RS model



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;…)



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

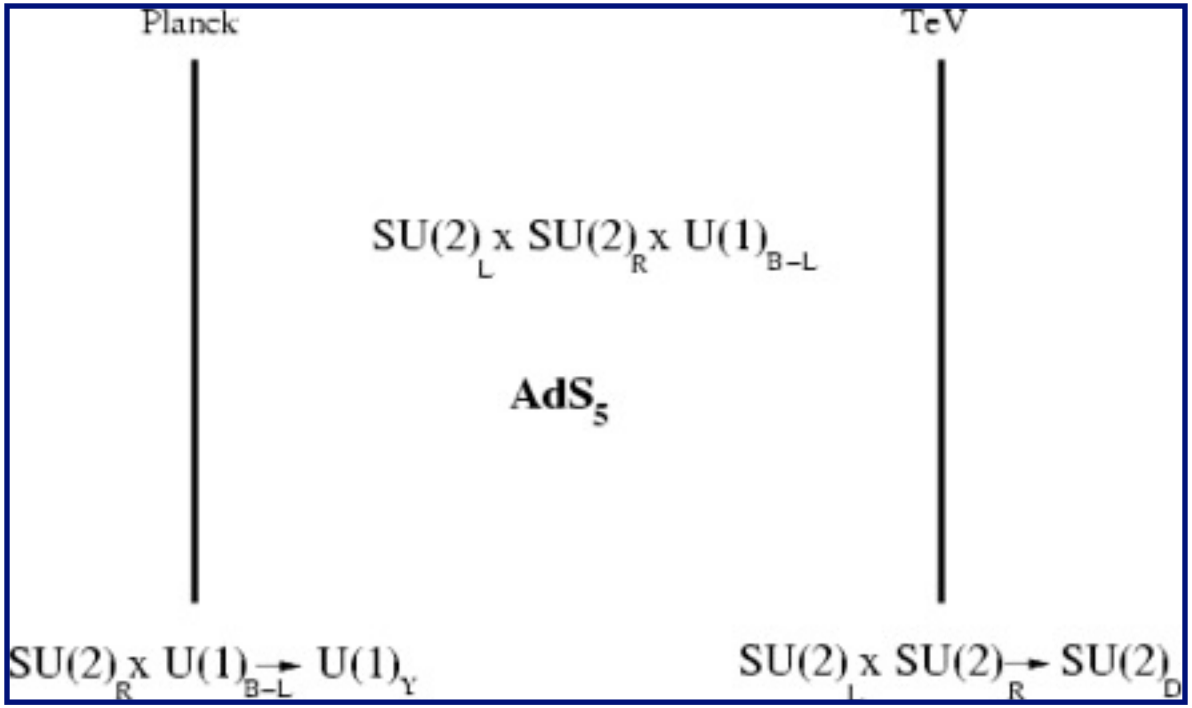
Still solves hierarchy problem since Higgs on IR

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

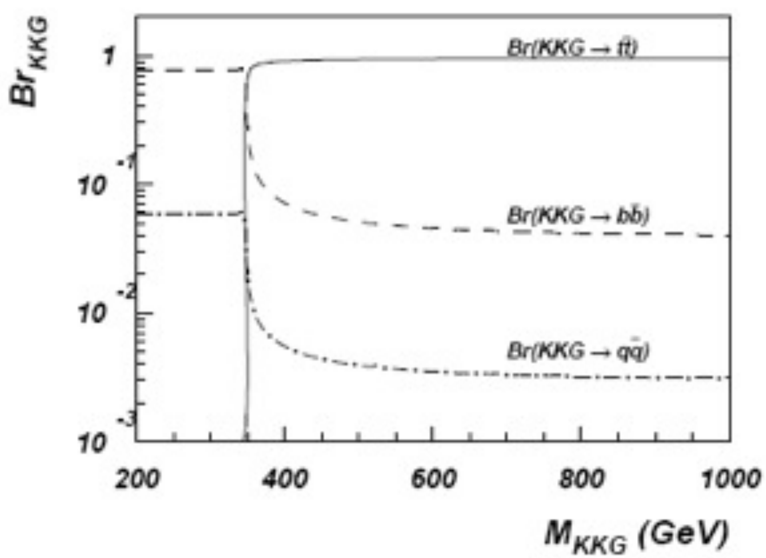


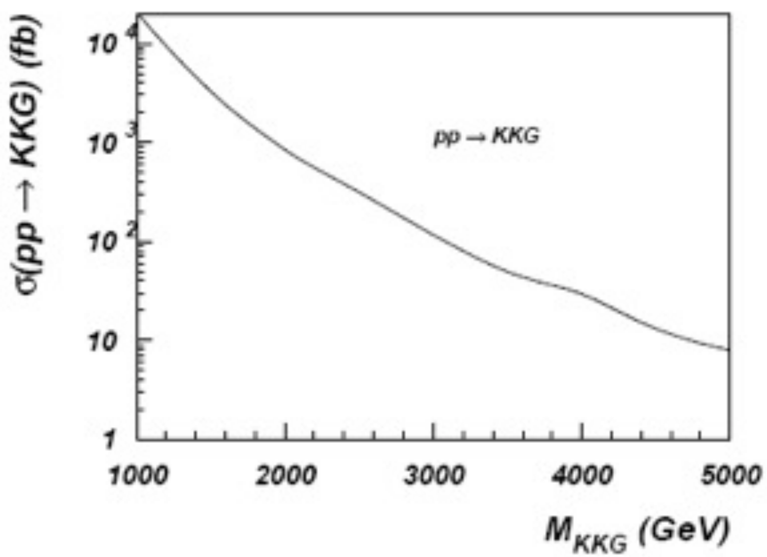
(Agashe, Delgado, May, Sundrum, `03)

- $S \sim 12p\ v^2/m_{KK}^2$ 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
- To also solve little hierarchy:

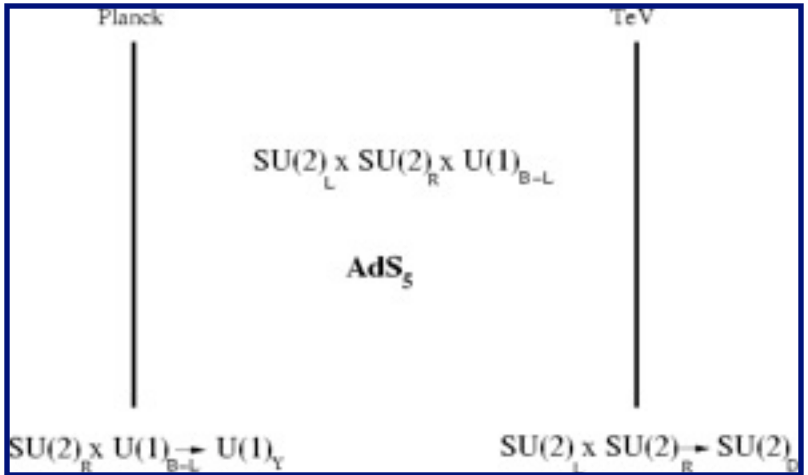
  Higgsless (gauge-phobic)

  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 $\to\infty$ 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 $\Lambda = 4\pi M_W / g \sim 1.6\,\mathrm{TeV}$ unitarity would be violated??

- Exchange of KK gauge bosons restores unitarity

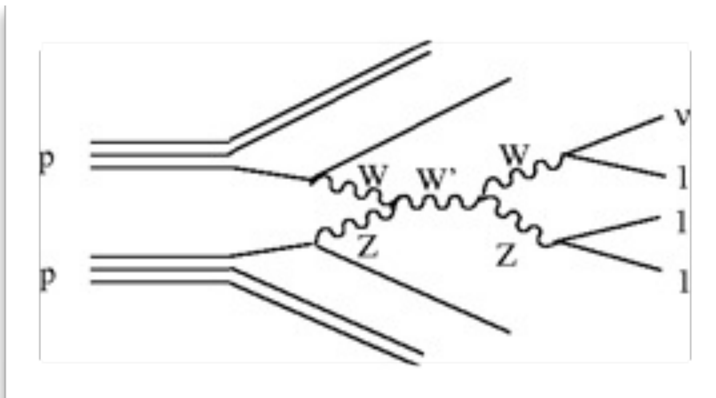
- Implies sum rules among masses and couplings

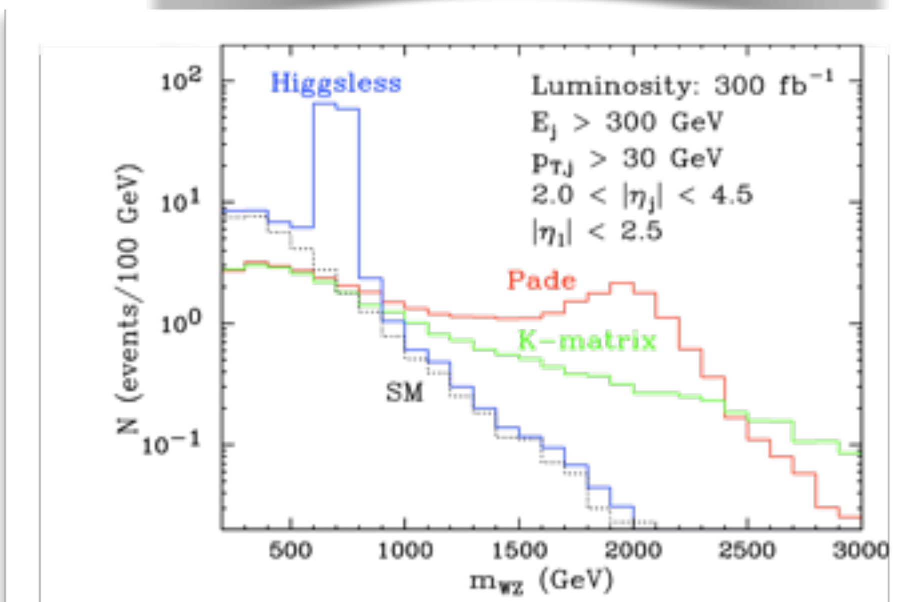
$$\begin{aligned} g_{WWWW} &= g_{WW\gamma}^2 + g_{WWZ}^2 + \sum_i g_{WWZ^i}^2 \\ \frac{4}{3} g_{WWWW} M_W^2 &= g_{WWZ}^2 M_Z^2 + \sum_i g_{WWZ^i}^2 M_{Z^i}^2 \end{aligned}$$

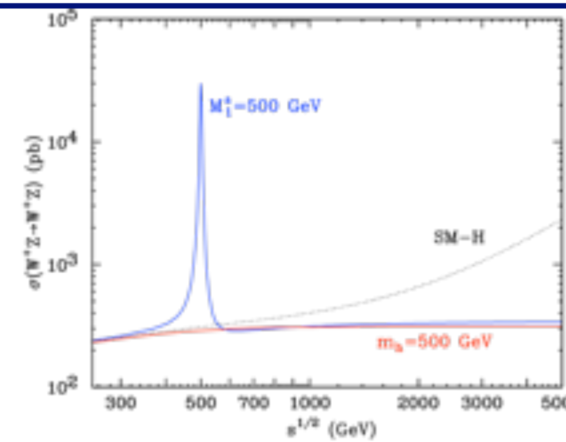
LHC predictions of Higgsless

(Birkedal, Matchev, Perelstein `04)

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







WZ→WZ

A more detailed study of same process including NLO QCD corrections

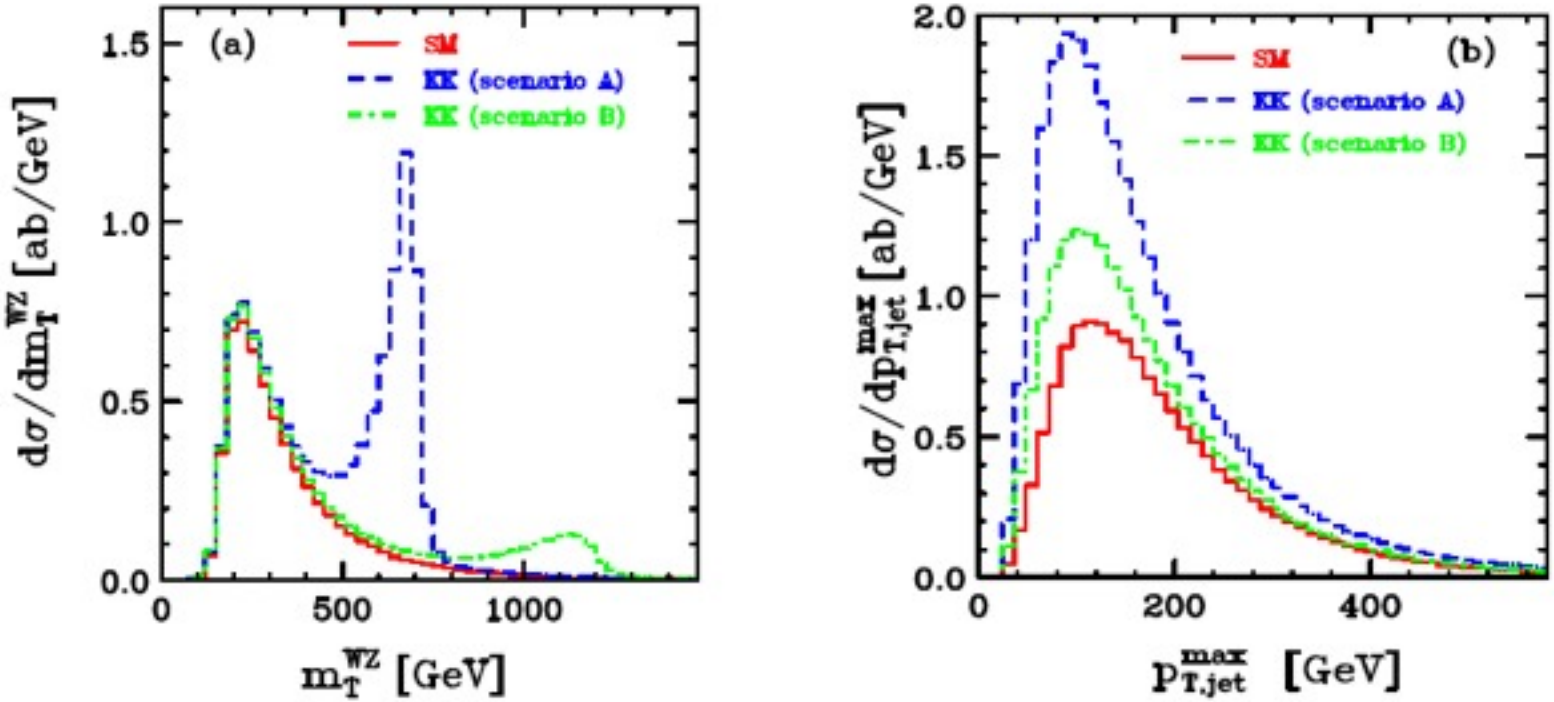


Figure 9: *Transverse cluster mass distribution (a) and transverse momentum distribution of the hardest tagging jet (b) for $pp \to W^+Zjj$. Shown are predictions for the SM (red, solid), and for the two Higgsless scenarios A (blue, dashed) and B (green, dot-dashed).*

Scale μ	σ^{LO} [fb]	σ^{NLO} [fb]	K factor
$(m_W + m_Z)/2$	0.359	0.355	0.989
Q	0.349	0.356	1.020
m_{W_2}	0.283	0.346	1.223

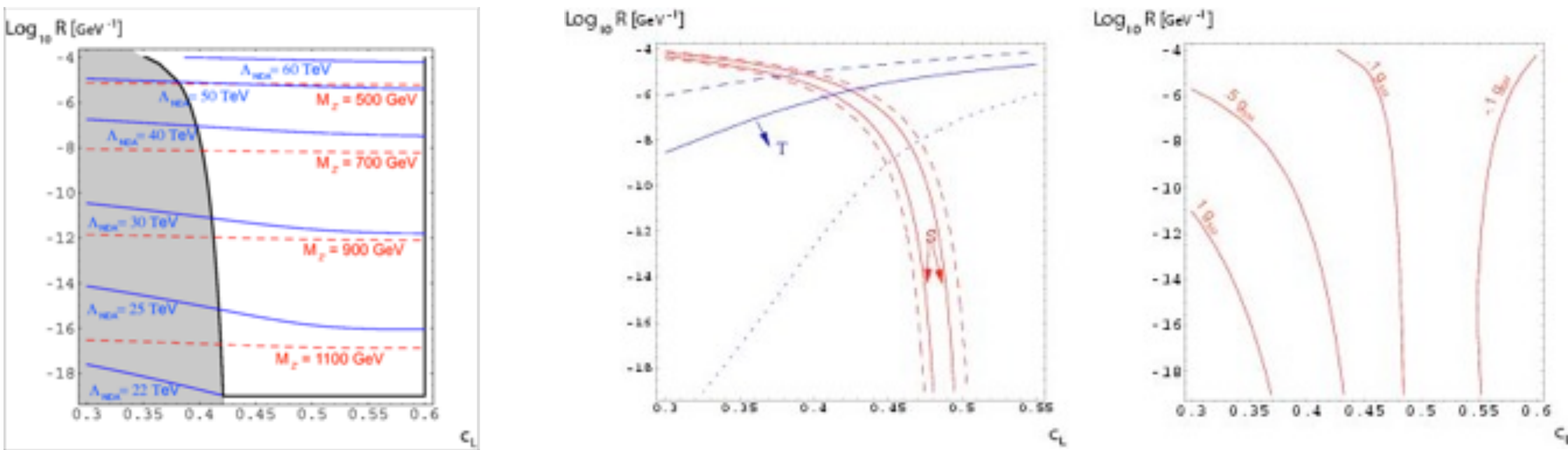
(Englert, Jäger, Zeppenfeld '08)

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



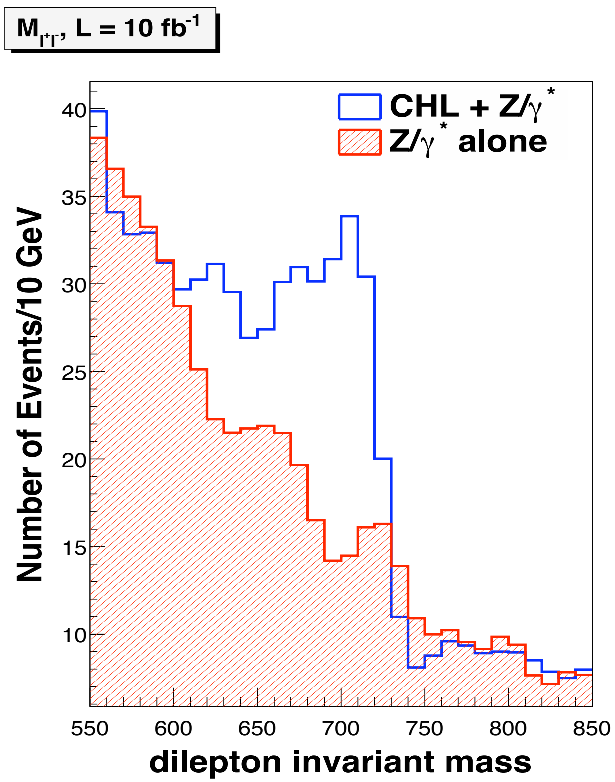
- S is sufficiently small
- KK modes sufficiently heavy
- Couplings to KK modes small

} BUT: 1% level tuning in c

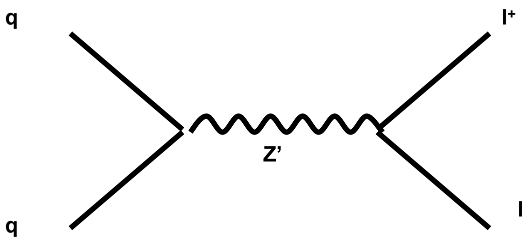
(Cacciapaglia, C.C.,Grojean, Terning, `04)

- 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



Process	σ(pb)	total # events	ϵ	total # : $(10\ \text{fb}^{-1})\cdot\sigma\cdot\epsilon$	# mass peak
$\gamma^*/Z(\ell^+\ell^-)$	0.59 pb	2×10^4	0.184	941	375
CHL + $\gamma^*/Z(\ell^+\ell^-)$	0.61 pb	2×10^4	0.202	1049	493
Difference				106	118



(Martin and Sanz '09)

A concrete example spectrum

(Cacciapaglia, Marandella, Terning, C.C.)

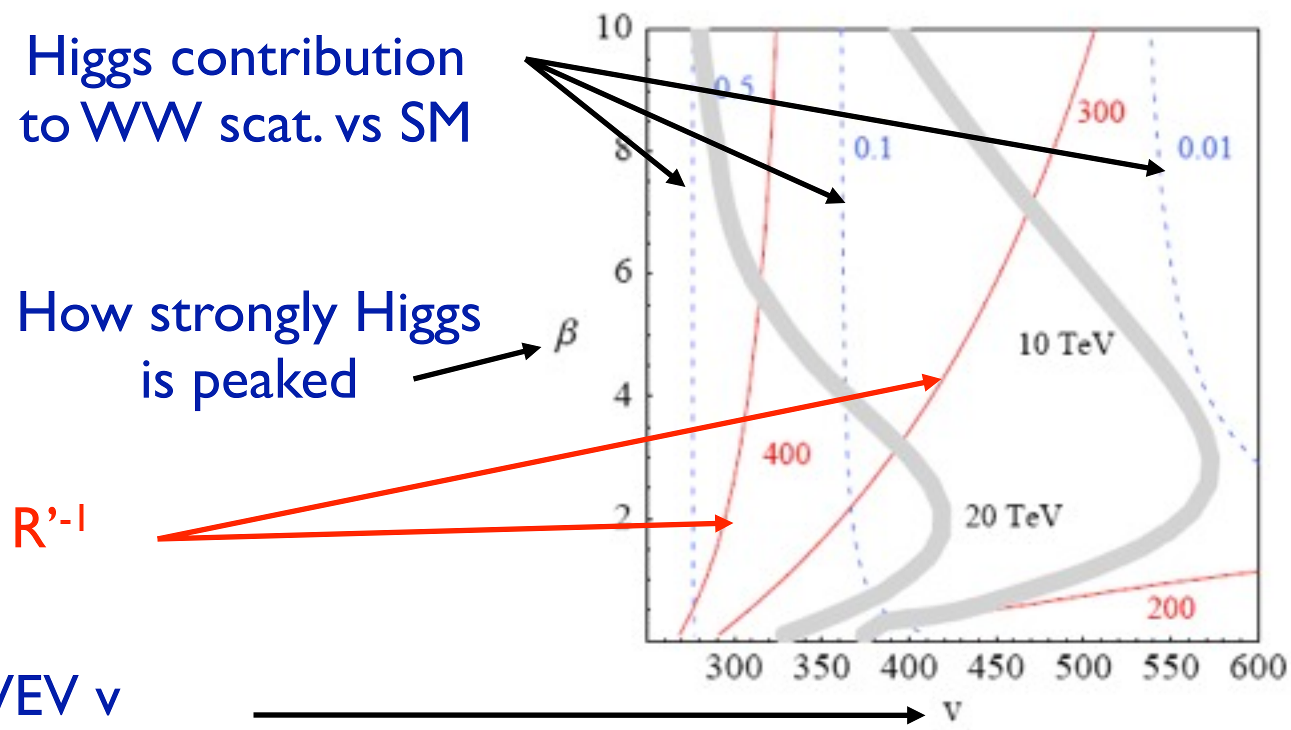
- Model with realistic 3rd generation
- Requires light t',b' states
- W', Z' around 700 GeV

$M_{t'}$	450 GeV	$g_{Z' t_L \bar{t}_L}$	$1.83\ g_{Z t_L \bar{t}_L}$
$M_{b'}$	664 GeV	$g_{Z' t_R \bar{t}_R}$	$4.02\ g_{Z t_R \bar{t}_R}$
$M_{W'}$	695 GeV	$g_{Z' b_L \bar{b}_L}$	$3.77\ g_{Z b_L \bar{b}_L}$
$M_{Z'}$	690 GeV	$g_{Z' b_R \bar{b}_R}$	$0.26\ g_{Z b_R \bar{b}_R}$
$M_{Z''}$	714 GeV	g_{ZWW}	$1.018\ g\, c_W$
$M_{G'}$	714 GeV	g_{ZZWW}	$1.044\ g^2 c_W^2$
$g_{W' u \bar{d}}$	$0.07\ g$	g_{WWWW}	$1.032\ g^2$
$g_{Z' q \bar{q}}$	$0.14\ g_{Z q \bar{q}}$	$g_{Z' WW}$	$0.059\ g\, c_W$
$g_{G' q \bar{q}}$	$0.22\ g_c$	$g_{Z W' W}$	$0.051\ g\, c_W$

The Gaugephobic Higgs

(Cacciapaglia, C.C., Marandella, Terning)

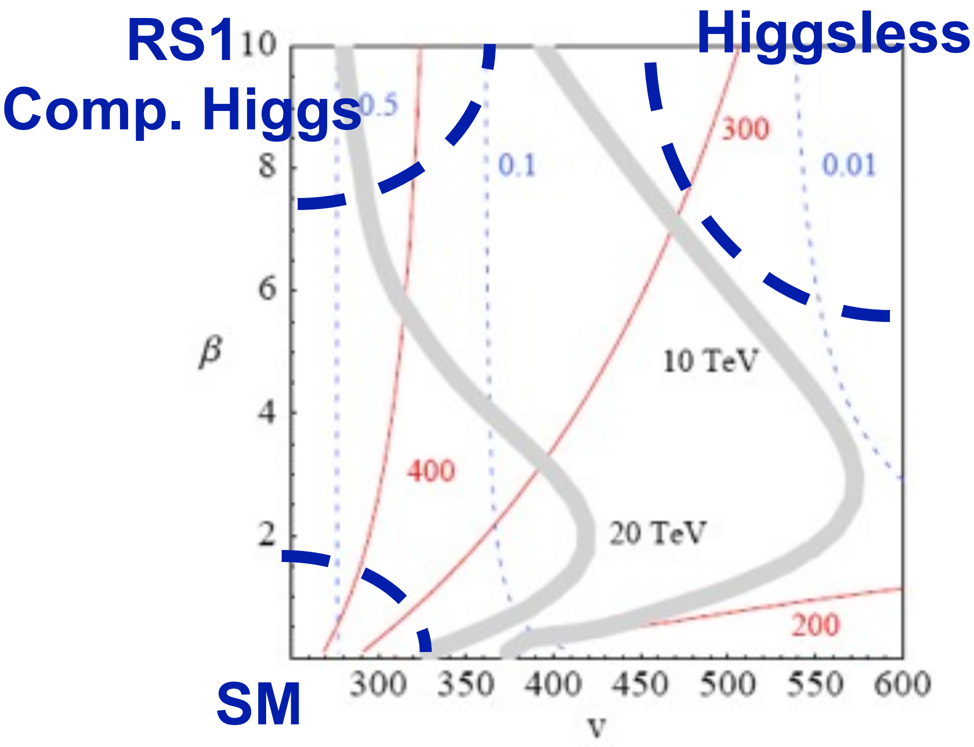
- Higgsless: crank up Higgs VEV to max, completely decouple Higgs
- Intermediate possibility: turn up Higgs VEV somewhat
- Coupling to gauge fields reduced, Higgs could be light



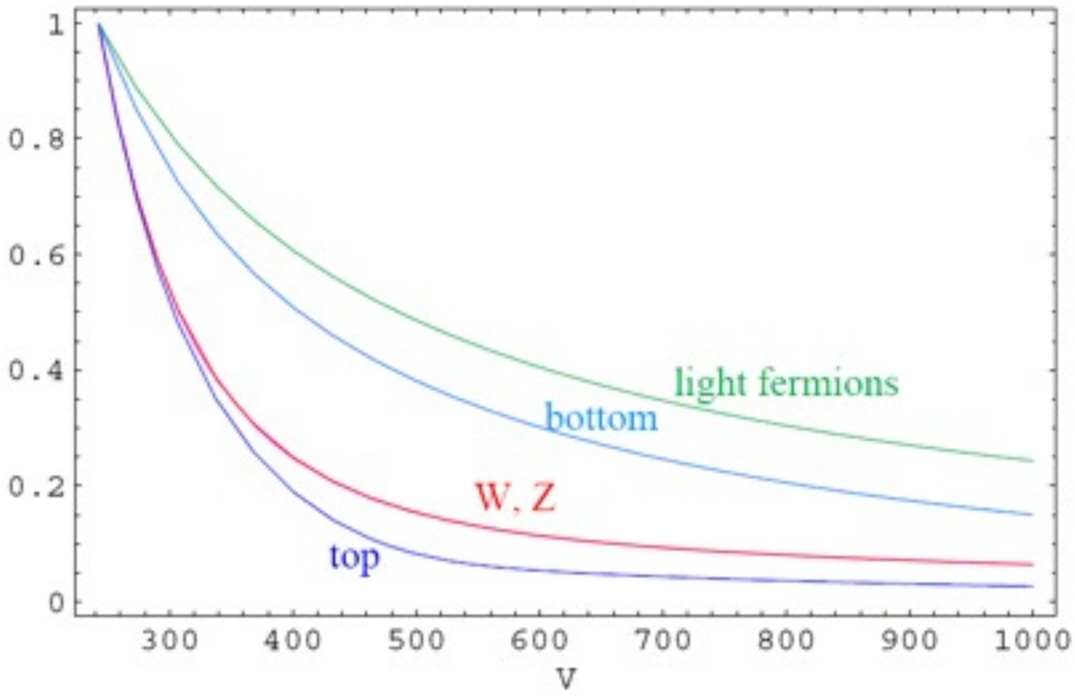
The Gaugephobic Higgs

(Cacciapaglia, C.C., Marandella, Terning)

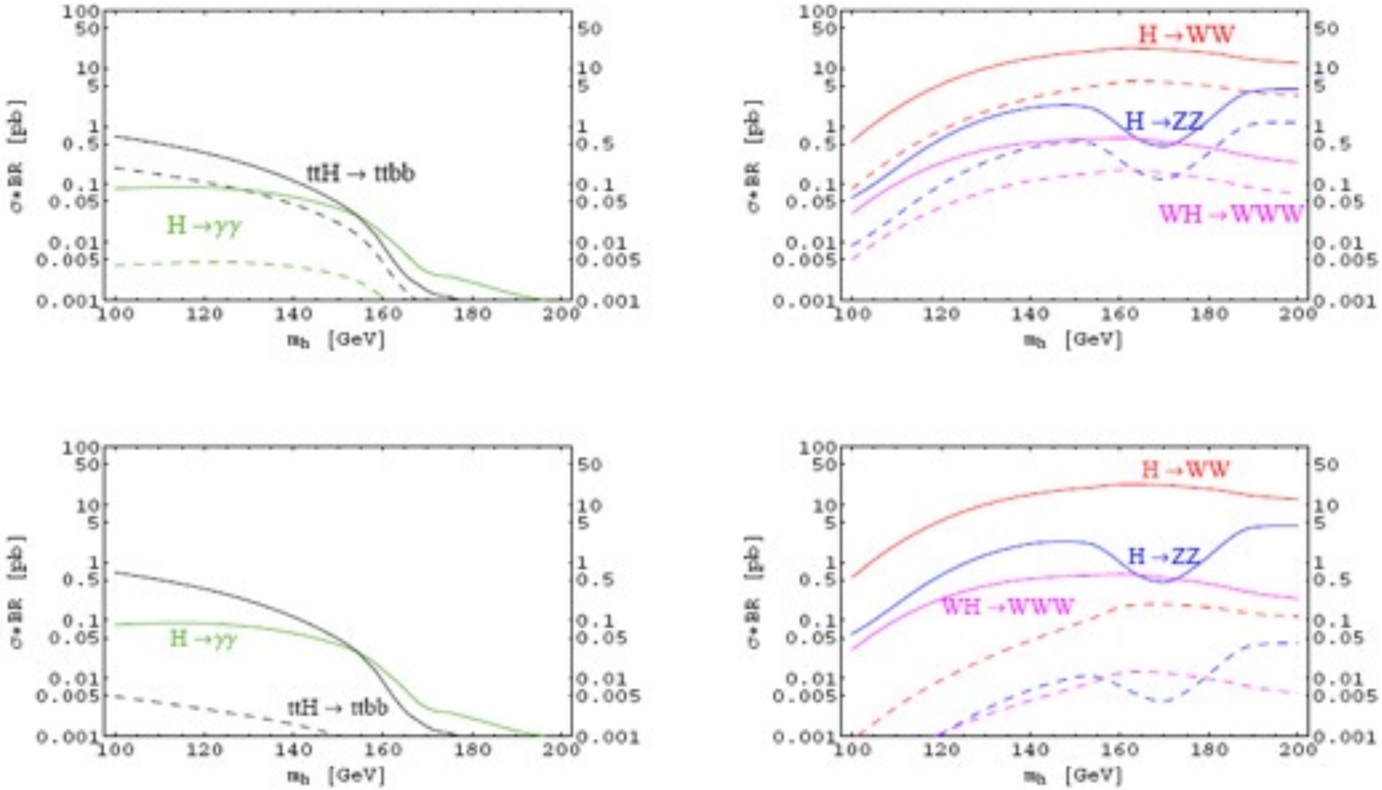
- Higgsless: crank up Higgs VEV to max, completely decouple Higgs
- Intermediate possibility: turn up Higgs VEV somewhat
- Coupling to gauge fields reduced, Higgs could be light



Suppression of the Higgs coupling:



Higgs phenomenology



Sample couplings

a) $V = 300$ GeV, $\beta = 2$	
g_{ttH}/SM	0.52
g_{WWH}/SM	0.54
g_{ZZH}/SM	0.54
g_{bbH}/SM	0.75
g_{ffH}/SM	0.81

b) $V = 500$ GeV, $\beta = 2$	
g_{ttH}/SM	0.08
g_{WWH}/SM	0.15
g_{ZZH}/SM	0.15
g_{bbH}/SM	0.38
g_{ffH}/SM	0.49

Sample spin 1 spectra

a) $V = 300$ GeV, $\beta = 2$	
$1/R'$	372.5 GeV
W'	918 GeV
Z'_1	912 GeV
Z'_2	945 GeV
G'	945 GeV

b) $V = 500$ GeV, $\beta = 2$	
$1/R'$	244 GeV
W'	602 GeV
Z'_1	598 GeV
Z'_2	617 GeV
G'	617 GeV

Sample fermion spectra

charge	a) $V = 300$ GeV	b) $V = 500$ GeV	
5/3	581 GeV	382 GeV	X_L
2/3	643 GeV	511 GeV	T_L
-1/3	1062 GeV	712 GeV	b_R
2/3	1058 GeV	693 GeV	T_R
5/3	1124 GeV	832 GeV	X_R
2/3	1160 GeV	831 GeV	$t_L - t_R$
-1/3	1242 GeV	917 GeV	b_L
2/3	1318 GeV	1114 GeV	$t_L - t_R$

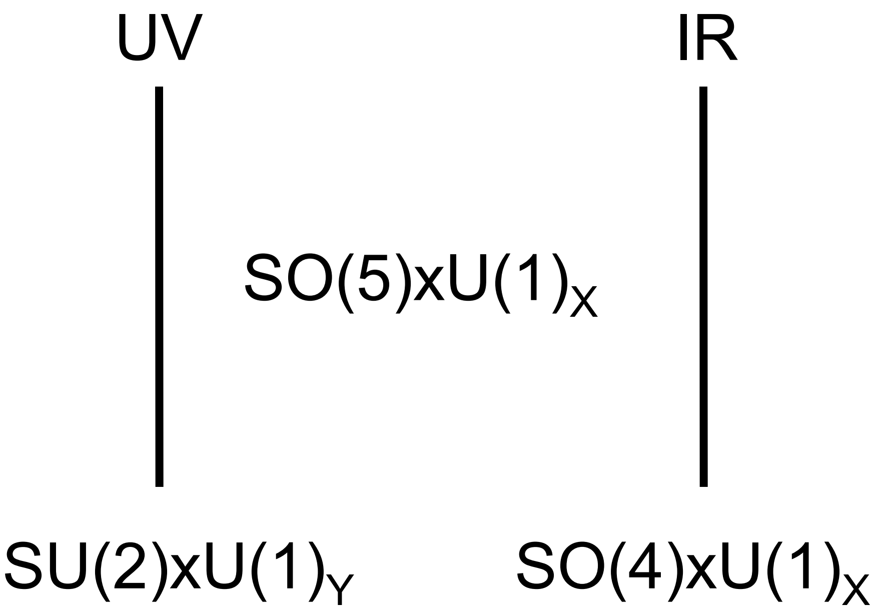
Composite pGB Higgs models

- 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 $m_\rho >> m_W$

- 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 - Hosotani mechanism (A_5 is Higgs)
- Sym. breaking pattern:
- $SO(5)\times U(1)_X$ global→ $SO(4)\times U(1)_X$ 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:

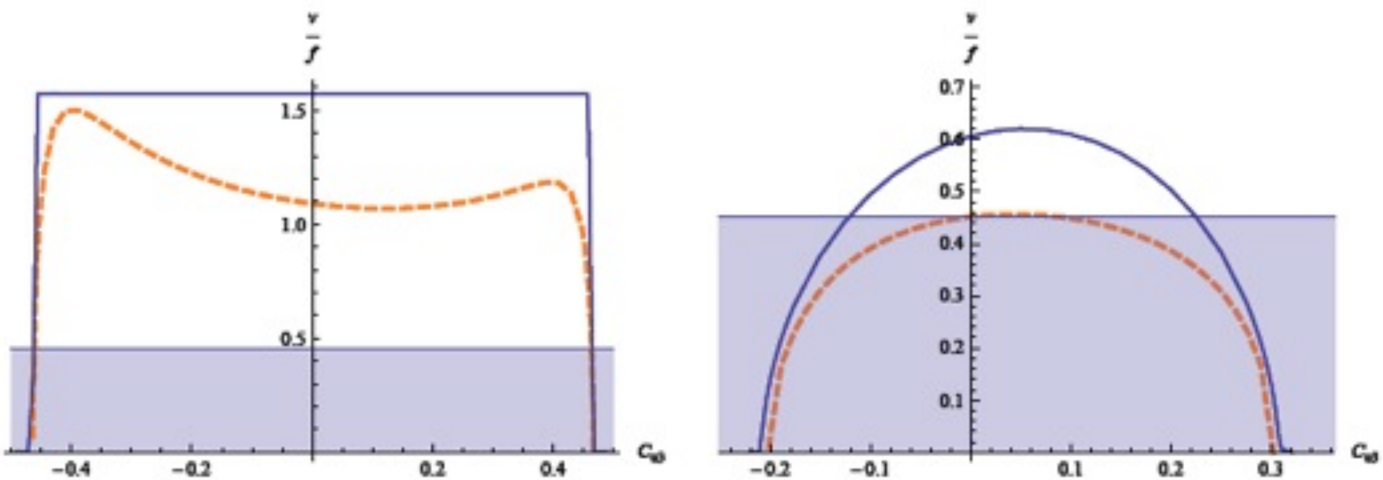
$$m_h^2 \propto \frac{g^2}{16\pi^2} f^2$$

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)

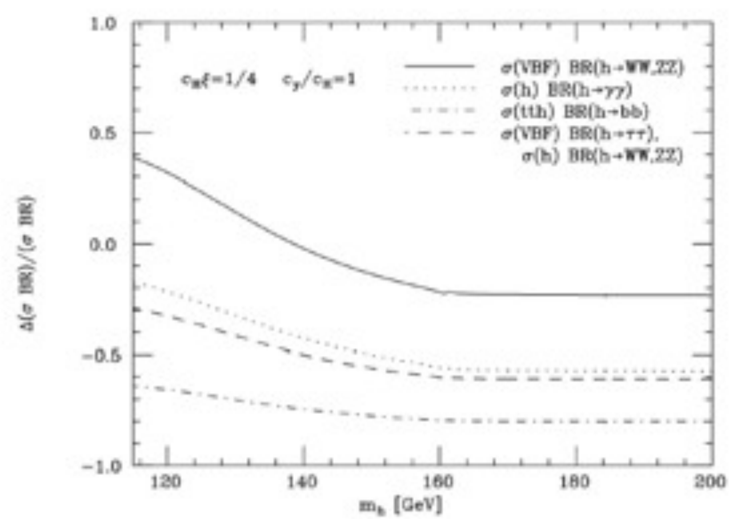


Experimental consequences of pGB MCH

•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

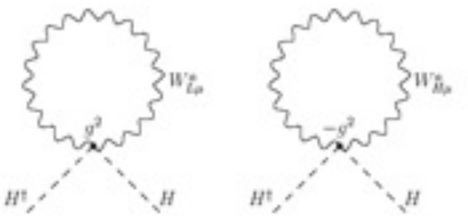
(Arkani-Hamed, Cohen, Katz, Nelson `02)

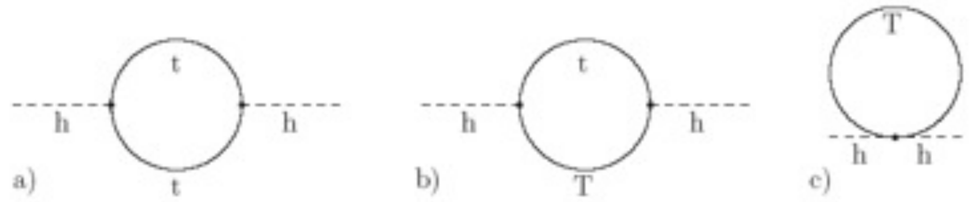
- Higgs is Goldstone again
- Added ingredient: "collective breaking": need at least two couplings simultaneously to break symmetry
- Mass suppressed, but quartic is large

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

- Now $m_h \sim f/(4\pi)$, 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”



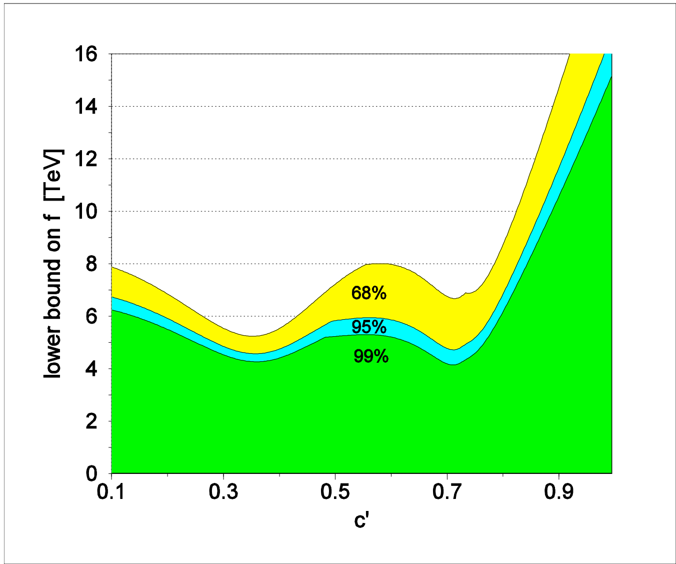


Gauge loops

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	$\bar{\square}$	1	$+2/3$	Q'_1	$\bar{\square}$	1	$-2/3$	L_1	$\bar{\square}$	1	0
Q_2	$\square$	1	$+2/3$	Q'_2	$\square$	1	$-2/3$	L_2	$\square$	1	0
q_3	1	$\square$	$-1/6$	q'_3, q''_3	1	$\square$	$+1/6$	ℓ_3	1	$\square$	$+1/2$
q_4	1	$\square$	$-7/6$	q'_4	1	$\square$	$+7/6$	ℓ_4	1	$\square$	$-1/2$
q_5	1	$\square$	$-7/6$	q'_5	1	$\square$	$+7/6$	ℓ_5	1	$\square$	$-1/2$
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 (little hierarchy)

- 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 (some of) these questions by 2014 for sure (2011-2012 if indeed 5-10 fb^{-1} data @ 8 TeV)