Models of TeV-scale Physics

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Outline

- Motivation
- SUSY and its little hierarchy
- Realistic RS models
- Higgsless models
- Composite Higgs
- Little Higgs models
- AdS/QCD?

1. Motivation: the little hierarchy

- Expect new TeV scale physics solves the hierarchy problem
- However, have not seen any trace of new TeV scale physics at LEP or Tevatron ("LEP paradox")
- Generic new TeV scale physics tightly constrained:

Dimensions six operators	$m_h = 115\ GeV$ $c_i = -1$	$m_h = 115\ GeV$ $c_i = +1$	$m_h = 300\ GeV$ $c_i = -1$	$m_h = 300\ GeV$ $c_i = +1$	$m_h = 800\ GeV$ $c_i = -1$	$m_h = 800\ GeV$ $c_i = +1$
$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10	7.5			
$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6	3.4		2.8	
$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1				
$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L$	8.4	8.8	7.5			
$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	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)

- Generic new physics is allowed only at 5-10 TeV

- **Little hierarchy**: why have we not seen indirect effects already (if it comes in at 1 TeV)?

- Flavor constraints could of course be much stronger, up to 10^5 TeV constraints possible…

2.The Little Hierarchy of SUSY (and a possible solution...)

- The minimization of the Higgs potential requires the following relation among mass parameters

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

- Loop corrections to the Higgs soft breaking mass:

$$\Delta m_{H_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{\Lambda}{m_{\tilde{t}}}$$

- But need a large stop mass to bring Higgs above LEP bound (m_{stop}>1.4 TeV):

$$\delta\lambda = \frac{3y_t^4 \sin^4\beta}{16\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

- Fine tuning of order

$$\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln \frac{\Lambda}{m_{\tilde{t}}} / (\frac{M_Z^2}{2}) \sim \mathcal{O}(0.1\%)$$

The sources of fine tuning:

1. need large m_{stop} for quartic
2. large log appearing in running

- Within MSSM that's it, need to live with it (large A_t can reduce the needed stop mass)
- Need to go beyond the MSSM to really fix it

A possible fix within SUSY (beyond MSSM)

•Cut off large log by also making Higgs a Goldstone of a symmetry broken at ~ 1 TeV ("double protection", "super-little Higgs")

•Generate an additional quartic contribution from a non-decoupling D-term

(Birkedal, Chacko, Gaillard;
Chankowski, Falkowski, Pokorski,Wagner;
Berezhiani, Chankowski, Falkowski, Pokorski;
Schmaltz, Roy;
C.C., Marandella, Shirman, Strumia)

A possible example: $SU(3)xU(1)_X xU(1)_Z$

	$SU(3)_W$	$U(1)_x$	$U(1)_z$
$\mathcal{H}_{u,d}$	$3,\ \bar{3}$	$\pm 1/3$	$\pm q$
$\Phi_{u,d}$	$3,\ \bar{3}$	$\pm 1/3$	$\pm q$
$\Psi_{u,d}$	1	0	q_Ψ

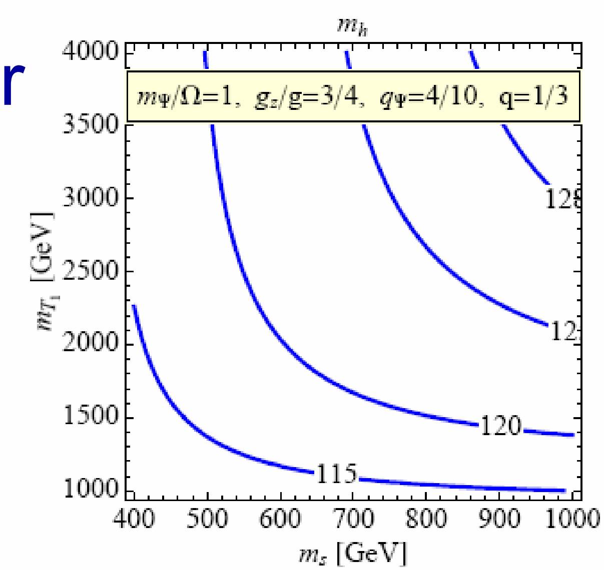
Contains Higgs

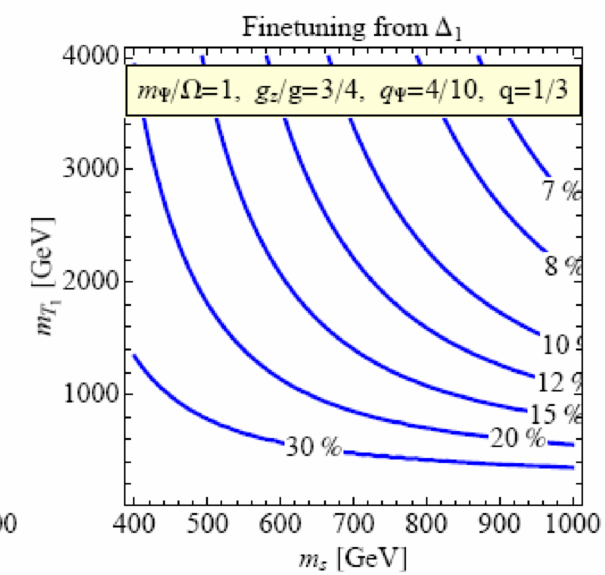
Breaks to global sym

Provides additional quartic

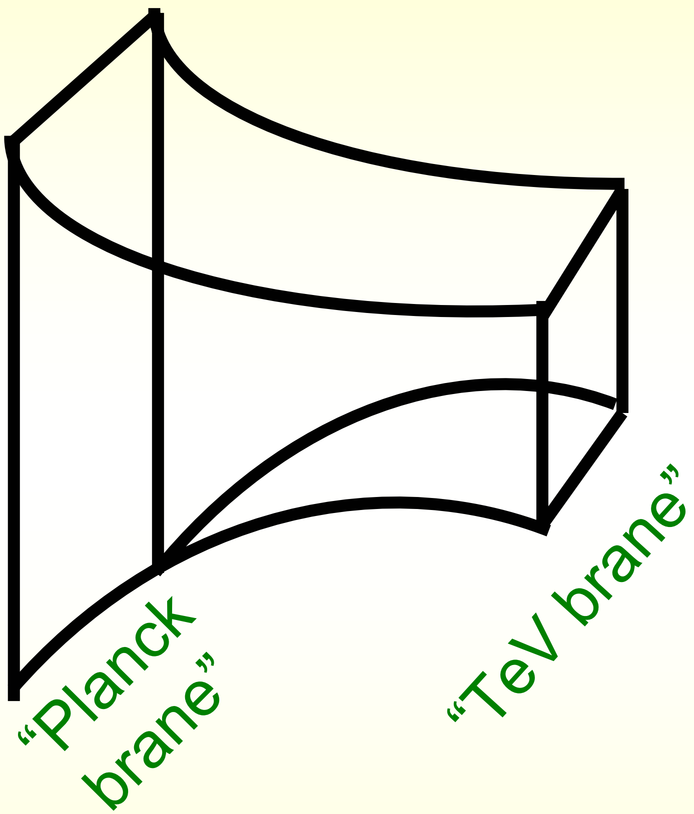
- Light MSSM
- Lightish top partner
- 3-4 TeV Z'
- Small tuning

(Bellazzini, C.C., Delgado, Weiler)





3. Realistic warped models

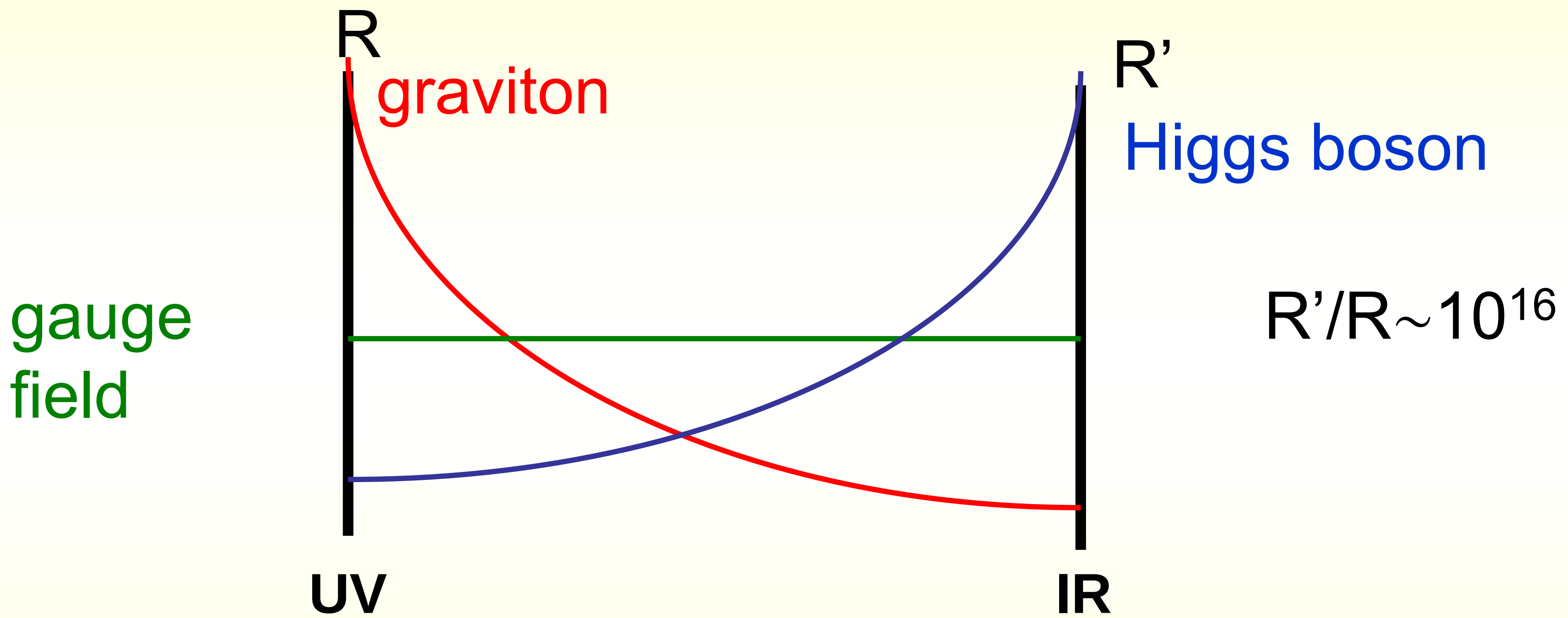


(Randall,Sundrum; Maldacena;…)

- 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
- Gauge field flat
- Higgs peaked at TeV

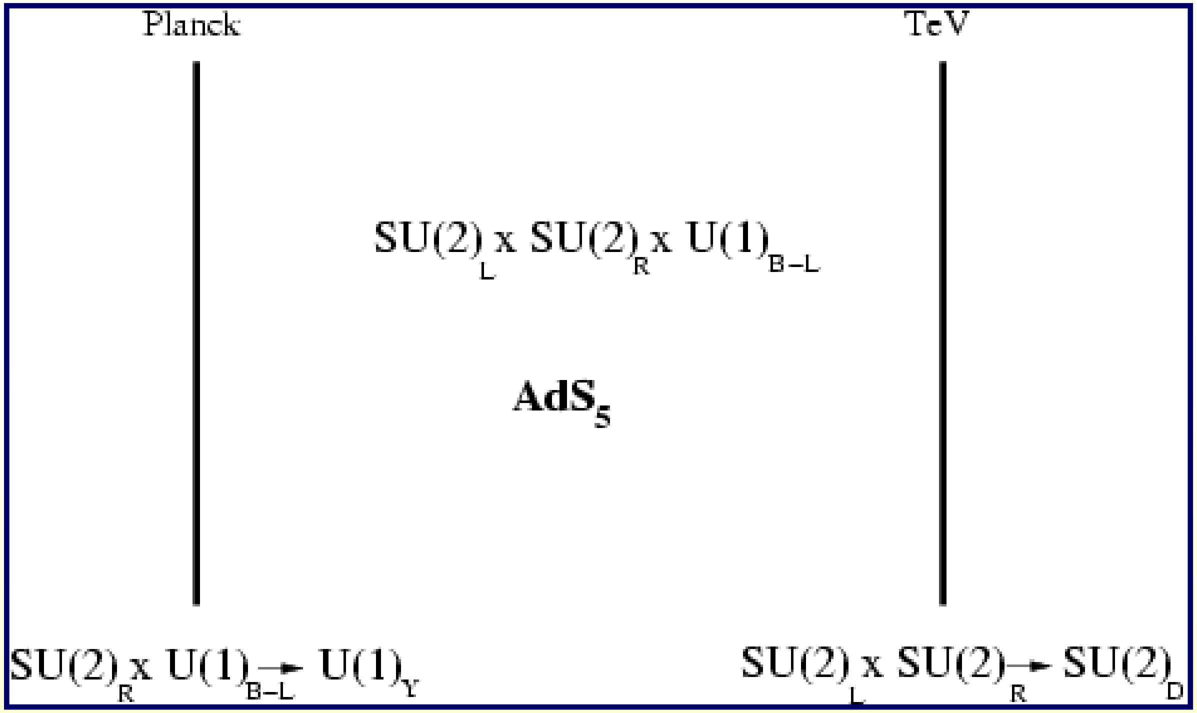


Solves the hierarchy problem.

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

Realistic RS models

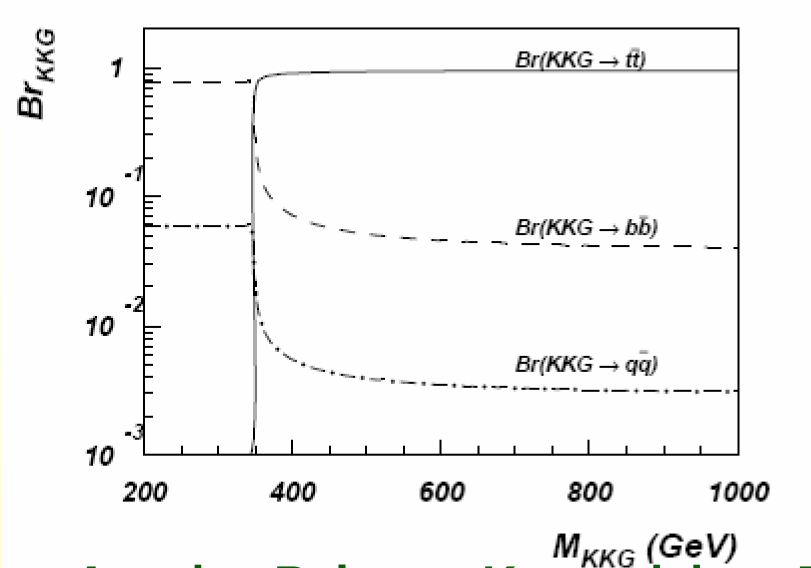
- Need to put fermions away from IR brane for FCNC
- To protect T-parameter need to include $SU(2)_R$ custodial symmetry

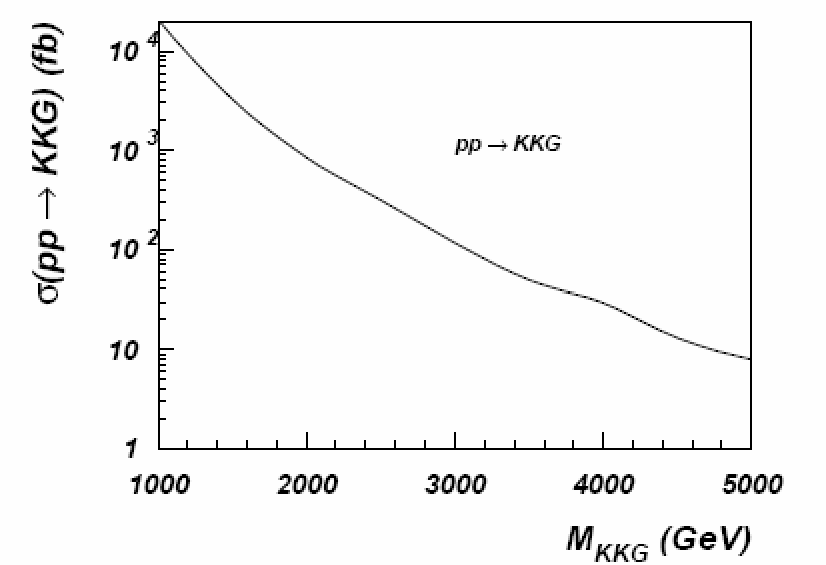


(Agashe, Delgado, May, Sundrum)

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

• Signals:
• Light top partners (see later)
• 3 TeV KK gluon, but mostly coupled to t_R





(From Agashe, Belyaev, Krupvnickas, Perez, Virzi; see also Davoudiasl, Randall, Wang) See talk by T. Tait

- 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 (see talks by A. Weiler and M. Neubert)
- To also solve little hierarchy:
  - Higgsless
  - Pseudo-Goldstone Higgs

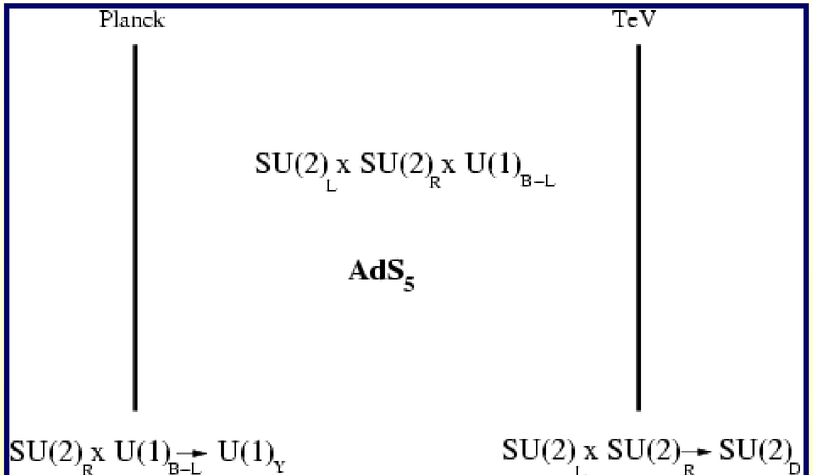
4. Higgsless models

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

•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

$$\text{at } z = R: \begin{cases} \partial_z (g_{5R} B_\mu + \tilde{g}_5 A_\mu^{R3}) = 0 \;\; \partial_z A_\mu^{La} = 0, \;\; A_\mu^{R1,2} = 0, \\ \tilde{g}_5 B_\mu - g_{5R} A_\mu^{R3} = 0, \end{cases}$$

$$\text{at } z = R': \left\{ \partial_z (g_{5R} A_\mu^{L\,a} + g_{5L} A_\mu^{R\,a}) = 0, \;\; \partial_z B_\mu = 0, \;\; g_{5L} A_\mu^{L\,a} - g_{5R} A_\mu^{R\,a} = 0. \right.$$

•Typical mass spectrum:

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

$$M_Z^2 = \frac{g_5^2 + 2\tilde{g}_5^2}{g_5^2 + \tilde{g}_5^2} \frac{1}{R'^2 \log\left(\frac{R'}{R}\right)}$$

•Get correct M_W/M_Z due to matching of g, g' to g_5, $\tilde{g}_5$

$$\sin\theta_W = \frac{\tilde{g}_5}{\sqrt{g_5^2 + 2\tilde{g}_5^2}} = \frac{g'}{\sqrt{g^2 + g'^2}}$$

- Lightest additional KK modes not too light:

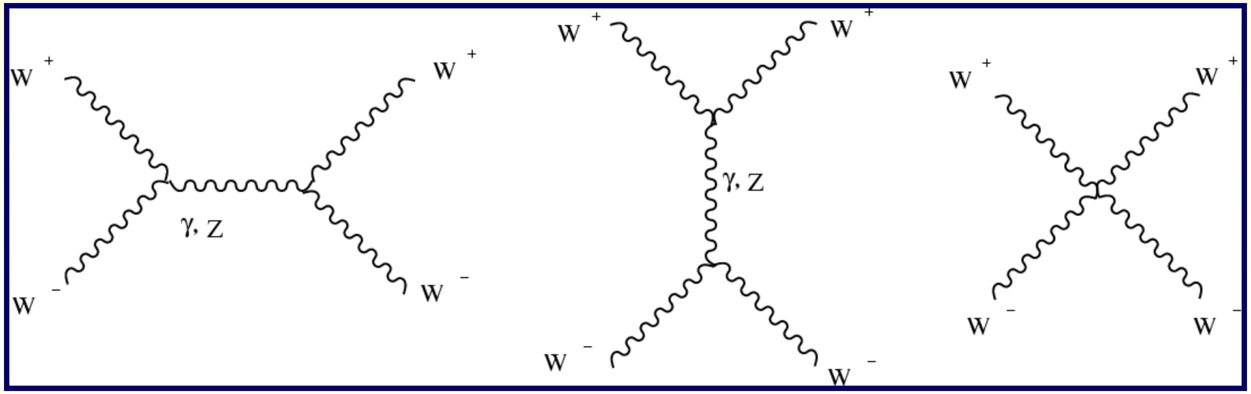
$$m_{W_n} = \frac{\pi}{2}\left(n + \frac{1}{2}\right)\frac{1}{R'}, \quad n = 1, 2, \ldots$$

- So mass ratio is log enhanced:

$$\frac{m_W}{m_{W'}} \sim \frac{4}{3\pi}\frac{1}{\sqrt{\log\left(\frac{R'}{R}\right)}}$$

But: usual argument for guaranteed discovery of Higgs

Massive gauge bosons without scalar violate unitarity:



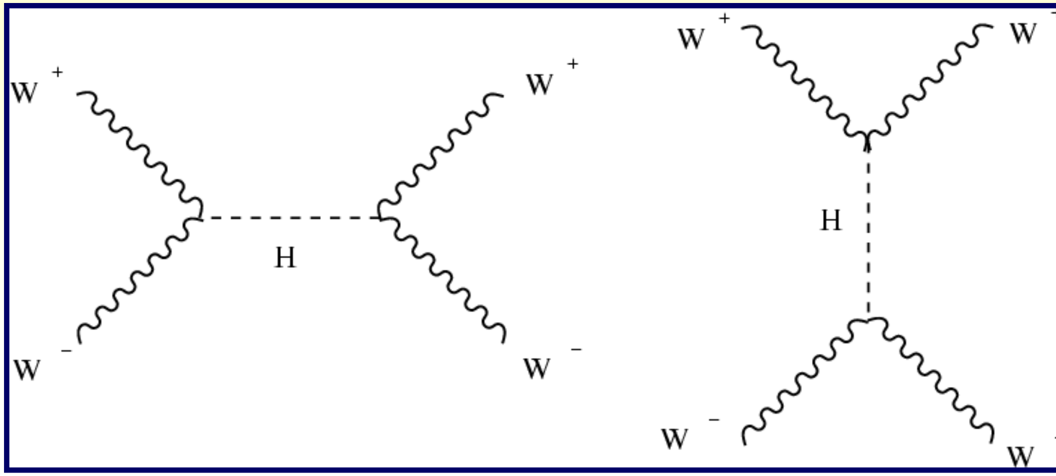
$$\mathcal{A} = A^{(4)} \frac{E^4}{M_W^4} + A^{(2)} \frac{E^2}{M_W^2} + \ldots$$

At energy scale $\Lambda = 4\pi M_W / g \sim 1.6 \text{ TeV}$

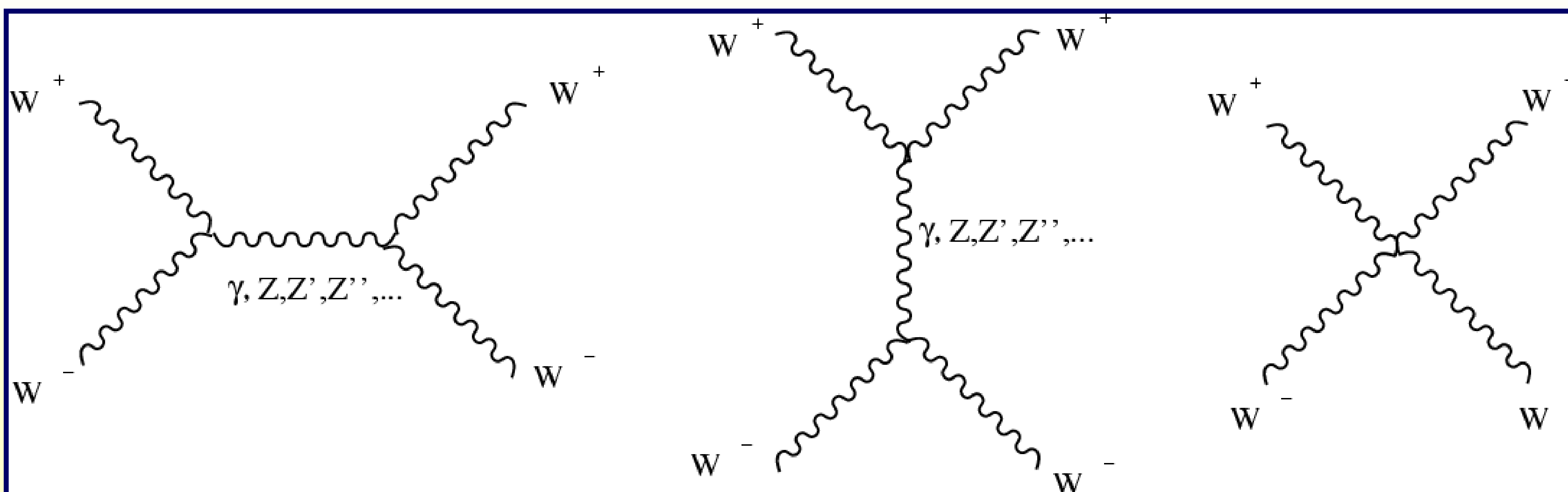
scattering amplitudes **violate unitarity**

Higgs exchange must become important **significantly below** this scale

In SM **Higgs exchange** will cancel growing terms in amplitude



In extra dimensional models, **exchange of KK modes** can play similar role as Higgs:



•**Predicts sum rules** among masses and couplings:

$$g_{WWWW} = g^2_{WW\gamma} + g^2_{WWZ} + \sum_i g^2_{WWZ^i}$$

$$\frac{4}{3} g_{WWWW} M_W^2 = g^2_{WWZ} M_Z^2 + \sum_i g^2_{WWZ^i} M^2_{Z^i}$$

For WW $\longrightarrow$ WW scattering (similar for WZ $\longrightarrow$ WZ)

•Predicts at least W', Z' below 1 TeV, with small but non-negligible coupling to light gauge bosons

$$g_{WZW^1} \leq 0.04$$

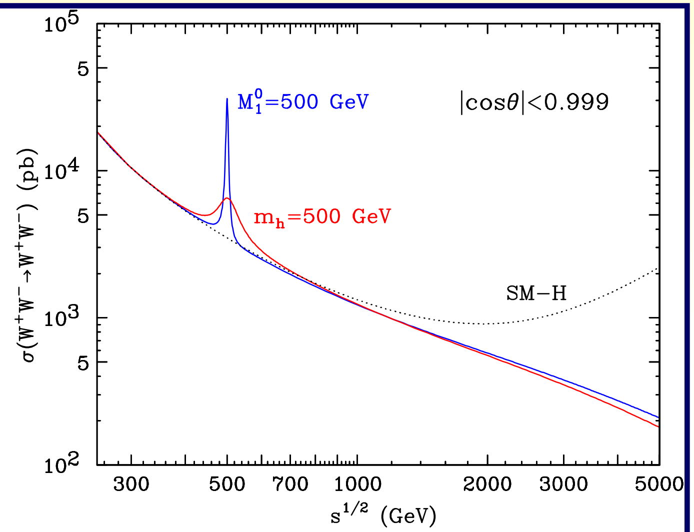
- Higgsless: (weakly coupled) dual to technicolor theories
- Solves little hierarchy, but generically large S-parameter

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

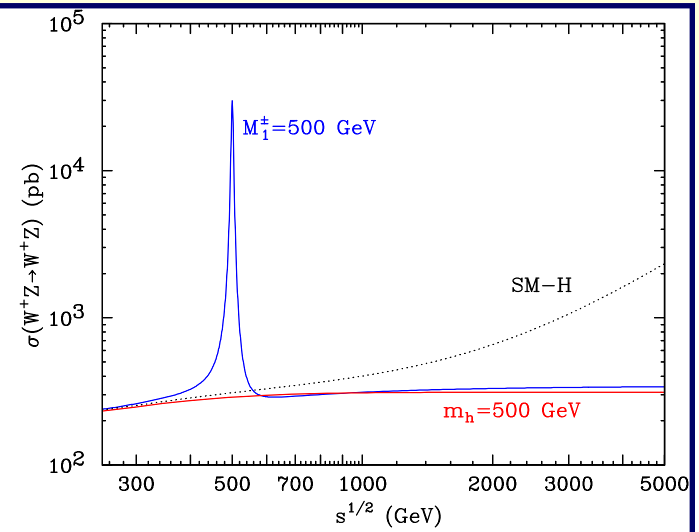
- S generically $\mathcal{O}(1)$ contrary to observations
- Can reduce via tuning shape of fermion wave function

LHC predictions

(Birkedal, Matchev, Perelstein)



WW → WW

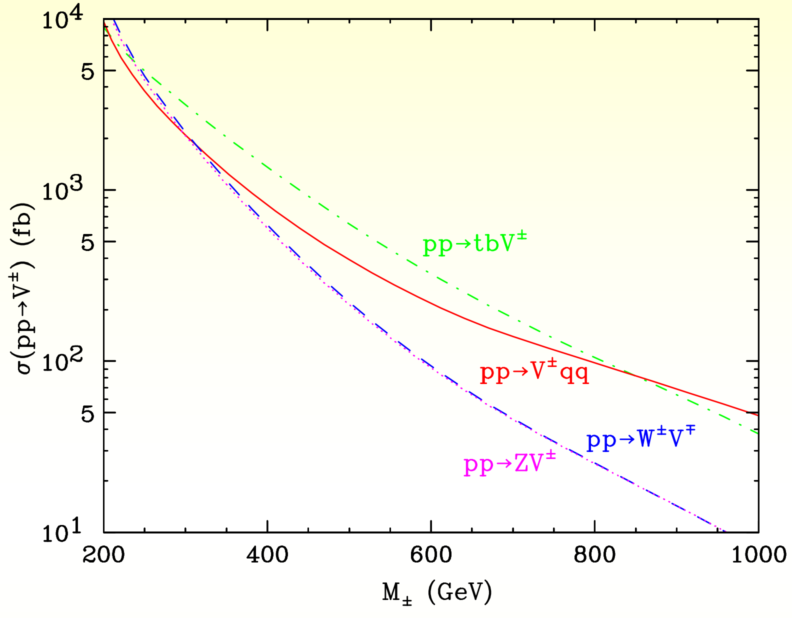


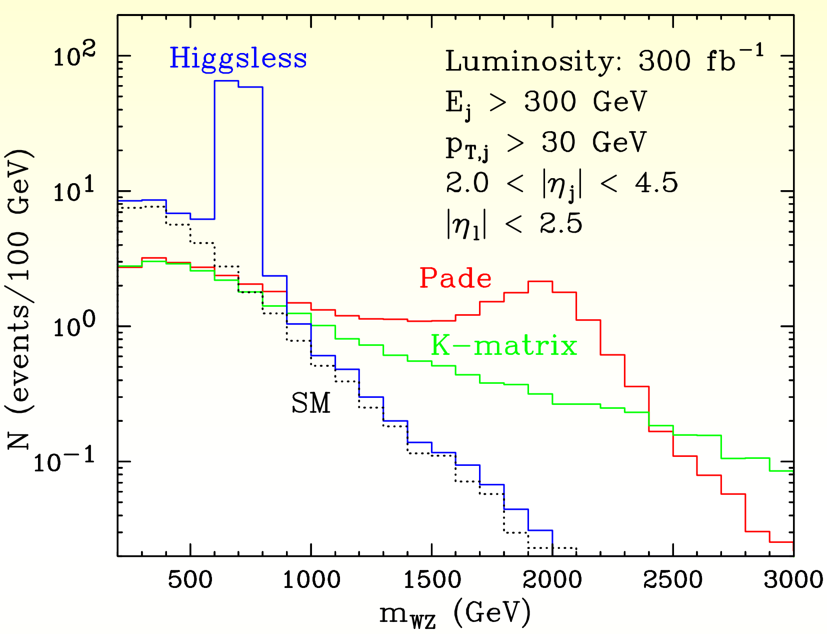
WZ → WZ

- WW scattering not that different from SM
- WZ scattering is **very different** (new peak!)

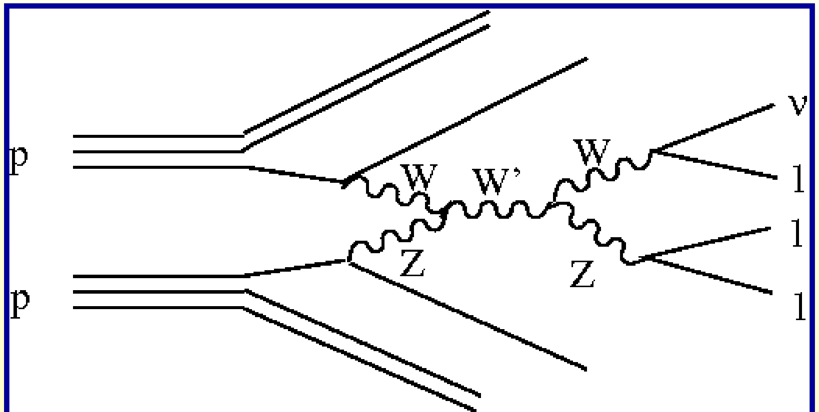
W' production at the LHC

(Birkedal, Matchev, Perelstein)





- Assumption W'ff, Z'ff coupling completely negligible



A serious recent study of same process including NLO QCD corrections

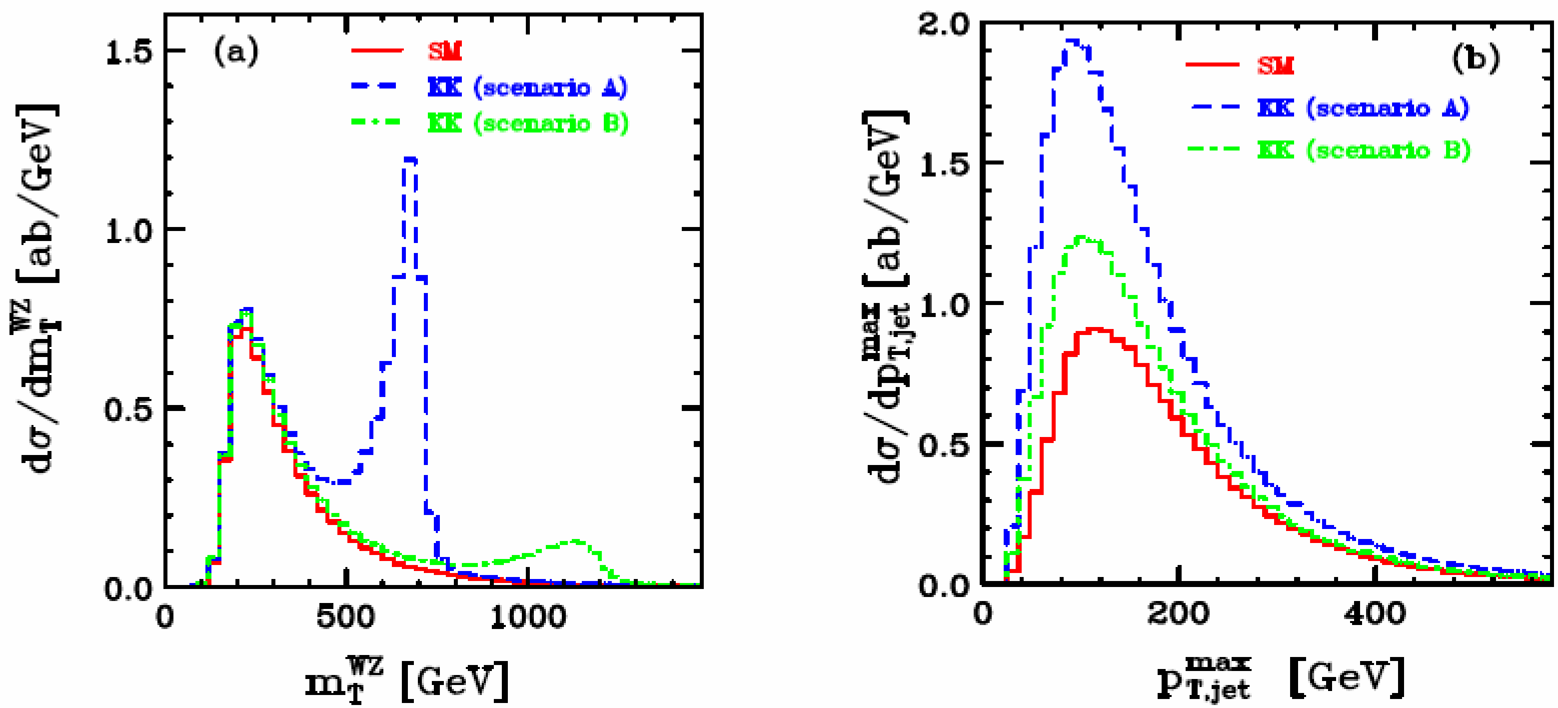


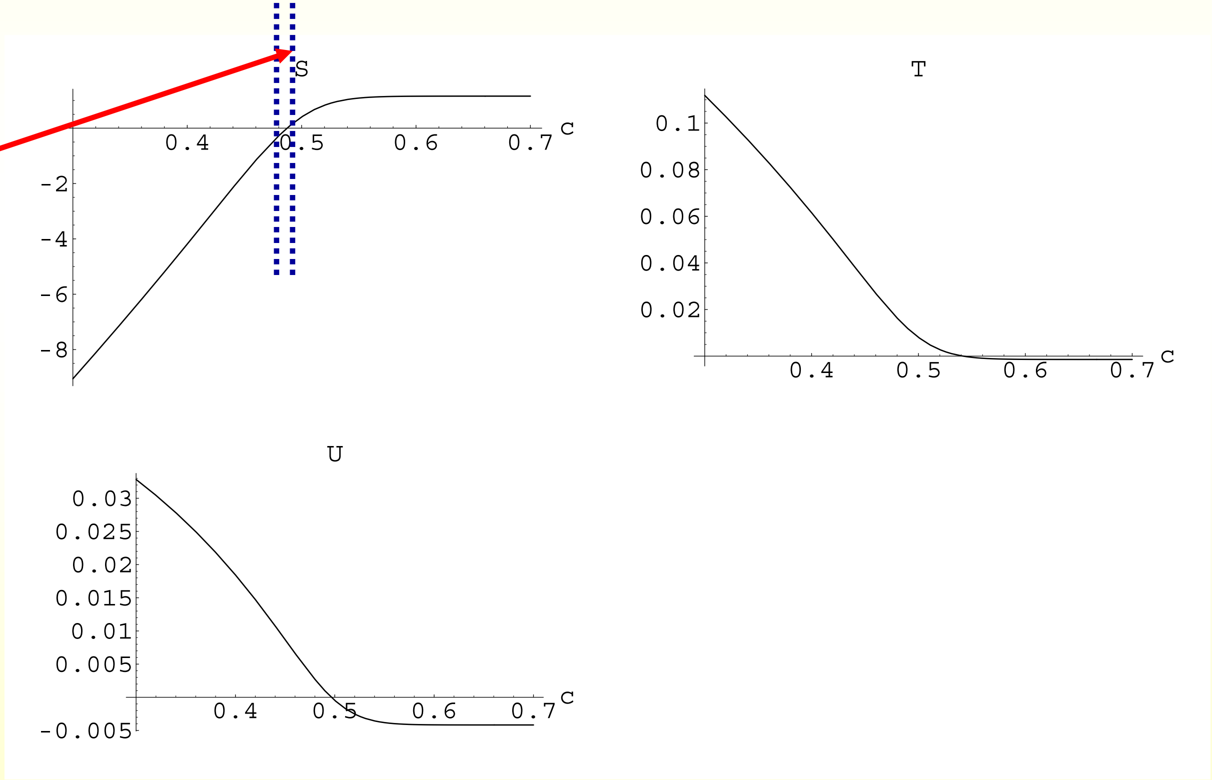
Figure 9: *Transverse cluster mass distribution (a) and transverse momentum distribution of the hardest tagging jet (b) for $pp \to W^+Zjj$. Shown are predictions for the SM (red, solid), and for the two Higgsless scenarios A (blue, dashed) and B (green, dot-dashed).*

(Englert, Jäger, Zeppenfeld)

Electroweak precision tests

- If fermions elementary, S parameter too large
- If fermions close to flat, S can be reduced

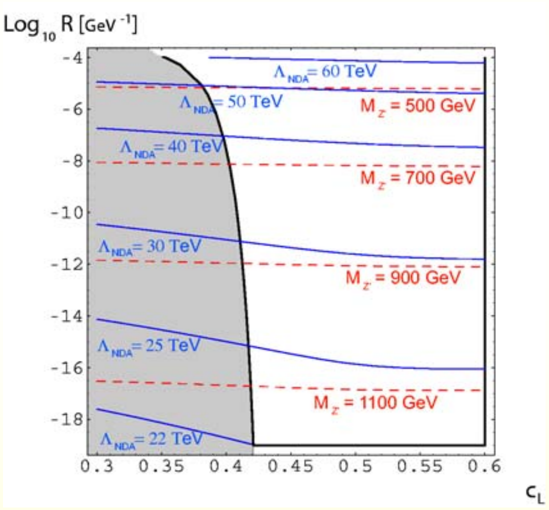
Need to be here % level tuning of c

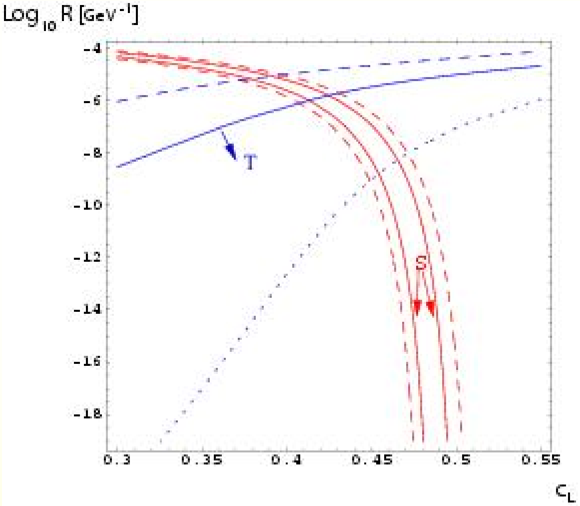


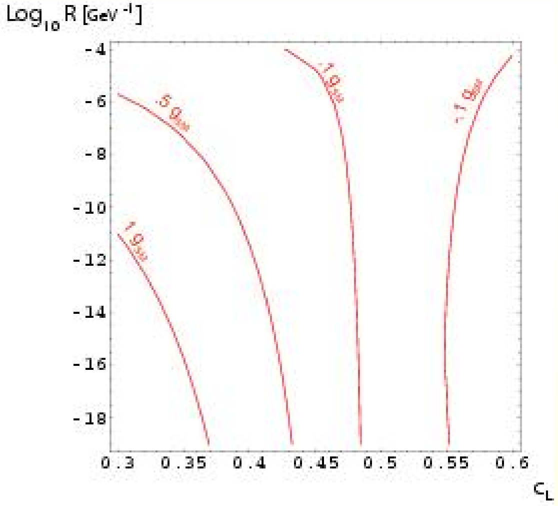
(Cacciapaglia, C.C.,Grojean, Terning)

Can find region where:

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



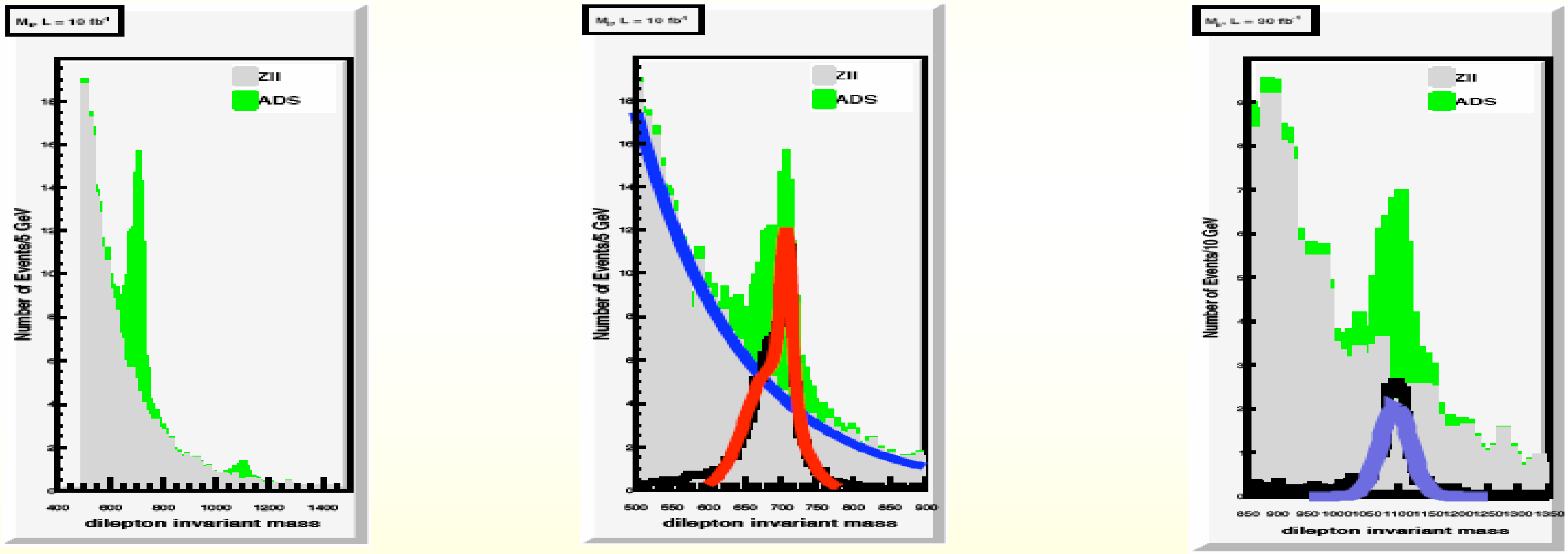




(Cacciapaglia, C.C.,Grojean, Terning)

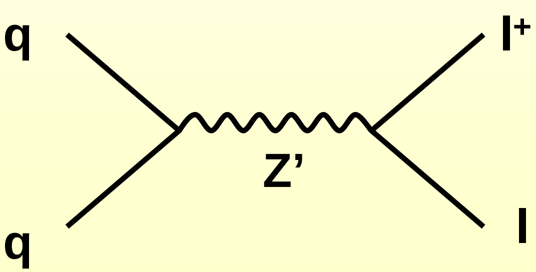
•Coupling to fermions not that small, DY will still be leading channel at LHC

Example $Z' \to l^+l^-$ DY at LHC for a sample point



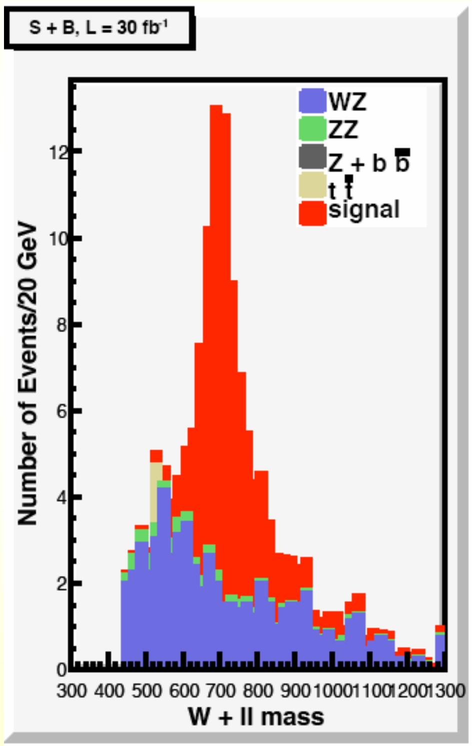
(To appear by Martin and Sanz)

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



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

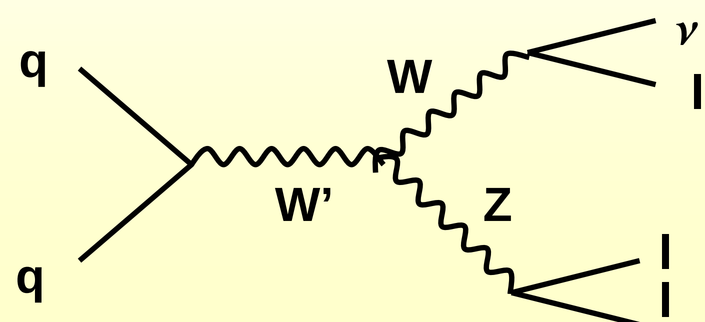
Example W’ DY at LHC for a sample point



Process	σ	ϵ	# events
$W_{1,2} \to WZ \to 3\ell\nu$	0.0065 pb	0.397	77
$WZ \to 3\ell + \nu$	0.965 pb	2.43×10^{-3}	70
$ZZ \to 4\ell(\text{miss-}\ell)$	0.116 pb	1.6×10^{-3}	6
$Z\bar{b} \to \ell^+\ell^-\bar{b}b$	11.4 pb	0	0
$\bar{t}t \to b\bar{b}\ell\ell'\nu\nu'$	22.8 pb	2.0×10^{-6}	2

Figure 11: Signal and background cross-sections, efficiencies, and number of events in $\mathcal{L} = 30$ fb^{-1}

(To appear by Martin and Sanz)



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

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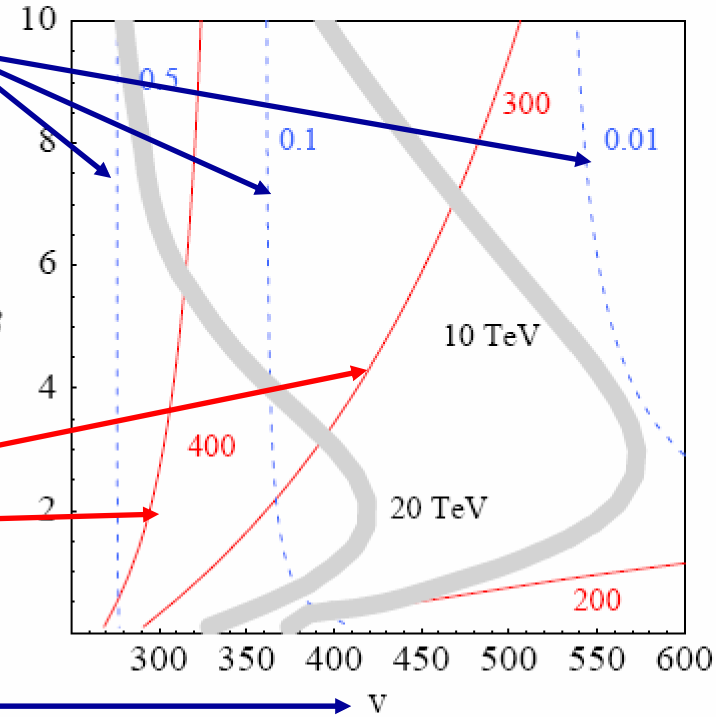

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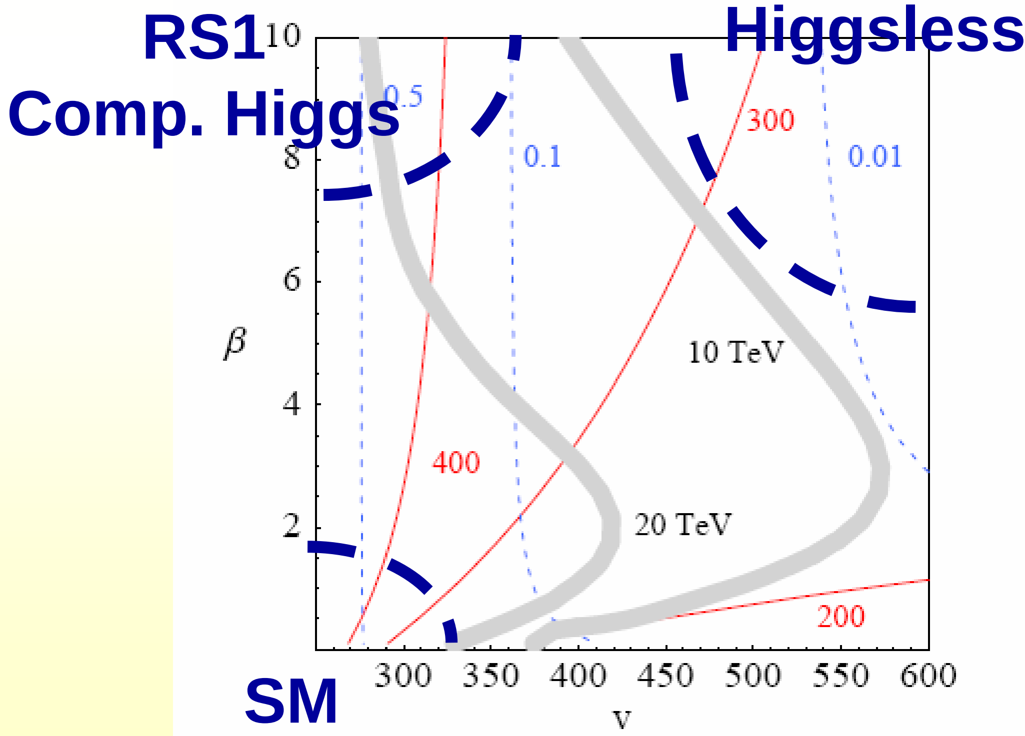
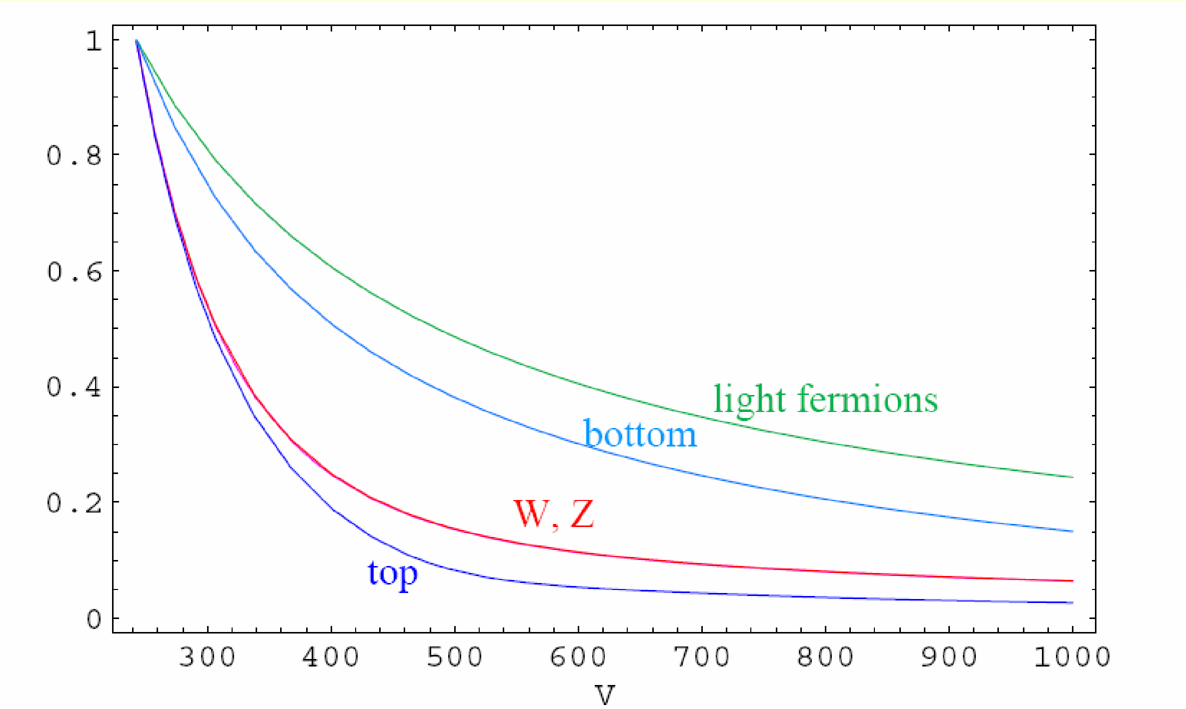
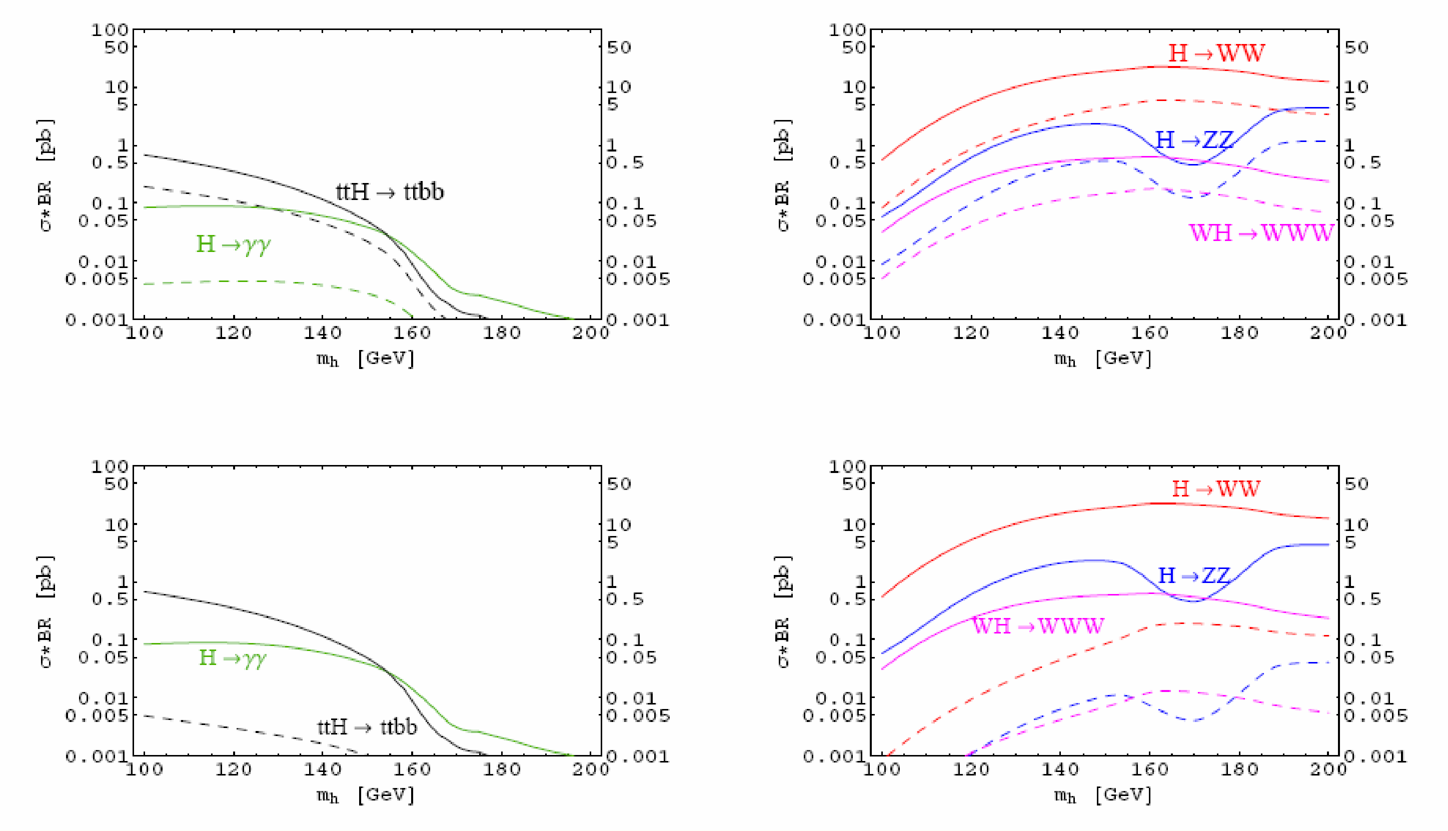


Suppression of the Higgs coupling:



Higgs phenomenology



Sample spectra

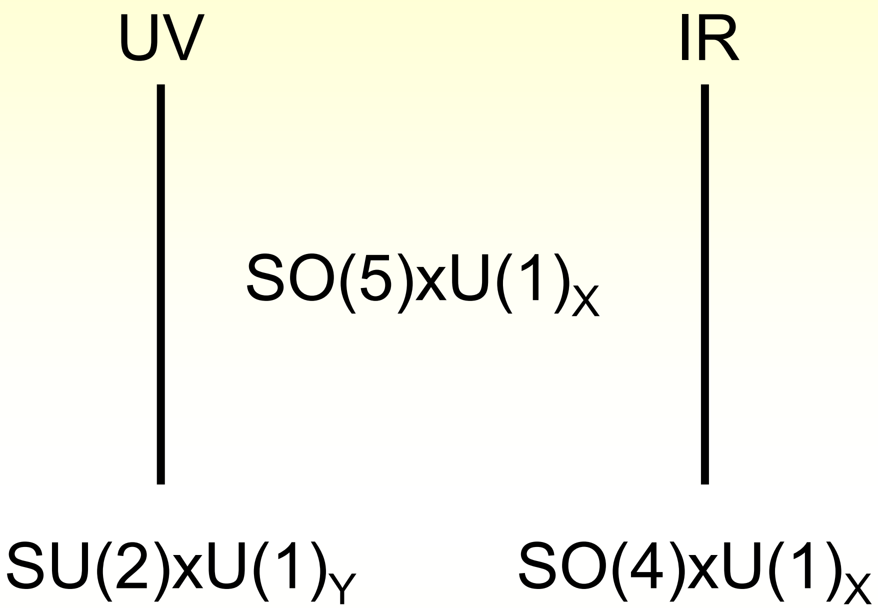
a) $V = 300$ GeV, $\beta = 2$	
$1/R'$	372.5 GeV
W'	918 GeV
Z'_1	912 GeV
Z'_2	945 GeV
G'	945 GeV

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

5. Composite pGB Higgs models

- In technicolor (or Higgsless): the 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



(Agashe, Contino, Pomarol)

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

Higgs potential:

$$V(h) = \underbrace{0\cdot|h|^2 + 0\cdot|h|^4}_{\text{Tree-level vanishes Due to PGB nature}} + \underbrace{\frac{g^2}{16\pi^2} f^4 \cos^n(|h|/f)}_{\text{Generic PGB pot.}}$$

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:

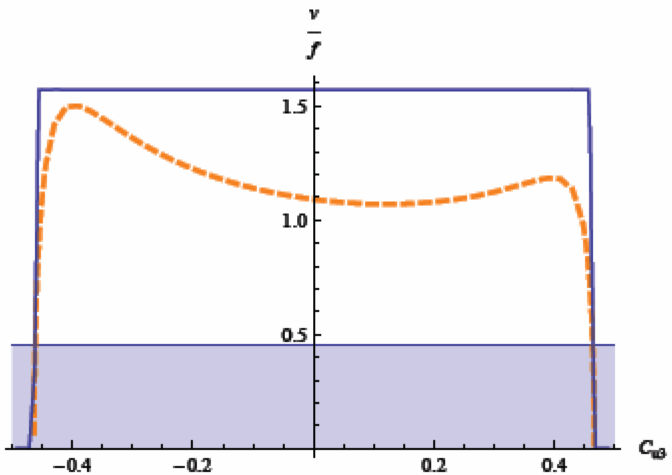
$$m_h^2 \propto \frac{g^2}{16\pi^2} f^2$$

Quartic:

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

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

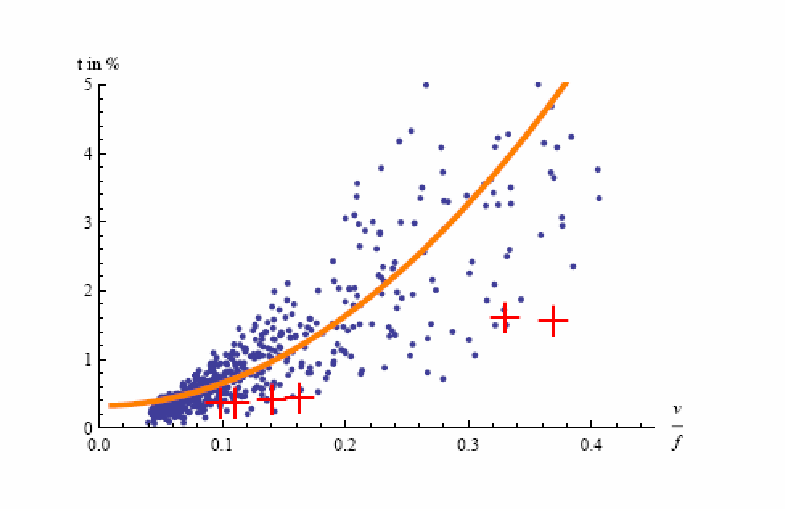
(C.C., Falkowski, Weiler)



•Fine tuning quantified:

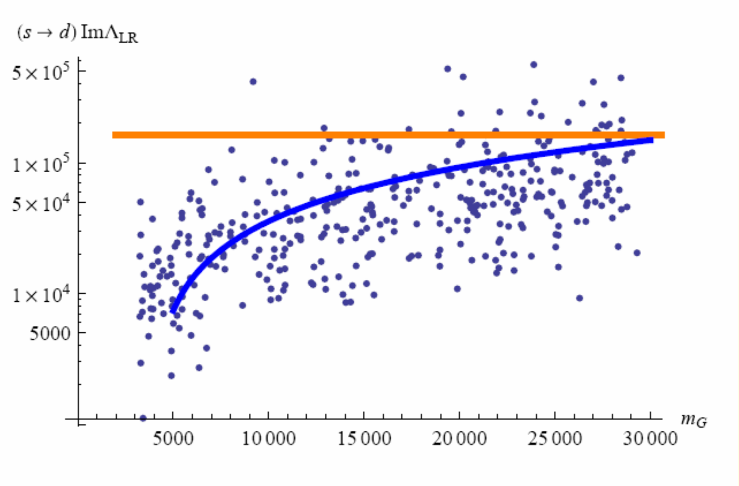
$$t \sim \frac{1}{4}\frac{v^2}{f^2}$$

•For v/f~0.1 about 0.5% tuning



•Also flavor slightly worse off than ordinary RS (see Weiler's talk)

•Flavor bound ~30 TeV

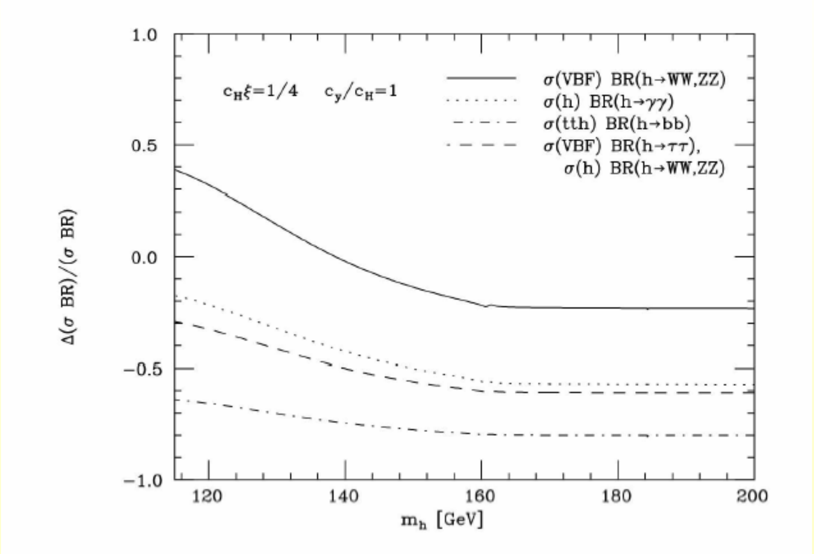


Experimental consequences of pGB MCH

•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)



6. Little Higgs models

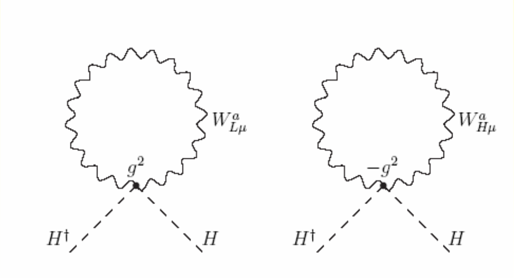
(Arkani-Hamed, Cohen, Katz, Nelson)

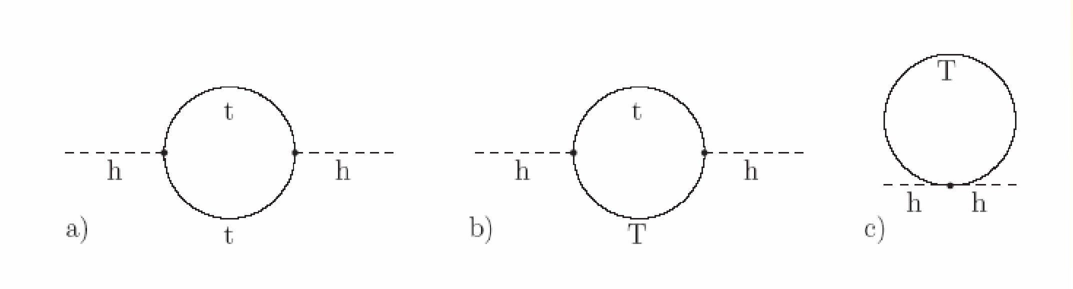
- Higgs is Goldstone again
- Added ingredient: “collective breaking”
- Mass suppressed, but quartic is large

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

- 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”





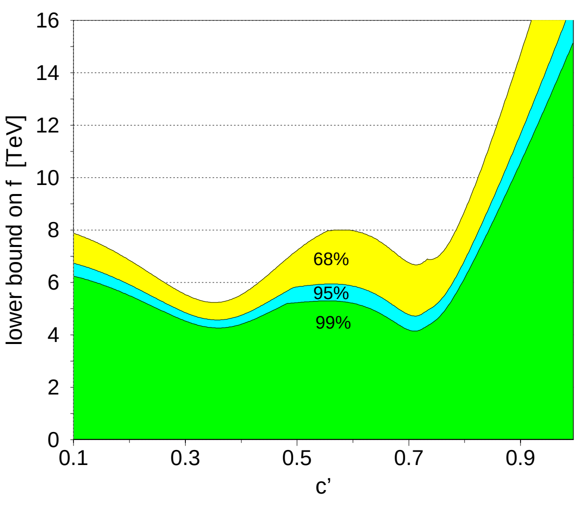
Gauge loops

Top loops

•But new particles themselves will contribute to EWPO’s

•Will force generically f>4 TeV

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



- Way out: ensure no tree-level EWP contribution

- New Z_2 parity needed dubbed T-parity **(Cheng, Low)**

- However, full model quite complicated

(C.C., Heinonen, Perelsetin, Spethmann)

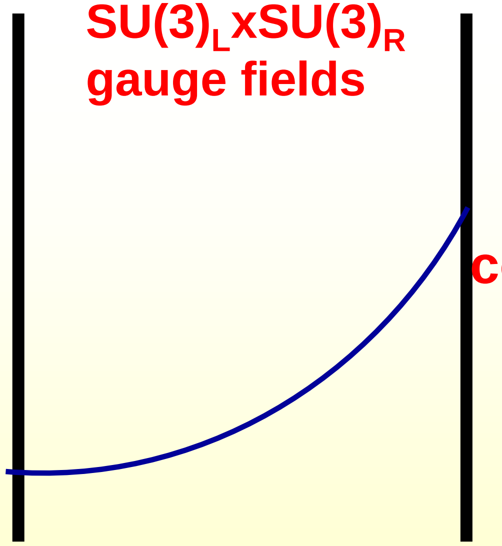
- For example, one generation…

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	$0\ )$

Much more on little Higgs in talk by Witek Skiba

7.AdS/QCD?

- Original motivation of AdS: describe duals of strongly interacting theories (eg. N=4 SUSY)
- Old question: can it be used for QCD itself?
- AdS/QCD proposal



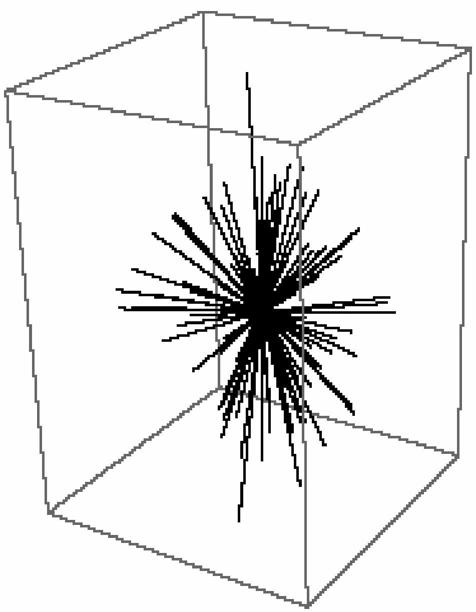
Observable	Measured (Central Value - MeV)	Model (MeV)
m_π	139.6	141
m_ρ	775.8	832
m_{a_1}	1230	1220
f_π	92.4	84.0
$F_\rho^{1/2}$	345	353
$F_{a_1}^{1/2}$	433	440
$g_{\rho\pi\pi}$	6.03	5.29

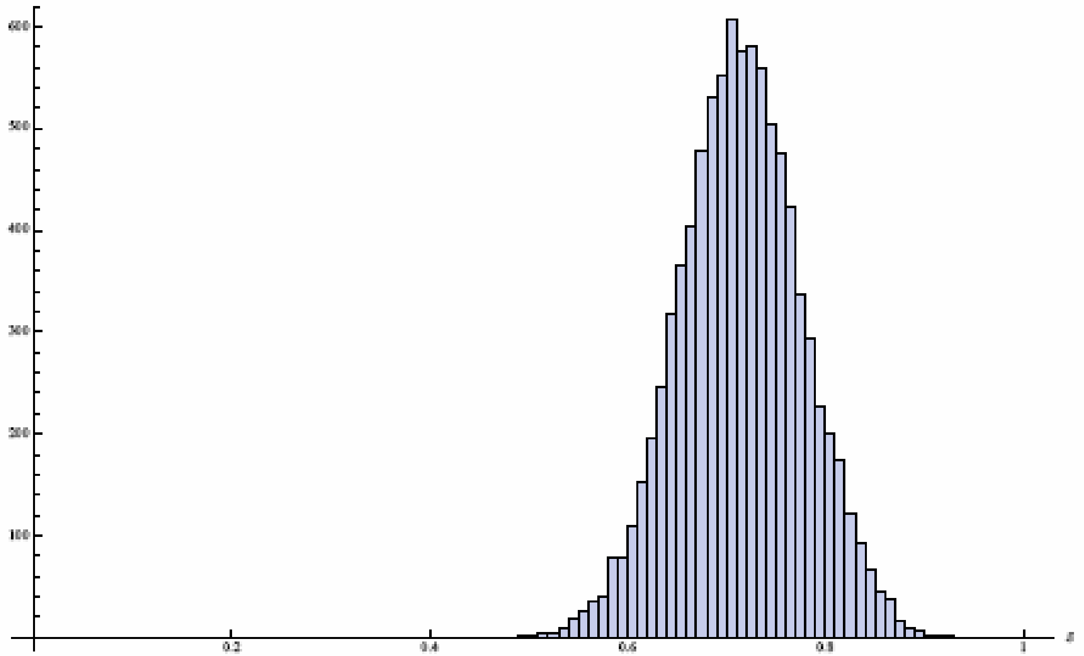
(Erlich, Katz, Son, Stephanov; da Rold Pomarol)

Observable	Measured (Central Value - MeV)	Model (MeV)
m_{K^*}	892	897
m_ϕ	1020	994
m_{K_1}	1272	1290
m_K	498	411
f_K	113	117
m_{f_2}	1275	1236
m_{ω_3}	1667	1656
m_{f_4}	2025	2058
m_η	548	520
m'_η	958	867

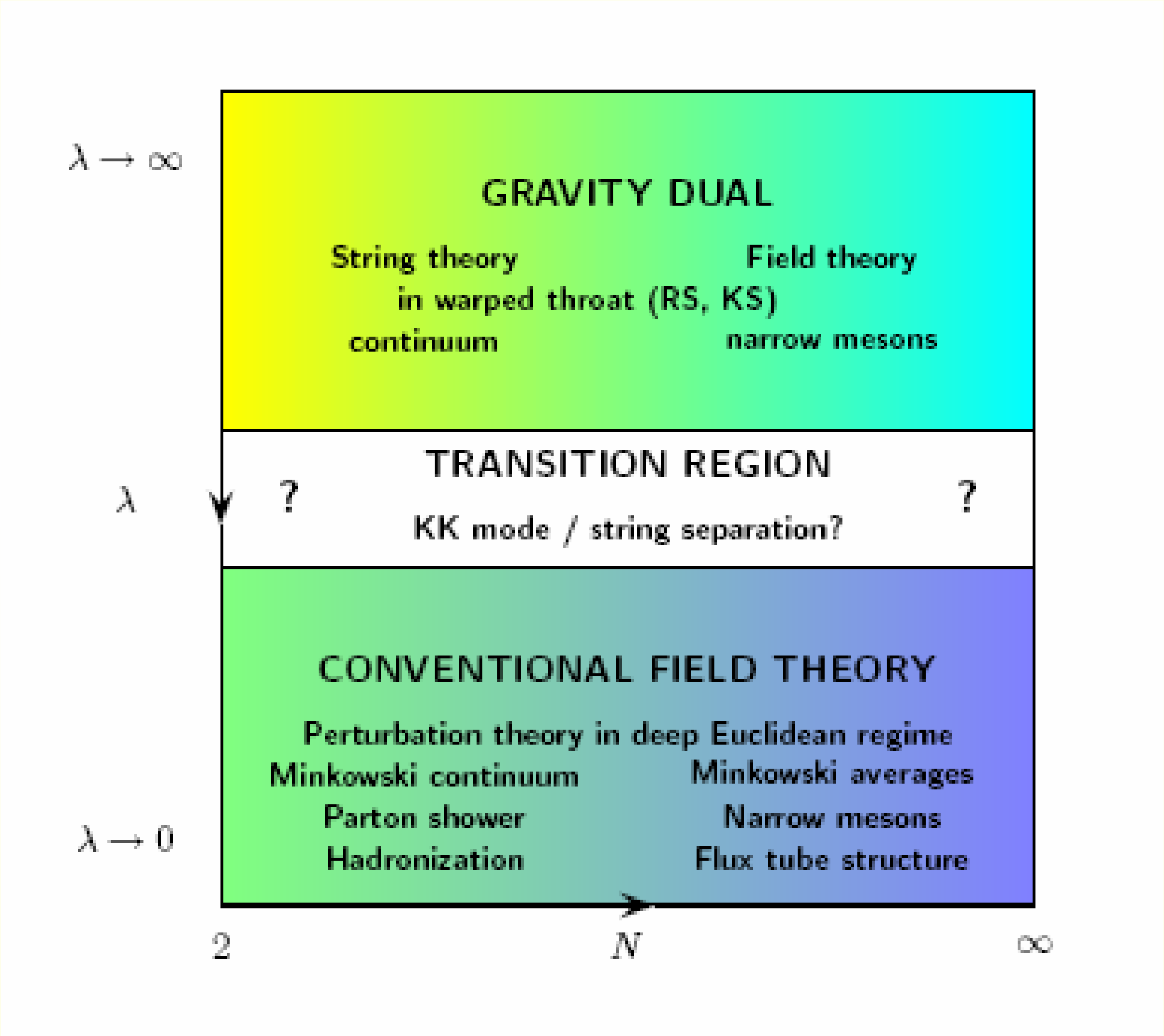
- However, dynamics does not seem to be properly captured. Eg. $m_n^2 \propto n^2$ rather than Regge
- Polchinsky, Strassler: at large ‘t Hooft coupling all partons at small x
- Strassler; Hoffman, Maldacena: likely no jets produced
- We verified the absence of jets in simplest AdS/QCD models

(C.C., Reece, Terning)





•The right phase diagram for QCD in (N,λ) would be:



Summary

TeV scale, little hierarchy and EWPO

SUSY: need additional source of higgs quartic
need RGE running of m_H stop at low scale

RS: original RS large EWP, flavor issues

Realtistic RS: custodial symmetry, bulk fields
little hierarchy remains

Higgsless: solves little hierarchy, but large S
need to tune S away

Summary

TeV scale, little hierarchy and EWPO

Composite pGB Higgs: some tuning left in higgs potential, might be hard to see

Little Higgs: simple models EWP issues
T-parity: models very complex

Don’t have a complete model where everything just fits together

Reality: Some combination of these ideas?
Completely different?