Can there be no Higgs?

Csaba Csáki
(Cornell University)

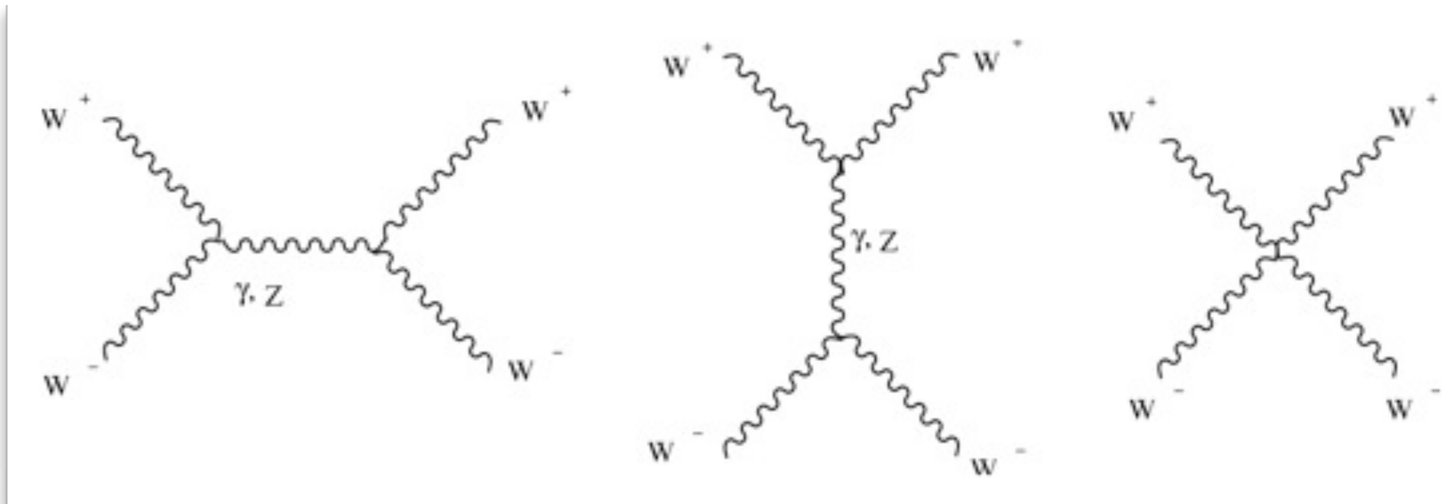
Michigan LHC Conference
Ann Arbor, December 13, 2010

The functions of the Higgs in the SM

- Gives mass to W, Z bosons
- Gives mass to fermions
- Restores unitarity of WW, WZ scattering

Unitarity

Massive gauge bosons without scalar violate unitarity:



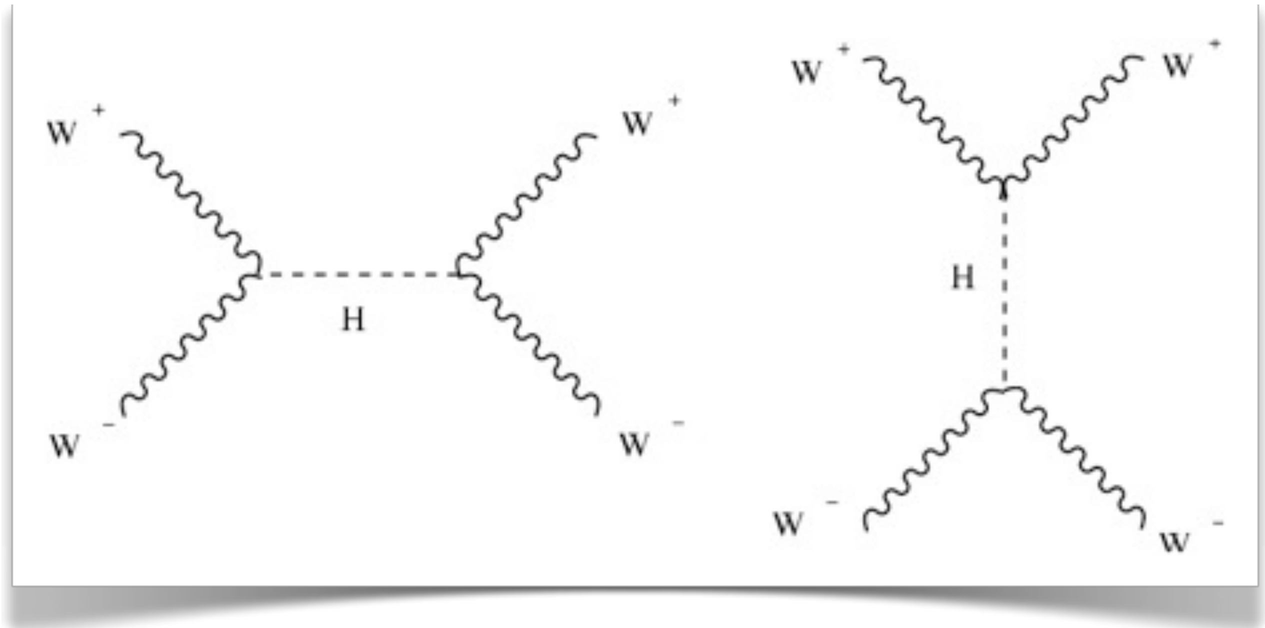
$$\mathcal{A} = A^{(4)} \frac{E^4}{M_W^4} + A^{(2)} \frac{E^2}{M_W^2} + \ldots$$

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

scattering amplitudes **violate unitarity**

If theory **perturbative**: **new** particle(s) should appear much **before** the unitarity violation scale to restore unitarity

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



Any other possibility?

- Particles other than scalar restore unitarity

- Unitarity is not restored at tree-level (but higher loops and non-perturbative effects important): strongly coupled theory (eg. technicolor)

I. Weakly interacting higgsless models

Focus on weakly coupled unitarity with new particles restoring unitarity

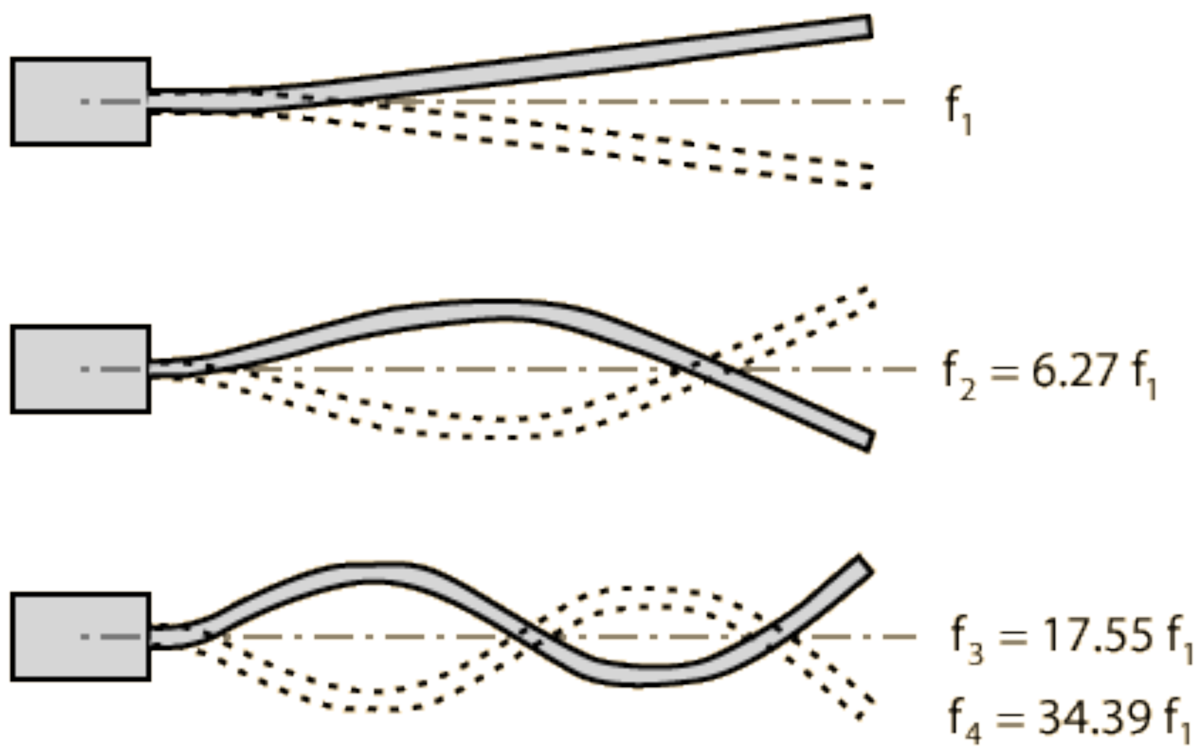
Extra dimensions (and their deconstructed 4D versions) offer an interesting possibility for this

Will discuss warped higgsless model

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

•**Idea**: use boundary conditions in extra dim's to break electroweak symmetry

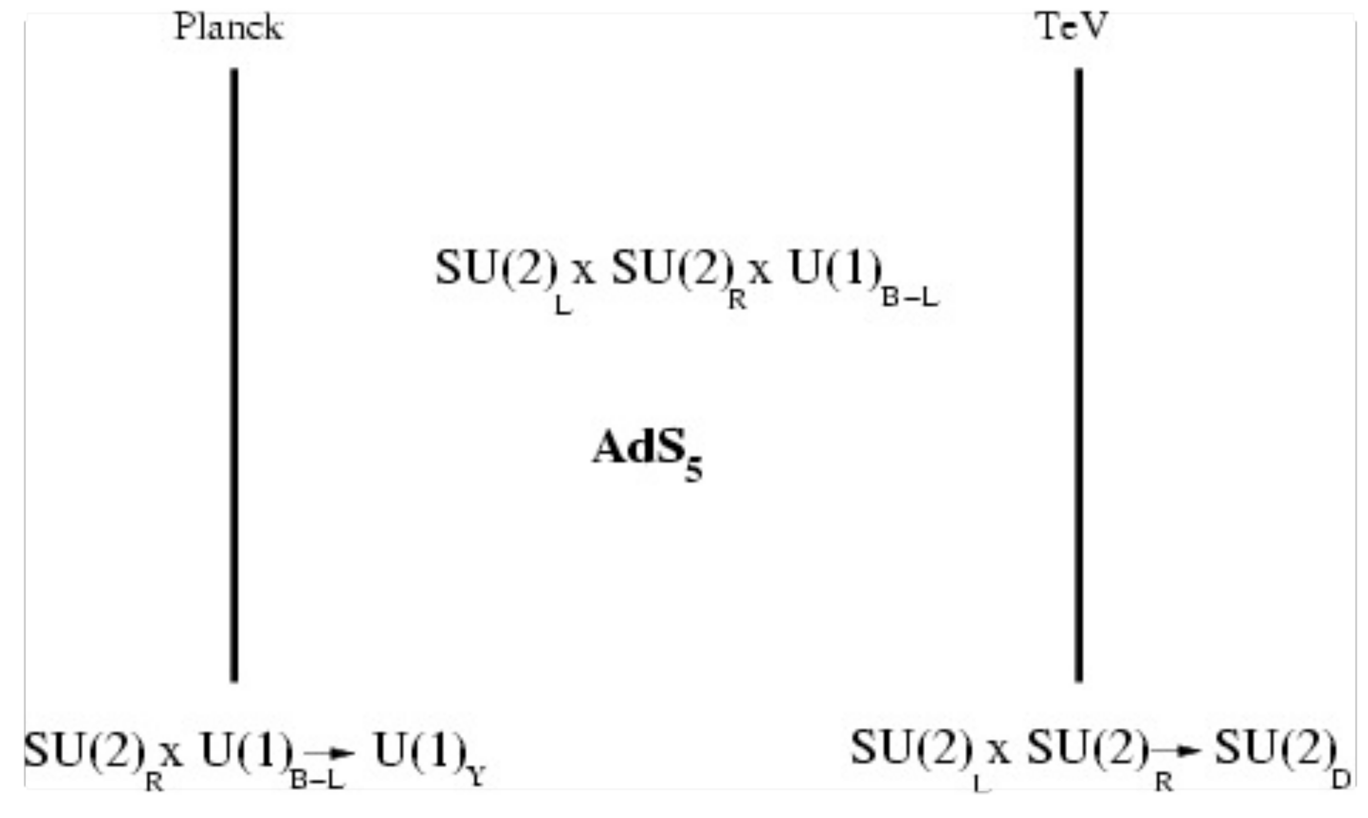
Observed mass spectrum depends on boundary conditions

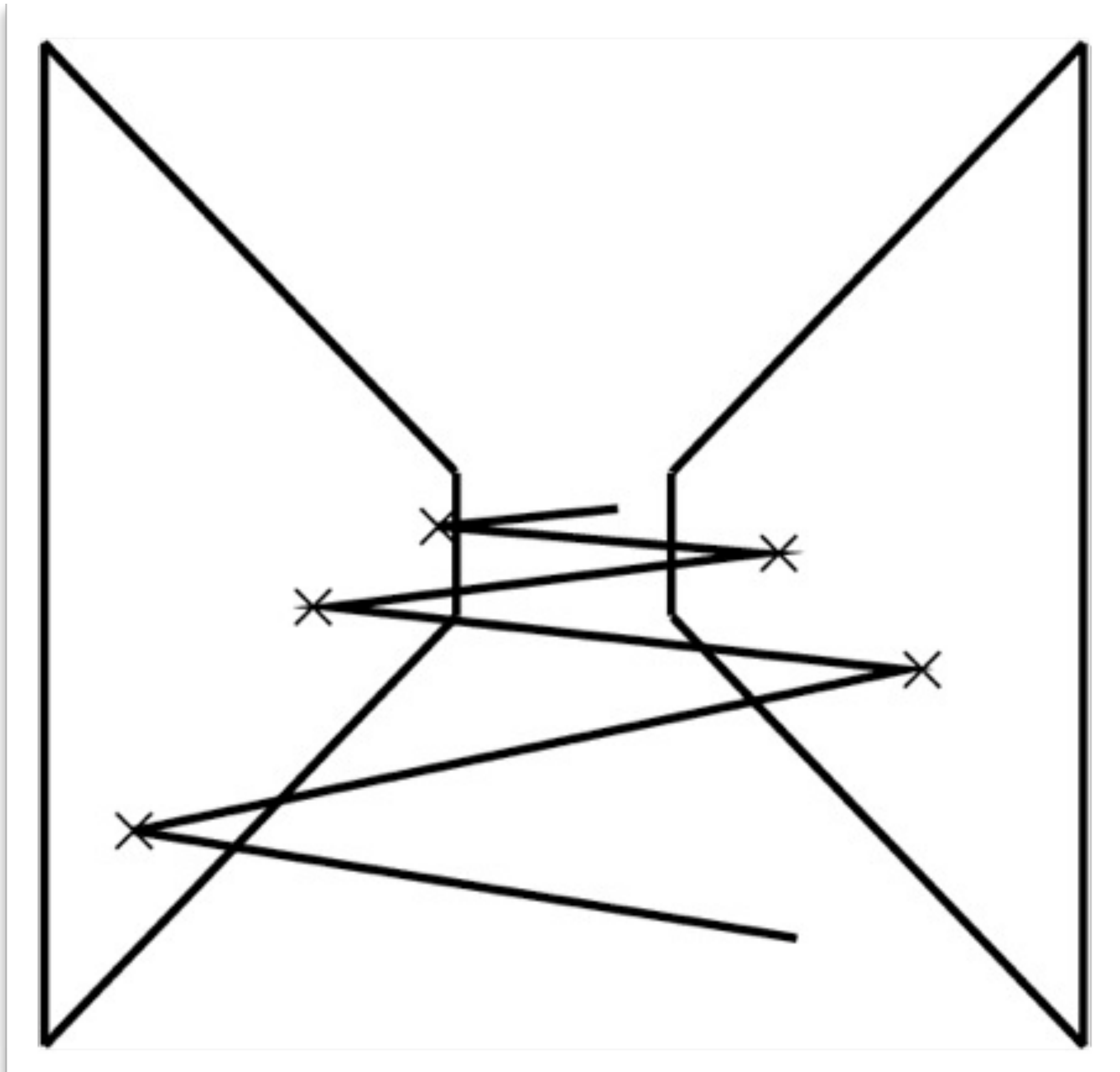


Just like the modes of a vibrating rod

Can obtain massive fields without a Higgs scalar

Warped higgsless model based on extra dimensions:





- SU(2)xSU(2)xU(1) gauge symmetry
- Need AdS background to get correct GB mass ratio
- Boundary conditions will follow symmetry breaking structure of Standard Model

How to enforce BC's?

- Add scalar Higgs on BOUNDARY
- Take scalar Higgs VEV $v \longrightarrow \infty$
- Effect of large Higgs VEV: gauge boson wave function REPELLED from brane
- In practice just a BC for gauge field
- Scalar Higgs itself decouples and plays no role

•In practice, just implies BC's for gauge fields

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

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

•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, $\tilde{g}_5$

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

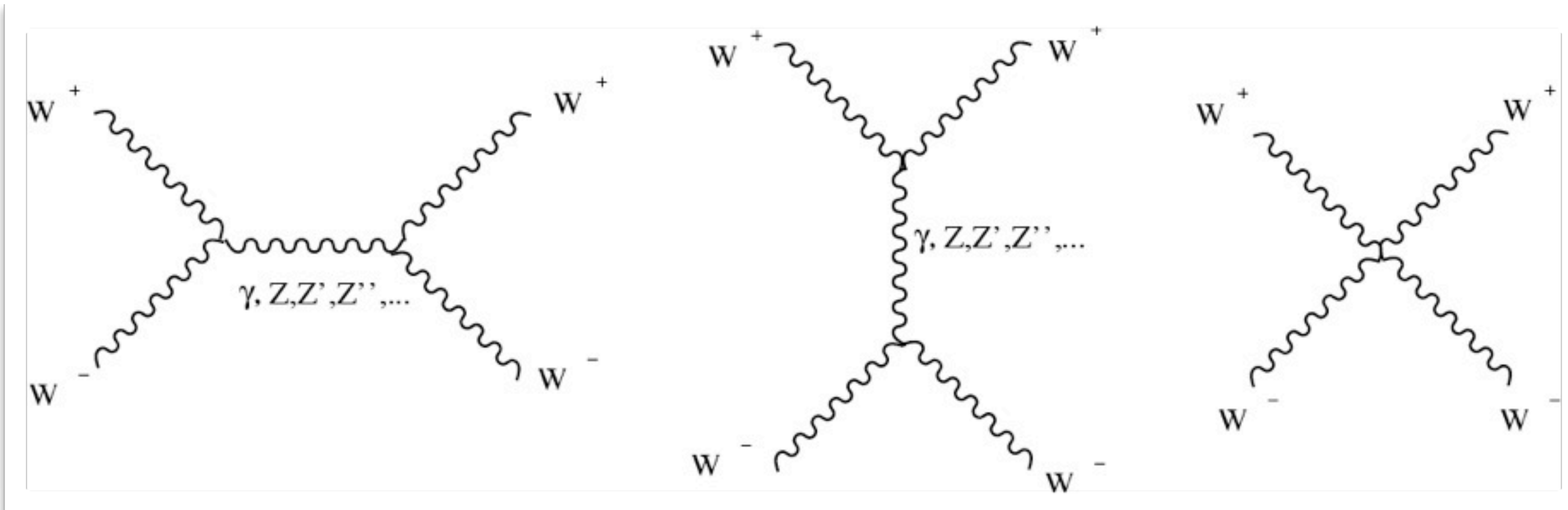
- Lightest additional KK modes not too light:

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

- So mass ratio is log enhanced:

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

Unitarity can be fixed via **exchange of KK modes** (instead of Higgs exchange)



•**<u>Predicts sum rules</u>** among masses and couplings:

$$
\begin{aligned}
g_{WWWW} &= g^2_{WW\gamma} + g^2_{WWZ} + \sum_i g^2_{WWZ^i} \\
\frac{4}{3} g_{WWWW} M^2_W &= g^2_{WWZ} M^2_Z + \sum_i g^2_{WWZ^i} M^2_{Z^i}
\end{aligned}
$$

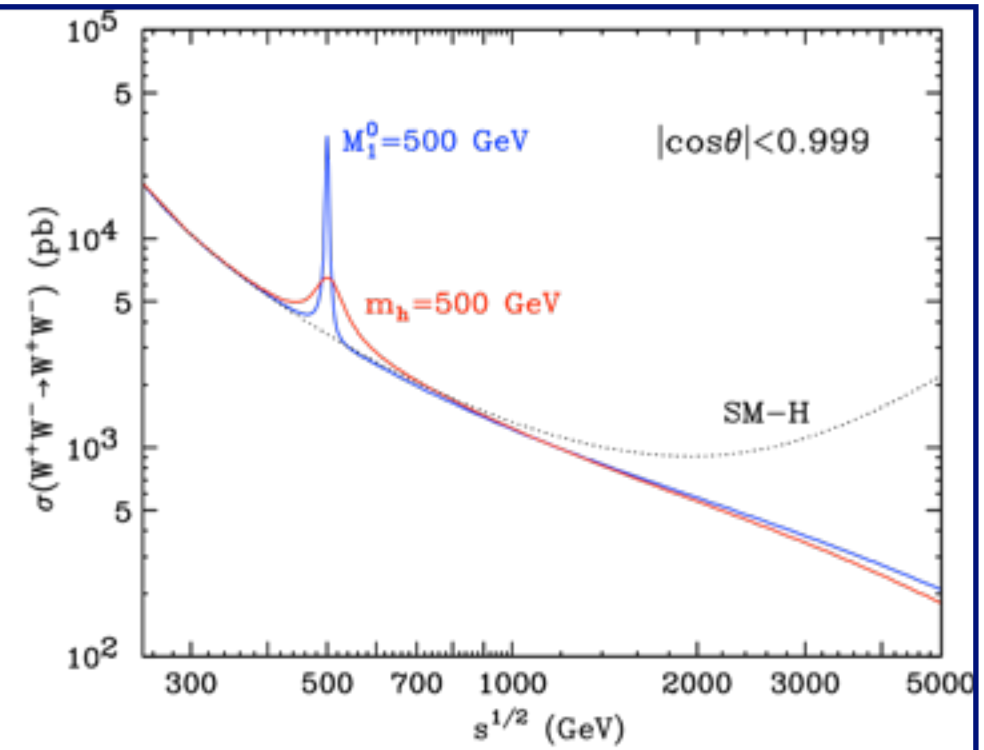
For WW → WW scattering (similar for WZ → WZ)

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

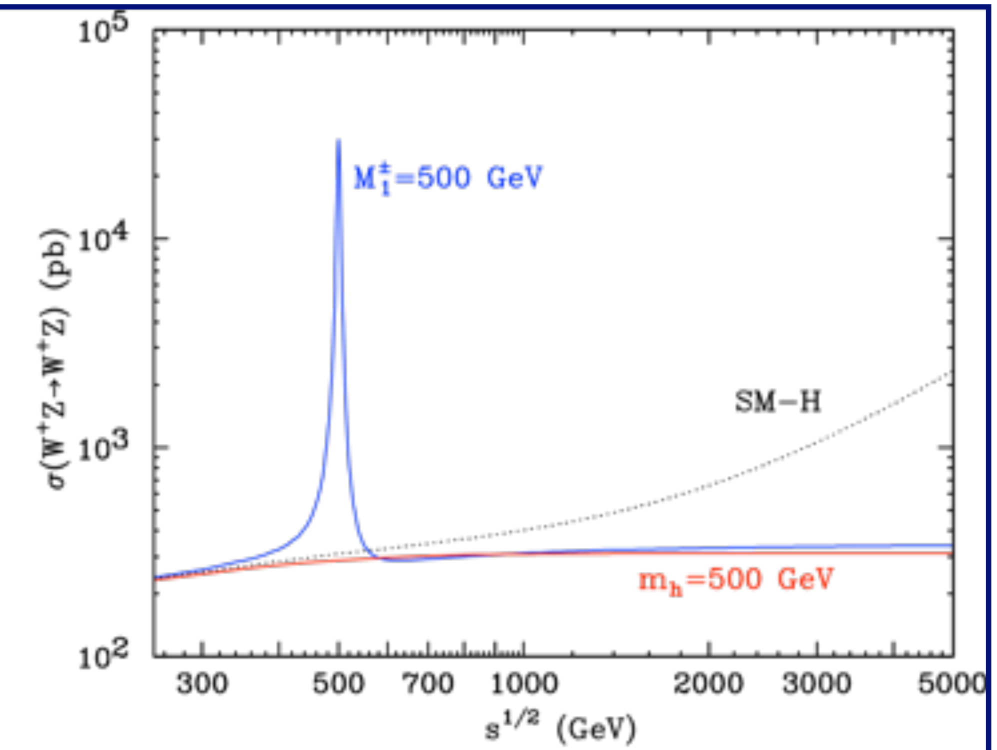
$$g_{WZW^1} \leq 0.04$$

Concrete predictions for the LHC

(Birkedal, Matchev, Perelstein '03)



WW → WW

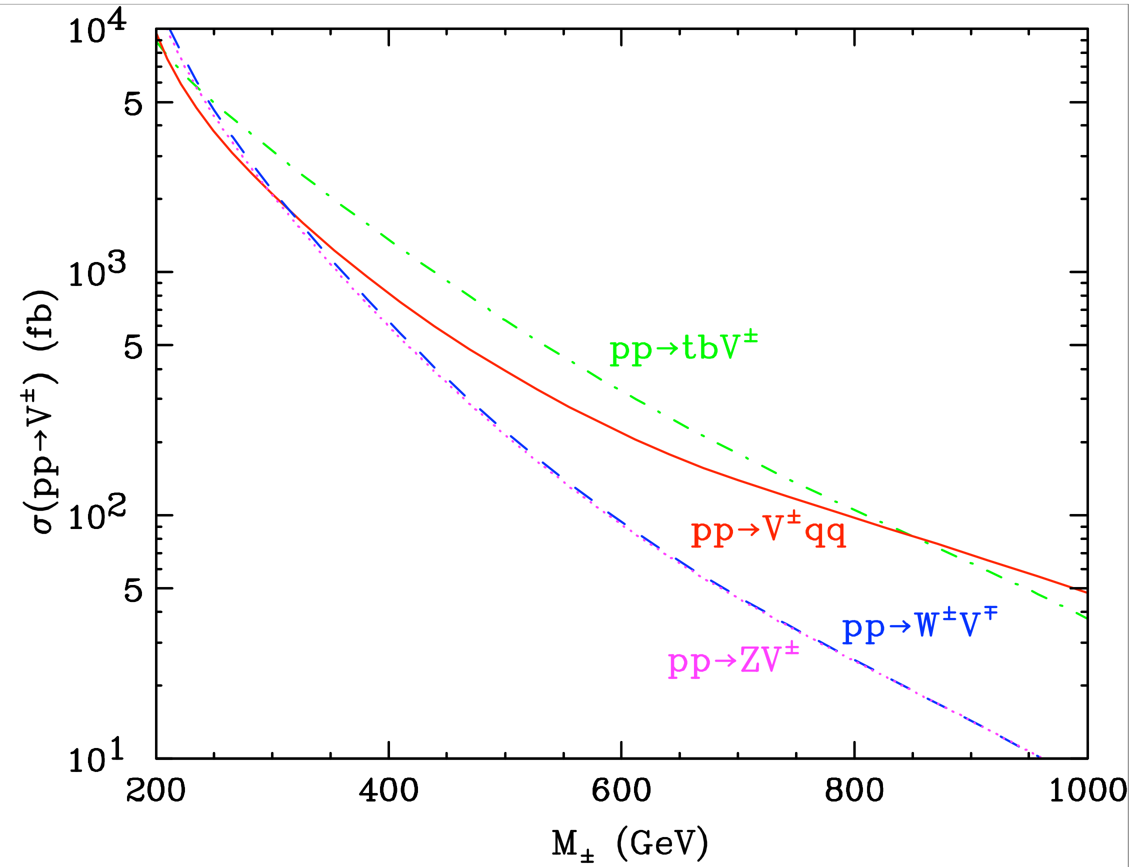


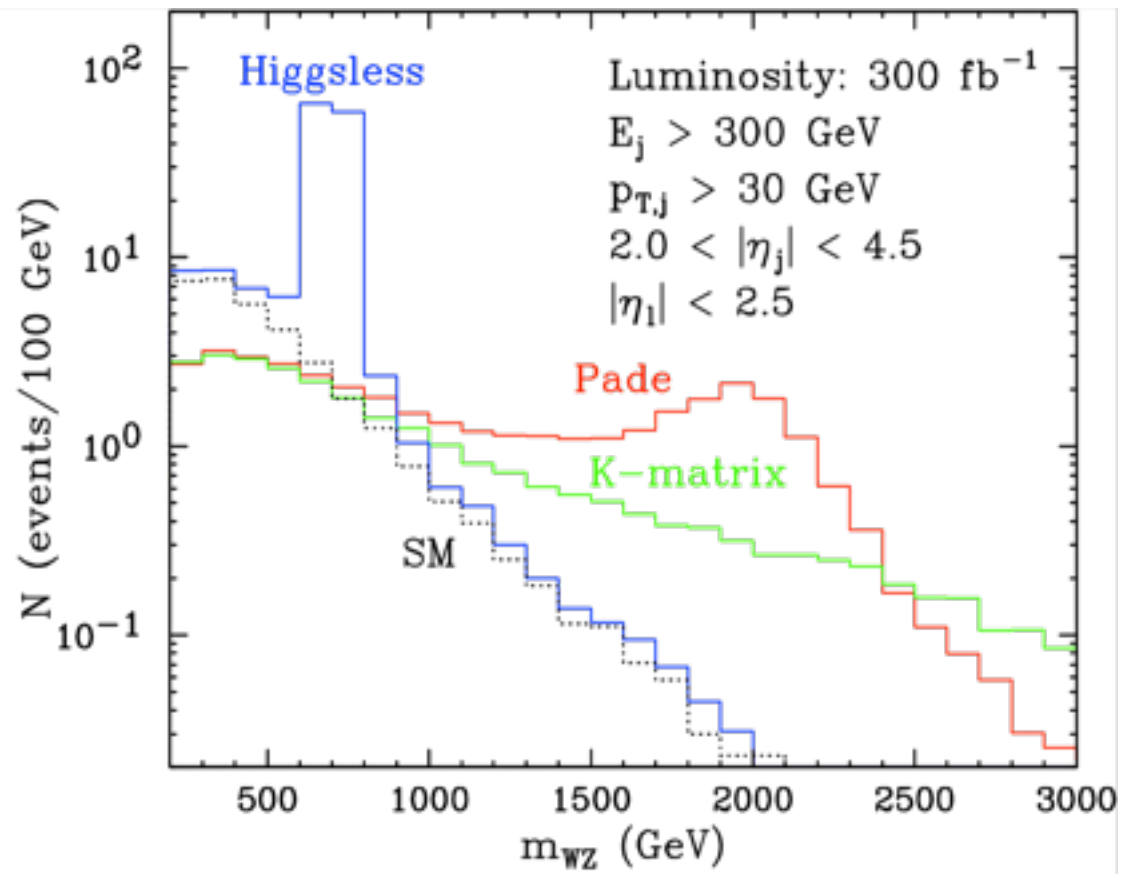
WZ→WZ

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

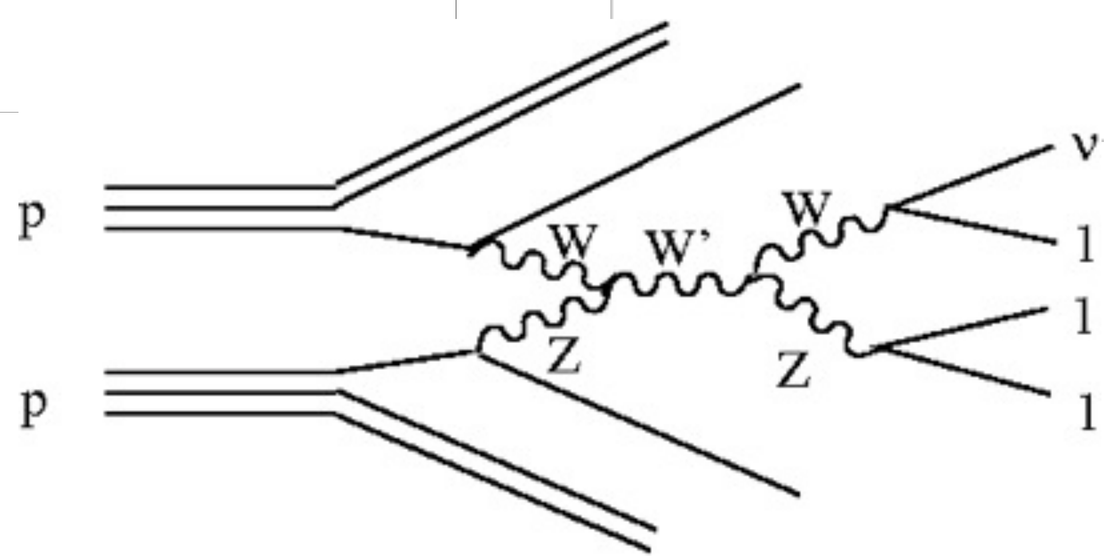
W' production at the LHC

(Birkedal, Matchev, Perelstein '03)





- 10 fb^{-1} will probe model up to $M_{W'}$ <550 GeV
- Need ~ 60 fb^{-1} to probe all the way to 1 TeV



A more detailed study of same process including NLO QCD corrections

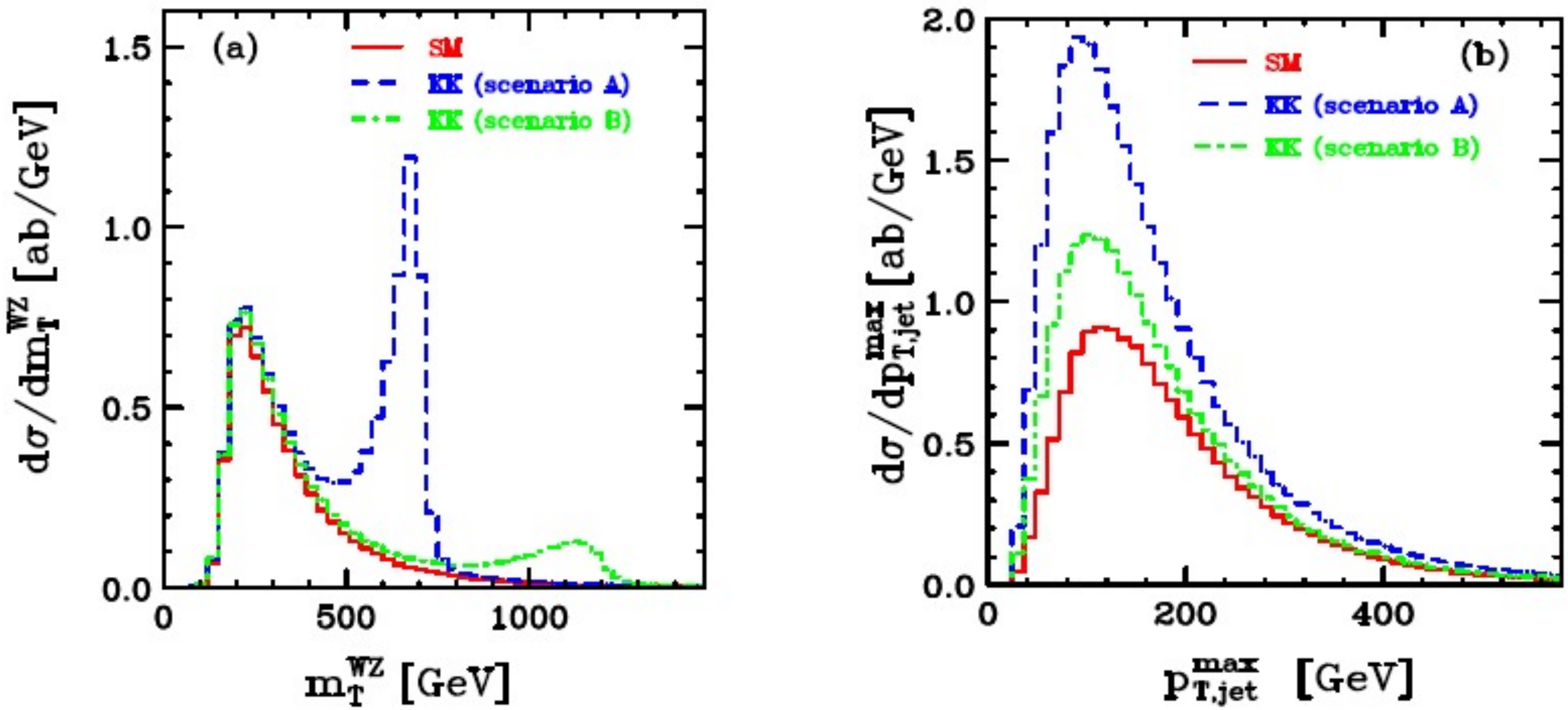


Figure 9: *Transverse cluster mass distribution (a) and transverse momentum distribution of the hardest tagging jet (b) for $pp \to W^+Zjj$. Shown are predictions for the SM (red, solid), and for the two Higgsless scenarios A (blue, dashed) and B (green, dot-dashed).*

Scale μ	$\sigma^{\rm LO}$ [fb]	$\sigma^{\rm NLO}$ [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)

Fermion masses in higgsless models

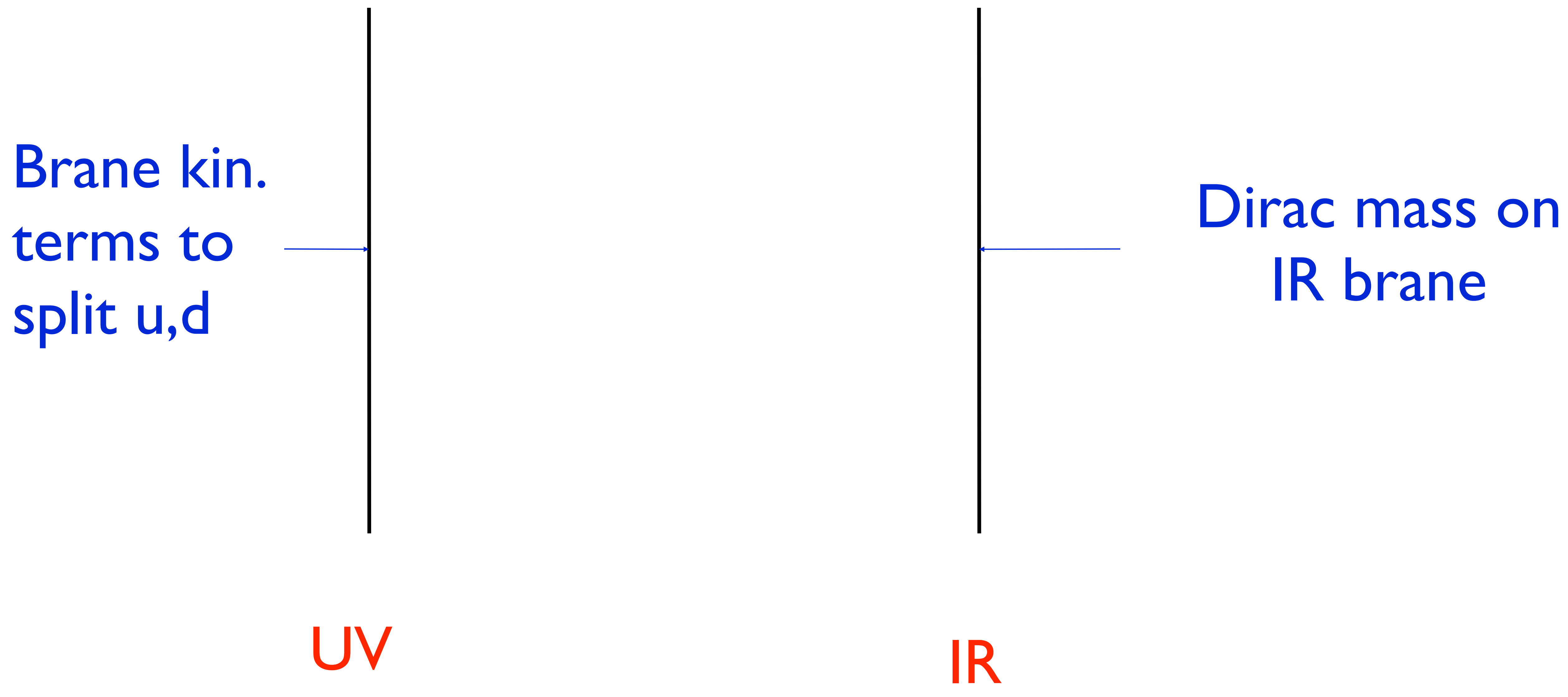
- 5D bulk fermions (Dirac fermions)

	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\square$	1	1/6
$\begin{pmatrix} u \\ d \end{pmatrix}_R$	1	$\square$	1/6
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	$\square$	1	$-1/2$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_R$	1	$\square$	$-1/2$

- Boundary conditions to get zero modes:

$$\begin{pmatrix} \chi u_L \\ \bar{\psi} u_L \\ \chi d_L \\ \bar{\psi} d_L \end{pmatrix} \begin{matrix} + & + \\ - & - \\ + & + \\ - & - \end{matrix} \qquad \begin{pmatrix} \chi u_R \\ \bar{\psi} u_R \\ \chi d_R \\ \bar{\psi} d_R \end{pmatrix} \begin{matrix} - & - \\ + & + \\ - & - \\ + & + \end{matrix}$$

- To get massive SM fermions



Electroweak precision & higgsless

- Higgsless: (weakly coupled) dual to technicolor theories

- Generically large S-parameter in technicolor

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

- S generically O(1) contrary to observations. In warped higgsless:

$$S \approx \frac{6\pi}{g^2 \log \frac{R'}{R}}, \quad T \approx 0$$

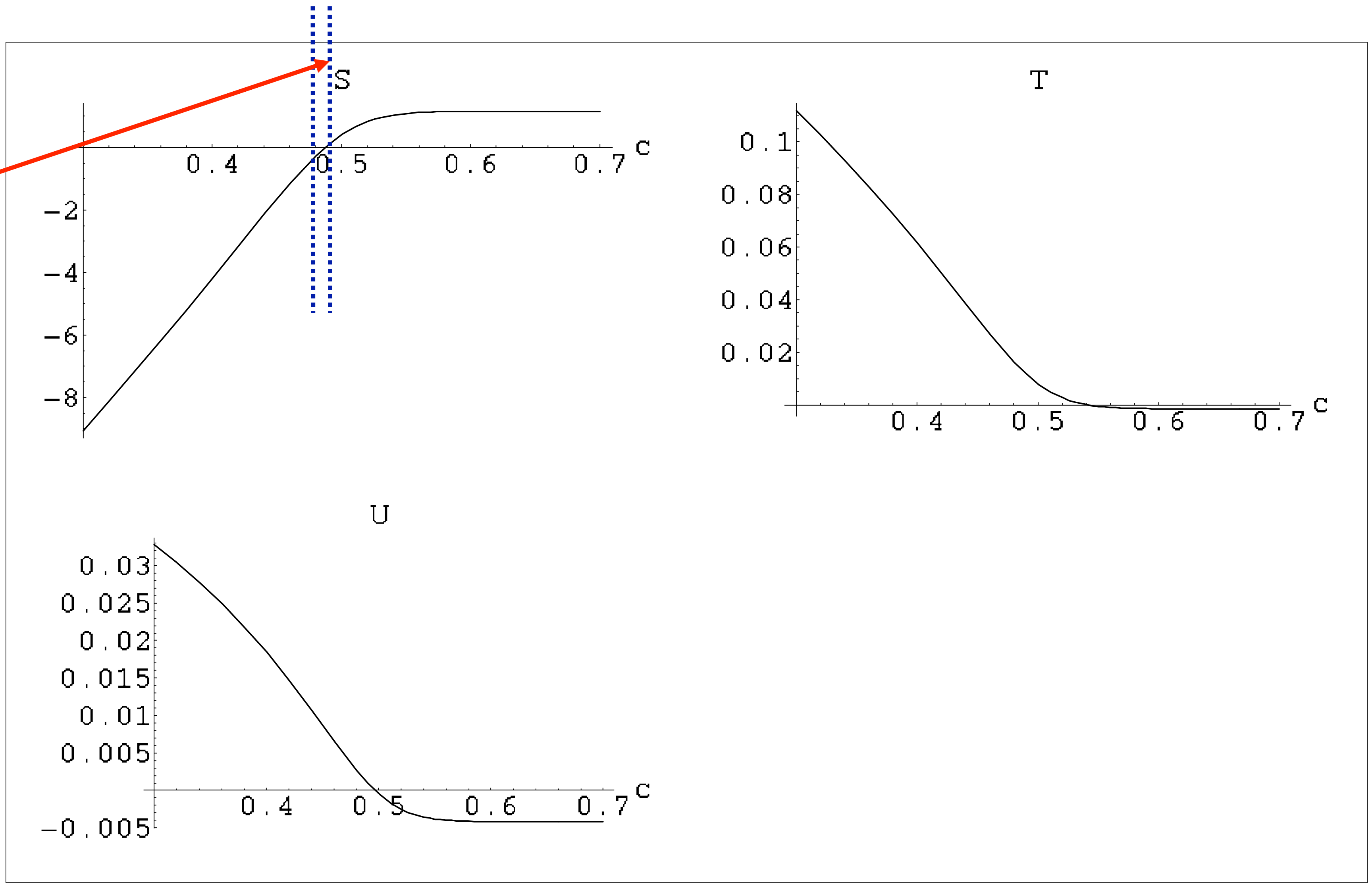
- However S model dependent, depends on how fermions are included in theory

Electroweak precision tests

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

$$S = \frac{2\pi}{g^2 \log \frac{R'}{R}} \left(1 + (2c-1) \log \frac{R'}{R}\right)$$

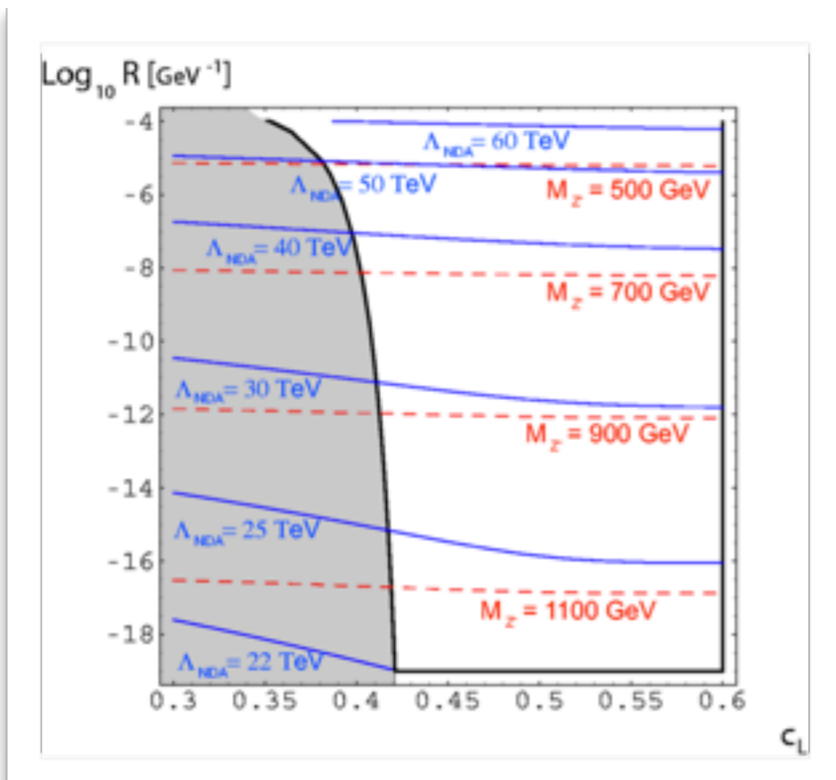
Need to be here % level tuning of c

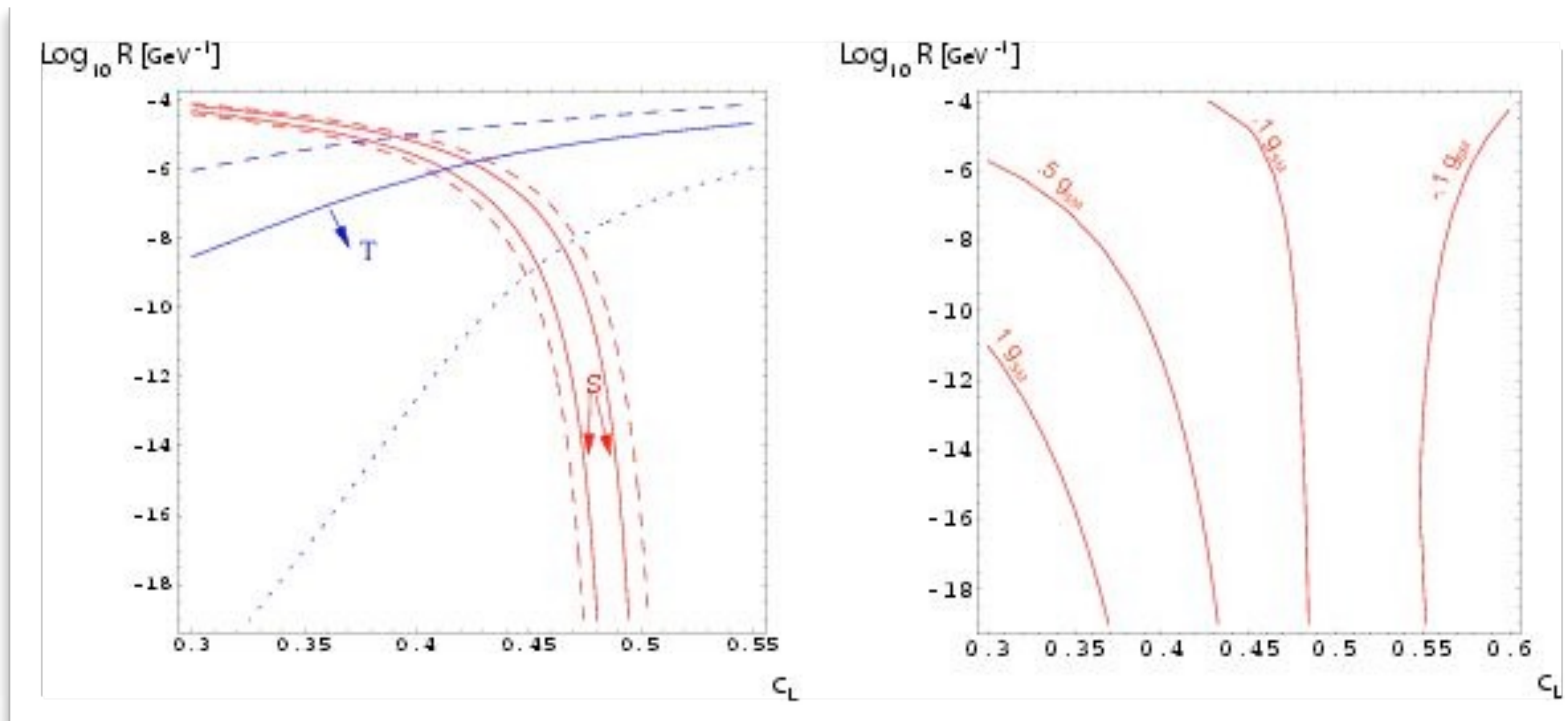


(Cacciapaglia, C.C.,Grojean, Terning '04)

Can find region where:

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

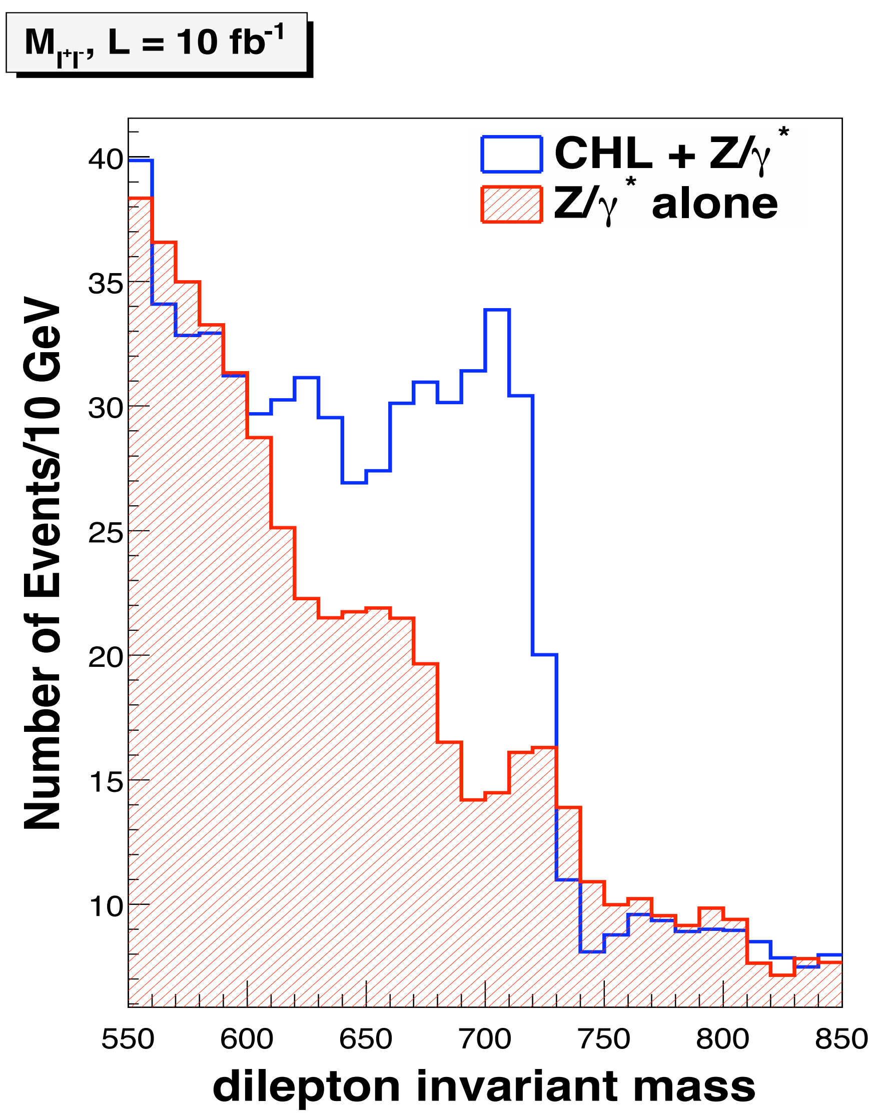




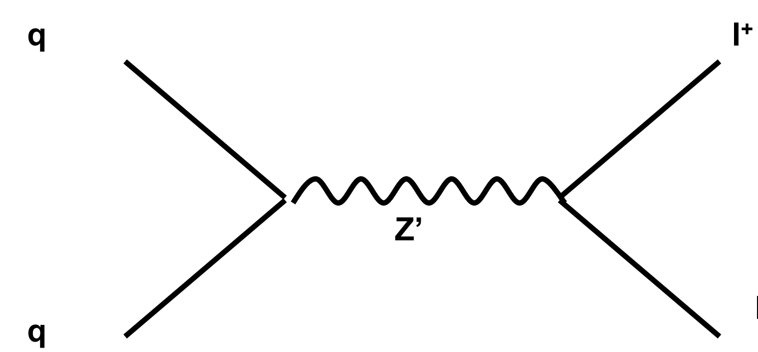
(Cacciapaglia, C.C.,Grojean, Terning '04)

•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



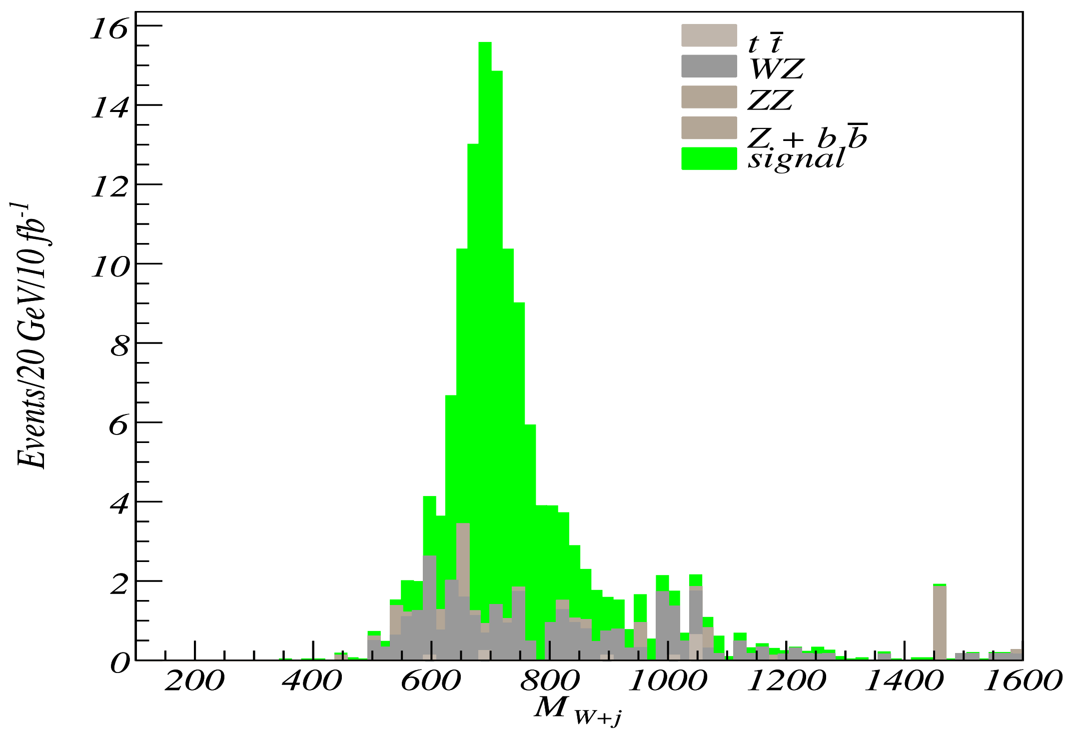
Process	σ(pb)	total # events	ϵ	total # : $(10\ \text{fb}^{-1}) \cdot \sigma \cdot \epsilon$	# mass peak
$\gamma^*/Z(\ell^+\ell^-)$	0.59 pb	2×10^4	0.184	941	375
CHL + $\gamma^*/Z(\ell^+\ell^-)$	0.61 pb	2×10^4	0.202	1049	493
Difference				106	118



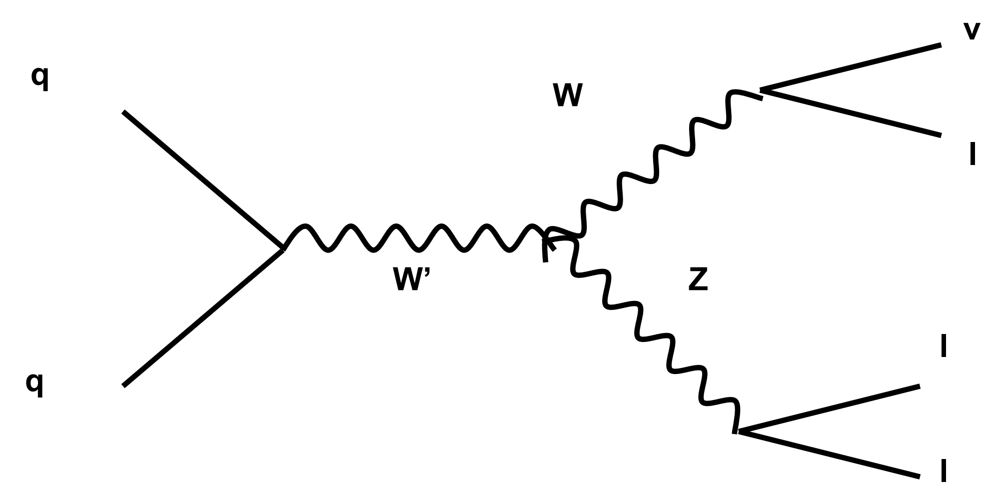
(Martin and Sanz '09)

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

Example W' DY at LHC for a sample point



84 signal vs. 17 background in 10 fb^{-1} data



(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}	$1.032\ g^2$
$g_{Z' q \bar{q}}$	$0.14\ g_{Z q \bar{q}}$	$g_{Z'WW}$	$0.059\ g\, c_W$
$g_{G' q \bar{q}}$	$0.22\ g_c$	$g_{ZW'W}$	$0.051\ g\, c_W$

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)

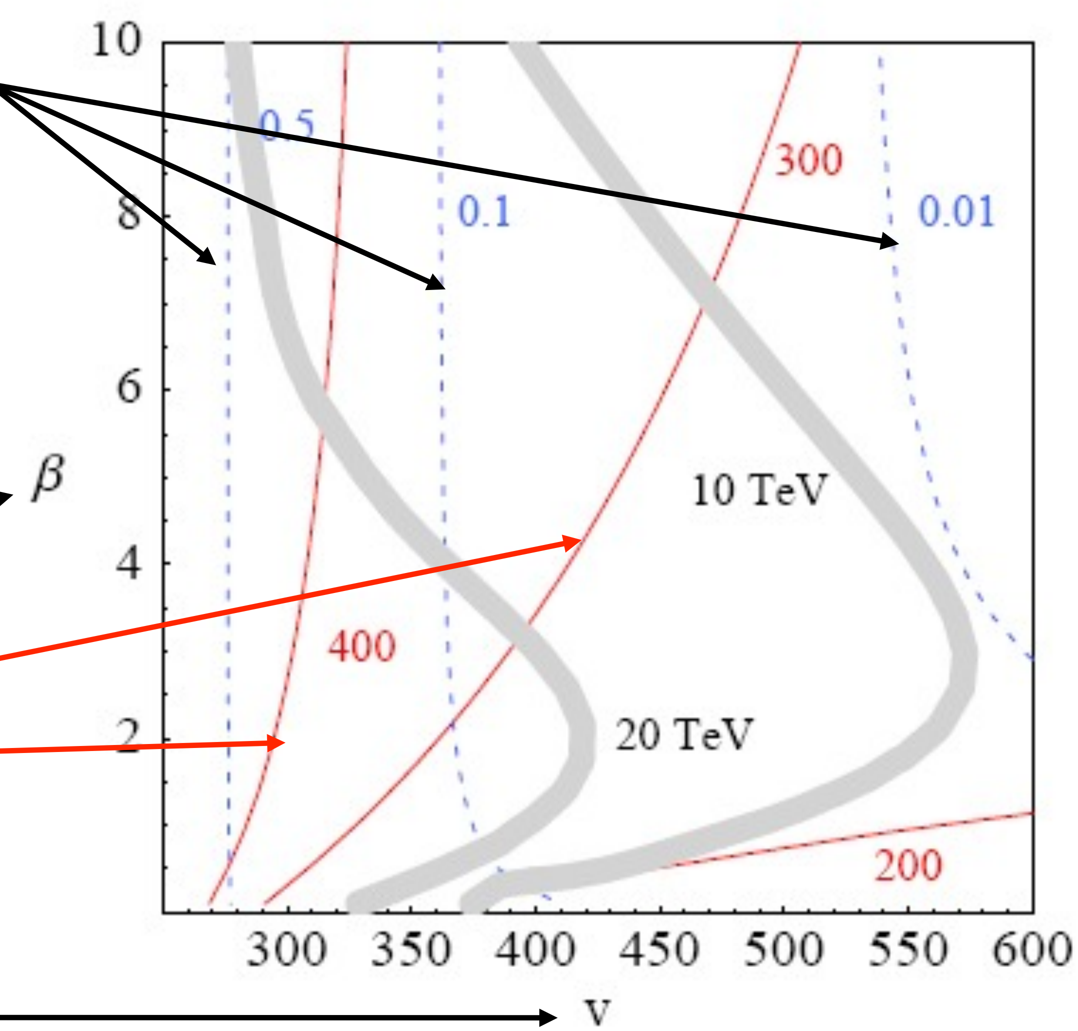
- Higgsless: crank up Higgs VEV to max, completely decouple Higgs
- Intermediate possibility: turn up Higgs VEV somewhat
- Coupling to gauge fields reduced, Higgs could be light

Higgs contribution to WW scat. vs SM

How strongly Higgs is peaked

R’-1

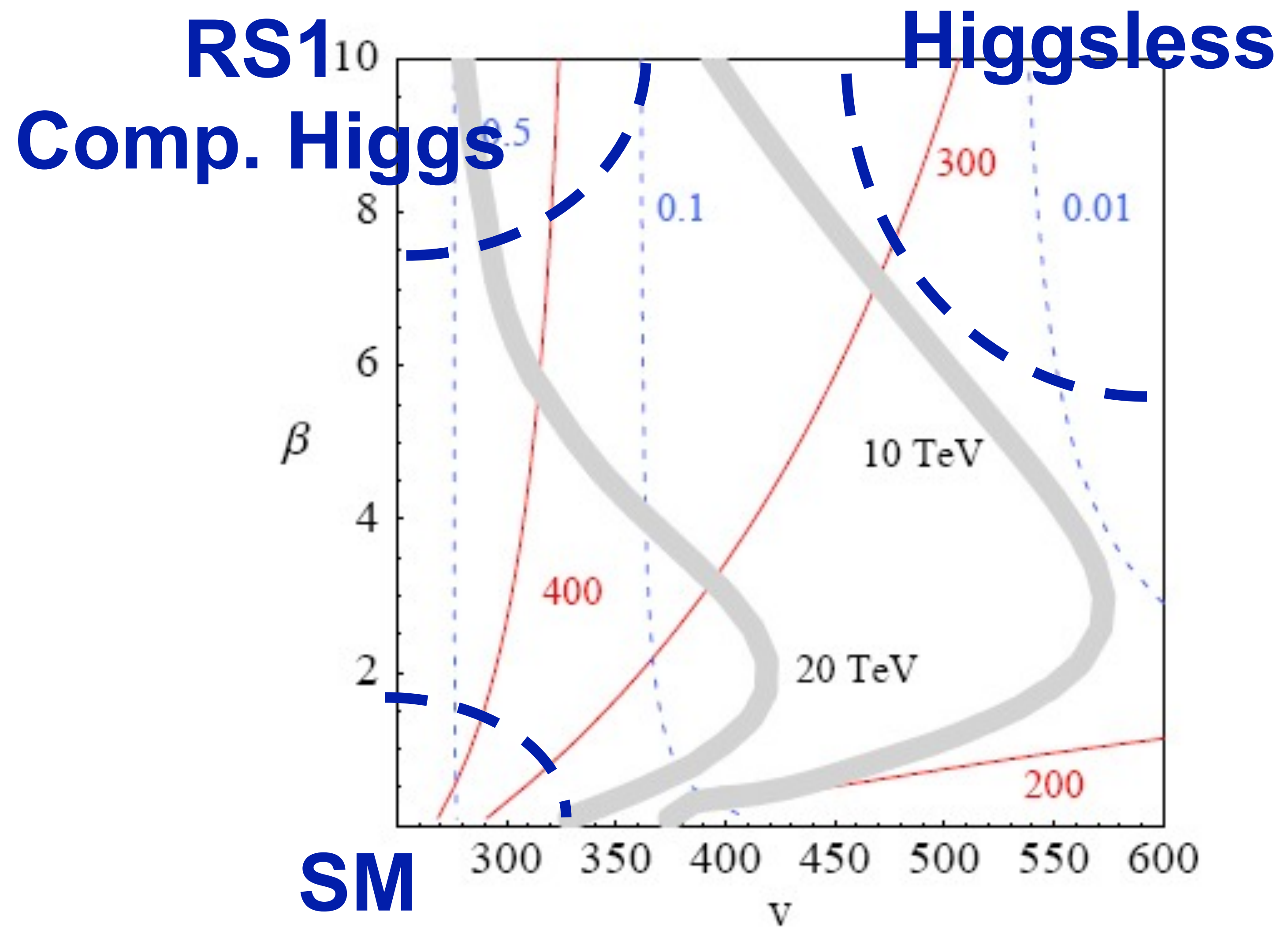
Effective VEV v



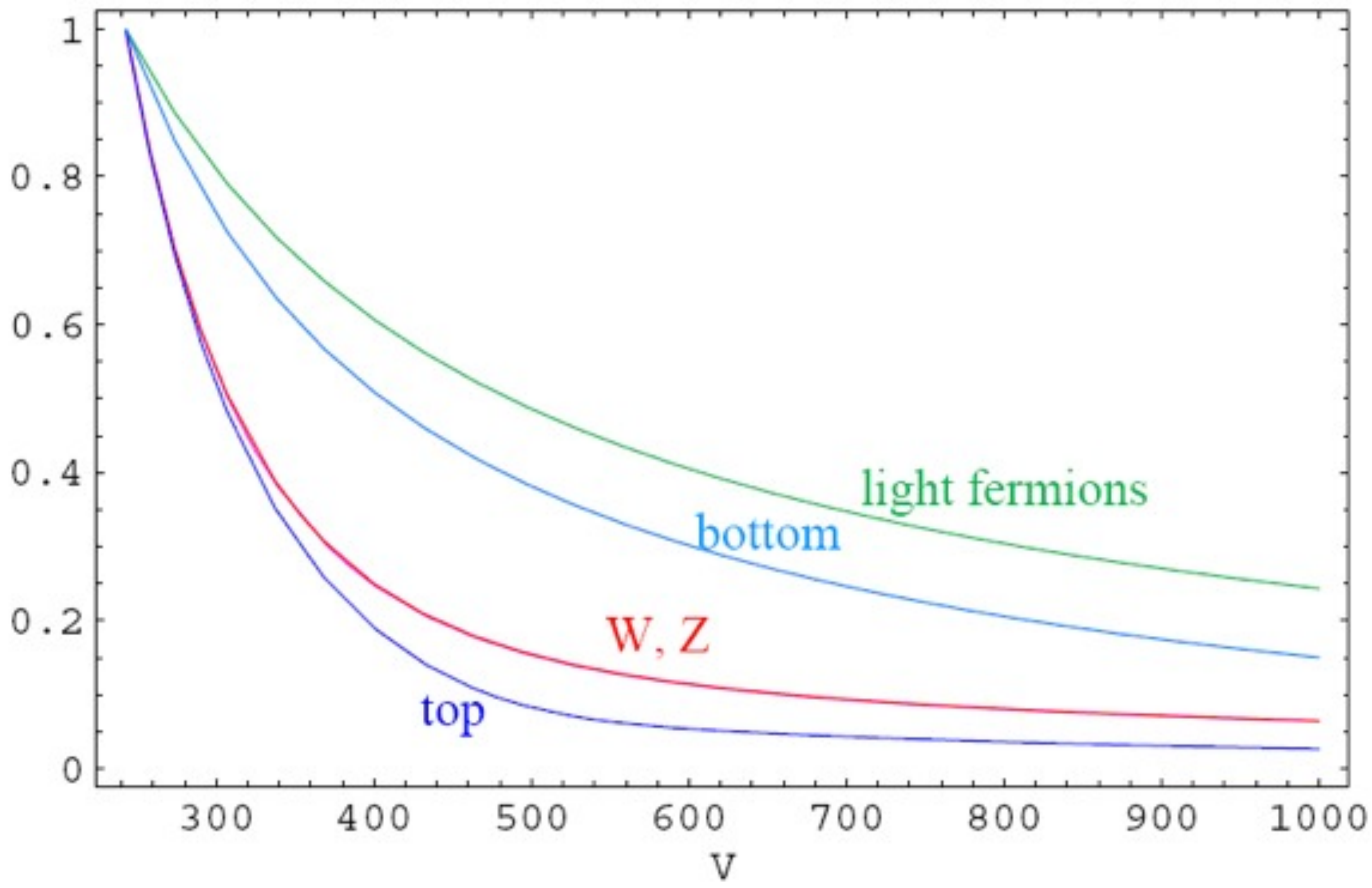
The Gaugephobic Higgs

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

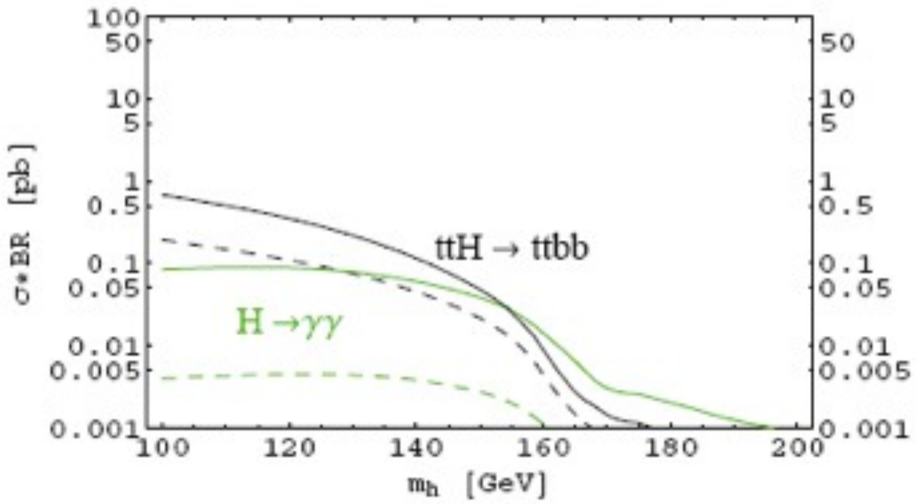
- Higgsless: crank up Higgs VEV to max, completely decouple Higgs
- Intermediate possibility: turn up Higgs VEV somewhat
- Coupling to gauge fields reduced, Higgs could be light

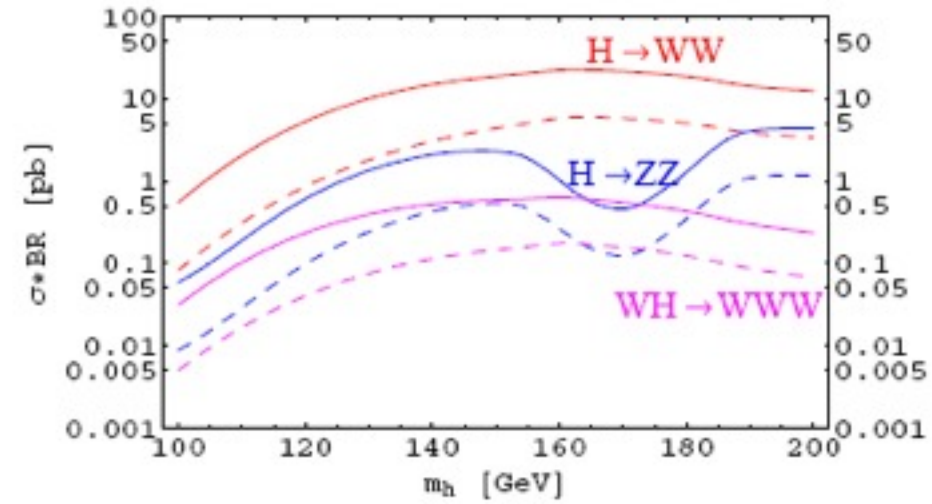


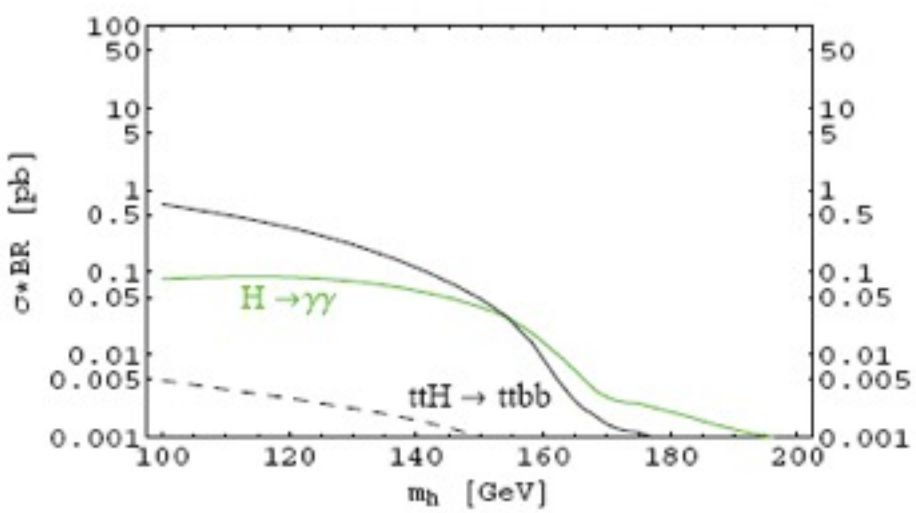
Suppression of the Higgs coupling:

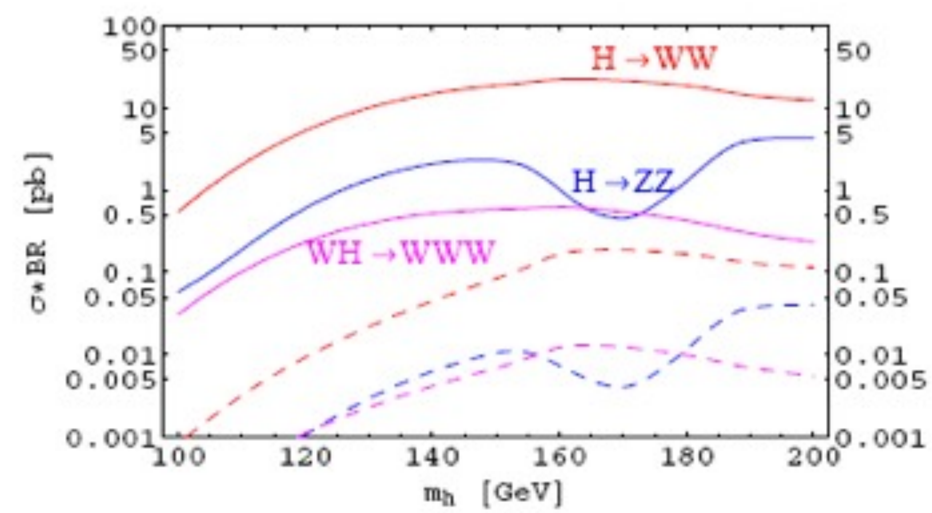


Higgs phenomenology









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	$t_L - t_R$

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

EWSB via monopole condensation

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

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

$$eg = 4\pi \frac{n}{2}$$

- 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

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

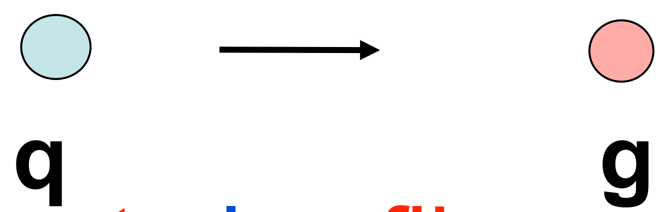
- Λ_{mag} is a dynamical of order few x 100 GeV

The Rubakov-Callan effect

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

- Angular mom. of EM. field: depends on direction from charge to pole

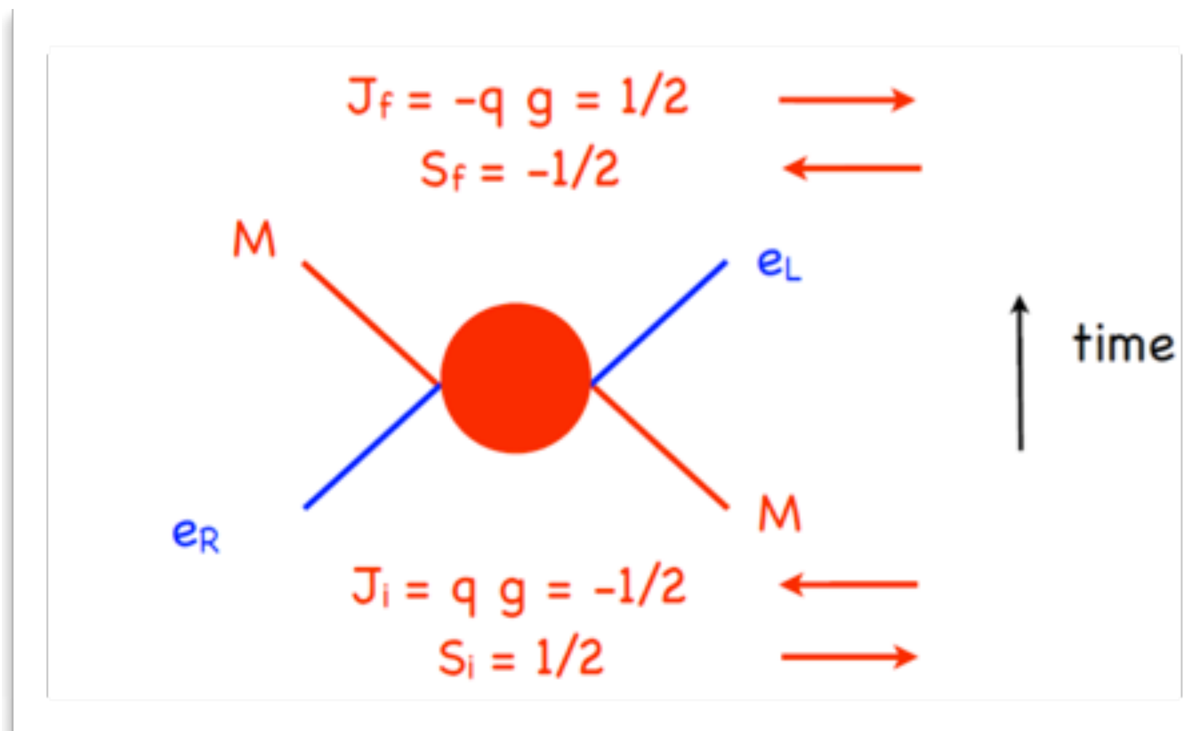
- In head-on scattering this direction changes, even though no force



- Spin of scattered fermion must also flip

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

$$\lambda^{(u)}_{ij}\, u^i_R N_L \left(u^j_L N_R\right)^\dagger$$



- 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, very naive estimate ~ pb **(A. Weiler)**

Summary

Main higgsless possibilities:

I. Weakly coupled

- New < TeV scale particle restores unitarity
- Example: warped higgless model
- Predicts W',Z' below TeV, sum rules
- To avoid EWP problem small SM fermion coupling, still testable at LHC with 10 fb^{-1}

II. Strongly coupled

- Unitarity not perturbatively restored
- Example: technicolor
- Interesting technicolor variant based on monopole condensation, expect lots of photons at LHC

The AdS/CFT picture for higgsless

Bulk of AdS	CFT
z (coord. in AdS)	Energy in CFT
UV brane	UV cutoff of CFT
IR brane	Spontaneous conformal sym br.
KK modes on IR	Composites of CFT
Modes on UV	Elementary fields
Gauge field in bulk	CFT has global sym.
Gauge sym. broken UV	Global sym. not gauged
Gauge sym. unbroken	Global sym weakly gauged
Higgs on IR brane	CFT produces comp. Higgs
BC breaking on IR	**Technicolor**