Electroweak Symmetry Breaking: To Higgs or not to Higgs

- Higgs mechanism. The Higgs as a UV moderator of EW interactions. Needs for New Physics beyond the Higgs.
- Review of possible scenarios :Gauge-Higgs Unification, Little Higgs, Composite Higgs, (5D) Higgsless models.

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The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive W, Z: 3 physical polarizations=eaten Goldstone bosons

$\Rrightarrow$ Where are these Goldstone's coming from? $\Lleftarrow$

common lore: from a scalar Higgs doublet

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

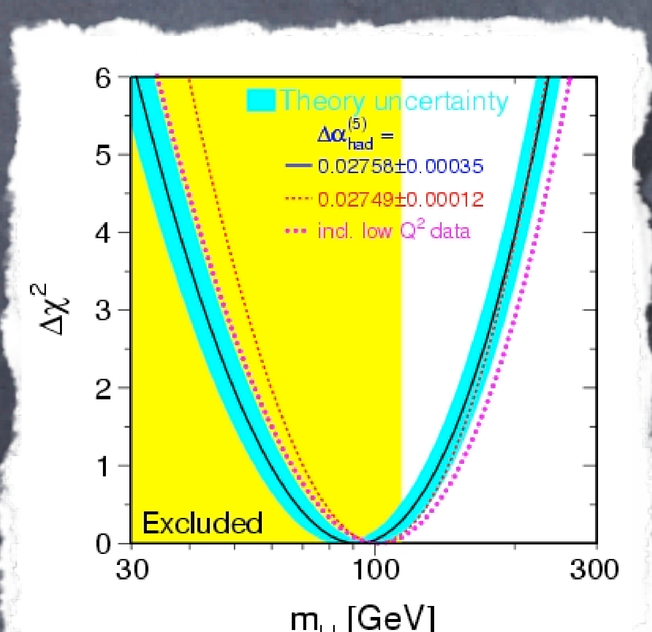
Higgs doublet = 4 real scalar fields

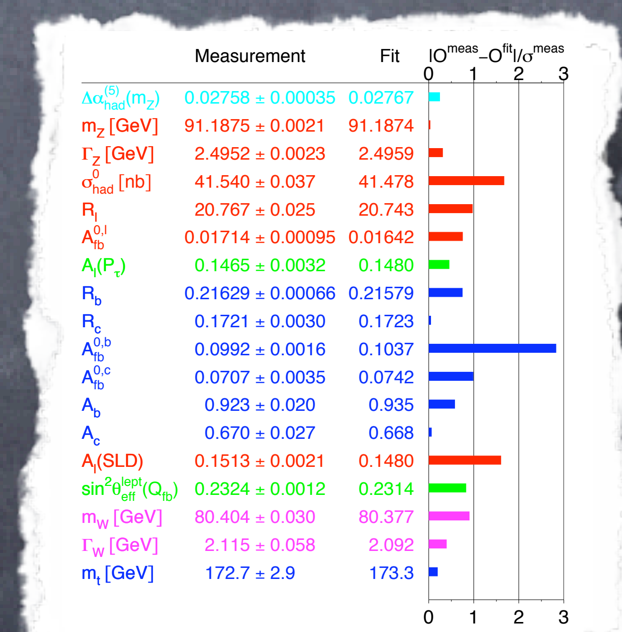
3 eaten Goldstone bosons

One physical degree of freedom the Higgs boson

Good agreement with EW data

(doublet ⇔ ρ=1)





	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ^0_{had} [nb]	41.540 ± 0.037	41.478	
R_l	20.767 ± 0.025	20.743	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1480	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.404 ± 0.030	80.377	
Γ_W [GeV]	2.115 ± 0.058	2.092	
m_t [GeV]	172.7 ± 2.9	173.3	

But the Higgs hasn't been seen yet...

other origins of the Goldstone's: condensate of techniquarks, A_5...

Which Higgs?

UnHiggs?

Private Higgs?

Little Higgs?

Gaugephobic Higgs?

Littlest Higgs?

Intermediate Higgs?

Slim Higgs?

Composite Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Twin Higgs?

Lone Higgs?

Gauge-Higgs?

Phantom Higgs?

Simplest Higgs?

Little Higgs

Little Higgs Models

[Arkani-Hamed et al. '02]

Higgs as a pseudo-Nambu-Goldstone boson

QCD: π^+, π^0 are Goldstone associated to $\frac{SU(2)_L \times SU(2)_R}{SU(2)_{\text{isospin}}}$

$\alpha_{em} \to 0, m_q \to 0$

LxR exact

$m_\pi = 0$

$\alpha_{em} \neq 0$

$m^2_{\pi^\pm} \approx \frac{\alpha_{em}}{4\pi} \Lambda^2_{QCD}$

EW pions

$\alpha_{top} \to 0, g, g' \to 0$

exact global sym.

$m_H = 0$

$\alpha_{top} \neq 0$

$m^2_H \approx \frac{\alpha_{top}}{4\pi} \Lambda^2_{\text{strong}}$

would require

$\Lambda_{\text{strong}} \sim 1 \text{ TeV}$

...too low !

Little Higgs = PNGB + Collective Breaking

$$m^2_H \approx \frac{\alpha_i \alpha_j}{(4\pi)^2} \Lambda^2_{\text{strong}}$$

Little Higgs = PNGB + Collective Breaking

Higgs $\in$ G/H

The coset structure is broken by 2 sets of interactions

$$\mathcal{L} = \mathcal{L}_{G/H} + g_1 \mathcal{L}_1 + g_2 \mathcal{L}_2$$

each interaction preserves a subset of the symmetry

Higgs remains an exact PNGB when either g_1 or g_2 is vanishing

littlest Higgs

SU(5)/SO(5)

24-10=14 PNGB

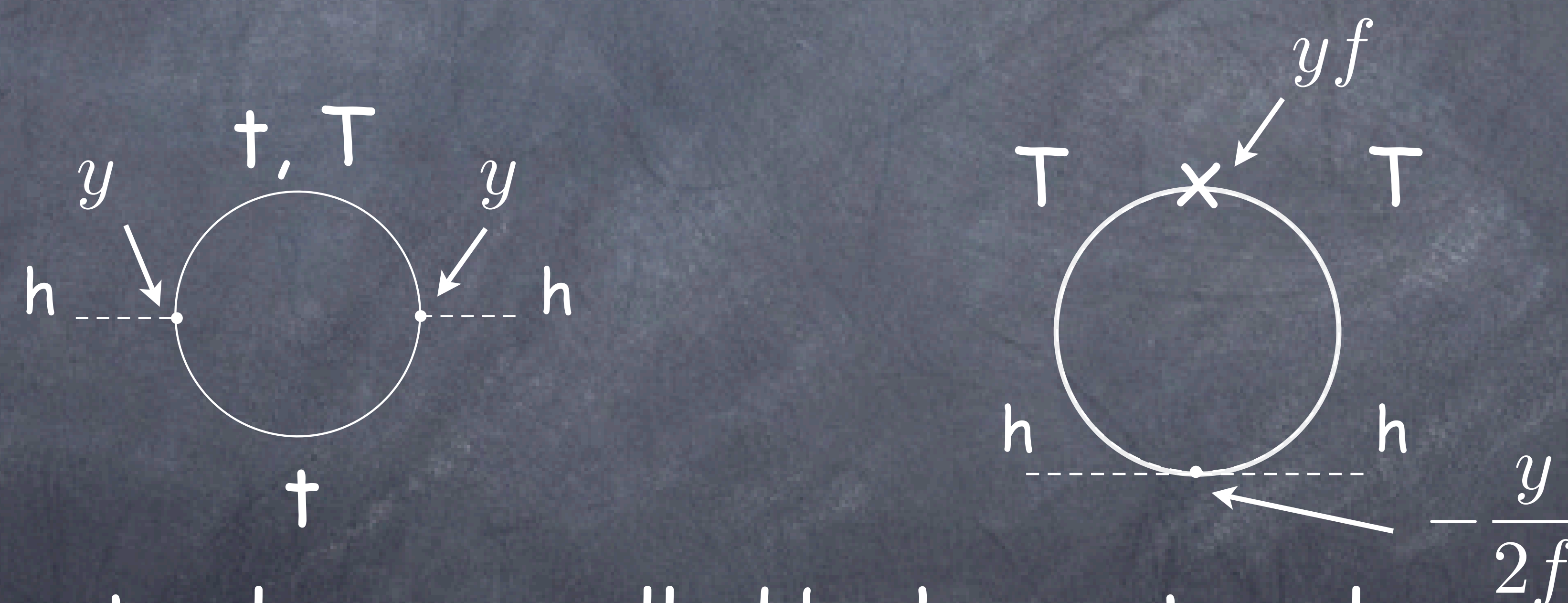
gauge $SU(2)_L \times SU(2)_R$ subgroup (broken to $SU(2)_D$)

14-3=11 PNGB left = 3_1, $2_{1/2}$, 1_0 Higgs?

if g_L or g_R vanishes, SU(3)/SU(2) global sym. and Higgs remains massless

LH = Λ^2 cancelled by same spin partner

gauge boson loops cancelled by heavy gauge boson loops

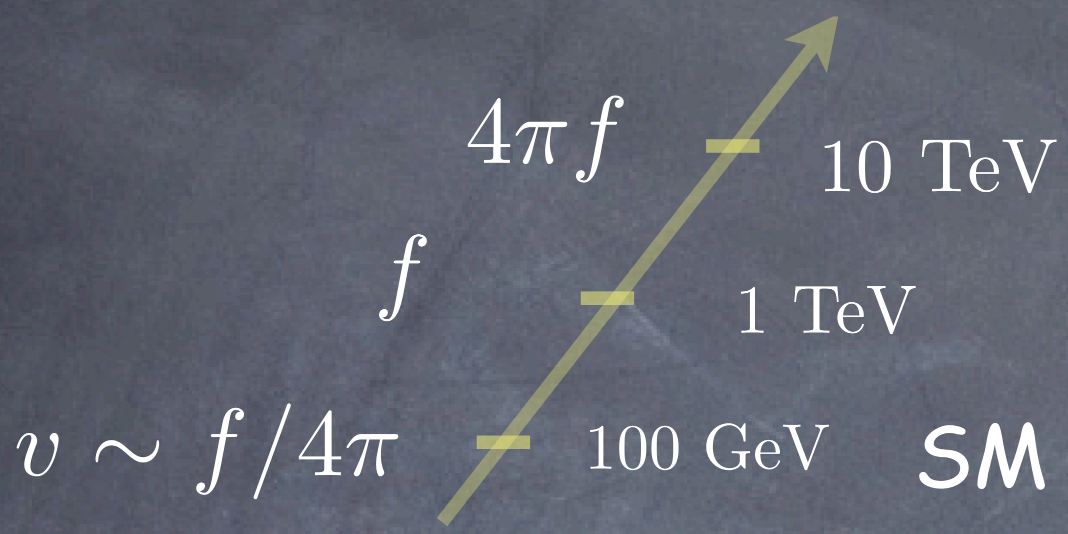


top loop cancelled by heavy toop loop

Relation among different couplings follows from global sym.

cancellation of div. occurs only at one-loop

Anatomy of Little Higgs models



UV completion

New particles (W', Z',top'...)

SM particles (Higgs,W,Z...)

cancellation of Higgs mass Λ^2 divergences

- W,Z loop cancelled by heavy W', Z' loops
- top loop cancelled by heavy top' loop
- Higgs loop cancelled by heavy scalar loops

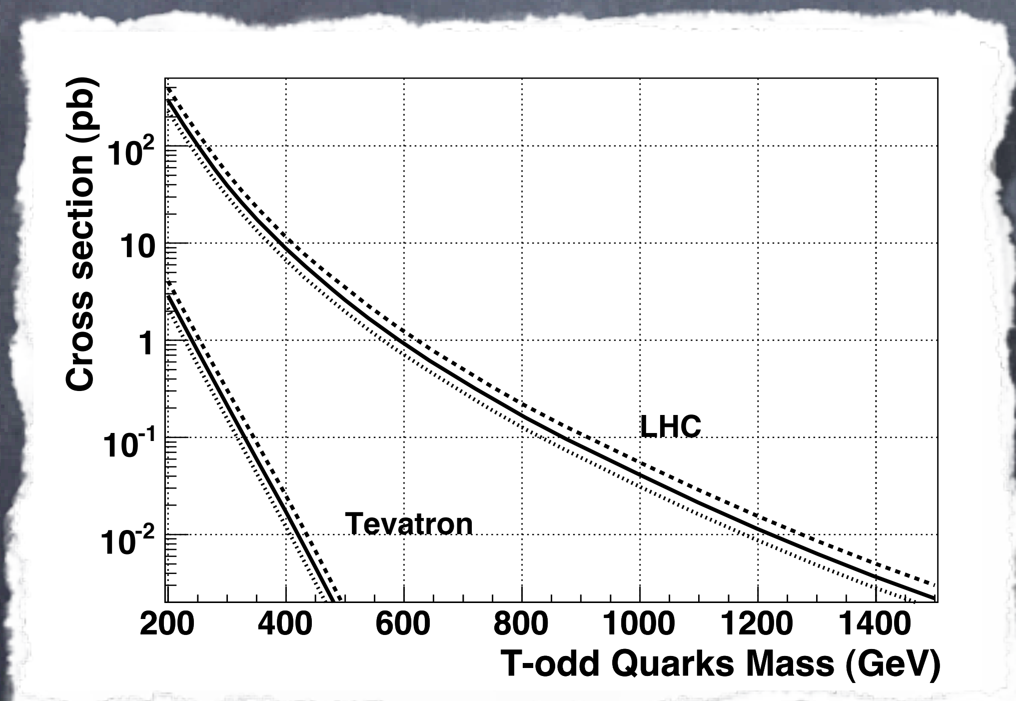
Little Higgs @ LHC

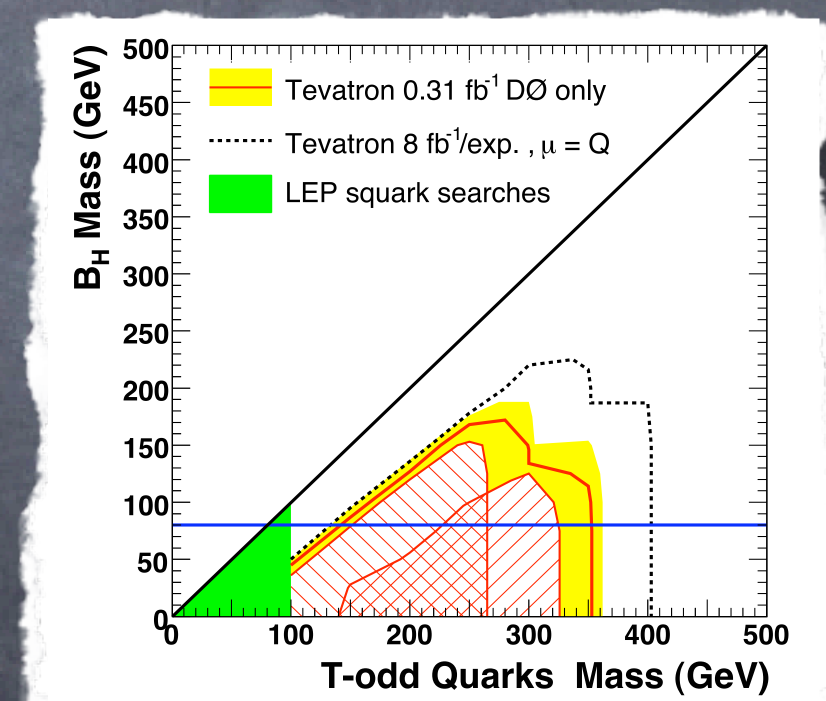
Confrontation of Little Higgs with EW data: needs for a T-parity

light particles = even $\Leftrightarrow$ heavy particles = odd

the Lightest T-odd Particle (usually partner of B_μ) is stable (DM?)

Little Higgs = jet+ missing E_T





[Carena, Hubisz, Perelstein, Verdier '07]

Interesting physics also associated to top partner

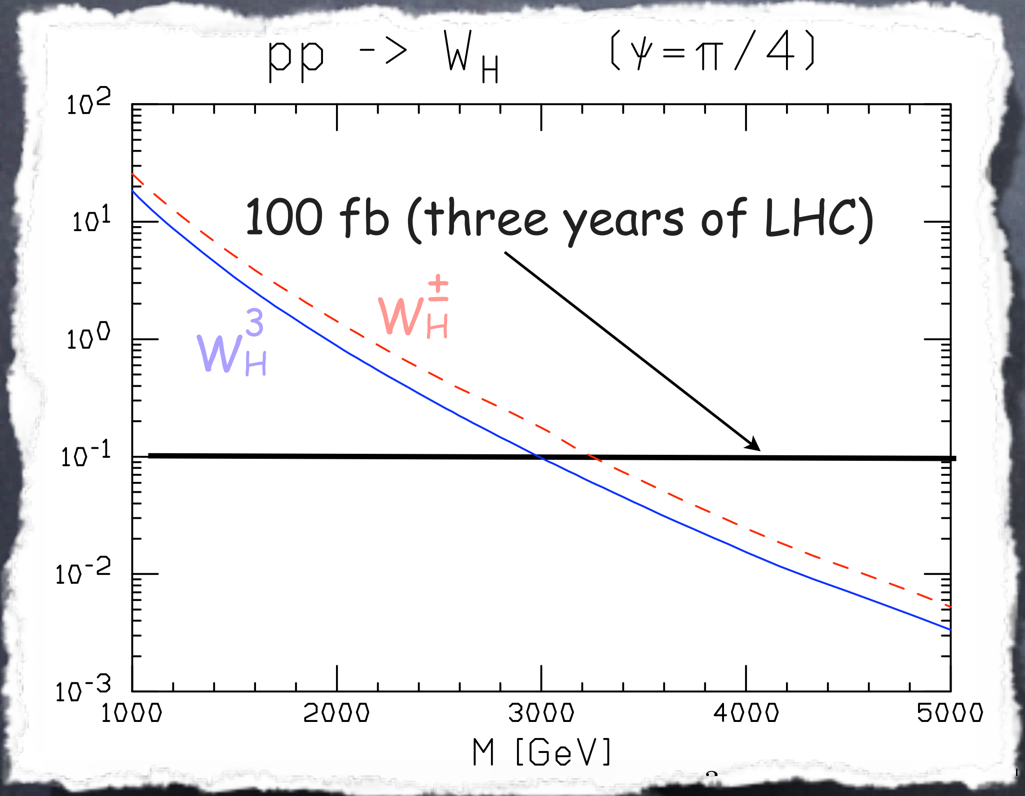
(pair production: $gg \to TT$)

Test of Little Higgs Structure

little Higgs models require a heavy top and heavy gauge bosons

to guarantee the cancellation of the Λ^2 divergences, the couplings of the new gauge bosons to the SM fermions is fixed

Burdman, Perelstein, Pierce '02



production cross section of heavy W_H and Z_H

Partial width of Z_H to fermions is proportional to $\cot^2\theta$

Partial width of Z_H into boson pairs (Zh and W^+W^-) is proportional to $\cot^2 2\theta$

(this follows from the particular coupling of the Higgs to the two SU(2) gauge groups)

$\cot\theta = g_1/g_2$ (two SU(2) gauge couplings)

Gauge-Higgs Unification

How to Get a Doublet from an Adjoint

Consider a 5D gauge symmetry G

$H \sim A_5^a$ will belong tho the adjoint rep. of G

The SM Higgs is not an adjoint of SU(2)xU(1), it is a doublet !

Consider a bigger gauge group

$$G \to SU(2)_l \times U(1)_y$$

Adj $\longrightarrow$ doublet + other rep.

SU(3)

$$\frac{1}{2}\begin{pmatrix} W_3 + W_8/\sqrt{3} & W_1 - iW_2 & W_4 - iW_5 \\ W_1 + iW_2 & -W_3 + W_8/\sqrt{3} & W_6 - iW_7 \\ W_4 + iW_5 & W_6 + iW_7 & -2W_8/\sqrt{3} \end{pmatrix}$$

SU(2)xU(1)

Adj

$2_{\sqrt{3}/2}$

Weak Mixing Angle

Manton '79
Fairlie '79

$$\delta_{U(1)} \begin{pmatrix} h_+ \\ h_0 \end{pmatrix} = \frac{3g}{2\sqrt{3}} \begin{pmatrix} h_+ \\ h_0 \end{pmatrix} = \frac{\sqrt{3}g}{2} \begin{pmatrix} h_+ \\ h_0 \end{pmatrix}$$

Proper U(1) normalization
(such that the doublet has a hypercharge 1/2)

$$g' = \sqrt{3}g \qquad U(1)_y = T_8/\sqrt{3}$$

$$\sin^2\theta_W = \frac{g'^2}{g^2+g'^2} = \frac{3g^2}{g^2+3g^2} = \frac{3}{4}$$

By embedding SU(2)xU(1) into a simple group, we got a prediction for the weak mixing angle

experimentally: $\sin^2\theta_W \approx 0.23$

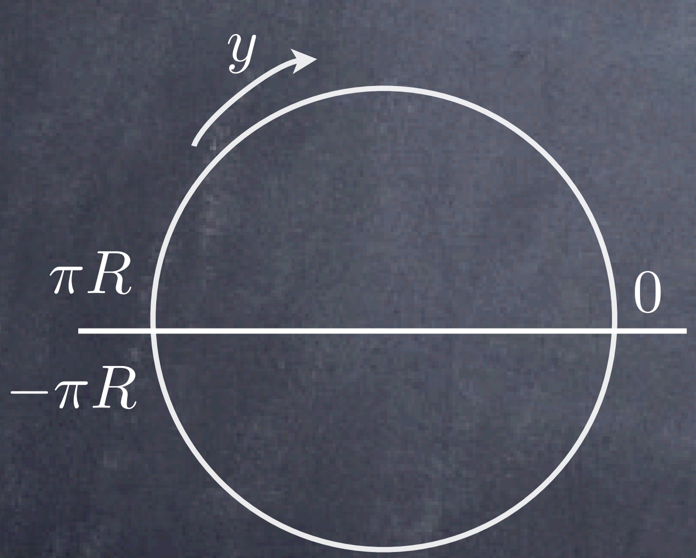
Towards a Complete Construction

so far we haven't broken any symmetry... we even enlarged the gauge group

We need to break G down to SU(2)xU(1)

we can achieve this breaking while compactifying the extra-dimension

Compactification on a Circle



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

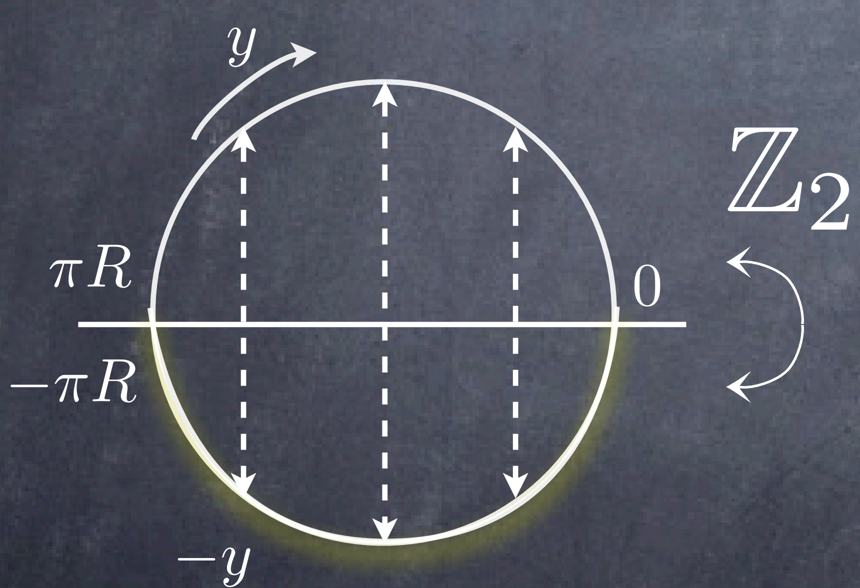
Towards a Complete Construction

so far we haven't broken any symmetry... we even enlarged the gauge group

We need to break G down to SU(2)xU(1)

we can achieve this breaking while compactifying the extra-dimension

Compactification on an Orbifold



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

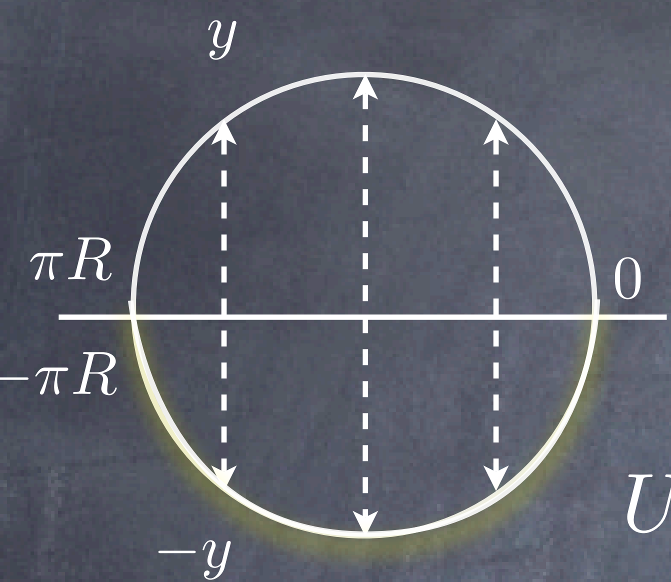
orbifold: $y \sim -y$

$$\phi(-y) = U\phi(y) \qquad U^2 = 1$$

U=+1: $\cos\left(\frac{ny}{R}\right)$ wavefunctions $\exists$ massless mode

U=-1: $\sin\left(\frac{ny}{R}\right)$ wavefunctions $\nexists$ massless mode

Orbifold breaking



orbifold $y \sim -y$

$\mathbb{Z}_2$

$$A_\mu(-y) = U A_\mu(y) U^\dagger$$

$$A_5(-y) = -U A_5(y) U^\dagger$$

$U^2 = 1$

Breaking of gauge group at the end-points of the orbifold $A_\mu(0) = U A_\mu(0) U^\dagger$

at the end-points, the surviving gauge group commute
with the orbifold projection matrix U

KK effective theory

zero mode: A_μ is independent of y

$$A_\mu = U A_\mu U^\dagger \qquad\qquad A_5 = -U A_5 U^\dagger$$

gauge symmetry breaking

(+ chiral fermions)

SU(3) → SU(2)xU(1) 5D Orbifold Breaking

$$U = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix} \qquad U \in SU(3) \qquad U^2 = 1$$

massless vectors A_μ

$$[A_\mu, U] = 0 \qquad A_\mu = \frac{1}{2}\begin{pmatrix} A^3_\mu + A^8/\sqrt{3} & A^1_\mu - iA^2_\mu & \\ A^1_\mu + iA^2_\mu & -A^3_\mu + A^8_\mu/\sqrt{3} & \\ & & -2A^8_\mu/\sqrt{3} \end{pmatrix} \qquad SU(2)\times U(1)$$

massless scalars A_5

$$\{A_5, U\} = 0 \qquad A_5 = \frac{1}{2}\begin{pmatrix} & & A^4_5 - iA^5_5 \\ & & A^6_5 - iA^7_5 \\ A^4_5 + iA^5_5 & A^6_5 + iA^7_5 & \end{pmatrix} \qquad \frac{SU(3)}{SU(2)\times U(1)}$$

Orbifold Projection as Boundary Conditions

$G \to H$ by orbifold projection

H subgroup

$A_\mu^H(-y) = A_\mu^H(y)$ which is equivalent to the BCs $\partial_5 A_\mu^H = 0$

$A_5^H(-y) = -A_5^H(y)$ at the fixed points $A_5^H = 0$

G/H coset

$A_\mu^{G/H}(-y) = -A_\mu^{G/H}(y)$ which is equivalent to the BCs $A_\mu^{G/H} = 0$

$A_5^{G/H}(-y) = A_5^{G/H}(y)$ at the fixed points $\partial_5 A_5^{G/H} = 0$

Wave-functions for flat space $Z_2 \times Z'_2$ orbifold

assuming Z and Z' commute

KK tower with a massless mode

(+,+) states: $\cos \frac{ny}{R} \Rrightarrow m_n = \frac{n}{R} \quad n = 0 \dots \infty$

(-,-) states: $\sin \frac{ny}{R} \Rrightarrow m_n = \frac{n}{R} \quad n = 1 \dots \infty$

(+,-) states: $\cos \frac{(2n+1)y}{2R} \Rrightarrow m_n = \frac{2n+1}{2R} \quad n = 0 \dots \infty$

(-,+) states: $\sin \frac{(2n+1)y}{2R} \Rrightarrow m_n = \frac{2n+1}{2R} \quad n = 0 \dots \infty$

Two examples

SU(3)

SU(2)xU(1) —— SU(2)xU(1)

0 πR

$(+,+)_\mu$, $(-,-)_5$: SU(2)xU(1)

$(-,-)_\mu$, $(+,+)_5$: SU(3)/SU(2)xU(1)

massless Higgs doublet

$SO(5)\times U(1)_X$

$SU(2)_L\times U(1)_Y$ —— $SO(4)\times U(1)_X$

0 πR

$(+,+)_\mu$, $(-,-)_5$: $SU(2)_L\times U(1)_Y$

$(-,-)_\mu$, $(+,+)_5$: SO(5)/SO(4)

massless Higgs doublet

$(-,+)_\mu$, $(+,-)_5$: $\dfrac{SO(4)\times U(1)_X}{SU(2)_L\times U(1)_Y}$

Residual Symmetry

$$\delta A^A_M = \partial_M \epsilon^A + g f^{ABC} A^B_M \epsilon^C$$

Gersdorff, Irges, Quiros '02

- In the bulk

higher dimensional gauge invariance forbids a mass term for A_5

- At the fixed points

$$G \to H \quad \begin{cases} \partial_5 A^H_\mu = 0 & A^H_5 = 0 & \partial_5 \epsilon^H = 0 \\ A^{G/H}_\mu = 0 & \partial_5 A^{G/H}_5 = 0 & \epsilon^{G/H} = 0 \end{cases}$$

(since $[H,H] \subset H$ $\quad [H, G/H] \subset G/H$, the only non-vanishing structure constants are f^{HHH}, $f^{G/H\, G/H\, H}$)

$$\delta A^H_\mu = \partial_\mu \epsilon^H + g f^{HHH} A^H_\mu \epsilon^H$$

$$\delta A^H_5 = 0$$

G/H acts non-linearly on the Higgs at the fixed points.
No local mass term allowed

$$\delta A^{G/H}_\mu = 0$$

$$\delta A^{G/H}_5 = \partial_5 \epsilon^{G/H} + g f^{G/H\, G/H\, H} A^{G/H}_5 \epsilon^H$$

Soft Breaking of Lorentz Invariance ?

- 5D $\Lleftarrow$ soft breaking

  no local (bulk or brane) mass counter-term

- 6D $\Lleftarrow$ not always soft breaking

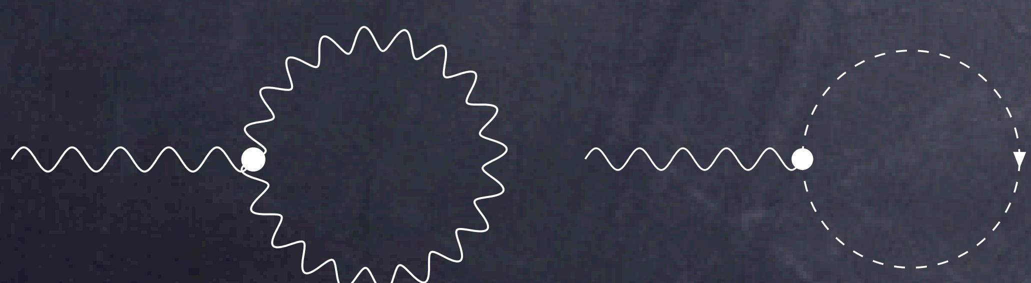
  F_{56} contains a mass term for the Higgs

  Tr (U F_{56}) is a local invariant operator at a fixed point

$$\mathrm{Tr}\ (UF_{56}(0)) \to \mathrm{Tr}\ (Ug(0)F_{56}(0)g^{-1}(0)) = \mathrm{Tr}\ (UF_{56}(0)g^{-1}(0)g(0)) = \mathrm{Tr}\ (UF_{56}(0))$$

↑ at the fixed points, U and g commute

Unless forbidden by a discrete symmetry,
we expect this operator to be generated at one loop



For Z_2 or $Z_2 \times Z_2$ orbifolds can define a parity that forbids the tadpole

For Z_4 orbifold, no such symmetry

a Λ^2 tadpole is generated at one loop

Experimental Signatures

the collider signals haven't been studied in details
(lack of fully realistic models?)

the main predictions of these models are

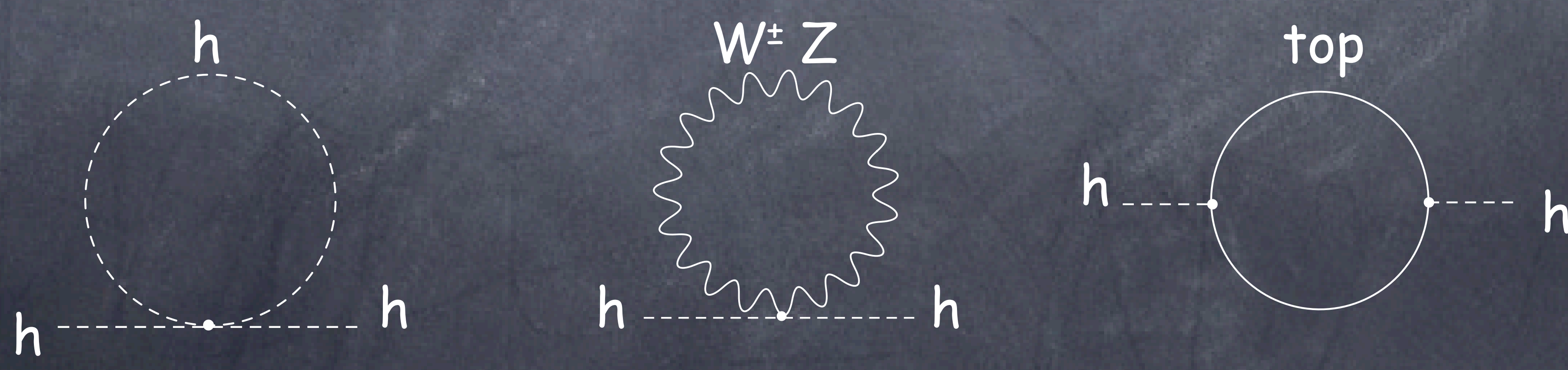
- KK excitations of W,Z around 500 GeV ~ 1 TeV
- KK excitations of G/H: gauge bosons with the quantum numbers of the Higgs doublets
- extra fermions (to cancel the top loop quadratic divergence)

Little Higgs, gauge-Higgs unification:
two concrete classes of models with

new particles/symmetries that populate the TeV scale
to stabilize the EW scale and suppress dangerous Λ^2 quantum corrections
to the Higgs mass

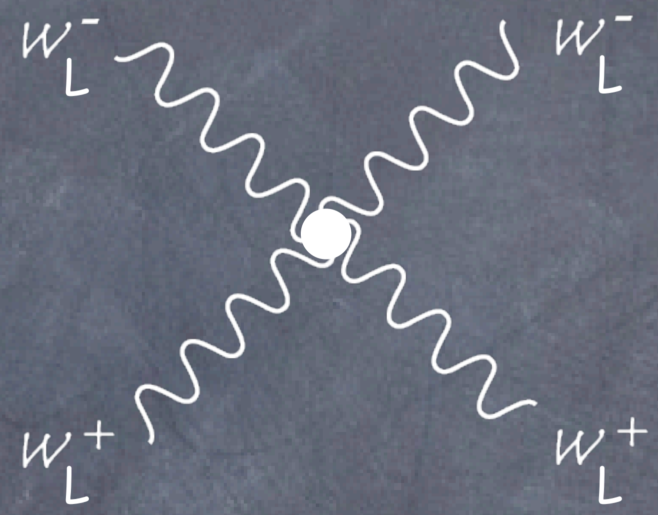
Models designed to address the question:

what is canceling the infamous divergent diagrams?



But this is assuming that we already know the answer to the central question of EW symmetry breaking

what is unitarizing the WW scattering amplitude?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^2 \quad \Rightarrow \quad \mathcal{A} \text{ finite}$$

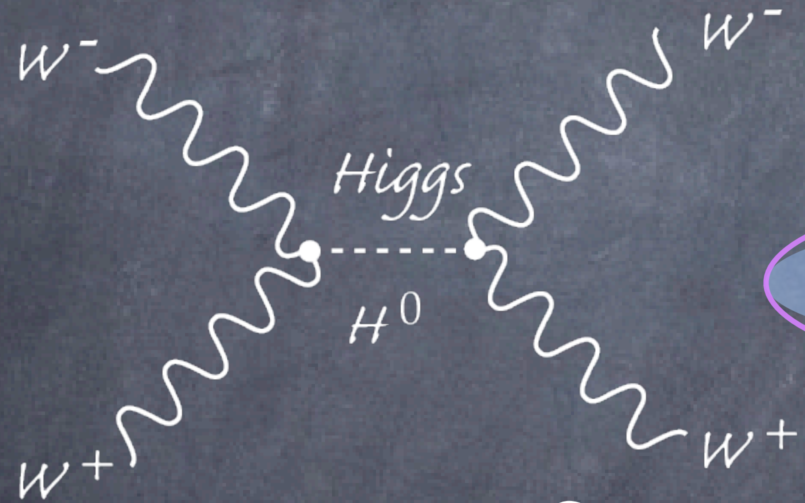
other way to unitarize the WW amplitude:

Higgsless models & composite Higgs

What is the mechanism of EWSB?

what is unitarizing the WW scattering amplitude?

Weakly coupled models

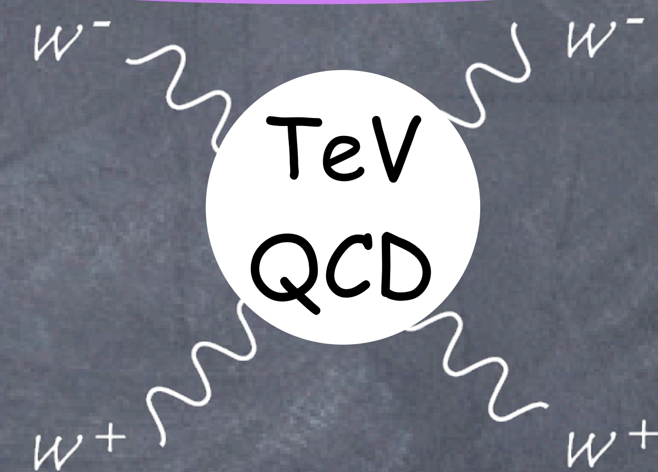


prototype: Susy

susy partners ~ 100 GeV

other ways?

Strongly coupled models



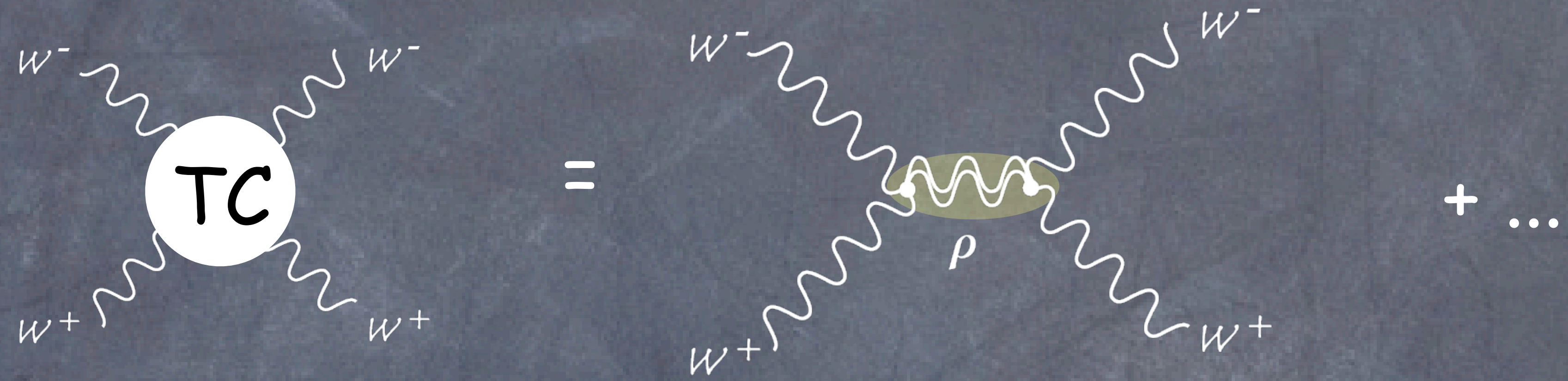
prototype: Technicolor

rho meson ~ 1 TeV

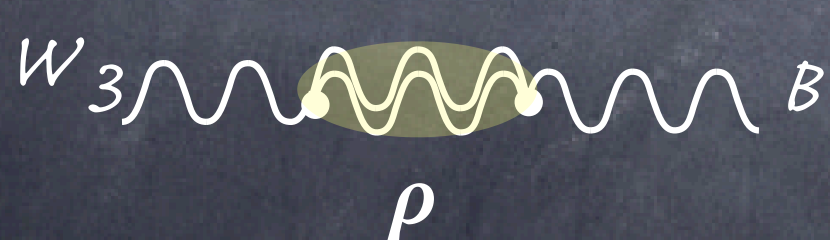
Strongly coupled models

a phenomenological challenge: how to evade EW precision data

The resonance that unitarizes the WW scattering amplitudes



generates a tree-level effect on the SM gauge bosons self-energy



$\hat{S}$ parameter of order m_W^2/m_ρ^2

In conflict with EW precision data from LEP

(exp: $|\hat{S}| < 10^{-3}$ @ 95% CL)

a theoretical challenge: need to develop tools to do computation

Back to “Technicolor” from Xdims

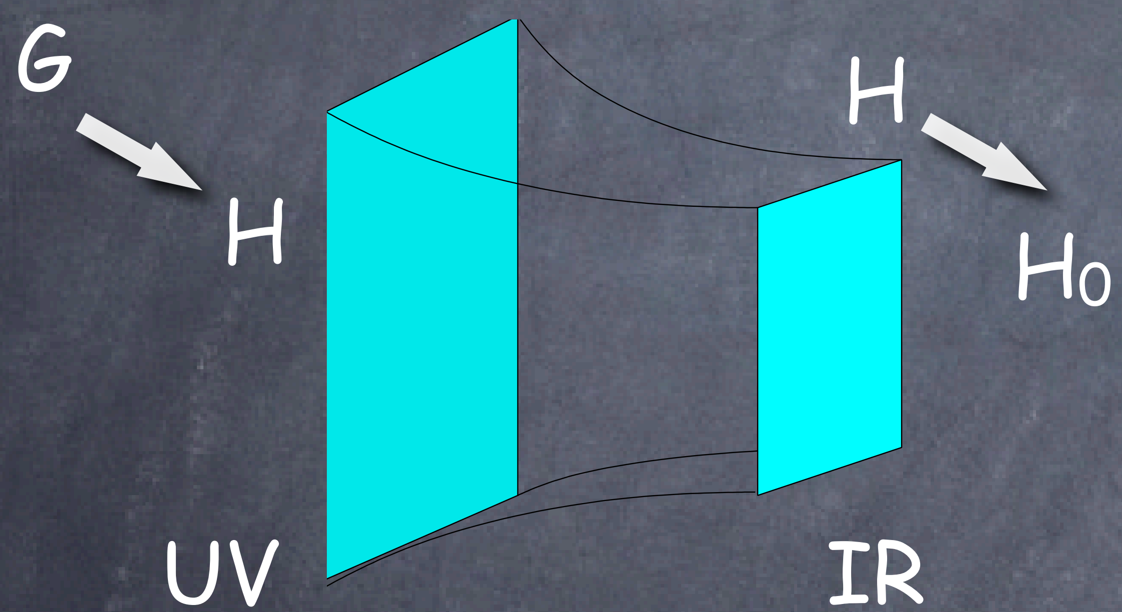
“AdS/CFT” correspondence for model-builder

Warped gravity with fermions and gauge field in the bulk and Higgs on the brane ⟺ Strongly coupled theory with slowly-running couplings in 4D

$$A_5 \to A_5 + \partial_5 \epsilon$$

$$h \to h + a$$

pseudo-Goldstone of a strong force



5D	4D
KK modes	vector resonances (ρ mesons in QCD)
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

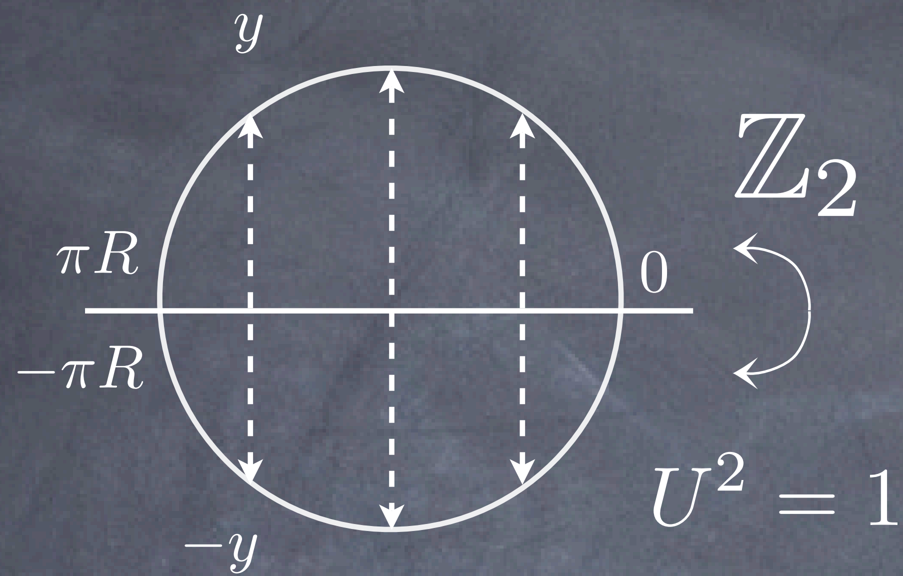
Advantages

- hierarchy problem addressed + gauge coupling unification
- weakly coupled description ➡ calculable models
- new approach to fermion embedding and flavor problem

Higgsless Models

Higgsless Approach

Csaki, Grojean, Murayama, Pilo, Terning '03
Csaki, Grojean, Pilo, Terning '03



Gauge symmetry breaking

In the gauge-Higgs unification models, we have been breaking bigger gauge groups down to SU(2)xU(1) by orbifold.

Why can't we break directly SU(2)xU(1) to $U(1)_{em}$ by orbifold?

Higgsless Models

mass without a Higgs

$$m^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2$$

momentum along extra dimensions ~ 4D mass

quantum mechanics in a box

⇓

boundary conditions generate a transverse momentum

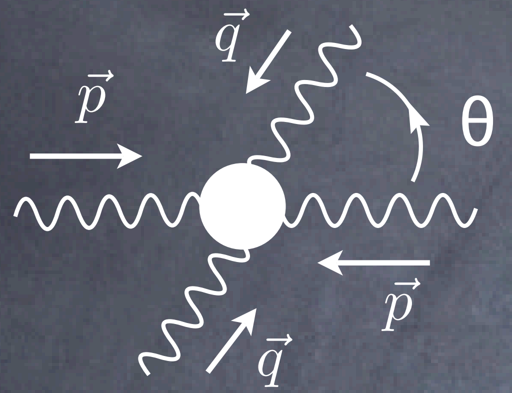
Is it better to generate a transverse momentum than introducing by hand a symmetry breaking mass for the gauge fields?

ie how is unitarity restored without a Higgs field?

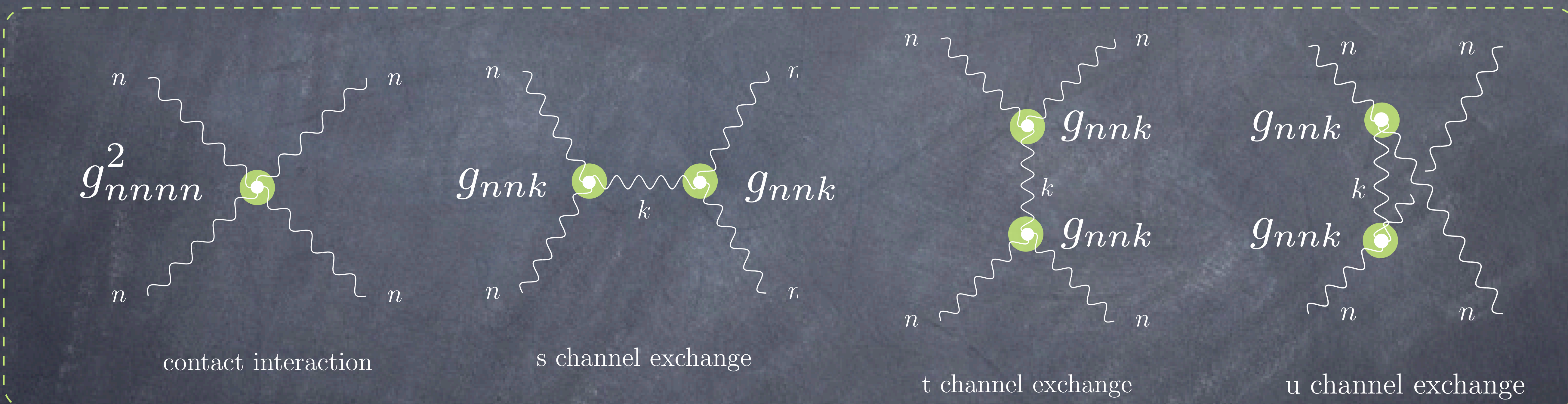
Unitarization of (Elastic) Scattering Amplitude

Same KK mode
'in' and 'out'

$$\epsilon^\mu_\perp = \left(\frac{|\vec{p}|}{M}, \frac{E\ \vec{p}}{M\ |\vec{p}|}\right)$$



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



$$\mathcal{A}^{(4)} = i \left(g^2_{nnnn} - \sum_k g^2_{nnk} \right) \left(f^{abe} f^{cde} (3 + 6c_\theta - c^2_\theta) + 2(3 - c^2_\theta) f^{ace} f^{bde} \right)$$

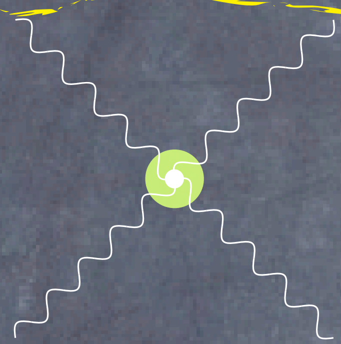
$$\mathcal{A}^{(2)} = i \left(4g^2_{nnnn} - 3 \sum_k g^2_{nnk} \frac{M^2_k}{M^2_n} \right) \left(f^{ace} f^{bde} - s^2_{\theta/2} f^{abe} f^{cde} \right)$$

KK Sum Rules

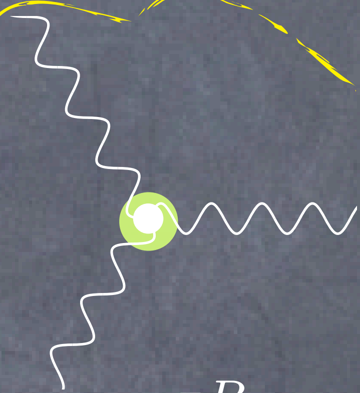
Csaki, Grojean, Murayama, Pilo, Terning '03

$$\mathcal{A}^{(4)} \propto g_{nnnn}^2 - \sum_k g_{nnk}^2 \qquad \mathcal{A}^{(2)} \propto 4g_{nnnn}^2 - 3\sum_k g_{nnk}^2 \frac{M_k^2}{M_n^2}$$

In a KK theory, the effective couplings are given by overlap integrals of the wavefunctions



$$g_{mnpq}^2 = g_{5D}^2 \int_0^{\pi R} dy\, f_m(y) f_n(y) f_p(y) f_q(y)$$



$$g_{mnp} = g_{5D} \int_0^{\pi R} dy\, f_m(y) f_n(y) f_p(y)$$

E^4 Sum Rule

$$g_{nnnn}^2 - \sum_k g_{nnk}^2 = g_{5D}^2 \int_0^{\pi R} dy\, f_n^4(y) - g_{5D}^2 \int_0^{\pi R} dy \int_0^{\pi R} dz\, f_n^2(y) f_n^2(z) \sum_k f_k(y) f_k(z) = 0$$

$$\sum_k f_k(y) f_k(z) = \delta(y-z)$$

Completness of KK modes

$$\mathcal{A}^{(4)} = 0$$

Warped Higgsless Model

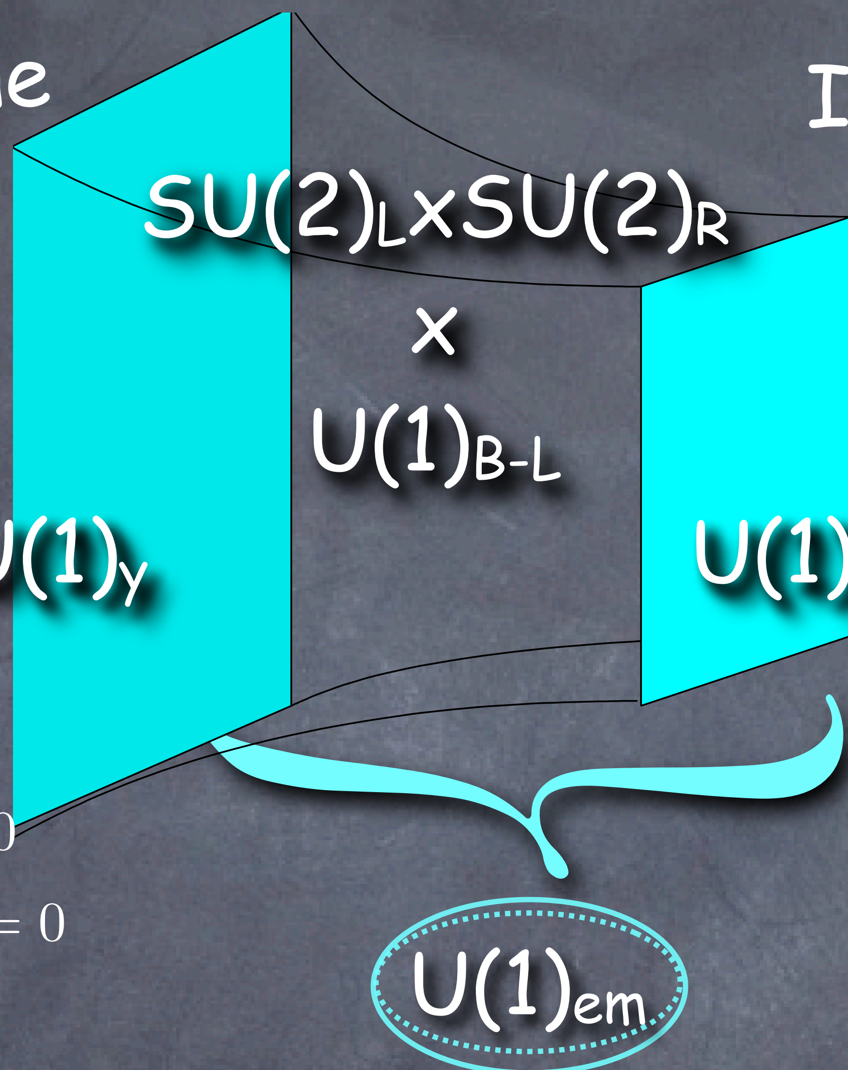
Csaki, Grojean, Pilo, Terning '03

UV brane

z = R_{UV} ~ $1/M_{Pl}$

IR brane

z = R_{IR} ~ 1/TeV



$SU(2)_L \times U(1)_Y$

$U(1)_{B-L} \times SU(2)_D$

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

$$\Omega = \frac{R_{IR}}{R_{UV}} \approx 10^{16}\ \mathrm{GeV}$$

$$A_\mu^{R\,\pm} = 0$$
$$g_5' B_\mu - g_5 A_\mu^{R\,3} = 0$$
$$\partial_5 (g_5 B_\mu + g_5' A_\mu^{R\,3}) = 0$$

$$A_\mu^{L\,a} - A_\mu^{R\,a} = 0$$
$$\partial_5 (A_\mu^{L\,a} + A_\mu^{R\,a}) = 0$$

BCs kill all A_5 massless modes: no 4D scalar mode in the spectrum

"light" mode:

$$M_W^2 = \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})} \qquad M_Z^2 \sim \frac{g_5^2 + 2g_5'^2}{g_5^2 + g'^2} \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

log suppression

KK tower:

$$M_{KK}^2 = \frac{\text{cst of order unity}}{R_{IR}^2}$$

Postponing Pert. Unitarity Breakdown

Is it a counter-example of the theorem by Cornwall et al.?

i.e. can we unitarize the theory without scalar field?

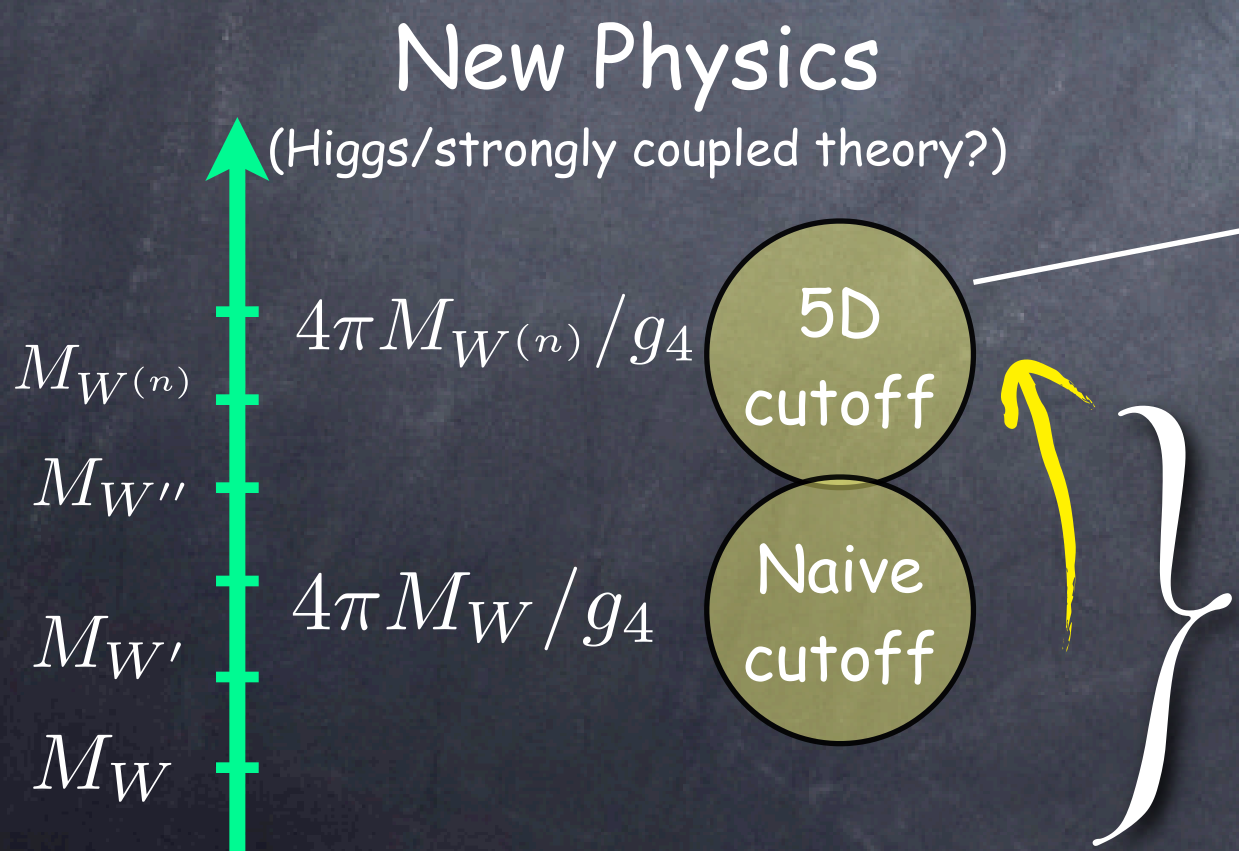
No!

$$g^2_{nnnn} \overset{E^4}{=} \sum_k g^2_{nnk} \overset{E^2}{=} \sum g^2_{nnk} \frac{3M_k^2}{4M_n^2}$$

the sum rules cannot be satisfied with a finite number of KK modes

(to unitarize the scattering of massive KK modes, you always need heavier KK states)

Pushing the need for a scalar to higher scale



With a finite number of KK modes

not directly set by the weak scale

flat space

$$\Lambda_{5D} = 24\pi^3/g_5^2 = (3\pi/g_4)\,\Lambda_{4D}$$

$$\left(g_4 = g_5/\sqrt{2\pi R} \;\; \& \;\; M_W = 1/R \right)$$

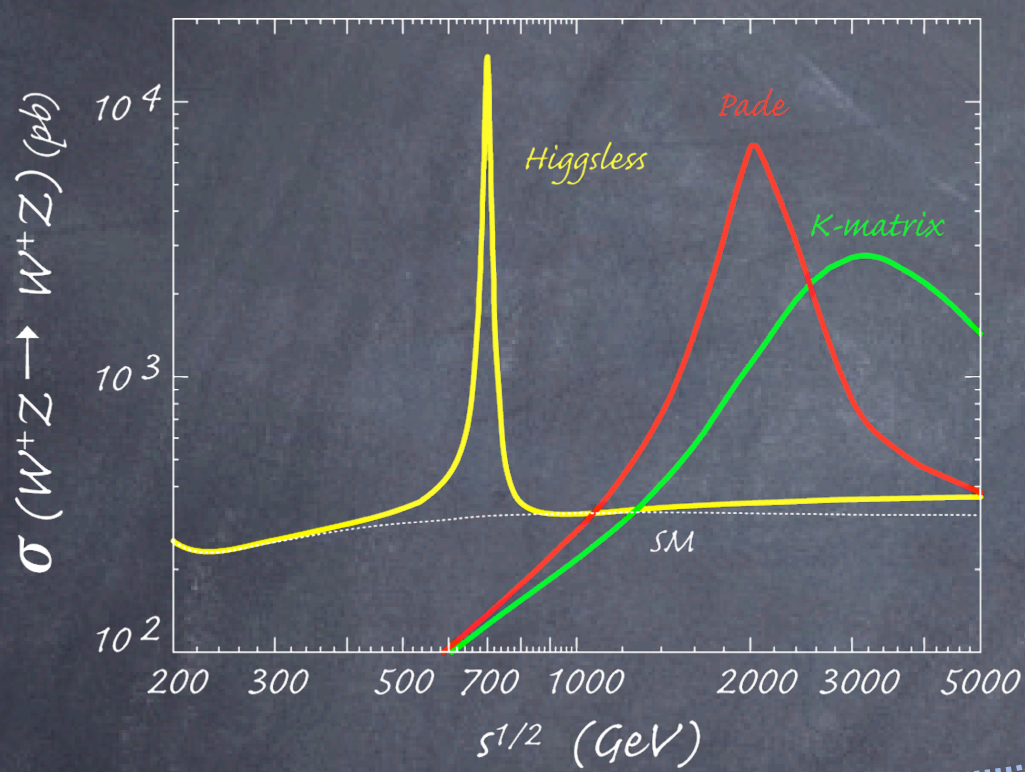
a factor 15 higher than the naive 4D cutoff thanks to the non-trivial KK dynamics

Collider Signatures

Birkedal, Matchev, Perelstein '05
He et al. '07

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

WZ elastic cross section

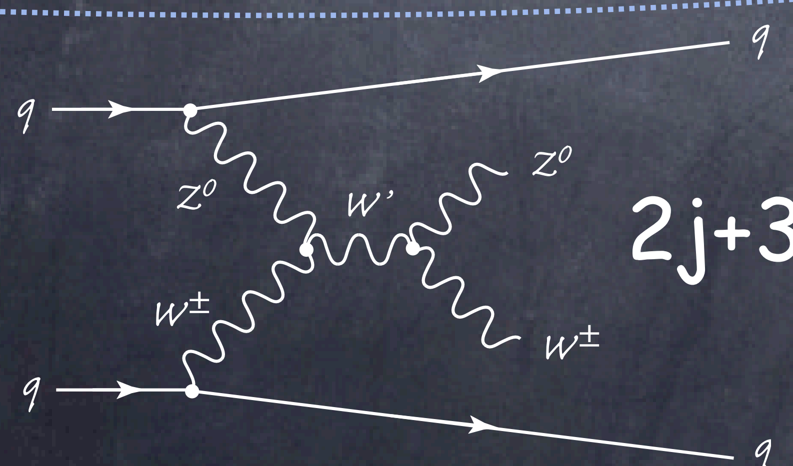


$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance

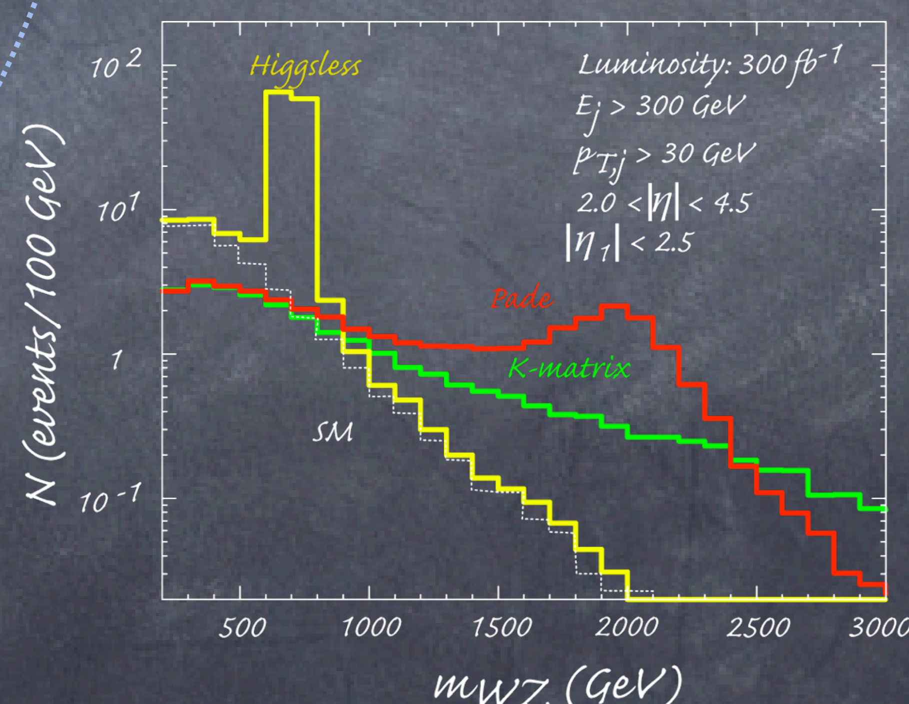
no resonance in WZ for SM/MSSM

W' production



$2j+3l+\not{E}_T$

VBF (LO) dominates over DY since couplings of q to W' are reduced



Number of events at the LHC, 300 fb^{-1}

discovery reach
@ LHC
(10 events)

$550\ \mathrm{GeV} \to 10\ \mathrm{fb}^{-1}$

$1\ \mathrm{TeV} \to 60\ \mathrm{fb}^{-1}$

should be seen within one/two year