

# (Understanding) EW symmetry breaking at the LHC

*Physics at the LHC - 2008*

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cea

# The SM and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

•  $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$  is a doublet of  $SU(2)_L$  but  $m_{\nu_e} \ll m_e$

• a mass term for the gauge field isn't invariant under gauge transformation

$$\delta A_\mu^a = \partial_\mu \epsilon^a + g f^{abc} A_\mu^b \epsilon^c$$



spontaneous breaking of gauge symmetry



# The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom  
massive W, Z: 3 physical polarizations=eaten Goldstone bosons

—  $\Rightarrow$  Where are these Goldstone's coming from?  $\Leftarrow$  —

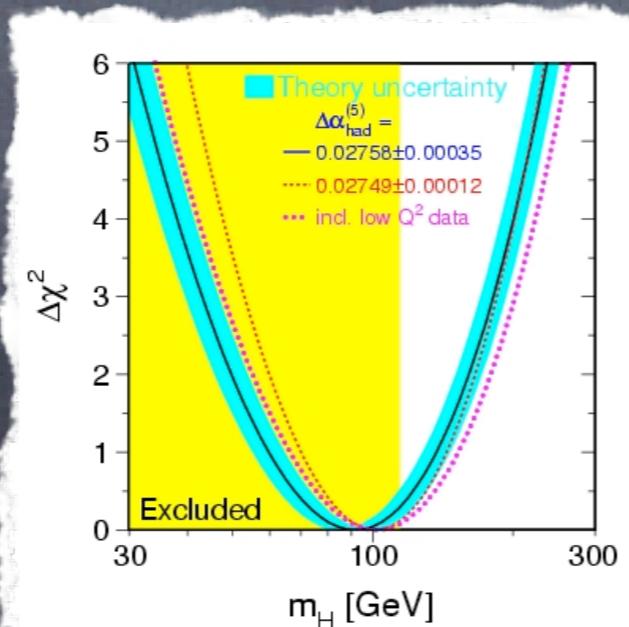
common lore: from a scalar Higgs doublet

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

Higgs doublet = 4 real scalar fields  
3 eaten Goldstone bosons

One physical degree of freedom  
the Higgs boson

Good  
agreement  
with EW data  
(doublet  $\Leftrightarrow \rho=1$ )



Measurement	Fit	$ O^{\text{meas}} - O^{\text{fit}} /\sigma^{\text{meas}}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	$0.02758 \pm 0.00035$	0.02767
$m_Z [\text{GeV}]$	$91.1875 \pm 0.0021$	91.1874
$\Gamma_Z [\text{GeV}]$	$2.4952 \pm 0.0023$	2.4959
$\sigma_{had}^0 [\text{nb}]$	$41.540 \pm 0.037$	41.478
$R_t$	$20.767 \pm 0.025$	20.743
$A_{tb}^{0,t}$	$0.01714 \pm 0.00095$	0.01642
$A_t(P_c)$	$0.1465 \pm 0.0032$	0.1480
$R_b$	$0.21629 \pm 0.00066$	0.21579
$R_c$	$0.1721 \pm 0.0030$	0.1723
$A_{tb}^{0,b}$	$0.0992 \pm 0.0016$	0.1037
$A_{tb}^{0,c}$	$0.0707 \pm 0.0035$	0.0742
$A_b$	$0.923 \pm 0.020$	0.935
$A_c$	$0.670 \pm 0.027$	0.668
$A_t(\text{SLD})$	$0.1513 \pm 0.0021$	0.1480
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{tb})$	$0.2324 \pm 0.0012$	0.2314
$m_W [\text{GeV}]$	$80.404 \pm 0.030$	80.377
$\Gamma_W [\text{GeV}]$	$2.115 \pm 0.058$	2.092
$m_t [\text{GeV}]$	$172.7 \pm 2.9$	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?

Gaugeophobic Higgs?

Littlest Higgs?

Slim Higgs?

Composite Higgs?

Fat Higgs?

Higgsless?

Portal Higgs?

Lone Higgs?

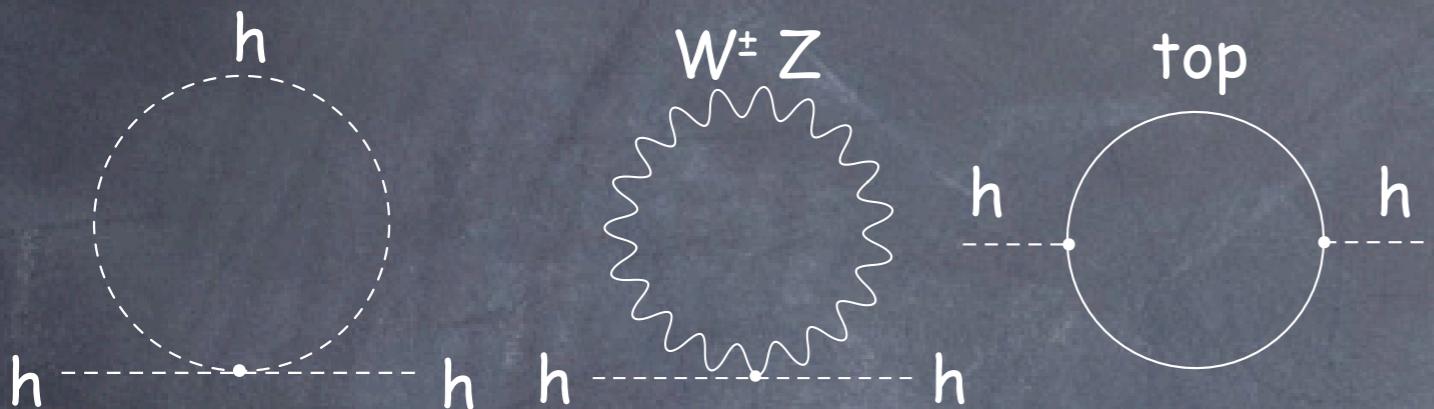
Gauge-Higgs?

Simplest Higgs?

Phantom Higgs?

# A light Higgs calls for New Physics

need new degrees of freedom to cancel  $\Lambda^2$  divergences  
and ensure the stability of the weak scale



$$m_H^2 \sim m_0^2 - (115 \text{ GeV})^2 \left( \frac{\Lambda}{400 \text{ GeV}} \right)^2$$

SM fails to provide a Dark Matter candidate  
but new physics in the EW sector around TeV  $\Rightarrow$  good relic abundance

New physics in the EW sector around TeV : still allowed by data

$$\left( (h^\dagger \sigma^a h) W_{\mu\nu}^a B^{\mu\nu} \right) / \Lambda^2 \quad |h^\dagger D_\mu h|^2 / \Lambda^2 \quad (h^\dagger h)^3 / \Lambda^2$$

# How to Stabilize the Higgs Potential

## ■ Goldstone's Theorem

spontaneously broken global symmetry  $\rightarrow$  massless scalar

... but the Higgs has sizable non-derivative  
couplings

## ■ The Spin Trick

$2s+1$  polarization states

a particle of spin  $s$ : ...with the only exception of a particle moving at the speed of light  
... fewer polarization states

Spin 1    Gauge invariance  $\rightarrow$  no longitudinal polarization

Spin 1/2    Chiral symmetry  $\rightarrow$  only one helicity

... but the Higgs is a spin 0 particle

$m=0$

# Symmetries to Stabilize a Scalar Potential

■ Supersymmetry

fermion  $\sim$  boson

■ Higher Dimensional  
Lorentz invariance

$\Leftarrow$  gauge-Higgs  
unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1                          4D spin 0

These symmetries cannot be exact symmetry of the Nature.  
They have to be broken. We want to look for a soft breaking in  
order to preserve the stabilization of the weak scale.

# Other symmetries?

## ■ Ghost symmetry

[Grinstein, O'Connell, Wise '07]

SM particle ~ ghost

It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60's proposed a trick to stabilize the ghosts (at the price of a violation of causality at the microscopic scale).

# *Little Higgs*

# Little Higgs Models

[Arkani-Hamed et al. '02]

## Higgs as a pseudo-Nambu-Goldstone boson

QCD:  $\pi^+, \pi^0$  are Goldstone associated to

$$\frac{SU(2)_L \times SU(2)_R}{SU(2)_{\text{isospin}}}$$

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

$$\alpha_{em} \neq 0$$

LxR exact

$$m_\pi = 0$$

$$m_{\pi^\pm}^2 \approx \frac{\alpha_{em}}{4\pi} \Lambda_{QCD}^2$$

EW pions

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

exact global sym.

$$m_H = 0$$

$$\alpha_{top} \neq 0$$

$$m_H^2 \approx \frac{\alpha_{top}}{4\pi} \Lambda_{\text{strong}}^2$$

would require

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

...too low !

Little Higgs = PNGB + Collective Breaking

$$m_H^2 \approx \frac{\alpha_i \alpha_j}{(4\pi)^2} \Lambda_{\text{strong}}^2$$

# Little Higgs = PNGB + Collective Breaking

$$\text{Higgs} \in G/H$$

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

$$SU(5)/SO(5)$$

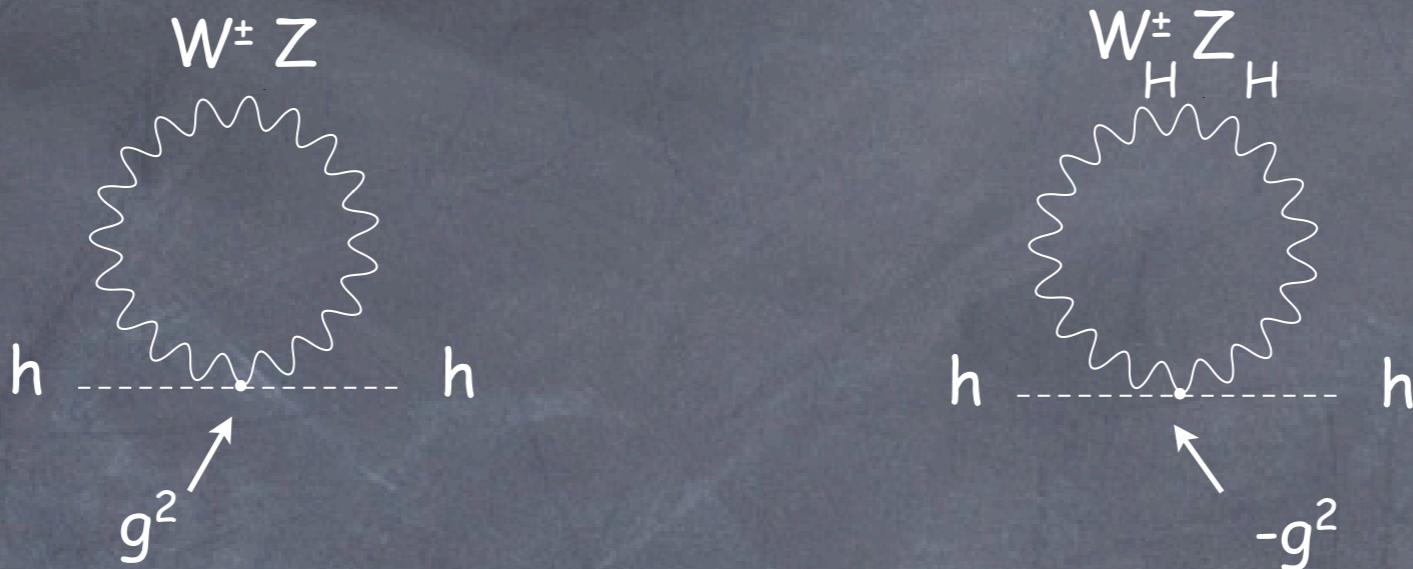
$$24-10=14 \text{ PNGB}$$

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

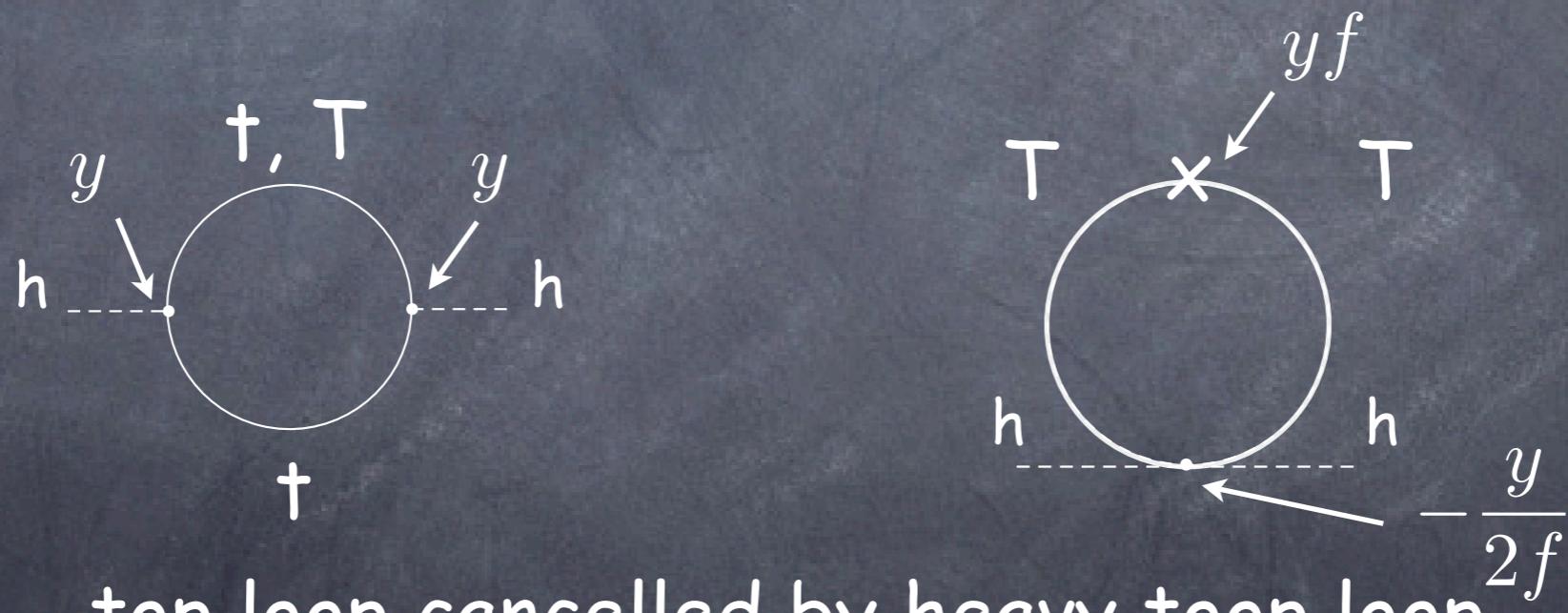
$$14-3=11 \text{ PNGB left} = 3_1, 2_{1/2}, 1_0$$

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

# $LH = \Lambda^2$ cancelled by same spin partner



gauge boson loops cancelled by heavy gauge boson loops



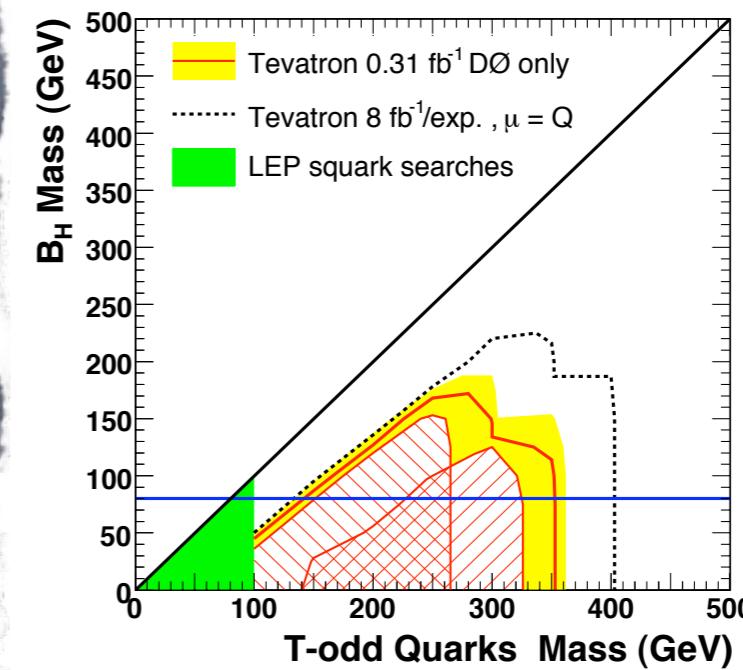
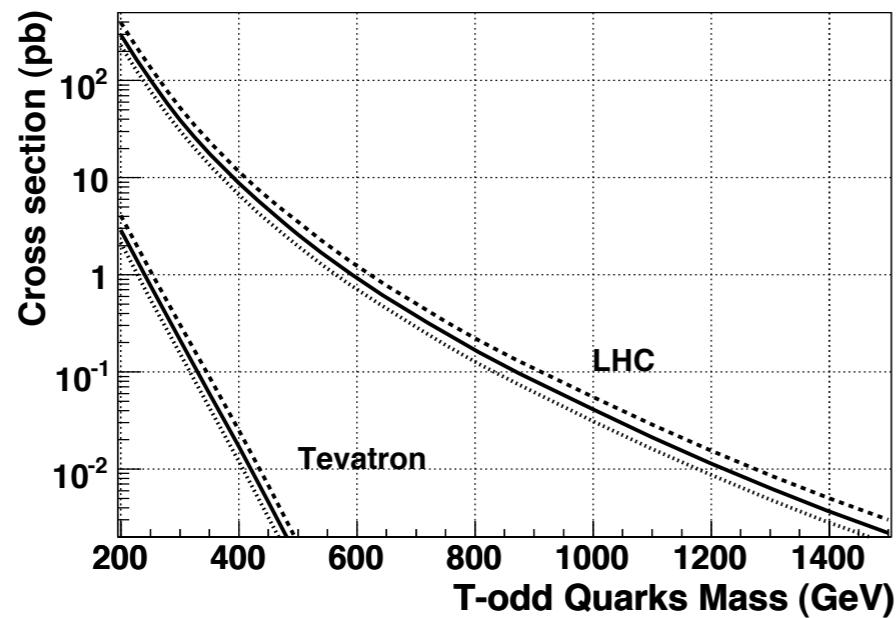
Relation among different couplings follows from global sym.

# Little Higgs @ LHC

Confrontation of Little Higgs with EW data: needs for a T-parity  
light particles = even  $\Leftrightarrow$  heavy particles = odd

the LTP, usually partner of  $B_\mu$ , is stable (DM candidate?)

Little Higgs = jet+ missing  $E_T$



[Carena, Hubisz, Perelstein, Verdier '07]

Interesting physics also associated to top partner  
(pair production:  $gg \rightarrow TT$ )

# Twin Higgs = PNGB + Discrete Symmetry

[Chacko, Goh, Harnik '05]

$$\text{Higgs} \in G/H$$

new interactions break the coset and generate a potential for the Higgs

discrete symmetry among these interactions  
⇒ enlarged symmetry of the Higgs potential

$$SU(4)/SU(3)$$

gauge  $SU(2)_L \times SU(2)_R$  subgroup with  $L \leftrightarrow R$

the potential is automatically  $SU(4)$  invariant

cancellation of  $\Lambda^2$  divergences by new particles which are SM singlets

▷ avoid conflict with EW precision tests

# What is the mechanism of EWSB?

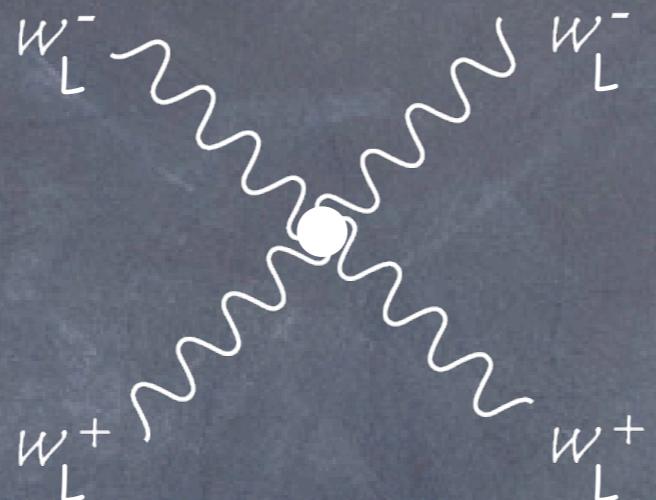
susy, LH, gauge-Higgs models assume that we already know the answer to

**What is unitarizing the WW scattering amplitudes?**

$W_L$  &  $Z_L$  part of EWSB sector  $\supset$  W scattering is a probe of Higgs sector interactions

$$\epsilon_l = \left( \frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$

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

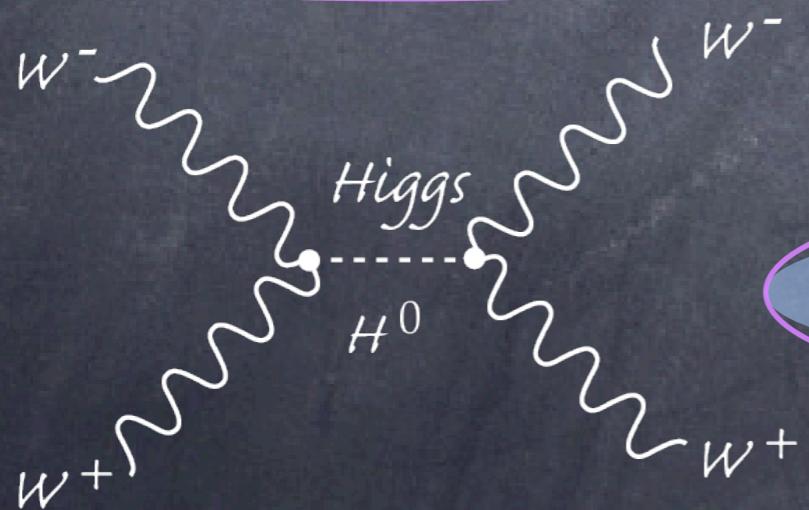


$W_L$  &  $Z_L$  part of EWSB sector  
(we have already discovered

75% of the Higgs doublet!)

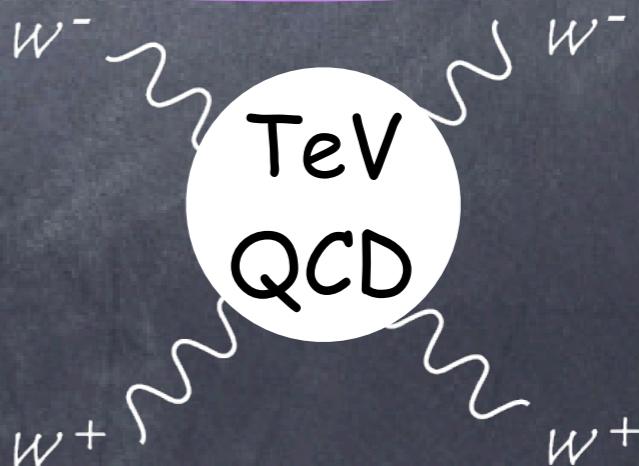
$\supset$  WW scattering is a probe  
of Higgs sector interactions

Weakly coupled models



prototype: Susy  
susy partners  $\sim 100$  GeV

Strongly coupled models



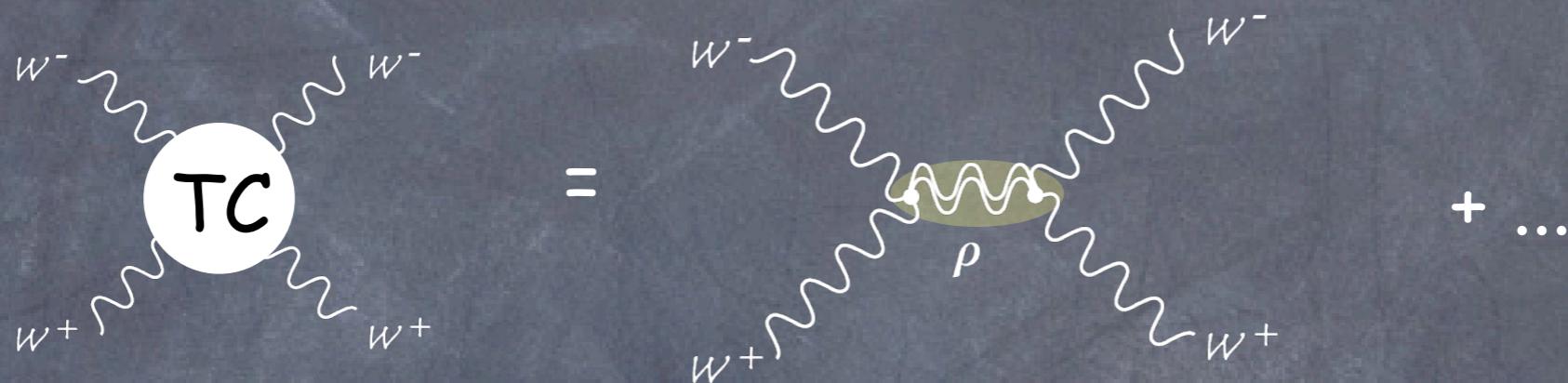
prototype: Technicolor  
rho meson  $\sim 1$  TeV

other ways?

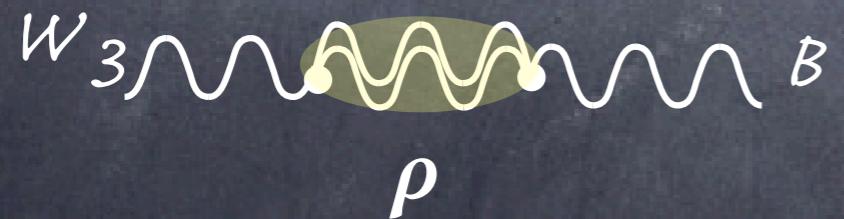
# Strongly coupled models

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  $m_W^2/m_\rho^2$   
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

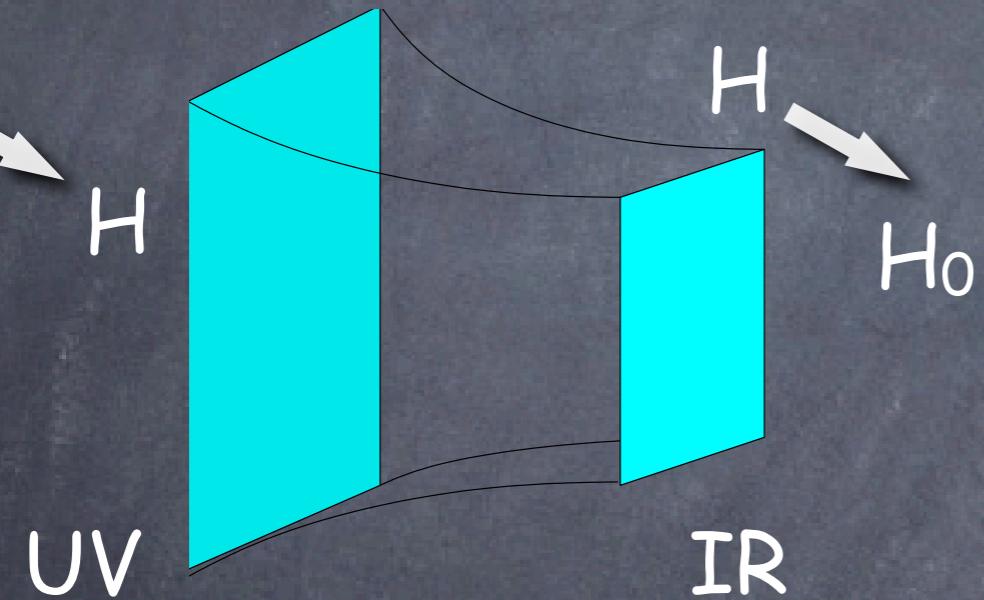
Warped gravity with fermions  
and gauge field in the bulk  
and Higgs on the brane

Strongly coupled theory  
with slowly-running couplings in 4D

$$A_5 \rightarrow A_5 + \partial_5 \epsilon$$

$$h \rightarrow h + a$$

pseudo-Goldstone of a strong force



5D

KK modes  
motion along 5th dim

UV brane

IR brane

bulk local sym.

4D

vector resonances ( $\rho$  mesons in QCD)

RG flow

UV cutoff

break. of conformal inv  
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 Models

mass without a Higgs

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

momentum along extra dimensions  $\sim$  4D mass

quantum mechanics in a box



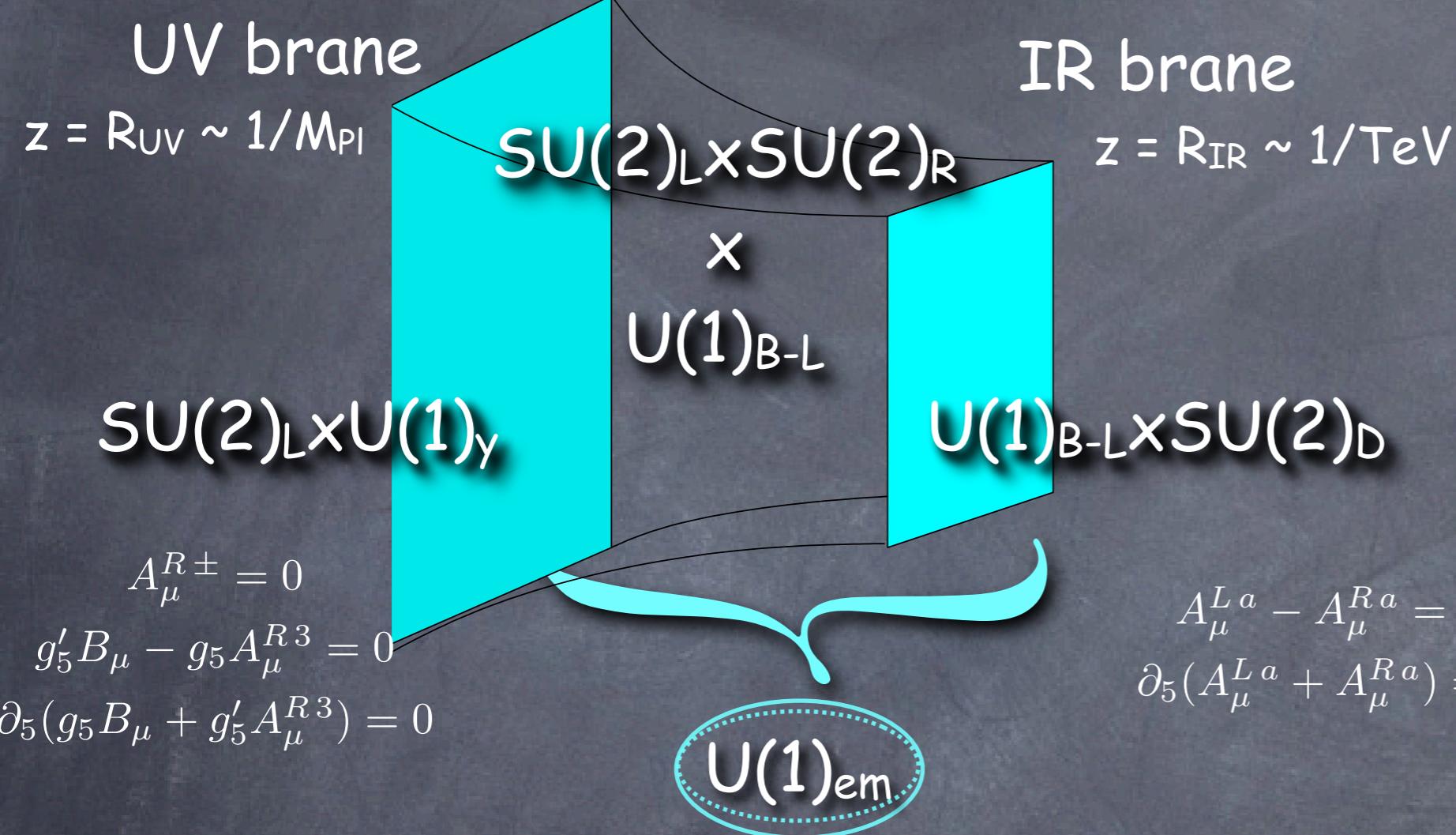
boundary conditions generate a transverse momentum

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?

# Warped Higgsless Model

Csaki, Grojean, Pilo, Terning '03



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

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

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

"light" mode:

$$M_W^2 = \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

log suppression

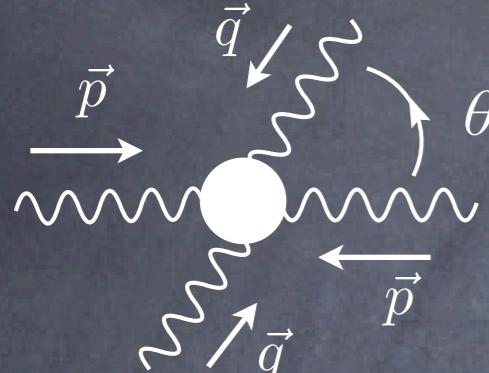
KK tower:

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

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

# Unitarization of (Elastic) Scattering Amplitude

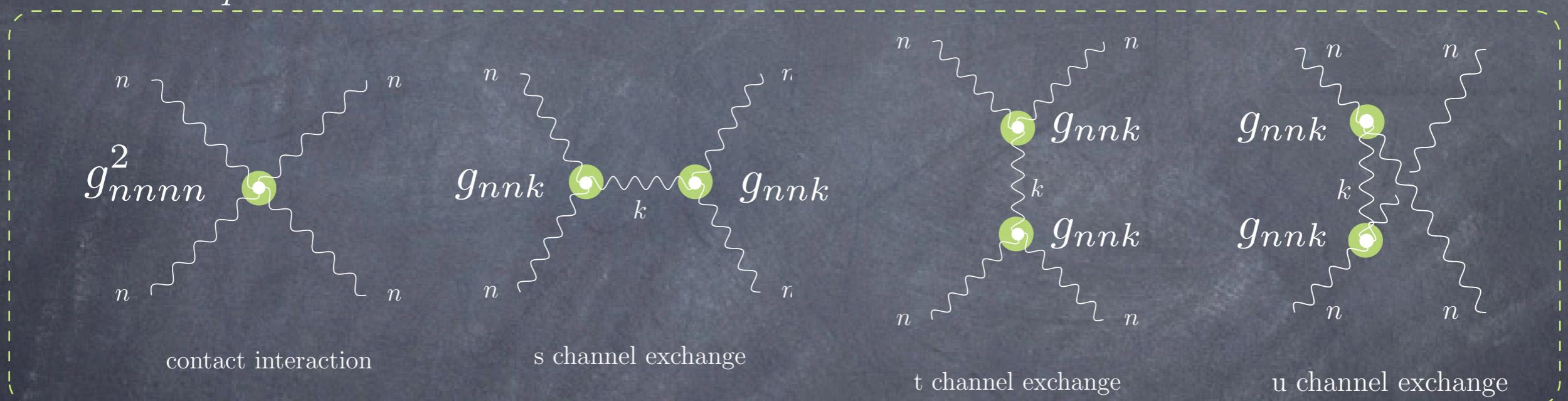
Same KK mode  
'in' and 'out'



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

Csaki, Grojean, Murayama, Pilo, Terning '03

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



contact interaction

s channel exchange

t channel exchange

u channel exchange

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

$\underbrace{\quad}_{=0}$  KK sum rules (enforced by 5D Ward identities)

$$\mathcal{A}^{(2)} = i \left( 4g_{nnnn}^2 - \underbrace{3 \sum_k g_{nnk}^2 \frac{M_k^2}{M_n^2}}_{=0} \right) \left( f^{ace} f^{bde} - s_{\theta/2}^2 f^{abe} f^{cde} \right)$$

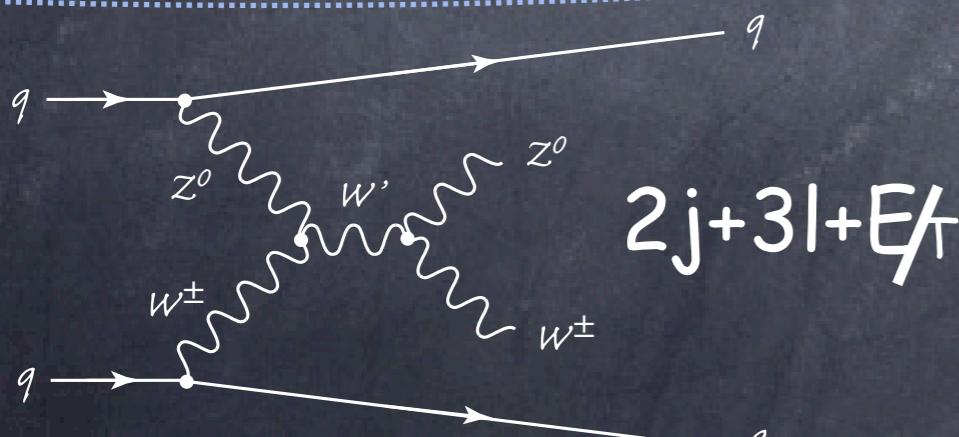
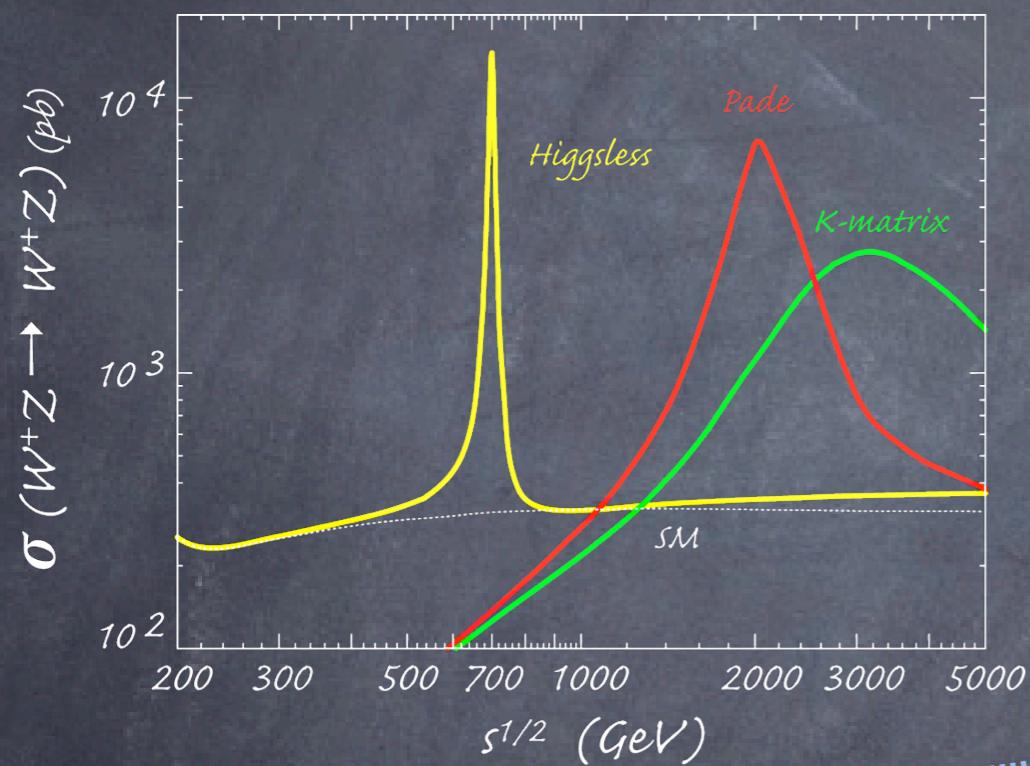
# Collider Signatures

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

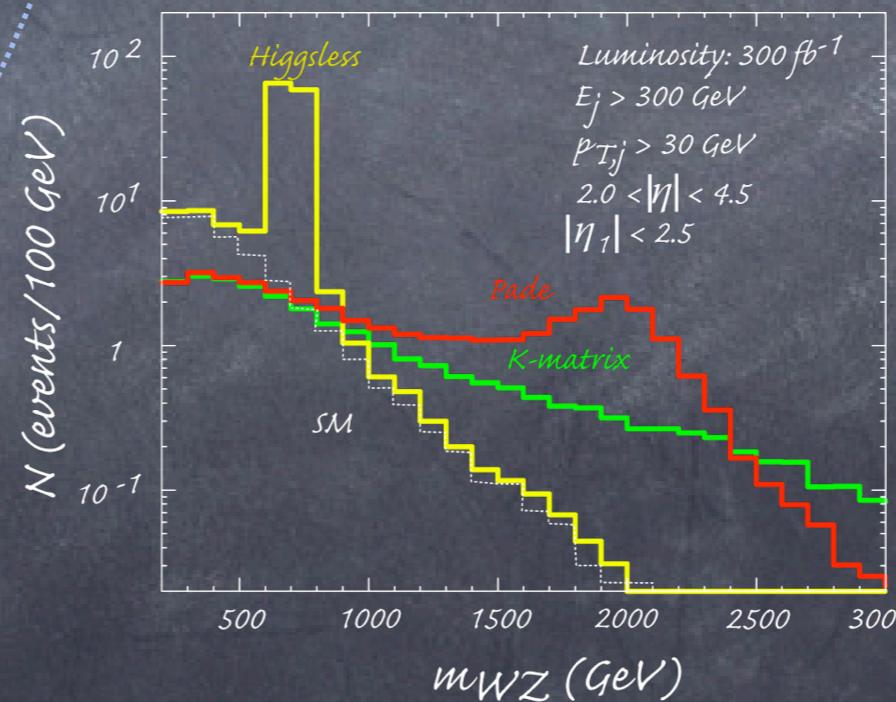


VBF (LO) dominates over DY since couplings of  $q$  to  $W'$  are reduced

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

a narrow and light resonance  
no resonance in WZ for SM/MSSM

## $W'$ production



discovery reach  
@ LHC  
(10 events)

$550 \text{ GeV} \rightarrow 10 \text{ fb}^{-1}$   
 $1 \text{ TeV} \rightarrow 60 \text{ fb}^{-1}$

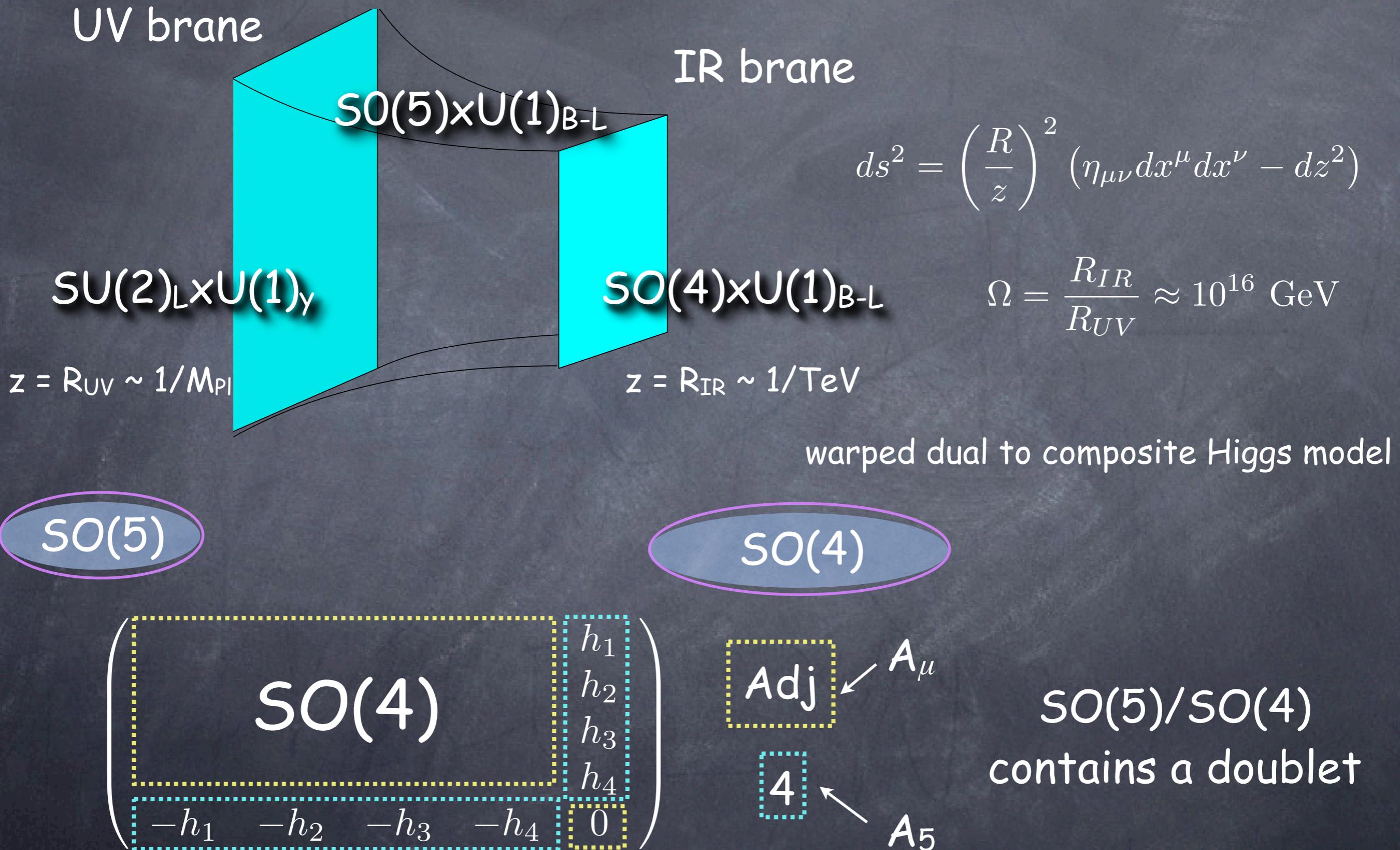
should be seen  
within one/two years

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

# *Composite Higgs Models*

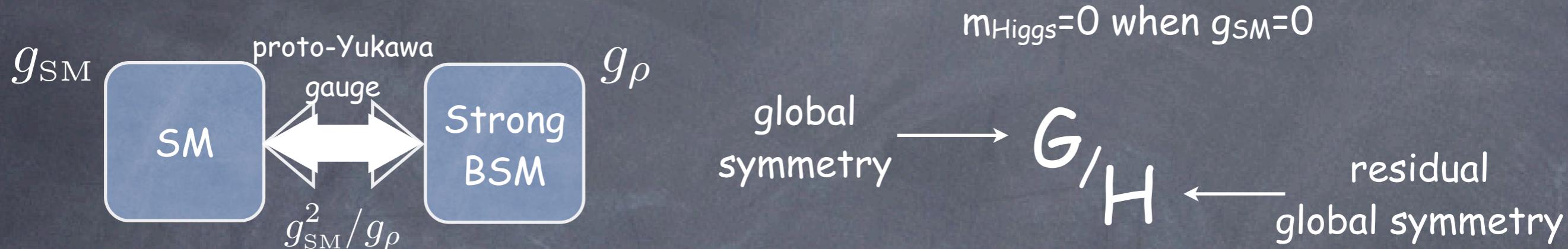
# Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

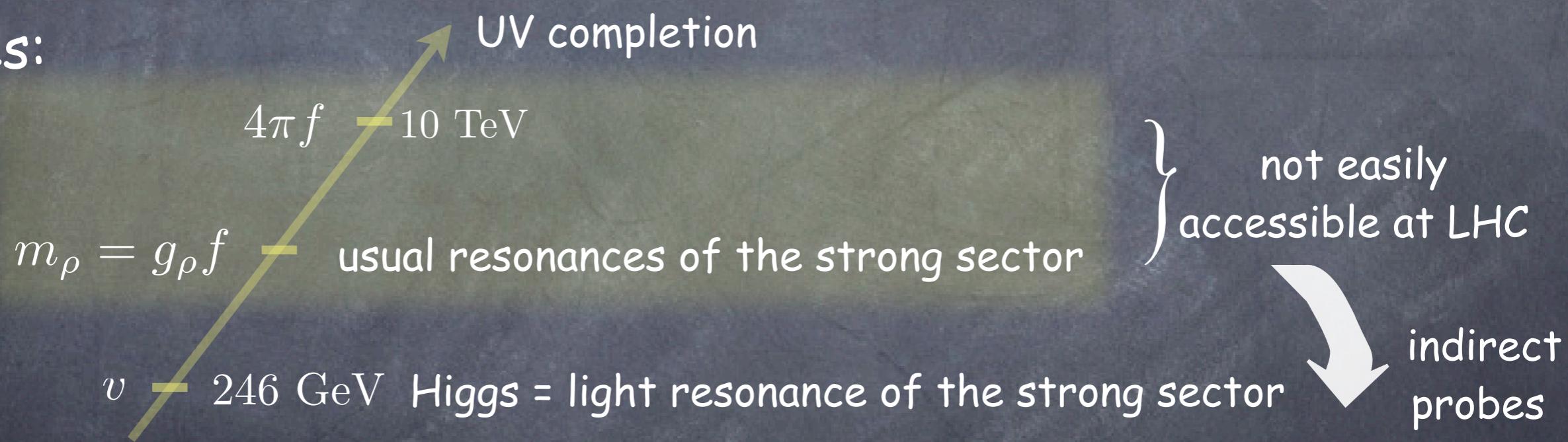


# How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



3 scales:



strong sector broadly characterized by 2 parameters

$m_\rho$  = mass of the resonances

$g_\rho$  = coupling of the strong sector or decay cst of strong sector  $f = \frac{m_\rho}{g_\rho}$

# Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else\*:  
is it elementary or composite?

?? evidence for fine-tuning & string landscape ???

?? Higgs forces have a secret hidden gauge origin ???

- ⌚ Model-dependent: production of resonances at  $m_\rho$
- ⌚ Model-independent: study of Higgs properties & W scattering
  - ⌚ strong WW scattering
  - ⌚ strong HH production
  - ⌚ Higgs anomalous coupling
  - ⌚ anomalous gauge bosons self-couplings

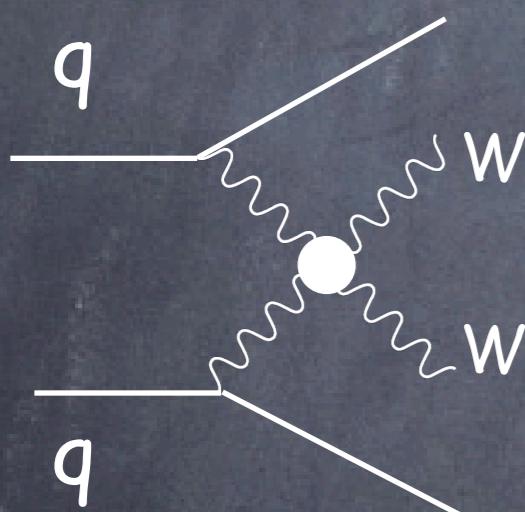
\* a likely possibility that precision data seems to point to,  
at least in strongly coupled models

# Strong W scattering @ LHC

Giudice, Grojean, Pomarol, Rattazzi '07

Even with a light Higgs, growing amplitudes (at least up to  $m_\rho$ )

$$\begin{aligned}\mathcal{A}(Z_L^0 Z_L^0 \rightarrow W_L^+ W_L^-) &= \mathcal{A}(W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0) = -\mathcal{A}(W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm) = \frac{c_H s}{f^2} \\ \mathcal{A}(W^\pm Z_L^0 \rightarrow W^\pm Z_L^0) &= \frac{c_H t}{f^2}, \quad \mathcal{A}(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) = \frac{c_H(s+t)}{f^2} \\ \mathcal{A}(Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0) &= 0\end{aligned}$$



$$\sigma(pp \rightarrow V_L V'_L X)_{c_H} = \left( c_H \frac{v^2}{f^2} \right)^2 \sigma(pp \rightarrow V_L V'_L X)_H$$

leptonic vector decay channels  
forward jet-tag, back-to-back lepton, central jet-veto  
with  $300 \text{ fb}^{-1}$

30 signal-events and 10 background-events

Bagger et al '95  
Butterworth et al. '02



LHC is sensitive to

$$c_H \frac{v^2}{f^2} \sim 0.5$$

i.e.  $4\pi f \sim 4 \text{ TeV}$

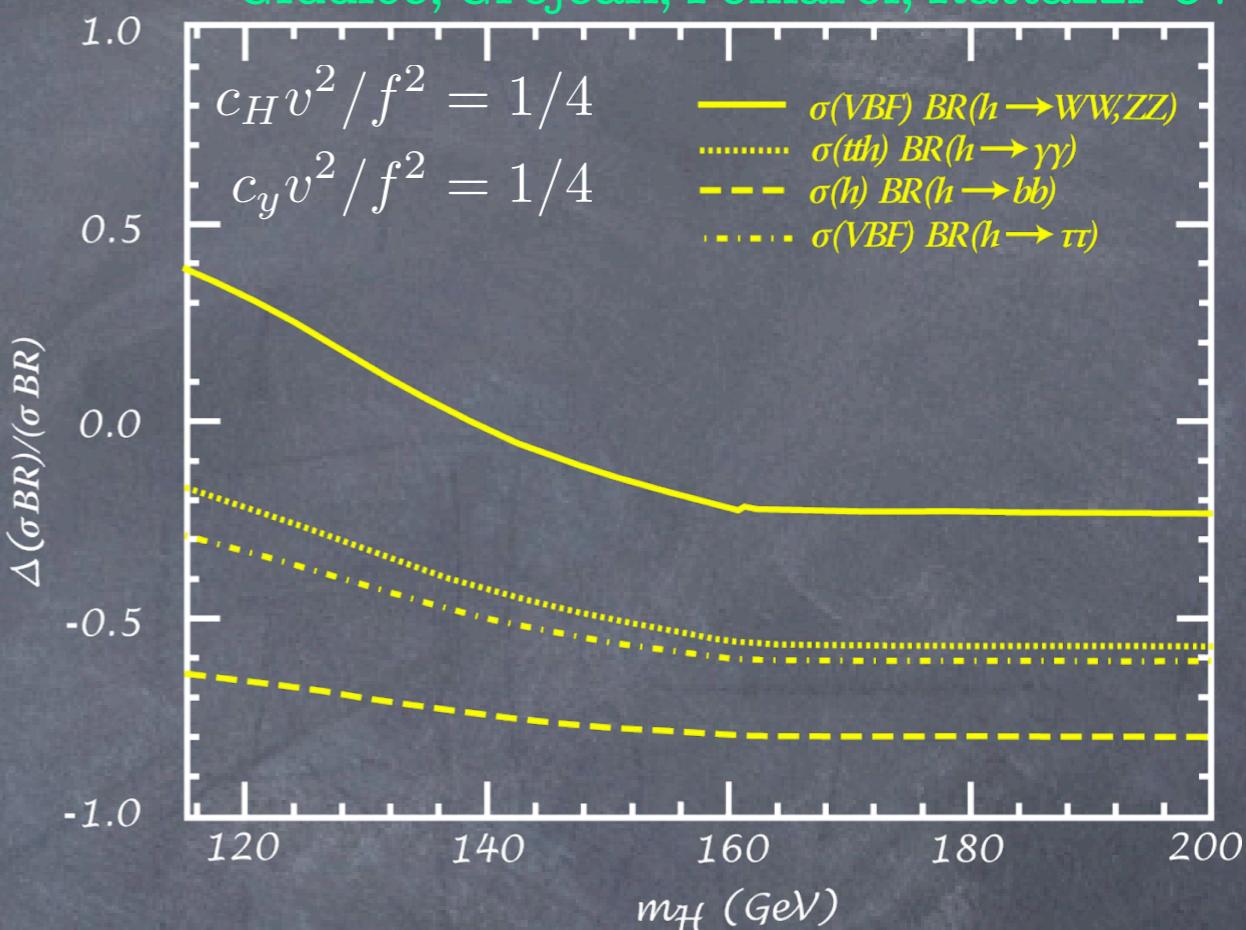
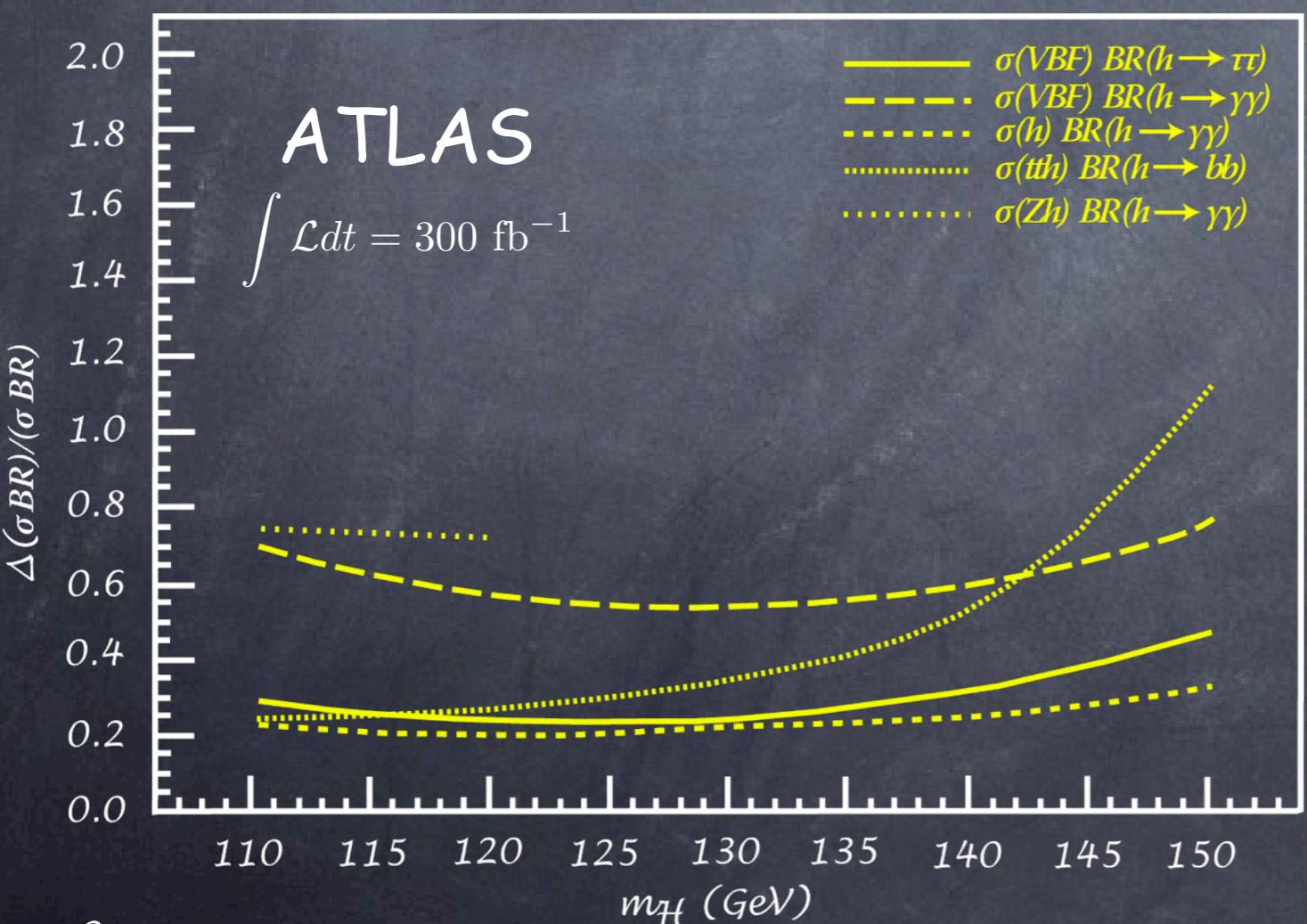
# Higgs anomalous couplings @ LHC

Giudice, Grojean, Pomarol, Rattazzi '07

$$\Gamma(h \rightarrow f\bar{f})_{\text{SILH}} = \Gamma(h \rightarrow f\bar{f})_{\text{SM}} [1 - (2c_y + c_H) v^2/f^2]$$

$$\Gamma(h \rightarrow gg)_{\text{SILH}} = \Gamma(h \rightarrow gg)_{\text{SM}} [1 - (2c_y + c_H) v^2/f^2]$$

observable @ LHC?



LHC can measure

$$c_H \frac{v^2}{f^2}, \quad c_y \frac{v^2}{f^2}$$

up to 0.2-0.4

i.e.  $4\pi f \sim 5 - 7 \text{ TeV}$

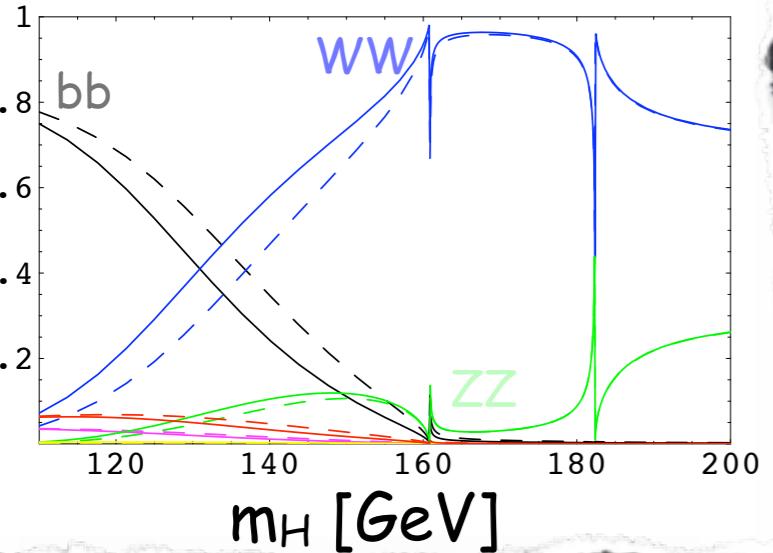
(ILC could go to few % ie  
test composite Higgs up to  $4\pi f \sim 30 \text{ TeV}$ )

# Higgs BRs and total width

Fermions embedded in 5+10 of SO(5)

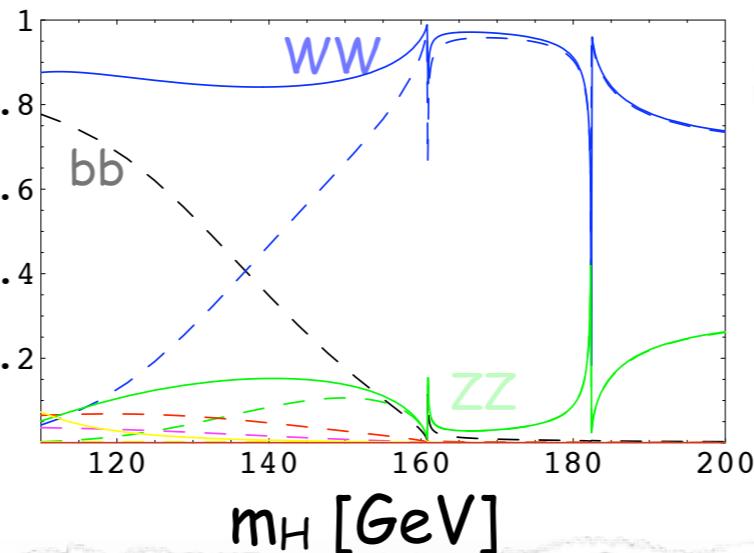
BRs

$v^2/f^2=0.2$



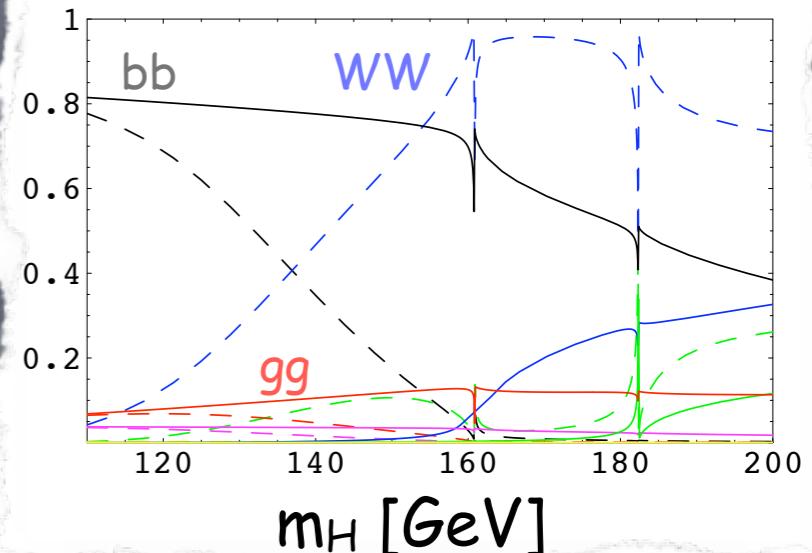
BRs

$v^2/f^2=0.5$



BRs

$v^2/f^2=0.95$



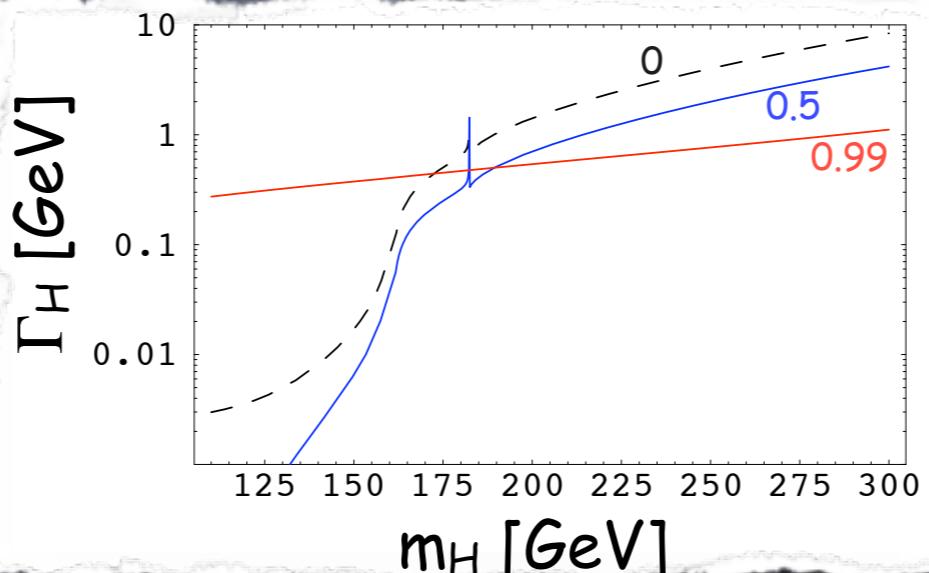
slight modifications

suppress bb

suppress WW

## Higgs total width

--- SM  
— composite Higgs



# Strong Higgs production: (3L+jets) analysis

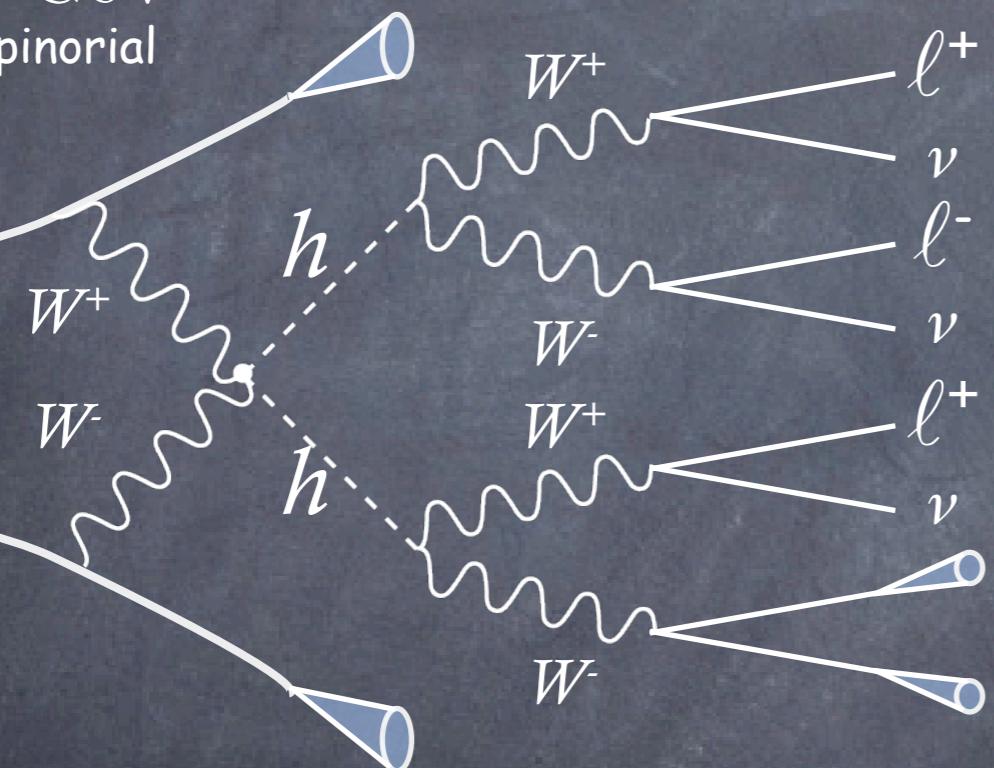
Contino, Grojean, Moretti, Piccinini, Rattazzi ‘in progress’

**strong boson scattering  $\Leftrightarrow$  strong Higgs production**

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow hh) = \mathcal{A}(W_L^+ W_L^- \rightarrow hh) = \frac{c_H s}{f^2}$$

$m_h = 180$  GeV  
fermions in spinorial

$c_H=1$



acceptance cuts	
jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(l\bar{l})} > 0.4(0.2)$
$ \eta_j  \leq 5$	$ \eta_j  \leq 2.4$

**Dominant backgrounds:**  $W1\bar{1}4j$ ,  $t\bar{t}W2j$ ,  $t\bar{t}2W$ ,  $3W4j$ ...

forward jet-tag, back-to-back lepton, central jet-veto

$v/f$	1	$\sqrt{.8}$	$\sqrt{.5}$
significance ( $300$ $fb^{-1}$ )	4.0	2.9	1.3
luminosity for $5\sigma$	450	850	3500

◀ good motivation to SLHC

# *Conclusions*

EW interactions need Goldstone bosons to provide mass to W, Z

EW interactions need a UV moderator/new physics  
to unitarize WW scattering amplitude

Not just the search for the Higgs boson  
(still another particle, even though the missing one?)

We are after the organizing principles of nature at high energies

fundamental interactions  $\Leftrightarrow$  gauge symmetries?

is SM fine-tuned or natural?

are there more than 4D?

...

LHC is prepared to discover the "Higgs"  
collaboration EXP-TH is important to make sure  
e.g. that no unexpected physics (unparticle, hidden valleys) is missed (triggers, cuts...)