Non-Standard Electroweak Symmetry Breaking

Higgs-Maxwell Particle Physics Workshop

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Christophe Grojean

CERN-TH & CEA-Saclay-IPhT

(Christophe.Grojean[at]cern.ch)

A Central Question in Particle Physics

Astro/Cosmo data (Dark matter and baryon asymmetry)
+
theoretical prejudice (hierarchy/naturality)

strongly suggest the presence of New Physics
around the weak scale that is supposed to play a crucial role in breaking the electroweak symmetry

What is the mechanism of EW symmetry breaking?

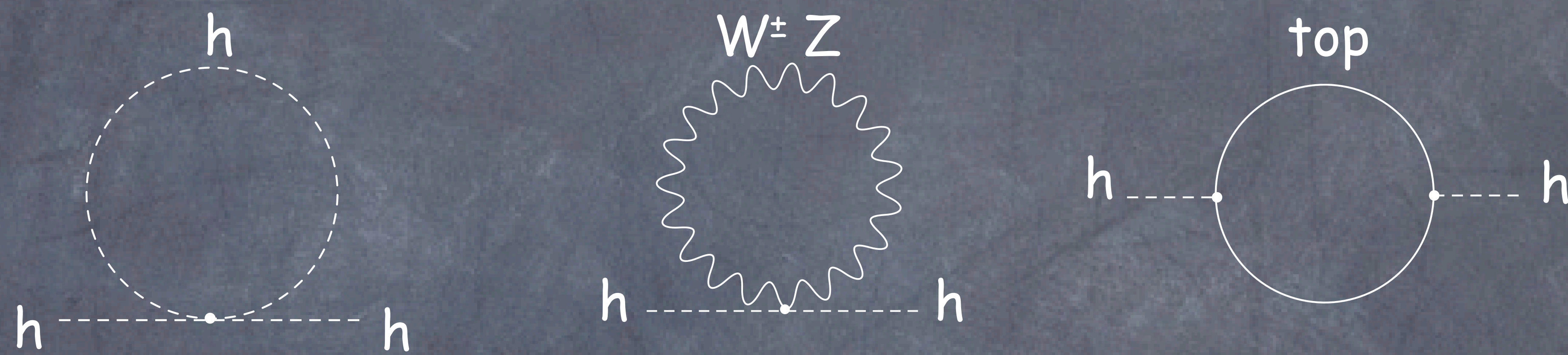
often said that the LHC is built to address this question

What is the mechanism of EWSB?

what we usually mean by that question is

what is cancelling the Higgs Λ^2 divergences?

what is ensuring the stability of the weak scale?



$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad\qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2$$

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

This cancellation requires new symmetries among the TeV scale population

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

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance $\longrightarrow$ no longitudinal polarization

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

$\searrow \nearrow$ m=0

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

- Supersymmetry

fermion ~ boson

- Higher Dimensional Lorentz invariance

$\Lleftarrow$ 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 of a violation of causality at the microscopic scale).

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.

$m_H = 0$

$\alpha_{top} \neq 0$

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

would require

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

...too low !

Little Higgs = PNGB + Collective Breaking

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

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

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

if g_L or g_R vanishes, SU(3)/SU(2) coset intact and Higgs remains massless

Twin Higgs = PNGB + Discrete Symmetry

[Chacko, Goh, Harnik '05]

Higgs $\in G/H$

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

discrete symmetry among these interactions
$\Rrightarrow$ 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

cancelation of Λ^2 divergences by new particles which are SM singlets

➲ avoid conflict with EW precision tests

Cancellation of Λ^2 divergences

- Supersymmetry — cancellation by opposite spin particles

top loop cancelled by stop loop
Higgs loop cancelled by higgsino loop
gauge boson loops cancelled by gaugino loops

- Little Higgs — cancellation by same spin particles

top loop cancelled by heavy toop loop
Higgs loop cancelled by heavy singlet/triplet scalars
gauge boson loops cancelled by heavy gauge boson loops

- Gauge-Higgs unification — cancellation by same spin particles

top loop cancelled by heavy toop loop
Higgs loop cancelled by heavy gauge boson loop
gauge boson loops cancelled by heavy gauge boson loops

What is the mechanism of EWSB?

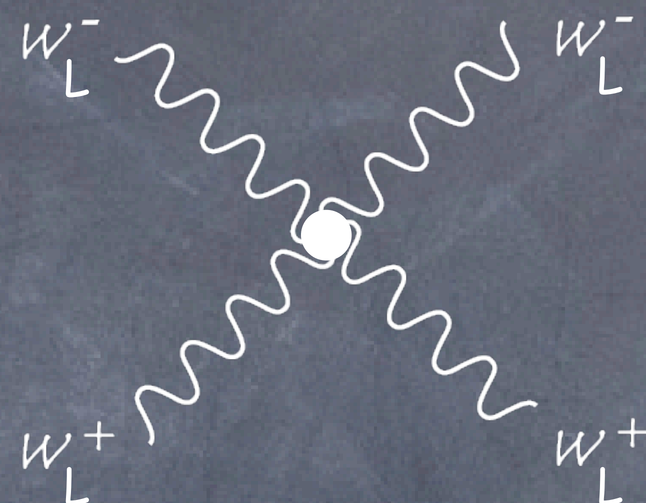
All these models assume that we already know the answer to

What is unitarizing the WW scattering amplitudes?

W_L & Z_L part of EWSB sector ⊃ W scattering is a probe of Higgs sector interactions

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

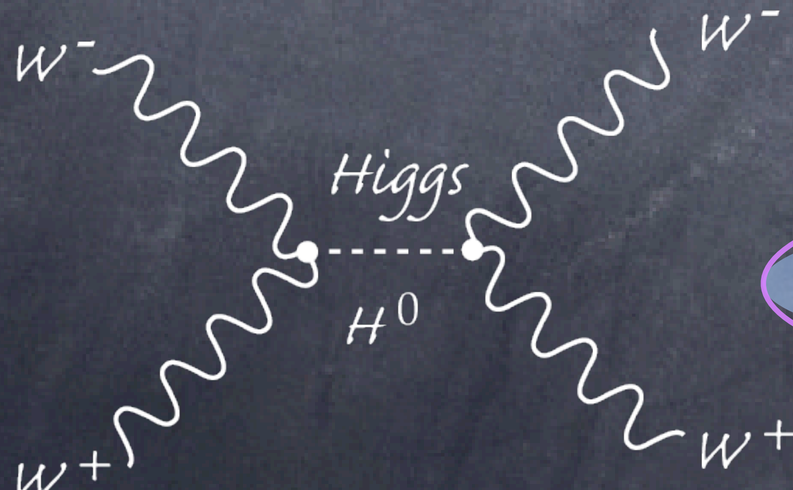
$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$



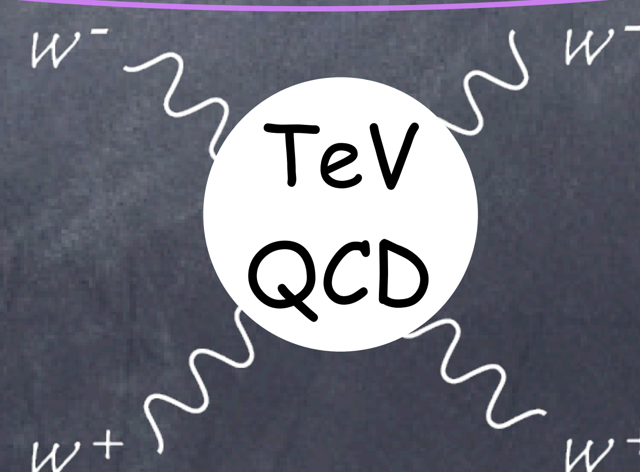
W_L & Z_L part of EWSB sector (we have already discovered 75% of the Higgs doublet!) ⊃ WW scattering is a probe of Higgs sector interactions

Weakly coupled models

Strongly coupled models



other ways?



prototype: Susy

susy partners ~ 100 GeV

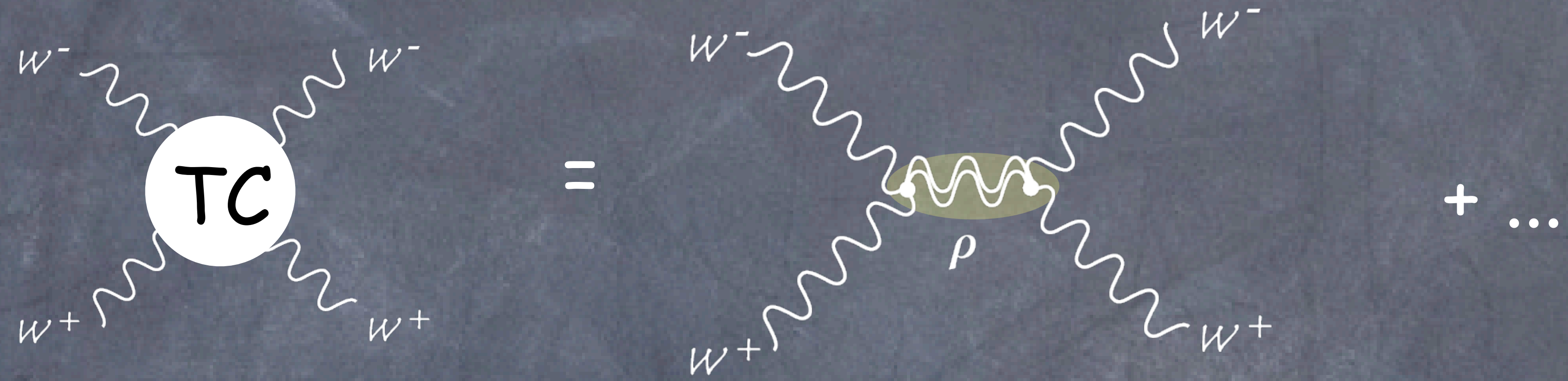
prototype: Technicolor

rho meson ~ 1 TeV

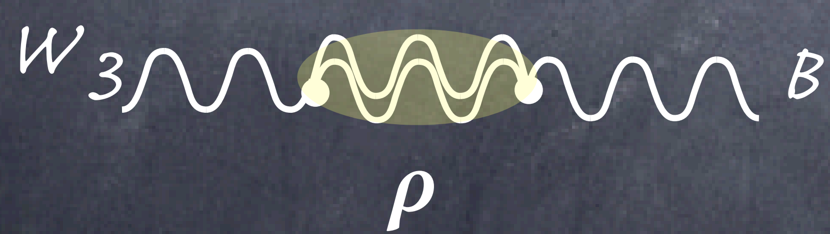
Strongly coupled models

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



S parameter of order 1.
Not seen at LEP

a theoretical challenge: need to develop tools to do computation

Back to "Technicolor" from Xdims

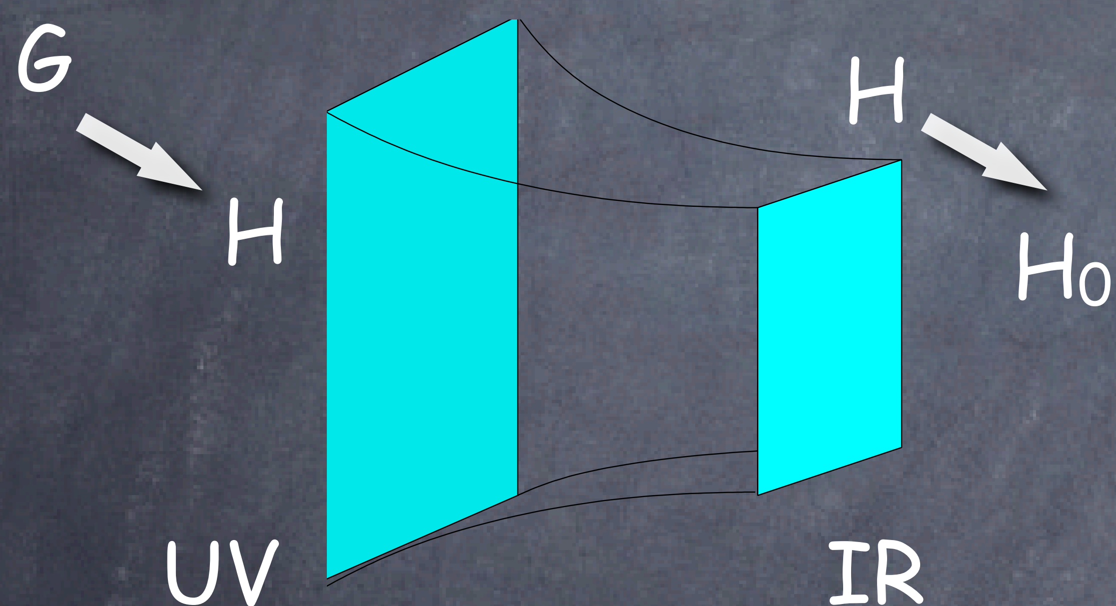
"AdS/CFT" correspondence for model-builder

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

The LHC might not see anything beyond the Standard Model...

Warped Higgsless Model

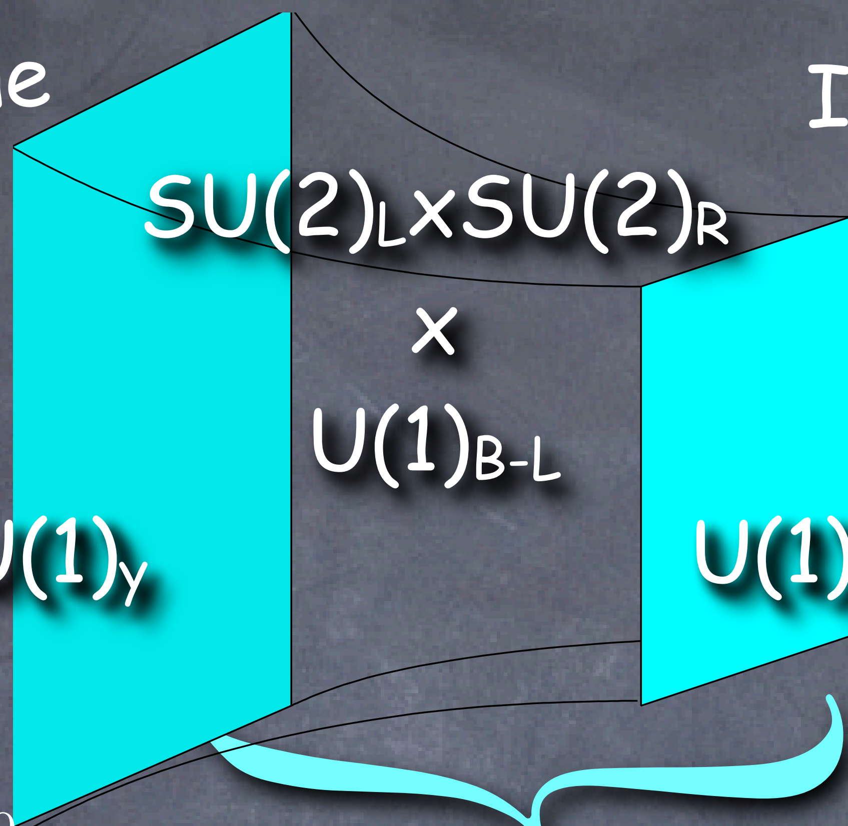
Csaki, Grojean, Pilo, Terning '03

UV brane

$z = R_{UV} \sim 1/M_{Pl}$

IR brane

$z = R_{IR} \sim 1/\text{TeV}$



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

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

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

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

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

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

$U(1)_{em}$

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

"light" mode:

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

log suppression

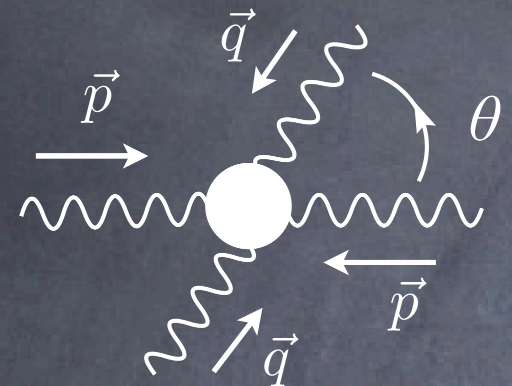
KK tower:

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

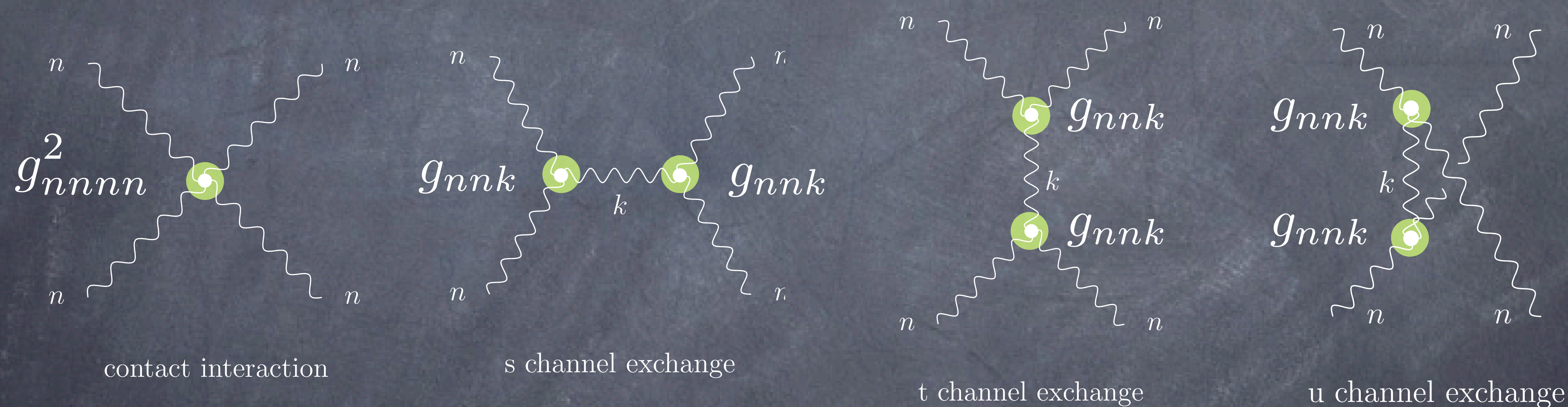
Unitarization of (Elastic) Scattering Amplitude

Same KK mode 'in' and 'out'

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



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



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

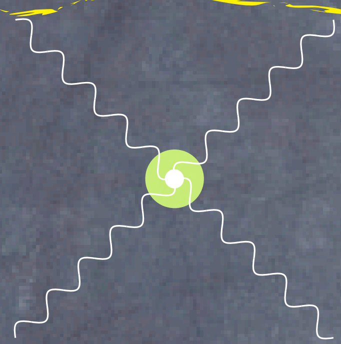
$$\mathcal{A}^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - s^2_{\theta/2}f^{abe}f^{cde}\right)$$

KK Sum Rules

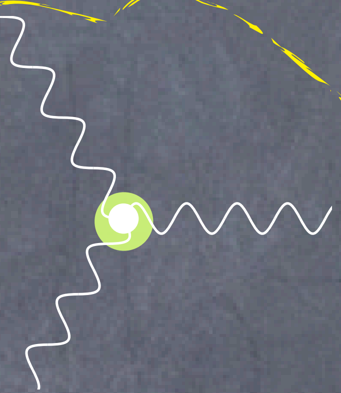
Csaki, Grojean, Murayama, Pilo, Terning '03

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

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



$$g_{mnpq}^2 = g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_m(z) f_n(z) f_p(z) f_q(z)$$



$$g_{mnp} = g_{5D} \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_m(z) f_n(z) f_p(z)$$

- E^4 Sum Rule

$$g_{nnnn}^2 - \sum_k g_{nnk}^2 = g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} f_n^4(z) - g_{5D}^2 \int_{R_{UV}}^{R_{IR}} dz \frac{R}{z} \int_{R_{UV}}^{R_{IR}} dz' f_n^2(z) f_n^2(z') \sum_k \frac{R}{z'} f_k(z) f_k(z') = 0$$

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

$$\sum_k \frac{R}{z'} f_k(z) f_k(z') = \delta(z - z')$$

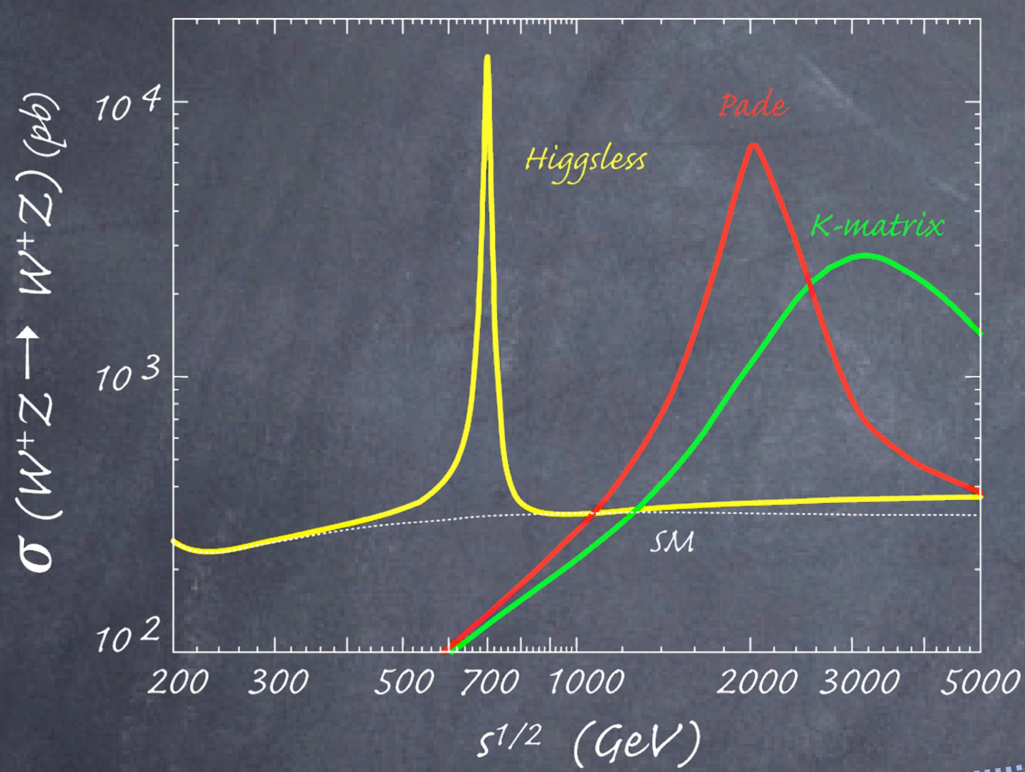
Completness of KK modes

Collider Signatures

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

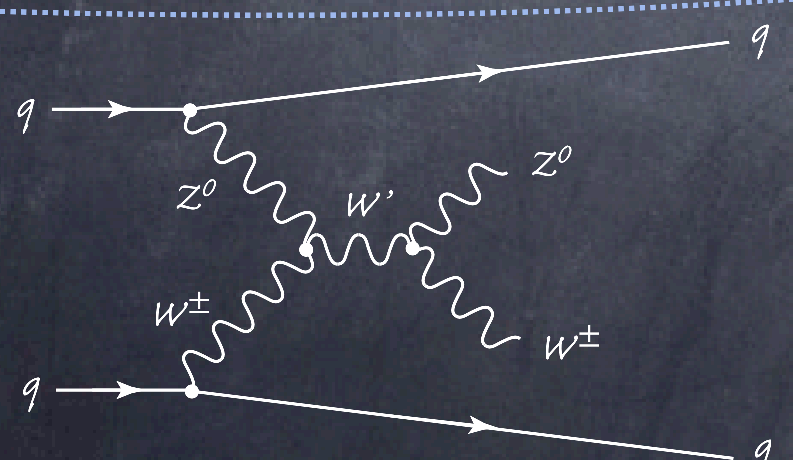
unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

WZ elastic cross section



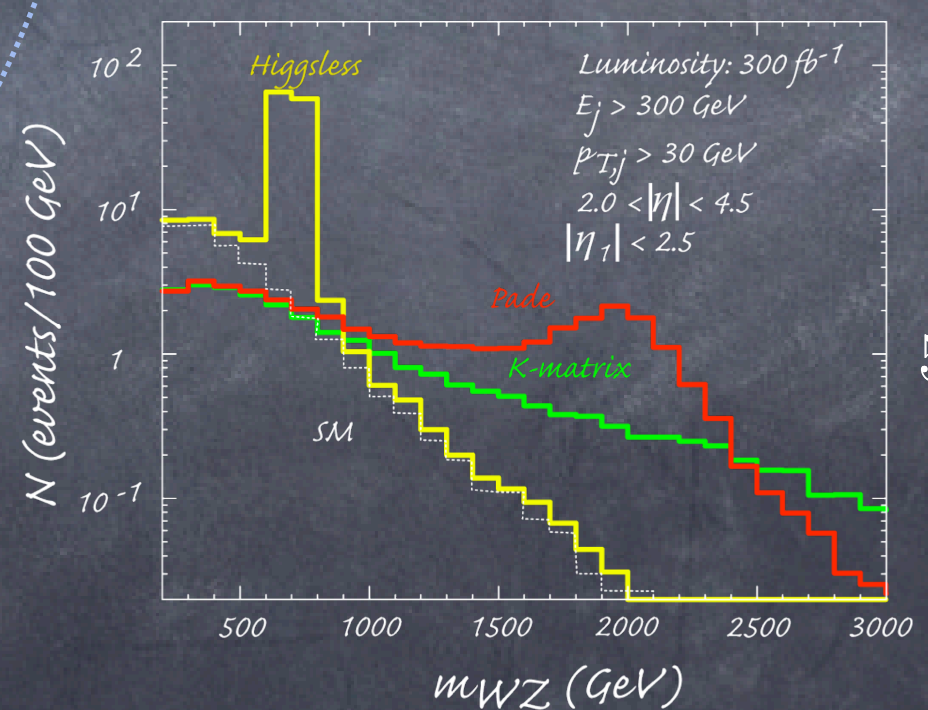
$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance



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

W' production



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

discovery reach @ LHC (10 events)

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

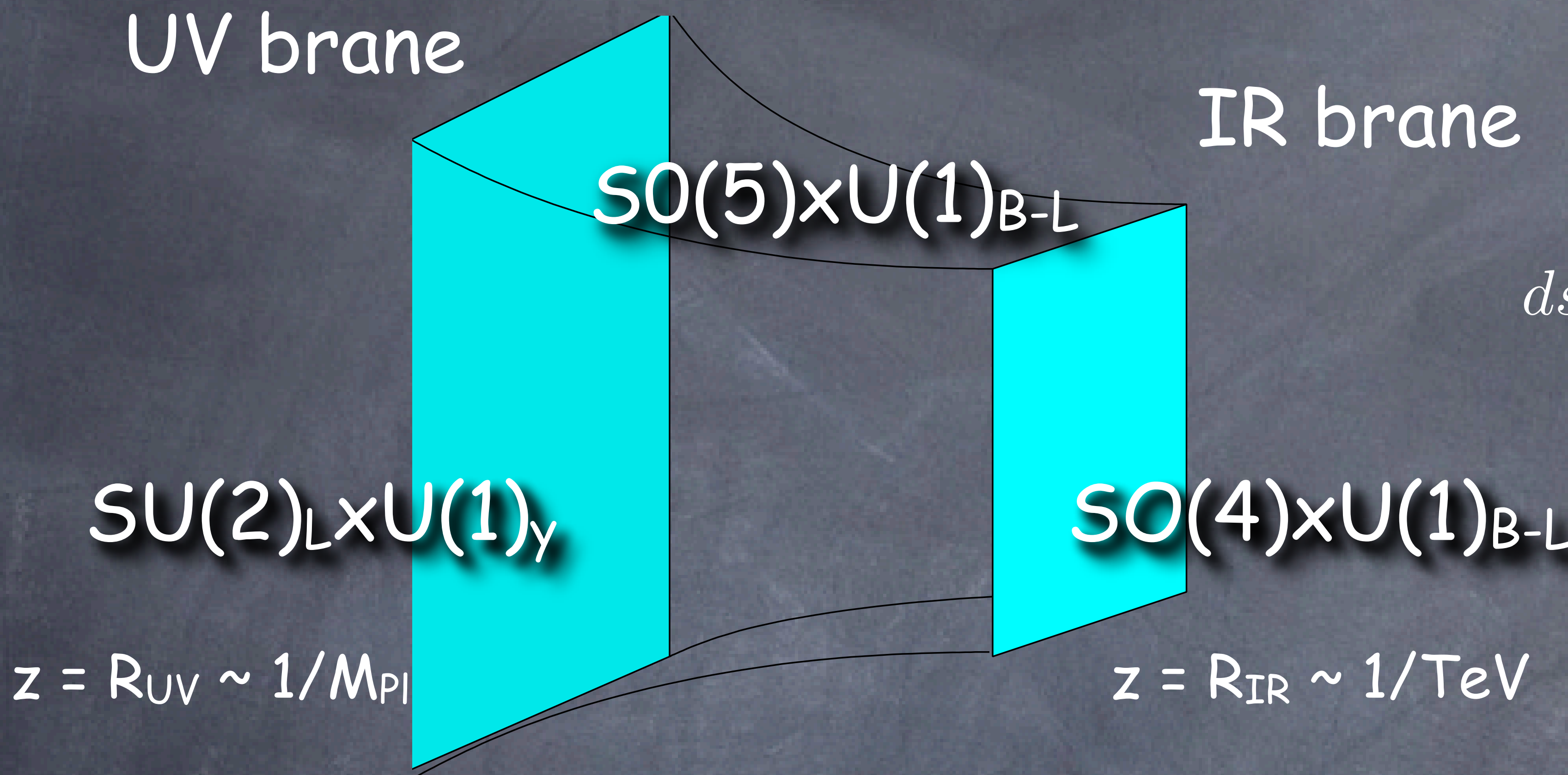
should be seen within one/two year

Composite Higgs Models

The LHC sees the Higgs
and nothing else...

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04



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

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

warped dual to composite Higgs model

SO(5)

SO(4)

$$\left(\begin{array}{cccc|c} & & & & h_1 \\ & \mathrm{SO(4)} & & & h_2 \\ & & & & h_3 \\ & & & & h_4 \\ \hline -h_1 & -h_2 & -h_3 & -h_4 & 0 \end{array}\right)$$

$\boxed{\text{Adj}} \leftarrow A_\mu$

$\boxed{4} \leftarrow A_5$

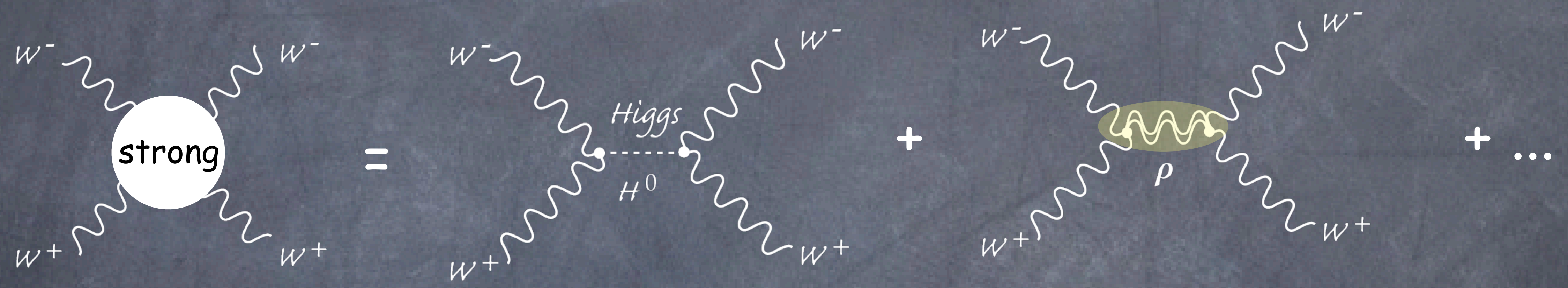
SO(5)/SO(4)
contains a doublet

Unitarity with Composite Higgs

Technicolor: W_L and Z_L are part of the strong sector

Higgs = composite object (part of the strong sector too)
its couplings deviate from a point-like scalar

Georgi, Kaplan '84



light Higgs
partial unitarization

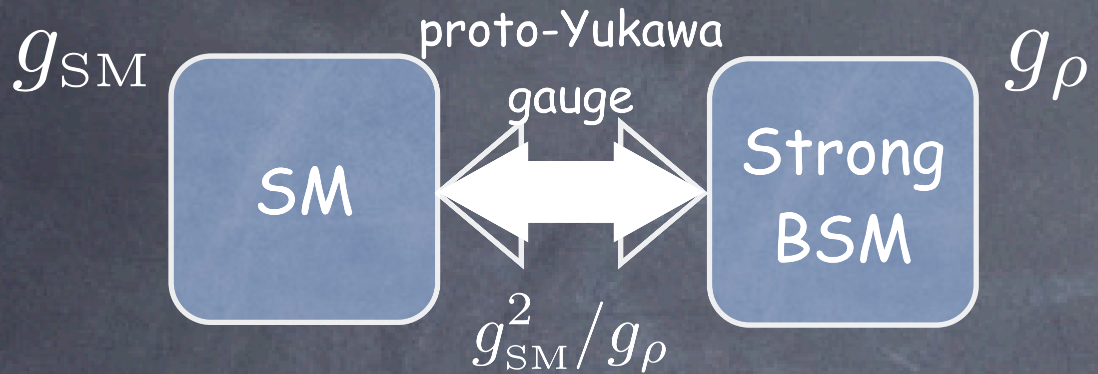
heavy rho

unitarization halfway between weak and strong unitarizations!

- ≠ susy: no naturalness pb ⊃ no need for new particles to cancel Λ^2 divergences
- ≠ technicolor: heavier rho ⊃ smaller oblique corrections; one tunable parameter: v/f. $\hat{S}_{\rm UV} \sim \frac{g^2 N}{96\pi^2}\frac{v^2}{f^2}$

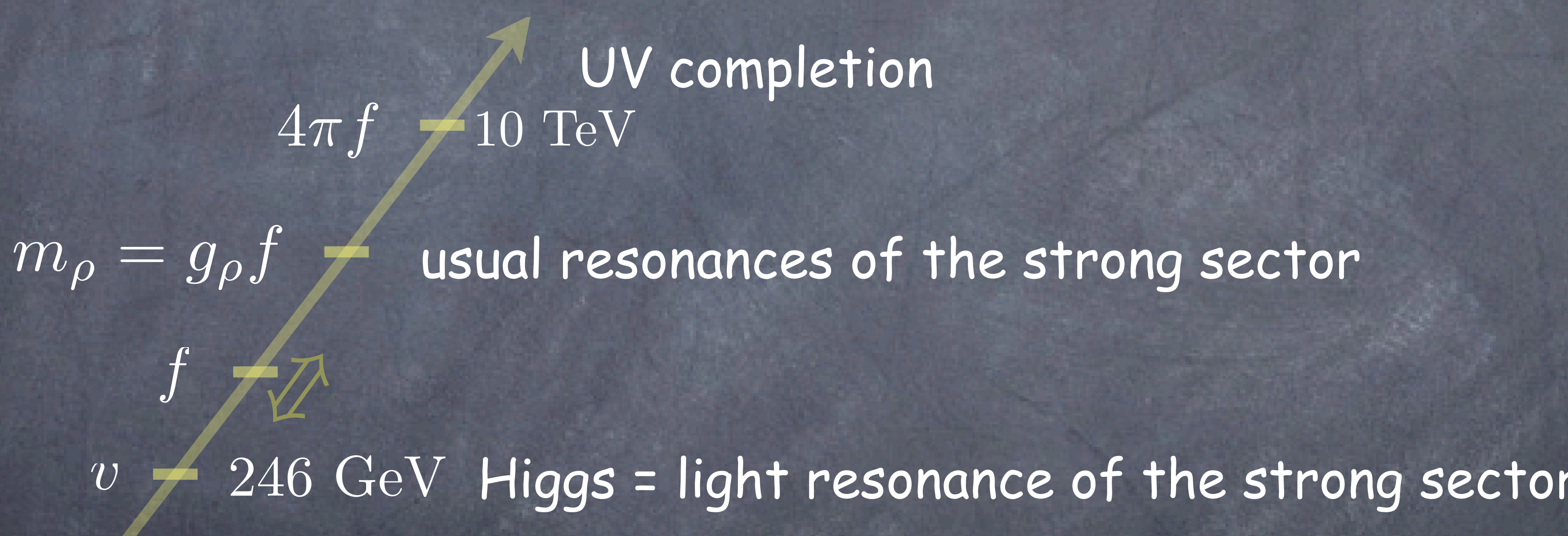
How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



$m_{Higgs}=0$ when $g_{SM}=0$

global symmetry $\longrightarrow$ G/H $\longleftarrow$ residual global symmetry



strong sector broadly characterized by 2 parameters

m_ρ = mass of the resonances

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

Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else*:

- evidence for string landscape???
- it will be more important then ever to figure out whether the Higgs is composite!

- **Model-dependent:** production of resonances at m_ρ
- **Model-independent:** study of Higgs properties & W scattering
  - Higgs anomalous coupling
  - strong WW scattering
  - strong HH production
  - gauge bosons self-couplings

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

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \boxed{\frac{c_H}{2f^2}} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$U = e^{i\begin{pmatrix} & H/f \\ H^\dagger/f & \end{pmatrix}} U_0$$

$$f^2 \operatorname{tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) = |\partial_\mu H|^2 + \frac{\sharp}{f^2}\left(\partial|H|^2\right)^2 + \frac{\sharp}{f^2}|H|^2\,|\partial H|^2 + \frac{\sharp}{f^2}\left|H^\dagger \partial H\right|^2$$

What distinguishes a composite Higgs?

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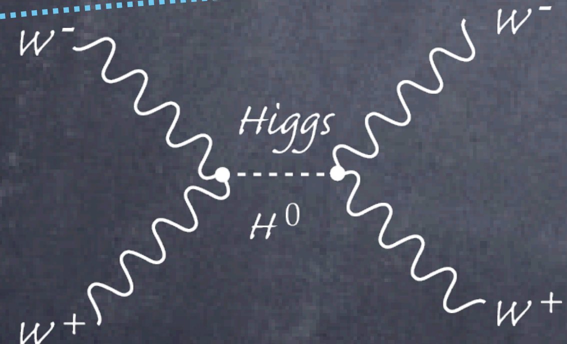
$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\displaystyle \frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2}$



$$= -\left(1 - c_H \frac{v^2}{f^2}\right) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

unitarization restored by heavy resonances

Falkowski, Pokorski, Roberts '07

Strong W scattering below m_ρ

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial_\mu\left(|H|^2\right)\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6\lambda}{f^2}|H|^6$$

custodial breaking

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

Goldstone sym.

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed by custodial symmetry

$$\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2} \Longrightarrow m_\rho \geq (c_W + c_B)^{1/2}\ 2.5\ \mathrm{TeV}$$

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\hat{S}, \hat{T} = a\left((1 - c_H\xi) \log m_h + c_H\xi \log\Lambda\right) + b$$

effective Higgs mass

$$m_h^{eff} = m_h \left(\frac{\Lambda}{m_h}\right)^{c_H v^2/f^2} > m_h$$

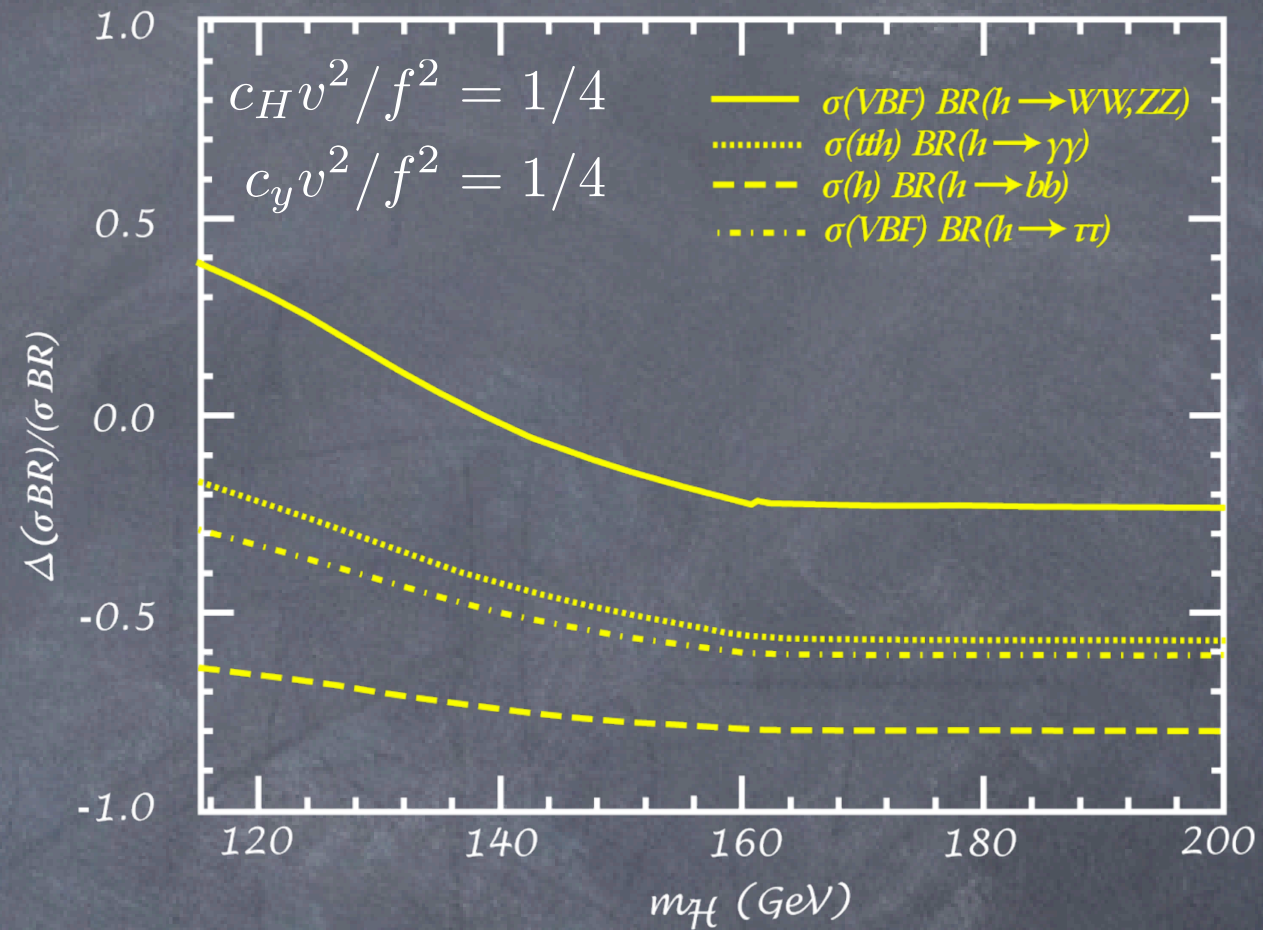
LEPII, for m_h~115 GeV: $c_H v^2/f^2 < 1/3 \sim 1/2$

IR effects can be cancelled by heavy fermions (model dependent)

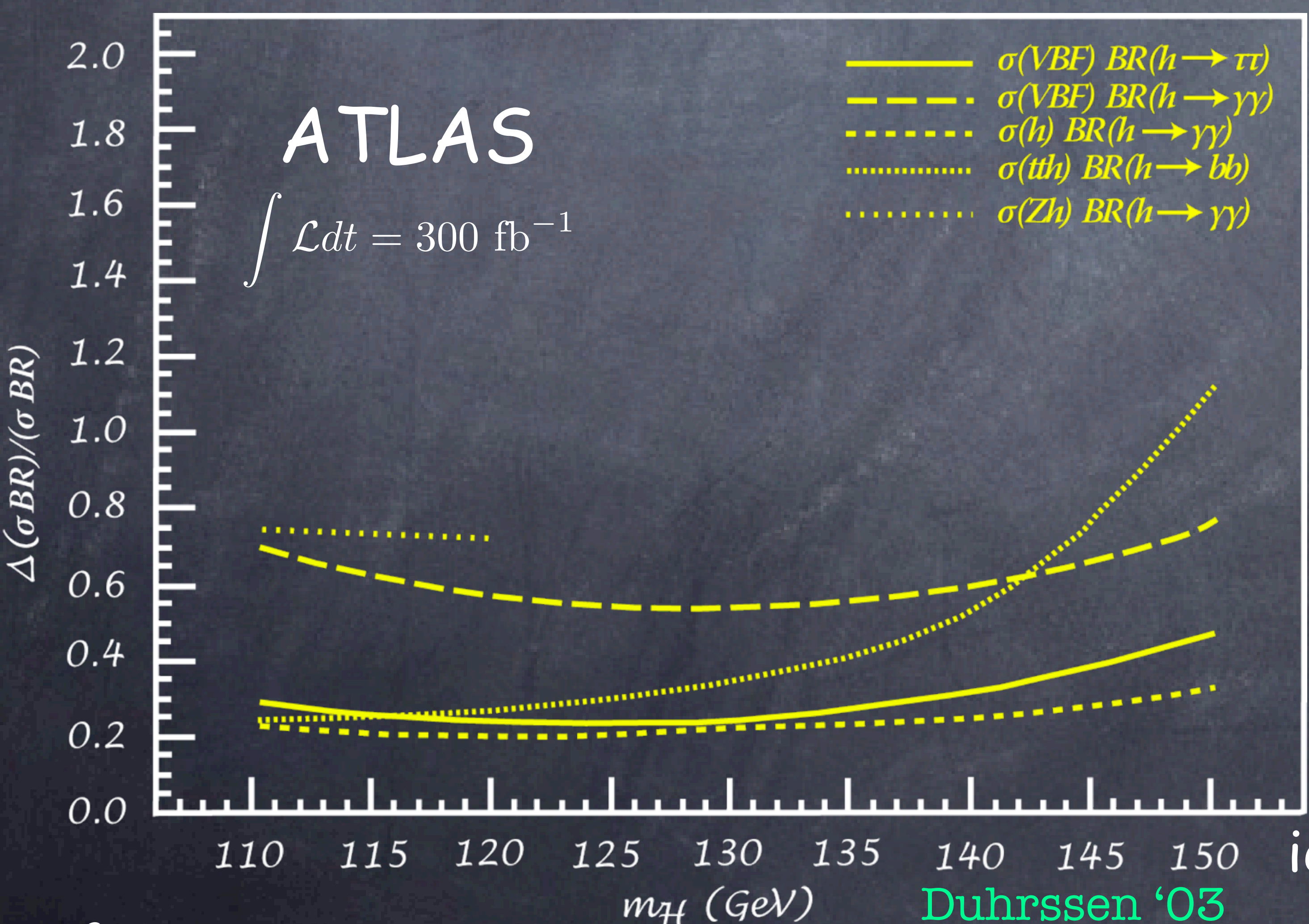
Higgs anomalous couplings

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

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



observable @ LHC?



Duhrssen '03

LHC can measure

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

up to 20-40%

(composite scale 5-7 TeV)

(ILC could go to few %

ie test composite Higgs up to $4\pi f \sim 30$ TeV)

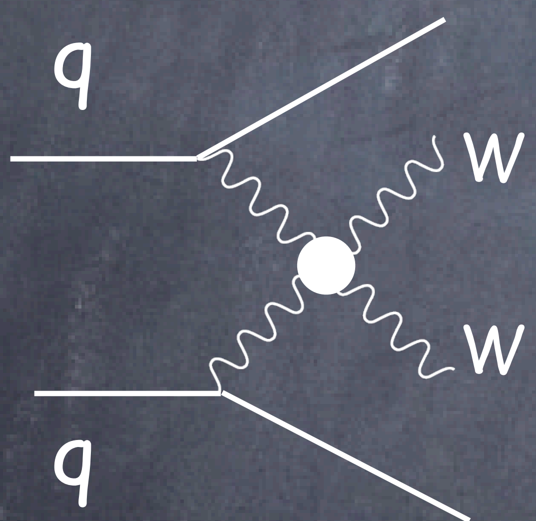
Strong W scattering

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2}$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \qquad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0$$



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\cancel{H}}$$

leptonic vector decay channels

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

with 300 fb^{-1}

30 signal-events and 10 background-events

Bagger et al '95
Butterworth et al. '02

⇒

LHC is sensitive to

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

bigger than

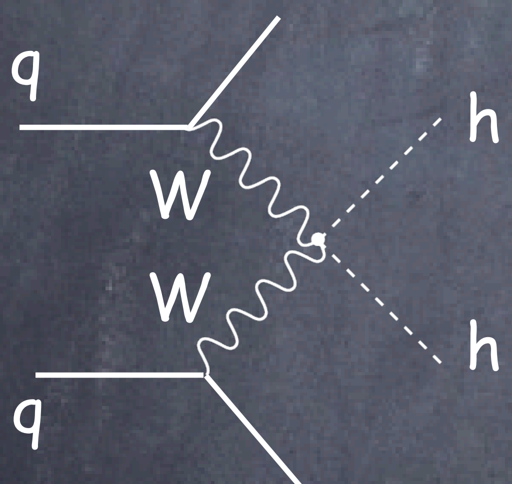
0.5 ~ 0.7

Strong Higgs production

O(4) symmetry between W_L, Z_L and the physical Higgs

strong boson scattering ⇔ strong Higgs production

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



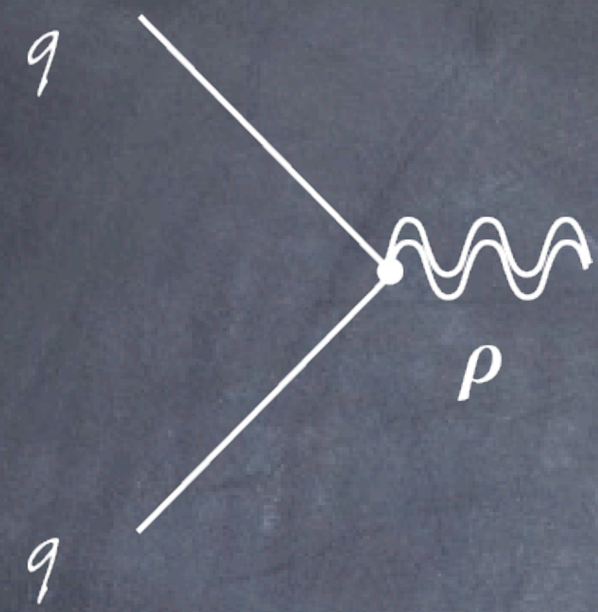
signal:
- hh → bbbb
- hh → 4W → $\ell^\pm \ell^\pm \nu\nu$jets

Sum rule (with cuts $|\Delta\eta| < \delta$ and $s < M^2$)

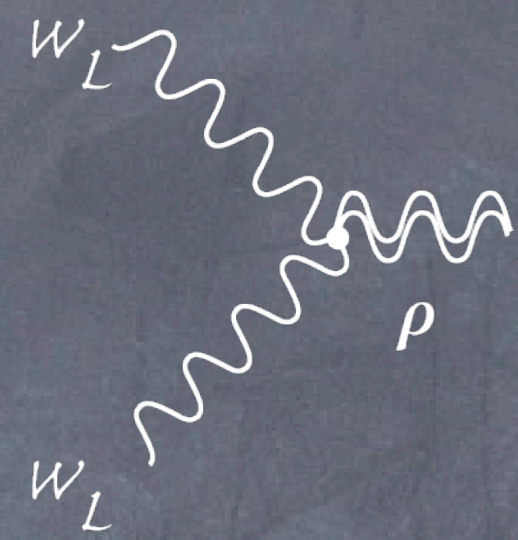
$$2\sigma_{\delta,M}\left(pp \to hhX\right)_{c_H} = \sigma_{\delta,M}\left(pp \to W_L^+ W_L^- X\right)_{c_H} + \frac{1}{6}\left(9 - \tanh^2\frac{\delta}{2}\right)\sigma_{\delta,M}\left(pp \to Z_L^0 Z_L^0 X\right)_{c_H}$$

Direct vs. indirect signals

direct production of (TeV) resonances



$$= \frac{g_{SM}^2}{g_\rho}$$



$$= g_\rho$$

$$\sigma\left(pp \to \rho_H^\pm + X\right) = \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{3\ \mathrm{TeV}}{m_\rho}\right)^6 0.5\ \mathrm{fb}$$

for larger g_ρ, the resonances are increasingly harder to see as

1/ they are broader and heavier

2/ they couple more and more weakly to fermions

LHC could reach a resonance around 4 TeV

Continuous Connections between Models

Composite Higgs $\Rightarrow$ Higgsless

reduce couplings Higgs/W,Z

"gaugephobic higgs"

Cacciapaglia, Csaki, Marandella, Terning '06

new realization of old

- ✓ bosonic technicolor Carone, Simmons '92
- ✓ topcolor assisted technicolor Hill '94

Exotic Scenarios

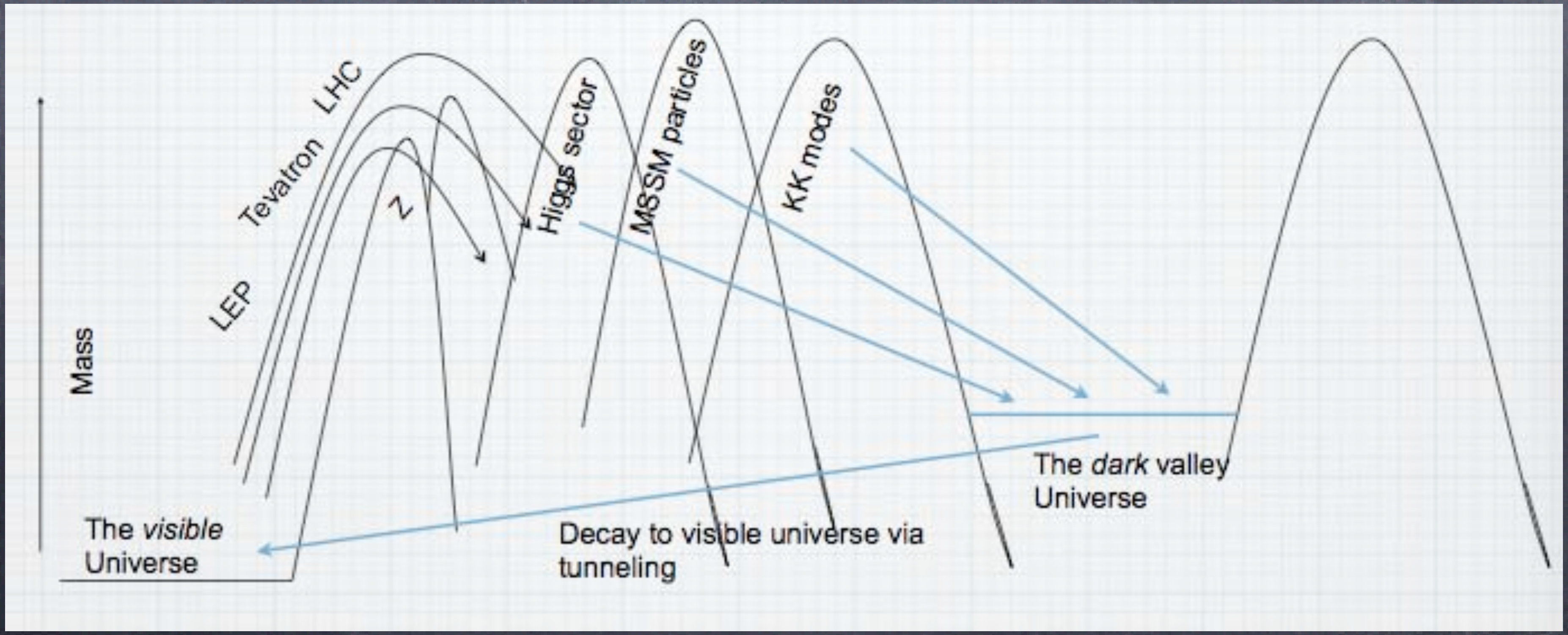
The LHC see many exciting signatures
beyond the Standard Model...

To complete the review...

- Hidden valley models

Strassler, Zurek '06

- low mass hidden sectors connected to SM through higher dimension operators
- hidden = neutral under SM gauge group, charged under high mass mediator
- possible decays to 'our' universe via tunneling



To complete the review...

- Unparticles

Georgi '07 + many others

  - example of hidden valley models with a hidden sector with a non-trivial conformal IR fixed point
  - unparticles look like a non-integral number of invisible particles

- Higgs portal

Patt, Wilczek '06,
Chang, Fox, Weiner '05,
O'Connel, Ramsey-Musolf, Wise '06,
Espinosa, Quiros '07
+...

  - more Higgs doublets or new Higgs singlets
  - dark matter candidates
  - strengthen the EW phase transition ⇒ EW baryogenesis?

Conclusions

EW interactions need a UV moderator
to unitarize WW scattering amplitude

"theorists are getting cold feet" J. Ellis

"they have done their best to predict the possible and impossible"
G. Giudice

Oblique corrections are a test of new physics

Need other observables to identify the nature of new physics

What is the mechanism of EW symmetry breaking?

	LHC	ILC	CLIC
1/ is there a Higgs?	✓	✓	✓
2/ what are the Higgs mass/couplings	✓/-	✓	✓
3/ is the Higgs a SM like weak doublet?	☁	✓	✓
4/ is the Higgs elementary or composite?	☁	✓	✓✓
5/ is EWSB natural or fine-tuned?	?	✓	✓✓
6/ are there new dimensions? new strong forces?	-	✓	✓