From Higgsless to Composite Higgs Models

based on works in collaboration with

G. Giudice, A. Pomarol and R. Rattazzi

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work in progress

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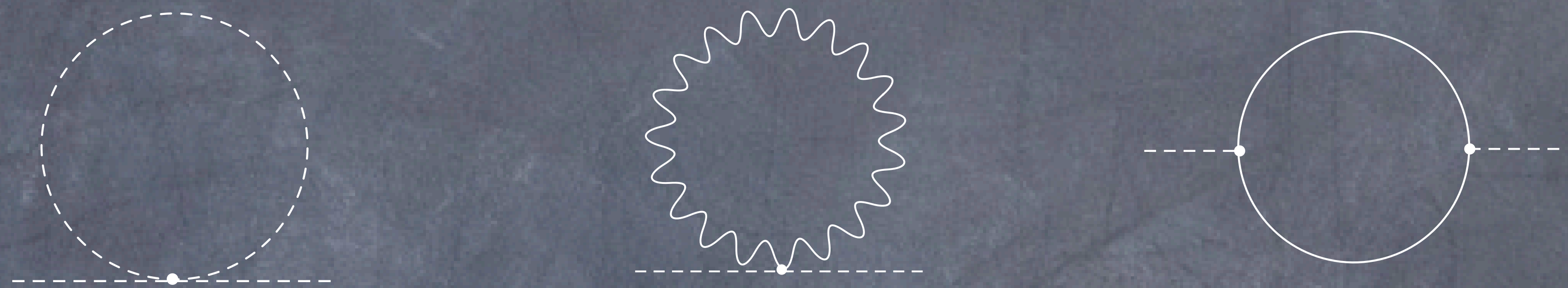
Main Question for the LHC

What is the mechanism of EW symmetry breaking?

what we usually mean by that question is really

what is canceling these infamous diagrams?



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

supersymmetry, gauge-Higgs, Little Higgs

But this is assuming that we already know the answer to

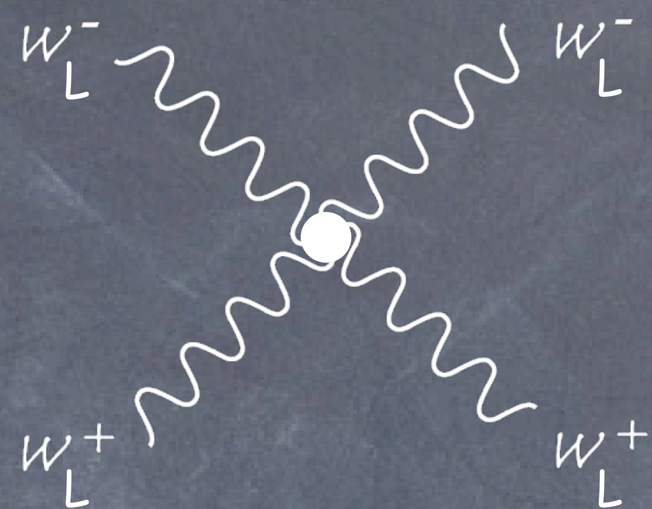
Main Question for the LHC

What is unitarizing the WW scattering amplitudes?

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

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

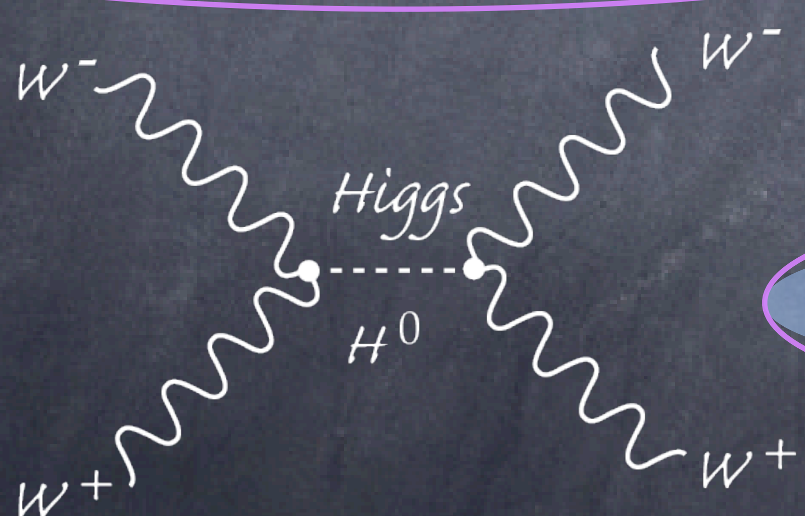
$$\mathcal{A} = g^2\left(\frac{E}{M_W}\right)^2$$



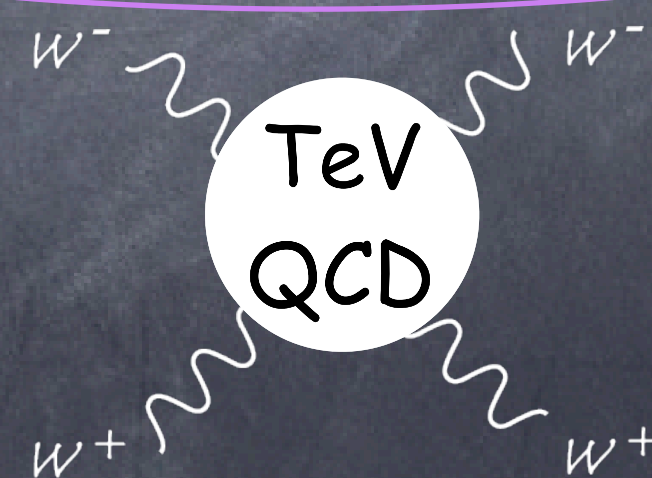
W_L & Z_L part of EWSB sector (we have already discovered 75% of the Higgs doublet!) ⊃ WW scattering is a probe of Higgs sector interactions

Weakly coupled models

Strongly coupled models



other ways?



prototype: Susy

susy partners ~ 100 GeV

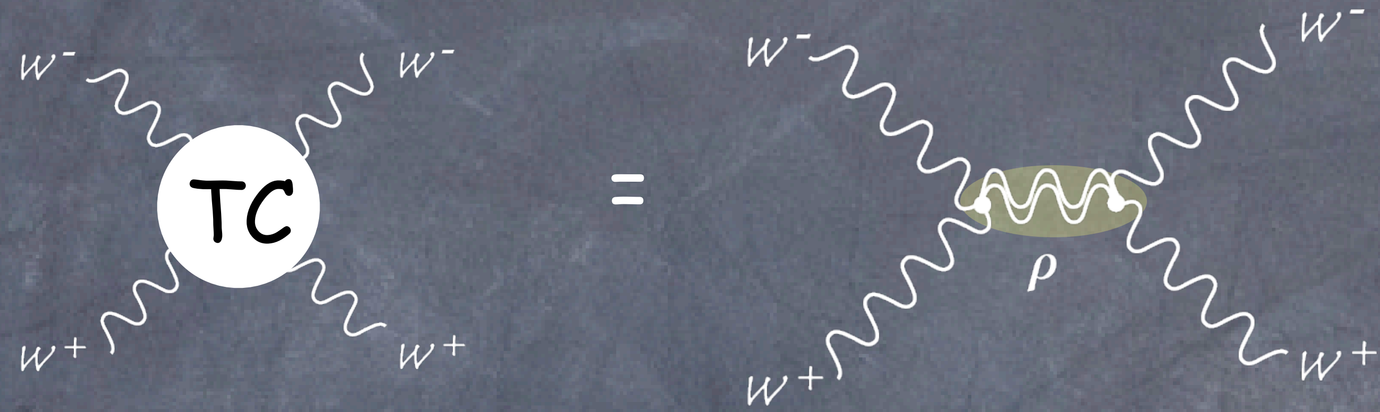
prototype: Technicolor

rho meson ~ 1 TeV

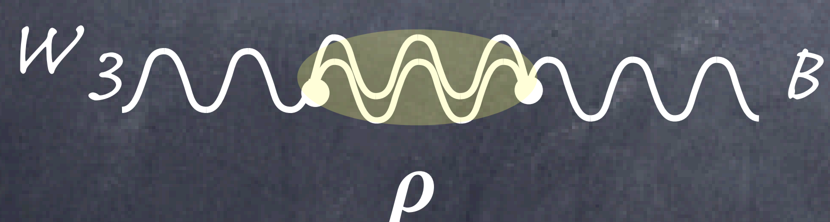
Strongly coupled models

a technical 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

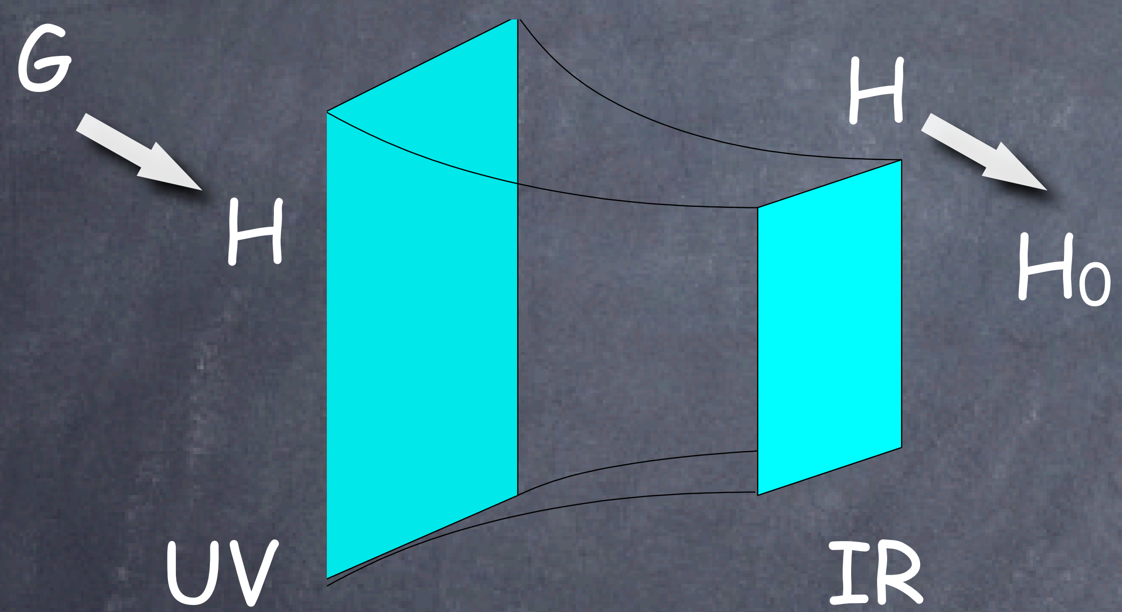
"AdS/CFT" correspondence for model-builder

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

- weakly coupled description ⊃ calculable models
- new approach to fermion embedding and flavor problem

Higgsless Models

Warped Higgsless Model

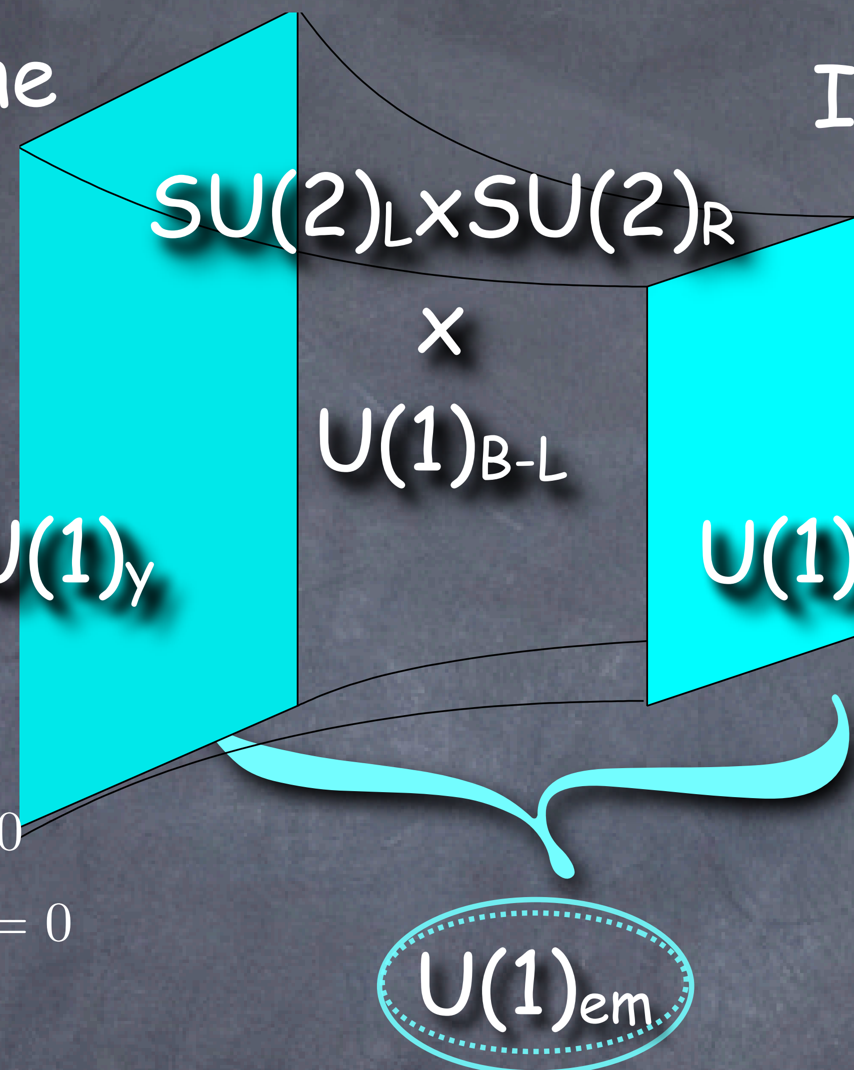
Csaki, Grojean, Pilo, Terning '03

UV brane

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

IR brane

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



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

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

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

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

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

"light" mode:

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

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

log suppression

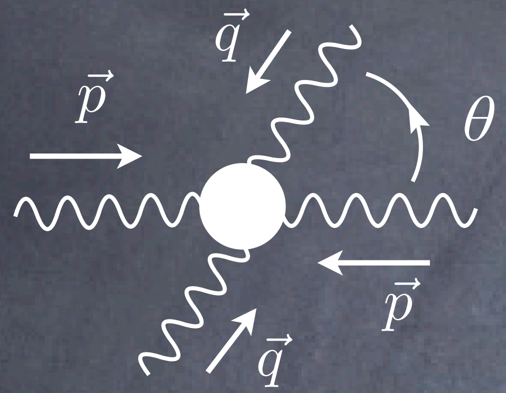
KK tower:

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

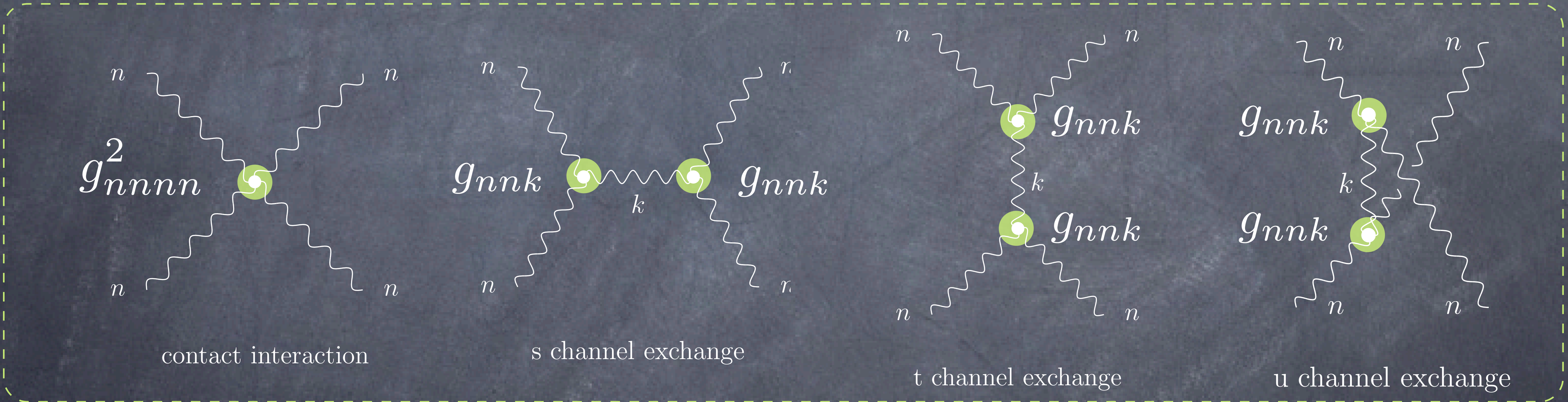
Unitarization of (Elastic) Scattering Amplitude

Same KK mode 'in' and 'out'

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



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



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

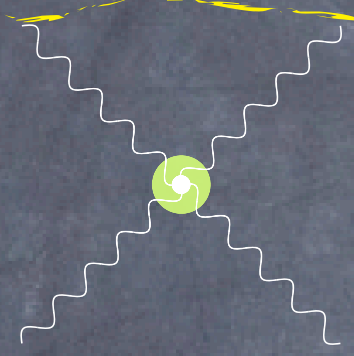
$$\mathcal{A}^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - s^2_{\theta/2}f^{abe}f^{cde}\right)$$

KK Sum Rules

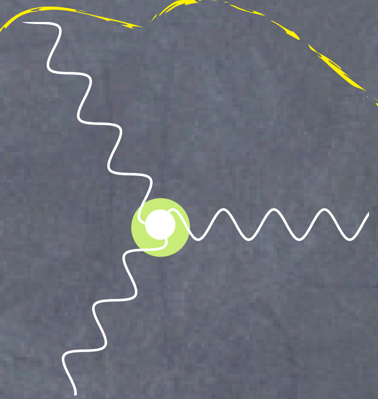
Csaki, Grojean, Murayama, Pilo, Terning '03

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

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



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



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

- E^4 Sum Rule

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

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

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

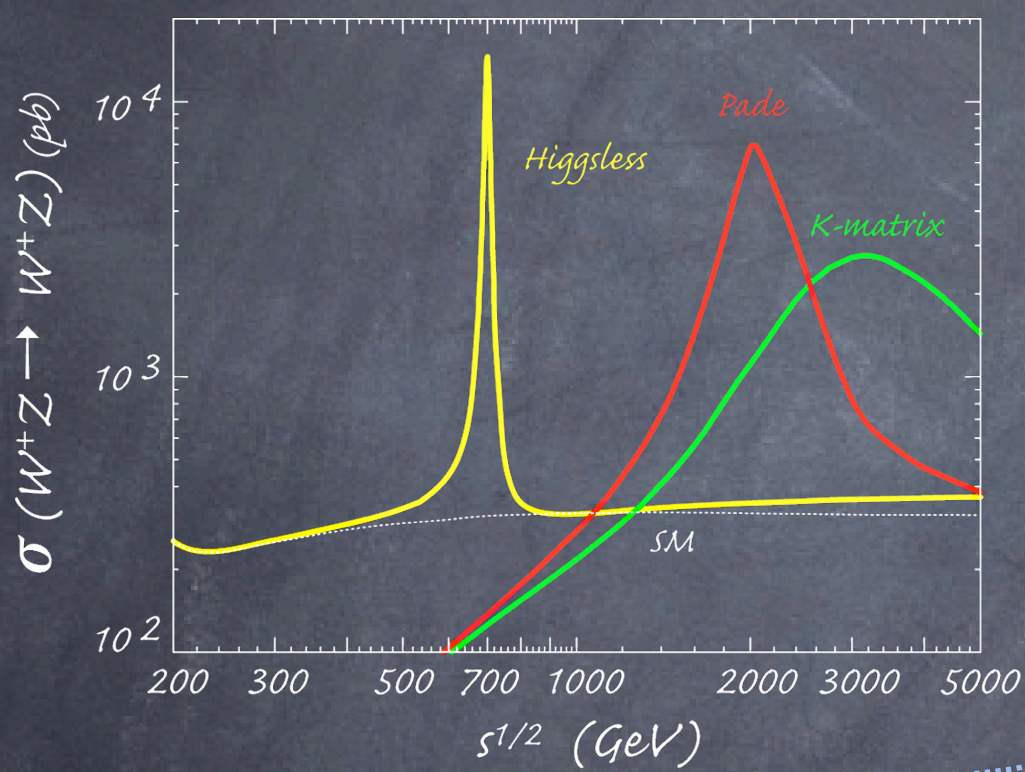
Completness of KK modes

Collider Signatures

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

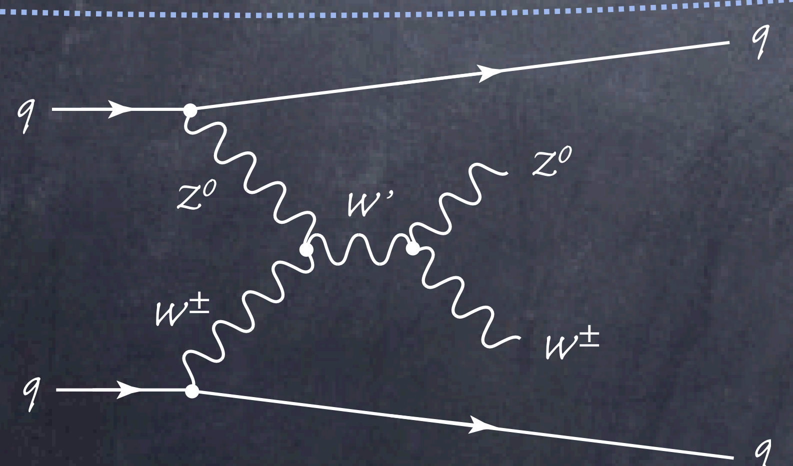
unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

WZ elastic cross section



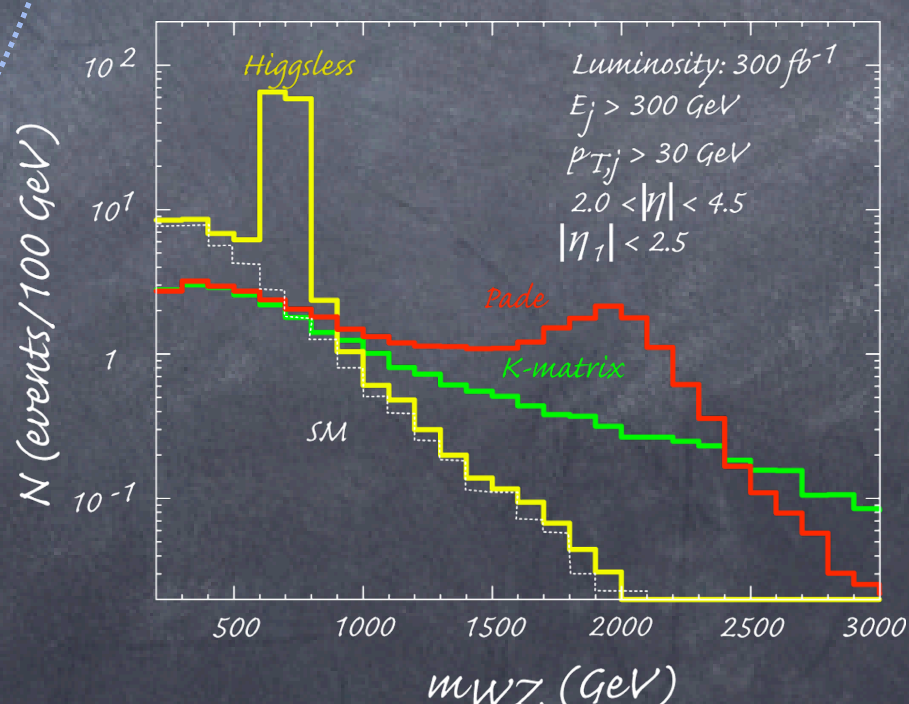
$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

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

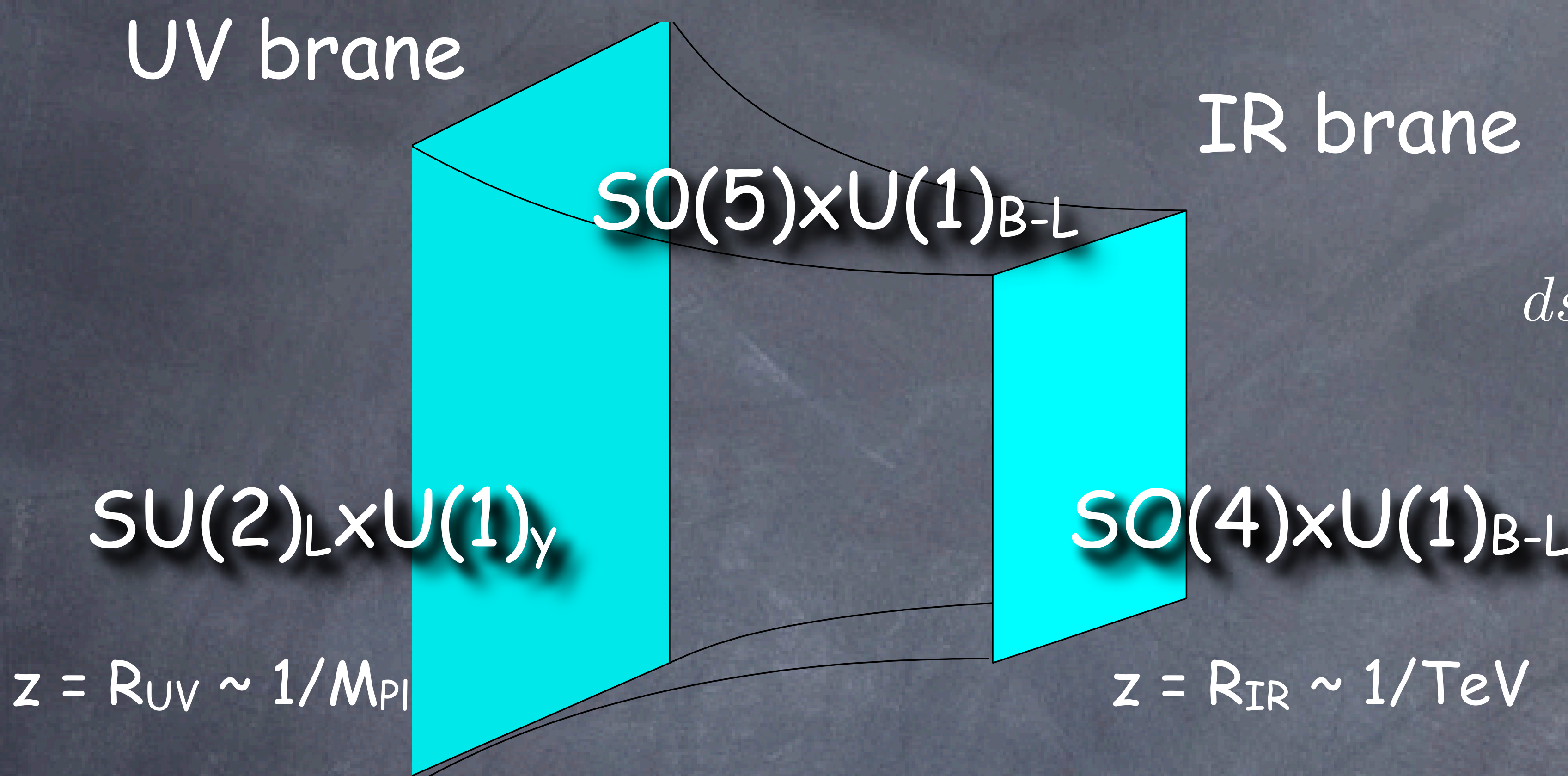
1 TeV $\to$ 60 fb^{-1}

should be seen within one/two year

Composite Higgs Models

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04



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

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

warped dual to composite Higgs model

SO(5) SO(4)

$$\begin{pmatrix} & \mathrm{SO(4)} & & & h_1 \\ & & & & h_2 \\ & & & & h_3 \\ & & & & h_4 \\ -h_1 & -h_2 & -h_3 & -h_4 & 0 \end{pmatrix}$$

Adj ← A_μ

4 ← A_5

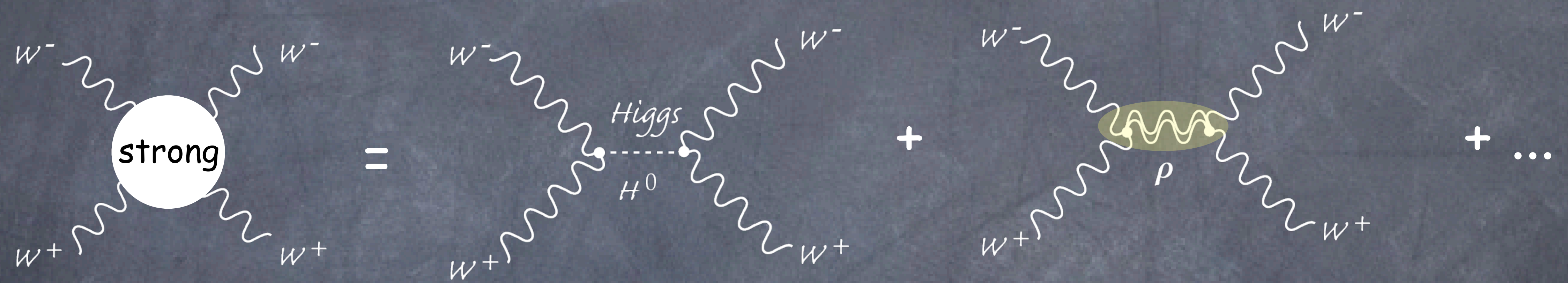
SO(5)/SO(4) contains a doublet

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

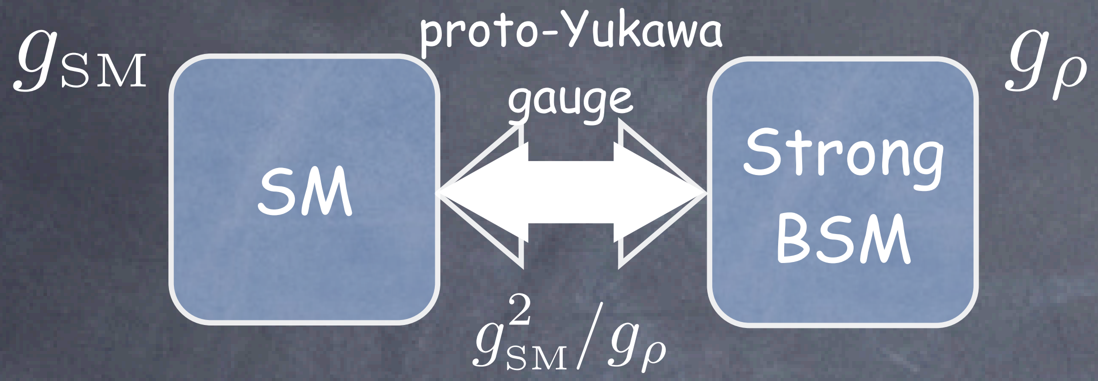
heavy rho

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. $\hat{S}_{\rm UV} \sim \frac{g^2 N}{96\pi^2}\frac{v^2}{f^2}$

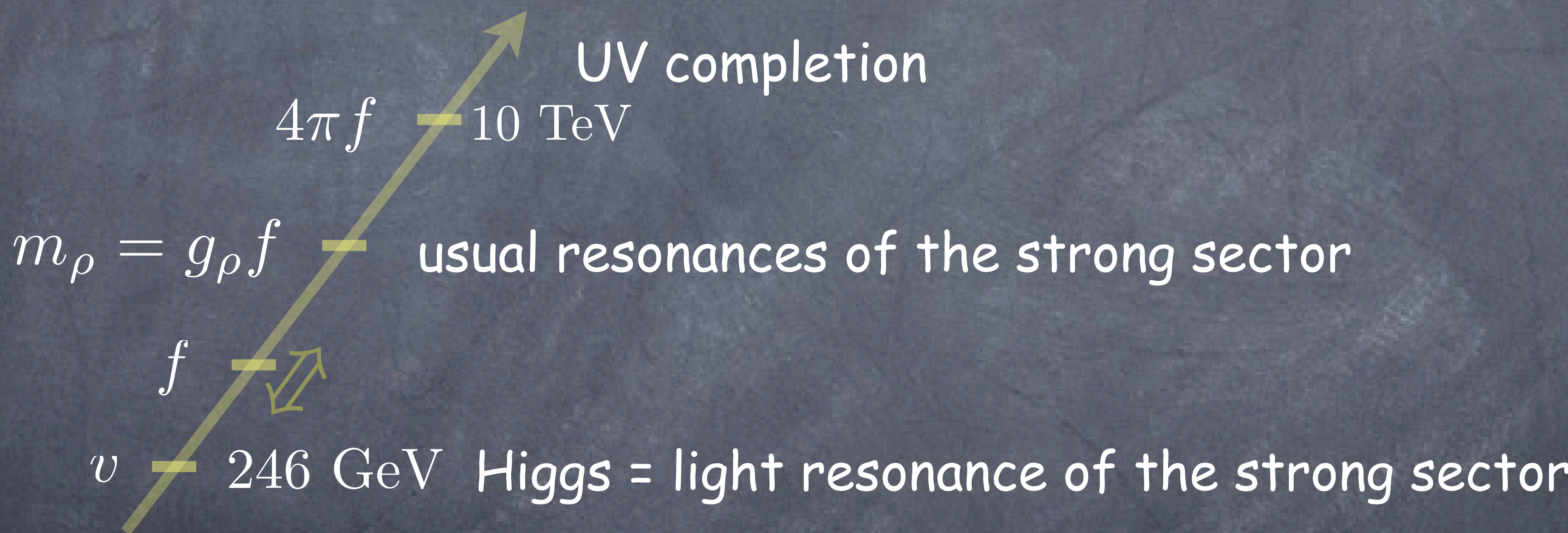
How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← 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 $f = \dfrac{m_\rho}{g_\rho}$

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

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

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

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

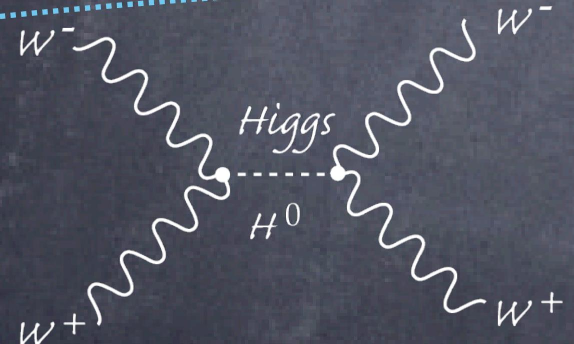
What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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



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

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)

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

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

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

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

removed by custodial symmetry

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

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

$$\Downarrow$$

$$\hat{S}, \hat{T} = a \left((1 - c_H v^2/f^2) \log m_h + c_H v^2/f^2\ \log \Lambda \right) + b$$

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)

Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right) y_{ij}\bar{f}_{Li}Hf_{Rj} = \left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$+\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

mass and interaction matrices are not diagonalizable simultaneously if c_{ij} are arbitrary

$\Rrightarrow$ FCNC

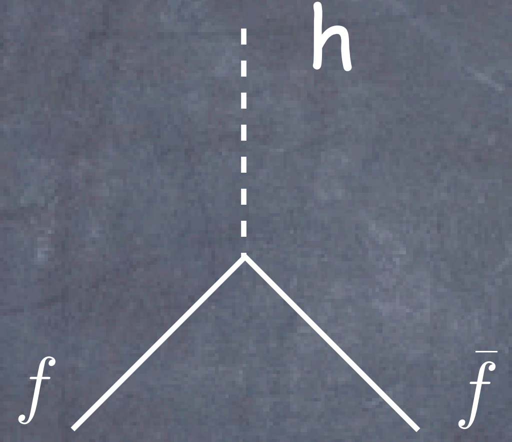
SILH: c_y is flavor universal

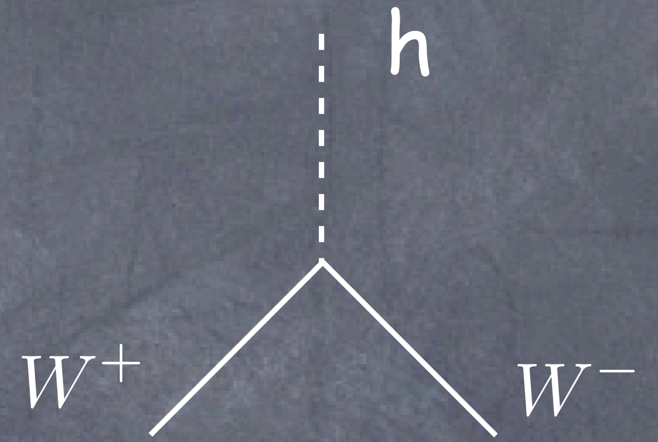
$\Rrightarrow$ Minimal flavor violation built in

Higgs anomalous couplings

Lagrangian in unitary gauge

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left(-\frac{m_H^2}{2v}(c_6 - 3c_H/2)h^3 + \frac{m_f}{v}\bar{f}f(c_y + c_H/2)h - c_H\frac{m_W^2}{v}hW_\mu^+W^{-\mu} - c_H\frac{m_Z^2}{v}hZ_\mu Z^\mu \right)\frac{v^2}{f^2} + \dots$$





$$g_{SM}\left(1 - (c_y + c_H/2)v^2/f^2\right)$$

$$g_{SM}\left(1 - c_H v^2/f^2\right)$$

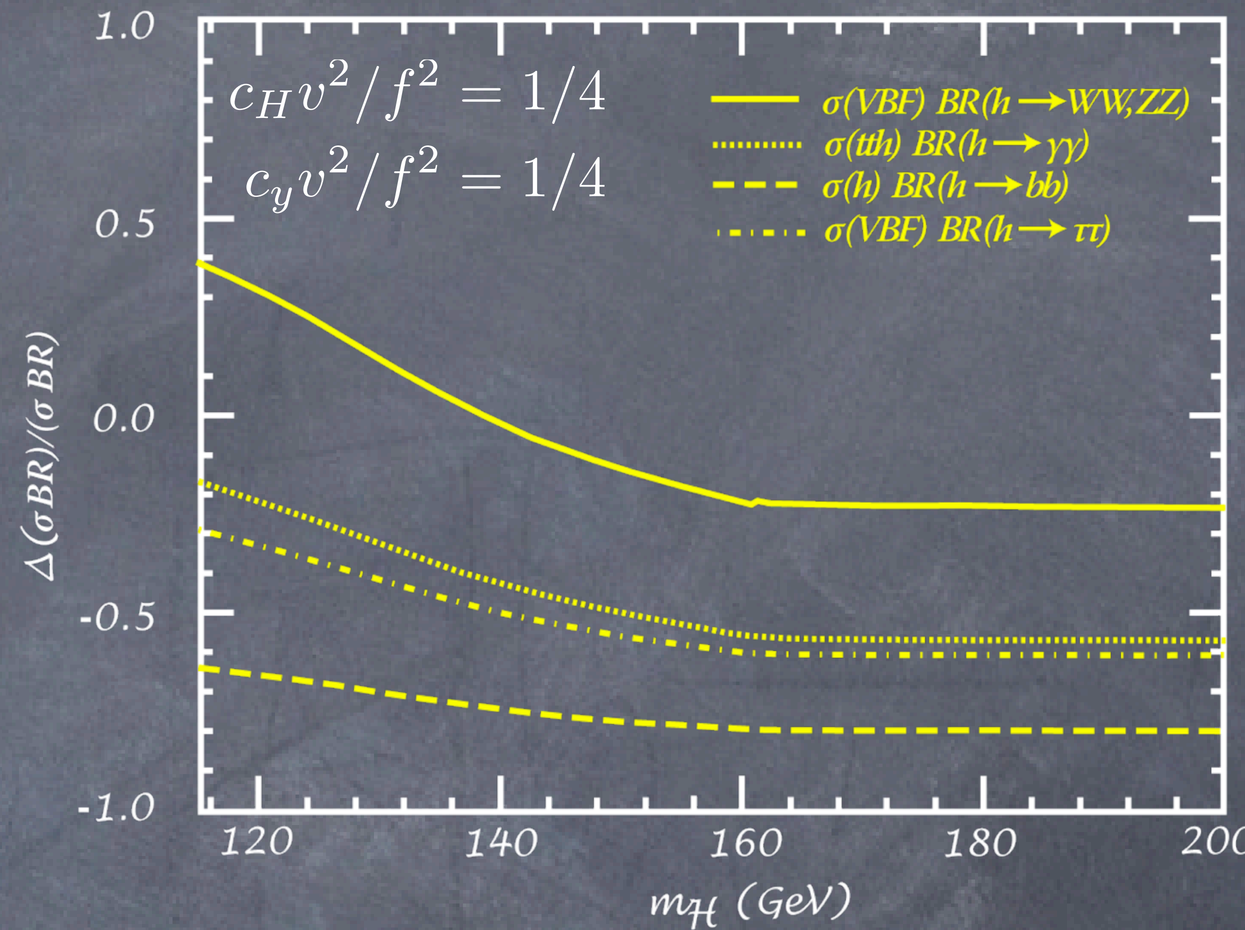
$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - (2c_y + c_H)\, v^2/f^2\right]$$

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

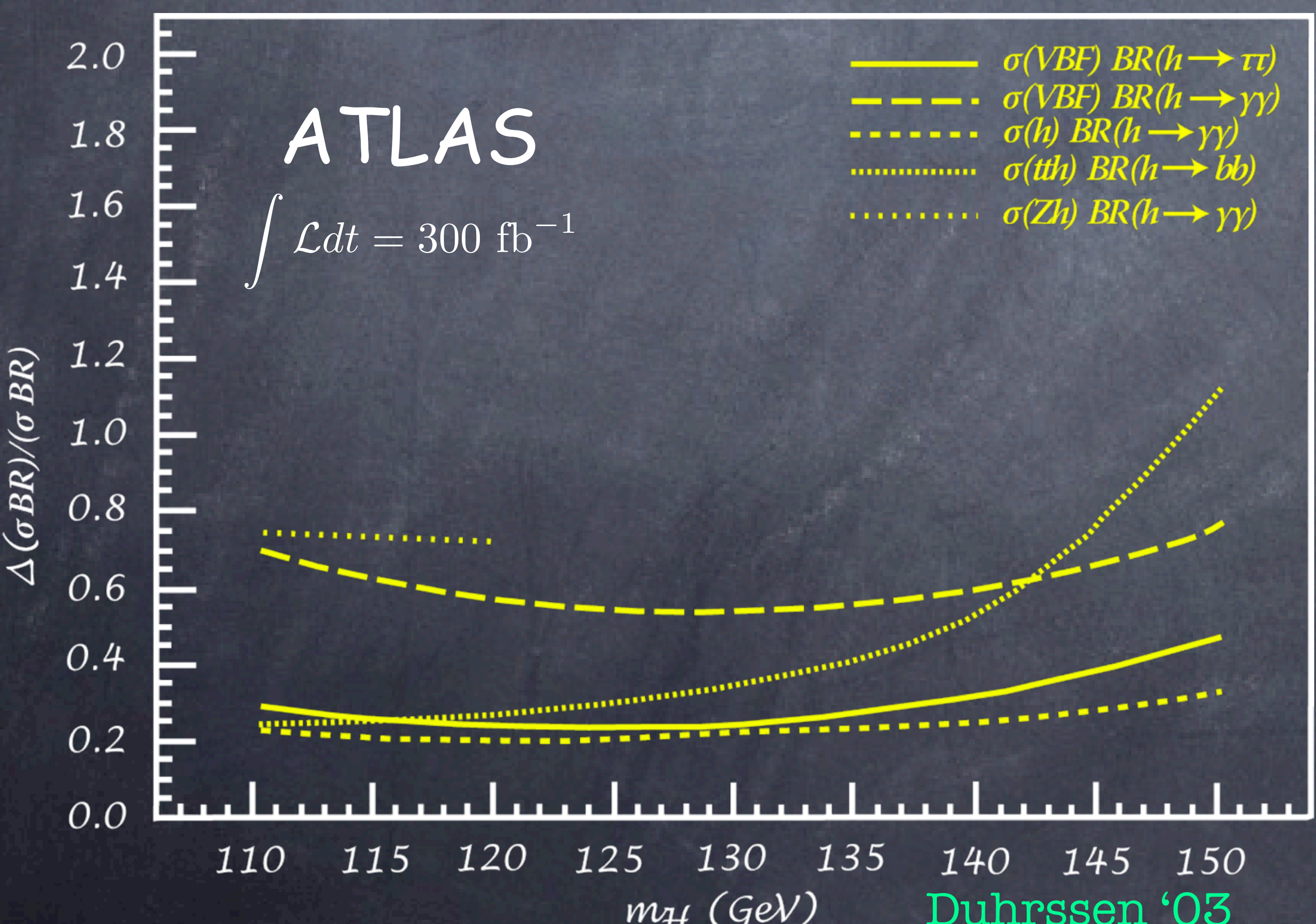
Higgs anomalous couplings

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

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



observable @ LHC?



Duhrssen '03

LHC can measure

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

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)

Higgs anomalous couplings for large v/f

The SILH Lagrangian is an expansion for small v/f
The 5D MCHM gives a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \quad \Rightarrow \quad g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM}$$

Fermions embedded in spinorial of SO(5)

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\rm SM}$$

universal shift of the couplings
no modifications of BRs

Fermions embedded in 5+10 of SO(5)

$$m_f = M \sin 2v/f$$

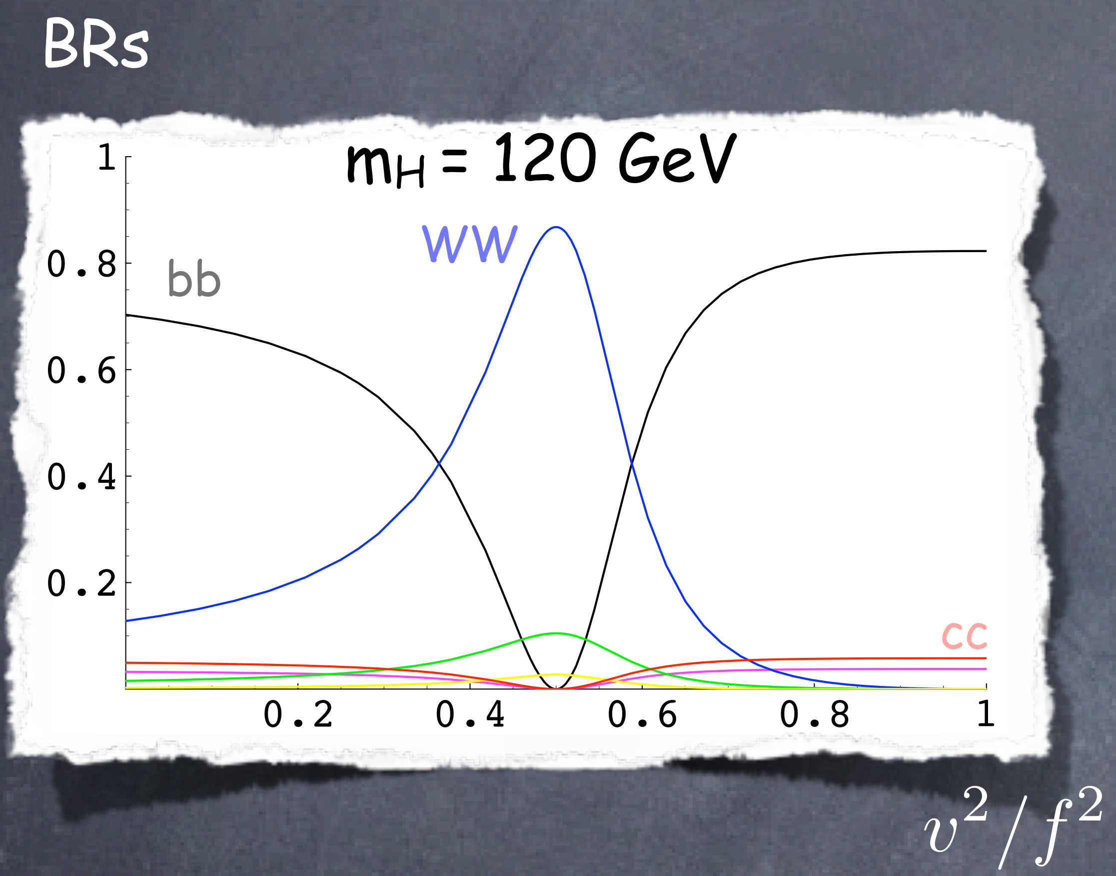
$$\Downarrow$$

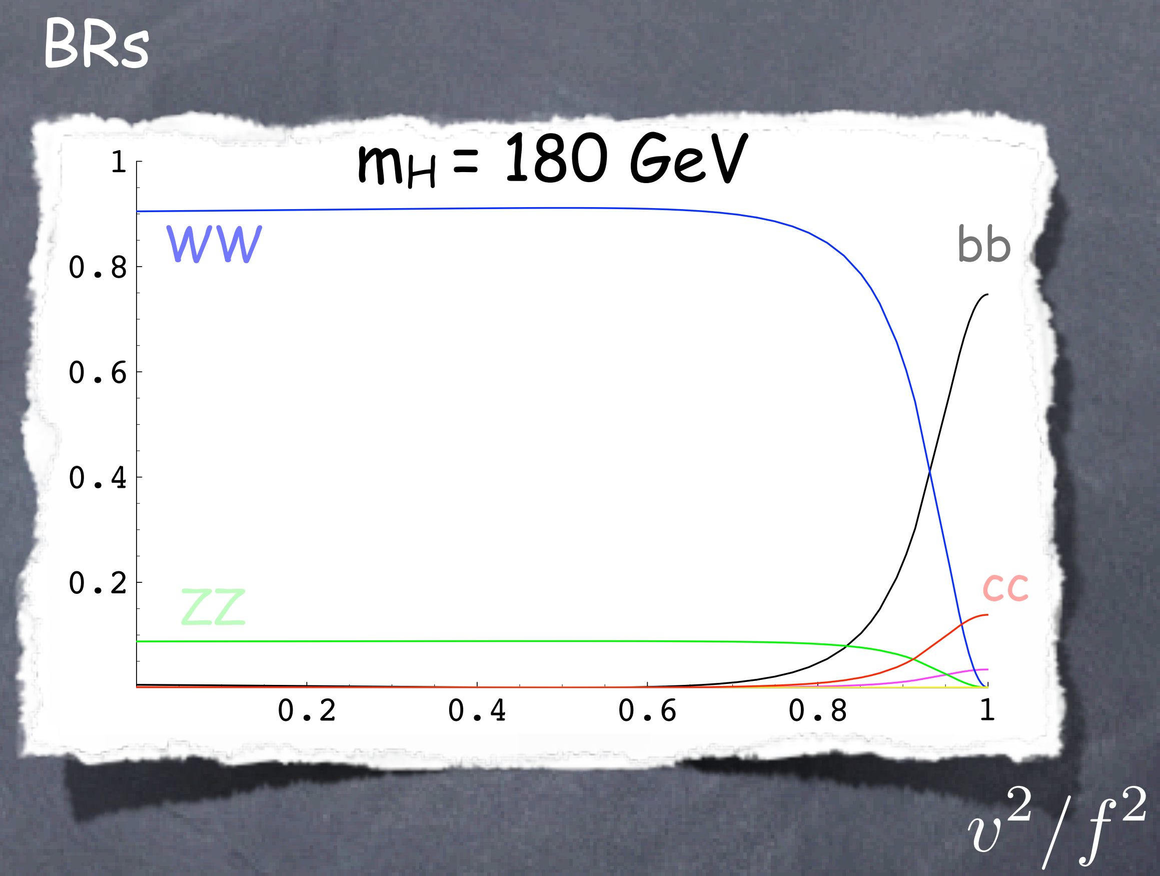
$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\rm SM}$$

BRs now depends on v/f

Higgs BRs

Fermions embedded in 5+10 of SO(5)





h→WW can dominate
even for low Higgs mass

BRs remain SM like
for large value of v/f

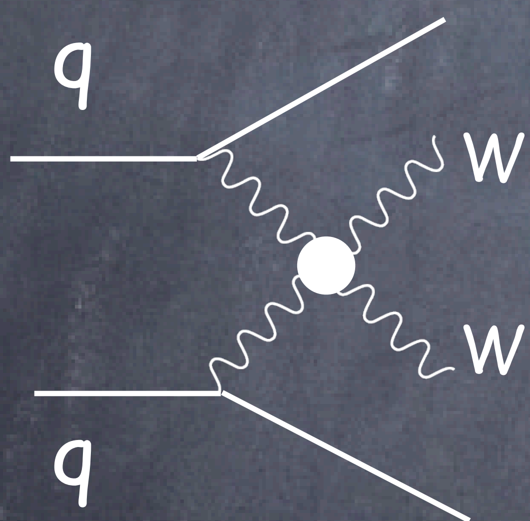
Strong W scattering

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

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

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

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



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not{H}}$$

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

LHC is sensitive to

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

bigger than

0.5 ~ 0.7

Bagger et al '95

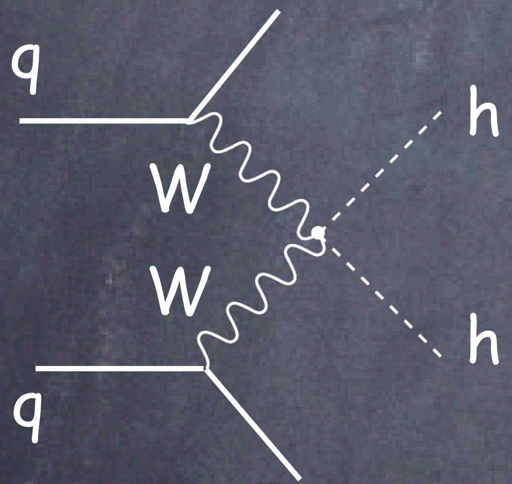
Butterworth et al. '02

Strong Higgs production

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

strong boson scattering ⇔ strong Higgs production

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

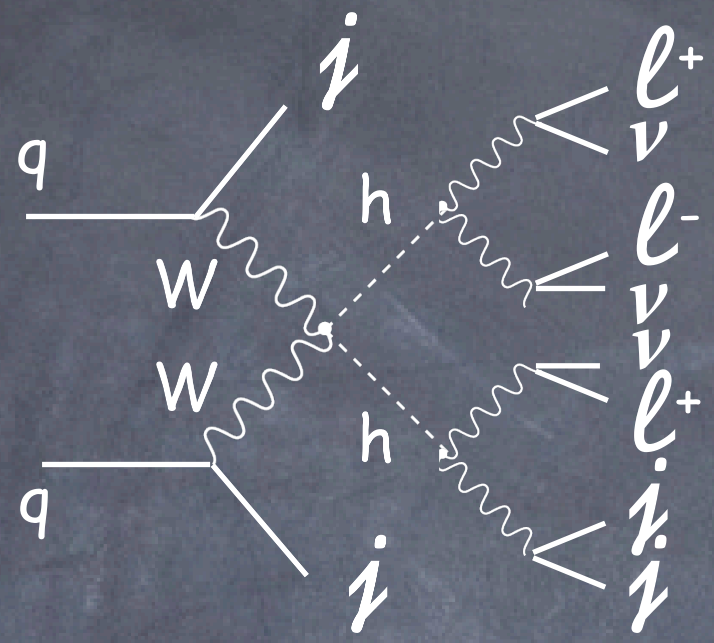


signal:
- hh → bbbb
- hh → 4W → $3\ell^{\pm}3\nu$+jets

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

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

Strong Higgs production



$\xi = 0$	$\sigma = 0.01\ \text{fb}$
$\xi = 0.5$	$\sigma = 0.1\ \text{fb}$
$\xi = 1$	$\sigma = 0.3\ \text{fb}$

Dominant backgrounds

- $t\bar{t}2W \to b\bar{b}4W \to 3l3\nu 2b2j$ $\quad\sigma = 3.5\ \text{fb}$
- $t\bar{t}W2j \to b\bar{b}3W2j \to 3l3\nu 2b2j$ $\quad\sigma = 1.9\ \text{fb}$
- $t\bar{t}W1j \to b\bar{b}3W2j \to 3l3\nu 2b1j$ $\quad\sigma = 3.1\ \text{fb}$
- $WZ4j \to 3l1\nu 4j$ $\quad\sigma = 40\ \text{fb}$

Cuts on
M_{jj} > 400 GeV
&
$|\eta_j|_{max}>2$

~ 10 events for signal and ~ 3 events for background
(@300 fb^{-1})

Gauge boson self-couplings

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W^+_\mu W^-_\nu$$

TGC are sensitive to the form factor operators

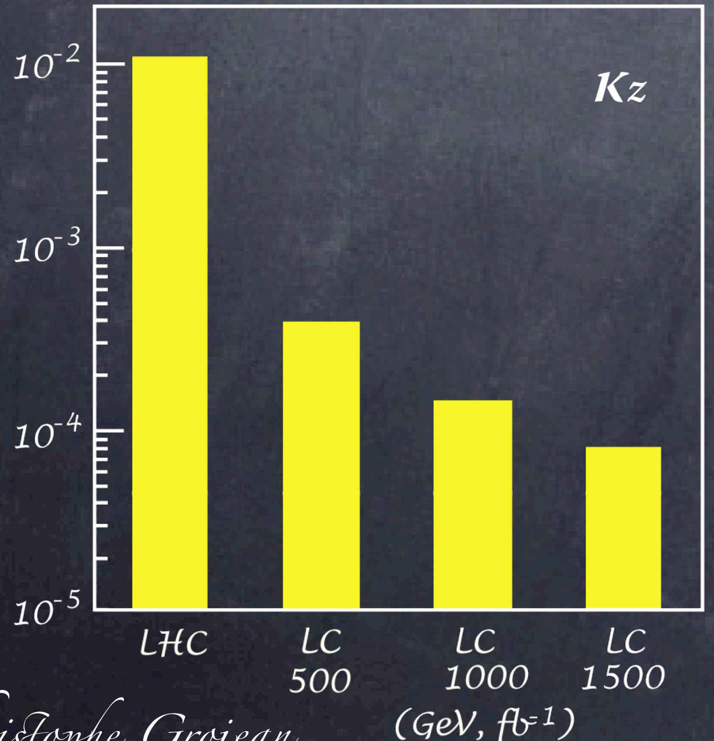
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW}+c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

@ LHC 100fb^{-1} $\quad g_1^Z \sim 1\% \qquad \kappa_\gamma \sim \kappa_Z \sim 5\%$

sensitive to resonance up to m_ρ~800 GeV

not competitive with the measure of S at LEPII

@ ILC



T. Abe et al, Snowmass '01

sensitive to resonance up to m_ρ~8TeV

Conclusions

EW interactions need a UV moderator
to unitarize WW scattering amplitude

Oblique corrections are a test of new physics

WW scattering and Higgs anomalous couplings should be able to tell us if the EWSB sector is strongly or weakly coupled.

LHC and ILC are complementary in the exploration
of the TeV scale population