New Ideas on ElectroWeak Symmetry Breaking

(a model-builder perspective)

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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?

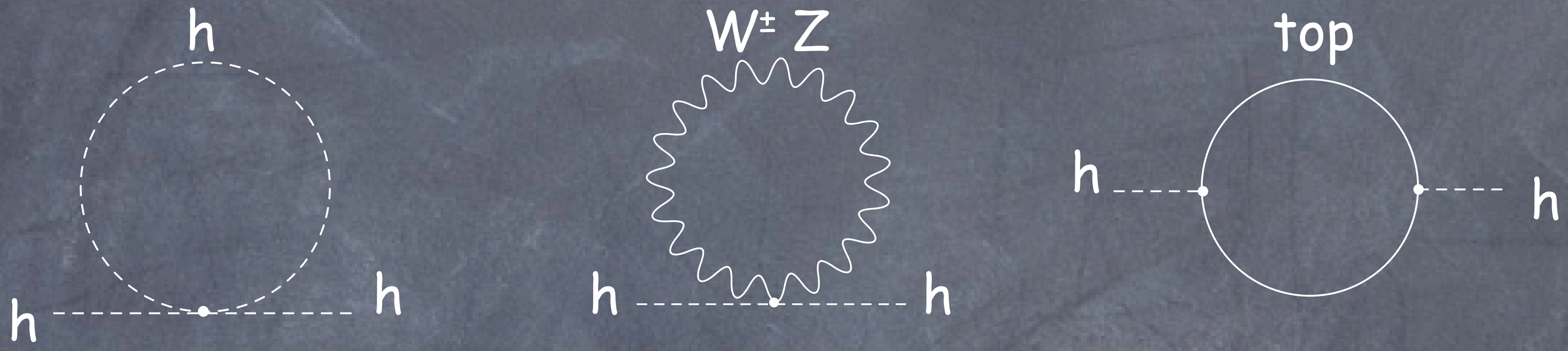
often said that the LHC is built to address this question

- what the LHC can tell us?
- what do we need another machine for?

What is the mechanism of EWSB?

actually 2 questions:

1/ what is canceling these infamous divergent diagrams?



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

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

need new degrees of freedom and new symmetries to cancel the divergences

supersymmetry, gauge-Higgs, Little Higgs

Cancellation of Λ^2 divergences

- Supersymmetry

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

- Little Higgs

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

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

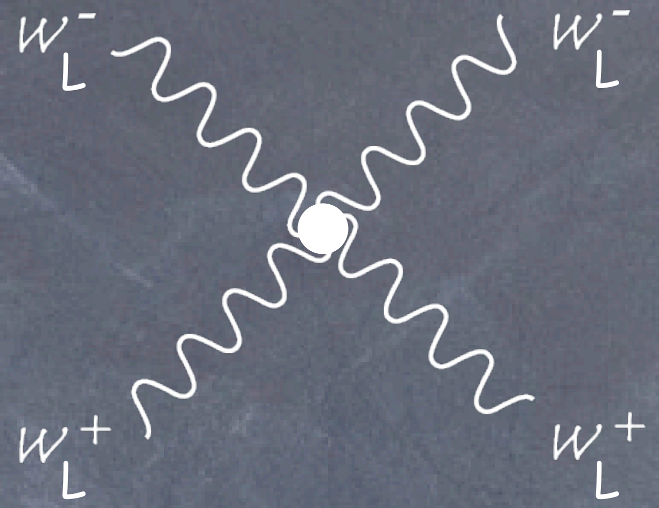
What is the mechanism of EWSB?

all these models assume that we already know the answer to the 2nd question:

2/ what is unitarizing the WW scattering amplitude?

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

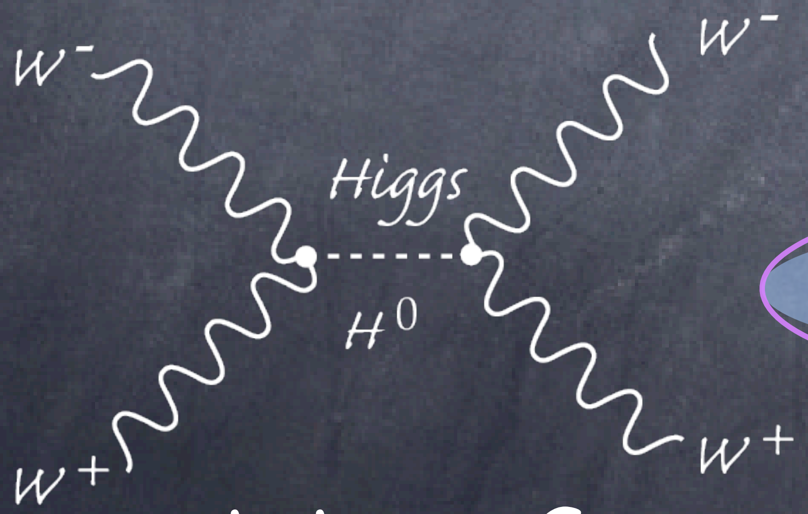
$$\mathcal{A} = g^2\left(\frac{E}{M_W}\right)^2$$



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

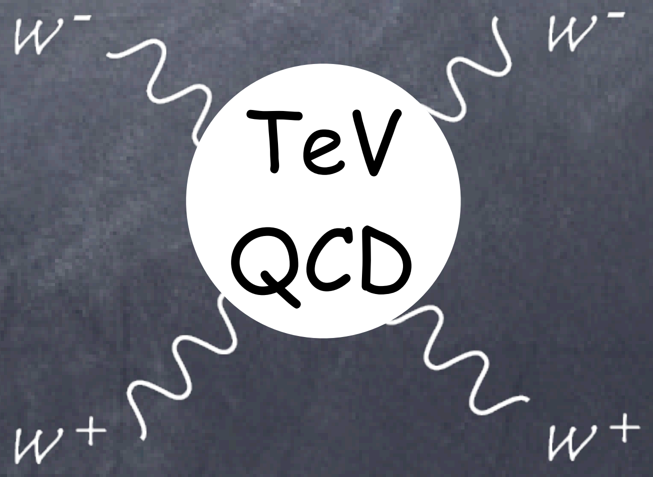
Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

Strongly coupled models



prototype: Technicolor

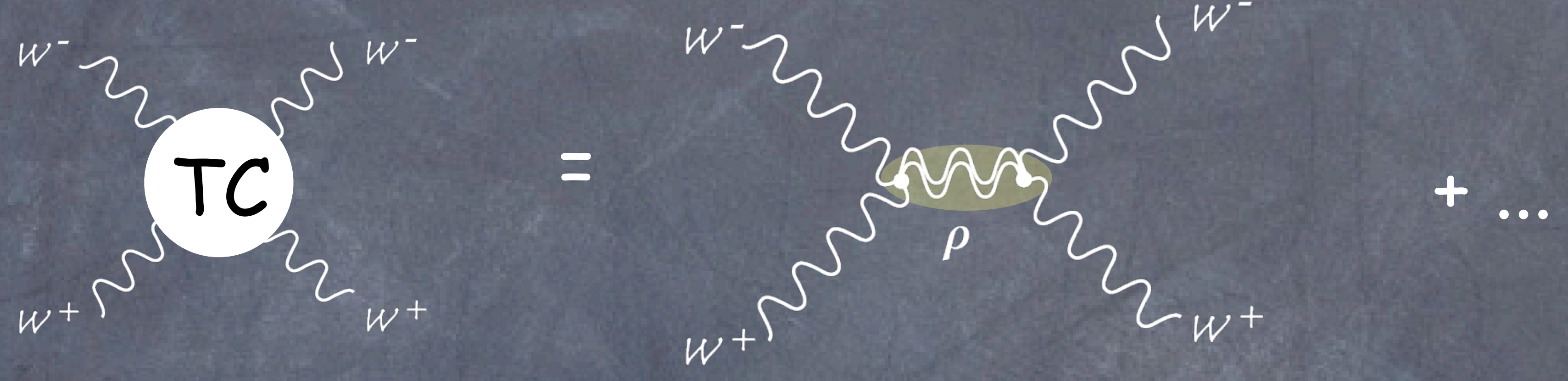
rho meson ~ 1 TeV

other ways?

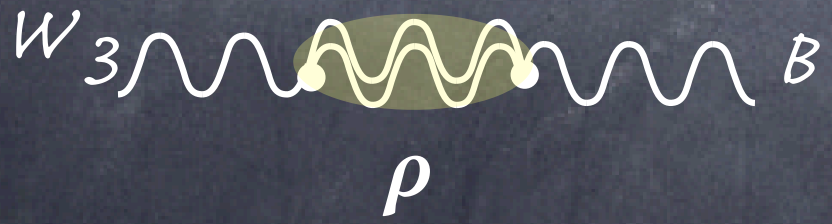
Strongly coupled models

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

Strongly coupled models

a theoretical challenge: need to develop tools to do computation

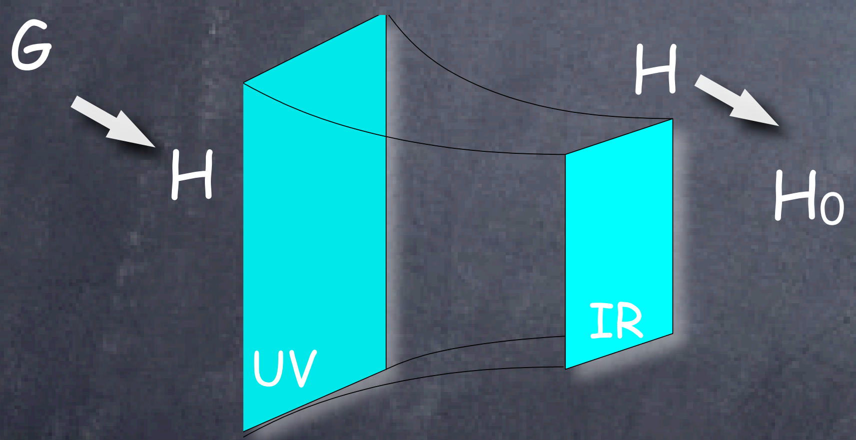
AdS/CFT correspondence

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
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

We can now build models and address their sensitivity on various parameters

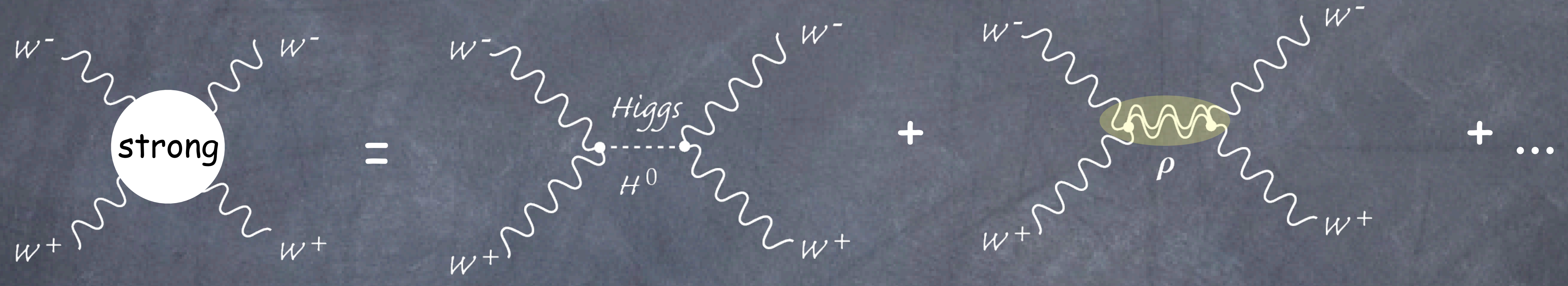
Composite Higgs Models

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

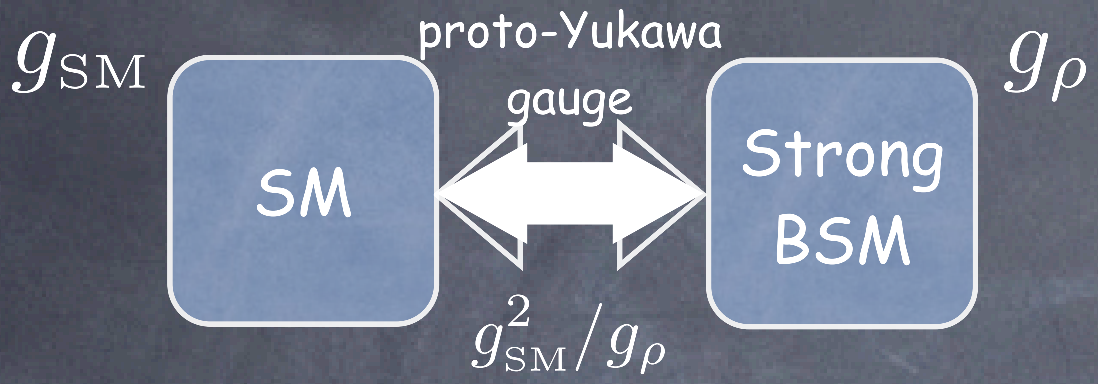
heavy rho

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?

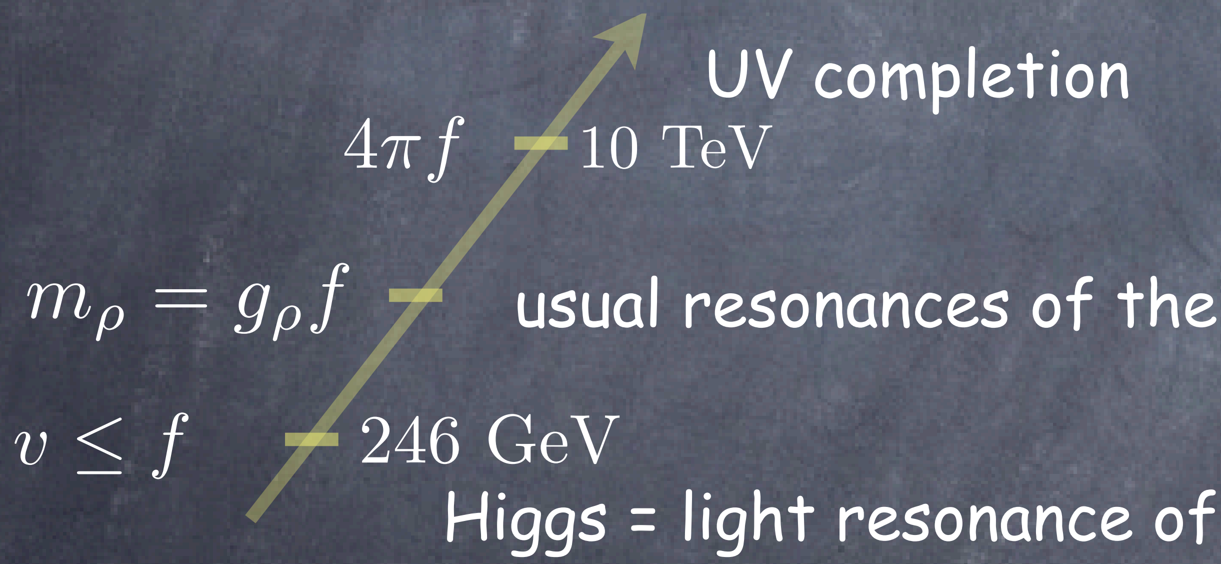
Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← residual global symmetry

example: SO(5)/SO(4),
4PGB=Doublet of $SU(2)_L$=Higgs



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

$H \supset U(1)_{em}$

➡ W_L & Z_L

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 $f = \frac{m_\rho}{g_\rho}$

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

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

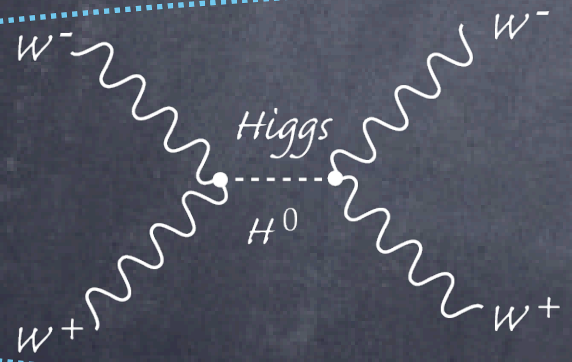
$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) (\partial^\mu h)^2 + \ldots$$

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 mρ)

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

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

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

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

removed
by custodial symmetry

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

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

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

$$\Downarrow$$

modified Higgs couplings to matter

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

$\xi = v^2/f^2$

effective
Higgs mass

$$m_h^{eff} = m_h \left(\frac{\Lambda}{m_h} \right)^{c_H \xi} > m_h$$

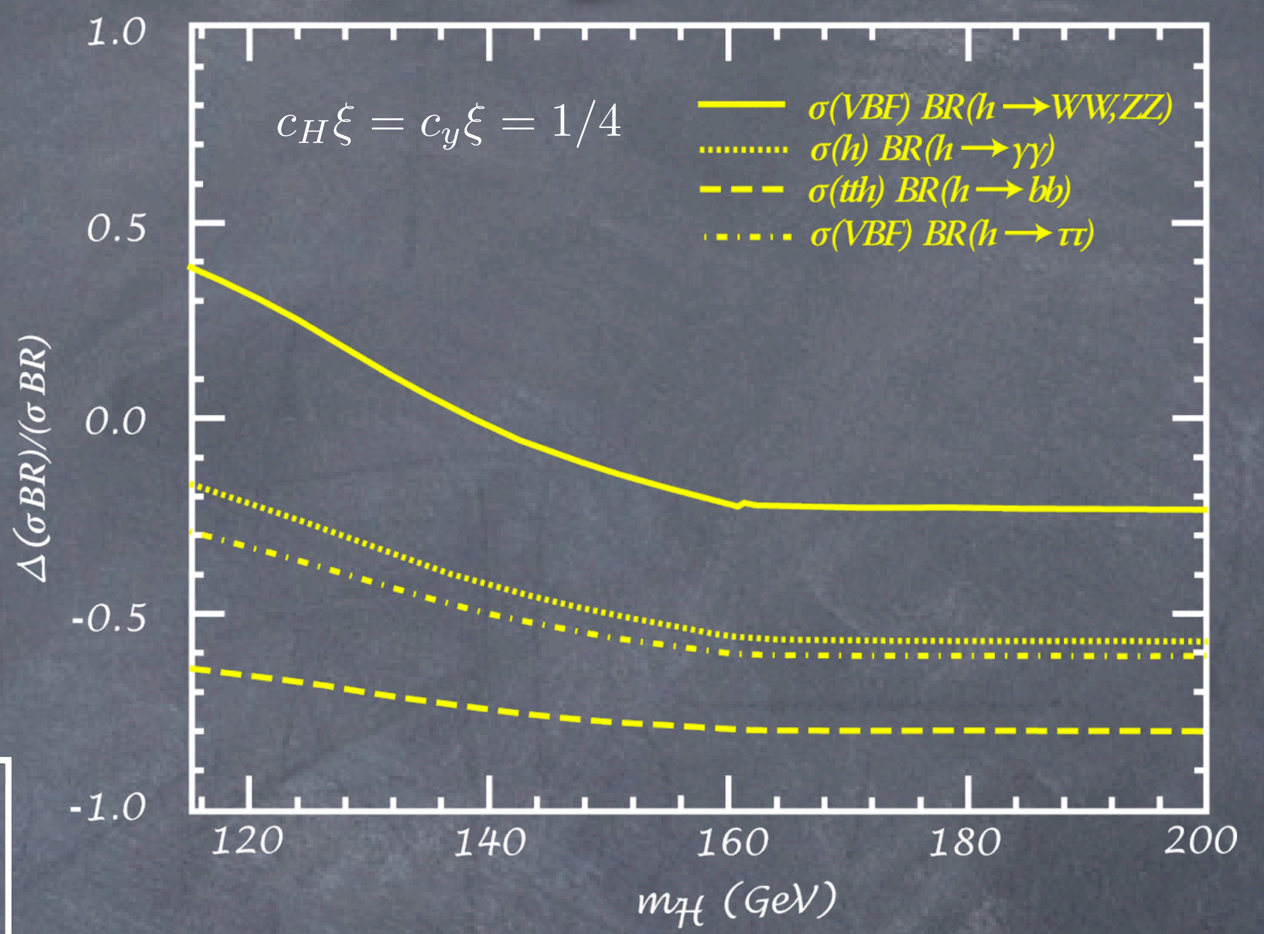
LEPII, for m_h~115 GeV: $\boxed{c_H \xi < 1/3 \sim 1/2}$

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

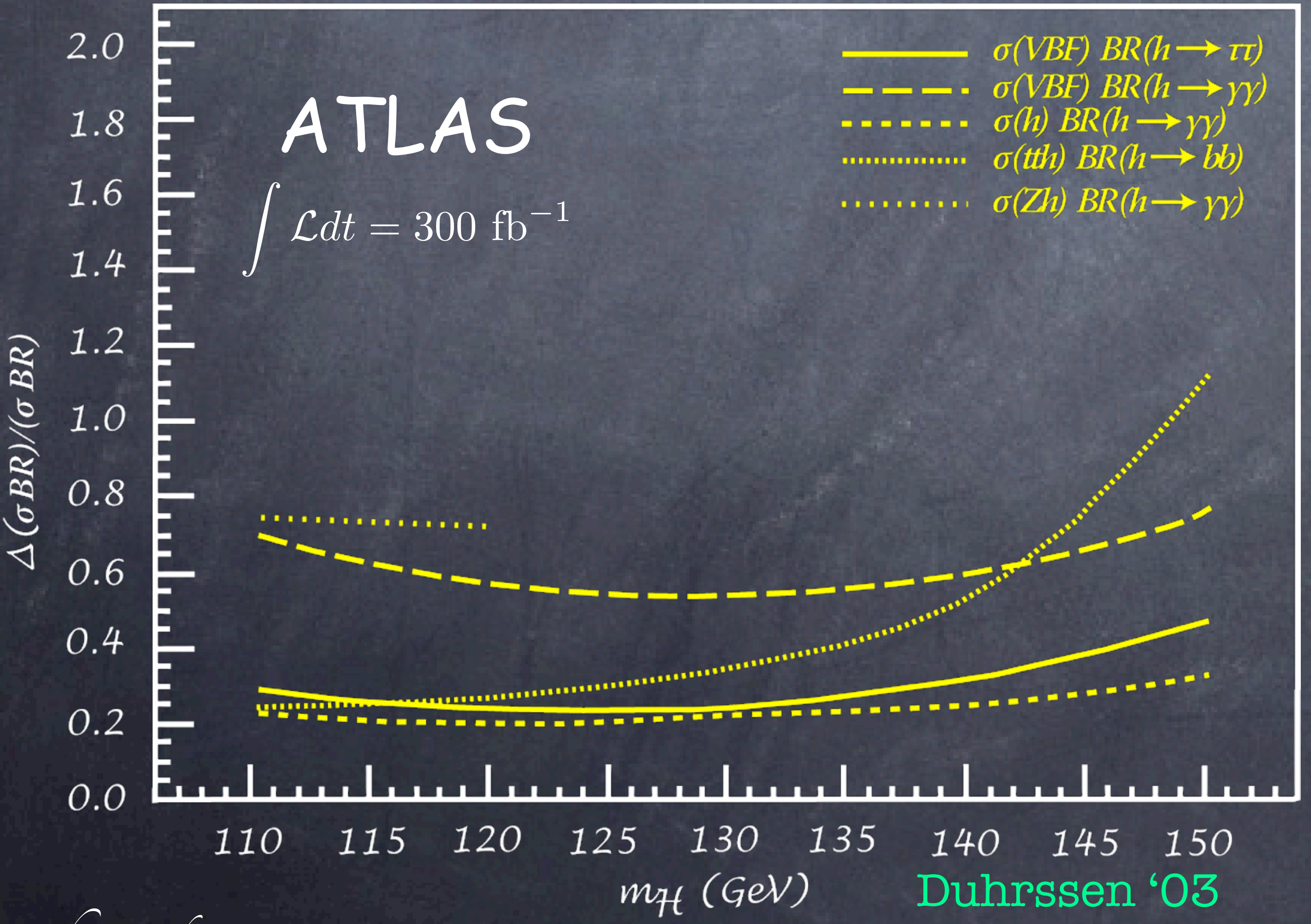
Higgs anomalous couplings

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

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



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)

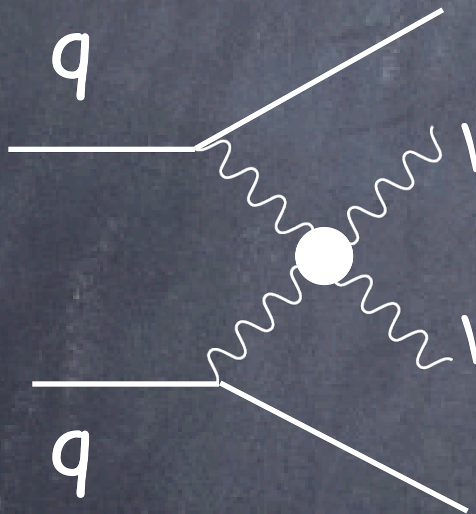
Strong W scattering

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

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

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

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



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

leptonic and semileptonic
vector decay channels
with 300 fb^{-1}

LHC is sensitive to

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

bigger than
0.5 ~ 0.7

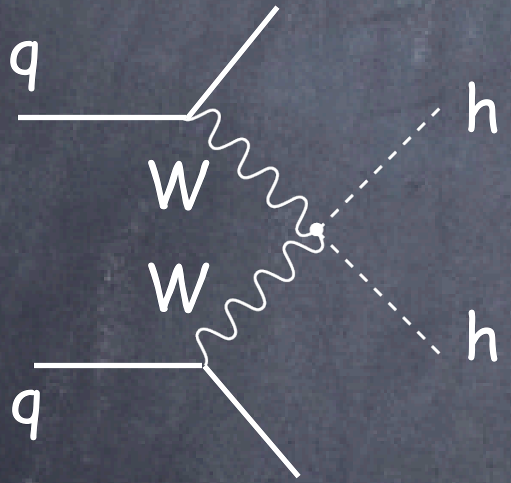
Bagger et al '95
Butterworth et al. '02

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:

- $hh \to bbbb$
- $hh \to 4W \to \ell^\pm\ell^\pm\nu\nu$jets

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

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

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

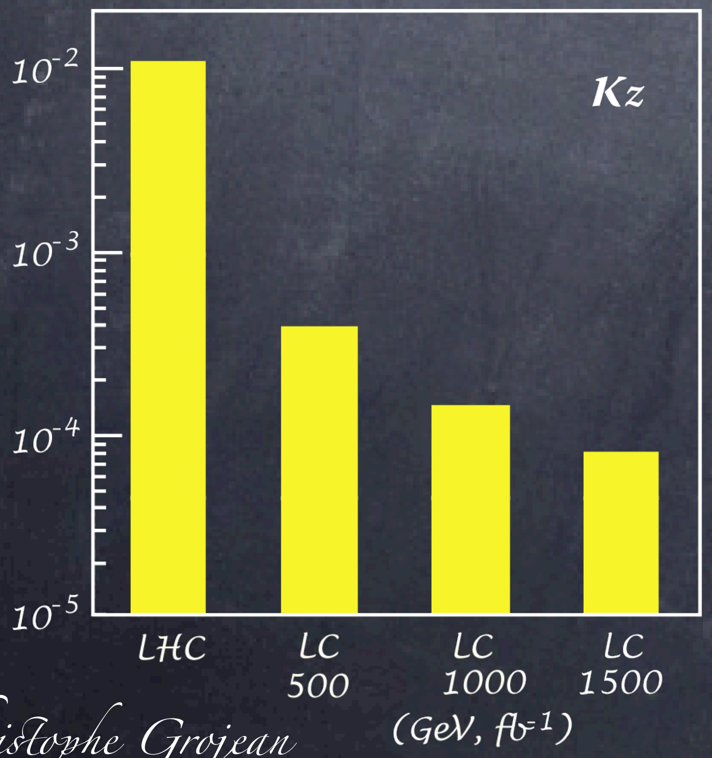
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

@ 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

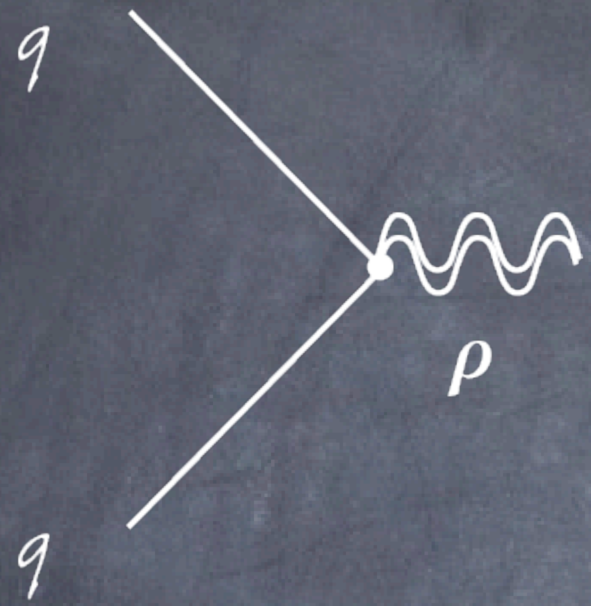


T. Abe et al, Snowmass '01

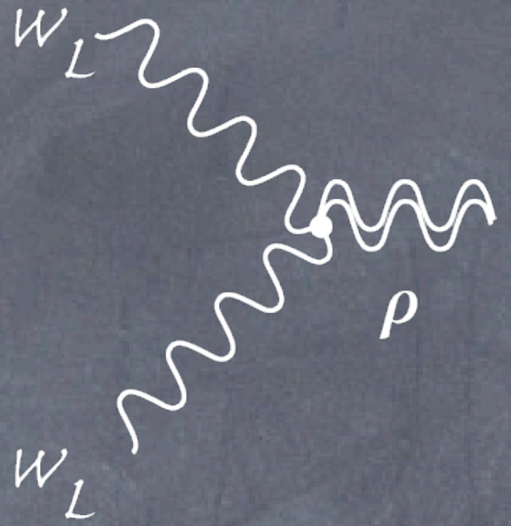
sensitive to resonance
up to m_ρ~8TeV

Direct vs. indirect signals

direct production of (TeV) resonances



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



$$= g_\rho$$

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

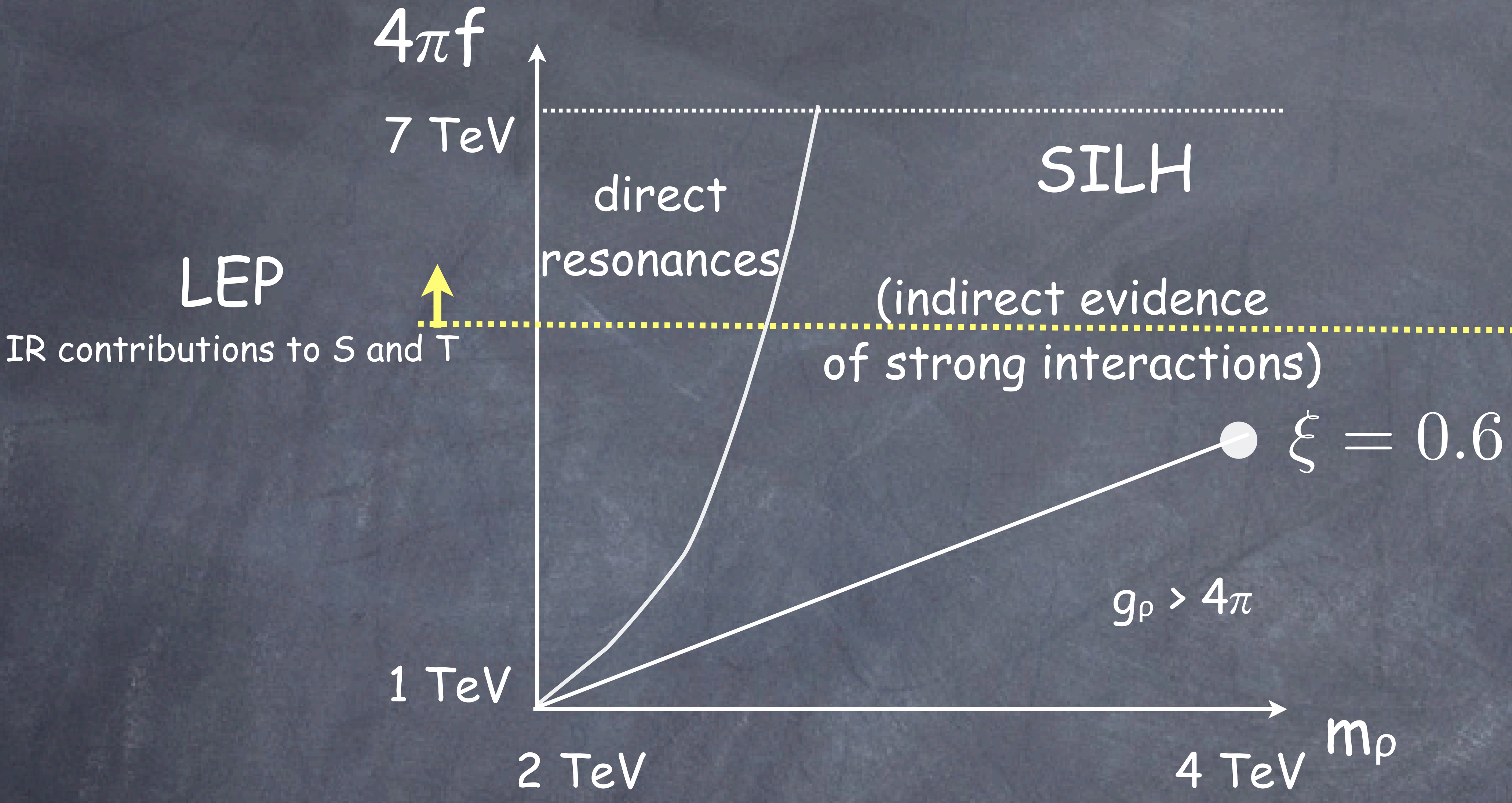
for larger g_ρ, the resonances are increasingly harder to see as

1/ they are broader and heavier

2/ they couple more and more weakly to fermions

LHC could reach a resonance around 4 TeV

Usefulness of SILH effective theory



halfway between model-dependent and blind operator analysis

- dominant effects are associated from strong self-Higgs interactions
- operator analysis: h → γ γ dominated by c_H and not $|H|^2 B_{\mu\nu}^2$ loop-suppressed

cannot apply the analysis Manohar, Wise '06

Higgsless Models

Higgsless Models

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

momentum along extra dimensions ~ 4D mass

quantum mechanics in a box

boundary condition to generate a transverse momentum

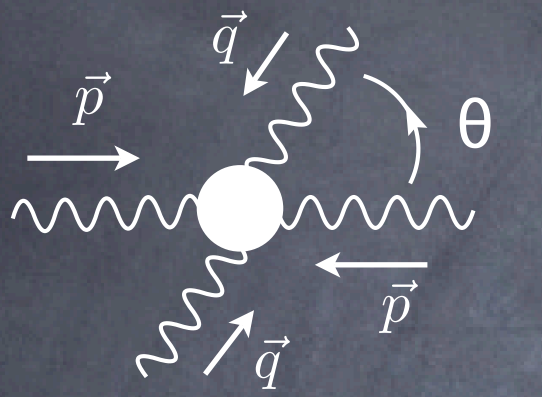
Is it better to generate a transverse momentum than introducing by hand a symmetry breaking mass for the gauge fields?

ie how is unitarity restored without a Higgs field?

Unitarization of (Elastic) Scattering Amplitude

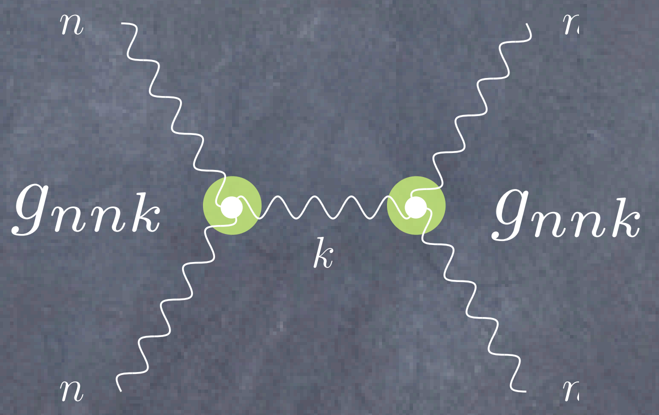
Same KK mode
'in' and 'out'

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

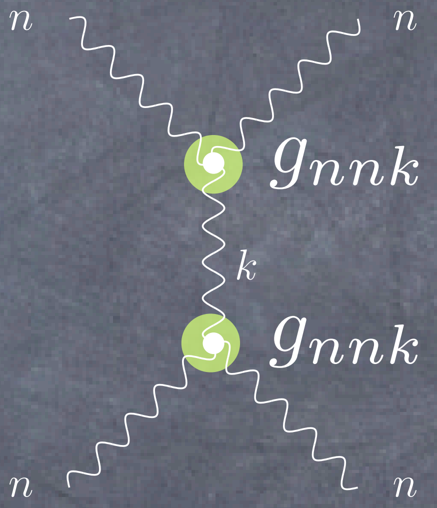


$$\mathcal{A} = \mathcal{A}^{(4)}\left(\frac{E}{M}\right)^4 + \mathcal{A}^{(2)}\left(\frac{E}{M}\right)^2 + \dots$$

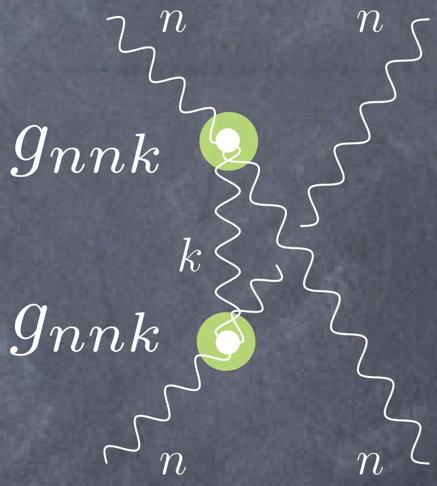
contact interaction



s channel exchange



t channel exchange



u channel exchange

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

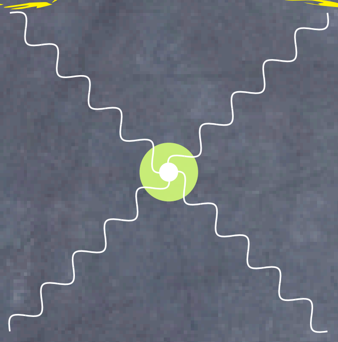
$$\mathcal{A}^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - s^2_{\theta/2}f^{abe}f^{cde}\right)$$

KK Sum Rules: another unitarization method

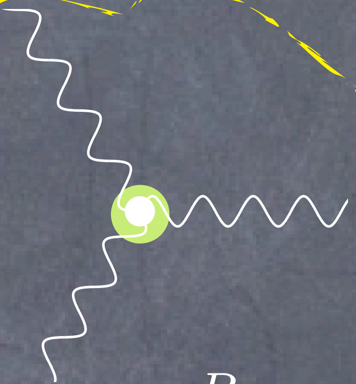
Csaki, Grojean, Murayama, Pilo, Terning '03

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

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

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

Warped Higgsless Model

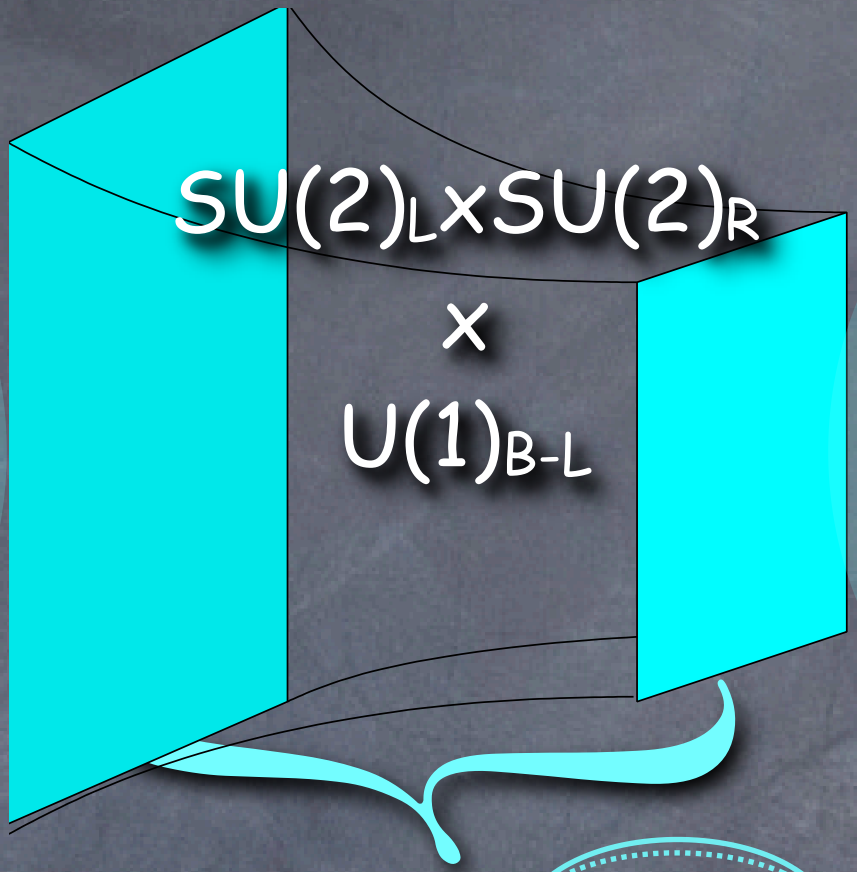
[Csaki, Grojean, Pilo, Terning '03]

$SU(2)_R \times U(1)_{B-L}$ → $U(1)_Y$

$$A_\mu^{R\pm} = 0$$

$$g_5' B_\mu - g_5 A_\mu^{R\,3} = 0$$

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



$SU(2)_L \times SU(2)_R$

×

$U(1)_{B-L}$

$U(1)_{em}$

$SU(2)_L \times SU(2)_R$ → $SU(2)_D$

$$A_\mu^{L\,a} - A_\mu^{R\,a} = 0$$

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

AdS geometry

➡ custodial symmetry

W around 80 GeV, KK around 1.2 TeV

"light" mode:

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

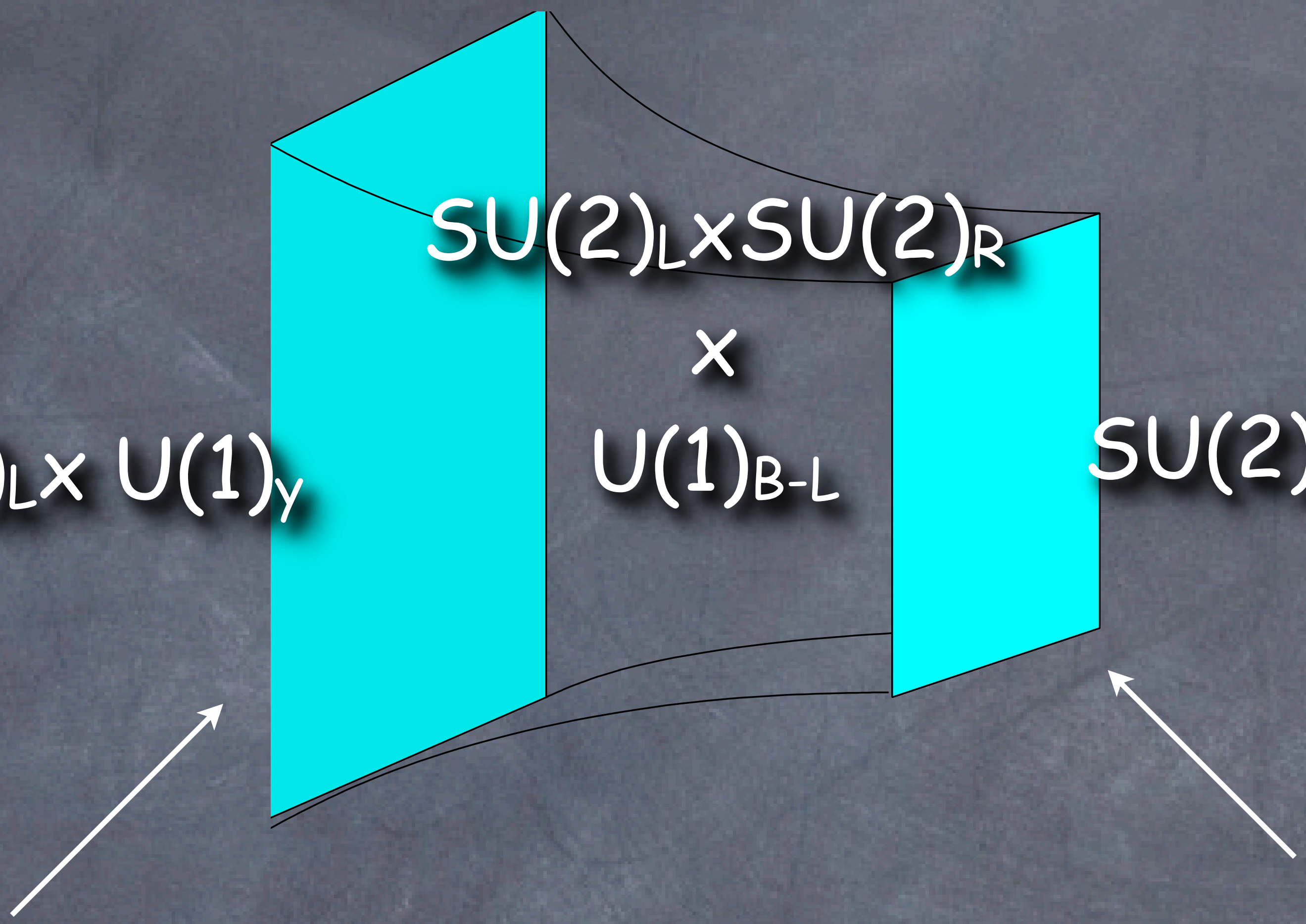
$$M_Z^2 \sim \frac{g_5^2 + 2 g_5'^2}{g_5^2 + g'^2} \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

log suppression

KK tower:

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

SM Fermions in Higgsless Models



$SU(2)_L \times SU(2)_R$

$\times$

$U(1)_{B-L}$

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

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

Chiral brane

no possible mass term

vector-like brane

isospin invariant mass only

(same mass for the top and bottom or electron and neutrino)

The fermions have to live in the bulk

Some Signatures

no Higgs but the absence of proof isn't the proof of the absence

- Deviations in the gauge bosons self-couplings
  - in usual gauge theories: $g_4^2 = g_3^2$
  - in higgsless theories, this relation is modified to take into account the exchange of KK excitations of W and Z
  - typically 1%-5% deviations compare to the SM self-couplings
- Non-universality of the couplings gauge boson/fermions

fermion mass ⇔ wavefunction profile in the bulk

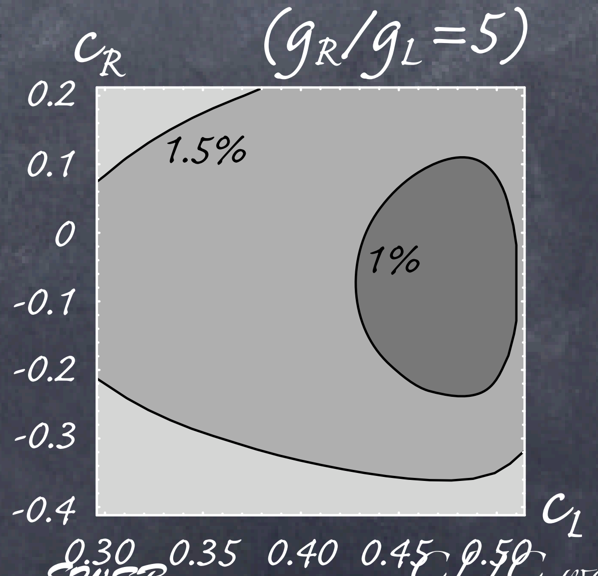
couplings ⇔ wavefunction overlap

different masses ⇔ different couplings to W and Z

First two generations

$$\frac{\delta g_{SM}}{g_{SM}} \approx \mathcal{O}\left(\frac{m}{\text{TeV}}\right) \approx 0.1\% \text{ at most}$$

Third generation



$Z_{b_L \bar{b}_L}$ deviations

difficult to get a
small deviation
in the perturbative regime

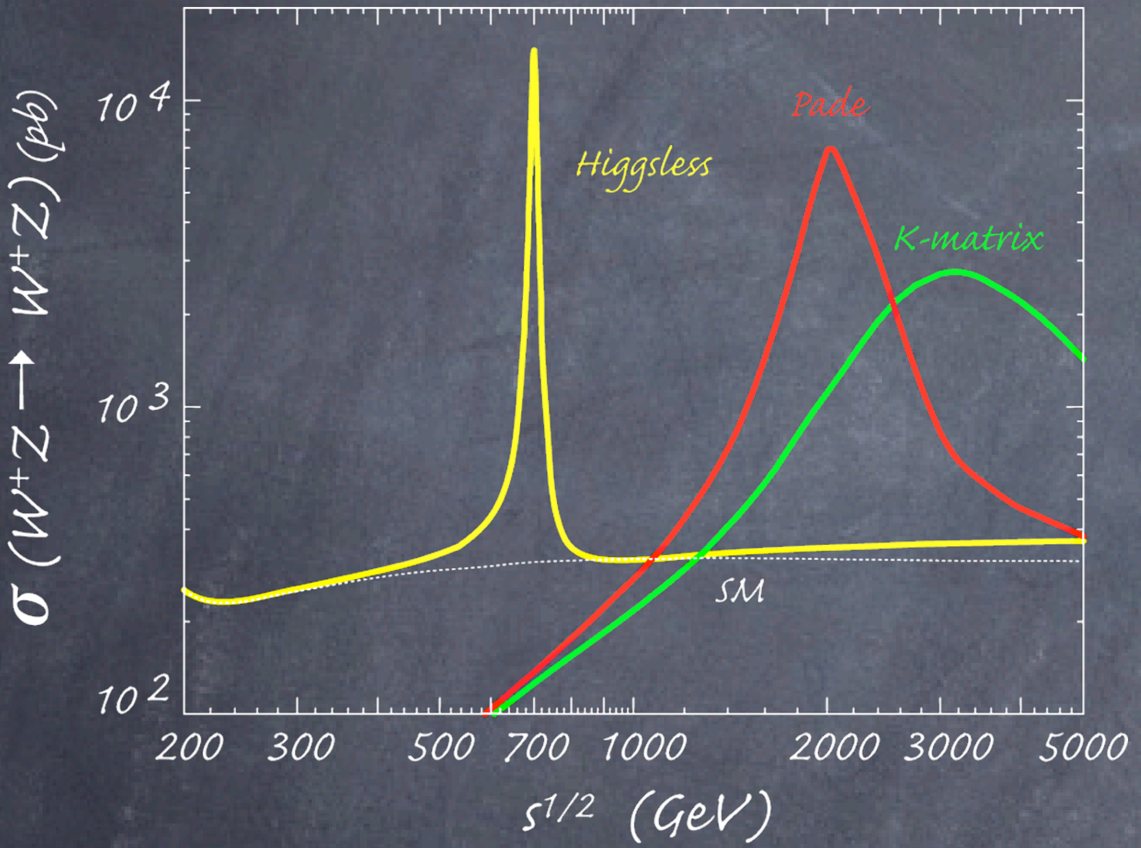
severe
constraints

Collider Signatures

[Birkedal, Matchev, Perelstein '05]

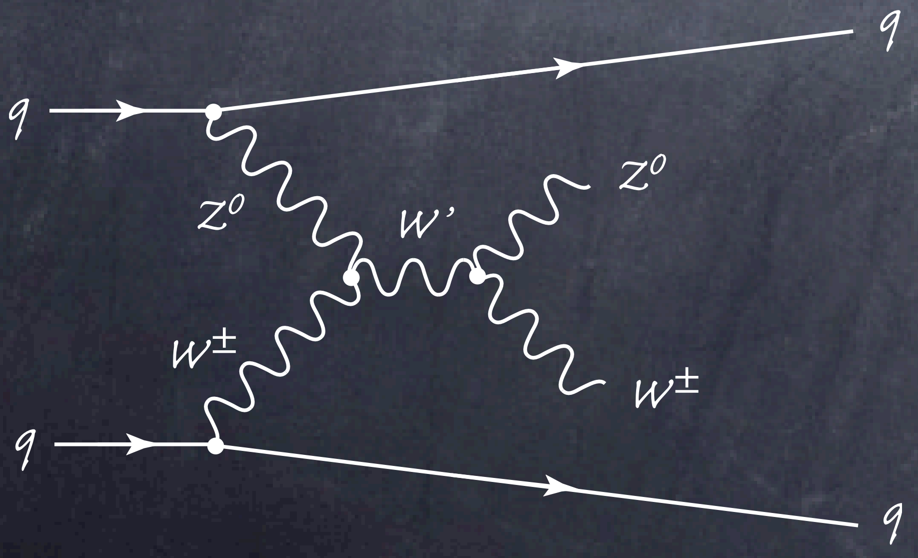
unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

WZ elastic cross section

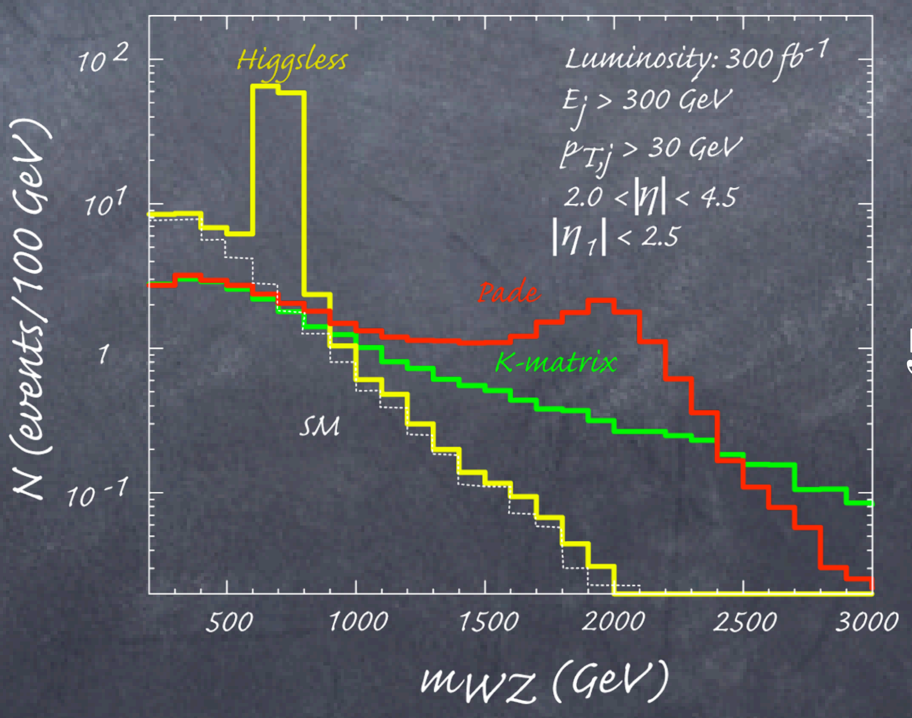


$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance



W' production



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

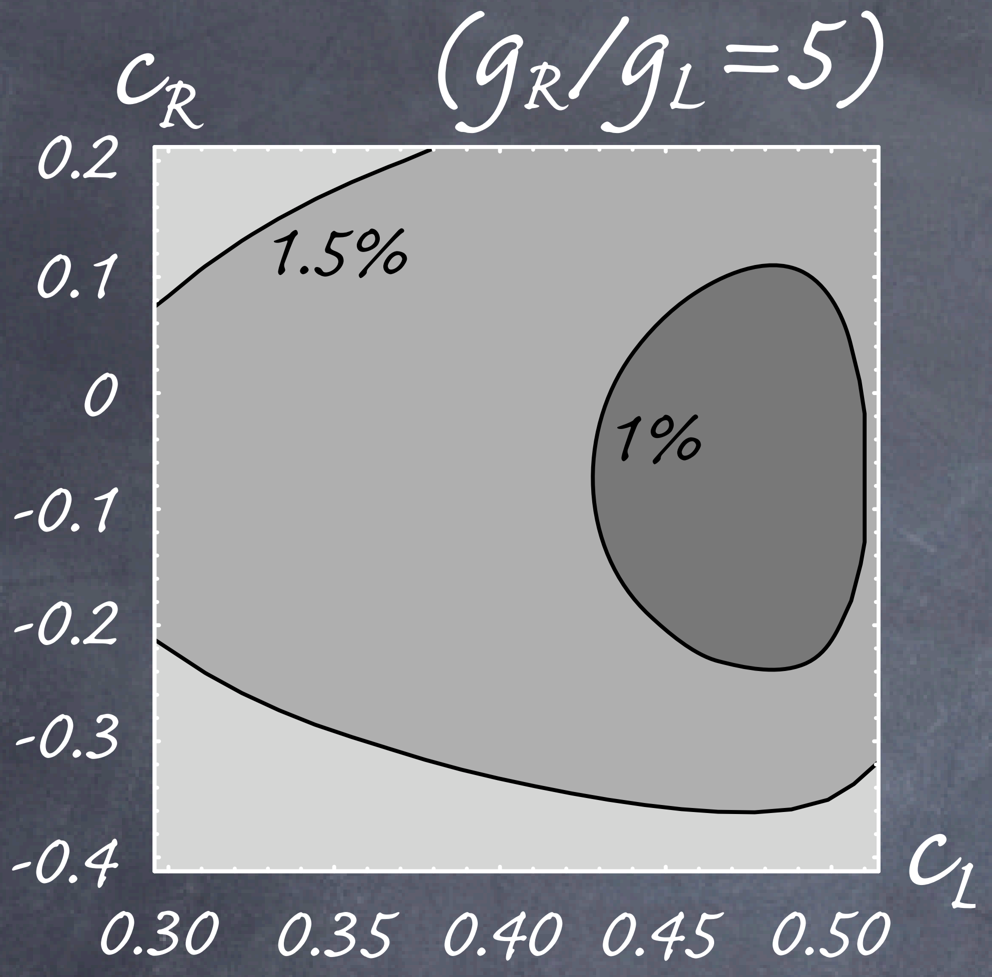
discovery reach
@ LHC
(10 events)

550 GeV → 10 fb^{-1}

1 TeV → 60 fb^{-1}

should be seen within one/two year

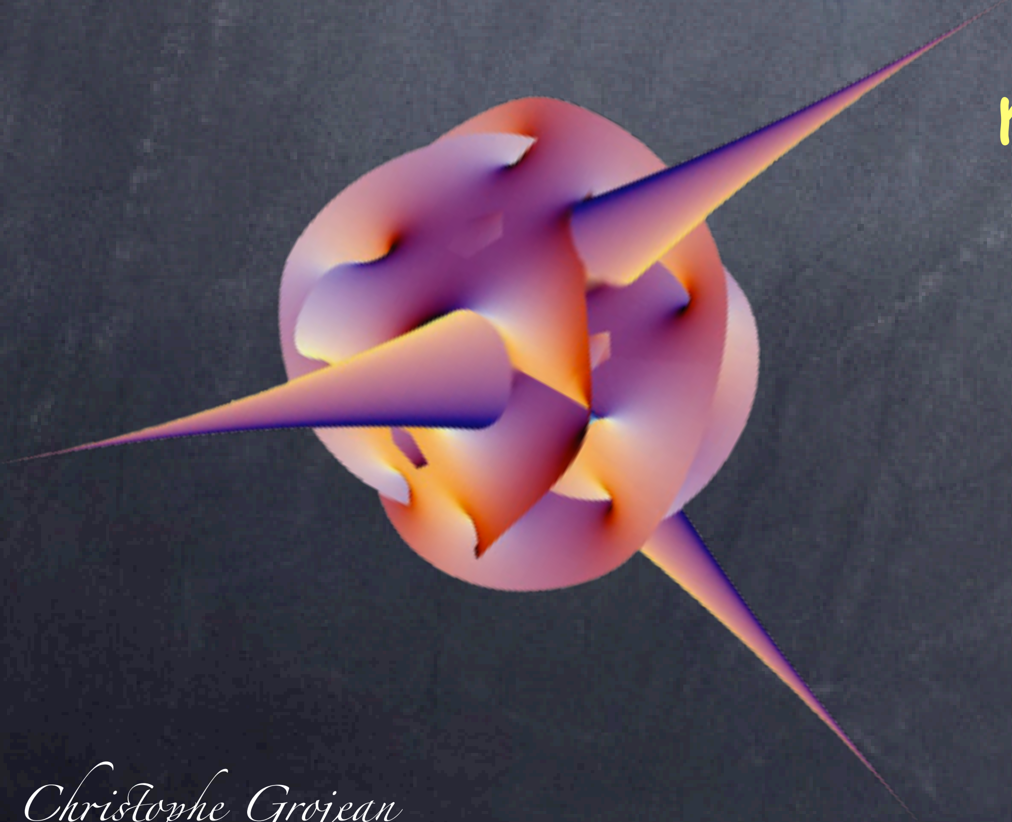
Open Issues $Z_{b_L \bar{b}_L}$



dual picture: fermion masses are generated from the interaction to the strongly coupled sector

How to get large top mass without spoiling the Zbb coupling?

introduce a scale for the W, Z masses
and another scale for the top mass
... like in topcolor models



multithroat construction

the top lives in one throat
while the W, Z masses originate
mostly from the other throats

prediction: a light PGB = the top-pion
strongly coupled to the third generation

[Cacciapaglia, Csaki, Grojean, Reece, Terning ‘05]
[Cacciapaglia, Csaki, Grojean, Terning ‘06]

Conclusions

"theorists are getting cold feet" J. Ellis

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

the ball is in experimentalists' hands

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?	-	✓	✓