

The Higgs and Beyond with the LHC

*Les rencontres de physique de la vallée d'Aoste
La Thuile*

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CERN-TH & CEA-Saclay-IPhT

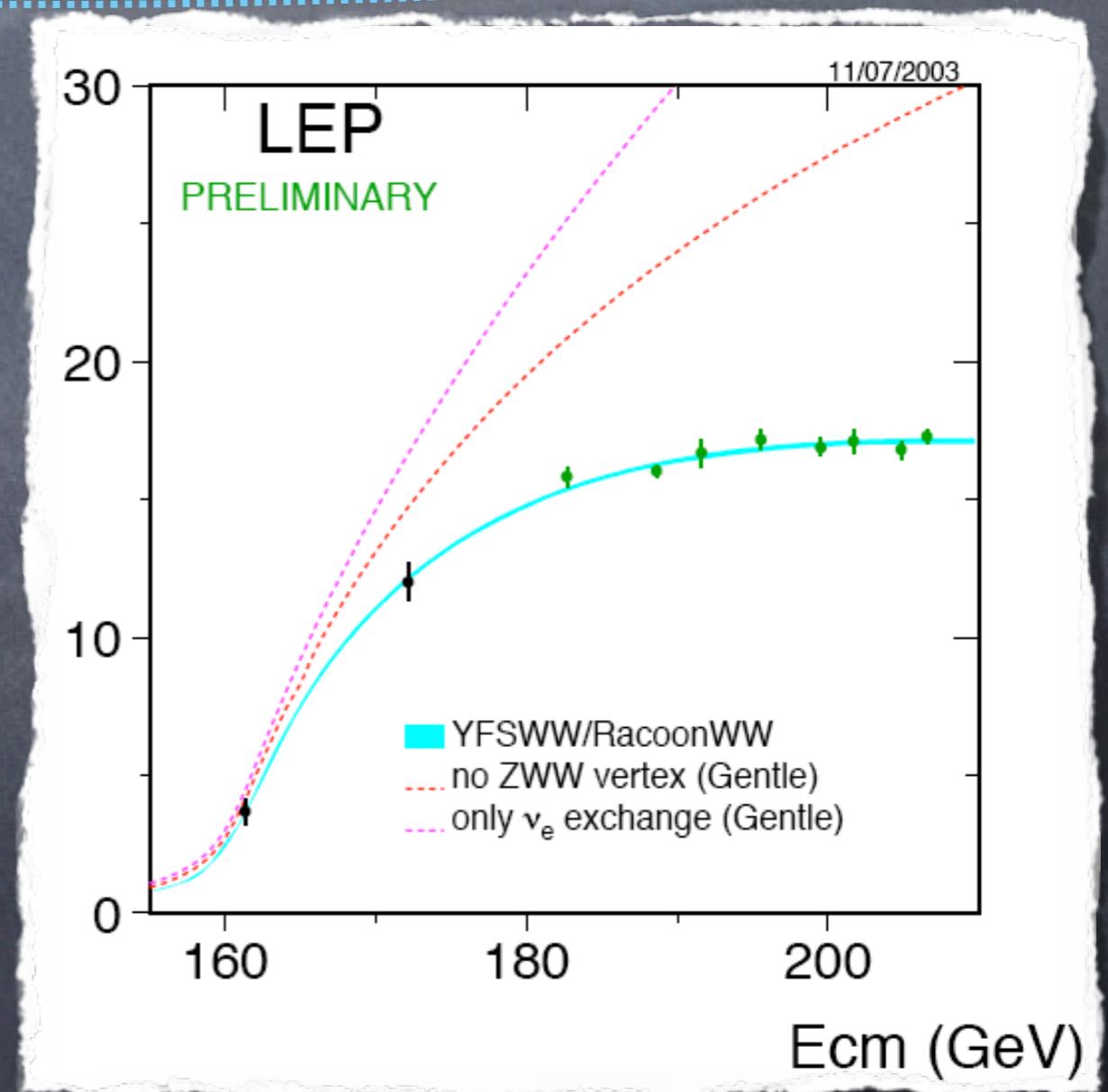
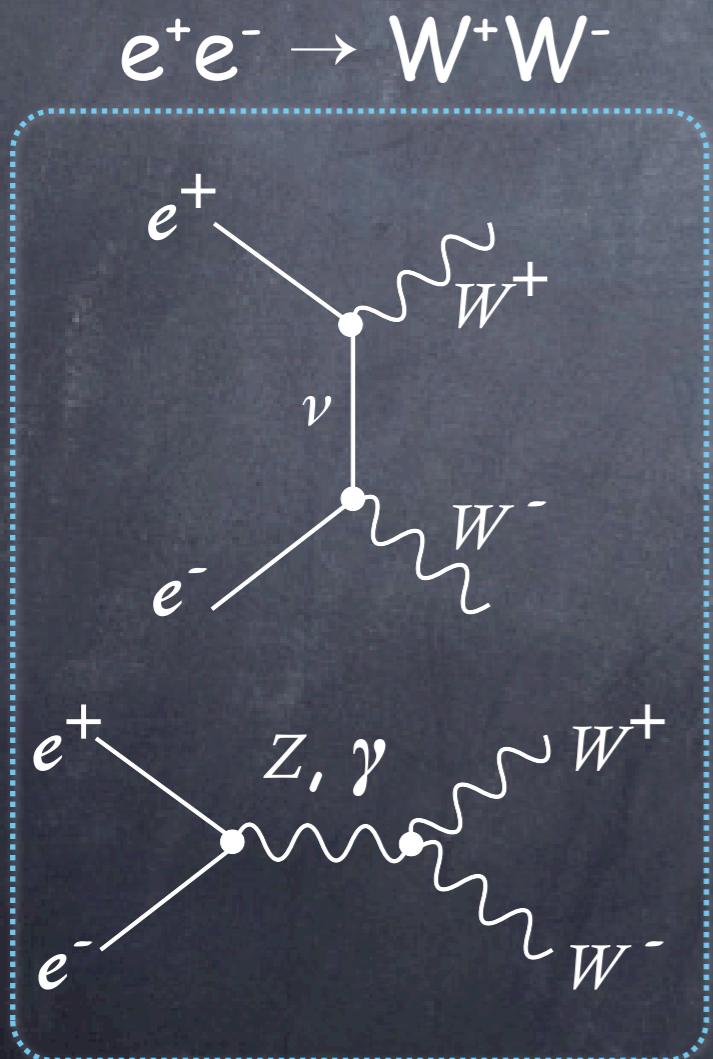
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cea

The Standard Model

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 Standard Model 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 —

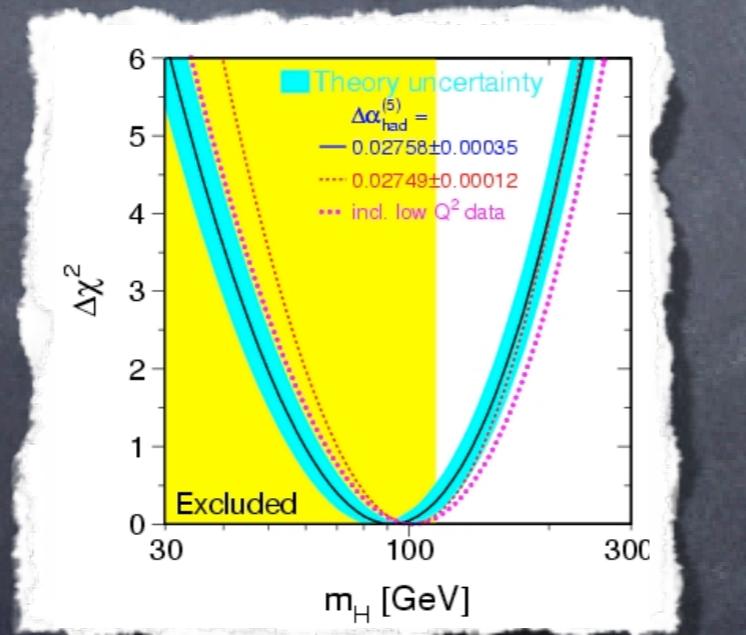
common lore: from a scalar Higgs doublet

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

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^{meas} - O^{fit} /\sigma$
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{lb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_T)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{lb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{lb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_{(SLD)}$	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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?

Gaugeophobic Higgs?

Littlest Higgs?

Composite Higgs?

Intermediate Higgs?

Slim Higgs?

Portal Higgs?

Fat Higgs?

Higgsless?

Peter's Higgs?

Lone Higgs?

Gauge-Higgs?

Twin Higgs?

Simplest Higgs?

Phantom Higgs?

Scattering amplitudes

non-linear realization of the gauge symmetry

W_L, Z_L are Goldstone bosons \sim pions of QCD

$$\Sigma = e^{i\sigma^a \pi^a/v}$$

2x2 matrix: $\pi^a \sim W_L, Z_L$

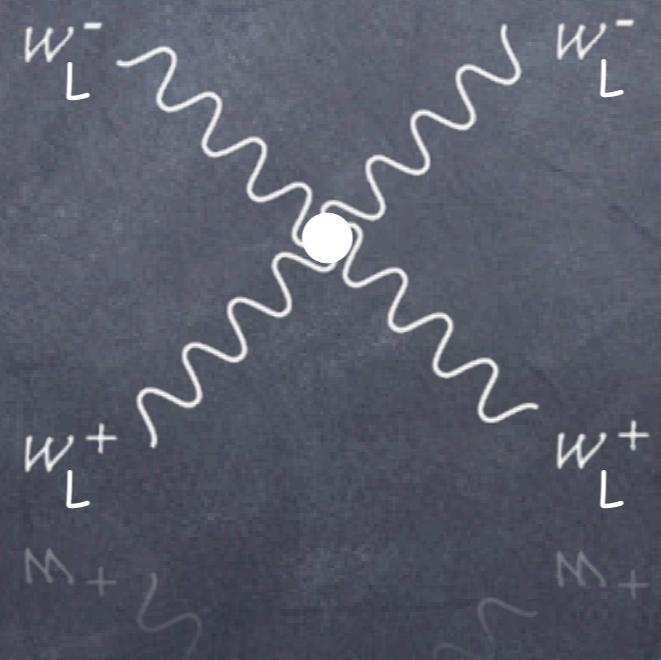
$$\mathcal{L}_{\text{mass}} = \frac{v^2}{4} \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma)$$

bad behavior of scattering amplitudes

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

scattering of W_L

scattering of QCD pions
(Goldstone equivalence theorem)



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

loss of perturbative unitarity
around 1.2 TeV

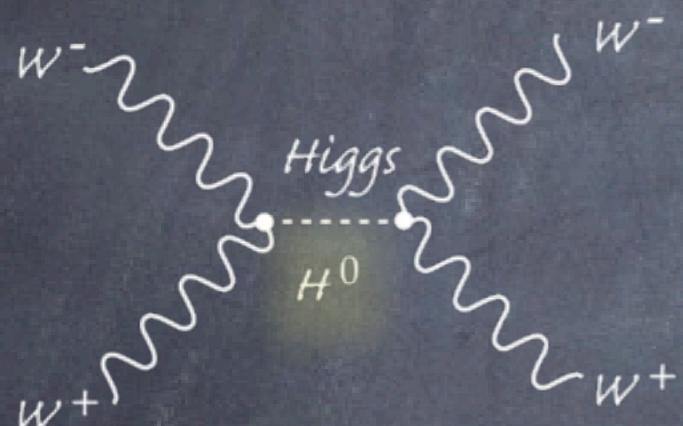
Need new degrees of freedom to cure the growth of the amplitudes

SM Higgs as a peculiar scalar resonance

A single scalar degree of freedom no charged under $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{\text{EWSB}} = a \frac{v}{2} h \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma) + b \frac{1}{4} h^2 \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma)$$

'a' and 'b' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2} \left(s - \frac{a s^2}{s - m_h^2} \right)$$

growth cancelled for
 $a = 1$
restoration of
perturbative unitarity

For $b = 1$: perturbative unitarity also maintained in inelastic channels

— 'a=1' & 'b=1' define the SM Higgs —

$\mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{EWSB}}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a/v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

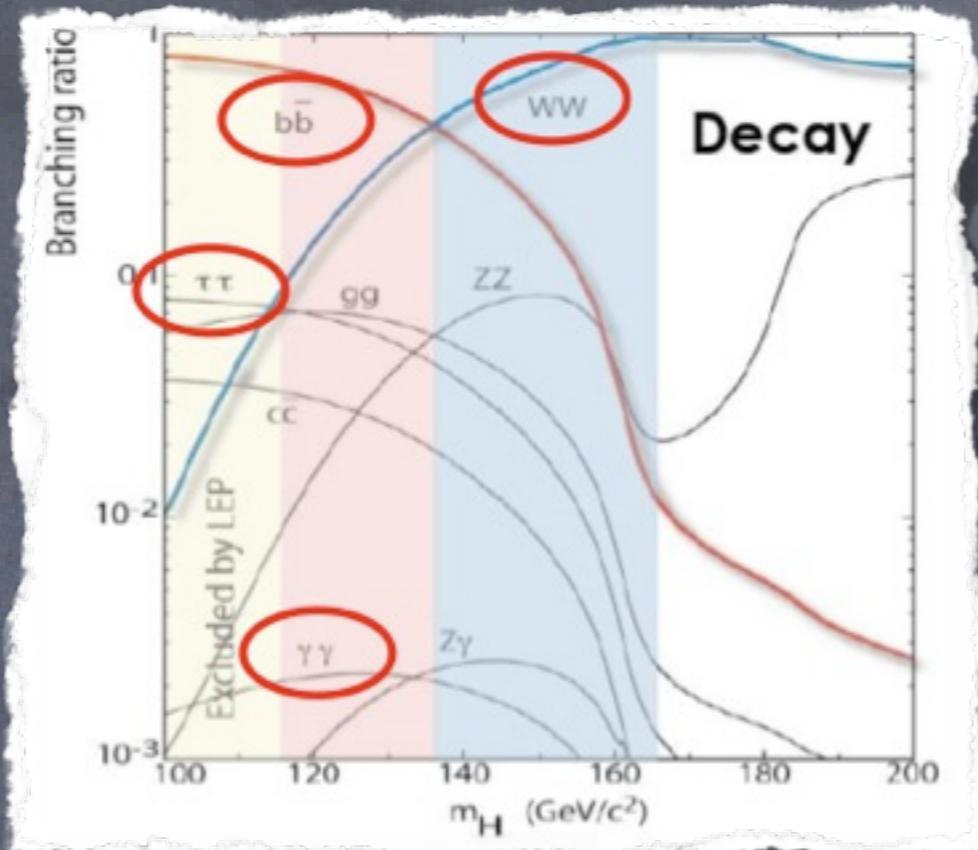
h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

SM Higgs

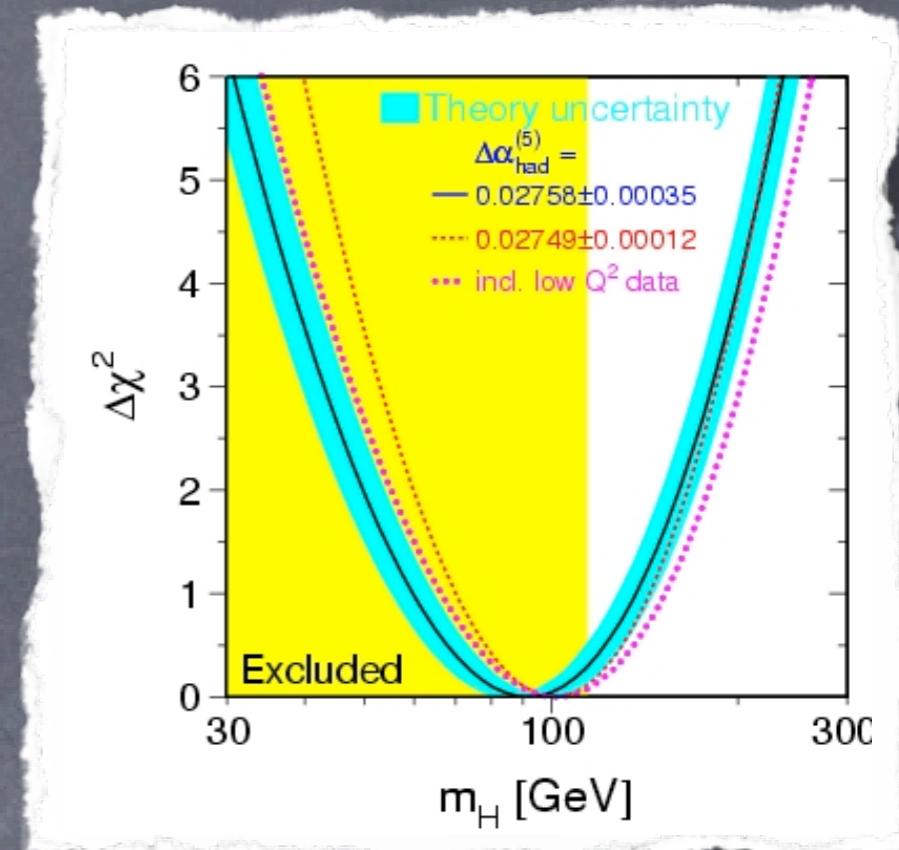
only SM particles
+
SM Higgs



all Higgs couplings
fixed



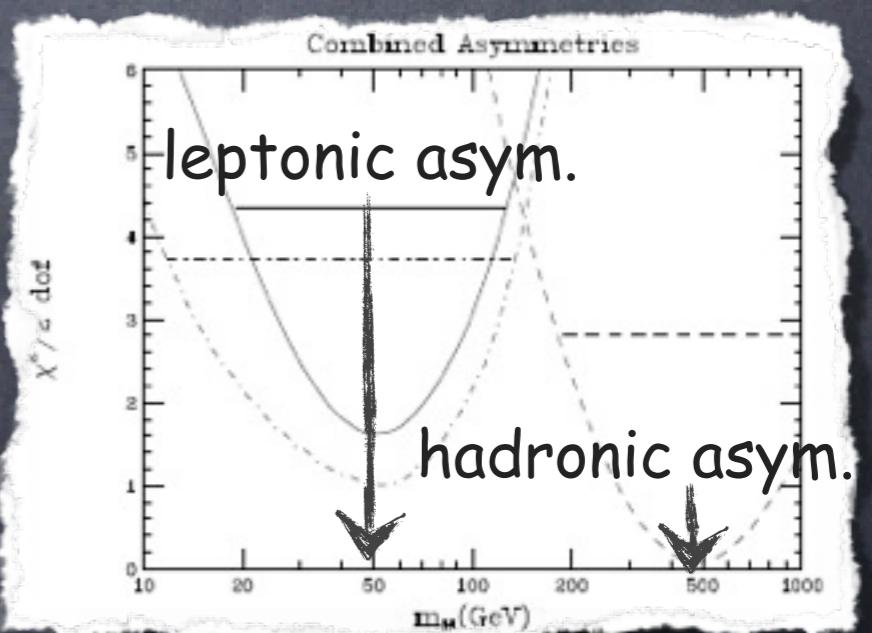
&



Quite a good fit to EW precision data... but

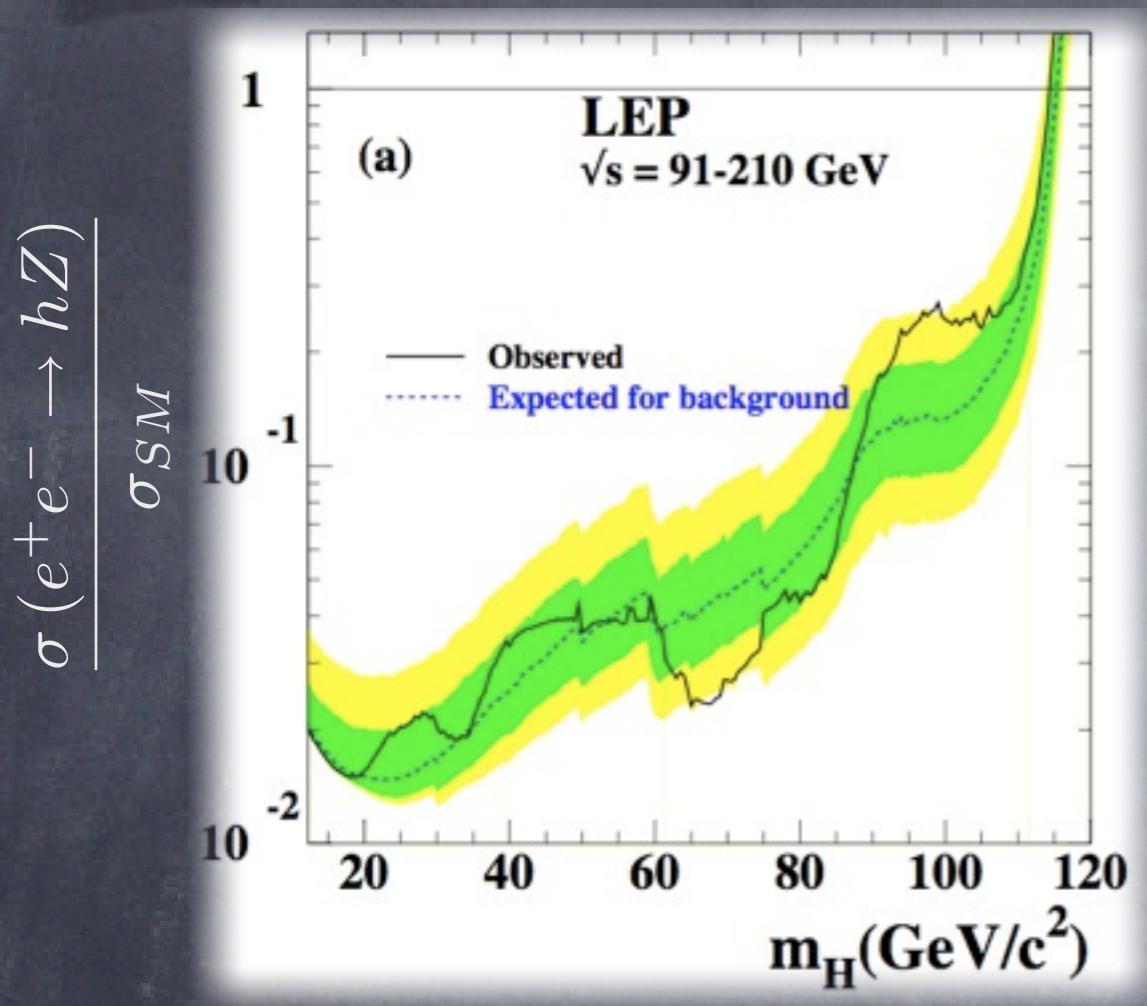
- best fit obtained for a Higgs mass already excluded by direct search
- tension between leptonic and hadronic asymmetries

Chanowitz '08



A light almost SM-like Higgs

SM-like=unitarity properties unchanged



Direct exclusion bound
is very sensitive to Higgs BR's

Suppressing SM BR's to 20%
allows for a Higgs around 90 GeV

For a light Higgs, it is very easy to
modify Higgs BR's without modifying
its couplings to SM particles

a light Higgs can decay only to light SM
particles, light particles to which it couples
weakly (eg. coupling to b quark is only $\sim 1/60$)

new particles with middle couplings to the Higgs
will significantly affect Higgs BR's

$$\Gamma_Z \sim 1000 \times \Gamma_H(m_H = 115 \text{ GeV})$$

easy to modify Higgs BR's
without destroying EW data

A light almost SM-like Higgs

Many physics-motivated models:

- **MSSM:** $h \rightarrow \chi\chi \rightarrow 6q/2l4q/4l2\nu$
- **NMSSM:** $h \rightarrow aa \rightarrow 2b2\bar{b}/4\tau/4g$
- **Little Higgs/Composite Higgs ($SO(6)/SO(5)$):** $h \rightarrow \eta\eta$

Many signatures-motivated models: Higgs=portal to New Sector

- New sector with string-like confinement: Quirks Harnik, Luty
- New sector with QCD-like confinement: Hidden valleys Strassler, Zurek
- New sector = CFT, ie no confinement: Unparticles Georgi

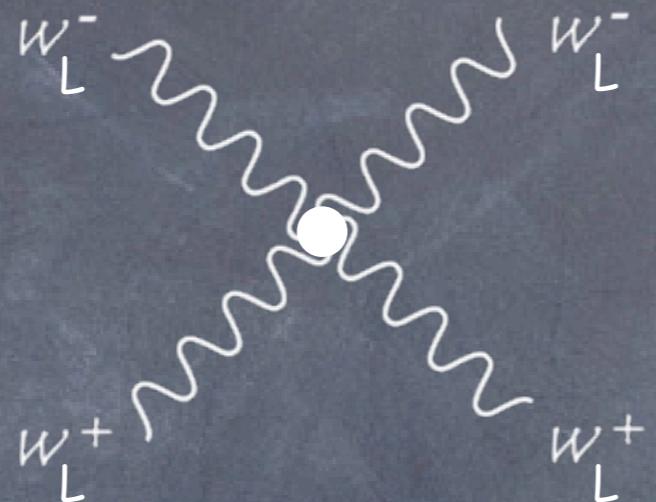
What is the mechanism of EWSB?

SM, susy, Little H., 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

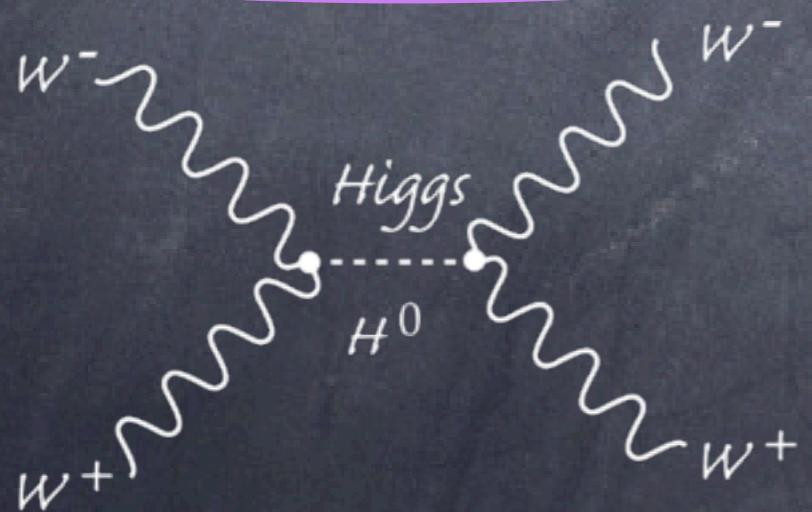
$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$



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

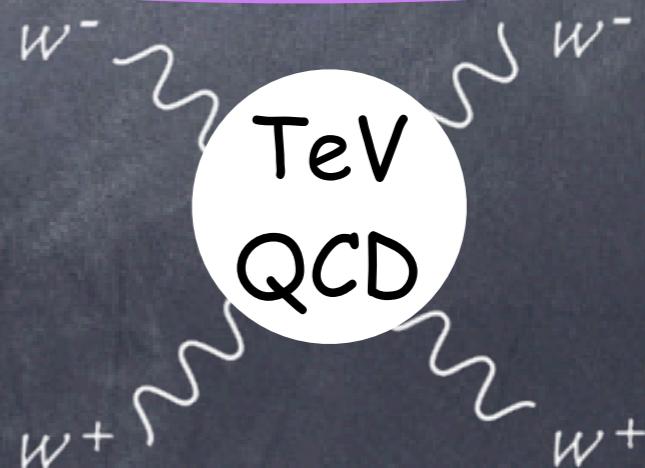
loss of perturbative unitarity
around 1.2 TeV

Weakly coupled models



prototype: Susy
susy partners ~ 100 GeV

Strongly coupled models



prototype: Technicolor
rho meson ~ 1 TeV

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



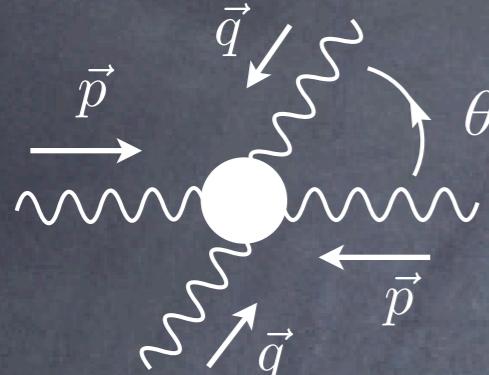
boundary conditions generate a transverse momentum

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?

Unitarization of (Elastic) Scattering Amplitude

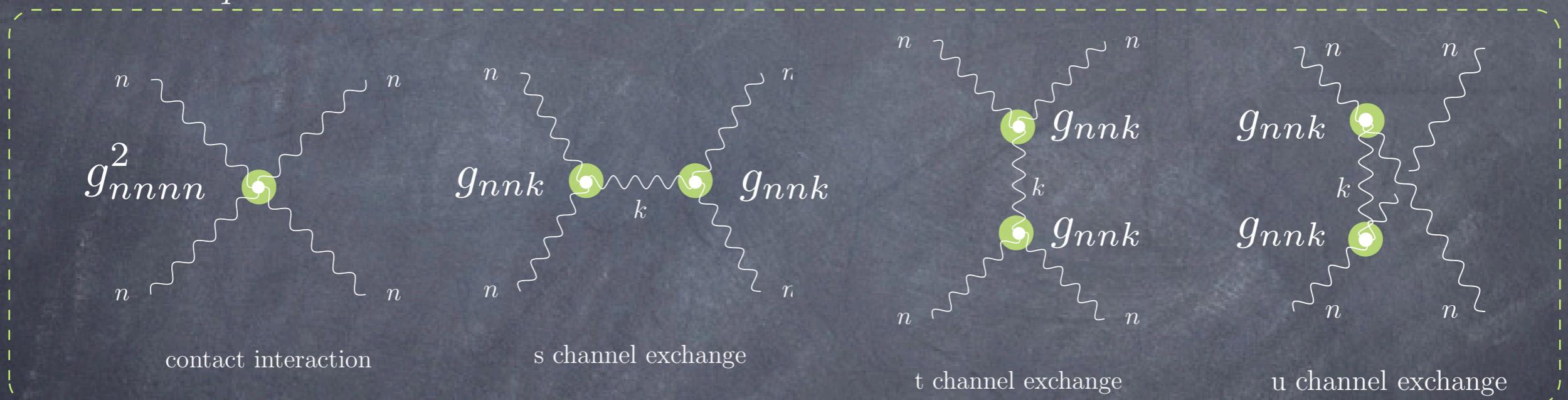
Same KK mode
'in' and 'out'



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

Csaki, Grojean, Murayama, Pilo, Terning '03

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



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

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

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

Postponing Pert. Unitarity Breakdown

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

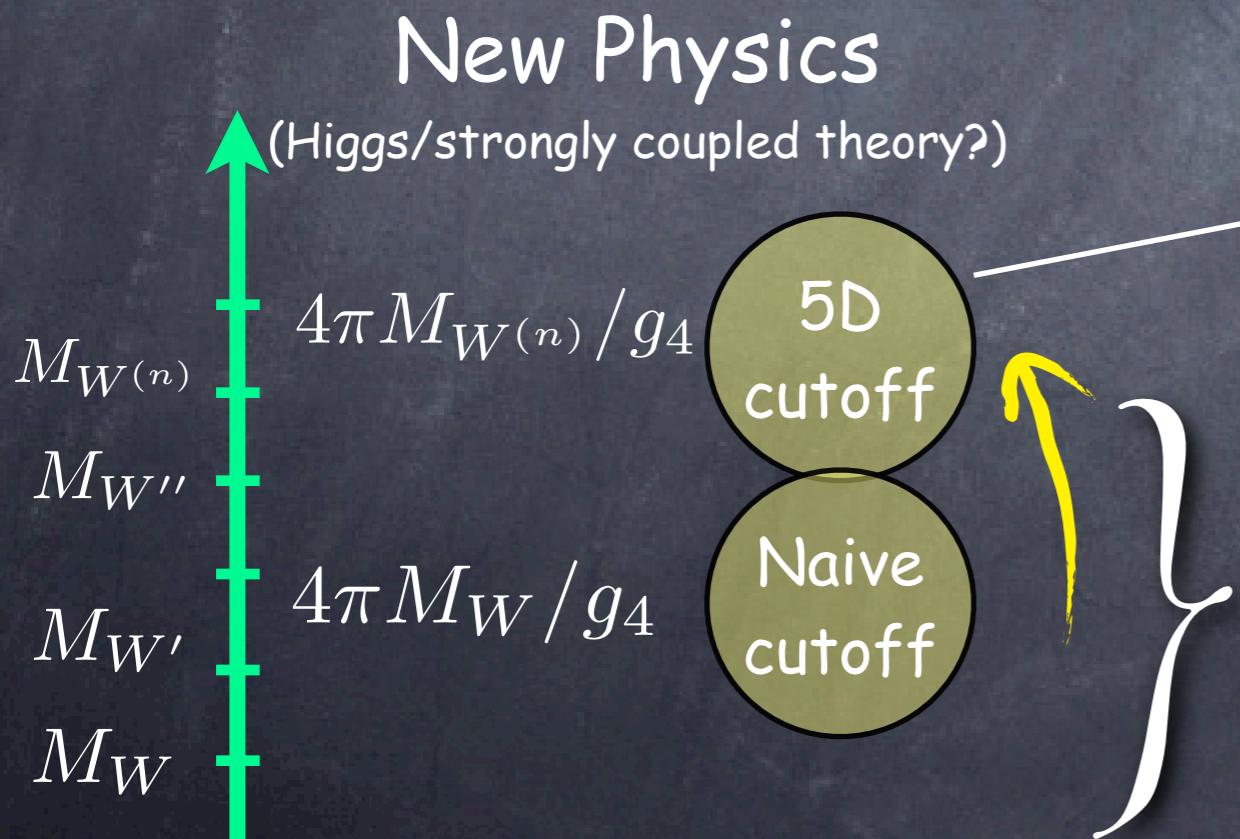
i.e. can we unitarize the theory without scalar field?

No!

$$g_{nnnn}^2 \stackrel{E^4}{=} \sum_k g_{nnk}^2 \stackrel{E^2}{=} \sum_k g_{nnk}^2 \frac{3M_k^2}{4M_n^2}$$

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

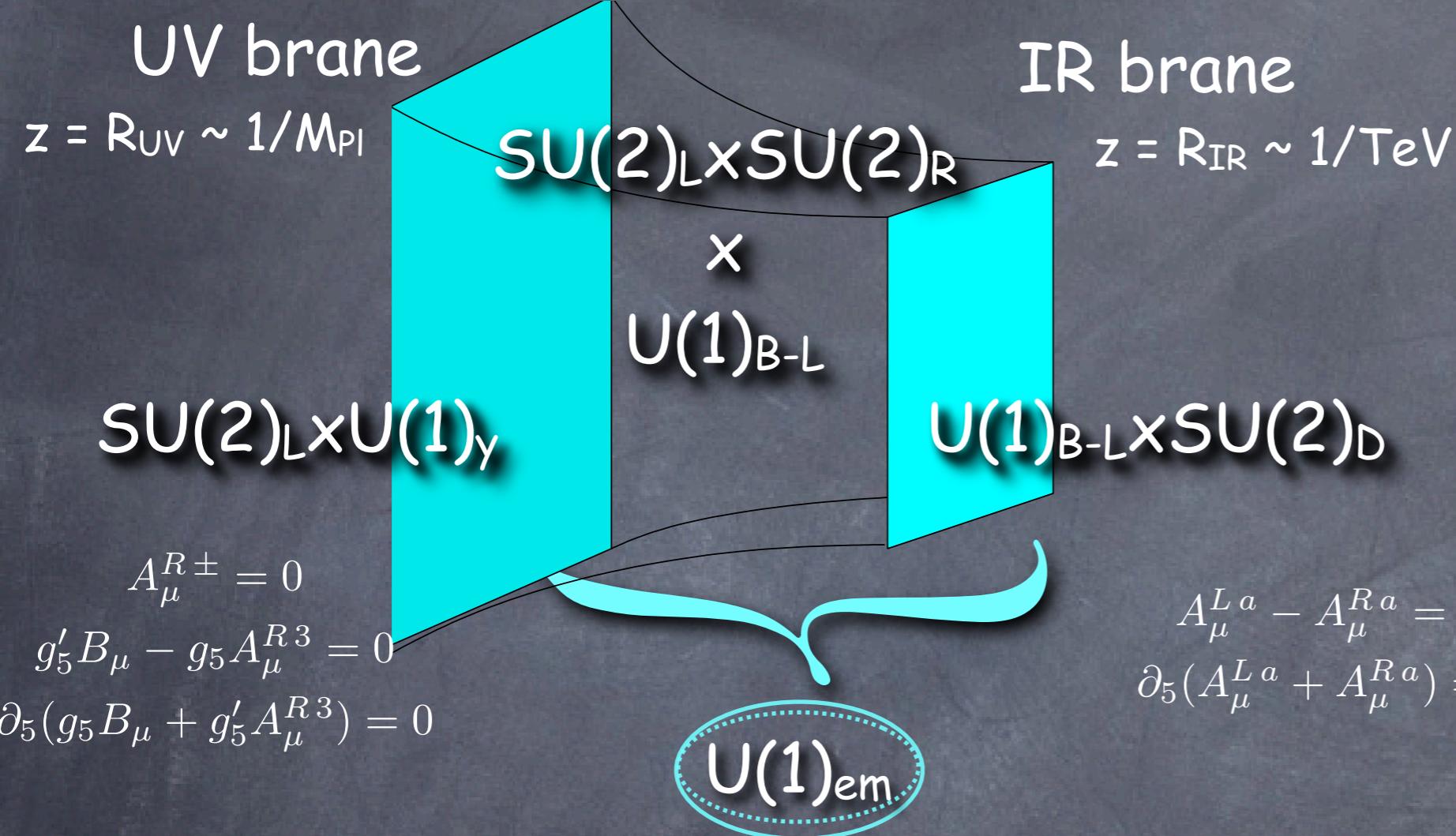
$$\Lambda_{5D} = 24\pi^3/g_5^2 = (3\pi/g_4) \Lambda_{4D}$$

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

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

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:

$$M_Z^2 \sim \frac{g_5^2 + 2g'^2_5}{g_5^2 + g'^2} \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

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

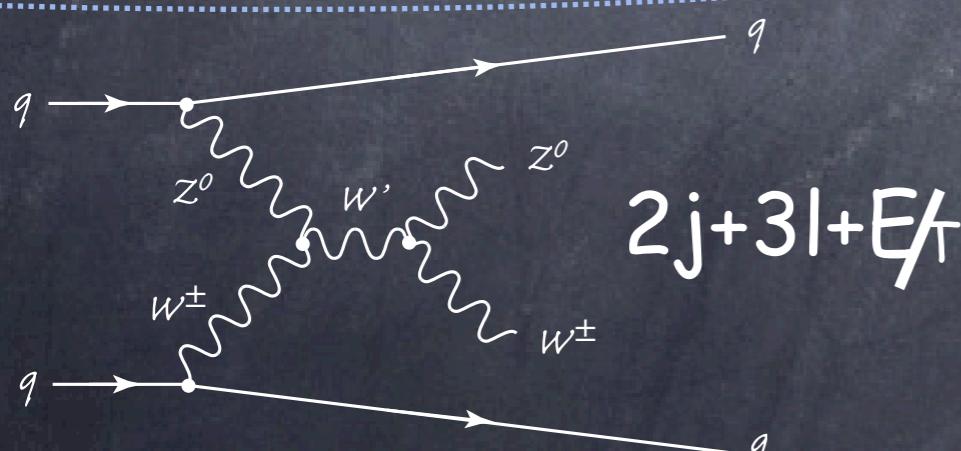
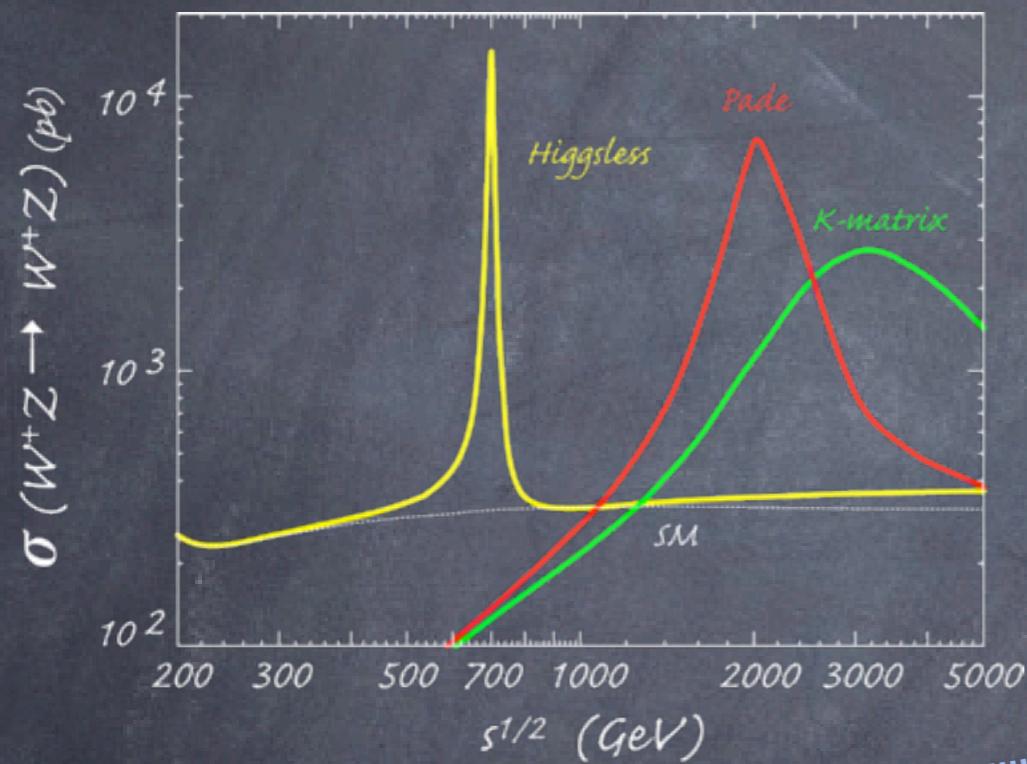
Collider Signatures

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



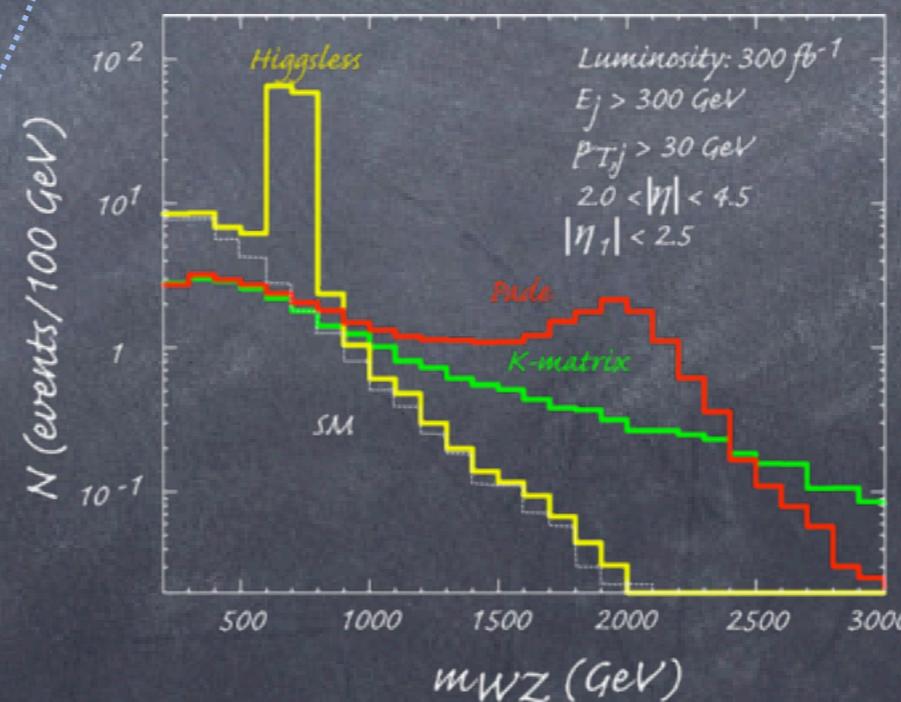
VBF (LO) dominates over DY since couplings of q to W' are reduced

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

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

W' production

discovery reach
@ LHC
(10 events)



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

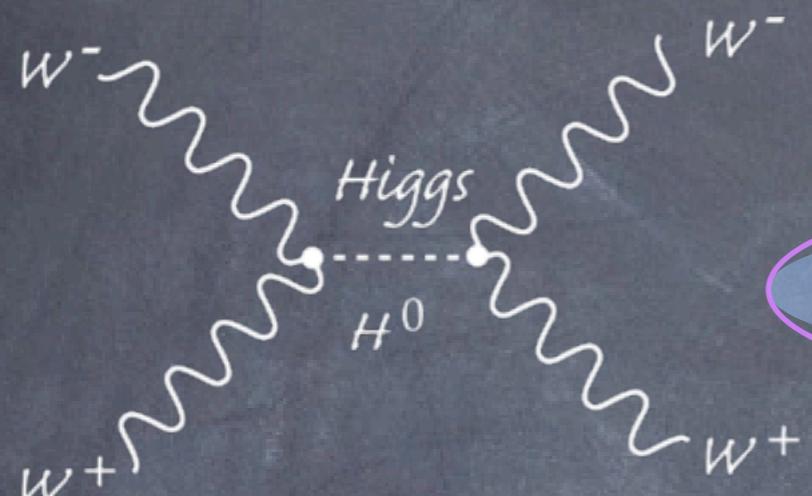
should be seen
within one/two years

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

Composite Higgs Models

Drawbacks of Usual Approaches

Weakly coupled models



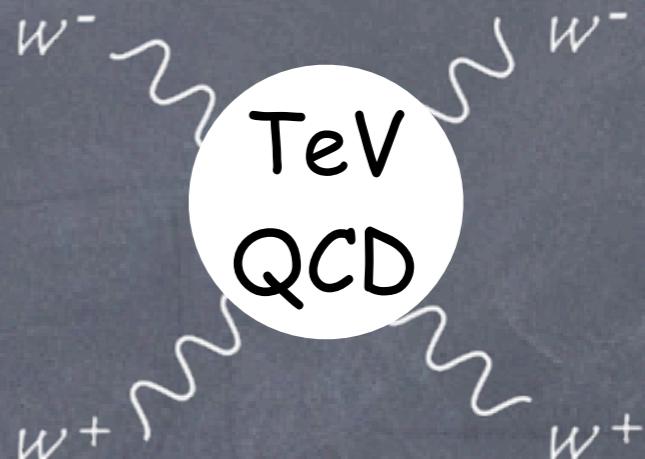
prototype: Susy
susy partners ~ 100 GeV

need new particles to stabilize
the Higgs mass

bounds on the masses of these particles


fine-tuning $O(1\%)$

Strongly coupled models



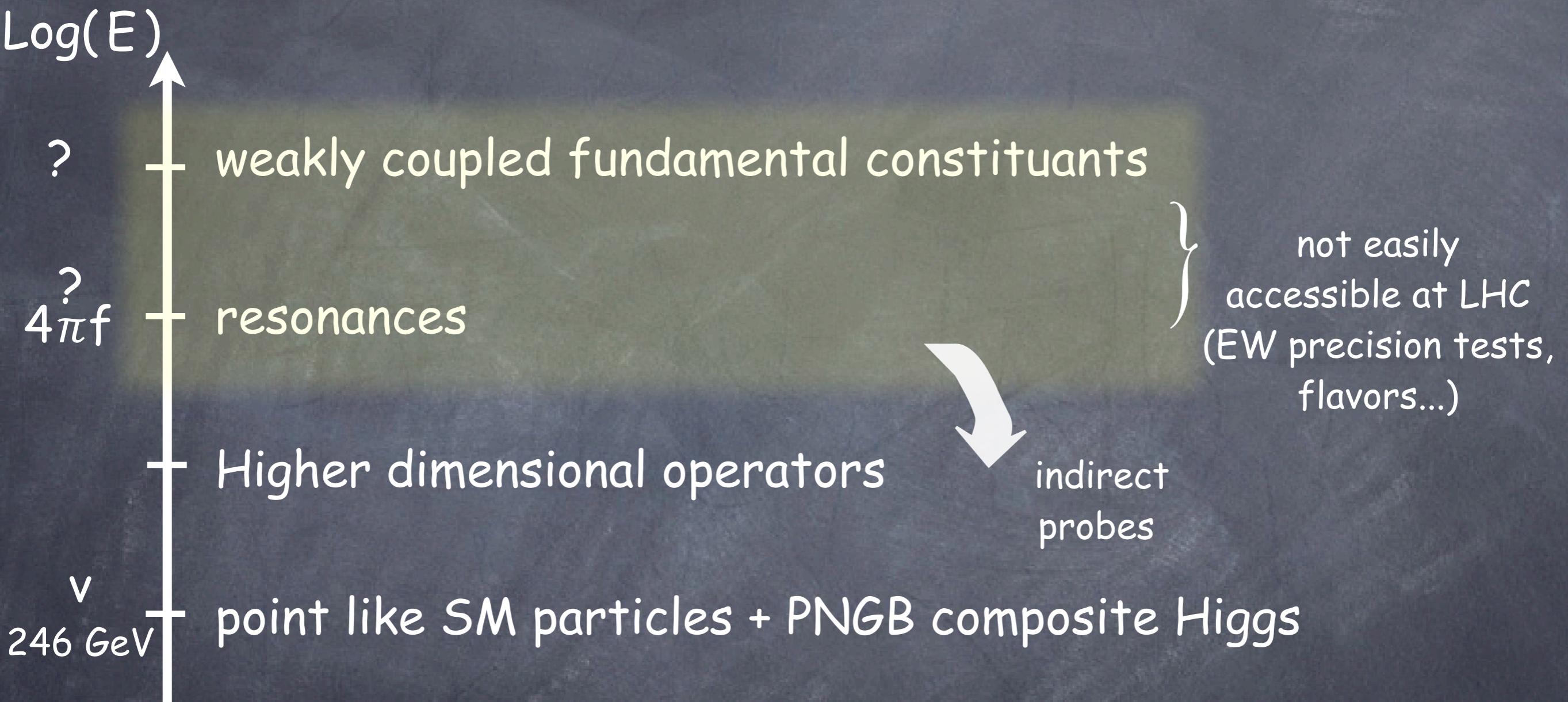
prototype: Technicolor
rho meson ~ 1 TeV

resonances needed for
unitarization generate EW
oblique corrections

$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \quad |\hat{S}| < 10^{-3}$$

$\xrightarrow{\text{@ 95\% CL}}$ $m_\rho > 2.5$ TeV

Physics of a light composite Higgs?



Higgs=resonance emerging from strong sector but it is light because it is a 4th Goldstone

Continuous interpolation between SM and TC

$$\xi = \frac{v}{f} = \frac{\text{weak scale}}{\text{strong coupling scale}}$$

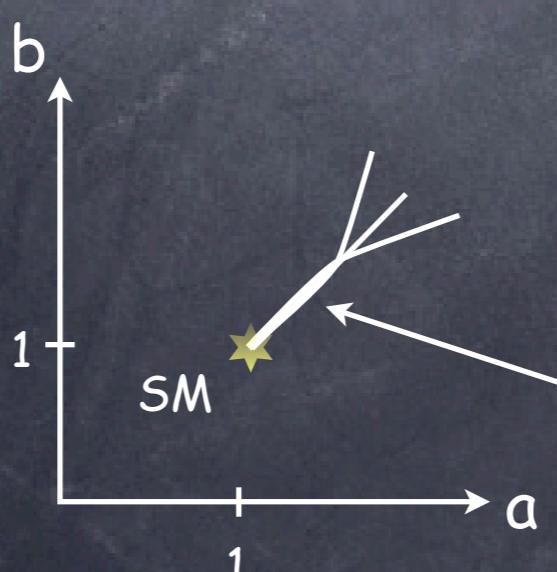
$\xi = 0$
SM limit

all resonances of strong sector,
except the Higgs, decouple

$\xi = 1$
Technicolor limit

Higgs decouple from SM;
vector resonances like in TC

Composite
vs.
SM Higgs



$$\mathcal{L}_{\text{EWSB}} = \left(a \frac{v}{2} h + b \frac{1}{4} h^2 \right) \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma)$$

universal behavior for large f
 $a=b=v/f$

Beyond the Higgs

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

Strong WW scattering

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

$$= -(1 - \xi) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation
of the growing amplitudes

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

$$\mathcal{A}(W_L^a W_L^b \rightarrow W_L^c W_L^d) = \mathcal{A}(s, t, u) \delta^{ab} \delta^{cd} + \mathcal{A}(t, s, u) \delta^{ac} \delta^{bd} + \mathcal{A}(u, t, s) \delta^{ad} \delta^{bc}$$

$$\mathcal{A}_{\text{LET}}(s, t, u) = \frac{s}{v^2}$$

LET=SM-Higgs \rightarrow Beyond the Higgs

$$\mathcal{A}_\xi = \xi \mathcal{A}_{\text{LET}}$$

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)

$$\frac{c_H}{2f^2} \left(\partial_\mu (|H|^2) \right)^2$$

$$\frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2} |H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2} |H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{i c_W}{2m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i$$

$$\frac{i c_B}{2m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu})$$

$$\frac{i c_{HW}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i$$

$$\frac{i c_{HB}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \rightarrow \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

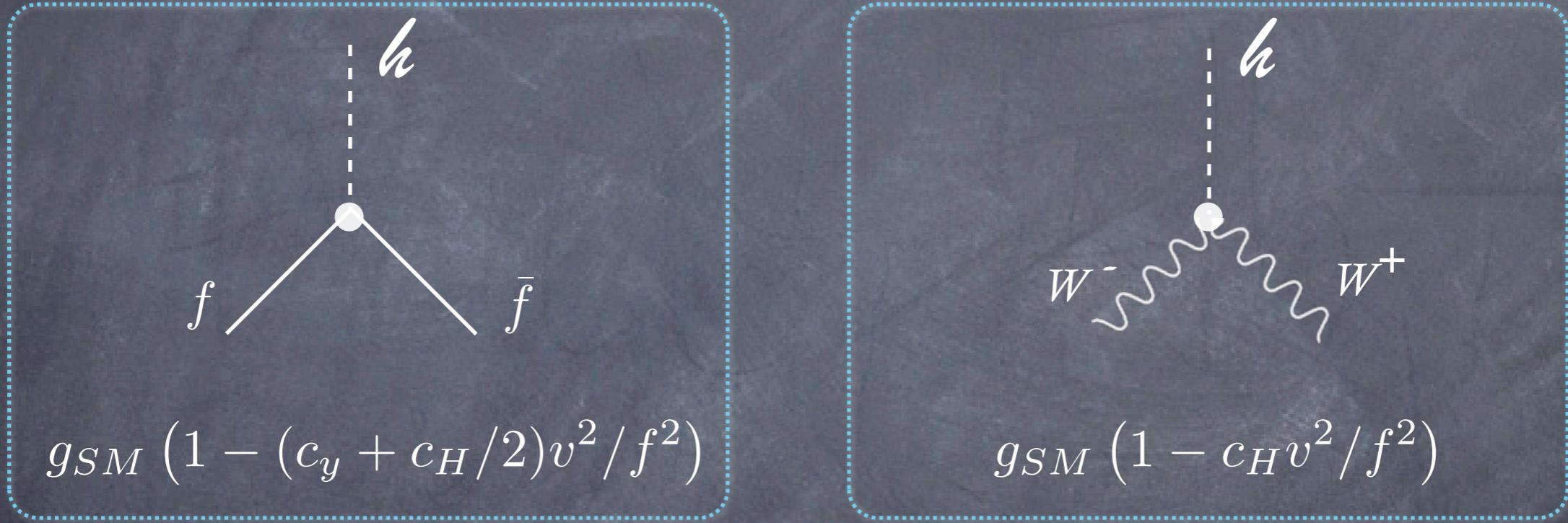
$$\frac{c_g}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$

Goldstone sym.

Higgs anomalous couplings

Lagrangian in unitary gauge

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



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

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

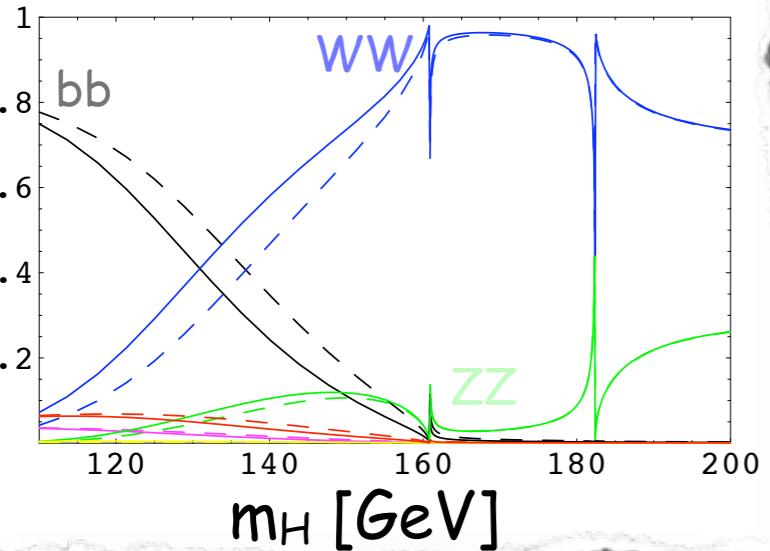
Note: same Lorentz structure as in SM. Not true anymore if form factor ops. are included

Higgs BRs and total width

Fermions embedded in 5+10 of SO(5)

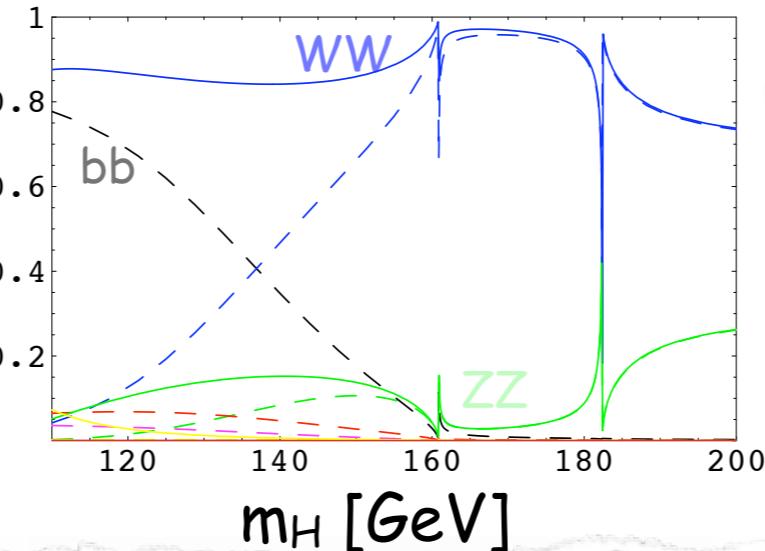
BRs

$v^2/f^2=0.2$



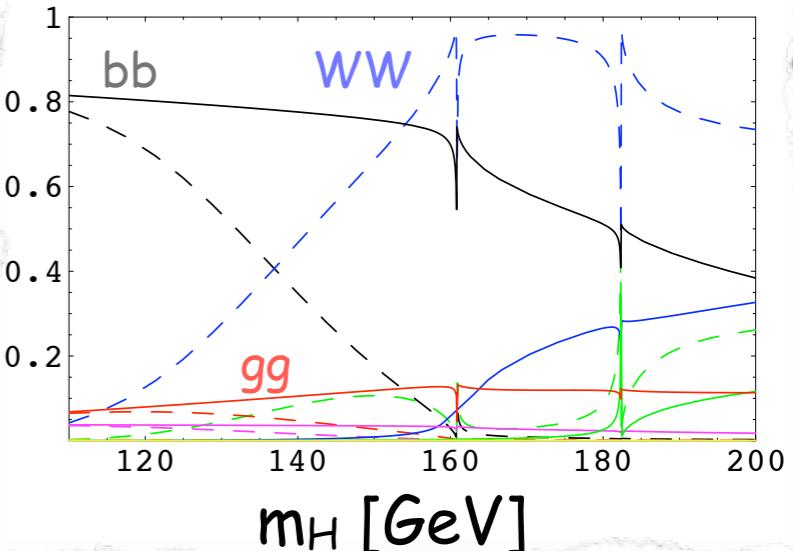
BRs

$v^2/f^2=0.5$



BRs

$v^2/f^2=0.95$



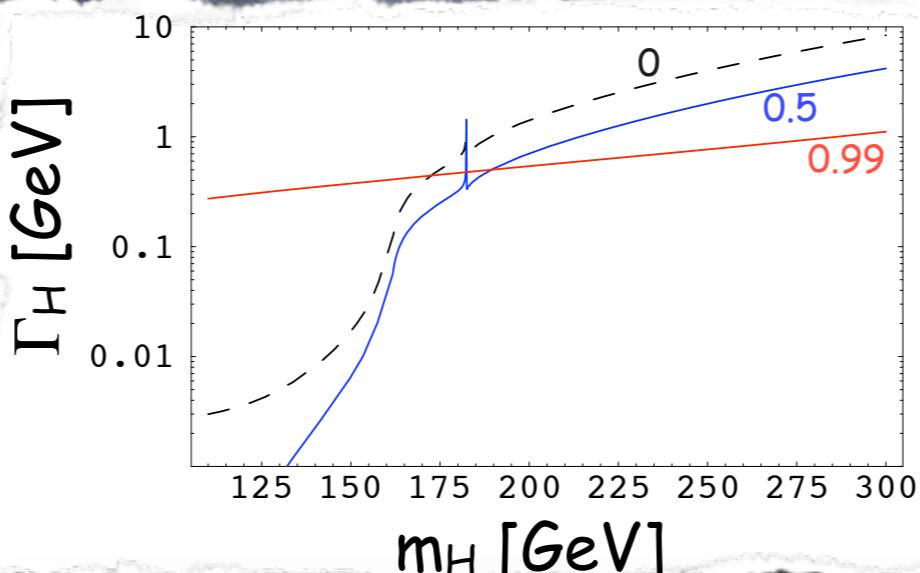
slight modifications

suppress bb

suppress WW

Higgs total width

--- SM
— composite Higgs



Beyond the Higgs

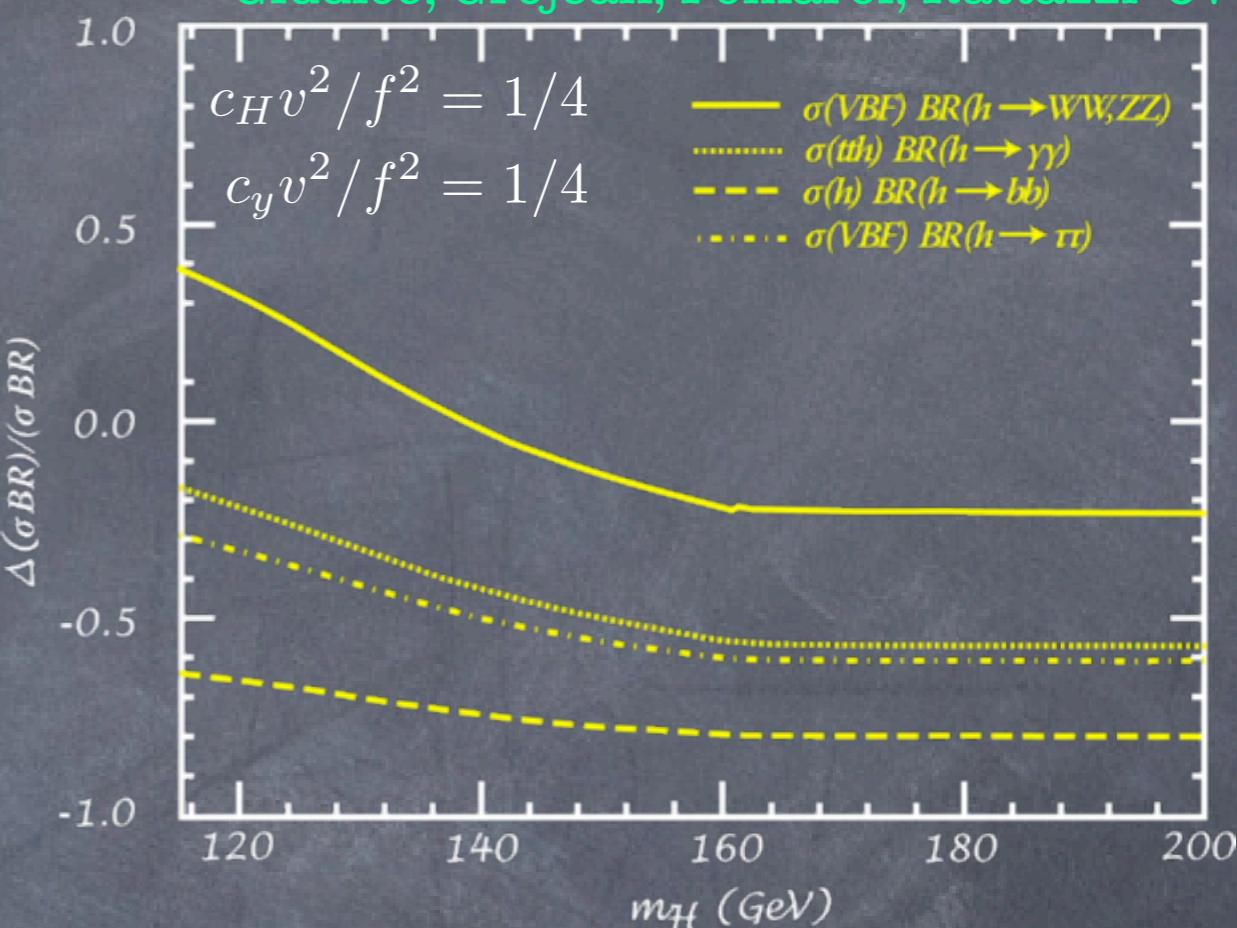
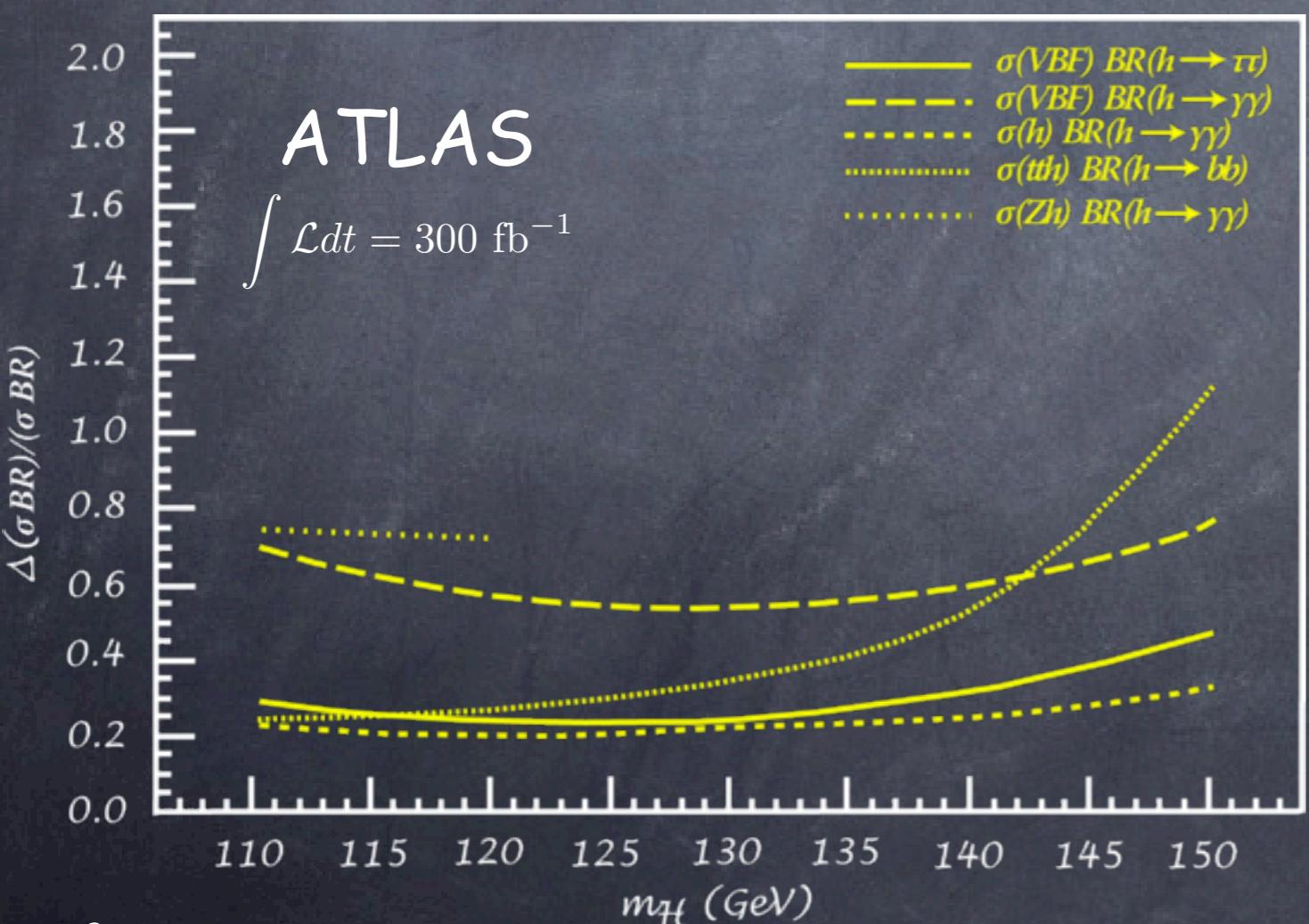
Higgs anomalous couplings @ LHC

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 $4\pi f \sim 30 \text{ TeV}$)

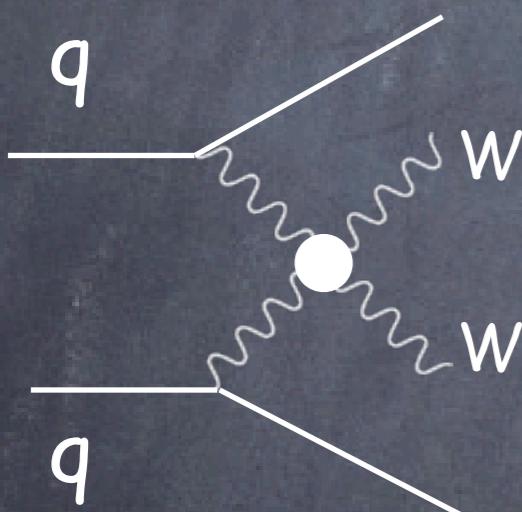
Strong WW scattering @ LHC

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

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

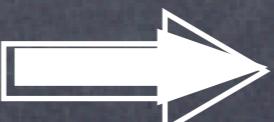
$$\mathcal{A}(W^\pm Z_L^0 \rightarrow W^\pm Z_L^0) = \frac{c_H t}{f^2}, \quad \mathcal{A}(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) = \frac{c_H(s+t)}{f^2}$$

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0) = 0$$



$$\sigma(pp \rightarrow V_L V_L X)_\xi = \xi^2 \sigma(pp \rightarrow V_L V_L X)_{\text{LET}}$$

leptonic vector decay channels
forward jet-tag, back-to-back lepton, central jet-veto



Bagger et al '95
Butterworth et al. '02

	LET($\xi = 1$)	SM bckg
ZZ	4.5	2.1
$W^+ W^-$	15.0	36
$W^\pm Z$	9.6	14.7
$W^\pm W^\pm$	39	11.1

$\mathcal{L} = 300 \text{ fb}^{-1}$

Strong Higgs production: (3L+jets) analysis

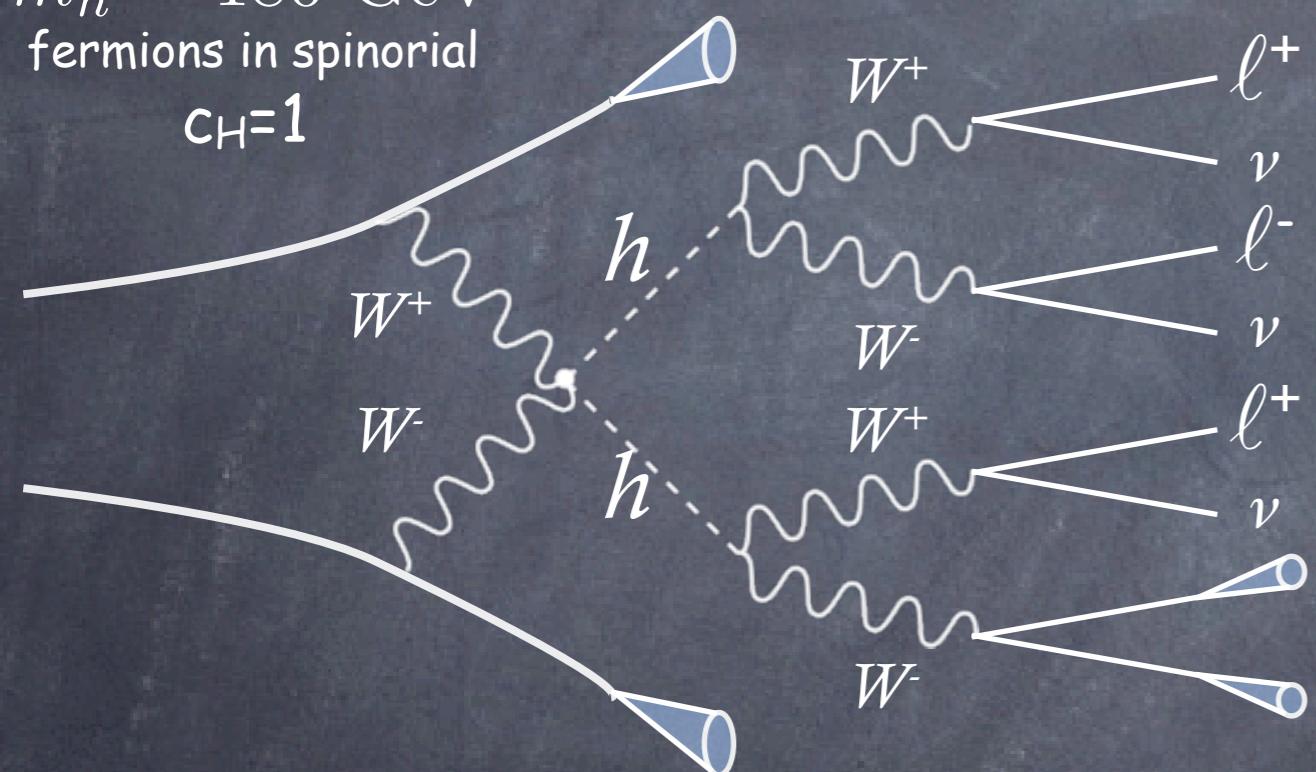
Contino, Grojean, Moretti, Piccinini, Rattazzi ‘in progress’

strong boson scattering \Leftrightarrow strong Higgs production

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

$m_h = 180$ 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 5σ	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

(its discovery has already been announced to journalists and politics, so it has to be there)

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...)