$E = mc^2$

New Theories For The Fermi Scale

The 2009 Europhysics Conference on High Energy Physics

Krakow, July 16-22, 2009

$E = \hbar\nu$

$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = 16\pi G\, T_{\mu\nu}$

Christophe Grojean

CERN-TH & CEA-Saclay-IPhT

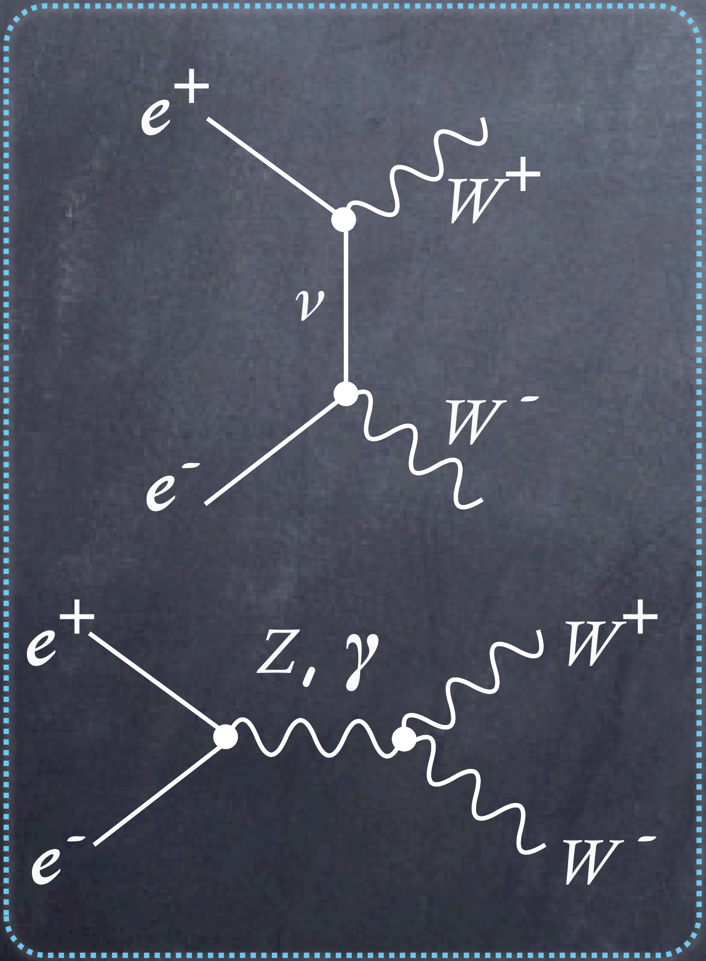
(Christophe.Grojean[at]cern.ch)

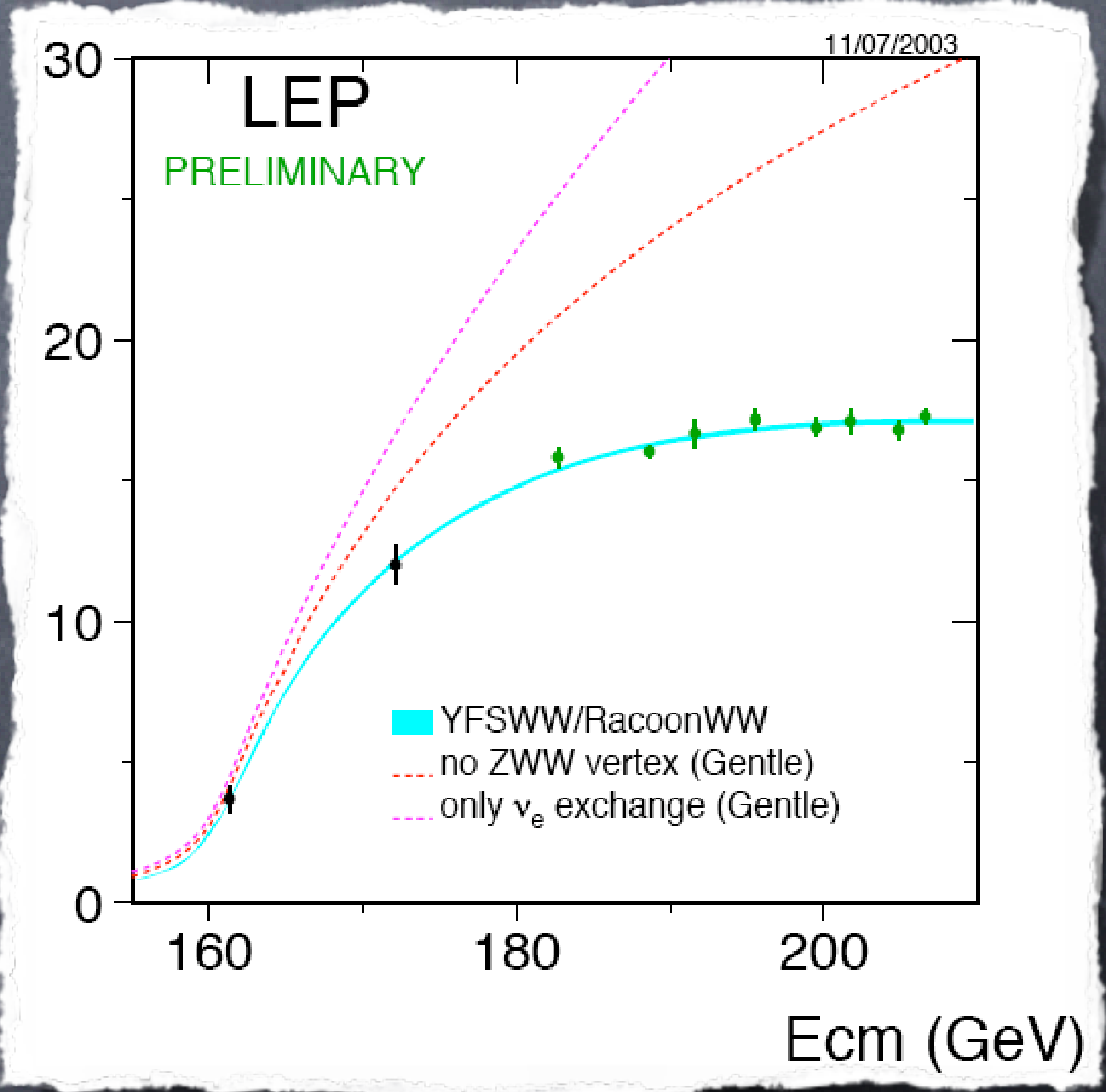
The Standard Model

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

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

$e^+e^- \rightarrow W^+W^-$





The Standard Model and the Mass Problem

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

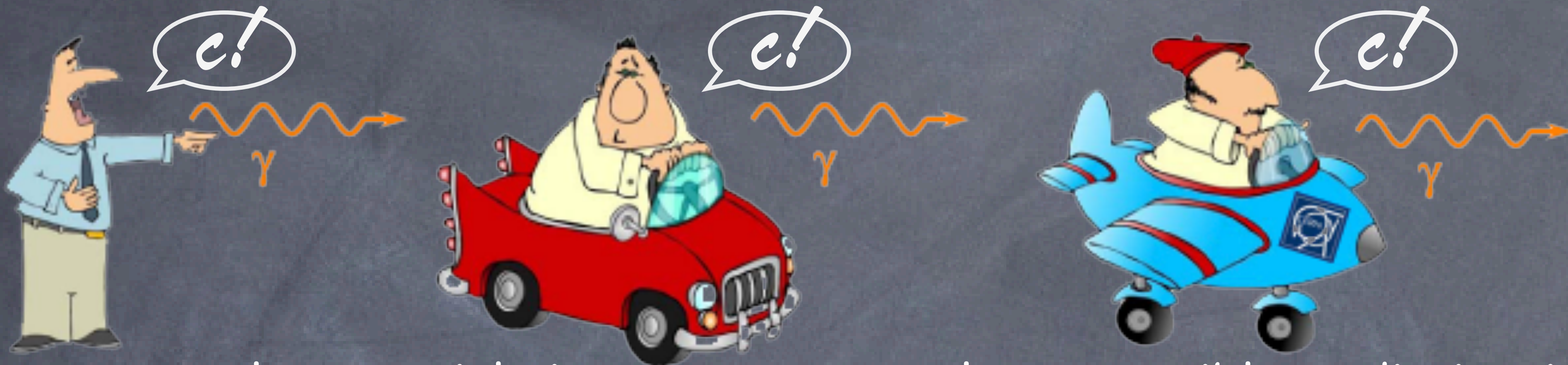
SU(3)$_C$xSU(2)$_L$xU(1)$_Y$

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 longitudinal polarization of massive W, Z



a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization

the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$\epsilon_L^\mu = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$ polarization vector grows with the energy ⇨ need UV moderator

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

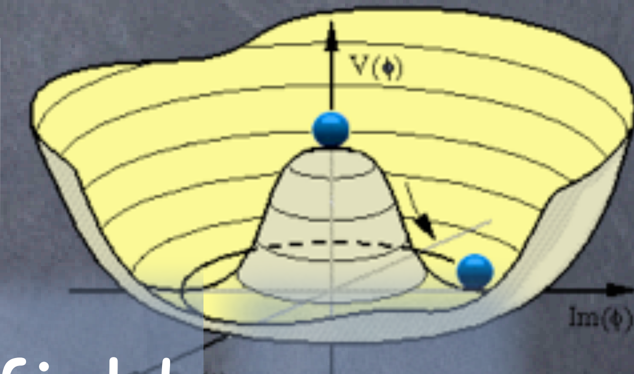
massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ Where are these Goldstone's coming from? ⇚

what is the sector responsible for the breaking $SU(2)_L \times SU(2)_R$ to $SU(2)_V$?

with which dynamics? with which interactions to the SM particles?

common lore: from a scalar Higgs doublet



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

Higgs doublet = 4 real scalar fields

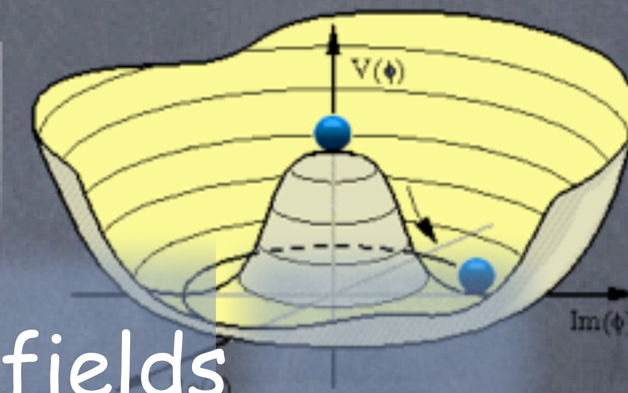
3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^\pm$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ **Where are these Goldstone's coming from?** ⇚



common lore: from a scalar Higgs doublet

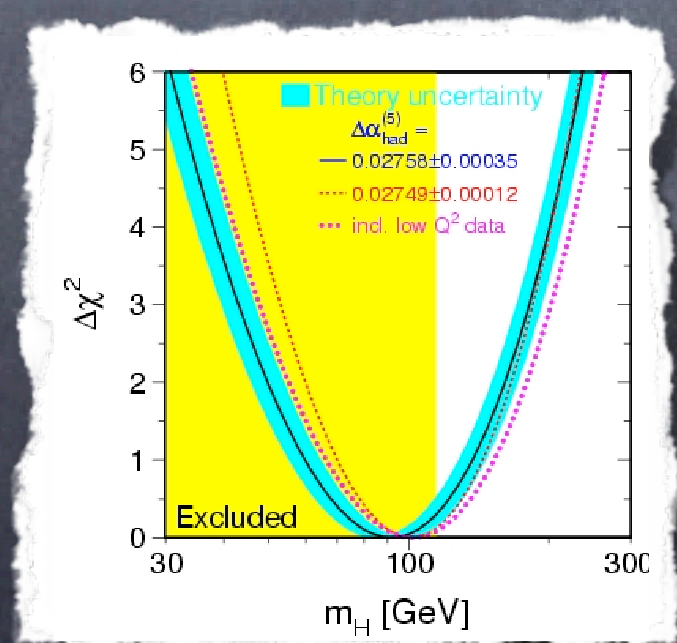
$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

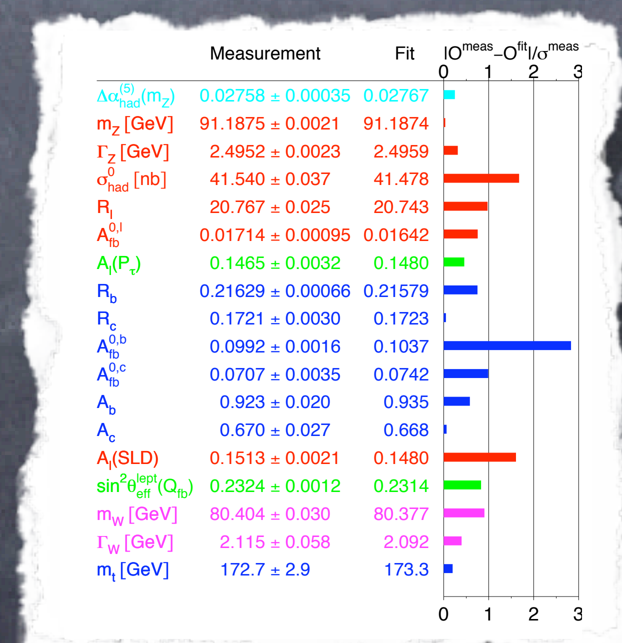
Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

Good agreement with EW data

(doublet ⇔ ρ=1)





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

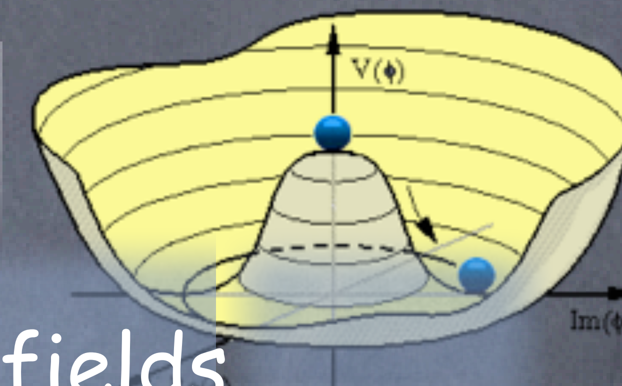
The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^\pm$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ **Where are these Goldstone's coming from?** ⇚

common lore: from a scalar Higgs doublet



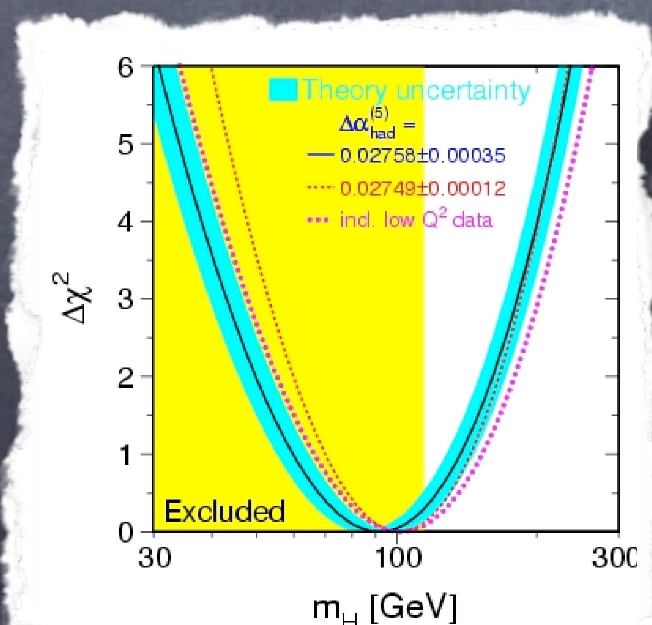
$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

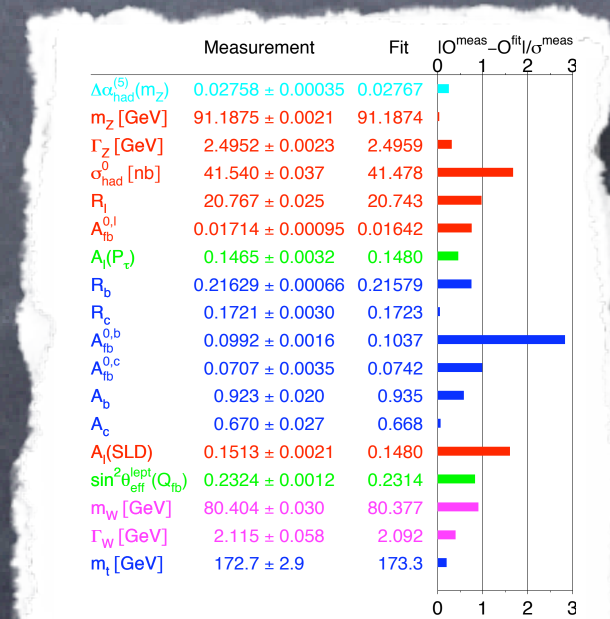
Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

Good agreement with EW data

(doublet ⇔ ρ=1)





	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	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	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(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...

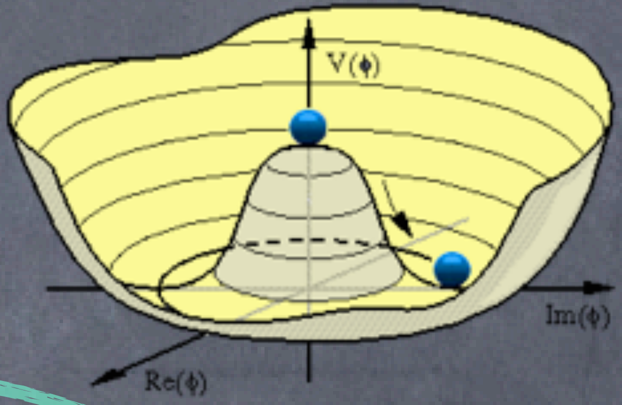
The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ Where are these Goldstone's coming from? ⇚

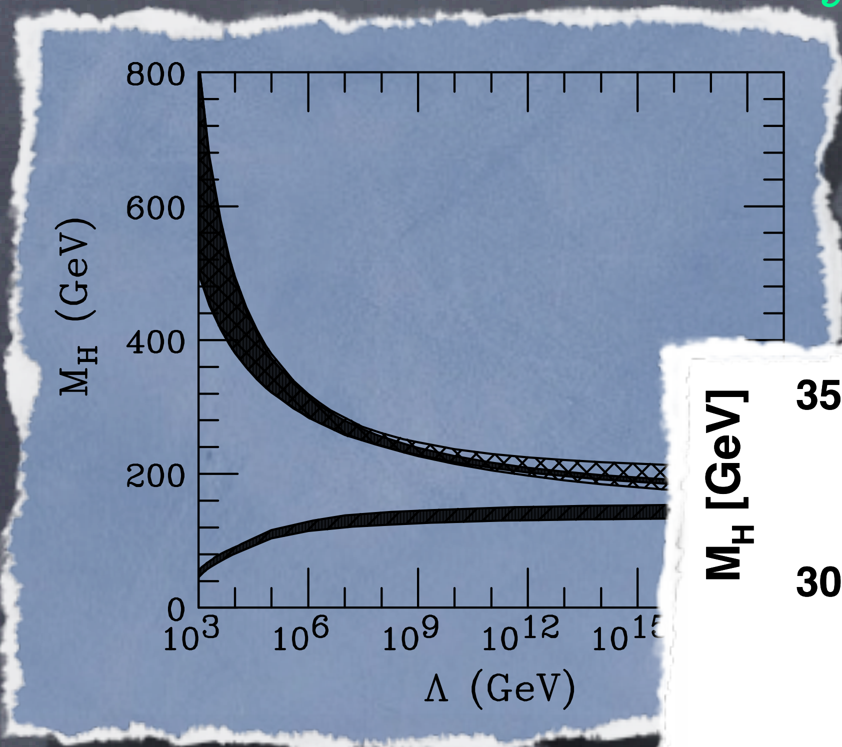
common lore: from a scalar Higgs doublet



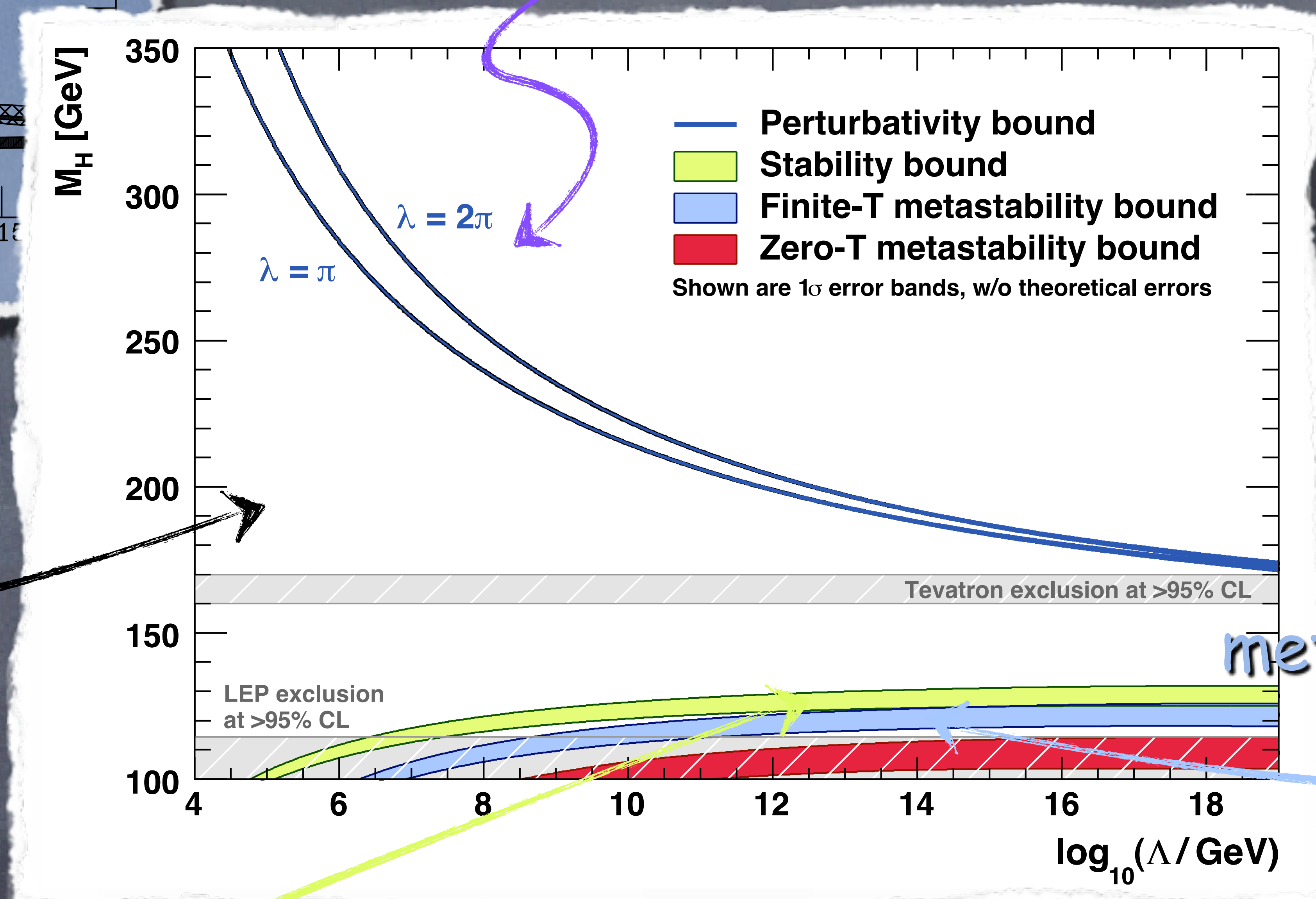
a (too?) simple picture that calls for new physics

- The Higgs has not been seen yet
- There is no dynamics: a description but not an explanation of EWSB
- Instability under radiative corrections: "the hierarchy problem"
- Instability under radiative corrections: triviality, stability...

Hambye, Riesselmann '97



blow-up



survival

metastable

collapse

Ellis, Espinosa, Giudice, Hoecker, Riotto '09

Only a light Higgs (130 GeV<m_H<170 GeV) allows for the absence of New Physics at low energy

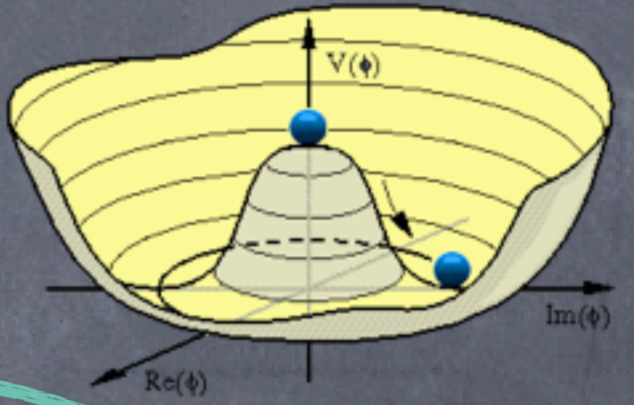
The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ Where are these Goldstone's coming from? ⇚

common lore: from a scalar Higgs doublet



a (too?) simple picture that calls for new physics

- The Higgs has not been seen yet
- There is no dynamics: a description but not an explanation of EWSB
- Instability under radiative corrections: "the hierarchy problem"
- Instability under radiative corrections: triviality, stability...

- Precisions measurements (g_μ-2, LR asymmetries etc)
- Neutrinos masses
- Dark matter
- Dark energy
- Matter-antimatter asymmetry
- Inflation
- Fermion mass and mixing hierarchies
- Strong CP problem
- Charge quantization & GUT
- Quantization of gravity

Which Higgs?

UnHiggs?
Private Higgs?
Guralnik's Higgs?
Little Higgs?
Gaugephobic Higgs?
Kibble's Higgs?
Littlest Higgs?
Buried Higgs?
Intermediate Higgs?
Slim Higgs?
Composite Higgs?
Fat Higgs?
Higgsless?
Portal Higgs?
Peter's Higgs?
Brout-Englert's Higgs?
Gauge-Higgs?
Lone Higgs?
Twin Higgs?
Simplest Higgs?
Phantom Higgs?

Supersymmetric Higgs(es)

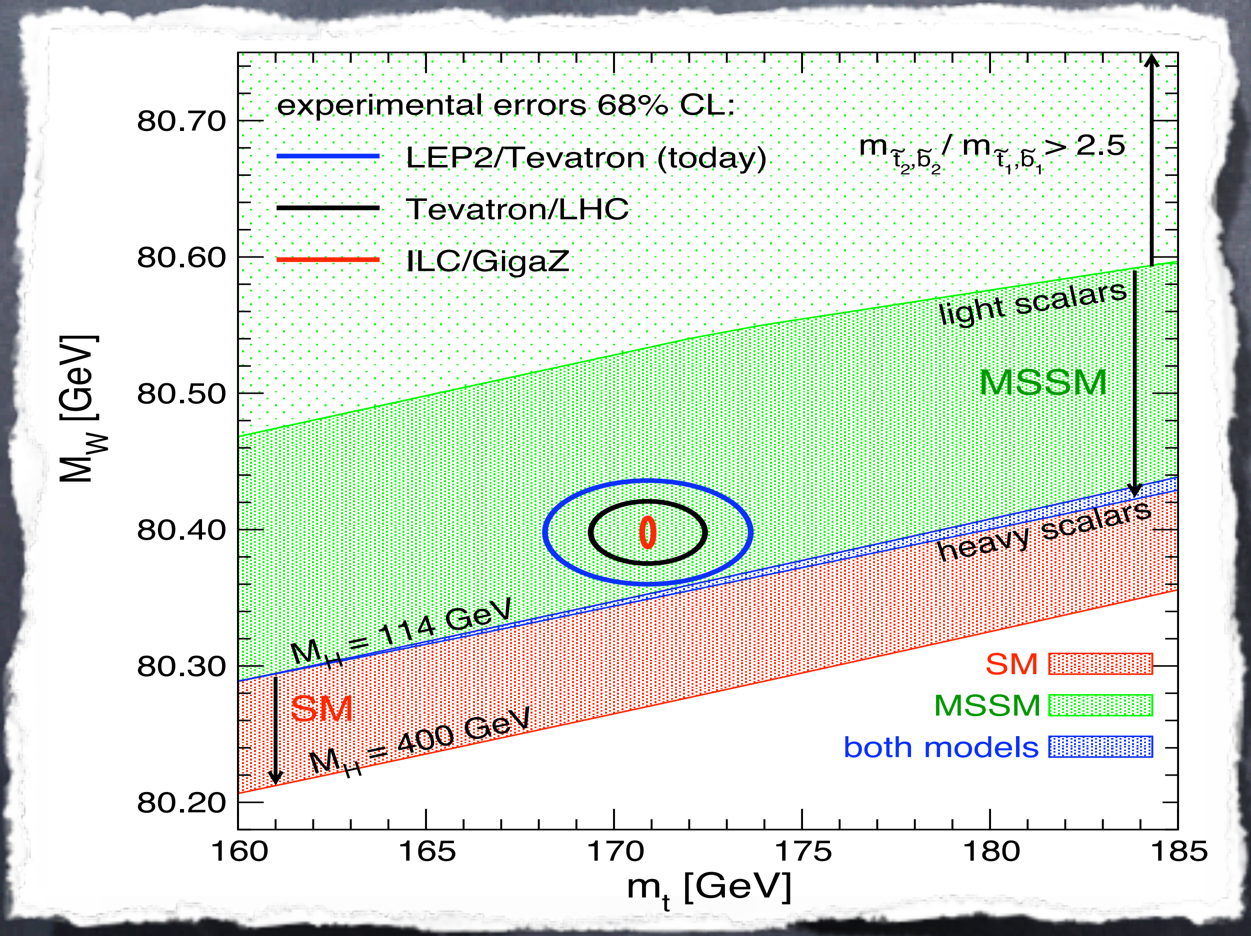
The Goodies of SUSY

SUSY has good assets:

- Absence of quadratic divergences
- Radiative EWSB,
- Gauge coupling unification,
- DM candidate(s),
- No large oblique corrections: R-parity ⊃ one-loop effects only...

Good fit to EW data

⇛



Heinemeyer et al '06

but...

The not so Goodies of SUSY

SUSY need new (super)particles that haven't been seen yet

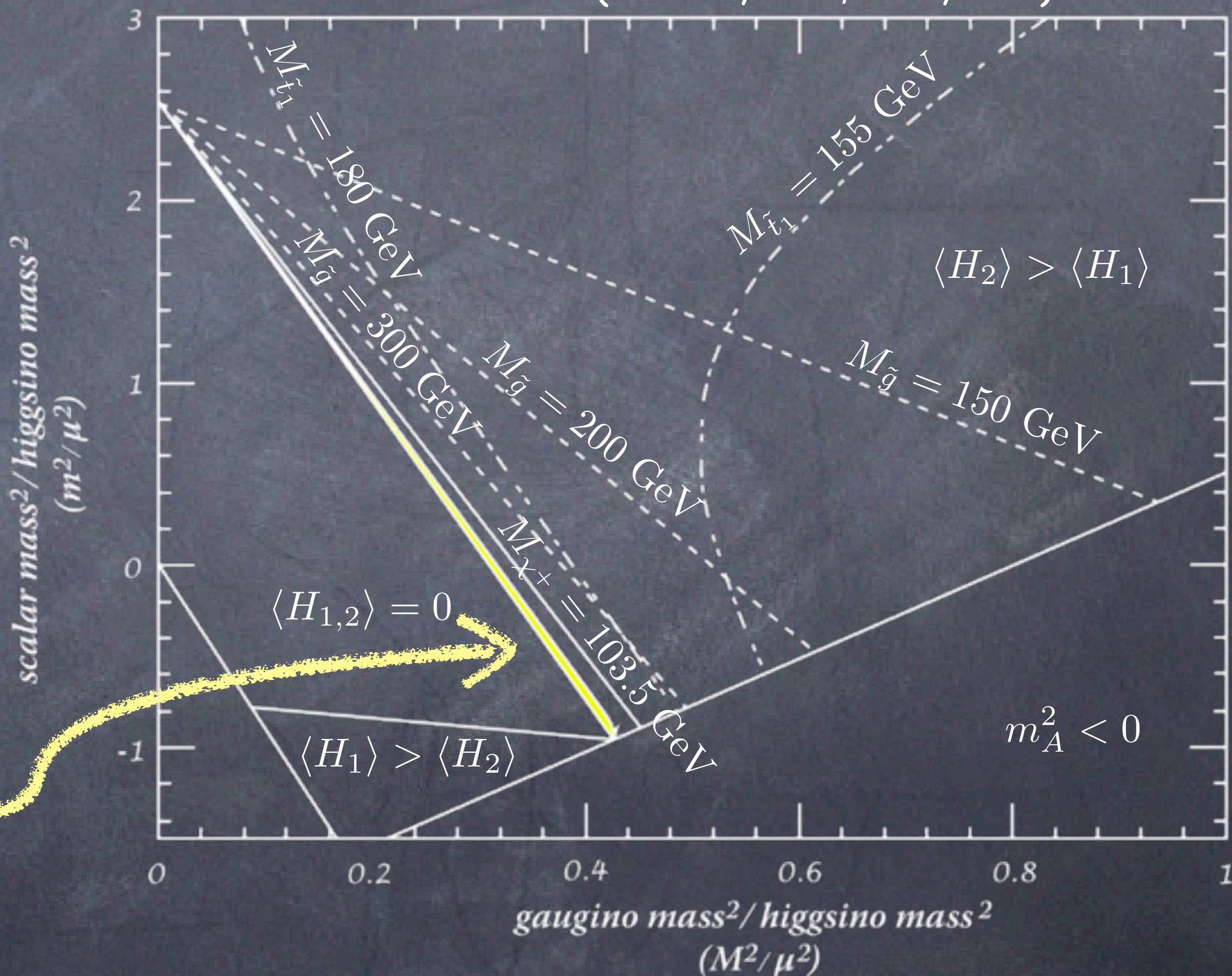
SUSY (at least MSSM) predicts a very light Higgs

- SUSY little hierarchy

large regions of parameter space ruled out

allowed region ~ 1%

(MSSM, tan β =10, A=0)



Giudice, Rattazzi '06

The not so Goodies of SUSY

SUSY need new (super)particles that haven't been seen yet

SUSY (at least MSSM) predicts a very light Higgs

- SUSY little hierarchy

$$V = (|\mu|^2 + m_{H_u}^2)\left|H_u^0\right|^2 + (|\mu|^2 + m_{H_d}^2)\left|H_d^0\right|^2 - B(H_u^0 H_d^0 + c.c.) + \frac{g^2 + g'^2}{8}\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

tree-level

$$m_h^2 = m_Z^2 \cos^2 2\beta$$

$$m_Z^2/2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

excluded

The not so Goodies of SUSY

SUSY need new (super)particles that haven't been seen yet

SUSY (at least MSSM) predicts a very light Higgs

- SUSY little hierarchy

one-loop level

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

$m_H > 115$ GeV ⇨ $m_{\tilde{t}} > 1$ TeV

$$\delta m_{H_u}^2 = -\frac{3\sqrt{2} G_F m_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda}{m_{\tilde{t}}} \qquad m_Z^2/2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

fine-tuned

requires some fine-tuning O(1%) in m_Z

The not so Goodies of SUSY

SUSY need new (super)particles that haven't been seen yet
SUSY (at least MSSM) predicts a very light Higgs

- SUSY little hierarchy

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

one-loop level

$m_H > 115$ GeV ⇨ $m_{\tilde{t}} > 1$ TeV

$$\delta m_{H_u}^2 = -\frac{3\sqrt{2} G_F m_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda}{m_{\tilde{t}}} \qquad m_Z^2/2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

requires some fine-tuning O(1%) in m_Z

fine-tuned

- SUSY DM

the correct prediction of the LSP relic density requires special relations among parameters with a high sensitivity to small variations

e.g., Arkani-Hamed, Delgado, Giudice '06

- SUSY Baryogenesis

need a peculiar susy spectrum with a stop much lighter than the susy breaking scale

e.g., Carena et al '08

- CP, Flavour...

Solving the susy little hierarchy pb

Various proposals on the market:

- singlet extensions of the Higgs sector: NMSSM and friends
  Fayet '76 + O(500) papers
- gauge extensions with new non-decoupled D-terms
  Batra, Delgado, Kaplan, Tait '03 + O(10) papers
- low scale susy breaking mediation (Λ~100 TeV)
  Casas, Espinosa, Hidalgo '03 + O(50) papers
- double protection: (super-little) Higgs as a Goldstone boson
  Birkedal, Chacko, Gaillard '04 + O(20) papers
- add higher dimensional terms: BMSSM Dine, Seiberg, Thomas '07

$$W_{\rm BMSSM} = \frac{\lambda_1}{M}(H_u H_d)^2 + \frac{\lambda_2}{M}\mathcal{Z}_{\rm soft}(H_u H_d)^2$$

+ no modification to Khaler potential

  - allow for heavier Higgs and much lighter susy (stops) particles
  - (meta)stable EW vacuum Blum, Delaunay, Hochberg '09
  - window for MSSM baryogenesis extended and more natural Blum, Nir '08
  - LSP can account for DM relic density in larger region of parameter space
    Bernal, Blum, Nir '09

- ... more models to come

Little Higgs

Which symmetry for the Higgs sector

symmetries of the EWSB can help to preserve the SM structure
i.e., to keep the oblique corrections under control

- Contribution to T

$$\frac{SU(2)_L \times U(1)_Y}{U(1)_{\rm em}} \to \frac{SU(2)_L \times SU(2)_R}{SU(2)_V} = \frac{SO(4)}{SO(3)}$$

custodial symmetry ⇨ no T parameter

- Contribution to S

$SU(2)_L$ preserves S, but it has to be broken: $S \sim \frac{v^2}{\Lambda^2}$

need v« Λ ➡ hierarchy problem again.

Higgs as a Goldstone boson

$$\frac{SO(4)}{SO(3)} \to \frac{SO(5)}{SO(4)}, \frac{SU(5)}{SO(5)} \ldots$$

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.

$m_H = 0$

$\alpha_{top} \neq 0$

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

would require

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

...too low !

Little Higgs = PNGB + Collective Breaking

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

Little Higgs = PNGB + Collective Breaking

Higgs ∈ 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

Little Higgs = PNGB + Collective Breaking

Higgs ∈ 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

littlest Higgs

SU(5)/SO(5)

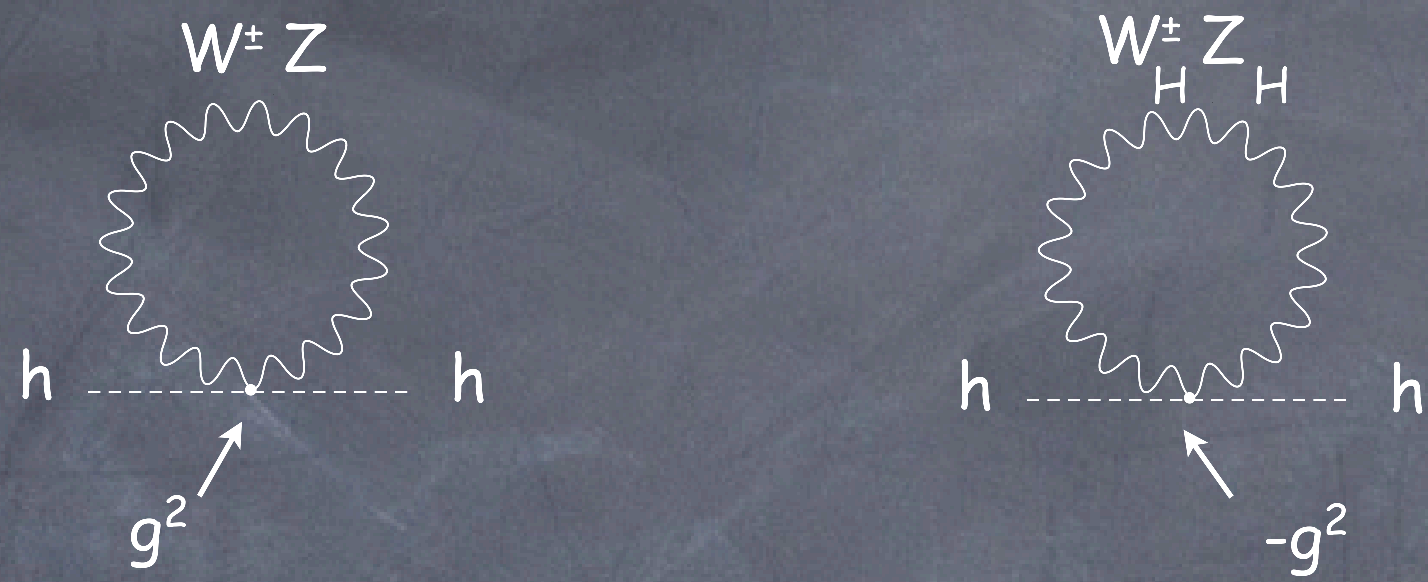
24-10=14 PNGB

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

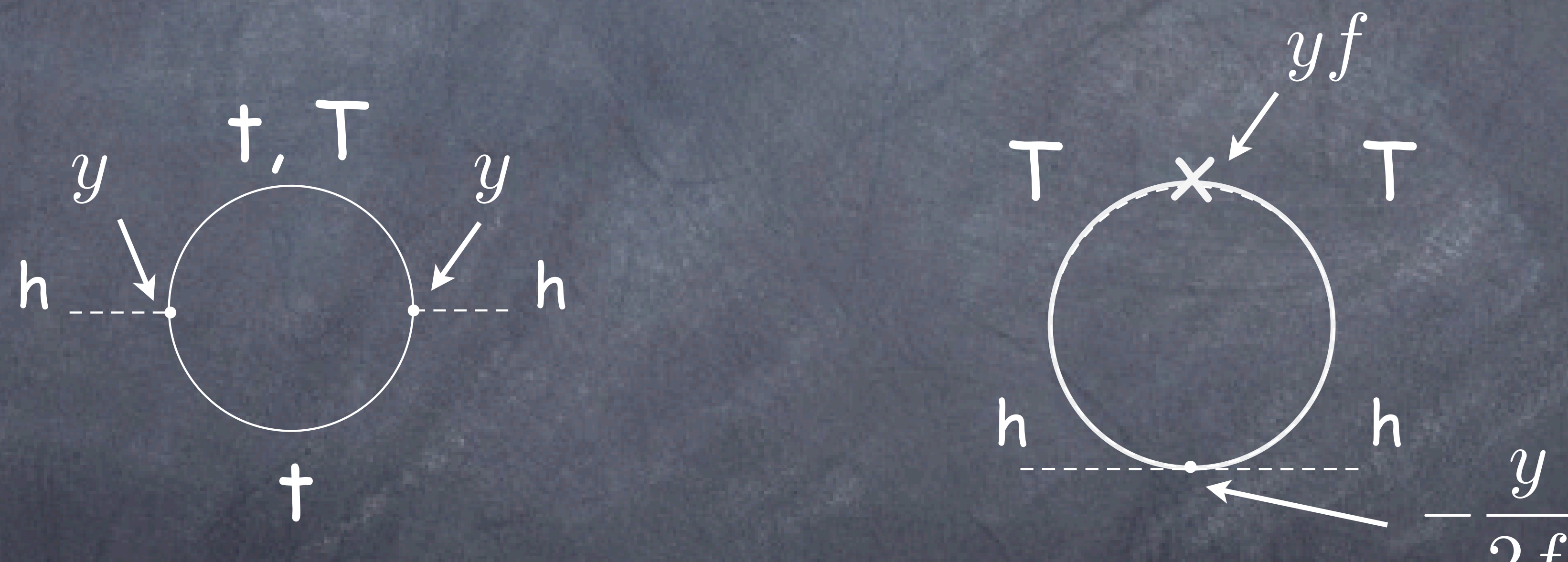
14-3=11 PNGB left = 3_1, $2_{1/2}$, 1_0 Higgs?

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

LH = Λ^2 cancelled by same spin partner



gauge boson loops cancelled by heavy gauge boson loops



top loop cancelled by heavy toop loop

Relation among different couplings follows from global sym.

cancellation of div. occurs only at one-loop

Little Higgs @ LHC

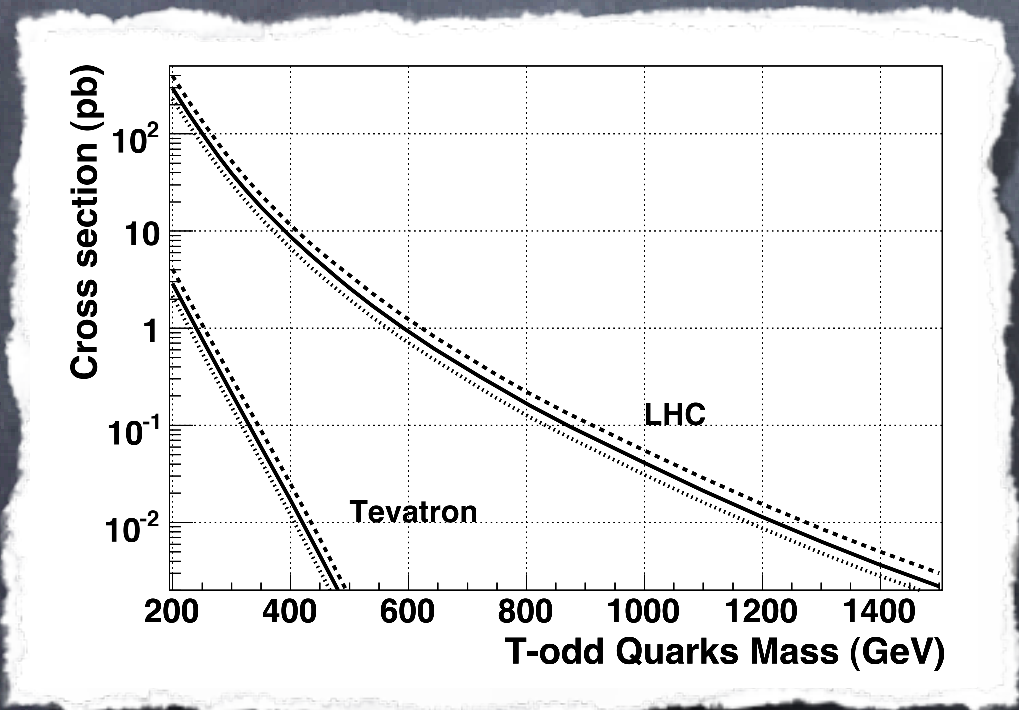
Confrontation of Little Higgs with EW data: needs for a T-parity

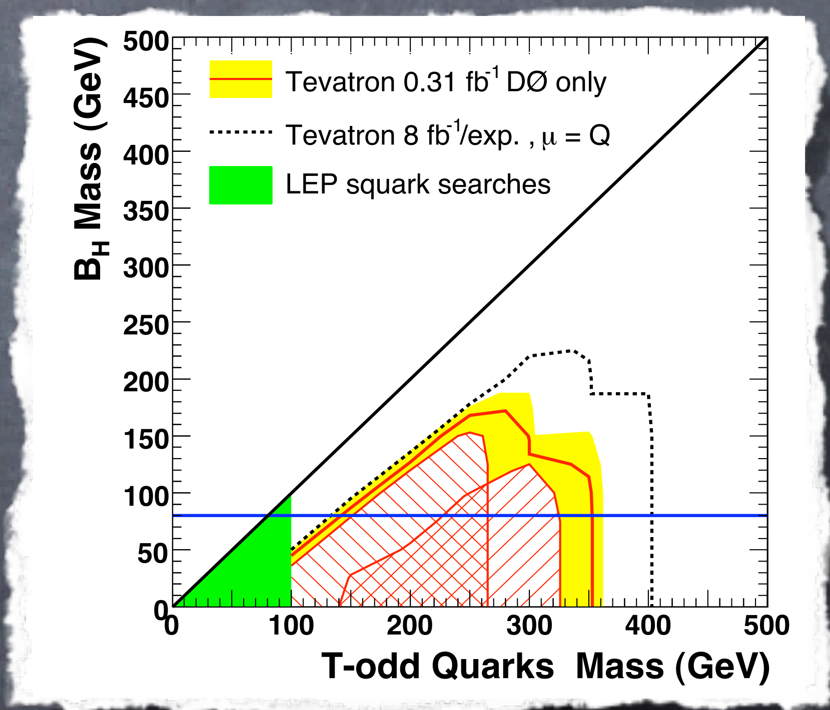
Cheng, Low '03

light particles = even ⇔ heavy particles = odd

the Lightest T-odd Particle (usually partner of B_μ) is stable (DM?)

Little Higgs = jet+ missing E_T





[Carena, Hubisz, Perelstein, Verdier '07]

Interesting physics also associated to top partner

(pair production: $gg \to TT$)

What is the mechanism of EWSB?

susy, LH... models assume that we already know the answer to

What is unitarizing the WW scattering amplitudes?

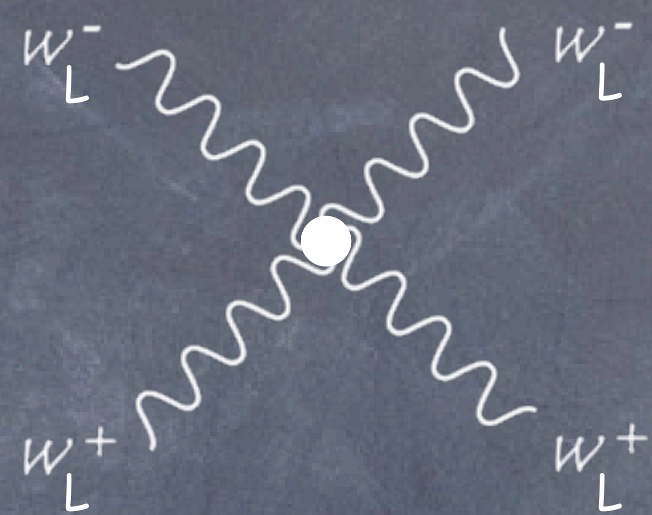
What is the mechanism of EWSB?

susy, LH... 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

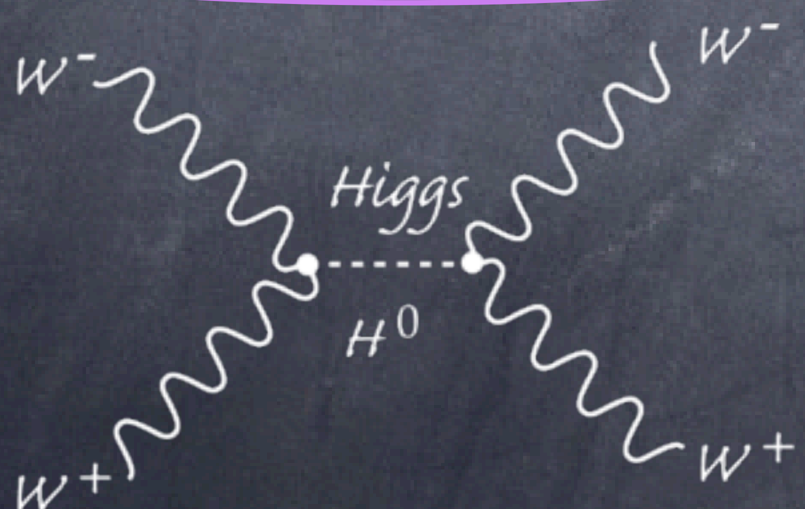
$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M} \frac{\vec{k}}{|\vec{k}|} \right)$$



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

loss of perturbative unitarity around 1.2 TeV

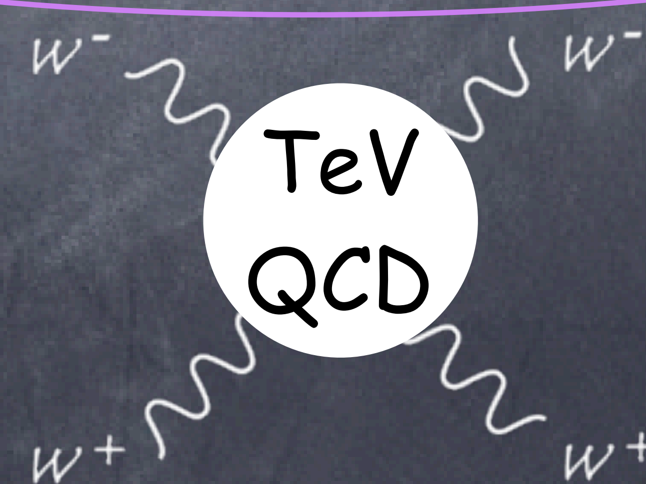
Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

Strongly coupled models



prototype: Technicolor

rho meson ~ 1 TeV

5D Higgsless Models

Higgsless Models

mass without a Higgs

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

momentum along extra dimensions ~ 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?

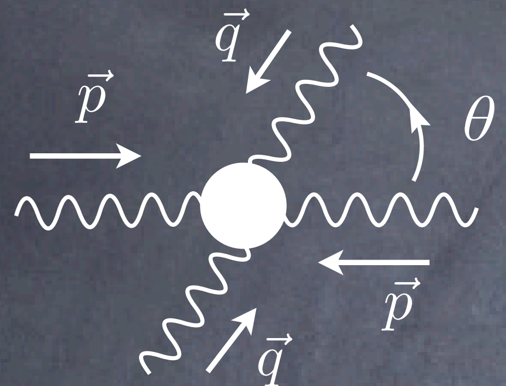
ie how is unitarity restored without a Higgs field?

Unitarization of (Elastic) Scattering Amplitude

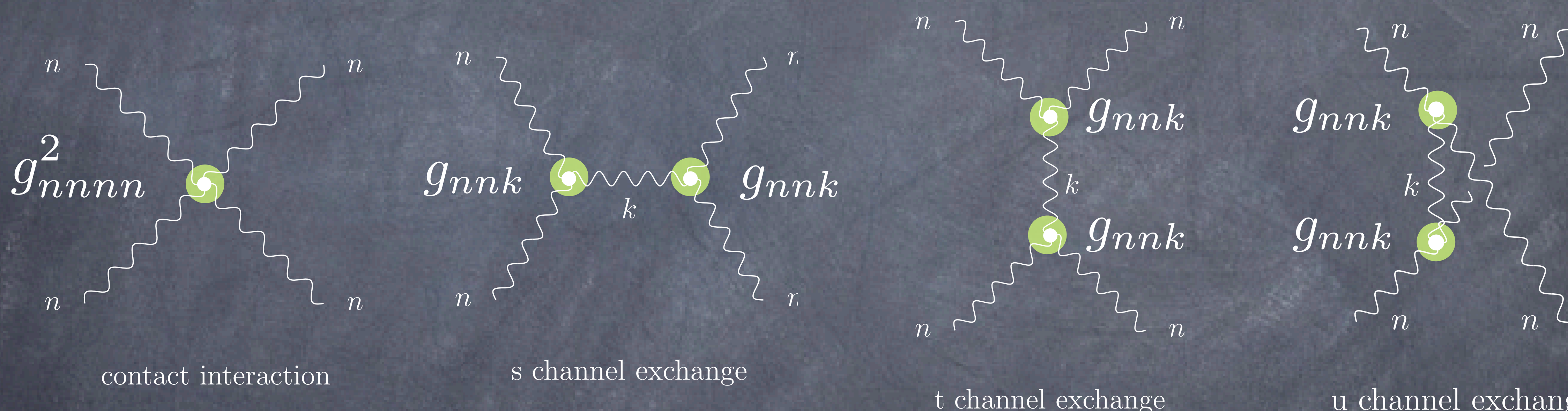
Csaki, Grojean, Murayama, Pilo, Terning '03

Same KK mode
'in' and 'out'

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



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



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

= 0 KK sum rules (enforced by 5D Ward identities)

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

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?

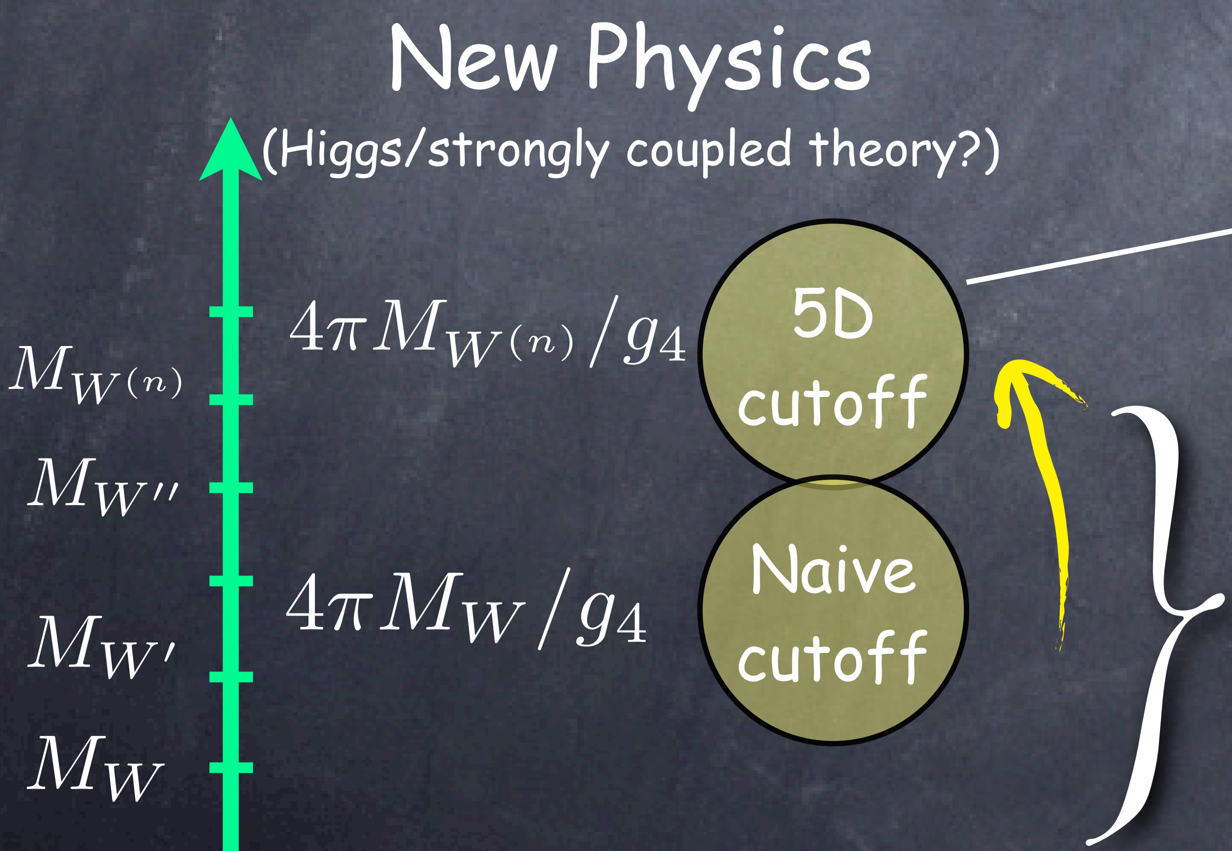
No!

$$g^2_{nnnn} \overset{E^4}{=} \sum_k g^2_{nnk} \overset{E^2}{=} \sum g^2_{nnk} \frac{3M_k^2}{4M_n^2}$$

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

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

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

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

Warped Higgsless Model

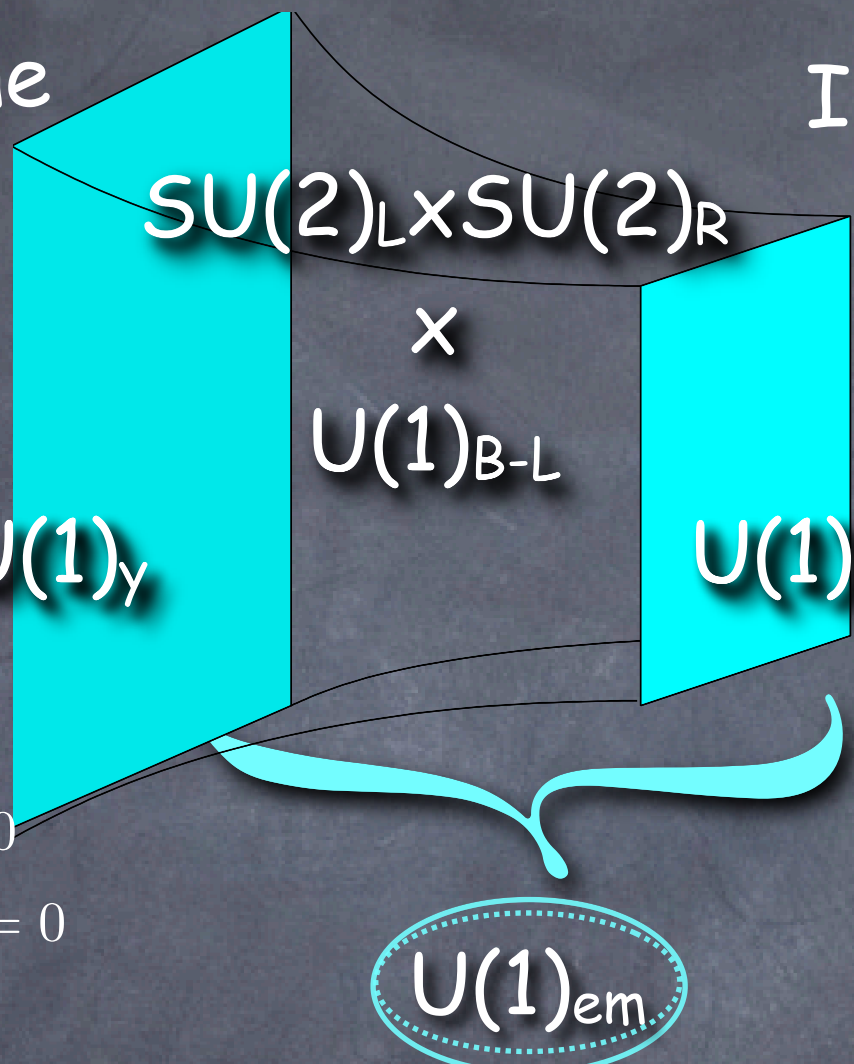
Csaki, Grojean, Pilo, Terning '03

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:

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

log suppression

KK tower:

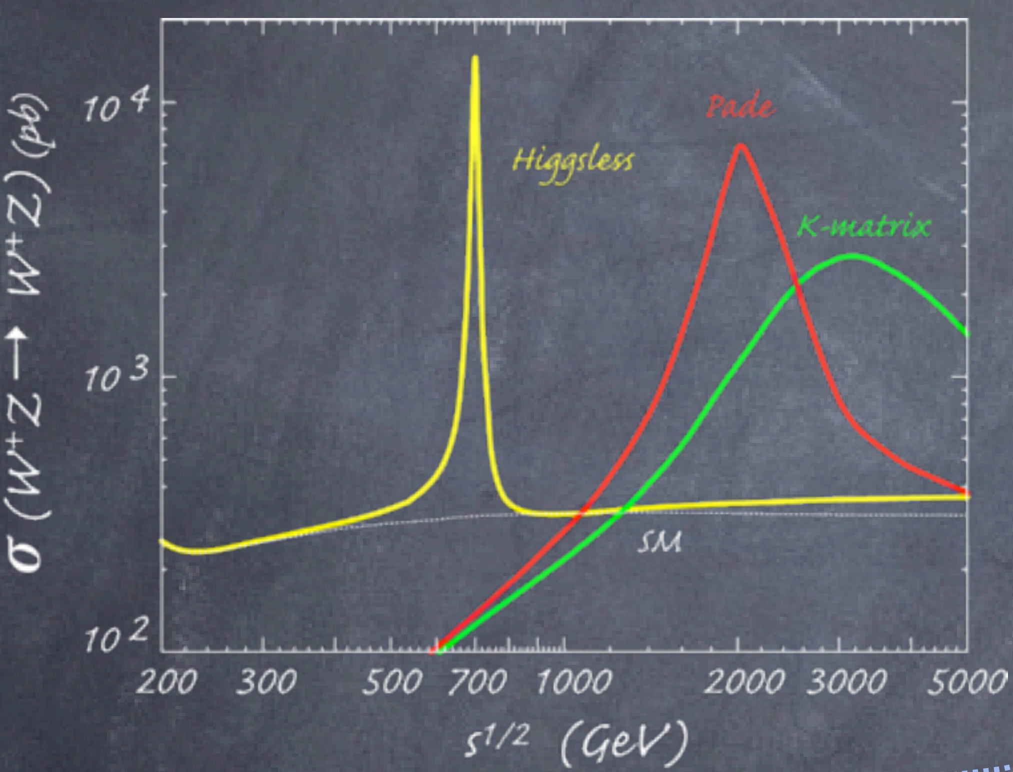
$$M_{KK}^2 = \frac{\text{cst of order unity}}{R_{IR}^2}$$

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

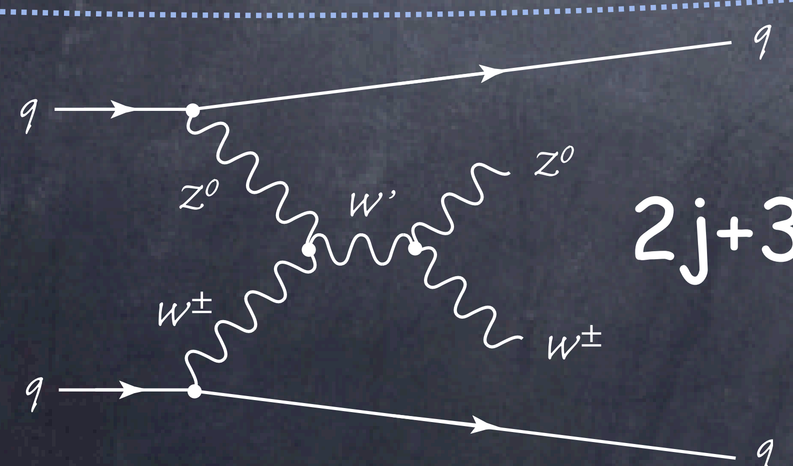


$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \qquad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance

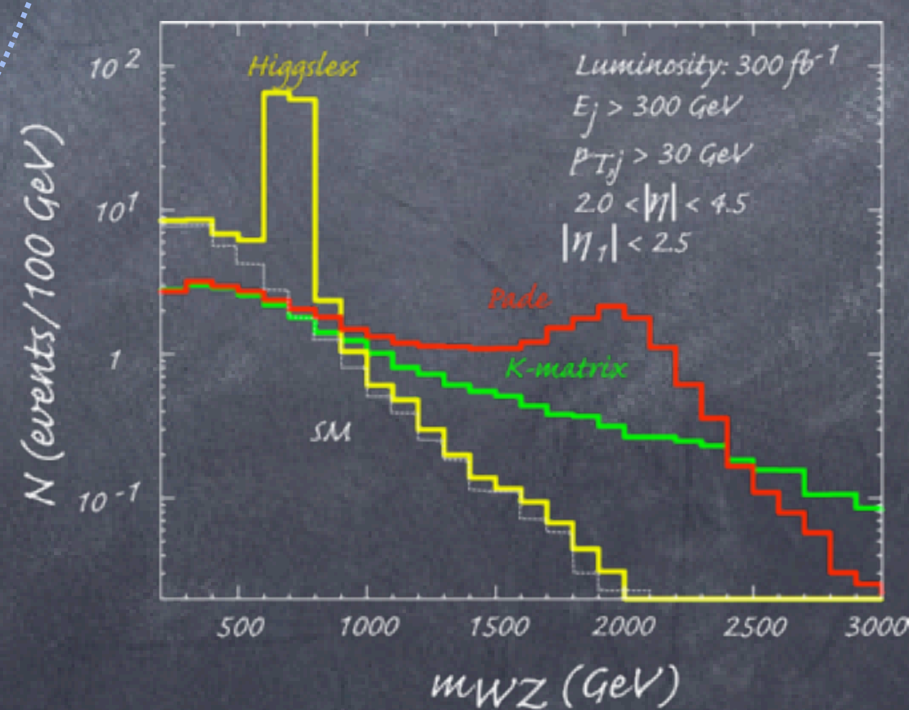
no resonance in WZ for SM/MSSM

W' production



2j+3l+$\not{E}_T$

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



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

Facing EW precision data

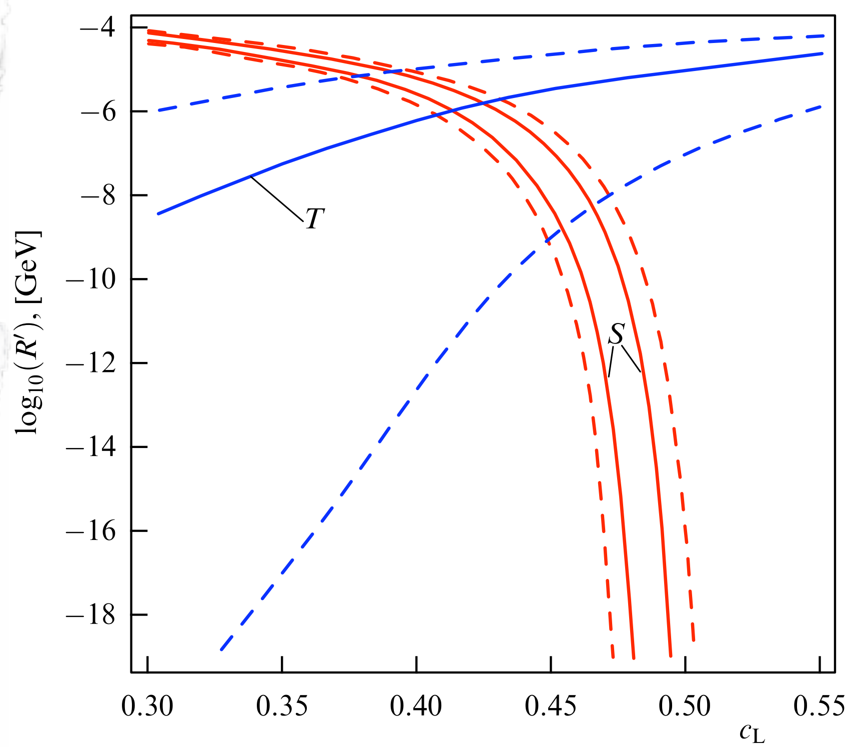
At the lowest order in the Log(R_{IR}/R_{UV}) expansion: S=T=Y=W=0

At next order $S = \dfrac{6\pi}{g^2 \log(R_{IR}/R_{UV})} \approx 1.15$ ...like in usual technicolor models

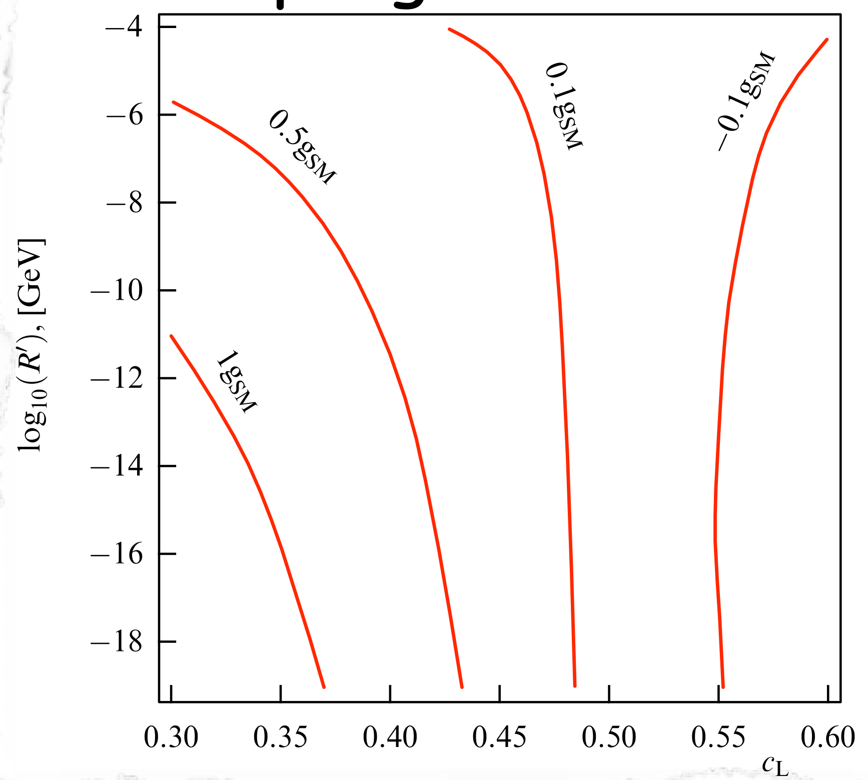
S can be tuned away by delocalizing the fermions in the bulk
they will decouple from W', Z' etc

Cacciapaglia et al '04, Foadi et al '04, Casalbuoni et al '05

oblique corrections



W' couplings to fermions



Setup stable under radiative corrections?

Dawson, Jackson '08

Composite Higgs Models

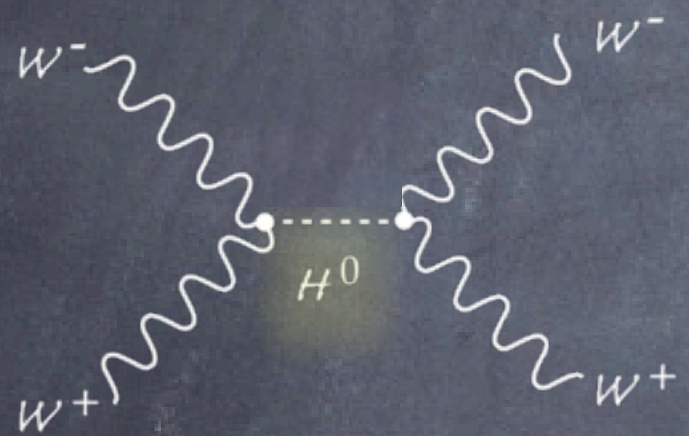
SM Higgs as a peculiar scalar resonance

W_L, Z_L are Goldstone bosons ~ pions of QCD $\Sigma = e^{i\sigma^a\pi^a/v}$

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

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

'a' and 'b' are arbitrary free couplings



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

4W contact   h exchange

growth cancelled for
a = 1
restoration of
perturbative unitarity

For b = a^2: perturbative unitarity also maintained in inelastic channels

'a=1' & 'b=1' define the SM Higgs

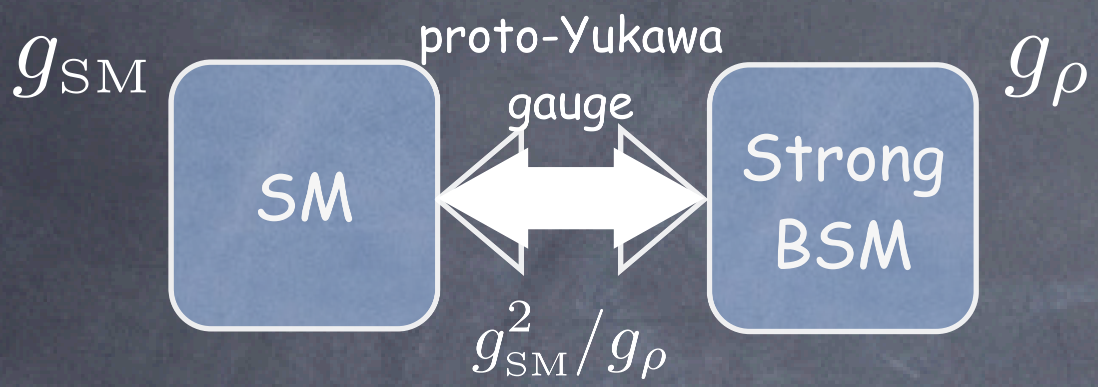
$\mathcal{L}_{\rm mass} + \mathcal{L}_{\rm EWSB}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

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

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

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

3 scales:

UV completion

$4\pi f$ — 10 TeV

$m_\rho = g_\rho f$ — usual resonances of the strong sector

} not easily accessible at LHC → indirect probes

v — 246 GeV Higgs = light resonance of the strong sector

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

Continuous interpolation between SM and TC

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

SM limit

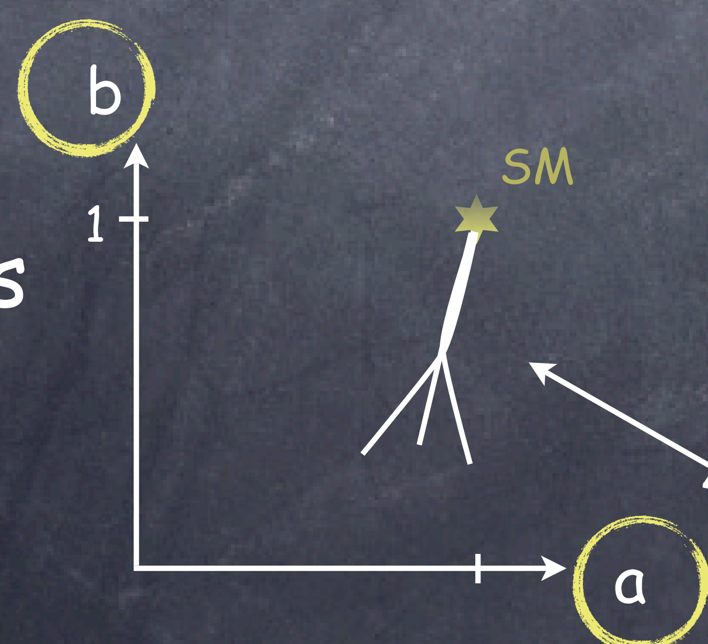
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. SM Higgs



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

Composite Higgs
universal behavior for large f
$a=1-\xi/2 \quad b=1-2\xi$

Continuous interpolation between SM and TC

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

SM limit

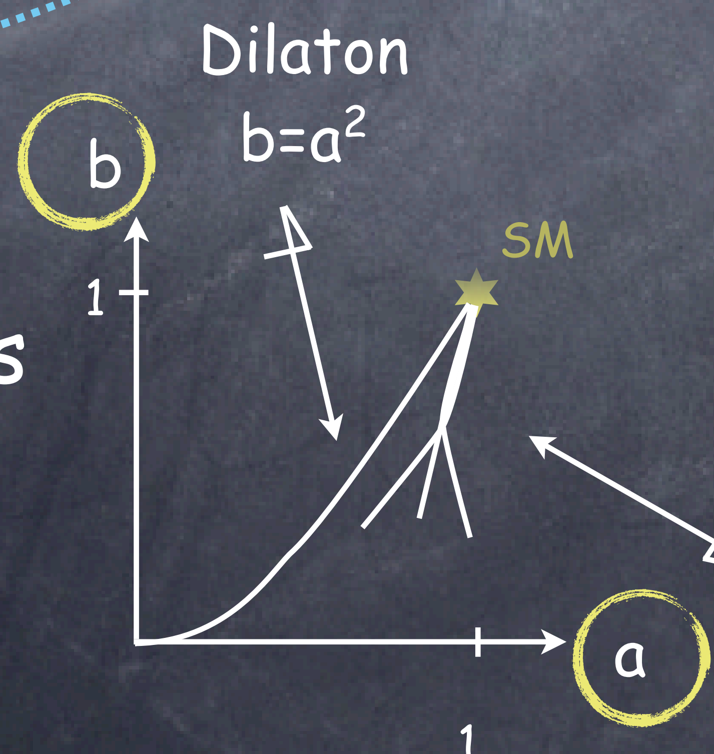
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. Dilaton



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

Composite Higgs universal behavior for large f

$a=1-\xi/2$ $b=1-2\xi$

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

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

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

$$\Downarrow$$

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

effective Higgs mass

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

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

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

Flavor Constraints

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

mass terms

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

Higgs fermion interactions

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

⇛ FCNC mediated by Higgs exchange ⇚

SILH: c_y is flavor universal

⇛ Minimal flavor violation built in ⇚

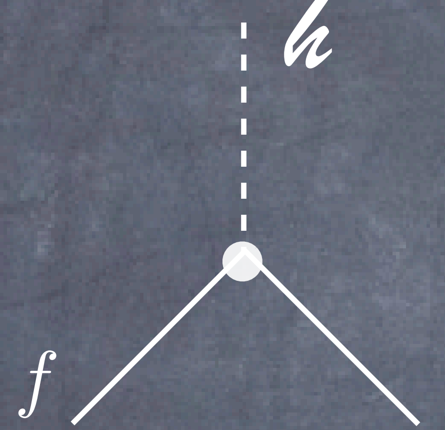
SM fermions = partially composite
rationale for mass hierarchy + built-in GIM suppression of FCNC's

cf Buras' talk Wednesday

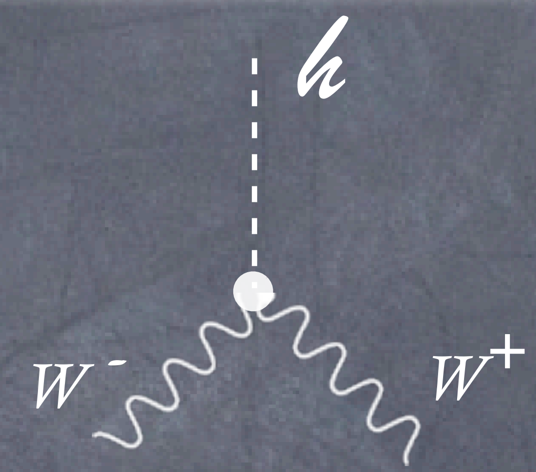
Higgs anomalous couplings

Lagrangian in unitary gauge

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



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



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

⇘ ⇙

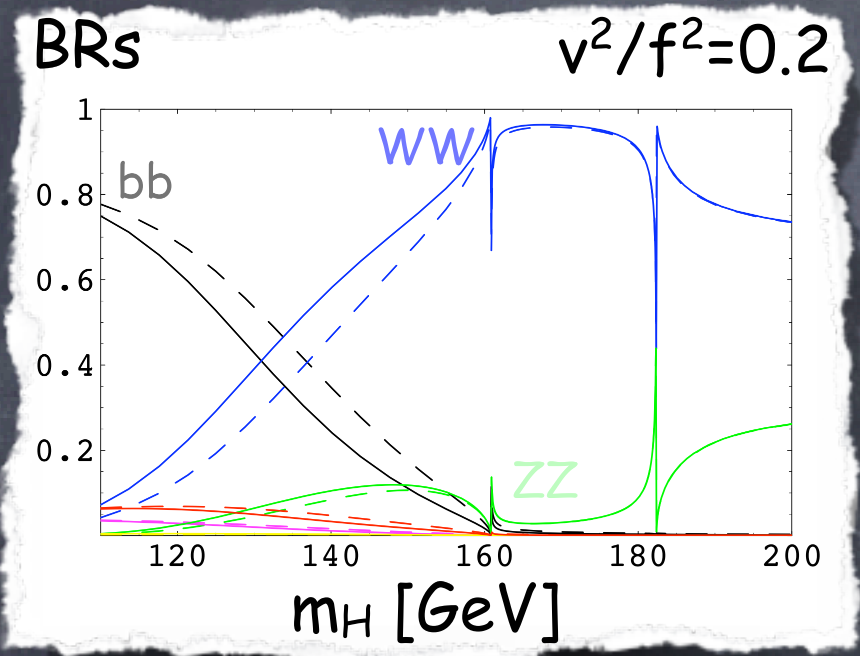
$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - (2c_y + c_H)\,v^2/f^2\right]$$

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

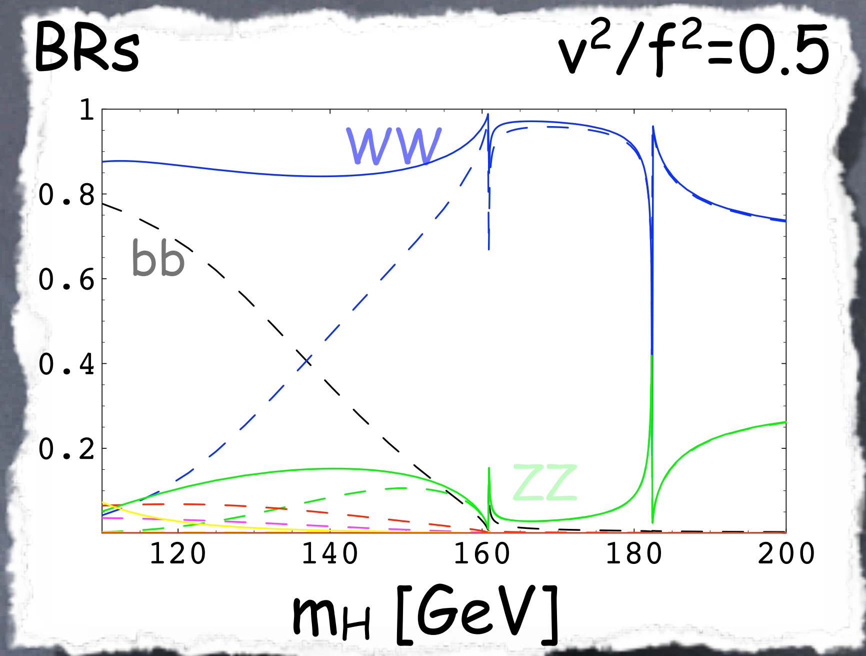
Note: same Lorentz structure as in SM. Not true anymore if form factor ops. are included

Higgs' BRs and Total Width

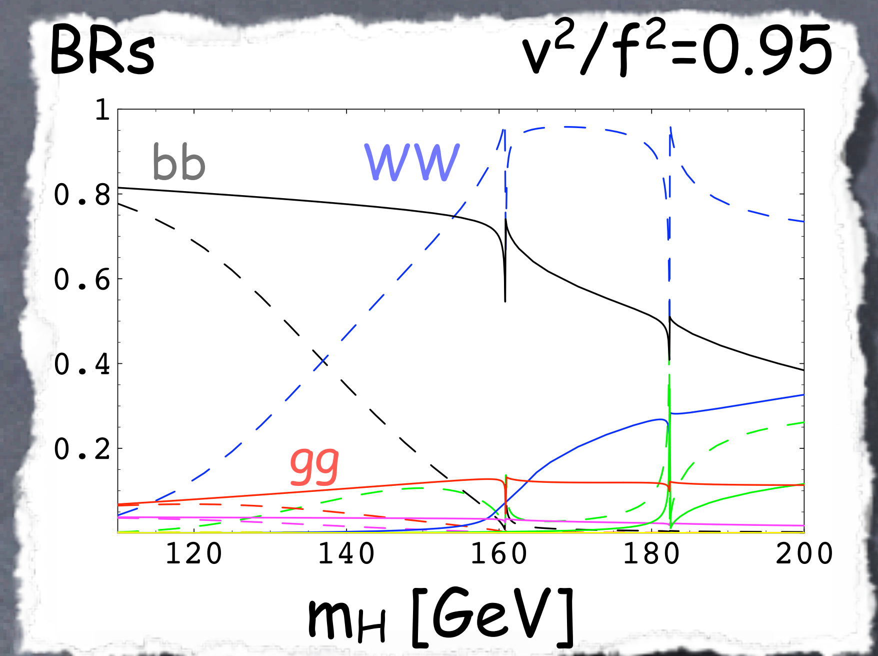
$MCHM_{5D}$ (Contino et al. '04) with fermions embedded in 5+10 of SO(5)



slight modifications

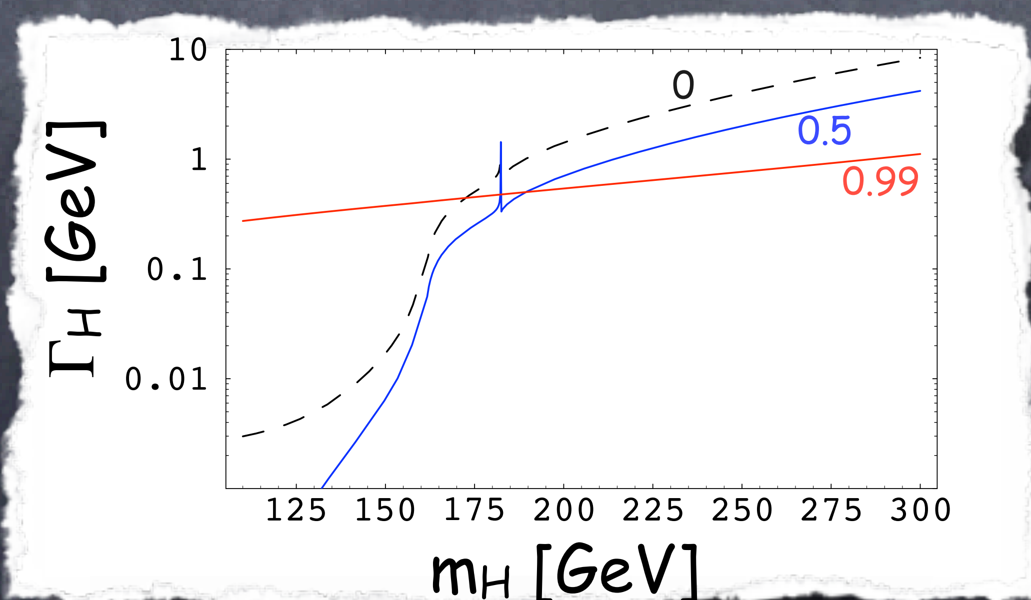


suppress bb



suppress WW

Higgs total width



- - - SM

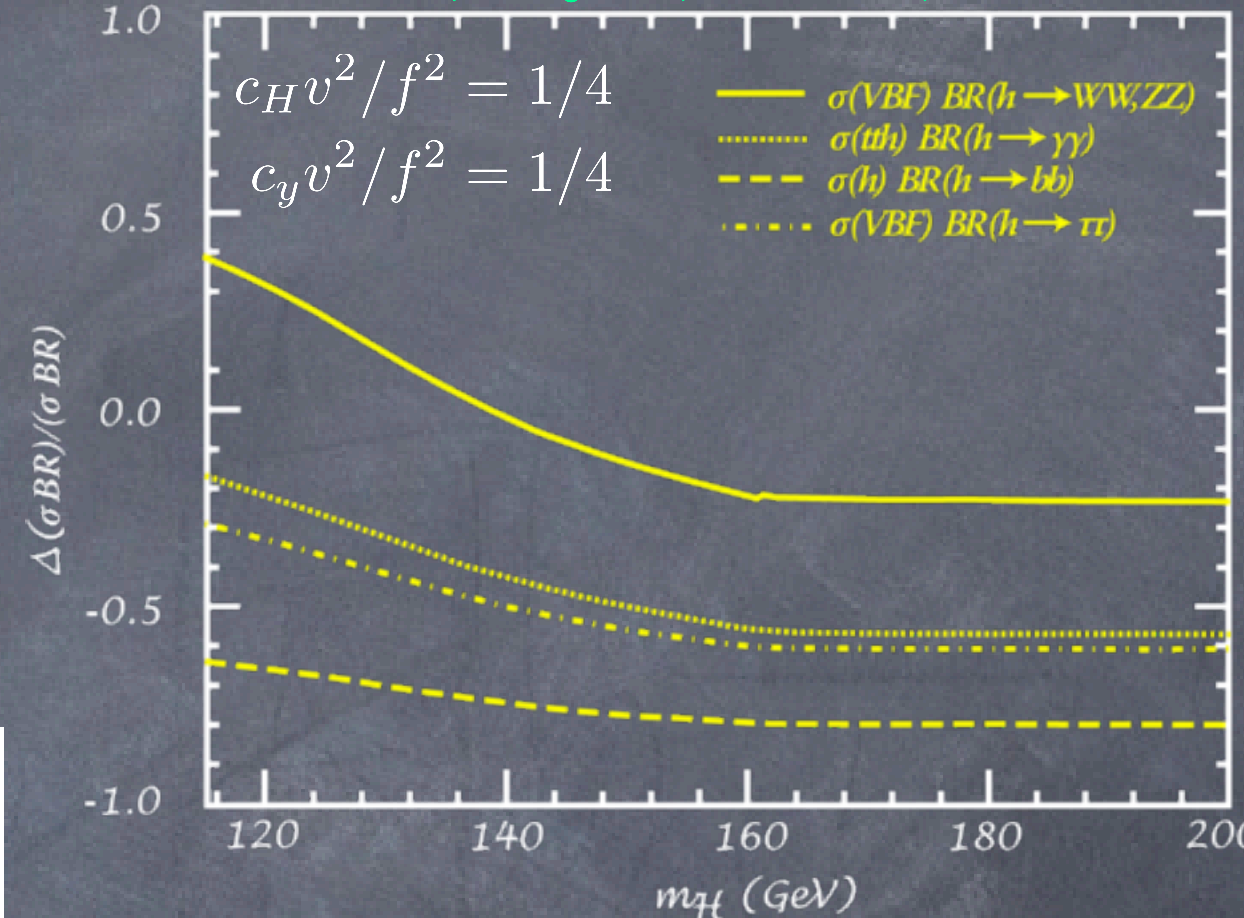
—— composite Higgs

Higgs anomalous couplings @ LHC

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

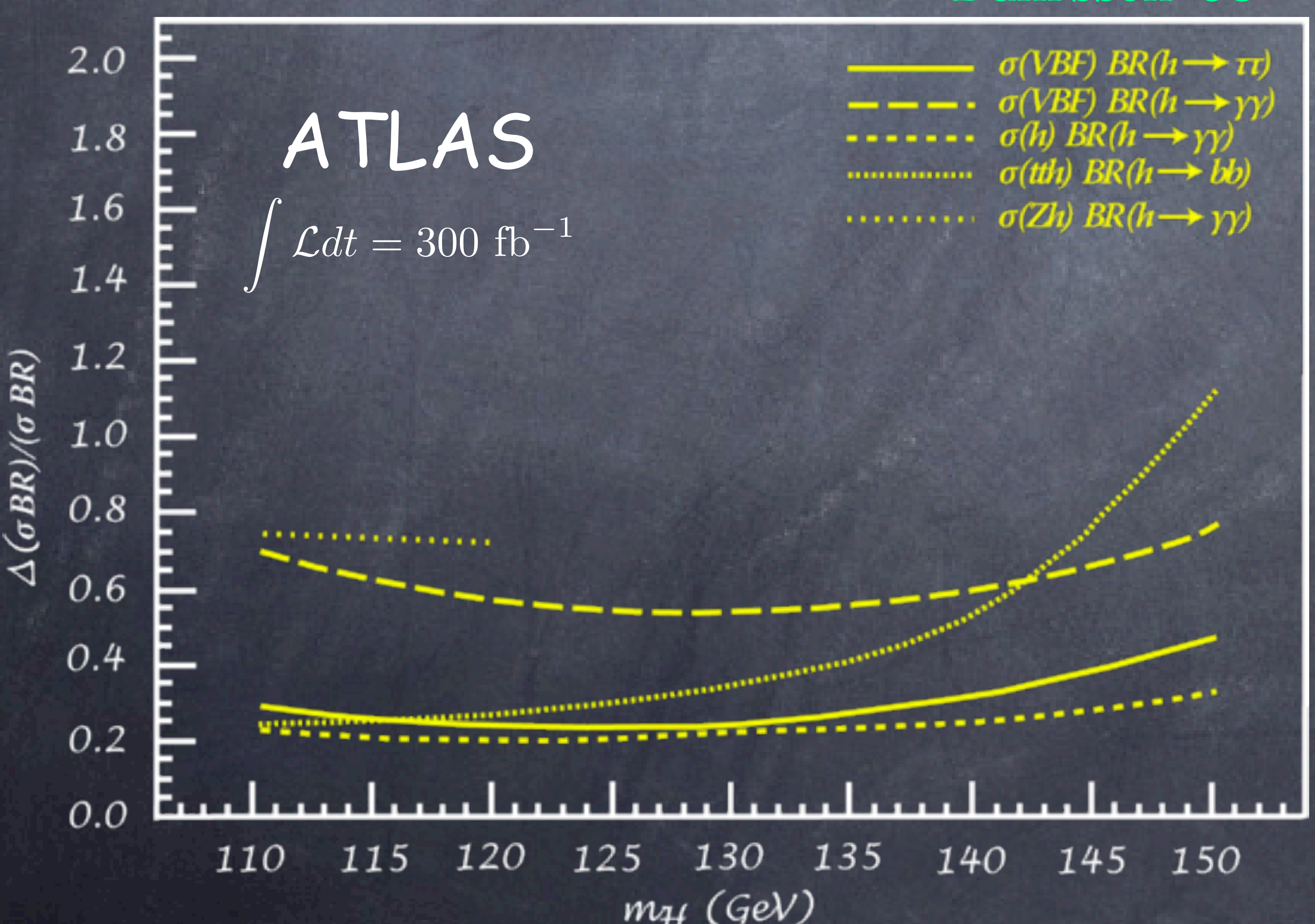
$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1 - \left(2c_y + c_H\right)v^2/f^2\right]$$

Giudice, Grojean, Pomarol, Rattazzi '07



observable @ LHC?

Duhrssen '03



LHC can measure

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

up to 0.2-0.4

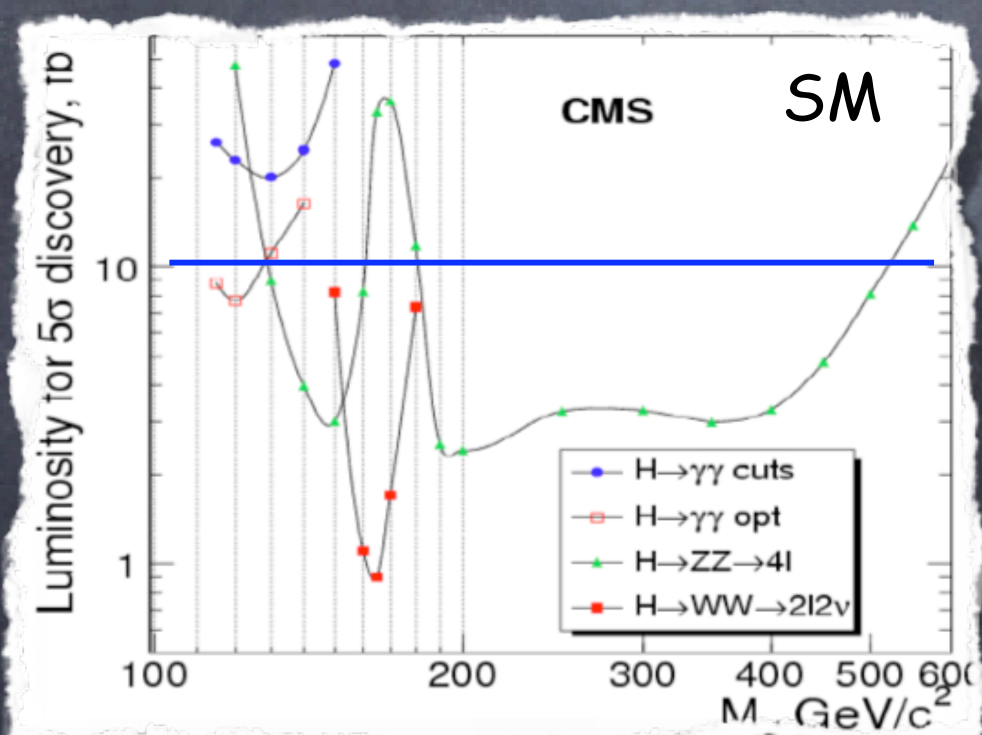
i.e. $4\pi f \sim 5-7$ TeV

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

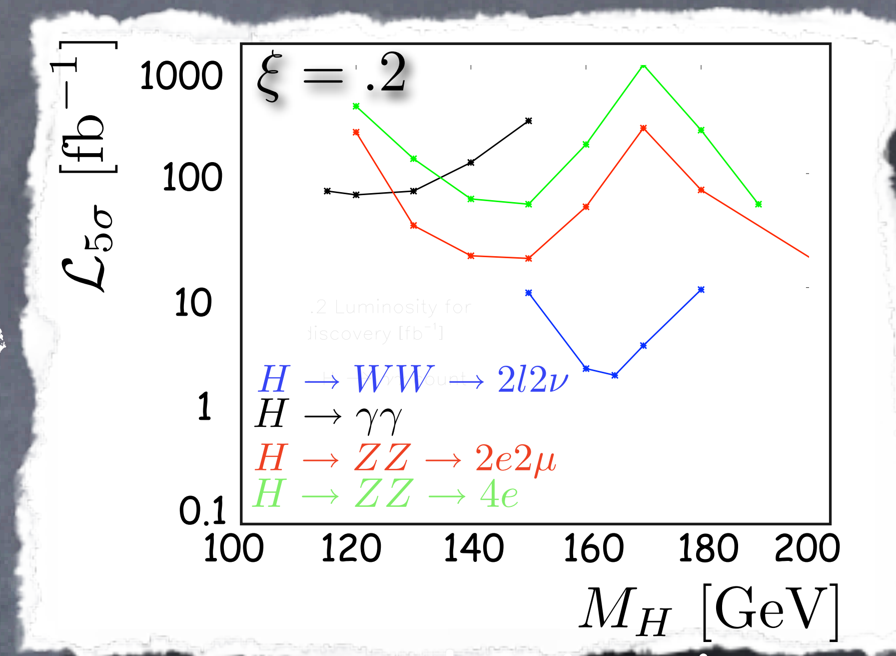
Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner 'in progress

the modification of Higgs couplings and BRs affects the Higgs search

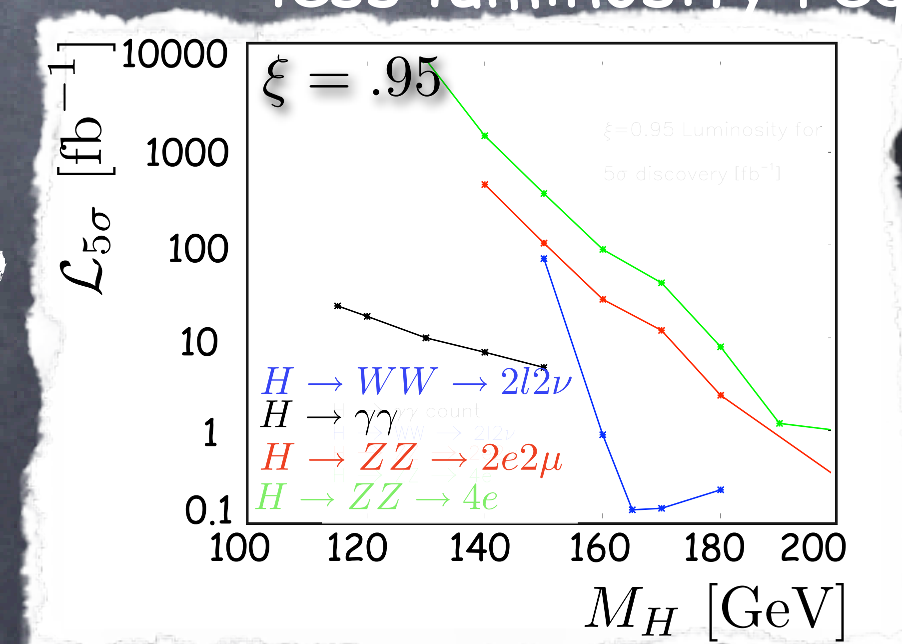


large
compositeness scale



more luminosity required

less luminosity required

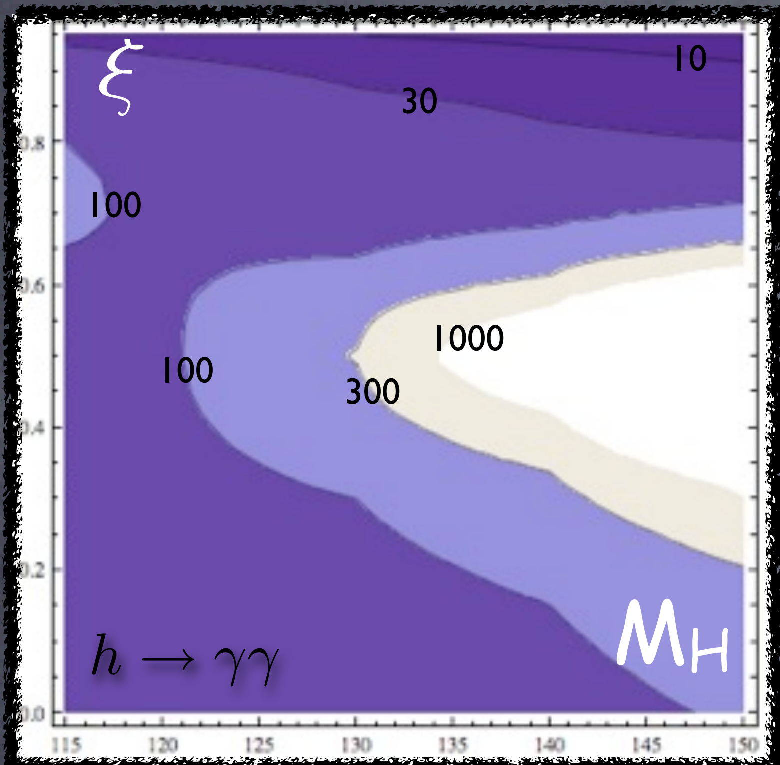


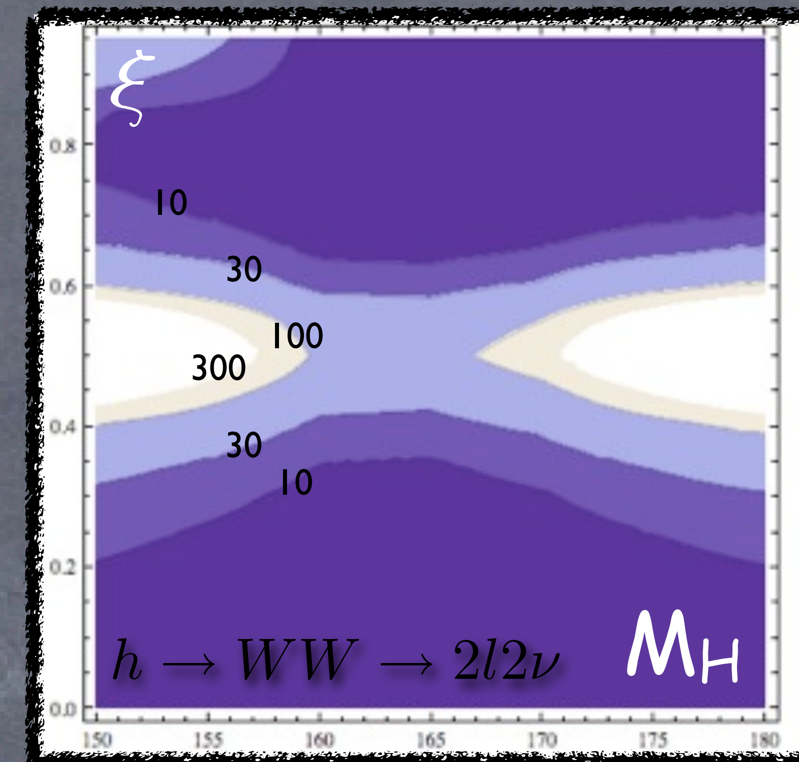
small
compositeness scale

Composite Higgs search @ LHC

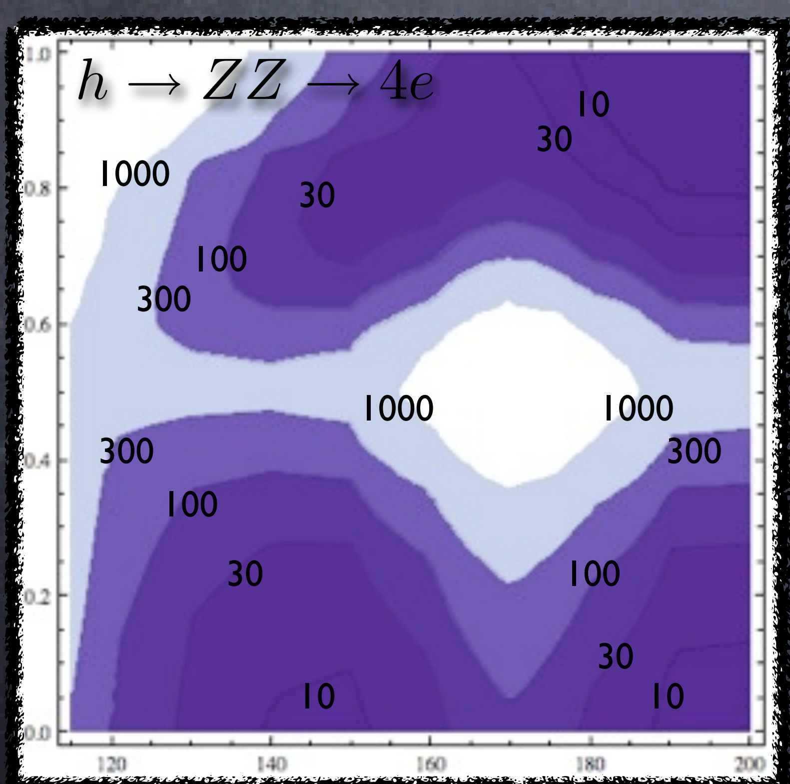
Espinosa, Grojean, Muehlleitner 'in progress

the modification of Higgs couplings and BRs affects the Higgs search

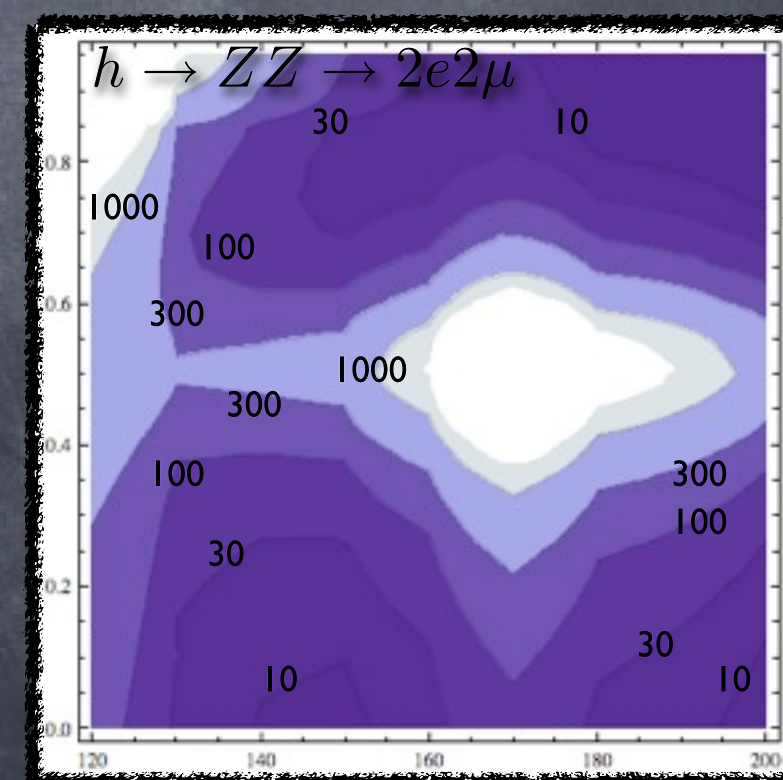




contour lines of luminosity needed for 5σ discovery in the (ξ,M_H) plane



(neglect effects from heavy resonances)



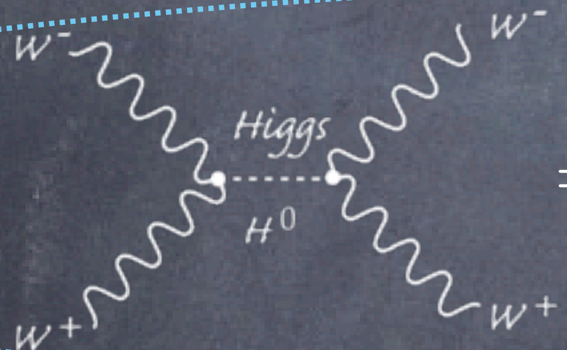
Strong WW scattering

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 $\dfrac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \dfrac{v^2}{2f^2} \equiv 1 - \xi/2$



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

no exact cancellation of the growing amplitudes

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

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

$$\mathcal{A}_{\mathrm{LET}}(s,t,u) = \frac{s}{v^2} \Longrightarrow \mathcal{A}_\xi = \frac{s}{f^2}$$

LET=SM-Higgs

unitarity restored by the exchange of heavy vector resonances

Falkowski, Pokorski, Roberts '07

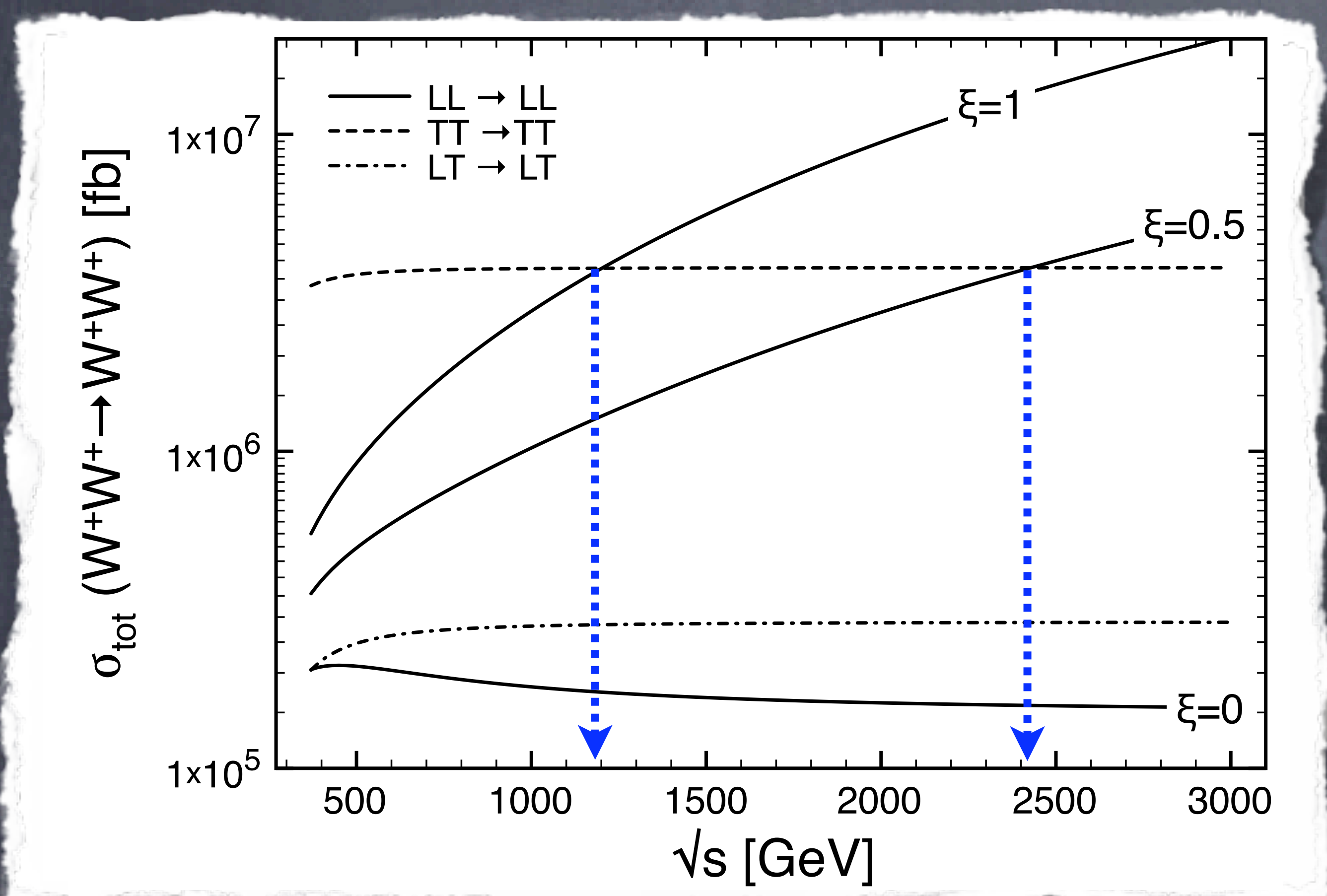
Onset of Strong Scattering

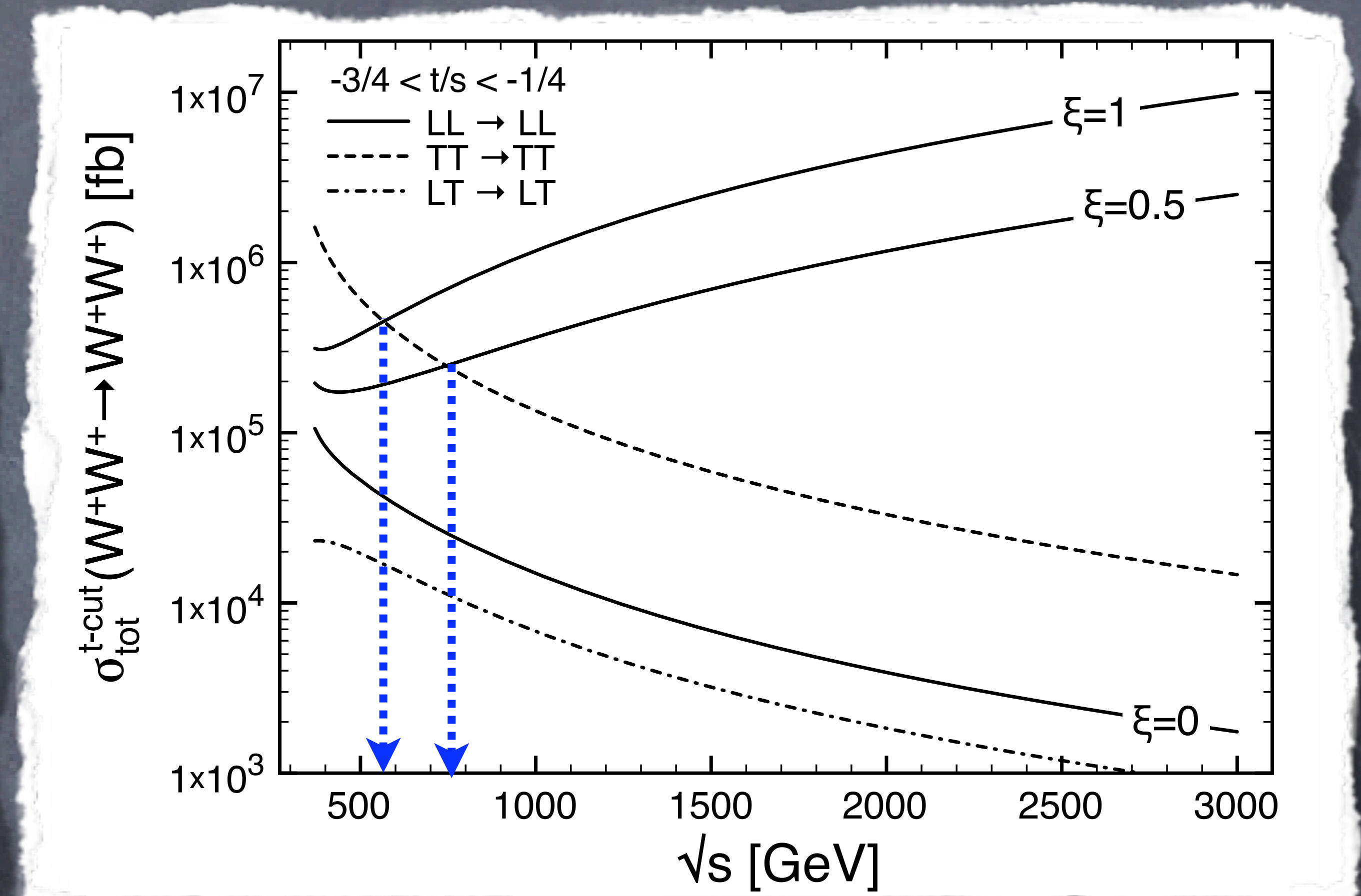
Contino, Grojean, Moretti, Piccinini, Rattazzi ‘to appear

NDA estimates: $(\mathcal{A}_{TT\to TT} \sim g^2) \sim (\mathcal{A}_{LL\to LL} \sim s/v^2)$ @ $\sqrt{s} \sim 2M_W$

but disentangling L from T polarization is hard

because of the structure of the amplitudes (Coulomb enhancement)





The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background

The dominance of T background will be further enhanced by the pdfs since the luminosity of W_T inside the proton is $\log(E/M_W)$ enhanced

The LHC is barely energetic enough to have access to strong scattering

Strong Higgs production: (3L+jets) analysis

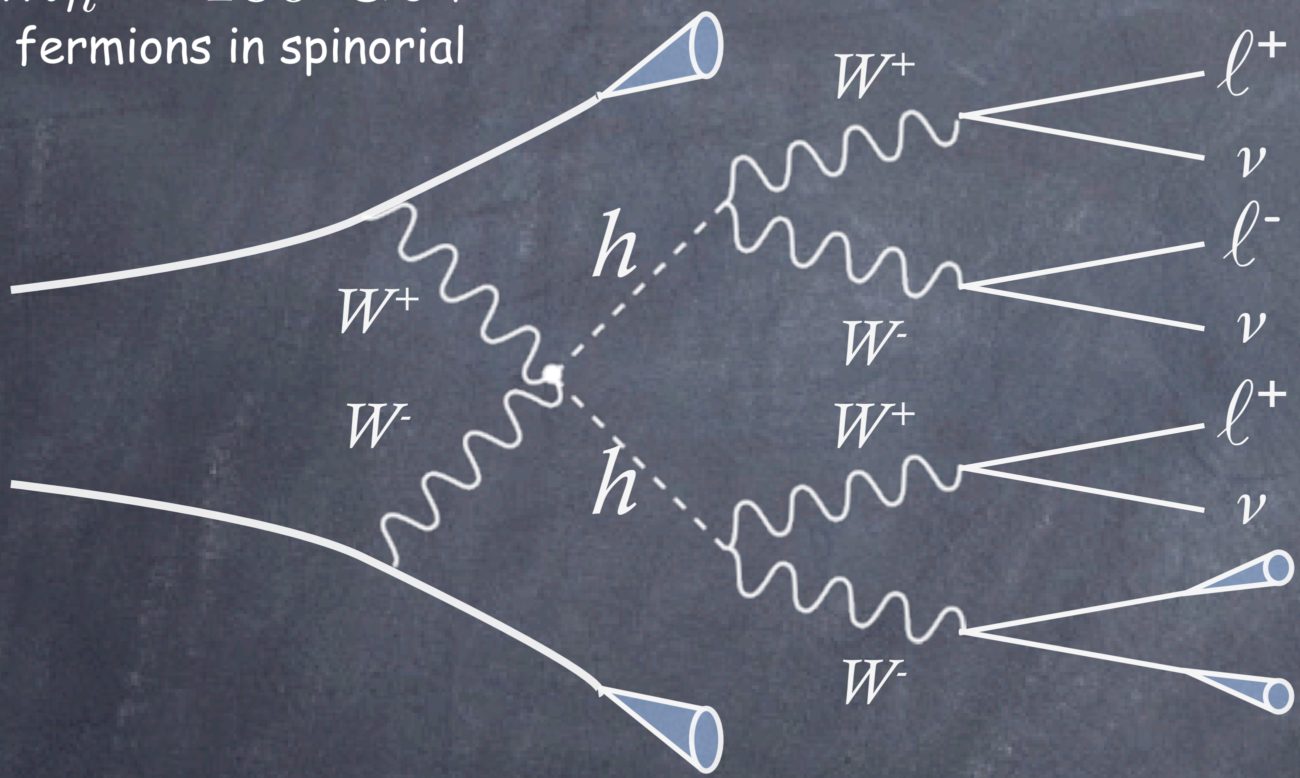
Contino, Grojean, Moretti, Piccinini, Rattazzi 'to appear

strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ GeV

fermions in spinorial



More complicated final states, smaller BRs but no T polarization pollution

acceptance cuts

jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

Dominant backgrounds: Wll4j, $t\bar{t}$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 for SLHC

The Fermi Scale in the Sky

I have focussed on collider signatures
but models for the Fermi scale can also be tested in the sky

- Dark Matter

  many talks at this conference

- Gravitational waves

  if 1st order EW phase transition then production of GW
  with a spectrum peaked around mHz

  e.g., Grojean, Servant '06 and references therein

- Cosmic rays?

  e.g., Wilczek's talk this morning

Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z
EW interactions also need a UV moderator/new physics
to unitarize WW scattering amplitude

(Higgs/No Higgs) ≈ (Weak/Strong EWSB) does not hold

the SM is certainly, at most, a limit of some dynamical models:
we need to identify and explore possible continuous deformations!

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...)

Should not forget that the LHC will be a top machine

and there are many reasons to believe that the top is an important agent of the Fermi scale