New Physics: Theoretical Developments

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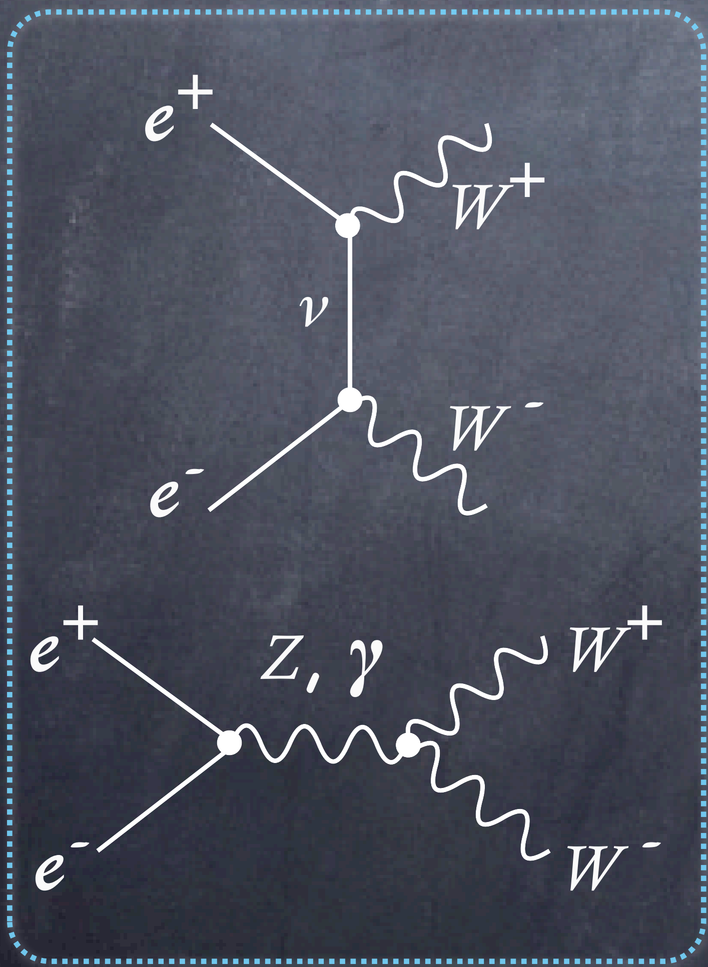
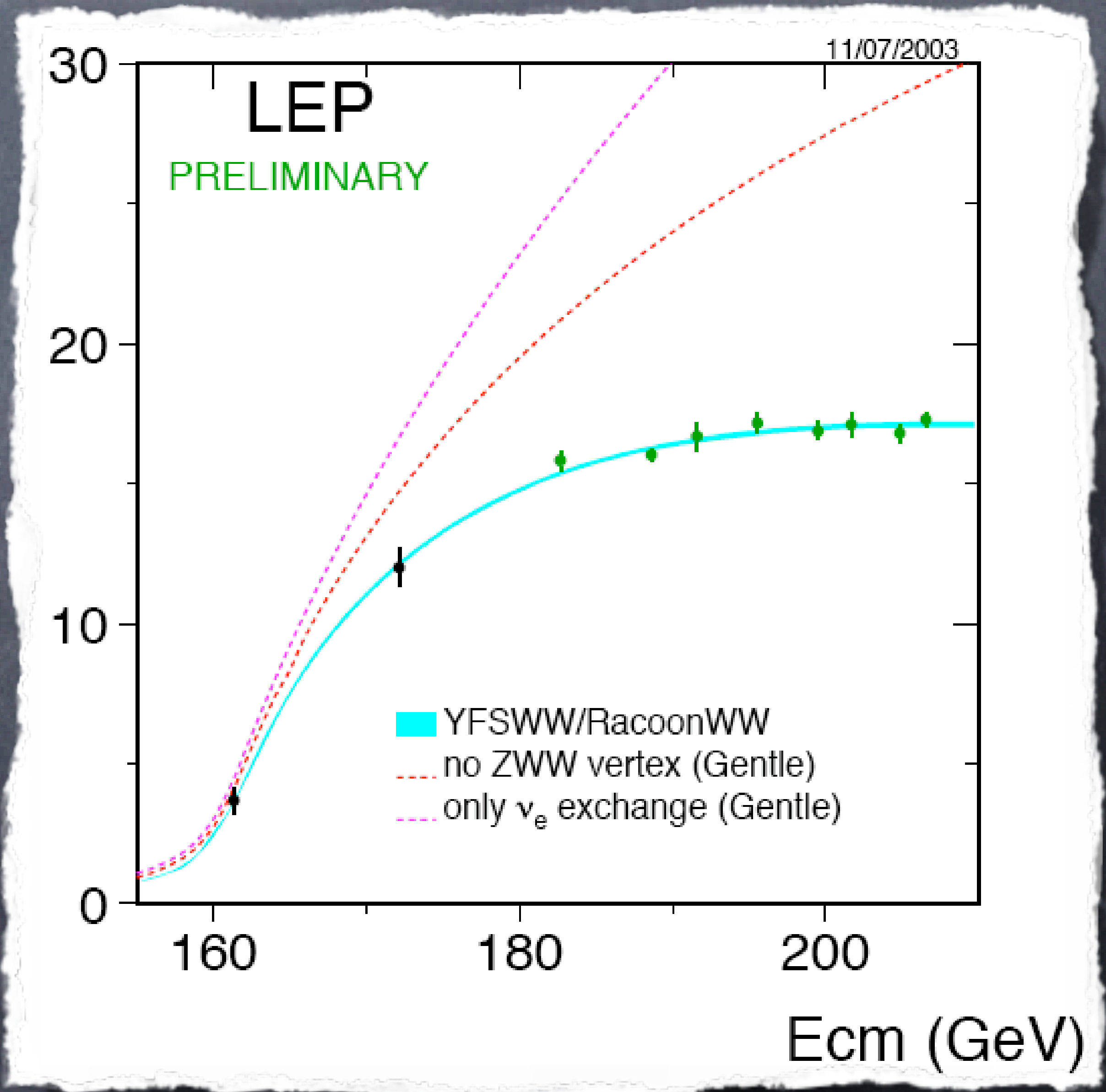
The Standard Model

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

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

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 $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ **spontaneous breaking of gauge symmetry** ⇐

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

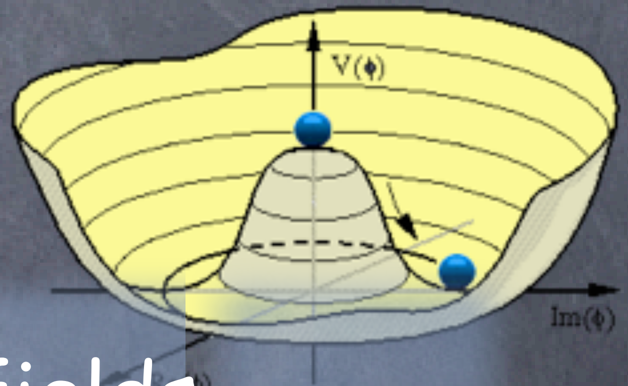
massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ 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

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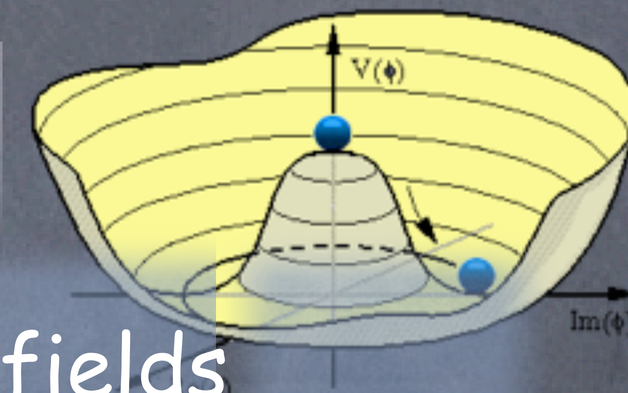

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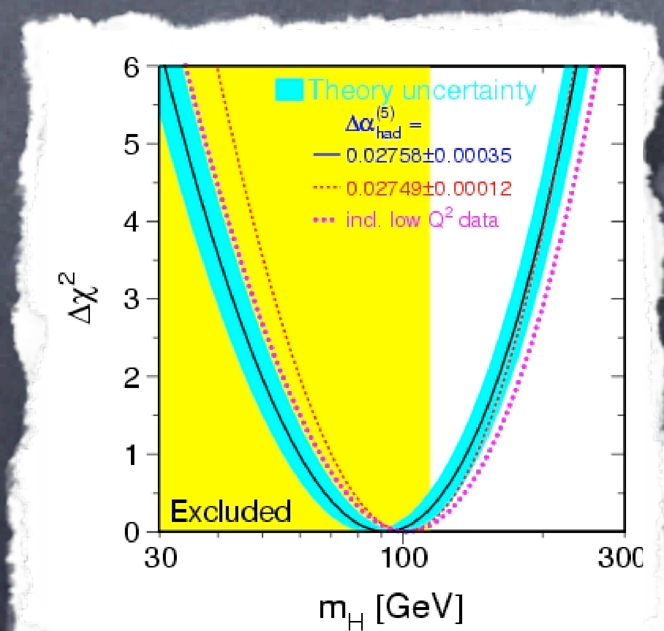
$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

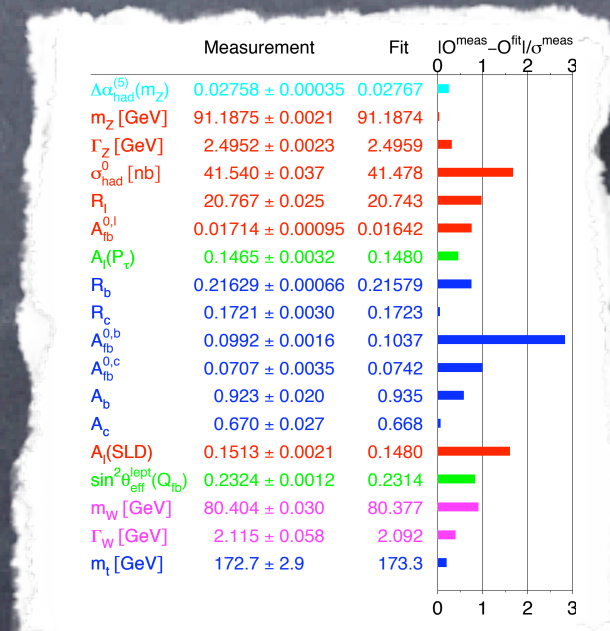
Higgs doublet = 4 real scalar fields

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...

Deformations of SM

- Why a single Higgs doublet?
  - why not? usual simplicity/minimality argument.
  - more Higgs doublets could be dangerous:
    - more complicated vacuum structure
    - possible Higgs-mediated FCNCs
  - triplet Higgs etc: custodial breaking ⇨ small vevs only

a flow, at low energy, towards a doublet seems a desirable feature

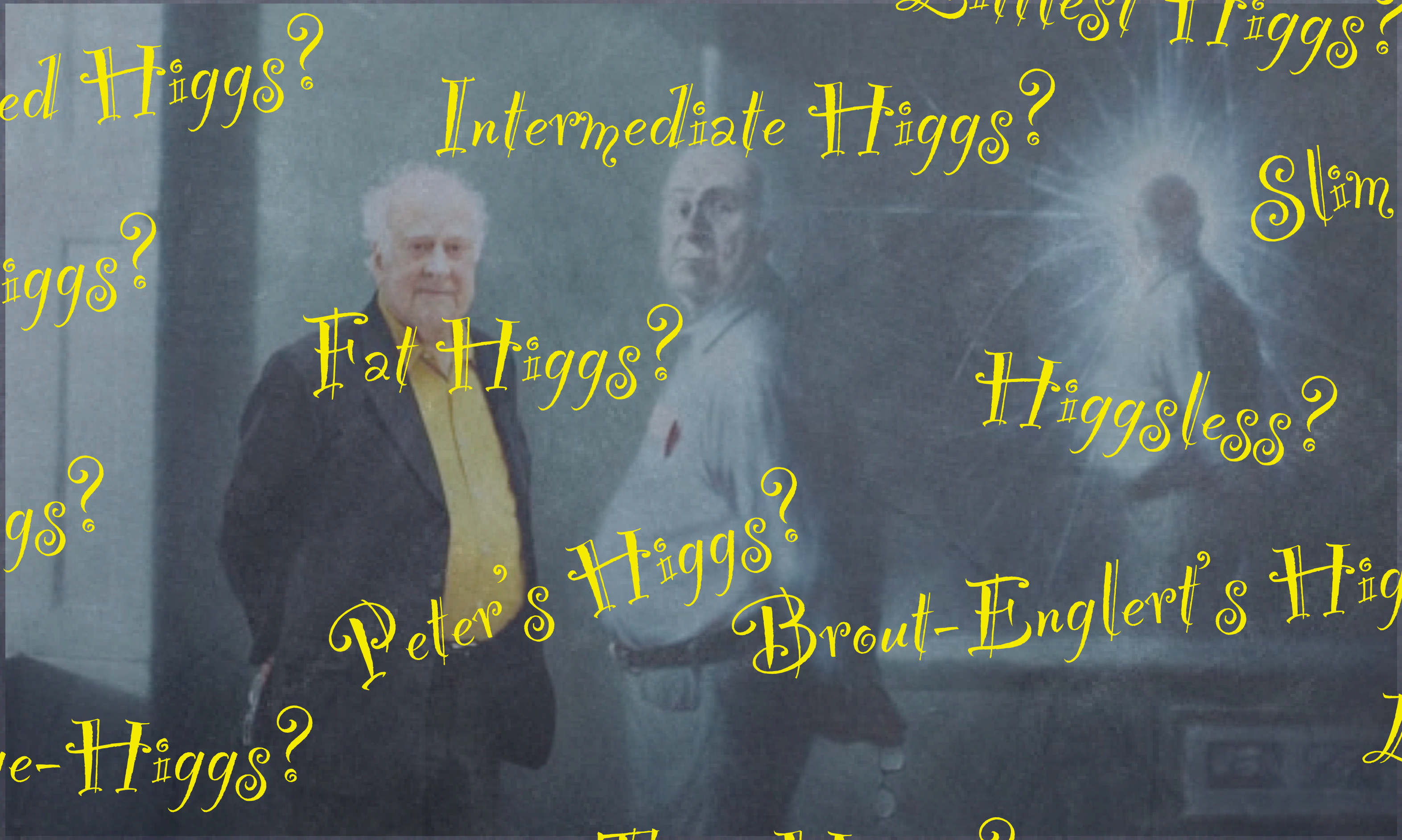
Which Higgs?

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?

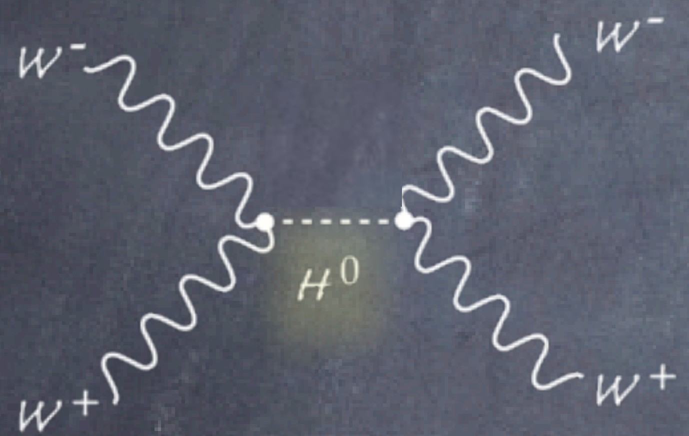
What is the SM Higgs?

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 ($WW \to hh$)

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

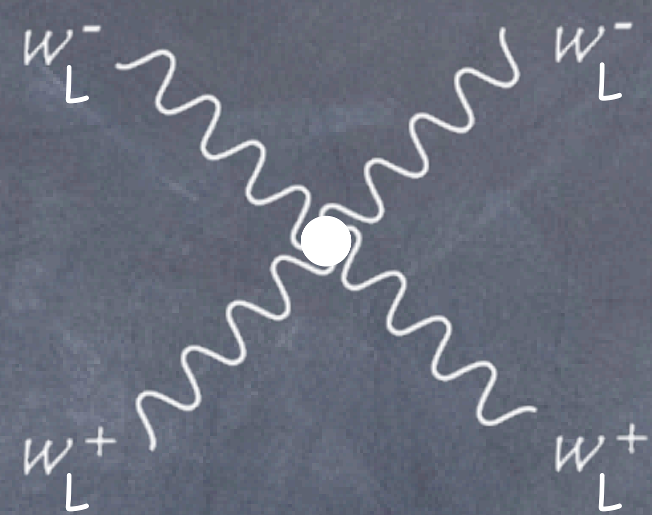
What is the mechanism of EWSB?

we need to understand not only the origin of the Goldstone's but also

What is unitarizing the WW scattering amplitudes?

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

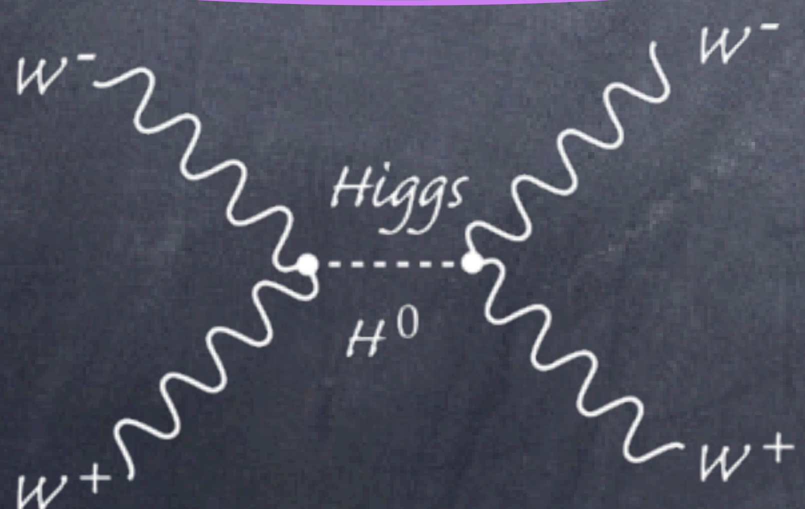
$$\iota = \left(\frac{|\mathbf{k}|}{\mathbf{M}}, \frac{\mathbf{E}}{\mathbf{M}} \frac{\mathbf{k}}{|\mathbf{k}|} \right)$$



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

loss of perturbative unitarity around 1.2 TeV

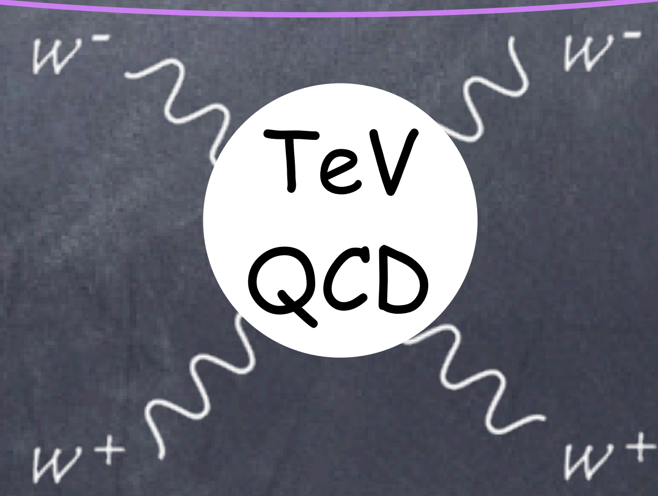
Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

Strongly coupled models



prototype: Technicolour

rho meson ~ 1 TeV

Solving the SUSY Little Hierarchy Pb

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

- More scalars: NMSSM and friends
  Fayet '76 + O(500) papers
- More gauge fields (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
- More symmetry: (super-little) Higgs as a Goldstone boson
  Birkedal, Chacko, Gaillard '04 + O(20) papers
- More interactions parametrized by higher dimensional terms: BMSSM
  Strumia '99; 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

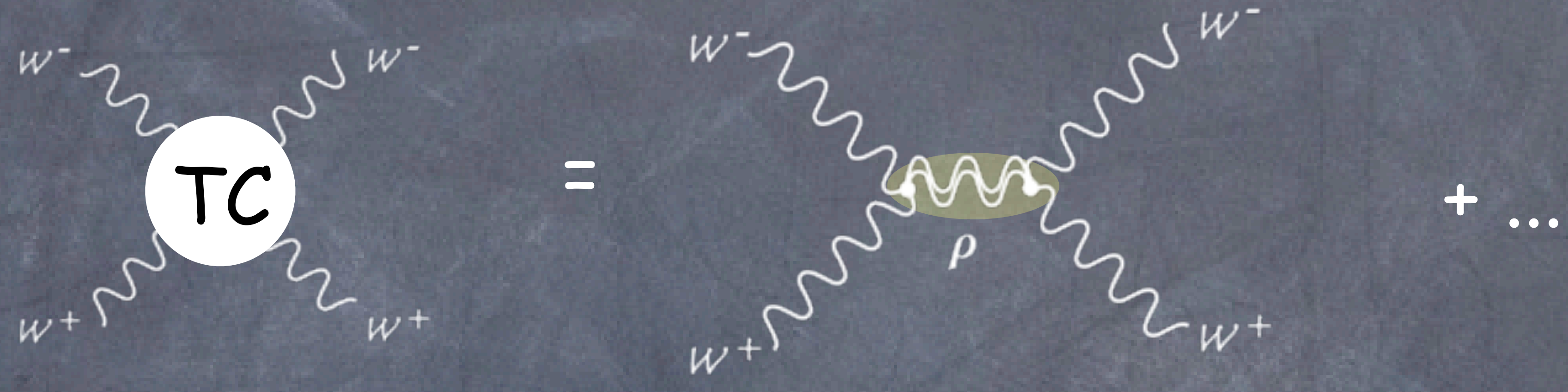
cf. Pokorski's talk

  - 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

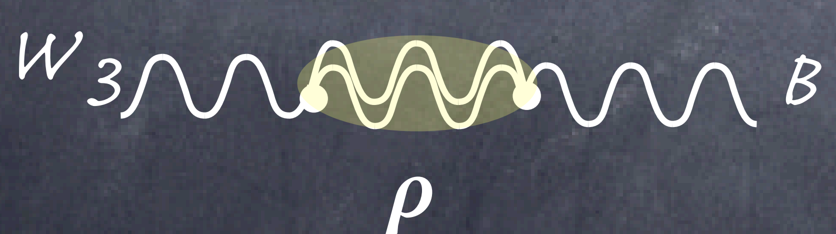
Strongly coupled models

a phenomenological challenge: how to evade EW precision data

The resonance that unitarizes the WW scattering amplitudes



generates a tree-level effect on the SM gauge bosons self-energy



$\hat{S}$ parameter of order m_W^2/m_ρ^2

In trouble with EW precision data from LEP

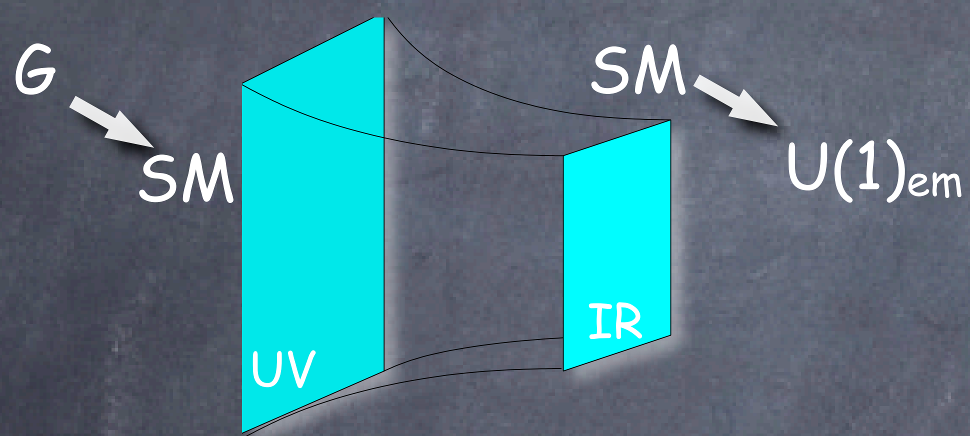
$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \quad \xrightarrow[\text{@ 95\% CL}]{|\hat{S}| < 10^{-3}} \quad m_\rho > 2.5 \text{ TeV}$$

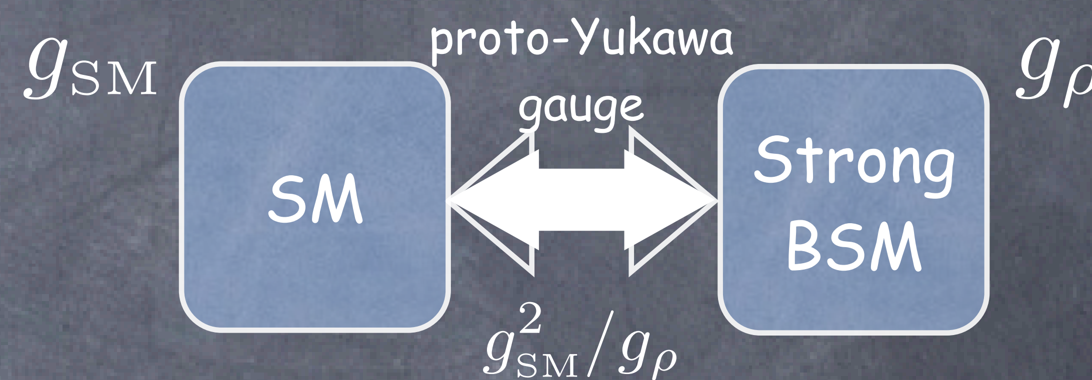
a theoretical challenge: need to develop tools to do computation

Holographic Approach to Strong Sector

"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





5D

KK modes
motion along 5th dim

UV brane

IR brane

bulk local sym.

4D

vector resonances (ρ mesons in QCD)
RG flow

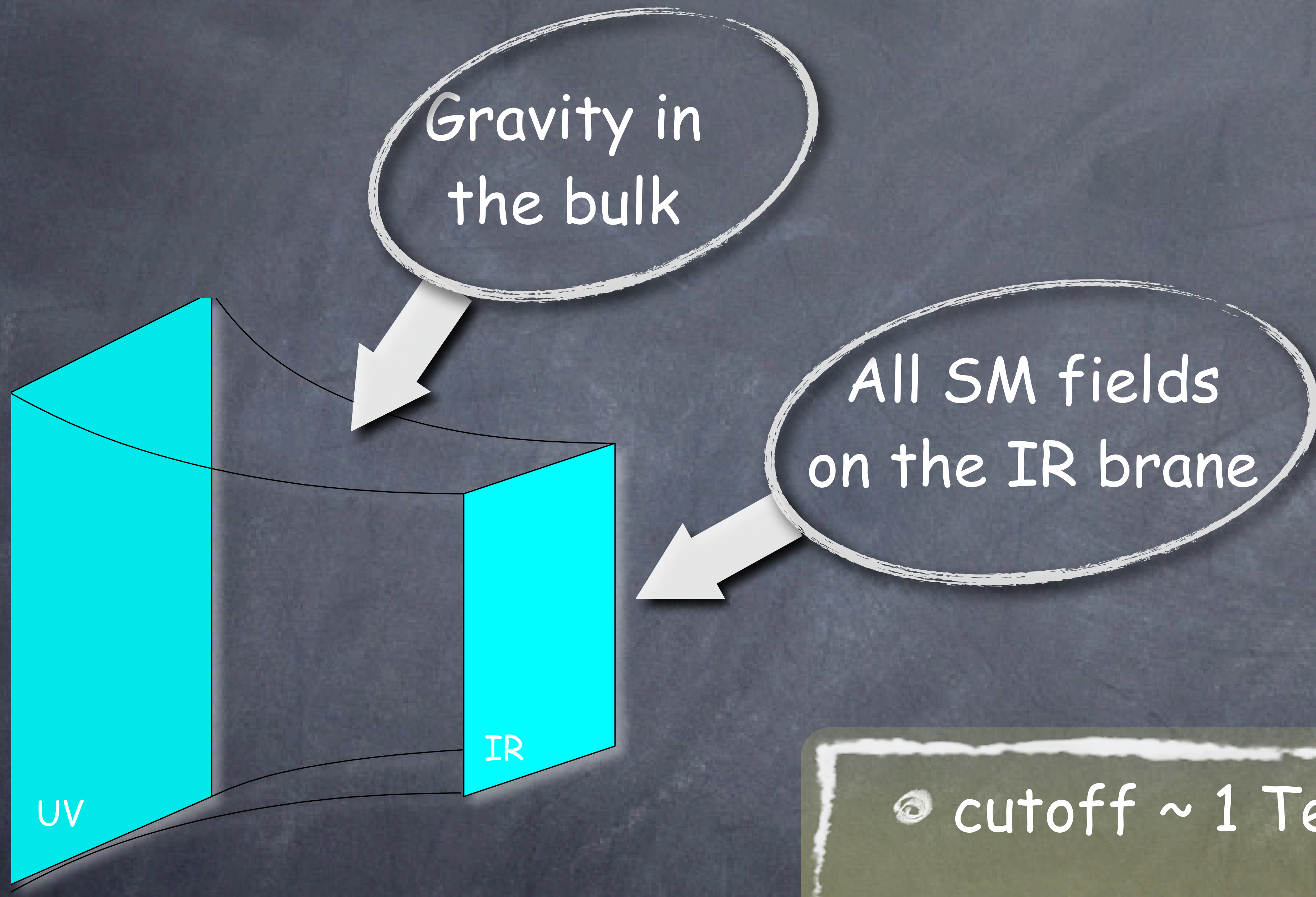
UV cutoff

break. of conformal inv.

global sym.

Holographic Models of EWSB

Original Randall-Sundrum proposal: '99



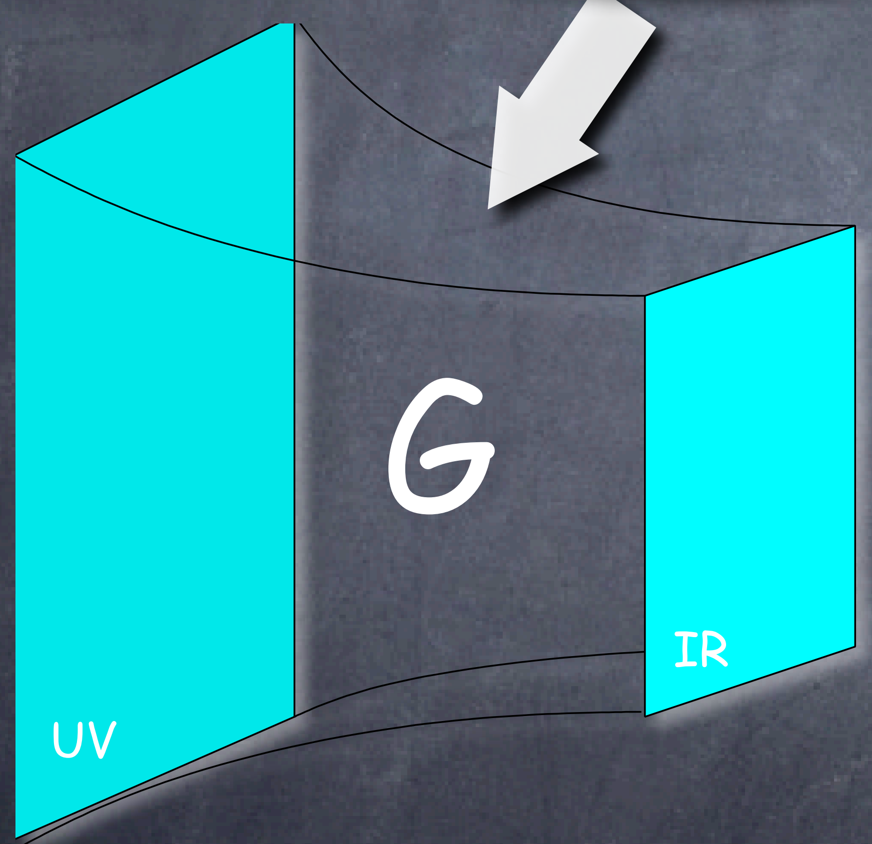
- cutoff ~ 1 TeV
- conflict with EW precision data
- problems with flavour

Holographic Models of EWSB

Bulk gauge fields: Pomarol, ‘00
Holographic technicolor=Higgsless: Csaki et al., ‘03
Holographic composite Higgs: Agashe et al., ‘04

Gauge fields + fermions in the bulk

Higgs on the IR brane
or
Gauge breaking by boundary conditions



$G=SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$G=SO(5) \times U(1)_X$
$G=SO(6) \times U(1)_X$

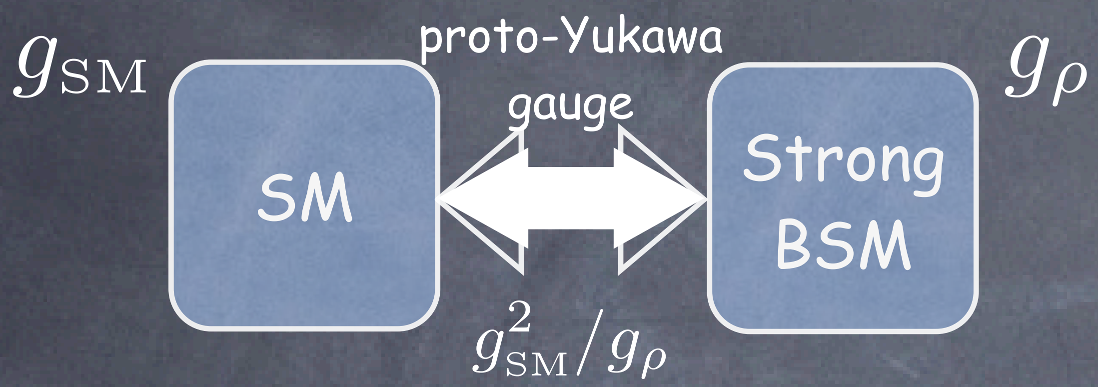
- UV completion: log running of gauge couplings
- Custodial symmetry from bulk $SU(2)_R$
- Dynamical ‘explanation’ of fermion masses
- Built-in flavour structure

Composite Higgs Models

- 5D gives concrete models
- 4D physics can be studied in a model independent way

4D Composite Higgs & Vector Resonances

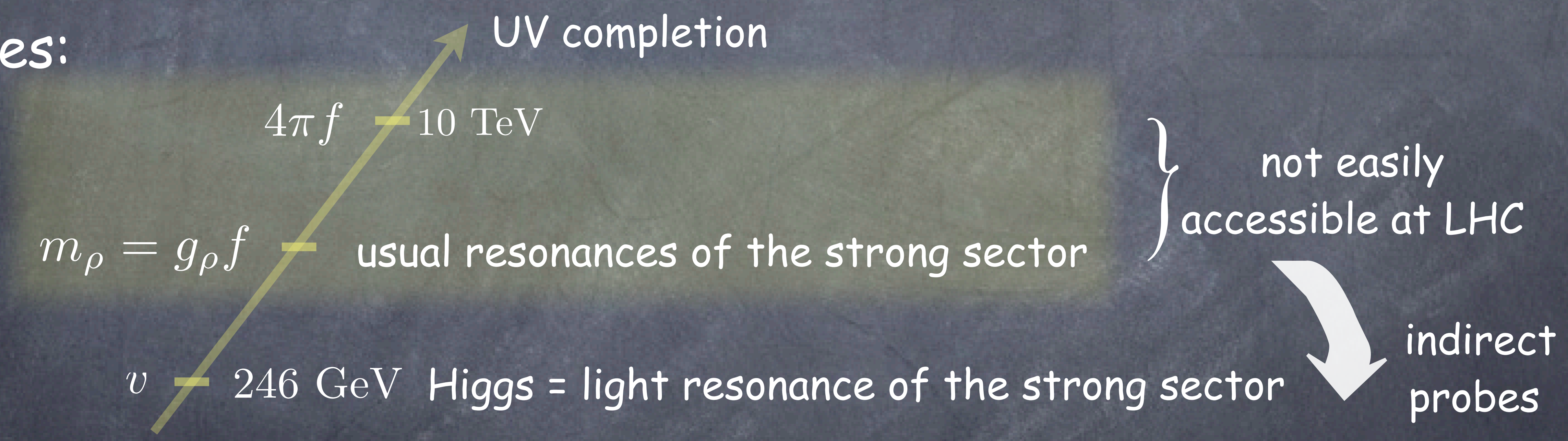
Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← residual global symmetry

3 scales:



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

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

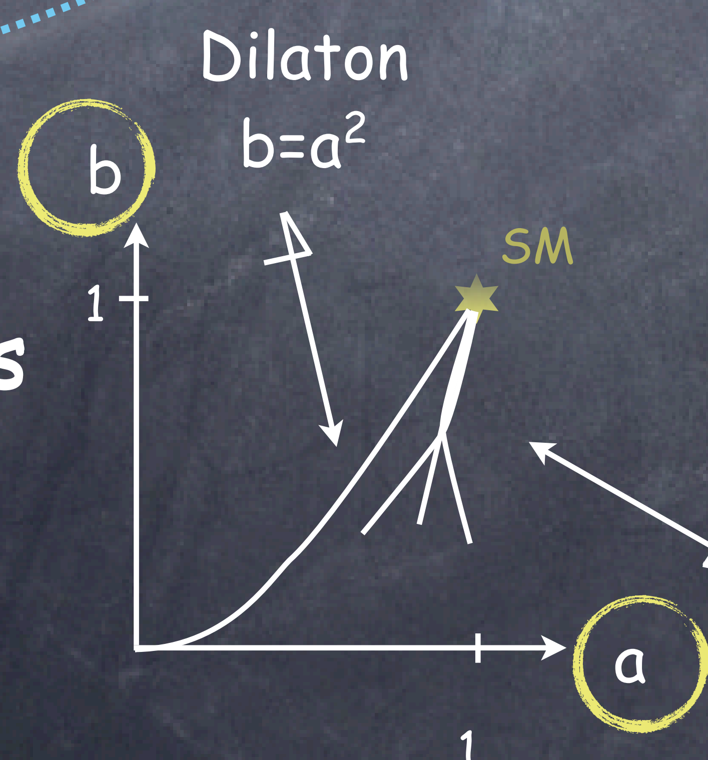
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs
vs.
SM Higgs
Dilaton



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

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

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

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

effective Higgs mass

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

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

lower bound on the Higgs compositeness scale

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

$\Rrightarrow$ FCNC mediated by Higgs exchange $\Lleftarrow$

SILH: c_y is flavor universal

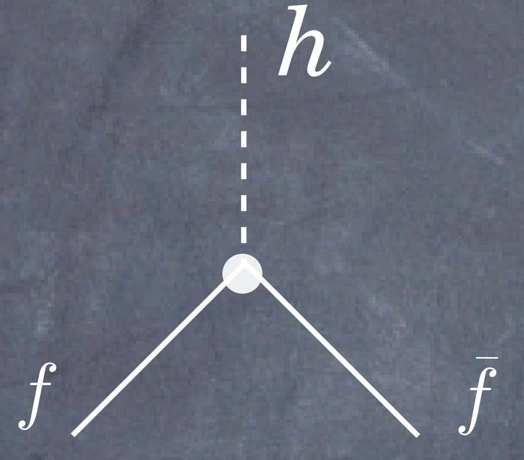
$\Rrightarrow$ Minimal flavor violation built in $\Lleftarrow$

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

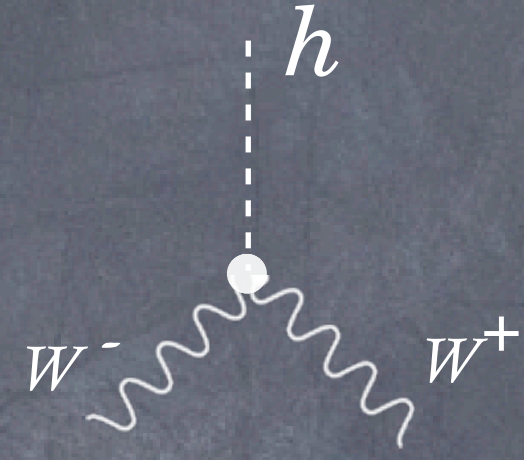
Higgs anomalous couplings

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 anomalous couplings @ LHC

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

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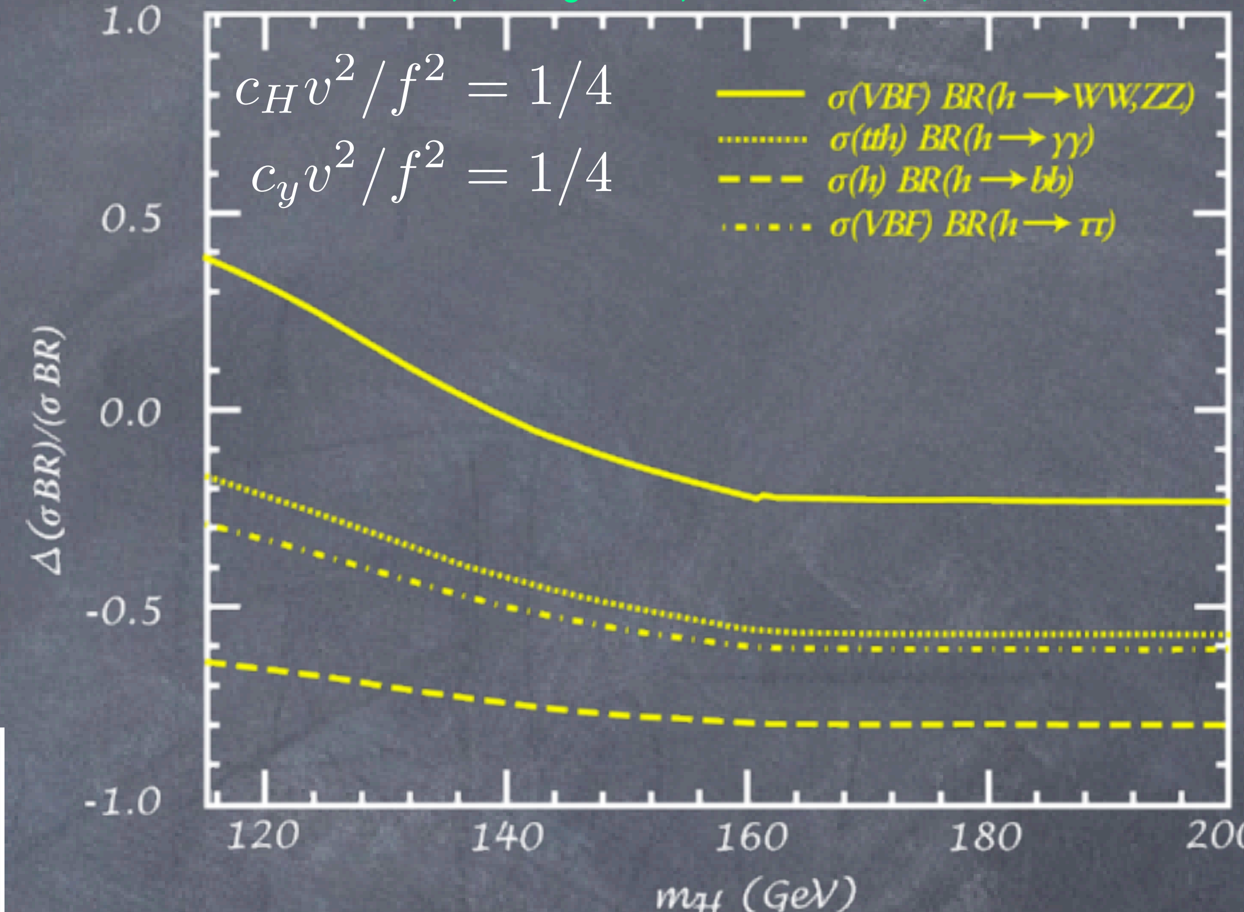
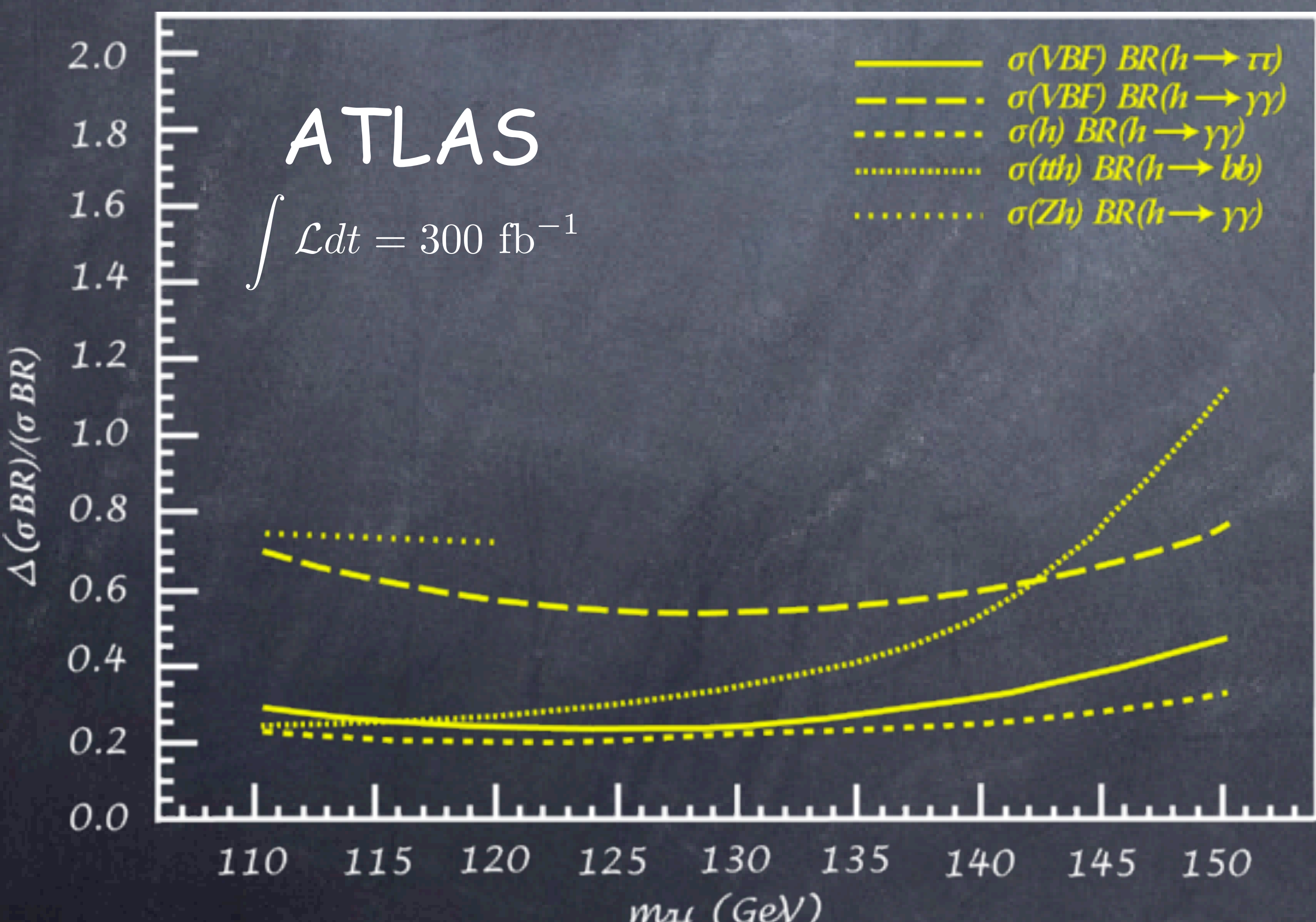
Giudice, Grojean, Pomarol, Rattazzi '07



observable @ LHC?

Duhrssen '03



LHC can measure

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

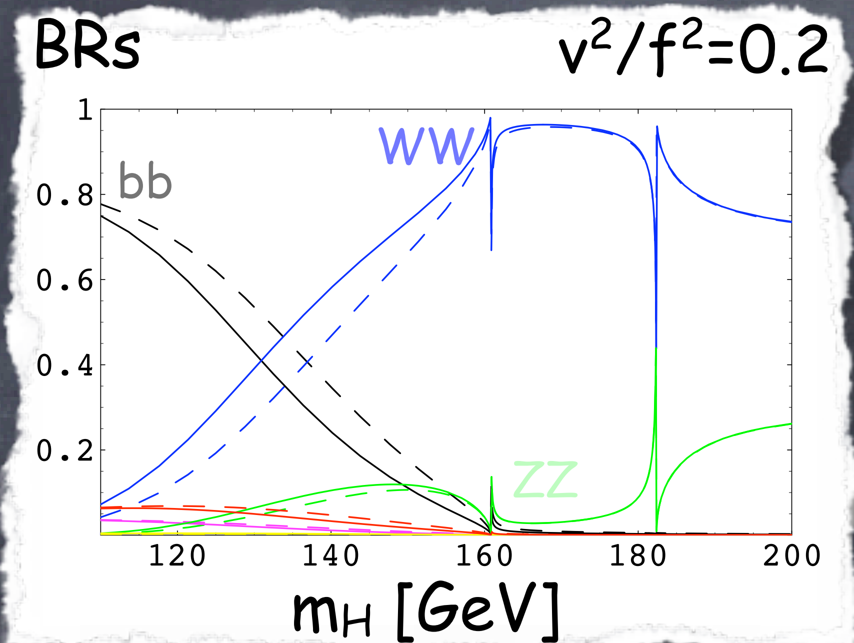
up to 0.2-0.4

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

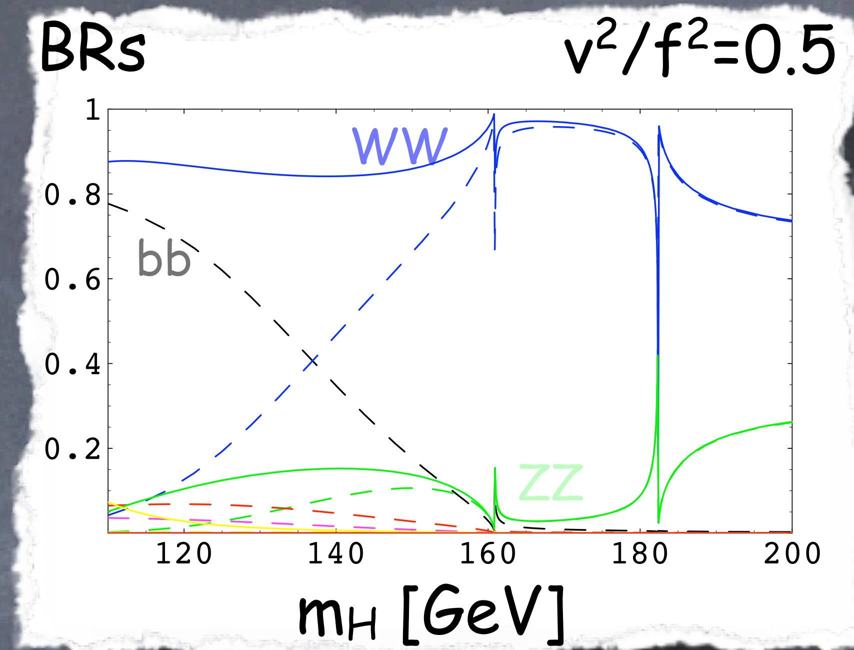
(ILC/CLIC could go to few % ie test composite Higgs up to $4\pi f \sim 30$ TeV)

Higgs' BRs and Total Width

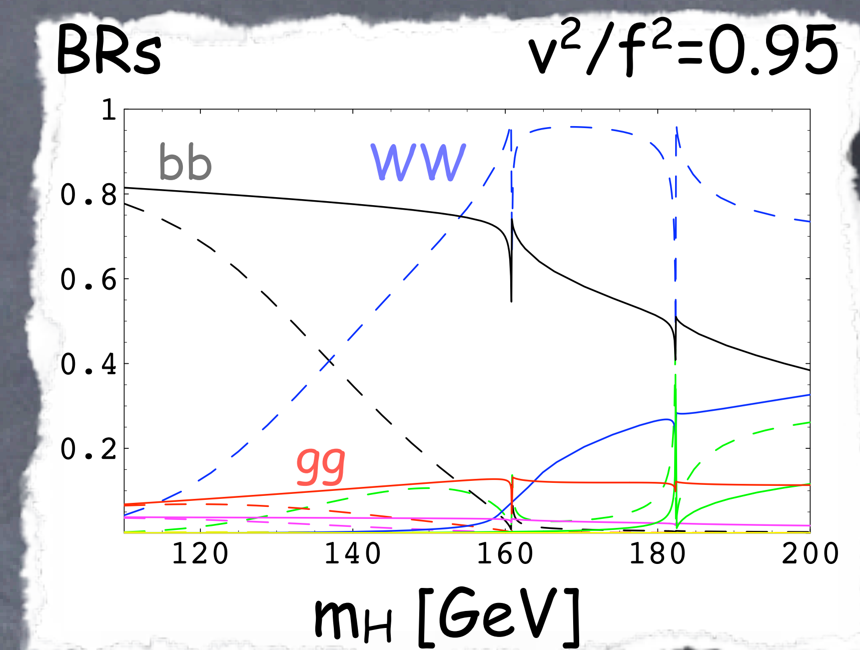
MCHM$_{5D}$ (Contino et al. '04) with fermions embedded in 5+10 of SO(5)



slight modifications

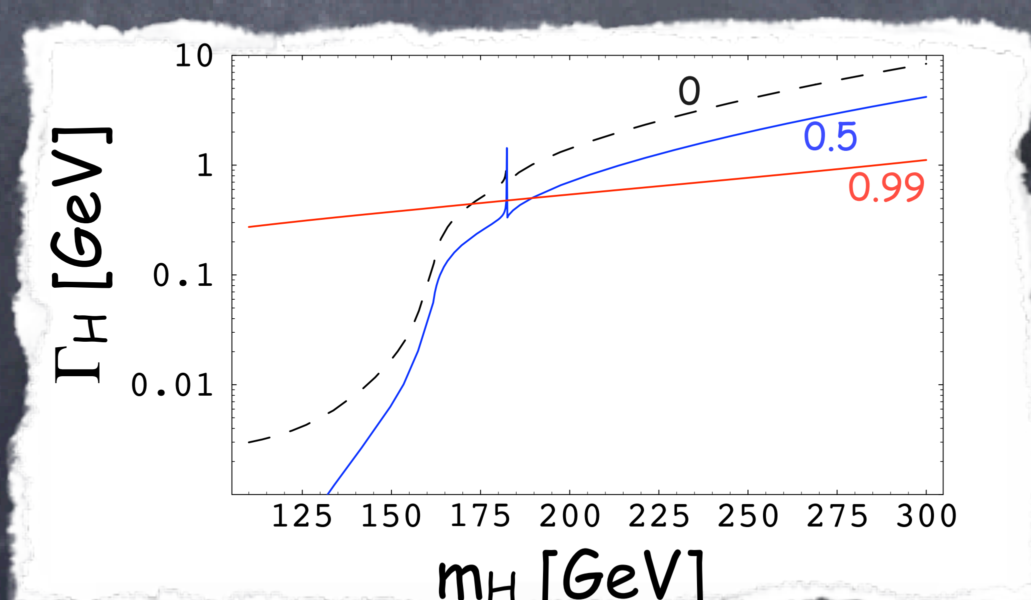


suppress bb



suppress WW

Higgs total width



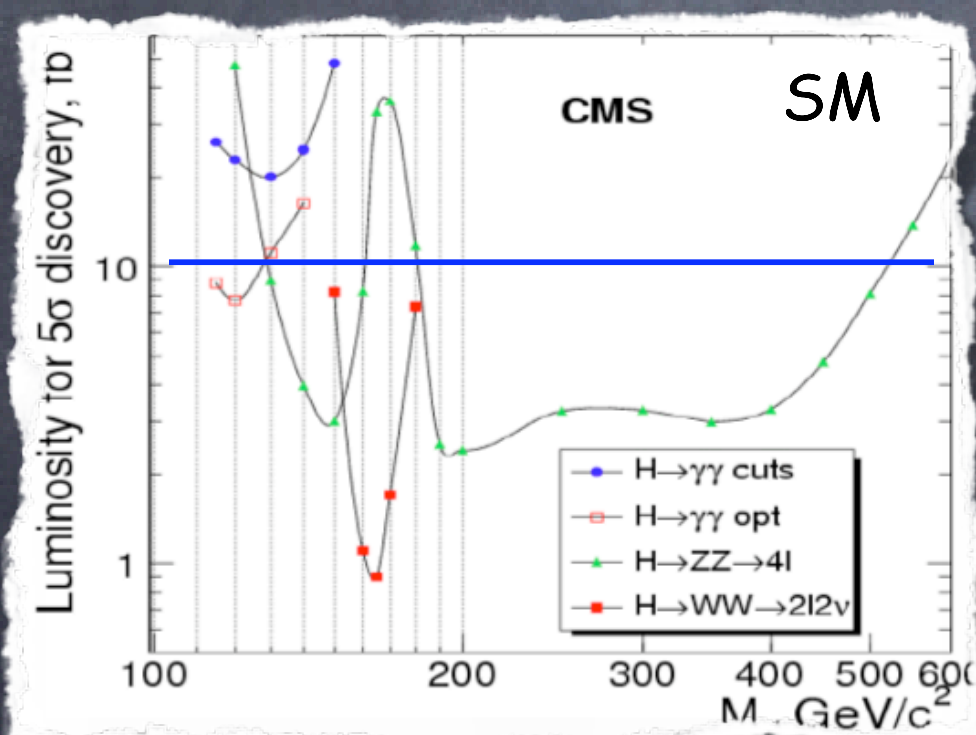
- - - SM

—— composite Higgs

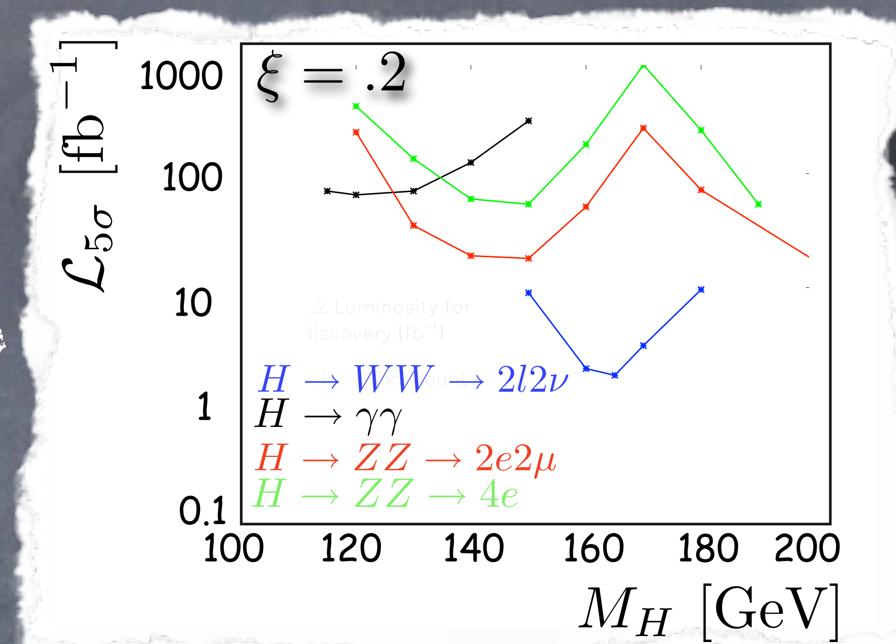
Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner 'in progress

the modification of Higgs couplings and BRs affects the Higgs search

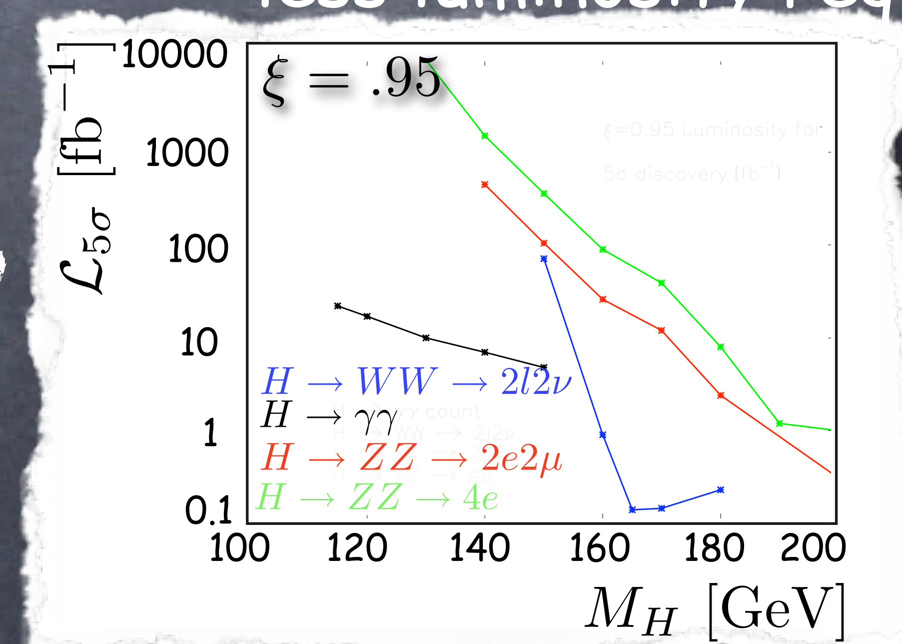


large
compositeness scale



more luminosity required

less luminosity required

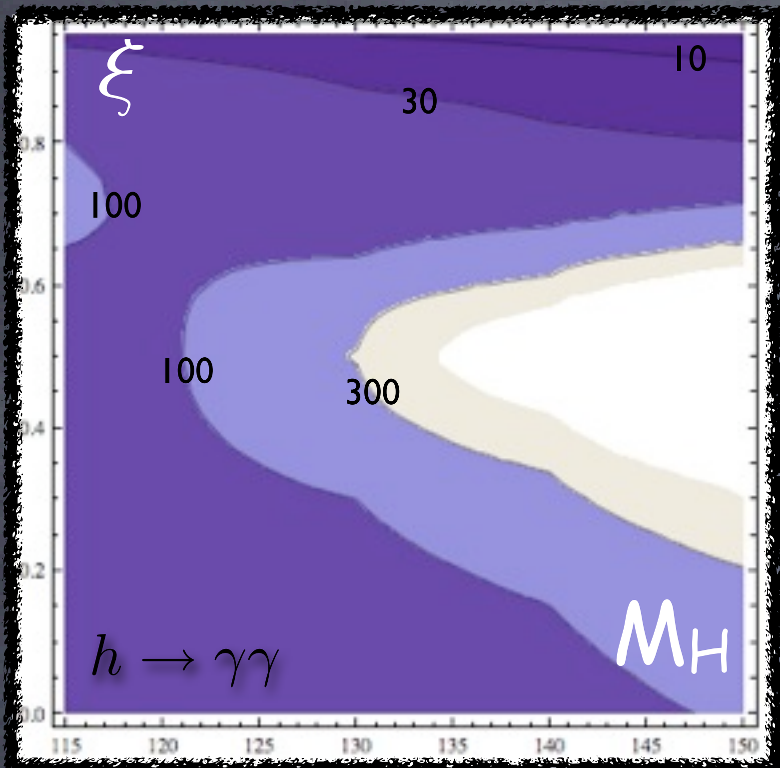


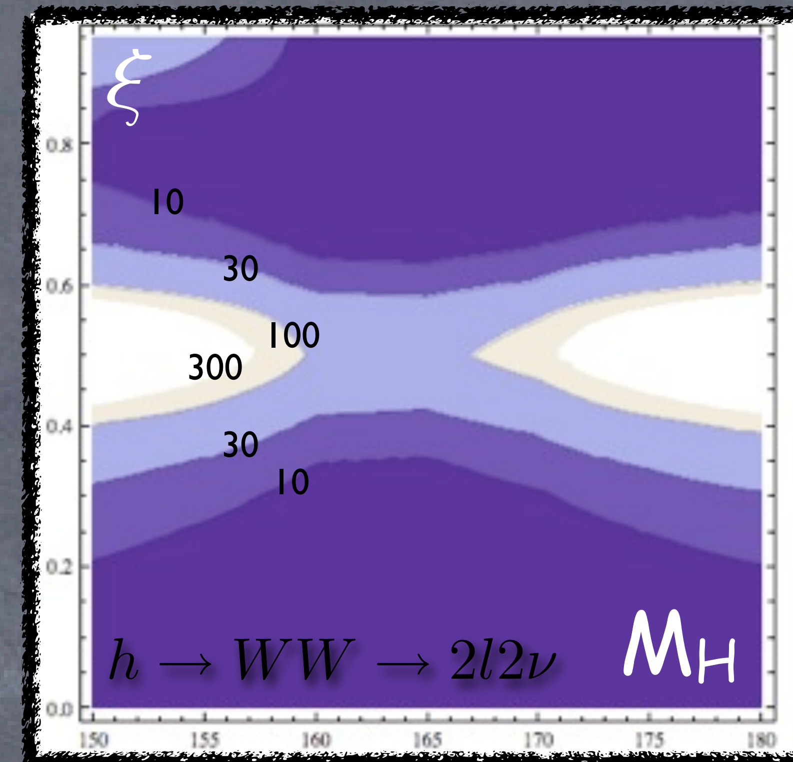
small
compositeness scale

Composite Higgs search @ LHC

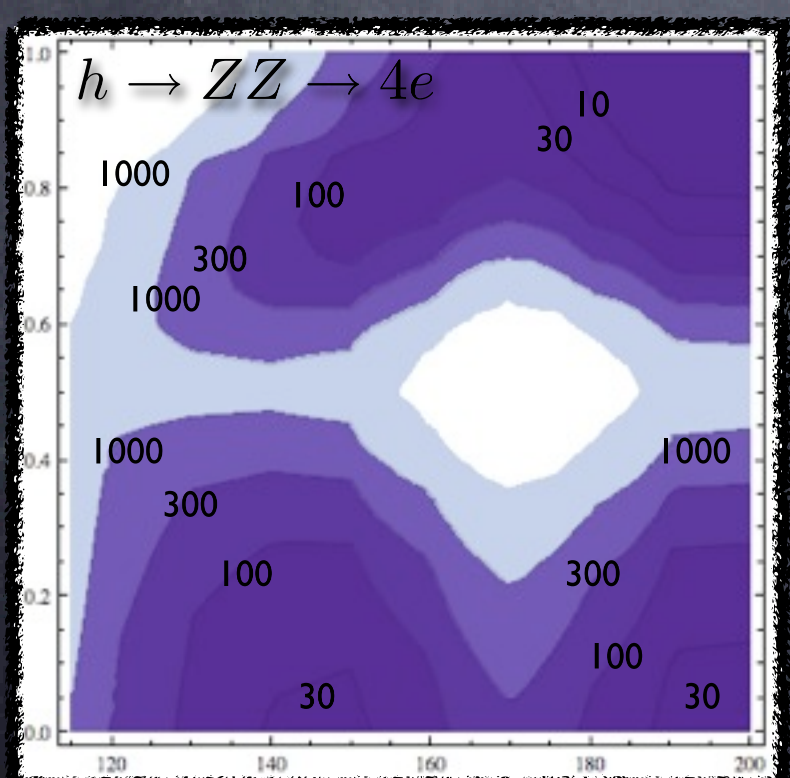
Espinosa, Grojean, Muehlleitner 'in progress

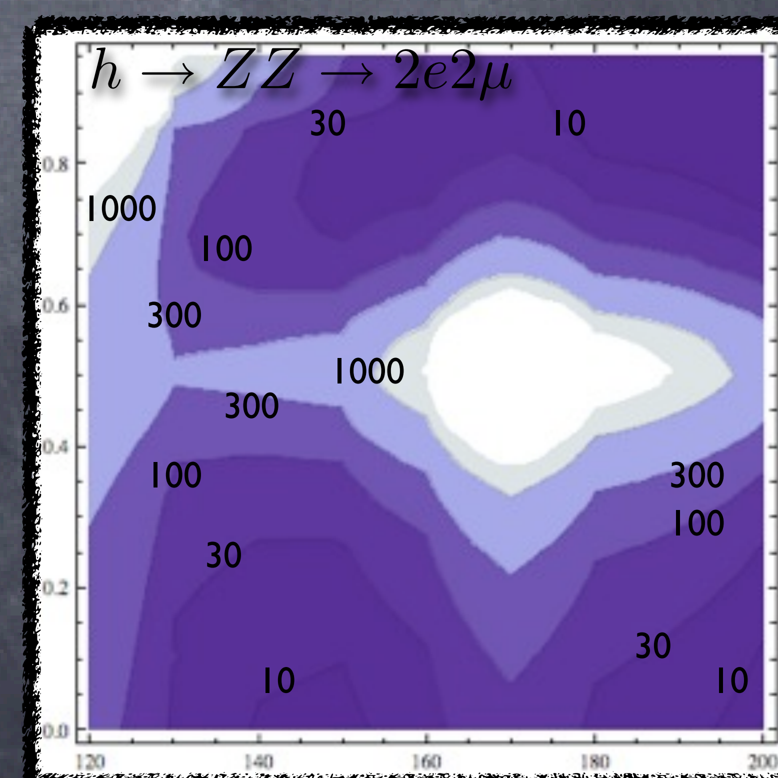
the modification of Higgs couplings and BRs affects the Higgs search





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





(neglect effects from heavy resonances)

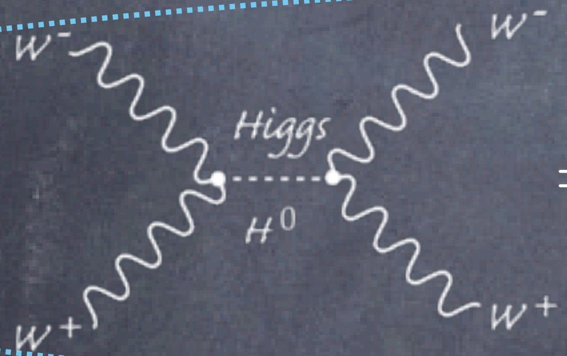
Strong WW scattering

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



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

no exact cancellation of the growing amplitudes

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

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

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

LET=SM-Higgs

unitarity restored by the exchange of heavy vector resonances

Falkowski, Pokorski, Roberts '07

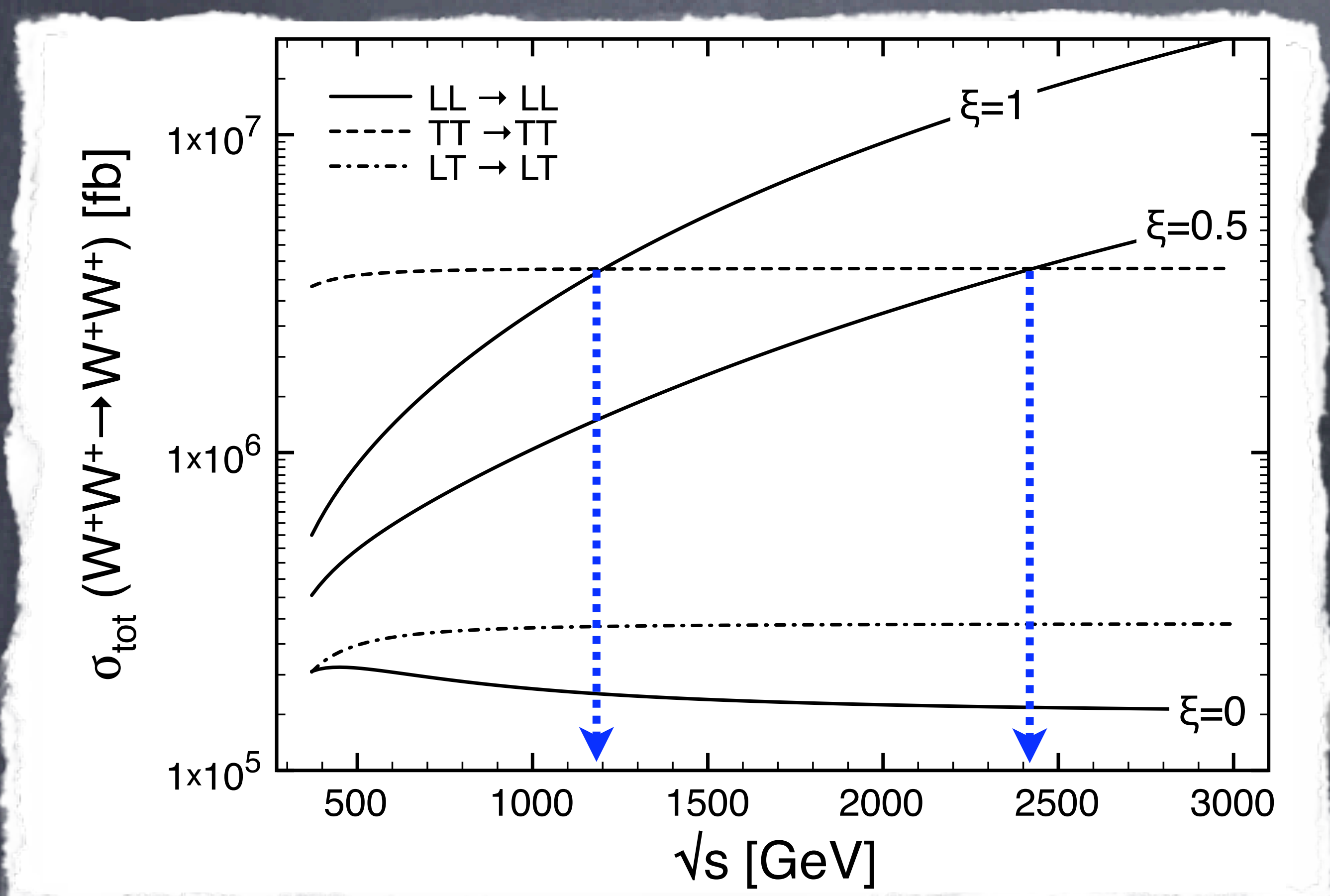
Onset of Strong Scattering

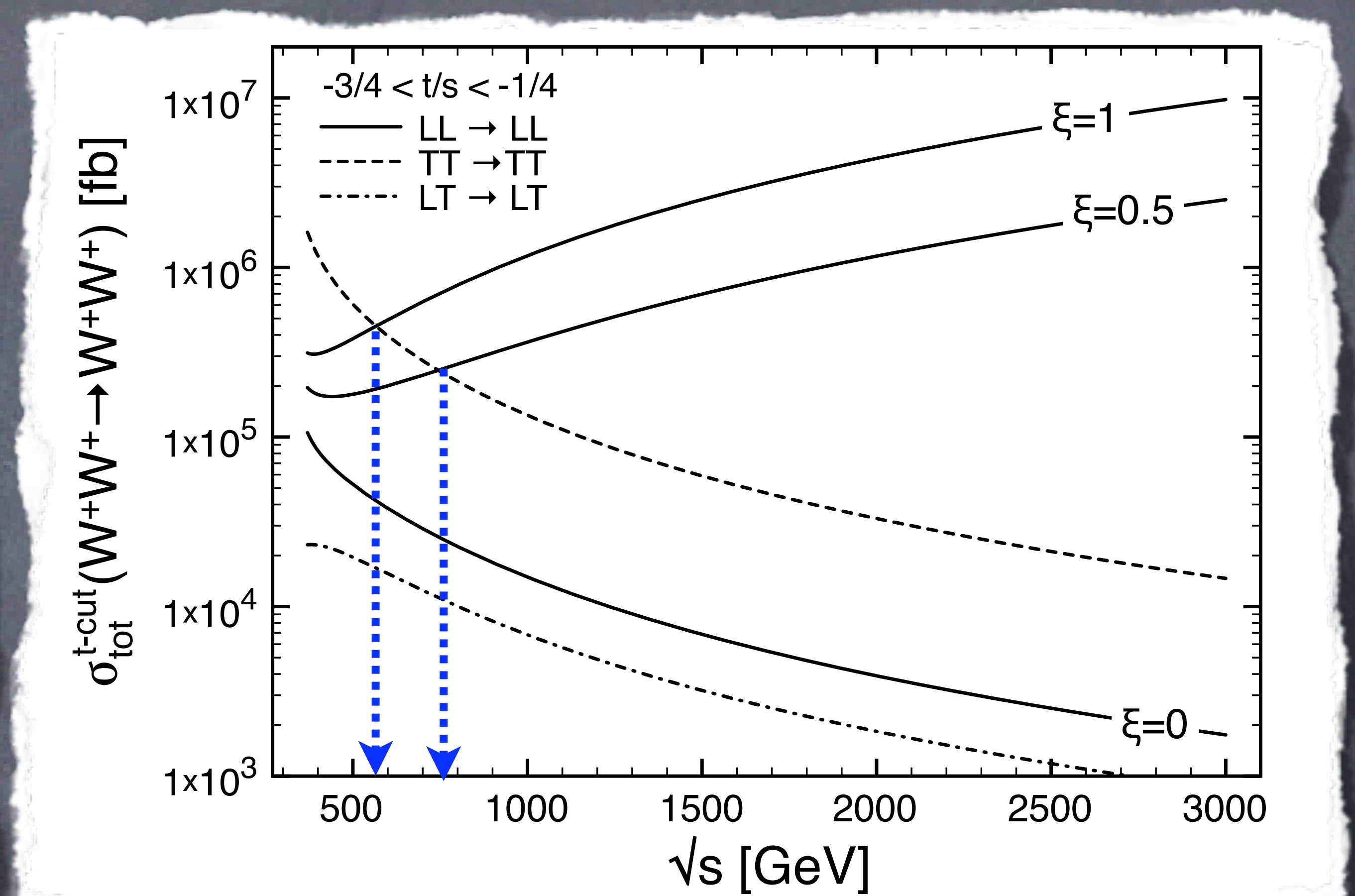
Contino, Grojean, Moretti, Piccinini, Rattazzi 'to appear

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

With LHC energy, access to strong scattering is difficult

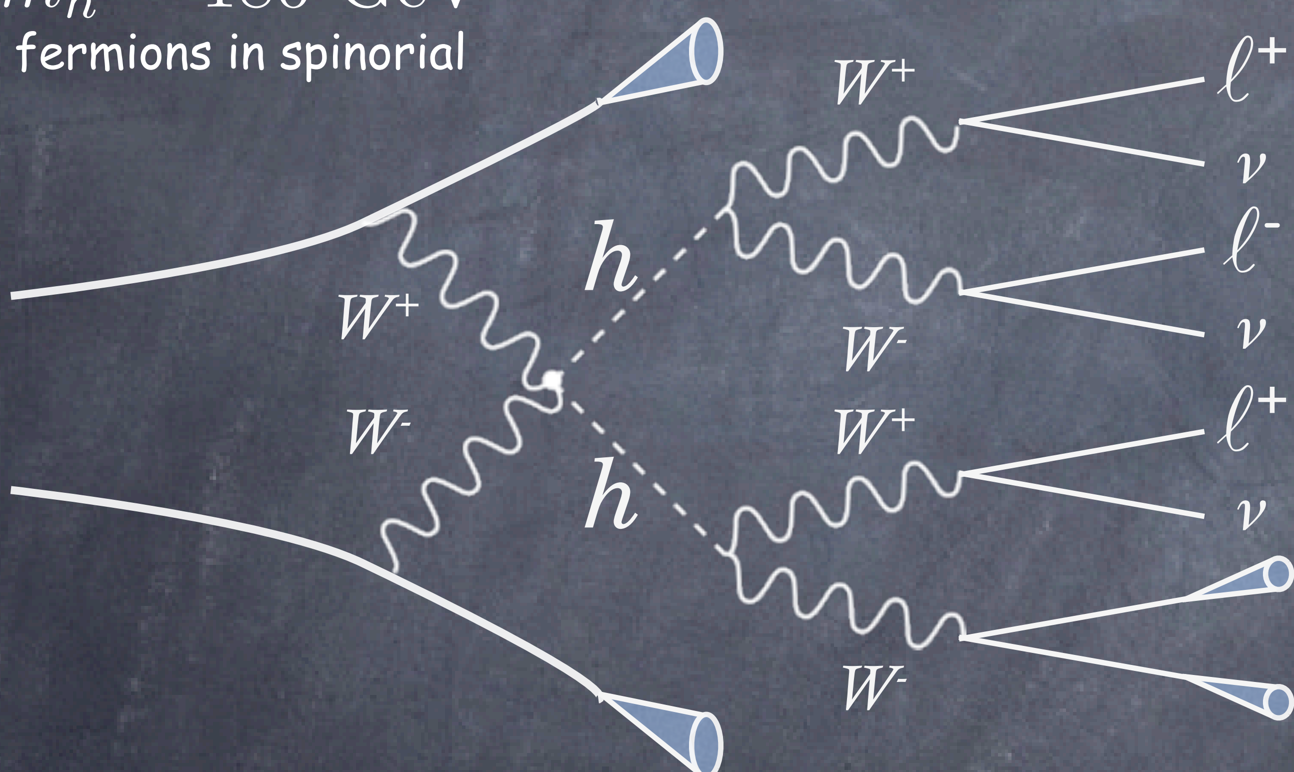
Strong Higgs production: (3L+jets) analysis

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: W$\ell\ell$4j, $\bar{t}t$W2j, $\bar{t}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

$\Lleftarrow$ good motivation for SLHC

Fermion Partners

The couplings of gauge bosons to fermions receive corrections
the heavier the fermion, the bigger the correction
expect O(10%) deviation in Zb_Lb_L, beyond exp. bound

custodial symmetry might be helpful to protect $Z_{b_L\bar{b}_L}$

Agashe, Contino, Da Rold, Pomarol '06

custodial embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2,\bar{2})_{2/3} \qquad t_R \equiv (1,1)_{-2/3} \quad b_R \equiv (1,1)_{1/3}$$

then b_L is an eigenstate of L ⇔ R and this ensures that $\delta Z_{b_L\bar{b}_L} = 0$

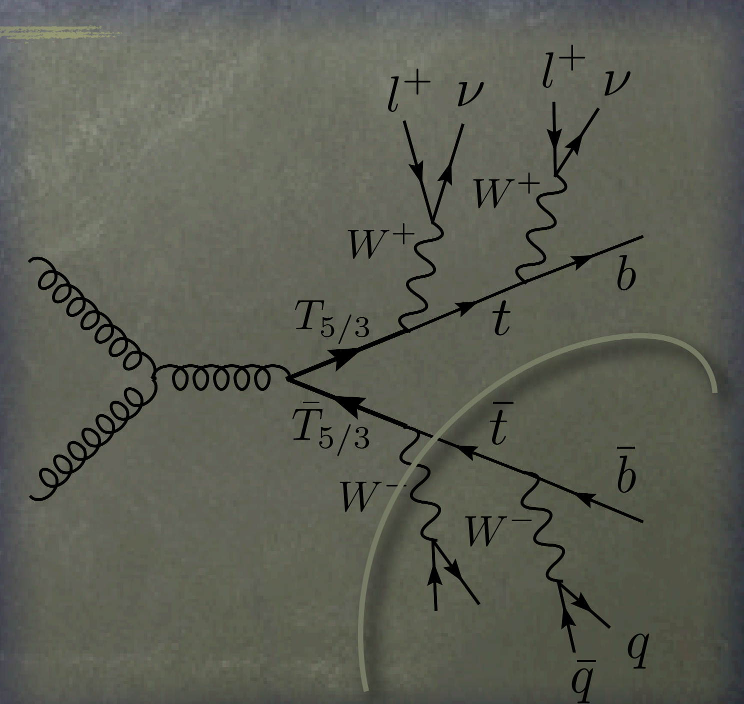
but we expect deviations in $Zt_L\bar{t}_L \quad Wt_L\bar{b}_L \quad Zb_R\bar{b}_R$

Search in same-sign di-lepton events

Contino, Servant '08

- *tt+jets* is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed

discovery potential (LHC_{14TeV})
$M_{5/3}$=500 GeV → 56 pb^{-1}
$M_{5/3}$=1 TeV → 15 fb^{-1}



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

SM Higgs = Ising model of HEP

- violent departures from SM are more or less excluded
- it is time to identify and explore 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 (quark) top machine

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