Deciphering EW Symmetry Breaking

Corfu Summer Institute 2010

on Elementary Particle Physics and Gravity

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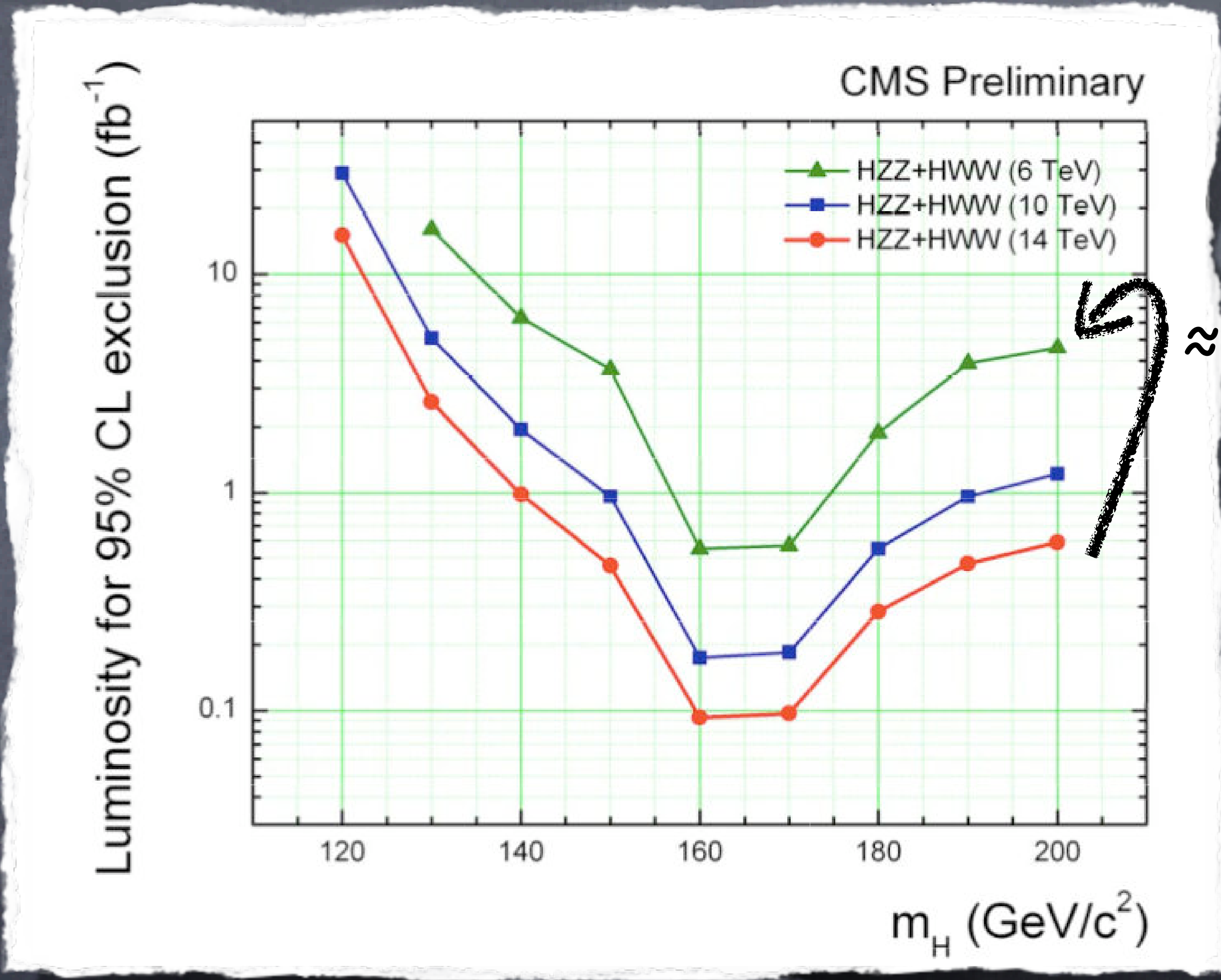
EWSB on March 29, 2010 23:59 (Geneva time)

waiting for collisions... and still building models

EWSB on December 31, 2011 (any time)



≈x7 luminosity

The Higgs might well not be on the agenda of Heuer's mandate

Higgs = "raison d'être" of LHC

- ≈500 physics papers over the last 5 years have an introduction starting like

  "The main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking",

  "How the electroweak gauge symmetry is spontaneously broken is one of the most urgent and challenging questions before particle physics."

- ≈9000 papers in Spires contain "Higgs" in their title
- ≈3×10^6 references in google
- ... no Nobel prize (so far)

Reasons of a success

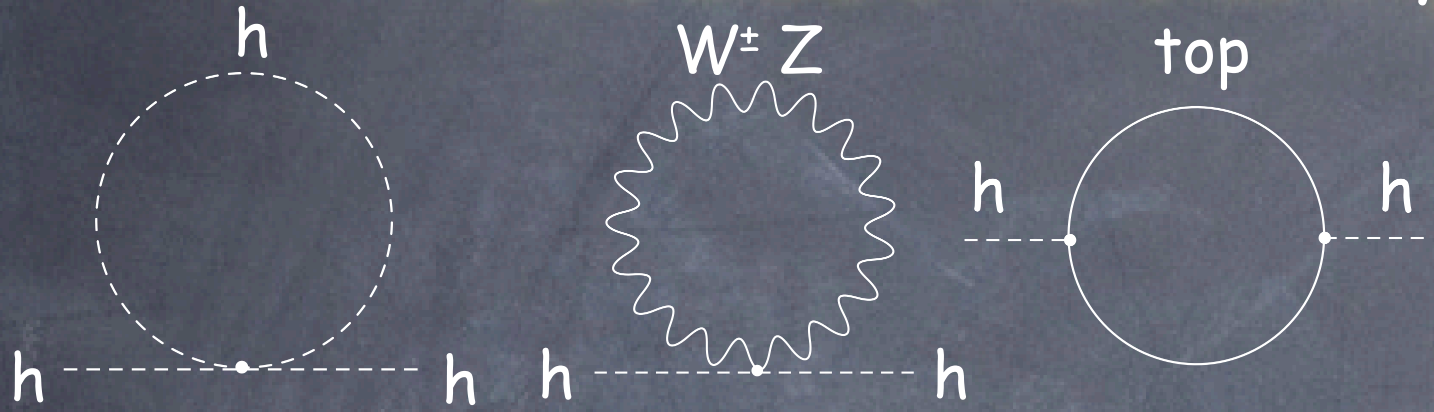
- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes
- screening of gauge boson self-energies

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

Beyond the Higgs: The hierarchy problem

need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale



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

R. Godbole + S. Pokorski's lectures

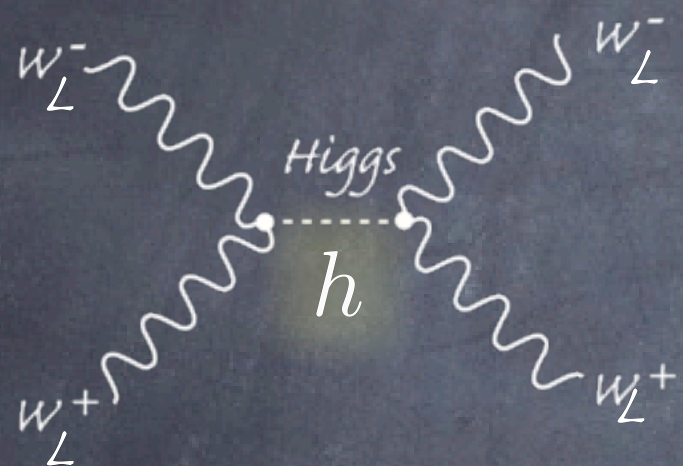
1. add a sym. such that a Higgs mass is forbidden until this sym. is broken
   - supersymmetry [Witten, '81]
   - gauge-Higgs unification [Manton, '79, Hosotani '83]
   - Higgs as a pseudo Nambu-Goldstone boson [Georgi-Kaplan, '84]
2. lower the UV scale
   - large extra-dimension [Arkani-Hamed-Dimopoulos-Dvali, '98]
   - 10^{32} species [Dvali '07]
3. remove the Higgs
   - technicolor [Weinberg '79, Susskind '79]

What is the SM Higgs?

A single scalar degree of freedom with no charge under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



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

growth cancelled for
a = 1
restoration of
perturbative unitarity

$\Sigma \approx$ Goldstone bosons of $SU(2)_L \times SU(2)_R / SU(2)_V \approx W_L, Z_L$

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'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW → WW

For b = a^2: perturbative unitarity in inelastic channels WW → hh

For ac=1: perturbative unitarity in inelastic WW → $\psi\,\psi$

'a=1', 'b=1' & 'c=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 $SU(2)_L \times U(1)_Y$

Higgs properties depend on a single unknown parameter (m_H)

What is the SM Higgs?

A single scalar degree of freedom with no charge under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar\psi_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

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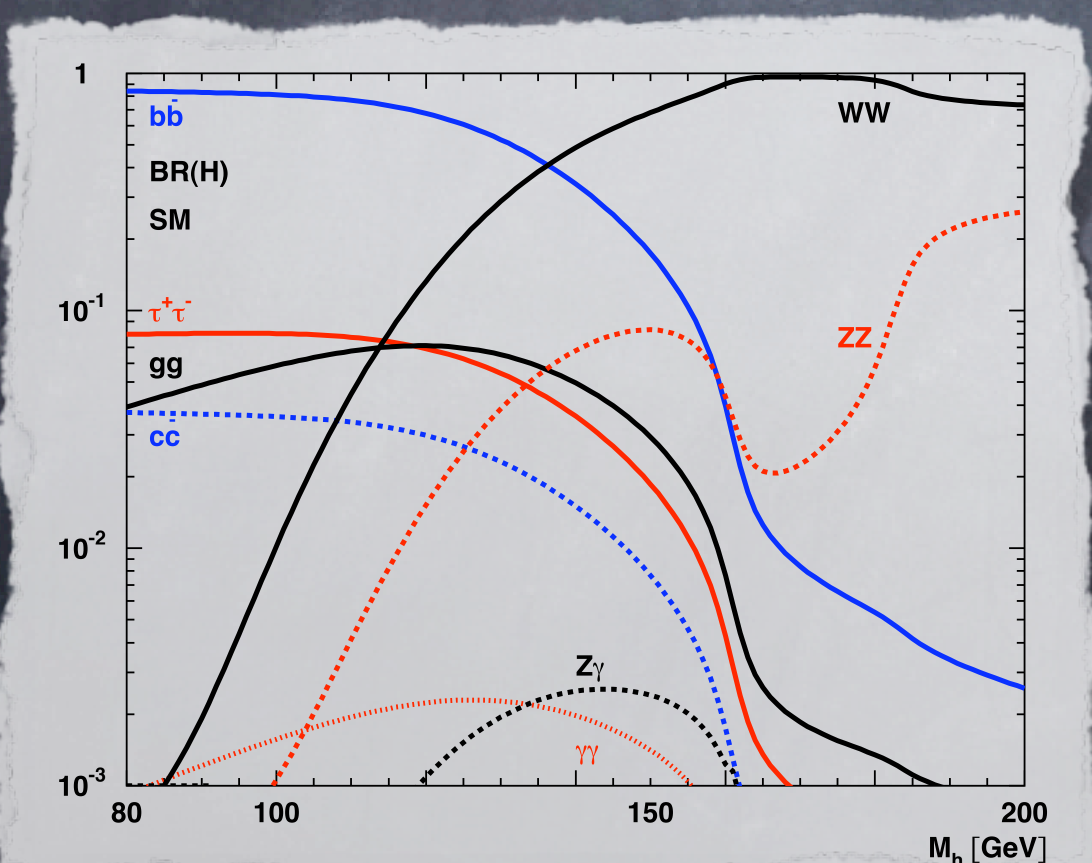
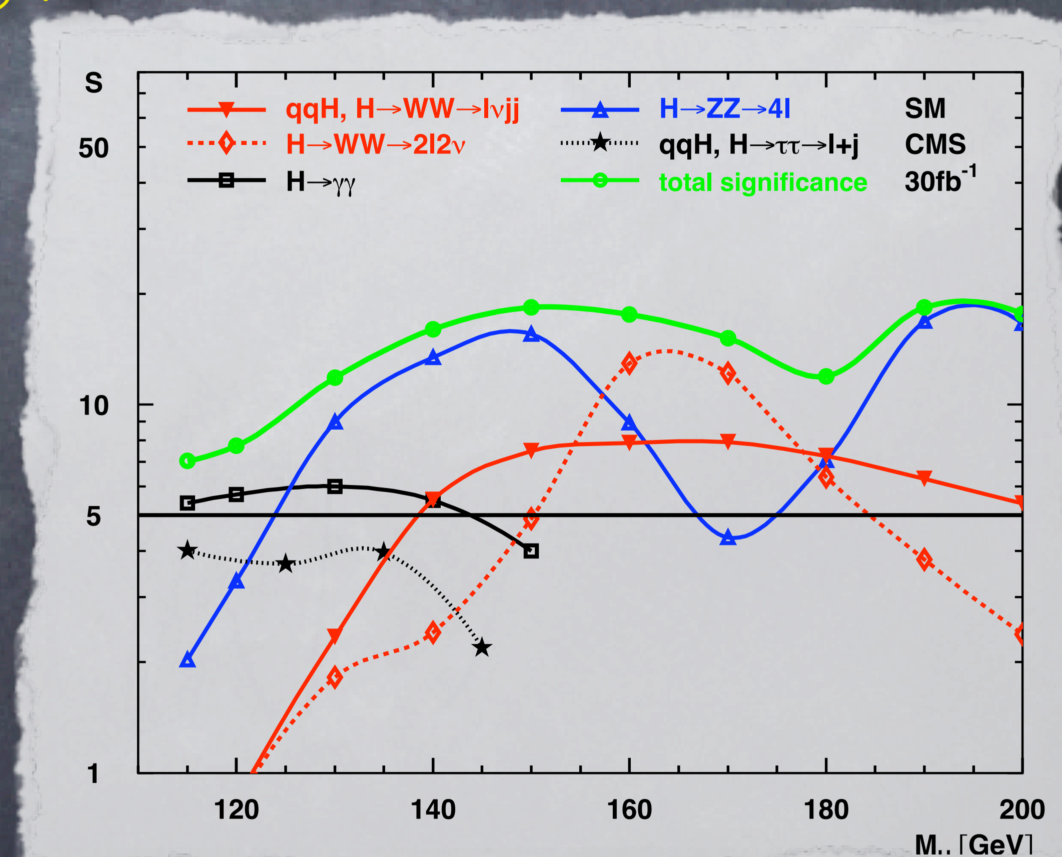
Higgs properties depend on a single unknown parameter (m_H)

A. Djouadi's lectures



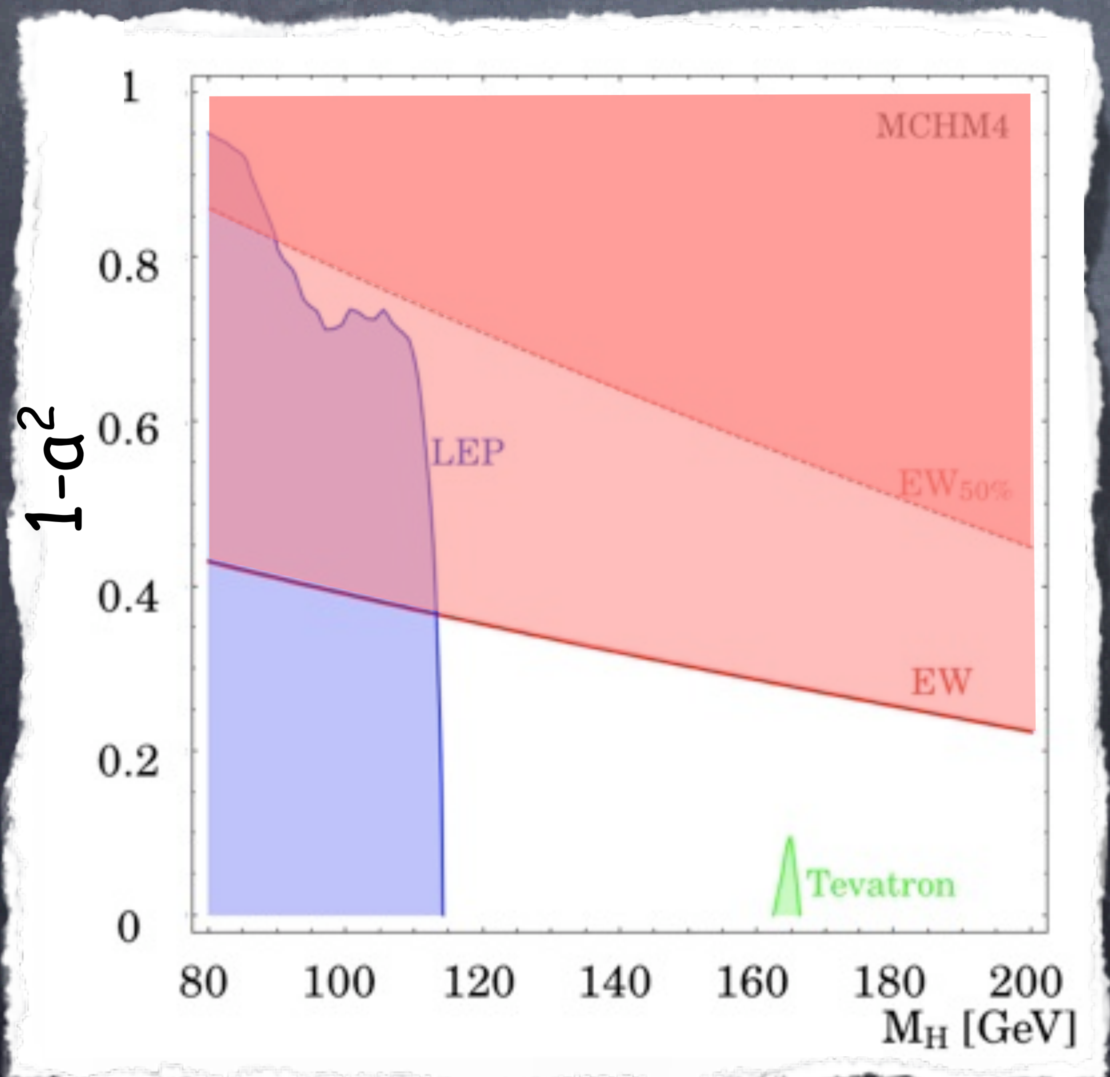


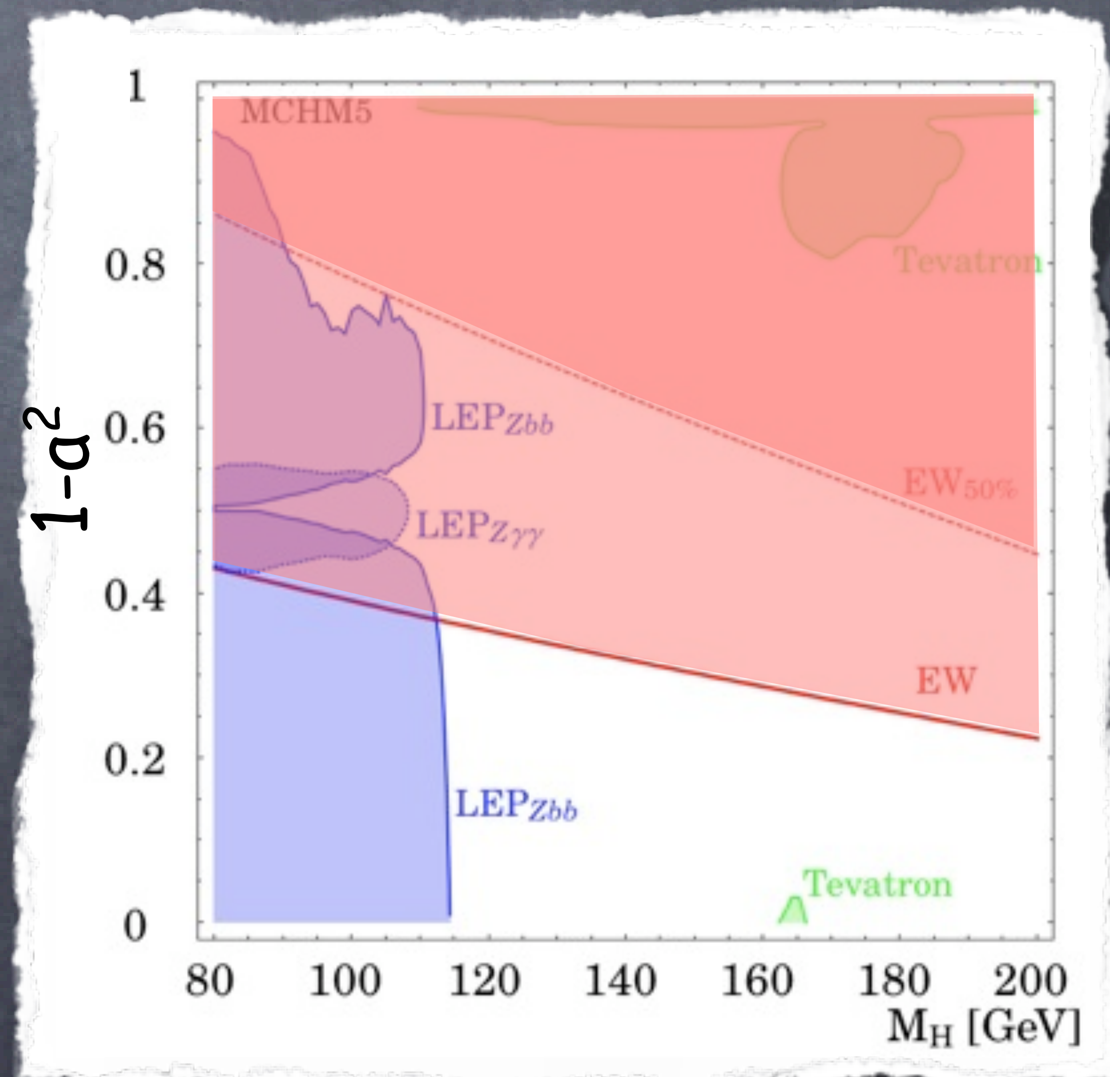
Deformation of the SM Higgs

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

generic 'a', 'b' & 'c'

Examples of constraints on the "Higgs" couplings





How many parameters for the Higgs?

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda_{ij}\bar{\psi}_L\Sigma\psi_R\left(1+c_{ij}\frac{h}{v}\right)$$
$$+c_g\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma\frac{h}{v}\gamma_{\mu\nu}\gamma^{\mu\nu}$$

- Minimal Flavour Violation setup? $c_{ij}=c$
- Loop suppressed decays to massless spin-1? $c_g \sim c_\gamma \sim \mathcal{O}\left(\frac{\alpha}{4\pi}\right)$

How to obtain a light composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

Higgs=Pseudo-Goldstone boson of the strong sector

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

$g_{\rm SM}$ SM $\overset{\text{proto-Yukawa, gauge}}{\longleftrightarrow}$ Strong BSM g_ρ

$g^2_{\rm SM}/g_\rho$

global symmetry $\longrightarrow$ G/H $\longleftarrow$ residual global symmetry

3 scales:

UV completion

$4\pi f$ — 10 TeV

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

not directly accessible to LC

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

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

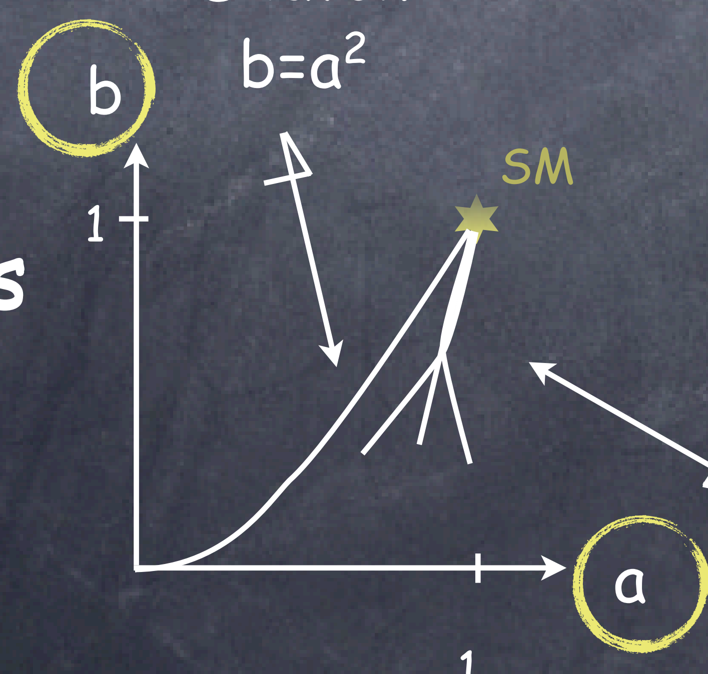
$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Dilaton
$b=a^2$

Composite Higgs
vs.
SM Higgs
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-v/2f b=1-2v/f

What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

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.

Higgs anomalous couplings for large v/f

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

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

MCHM4

Fermions embedded in spinorial of SO(5)

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

$$\Downarrow$$

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

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

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

$$\Downarrow$$

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

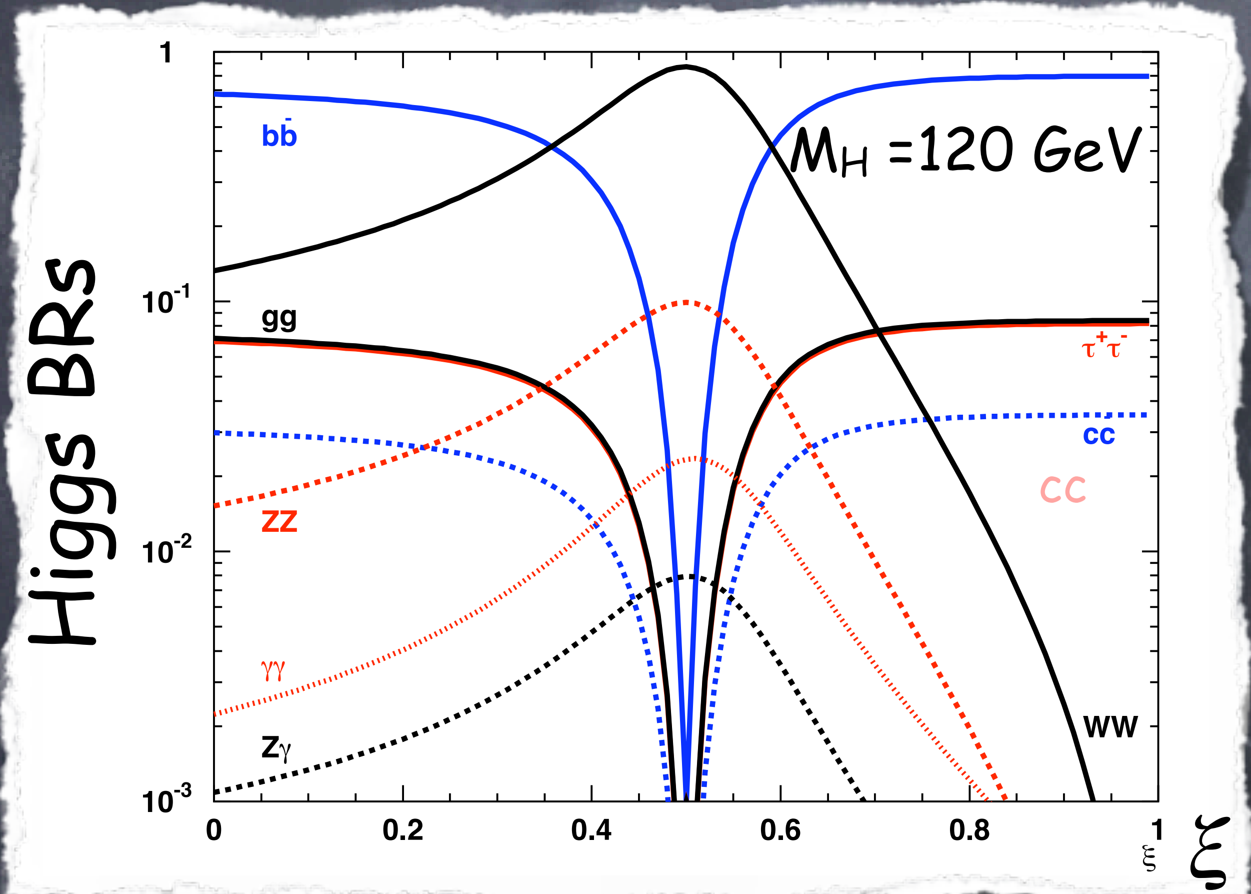
BRs now depends on v/f

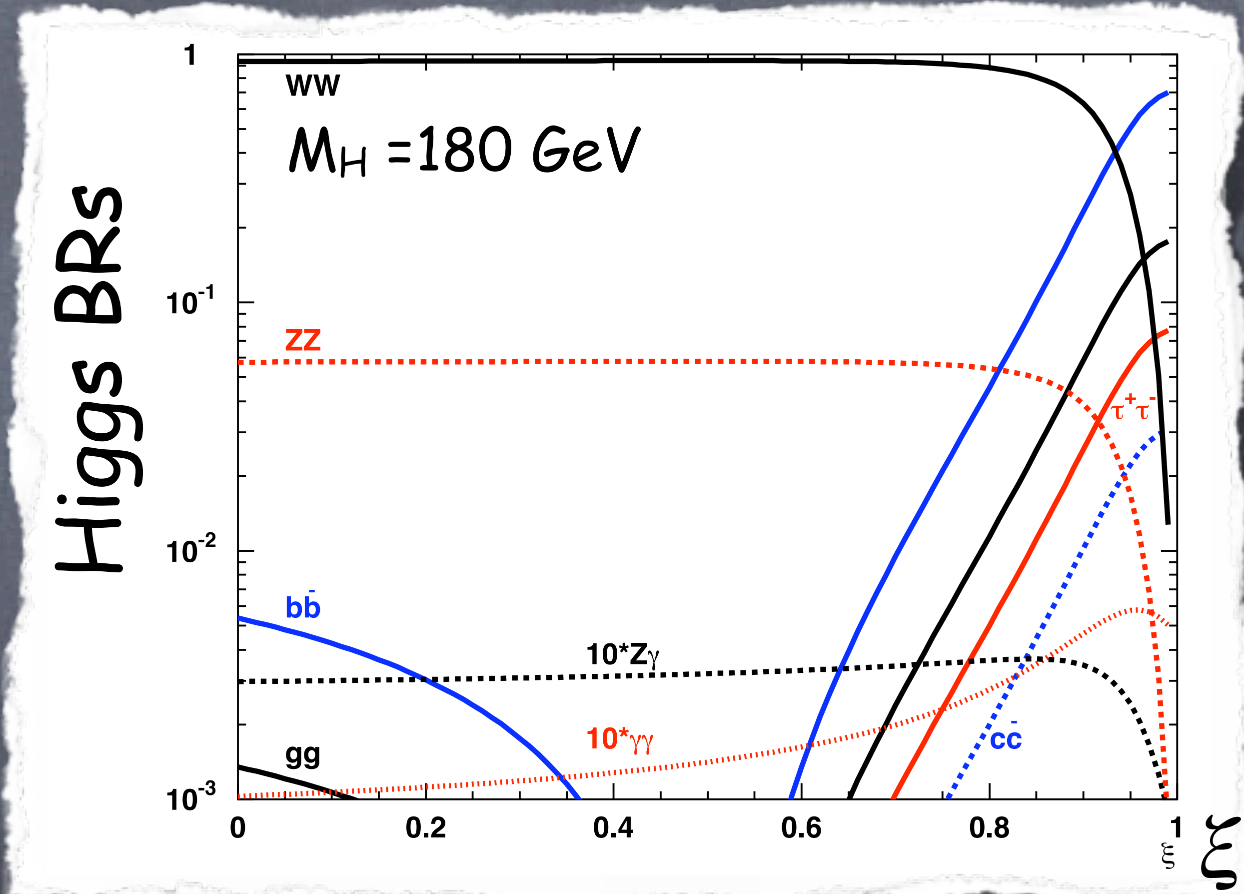
$$(\ \xi = v^2/f^2\ )$$

Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)





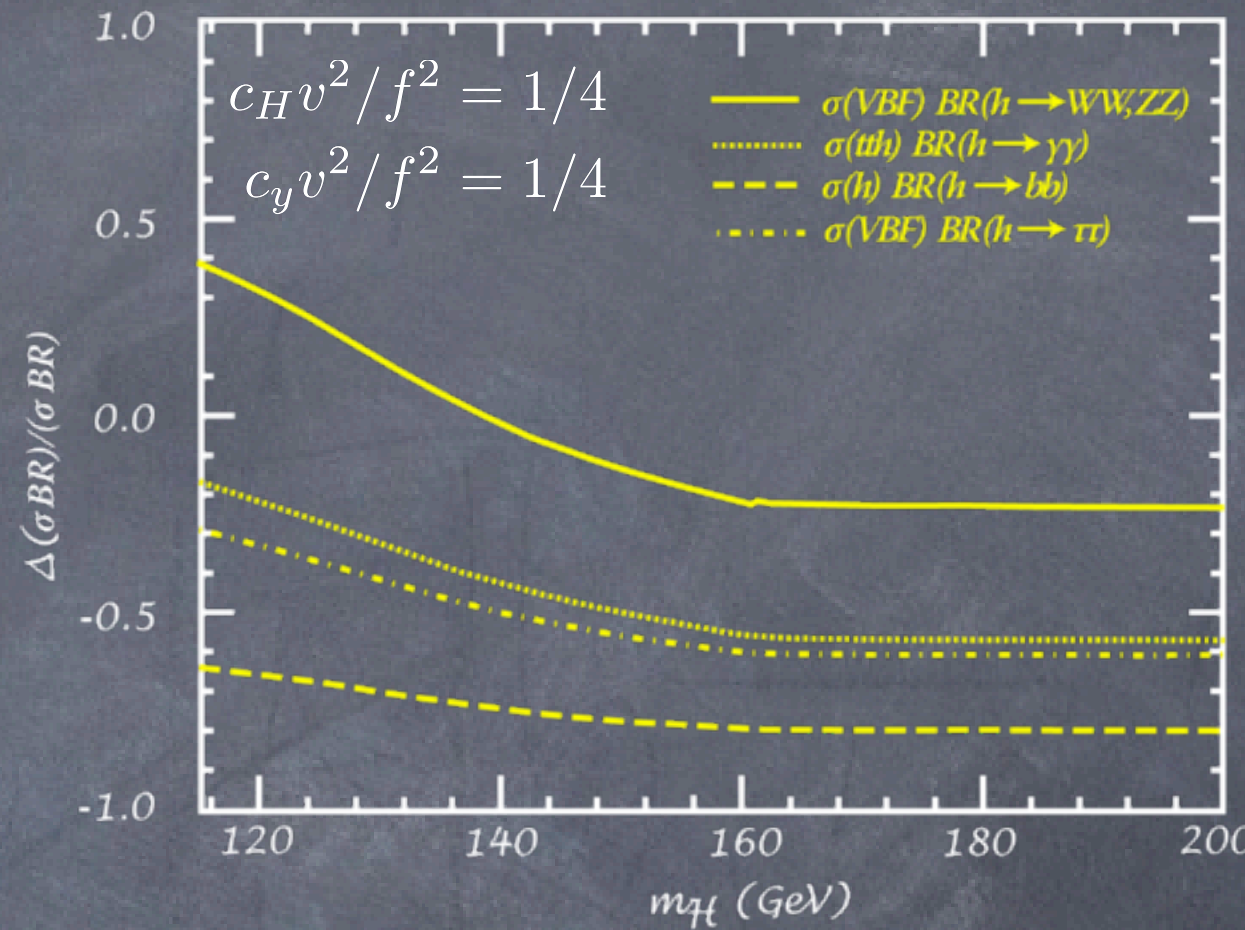
h→WW can dominate even for low Higgs mass

BRs remain SM like except for very large values of v/f

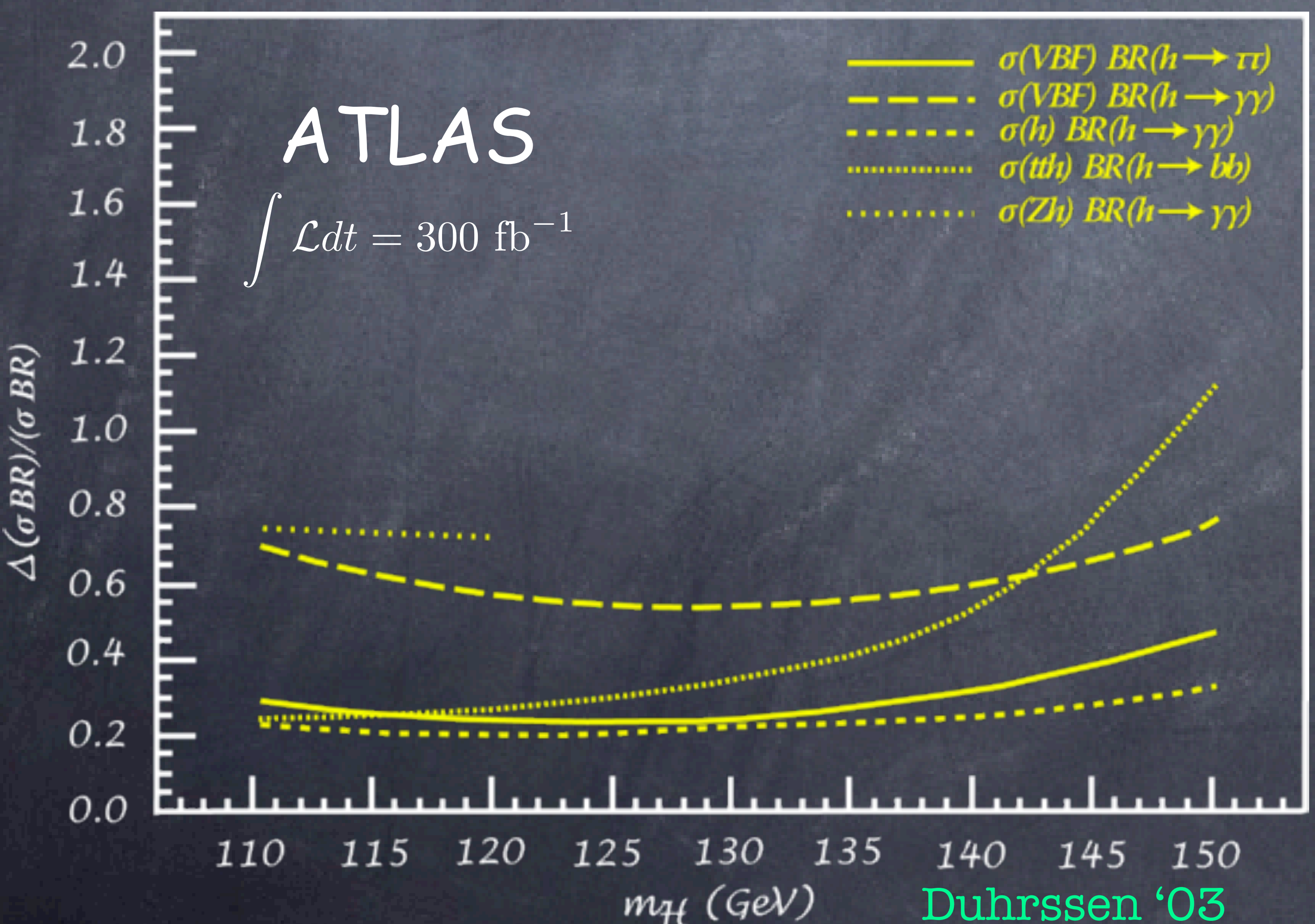
Higgs anomalous couplings @ LHC

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

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



observable @ LHC?



Duhrssen '03

LHC can measure

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

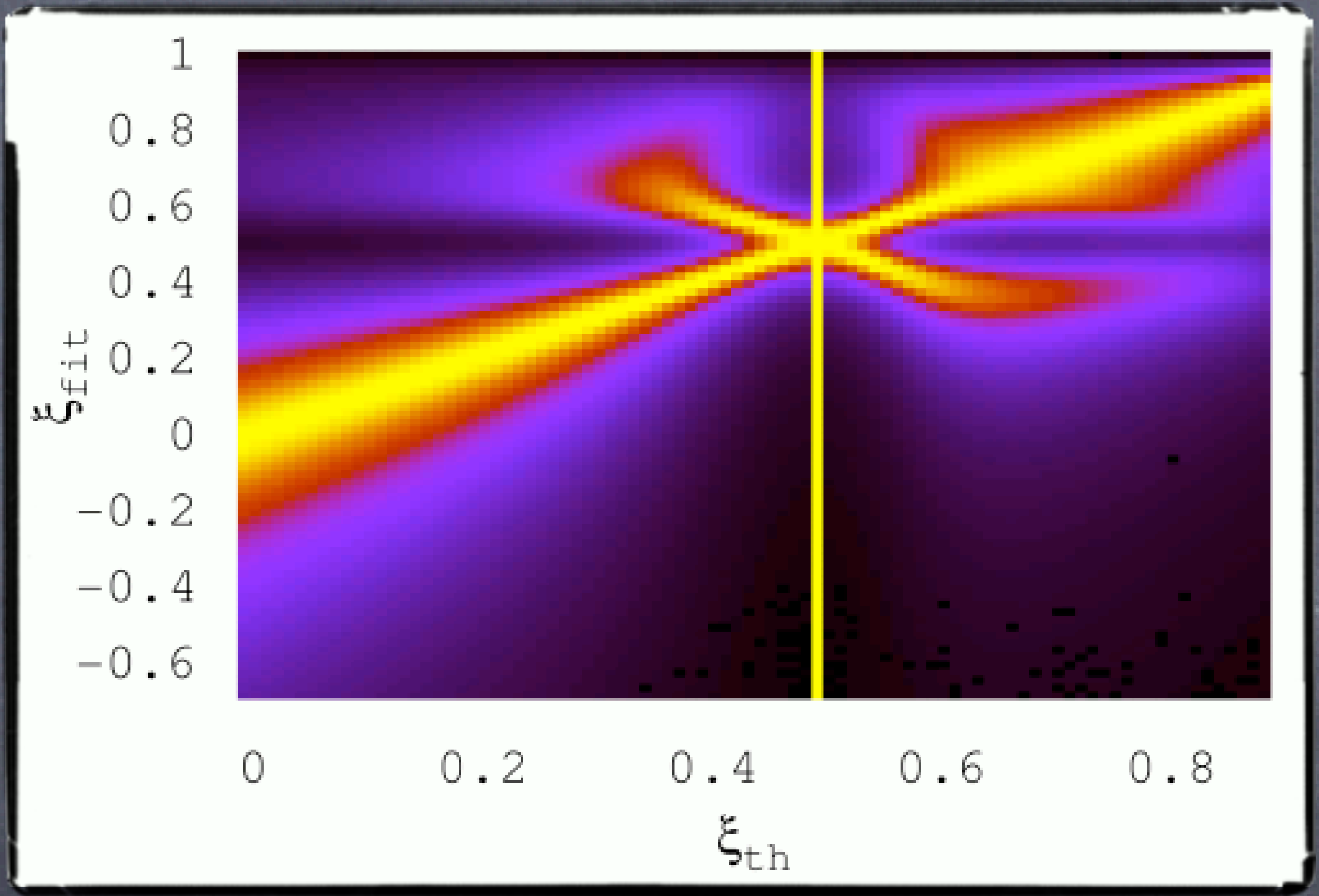
up to 0.2-0.4

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

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

Composite Higgs couplings @ LHC

The LHC sensitivity on Higgs couplings is improved if a particular structure of couplings is assumed



Bock, Lafaye, Plehn, Rauch, Zerwas & Zerwas '10

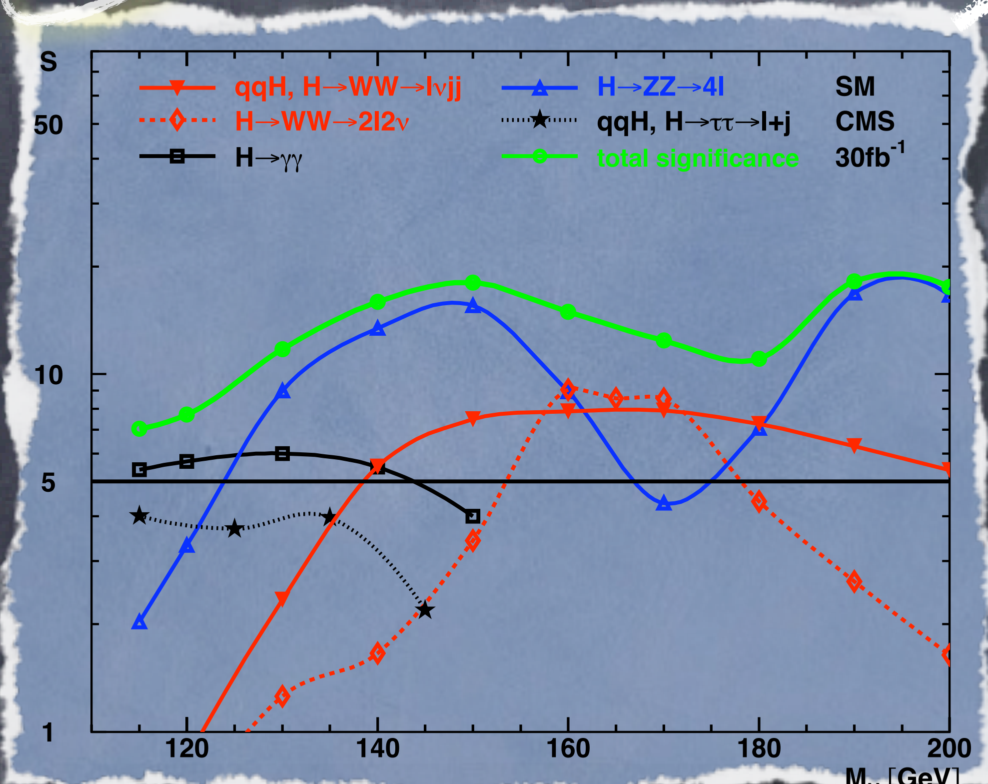
Compared to the general analysis the typical error bars on Higgs couplings are reduced by at least a factor 1/2, now ranging around 10% for a Higgs mass of 120 GeV with 30/fb at LHC_{14TeV}

Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

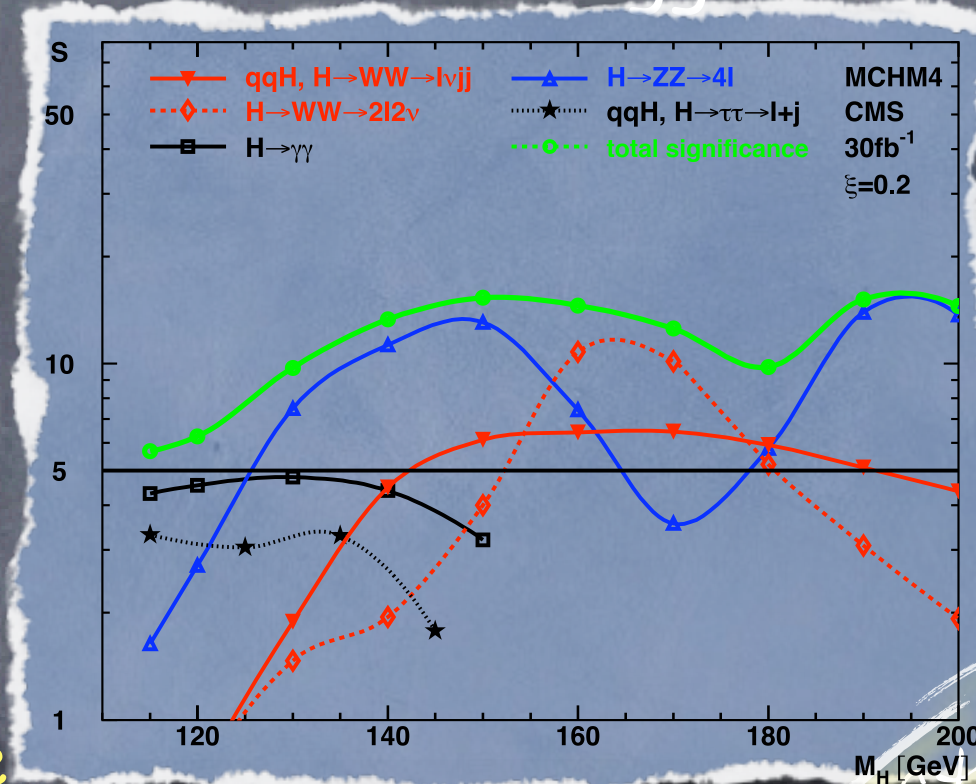
the modification of Higgs couplings and BRs affects the Higgs search

SM



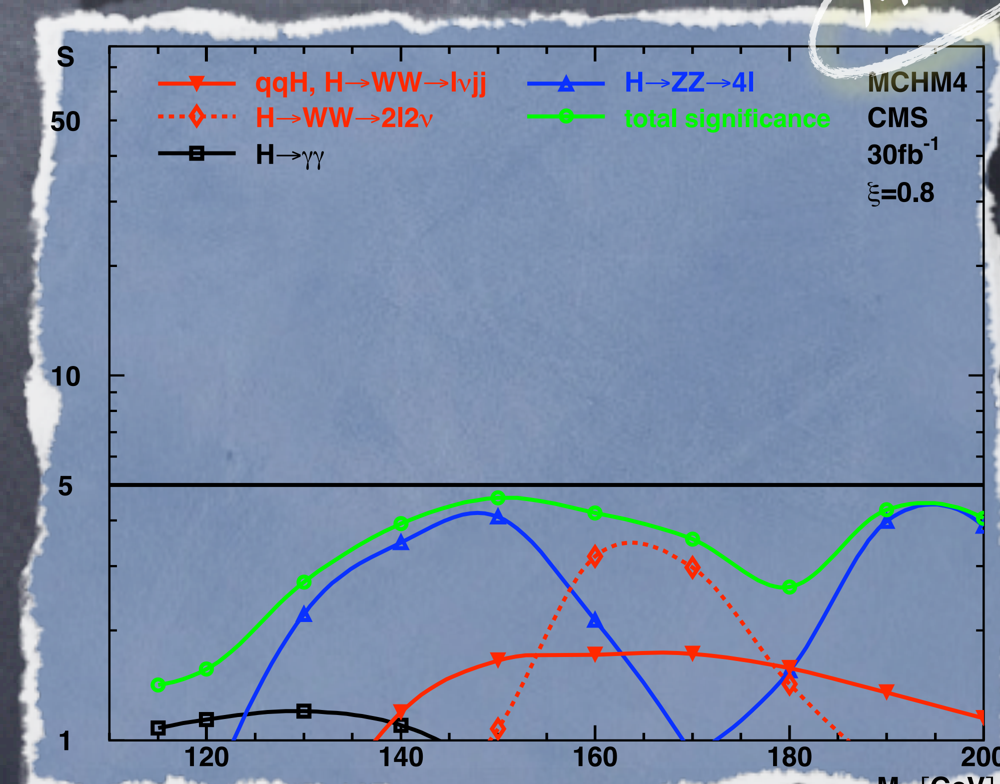
large

compositeness scale



signal significance for L=30/fb

MCHM4



small

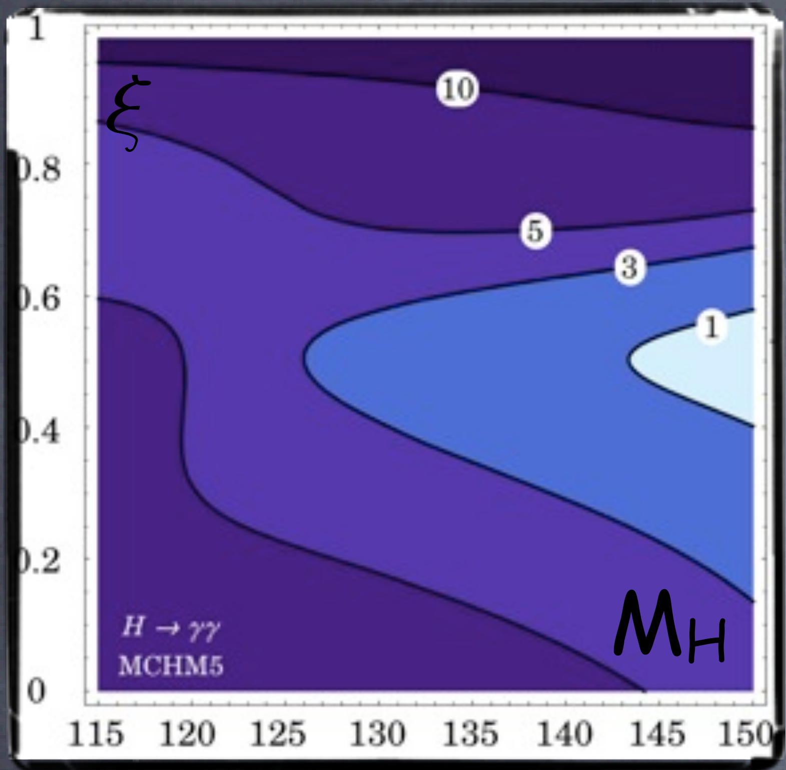
compositeness scale

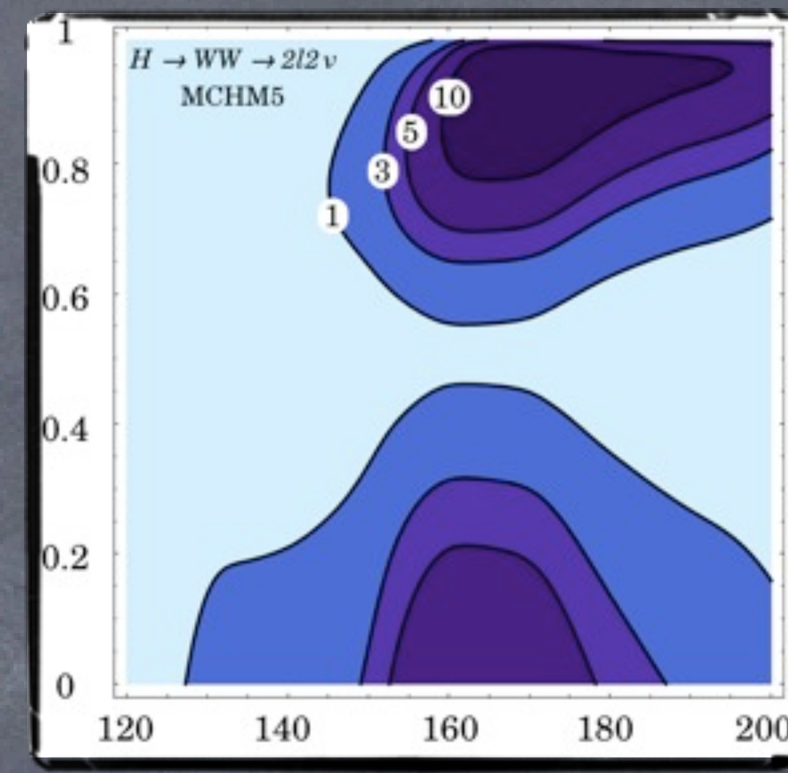
Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

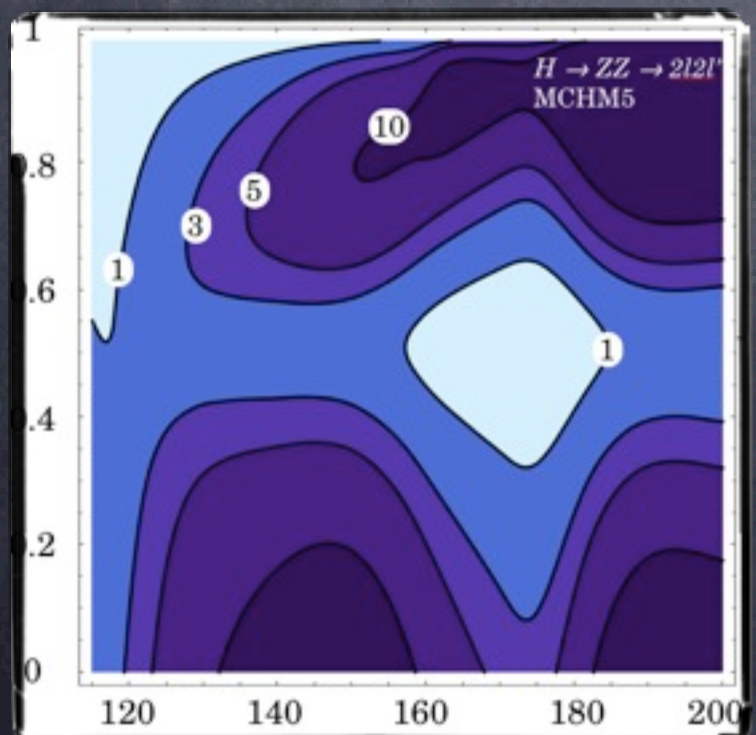
the modification of Higgs couplings and BRs affects the Higgs search

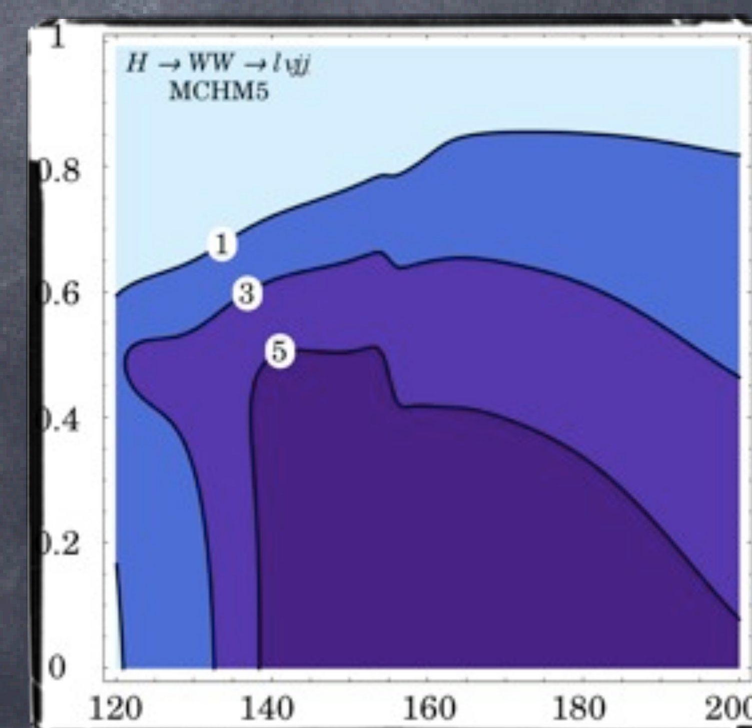
MCHM5





contour lines of
signal significance
for L=30/fb
in the (ξ,M_H) plane

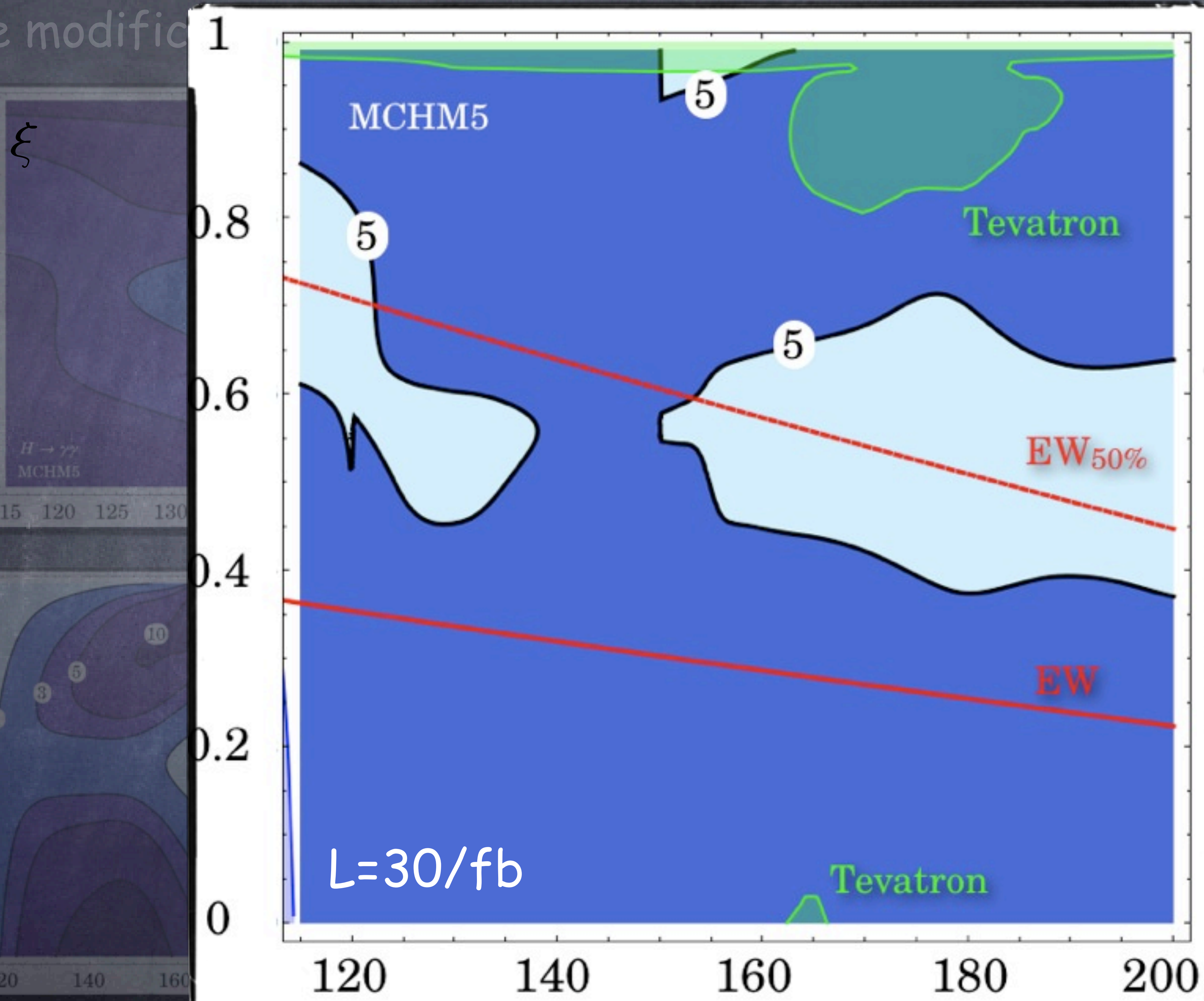




(neglect effects from heavy resonances)

Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

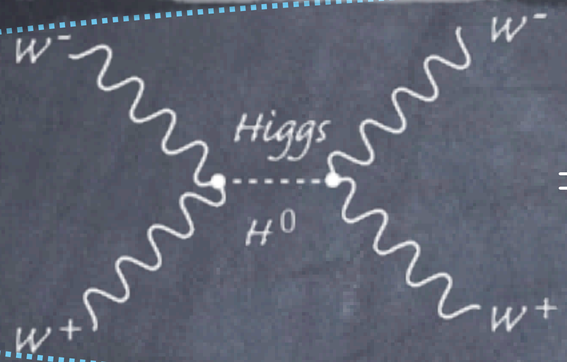


How to probe the composite nature of Higgs?

Look at pair production of strong states

- strong WW scattering

Giudice, Grojean, Pomarol, Rattazzi '07



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

no exact cancellation of the growing amplitudes

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

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

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

LET=SM-Higgs

- strong double Higgs production

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

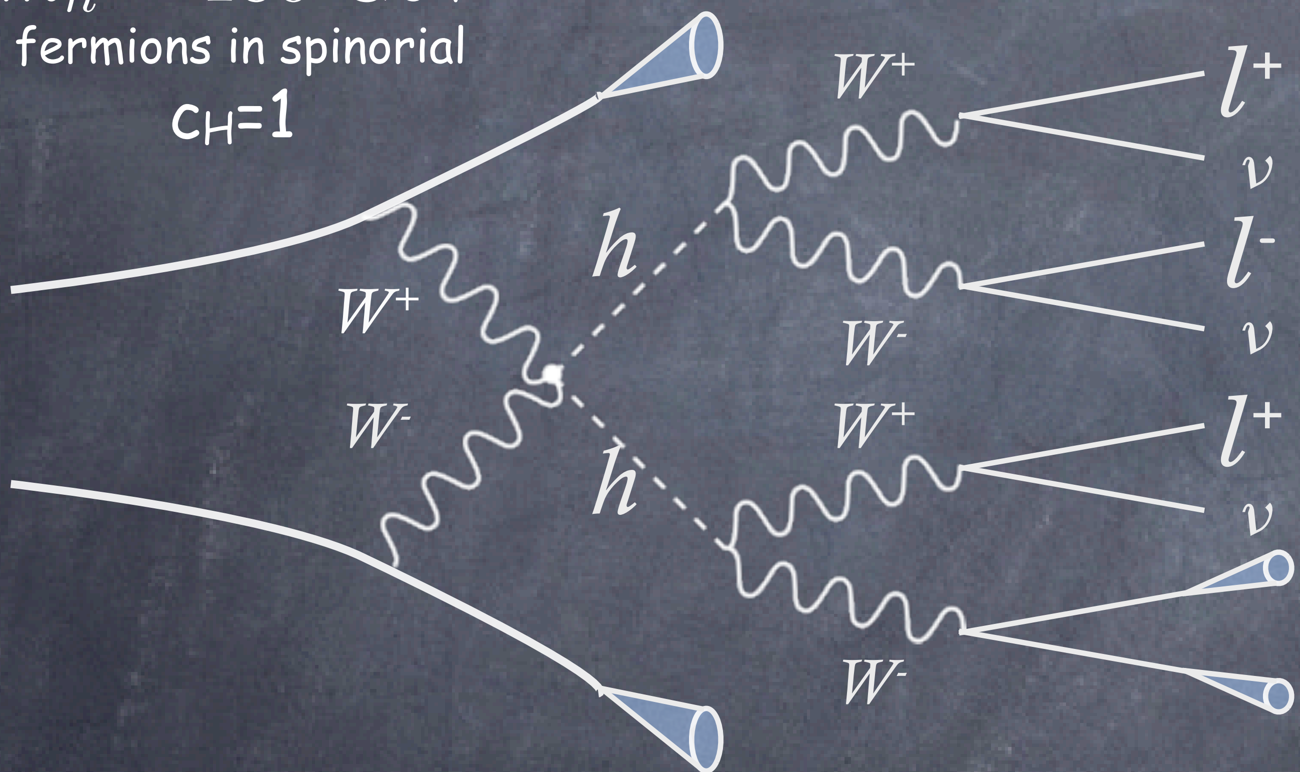
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ GeV

fermions in spinorial

c_H=1



acceptance cuts

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

Dominant backgrounds: Wll4j, $\bar{t}t$W2j, $\bar{t}t$2W(j), 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

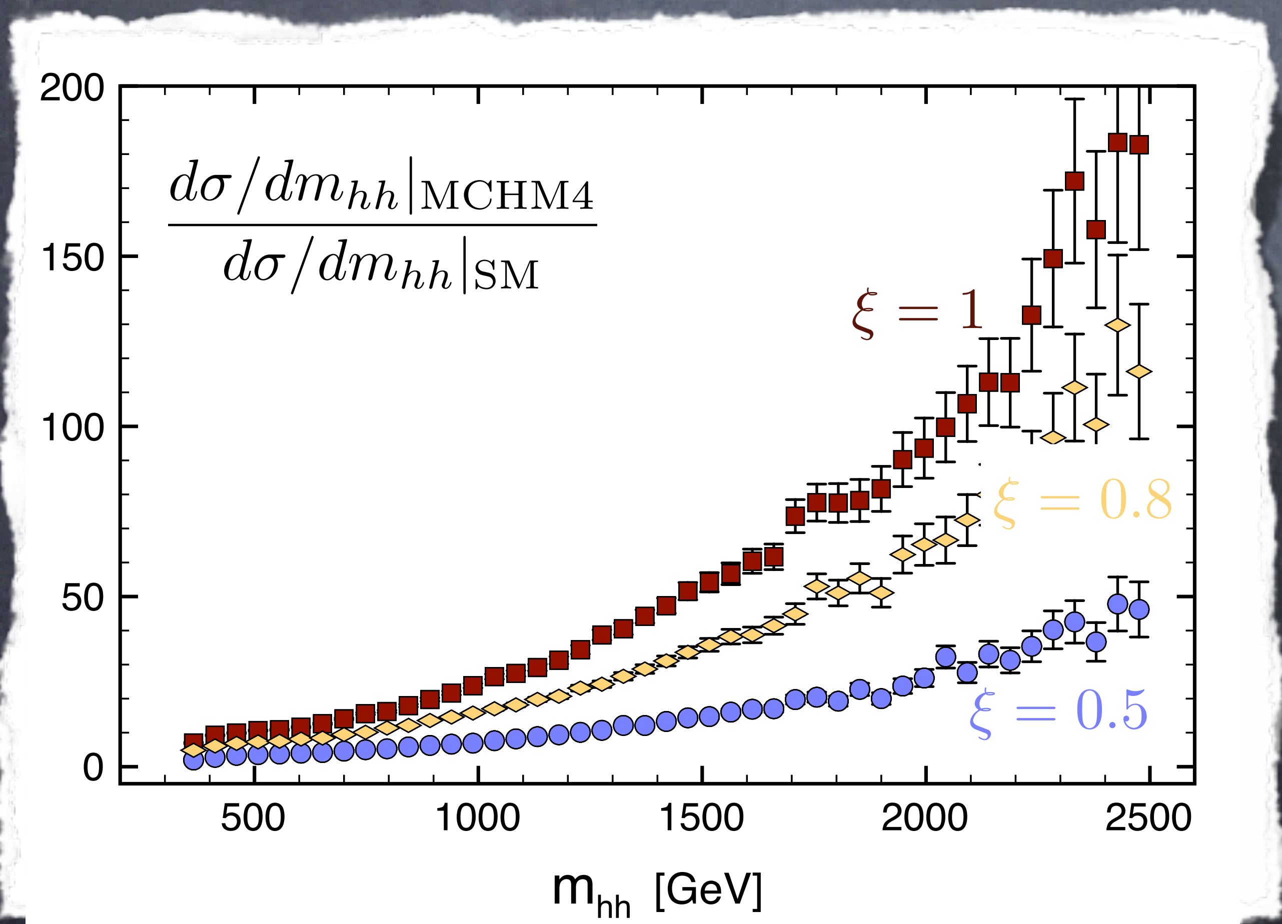
⇚ good motivation to SLHC

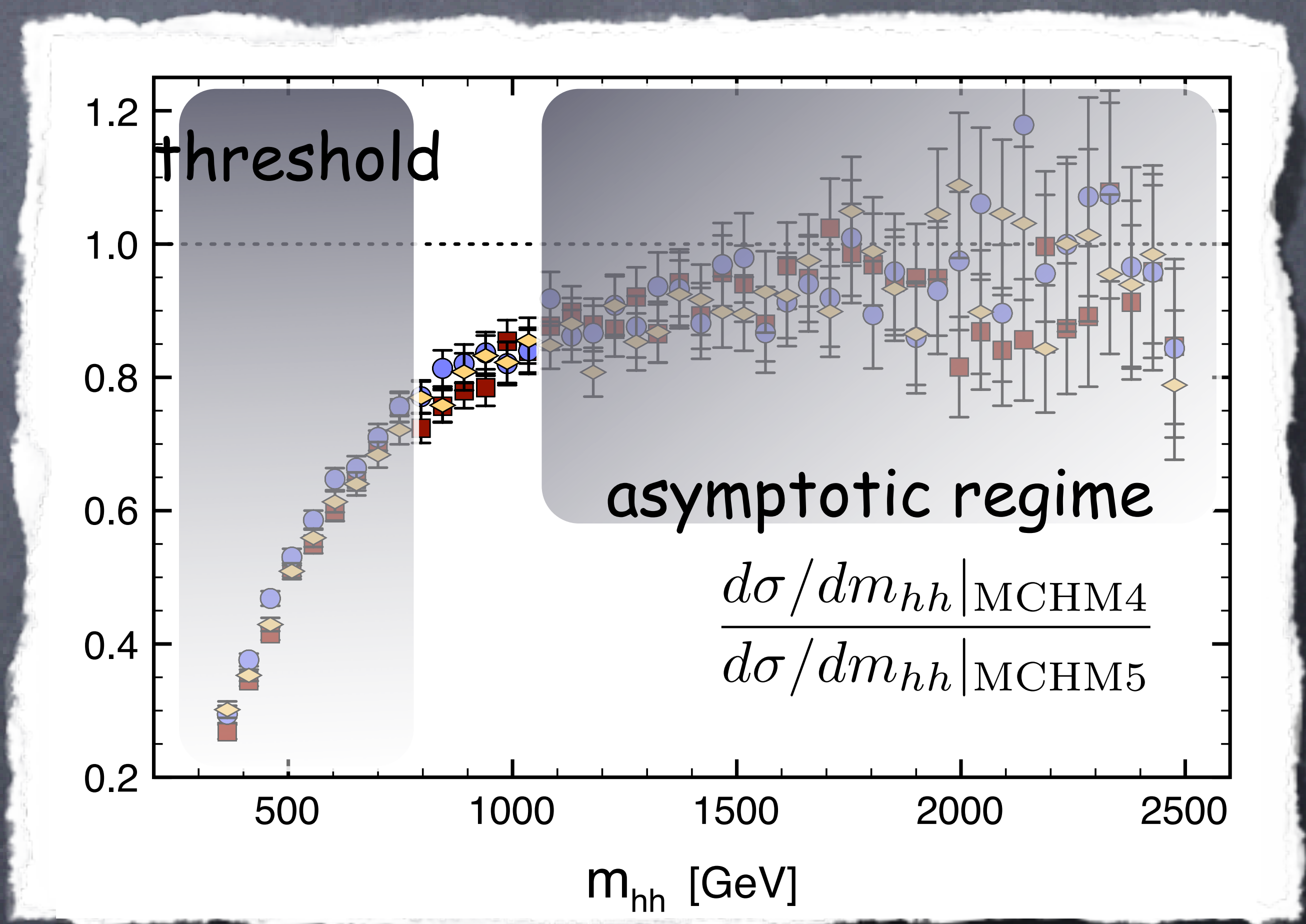
Isolating Hard Scattering

isolate events with large m_{hh}

luminosity factor drops out in ratios: extract the growth with m_{hh}

measure H^3 measure $b-a^2$





Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z

$\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$

EW interactions also need a UV moderator/new physics

to unitarize WW scattering amplitude

We'll need another Gargamelle experiment

to discover the still missing neutral current of the SM: the Higgs

weak NC $\Leftrightarrow$ gauge principle

Higgs NC $\Leftrightarrow$?

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...)

Conclusions