Alternatives to SUSY

SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

Alternatives to SUSY

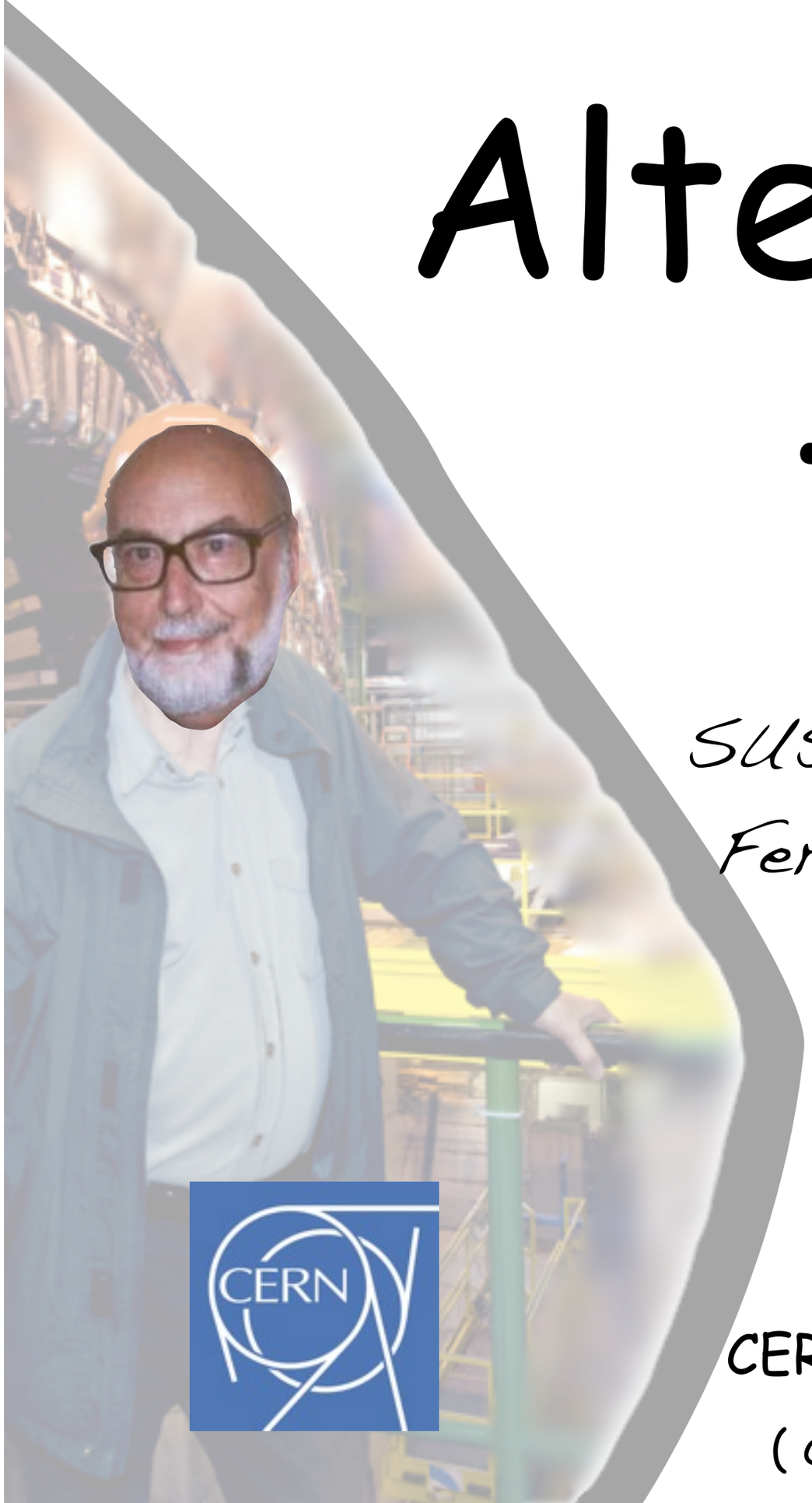
SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)



Alternatives to SUSY

SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

Alternatives to SUSY

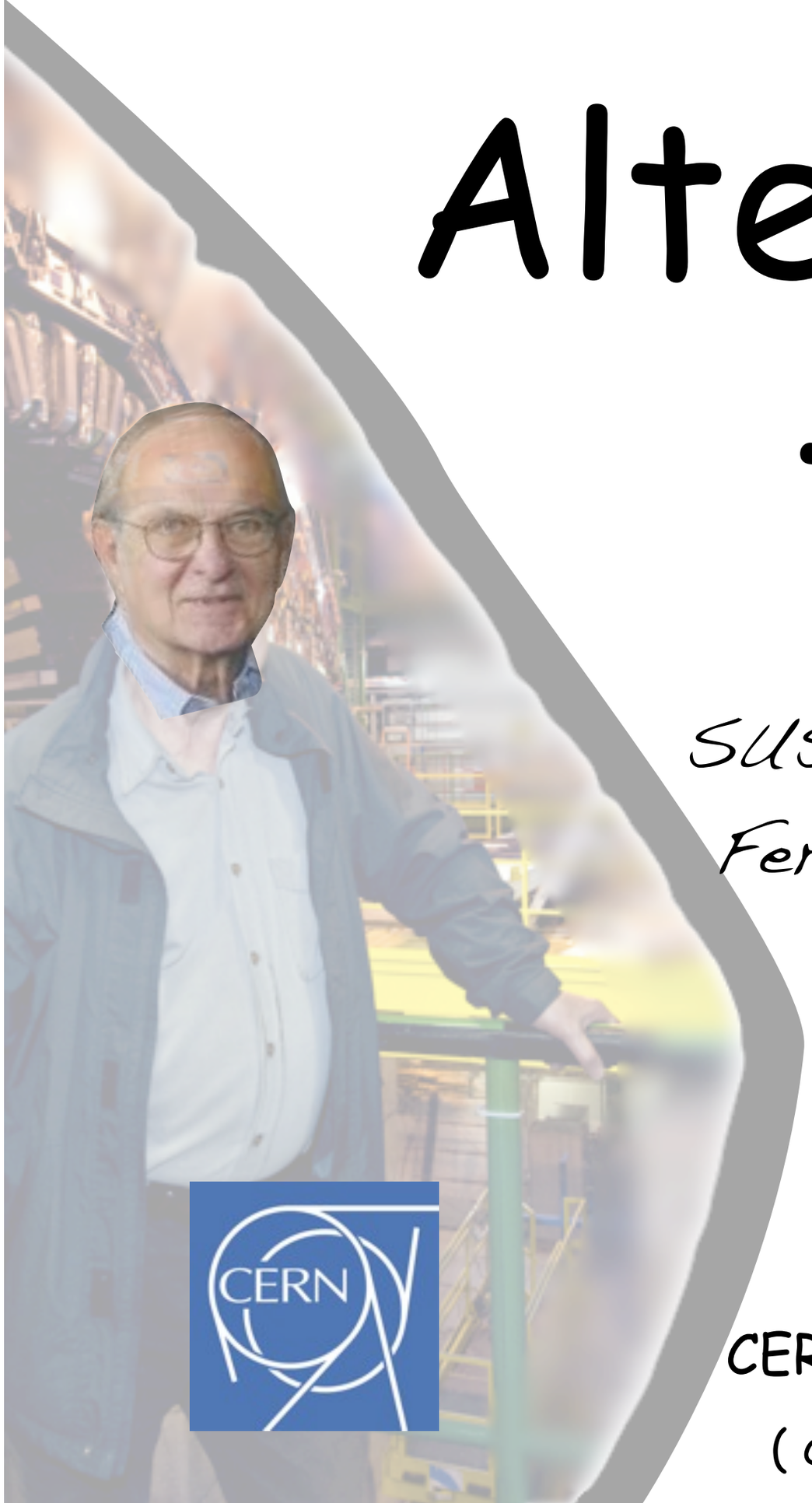
SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)



Alternatives to SUSY

SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

Alternatives to SUSY

SUSY 2011 conference

Fermilab, August 28 - Sept. 2 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

Where are these Goldstone's coming from?

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

Where are these Goldstone's coming from?

- Are they fundamental scalar degrees of freedom?

  $\Rightarrow$ require at least one additional degree of freedom (the Higgs boson!)

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rrightarrow$ UV behavior of these Goldstone's? $\Lleftarrow$

Where are these Goldstone's coming from?

- Are they fundamental scalar degrees of freedom?

  $\Rrightarrow$ require at least one additional degree of freedom (the Higgs boson!)

- Are they composite fields? What are made of then?

  $\Rrightarrow$ require new strong interactions that are likely to produce other bound states

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rrightarrow$ UV behavior of these Goldstone's? $\Lleftarrow$

Where are these Goldstone's coming from?

- Are they fundamental scalar degrees of freedom?

  $\Rrightarrow$ require at least one additional degree of freedom (the Higgs boson!)

- Are they composite fields? What are made of then?

  $\Rrightarrow$ require new strong interactions that are likely to produce other bound states

- Are they components of gauge fields in higher dimensions?

  see e.g. Hosotani's talk yesterday

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rrightarrow$ UV behavior of these Goldstone's? $\Lleftarrow$

Where are these Goldstone's coming from?

- Are they fundamental scalar degrees of freedom?

  $\Rrightarrow$ require at least one additional degree of freedom (the Higgs boson!)

- Are they composite fields? What are made of then?

  $\Rrightarrow$ require new strong interactions that are likely to produce other bound states

- Are they components of gauge fields in higher dimensions?

  see e.g. Hosotani's talk yesterday

At which scale should we expect to see something?

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

Lee, Quigg & Thacker '77

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

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

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

Lee, Quigg & Thacker '77

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

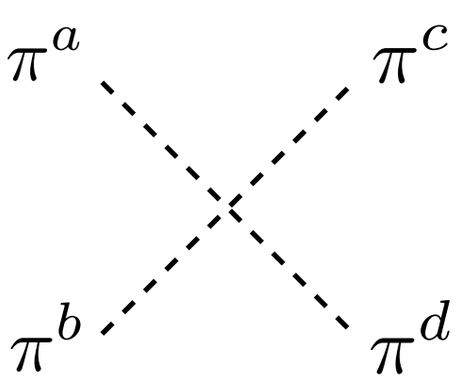
$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



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

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

Lee, Quigg & Thacker '77

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

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

⇛ UV behavior of these Goldstone's? ⇚

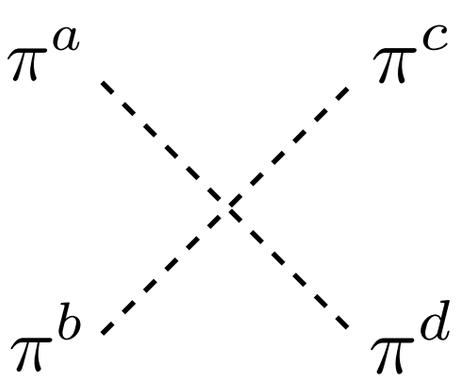
$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

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

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



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

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

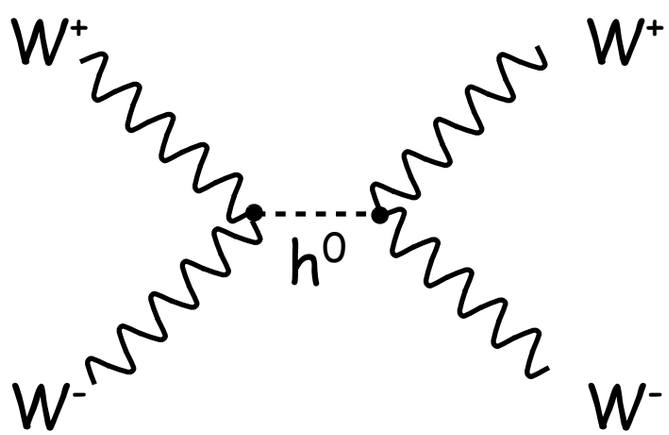
the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

Lee, Quigg & Thacker '77

Weak vs. Strong EWSB

what is unitarizing the WW scattering amplitude?

Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

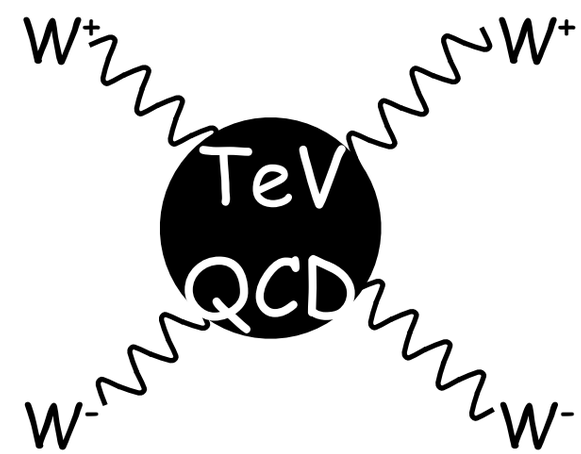
need new particles to stabilize the Higgs mass

bounds on the masses of these particles

$\Downarrow$

fine-tuning O(1%)

Strongly coupled models



prototype: Technicolor

rho meson ~ 1 TeV

resonances needed for unitarization

generate EW oblique corrections

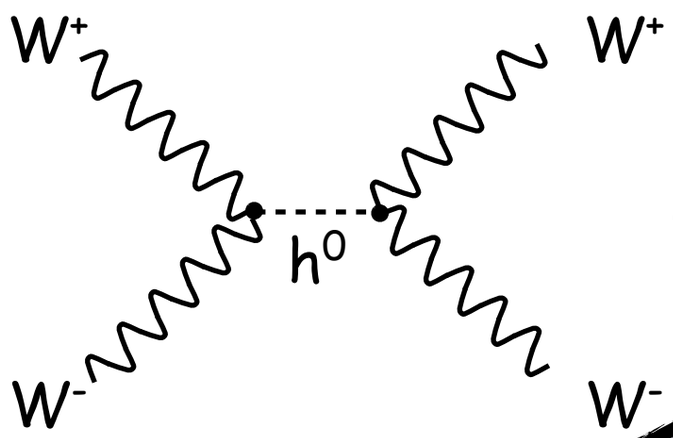
$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \xrightarrow[\text{@95\% CL}]{|\hat{S}| < 10^{-3}} m_\rho > 2.5 \text{ TeV}$$

other ways?

Weak vs. Strong EWSB

what is unitarizing the WW scattering amplitude?

Weakly coupled models



prototype: Susy

susy part[illegible] 100 GeV

Symmetry

need new particles to stabilize the Higgs mass

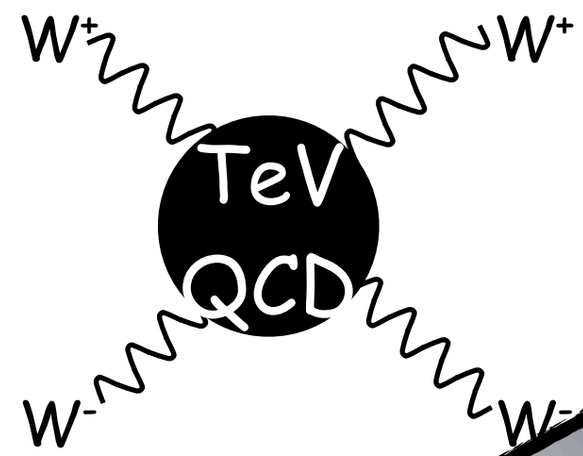
bounds on the masses of these particles

⇓

fine-tuning O(1%)

other ways?

Strongly coupled models



prototype: Technicolor

[illegible] 1 TeV

dynamics

resonances needed for unitarization

generate EW oblique corrections

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

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

3 Goldstone's

Chacko, Batra '08

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

3 Goldstone's

BSM

G/H

$W^{\pm}_L$ & Z_L & h

at least a 4th Goldstone

Chacko, Batra '08

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM: $SO(4)/SO(3)$ → BSM: G/H

$W^{\pm}_L$ & Z_L → $W^{\pm}_L$ & Z_L & h

3 Goldstone's → at least a 4th Goldstone

Examples:

$SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ← Next MCHM

Gripaios, Pomarol, Riva, Serra '09

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

Chacko, Batra '08

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ← Minimal Composite Two Higgs Doublets

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

How to probe the composite nature of the Higgs?

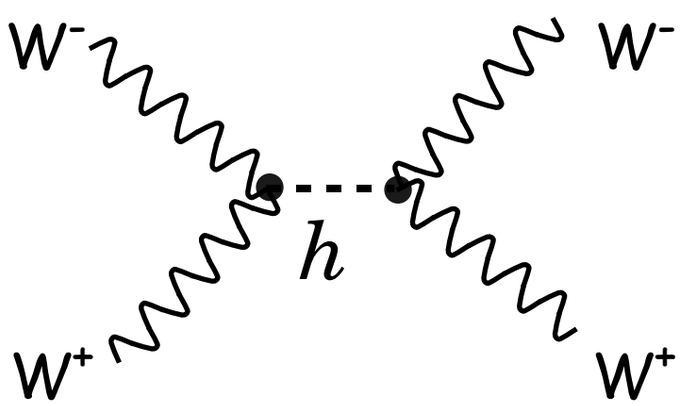
1. Anomalous couplings

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_L$

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

'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

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_L$

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

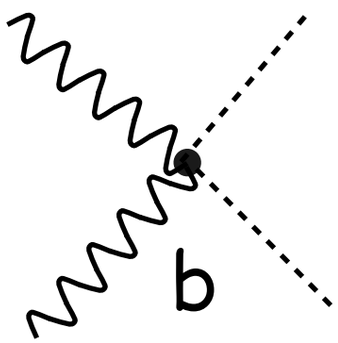
'a', 'b' and 'c' are arbitrary free couplings

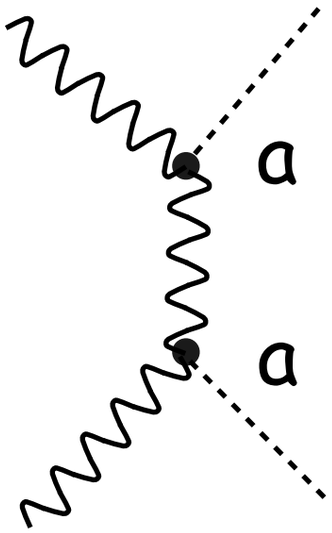
For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10





What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_L$

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

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

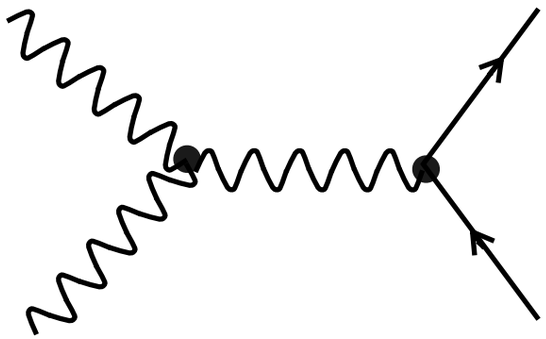
For a=1: perturbative unitarity in elastic channels $WW \to WW$

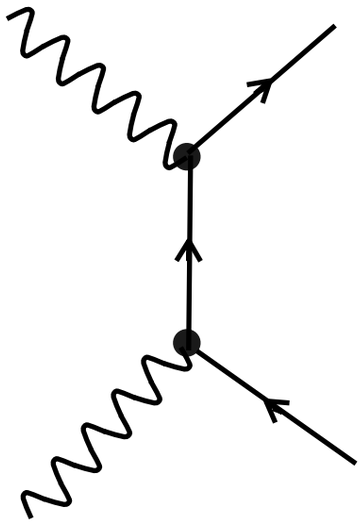
For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

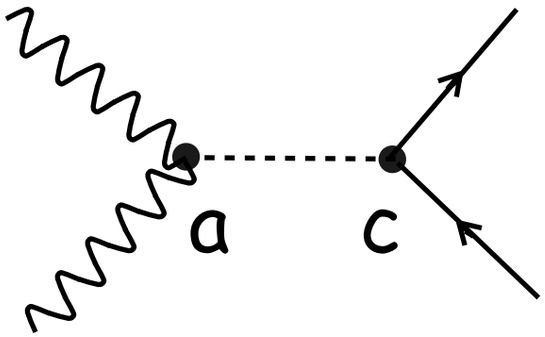
For ac=1: perturbative unitarity in inelastic $WW \to \psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10







What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_L$

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

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

For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

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

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

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\rm EWSB}$ 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 a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet that acquires a vev

$SU(2)_L \times U(1)_Y$ linearly realized $\Leftrightarrow$ Standard Model $\Leftrightarrow$ a=b=c=1

renormalizable level = uniqueness

What is a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet that acquires a vev

$SU(2)_L \times U(1)_Y$ linearly realized $\Leftrightarrow$ Standard Model $\Leftrightarrow$ a=b=c=1

renormalizable level = uniqueness

non-renormalizable level

$SU(2)_L \times U(1)_Y$ linearly realized & a, b, c ≠ 1 $\Leftrightarrow$ Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

$$\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}$$

Anomalous composite-Higgs couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

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

a = 1-ξ/2 b = 1-2ξ c = 1-ξ/2

PGB Higgs: Strong EWSB with 2 Scales

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

$\xi = 0$

SM limit

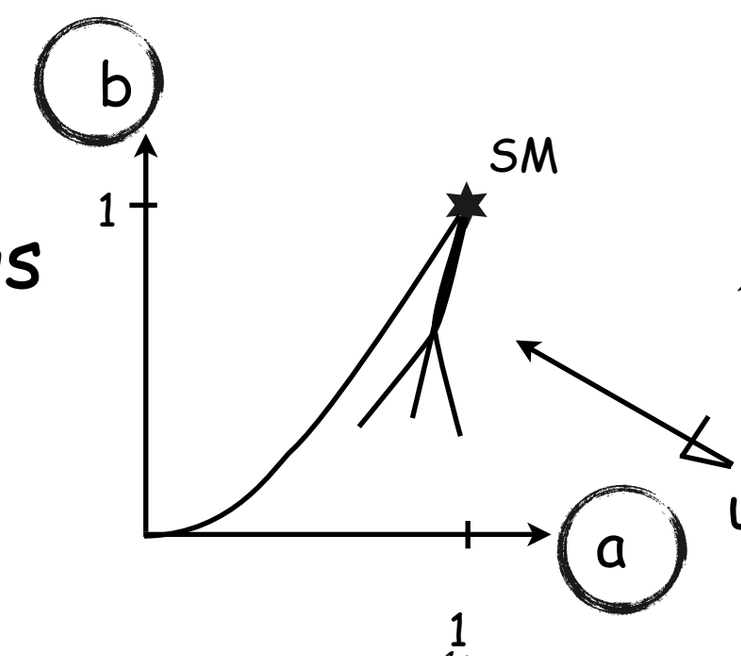
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs
vs.
SM Higgs



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

Composite Higgs
universal behavior for large f
$a=1-v^2/2f^2$ $b=1-2v^2/f^2$

PGB Higgs: Strong EWSB with 2 Scales

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

$\xi = 0$

SM limit

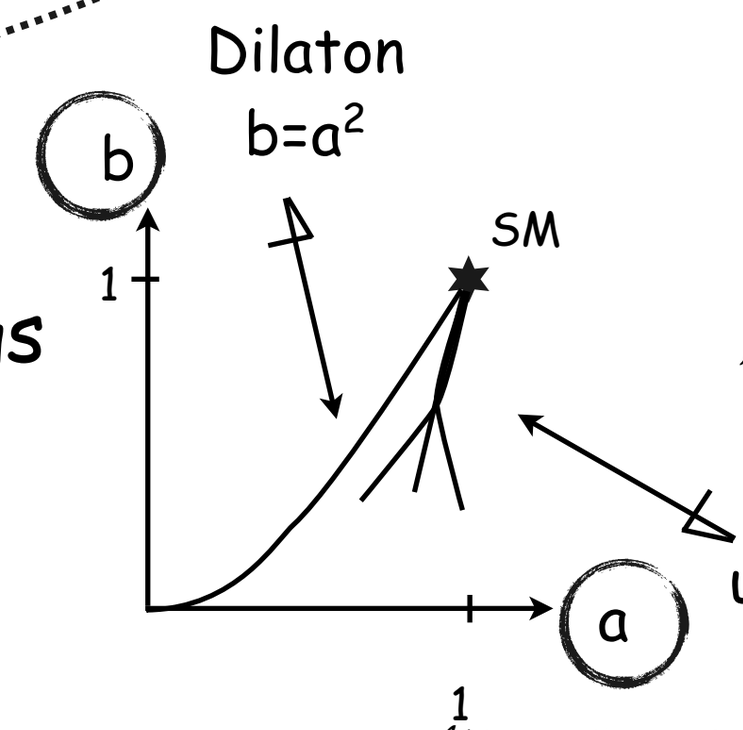
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs
vs.
Dilaton Higgs



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

Composite Higgs
universal behavior for large f
$a=1-v^2/2f^2$ $b=1-2v^2/f^2$

Composite Higgs vs generic anomalous couplings

generic anomalous couplings can be quite complicated, e.g.

$$\mathcal{L}_{h-Z} = m_Z h \left(c_1 Z_\mu Z^\mu + \frac{c_2}{m^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{c_3}{m^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

...many coefficients, various possible origins

Composite Higgs vs generic anomalous couplings

generic anomalous couplings can be quite complicated, e.g.

$$\mathcal{L}_{h-Z} = m_Z h \left(c_1 Z_\mu Z^\mu + \frac{c_2}{m^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{c_3}{m^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

...many coefficients, various possible origins

if Higgs emerges as a bound state of strongly interacting theory

a few coefficients only and related to symmetries of the coset space

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

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

custodial breaking

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

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

(other resonances etc give subleading contributions)

very predictive models:

given the coset space, the Higgs couplings depend only on ξ

Effective Lagrangian

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)

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

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

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

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

Goldstone sym.

Deformation of the SM Higgs: current constraints

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

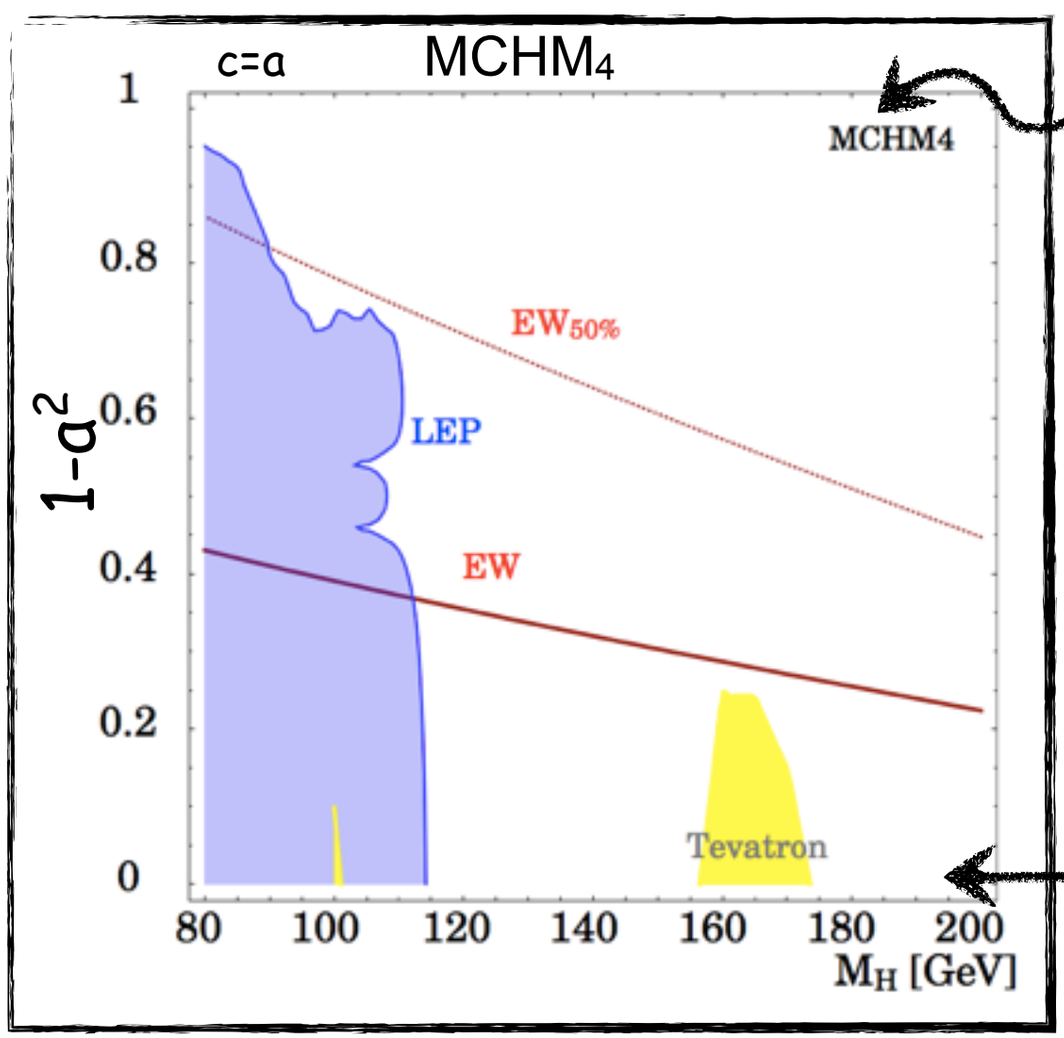
$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

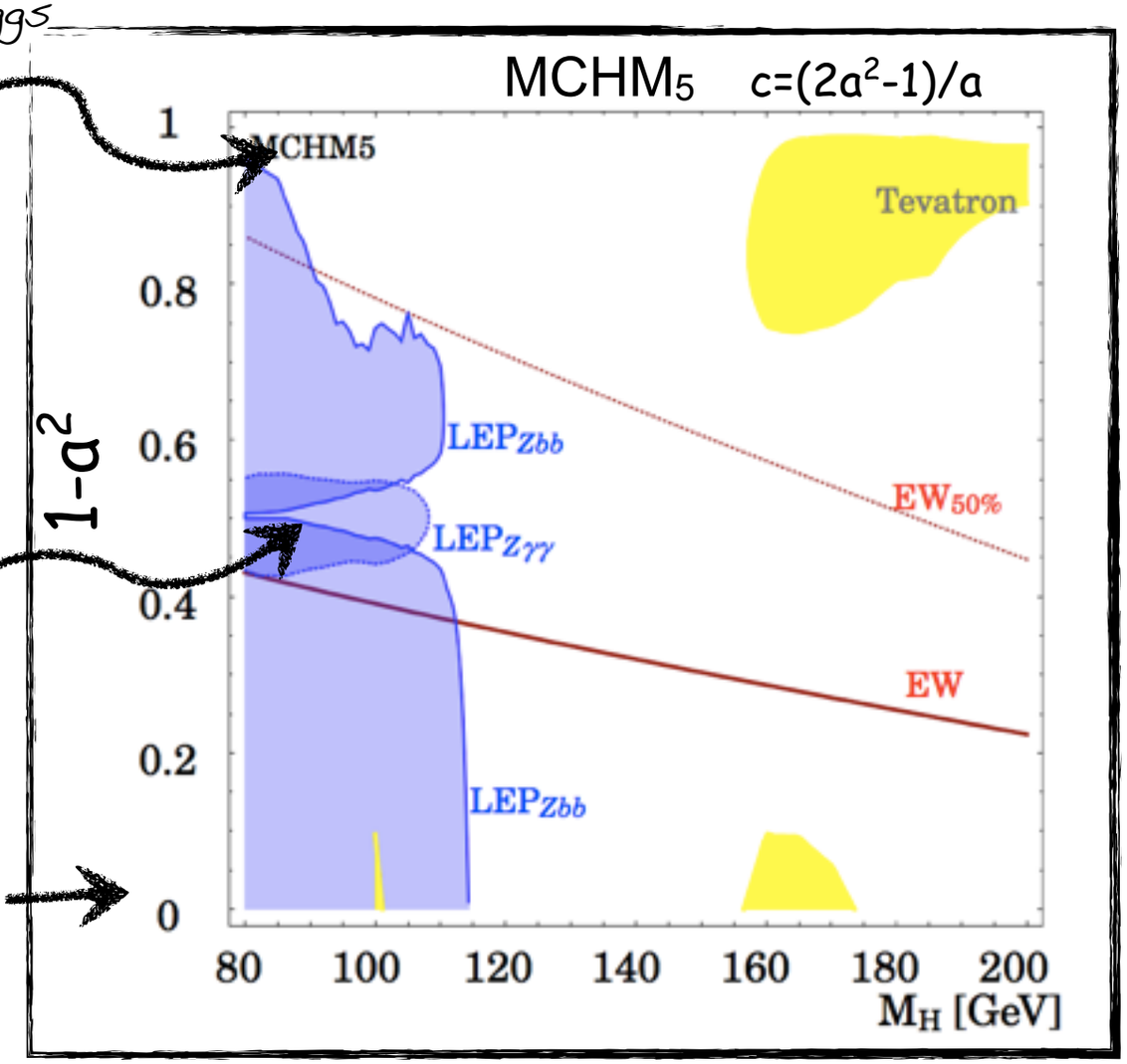
SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a' (and marginally 'c')

Espinosa, Grojean, Muehlleitner '10

gaugephobic Higgs

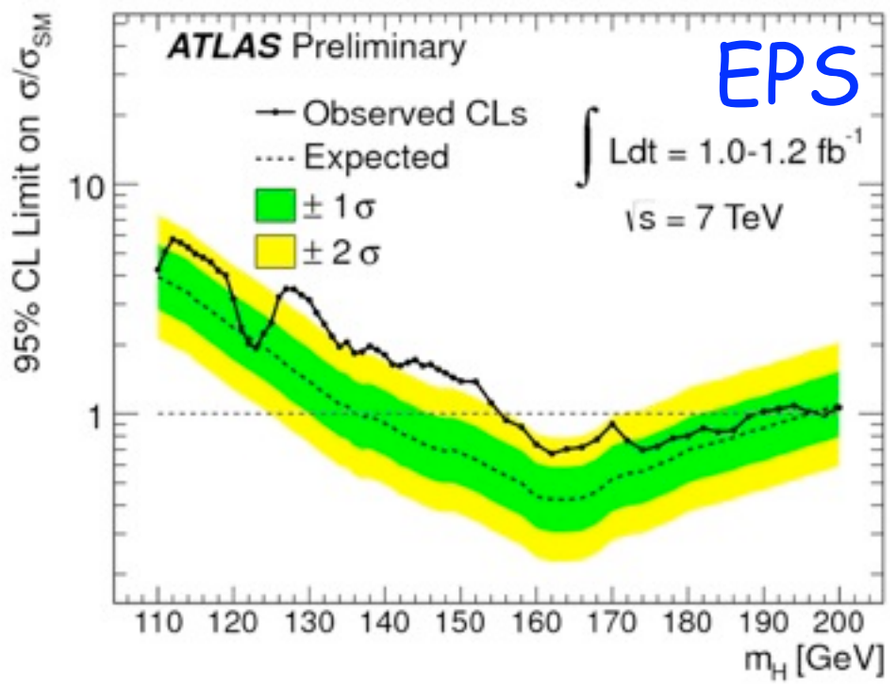


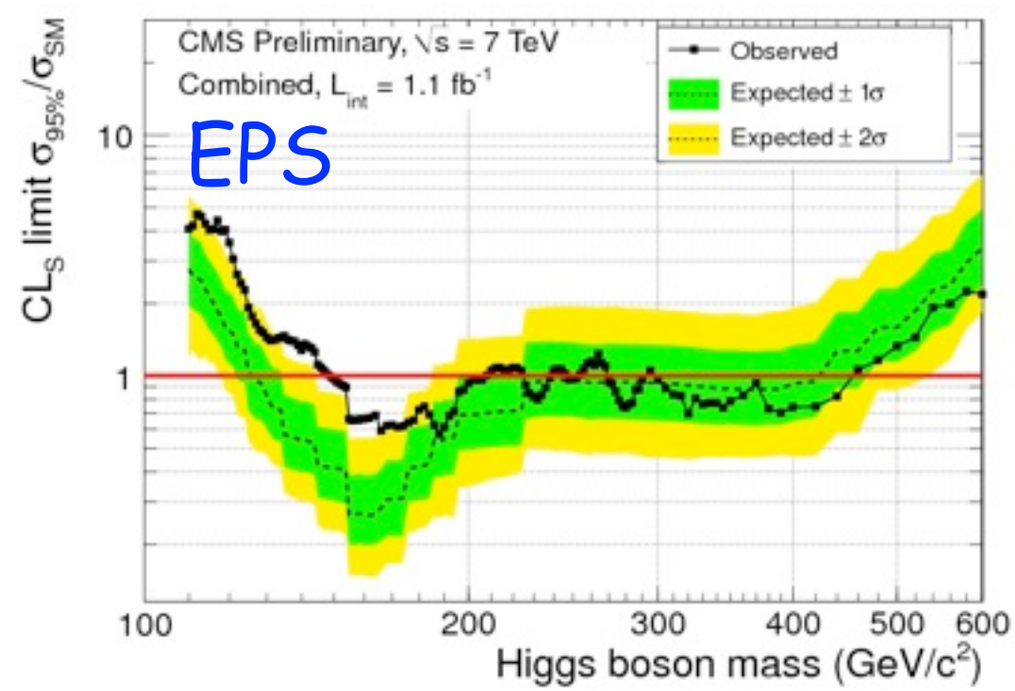


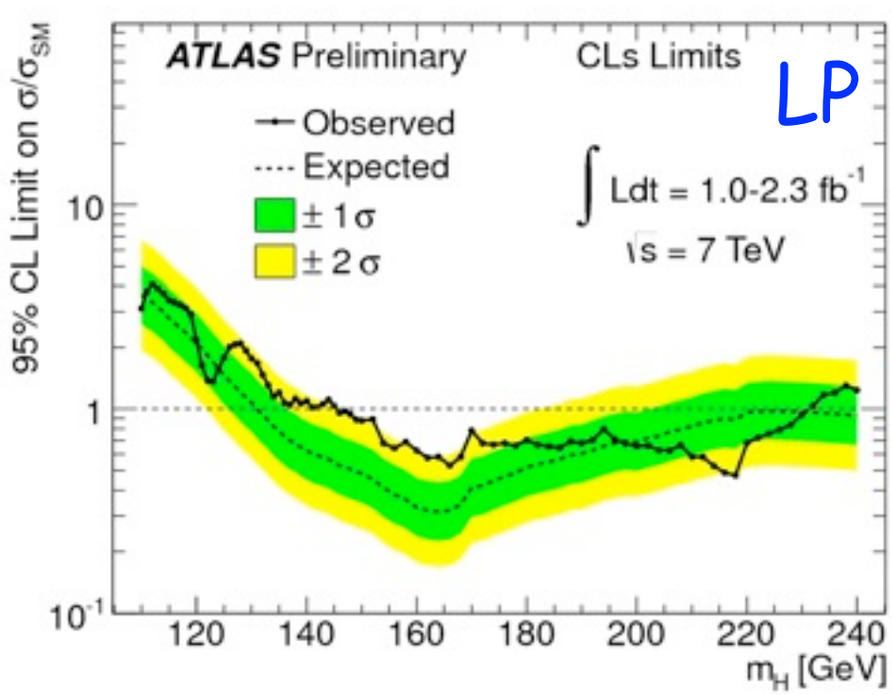
fermiophobic Higgs

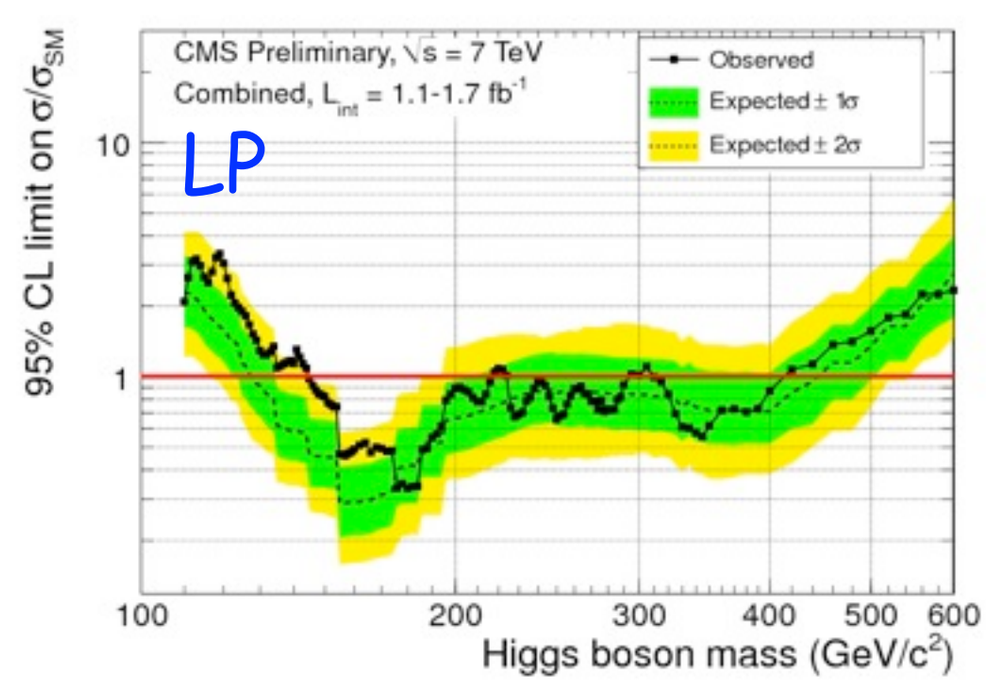
SM limits

Deformation of the SM Higgs: LHC constraints



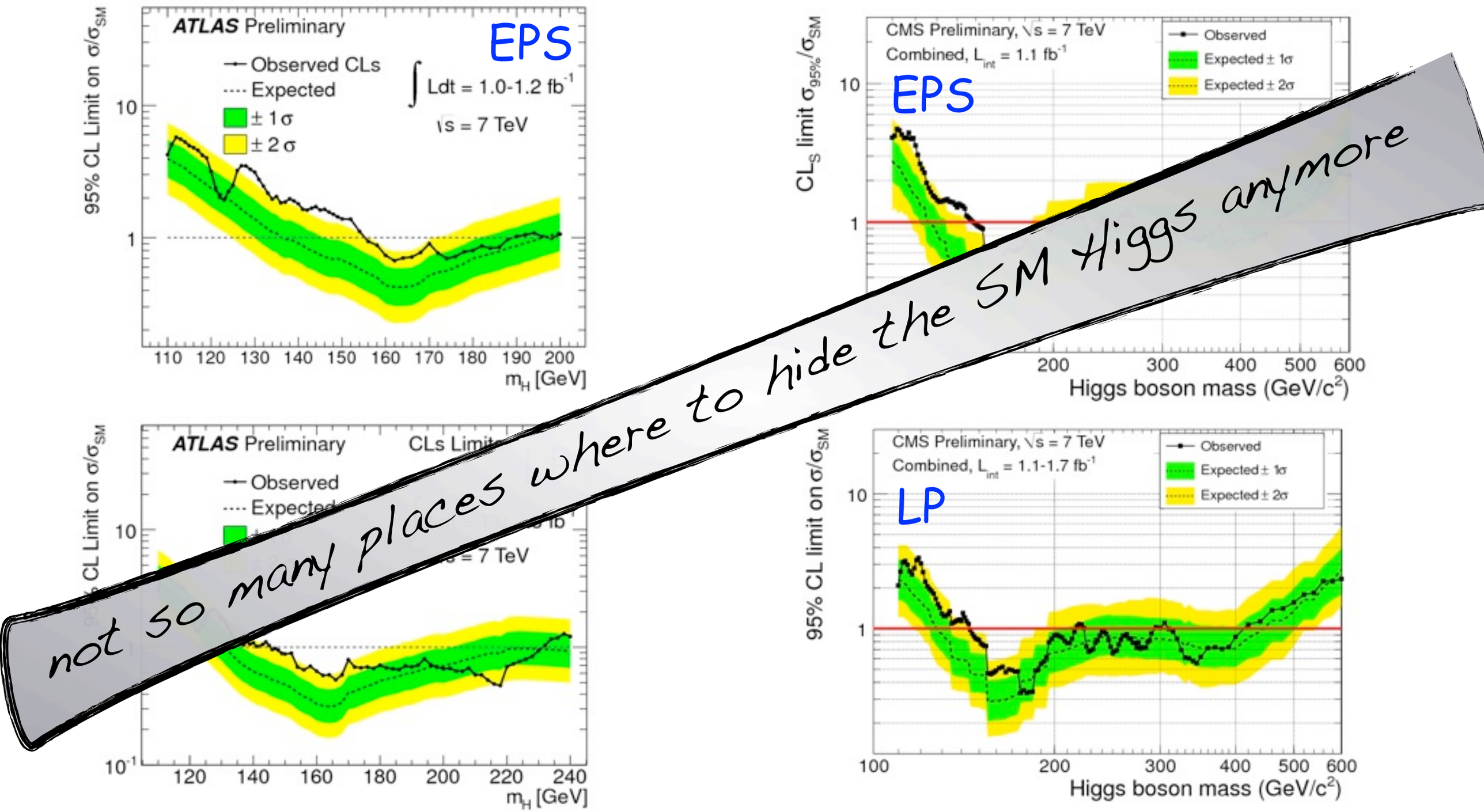






LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

Deformation of the SM Higgs: LHC constraints

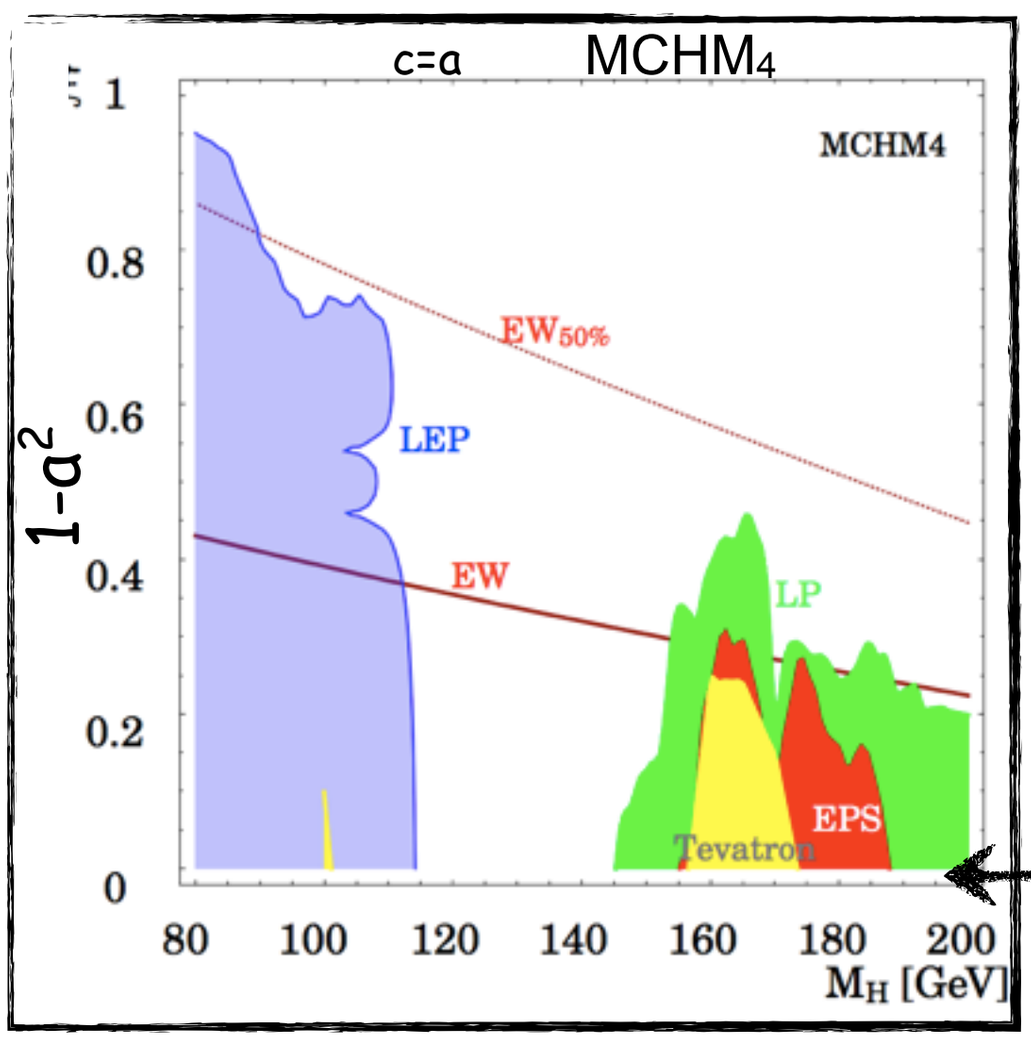


LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

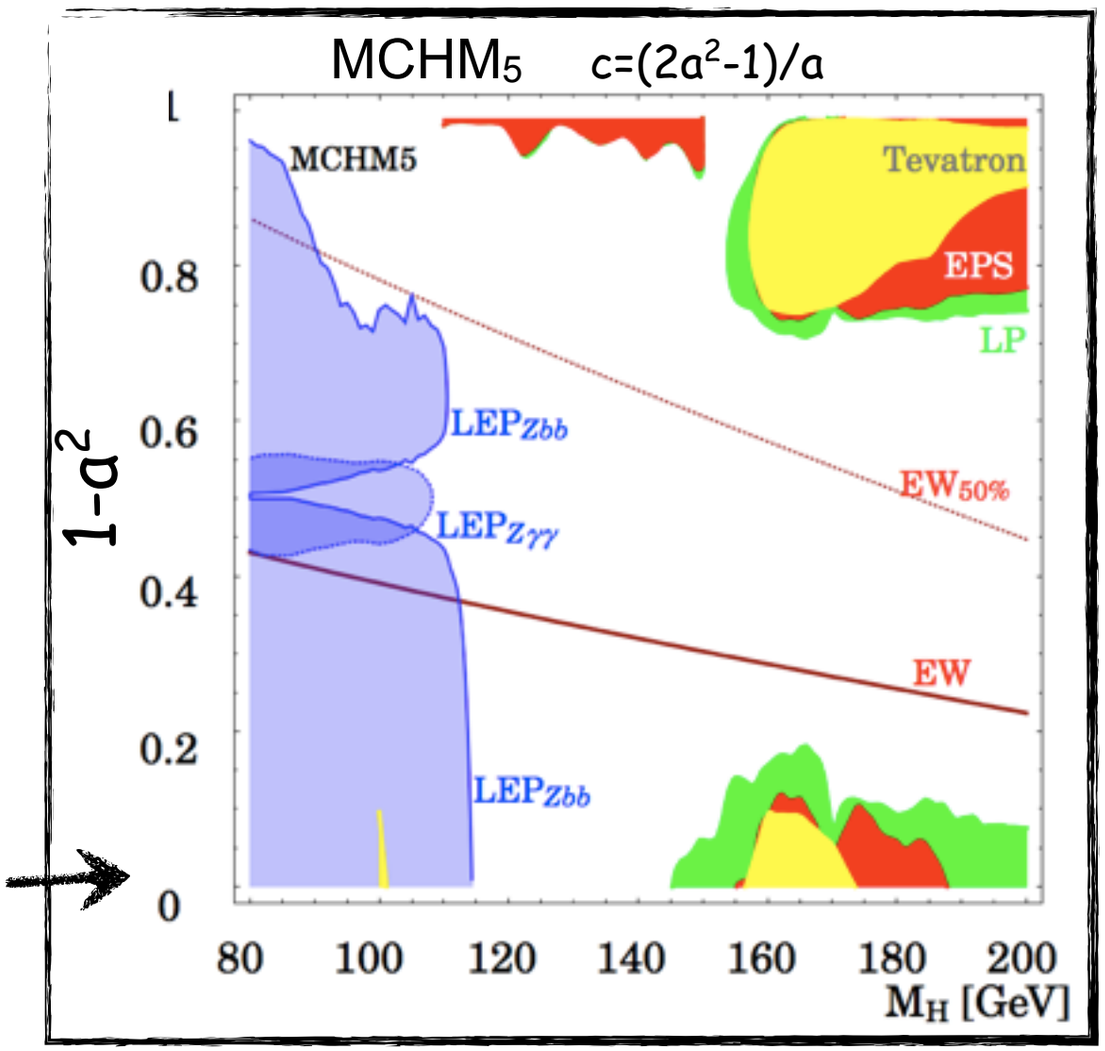
Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



SM limits

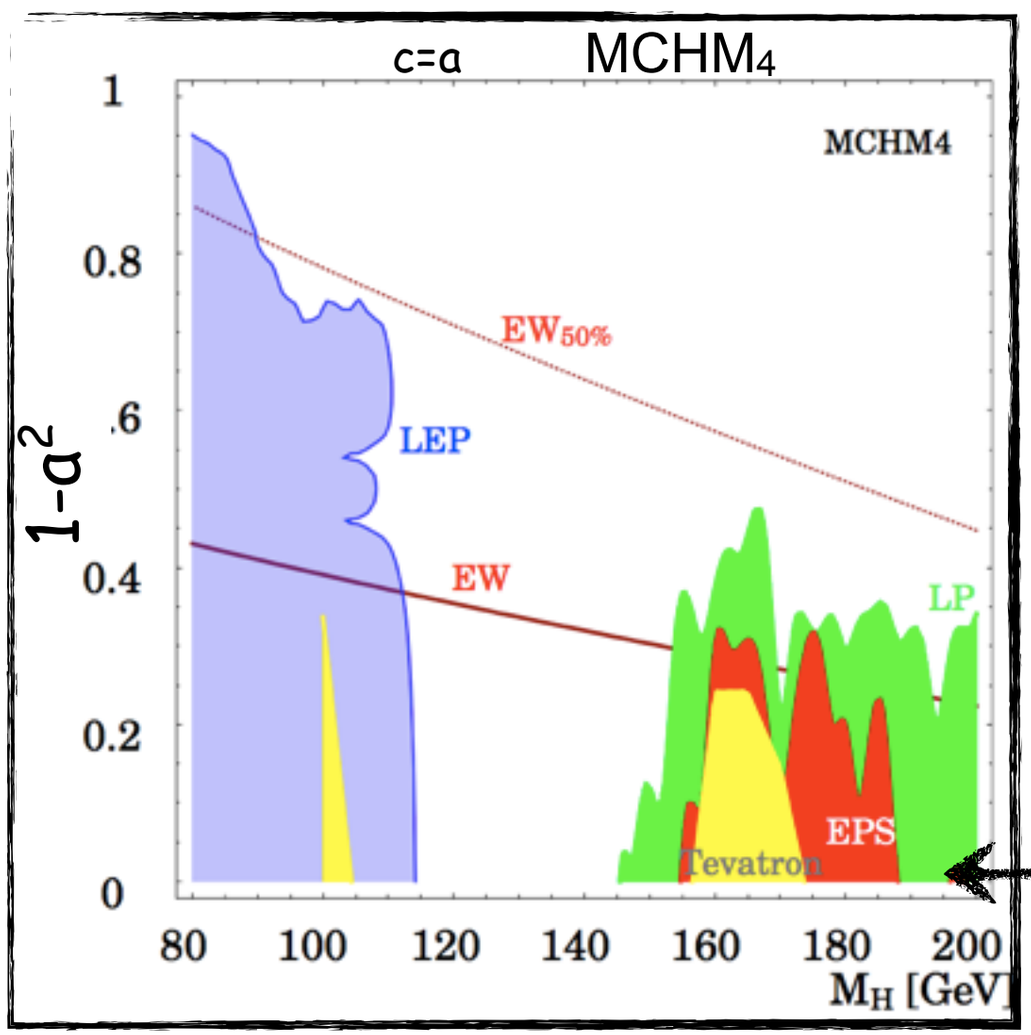


LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

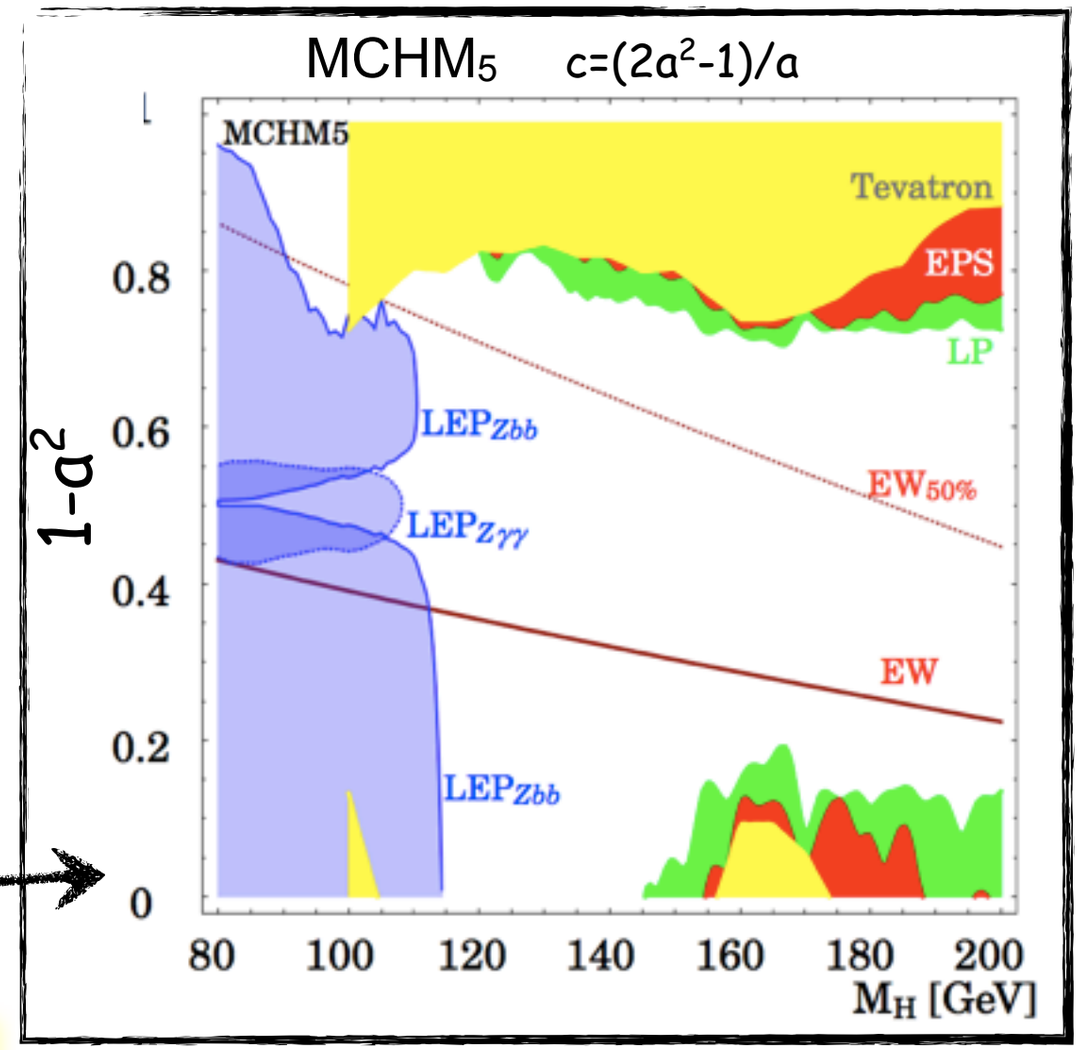
Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



SM limits



Be careful

- rescaling combination ≠ combination of the rescaled channels
  (can be particularly important far away from SM)
- effeciency of the cuts may also depends on ξ

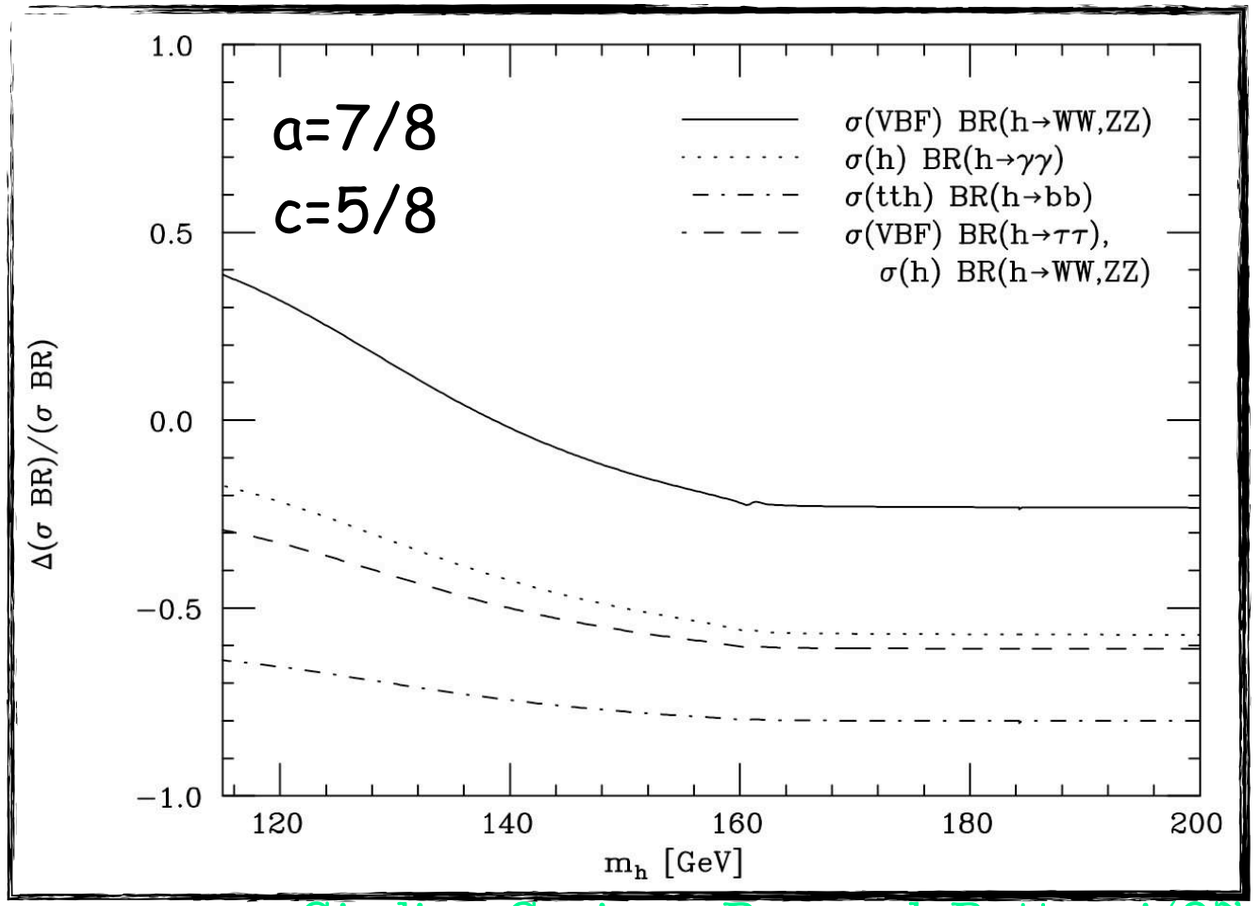
Higgs anomalous couplings @ LHC

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+b_3\frac{h^3}{v^3}+\ldots\right)-\lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}+c_2\frac{h^2}{v^2}+\ldots\right)$$

$$a=\sqrt{1-\xi} \qquad b=1-2\xi \qquad b_3=-\frac{4}{3}\xi\sqrt{1-\xi} \qquad c=\left(\sqrt{1-\xi},\frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2=-(\xi,4\xi)$$

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

$$\Gamma(h\to f\bar{f}) = (2c-1)\,\Gamma(h\to f\bar{f})_{\rm SM} \quad \Gamma(h\to ZZ) = (2a-1)\,\Gamma(h\to ZZ)_{\rm SM}$$



Giudice, Grojean, Pomarol, Rattazzi '07

LHC can probe

Δa & Δc
up to ~ 0.1÷0.2
i.e. $4\pi f$ ~ 5÷7 TeV

compositeness scale of the Higgs

(ILC/CLIC could go to few %, ie, test composite Higgs up to $4\pi f$ ~ 30/60 TeV)

How to probe the composite nature of the Higgs?

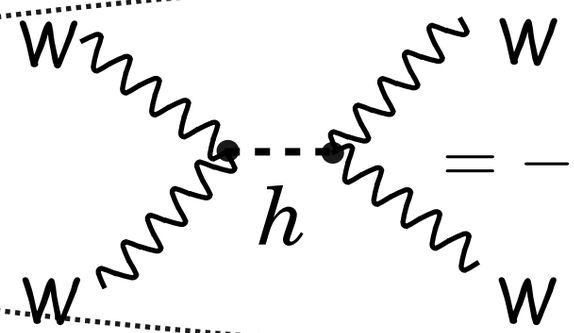
2. Strong scattering

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

- strong WW scattering



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

no exact cancellation of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \underbrace{\left(1-a^2\right)\frac{s}{v^2}}_{\frac{s}{f^2}}$$

large $\mathcal{L}_{int}$ needed

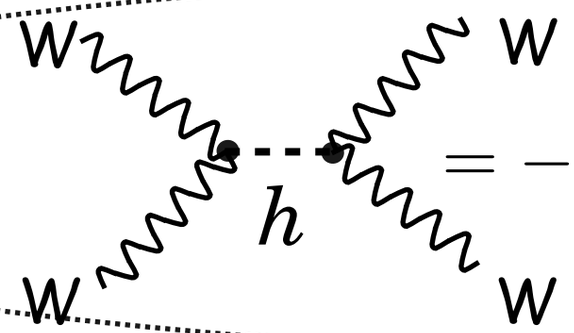
not competitive with the measurement of 'a' via anomalous couplings

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

strong WW scattering



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

no exact cancellation of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \underbrace{\left(1-a^2\right)\frac{s}{v^2}}_{\frac{s}{f^2}}$$

large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

strong double Higgs production

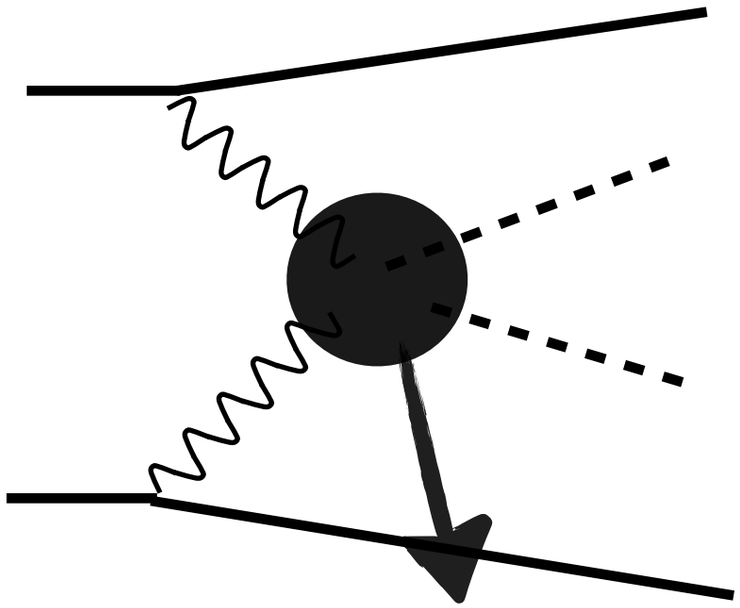
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

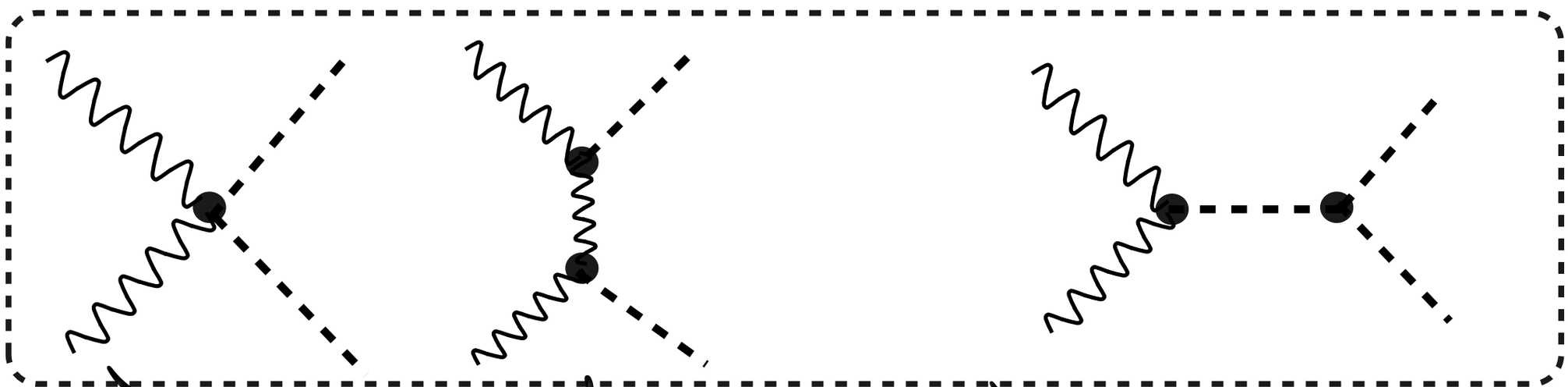
Double Higgs production: 'b' and 'd_3' couplings



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

$$V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

SM: $a=b=d_3=d_4=1$



$$\underset{m_{hh}^2 \gg m_W^2}{\mathcal{A} \sim} \left(b-a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\underset{m_{hh}^2 \sim 4m_h^2}{\mathcal{A} \sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

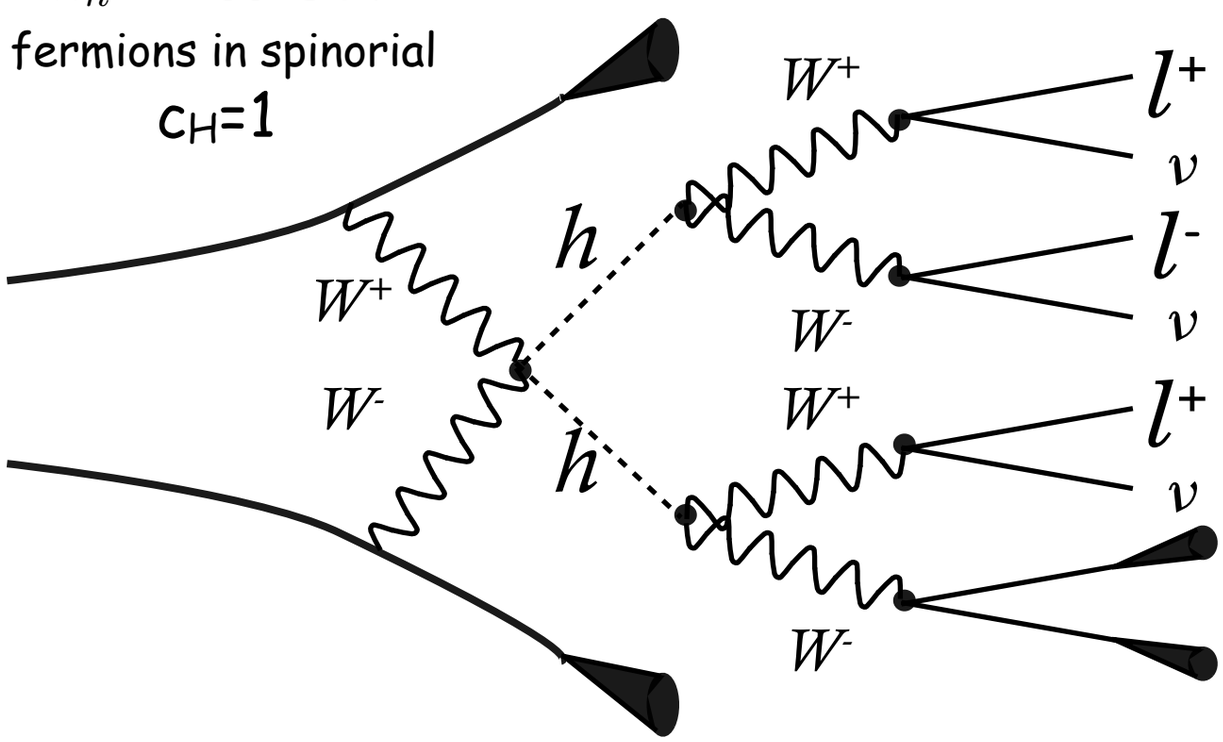
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ 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, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

forward jet-tag, back-to-back lepton, central jet-veto

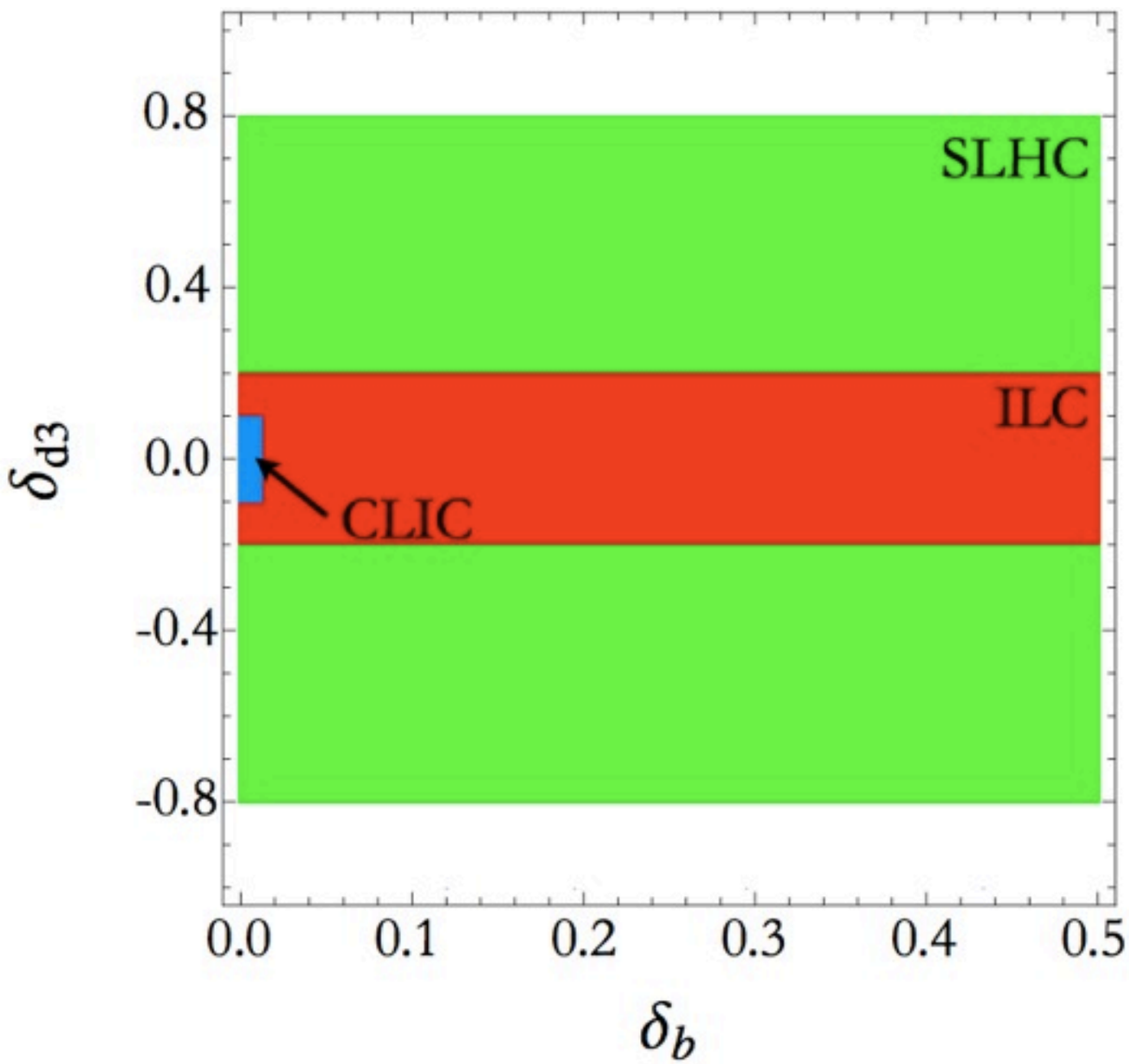
v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

⇐ good motivation to SLHC

Measuring the non-linearities of the Higgs

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) \qquad V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3$$



- (S)LHC is barely sensitive to d_3 and b
- ILC has a sensitivity on d_3 but not on b
- CLIC can probe both d_3 and b

How to probe the composite nature of the Higgs?

3. Identifying discrete symmetries of strong sector

Geometry of Coset from $W^+W^- \to 3h$

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Strong EWSB

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{E^2}{f^4}\frac{E^2}{(4\pi f)^2}$$

$$E/f \leftrightarrow g$$

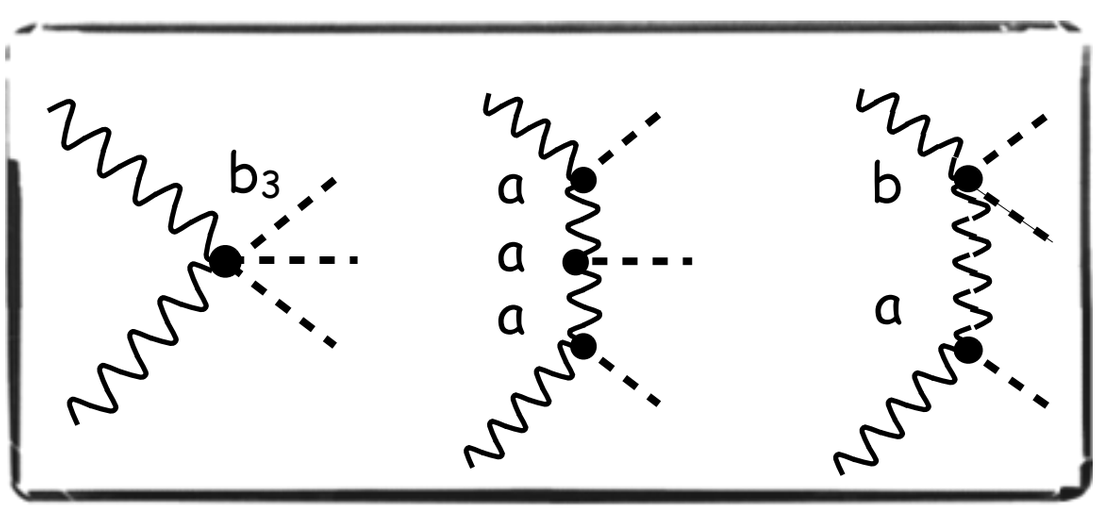
SM

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

a process with an odd # of PGBs
requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone

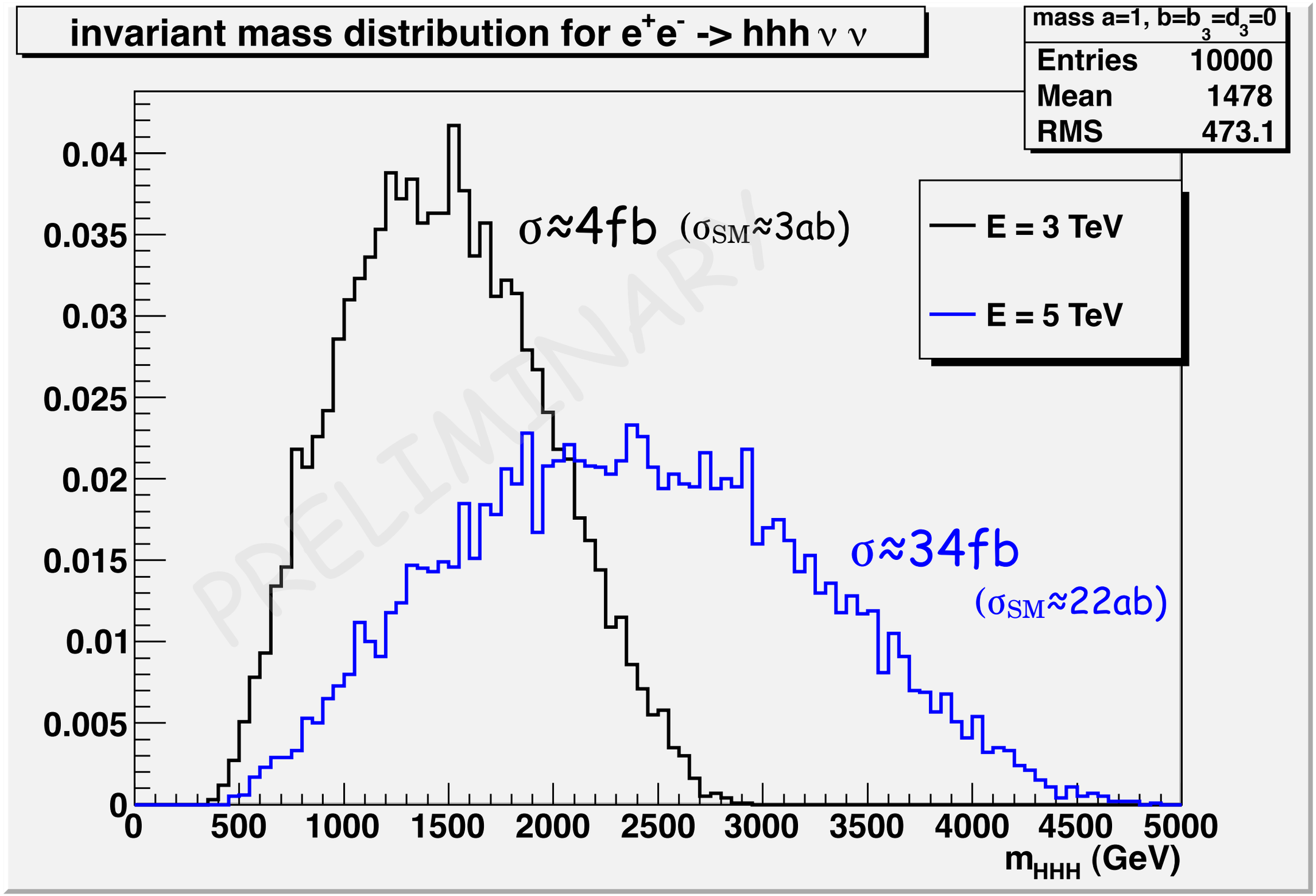


$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\left(\underbrace{a(b-a^2)-\frac{3}{4}b_3}_{\text{=0 for symmetric coset}}\right) + \sharp\, s \times \underbrace{\left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

$W^+W^- \to 3h$ @ CLIC

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

non-symmetric coset



How to probe the composite nature of the Higgs?

4. Detecting heavy resonances

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

elementary spin-1

$g=2 \Leftrightarrow \Lambda \gg M/e \Leftrightarrow W' \to W\gamma$ highly suppressed

gyromagnetic ratio of any elementary particle of mass M coupled to photon must be g=2 at tree-level to maintain perturbative unitarity up to energy $\Lambda \gg M/e$

Ferrara, Porrati, Telegdi '92

$(g-1)B^{\mu\nu}W'^{+}_{\mu}W'^{-}_{\nu}$ dimension-4 operator mediating $W' \to W\gamma$ after W-W' mixing

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

elementary spin-1

$g=2 \;\Leftrightarrow\; \Lambda \gg M/e \;\Leftrightarrow\;$ W'→Wγ highly suppressed

gyromagnetic ratio of any elementary particle of mass M coupled to photon must be g=2 at tree-level to maintain perturbative unitarity up to energy $\Lambda \gg M/e$

Ferrara, Porrati, Telegdi '92

composite spin-1

$g\neq 2 \;\;\&\;\; \Lambda > 5\div 10\, M \;\Leftrightarrow\;$ W'→Wγ allowed and potentially large

$(g-1)B^{\mu\nu}W'^{+}_{\mu}W'^{-}_{\nu}$ dimension-4 operator mediating W' →Wγ after W-W' mixing

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

We'll need another Gargamelle experiment
to discover the still missing neutral current of the SM: the Higgs

weak NC ⇔ gauge principle

Higgs NC ⇔ ?

Strong EWSB w/o an elementary Higgs can be very similar to SM
it might take some time to decipher the true dynamics of EWSB!

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

An Emergency Tire Even Beyond the SM

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]