Alternative Higgs Physics

IRFU-SPP Seminar

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Christophe Grojean

CERN-TH

(christophe.grojean@cern.ch)

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 discover the Higgs boson*”

- ≈9000 papers in Spires contain “Higgs” in their title
- ≈3x10^6 references in google (≈1% of M. Jackson)
- ... 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

Electroweak Symmetry Breaking

symmetry breaking: new phase with more degrees of freedom

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

⇛ UV physics of these Goldstone's? ⇚

Where are these Goldstone's coming from?

- Are they fundamental scalar degrees of freedom?
  - ⇛ require at least one additional degree of freedom (the Higgs boson!)
- Are they composite fields? What are made of then?
  - ⇛ require new strong interactions that are likely to produce other bound states
- Are they components of gauge fields in higher dimensions?
  - ⇛ require new space dimensions

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

⇛ UV behavior of these Goldstone's? ⇚

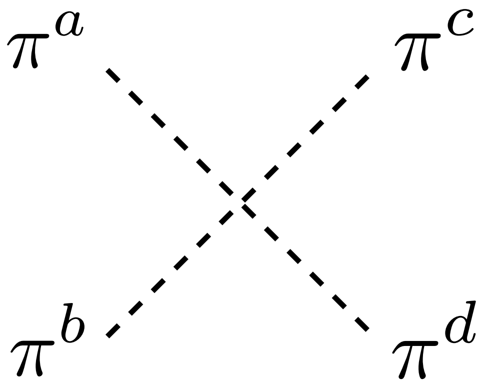
$$\Sigma = e^{i\sigma^a\pi^a/v}$$

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

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

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

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 4πv (≈1÷3TeV)

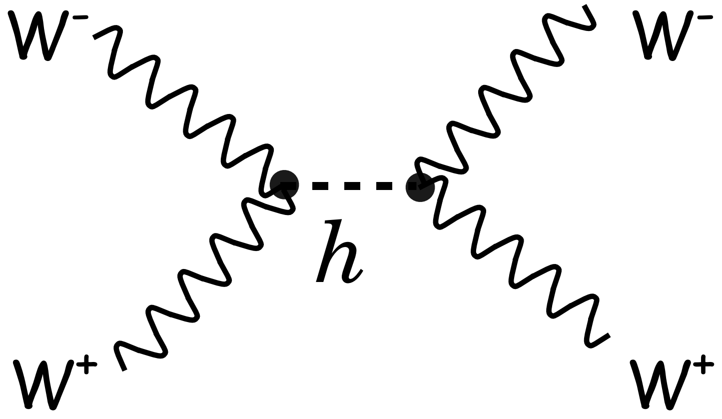
Lee, Quigg & Thacker '77

What is the SM Higgs?

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

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

'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

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

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

Cornwall, Levin, Tiktopoulos '73

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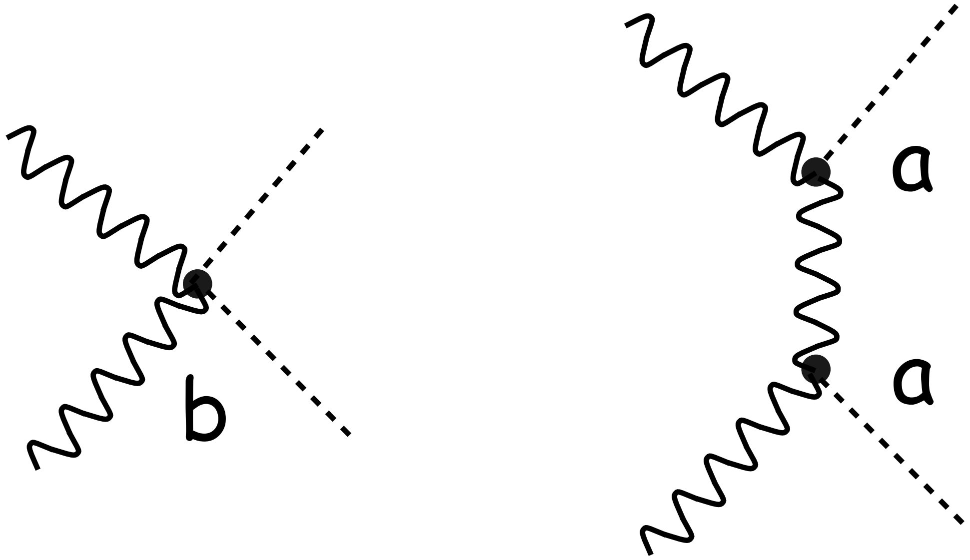

What is the SM Higgs?

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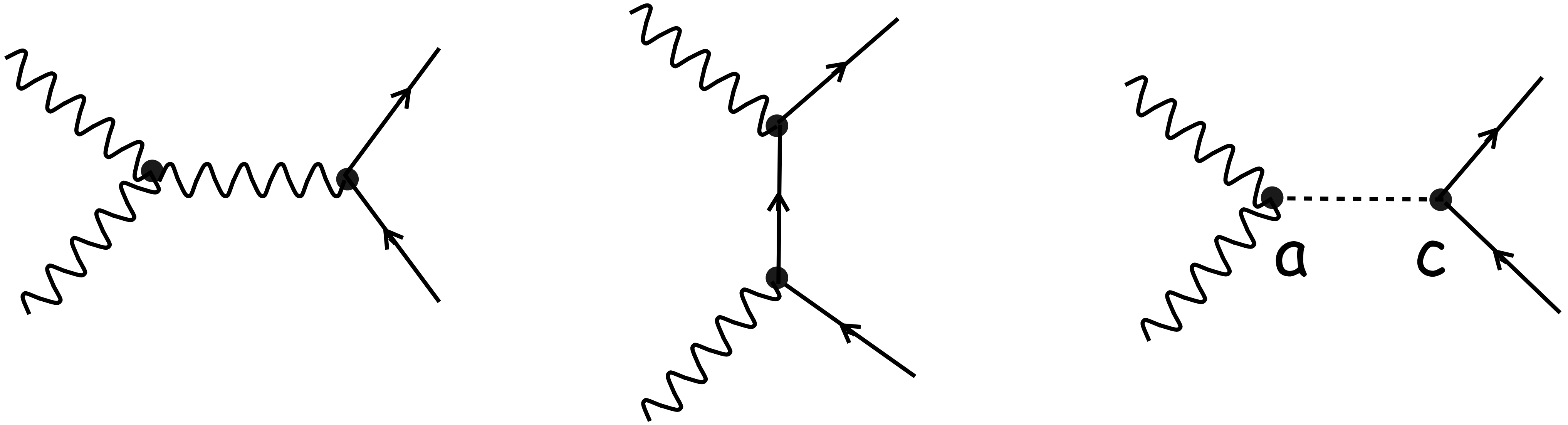

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For ac=1: perturbative unitarity in inelastic WW → $\psi\,\psi$

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

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\text{EWSB}}$ 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 andZ_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

renormalizable level = uniqueness

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

non-renormalizable level

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

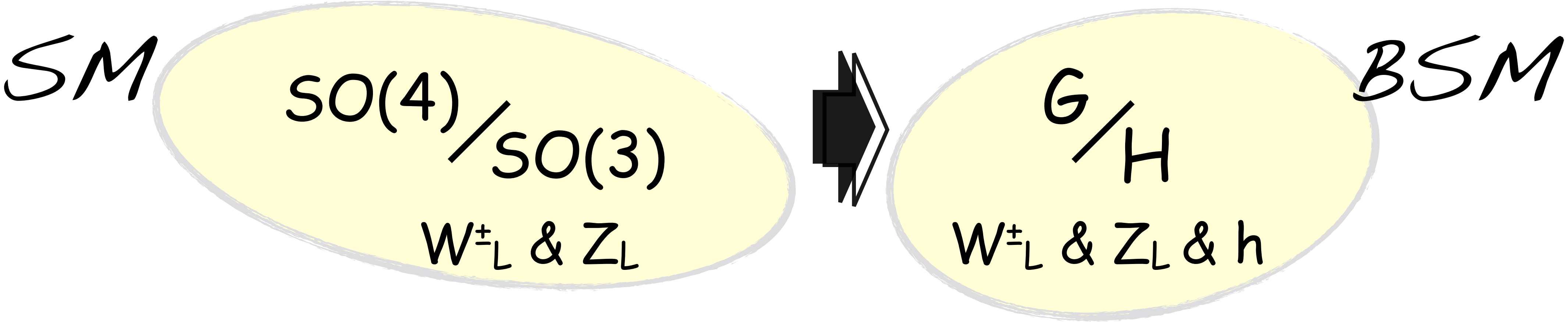
deviations of Higgs couplings originate from higher dimensional operators

$$\underbrace{\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi}_{\text{relevant for composite Higgs models}} \quad \underbrace{|H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}}_{\text{irrelevant for composite Higgs models}}$$

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)



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

SO(6)/SO(4)xSO(2): 8 PGBs=H_1+H_2
Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Higgs as a PGB: a natural extension of SM

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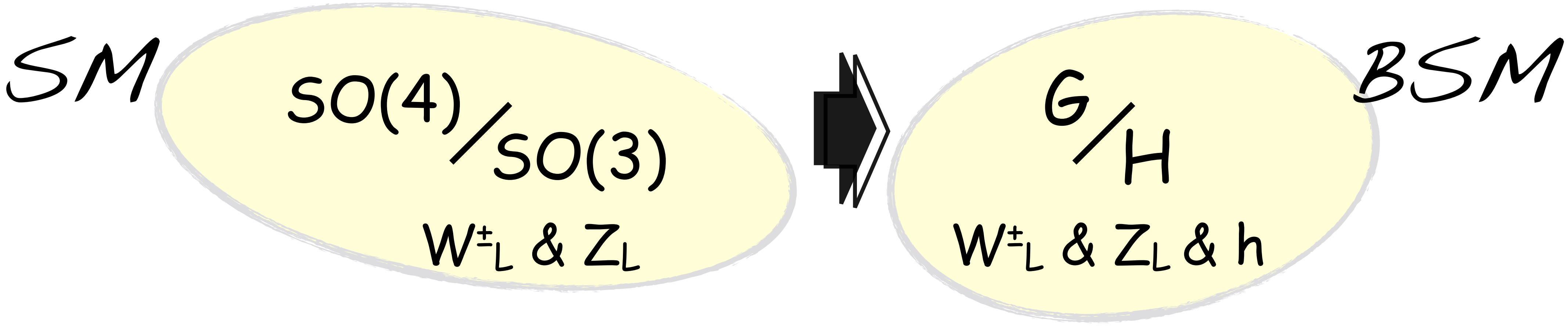


SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

BSM

G/H

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

How can we tell the difference with the SM Higgs?

Deformation of the SM Higgs: current constraints

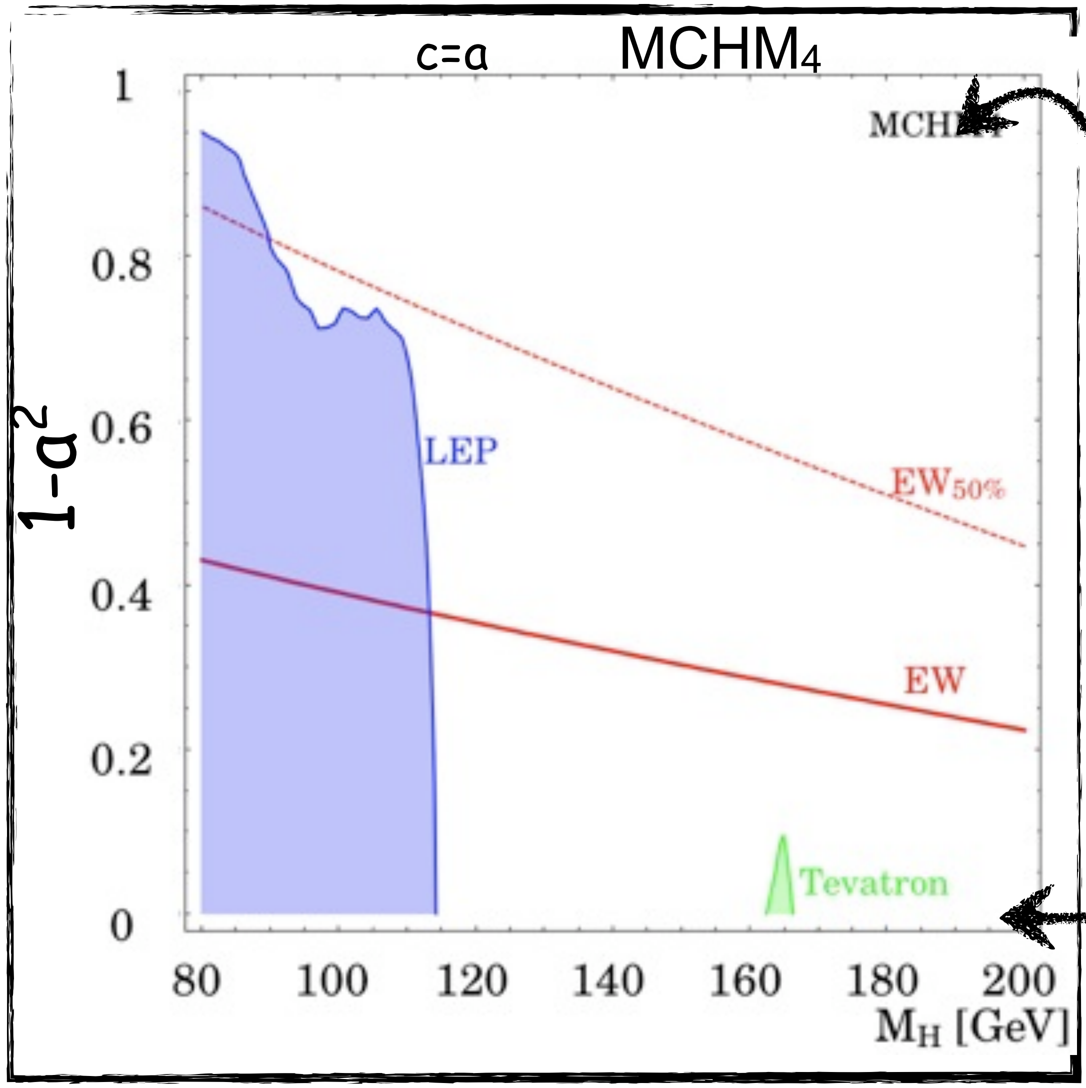
$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ 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’)

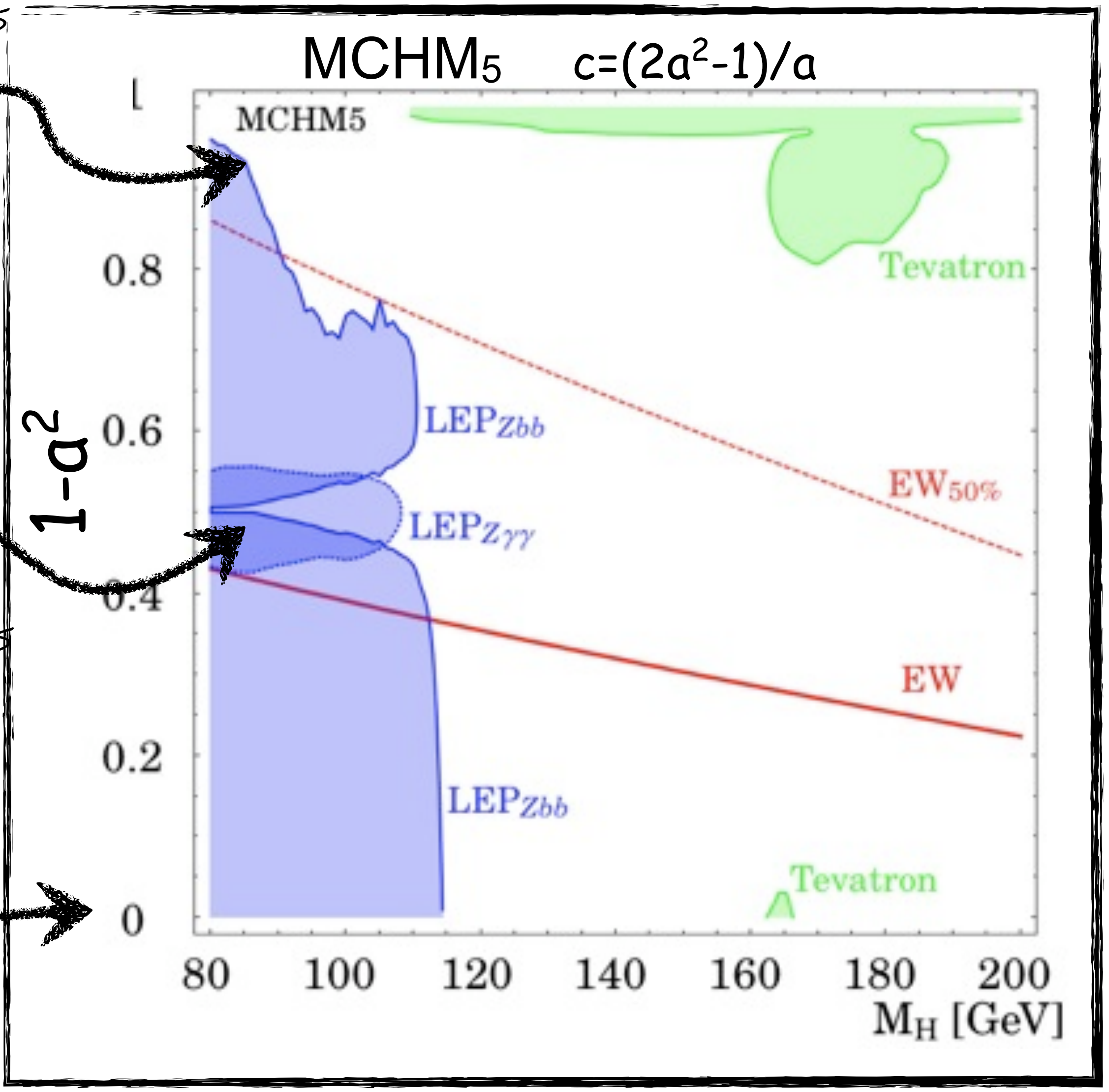
Espinosa, Grojean, Muehlleitner ’10


c=a MCHM4

gaugephobic Higgs

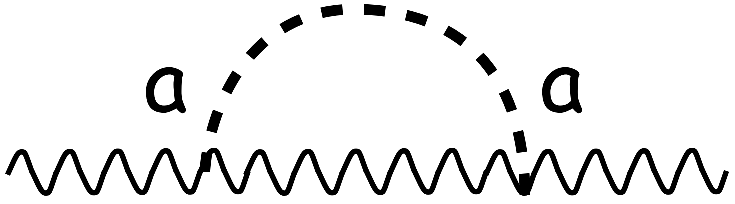
fermiophobic Higgs

SM limit


MCHM5 c=(2a²-1)/a

Deformation of the SM Higgs: EW constraints

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables



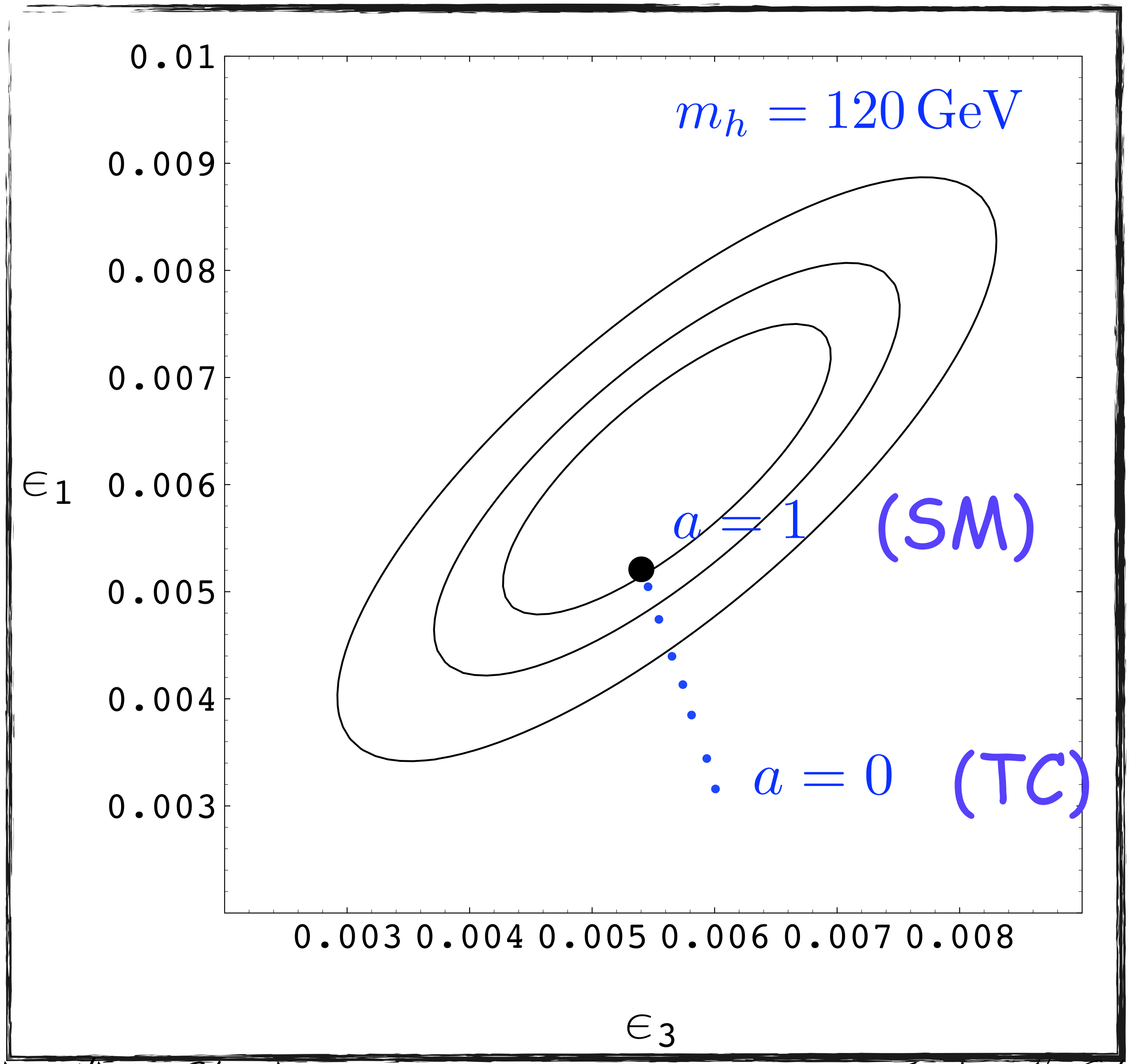
$$\epsilon_{1,3} = c_{1,3} \log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}\, \left(1 - a^2\right) \log(m_\rho^2/\mu^2) + \text{finite terms}$$

$$c_1 = +\frac{3}{16\pi^2} \frac{\alpha(m_Z)}{\cos^2\theta_W}$$

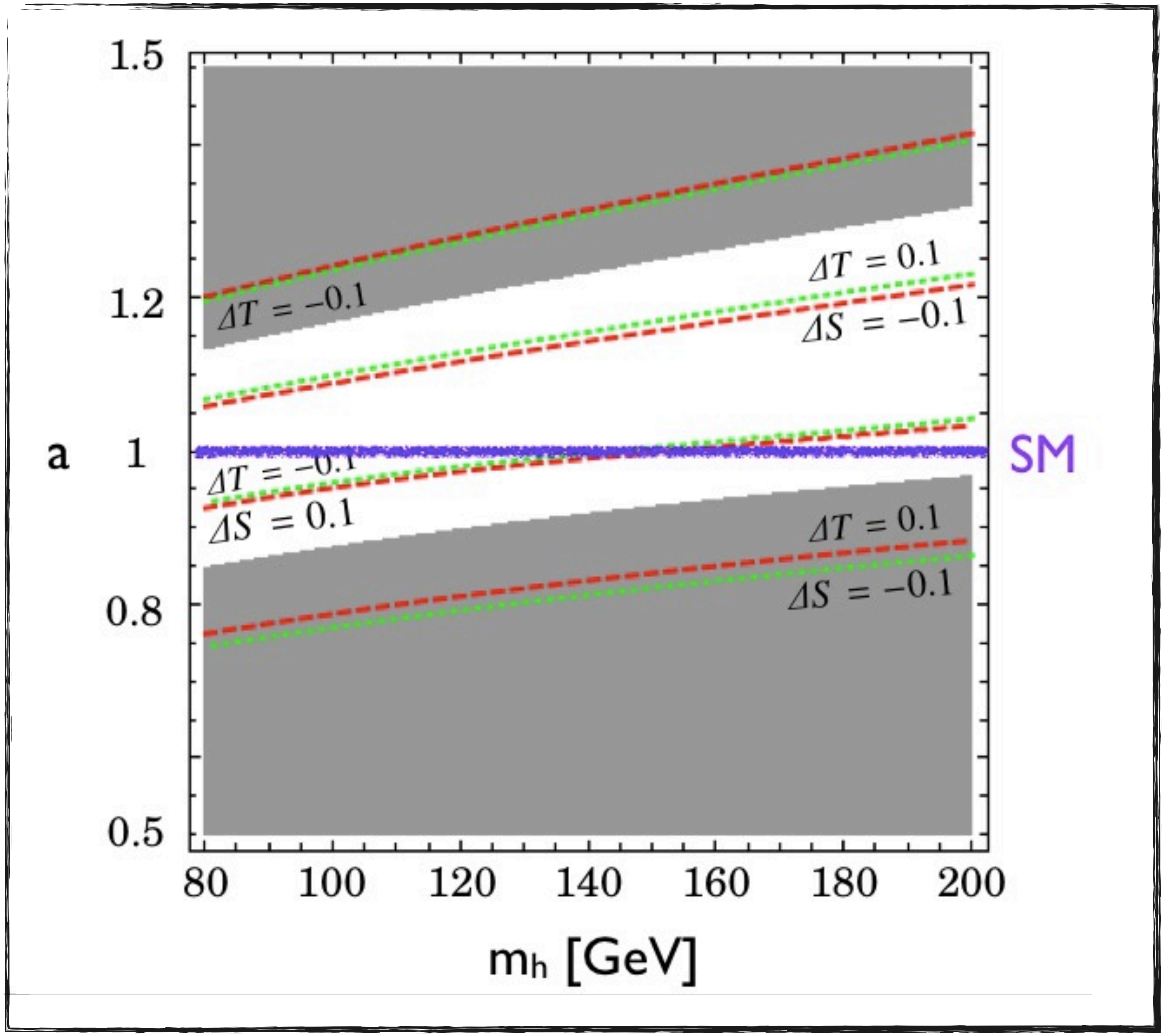
$$c_3 = -\frac{1}{12\pi} \frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\, \left(1 - a^2\right) \log(m_\rho^2/m_h^2)$$

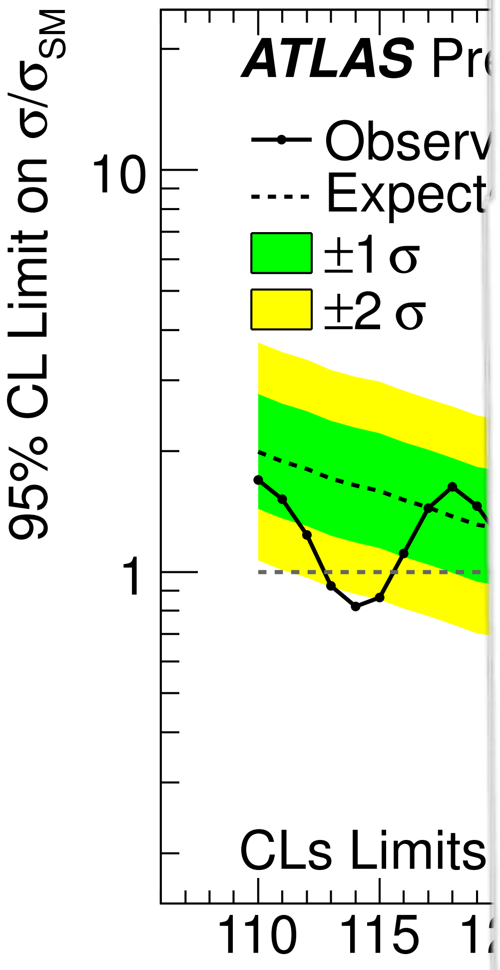
Barbieri, Bellazzini, Rychkov, Varagnolo '07

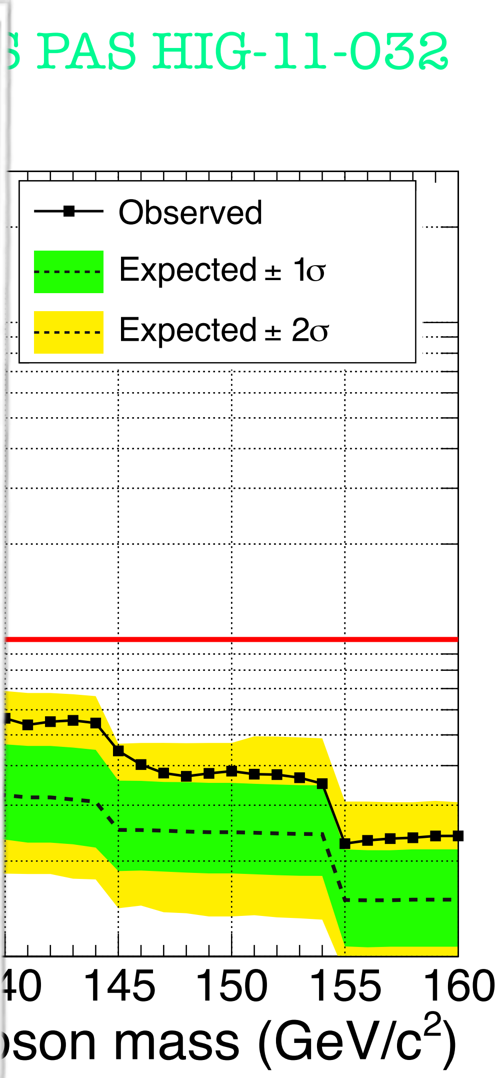


EW data constraints on 'a'



Higgs bounds: news from last December

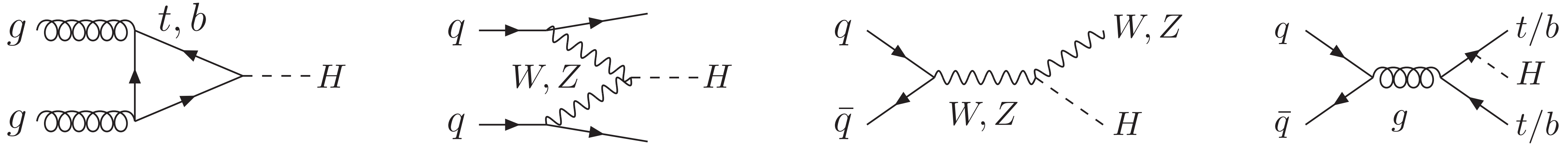




≈131 GeV

≈127 GeV

Rescaling Higgs Searches



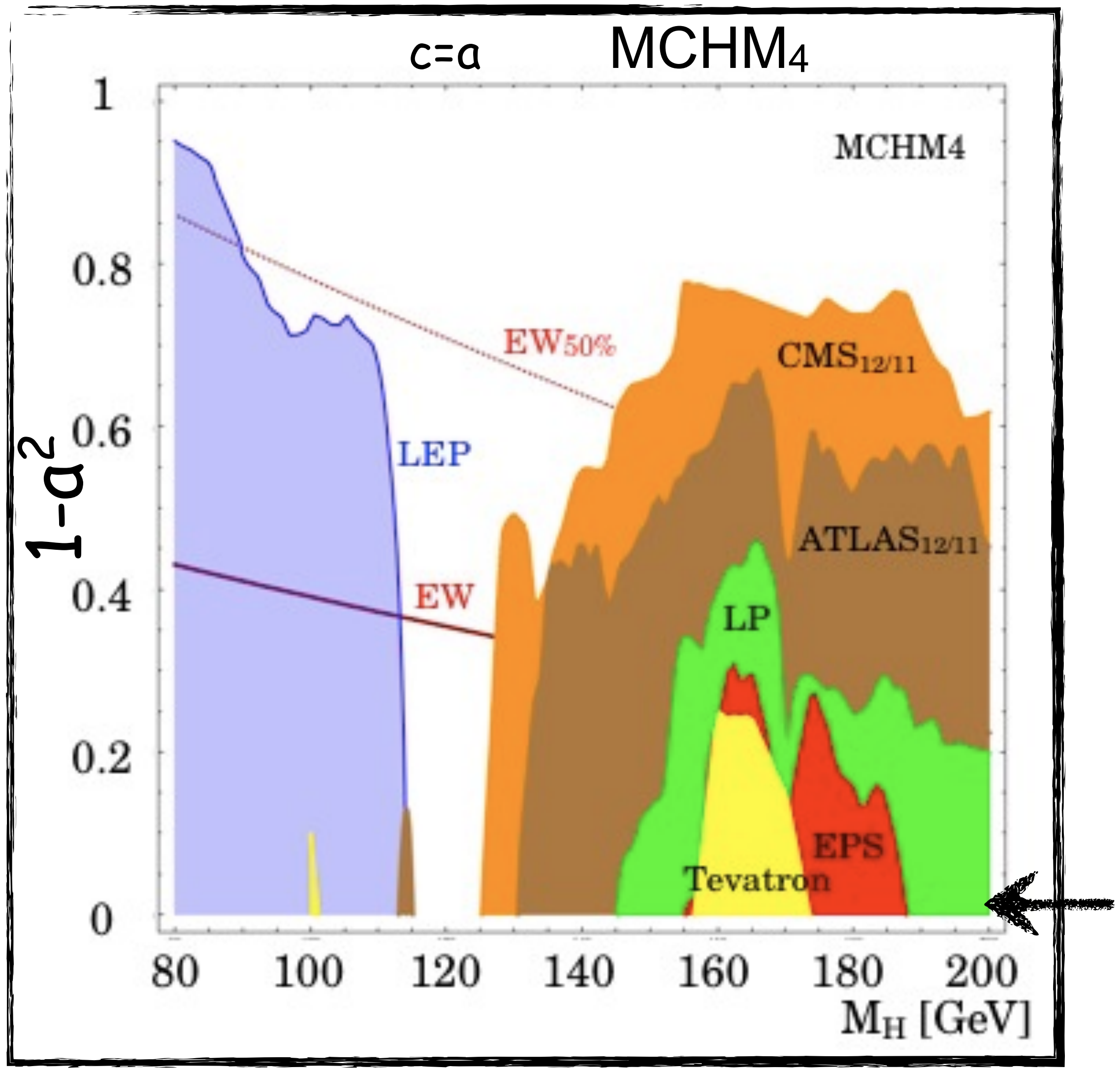
$\frac{\sigma_{NLO}}{\sigma_{NLO}^{SM}}$	c^2	a^2	a^2	c^2

$$\Gamma(H \to f\bar{f}) = c^2\,\Gamma^{SM}(H \to f\bar{f})\,,$$
$$\Gamma(H \to VV) = a^2\,\Gamma^{SM}(H \to VV)\,,$$
$$\Gamma(H \to gg) = c^2\,\Gamma^{SM}(H \to gg)\,,$$
$$\Gamma(H \to \gamma\gamma) = \frac{\left(cI_\gamma + aJ_\gamma\right)^2}{(I_\gamma + J_\gamma)^2}\,\Gamma^{SM}(H \to \gamma\gamma)\,,$$

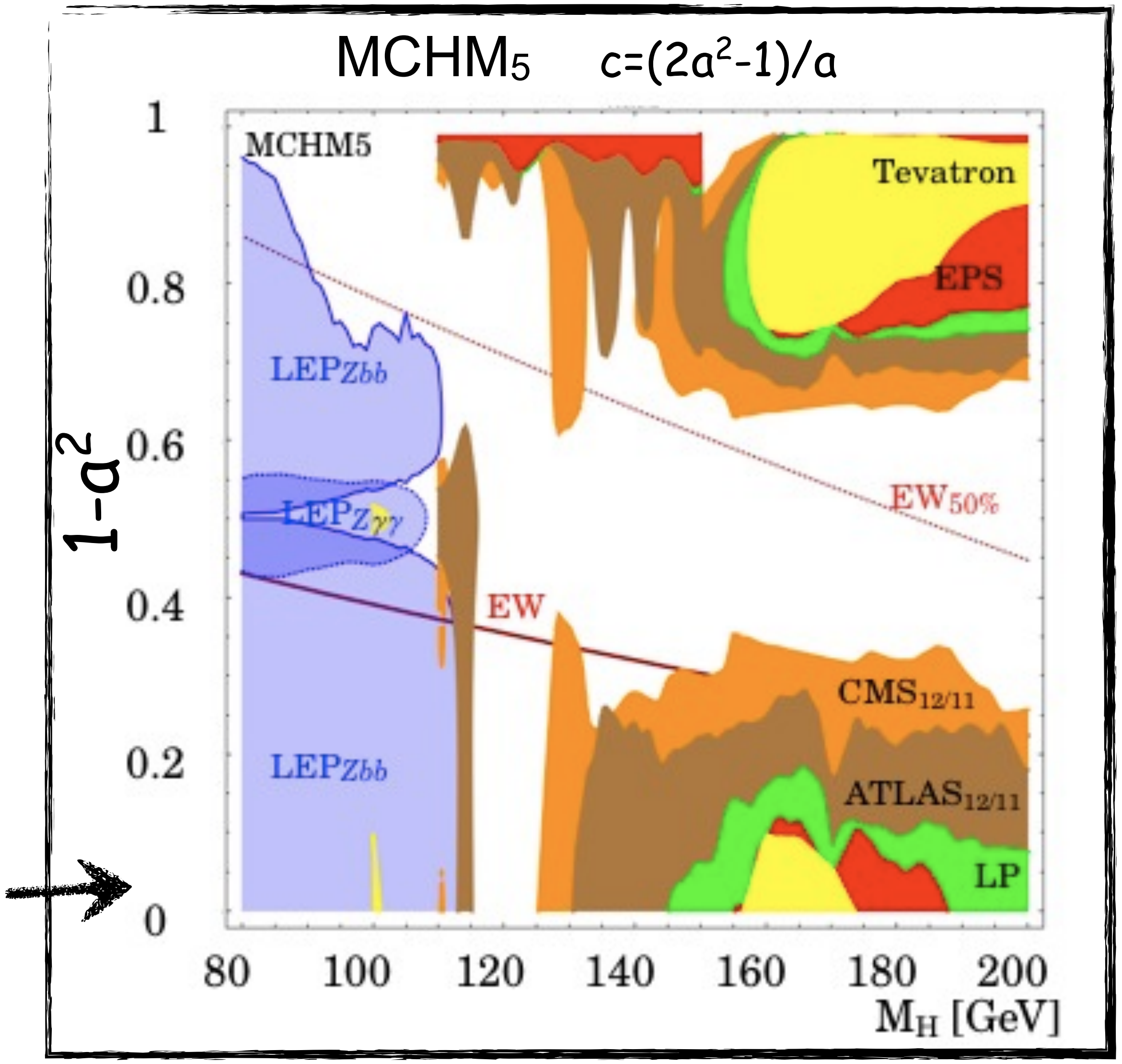
Deformation of the SM Higgs: current constraints

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

Espinosa, Grojean, Muehlleitner '11



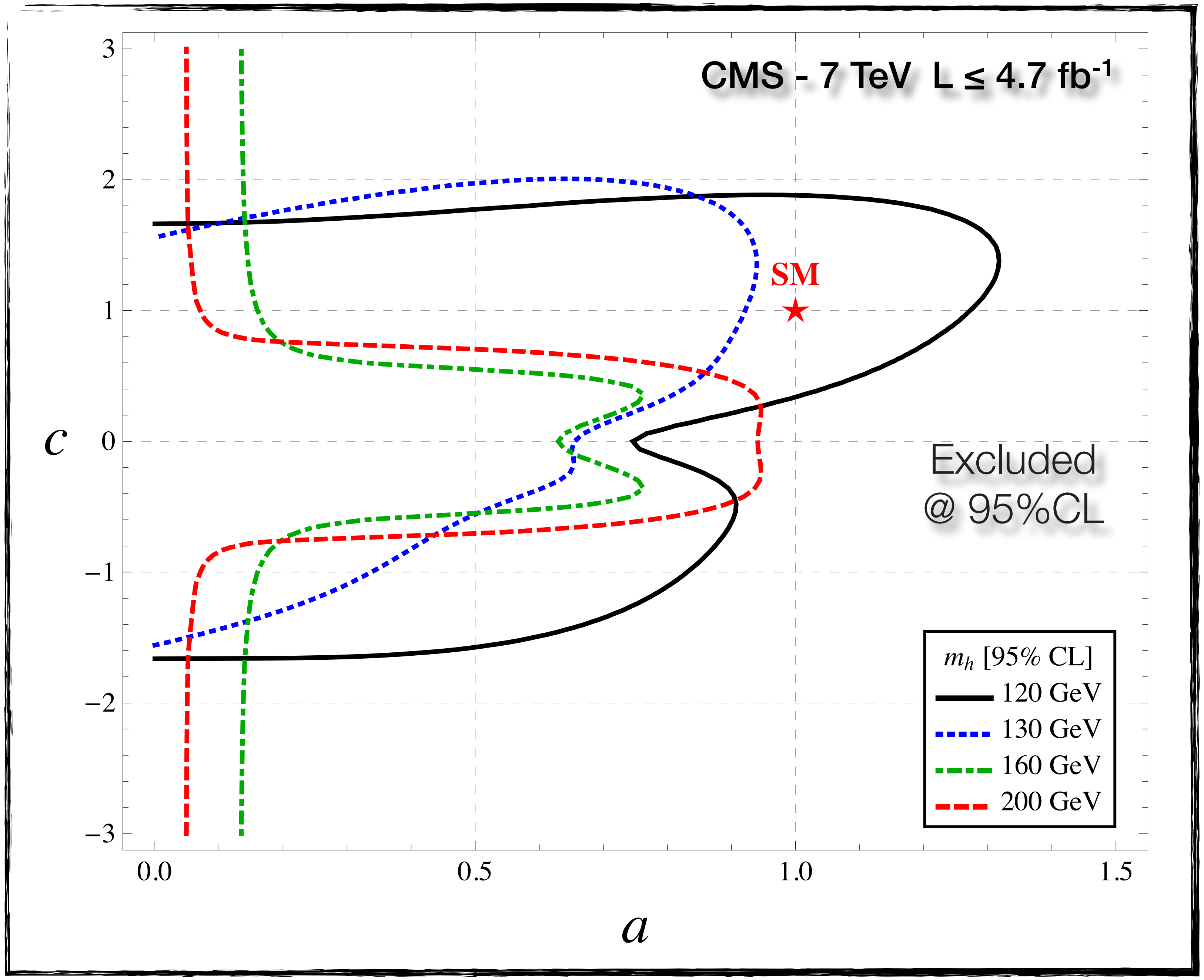
SM limits



LHC tsunami!

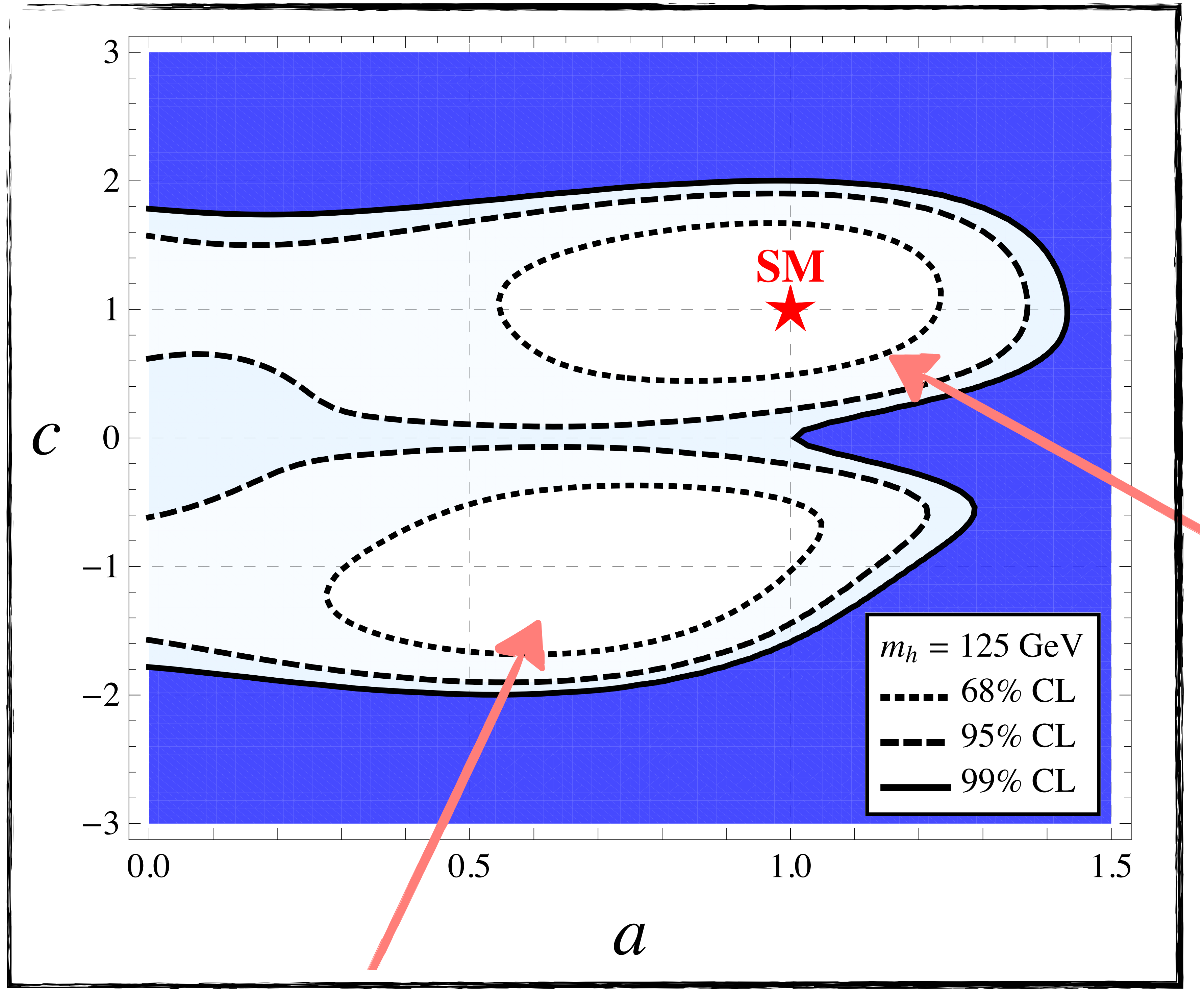
the LHC can do much more than simply excluding the SM Higgs

LHC constraints: model independent analysis



Azatov, Contino, Galloway ‘to appear

A Hint for a non-SM Higgs?



(a=1,c=1)

(a=0.7,c=-1)

Azatov, Contino, Galloway 'to appear

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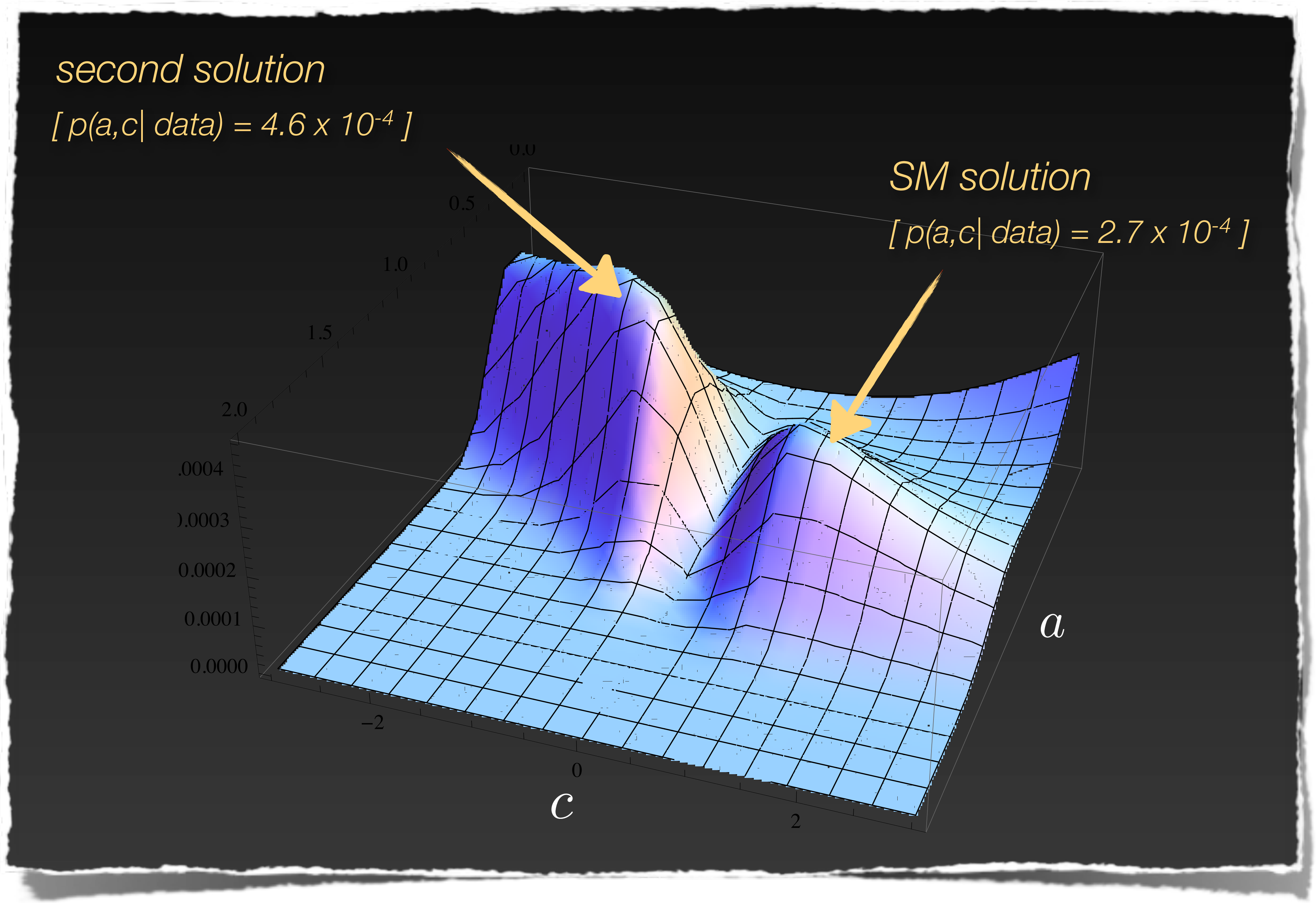
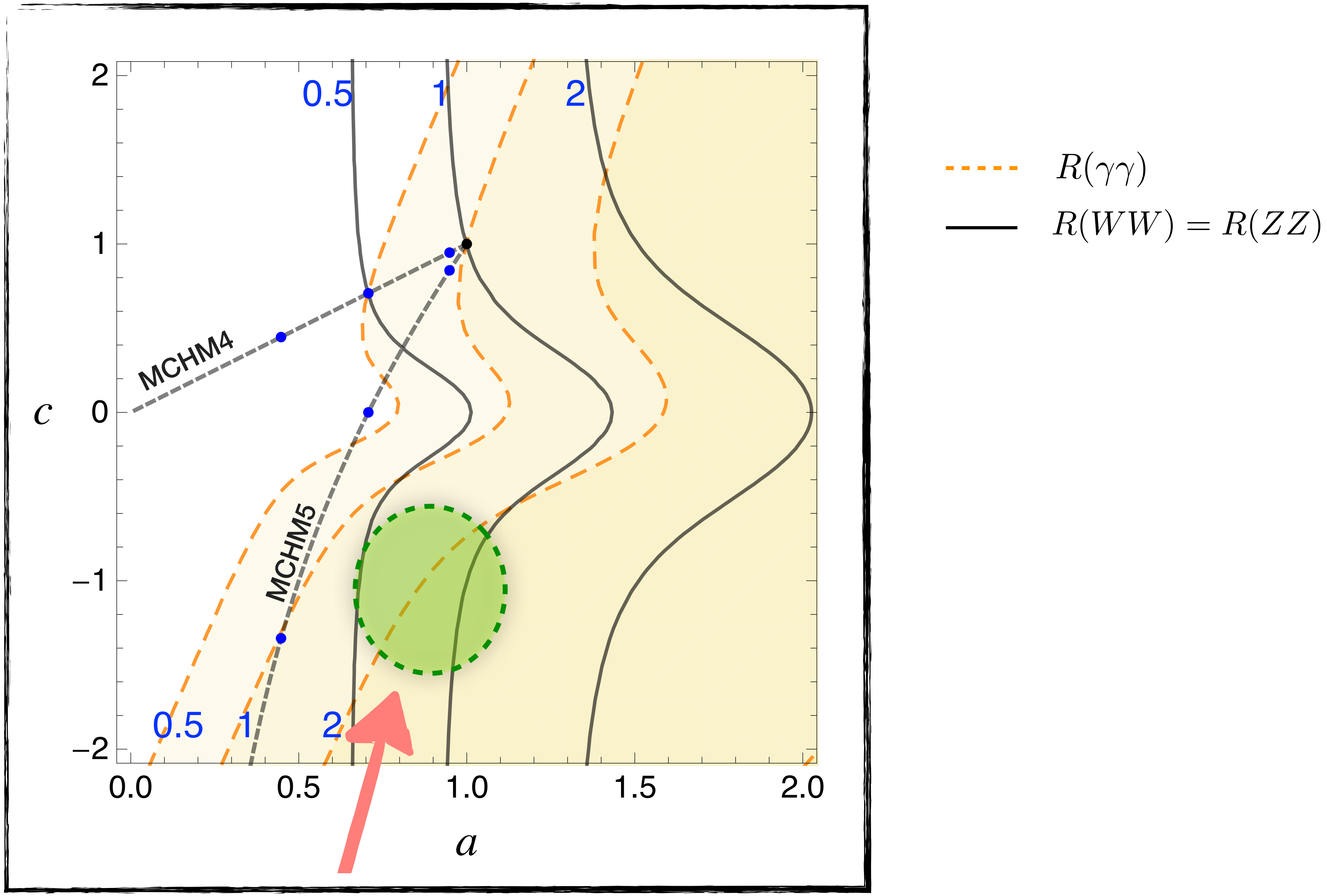


second solution
[p(a,c| data) = 4.6 x 10^{-4}]

SM solution
[p(a,c| data) = 2.7 x 10^{-4}]

Azatov, Contino, Galloway ‘to appear

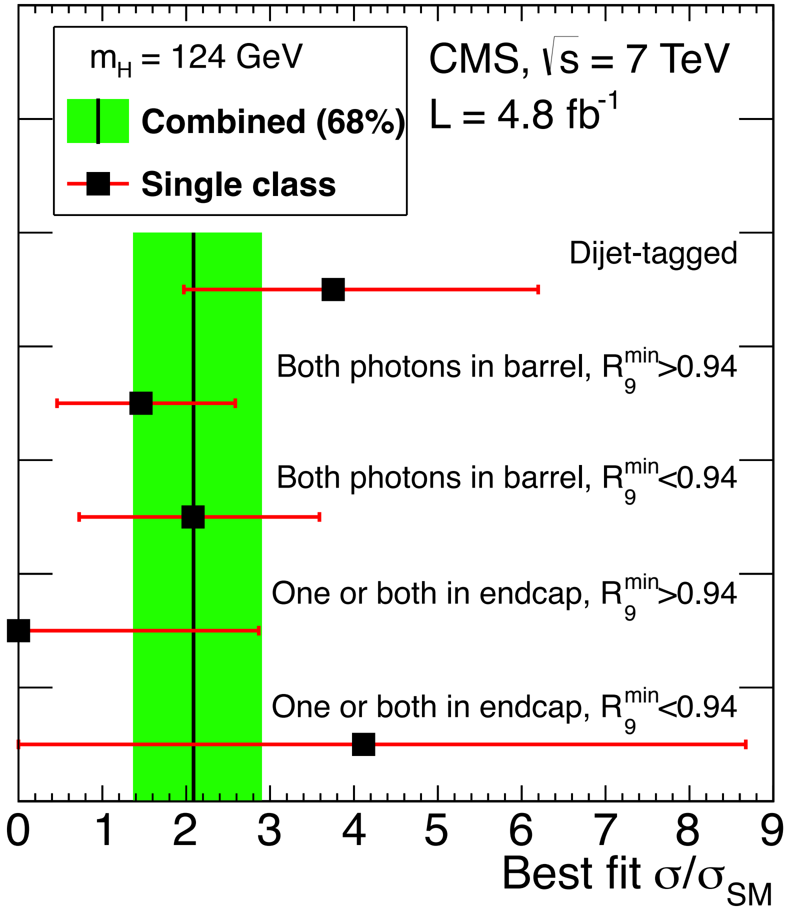
A Hint for a non-SM Higgs?

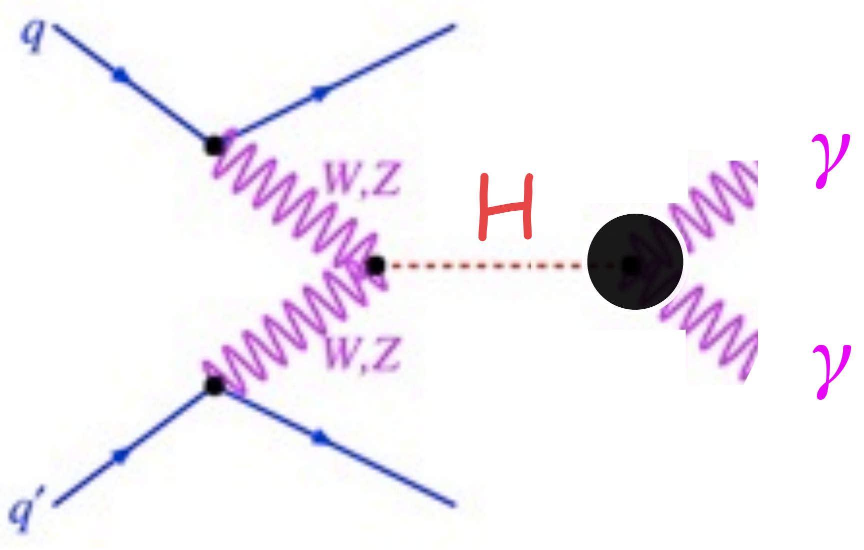


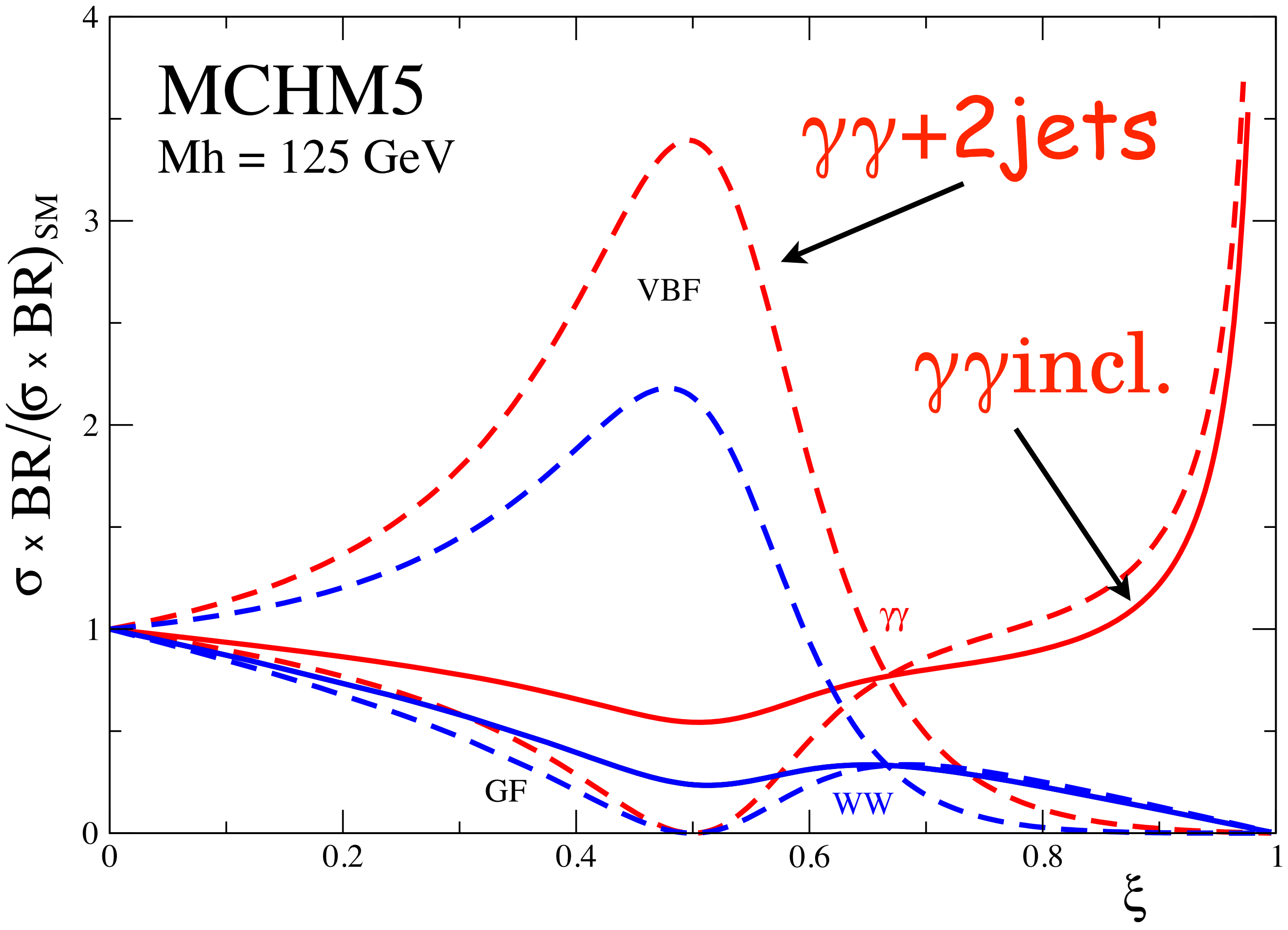
Azatov, Contino, Galloway ‘to appear

News from Yesterday

CMS PAS HIG-11-033







Espinosa, Grojean, Troot 'in progress

How to probe the composite nature of the Higgs?

1. Anomalous Higgs couplings

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

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

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

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

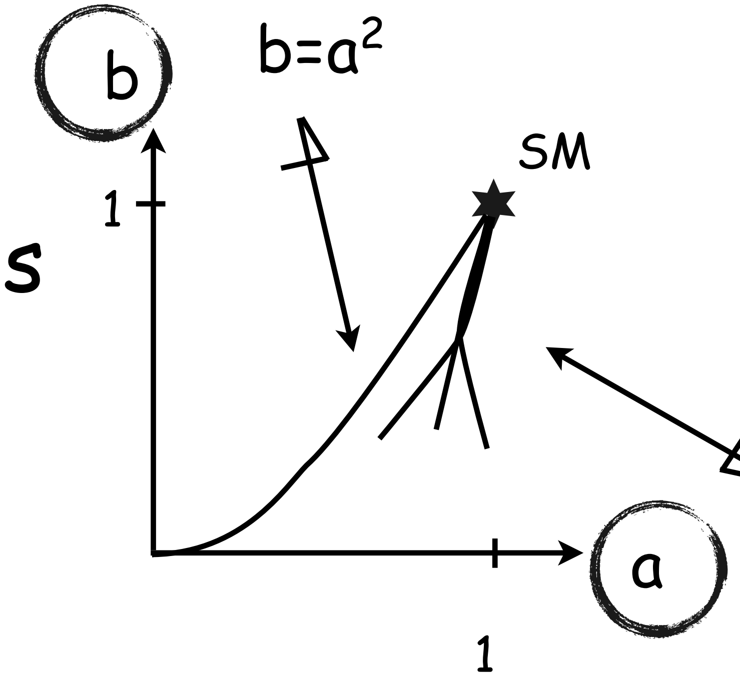
all resonances of strong sector,
except the Higgs, decouple

$$\xi = 1$$

Technicolor limit

Higgs decouple from SM;
vector resonances like in TC

Composite Higgs
vs.
SM Higgs



Dilaton
$b=a^2$

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

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

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)

$$\frac{c_H}{2f^2}\left(\partial^\mu \left|H\right|^2\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}\left|H\right|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6 \lambda}{f^2}\left|H\right|^6$$

custodial breaking

- **Form factor operators** (sensitive to the scale mρ)

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

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W_{\mu\nu}^i \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\left(D^\mu H\right)^\dagger \left(D^\nu H\right) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$

Goldstone sym.

Minimal Composite Higgs Examples

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

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \quad \Rrightarrow \quad g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM} \quad \Rrightarrow \quad \begin{cases} a = \sqrt{1-\xi} \\ b = 1-2\xi \end{cases}$$

MCHM4

Fermions embedded in spinorial of SO(5)

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

$$\Downarrow$$

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

$$\Downarrow$$

$$c = \sqrt{1-\xi}$$

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

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

$$\Downarrow$$

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

$$\Downarrow$$

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

BRs now depends on v/f

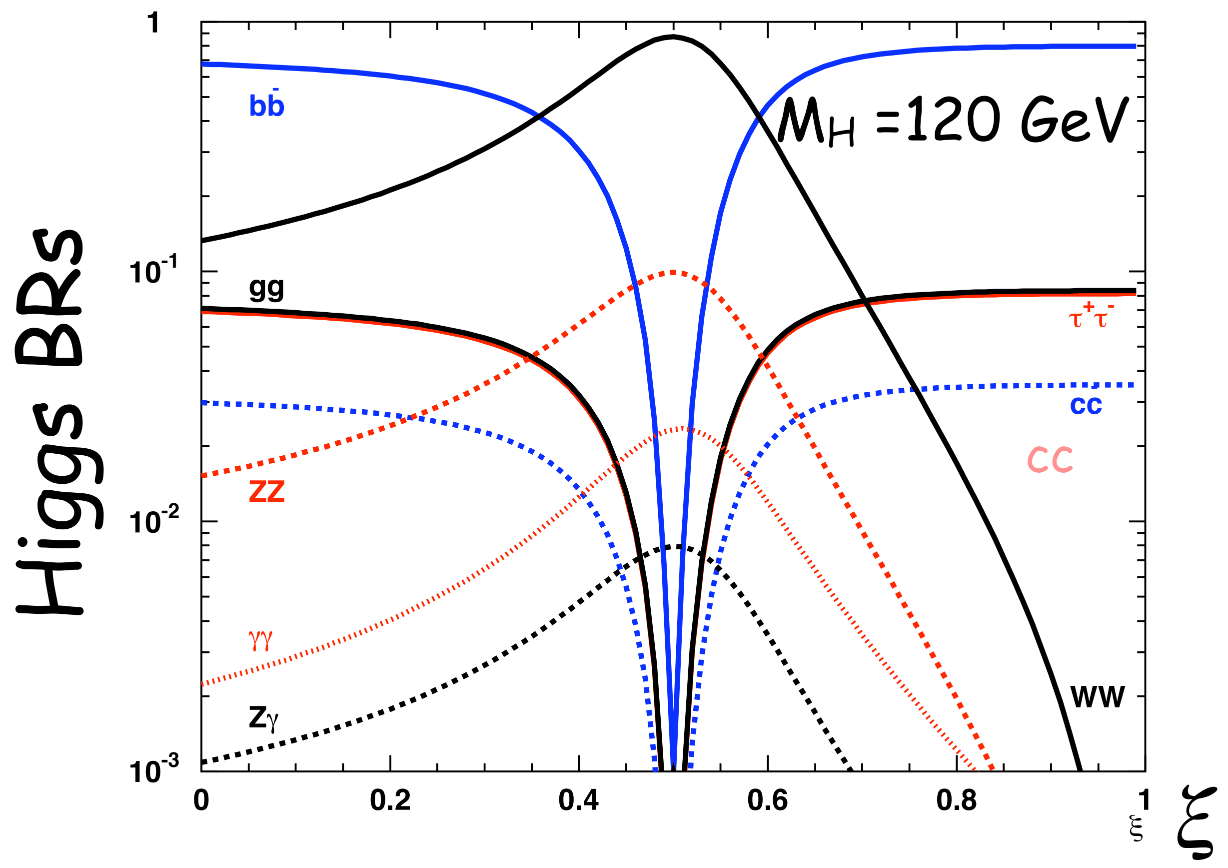
$$(\xi = v^2/f^2)$$

Higgs BRs - MCHM$_5$

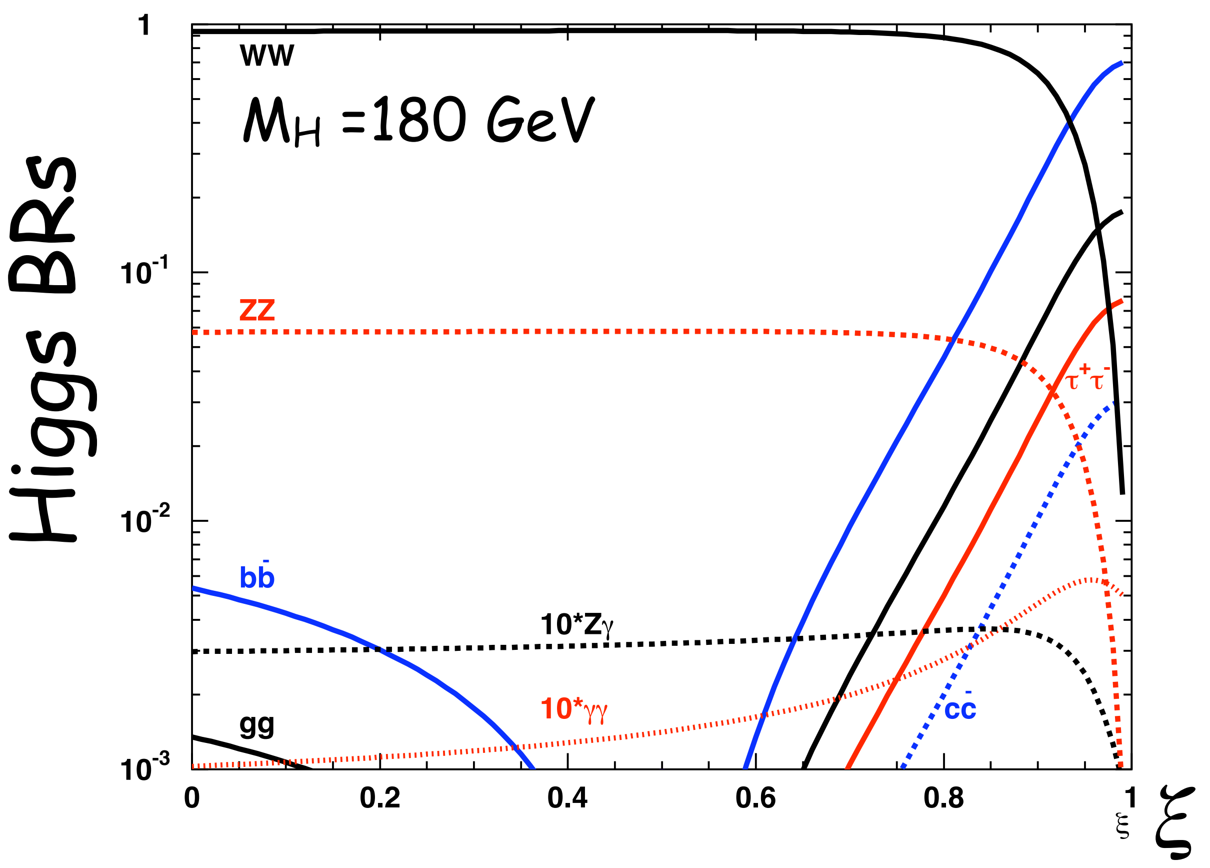
MCHM$_5$

Fermions embedded in 5+10 of SO(5)

$$a = \sqrt{1-\xi} \qquad b = 1 - 2\xi \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$



h→WW can dominate
even for low Higgs mass



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

How to probe the composite nature of the Higgs?

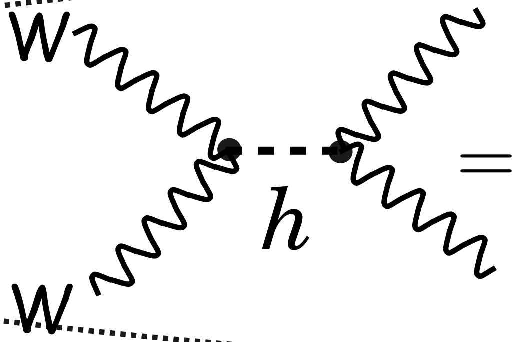
2. Probing strong scatterings

How to probe the strong dynamics?

pair production of light states beloging to the strong sector

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

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

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

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

- strong double Higgs production

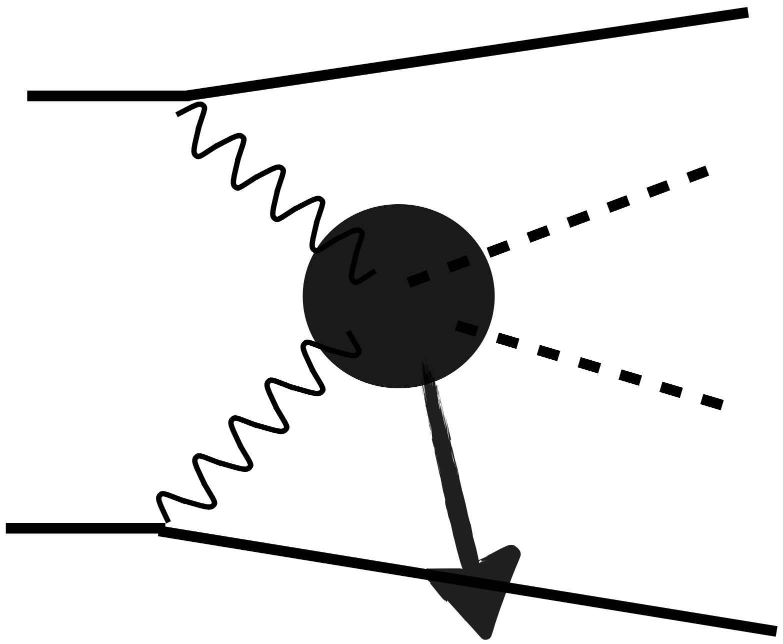
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

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

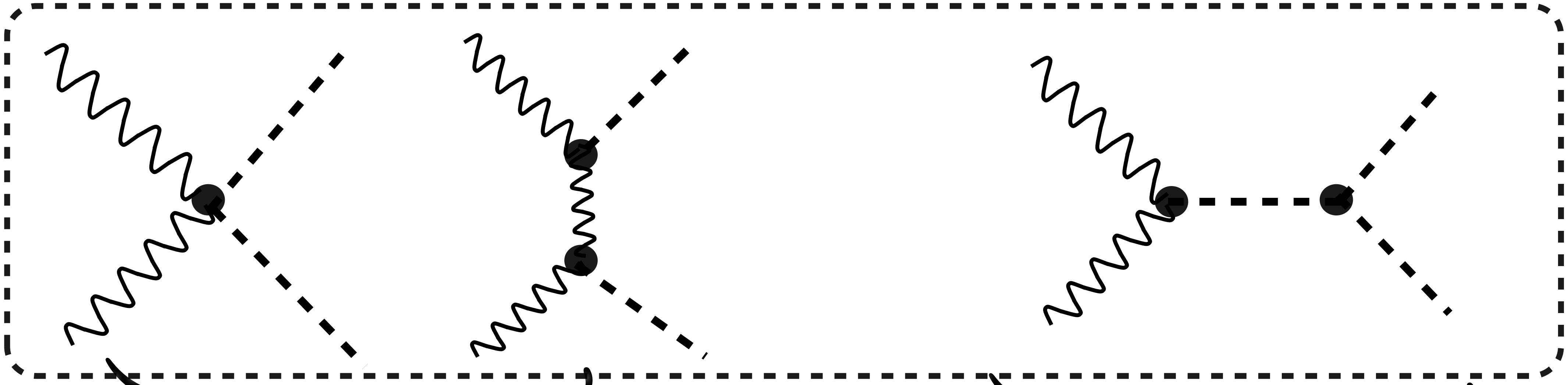
Double Higgs production



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

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

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



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

asymptotic behavior
sensitive to strong interaction

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

threshold effect
anomalous coupling'

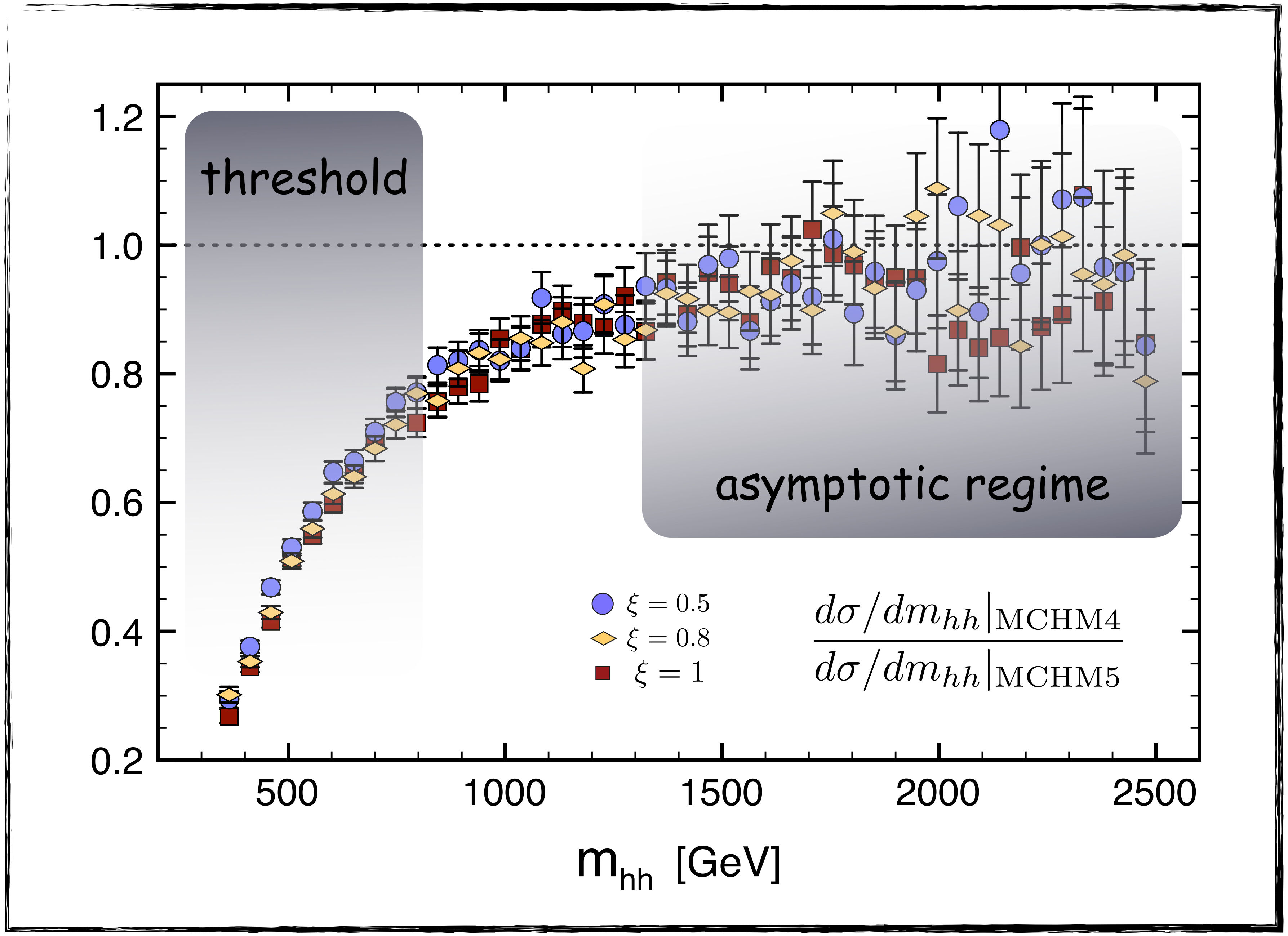
Isolating Hard Scattering

Contino, Grojean, Moretti, Piccinini, Rattazzi ’10

isolate events with large m_{hh}

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

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



two models with
same asymptotic regime but
different higgs-self-coupling

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

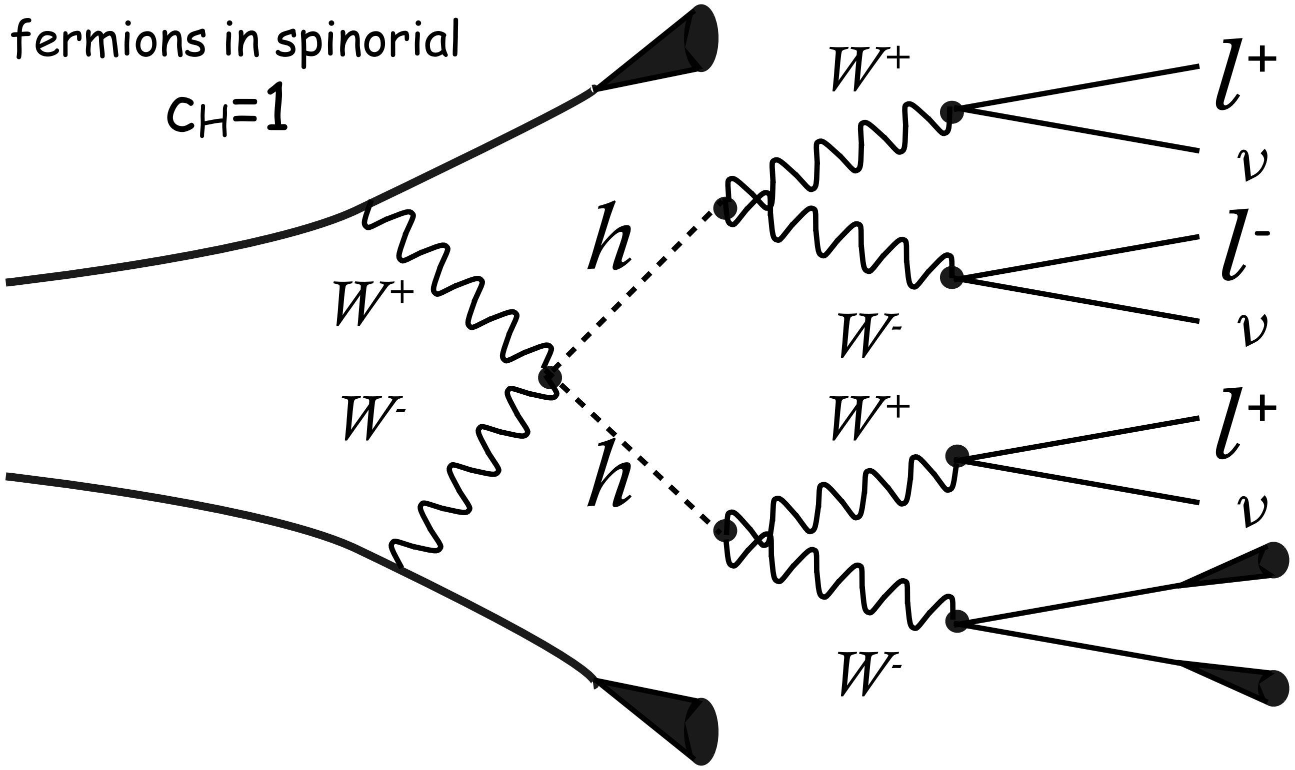
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ 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

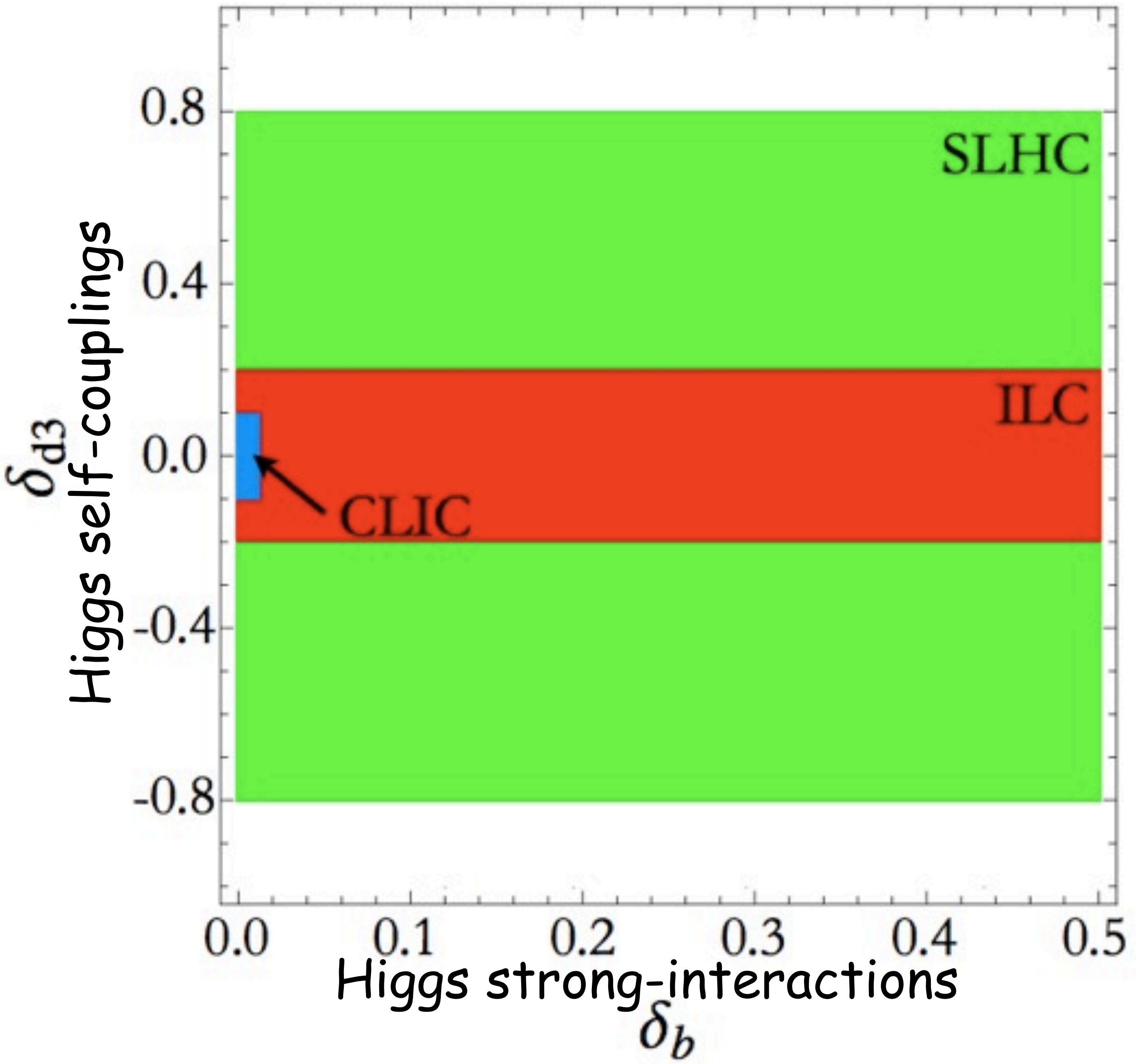
v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

⇚ good motivation to SLHC

Measuring Higgs Non-Linearities

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

Which probe of strong dynamics?

- Higgs self-couplings controls the dynamics of EWSB ➪ red herring (various weak states can modify h^3)
- to learn about strong interactions triggering EWSB ➪ need to measure quadratic coupling b to Goldstones!

How to probe the composite nature of the Higgs?

3. Probing discrete symmetries of the 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

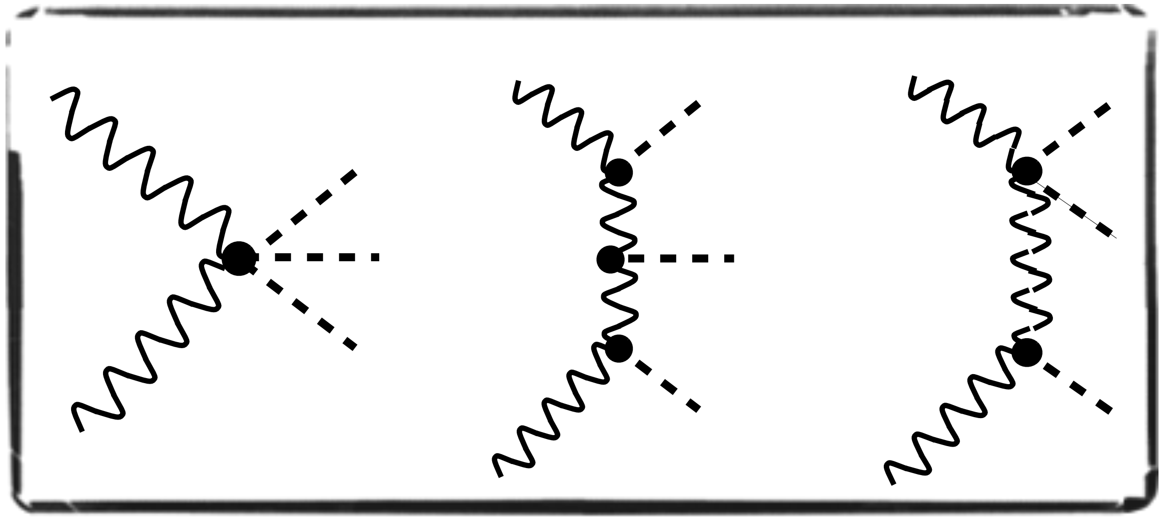
$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

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

selection rule

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

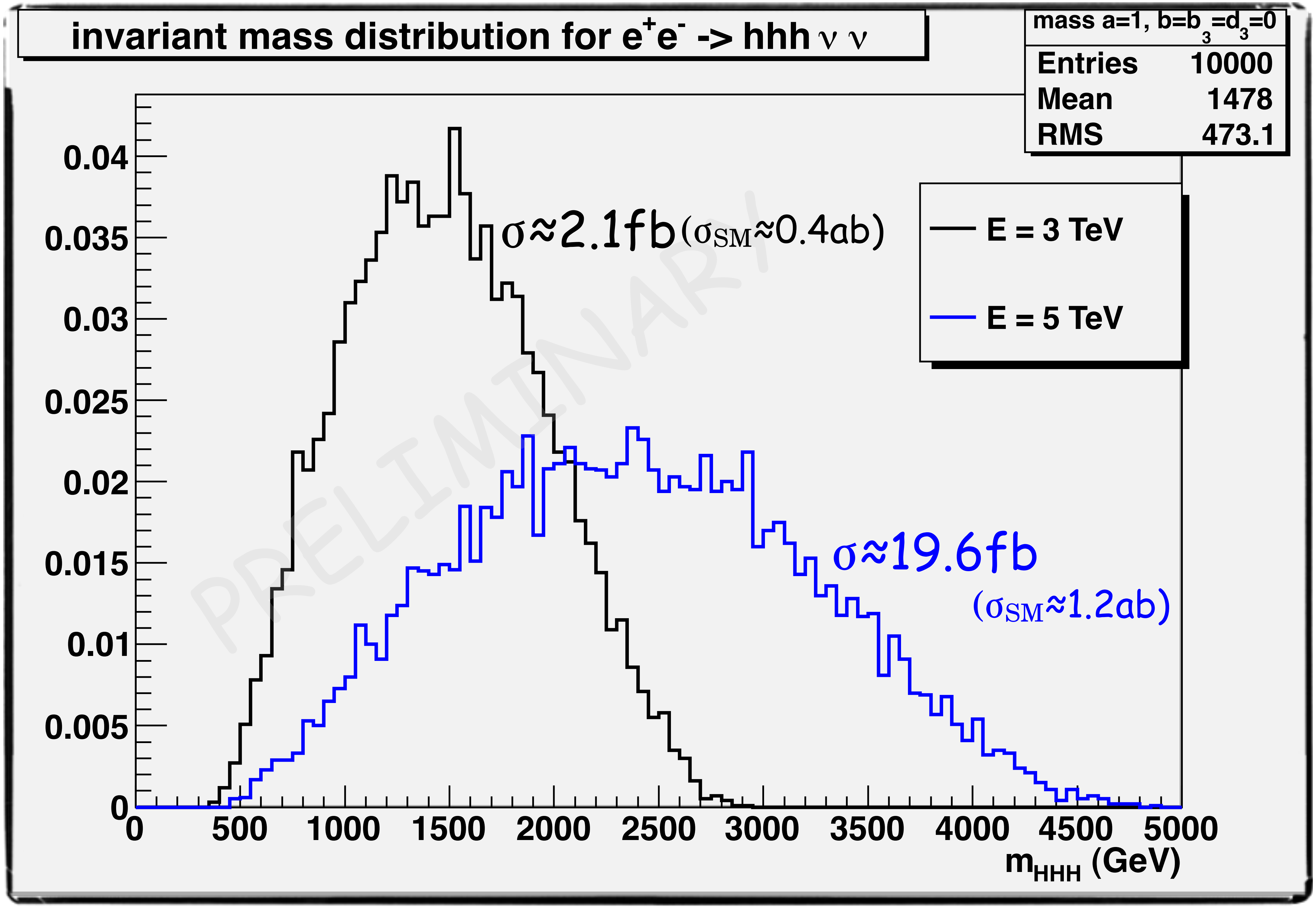


$$A_{WW\to 3h} \sim 4i\frac{s}{v^3}\left(\underbrace{a(b-a^2)-\frac{3}{4}b_3}_{\text{=0 for symmetric coset}}\right) + \sharp\, s \times \underbrace{\left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

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

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

non-symmetric coset

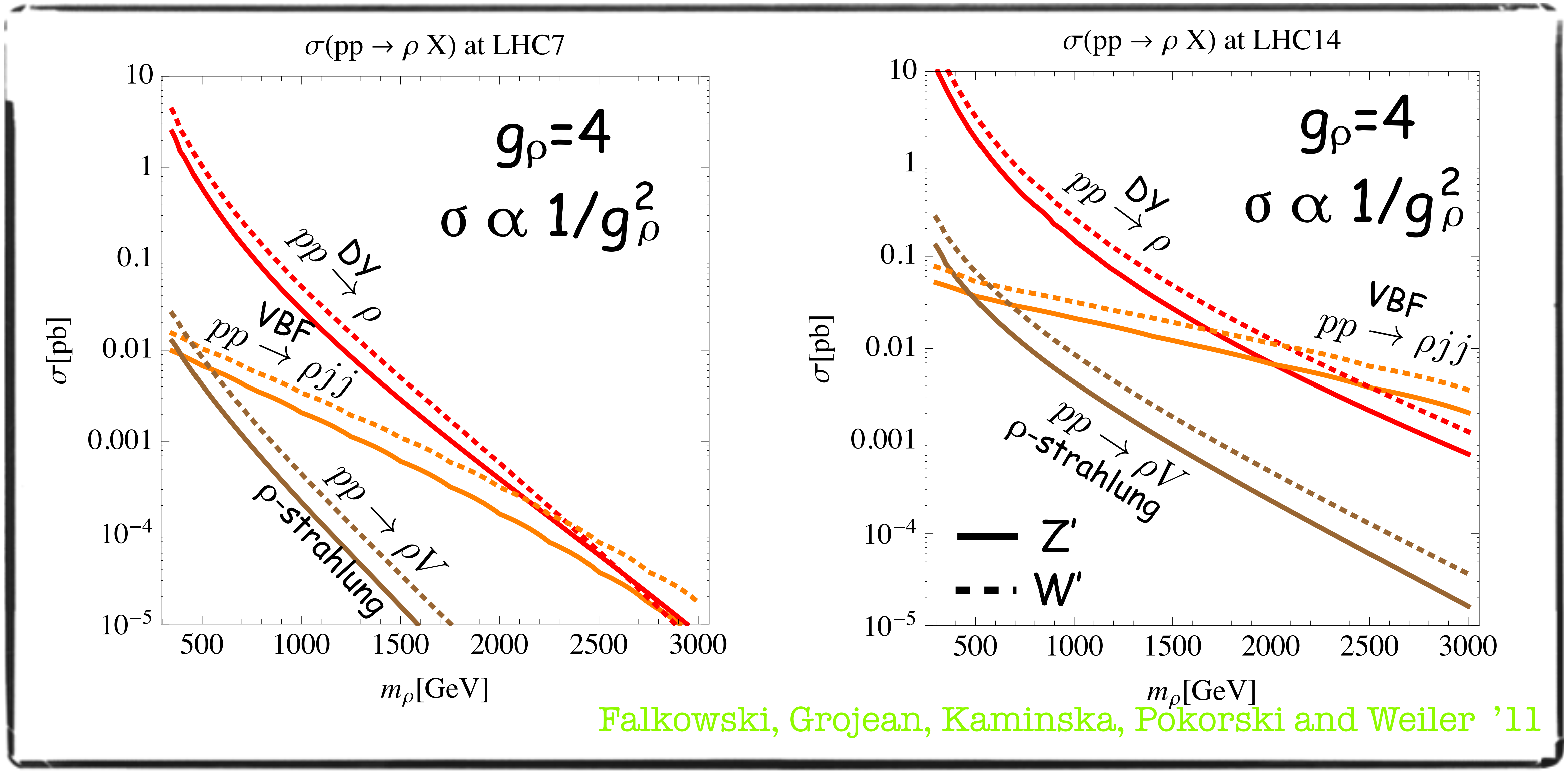


How to probe the composite nature of the Higgs?

4. Resonances production

Resonance Searches

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



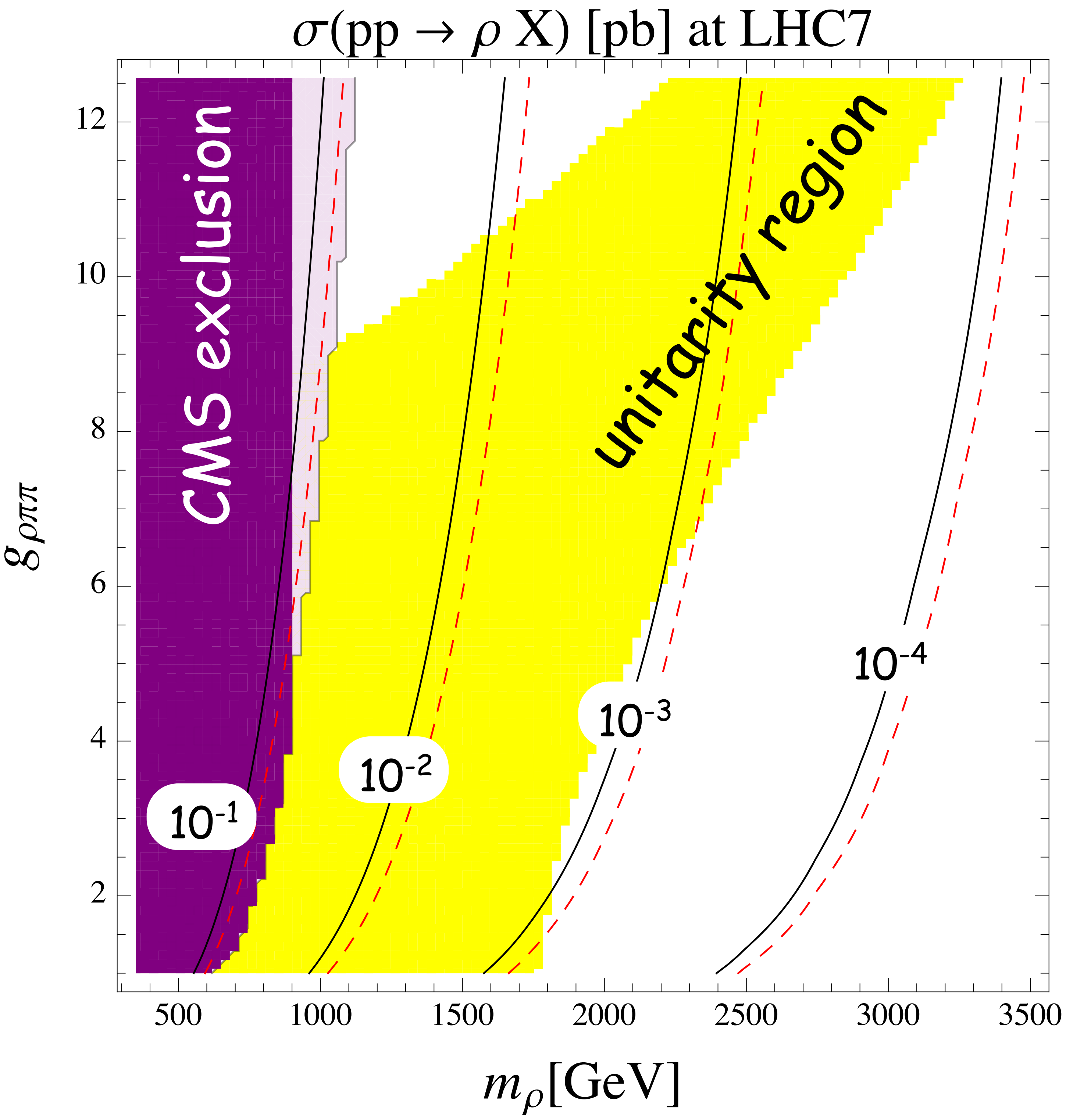
Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

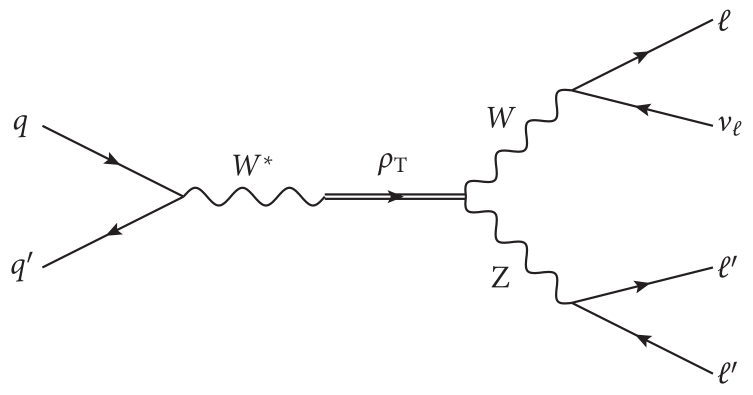
VBF vs. DY:
- 3-body final state
- qq initiated process ⇨ PDFs become more dominant at large x

Resonance Searches

Falkowski, Grojean, Kaminska, Pokorski and Weiler ’11

higgsless setup





- Current best limits from the $1 fb^{-1}$ CMS search for WZ resonances

CSM-PAS-EXO-11-041

- D0 search for WW and WZ resonances gives weaker bounds

Abazov et al, ’10

- LHC limits on leptonic Z’ and W’ resonances are not competitive because of the small leptonic branching fraction

Resonance Searches vs Indirect Probes

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

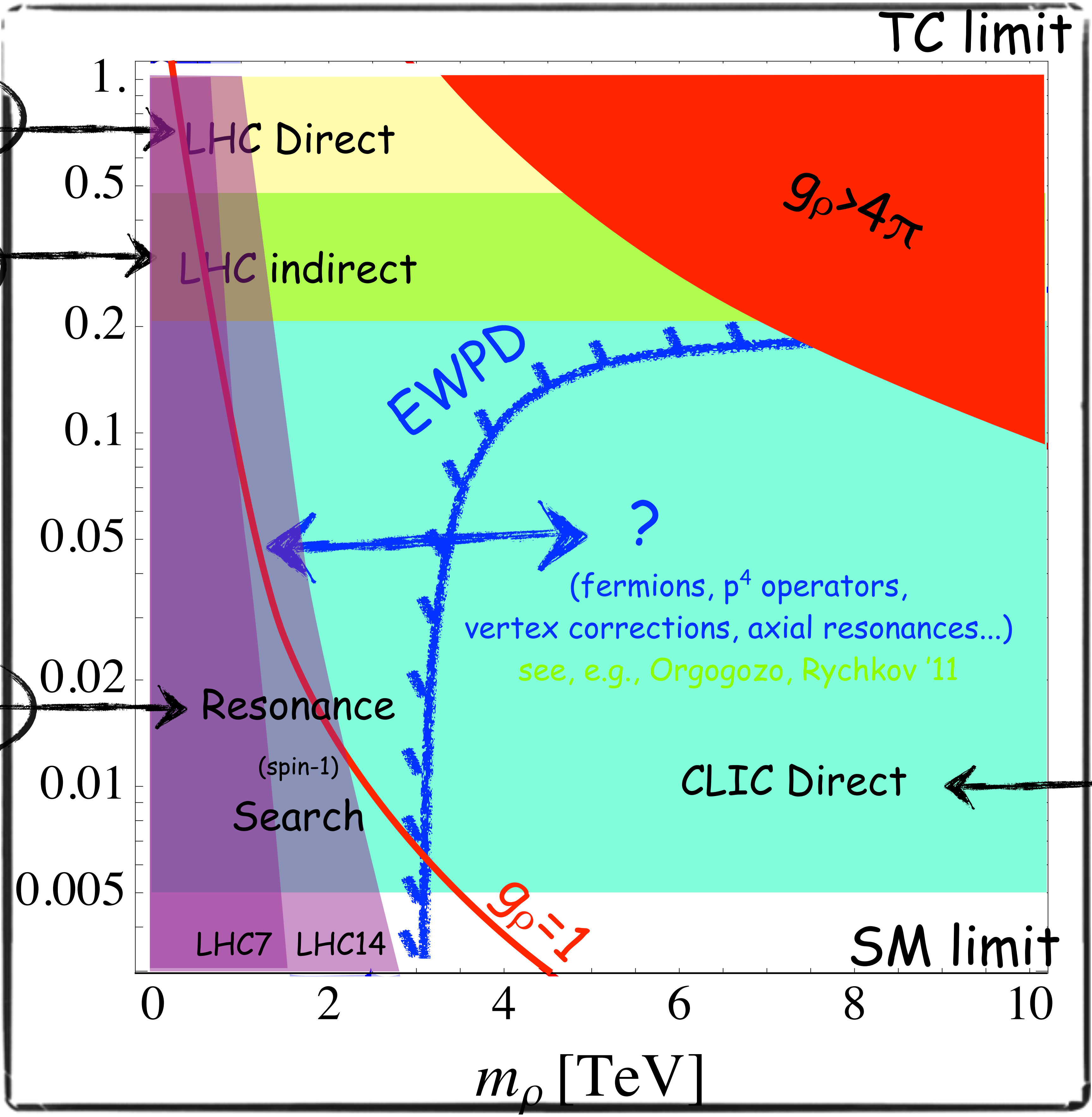
Strong WW scattering

Anomalous Higgs couplings

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$

Resonance searches

NB:
the lower the scale of strong interaction, the more difficult to see resonances
(broader resonances & weaker couplings to light SM quarks)



(fermions, p^4 operators, vertex corrections, axial resonances...)

see, e.g., Orgogozo, Rychkov ’11

Strong WW scattering @ CLIC

Resonance vs Heavy Gauge Boson

Grojean, Salvioni, Torre ’11

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

elementary spin-1

g=2 ⇔ Λ >> M/e ⇔ 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 Λ >> M/e

Ferrara, Porrati, Telegdi ’92

composite spin-1

g≠2 & Λ > 5÷10 M ⇔ 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

Fermionic Resonances

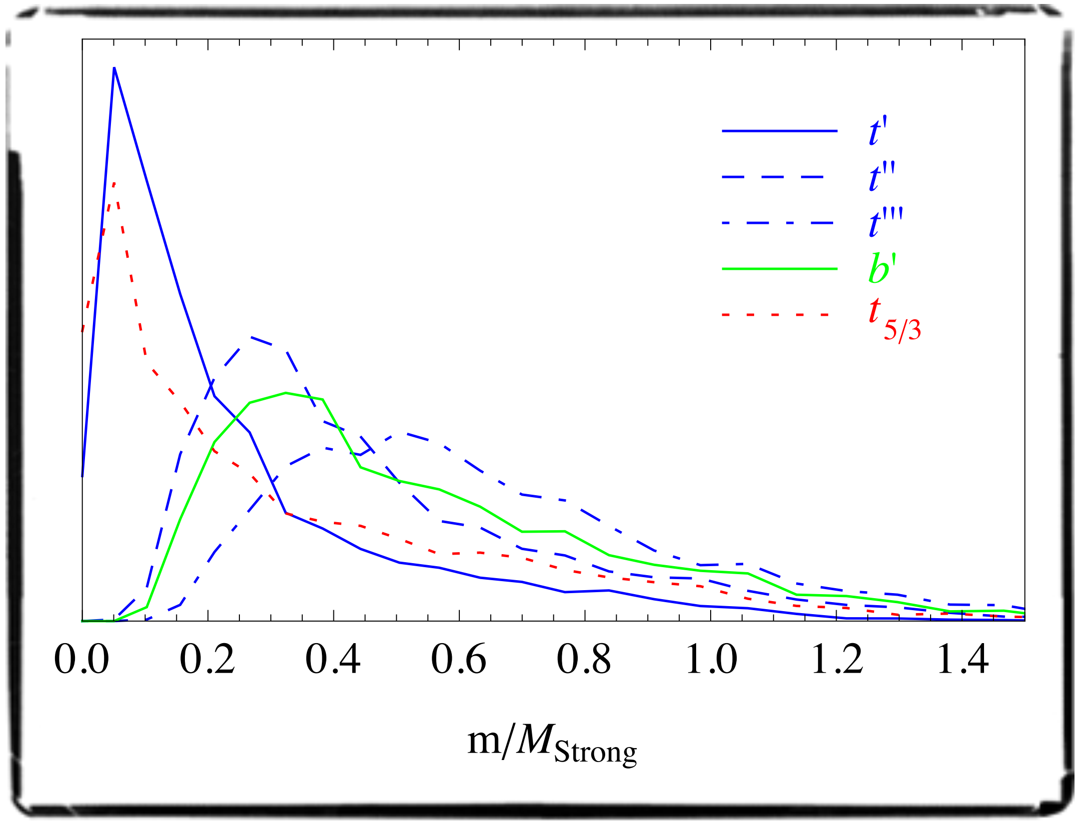
[Agashe, Contino, Da Rold, Pomarol '06]

- Custodial symmetry: exotic top partners

SU(2)LxSU(2)R embedding

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

⇨ $\delta_{Zb_L\bar{b}_L}$=0



Panico, Wulzer '11

partial compositness

⇓ ⇓

the heavier the SM quark,
the lighter its resonances and partners

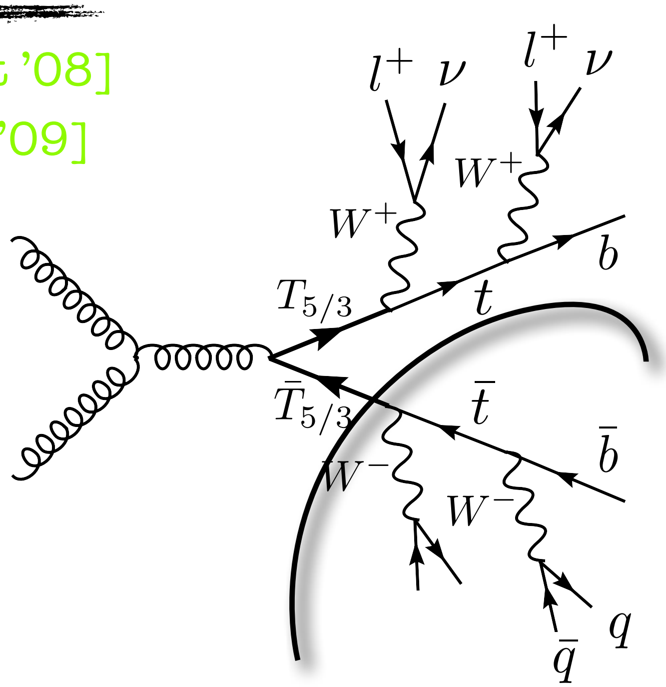
the top sector is
a promizing place to look
for strong dynamics

Searching for Exotic Top Partners

Search in same-sign di-lepton events

[Contino, Servant ’08]
[Mrazek, Wulzer ’09]

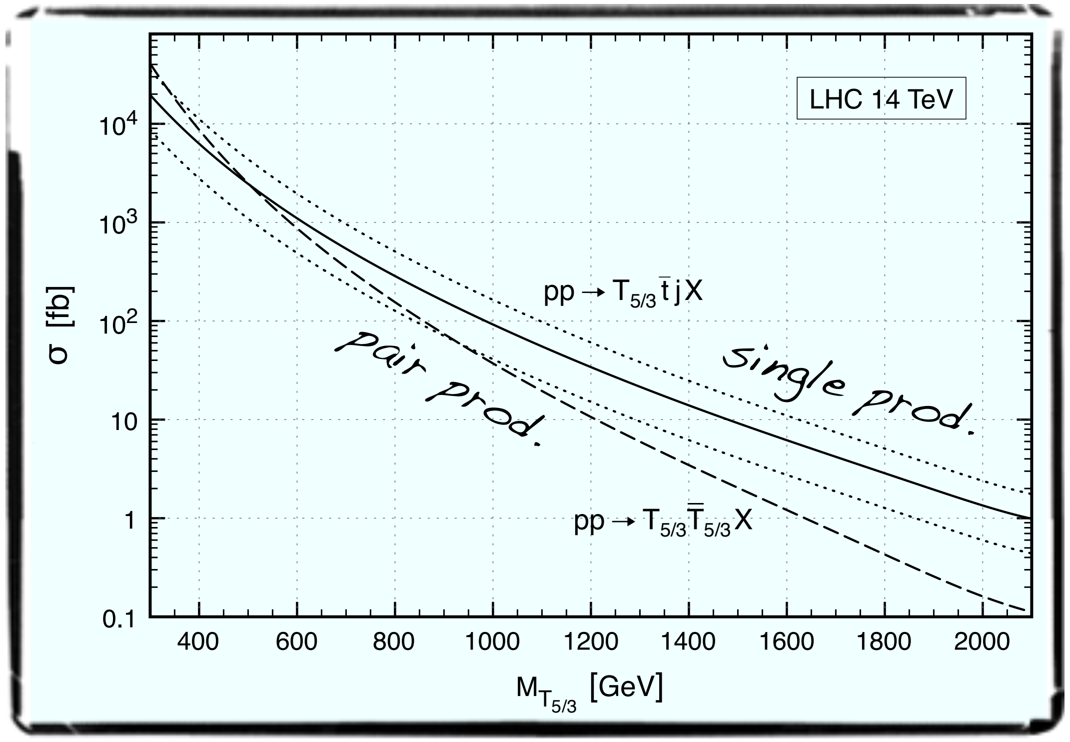
- tt+jets is not a background [except for charge mis-ID and fake e$^-$]
- the resonant (tW) invariant mass can be reconstructed



discovery potential (LHC$_{14\text{TeV}}$)

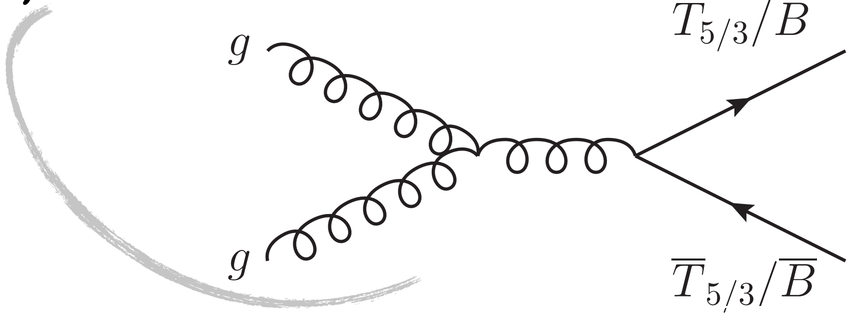
M$_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

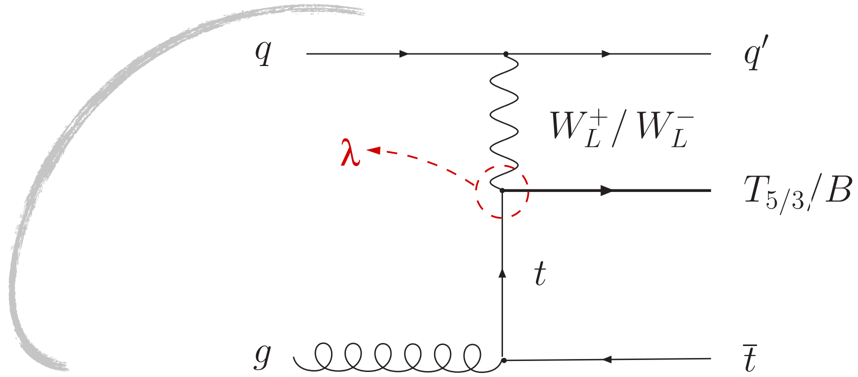
M$_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}



[Contino, Servant ’08]

Pair production (model independent)





Single production (model dependent)

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 a long time to decipher the true dynamics of EWSB!