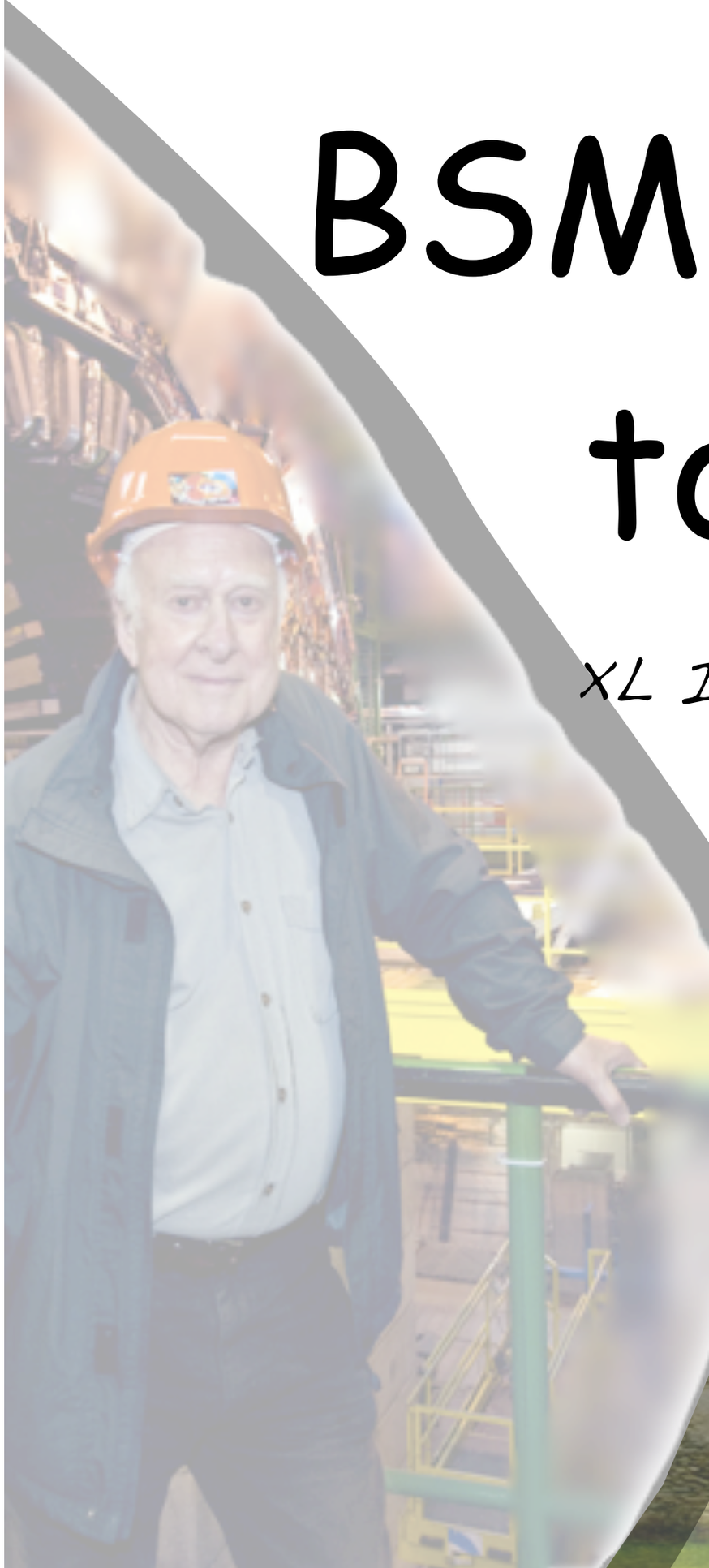


BSM: From the LHC to the Future

XL International Meeting on Fundamental Physics

Benasque, 24 May -- 3 June 2012

Christophe Grojean

CERN-TH

(christophe.grojean@cern.ch)

The Question(s) of the Year

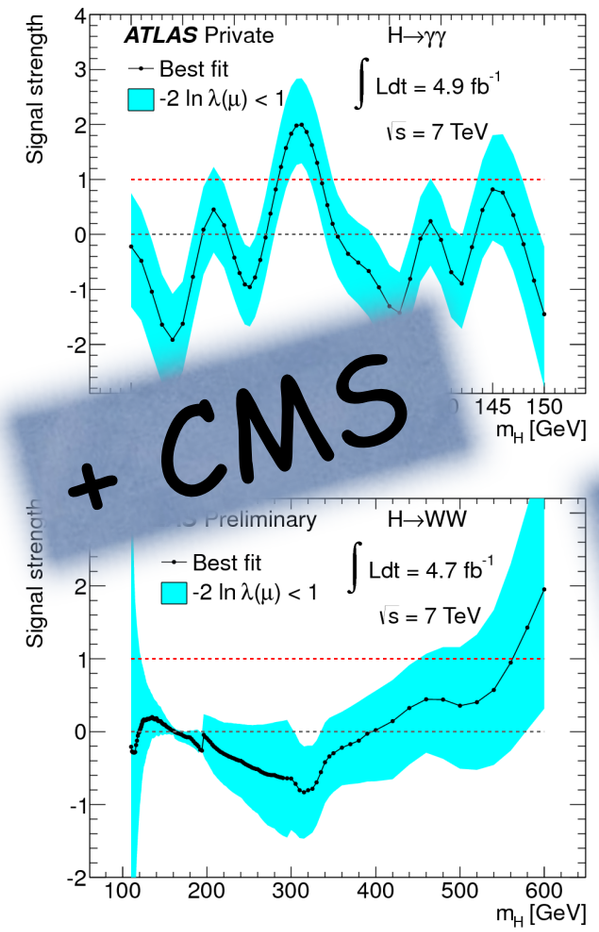
- Is N. Sarkozy going to be re-elected?
- Is the € going to survive?
- Is the Higgs boson going to be discovered?

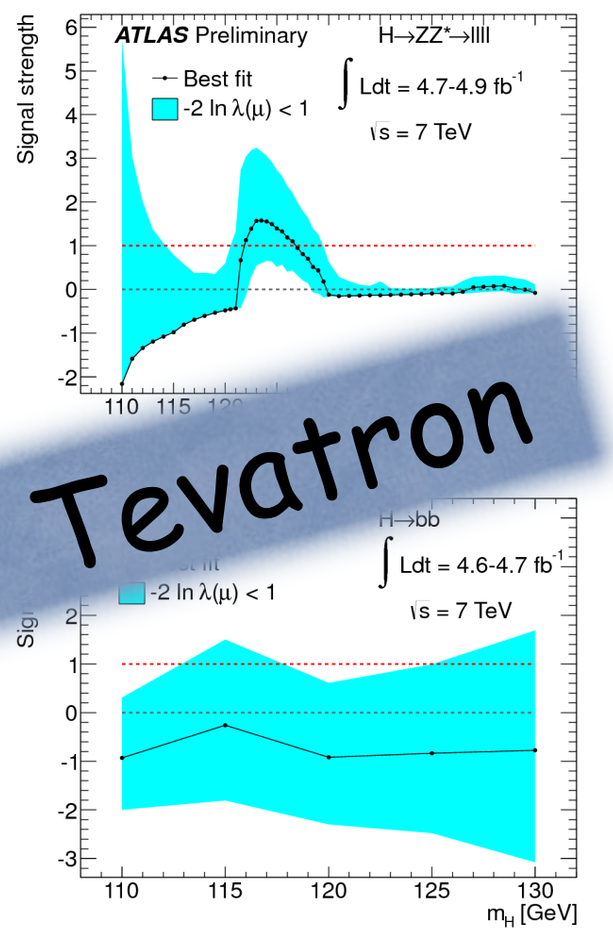
- Where should you invest your money?
  - Greece?
  - Portugal/Italy/(Spain)?
  - Netherlands?
  - Germany?

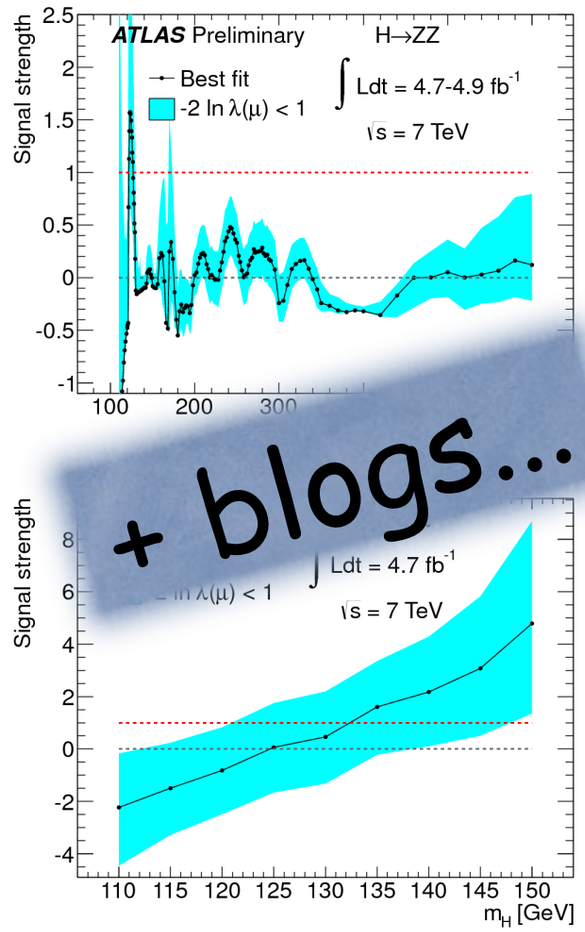
- Which physics to expect Beyond the Standard Model?
  - Technicolor/Higgsless?
  - (C)MSSM?
  - Natural/Split SUSY? Composite Higgs?
  - SM?

Facts that we have to live with

signal strength $$\mu_i = \frac{\sum_j \mathcal{A}_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)}{\sum_j \mathcal{A}_{ji}\,\sigma(j \to h) \times \mathrm{Br}(h \to i)\;|_{\mathrm{SM}}}$$







+ CMS

+ Tevatron

+ blogs...

Still not enough information:

Correlations?

Exact likelihoods?

Chiral Lagrangian for a light Higgs

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2}m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\,\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\,\frac{h}{v} + c_{2gg}\,\frac{h^2}{v^2}\ldots\right)\right]$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}\, G^2_{\mu\nu}\,\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}\, G_{\mu\rho}G_{\rho\nu}\,\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$
  - ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
- ☑ no Higgs FCNC
  - ↖ Flavor

Contino, Grojean, Moretti, Piccinini, Rattazzi '10 Azatov, Contino, Galloway '12

Chiral Lagrangian for a light Higgs

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots$$

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$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi \frac{h}{v} \ldots\right)$$

$$+ G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2}\ldots\right)\Bigg]$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}G_{\mu\nu}^2\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

still too much freedom

⇓

dynamical assumptions needed

⇓

to explore deformations of the SM

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$
  - ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
- ☑ no Higgs FCNC
  - ↖ Flavor

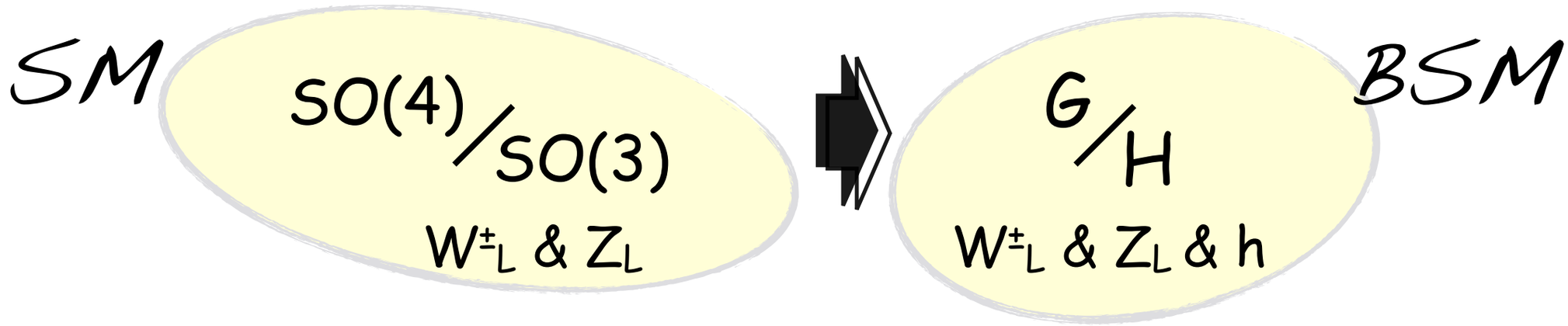
Contino, Grojean, Moretti, Piccinini, Rattazzi '10 Azatov, Contino, Galloway '12

The New Physics Mass Gap

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

The New Physics Mass Gap

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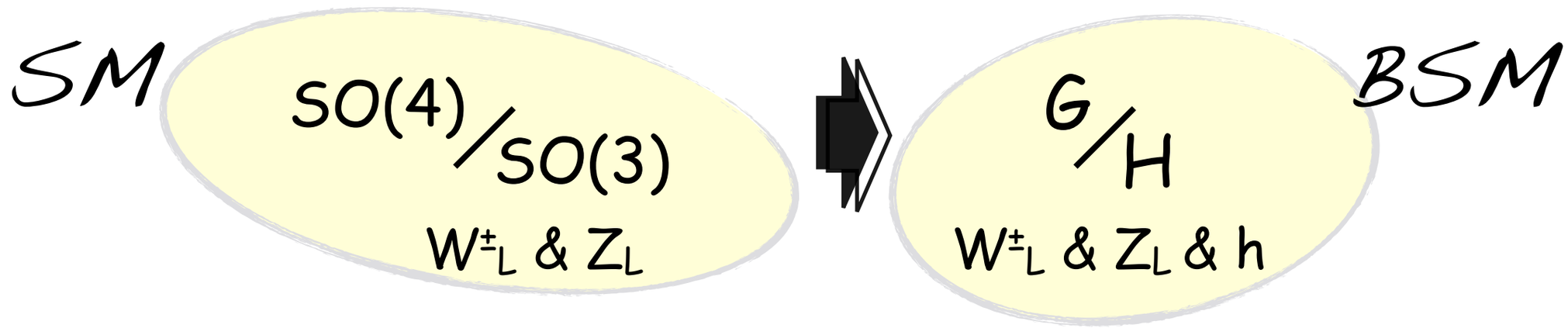


How can we tell the difference with the SM Higgs?

What are the experimental constraints?

SILH Effective Lagrangian

Giudice, Grojean, Pomarol, Rattazzi '07

At the moment, we don't need to know what the Higgs is made of

⇛ chiral Lagrangian for the composite Higgs ⇚

■ 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.

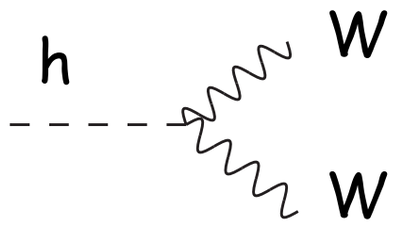
2 parameter Higgs physics @ LHC$_{2011\text{-}2012}$

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

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

$$\frac{c_y y_\psi}{f^2}|H|^2 \bar{\psi}_L H \psi_R$$

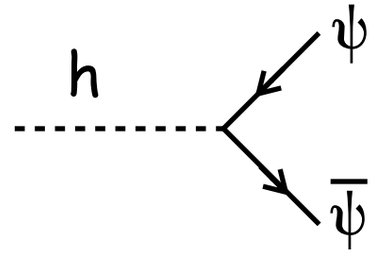
Controls the hWW, hZZ couplings



$$a\, g^{SM}_{hVV}$$

$$a = 1 - c_H\,\xi/2$$

Controls the hψψ couplings



$$c\, g^{SM}_{h\psi\psi}$$

$$c = 1 - (c_H + 2c_y)\,\xi/2$$

Explicit (and calculable) models built in AdS$_5$ spacetimes

Agashe, Contino, Pomarol '04 — Contino, Da Rold, Pomarol '06

MCHM5

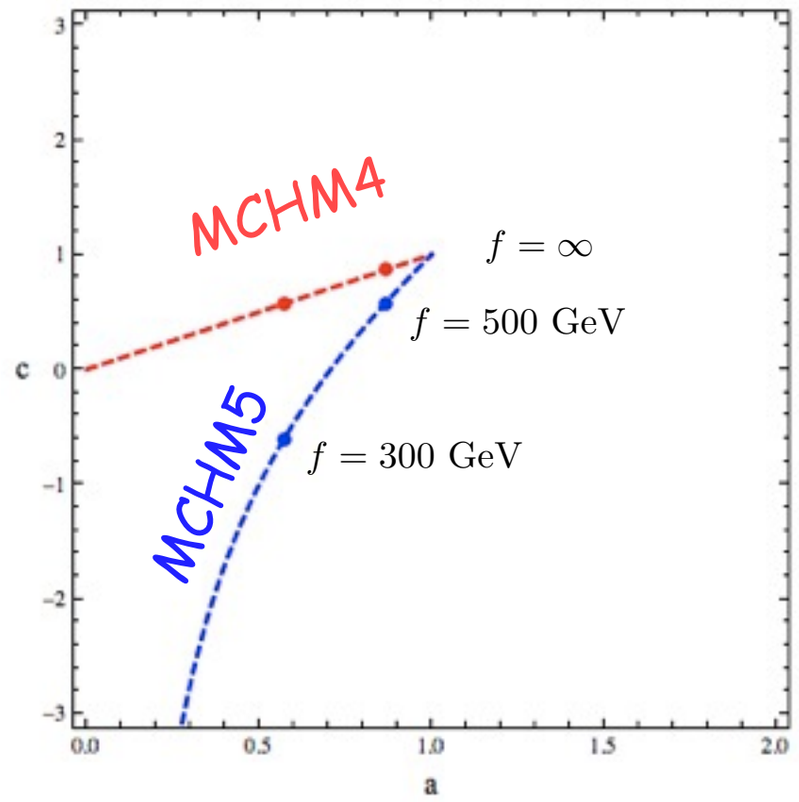
$$a = \sqrt{1-\xi} \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

MCHM4

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

disfavored by EW data (Zbb)

SM is recovered as a limit when the compositeness scale is well above weak scale



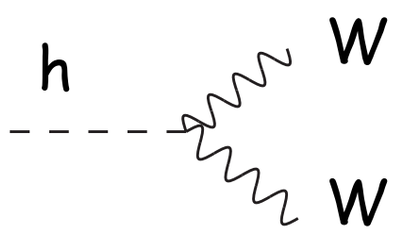
2 parameter Higgs physics @ LHC$_{2011\text{-}2012}$

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

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

$\frac{c_y y_\psi}{f^2}|H|^2 \bar{\psi}_L H \psi_R$

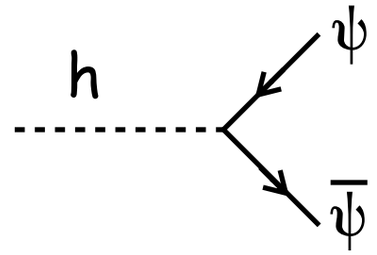
Controls the hWW, hZZ couplings



$a\, g^{SM}_{hVV}$

$a = 1 - c_H\, \xi/2$

Controls the hψψ couplings

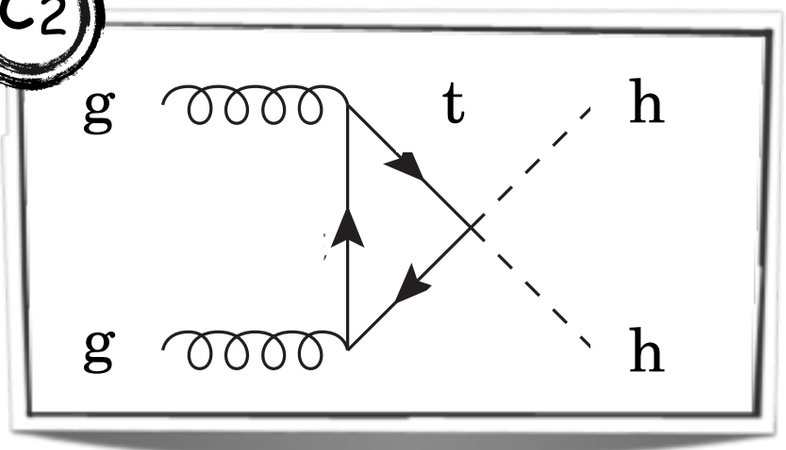


$c\, g^{SM}_{h\psi\psi}$

$c = 1 - (c_H + 2c_y)\, \xi/2$

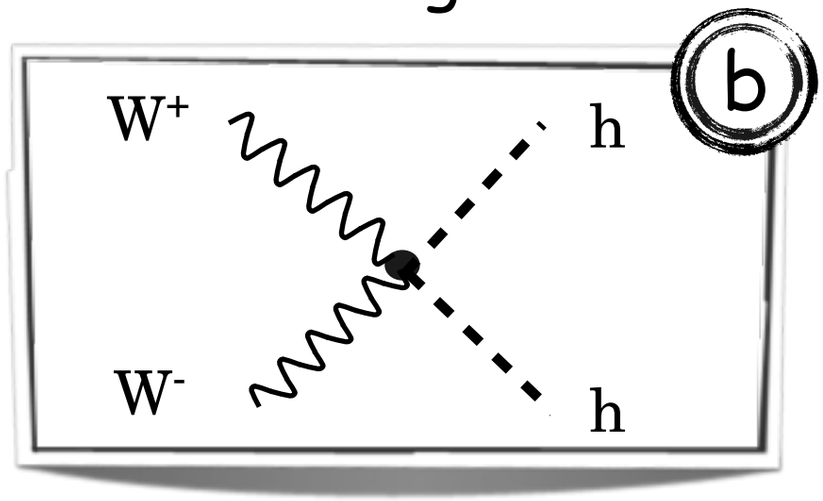
other couplings are very interesting as they are directly testing non-linearities/strong interactions of the Higgs

c2



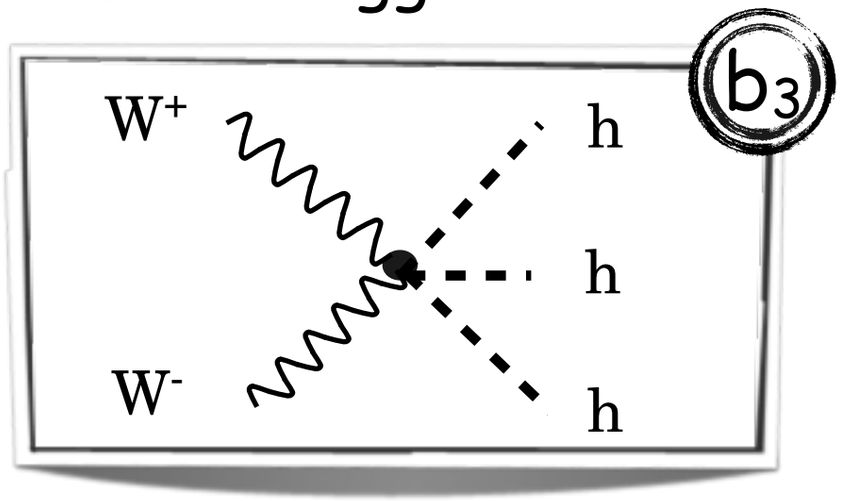
Grôber, Mühlleitner '10
Contino et al '12
Gillioz et al 'to appear

b



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

b3



Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm 'to appear

but they are not on agenda of the current LHC run

2 parameter Higgs physics @ LHC$_{2011\text{-}2012}$

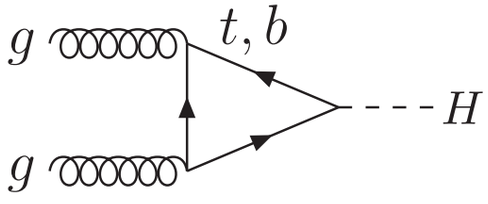
- Higgs couplings modified w.r.t. SM but same kinematics

  (particular to single Higgs process - with more than one Higgs, sensitive to derivative couplings)

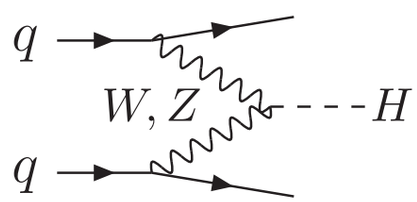
- Background processes unaffected

⇓ ⇓ ⇓

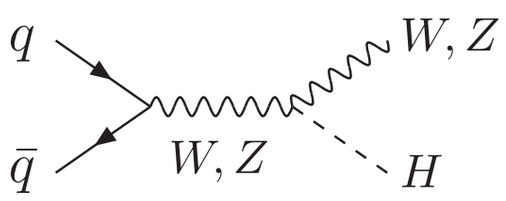
simple rescaling of SM searches



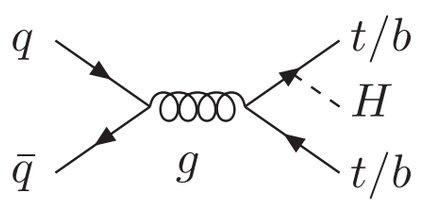
c^2



a^2



a^2



c^2

$$\frac{\sigma_{NLO}}{\sigma_{NLO}^{SM}}$$

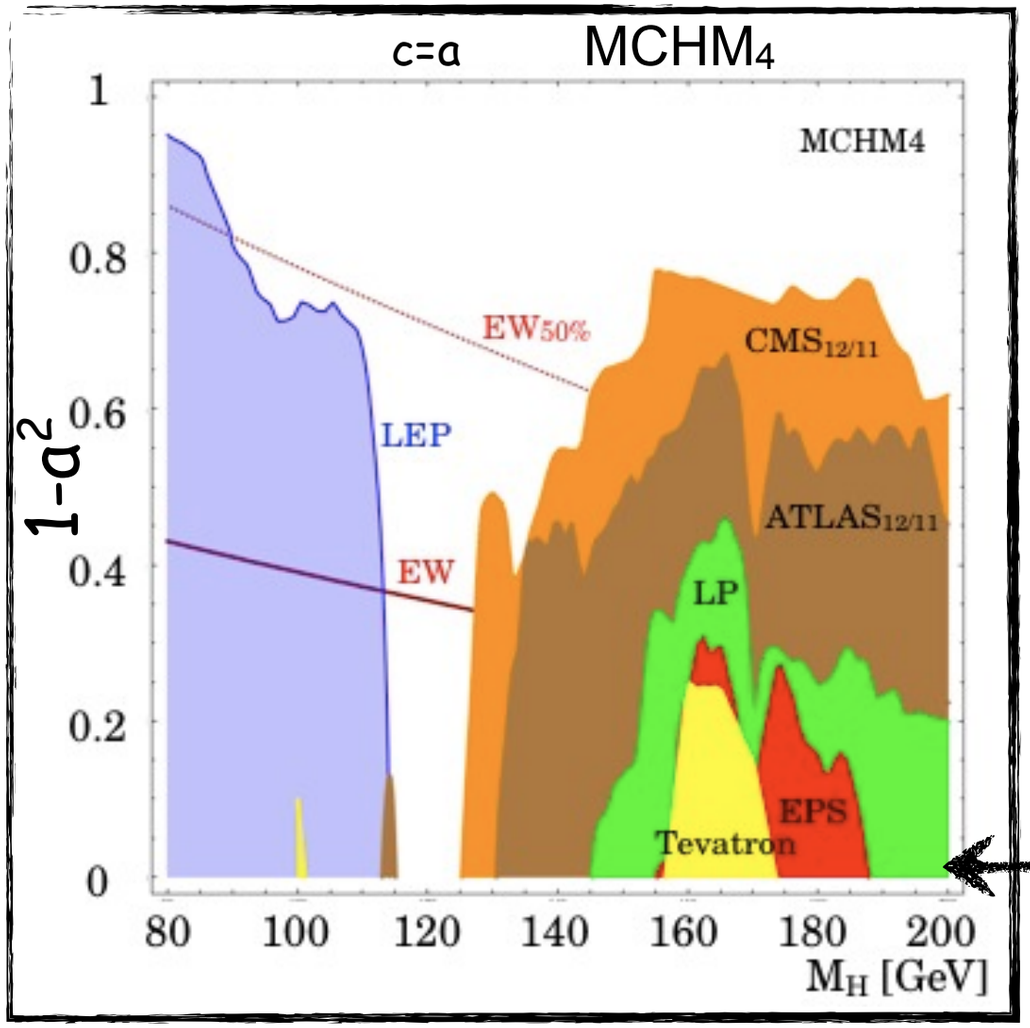
The QCD NLO rescale trivially in the flavor universal limit. Not the EW NLO

$$\Gamma(H \to f\bar{f}) = c^2\,\Gamma^{SM}(H \to f\bar{f})\,,$$
$$\Gamma(H \to VV) = a^2\,\Gamma^{SM}(H \to VV)\,,$$
$$\Gamma(H \to gg) = c^2\,\Gamma^{SM}(H \to gg)\,,$$
$$\Gamma(H \to \gamma\gamma) = \frac{(cI_\gamma + aJ_\gamma)^2}{(I_\gamma + J_\gamma)^2}\Gamma^{SM}(H \to \gamma\gamma)\,, \quad \simeq (1.26\,a - 0.26\,c)^2 \text{ for } m_h = 125\text{GeV}$$

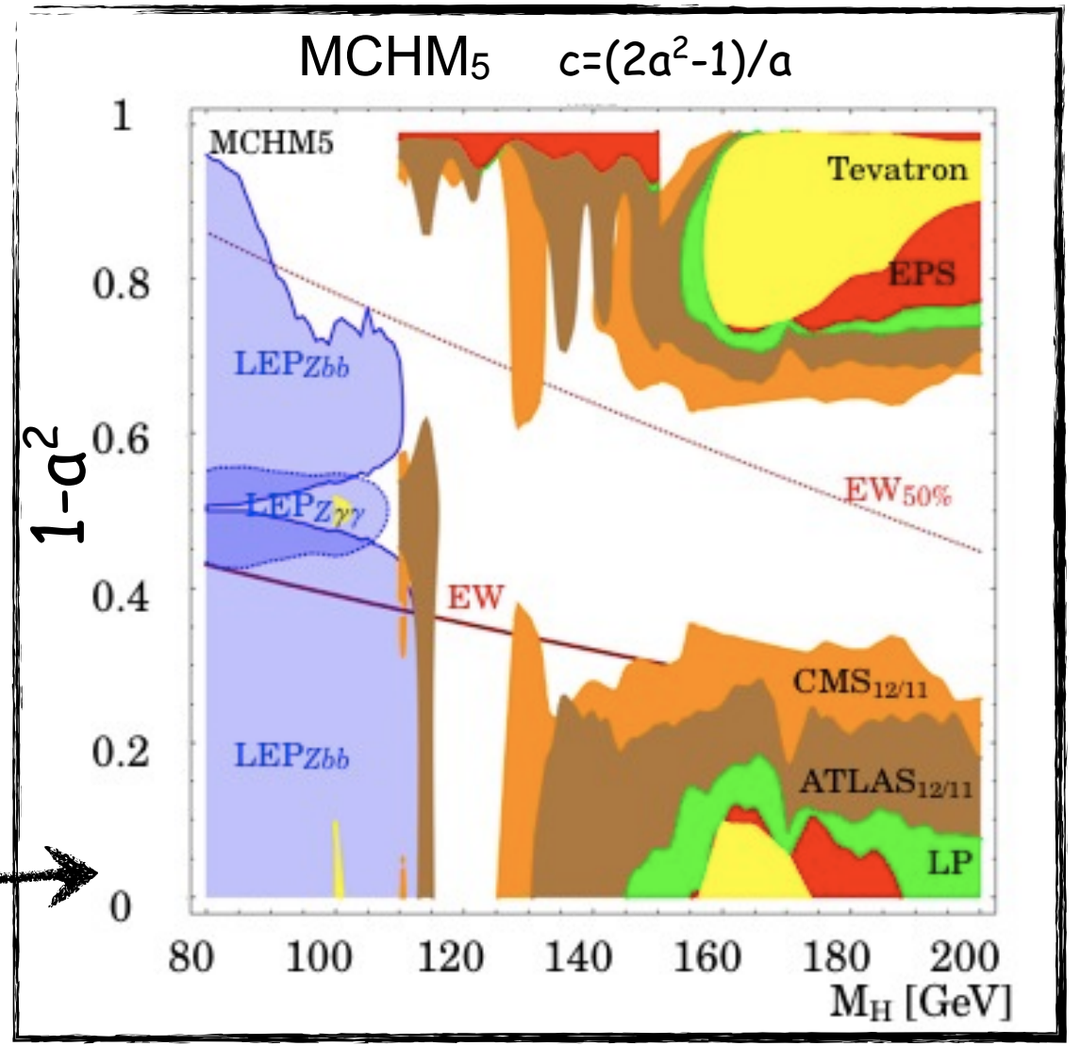
Deformation of the SM Higgs: current constraints

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

Espinosa, Grojean, Muehlleitner '11



SM limits



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

for similar analysis, see also Azatov, Contino, Galloway '12

Model independent χ^2 fit to LHC excess @ 125

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

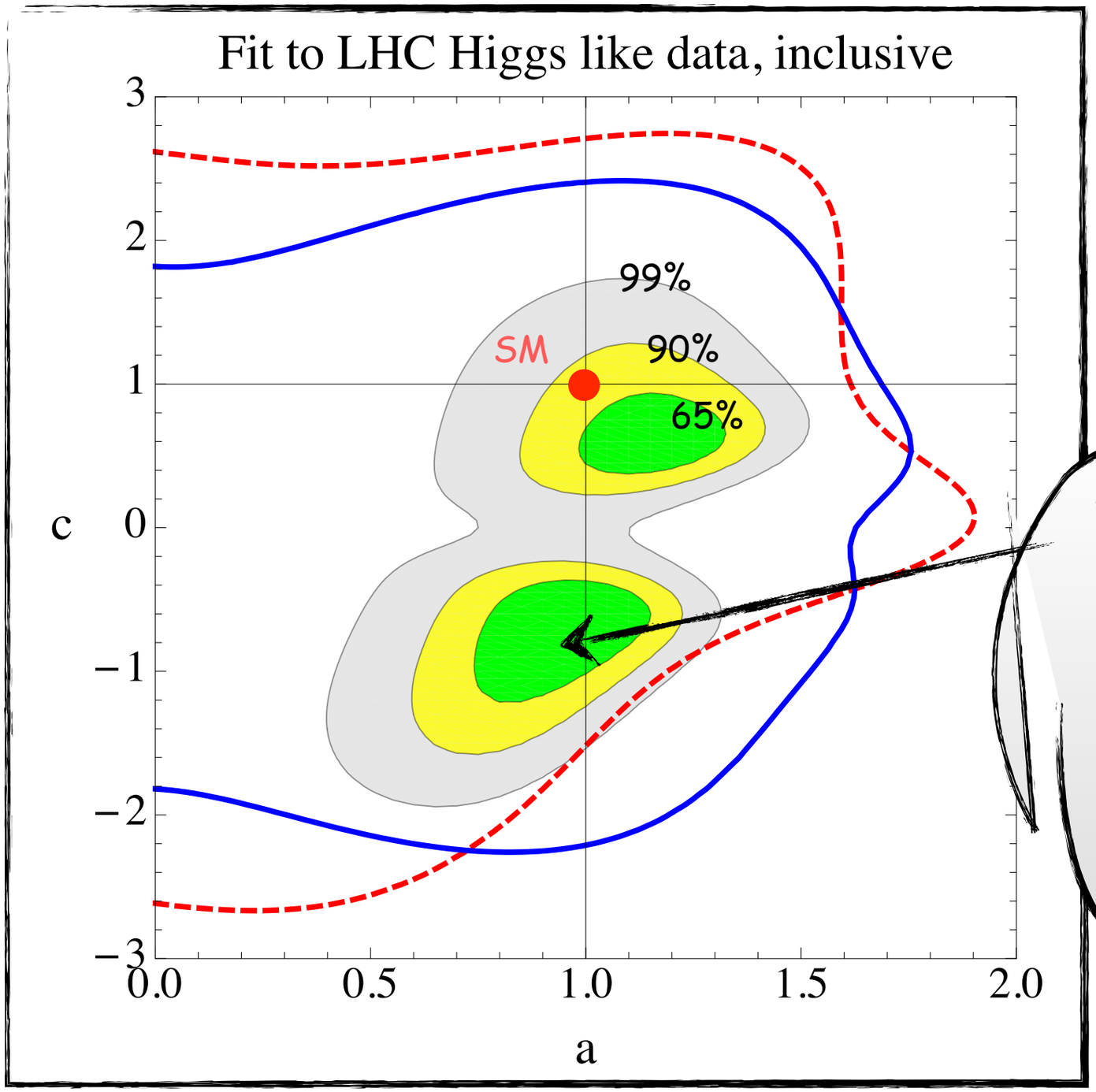
CMS 95%CL exclusion

SM 82%CL away from best fit point

Two minima:

(a,c)=(1.13,0.58)
χ^2=2.86

(a,c)=(0.96,-0.64)
χ^2=1.96



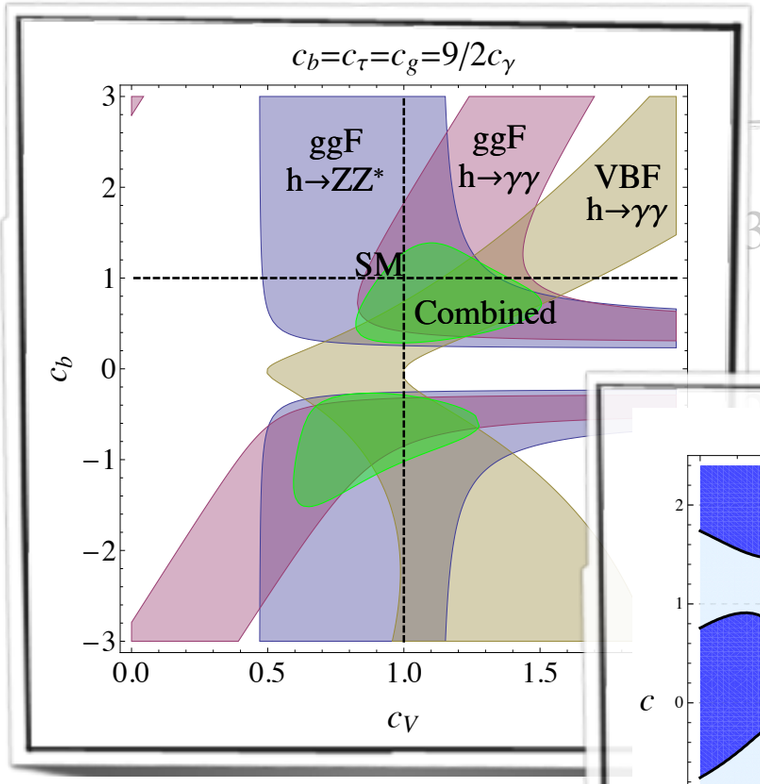
note: a fermiophobic Higgs is disfavored by data (mostly VBF channels)

"disfermiophilia"

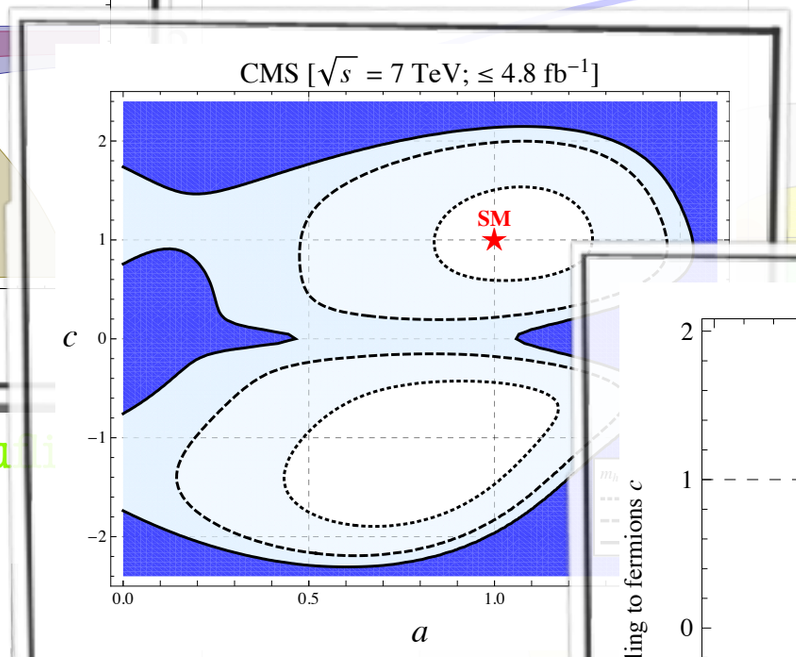
the current data prefers "negative" coupling to fermions
≈
positive interference between top and W in $\gamma\gamma$ channel

Model independent χ^2 fit to LHC excess @ 125

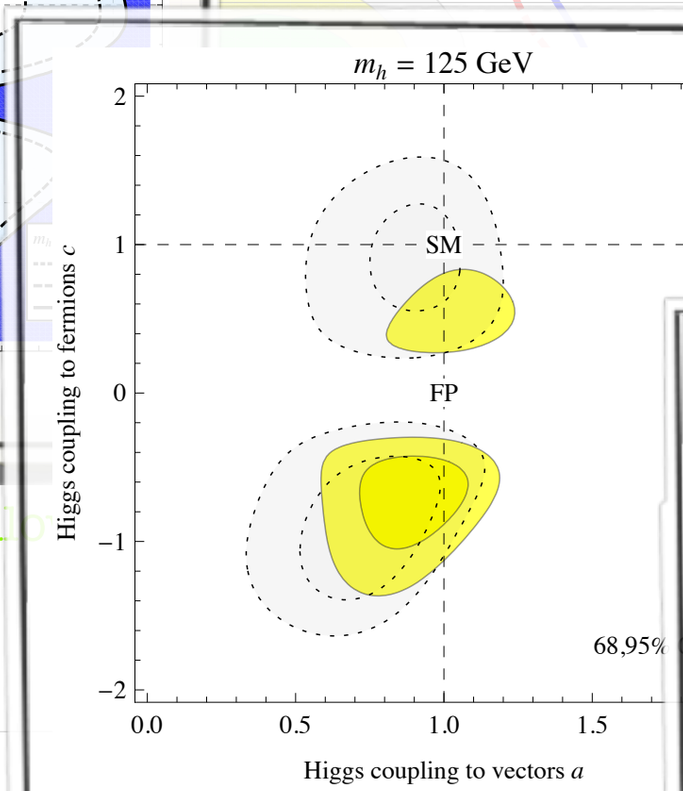
Espinosa, Grojean, Muhlleitner, Trott '12



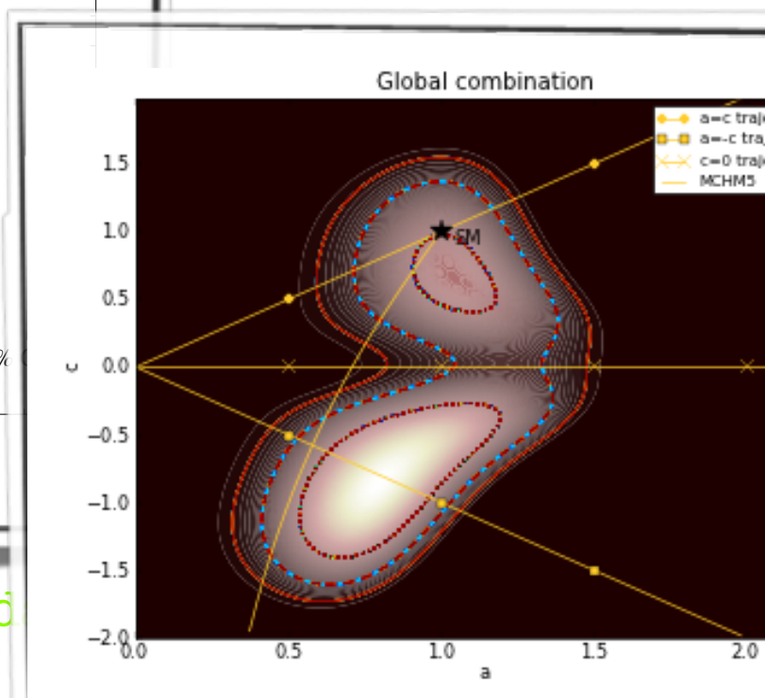
Carni, Falkowski, Ku
Volansky '12



Azatov, Contino, Gall
'12



Giardino, Kannike, Raid
Strumia '12



Ellis, You '12

Model independent χ^2 fit to LHC excess @ 125

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

CMS

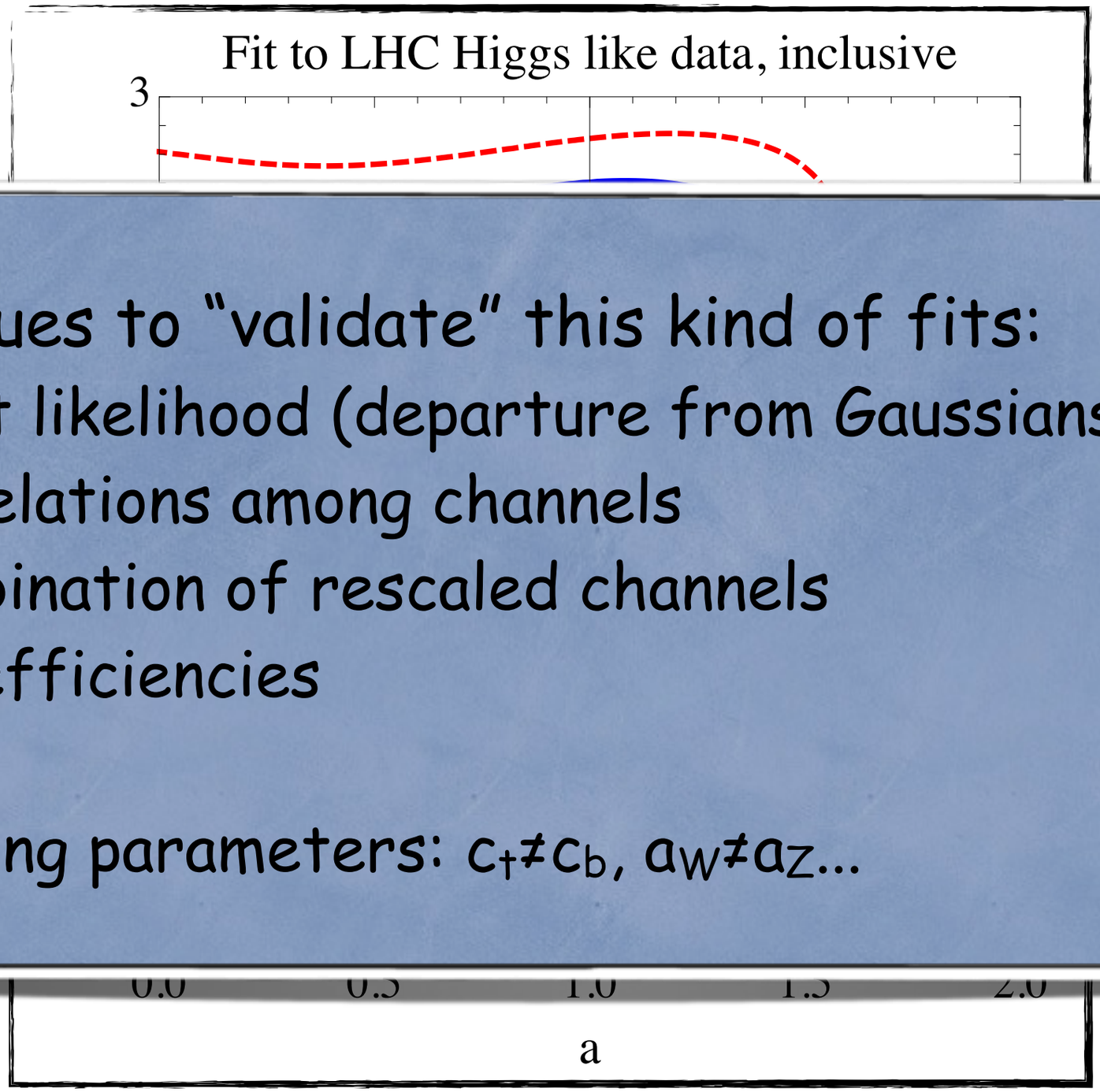
be

Tw

(a,

(a,c)=(0.96,-0.64)

χ^2=1.96



note: a fermiophobic Higgs is disfavored by

many issues to "validate" this kind of fits:

1. exact likelihood (departure from Gaussians...)
2. correlations among channels
3. combination of rescaled channels
4. cut efficiencies
5. ...
6. missing parameters: $c_t \neq c_b$, $a_W \neq a_Z$...

for similar analyses, see also

Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

Model independent χ^2 fit to (Moriond) LHC data

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

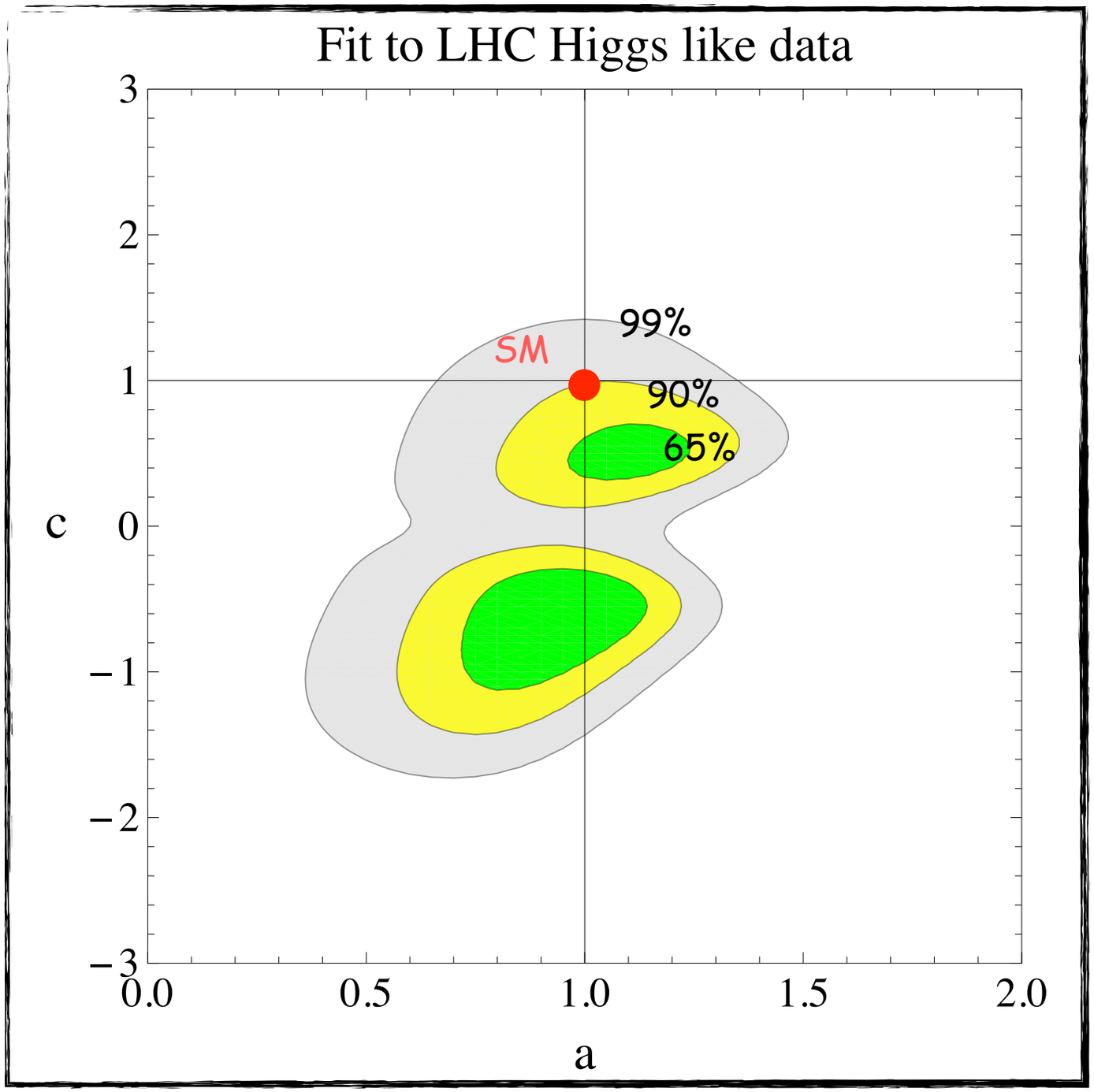
CMS 95%CL exclusion

SM 88%CL away from best fit point (~2σ)

Two minima:

(a,c)=(1.18,0.55)
χ^2=7.5

(a,c)=(0.99,-0.64)
χ^2=6.3

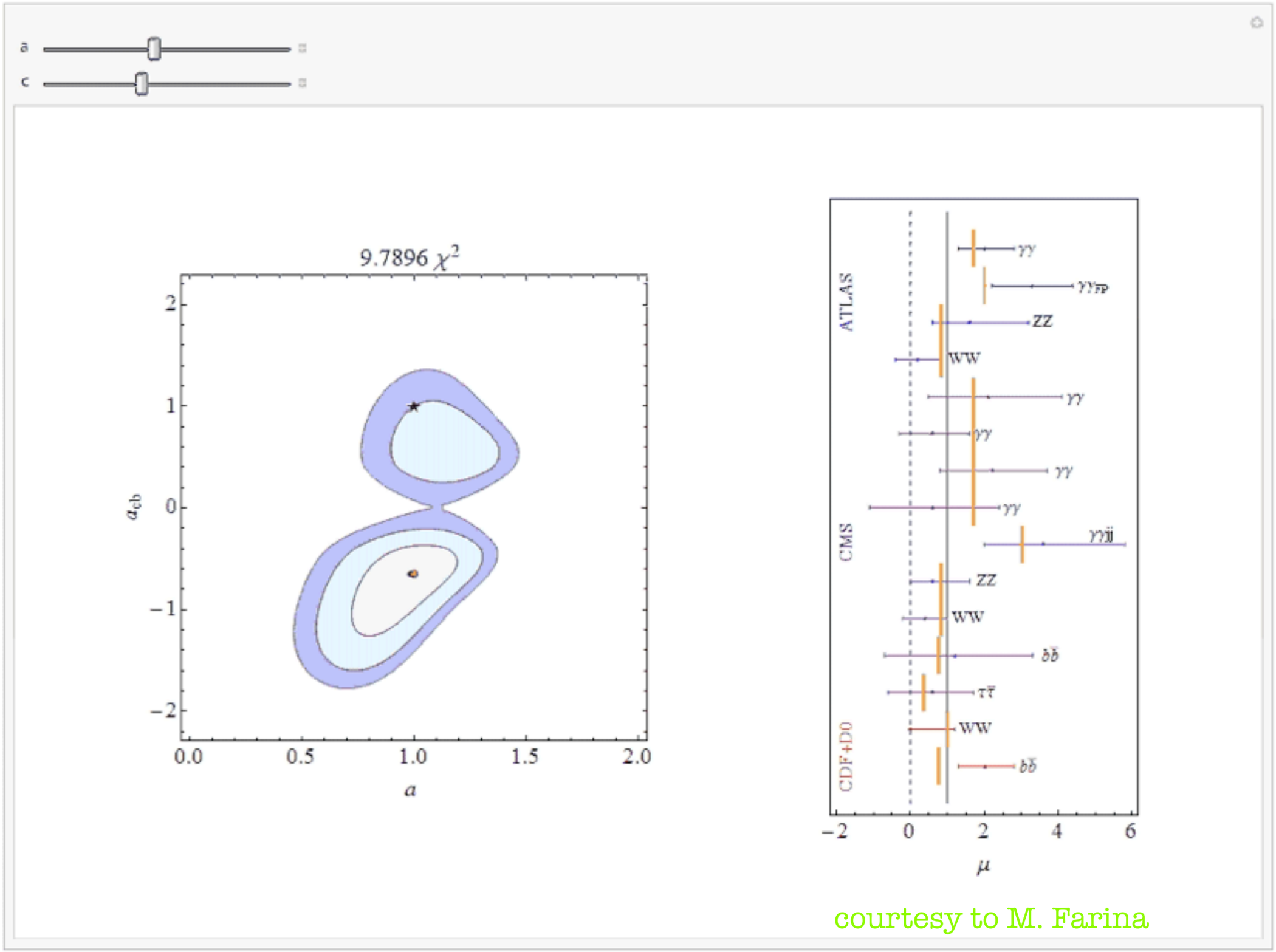


note: a fermiophobic Higgs is disfavored by data (mostly VBF channels) at 97%CL

for similar analyses, see also Azatov, Contino, Galloway '12

Carni, Falkowski, Kuflik, Volansky '12

Model independent χ^2 fit to LHC data



courtesy to M. Farina

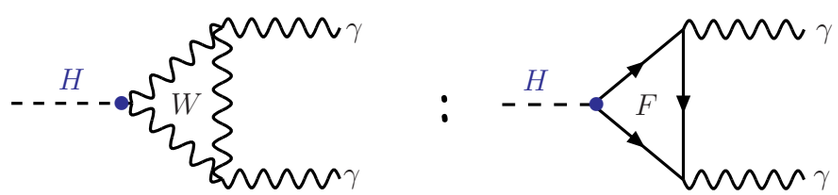
Fermiophilia or Disfermiophilia?

difficult!

Farina, Grojean, Maltoni, Salvioni, Thamm 'in progress

difference is physically relevant only in the presence of strong interference with single $h\psi\psi$ coupling

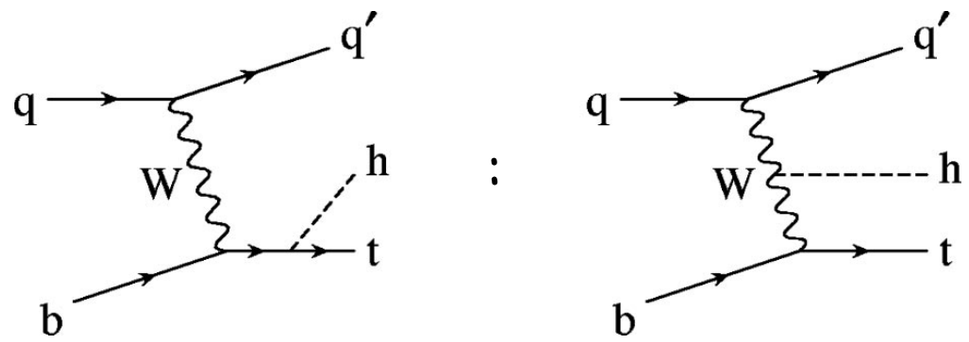
$h \to \gamma\gamma$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 1.4$

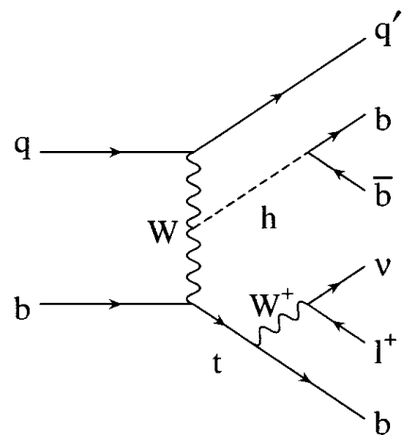
rare decay and one needs some largish luminosity to be sensitive to the sign of c

$qb \to q'th$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

look at final state: $3b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$.



Maltoni, Stelzer, Willenbrock '01

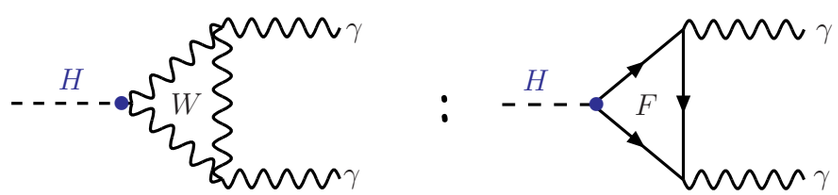
Fermiophilia or Disfermiophilia?

difficult!

Farina, Grojean, Maltoni, Salvioni, Thamm 'in progress

difference is physically relevant only in the presence of strong interference with single $h\psi\psi$ coupling

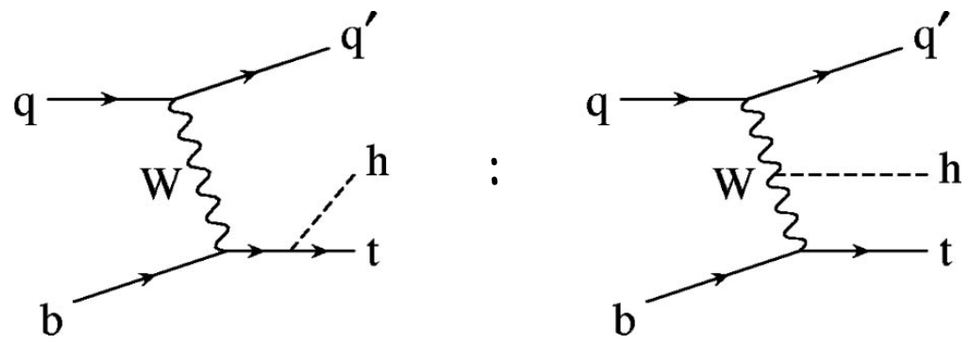
$h \to \gamma\gamma$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 1.4$

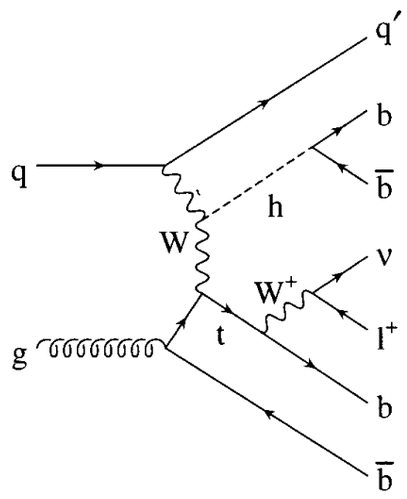
rare decay and one needs some largish luminosity to be sensitive to the sign of c

$qb \to q'th$



@m_H=125GeV $\quad \dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

look at final state: $4b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$.

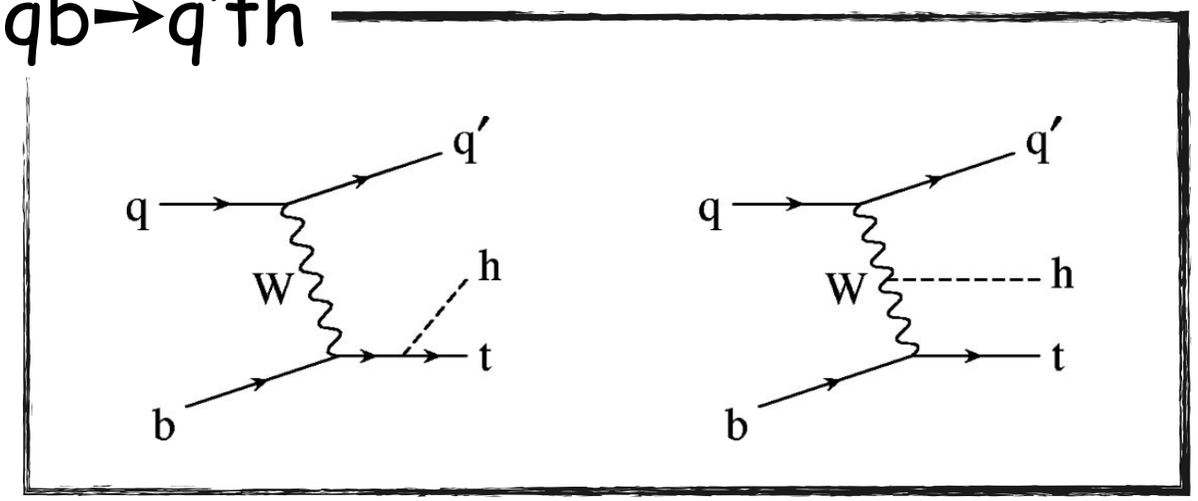


Maltoni, Stelzer, Willenbrock '01

Fermiophilia or Disfermiophilia?

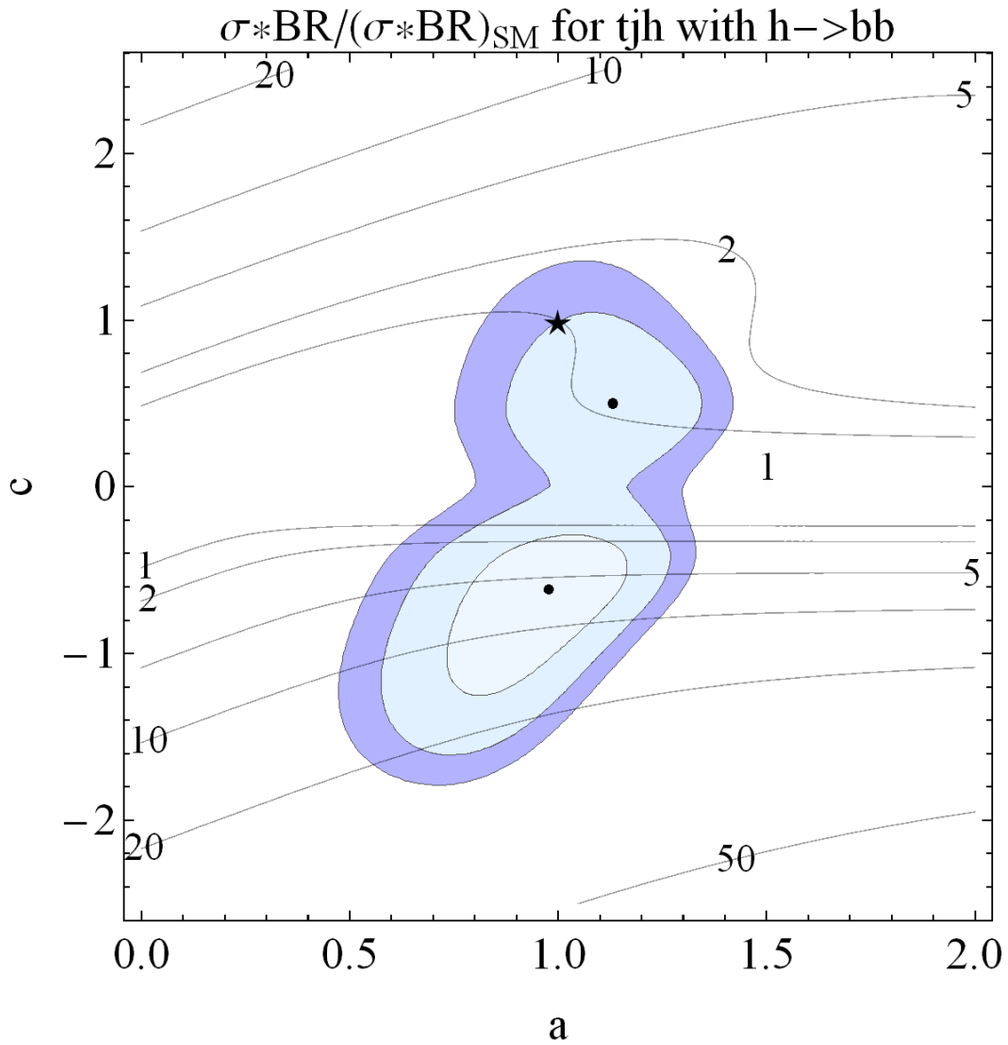
Farina, Grojean, Maltoni,
Salvioni, Thamm 'in progress

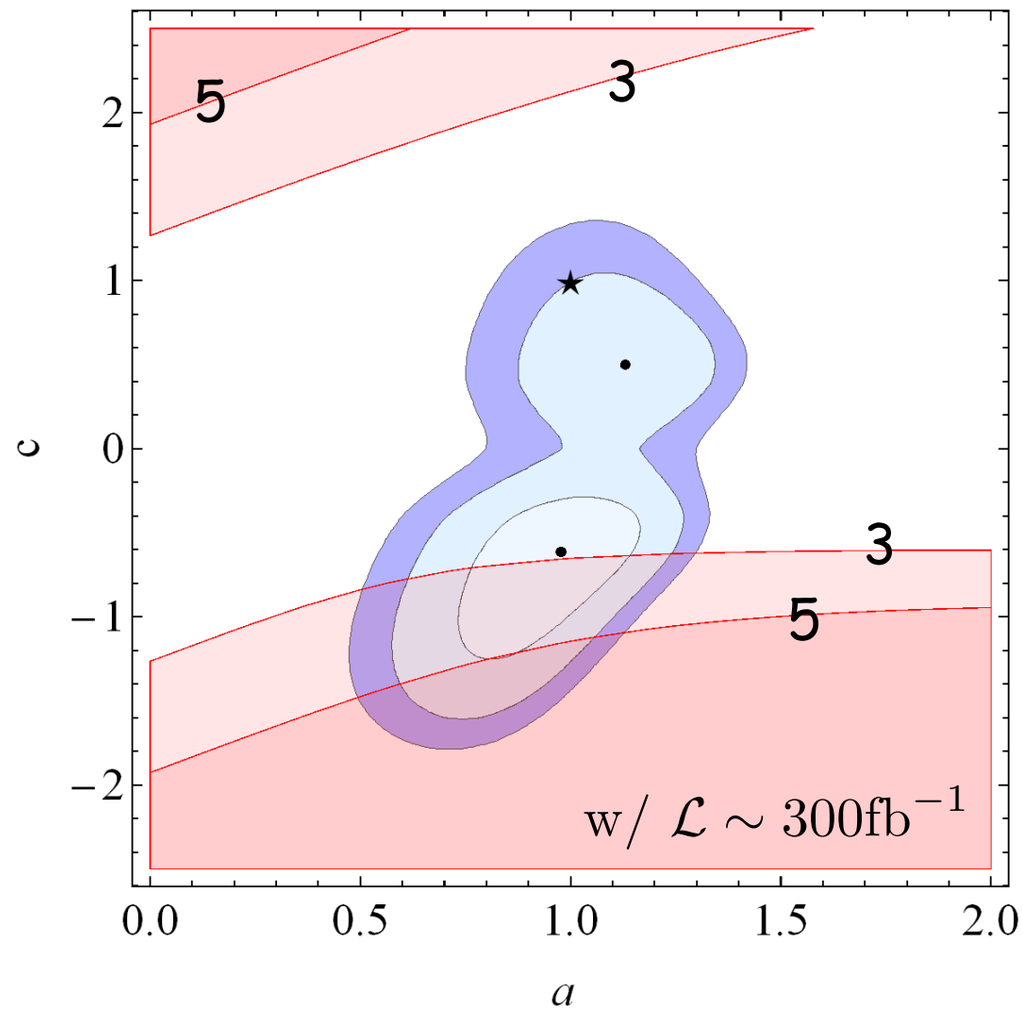
qb→q'th



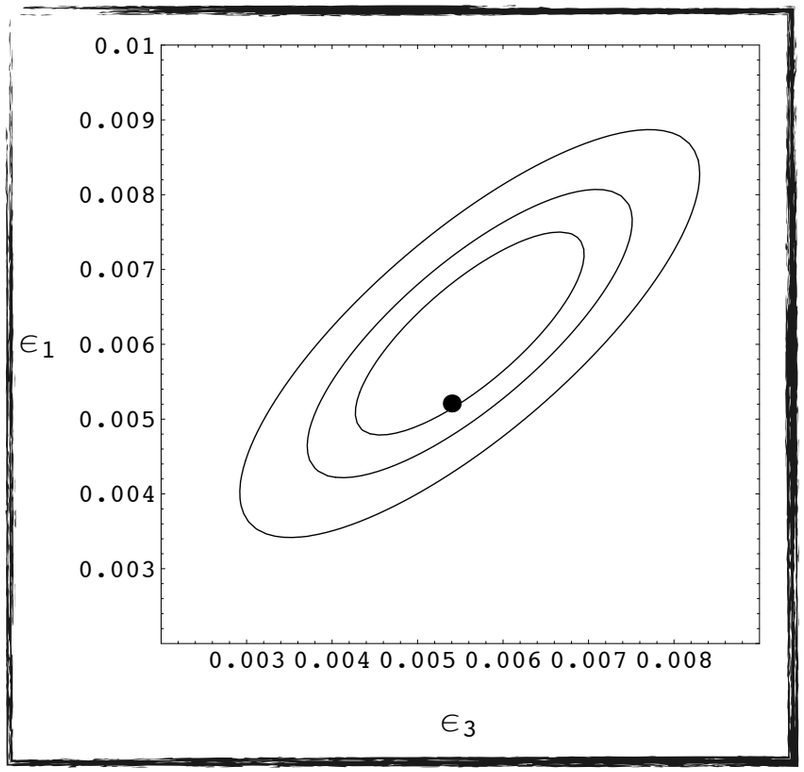
the sign ambiguity will remain with us for a long time!

$$S/\sqrt{S+B}$$





A tension between LHC and EW data?



EW fit strongly suggests custodial symmetry

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

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

$$\frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \Rrightarrow \rho = 1 \text{ ie } \epsilon_1 = \hat{T} = 0$$

✓

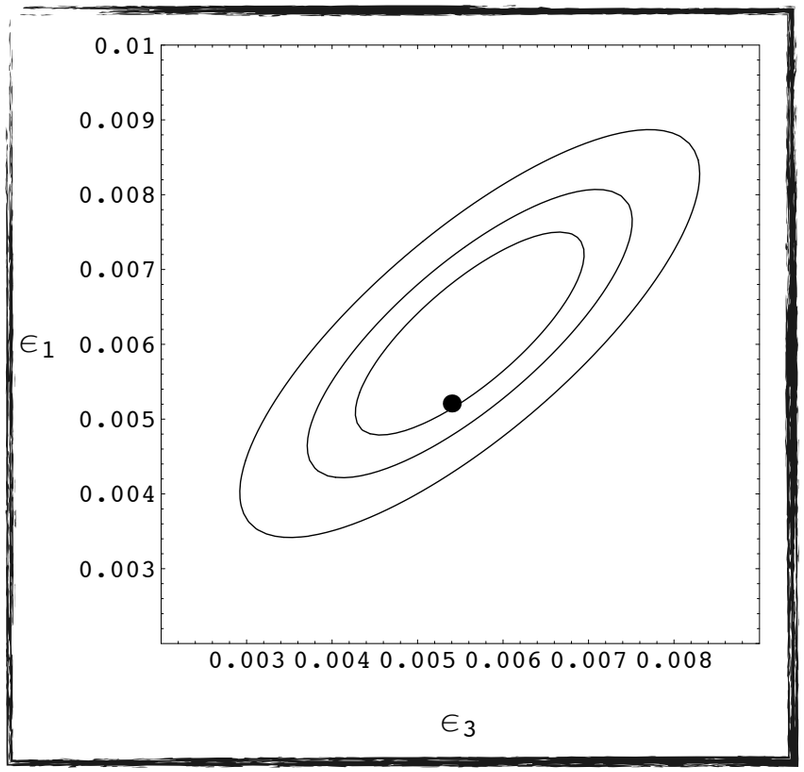
also $\Rrightarrow$ $\mu_{ZZ} = \mu_{WW}$

$$\left(\mu_i = \frac{\sum_j \mathcal{A}_{ji}\, \sigma(j \to h) \times \mathrm{Br}(h \to i)}{\sum_j \mathcal{A}_{ji}\, \sigma(j \to h) \times \mathrm{Br}(h \to i)\ |_{\mathrm{SM}}} \right)$$

$$\frac{v^2}{8}\mathrm{Tr}^2\left(\Sigma^\dagger D_\mu \Sigma \sigma^3\right) \Rrightarrow \rho = 2 \quad \text{ie} \quad \epsilon_1 = \hat{T} = 1$$

strongly disfavored

A tension between LHC and EW data?



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✓

also $\Rrightarrow$ $\mu_{ZZ} = \mu_{WW}$ ✗

but

Channel [Exp]	$\mu_{119.5}$ $(\mu^L_{119.5})$	μ_{124} (μ^L_{124})	μ_{125} (μ^L_{125})
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [ATLAS]	$-0.5^{+0.5??}$ (5.1)	$1.6^{+1.4}_{-0.8}$ (4.7)	$1.4^{+1.3}_{-0.8}$ (4.1)
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar{\nu}$ [ATLAS]	$0.0^{+1.2}_{-1.3}$ (2.4)	$0.1^{+0.7}_{-0.7}$ (1.6)	$0.1^{+0.7}_{-0.6}$ (1.4)

1. has LHC identified a violation of the custodial symmetry?
2. if yes, how to reconcile LHC data with EW data?

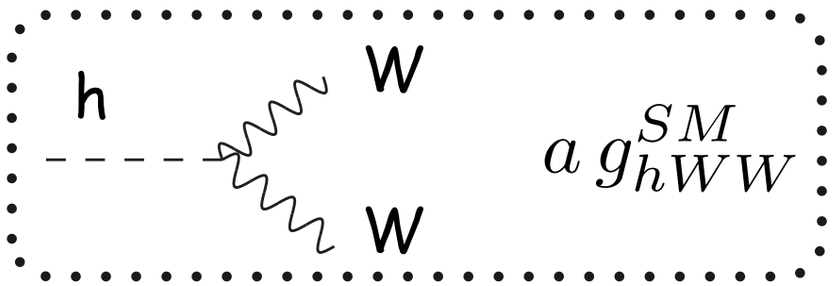
$$\frac{v^2}{8}\mathrm{Tr}^2\left(\Sigma^\dagger D_\mu \Sigma \sigma^3\right) \Rrightarrow \rho = 2 \quad \text{ie} \quad \epsilon_1 = \hat{T} = 1$$

strongly disfavored

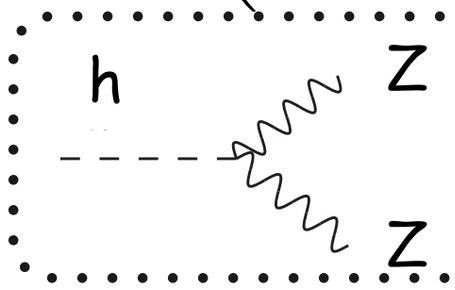
DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni '12

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

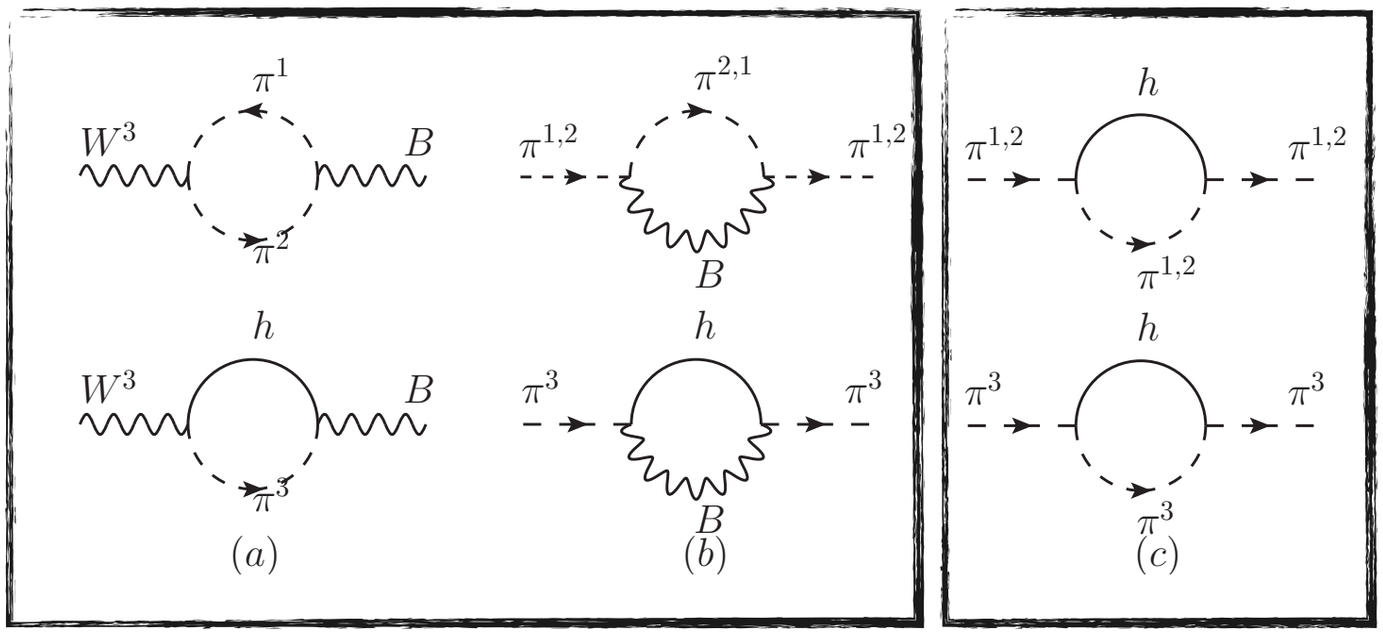


$a\, g^{SM}_{hWW}$



$(a + a_{cb})\, g^{SM}_{hZZ}$

EWPT



Log(Λ) UV sensitivity

$$\Delta\epsilon_1 = -\frac{3}{16\pi}\frac{\alpha(m_Z)}{\cos^2\theta_W}\left[1-(a+a_{cb})^2 + \left(\frac{g}{g'}\right)^2 (a^2-(a+a_{cb})^2)\right]\log\left(\frac{\Lambda^2}{m_h^2}\right)$$

$$\Delta\epsilon_3 = +\frac{1}{48\pi}\frac{\alpha(m_Z)}{\sin^2\theta_W}\left[1-(a+a_{cb})^2\right]\log\left(\frac{\Lambda^2}{m_h^2}\right).$$

Λ^2 UV sensitivity

$$\Delta\epsilon_1 = \left((a+a_{cb})^2 - a^2\right)\frac{\Lambda^2}{16\pi^2 v^2}$$

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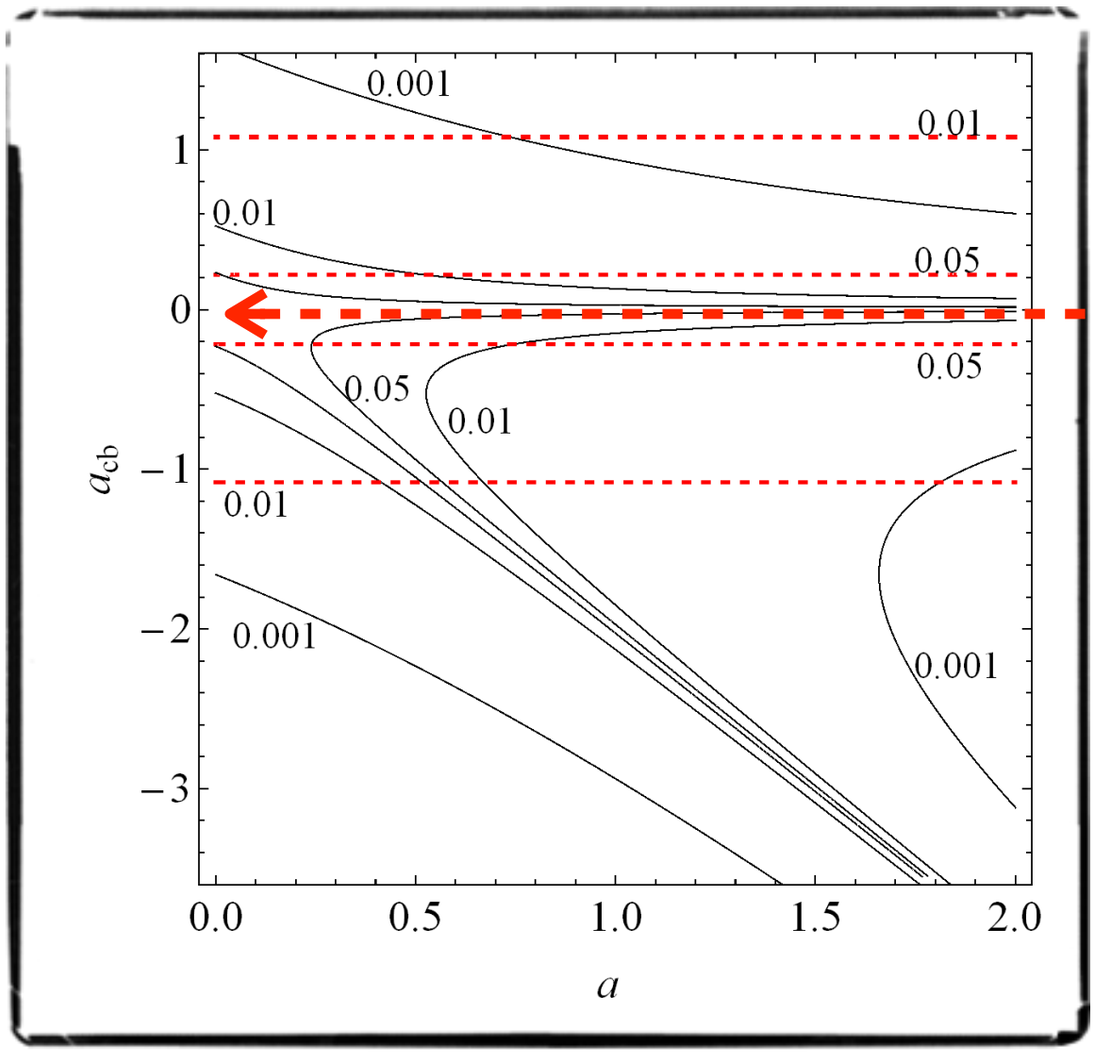
$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

EWPT highly model-dependent

tuning between tree-level and loop contributions?

new light states?



Amount of fine-tuning in EWPT

custodial invariance

Λ^2 UV sensitivity

ie

could be as bad as the hierarchy problem

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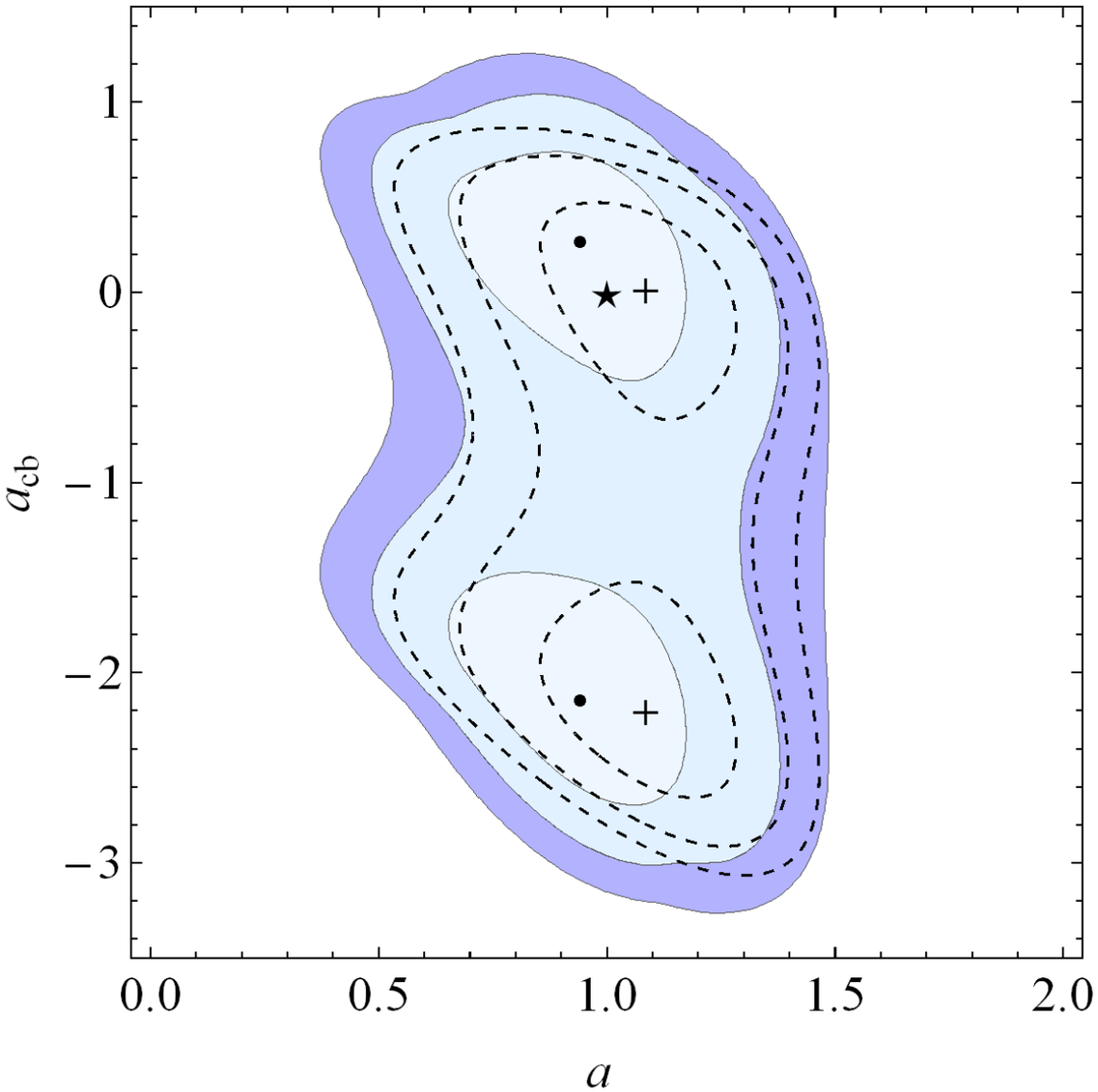
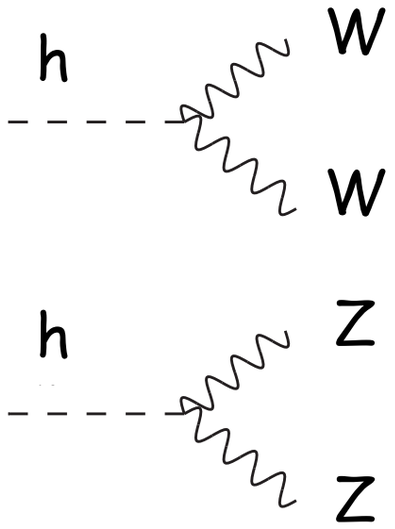
$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

Fit to LHC data



---------- c = 1

———————— marginalization over c



$$a\, g^{SM}_{hWW}$$

$$(a + a_{cb})\, g^{SM}_{hZZ}$$

LHC data are symmetric under

$$(a + a_{cb}) \leftrightarrow -(a + a_{cb})$$

i.e.

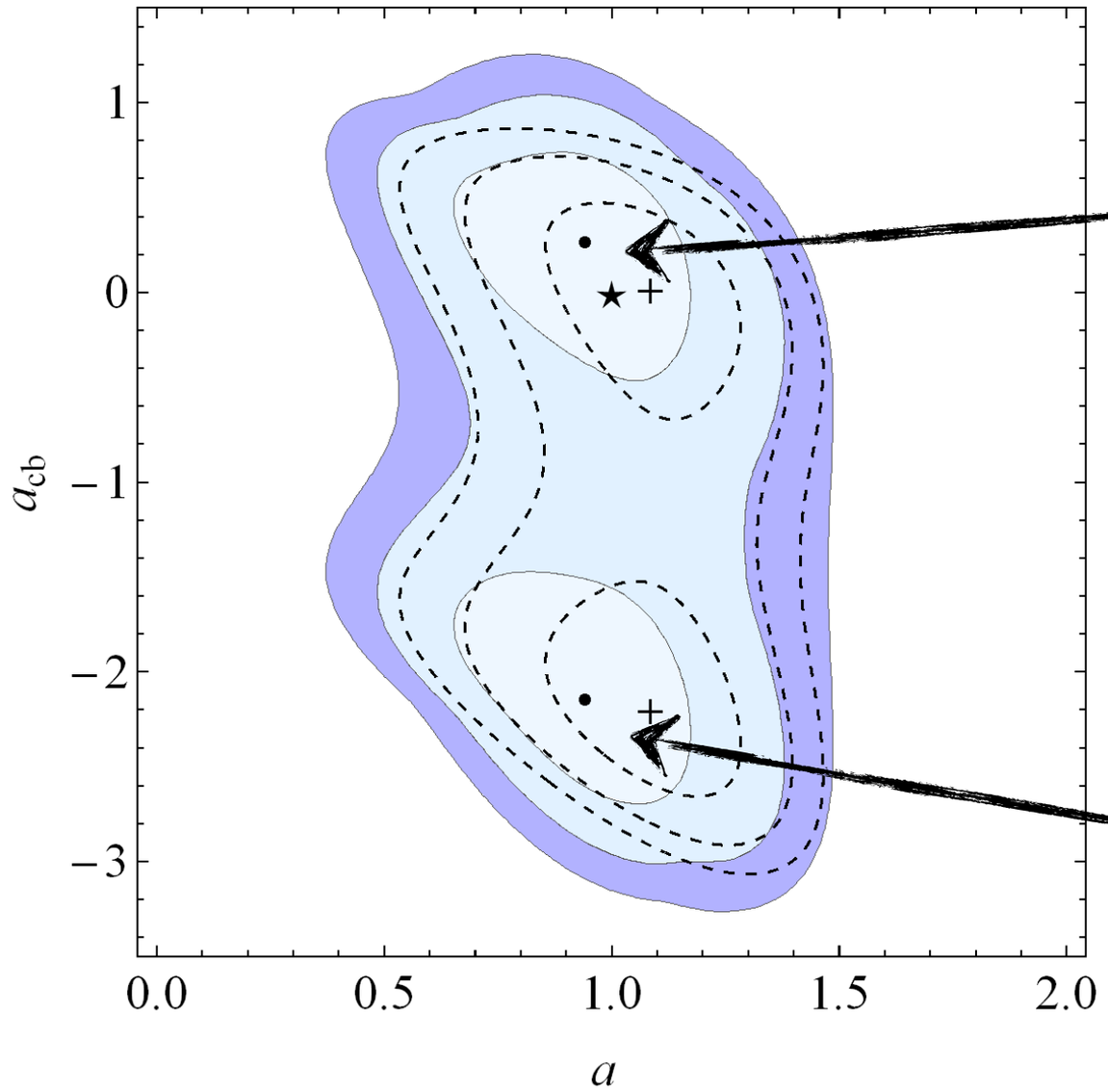
$$(a, a_{cb}) \leftrightarrow (a, -(2a + a_{cb}))$$

DisZphilia or how to live with custodial breaking

Farina, Grojean, Salvioni '12

$$\mathcal{L}_{cb} = -\frac{v^2}{8}\left(\mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right]\right)^2 \left(t_{cb} + 2a_{cb}\frac{h}{v} + \cdots\right)$$

Fit to LHC data



---------- c = 1

———— marginalization over c

$$2\,\frac{h}{v}\left(m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)$$

the two solutions can only be distinguished in the presence of interference with a single hZZ vertex

$$2\,\frac{h}{v}\left(m_W^2 W_\mu^+ W_\mu^- - \frac{1}{2}m_Z^2 Z_\mu Z_\mu\right)$$

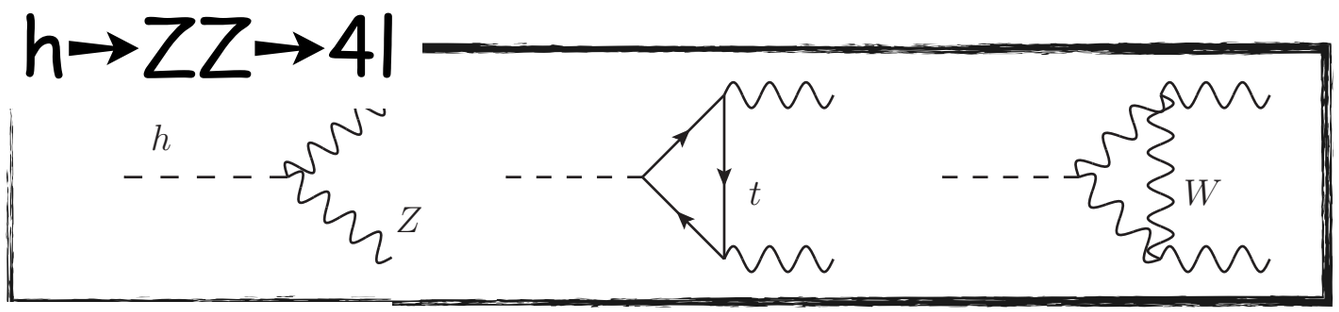
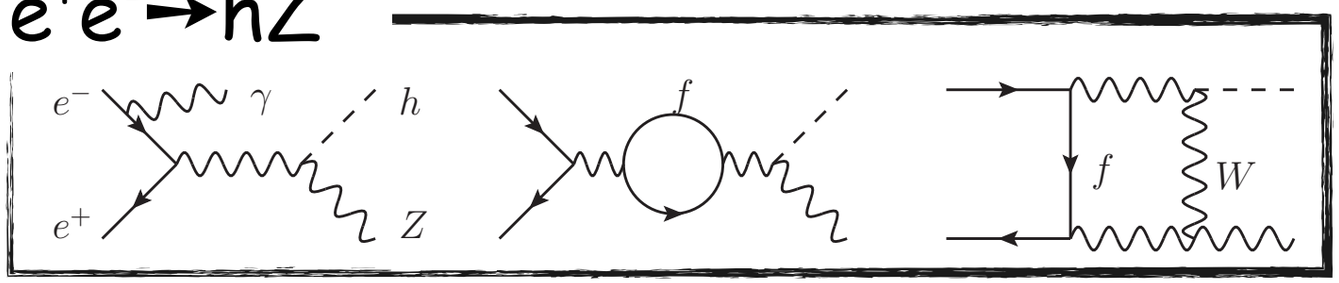
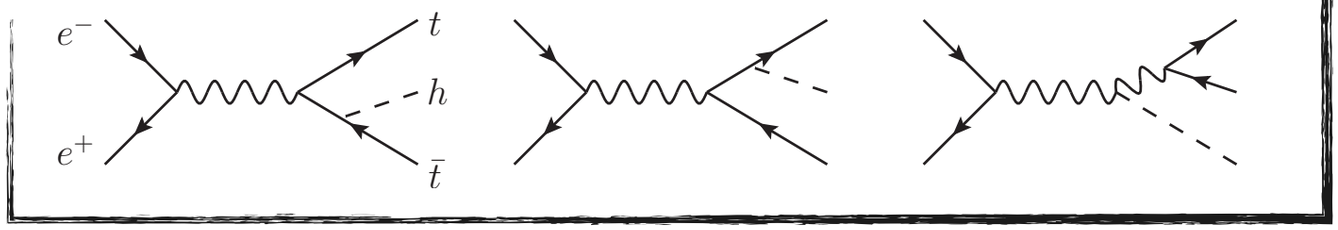
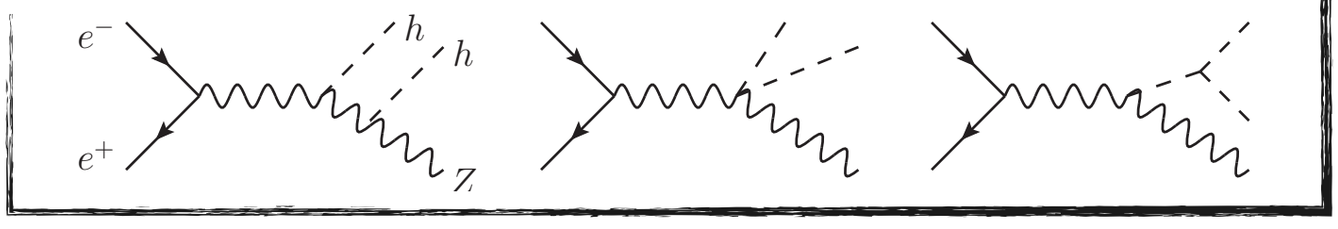
"disZphilia"

Zphilia or DisZphilia?

difficult!

Farina, Grojean, Salvioni '12

difference is physically relevant only in the presence of interference with single hZZ coupling

	TH prediction	ILC ($\sqrt{s}$=800GeV and 1ab^{-1})	
$h\to ZZ\to 4l$ 	$\Delta = \left\|\frac{\Gamma_Z^+ - \Gamma_Z^-}{\Gamma_Z^+ + \Gamma_Z^-}\right\| = \delta \approx 1\%$	≈1%	☠
$e^+e^-\to hZ$ 	$\Delta = \left\|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right\| \approx 15\%$	≈5%	☺
$e^+e^-\to tth$ 	$\Delta = \left\|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right\| \lesssim 4\%$	≈10%	☠
$e^+e^-\to Zhh$ 	$\Delta = \left\|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right\| \approx 50\%$	≈10%	☺

Signs of New Particles?

Espinosa, Grojean, Muhlleitner, Trott '12

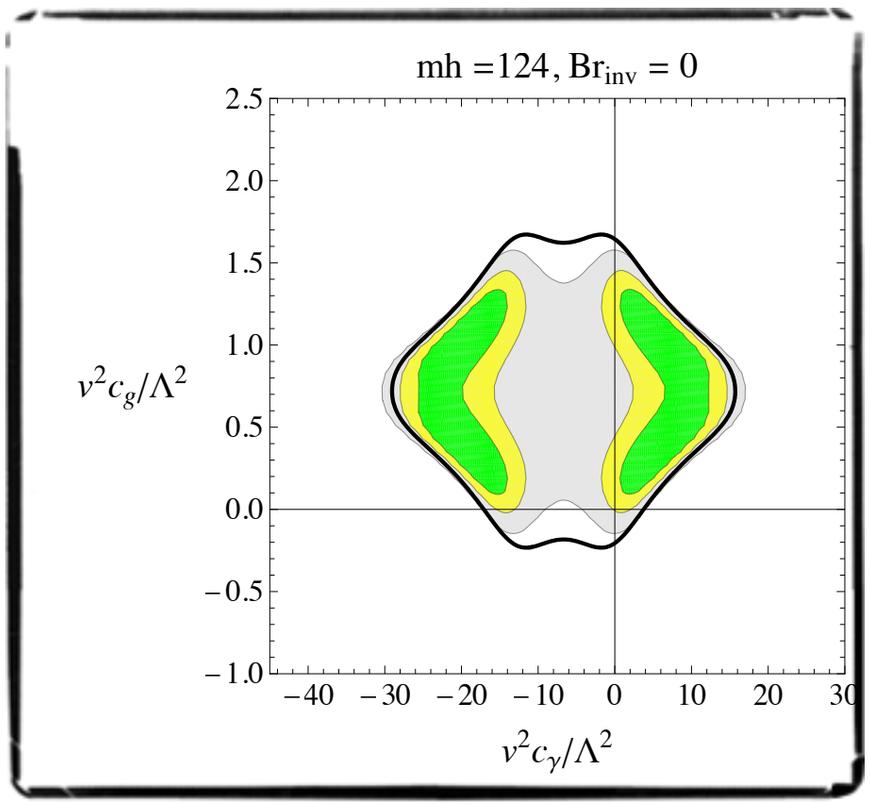
The Higgs can couple to new particles

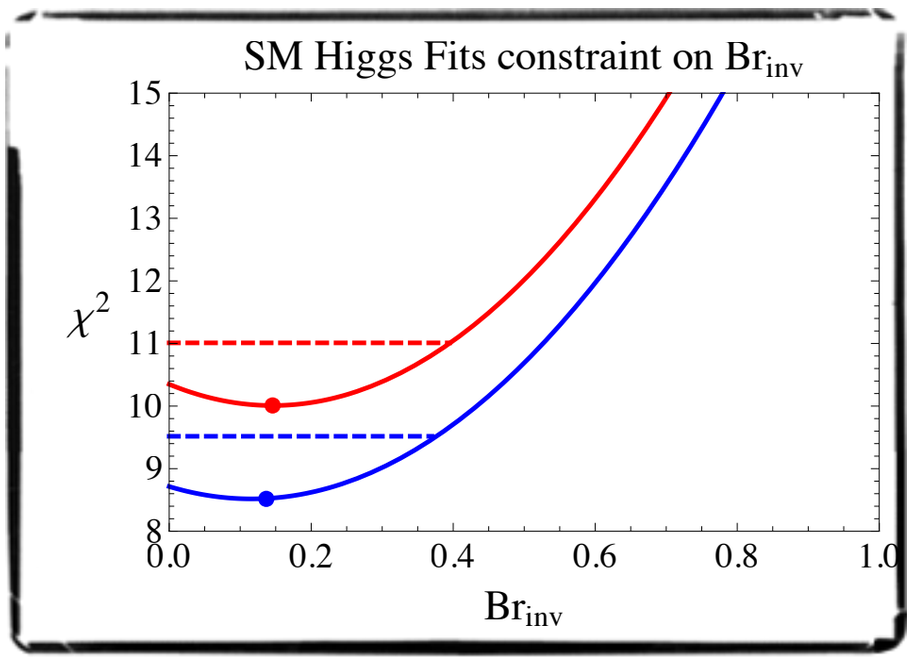
charged under SM gauge group

neutral under SM gauge group

$$\mathcal{L} = -\frac{\tilde{c}_\gamma e^2}{32\pi^2\Lambda^2} H^\dagger H\, F_{\mu\nu}F^{\mu\nu} - \frac{\tilde{c}_g g_s^2}{32\pi^2\Lambda^2} H^\dagger H\, G^a_{\mu\nu}G^{a\,\mu\nu}$$

$$\mathrm{Br}(h\to f) \equiv \frac{\Gamma(h\to f)}{\Gamma_{\rm SM}+\Gamma_{inv}} = (1-\mathrm{Br}_{inv})\times \mathrm{Br}_{SM}(h\to f)$$





Search for Invisible Decays with Visible Channels

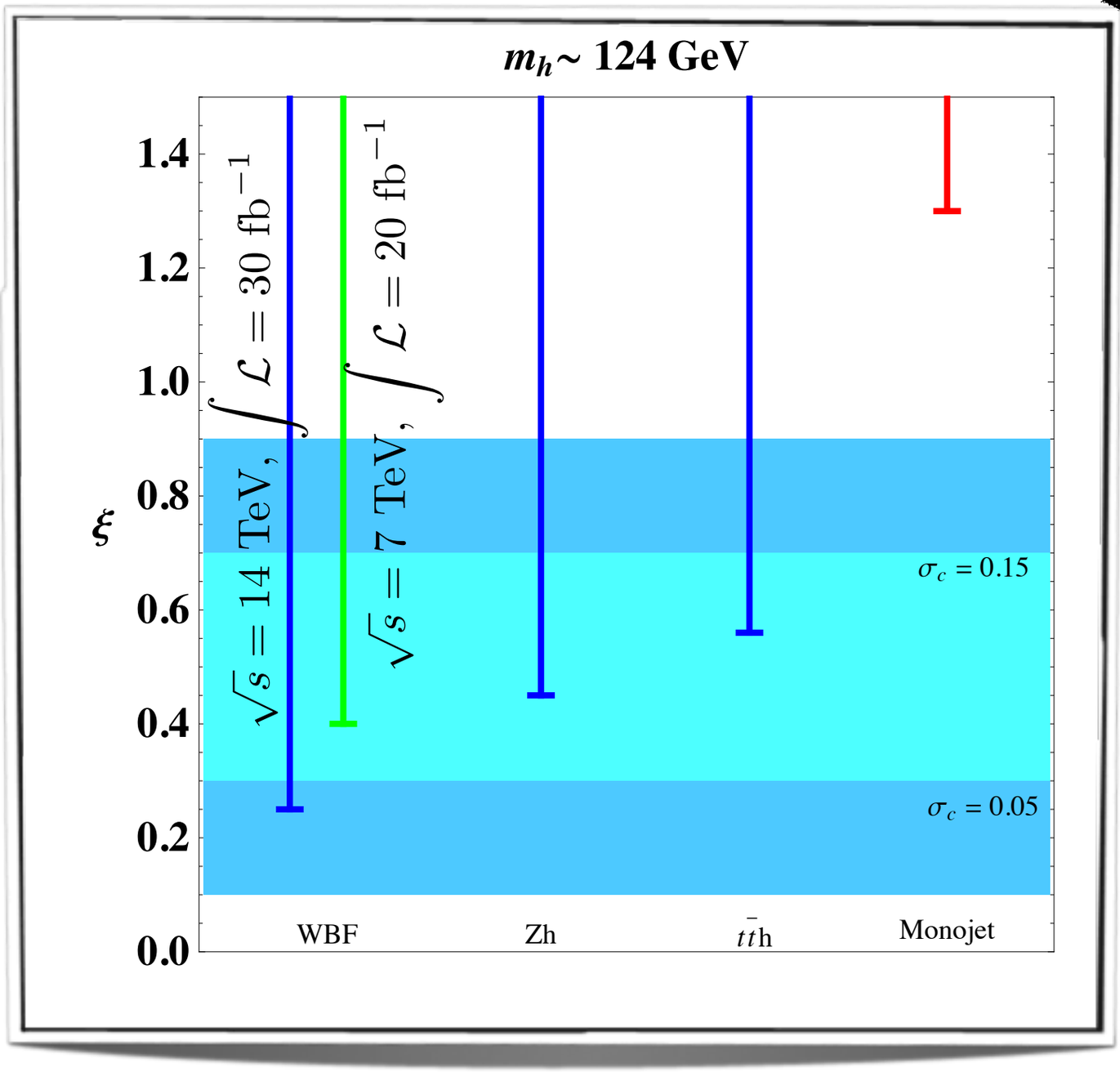
Espinosa, Grojean, Muhlleitner, Trott '12

direct (vertical) vs indirect (horizontal) searches

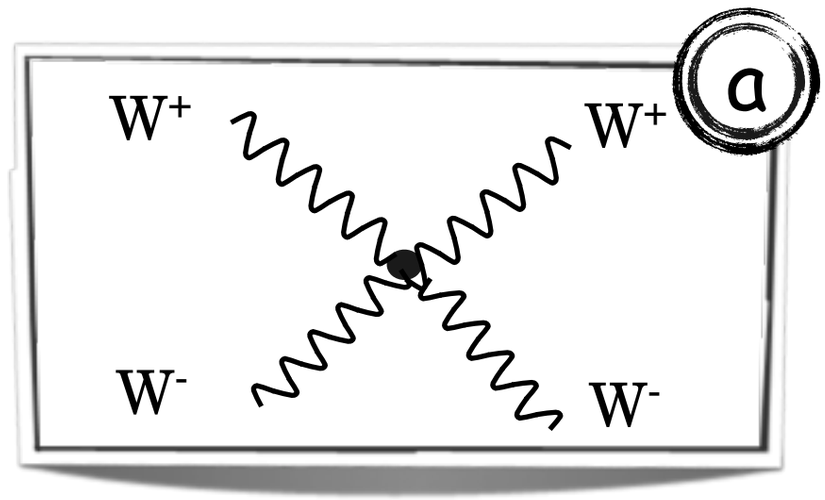
Values of

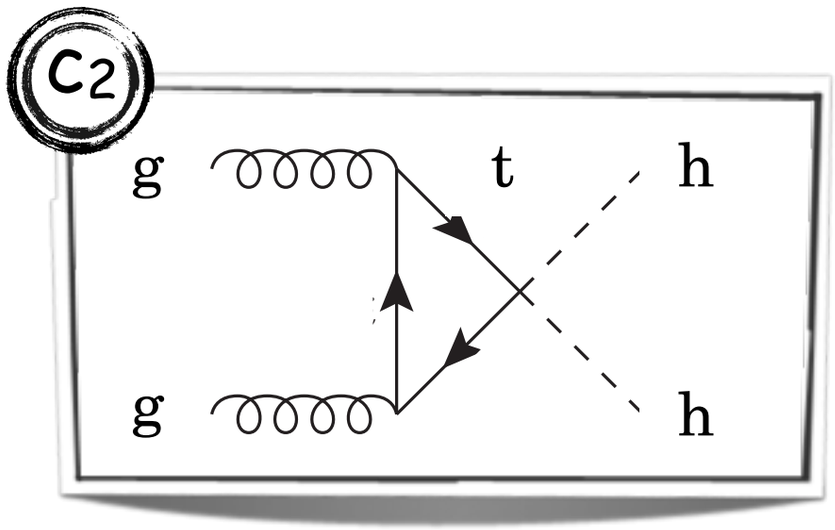
$$\xi = \sigma/\sigma_{SM} BR(h \to inv)$$

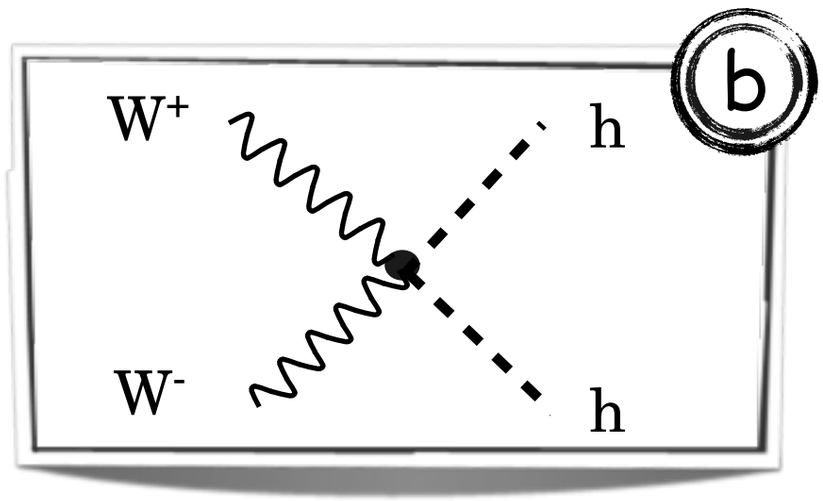
for which a 95%CL limit can be imposed

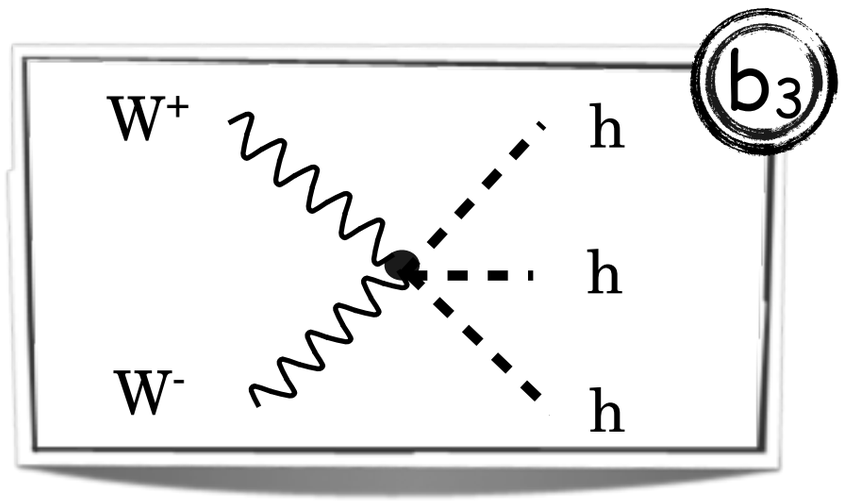


What to measure next?







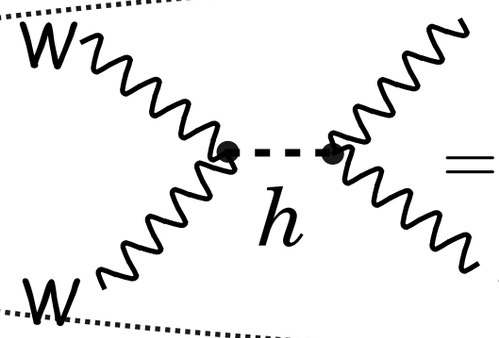


How to probe the strong dynamics?

pair production of light states beloging to the strong sector

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

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

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

Scale of Strong WW scattering?

$$\mathcal{A}_{TT\to TT} \sim g^2 f(t/s)$$

f is a rational fct
expected O(1) for t~-s/2

$$\mathcal{A}_{LL\to LL} \sim \frac{s}{v^2}$$

onset of strong scattering at the weak scale

hard cross-section
(t~-s/2)

$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} = N_h \frac{s^2}{M_W^4}$$

'inclusive' cross-section
$(-s + Q^2_{\rm min} < t < -Q^2_{\rm min})$

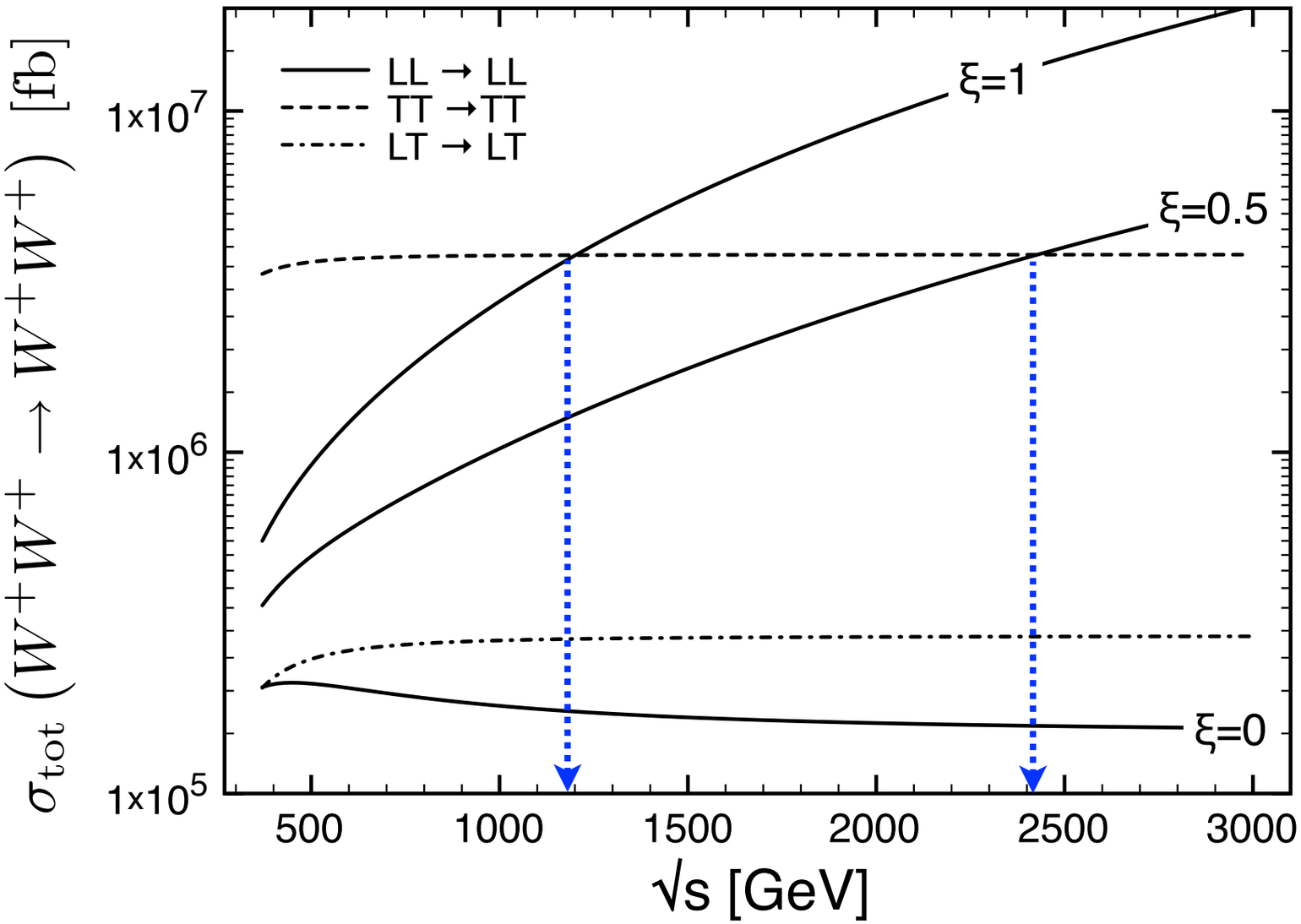
$$\frac{\sigma_{LL\to LL}(Q_{\rm min})}{\sigma_{TT\to TT}(Q_{\rm min})} = N_s \frac{s\, Q^2_{\rm min}}{M_W^4}$$

NDA estimates

$$N_h \sim 1 \qquad N_s \sim 1$$

Total cross sections

disentangling L from T polarization is hard

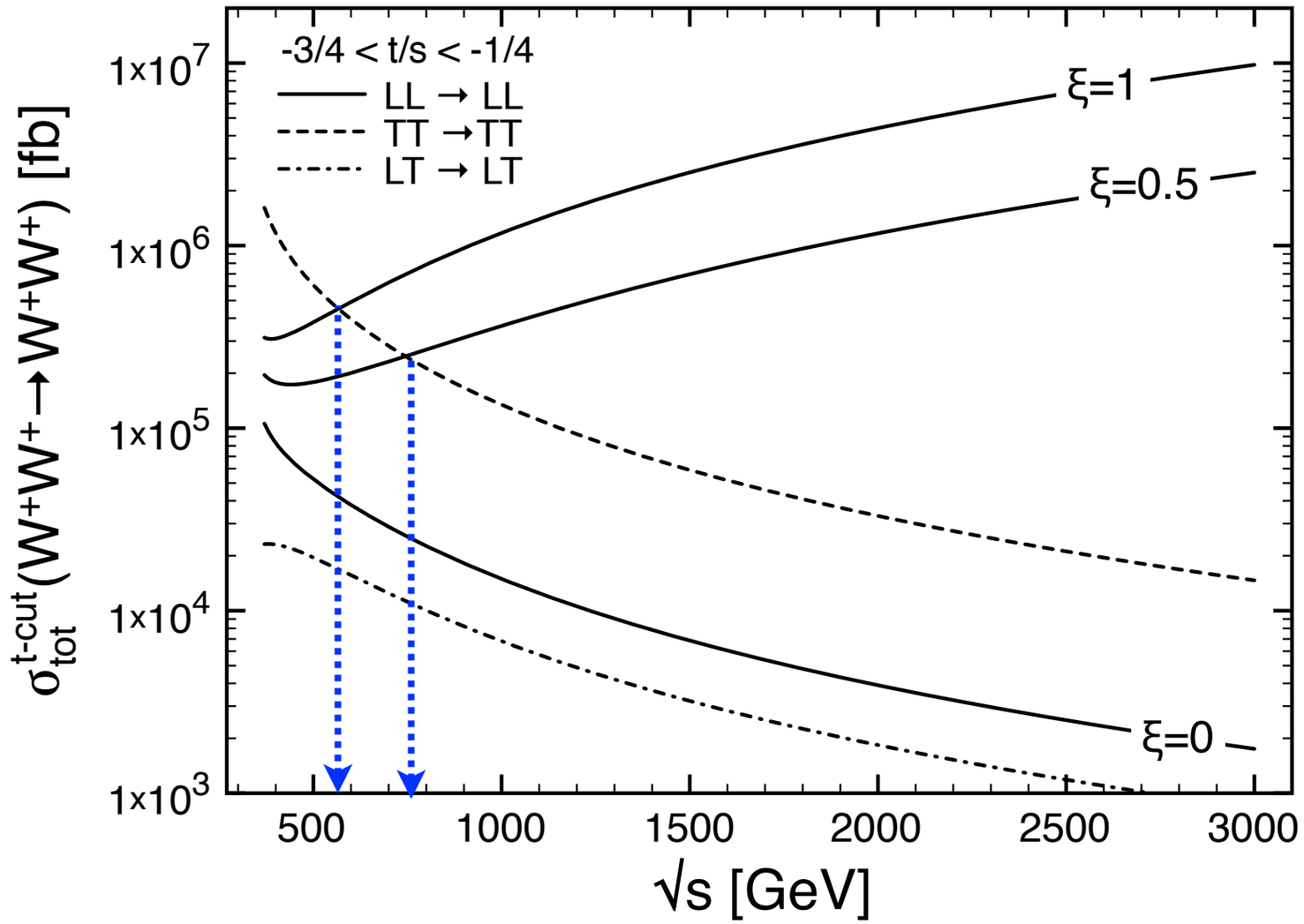


The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background

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

Hard scattering (central region)

we need to look at the central region, i.e. large scattering angle,
to be sensitive to strong EWSB

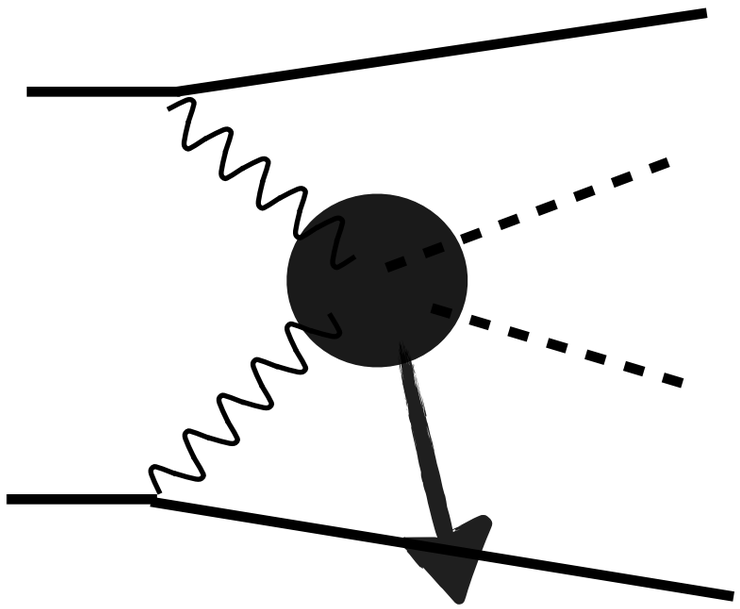


$$\frac{\sigma^{\rm hard}_{LL\to LL}}{\sigma^{\rm hard}_{TT\to TT}} \simeq \left(\frac{\sqrt{s}}{7.4 M_W}\right)^4 \xi^2$$

$$N_h = 1/2304$$

- hard cross-section = faster growth with energy
- onset of strong scattering still at high scale

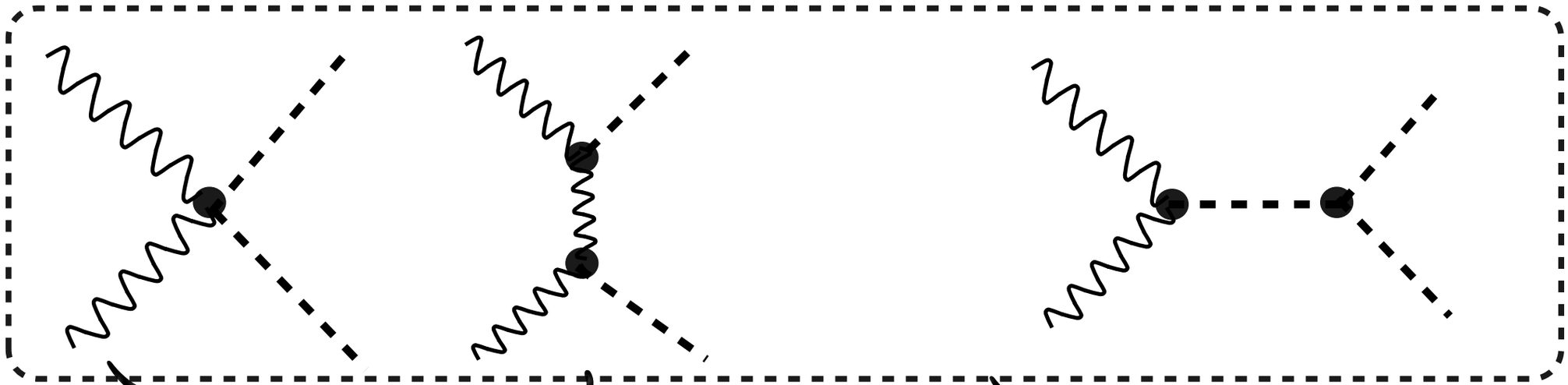
Double Higgs production (VBF)



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

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

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

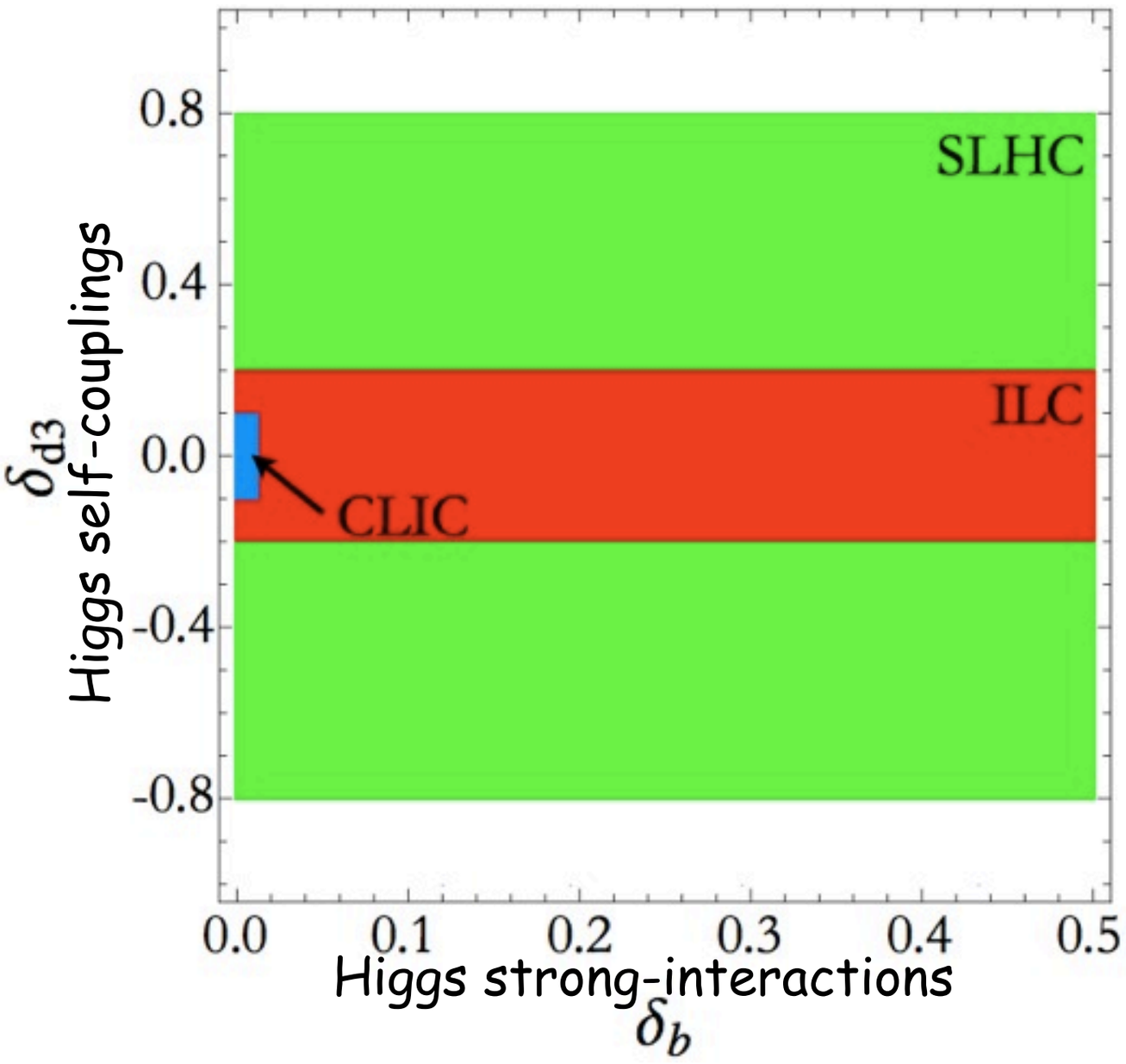
$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

Measuring Higgs Non-Linearities

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

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



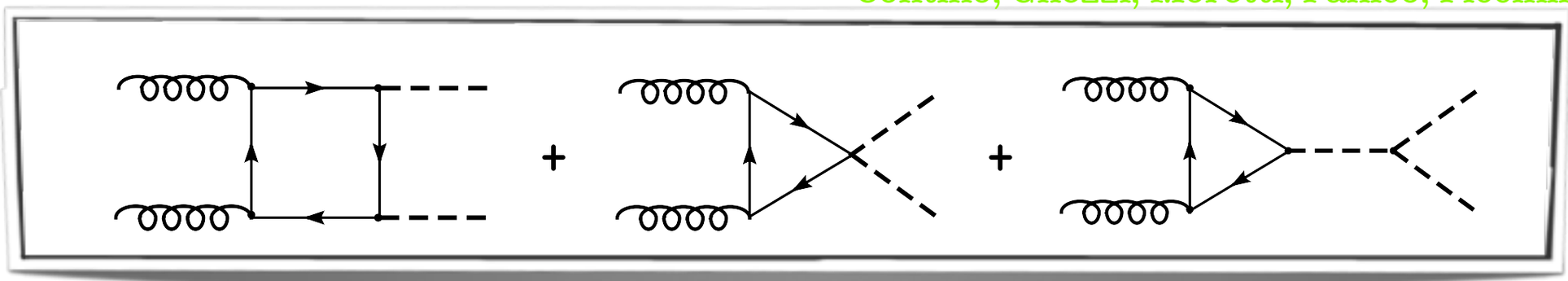
- (S)LHC is barely sensitive to d_3 and b
- ILC has a sensitivity on d_3 but not on b
- CLIC can probe both d_3 and b

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!

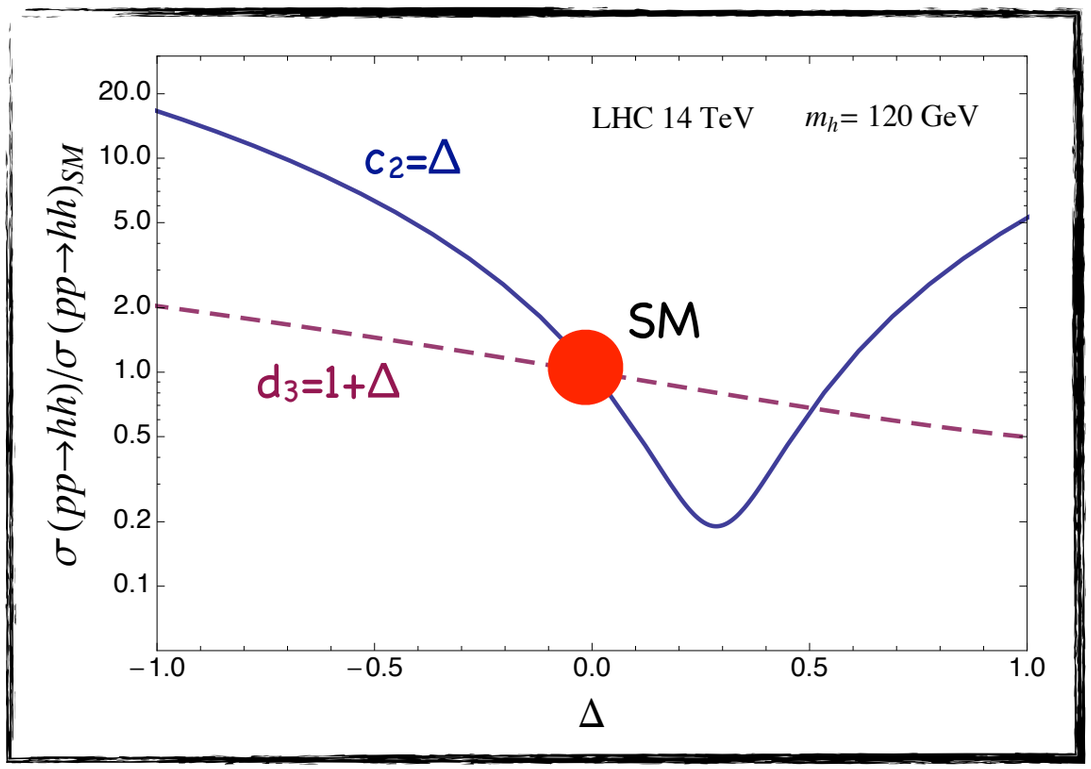
Double Higgs production (ggF)

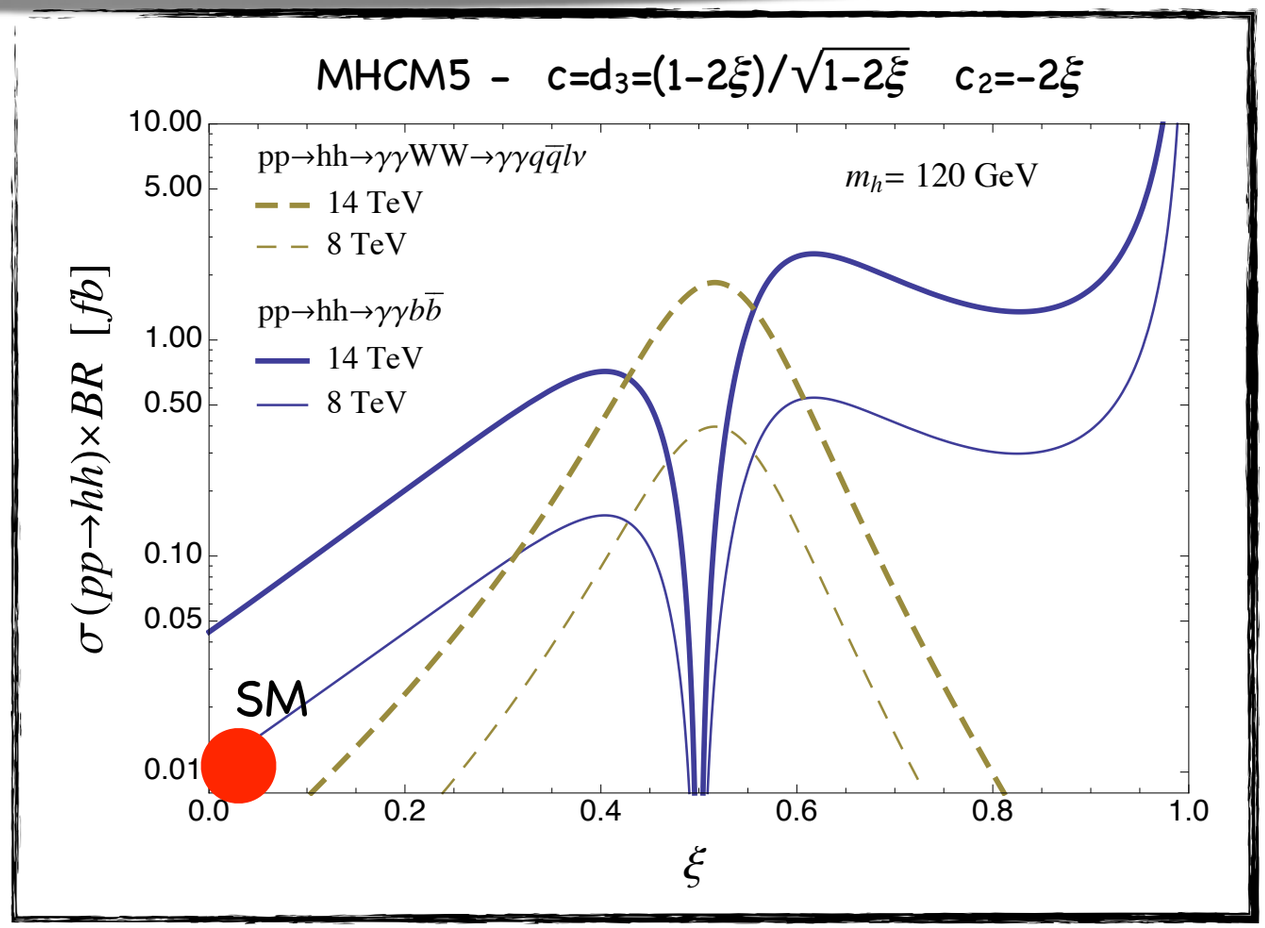
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, '12



- $\sigma(gg\to hh)$ much more sensitive on new tthh couplings c_2 than on trilinear d_3

[First noticed by:
Dib, Rosenfeld, Zerwekh '06
Grober and Muhlleitner, '10]





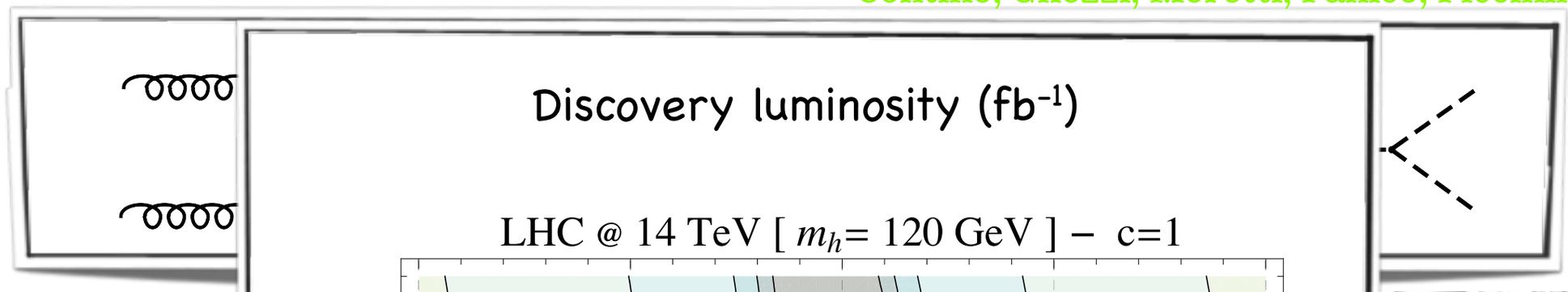
- If $BR(h)\simeq BR(h)_{SM}$ best channel is $hh\to bb\gamma\gamma$

Baur, Plehn, Rainwater '04

- If $c\simeq 0$ (fermiophobic Higgs) a very promising channel is $hh\to WW\gamma\gamma\to Wqql\nu\gamma\gamma$

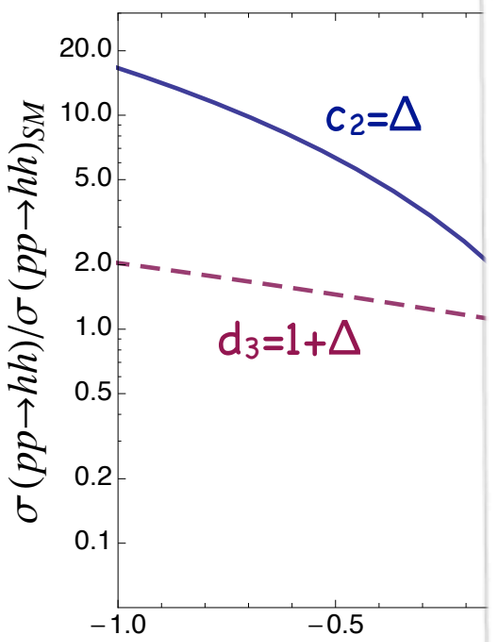
Double Higgs production (ggF)

Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer, '12

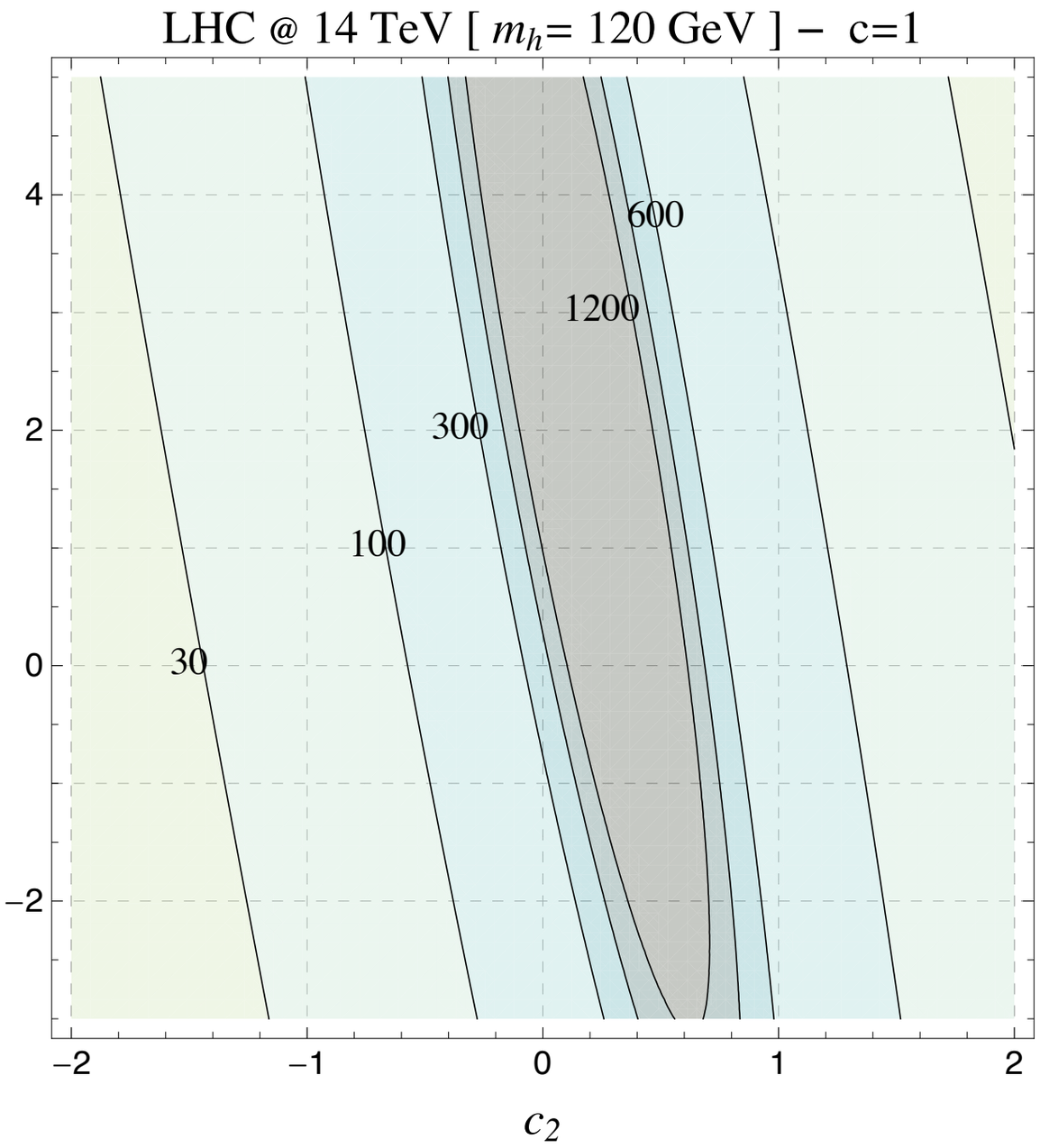


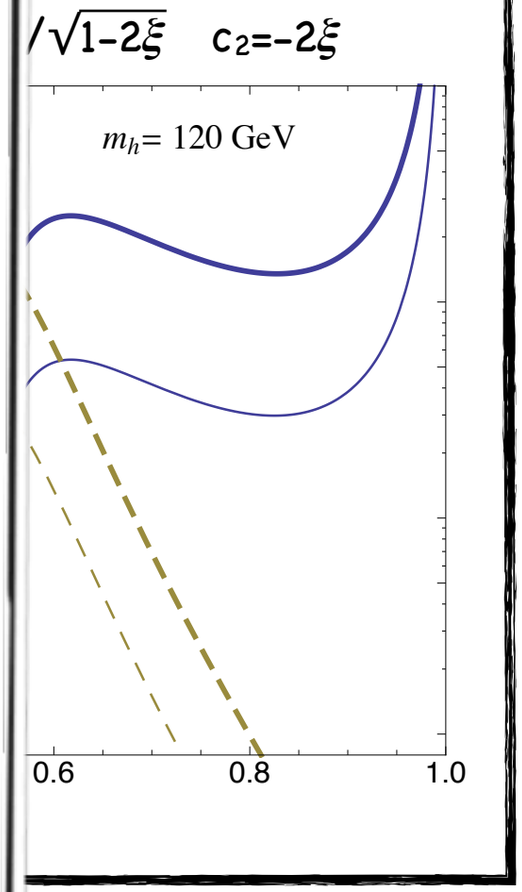
- σ(gg→hh) much
  tthh couplings c

[First noticed by:
Dib, Rosenfeld, Zer
Grober and Muhlle



Discovery luminosity (fb^{-1})





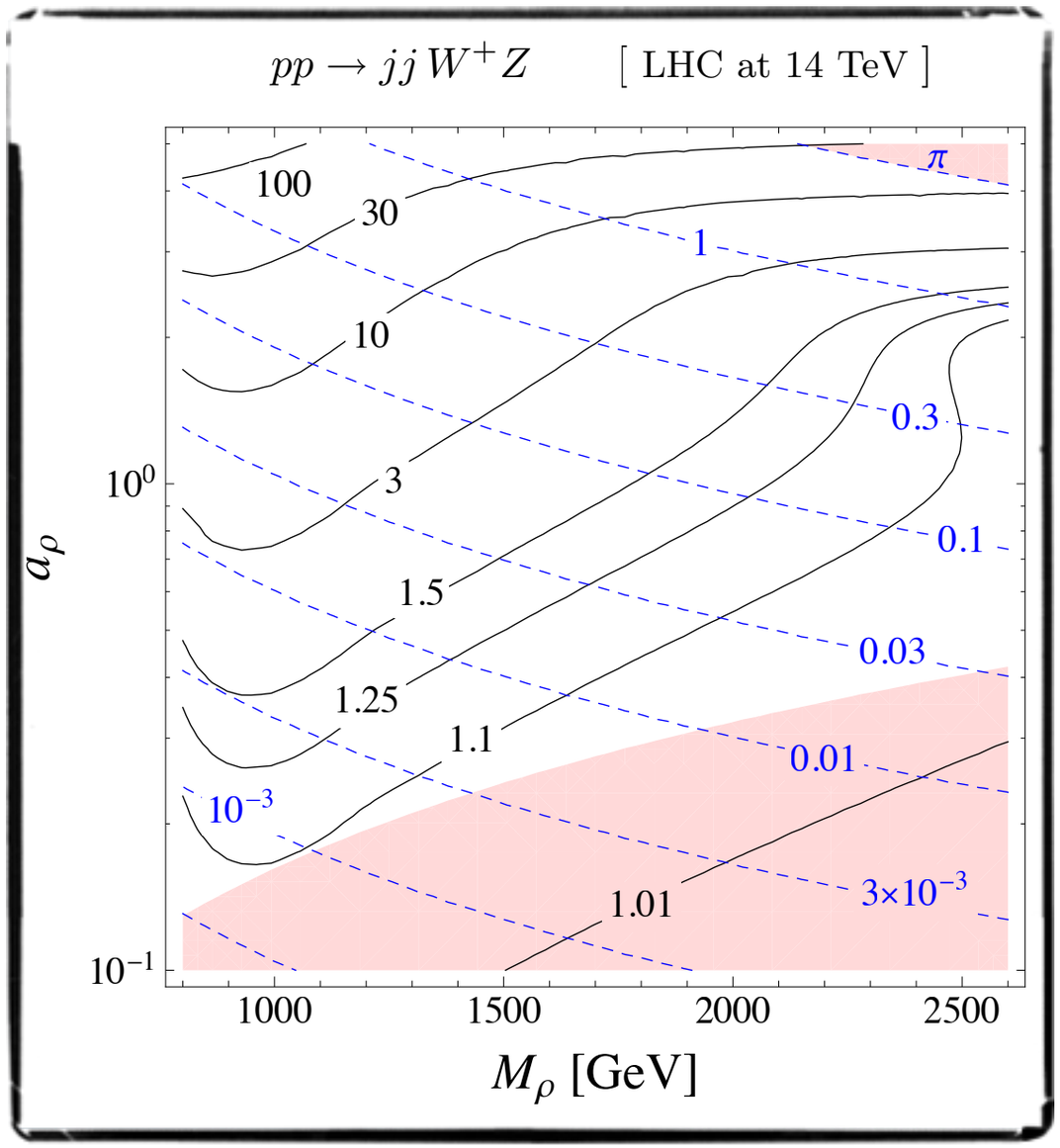
el is hh→bbγγ
Baur, Plehn, Rainwater '04

a very promising

γγ

Resonances Effects in WW Scatterings

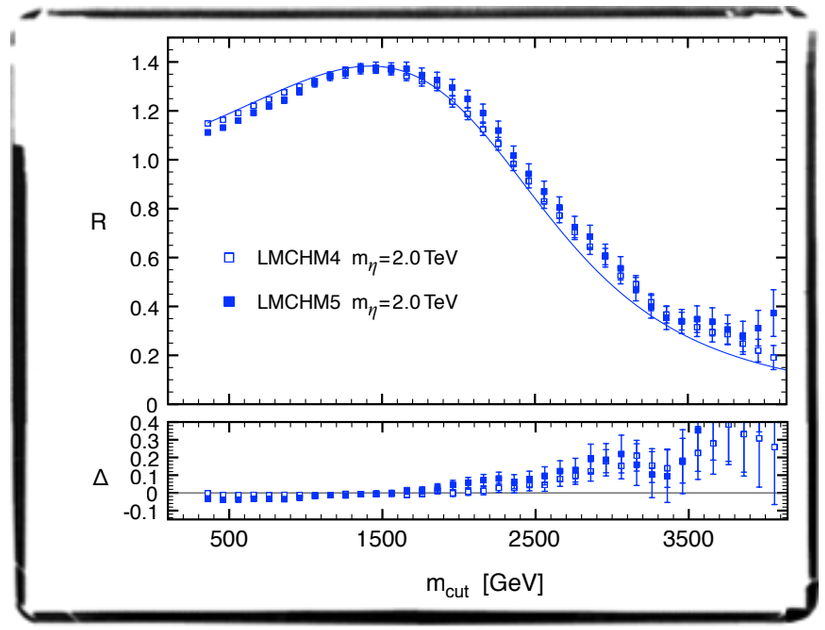
Contino, Marzocca, Pappadopulo, Rattazzi '11



$\xi = 0.5$

$m_{\rm cut} = 800\,{\rm GeV}$

$R = \dfrac{\sigma(\rho_L)}{\sigma({\rm LET})}$ $\qquad \dfrac{\Gamma_{\rho_L}}{m_{\rho_L}}$

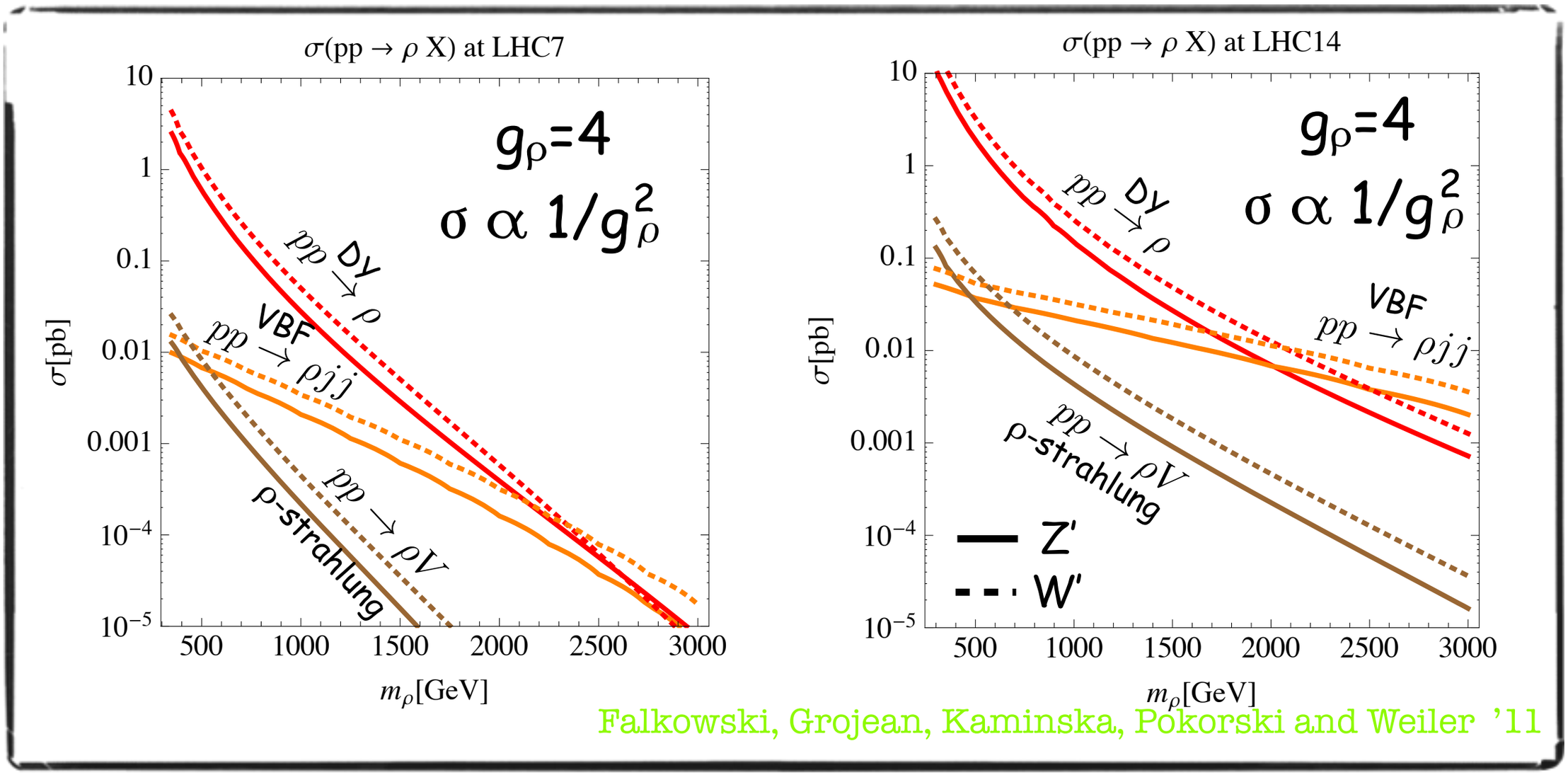


channel complementary
to pin down the nature of the resonance

		W^+W^-	W^+Z	W^+W^+	hh
ρ	(1,3)	↑	↑	↓	↓
η	(1,1)	↑	↓	↓	↑
Δ	(3,3)	↑	↑	↑	↑

Resonance Searches: di-boson final states

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

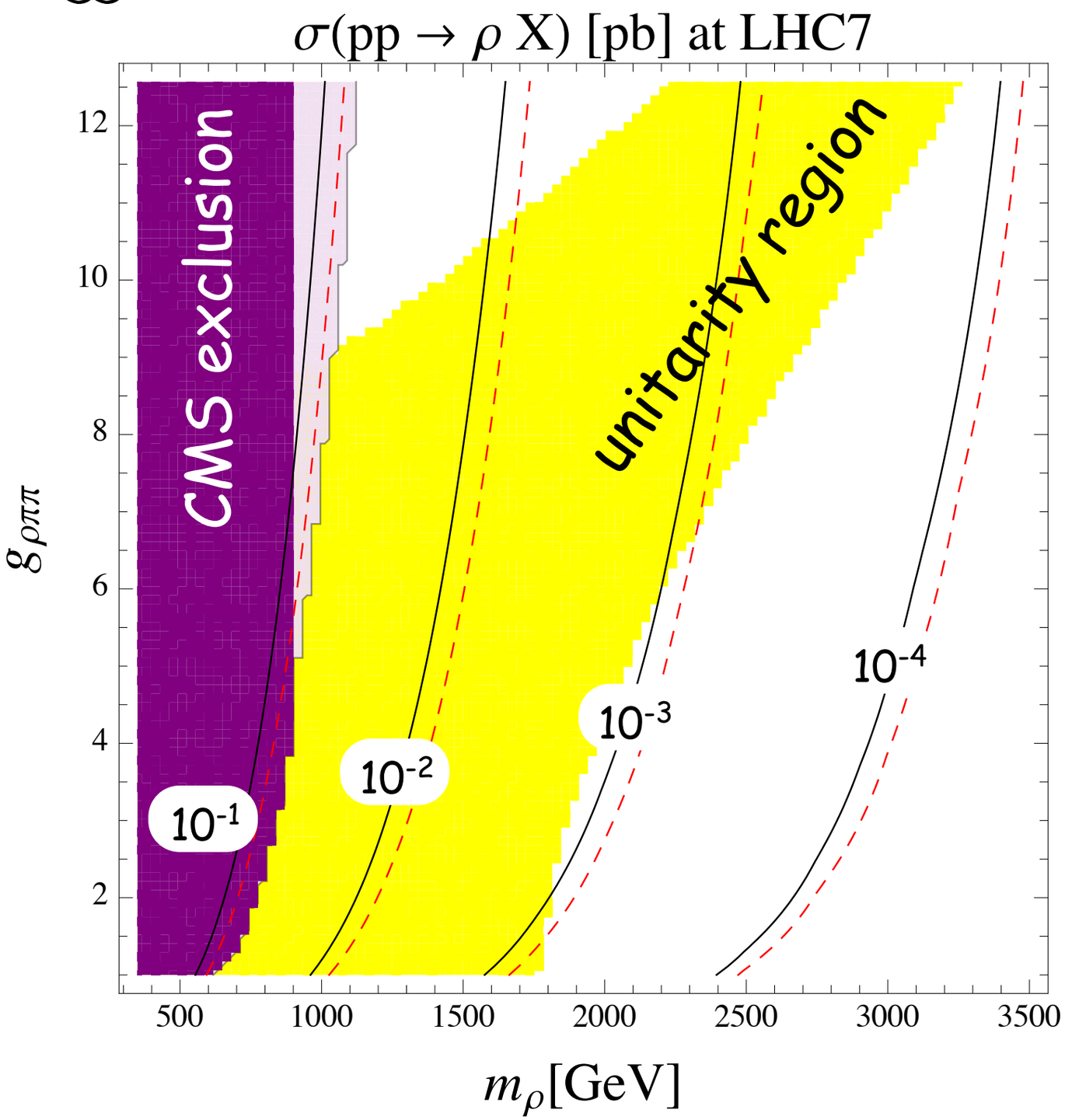
VBF vs. DY:
- 3-body final state
- qq initiated process ➪ PDFs become more dominant at large x

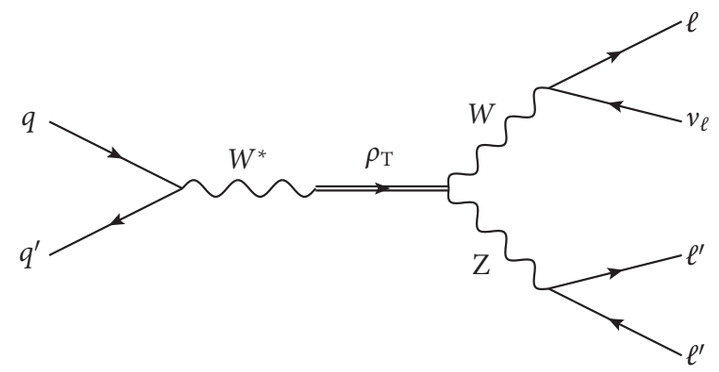
(NB: DY can be enhanced by larger direct couplings of resonances to light quarks but severe dijet constraints)

Resonance Searches

Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

higgsless setup





- Current best limits from the 1fb^{-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

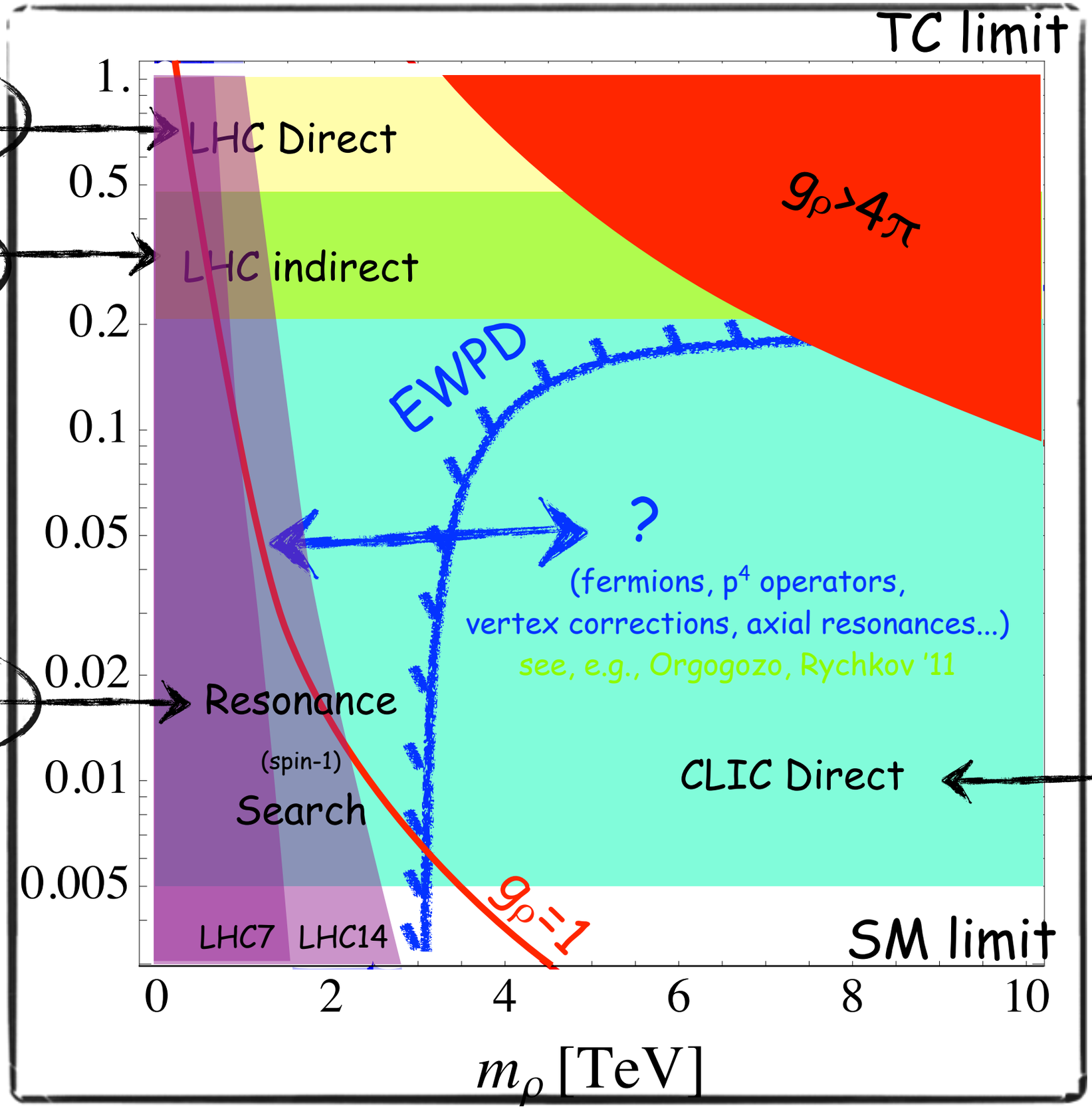
Strong WW scattering

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)



Resonance searches

Strong WW scattering @ CLIC

Fermionic Resonances

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

- Custodial symmetry: exotic top partners

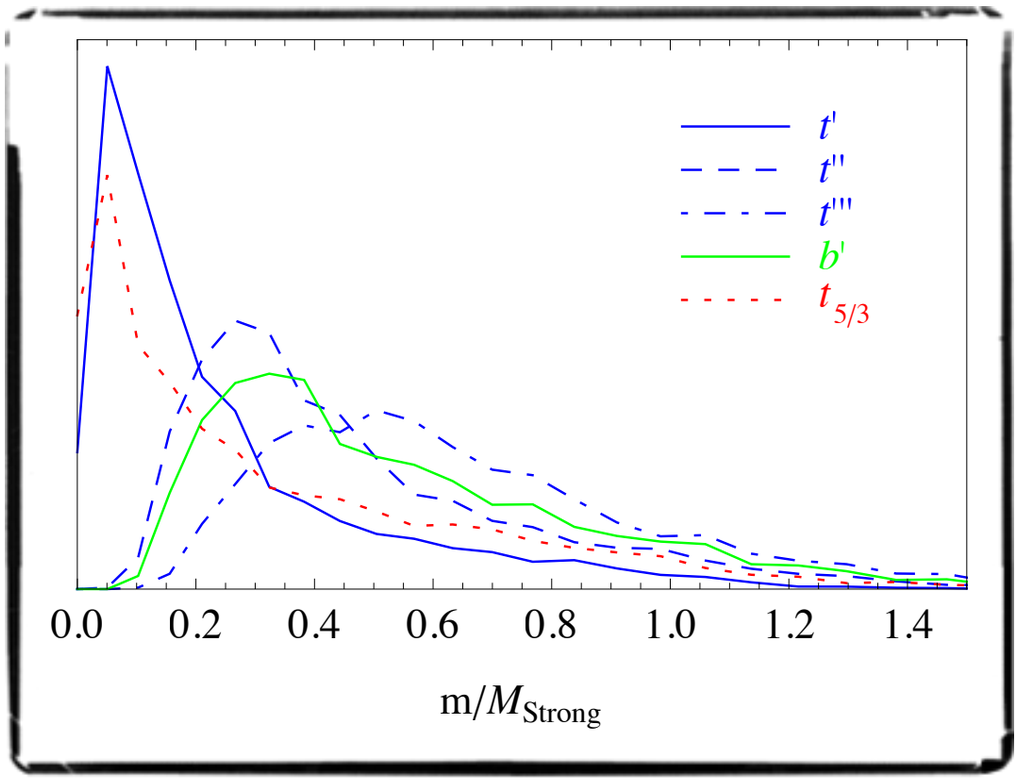
$SU(2)_L \times SU(2)_R$ embedding

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

$$t_R \equiv (1,1)_{2/3}$$

$$b_R \equiv (1,1)_{-1/3}$$

➪ $\delta_{Zb_L\bar{b}_L}=0$



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

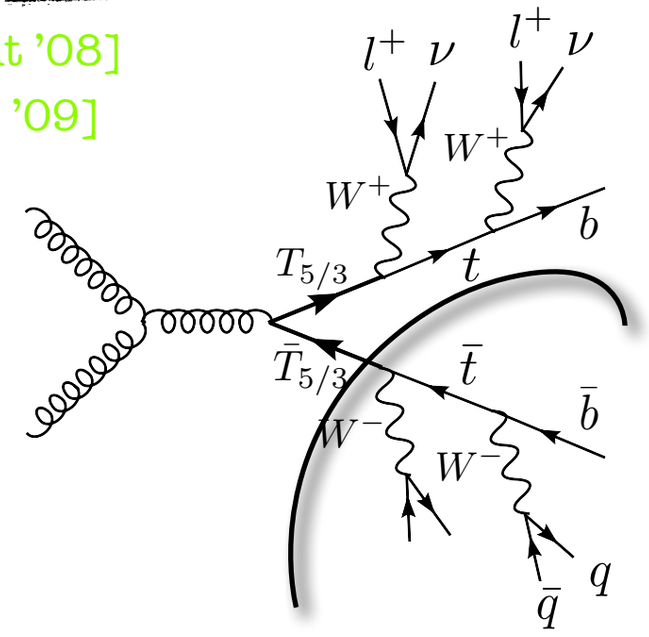
[Contino, Servant '08]
[Mrazek, Wulzer '09]

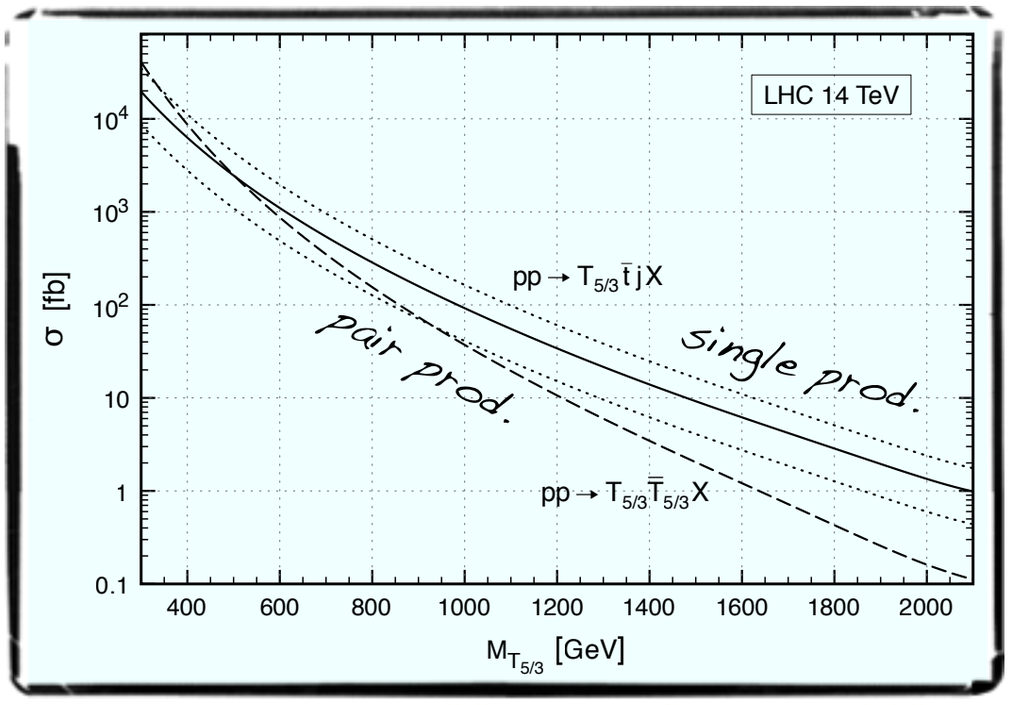
- tt+jets is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed

discovery potential (LHC_{14TeV})

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

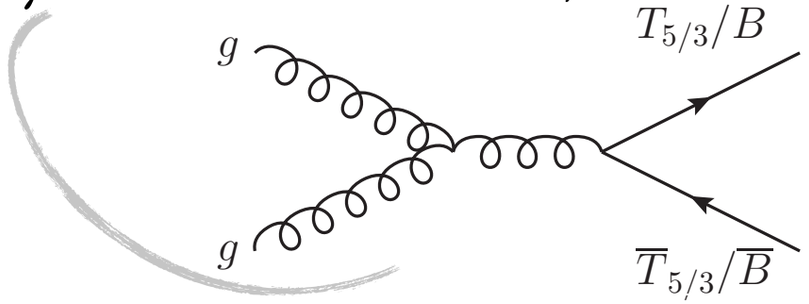
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

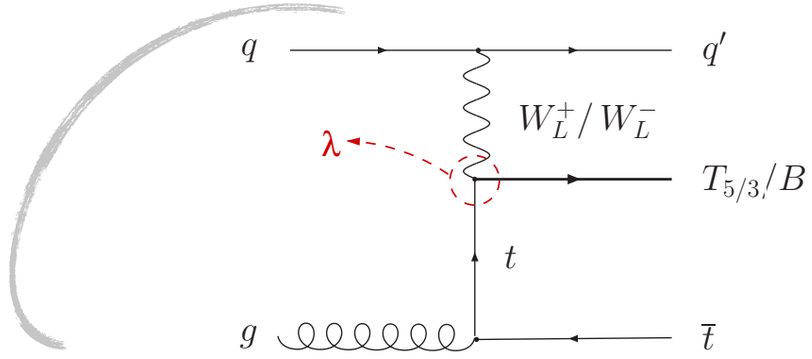




[Contino, Servant '08]

Pair production (model independent)





Single production (model dependent)

The Question of the next Decade(s)

What is really this Higgs boson that might have been discovered at ~ 125GeV?

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]