Effective Higgs at the LHC

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Particle Physics in the LHC era
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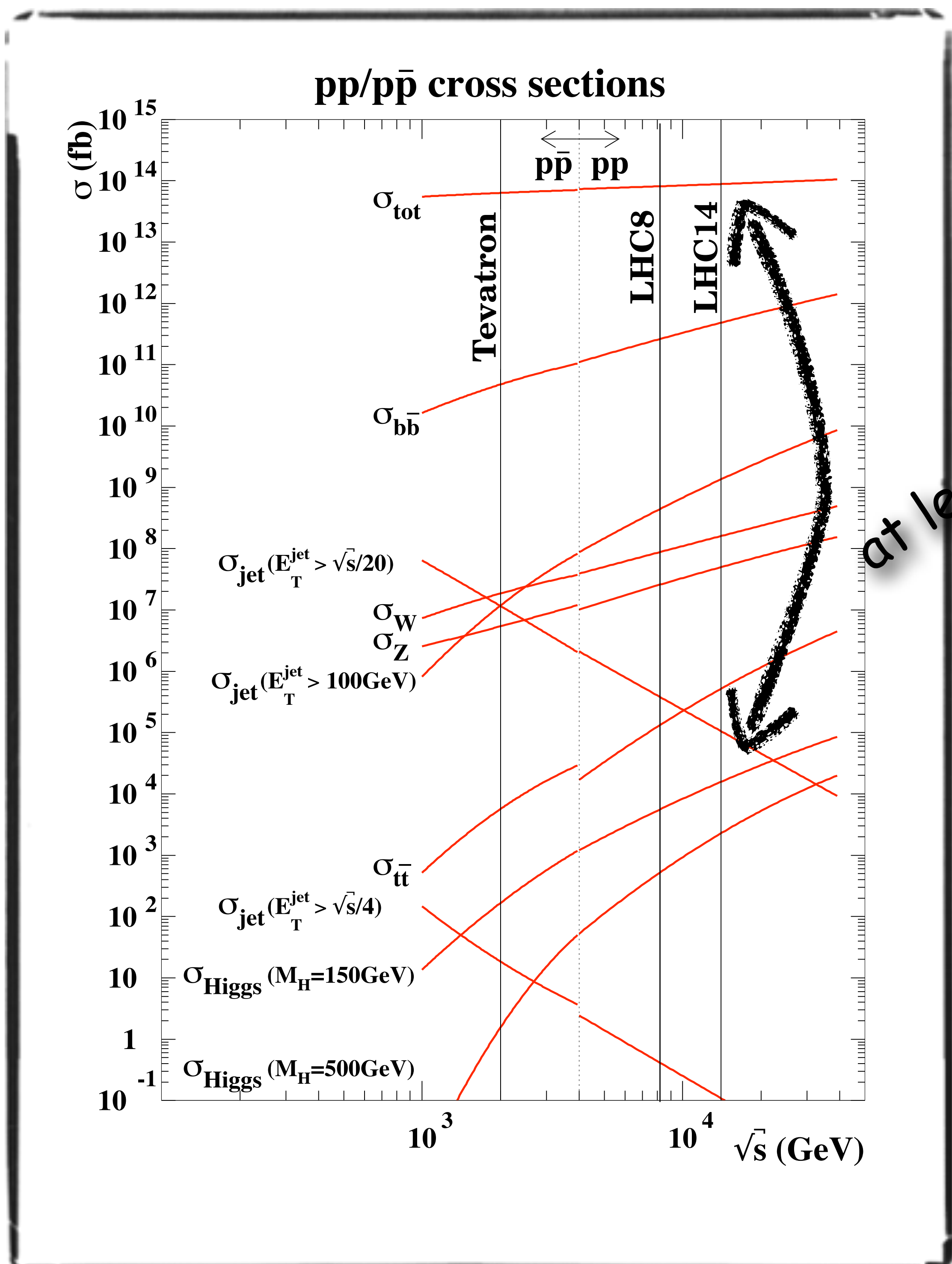
*iCrea
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background



at least 10 orders of magnitude

only 1 out of 100 billions events are "interesting"

(for comparison, Shakespeare's 43 works contain only 884,429 words in total)

furthermore many of the background events furiously look like signal events

SM Higgs @ LHC

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orders
gnitude

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... like finding the paper you are looking for in John Ellis' office

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Where are we?

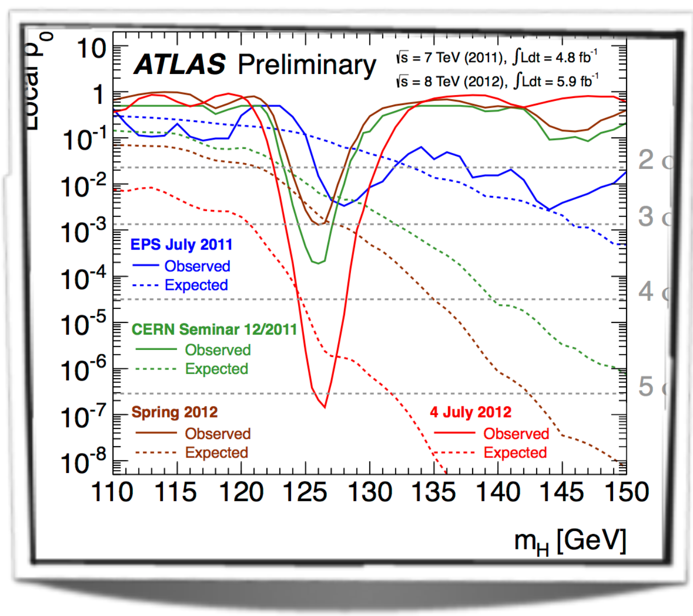
we are living a privileged moment in the history of HEP

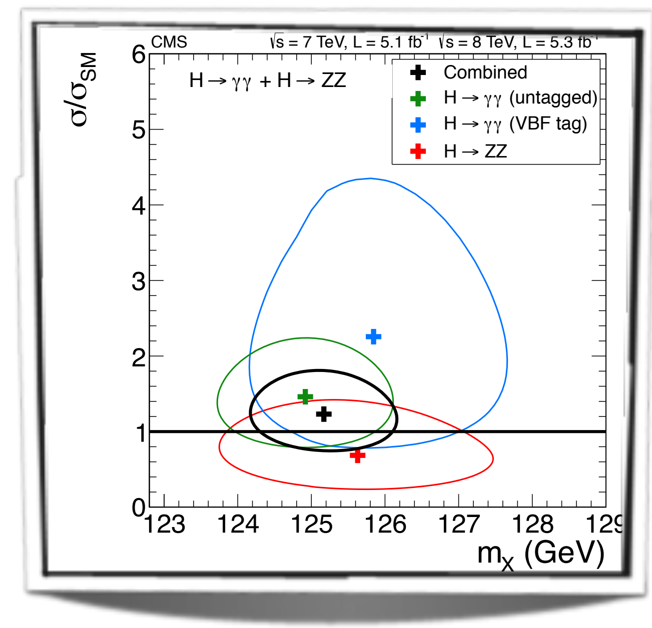
"We have found a new particle" CMS

Where are we? What's next?

we are living a privileged moment in the history of HEP

"We have found a new particle" CMS





"this discovery came at half the LHC design energy, much more severe pileup, and one-third of the integrated luminosity that was originally judged necessary" ATLAS

Higgs is the most exotic particle of the SM

its discovery has profound implications

- Spin 0? Against naturalness: small mass only if protected by symmetry
- Couplings not dictated by gauge symmetry? Against gauge principle (elegance, predictivity, robustness, variety) which used to rule the world (gravity, QCD, QED, weak interactions)
- Symmetry breaking? ground state doesn't share the full symmetry of interactions

What's next?

" With great power comes great responsibility "

Voltaire & Spider-Man

which, in particle physics, really means

" With great discoveries come great measurements "

BSMers desperately looking for anomalies
(true credit: F. Maltoni
actually, first google hit gives a link to an article of
the Guardian on... the Higgs boson!)

1

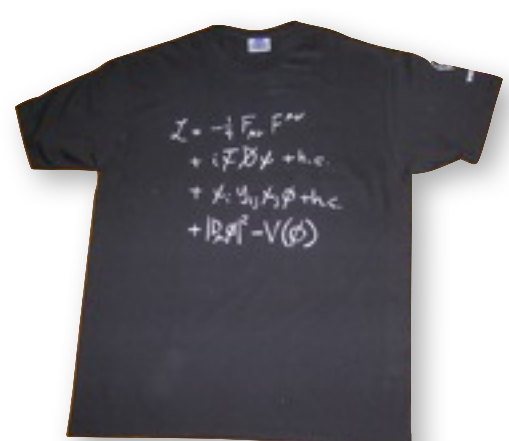
Higgs properties

J^{PC}

Important & nice to see progresses but
"this question carries a similar potential
for surprise as a football game between
Brazil and Tonga" Resonaances

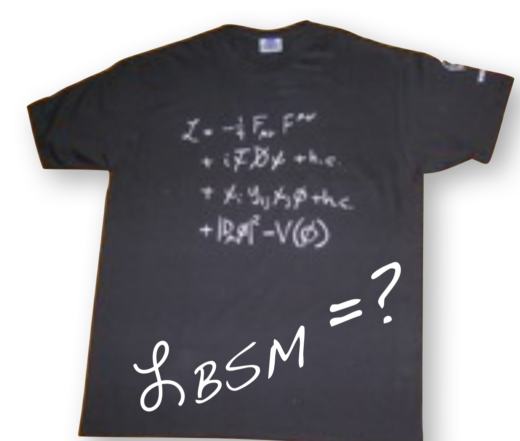
2

Higgs couplings



3

BSM implications



Chiral Lagrangian for a light Higgs-like scalar

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

$$-\left(m_W^2 W_\mu W^\mu + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2c_V\frac{h}{v} + b_V\frac{h^2}{v^2} + \dots\right)$$

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

O(p²)

$$+\frac{\alpha_{em}}{8\pi}\left(2\,c_{WW}\,W^+_{\mu\nu}W^{-\,\mu\nu} + c_{ZZ}\,Z_{\mu\nu}Z^{\mu\nu} + 2\,c_{Z\gamma}\,Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\,\gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

$$+\frac{\alpha_s}{8\pi}c_{gg}\,G^a_{\mu\nu}G^{a\,\mu\nu}\,\frac{h}{v}$$

$$+c_W\left(W^-_\nu D_\mu W^{+\,\mu\nu} + W^+_\nu D_\mu W^{-\,\mu\nu}\right)\frac{h}{v} + c_Z\,Z_\nu\partial_\mu Z^{\mu\nu}\,\frac{h}{v}$$

$$+\left(\frac{c_W}{\sin\theta_W\cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right)Z_\nu\partial_\mu\gamma^{\mu\nu}\,\frac{h}{v}$$

O(p⁴)

$$+\mathcal{O}\left(p^6\right)$$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

SM

$$a = b = c = d_3 = d_4 = 1$$

$$c_{2\psi} = c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{\gamma\gamma} = \dots = 0$$

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even

  ↖ $\gamma\gamma$ ↖ WW & ZZ

- ☑ custodial symmetry

  ↖ EWPD

- ☑ no Higgs FCNC
  (generalization of Glashow-Weinberg th.)

  ↖ Flavor

Chiral Lagrangian for a light Higgs-like scalar

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

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

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

$$+\frac{\alpha_{em}}{8\pi}\left(2\, c_{WW}\, W^+_{\mu\nu}W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu}Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

still large LO parameter space

⇓ ⇓ ⇓

4 operators @ O(p^2): c_V, c_t, c_b, c_T

2 operators @ O(p^4): c_g c_γ

(contribute to the same order as O(p^2) to gg→h and h→$\gamma\gamma$)

Not enough data/sensitivity to determine all these parameters

⇓ ⇓ ⇓

But we can put some of the SM structures under probation

assumptions:

- ☑ spin-0 & CP-even

  ↖ $\gamma\gamma$ ↖ WW & ZZ

- ☑ custodial symmetry

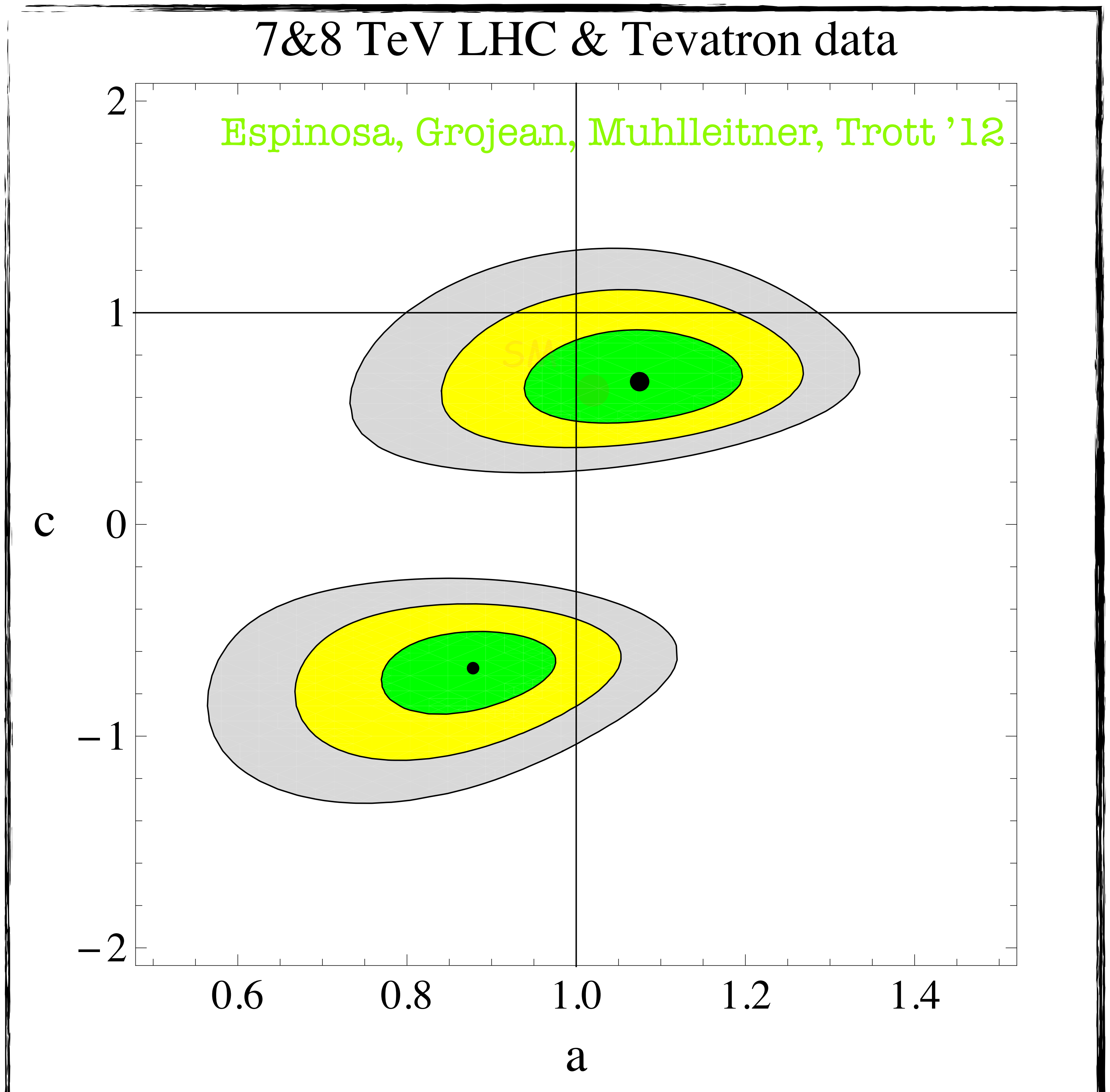
  ↖ EWPD

- ☑ no Higgs FCNC (generalization of Glashow-Weinberg th.)

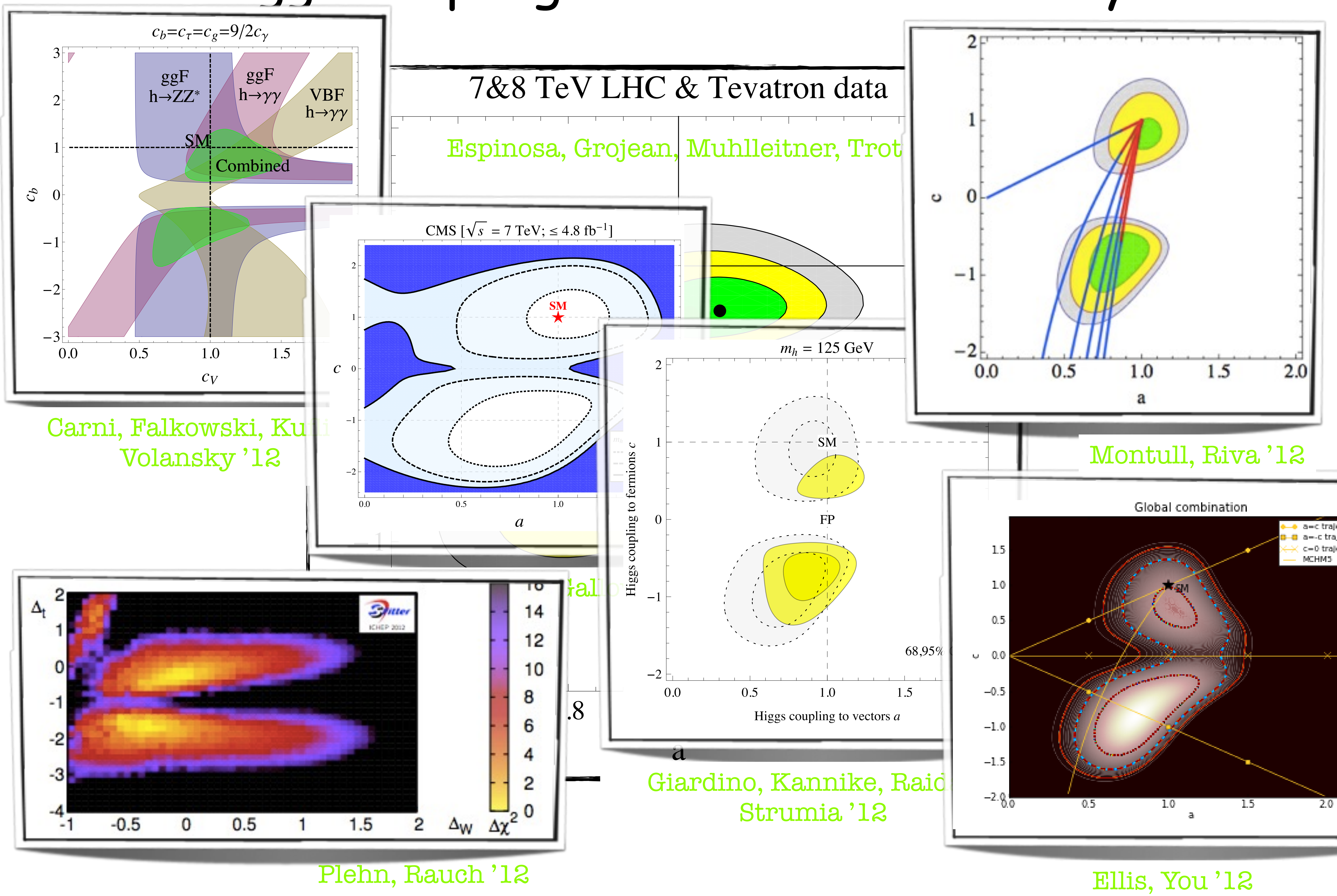
  ↖ Flavor

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Higgs coupling fits: test of unitarity

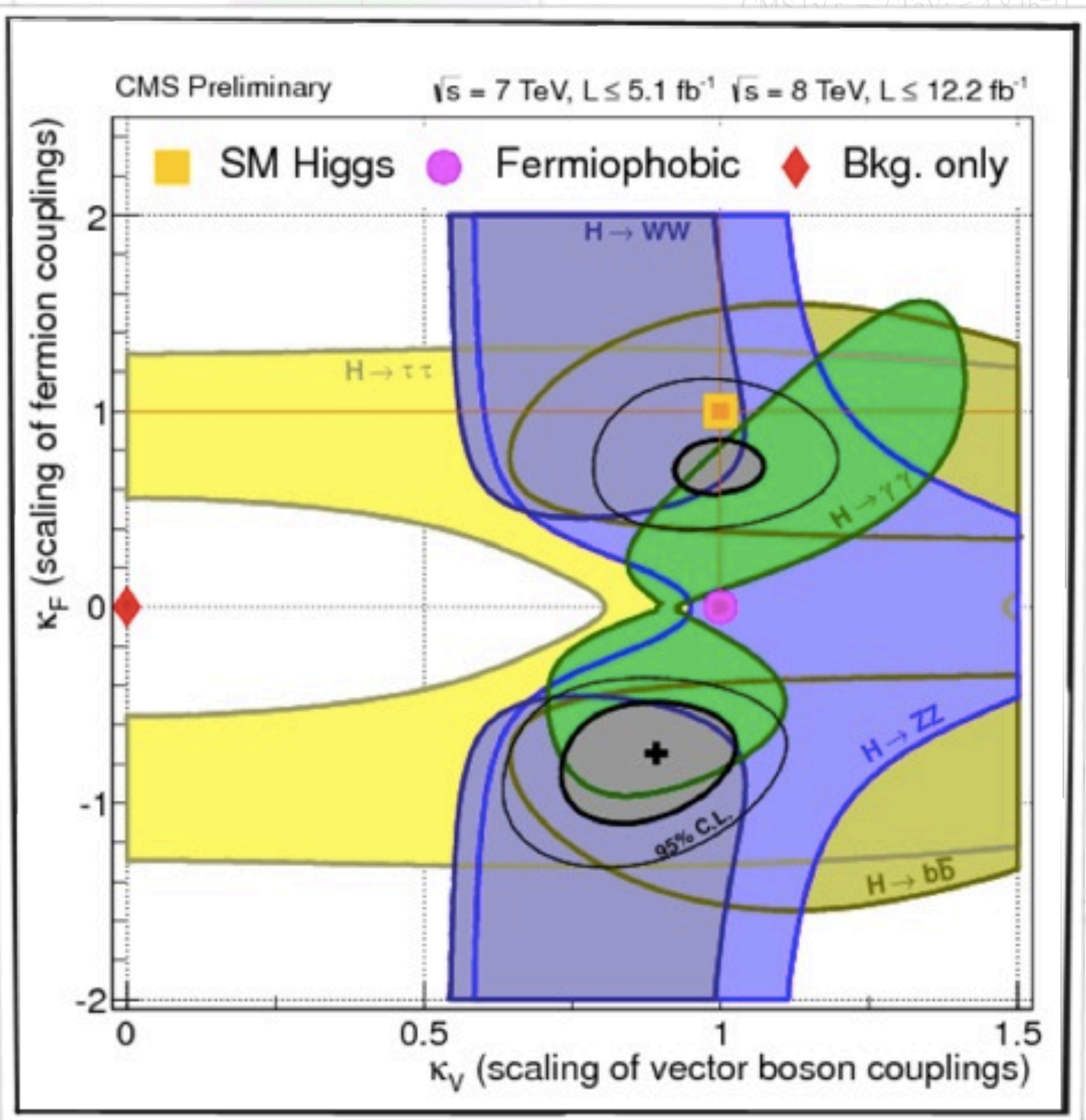


Higgs coupling fits: test of unitarity

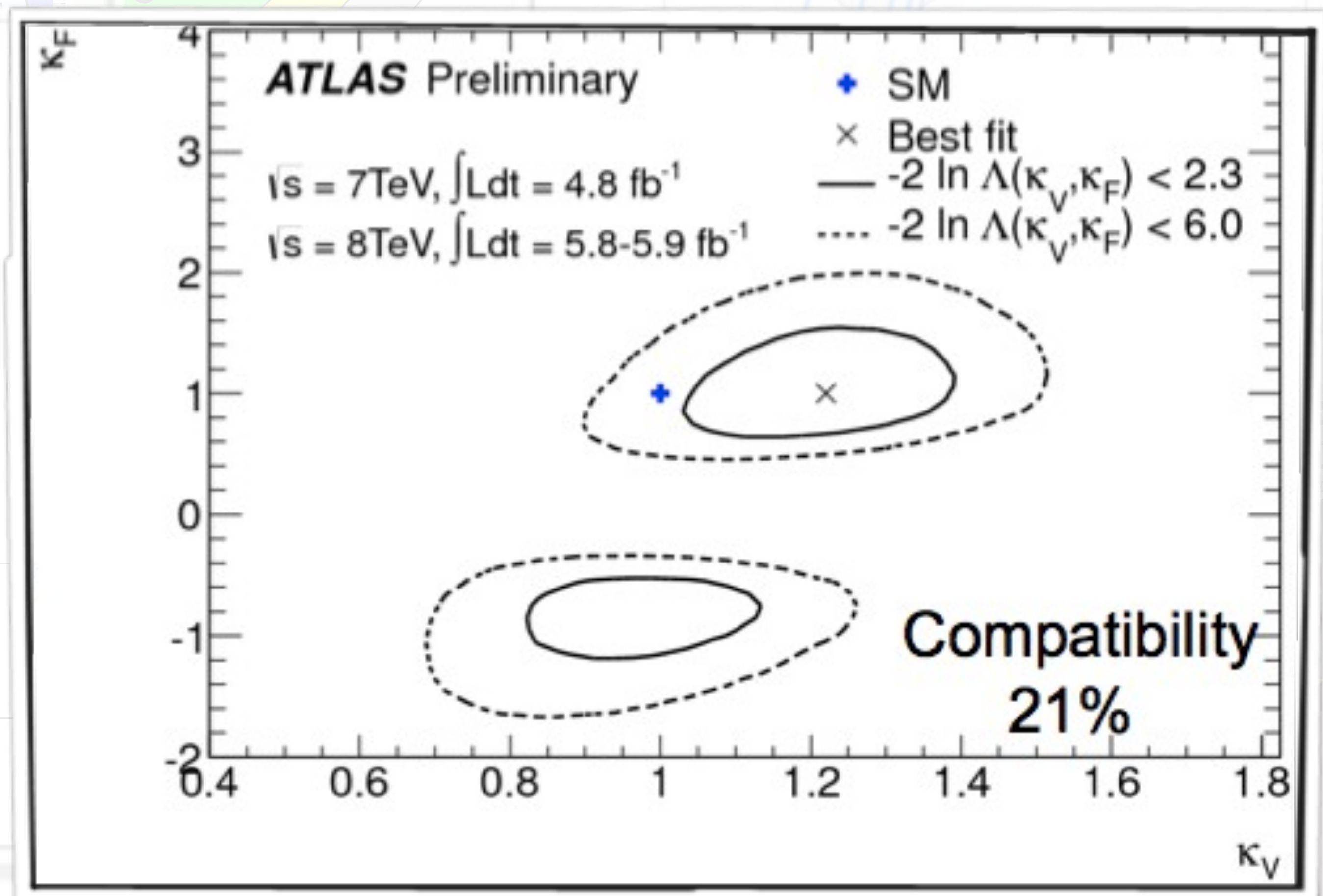


Higgs coupling fits: test of unitarity

don't leave it in the hands of theorists!



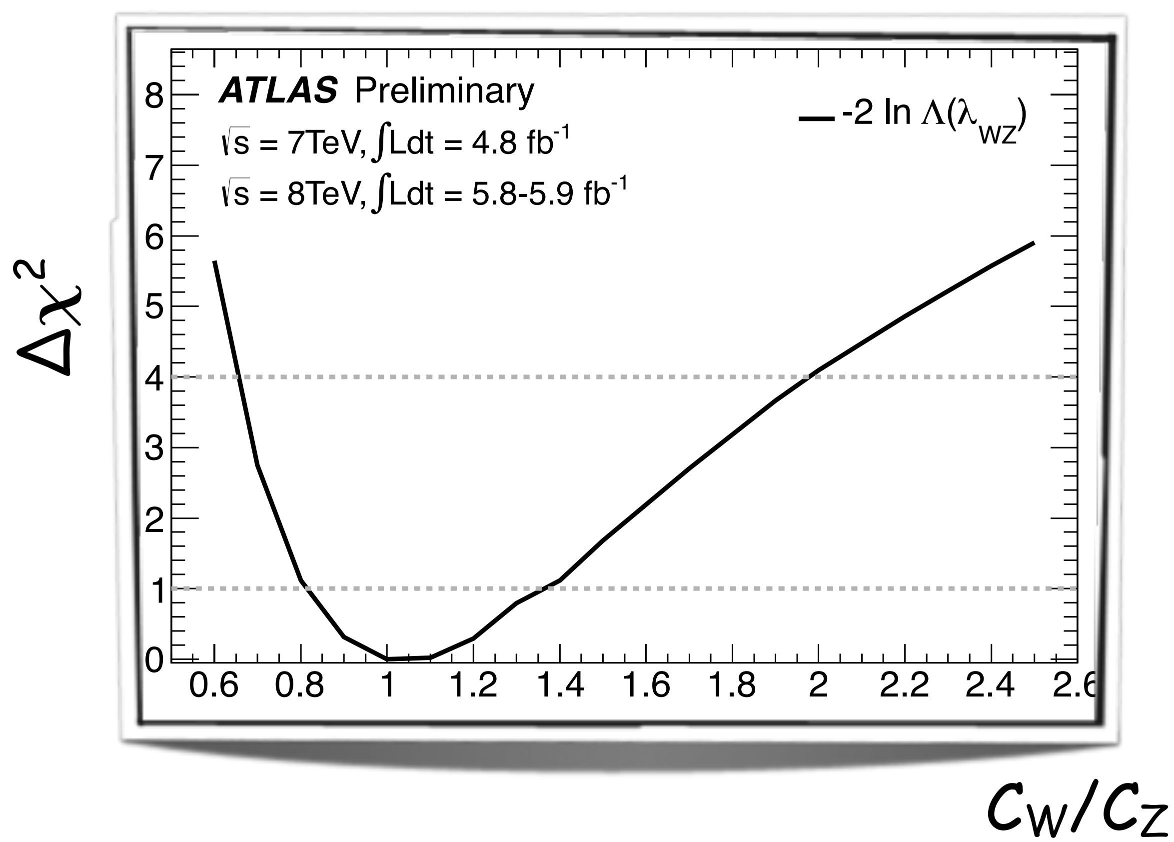
CMS

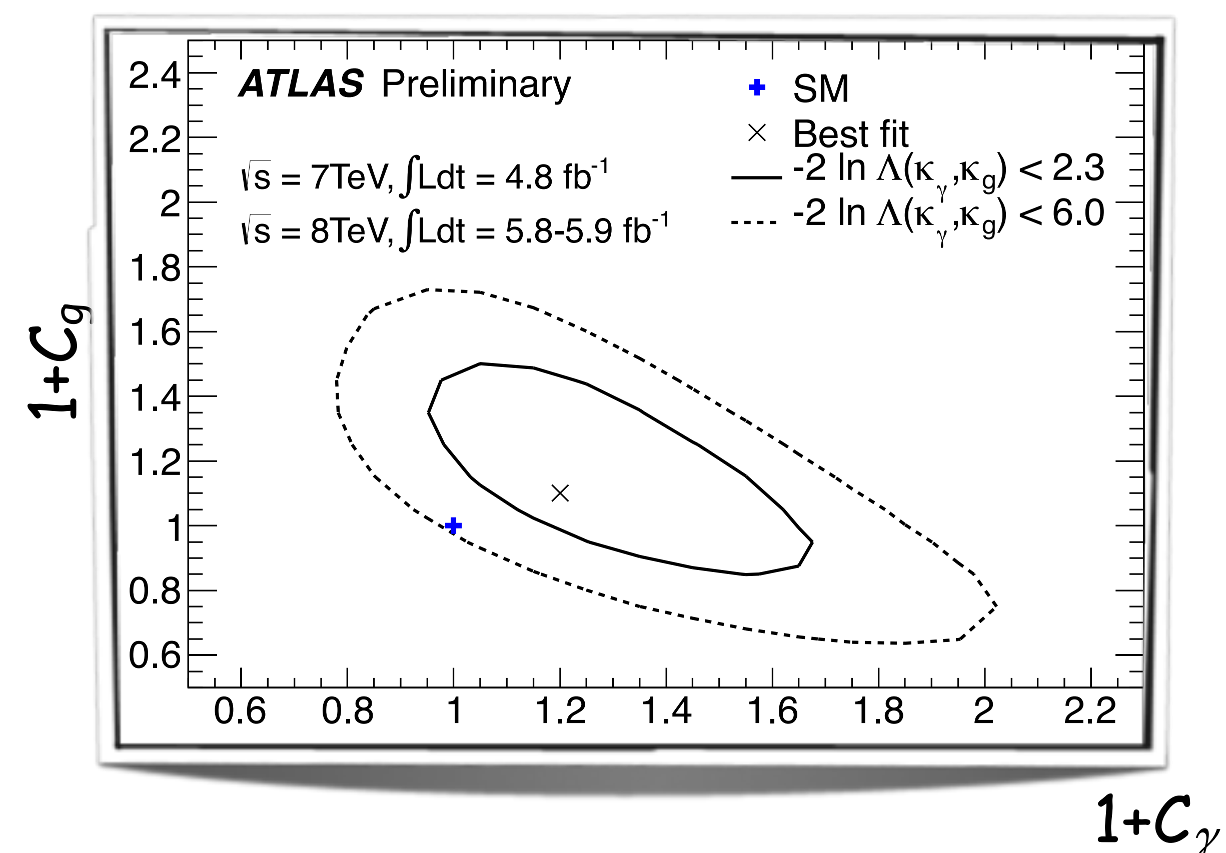


ATLAS

χ^2 fit: other tests of the SM structures

- custodial symmetry: $C_W=C_Z$?
- probing the weak isospin symmetry: $C_u=C_d$?
- quark and lepton symmetry: $C_q=C_l$?
- new non-SM particle contribution: BR_{inv}? $C_g=C_\gamma=0$?





ATLAS-CONF-2012-127

Some tensions
but no statistically significant deviations from the SM structure

Is the Higgs part of an SU(2) doublet?

Does New Physics flow towards the SM in the IR?
i.e. is the Higgs part of an SU(2) doublet?

need to promote the chiral Lagrangian to an SM gauge invariant Lagrangian

pioneering work by Buchmuller-Wyler '86

complete classification by Grzadkowski et al '1008.4884

28 CP⁺ operators
(+ 25 4-Fermi operators)

only
14 of these
operators
can be generated
at tree-level by NP

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

CP-odd

doublet?

$b_V - 1 = 2(c_V^2 - 1)$

$3 b_{3V} = 4\, c_V (b_V - c_V^2)$

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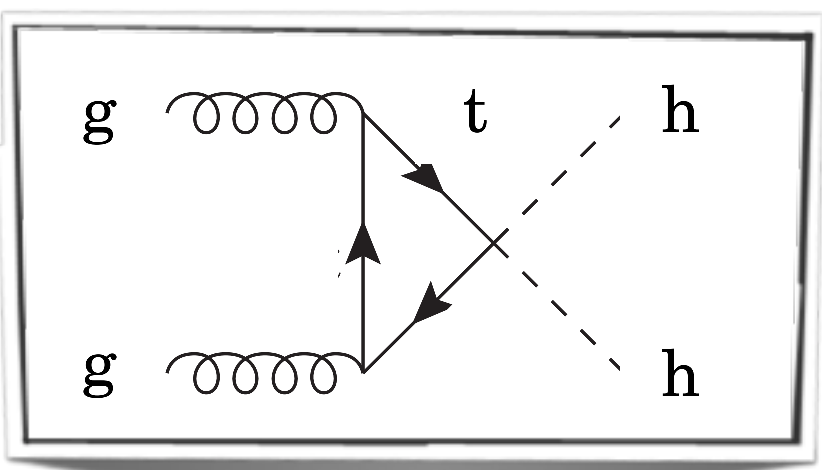
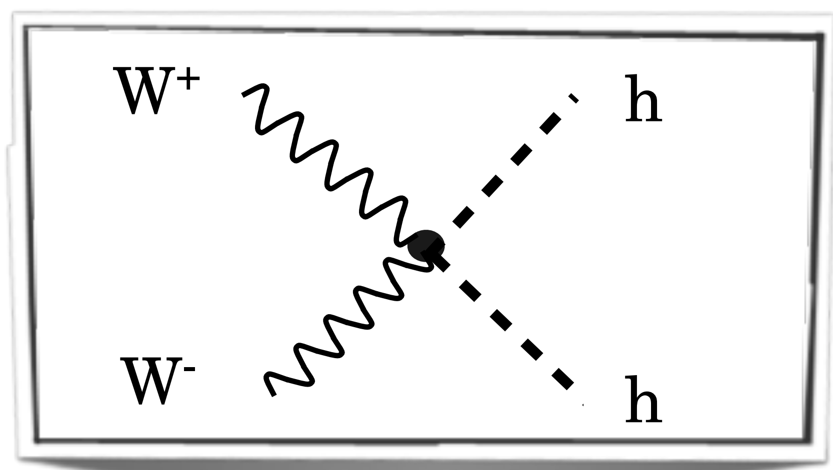
Higgs doublet?

not an easy question at the LHC since we need multi-Higgs couplings



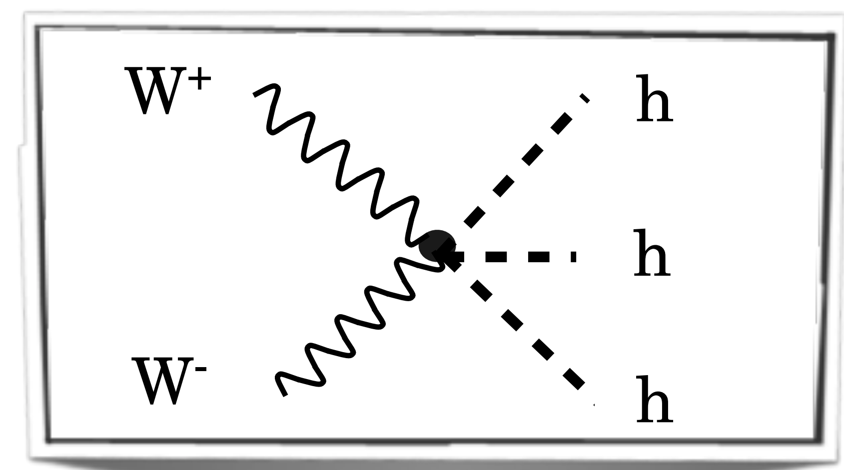
Grôber, Mûhlleitner '10
Contino et al '12
Gillioz et al '12



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

$$b_V - 1 = 2(c_V^2-1) + \cancel{O(c_V^2-1)^2}$$

for PGB Higgs



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

$$3 b_{3V} = 4\, c_V(b_V - c_V^2) + \cancel{O(c_V^2-1)^2}$$

for PGB Higgs

Effective Higgs

NP

typical mass scale

$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2 / g_*

effective approach valid iff

mass gap: $M \gg g_{SM}\, v$

weakly coupled NP

$g_* \sim g_{SM}$

MSSM in the decoupling limit

strongly coupled NP

$g_* \gg g_{SM}$

composite Higgs models

in both cases, Higgs couples to NP with g_*

Higgs power counting

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 $m_\rho = g_\rho f$) (g_{SM} factors in V)

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

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

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

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

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Giudice, Grojean, Pomarol, Rattazzi '07

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

custodial breaking

Form factor operators (sensitive to the scale $m_\rho = g_\rho f$) (g_{SM} factors in V)

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

Goldstone sym.
(PGB Higgs)

Higgs power counting

$$\Delta\mathcal{L}_B = \frac{\bar{c}_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3$$
$$+ \frac{\bar{c}_u}{v^2} y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2} y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2} y_l\, H^\dagger H\, \bar{L}_L H l_R + h.c.$$
$$+ \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$
$$+ \frac{i\bar{c}_{HW} g}{m_W^2}\left(D^\mu H\right)^\dagger \sigma^i \left(D^\nu H\right) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}\left(D^\mu H\right)^\dagger\left(D^\nu H\right) B_{\mu\nu}$$
$$+ \frac{\bar{c}_\gamma {g'}^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,$$

generic new physics

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_y \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{g^2}{16\pi^2}\frac{v^2}{f^2}\right)$$

<u>note</u>: in decoupled MSSM, selection rule ⇒ cH ~ $O(m_W^4/M^4)$

dynamics with Higgs as PGB

$$\bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{g^2}{16\pi^2}\frac{v^2}{f^2}\right) \times \frac{g_{SM}^2}{g_*^2}$$

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07

Contino, Ghezzi, Grojean, Muhlleitner, Spira 'to appear

probing Higgs interactions: g_* or f

$$\frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)$$

$$\frac{\bar{c}_\psi y_\psi}{v^2}\;H^\dagger H\,\bar{\psi}_L H\psi_R + h.c.$$

$$\frac{\bar{c}_6\lambda_4}{v^2}\left(H^\dagger H\right)^3$$

Parametrize corrections to tree-level Higgs couplings:

$$\frac{\Delta c}{c_{SM}} \sim \frac{v^2}{f^2} \equiv \xi$$

$$c_V = 1 - \frac{\bar{c}_H}{2} \qquad c_\psi = 1 - \left(\frac{\bar{c}_H}{2} + \bar{c}_\psi\right) \qquad d_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07 Contino, Ghezzi, Grojean, Muhlleitner, Spira 'to appear

probing NP scale: M = g* f

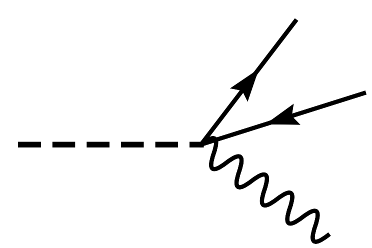
$$\boxed{\begin{array}{l} \dfrac{\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right) \left(D^\nu W_{\mu\nu}\right)^a \\ \dfrac{\bar{c}_B g'}{2m_W^2} \left(H^\dagger i \overleftrightarrow{D}^\mu H\right) \left(\partial^\nu B_{\mu\nu}\right) \end{array}} \Rightarrow \begin{array}{c} D_\mu W^+_{\mu\nu} W^-_\nu h \\ \partial_\mu Z_{\mu\nu} Z_\nu h \\ \partial_\mu \gamma_{\mu\nu} Z_\nu h \end{array}$$

one linear combination fixed due to (accidental) custodial invariance

Use equations of motions: $D_\mu V_{\mu\nu} V_\nu h = \boxed{(m_V^2 V_\nu} + \boxed{\bar{\psi}\gamma_\nu \psi) V_\nu h}$

subleading correction to tree-level couplings $\boxed{\Delta c_{W^\pm, Z} \sim \left(\frac{m_W^2}{\Lambda^2}\right)}$

contact correction to three-body decays



$$\frac{\delta \mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{\Lambda^2}\right)$$

inclusive WW,ZZ rates

slide courtesy @ R. Contino

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07

Contino, Ghezzi, Grojean, Muhlleitner, Spira 'to appear

probing NP scale: M = g_* f

$$\frac{\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^a$$

$$\frac{\bar{c}_B g'}{2m_W^2}\left(H^\dagger i \overleftrightarrow{D}^\mu H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

$\Rightarrow$

$$D_\mu W^+_{\mu\nu} W^-_\nu h$$

$$\partial_\mu Z_{\mu\nu} Z_\nu h$$

$$\partial_\mu \gamma_{\mu\nu} Z_\nu h$$

one linear combination fixed due to (accidental) custodial invariance

direct(tree-level) contribution to EW oblique corrections

$\Rightarrow$ LEP already puts strong bounds on these operators

$$\hat{S} = (\bar{c}_W + \bar{c}_B) \lesssim 10^{-3}$$

correction to WW, ZZ decay rates too small

$$\frac{\Gamma(h \to W^{(*)}W^*)}{\Gamma(h \to W^{(*)}W^*)_{SM}} \simeq 1 - 2\,\bar{c}_W$$

$$\frac{\Gamma(h \to Z^{(*)}Z^*)}{\Gamma(h \to Z^{(*)}Z^*)_{SM}} \simeq 1 - 1.8\,\bar{c}_W - 0.6\,\bar{c}_B$$

inclusive rates

slide courtesy @ R. Contino

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07 Contino, Ghezzi, Grojean, Muhlleitner, Spira 'to appear

probing NP scale: M = g* f

$$\frac{\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^a i \overleftrightarrow{D}^\mu H\right)\left(D^\nu W_{\mu\nu}\right)^a$$

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$\Rightarrow$

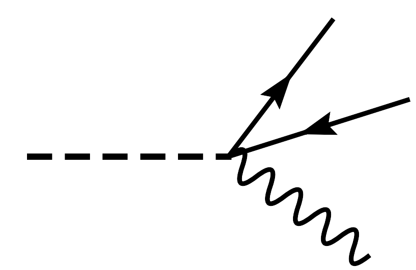
$D_\mu W^+_{\mu\nu} W^-_\nu h$

$\partial_\mu Z_{\mu\nu} Z_\nu h$

$\partial_\mu \gamma_{\mu\nu} Z_\nu h$

one linear combination fixed due to (accidental) custodial invariance

possible strategy: new contribution is local, cut on $q^2 = m(ll)^2$



$$\frac{d\Gamma}{dq^2} \Big/ \left(\frac{d\Gamma}{dq^2}\right)_{SM} \approx 1 + \bar{c}_{W,B}\left(\frac{q^2}{m_h^2}\right) \lesssim 1 + \bar{c}_{W,B}\,\frac{16\pi^2}{g^2}$$

NP could in principle be seen in differential distributions in h→ZZ*→4l

Azatov, Falkowski, Grojean, Kuflik, 'in progress

slide courtesy @ R. Contino

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07 Contino, Ghezzi, Grojean, Muhlleitner, Spira 'to appear

loop operators

$$\frac{i\,\bar c_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^a (D^\mu H)\, W^a_{\mu\nu}$$

$$\frac{i\,\bar c_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger\,(D^\mu H)\, B_{\mu\nu}$$

$$\frac{\bar c_\gamma\, g'^2}{m_W^2}\; B_{\mu\nu}B^{\mu\nu}\; H^\dagger H$$

$$\frac{\bar c_g\, g_S^2}{m_W^2}\; G_{\mu\nu}G^{\mu\nu}\; H^\dagger H$$

$$W^+_{\mu\nu}W^-_{\mu\nu}h,\quad Z_{\mu\nu}Z_{\mu\nu}h,$$

$$\gamma_{\mu\nu}\gamma_{\mu\nu}h,\quad Z_{\mu\nu}\gamma_{\mu\nu}h$$

one linear combination starts at dim=8

$$c_{Z\gamma} = \frac{c_{WW}}{\sin(2\theta_W)} - \frac{c_{ZZ}}{2}\cot(\theta_W) - \frac{c_{\gamma\gamma}}{2}\tan(\theta_W)$$

$$G_{\mu\nu}G_{\mu\nu}h$$

Corrections to $h\to WW, ZZ$ rates: $\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{m_W^2}{16\pi^2 f^2}\right)$ too small

Corrections to $h\to WW, ZZ$ differential distributions and $h\to\gamma Z$ rate: $\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right)$ test Higgs strong interactions

Corrections to $h\to\gamma\gamma$ rate: (PGB scenario) $\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right)\times\left(\frac{g_{SM}^2}{g_*^2}\right)$ subdominant compared to cH and ct effects $\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right)$

slide courtesy @ R. Contino

RG-improved Higgs physics

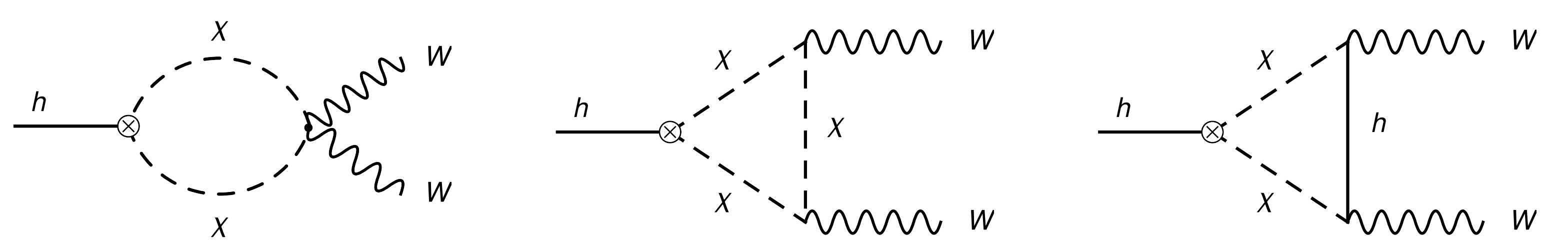
Grojean, Jenkins, Manohar, Trott 'to appear

the previous estimates were based on the values of the Wilson coefficients @ NP scale
RG effects can change the picture

$$\bar{c}_i(\mu) \simeq \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha}{8\pi} \log\left(\frac{\mu^2}{M^2} \right) \right) \bar{c}_j(M)$$

anomalous dimensions

dominant effects: loops of Goldstone bosons (couplings g*)



$$\mu \frac{d}{d\mu} \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{8\pi} \gamma \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} \qquad \gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ 1/12 & 0 & 0 \\ ?? & 0 & 0 \end{pmatrix}$$

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$$\bar{c}_{W+B}(\mu) = \underbrace{\bar{c}_{W+B}(M)}_{\frac{m_W^2}{M^2}} + \# \frac{g^2}{16\pi^2} \underbrace{\log\left(\frac{\mu^2}{M^2}\right) \bar{c}_H(M)}_{}$$

$$\frac{m_W^2}{M^2} \quad \text{>>} \quad \frac{g^2}{16\pi^2}\frac{v^2}{f^2} = \frac{g_*^2}{16\pi^2}\frac{m_W^2}{M^2} \times \text{Log}$$

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$$\frac{m_W^2}{M^2} \gg \frac{g^2}{16\pi^2}\frac{v^2}{f^2} = \frac{g_*^2}{16\pi^2}\frac{m_W^2}{M^2} \times \text{Log}$$

$$\bar{c}_{HW+HB}(\mu) = \bar{c}_{HW+HB}(M) + \# \frac{g^2}{16\pi^2} \log\left(\frac{\mu^2}{M^2}\right) \bar{c}_H(M)$$

$$\frac{g^2}{16\pi^2}\frac{v^2}{f^2} \sim \text{or} \ll \frac{g^2}{16\pi^2}\frac{v^2}{f^2} = \frac{g_*^2}{16\pi^2}\frac{m_W^2}{M^2} \times \text{Log}$$

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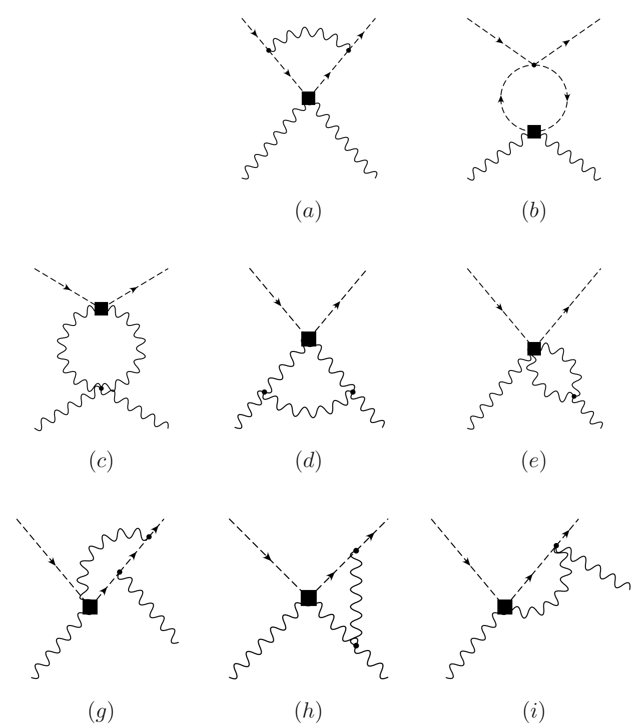
the case of $\gamma\gamma$
(no loop of Goldstone, need loops of weakly coupled fields)



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the case of $\gamma\gamma$
(no loop of Goldstone, need loops of weakly coupled fields)

$$c_{\gamma\gamma}(M_h) = \left[1 - \underbrace{\# \log \frac{M_h}{\Lambda}}_{\frac{g^2}{16\pi^2} \frac{v^2}{f^2}} \right] c_{\gamma\gamma}(\Lambda) - \# \frac{g^2}{8\pi^2} \underbrace{\log \frac{M_h}{\Lambda}}_{} c_{W+B}(\Lambda)$$

$$\frac{g^2}{16\pi^2} \frac{m_W^2}{M^2} = \frac{g^2}{16\pi^2} \frac{v^2}{f^2} \frac{g^2}{g_*^2} \times \text{Log}$$

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for weak models (g_*~g)

dominant contribution forgotten up to now

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott 'to appear

the previous estimates were based on the values of the Wilson coefficients @ NP scale

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$$\bar{c}_i(\mu) \simeq \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha}{8\pi} \log\left(\frac{\mu^2}{M^2}\right)\right) \bar{c}_j(M)$$

the case of $\gamma\gamma$

(no loop of Goldstone, need loops of weakly coupled fields)

$$c_{\gamma\gamma}(M_h) = \underbrace{\left[1 - \# \log \frac{M_h}{\Lambda}\right] c_{\gamma\gamma}(\Lambda)}_{\frac{g^2}{16\pi^2} \frac{v^2}{f^2} \frac{g^2}{g_*^2}} - \underbrace{\# \frac{g^2}{8\pi^2} \log \frac{M_h}{\Lambda} c_{W+B}(\Lambda)}_{\frac{g^2}{16\pi^2} \frac{m_W^2}{M^2} = \frac{g^2}{16\pi^2} \frac{v^2}{f^2} \frac{g^2}{g_*^2} \times \mathrm{Log}}$$

for strong PGB models

important contribution forgotten up to now

but screened by c_H and c_t contributions (unless large Log)

c_H and c_t $\quad \frac{g^2}{16\pi^2} \frac{v^2}{f^2}$

RG-Higgs physics: Don't forget LEP!

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

$$\mu\frac{d}{d\mu}\begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{8\pi}\gamma\begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix}$$

$$\gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ 1/12 & 0 & 0 \\ ?? & 0 & 0 \end{pmatrix}$$

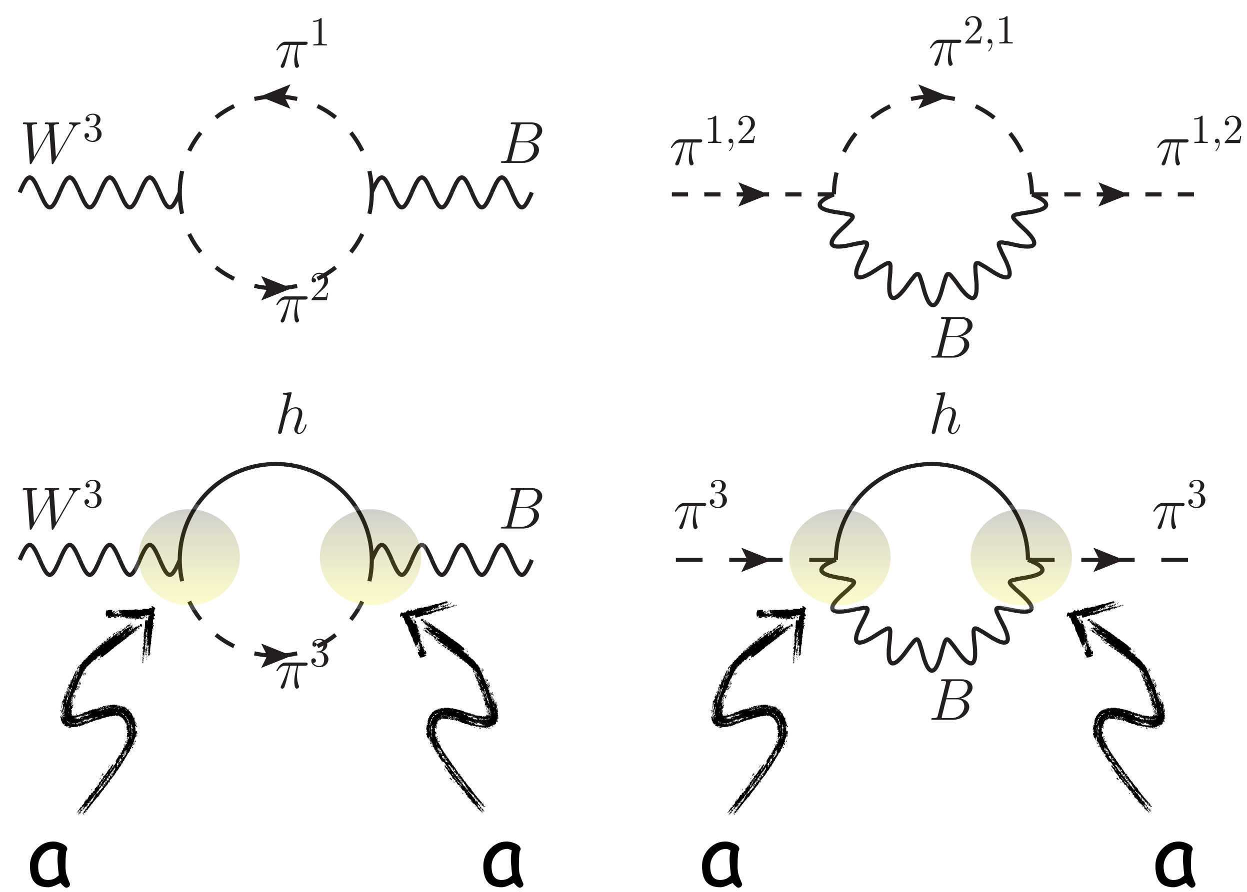
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



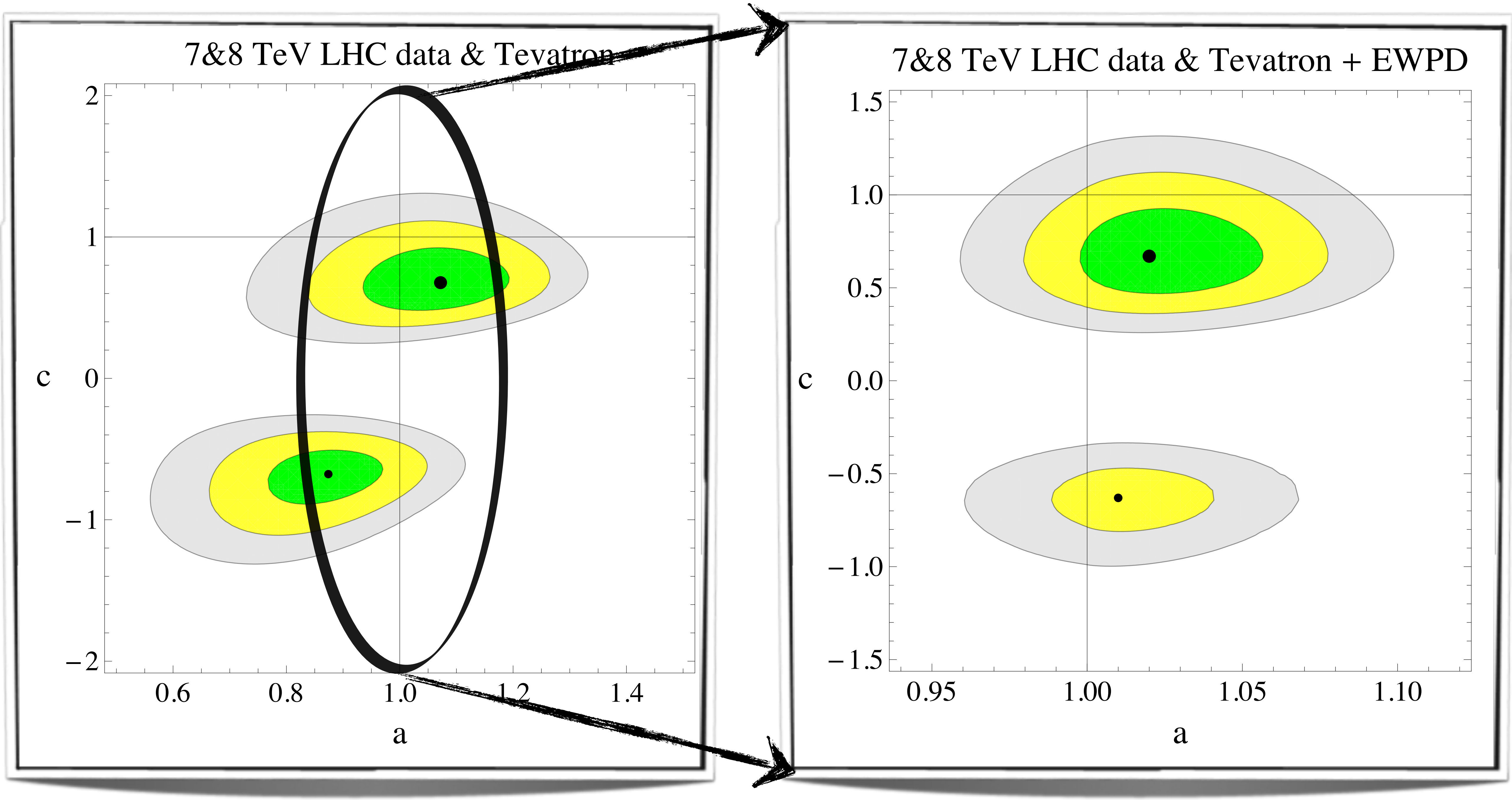
As per G. Passarino's request: Roseta's iPad mini $a=c_V=\kappa_V$

Log. div. cancel only for a=1 (SM)

a≠1 log. sensitivity on the scale of new physics

RG-Higgs physics: Don't forget LEP!

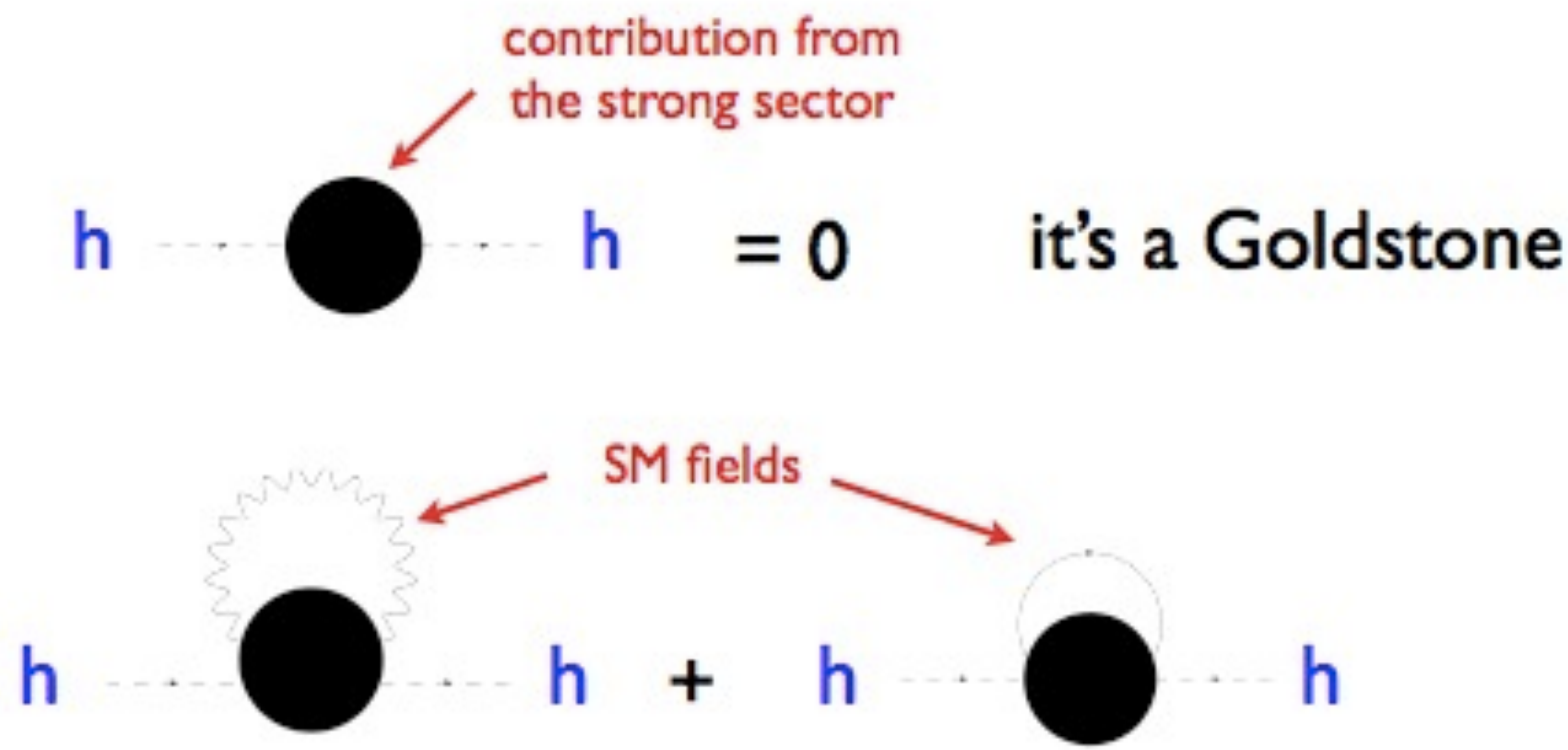
Espinosa, Grojean, Muhlleitner, Trott '12



EW data prefer value of 'a' close to 1

Light composite Higgs from "light" resonances

The interactions between the strong sector and the SM generate a potential for the Higgs



Impossible to compute the details of the potential from first principles
but using general properties on the asymptotic behavior of correlators
(saturation of Weinberg sum rules with the first few lightest resonances)
it is possible to estimate the Higgs mass

Pomarol, Riva '12

$$m_h^2 \approx \frac{3}{\pi^2}\frac{m_t^2 m_Q^2}{f_{G/H}^2}$$

Marzocca, Serone, Shu '12

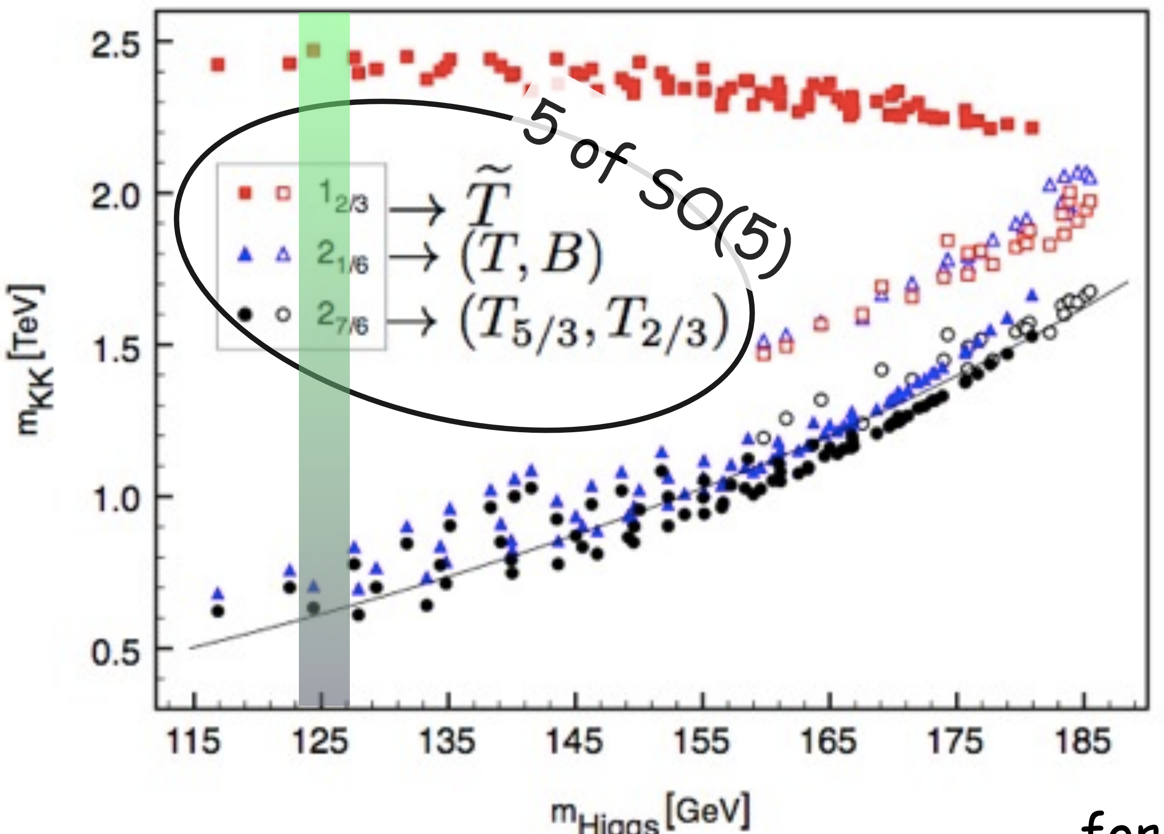
$$m_Q \lesssim 700\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\left(\frac{160\ \text{GeV}}{m_t}\right)\left(\frac{f}{500\ \text{GeV}}\right)$$

fermionic resonances below ~ 1 TeV
vector resonances ~ few TeV (EW precision constraints)
~ for a natural (<20% fine-tuning) set-up ~

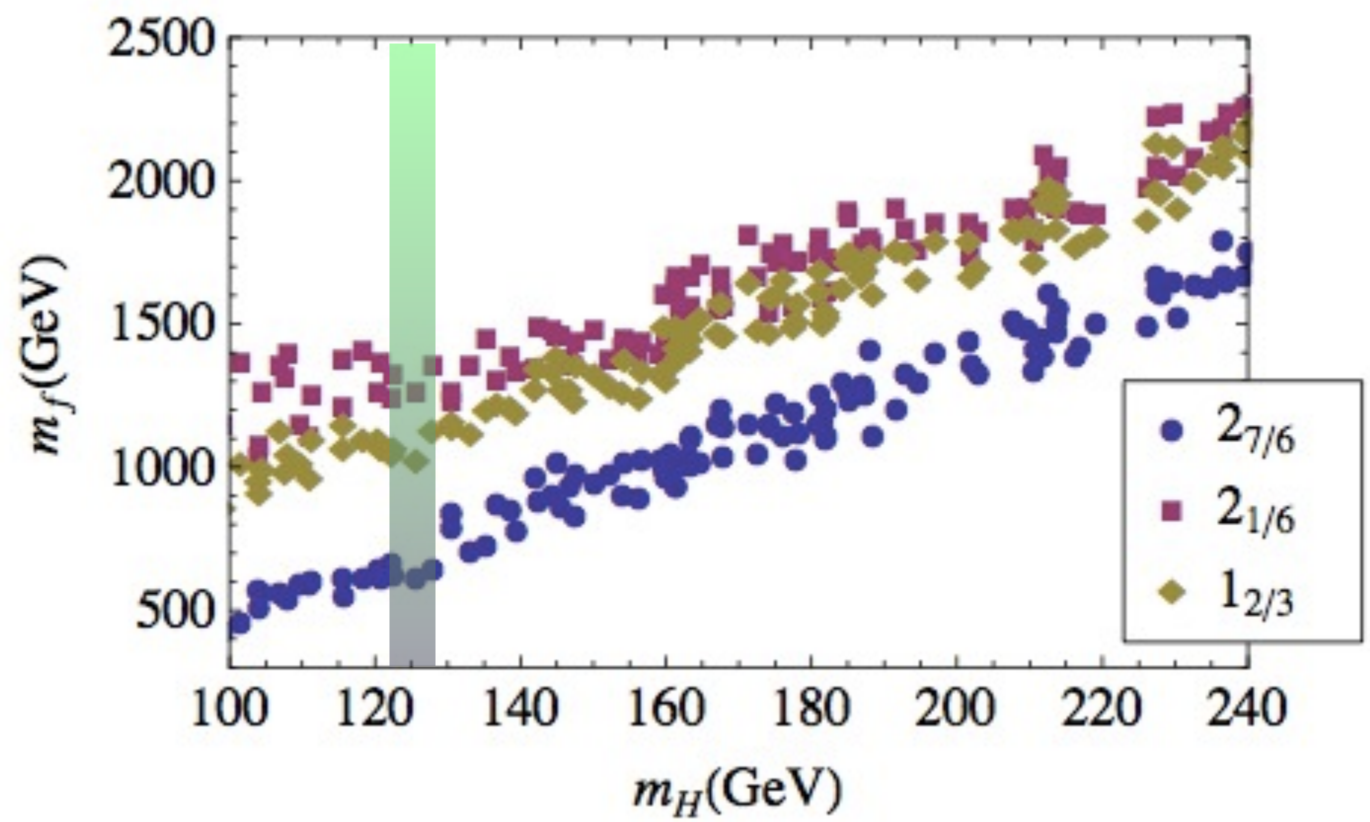
Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



De Curtis, Redi, Tesi '11



for similar results, see also

Matsedonskyi, Panico, Wulzer '12 & Marzocca, Serone, Shu '12

Nice AdS/CFT interpretation

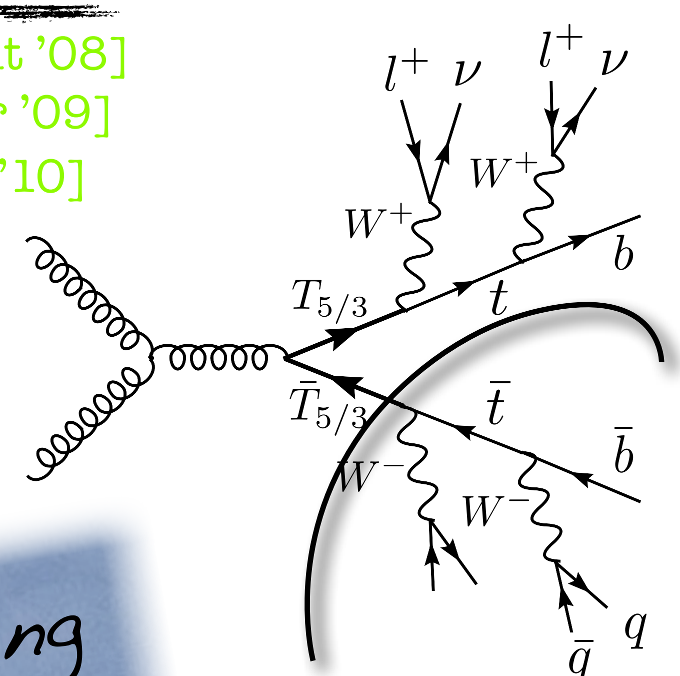
$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

$$M_\Psi = 1/2 \leftrightarrow \dim[\mathcal{O}_\Psi] = 3/2 \leftrightarrow \text{light free field decoupled from CFT}$$

Rich phenomenology of the top partners

Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]



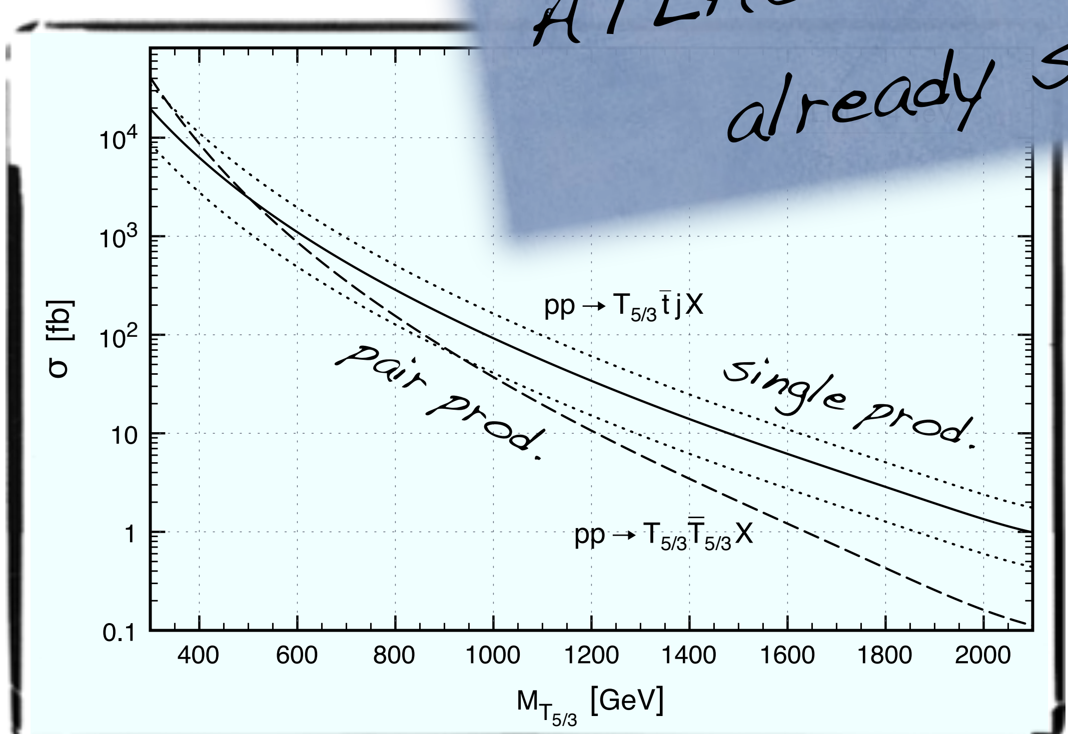
- *tt+jets* is not a background [except for charge mis-ID and fake e⁻]
- the resonant (*tW*) invariant mass can be reconstructed

discovery potential (LHC_{14TeV})

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

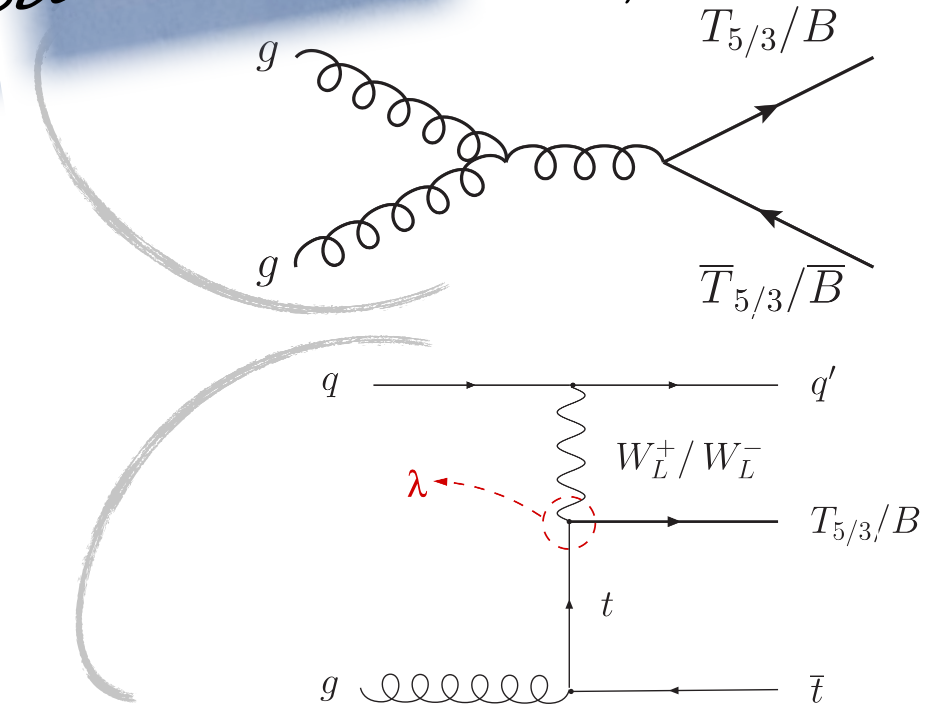
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

ATLAS & CMS searches ongoing
already stringent bounds



[Contino, Servant '08]

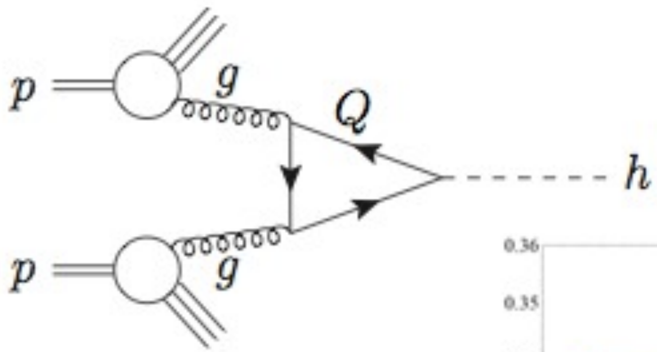
(model independent)



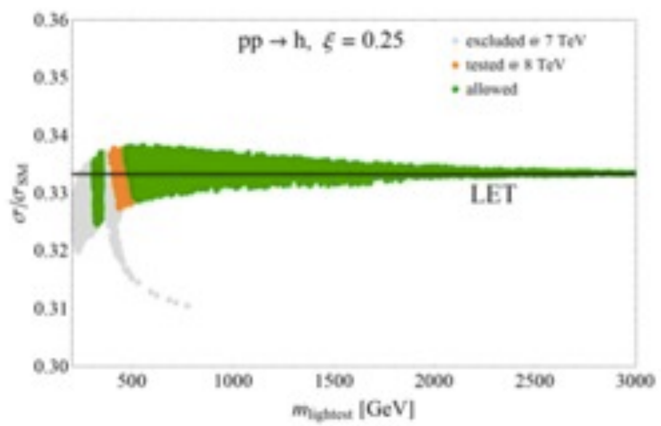
Single production (model dependent)

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\mathrm{TeV}} \approx 50$ pb



two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

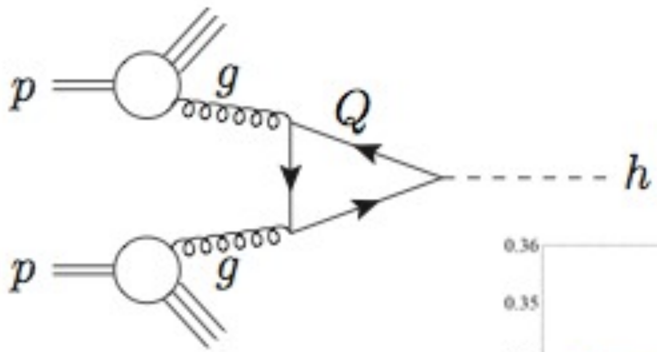
Falkowski '07

Azatov, Galloway '11

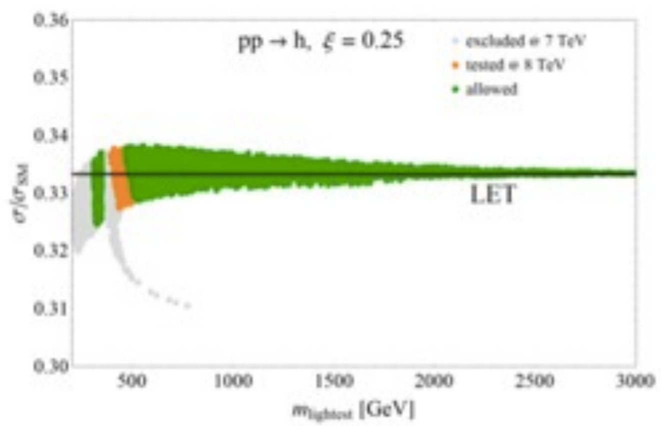
Delaunay, Grojean, Perez, Zielger 'to appear

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma_{14\mathrm{TeV}}^{SM} \approx 50$ pb



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- ☑ T's run in the loops
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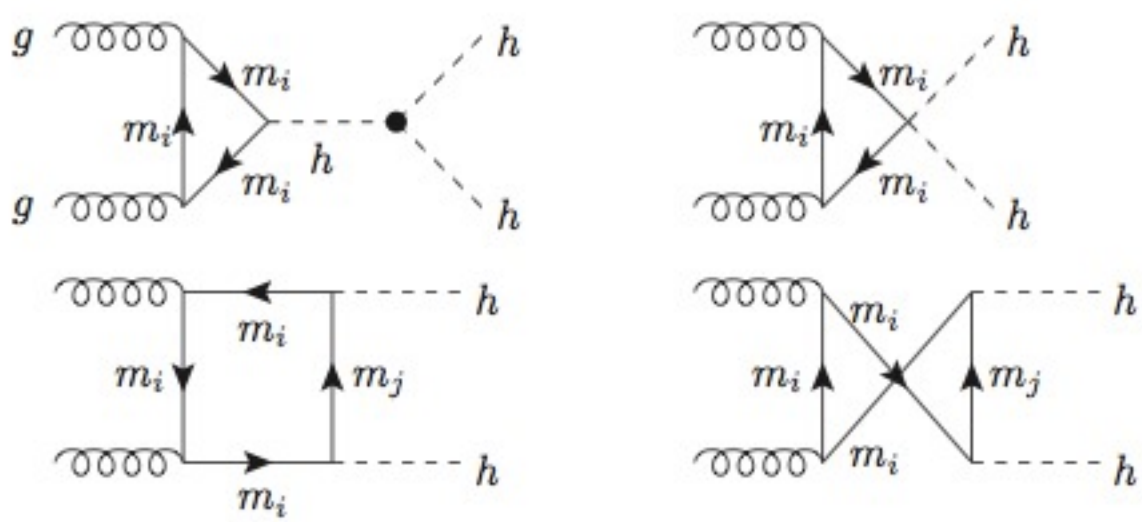
Falkowski '07

Azatov, Galloway '11

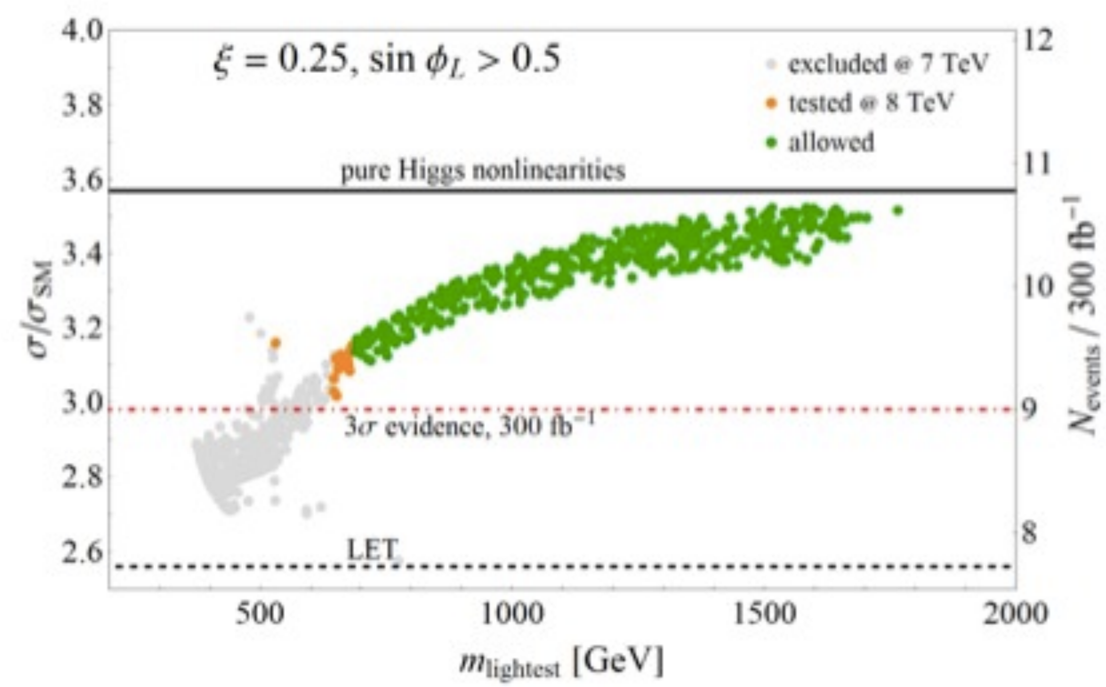
Delaunay, Grojean, Perez, Zielger 'to appear

~ small sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



$\sigma_{14\mathrm{TeV}}^{SM} = 17.9$fb



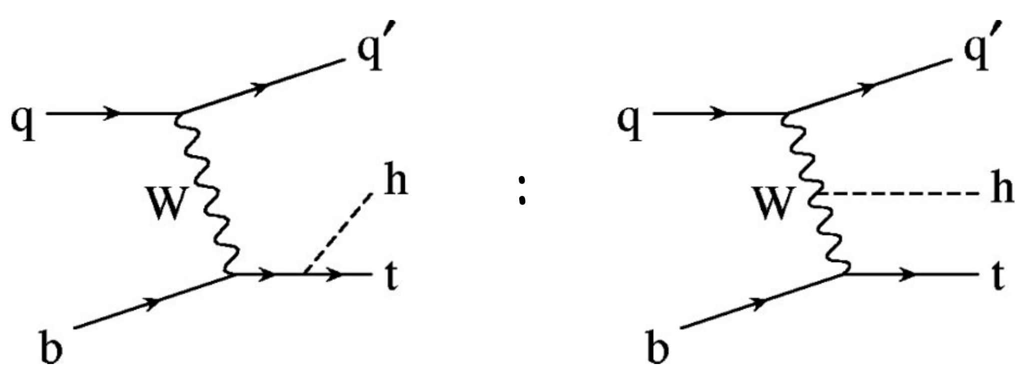
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q'th

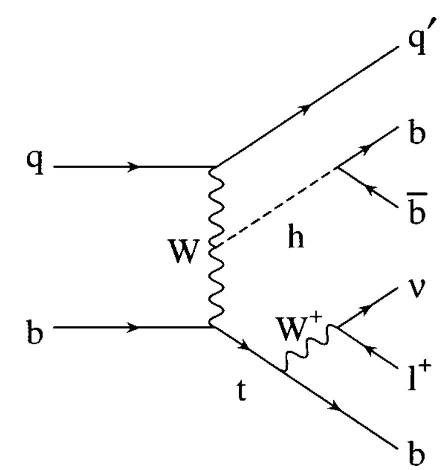


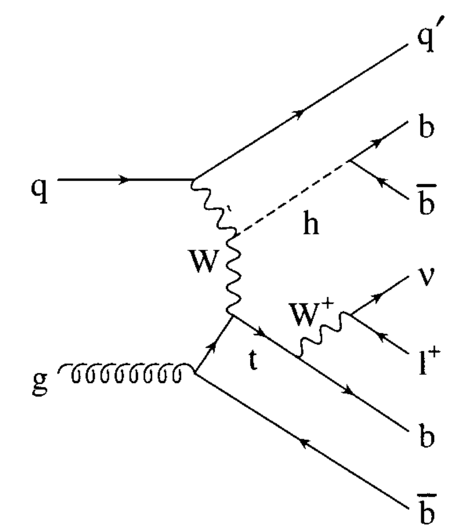
@m$_H$=125GeV $\dfrac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$

Farina, Grojean, Maltoni, Salvioni, Thamm '12

look at final states:

$3\, b + 1\,\mathrm{fwd\ \ jet} + l^{\pm} + \not{p}^T$. $4\, b + 1\,\mathrm{fwd\ \ jet} + l^{\pm} + \not{p}^T$.



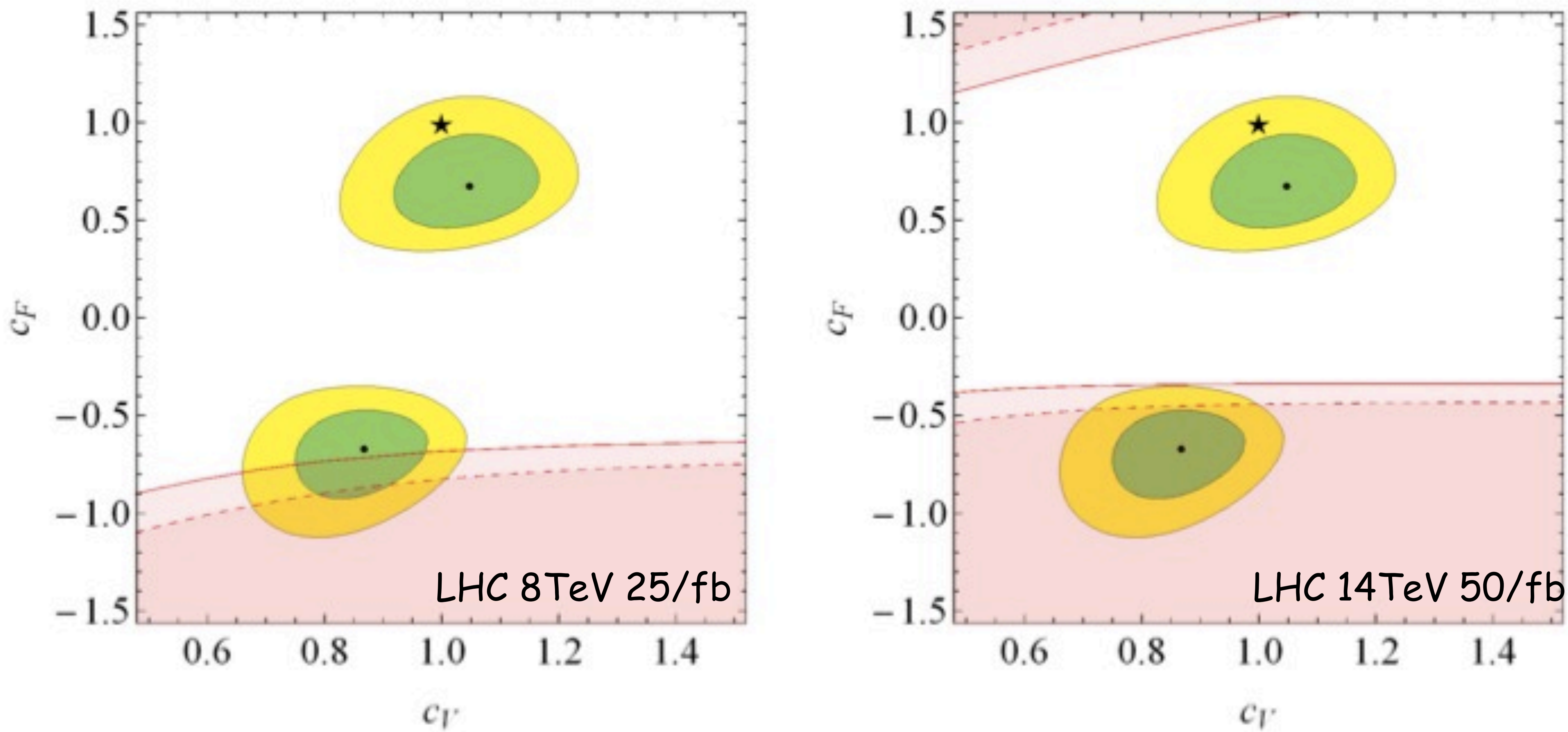


	$\sigma(pp \to tjh)$ [fb]		$\sigma(pp \to tjh\bar{b})$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.3	252.7	12.14	181.4
14 TeV	80.6	1042	59.6	828.5

Top partners & Higgs physics

direct measurement of top-higgs coupling

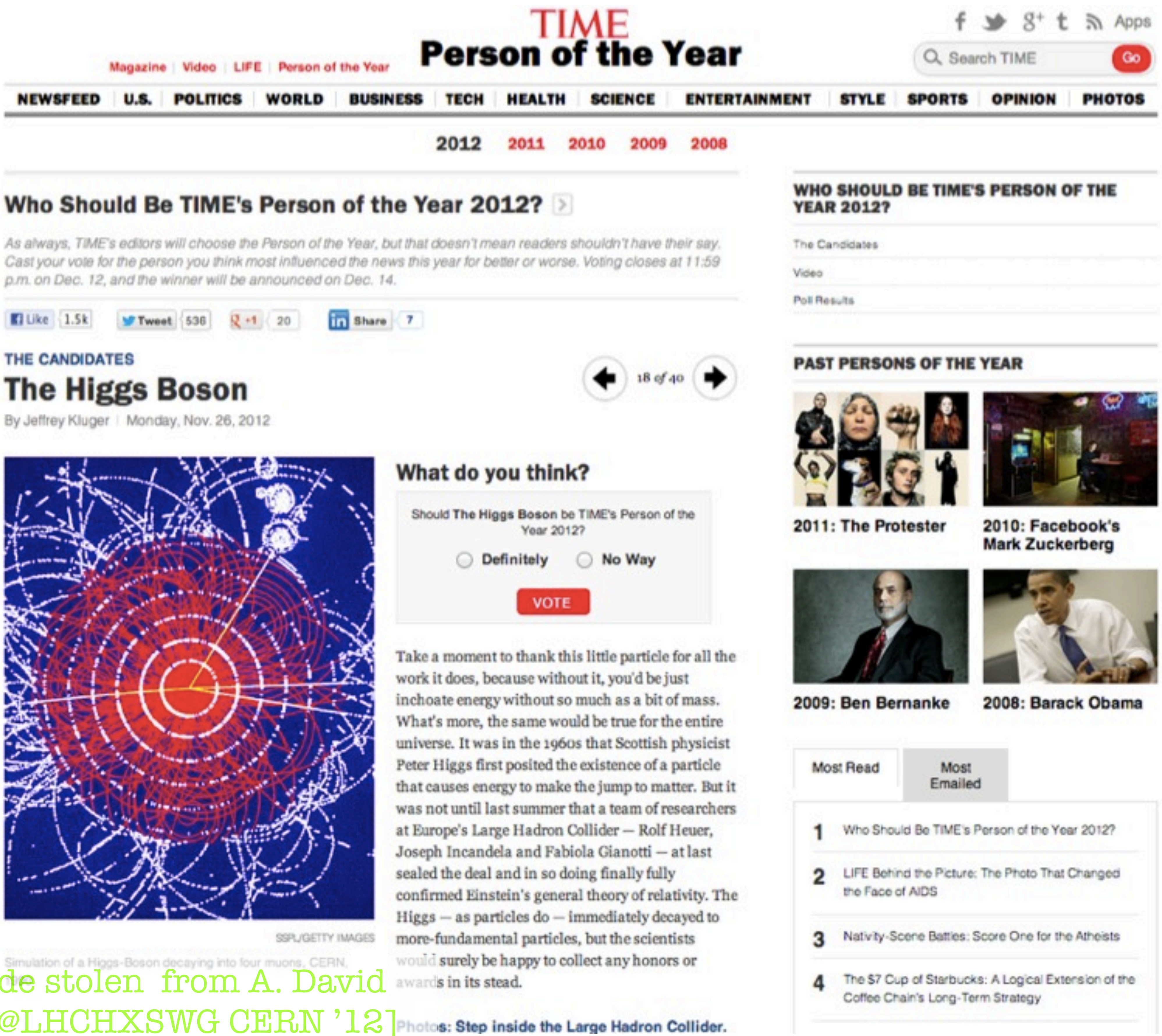
single-top in association with Higgs



68% and 95% CL exclusion region vs current Higgs coupling fit

Farina, Grojean, Maltoni, Salvioni, Thamm '12

Conclusions: Higgs = Person of year?



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Person of the Year
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Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

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THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger | Monday, Nov. 26, 2012

SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN.

What do you think?

Should The Higgs Boson be TIME's Person of the Year 2012?
Definitely No Way
VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?
The Candidates
Video
Poll Results

PAST PERSONS OF THE YEAR
2011: The Protester
2010: Facebook's Mark Zuckerberg
2009: Ben Bernanke
2008: Barack Obama

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Conclusions: Higgs = Person of year?

as of 06/2012

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Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

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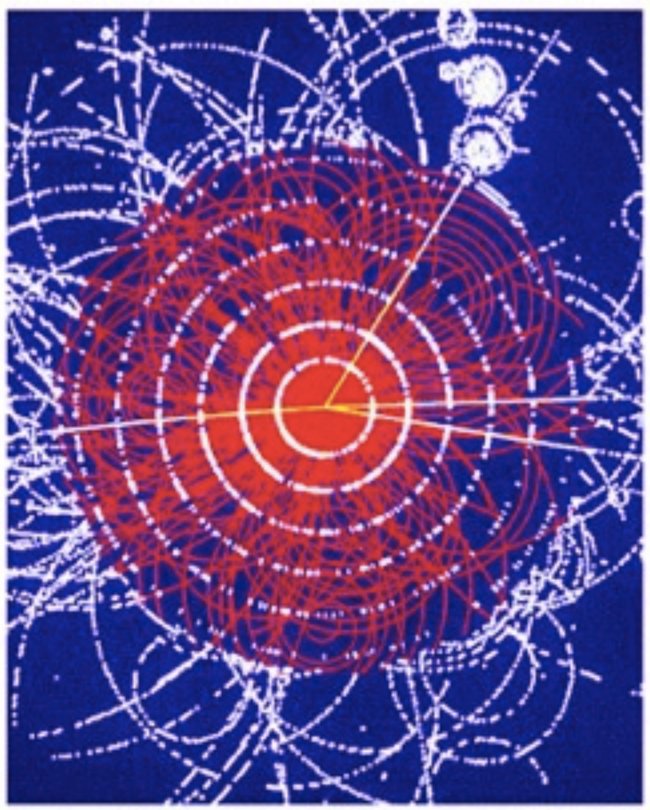
THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger | Monday, Nov. 26, 2012



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Simulation of a Higgs-Boson decaying into four muons, CERN.

What do you think?

Should The Higgs Boson be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

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Gabby Douglas	533,606	74,583
Stephen Colbert	526,534	66,301
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Hillary Clinton	506,973	84,007
Ai Weiwei	480,147	72,596
Mohamed Morsi	427,956	1,023,857
Roger Goodell	397,952	93,874
Sheldon Adelson	388,787	151,562
Malala Yousafzai	297,535	46,968
E.L. James	272,248	99,274
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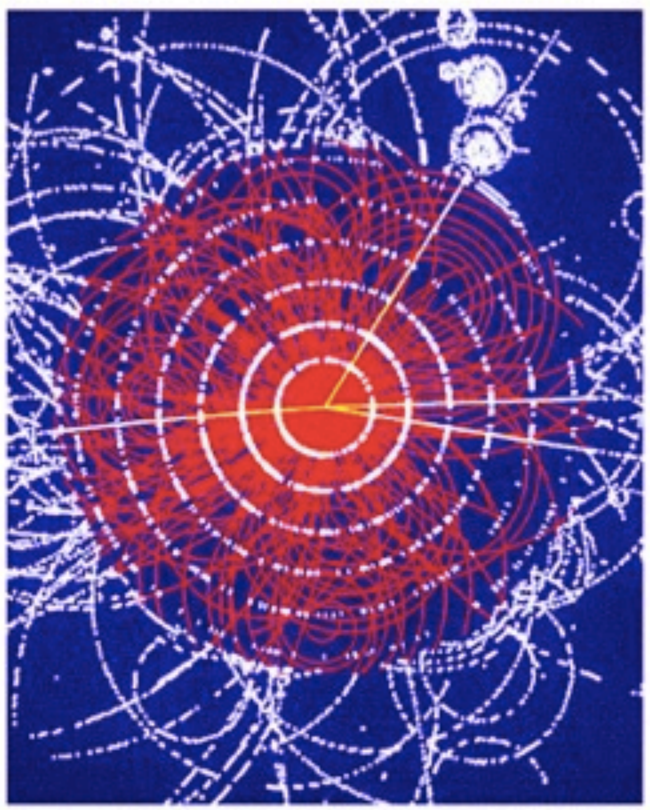

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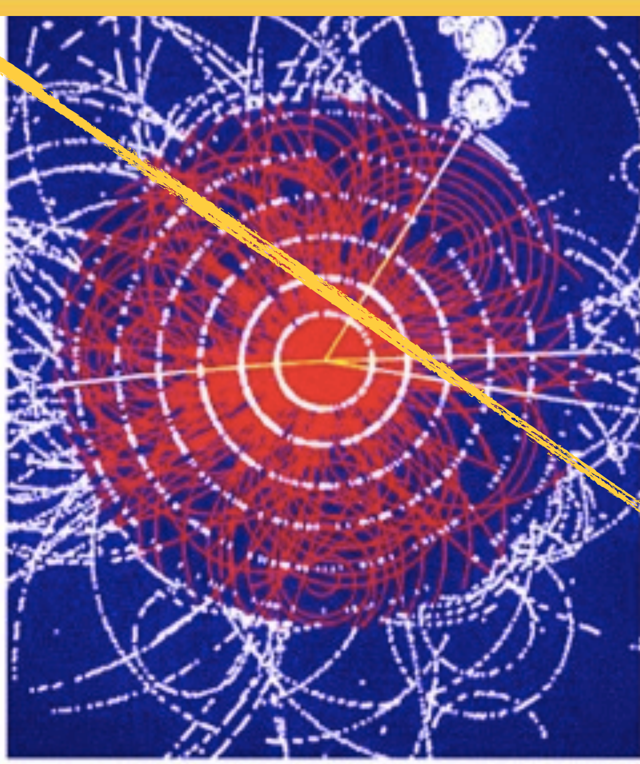

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