Extended Higgs sector

ACP Winter conference

Higgs Quo Vadis?

Aspen, March 13, 2013

Christophe Grojean

ICREA@IFAE/Barcelona

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INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

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Where are we?

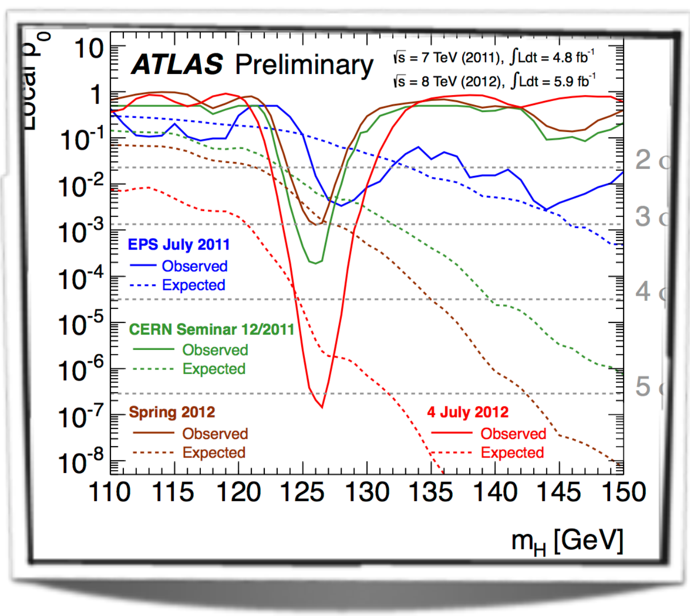
we are living a privileged moment in the history of HEP

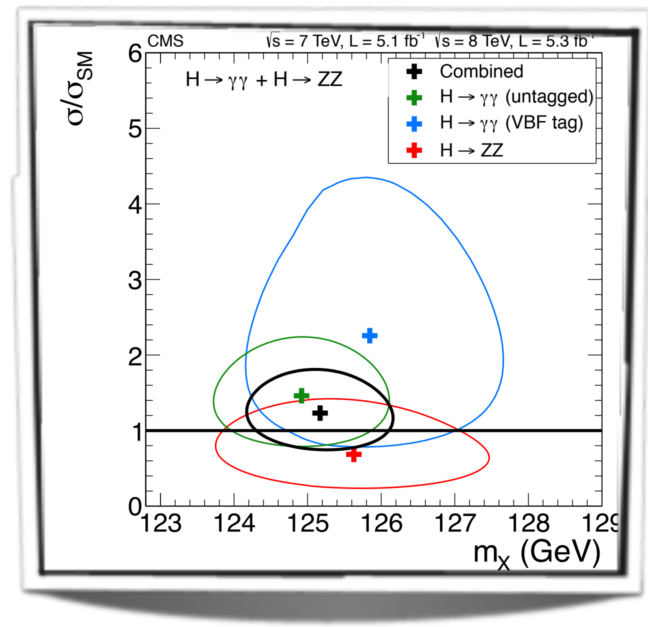
"We have found a new particle" CMS

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 does come with the Higgs?

We know that the Higgs is not the end of the story

- dark matter
- matter antimatter asymmetry
- hierarchy/naturalness problem
- ...

All these point towards an extended EW/Higgs sector

but so far this extension has been very elusive

- Direct searches @ LHC: M_{new} >~ O(500 GeV) unless reduced couplings to fermions
- EW precision data: M_{new} >~ O(TeV) unless some selection rules (eg R-parity)
- Flavor data: M_{new} >~ O(1000 TeV) unless some protection (eg MVF...)
- ...

HEP future:

exploration/discovery era or consolidation/measurement era?

let's use what we have at our disposal (the Higgs) to explore BSM sector

Effective Higgs from an extended sector

let's assume that NP can be characterized by a unique scale and a coupling

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

$g_* \sim g_{SM}$ ie $f \sim M$

MSSM in the decoupling limit

strongly coupled NP

$g_* \gg g_{SM}$ ie $f \ll M$

composite Higgs models

in both cases, Higgs couples to NP with g_*

Effective Higgs from an extended sector

Assuming the NP flows towards the SM in the IR we can describe it in terms of an effective field theory

Lagrangian with higher dimensional ops invariant under SM gauge symmetry
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

CP-odd

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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.

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)

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

custodial breaking

Form factor operators (sensitive to the scale M = g* f) (g_{SM} factors inside V)

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{M^2}\frac{g_*^2}{16\pi^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{M^2}\frac{g_*^2}{16\pi^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

Goldstone sym.
(PGB Higgs)

Higgs power counting

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

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 ⇒ $c_H \sim O(m_W^4/M^4)$

dynamics with Higgs as PGB

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

Effective Higgs phenomenology

Giudice, Grojean, Pomarol, Rattazzi '07

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

$$\frac{\Gamma(\bar{\psi}\psi)}{\Gamma(\bar{\psi}\psi)_{SM}} \simeq 1 - \bar{c}_H - 2\,\bar{c}_\psi\,,$$

$$\frac{\Gamma(h\to W^{(*)}W^*)}{\Gamma(h\to W^{(*)}W^*)_{SM}} \simeq 1 - \bar{c}_H + 2.2\,\bar{c}_W + 3.7\,\bar{c}_{HW}\,,$$

$$\frac{\Gamma(h\to Z^{(*)}Z^*)}{\Gamma(h\to Z^{(*)}Z^*)_{SM}} \simeq 1 - \bar{c}_H + 2.0\,\left(\bar{c}_W + \tan^2\theta_W\,\bar{c}_B\right) + 3.0\,\left(\bar{c}_{HW} + \tan^2\theta_W\,\bar{c}_{HB}\right) - 0.26\,\bar{c}_\gamma\,,$$

$$\frac{\Gamma(h\to Z\gamma)}{\Gamma(h\to Z\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.12\,\bar{c}_t - 5\cdot 10^{-4}\,\bar{c}_c - 0.003\,\bar{c}_b - 9\cdot 10^{-5}\,\bar{c}_\tau + 4.2\,\bar{c}_W + 0.19\left(\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma \sin^2\theta_W\right)\frac{4\pi}{\sqrt{\alpha_2\alpha_{em}}}\,,$$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{SM}} \simeq 1 - \bar{c}_H + 0.54\,\bar{c}_t - 0.003\,\bar{c}_c - 0.007\,\bar{c}_b - 0.007\,\bar{c}_\tau + 5.04\,\bar{c}_W - 0.54\,\bar{c}_\gamma\,\frac{4\pi}{\alpha_{em}}\,,$$

$$\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)_{SM}} \simeq 1 - \bar{c}_H - 2.12\,\bar{c}_t + 0.024\,\bar{c}_c + 0.1\,\bar{c}_b + 22.2\,\bar{c}_g\,\frac{4\pi}{\alpha_2}\,.$$

Higgs power counting: SUSY vs Composite

generic new physics

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

weakly coupled NP

g* ~ gSM ie f ~ M

MSSM in the decoupling limit

$$\bar{c}_H \sim O\left(\cancel{\frac{v^2}{f^2}}\right) + O\left(\frac{\alpha_{SM}}{4\pi}\frac{m_W^2}{M^2}\right)$$

$1 - \sin(\beta - \alpha)$

$$\bar{c}_u \sim 1 - \frac{\cos\alpha}{\sin\beta} \sim \frac{m_Z^2}{M_H^2}\frac{1}{\tan^2\beta}$$

$$\bar{c}_d \sim 1 + \frac{\sin\alpha}{\cos\beta} \sim \frac{m_Z^2}{M_H^2}$$

$$\bar{c}_g \sim \bar{c}_\gamma \sim O\left(\frac{g_*^2}{16\pi^2}\frac{m_W^2}{m_{\tilde{t}}^2}\right)$$

M_H heavy CP⁺ Higgs $\quad m_{\tilde{t}}$ stop mass

strongly coupled NP

g* >> gSM ie f << M

composite Higgs models

$$\bar{c}_{H,y} \sim O\left(\frac{v^2}{f^2}\right)$$

$$\vee\!\vee$$

$$\bar{c}_{W,B} \sim O\left(\frac{g^2}{g_*^2}\frac{v^2}{f^2}\right)$$

$$\vee\!\vee$$

$$\bar{c}_{HW,HB} \sim O\left(\frac{g^2}{16\pi^2}\frac{v^2}{f^2}\right)$$

$$\vee\!\vee$$

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

Stop mass constraints from Higgs global fit

Espinosa, Grojean, Sanz, Trott '12

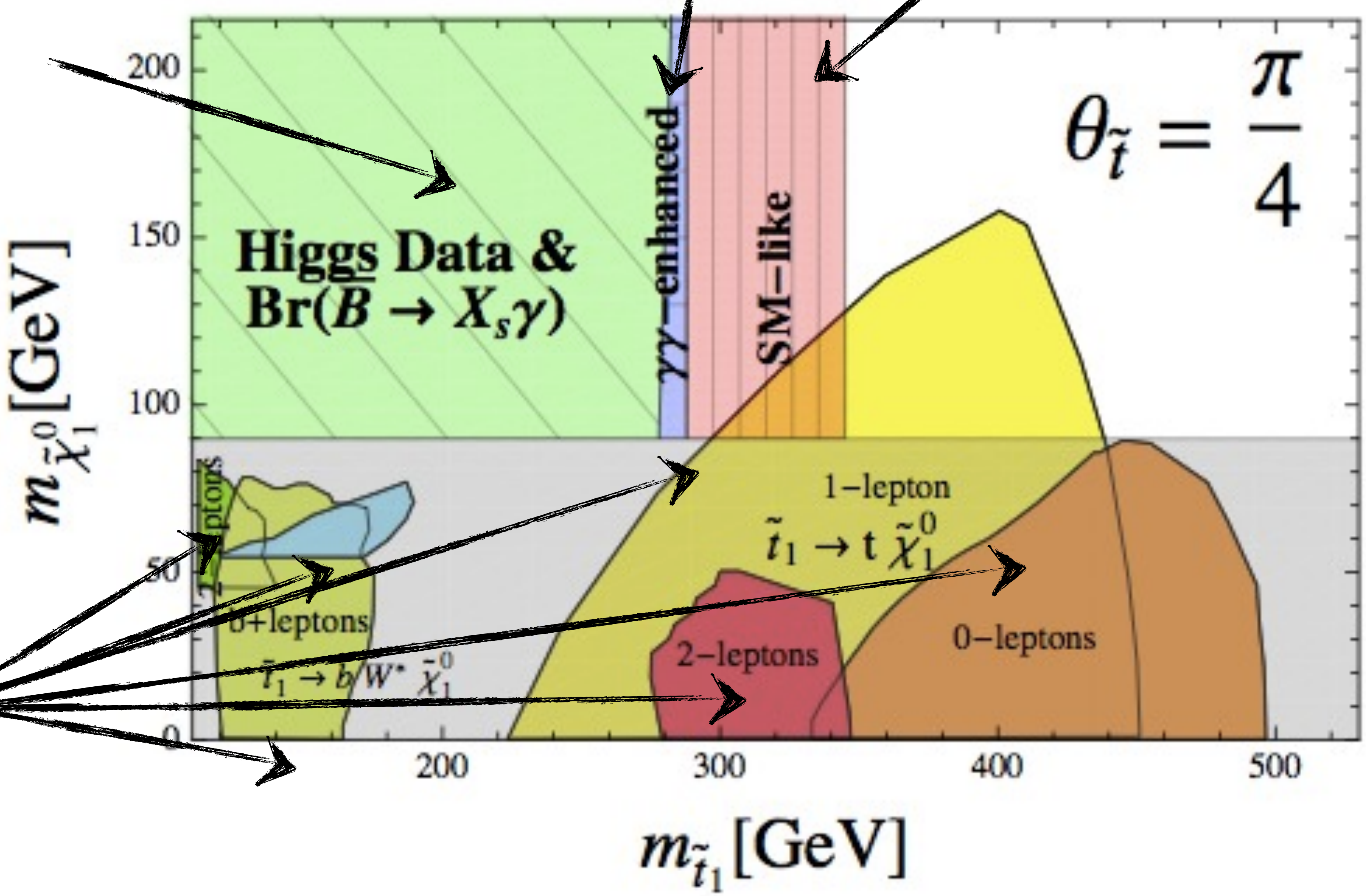
BR($B_s \to X_s \gamma$) prefers degenerate stops ⊃ kills the low stop mass region

then Higgs data put a lower bound of the stop mass

prospects
$\mu_i = \mu^{ICHEP}$, $\sigma_i = \sigma^{ICHEP}/2$

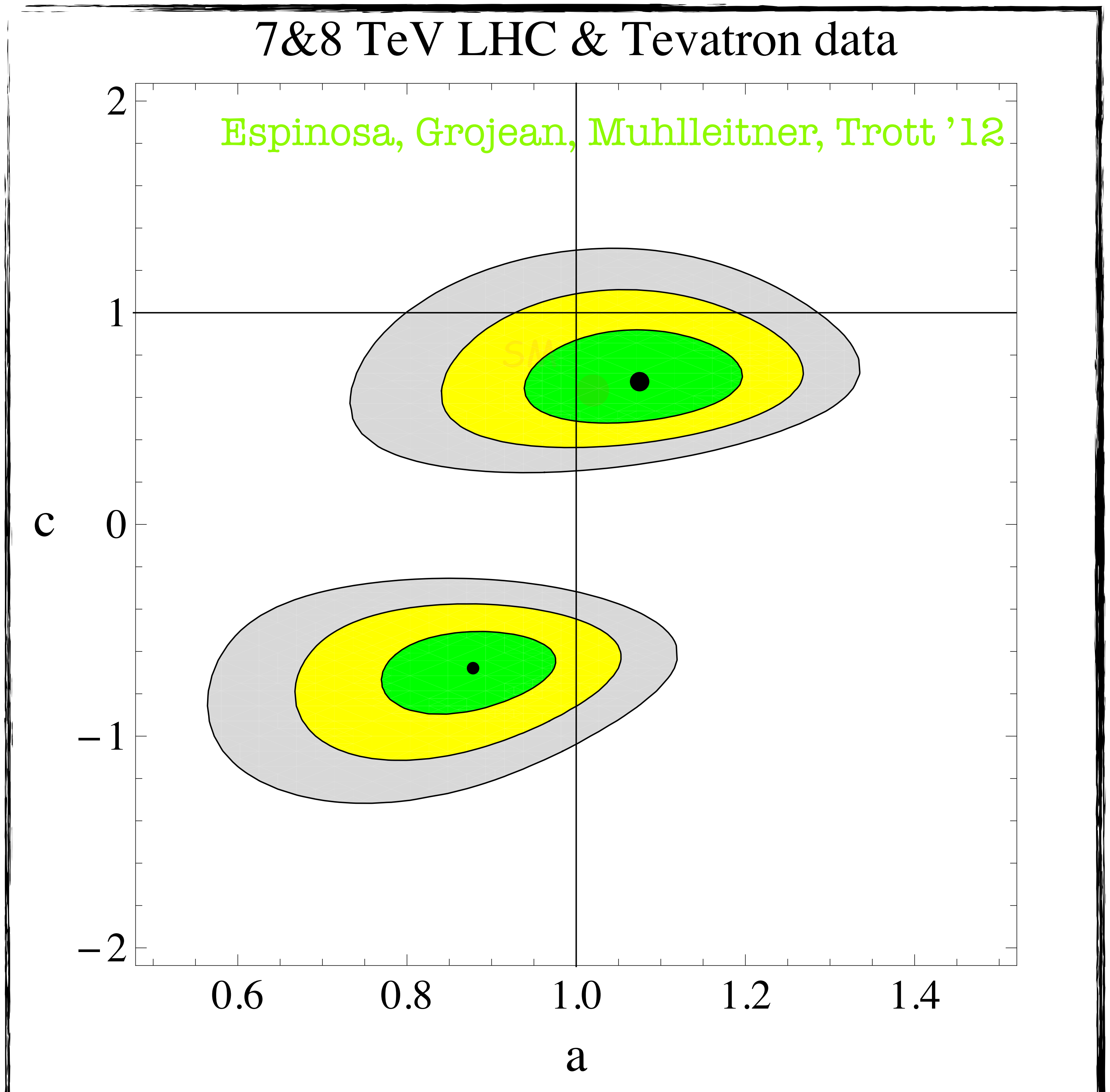
prospects
$\mu_i = 1$, $\sigma_i = \sigma^{ICHEP}/2$

lower bound from
Higgs searches
(current data)

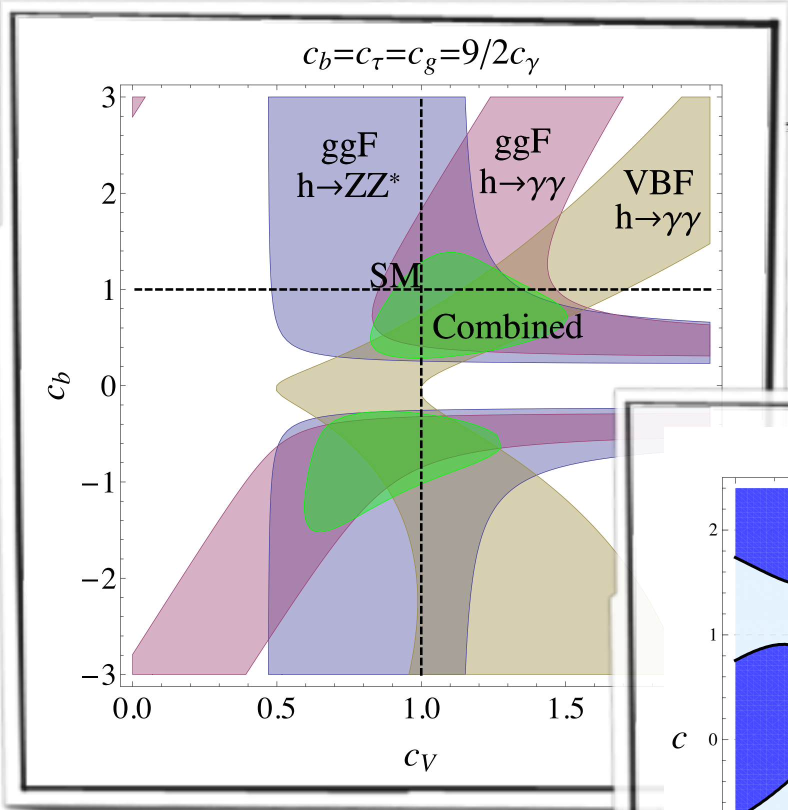


direct searches

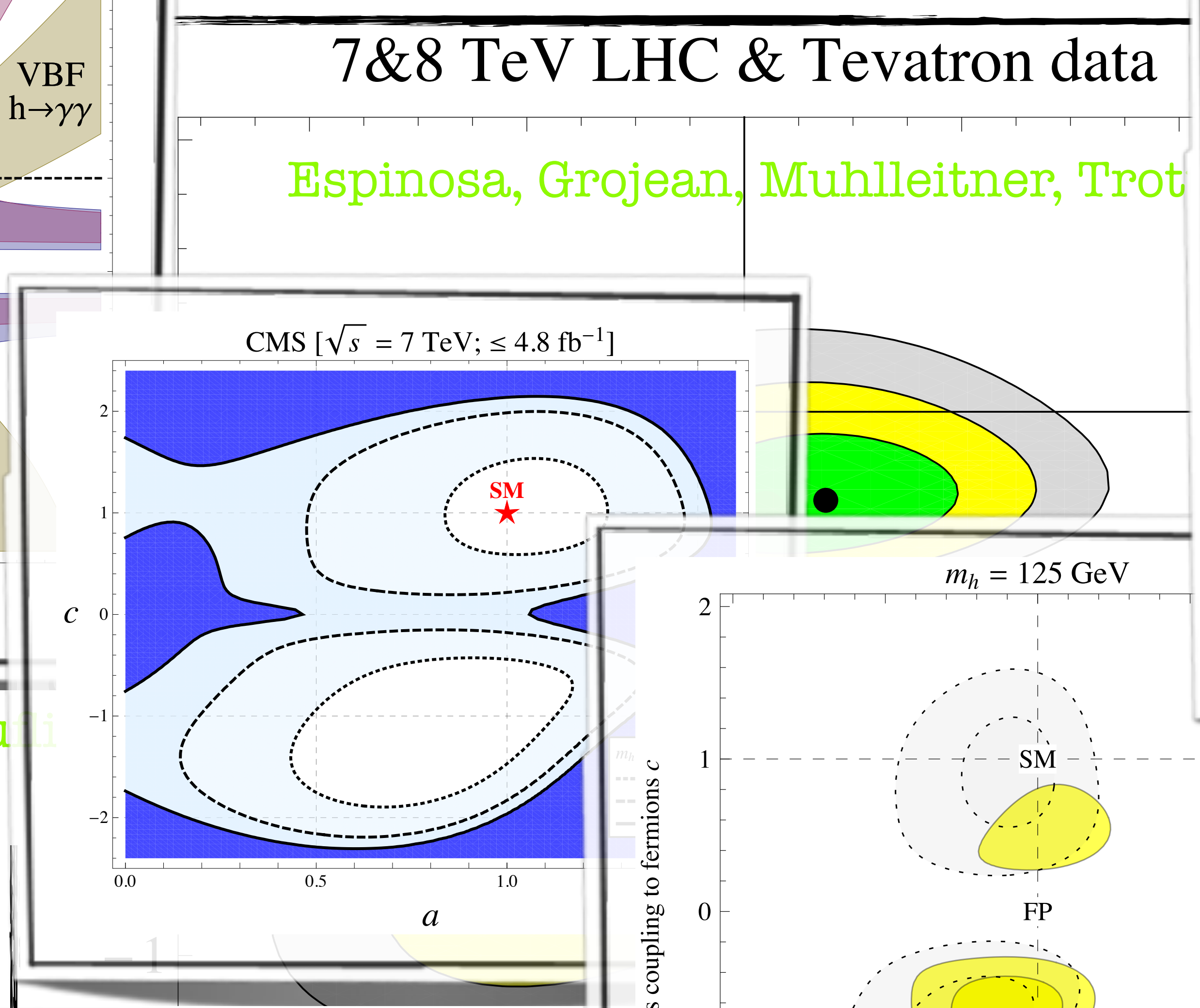
Higgs coupling fits



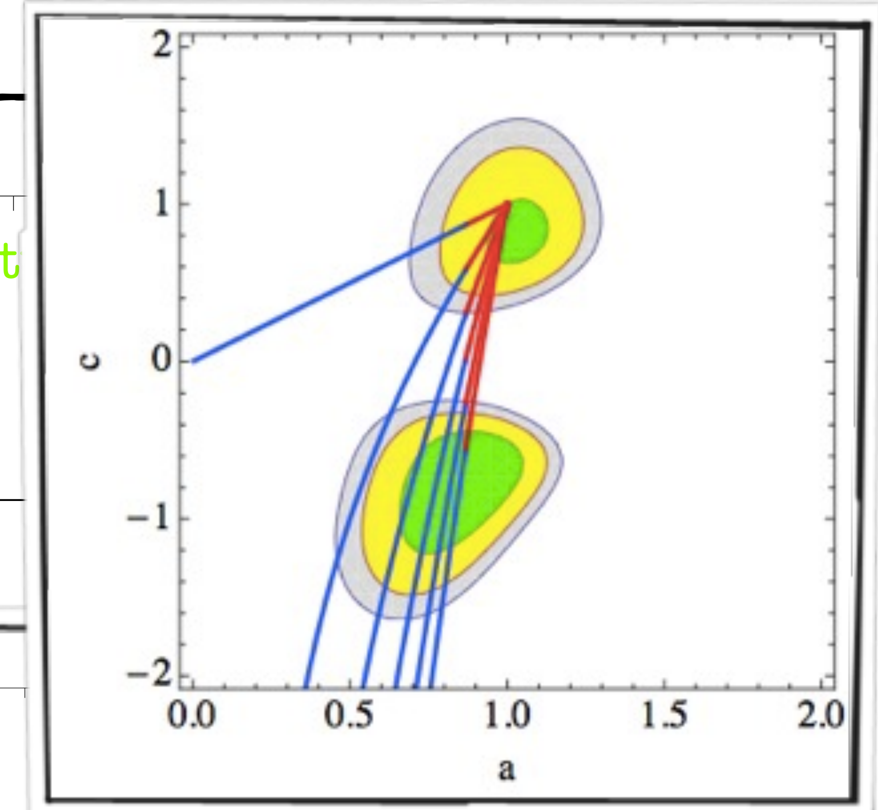
Higgs coupling fits



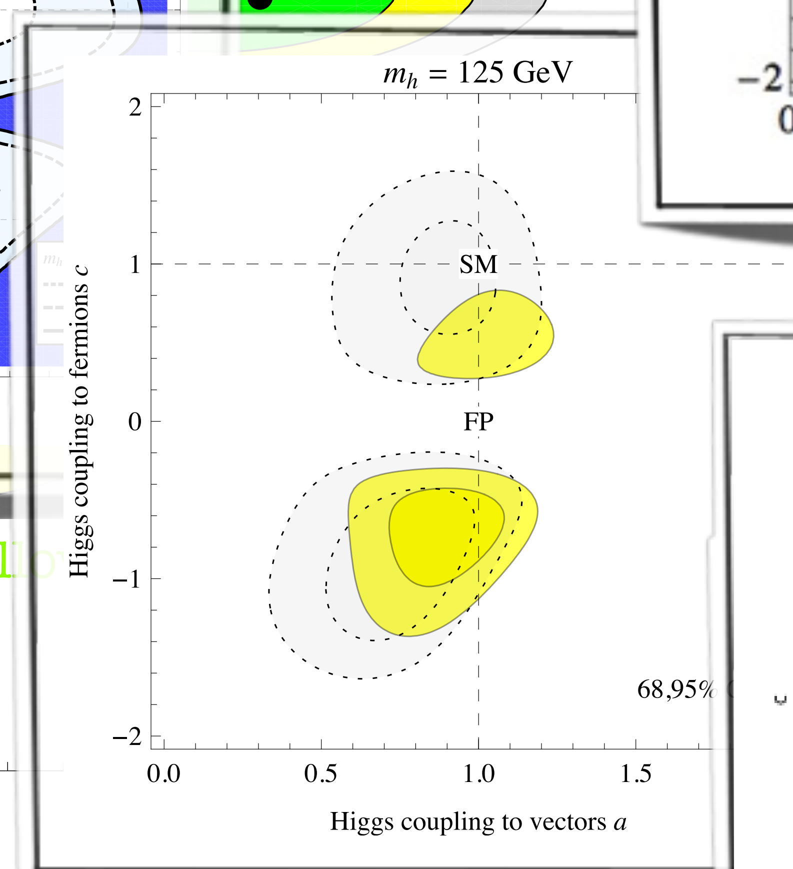
Carni, Falkowski, Kuflik, Volansky '12



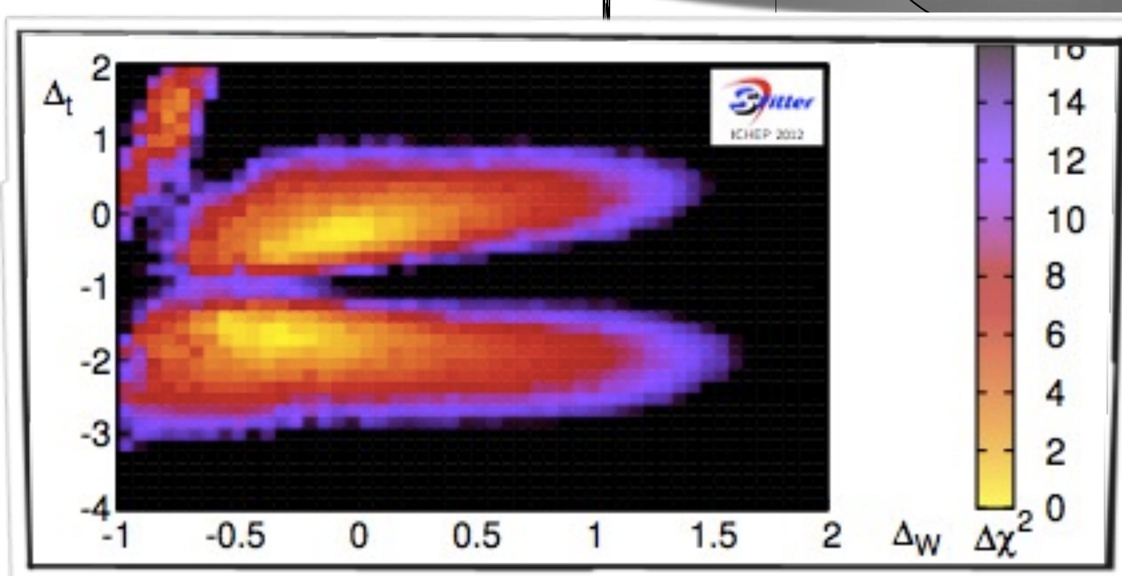
Espinosa, Grojean, Muhlleitner, Trott



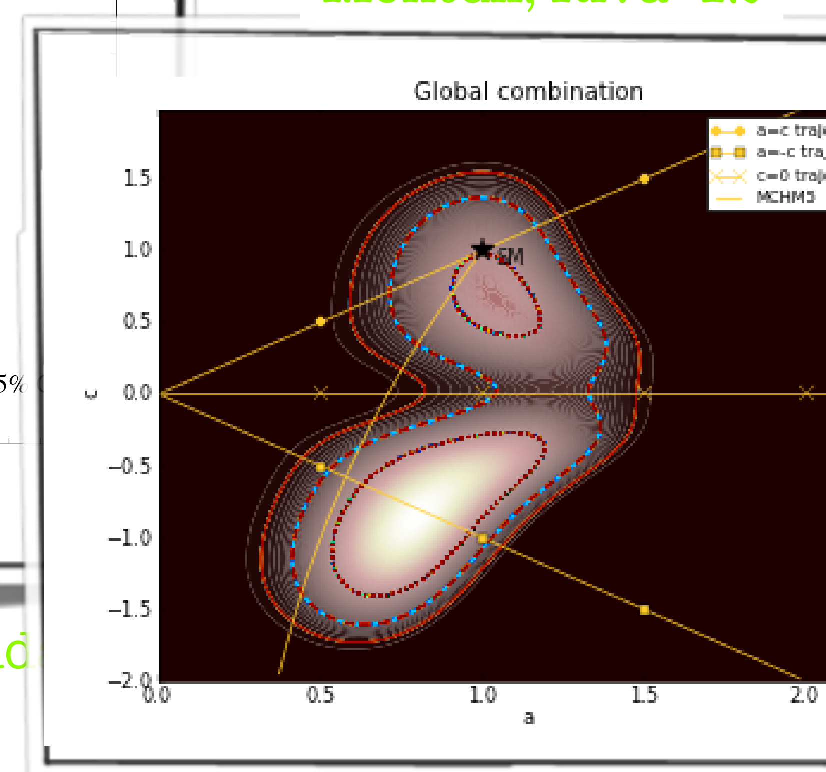
Montull, Riva '12



Giardino, Kannike, Raidal, Strumia '12



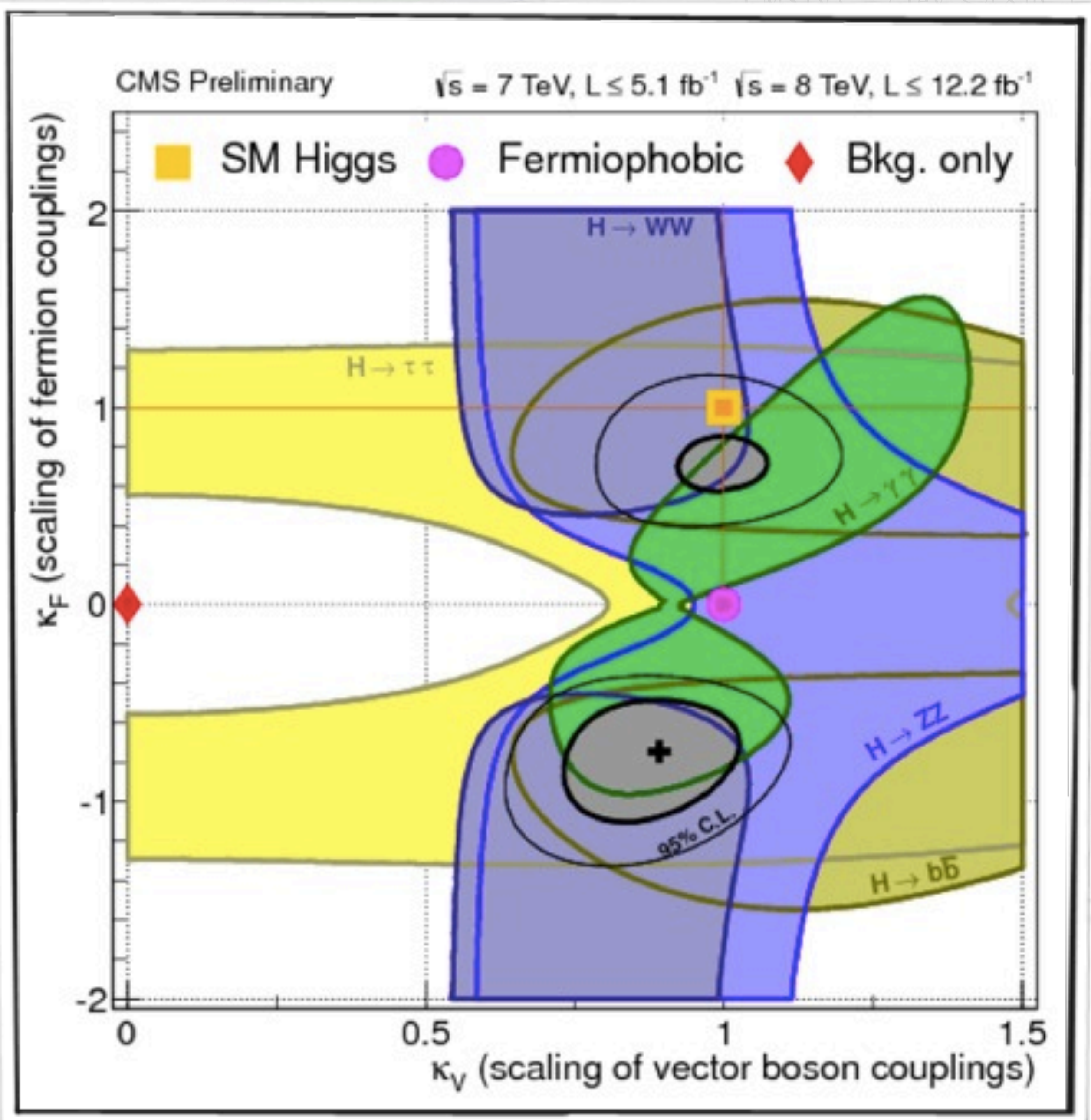
Plehn, Rauch '12



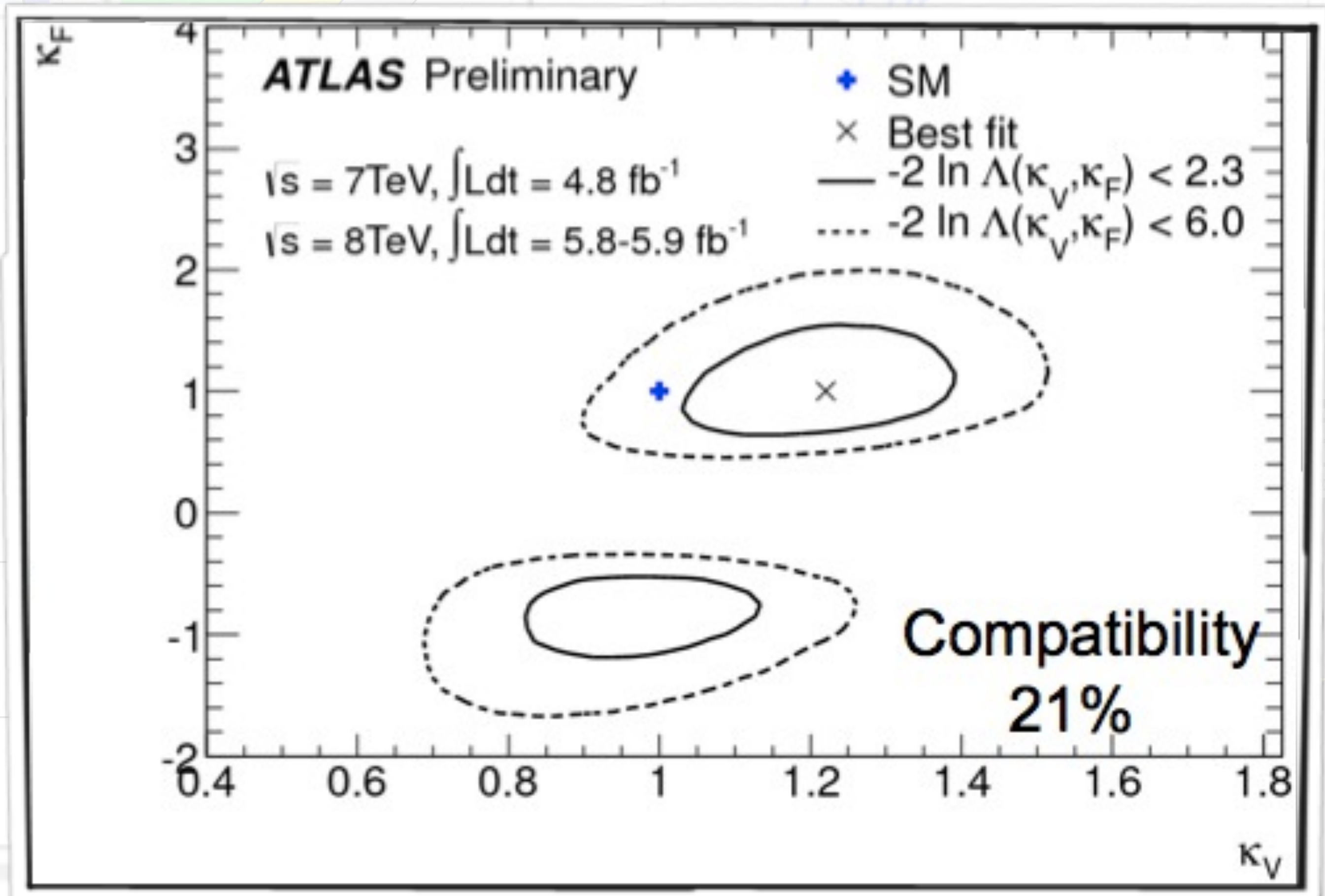
Ellis, You '12

Higgs coupling fits

don't leave it in the hands of theorists!



CMS



ATLAS

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13 Elias-Miro, Espinosa, Masso, Pomarol '13

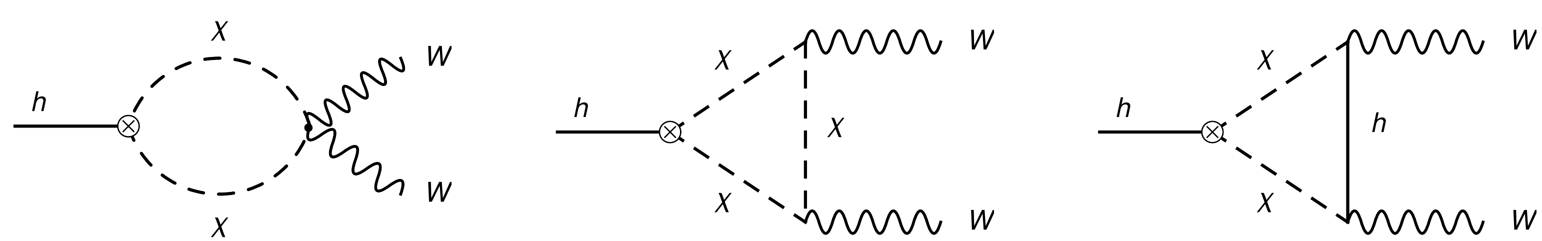
the previous estimates were based on the values of the Wilson coefficients @ NP scale

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_*)



$$\mu \frac{d}{d\mu} \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{4\pi} \gamma \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} \qquad \gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ -1/6 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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anomalous dimensions

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

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

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

RG-Higgs physics: Don't forget LEP!

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

$$\mu \frac{d}{d\mu} \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{4\pi} \gamma \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix}$$

$$\gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ -1/6 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

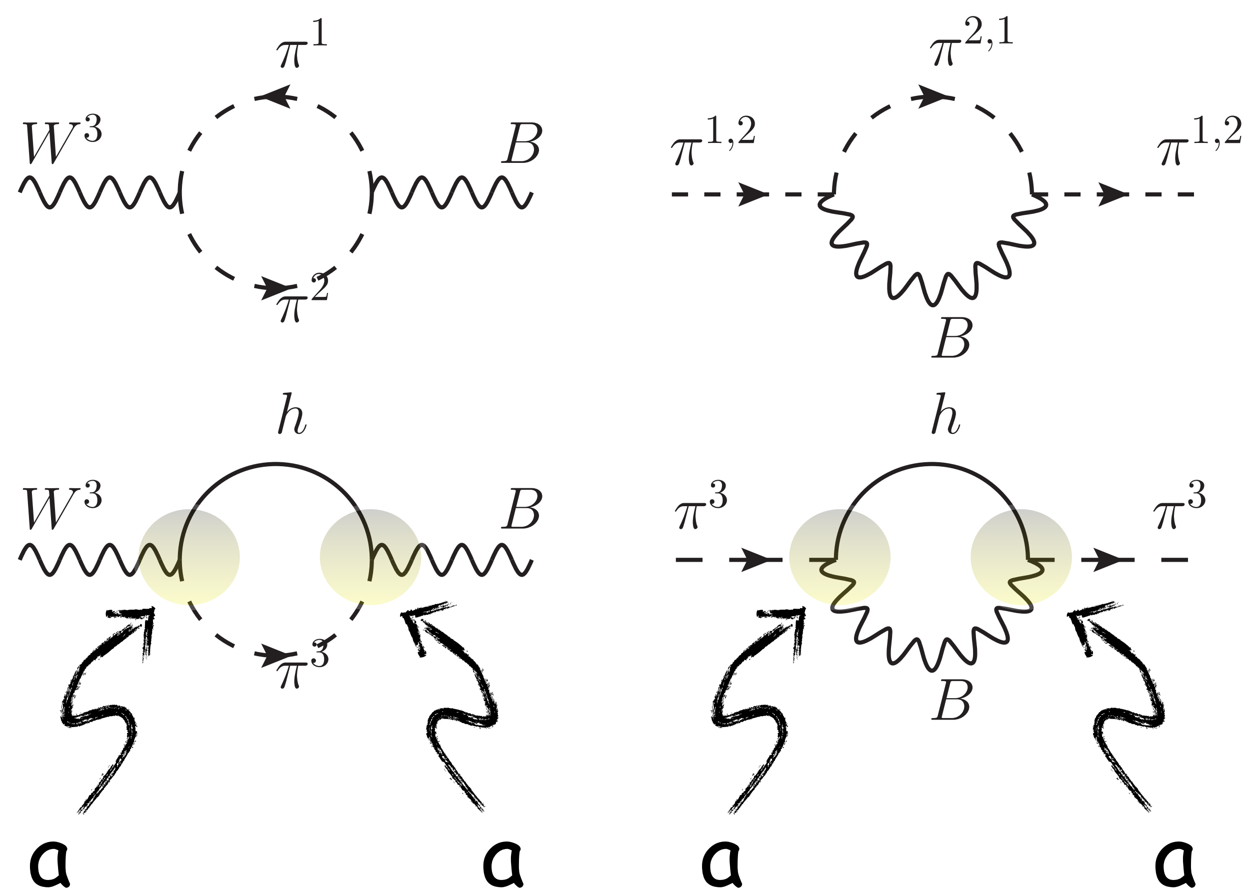
$$\epsilon_{1,3} = c_{1,3} \log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}\, \left(1 - a^2\right) \log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



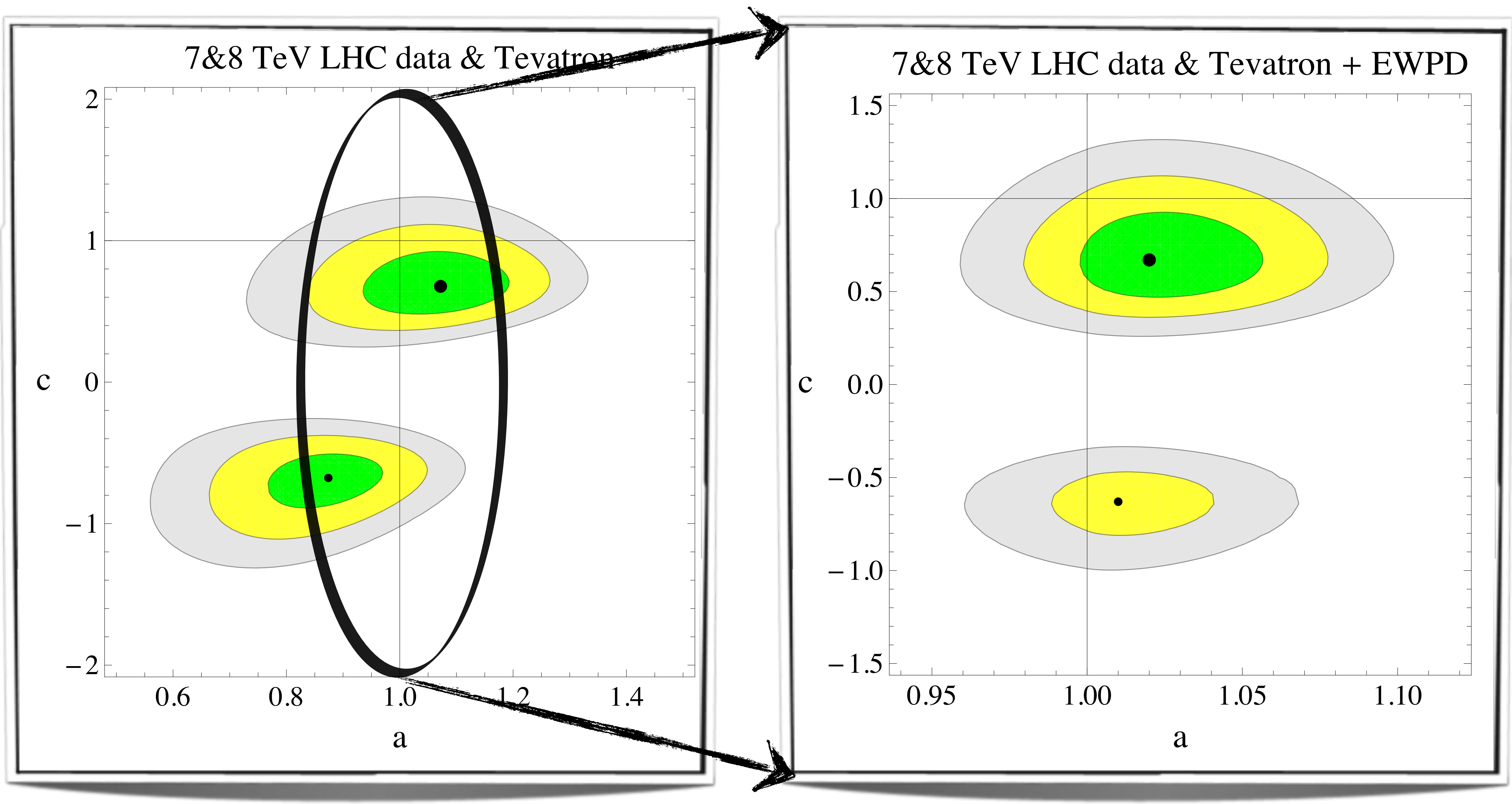
Log. div. cancel only for a=1 (SM)

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

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

RG-Higgs physics: Don't forget LEP!

Espinosa, Grojean, Muhlleitner, Trott '12



EW data prefer value of 'a' close to 1

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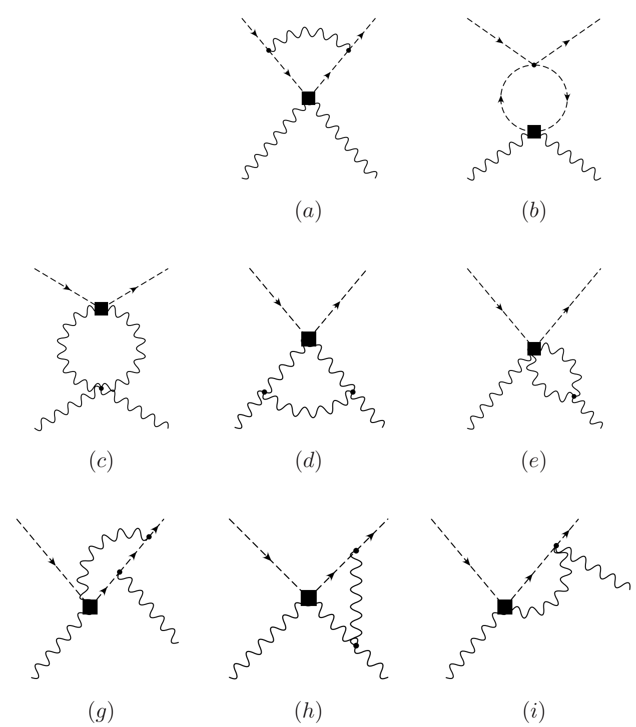
the case of $\gamma\gamma$

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



RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13 Elias-Miro, Espinosa, Masso, Pomarol '13

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

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for weak models (g_*~g)

contribution ~ EW NLO but forgotten up to now

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for strong PGB models

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for strong PGB models

contribution >> EW NLO and forgotten up to now

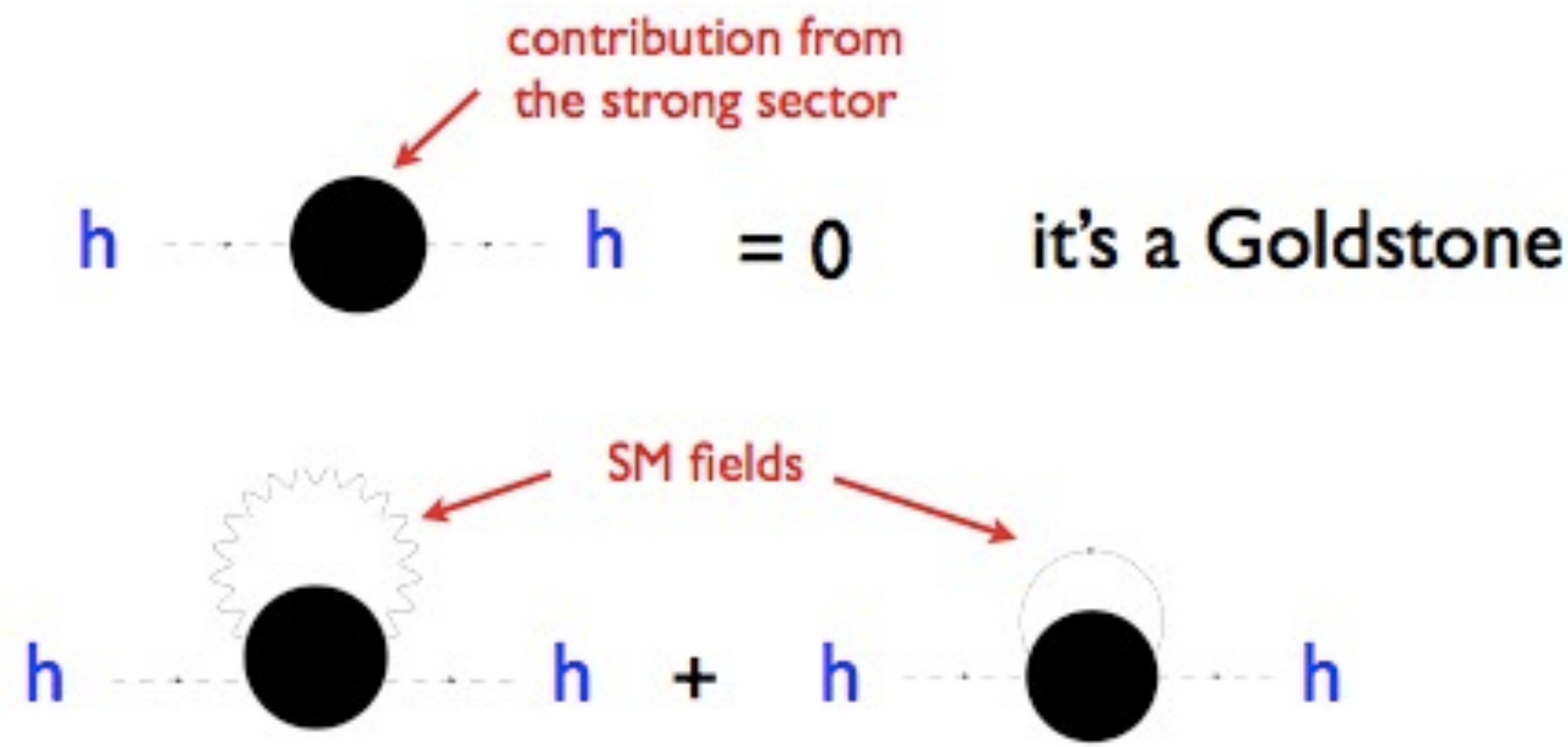
the mixing can even have larger effect in non-SILH dynamics

S oblique parameter can induce h ➛ $\gamma\gamma$

Grojean, Jenkins, Manohar, Trott '13

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

Marzocca, Serone, Shu '12

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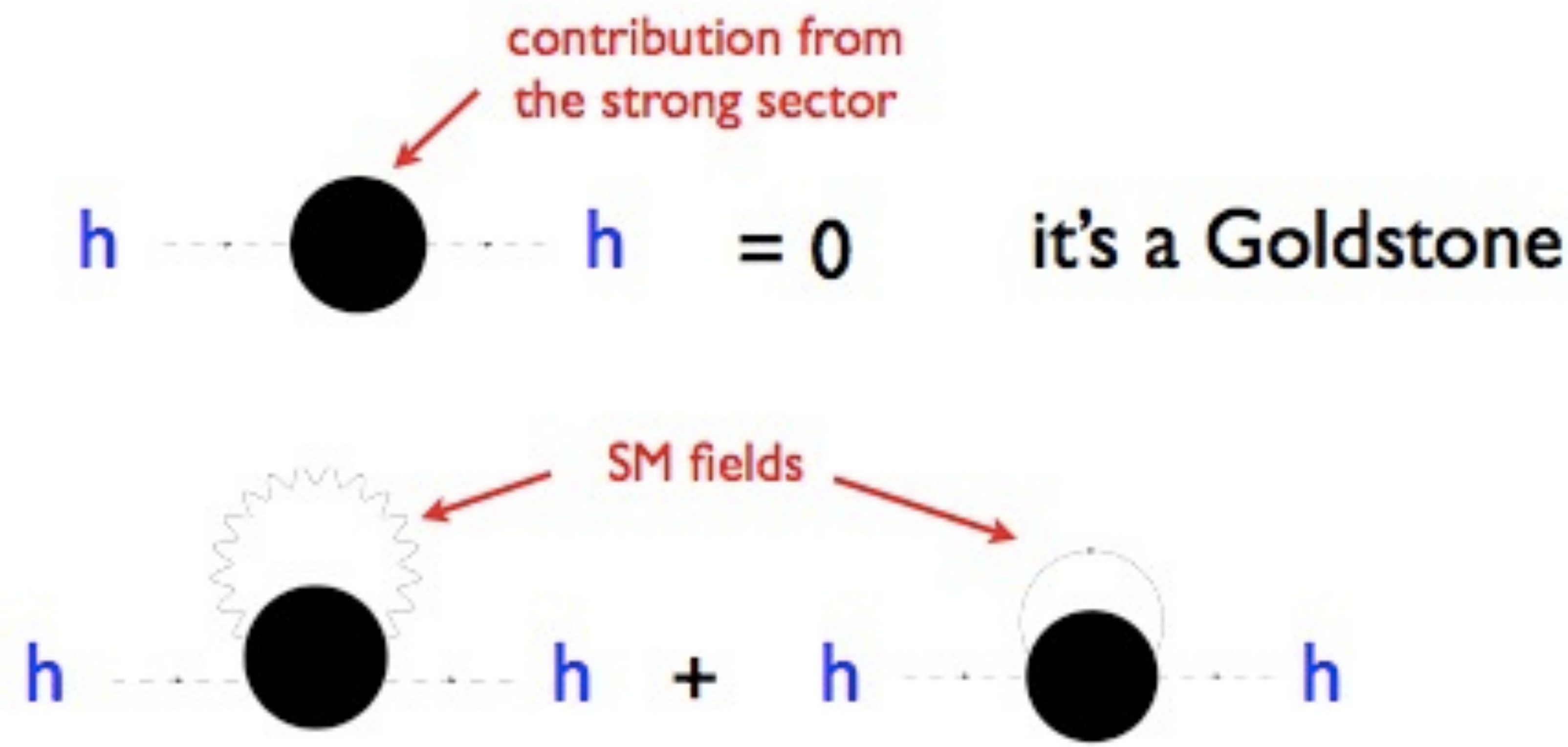

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Pomarol, Riva '12

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

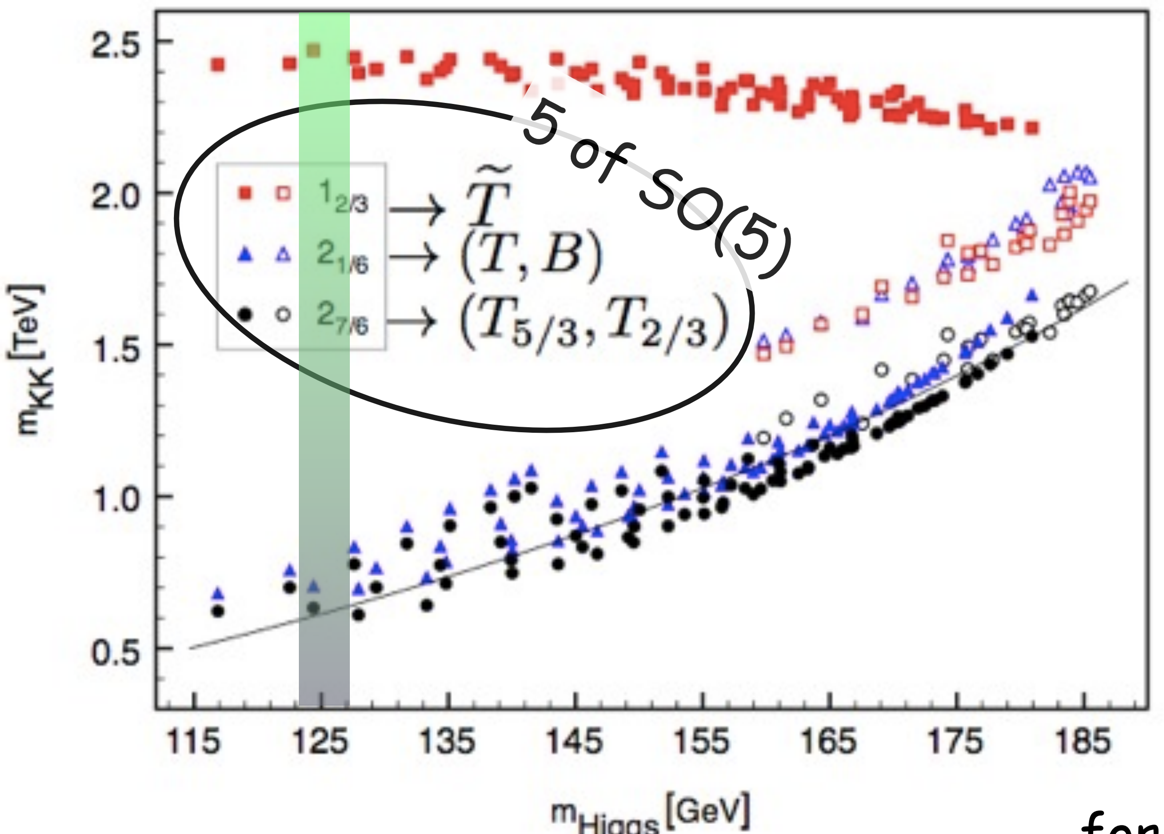
$$m_Q \lesssim 700\ \mathrm{GeV}\left(\frac{m_h}{125\ \mathrm{GeV}}\right)\left(\frac{160\ \mathrm{GeV}}{m_t}\right)\left(\frac{f}{500\ \mathrm{GeV}}\right)$$

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

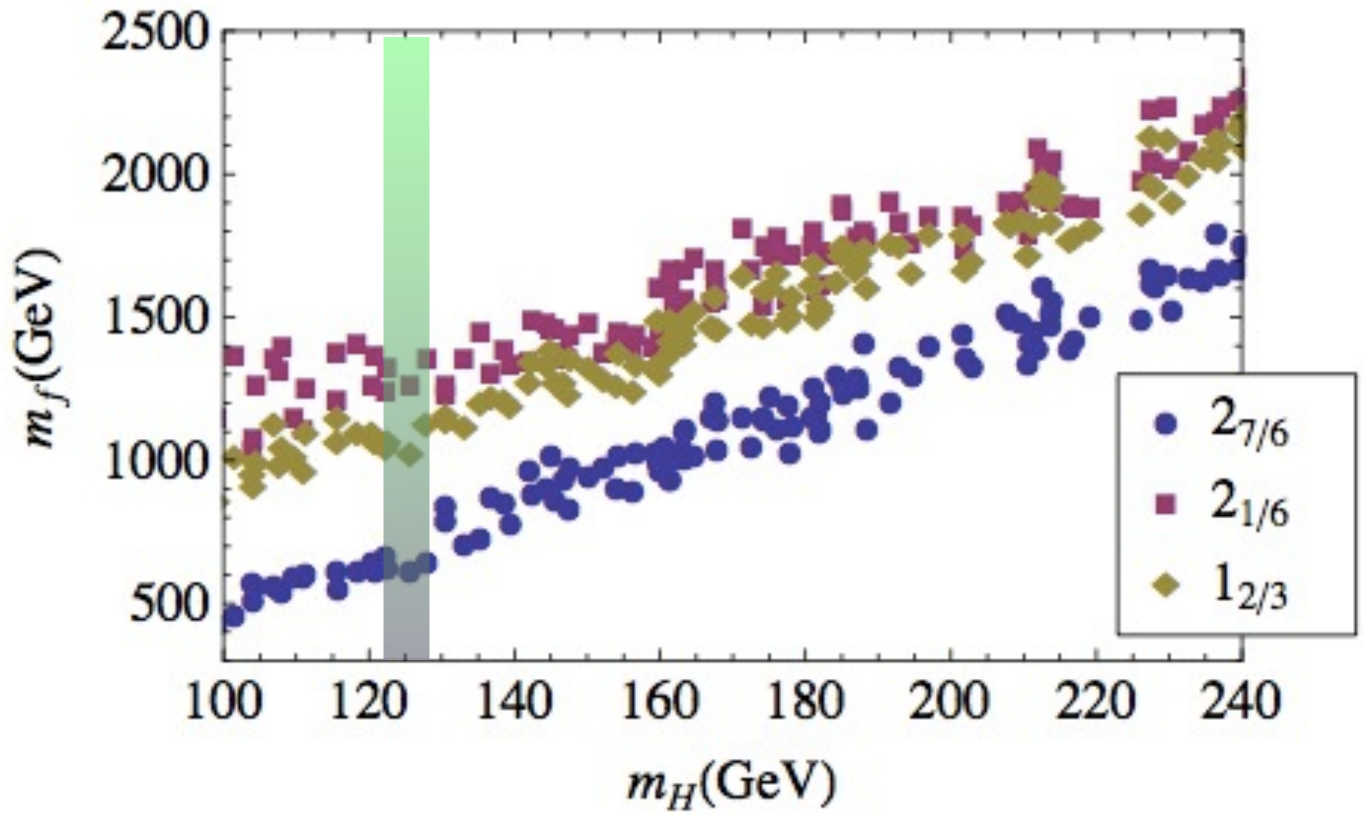
Light composite Higgs from "light" resonances

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

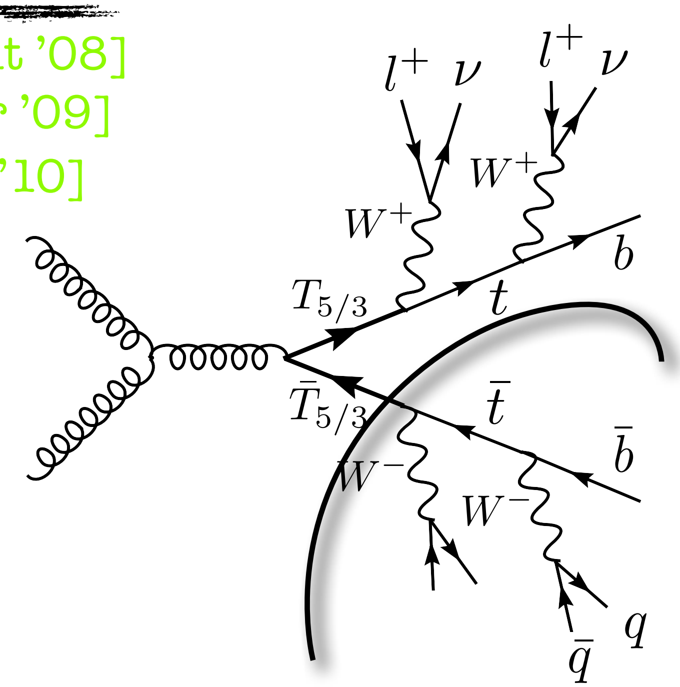
$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

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

Rich phenomenology of the top partners

Search in same-sign di-lepton events

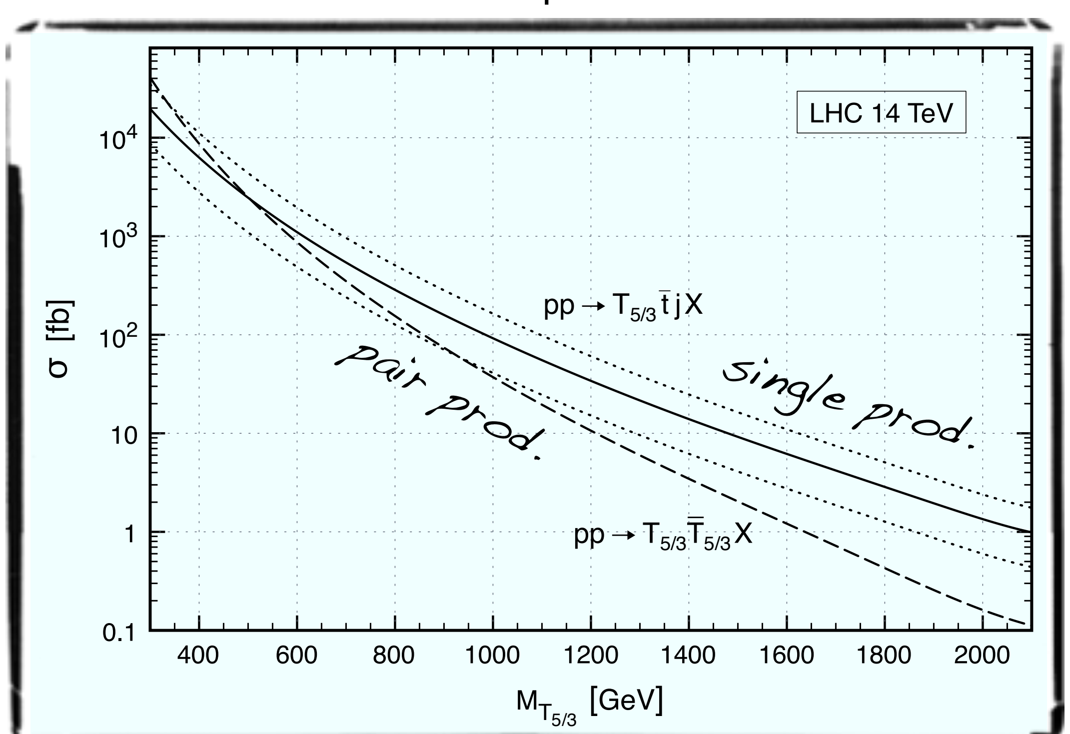
[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]



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

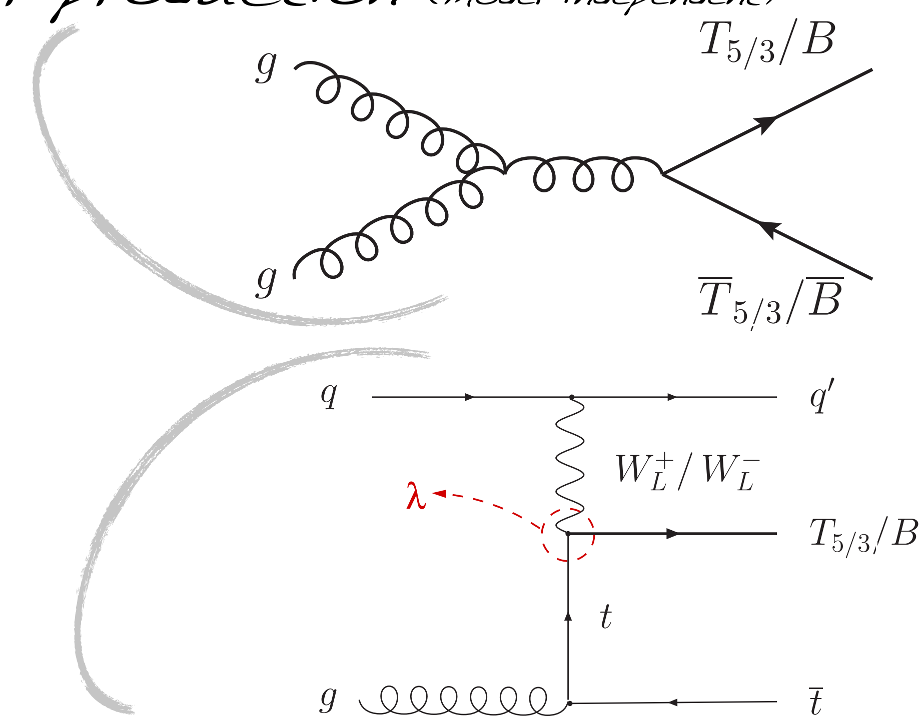
discovery potential (LHC_{14TeV})
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

Dissertori, Furlan, Moortgat, Nef '09]
4



[Contino, Servant '08]

Pair production (model independent)



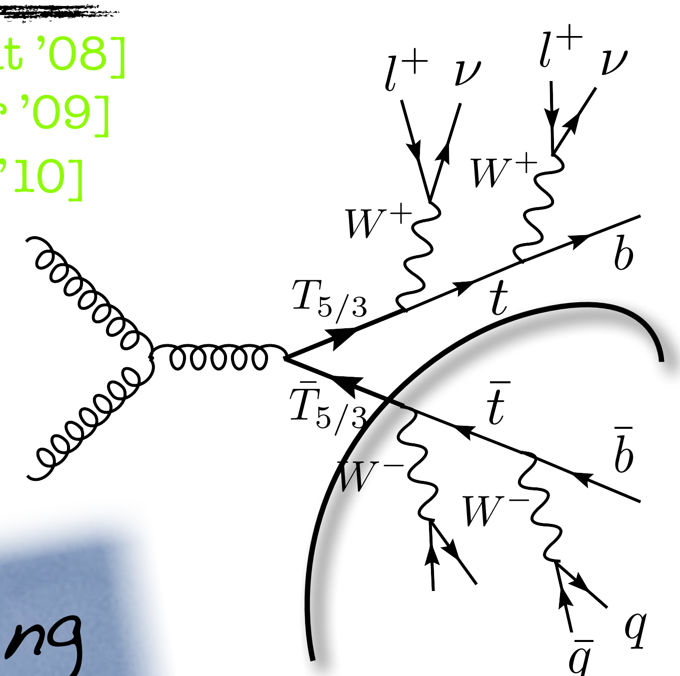
Single production (model dependent)

Rich phenomenology of the top partners

Search in same-sign di-lepton events

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

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



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

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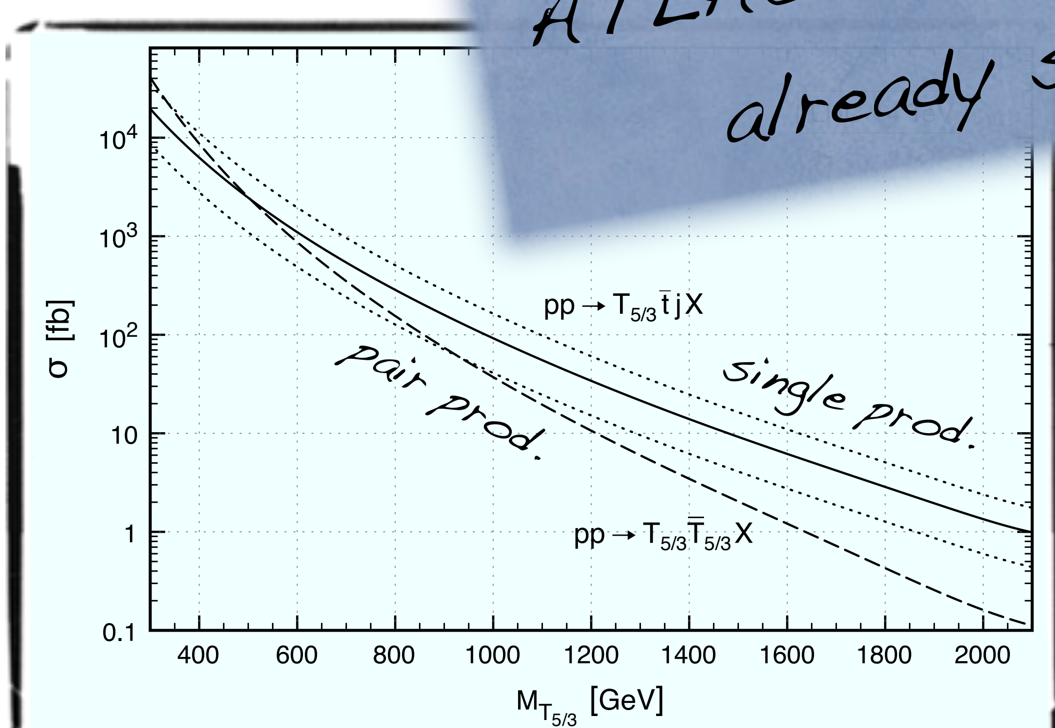
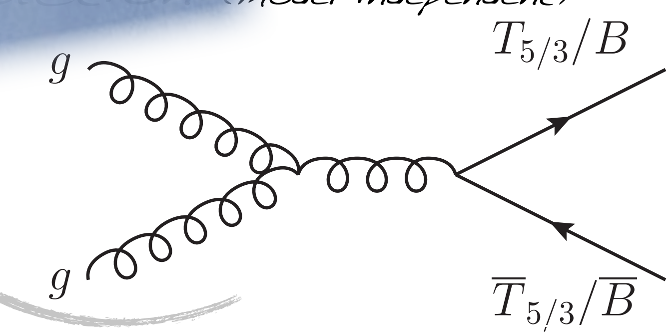
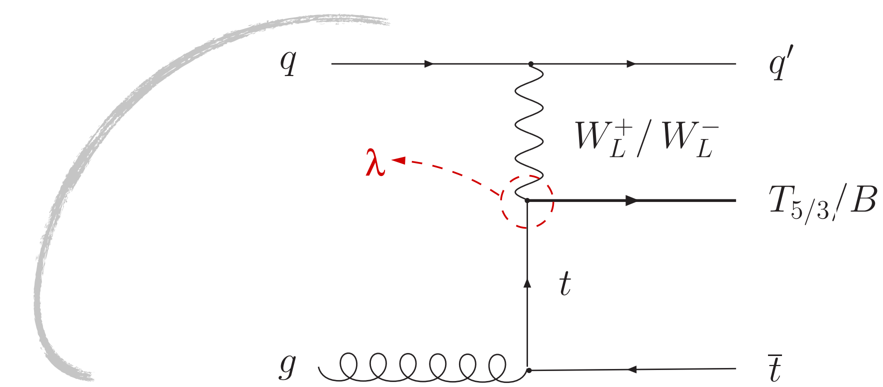
ATLAS & CMS searches ongoing
already stringent bounds



[Contino, Servant '08]

(model independent)

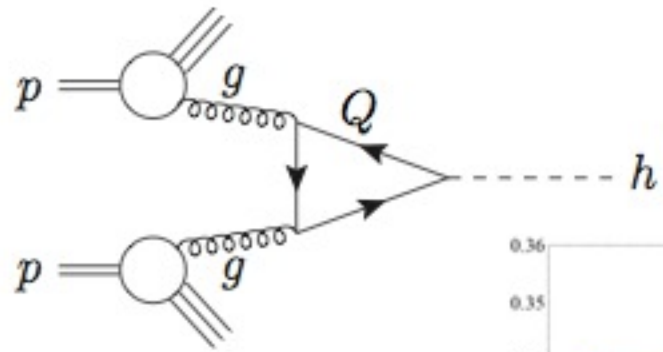




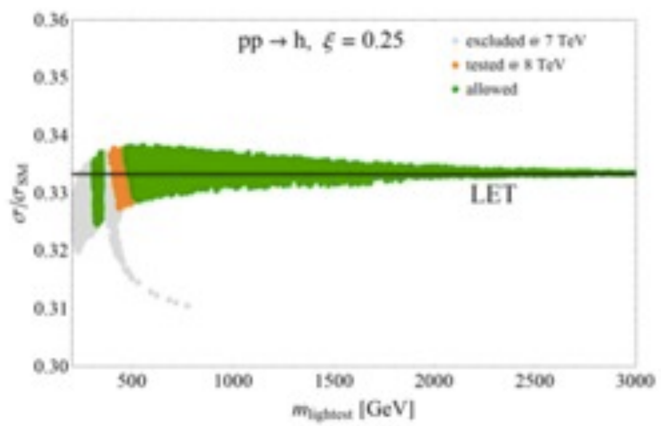
Single production (model dependent)

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

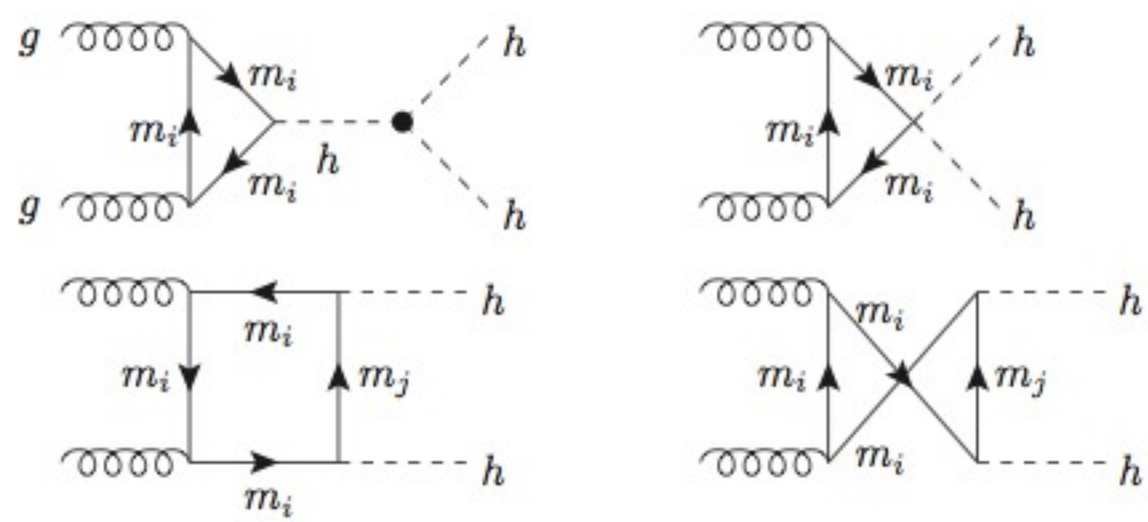
Falkowski '07

Azatov, Galloway '11

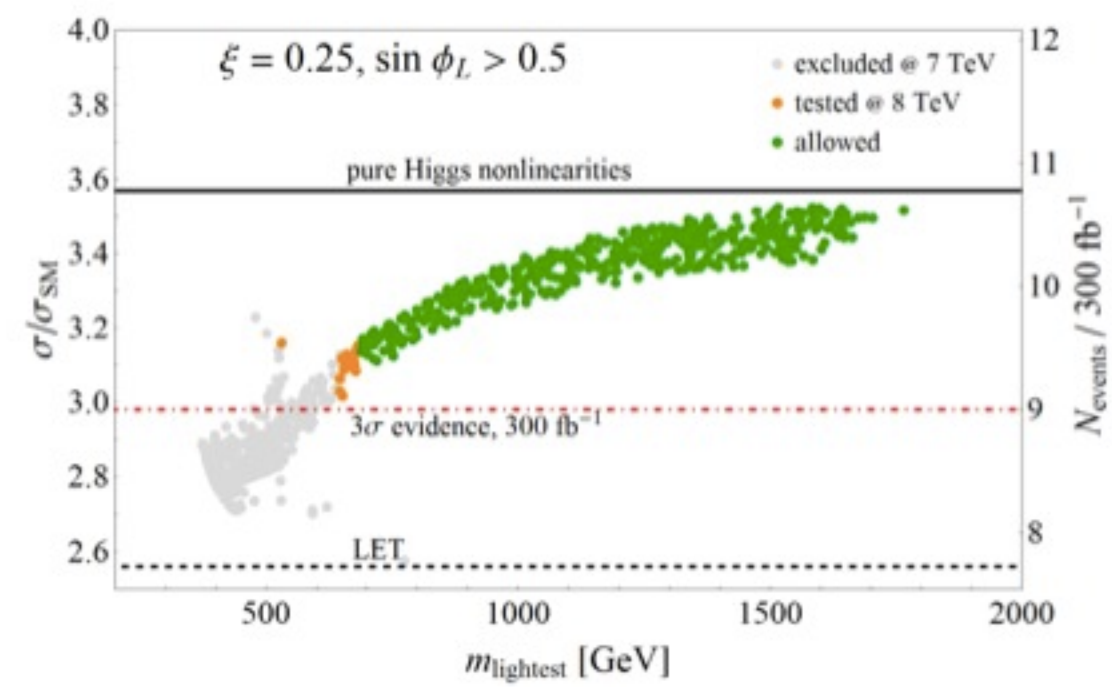
Delaunay, Grojean, Perez, Zielger 'to appear

~ small sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



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



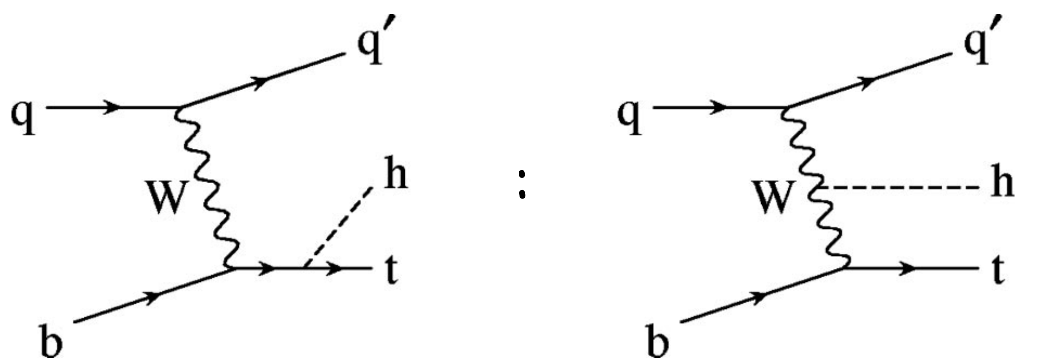
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q′th



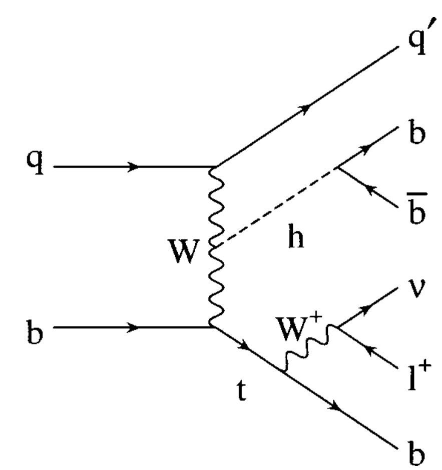
@m_H=125GeV $$\frac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$$

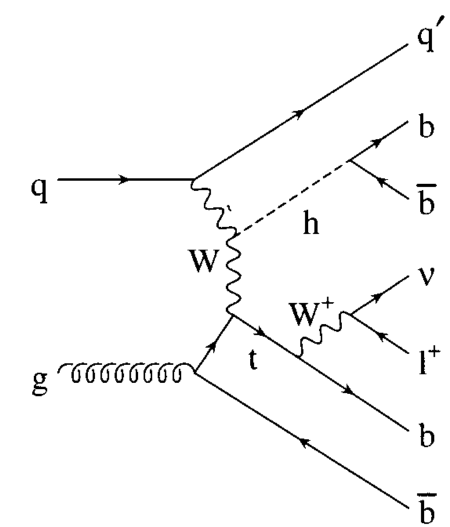
Farina, Grojean, Maltoni, Salvioni, Thamm ’12

	$\sigma(pp \to tjh)$ [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

look at final states:

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

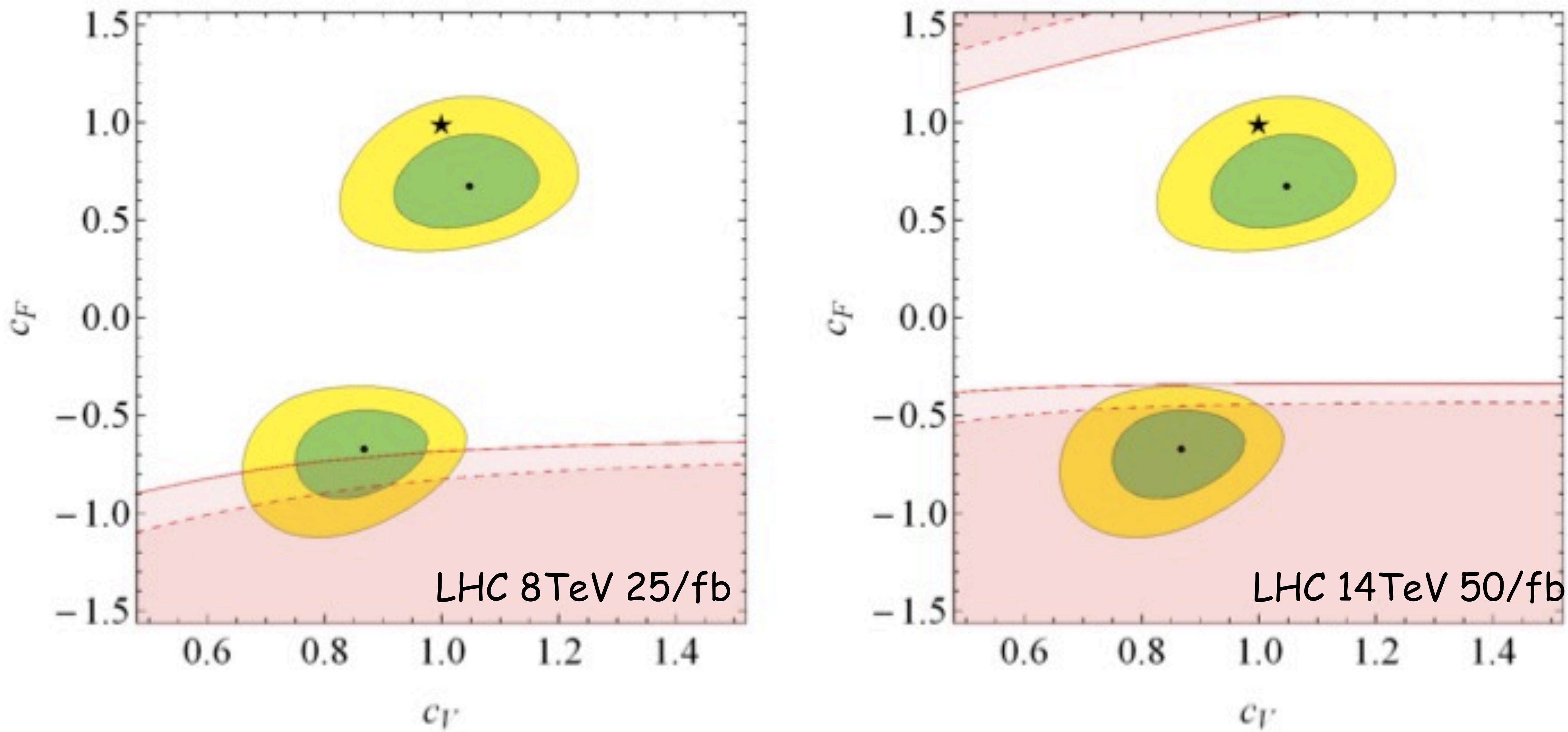




Top partners & Higgs physics

direct measurement of top-higgs coupling

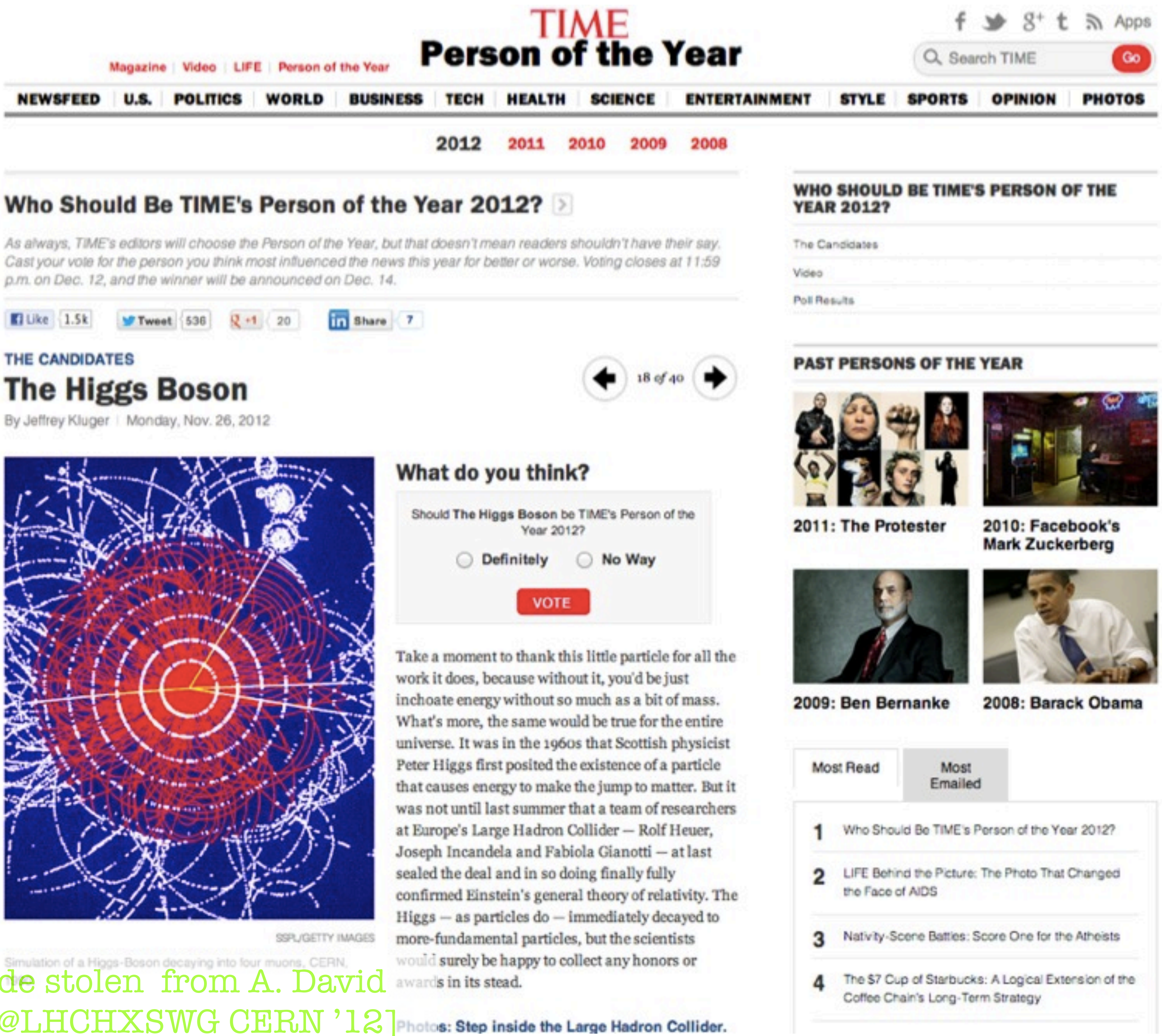
single-top in association with Higgs



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

Farina, Grojean, Maltoni, Salvioni, Thamm '12

Conclusions: Higgs = Person of 2012?



TIME
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.

Like 1.5k | Tweet 536 | +1 20 | Share 7

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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[slide stolen from A. David talk@LHCHXSWG CERN '12]

Conclusions: Higgs = Person of 2012?

as of 06/12/12

TIME
Person of the Year

Magazine | Video | LIFE | Person of the Year

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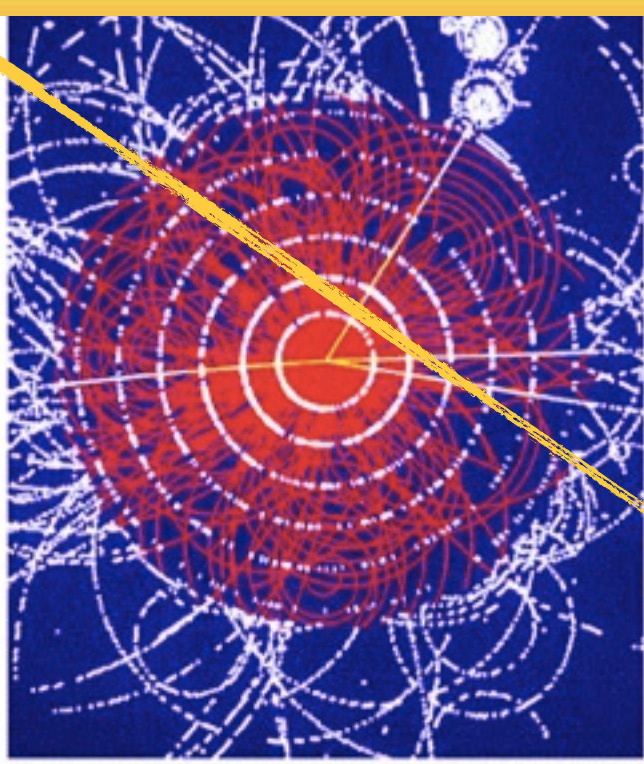

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Photos: Step inside the Large Hadron Collider.

2011: The

2009: Ben

Most Read

1 Who S

2 LIFE B the Fa

3 Nativ

4 The $7 Coffee

Name	Definitely	No Way
Kim Jong Un	4,295,657	129,581
[illegible]	924,111	58,864
[illegible]	667,023	74,312
[illegible]	563,922	53,253
[illegible]	533,606	74,583
[illegible]	526,534	66,301
[illegible]	521,277	87,263
[illegible]	506,973	84,007
[illegible]	480,147	72,596
[illegible]	427,956	1,023,857
[illegible]	397,952	93,874
[illegible]	388,787	151,562
[illegible]	297,535	46,968
[illegible]	272,248	99,274
[illegible]	264,088	156,161
[illegible]	95,701	58,080
[illegible]	95,600	94,624
Barack Obama	84,161	96,045
Felix Baumgartner	72,234	78,747
The Higgs Boson Particle	68,927	54,589
Pussy Riot	53,194	77,026
Bill Clinton	45,108	80,799
Sandra Fluke	39,730	79,275
Michael Phelps	39,616	87,722
Mitt Romney	[illegible]	116,700
Joe Biden	[illegible]	96,187
John Roberts	23,240	74,646
Mo Farah	20,577	75,041
Benjamin Netanyahu	20,450	125,499
Marissa Mayer	19,636	83,571
Michael Bloomberg	19,509	93,629
Paul Ryan	16,662	103,846
Jay-Z	13,558	105,935
Tim Cook	12,406	95,050
Mario Draghi	12,303	80,305
Xi Jinping	10,092	77,441
Bo Xilai	8,015	93,314
Karl Rove	5,336	103,841

??

20/40

[slide stolen from A. David talk@LHCHXSWG CERN '12]

Conclusions: Higgs = Person of 2012?

as of 06/12/12

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