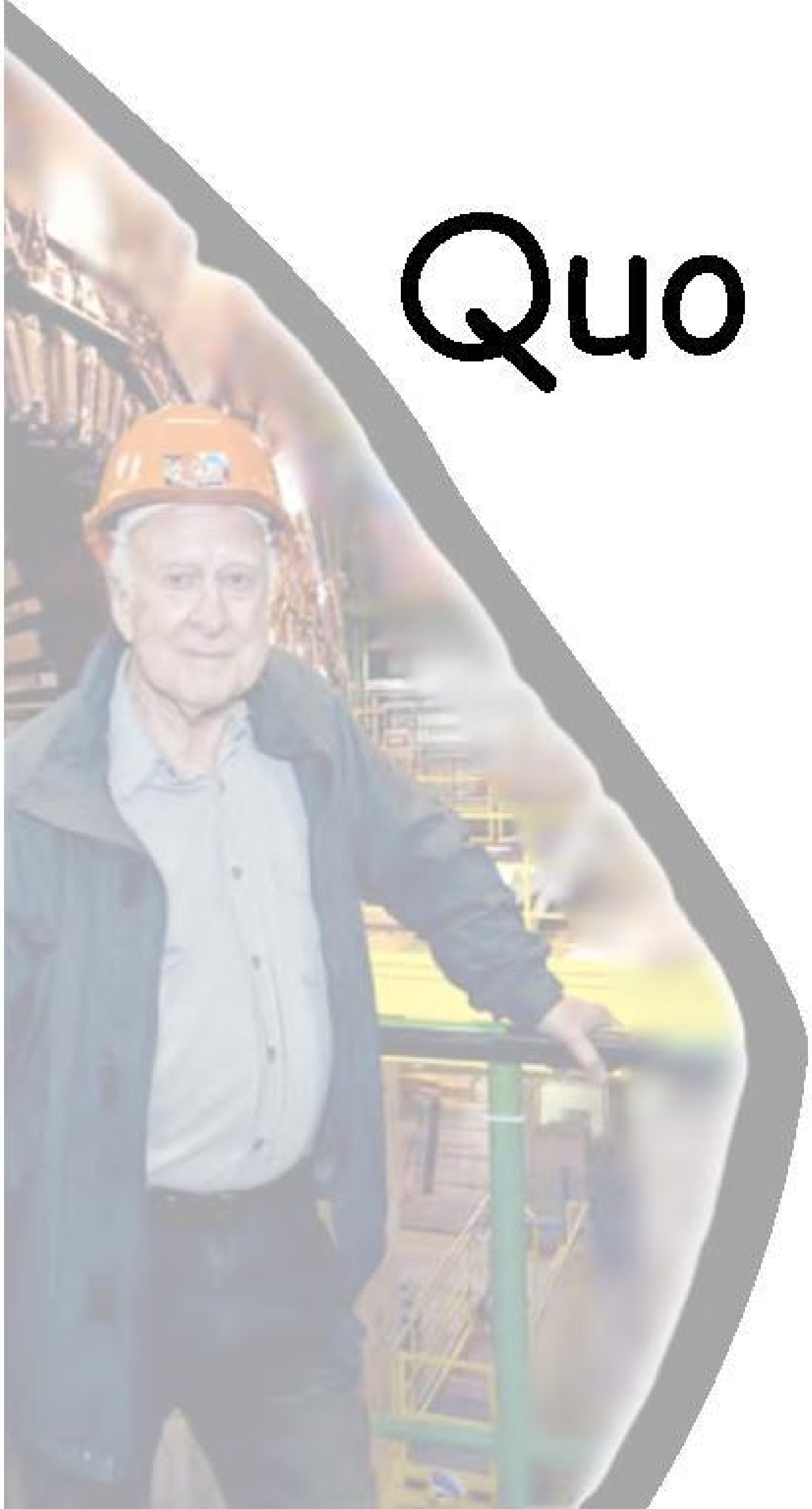

Quo Vadis Higgs?

Kavli-IPMU Seminar

January 23, 2013

Christophe Grojean

ICREA@IFAE/Barcelona

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*iCrea

INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

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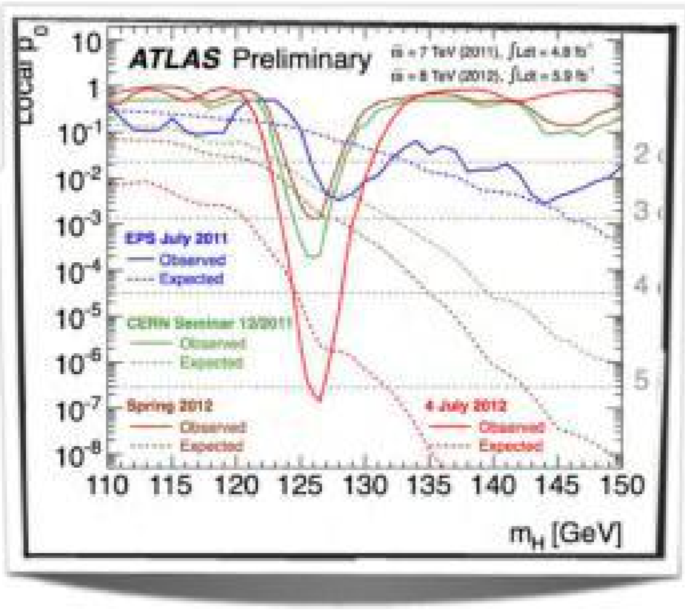

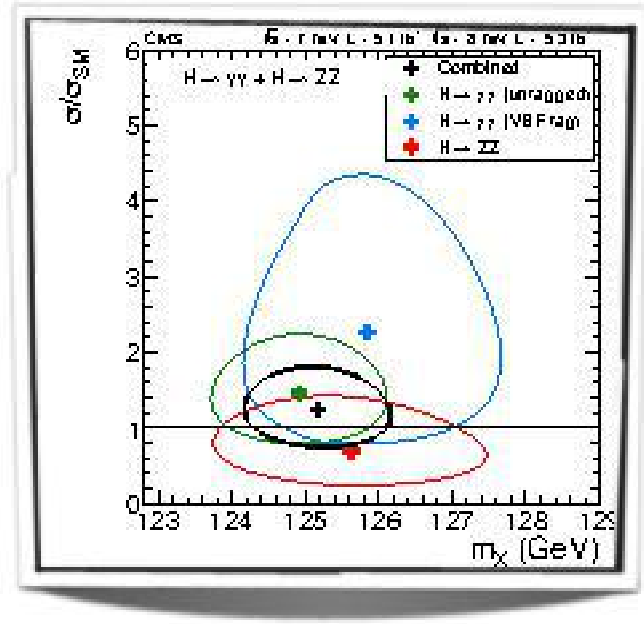

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BSMers desperately looking for anomalies
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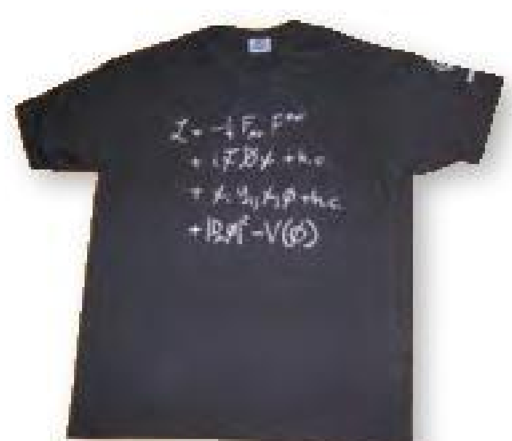

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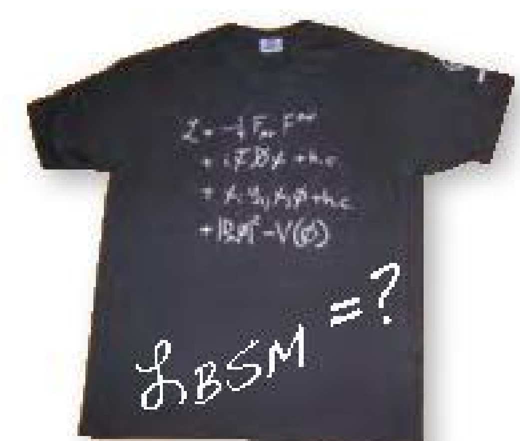
BSM implications



Chiral Lagrangian for a light Higgs-like scalar

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Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

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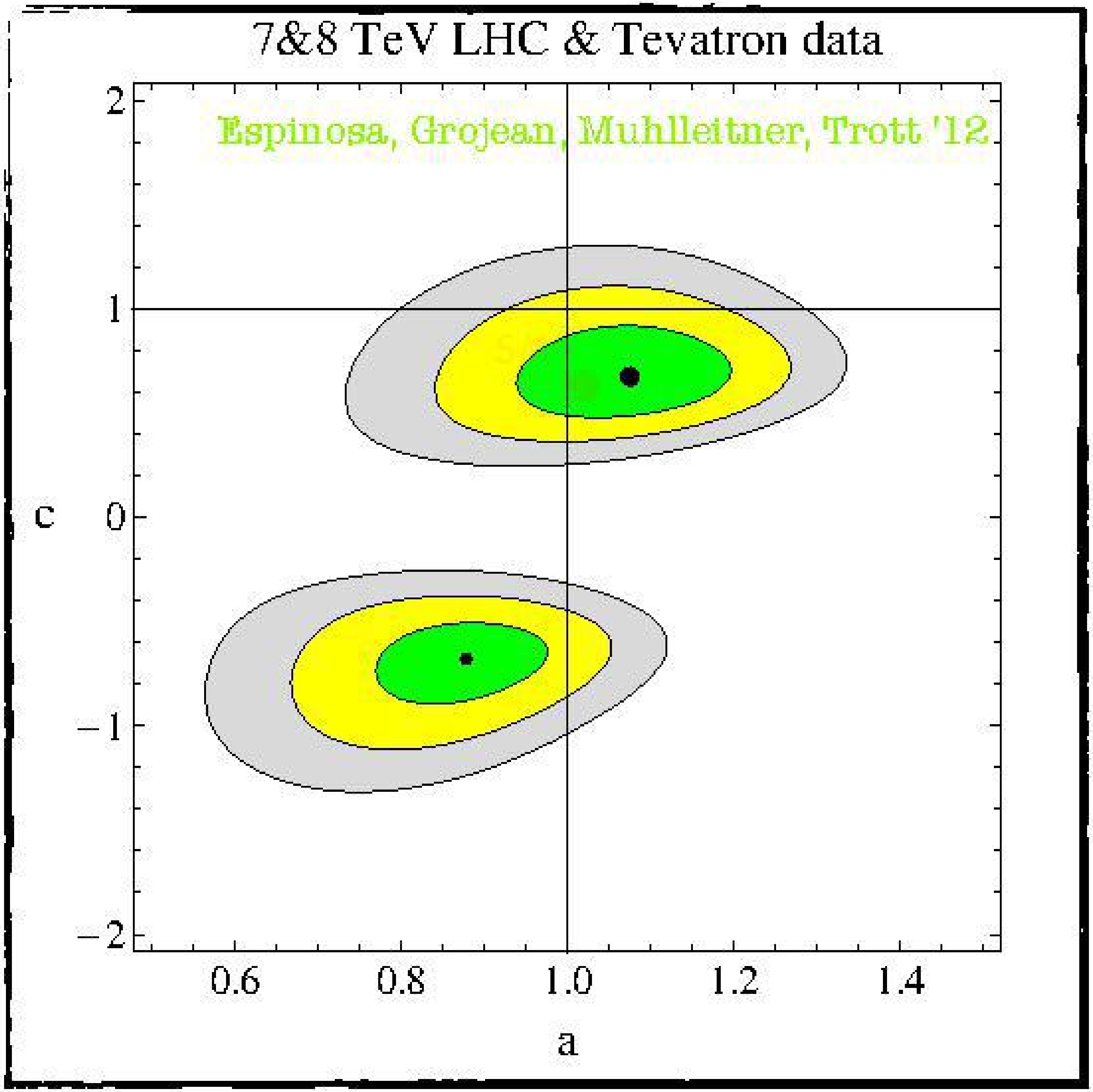

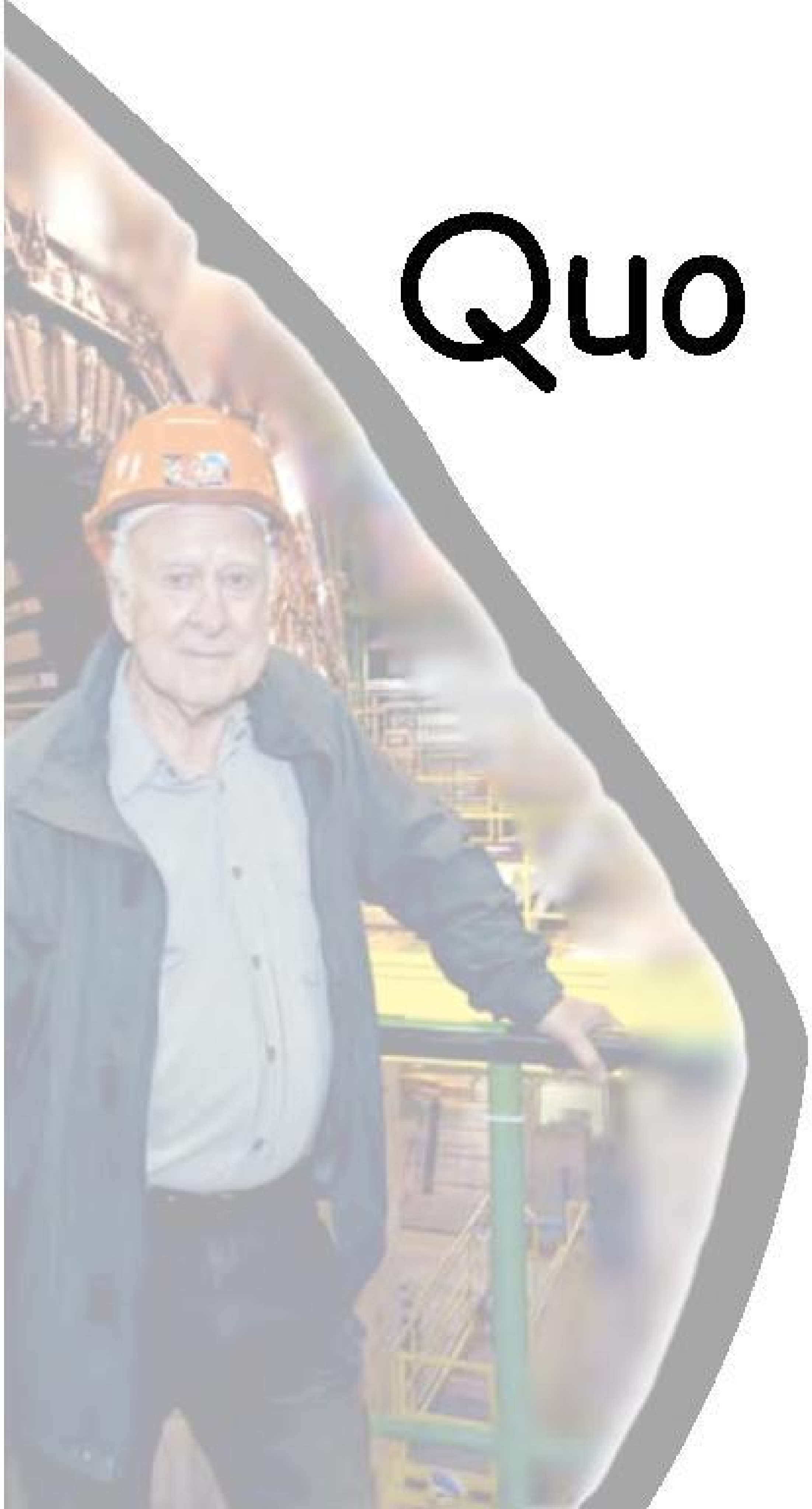

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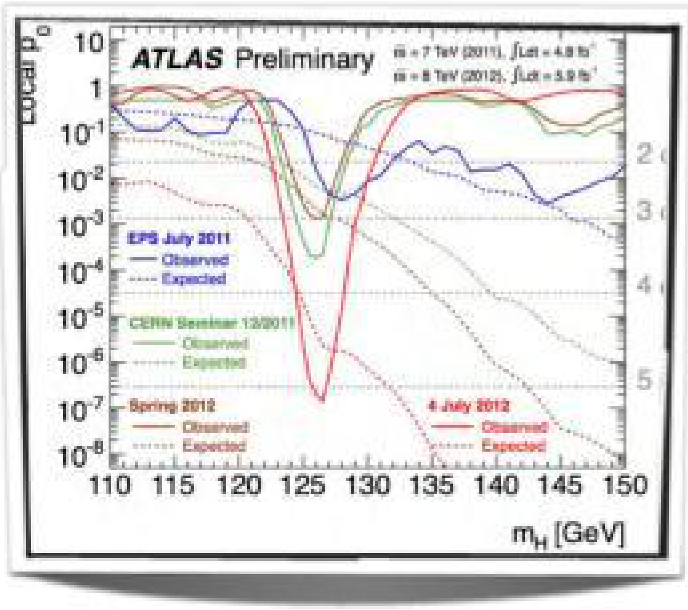

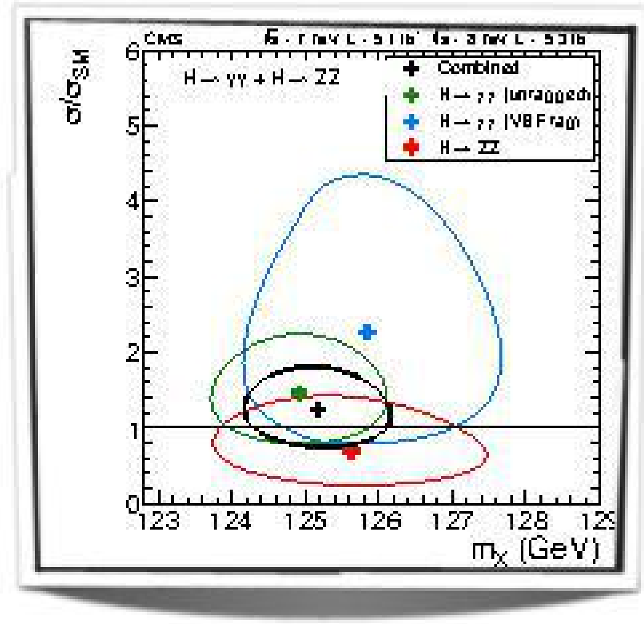

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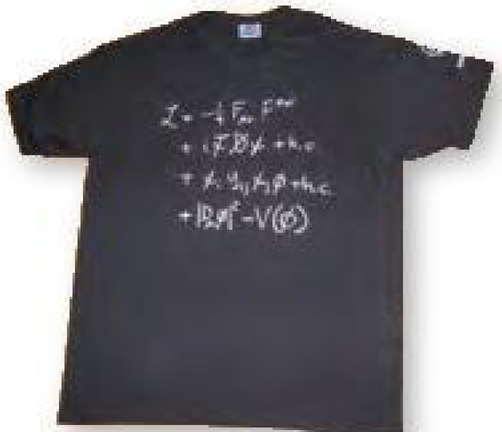

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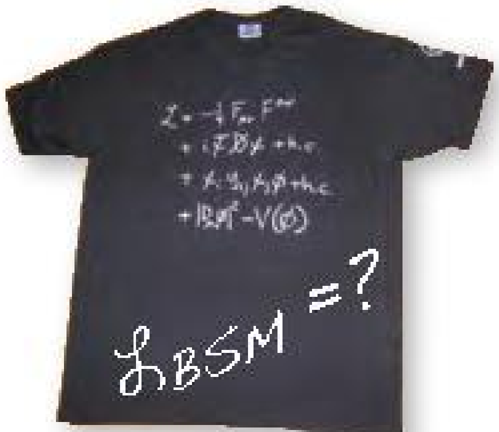

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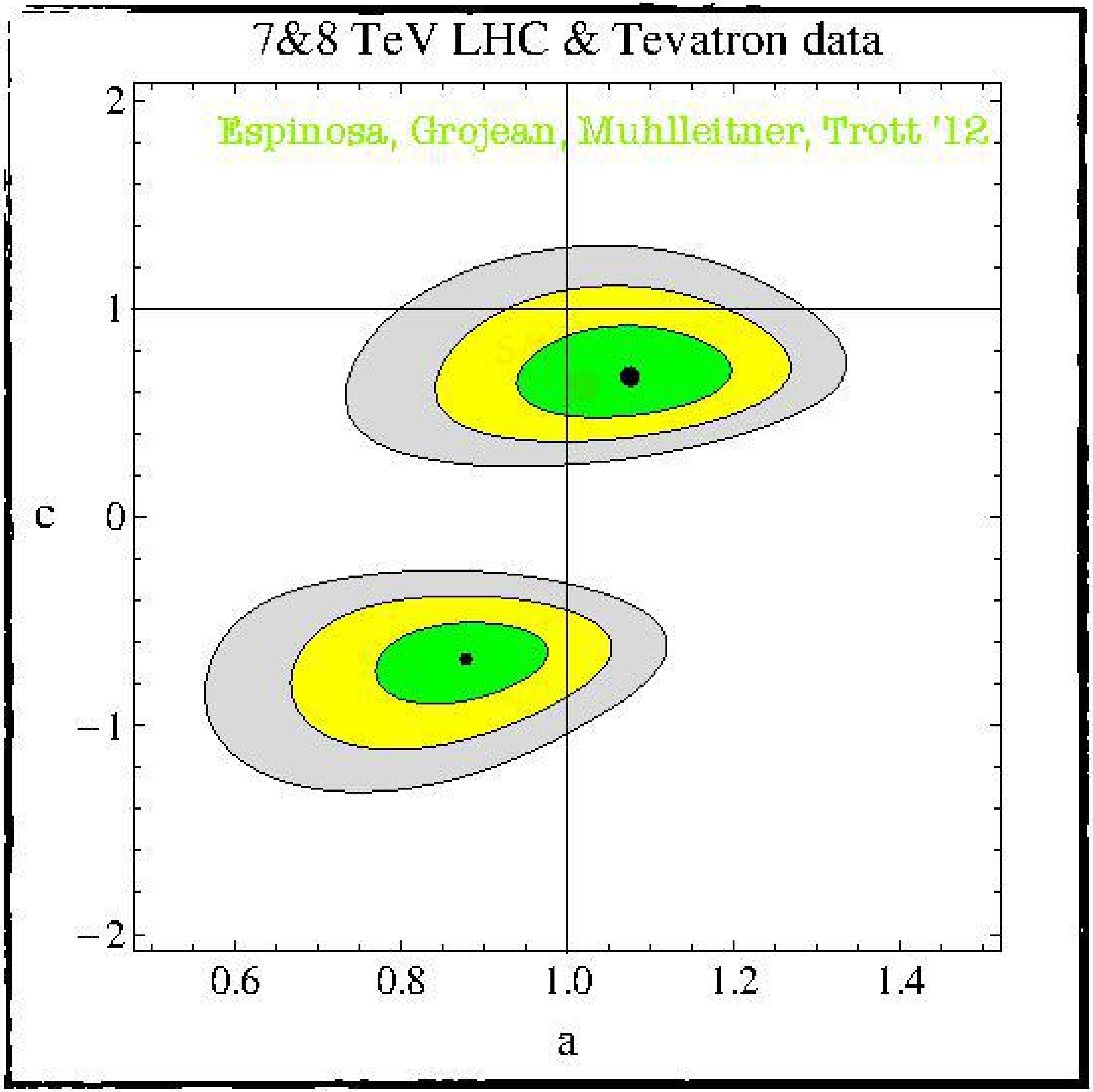

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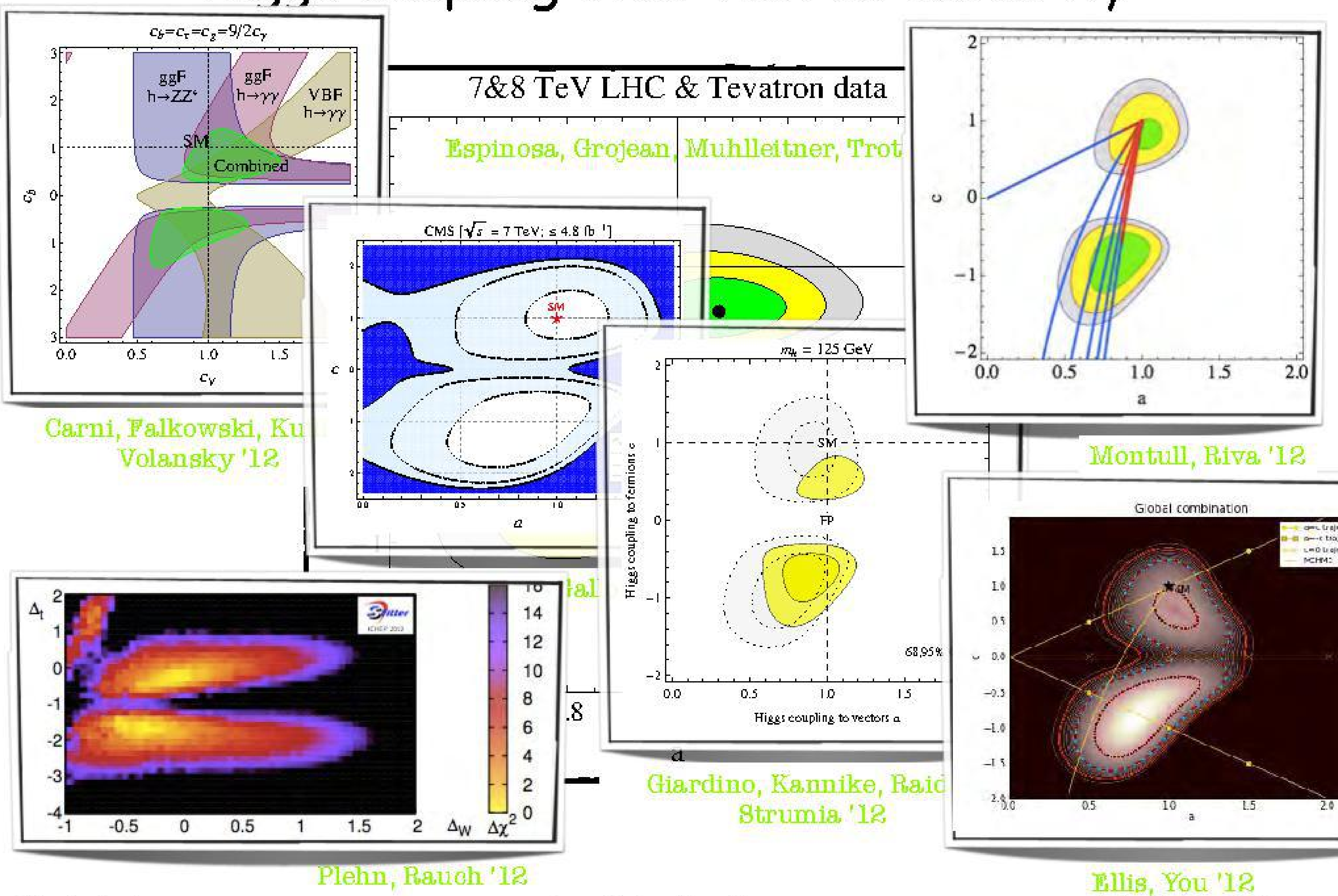

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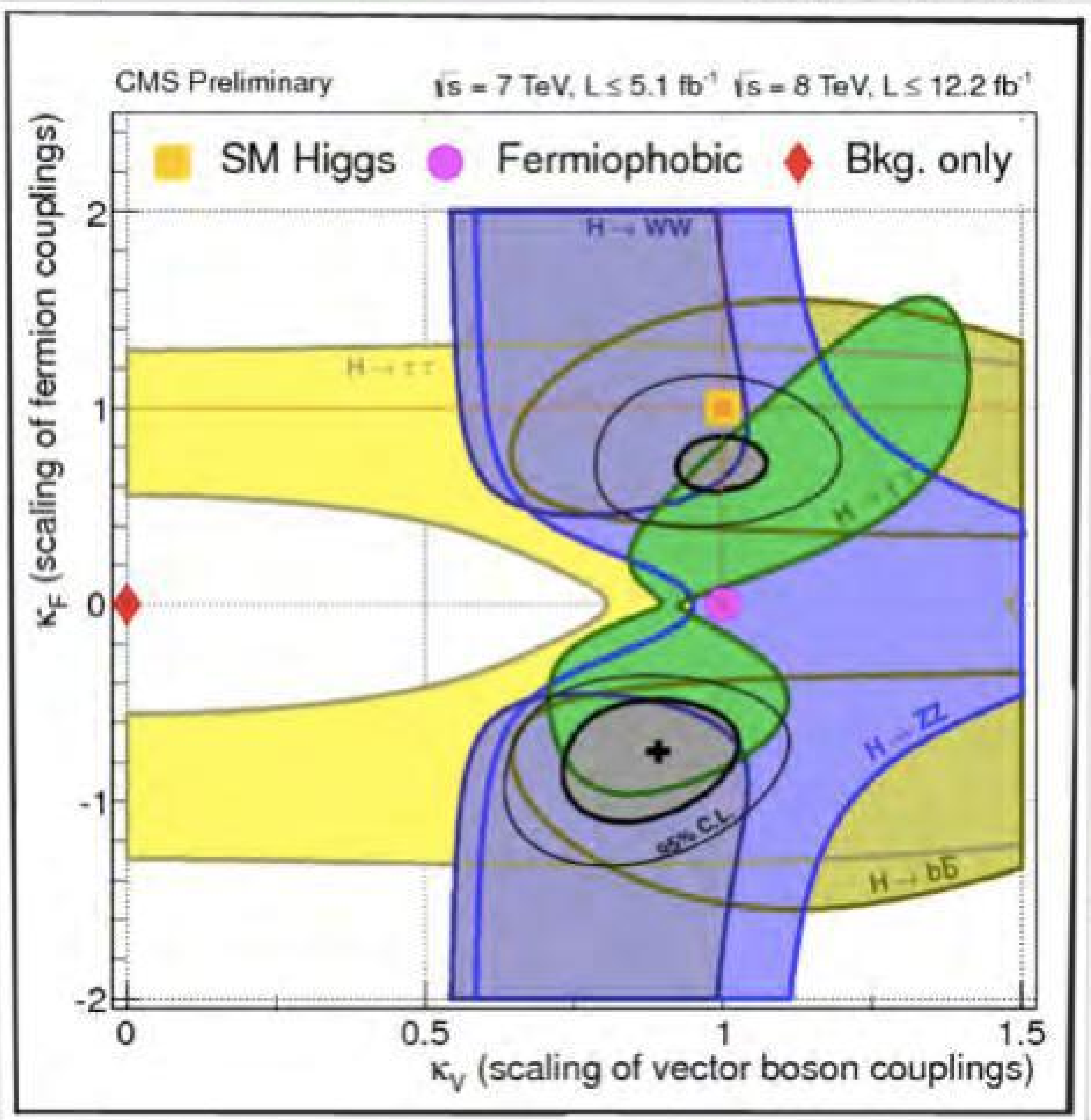
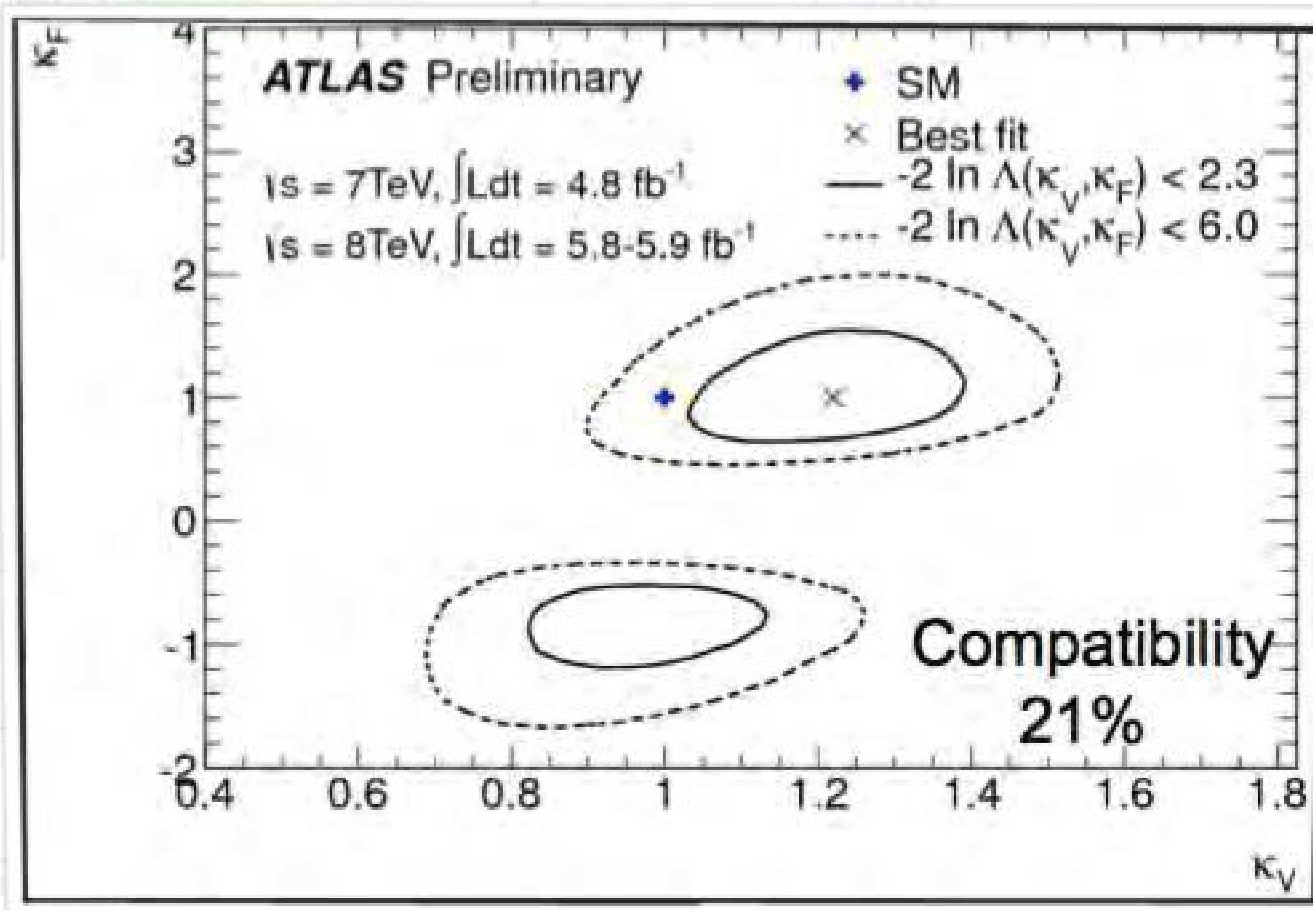
don't leave it in the hands of theorists!



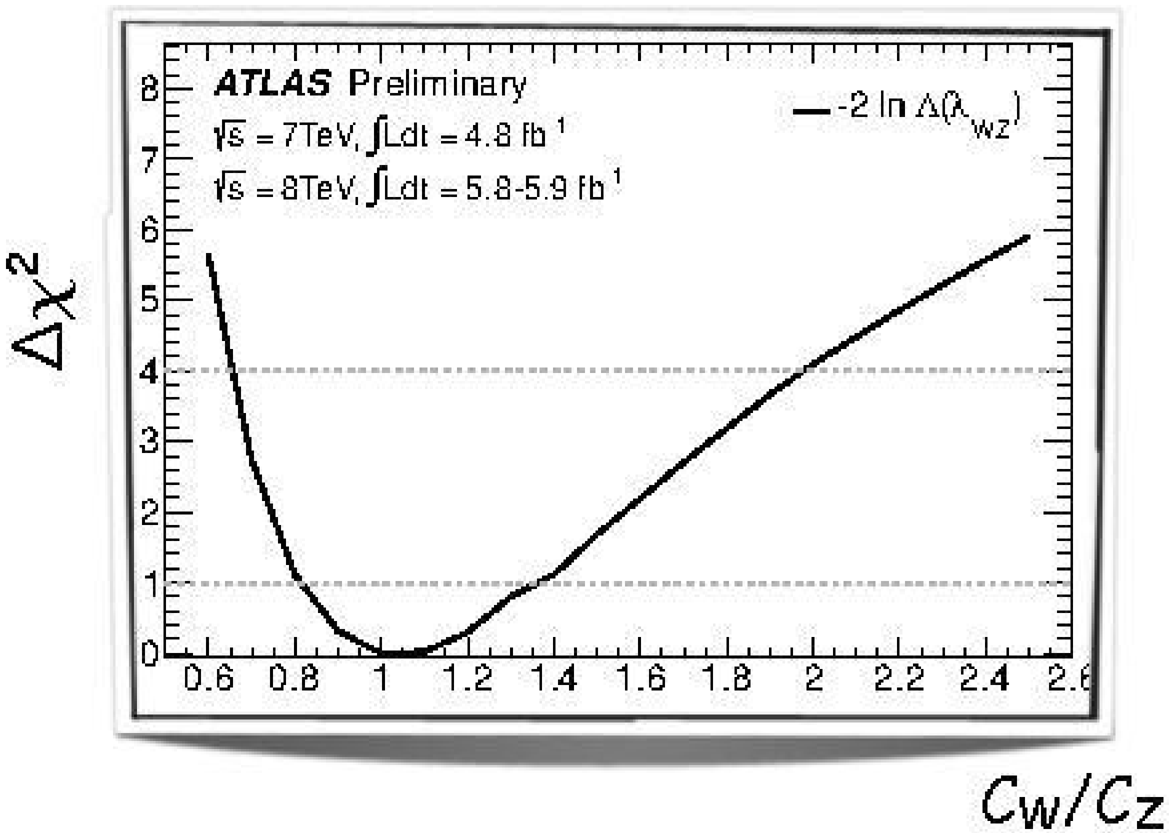
CMS

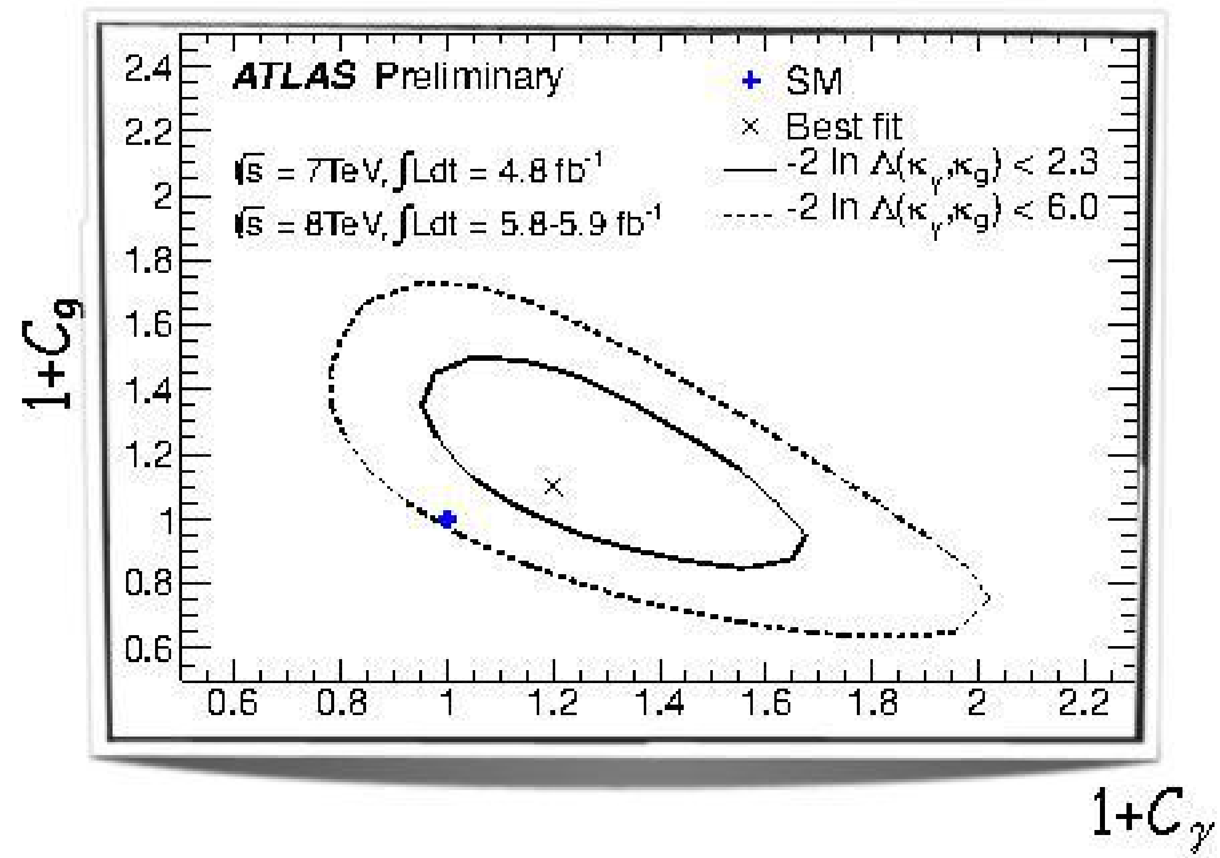


ATLAS

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^* (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(q_p d_r \varphi)$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(l_p\gamma^\mu l_r)$
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$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(u_p\gamma^\mu d_r)$

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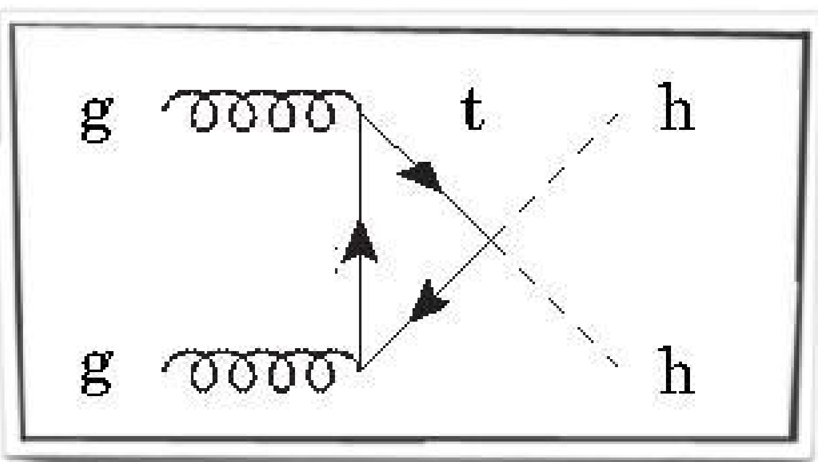
need to promote the chiral Lagrangian to an SM gauge invariant Lagrangian

pioneering work by Buchmuller-Wyler '86

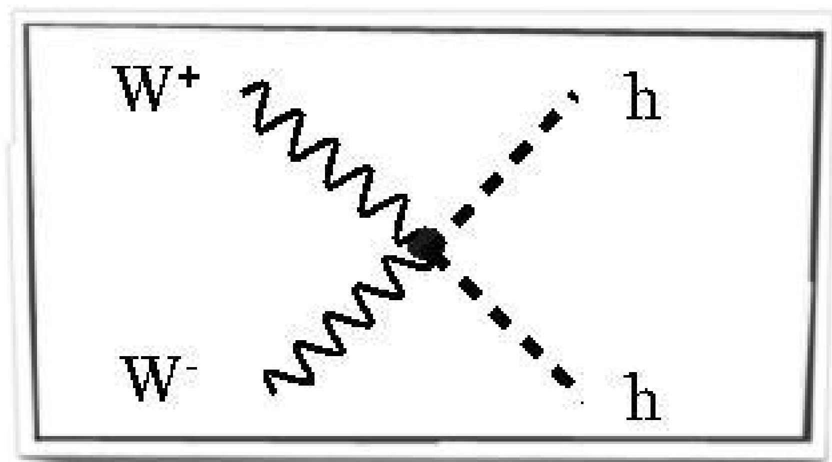
complete classification by Grzadkowski et al '1008.4884

Higgs doublet?

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



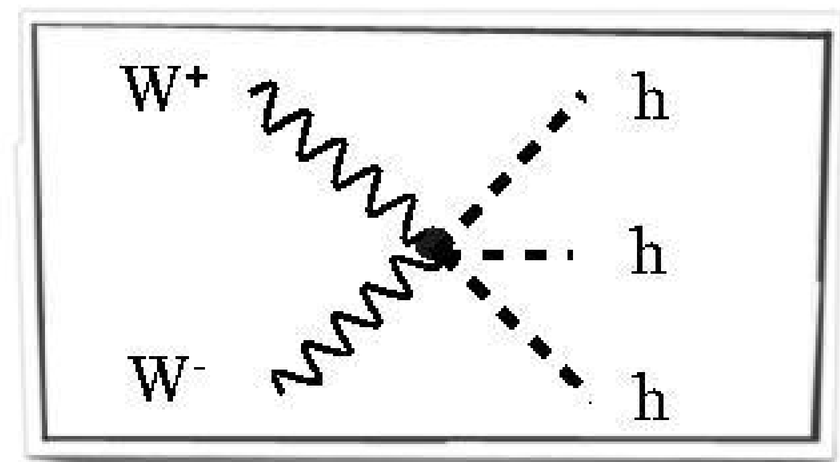
Gröber, Mühlleitner '10
Contino et al '12
Gillioz et al '12



Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

for PGB Higgs

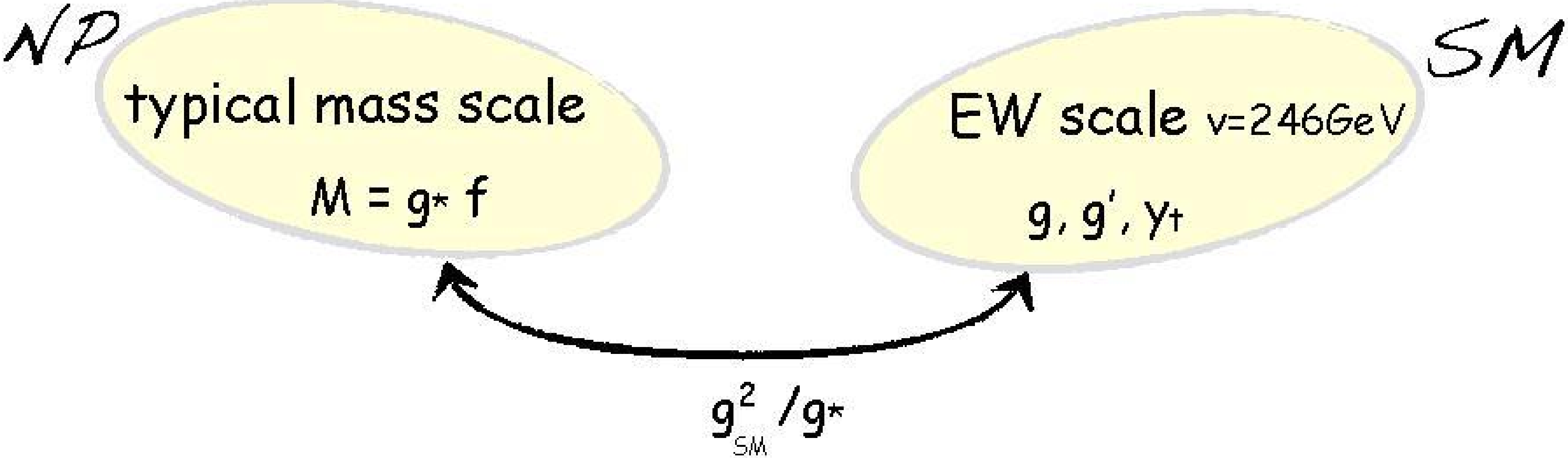


Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'to appear

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

for PGB Higgs

Effective Higgs



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

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

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

Higgs power counting

Giudice, Grojean, Pomarol, Rattazzi '07

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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

$$c_H, c_T, c_6, c_y \sim O\left(\frac{v^2}{f^2}\right), \quad c_W, c_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad c_{HW}, c_{HB}, c_\gamma, c_g \sim O\left(\frac{g^2}{16\pi^2}\frac{v^2}{f^2}\right)$$

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

dynamics with Higgs as PGB

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

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07

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

probing Higgs interactions: g_* or f

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

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

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

Parametrize corrections to tree-level Higgs couplings:

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

$$c_V = 1 - \frac{\bar{c}_H}{2} \qquad c_\psi = 1 - \left(\frac{c_H}{2} + c_\psi\right) \qquad d_3 = 1 + c_6 - \frac{3}{2}c_H$$

Probing Higgs New Physics

Giudice, Grojean, Pomarol, Rattazzi '07

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

probing NP scale: $M = g_* f$

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

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

$\Rightarrow$

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

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

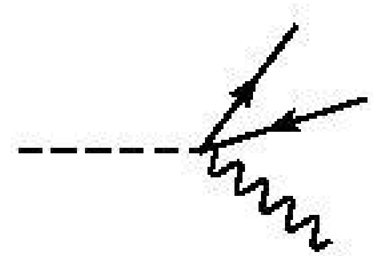
$$\partial_\mu \gamma_{\mu\nu} Z_\nu h$$

one linear combination fixed due to (accidental) custodial invariance

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

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

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: $M = g_* f$

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

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

⇒

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

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

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

one linear combination fixed due to (accidental) custodial invariance

direct(tree-level) contribution to EW oblique corrections

⇒ 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

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

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

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

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

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

→

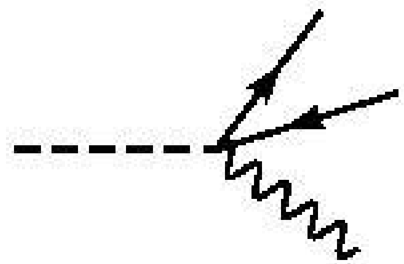
$D_\mu W^+_{\mu\nu} W_\nu\, h$

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

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

one linear combination fixed due to (accidental) custodial invariance

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



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

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

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

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

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

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

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

one linear combination starts at dim=8

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

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

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

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 c_H and c_t effects $\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \left(\frac{v^2}{f^2}\right)$

slide courtesy @ R. Contino

RG-improved Higgs physics

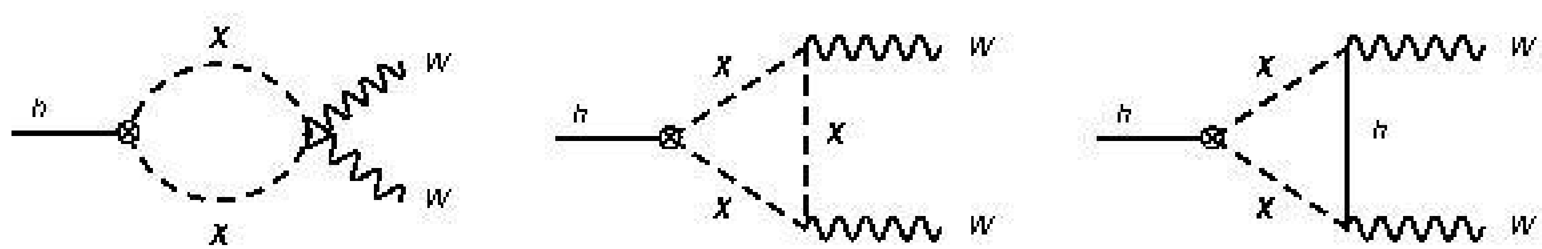
Grojean, Jenkins, Manohar, Trott '13

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*)



$$\mu \frac{d}{d\mu} \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{8\pi} \gamma \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} \qquad \gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ \text{-1/6} & 0 & 0 \\ ?? & 0 & 0 \end{pmatrix}$$

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↑ anomalous dimensions

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

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

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

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

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

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

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13

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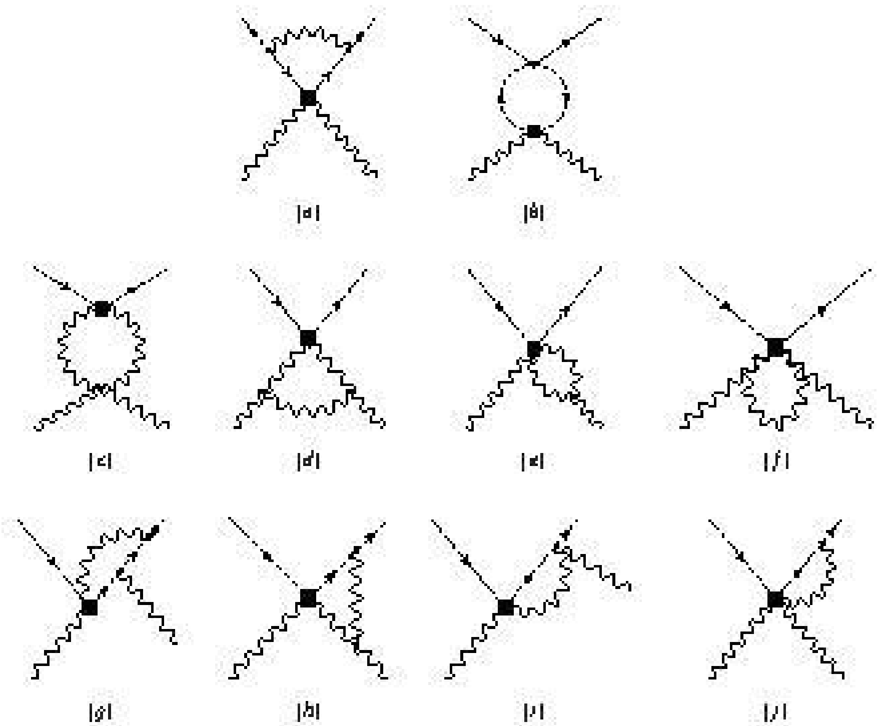
$$\bar{c}_i(\mu) \simeq \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha}{8\pi} \log\left(\frac{\mu^2}{M^2} \right) \right) \bar{c}_j(M)$$

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



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

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

for weak models ($g_* \sim g$)
dominant contribution forgotten up to now

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13

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RG effects can change the picture

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

the case of $\gamma\gamma$

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

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

$$\underbrace{\qquad}_{\frac{g^2}{16\pi^2} \frac{v^2}{f^2} \frac{g^2}{g_*^2}} \qquad \underbrace{\qquad}_{\frac{g^2}{16\pi^2} \frac{m_W^2}{M^2} = \frac{g^2}{16\pi^2} \frac{v^2}{f^2} \frac{g^2}{g_*^2} \times \mathrm{Log}}$$

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

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

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

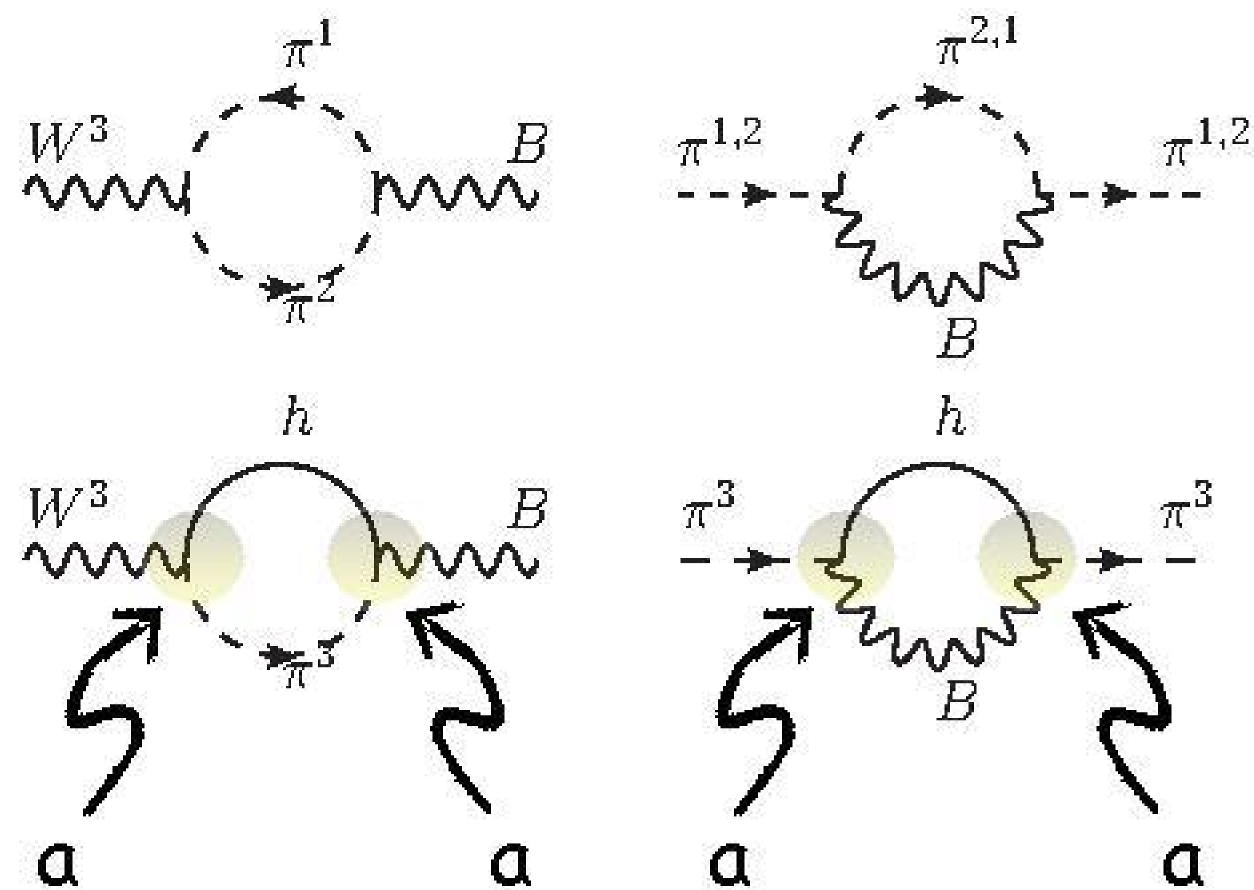
$$\epsilon_{1,3} = c_{1,3} \log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3} \, (1-a^2) \log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

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

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

Barbieri, Bellazzini, Rychkov, Varagnolo '07



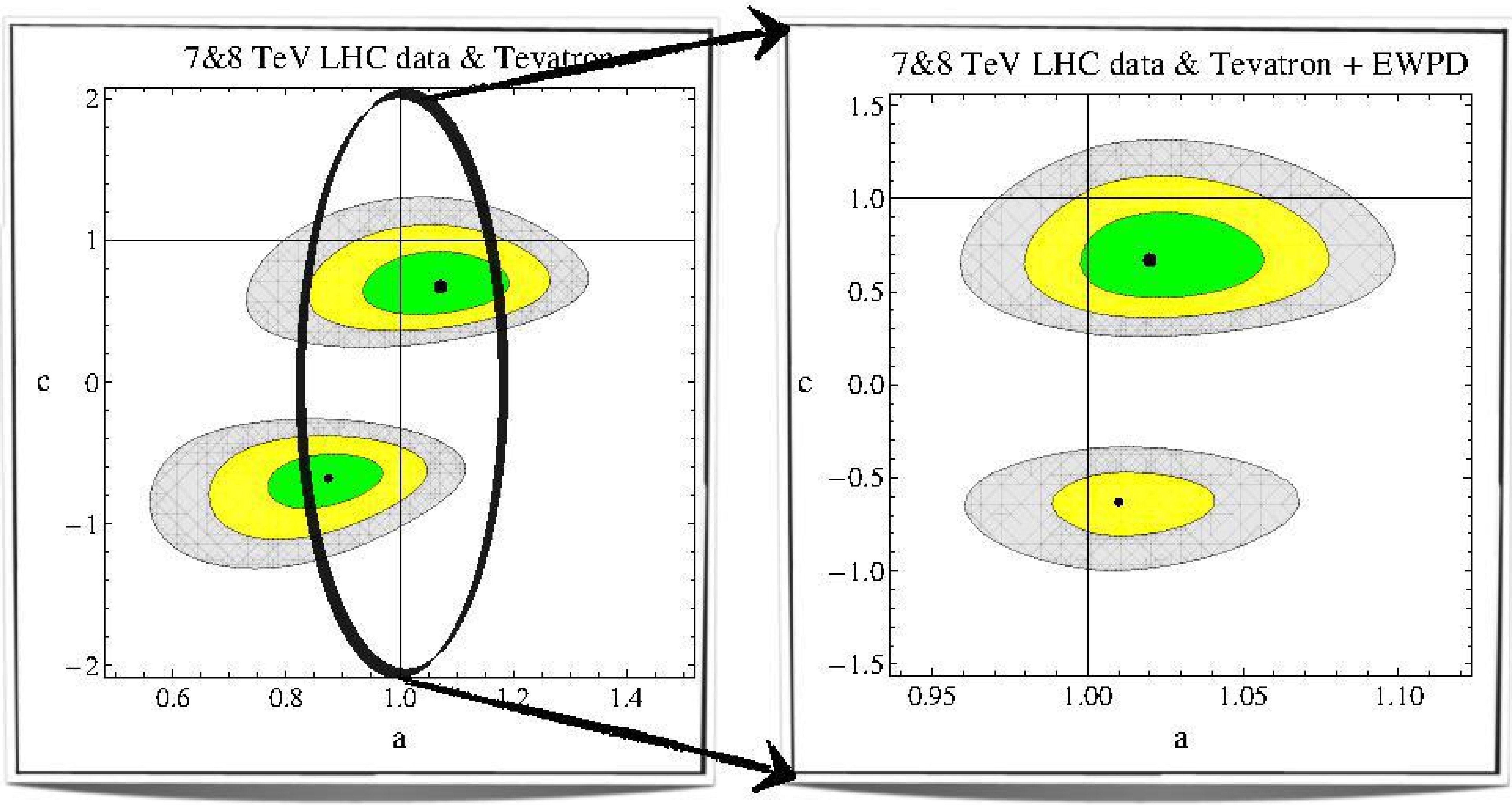
Log. div. cancel only for a=1 (SM)

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

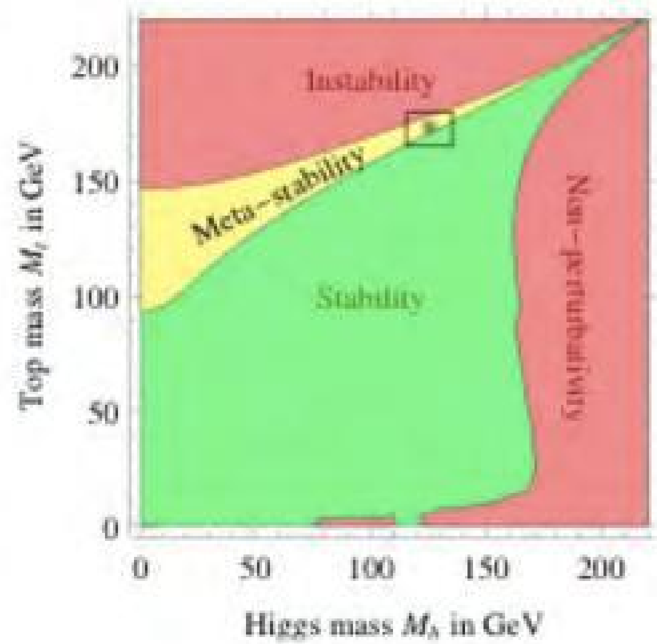
Early Universe Implications

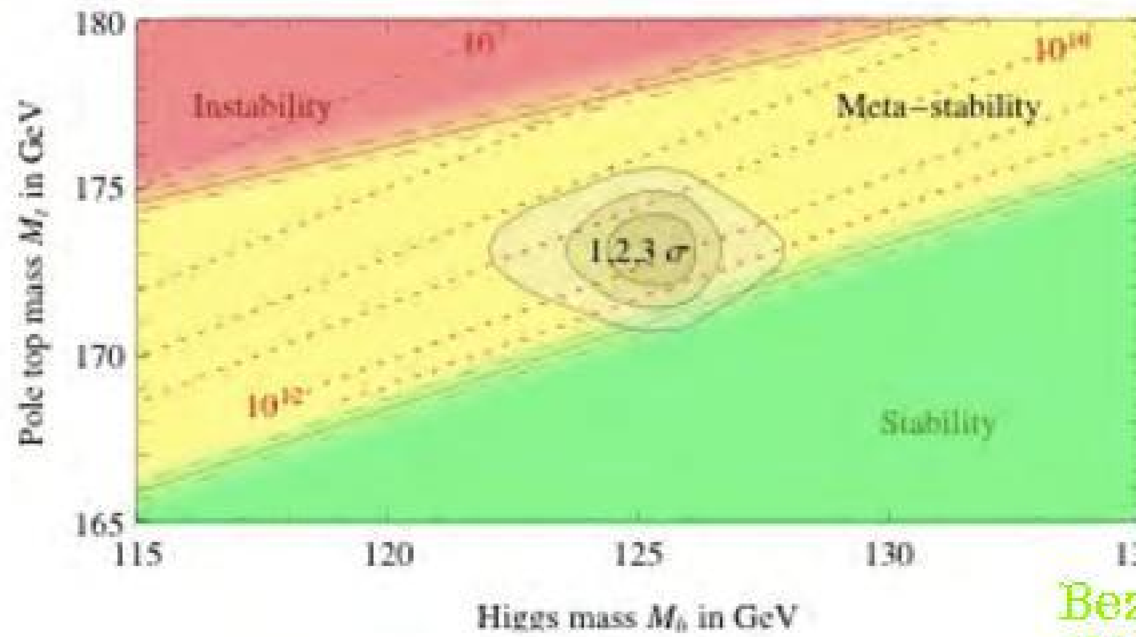
The fate of the EW vacuum

Many of my theory colleagues also started wild speculations/extrapolations

the SM vacuum is stable/metastable

and the validity of the SM can be extended up to the Planck scale!





Bezrukov et al '12
Degrassi et al '12

It is almost certain (>4σ) that $m_H > M_{mestability}$ and totally certain that $m_H < M^{h^3}_{Landau}$

(even though this certainty might by questioned by threshold effects at the Planck scale Holthausen, Lim and Lindner '12)

Not totally clear yet if m_H is above $M_{stability}$, but rather important question since

- ☑ if $m_H > M_{stability}$, the Higgs could serve as an inflaton
- ☑ if $m_H = M_{stability}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

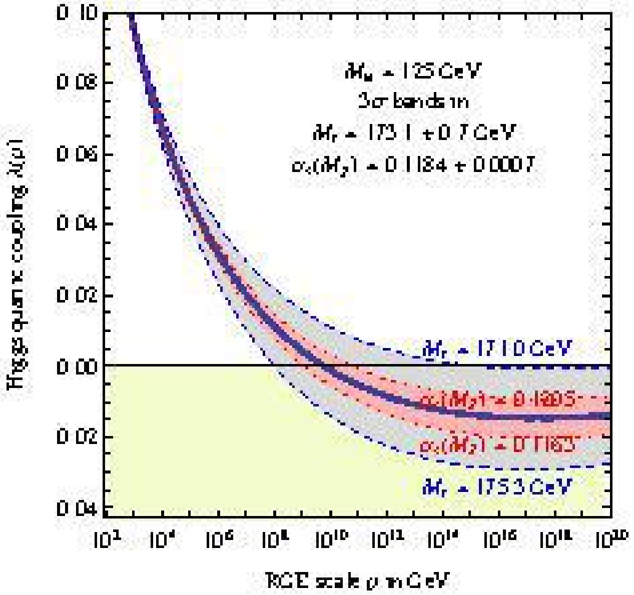
Bezrukov et al '12

need precise Higgs&top mass/couplings (and α_s) measurements (ILC, μ coll.)

and better understanding of pole vs MS top mass Alekhin, Djouadi, Moch '12

From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations



$$\lambda(M_{\rm Pl}) = -0.0144 + 0.0028\left(\frac{M_h}{\rm GeV} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\rm th}$$

Degrassi et al '12

is the Higgs potential vanishing potential at M_{Pl}?

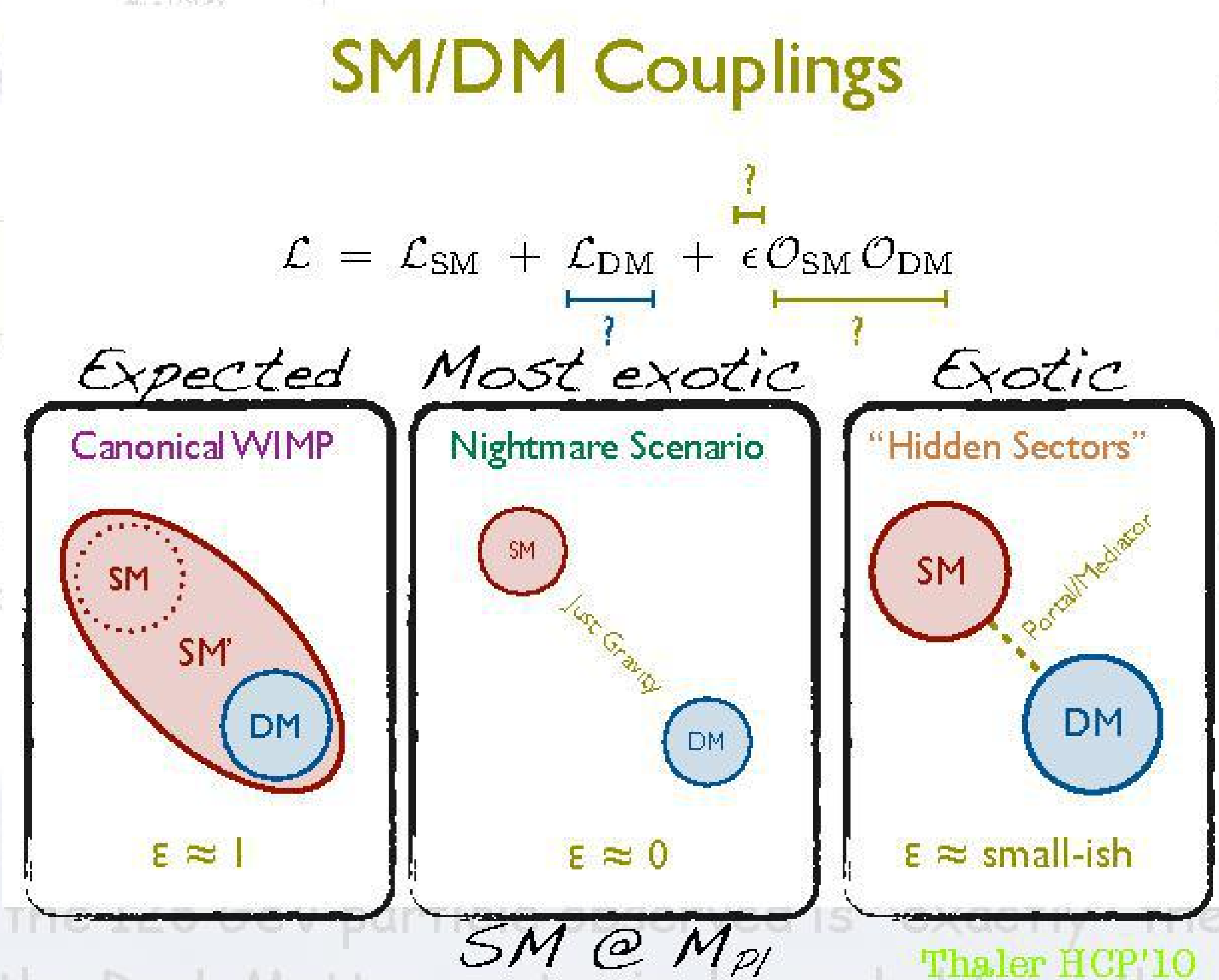
Froggatt, Nielsen, Takanishi '01
Arkani-Hamed et al '08
Shaposhnikov, Wetterich '09

EWSB determined by Planck physics? M_{Pl} calculable from weak scale non-gravitational quantities?
absence of new energy scale between the Fermi and the Planck scale?
Anthropic vs. natural EWSB...

But these implications are based on the assumptions
(1) that the 126 GeV particle observed is *exactly* the SM Higgs
(2) that the Dark Matter sector is decoupled from the weak sector

From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations



Thaler HCP'10

EWSB determine ... itational quantities?

absen ... ck scale?

B ... ions

(1) that ... the SM Higgs

(2) that the Dark Matter sector is decoupled from the weak sector

Weakly coupled models

Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

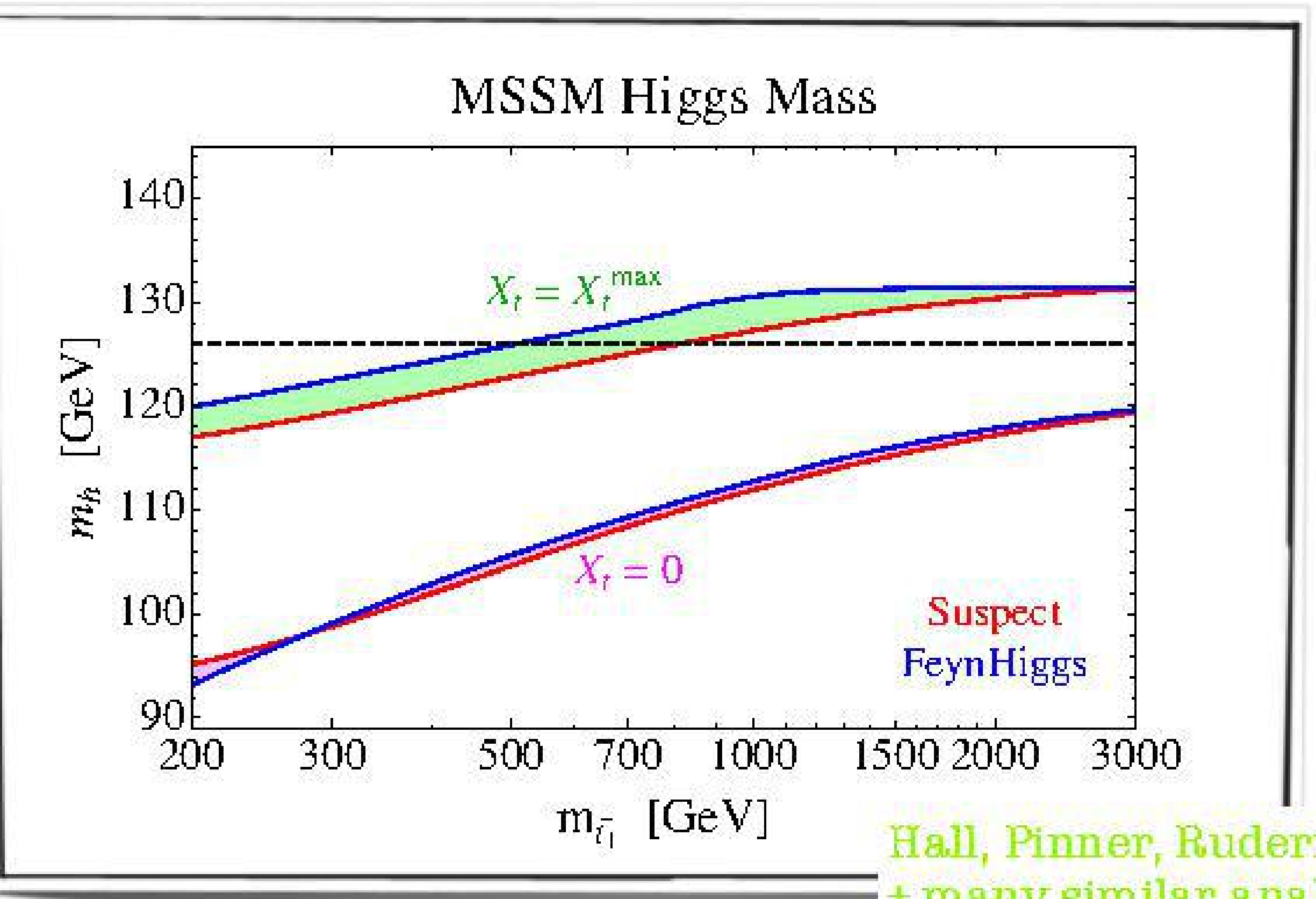
high Higgs mass
implies
susy is badly broken

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

(125 GeV)^2

($\geq$ 87GeV)^2

substantial loop contribution
from stops



Hall, Pinner, Ruderman '11
+ many similar analysse

large mixing
heavy stops

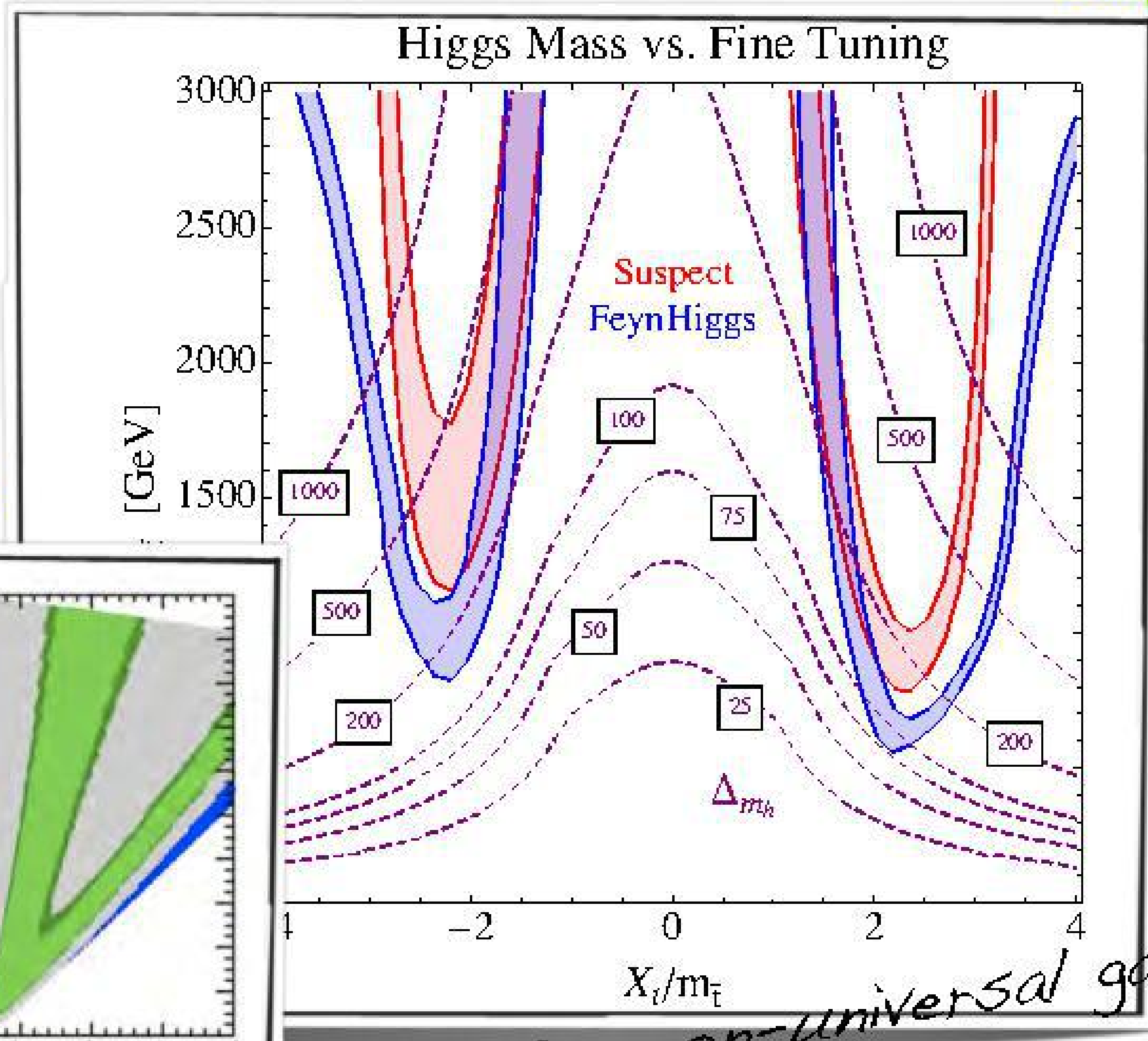
$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700 \text{ GeV}$$

$\Downarrow$ $\Downarrow$

irreducible
fine-tuning ~ O(1%)

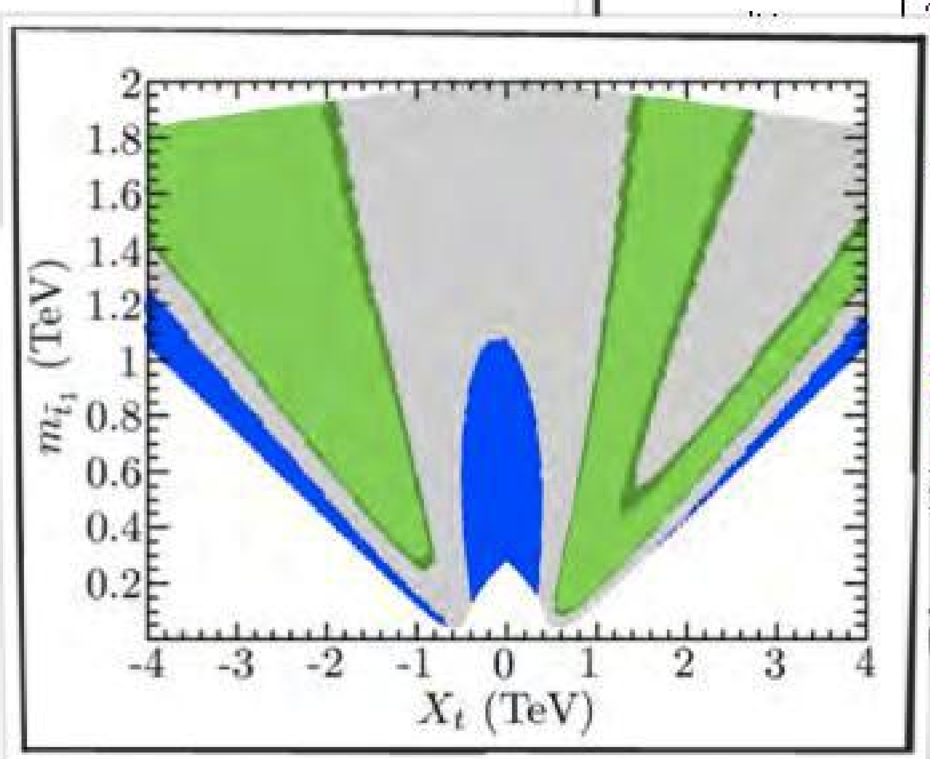
MSSM fine-tuning

Hall, Pinner, Ruderman '11



with larger TH uncertainties, the lower bound can go down:

S. Heinemeyer et al '11



call for non-universal gaugino masses?

maximal mixing requires tricky engineering

$$m^2_{\tilde{t}}(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m^2_{\tilde{t}}(M_G)$$
$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

⋯→ generically $A_t/m_{\tilde{t}} \leq 1$

Dermisek, Kim '06

Natural SUSY

SUSY fine-tuning troubles originate from

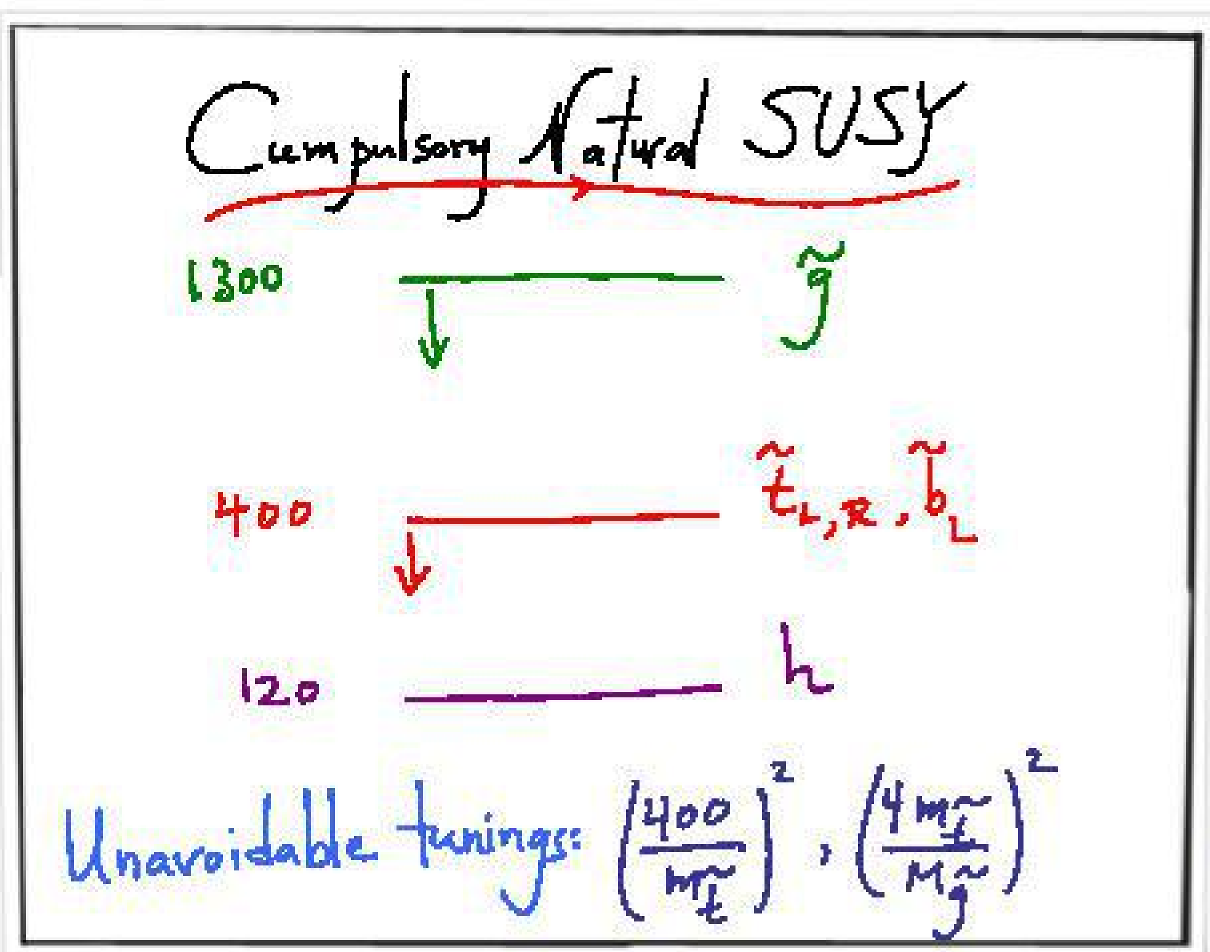
LHC2TSP WG2

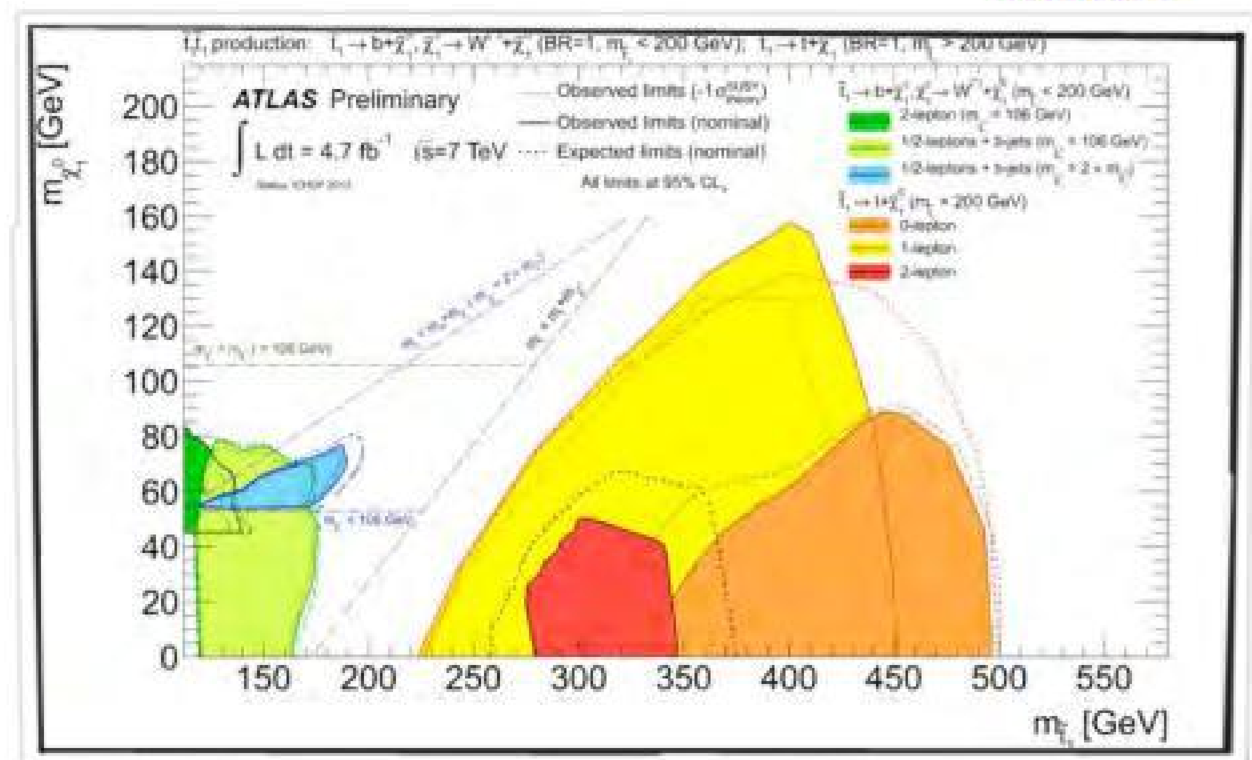
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

light higgsinos

light stops (1-loop)
light gluinos (2-loops)

ATLAS





Arkani-Hamed @ SavasFest

new Goldwin's law: every HEP review talk has to show a slide by Nima

Higgs Couplings in Natural SUSY

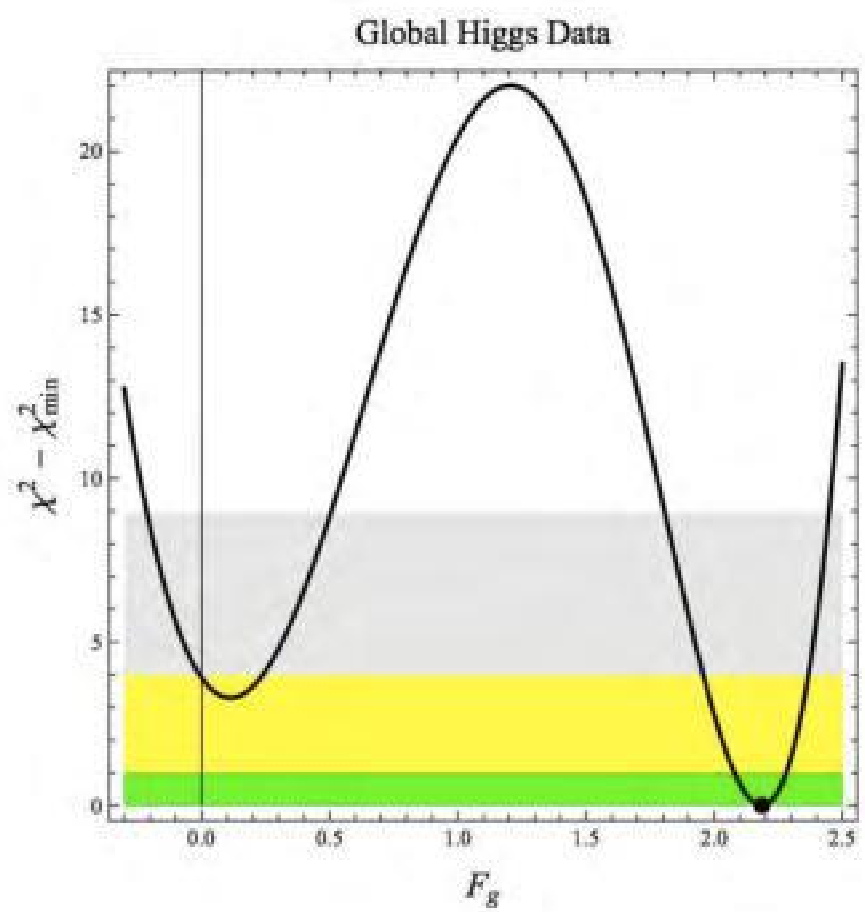
Espinosa, Grojean, Sanz, Trott '12

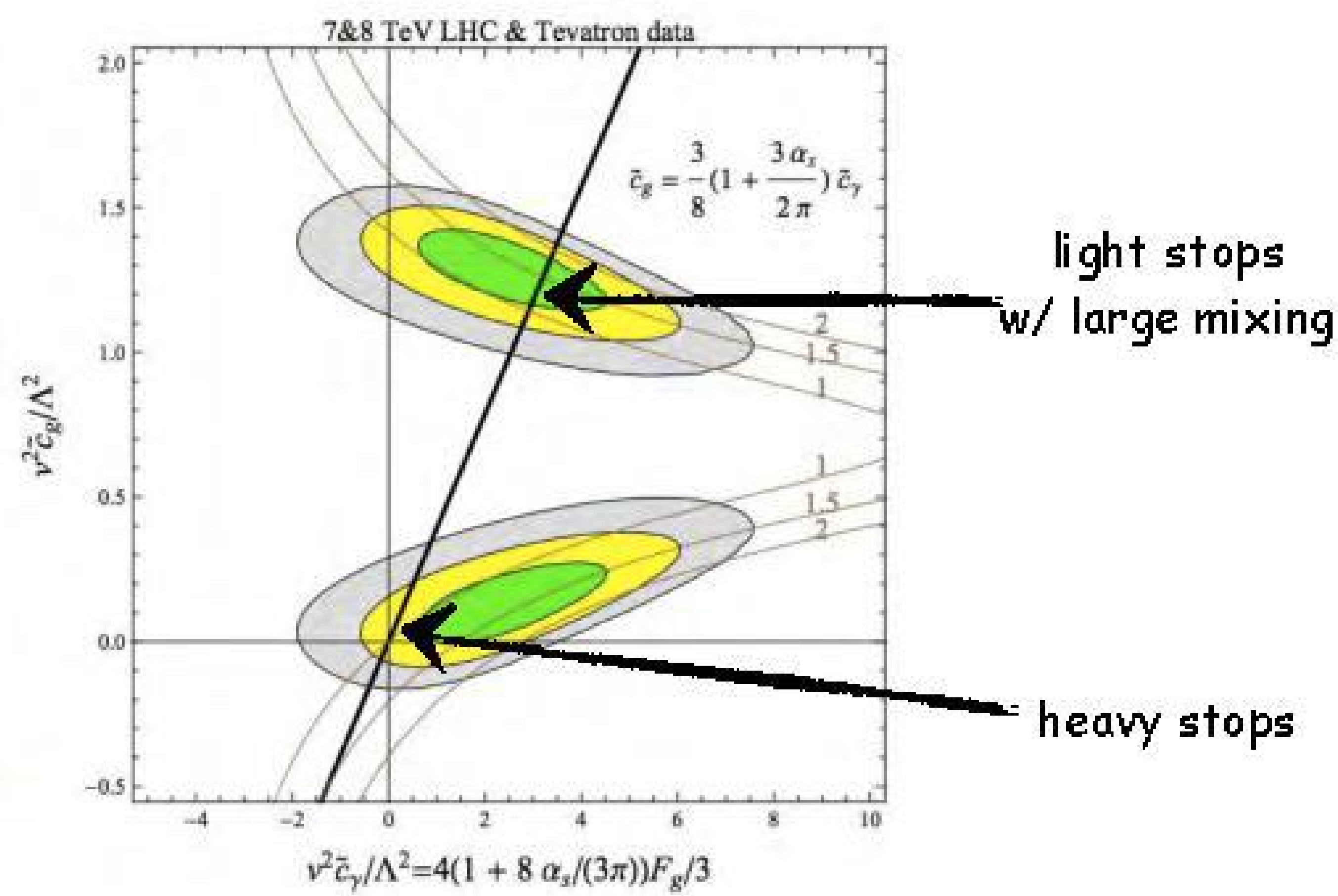
the light stops affect the radiative processes

$$\frac{\sigma(gg\to h)}{\sigma^{SM}(gg\to h)} \simeq \frac{\Gamma(h\to gg)}{\Gamma^{SM}(h\to gg)} \simeq |1+r_g|^2 \qquad\qquad \frac{\Gamma(h\to\gamma\gamma)}{\Gamma^{SM}(h\to\gamma\gamma)} \simeq |1+r_\gamma|^2$$

$$r_g = \frac{C_g(\alpha_s)\,F_g(m_{\tilde t_1}, m_{\tilde t_2}, \theta_{\tilde t})}{F_g^{SM}(m_t, m_b\cdots)} \qquad\qquad r_\gamma = \frac{N_c\,Q_{\tilde t}^2\,C_\gamma(\alpha_s)F_g(m_{\tilde t_1}, m_{\tilde t_2}, \theta_{\tilde t})}{F_\gamma^{SM}(m_t, W, m_b\cdots)}$$

$$F_g = \frac{1}{3}\left[\frac{m_t^2}{m_{\tilde t_1}^2} + \frac{m_t^2}{m_{\tilde t_2}^2} \quad \frac{1}{4}\sin^2(2\,\theta_t)\,\frac{\delta m^4}{m_{\tilde t_1}^2\,m_{\tilde t_2}^2}\right]$$





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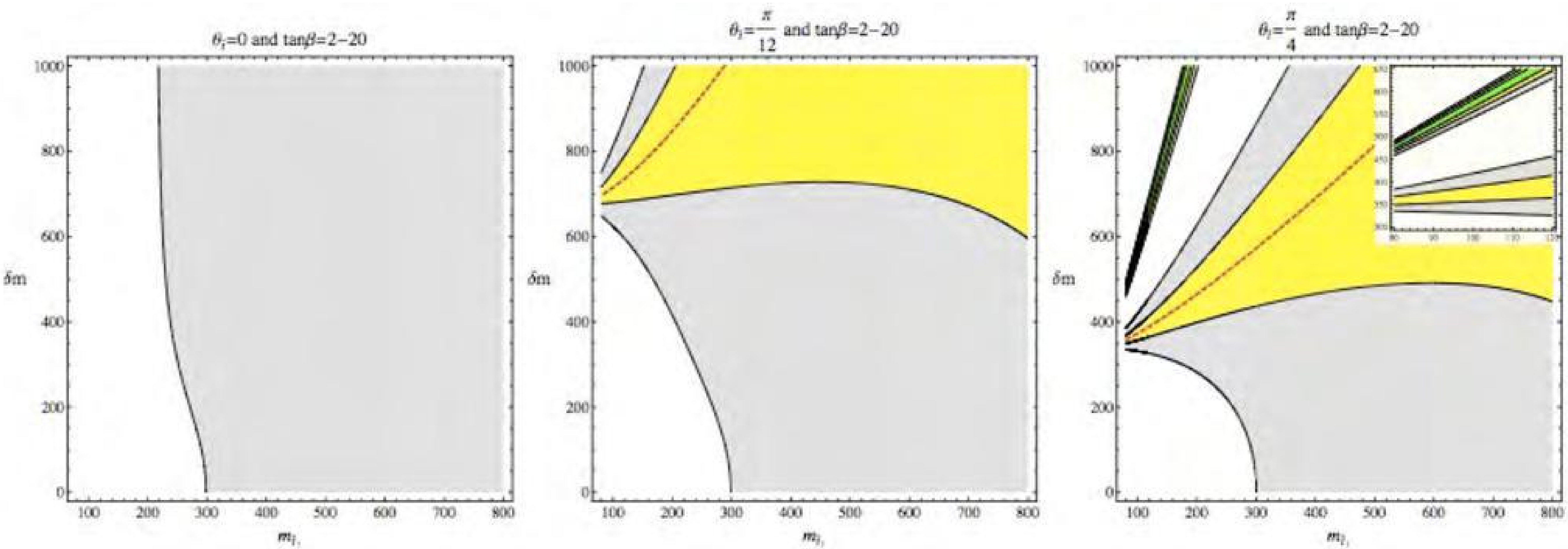
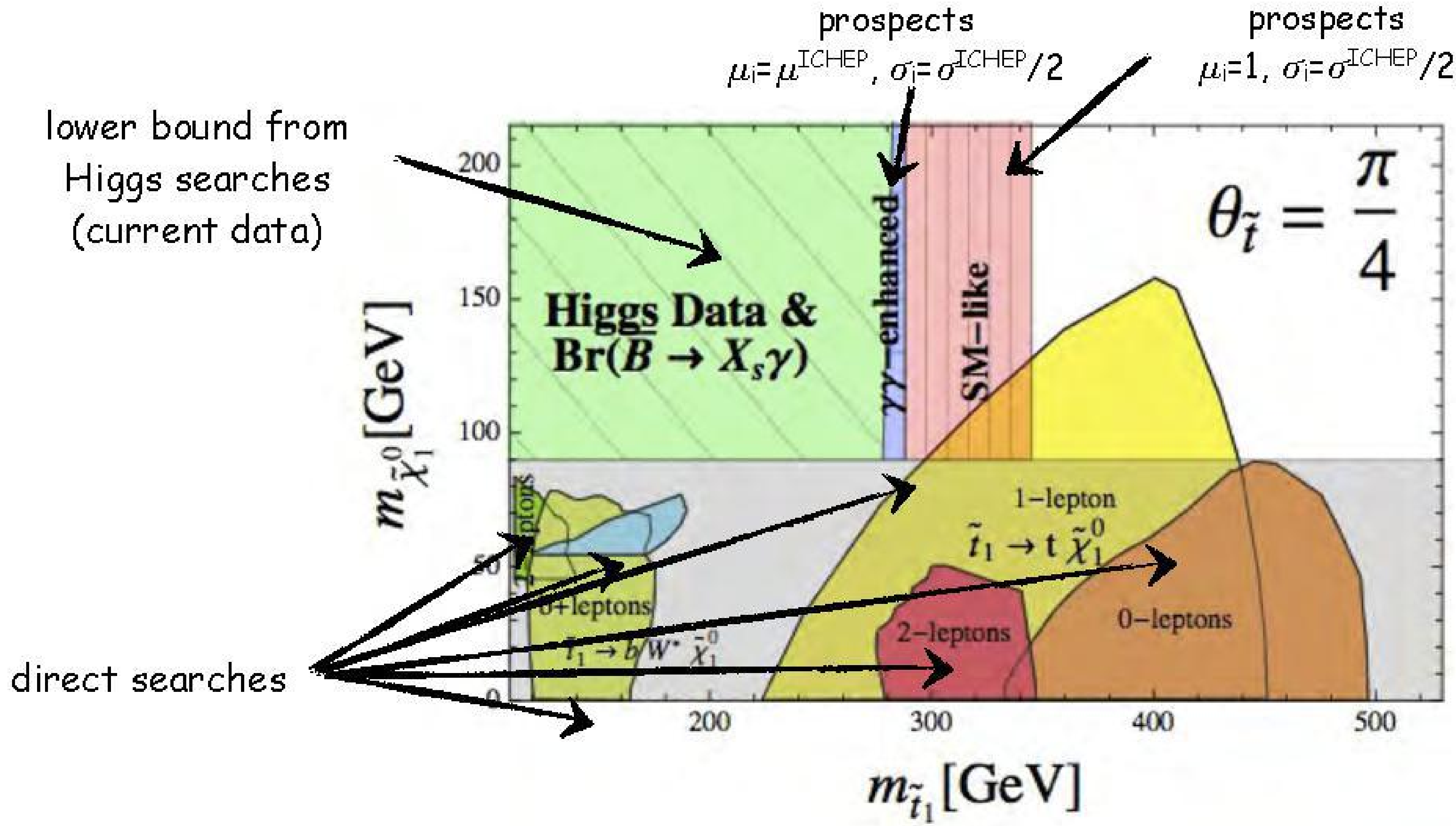


Stop mass constraints from Higgs global fit

Espinosa, Grojean, Sanz, Trott '12

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

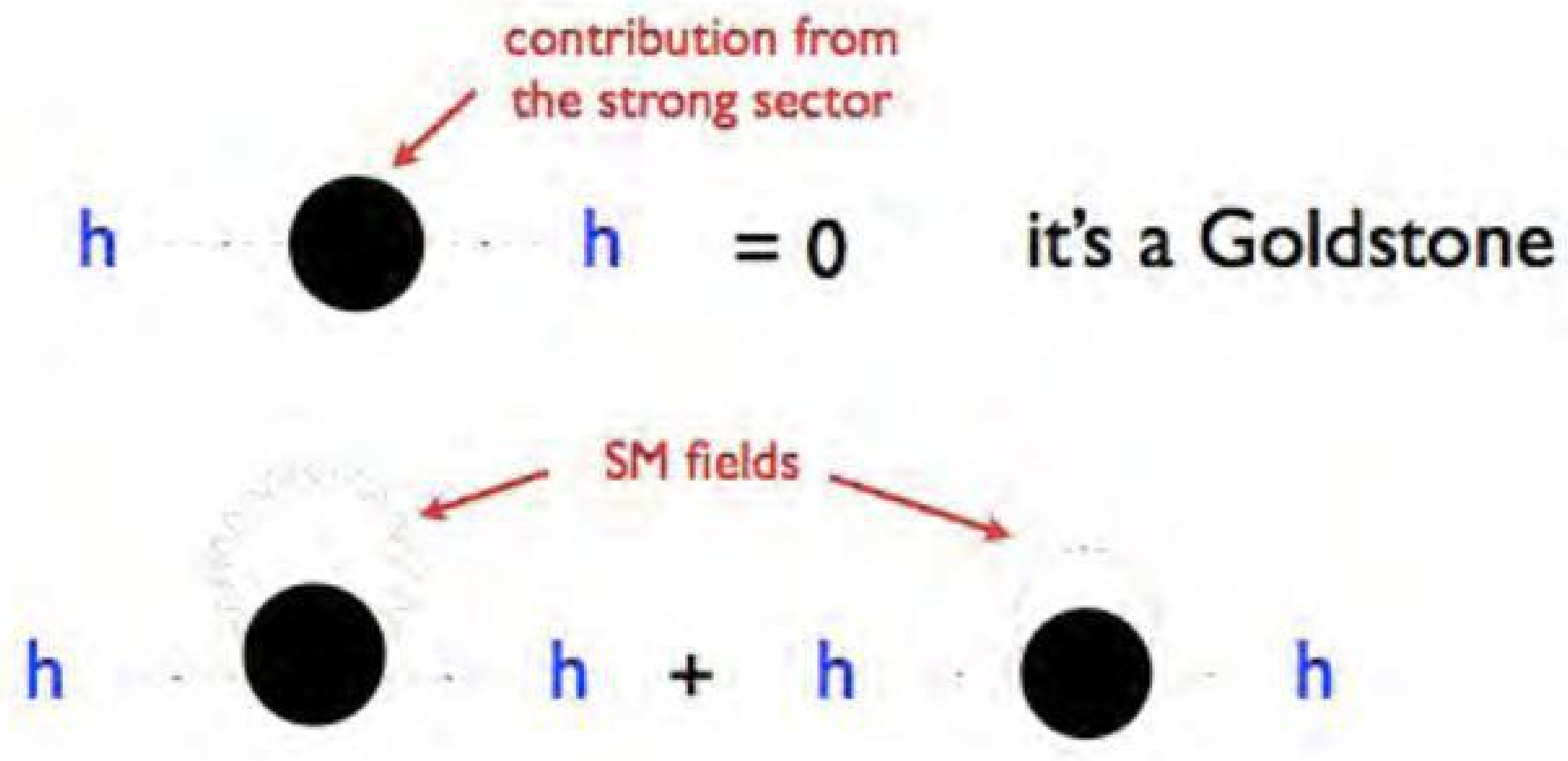
then Higgs data put a lower bound of the stop mass



Strongly coupled models

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

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

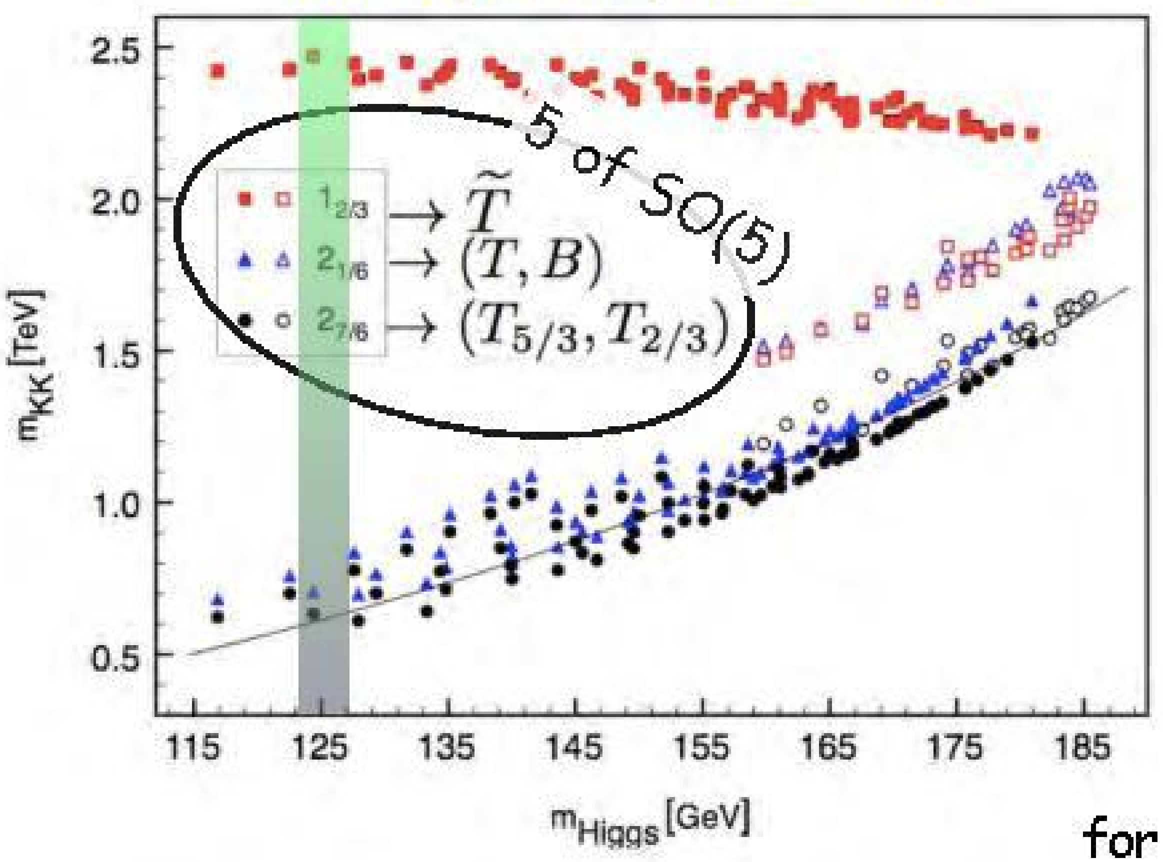
$$m_Q \lesssim 700\ \text{GeV}\left(\frac{m_h}{125\ \text{GeV}}\right)\left(\frac{160\ \text{GeV}}{m_t}\right)\left(\frac{f}{500\ \text{GeV}}\right)$$

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

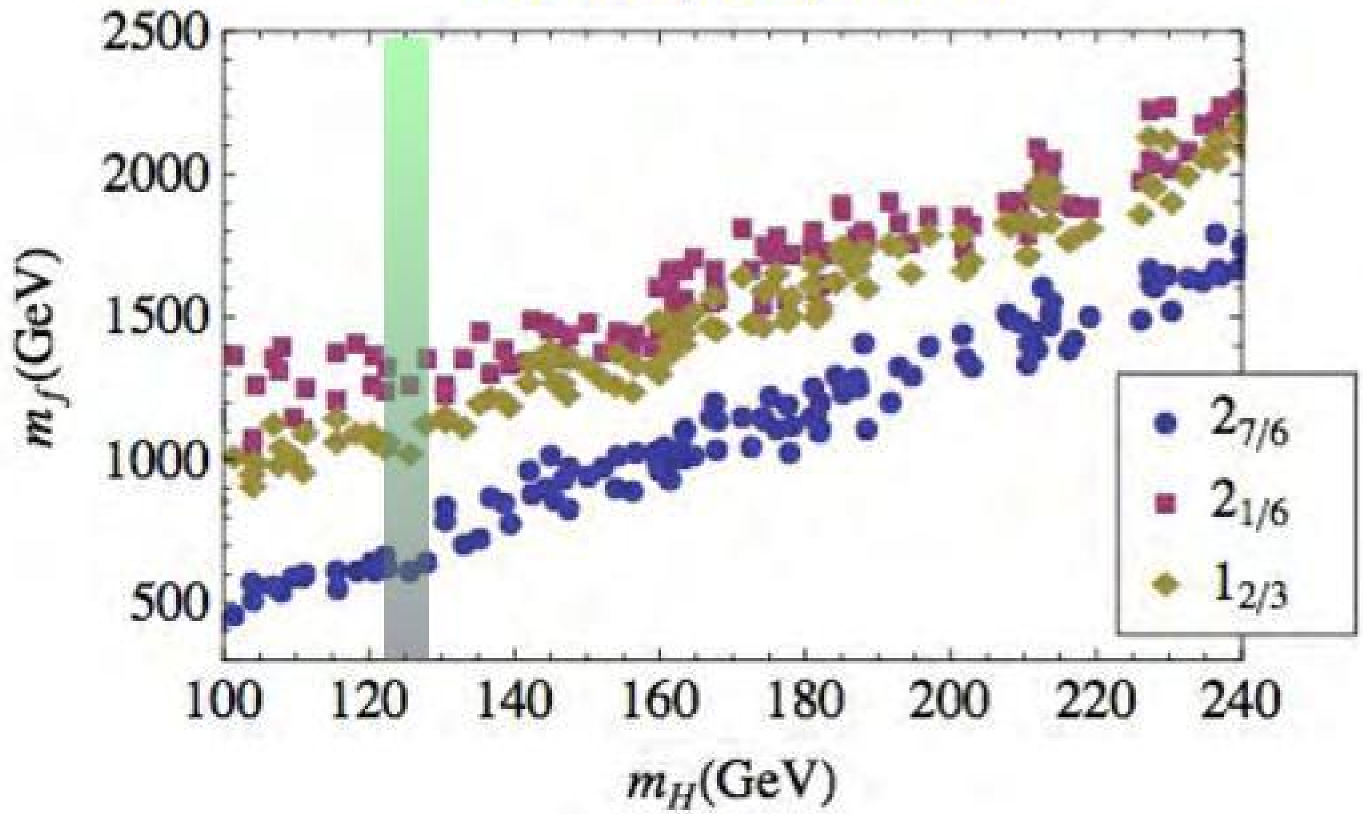
Light composite Higgs from "light" resonances

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

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

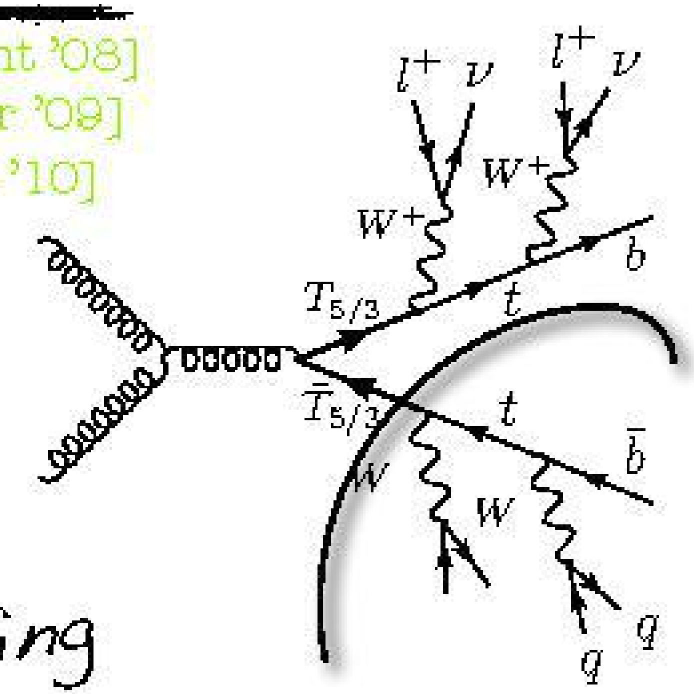
$$M_\Psi = 1/2 \leftrightarrow \dim[\mathcal{O}_\Psi] = 3/2 \leftrightarrow \text{light free field decoupled from CFT}$$

Rich phenomenology of the top partners

Search in same-sign di-lepton events

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

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



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

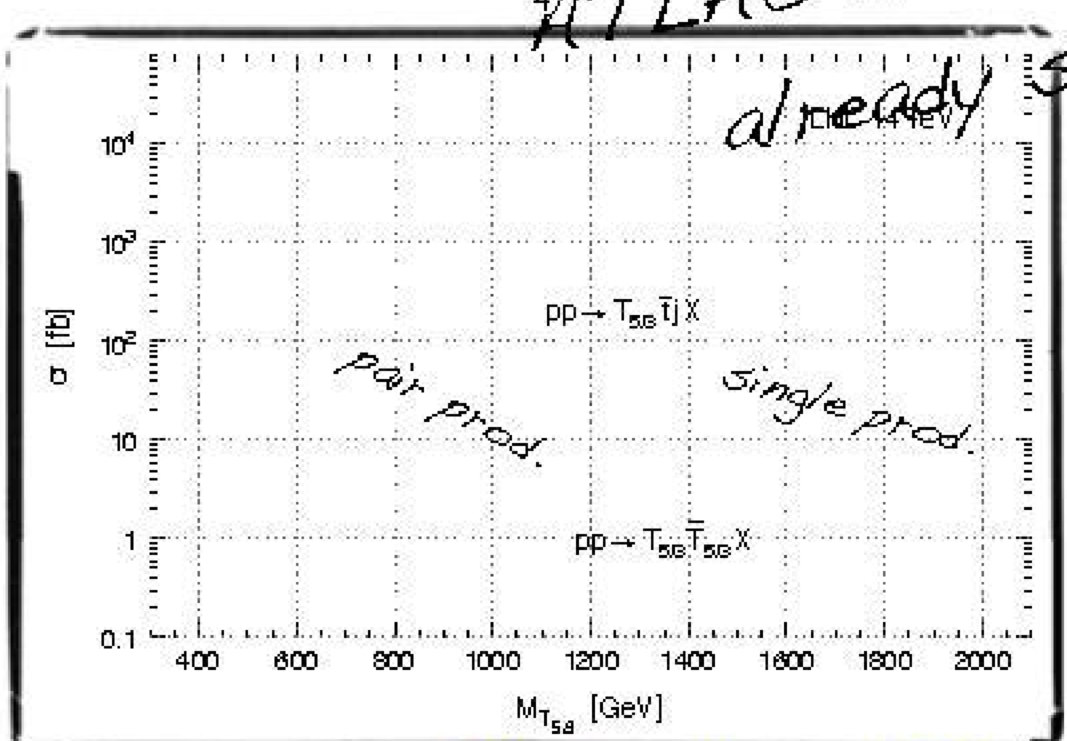
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

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

[Dissertori, Furlan, Moortgat, Nef '09]

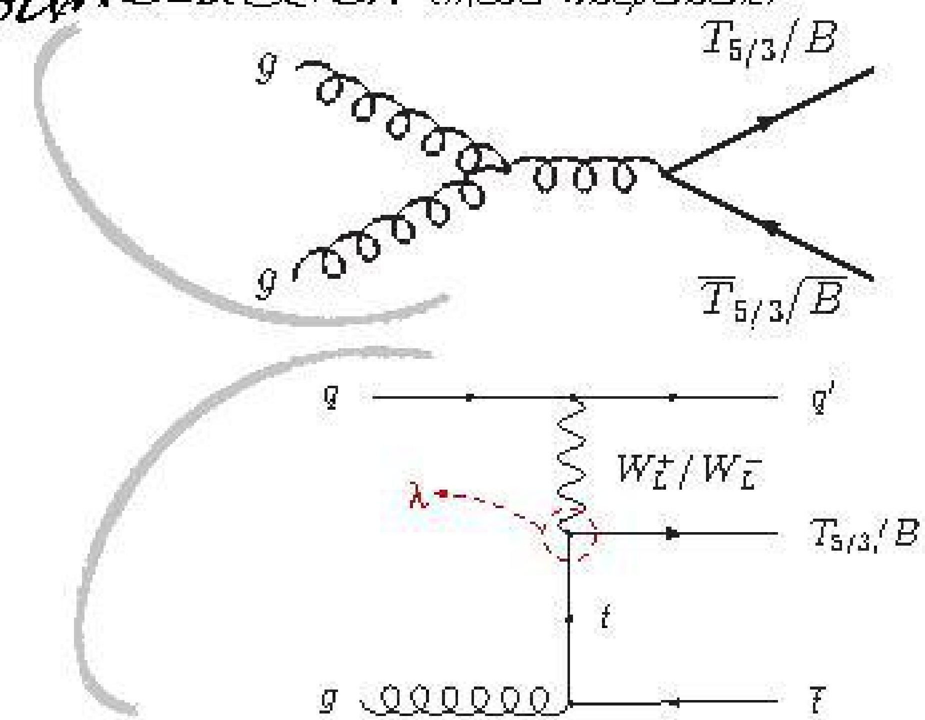
ATLAS & CMS searches ongoing

already stringent bounds



[Contino, Servant '08]

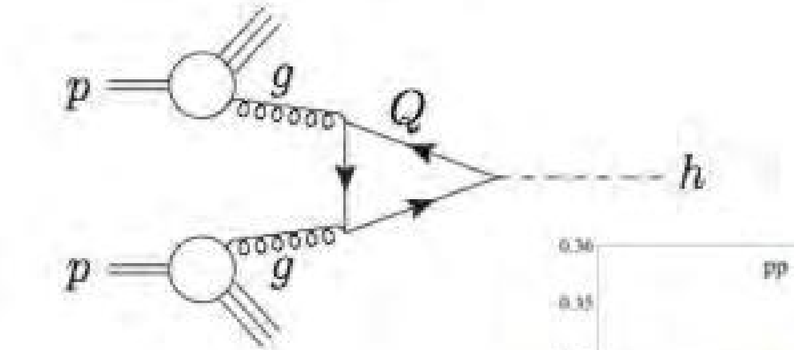
Pair production (model independent)



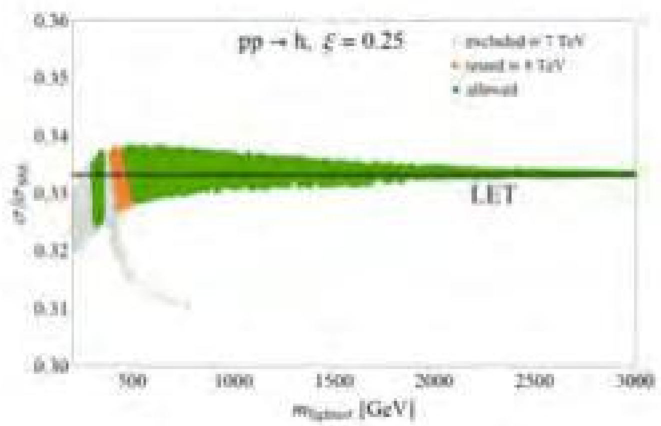
Single production (model dependent)

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

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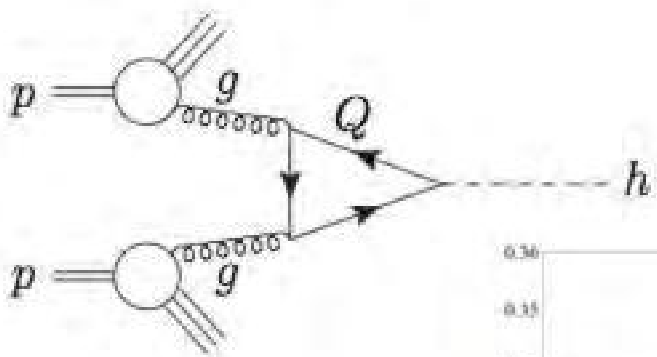

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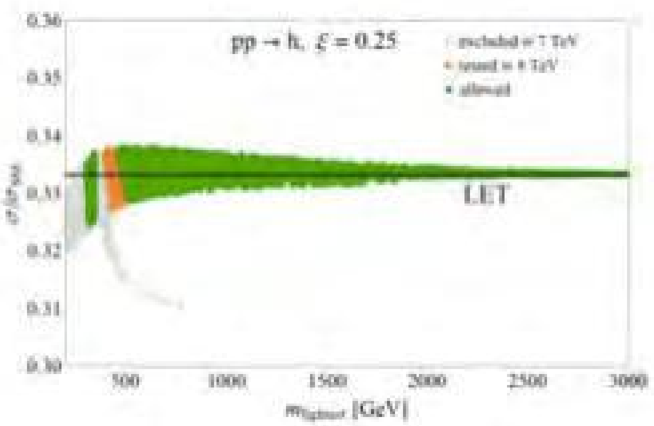

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- ☑ T's run in the loops
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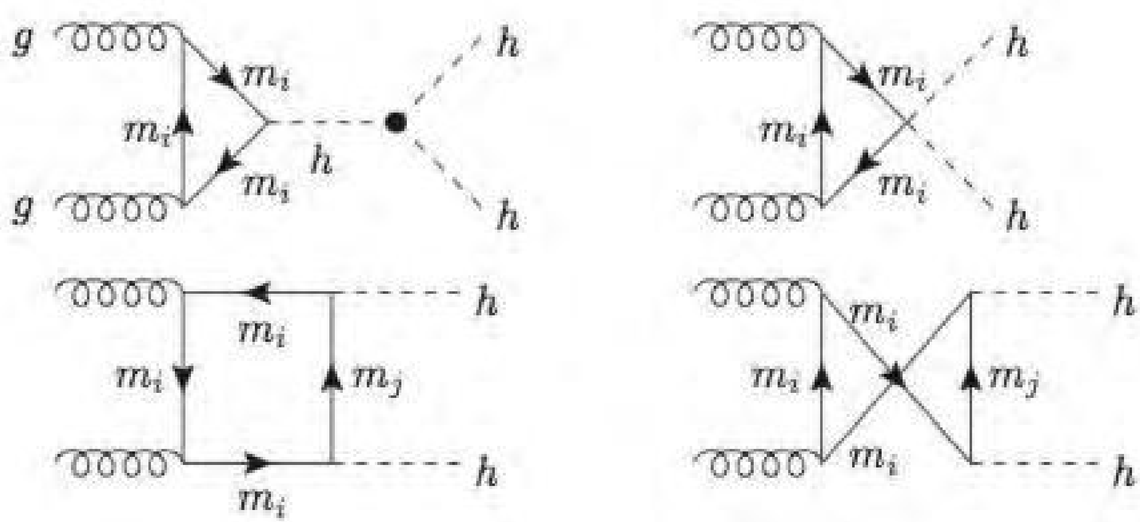
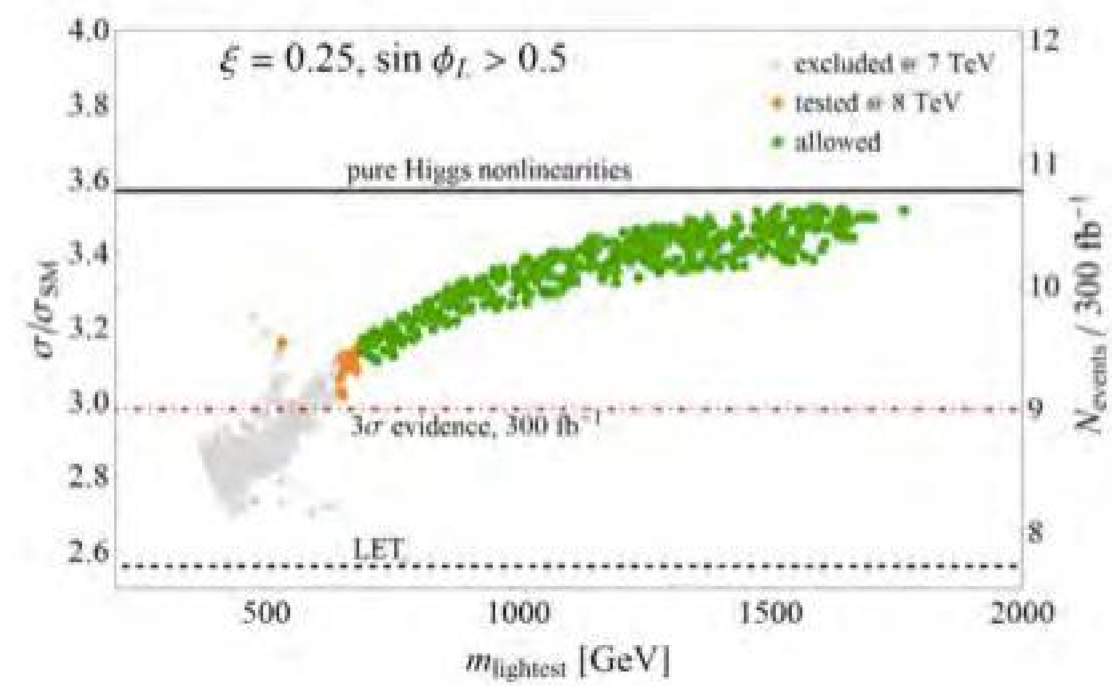
~ small sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



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



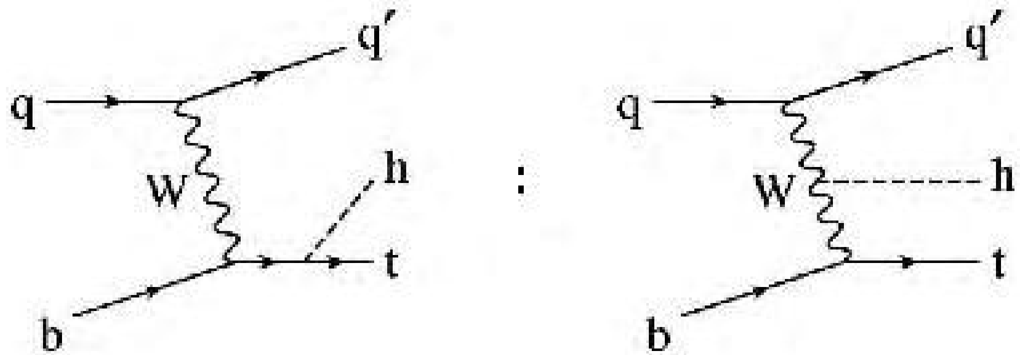
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q'th

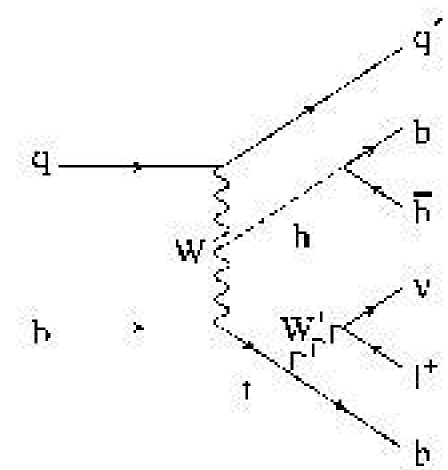


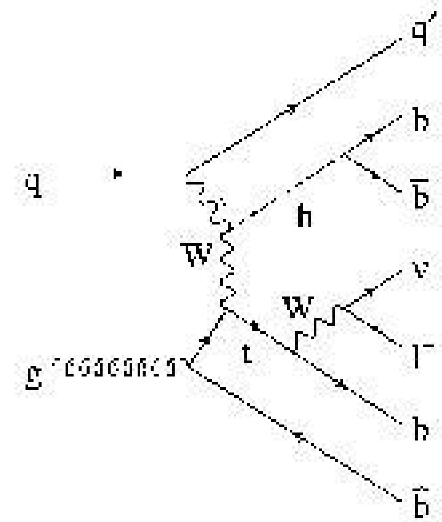
@m_H=125GeV $\quad \frac{\mathcal{A}_W - \mathcal{A}_t{}^2}{\mathcal{A}_W + \mathcal{A}_t{}^2} \approx 13$

Farina, Grojean, Maltoni, Salvioni, Thamm '12

look at final states:

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



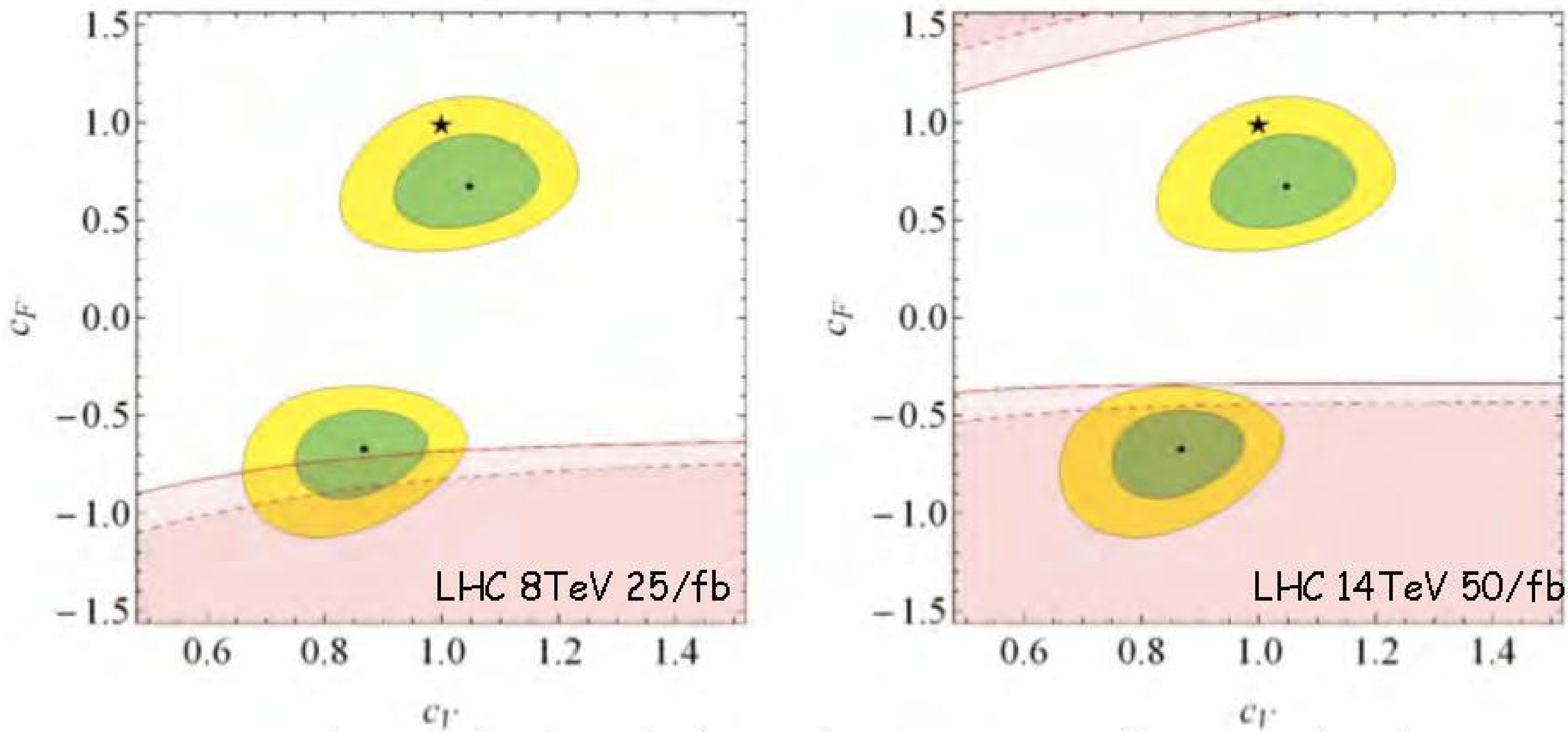


	$\sigma(pp \to tjh)$ [fb]		$\sigma(pp \to tjh\bar{b})$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.3	252.7	12.14	181.4
14 TeV	80.6	1042	59.6	828.5

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?

TIME

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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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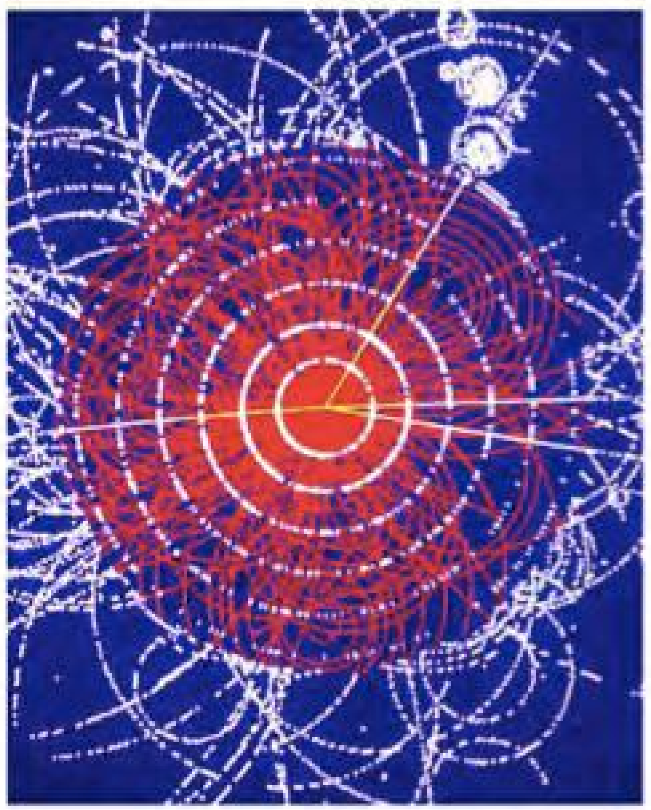
THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger Monday, Nov. 26, 2012



SPL/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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2. LIFE Behind the Picture: The Photo That Changed the Face of AIDS
3. Nativity-Scene Battles: Score One for the Atheists
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[slide stolen from A. David talk@LHCHXSWG CERN '12]

Conclusions: Higgs = Person of year?

as of 06/2012

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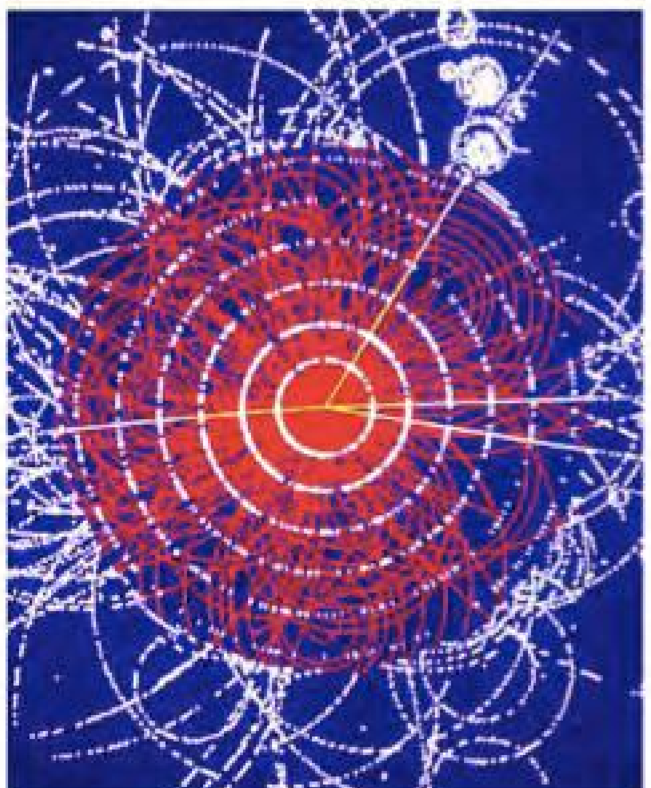

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WHO SHOU… YEAR 2012

The Candidates · Video · Poll Results

PAST PERS…

2011: The …

2009: Ben …

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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
Jon Stewart	924,111	58,864
Undocumented Immigrants	667,023	74,312
Aung San Suu Kyi and Thein Sein	563,922	53,253
Gabby Douglas	533,606	74,583
Stephen Colbert	526,534	66,301
Chris Christie	521,277	87,263
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
Bashar Assad	264,088	156,161
The Mars Rover	95,701	58,080
Psy	95,600	94,624
Barack Obama	84,161	96,045
Felix Baumgartner	72,224	78,747
The Higgs Boson Particle	68,927	54,589
Pussy Riot	53,194	77,026
Bill Clinton	45,108	80,799
Sandra Fluke	30,730	79,275
Michael Phelps	39,616	87,722
Mitt Romney	29,[illegible]	116,700
Joe Biden	27,61[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 year?

as of 06/2012

TIME
Person of the Year

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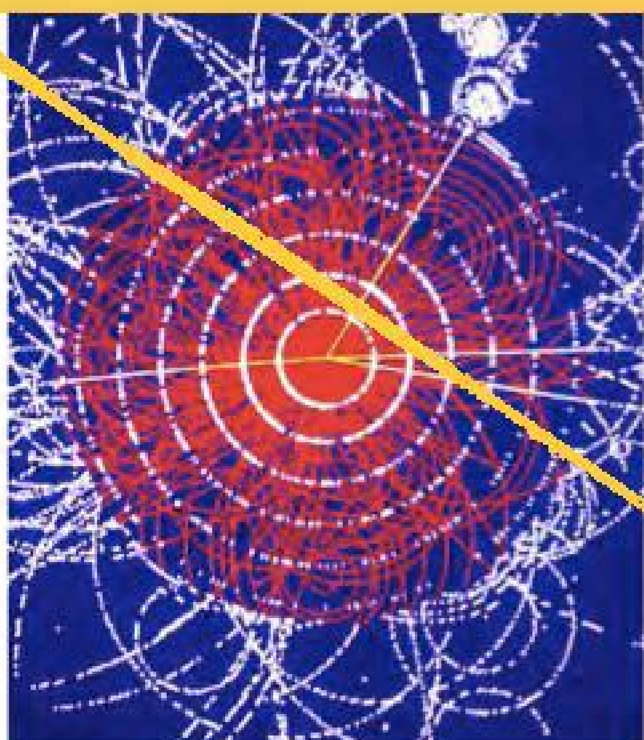

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VOTE

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.

2011: The

2009: Ben

Most Read

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4 The $7 Coffee

Name	Definitely	No Way
Kim Jong Un	4,295,657	129,581
	924,111	58,864
	667,023	74,312
	563,922	53,253
	533,606	74,583
	526,534	66,301
	521,277	87,263
	506,973	84,007
	480,147	72,596
	427,956	1,023,857
	397,952	93,874
	388,787	151,562
	297,535	46,968
	272,248	99,274
	264,088	156,161
	95,701	58,080
	95,600	94,624
Barack Obama	84,161	96,045
Felix Baumgartner	[illegible]	[illegible]
The Higgs Boson Particle	68,927	54,589
Pussy Riot	53,194	77,026
Bill Clinton	45,108	80,799
Sandra Fluke	[illegible]	79,275
Michael Phelps	39,616	87,722
Mitt Romn[illegible]	[illegible]	116,700
Joe Bi[illegible]	27,61[illegible]	96,187
J[illegible] 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

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

Conclusions: Higgs = Person of year?

as of 06/2012

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