Single top & New Physics

CMS single top workshop
Naples, December 19-20, 2013

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*iCrea
INSTITUCIÓ CATALANA DE
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Why single top & new physics

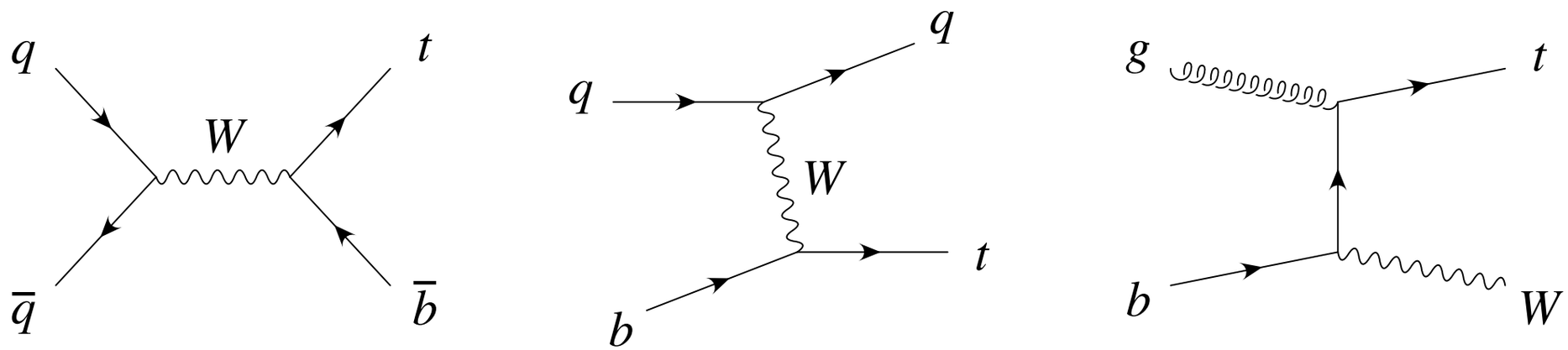
Top = heaviest particle

⇓ ⇓

strongest coupling to Higgs/EWSB

⇓

studying its EW production
will teach us about EW symmetry breaking sector



σ(pb)	s-channel	t-channel	Wt
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$0.90 \pm 5\%$	$2.1 \pm 5\%$	$0.1 \pm 10\%$
LHC ($\sqrt{s} = 14$ TeV pp)	$10.6 \pm 5\%$	$250 \pm 5\%$	$75 \pm 10\%$

x10/100

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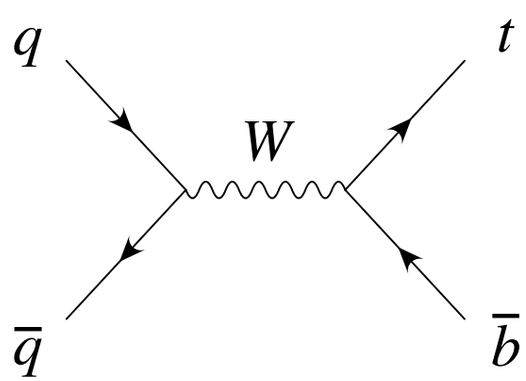

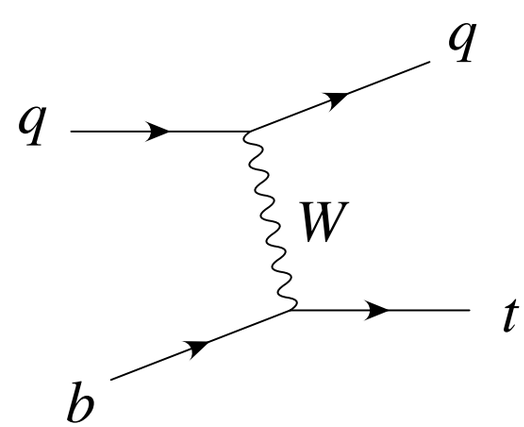

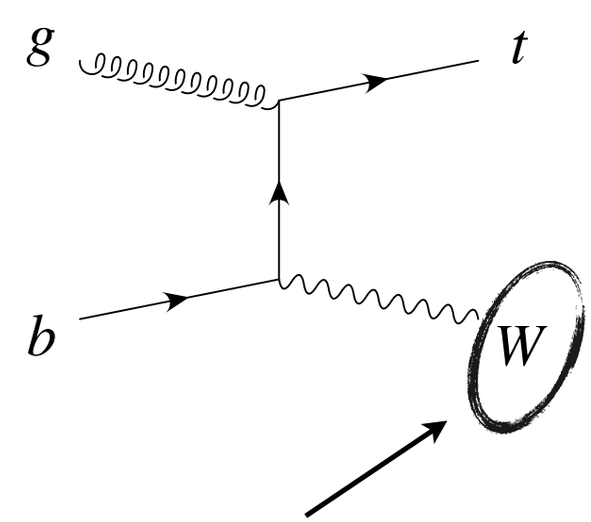

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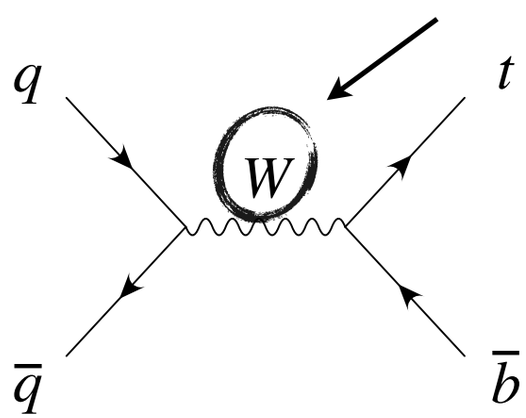
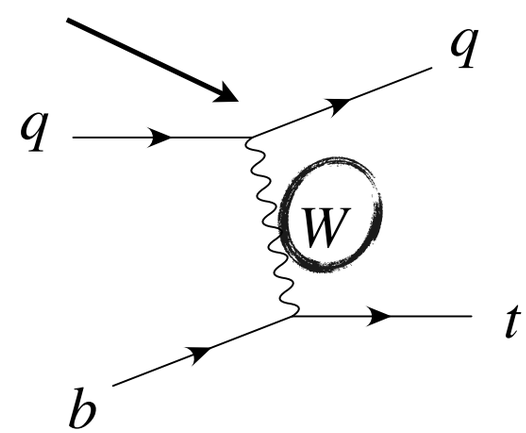
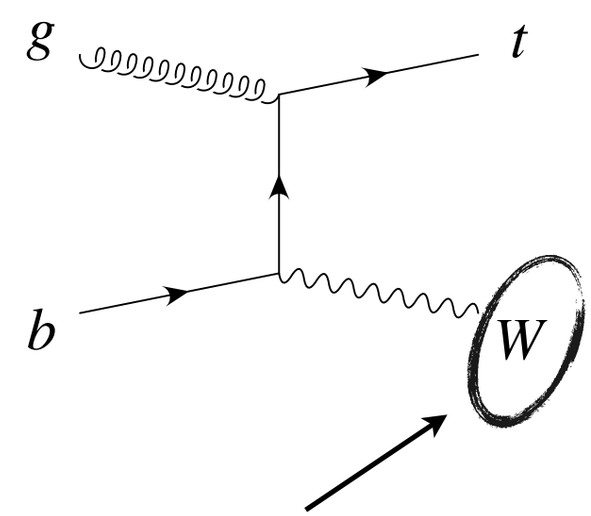
sensitive to W'







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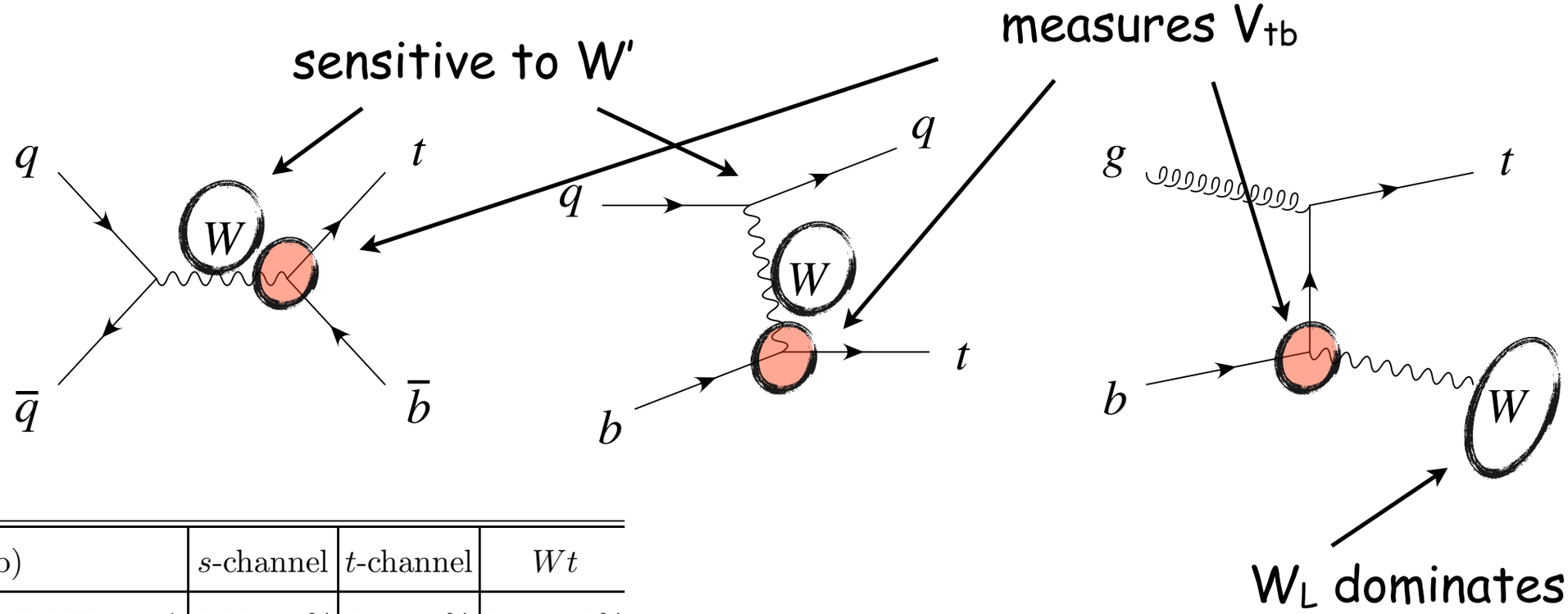

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x10/100

⇒ probe top/EWSB interactions

Higgs&top: a so important couple

1. The top Yukawa coupling is fueling several fundamental issues of the SM

- it destabilizes the weak scale, aka the hierarchy problem (m_H^2 corrections)
- it destabilizes our vacuum (λ corrections)
- it controls the birth ($gg \to h$) and the death ($h \to \gamma\gamma$) of the Higgs

2. We have only an indirect knowledge of this important coupling

- tth is the mainstream channel to directly see the top Yukawa
- th is an interesting challenger and offers complementarity information

3. The top-Higgs offsprings

- stops in susy
- fermionic top partners in Little Higgs/composite Higgs: t' $t^{5/3}$ ...

Outline

1. Top & Higgs sector
   - Degeneracy in Higgs couplings determination
   - t+h as an alternative to tth?

2. Top partners and vector-like top
   - composite Higgs models

Disclaimer:
not a comprehensive talk on single-top & new physics

1

Top & Higgs sector

Now what? What's next?

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" With great power comes great responsibility"

Voltaire & Spider-Man

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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!)

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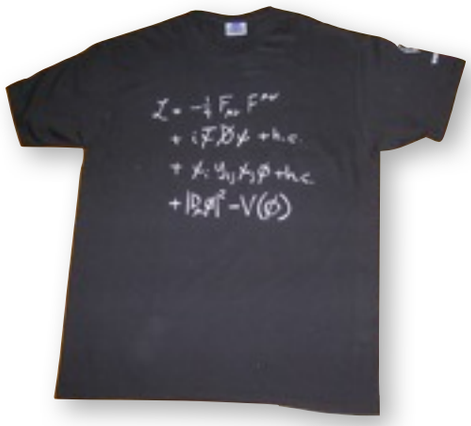
Higgs properties

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

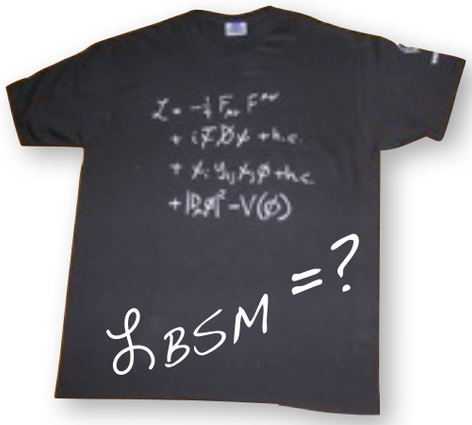
2

Higgs couplings



3

BSM implications



Higgs couplings = test of Naturalness?

$$\delta m_H^2 = -(125\ \mathrm{GeV})^2 \left(\frac{\Lambda}{600\ \mathrm{GeV}}\right)^2$$

$$+ \quad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$$\sim m_H^2$$

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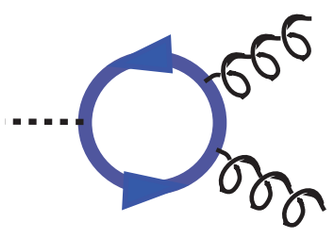
generically



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2 \qquad \frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

$$BR(h\to ii) = BR_{\text{SM}}$$

$$\Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

nice to be able to measure Γ

Generically, natural scenarios come with deviations of the Higgs coupling

Chiral Lagrangian for a light Higgs-like scalar

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

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

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

$O(p^2)$

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

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

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

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

$O(p^4)$

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

Contino, Grojean, Moretti, Piccinini, Rattazzi '10 + many others refs.

SM

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

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

A few (reasonable) assumptions:

- ☑ spin-0 & CP-even
  - $\gamma\gamma$
  - WW & ZZ
- ☑ custodial symmetry
  - EWPD
- ☑ no Higgs FCNC
  (generalization of Glashow-Weinberg th.)
  - Flavor

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

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

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

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

$$+ O(p^6)$$

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 $gg \to h$ and $h \to \gamma\gamma$)

$O(p^2)$

$O(p^4)$

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
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  - ↖ Flavor

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Higgs coupling fits

Espinosa, Grojean, Muhlleitner, Trott '12

Atlas 95%CL exclusion

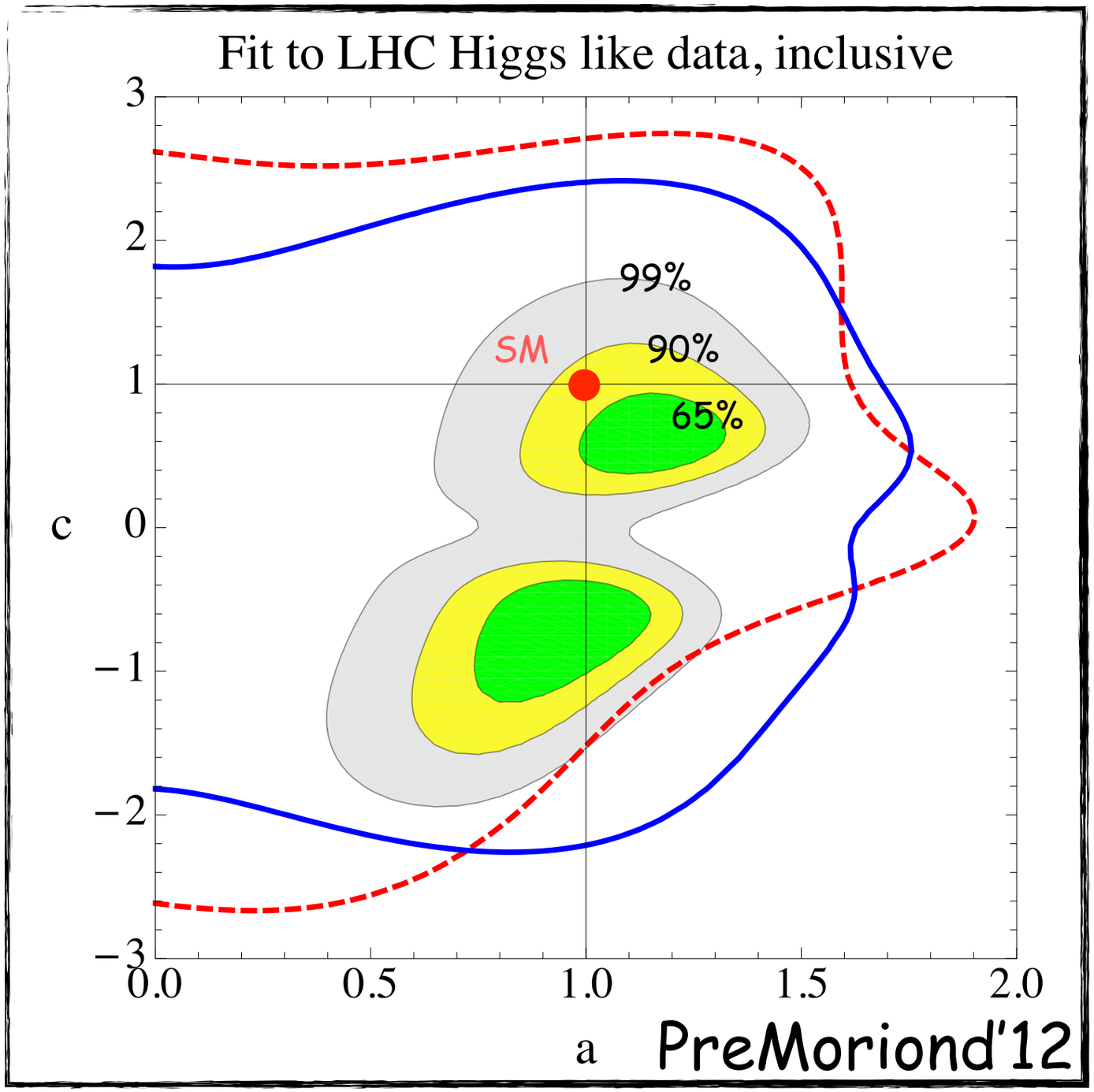
CMS 95%CL exclusion

SM 82%CL away from best fit point

Two minima:

(a,c)=(1.13,0.58)
χ^2=2.86

(a,c)=(0.96,-0.64)
χ^2=1.96



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

for similar analyses, see also

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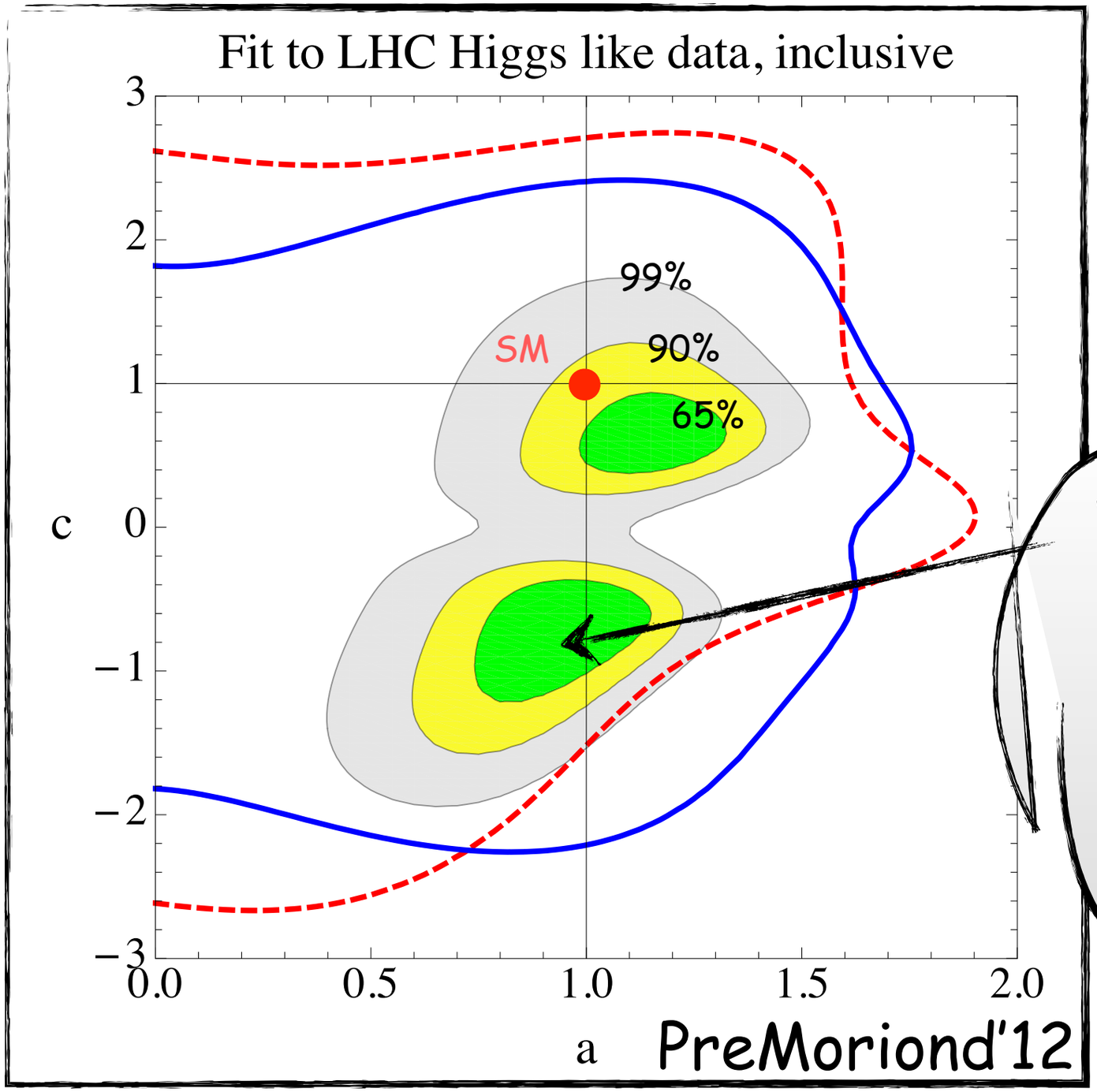

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"disfermiophilia"

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

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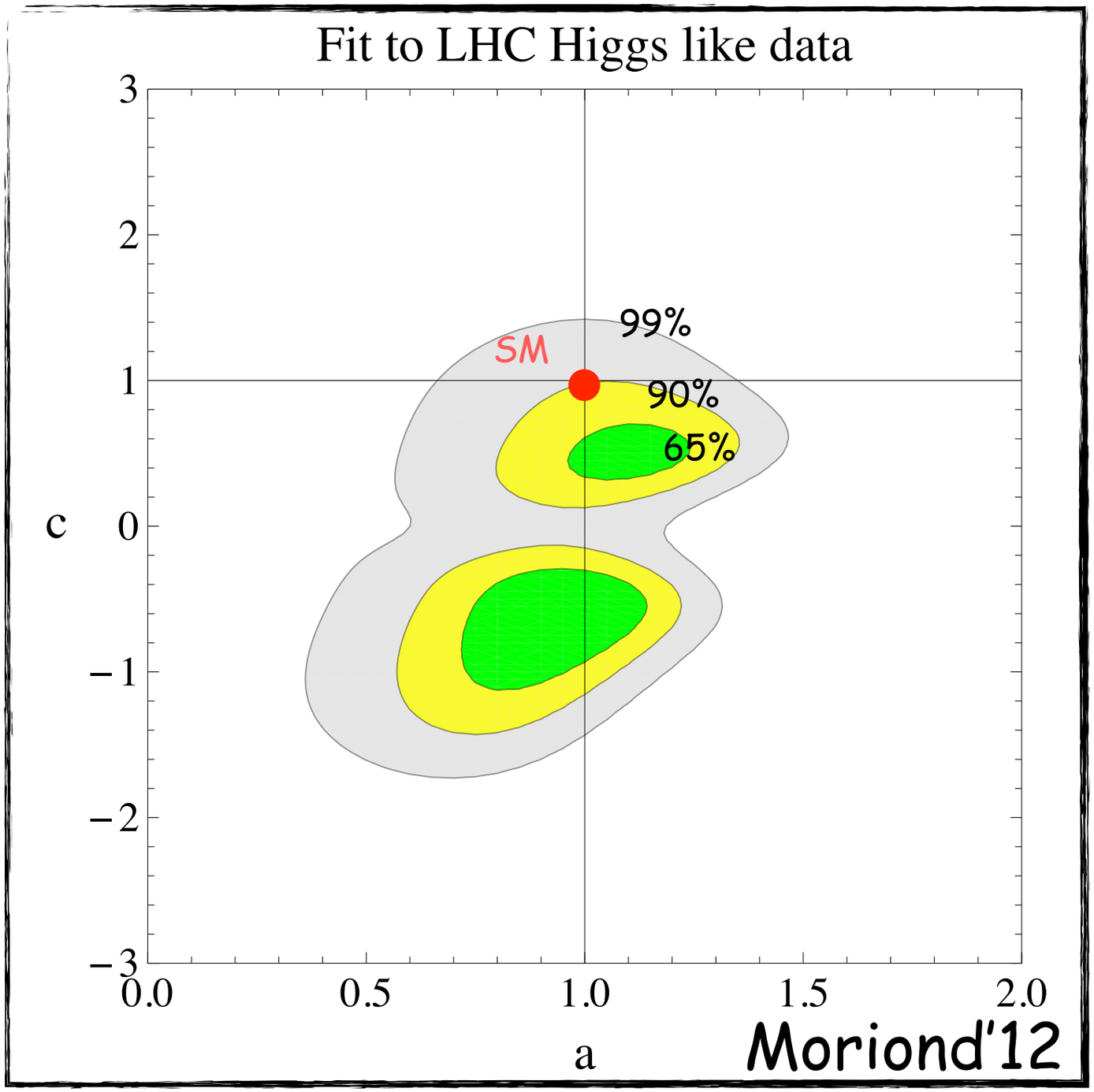

note: a fermiophobic Higgs is disfavored by data (mostly VBF channels) at 97%CL

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

Two minima:

(a,c)=(1.18,0.55)
χ^2=7.5

(a,c)=(0.99,-0.64)
χ^2=6.3

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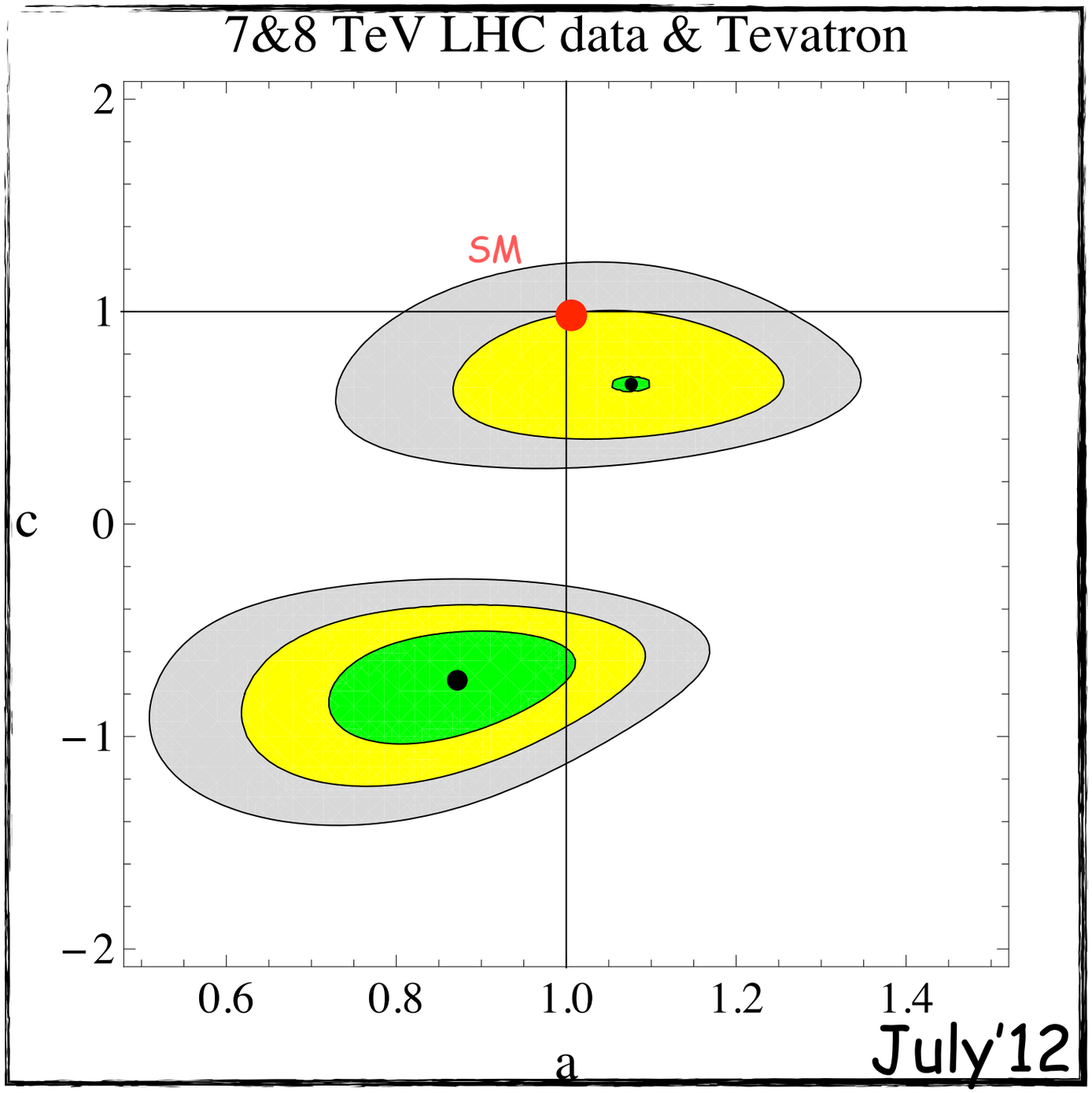

SM 93%CL away from best fit point (~1.8σ)

Two minima:

(a,c)=(0.86,-0.64)
χ^2=41

(a,c)=(1.05,0.63)
χ^2=41.4

note: a fermiophobic Higgs is disfavored by data (mostly VBF channels) at 99.99%CL ie 4σ

Warning

need to rescale independently 7 & 8 data sets

(on July 4th, only 7 and 7+8 combination were available)

for similar analyses, see also

Giardino, Kannike, Raidal, Strumia '12
Carni, Falkowski, Kuflik, Volansky, Zupan '12
Corbet, Eboli, Gonzalez-Fraile, Gonzalez-Garcia '12
Ellis, You '12 Montull, Riva '12

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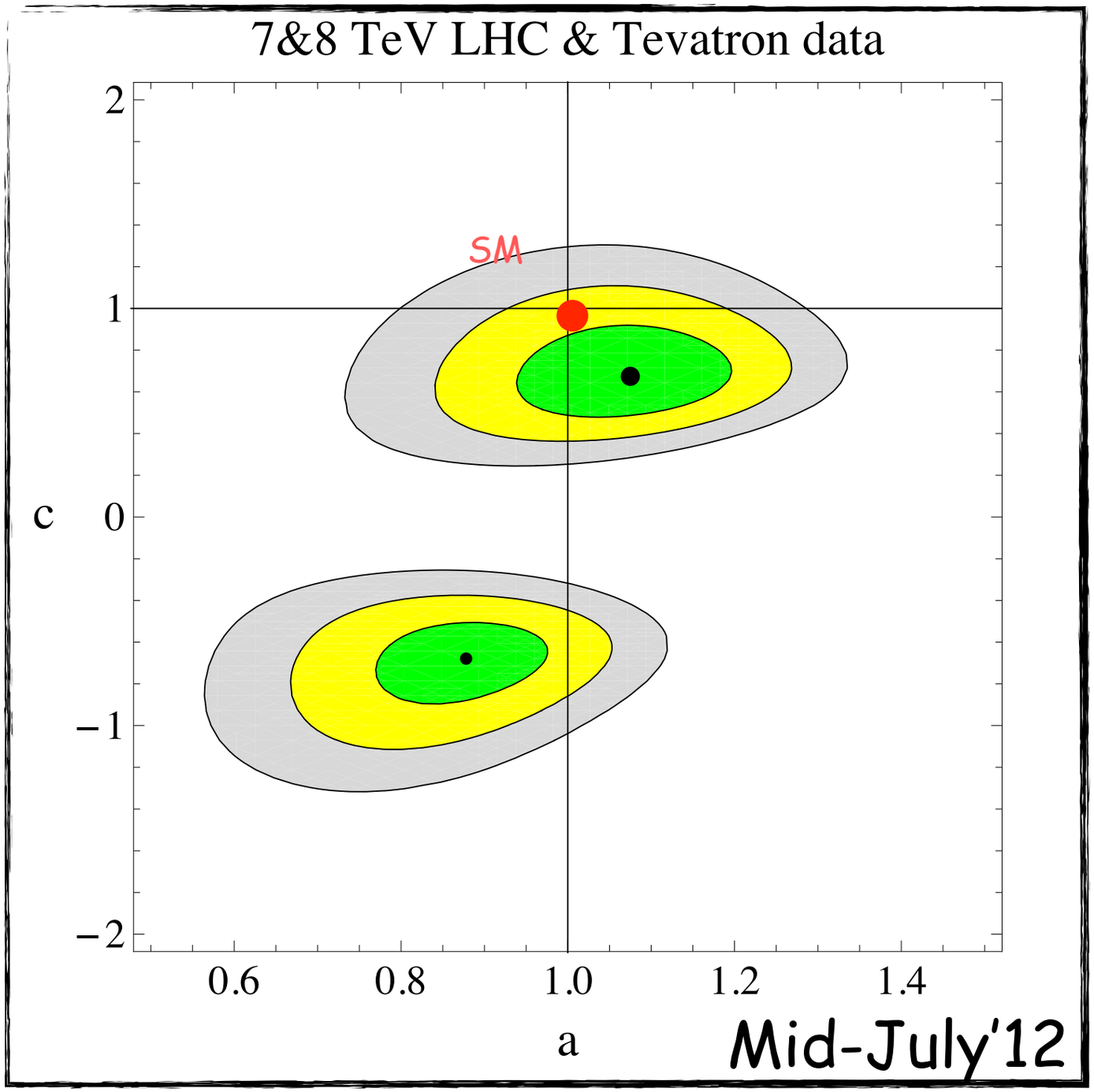

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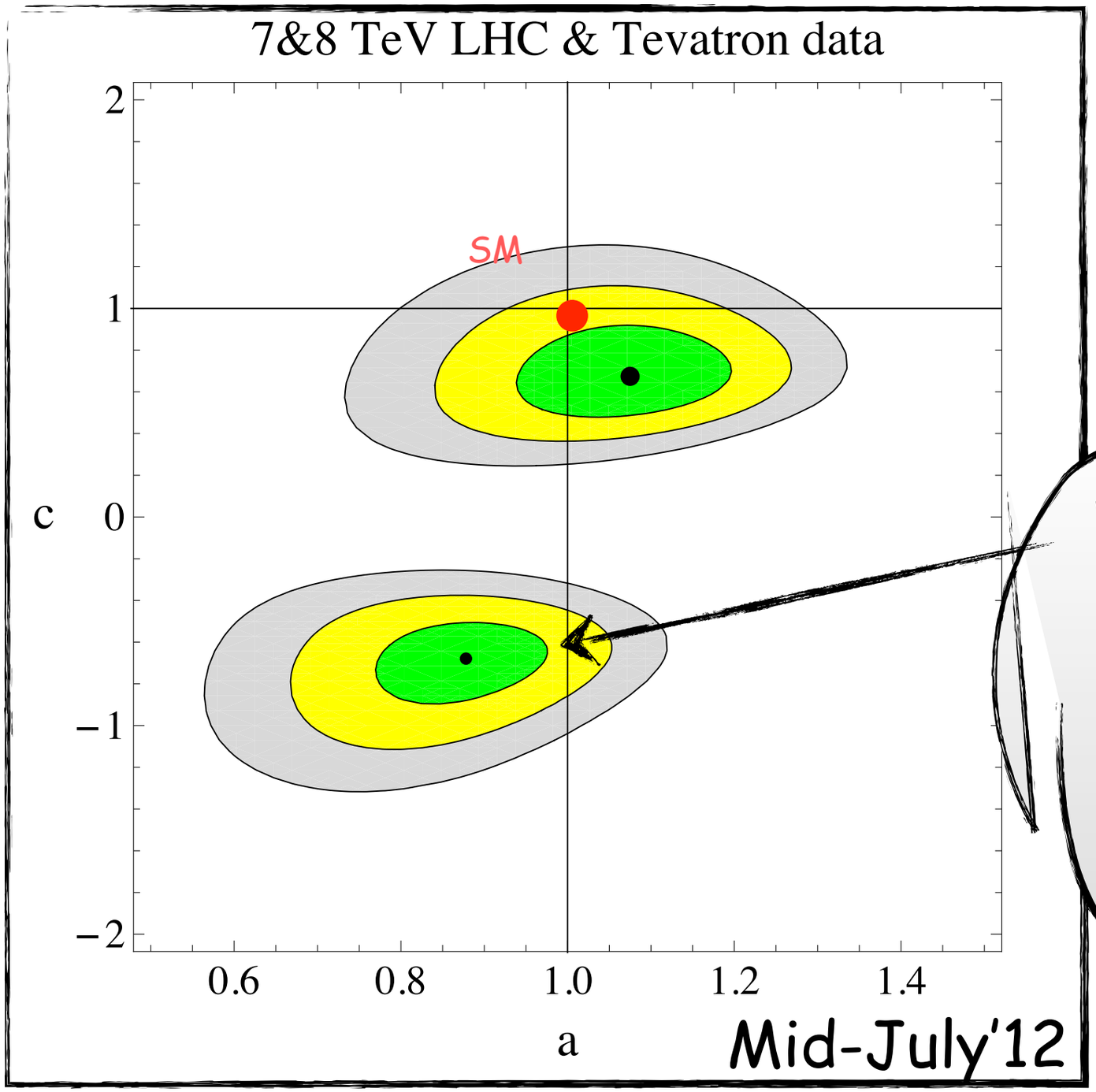

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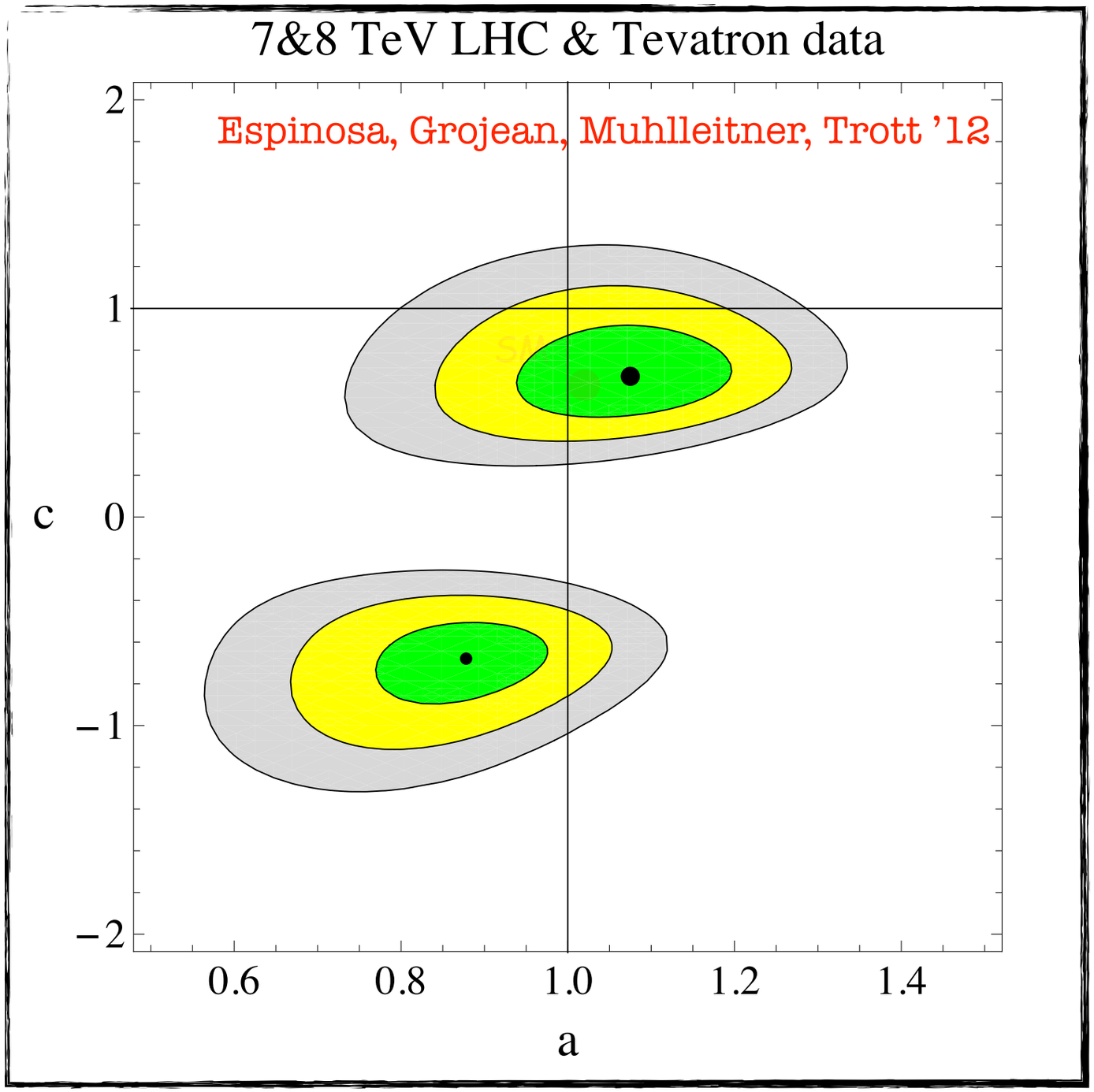

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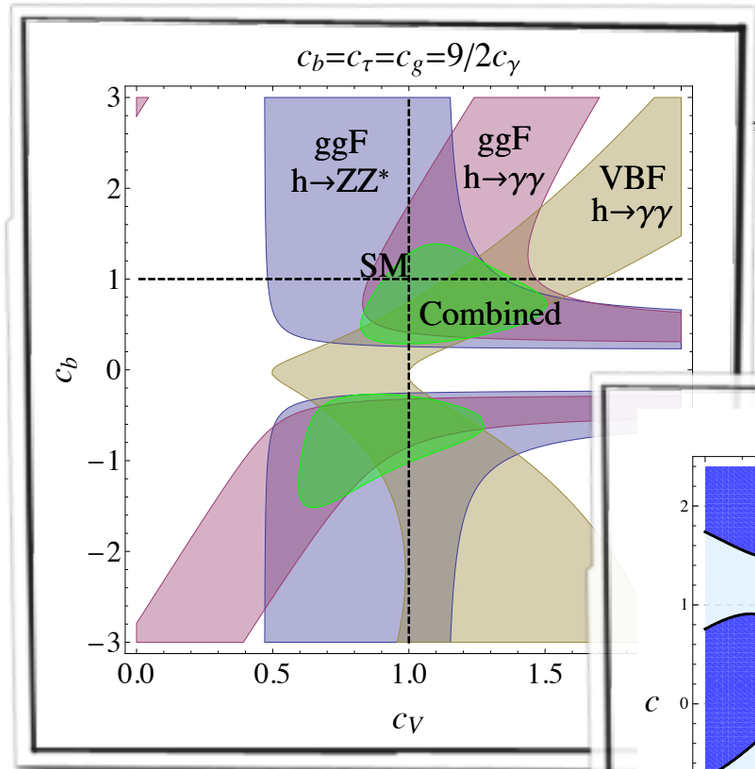
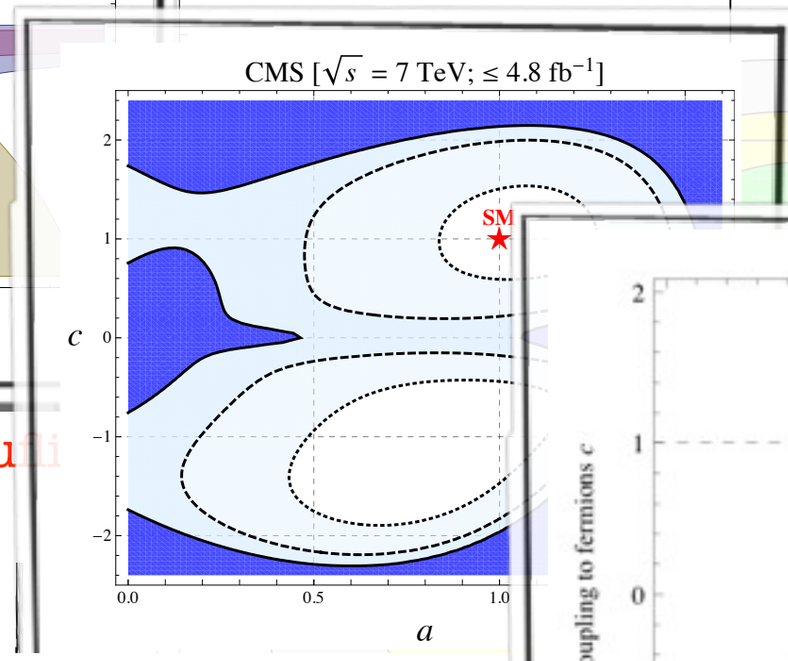


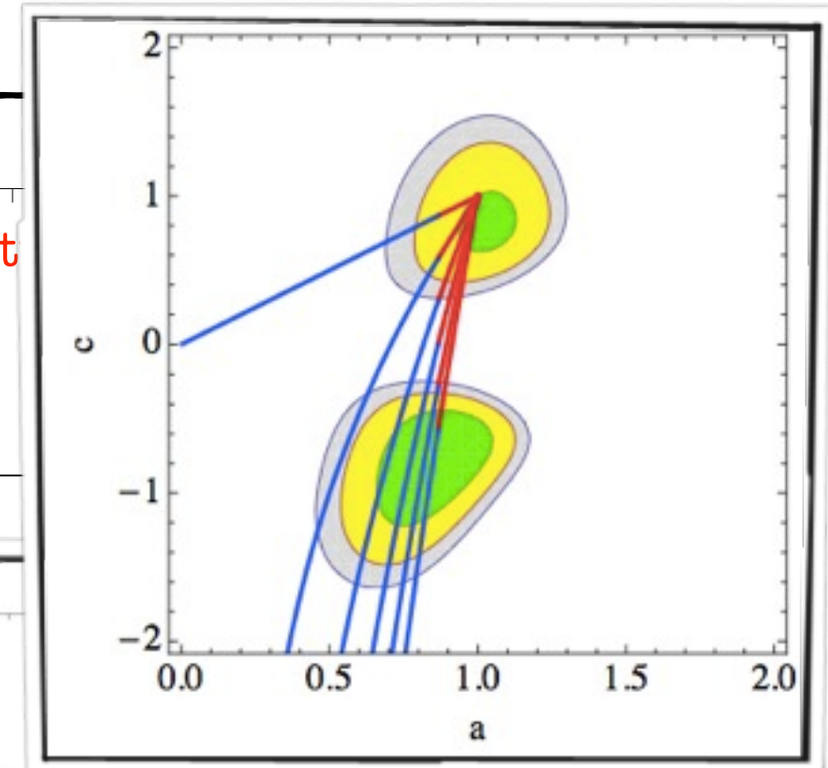
Carni, Falkowski, Ku
Volansky '12

7&8 TeV LHC & Tevatron data

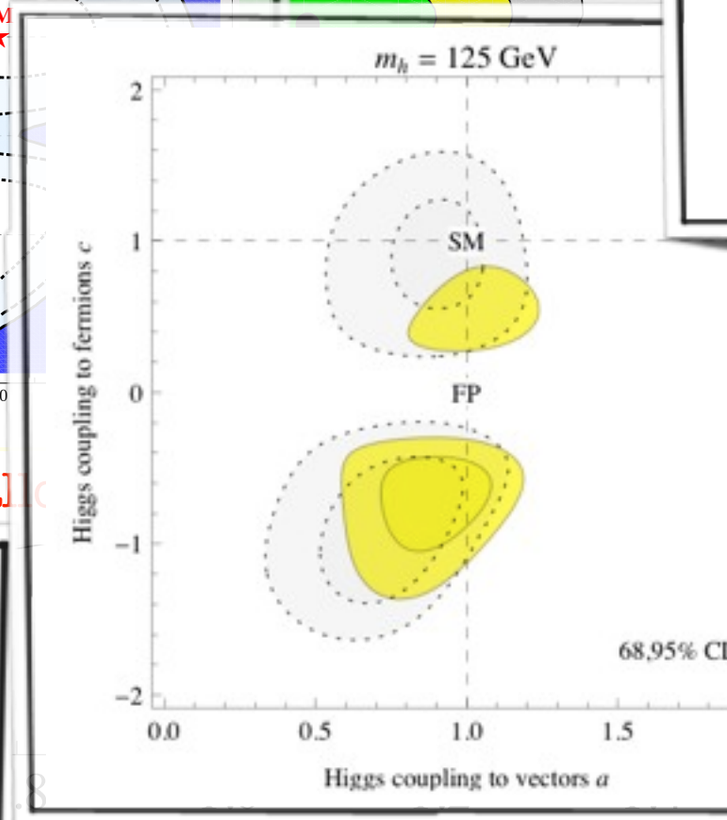
Espinosa, Grojean, Muhlleitner, Trot



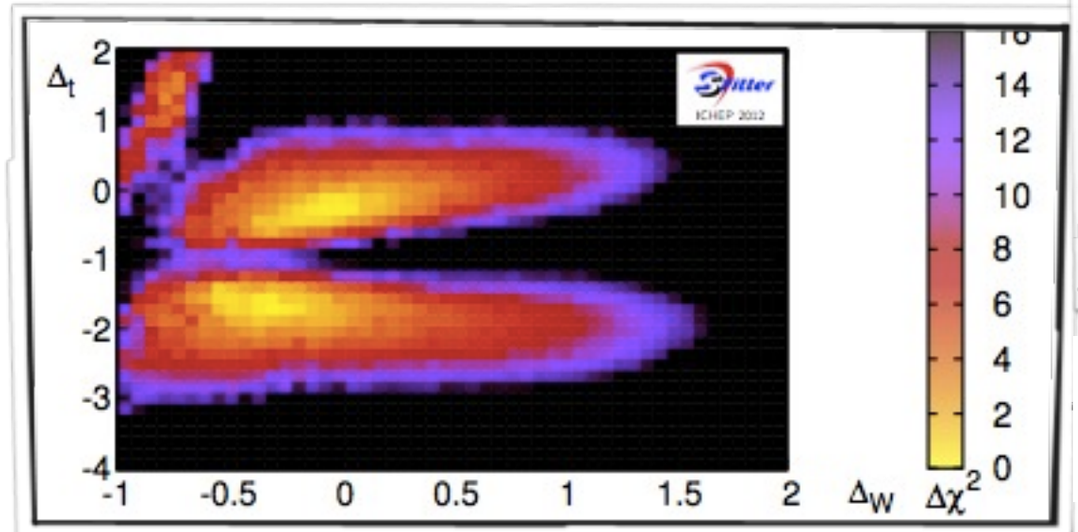
Azatov, Contino, Gal



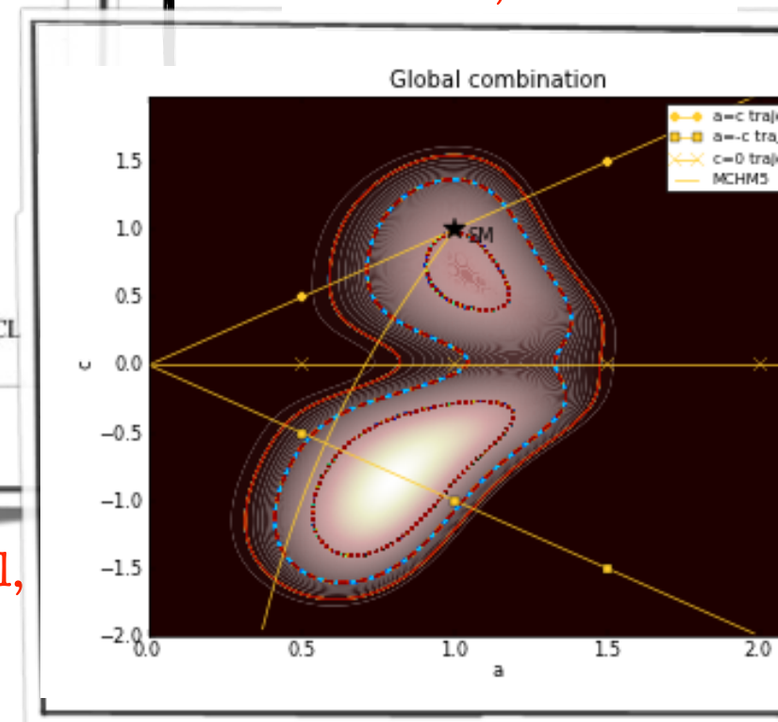
Montull, Riva '12



Giardino, Kannike, Raidal,
Strumia '12



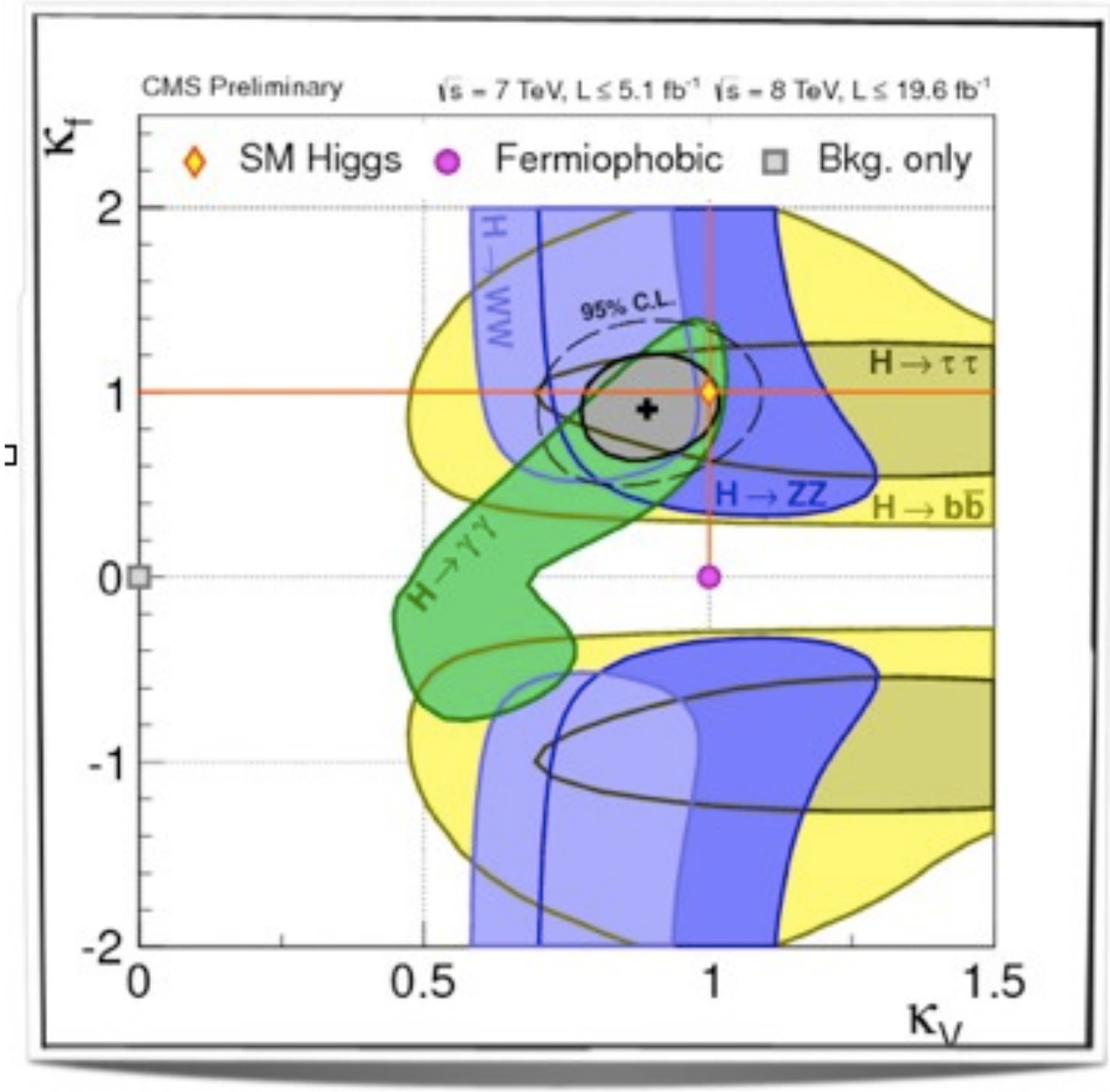
Plehn, Rauch '12



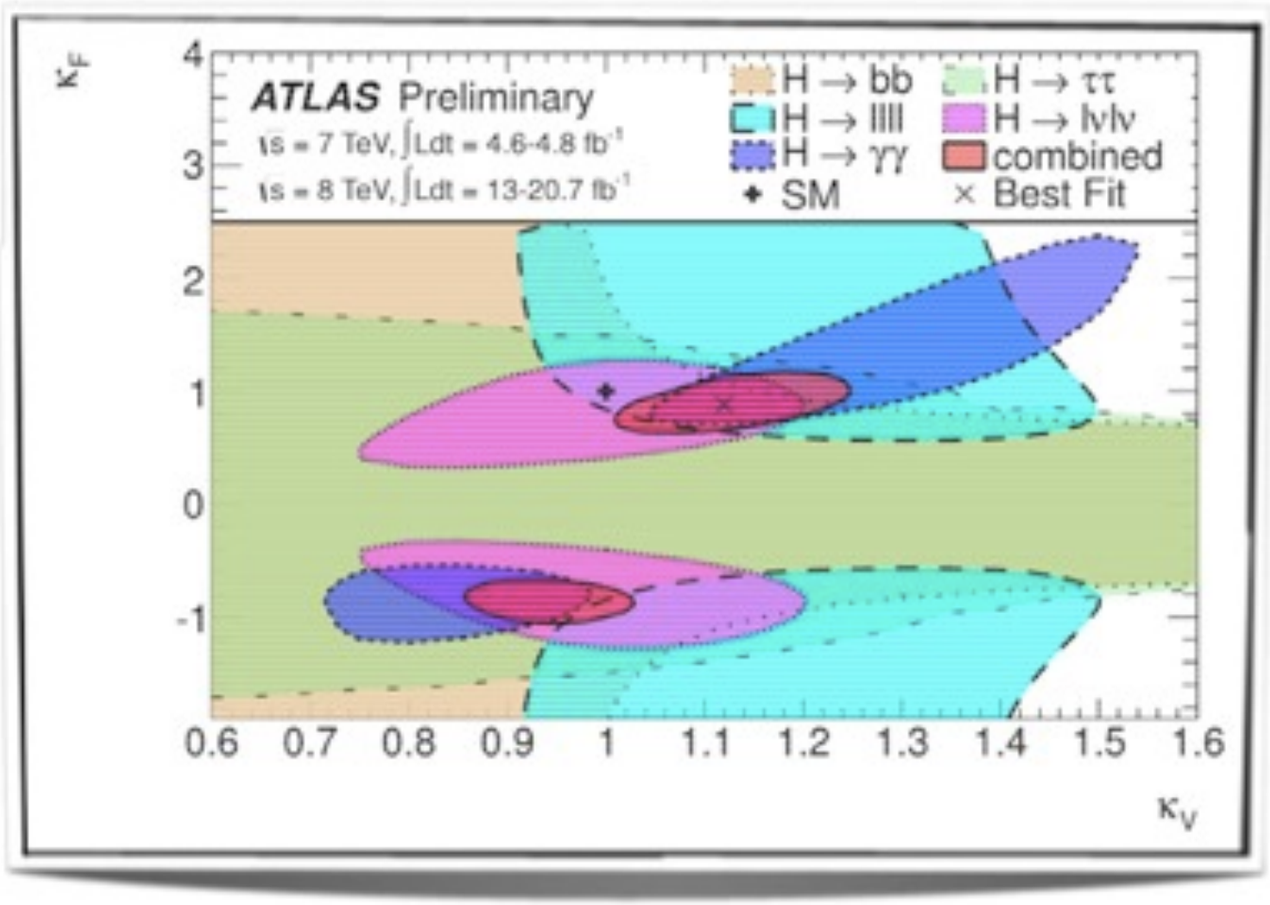
Ellis, You '12

Higgs coupling fits

don't leave it in the hands of theorists!



CMS



ATLAS

Two local minima

- Defining

$$\mu = \frac{\sigma \times \mathrm{BR}}{[\sigma \times \mathrm{BR}]_{\mathrm{SM}}}$$

then for the inclusive, VBF and associated production one has

$$\mu_{\mathrm{incl}} \sim (1.26 c_V - 0.26 c_F)^2 \,, \qquad \mu_{\mathrm{VBF}} \sim \mu_{\mathrm{ass\,prod}} \sim c_V^2 \frac{(1.26 c_V - 0.26 c_F)^2}{c_F^2}$$

Recall

W loop

top loop

$$\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\mathrm{SM}} \simeq (1.26 c_V - 0.26 c_F)^2$$

- Looking only at $\gamma\gamma$, if a 'true' signal (c_V^t, c_F^t) is assumed, then in addition to $(c_V, c_F) = (c_V^t, c_F^t)$ there is **another point giving the same event yields**:

$$c_V = c_V^t \left| \frac{1.26 c_V^t - 0.26 c_F^t}{1.26 c_V^t + 0.26 c_F^t} \right| \,, \qquad c_F = -c_F^t \left| \frac{1.26 c_V^t - 0.26 c_F^t}{1.26 c_V^t + 0.26 c_F^t} \right|$$

Injecting the SM as true signal, one gets $(c_V, c_F) = (0.66, -0.66)$

- Including all other channels and real data, obtain the plots shown before.

slide stolen from E. Salvioni

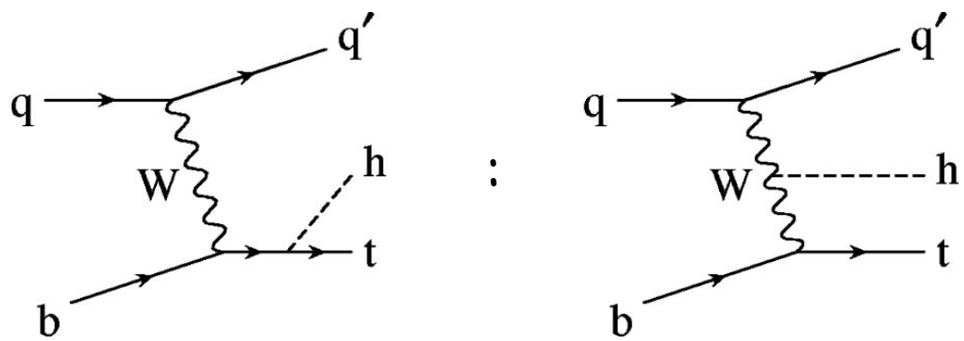
Breaking the degeneracy

direct measurement of top-higgs coupling

- indirect: combination of various channels (indirect)
- direct: tth, still challenging and won't be sensitive to the sign of the coupling

new process with large interference

qb→q'th

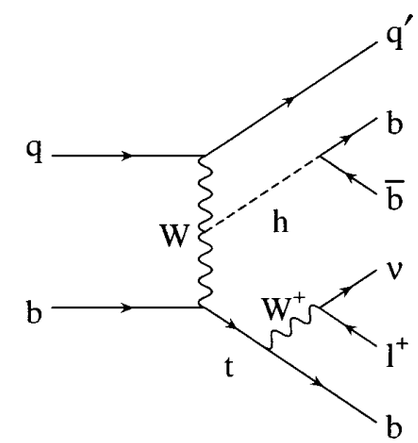


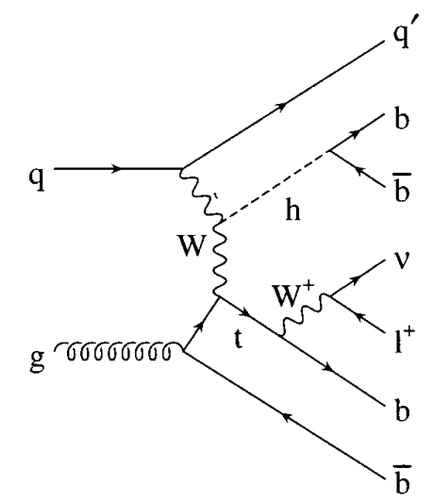
@m_H=125GeV $\quad \frac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$ (enhancement of ~2 only for h →$\gamma\gamma$)

Farina, Grojean, Maltoni, Salvioni, Thamm '12

look at final states:

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





	$\sigma^{\rm LO}(pp \to thj)$ [fb]		$\sigma^{\rm LO}(pp \to thjb)$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.4	252.7	5.4	79.2
14 TeV	80.4	1042	26.9	363.5

	$\sigma^{\rm NLO}(pp \to thj)$ [fb]	
	$c_F = 1$	$c_F = -1$
8 TeV	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.}$
14 TeV	$88.2^{+1.7}_{-0.}$	982^{+28}_{-0}

$p_T^b > 25$ GeV and $|\eta^b| < 2.5$

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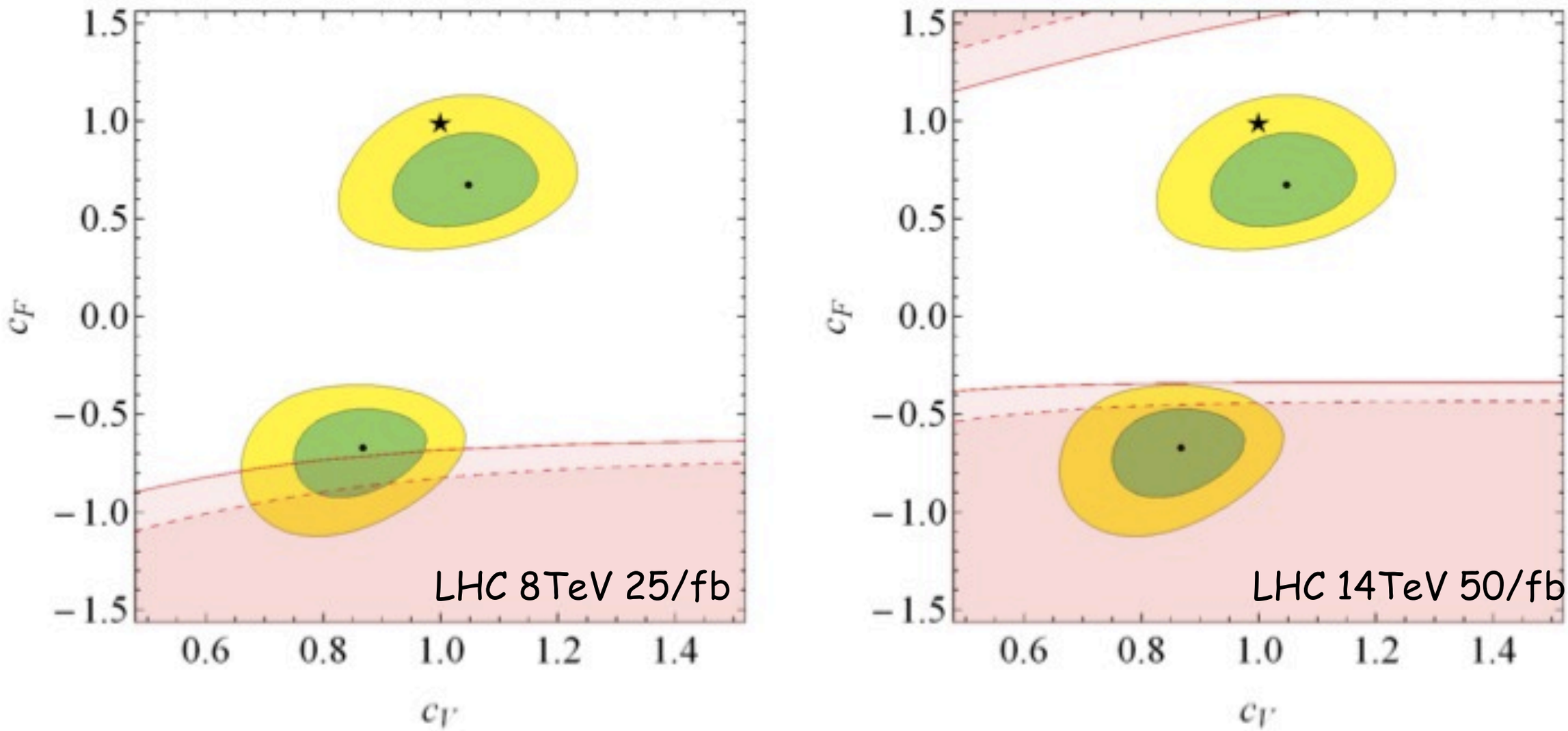

68% and 95% CL exclusion region vs current Higgs coupling fit

Farina, Grojean, Maltoni, Salvioni, Thamm '12

Short vs long distance contributions to gg→h

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate
doesn't "see" the finite mass of the top

(*) unless it doesn't decouple
(e.g. 4th generation)

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⇒ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

⇐

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\mathrm{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\mathrm{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

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but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

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t+h is another channel that could directly probe the top Yukawa coupling

Constraining all possible SM deformations

59 deformations of the SM by dim-6 operators

11 *tree-level* operators

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
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8 *loop-level* dipole operators

$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}_{DB}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W_{\mu\nu}^a$	$\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W_{\mu\nu}^a$	$\mathcal{O}_{DW}^e = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W_{\mu\nu}^a$
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SM: 942 fb (MCFM)

+ 25 *tree-level* four-fermion operators

+ 8 bosonic operators

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constrained by LEP for light generations
not the 3rd generation!

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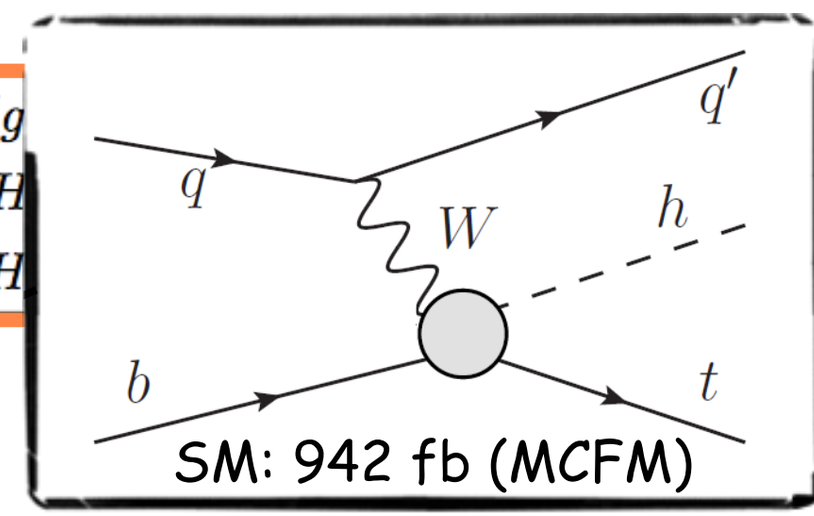

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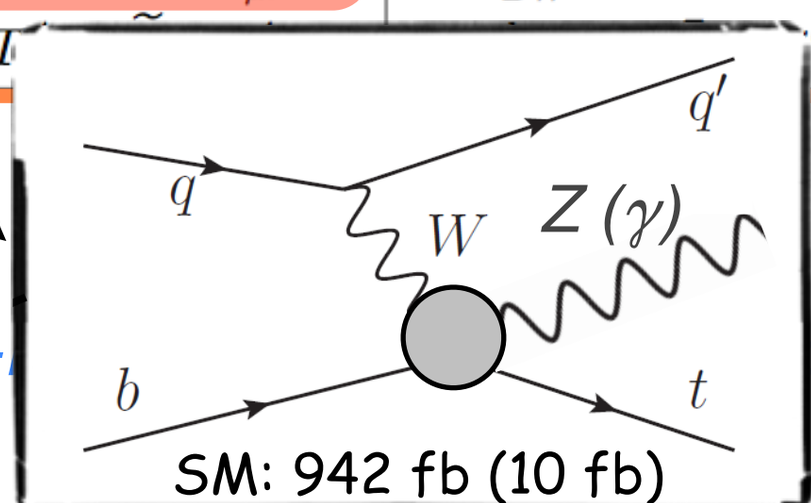

SM: 942 fb (10 fb)

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+ 8 bosonic operators

1

Top partners

Fermionic Resonances for a Composite Higgs

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

- Custodial symmetry: exotic top partners

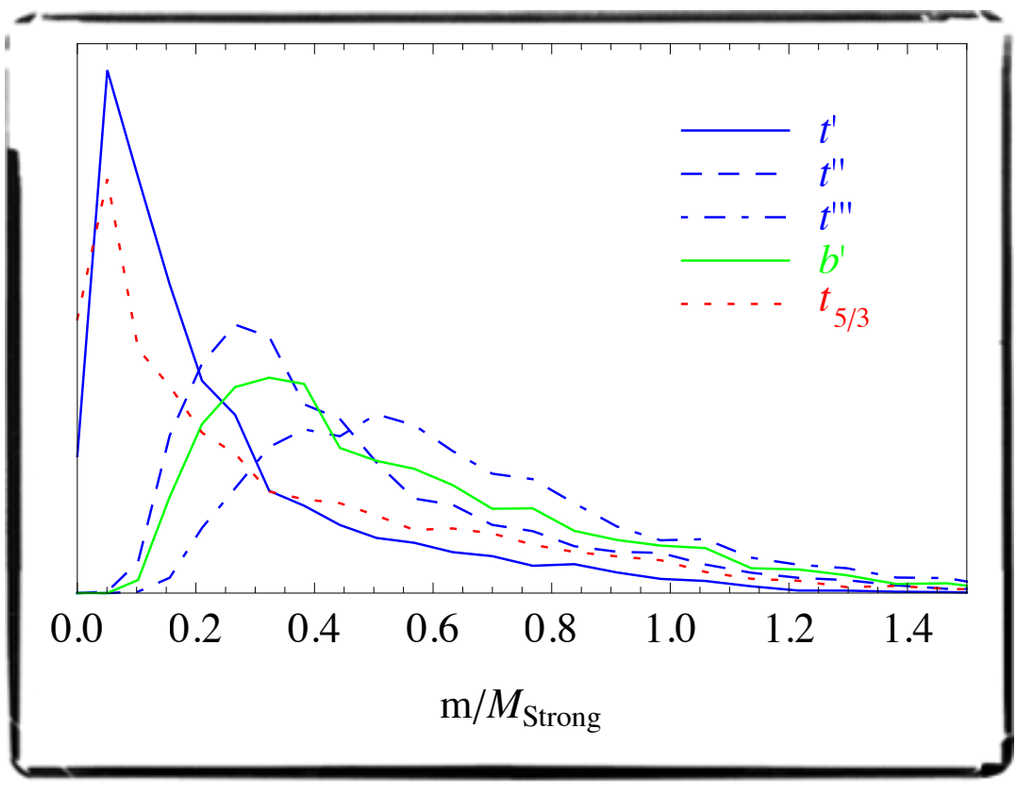
$SU(2)_L \times SU(2)_R$ embedding

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

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

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

⇨ $\delta_{Zb_L\bar{b}_L}=0$



Panico, Wulzer '11

partial compositness

⇓ ⇓

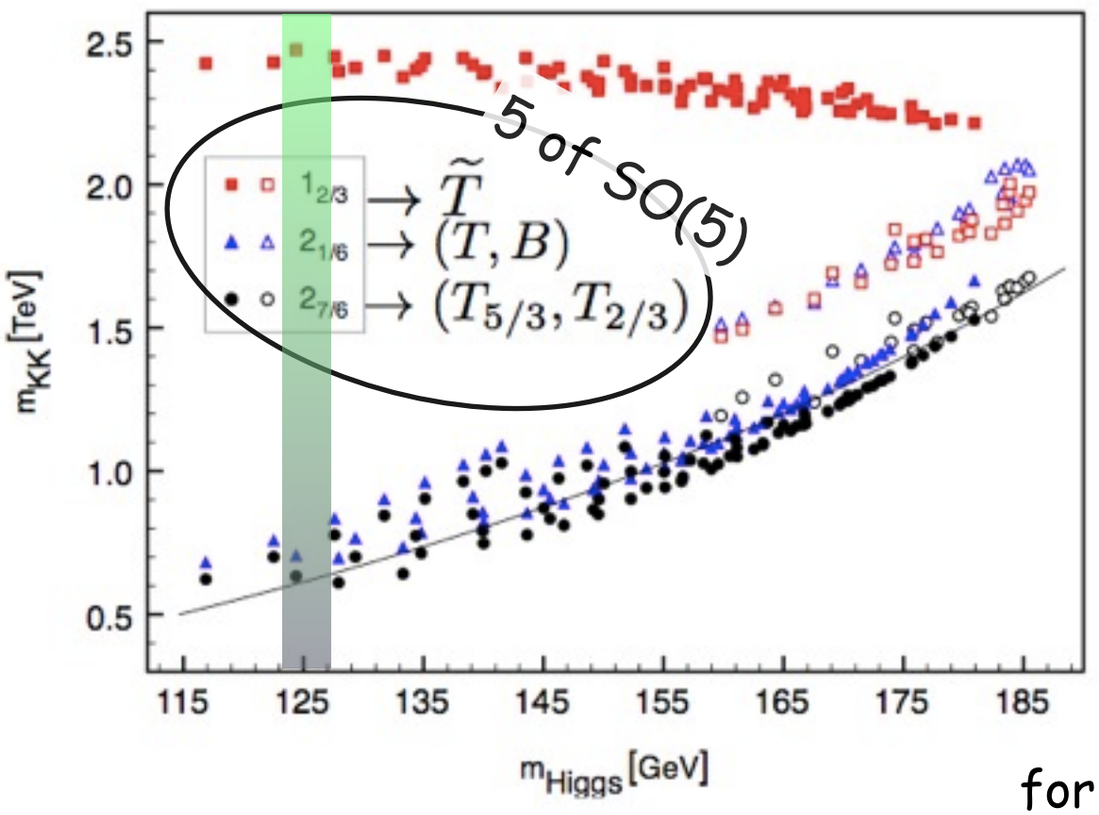
the heavier the SM quark,
the lighter its resonances and partners

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

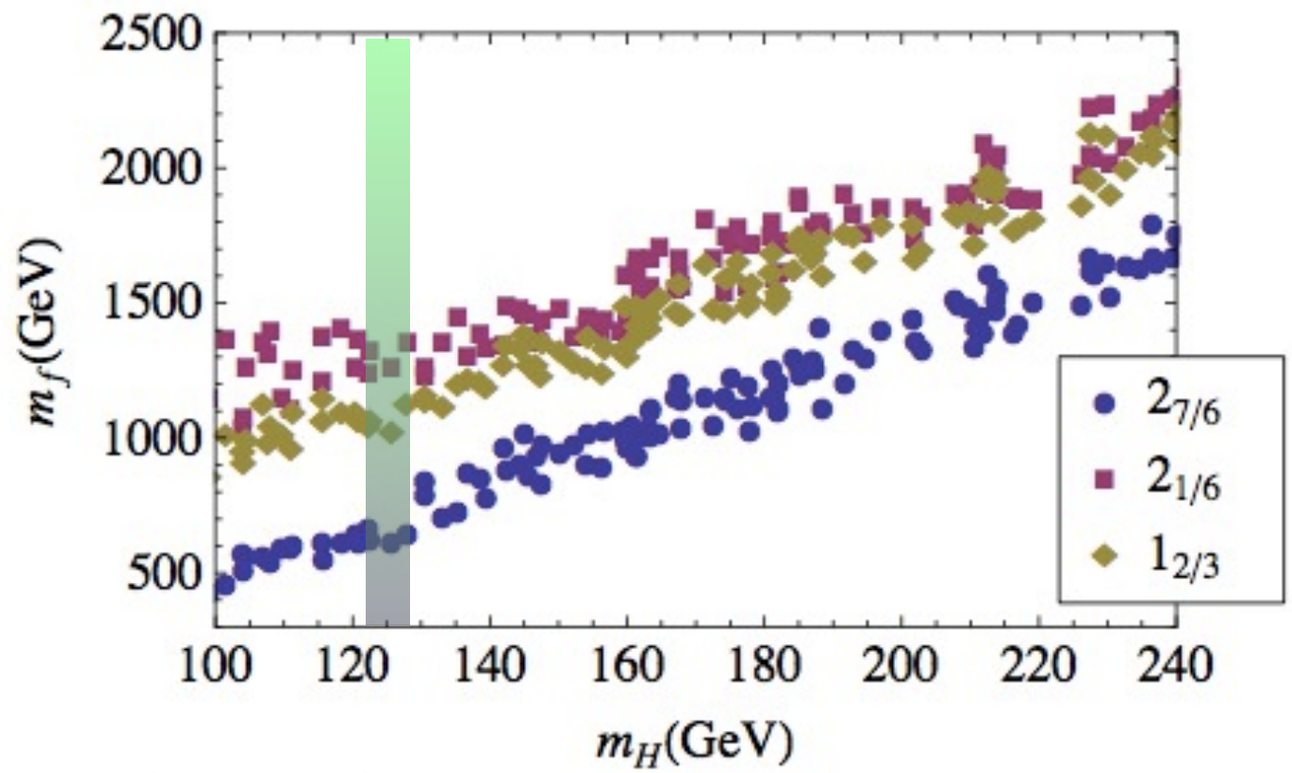
Light composite Higgs from "light" resonances

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

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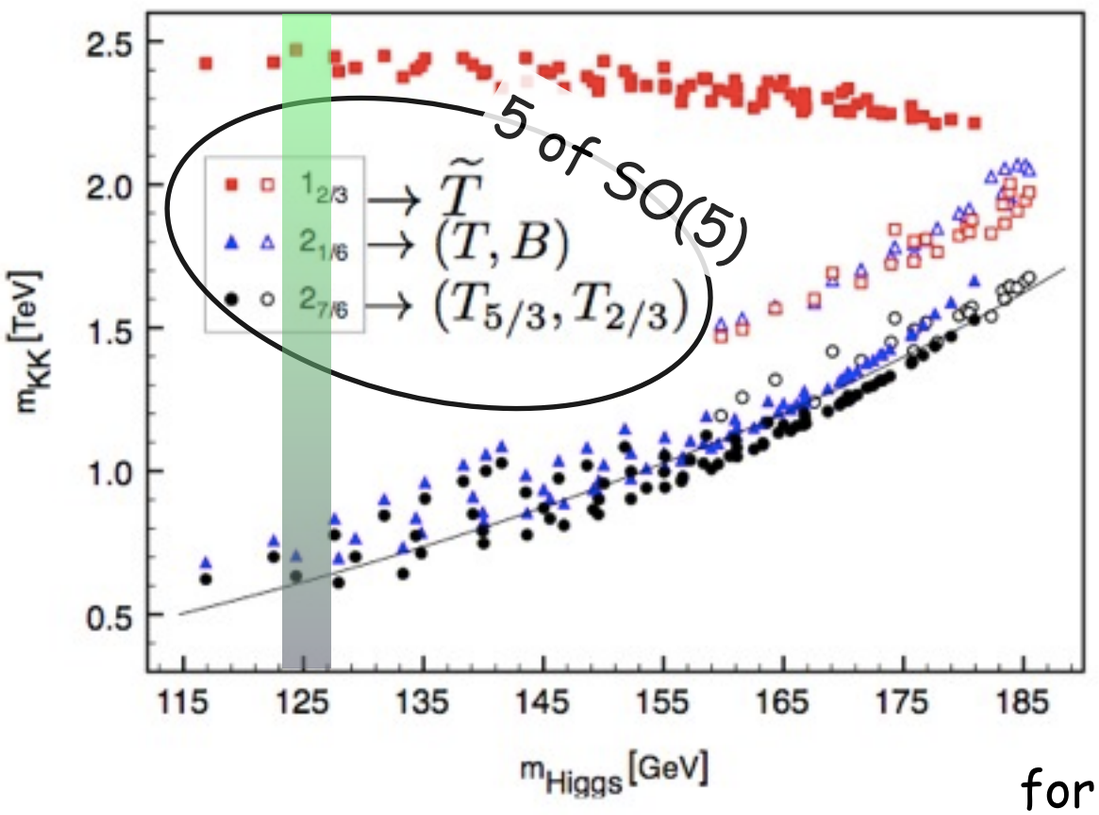

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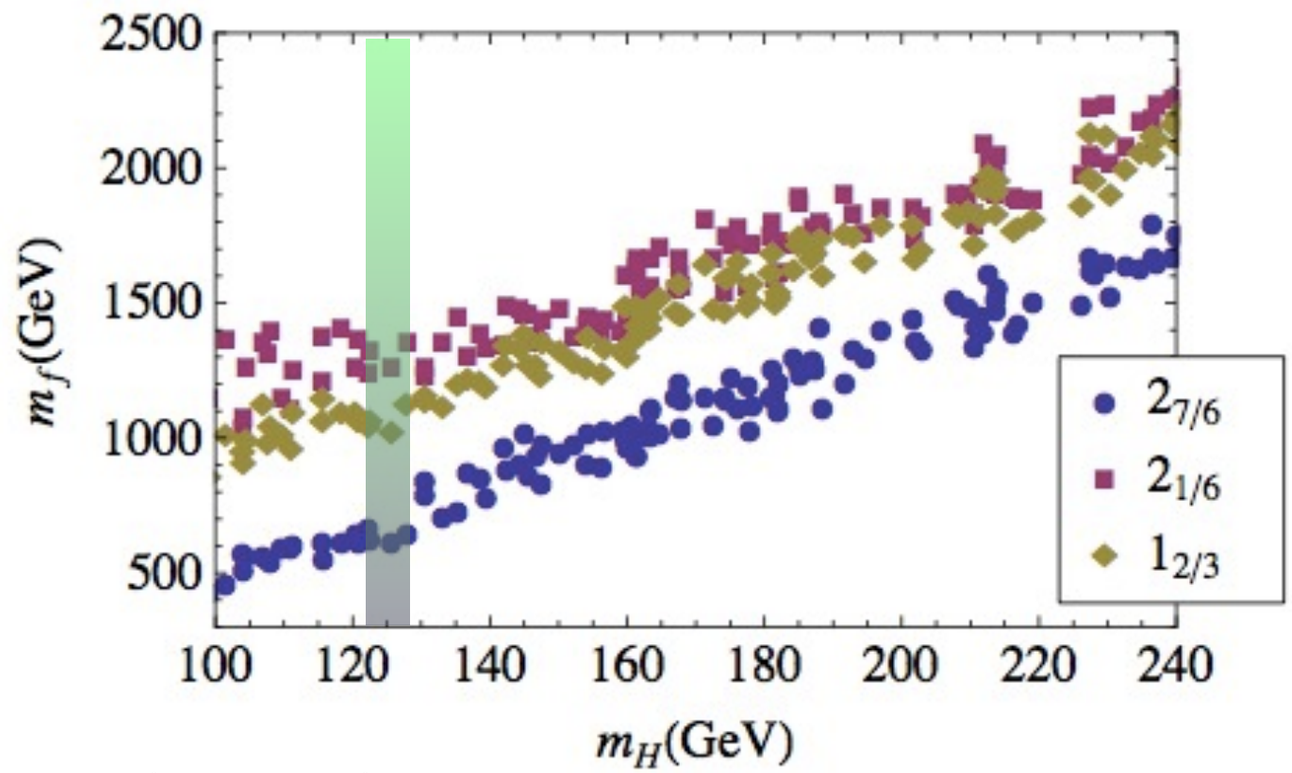

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Nice AdS/CFT interpretation

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

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

Searching for Exotic Top Partners

Search in same-sign di-lepton events

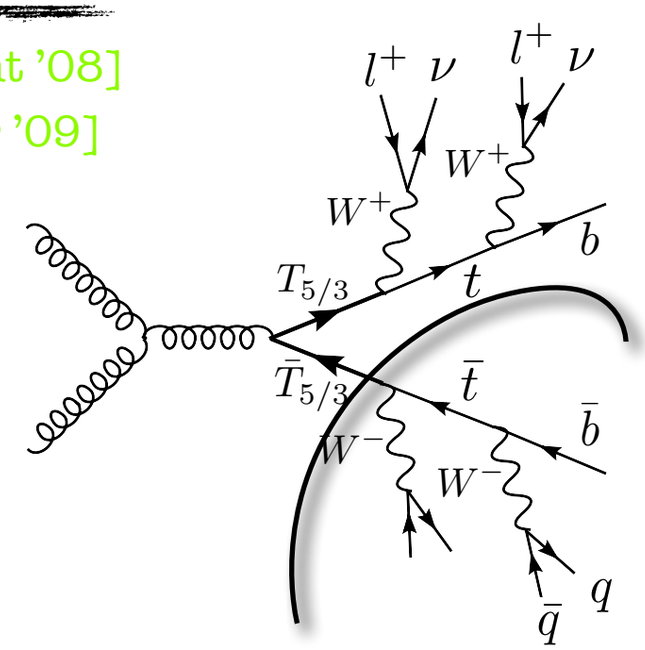
[Contino, Servant '08]
[Mrazek, Wulzer '09]

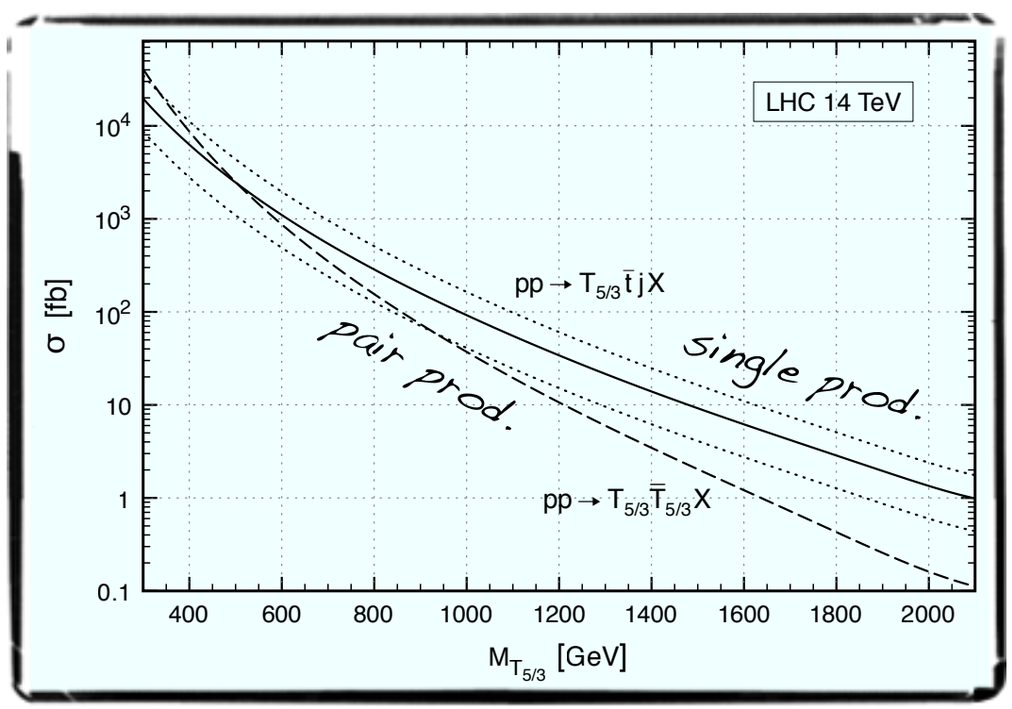
- tt+jets is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed

discovery potential (LHC_{14TeV})

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

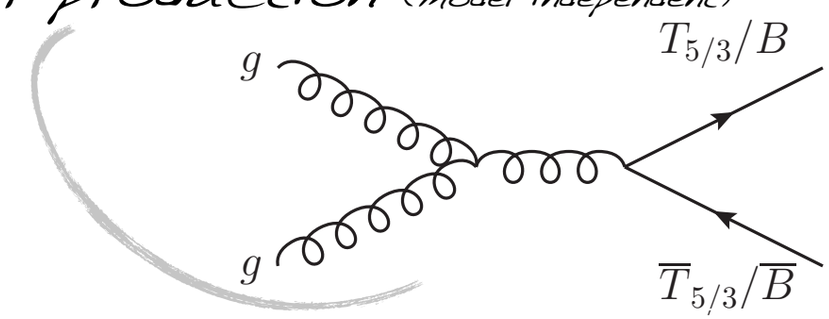
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

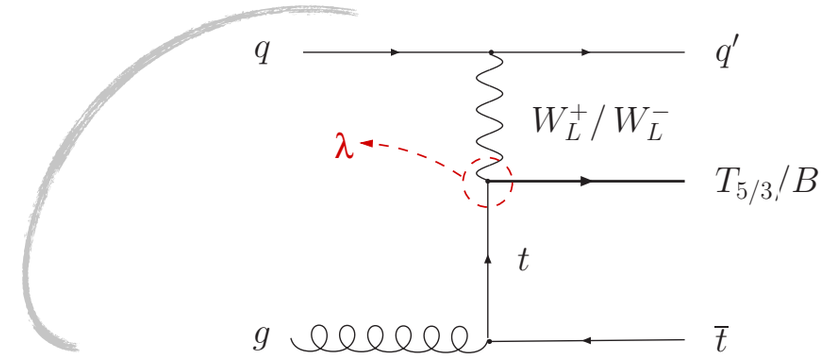




[Contino, Servant '08]

Pair production (model independent)

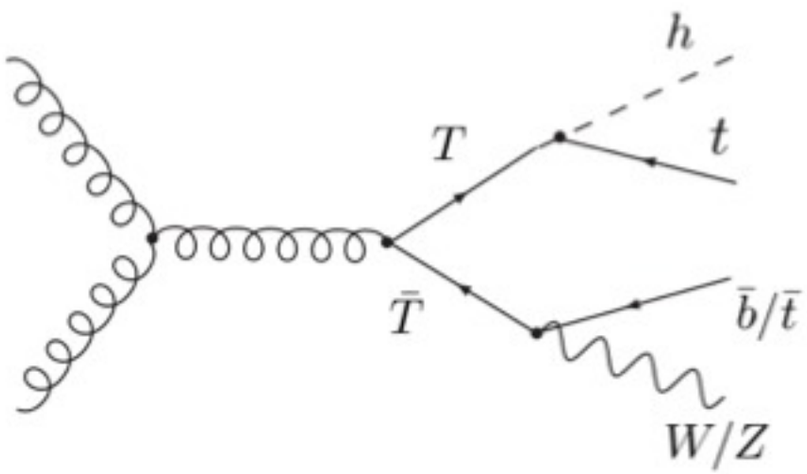




Single production (model dependent)

Rich phenomenology of the top partners

$T^{2/3}$



$l^{\pm}$ + 4b final state

Aguilar-Saavedra '09

$T\bar{T} \to Ht\,W^-\bar{b} \to HW^+bW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$,

$T\bar{T} \to Ht\,V\bar{t} \to HW^+b\,VW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$

$l^{\pm}$ + 6b final state

Aguilar-Saavedra '09

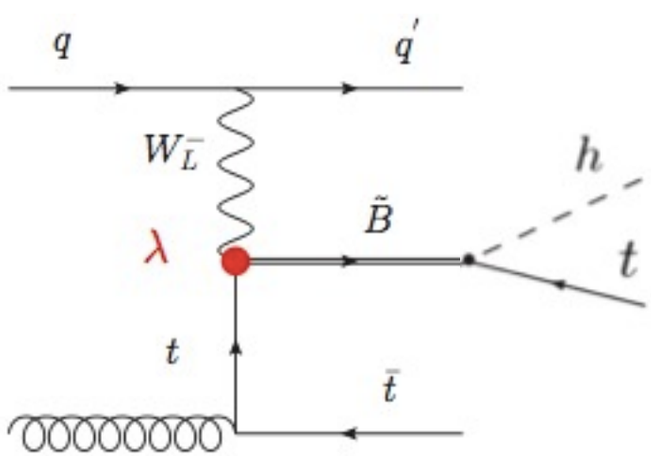
$T\bar{T} \to Ht\,H\bar{t} \to HW^+b\,HW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$

$\gamma\gamma$ final state

Azatov et al '12

$thbW/thtZ/thth,\ h \to \gamma\gamma$

$B^{-1/3}$

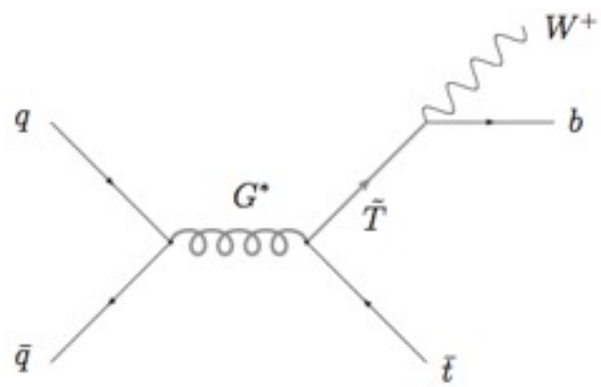


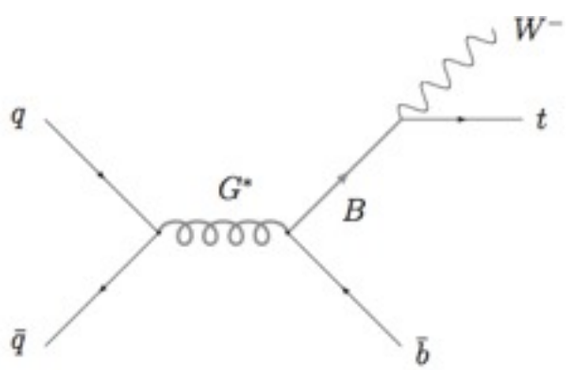
$l^{\pm}$ + 4b final state

Vignaroli '12

$pp \to (\tilde{B} \to (h \to bb)b)t + X$

Rich phenomenology of the top partners





$$q\bar{q} \to G^* \to \underset{\to Wb\bar{t}}{\tilde{T}\bar{t}} + \underset{\to Wt\bar{b}}{\tilde{B}\bar{b}}$$

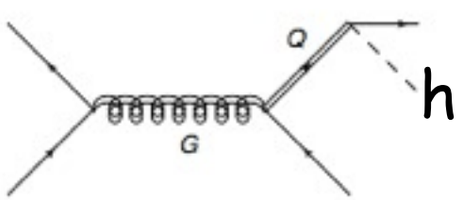
same final states as $t\bar{t}$

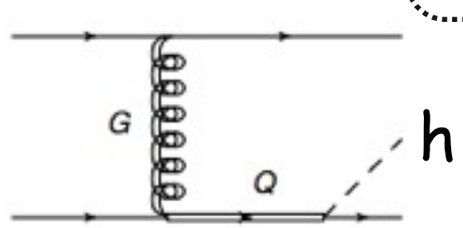
Bini, Contino, Parisse, Vignaroli '11

Barcelo, Carmona, Masip, Santiago '11

$$pp \to G \to T\bar{t} + \bar{T}t \to Ht\bar{t} \to 4b + 2j + l + \not{E}_T$$

Carmona, Chala, Santiago '12



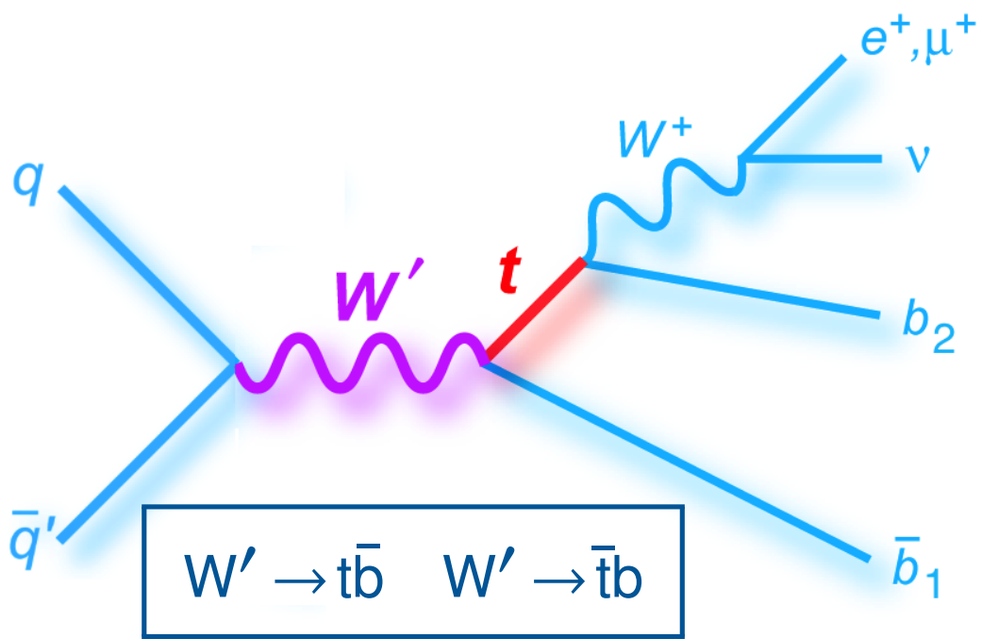


1

Other BSM searches with single top

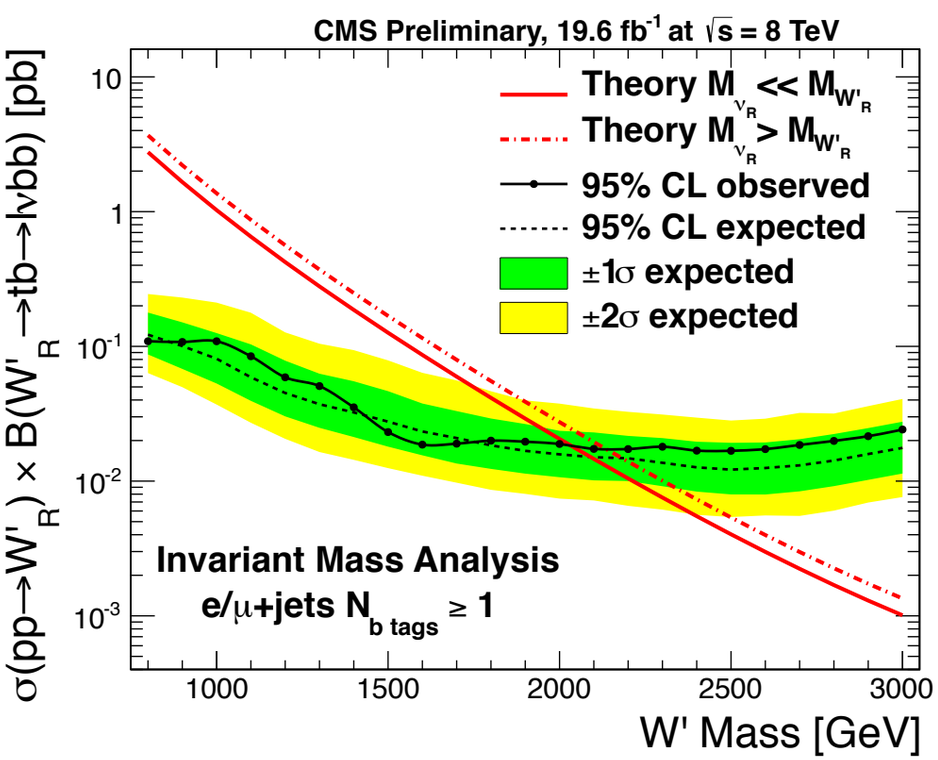
W'

e.g. O.M. Kind @ top'13

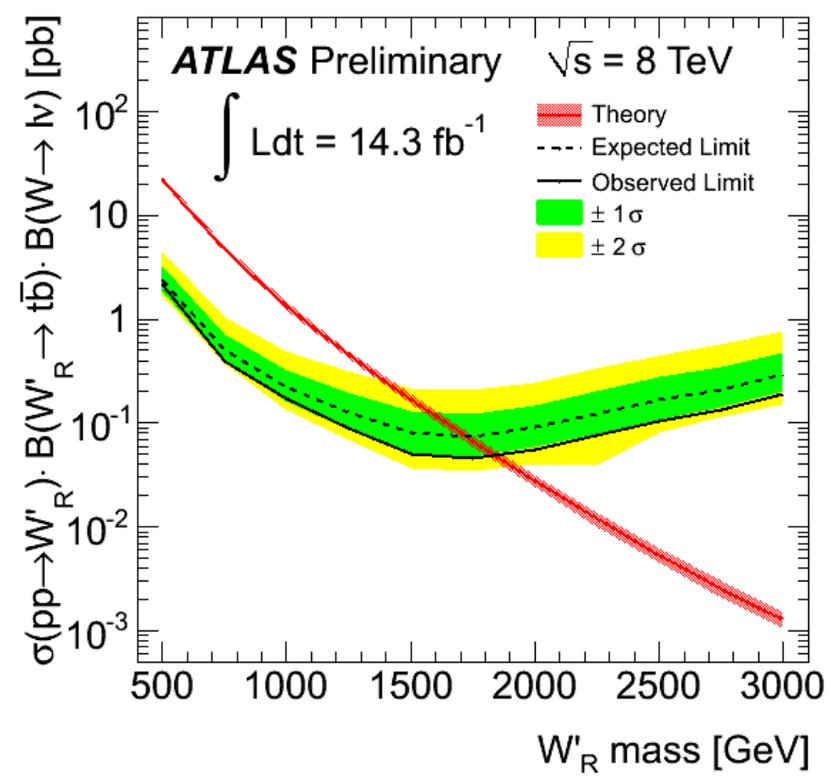


$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left(g'_{R_{ij}} (1+\gamma^5) + g'_{L_{ij}} (1-\gamma^5) \right) W'^\mu f_j + h.c.$$

$g'_{L,R}$ = left/right-handed couplings $\quad V' = \begin{cases} V_{CKM}; \text{ quarks} \\ \delta_{ij}; \text{ leptons} \end{cases}$



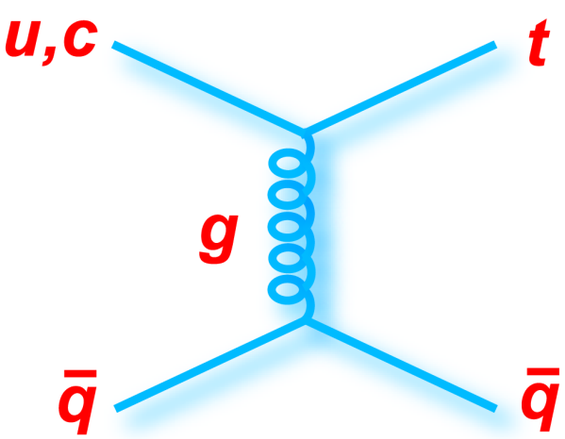
CMS-PAS-B2G-12-0120



ATLAS-CONF-2013-050

FCNC top production

e.g. E.. Yazgan @ top'13



FCNC in production: qg → t

- ATLAS-CONF-2013-063

  ATLAS: $\sqrt{s} = 8\,\text{TeV}$, $\int L\,dt = 15.2\,/\text{fb}$

- PLB 712 (2012) 351

  ATLAS: $\sqrt{s} = 7\,\text{TeV}$, $\int L\,dt = 2.05\,/\text{fb}$

➔ No evidence for FCNC found

Conclusions

'top + Higgs' is a crucial couple for HEP

single top channel can help us understanding EWSB

understanding the top sector will tell us if the universal is

- ☑ natural
- ☑ metastable
- ☑ near-critical