LOOKING FOR THE HIGGS BOSON WITHOUT (TOO MUCH) PREJUDICE

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  (UNIVERSITY OF ROME “LA SAPIENZA”)

The starting point (and main assumption):

- Evidence for Electroweak Symmetry Breaking

massive (light) spin-1 particles $\{W_\mu^\pm,\, Z_\mu\}$

$$\{\chi^\pm,\, \chi^0\}$$

Longitudinal polarizations =
Nambu-Goldstone bosons of $SU(2)_L \times U(1)_Y \to U(1)_{em}$

strongly coupled at $E \sim 4\pi f = 4\pi \left(\frac{m_V}{g}\right)$

$$\{W_\mu^T,\, Z_\mu^T\}$$

Transverse polarizations =
gauge fields

elementary up to $E \gg 4\pi \left(\frac{m_V}{g}\right)$

Top-Down Approach

UV

PERTURBATIVE MODEL

$SU(2)_L \times U(1)_Y$ Linearly Realized

↓

IR

LOW-ENERGY PHENOMENOLOGY

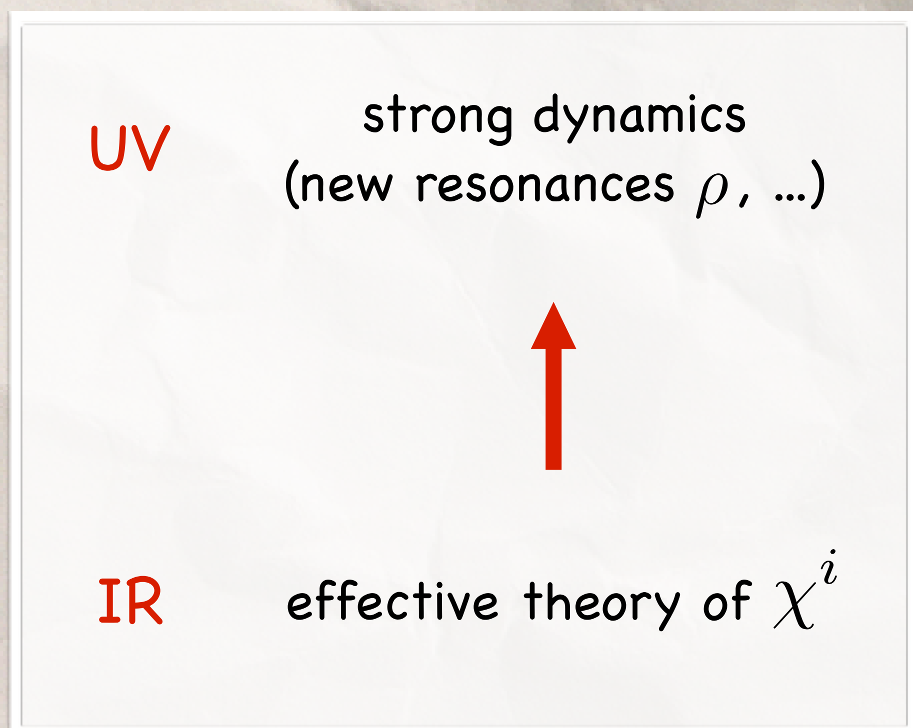
verify model's predictions

in this talk I will rather follow a

Bottom-Up Approach

Scenario #1

no linear regime



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UV — strong dynamics (new resonances ρ, ...)

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IR — effective theory of χ^i

Scenario #2

$SU(2)_L \times U(1)_Y$ linear + perturbativity

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UV — weakly coupled theory

$[\chi^i, \phi^a]$

Higgs bosons (ϕ^a)

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Scenario #3

$SU(2)_L \times U(1)_Y$ linear + strong dynamics

UV — strong dynamics (new resonances ρ, ...)

↑

$[\chi^i, \phi^a]$

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Notice: the light scalar might be an "impostor" (light dilaton ?), have nothing to do with EWBS, so that we would be in scenario #1 (no linear regime)

Rules (CCWZ):

[Coleman, Wess, Zumino PRD 117 (1969) 2239
Callan, Coleman, Wess, Zumino PRD 117 (1969) 2247]

[1.] Any $U(1)_{em}$ locally-invariant Lagrangian can be dressed up with NG-bosons and rewritten ad manifestly $SU(2)_L \times U(1)_Y$ invariant

Ex: $$\mathrm{Tr}\left[W_\mu^2\right] \longrightarrow \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D_\mu \Sigma)\right] \qquad (\Sigma = \exp(i\chi/v))$$

$$W_\mu^+ W_\mu^- Z_{\mu\nu} \longrightarrow \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger \sigma^a W^a_{\mu\nu} (D_\nu \Sigma)\right]$$

[2.] Fields must come in multiplets of $U(1)_{em}$
(i.e. not necessarily of $SU(2)_L \times U(1)_Y$)

Possible Extra Rules:

- The EWSB sector has an approximate custodial $SU(2)_c$ invariance:

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ $\Rightarrow$ $SU(2)_L \times SU(2)_R \rightarrow SU(2)_c$

or equivalently

$SO(4) \rightarrow SO(3)$

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- The Higgs is a (pseudo) NG boson of a larger symmetry breaking

Ex: $SO(5) \to SO(4)$ $H = [\chi^i,\, h]$

Additional invariance (broken by spurions only): $h(x) \to h(x) + \alpha$ $T_h \in \mathrm{Alg}\left\{\frac{SO(5)}{SO(4)}\right\}$

(Higgs shift symmetry)

Chiral Lagrangian for a light Higgs

Assumptions:

- Higgs boson is a scalar, singlet of $U(1)_{em}$ $(SU(2)_c)$
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Chiral expansion parameter = $\left(\frac{\partial_\mu}{\Lambda}\right)$ $\quad \Lambda \lesssim 4\pi v = \Lambda_s$

The cutoff can be made larger if the Higgs partly unitarizes all scattering amplitudes

Ex: Higgs is a pNG boson

$$\Lambda \lesssim 4\pi f = \frac{4\pi v}{\sqrt{\xi}} \qquad \xi = \left(\frac{v}{f}\right)^2$$

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

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[RC Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089 ; Azatov, R.C. , Galloway, JHEP 1204 (2012) 127]

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o(p^2) terms

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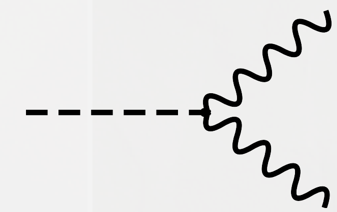

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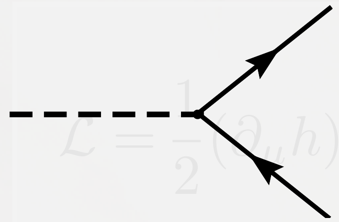

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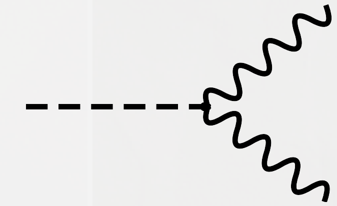

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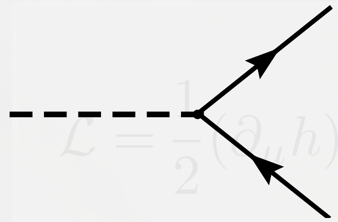

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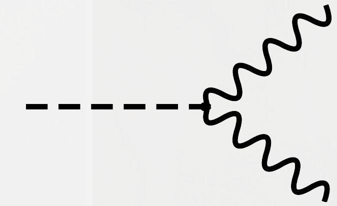

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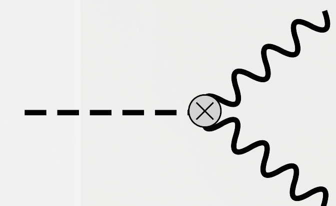

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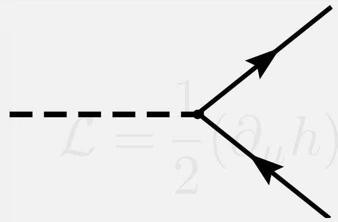

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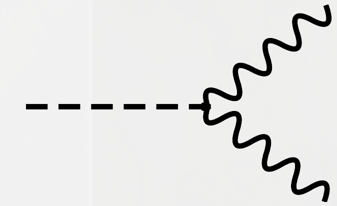

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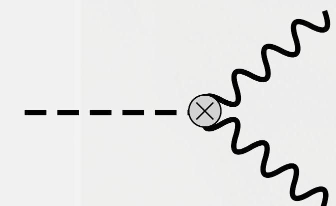

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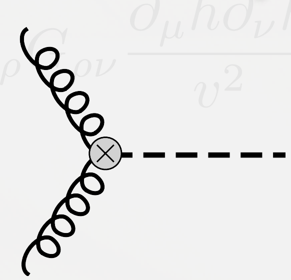
Modify gg single production and γγ decay



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[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

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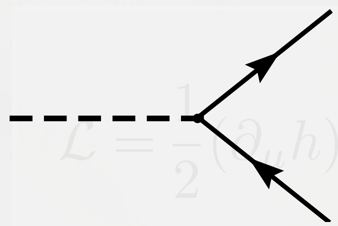
$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots\right]$$

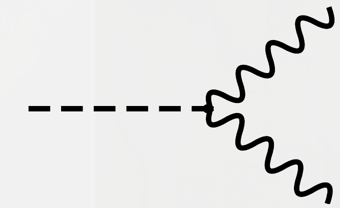
$$+ \ldots$$

Controls the $h\psi\psi$ coupling



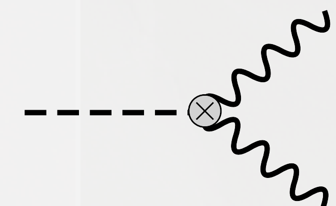
$$= c_\psi \cdot g^{SM}_{h\psi\psi}$$

Controls the hWW, hZZ couplings



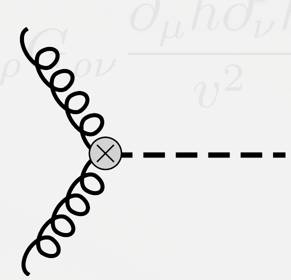
$$= a \cdot g^{SM}_{hWW}$$

$O(p^4)$ correction to hVV couplings



$$c_{ij} \sim \left(\frac{g_* v}{\Lambda}\right)$$

Modify gg single production and γγ decay



$$c_{ij} \sim \left(\frac{g_* v}{\Lambda}\right)\left(\frac{\lambda^2}{g_*^2}\right)$$

extra suppression for a pNG Higgs

[Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706 (2007) 045]

Chiral Lagrangian for a light Higgs

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

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

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

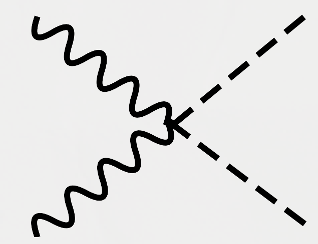
$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \dots$$

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

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

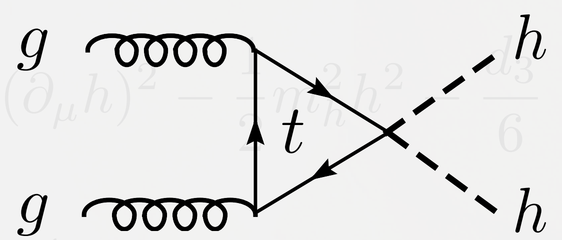
$$+ \dots$$

Contributes to WW→hh

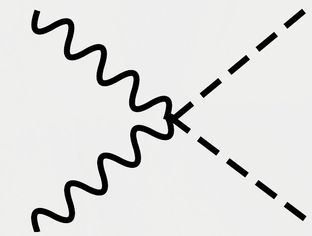


Chiral Lagrangian for a light Higgs

Contributes to gg→hh



Contributes to WW→hh



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

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

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

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

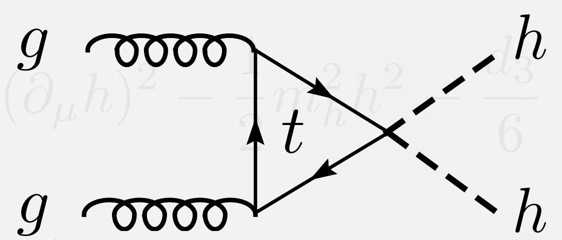
$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\,\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\,\frac{h}{v} + c_{2gg}\,\frac{h^2}{v^2}\ldots\right)\right]$$

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

$$+ \ldots$$

Chiral Lagrangian for a light Higgs

Contributes to gg→hh



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

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

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

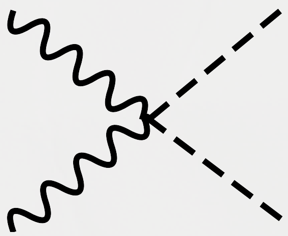
$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu} W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

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

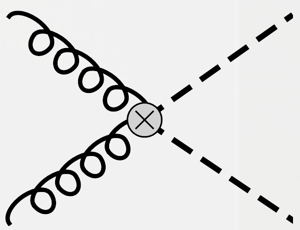
$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2}\, G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2}\, G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

Contributes to WW→hh



$O(p^4)$ contribution to gg→hh



$$c_{2hh} \sim \left(\frac{g_*^2 v^2}{\Lambda^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$$

Chiral Lagrangian for a light Higgs

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

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

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

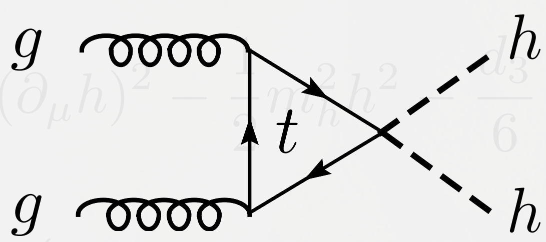
$$+\frac{g^2}{16\pi^2}\left(c_{WW} W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ} Z^2_{\mu\nu} + c_{Z\gamma} Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

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

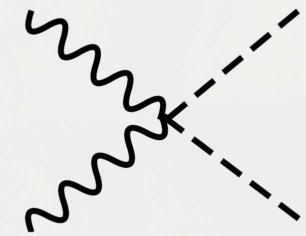
$$+\frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h\,\partial_\nu h}{v^2} + \ldots\right]$$

$$+\ldots$$

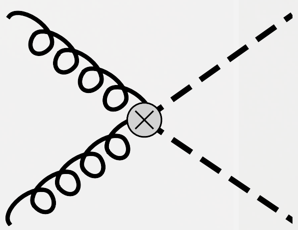
Contributes to gg→hh



Contributes to WW→hh

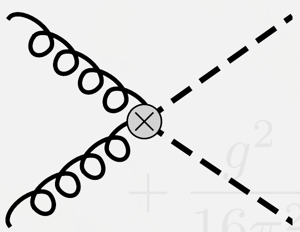


O(p^4) contribution to gg→hh



$$c_{2hh} \sim \left(\frac{g_*^2 v^2}{\Lambda^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$$

O(p^6) contribution to gg→hh



$$c_{hhgg} \sim \left(\frac{g_*^2 v^2}{\Lambda^2}\right)$$

How to use the Chiral Lagrangian

- Rules of chiral expansion:

  LO = tree-level $O(p^2)$

  NLO = 1-loop $O(p^2)$ + tree-level $O(p^4)$

  NNLO = 2-loops $O(p^2)$ + 1-loop $O(p^4)$ + tree-level $O(p^6)$

  $\vdots$

- QCD corrections (expansion in α_s) factorize

How to use the Chiral Lagrangian

- Rules of chiral expansion:

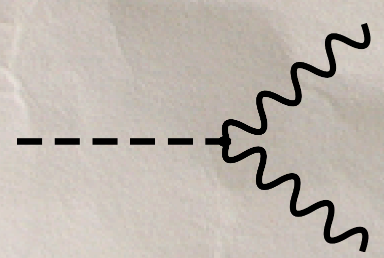
  LO = tree-level $O(p^2)$

  NLO = 1-loop $O(p^2)$ + tree-level $O(p^4)$

  NNLO = 2-loops $O(p^2)$ + 1-loop $O(p^4)$ + tree-level $O(p^6)$

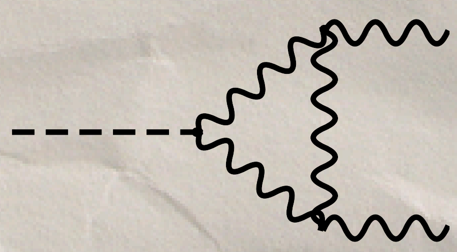
  ⋮

Ex: $h \to WW$



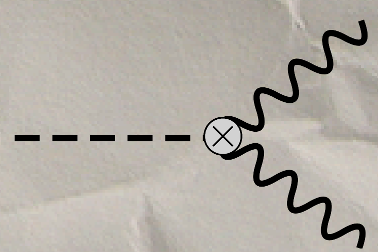
$$\frac{m_W^2}{v}$$

+



$$\frac{m_W^2}{v}\left(\frac{g^2}{16\pi^2}\right)$$

+



$$\frac{E^2}{v}\left(\frac{g^2}{16\pi^2}\right)$$

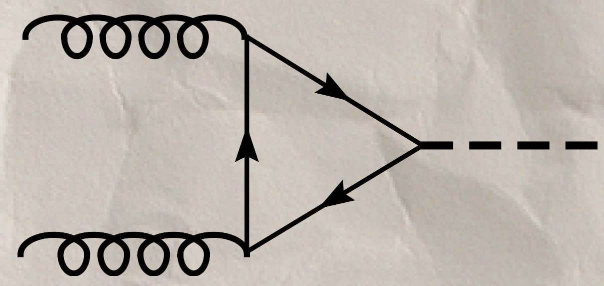
+ . . .

LO

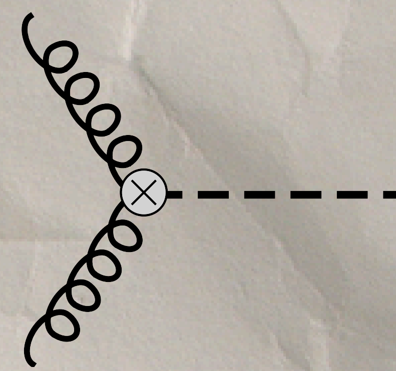
NLO

Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



+

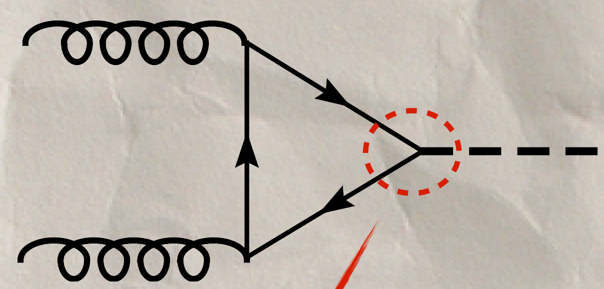


$$c_t \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2} \, F\left(\frac{m_h^2}{m_t^2}\right)$$

$$c_{gg} \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2}$$

Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



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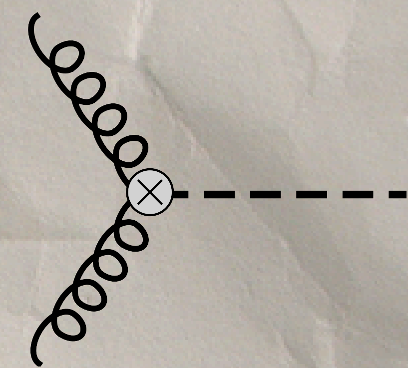


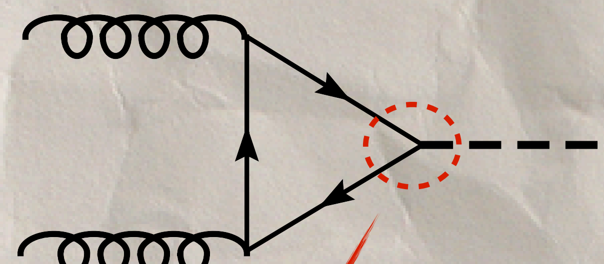
$$c_t \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2} \, F\left(\frac{m_h^2}{m_t^2}\right)$$

$$c_{gg} \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2}$$

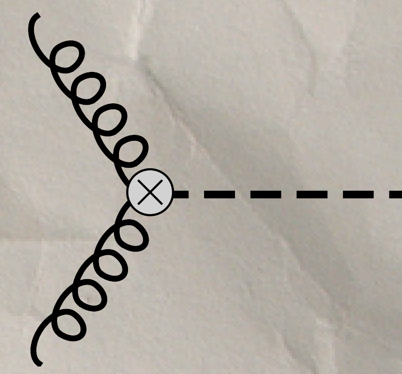
$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



+



$$c_t \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2} \, F\left(\frac{m_h^2}{m_t^2}\right)$$

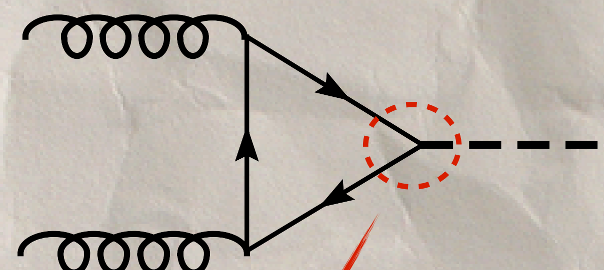
$$c_{gg} \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2}$$

$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

from Higgs non-linearities

Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



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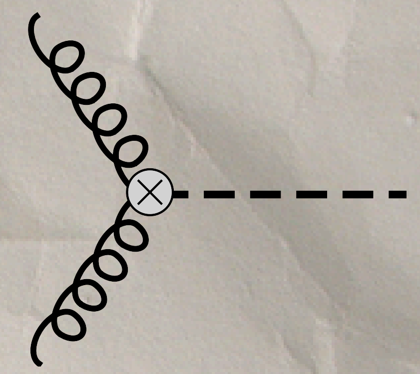


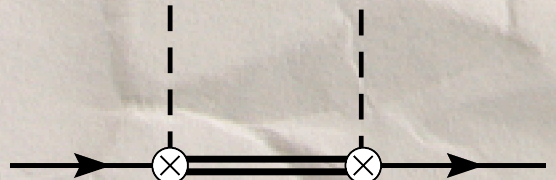
$$c_t \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2} F\left(\frac{m_h^2}{m_t^2}\right)$$

$$c_{gg} \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2}$$

$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

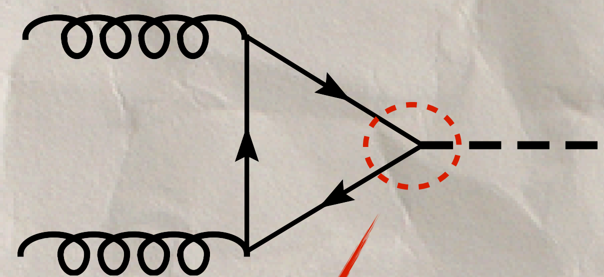
from Higgs non-linearities

from corrections to wave-function



Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



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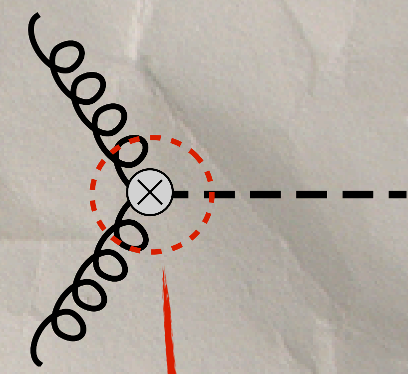
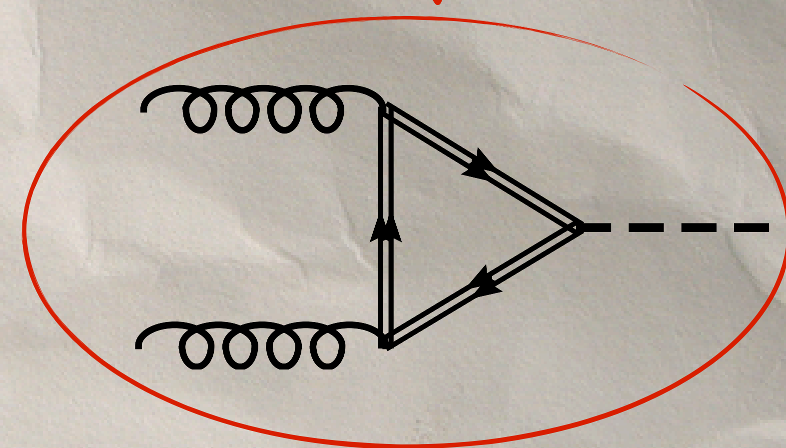


$$c_t \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2} \, F\left(\frac{m_h^2}{m_t^2}\right)$$

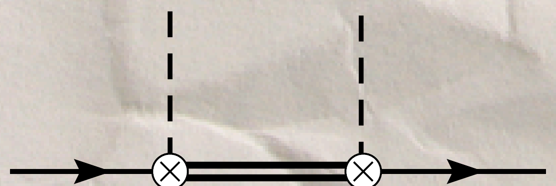
$$c_{gg} \, \frac{m_h^2}{v} \, \frac{g_s^2}{16\pi^2}$$



$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

from Higgs non-linearities

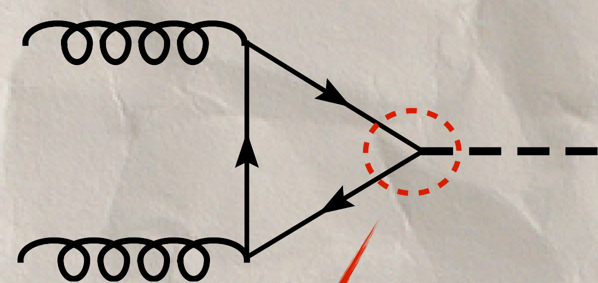
from corrections to wave-function



$$c_{gg} \sim \left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$$

Single Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



$$c_t \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2} F\left(\frac{m_h^2}{m_t^2}\right) \quad + \quad c_{gg} \frac{m_h^2}{v} \frac{g_s^2}{16\pi^2}$$

In minimal pNG Higgs models with partial compositeness loops of heavy fermions exactly cancel the wave function correction

Falkowski, PRD 77 (2008) 055018

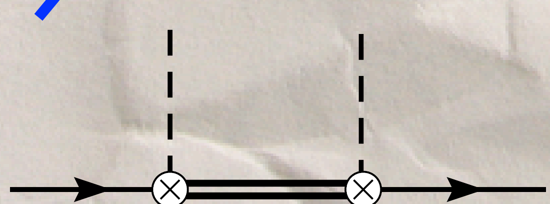
Low, Rattazzi, Vichi, JHEP 1004 (2010) 126

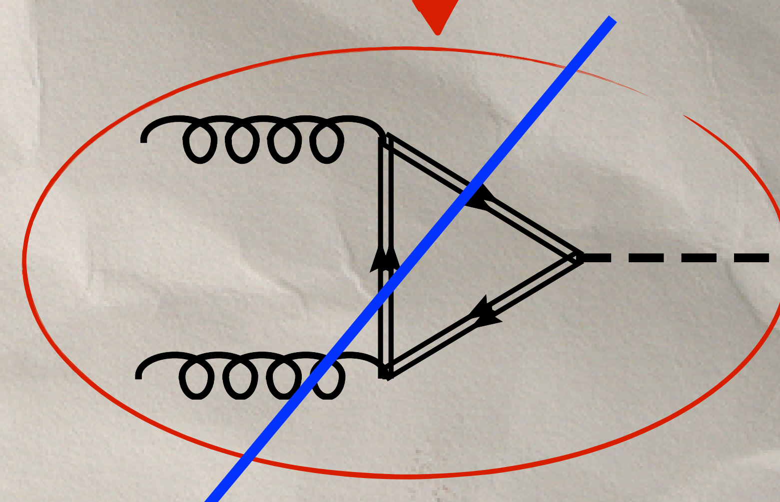
Azatov, Galloway, PRD 85 (2012) 055013

$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

from Higgs non-linearities

from corrections to wave-function

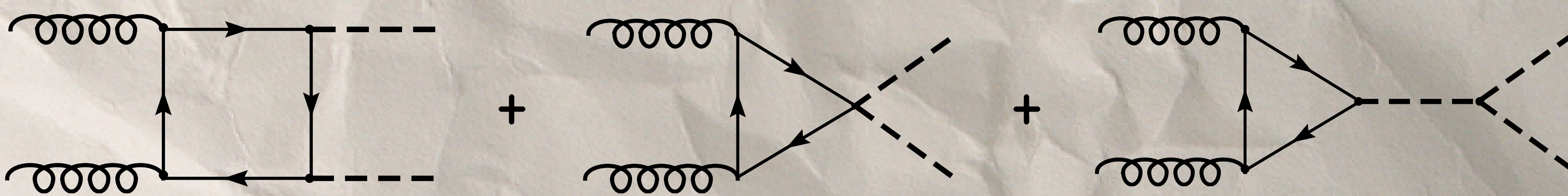




$$c_{gg} \sim \left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)$$

Double Higgs production via gluon fusion

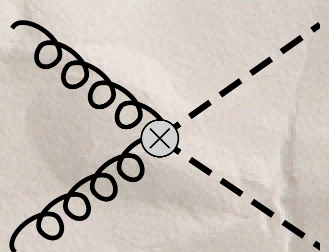
in models with partial compositeness and pNG Higgs



$$\frac{\hat{s}}{v^2}\frac{g_s^2}{16\pi^2}\left[c_t^2\, F_\Box\left(\frac{\hat{s}}{m_t^2}\right) + \left(c_{2t} + c\, d_3\, \frac{m_h^2}{\hat{s}}\right) F_\triangle\left(\frac{\hat{s}}{m_t^2}\right)\right]$$

$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

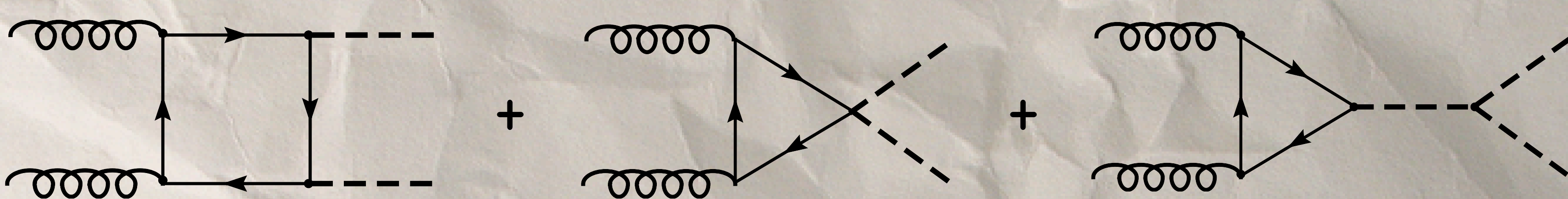
$$c_{2t} = O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$



$$\frac{\hat{s}}{v^2}\frac{g_s^2}{16\pi^2}\left(c_{2gg} + \frac{\hat{s}}{\Lambda^2}\, c_{hhgg} + \dots\right)$$

Double Higgs production via gluon fusion

in models with partial compositeness and pNG Higgs



$$\frac{\hat{s}}{v^2}\frac{g_s^2}{16\pi^2}\left[c_t^2\,F_\square\left(\frac{\hat{s}}{m_t^2}\right)+\left(c_{2t}+c\,d_3\,\frac{m_h^2}{\hat{s}}\right)F_\triangle\left(\frac{\hat{s}}{m_t^2}\right)\right]$$

$$c_t = 1 + O(\xi) + O\left[\left(\frac{g_*^2 v^2}{M^2}\right)\left(\frac{\lambda^2}{g_*^2}\right)\right]$$

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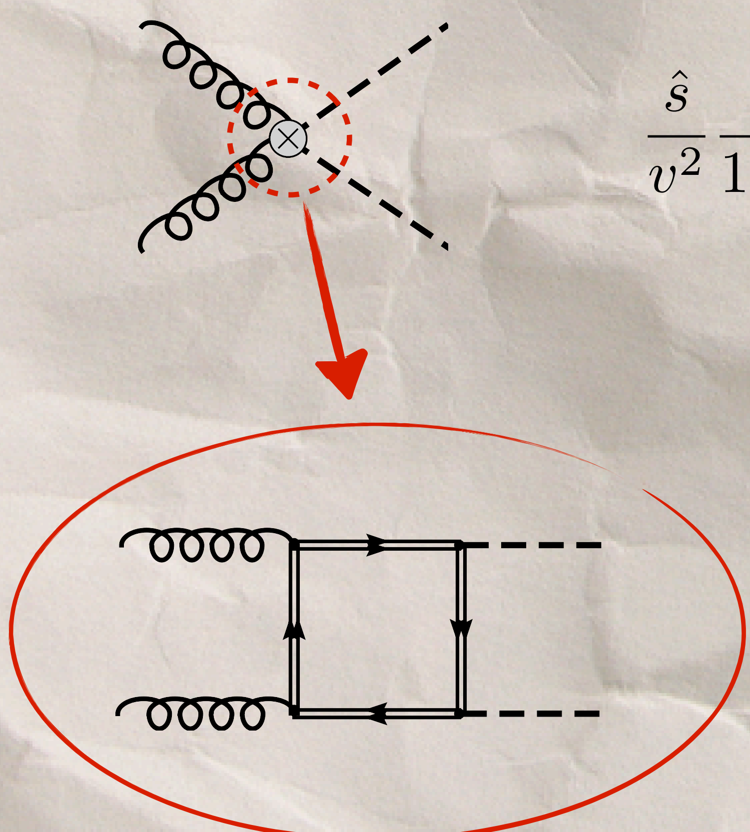

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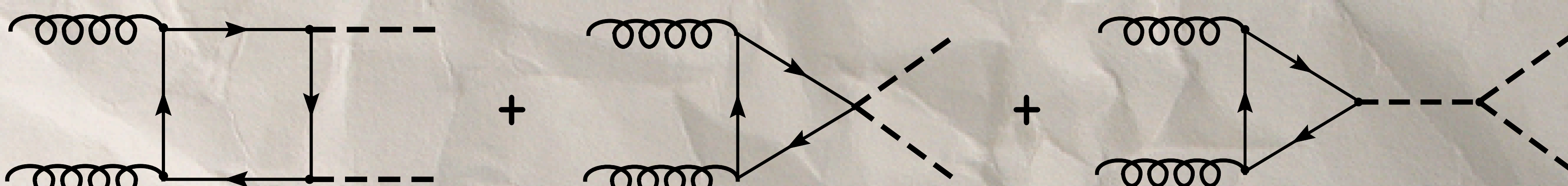

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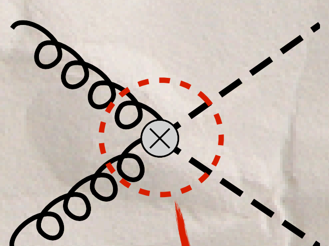

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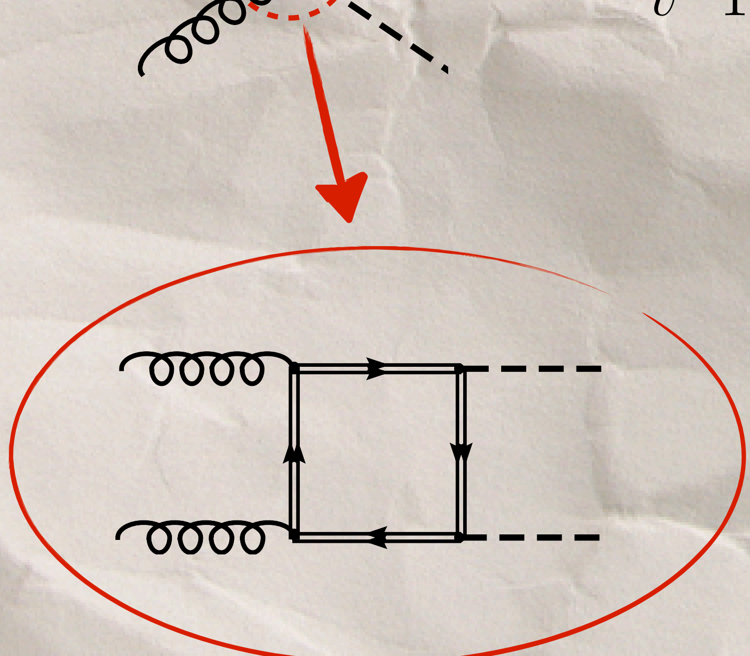

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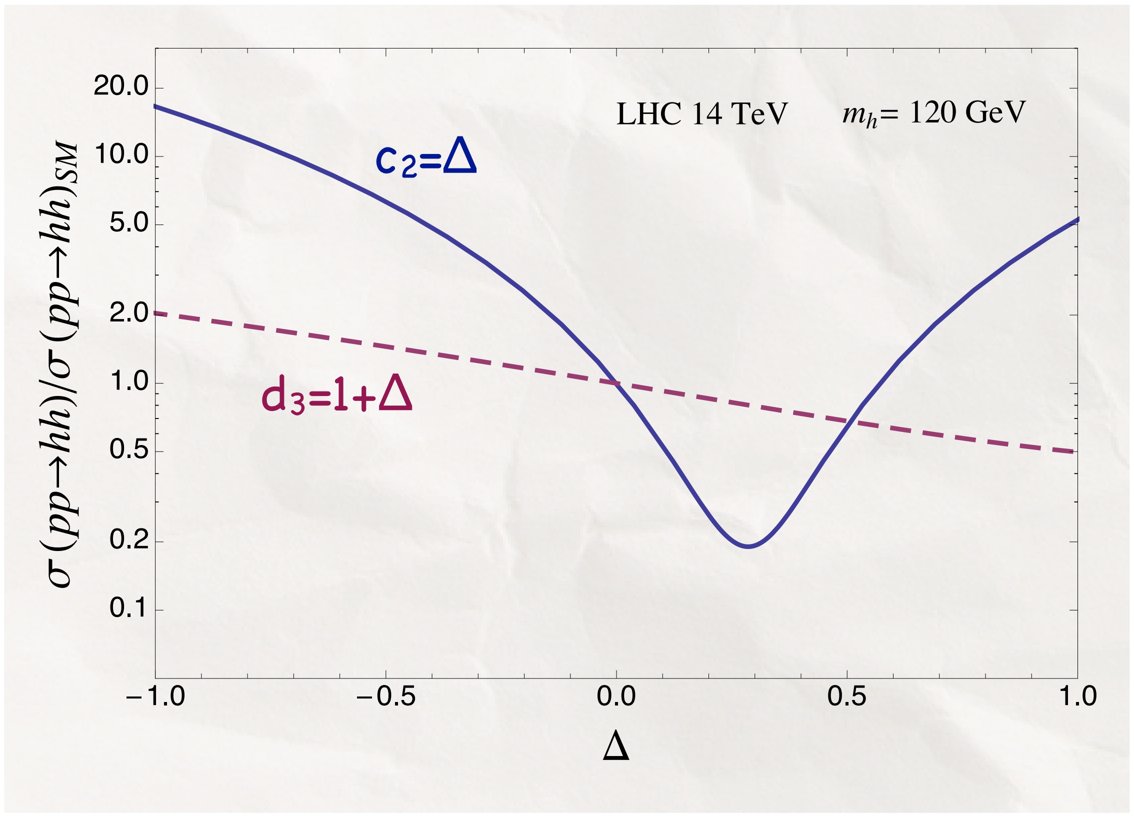
In minimal pNG Higgs models with partial compositeness loops of heavy fermions cancel the wave function correction only at zero Higgs momentum

The $O(p^6)$ terms might be numerically important

Double Higgs production via gluon fusion

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

  [First noticed by:
  Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074
  Grober and Muhlleitner, JHEP 1106 (2011) 020]



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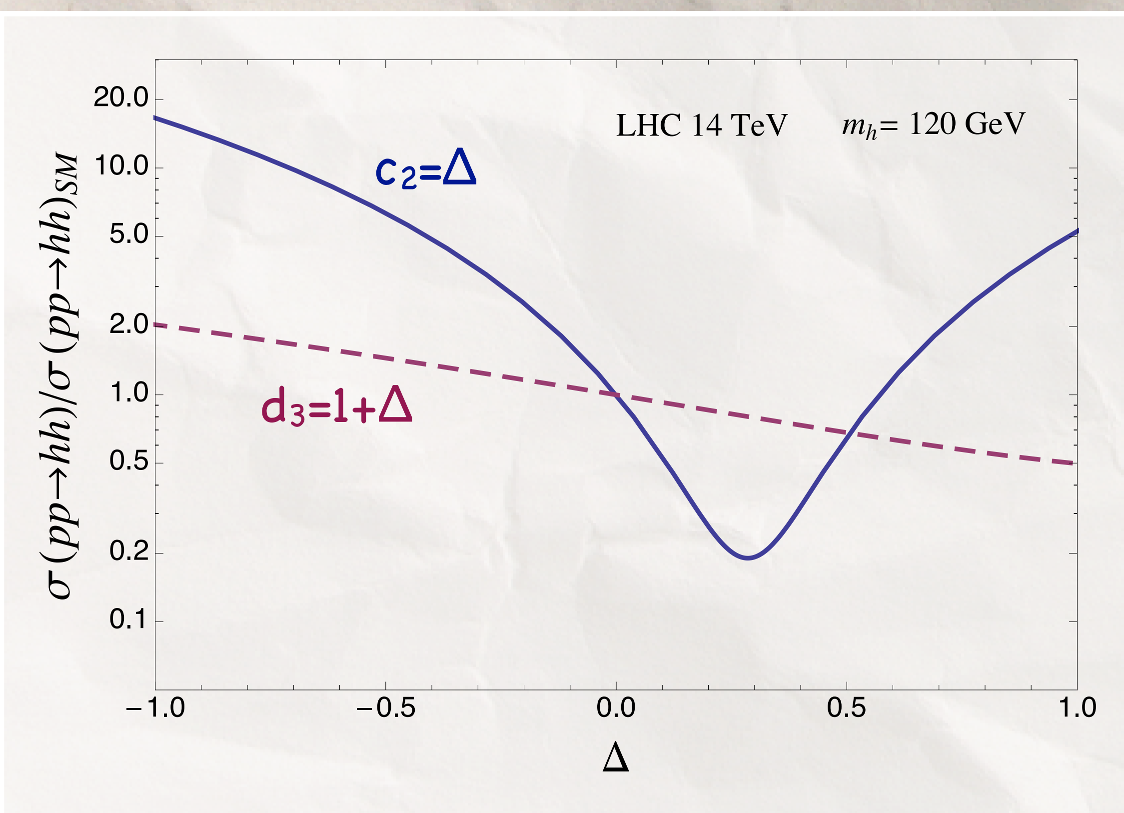

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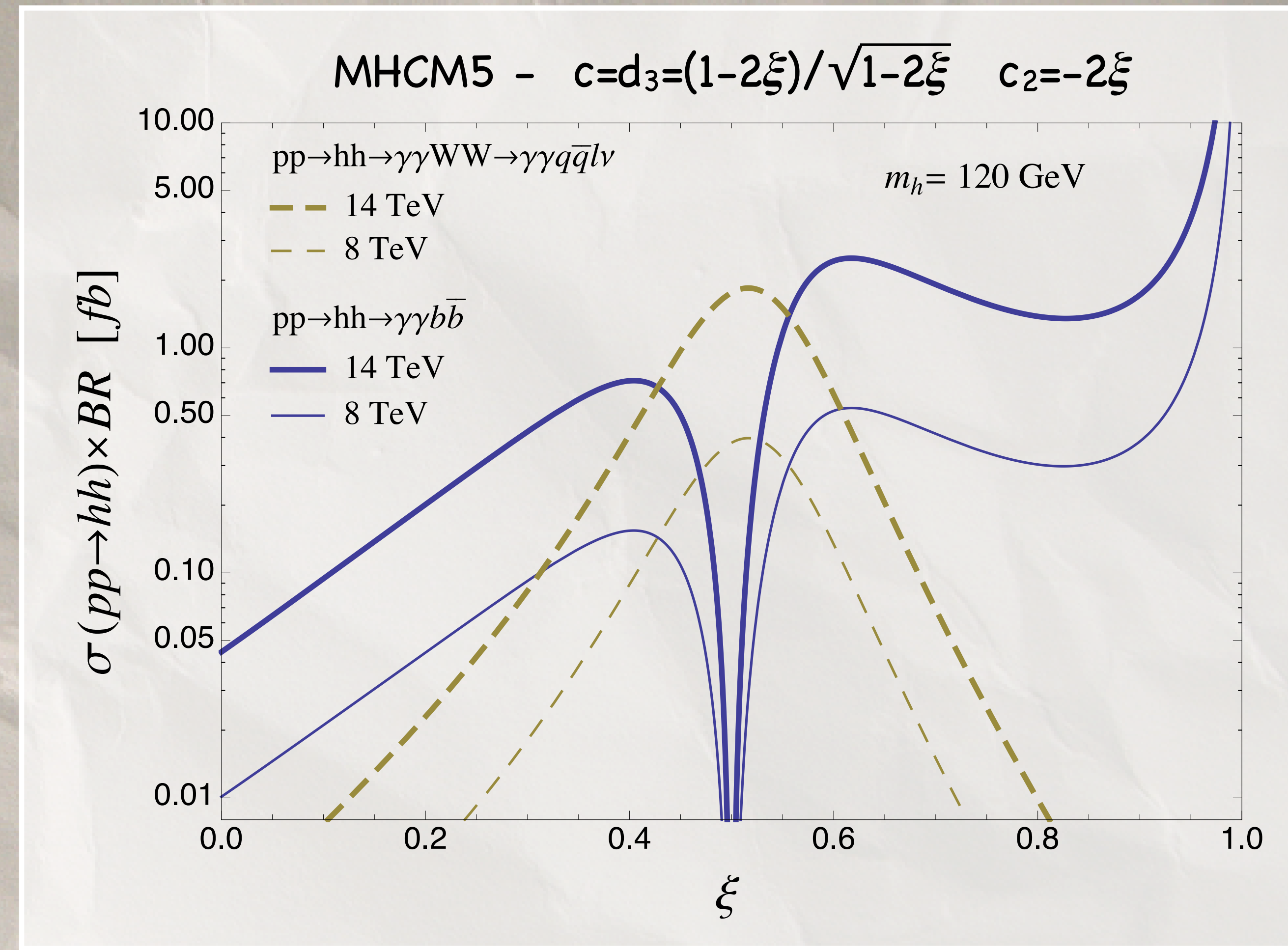


- If $BR(h)\simeq BR(h)_{SM}$ best channel is $hh\to bb\gamma\gamma$

  [Baur, Plehn, Rainwater, PRD 69 (2004) 053004]

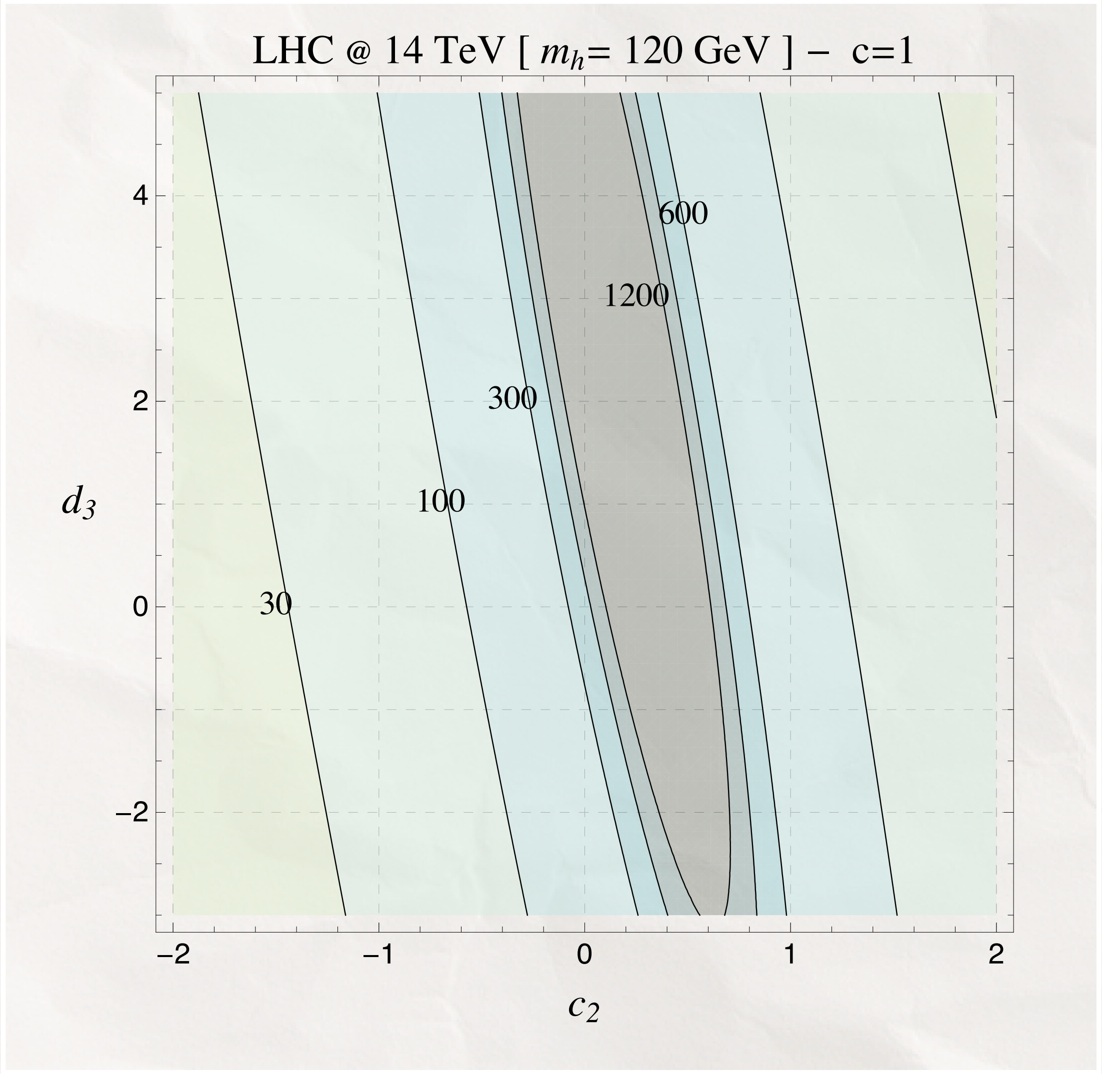
  ξ=0.15 ➡ $\sigma(gg\to hh)\times BR \sim 3\ [\sigma(gg\to hh)\times BR]_{SM}$

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

  ξ=0.5 (c=0), $\sqrt{s}$=8TeV ➡ $\sigma(gg\to hh)\times BR \sim 0.7$fb

Extracting c_2 from $gg \to hh \to b\bar{b}\gamma\gamma$

Discovery luminosity (fb^{-1})



Ex: $\sqrt{s}$=14TeV L=300fb^{-1} ➡ c_2>0.8 c_2<−0.2

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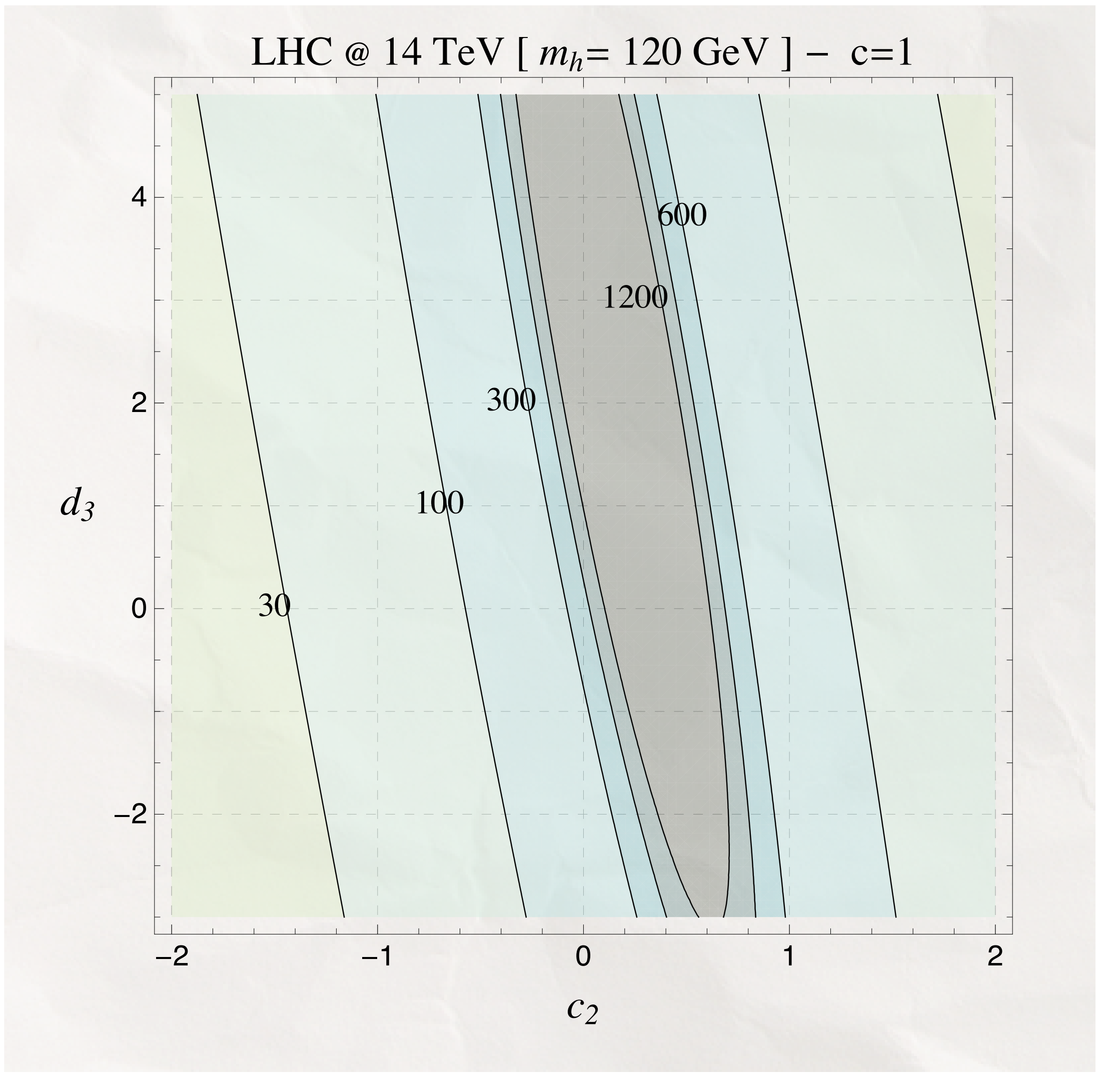

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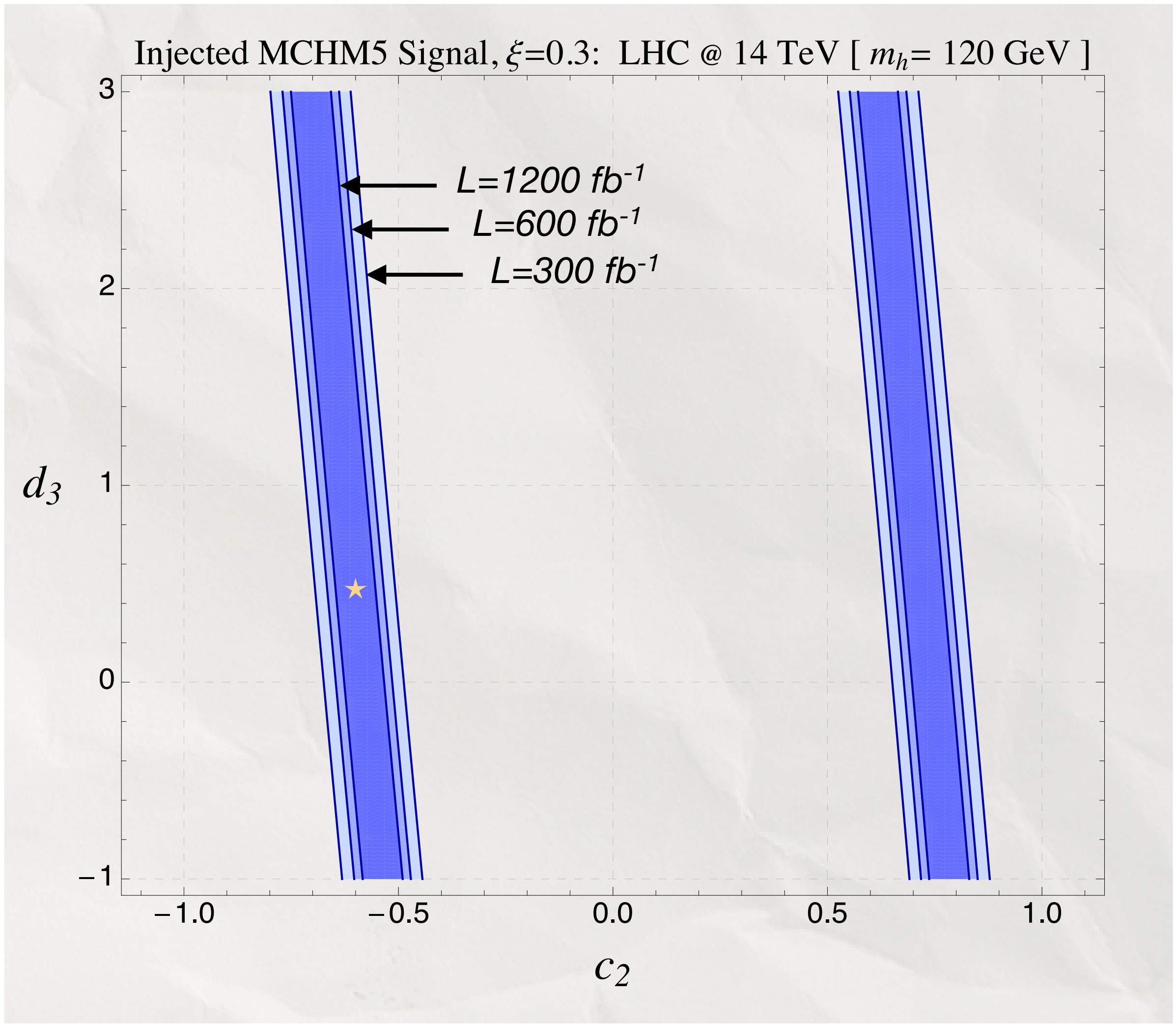
Precision on couplings (curves at 68% prob.)



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Ex: Injected ξ=0.3 ($c=d_3=0.48$ $c_2=-0.6$)

$\Delta c_2/c_2$ = 15-20%

Fit of Higgs couplings with current data

- Current information made public by experimental collaborations is (often) not sufficient to allow theorists to make a rigorous fit

Need: [1] cut efficiencies for each Higgs production mode and event category

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- Best if fit is done by experimentalists; theorists can give support on how to perform calculations (with chiral Lagrangian)

Fit of Higgs couplings with current data

- For the impatient: I'll show a fit performed with reasonable simplifying assumptions.

We concentrate on leading effects and keep only two parameters: (a,c)

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☞ *see talks by Azatov for more details*

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- Similar fits done by several other groups: ☞ *see talks by Falkowski, Grojean, Strumia*

  Carmi, Falkowski, Kuflik, Volansky, arXiv:1202.3144

  Espinosa, Grojean, Muhlleitner, Trott, arXiv:1202.3697

  Giardino, Kannike, Raidal, Strumia, arXiv:1203.4254

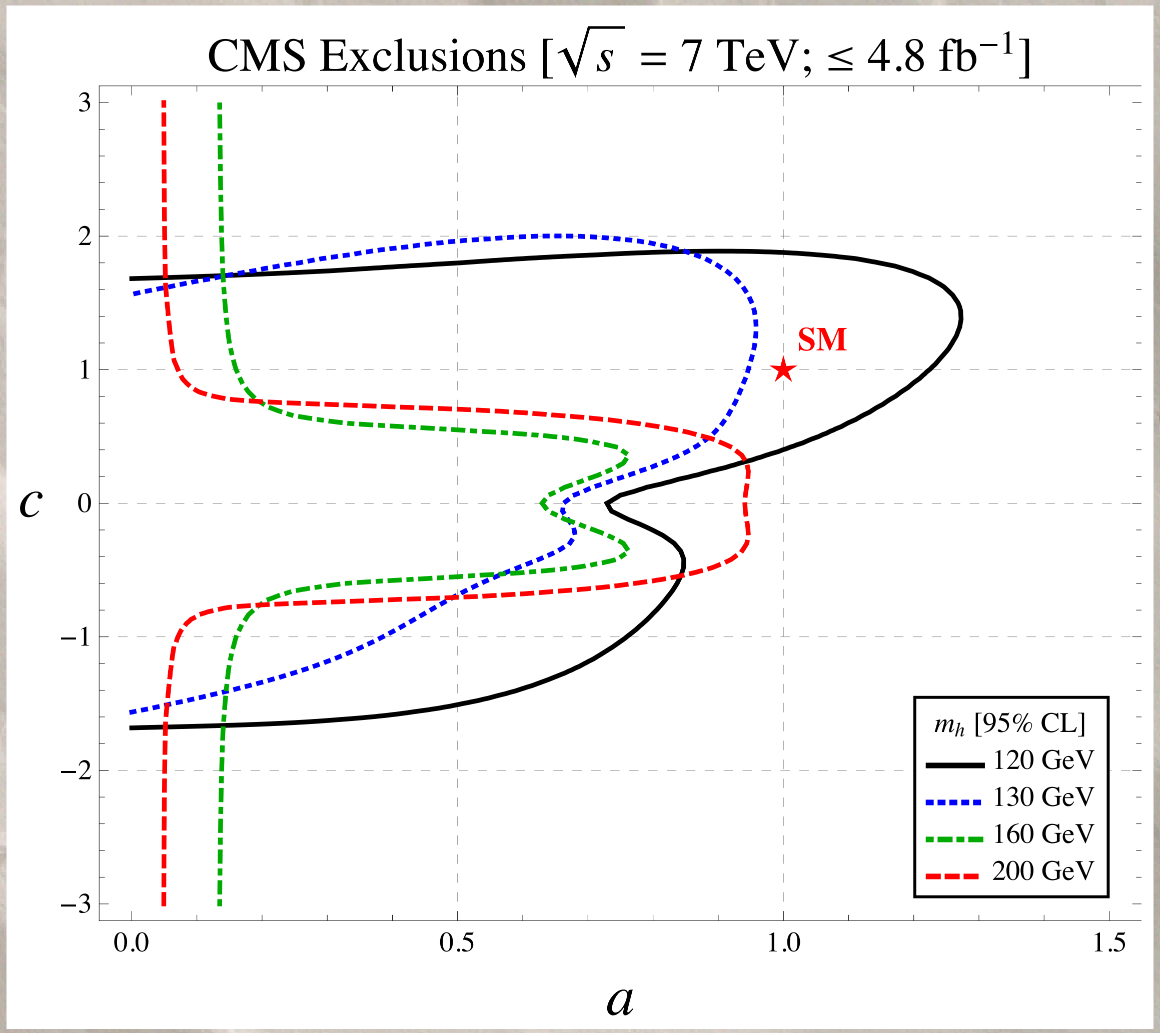
  Ellis and You, arXiv:1204.0464

  Farina, Grojean, Salvioni, arXiv:1205.0011

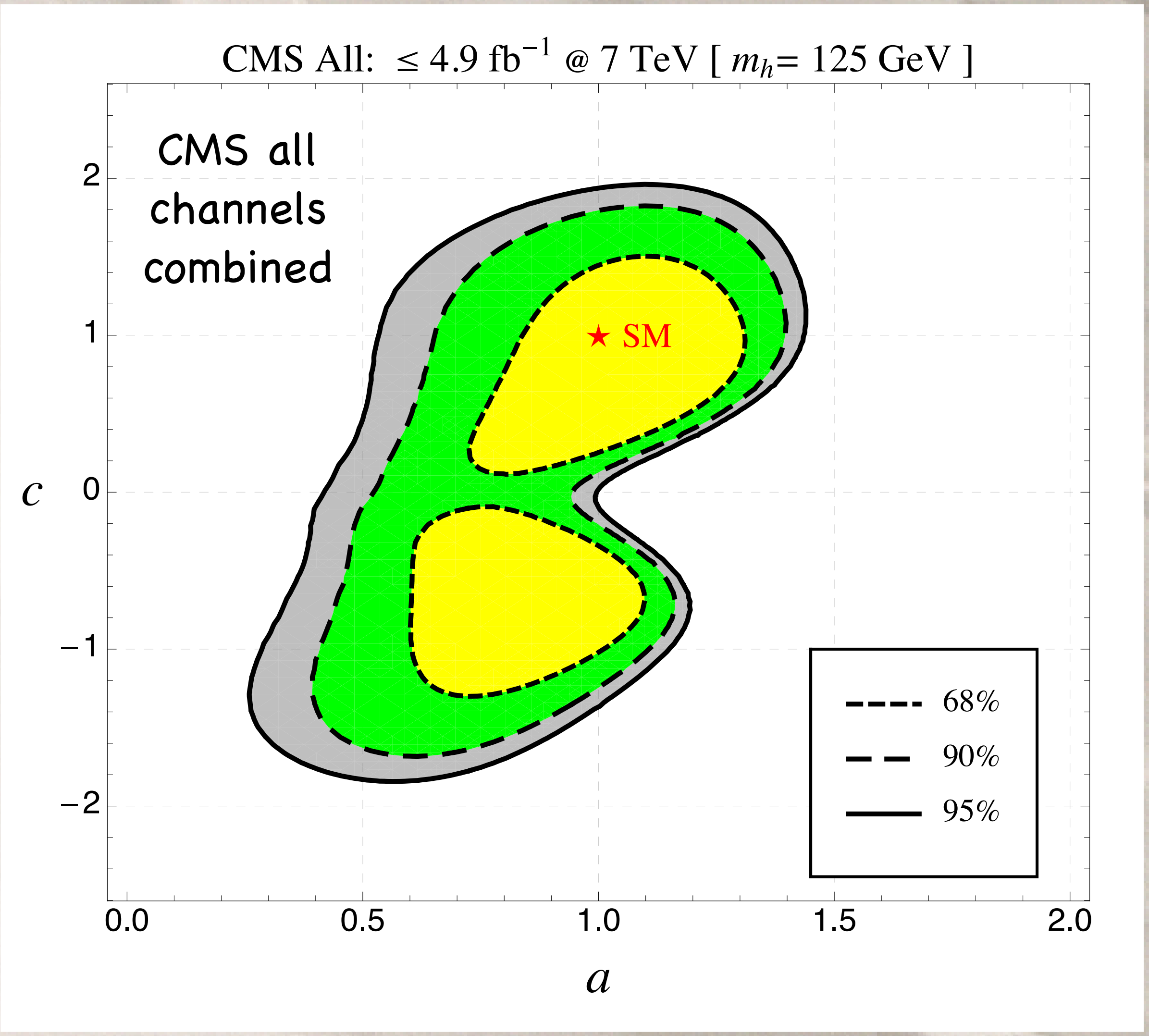
  Klute, Lafaye, Plehn, Rauch, Zerwas, arXiv:1205.2699

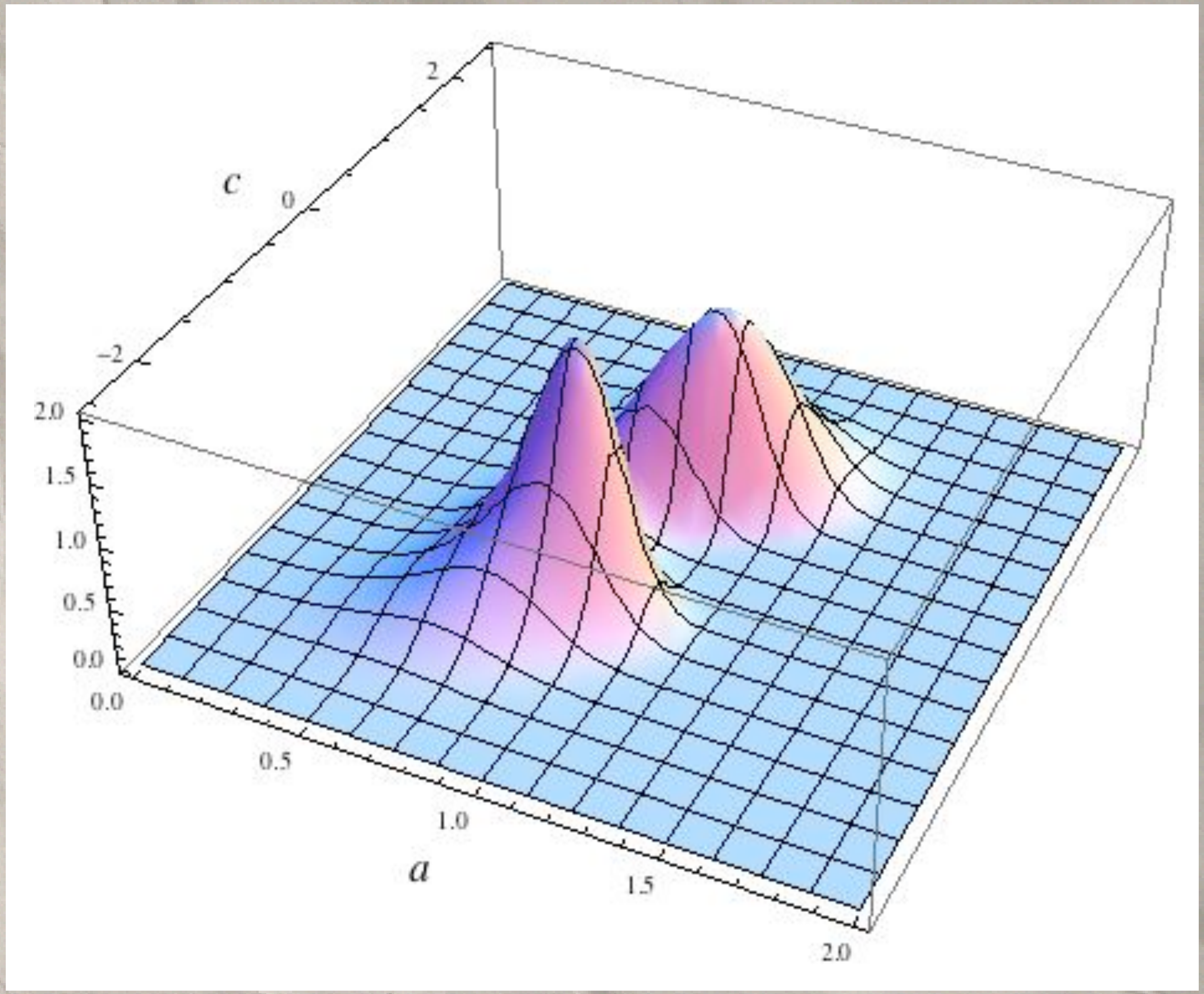
  ⋮

95% Exclusion for various mH



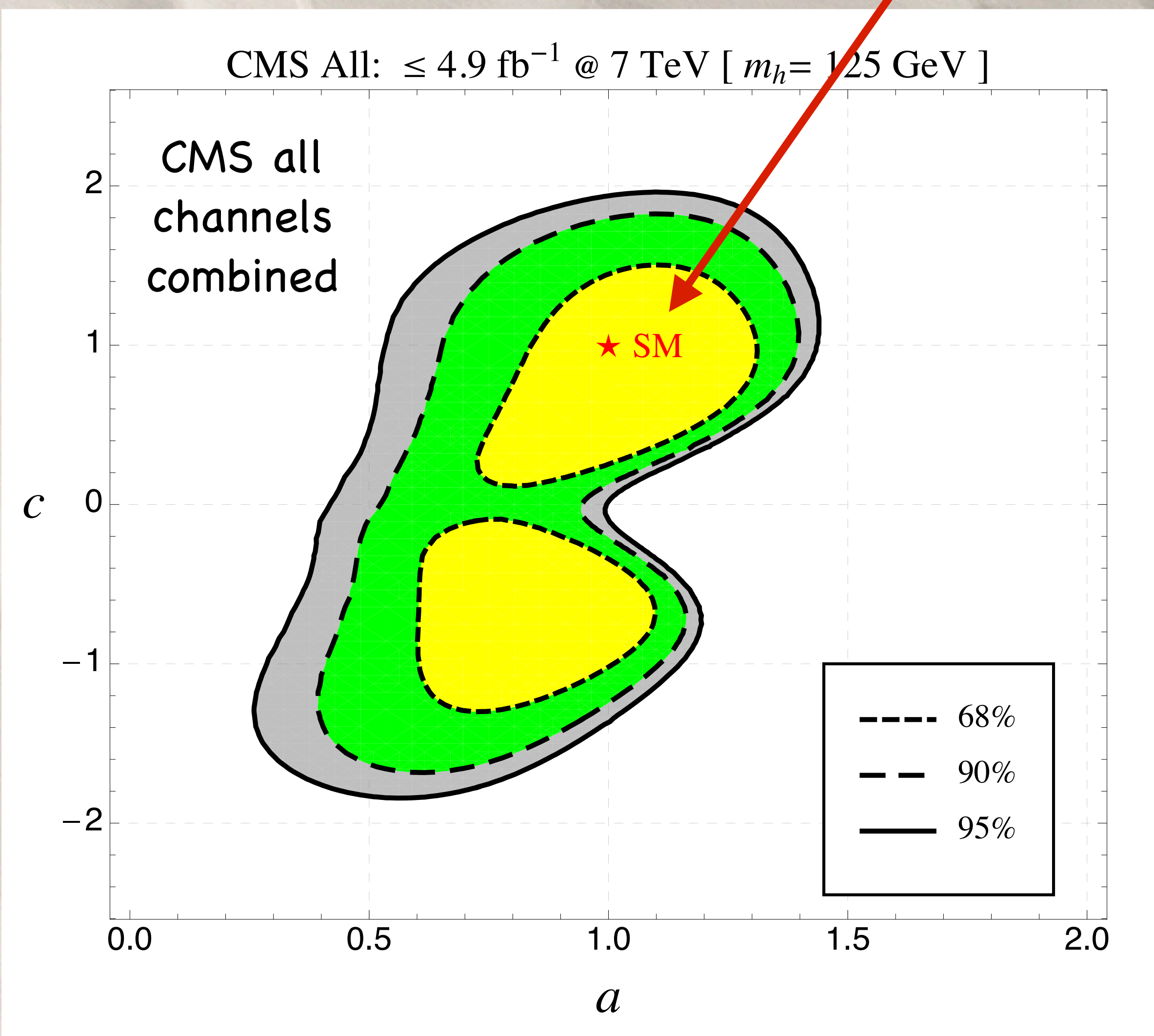
Fit at m_H=125GeV

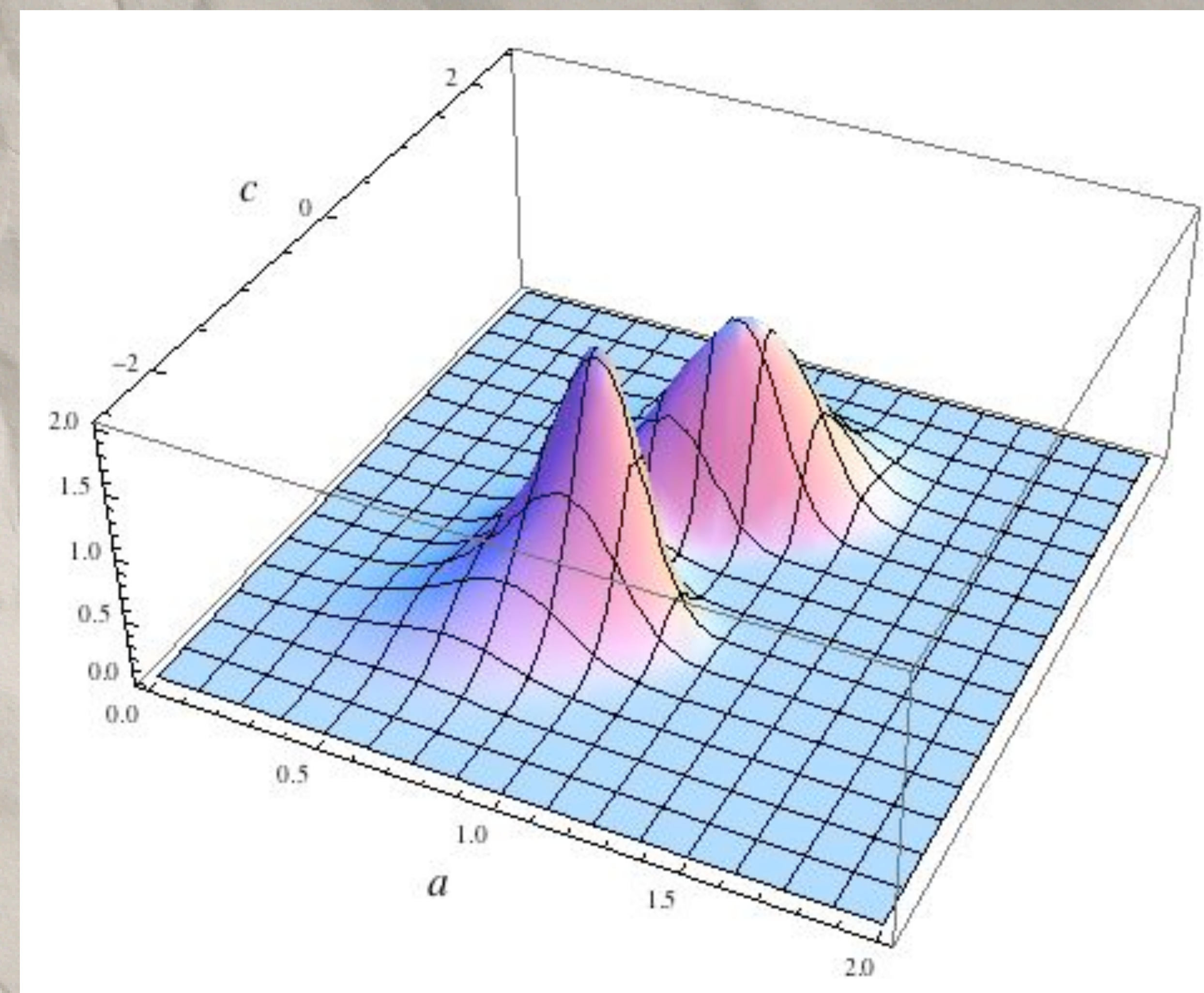




Fit at m_H=125GeV

First solution SM-like
(a=1.0, c=0.75)





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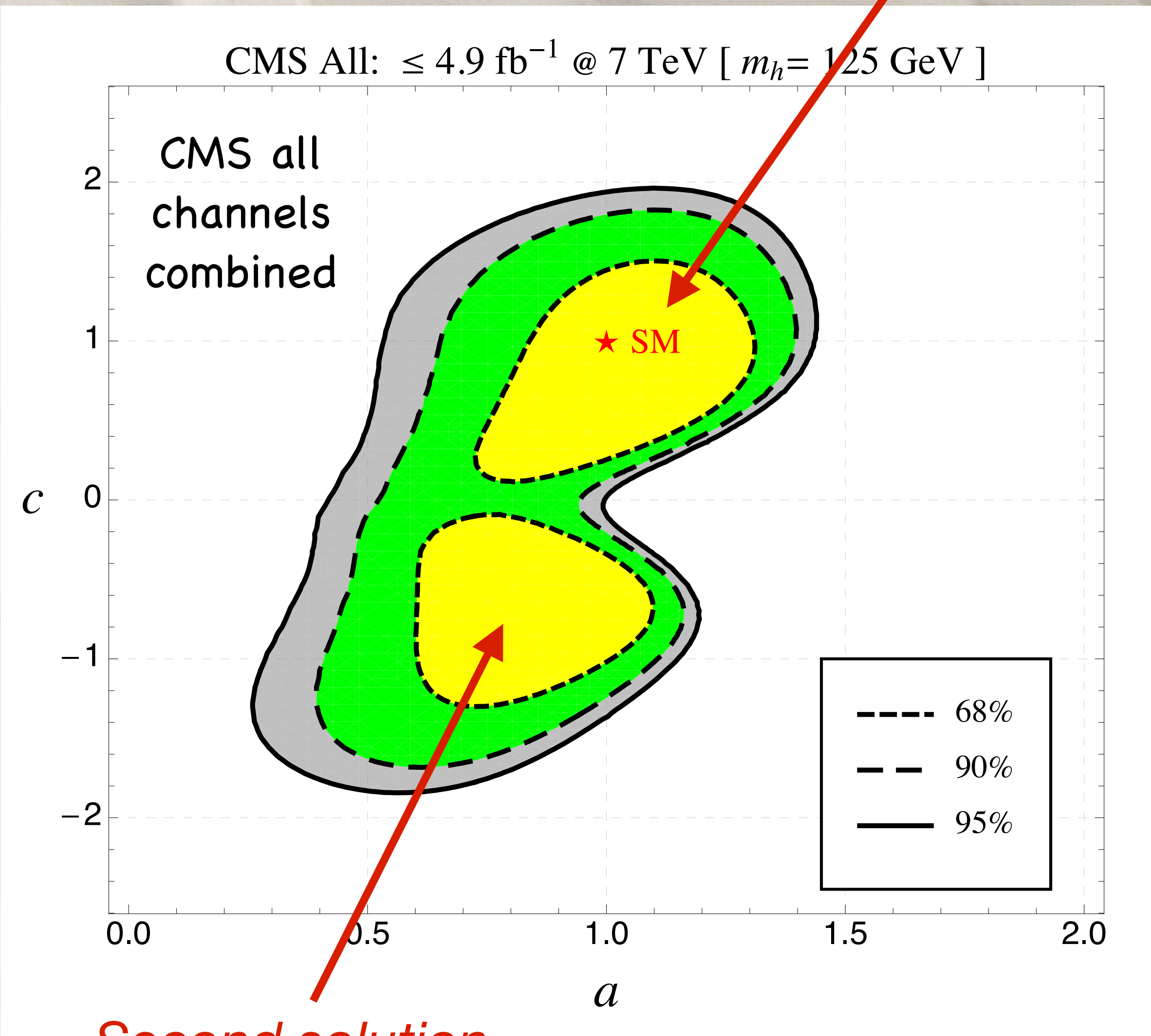

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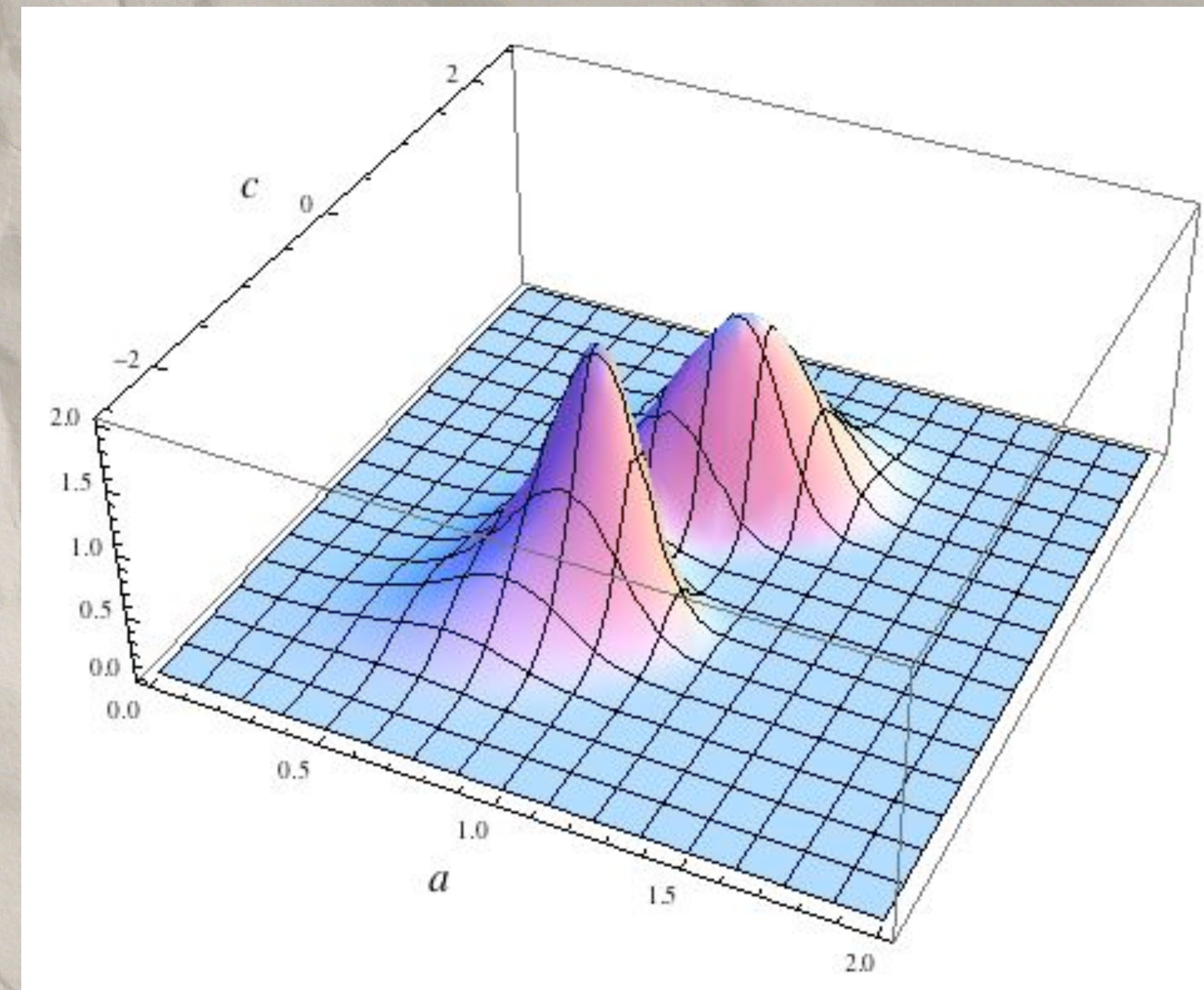

Second solution due to degeneracy in $\gamma\gamma$:

$$a_2 \simeq +a_1 \frac{4.5\,a_1 - c_1}{4.5\,a_1 + c_1}$$

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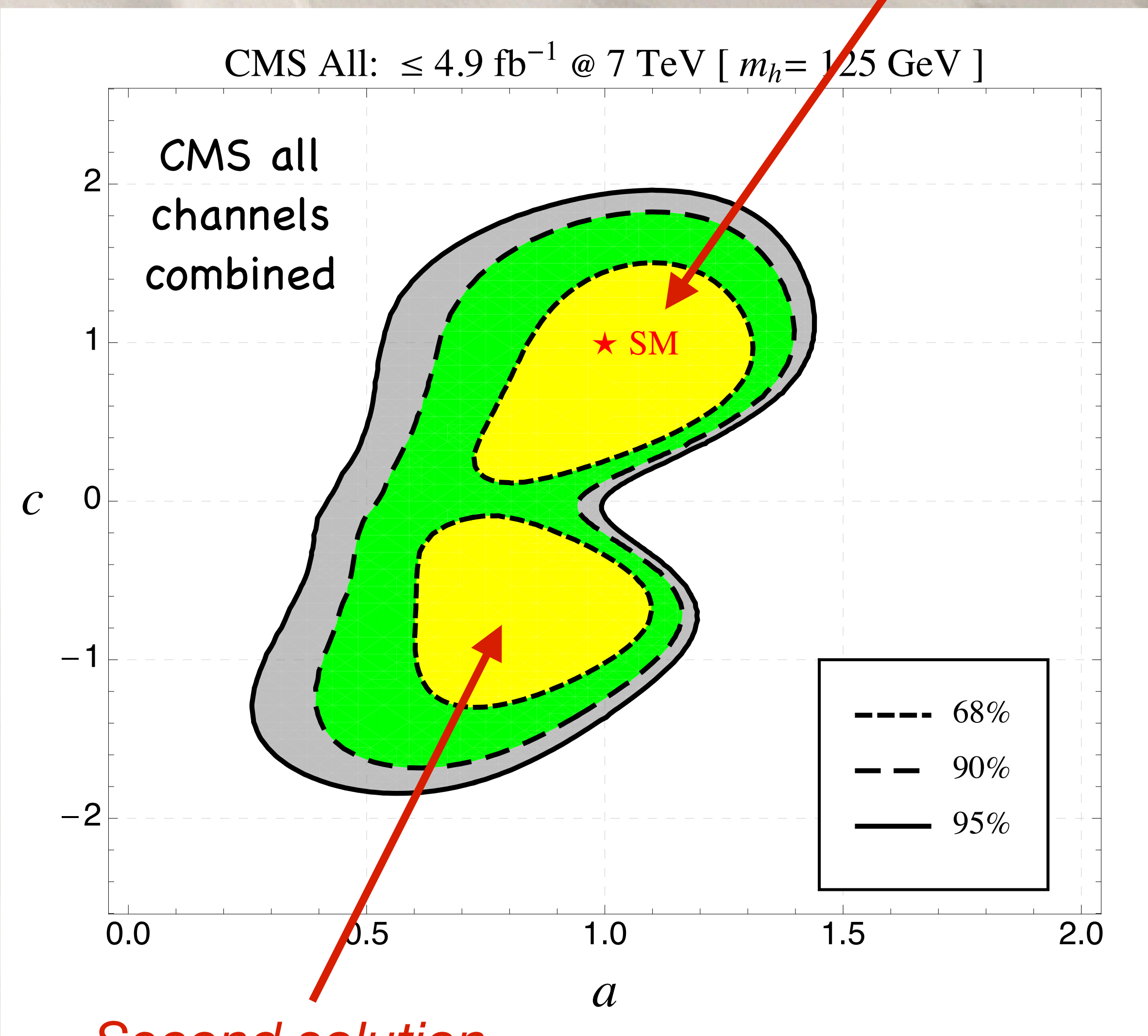

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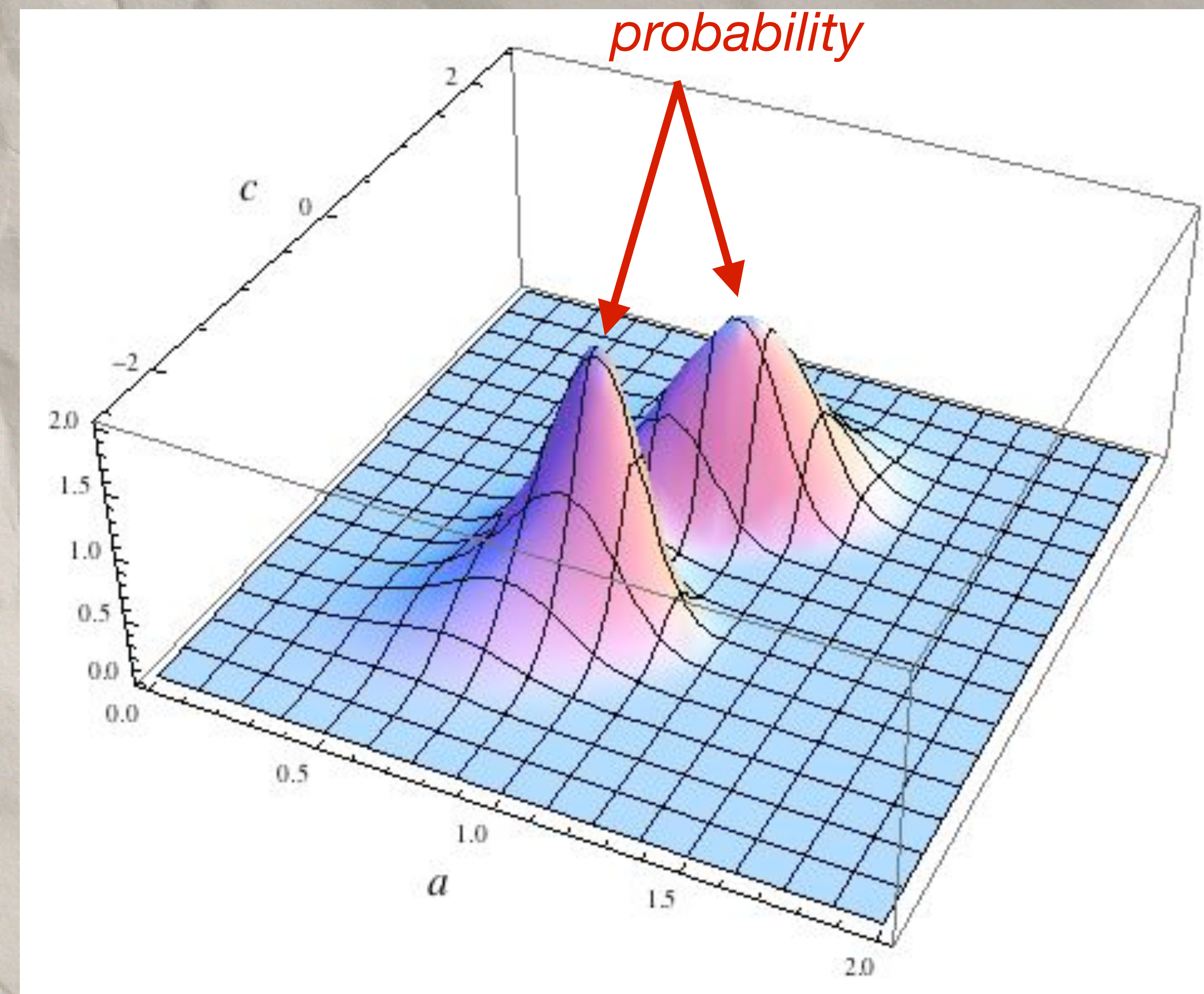

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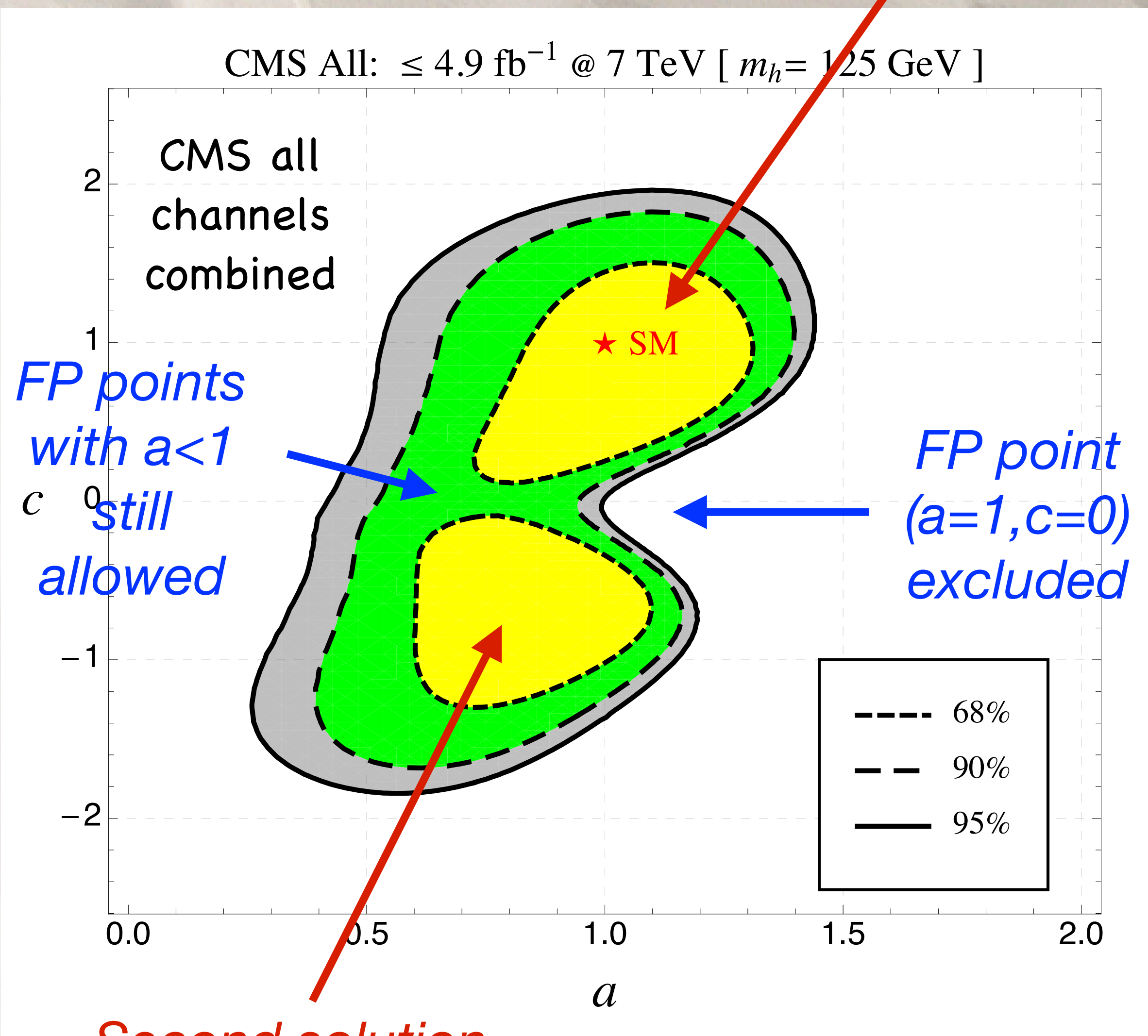

FP points with a<1 still allowed

FP point (a=1,c=0) excluded

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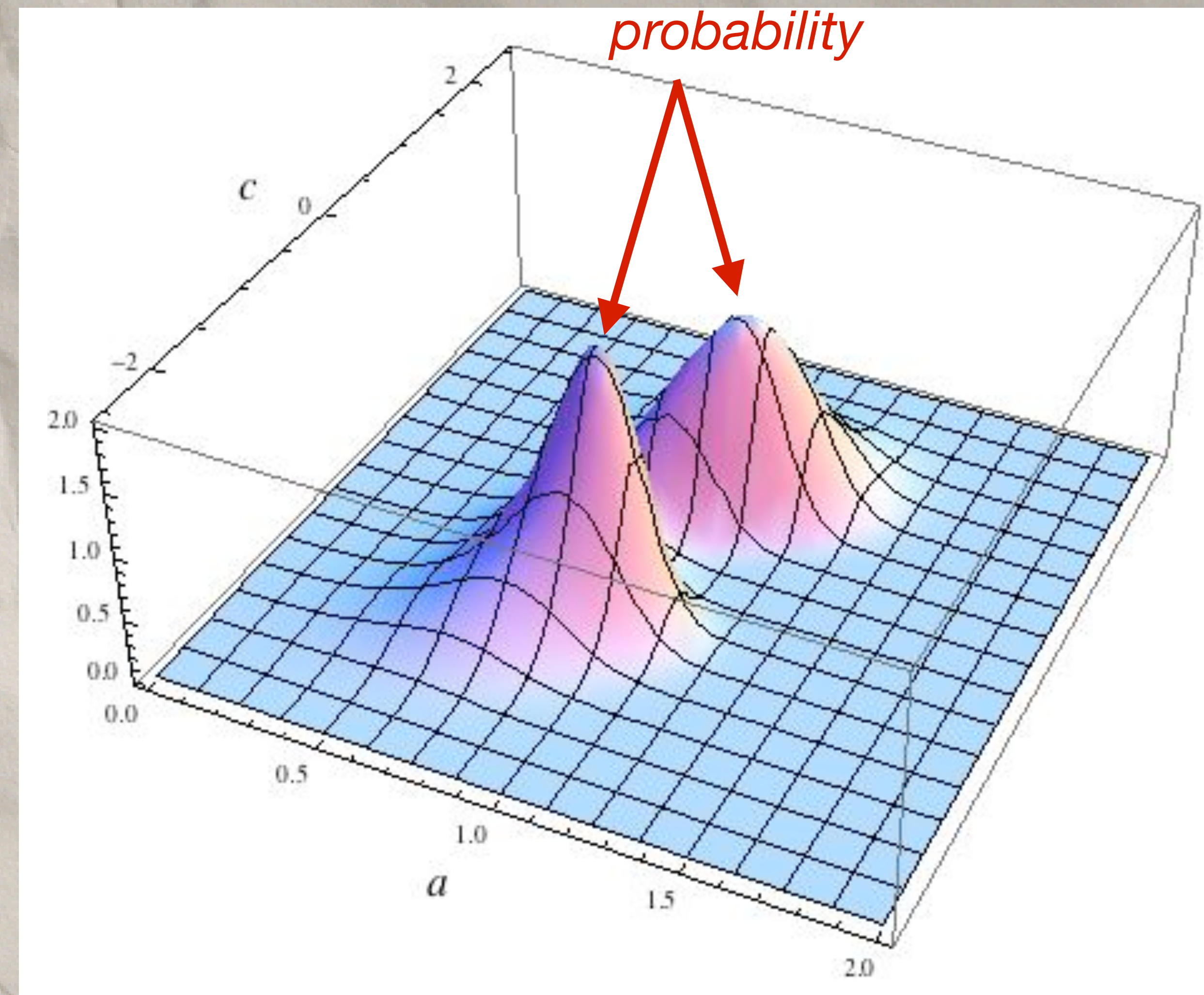

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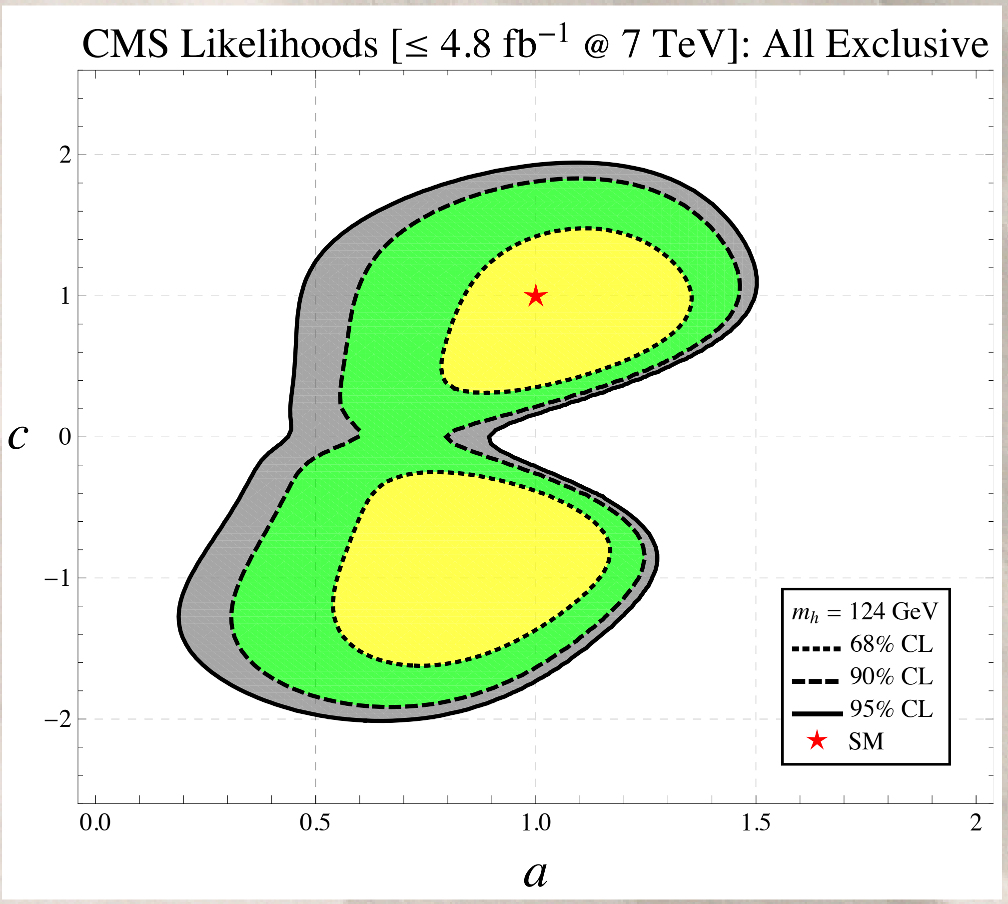
The importance of being "exclusive"

(from J. Galloway, talk at Pheno 2012)

CMS all channels combined:
WW and $\gamma\gamma$ fully EXCLUSIVE



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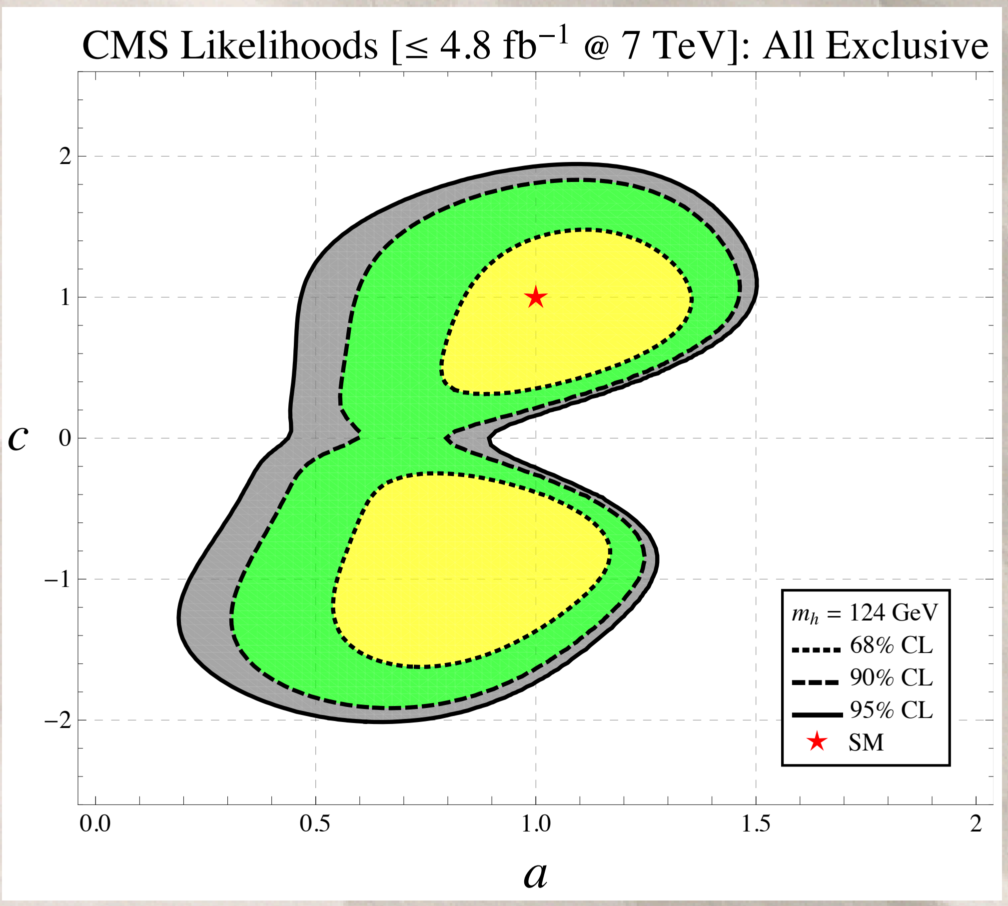

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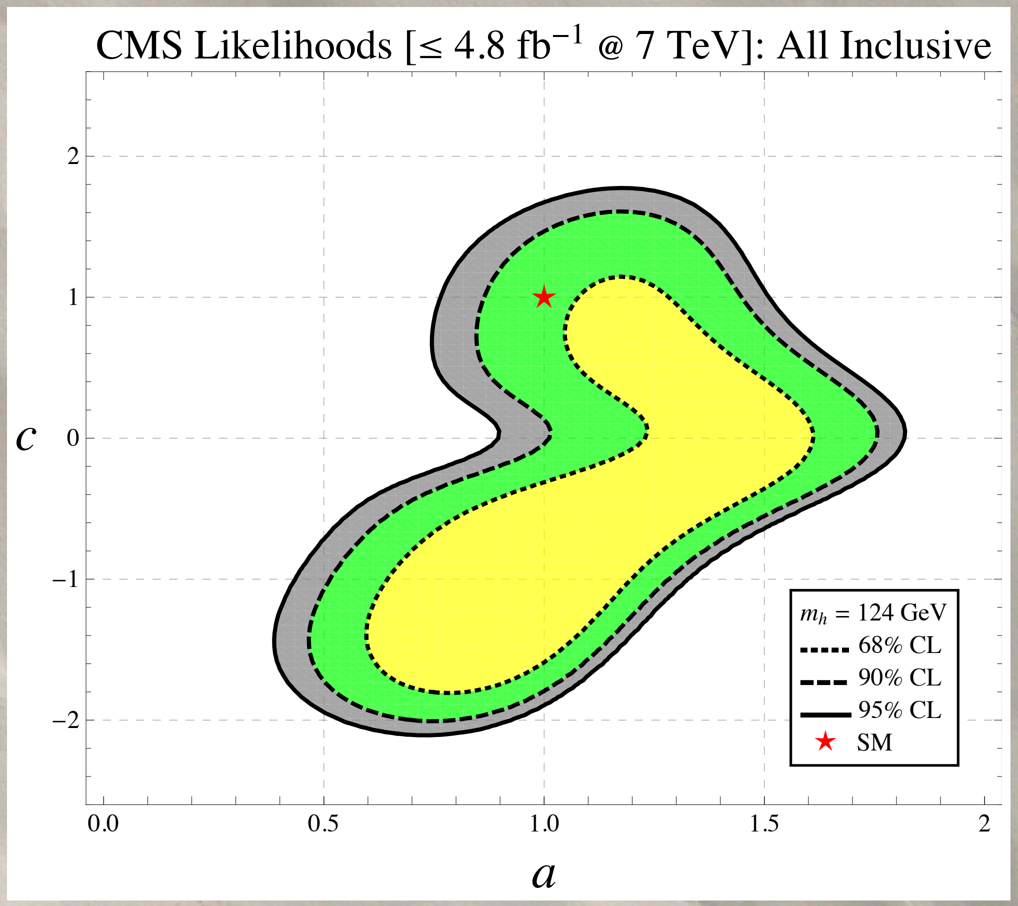

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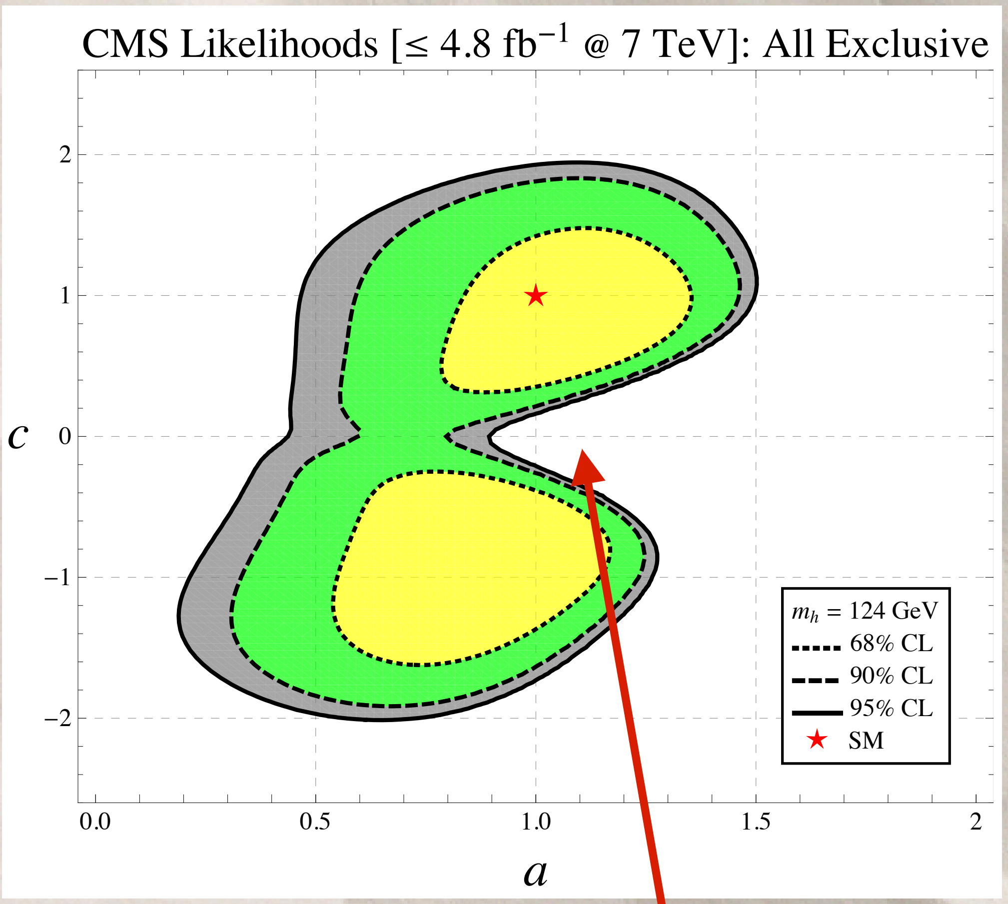

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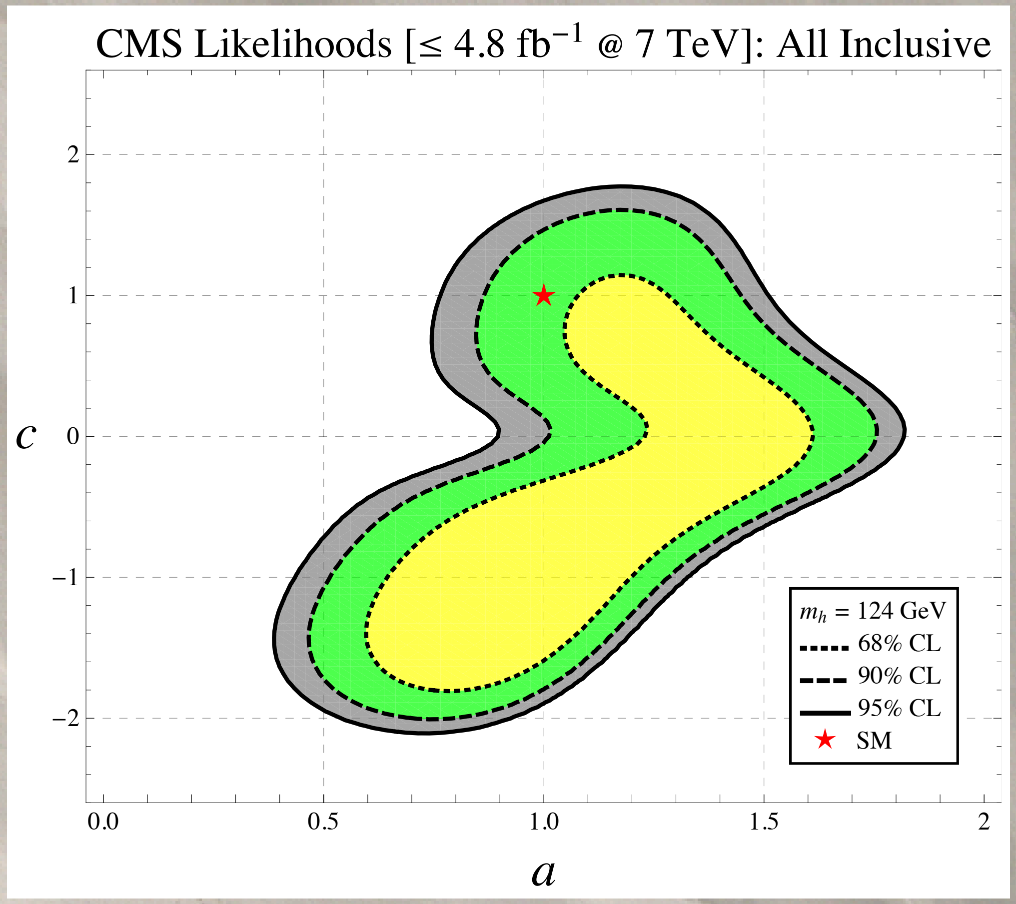

absence of excess in WWjj and exclusive $\gamma\gamma$ analysis of CMS rule out FP region with a>1

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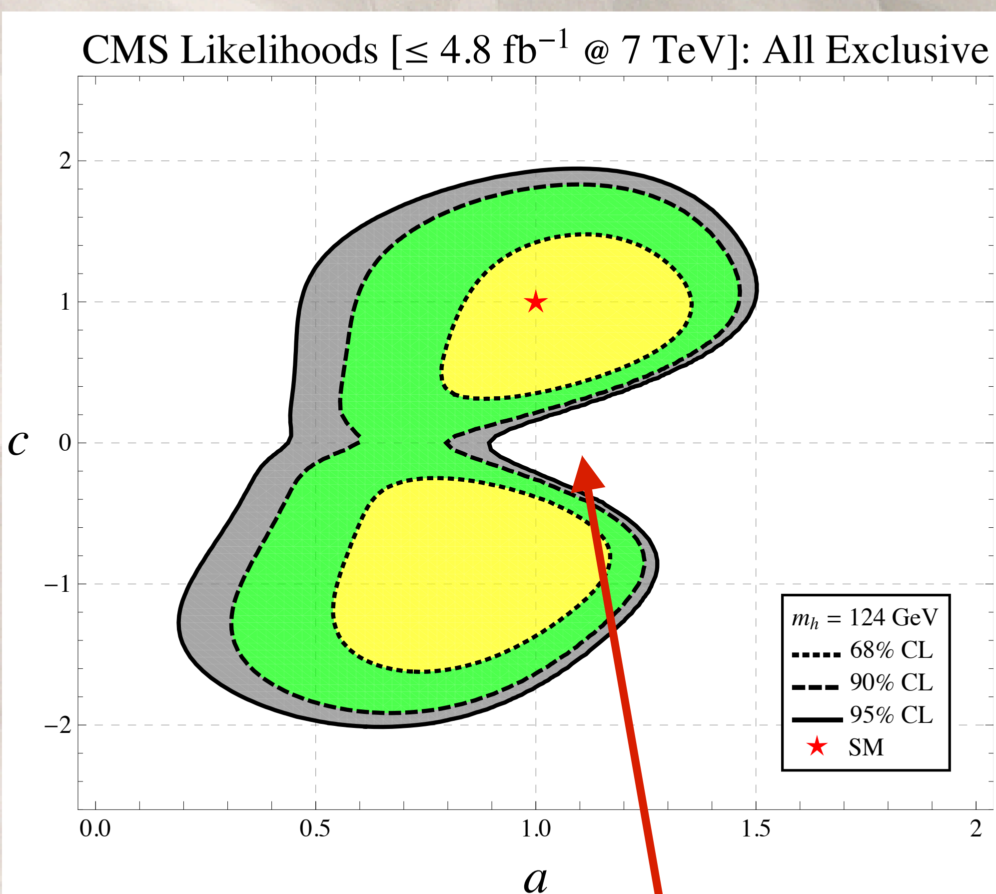

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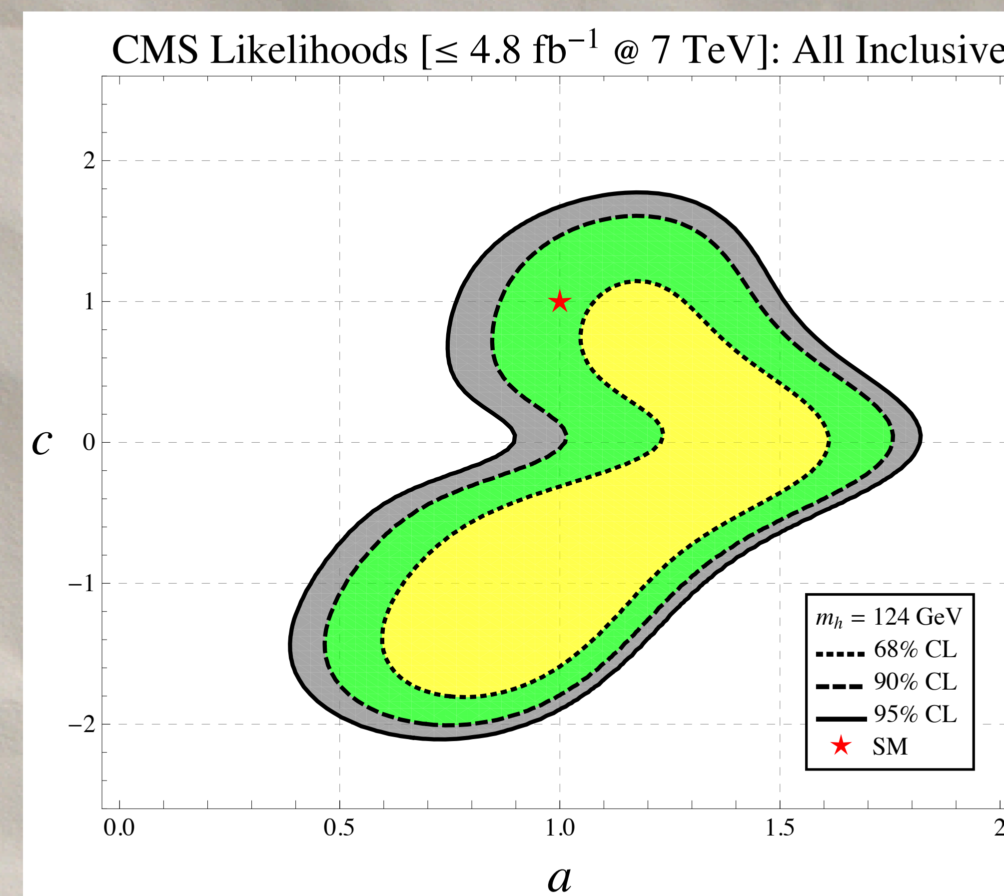

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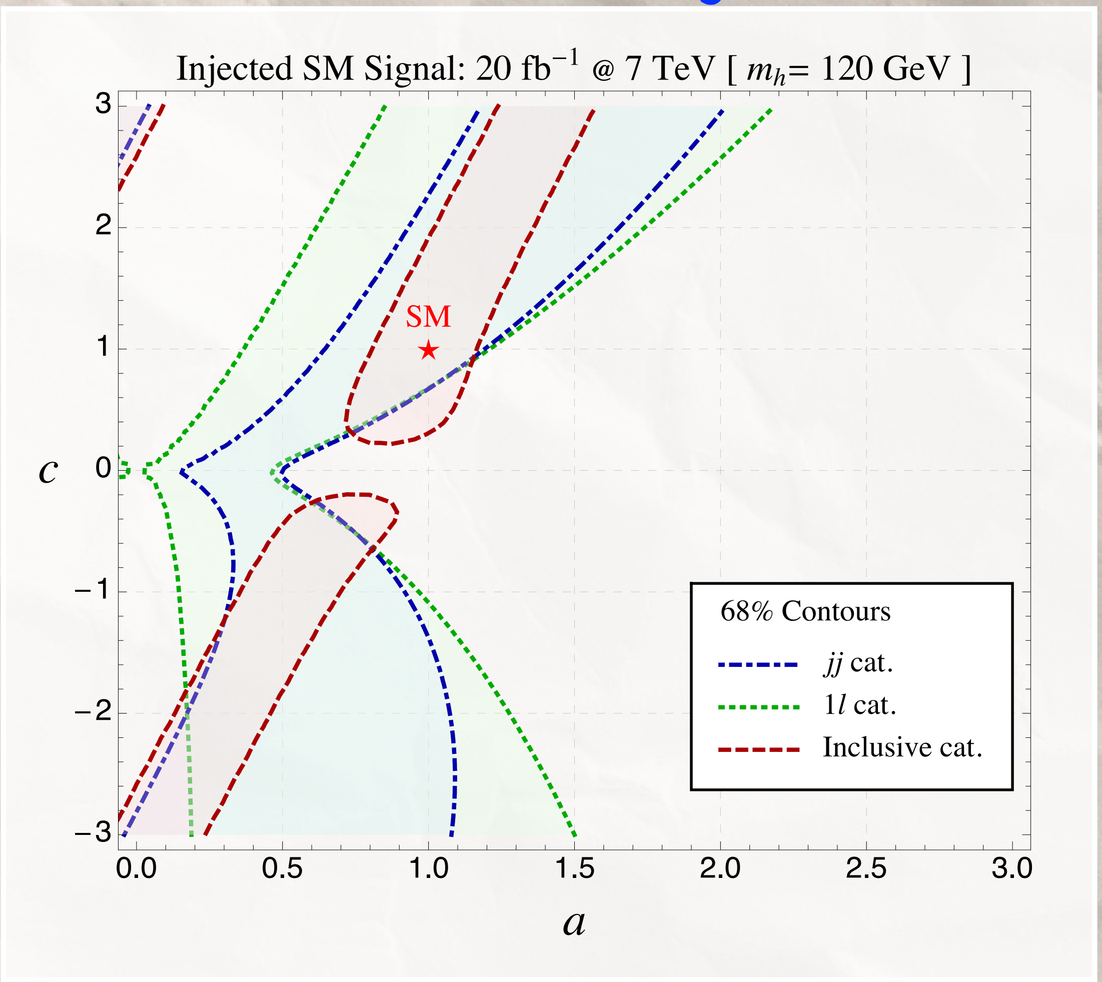
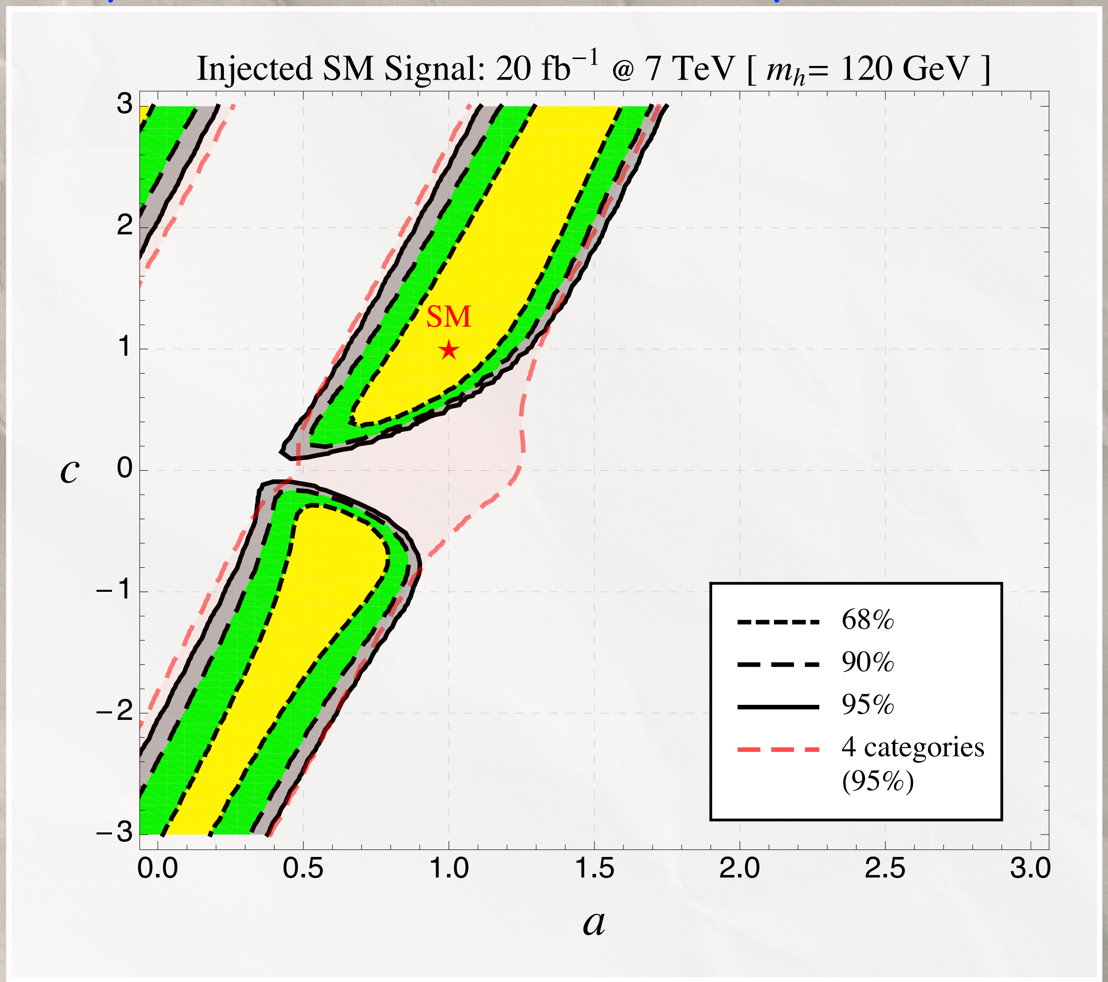
Moral: Exclusive analyses probe individual Higgs productions and are much more powerful than inclusive ones

Exclusive vs Inclusive: the $h \to \gamma\gamma$ channel

Projection at 20 fb^{-1} (SM injected)
Breakdown of exclusive categories



Projection at 20 fb^{-1} (SM injected)
Fully exclusive vs inclusive analysis



$$\mu_{jj} \sim \mu_{1l} \sim a^2 \, \frac{(4.5\,a - c)^2}{c^2}$$

$$\mu_{incl} \sim (c^2 + \zeta\, a^2)\, \frac{(4.5\,a - c)^2}{c^2}$$

results from:
Azatov, R.C., Del Re, Galloway, Grassi, Rahatlou, arXiv:1204.4817

Shall we break the degeneracy ?

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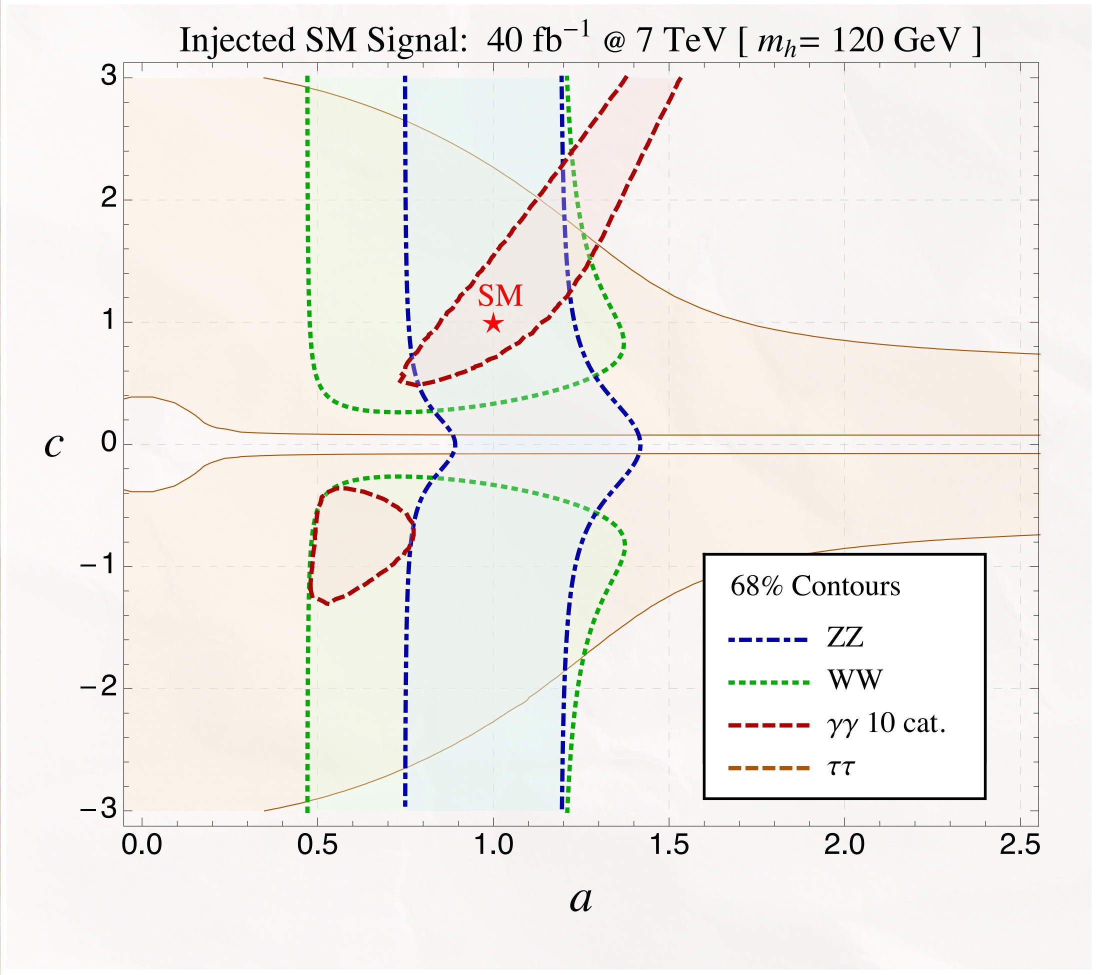

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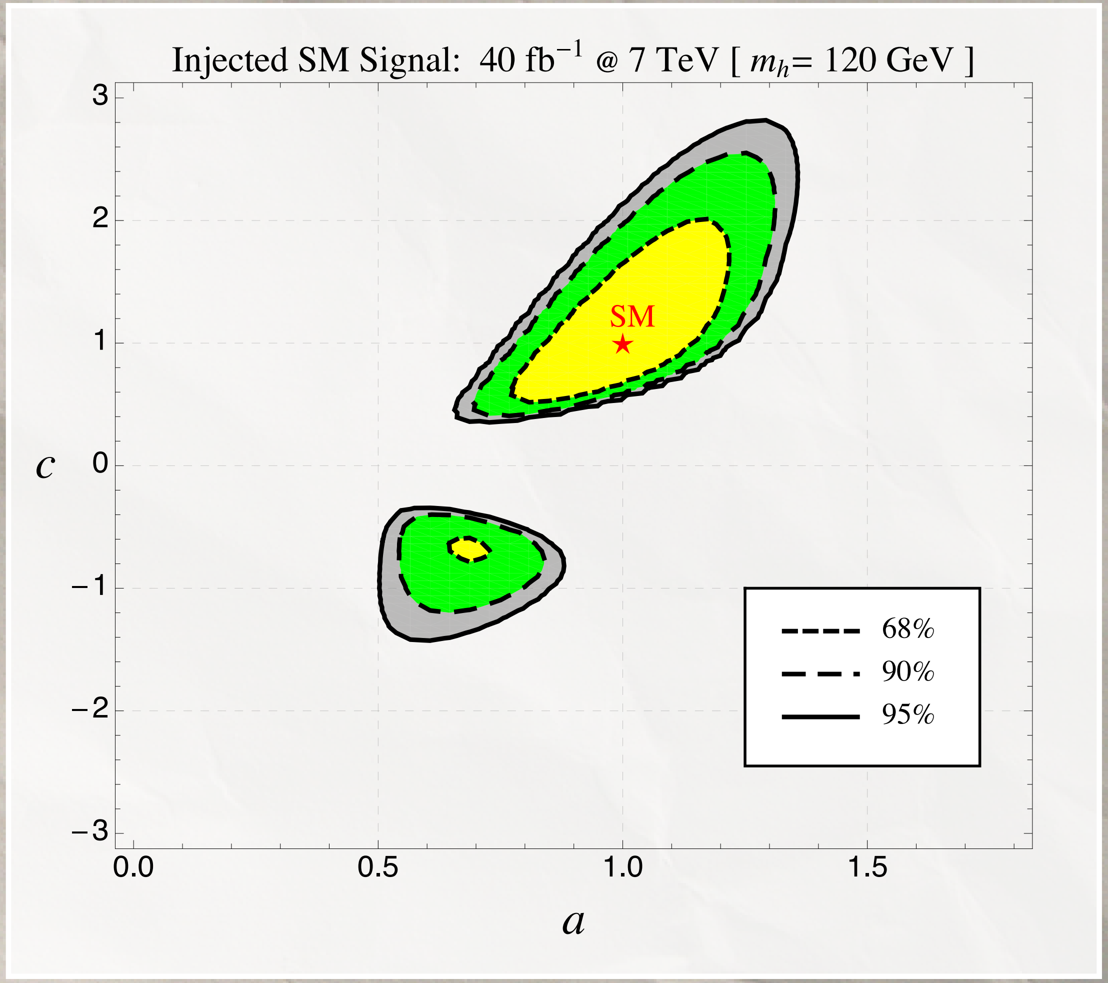

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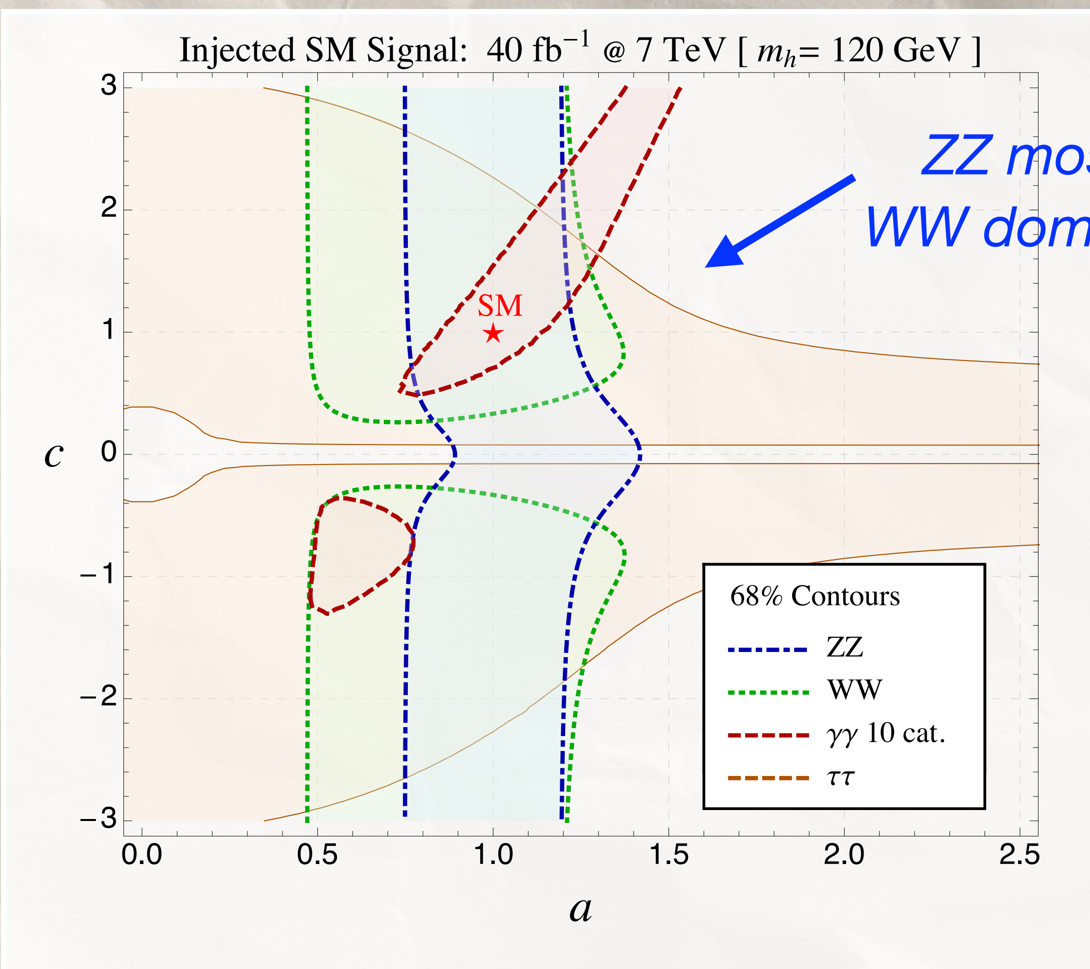

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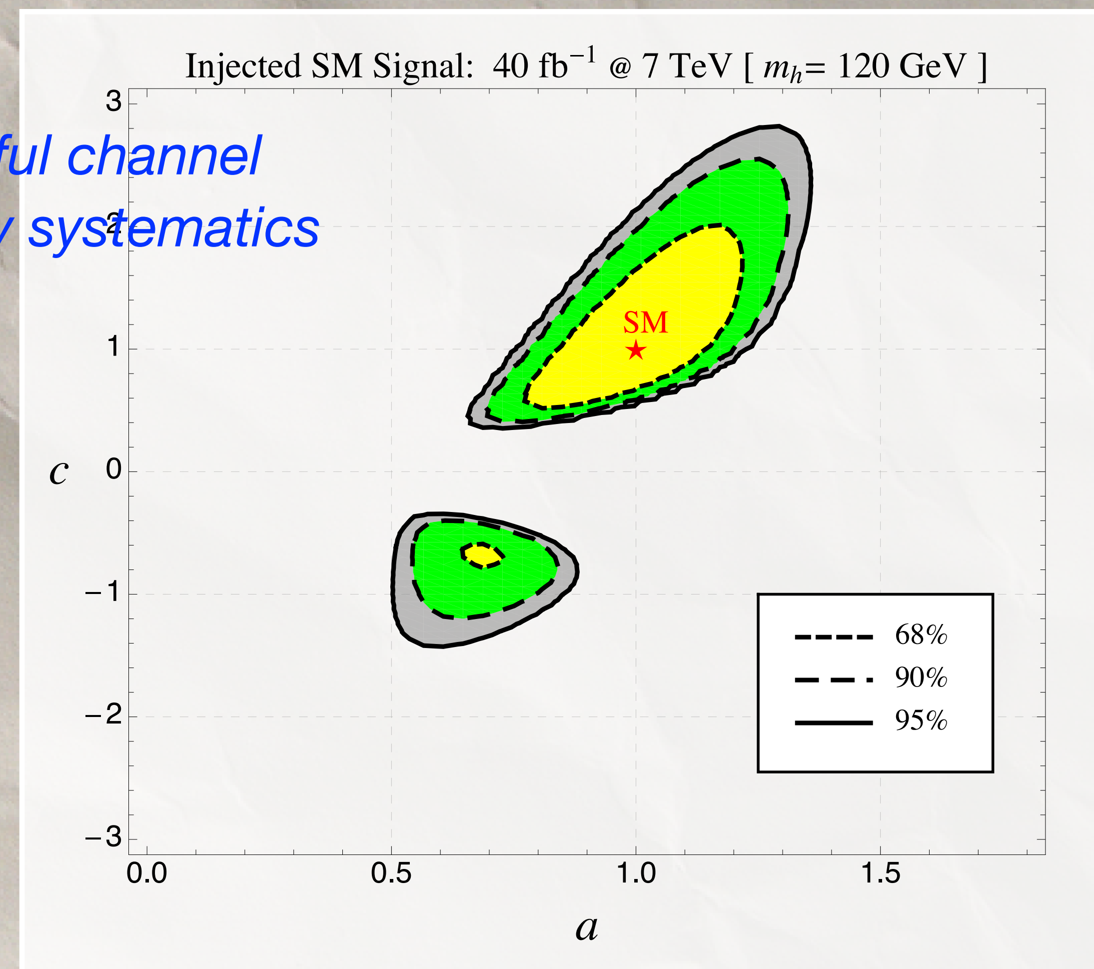

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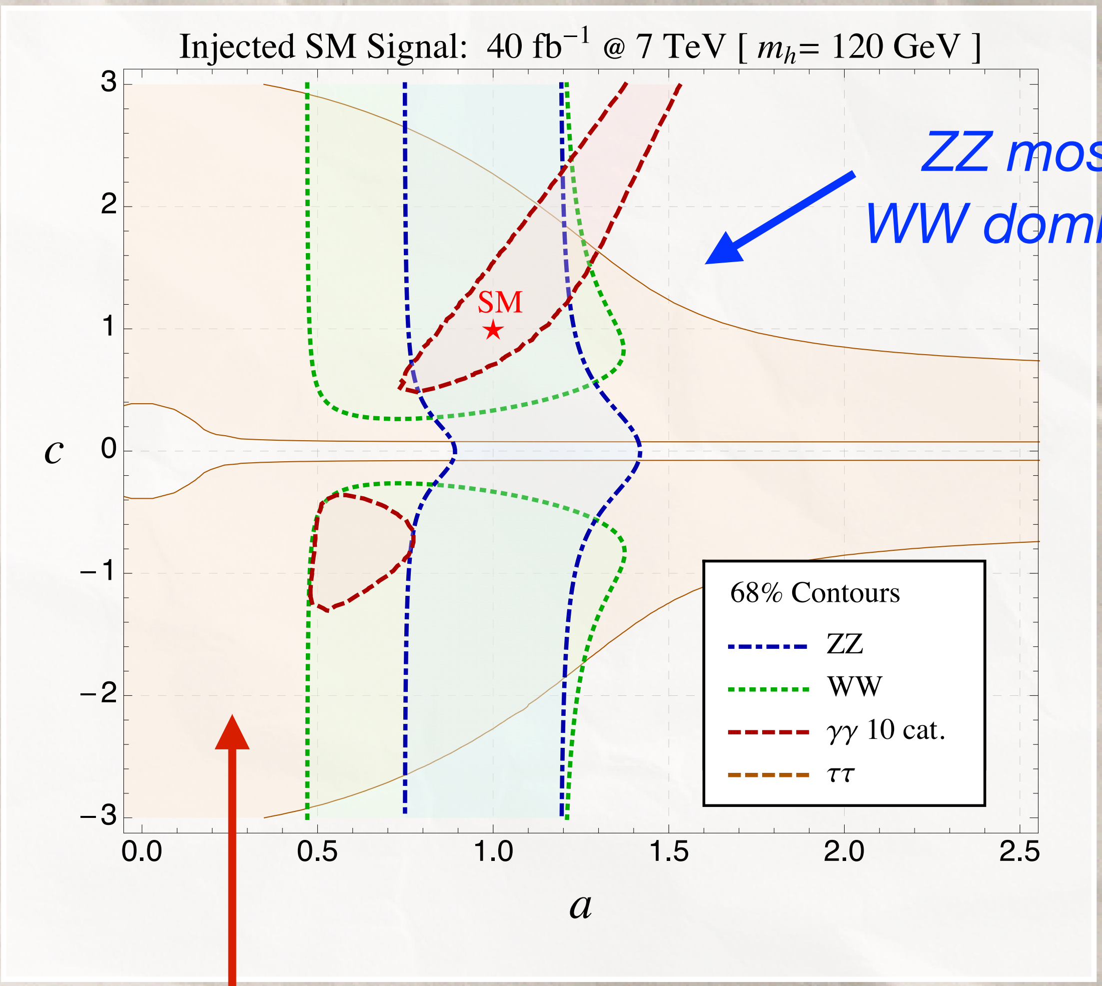

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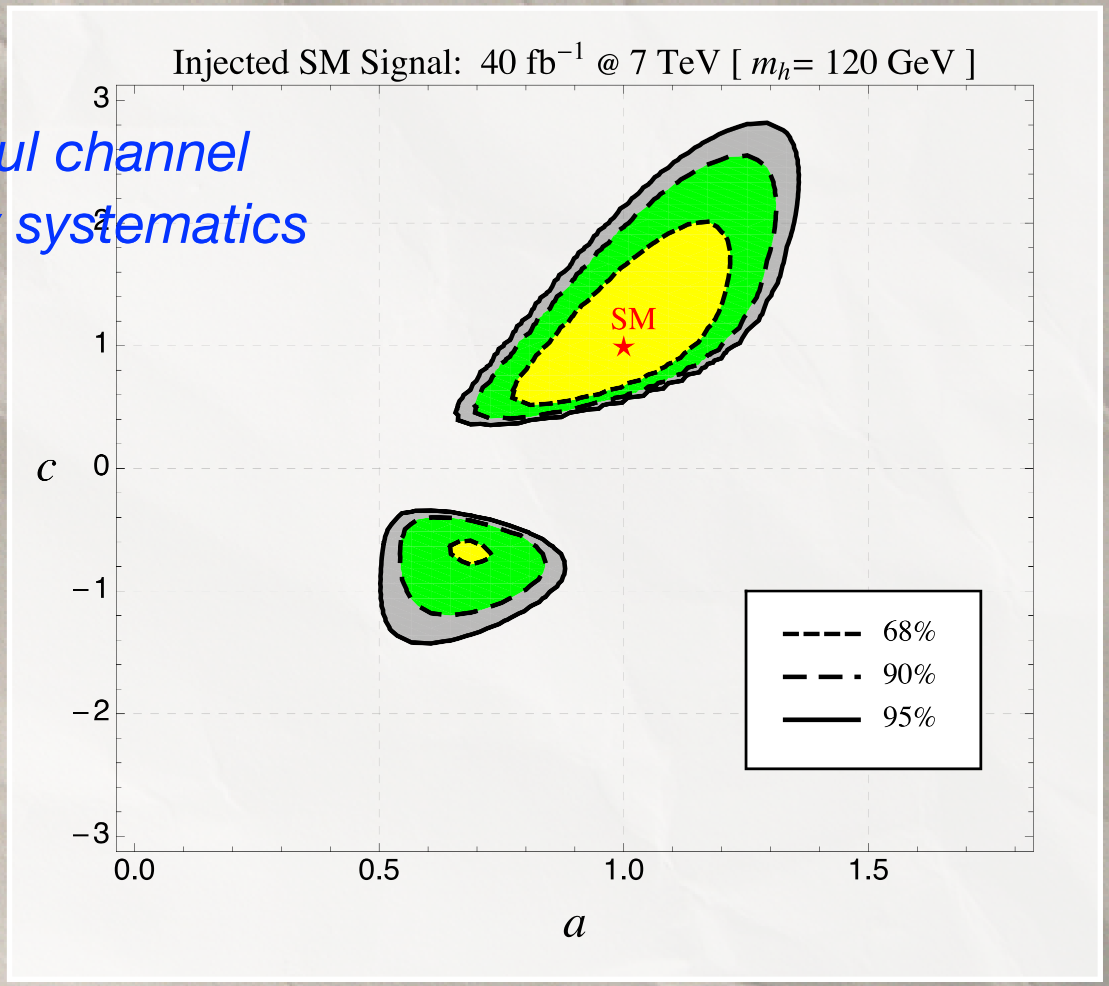

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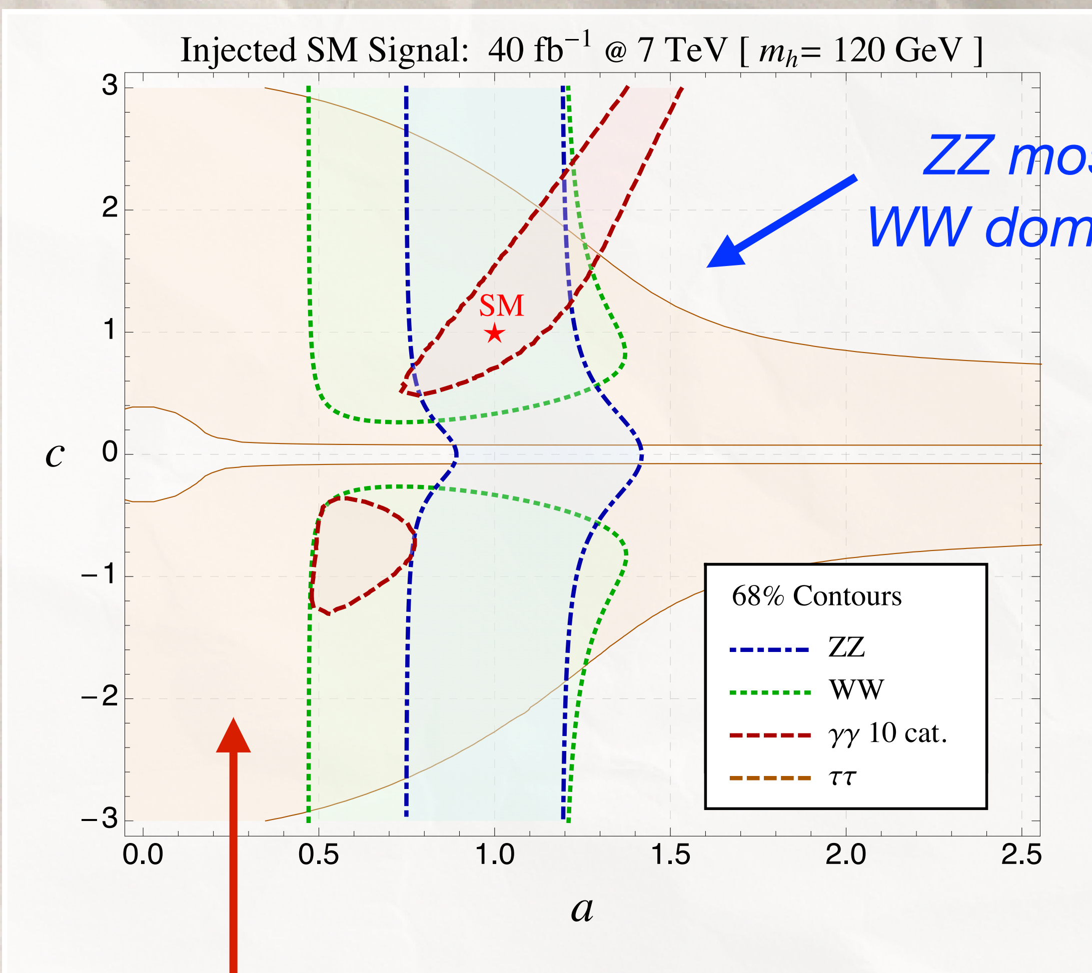

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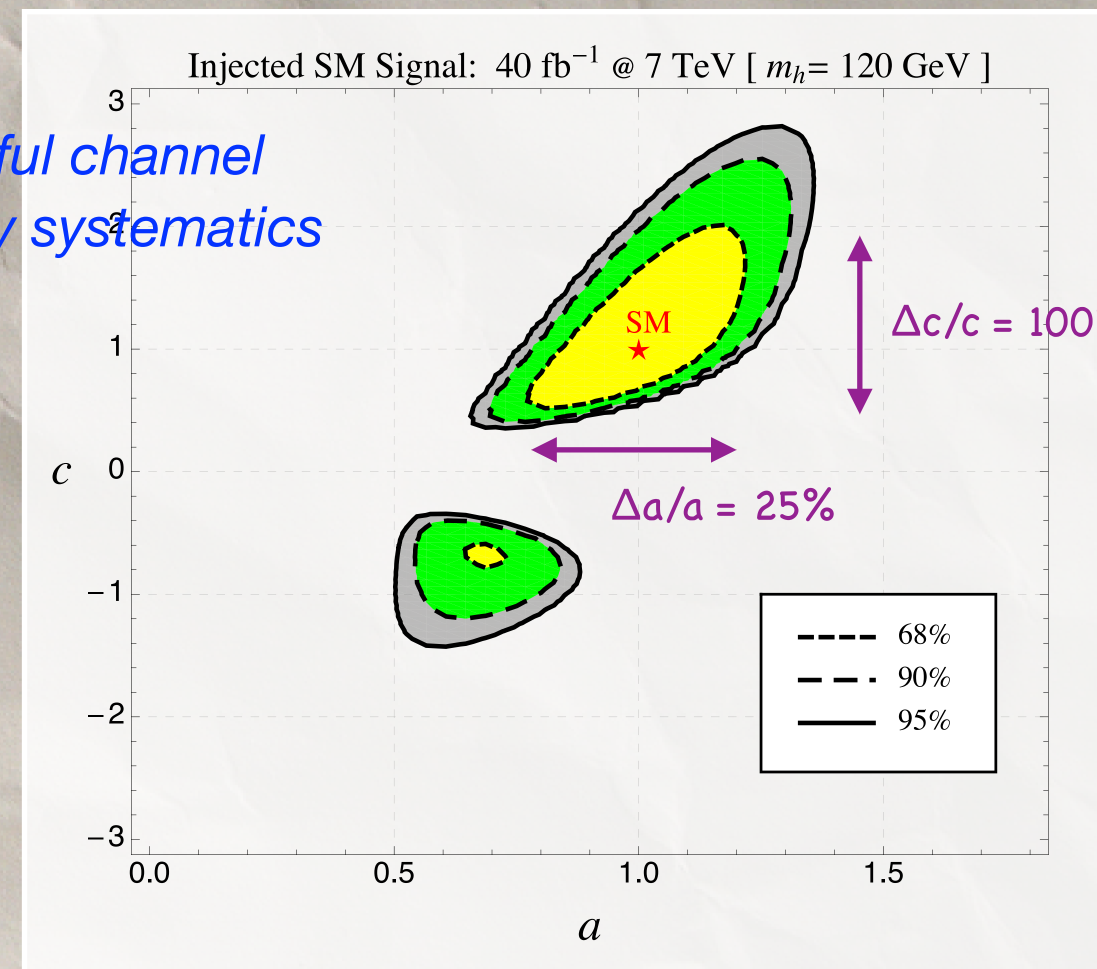

$\Delta c/c$ = 100%

$\Delta a/a$ = 25%

results from:
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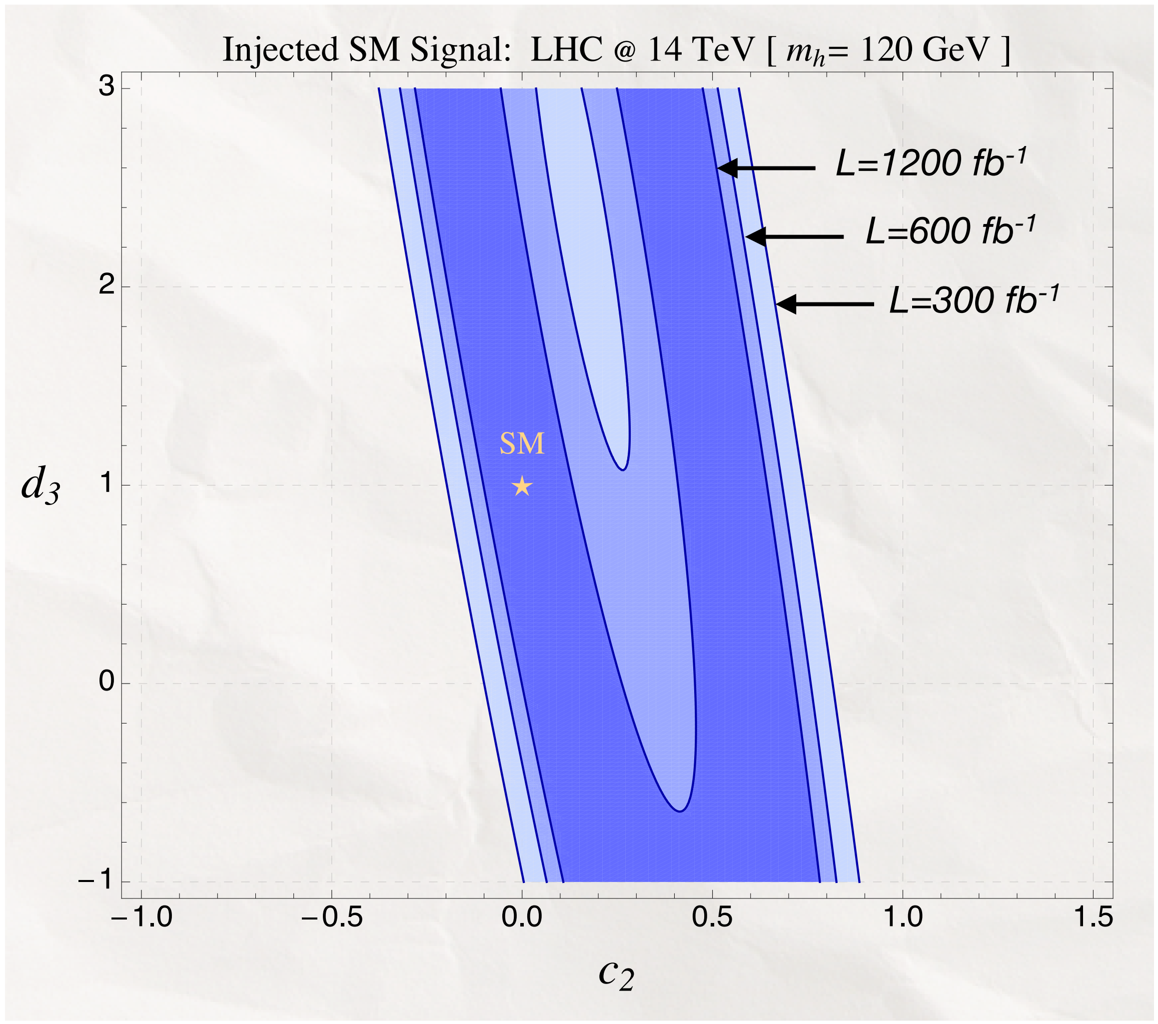
- First fit to (a,c) based on LHC data shows: i) SM is in good shape; ii) there is a second, degenerate solution
- Exclusive vs Inclusive analyses much more powerful in a model-independent approach
- Double Higgs production via gluon fusion ($gg \to hh$) strongly sensitive on tthh coupling (c_2)

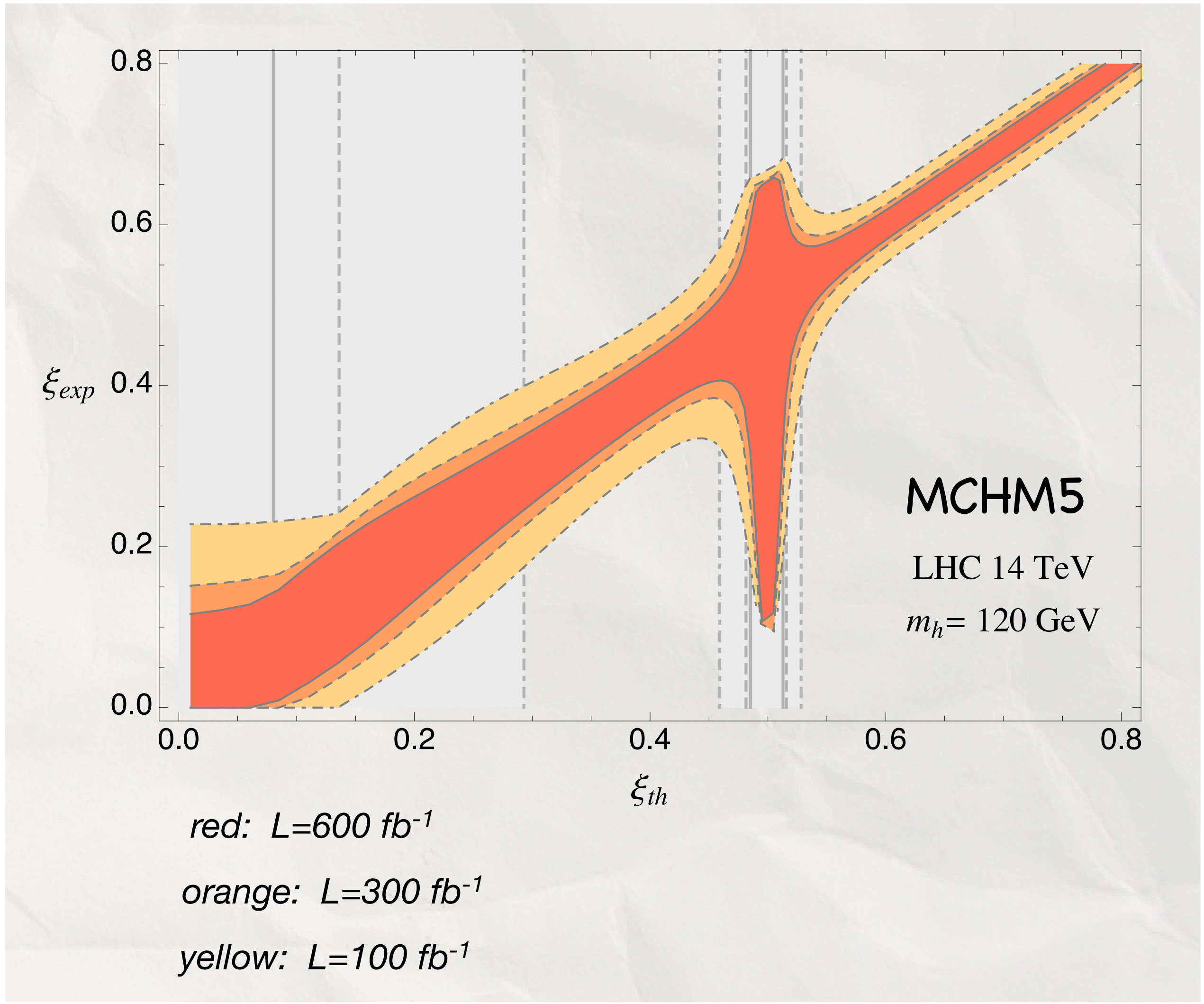
EXTRA SLIDES

Double Higgs production via gluon fusion

Precision on couplings (curves at 68% prob.)



Precision on couplings (curves at 68% prob.)

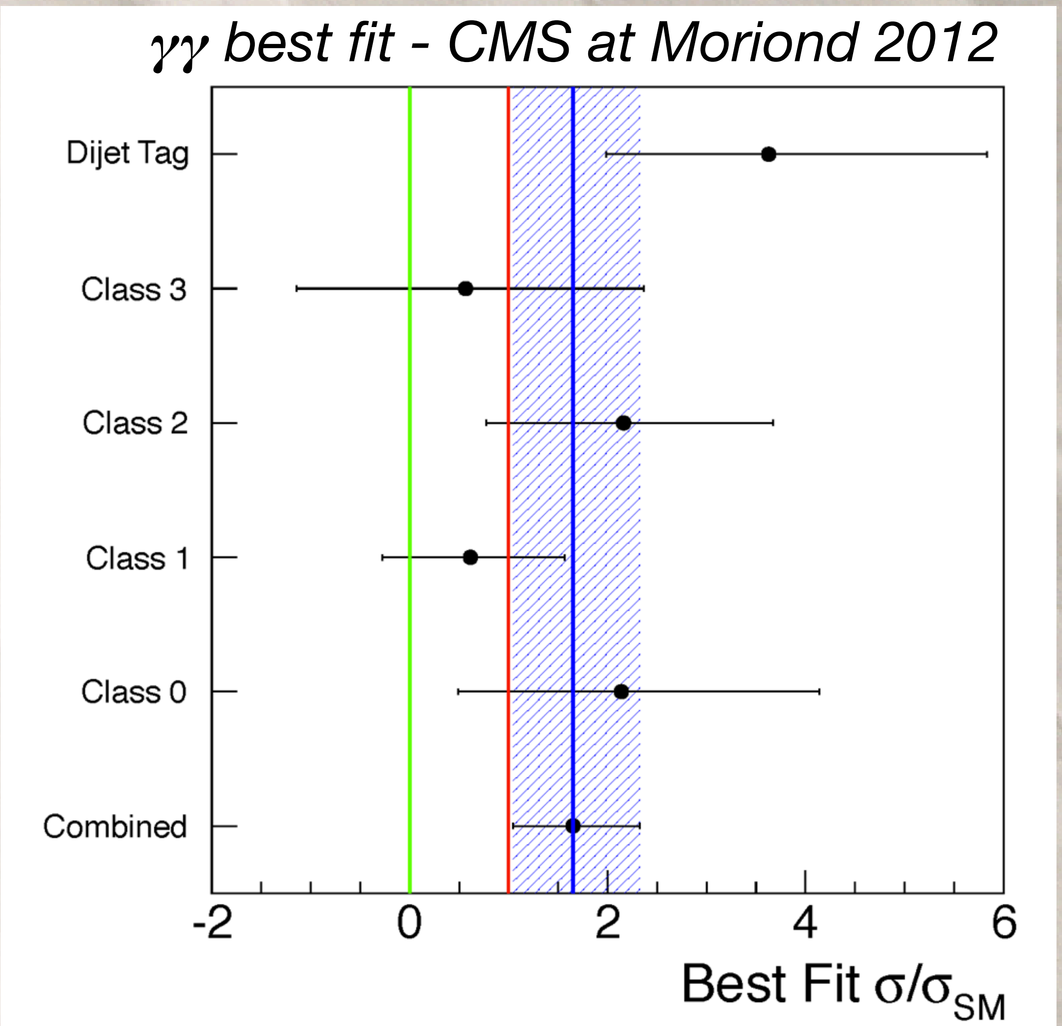


results from:

R.C., Ghezzi, Moretti, Panico, Piccinini, Wulzer, arXiv:1205.5444

Ex: with L=300fb^{-1} $\Delta\xi/\xi$ = 30% for ξ=0.2

Exclusive vs Inclusive: the h→$\gamma\gamma$ channel



First solution:
(a=1.0, c=0.75)

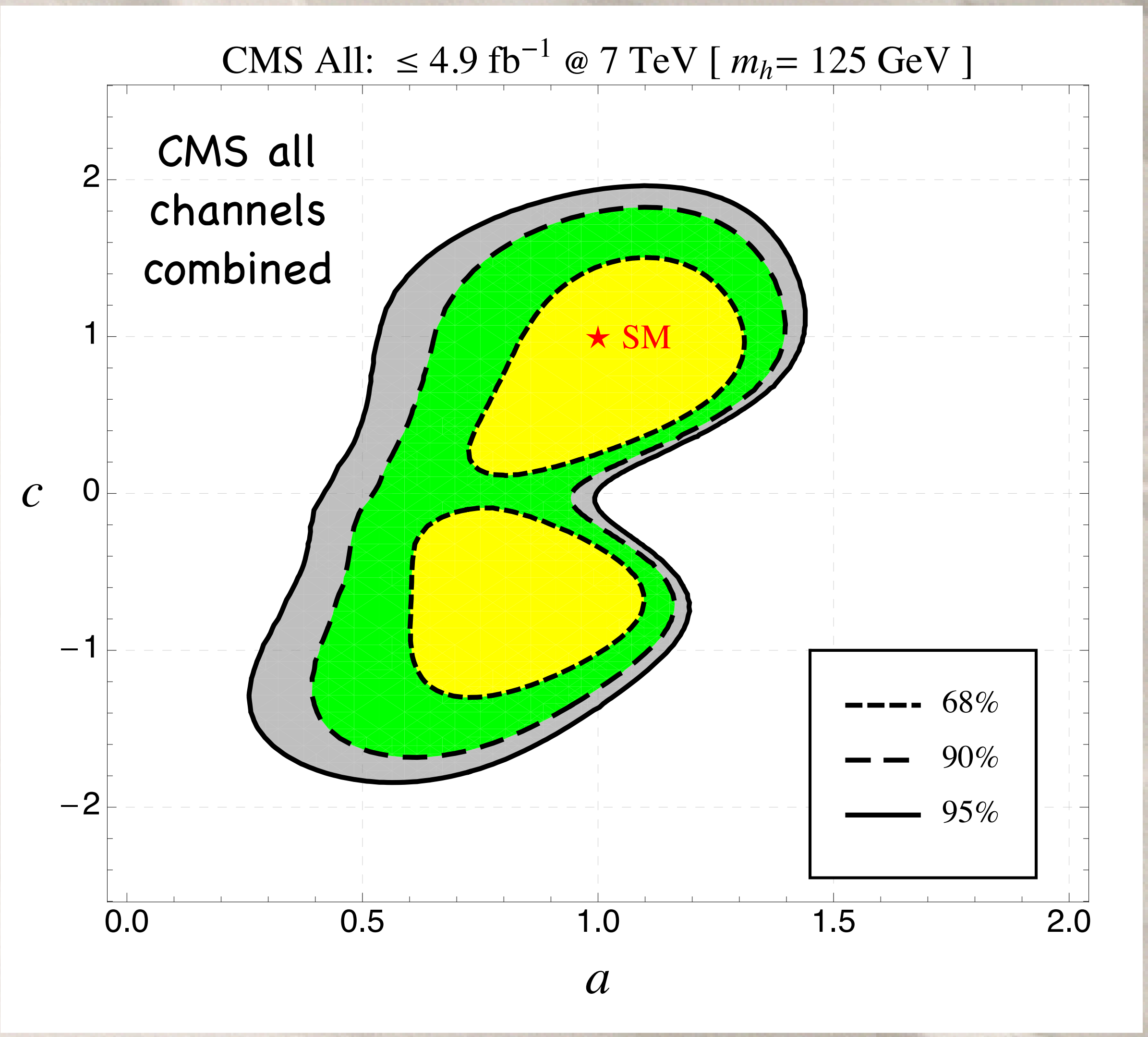
$$\mu(\gamma\gamma jj) \sim 2$$
$$\mu(\gamma\gamma\ incl) \sim 1$$
$$\mu(WW2j) \sim 1.2$$
$$\mu(WW0j, WW1j) \sim 1.7$$

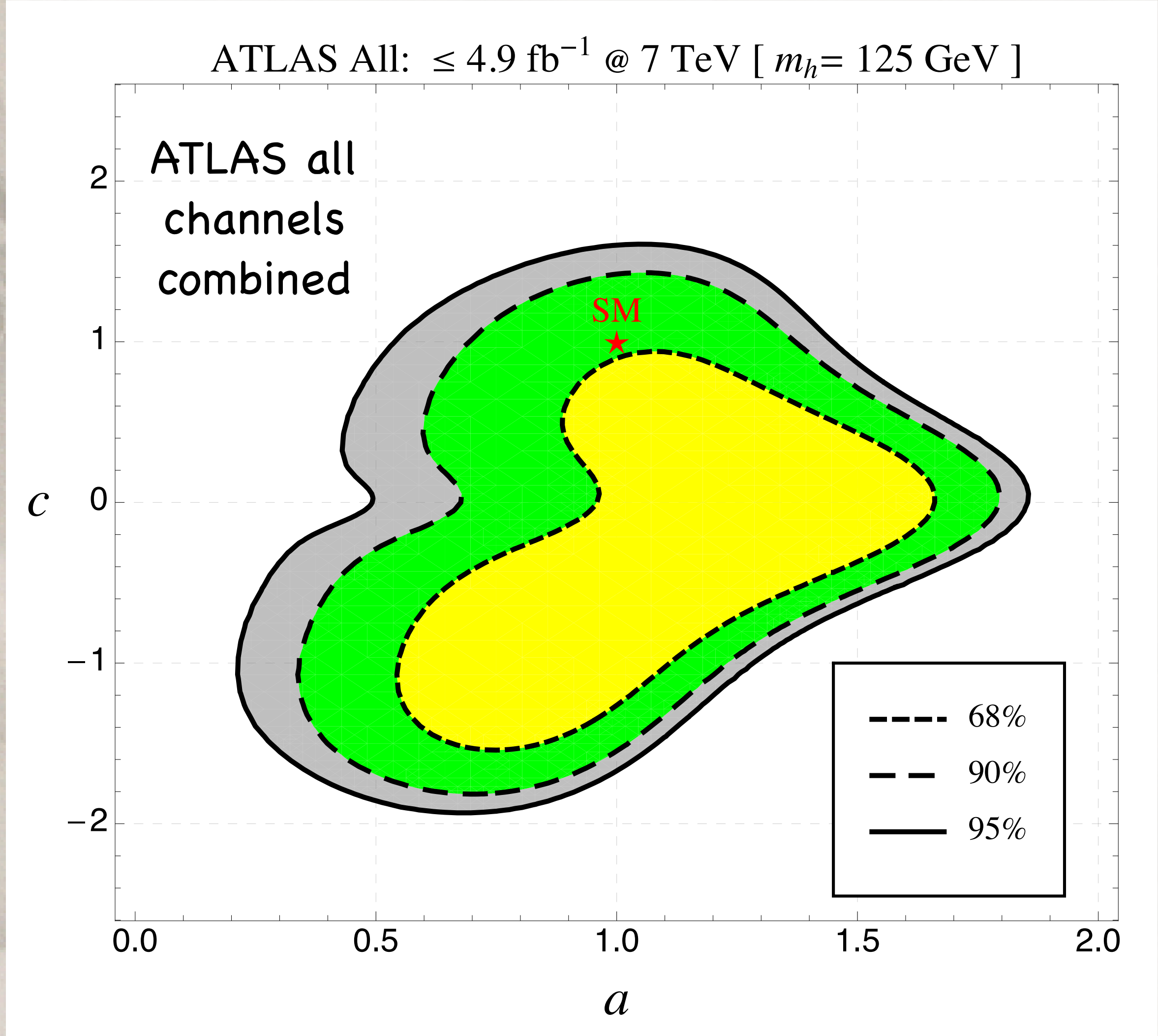
Second solution
(a=0.85, c=-0.6)

$$\mu(\gamma\gamma jj) \sim 2.4$$
$$\mu(\gamma\gamma\ incl) \sim 1.3$$
$$\mu(WW2j) \sim 1.1$$
$$\mu(WW0j, WW1j) \sim 0.7$$

$$\mu(i) \equiv \frac{\sigma \times BR(i)}{[\sigma \times BR(i)]_{SM}}$$

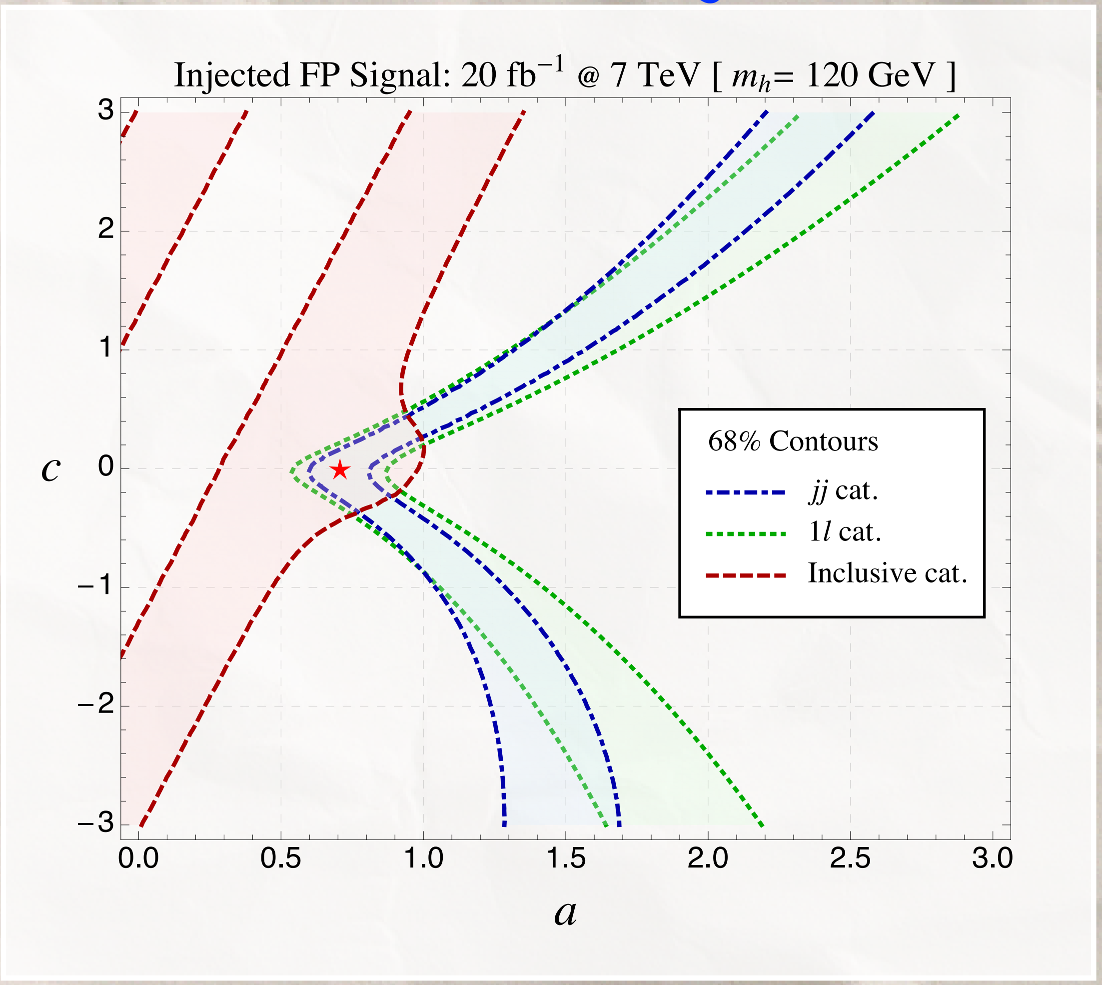
Fit at m_H=125GeV



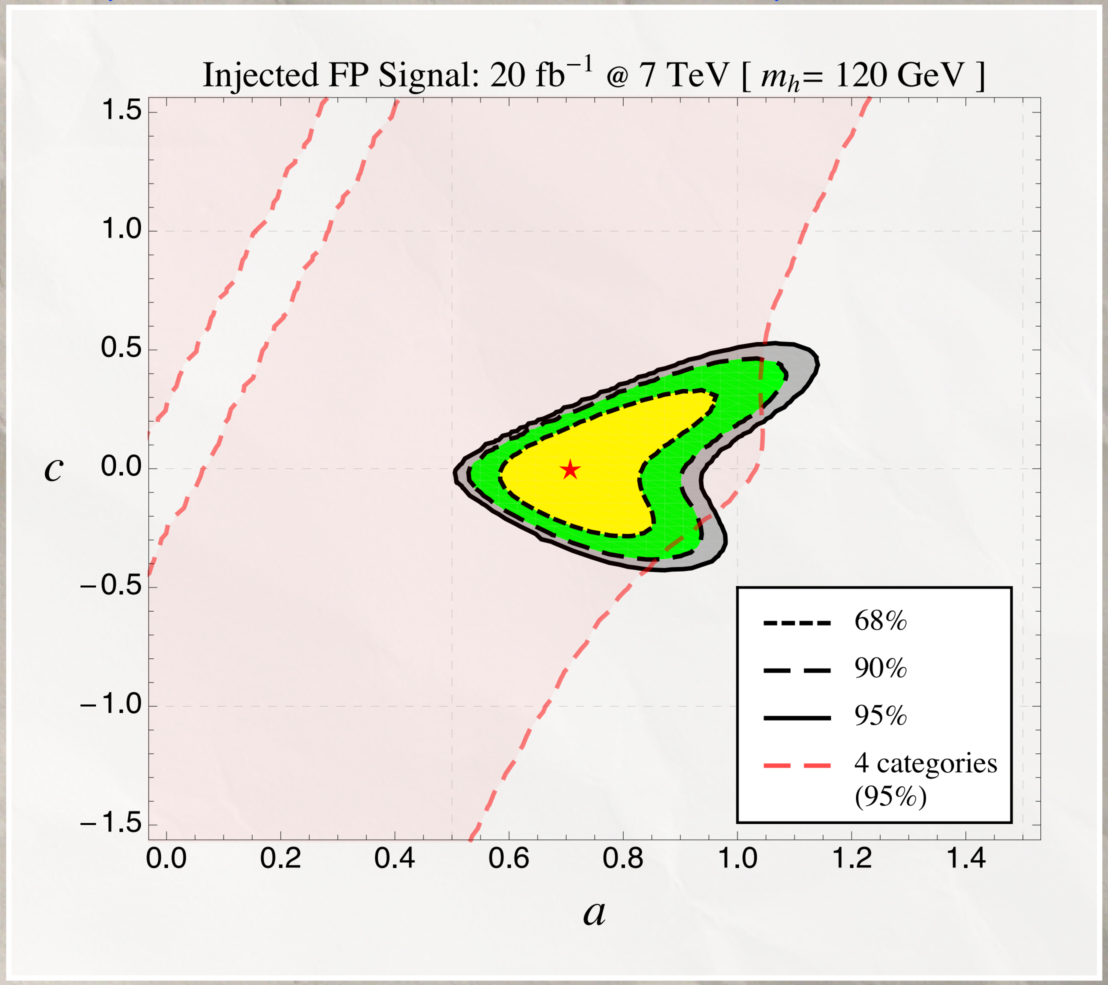


Exclusive vs Inclusive: the h→$\gamma\gamma$ channel

FP signal (a=1/√2, c=0) injected
Breakdown of exclusive categories



FP signal (a=1/√2, c=0) injected
Fully exclusive vs inclusive analysis

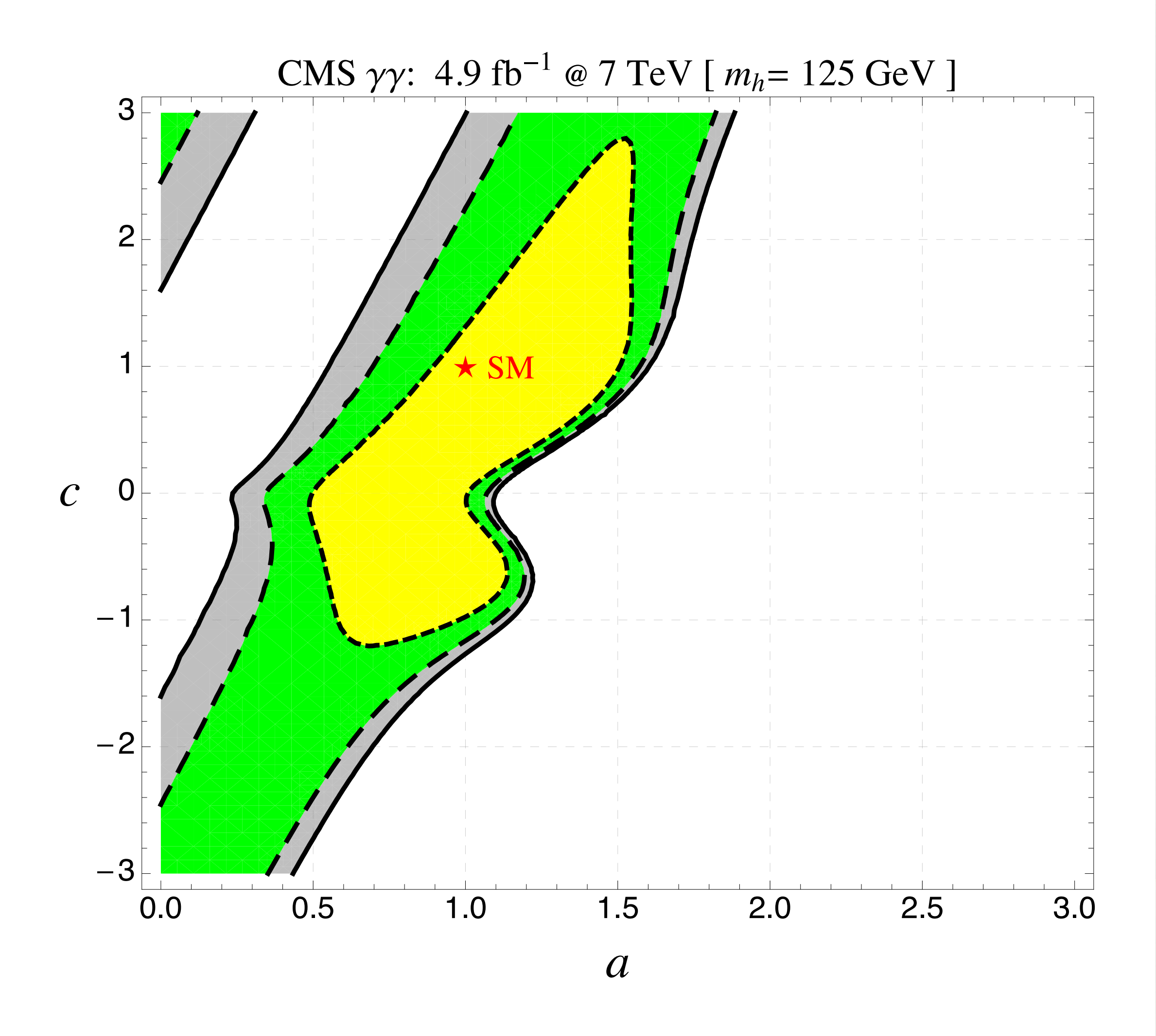


results from:
Azatov, R.C., Del Re, Galloway, Grassi, Rahatlou,
arXiv:1204.4817

FP point (a=1/√2, c=0) still allowed by CMS combined limits for 123 GeV< m_H < 130GeV

Exclusive vs Inclusive: the h→$\gamma\gamma$ channel

Fit of $\gamma\gamma$ based on CMS data



courtesy of A. Azatov

Shall we break the degeneracy ?