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Workshop on Strongly Coupled Physics Beyond the Standard Model

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Hunting the composite Higgs at the LHC

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Hunting the Composite Higgs at the LHC

A look to the Higgs searches without prejudice

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[based on work in progress with A. Azatov and J. Galloway]

Goal:

Determining the Higgs properties and understanding its role in the EWSB mechanism without *theoretical* prejudice

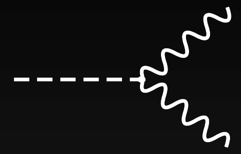
The theoretical framework:

most general Lagrangian for a light Higgs
[assuming custodial symmetry]

$$
\begin{aligned}
\mathcal{L} = &\frac{1}{2}(\partial_\mu h)^2 - V(h) \\
&+ \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \cdots\right) \\
&- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c. \\
&+ \Delta\mathcal{L}^{(4)}
\end{aligned}
$$

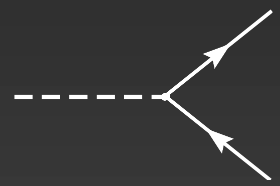
$$
V(h) = \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 \ldots
$$

Controls the hWW, hZZ couplings



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

Controls the hqq coupling



$$= c \cdot g^{SM}_{hqq}$$

[R.C. Grojean, Moretti, Piccinini, Rattazzi, JHEP 1005 (2010) 089]

$$\Delta\mathcal{L}^{(4)} = \sum_i O_i \qquad F_i(h) = \alpha_i^{(0)} + \alpha_i^{(1)} h + \alpha_i^{(2)} h^2 + \dots$$

$$O_1 = \mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right] (\partial_\nu F_1(h))^2$$

$$O_2 = \mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D_\nu\Sigma)\right] \partial^\mu\partial^\nu F_2(h)$$

$$O_{GG} = G_{\mu\nu}G^{\mu\nu}\, F_{GG}(h)$$

$$O_{BB} = B_{\mu\nu}B^{\mu\nu}\, F_{BB}(h)$$

$$O_W = D_\mu W^a_{\mu\nu}\, \mathrm{Tr}\left[\Sigma^\dagger \sigma^a i \overleftrightarrow{D}_\nu \Sigma\right] F_W(h)$$

$$O_B = -\partial_\mu B_{\mu\nu}\, \mathrm{Tr}\left[\Sigma^\dagger i \overleftrightarrow{D}_\nu \Sigma\, \sigma^3\right] F_B(h)$$

$$O_{WH} = i\, W^a_{\mu\nu}\, \mathrm{Tr}\left[(D^\mu\Sigma)^\dagger \sigma^a D^\nu\Sigma\right] F_{WH}(h)$$

$$O_{BH} = -i\, B_{\mu\nu}\, \mathrm{Tr}\left[(D^\mu\Sigma)^\dagger (D^\nu\Sigma)\sigma^3\right] F_{BH}(h)$$

$$O_{W\partial H} = \frac{1}{2} W^a_{\mu\nu}\, \mathrm{Tr}\left[\Sigma^\dagger \sigma^a i \overleftrightarrow{D}^\nu \Sigma\right] \partial^\nu F_{W\partial H}(h)$$

$$O_{B\partial H} = -\frac{1}{2} B_{\mu\nu}\, \mathrm{Tr}\left[\Sigma^\dagger i \overleftrightarrow{D}^\nu \Sigma\sigma^3\right] \partial^\nu F_{W\partial B}(h)$$

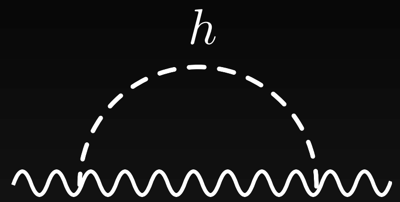
Contribute to the S parameter

$$\hat{S} = 4g^2 \left(\alpha_W^{(0)} + \alpha_B^{(0)}\right)$$

Modify gg production and γγ decay

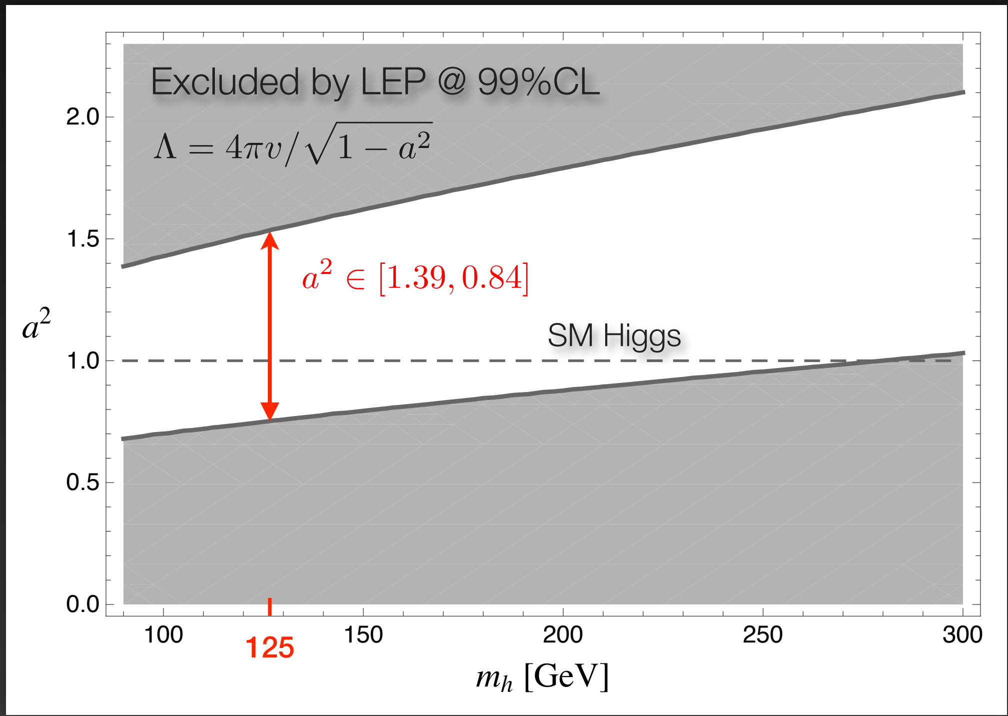
Notice: LEP precision tests only constrain a

$$\Delta\epsilon_{1,3} = c_{1,3}\,\log\left(\frac{\Lambda^2}{m_Z^2}\right) - a^2\,c_{1,3}\,\log\left(\frac{\Lambda^2}{m_h^2}\right)$$



$$\Delta\epsilon_{1,3} \equiv c_{1,3}\,\log\left(\frac{\Lambda^2}{m_{h,eff}^2}\right)$$

$23\,\mathrm{GeV} \leq m_{h,eff} \leq 280\,\mathrm{GeV}$ @ 99% CL



SM case: $a = b = c = d_3 = d_4 = 1$

all other couplings = 0

Composite Higgs examples: $\xi = \left(\frac{v}{f}\right)^2$

$\xi \to 0$ SM limit

$\xi \to 1$ naive TC limit

[1] $a = c = \sqrt{1-\xi}$

MCHM4 [Agashe, R.C., Pomarol, NPB 719 (2005) 165]

Minimal Conformal TC

[Galloway, Evans, Luty, Tacchi, JHEP 1010 (2010) 086]

[2] $a = \sqrt{1-\xi}$

MCHM5 [R.C., DaRold, Pomarol, PRD 75 (2007) 055014]

$$\boxed{c = \frac{1-2\xi}{\sqrt{1-\xi}}} \longrightarrow \quad \xi \to 0.5$$

fermiophobic limit $\mathcal{L}_{yuk} = \lambda_t f \sin[2(\theta + h(x)/f)]\, \bar{t}_L t_R + h.c.$

$\rightarrow$ for this talk: $a\,,\,c$ we set all other couplings = 0

What do current SM searches do ?

- combined limits on $\mu \equiv \frac{n_s}{n_s^{SM}}$

Prior

flat for $\mu > 0$

$n_s = \mu \times n_s^{SM}$

n_b

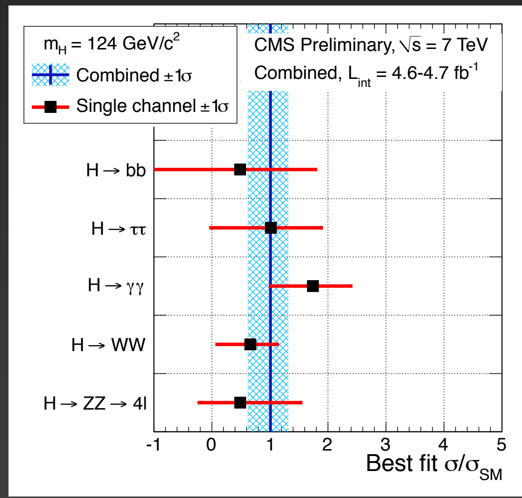
n_{obs}

$$p(\mu|data) = \underbrace{p(n_{obs}|\mu\, n_s^{SM} + n_b)}_{\text{Likelihood}} \times \pi(\mu)$$

$$= \frac{1}{n_{obs}!} e^{-(\mu \cdot n_s^{SM} + nb)} \left(\mu \cdot n_s^{SM} + n_b\right)^{n_{obs}}$$

same rescaling μ *for all channels* ⟷ $a = c = \sqrt{\mu}$

- (in case of excess) best fit of μ for each channel



What would a theorist need ? (to perform his own analysis)

[1] *The likelihood* $p_i(\mu|data)$ *for each channel* i

[2] *The cut efficiencies* ζ_i^p *for each channel* i *and Higgs production mode* p

$$\mu^i \equiv \frac{n_s^i}{(n_s^i)^{SM}} = \frac{\sum_p \sigma_p \times \zeta_i^p}{\sum_p \sigma_p^{SM} \times \zeta_i^p} \times \frac{BR_i}{BR_i^{SM}}$$

[1] + [2] allow one to derive the 2D likelihhod: $p_i(\mu^i(a,c)|data)$

✘ *neither [1] nor [2] are currently provided by ATLAS and CMS !*

Our technique to reconstruct the likelihood from the 95%CL limits

- *in general* $p(\mu|data)$ *depends on 3 unkowns (* n_s^{SM}, n_b , n_{obs} *)*

- *BUT: in the asymptotic (Gaussian) limit* $n_{obs} \gg 1$ *only 2 combination appear:*

$$\frac{1}{n_{obs}!}\, e^{-(\mu \cdot n_s^{SM} + nb)} \left(\mu \cdot n_s^{SM} + n_b\right)^{n_{obs}} \longrightarrow \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{\frac{-(\mu - \bar{x})^2}{2\sigma^2}\right\}$$

$$\bar{x} = \frac{(n_{obs} - n_b)}{n_s^{SM}} \qquad \sigma^2 = \frac{n_{obs}}{(n_s^{SM})^2}$$

- *ATLAS and CMS give 2 numbers (for each mH):* *(i) the EXPECTED 95%CL limit on* μ

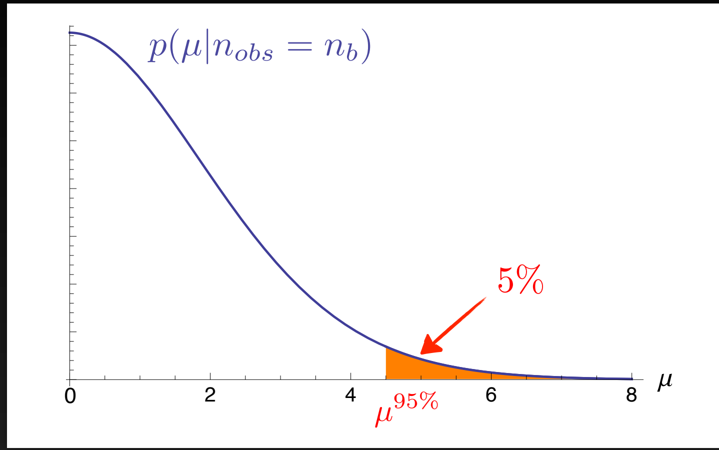
  (ii) the OBSERVED 95%CL limit on μ

[1] *Expected* 95%CL exclusion limits

$$\boxed{n_{obs} = n_b}$$

$$\frac{\int_0^{\mu_{95\%}} d\mu \;\; p(\mu|n_{obs} = n_b)}{\int_0^{\infty} d\mu \;\; p(\mu|n_{obs} = n_b)} = 0.95$$

$$\mu^{95\%} \simeq 1.96\, \sigma_{EXP} = 1.96\, \frac{\sqrt{n_b}}{n_s}$$



Notice: *since the product of Gaussians is still a Gaussian with* $\frac{1}{\sigma^2_{comb}} = \sum_i \frac{1}{\sigma_i^2}$

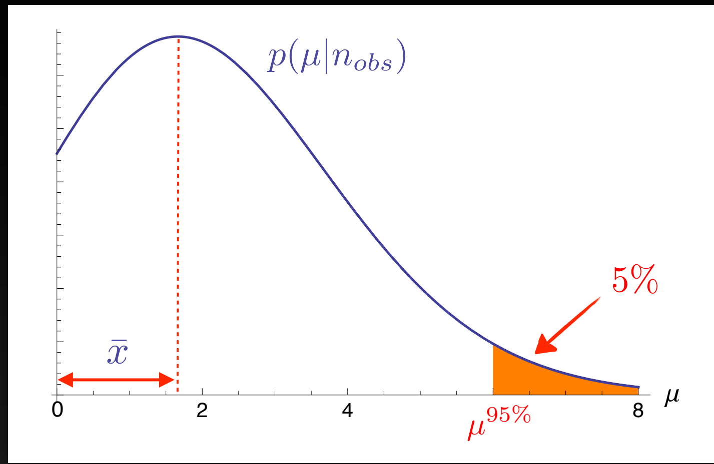
the combined limit of several channels is:

$$\mu^{95\%}_{comb} = \frac{1}{\sqrt{\sum_i \frac{1}{(\mu_i^{95\%})^2}}}$$

✔ *combining the* ***expected*** *limits in inverse quadrature is justified in the Gaussian approximation*

[2] ***Observed*** *95%CL exclusion limits*

$$\frac{\int_0^{\mu_{95\%}} d\mu \;\; p(\mu|n_{obs})}{\int_0^{\infty} d\mu \;\; p(\mu|n_{obs})} = 0.95$$



- *2 unknowns ($\bar{x}$, σ_{OBS}) and only 1 experimental number :*

We assume: $\sigma_{OBS} = \frac{\sqrt{n_{obs}}}{n_s^{SM}} \simeq \sigma_{EXP} = \frac{\sqrt{n_b}}{n_s^{SM}}$ *and extract* $\bar{x} = \frac{n_{obs} - n_b}{n_s^{SM}}$ *from* $\mu^{95\%}$

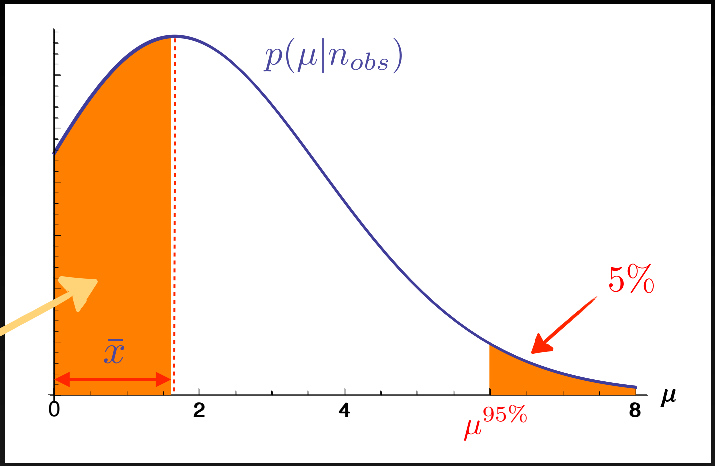
This is a good approximation for:

$$\boxed{\frac{|n_{obs} - n_b|}{n_{obs}} \ll 1 \qquad \frac{|n_{obs} - n_b|}{n_s^{SM}} \lesssim 1}$$

fluctuations can be large compared to signal but must be small compared to background

[2] **Observed** 95%CL exclusion limits

$$\frac{\int_0^{\mu_{95\%}} d\mu \;\; p(\mu|n_{obs})}{\int_0^{\infty} d\mu \;\; p(\mu|n_{obs})} = 0.95$$



Notice: combining observed limits in quadrature

(assuming $\mu^{95\%} \simeq 1.96\,\sigma_{OBS}$)

means discarding this area

- 2 unknowns ($\bar{x}$, σ_{OBS}) and only 1 experimental number :

We assume: $\sigma_{OBS} = \frac{\sqrt{n_{obs}}}{n_s^{SM}} \simeq \sigma_{EXP} = \frac{\sqrt{n_b}}{n_s^{SM}}$ and extract $\bar{x} = \frac{n_{obs} - n_b}{n_s^{SM}}$ from $\mu^{95\%}$

This is a good approximation for:

$$\frac{|n_{obs} - n_b|}{n_{obs}} \ll 1$$

$$\frac{|n_{obs} - n_b|}{n_s^{SM}} \lesssim 1$$

fluctuations can be large compared to signal but must be small compared to background

Including systematic errors

Systematic errors are modeled by ATLAS and CMS as nuisance parameters with Log-Normal pdfs:

$$p(\mu|data) = \int_{-\infty}^{+\infty} d\theta_b \int_{-\infty}^{+\infty} d\theta_s \;\; p(n_{obs}|\mu \cdot n_s\, e^{\theta_s k_s} + n_b\, e^{\theta_b k_b})\, e^{-\theta_b^2/2}\, e^{-\theta_s^2/2} \qquad k_{s,b} = \frac{\sigma_{s,b}}{n_{s,b}}$$

For $\sigma_{s,b}/n_{s,b} \ll 1$ *the error pdfs can be approximated by (truncated) Gaussians:*

$$p(\mu|data) \simeq \int_{-n_b/\sigma_b}^{+n_b/\sigma_b} d\theta_b \int_{-n_s/\sigma_s}^{+n_s/\sigma_s} d\theta_s \;\; p(n_{obs}|\mu \cdot (n_s + \sigma_s\theta_s) + n_b + \sigma_b\theta_b)\, e^{-\theta_b^2/2}\, e^{-\theta_s^2/2}$$

truncation guarantees the number of events stays positive

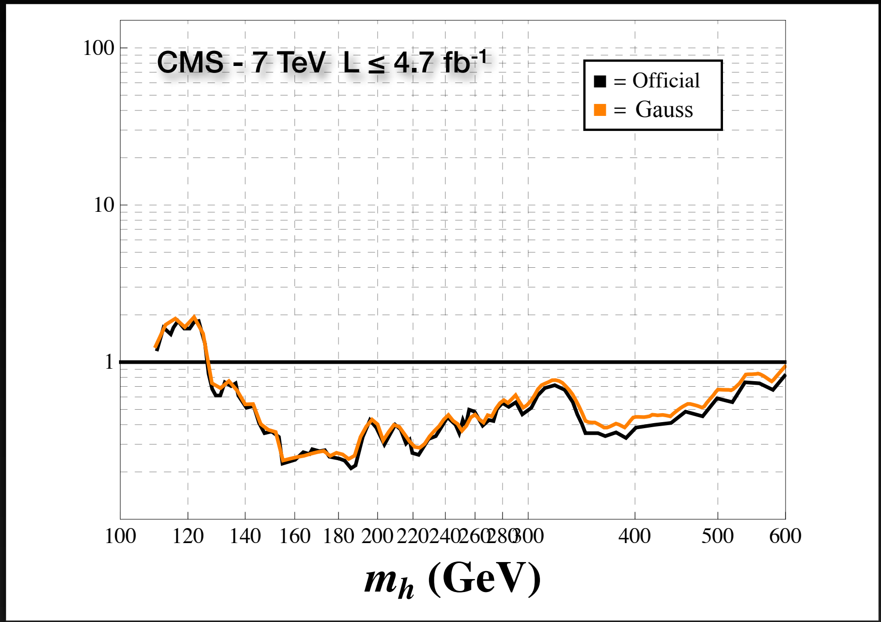
For small fluctuations the final probability can be approximated with a Gaussian with standard deviation $\sigma_\mu = \sqrt{n_{obs} + \sigma_b^2}$

In the asymptotic limit:

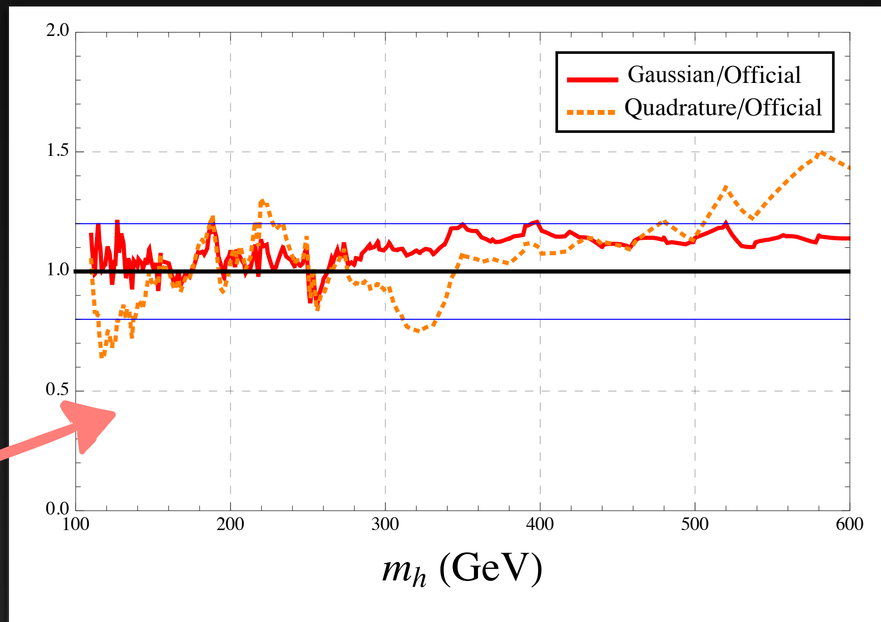
$$p(\mu|data) \simeq \frac{e^{-\frac{(\mu\, n_s + n_b - n_{obs})^2}{2(n_{obs} + \sigma_b^2 + \mu^2\sigma_s^2)}}}{\sqrt{2\pi(n_{obs} + \sigma_b^2 + \mu^2\sigma_s^2)}} \xrightarrow{\frac{\sigma_s}{n_s}\frac{n_{obs} - n_b}{\sqrt{\sigma_b^2 + n_{obs}}} \ll 1} \frac{e^{-\frac{(\mu - \bar{x})^2}{2\sigma_\mu^2}}}{\sqrt{2\pi}\sigma_\mu}$$

Combination using our technique (Gaussian approx.) vs official one (CMS)

SM Observed 95%CL limit - all channels combined



SM Observed 95%CL limit - our method/official



Agreement better than ~20% for all mH values

Naive quadrature less accurate, though not much off

Testing our technique (Gaussian approx.) : the WW channel (CMS)

- *CMS WW search: 5 event categories (0jets OF/SF, 1jet OF/SF, 2jets)*
  two kind of analyses: BDT and Cut-Based

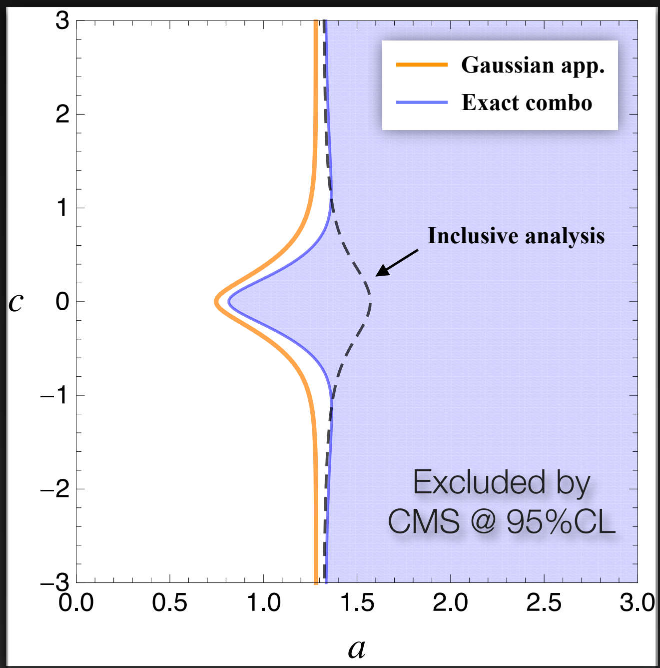
- *Numbers of events (sig, back, obs) are provided for each category for the cut-based analysis: likelihood can be constructed !*

- *Efficiencies are not given: we assume gg-fusion dominates in 0jet, 1jet categories, and VBF dominates in 2jet*

Gaussian approximation works well

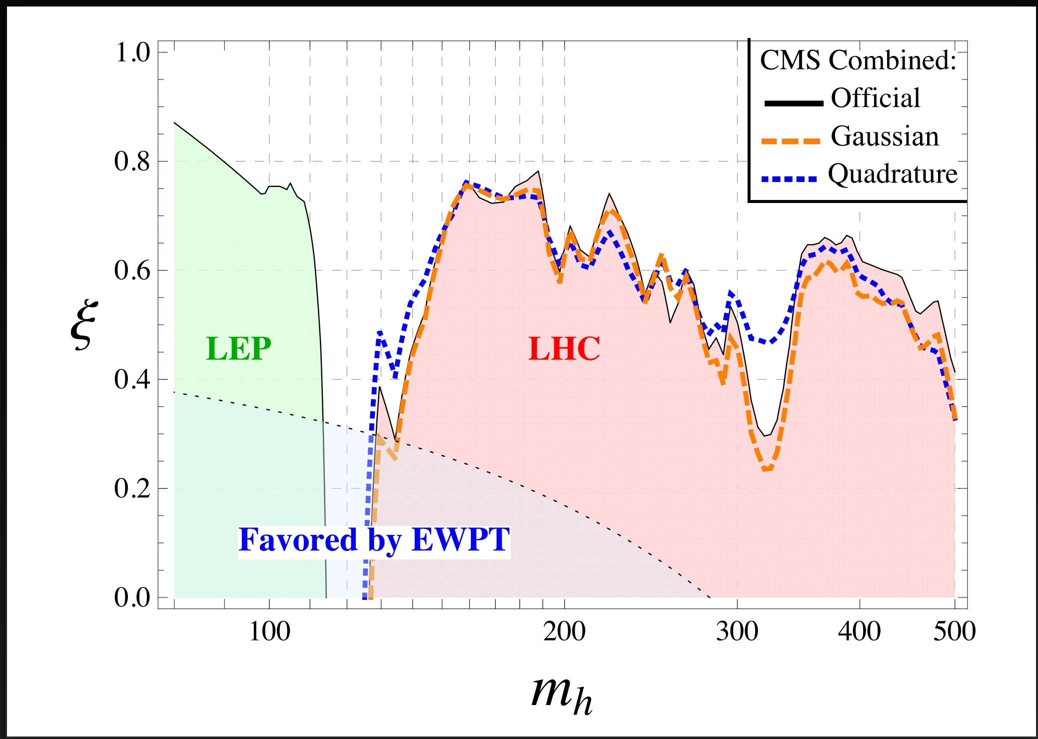
An inclusive analysis (1 category) + assuming constant efficiencies gives a much less strong exclusion in the fermiophobic limit

Observed 95%CL exclusion - mH=120GeV



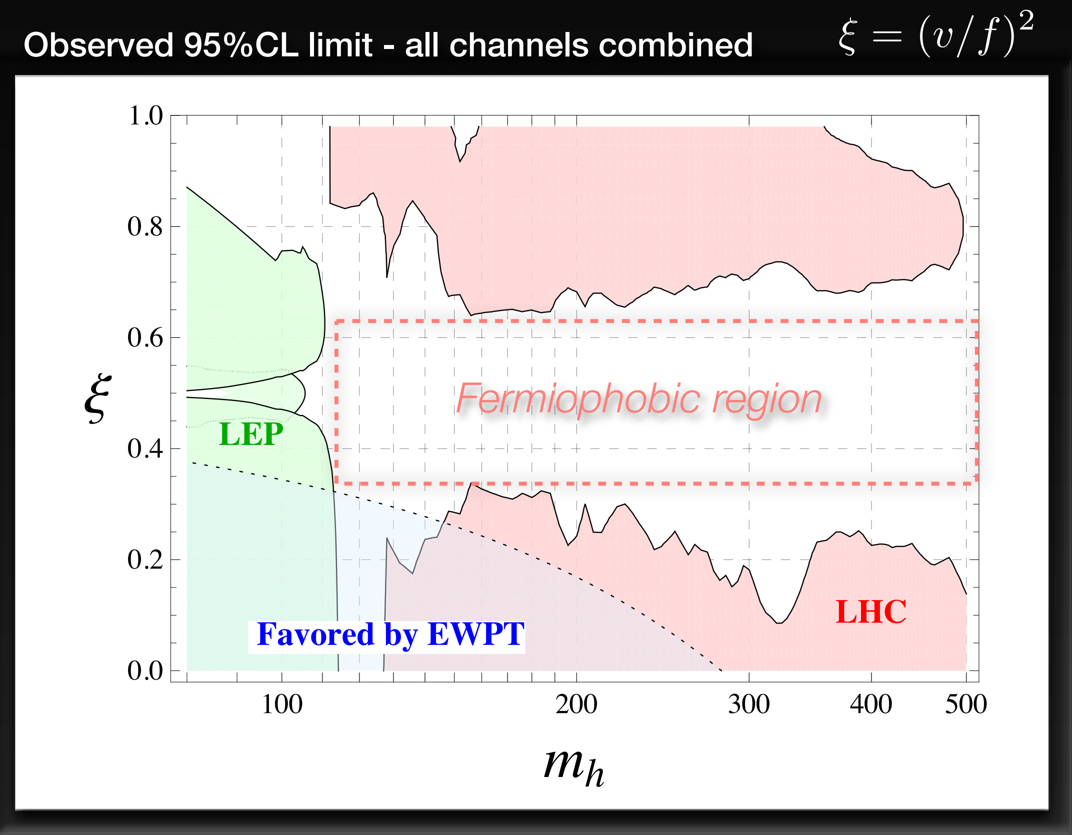
Results : models with a universal rescaling (MCHM4, MCTC)

Observed 95%CL limit - all channels combined $\xi = (v/f)^2$



- *Official CMS combination can be used:* $\mu = 1 - \xi$
- *Heavy Higgs is excluded unless* $g_{Higgs} \lesssim 0.5\, g_{Higgs}^{SM}$

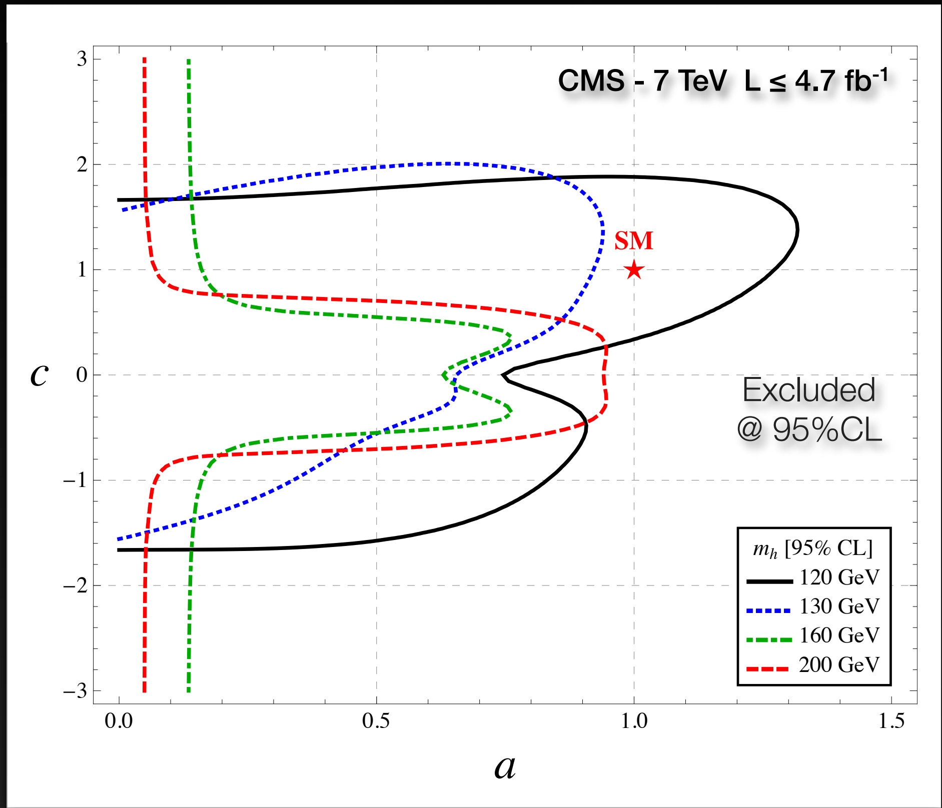
Results : MCHM5 (model with a non-universal rescaling)



- *heavier Higgs still allowed if (moderately) fermiophobic* ($|g_{htt}/g_{htt}^{SM}| \lesssim 0.5$)

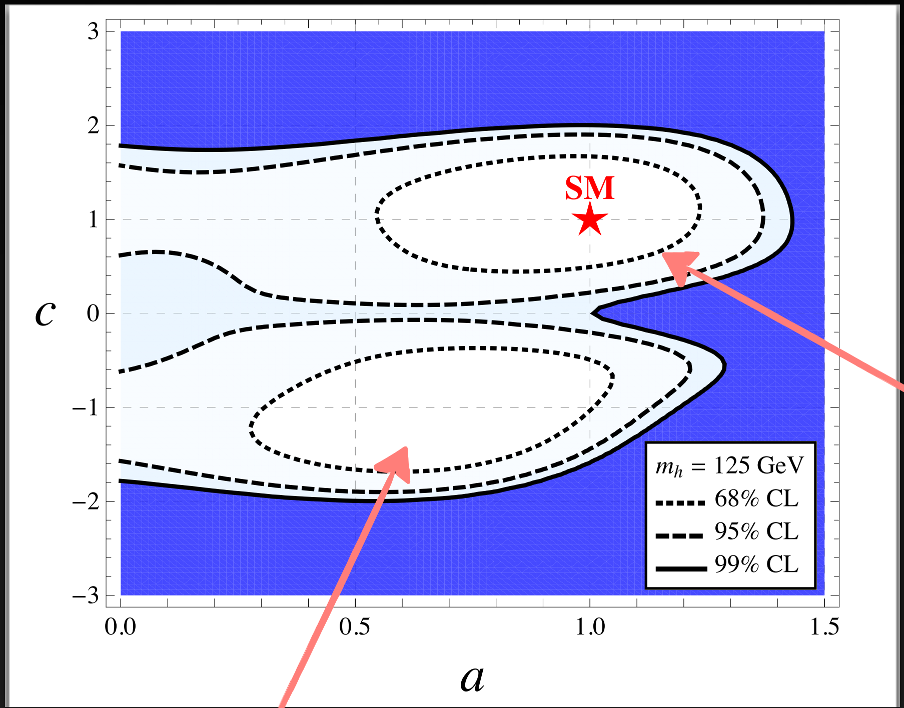
Results : a model-independent analysis

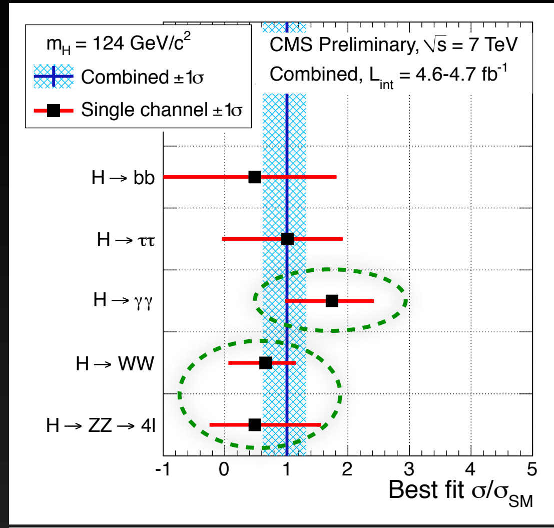
Observed 95%CL limit - all channels combined



The 125 GeV excess: a theorist's look at the data

CMS data - all channels combined mH = 125 GeV





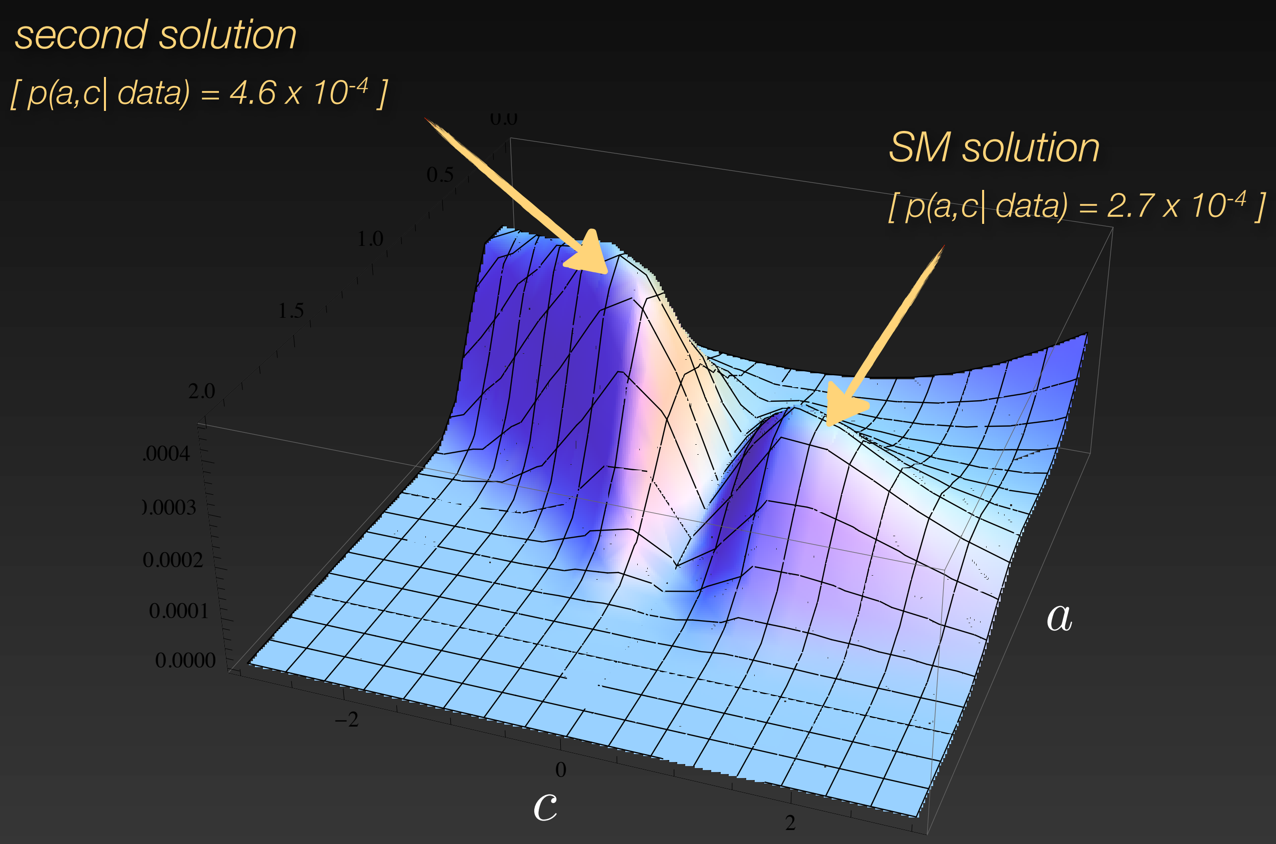
the SM solution gives a good fit

a second solution $(a, c) \sim (0.7, -1)$ *is singled out (with higher probability) where:*

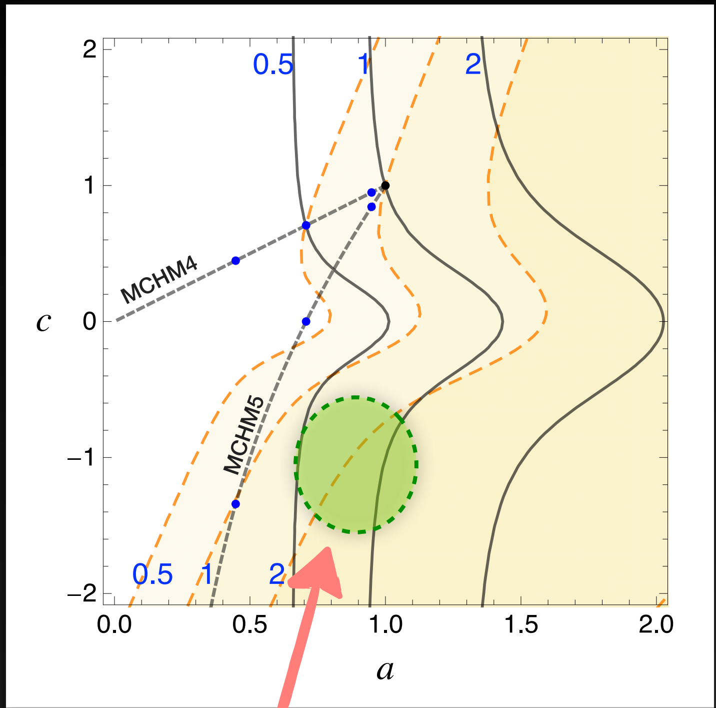
$R(\gamma\gamma) \sim 1.5 \quad R(WW) = R(ZZ) \sim 0.5$

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

The 125 GeV excess: a theorist's look at the data



The 125 GeV excess: a theorist's look at the data



$R(\gamma\gamma)$

$R(WW) = R(ZZ)$

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

Not accessible in the MCHM

Region preferred by CMS: $R(\gamma\gamma) \sim 1.5 \quad 0.5 \lesssim R(WW), R(ZZ) \lesssim 1$

[$c/a < 0$ *gives positive interference in* $\Gamma(\gamma\gamma) \propto |1.8\,c - 8.3\,a|^2$]

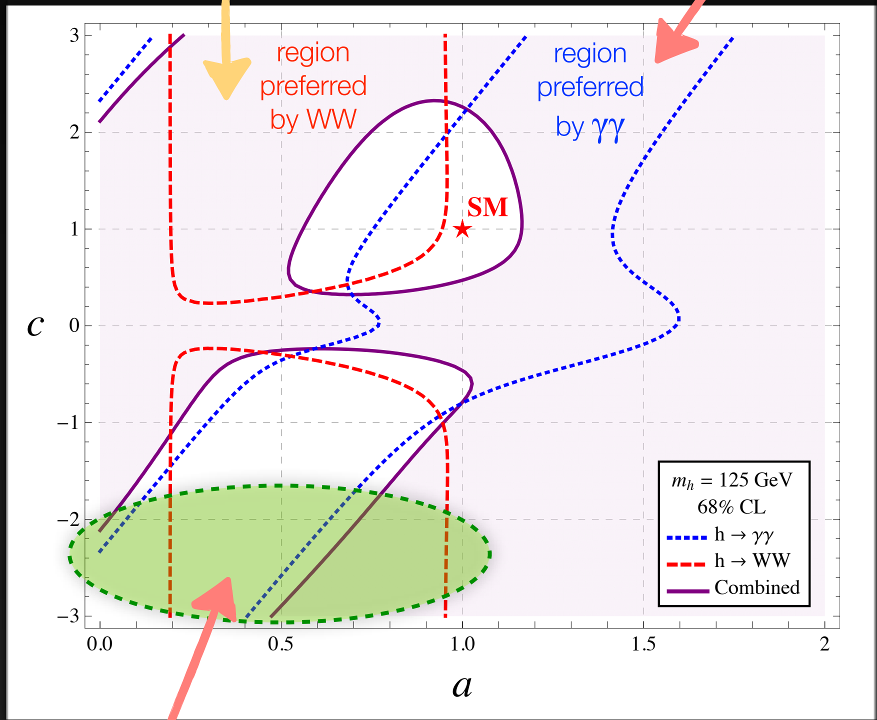
The 125 GeV excess: a theorist's look at the data

WW mostly sensitive to a

$$R(WW) \sim c^2 \times \frac{a^2}{c^2} = a^2$$

degenerate region with an inclusive $\gamma\gamma$ analysis

$$R(\gamma\gamma) \propto c^2 \frac{|1.8\, c - 8.3\, a|^2}{c^2}$$



degeneracy can be lifted by an exclusive $\gamma\gamma$ analysis (up to twofold ambiguity)

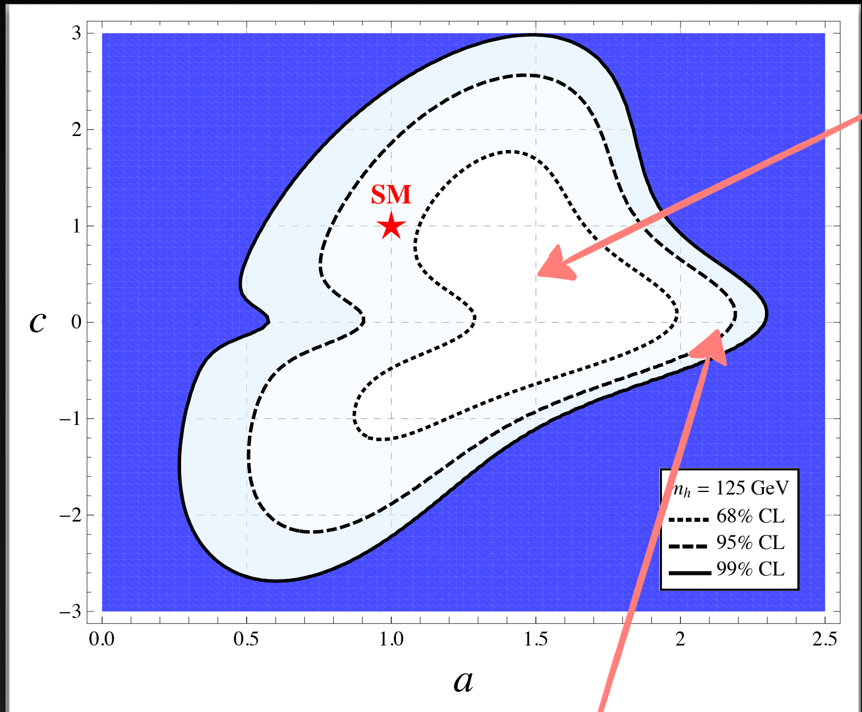
[Azatov, R.C., DelRe, Galloway, Grassi, Rahatlou, work in progress]

region with large $|c|$ excluded by (inclusive) $\tau\tau$ searches

$$R(\tau\tau)_{incl} \sim c^2 \times \frac{c^2}{c^2} = c^2$$

The 125 GeV excess: a theorist's look at the data

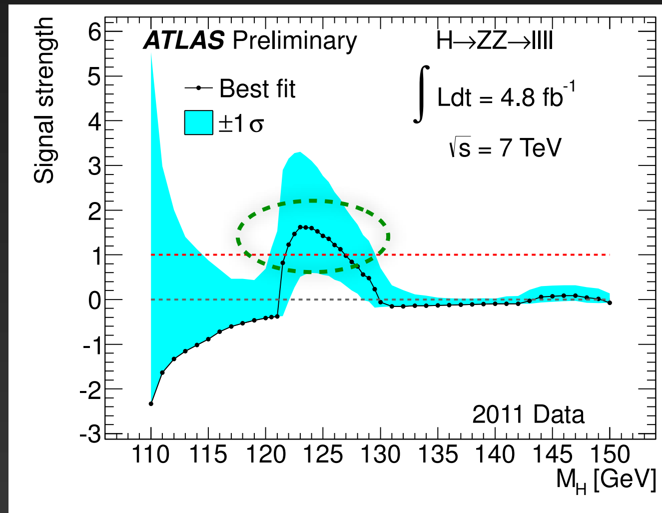
ATLAS data - all channels combined mH = 125 GeV



best fit for $(a, c) \sim (1.5, 0.4)$ *where:*

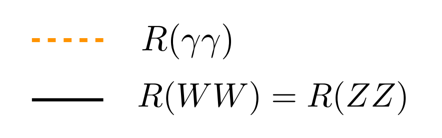
$R(\gamma\gamma) \sim 2 \qquad R(WW) = R(ZZ) \sim 1.4$

fit driven by the excess in ZZ

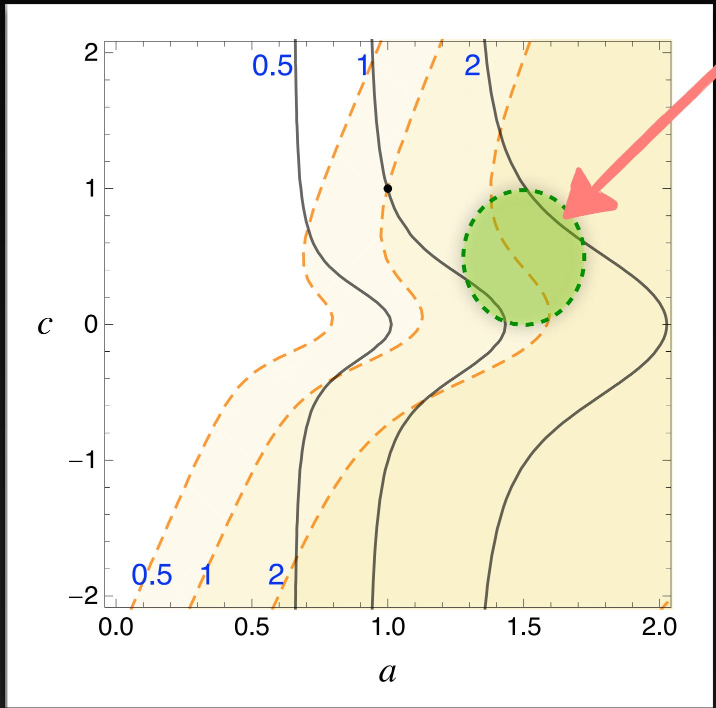


more inclusive WW analysis of ATLAS less powerful than the one of CMS for small c

The 125 GeV excess: a theorist's look at the data



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



Region preferred by ATLAS:

$R(\gamma\gamma) \sim 2$

$R(WW) = R(ZZ) \sim 1.4$

Conclusions

- A model-independent analysis of the Higgs searches is possible and should be carried through by the experimentalists

- Experimental collaborations should provide Likelihoods and efficiencies

- We have described an approximate method valid in the asymptotic (Gaussian) limit to extract the Likelihoods from published limits

- Exclusive searches vs inclusive ones give a better sensitivity (ex: WW, $\gamma\gamma$)

- Best fit of CMS data for: (a~0.6, c~-1) with R[$\gamma\gamma$]~1.5, R[WW,ZZ]~0.5

  Best fit of ATLAS data for: (a~1.5, c~0.4) with R[$\gamma\gamma$]~2, R[WW,ZZ]~ 1.4

  More data will tell !