Interpreting the LHC Higgs results

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based on the paper
"Higgs Couplings at the End of 2012"
arXiv:1212.5244, to appear in JHEP

in collaboration with
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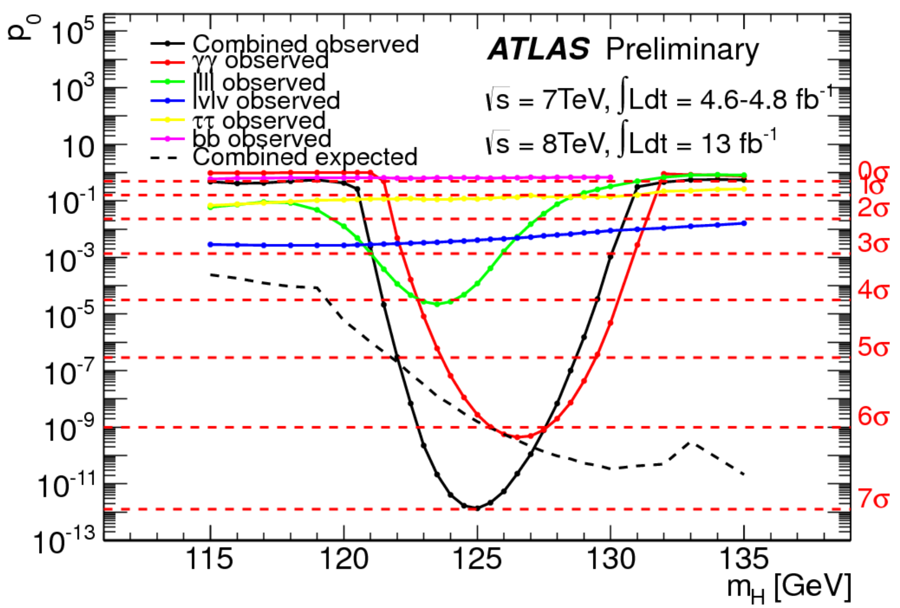
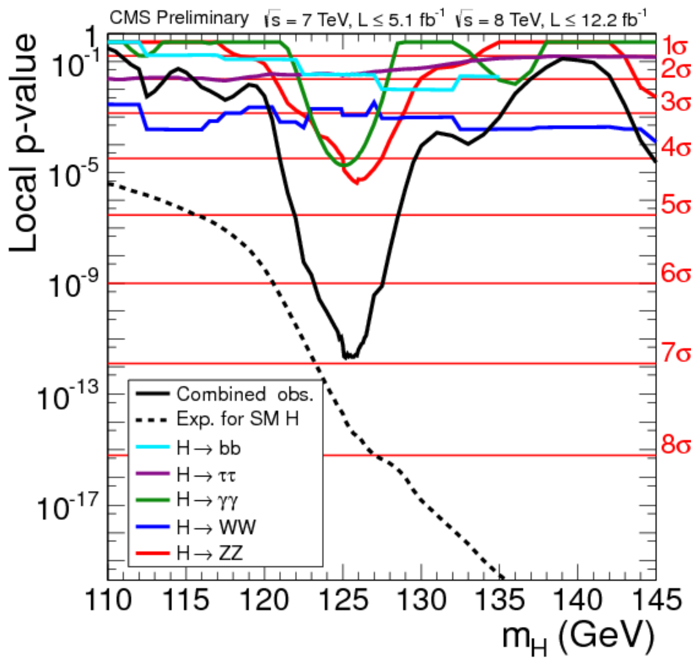
John Gunion, and Sabine Kraml

Likelihoods for the LHC Searches
21 January 2013

The Higgs boson has been found





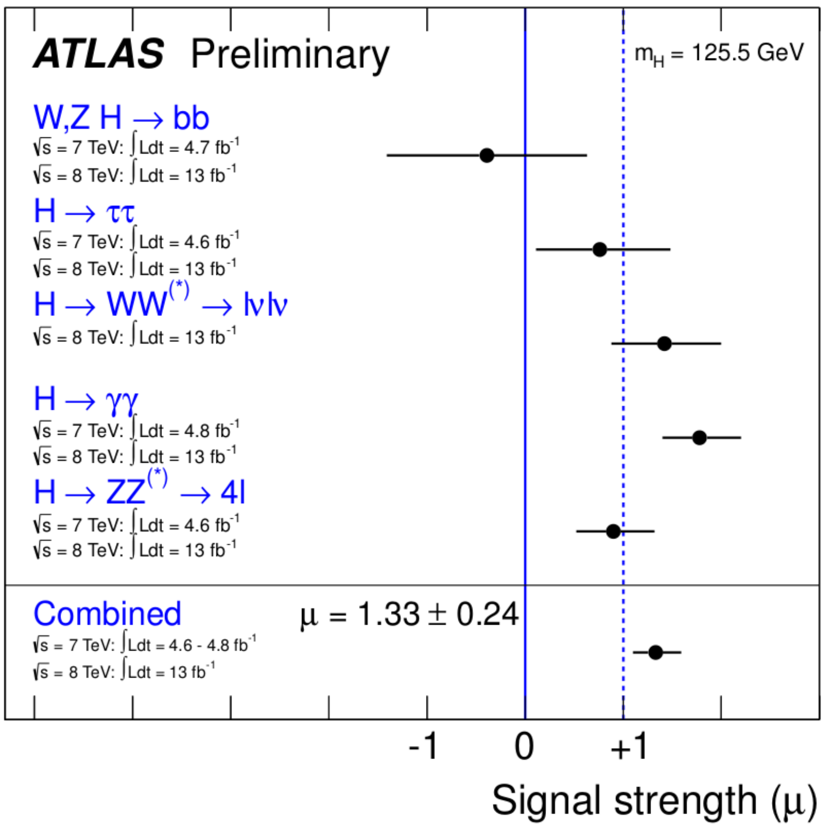
- Last update at HCP2012 in Kyoto (in November) and at the open session of the CERN Council (in December)
- Tevatron is still competitive for H → bb and analyses are still underway

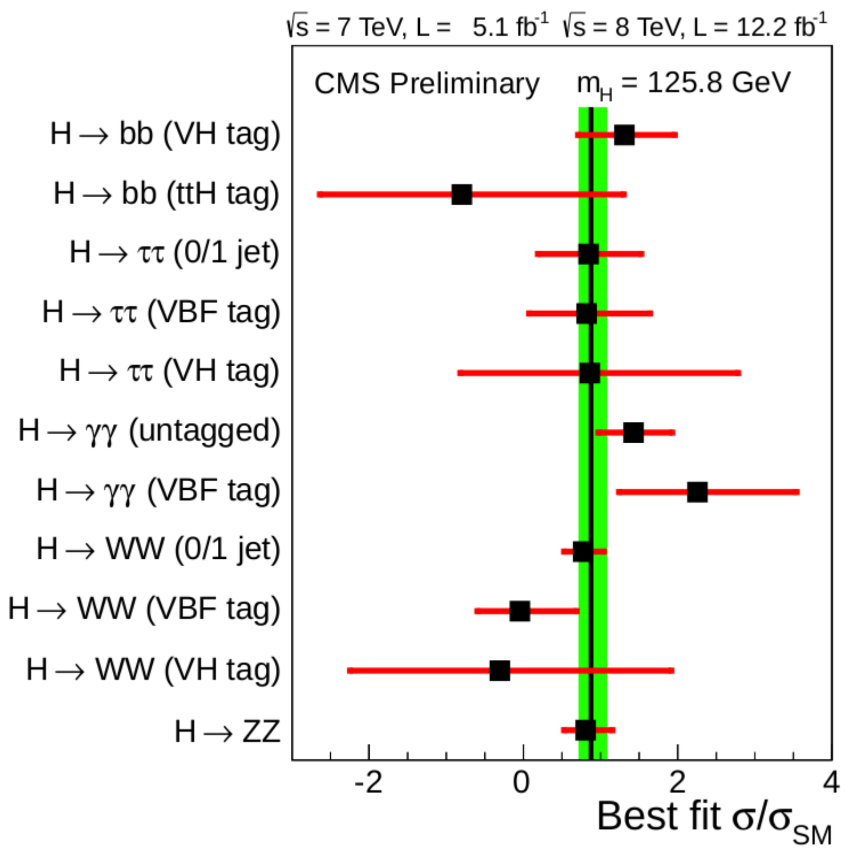
Standard Model Higgs... or New Physics?

(taken from Alexey Drozdetskiy's talk at HCP2012)

What we know about it

$$\mu_i = \frac{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{observed}}{[\sum_j \sigma_{j\to h} \times \mathrm{Br}(h \to i)]_{SM}}$$





What we know about it

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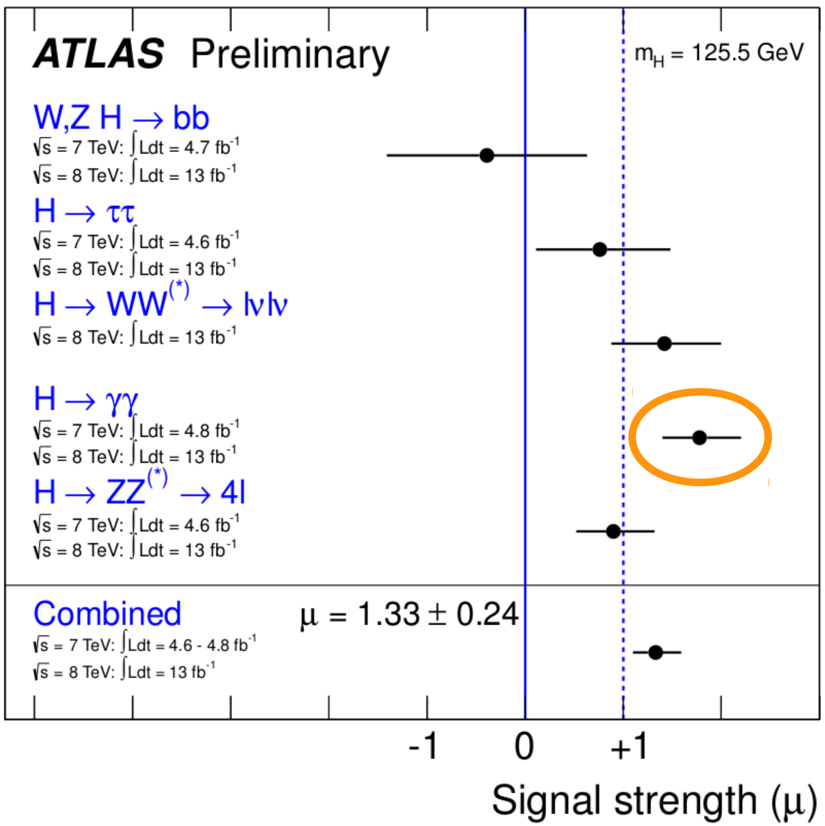
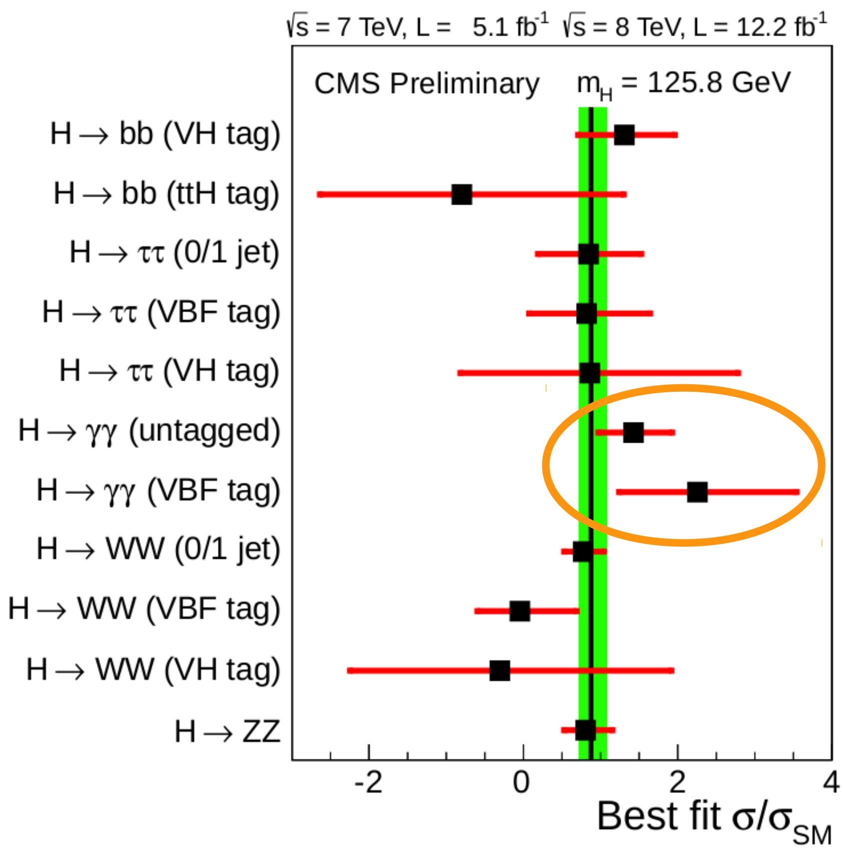
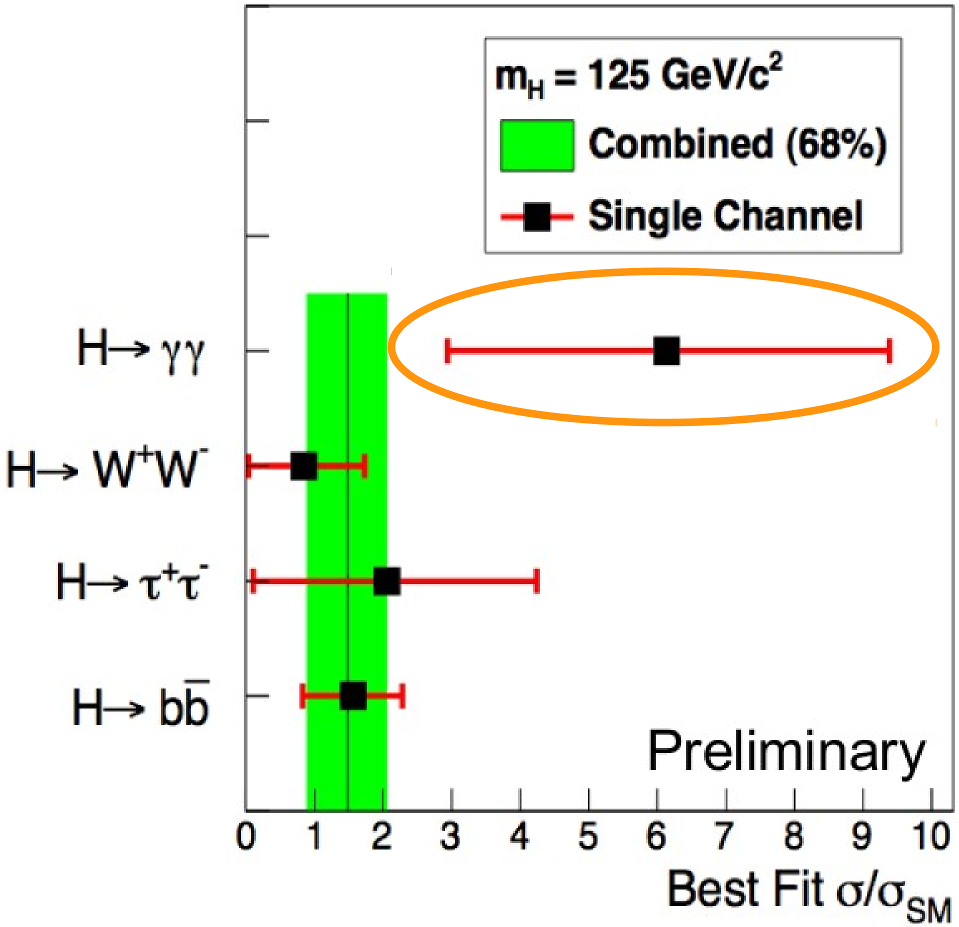




What we know about it (2)

Tevatron (HCP2012)

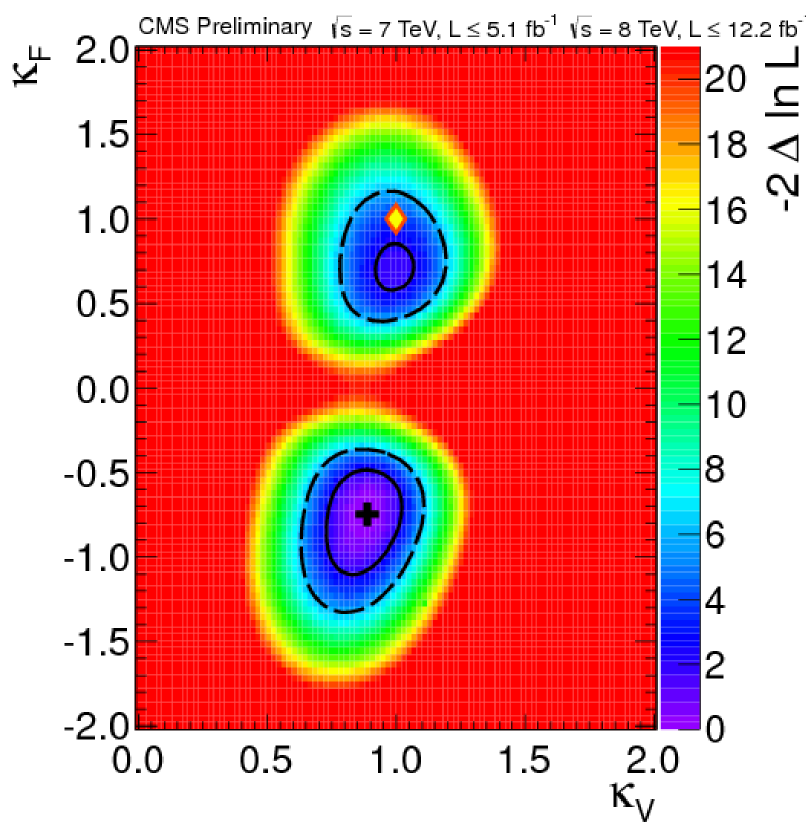


How can we go beyond this information to understand what is in the data?

How well can we determine the Higgs couplings and constrain models of New Physics?

Fits from experiments

- experimental collaborations are already testing the coupling structure of the new particle
- scaling factors κ parametrize deviations from the SM Higgs couplings (follows the interim recommendations from the LHC Higgs XS WG)



but:

- we want to combine the information from ATLAS, CMS and Tevatron
- we want to study the implications on various BSM models, use different parametrizations

→ theorists should be able to fit the Higgs results

Our parametrization

- We first need to specify a Lagrangian. Our choice:

$$\mathcal{L} = g\left[C_V\left(m_W W_\mu W^\mu + \frac{m_Z}{\cos\theta_W} Z_\mu Z^\mu\right) - C_U \frac{m_t}{2m_W}\bar{t}t - C_D \frac{m_b}{2m_W}\bar{b}b - C_D \frac{m_\tau}{2m_W}\bar{\tau}\tau\right] H$$

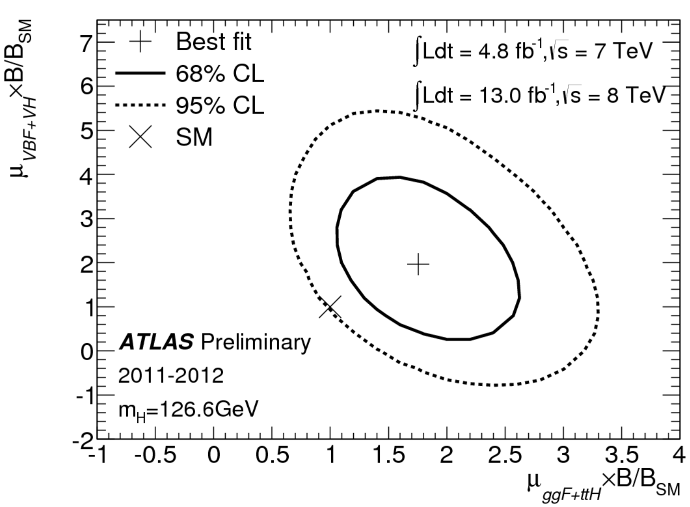
Scaling factors C (= κ) parametrize deviations from the SM

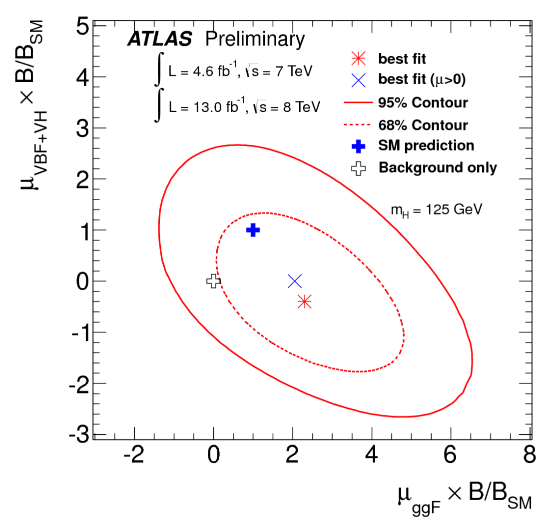
- We calculate $\overline{C}_g$ (for gluon-gluon fusion) and $\overline{C}_\gamma$ (for $H \to \gamma\gamma$) from C_U, C_D, C_V and we allow for additional particles in the loop: ΔC_g and ΔC_γ
  → $C_g = \overline{C}_g + \Delta C_g$ and $C_\gamma = \overline{C}_\gamma + \Delta C_\gamma$

- Total Higgs width: a priori not accessible at the LHC
  → we can in general only determine ratio of couplings
  ... but here we assume BR(H → invisible/undetected) = 0

Experimental data we use
ATLAS

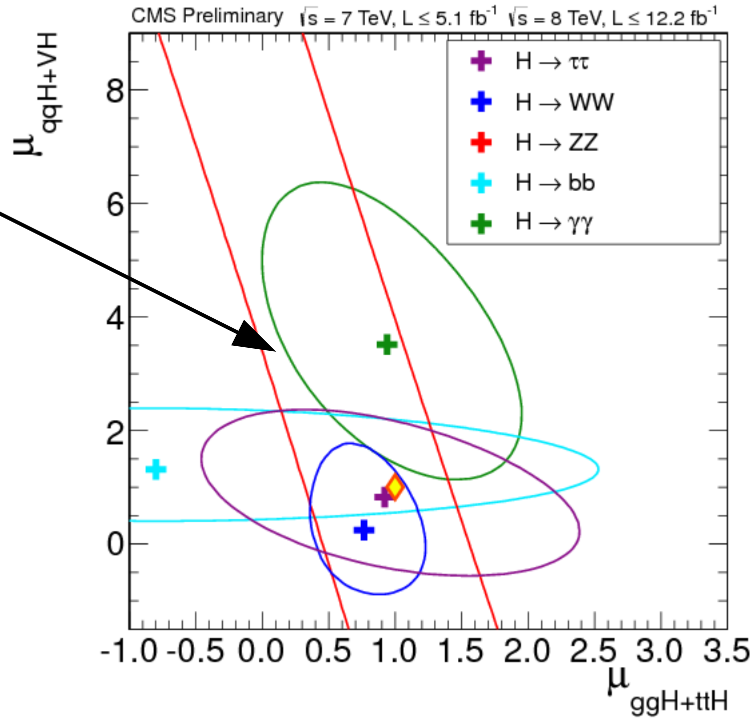
Channel	Signal strength μ	M_H (GeV)	Production mode			
			ggF	VBF	VH	ttH
$H \to \gamma\gamma$ (4.8 fb^{-1} at 7 TeV + 13.0 fb^{-1} at 8 TeV) [4]						
$\mu(\text{ggF}+\text{ttH},\gamma\gamma)$	1.85 ± 0.52	126.6	100%	–	–	–
$\mu(\text{VBF}+\text{VH},\gamma\gamma)$	2.01 ± 1.23	126.6	–	60%	40%	–
$H \to ZZ$ (4.6 fb^{-1} at 7 TeV + 13.0 fb^{-1} at 8 TeV) [6,11]						
Inclusive	$1.01^{+0.45}_{-0.40}$	125	87%	7%	5%	1%
$H \to WW$ (13.0 fb^{-1} at 8 TeV) [8,11]						
$e\nu\mu\nu$	$1.42^{+0.58}_{-0.54}$	125.5	95%	3%	2%	–
$H \to b\bar{b}$ (4.7 fb^{-1} at 7 TeV + 13.0 fb^{-1} at 8 TeV) [11,50]						
VH tag	-0.39 ± 1.02	125.5	–	–	100%	–
$H \to \tau\tau$ (4.6 fb^{-1} at 7 TeV + 13.0 fb^{-1} at 8 TeV) [51]						
$\mu(\text{ggF},\tau\tau)$	2.41 ± 1.57	125	100%	–	–	–
$\mu(\text{VBF}+\text{VH},\tau\tau)$	-0.26 ± 1.02	125	–	60%	40%	–





Experimental data we use
CMS

Channel	Signal strength μ	M_H (GeV)	Production mode			
			ggF	VBF	VH	ttH
$H \to \gamma\gamma$ (5.1 fb^{-1} at 7 TeV + 5.3 fb^{-1} at 8 TeV) [2,5,12]						
μ(ggF + ttH, $\gamma\gamma$)	0.95 ± 0.65	125.8	100%	–	–	–
μ(VBF + VH, $\gamma\gamma$)	3.77 ± 1.75	125.8	–	60%	40%	–
$H \to ZZ$ (5.1 fb^{-1} at 7 TeV + 12.2 fb^{-1} at 8 TeV) [7,12]						
Inclusive	$0.81^{+0.35}_{-0.28}$	125.8	87%	7%	5%	1%
$H \to WW$ (up to 4.9 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV) [10,12,52]						
0/1 jet	$0.77^{+0.27}_{-0.25}$	125.8	97%	3%	–	–
VBF tag	$-0.05^{+0.74}_{-0.55}$	125.8	17%	83%	–	–
VH tag	$-0.31^{+2.22}_{-1.94}$	125.8	–	–	100%	–
$H \to b\bar{b}$ (up to 5.0 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV) [12,53,54]						
VH tag	$1.31^{+0.65}_{-0.60}$	125.8	–	–	100%	–
ttH tag	$-0.80^{+2.10}_{-1.84}$	125.8	–	–	–	100%
$H \to \tau\tau$ (up to 5.0 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV) [12,55,56]						
0/1 jet	$0.85^{+0.68}_{-0.66}$	125.8	76%	16%	7%	1%
VBF tag	$0.82^{+0.82}_{-0.75}$	125.8	19%	81%	–	–
VH tag	$0.86^{+1.92}_{-1.68}$	125.8	–	–	100%	–



Experimental data we use
Tevatron

Channel	Signal strength μ	M_H (GeV)	Production mode			
			ggF	VBF	VH	ttH
$H \to \gamma\gamma$ [59]						
Combined	$6.14^{+3.25}_{-3.19}$	125	78%	5%	17%	–
$H \to WW$ [59]						
Combined	$0.85^{+0.88}_{-0.81}$	125	78%	5%	17%	–
$H \to b\bar{b}$ [14]						
VH tag	$1.56^{+0.72}_{-0.73}$	125	–	–	100%	–

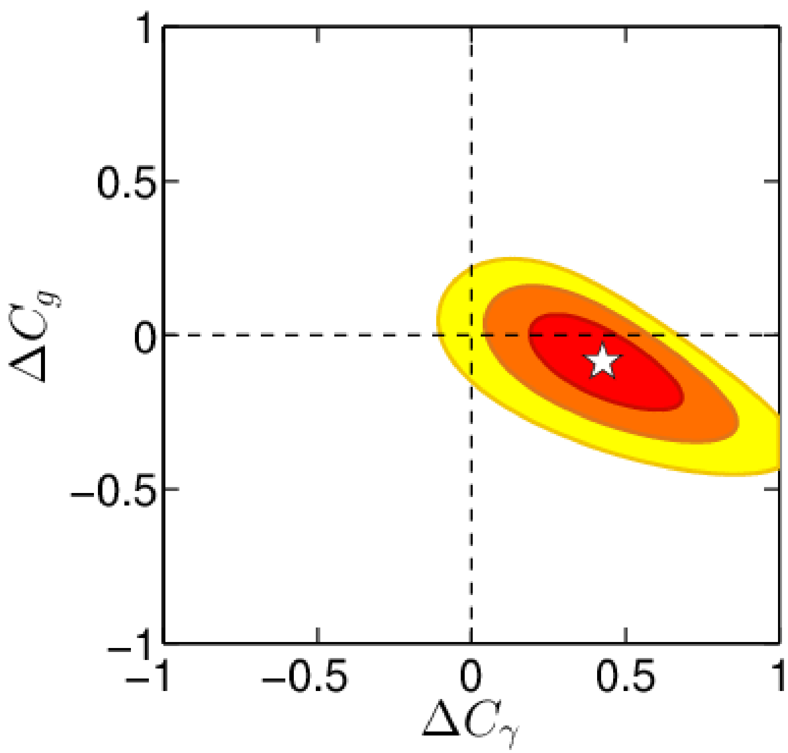
Our fitting procedure

relies on several assumptions
(will be discussed afterwards)

- simple χ^2 fit: $\chi^2 = \sum_k \frac{(\mu_k - \mu_k^{\exp})^2}{\Delta\mu_k^2}$
- when we use ($\mu_{ggF+ttH}$, μ_{VBF+VH}) information we take into account correlations
- μ_k: rescaling of the SM prediction (given by the LHC Higgs XS WG)
- we take into account the different efficiencies for the various production mechanisms
- when showing contours of $\Delta\chi^2$:
  we profile the likelihood over the unseen parameters

I) ΔC_g , ΔC_γ fit

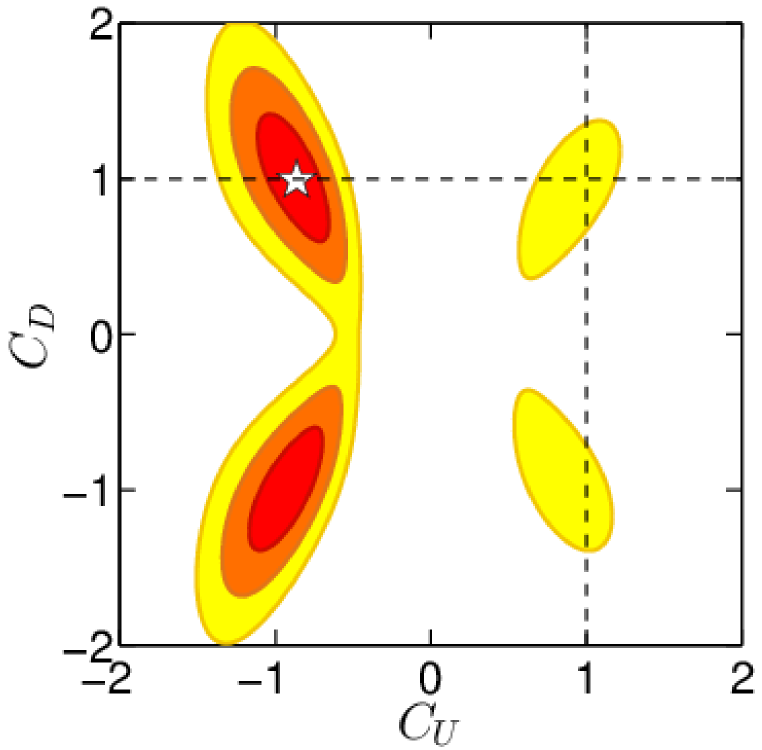
- we assume $C_U = C_D = C_V = 1$ — ΔC_g and ΔC_γ are free to vary
  → new physics as additional particles in the loops
- relevant in the context of Universal Extra Dimensions, VLQ, ...



- SM: >2 sigma away from best fit due to the excess in $H \to \gamma\gamma$
- Observed gluon-gluon fusion rate well compatible with the SM

II) C_U , C_D , C_V fit

- we assume $\Delta C_g = \Delta C_\gamma = 0$ — C_U, C_D and C_V are free to vary
  → modified Higgs sector + no new particles in the loops
- can arise with extended Higgs sectors (e.g. 2HDM with heavy H^+)



- SM: >2 sigma away from best fit due to the excess in $H \to \gamma\gamma$
- $C_U < 0$ (sign opposite to C_V)
  ⇒ constructive interference with W preferred at the level of 2.6σ
- single top production in association with a Higgs boson could soon discriminate $C_U > 0$ and $C_U < 0$
  [Biswas, Gabrielli and Mele '12; Farina et al. '12]

How reliable are our fits?
Is it the best thing a theorist can do with the LHC results?
Let's have another look at where we started...

Fitting procedure

$$\chi^2 = \sum_k \frac{(\mu_k - \mu_k^{\text{exp}})^2}{\Delta\mu_k^2}$$

what we assume here:

- the PDFs of the experimental μ are Gaussian
- the Higgs mass is fixed (common to all channels)
- all the channels are independent (no correlation)
- the efficiencies are exactly known for the various production mechanisms

besides:

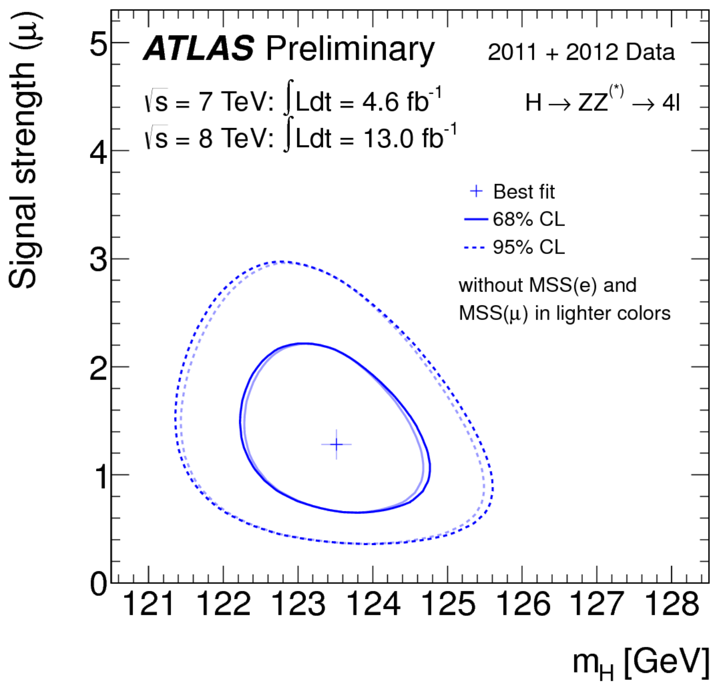
- should we use all the subcategories of a final state?
  or the combined μ reported by the experiment?
  or something else?
  (e.g. 12 subcategories in ATLAS $H \rightarrow \gamma\gamma$ at 8 TeV)

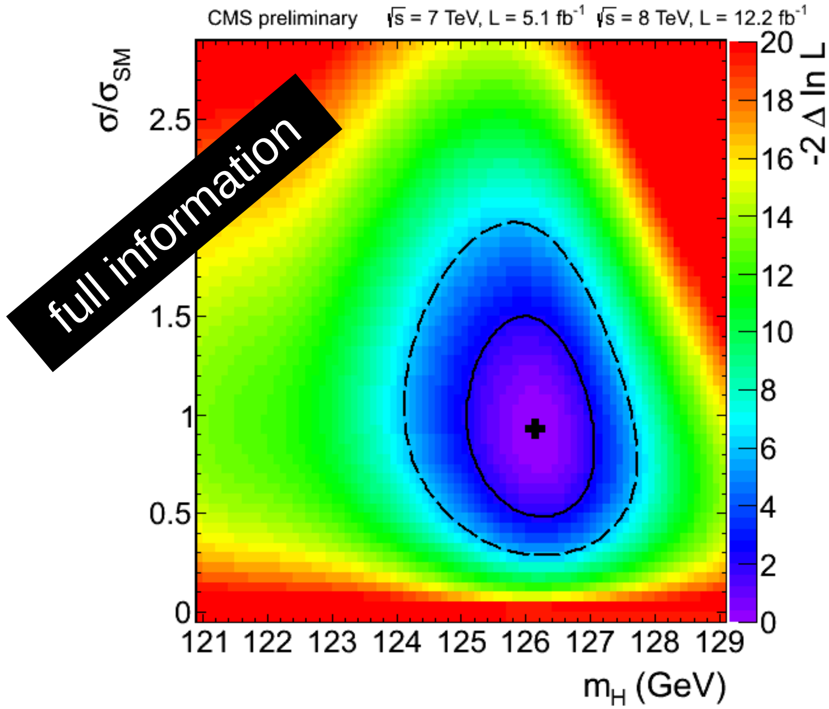
PDFs of the experimental μ

- What is usually reported by the experiments is the 68% CL range.
- The best thing we can do is then to assume that μ is normally distributed
  → how valid is this approximation?
  what about the tails of the distribution?
- Moreover: some reported 68% CL ranges are quite asymmetric
  example: CMS $\mu(H \to WW, \text{VBF tag}) = -0.05^{+0.74}_{-0.55}$
  → how should we include this in the fit?
  two half-gaussians? or better motivated distribution?
- The ignorance on the shape of the PDF of μ is a sizeable source of uncertainty in our analyses
  → would be very useful for us to have this information

The Higgs mass

- We would like to treat the Higgs mass as a nuisance parameter in our fit
- Very important for the two high resolution channels ($H \to ZZ$ and $H \to \gamma\gamma$)
- This information is available for $H \to ZZ$ (inclusive channel)





- Unfortunately available only for the combination of $H \to \gamma\gamma$

About efficiencies and subcategories

- most of the Higgs searches are not inclusive
  → subcategories with different sensitivity to the production mechanisms
- Example: CMS H → γγ

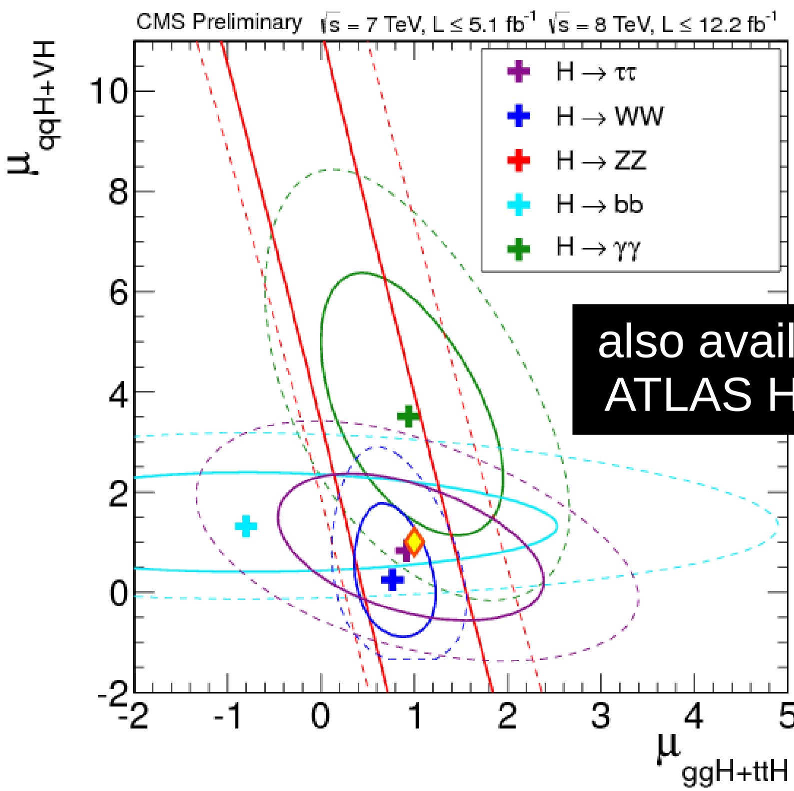
Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

- Implement all the subchannels ⇒ loose correlations
  Implement the combined value ⇒ loose information on efficiencies

  Is there an alternative?

2D χ^2 distributions



- Theoretically defined μ: pure production channels
- ggF and ttH lumped together (because low sensitivity on ttH)
- VBF and VH lumped together (because coupling to W and Z)
- Correlations and efficiencies are taken into account

- Fit of the 68% CL contour + 2D Gaussian approximation

$$\Rightarrow \chi_i^2 = \begin{pmatrix} \mu_{i,ggH/\bar{t}tH} - \hat{\mu}_{i,ggH/\bar{t}tH} \\ \mu_{i,VBF/VH} - \hat{\mu}_{i,VBF/VH} \end{pmatrix}^T V_i^{-1} \begin{pmatrix} \mu_{i,ggH/\bar{t}tH} - \hat{\mu}_{i,ggH/\bar{t}tH} \\ \mu_{i,VBF/VH} - \hat{\mu}_{i,VBF/VH} \end{pmatrix}$$

- First introduced in fits by [Cacciapaglia, Deandrea, Drieu La Rochelle, Flament '12]

Going further

- ($\mu_{ggF+ttH}$, μ_{VBF+VH}) plots are great and should be generalized
  The full likelihood in addition to the 68% and 95% CL contours would be valuable in order to get rid of the Gaussian approximation

- However...
  - not suitable to test custodial symmetry
  - not appropriate once ttH measurements become precise
  - it is for a fixed Higgs mass

- Our theorist dream would be to have the full likelihood in the 6D plane (m_H , μ_{ggF} , μ_{ttH} , μ_{VBF} , μ_{WH} , μ_{ZH})

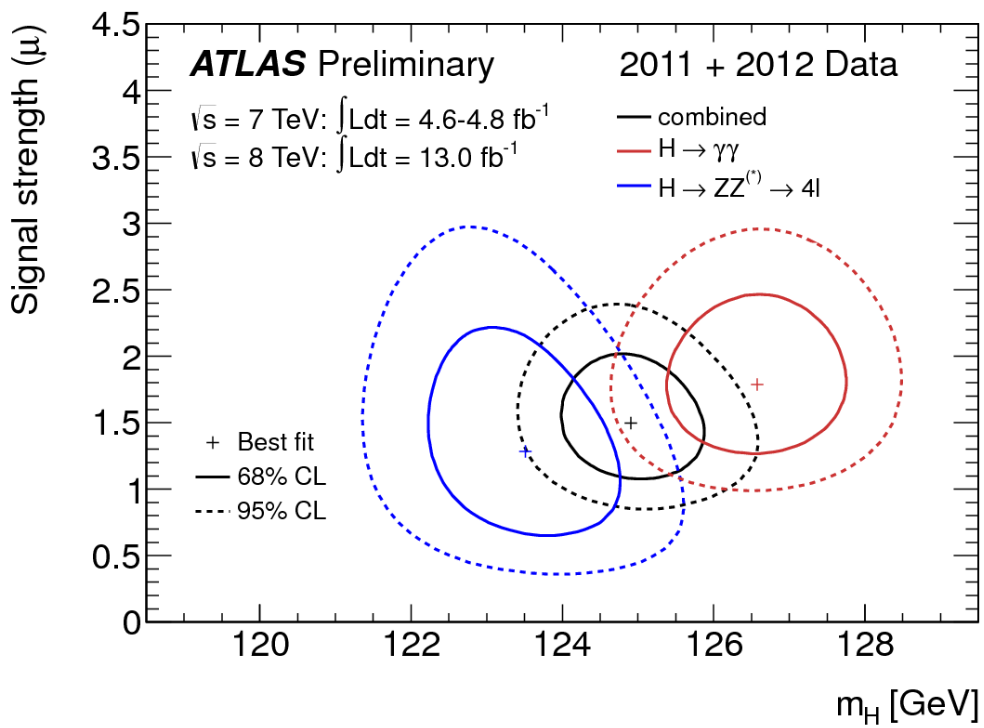
How the likelihood could be provided

- The full likelihood in the 6D plane, $L(m_H , \mu_{ggF} , \mu_{ttH} , \mu_{VBF} , \mu_{WH} , \mu_{ZH})$, could be provided for each channel as:
  - grid in the form of text file (e.g. on HepData)
    (not necessarily a huge file: we do not need an extremely fine grid)
  - analytic form / RooStats implementation?
- This is in line with the recommendations 3b and 3c from "Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results" [Kraml et al. '12]

Conclusion

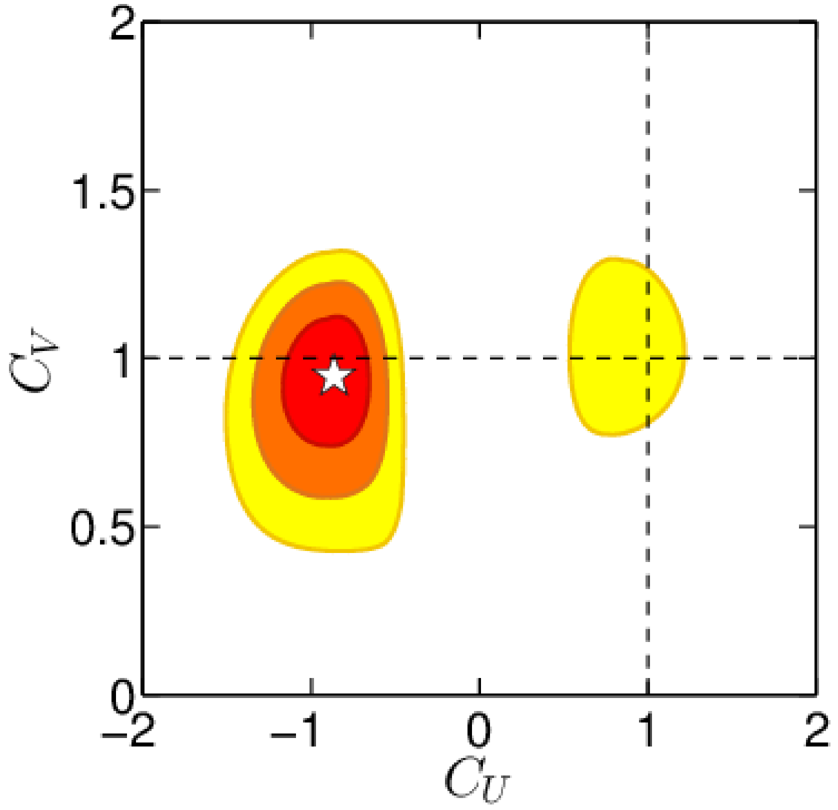
- impressive results in the Higgs searches from ATLAS and CMS
- channel-by-channel decomposition of experimental results is crucial
- fits from theorists are necessary to fully exploit the LHC Higgs results
- more information on the likelihoods from the experiments would be immensely helpful to this end
- what I did not talk about: correlations between channels (final states). can they be large?
- many New Physics models to explore in light of what we learned on the 125 GeV Higgs boson!

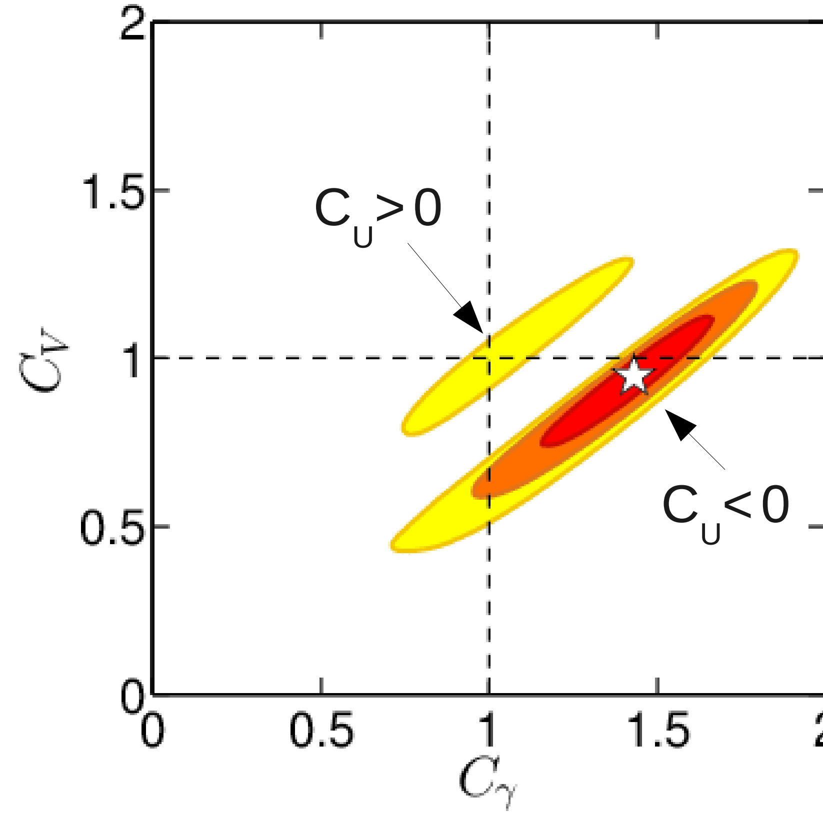
Backup
About the ATLAS mass discrepancy



- is the discrepancy mainly due to statistics or unknown systematics?
- assuming that we work at fixed Higgs mass, e.g. 125.5 GeV:
  should we read the value of μ(ZZ) at
  - 123.5 GeV (best fit for H → ZZ) and rescale the theory prediction at 125.5 GeV?
  - 125.5 GeV directly?

Backup
II) C_U , C_D , C_V fit





- C_V tend to be larger for $C_U > 0$
- Strong correlation between C_γ and C_V

Backup
Goodness-of-fit

- all of our fits disfavour the Standard Model at more than 2σ

Fit	Standard Model	$\Delta C_\gamma, \Delta C_g$	C_U, C_D, C_V	$C_U, C_D, C_V, \Delta C_\gamma, \Delta C_g$
$\chi^2_{\rm min}$	20.2	12.3	12.0	11.5
$\chi^2_{\rm min}$/d.o.f.	0.96	0.65	0.66	0.72

- significant improvement of χ^2/d.o.f. (hence the *p*-value) when allowing for an enhanced $H\gamma\gamma$ rate

- marginal amelioration of the fit from 2 to 5 parameters