Higgs couplings after Moriond

Béranger Dumont

LPSC
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GDR Terascale @ Montpellier
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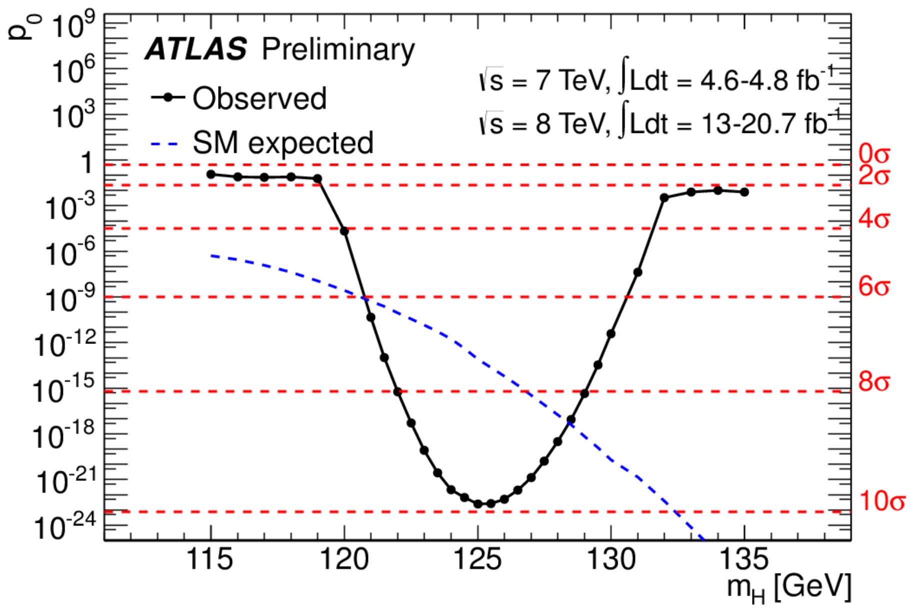
The Higgs boson has been found



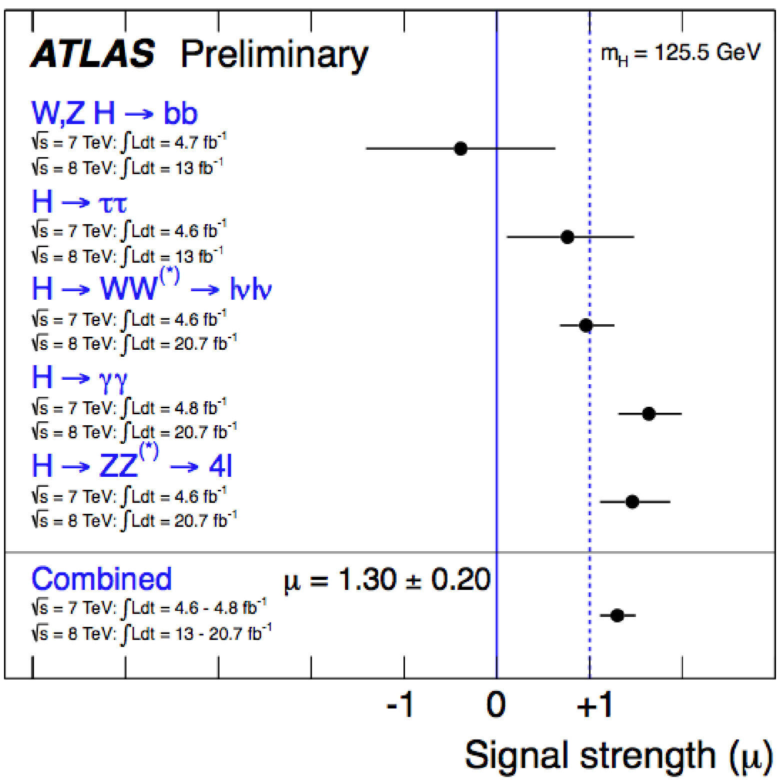
CMS preliminary

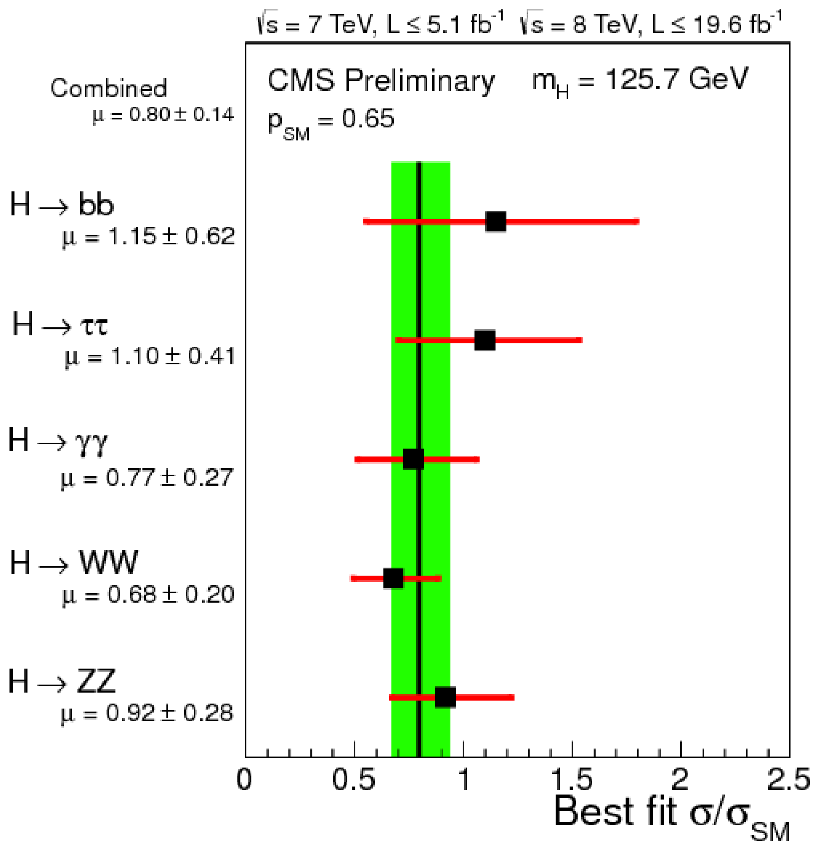
Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
$\tau\tau$	2.6	2.8

- previous update in Moriond (in March)
  → almost all bosonic channels have been updated with full luminosity
- also, final results from Tevatron! (arXiv:1303.6346)
  very competitive for H→bb
- consistent mass measurement ~ 125.6 GeV

What we know about it
signal strengths

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





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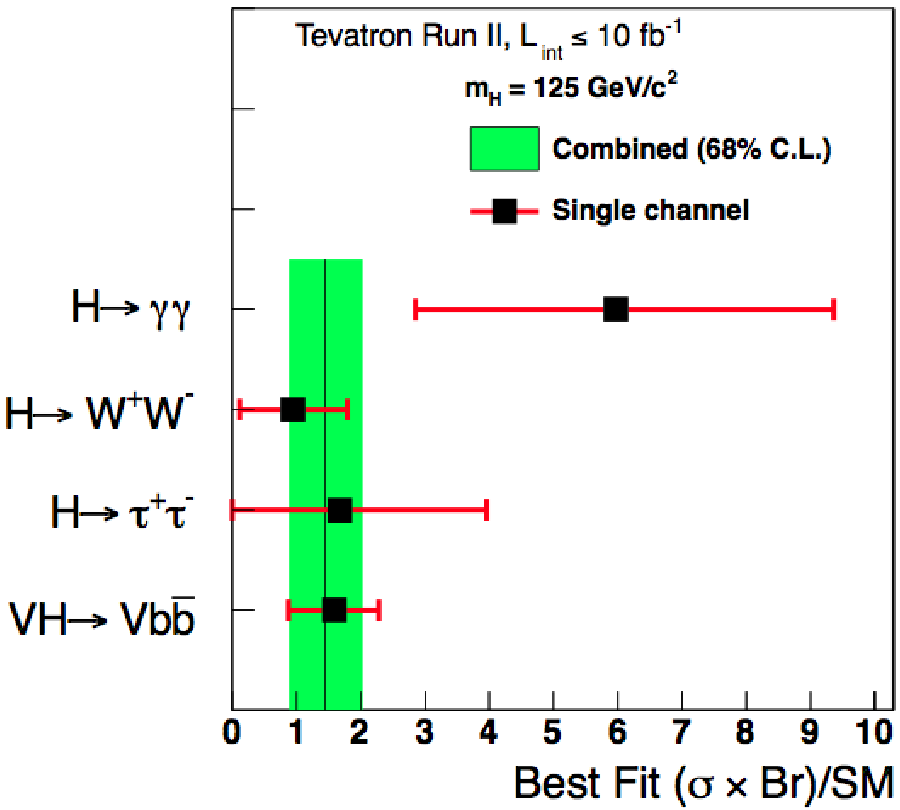
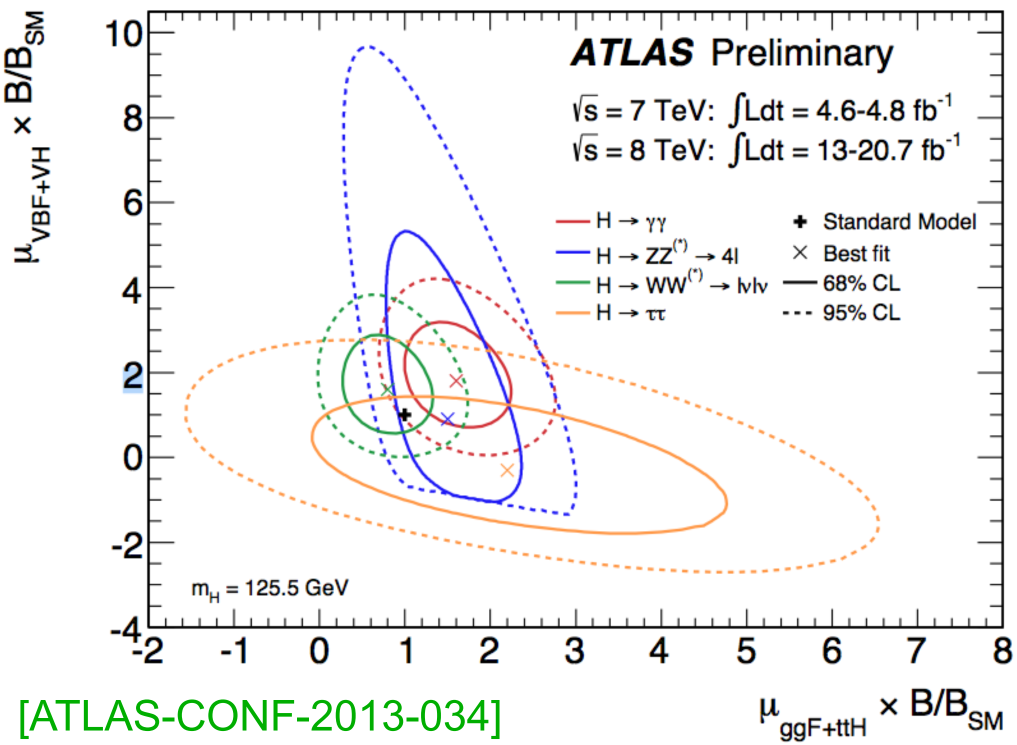


...but New Physics modify not only the Higgs decays but also its production

how can we use the experimental information in a correct way?

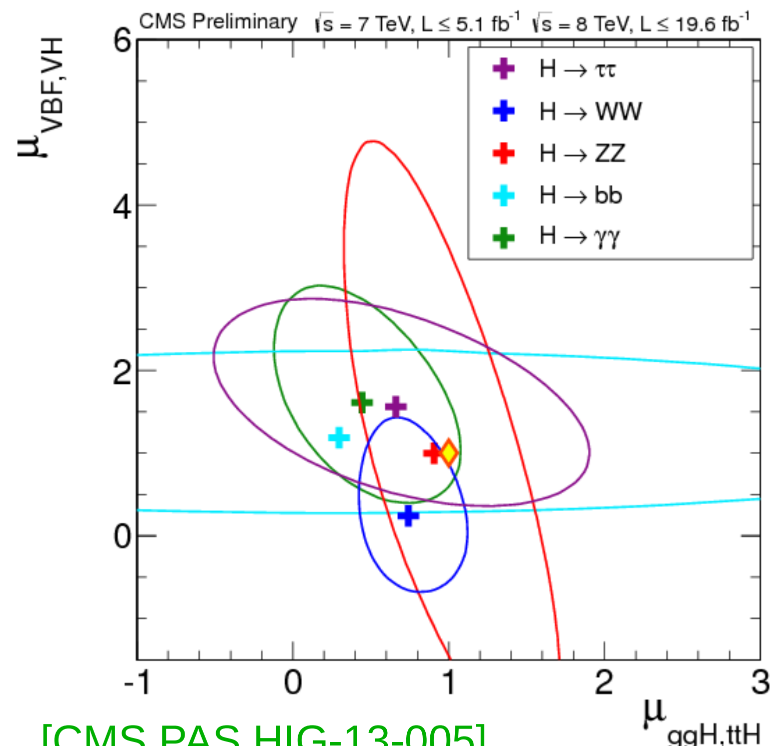
2D μ plots from ATLAS and CMS

ATLAS



[ATLAS-CONF-2013-034]

CMS

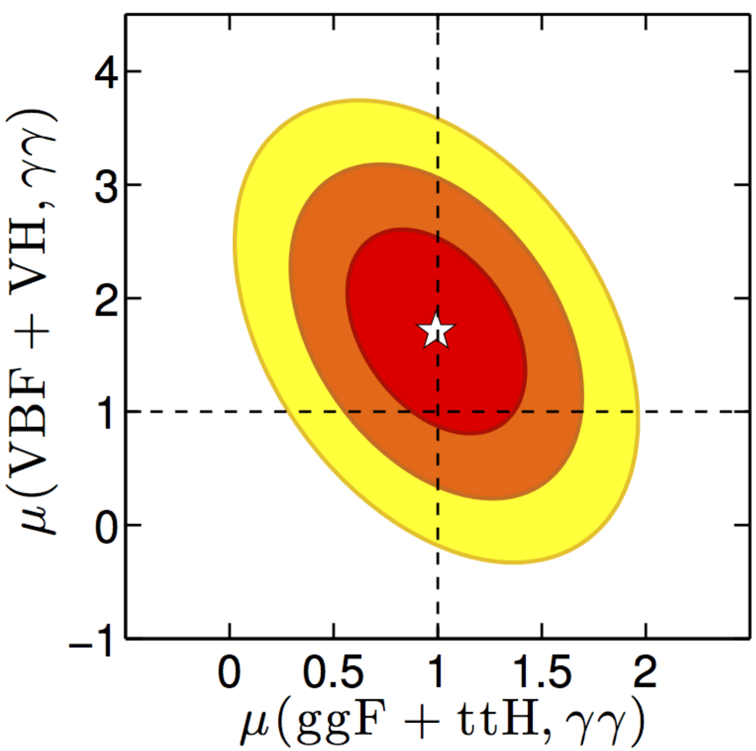


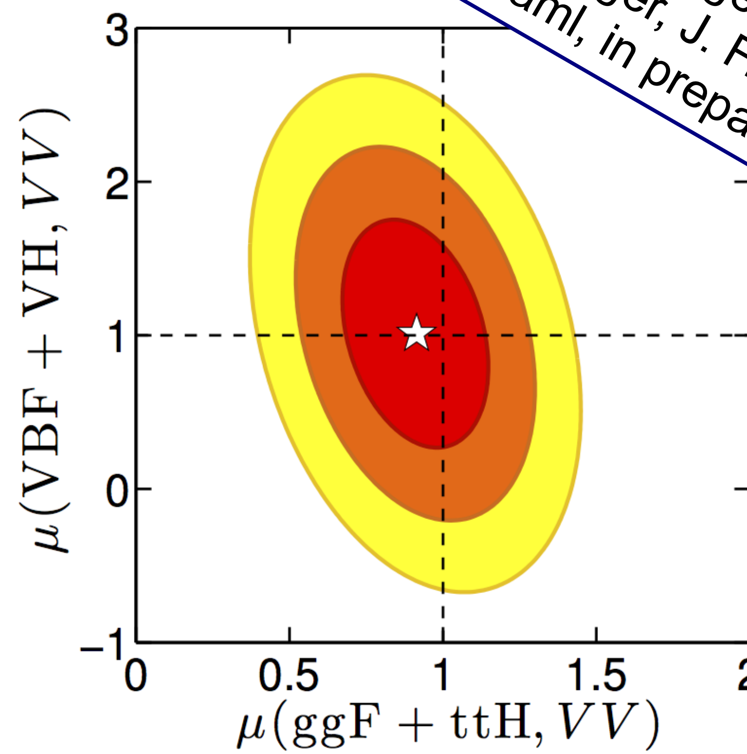
[CMS PAS HIG-13-005]

whenever possible, we check the validity of the Gaussian approximation → usually fairly good

Combined 2D μ plots bosonic channels

[G. Belanger, BD, U. Ellwanger, J. F. Gunion, S. Kraml, in preparation]



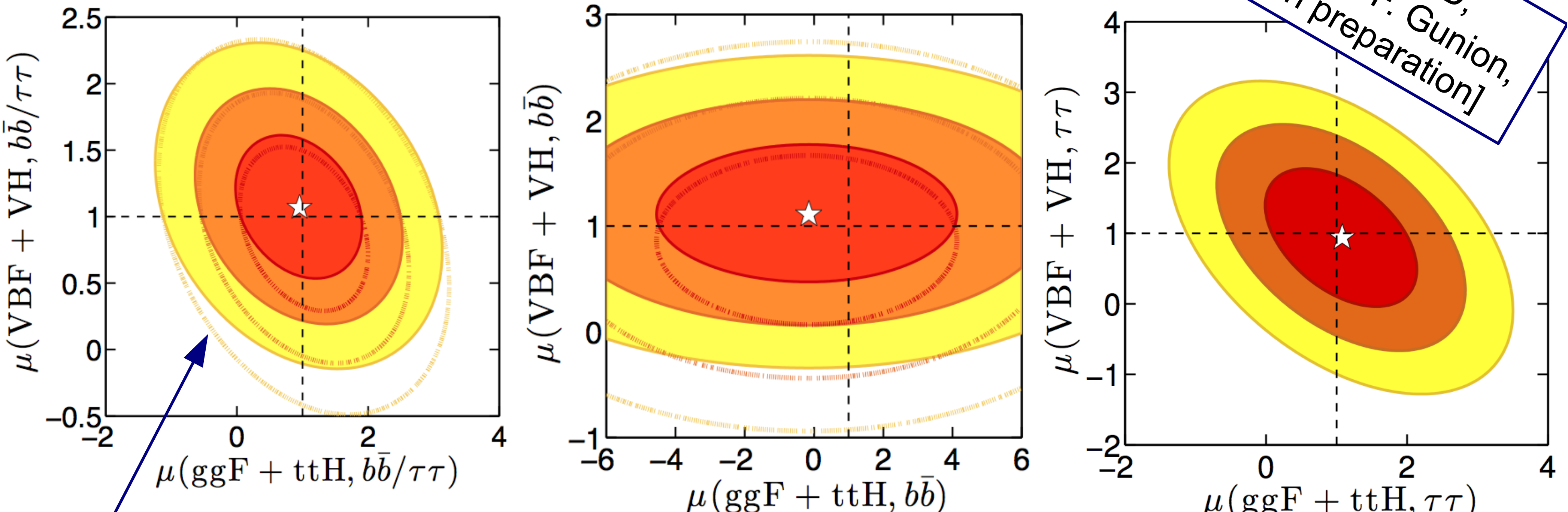


	$\mu(\mathrm{ggF}+\mathrm{ttH},Y)$	$\mu(\mathrm{VBF}+\mathrm{VH},Y)$	ρ
$\gamma\gamma$	0.99 ± 0.28	1.71 ± 0.59	-0.38
VV	0.91 ± 0.16	1.01 ± 0.49	-0.30

identical with or without Tevatron!

Combined 2D μ plots fermionic channels

[G. Belanger, BD, U. Ellwanger, J. F. Gunion, S. Kraml, in preparation]



without Tevatron

	$\mu(\mathrm{ggF}+\mathrm{ttH}, Y)$	$\mu(\mathrm{VBF}+\mathrm{VH}, Y)$	ρ
$b\bar{b}/\tau\tau$	0.93 ± 0.64	1.08 ± 0.36	-0.27
$b\bar{b}$	-0.22 ± 2.86	1.13 ± 0.43	0
$\tau\tau$	1.07 ± 0.71	0.94 ± 0.65	-0.47

Higgs couplings fits and invisible decays

based on:
G. Belanger, BD, U. Ellwanger, J. F. Gunion, and S. Kraml
[arXiv:1212.5244, JHEP02(2013)053] and [arXiv:1302.5694, to appear in PLB]
(update in preparation)

Higgs couplings

How can we use this information to constrain the couplings of the Higgs?

- 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 parametrize deviations from the SM

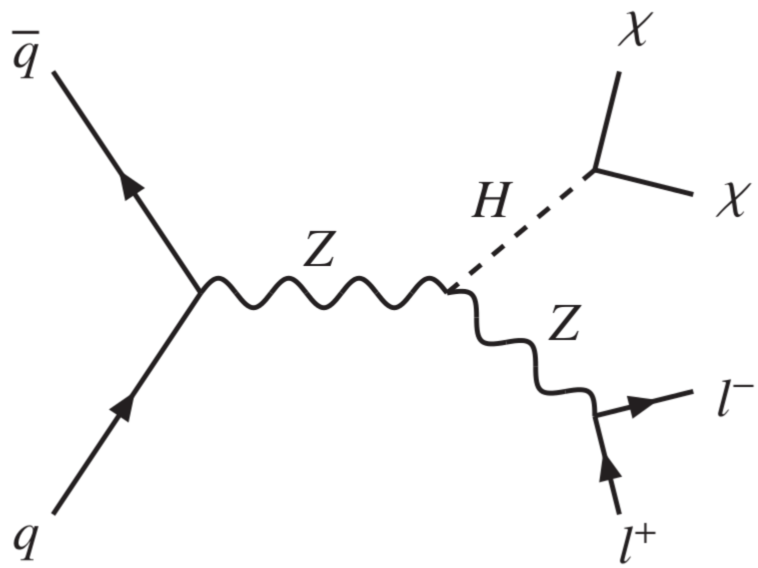
- We calculate $\overline{C}_g$ (for gluon-gluon fusion) and $\overline{C}_\gamma$ (for H→γγ) from C_U, C_D, C_V and we allow for additional particles in the loop: ΔC_g and ΔC_γ
  → $C_g = \overline{C}_g + \Delta C_g$ and $C_\gamma = \overline{C}_\gamma + \Delta C_\gamma$

- Total Higgs width: not accessible at the LHC. 2 possibilities:
  1) assume that BR(H→invisible/undetected) = 0
  2) allow for H→invisible/undetected

Searches for invisible decays of the Higgs boson

ATLAS

$ZH \to \ell\ell + \text{invisible}$



[ATLAS-CONF-2013-011]

$$\mathcal{B}(H \to \text{inv.}) < 0.65 \text{ at } 95\% \text{ CL}$$

Searches for invisible decays of the Higgs boson

ATLAS

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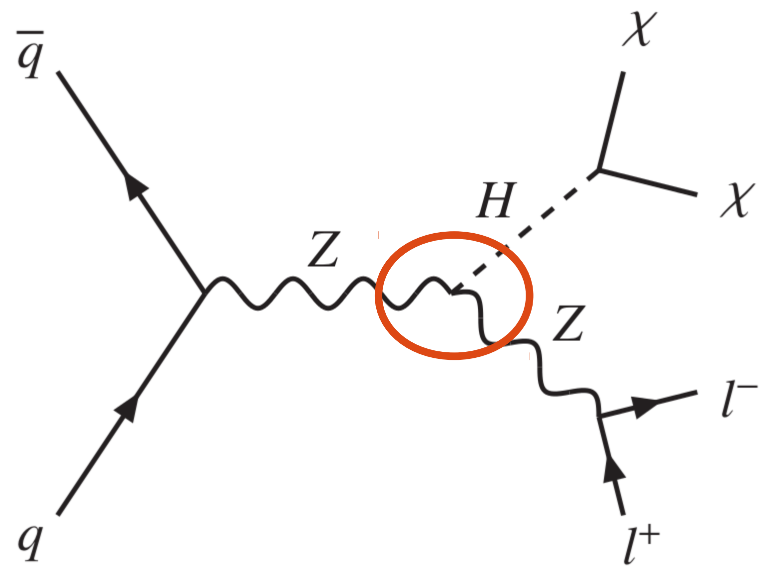


[ATLAS-CONF-2013-011]

$$C_V^2\,\mathcal{B}(H \to \text{inv.}) < 0.65 \text{ at } 95\% \text{ CL}$$

see also earlier studies based on *e.g.* monojet searches [Djouadi *et al.* '12]

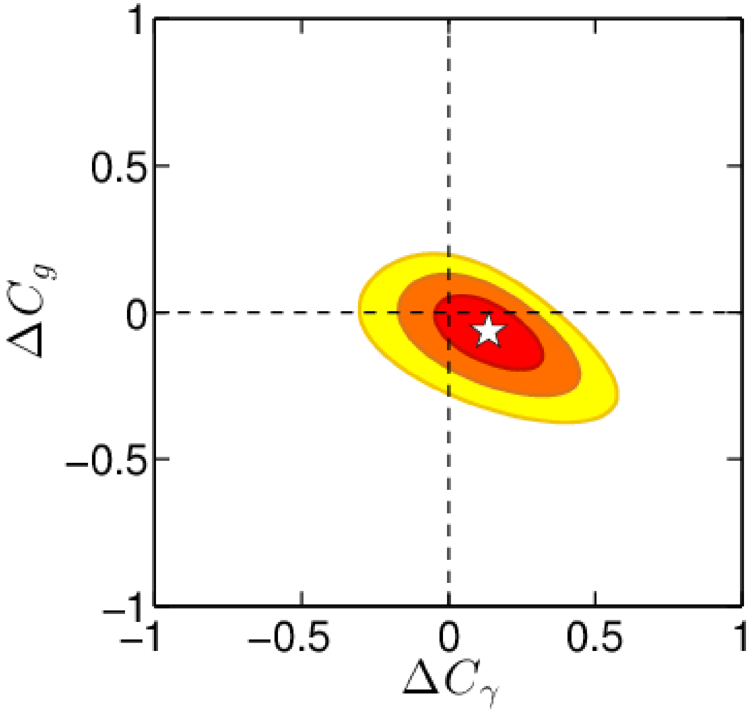
Fitting procedure

- simple χ² fit: $\chi^2 = \sum_k \frac{(\mu_k - \mu_k^{\rm exp})^2}{\Delta\mu_k^2}$
- μ_k: rescaling of the SM prediction (given by the LHC Higgs XS WG)
- when showing contours of $\Delta\chi^2$:
  we profile the likelihood over the unseen parameters

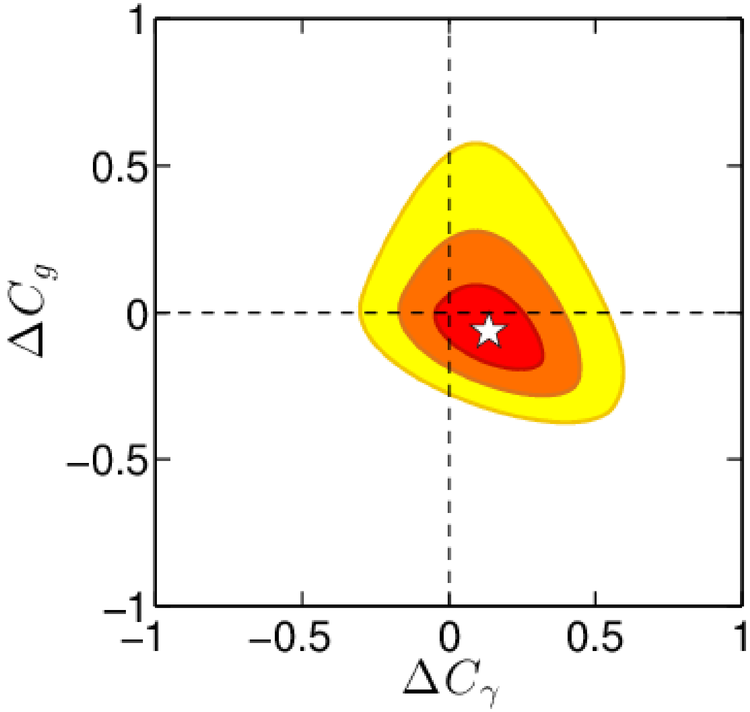
I) ΔC_g , ΔC_γ fit

- 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, ...

BR(H→invisible/undetected) = 0



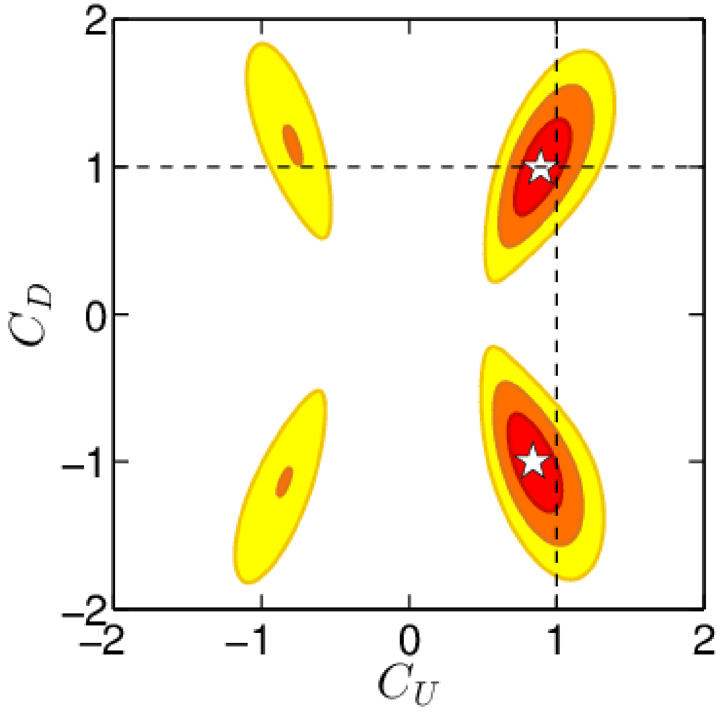
BR(H→invisible/undetected) free



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^+)

BR(H→invisible/undetected) = 0



- $C_U < 0$ (sign opposite to C_V): constructive interference with W disfavored at the level of 2.4σ
- minimum with $C_D > 0$ and $C_D < 0$ are practically equivalent

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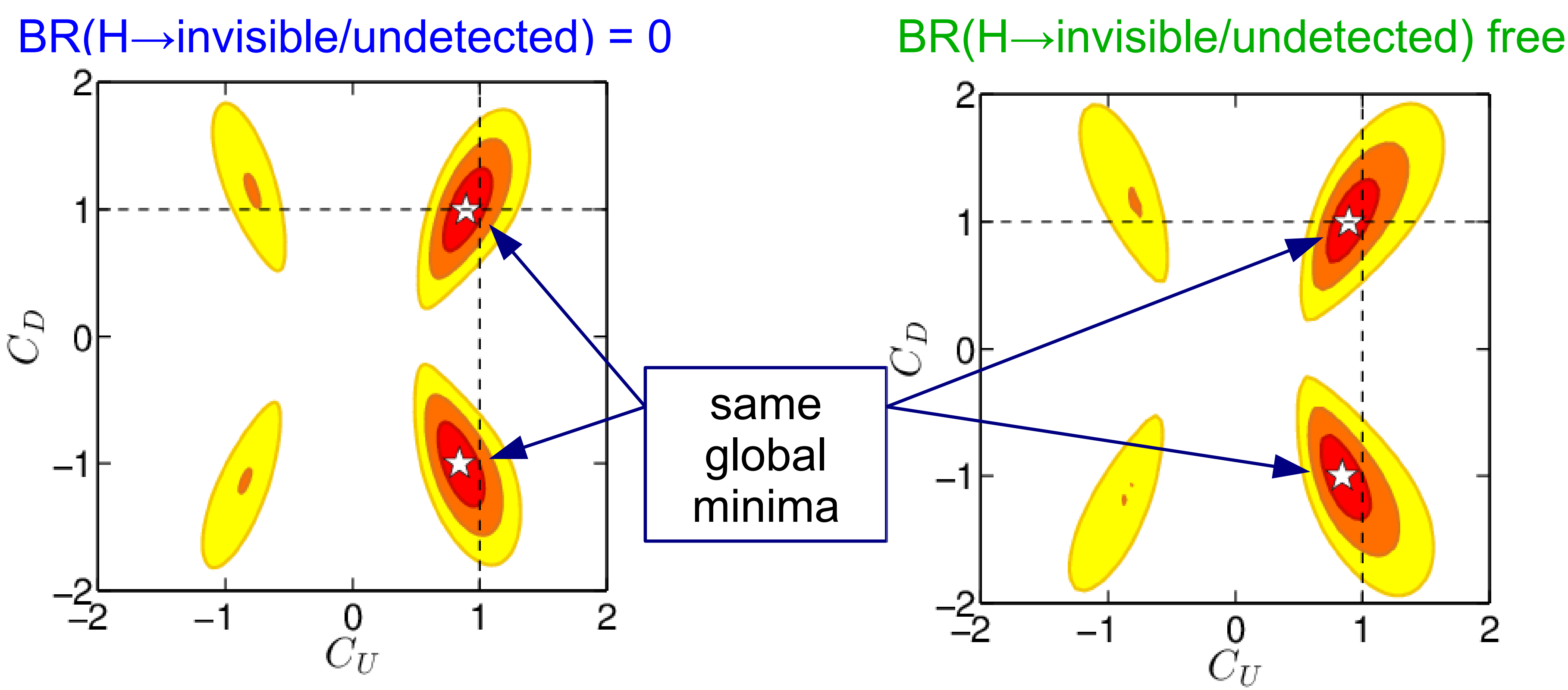
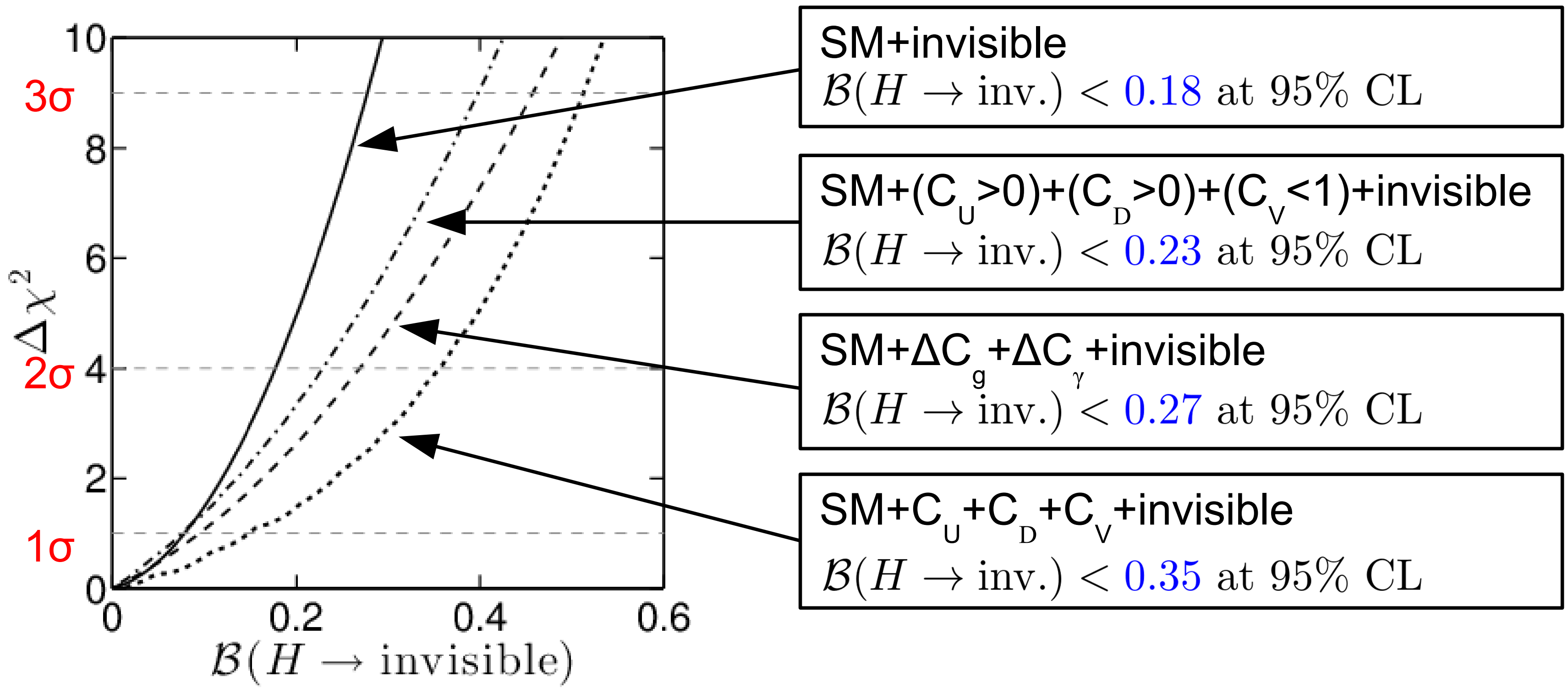


Invisible decays of the Higgs boson



if invisible = dark matter:
interplay between direct searches and H→invisible
(on backup slides – feel free to ask questions!)

A Bayesian view of the Higgs sector with higher dimensional operators

based on:
BD, S. Fichet, G. von Gersdorff [arXiv:1304.3369]

Philosophy of our EFT approach

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{\alpha_i}{\Lambda^{n_i}} \mathcal{O}_i$$

we consider dimension-6 operators only

underlying assumptions

- the observed state at ~125 GeV is
  - CP-even
  - spin 0
  - and belongs to a $SU(2)_L$ doublet
- there is a mass gap between the SM and New Physics (arising at the scale Λ)

complementarity with the "anomalous couplings" approach → less general but...

- clear ordering between operators
- fully consistent theoretical framework

Our basis of relevant operators

$$\mathcal{O}_D = J^a_{H\,\mu} J^a_\mu\,, \quad \mathcal{O}_{D^2} = |H|^2 |D_\mu H|^2$$

$$\mathcal{O}_{WW} = H^\dagger H\,(W^a_{\mu\nu})^2\,, \quad \mathcal{O}_{BB} = H^\dagger H\,(B_{\mu\nu})^2$$

$$\mathcal{O}_{WB} = H^\dagger W_{\mu\nu} H\, B_{\mu\nu}\,, \quad \mathcal{O}_{GG} = H^\dagger H\,(G^a_{\mu\nu})^2$$

$$\mathcal{O}_t = 2y_t\,|H|^2\, H\bar{t}_L t_R\,, \quad \mathcal{O}_b = 2y_b\,|H|^2\, H\bar{b}_L b_R\,, \quad \mathcal{O}_\tau = 2y_\tau\,|H|^2\, H\bar{\tau}_L \tau_R$$

no custodial-symmetry violating operators

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no custodial-symmetry violating operators

$$\mathcal{L}^{\rm tree}_{v,f} = \lambda_Z\,h\,(Z_\mu)^2 + \lambda_W\,h\,W^+_\mu W^-_\mu + \sum_f \lambda_f\,h\,\bar{f}_L f_R$$

couplings to gauge bosons and fermions

$$\begin{aligned}\mathcal{L}^{\rm tree}_t \;&=\; \zeta_\gamma\,h\,(F_{\mu\nu})^2 + \zeta_g\,h\,(G_{\mu\nu})^2 + \zeta_{Z\gamma}\,h\,F_{\mu\nu}Z_{\mu\nu} \\ &+\; \zeta_Z\,h\,(Z_{\mu\nu})^2 + \zeta_W\,h\,W^+_{\mu\nu}W^-_{\mu\nu}\end{aligned}$$

tree-level contribution to the tensor couplings

$$\mathcal{L}^{1-{\rm loop}} = \lambda_\gamma\,h\,(F_{\mu\nu})^2 + \lambda_g\,h\,(G_{\mu\nu})^2 + \lambda_{Z\gamma}\,h\,F_{\mu\nu}Z_{\mu\nu}$$

couplings of the loop-induced processes

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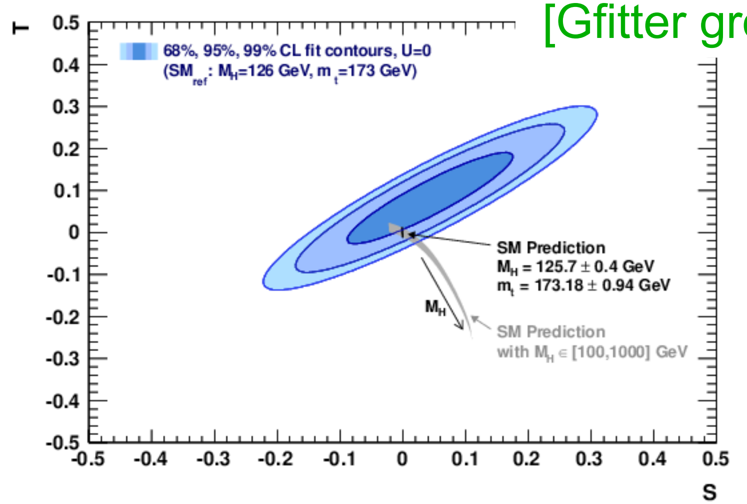
couplings of the loop-induced processes

Experimental constraints

- Higgs properties:
  all measurements up-to-date (incl. limits on H → Zγ)
  → implemented as in the Higgs couplings fits

[Gfitter group '12]



- electroweak precision observables:
  Peskin–Takeuchi S & T parameters

- measurements of the Triple Gauge Vertices (TGV) WWγ, WWZ:
  $\kappa_\gamma = 0.973^{+0.044}_{-0.045}$, $g_1^Z = 0.984^{+0.022}_{-0.019}$ [LEPEWWG/TGC/2005-01]

Bayesian inference & MCMC

in a model M, having:

- parameters of interest ϕ,
- other parameters ψ,

the posterior probability on ϕ given the experimental data is:

$$\underbrace{p(\phi|d,M)}_{\text{marginal posterior on the parameters of interest}} \propto \int \underbrace{L(\phi,\psi)}_{\text{likelihood}}\, \underbrace{\pi(\phi,\psi|M)}_{\text{prior}}\, d\psi$$

$$\text{with } L = L_{\mathrm{Higgs}} \times L_{S,T} \times L_{\mathrm{TGV}}$$

$$\pi(\alpha_i) = 1 \text{ (uniform prior)}$$

we sample the posterior probability distribution using Markov Chain Monte Carlo (MCMC)

Setup of the analysis

We consider 2 cases:

	I) Democratic HDOs	II) Loop-suppressed $\mathcal{O}_{FF}$'s
Λ	$4\pi v$	$4\pi v$
β_{FF}	$[-1,1]$	$[-1/16\pi^2, 1/16\pi^2]$
Other β	$[-1,1]$	$[-1,1]$

where $\beta_i = \alpha_i v^2/\Lambda^2$

$$FF = WW,\ WB,\ BB,\ GG$$

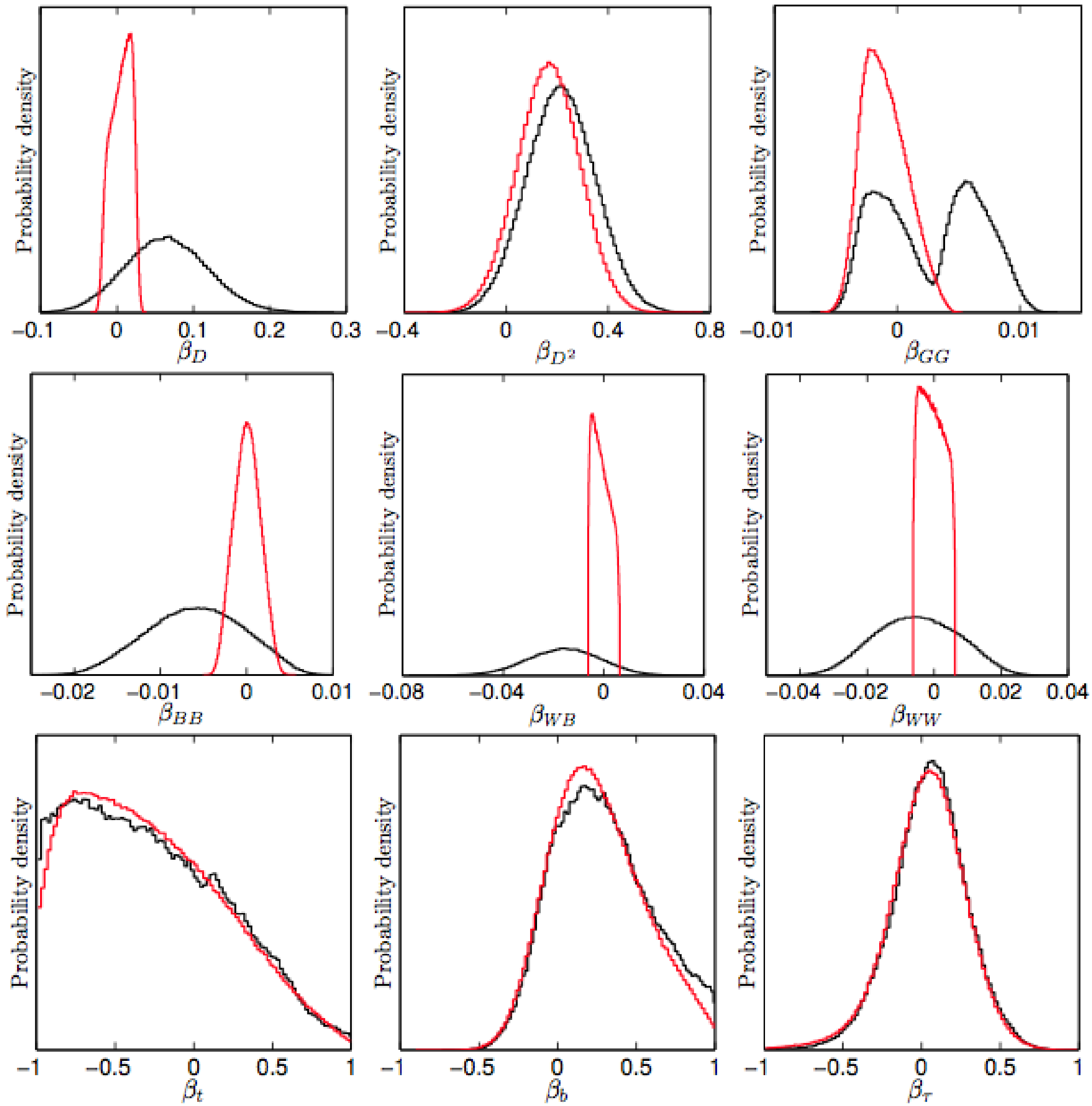
loop suppression of the operators
that cannot be generated at tree-level
within a perturbative UV theory

We fix $\Lambda = 4\pi v \approx 3\ \mathrm{TeV}$ but the dependence in Λ is mild
$\rightarrow$ results remain valid for TeV-scale New Physics

Results
1D probability distributions

- black line
  → democratic HDOs
- red line
  → loop suppressed $\mathcal{O}_{FF}$'s

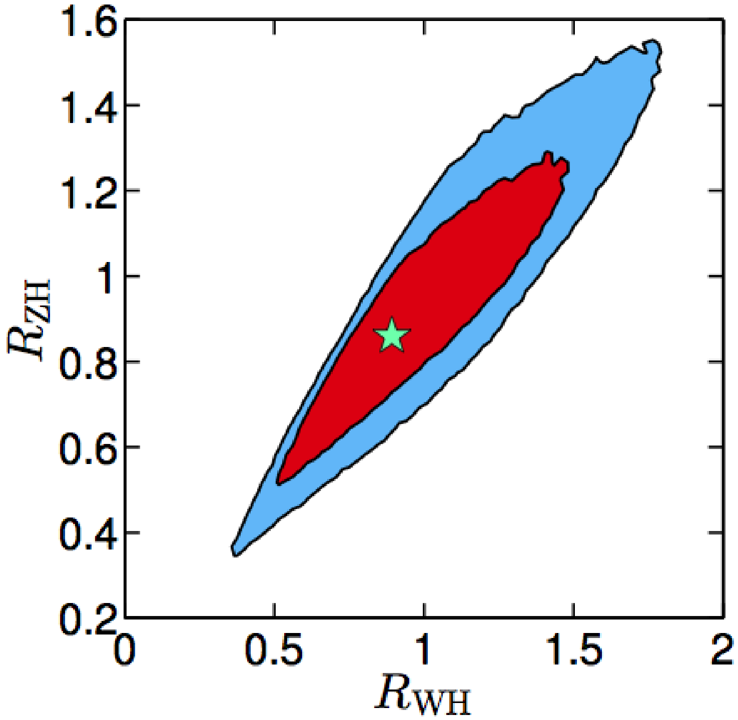
- β_{FF} are $\mathcal{O}(0.01)$
- β_f can go up to $\mathcal{O}(1)$



Results
associated production

$$R_{\mathrm{VH}} = \frac{\sigma_{\mathrm{VH}}}{\sigma_{\mathrm{VH}}^{\mathrm{SM}}}$$

democratic HDOs



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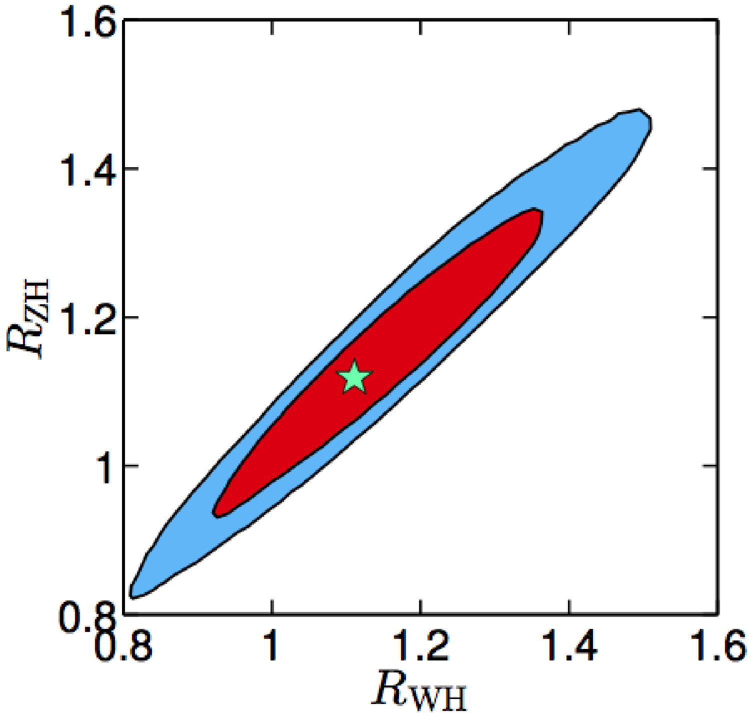
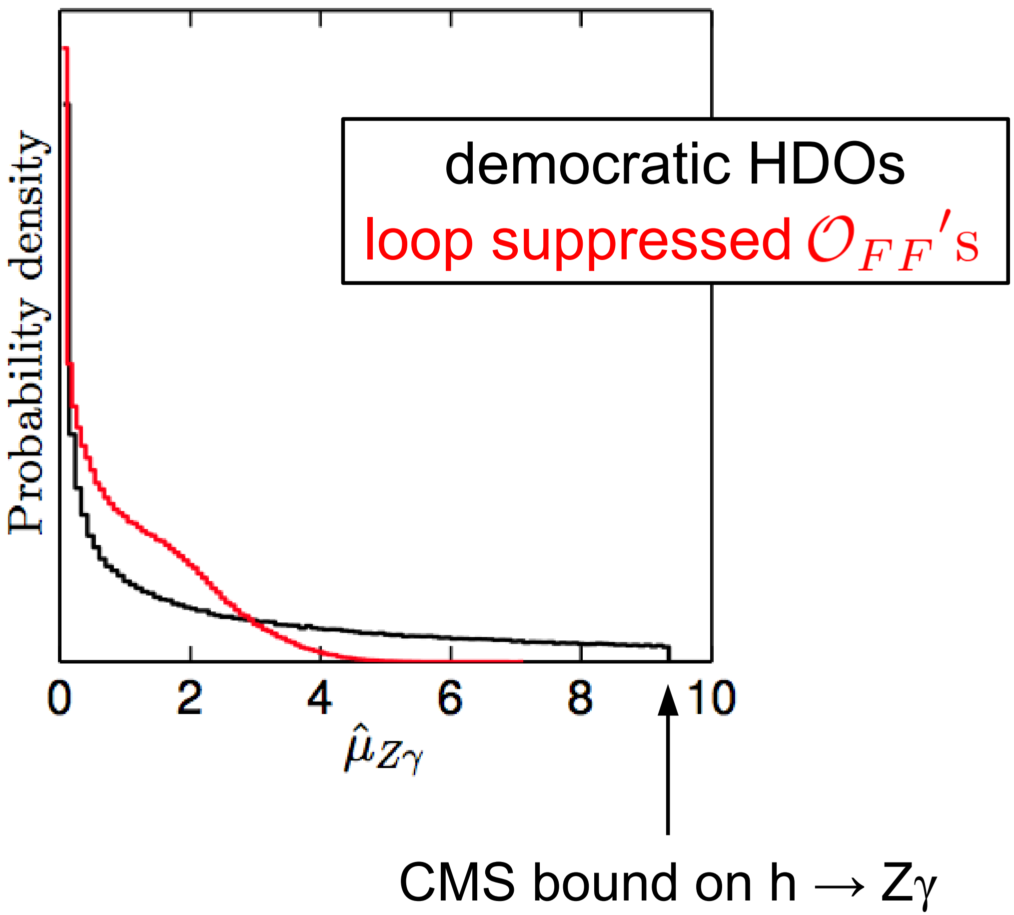


- tensorial couplings → sizeable change in the rescaling of WH and ZH
- we plead for a clear separation of WH and ZH in the LHC Higgs results

Results
h → Zγ



- possible large deviations from the SM value:
  comes from tensorial coupling $\zeta_{Z\gamma}$
- future measurements of h → Zγ
  ⇒ important constraints on our HDO parameters

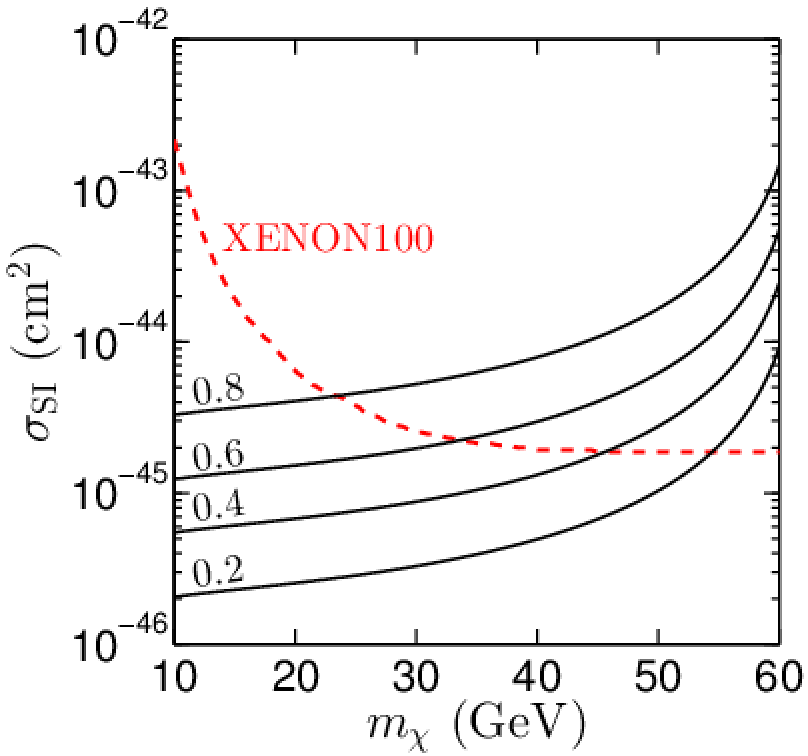
Conclusion

- overall, the observed Higgs boson seems very SM-like
(but still waiting for updates, especially in fermionic channels)
- precision era in Higgs physics has only just begun
however Higgs results are already a unique probe of New Physics
- model-independent studies as a first step in the study of the implications of the new boson
→ time has come to fully explore the consequences for BSM models

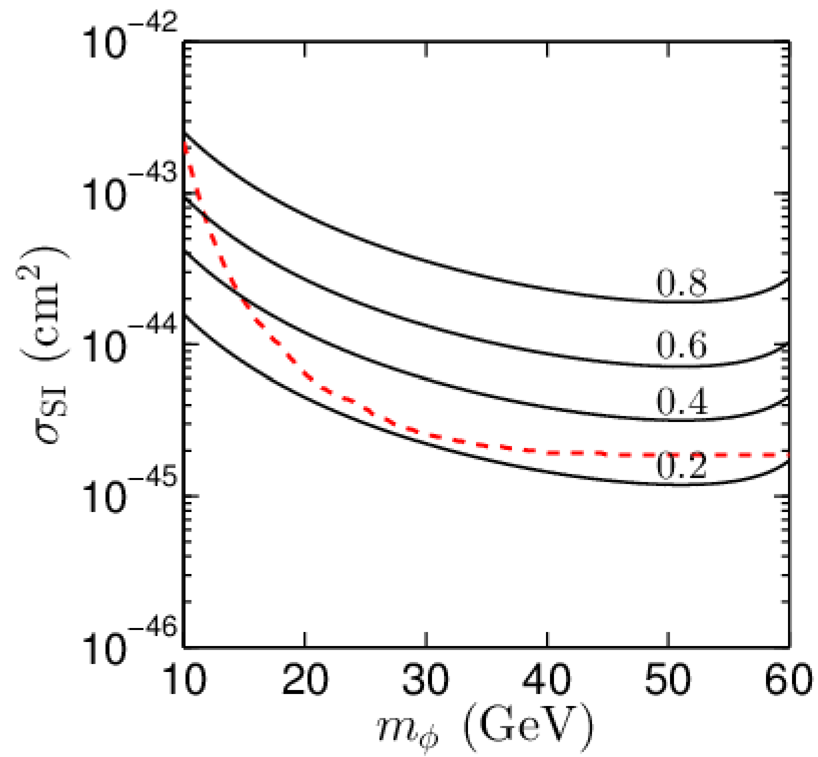
Invisible decays of the Higgs boson and dark matter

if invisible = dark matter:
interplay between direct searches and H→invisible

Majorana dark matter



scalar dark matter



Tensorial couplings and angular distributions

The amplitude associated to a hVV vertex (with the V's possibly off-shell) is in general

$$\mathcal{M}(hVV)^{\lambda_1,\lambda_2} = e^{\mu(*)}_{\lambda_1} e^{\nu(*)}_{\lambda_2} \left(i a_V \lambda_V^{\rm SM} g^{\mu\nu} - i2\zeta_V q_1.q_2 \left[g^{\mu\nu} - \frac{q_1^\mu q_2^\nu}{q_1.q_2} \right] \right) , \qquad (4.1)$$

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 + 20.7 fb^{-1} at 8 TeV) [1, 2]						
$\mu(\mathrm{ggF+ttH}, \gamma\gamma)$	1.60 ± 0.41	125.5	100%	–	–	–
$\mu(\mathrm{VBF+VH}, \gamma\gamma)$	1.94 ± 0.82	125.5	–	60%	40%	–
$H \to ZZ$ (4.6 fb^{-1} at 7 TeV + 20.7 fb^{-1} at 8 TeV) [3, 2]						
$\mu(\mathrm{ggF+ttH}, ZZ)$	1.50 ± 0.50	125.5	100%	–	–	–
$\mu(\mathrm{VBF+VH}, ZZ)$	1.50 ± 2.52	125.5	–	60%	40%	–
$H \to WW$ (4.6 fb^{-1} at 7 TeV + 20.7 fb^{-1} at 8 TeV) [4, 5]						
$\mu(\mathrm{ggF+ttH}, WW)$	0.79 ± 0.35	125.5	100%	–	–	–
$\mu(\mathrm{VBF+VH}, WW)$	1.71 ± 0.76	125.5	–	60%	40%	–
$H \to bb$ (4.7 fb^{-1} at 7 TeV + 13.0 fb^{-1} at 8 TeV) [6, 2]						
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) [2]						
$\mu(\mathrm{ggF+ttH}, \tau\tau)$	2.31 ± 1.61	125.5	100%	–	–	–
$\mu(\mathrm{VBF+VH}, \tau\tau)$	-0.20 ± 1.06	125.5	–	60%	40%	–

Table 1: ATLAS results, as employed in this analysis. The following correlations are included in the fit: $\rho_{\gamma\gamma} = -0.27$, $\rho_{ZZ} = -0.46$, $\rho_{WW} = -0.18$, $\rho_{\tau\tau} = -0.49$.

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 + 19.6 fb^{-1} at 8 TeV) [7, 8]						
$\mu(\text{ggF} + \text{ttH}, \gamma\gamma)$	0.46 ± 0.40	125.7	100%	–	–	–
$\mu(\text{VBF} + \text{VH}, \gamma\gamma)$	1.68 ± 0.87	125.7	–	60%	40%	–
$H \to ZZ$ (5.1 fb^{-1} at 7 TeV + 19.6 fb^{-1} at 8 TeV) [9]						
$\mu(\text{ggF} + \text{ttH}, ZZ)$	0.98 ± 0.46	125.8	100%	–	–	–
$\mu(\text{VBF} + \text{VH}, ZZ)$	1.07 ± 2.37	125.8	–	60%	40%	–
$H \to WW$ (up to 4.9 fb^{-1} at 7 TeV + 19.5 fb^{-1} at 8 TeV) [10, 11, 12, 8]						
$\mu(\text{ggF} + \text{ttH}, WW)$	0.78 ± 0.23	125.7	100%	–	–	–
$\mu(\text{VBF} + \text{VH}, WW)$	0.33 ± 0.70	125.7	–	60%	40%	–
$H \to b\bar{b}$ (up to 5.0 fb^{-1} at 7 TeV + 12.1 fb^{-1} at 8 TeV) [13, 14, 8]						
VH tag	$1.31^{+0.68}_{-0.61}$	125.7	–	–	100%	–
ttH tag	$-0.15^{+2.82}_{-2.90}$	125.7	–	–	–	100%
$H \to \tau\tau$ (4.9 fb^{-1} at 7 TeV + 19.4 fb^{-1} at 8 TeV) [15, 8]						
$\mu(\text{ggF} + \text{ttH}, \tau\tau)$	0.67 ± 0.79	125.7	100%	–	–	–
$\mu(\text{VBF} + \text{VH}, \tau\tau)$	1.59 ± 0.83	125.7	–	60%	40%	–

Table 2: CMS results, as employed in this analysis. The following correlations are included in the fit: $\rho_{\gamma\gamma} = -0.48$, $\rho_{ZZ} = -0.73$, $\rho_{WW} = -0.21$, $\rho_{\tau\tau} = -0.47$.

Experimental data we use
Tevatron

Channel	Signal strength μ	m_H (GeV)	Production mode			
			ggF	VBF	VH	ttH
$H \to \gamma\gamma$ [17]						
Combined	$5.97^{+3.39}_{-3.12}$	125	78%	5%	17%	–
$H \to WW$ [17]						
Combined	$0.94^{+0.85}_{-0.83}$	125	78%	5%	17%	–
$H \to b\bar{b}$ [17]						
VH tag	$1.59^{+0.69}_{-0.72}$	125	–	–	100%	–

Table 3: Tevatron results for up to 10 fb^{-1} at $\sqrt{s} = 1.96$ TeV, as employed in this analysis.

- Tevatron $H\to\tau\tau$ is omitted (large uncertainties)
- $H\to\gamma\gamma$ and $H\to WW$ are approximated as inclusive searches (ratio of inclusive cross sections for $p\bar{p}$ collisions at 2 TeV)

Computation of C_g and C_γ in the coupling fit

$$\bar{C}_g^2 = \frac{C_U^2 \sigma_{\mathrm{ggF}}^{tt} + C_D^2 \sigma_{\mathrm{ggF}}^{bb} + C_U C_D \sigma_{\mathrm{ggF}}^{tb}}{\sigma_{\mathrm{ggF}}^{tt} + \sigma_{\mathrm{ggF}}^{bb} + \sigma_{\mathrm{ggF}}^{tb}}$$

taken from HIGLU (with EW corrections switched off)

$$C_g^2 = \left(\sqrt{\bar{C}_g^2} + \Delta C_g \right)^2$$

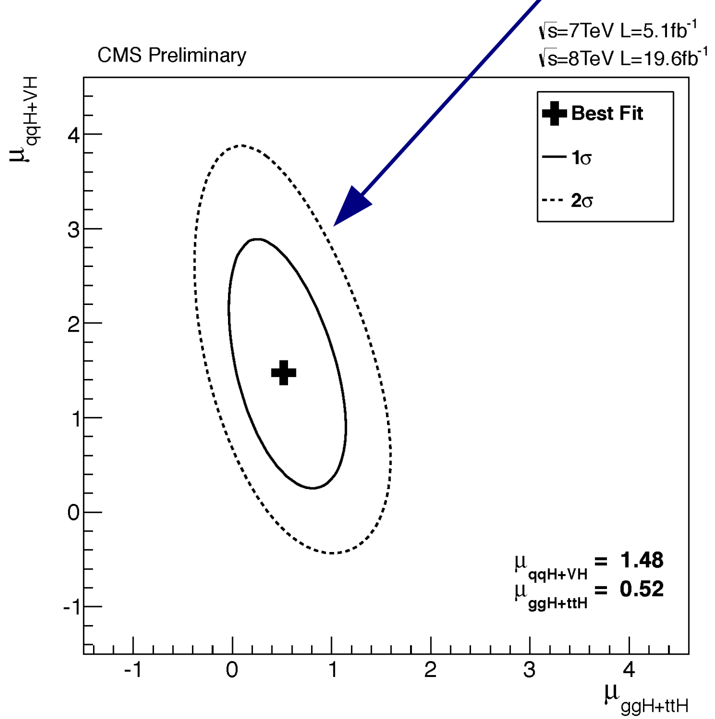
$$\bar{C}_\gamma^2 = \frac{C_V^2 \Gamma_{\gamma\gamma}^{WW} + C_U^2 \Gamma_{\gamma\gamma}^{tt} + C_D^2 \Gamma_{\gamma\gamma}^{bb} + C_D^2 \Gamma_{\gamma\gamma}^{\tau\tau} + \mathrm{interferences}}{\Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{bb} + \Gamma_{\gamma\gamma}^{\tau\tau} + \mathrm{interferences}}$$

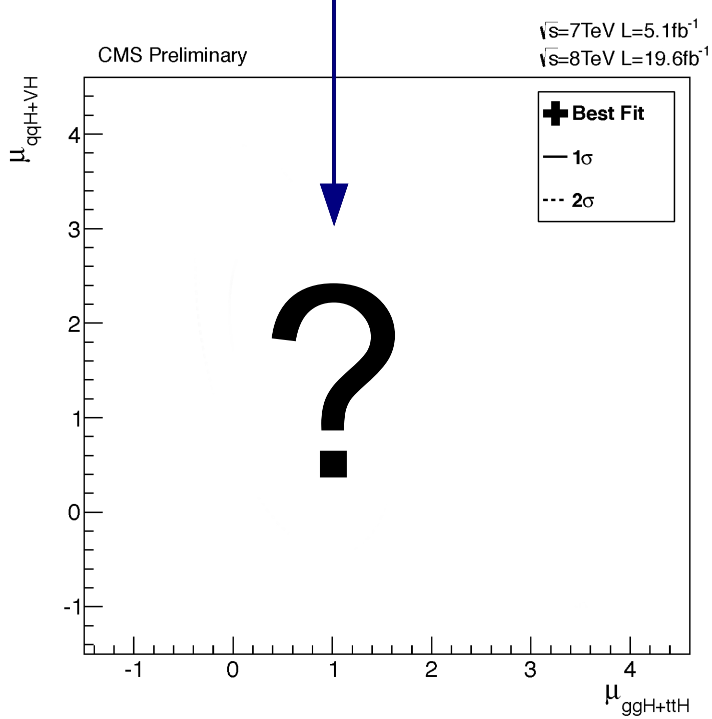
taken from HDECAY (with EW corrections switched off)

$$C_\gamma^2 = \left(\sqrt{\bar{C}_\gamma^2} + \Delta C_\gamma \right)^2$$

A word on CMS H→γγ

	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$





Goodness-of-fit

Fit	Standard Model	$\Delta C_\gamma, \Delta C_g$	C_U, C_D, C_V	$C_U, C_D, C_V, \Delta C_\gamma, \Delta C_g$
$\chi^2_{\rm min}$	19.0	17.6	17.6	17.2
$\chi^2_{\rm min}$/d.o.f.	0.86	0.88	0.93	1.01
dominant contributions to $\chi^2_{\rm min}$	ATLAS $\gamma\gamma$ Tevatron $\gamma\gamma$ CMS WW	CMS $\gamma\gamma$ ATLAS $\gamma\gamma$ Tevatron $\gamma\gamma$	ATLAS $\gamma\gamma$ CMS WW Tevatron $\gamma\gamma$	CMS $\gamma\gamma$ ATLAS $\gamma\gamma$ Tevatron $\gamma\gamma$

- no improvement of χ^2/d.o.f. (hence the *p*-value) when allowing for additional freedom
- most of the "tensions" in the fit come from $\gamma\gamma$

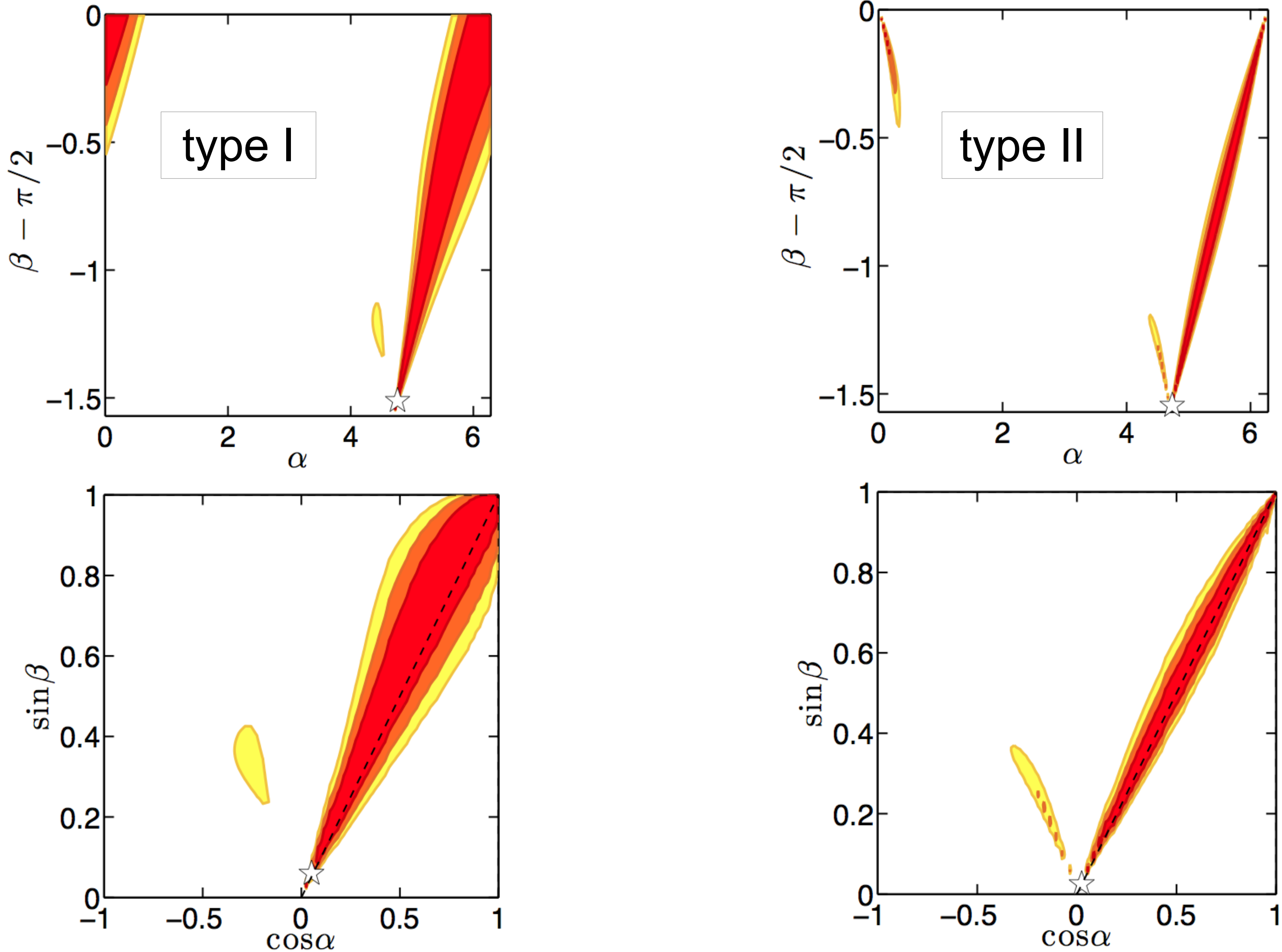
Two Higgs Doublet Model

- model-dependent study: 2HDM type I and II in the decoupling regime
- 2 parameters: α and β

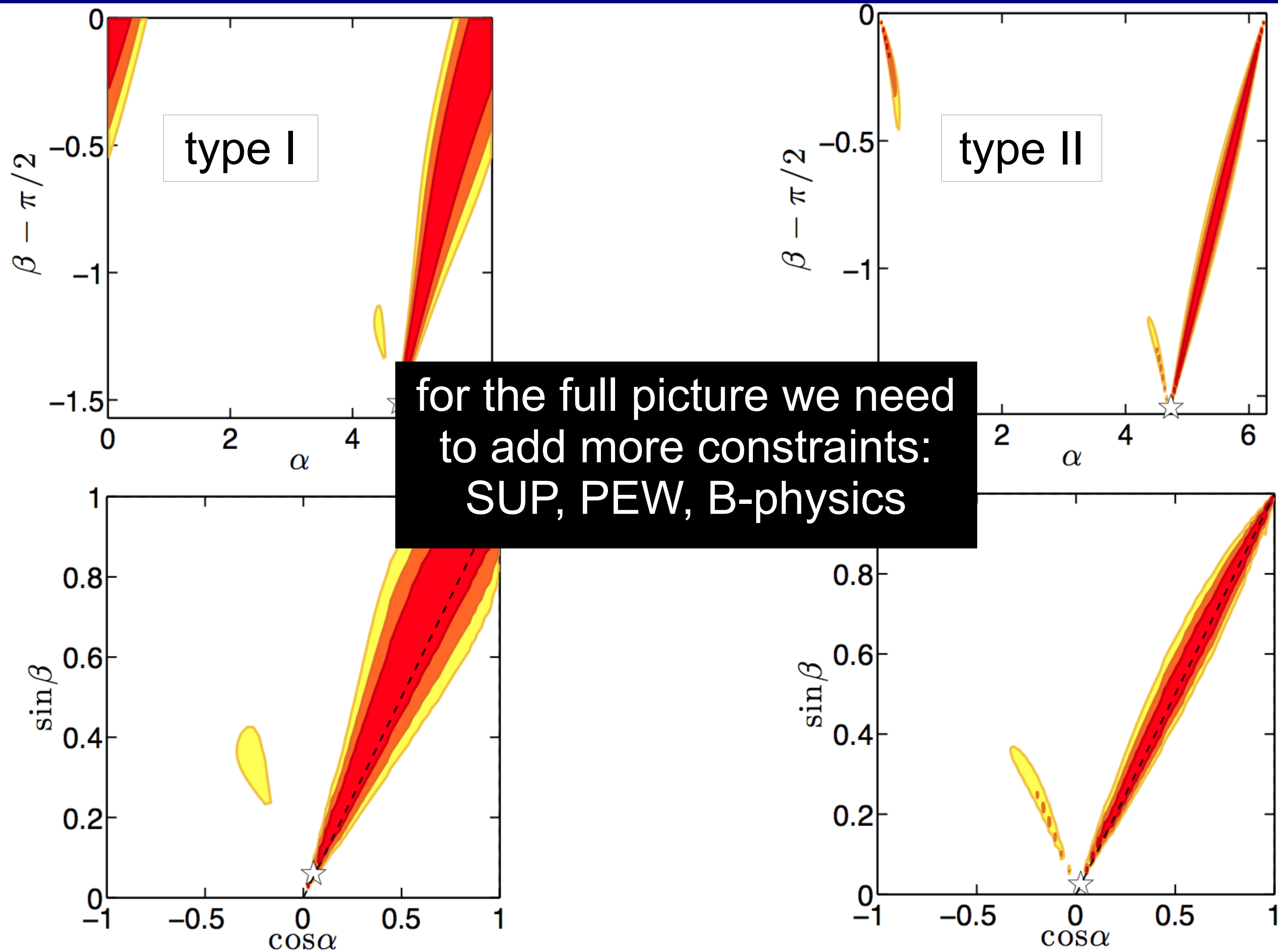
	Type I and II	Type I		Type II	
Higgs	VV	up quarks	down quarks & leptons	up quarks	down quarks & leptons
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
A	0	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

- in both cases we have:
  - $|C_V| < 1$
  - $|C_U| < 1.4$ if $\tan\beta > 1$
- both h and H could be the 125.5 GeV observed state

Two Higgs Doublet Model
h^0 results



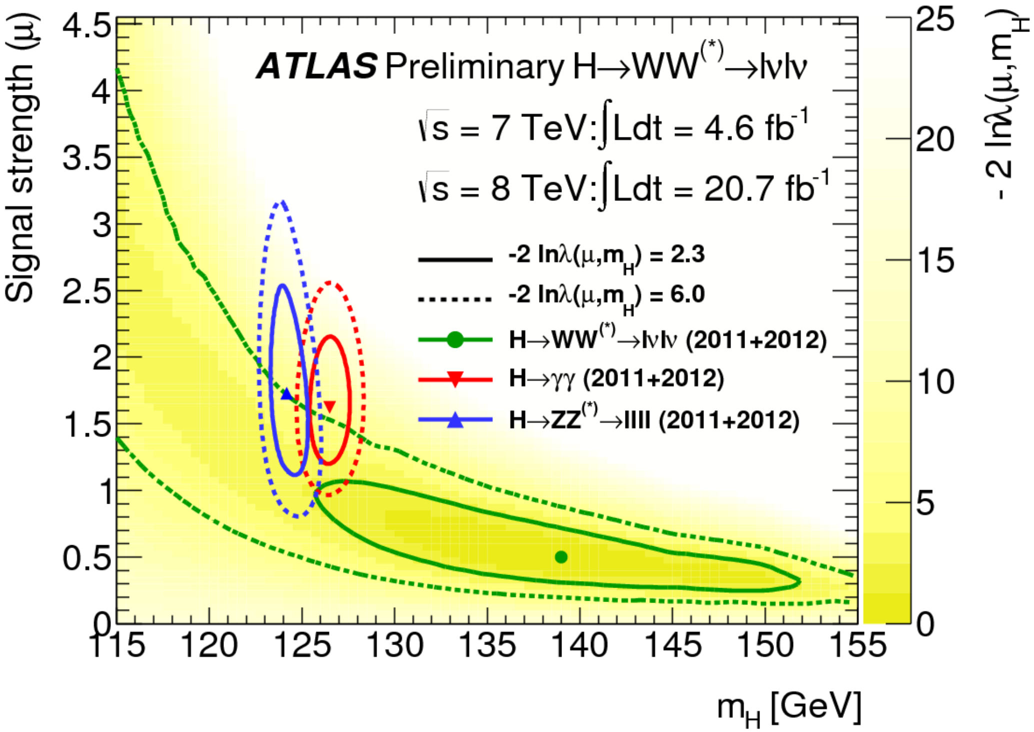
Two Higgs Doublet Model
h^0 results

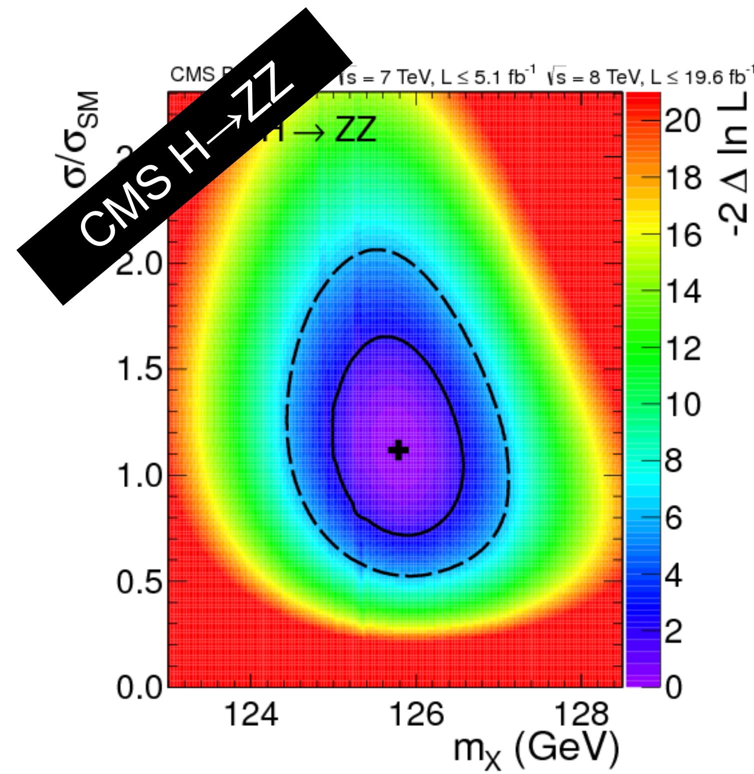


for the full picture we need to add more constraints: SUP, PEW, B-physics

Dependence on m_H

- we would like to treat the Higgs mass as a nuisance parameter
- a priori important for the two high resolution channels ($H \to ZZ$ and $H \to \gamma\gamma$)





- unfortunately impossible to use together with the 2D μ information