What does the Higgs boson tell us about New Physics?

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Séminaire des doctorants
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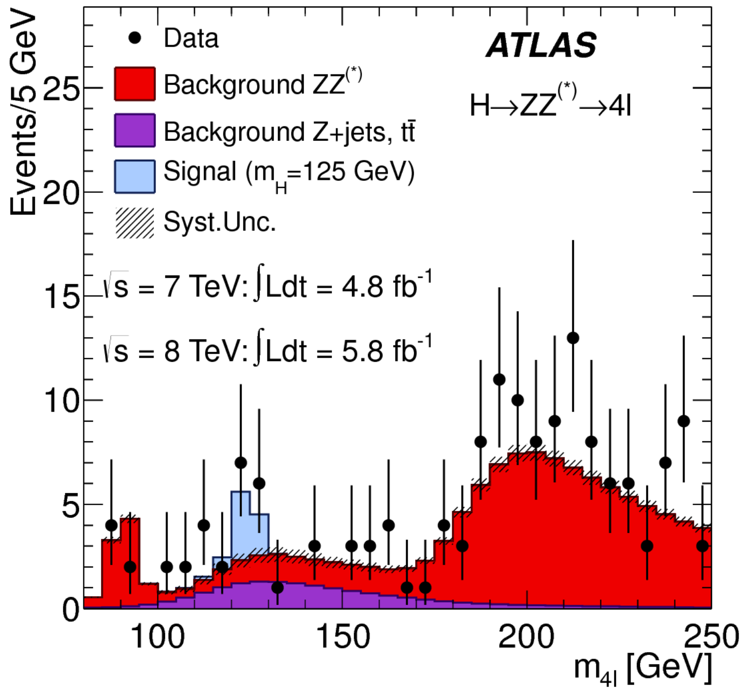
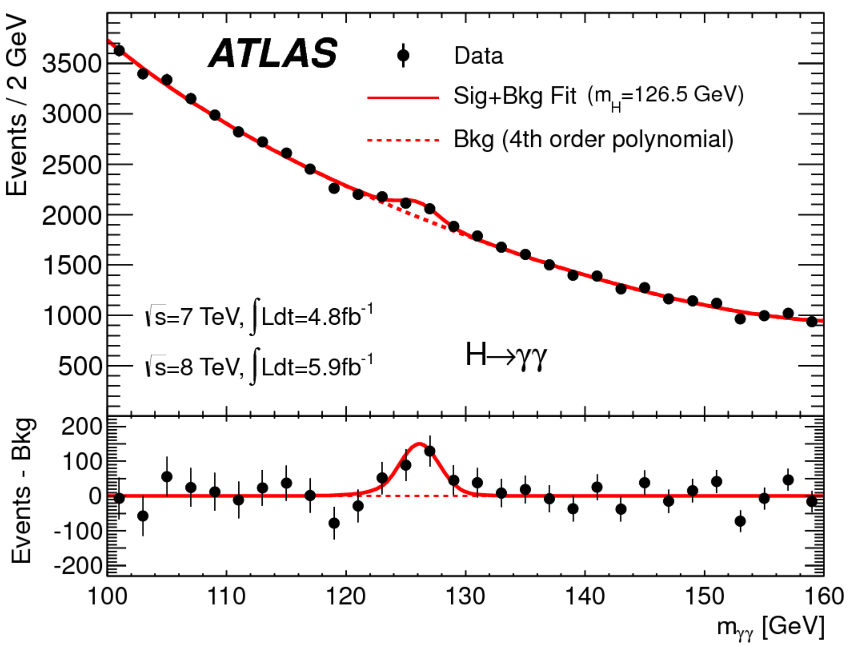
Discovery of a new particle

on July 4th:

discovery of a new particle “consistent with the Higgs boson” at the LHC

mass ≈ 125 GeV





the Higgs boson has been theorized in 1964

long-awaited discovery after 30 years of search!

Standard Model Lagrangian

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs}$$

- Follows from the local $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry
  ($SU(3)_C$: QCD; $SU(2)_L \times U(1)_Y$: electroweak)
- interaction between fermions and gauge bosons (g, W, Z, γ)
- nice & simple, experimentally tested with high accuracy

- we need to break the electroweak symmetry!
  → gives mass to the W and Z bosons
  → gives masses to the fermions (for free)
- but *ad hoc* and not so well-known...

Standard Model Higgs

$$\mathcal{L}_{\text{Higgs}} = |D_\mu H|^2 - \mu^2|H|^2 + \lambda|H|^4 + Y^{ij}\bar{f}_L^i f_R^j H$$

quadratic divergences?

the hierarchy problem:
we want $\mu \sim \mathcal{O}(100\ \text{GeV})$
we obtain $\mu \sim \mathcal{O}(10^{18}\ \text{GeV})$

vacuum instability?

what if $\lambda < 0$?

flavor structure?

lack of understanding

most of the problems of the Standard Model come from the Higgs sector!

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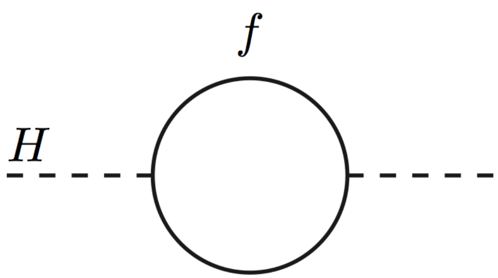


quantum corrections to the Higgs mass parameter from New Physics arising at the scale Λ_{UV}

$$\hookrightarrow \Delta\mu^2 \propto \Lambda_{\mathrm{UV}}^2 \sim \mathcal{O}(M_{\mathrm{Pl}}^2)$$

remain true if the new particles are only indirectly coupled to the Higgs

The Higgs mass parameter is naturally pushed to M_{Pl}

...but we know that $m_H \approx 125$ GeV!

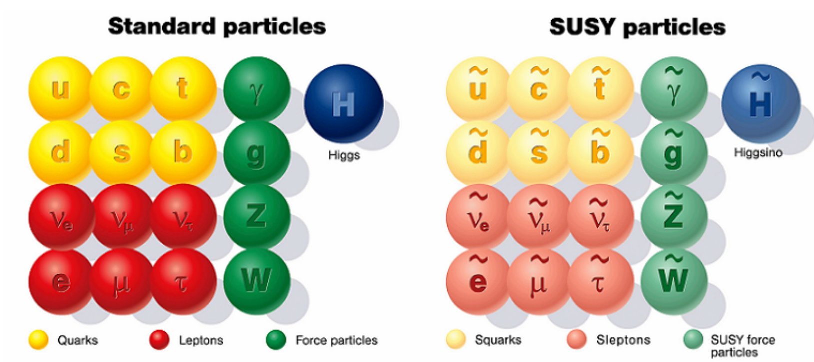
→ we **need** New Physics to explain the smallness of m_H compared to M_{Pl}

Possible solutions to the hierarchy problem

two popular solutions to the
hierarchy problem

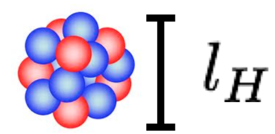
supersymmetry

additional symmetry relating fermions and bosons
→ predicts “superpartners” of the existing particles (spin differing by ½ unit)



composite Higgs

Higgs boson: hadron of new strong force
corrections to m_H screened above $1/l_H$

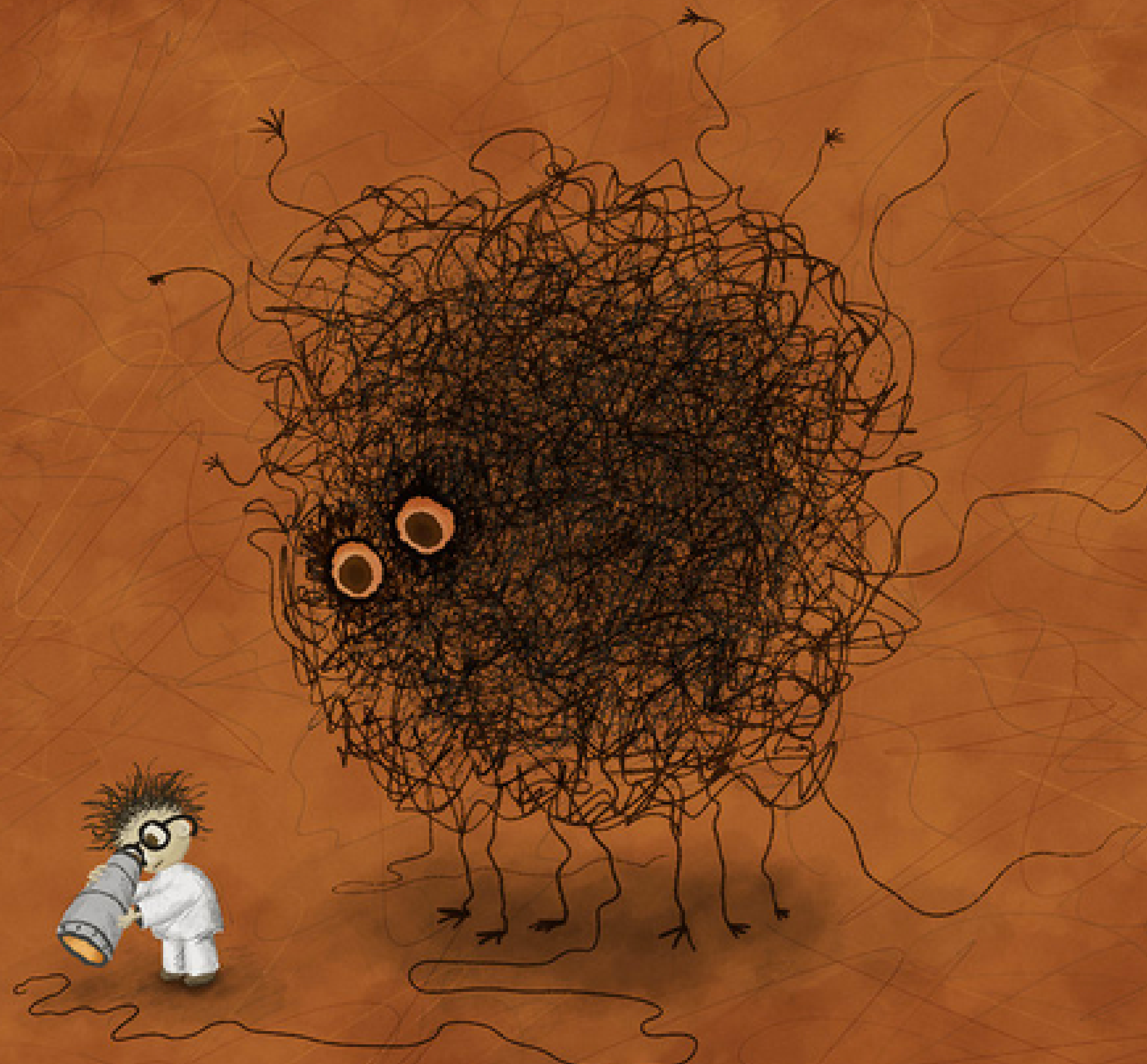


→ generically predicts (light) top partners

in both cases:

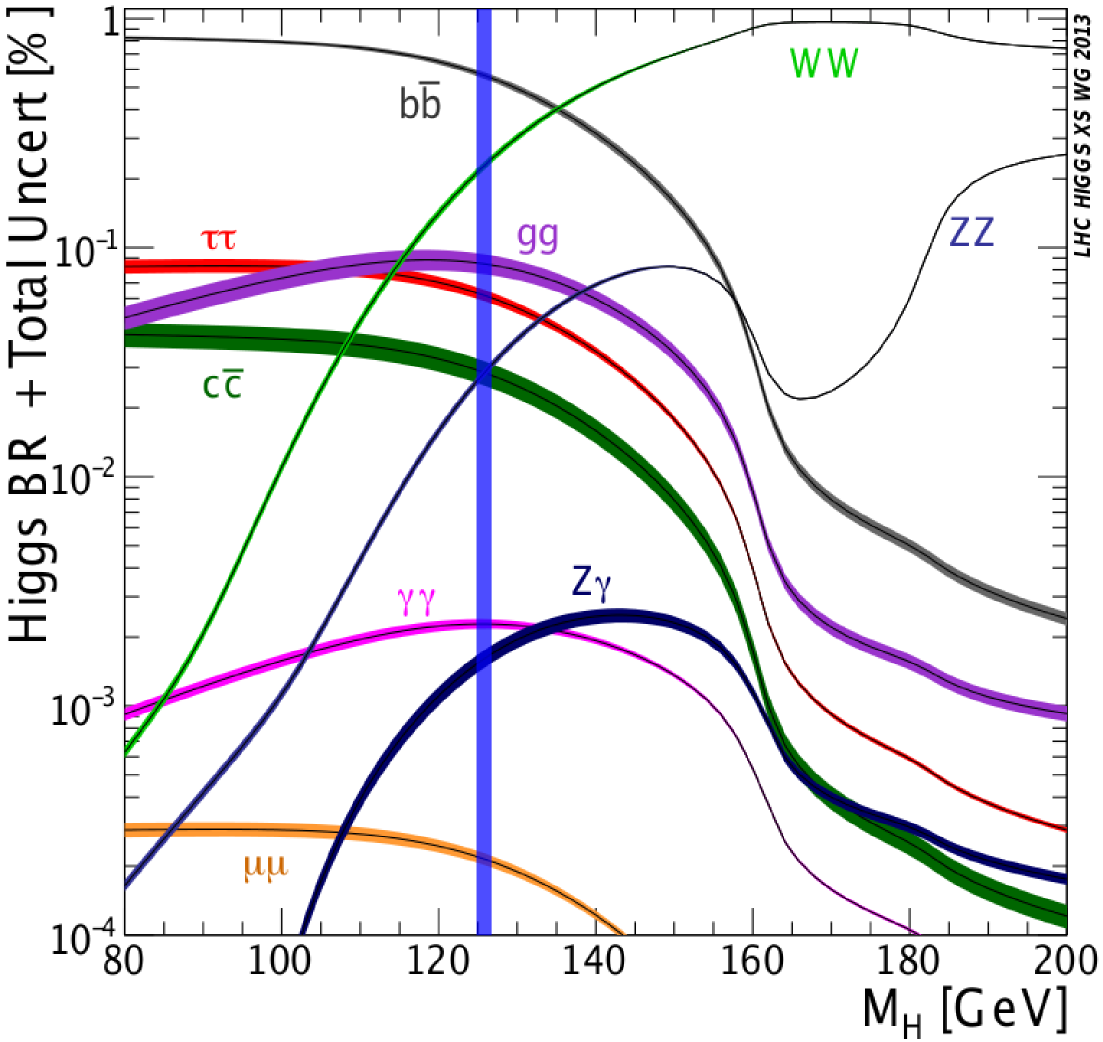
- natural to expect new particles at the TeV scale, i.e. accessible at the LHC!
- sizeable modifications of the properties of the Higgs are possible: probed at the LHC!

Standard Model Higgs... or New Physics?



taken from Alexey Drozdetskiy's talk at HCP2012

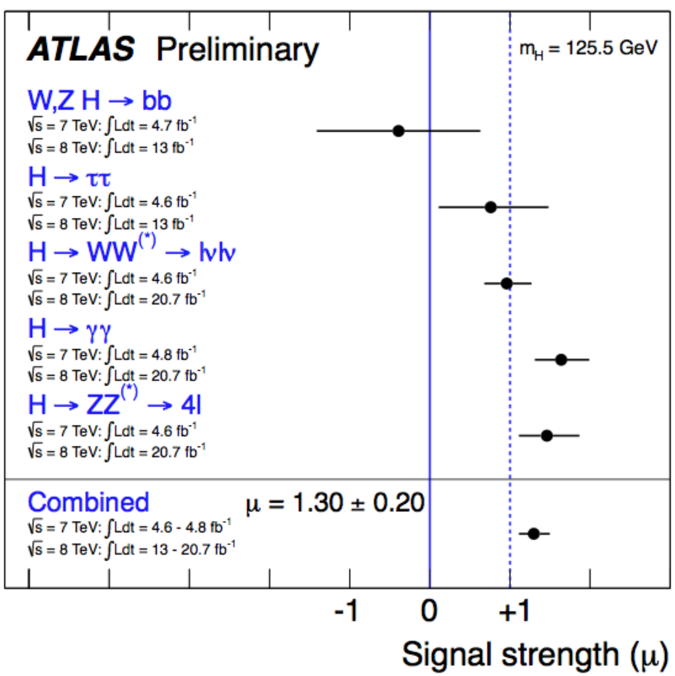
Accessible decays of the Higgs boson

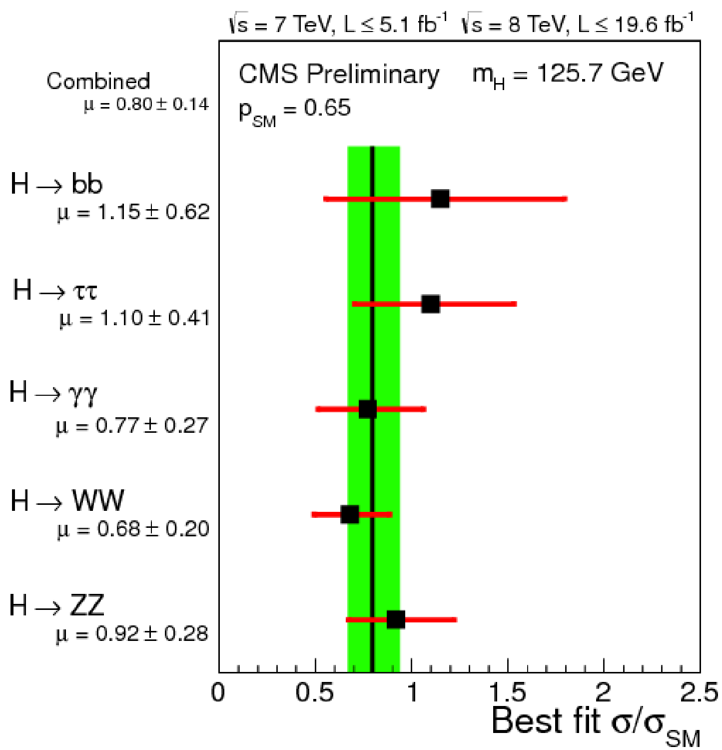


- m_H ~ 125 GeV is interesting: many channels are accessible!
- the mass of the new particle is inferred from the γγ and ZZ channels
- H → gg and H → cc channels: not accessible at the LHC (QCD background)

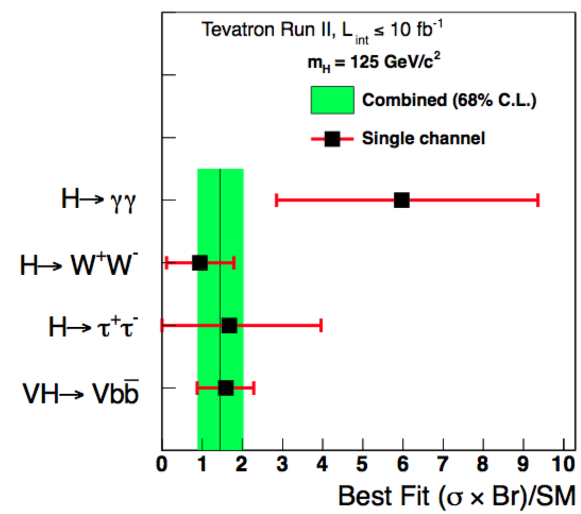
Searches for the Higgs boson

- new particle at observed 125.5 GeV with > 7σ significance by ATLAS and CMS! almost all bosonic searches have been updated with full luminosity
- results summarized in terms of signal strengths: $\mu_i = \dfrac{\left[\sum_j \sigma_{j\to h} \times \mathcal{B}(h \to i)\right]_{\text{observed}}}{\left[\sum_j \sigma_{j\to h} \times \mathcal{B}(h \to i)\right]_{\text{SM}}}$





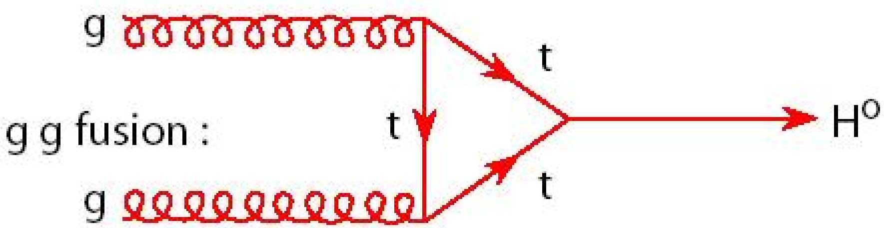
Tevatron
final results

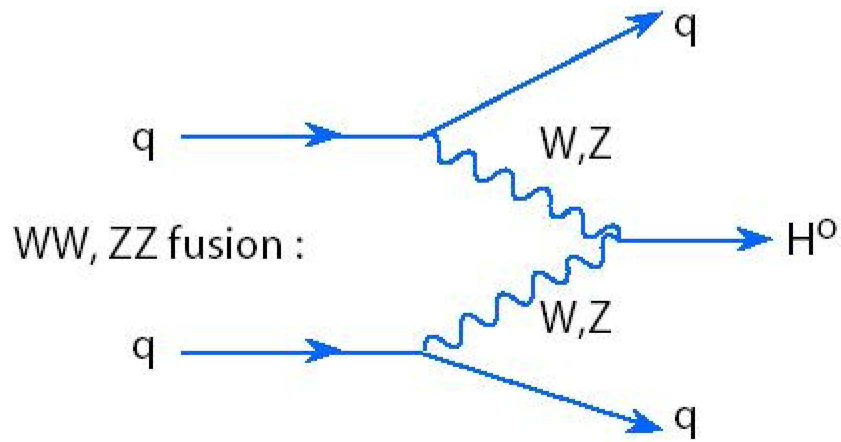


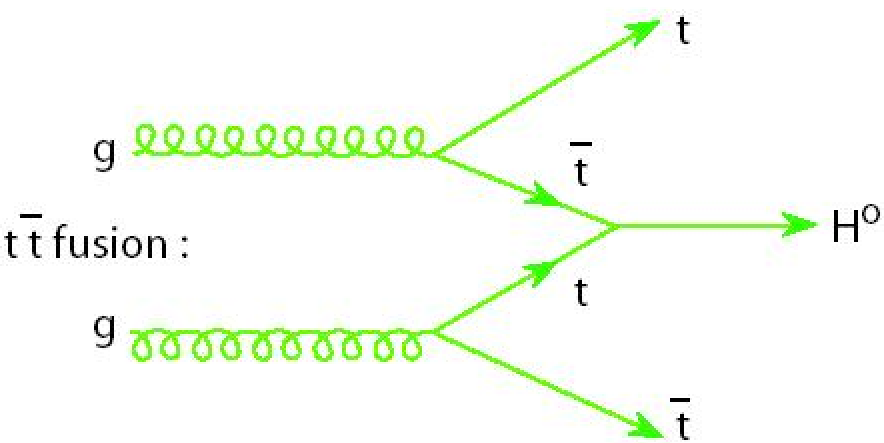
Production of a Higgs boson

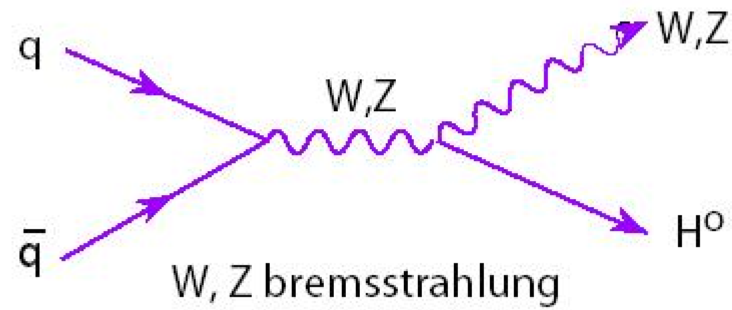
...but New Physics modifies not only the Higgs decays but also its production!

(Vector Boson Fusion)









(not observed yet)

(associated production)

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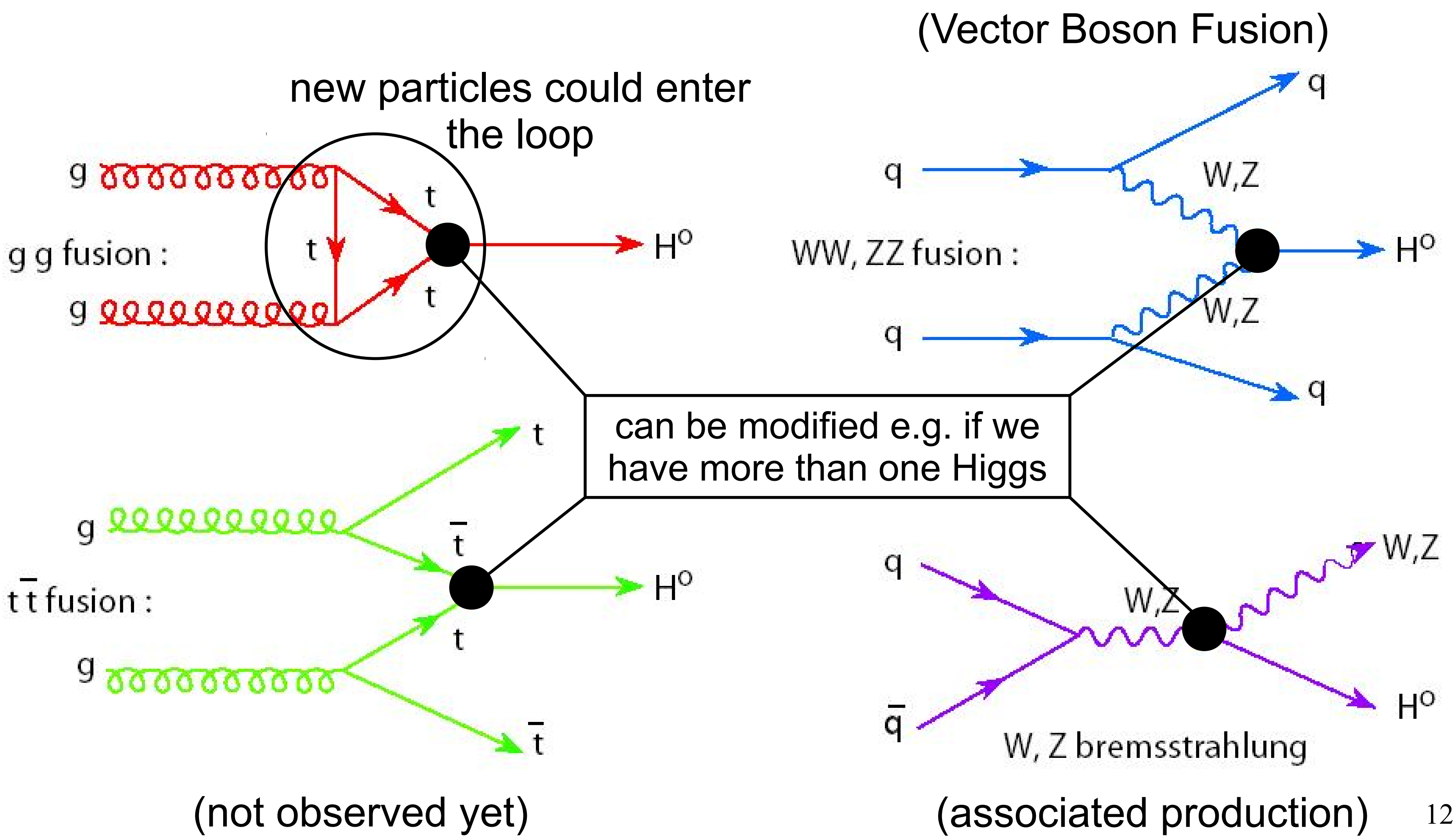
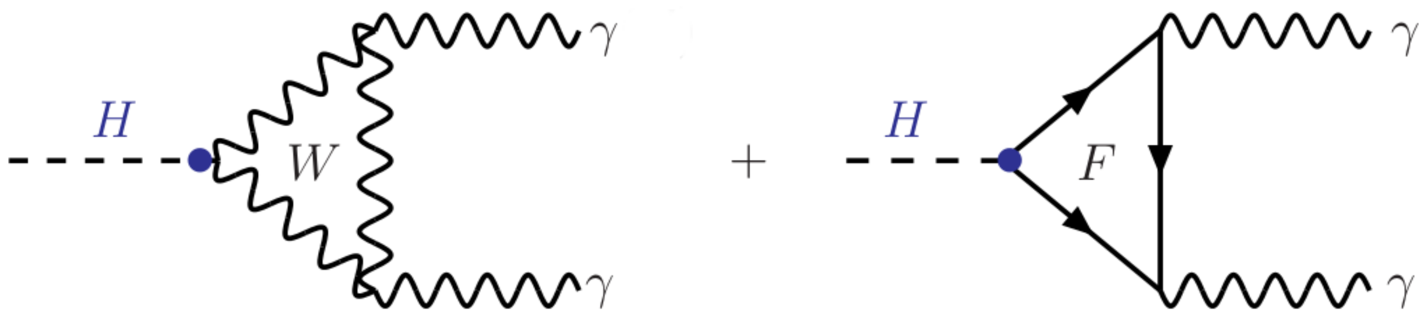


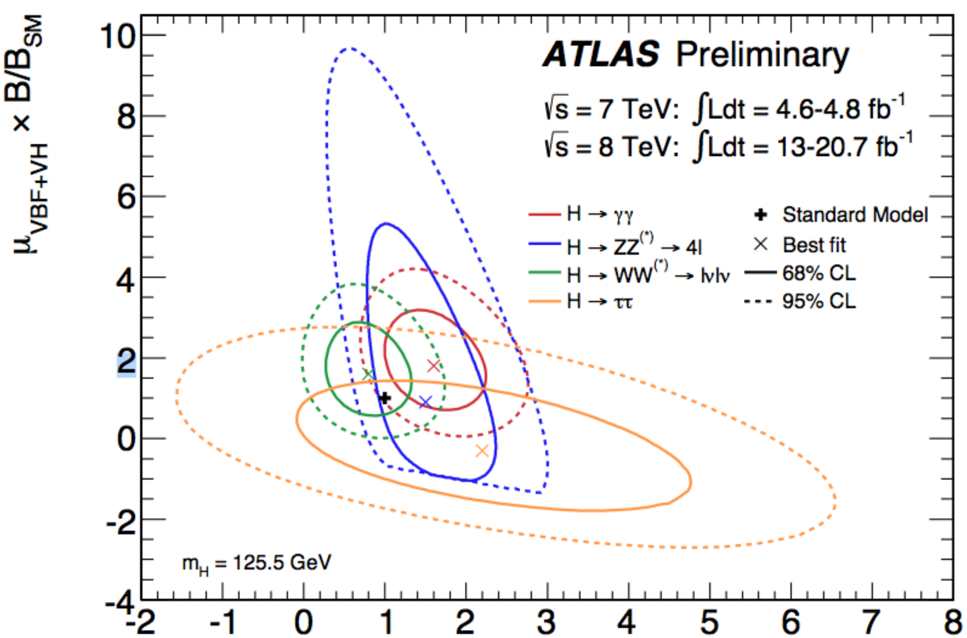
A word on H→γγ



- contribution from the W is 5 times larger than from the top quark
- small contributions from bottom and lighter quarks
- new particles in the loop could change the Hγγ rate!
  (e.g. charged Higgses, charginos, staus, ...)

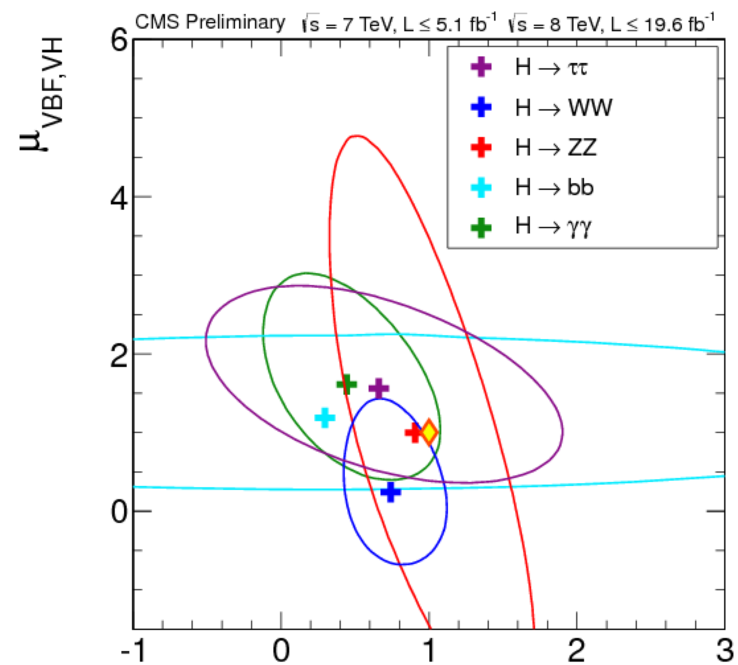
2D μ plots from ATLAS and CMS

ATLAS



[ATLAS-CONF-2013-034]

CMS



[CMS PAS HIG-13-005]

we implement these results using the Gaussian approximation (validity checked ✓)

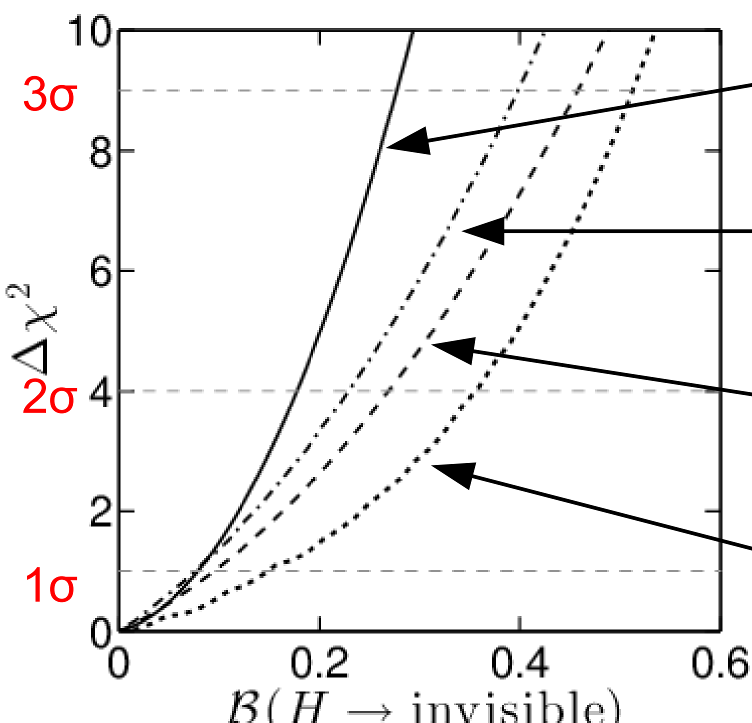
Understanding what we observe

The Higgs is Standard Model-like so far
→ provides constraints on theories Beyond the Standard Model

- we have performed various couplings fits of the observed new particle

  example of result:

G. Belanger, BD, U. Ellwanger, J. F. Gunion, and S. Kraml, [arXiv:1212.5244] and [arXiv:1302.569]



SM+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.18$ at 95% CL

SM+(C_U>0)+(C_D>0)+(C_V<1)+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.23$ at 95% CL

SM+ΔC_g+ΔC_γ+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.27$ at 95% CL

SM+C_U+C_D+C_V+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.35$ at 95% CL

Philosophy of our EFT approach

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

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

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

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

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

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

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

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

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 to gauge bosons and fermions

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

tree-level contribution to the tensor couplings

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these operators cannot be generated at tree-level within a perturbative UV theory

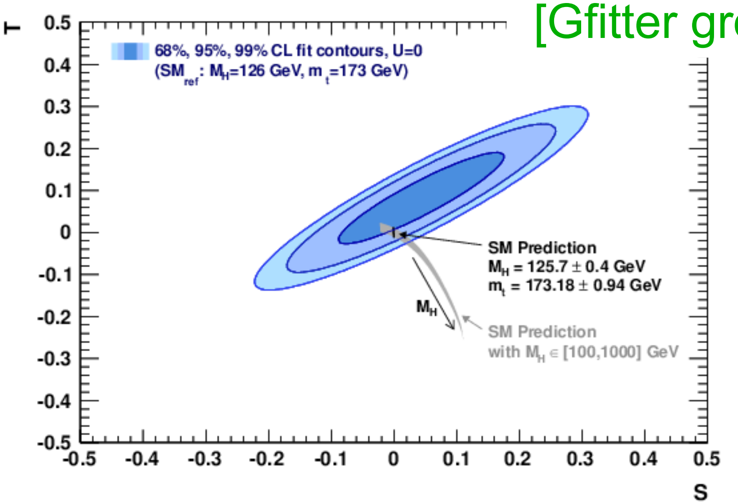
Scenario I) democratic HDOs
→ all operators on equal footing

Scenario II) loop suppressed $\mathcal{O}_{FF}$'s compared to the other operators
$FF = WW,\, WB,\, BB,\, GG$

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:

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

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

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

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

Setup of the analysis

scan ranges for the 2 scenarios we consider:

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

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

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

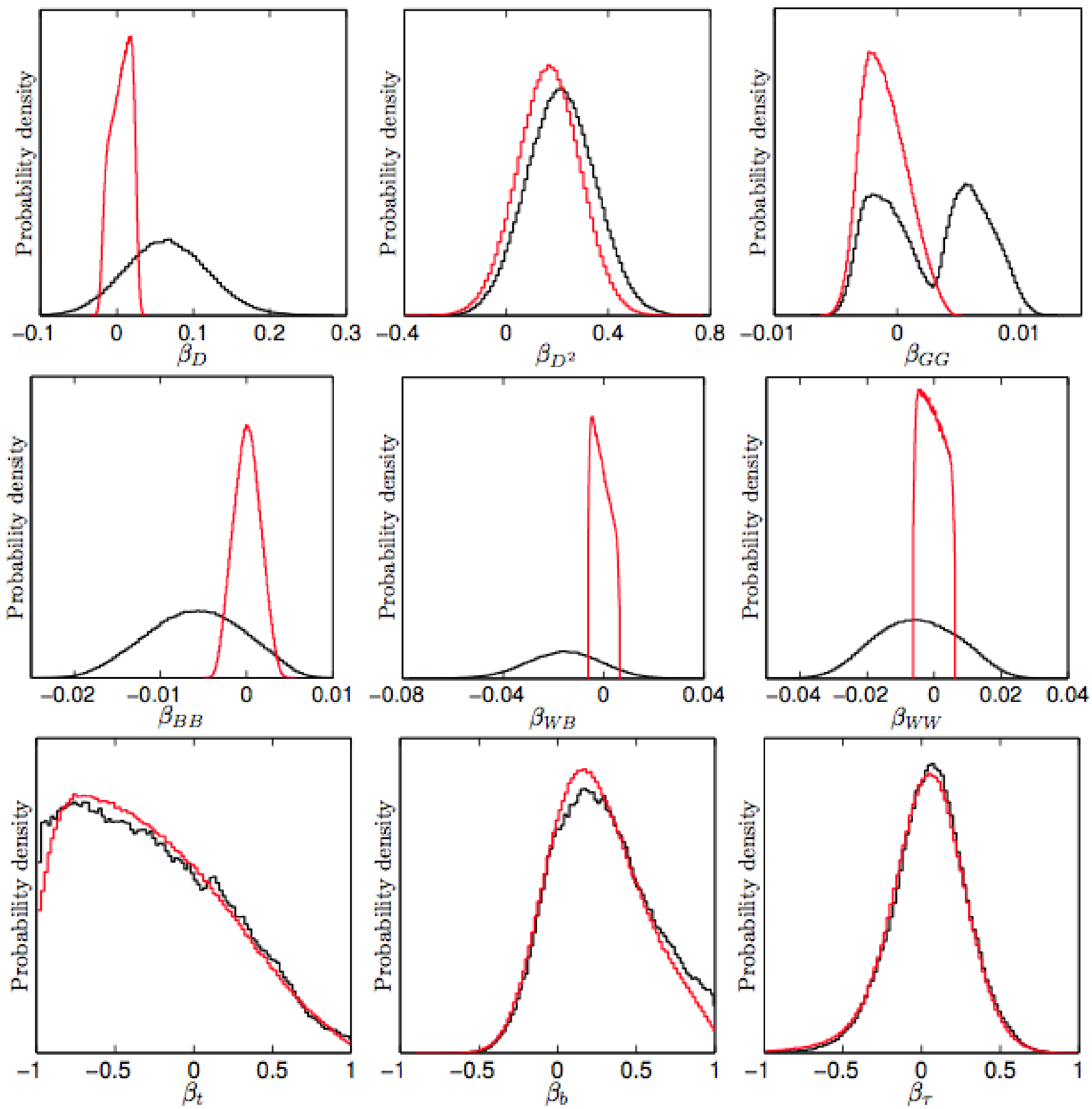
Results
1D probability distributions

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

- β_{FF} are $\mathcal{O}(0.01)$
  $FF = WW,\ WB,\ BB,\ GG$
- β_f can go up to $\mathcal{O}(1)$

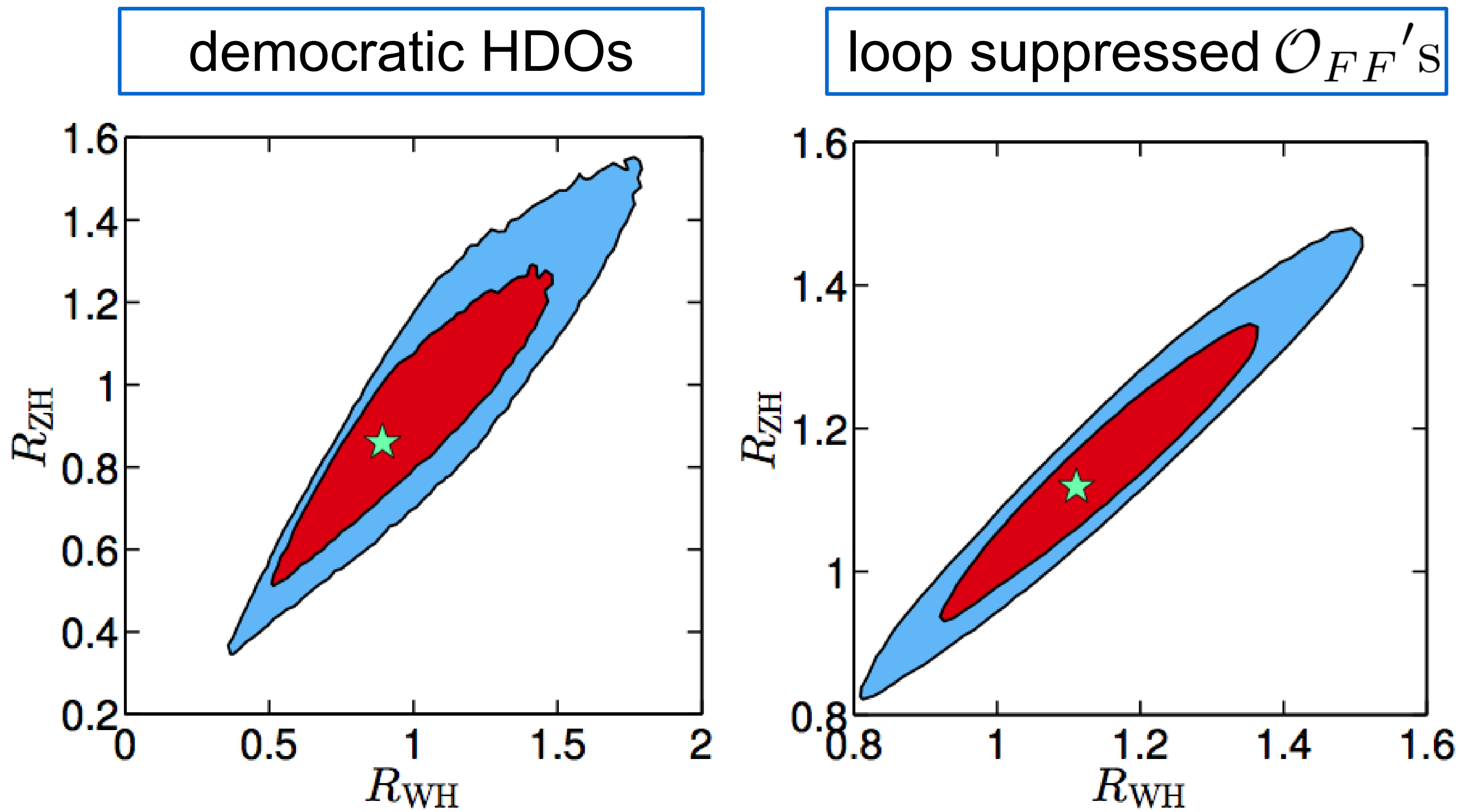
where $\beta_i = \alpha_i v^2/\Lambda^2$

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



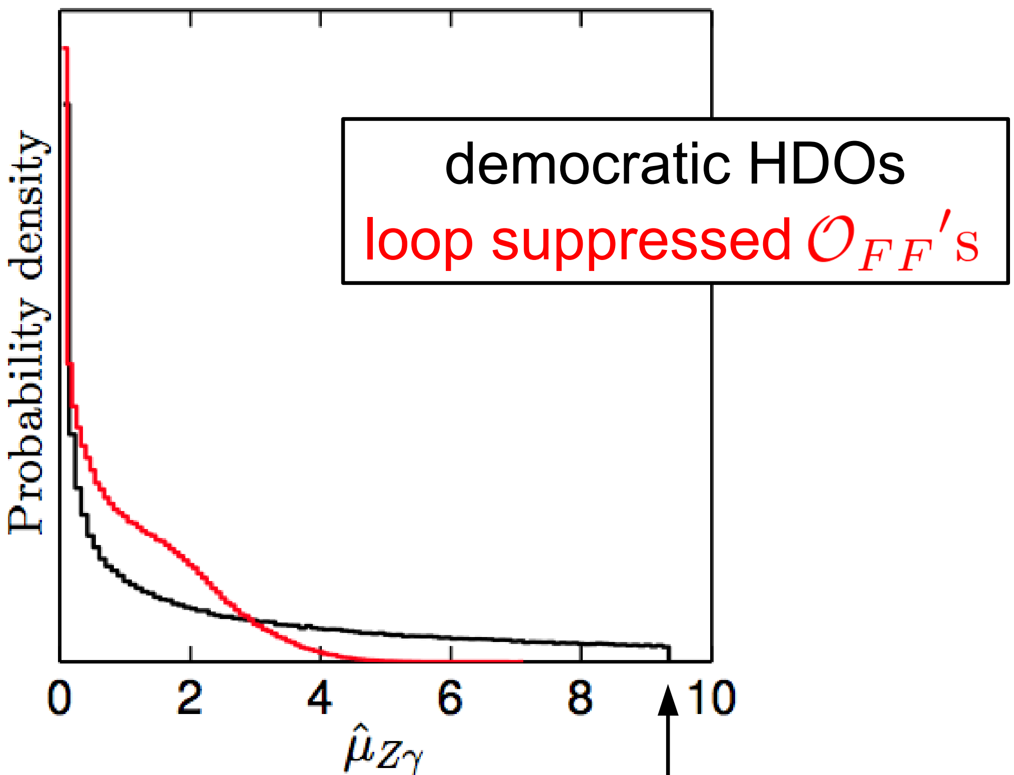
Results
associated production

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



- 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



CMS bound on 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)

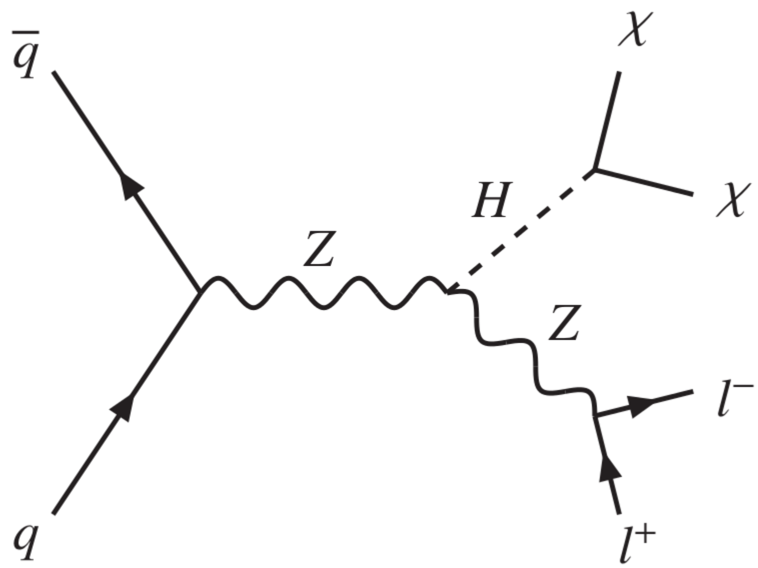
- precision era in Higgs physics has only just begun
however Higgs results are already a unique probe of New Physics

- 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

Searches for invisible decays of the Higgs boson

ATLAS

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



[ATLAS-CONF-2013-011]

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

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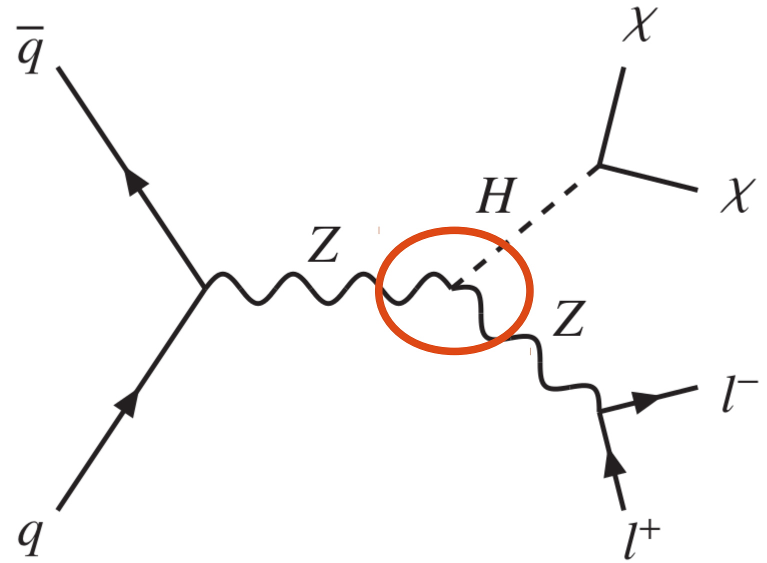
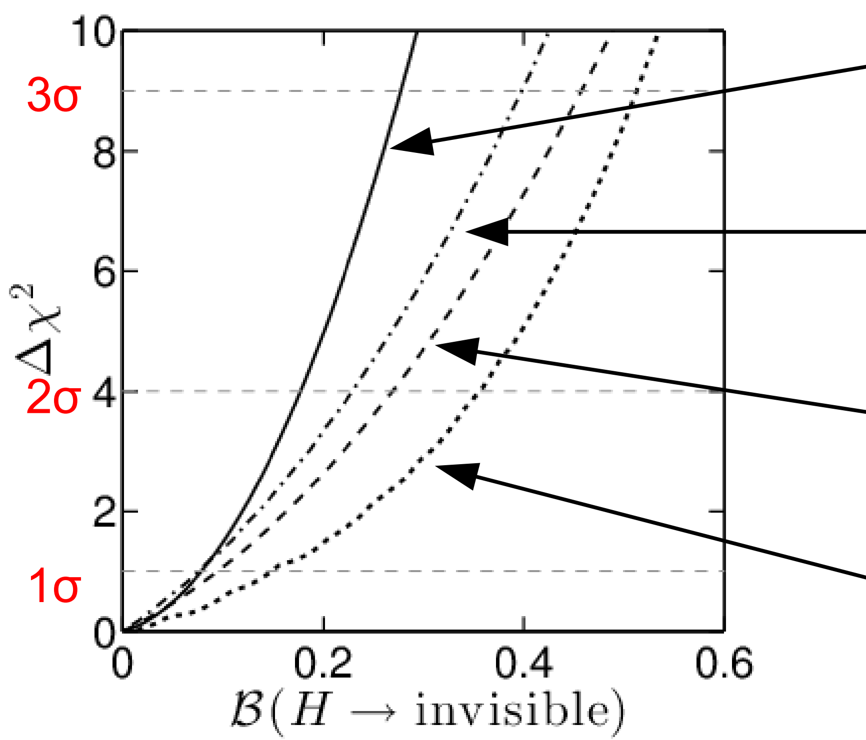


[ATLAS-CONF-2013-011]

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

see also earlier studies based on *e.g.* monojet searches [Djouadi *et al.* '12]
…but so far global fits are more constraining

Invisible decays of the Higgs boson



SM+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.18$ at 95% CL

SM+(C_U>0)+(C_D>0)+(C_V<1)+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.23$ at 95% CL

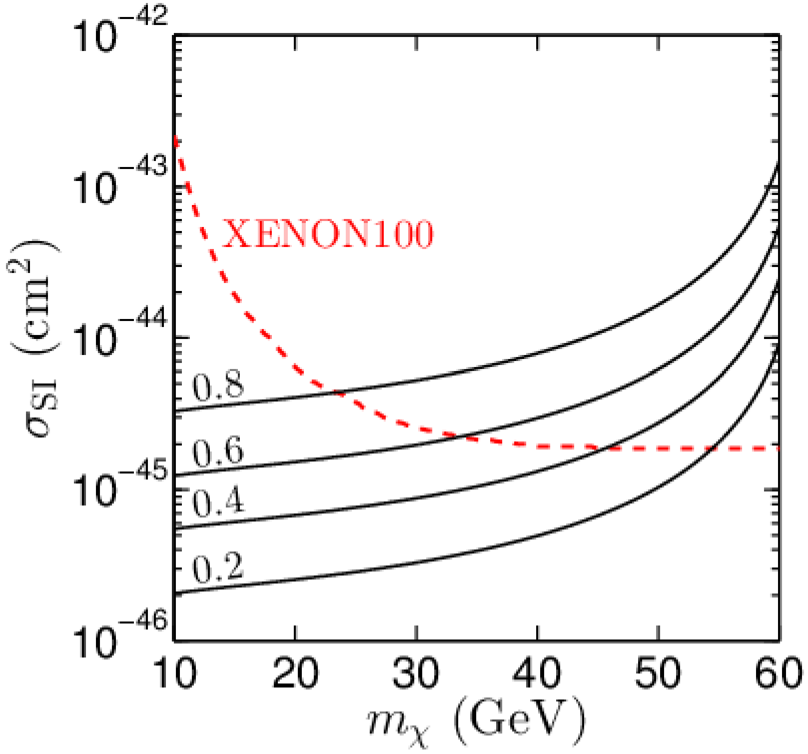
SM+ΔC_g+ΔC_γ+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.27$ at 95% CL

SM+C_U+C_D+C_V+invisible
$\mathcal{B}(H \to \text{inv.}) < 0.35$ at 95% CL

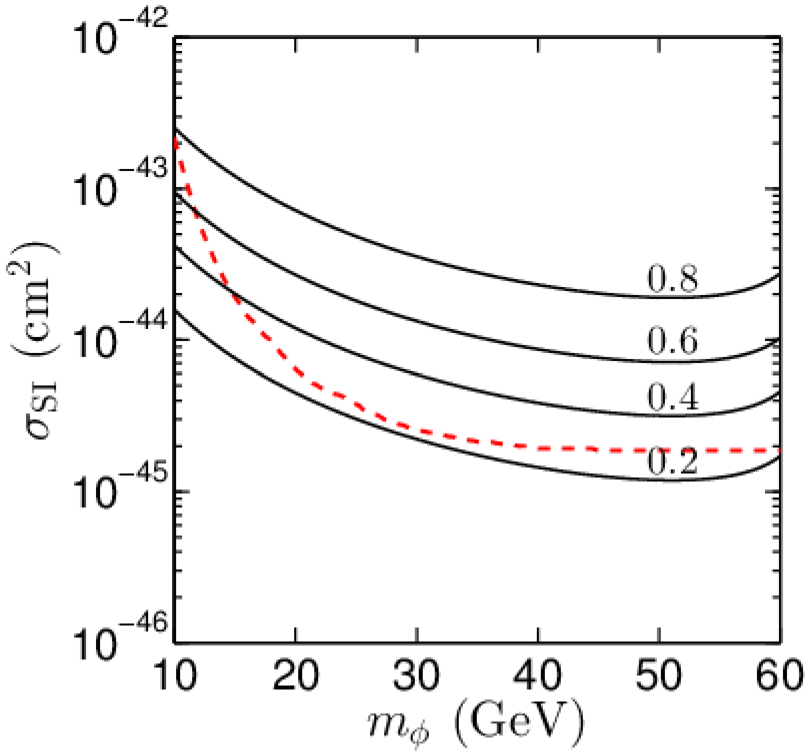
Invisible decays of the Higgs boson and dark matter

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

Majorana dark matter



scalar dark matter



Tensorial couplings and kinematic distributions

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

$$\mathcal{M}(hVV)^{\lambda_1,\lambda_2} = e_{\lambda_1}^{\mu(*)} e_{\lambda_2}^{\nu(*)} \left(i a_V \lambda_V^{\text{SM}} g^{\mu\nu} - i 2\zeta_V q_1.q_2 \left[g^{\mu\nu} - \frac{q_1^\mu q_2^\nu}{q_1.q_2} \right] \right) , \qquad (4.1)$$

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]						
$\mu(\text{ggF}+\text{ttH},\gamma\gamma)$	1.60 ± 0.41	125.5	100%	–	–	–
$\mu(\text{VBF}+\text{VH},\gamma\gamma)$	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]						
$\mu(\text{ggF}+\text{ttH},ZZ)$	1.50 ± 0.50	125.5	100%	–	–	–
$\mu(\text{VBF}+\text{VH},ZZ)$	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]						
$\mu(\text{ggF}+\text{ttH},WW)$	0.79 ± 0.35	125.5	100%	–	–	–
$\mu(\text{VBF}+\text{VH},WW)$	1.71 ± 0.76	125.5	–	60%	40%	–
$H \to b\bar{b}$ (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]						
$\mu(\text{ggF}+\text{ttH},\tau\tau)$	2.31 ± 1.61	125.5	100%	–	–	–
$\mu(\text{VBF}+\text{VH},\tau\tau)$	-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

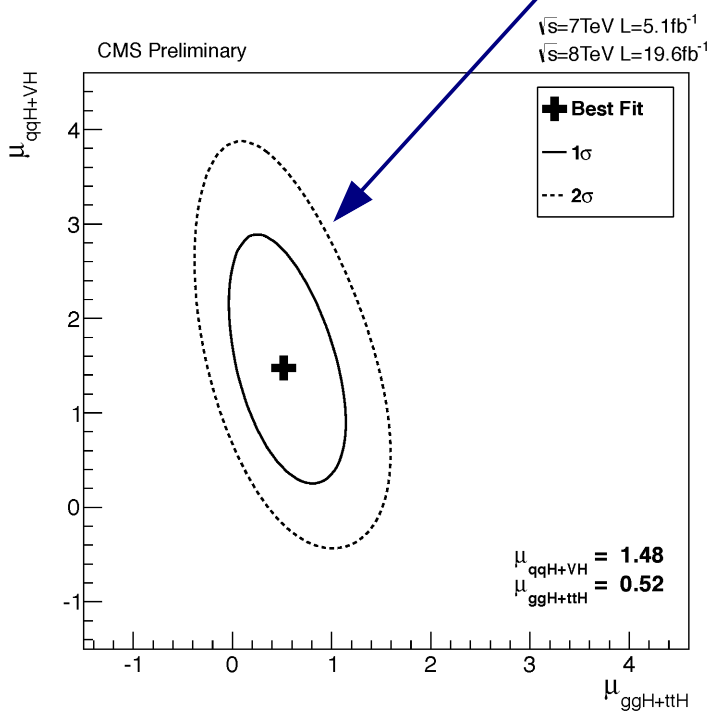
Channel	Signal strength μ	m_H (GeV)	Production mode ggF	VBF	VH	ttH
		$H \to \gamma\gamma$ [17]				
Combined	$5.97^{+3.39}_{-3.12}$	125	78%	5%	17%	–
		$H \to WW$ [17]				
Combined	$0.94^{+0.85}_{-0.83}$	125	78%	5%	17%	–
		$H \to b\bar{b}$ [17]				
VH tag	$1.59^{+0.69}_{-0.72}$	125	–	–	100%	–

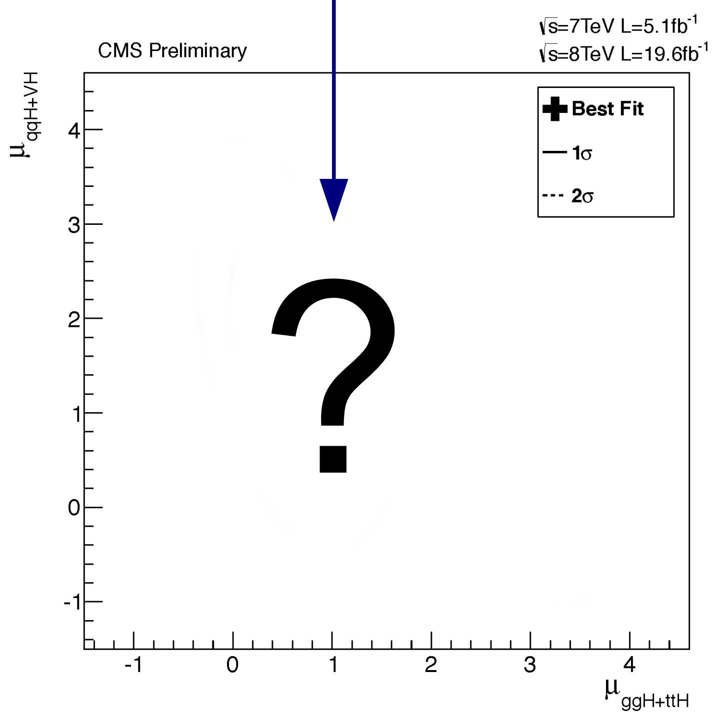
Table 3: Tevatron results for up to 10 fb^{-1} at $\sqrt{s} = 1.96$ TeV, as employed in this analysis.

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

A word on CMS $H \to \gamma\gamma$

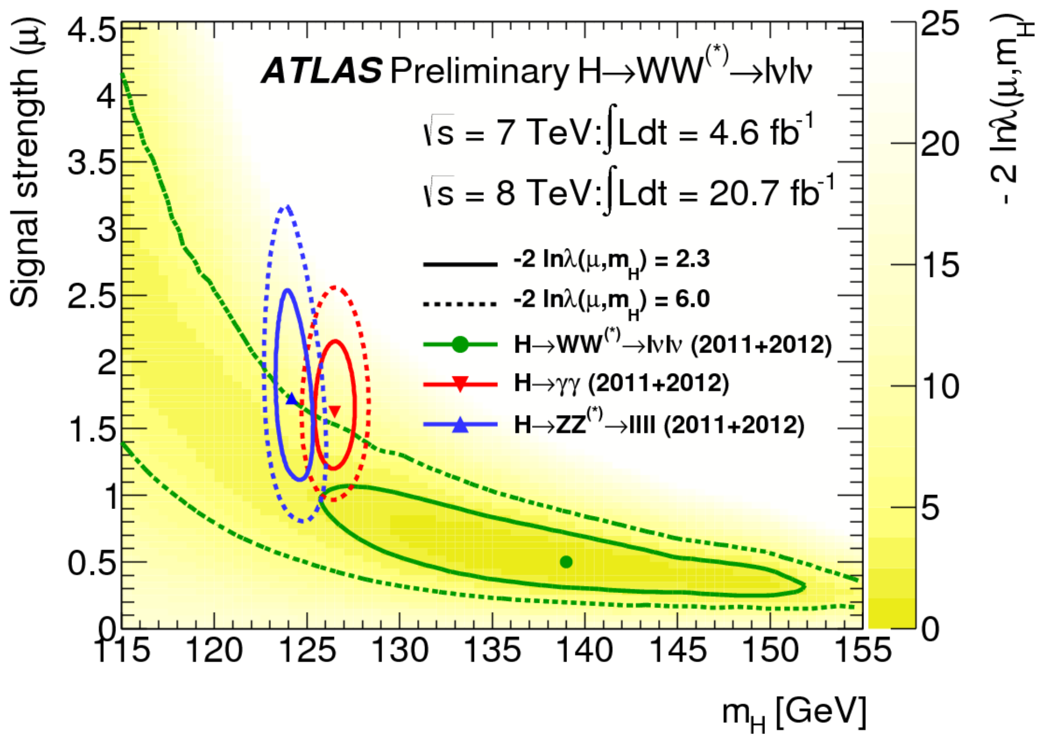
	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

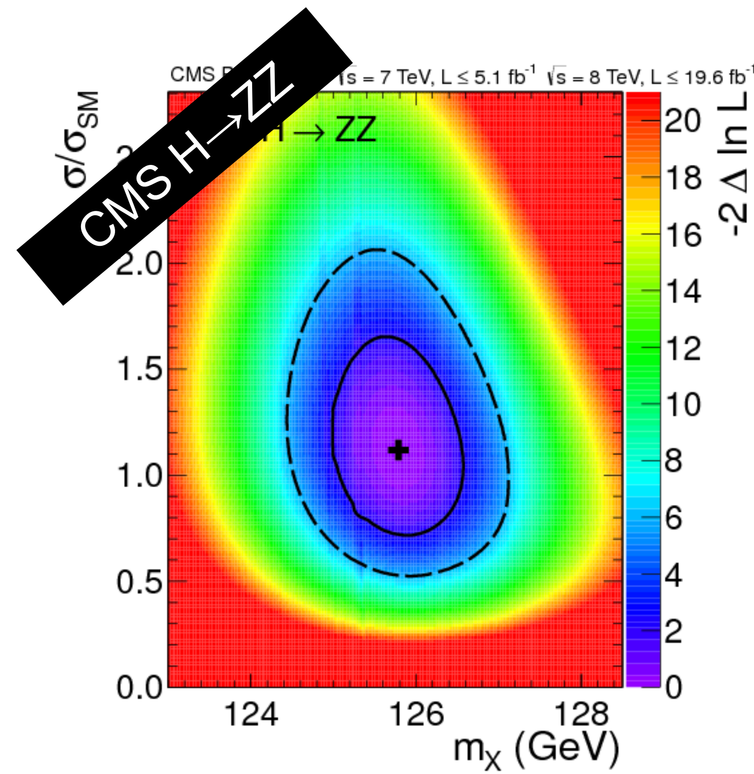




Dependence on m_H

- 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