Properties of discovered Higgs-like resonance in CMS

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Higgs Hunting 2013
Orsay – 26 July 2013

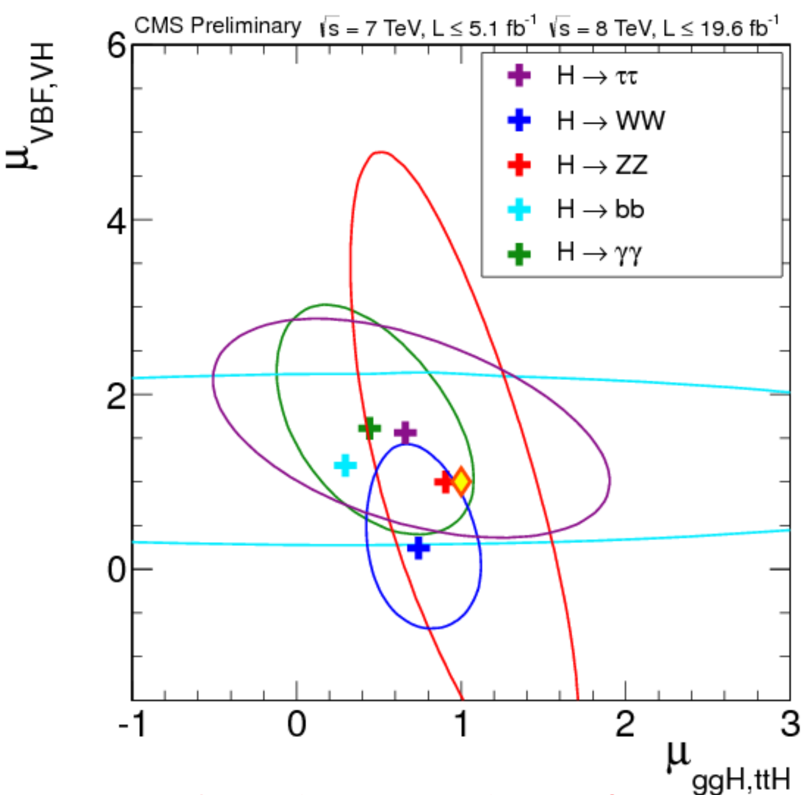
Any news?

- **Bird's-eye view:**
  - H->ZZ/WW/$\gamma\gamma$ well established (~7σ,3σ,4σ) and evidence in bb, $\tau\tau$ decays (~3.5σ)
  - properties measurement:
    - looking at rates in different channel: **production/decay, detailed fit to couplings** (SM/BSM driven)
    - shape analyses -> **spin/parity** (model independence)
    - SM self-consistency: **mass and self couplings** (... not covered here)

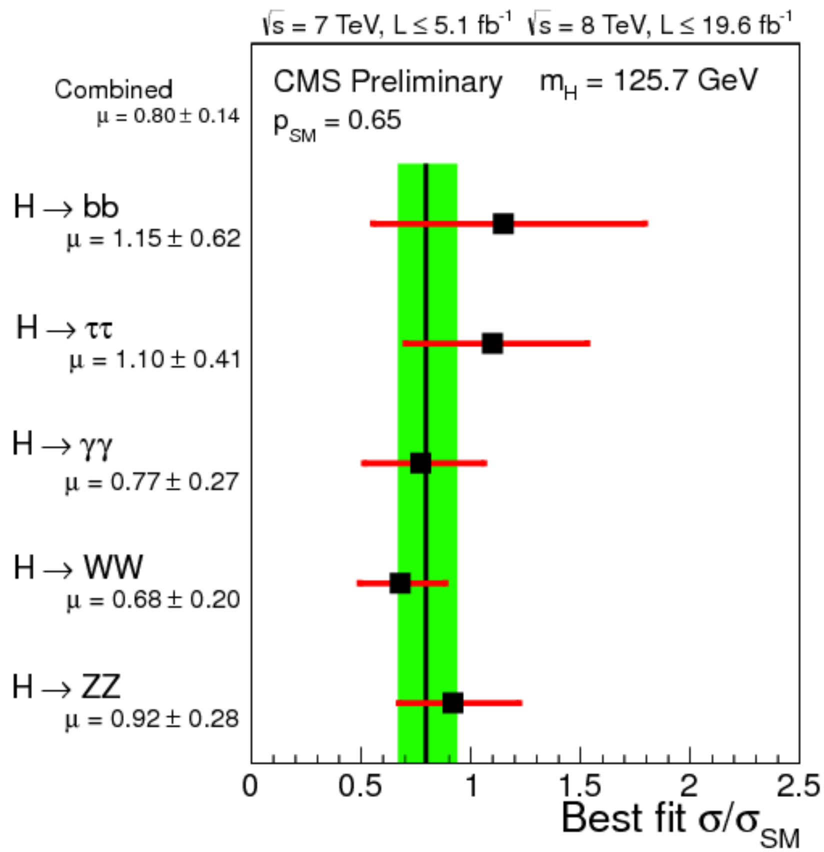
- **Hot from the press:**
  - **properties in H->$\gamma\gamma$**
    (CMS-HIG-13-016 see dedicated talk on Thursday)
  - various interesting channels published recently (WW,ZZ high mass; VBF H->bb, ttH, ...) but **no new combination since Moriond** ...
    (CMS-HIG-13-005)

  - **projections at high lumi** reviewed for Snowmass process

Production and decay modes



Combined > 3σ evidence for $\mu_{VBF,VH} / \mu_{ggH,ttH} > 0$



Overall signal strenght $\mu = 0.80 \pm 0.14$

Nature has chosen a mass such that plenty of opportunities to check couplings:

BR(bb) ~ 60%, BR(WW) ~ 20%, BR(gg) ~ 9%, BR(ττ) ~ 6%, BR(ZZ) ~ 3%, BR(cc) ~ 3%, BR(γγ) ~ 0.2%, BR(μμ)~0.02%

SM-driven benchmark for couplings

- Systematizing the approach (HXSWG arXiv:1209.0040):

narrow width approximation $$\sigma_i \cdot BR_i = \frac{\boxed{\sigma_i \cdot \Gamma_i}}{\boxed{\Gamma_H}}$$

SM modifiers for

production $$k_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

decay $$k_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

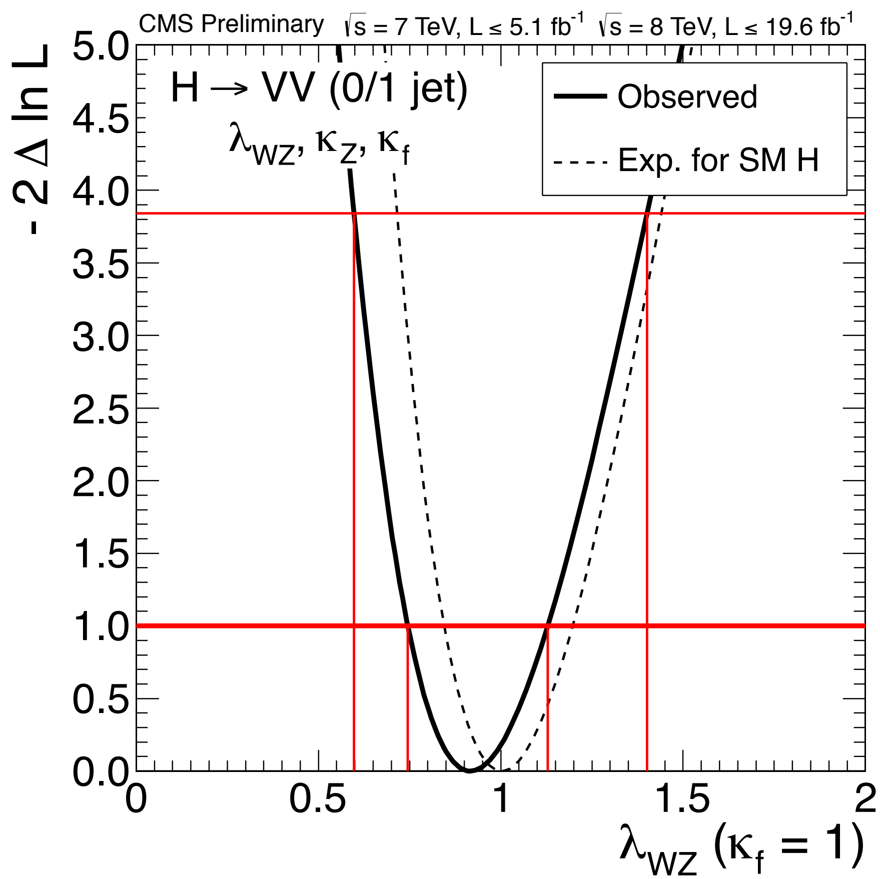
- k_W k_Z k_t present in production and decay
- k_b (assumed the same for b,s)
- k_τ (assumed the same for τ,μ)
- loop induced couplings:
  k_{gg} (prod) and $k_{Z\gamma}$ $k_{\gamma\gamma}$ (decay) can be
  - left unresolved : model independent
  - $k_i(k_b\ k_t\ k_W ...)$: SM driven (NLO QCD)

Total width $$\frac{\Gamma_H}{\Gamma_H^{SM}}$$

- not observable (~4MeV)
  -> 1 overall constraint missing
- measure ratios or impose external constraints:
  - no invisible decays:
    $$\Gamma_H = \sum_i \Gamma_i$$
  - custodial symmetry and EWK precision data
    $$\lambda_{WZ} = \frac{k_W}{k_Z} = 1 \qquad k_V \leq 1$$

Is it a Higgs? Custodial symmetry

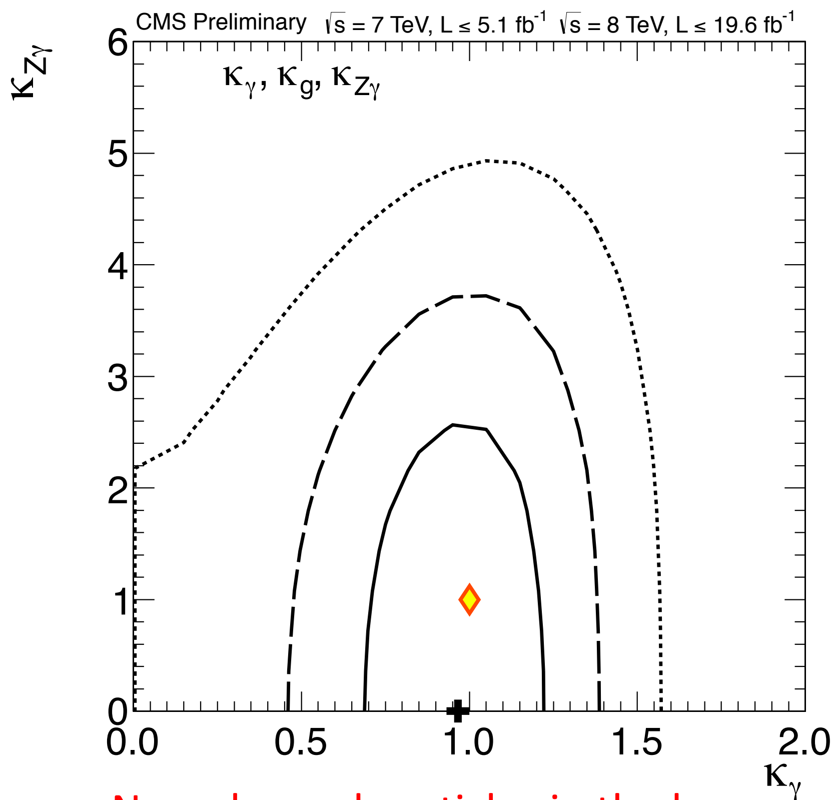
- Higgs role in the VV unitarization -> k_V may be modified but k_W/k_Z (related to M_W/M_Z) define the structure of EWSB mechanism

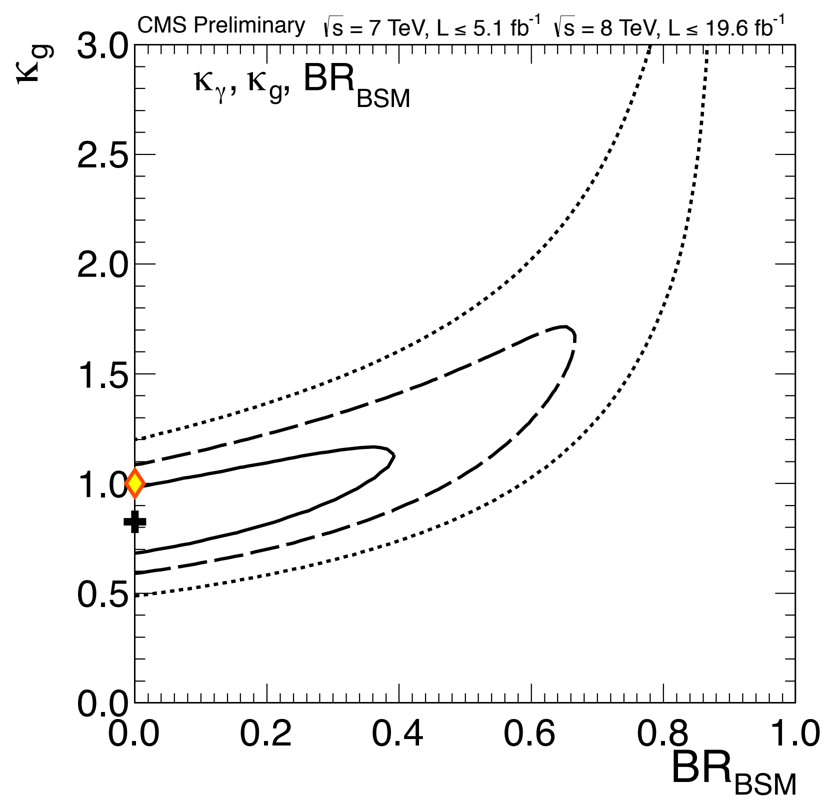


Ratio of H->WW and H->ZZ events with less than 2 jets (ggH dominated) -> **quasi model-independent test** (*k_f=1*)

Door to NP? New particles in loop and/or decay

Assuming tree level couplings as in SM





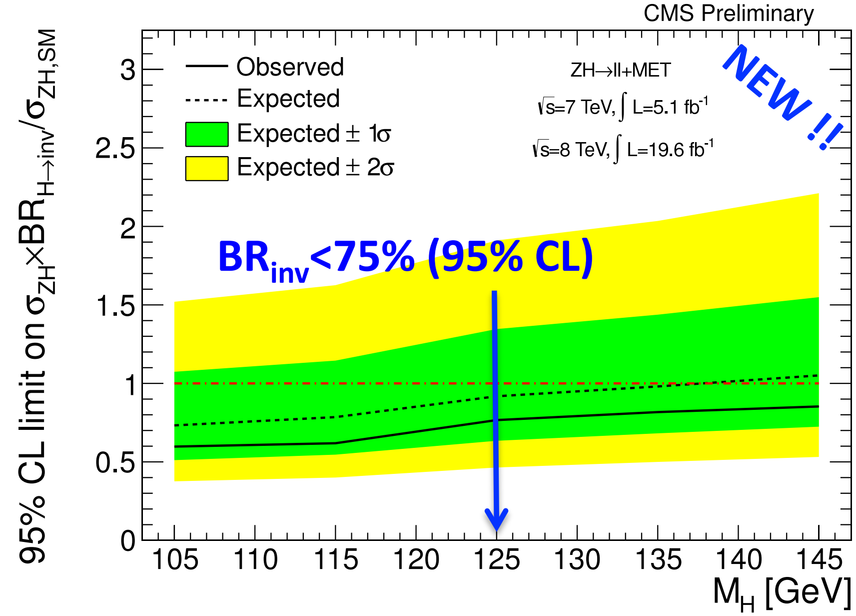
- New charged particles in the loop -> modification of few tens of % possible (Zγ/γγ may solve degeneracy between theories)
- Degeneracy: if non-SM production and decay into non visible final states

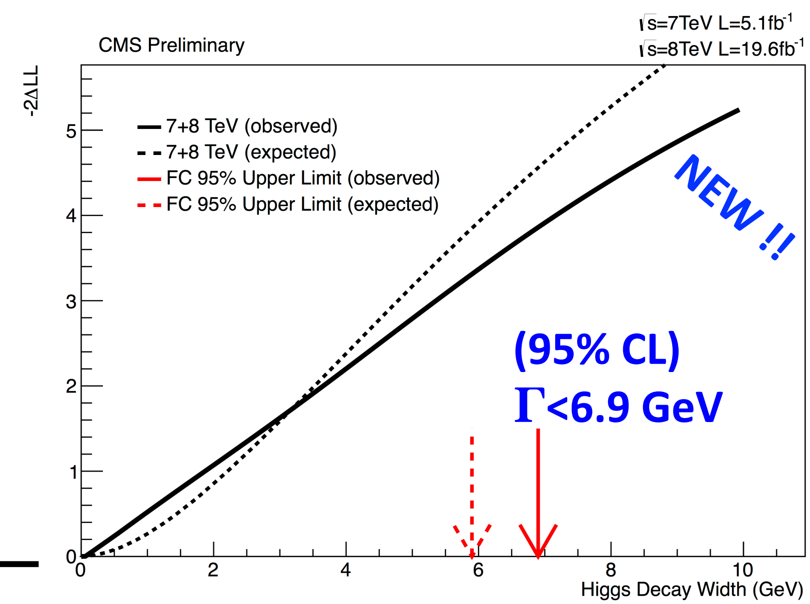
Invisible BR and width

- **Degeneracy can be solved with:**
  - **direct search of H->invisible**
    - new ZH analysis (HIG-13-018)
    - further improvement expected from VBF channel
  - **direct measurement of width** (Γ_{SM} ~4MeV)
    - limited by detector resolution (~GeV):
      new $\gamma\gamma$ result (HIG-13-016)
    - new technique based on counting H->ZZ->4l events with h off-shell (arXiv:1307.4935)

      now: Γ_H<90 MeV -> BR$_{inv}$<0.84

      (Γ_H<5-10 MeV at high lumi)





(see K. Melnikov, K.Kaadze and M.Kenzie talks)

BSM driven benchmarks

Beyond minimal SM: **mixing with EW-singlet** (typically as door to new physics, eg “hidden valley” models)

-> h126 + second resonance which unitarize the theory together, same kinematic as SM but rescaled couplings and width

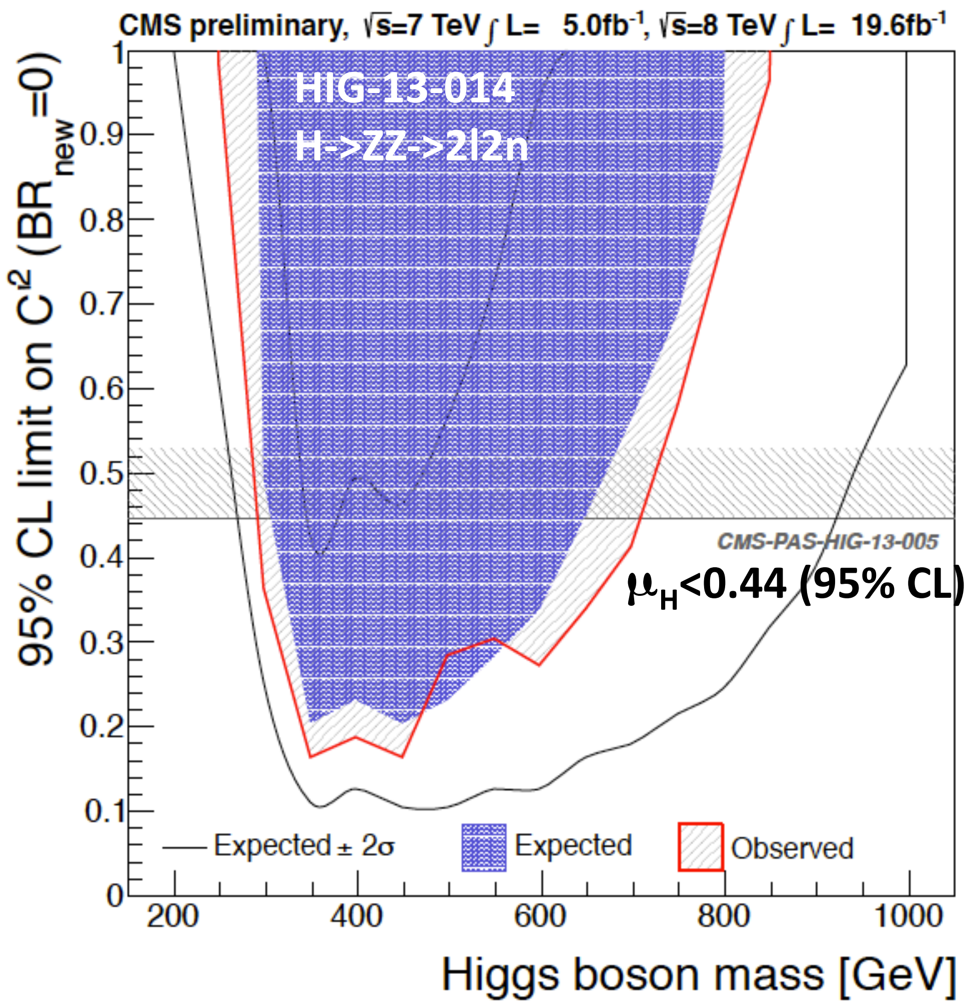
- **direct search of second heavy Higgs**

$$\mu_H' = \cos^2\theta \times \mu_H^{SM}$$

$$\Gamma_H' = \cos^2\theta \times \Gamma_H^{SM}$$

- **h126 observed signal strenght put limits on θ -> indirect limits on second resonance**

$$\mu_h' = \sin^2\theta \times \mu_h^{SM}$$



(see talk from J.Wang)

2 Higgs Doublet Model

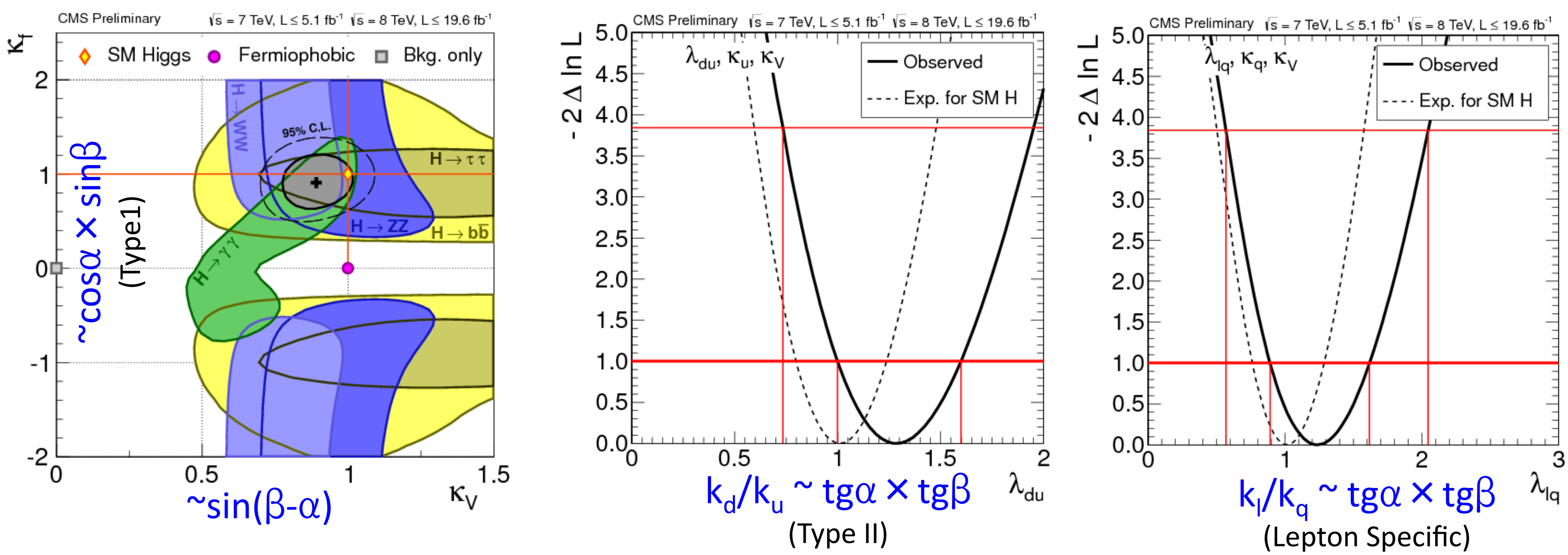
Next step: one degree of freedom more allowing coupling to rescale differently for leptons/quarks, up/down fermions … **(Type 1,2,3,4 2HDM)**

- Direct search for new resonances: **H (CP-even), A (CP-odd), $H^{\pm}$**

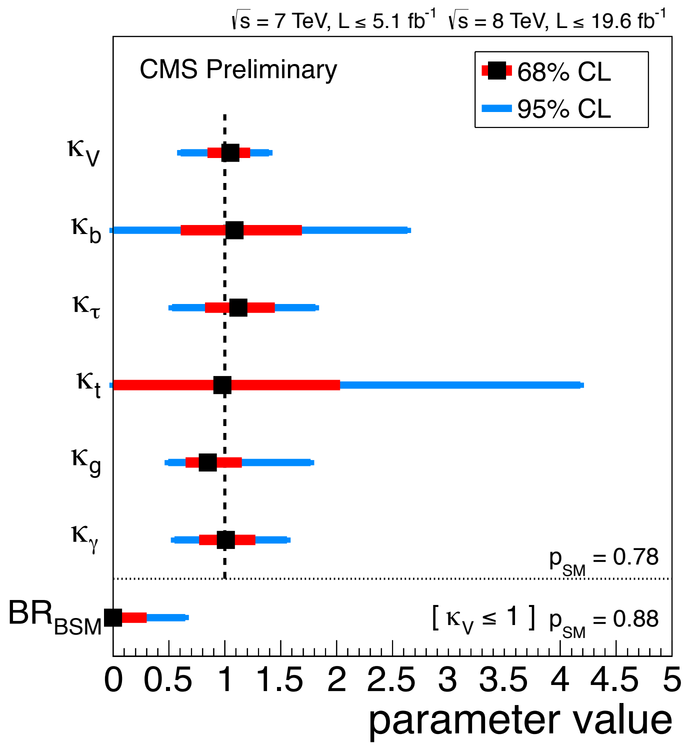
  heavy A/H->ttbar (most important!)   A->Zh, H->hh, charged Higgses …

  heavy higgs into VV: still room for low sin(β-α)

- Precision measurement on h126



Completely general interpretation



❑ Model independent parameterization: all couplings free

- new ttH combination ($\gamma\gamma$, bb, $\tau\tau$) will improve k_t

CMS PAS HIG-13-015, CMS PAS HIG-13-019 and arXiv:1303.0763

❑ **Let's set the scale:**

maximum allowed deviation assuming no other new EWSB states observed at LHC

arXiv 1206.3560

	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$
LHC 3000 fb^{-1} (%)	[2,5]	[7,10]	[4,7]

❑ Expectations at high lumi LHC and ILC

(look at CMS White paper for details)

https://indico.fnal.gov/getFile.py/access?contribId=10&sessionId=0&resId=0&materialId=slides&confId=6969 (J.Olsen @ Seattle, Snowmass)

Beyond rates…

Couplings extracted from **rates** in different channels

-> **much more info are available in our data!**

❑ Shape analysis -> **tensor structure of the amplitude** of Higgs production and decay (aka spin/parity analysis)

- most general spin 0 H-VV amplitude

$$A\left(X \to V_1 V_2\right) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^{\alpha} q_2^{\beta} \right)$$

SM (ZZ,WW) SM (γγ) 0-

(more complicated amplitudes for spin1 and spin2 available Phys.Rev. D86 (2012) 095031)

- ***a_i*** values are connected to observables (angles, masses) through analytical (MELA) or Matrix Element packages

- analysis:
  - extraction of ***a_i*** **couplings from shape fit** (more dof -> more lumi)
  - **hypothesis testing**: compare data to kinematic shapes expected for fixed/given set of a_i values
    (some extreme hypothesis already excluded with low statistics)

Spin/parity: hypothesis testing

- H->4l: 5 angles + 2 masses collapsed into a single likelihood kinematic discriminant
- H->WW: kinematic not close -> 2D m_T-m_{ll} analysis
- H->$\gamma\gamma$: angle between 2 photons

(HIG-13-016)

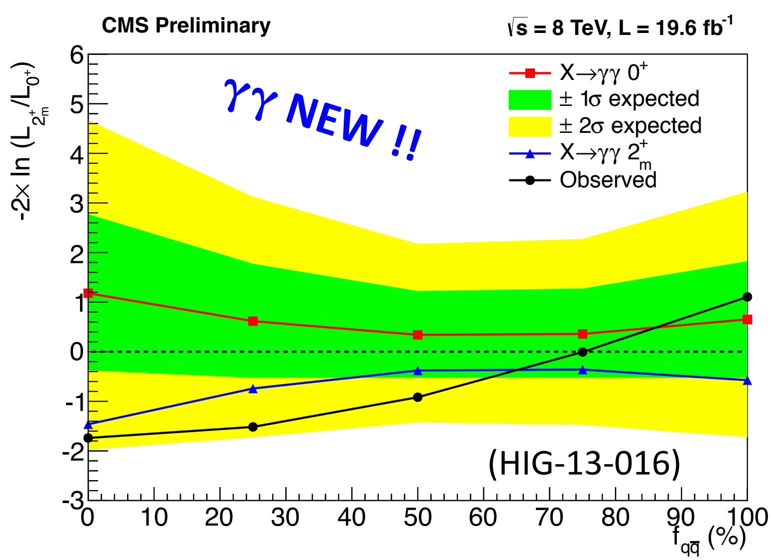
(spin 1 excluded by ZZ)

CLs results	ZZ->4l	WW->2l2n	comb ZZ-WW	$\gamma\gamma$ NEW !!
0^-	**0.16%**	-	-	N/A
0_h^+	8.1%	-	-	-
2_m^+ (gg)	1.5%	14%	**0.6%**	60.9%
2_m^+ (qq)	**0.1%**	-		16.9%

- **Production mechanism (qqbar, gg)** is very model dependent

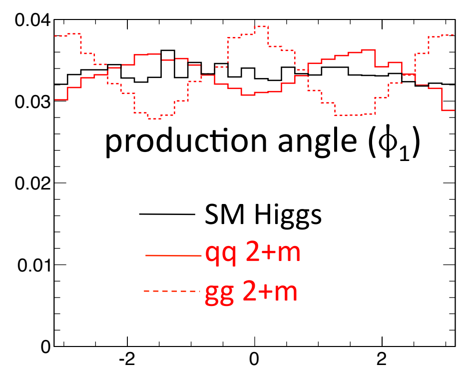
-> exclusion as a function of fraction of qqbar production

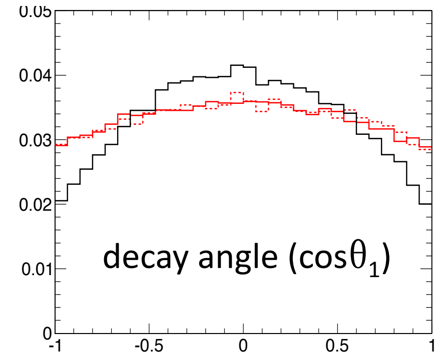
(see M.Kenzie and P.Milenovic talks)



Production independence

❑ **Production mechanism (qqbar, gg)**
affects production angles

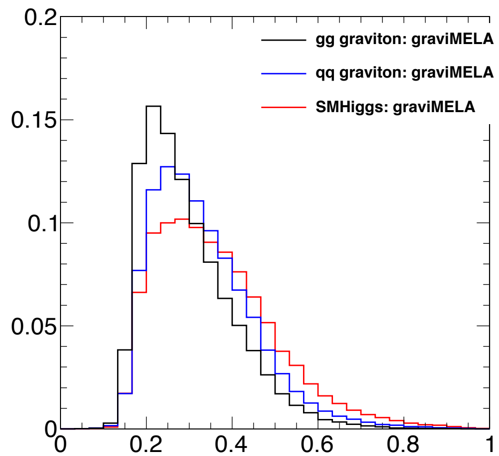


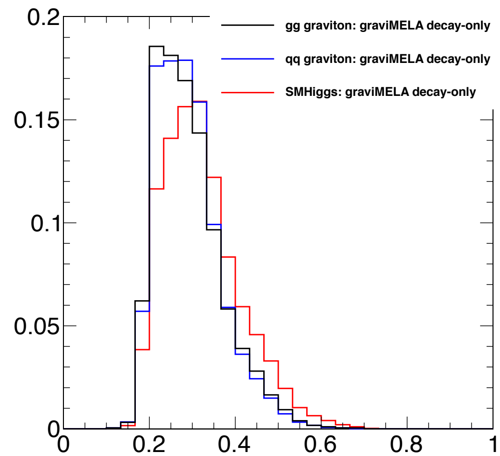


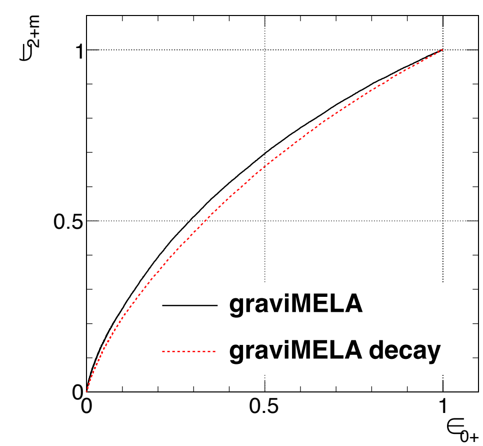
General approach (valid for ALL possible production modes, eg VH, VBF..)

- discriminant without production angles
- VERY general results (small lost in separation power)

gen level study with smearing and acceptance cuts (HXSWG)







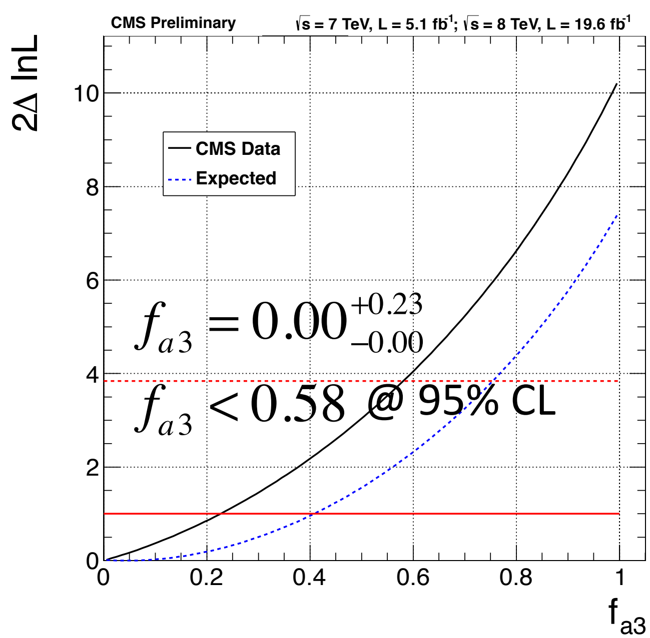
Model independence: CP mixing fit

- **Extract couplings from fit to kinematical distributions**

$$A(X \to V_1 V_2) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

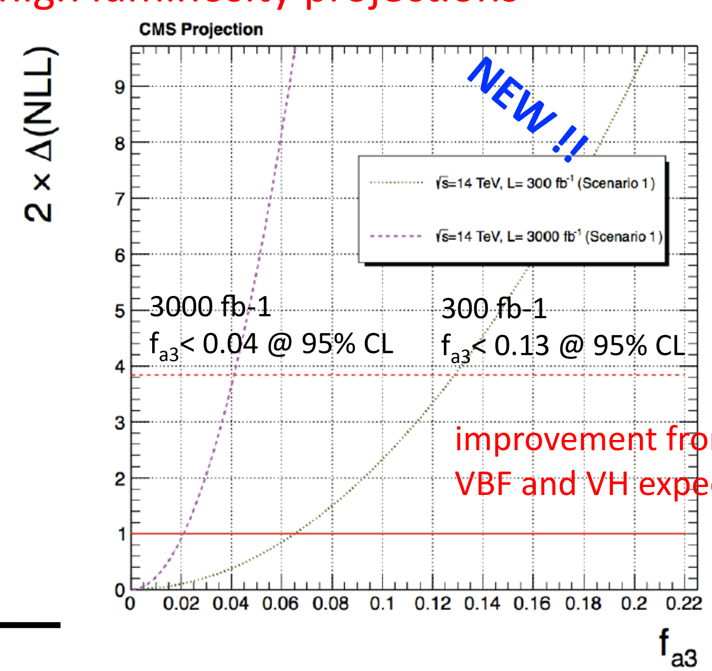
f_{a3} (fraction of a_3 component over total xsec) very important parameter which quantify the CP-mixing of the resonance, as predicted in SUSY models

- (only?) alternative spin/parity hypothesis really theoretically motivated
- **first measurement in H->4l**



- expected very small: 0- has not LO couplings to VV

-> CMS high luminosity projections



What else?

- **Mass:** wonderful measurements available
  (high lumi $\delta m \sim 150$ MeV)

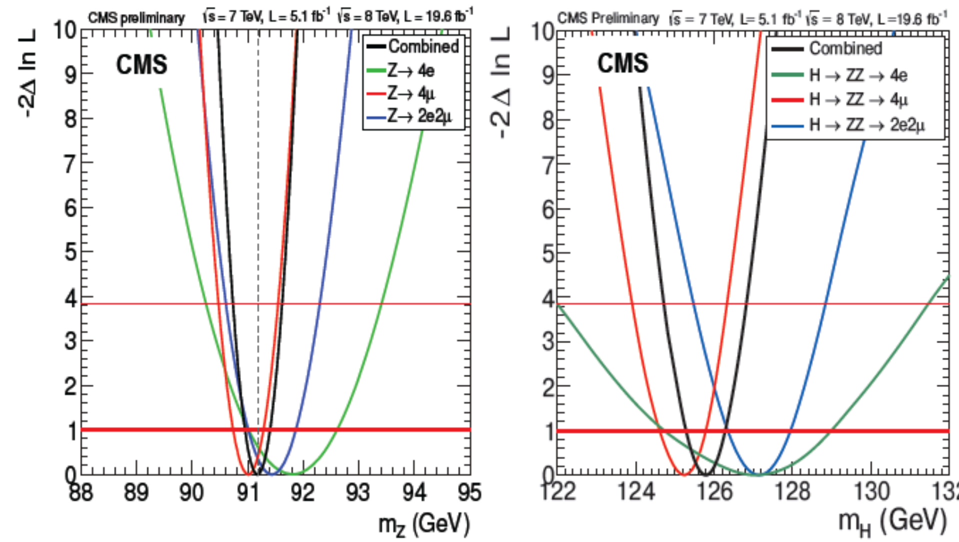
-> SM self-consistency

-> metastability of the universe

(m_{top} uncertainty will dominate)

$$m_h^2 = 2\lambda_{SM} v^2$$

$$\frac{\delta\lambda_{SM}}{\lambda_{SM}} \sim 1.6\% \quad \frac{\delta m}{m} \sim 0.25\%$$



4μ	91.01 ± 0.27 (stat.&syst.)	$125.2^{+0.5}_{-0.6}$ (stat.&syst.)
2e 2μ	91.43 ± 0.43 (stat.&syst.)	$127.2^{+0.8}_{-0.8}$ (stat.&syst.)
4e	91.80 ± 0.80 (stat.&syst.)	$127.0^{+1.9}_{-2.3}$ (stat.&syst.)

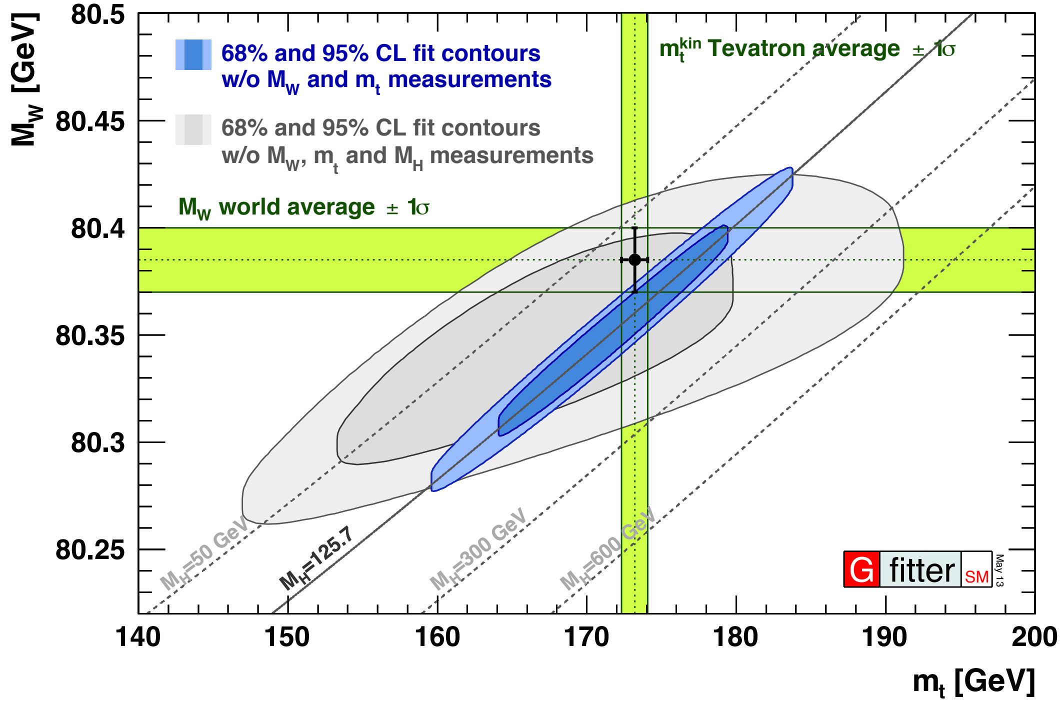
- **Self-couplings**: gg->h*->hh

arXiv:1305.6397

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\;-15\,\%^b$
NMSSM	$-25\,\%$
LHC 3 ab^{-1} [36]	$[-20\,\%, +30\,\%]$

Conclusions

- Last free parameter (m_h) measured -> **SM is over-constrained and still in good health**



- **Plenty of room for very well motivated BSM extensions (eg, EW-singlet, 2HDM)**
  - With high energy/luminosity (and a well done upgrade!!) we can improve the precision of couplings and CP violation down to 1-10% at LHC
  - **Not just about precision physics (yet?)… LHC is a discovery machine:**
    -> direct searches may open the door to NP much sooner!!!

Properties of discovered Higgs-like resonance in CMS - BACKUP -

S.Bolognesi
(Johns Hopkins University)

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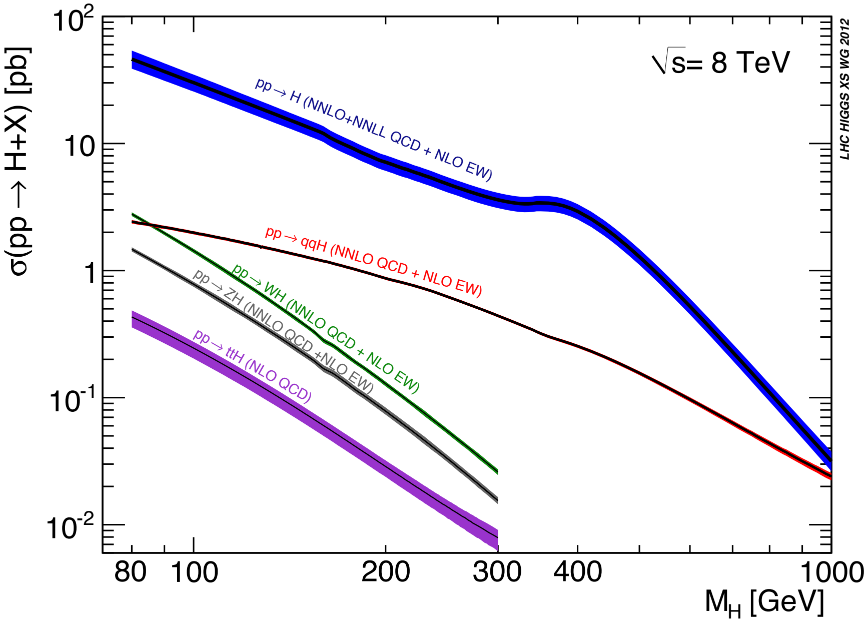
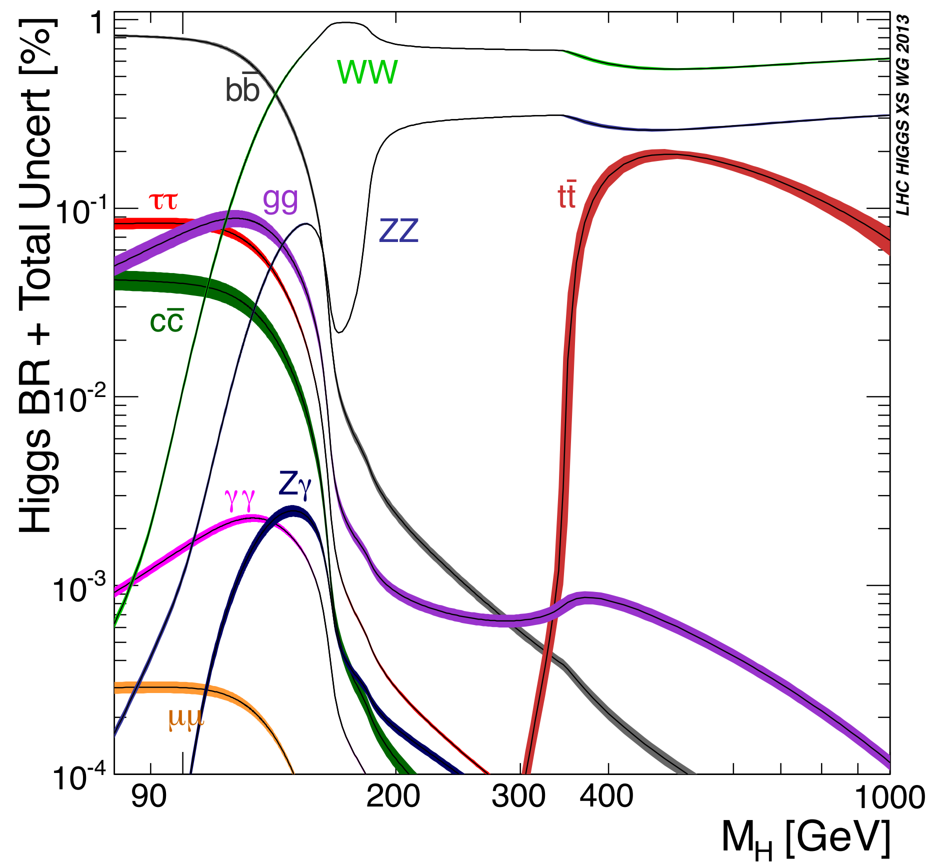
Production and decay modes

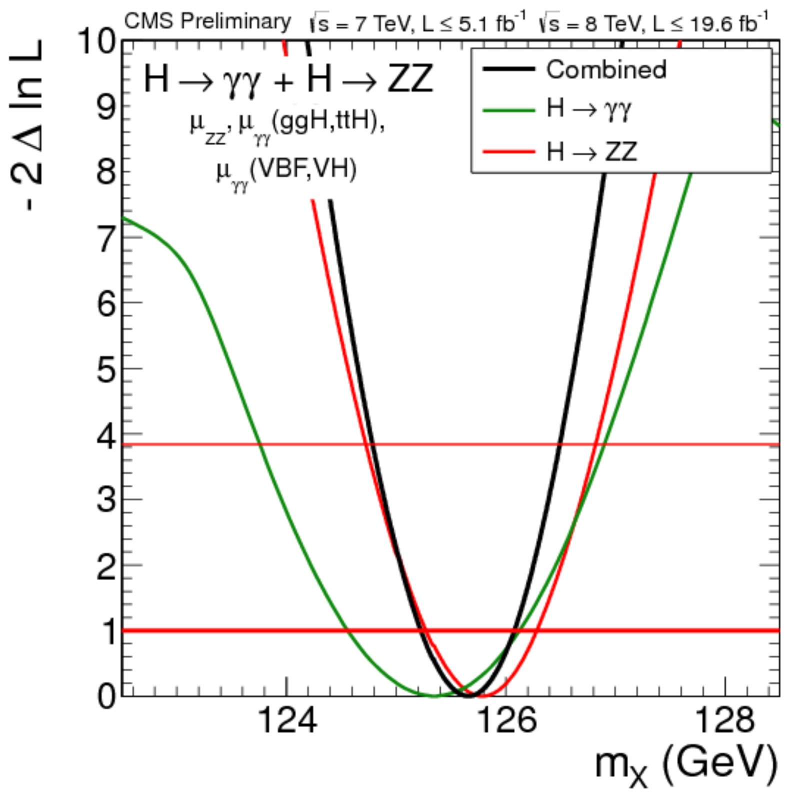
The first slide of any respectable talk about Higgs properties 2 years ago …

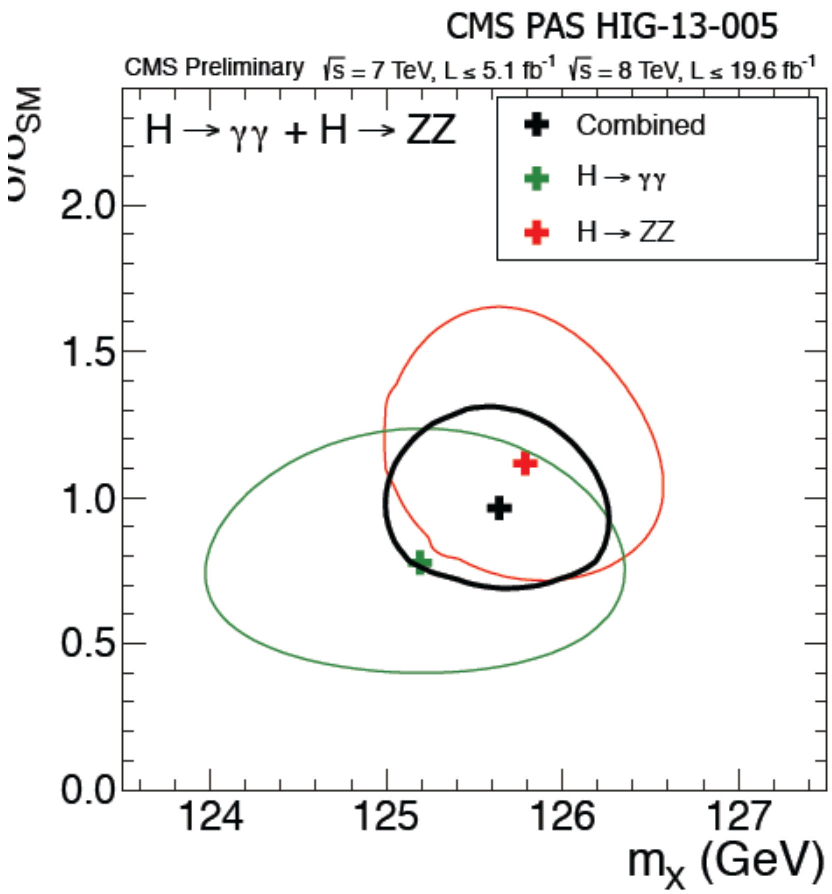




… today is just **a due praise to the Higgs Cross Section group**

Mass: ZZ , γγ





$M(\gamma\gamma) = 125.4 \pm 0.5 \pm 0.6$

$M(4\ell) = 125.8 \pm 0.5 \pm 0.2$

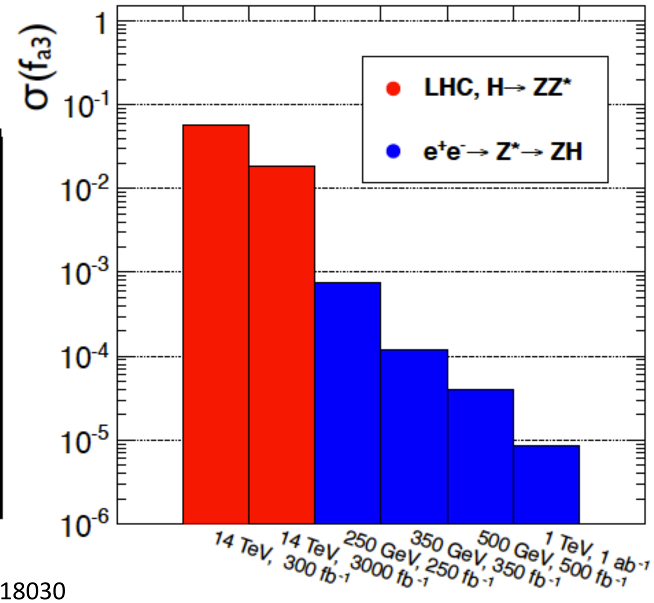
Projections for CP violation

❑ LHC-ILC comparison (Snowmass Seattle, EPS)

Gen-level study with background (resolution smearing, acceptance cuts only for LHC case not for ILC, only gg exploited at LHC)

CP violation ~3σ discovery potential

	√s (Lumi)	f_{a3}	$\sigma(f_{a3})$
LHC gg→X →ZZ(4l)	14TeV(300/fb)	0.18	0.06
	14TeV(3000/fb)	**0.06**	0.02
e+e- →Z* →Z(ll)X(bb)	250GeV(250/fb)	2.00E-03	7.00E-04
	350GeV(350/fb)	3.56E-04	1.12E-04
	500GeV(500/fb)	1.16E-04	3.90E-05
	1TeV(1000/fb)	**2.00E-05**	7.00E-06



Y. Gao talk @ EPS 2103 Stockholm
http://indico.cern.ch/contributionDisplay.py?contribId=474&sessionId=15&confId=218030 22