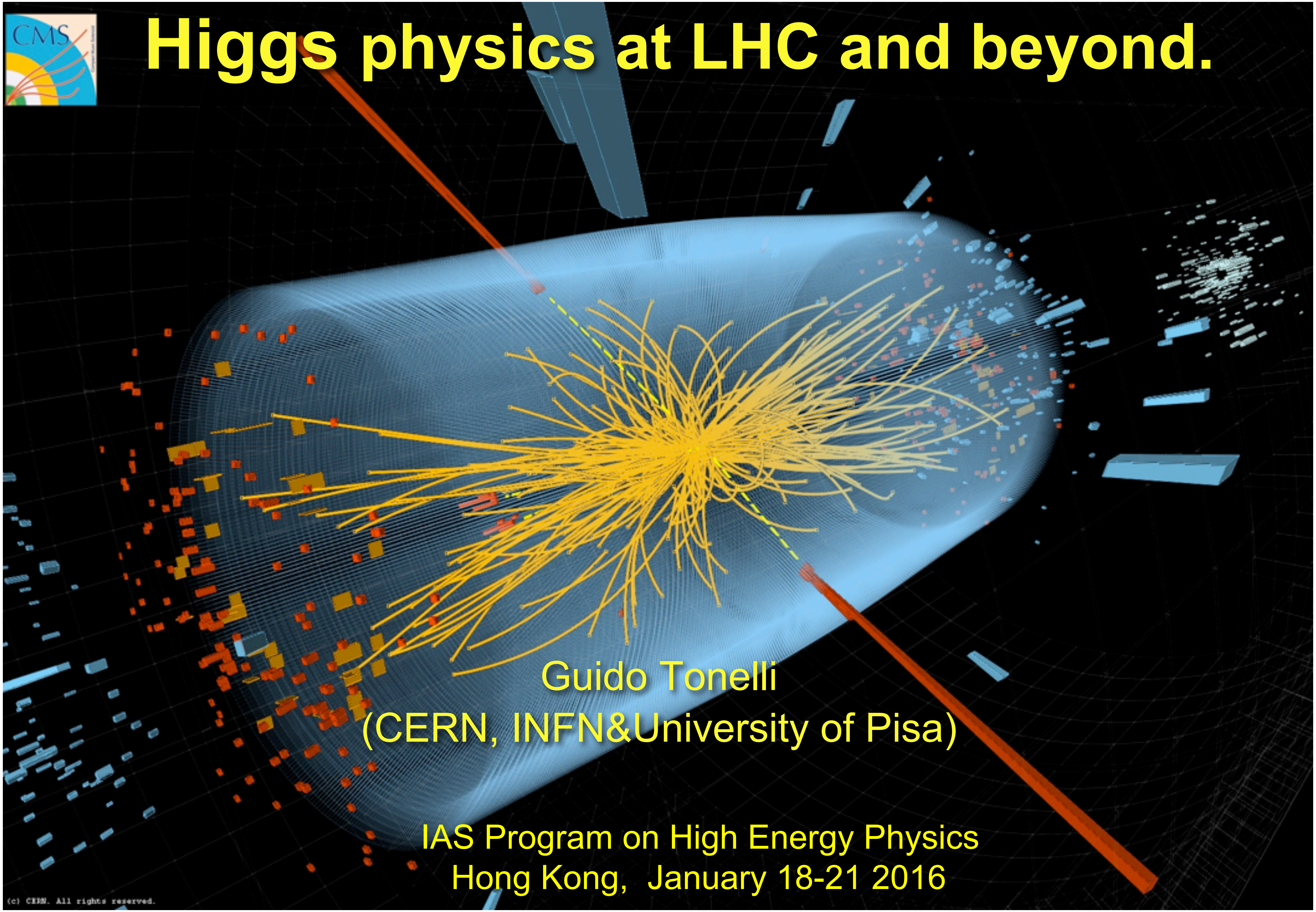
Higgs physics at LHC and beyond.



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IAS Program on High Energy Physics
Hong Kong, January 18-21 2016

From search to precision measurement.

In the post-discovery era, focus moves from search to precision measurements.

Characteristics of the SM Higgs:

Decay modes

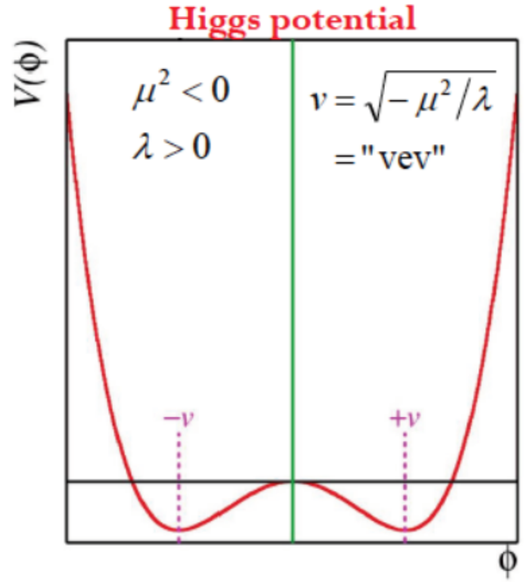
Coupling to other SM particles

Mass

Spin and Parity

Width and lifetime

Self-coupling.



$$L = \left(D_\mu \phi\right)^* \left(D^\mu \phi\right) - \left(\mu^2 \phi^2 + \lambda \phi^4\right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

$$g_{HVV} = 2\frac{m_V^2}{v} \qquad g_{Hff} = \frac{m_f}{v}$$

$$m_H = \sqrt{2\lambda} v$$

λ, μ unknown → m_H is a free parameter of the SM

LHC combined measurement of m_H.

- $H \rightarrow \gamma\gamma$: Events are divided into different $m_{\gamma\gamma}$ categories to improve sensitivity.
- $H \rightarrow ZZ \rightarrow e^-e^+\mu^-\mu^+$, $e^-e^+e^-e^+$, $\mu^-\mu^+\ \mu^-\mu^+$ analyzed separately
  ATLAS: 2D fit to $m_{4\ell}$ and BDT background discriminant
  CMS : 3D fit to $m_{4\ell}$, BDT background discriminant and per-event uncertainty in $m_{4\ell}$

$$\Lambda(\alpha) = \frac{L\left(\alpha, \hat{\theta}(\alpha)\right)}{L\left(\hat{\alpha}, \hat{\theta}\right)} = \frac{\text{Maximum likelihood for a given } \alpha}{\text{Global maximum likelihood}}$$

α = parameters of interest (eg. m_H)
θ = nuisance parameters (eg. systematics)

$\hat{\alpha}, \hat{\theta} =$ Best fit values

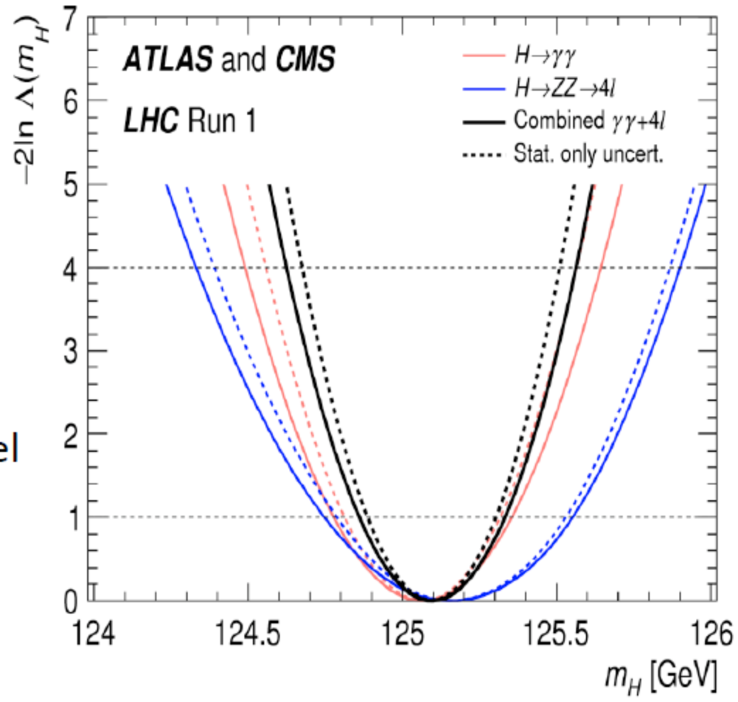
$L(\alpha,\theta)$ = product of signal and background PDFs.

To combine: multiply likelihood terms for each channel

$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}(m_H), \hat{\mu}^{\gamma\gamma}_{VBF+VH}(m_H), \hat{\mu}^{4\ell}(m_H), \hat{\theta}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4\ell}, \hat{\theta}\right)}$$

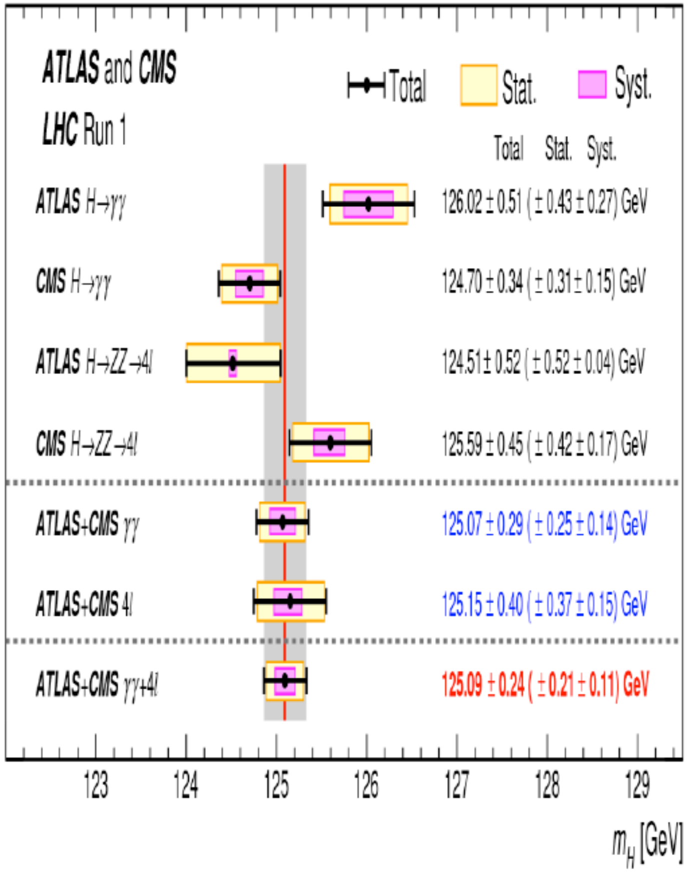
μ = signal strenght modifiers

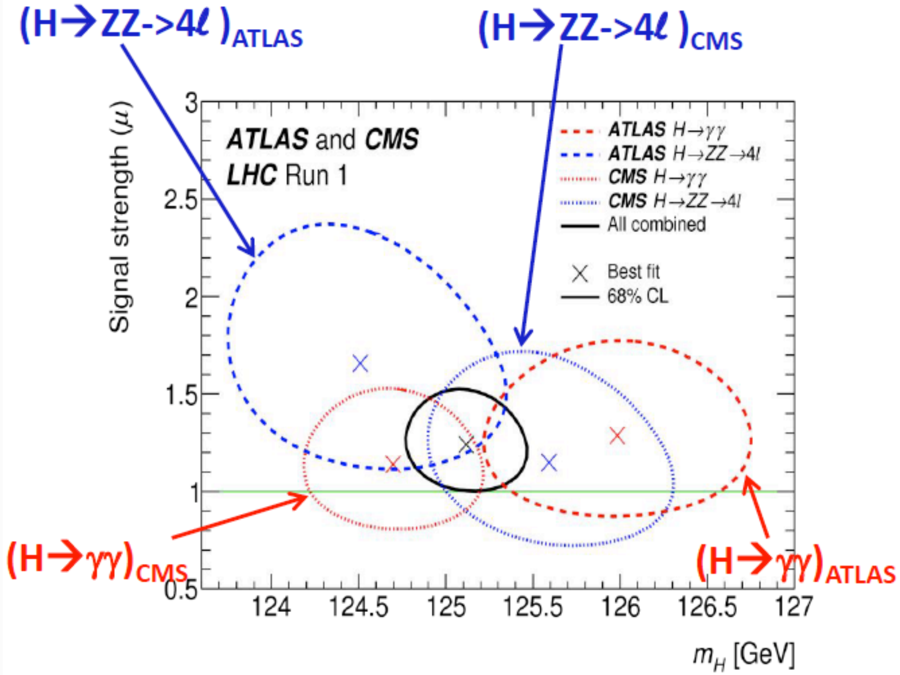
Phys. Rev. Lett. 114 (2015) 191803



Results.

Phys. Rev. Lett. 114 (2015) 191803





$m_H = 125.09 \pm 0.21 \pm 0.11$ GeV

Statistical uncertainty dominates. Along with theory developments in cross-sections, allows detailed couplings comparisons.

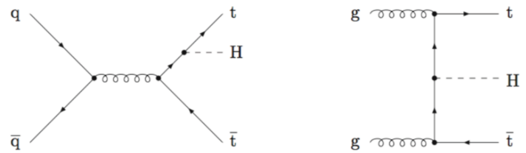
We have already entered the Higgs precision era: ±0.19%.

Phase space explored by CMS (so far).

	ggH	qqH	VH	ttH	Significance Observed (expected)	σ_m/m
H→ZZ (4ℓ)	✓	✓	✓		6.5 (6.3) σ	1-2 %
H→ γγ	✓	✓	✓	✓	5.6 (5.3) σ	1-2 %
H→WW(2ℓ2ν)	✓	✓	✓	✓	4.7 (5.4) σ	15 %
H→ ττ	✓	✓	✓	✓	3.2 (3.7) σ	10-20%
H→ bb		✓	✓	✓	2.6 (2.7) σ	10%
H→μμ		✓	✓		0.4 (<0.1) σ	1-2%

Preliminary results on ttH

Extremely challenging production mechanism (tiny cross sections at LHC Run 1). Very important to establish the direct coupling of the Higgs to the heaviest quark

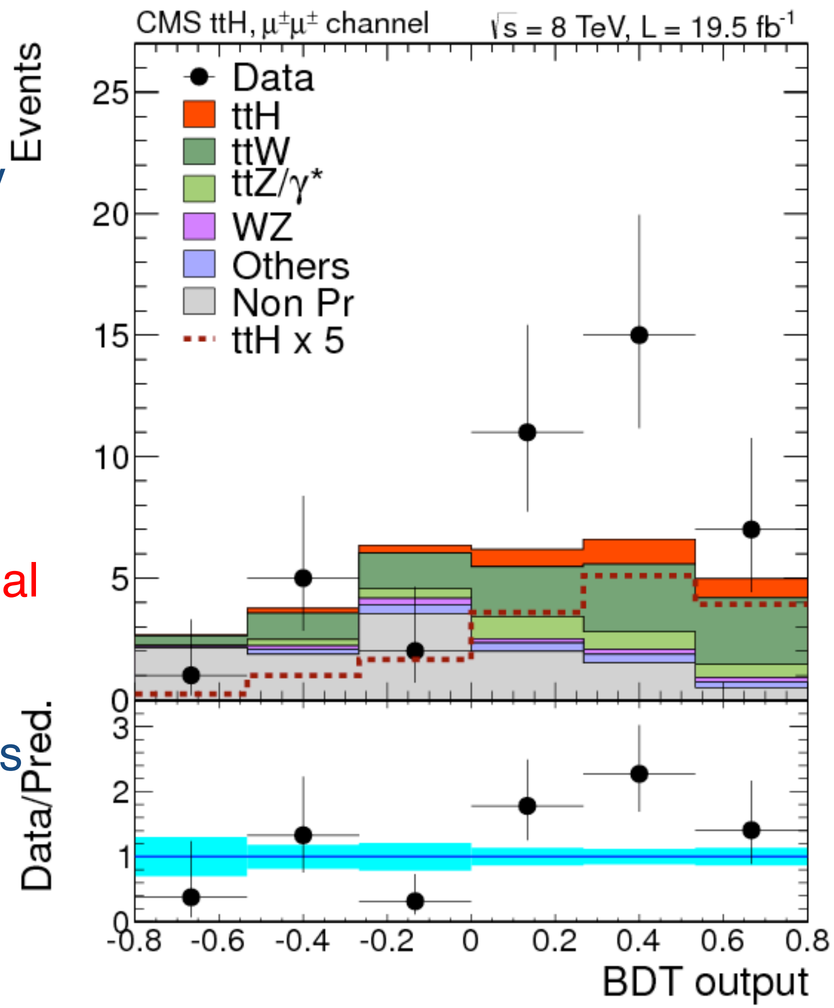


Directly sensitive to top Yukawa coupling (only indirectly tested via loops ggH and Hγγ). Comprehensive studies performed by CMS considering many final states including multi-leptons, b-jets, and γγ.

CMS reported an excess of events with respect to the background only hypothesis corresponding to 3.4 standard deviations and a best-fit value for a Higgs signal strength of 2.8 ±1.0 at 68%.

Compared to the SM expectation the observed excess is equivalent to a 2-standard-deviation upward fluctuation.

To be watched carefully in new data at 13TeV



Indirect measurement of Γ_H

H→ZZ→4ℓ , H→2ℓ2ν, (ℓ=e,μ),

Breit-Wigner production gg→H→ZZ:

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}\,g^2_{HZZ}}{\left(m^2_{ZZ}-m^2_H\right)^2+m^2_H\Gamma^2_H}$$

On-peak (105.6<$m_{4\ell}$<140.6 GeV) and off-peak cross sections ($m_{4\ell}$> 220 GeV):

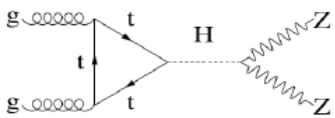
$$\sigma^{\text{on-shell}} = \int_{|m-m_H|\le n\Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\,g^2_{HZZ}}{m_H\Gamma_H}$$

$$\sigma^{\text{off-shell}} = \int_{m-m_H\gg\Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH}\,g^2_{HZZ}}{(2m_Z)^2}$$

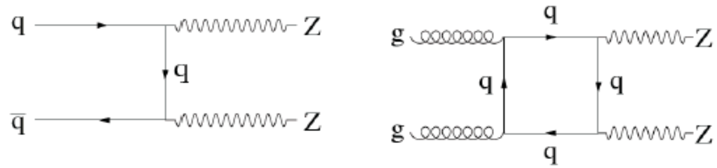
$$\boxed{\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H}$$

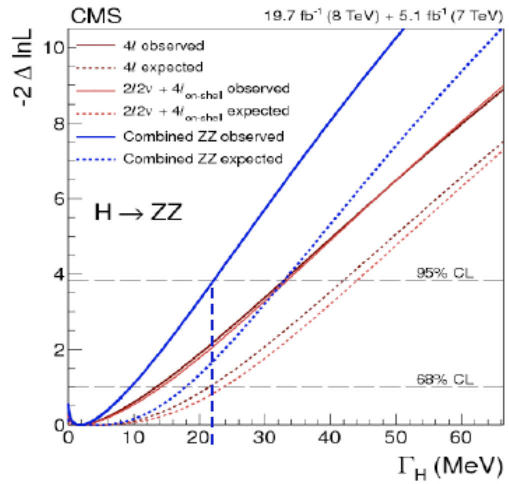
- Must include interference between gg→H→ZZ and gg→Box→ZZ
- K-factor of gg→ZZ not well known, assume the same as signal and add a sytematic uncertainty.

Phys. Lett. B 736 (2014) 64



Dominant backgrounds:





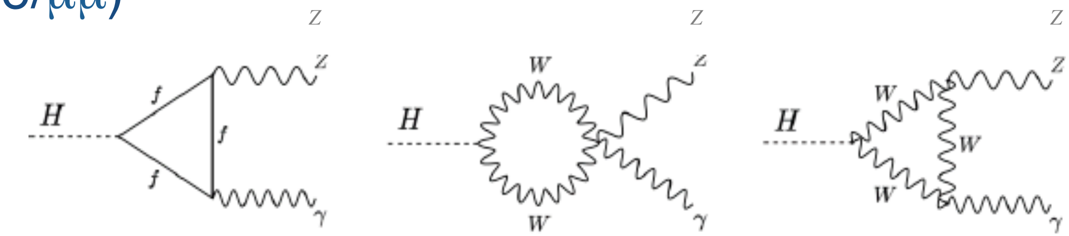
Γ_H< 22 MeV at 95% CL

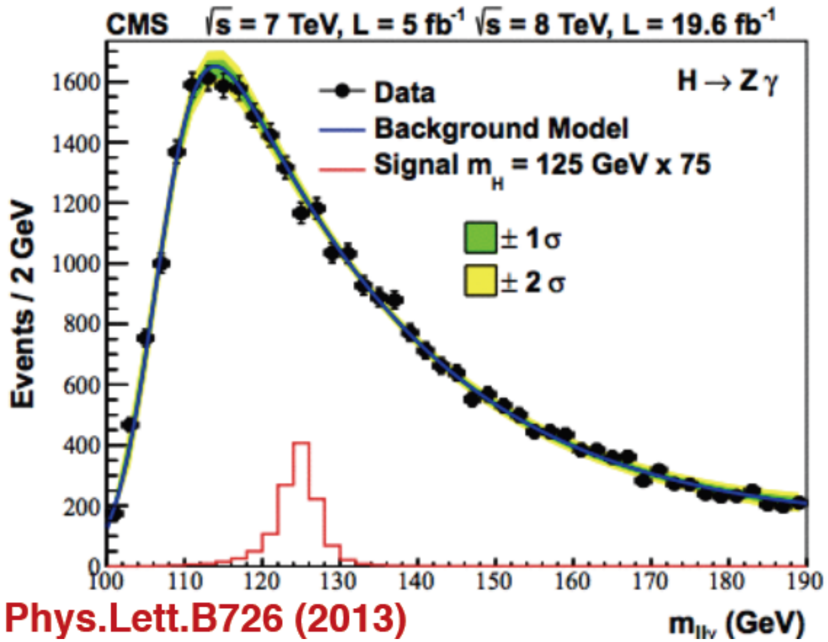
Rare decays: H→Zγ

Very sensitive to possible contributions from new physics via decay loops of new, heavy charged particles.

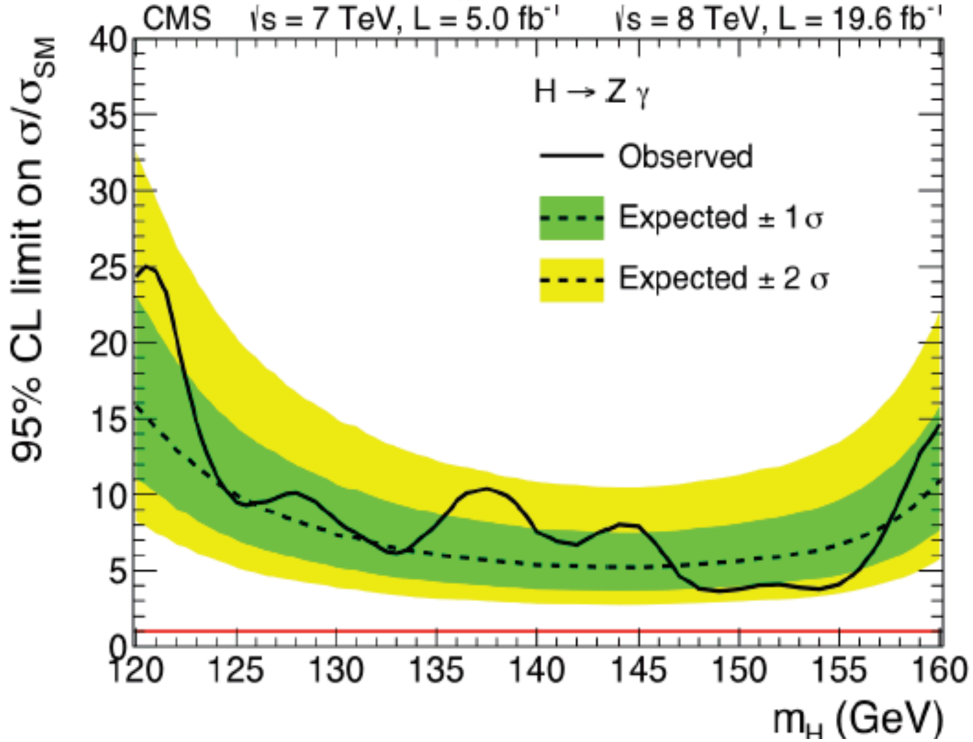
BR_{SM} 1.54x10^{-3} (~10^{-4} including Z→ee/μμ)

CMS results BR<9.5BR_{SM}





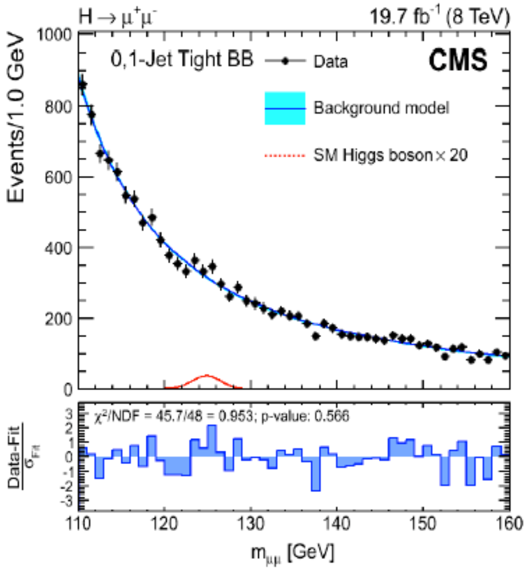
Phys.Lett.B726 (2013)

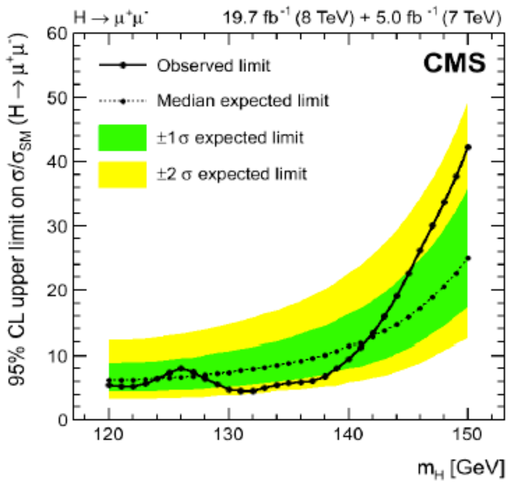


Very rare decays: H→μμ and H→ee

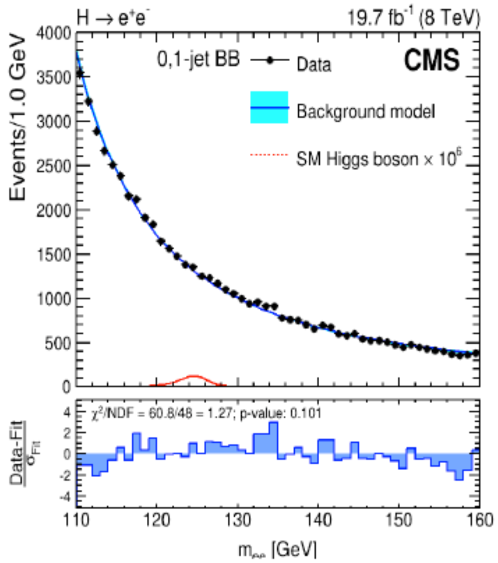
PLB 744 (2015) 184

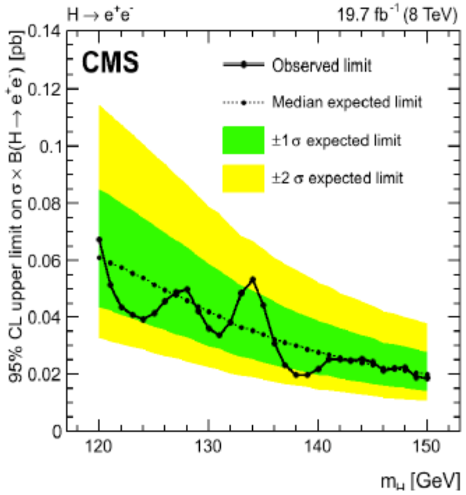
H→μμ





H→ee





- H→μμ, H→ee cleanest of fermionic decays.
- $B_{SM}(H\rightarrow\mu\mu) = 2.2\text{x}10^{-4}$
- $B_{SM}(H\rightarrow ee) = 5 \text{ x } 10^{-9}$
- search performed in [120,150] GeV
- $\sigma B(H\rightarrow\mu\mu)<0.033$ pb, 95% CL

  $B(H\rightarrow\mu\mu)<0.0016$, 95% CL

  $$\mu = 0.8^{+3.5}_{-3.4}$$
- $\sigma B(H\rightarrow ee)<0.041$ pb, 95% CL

  $B(H\rightarrow ee)<0.0019$ ($3.7\text{x}10^5$ B_{SM})

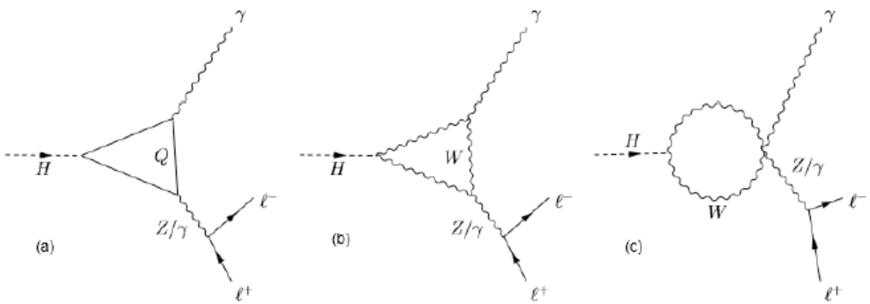
Run 1 data show that couplings to fermions are not universal.

Very rare decays: H→γ*γ→llγ, H→(J/Ψ)γ→llγ

H→γ*γ→llγ $BR_{SM}=2\text{-}3\times10^{-5}$; CMS results: $BR<7.7BR_{SM}$

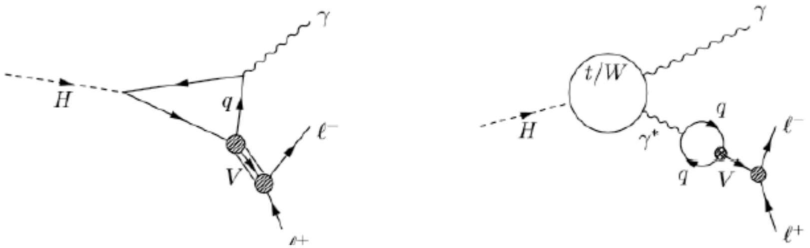
arXiv:1507.03031

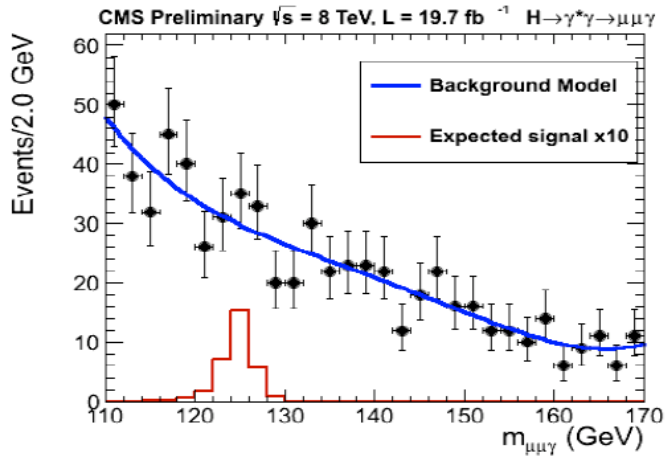
Dominant SM processes:

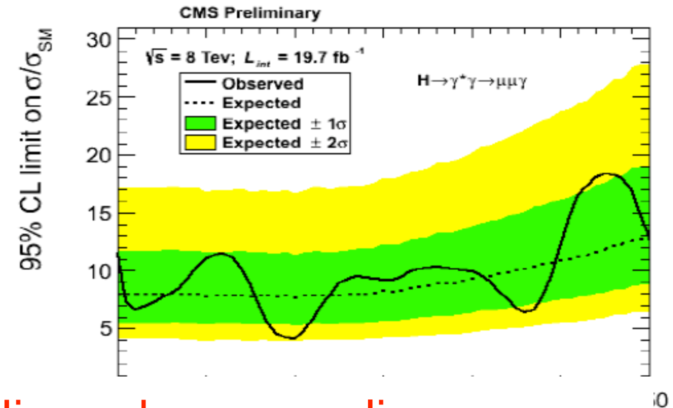


$$\frac{\Gamma(H\to\gamma^*\gamma\to ee\gamma)}{\Gamma(H\to\gamma\gamma)}\approx 2.9\%\,;\quad \frac{\Gamma(H\to\gamma^*\gamma\to \mu\mu\gamma)}{\Gamma(H\to\gamma\gamma)}\approx 1.1\%\,;$$

$$\frac{\Gamma(H\to Z\gamma\to \ell\ell\gamma)}{\Gamma(H\to\gamma\gamma)}\approx 2.2\%$$





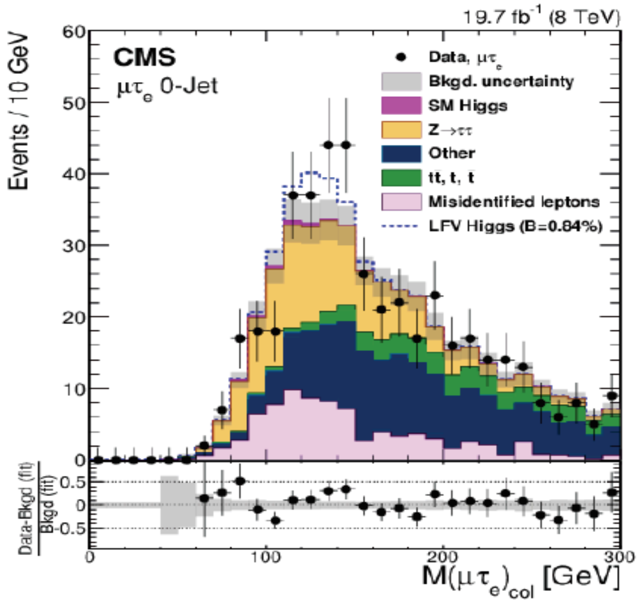


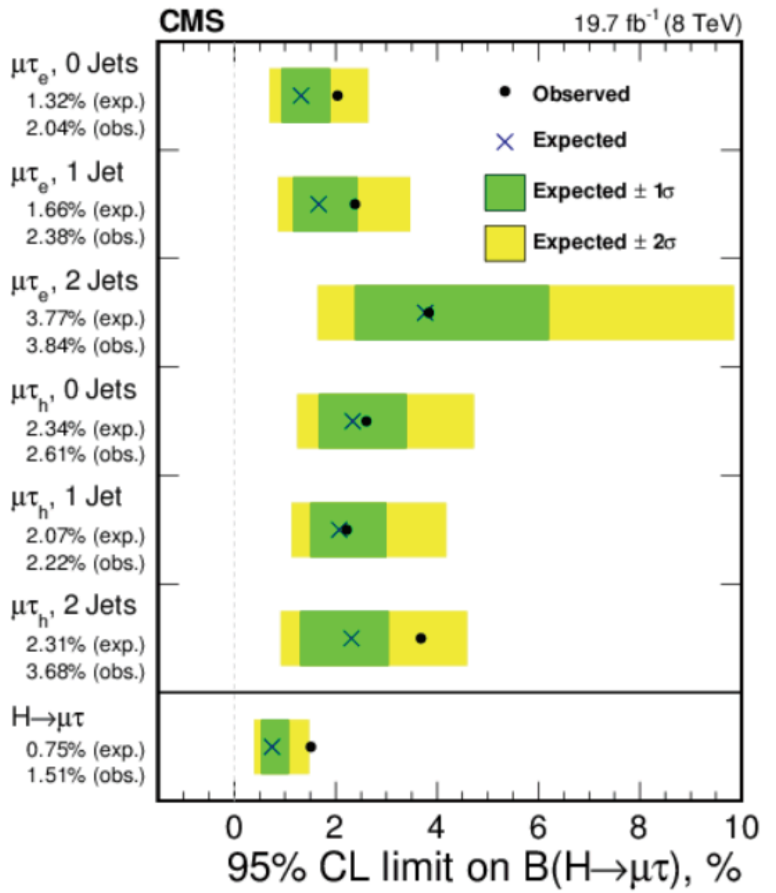
H→(J/Ψ)γ→llγ $BR_{SM}=2.8\times10^{-6}$; important to probe Higgs charm coupling

CMS results $BR<540BR_{SM}$

Search for LFV decays of the Higgs

- i.e. H→$\mu\tau$ (CMS performed a search based on the well known topologies $\mu\tau_e$ and $\mu\tau_{had}$)





CMS-HIG-14-005, submitted to PLB

BR<1.51% at 95%CL (0.75% expected)
Slight excess (2.5σ) observed by CMS.

To be watched carefully in new data at 13TeV

Study of the H invisible decay width.

There is still room for decays of H into invisible particles (coupling to light dark matter, Hidden Valley models, RH neutrinos etc).

The search is done using two complementary approaches

a) Fitting the invisible decay width from the coupling fits. Assuming SM coupling with possible BSM contributions in the loops

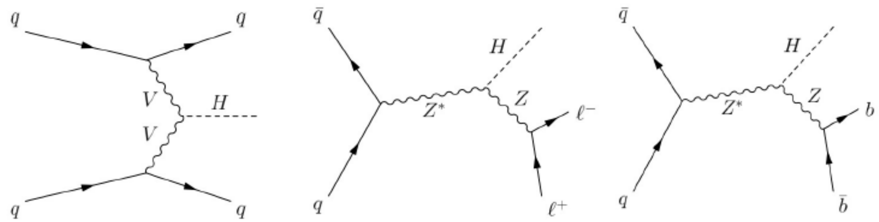
BR_{BSM}<38% at 95%CL @ 125GeV.

CMS-PAS-HIG-13-005

b) Using dedicated channels in looking for VBF production or associated production of a Higgs boson with a Z decaying leptonically or in b-jets.

BR(H→$\chi\chi$)<58% at 95%CL @ 125GeV.

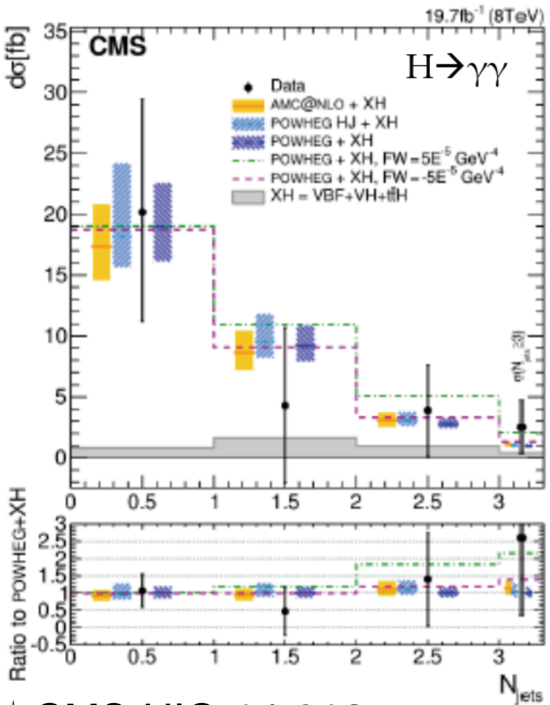
arXiv: 1404.1344



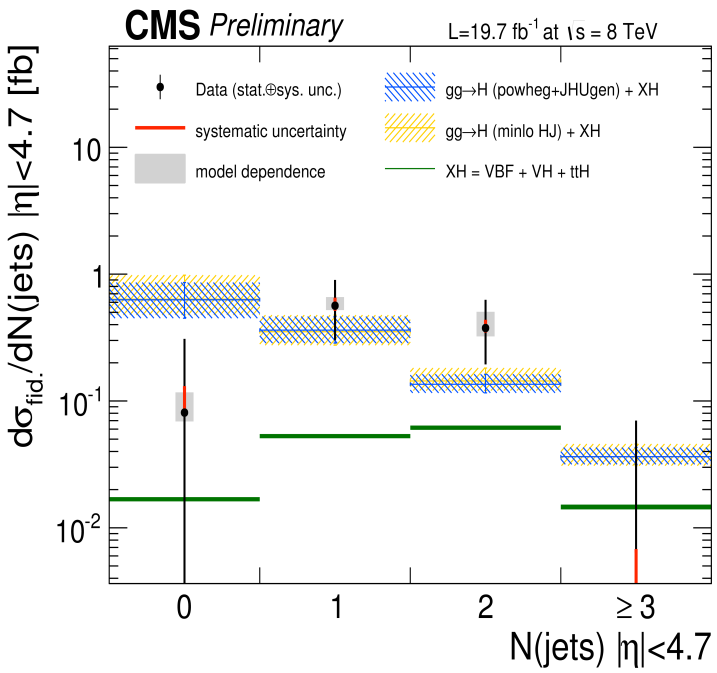
Still room for suprises.

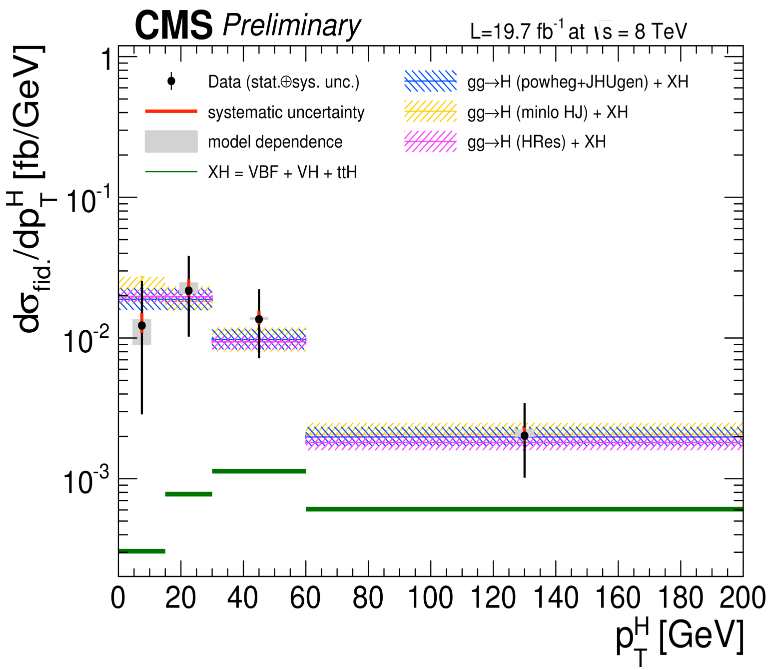
Differential Distributions

- Sufficient statistics to produce the preliminary measurements in ZZ and $\gamma\gamma$.
  - Results compared to the most precise theoretical calculations.



CMS-HIG-14-016



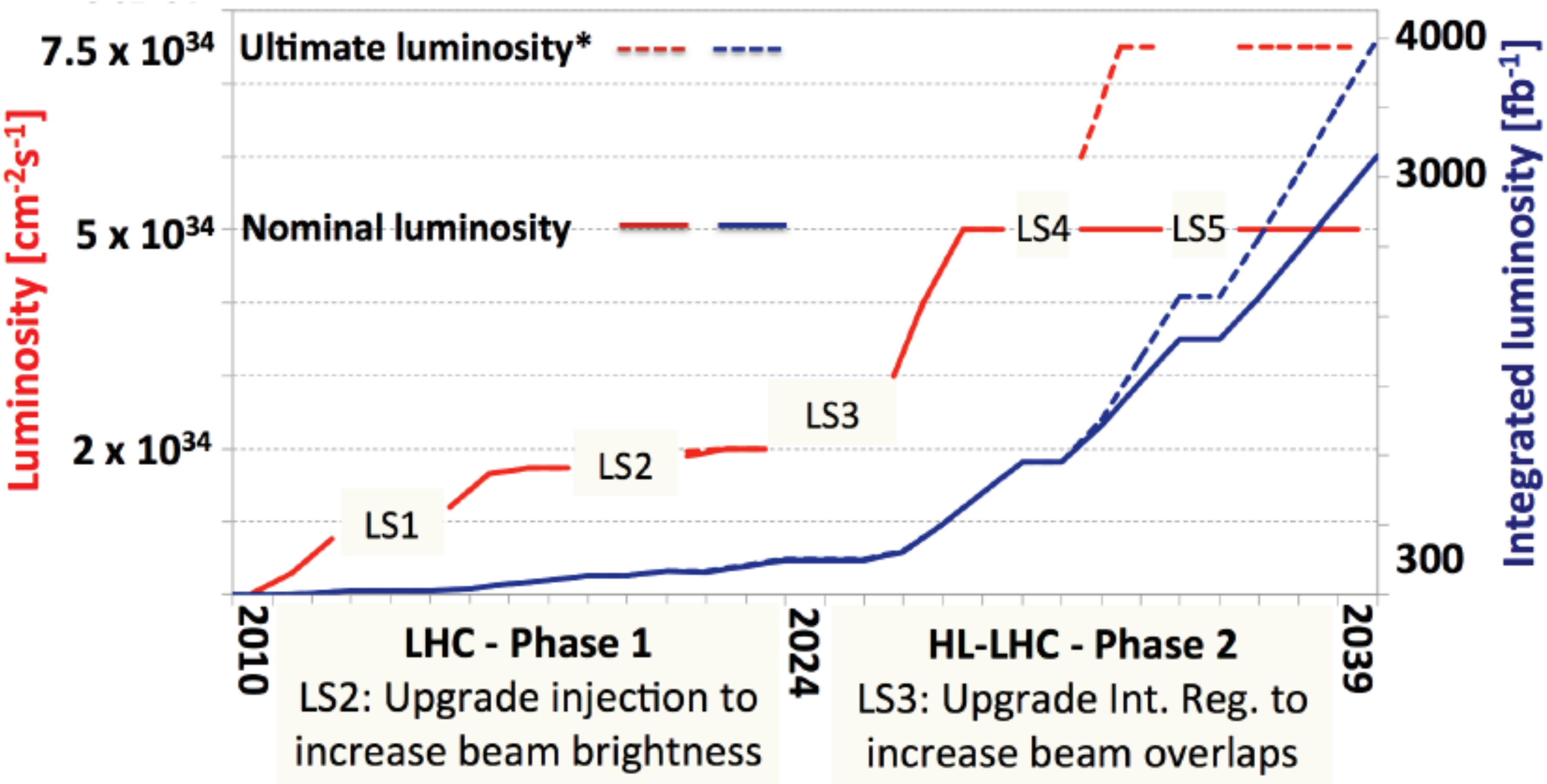


CMS-HIG-14-028

- **No deviation from SM predictions (but statistics is still not large enough to challenge properly the predictions).**

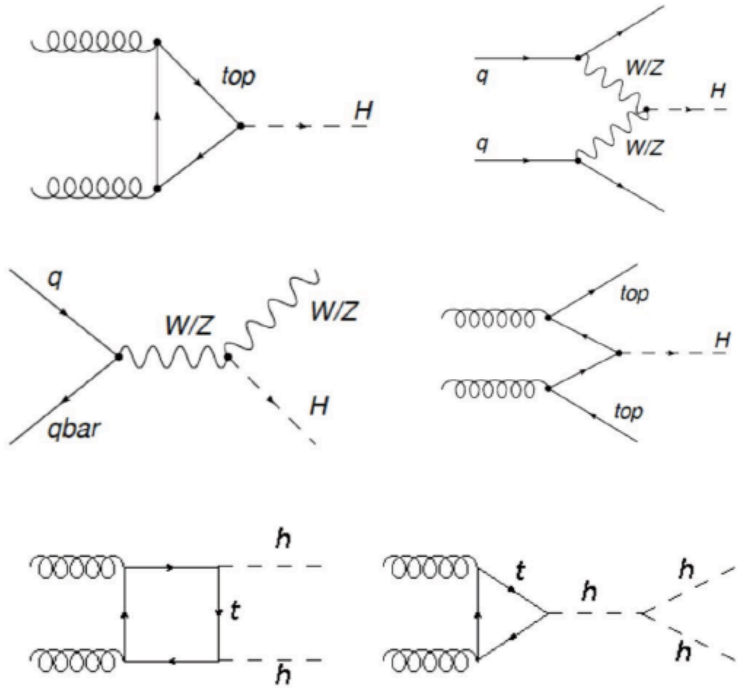
New (possible) schedule for HL-LHC.

LHC producing 150-200 million Higgs.



HL-LHC is a Higgs factory

Higgs bosons at $\sqrt{s}$=14 TeV 3000 fb^{-1}	
HL-LHC total	170 M
VBF (main decays)	13M
ttH (main decays)	1.8M
$H \to Z\gamma$	230k
$H \to \mu\mu$	37k
HH (all)	121k



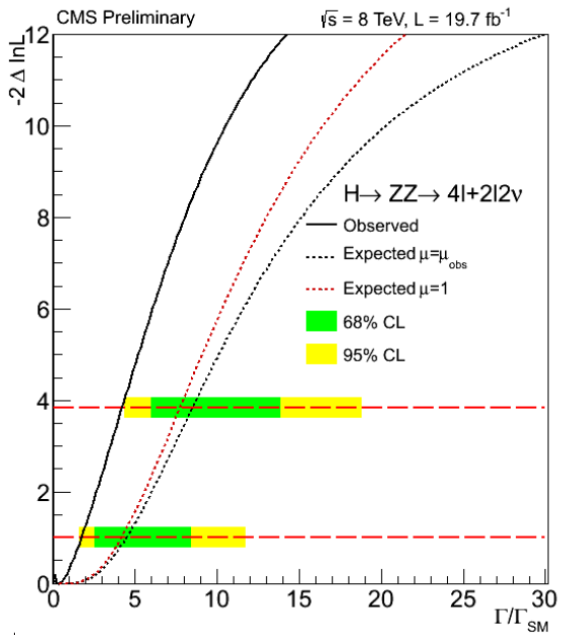
- Higgs physics goals
  - Rare decays and couplings
  - Spin/parity
  - Higgs pair productions

Higgs mass and width at HL-LHC

The large statistics in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ will allow a measurement of m_H challenging the systematics errors. We could also make the best use of VBF and possibly other exclusive channels. Large effort needed on the theory side: 50MeV on Δm_H corresponds to 0.5% uncertainty on the BR measurement.

Expectations for Δm_H@3000fb^{-1}: 15MeV(stat)±25MeV(syst).

It could be challenged only by a dedicated lepton Collider.



For the measurement of the width we'll continue using the powerful constraints from the off-shell Higgs.

The high statistics will bring sensitivity on the width down to the SM-level: $\Gamma_H=4.2^{+1.5}_{-2.1}$ MeV.

An independent handle to check for significant anomalous BR.

Observe rare/difficult decays with 3000fb^{-1}

- **ttH**

  Signal observation 7-8σ in single decay modes (i.e. ttH($\gamma\gamma$)); projected sensitivity on k_{top}~10%.

- **H→$\mu\mu$**

  Signal observation >7σ; 10-15% precision on the signal strength. Measure the coupling the second lepton generation.

- **H→invisible**

  Using ZH→ll+high missing E_T

  BR(H→$\chi\chi$)<6-17% at 95%CL.

$H \rightarrow Z\gamma$

- γZ like $\gamma\gamma$ and gg loop induced, but sensitive to effects invisible in $\gamma\gamma$ and gg (because of chiral couplings)

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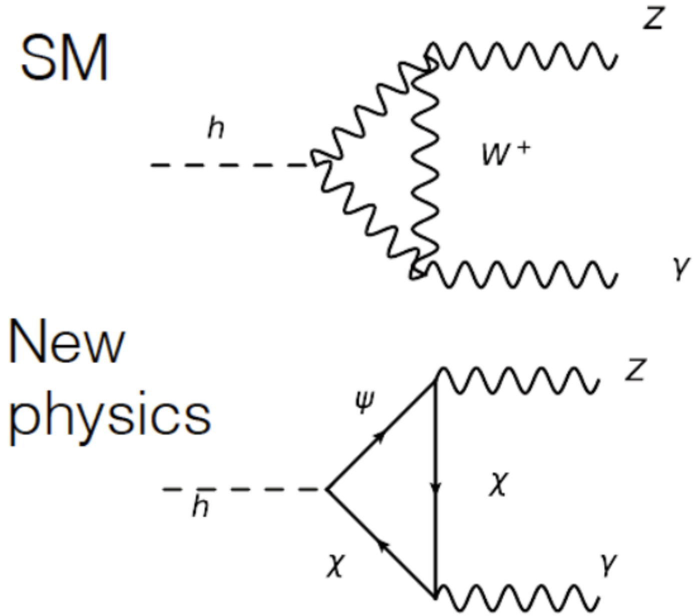
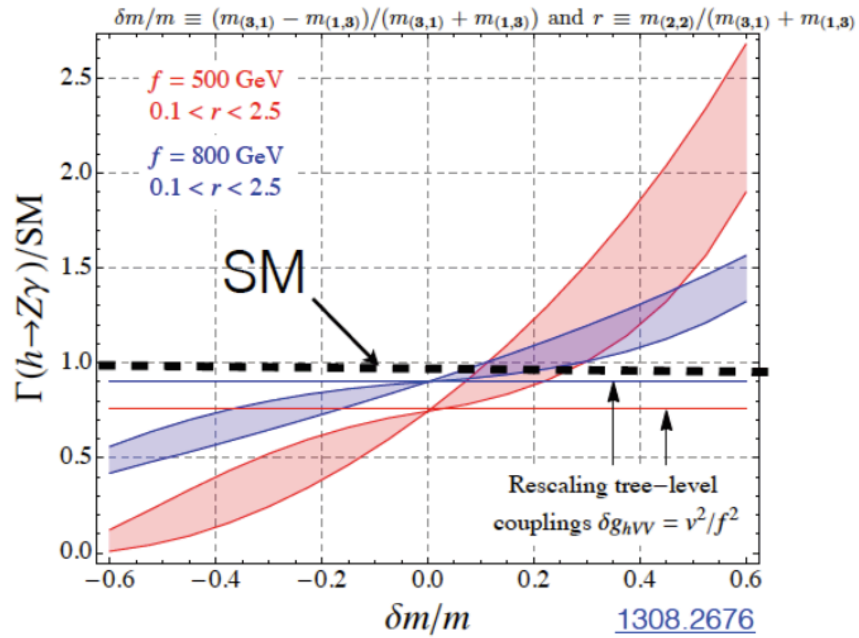
- In composite Higgs: Not protected by Goldstone symmetry, large γZ while $\gamma\gamma$ and gg small





At HL-LHC signal observation ~4σ; 20-25% precision on the signal strength.

H→cc?

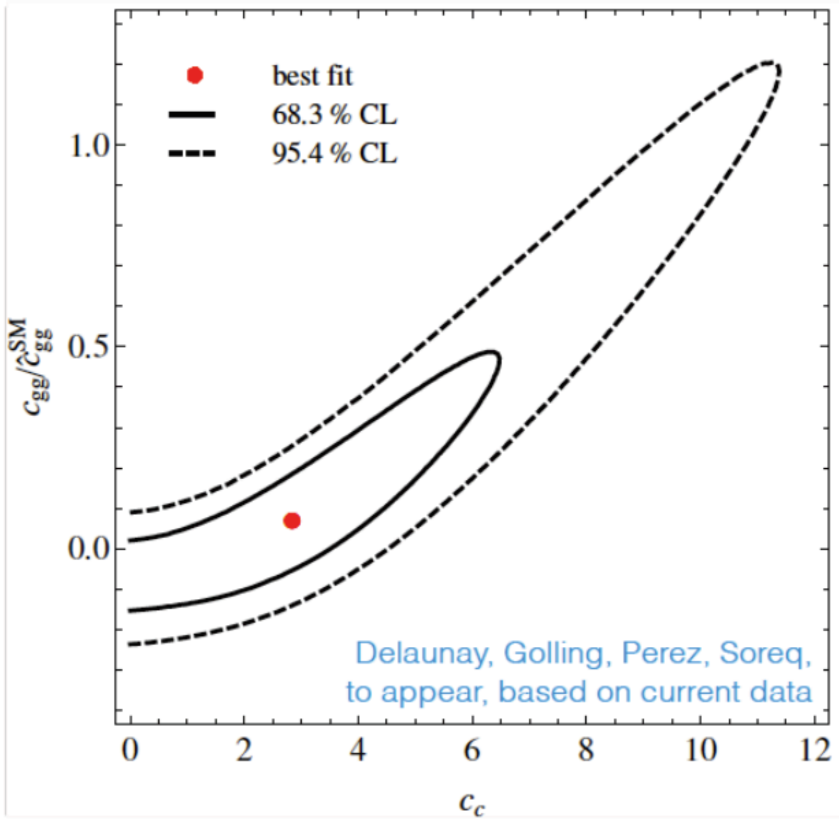
- Hcc coupling can still be 4-8 x SM

$$\mathcal{L} = c_c \, h \frac{m_c}{v} \bar{c}c + \ldots$$

- In composite Higgs

$$c_c \simeq 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\epsilon_c^2 \frac{g_\psi^2 v^2}{m_\psi^2}\right)$$

large for composite charm and light charm partners



Measuring it?

Like H→bb, but with charm tagging?

Or via H→ J/ψ γ ? 1306.5770

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What precision is necessary on the couplings?

- SM couplings can be modified by new physics entering the loops.
- Typical effect on the couplings from a heavy particle M or new physics at scale M.

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2$$

- For new physics at the ~1TeV mass scale →Δ~5%

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

- Higher scales imply smaller effects

arXiv:1310.8361

Perspectives for LHC13 and Run2

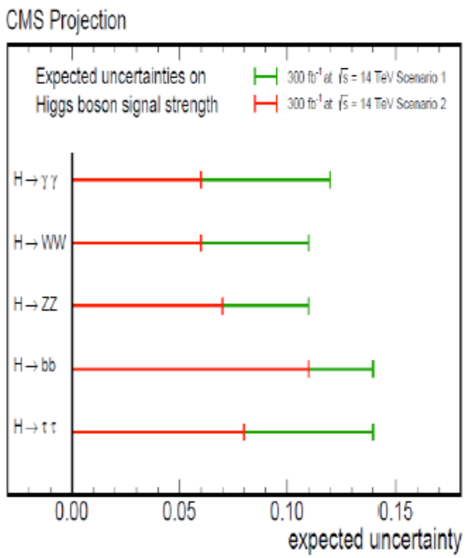
arXiv:1307.7135

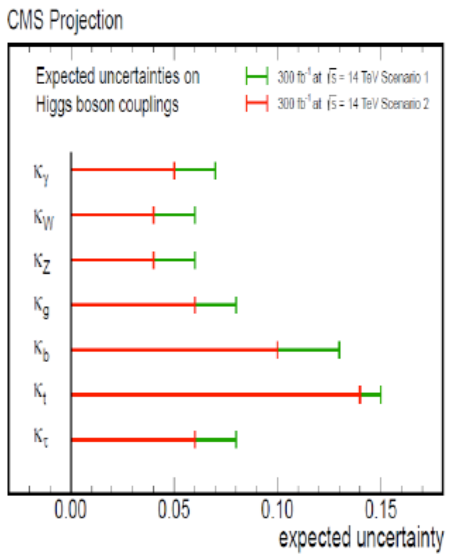
process	σ[pb] 8 TeV	σ[pb] 13 TeV	ratio
ggF	19.3	43.9	2.3
VBF	1.58	3.75	2.4
WH	0.705	1.38	2.0
ZH	0.415	0.870	2.1
ttH	0.129	0.509	3.9
bbH	0.204	0.512	2.5

Expected precision with L=300 fb^{-1}:

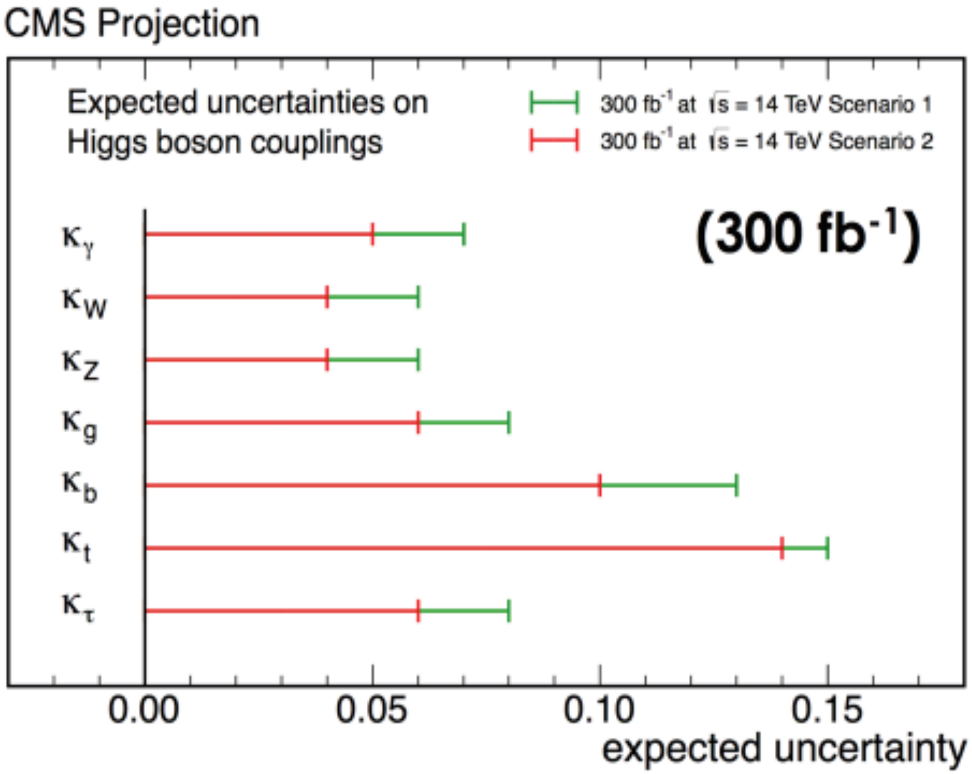
- 6% -14% in signal strength for individual channels.
- 5% in couplings to gauge bosons, 10% in couplings to fermions.
- 10%-20% sensitivity to CP-odd admixtures to scalar Higgs.

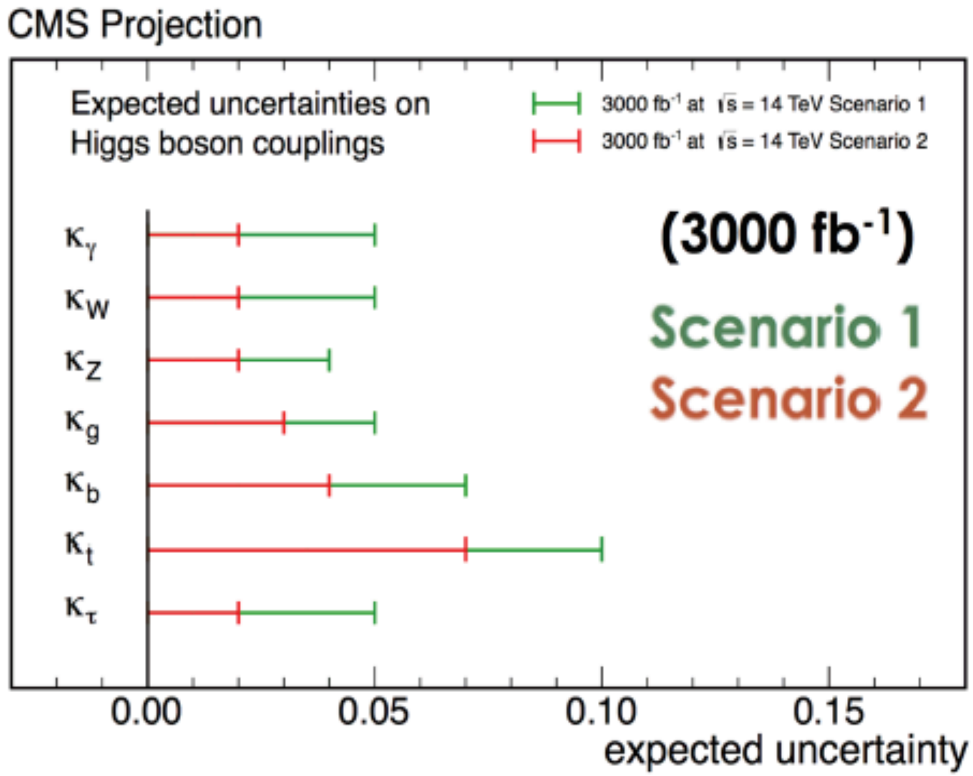
- With L=300 fb^{-1} and 13 TeV colision energy about 15 million Higgs will be produced (LHC Run II → Higgs Factory).
- High precision measurements of Higgs properties are very important to look for deviations from SM implying new physics.





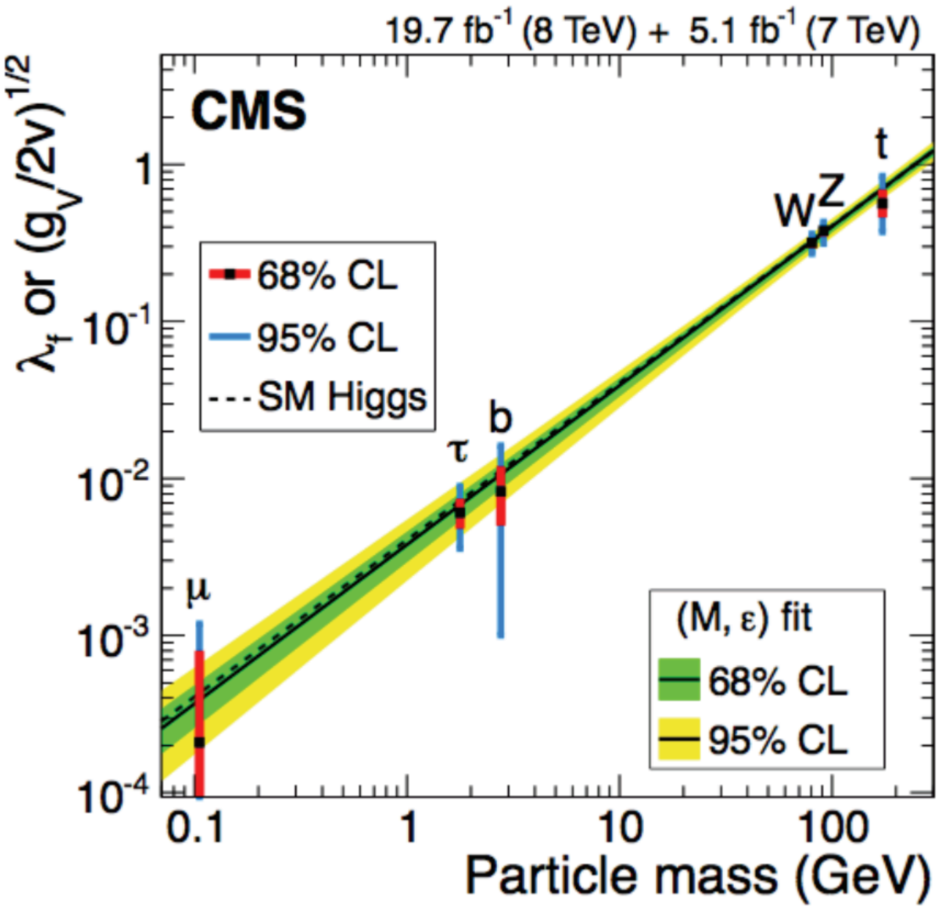
Perspectives on the couplings

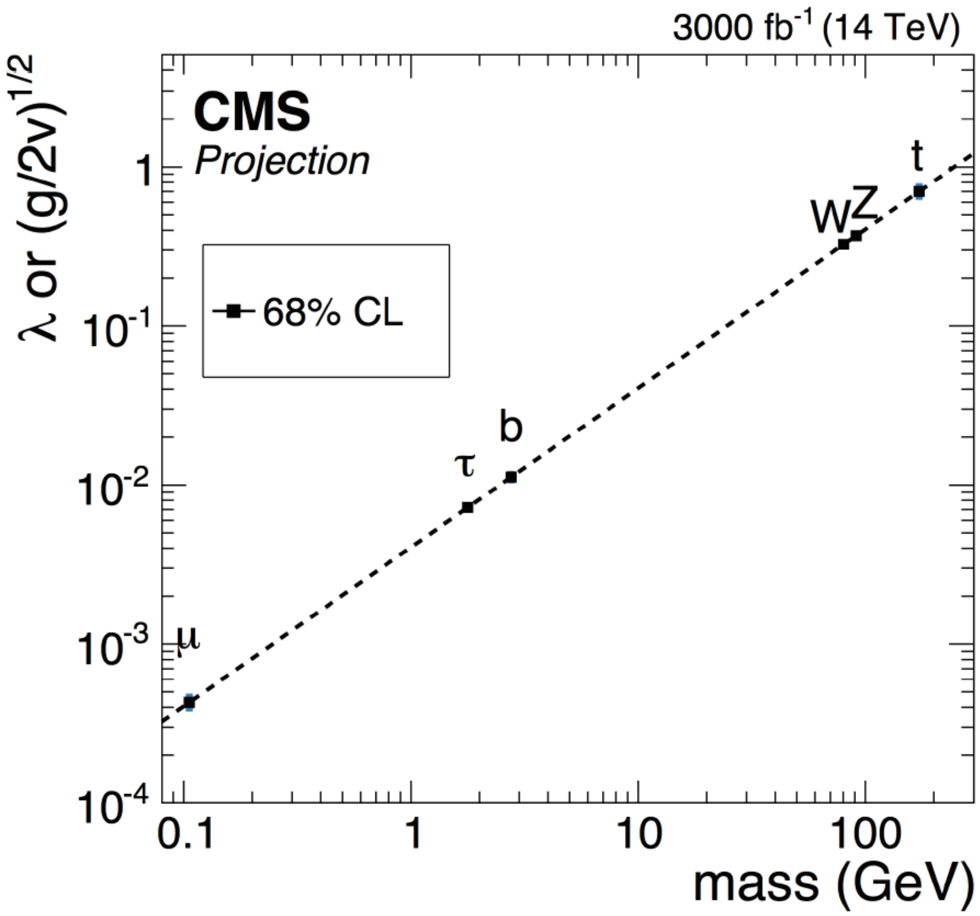




Allowing new physics entering the loops: ultimate precision 2-10%.

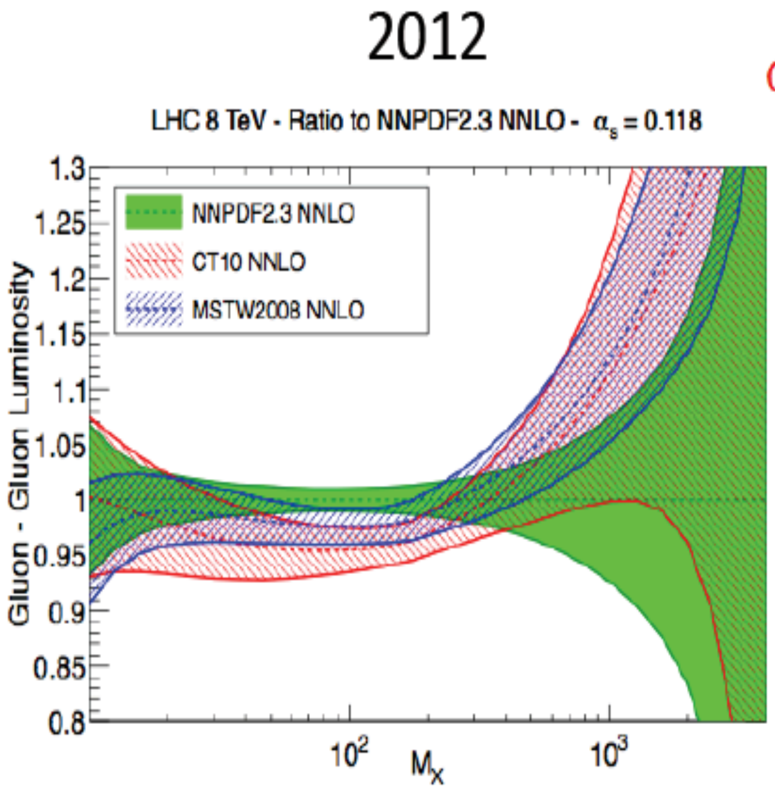
Perspectives on the couplings



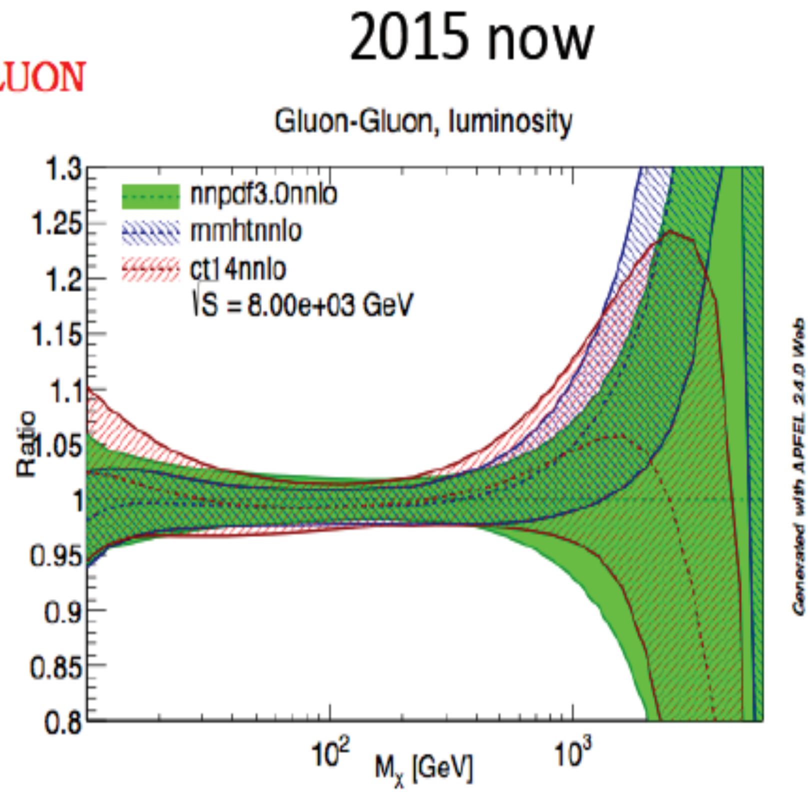


Allowing no new physics: percent level precision for most of the couplings

Recent improvements in PDFs.



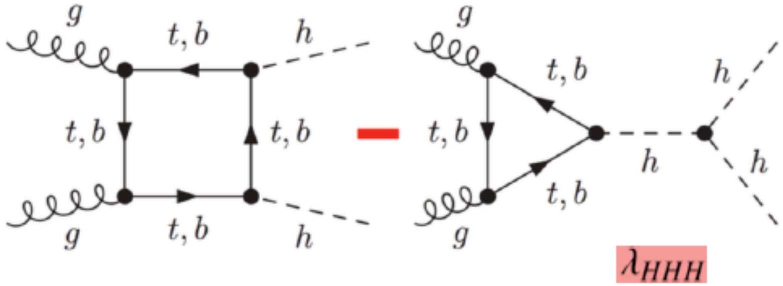
GLUON-GLUON

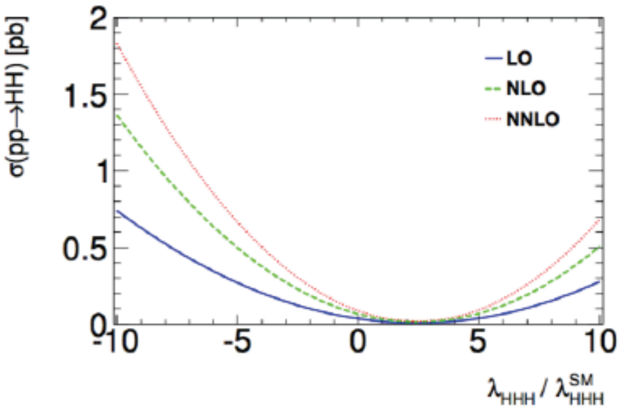


For 125 GeV ggH, PDF uncertainty decreases from 7% → 3%

H self-coupling: HH production

- Probe Higgs self-interaction
  - crucial to test the Higgs sector to its full extent
  - primary channel to extract information on the Higgs potential → structure of the EWK Phase Transition
- Two interfering diagrams (destructive)



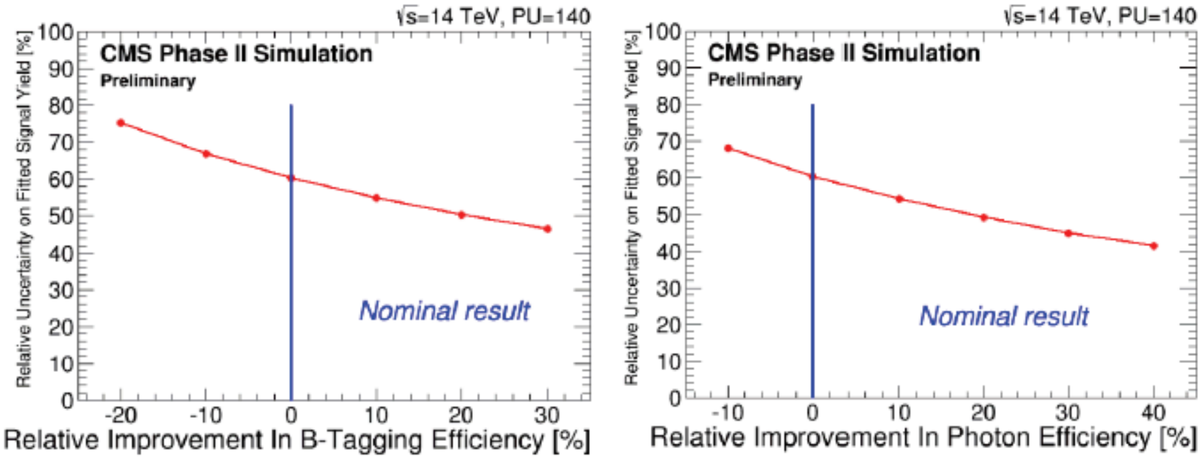


- SM cross section @ 14 TeV: 40.8 fb (NNLO)

~10^5 HH events produced with 3000fb^{-1} at HL-LHC
……but very large background (or tiny BR).

HH→bbγγ

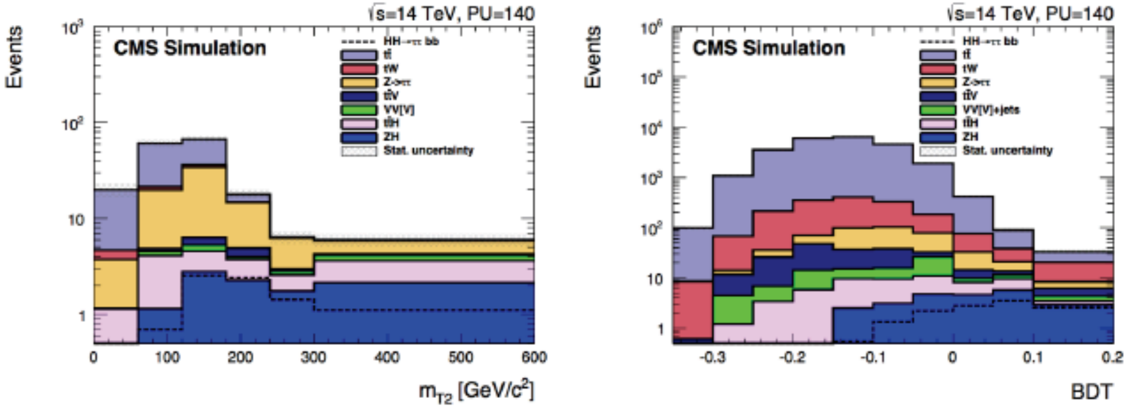
- Branching ratio only 0.26%, total yield 320 events for 3000 fb^{-1}
- Much larger resonant and non-resonant backgrounds



- Both experiments expect 8-9 events after event selections corresponding to ~1.3 σ per experiment
- CMS also evaluated the impact on the sensitivity as the B-tagging/photon efficiencies change

HH→bbττ

- Branching ratio 7.3%, total yield 8900 events for 3000 fb^{-1}
- Much larger resonant and non-resonant backgrounds
- CMS studied it in $\tau_\mu\tau_h$ and $\tau_h\tau_h$ final states, expects a combined bbττ significance 0.9 σ



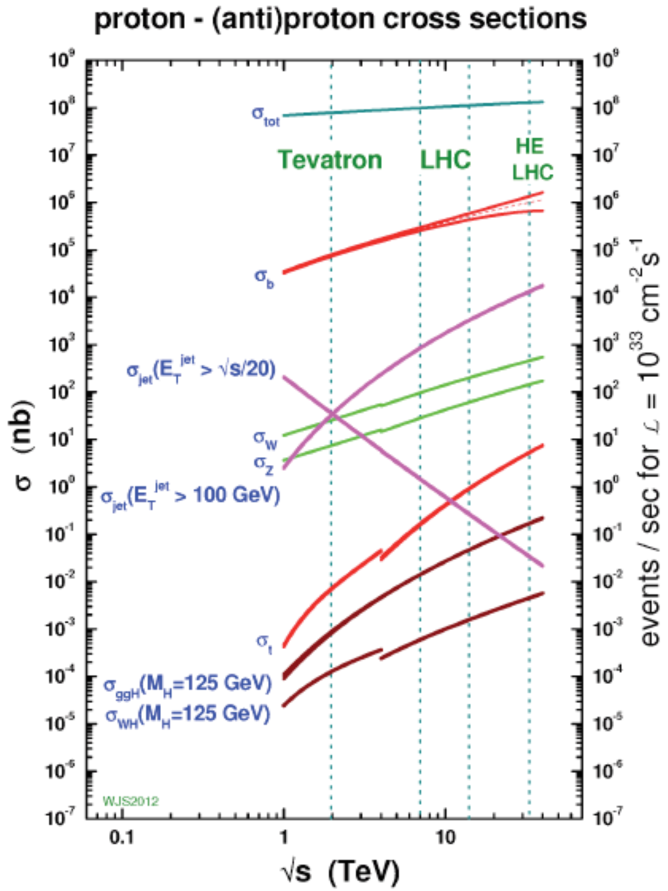
- 1.9 σ expected by combing bbγγ and bbττ, with an uncertainty 54% on signal strength
- Significant improvements are expected by adding more channels and using MVA techniques

Higgs-pair production

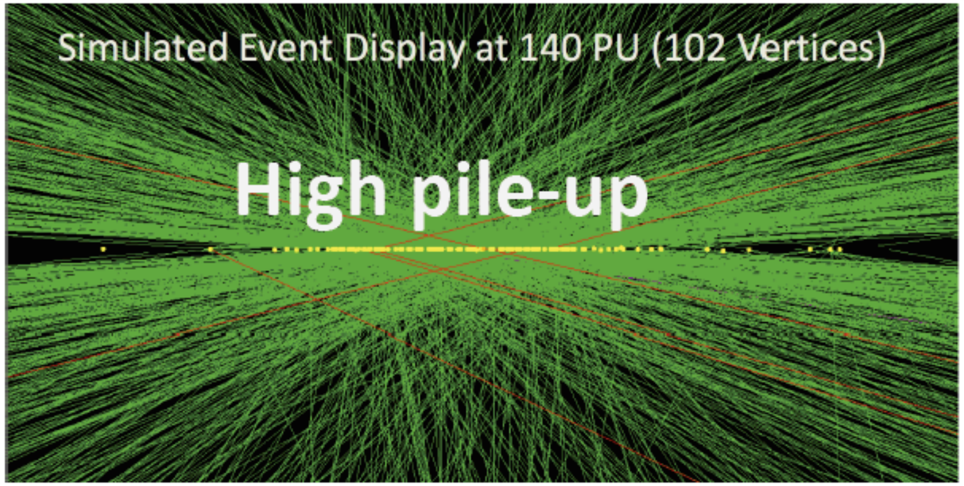
- It could be a flagship channel for HL-LHC
  - $bb\gamma\gamma$ established channel
  - bbWW looks very difficult (~10^4 events but very large background)
  - $bb\tau\tau$ seems more promising
  - $bb2l2\nu$ could be interesting (~700 events)
  - bbbb?!?!
  - others?!?!
- With reasonable extrapolations one would expect to reach 3σ per experiment.

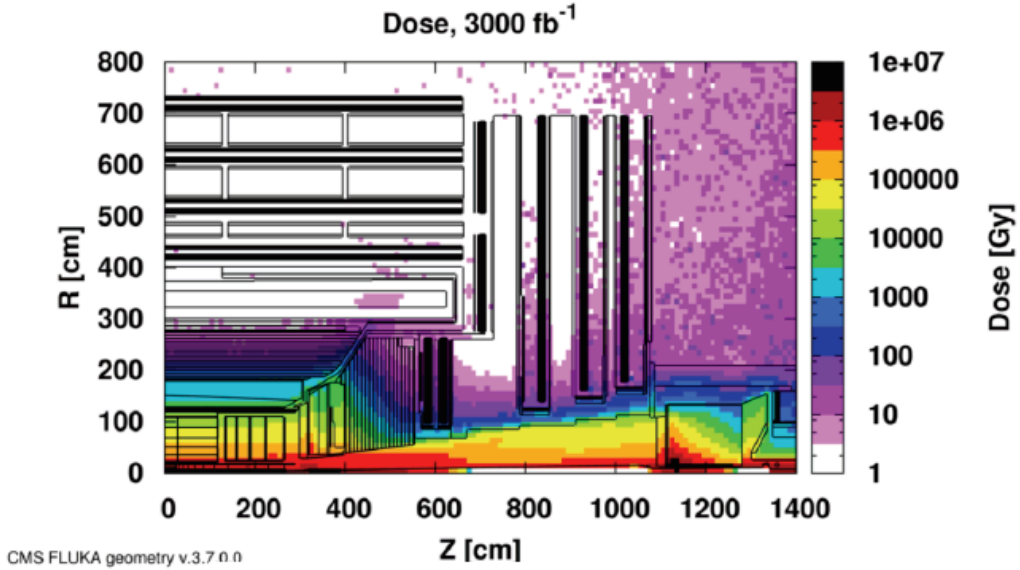
Plenty of room for new ideas

Some of the challenges



Trigger in a high lumi environment





High radiation level

Conclusion

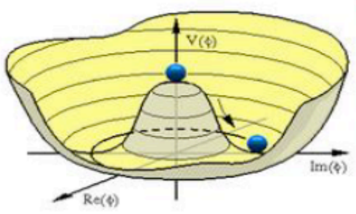
- The discovery of the Higgs boson has opened a new era in physics.
- From now on the hunt for physics beyond the standard model will proceed along two deeply connected lines of research:
  - a) direct searches based on the study of collisions at the largest possible energy
  - b) indirect searches based on precision measurement of the Higgs properties and couplings
- While we'll continue looking for new particles and new interactions at LHC, we have already entered the era of Higgs precision measurements.
- New measurements and further improvements in the precision study of the Higgs sector will be soon produced by the current LHC_13 run.
- Ultimate precision on key parameters for Higgs physics will be achievable only with the full exploitation of HL-LHC.

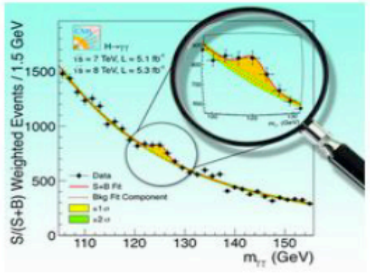
CMS public results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

TWiki > CMSPublic Web > PhysicsResults > PhysicsResultsHIG (2015-07-27,

CMS Higgs Physics Results

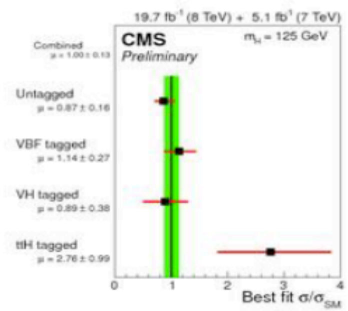




Preliminary Results

Publications

Highlights



Values of the best-fit σ/σSM for the combination (solid vertical line) and for subcombinations by analysis tags targeting individual production mechanisms: png

Compact Muon Solenoid
LHC, CERN

Higgs Physics Publications

Higgs Physics Publications
- Legacy Papers
- The 125-GeV Higgs Boson
  - Combinations
  - Mass
  - Couplings
  - Spin/Parity
  - Width
- Decay Modes
  - Vector Bosons
  - WW
  - ZZ
  - $\gamma\gamma$
  - $Z\gamma$
  - Fermions
  - $\tau\tau$
  - $\mu\mu$ and ee
  - bb
  - Invisible
  - Lepton Flavour Violating
- Rare Production Modes
  - VBF
  - VH
  - ttH
- Searches
  - Supersymmetry
  - Exotica
  - Charged Higgs Bosons
- Results with Partial Data
  - 7 TeV Data
  - 7 and 8 TeV Data
  - 8 TeV Data
- Recent Preliminary Results in the Higgs Physics Group