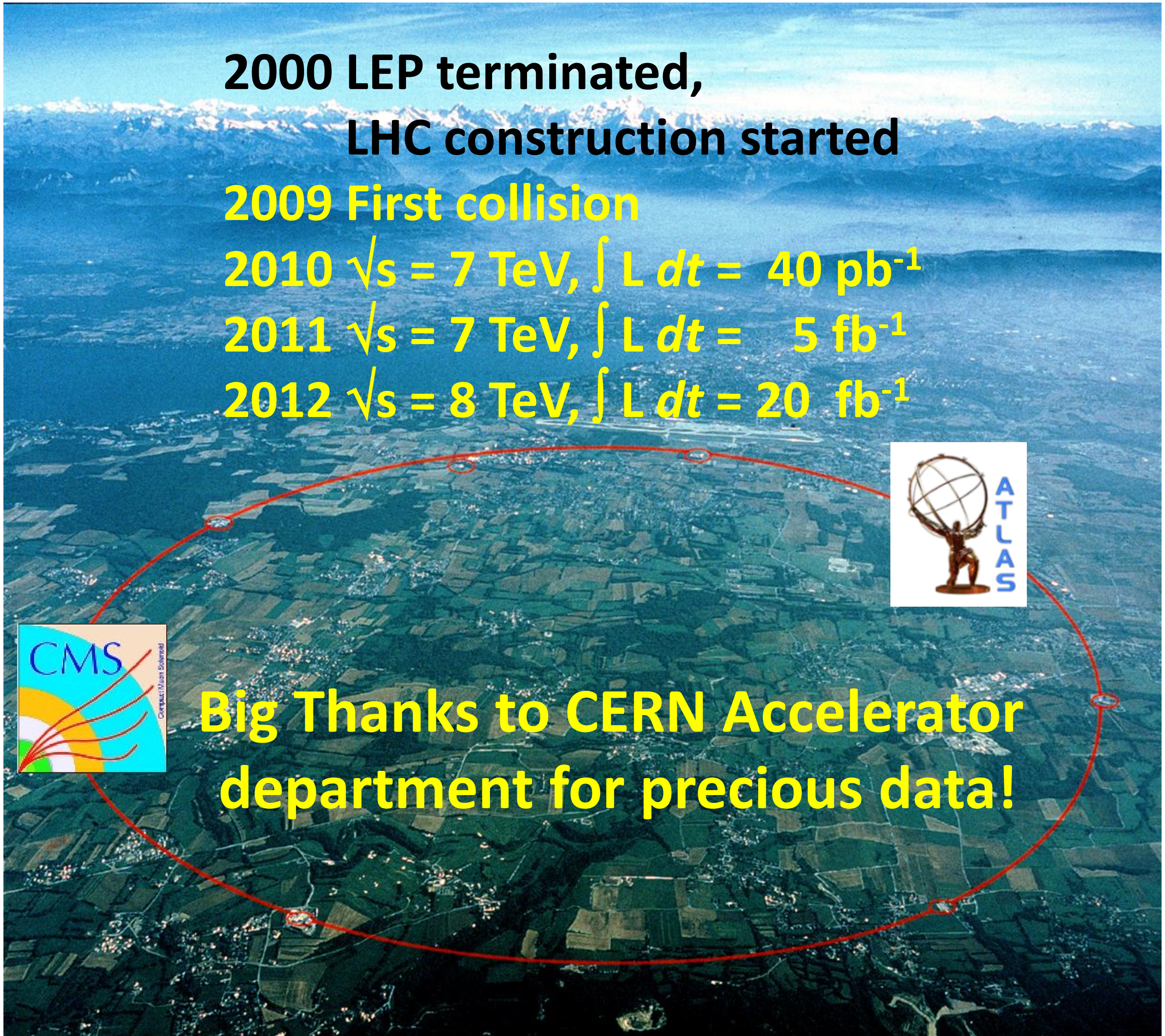
LHC results and prospects
Higgs and other SM studies

On behalf of
ATLAS and CMS collaborations
Yuji Enari
ICEPP, the Tokyo University

LEP to LHC for Higgs search



2000 LEP terminated,
LHC construction started

2009 First collision

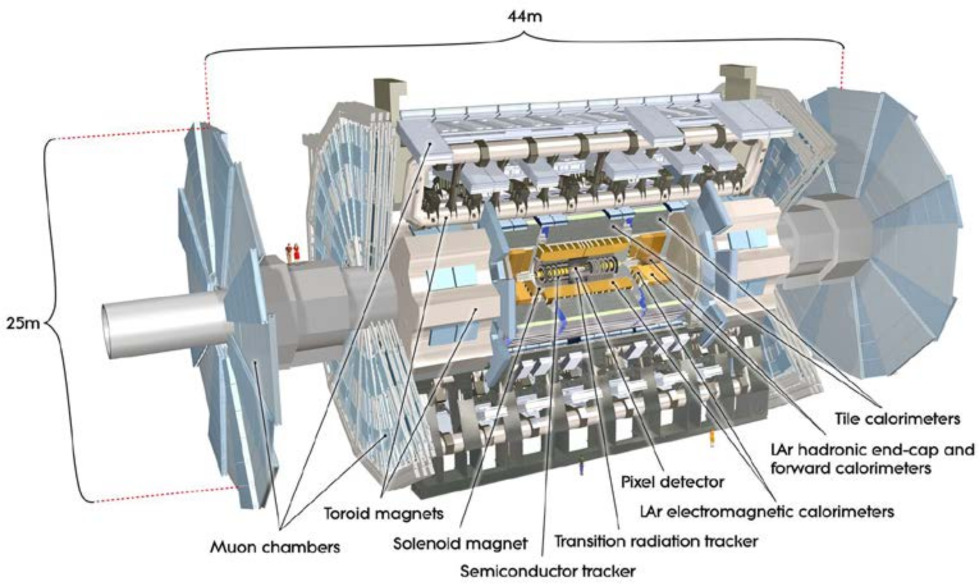
2010 $\sqrt{s}$ = 7 TeV, $\int L\, dt$ = 40 pb^{-1}

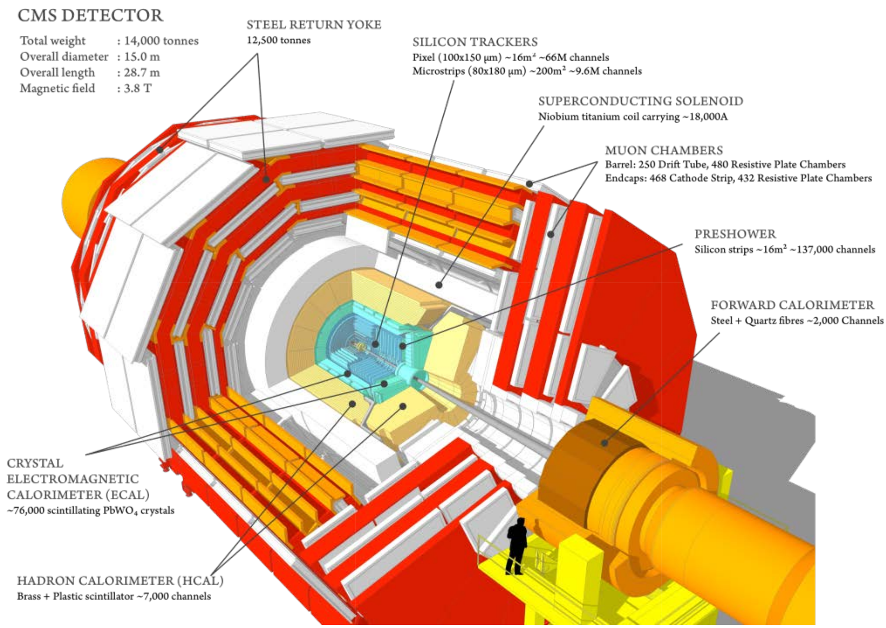
2011 $\sqrt{s}$ = 7 TeV, $\int L\, dt$ = 5 fb^{-1}

2012 $\sqrt{s}$ = 8 TeV, $\int L\, dt$ = 20 fb^{-1}

Big Thanks to CERN Accelerator department for precious data!

ATLAS and CMS detector

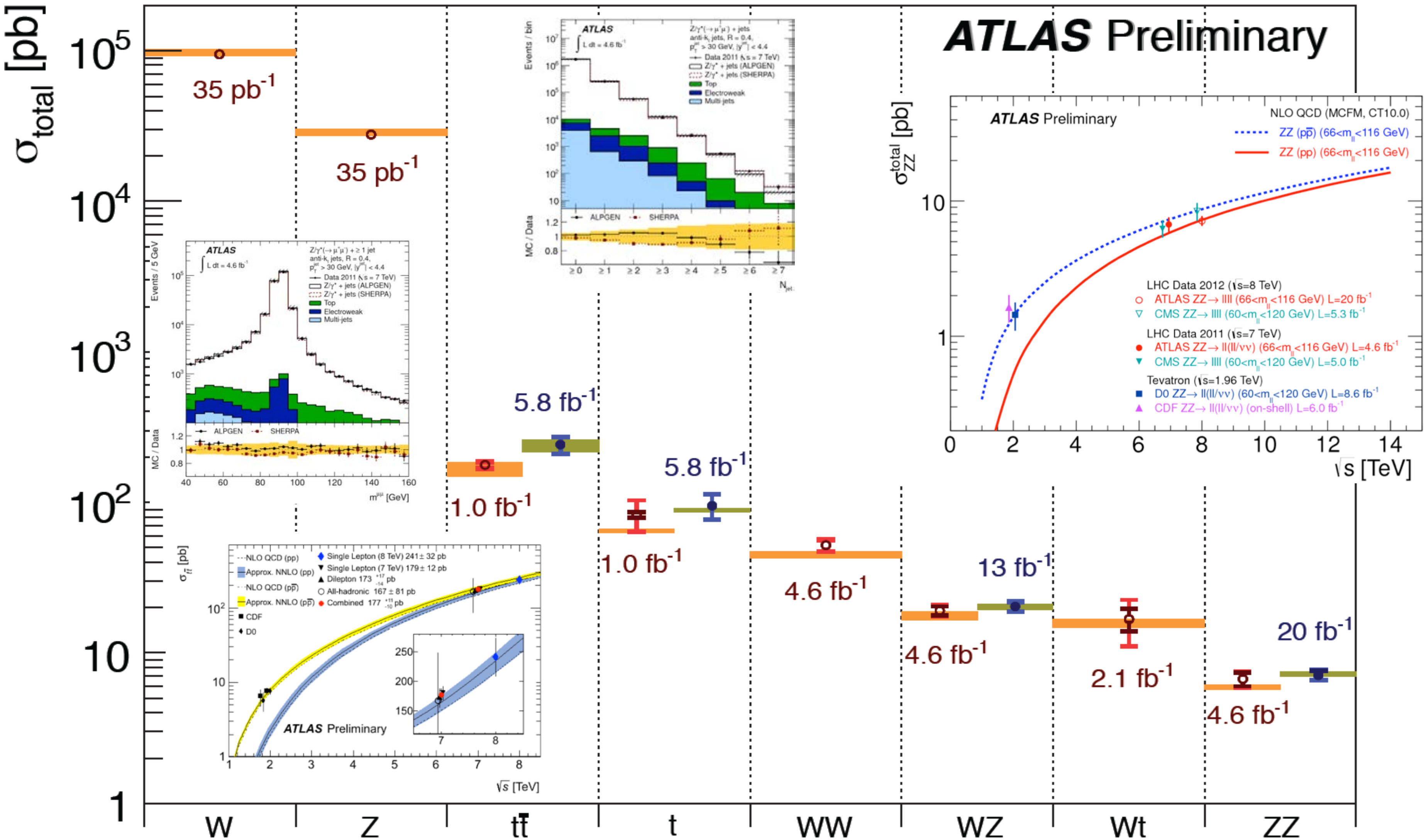




Designed for Higgs discovery and New Physics search

- Excellent vertex and tracking system
- Excellent calorimetry
- Large coverage for muon detection
- Good hermetisity for Missing Et

Road to the discovery

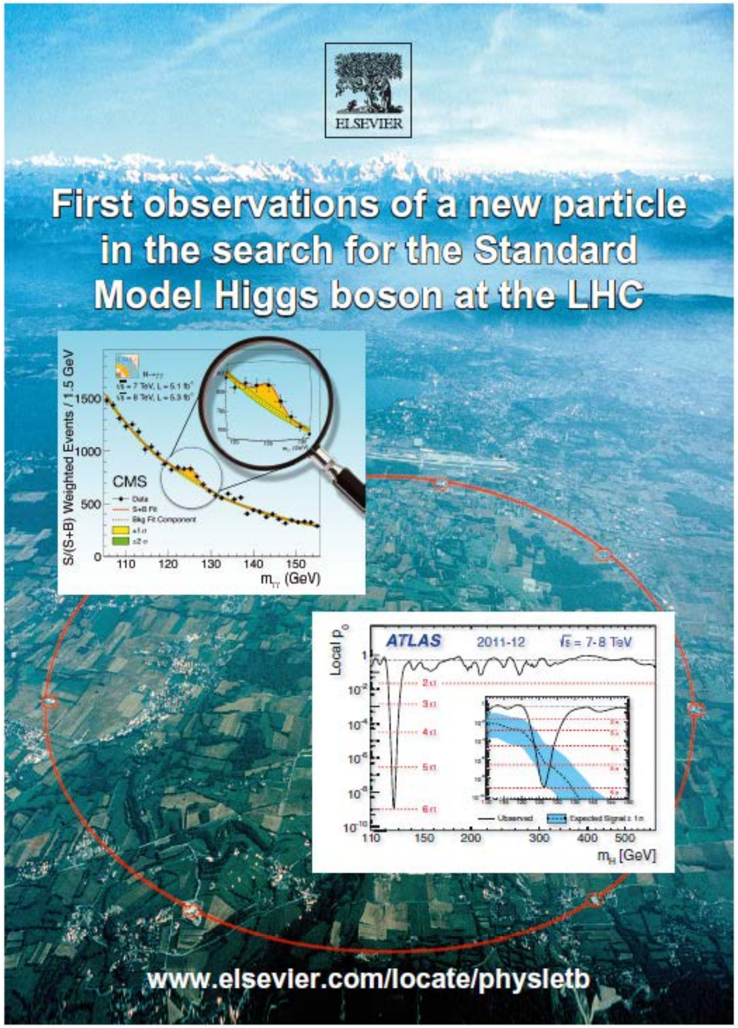


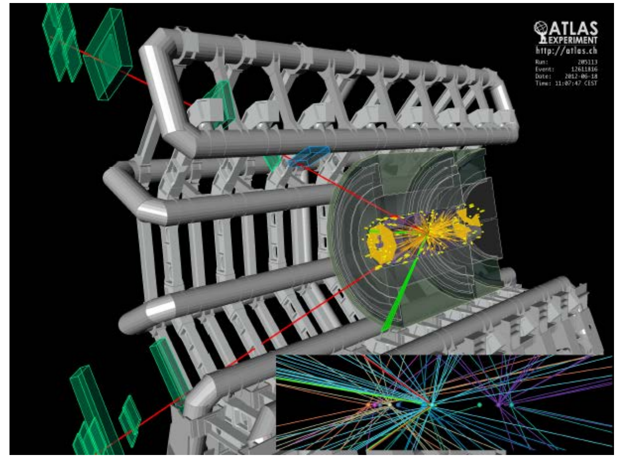
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

Higgs discovery 2012 July



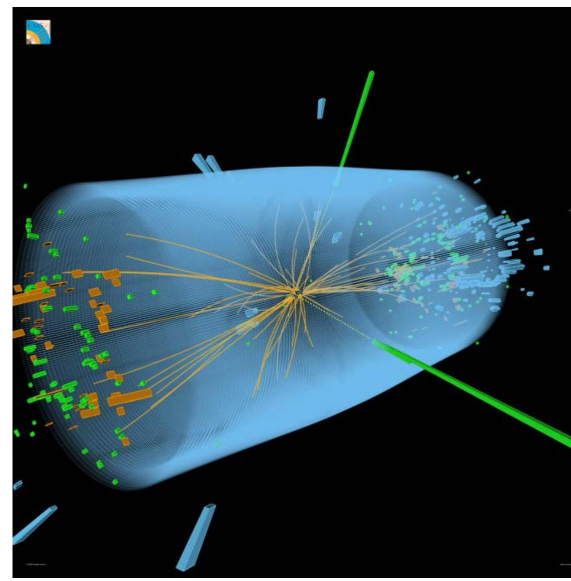


Phys. Lett. B 716 (2012) 1

H→ZZ*→$e^+e^-\mu^+\mu^-$ candidate

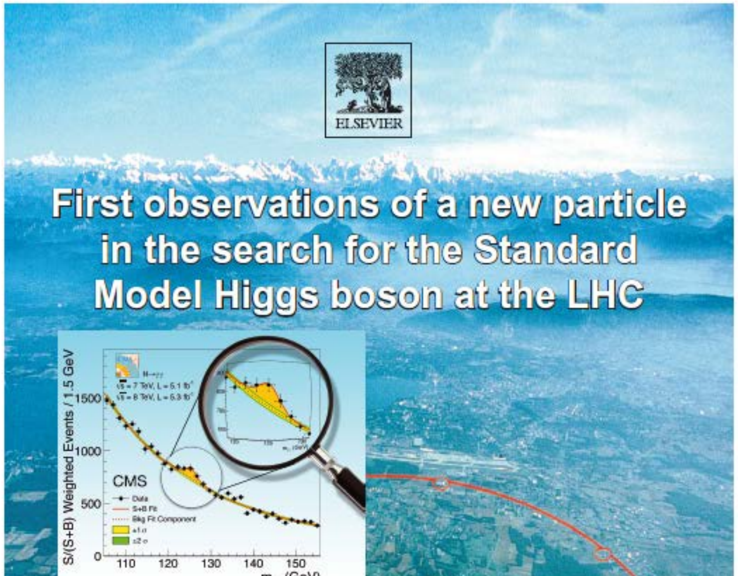
Phys. Lett. B 716 (2012) 30

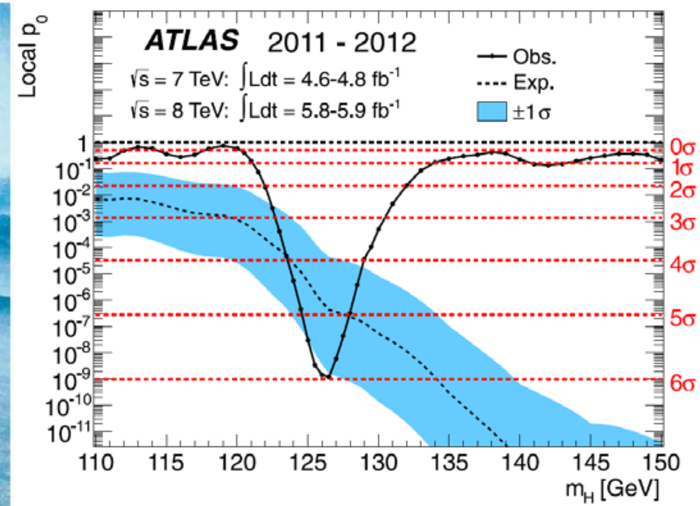
H→$\gamma\gamma$ candidate

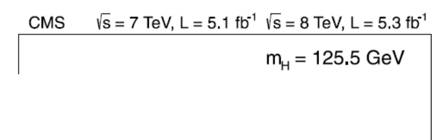


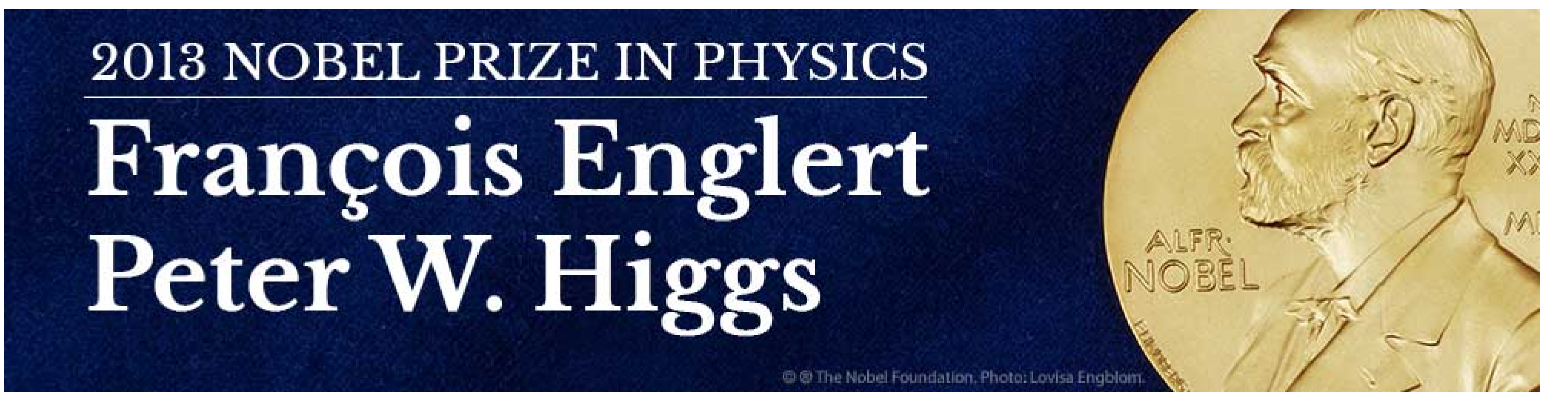
- Observation of Higgs-like resonance at 125.5 GeV
- The rate is compatible with SM.

Higgs discovery 2012.July



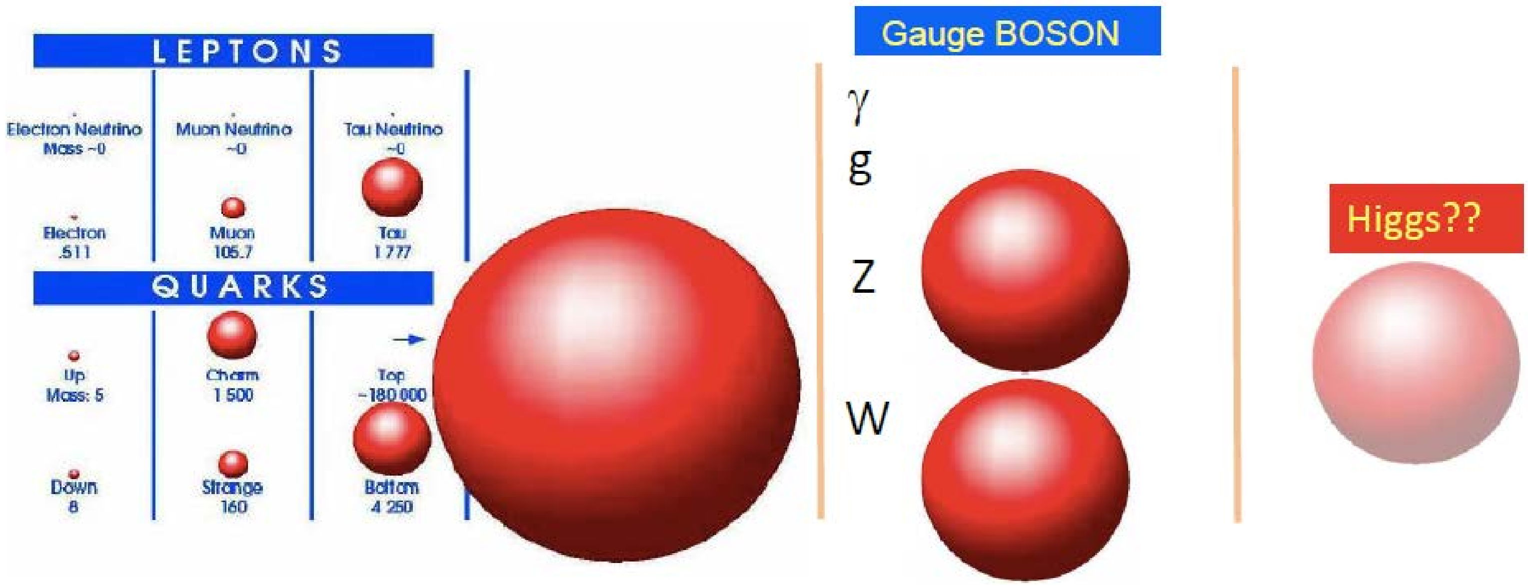






Many congratulations !

Next Era for Higgs sector

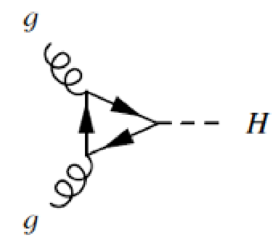


- The discovery : fill last missing piece of SM
- We can describe how particles have mass.
- Next is to proceed precise measurement on
  - Rates and couplings
  - Spin and Parity

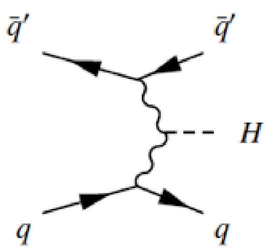
→ Reveal the physics behind or beyond the Standard Model.

Processes (production and decay)

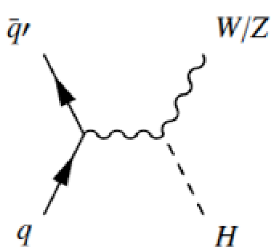
LHC Higgs Xsec WG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



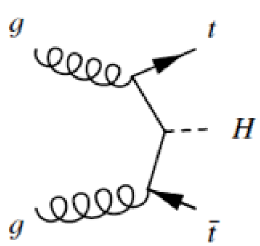
ggF: σ = 19.2 pb



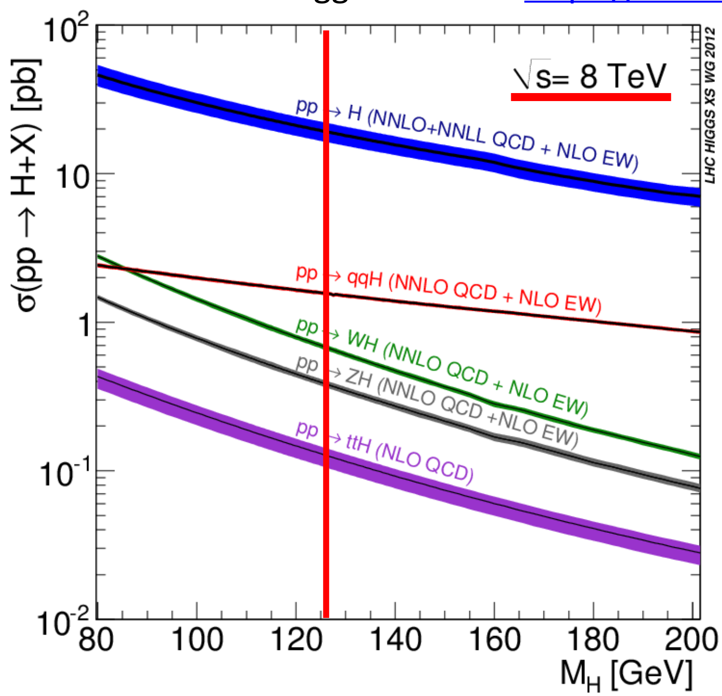
VBF: σ = 1.6 pb

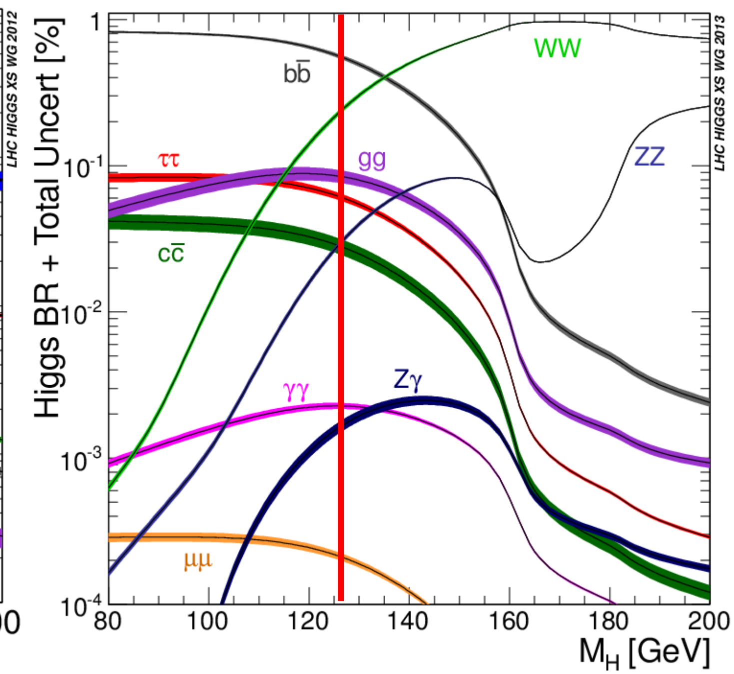


WH: σ = 0.7 pb
ZH: σ = 0.4 pb



ttH: σ = 0.13 pb





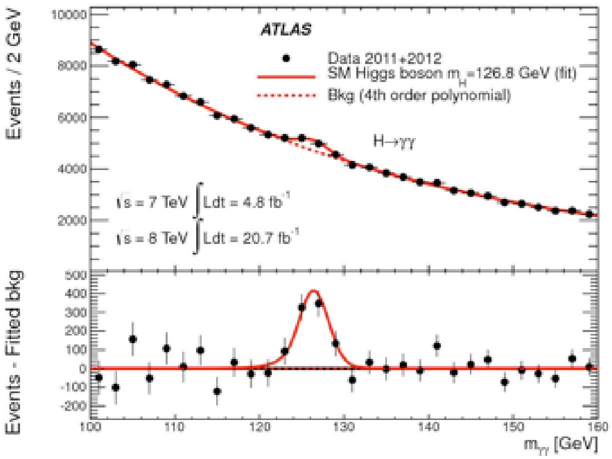
Br(H→WW) : 22% Br(H→bb) : 57%
Br(H→ZZ) : 2.8% Br(H→ττ) : 6.2%
Br(H→γγ) : 0.23%

- Measure possible combinations of production process and decays.
- Events can be categorized by associated objects in order to enhance production process.
- M_H ~ 125 GeV is perfect point for this measurement.

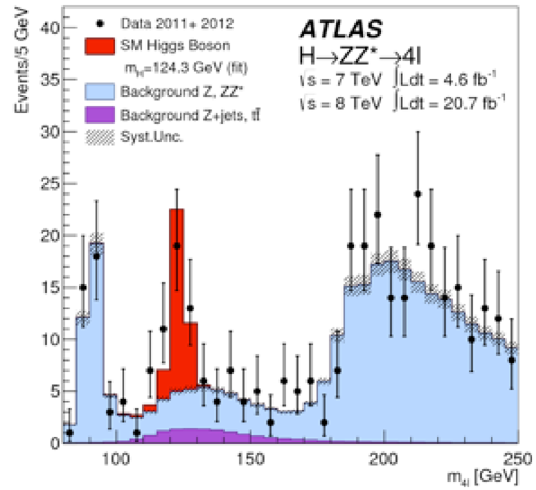
Higgs→bosons

ATLAS

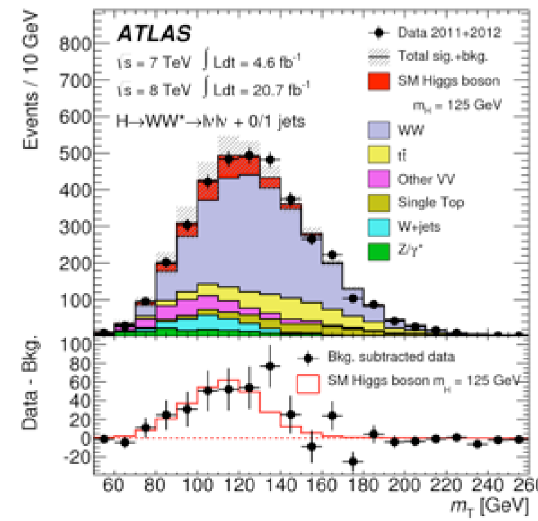
H→ γγ *arXiv:1307.1427*



H→ZZ *arXiv:1307.1427*

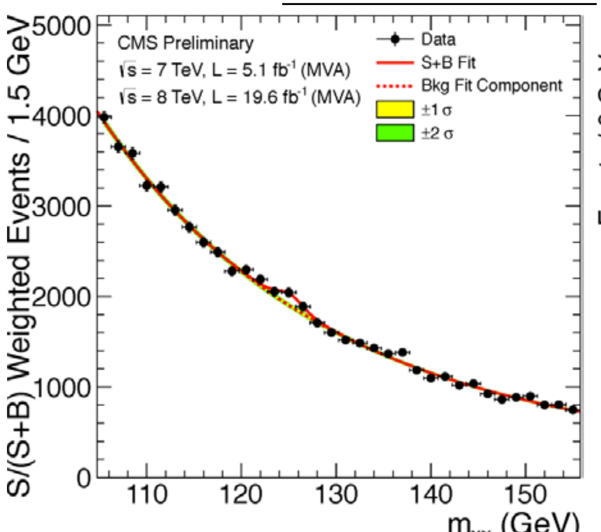


H→WW *arXiv:1307.1427*

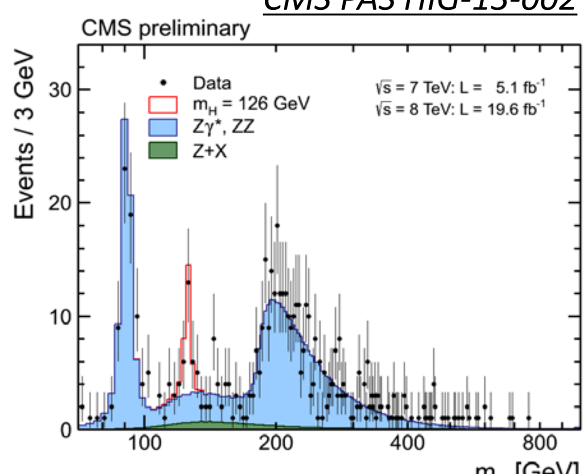


CMS

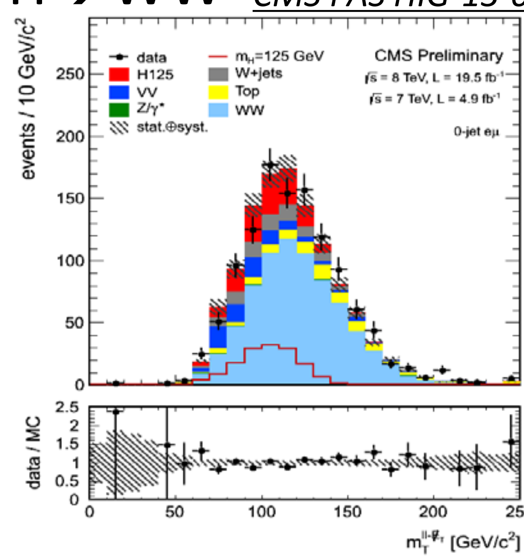
H→ γγ *CMS PAS HIG-13-016*



H→ZZ *CMS PAS HIG-13-002*

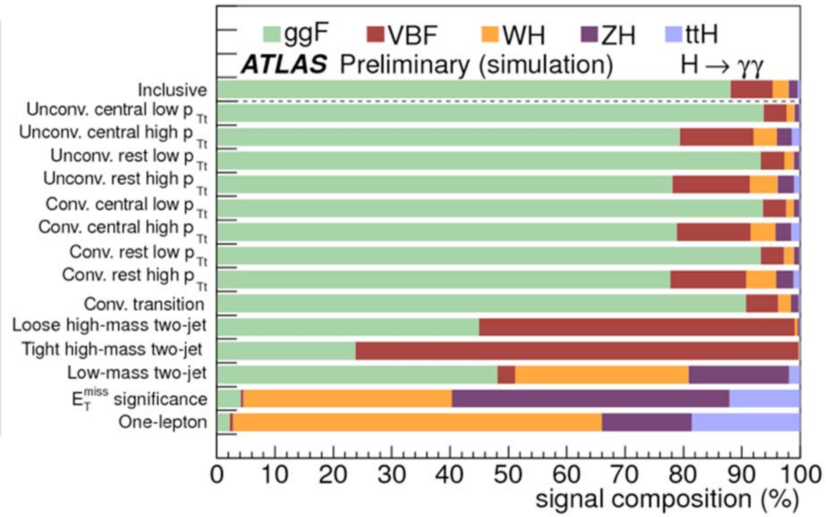


H→WW *CMS PAS HIG-13-003*



Summary on H→bosons

- Split data sample to enhance S/B
  - Detector response, Physics backgrounds
  - **Signal prod. process**
- MVA analysis
  - Both in Object IDs and final analysis.
  - More often used in CMS.



Significance

$\sqrt{S}$ = 7 TeV, 8 TeV
5 fb^{-1} + 20 fb^{-1}

	ATLAS		CMS	
	Obs	Exp	Obs	Exp
H→ γγ	7.4	4.3	3.2	4.2
H→ZZ	6.6	4.4	6.7	7.1
H→WW	3.8	3.8	4.0	5.1

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

μ = 1.30±0.20 (ATLAS) **μ = 0.80±0.14** (CMS)

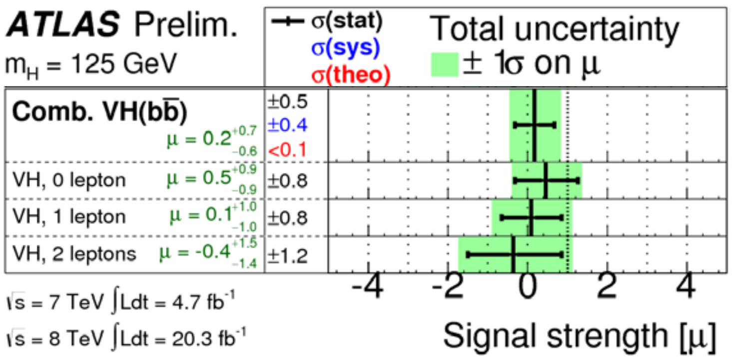
ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{syst}$ GeV
CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}$ GeV

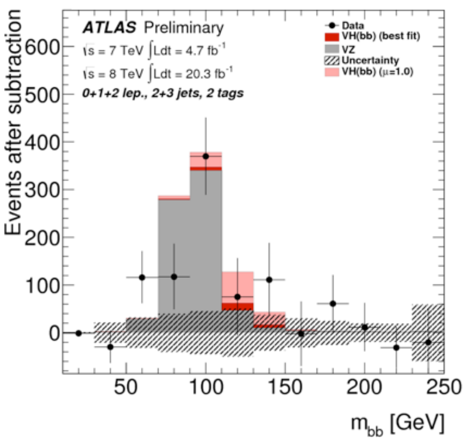
Each observed significance is > 3 σ. Rates are consistent with SM.

Higgs→fermions

- VH, H→bb ATLAS CONF-2013-079 CMS PAS HIG-13-012

V: W→lν, Z→ ll, νν





Analysis verified by Diboson. VZ, Z→bb.

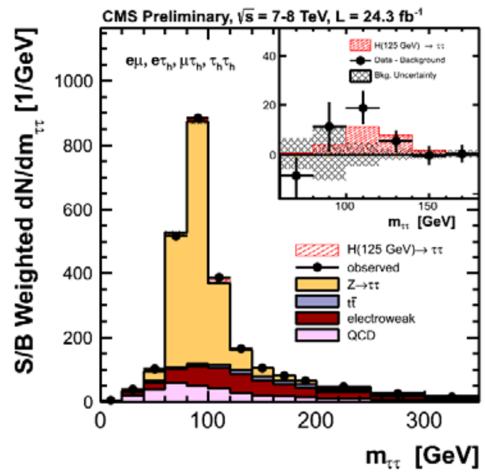
95% CL exp (obs) limit:

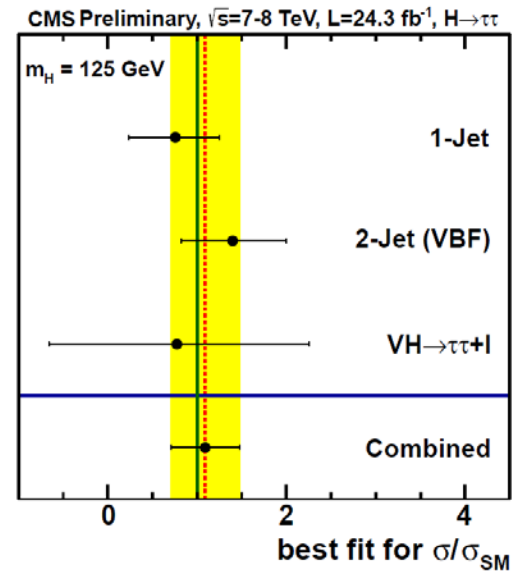
ATLAS: 1.3 (1.4) x SM

CMS: 0.95(1.9) x SM

→ 2 σ sensitivity

- H→ττ CMS-PAS-HIG-13-004





Three analyses

- lepton-lepton
- lepton-hadron
- hadron-hadron

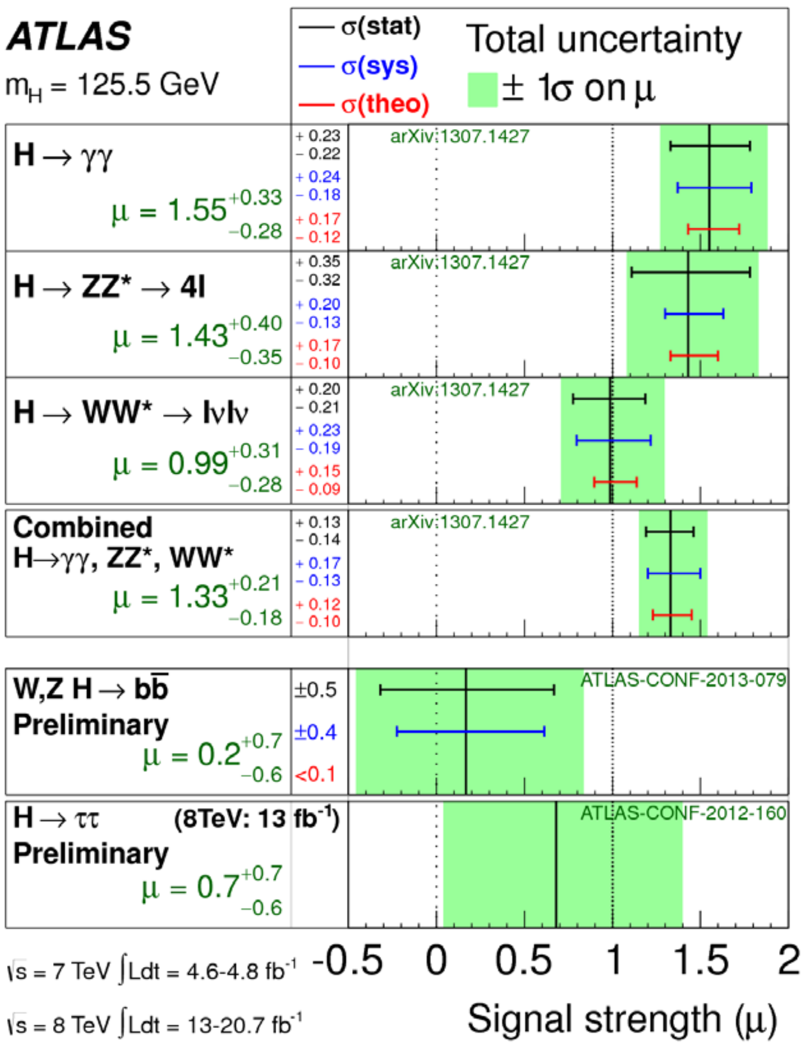
Categorized by ggF, VBF, WH

CMS observed **μ = 1.1 ± 0.4**

→ Significance of 2.93

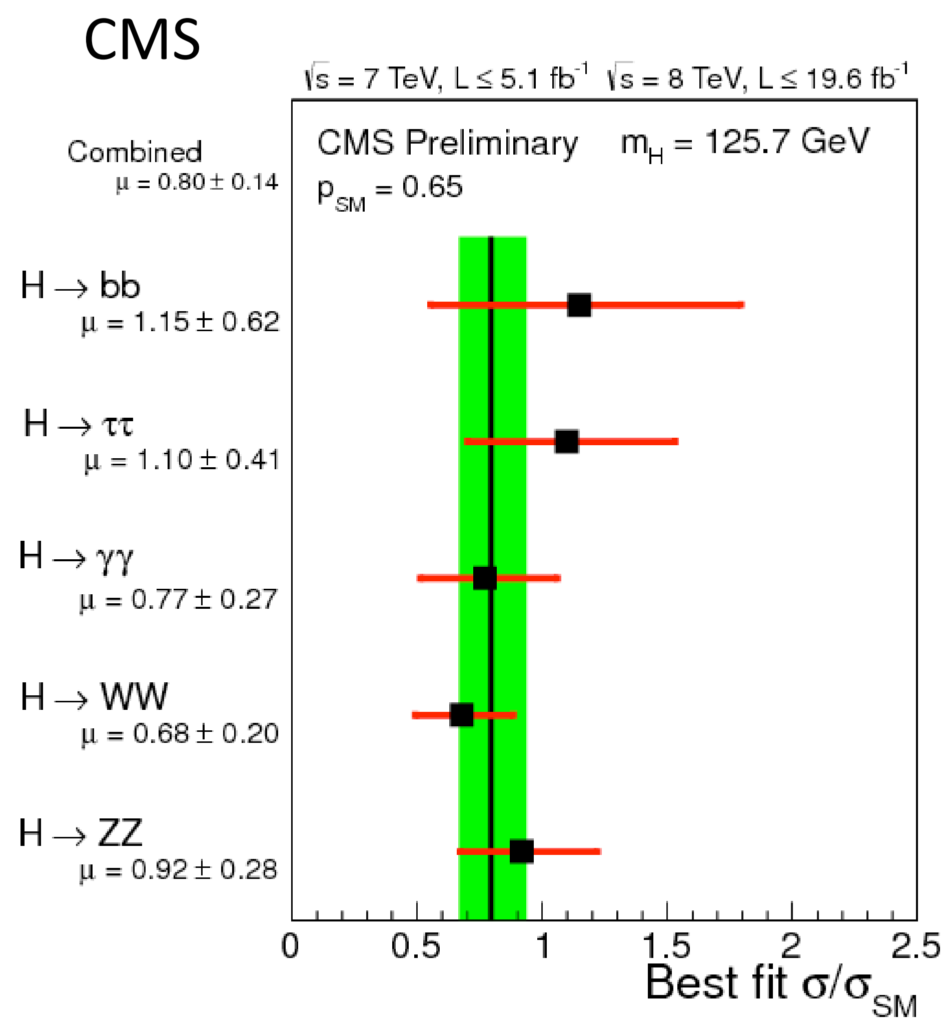
ATLAS: full data set analysis coming.

Signal strength: probe production rate



$$\mu = 1.33 \, ^{+0.21}_{-0.18}$$

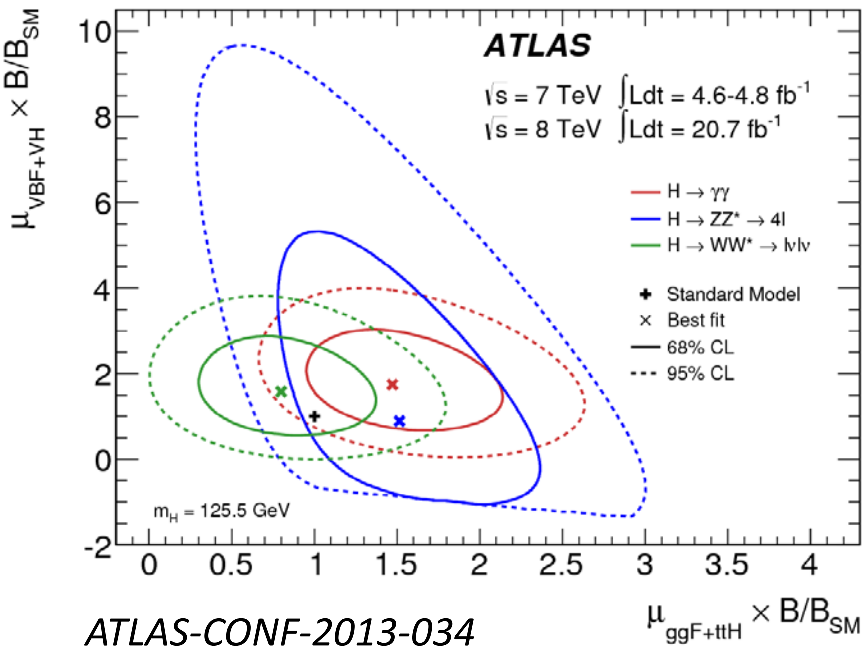
arXiv:1307.1427v1



$$\mu = 0.80 \pm 0.14$$

CMS-PASC-HMISG-P-A13S--H00I

Signal strength: probe production rate



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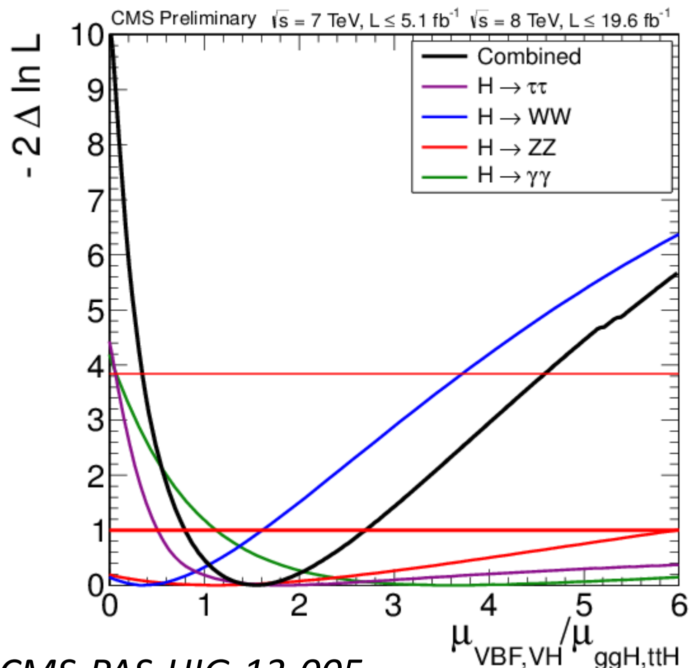


CMS-PAS-HIG-13-005

$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3}\,(\text{stat})^{+0.6}_{-0.4}\,(\text{syst})$$

→ Significance: 3.3 σ

$$\frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.54\,^{+1.16}_{-0.74}$$

→ Significance: 3.2 σ

Evidence of VBF Higgs production.

- ggF well established, evidence for VBF
- Indication of VH, what about is ttH?

ttH production

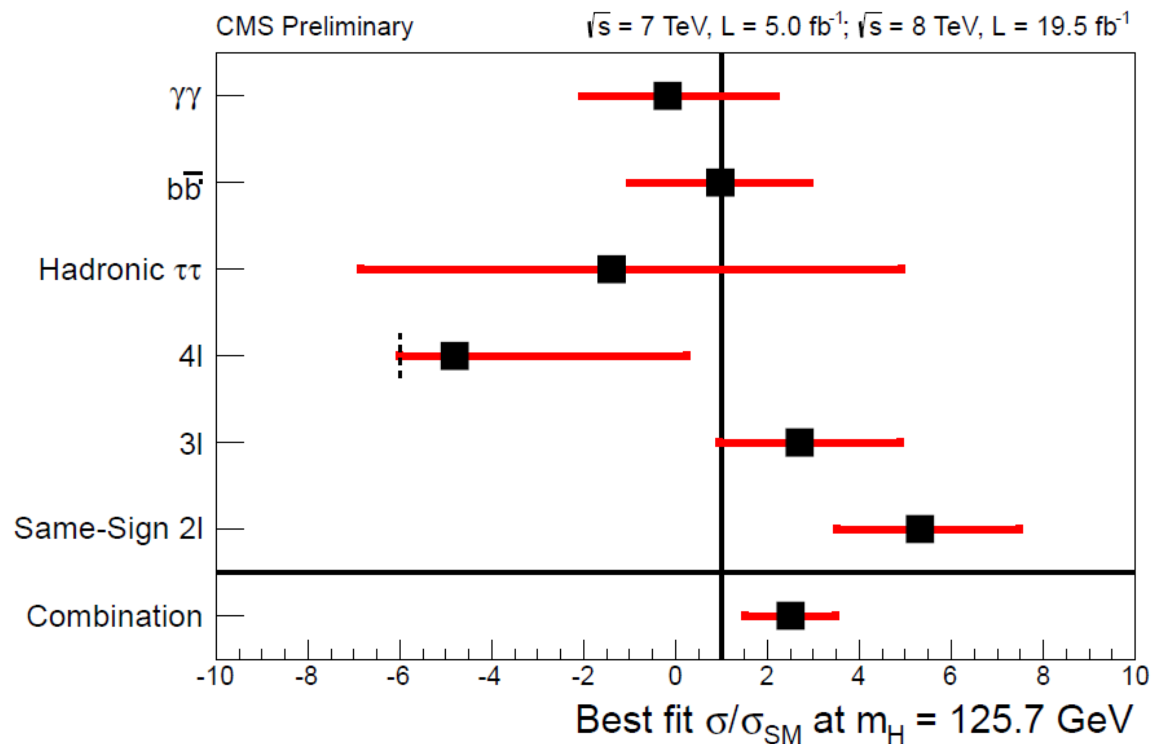
- Can probe top Yukawa coupling directly.
- Very challenging analysis with low cross section.

CMS explore full analysis on ttH

Link to CMS ttH combination

ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

95% CL limit:
1.8 x SM (exp), 4.3 x SM (obs)



ATLAS: full analysis is under way.

Need to wait new data to establish measurement on ttH production.

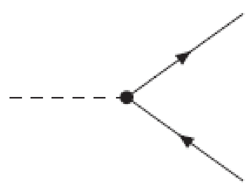
Coupling measurement

- Extracting Higgs coupling from σxBr requires assumptions at LHC

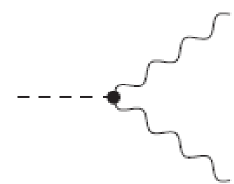
$$\sigma \cdot B\,(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- Total width is not measurable, we assume
  - Total width controlled by H→bb
  - H→cc is 5% unmeasured contribution
    - Scale with bb
    - bb/cc scale with ττ
  - <u>No new invisible modes</u>
- In measurement, introduce scaling parameter, κ_x^2, which scales cross section and decay width to probe them.

$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon}$$



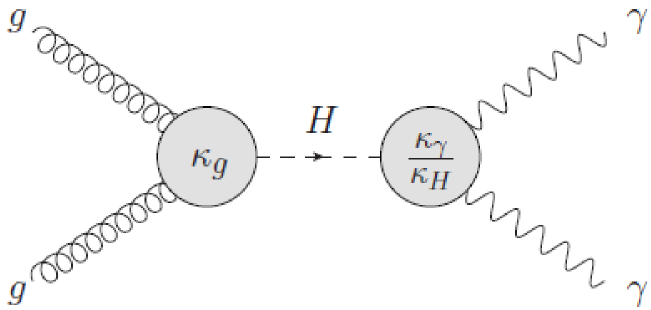
$$g_{HVV} = \frac{2m_V^2}{\upsilon}$$

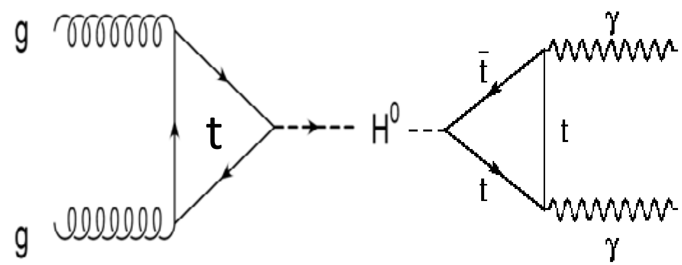


$$\Rightarrow g_{Hff} = \boxed{\kappa_f} \cdot \frac{\sqrt{2}m_f}{\upsilon}$$

$$\Rightarrow g_{HVV} = \boxed{\kappa_V} \cdot \frac{2m_V^2}{\upsilon}$$

Treatment of loop





- ggH: κ_g, Hγγ: κ_γ/κ_H

$$(\sigma\cdot BR)(gg\to H\to\gamma\gamma)=\left[\sigma(gg\to H)\cdot BR(H\to\gamma\gamma)\right]_{SM}\times\frac{\kappa_g^2\cdot\kappa_\gamma^2}{\kappa_H^2}$$

κ_H^2 : the scale factor to the total Higgs decay width

→ This allows to probe BSM in the loop

$$\kappa_H^2=\sum\kappa_x^2\cdot\frac{BR_{SM}(H\to xx)}{1-BR_{BSM}}$$

- Decompose Loops (if necessary)

ggH:

$$\sigma_{SM}=\sigma_{tt}+\sigma_{bb}+\sigma_{tb}$$

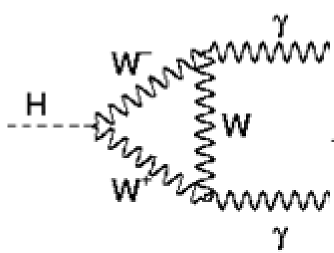
$$=\kappa_t^2\sigma_{tt}+\kappa_b^2\sigma_{bb}+\kappa_t\kappa_b\sigma_{tb}$$

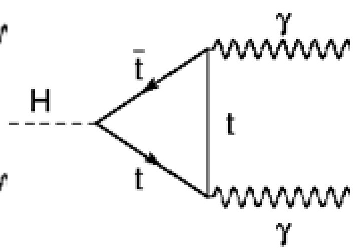
$$\kappa_g^2=\frac{\sigma}{\sigma_{SM}}=\frac{\kappa_t^2\sigma_{tt}+\kappa_b^2\sigma_{bb}+\kappa_t\kappa_b\sigma_{tb}}{\sigma_{tt}+\sigma_{bb}+\sigma_{tb}}$$

$$\approx 1.058\kappa_t^2+0.007\kappa_b^2-0.065\kappa_t\kappa_b \ {}^{*}$$

(M_H=125.5 GeV)

Hγγ:





$$\kappa_\gamma^2=\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}}=\frac{\kappa_t^2\Gamma_{\gamma\gamma}^{tt}+\kappa_W^2\Gamma_{\gamma\gamma}^{WW}+\kappa_t\kappa_W\Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt}+\Gamma_{\gamma\gamma}^{WW}+\Gamma_{\gamma\gamma}^{tW}}$$

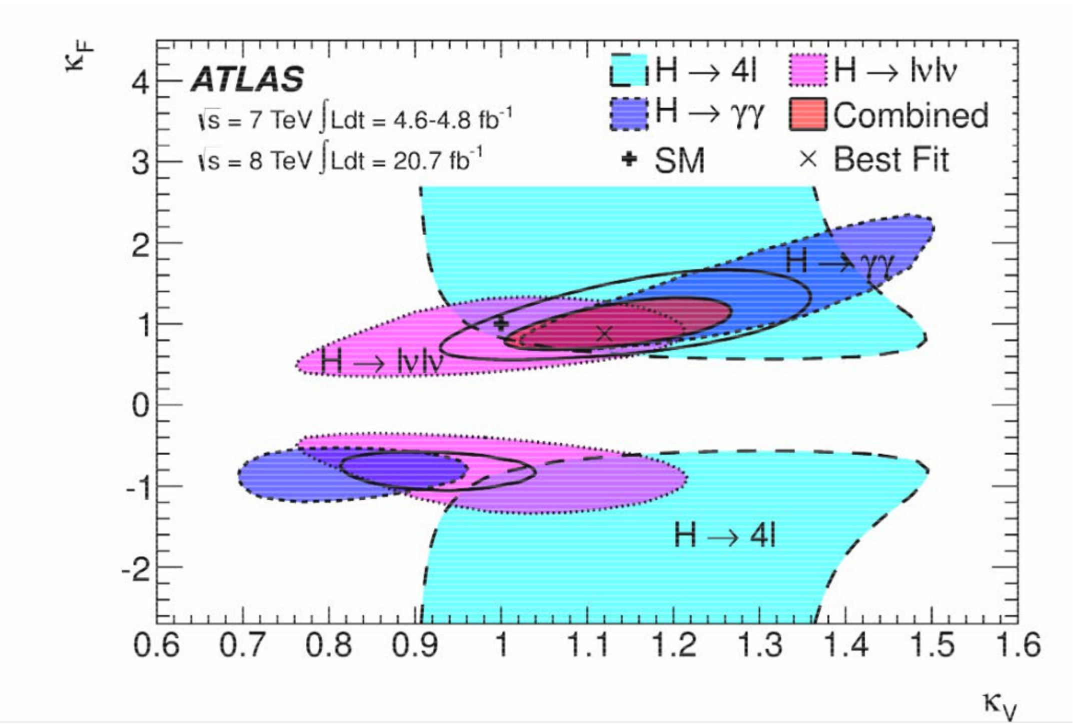
$$\approx 0.07\kappa_t^2+1.59\kappa_W^2-0.66\kappa_t\kappa_W \ {}^{*}$$

Fermion and Boson Coupling

Assume

- $\kappa_F : \kappa_t = \kappa_b = \kappa_\tau = .., \kappa_V : \kappa_W = \kappa_Z$
- No BSM contribution to Γ_H

Prove κ_F and κ_V



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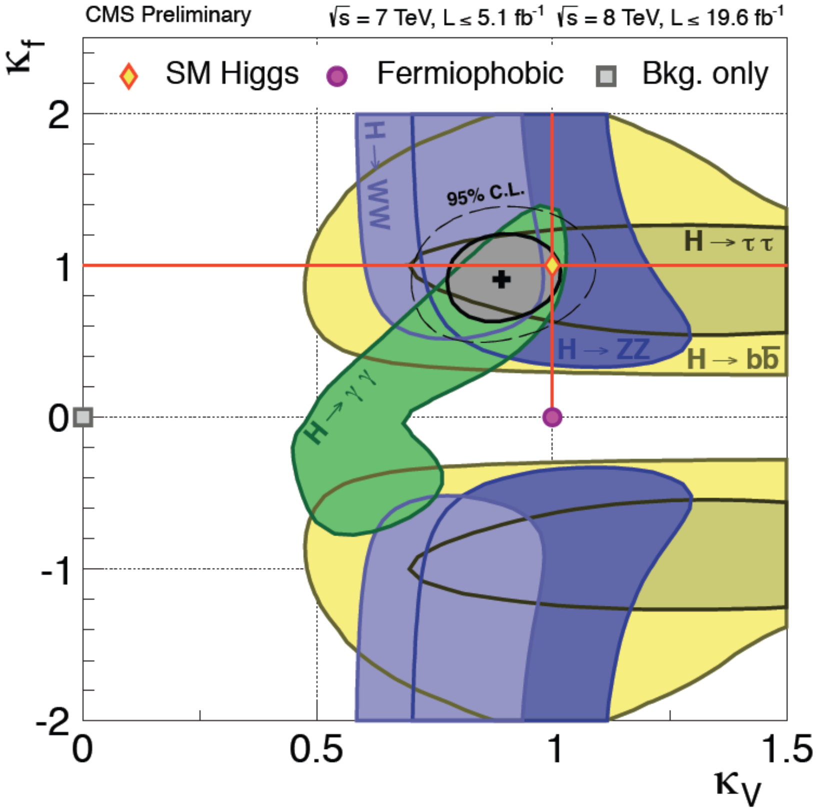
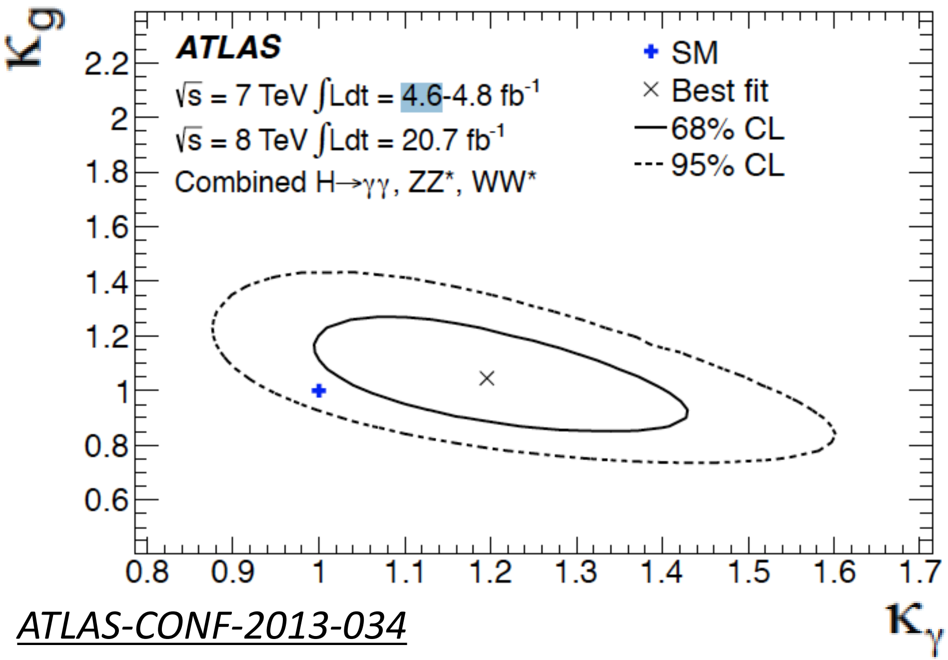


CMS-PAS-HIG-13-005

Proving new particle via loop

- Assume $\kappa_b = \kappa_W = \kappa_Z = \kappa_t = \kappa_\tau = 1$ and prove κ_g and κ_γ
- Due to ggH and $H \rightarrow \gamma\gamma$ decay loop, this is sensitive to new physics.



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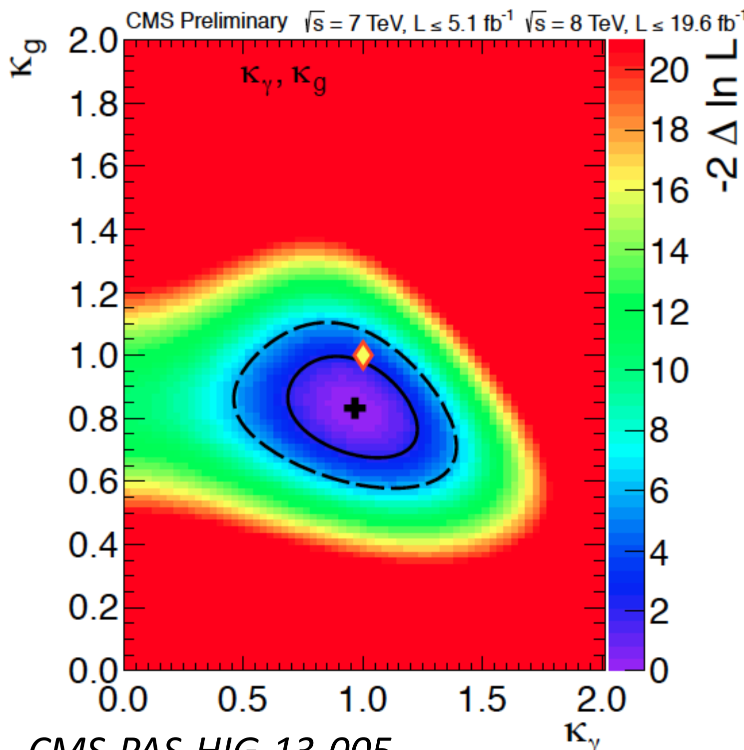


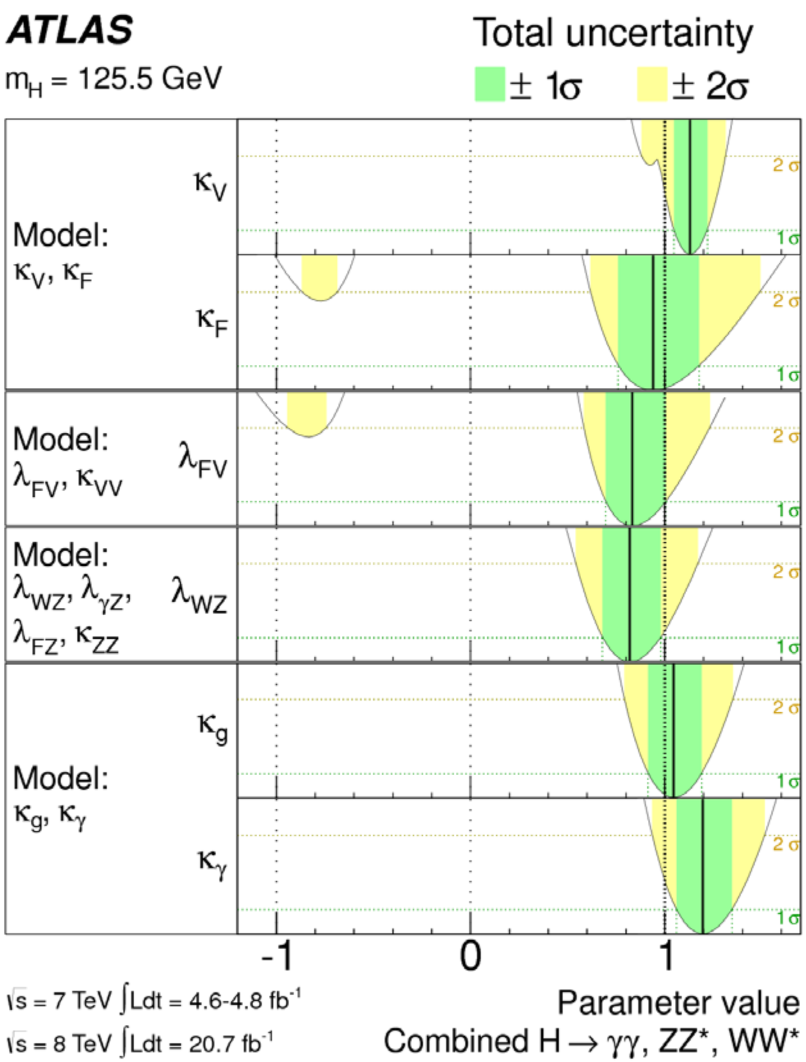
CMS-PAS-HIG-13-005

@68% CL	ATLAS	CMS
κ_g	1.04 ± 0.14	[0.63, 1.05]
κ_γ	1.20 ± 0.15	[0.59, 1.30]

Consistent with 1.

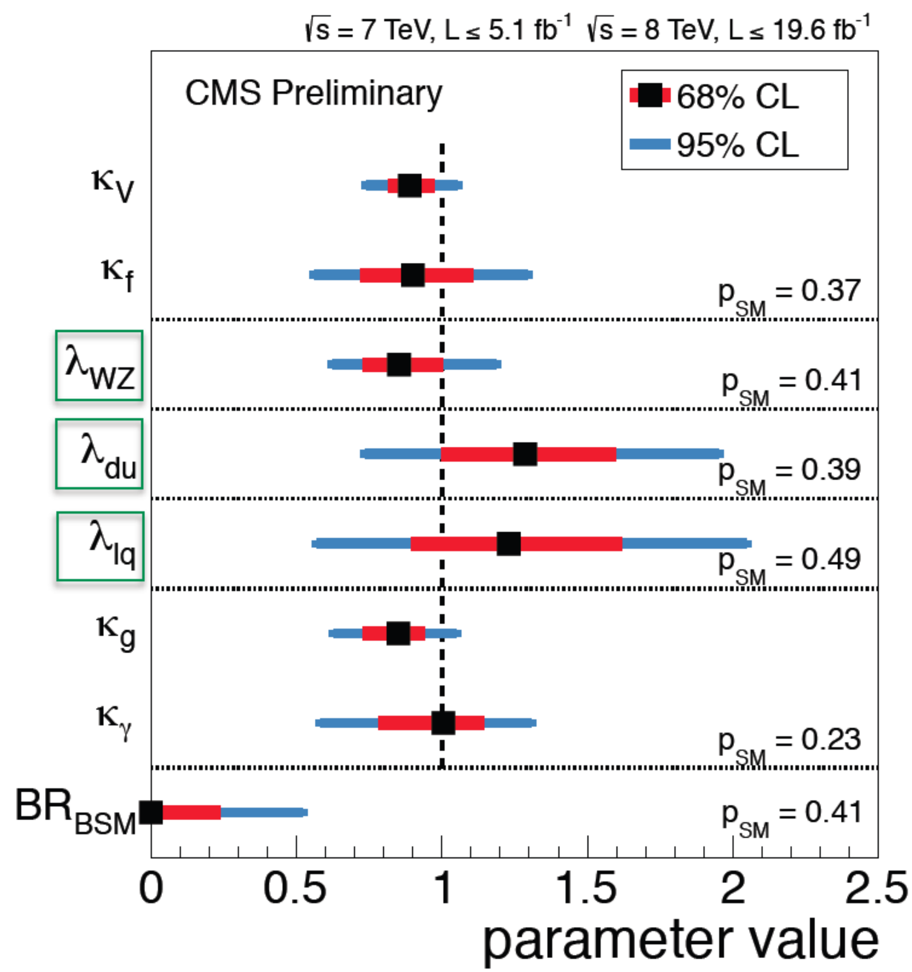
No indication of BSM.

Coupling summary



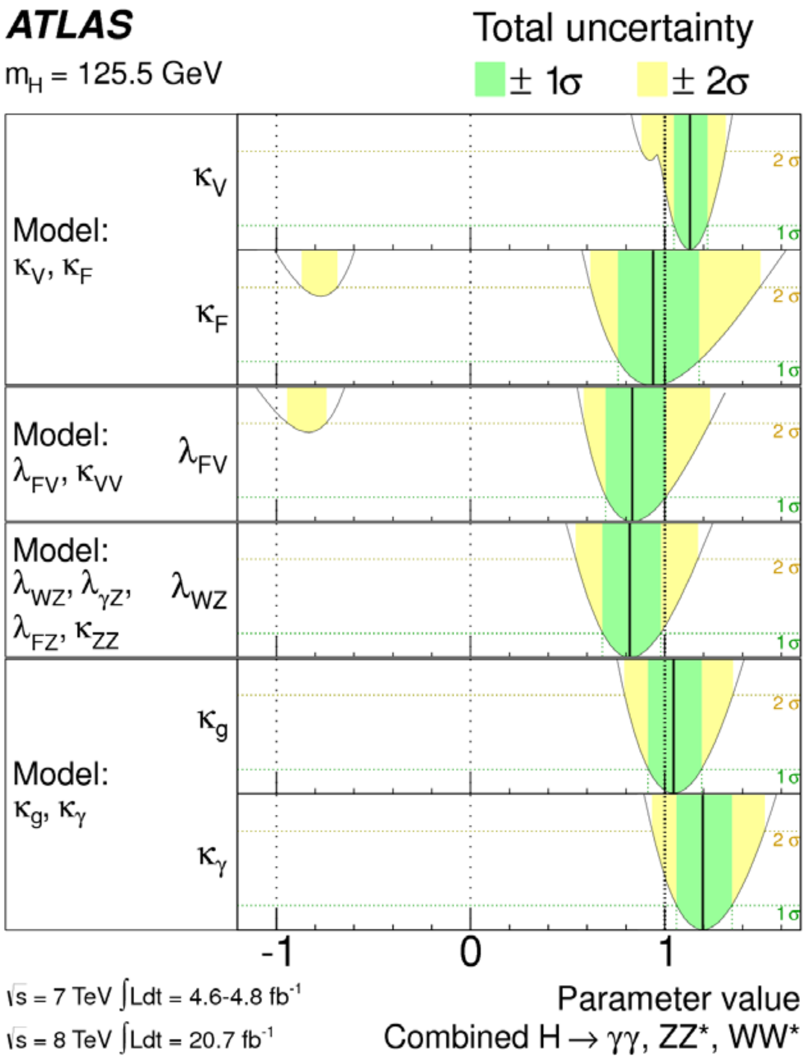
ATLAS-CONF-2013-034

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

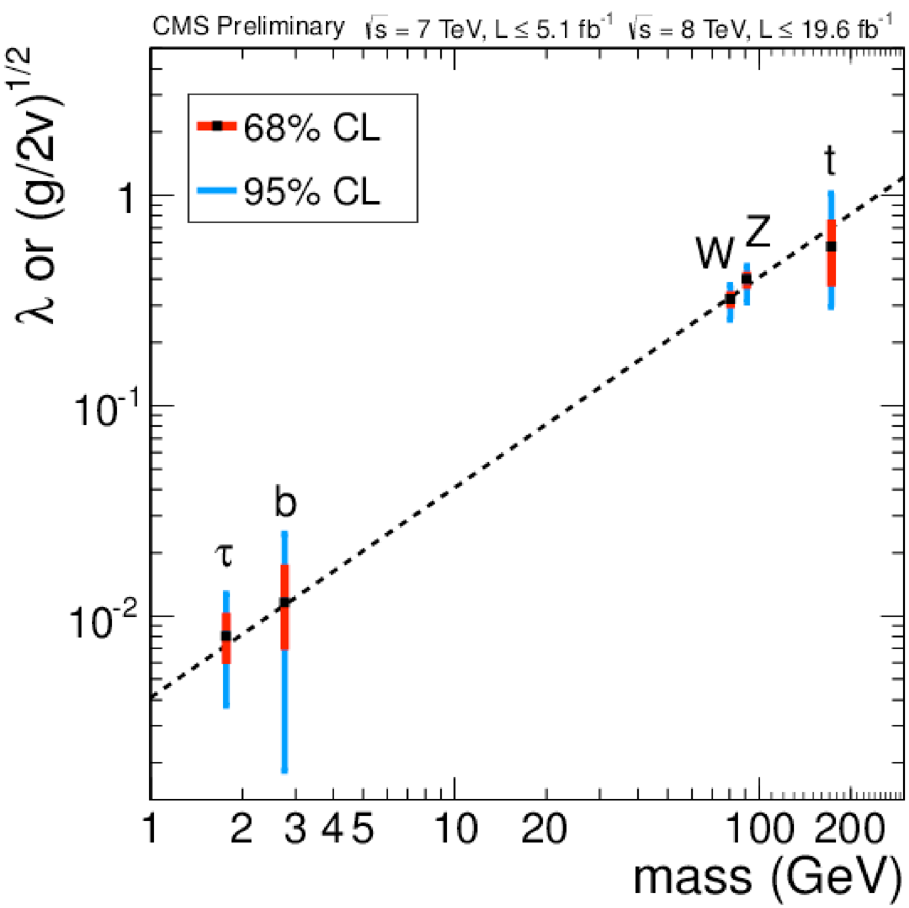


CMS-PAS-HIG-13-005

Coupling summary



$\lambda = \kappa_f m_f / v \qquad g = 2\,\kappa_V m_V^2 / v$

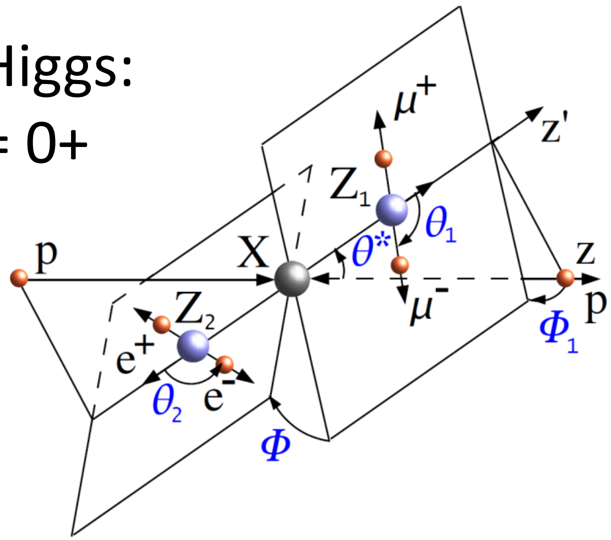


- Higgs coupling strength nicely scales with Mass!

Measurement on Spin and parity

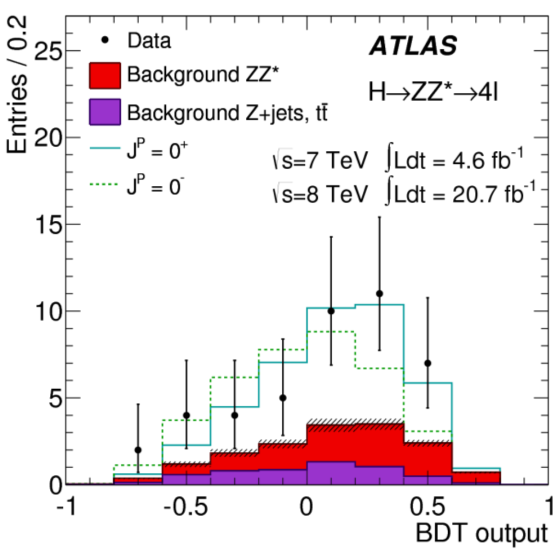
- Probe Spin and Parity by event kinematics

SM Higgs:
$J^P = 0+$

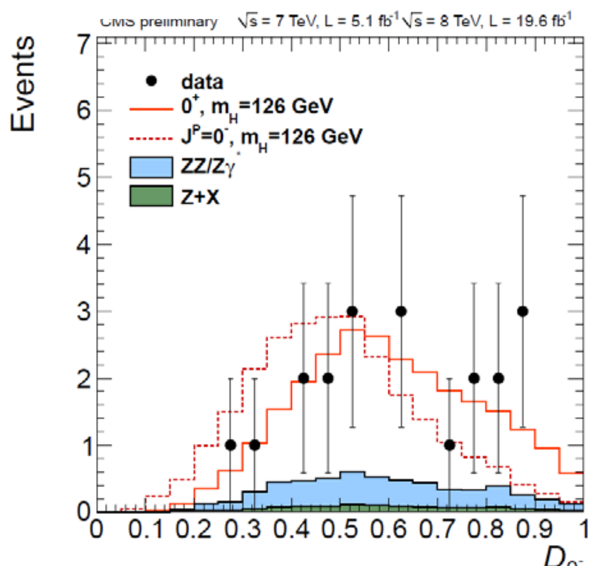


	H→γγ	H→WW	H→ZZ
J^P = 0+ vs 0-	---	---	✔
J^P = 0+ vs 1-	*	✔	✔
J^P = 0+ vs 1+	*	✔	✔
J^P = 0+ vs 2+	✔	✔	✔

* Excluded by Landau-Yang theorem



ATLAS-CONF-2013-040



CMS:arXiv:1212.6639

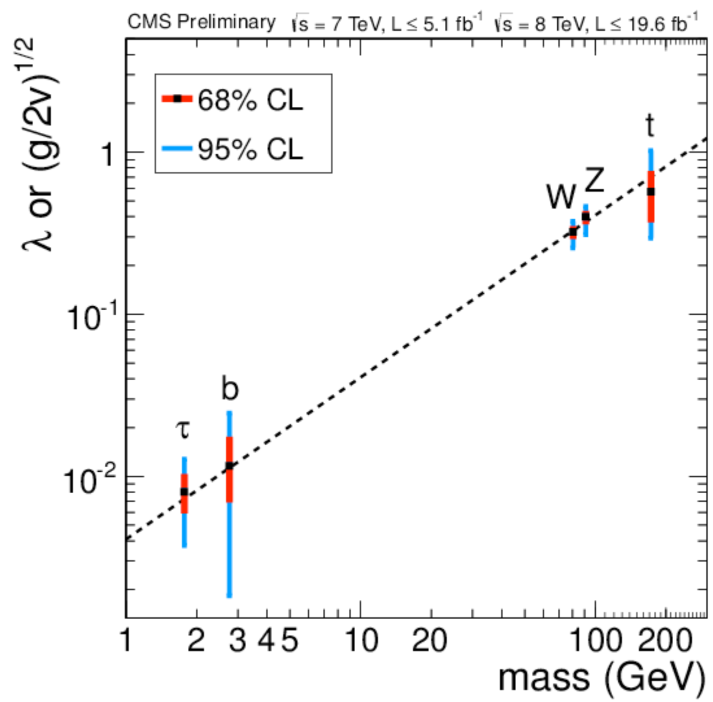
CL on Exclusion

	ATLAS	CMS
J^P = 0-	97.8%	99.8%
J^P = 1	99.7	>99.9%
J^P = 2+	99.9%	99.4%

Data favor J^P = 0+
→ **SM Higgs.**

Summary on property measurements

After discovery of Higgs-like boson



- Rate
  - ggH well established
  - Evidence for VBF
  - Indication of VH
  - Well progress on ttH and H→ff
- Coupling analysis
  - All consistent with SM
  - No indication of BSM in loop
- Spin and Parity
  - Based on angular analyses, J^P = 0-, 1+, 1-, 2+ are excluded more than 99% CL. Data favor J^P=0+ as Standard Model expectation.

Observed Higgs-like boson is now a Higgs boson.

Prospects: Upgrade on LHC

- LHC upgrade project

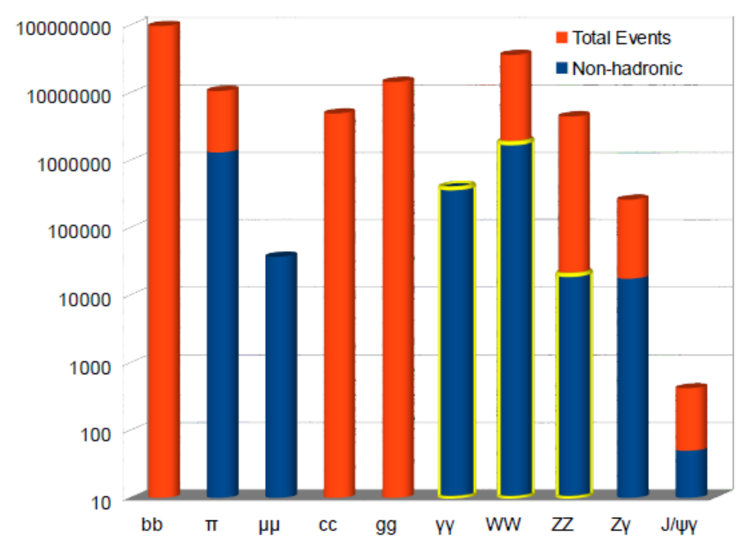
2014	2015	2018	2020	2022		2032
LS1	Run-2	LS2	Run-3	LS3	Hi-Lumi	

Run-2	Run-3	Hi-Lumi
$\sqrt{s}$ = 13-14 TeV	$\sqrt{s}$ = 14 TeV	$\sqrt{s}$ = 14 TeV
$L = 1 \times 10^{34}$	$L = 2 \times 10^{34}$	$L = 5 \times 10^{34}$
$\int Ldt$ = 100 fb^{-1}	$\int Ldt$ = 300 fb^{-1}	$\int Ldt$ = 3000 fb^{-1}

Accelerator, Detector upgrades.

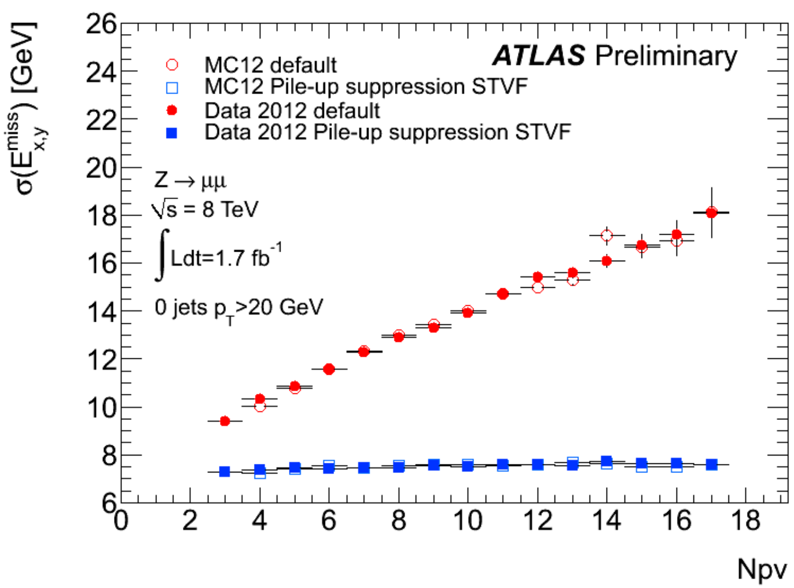
- LHC is Higgs factory

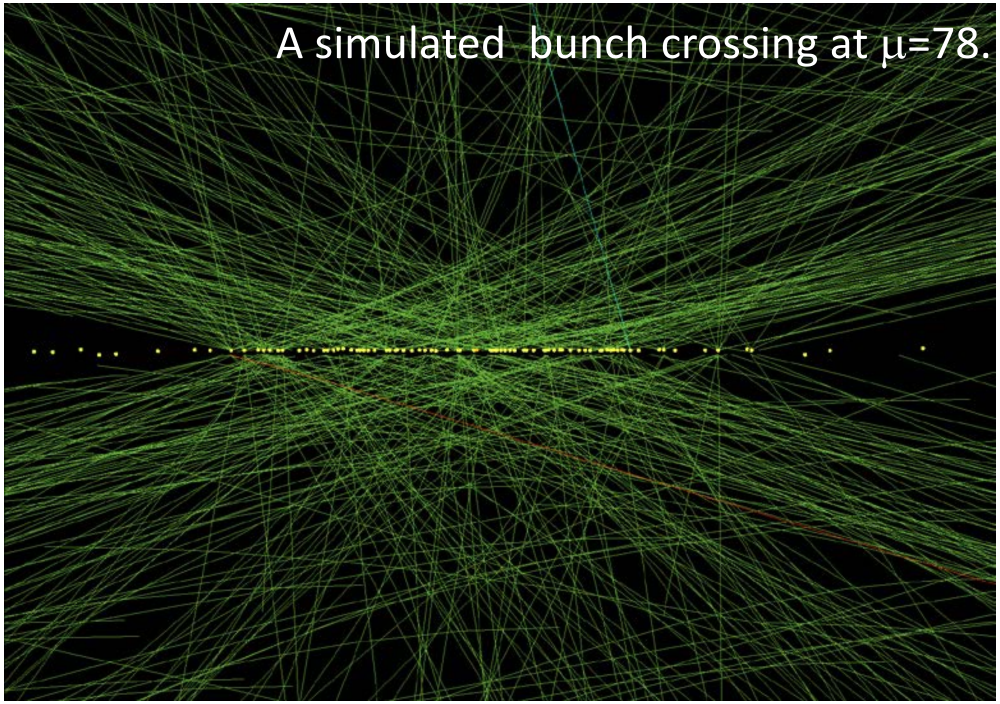
  With 3000 fb^{-1},
  - Over 100 M Higgs boson
  - 20k H→ZZ→4 leptons
  - 400k H→γγ
  - 50 H→J/psi γ
- Today's result
  - For "European Strategy / ECFA workshop
  - Consider only hadron colliers scenarios.



Upgrade on the detector

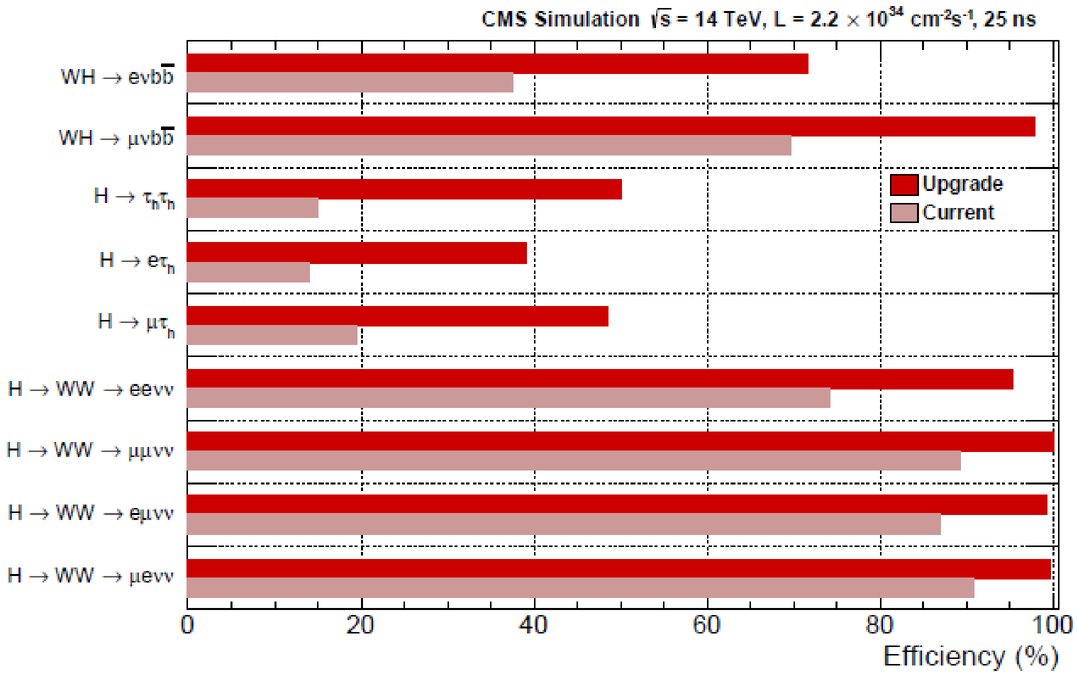
- For Physics analysis:
  Need huge statistics → high luminosity is welcome!
- Challenge: Trigger and reconstruction under huge pileups.
  - Now: designed upto 23, can handle 80.
  - But not under 140.





Detector upgrade

- Enforce trigger performance
  - Ex. CMS Muon trigger coverage (|η|<2.5→|η|< 4.0)



CMS note 13-002
ArXiv:1307.7135v1

- For pileups
  - Upgrade inner tracker(pixel)
  - Readout electronics
  - Forward detector replacements.

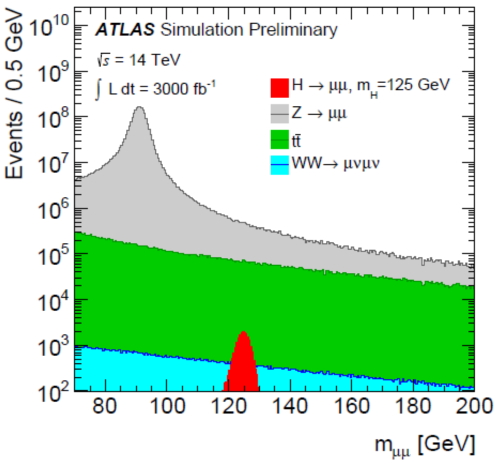
Effects are studied by Simulation
- Recover degradation due to pileups
- Projections assume based on current ID performance.

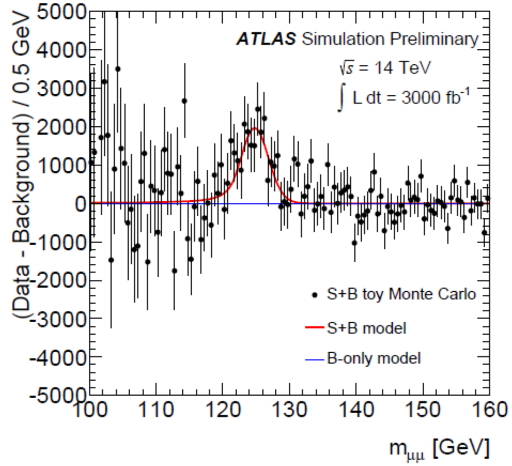
CMS PAS FTR-13-003, ATL-PHYS-PUB-2013-009

Probe on rare decays with 3000 fb^{-1}

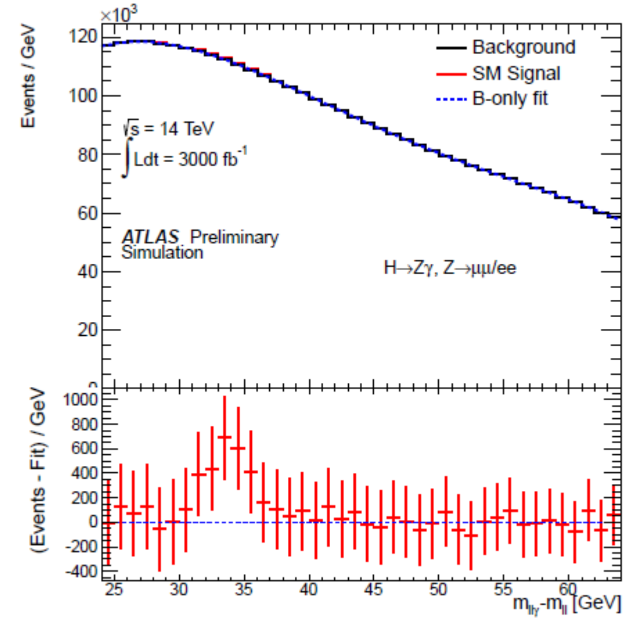
ATLAS-PHYS-PUB-2013-014

H→μμ

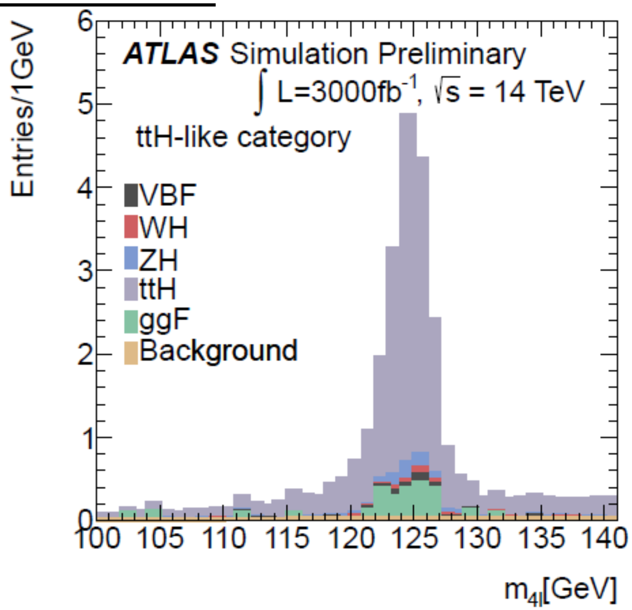




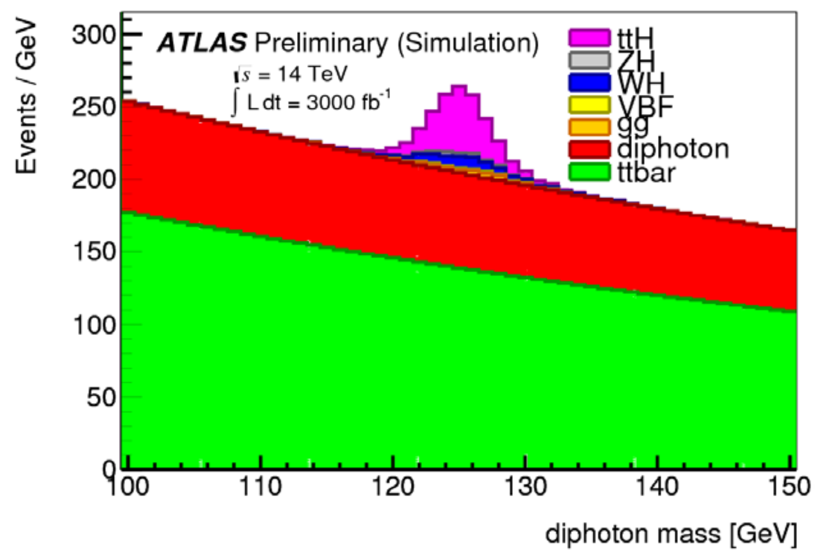
H→Zγ



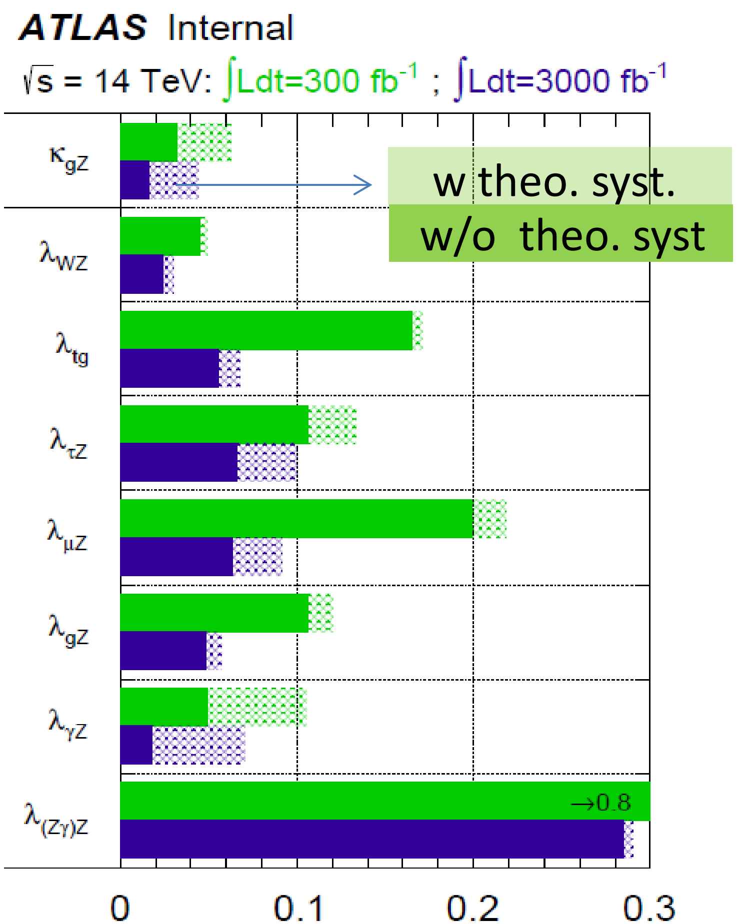
ttH, H→ZZ→4l



ttH, H→γγ



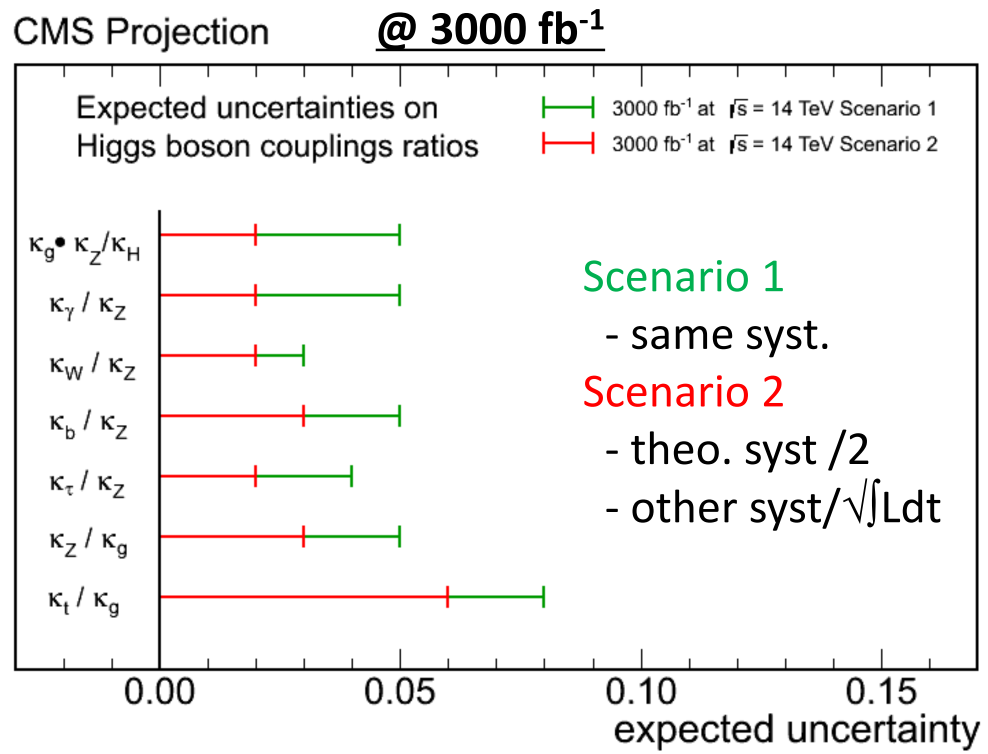
Expected sensitivity on the couplings



Keep current experimental uncertainties.

$$\Delta\lambda_{XY}=\Delta\left(\frac{\kappa_X}{\kappa_Y}\right)$$

ATL-PHYS-PUB-2013-009

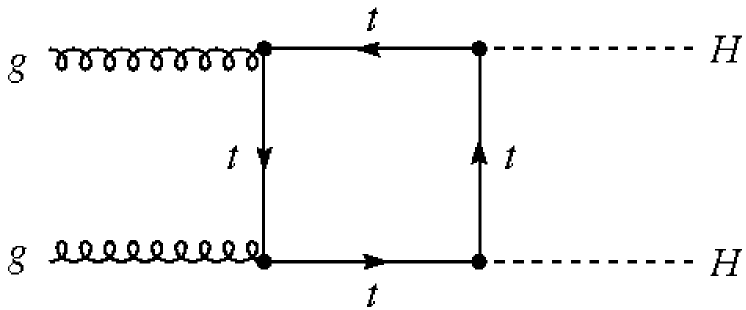


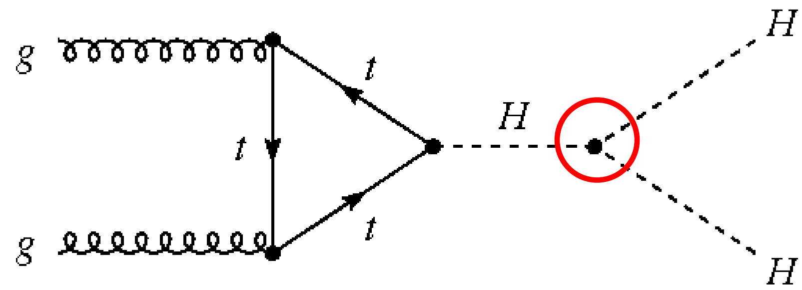
CMS NOTE-13-002

- With 3000 fb^{-1}, systematics need to improve including theoretical uncertainties.

Higgs couplings can be measured at ~ 5% level with 3000 fb^{-1}.

Higgs pair production





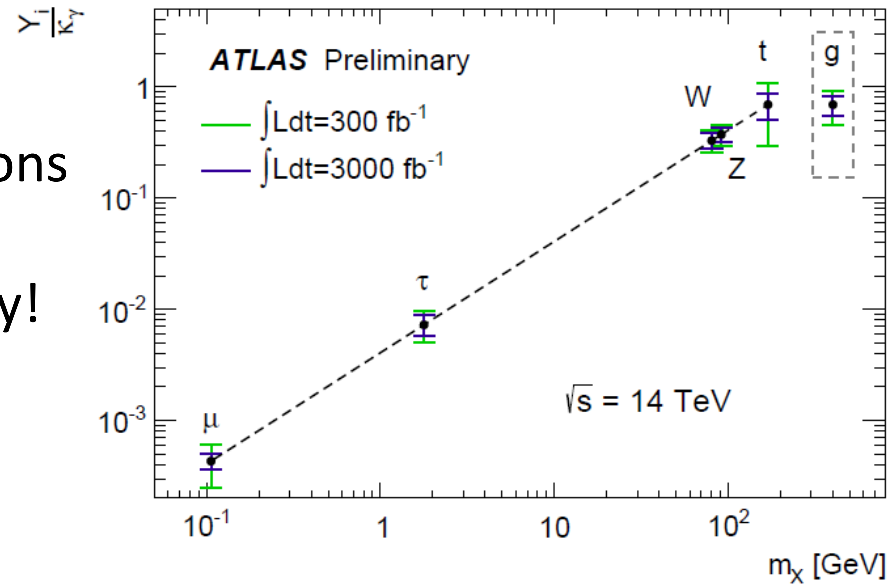
- Higgs self-coupling is an intrinsic property of Higgs model. This is crucial test of the electro weak symmetry breaking mechanism.
- Higgs self coupling (λ_{HHH}) gives negative interference in Higgs pair production.
  - $\lambda_{HHH} = 1$: σ (NLO) = 34 fb
    → $\lambda_{HHH} = 0(2)$: σ (NLO) = 71 (16) fb
- Measurement of the pair production is very challenging. Need further studies.
  - Large irreducible background from "single" Higgs+X processes
  - High pileups conditions at High Lumi Runs.

Mode	bbWW	bb$\tau\tau$	WWWW	$\gamma\gamma$bb	$\gamma\gamma\gamma\gamma$
Expected events	30000	9000	6000	320	1

@ 3000 fb^{-1}

Summary on prospects

- 3000 fb^{-1} of data provides rich program on Higgs sector
  - Rare processes
    - H→μμ, Zγ, J/psi γ
  - Precise measurement
    On ttH: including H→γγ, ZZ→4leptons
    Couplings : could reach ~ 5% level
    Progress on Theory side is necessary!
  - Probe self-coupling
    - Pair production can access
    - Need more studies
  - New states
    - A lot of potential to search new bosons!



- Difficult area for LHC
  - H→cc
  - Total width
    - With H→γγ, ZZ, could reach
      < 920 MeV (@ 300 fb^{-1})
      < 200 MeV (@3000 fb^{-1}) but hard to reach SM level (4.2 MeV).

Final remark

- ATLAS and CMS discover a Higgs boson
  - J^P = 0-, 1+, 1-, 2+ are excluded more than 99% CL.
  - Rates and couplings consistent with Standard Model

Higgs Bosons — H^0

Mass $m = 125.9 \pm 0.4$ GeV (from PDG)

→ This is great success of nice collaboration of
  - Accelerator, Theory and Experiments

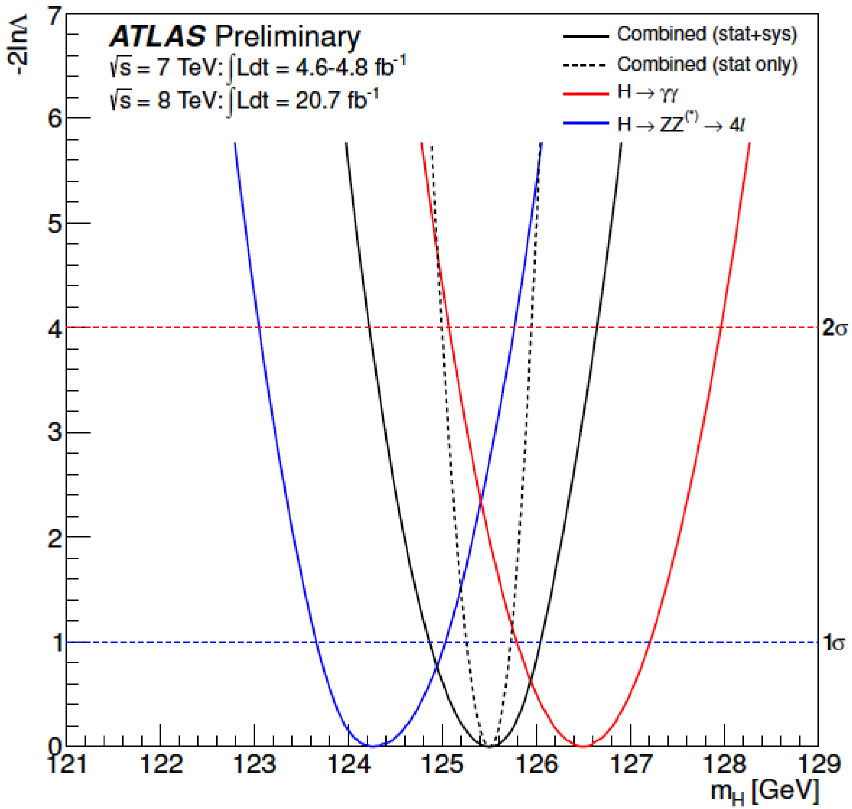
- LHC will run for revealing physics behind Standard Model for next decades.
- Look forward to nice collaboration with Linear collider!

Backup

Higgs Mass Measurement

ATLAS

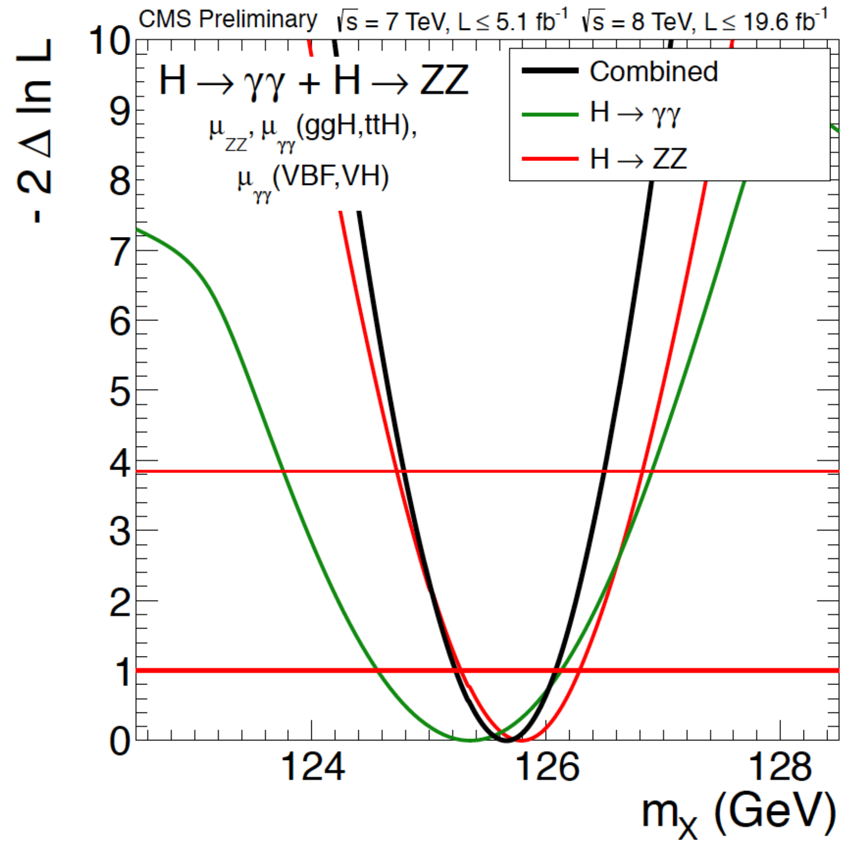
ATLAS-CONF-2013-014



$$ATLAS: M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{syst}\ GeV$$

CMS

CMS-PAS-HIG-2013-005

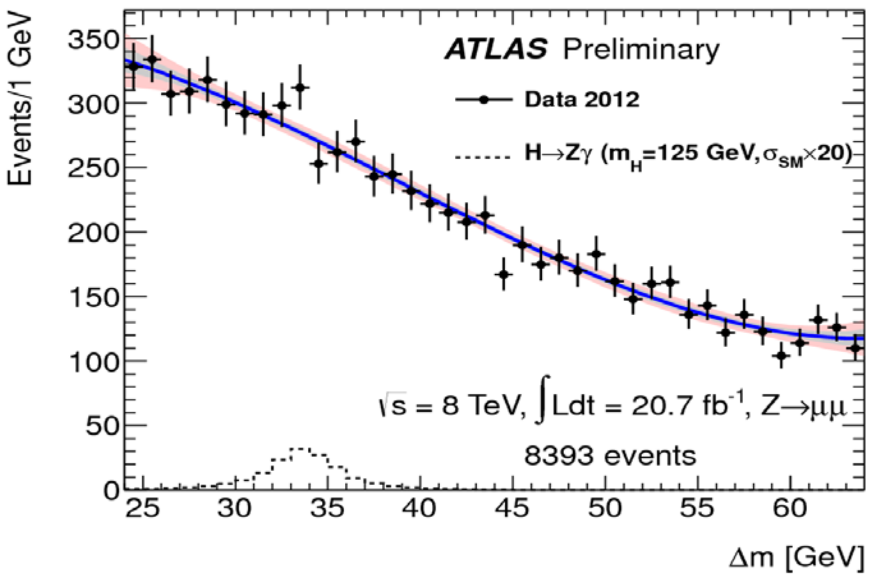


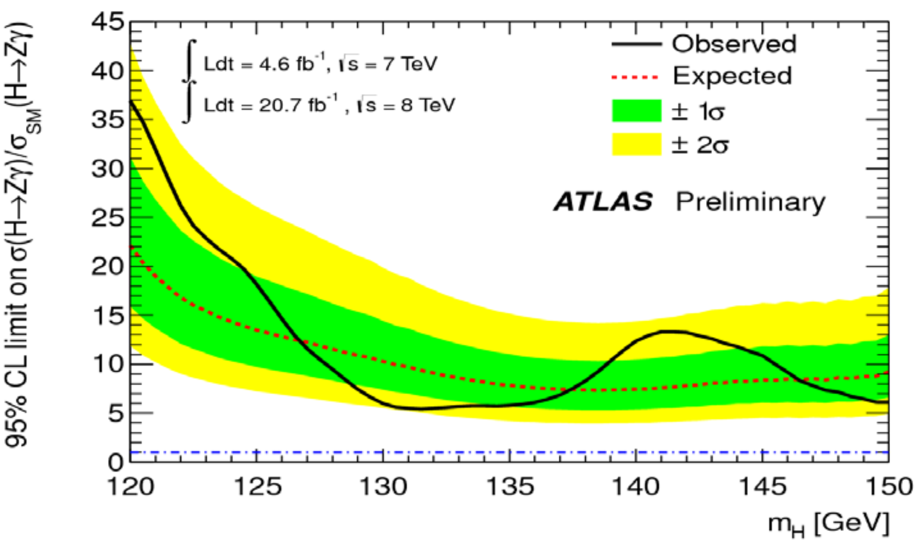
$$CMS: M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{syst}\ GeV$$

$$From{-}\gamma\gamma: \Gamma_H < 6.9 GeV@95\%CL\ (direct)$$

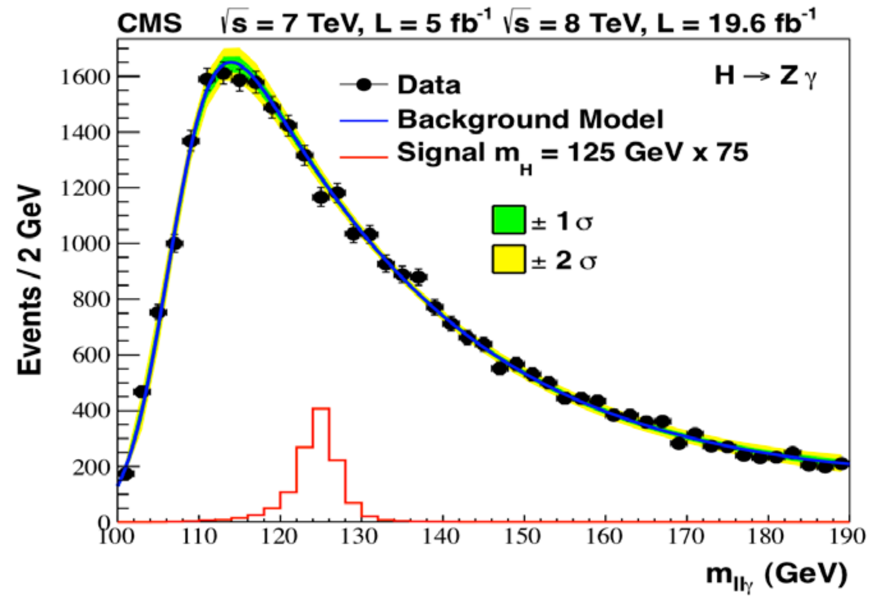
Rare decays (H→Zγ)

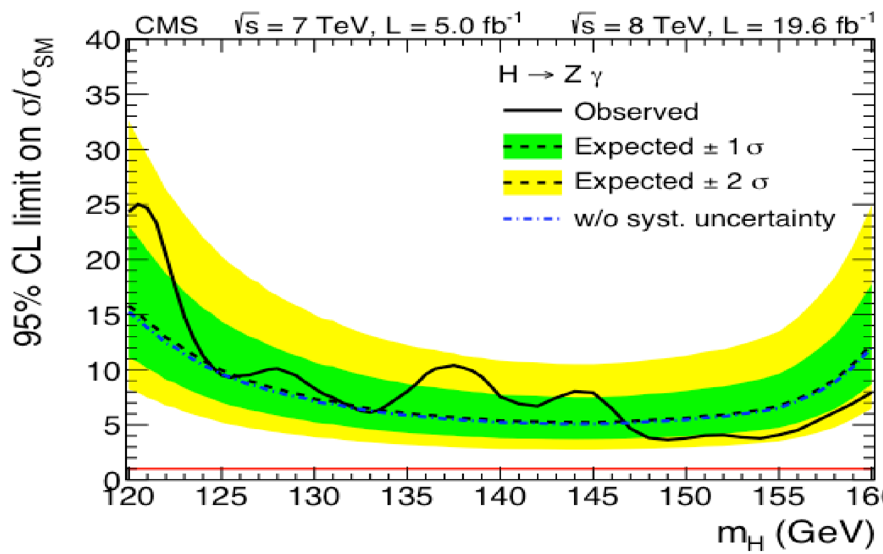
ATLAS





CMS

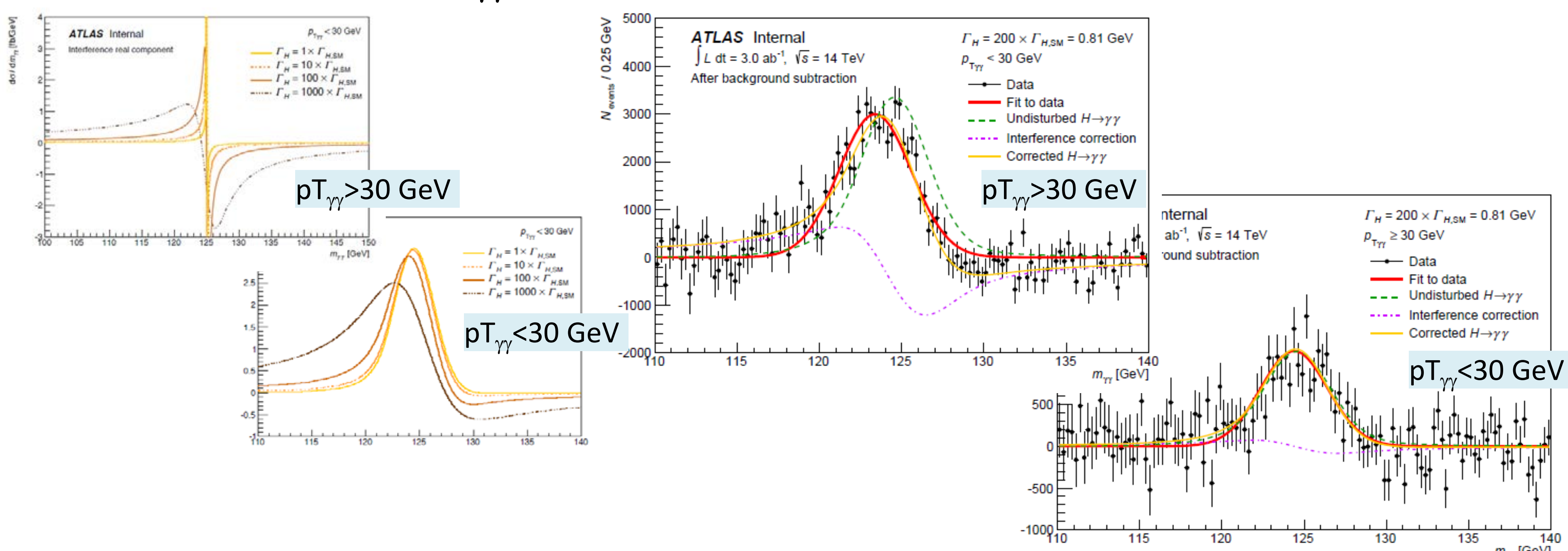




Direct Higgs width measurement

- CMS extracted Γ_H < 6.9 GeV from with of H→γγ
  - SM: Γ_H = 4.2 MeV
- Use interference between signal and background
  - Makes shifts on the mass peak
  - Measure $pT_{\gamma\gamma}$<30 GeV and >30 GeV

Dixon and Li arXiv:1305.3854



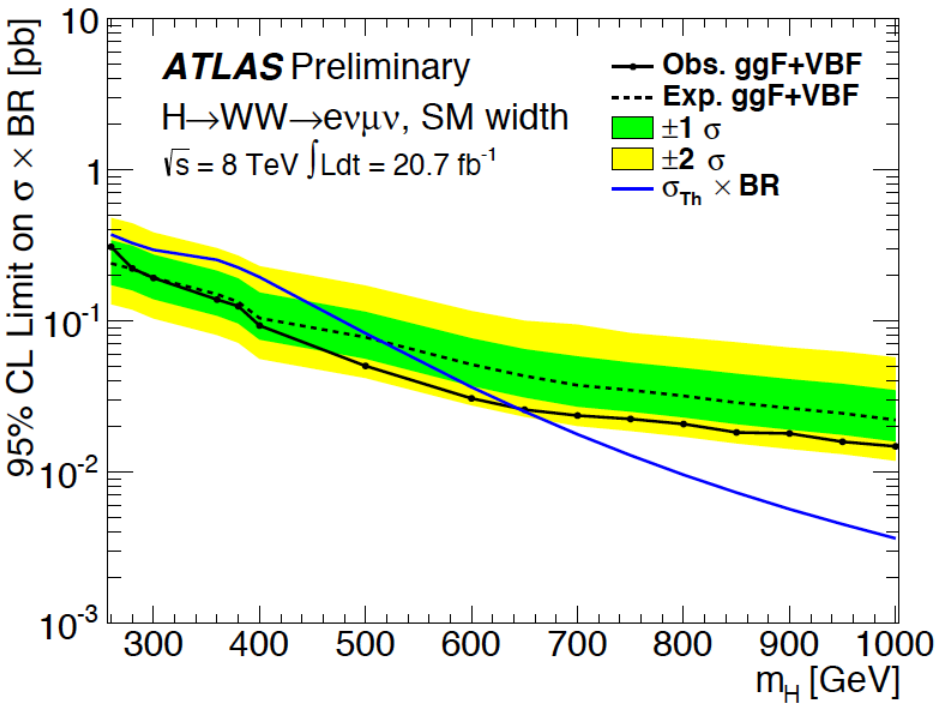
With H→γγ, ZZ, could reach : Γ_H < 920 MeV (@ 300 fb^{-1})
Γ_H < 200 MeV (@3000 fb^{-1})

ATL-PHYS-PUB-2013-01

Heavy Higgs

ATLAS

ATLAS-CONF-2013-067

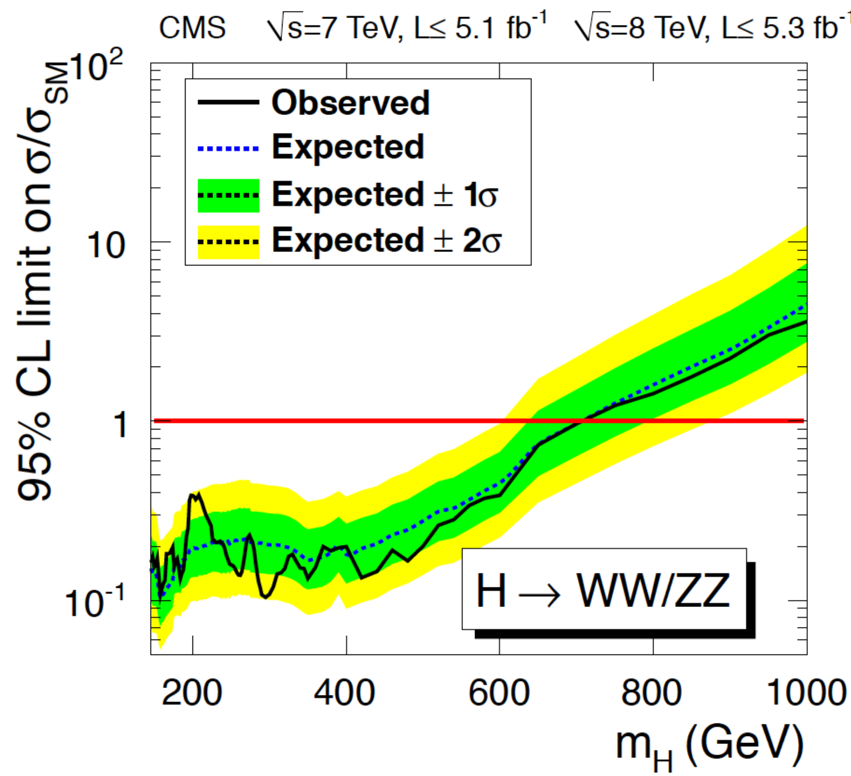


95% CL limit on σxBR

$260\ \text{GeV} < M_H < 640\ \text{GeV}$

CMS

CMS:arXiv:1304.0213v2

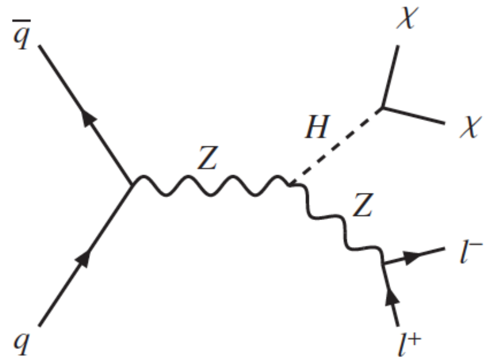


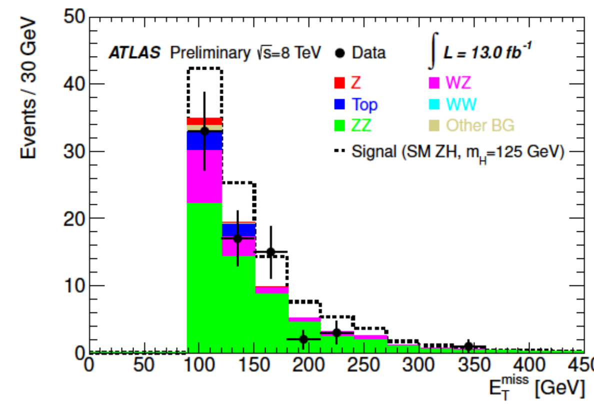
95% CL limit on σxBR

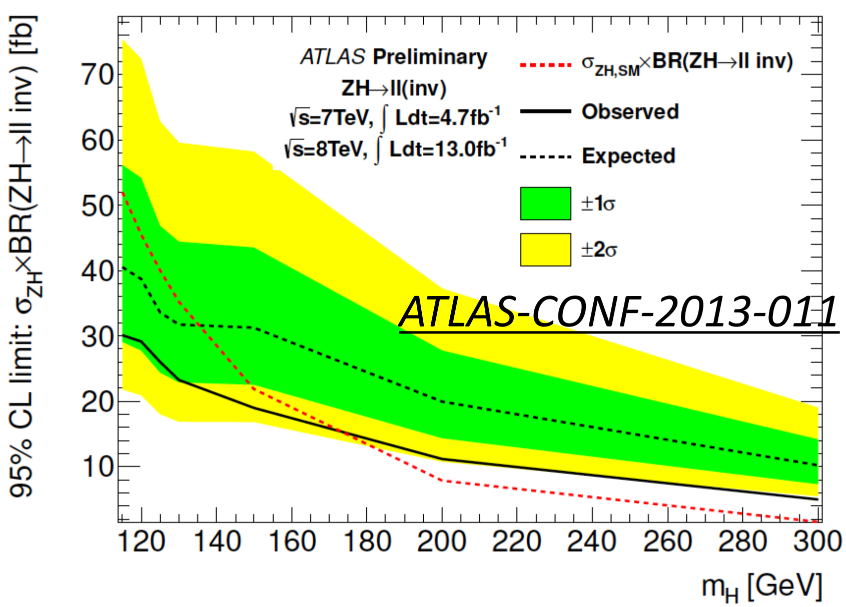
$145\ \text{GeV} < M_H < 710\ \text{GeV}$

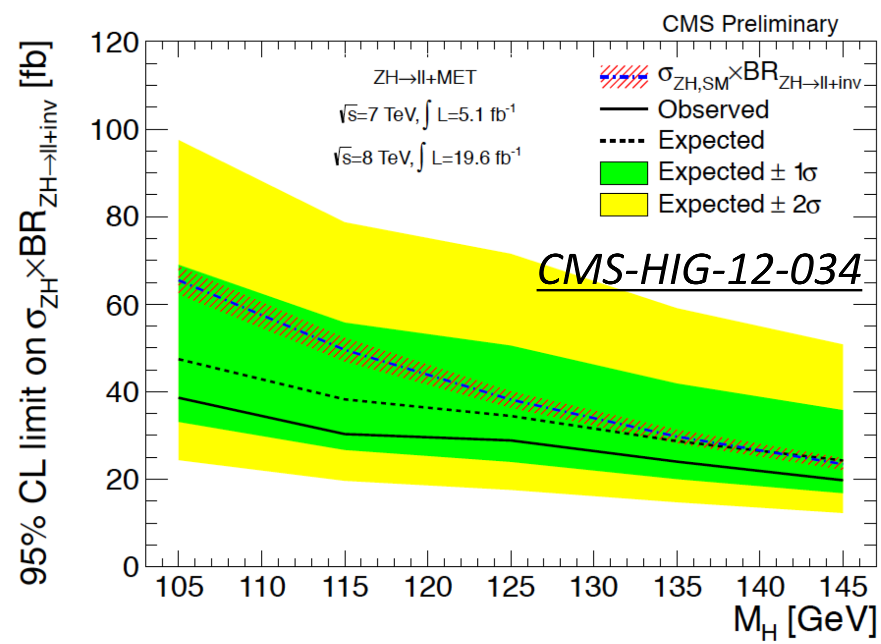
Heavy Higgs, invisible Higgs decay

- ZH, Z→ll H→$\chi\chi$
  - Assume Br(H→$\chi\chi$)=100%









Present performance (ATLAS)