Higgs: Current and Future Measurements

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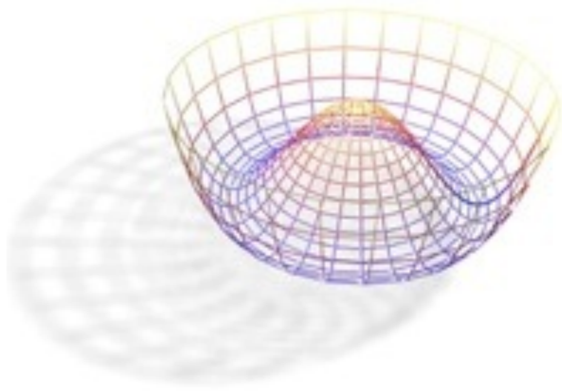
08.11.2013

Outline



- Introduction
  - Short history
  - LHC, ATLAS detector, LHC experiments
  - Higgs production at the LHC
- Characterising the boson
  - Main results from ATLAS in 2013
- Prospects
- Summary, outlook, and discussion

Page of Higgstory

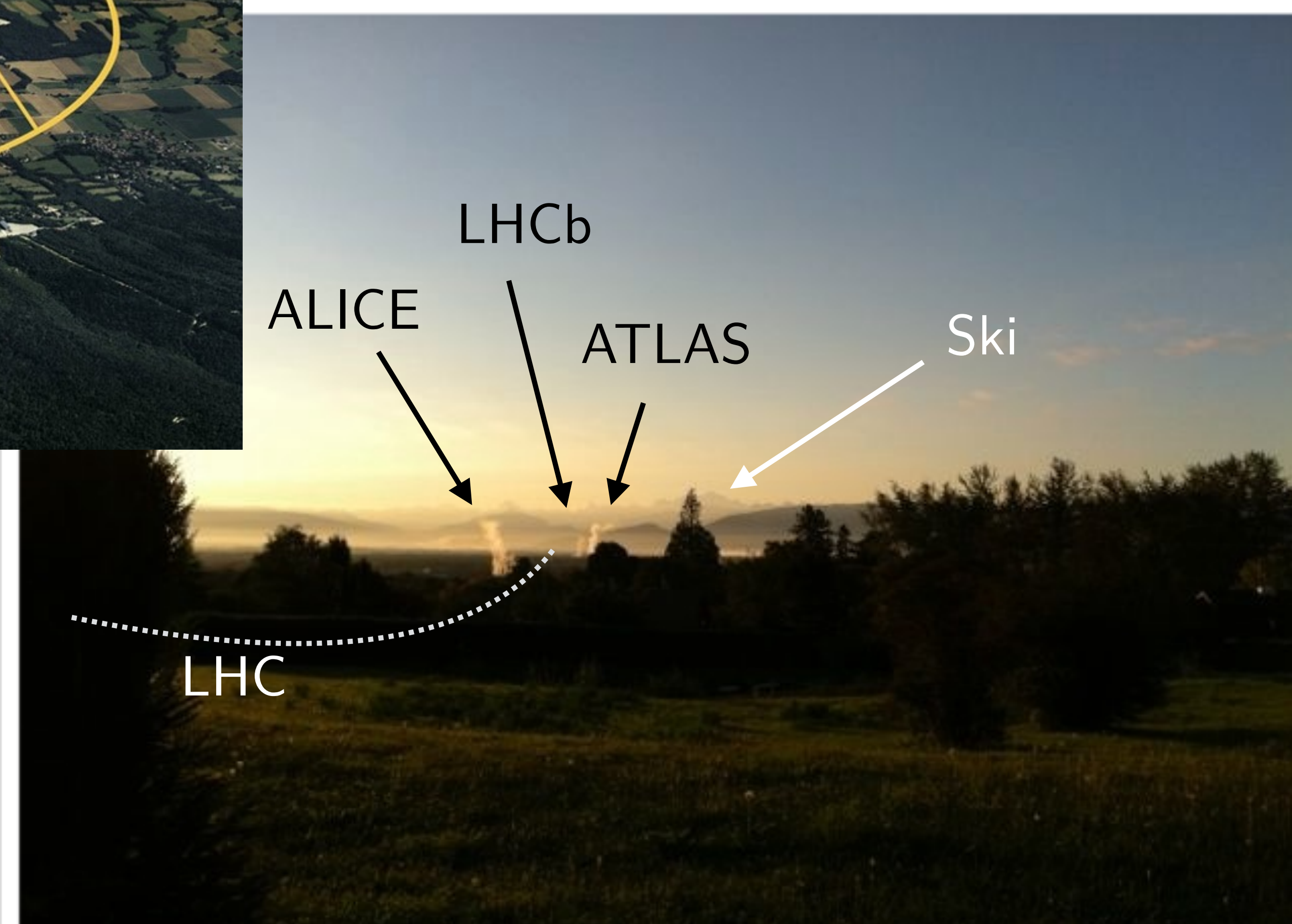
- Chronology: 50 years of patience
  - Englert, Higgs, et al. published their idea(s) starting in 1964.
  - SppS: 1981-1984, LEP: 1989-2000, Tevatron: 1993-2011
  - 1998-2008: Construction of Large Hadron Collider (LHC) and associated detectors.
  - 2010-2012: Run-1 of Phase-0 at the LHC. Delivered luminosity: ~25/fb.
  - 4th July 2012: discovery by both ATLAS and CMS of a new resonance at 125 GeV.
  - March 2013 (Moriond): confirmation of the SM-like properties of the boson. It's a Higgs boson.
  - 23rd October 2013: recognition at large by scientific community. Nobel prize in Physics awarded to Englert and Higgs (and CERN, ATLAS, and CMS).

ATLAS claim: 5σ excess at m_H ~ 126.5 GeV

CMS claim: new boson with a mass of 125.3±0.6 GeV at 4.9σ significance

… for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider

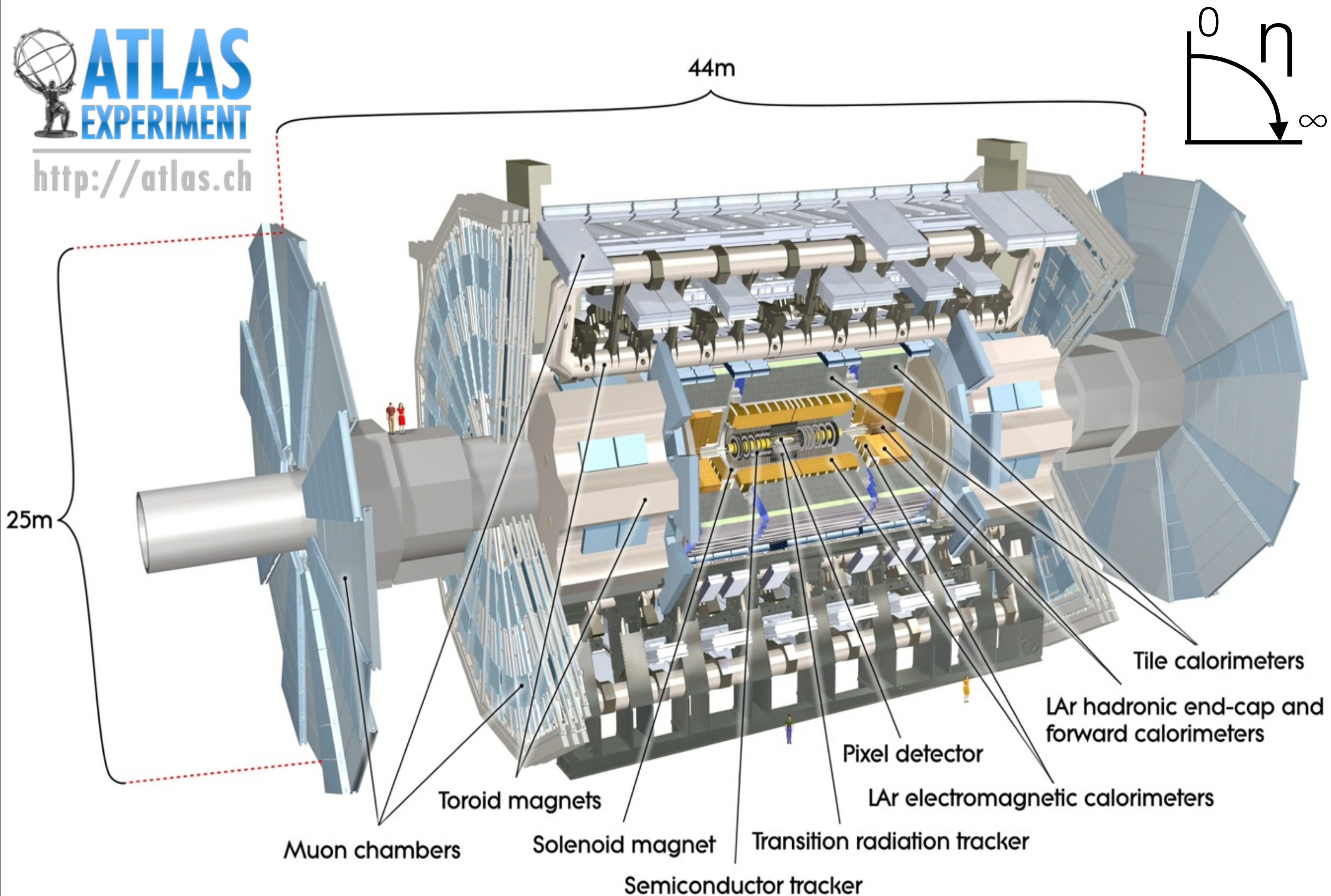
Large Hadron Collider



Usual aerial view of the Geneva area.

(Very) early morning view from my place (run coordinator at work, 2011)

ATLAS Detector



- ATLAS is a multi-purpose detector built to observe a wide spectrum of events from the proton-proton (pp) collisions produced at the LHC.
- Complicated devices, operated and fine-tuned by more than 3000 collaborators worldwide.

Muon Spectrometer: $|\eta| < 2.7$
Air-core toroids with gas chambers. Provides L1 trigger and standalone measurement.

$\sigma/p_T < 10\%$ up to p_T=1TeV

Hadronic Calorimeter:

Scintillating Fe tiles in barrel ($|\eta| < 1.7$)
Cu/W in LAr in forward region ($|\eta| < 4.9$)

Provides L1 trigger, jet measurement, and missing energy.

$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$

Electromagnetic Calorimeter: $|\eta| < 3.2$
Pb in LAr with accordion geometry.

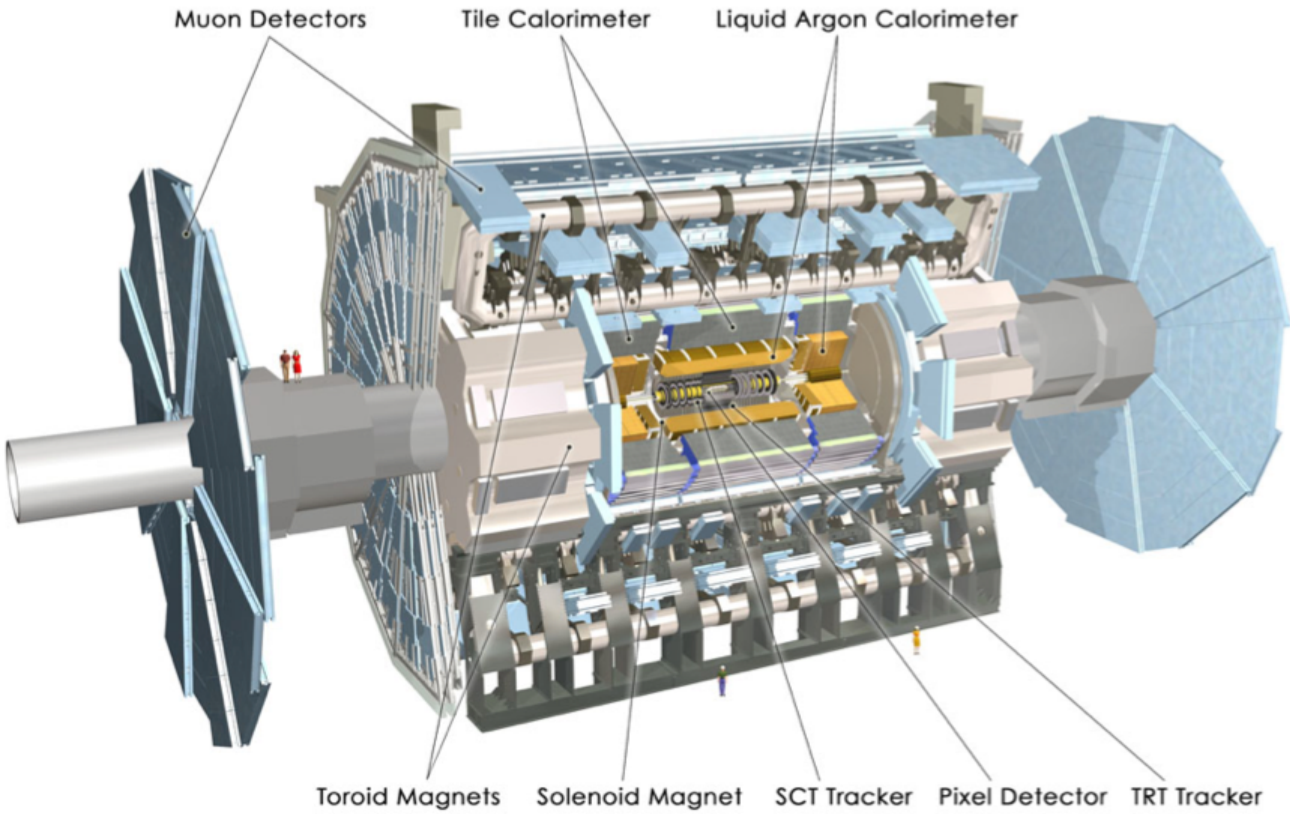
Provides L1 trigger, energy, identification, and position measurement.

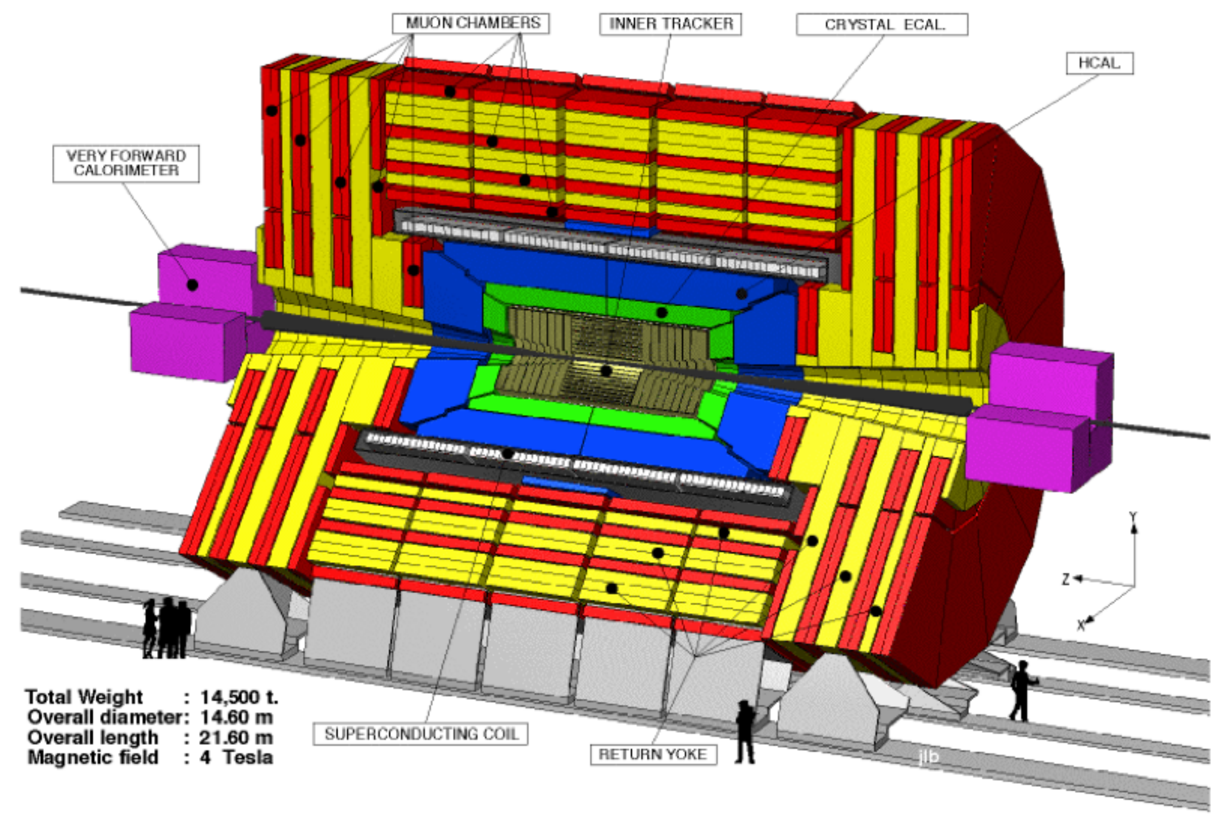
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

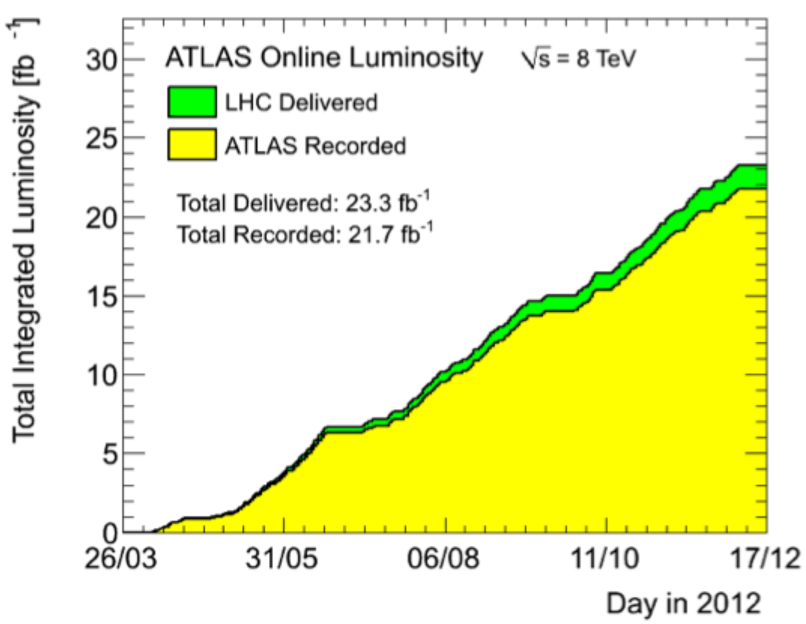
Inner Detector / Tracker: $|\eta| < 2.5$,
B=2T Si Pixels+Strips, Transition Radiation Tracker. Provides precise tracking, vertexing, em/hadron separation.

$\sigma/p_T \sim 0.05\% p_T \oplus 1\%$

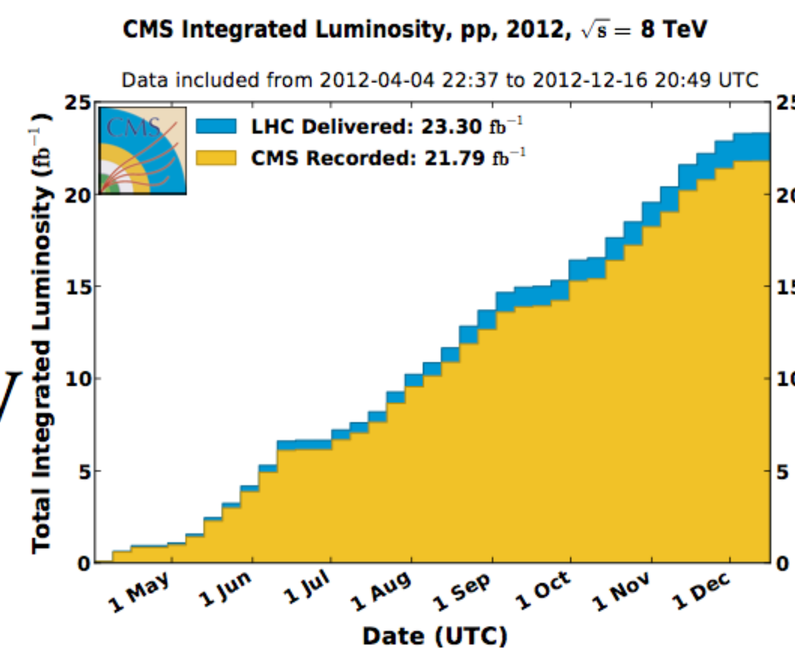
ATLAS and CMS Experiments





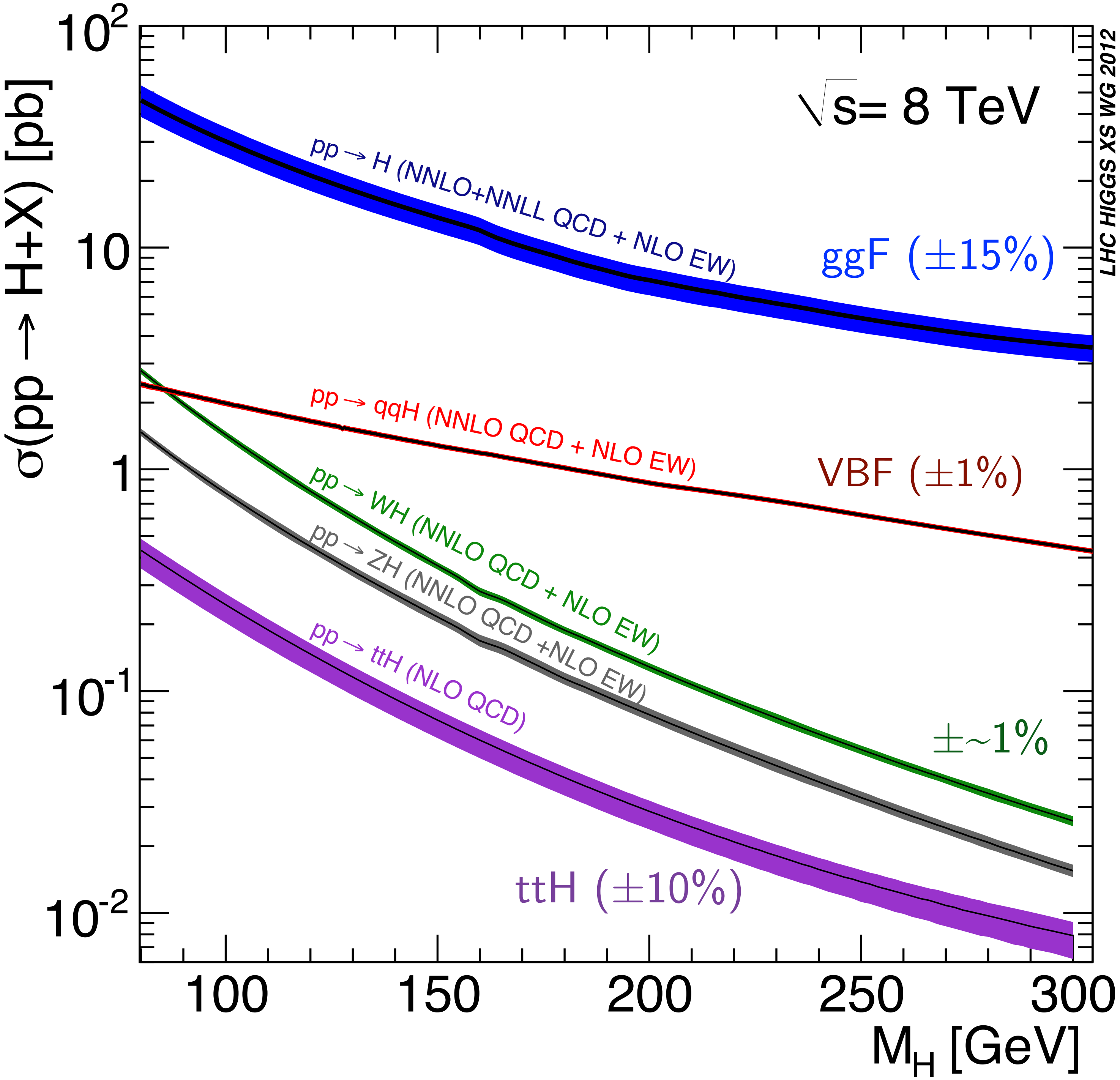


- Excellent performance of both ATLAS and CMS detectors!
  - ~20/fb of data at 8 TeV
  - ~5/fb of data at 7 TeV



Higgs Production at the LHC

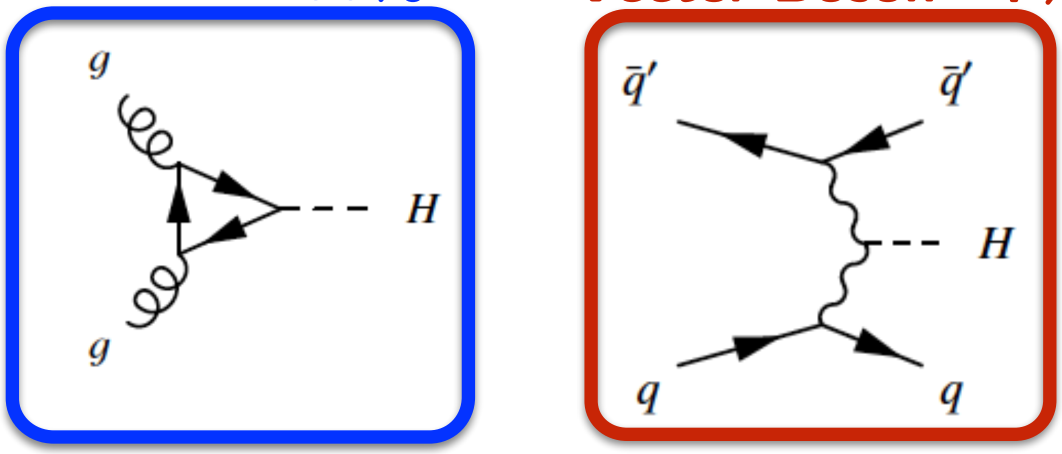
- Total cross-sections calculated to better than 15%.



Fusion

Gluon - 90%

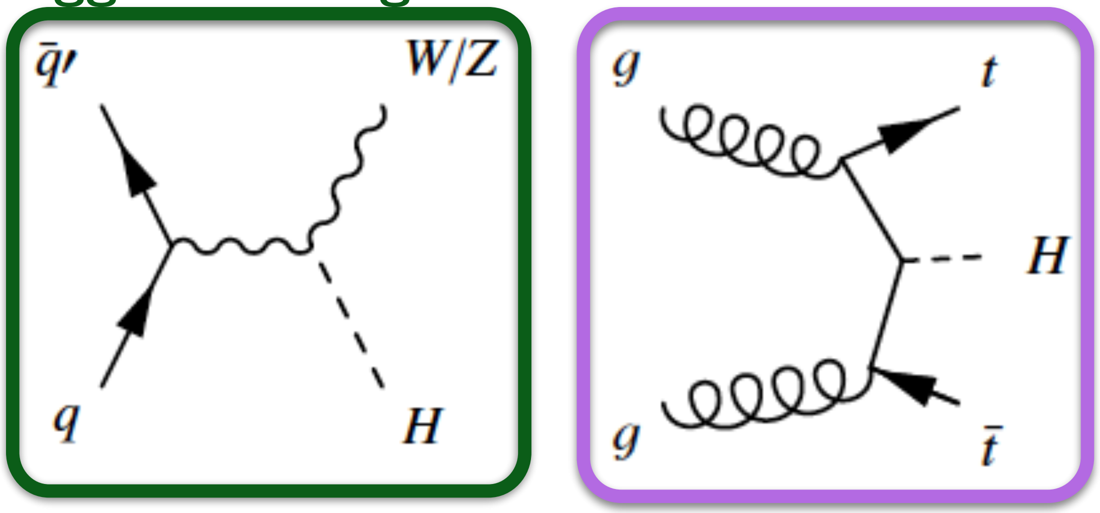
Vector-Boson - 7%



Associate Production

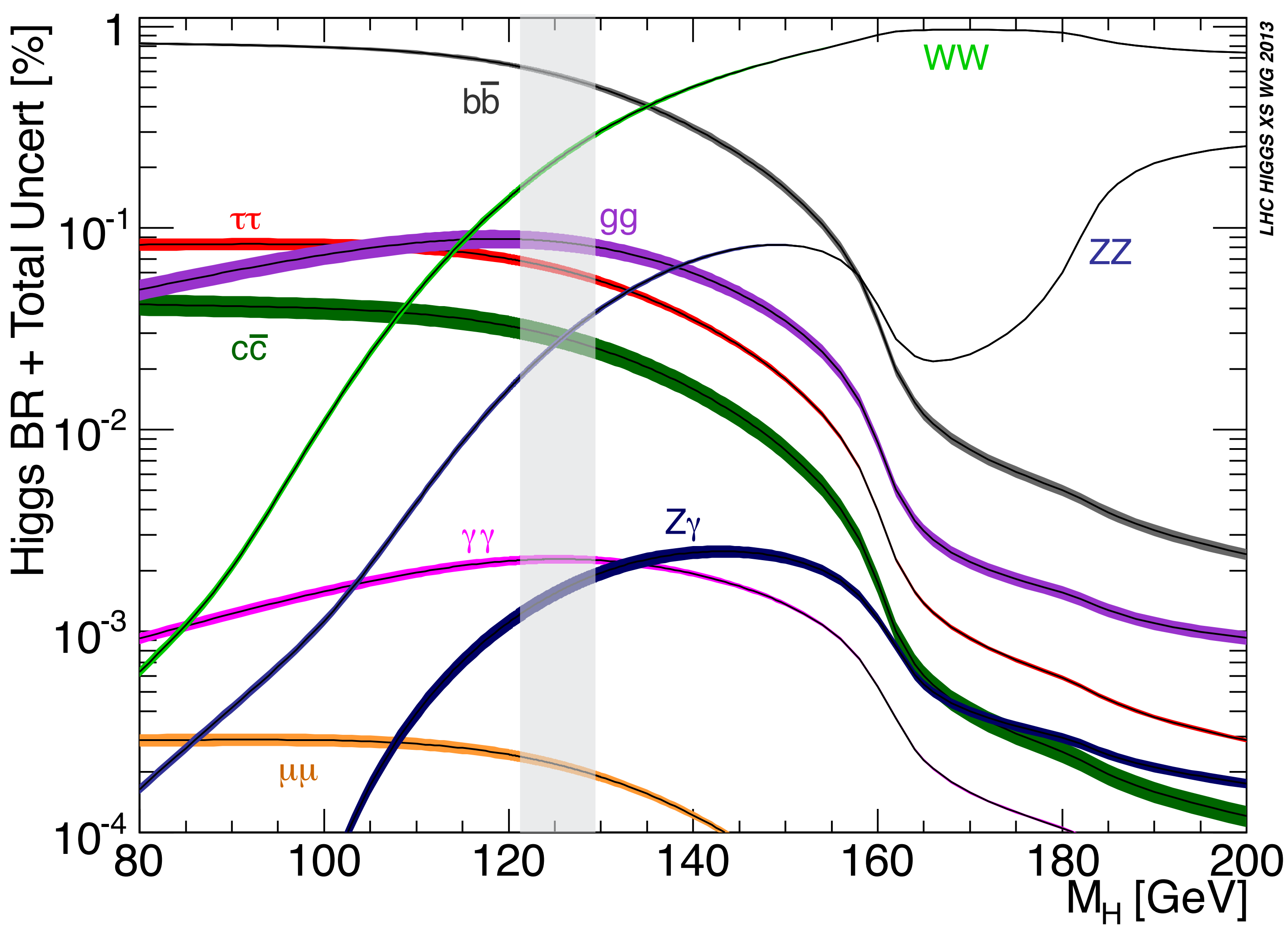
Higgs-strahlung - 2%

ttH - 1%



Signatures

- Experimental dream: 125 GeV gives access to all decays!

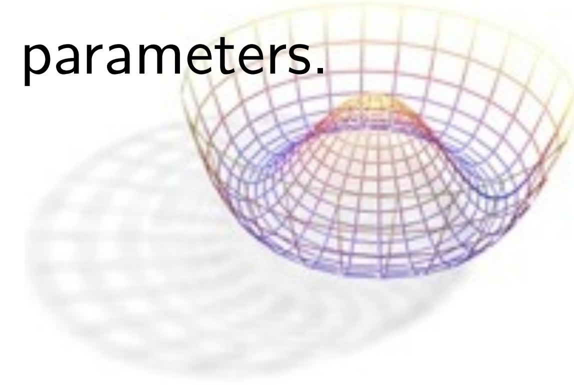


- Precise measurements depend on the signatures and furthermore on performances:
  - bb: b-tagging
  - WW: charged leptons, missing energy
  - gg/qq/ττ: jet measurements
  - ZZ: charged leptons
  - γγ: EM signature

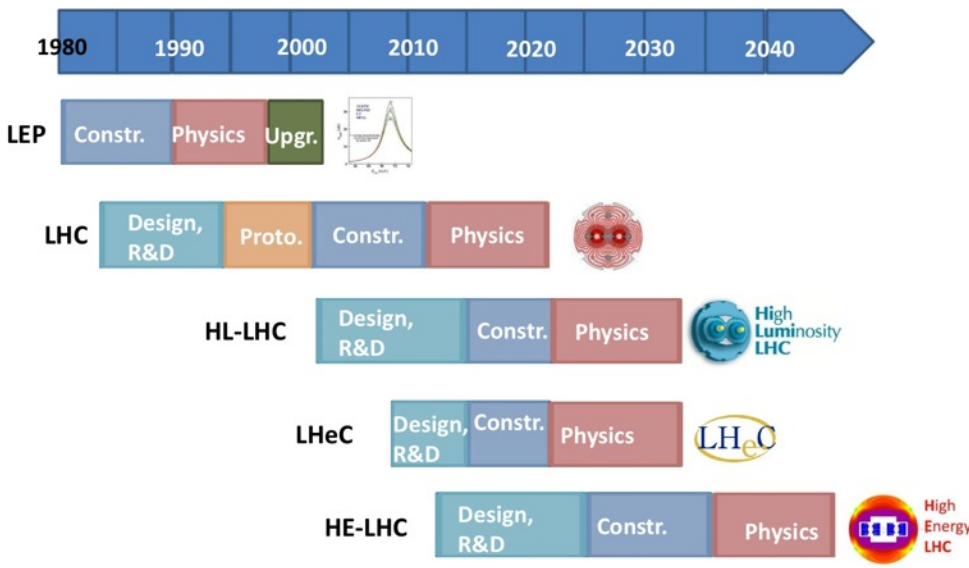
Important contributions at LAPP/LPSC by combining the experience of detectors, e/γ/jet/MET performances, data quality, and physics analysis groups.

Higgs Boson

- Characterise by measuring the basics: physical properties and SM scale parameters.



- Accessible today (with 25/fb):
  - Mass: the position of the resonance
  - Signal strength ($\mu = \sigma/\sigma_{SM}$) and production modes (μ_i)
  - Couplings ($\kappa_i = \Gamma_i/\Gamma$, $\lambda_i = \kappa_i/\kappa$)
  - Spin, parity, and differential cross-sections
  - Beyond the standard model (BSM): search for secondary resonances
- Accessible in the future:
  - Run-2 [2018, 100/fb] : All of the above with better precision.
  - Phase-1 [2022, 300/fb] : Rare decays
  - Phase-2 [HL-LHC, 2030, 3000/fb] :
    - Width
    - Deeper couplings (self, top)



For presentation purposes only, not an official schedule.

ATLAS Results

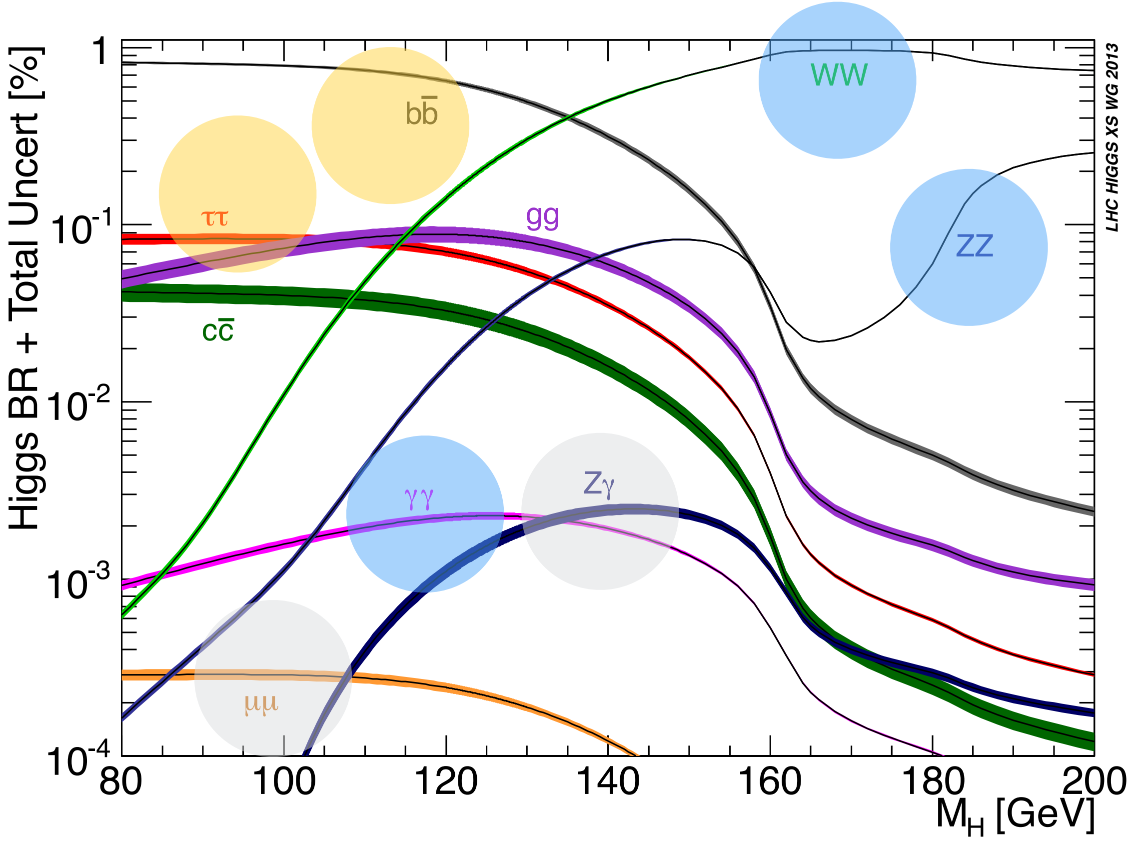
- Production of results is rich:

Higgs couplings and spin papers NEW

- Evidence for spin-0 nature of the Higgs boson using ATLAS data Paper and Plots
- Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC Paper and Plots

Higgs Results for Winter 2013 Conferences

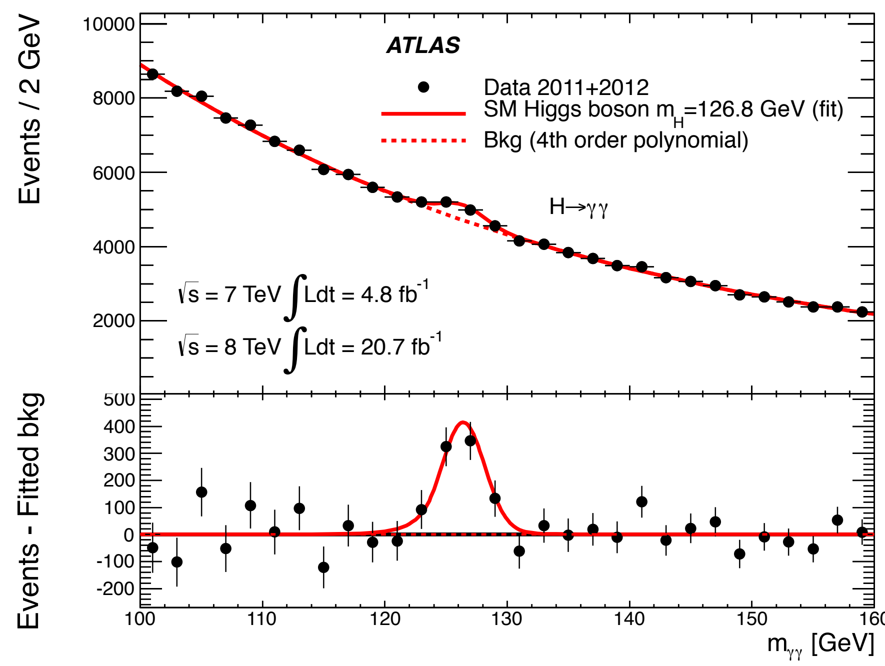
Channel	Conference note	L	Date
Spin Combination	ATLAS-CONF-2013-040	up to 25 fb-1	16/04/2013
Couplings Combination	ATLAS-CONF-2013-034	up to 25 fb-1	14/03/2013
Higgs to Diphoton spin	ATLAS-CONF-2013-029	21 fb-1	13/03/2013
Higgs to WW(lvlv) spin	ATLAS-CONF-2013-031	21 fb-1	11/03/2013
Higgs to WW(lvlv)	ATLAS-CONF-2013-030	25 fb-1	11/03/2013
2HDM WW(lvlv)	ATLAS-CONF-2013-027	13 fb-1	11/03/2013
Combined of Mass	ATLAS-CONF-2013-014	up to 25 fb-1	05/03/2013
Higgs to Diphoton	ATLAS-CONF-2013-012	25 fb-1	05/03/2013
Higgs to 4 leptons	ATLAS-CONF-2013-013	25 fb-1	05/03/2013
ZH (invisible decays)	ATLAS-CONF-2013-011	18 fb-1	05/03/2013
Higgs to dimuon	ATLAS-CONF-2013-010	21 fb-1	05/03/2013
Higgs to Zgamma	ATLAS-CONF-2013-009	25 fb-1	05/03/2013

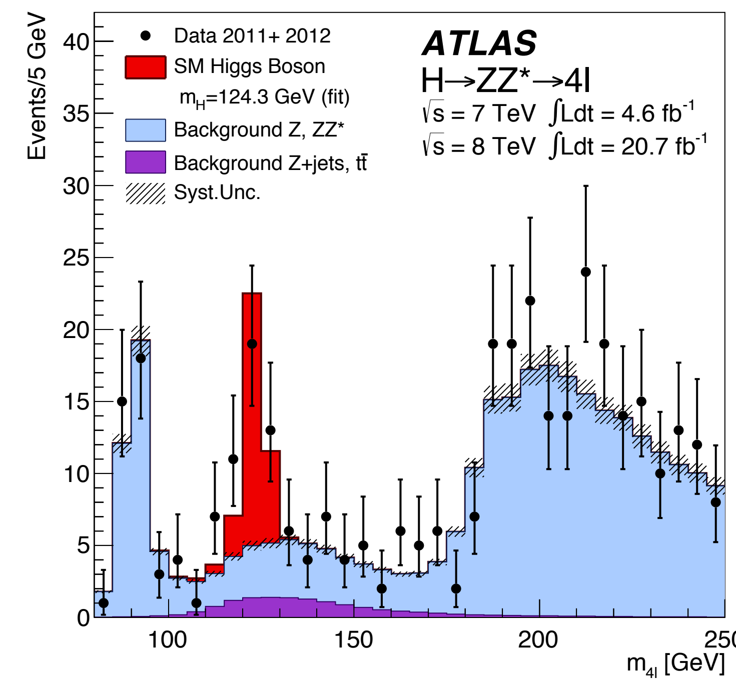


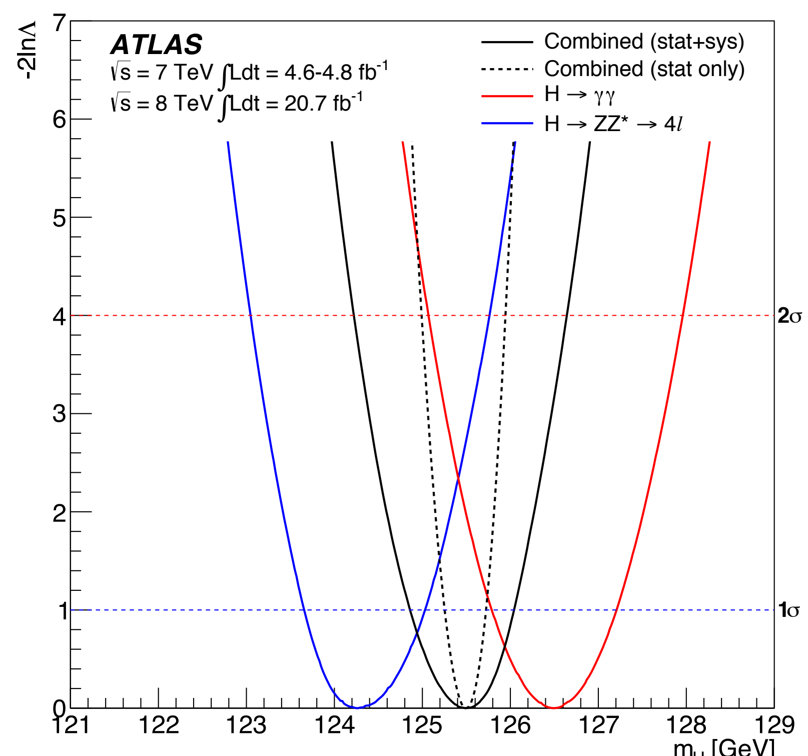
TWiki: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

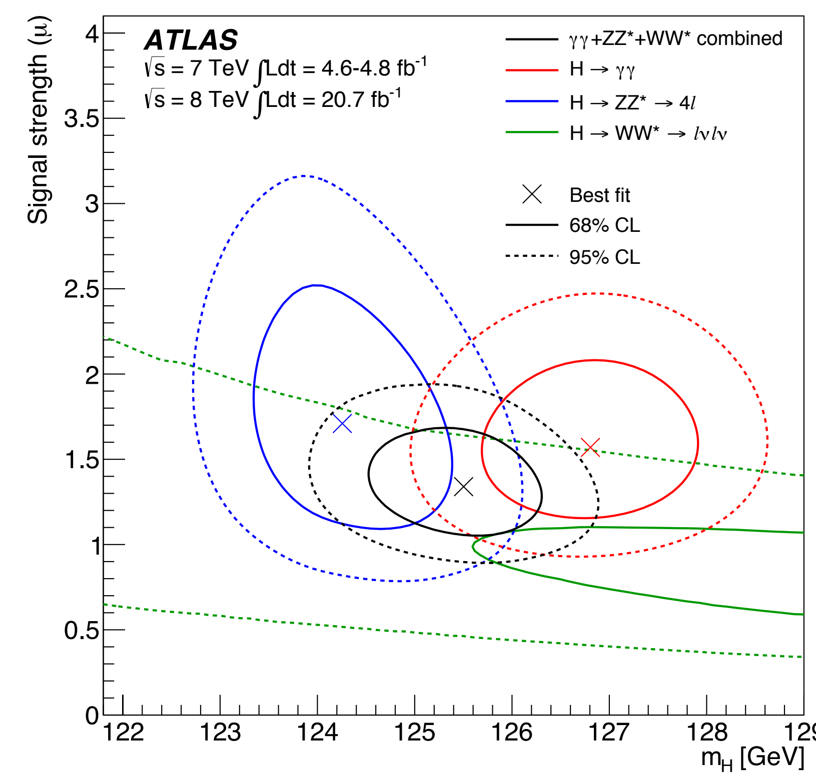
Mass

- Mostly high-resolution channels supported by higher-statistics channel:
  - High-resolution: $ZZ \to 4$ leptons, diphoton
  - Statistics: WW
- Mass difference of 2.3GeV.
  - Compatibility of 8% between measurements with conservative systematics estimates.





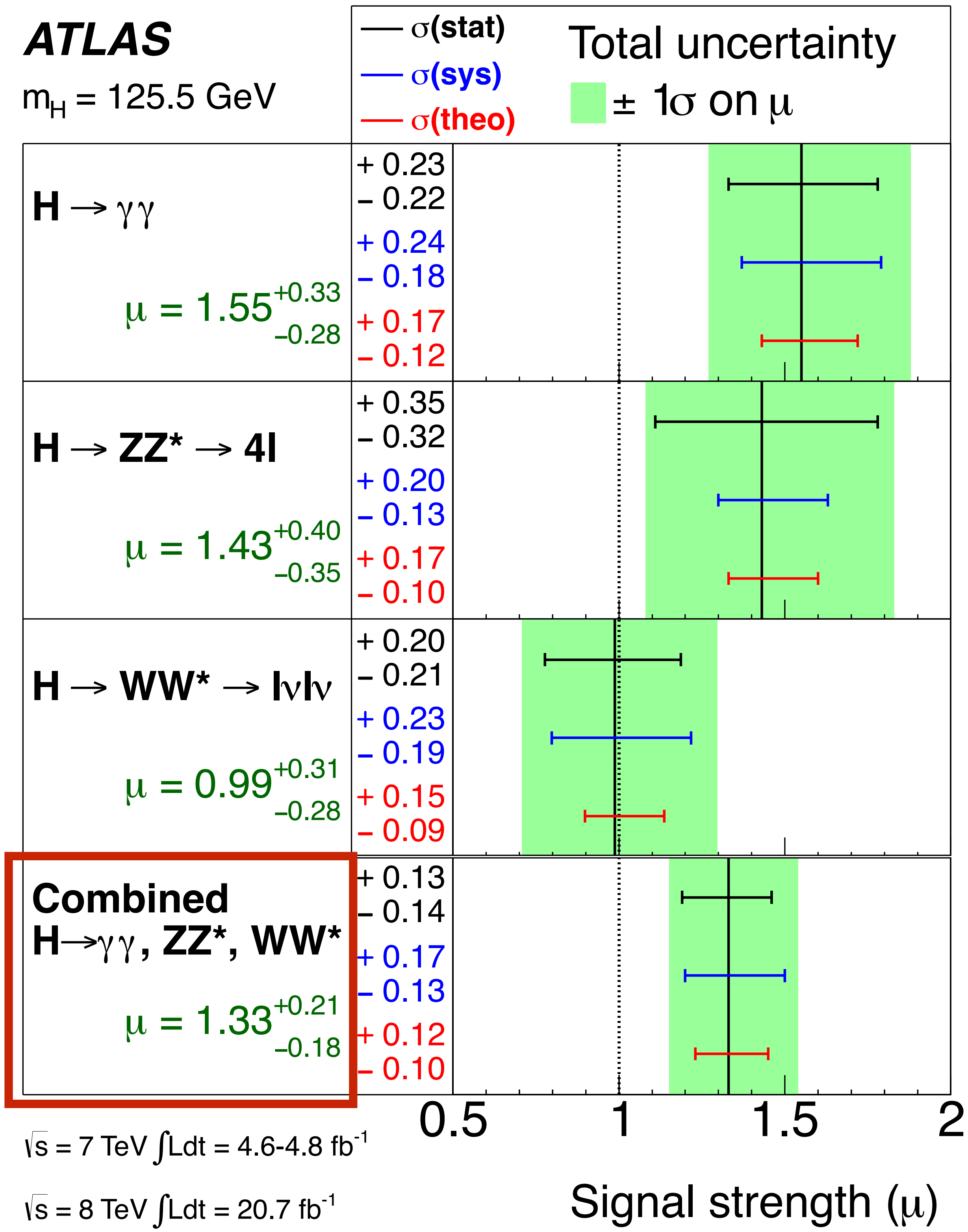


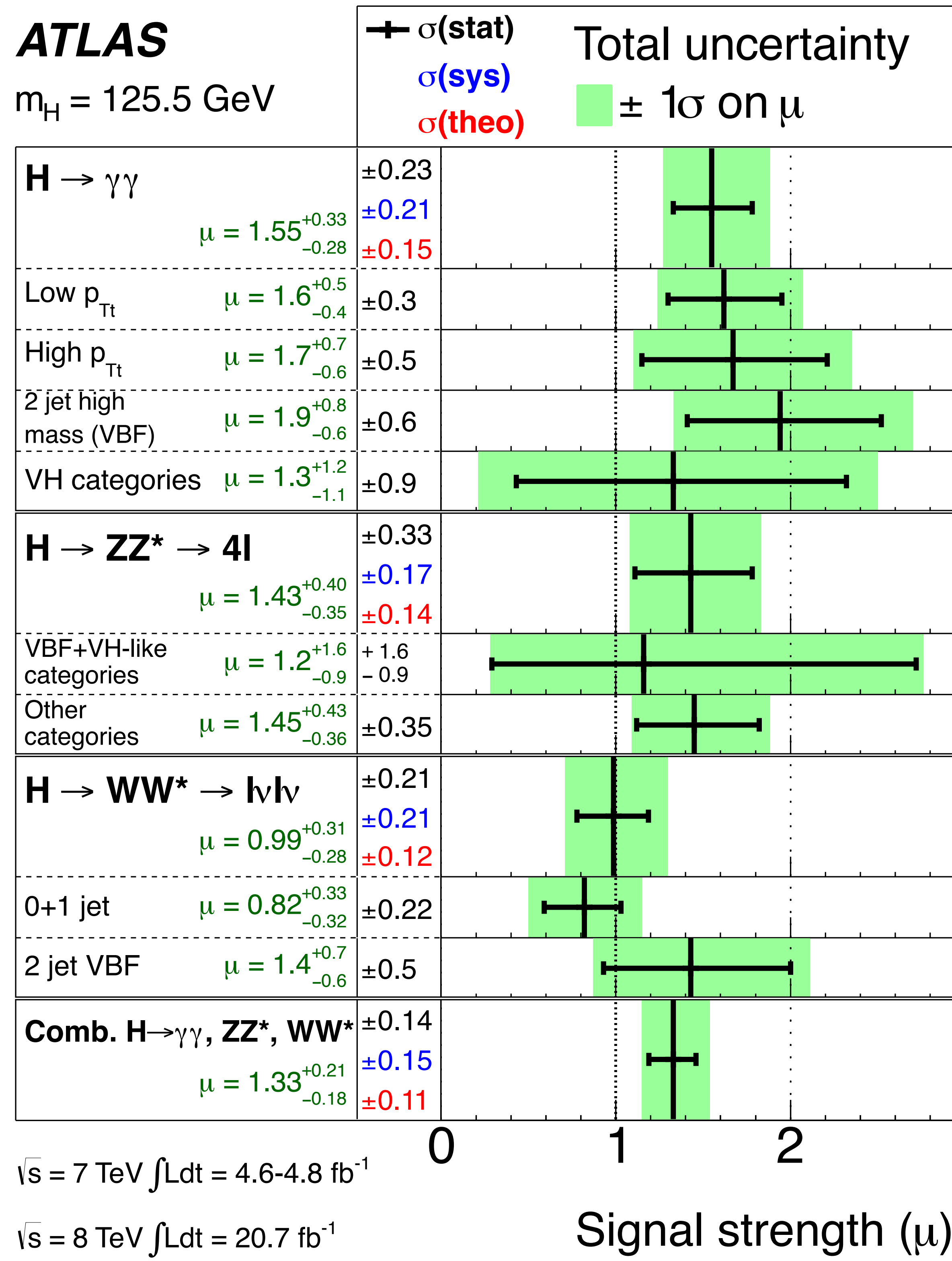


$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\ \text{GeV}$$

Phys. Lett. B 726 (2013), pp. 88-119

Signal Strength





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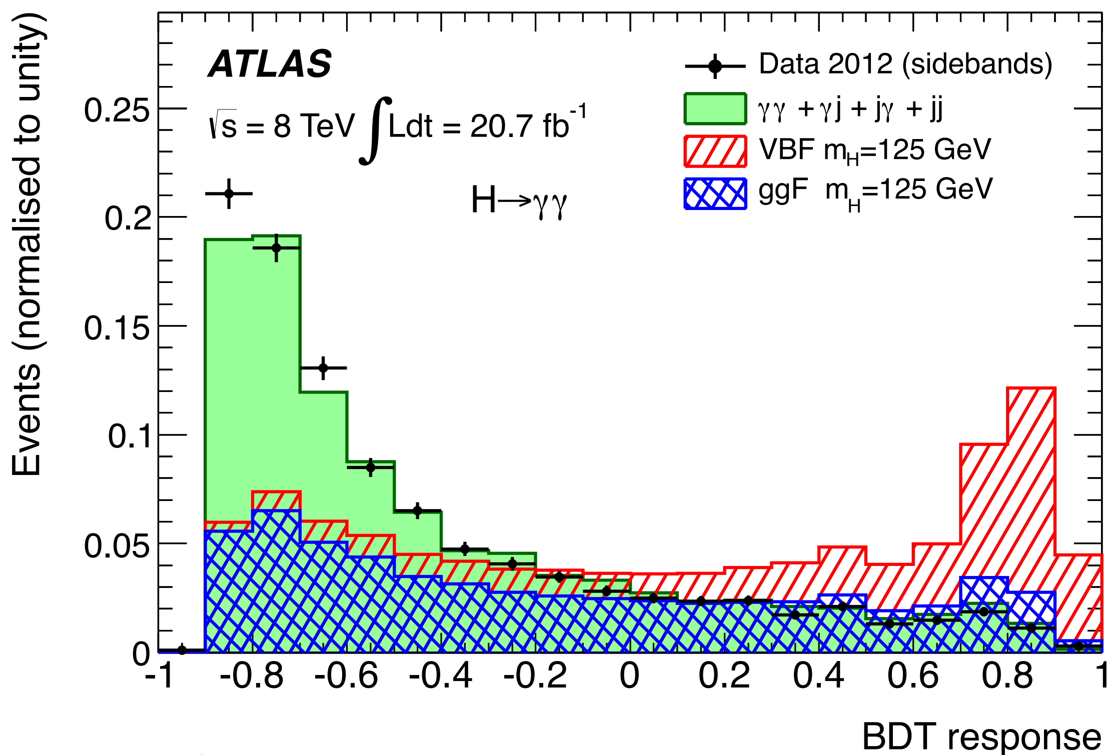
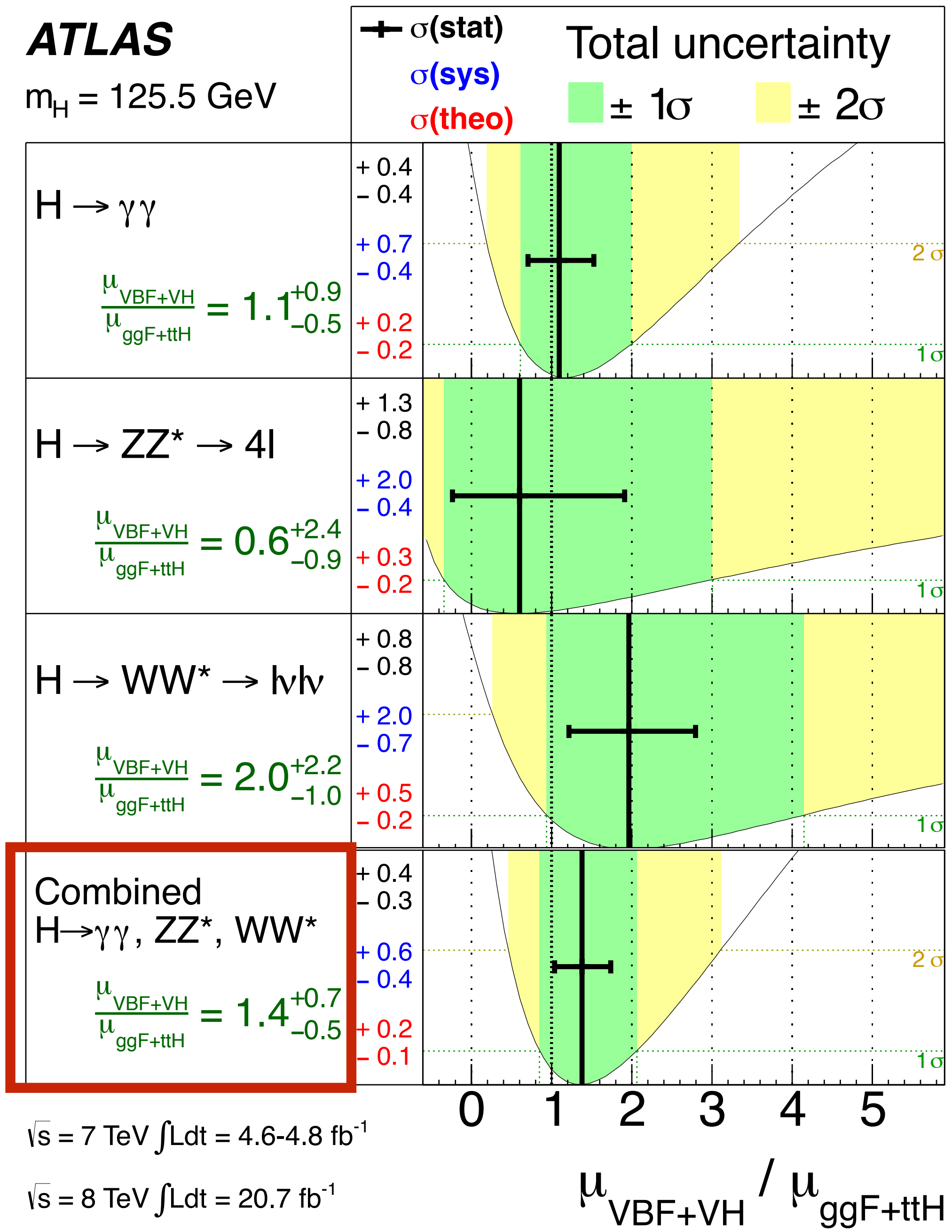
Production Modes

- Group the production modes with the mediator:
  - fermions (ggH and ttH)
  - boson (VBF and VH)
- Measure the ratio $\mu_{VBF+VH}/\mu_{ggF+ttH}$ to eliminate the different branching ratios.



Important contributions at LAPP for the VBF +VH channels, within the H → γγ group



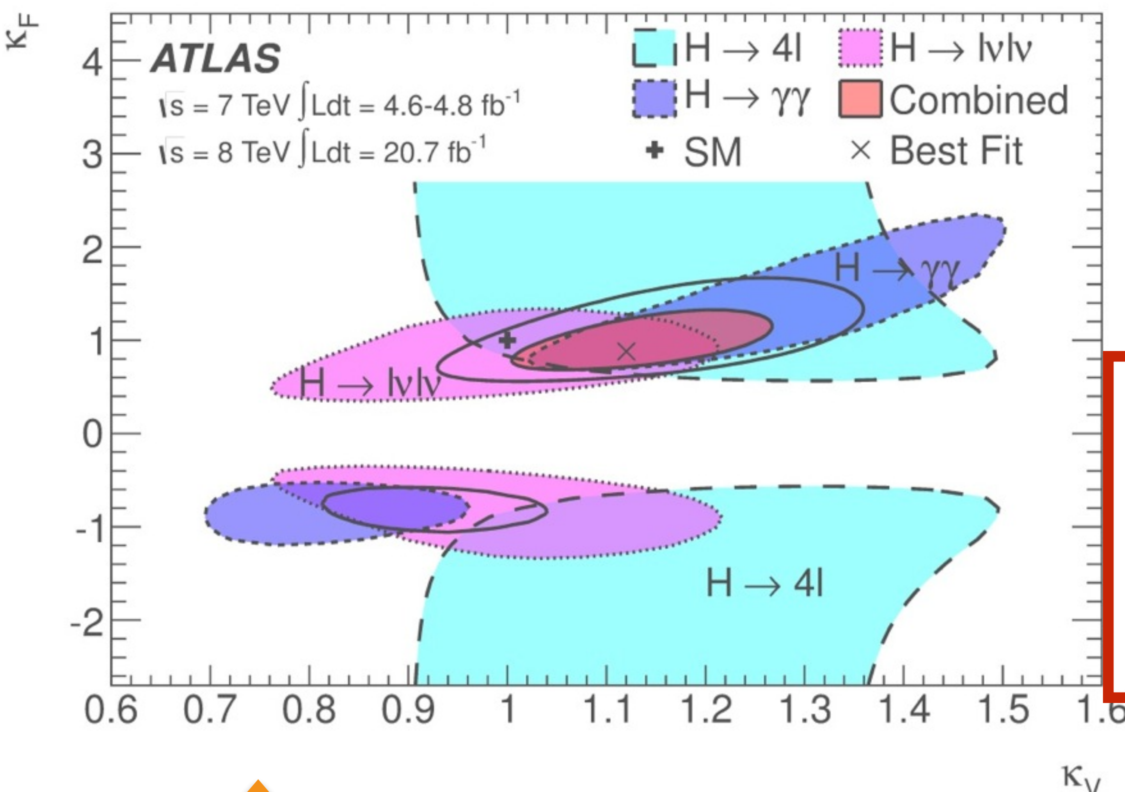
This result provides evidence at the 3.3σ level that a fraction of Higgs boson production occurs through VBF!

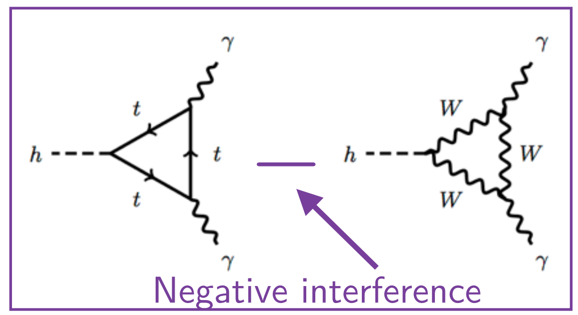
Phys. Lett. B 726 (2013), pp. 88-119

Couplings

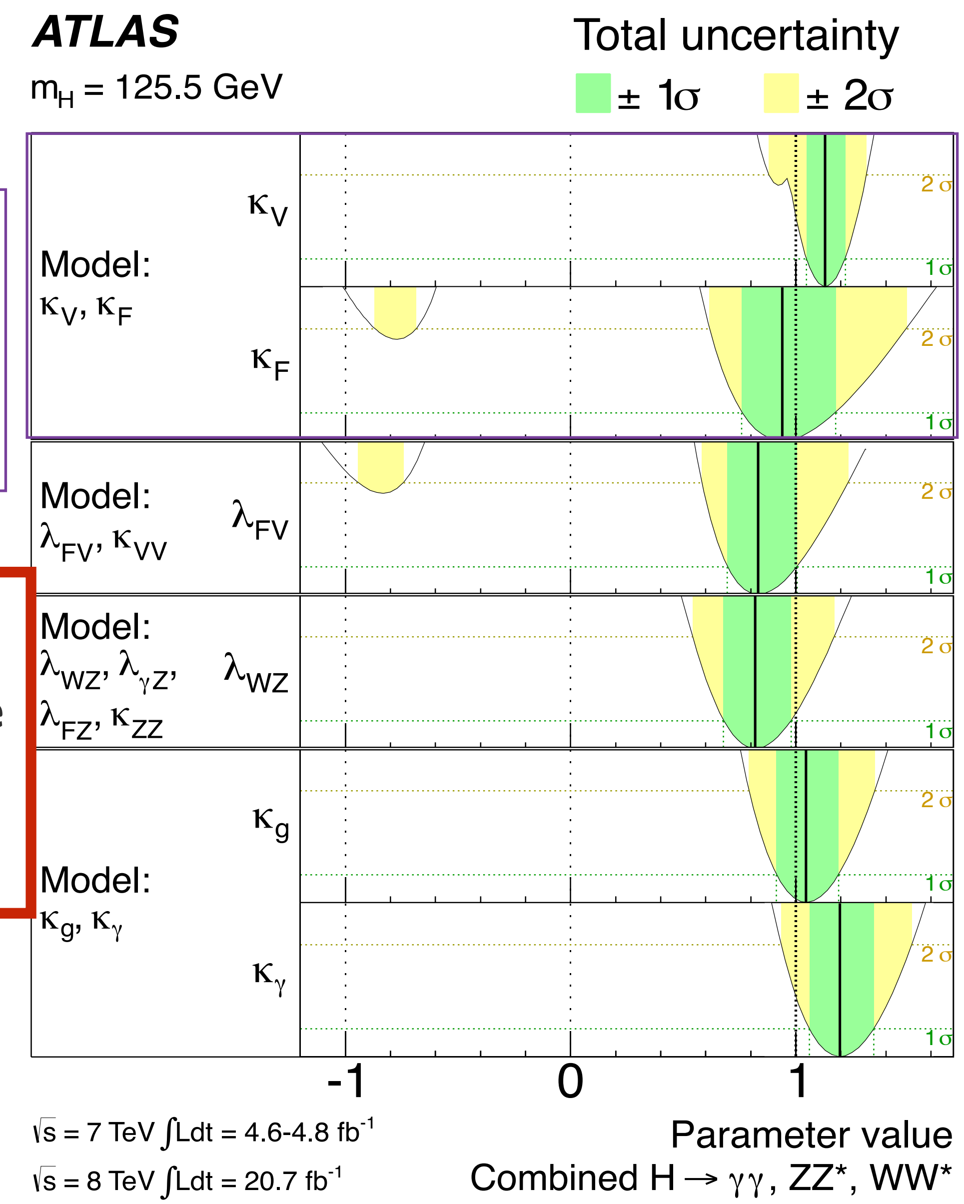
- Different benchmark scenarios with simple assumptions:
  - Single resonance
  - Zero-width approximations
  - SM Lagrangian structure unaltered: JP = 0+ (next slide)

Probed couplings	Parameters of interest
Couplings to fermions and bosons	κ_V, κ_F
	$\lambda_{FV}, \kappa_{VV}$
Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$
	$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$
Vertex loops	κ_g, κ_γ





Compatible with SM. Data prefers a positive relative sign between the κ's, as in the SM.



Important contributions at LAPP within the H → γγ and statistical combination groups.

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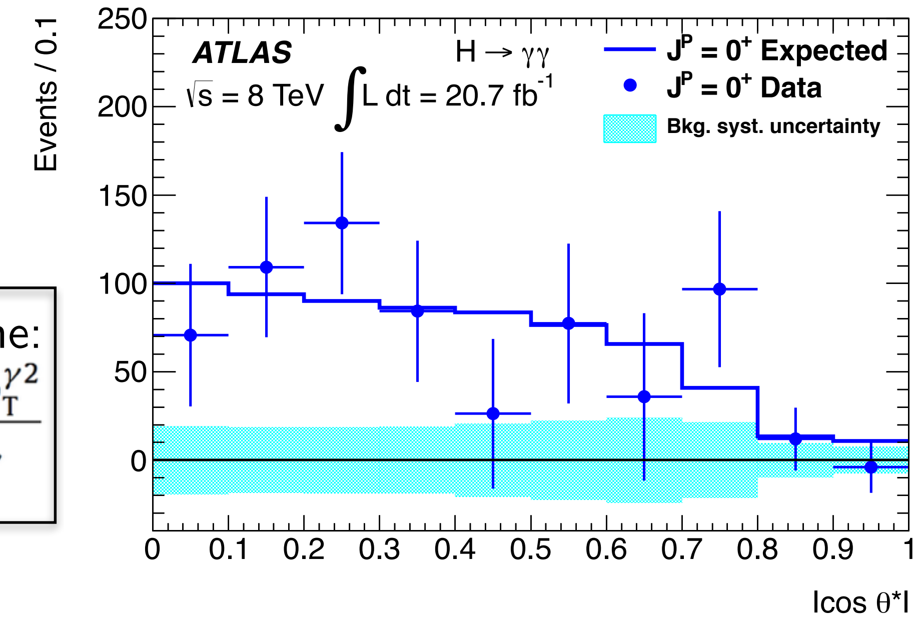
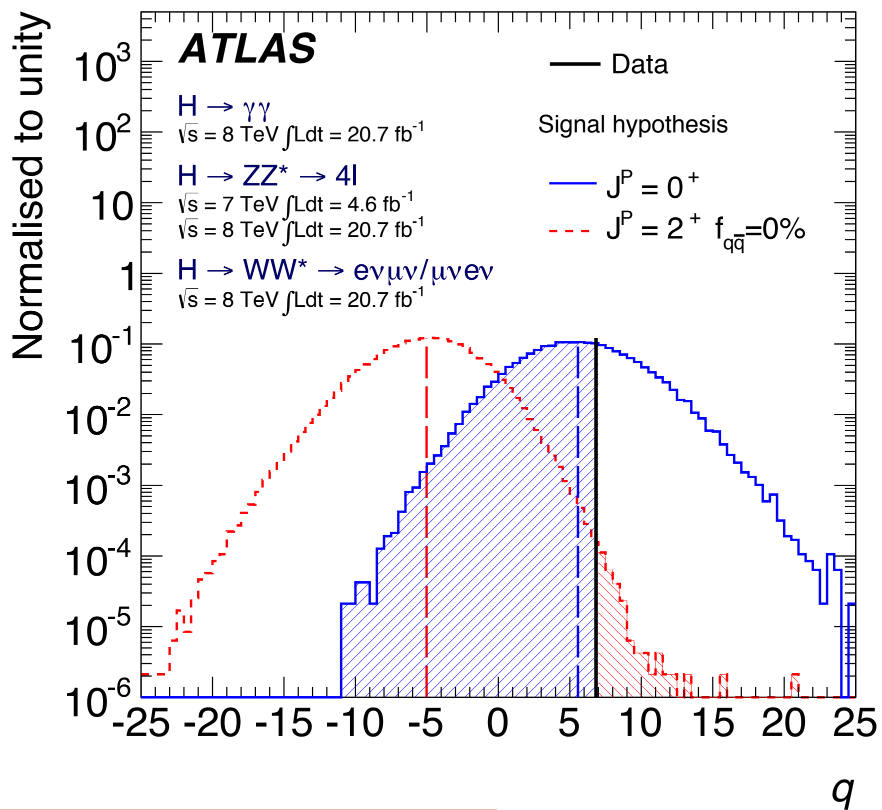
Spin and Parity

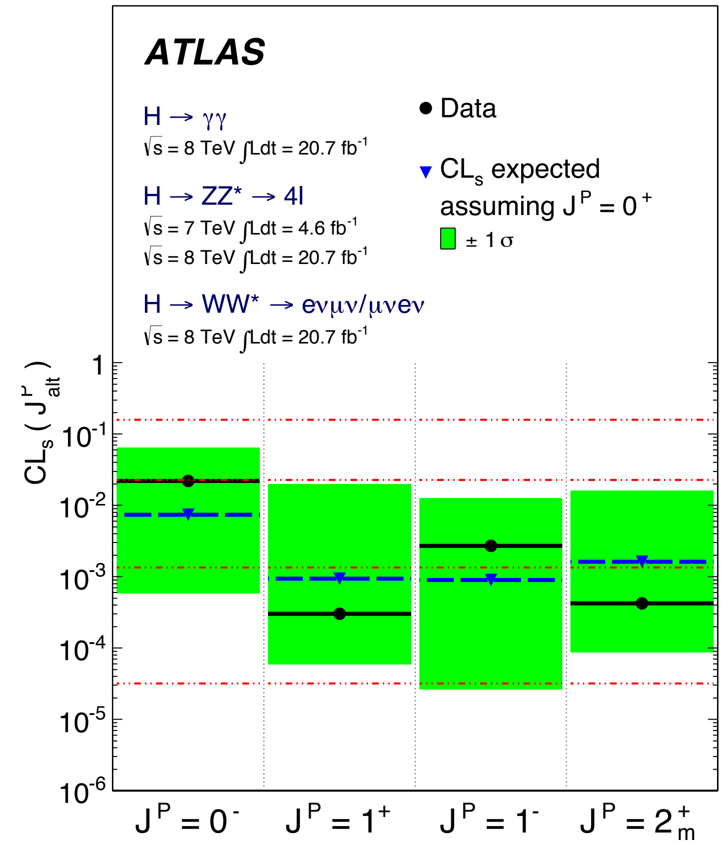
- Invariant mass used to discriminate signal and backgrounds.
- Rely on angular distributions for each spin hypotheses.
- Tested hypotheses:
  - JP = 0+,0-,1+,1-,2+
  - Data favour J=0 or J=2 because of γγ
    - cf. Landau-Yang theorem
  - ZZ rejects 0- alone
  - ZZ and WW rejects 1+,1- at 99.7%CL
  - 2+ rejected at 99.9%CL

H → γγ : Collins-Soper frame:

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\,\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$







SM expectation favoured: Spin-0, positive parity.

Phys. Lett. B 726 (2013), pp. 120-144

Tagging it 'Standard'

- Mass: $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
- Strength: $\mu = 1.33 \pm 0.14(\text{stat}) \pm 0.15(\text{sys})$
- VBF evidence: 3.3σ $\mu_{\text{VBF}}/\mu_{\text{ggF}+ttH} = 1.4^{+0.4}_{-0.3}\,(\text{stat})^{+0.6}_{-0.4}(\text{sys})$
- Couplings:
  - constrained at $\pm$10%
  - no significant anomalous contributions to gg $\rightarrow$ H and H $\rightarrow$ γγ loops observed.
- Spin:
  - evidence for the spin-0 nature
  - positive parity strongly preferred.
- Conclusion: we have found the first scalar boson of the SM.

Similar conclusions at CMS

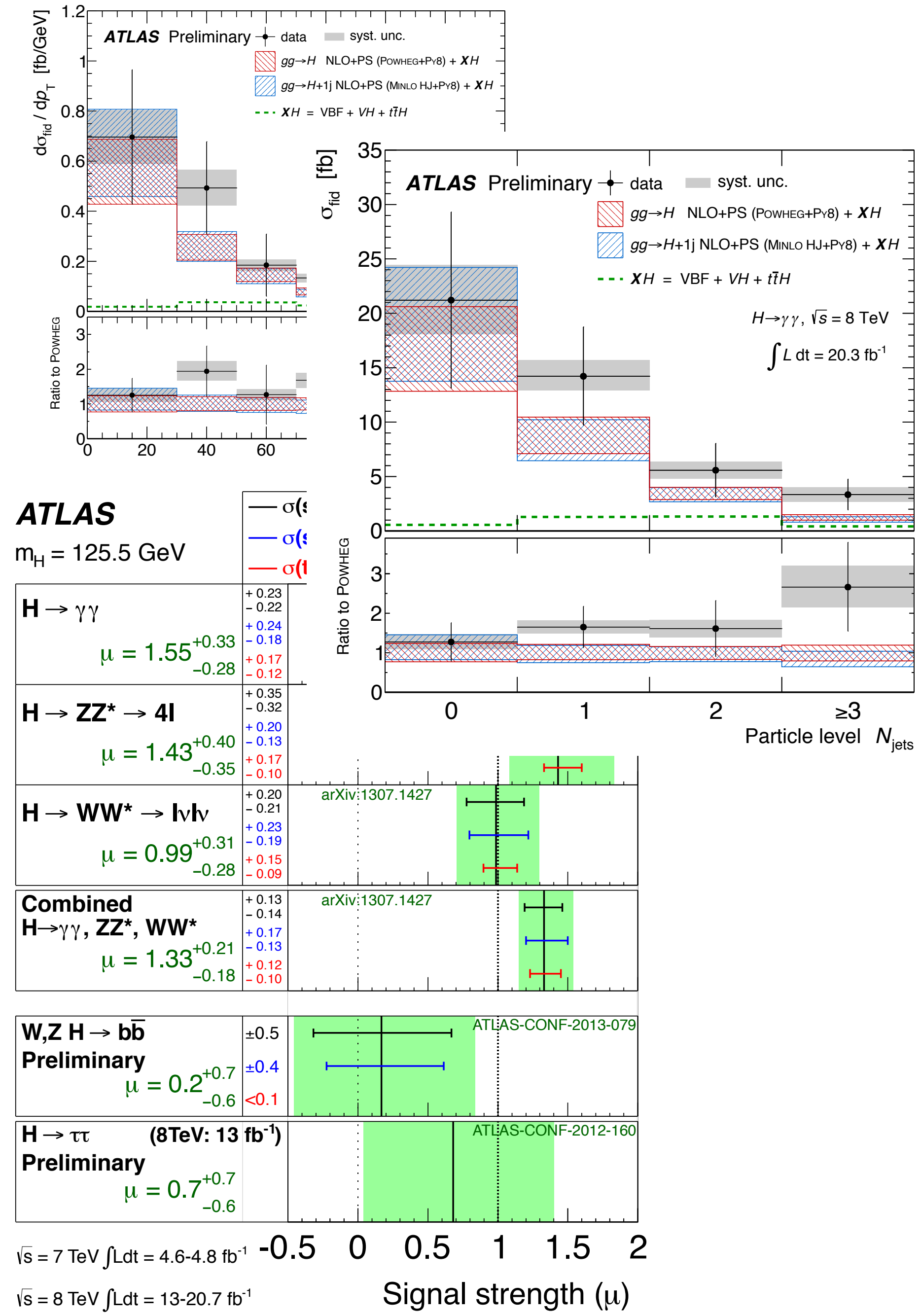
Looks a lot like the Standard Model!

ATLAS Latest Results

- There are more interesting searches and measurements:

Higgs Results for 2013 Summer Conferences NEW

Channel	Conference note	L	Date
Charged Higgs tau nu + jets	ATLAS-CONF-2013-090	20 fb-1	27/09/2013
High Mass WW(lvlv)	ATLAS-CONF-2013-067	21 fb-1	18/07/2013
Higgs to Diphoton differential cross sections	ATLAS-CONF-2013-072	21 fb-1	18/07/2013
Higgs in VH(WW)	ATLAS-CONF-2013-075	25 fb-1	18/07/2013
Higgs in VH(bb)	ATLAS-CONF-2013-079	25 fb-1	18/07/2013
ttH (diphoton)	ATLAS-CONF-2013-080	20 fb-1	25/07/2013
FCNC top to Higgs (diphoton) Charm	ATLAS-CONF-2013-081	25 fb-1	25/07/2013

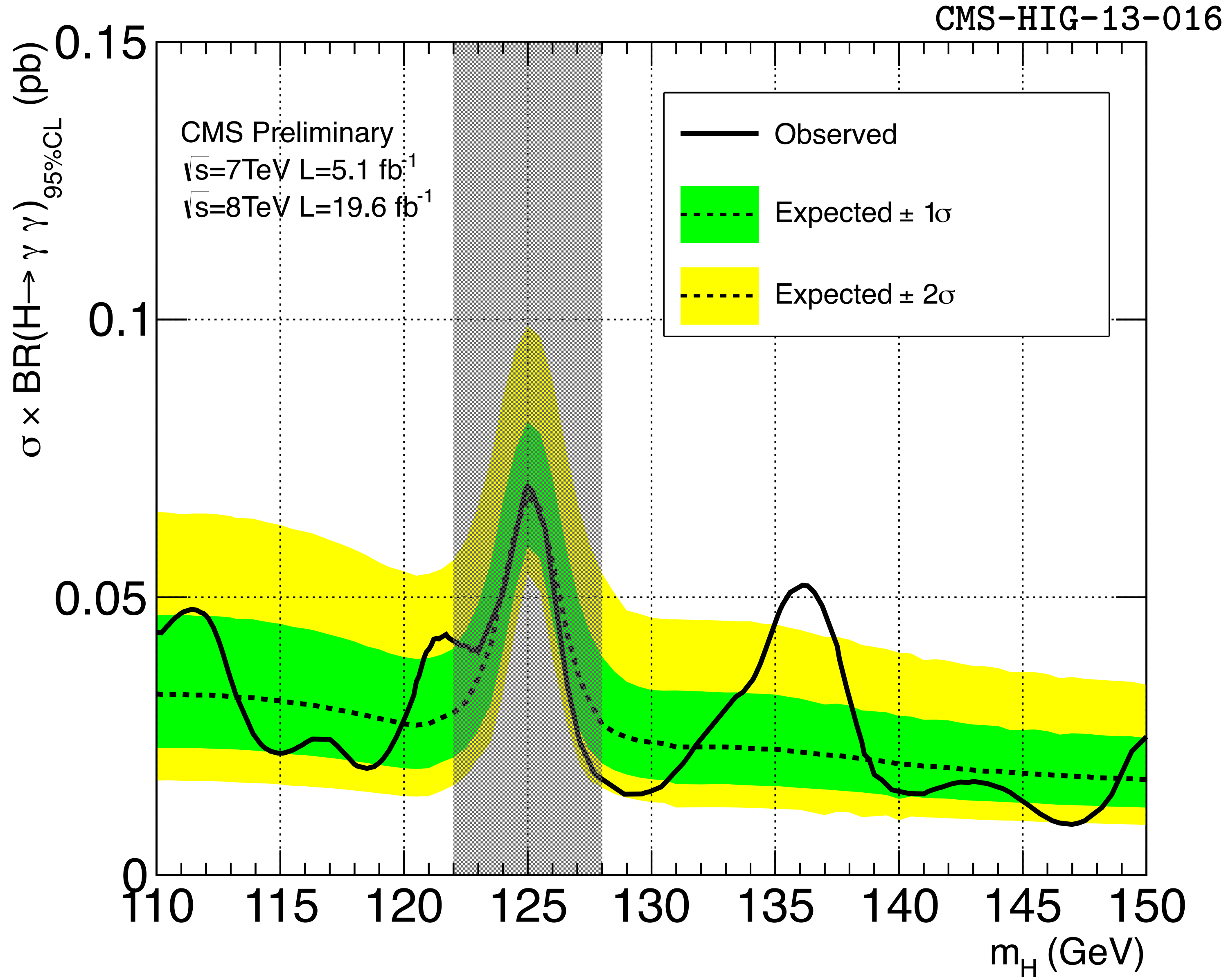


- No time to go in details, unfortunately...

TWiki: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

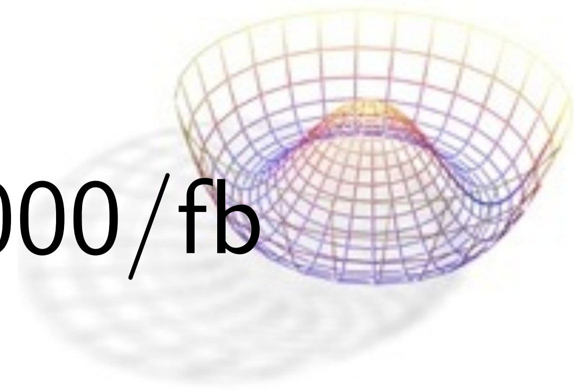
Upcoming Analysis

- Look for additional narrow resonance(s) in the $\gamma\gamma$ channel. Realistically, set a cross-section limit on such production.
  - Search for particles beyond the standard model (including Higgs).
  - Also motivated by the CMS "excess" at ~136 GeV.
- Made model-independent, and within a fiducial phase-space.
  - Many models predict such narrow resonances.
  - Anyone can test their favourite models against the fiducial cross-section limit.



Stay tuned!

Prospects

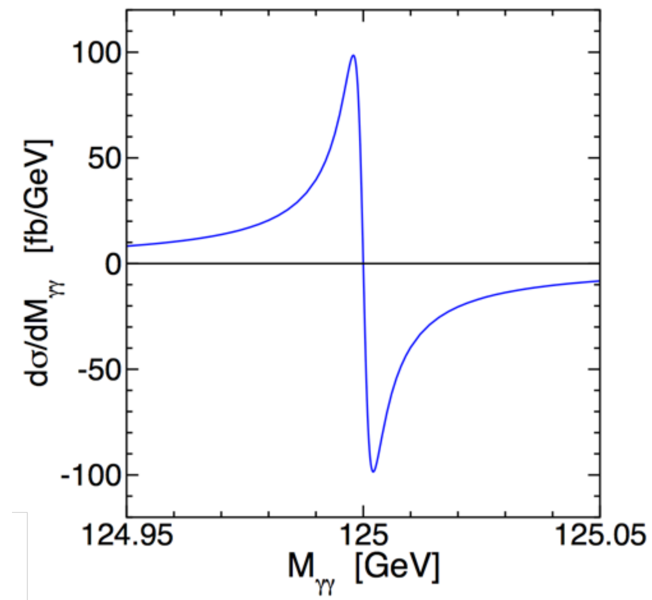


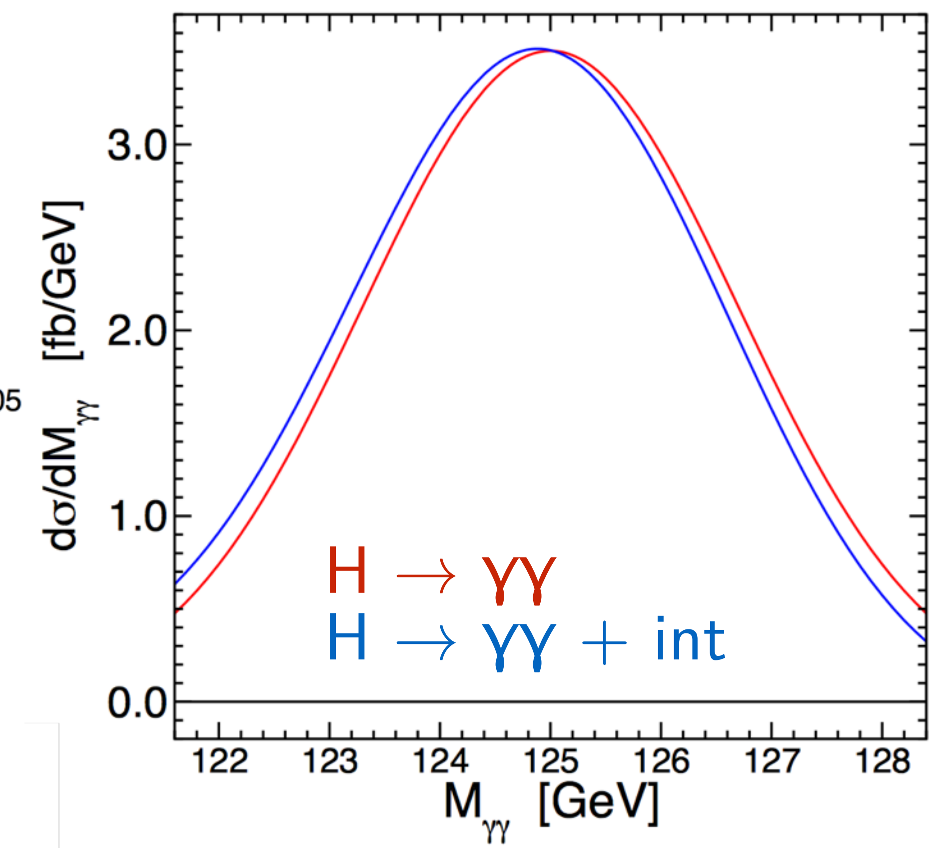
- Era of precision at the LHC: 300/fb — 3000/fb
  - Mass shall be known at ~50MeV
  - Couplings (ratios) will be determined to better than 10%
  - Access to rare decays (Zγ,μμ)
  - Access to rare couplings:
    - Self-coupling through bb final states
  - Width: access indirectly through γγ channel

Prospects: Higgs Width

- Interference between $H \to \gamma\gamma$ and $gg \to \gamma\gamma$ can become destructive.
  - Look for a mass shift in $m_{\gamma\gamma}$ and relate the shift to Γ.
- Analysis strategies:
  - Difference with non-$\gamma\gamma$ masses (independent channels).
  - Improve sensitivity with differential analysis:
    - Bins in $p_{T,H}$ could help the discrimination and cancellation of systematics.
    - Current prospects indicate the sensitivity could reach $10\Gamma_{SM}$ with 2/ab (95%CL).
  - Interest in French groups; ANR proposal submitted and under review!

arxiv: 1208.1533, 1305.3854

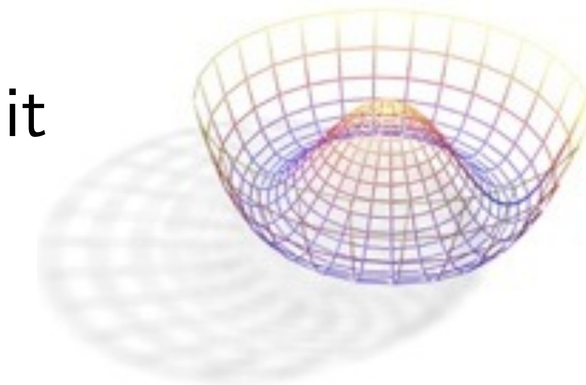




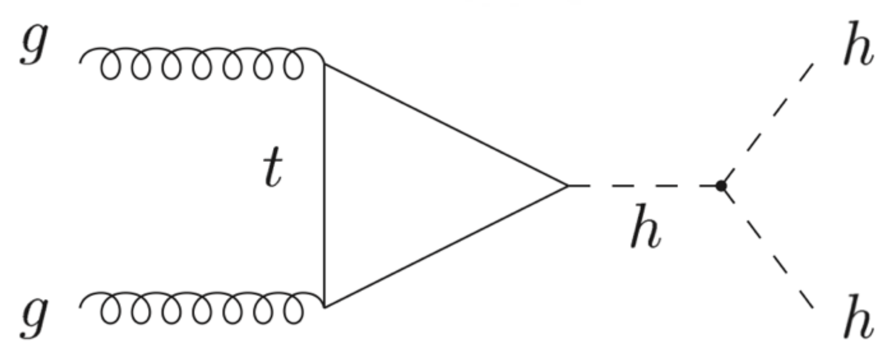
Interference term is odd around the central value

… pushes mass downwards

Prospects: Higgs Self-Coupling

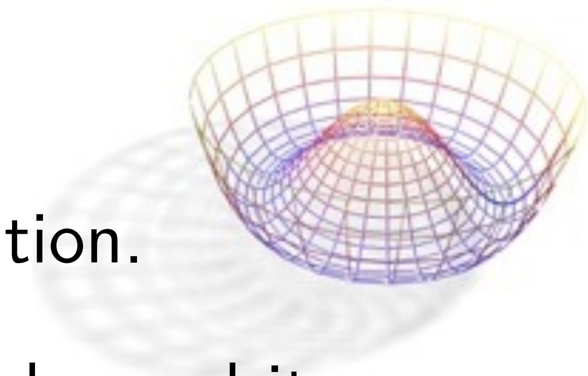


- To understand the physics behind the EW symmetry breaking, it is mandatory to measure the Higgs potential i.e. self-couplings.
- Look for the signature of two Higgs bosons: *hhh*
  - Combination of high-cross-section channels is necessary
    - bb, WW, ττ
    - Unlucky that $m_H \sim$ 125GeV, which makes b,τ channels harder.
    - Barely within reach with 3000/fb (30-40% precision, probably very optimistic)



- Interest in French groups, alongside with ATLAS upgrades
  - Experience acquired with the H → γγ channel, LAr upgrade.
  - Improve bb, Pixel (alpine) upgrade.
  - See Carolina's talk for more details about upgrades.

Summary and Outlook

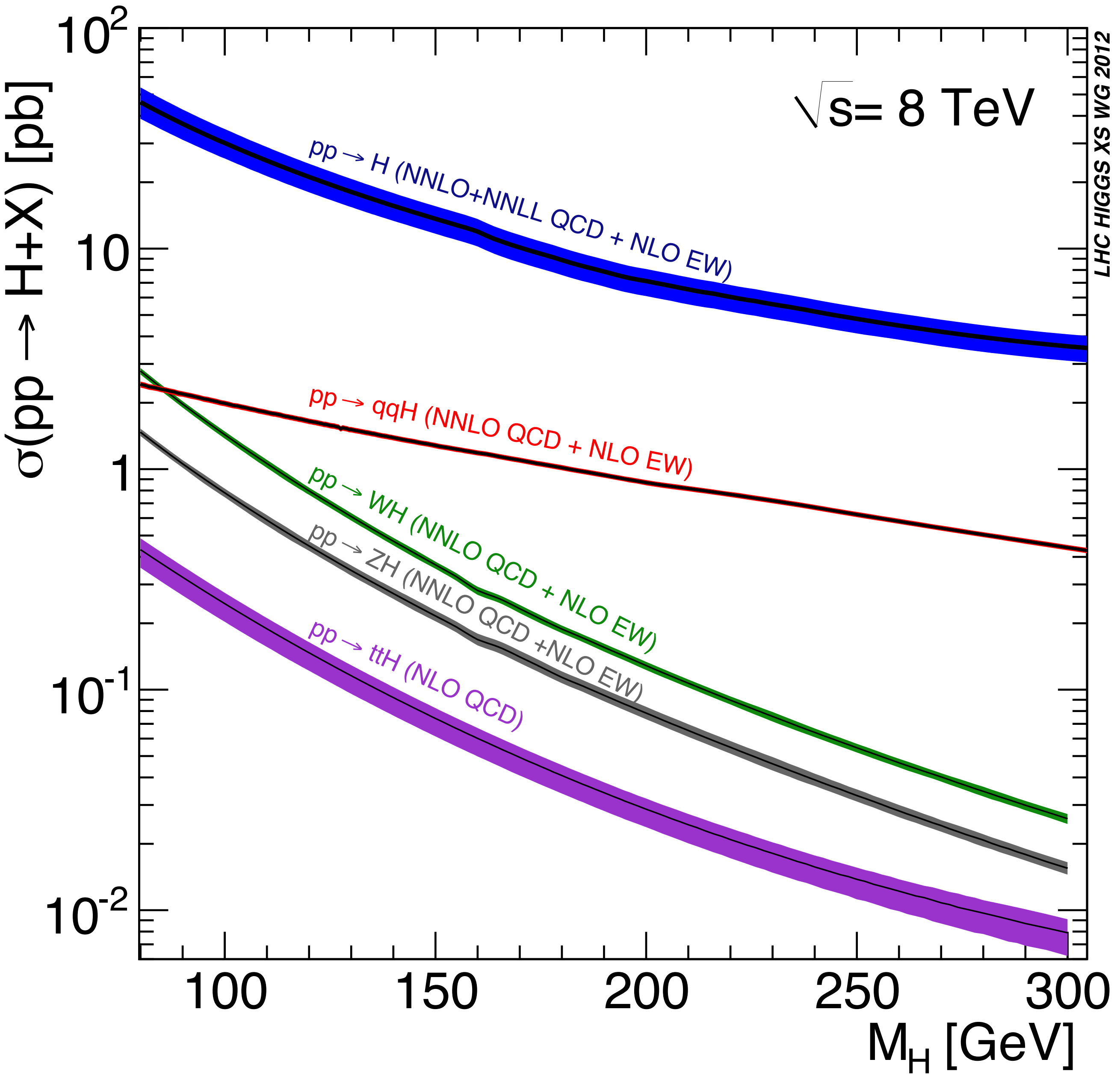


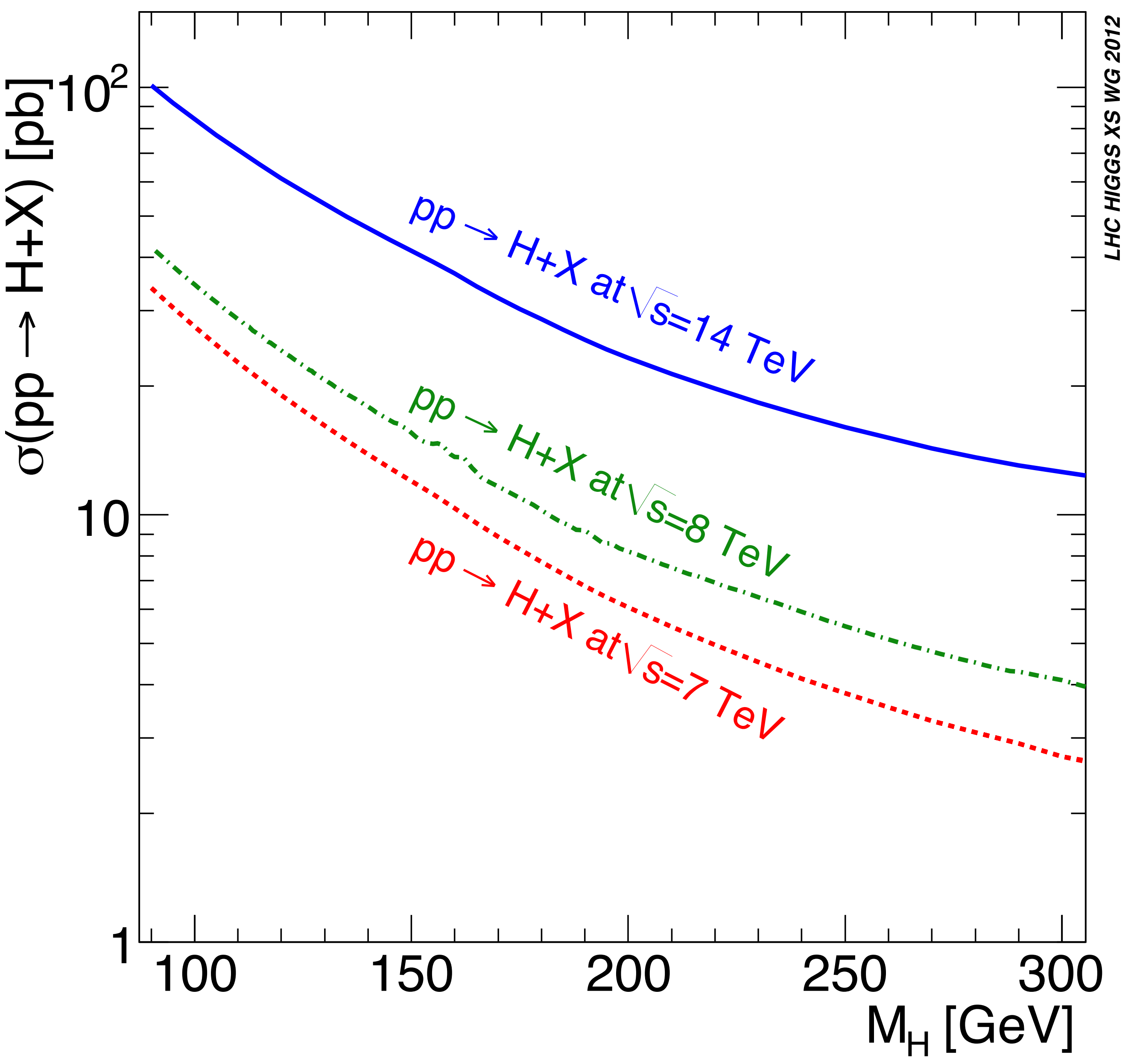
- **Summary:**
  - Early SM Higgs analyses already provided loads of information.
  - The SM survives, without outrageous signs of new physics beyond it.
- **Outlook:**
  - W/Z discovered at SppS ; really measured at LEP (and LHC).
  - top discovered and characterised at Tevatron ; really measured at LHC.
  - H discovered and characterised at LHC ; really measured at **[placeholder]**.
    - Always the possibility of discovering new physics while walking the path.
  - Interesting experiments and analyses will continue for a long time.
    - See you in 30 years...

Extra Material

Higgs Production at the LHC

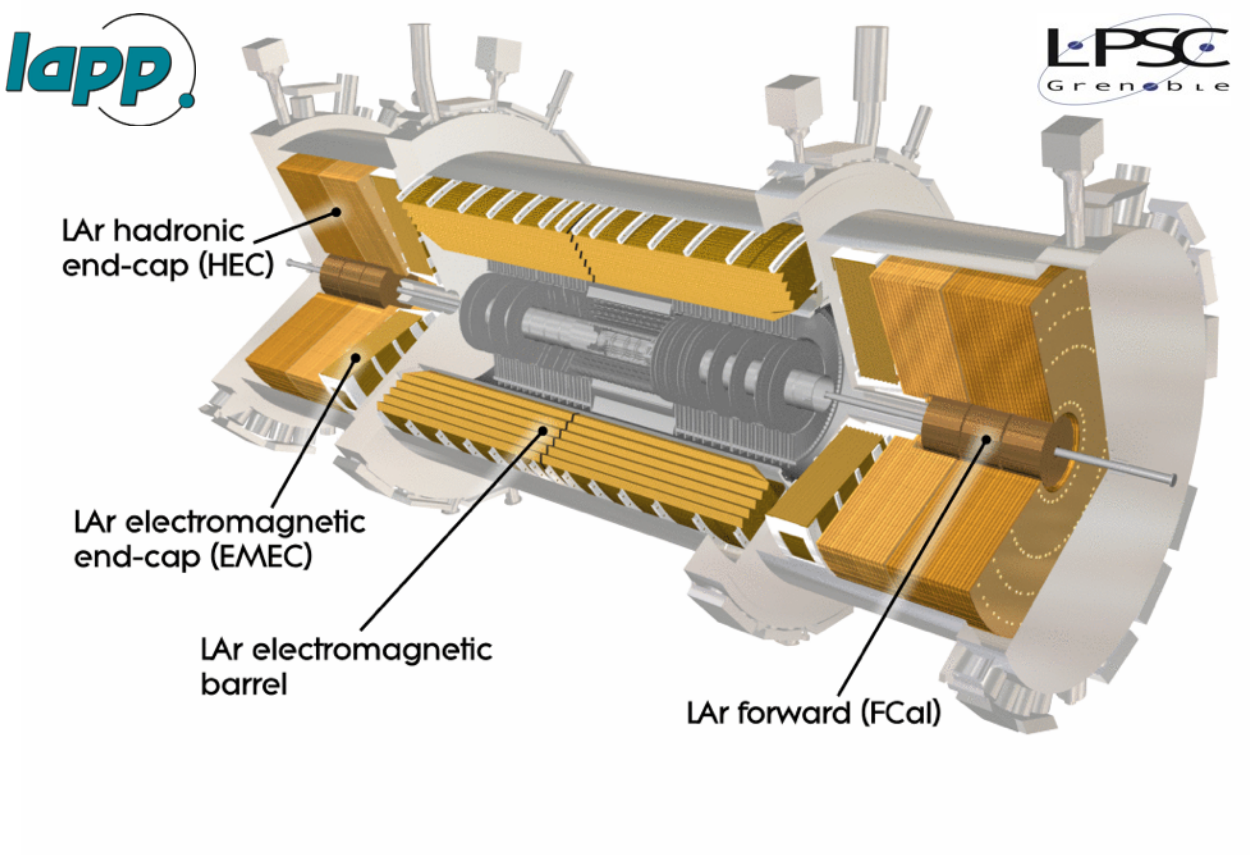
- Operating a higher center-of-mass energy helps a lot...

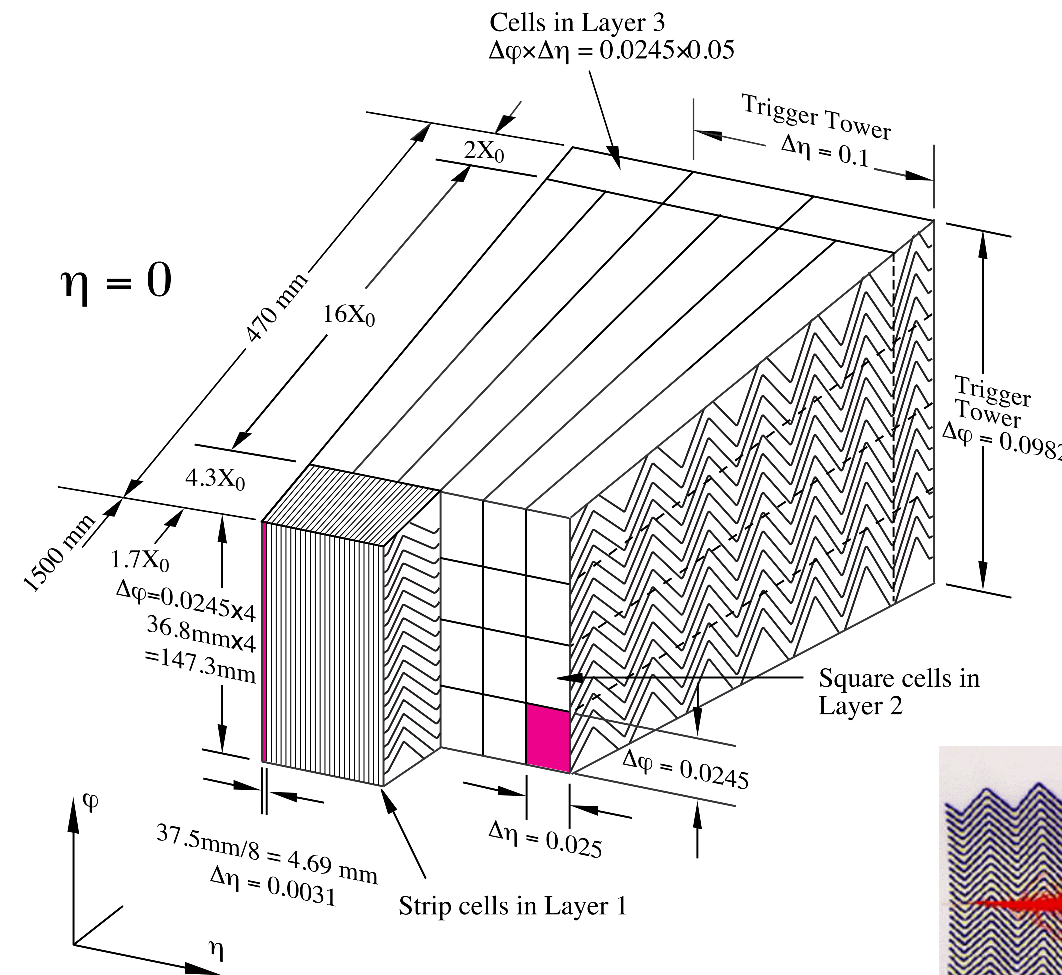




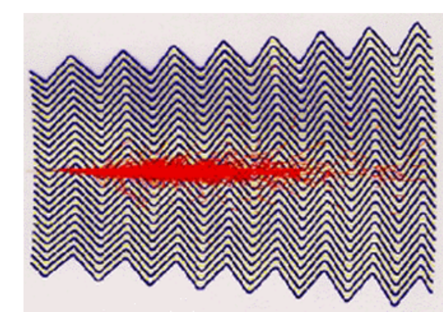
LAr Calorimeter

ATLAS Liquid Argon Calorimeter



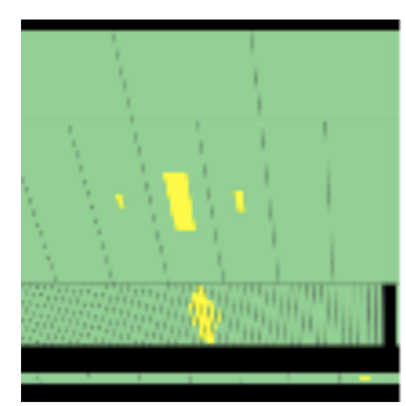


Full azimutal acceptance

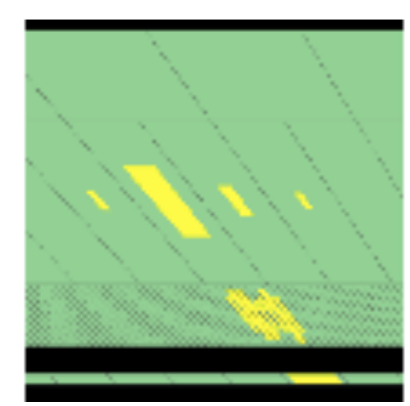


Contain the shower

- Precise energy measurements.
- High granularity:
  - Discrimination
  - Vertex reconstruction (pointing)



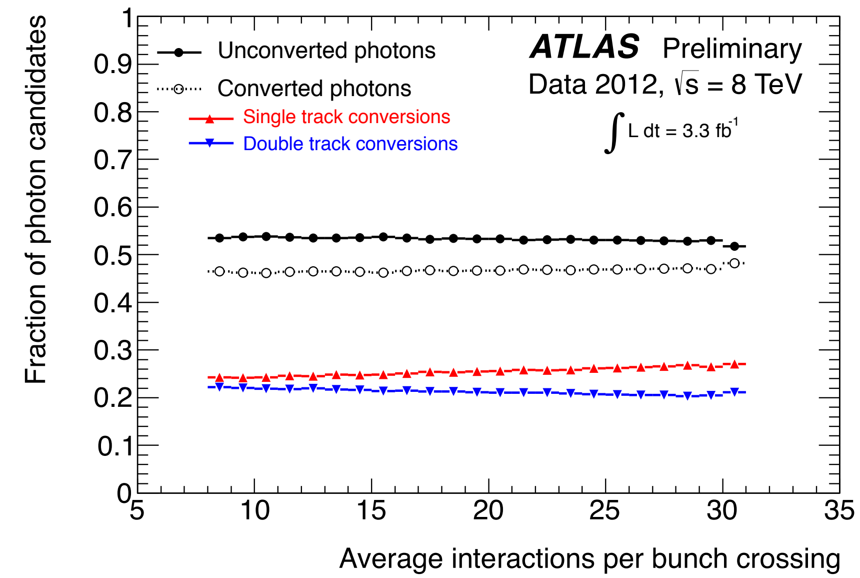
Single object

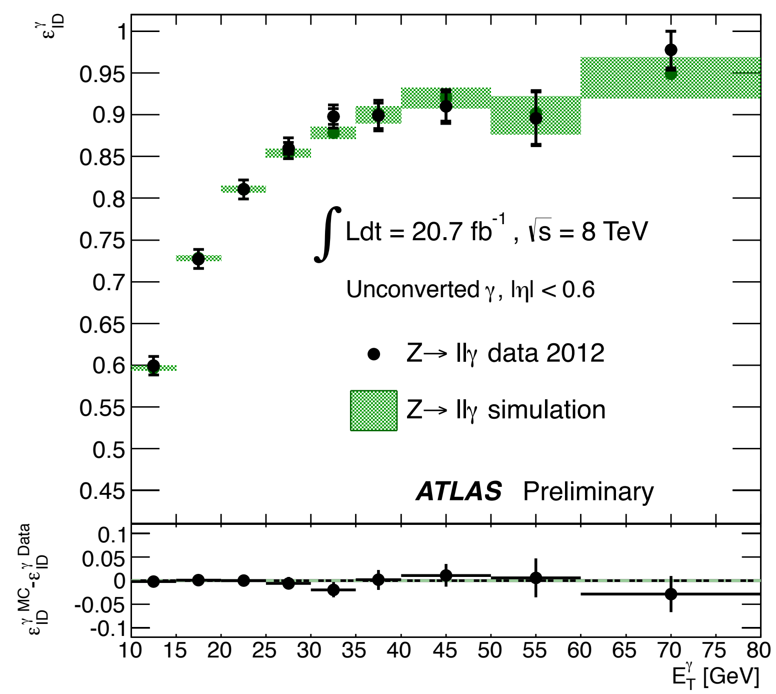


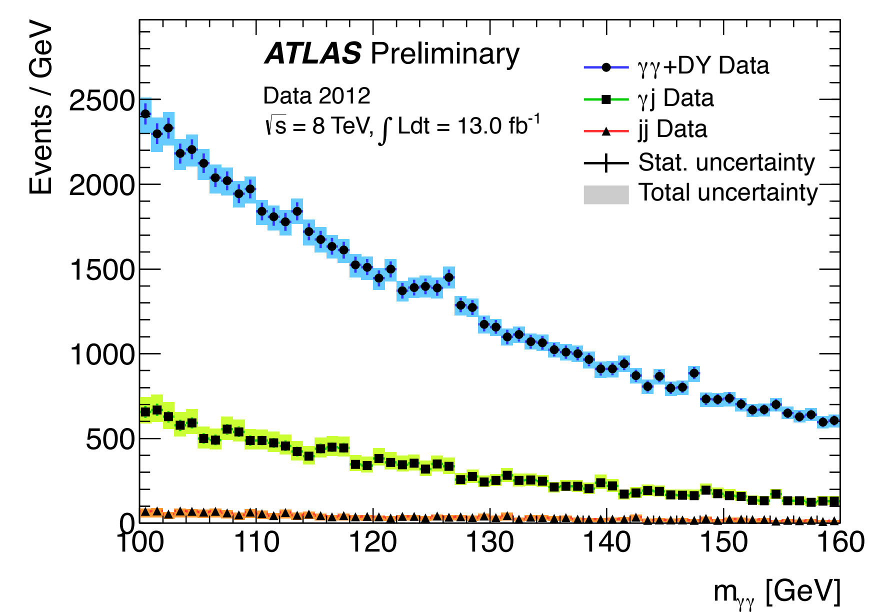
Two objects

Combined Performances

- Most of the time is put into understanding the detector and associated performances.
  - Efficiency of reconstructed objects.
  - Robustness versus changing data-taking conditions (mostly pile-up).
- "Auxiliary" measurements.
  - Background yields and shapes.
  - Control regions.
- Direct impact on final Higgs analyses.
- A nice example, photon efficiency:
  - 5.3% error (2012) $\rightarrow$ 2.4% error (2013)
  - Combine two photons into a Higgs event: decrease uncertainty on yield by a factor of $\sim$4.







The diPhoton Channel

- Analysis: improve sensitivity by categorising