Status and Prospects of the Higgs Sector Physics in ATLAS

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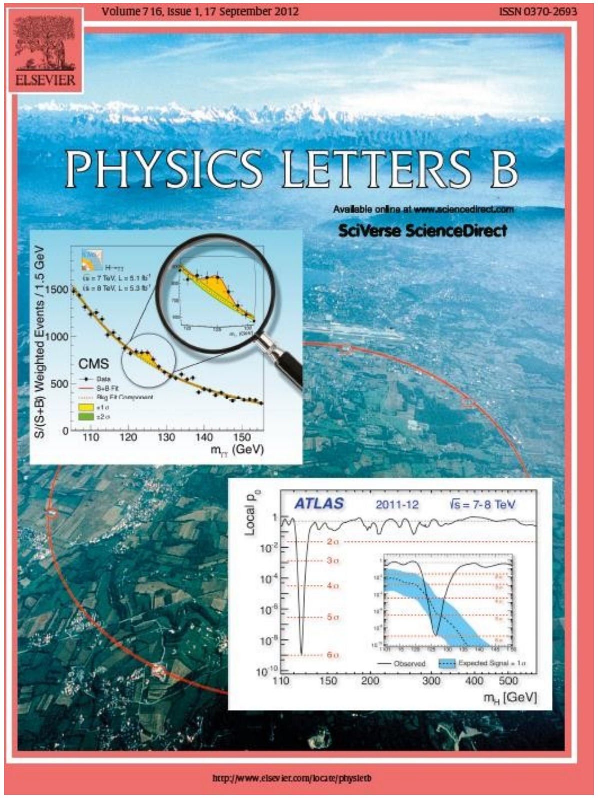
Outline

- LHC and Run1 data-taking
- Experimental performances
- The Higgs Mechanism
- Individual SM Higgs results:

H → γγ
H → WW(2l2ν)
H → ZZ(4l)
H → ττ
H → bb and ttH
H → μμ

- Property measurements
  - **Mass**
  - **Couplings**
  - **Spin and Parity**
- Future Prospects at LHC and beyond



Not covered in this talk:

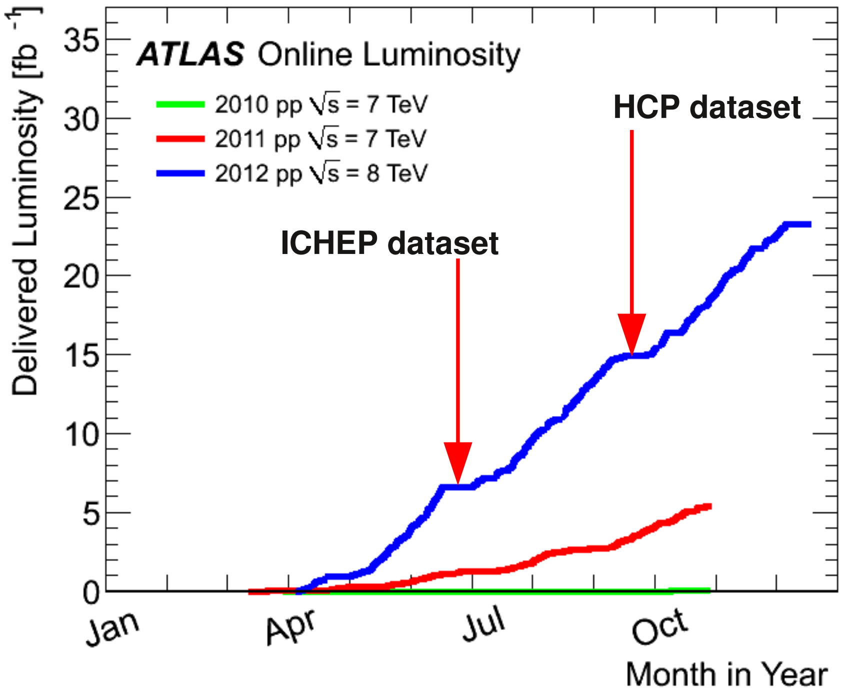
- High mass Higgs searches
- BSM Searches (H →Zγ H → invis., MSSM Higgs, ...)
- TeVatron results
- EW Fit

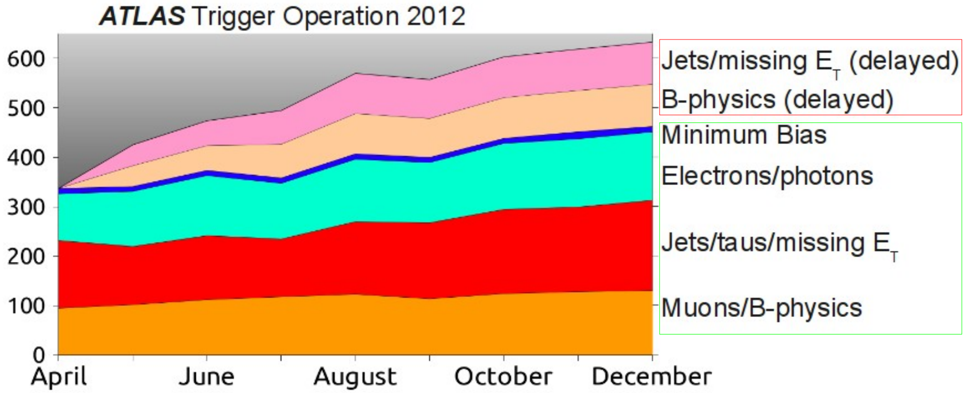
LHC Luminosity

Higgs Results based on 2011+2012 data

Luminosity is measured with forward detectors and calibrated with beam separation scans

Luminosity during data-taking:	2012	2011
• Peak Luminosity [$cm^{-2}s^{-1}$]:	$7.7x10^{33}$	$3.7x10^{33}$
• Max. average int. per b.c. :	37	24
• ATLAS Luminosity uncert.:	2.8% prel.	1.8%





ATLAS L1/HLT rates: 75 kHz/400 Hz*

*: promptly reconstructed, ATLAS has 200 Hz more of deferred data.

~29 fb^{-1} of data delivered during Run 1

Thanks to the LHC for the exceptional Run 1 performance!

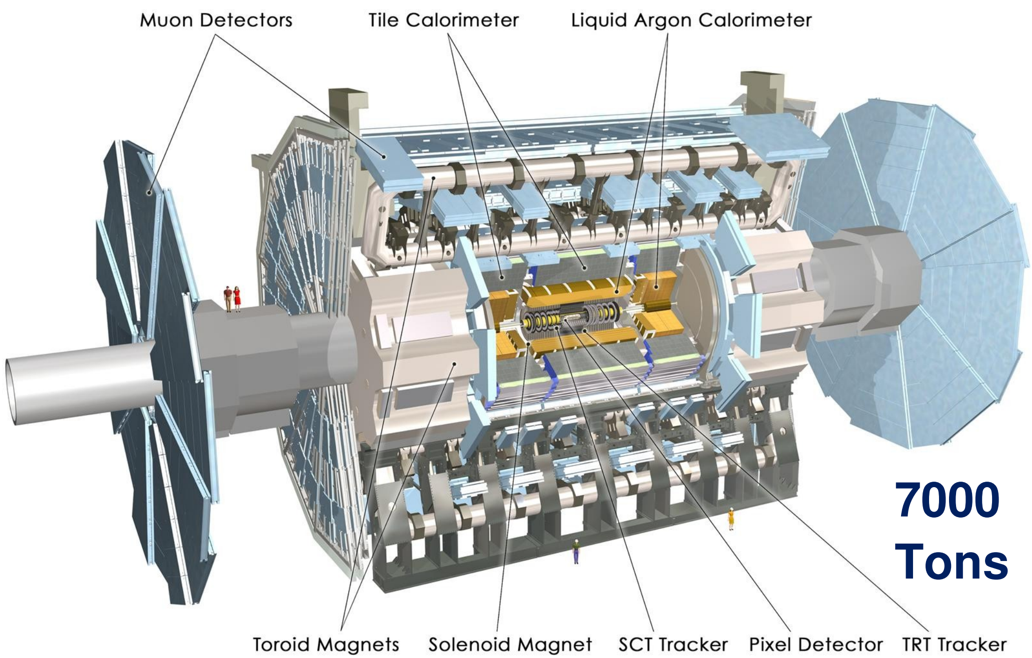
ATLAS Detector

	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

ATLAS Collaboration
38 Countries
169 Institutions
3000 Scientific Authors total
(~2000 with a PhD)

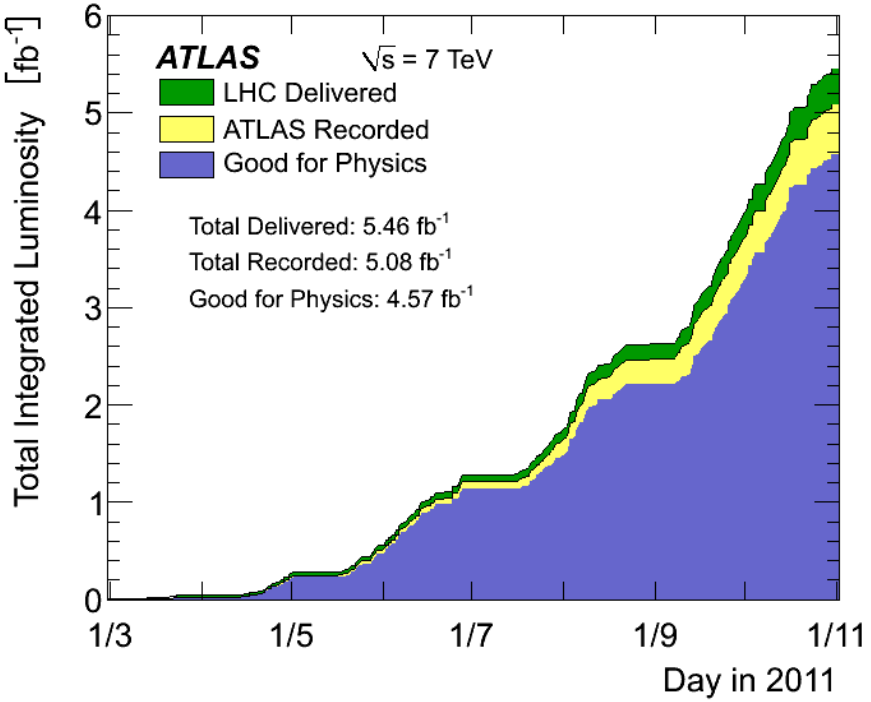
45 m

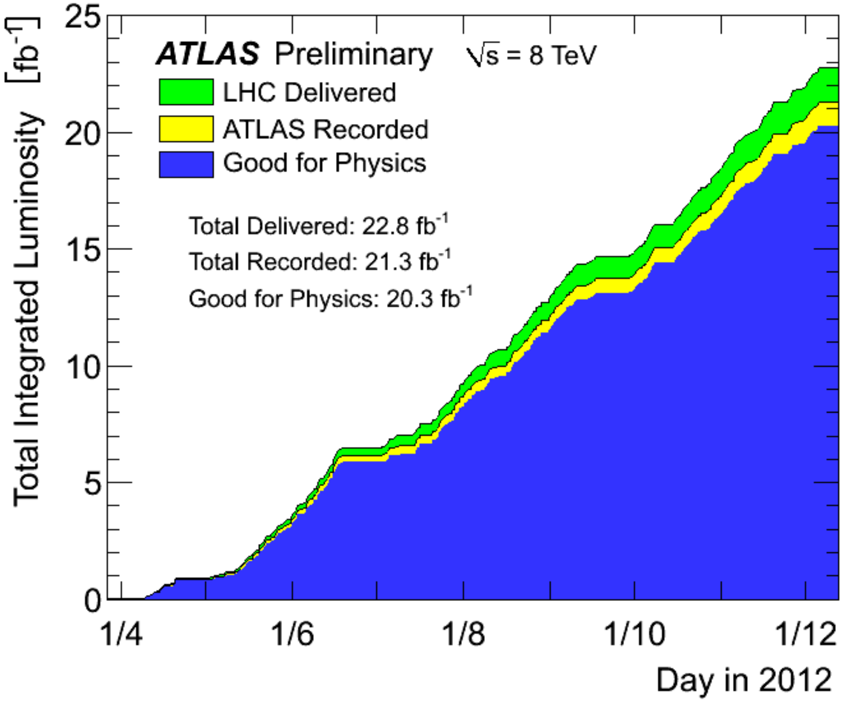
24 m



7000 Tons

Data taking & Quality efficiency



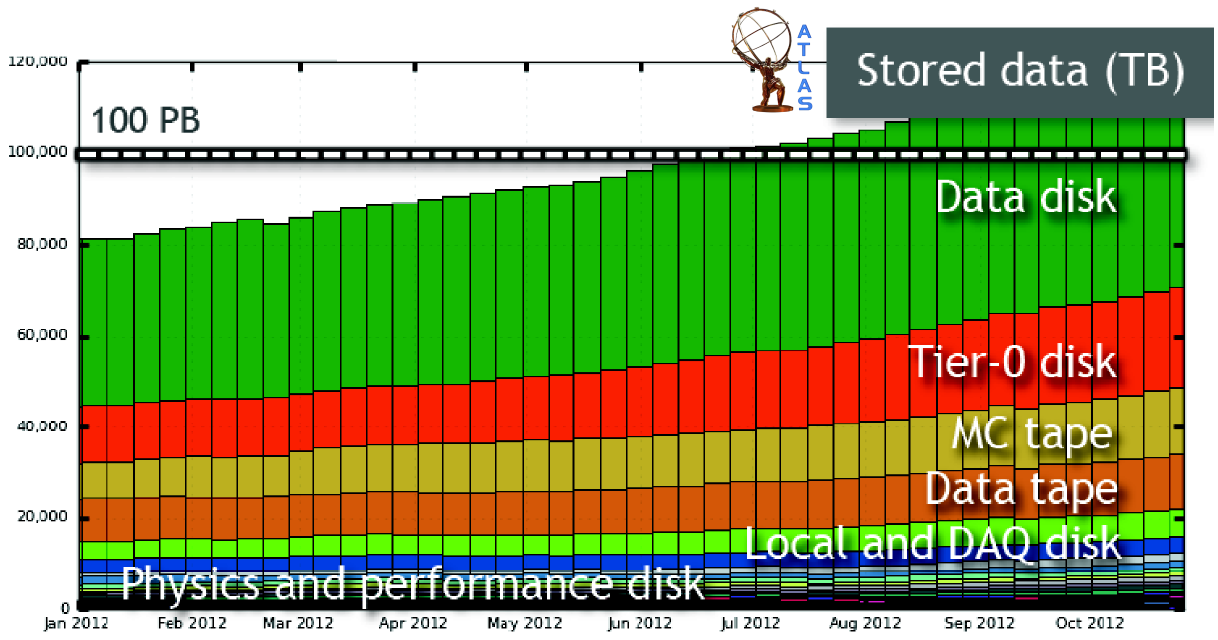


- ATLAS data-taking efficiency for 2012 (2011) was 93.1% (93.0%)
- The ATLAS good quality data was 95.8% (90.0%) of the recorded data
  - High DQ partly due to eff. recovery from large data reprocessing
  - Given the high DQ efficiency, we use a common set of "good quality data" across all analyses

Overall 88% of delivered luminosity is used for ATLAS physics analysis.

Computing and Simulation

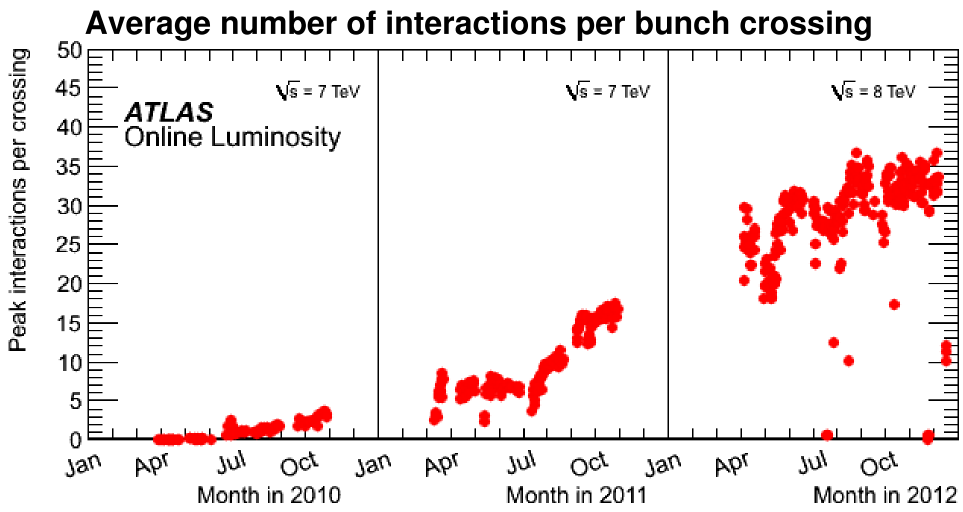
The fast duty cycle of the LHC analyses is possible thanks to the Tier0 and GRID resources

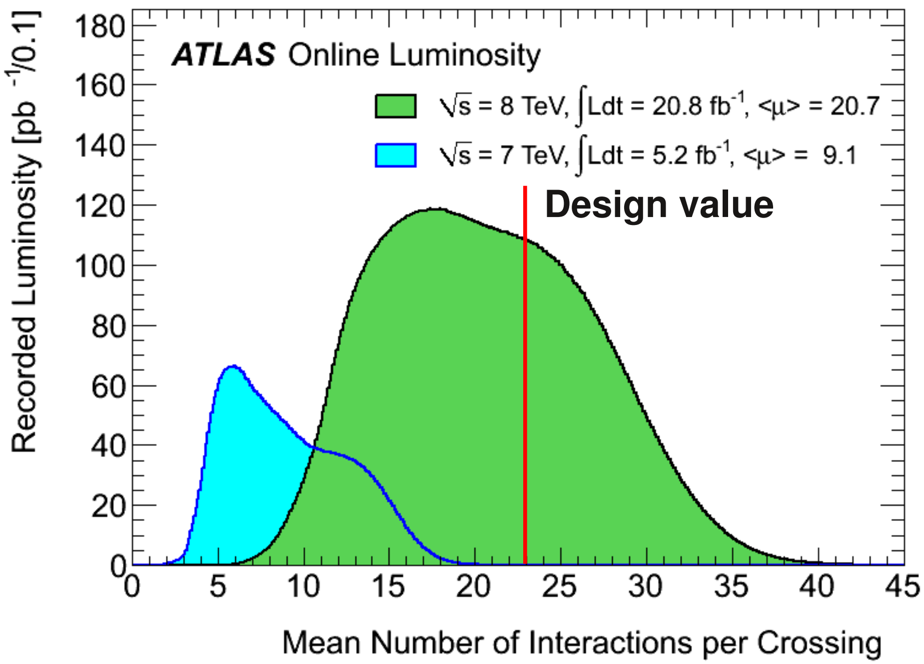


Just in 2012, ATLAS experiment produced >3 billions of MC events on the GRID and processed ~3 billions of data events at Tier0 (of these 2 billions have been reprocessed at Tiers1).

On a single machine, it would require more than 15 thousands years (without considering user and group analyses, calibrations, reprocessings, ...).

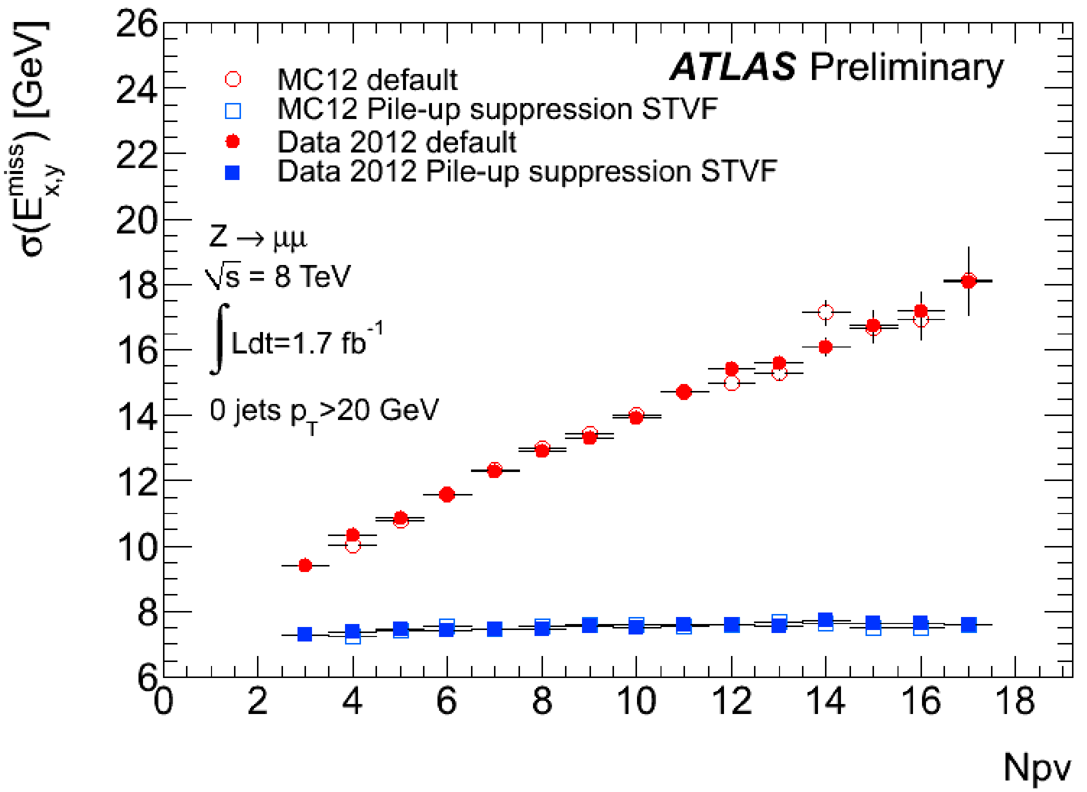
Pileup conditions in 2011 and 2012

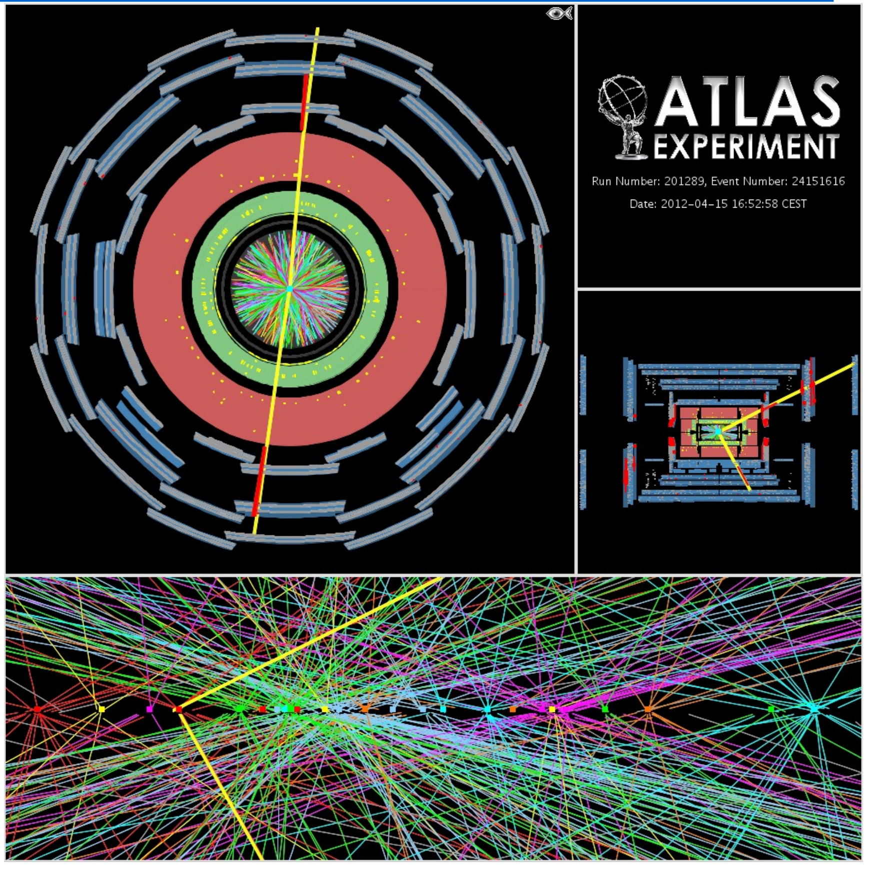




- 2012 data-taking was a high pileup environment (~factor 2 higher than in 2011) with sizable impact on physics, jets, E_T^{miss} and tau reconstruction, as well as on trigger rates and computing...

Pileup Performance

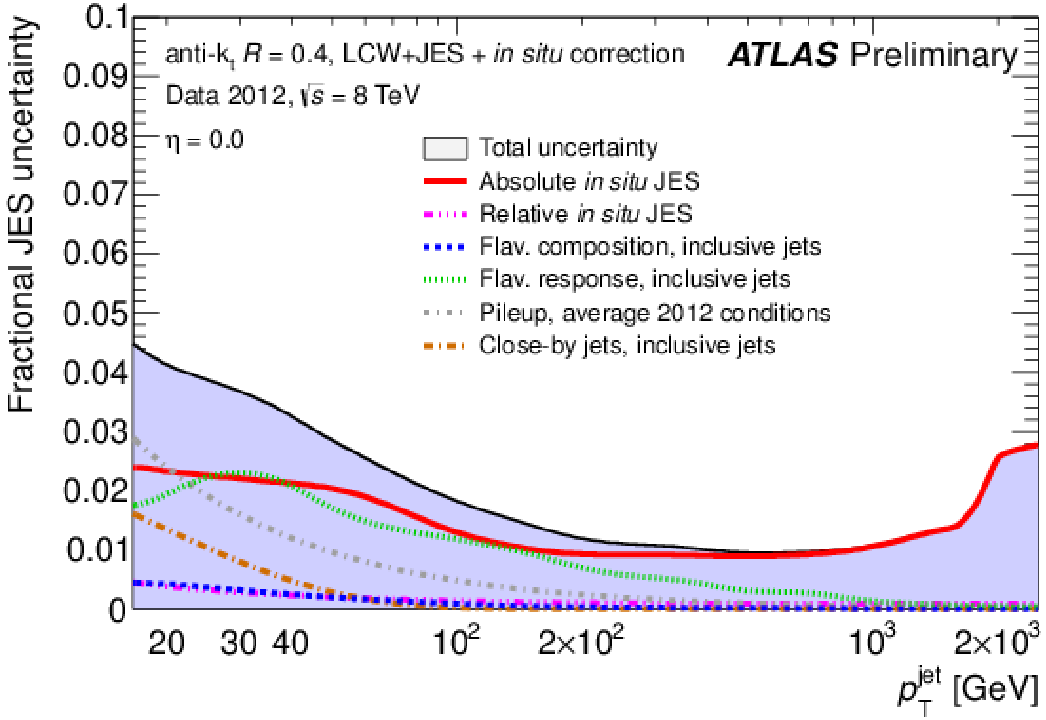


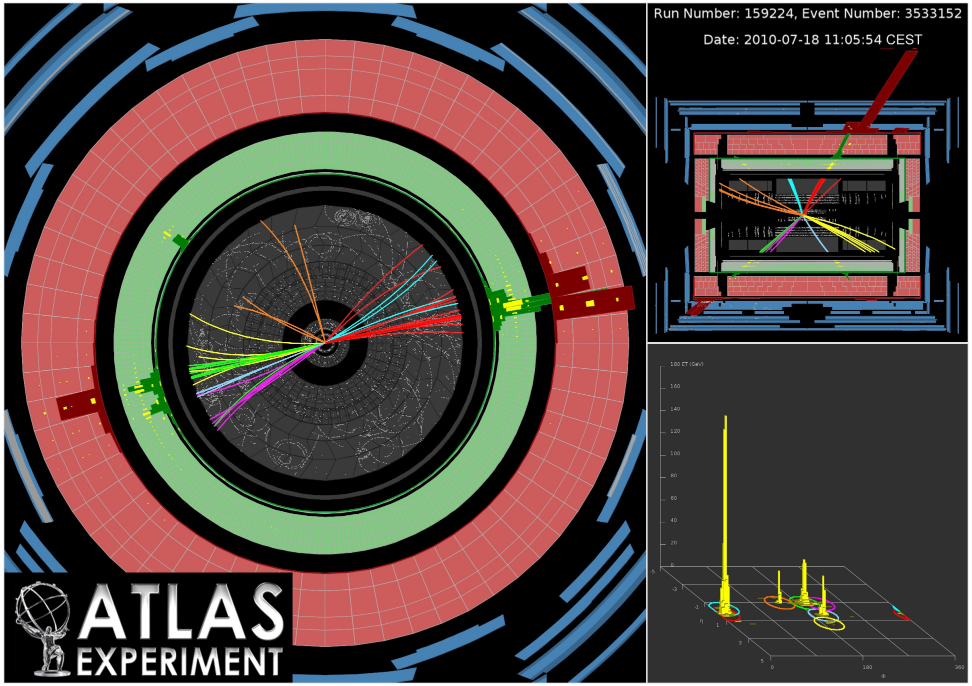


Z → μμ event with Npv= 25

- The pileup affects the physics object reconstruction and degrades the performance.
- ATLAS optimized the reconstruction in 2012 to reduce the dependence vs the number of interactions per bunch crossing.
- The pileup dependence of the MET is reduced by weighting the objects contribution by the fraction of momentum associated to the primary vertex of the hard scattering.

Jets and Leptons performance

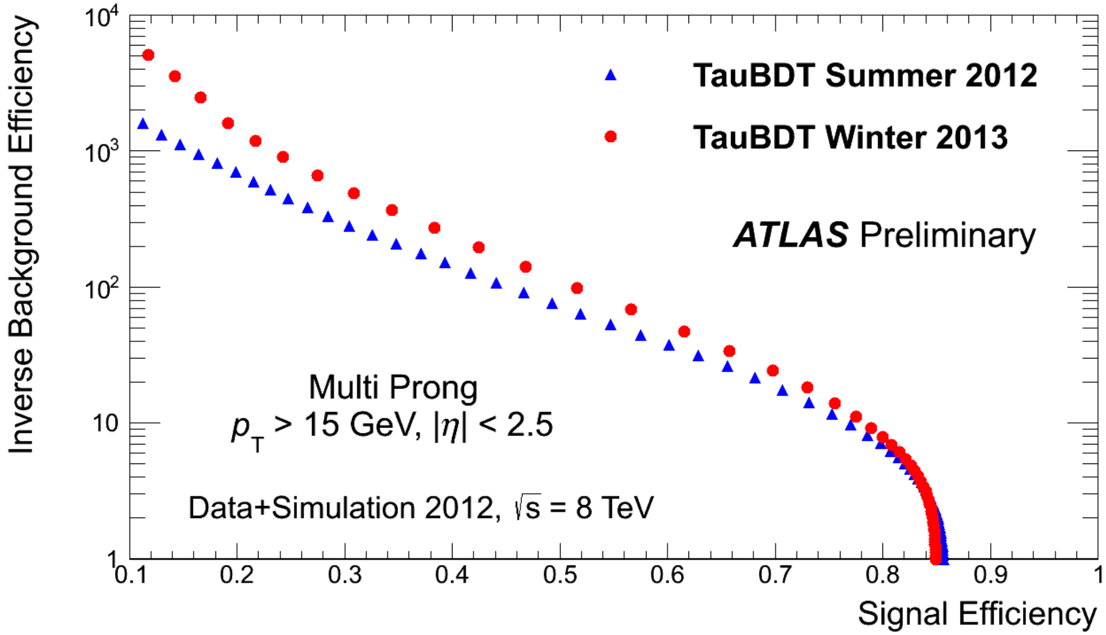


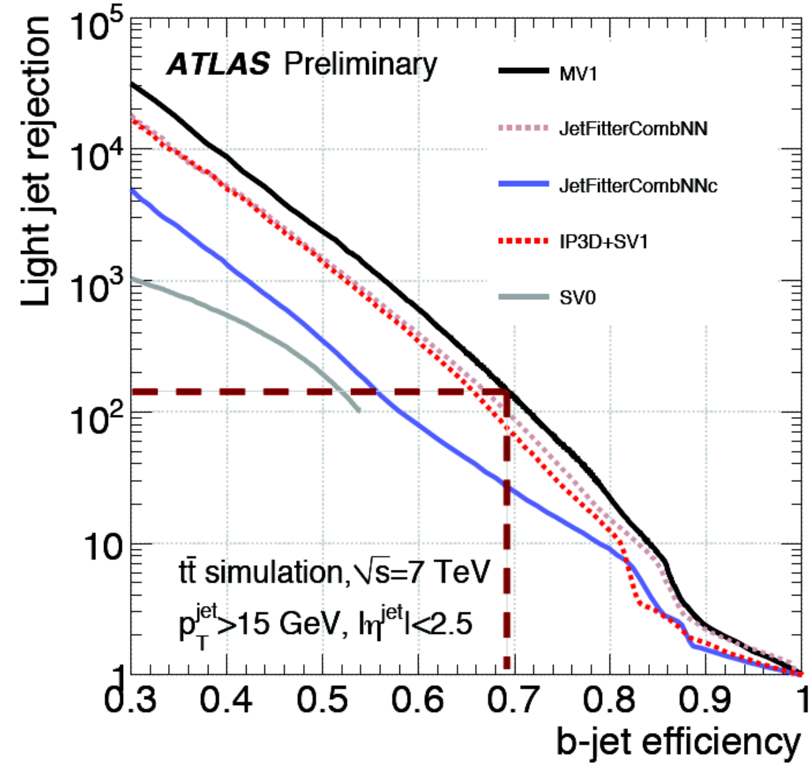


Leading jet pT of 1.12 TeV

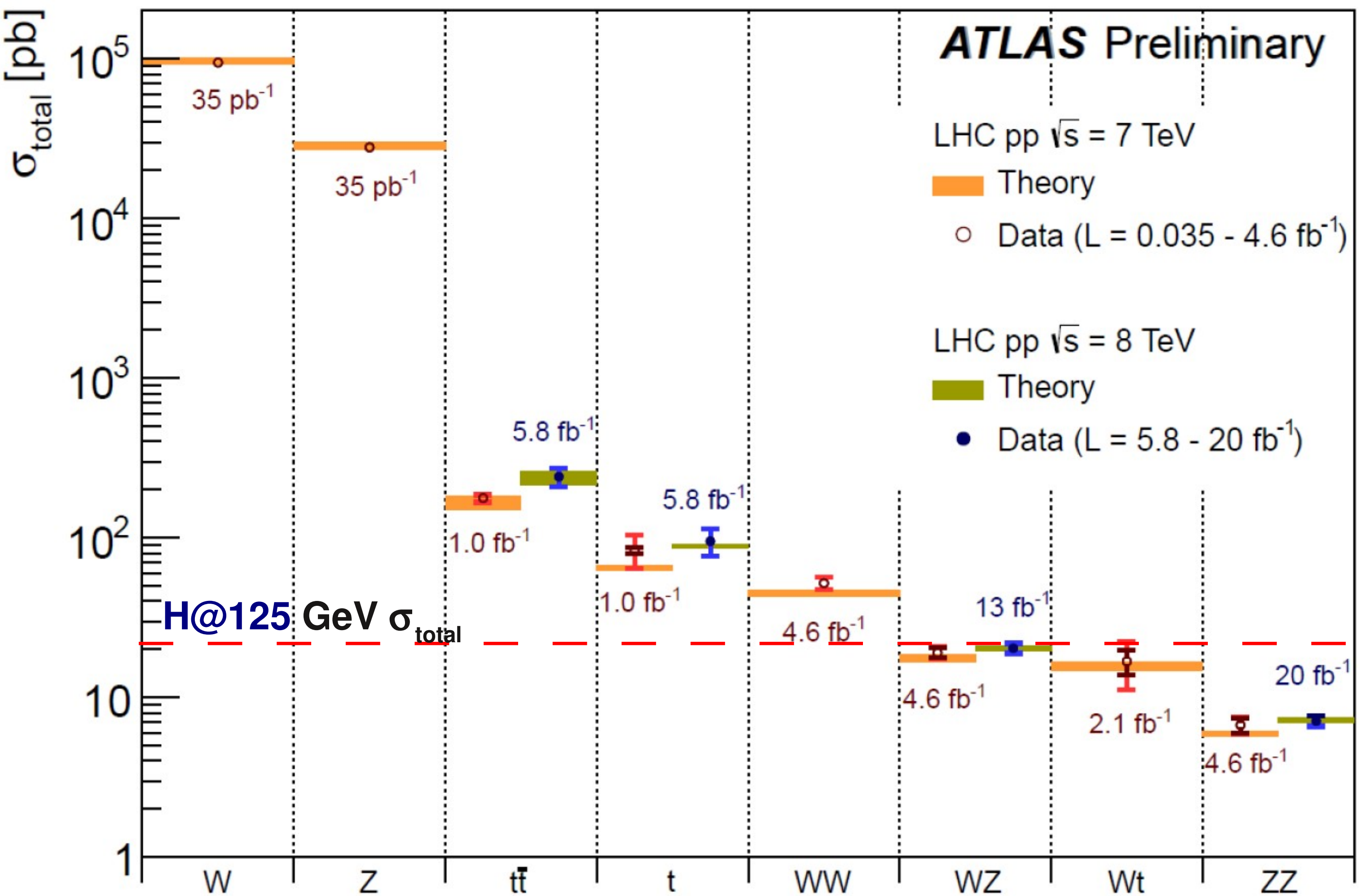
- Precise knowledge of the Jet Energy scale and its uncertainties has been achieved.
- Isolation requirements are frequently applied to leptons to reduce the fake rate.
- The experiment succeeded in obtaining a low dependence wrt pileup observables.

Tau and Flavor-tagging performance





- ATLAS employs Multivariate techniques for τ identification and heavy flavor jet idenification.
- Heavy flavor jets identification combines both the 3D IP significance of the tracks as well as the informations on the tracks associated to the secondary vertex.



Inner error: stat
Outer error: total

- Good agreement with SM expectations within uncertainties.
- Experimental uncertainties are in some cases at the level of the theor. predictions

Preliminary measurements of the cross-sections down to few pb (~tens of fb in some cases if we include also the BR).
Comparable to Higgs production σ_{total}

Higgs Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

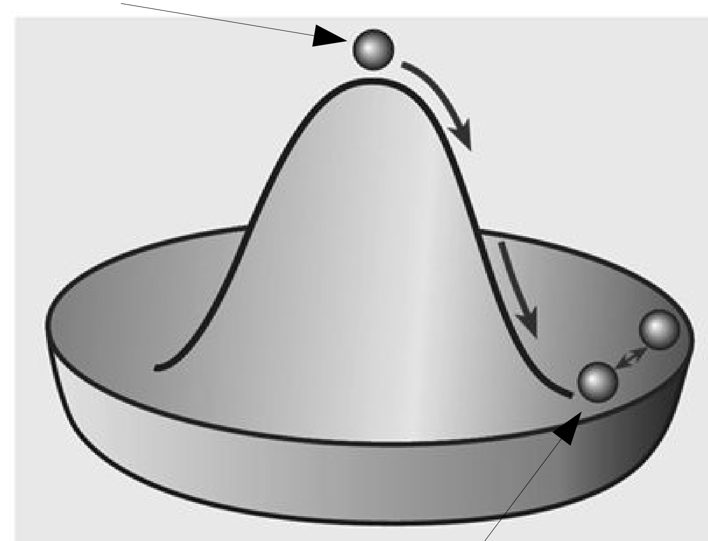
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

- EW Gauge bosons in previous formulation of the SM were massless.
- Four seminal papers in 1964 proposed a spontaneous symmetry breaking mechanism in relativistic gauge theory.
- The introduction of a complex scalar doublet allow to give mass to the W and Z bosons after symmetry breaking.
- Remaining d.o.f. is a new scalar particle → the Higgs boson

- Model is capable of very precise predictions, but it has one free parameter not predicted by the theory: the mass of the Higgs boson.

J. Ellis et al. A Phenomenological Profile of the Higgs Boson(1976):
“[...] We apologize to experimentalists for having no idea what is the mass of the Higgs boson...”

Higgs Mechanism (2)



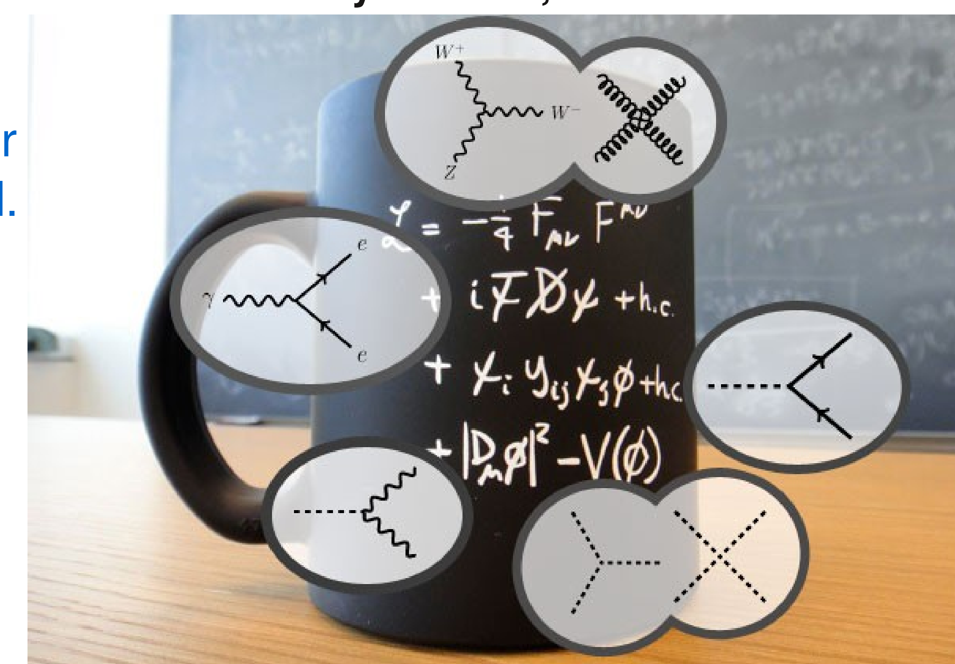
- The SSB mechanism introduces a new potential in the Lagrangian, which is symmetric, but its minima are not (“mexican hat”).

- The symmetry of the lagrangian is broken when a ground state is chosen → the symmetry is not evident in the ground state.

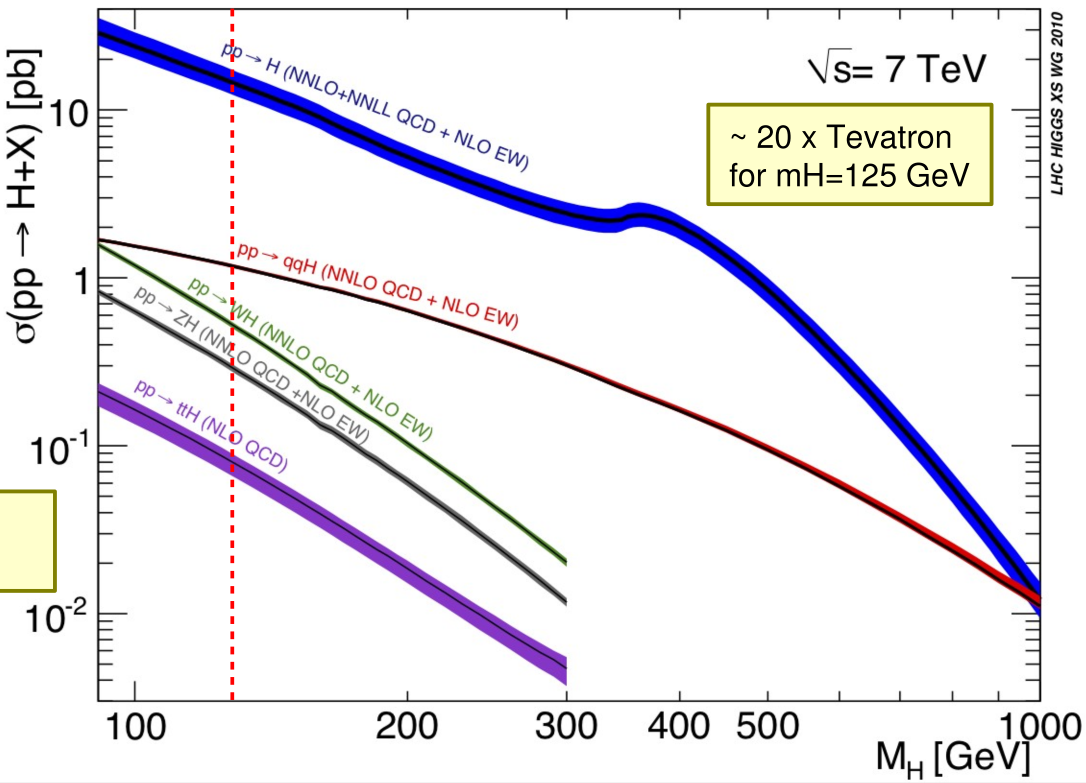
- 3 of the 4 degrees of freedom of the complex scalar doublet mix with the $W^{\pm}$ and Z bosons, giving mass to them, while the photon stays massless.

- Remaining degree of freedom is the a new scalar particle: only scalar particle of the Standard Model.

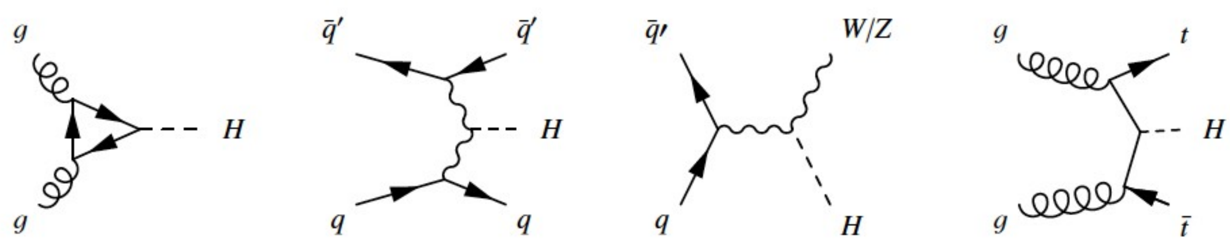
- Particles couples to the field proportionally to their mass (Yukawa coupling)



SM Higgs prod. rates



σ(H125 GeV) @pp √s=8TeV
22.3 pb



(a) $gg \to H$ — **87%**

(b) VBF — **7%**

(c) VH — **5%**

(d) $t\bar{t}H$ — **1%**

Huge progress also in the theoretical predictions of numerous and complex backgrounds
Excellent achievements of the theory community; very fruitful discussions with the experiments (e.g. through LHC Higgs Cross Section WG, LPCC, etc.)

SM Higgs decays modes

SM Higgs coupling:

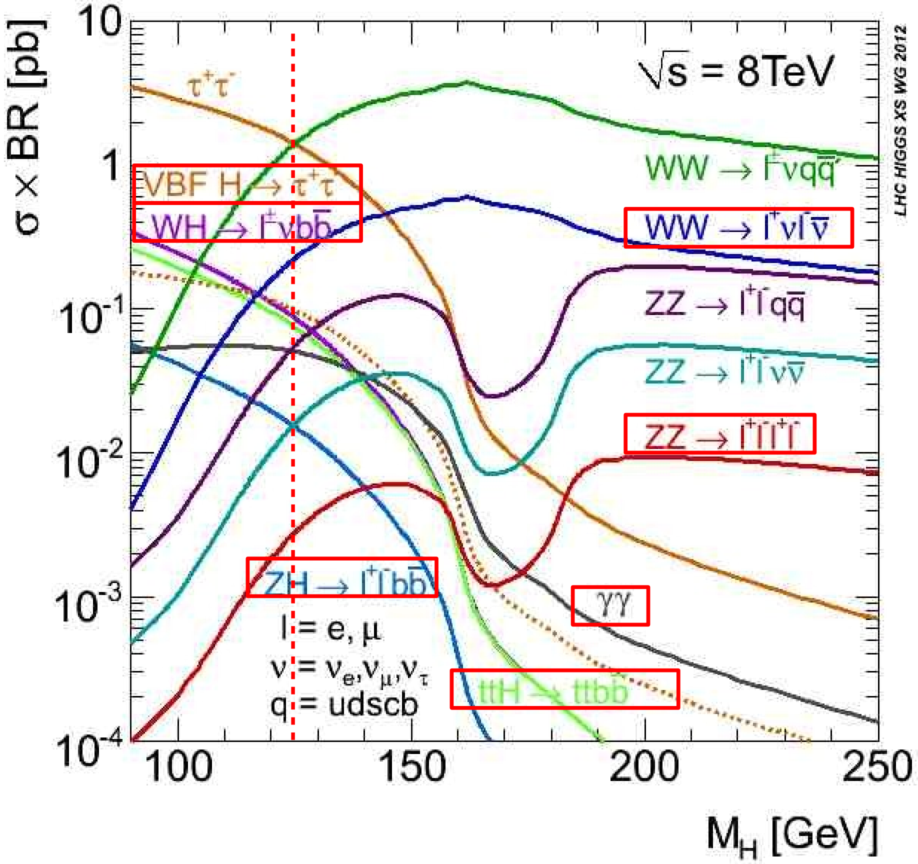
$$\Gamma_{Hff} \sim m_f^2$$

$$\Gamma_{HVV} \sim m_V^4$$

To establish its nature it is important to measure the couplings to SM particles (bosons, quarks, leptons) through its decays and production modes.

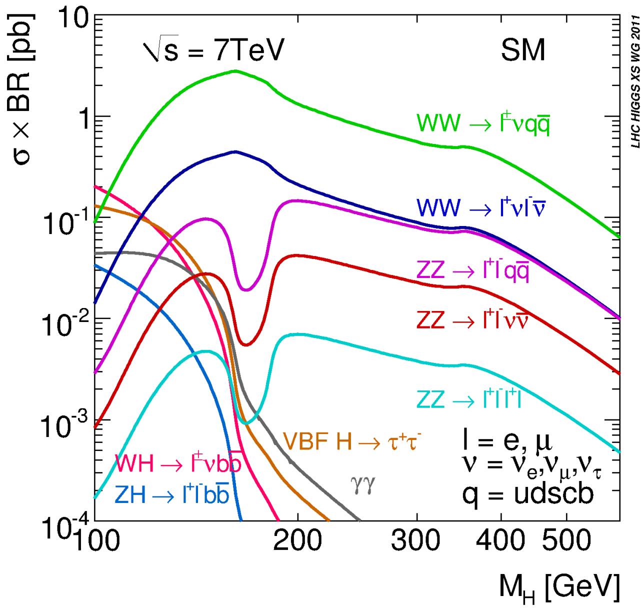
For a mass of 125 GeV, the following SM Higgs decays are accessible:
H → γγ, H → ZZ, H → WW, H → bb, H → ττ

σxBR: Experimentally most sensitive channels vs mH



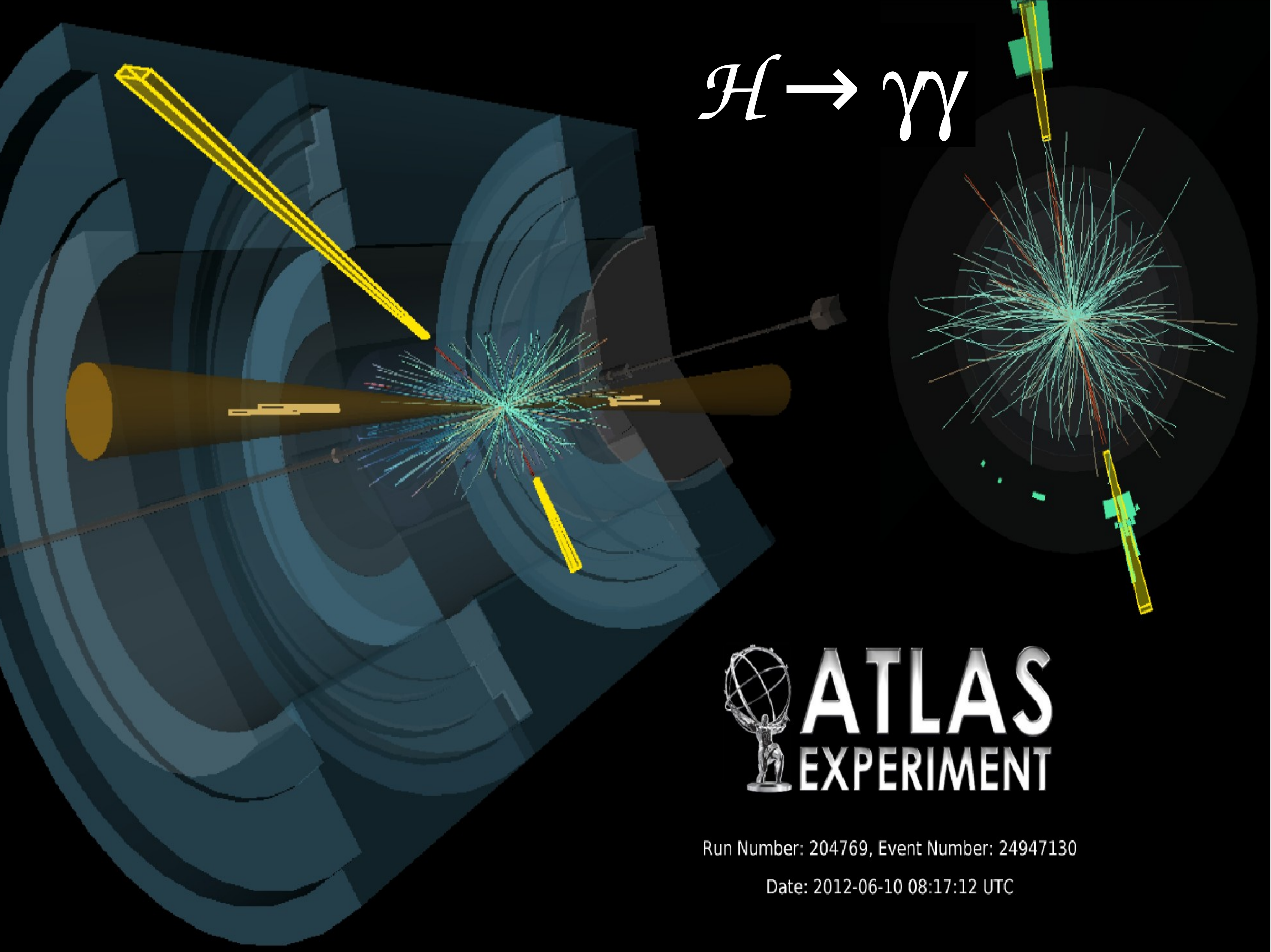
SM Higgs search channels

Depending on Higgs mass different channels are relevant.



Channel	Mass range (GeV)	Comments
Z/WH → Z/Wbb ttH	110 – 150	Performed in multiple categories
H → ττ	110 – 150	Good Signal/background Fair mass resolution
H → μμ	110 – 150	Very Low BR Good mass resolution
H → γγ	110 – 150	Low BR, best mass resolution
H → WW* → lνlν	110 – 300	Most sensitive in a large mass range
H → ZZ* → llll	110 – 600	Low background, good mass resolution

Experimentally, **experimental acceptance**, **background rejections** and **resolution** are important factors.


$\mathcal{H} \to \gamma\gamma$
ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

$\mathcal{H} \rightarrow \gamma\gamma$

Features:

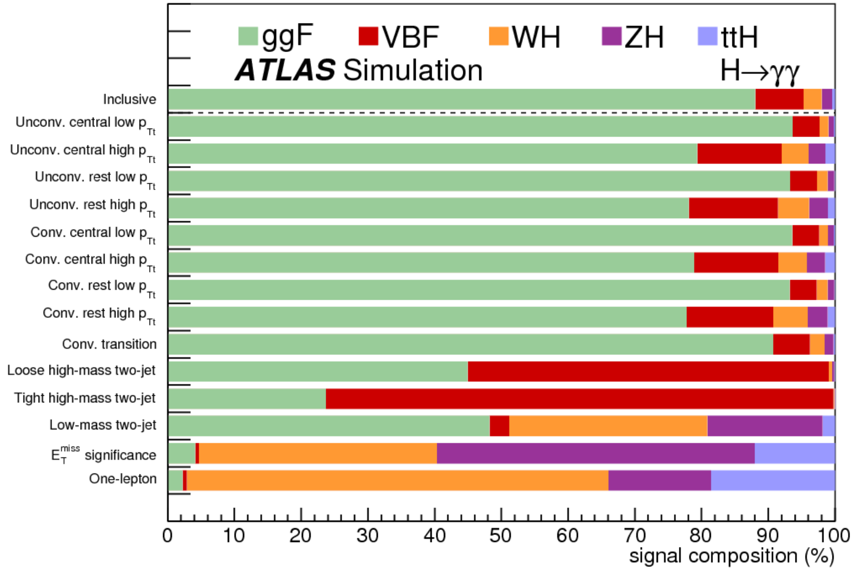
- Data sample divided in exclusive final states and the analysis is further optimized to sub-leading production modes (VBF and VH).
- Robust cut-based selection is used to define the categories.

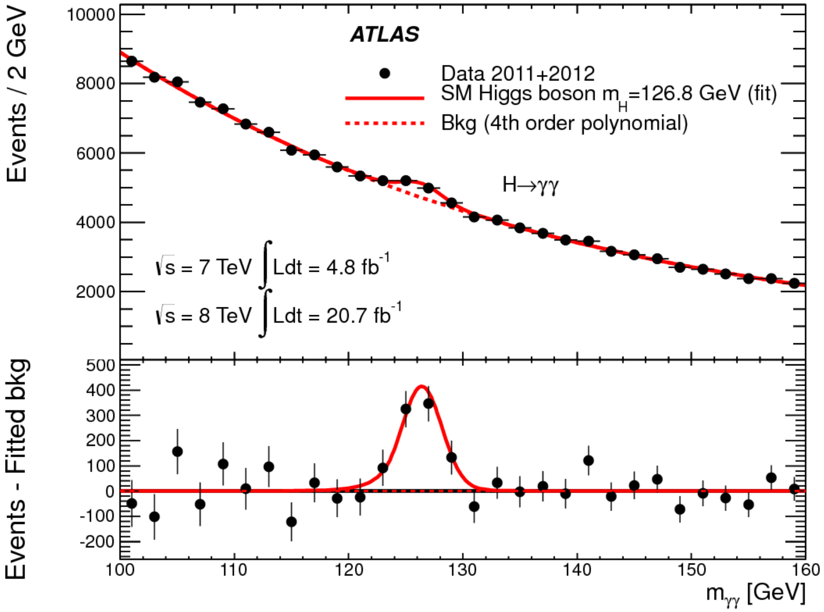
The main backgrounds:

- **Irreducible**: Di-photon $\gamma\gamma$
- **Reducible**: Photon + jets, di-jets (jet is misidentified as γ), EW

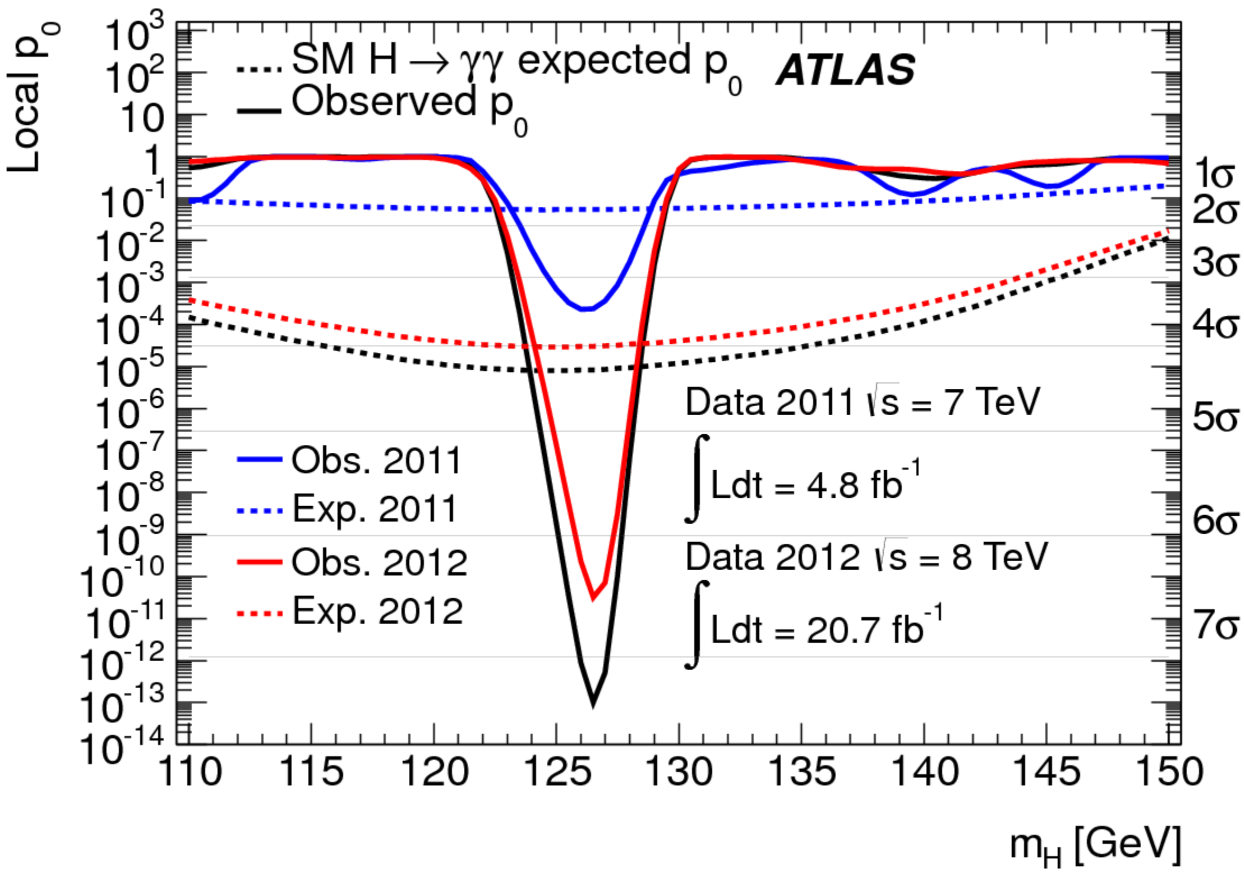
Main Discriminant variable:

$m_{\gamma\gamma}$, narrow resonance on a steep falling background. $m_{\gamma\gamma} = \sqrt{E_1^\gamma E_2^\gamma (1 - \cos\alpha_{12})}$





$H \rightarrow \gamma\gamma$ results

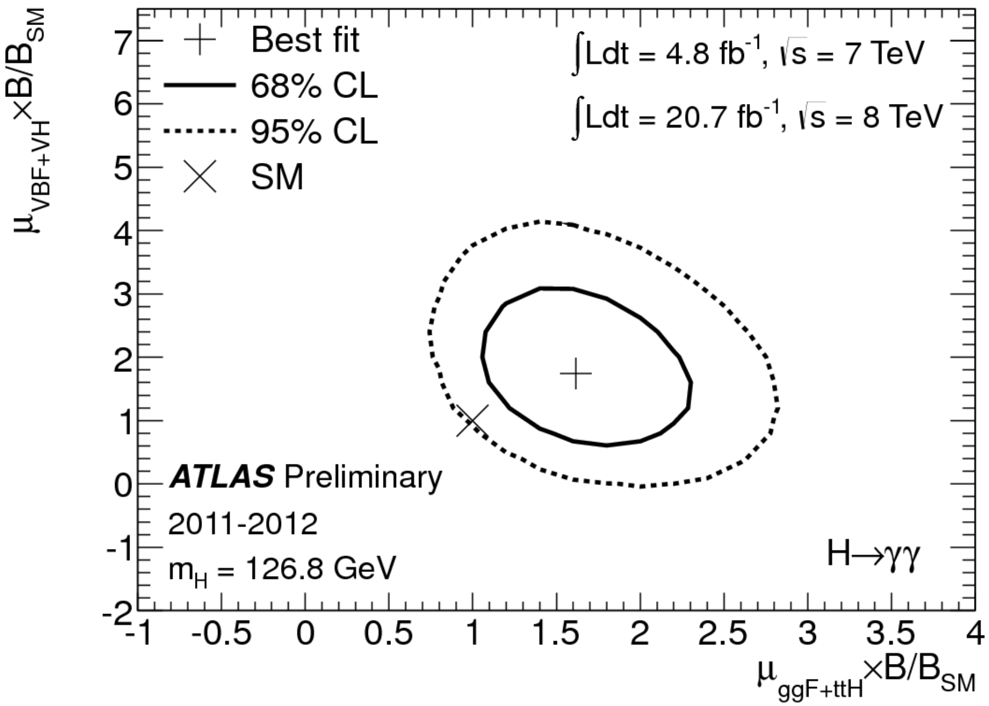


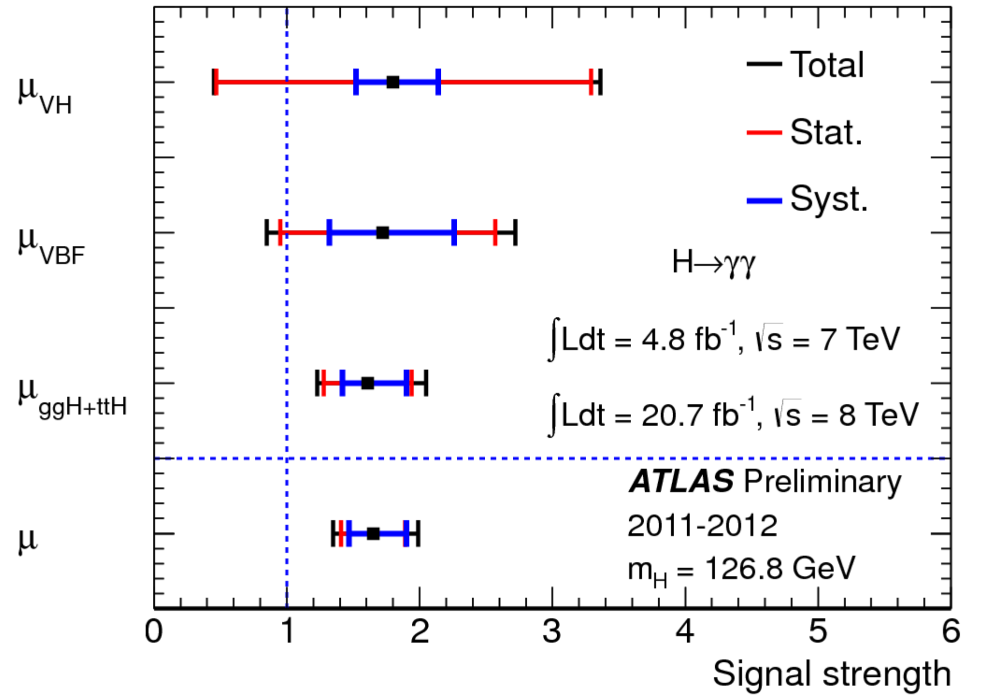
Significance at m_H = 126.8 GeV:

7.4 σ (expected 4.3)

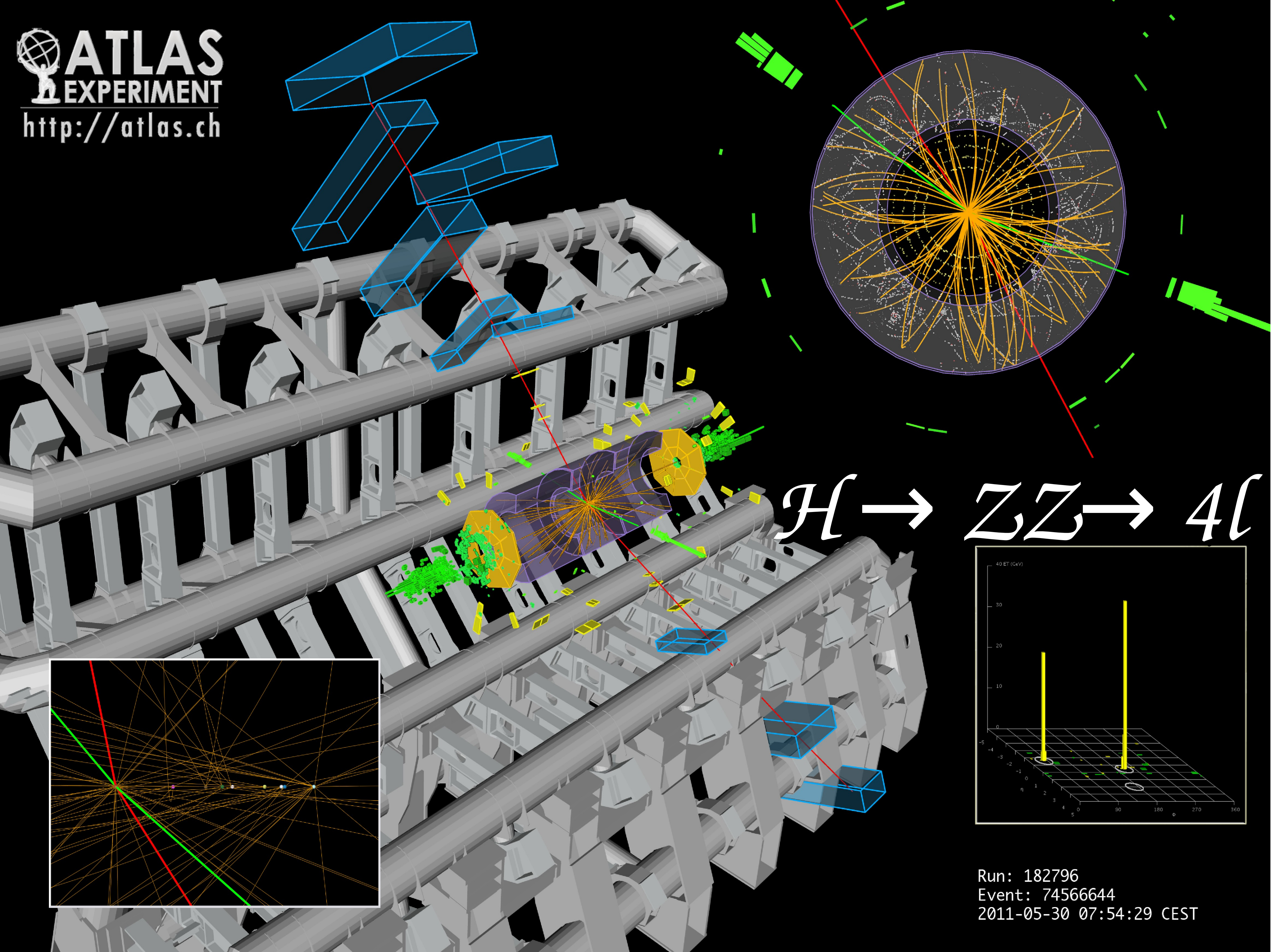
- Clear single channel discovery
- ATLAS 7+8 TeV σ/σ_{SM} (@ 126.8 GeV) = 1.65 ±0.24 (stat.) $^{+0.25}_{-0.18}$ (syst.)

$\mathcal{H} \rightarrow \gamma\gamma$ couplings





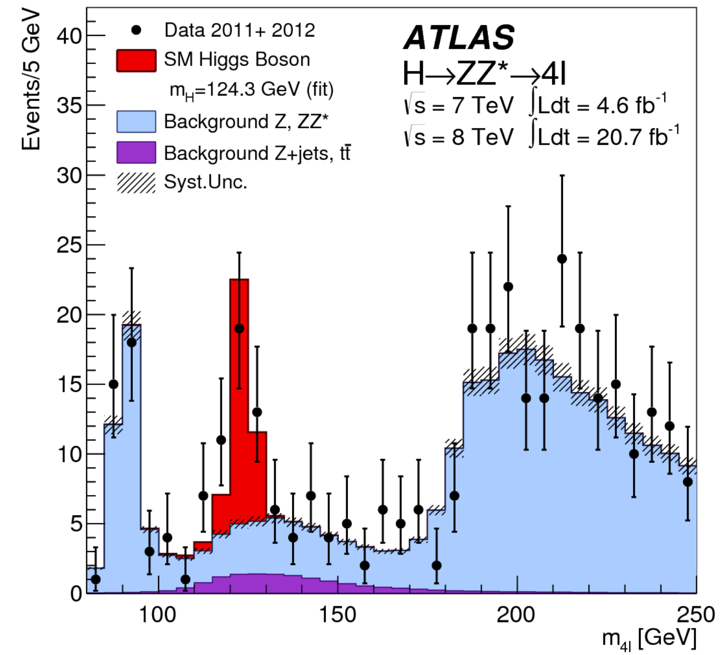
- New ATLAS results are inline with previous results and are compatible with SM within 2 sigmas.


ATLAS EXPERIMENT
http://atlas.ch
$\mathcal{H} \rightarrow ZZ \rightarrow 4l$
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

$H \to ZZ \to 4\ell$

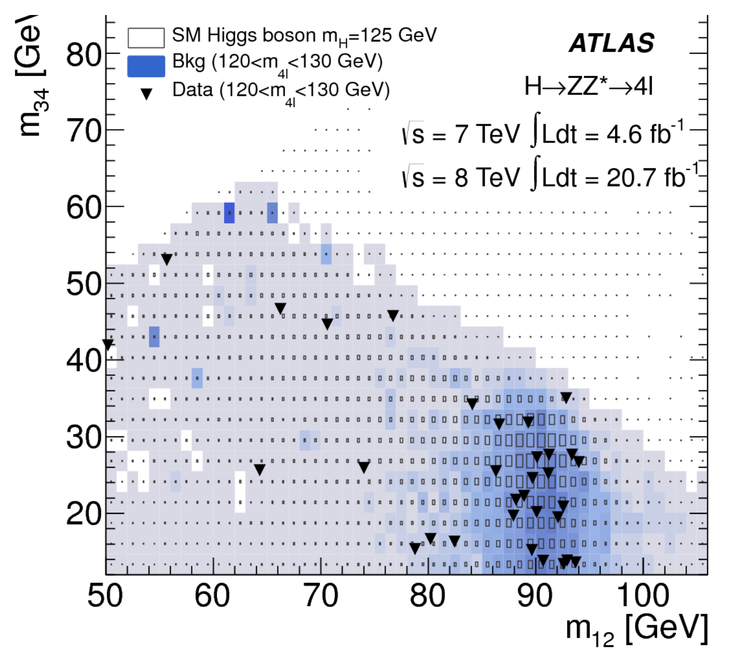
"Golden channel"

- Three different channels: 4e, 4μ, 2e2μ
- Very high S/B
- ATLAS applies tight cuts
- Number of Higgs events under the peak is ~20
- Low stat channel @125 GeV



Main backgrounds:

- ZZ* (irreducible)
- ttbar, Z+jets

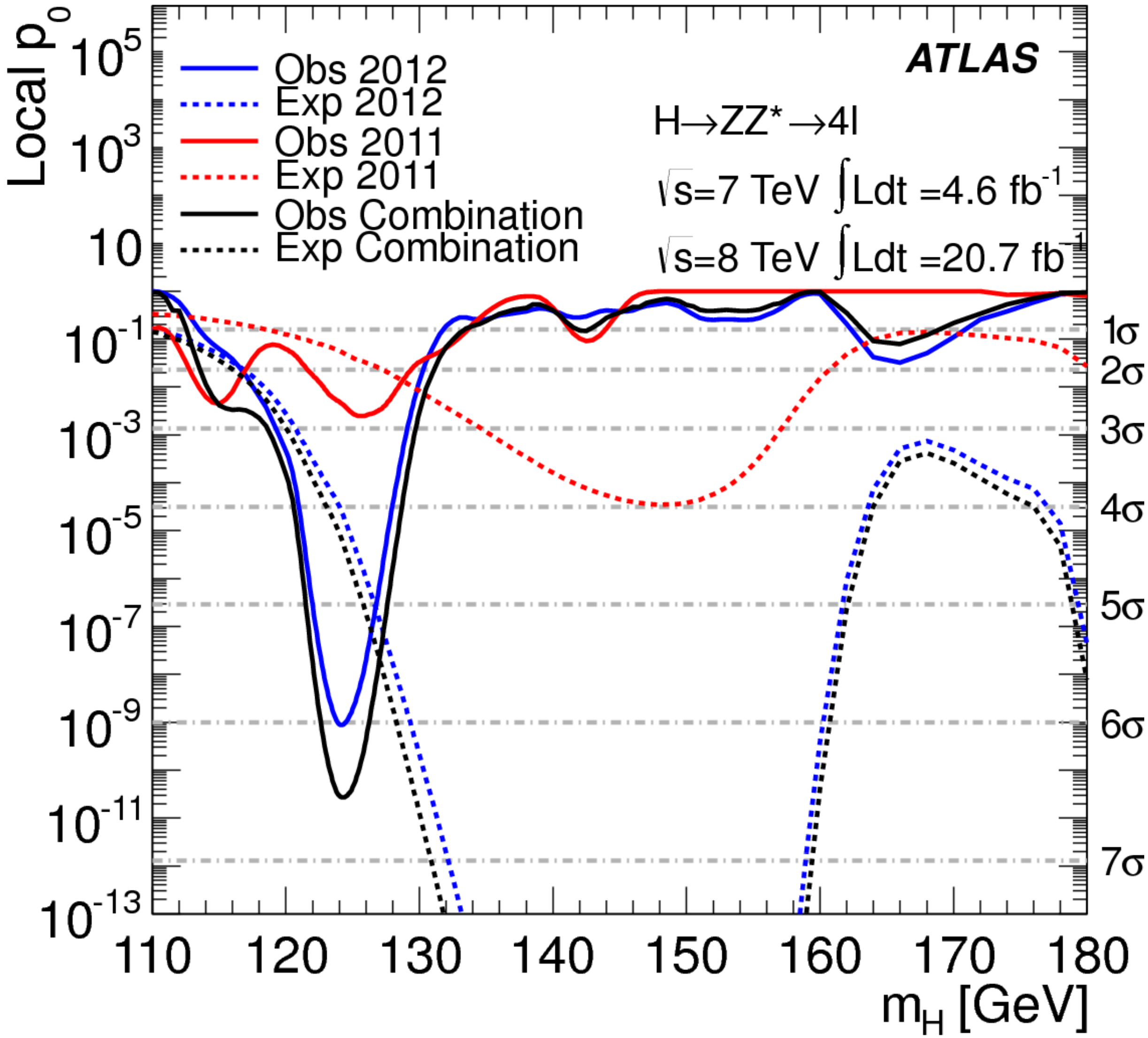


Signal Extraction:

- 1D fit of m4l is performed

Additional lepton-tag category (VH-like)

$H \rightarrow ZZ \rightarrow 4l$ p-value

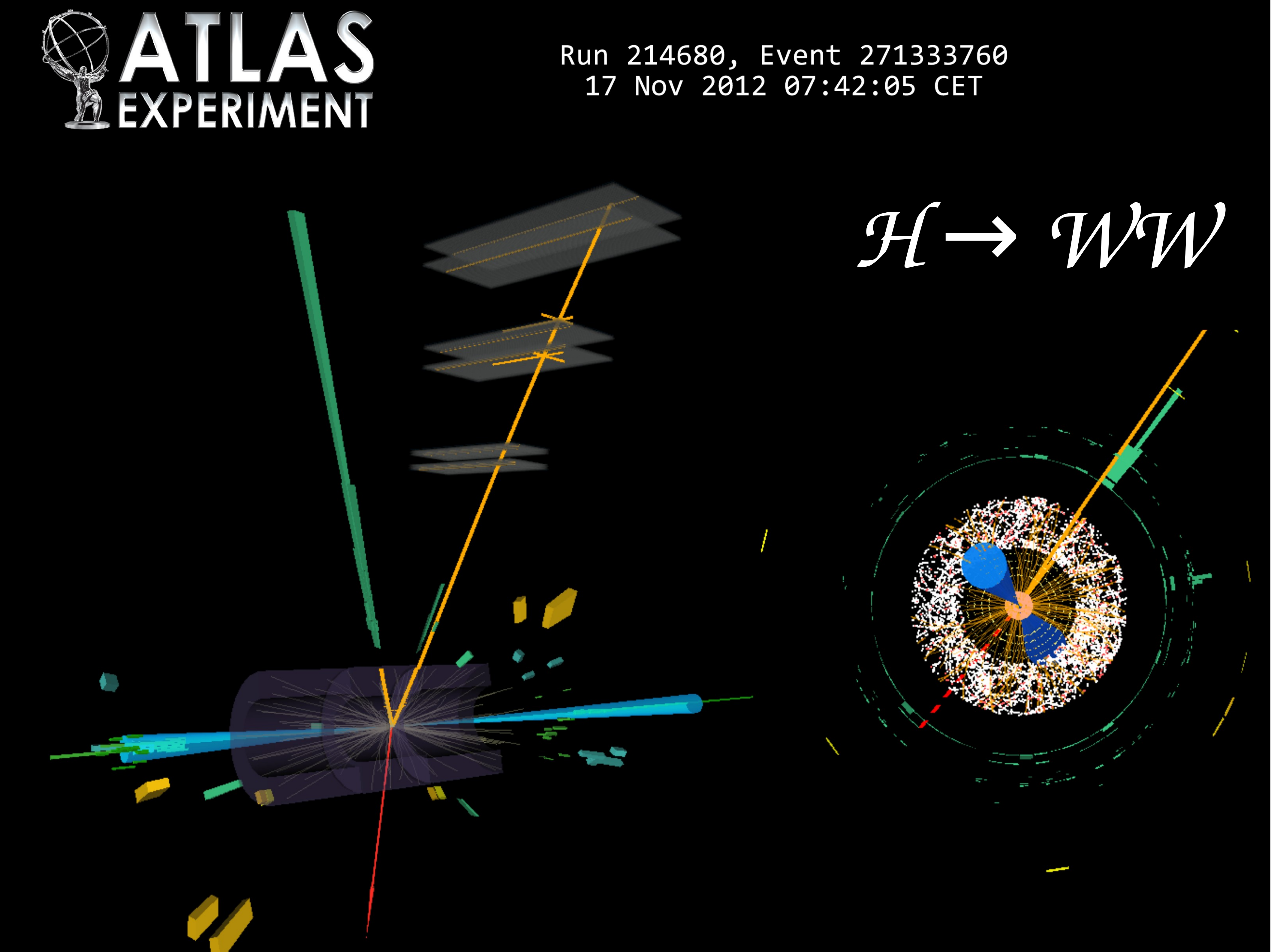


Significance at m_H = 124.3 GeV:

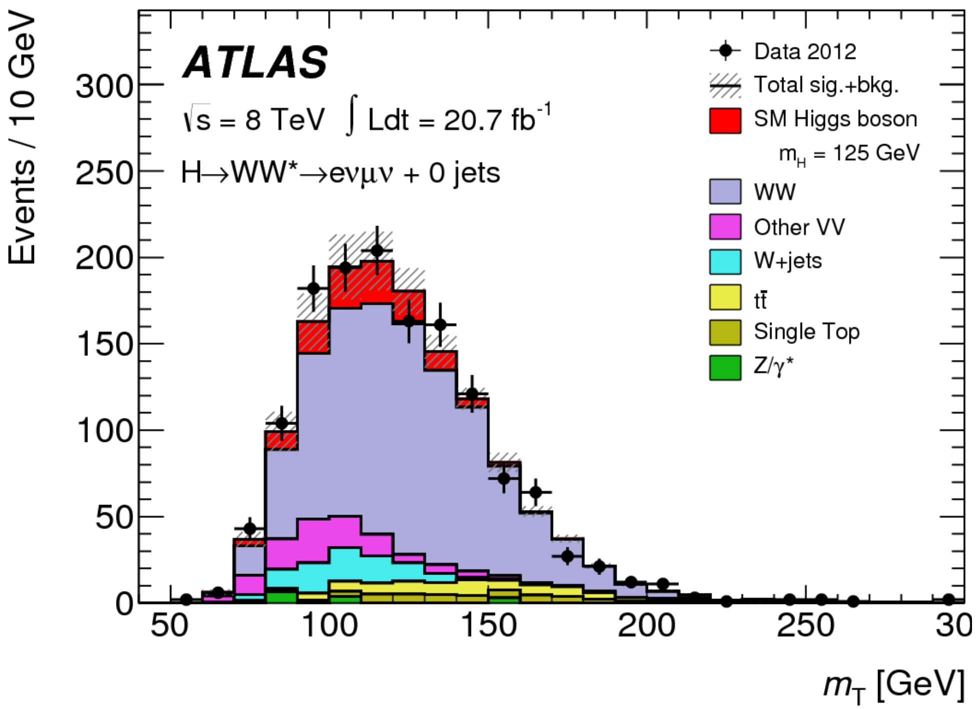
6.6 σ (expected 4.1)

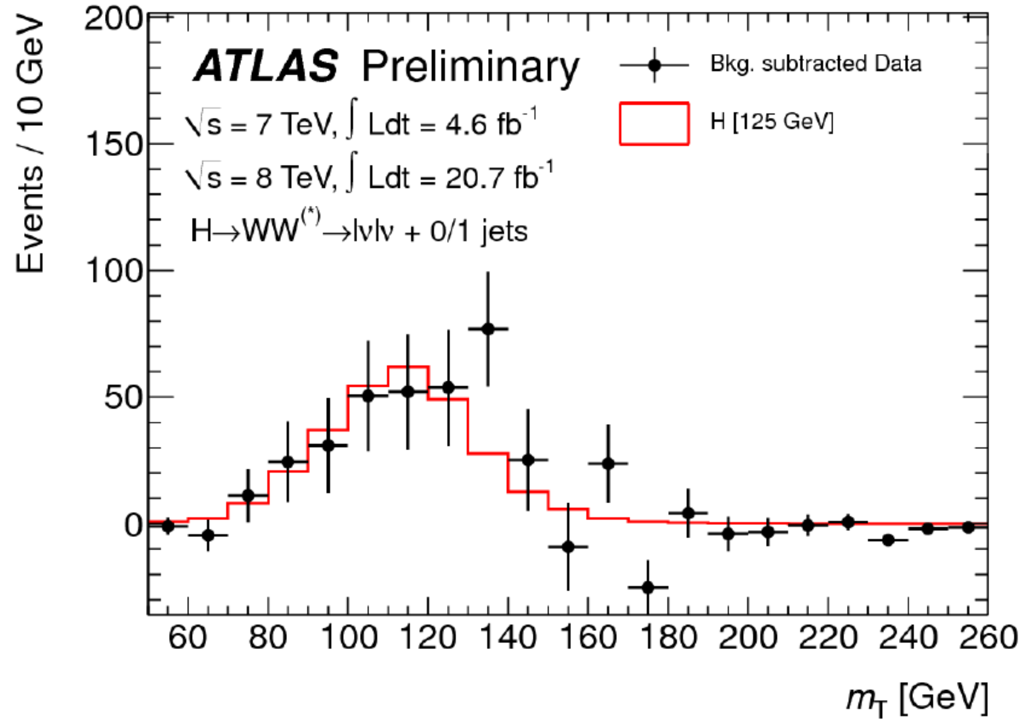
ATLAS: 7+8 TeV

σ/σ_{SM} @ 124.3 GeV = $1.7^{+0.5}_{-0.4}$


ATLAS EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
$\mathcal{H} \rightarrow \mathcal{WW}$

$H \to WW \to 2l2\nu$





$$m_T^2 = \left(\sqrt{m_{ll}^2 + p_{T_{ll}}^2} + E_T^{miss}\right)^2 - \left(p_{T_{ll}} + E_T^{miss}\right)^2$$

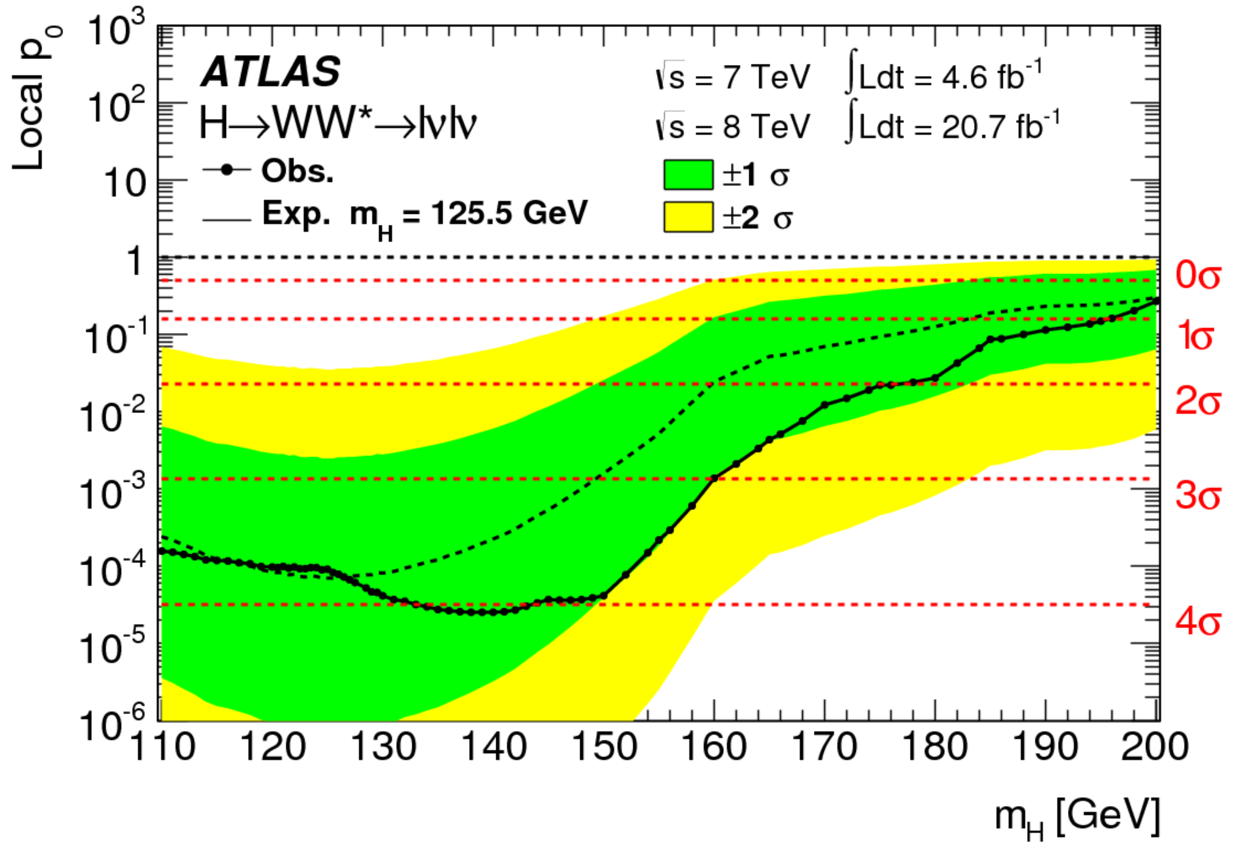
Features:

- ATLAS divides the data in 0jet and 1jet and 2jet (VBF) categories.
- High production rate, but poor mass resolution
- Signal is extracted from a 2D fit techniques of m_{ll} vs m_T

The main backgrounds:

- **Irreducible**: WW
- **Reducible**: top, Z+jets, W+jets

$H \rightarrow WW \rightarrow ll\nu\nu$ results



Significance m_H=125 GeV:

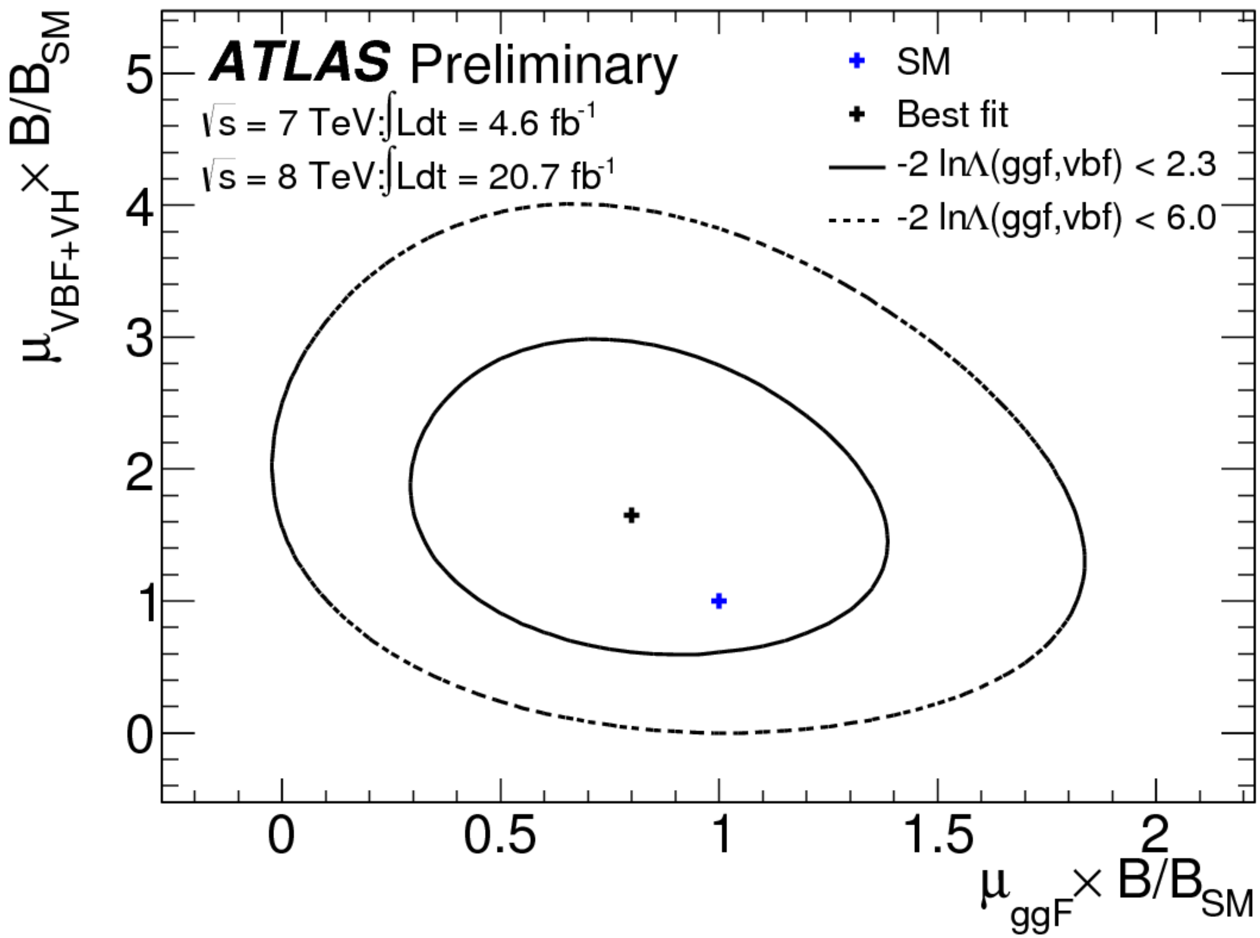
3.7 σ (expected 3.8)

VBF-only Significance:

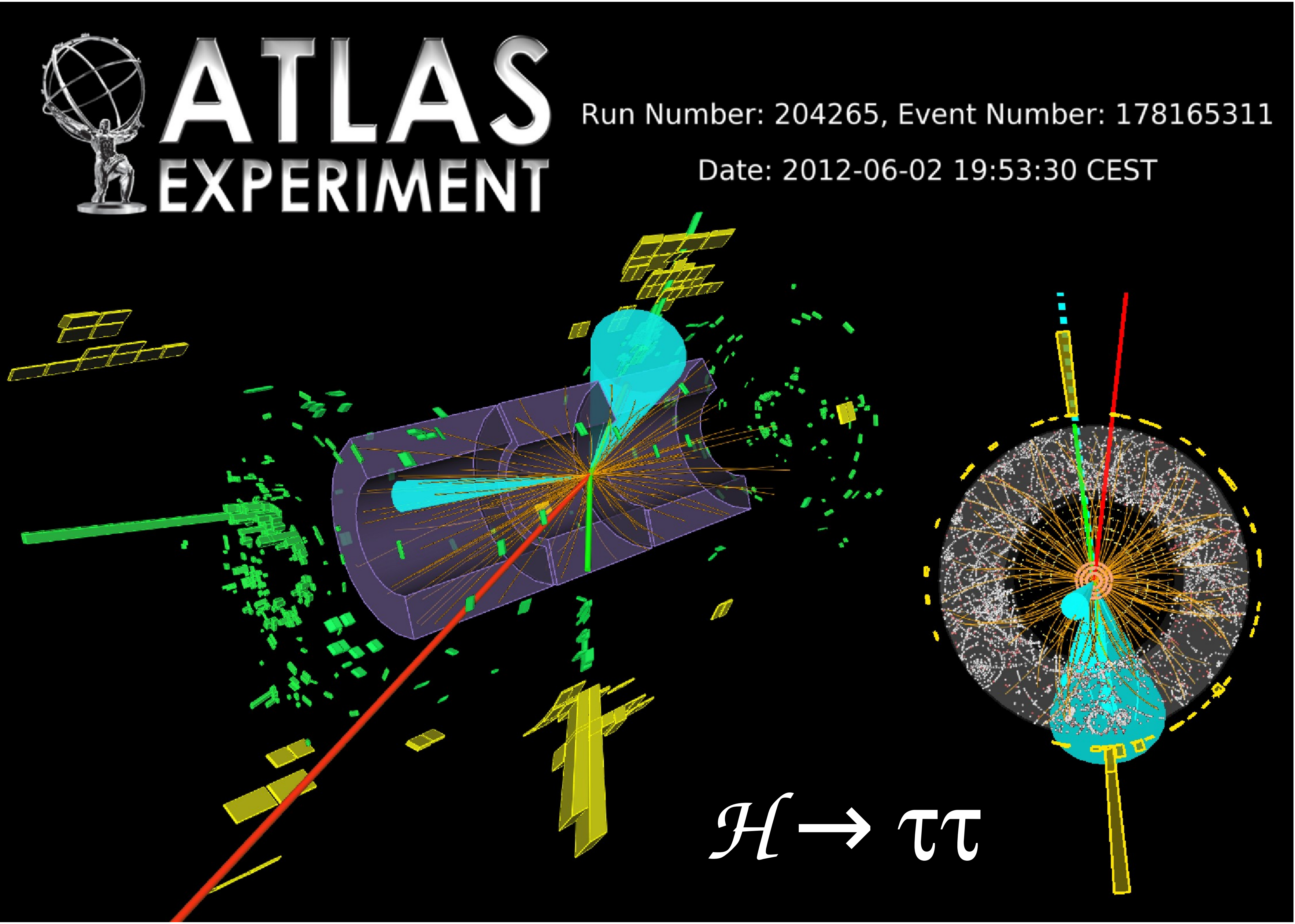
2.5 σ (expected 1.6)

ATLAS: 7+8 TeV σ/σ_{SM} @ 125 GeV = 1.01± 0.31

$H \rightarrow WW \rightarrow 2l2\nu$ couplings



- Result are compatible with SM within 1 sigma.


ATLAS
EXPERIMENT
Run Number: 204265, Event Number: 178165311
Date: 2012-06-02 19:53:30 CEST
$\mathcal{H} \to \tau\tau$

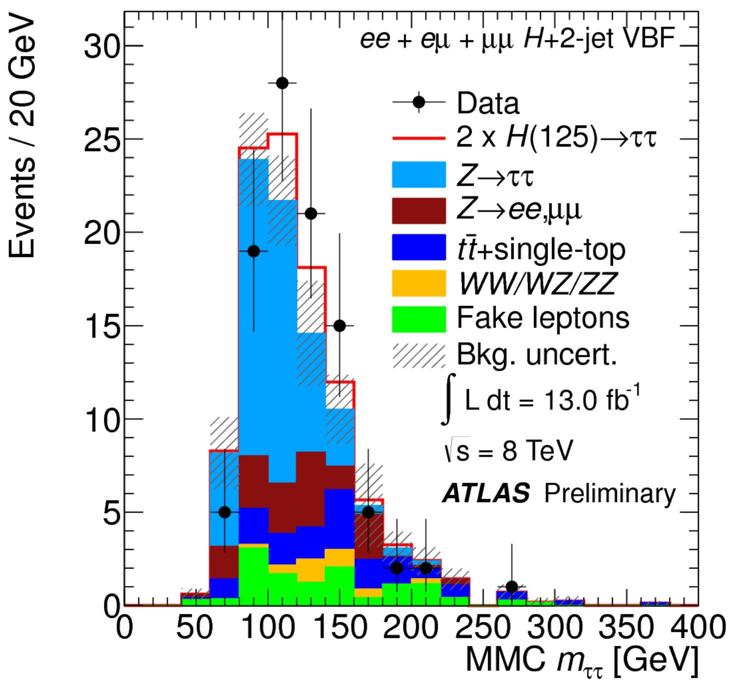
$H \rightarrow \tau\tau$ Analysis

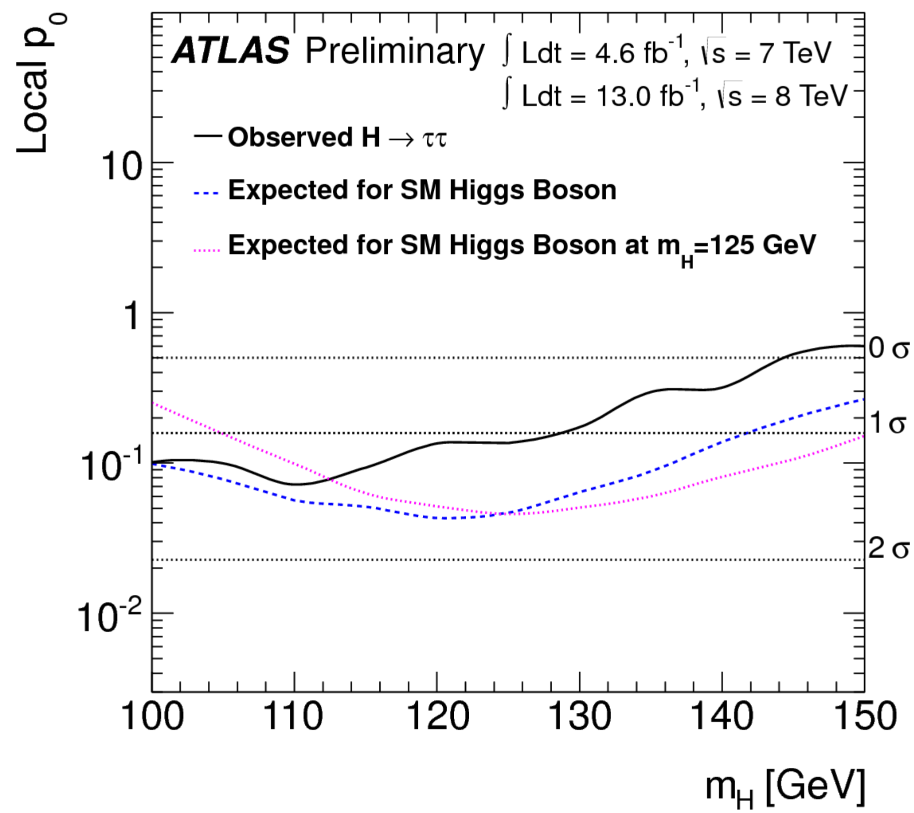
Features:

- Events are separated in 0-jet, 1-jet and 2-jets (VBF) categories.
- ATLAS exploits the $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ final states
- Signal is extracted from a binned fit of the $m_{\tau\tau}$ mass.
- ATLAS results with full 2012 statistics will be available soon

The main backgrounds:

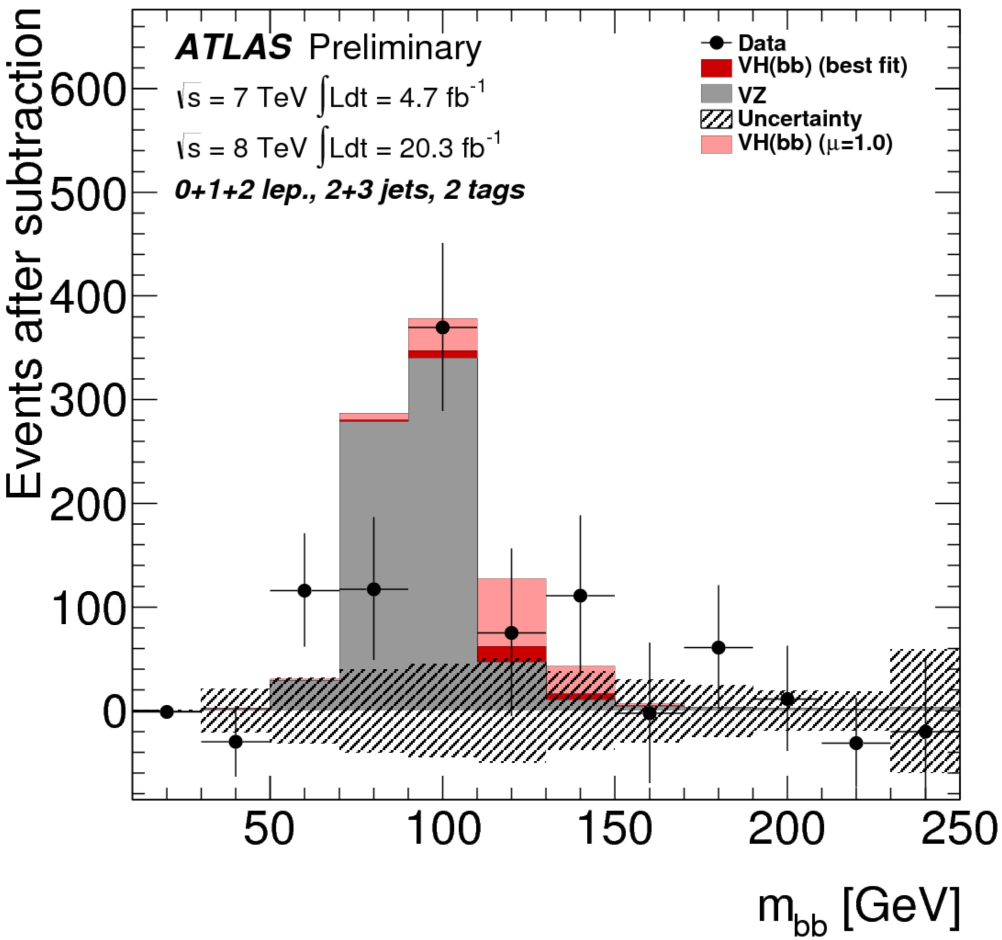
- **Irreducible**: $Z \rightarrow \tau\tau$
- **Reducible**: top, Z+jets, W-jets, multijets

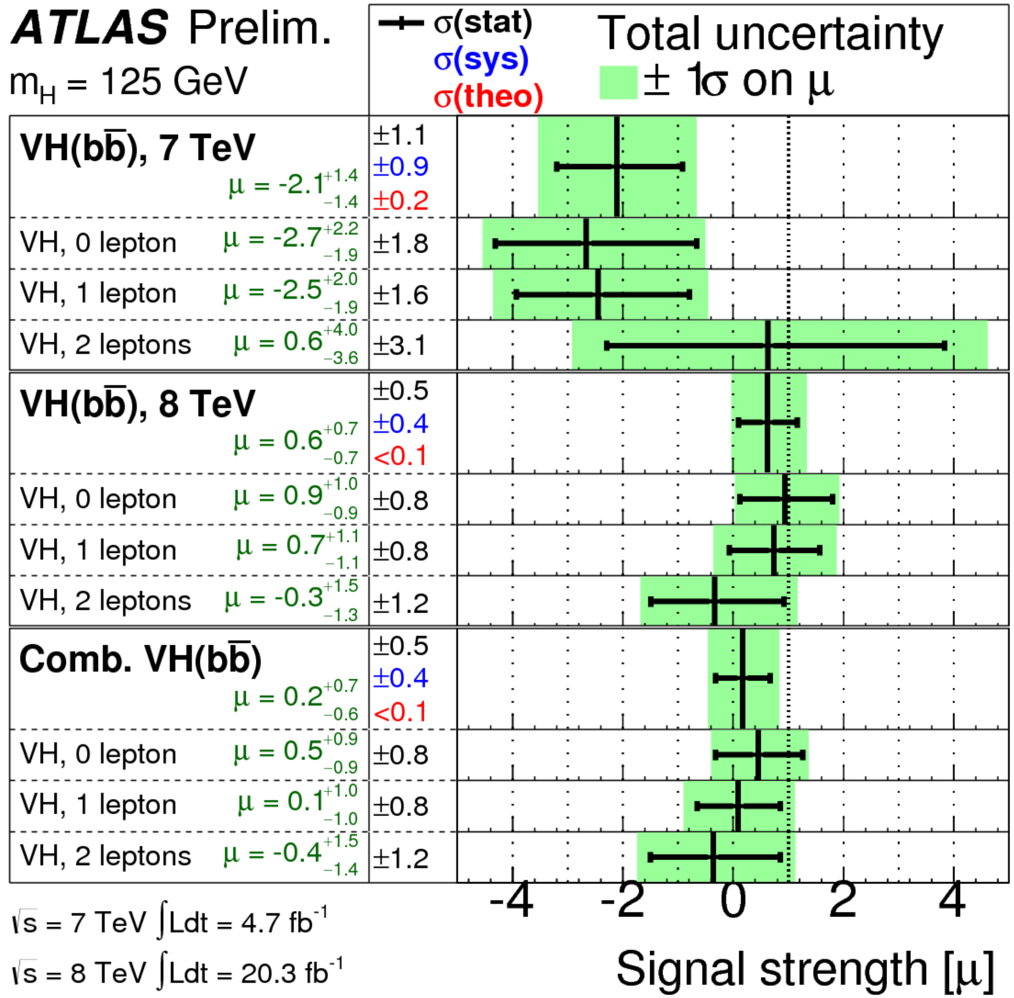




ATLAS Result not yet updated with full statistics.

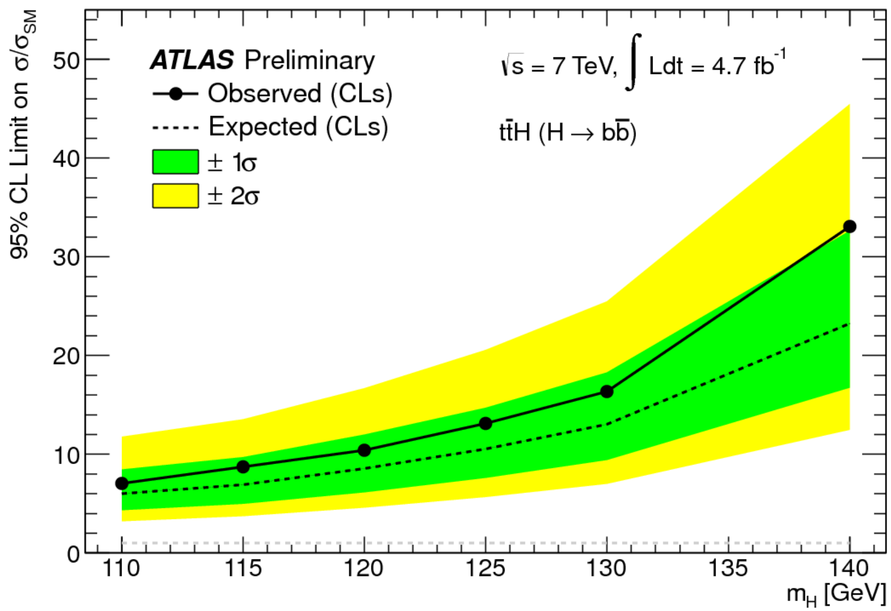
$\mathcal{H} \rightarrow bb$

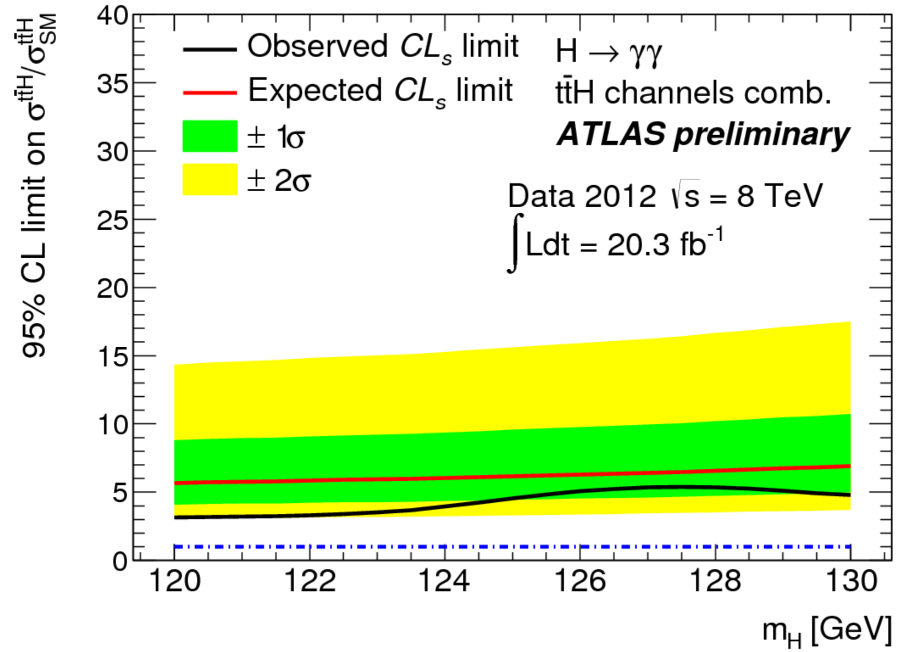




- Results are updated to full Run 1 statistics
- Signal region defined by the presence of 2 b-tagged jets and large MET or 1 or 2 leptons. 0-tag, 1-tag used as CRs.
- Main backgrounds are VZ and ttbar
- Poor mass resolution and low purity

ttH (H->bb, H->gamgam)



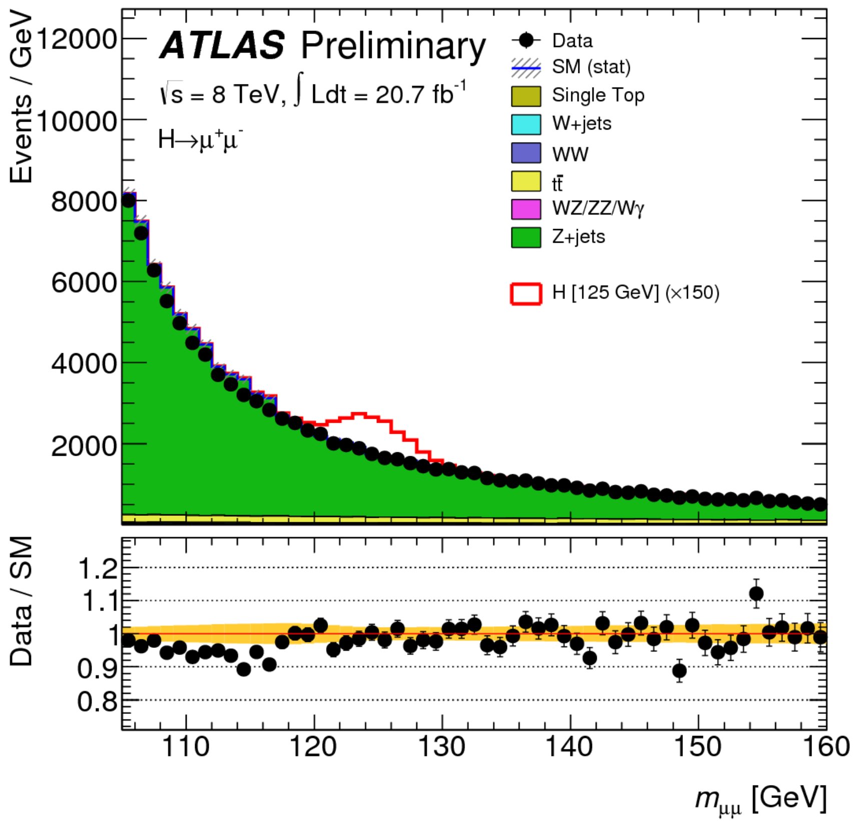


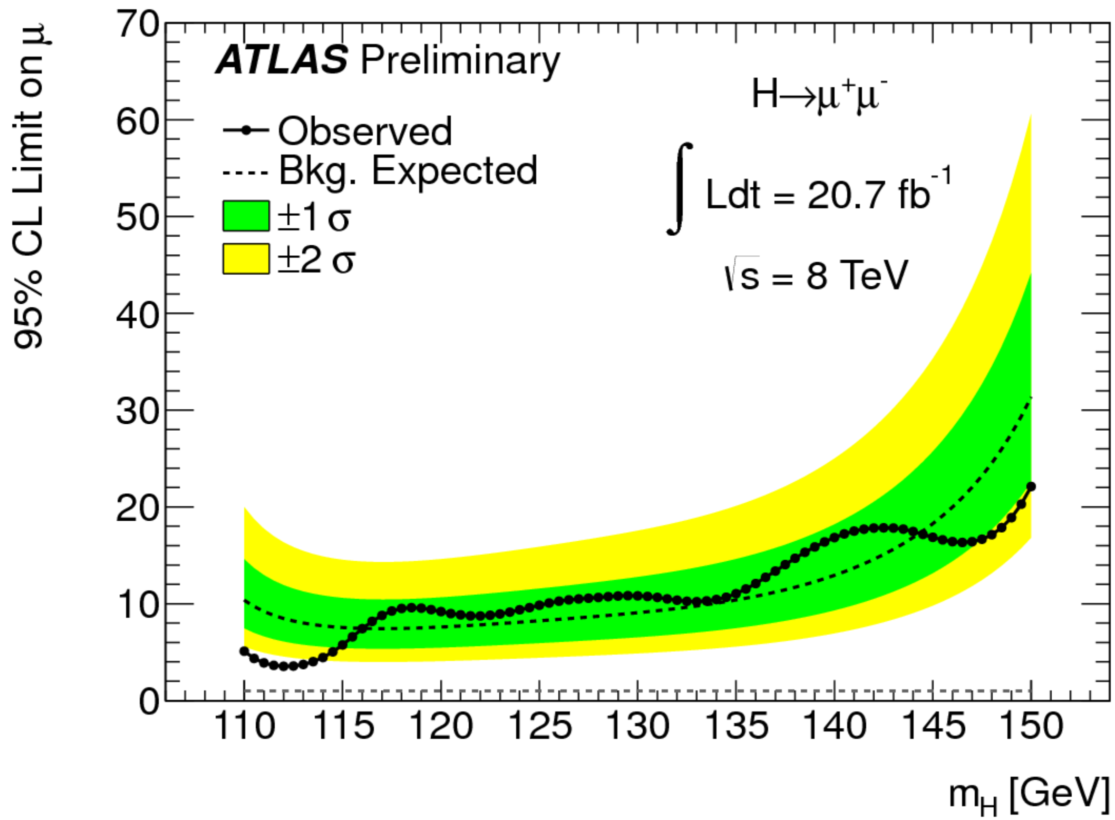
- ttH (H → bb) results still based on 2011 data.
- Multiple categories are defined based on the jet and b-tagged jets multiplicity. Final states with 1 lepton are considered.
- Waiting for 2012 results. $\sqrt{s}$=8TeV already gives a gain of ~50% in rate.

- ttH (H → γγ) results based on 2012 data.
- Robust channel, but it requires more statistics

- ttH (H → WW, ττ) under study.

$\mathcal{H} \to \mu\mu$





- Search for a small resonance on top of Drell-Yan background.
- Events split in central/non-central muons Background modelled with Breit-Wigner+exponential

- Limit @ m_H=125 GeV: 9.8xSM (8.2 expected)

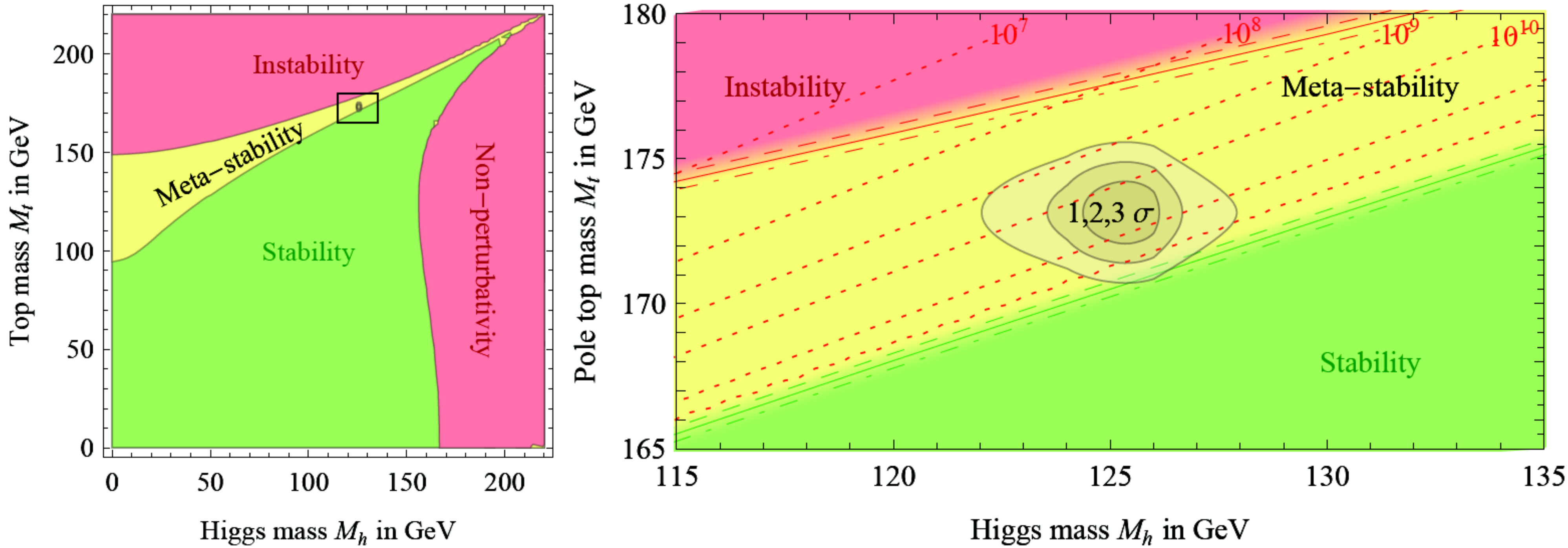
Mass

Couplings

Spin/Parity

Why we can call the new particle a Higgs Boson with high C.L.

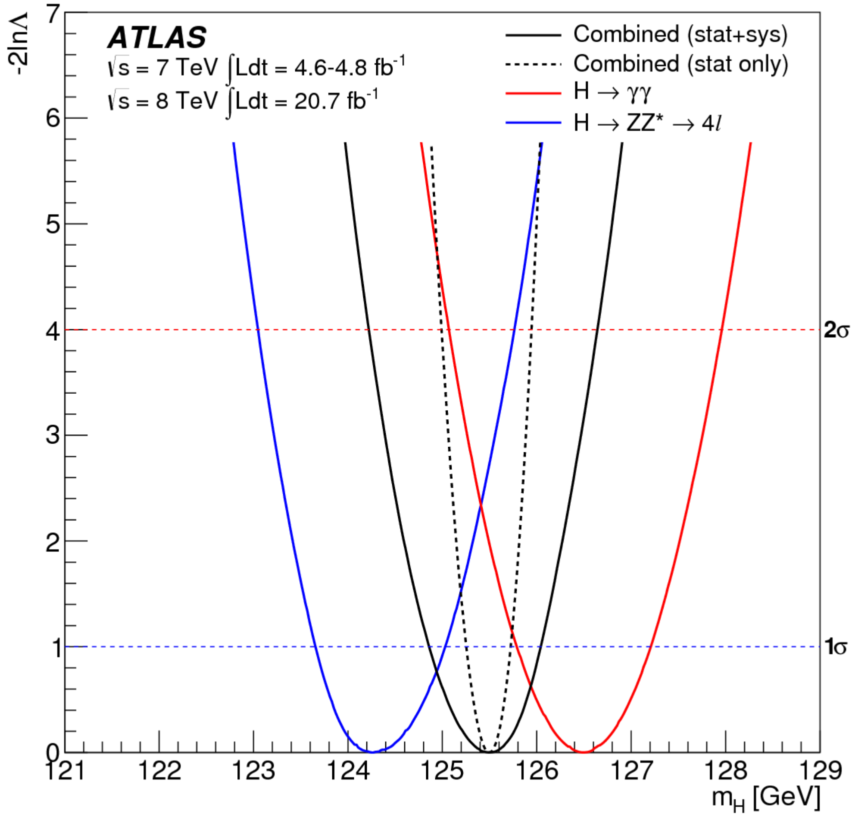
Higgs Mass measurement



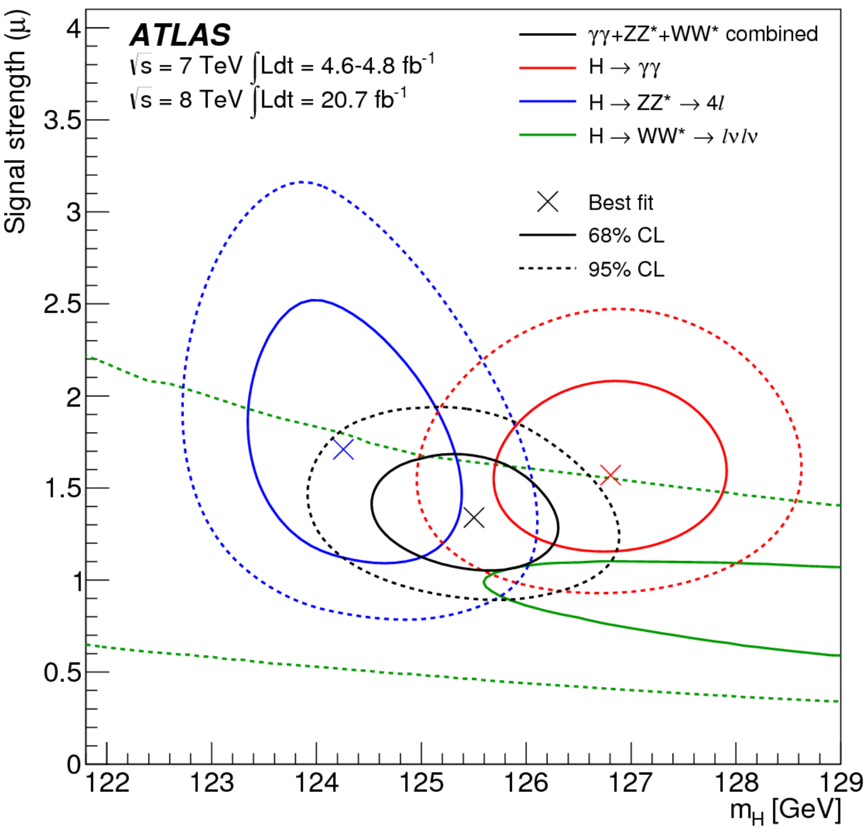
- Why the measurement of the Higgs (and top) mass is not an idle matter.
- EW Vacuum stability up to Planck scaled excluded @ 95 C.L.

G.Degrassi, S. Di Vita, J. Elias-Miró, J. Espinosa, G.F. Giudice, G. Isidori, A. Strumia. [hep-ph/1205.6497]

Mass combination

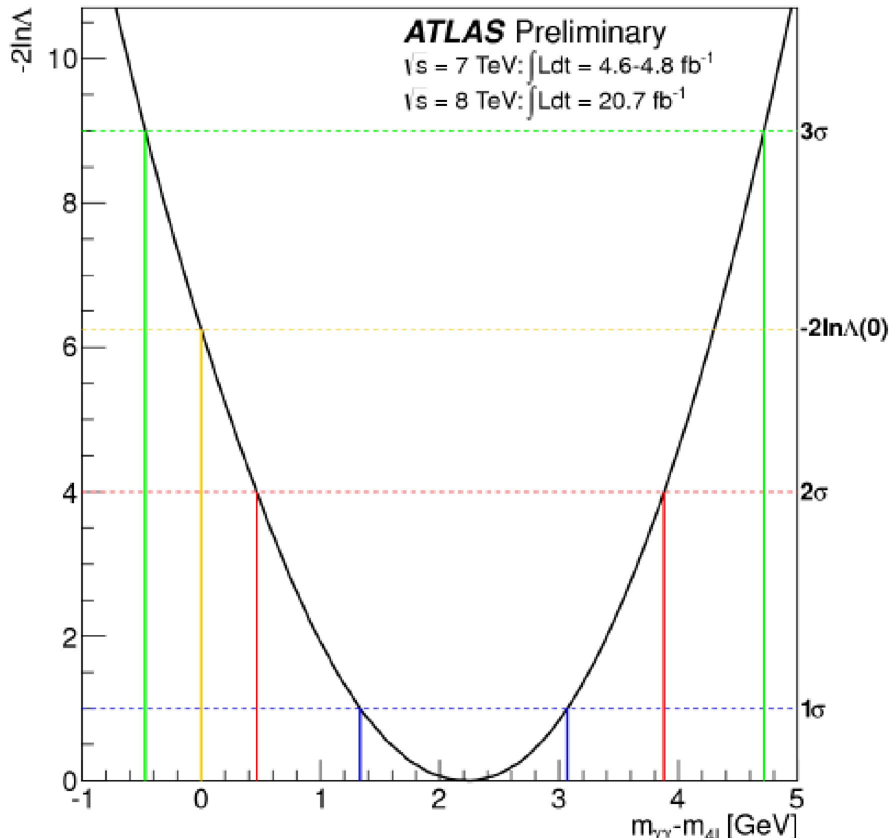


m_H = 125.5 ±0.2(stat) $^{+0.5}_{-0.6}$ (syst) GeV



- The two signal strengths are treated as independent nuisance parameters and allowed to vary independently.
- ATLAS Council Dec 2012 result was : m_H = 125.2 ± 0.3 (stat) ± 0.6 (sys) GeV

Mass measurement

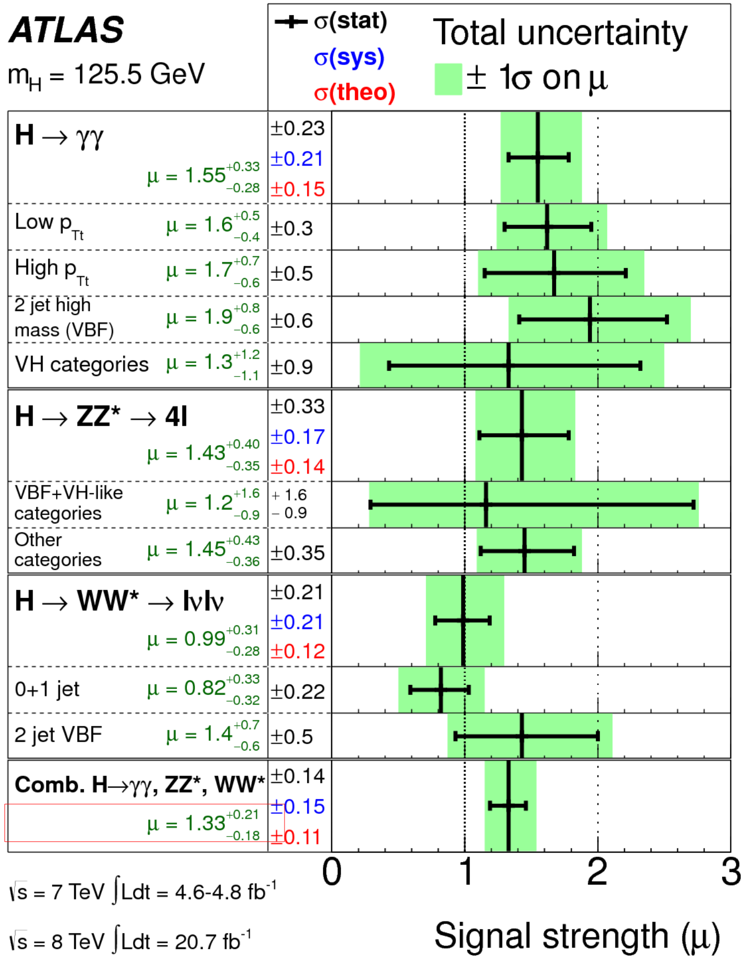


$H \rightarrow ZZ$: $m_H = 124.3\ ^{+0.6}_{-0.5}$(stat) $^{+0.5}_{-0.3}$(syst) GeV

$H \rightarrow \gamma\gamma$: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

- ATLAS mass difference is reduced: $\Delta m_H = 2.3\ ^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV, 2.4 σ from $\Delta m_H = 0$ (p = 1.5%). Δm_H was 3.0 GeV and 2.8 σ in Dec. 2012
- $m_{\gamma\gamma}$ sysematics dominated by the photon energy scale.
- m_{4l} mainly from muon momentum scale.

Signal Strength



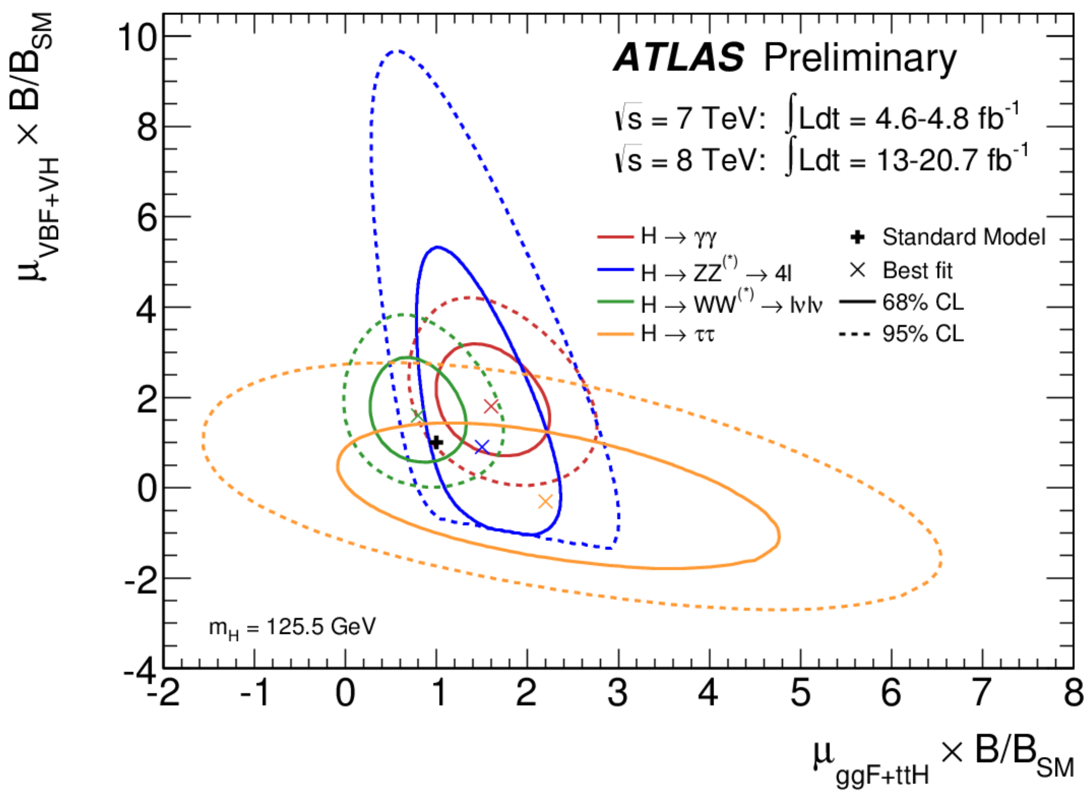
$\mu = \sigma/\sigma_{SM}$

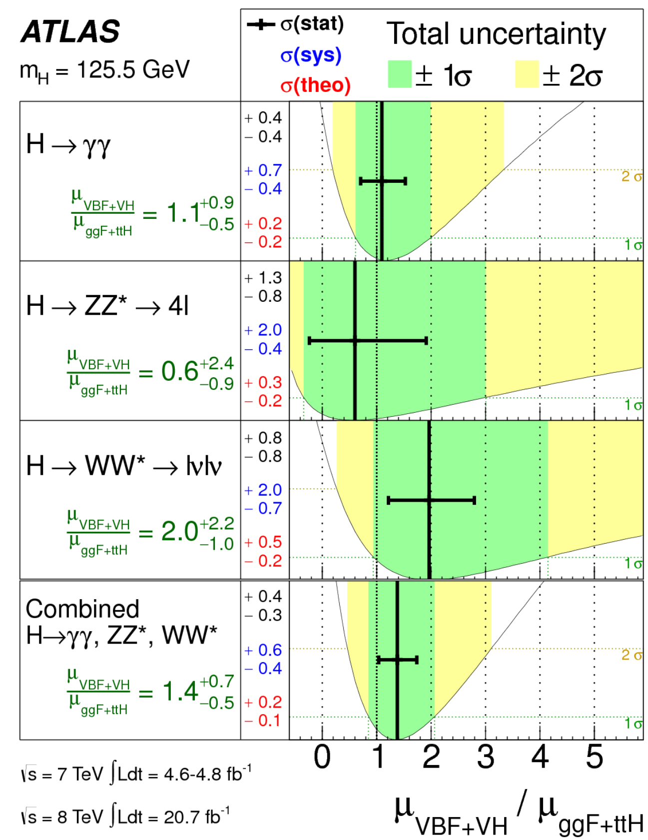
$\mu = 0$ no Higgs

$\mu = 1$ SM Higgs

- The best fit of the signal strength is compatible with the SM.
- H → bb and H → ττ to be added soon

Couplings

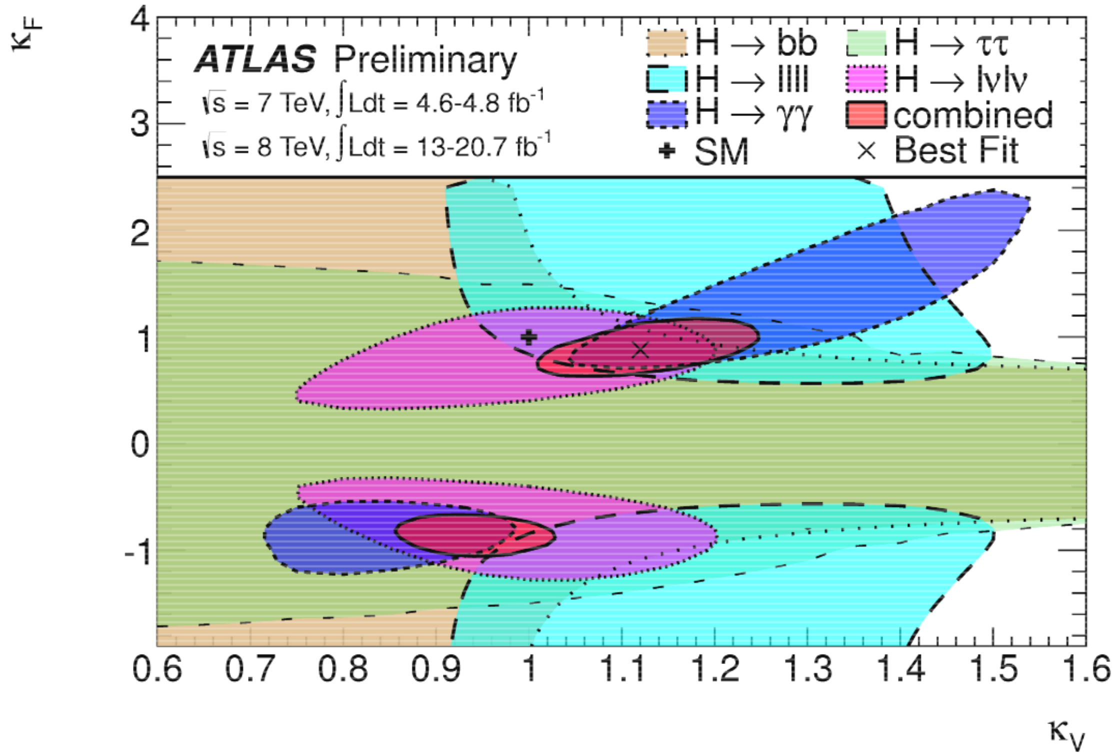




- Sensitivity of each channel to different production modes

- H → γγ and ATLAS H → WW provide good sensitivity to VBF production mode. ATLAS excluded $\mu_{VBF} / \mu_{ggF+ttH}=0$ at 3.1σ

κ_V vs κ_F



- Couplings are grouped: $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Assumptions:

– gg → H and H → γγ only through SM particles

→ only SM particles contribute to decay

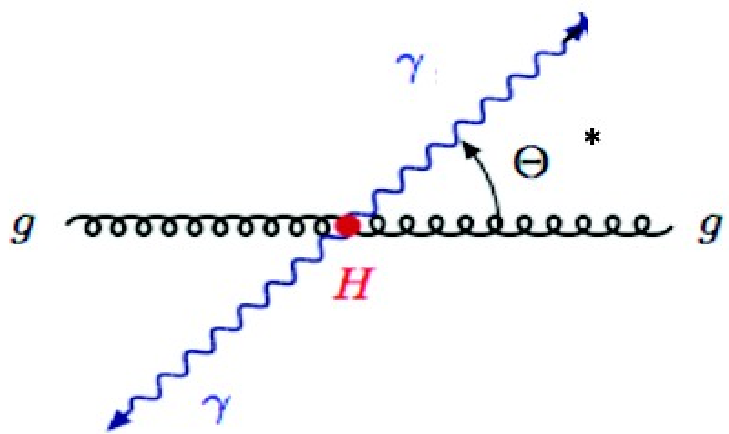
- With current data, sensitivity to κ_F is mostly through top in loops.

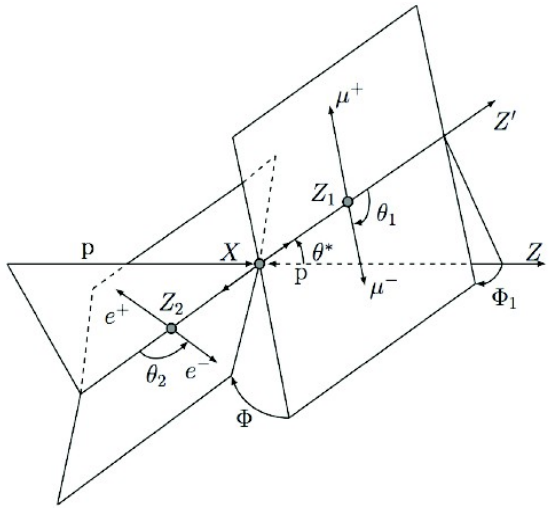
  It will improve with more precise ττ measurement

Spin Measurement

- Critical to establish J^P of the new boson.
- Kinematic distributions are used to distinguish different signal models
  - Probe different amplitude structures.
- Test compatibility of data with distinct simple models.
- ATLAS results from $H \to ZZ$ and $H \to WW$ and $H \to \gamma\gamma$ analyses

J^P	Description
0^-	CP-odd scalar
0_h+	CP-even w/ HD operators
1^+	Axial-vector
1^-	Vector
2_m^+ (gg)	gg -> min coupling grav
2_m^+(qq)	qq->min coupling grav





- ATLAS uses BDT and MELA for $H \to ZZ$, BDT for $H \to WW$ and 1D fit for $H \to \gamma\gamma$

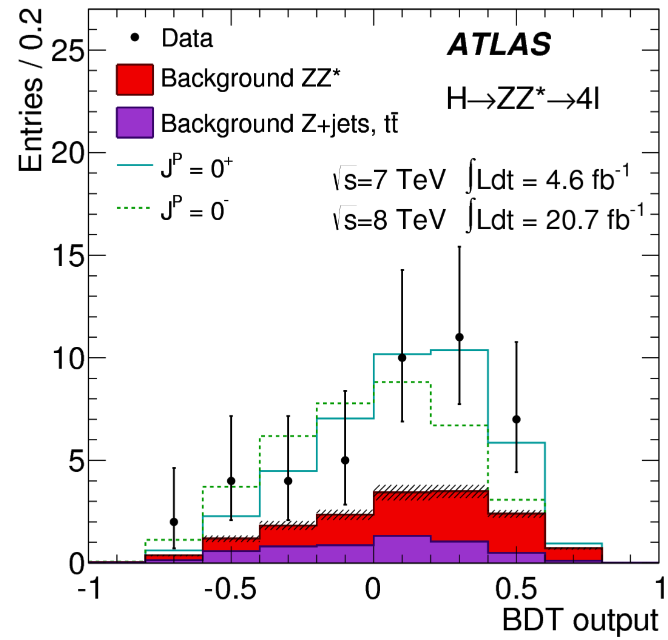
Spin Results

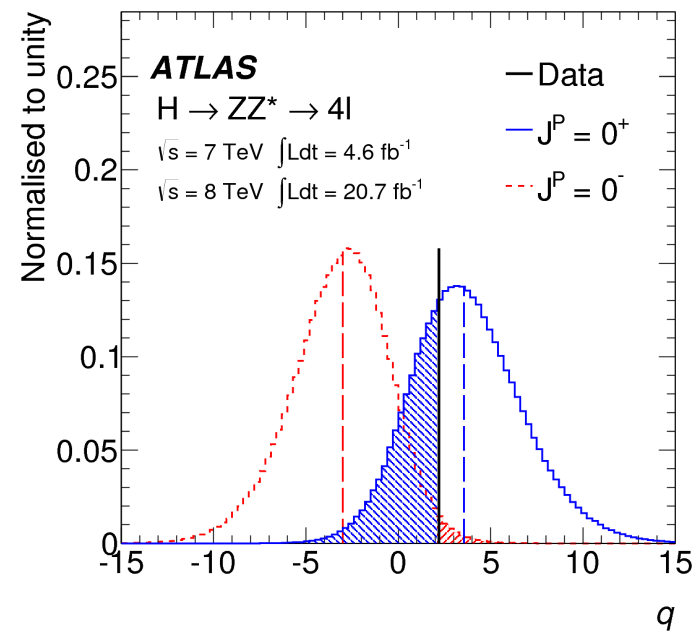
- Compatibility with spin/parity hypothesis is evaluated with a log-likelihood ratio.
- Often based on BDT distributions built from quantities sensitive to spin/parity

- Distributions corresponds to pseudo-experiments.

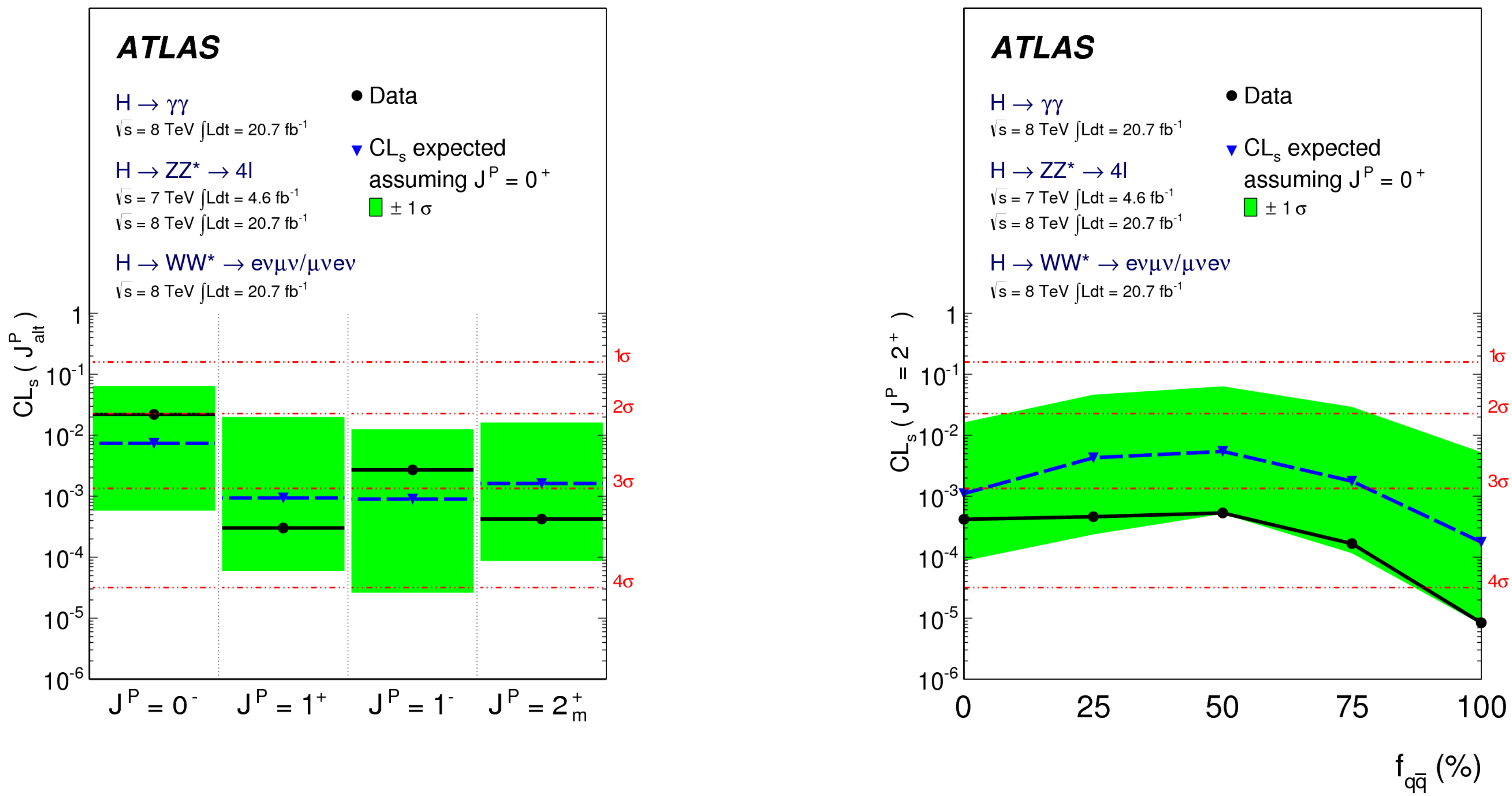
- Similar studies of spin and parity for $H \rightarrow \gamma\gamma$ and $H \rightarrow WW$

- Shown in the plots is the $H \rightarrow ZZ^*$ sensitivity to the particle parity.





Spin Results (2)

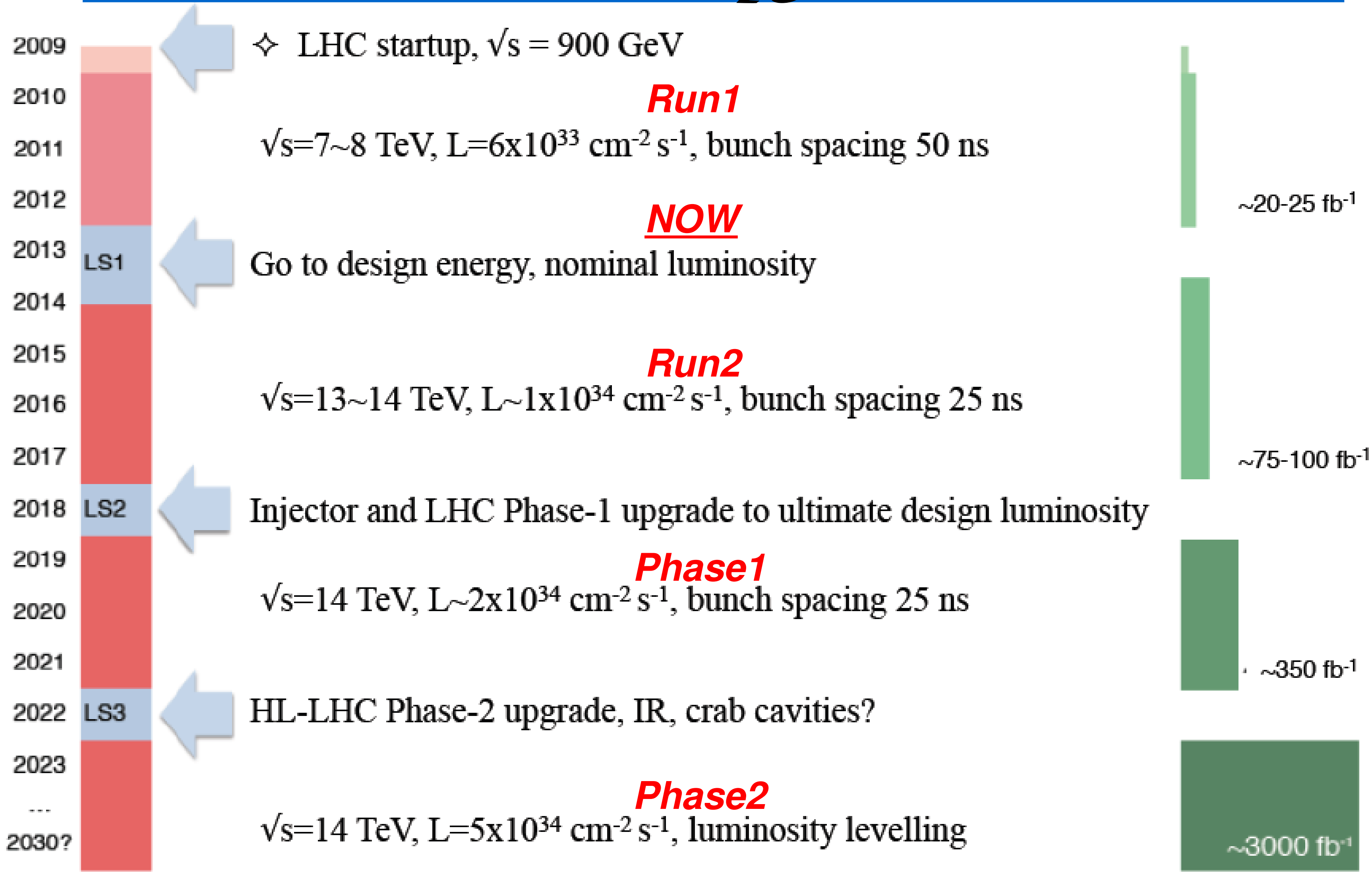


- Analyses are re-optimized for spin analysis
- $H \to ZZ$ analysis disfavour 0^-, 1^+ and 1^- hypotheses at $>2\sigma$. It is inconclusive for 2_m^+.
- $H \to WW$ and $H \to \gamma\gamma$ are complementary in probing the 2_m^+ as a function of the qqbar fraction.

Observed results disfavour 2_m^+ hypothesis by more than 3σ.

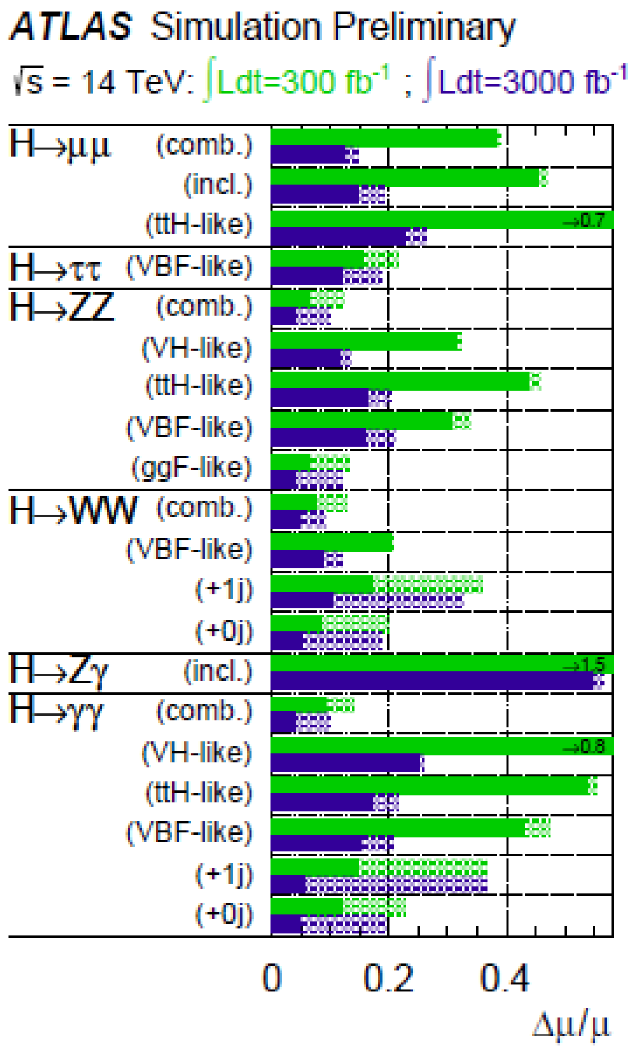
Higgs Sector Measurements Prospects

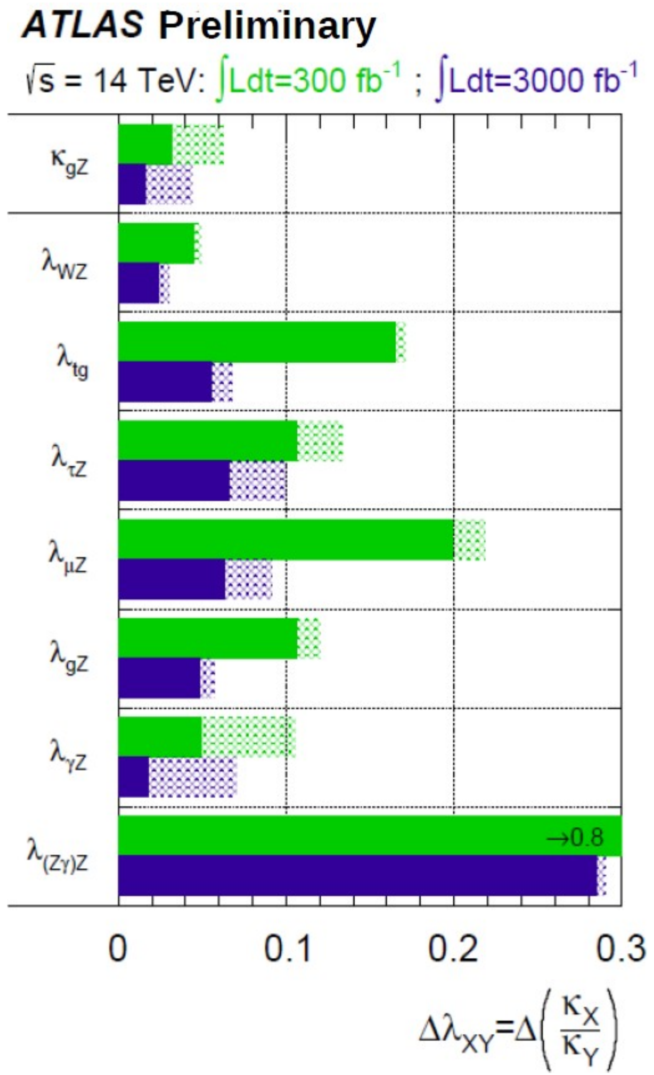
LHC Upgrade



- In parallel design of ILC, CLIC
- At CERN for >2030: HE-LHC, VHE-LHC, TLEP,...

ATLAS Sensitivity

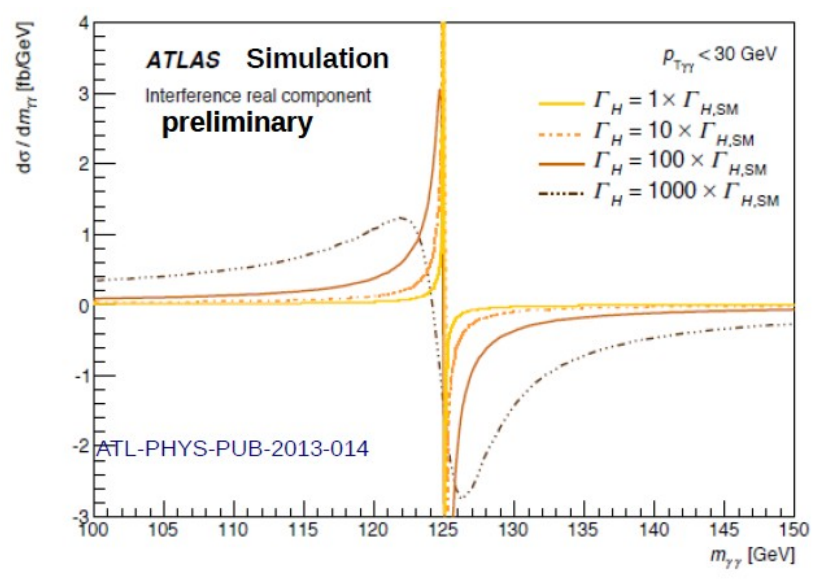


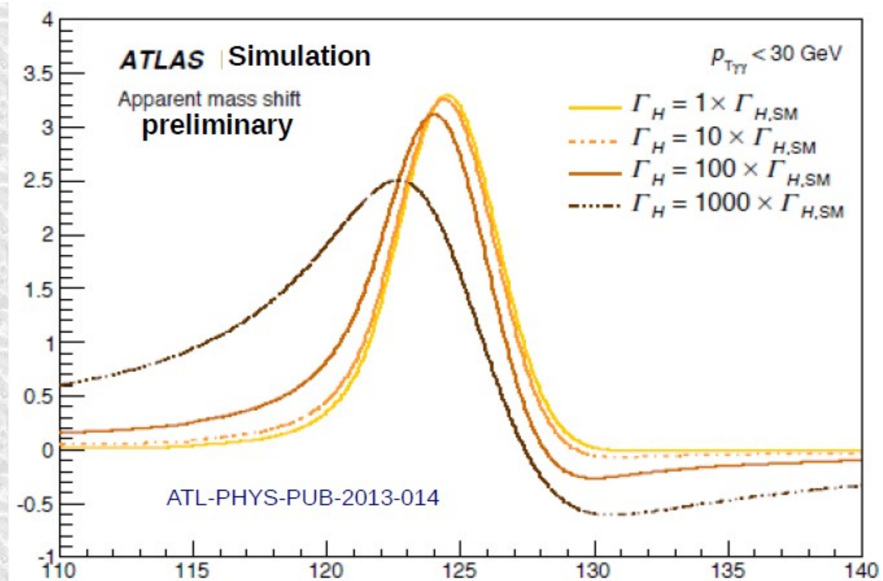


- Run-2 will give the opportunity to measure more precisely rare production modes (ttH, VH and VBF) and improve the measurement of the mass and couplings.
- Phase-1 and phase-2 will allow to measure rare decays (H → μμ and H ->Zγ)

Higgs width study

- SM Higgs width for m_H=125 GeV is about 4 MeV. Not possible to measure the width directly.
- Interference between signal and background should shift the apparent peak position (Dixon and Li arXiv:1305.3854)





Interference of the $H \rightarrow \gamma\gamma$ with the $\gamma\gamma$ continuum has an effect on the production rate and on the peak position as a function of $p_T^{\gamma\gamma}$, that can be measured comparing results with low and high $p_T^{\gamma\gamma}$.

Summary

• Outstanding performance from the LHC team and experiments. majority of the Higgs decay channels have been updated to full Run 1 statistics

• Measurement the properties of the new boson are in progress:
- ATLAS measured the mass with high accuracy.
- Signal strength and Fermionic and Bosonic couplings are compatible with the Standard Model Higgs.
- Spin/Parity: high compatibility with spin-0^+

• Many years of Higgs sector measurements are ahead of us

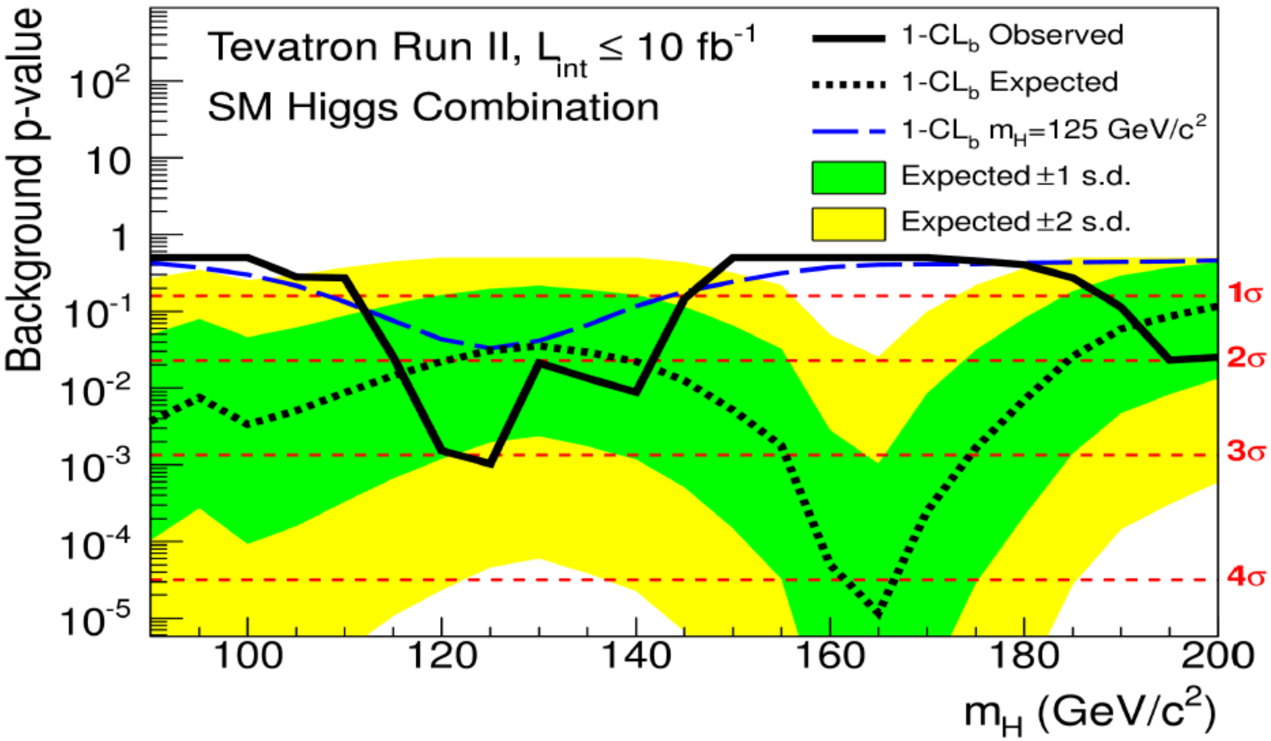
•*[Physics Nobel Prize 2013 Press Release:]*
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

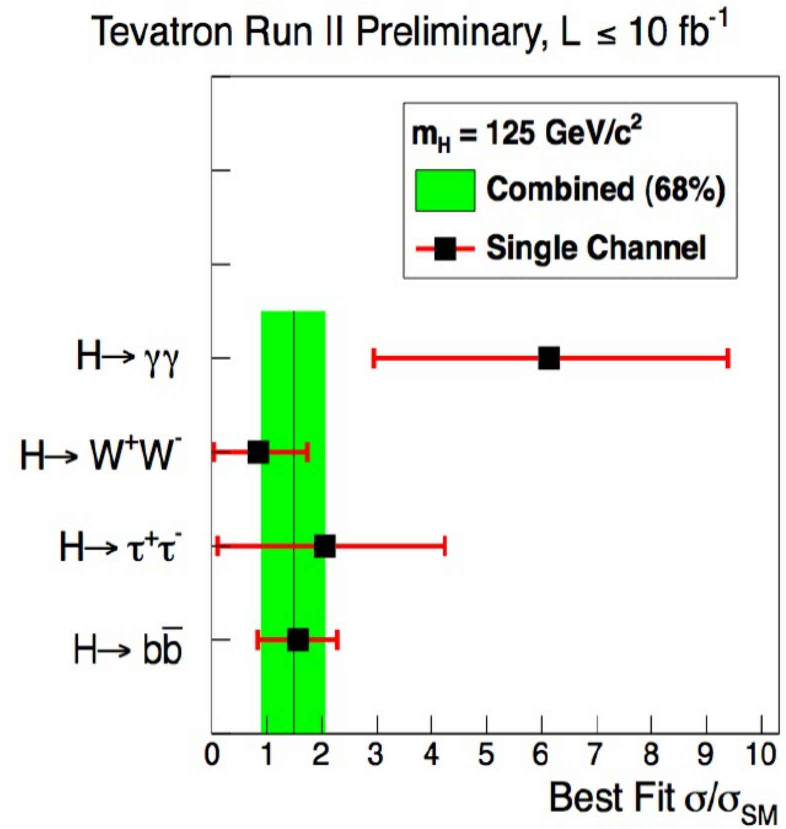
Conclusions

Bonus Slides

TeVatron Results

TeVatron updated their Higgs boson search results with ~10 fb^{-1}
Most sensitive channels are (V)H → (V)bb, H → WW. Analyses of H → γγ and H → ττ are also included.

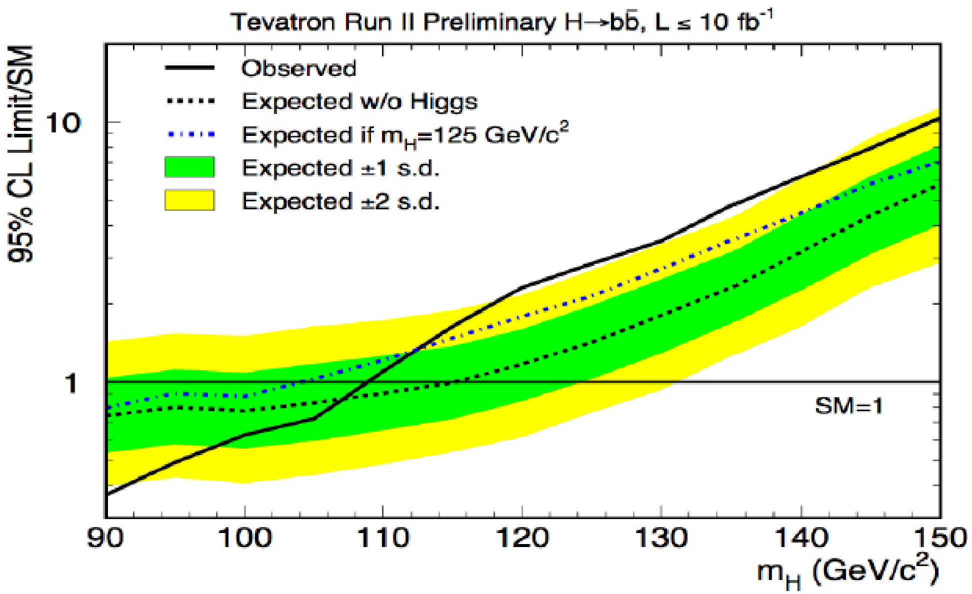


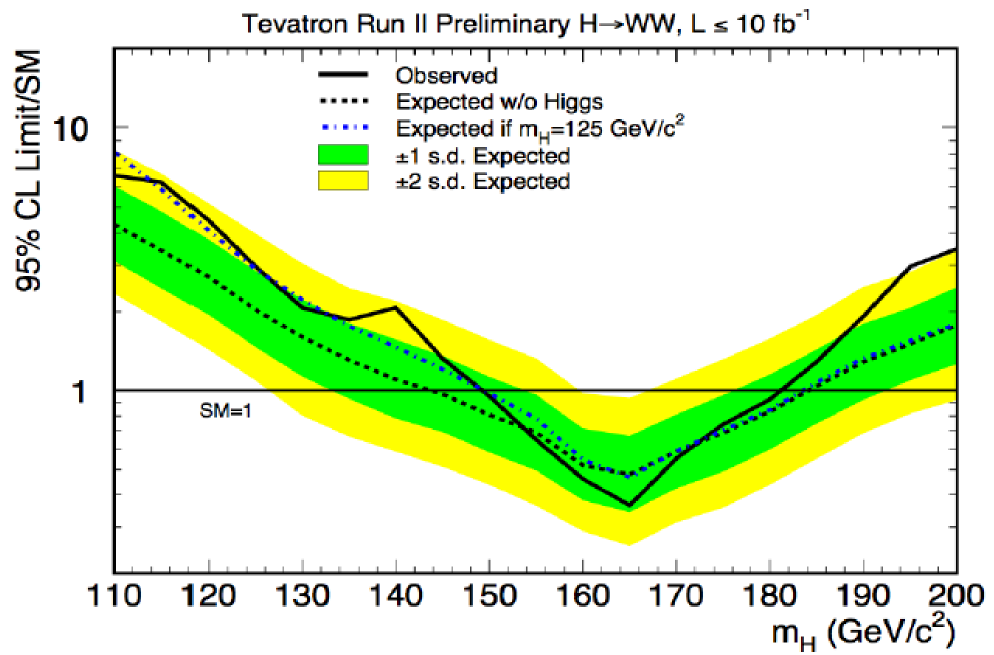


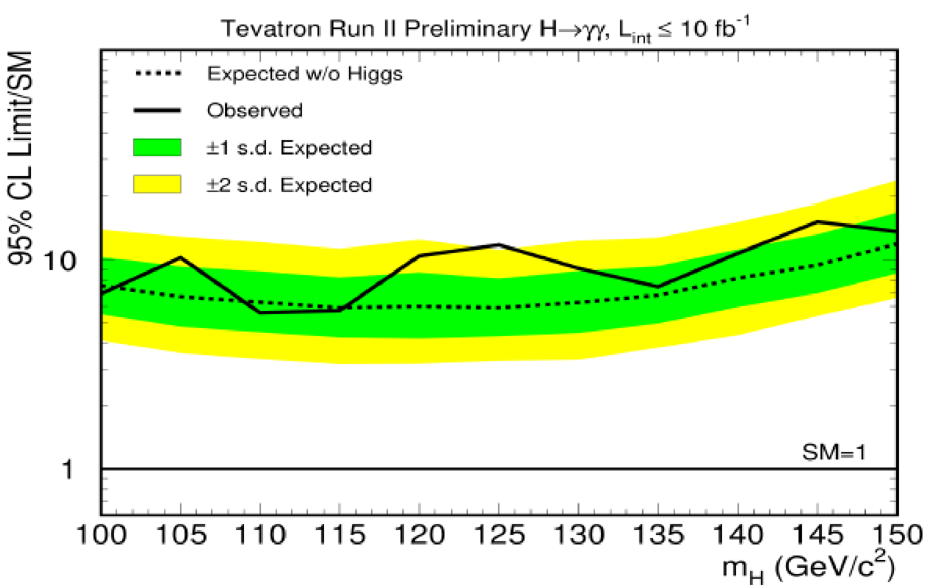
The minimum p-value is found to be 3.1σ at mH =125GeV.

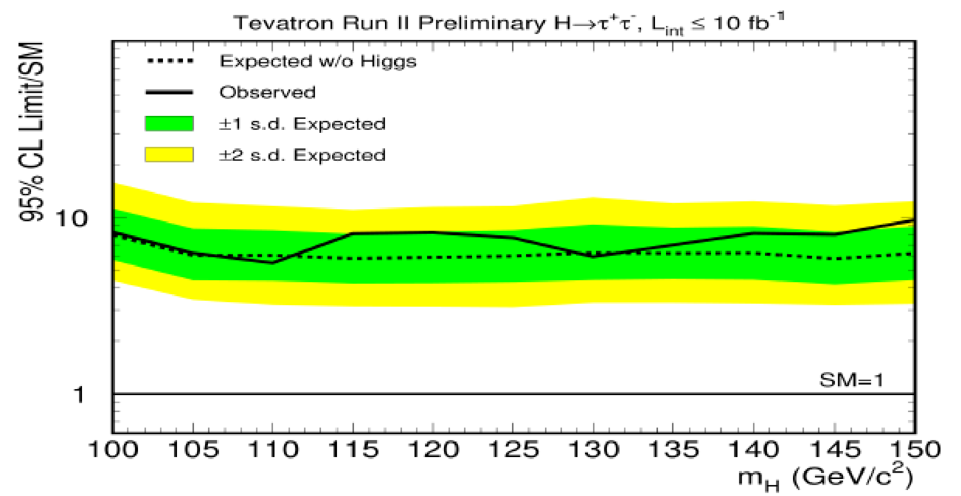
Fit to signal strength (1.4±0.6)xSM @125 GeV

TeVatron Limits by channel

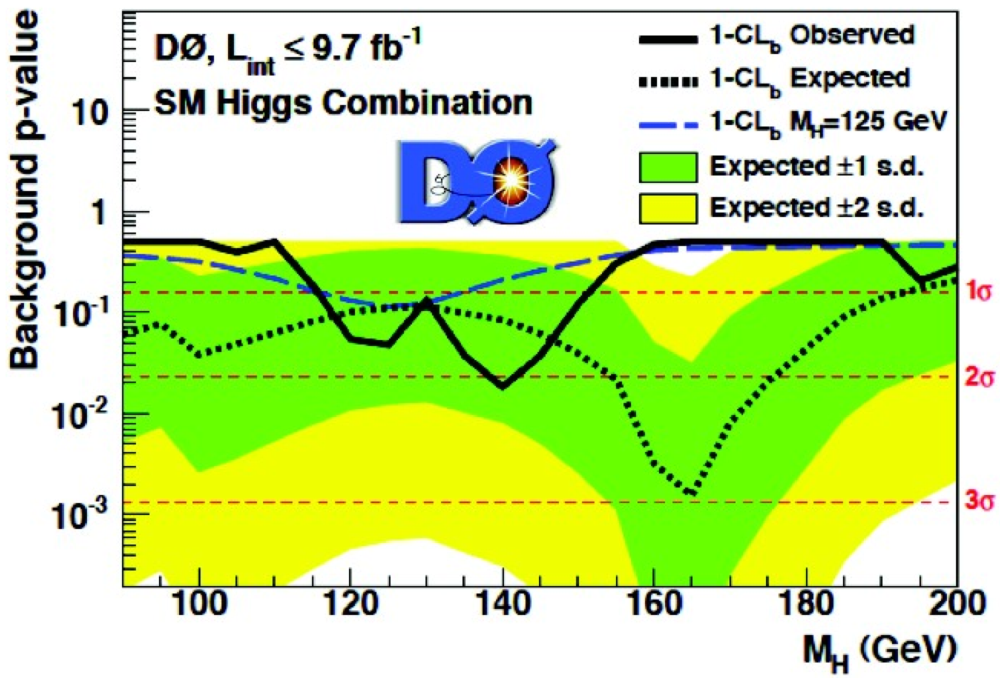


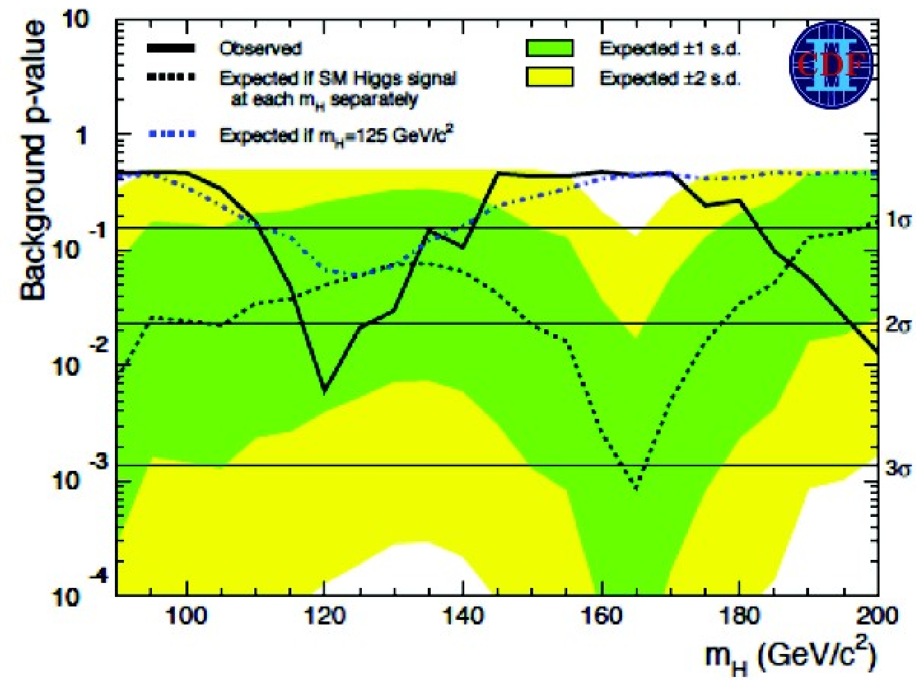






TeVatron Results by experiment





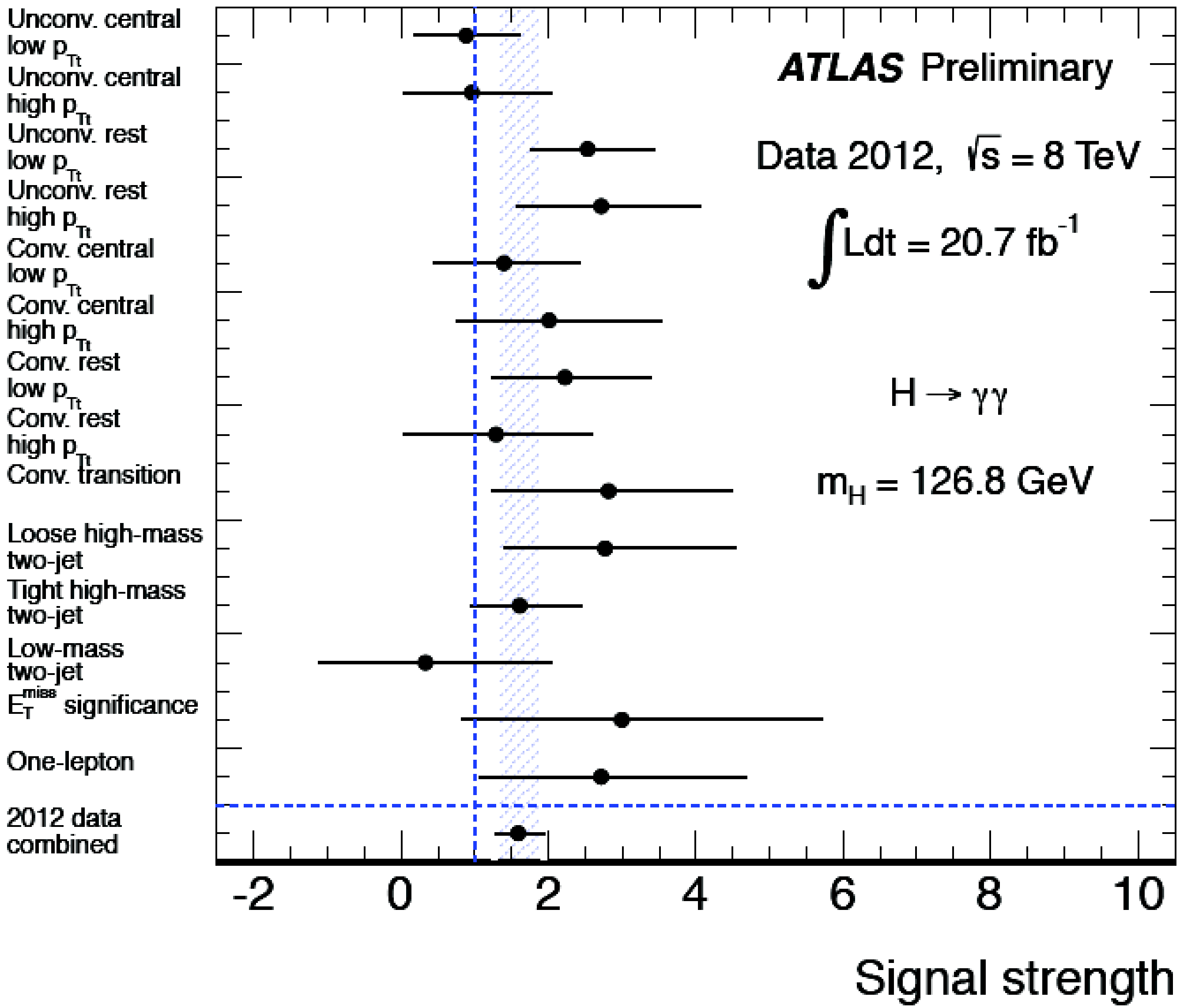
Local p-value distributions as a function of the Higgs mass for D0 and CDF experiments:

- D0: 1.7 σ @ m_H=125 GeV
- CDF: 2.0 σ @ m_H=125 GeV

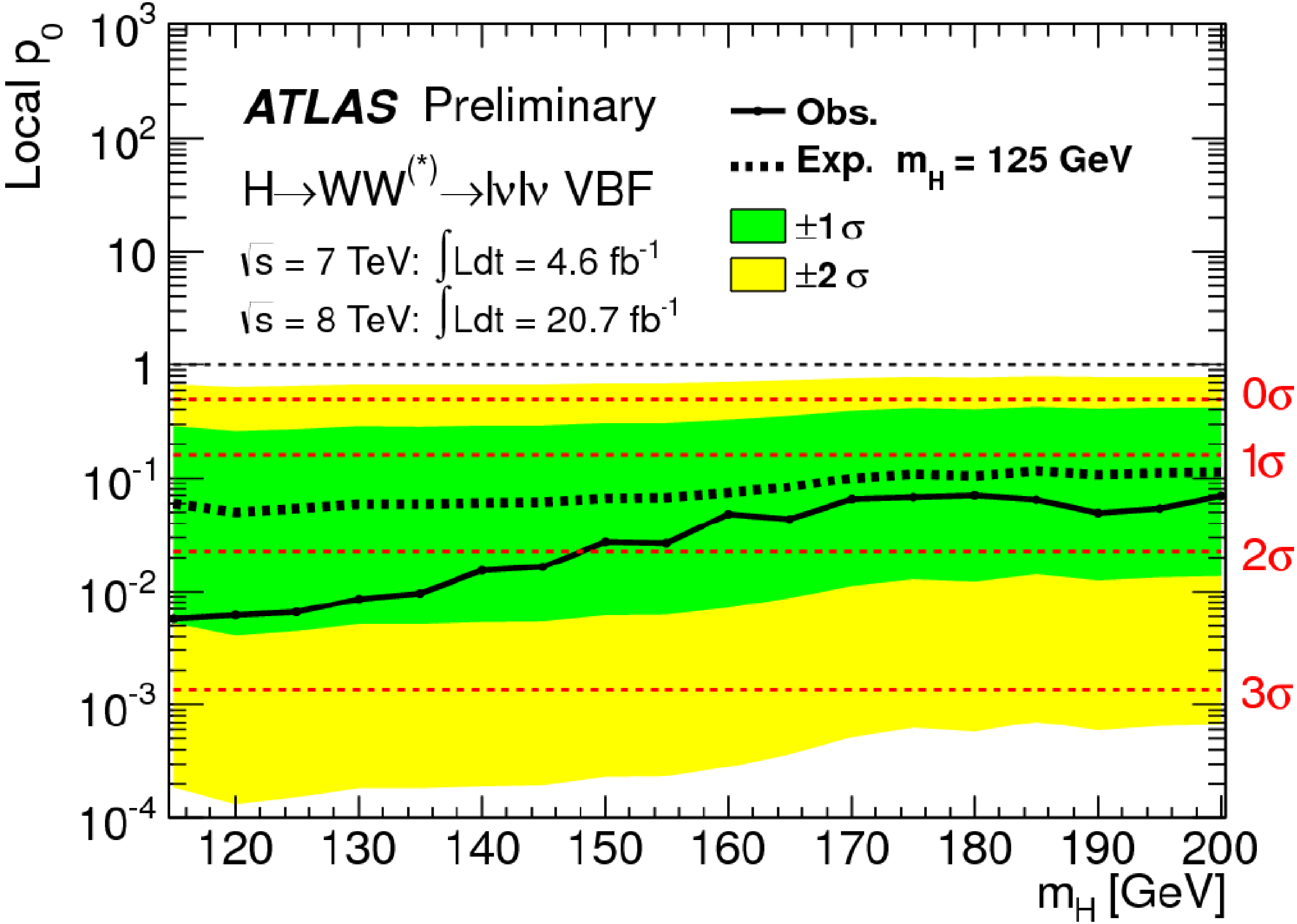
Documents

	ATLAS	CMS
$H \rightarrow \gamma\gamma$	ATLAS-CONF-2013-012 ATLAS-CONF-2013-029	HIG-13-004
$H \rightarrow ZZ \rightarrow 4l$	ATLAS-CONF-2013-013	HIG-13-002
$H \rightarrow WW \rightarrow 2l2n$	ATLAS-CONF-2013-030 ATLAS-CONF-2013-031	HIG-13-001
$H \rightarrow \tau\tau$	ATLAS-CONF-2012-160	HIG-13-004 HIG-12-051 HIG-12-053
$H \rightarrow bb$	ATLAS-CONF-2013-079	HIG-12-044
ttH	ATLAS-CONF-2013-080	HIG-12-025
Combination	arXiv:1307.1427 arXiv:1307.1432	HIG-12-045
Upgrade	ATLAS-PHYS-PUB-2013-014	

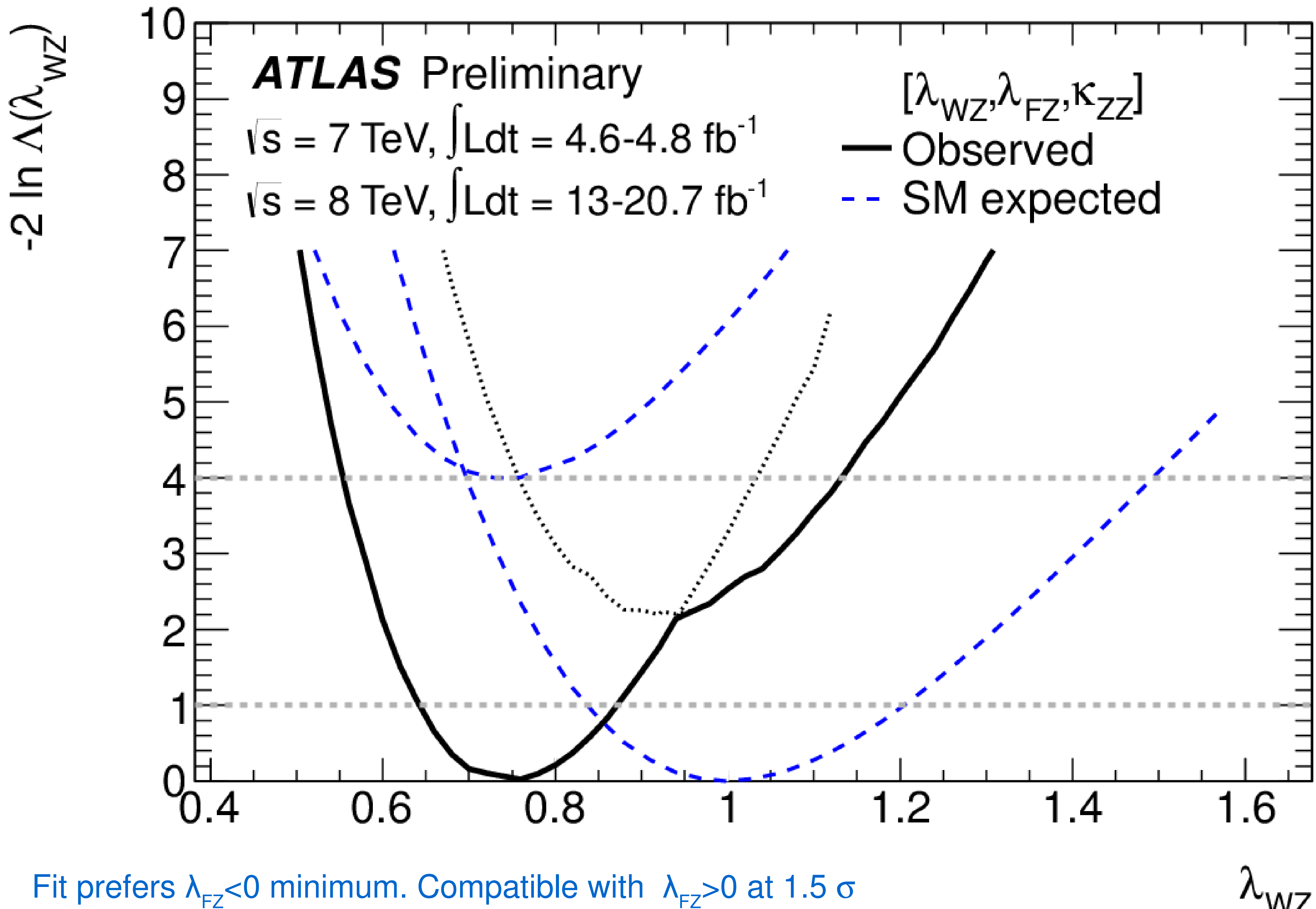
$H \to \gamma\gamma$ categories



$H \rightarrow WW$ VBF

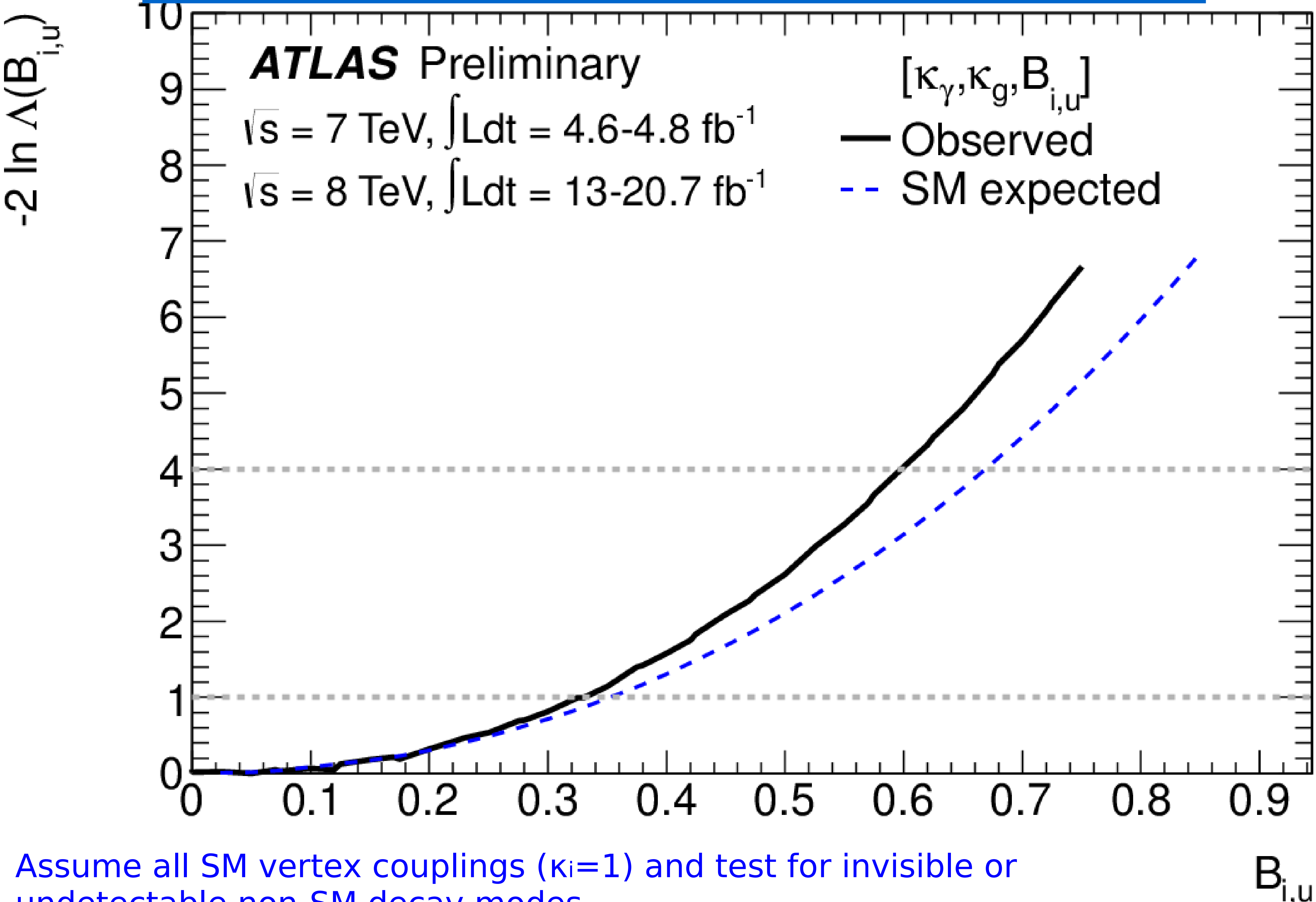


Custodial Symmetry



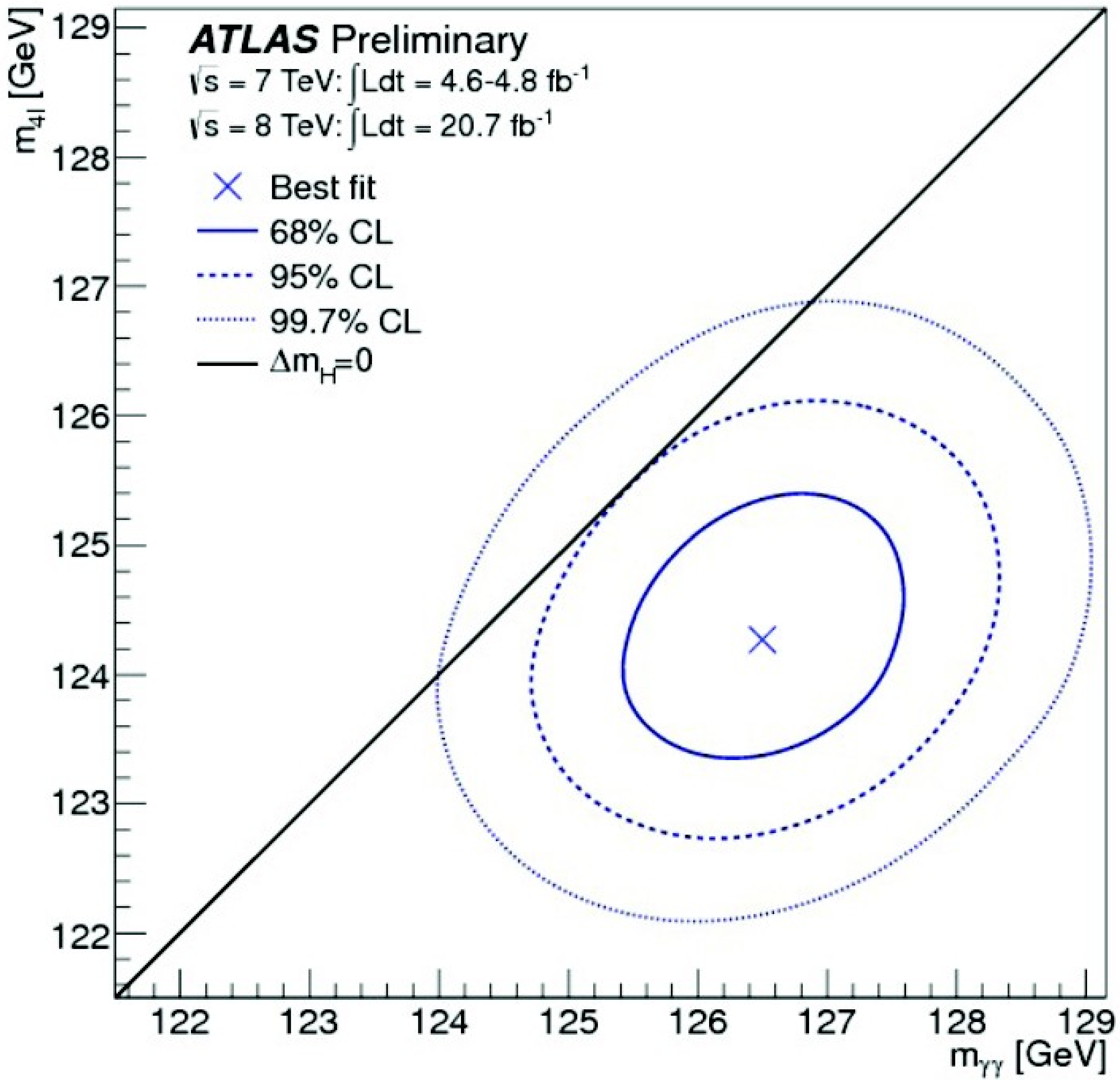
Fit prefers $\lambda_{FZ}<0$ minimum. Compatible with $\lambda_{FZ}>0$ at 1.5 σ

Invisble channels

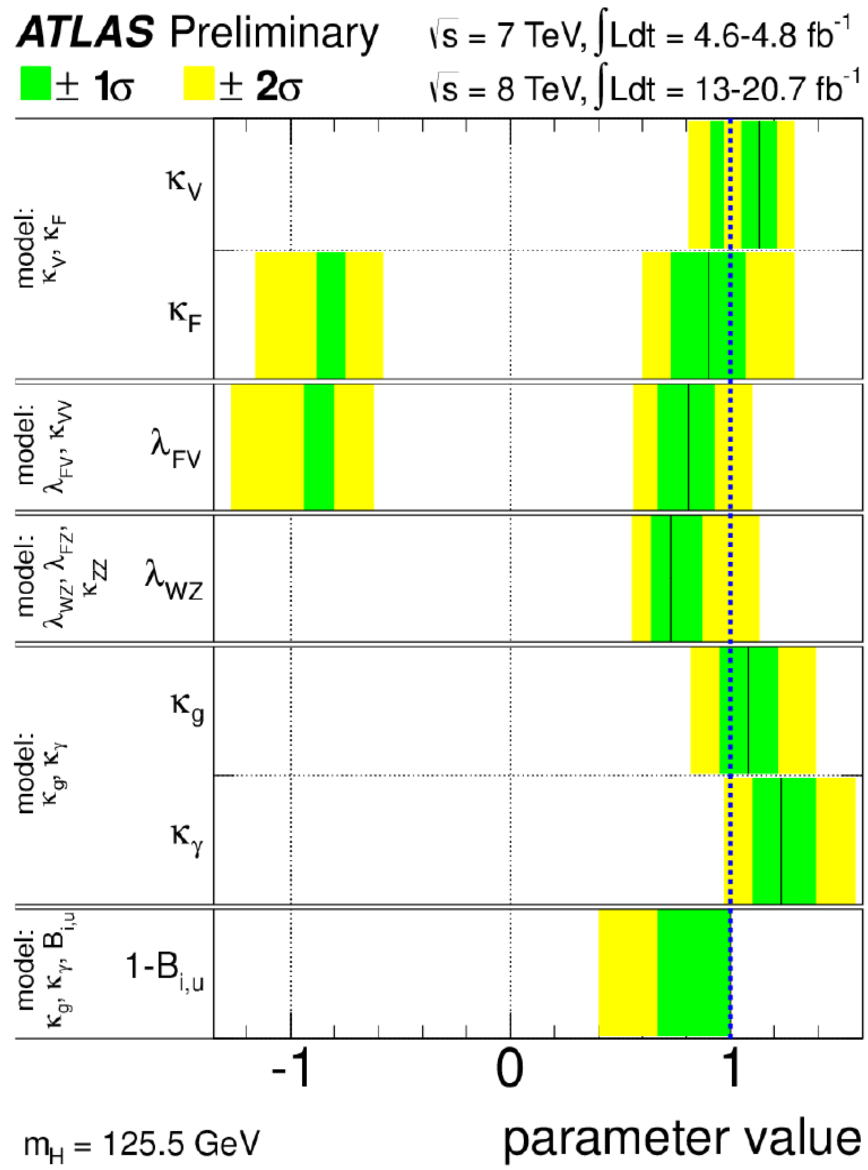


Assume all SM vertex couplings (κ_i=1) and test for invisible or undetectable non-SM decay modes

Mass difference



Summary of couplings



Parameter measurements are correlated

Spin Models

Table 1: Choice of coupling parameters for the spin-2 model considered in the current analysis. The notation follows the one adopted in [12]. (from JHU)

J^P	Production configuration	Decay configuration	Comments
2^+_m	$gg \to X: \ g_1 = 1$ $q\bar{q} \to X: \ g_1 = 1$	$g_1 = g_5 = 1$	Graviton-like tensor with minimal couplings

General amplitude for spin-2 H→VV

$$A(X \to VV) = \Lambda^{-1} \Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$
$$+ g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
$$+ g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \Big]$$

Cannot exclude generic spin-2 with current data set

ATLAS Mass Systematics

- ***4 leptons***
  - Dominated by 4 muons (best resolution, less background)
    - Muon momentum-scale uncertainty : 0.2%
      (from Z, $J/\psi \rightarrow \mu\mu$)
  - electron E-scale = > see below

- ***γγ***
  - Per category systematic uncertainties:
    - method ~ 0.3 % : (mainly from $Z \rightarrow ee$ MC/data)
    - material in front of calorimeter: ~ 0.3%, up to 0.7%
    - relative calibration presampler/calorimeter : ~ 0.1%

    In each of the above: extrapolation in E $\oplus$ transfer from e to γ
  - Additional (global) syst uncertainties:
    - E1/E2, linearity, lateral leakage, conversion fraction … 0.32%
  - Global mass systematic uncertainty: 0.55% = 0.7 GeV