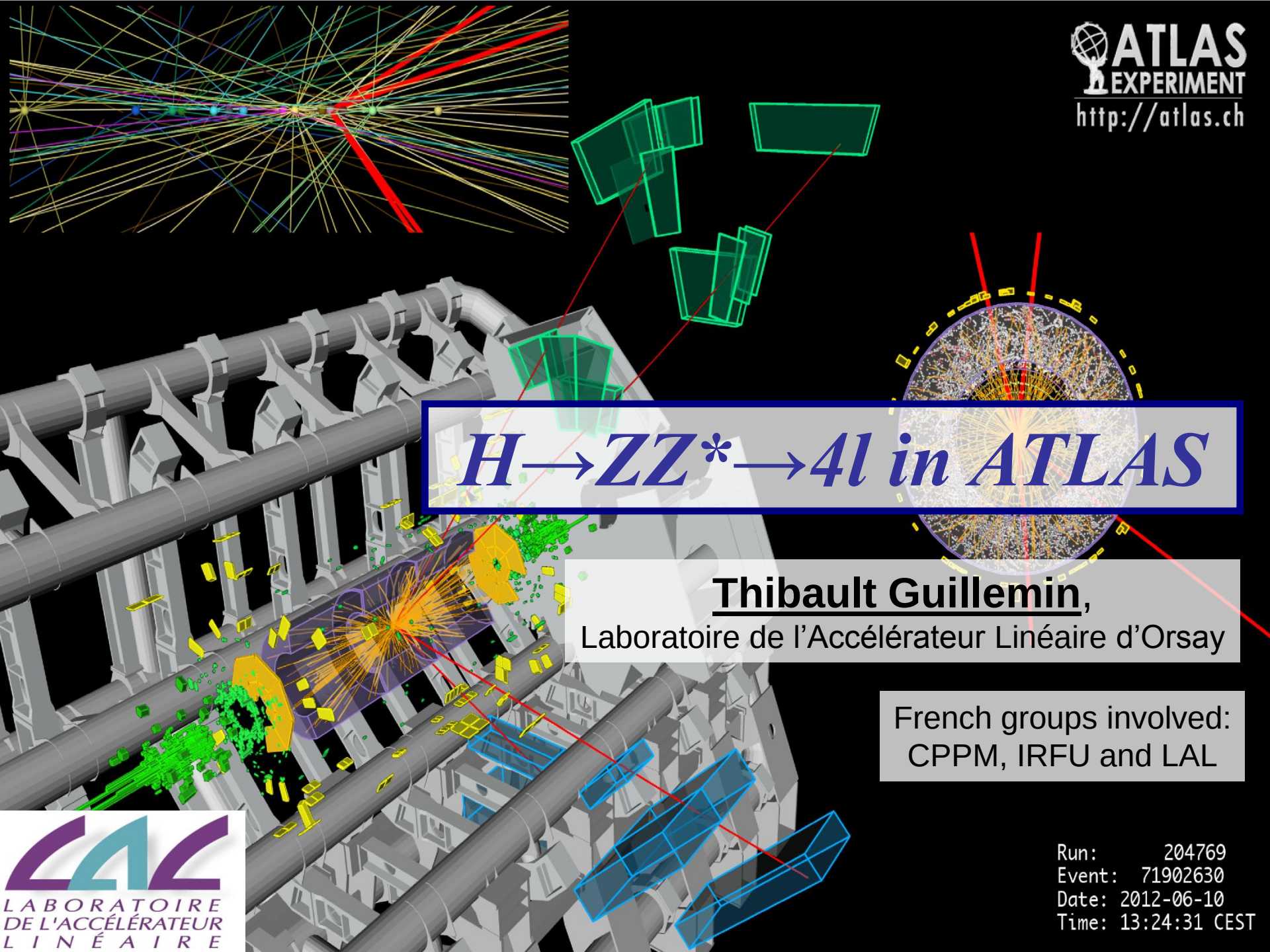


$H \rightarrow ZZ^* \rightarrow 4l$ in ATLAS

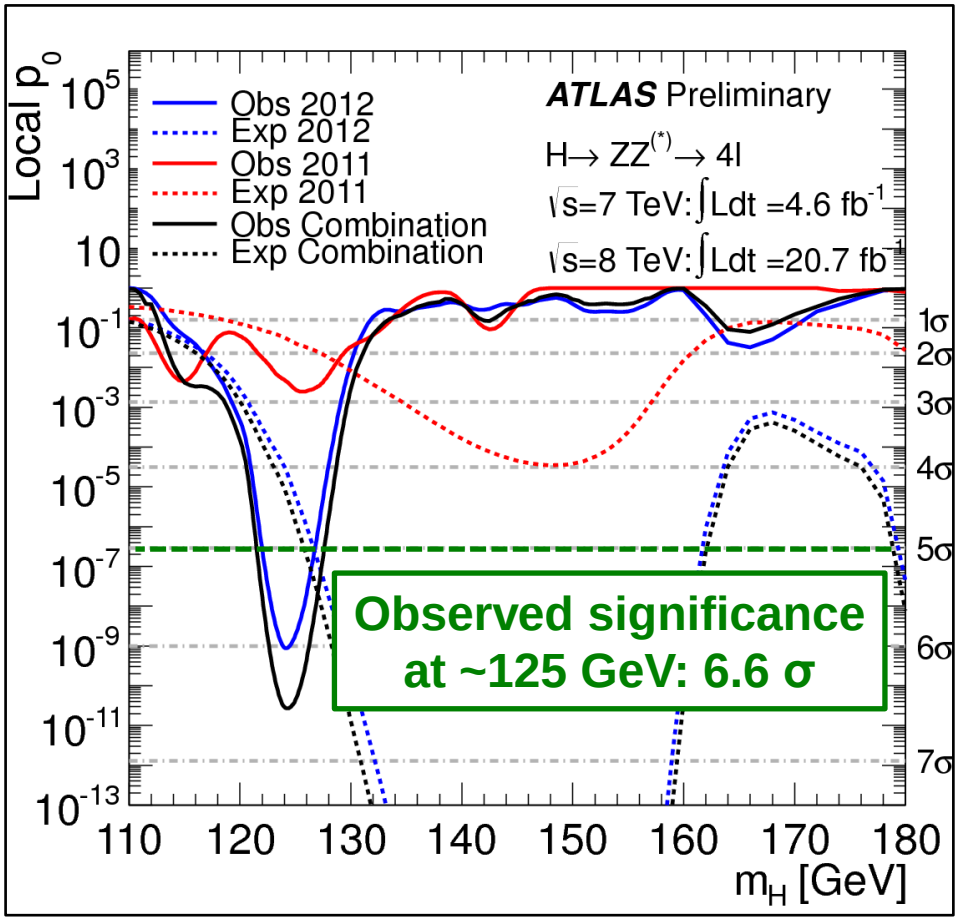
Thibault Guillemin,
Laboratoire de l'Accélérateur Linéaire d'Orsay

French groups involved:
CPPM, IRFU and LAL

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Thibault Guillemin

Observation of the process pp → H → ZZ*→ 4l with the full LHC Run I statistics



Outline:

1) Analysis overview
2) Mass measurement
3) Coupling measurement
4) Spin/P measurement

Reference: ATLAS-CONF-2013-013

Analysis overview (1/4) - Event selection

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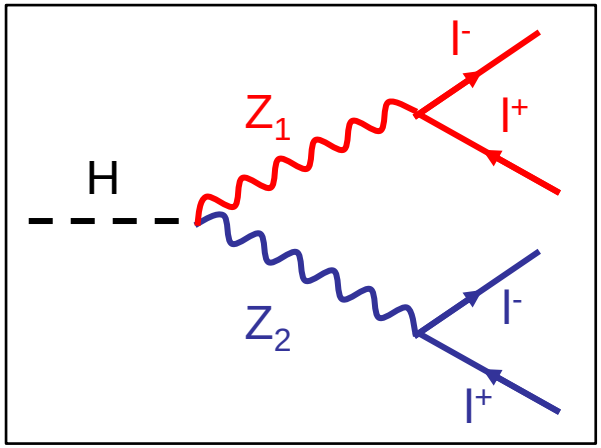
Highest purity Higgs decay channel (S/B~1.5)
Small rate (~2 events produced per fb^{-1})



- Muon (electron) selection:

p_T> 6 (7) GeV and |η|<2.7 (2.47)

- Lepton quadruplet selection:

- two same-flavour opposite charge lepton pairs

- three leading leptons satisfy p_T>20/15/10 GeV

- $50 < m_{Z1} < 106$ GeV

- m_{Z2} >12 GeV

In addition: track isolation, calorimeter isolation and impact parameter significance cuts applied on the four leptons

Analysis splitted in four subchannels: 4μ, 2μ2e, 2e2μ and 4e

Overall signal acceptance: 39% 4μ, 26% 2e2μ, 19% 4e

Analysis overview (2/4) - Performances

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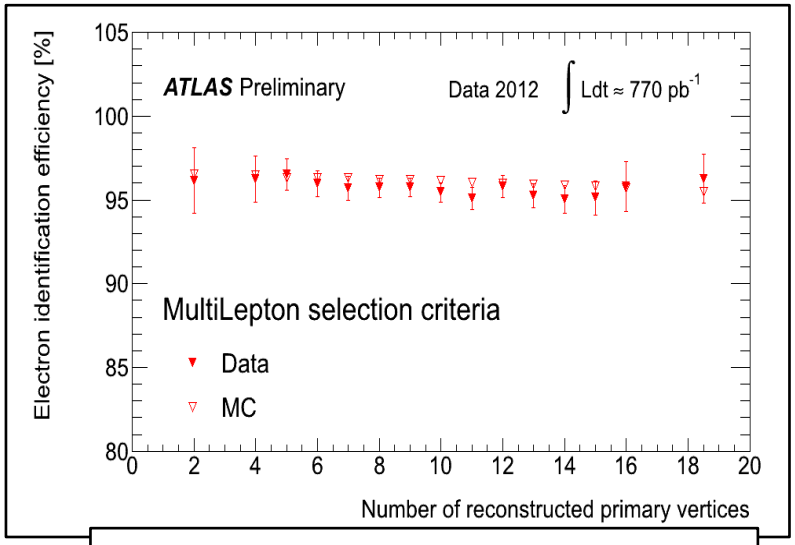
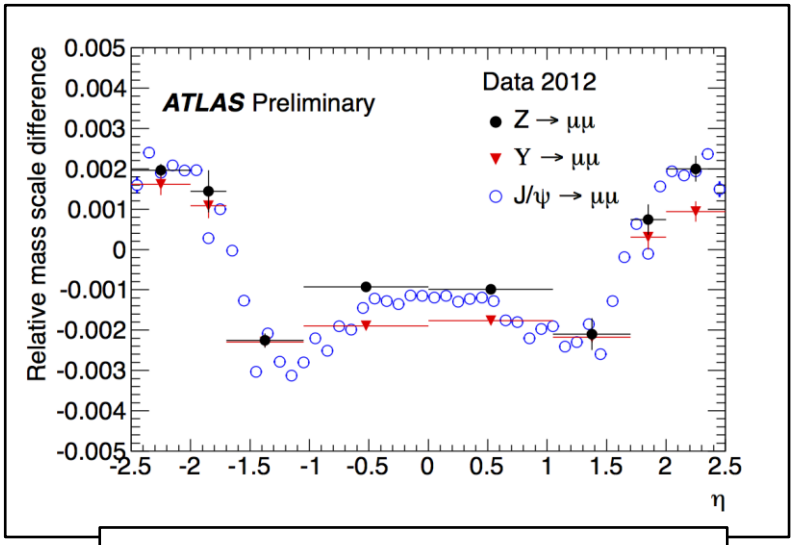
Two aspects of the detector performances are crucial in this channel:

- **Lepton identification and reconstruction efficiency at low momentum**
- **Lepton momentum/energy resolution and scale**

All the techniques developed to reach high performances in these areas are validated using high statistics W, Z, J/ψ and Υ data samples.



Electron identification stable versus the number of primary vertices at the 1% level



Relative data/MC muon momentum scale difference below 0.3%

Analysis overview (3/4) - Backgrounds

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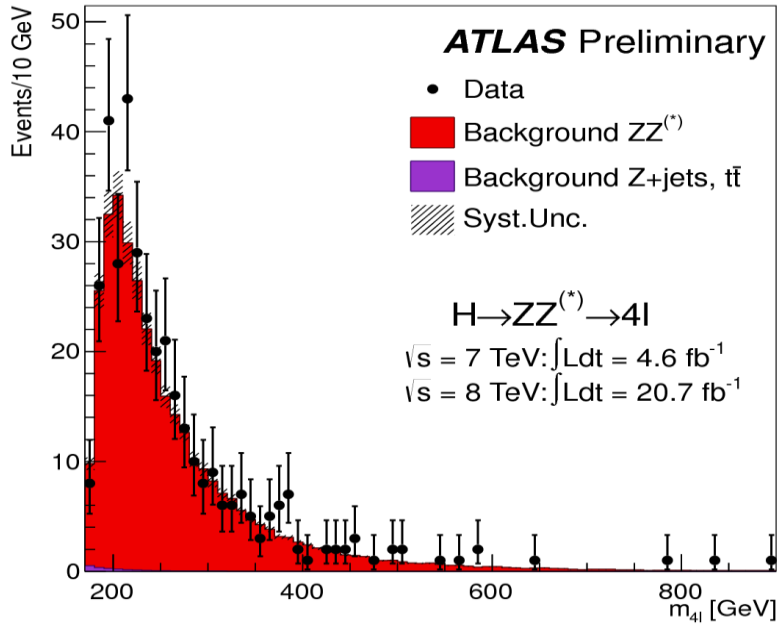
Backgrounds can be classified in two categories:

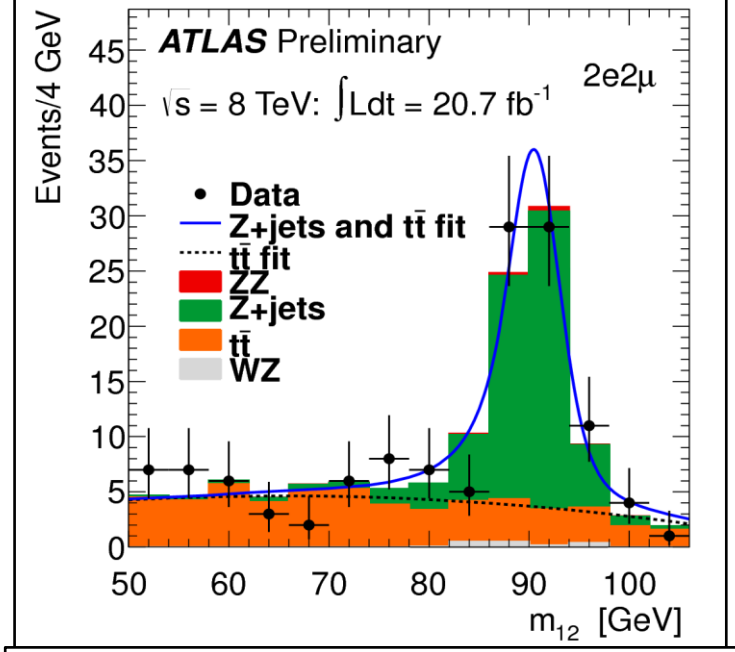
- **Irreducible background: ZZ*** ➔ predicted from simulation
- **Reducible backgrounds: Z+jets, ttbar** ➔ estimated from data



m4l > 160 GeV

N_{obs} = 376 ± 19 events

N_{exp} = 348 ± 14 events



Z+μμ control region

Sub-leading pair: no isolation requirements and one lepton must fail the impact parameter cut

Analysis overview (4/4) - Signal region

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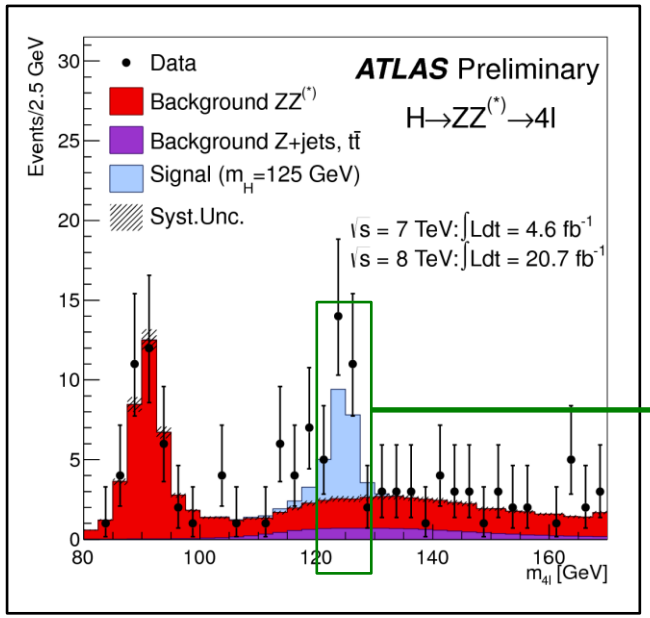
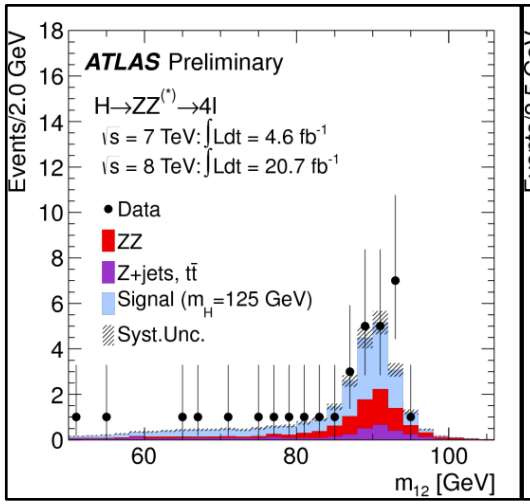
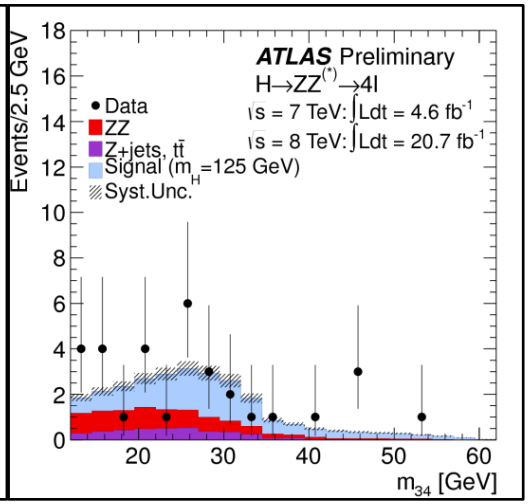
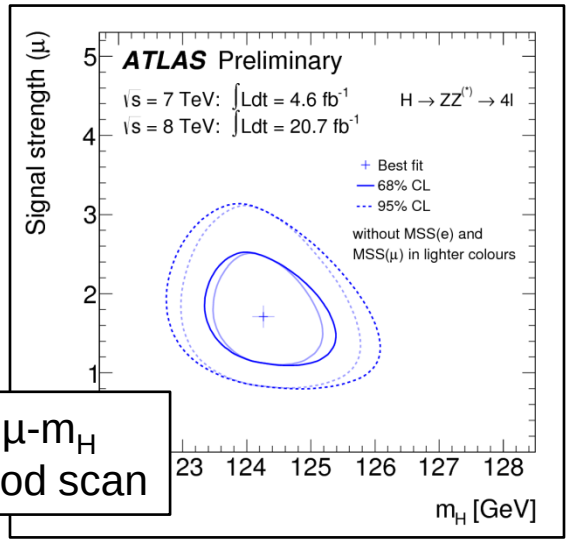






	Signal	ZZ*	Z+jets,tt	Exp.	Obs.
Yield	15.9	7.4	3.7	27.1	32

S/B from ~1 to ~2 (4e, 4μ)



2-D μ-m_H likelihood scan

Signal strength = $(\sigma \times B.R)_{mes}/(\sigma \times B.R)_{SM}$

B.R. rapidly increasing around 125 GeV:

- 124 GeV: $\mu \sim 1.8$
- 125 GeV: $\mu \sim 1.6$
- 126 GeV: $\mu \sim 1.4$

Best fit mass 124.3 GeV:

$\mu = 1.7 \pm 0.5$

Mass measurement (1/2) - Z mass constraint, FSR recovery

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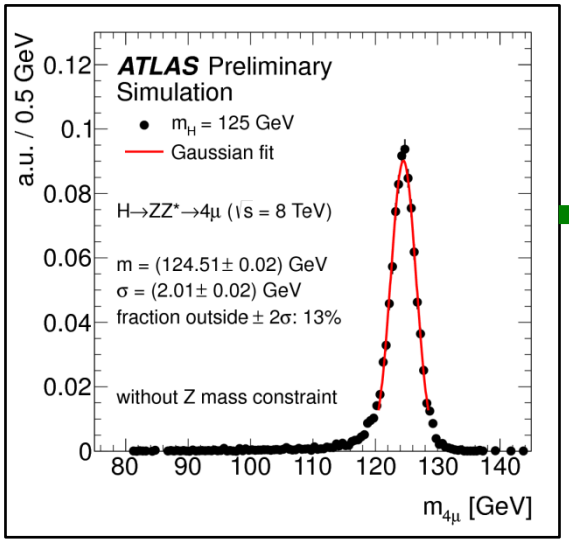
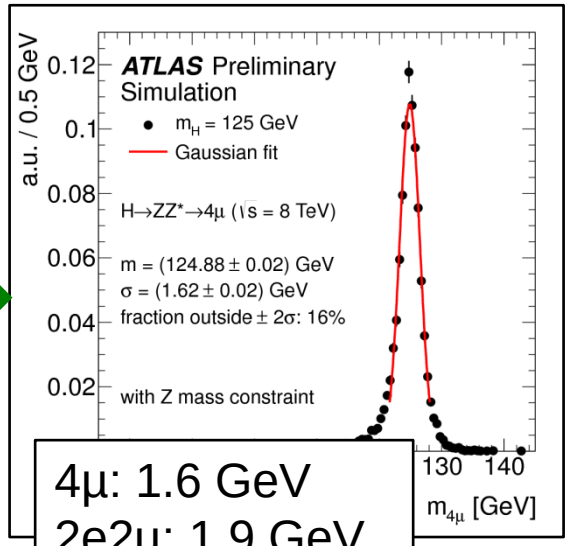
Z mass constraint



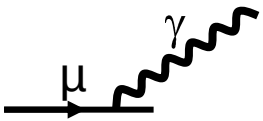
Determine event-by-event the most probable m_{ll} value taking into account the Z-lineshape and the lepton momentum uncertainties

σ(m4l) improved by ~15%



4μ: 1.6 GeV
2e2μ: 1.9 GeV
4e: 2.4 GeV

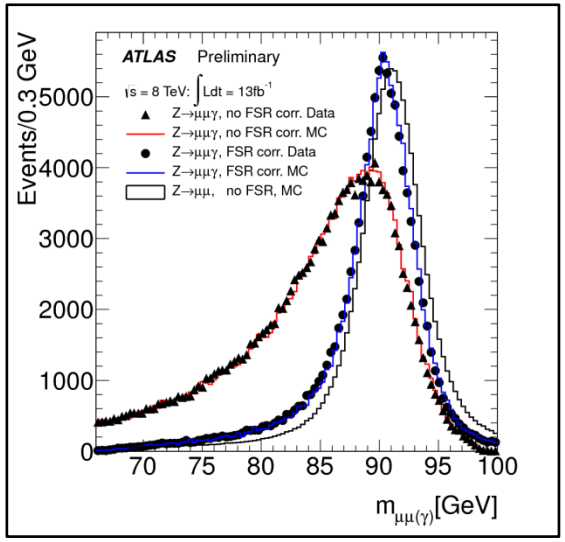
Final State Radiation recovery



Include the photon in the invariant mass computation if:

- $66<m_{12}<89$ GeV
- $p_{T\gamma}>1$ GeV in a ΔR cone of ~0.1

➔ **purity of ~85%**



- In the full m4l range:

7/225 events are corrected (4% expected from MC).

- In particular: one 2μ2e event is corrected from 109 to 123 GeV.

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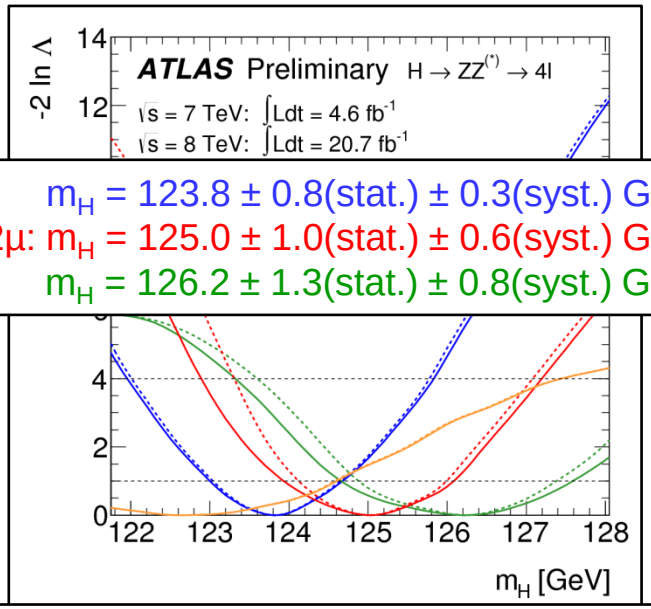
Mass measurement (2/2) - Results

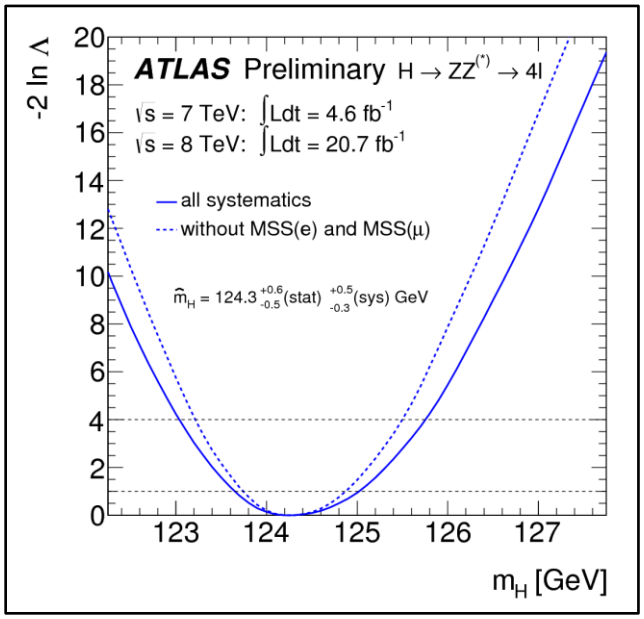
Mass fit per subchannel



4μ: m_H = 123.8 ± 0.8(stat.) ± 0.3(syst.) GeV
2e2μ: m_H = 125.0 ± 1.0(stat.) ± 0.6(syst.) GeV
4e: m_H = 126.2 ± 1.3(stat.) ± 0.8(syst.) GeV

The main systematics comes from the momentum/energy scale uncertainty: 0.3 GeV for 4μ and 0.8 GeV for 4e.

Combined mass fit



m_H = 124.3 ± 0.6(stat.) ± 0.5(syst.) GeV

Previous result (18 fb^{-1} versus 25 fb^{-1}): **m_H = 123.5 ± 0.9(stat.) ± 0.3(syst.) GeV**

Two distinct effects are produced by the new candidates:

- The central value in the 4μ subchannel has changed from 123.2 to 123.8 GeV.
- The relative weight of the 4μ subchannel has decreased.

Higgs coupling measurement (1/3) - Categories

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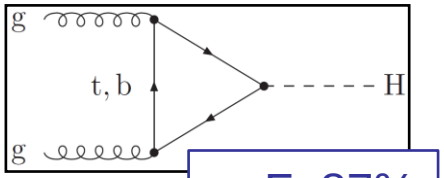
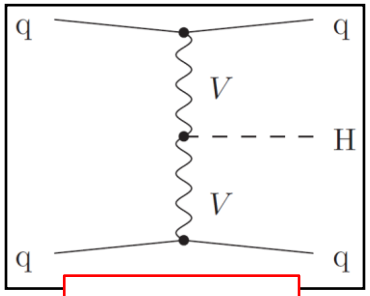
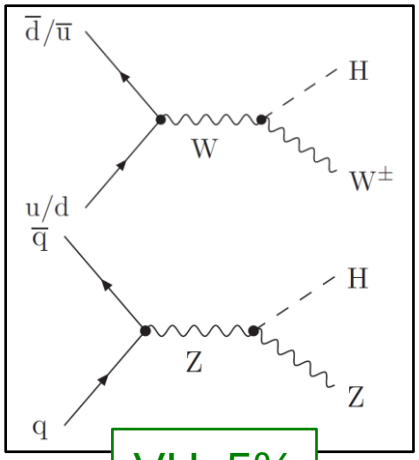
Four production mechanisms for the Higgs in p-p collisions



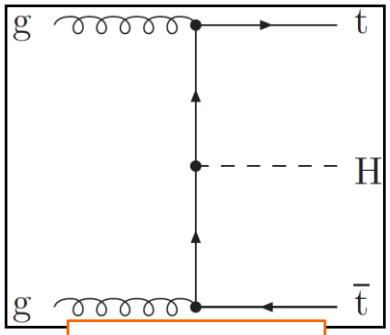
ggF: 87%



VBF: 7%



VH: 5%



ttH: 0.6%

Measuring the production rate in categories matching closely the production mechanisms is crucial to improve the precision on the couplings.

Events classified in three exclusive categories

4l selection → VBF-like category: 2 jets (E_T>25 GeV), m(jj) > 350 GeV, $|\Delta\eta(jj)| > 3.4$ → VH-like category: 1 additional lepton (p_T>8 GeV) → ggF-like category (splitted in the four lepton subchannels)

Higgs coupling measurement (2/3) - VBF-like event

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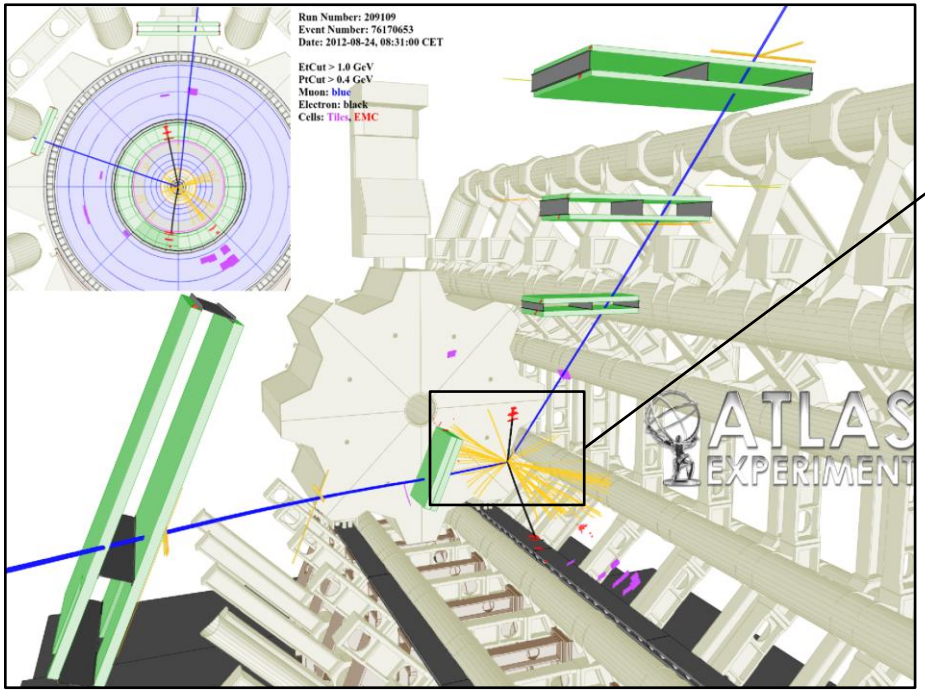
A category is not 100% pure and receives contributions from other production mechanisms.

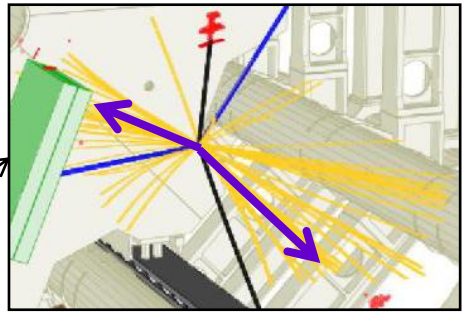
Event yield Category / Production	ggF	VBF	VH
ggF-like	15.7	0.93	0.76
VBF-like	0.31	**0.49**	0.01
VH-like	0.07	-	0.17

In 120-130 GeV: observed 1 event in the VBF-like category

0.1 ZZ* expected, S/B ~ 5 and VBF-purity ~60%

No VH-like event observed





2e2μ event

m(4l) = 123.5 GeV

m(jj) = 895.7 GeV

$|\Delta\eta(jj)| = 3.4$

Higgs coupling measurement (3/3) - Results

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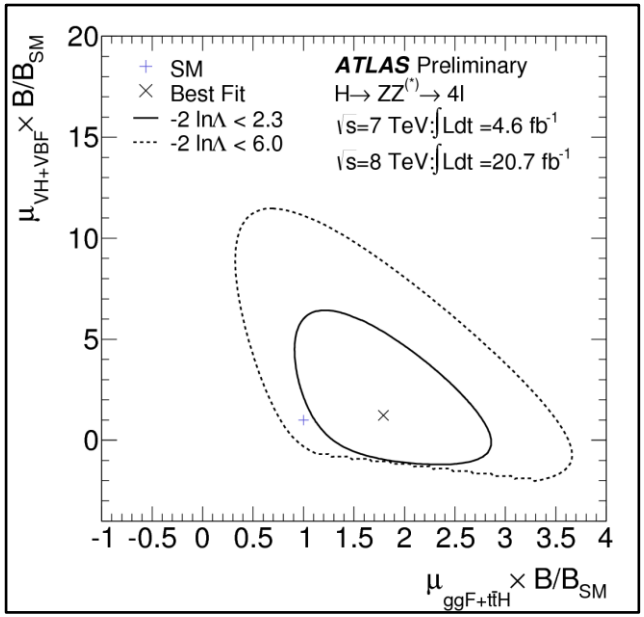
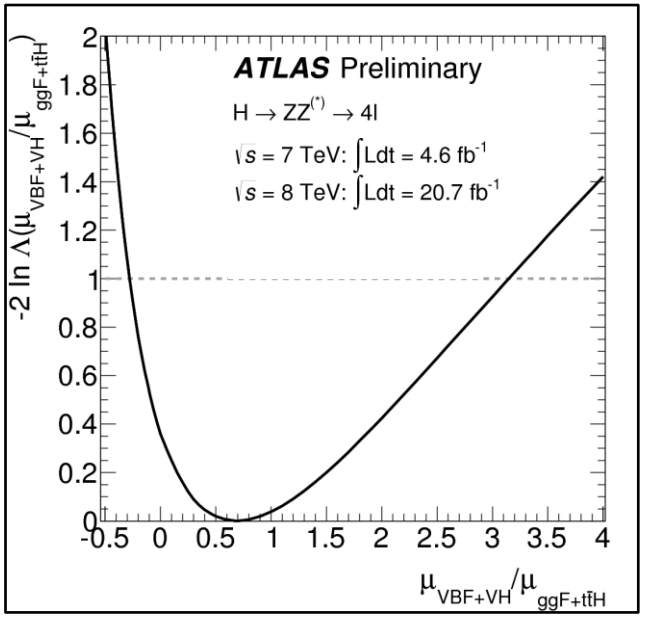
See Narei Lorenzo Martinez's presentation

- Combining the different decay channels allows to probe the couplings (for instance, H→bb is studied only in the VH mode).
- Input from the ZZ* decay channel illustrated here in the case where production mechanisms are grouped into top (ttH) versus gauge (ZH/WH) couplings.



Degeneracy with the branching ratio for a single decay channel



$$\mu_{VBF+VH} / \mu_{ggF+ttH} = 0.7^{+2.4}_{-1.0}$$

Spin/parity determination (1/2) - Overview

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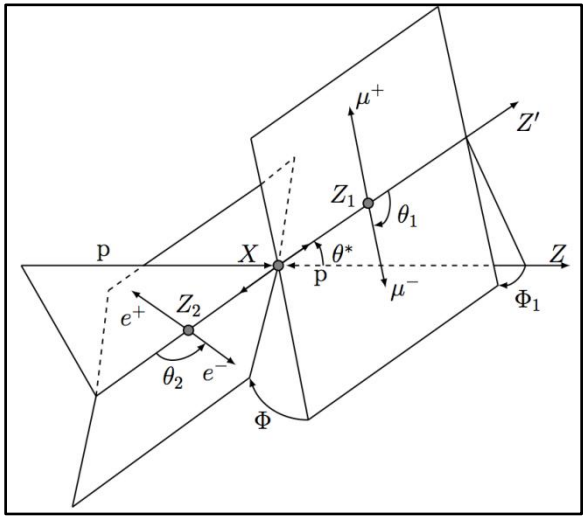

Observables sensitive to the J^p state (via the Z_1 and Z_2 helicity amplitudes):

- 1 production angle: θ^*
- 4 decay angles: θ_1, θ_2, Φ, Φ_1
- masses of Z_1 and Z_2

For spin-0: no dependency versus θ^* and Φ_1

5 hypotheses for J^P states are tested against the SM hypothesis 0^+: 0^-, 1^-, 1^+, 2^-, 2^+

Monte-Carlo generator used: JHU (full spin and helicity correlations)

Two approaches used to build multivariate discriminants between hypotheses:

1) a matrix-element method (input distributions built from first principles and acceptance corrections applied)
2) a boosted-decision tree method (training on large fully simulated Monte-Carlo samples).

See Camilla Maiani's presentation for the full results

The particular strength of the ZZ* channel is its ability to distinguish between 0^- and 0^+.

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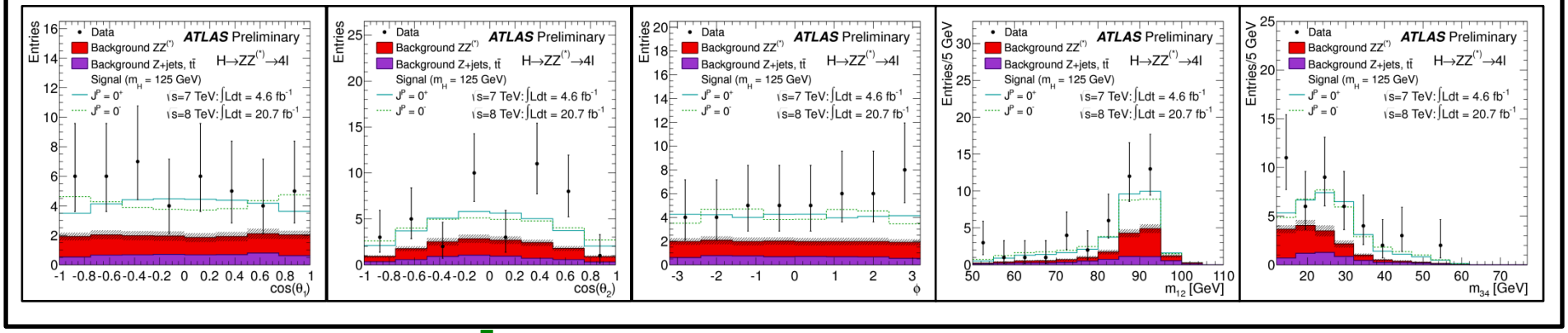
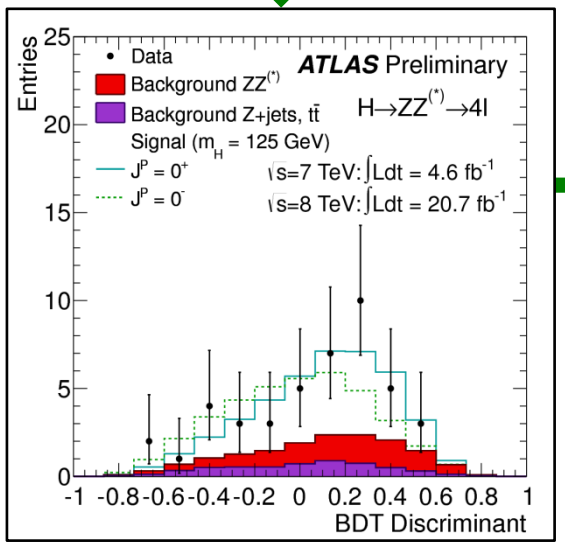
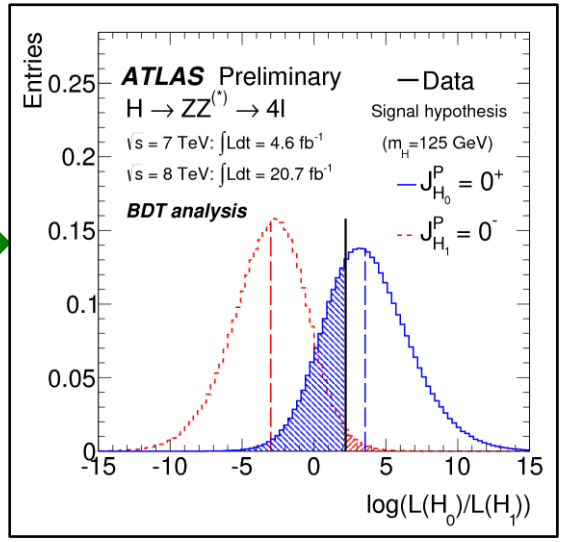
Spin/parity determination (2/2) - $0^+/0^-$ comparison

Select events with m4l in the 115-130 GeV range







Compared to 0^+, 0^- excluded at 97.8% CL using CLs

Summary and prospects

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Higgs properties probed in the H→ZZ*→4l channel:

- **m_H = 124.3 ± 0.6(stat.) ± 0.5(syst.) GeV**
- At the ATLAS $\gamma\gamma$+4l combined mass (125.5 GeV): **μ = 1.5 ± 0.4**
- **Production rate measured separately in the ggF, VBF and VH topologies** to enhance the coupling measurement sensitivity
- The spin/parity hypothesis **0^- is excluded at ~3σ** (compared to 0^+).

Prospects

- Publish the Run I results (the use of per-event m4l errors and of a multivariate discriminant against ZZ* should allow to improve the accuracy on m_H and μ by ~20-30%).
- With more data from 2015: differential cross sections, refined categories for couplings, CP even/odd components,…