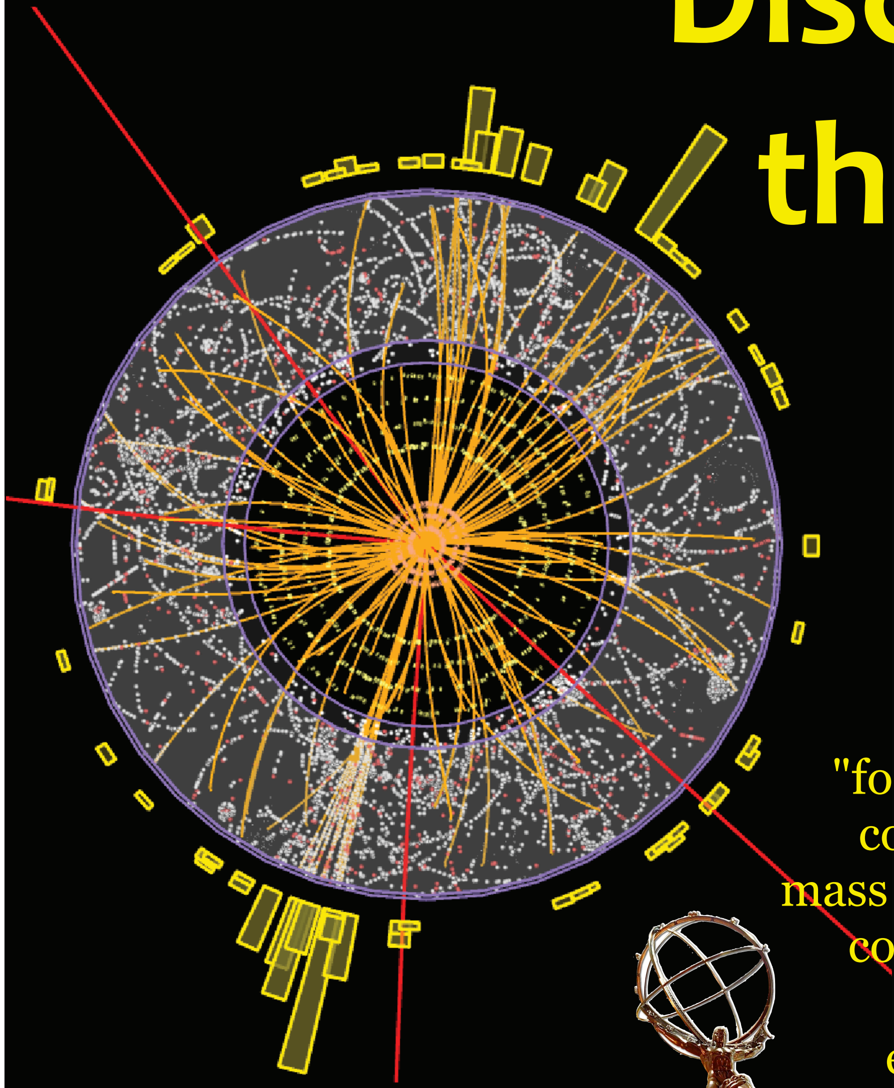
Discovery & status: the Higgs particle

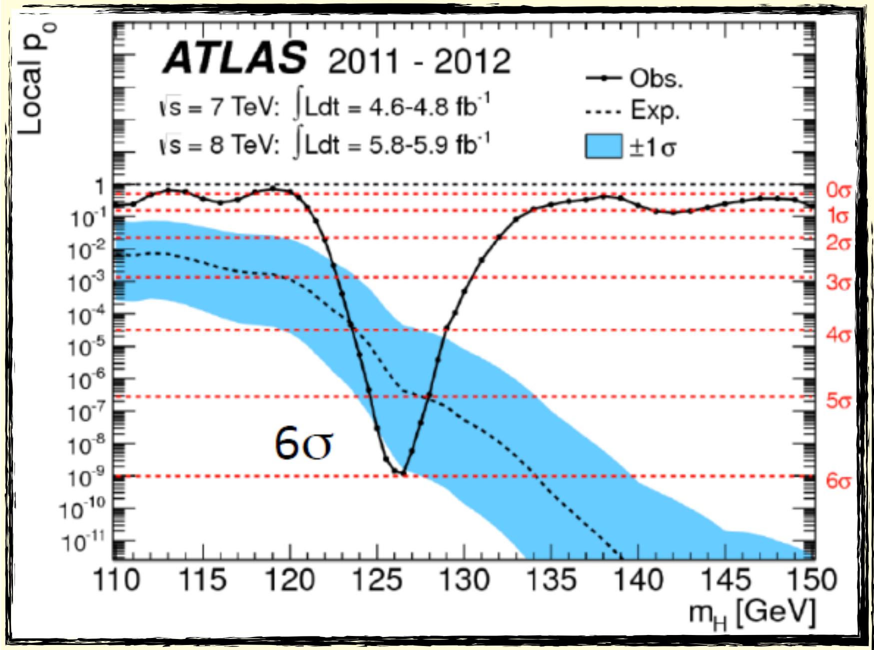


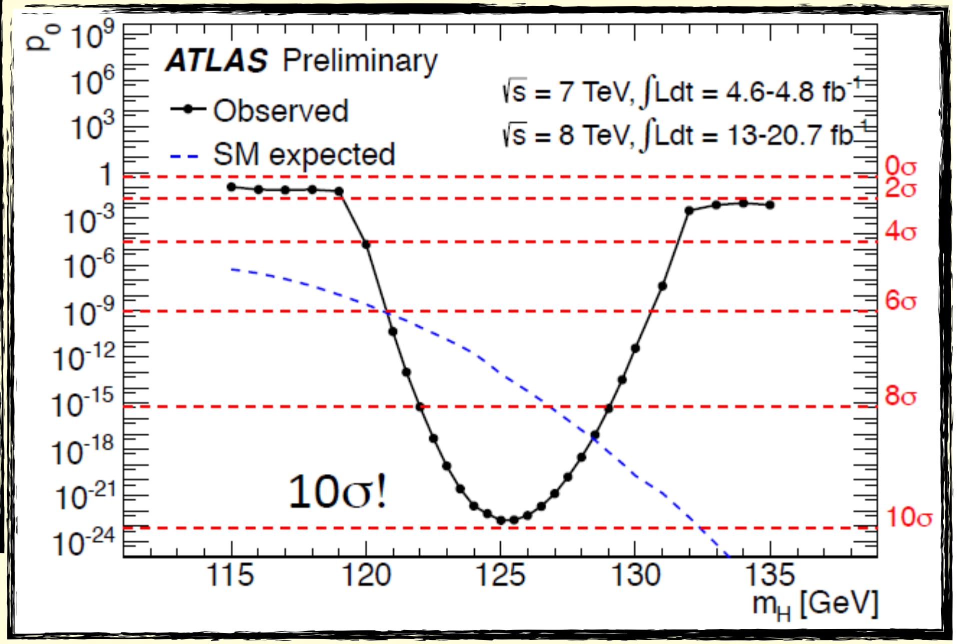
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Stan Bentvelsen
for Nikhef-ATLAS team

NIKHEF

From Higgs discovery to now

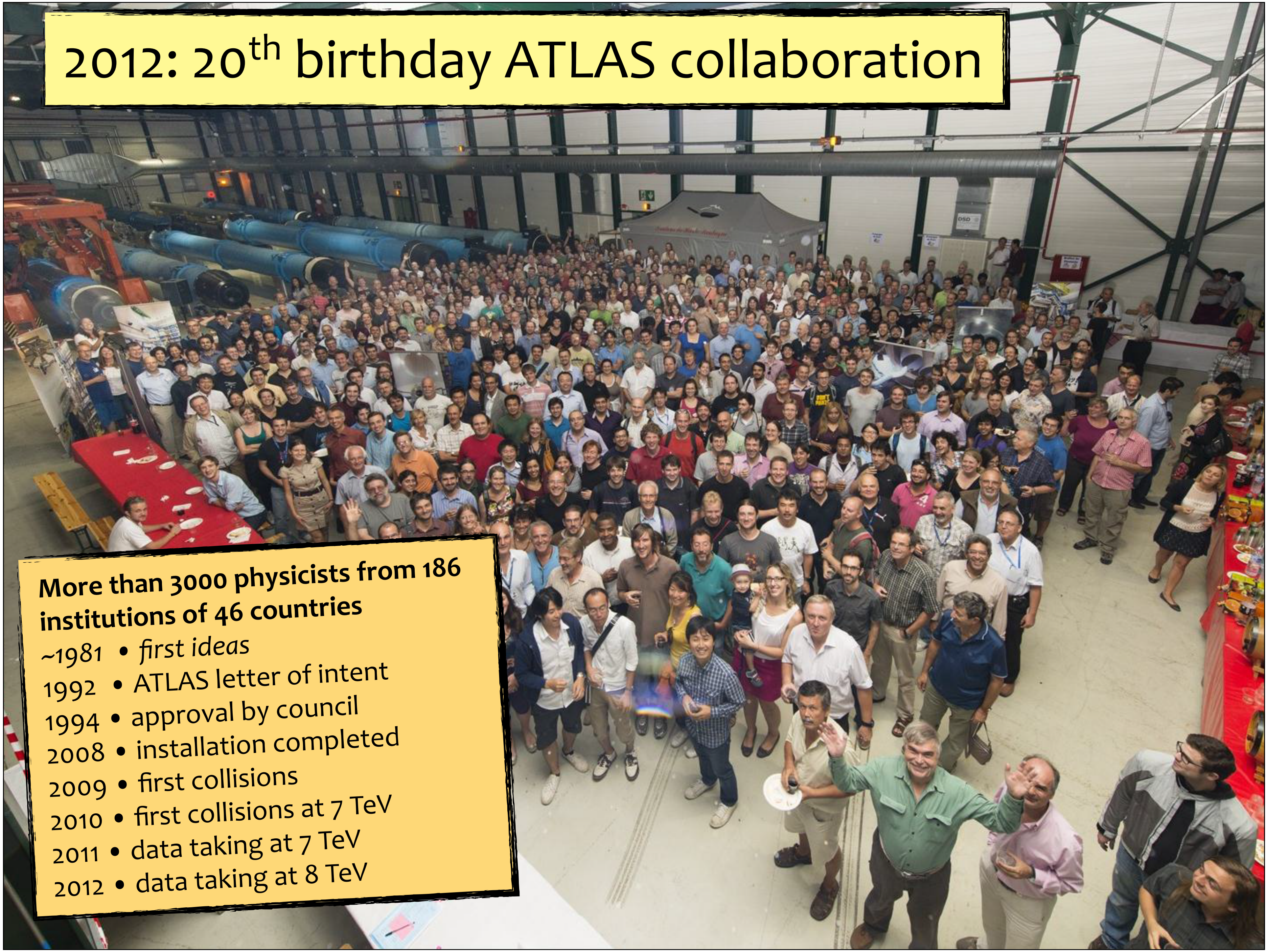




July 4th 2012 Discover
Higgs-like boson

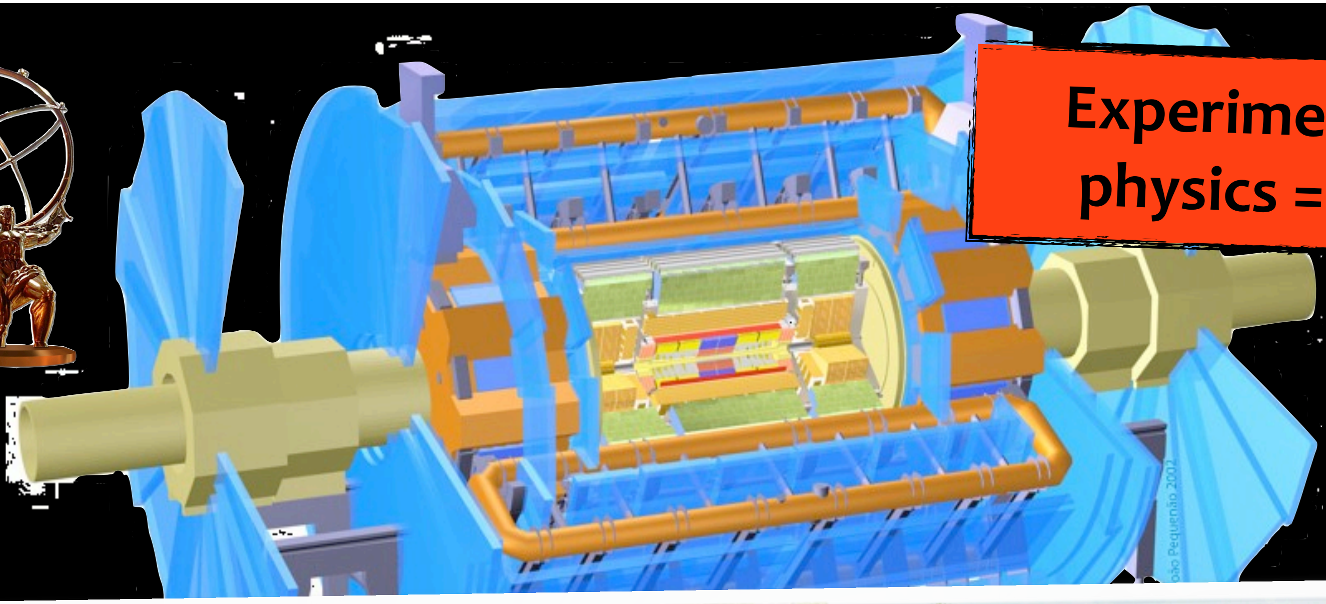
October 2013
SM Higgs boson

2012: 20th birthday ATLAS collaboration



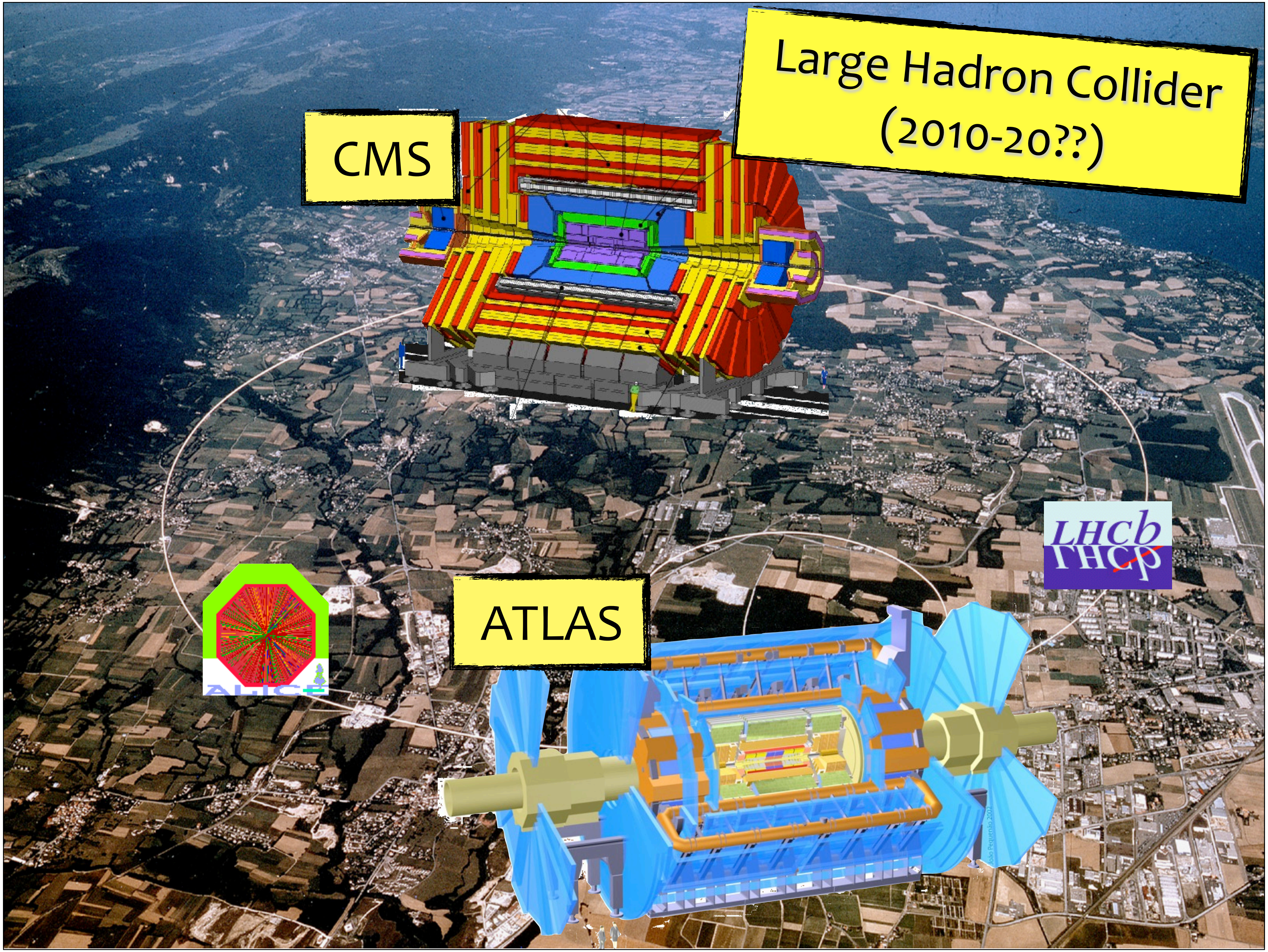
More than 3000 physicists from 186 institutions of 46 countries

~1981 • *first ideas*
1992 • ATLAS letter of intent
1994 • approval by council
2008 • installation completed
2009 • first collisions
2010 • first collisions at 7 TeV
2011 • data taking at 7 TeV
2012 • data taking at 8 TeV

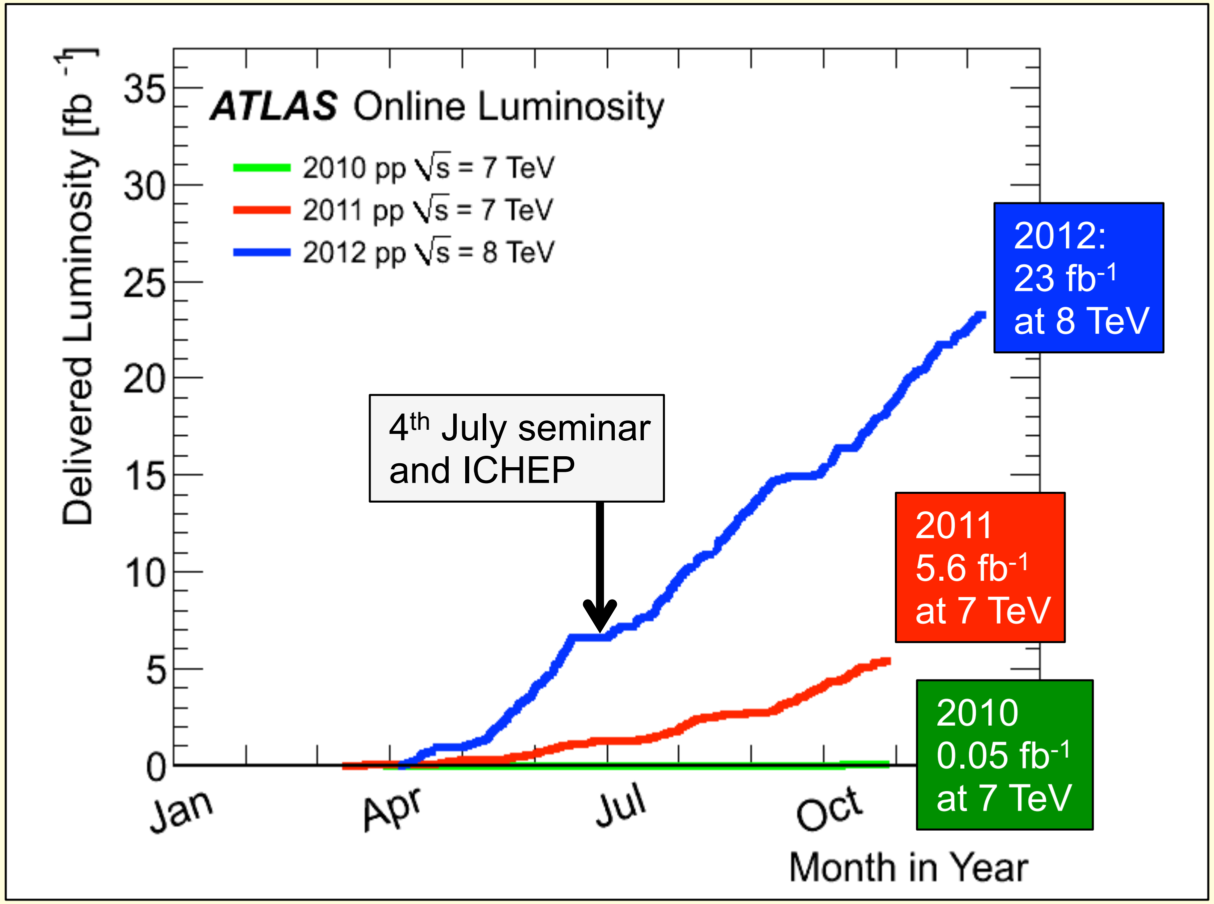


Experimental particle physics = team work

FOM/Nikhef - Radboud University - University of Amsterdam


Large Hadron Collider
(2010-20??)
CMS
ATLAS
LHCb

LHC Delivered Luminosity to ATLAS



~ **5 billion** events recorded in total (2010-2012)

~ **120 PB** of data (including real and simulated data) as of today

The most powerful particle factory in world to produce massive particles in proton-proton collisions

- **> 2,000,000,000 W**
- **> 700,000,000 Z**
- **> 8,000,000 top pair**
- **> 600,000 Higgs**

Major experimental challenge: pileup!

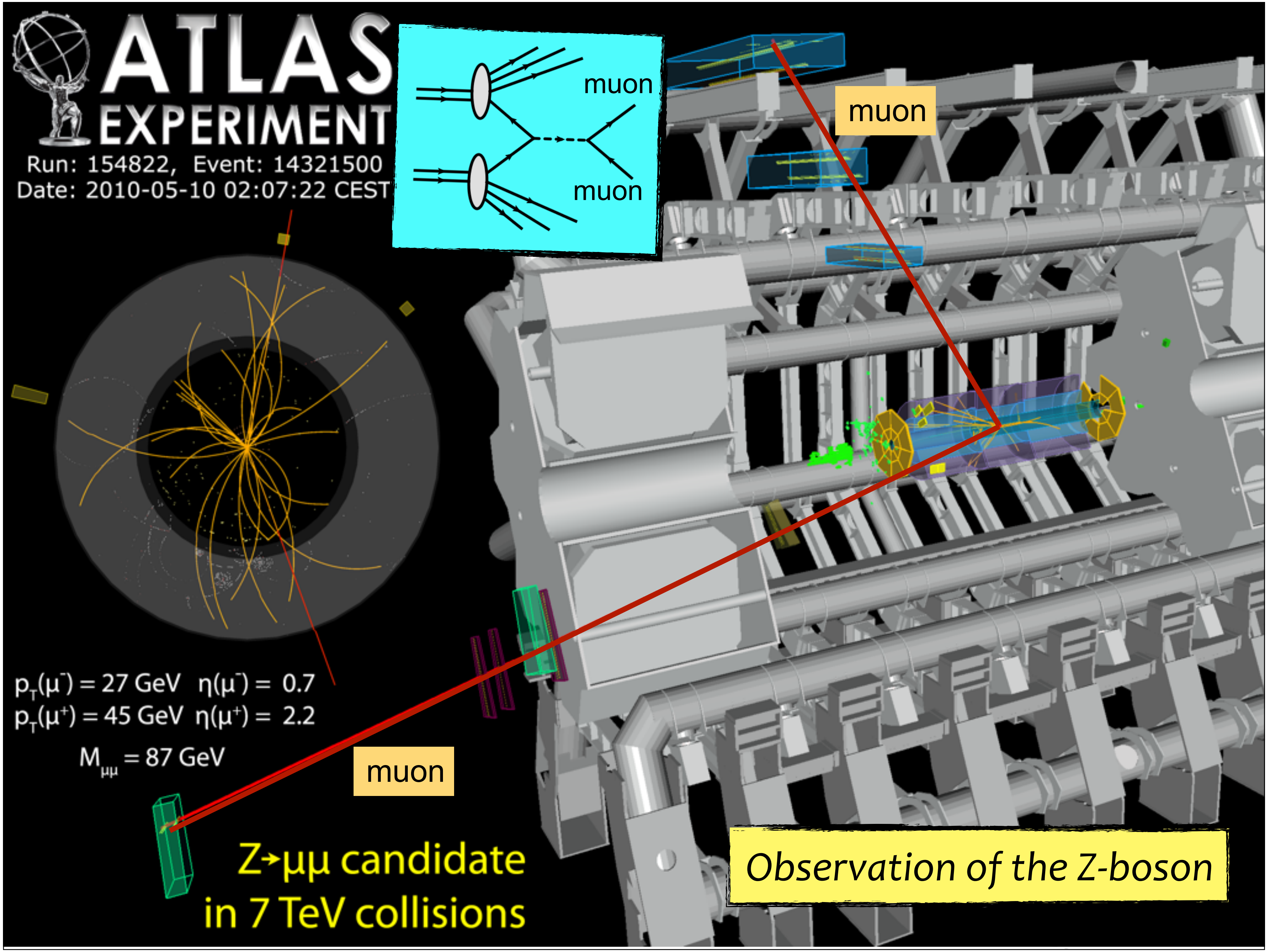
~<25? interactions in each bunch cross in 2012

Excellent ATLAS Performance

The ATLAS detector has performed remarkably well through the hard work of the collaboration to keep working at top shape

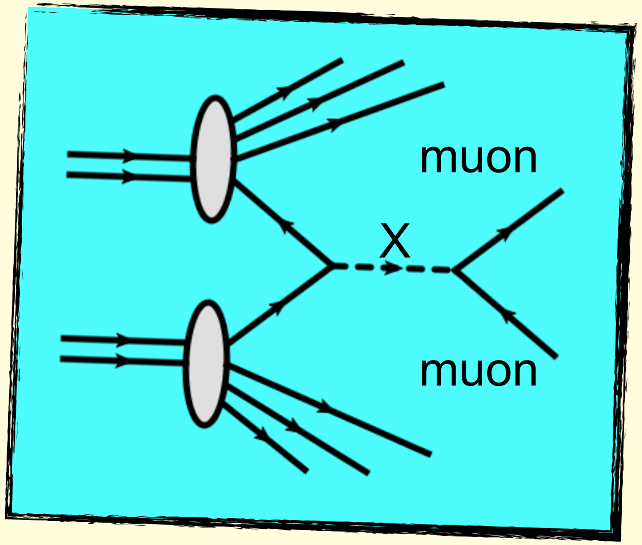
ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

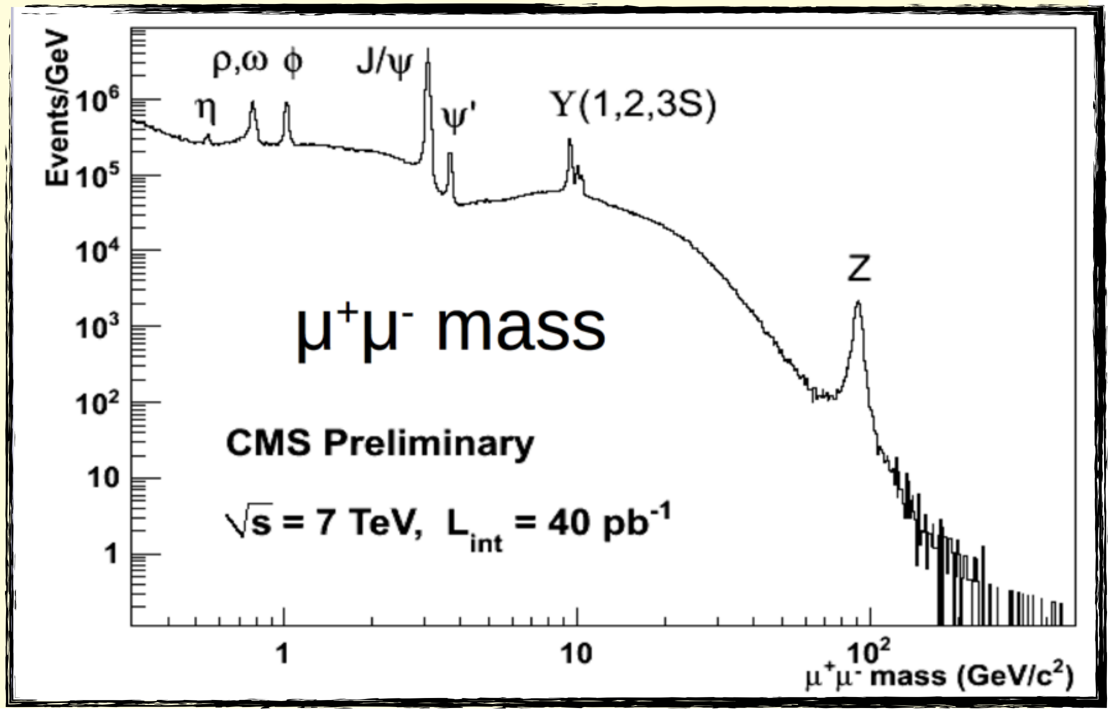
Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.


ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
muon
muon
muon
muon
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions
Observation of the Z-boson

Re-discovery of resonances

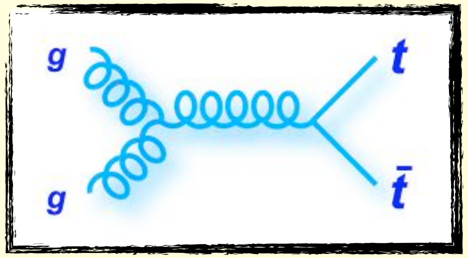
- The experiments are working remarkably
  - Operations, detector performance and simulation
- The SM is in great shape
  - N(N)LO calculations match data very well

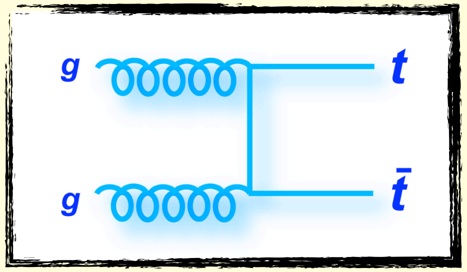


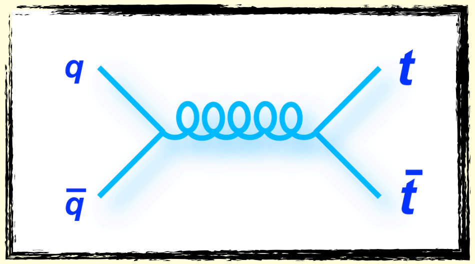


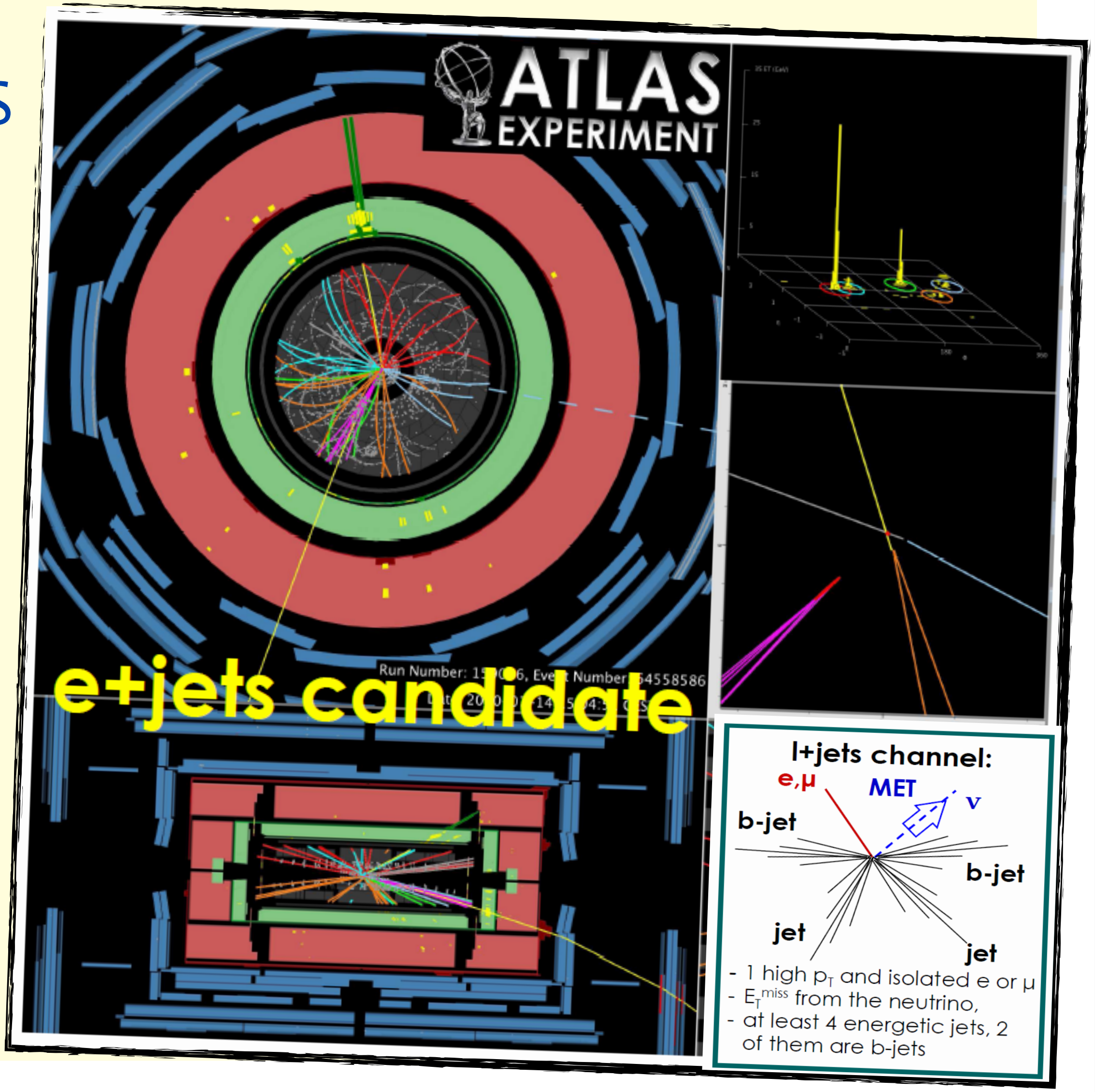
Known processes in the SM

- Complex signature
  - top-quarks in ATLAS



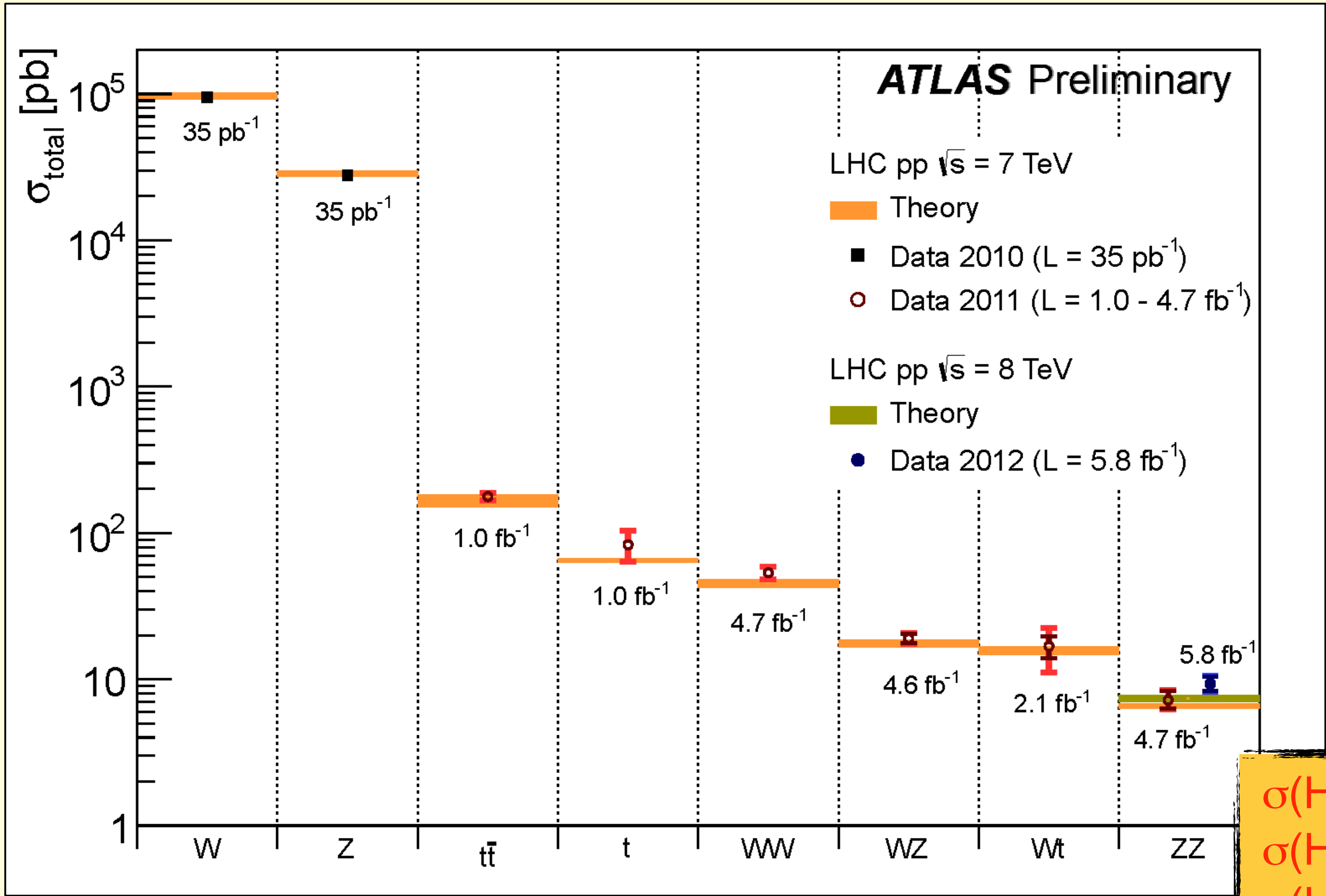






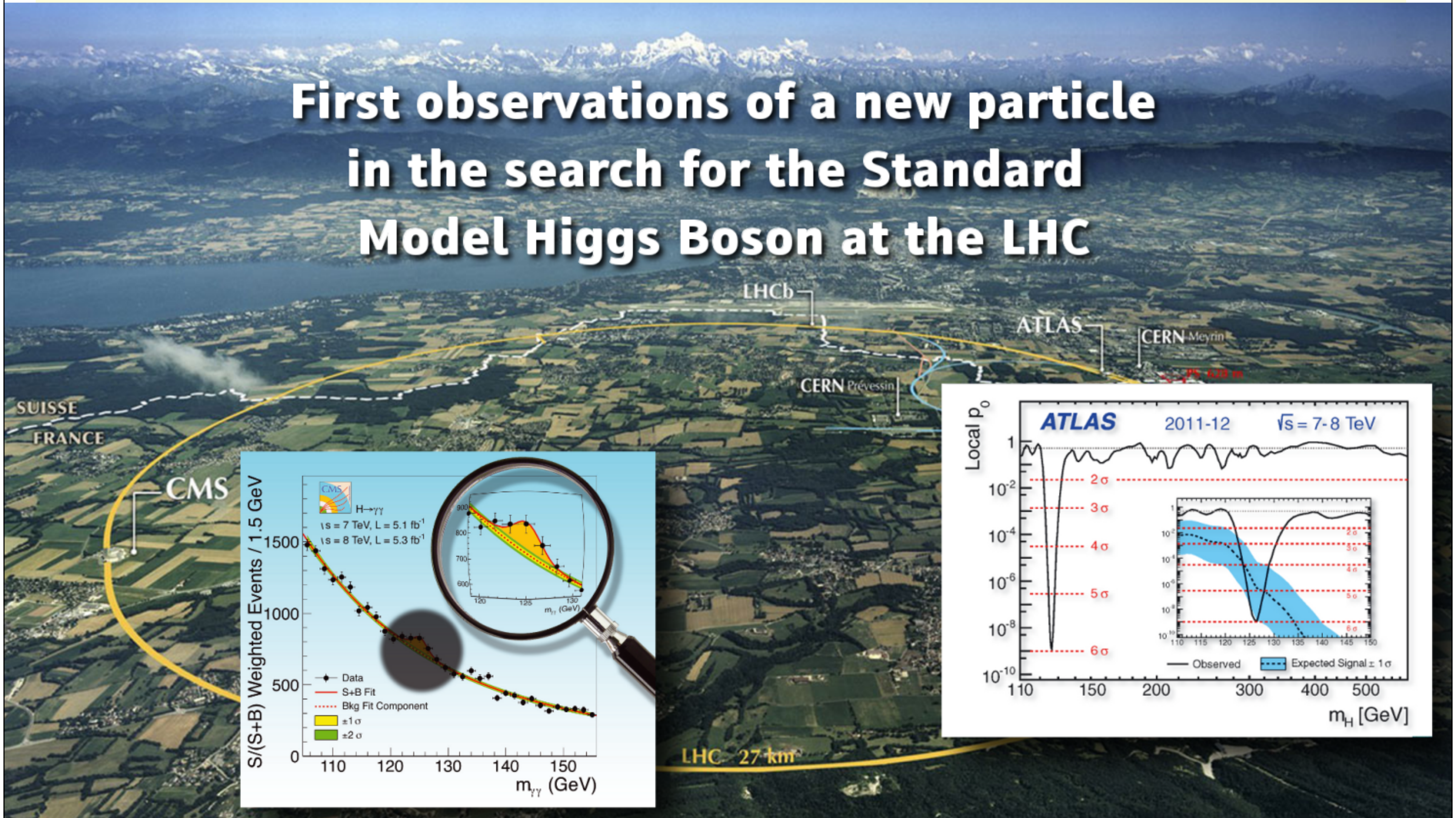
Re-establish SM at the LHC

→ the steppingstone for discoveries



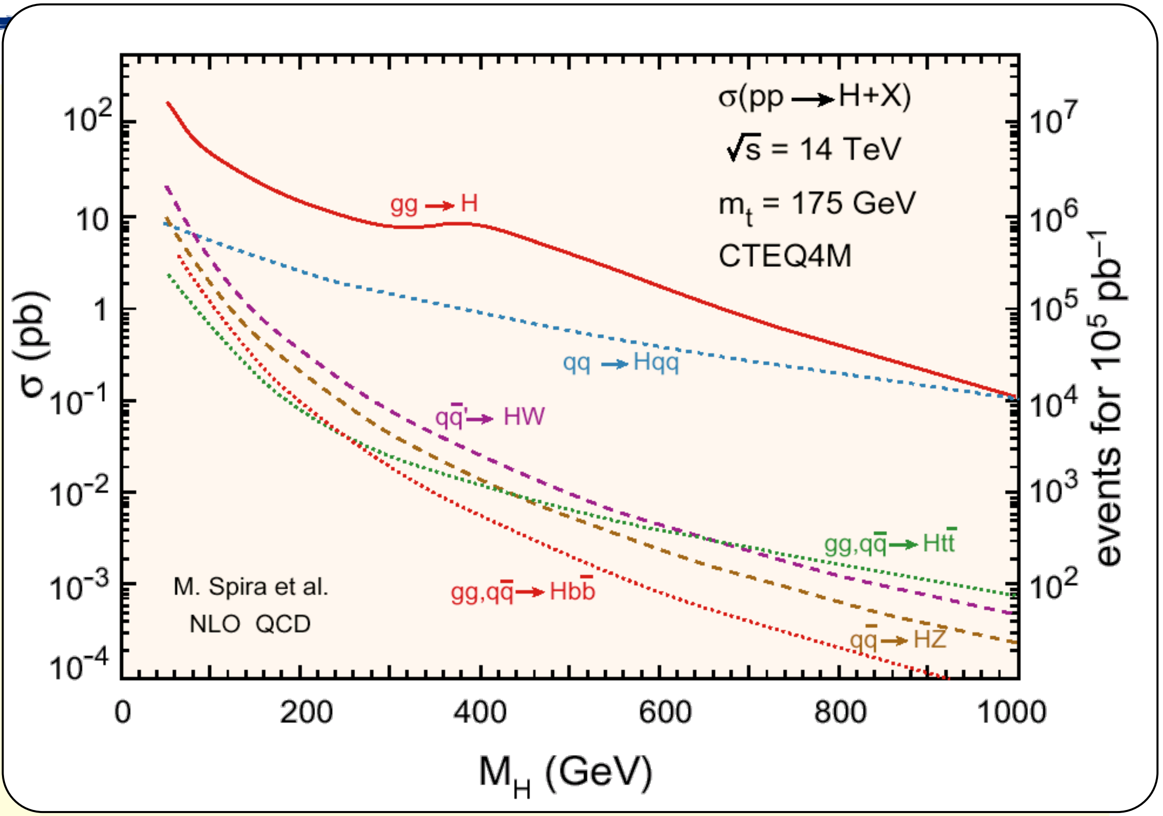
$\sigma(H)$ = 22.28 pb
$\sigma(H \rightarrow \gamma\gamma)$ = 0.05 pb
$\sigma(H \rightarrow ZZ)$= 0.59 pb

July 2012 – Revolution in Particle Physics

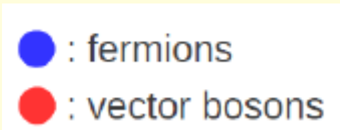


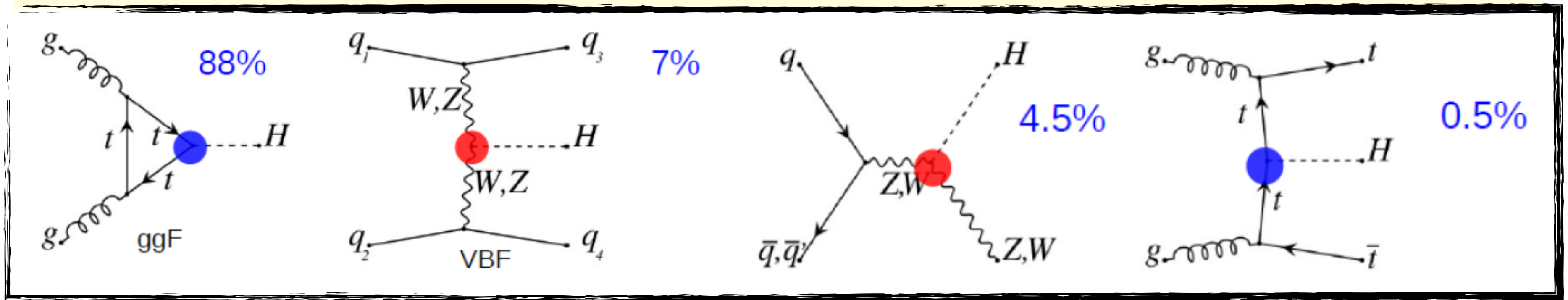
Higgs production

- Pre-discovery
  - Gluon fusion dominant
    - factor 10 larger than at Tevatron

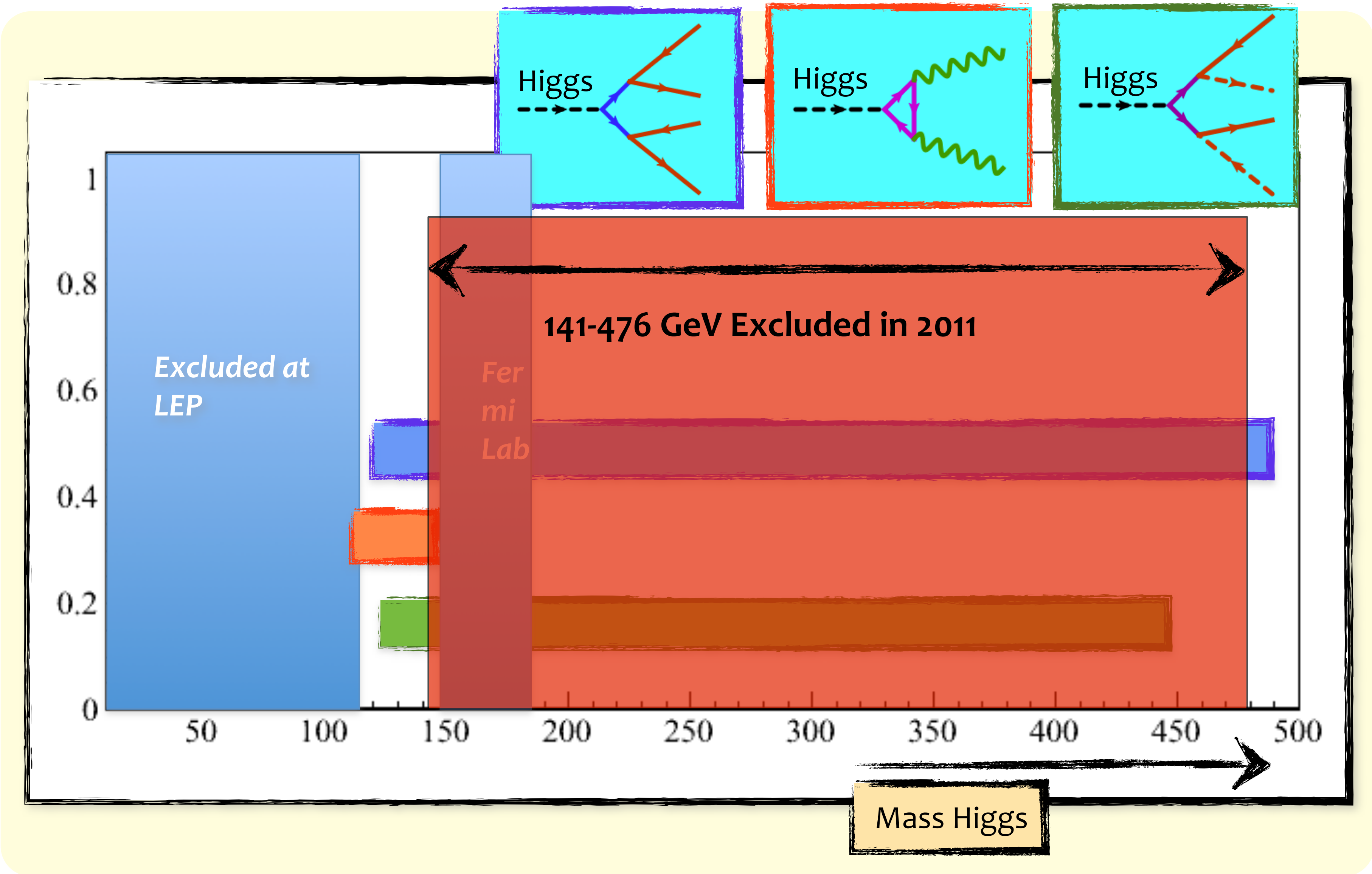


- Higgs @ 125 GeV:



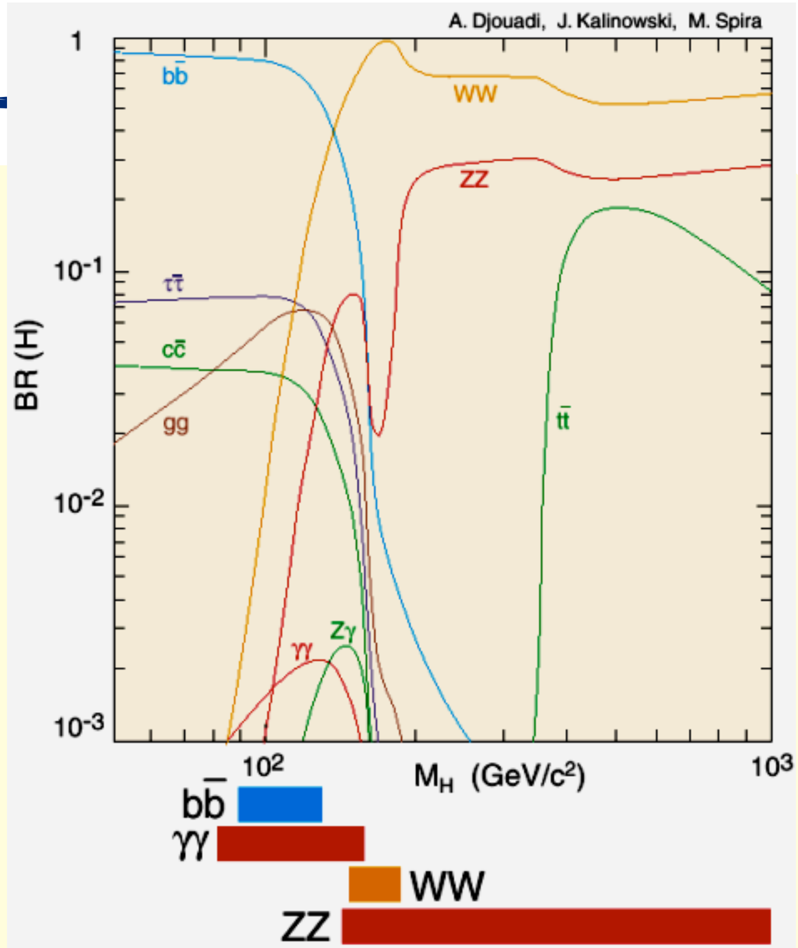


Higgs discovery scenario’s



Higgs decay

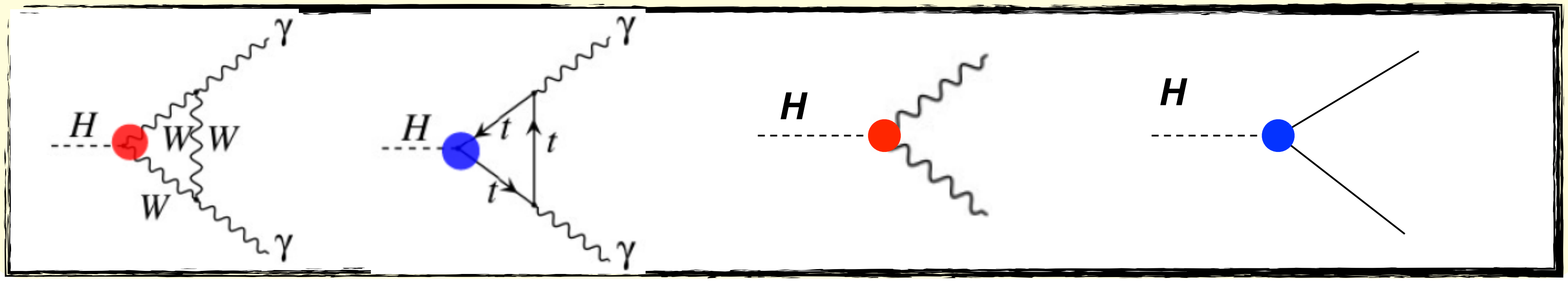
- Decay depends on mass and couplings



g_F (Yukawa coupling) =√2 m_F/ν

g_V (Gauge coupling) = $2m_V^2/\nu$

(ν is the vacuum expectation value)



New -- After the Higgs Discovery

- **$H \to \gamma\gamma$, ZZ*, WW* analysis updates based on full 2011-2012 dataset ($4.6\ fb^{-1}$ @ 7TeV, $20.7\ fb^{-1}$ @ 8TeV)**

- Higgs mass from $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$
- Signal strengths ($\mu = \sigma/\sigma_{SM}$)
- Sensitivity to vector boson fusion
- Comparison of decay rates
- Couplings
- Spin and parity
- Searches in rare decay modes

New ATLAS Higgs Papers

arXiv:1307.1427 Sub. Phys. Lett. B (Mass, Couplings)
arXiv:1307.1432 Sub. Phys. Lett. B (Spin-parity)

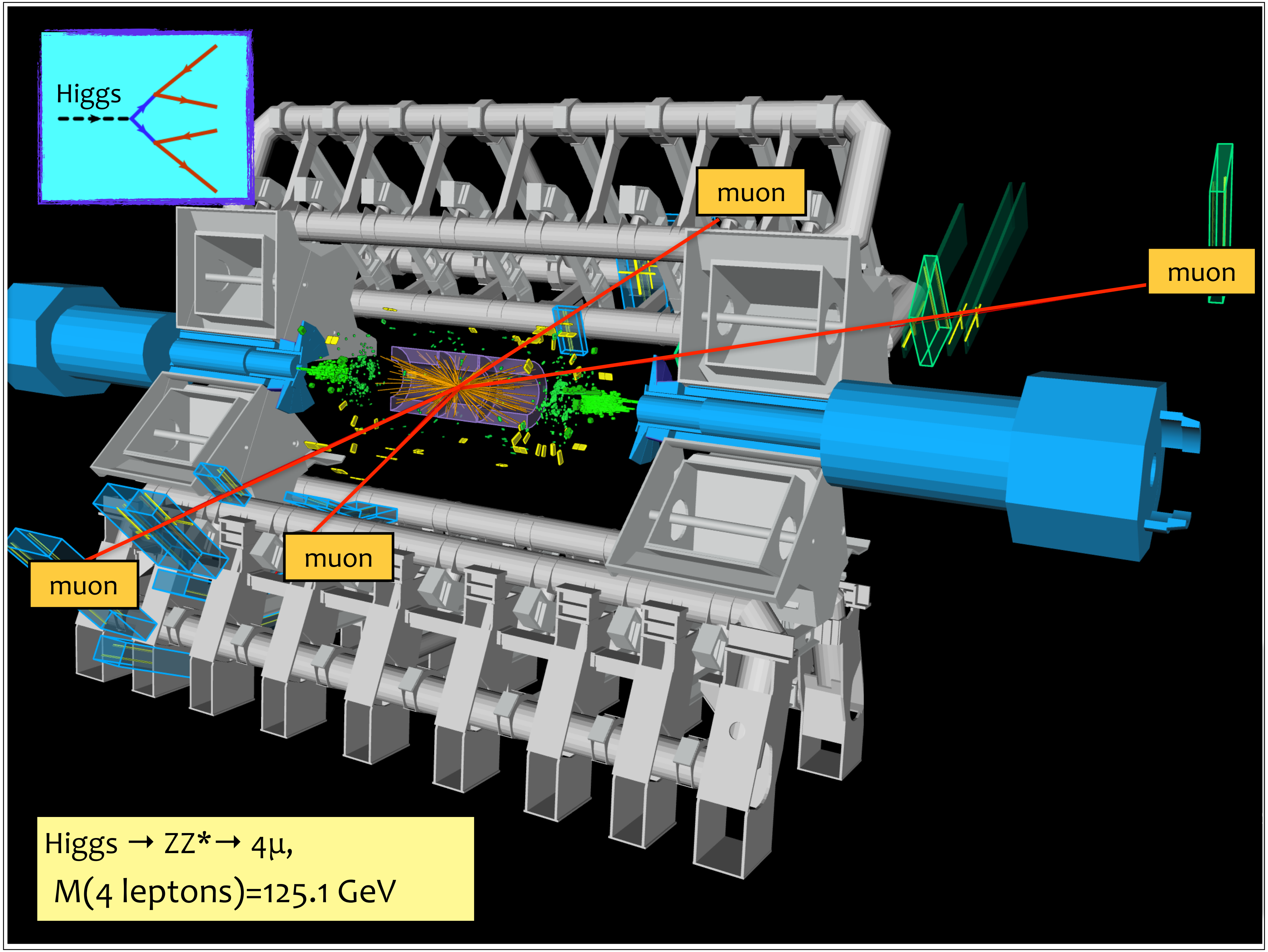
New ATLAS Higgs Pub Notes

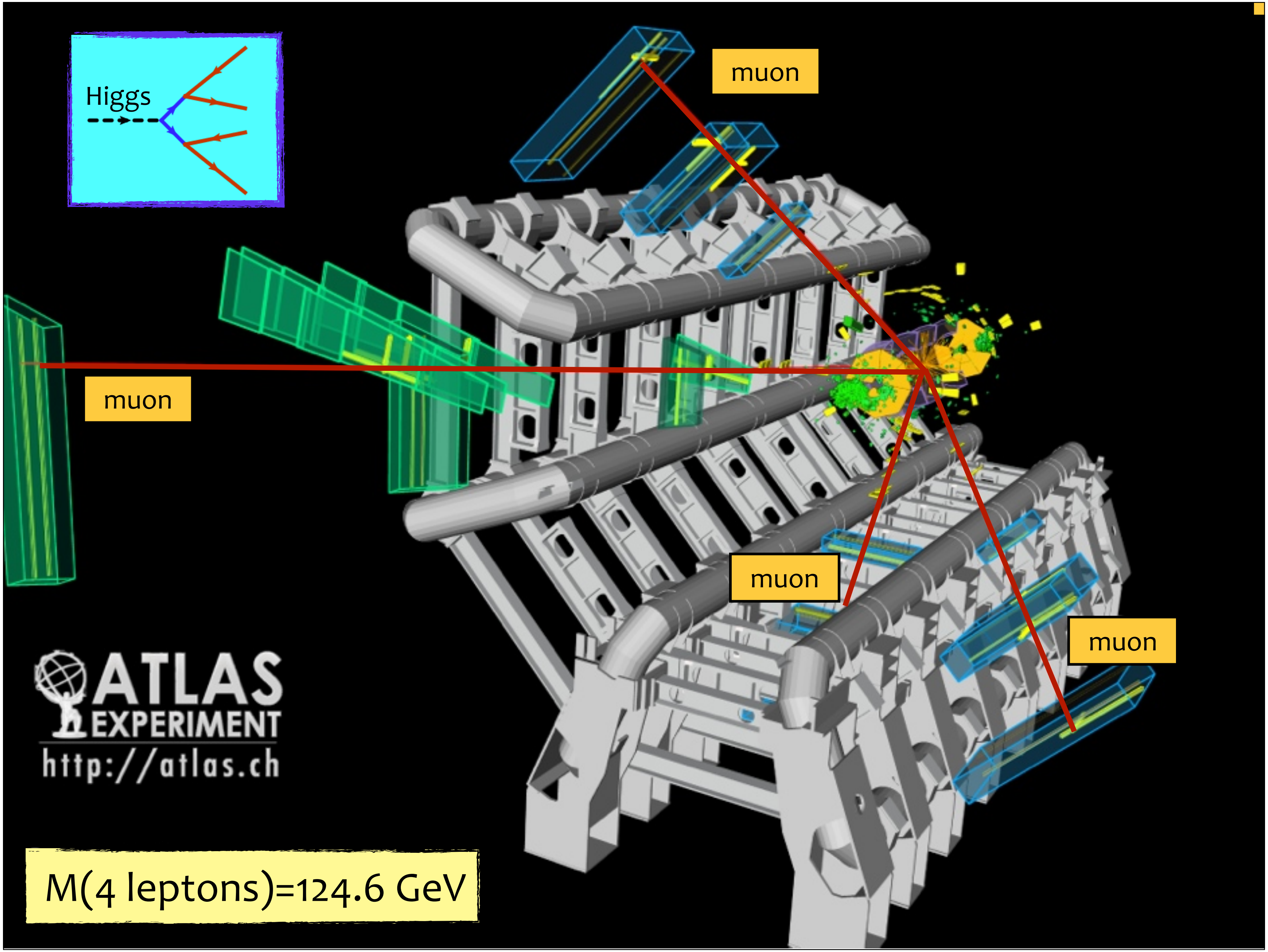
Property measurement

ATLAS-CONF-2013-012 ($\gamma\gamma$)
ATLAS-CONF-2013-013 (ZZ*)
ATLAS-CONF-2013-031 (WW*)
ATLAS-CONF-2013-040 (Spin)
ATLAS-CONF-2013-079 ($VH \to bb$)
ATLAS-CONF-2012-160 ($H \to \tau\tau$)
ATLAS-CONF-2013-075 (WW*)
ATLAS-CONF-2013-029 ($\gamma\gamma$)

Searches

ATLAS-CONF-2013-009($Z\gamma$)
ATLAS-CONF-2013-010($\mu\mu$)
ATLAS-CONF-2013-067($HMH \to WW$)
ATLAS-CONF-2013-072 (diff σ $H \to \gamma\gamma$)
ATLAS-CONF-2013-075($VH \to WW$)
ATLAS-CONF-2013-080($tt + H \to \gamma\gamma$)
ATLAS-CONF-2013-081($t \to cH$)

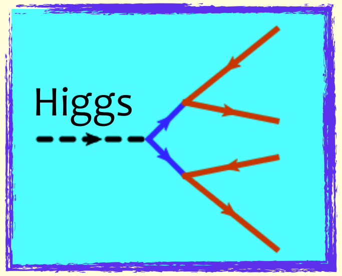

Higgs
muon
muon
muon
muon
Higgs → ZZ*→ 4μ,
M(4 leptons)=125.1 GeV

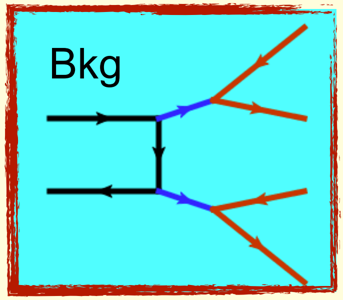

Higgs
muon
muon
muon
muon
ATLAS EXPERIMENT
http://atlas.ch
M(4 leptons)=124.6 GeV

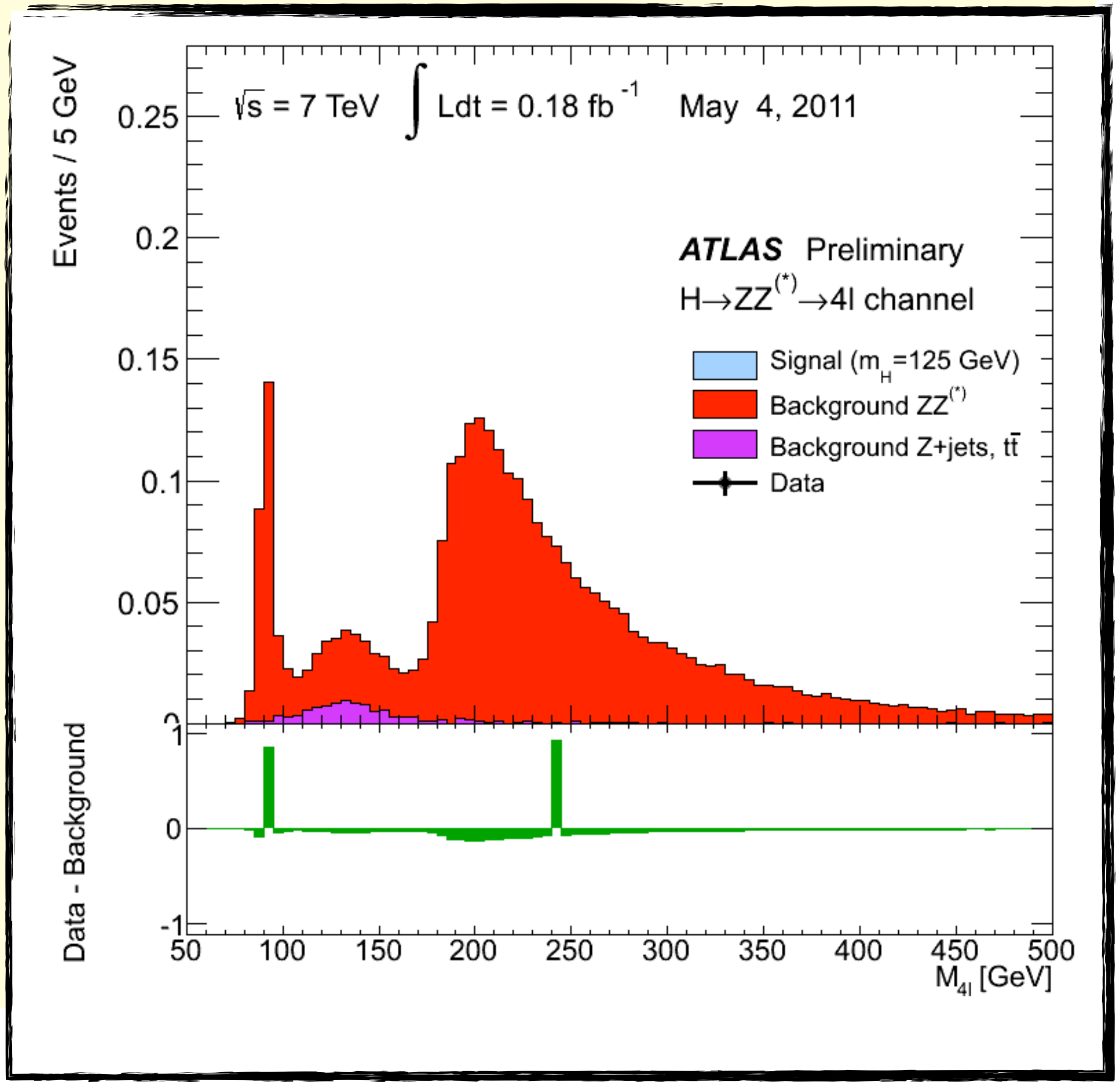
H→ZZ*→4 leptons

BR (H→ZZ*) = 2.63% (M_H= 125 GeV).
Total ~65 H→ZZ*→4l events produced at LHC

- Events in 3 categories:
  - VBF(jets),
  - VH(lepton)
  - ggF-like (the rest)

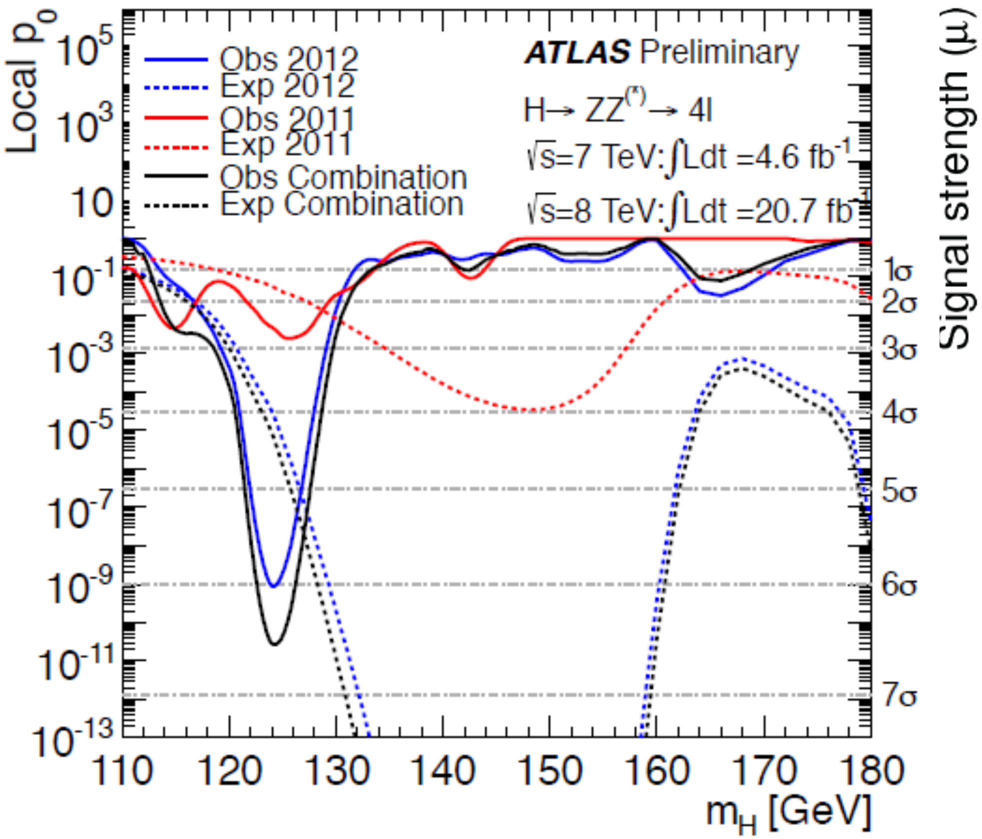


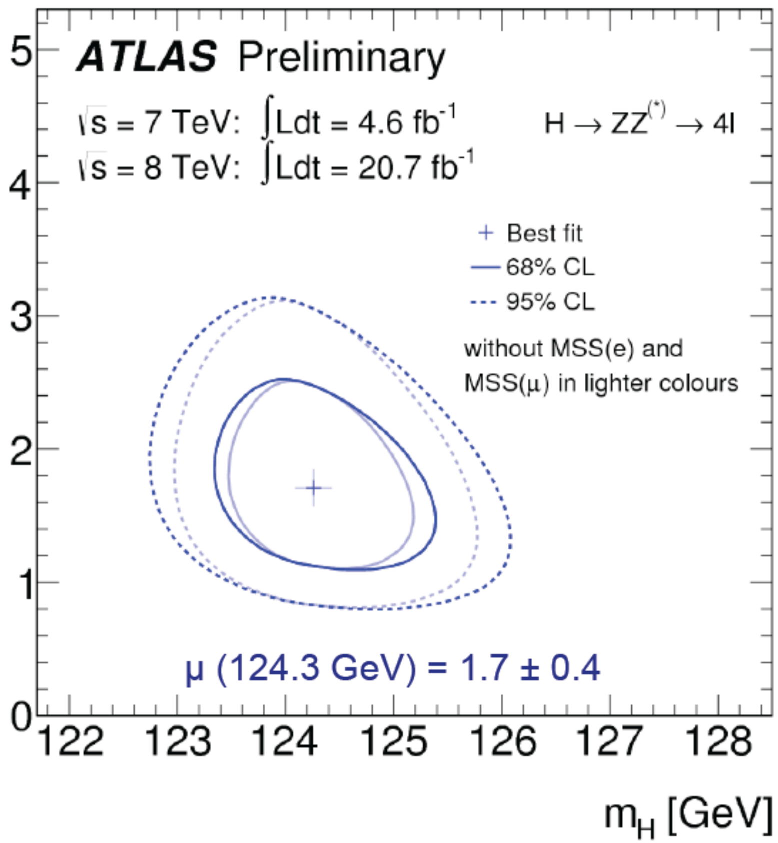




H→ZZ*→4 leptons

arXiv:1307.1427



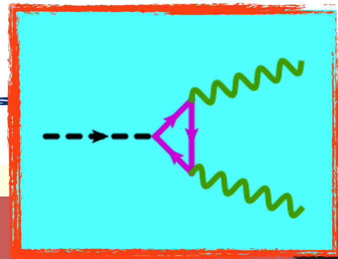


Signal Significance :
6.6σ (4.4σ expected)
Exceeding discovery criteria

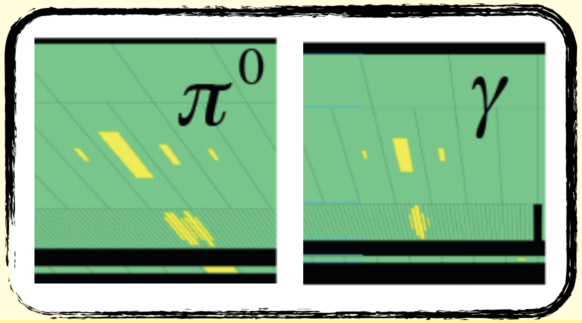
Signal strength:
$\mu = 1.7^{+0.5}_{-0.4}$
at mass = 124.3 GeV

H→γγ

$H \rightarrow \gamma + \gamma$

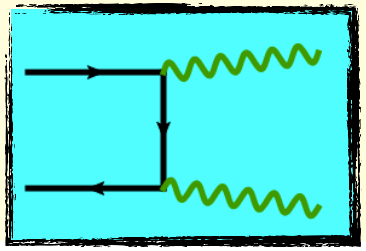


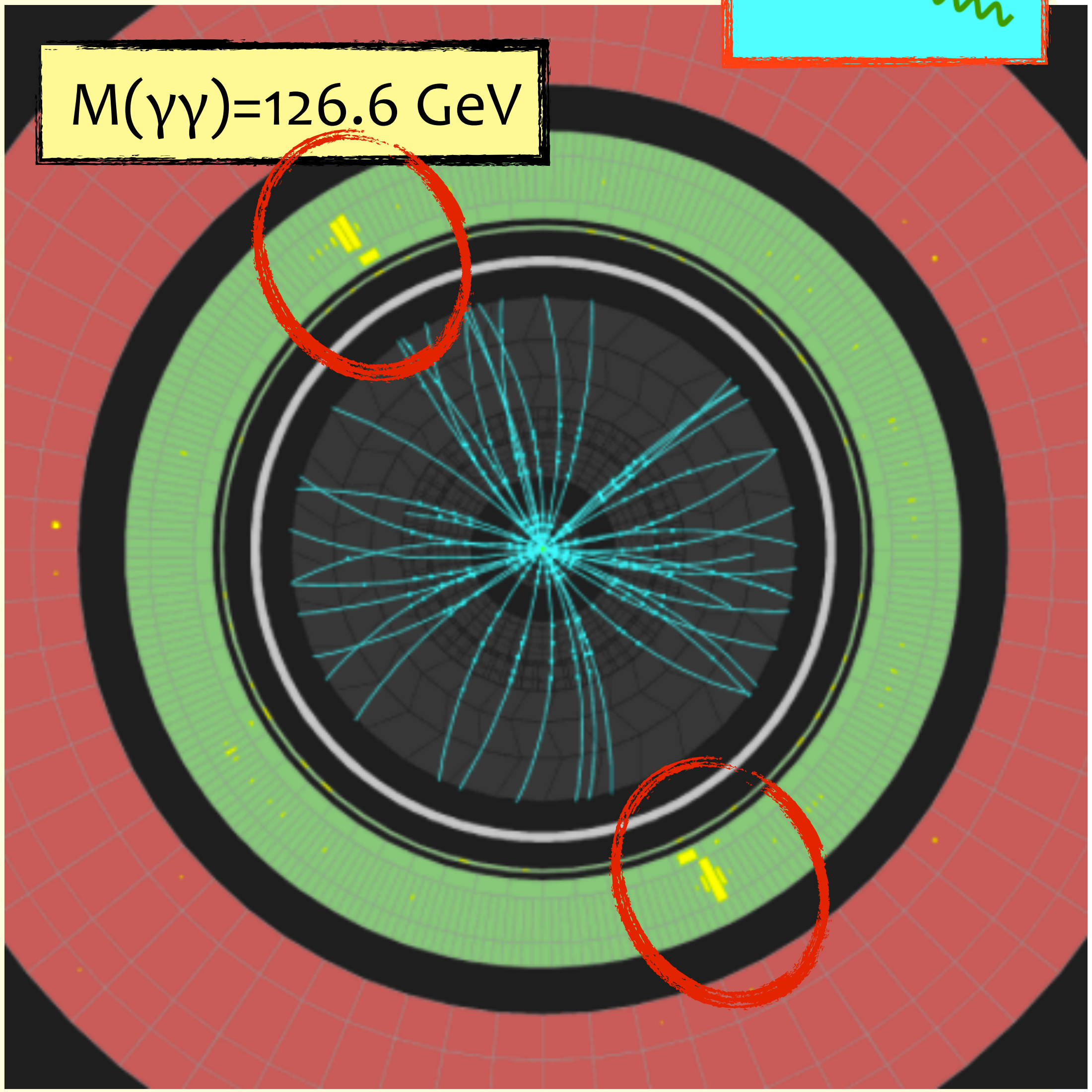
- Background
  - ‘Fake’ fotons
    - pion decay



Energy deposit in calorimeter

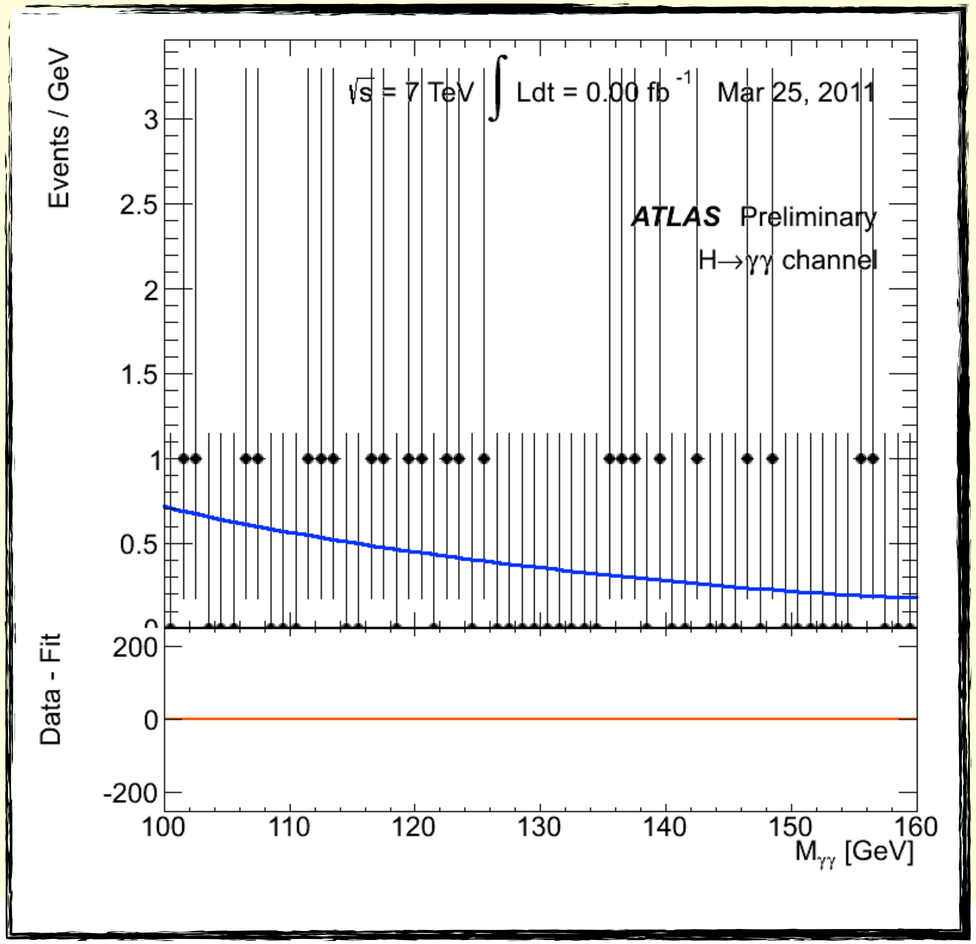
  - ‘Background’
    - γγ, γ-jet, jet-jet

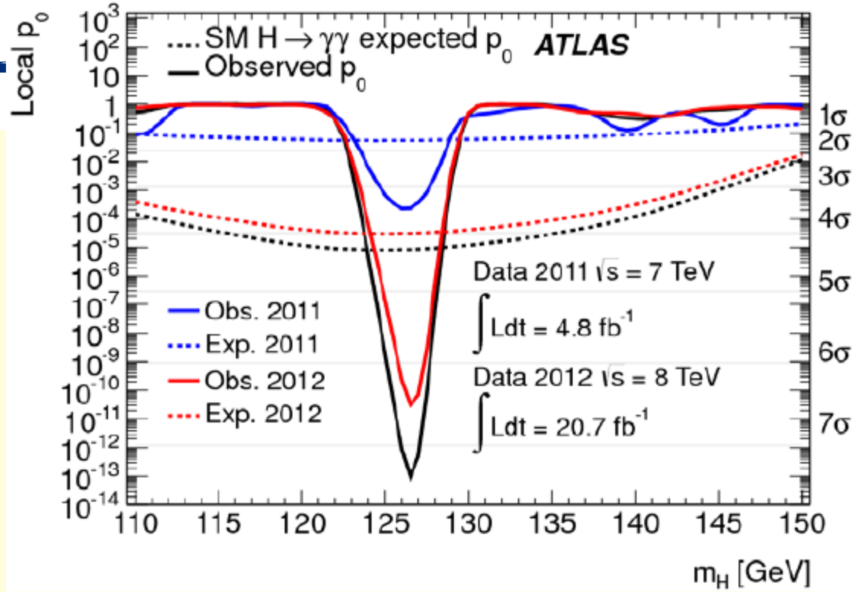




2 fotonen

- Two photon invariant mass
  - as function of day/year

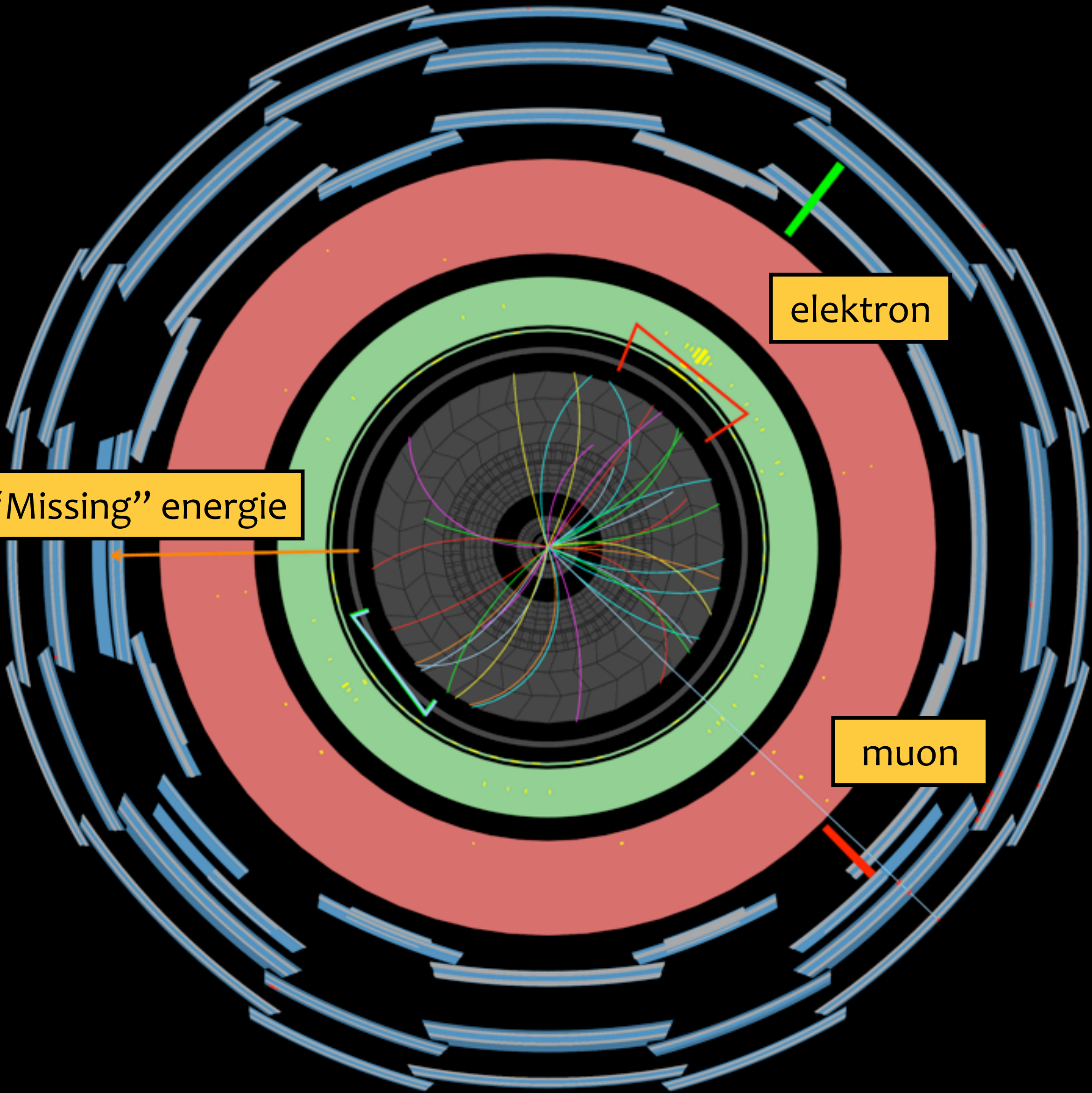


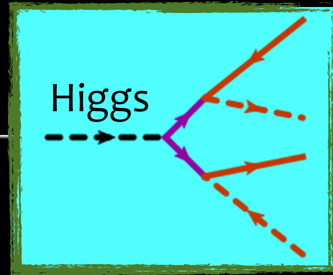


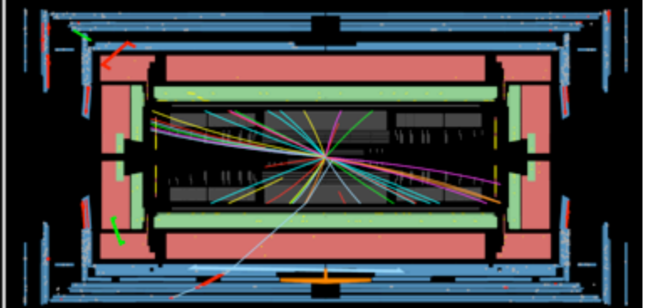
Signal Significance :
7.4σ (4.3σ expected)
Exceeding discovery criteria

Signal strength
μ = 1.57±0.24(stat) ±0.22(syst)
at mass = 126.8 GeV

$H \rightarrow WW^* \rightarrow l\nu l\nu$







ATLAS EXPERIMENT

Run Number: 189483, Event Number: 90659667

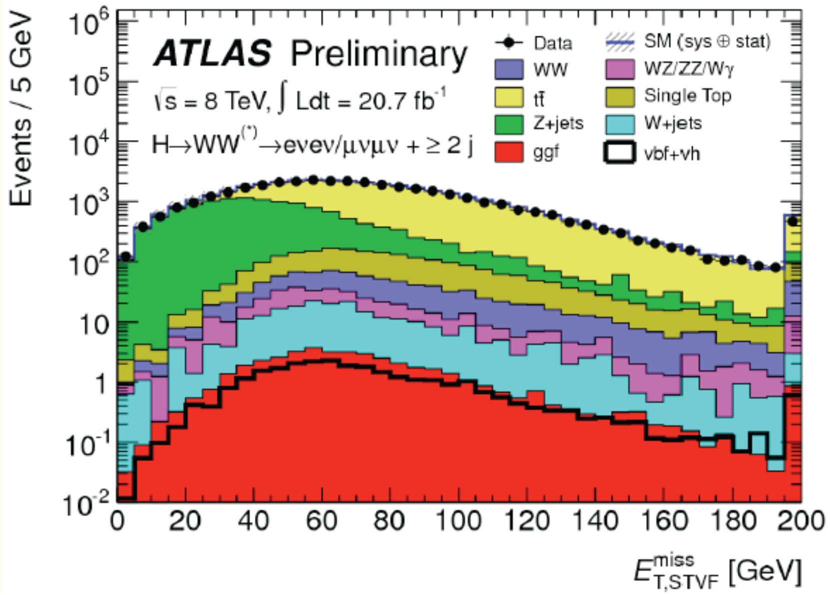
Date: 2011-09-19 10:11:20 CEST

NIKHEF

H→WW*→lνlν

- ee,eμ,μμ + 2ν final state (large E_T^{miss}):
  - ~80% of overall significance from eμ channel (large DY background for ee and μμ channels)
  - N_{jet} classification (0,1, >= 2 jet) to separate ggF and VBF processes
  - Main backgrounds: WW, Wt, top, W+jets, Z+jets

Observed (N_{jet} = 0, 1, >=2) ~25 fb^{-1}	Expected purity s/s+b (√s=8 TeV)
831, 309, 55	**152**/1188 = 12.8%

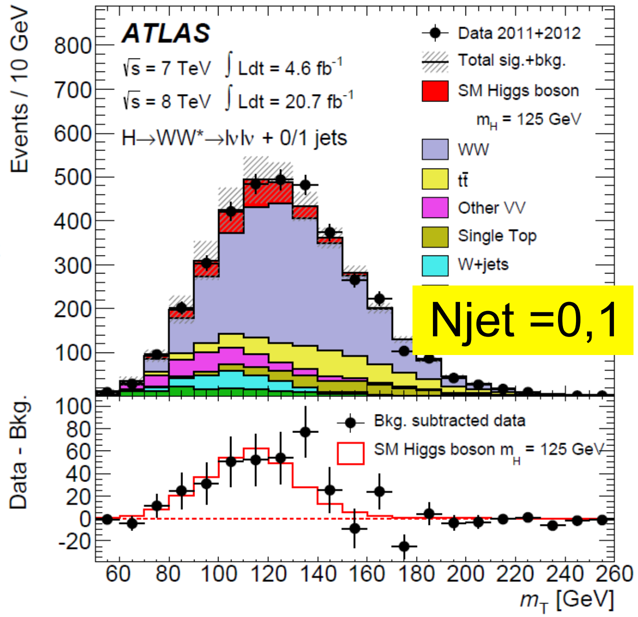


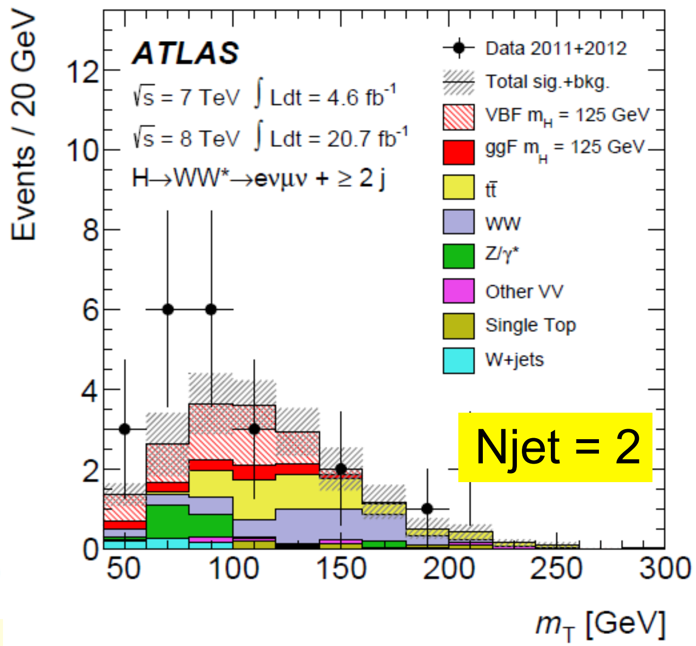
H→WW*→lνlν

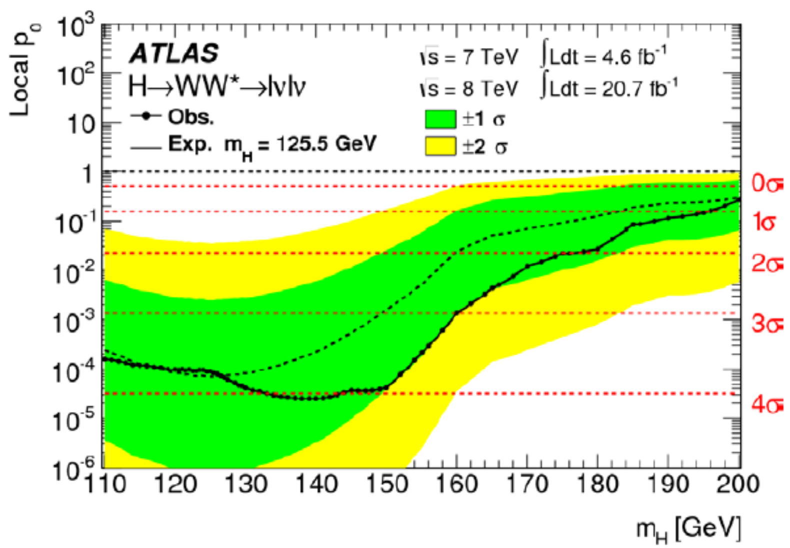
arXiv:1307.1427

The final discriminant

$$m_T^2 = \left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2$$

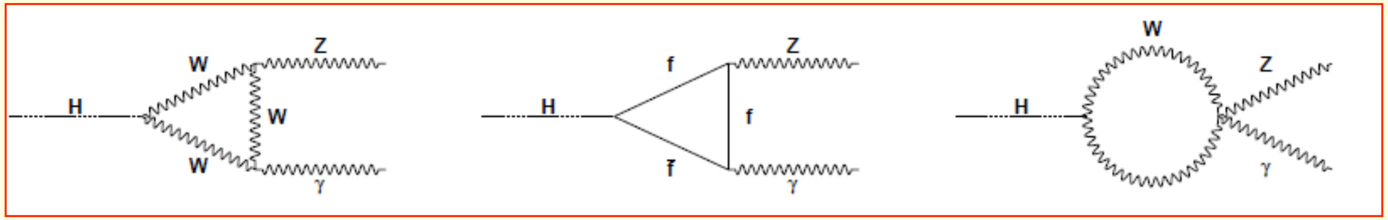






3.8σ (3.8σ expected at 125.5)

Extending the search: $H \rightarrow Z\gamma \rightarrow ll\gamma$

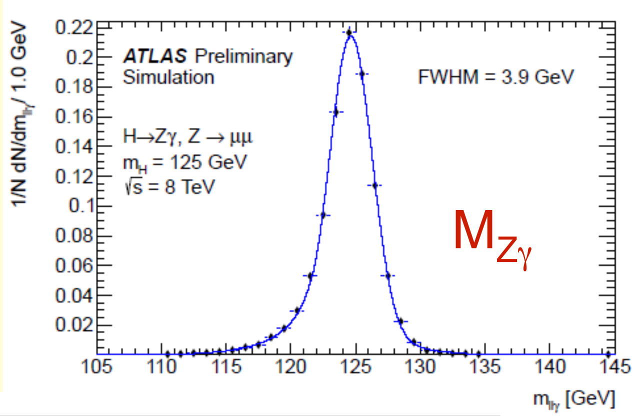


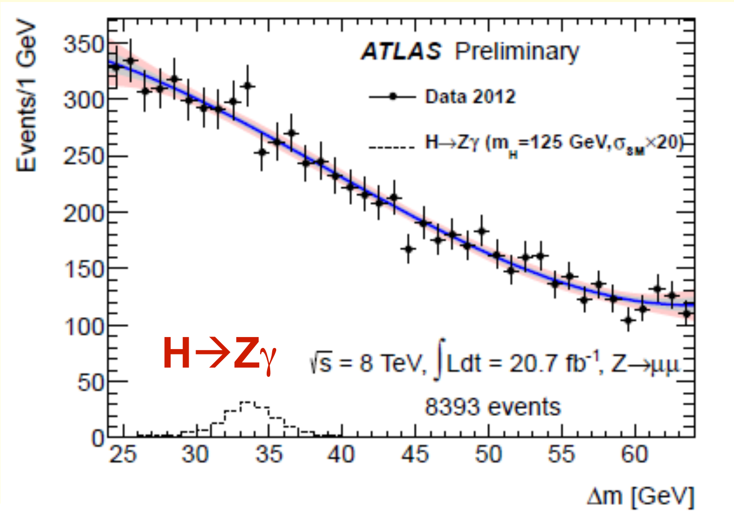
$BR(H \rightarrow Z\gamma)$=0.15%

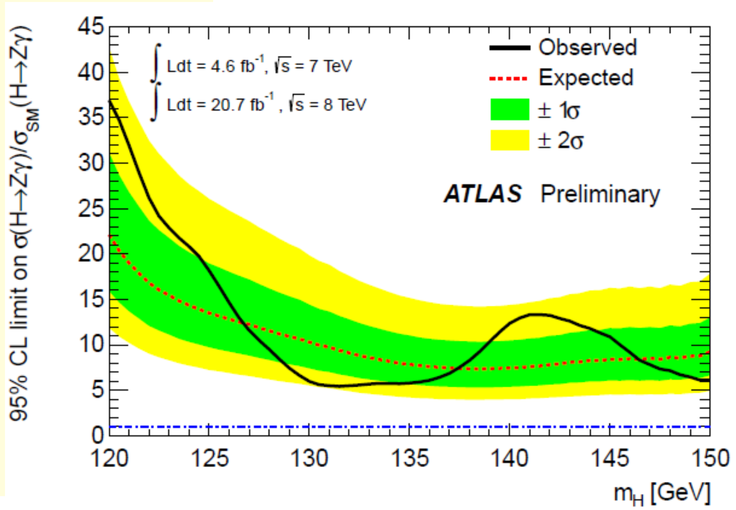
- **$H \rightarrow Z\gamma$** is another high resolution channel
- Sensitive to new particles through loops
- For SM Higgs with mass = 125 GeV:

$$\sigma_H \times Br(H \rightarrow Z\gamma \rightarrow \ell\ell\gamma) \sim 2.3 \text{ fb}$$

~ 55 events in 2011+2012 dataset



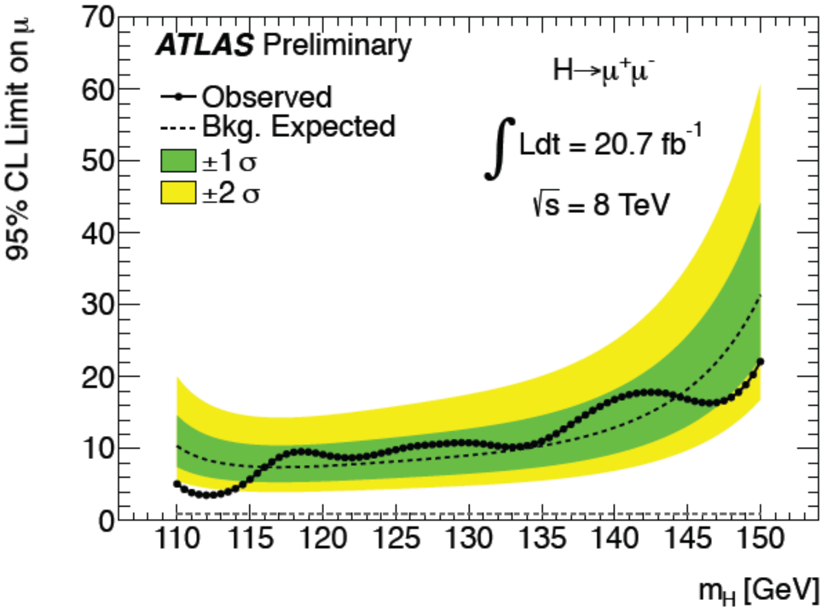


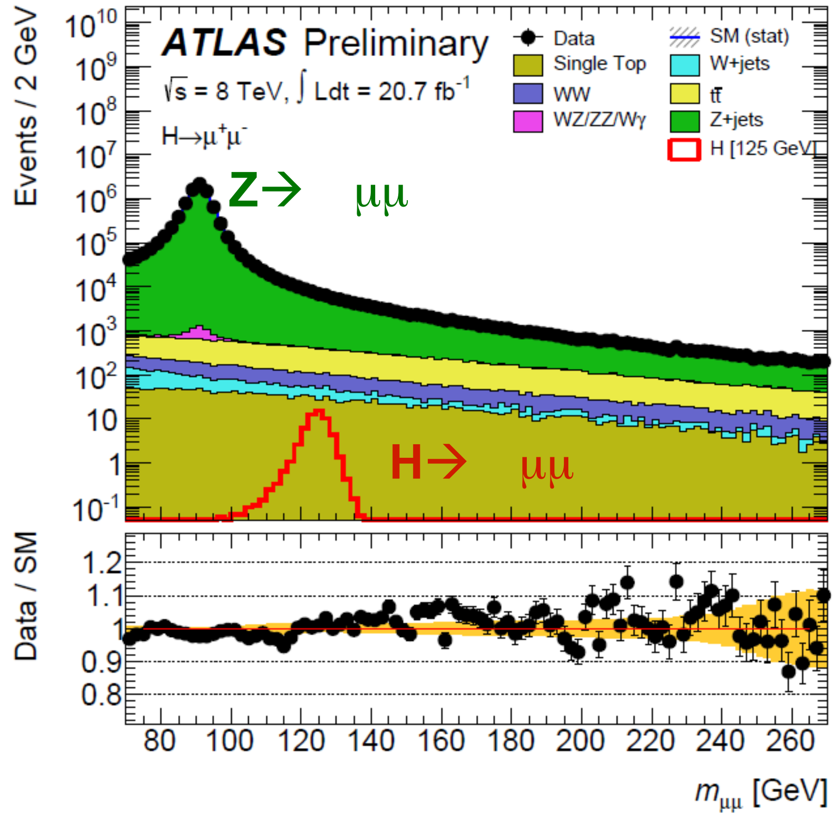


Direct lepton coupling: H→μμ

$$B(H[125] \rightarrow \mu\mu) = 2.2 \times 10^{-4}$$

	$\|m_H - m_{\mu\mu}\| \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15806 ± 125
W+jets	88 ± 6
Total Bkg.	17697 ± 126
Observed	17442



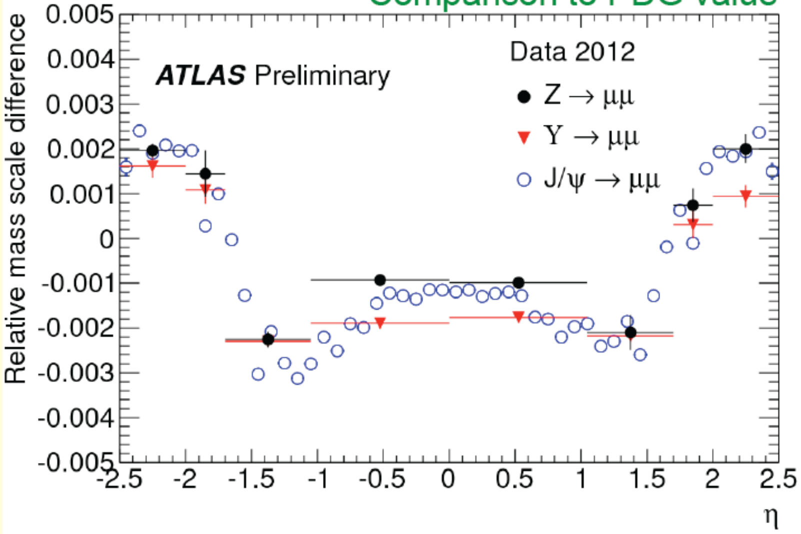


Need much higher luminosity for observation of this channel

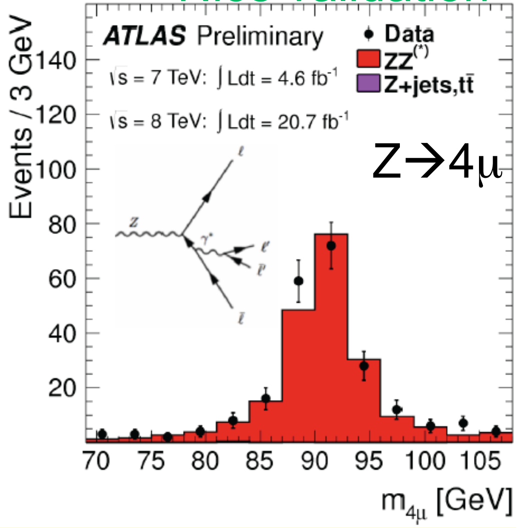
Higgs mass: Lepton Energy/Momentum Calibration

Muons

Comparison to PDG value

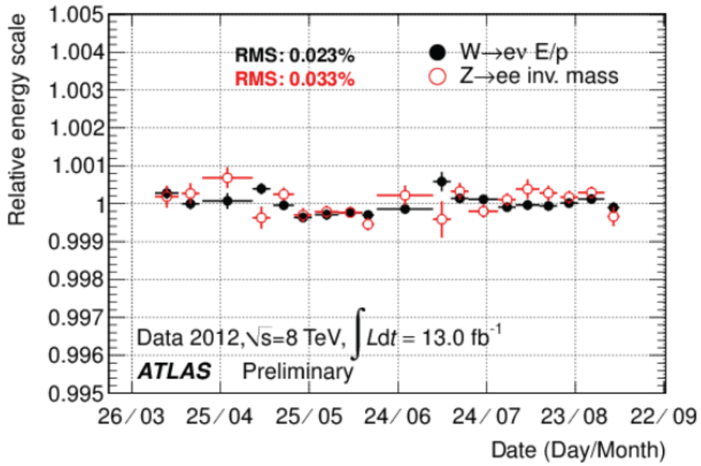


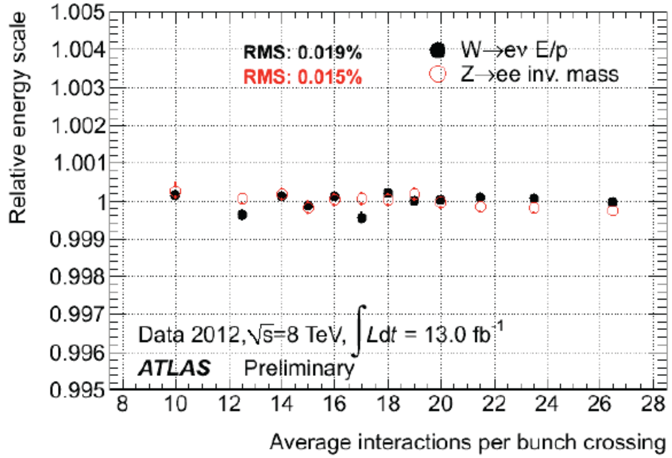
Nice validation



Electrons

Stability of EM calorimeter response vs time/pile-up better than 0.1%

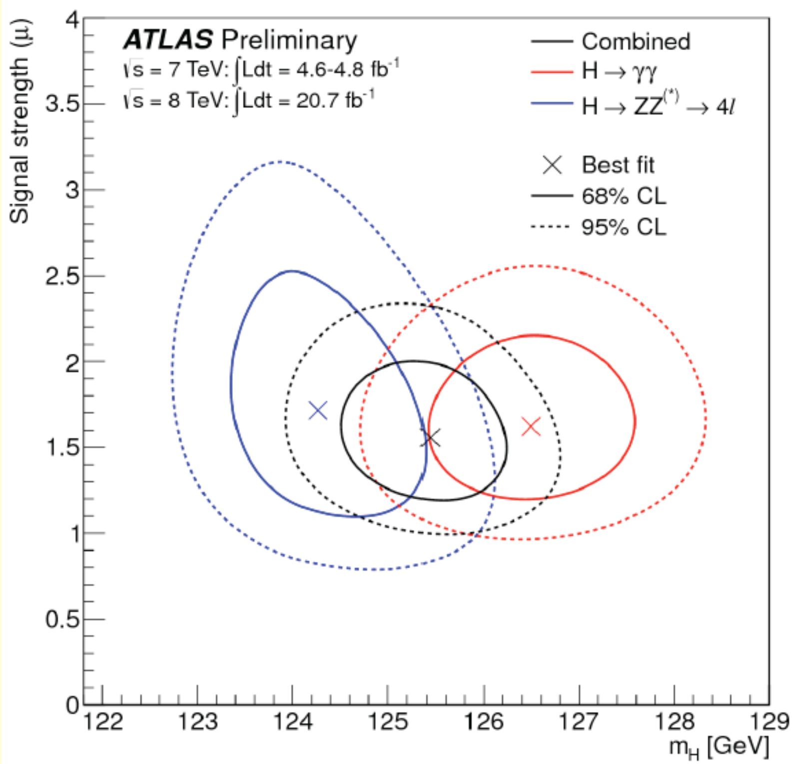




Mass Combination (4l, γγ)

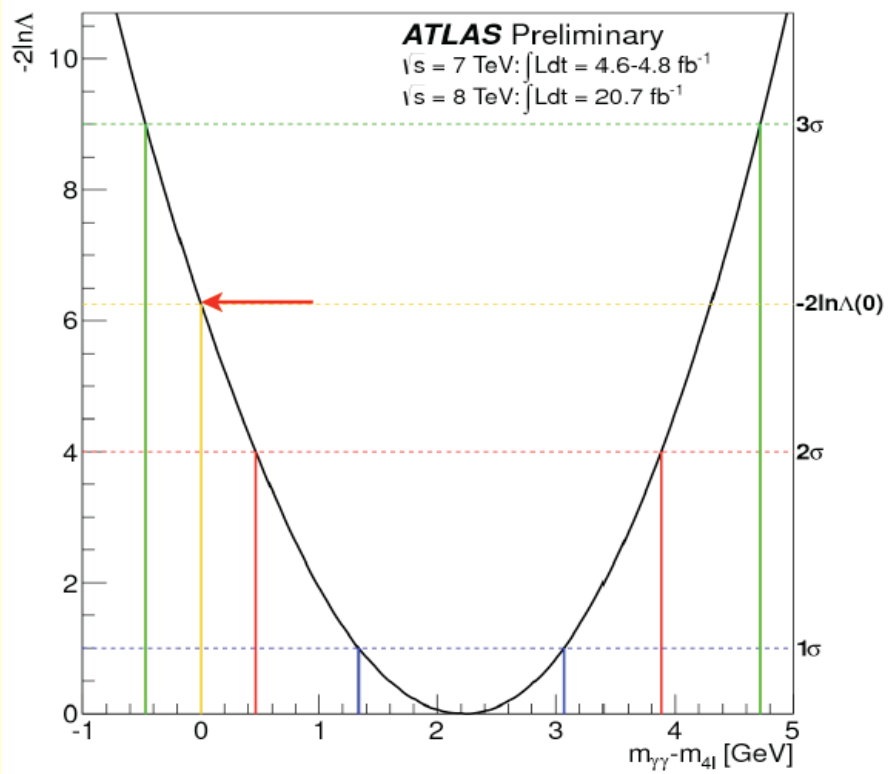
- Combined mass measurement
  - m_H=125.5 ± 0.2(stat) ± 0.6(syst) GeV

Prob. to observe
Δm≥2.3 GeV ~ 1.5% (2.4σ)



$$m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst)\ \text{GeV}$$

$$m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)\ \text{GeV}$$



Two measurements are 2.3 GeV apart:

$$\Delta m_H = 2.3^{+0.6}_{-0.7}(stat) \pm 0.6(syst)\ \text{GeV}$$

Higgs Signal Strength

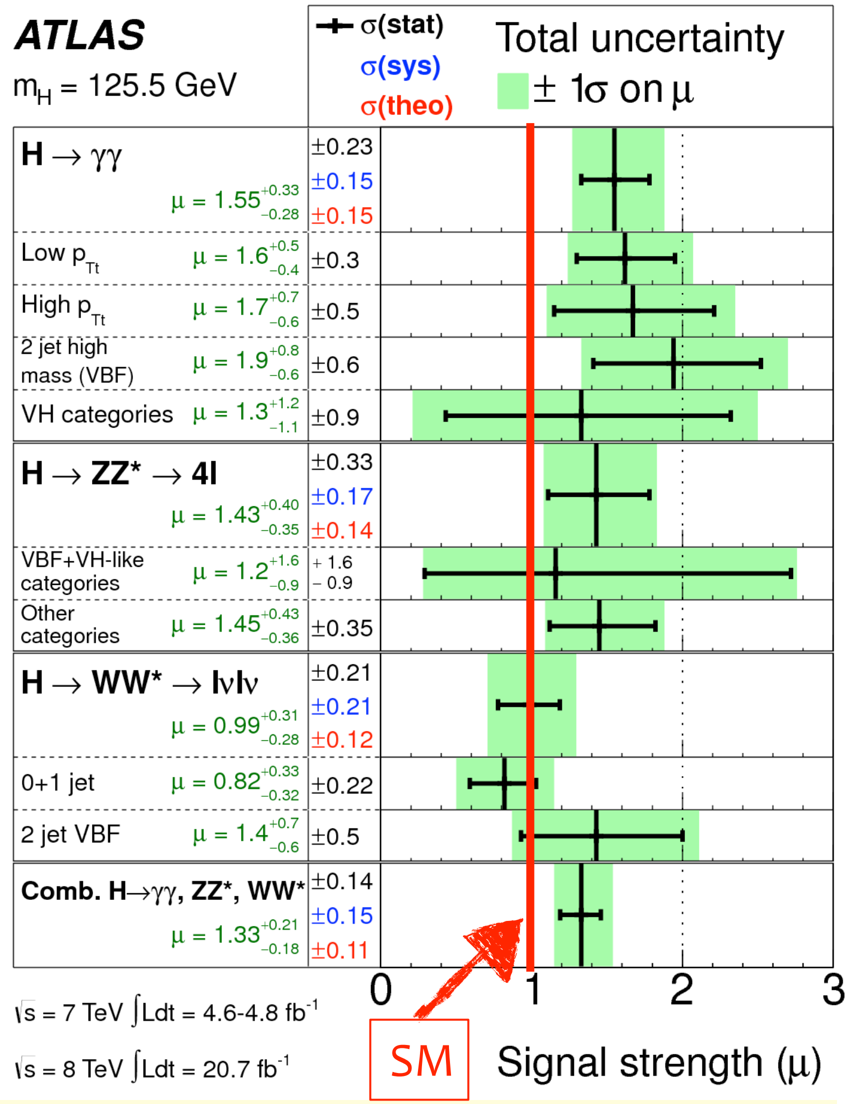
Signal strength $\mu = \sigma/\sigma_{SM}$

Combination of diboson final states
$H \to \gamma\gamma$
$H \to ZZ(*) \to 4l$
$H \to WW(*) \to l\nu l\nu$
measured at combined m_H=125.5 GeV

- Variation due to m_H uncertainty: ±3%
- Compatibility with SM (μ=1): 7%
- Largest deviation $\mu_{\gamma\gamma}$: 1.9 σ

Including preliminary μ_{bb}, $\mu_{\tau\tau}$: μ=1.23 ± 0.18

ATLAS also sets preliminary (95%CL) limits:
$H \to \mu\mu$: μ<9.8 (20.7 fb^{-1})
$H \to Z\gamma$: μ<18.2 (4.6 fb^{-1} + 20.7 fb^{-1})



μ = 1.33 ± 0.14 (stat) ± 0.15 (sys) ± 0.11 (theo)

Vector vs Fermion Couplings

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$ (>0)

$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

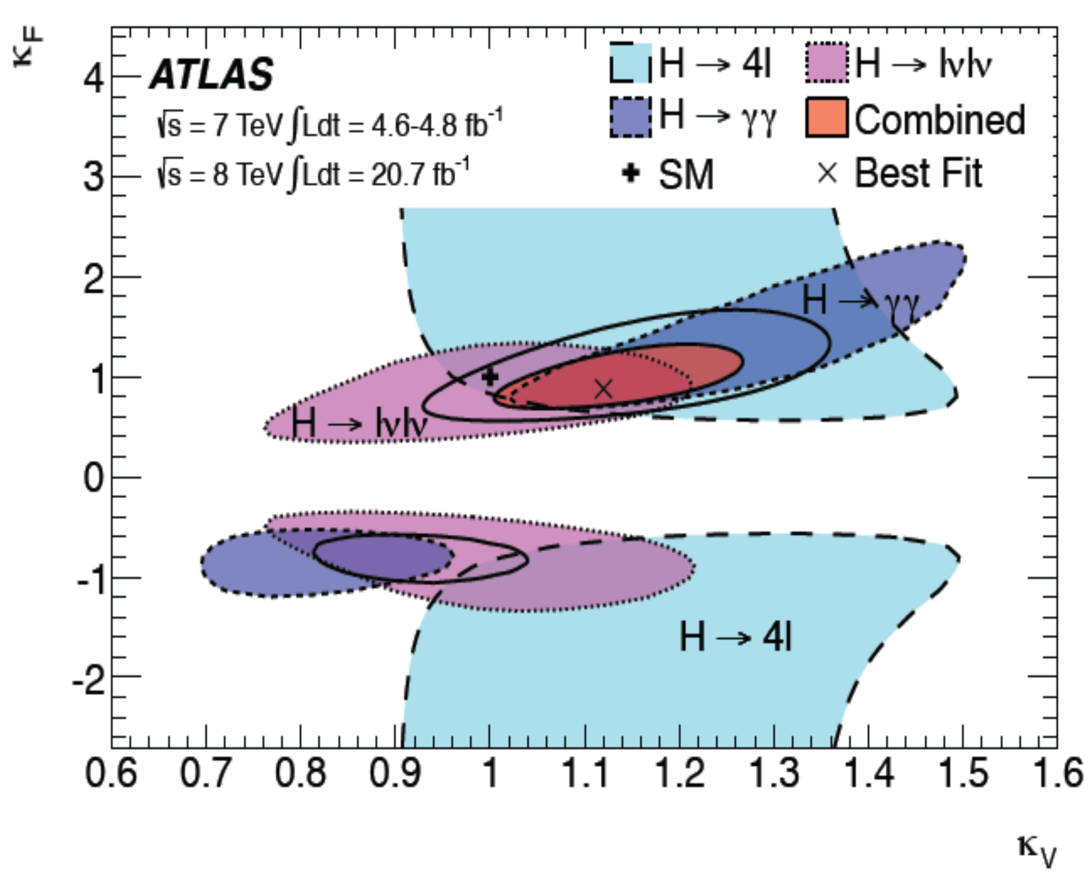
(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

$\kappa_F = g_F/g_{F,SM}$ $\kappa_V = g_V/g_{V,SM}$

Assume no BSM contributions to loops: gg→H and H→γγ, and no BSM decays (no invisible decays)

- **κ_F = 0 is excluded (>5σ)**

Double minimum from interference between vector(W) and fermion(top) in H→γγ

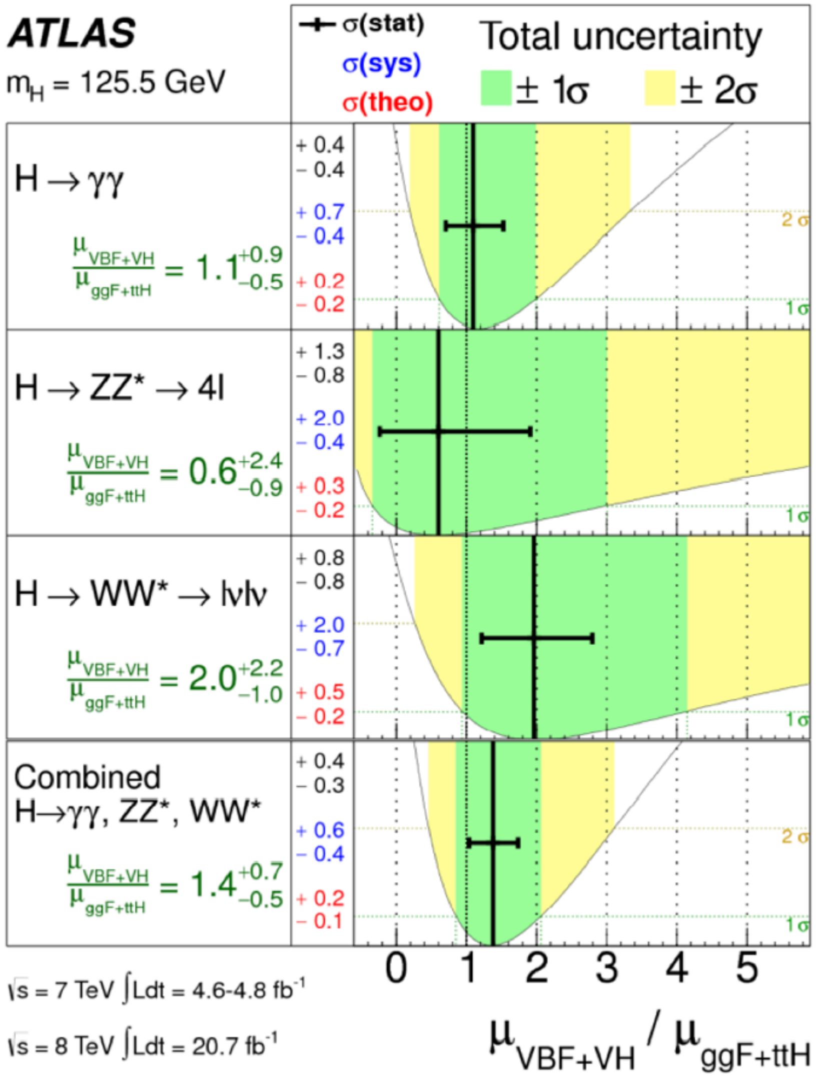


Evidence Vector-Boson-Fusion

- VBF enhanced analyses
  - in $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*\rightarrow 4l$ and $H\rightarrow WW^*\rightarrow l\nu l\nu$ all find a VBF component consistent with the SM expectation.
- Combined the VBF(+VH) to ggF(+ttH) ratio:

$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.4^{+0.7}_{-0.5}$$

  - 3.3 σ evidence that a non-zero fraction of Higgs events is produced via VBF



Studies on Spin-Parity

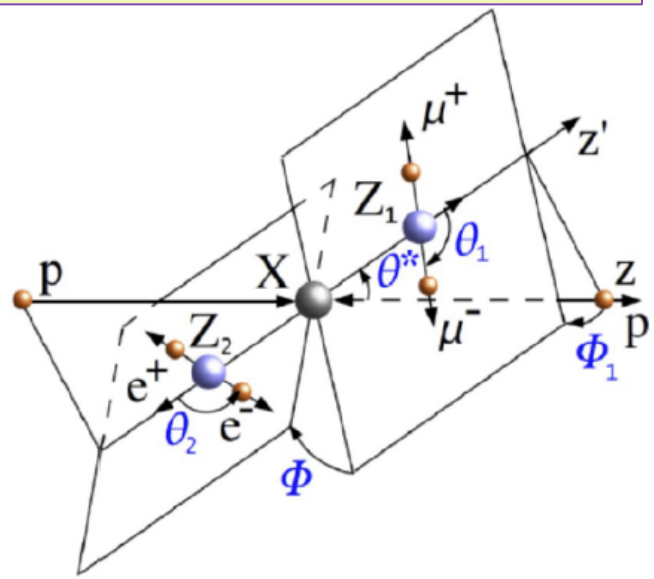
Spin 1 hypothesis: strongly disfavored by Landau-Yang theorem,
main interest is to test the SM 0^+ hypothesis against 2^+: start with spin 2 tensor with minimal couplings to SM particles (2^+_m)

Spin 2^+_m discrimination is tested for possible mixtures of gluon and quark initiated production

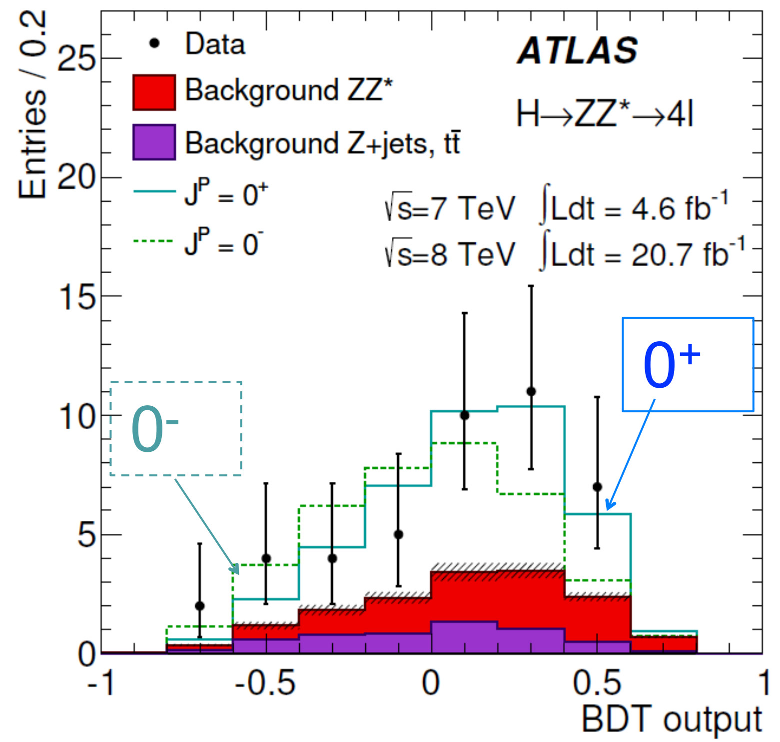
$H \rightarrow ZZ^* \rightarrow 4l$ analysis is also testing other spin parity states, as 0+ vs 0- etc. with gluon-fusion production

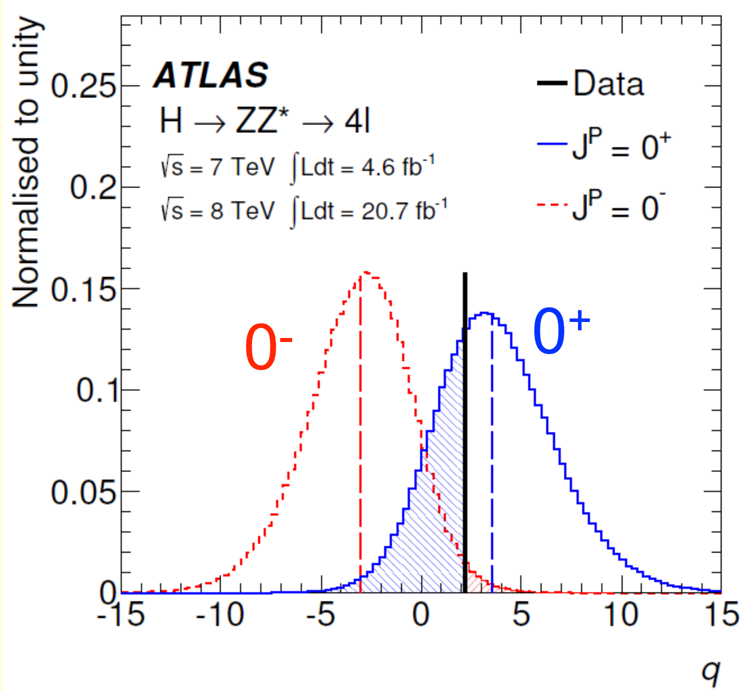
Spin studies in three different decay modes

- **$H \rightarrow \gamma\gamma$**: fully reconstructed, however only production angle θ^* available
- **$H \rightarrow ZZ^*$**: fully reconstructed, decay of Z bosons provides full information on the Z decay planes 5 decay angles as shown, and m_{Z1}, and m_{Z2}
- **$H \rightarrow WW^*$**: direct calculation of decay angles not possible, use other kinematic distributions



Spin Analysis with H→ZZ*→4l





BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l

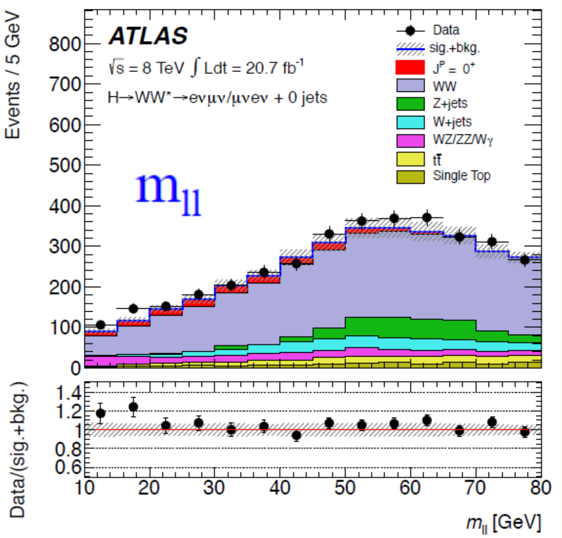
+ production and decay angles

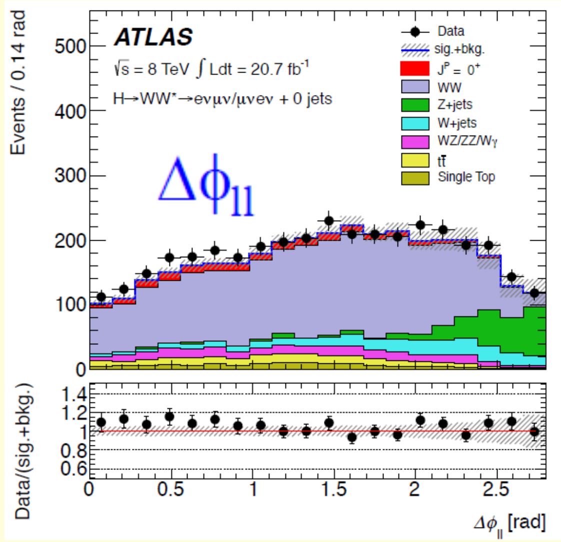
Exclusion **(1-CL_s):**

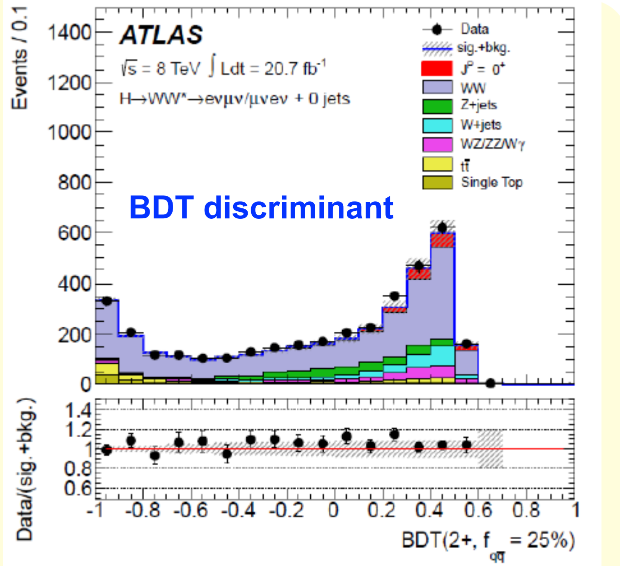
Observed 0^- exclusion 97.8%
Observed 1^+ exclusion 99.8%

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Spin Analysis With H→ WW*

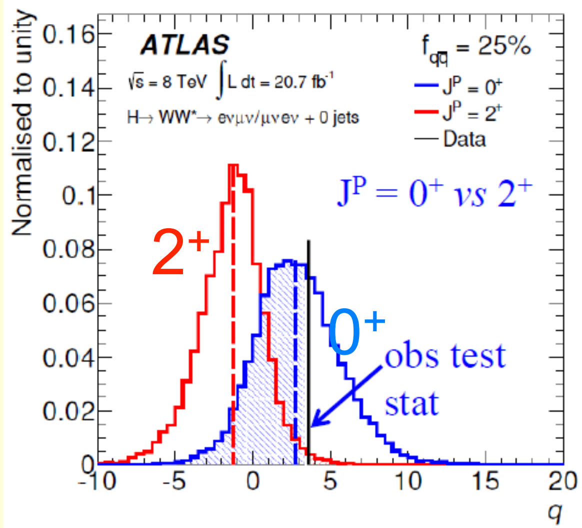






$J^P = 0^+ \; vs \; 2^+$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048



Exclusion **(1-CL$_s$):**

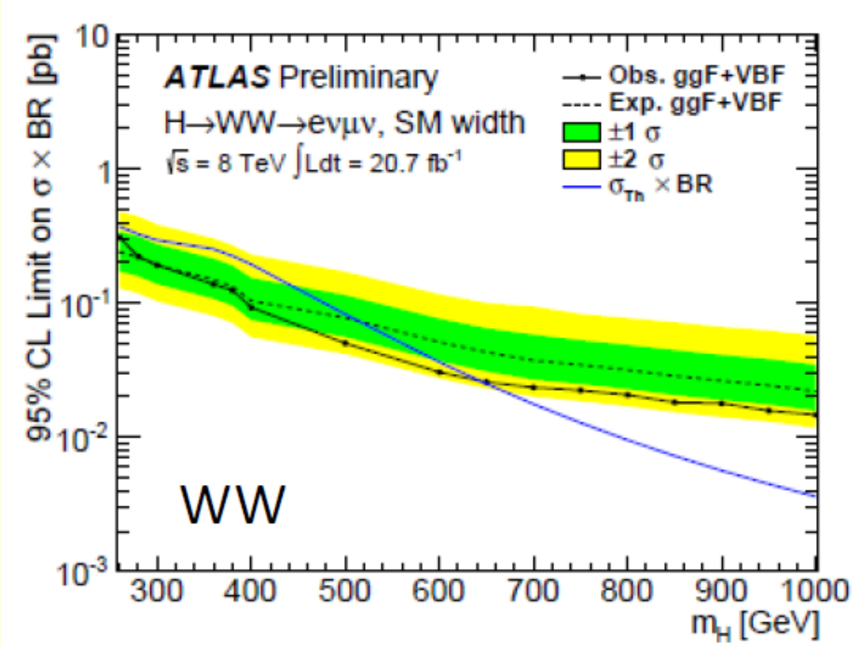
Observed 2$^+$ (qq=100%) exclusion 99.96%

Observed 2$^+$ (qq = 0%) exclusion 95.2%

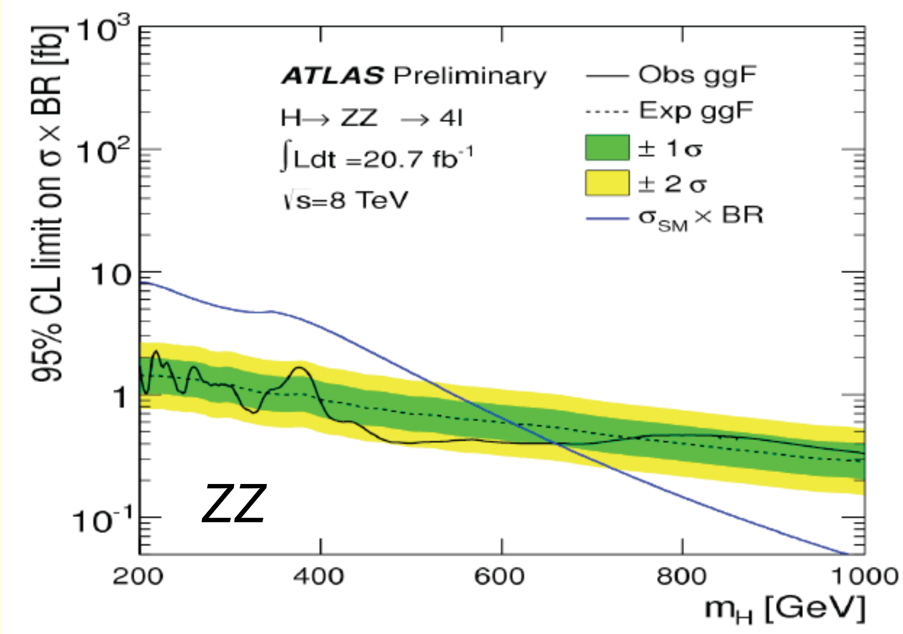
Search for High Mass H→ZZ, WW

Extend the Higgs search to high mass assume SM-like width, and decay to

WW→ lνlν*



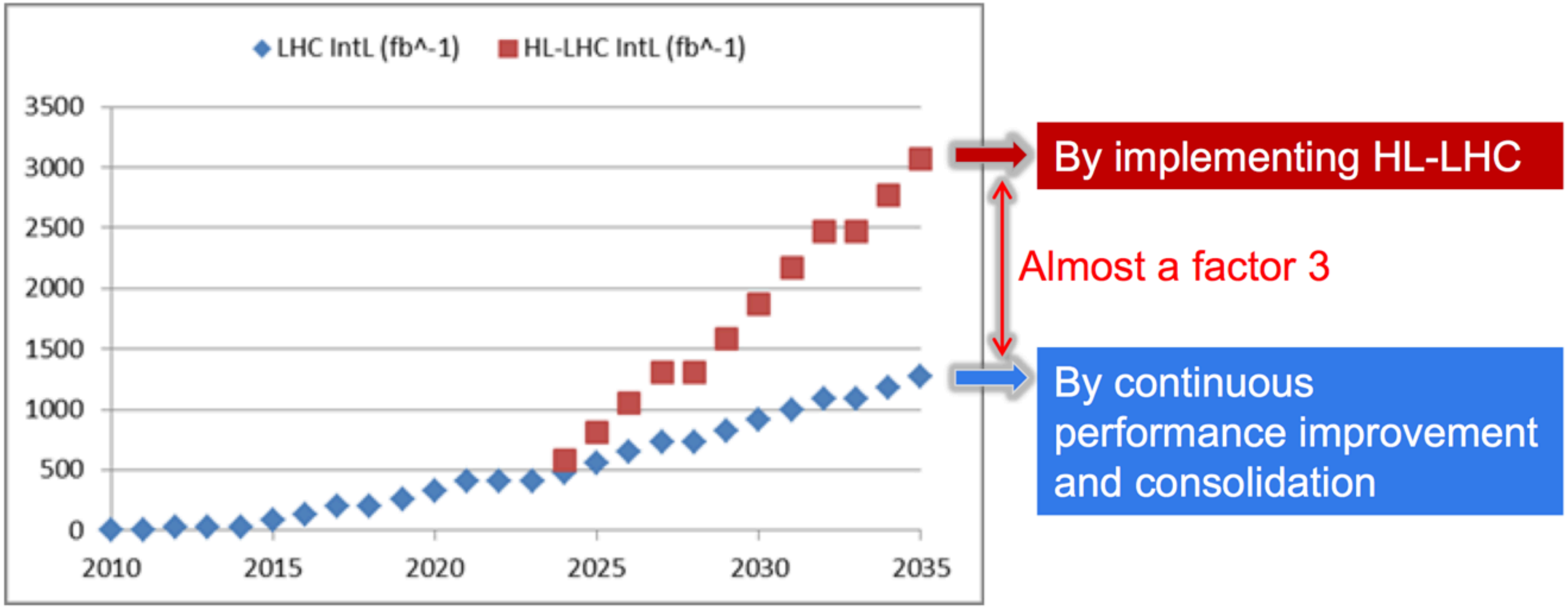
ZZ→ 4l*



95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

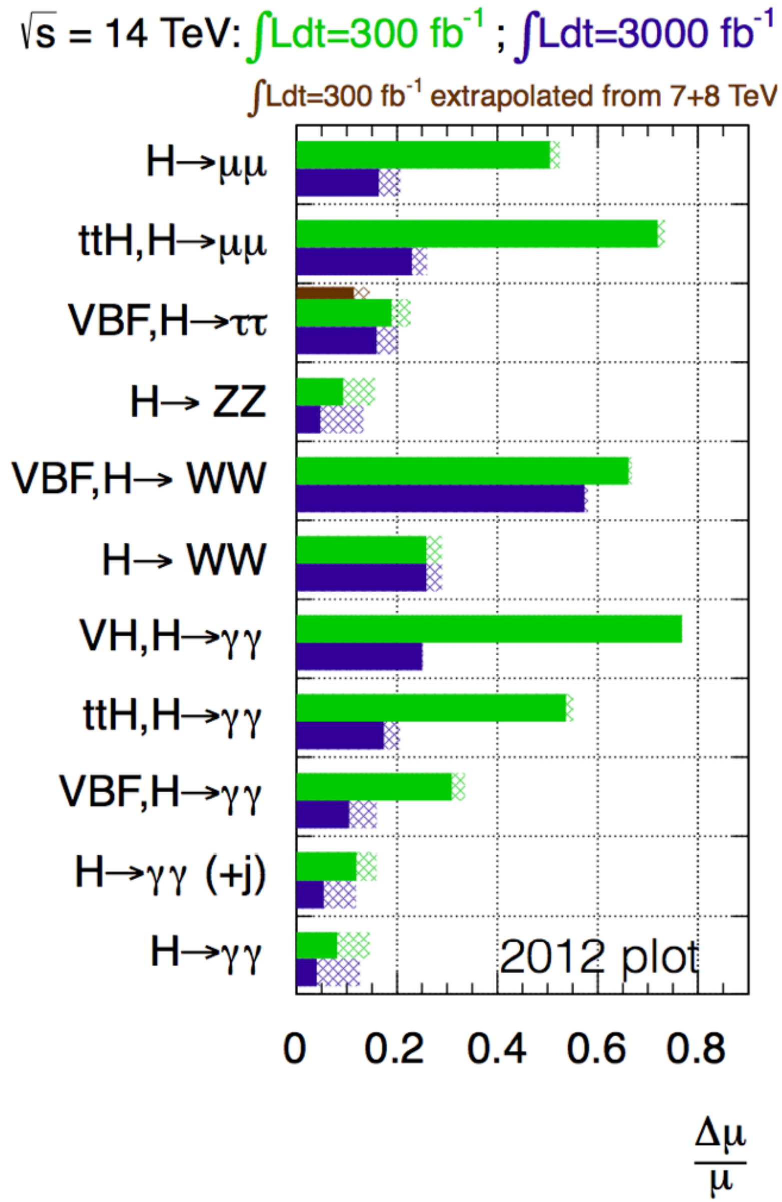
High Luminosity LHC

- Goal of HL-LHC project:
  - 250 – 300 fb^{-1} per year
  - 3000 fb-1 in about 10 years

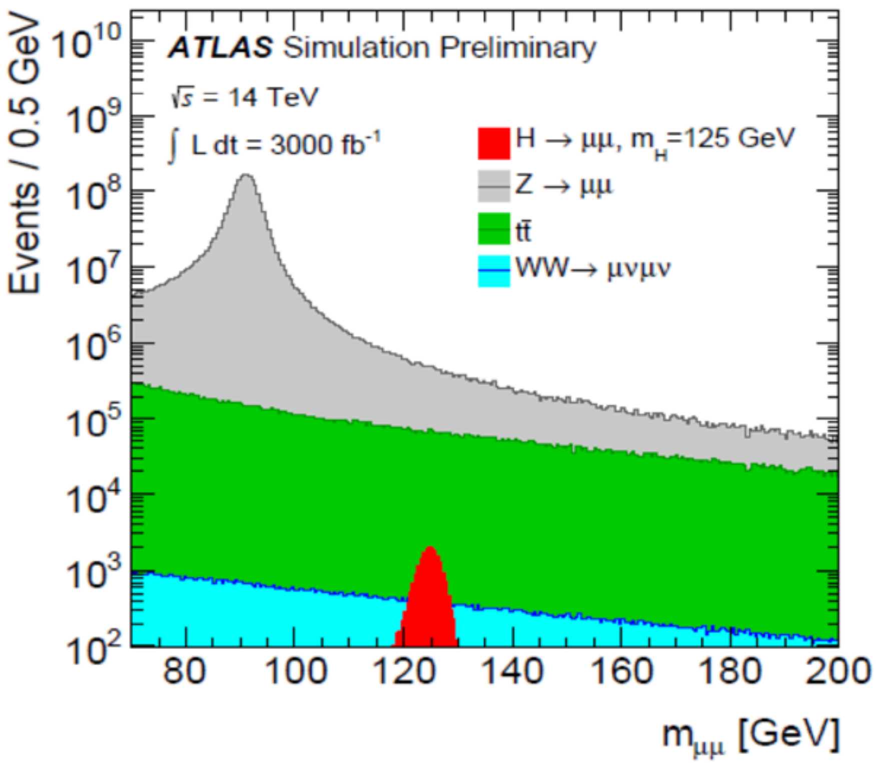


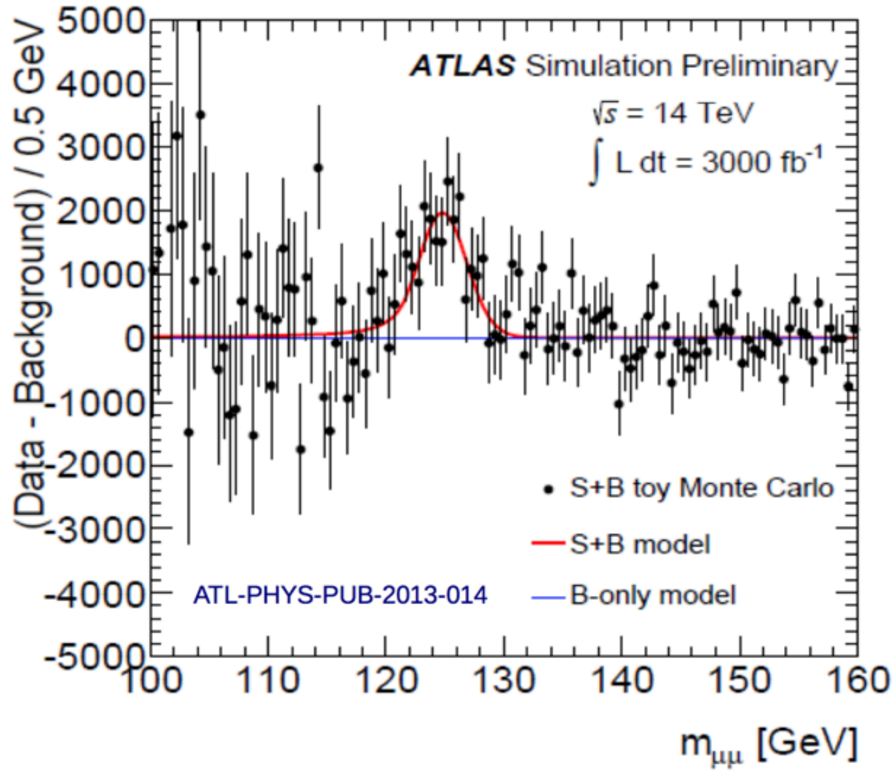
Future for Higgs

- What brings HL-LHC?
  - Increased precision on existing channels
  - Observation of rare decays Zγ, μ+μ−, cc
  - Double Higgs production
  - Longitudinal Vector-Boson Scattering



New possibilities @ 3000 fb^{-1}

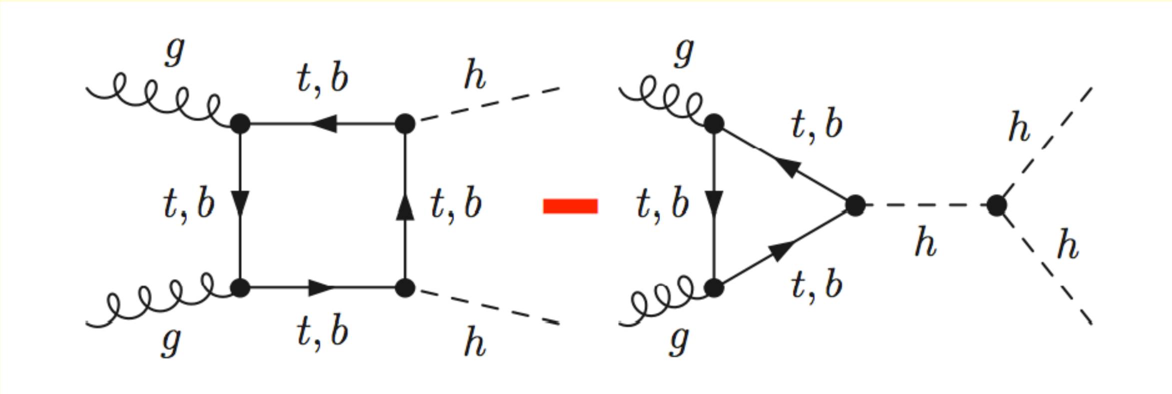




- $H \to \mu\mu$
  - Allows direct study of coupling to two different leptons
  - Test lepton flavour-violation carefully

Di-Higgs production

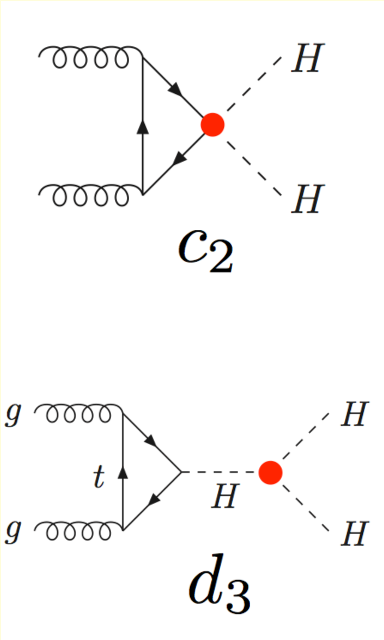
- The observation Higgs poses questions about
  - Its gravitational impact
  - We need to demonstrate the potential i.e. measure the self-coupling
- Test of structure of Higgs potential
  - Not an easy measurement, because of box–vertex destructive interference: cross section of 40±3 fb

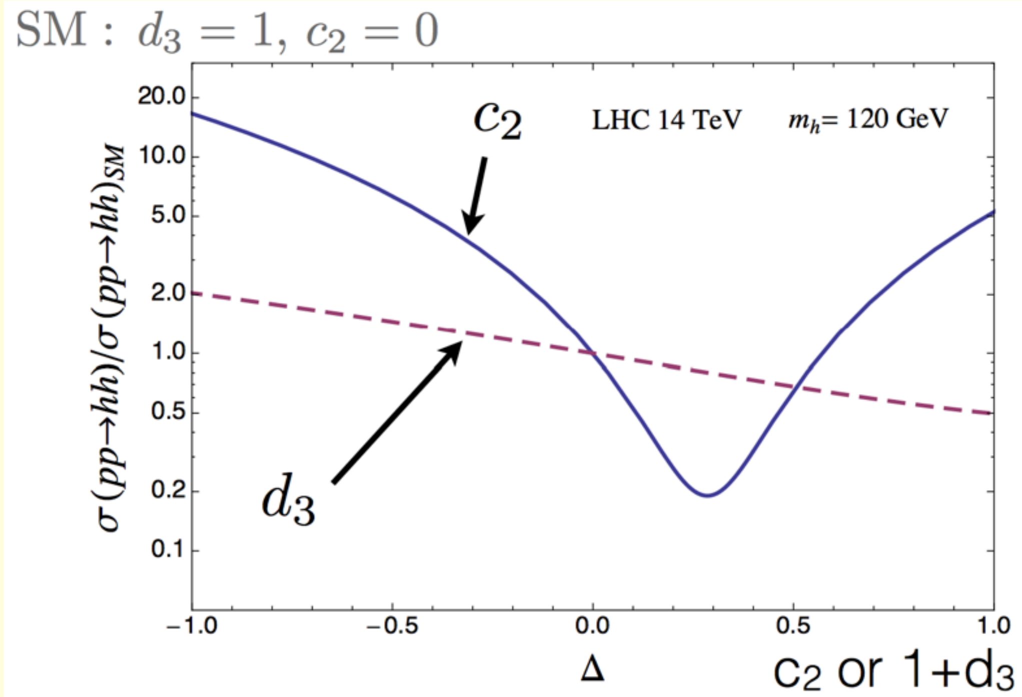


bbWW	30000
bbττ	9000
WWWW	6000
γγbb	320
γγγγ	1

D-Higgs anomalous production

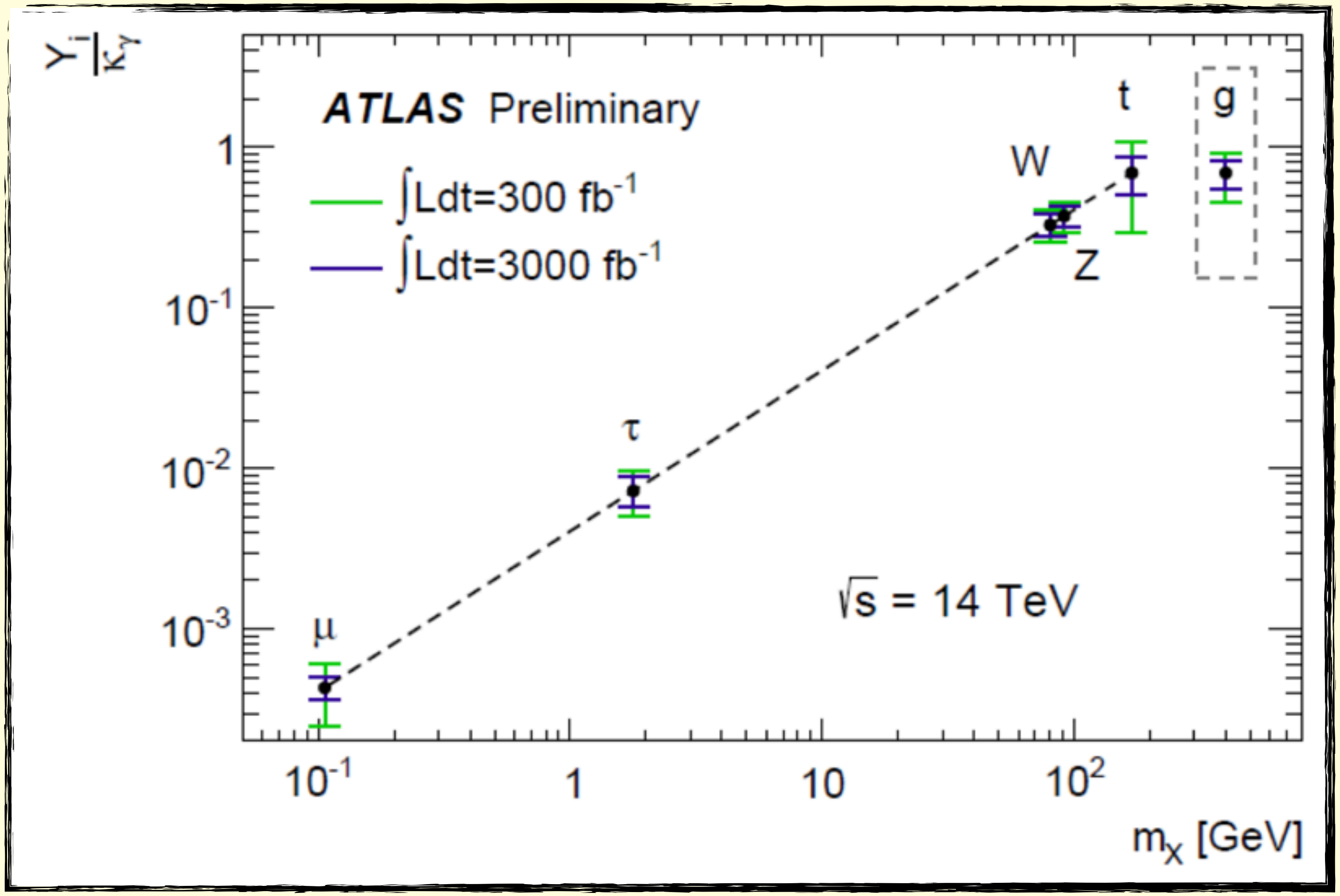
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - m_t \bar{q}_L t_R \left(1 + c_t \frac{h}{v} + c_2 \frac{h^2}{v^2}\right)$$





- Only promising for non-SM behavior

The Higgs coupling strength plot



Is this the 'blueband' plot for the next decade?

Summary

- LHC Run I (2010-2013) a great success for ATLAS
  Discovery of a new boson, and first measurement of
  - its mass, ..

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

  - its coupling parameters (all consistent with a SM Higgs)

$$\text{Strong evidence} \quad J^p = 0^+$$

  - No significant evidence yet for fermionic decays, but results are consistent with SM Higgs hypothesis
  - Search for high mass Higgs and SM and narrow width approach.
- Many analyses of Run I data are ongoing, so more results to come ....