Higgs Physics at the ATLAS Experiment

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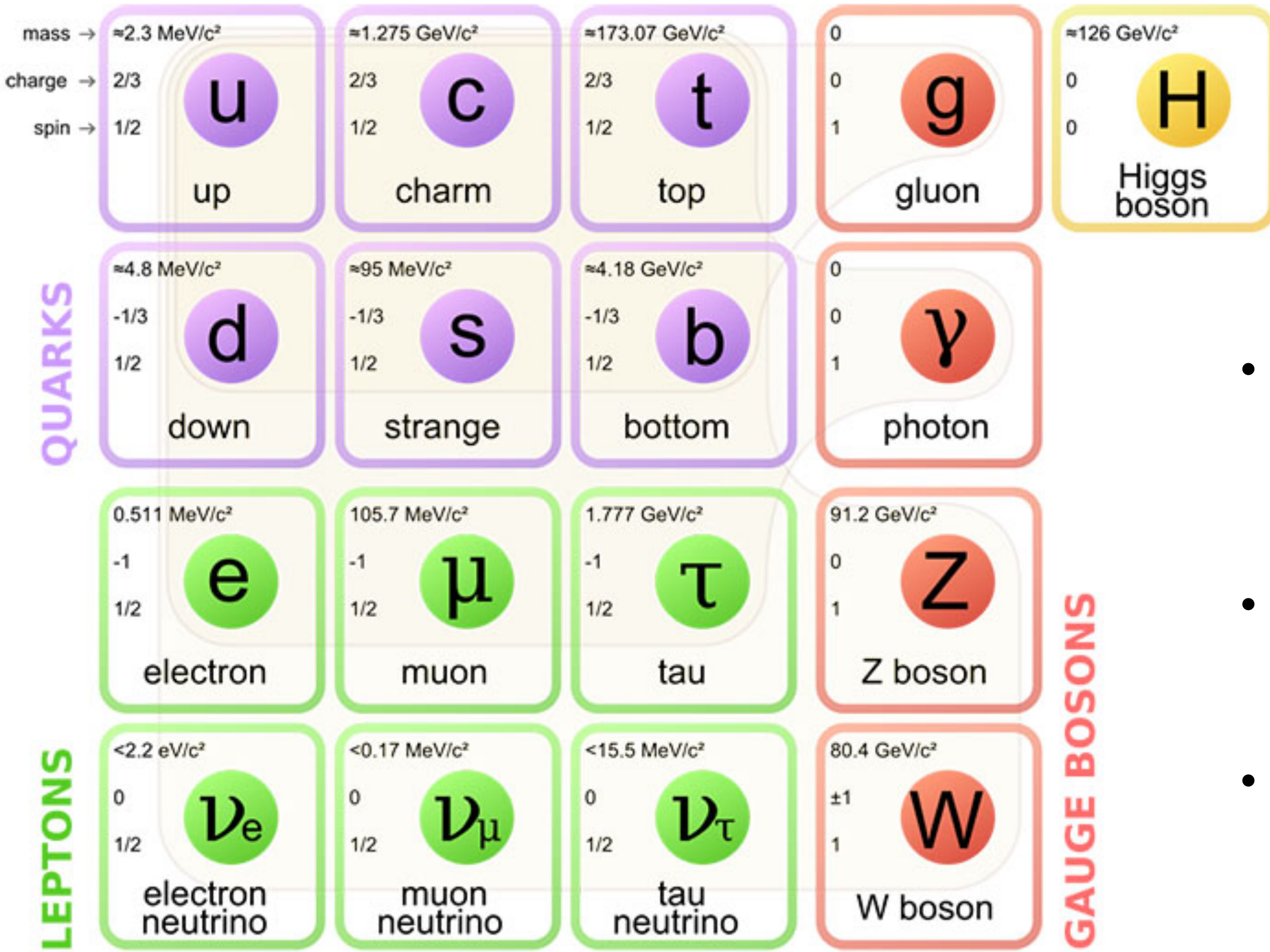
October 28, 2020

Outline

- Introduction to Higgs particle
- Overview on Higgs searches
- Higgs property measurements
- Observation of $H \rightarrow bb$
- Summary & outlook

Standard Model



- SM is not a final theory to describe everything
- SM beautiful and successful
- Higgs as the origin of mass

The Higgs Particle

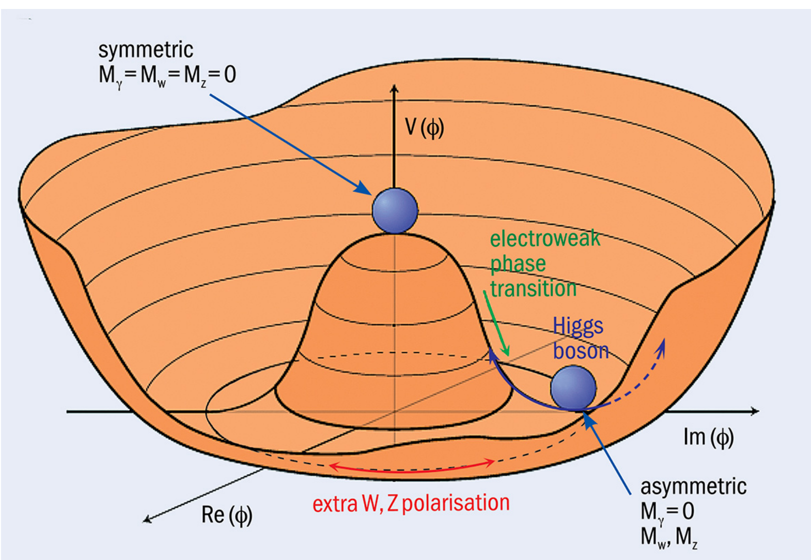
- In 1964, a new, massive boson of spin zero proposed to explain how elementary particles get their masses

F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321

P.W. Higgs, Phys. Rev. Lett. 12 (1964) 123
Phys. Rev. Lett. 13 (1964) 508

G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585

- In the universe, a Higgs "field" pervades all of space, turning mass-less particles moving through it into the massive ones



$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

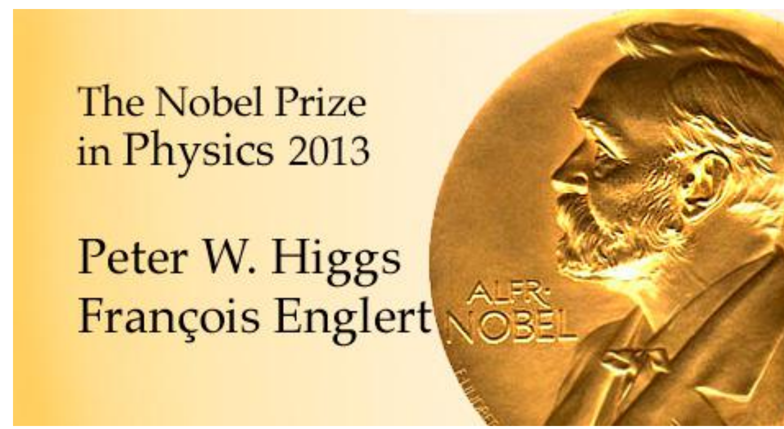
$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

Higgs Discovery

July 4, 2012, the Director General of CERN, Rolf Heuer, declared

"We have now found the missing cornerstone of particle physics. We have a discovery. We have observed a new particle that is consistent with a Higgs boson."

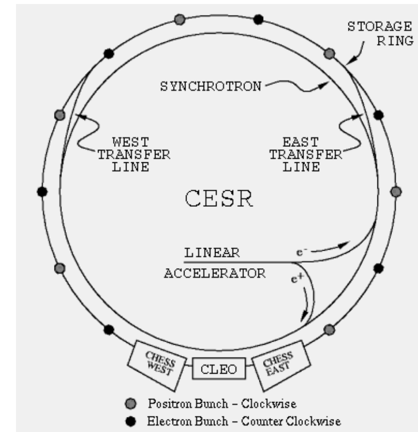


Outline

- Introduction to Higgs particle
- Overview on Higgs experimental searches
  1) Pre-LEP searches
  2) LEP-1 and LEP-2 searches
  3) Tevetron result
  4) LHC discovery
- Higgs property measure
- Observation of H→bb
- Summary and outlook

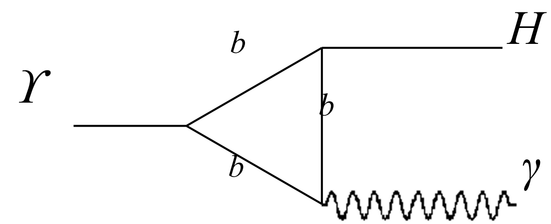
Experiment Names

- DORIS: “Double Ring Storage”, 289m, 1974-2012, DESY
- CESR： the Cornell Electron Storage Ring (CUSB, CLEO）
- Tevatron: Fermilab, 1987-2011, proton-antiproton (CDF, D0)
- LEP： the Large Electron-Positron collider(ALEPH, DLEPHI, OPAL, L3)
- LHC： the Large Hadron Collider (ALICE, ATLAS, CMS, LHCb)

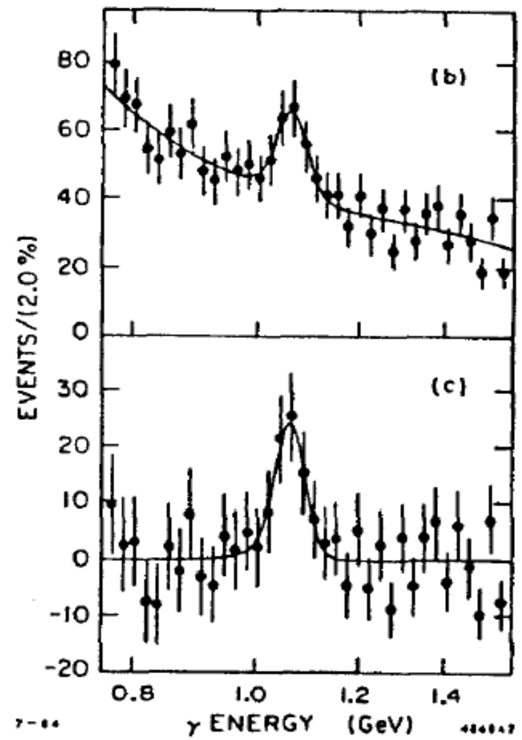


Pre-LEP Era: a false signal in 1984

- Crystal Ball collaboration at the DORIS e^+e^- storage ring at DESY was looking for low-mass Higgs in Upsilon decay: $\Upsilon \rightarrow H+\gamma$



- Early in 1984, a peak in γ energy spectrum was seen, corresponding to a resonance with mass 8.32 GeV. High signal significance: $>5\sigma$ in 2 independent data samples
- Reported at ICHEP 1984 in Leipzig, Germany ; production rate ~2 orders of magnitude larger than SM Higgs prediction
- Signal not confirmed at Cornell CESR; with more DORIS data in late 1984, Crystal Ball signal disappeared



Top: ***inclusive γ spectrum (>8 particles)***
Bottom: ***bkg-subtracted spectrum***

Pre-LEP Era: First Higgs limits

- **CUSB** **collaboration at CESR (Cornell Electron Storage Ring) searched in channel $\Upsilon \rightarrow H + \gamma$: 90% CL exclusion in range 211 MeV < m_H < 5 GeV (1989)**
  Proceedings of ICHEP 1988

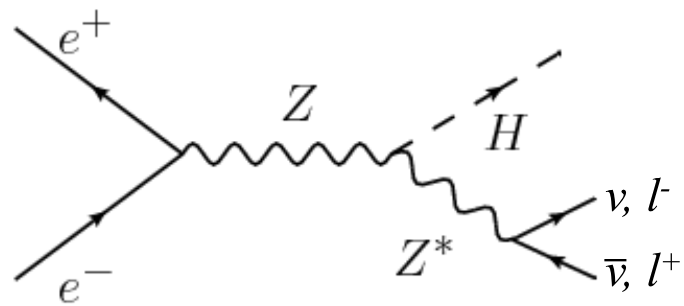
- **SINDRUM** **experiment at the Paul Scherrer Inst. proton cyclotron (Switzerland) searched for Higgs in pion decays: $\pi^+ \rightarrow e^+ + \nu_e + H$, $H \rightarrow e^+e^-$**
  90% CL exclusion in range 10 MeV < m_H < 110 MeV (1989)
  Measurement of the decay $\pi^+ \rightarrow e^+\nu_e e^+e^-$ and search for a light Higgs boson,
  Phys. Lett. B 222, 533

- **CLEO** **collaboration at CESR searched in channel**
  $B \rightarrow K + H^0$, $H^0 \rightarrow$ pair of muons, pions or kaons
  90% CL exclusion in range 0.2 GeV < m_H < 3.6 GeV (1990)
  Search for a neutral Higgs boson in B-meson decay
  Phys. Rev. D. 40, 712

LEP-1: from 1989 to 1995

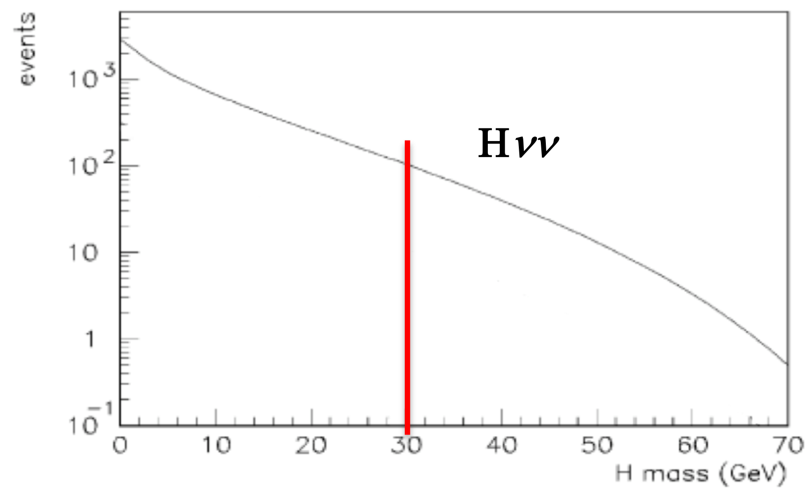
- *On July 14, 1989, the 200th anniversary of the French revolution, the first particles went around LEP, a 27-km ring, at CERN*

- *Plans to search for the Higgs boson at LEP were underway in the early 1980s with the ALEPH, DELPHI, L3 and OPAL detectors. LEP-1 was to operate at the Z pole ($M_Z = 91.188 \pm 0.002$ GeV)*



- *Search in the Higgsstrahlung channels:*
  $e^+e^- \rightarrow Z \rightarrow Hl^+l^-$ and $H\nu\nu$

- *Number of Higgs bosons expected to be produced per 10^6 Z decays at LEP-1 (~100 events at m_H=30 GeV)*



LEP-1: Final Higgs Combination

Number of Z decays collected by the LEP-1 experiments, and 95% CL Higgs exclusions (with full LEP-1 integrated luminosity)

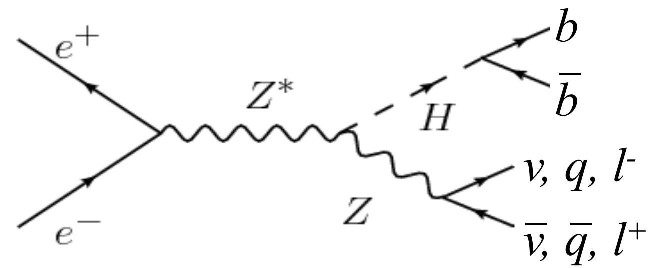
Experiment	Data sample	Had. Z decays [10^6]	Mass limit [GeV]
ALEPH	1989 - 1995	4.5	63.9
DELPHI	1990 - 1993	1.6	58.3
L3	1990 - 1994	3.1	60.1
OPAL	1990 - 1995	4.4	59.6

Higgs physics at LEP-1, Andre Sopczak

Physics Reports 359 (2002) 169, pages 206, 207.

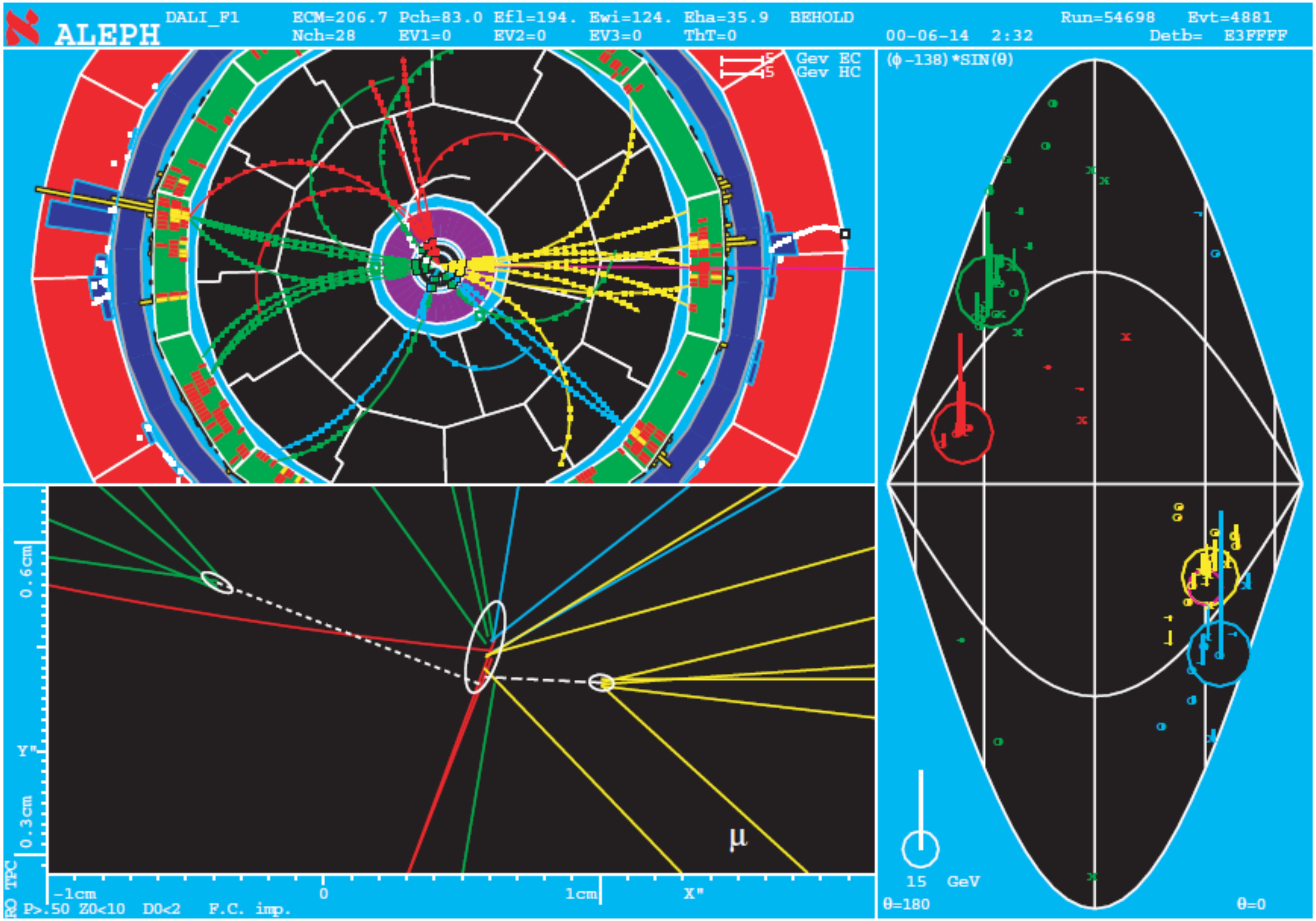
LEP-2: *up to 1999*

- *LEP-2 started in 1995 at √s=130 GeV, going up to 202 GeV by 1999*
- *Most data collected in 1998-99*
  Total: 2461 pb^{-1} (sum of 4 exp.)



- *4-jet channel in ALEPH (and later DELPHI) was the most sensitive*
- *No indication of Higgs production was found up to 1999*
  - 95% CL limit: 107.9 GeV (CERN-EP-2000-055) (ALEPH, DELPHI, L3, OPAL)
- *It was decided to push the machine to even higher collision energies : 206.6 GeV, 536 pb^{-1} in 2000 by 4 experiments*
- *In late June 2000, ALEPH found the first candidate in the 4-jet channel: the so-called candidate (c) (114 GeV, at a center-of-mass energy of 206.6 GeV)*

ALEPH candidate (c) 54698 4881 M=114.3GeV E_{cm} = 206.7 GeV



LEP-2: Final Publication

- **ALEPH**: 'Observation of an excess in the search for the SM Higgs boson at ALEPH'. Phys.Lett. B 495, 1 (2000): An excess of 3σ beyond the background expectation found, consistent with the production of the Higgs boson with a mass near 114GeV/c^2. Much of this excess is seen in the four-jet analyses, where three high purity events are selected (link).

- **DELPHI**: 'Search for the SM Higgs boson at LEP in the year 2000'. Phys. Lett. B 499, 23 (2001): No evidence for a Higgs signal is observed in the kinematically accessible mass range,

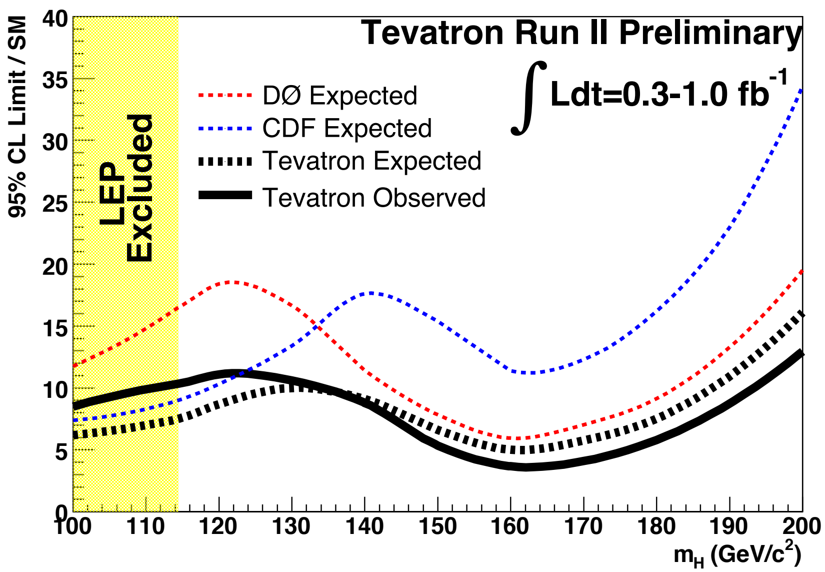
The accelerator was switched off for the last time at 8:00 am on 2 November, 2000

limit on the mass of the standard model Higgs boson of 112.0 GeV is set at the 95% confidence level. The most significant high mass candidate is a Hνν event. It has a reconstructed Higgs mass of 115 GeV and it was recorded at √s = 206.4 GeV. (link).

- **OPAL**: 'Search for the SM Higgs boson in e+e- collisions at √s≈192-209 GeV'. Phys. Lett. B 499, 38 (2001): A lower bound of 109.7 GeV is obtained on the Higgs boson mass at the 95% confidence level. At higher masses, the data are consistent with both the background and the signal-plus-background hypotheses (link).

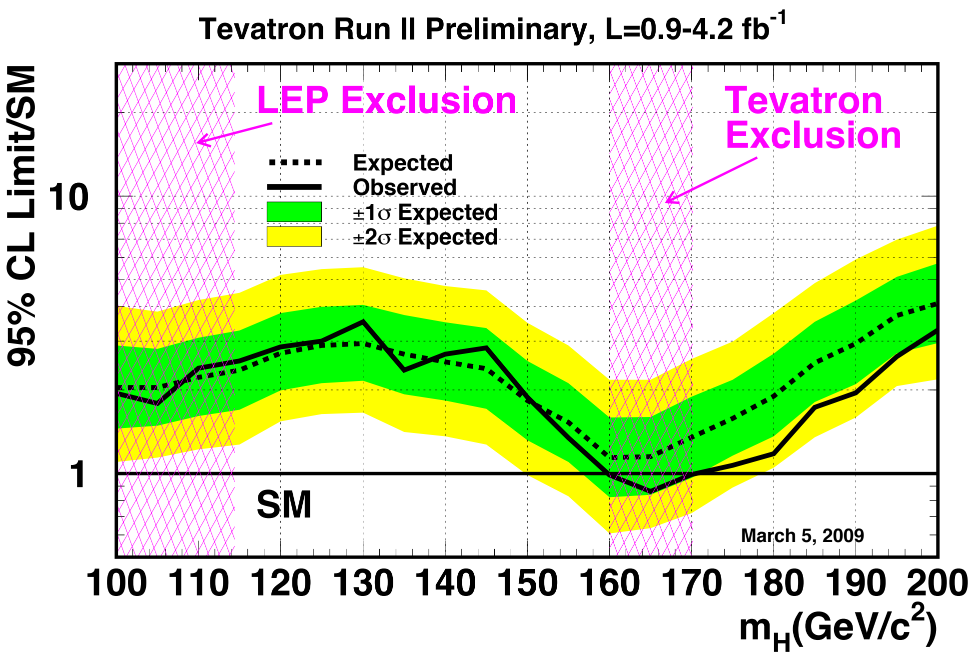
Tevetron 2009: First Exclusion

- *Mid-2005: first fb^{-1}*
- *2006: first CDF+D0 limits:*



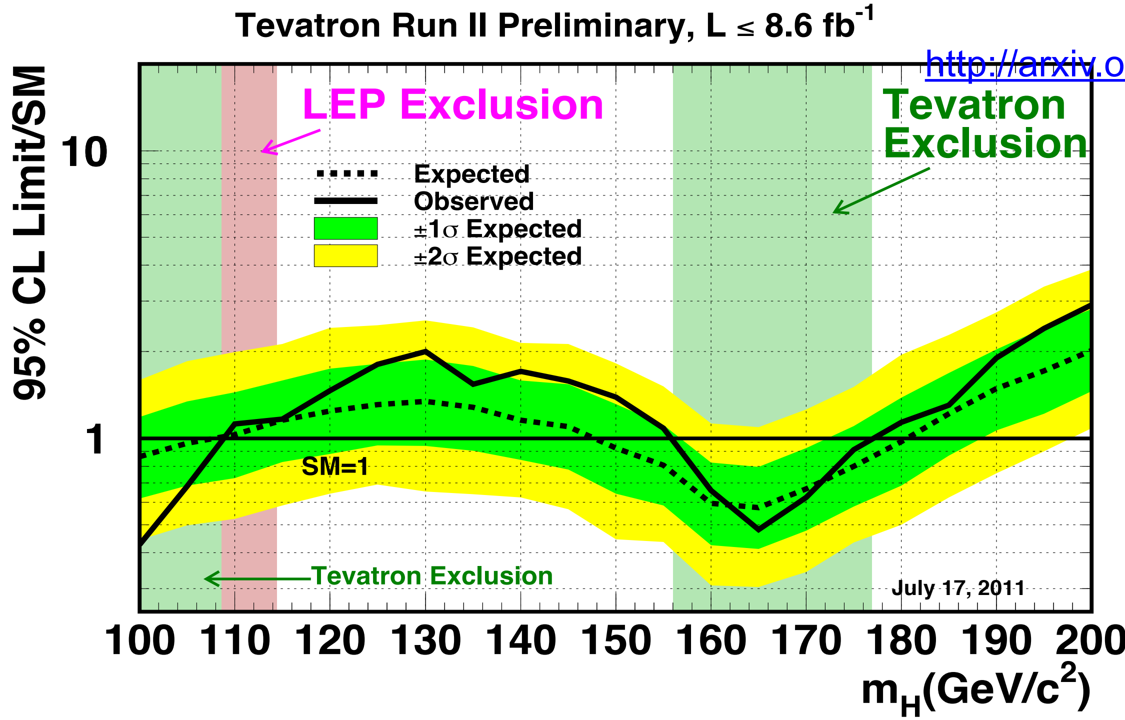
- *Limits: 10.4 (3.8) times SM @ m_H=115(160) GeV*
- *CDF Note 8384, D0 Note 5227*

- *Winter 2009: First mass range excluded after LEP (at 95%CL): $160<m_H<170$ GeV* arXiv:0903.4001 [hep-ex]
- *Press release on March 13, 2009 (link)*



- *Production:* $q\bar{q}\to W/ZH$, $gg\to H$, $q\bar{q}\to q'\bar{q}'H$ (VBF)
- *Decay:* $H\to bb$, $H\to W^+W^-$, $H\to\tau^+\tau^-$, $H\to\gamma\gamma$

TEVATRON EPS-HEP 2011 (July)



http://arxiv.org/abs/1107.5518

Channels:

- ***Production:*** $\bar{q}q \to W/Z\ H$, $gg \to H$, $\bar{q}q \to \bar{q}'q'H$ ***(VBF)***
- ***Decay:*** $H \to b\bar{b}$, $H \to W^+W^-$, $H \to ZZ$, $H \to \tau^+\tau^-$, $H \to \gamma\gamma$
- ***165 final states (71 CDF, 94 D0)***

- ***Excess in 125<m_H<155 GeV (approx. 1 sigma)***
- ***95% CL exclusion: 156-177 GeV (expected: 148-180 GeV)***

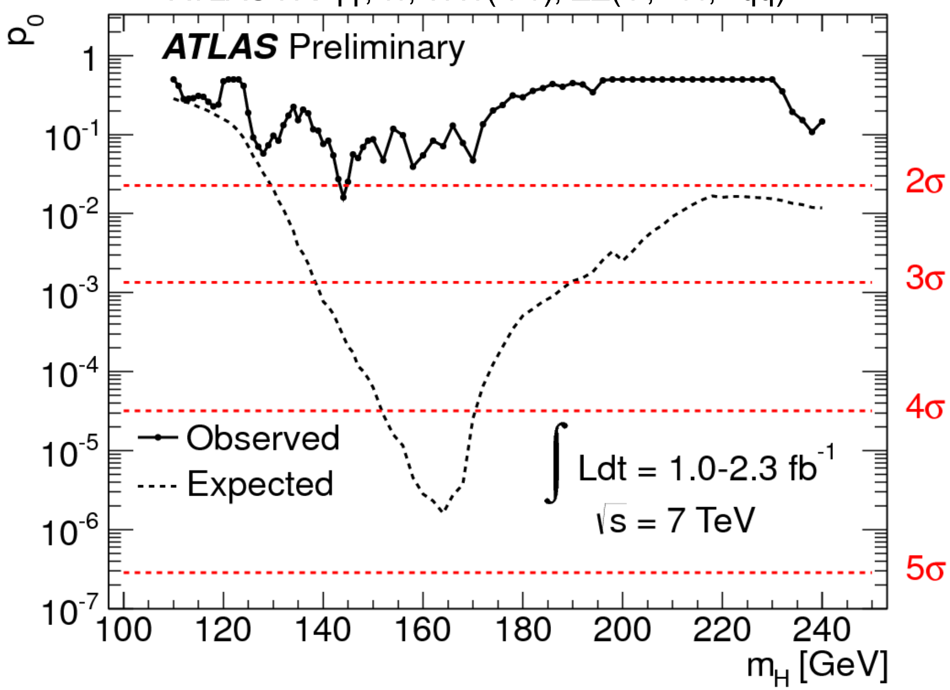
LHC-Era: EPS 2011 (July)   LP 2011 (August)

Both ATLAS and CMS see >2σ excess at low mass in H→WW→lνlν channel

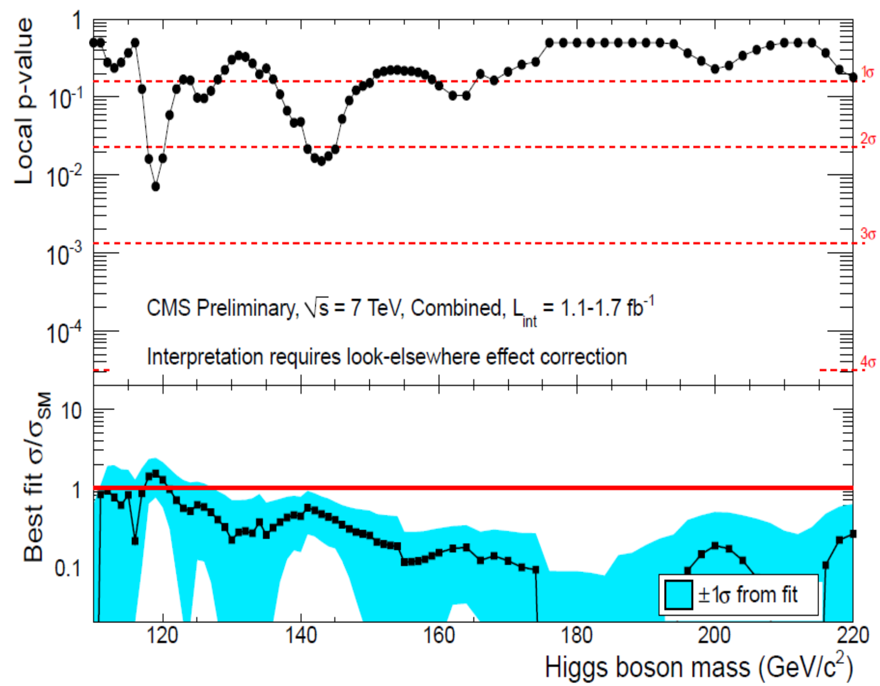
> ***p_0: probability that the background fluctuates to the observed data (or higher)***

p_0 = Local p-value

ATLAS H→γγ, ττ, WW(lνlν), ZZ(4l, llνν, llqq)



H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)



ATLAS (LP11)

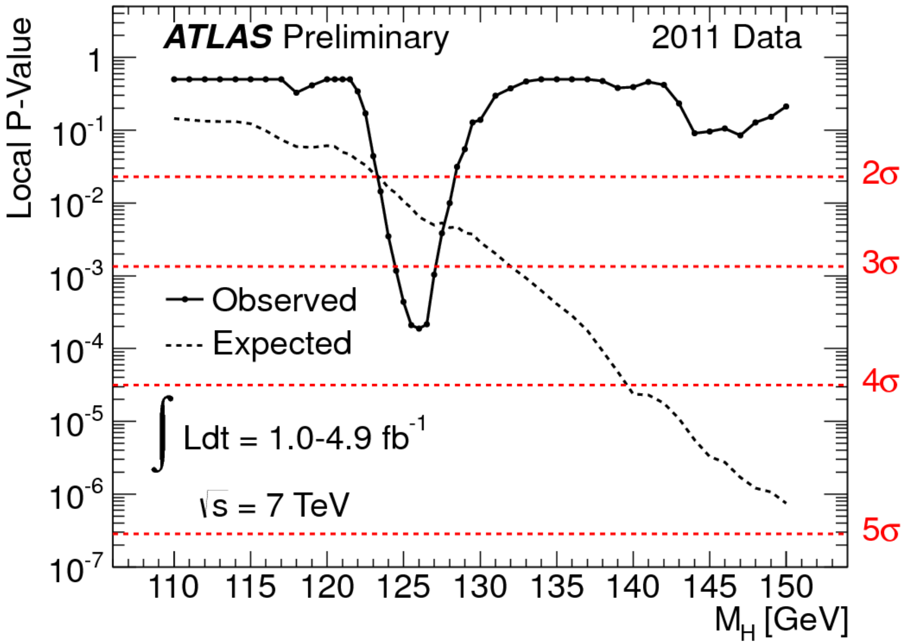
largest local excess: 2.1σ at 145 GeV

CMS (LP11)

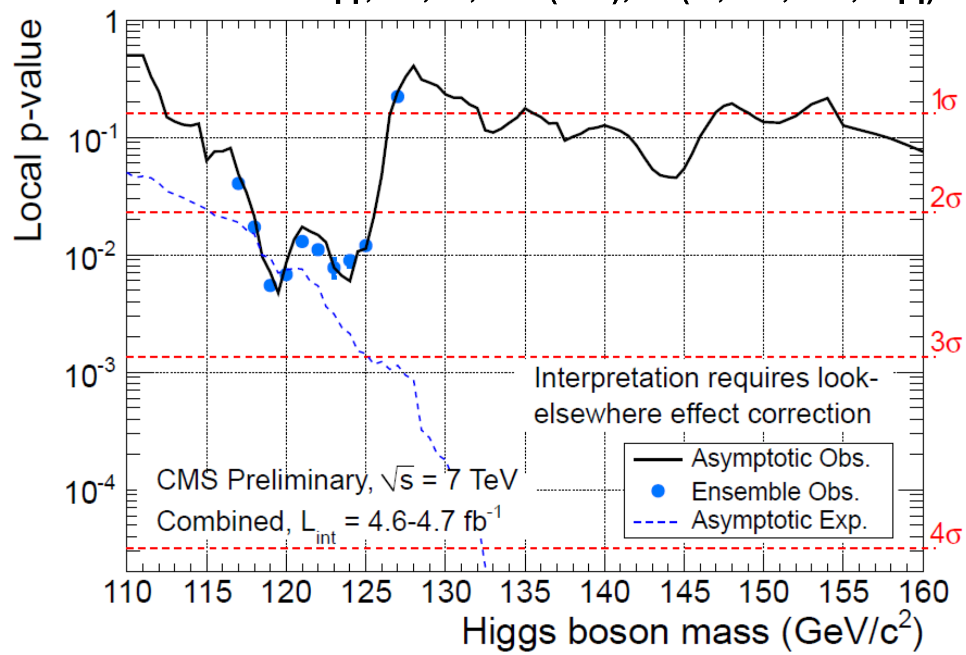
largest local excess: 2.3σ at 120 GeV

LHC Era: CERN Council (Dec 2011)

H→γγ, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq, llbb)
red: 4.9 fb^{-1} green: 1 fb^{-1}, black: 2 fb^{-1}



H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)



Largest local excess: 3.6σ at 126 GeV

Largest local excess: 2.6σ at ~120 GeV

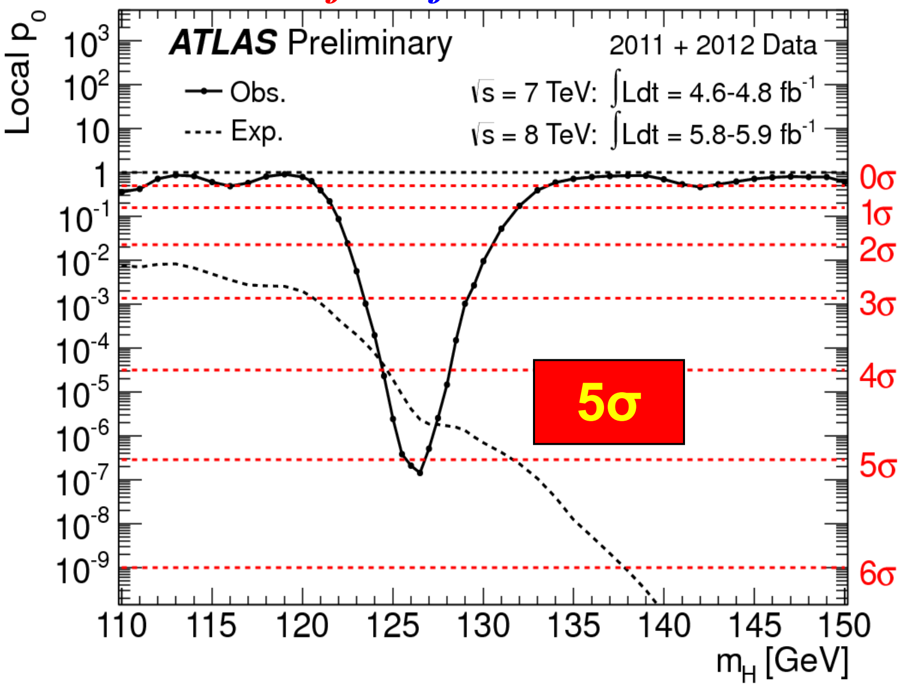
Fabiola Gianotti

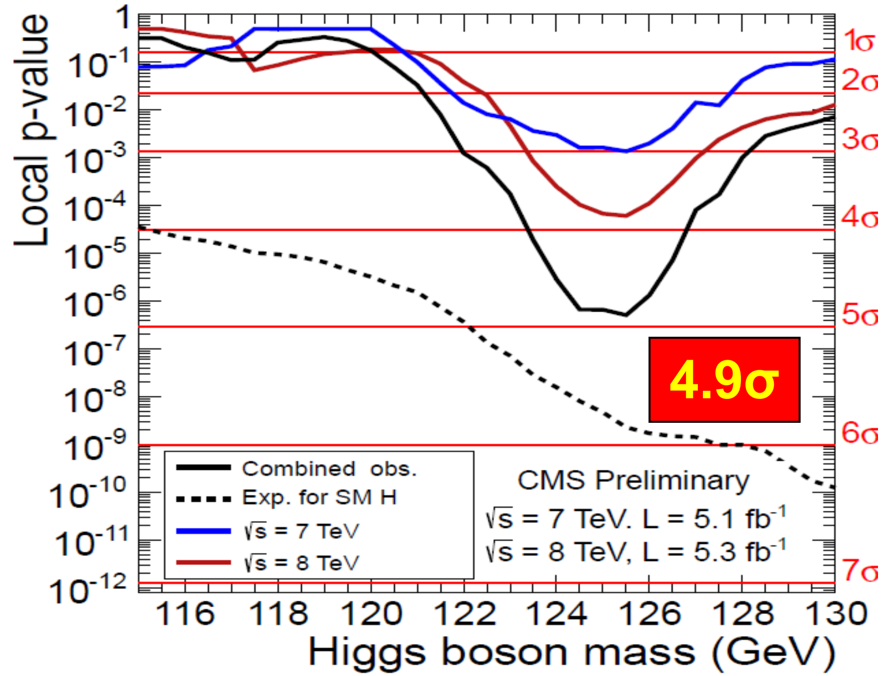
Guido Tonelli

LHC Era: July 4, 2012 and ICHEP 2012

γγ, 4l updated with ~6 fb^{-1} of 8 TeV data

All channels updated with ~5 fb^{-1} of 8 TeV data





Largest local excess:

5σ at m_H = 126.5 GeV

With LEE in 110 < m_H < 150 GeV, global significance: 4.3σ

Largest local excess:

4.9σ around m_H = 125 GeV (using H→γγ and H→4l: 5.0σ)

With LEE in 110 < m_H < 145 GeV, global significance: 4.4σ

LHC Era: The discovery of the Higgs boson

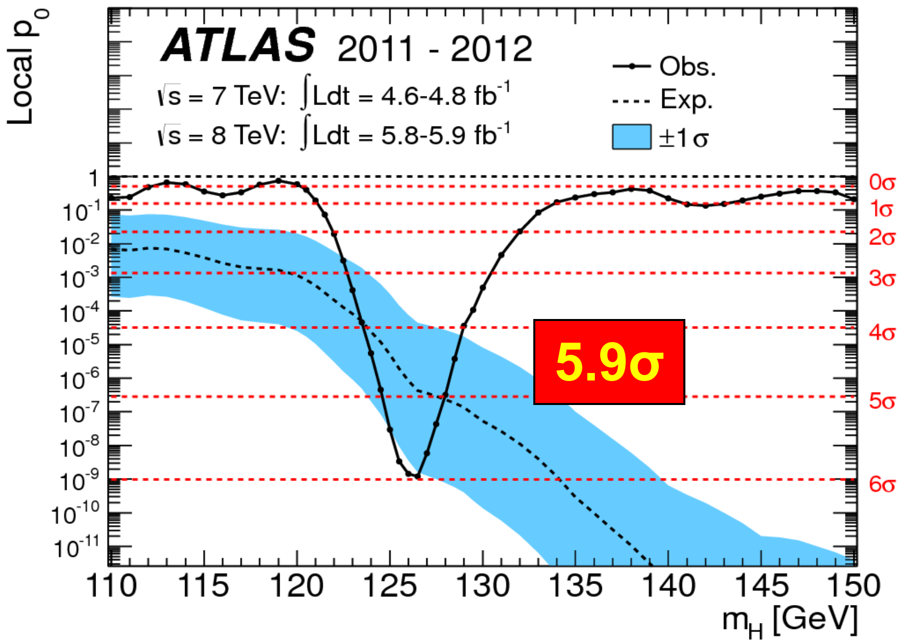
July 4 2012, "Discovery!"

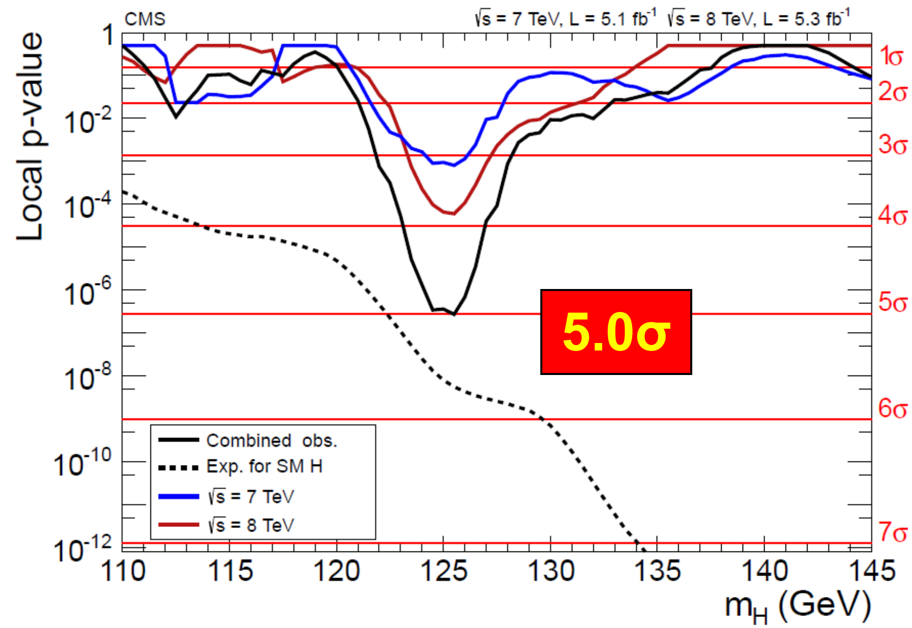
LHC Era: July 4, 2012

On July 4, 2012 the Higgs working group had a celebratory drink.

LHC ERA: July 2012 publications

On July 31, 2012
ATLAS and CMS submitted papers to Physics Letters B.
ATLAS added 2012 data to the H→WW→ lvlv





ATLAS [PLB 716 (2012) 1-29](), ***Sept 17 (2012)***

Largest local excess:
5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lvlv, lvqq), ZZ(4l, llvv, llqq)

CMS [PLB 716 (2012) 30-61](), ***Sept 17 (2012)***

Largest local excess:
5.0σ at m_H= 125.5 GeV

H→γγ, bb, ττ, WW(lvlv), ZZ(4l, llττ, llvv, llqq)

The Party is OVER?

What to do after the discovery?

Outline

- ➢ Introduction to Higgs particle
- ➢ Overview on Higgs experimental searches
- ➢ Higgs property measurements at ATLAS
- ➢ Observation of H→bb
- ➢ Summary and outlook

Status: June 2020

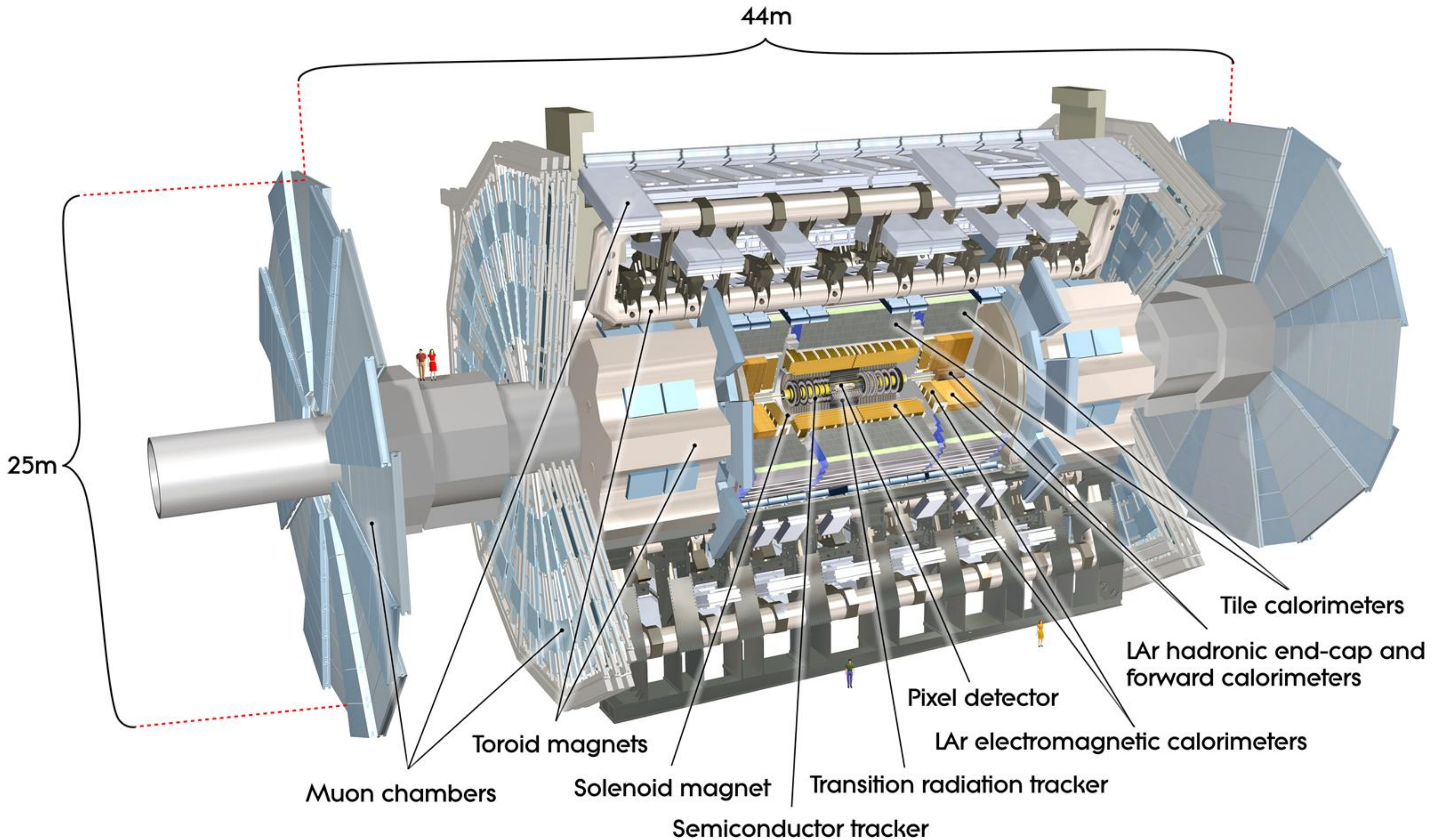
Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

ATLAS Collaboration

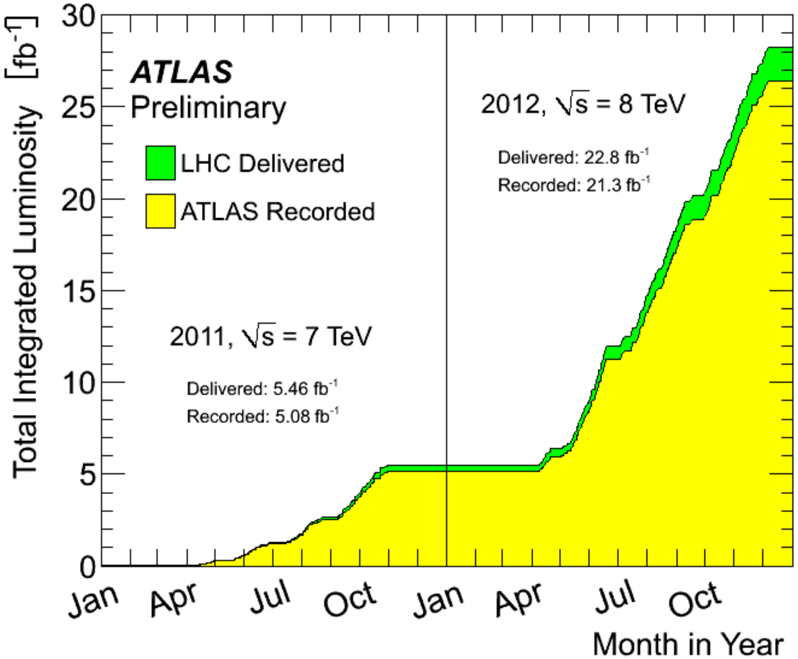
181 institutions (237 institutes) from 38 countries

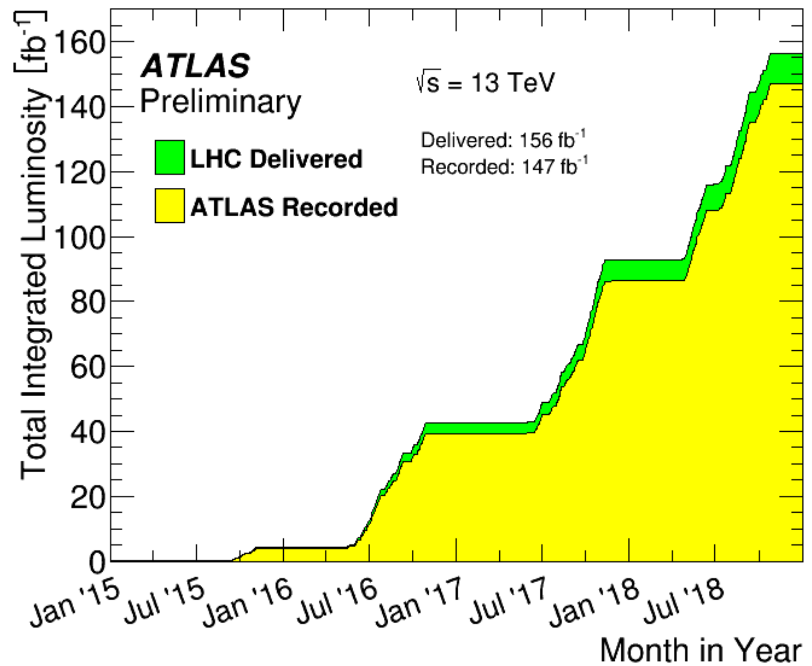
ATLAS EXPERIMENT

ATLAS Detector



ATLAS Data Samples





- Run-1 data of 25 fb^{-1}: 7 TeV pp collisions in 2011, 8 TeV in 2012
- Run-2 data of 140 fb^{-1}: 13 TeV pp collisions 2015-2018

Where it from?

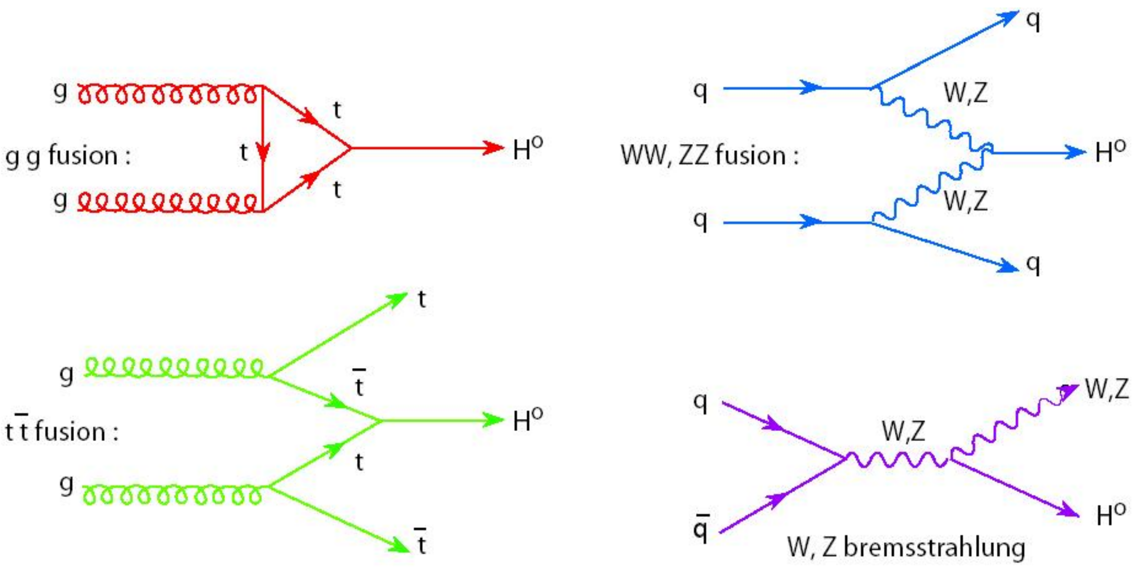
Where it go?

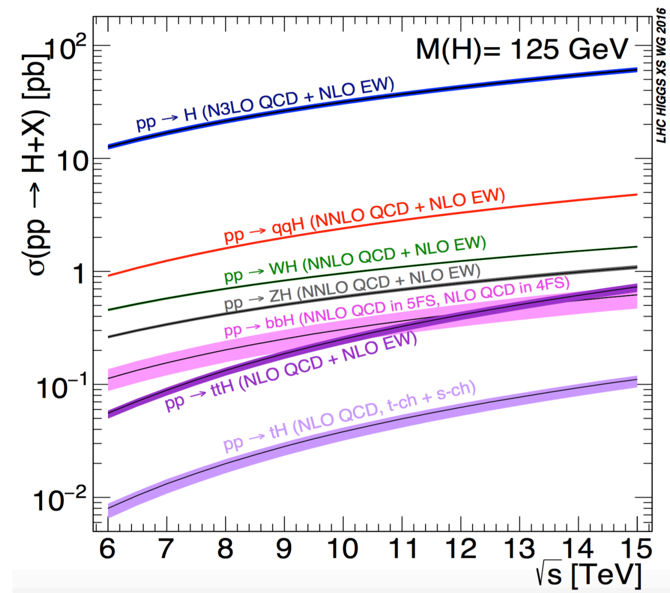
HIGGS

What is it?

- Mass
- Width
- Spin
- CP
- Couplings

Higgs Production @LHC





2012-08-14
Higgs discovery
Phys. Lett. B 716 (2012) 1-29

2018-07-24
ttH observation
Phys. Lett. B 784 (2018) 173

2020-07-07
ZH observation
arXiv:2007.02873

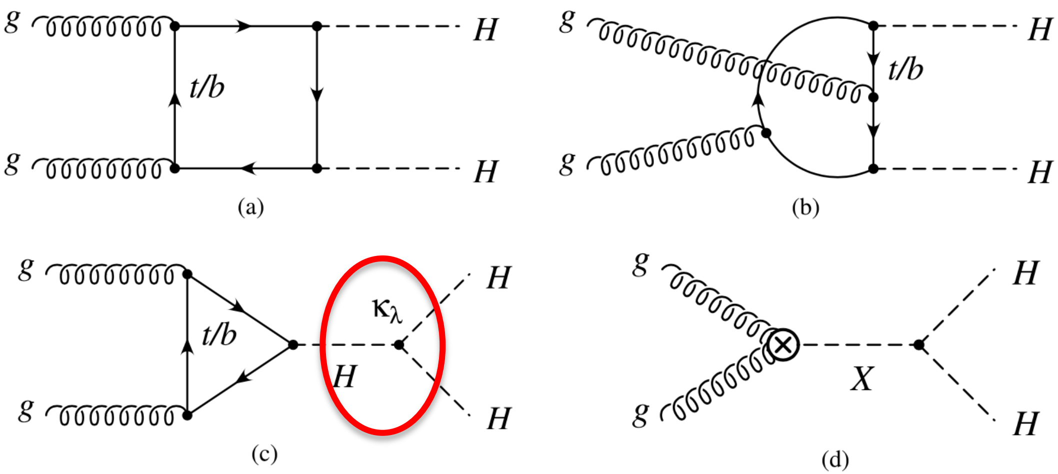
WH
bbH
tH

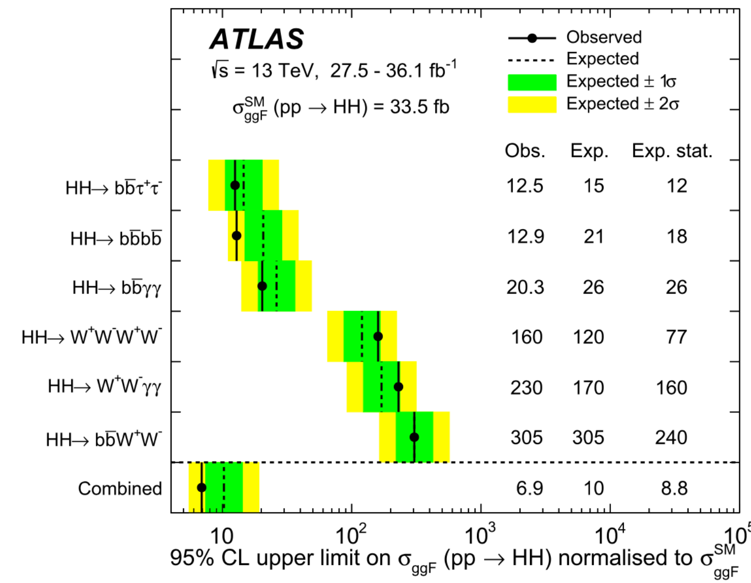
2016-08-05
VBF observation
JHEP 08 (2016) 045

2018-09-14
VH observation
Phys. Lett. B 786 (2018) 59

Di-Higgs Production

[Phys. Lett. B 800 (2020) 135103]





Prospect study with 3000/fb at 14 TeV

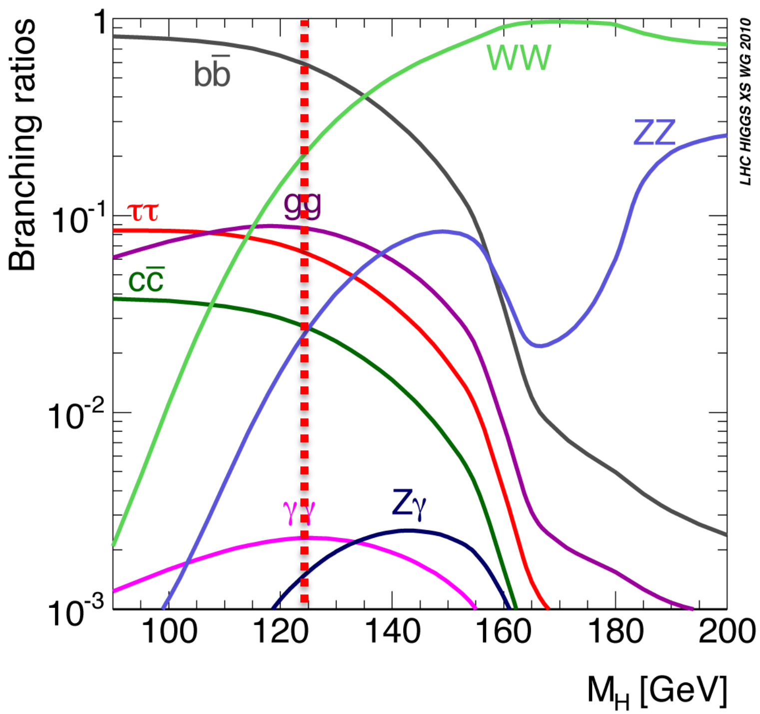
[ATL-PHYS-PUB-2018-053]

Channel	Statistical-only	Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

Scenario	1σ CI	2σ CI
Statistical uncertainties only	$0.4 \le \kappa_\lambda \le 1.7$	$-0.10 \le \kappa_\lambda \le 2.7 \cup 5.5 \le \kappa_\lambda \le 6.9$
Systematic uncertainties	$0.25 \le \kappa_\lambda \le 1.9$	$-0.4 \le \kappa_\lambda \le 7.3$

Final state	Allowed κ_λ interval at 95% CL	
	Obs.	Exp.
$b\bar{b}b\bar{b}$	$-10.9 - 20.1$	$-11.6 - 18.8$
$b\bar{b}\tau^+\tau^-$	$-7.4 - 15.7$	$-8.9 - 16.8$
$b\bar{b}\gamma\gamma$	$-8.1 - 13.1$	$-8.1 - 13.1$
Combination	$-5.0 - 12.0$	$-5.8 - 12.0$

Higgs Decay



Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

2013-08-13
H→γγ: 7.4σ (4.3σ)
H→ZZ*: 6.6σ (4.4σ)
Phys. Lett. B 726 (2013) 88-199

2015-07-16
H→WW*: 6.1σ (5.8σ)
Phys. Rev. D 92, 012006 (2015)

2016-08-05
H→ττ: 5.5σ (5.0σ)
JHEP 08 (2016) 045

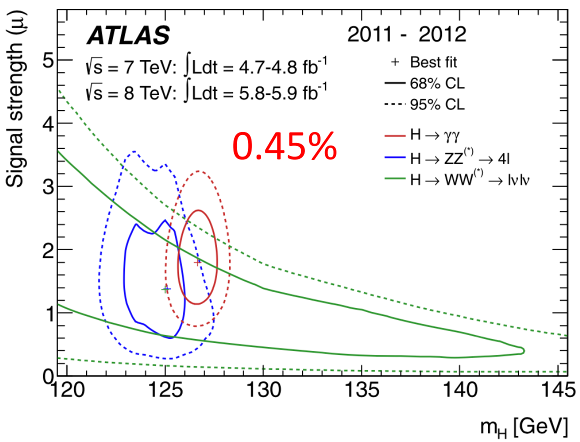
2018-09-14
H→bb: 5.4σ (5.5σ)
Phys. Lett. B 786 (2018) 59

H→Zγ
H→cc
H→gg
H→μμ
H→??

Higgs Mass Measurement

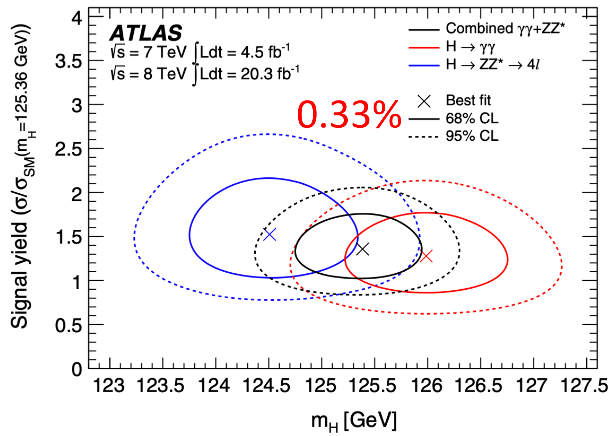
[Phys. Lett. B 716 (2012) 1-29]

$126.0 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (sys) GeV}$



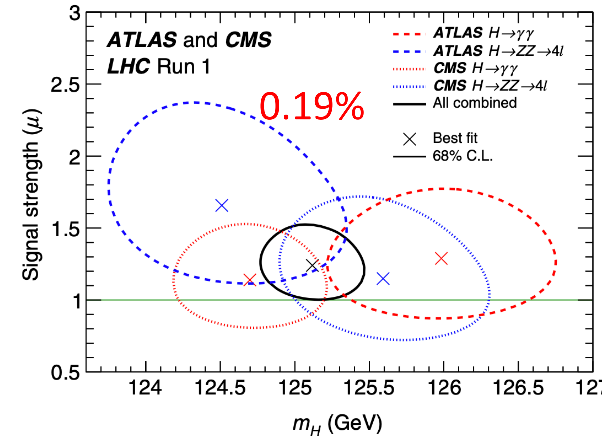
[Phys. Rev. D. 90 (2014) 052004]

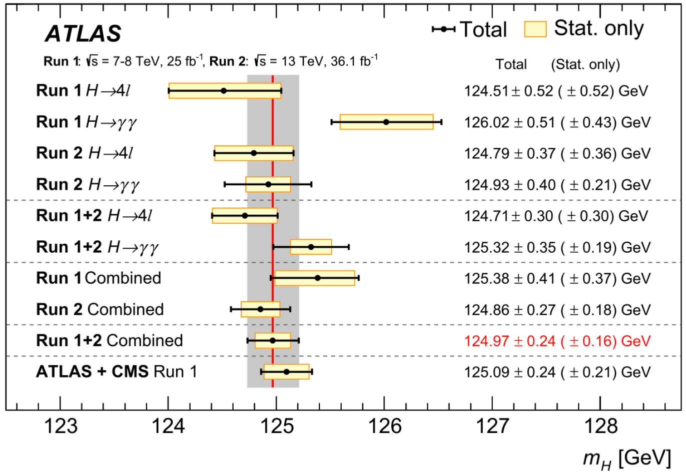
$125.36 \pm 0.37\text{(stat)} \pm 0.18\text{(syst) GeV}$



[Phys. Rev. Lett. 114 (2015) 191803]

$125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$





[Phys. Lett. B 784 (2018) 345-366]

TLAS Run-1 + Run-2 (15-16)

$$m_H = 124.97 \pm 0.24 \text{ GeV}$$

0.19%

With full Run-2 datasets, the ATLAS and CMS combination shall provide more precise result on Higgs mass

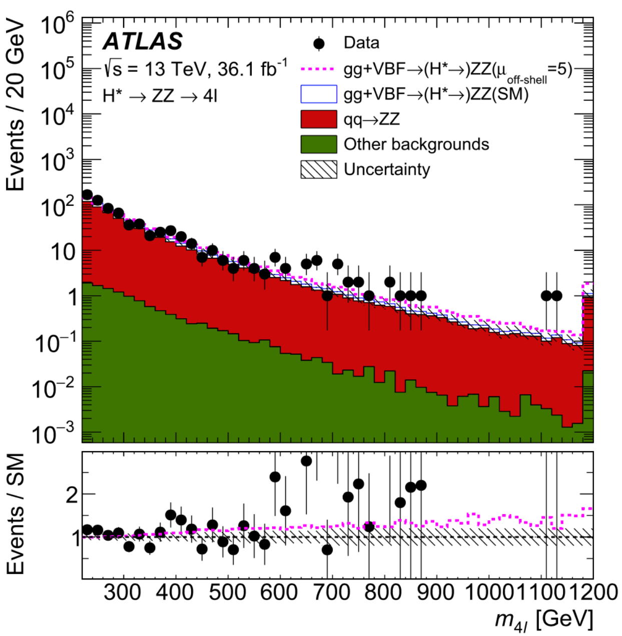
Higgs Width from H→ZZ

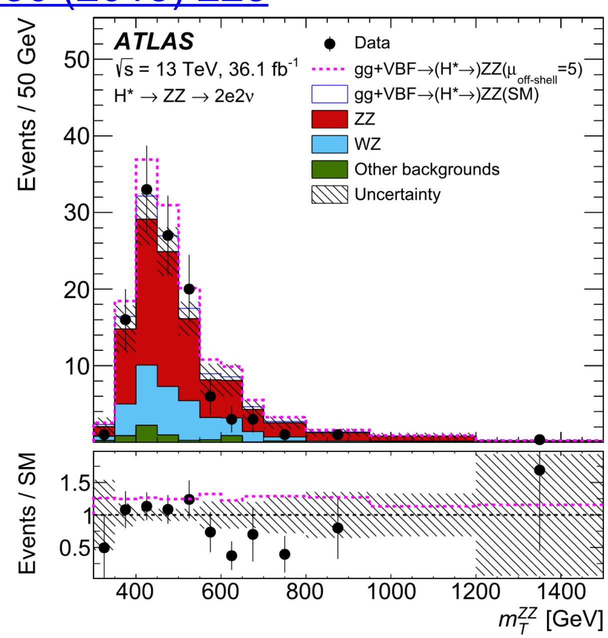
$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}}$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

- Assume that the on- shell and off-shell coupling modifiers are the same
- Using 36.1 fb^{-1} pp collision
- 95% CL upper limit on total width:
  - Observed: 14.4 MeV
  - Expected: 15.2 MeV

Phys. Lett. B 786 (2018) 223





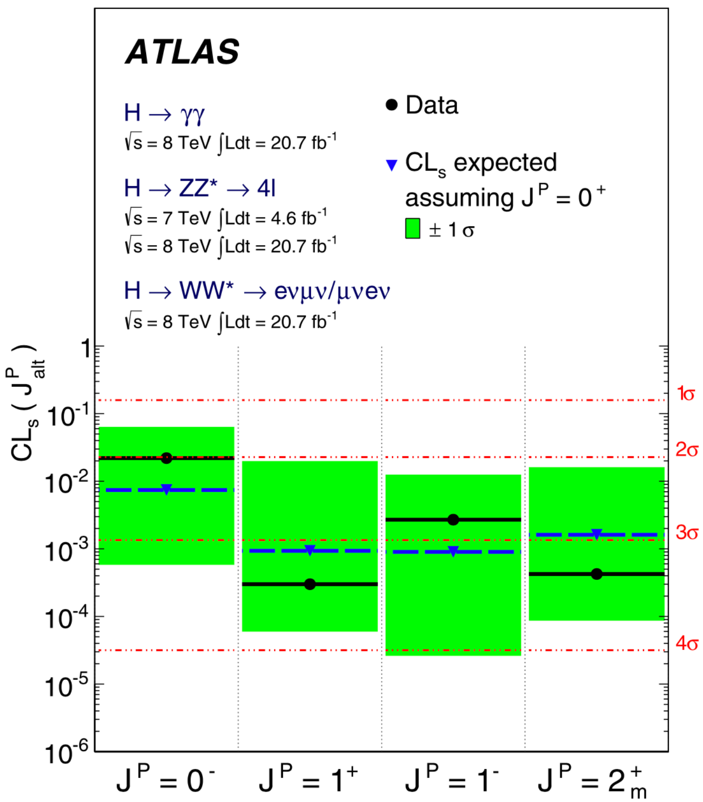
CMS

- HIG-18-002
- Measurement in 4-lepton final state
- Incorporates:
  - 80.2 fb^{-1} of 13 TeV p+p collisions
  - Combines with 7 and 8 TeV Run-I data
- Width:
  - Observed: $3.2^{+2.8}_{-2.2}$ MeV
  - Expected: $4.1^{+5.0}_{-4.0}$ MeV

Higgs CP measurement

$$\tilde{q} = \log \frac{\mathcal{L}\left(J^P_{\mathrm{SM}}, \hat{\hat{\mu}}_{J^P_{\mathrm{SM}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{SM}}}\right)}{\mathcal{L}\left(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}}\right)}$$

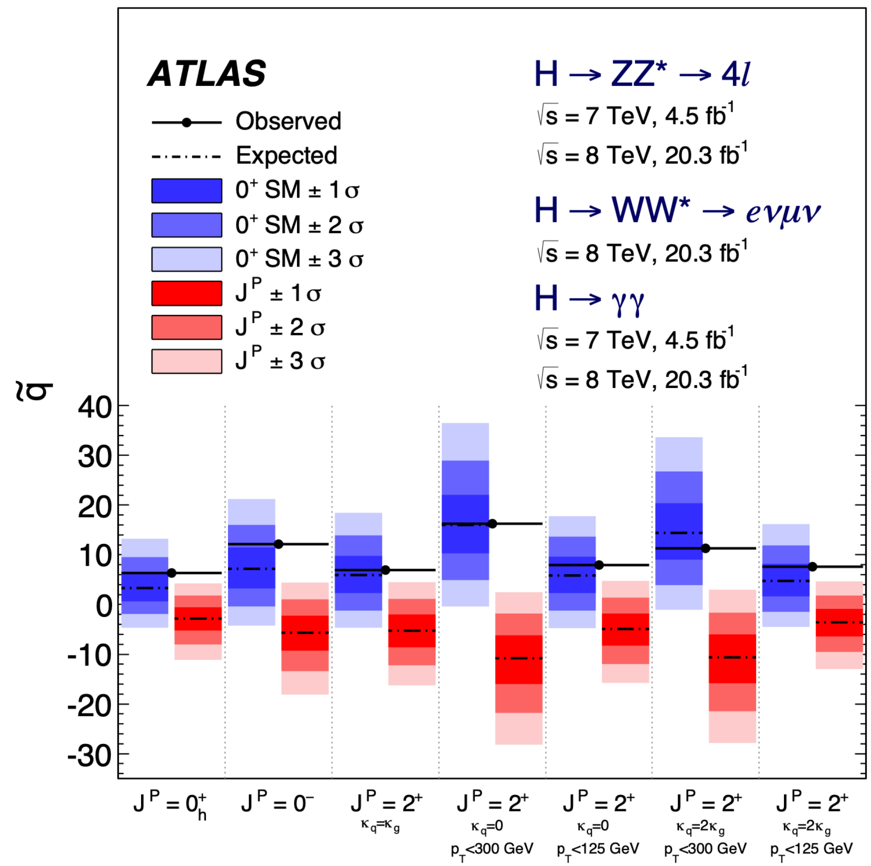
Phys. Lett. B 726 (2013) 120-144



$$\mathrm{CL_s}\left(J^P_{\mathrm{alt}}\right) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}.$$

Excluded at confidence levels above 97.8%

Eur. Phys. J. C75 (2015) 476



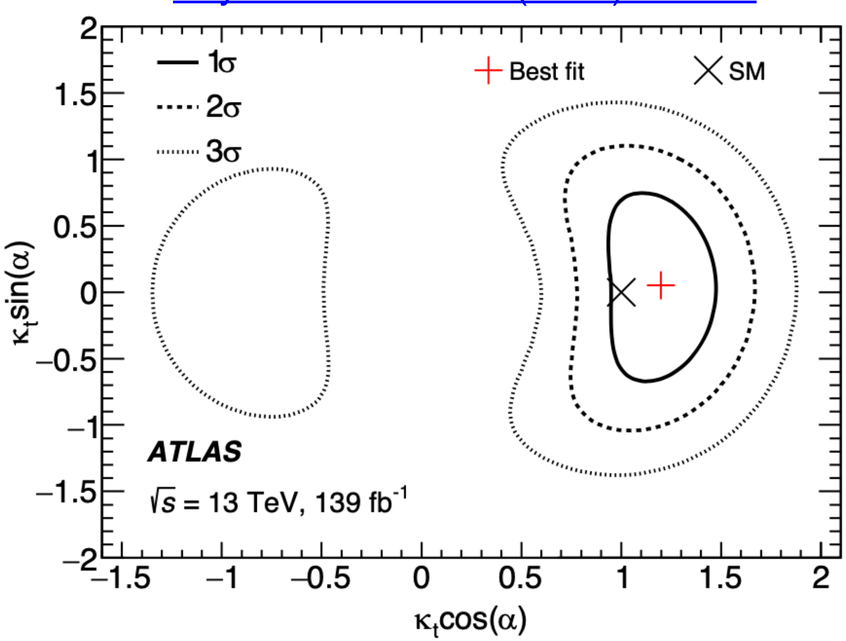
All alternative hypotheses rejected at a >99.9% CL in favor of the SM hypothesis

Higgs CP Mixing

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

- CP even: $\alpha=0$, $\kappa_t = 1$
- CP odd: $\alpha=90^o$

Phys. Rev. Lett. 125 (2020) 061802

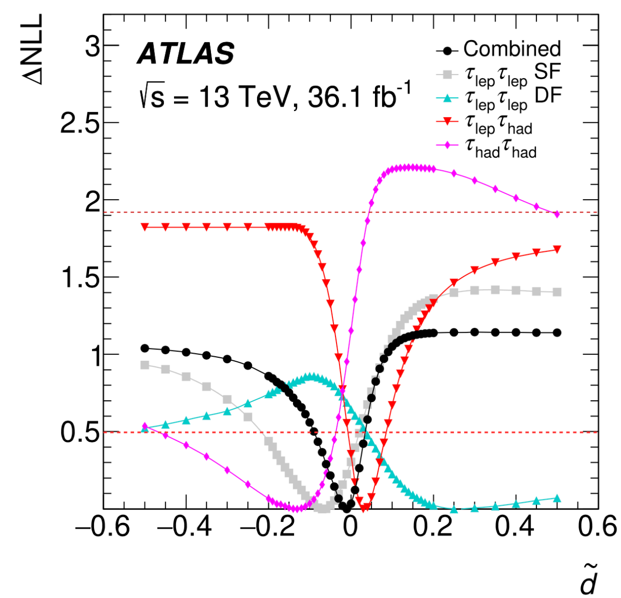


$|\alpha| > 43°$ is excluded at 95% CL

$$\mathcal{M} = \mathcal{M}_{SM} + \tilde{d}\cdot\mathcal{M}_{CP\text{-}odd}$$

$$\mathcal{O}_{opt} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{CP\text{-}odd})}{|\mathcal{M}_{SM}|^2}$$

Phys. Lett. B 805 (2020) 135426

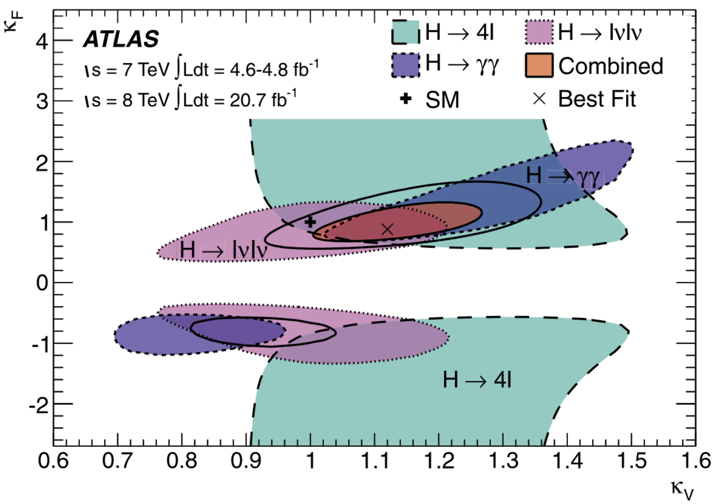


- Observed interval at 68% CL:

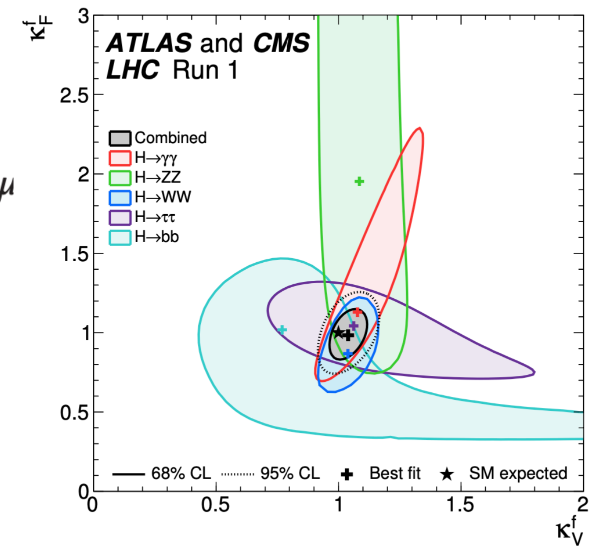
$\tilde{d} \in [-0.090, 0.035]$

Higgs Coupling

Phys. Lett. B 726 (2013) 88-199



JHEP 08 (2016) 045



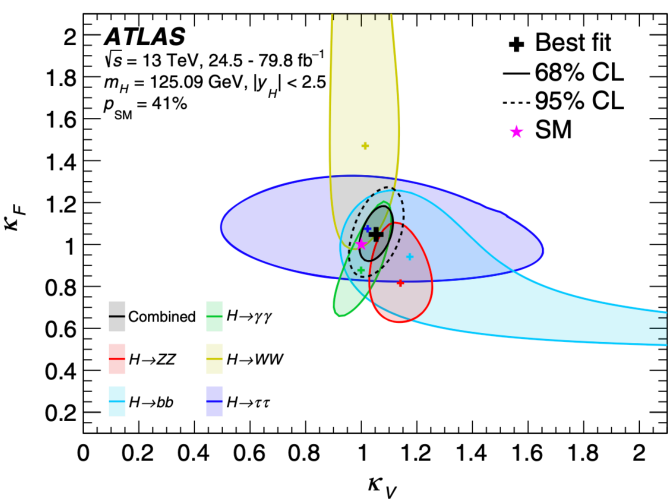
$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

$$\kappa_F \in [0.76, 1.18],$$

$$\kappa_V \in [1.05, 1.22]$$

Phys. Rev. D 101 (2020) 012002



$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

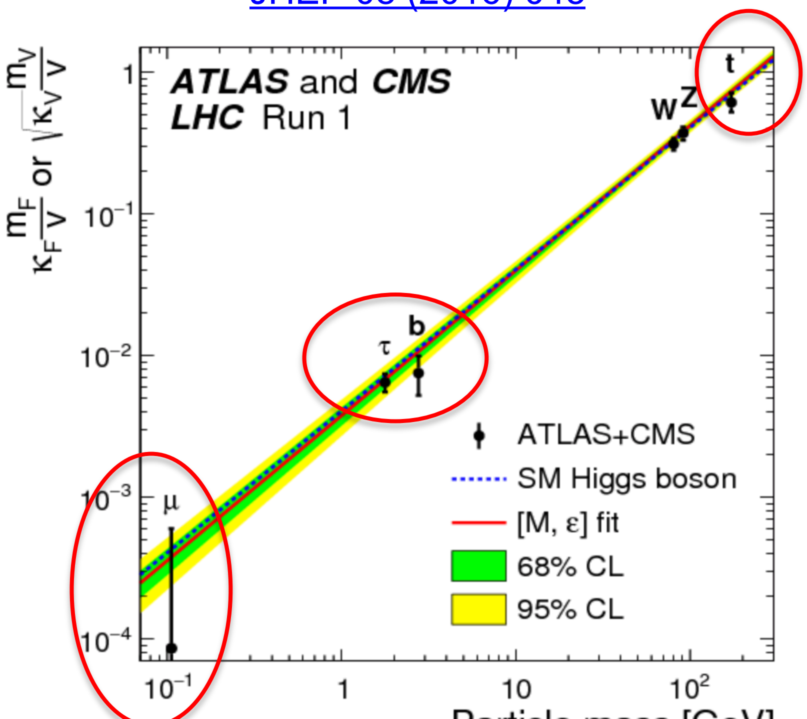
Both parameters agree with the SM prediction within 1 sigma band

希格斯粒子与玻色子/费米子的耦合强度的测量精度

$$\kappa_{F,i} \cdot \ y_{F,i}/\sqrt{2} = \kappa_{F,i} \cdot \ m_{F,i}/v$$

$$\sqrt{\kappa_{V,i} \cdot \ g_{V,i}/2v} = \sqrt{\kappa_{V,i}} \cdot \ m_{V,i}/v$$

JHEP 08 (2016) 045

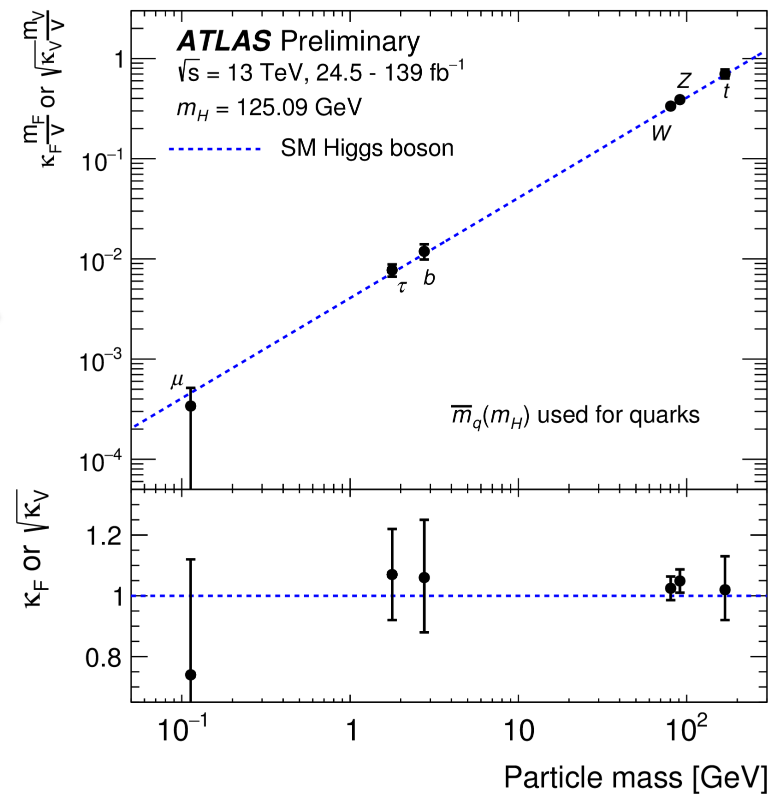


H→μμ results:

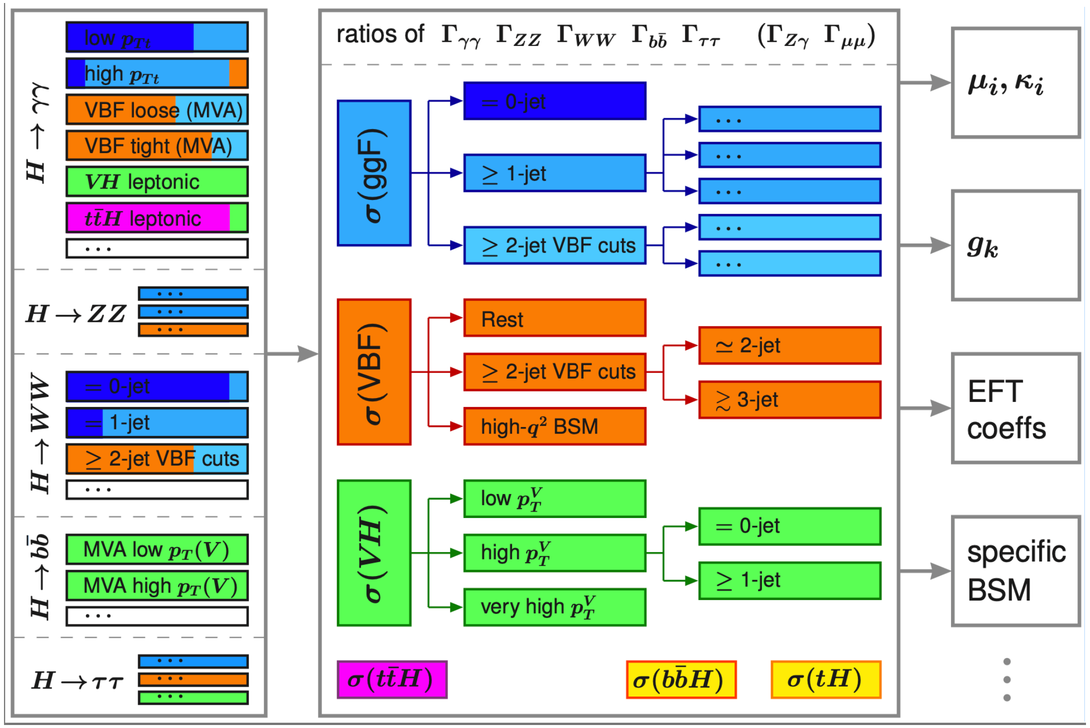
ATLAS-CONF-2019-028

The rest results (<79.8/fb):

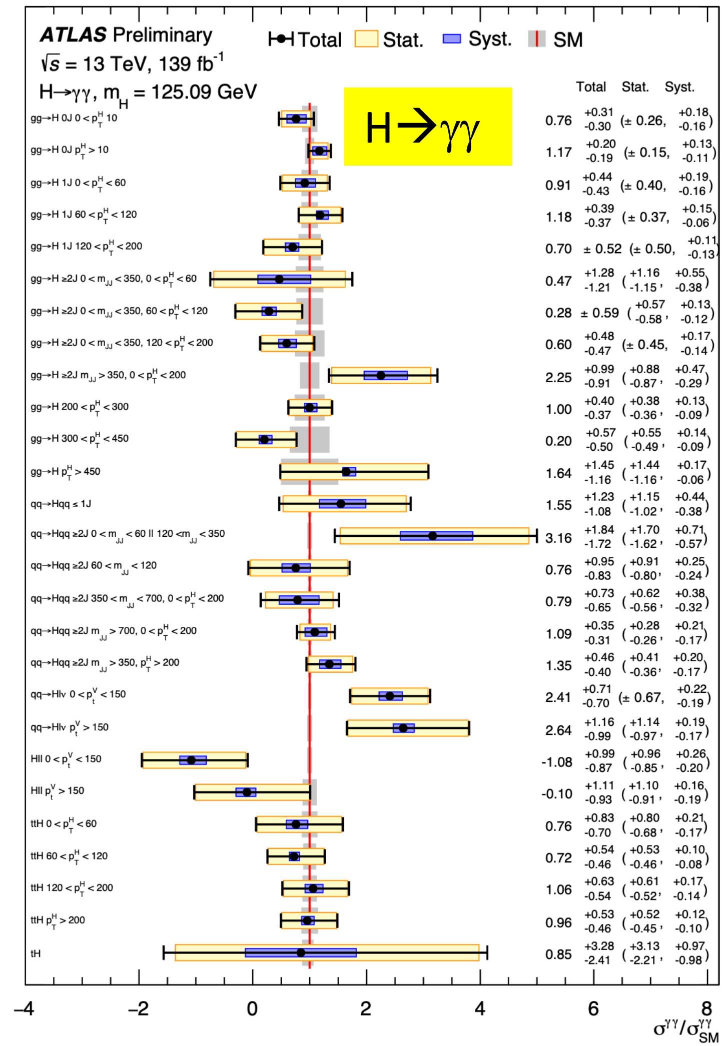
ATLAS-CONF-2019-005



Higgs STXS Measurement



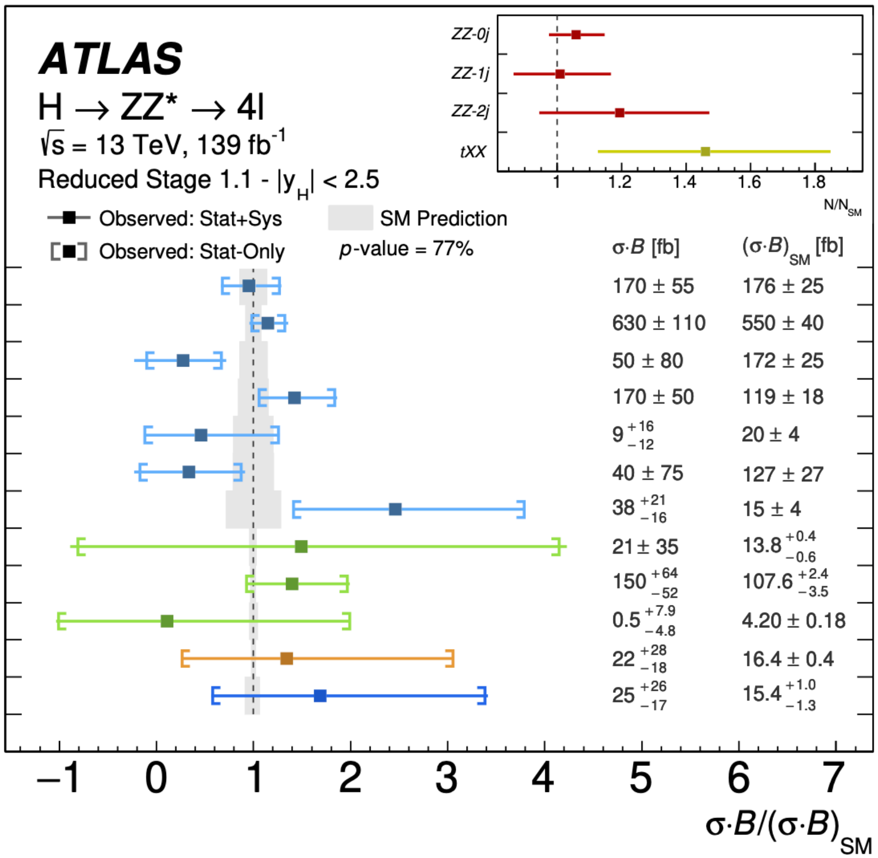
ATLAS-CONF-2020-026



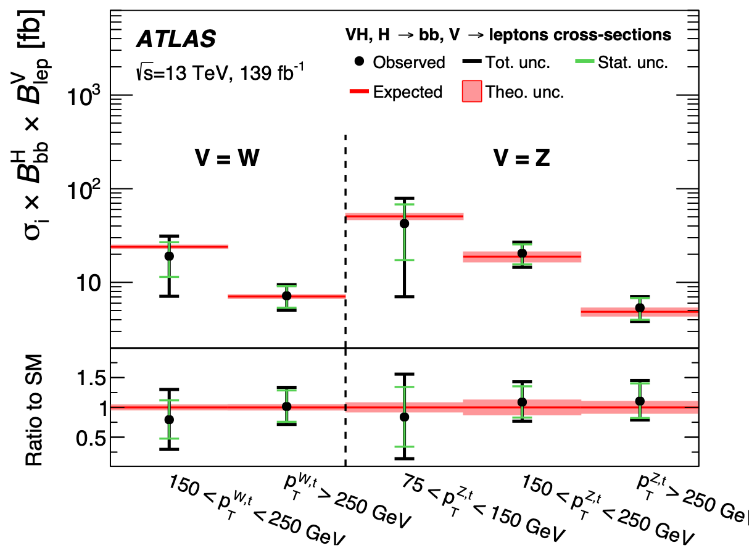
- Minimizing the dependence on theo. uncertainties
- Maximizing experimental sensitivity
- Isolation of possible BSM effects
- Minimizing the number of bins without loss of experimental sensitivity

Higgs STXS Measurment

H→ZZ arXiv:2004.03447



VH, H→bb arXiv:2007.02873

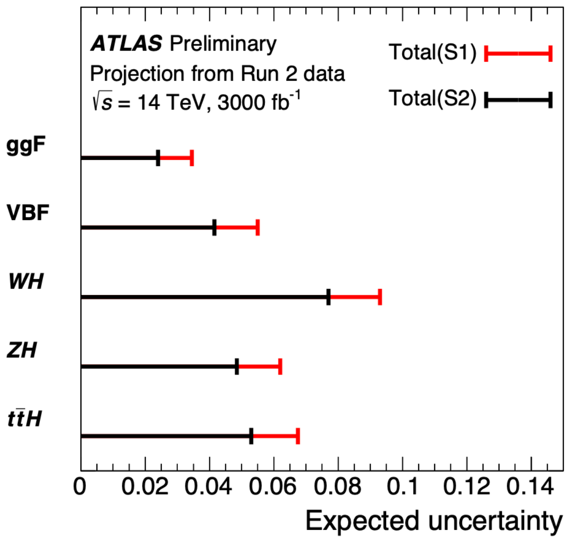


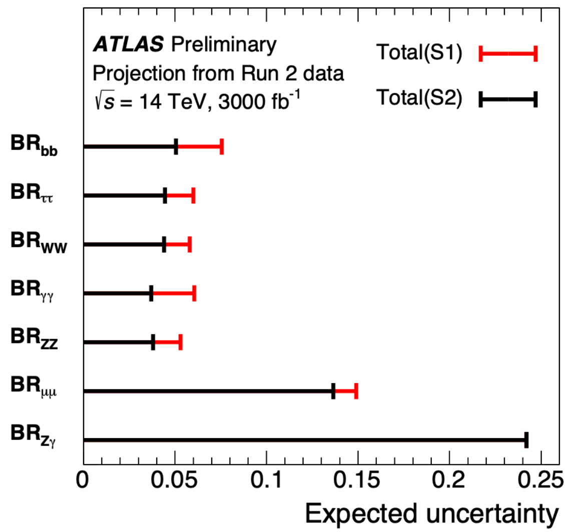
More statisics needed to reduce the uncertainty

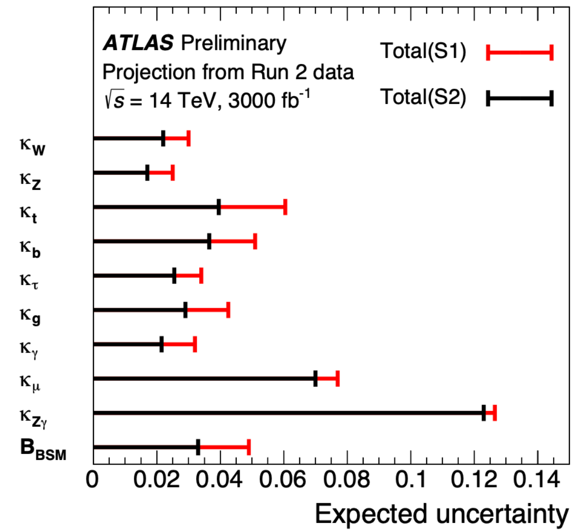
Higgs Prospect @HL-LHC

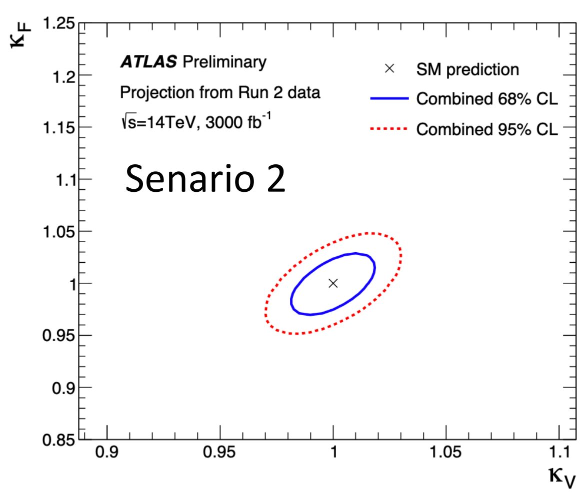
S1: scenario 1 with sys. same as Run-2; S2: sys. halved

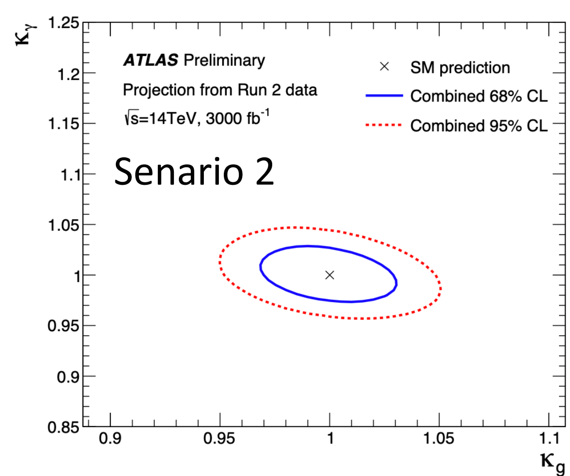
ATL-PHYS-PUB-2018-054

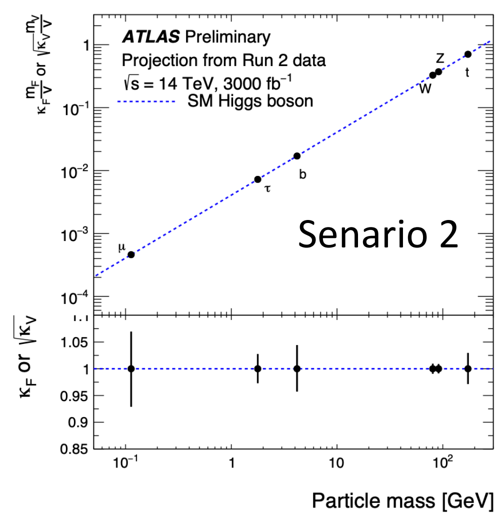












Outline

- Introduction to Higgs particle
- Overview on Higgs experimental searches
- Higgs property measurements
- Observation of $H \rightarrow bb$ at ATLAS
- Summary

Contents lists available at ScienceDirect

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Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector

The ATLAS Collaboration *

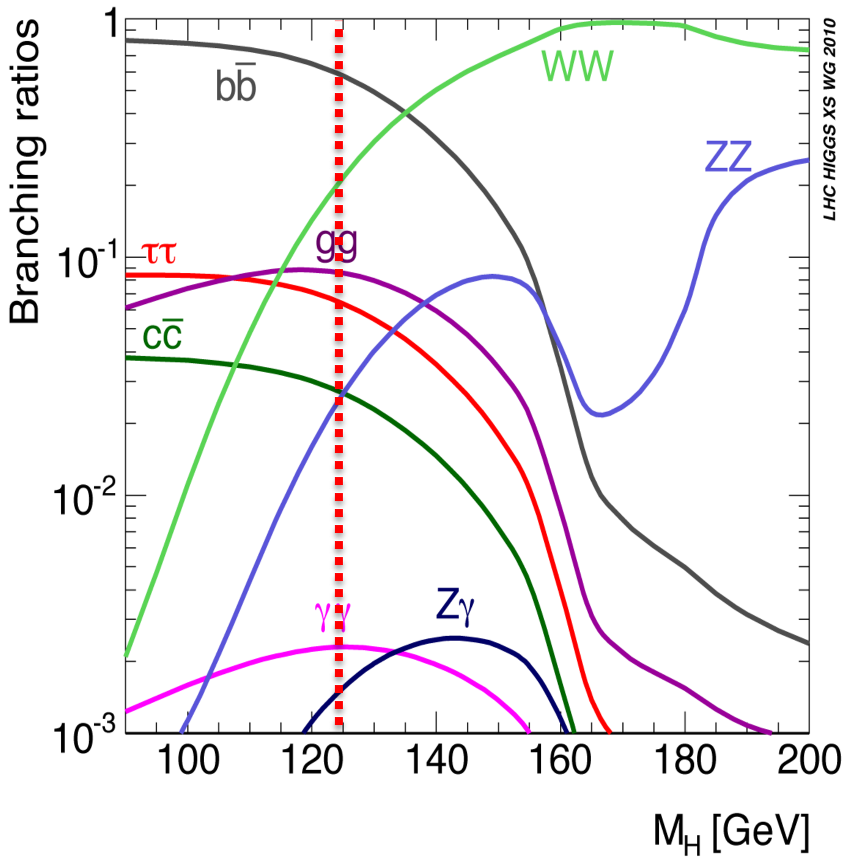
ARTICLE INFO

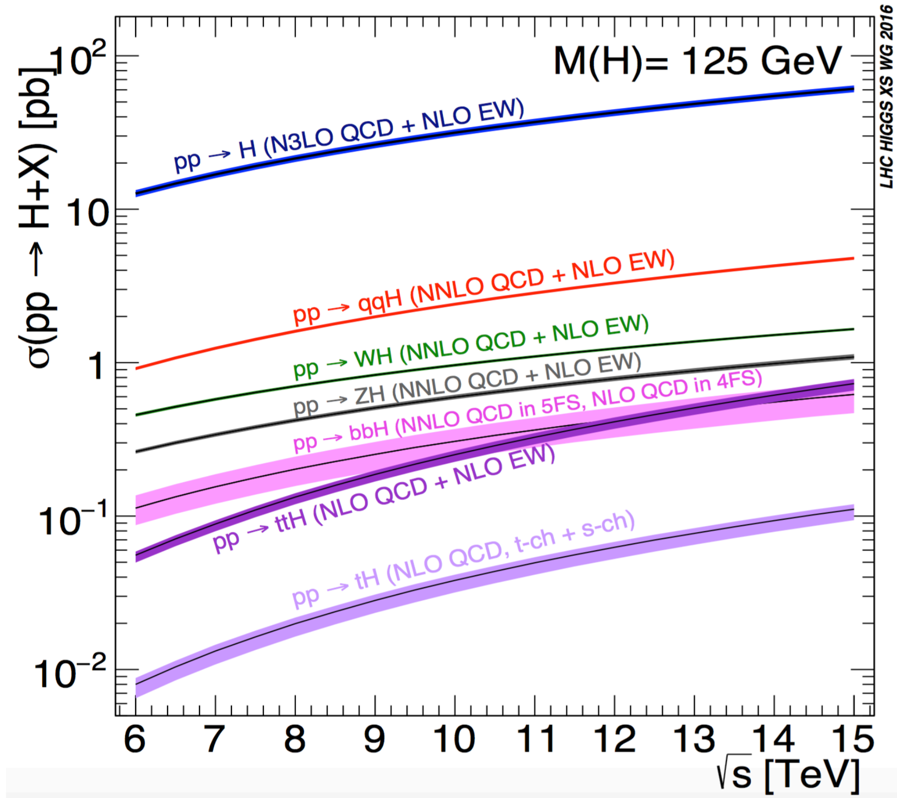
Article history:
Received 25 August 2018
Accepted 6 September 2018
Available online 14 September 2018
Editor: M. Doser

ABSTRACT

A search for the decay of the Standard Model Higgs boson into a $b\bar{b}$ pair when produced in association with a W or Z boson is performed with the ATLAS detector. The data, corresponding to an integrated luminosity of 79.8 fb^{-1} were collected in proton–proton collisions during Run 2 of the Large Hadron Collider at a centre-of-mass energy of 13 TeV. For a Higgs boson mass of 125 GeV, an excess of events over the expected background from other Standard Model processes is found with an observed (expected) significance of 4.9 (4.3) standard deviations. A combination with the results from other searches in Run 1 and in Run 2 for the Higgs boson in the $b\bar{b}$ decay mode is performed, which yields an observed (expected) significance of 5.4 (5.5) standard deviations, thus providing direct observation of the Higgs boson decay into b-quarks. The ratio of the measured event yield for a Higgs boson decaying into $b\bar{b}$ to the Standard Model expectation is $1.01 \pm 0.12(\text{stat.})^{+0.16}_{-0.15}(\text{syst.})$. Additionally, a combination of Run 2 results searching for the Higgs boson produced in association with a vector boson yields an observed (expected) significance of 5.3 (4.8) standard deviations.

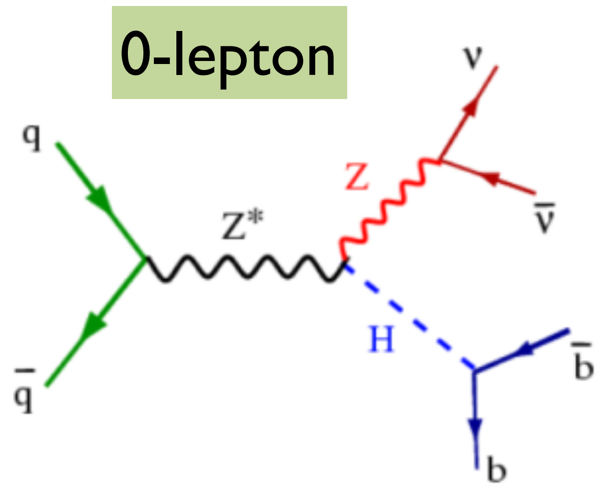
VH, H→bb

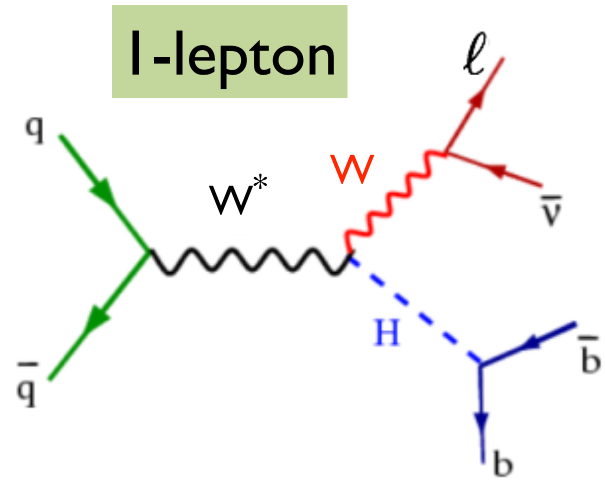


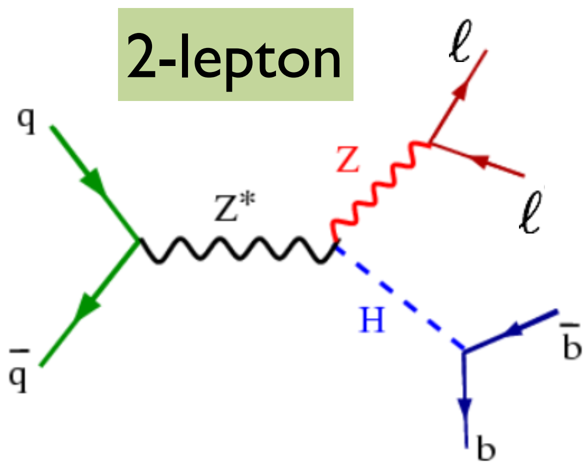


8 years to observe this decay mode, even with Br=57.5%

Analysis of WH/ZH, H→bb

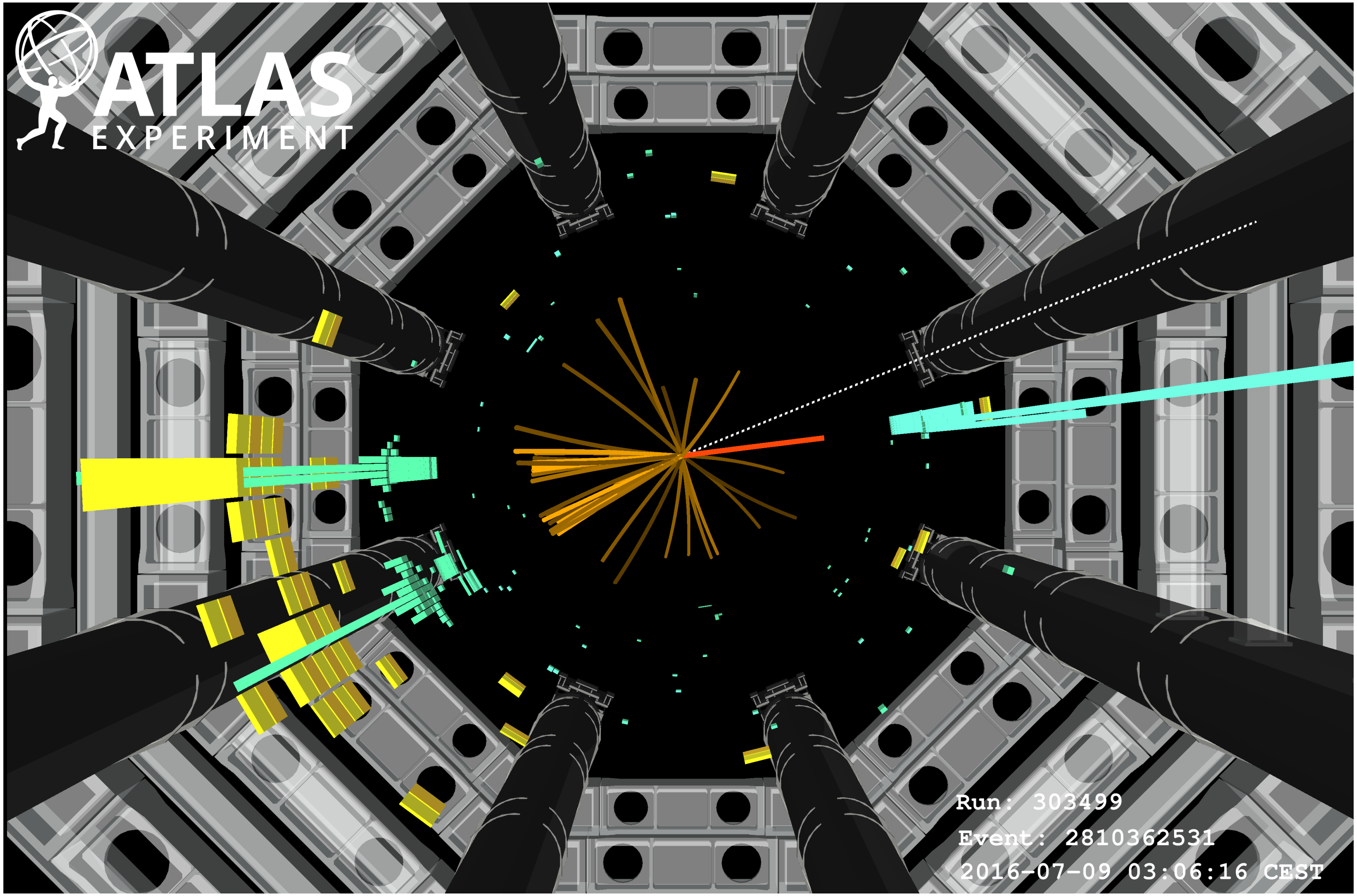






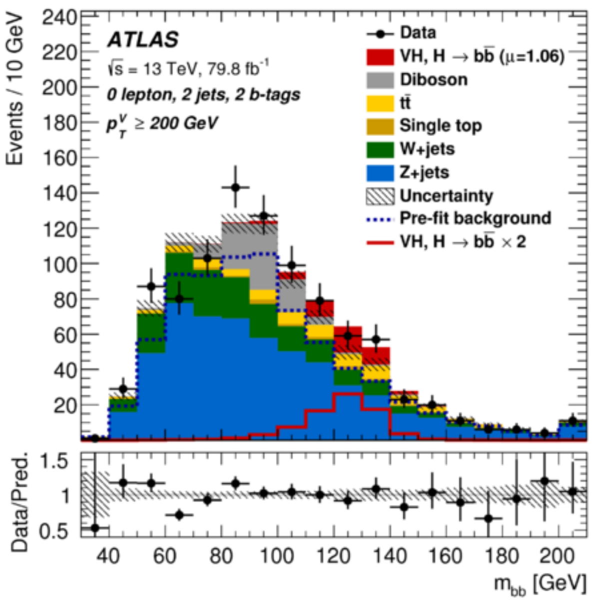
- Categorized into 0-lepton, 1-lepton, and 2-lepton final states (e, μ)
- Single-lepton triggers for 1/2-lepton channels, MET trigger for 0/1-lepton (W→μν)
- Exactly 2 or 3 jets for 0/1-lepton channels, 2 or >=3 jets for 2-lepton
- Exactly 2 b-jets (p_T>20 GeV) at 70% b-tagging efficiency; the leading b-jet with p_T>45 GeV

Event Display of WH, H→bb

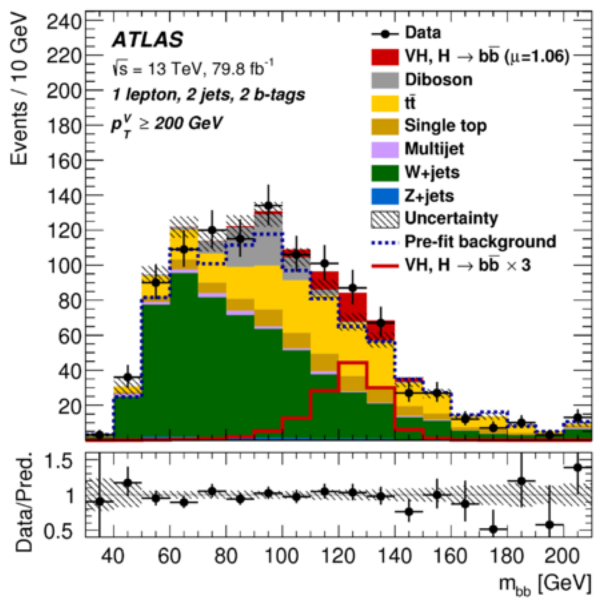


Background Composition

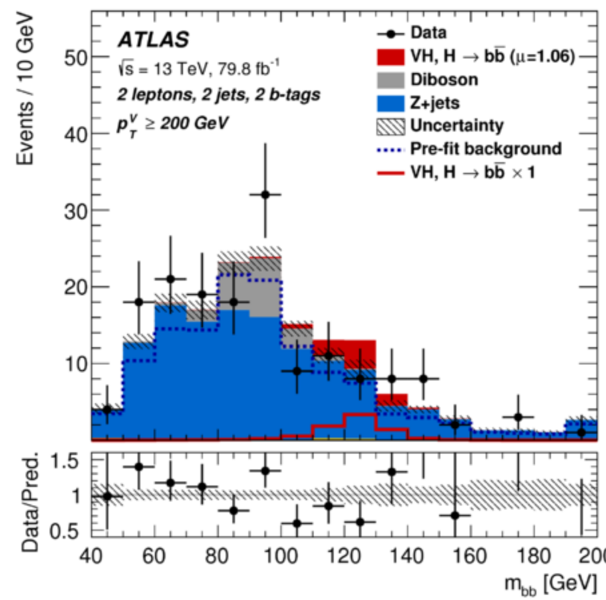
0-lepton



1-lepton



2-lepton



- Main backgrounds: Z+jets, W+jets, ttbar, and single-top
- Dedicated control regions (CR) for background normalizations: W+HF, ttbar
- Resonant diboson VZ, Z→bb background, with lower mbb than VH signal
- Multi-jet background negligible in 0- and 2-lepton, <5% in 1-lepton (data-driven)

Event Selections

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 *loose* leptons with $p_T > 7$ GeV	1 *tight* electron $p_T > 27$ GeV	1 *tight* muon $p_T > 25$ GeV	2 *loose* leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ GeV
E_T^{miss}	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_T		> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$		
b-jets		Exactly 2 b-tagged jets		
Leading b-tagged jet p_T		> 45 GeV		
H_T	120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\boldsymbol{E}_T^{miss}, \textbf{jets})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{bb})$	$> 120°$	–		–
$\Delta\phi(\boldsymbol{b_1}, \boldsymbol{b_2})$	$< 140°$	–		–
$\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{p}_T^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			75 GeV $< p_T^V <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Selection cuts opimized to suppress backgrounds, while keeping signal yields as high as possible

Multivariate Analysis (BDT)

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	$\times$	$\times$
E_T^{miss}	$\times$	$\times$	
$p_T^{b_1}$	$\times$	$\times$	$\times$
$p_T^{b_2}$	$\times$	$\times$	$\times$
m_{bb}	$\times$	$\times$	$\times$
$\Delta R(\vec{b}_1, \vec{b}_2)$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{b}_1, \vec{b}_2)\rvert$	$\times$		
$\Delta\phi(\vec{V}, \vec{bb})$	$\times$	$\times$	$\times$
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			$\times$
m_{eff}	$\times$		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		$\times$	
m_T^W		$\times$	
$m_{\ell\ell}$			$\times$
$E_T^{miss}/\sqrt{S_T}$			$\times$
m_{top}		$\times$	
$\lvert\Delta Y(\vec{V}, \vec{bb})\rvert$		$\times$	
		Only in 3-jet events	
$p_T^{jet_3}$	$\times$	$\times$	$\times$
m_{bbj}	$\times$	$\times$	$\times$

Boosted Decision Trees trained and classified for each signal region separately

Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

In order to maximize the sensitivity, 8 signal regions are considered, with 6 control regions to better control the main backgrounds

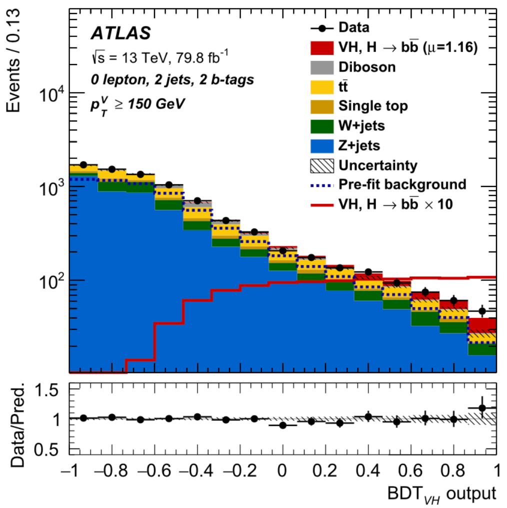
$N^{SR} = \sigma \times L \times \varepsilon^{SR}$

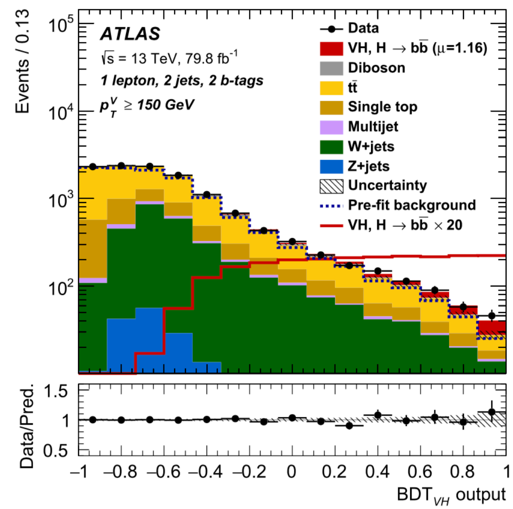
$N^{CR} = \sigma \times L \times \varepsilon^{CR}$

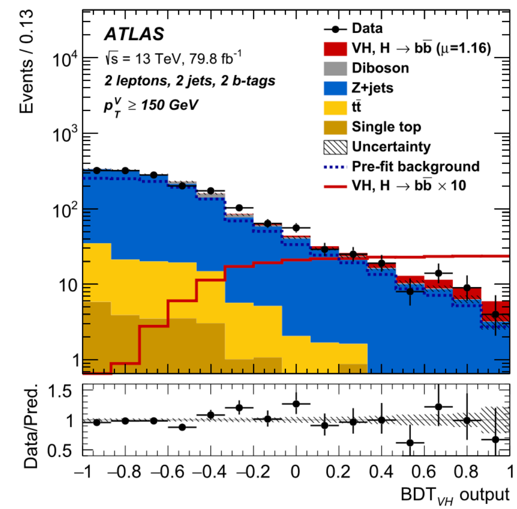
Signal Regions ($p_T V$ > 150 GeV)

0-lepton | 1-lepton | 2-lepton

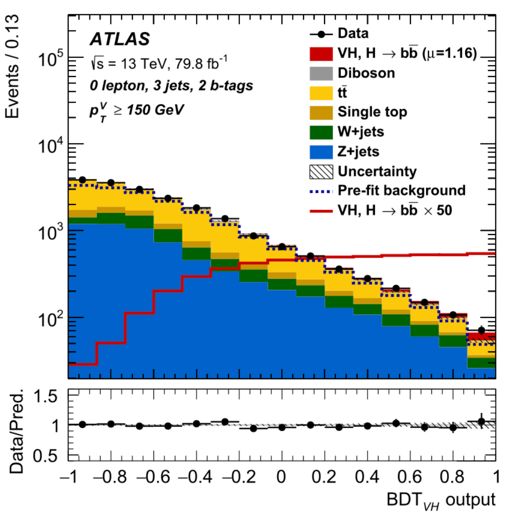
2-Jet SR

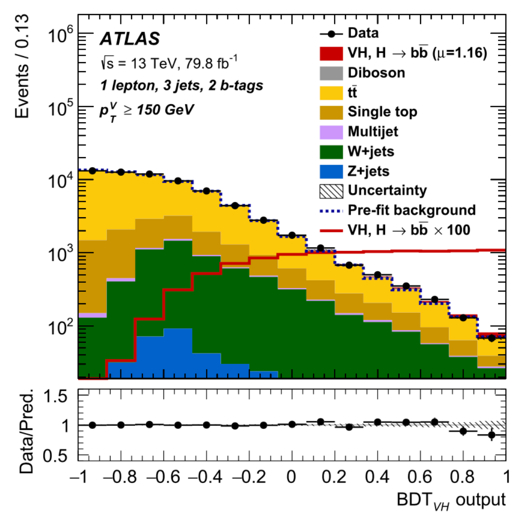


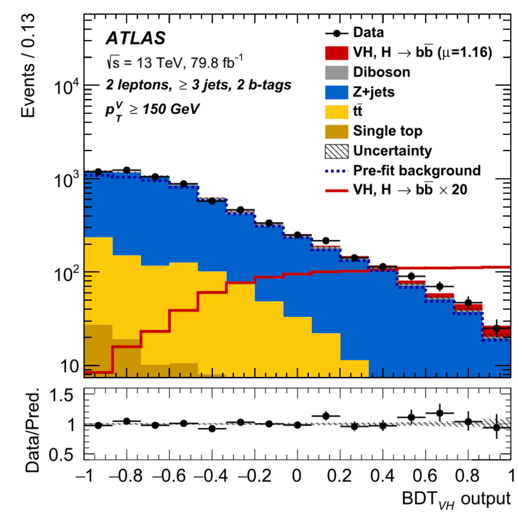




3-Jet (>=3J) SR

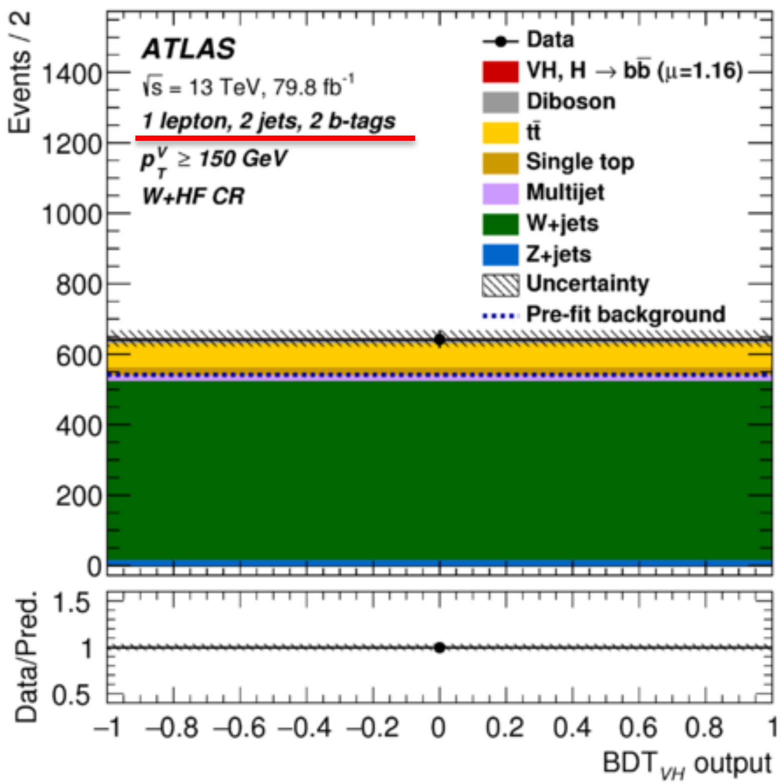


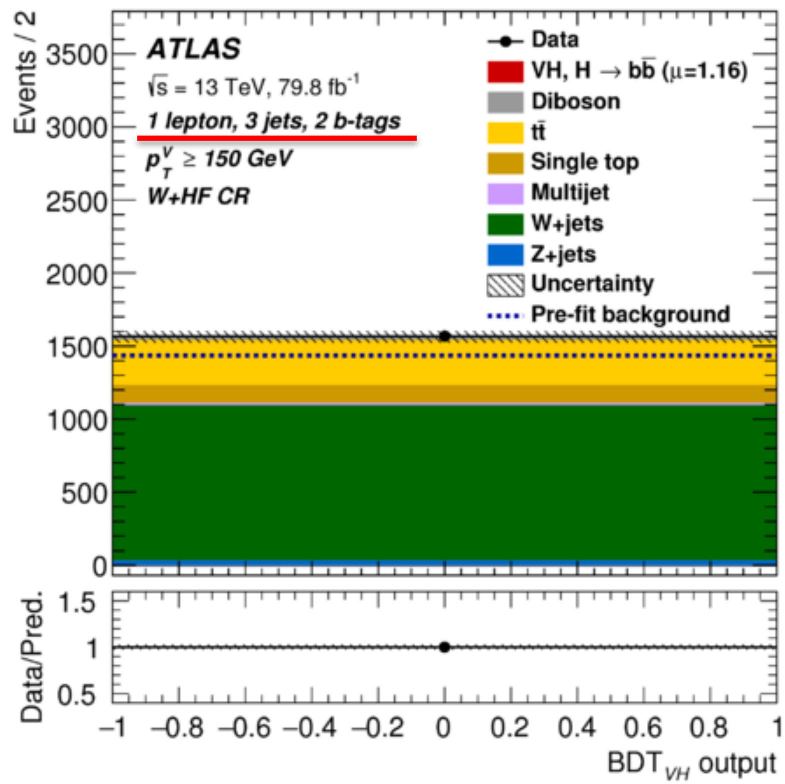




Control Regions: W+HF

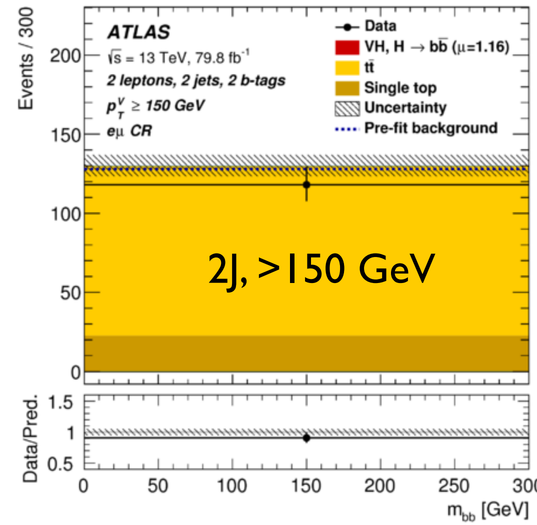
- Heavy flavor (HF): 2 jets from bb, bc, cc, or bl quark pairs
- Two additional selections after nominal cuts: m_{bb} < 75 GeV, m_{top} > 225 GeV
- Predicted purity: 75-78%



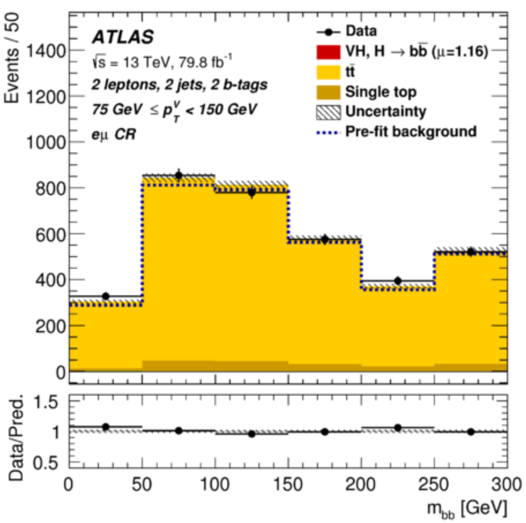


Control Regions: Top

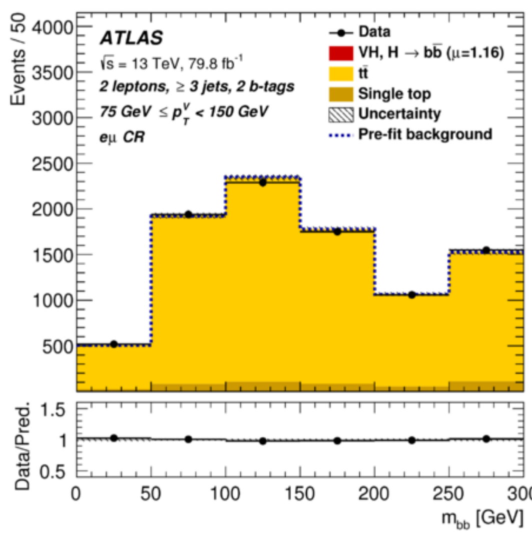
- Four ttbar CR's for the 2-lepton analysis, with eμ final state only
- More than 99% from single top and ttbar, 88-97% ttbar only

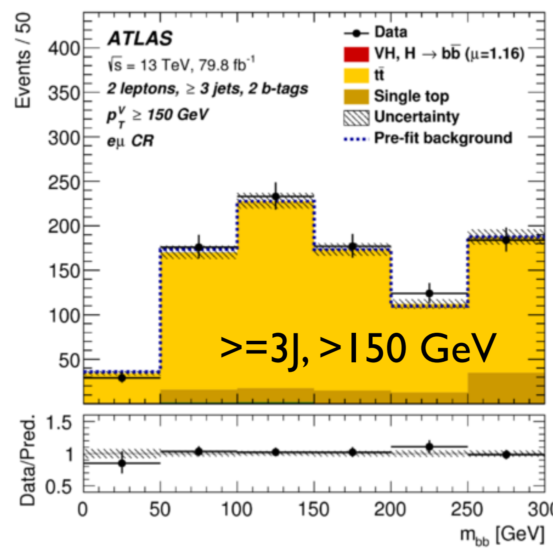


2J, [75, 150]GeV



>=3J, [75, 150]GeV





Systematic Uncertainties

- Experimental uncertainties
  - Dominant uncertainties: flavour-tagging efficiency correction factors, jet energy scale and the modeling of the jet energy resolution
  - Uncertainties from lepton's reconstruction, identification, isolation and trigger efficiencies with a small impact on the result
  - MET trigger and MET uncertainty from track's uncertainties
  - Luminosity: 2.1% for 2015 data, 3.4% for 2016
- Theoretical uncertainties
  - Samples and methods used
  - Backgrounds
  - Signal
- Impact of uncertainties on the final result

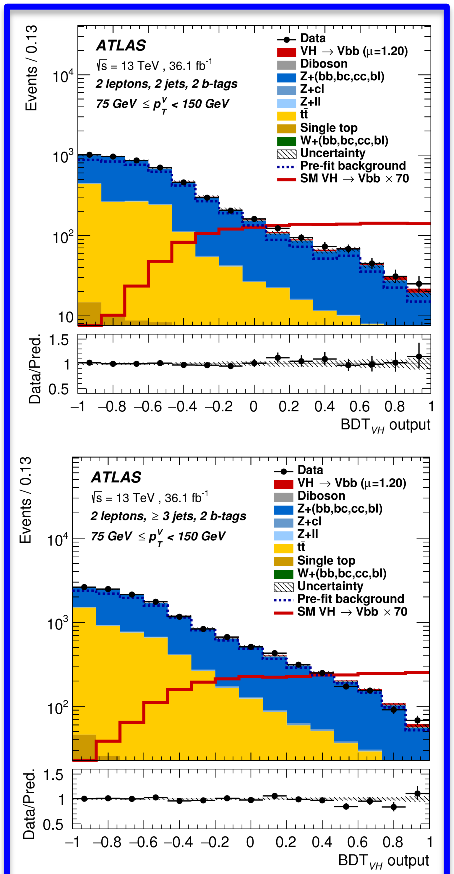
Impact of Systematics Uncertainties

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{miss}		0.014
Leptons		0.009
b-tagging	*b*-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
$Z+$jets		0.055
$W+$jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

- Signal strength: $\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$
- A simultaneous fit to all SR's and CR's can be used to estimate impacts of uncertainties, when all experimental and theoretical sys. considered.
- The analysis is limited by systematical uncertainties: 0.31 (syst.) vs. 0.24 (stat)
- The main sources of uncertainties are: signal modeling, background modeling, MC statistics, b-tagging.

Statistical Analysis Strategy

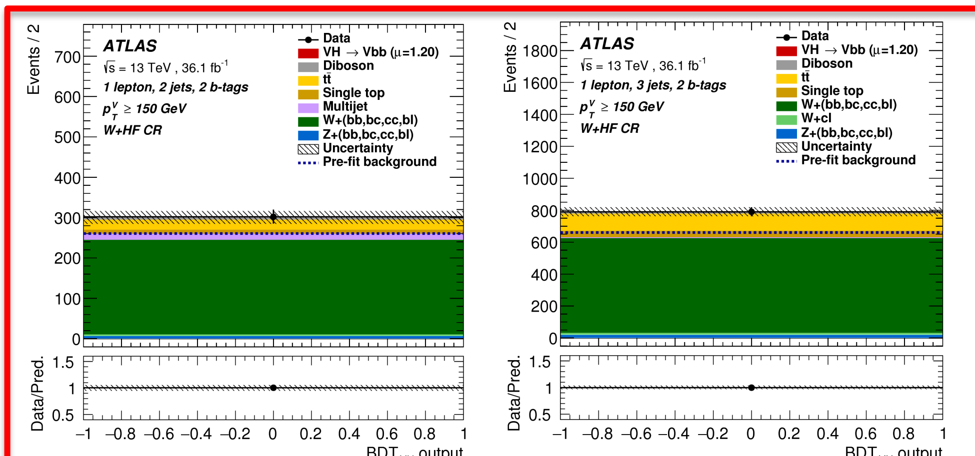
A simultaneous likelihood fit is performed on 8 signal regions and 6 control regions: 6 SRs (page 9); 4 top CR (page 11); 2 SRs + 2 CRs here



Channel	SR/CR	Categories: 75 GeV < p_T^V < 150 GeV		Categories: p_T^V > 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR			BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

8 SRs

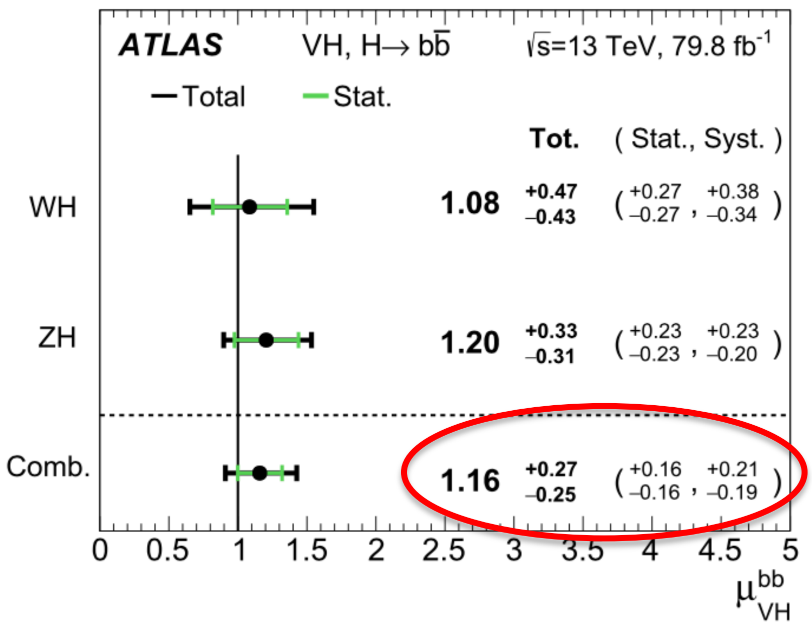
6 CRs

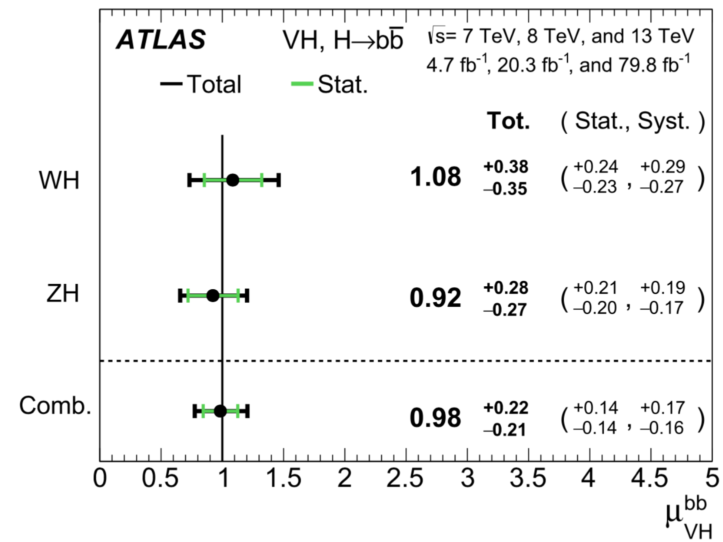


Results with 13 TeV in VH, H→bb

Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH, H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

Run II only

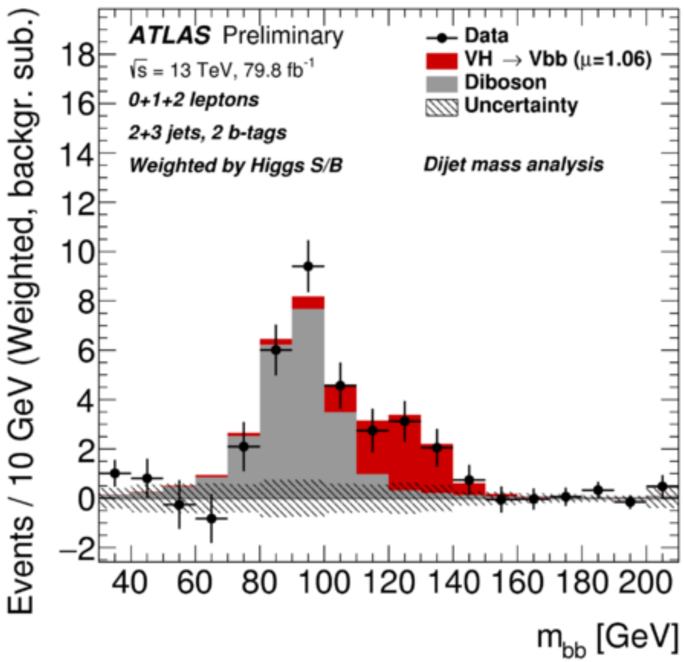




Significance with Run I + II:

4.9 σ observed (5.1σ expected)

H→bb Observation



VH, H→bb结果联合其它分析结果

Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ Combination	5.5	5.4

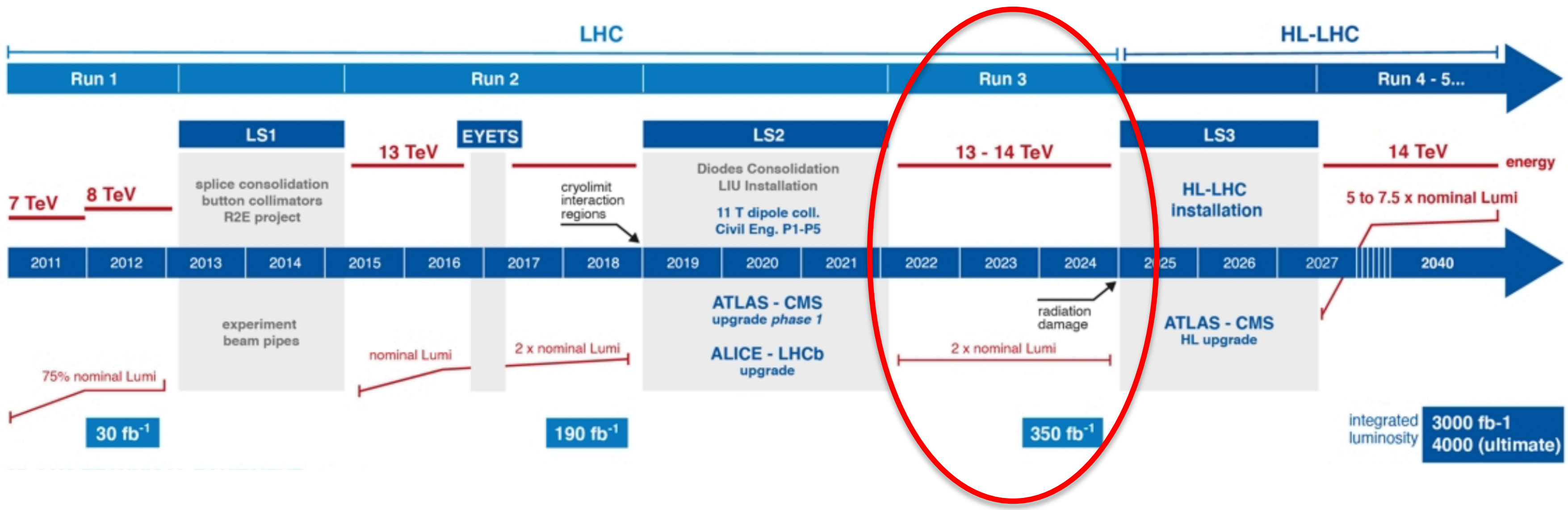
H→bb和ttH过程首次观测一起被美国物理学会评选的"2018年物理学十大进展"之一

科技部新闻稿

档的撰稿人(Supporting Note Editor)。从 ATLAS 实验 2015 年第二期运行开始，山东大学和中国科技大学分别参与了 W(lν)H 和 Z(νν)H 子分析道的研究。山东大学对 W(lν)H 分析道的信号选择、本底估计、统计分析等做出了重要贡献，其中提出了压低顶夸克本底的新方法，提高了信号灵敏度，并代表 H→bb 分析团队在 ATLAS 合作组内做了两次物理结果"批准"报告(Approval talk)，以及担任内部支持文档的撰稿人。中国科技大学对 ATLAS 二期新实验条件下 H→bb 分析软

Summary

- Long-time effort from Higgs search to Higgs discovery
- Many precise measurements on Higgs property on-going after its discovery
- A detailed observation study presented for H→bb



Outlook

Now the discovered Higgs looks more and more like to be the SM Higgs!

But

It is really a brand-new particle

- First 0^+ particle, no other?
- Higgs self-interaction, SM case?
- Higgs mechanism?
- Neutrino mass?
- Dark matter?

Linear Collider

Mature detailed TDR studies based on extensive R&D

Industrial production of cavities (established for XFEL)

Major Japanese community initiative to host ILC as a global project

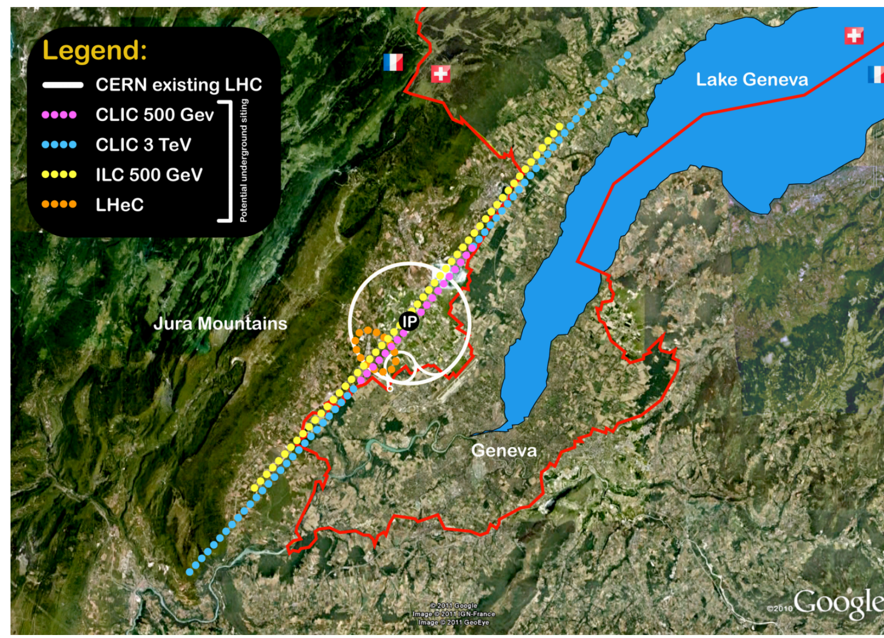
Goal to start data taking before 2030

Baseline 250 → 500 GeV (upgradeable to 1 TeV)

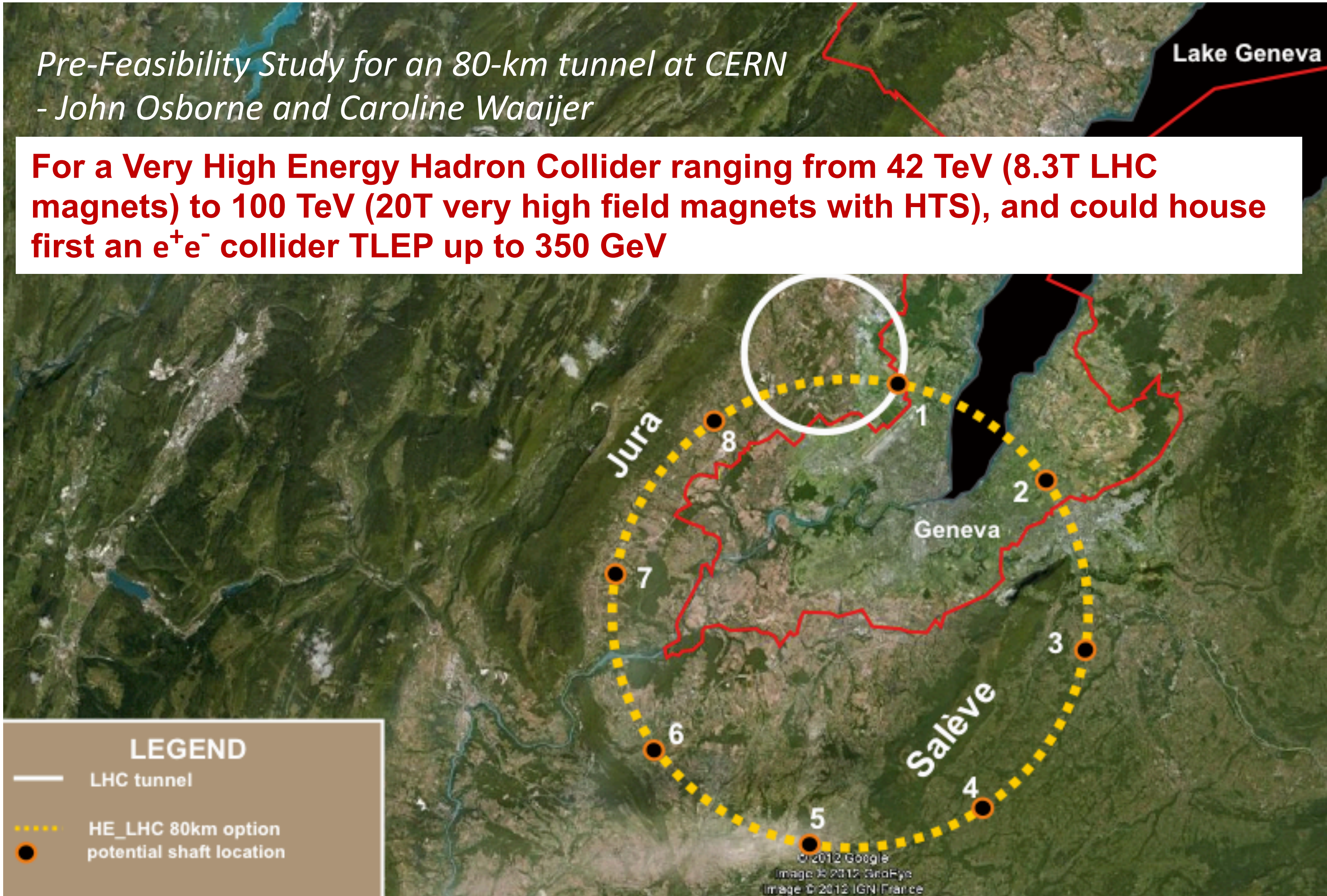
Compact Linear Collider CLIC

Detailed CDR studies based on extensive R&D

Prove of principle of the two-beam acceleration



Future Colliders

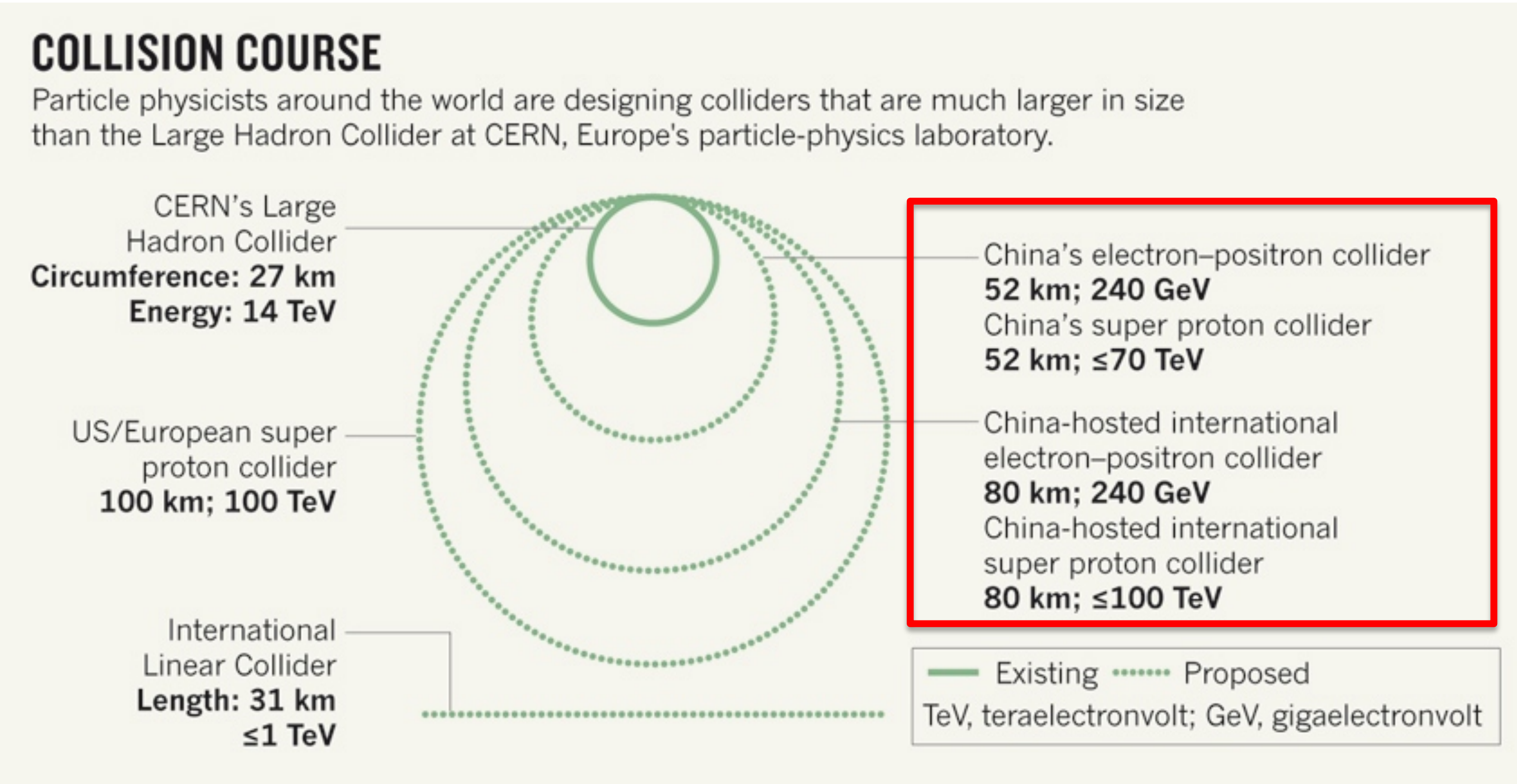


For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider TLEP up to 350 GeV

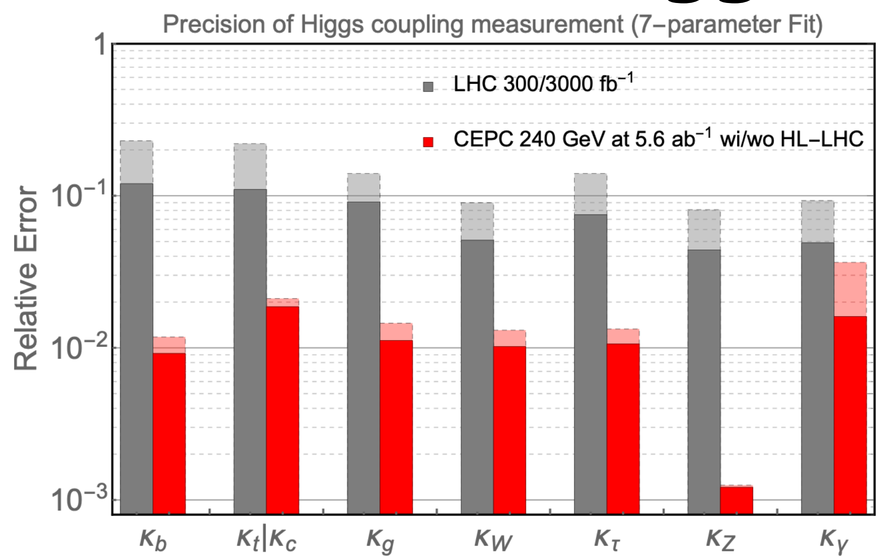
Future Collider in China

Nature reported on July 22, 2014:

http://www.nature.com/news/china-plans-super-collider-1.15603



Prospect from Future Higgs Factory



arXiv:1801.09037

arXiv:1905.00382

Observable	Current range	HL-LHC	ILC250	ILC250+500	CLIC380	CLIC3000	CEPC	FCC240	FCC365	LHeC
		$\delta y/y$ (%)								
$y_t/y_t^{\rm SM}$	$1.02^{+0.19}_{-0.15}$ [35] $1.05^{+0.14}_{-0.13}$ [36]	3.4	–	6.3	–	2.9	–	–	–	–
$y_b/y_b^{\rm SM}$	$0.91^{+0.17}_{-0.16}$ [35] $0.85^{+0.13}_{-0.14}$ [36]	3.7	1.0	0.60	1.3	0.2	1.0	1.4	0.67	1.1
$y_\tau/y_\tau^{\rm SM}$	0.93 ± 0.13 [35] 0.95 ± 0.13 [36]	1.9	1.2	0.77	2.7	0.9	1.2	1.4	0.78	1.3
$y_c/y_c^{\rm SM}$	< 6.2 [40, 41]	< 220	1.8	1.2	4.1	1.3	1.9	1.8	1.2	3.6
$y_\mu/y_\mu^{\rm SM}$	$0.72^{+0.50}_{-0.72}$[35] < 1.63 [36]	4.3	4.0	3.8	–	5.6	5.0	9.6	3.4	–
$y_e/y_e^{\rm SM}$	< 611 [42]	–	–		–	–	–	–	$< 1.6^{(+)}$	–

Thanks!