Review of Higgs Boson results

Paolo Azzurri – INFN Pisa
on behalf of ATLAS and CMS

4th World Summit on Exploring the Dark Side of the Universe
La Réunion Island 7–11 Nov 2022

Outlook

- the Higgs Boson, searches and discovery at the LHC
- status of LHC measurements 10 year later
  - mass, width, quantum numbers
  - decays to fermions (3rd & 2nd generation), invisible
  - combined results on couplings, differential, EFT interpretations
  - double-Higgs production and couplings
- the future of Higgs physics
  - Run3 and HL-LHC
  - future e+e- factory

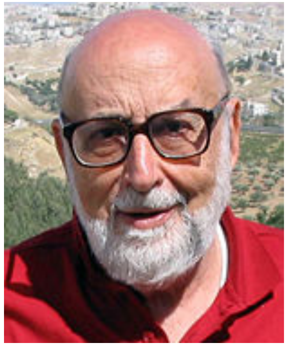
forgive me some bias towards CMS plots

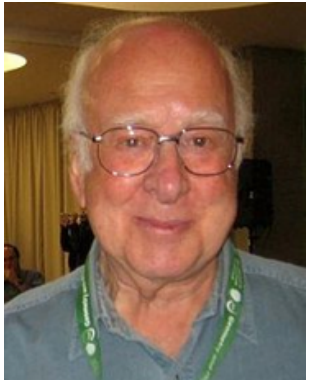
1964

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)






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)

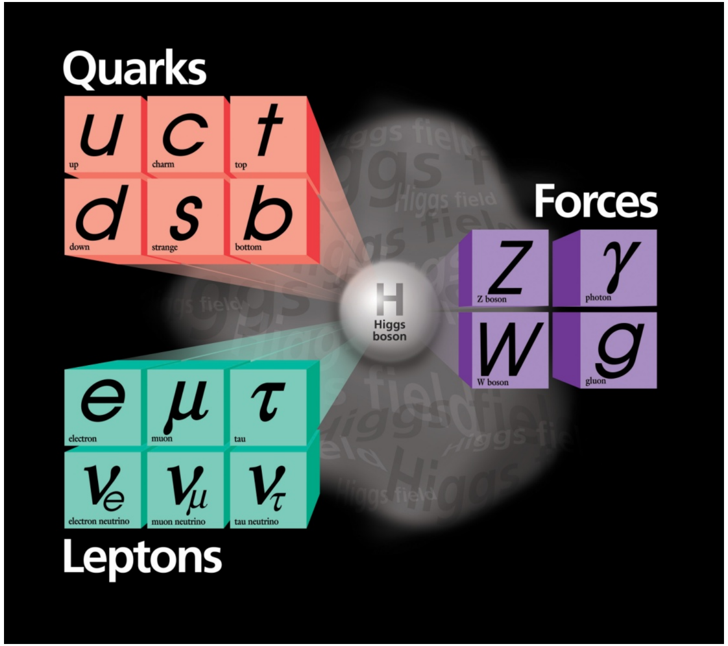
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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

2013

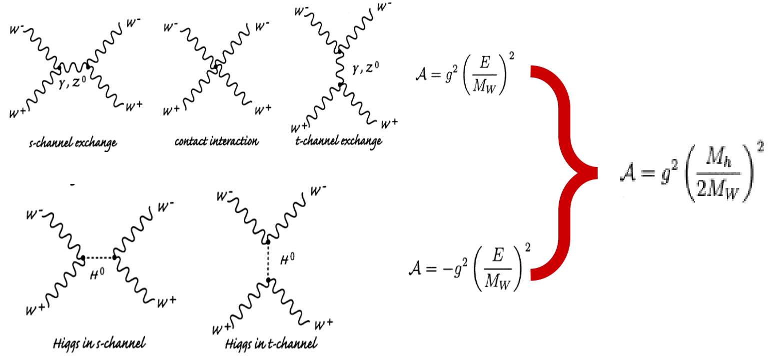
the Higgs boson

The field permeates the universe giving mass to elementary particles



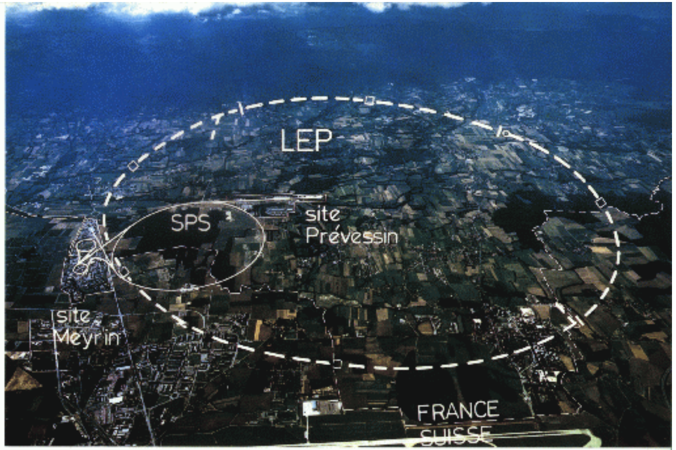
The mechanism predicts an (the only) elementary particle with zero spin : the Higgs boson

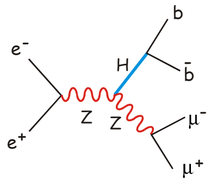
Zero charge, even parity and charge conjugation

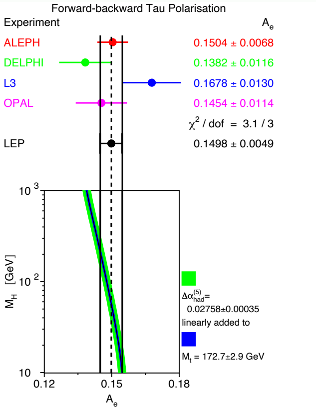


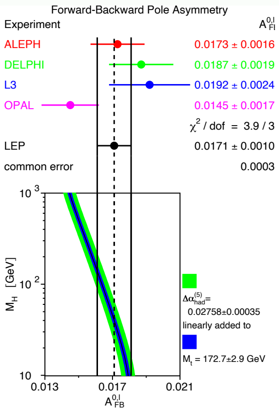
vector boson scattering unitarity

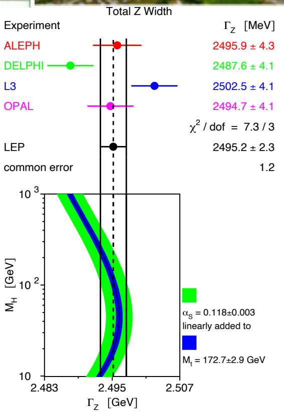
Higgs boson searches

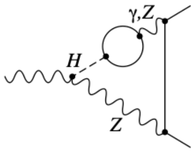


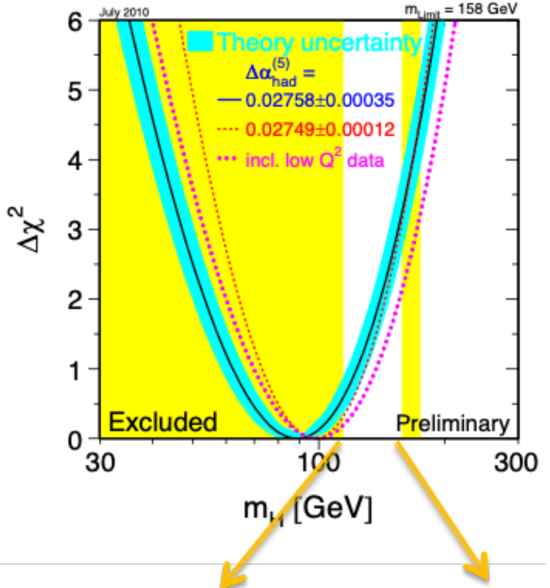








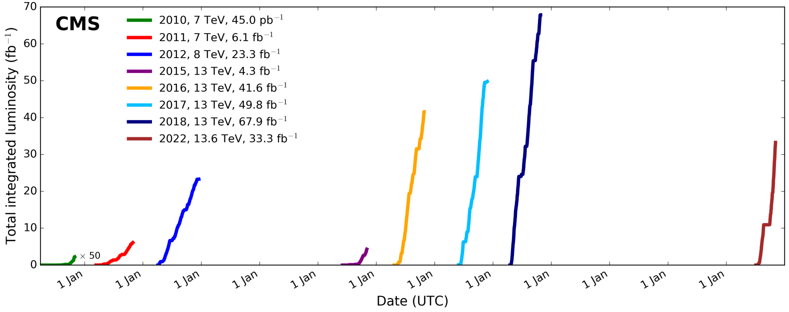




$114 < m_H < 158$ GeV

the LHC, ATLAS, CMS and the Higgs boson

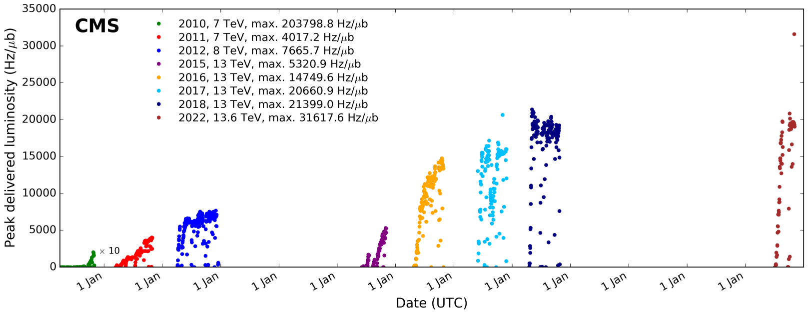
the LHC



7 TeV – 8 TeV
Run 1

13 TeV
Run 2

13.6 TeV
Run3



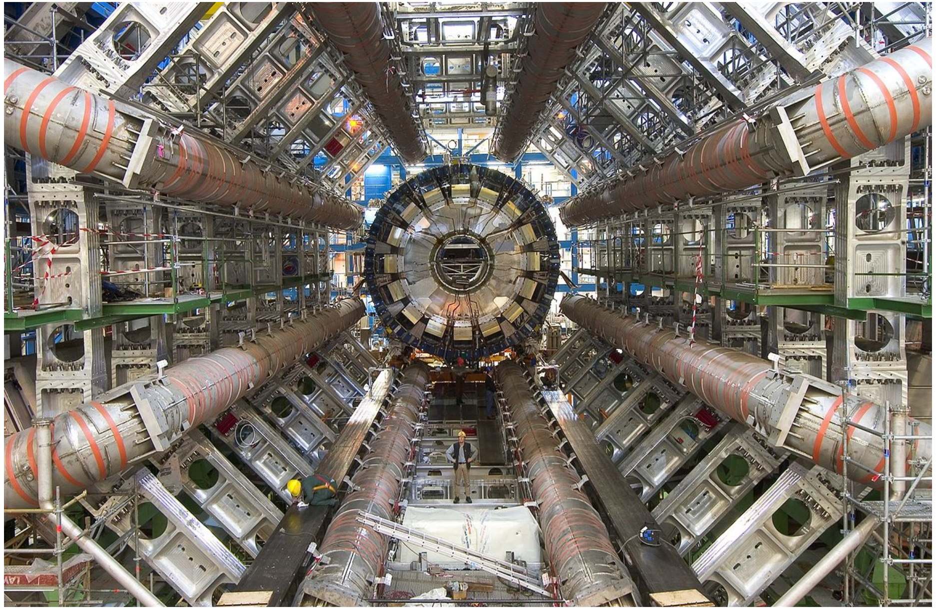
in the former LEP tunnel

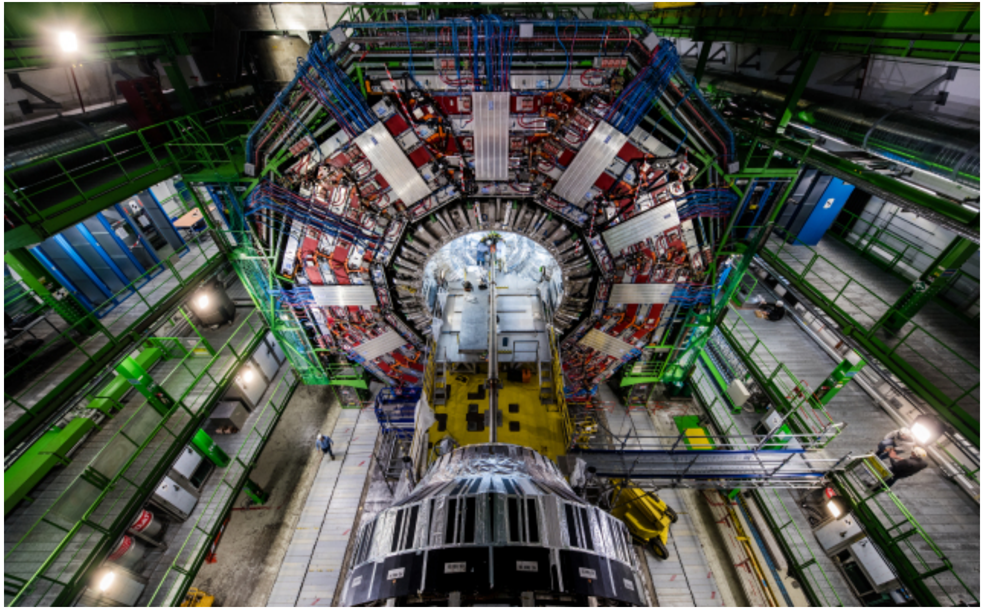
ATLAS & CMS

7000 tons
D=25 m
L=46 m
B=2T (4T toroid)

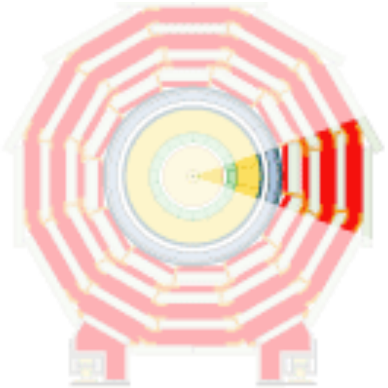
about 100 M channels
40 MHz (collision) rate

14000 tons
D=15 m
L=29 m
B=3.8 T

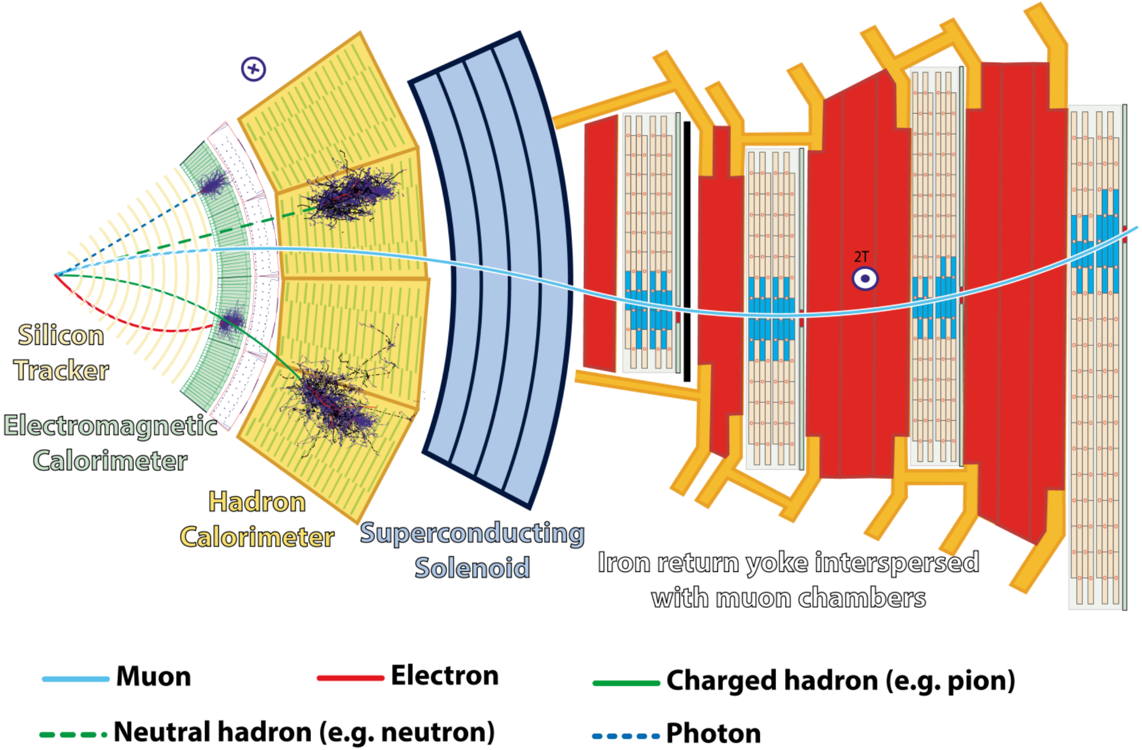




Particles through CMS

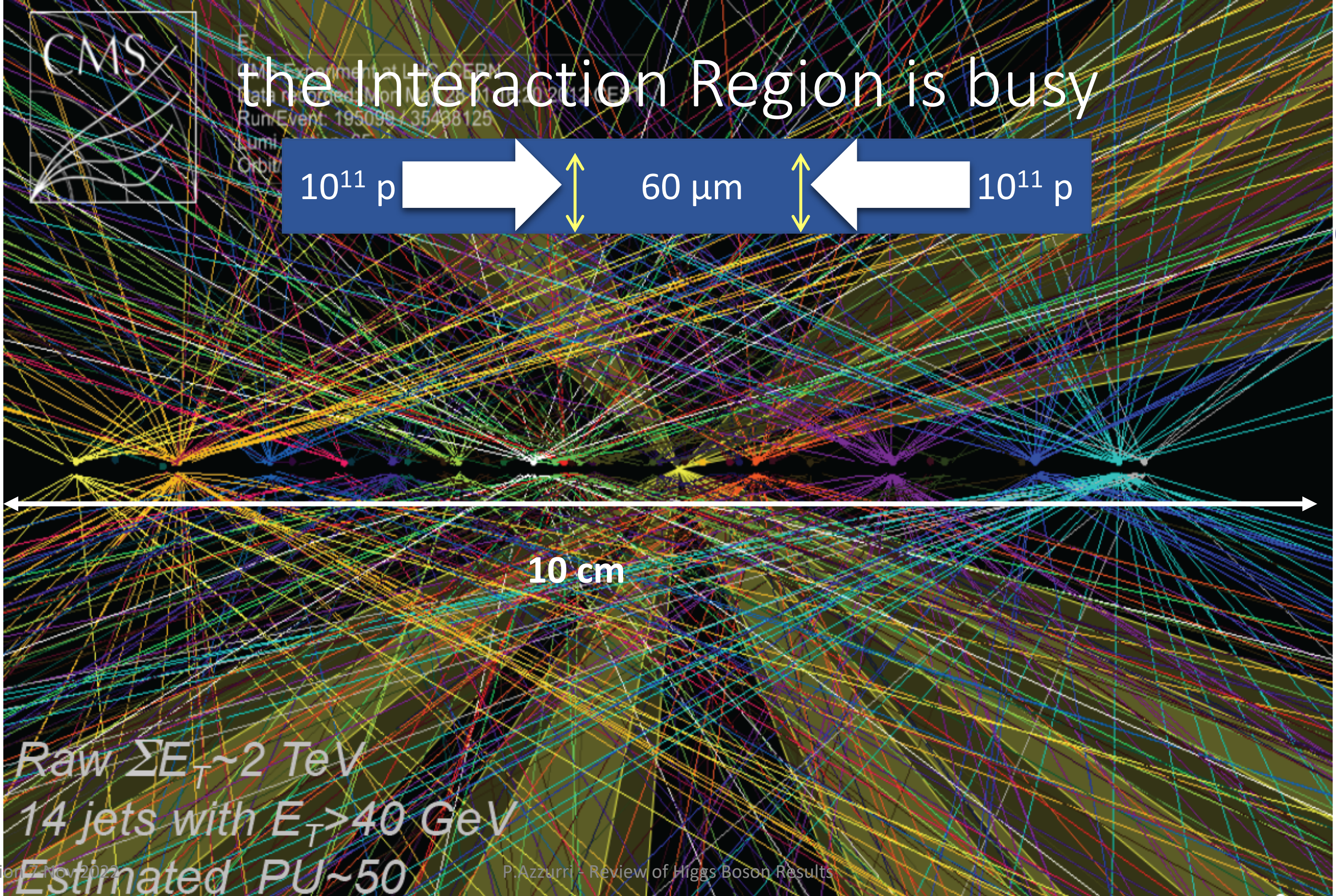


Transverse slice through CMS



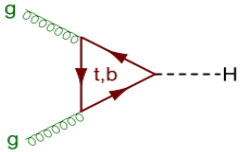
similar sketch for ATLAS .. but different detectors

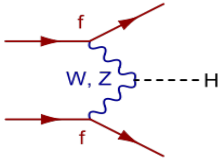
the Interaction Region is busy

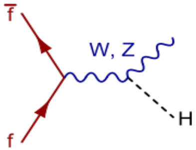


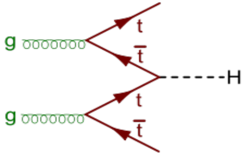
production and decay at the LHC

87%	7%	4%	1%

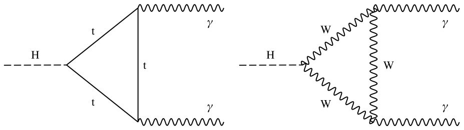


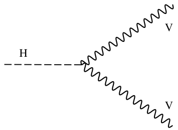


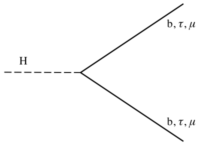




gluon fusion (ggF)	vector boson fusion (VBF)	Higgs-strahlung (VH)	top quark fusion (ttH)







$H \rightarrow \gamma\gamma$

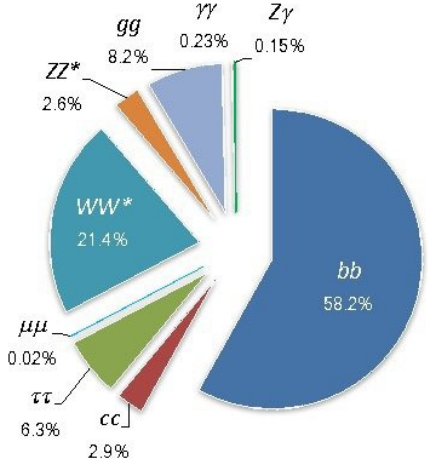
0.23%

$H \rightarrow ZZ^*, WW^*$

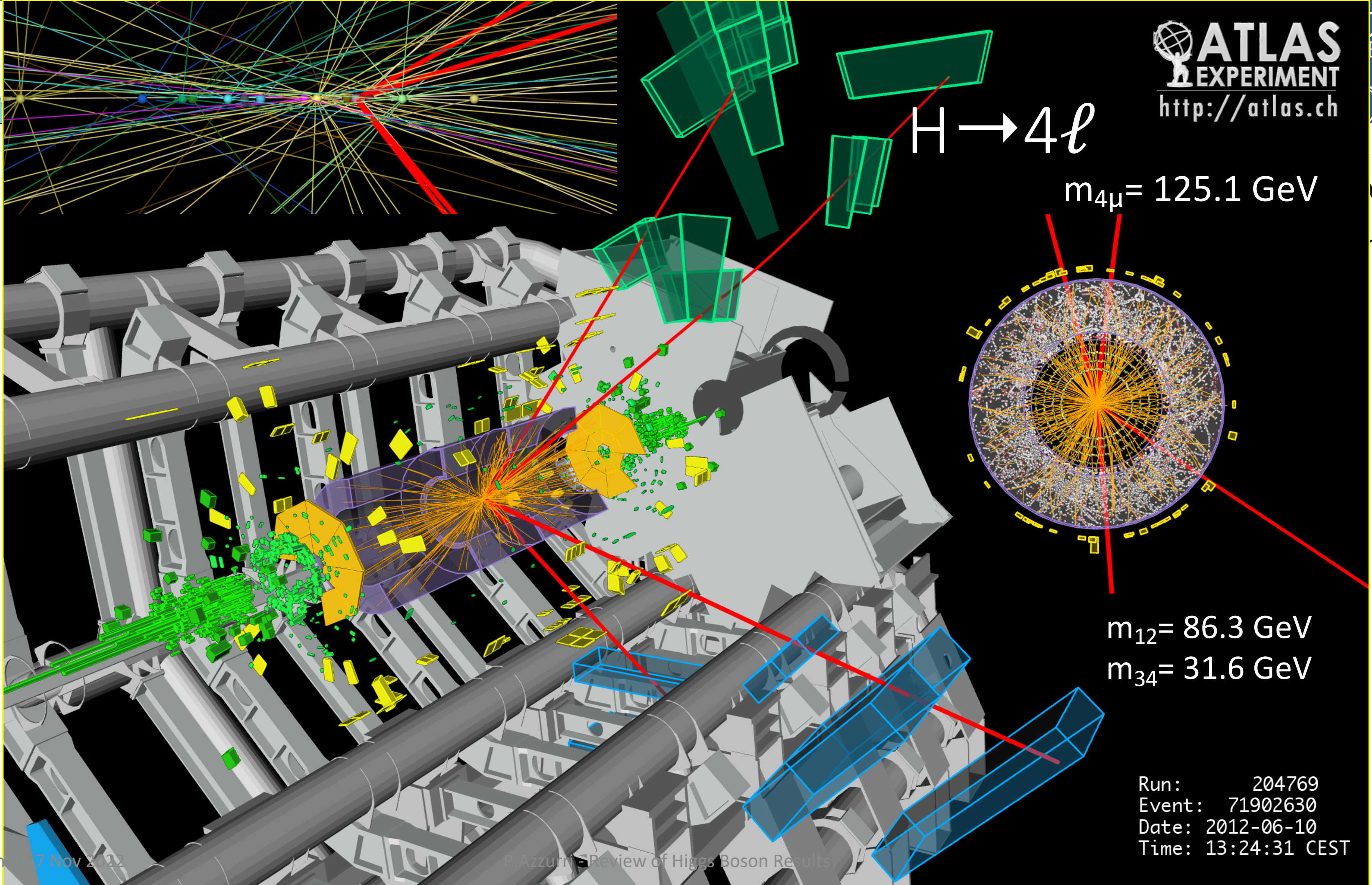
2.7%, 22%

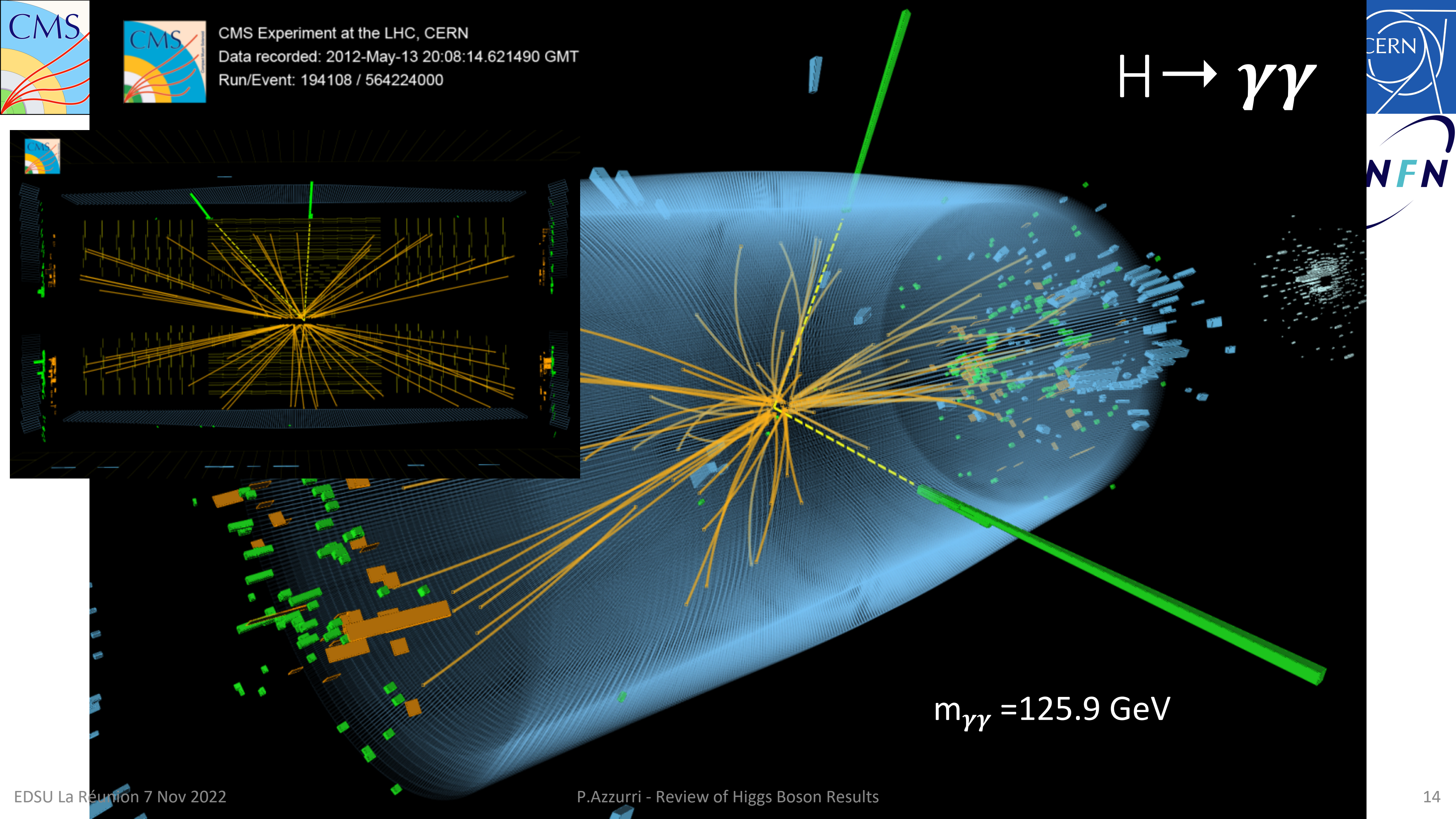
$H \rightarrow ff$

58% bb
6.2% $\tau\tau$
2.9% cc
0.02% $\mu\mu$



the golden channels
at discovery and now

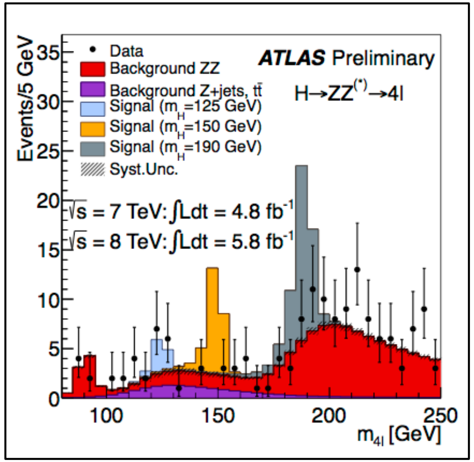

ATLAS EXPERIMENT
http://atlas.ch
$H \rightarrow 4\ell$
$m_{4\mu}$= 125.1 GeV
m_{12}= 86.3 GeV
m_{34}= 31.6 GeV
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

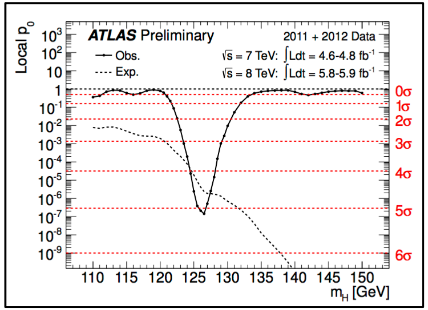

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
$H \to \gamma\gamma$
$m_{\gamma\gamma}$ =125.9 GeV

https://indico.cern.ch/event/197461/

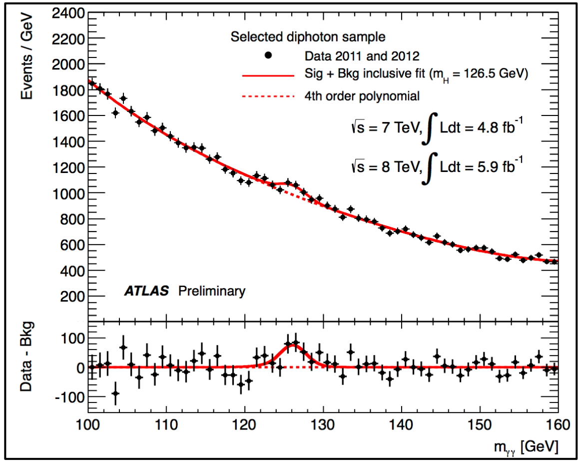
July 4th 2012

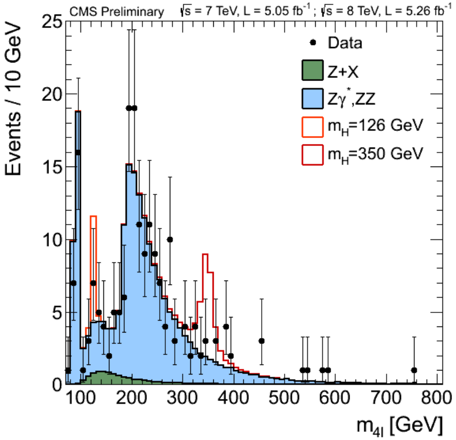
$H \rightarrow 4\ell$

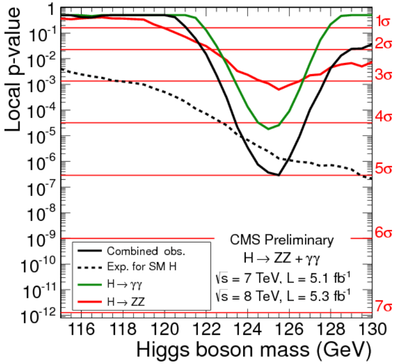




ATLAS 5.0σ @126.5 GeV

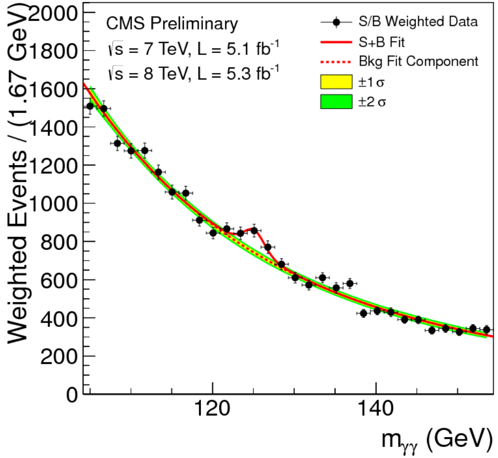




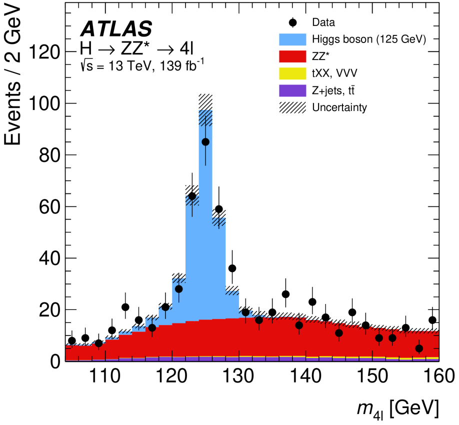


CMS 5.0σ @125.3 GeV

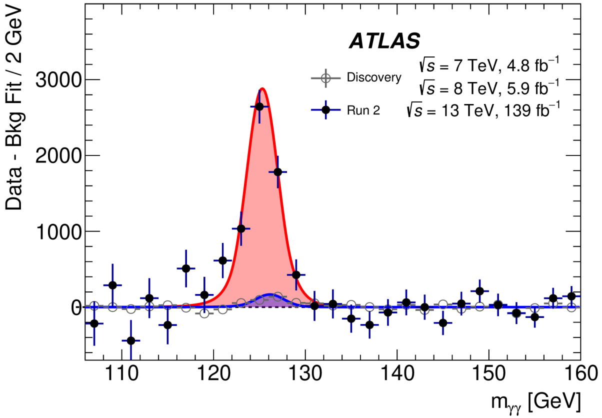
$H \rightarrow \gamma\gamma$



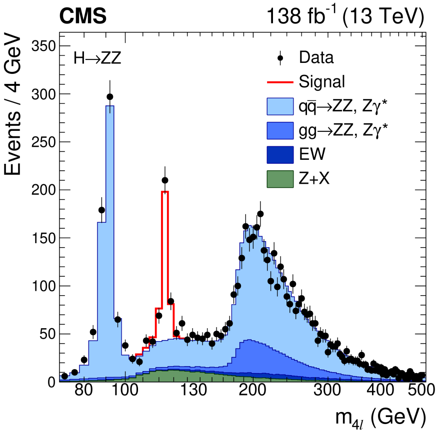
10 years later



30 times more Higgs bosons

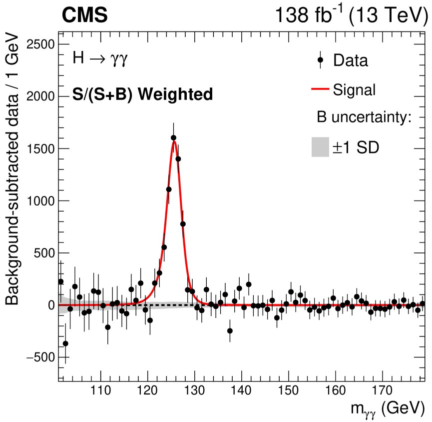


H→4ℓ



[Nature 607 (2022) 52-59]

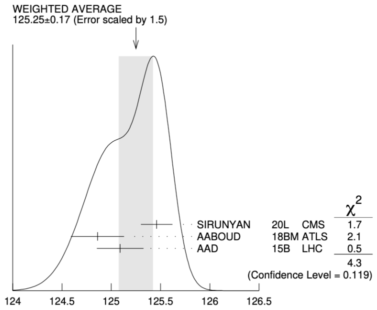
[Nature 607 (2022) 60-68]



H→ γγ

mass, width, quantum numbers

The Higgs Boson mass



fits of per-event m_H, $\boldsymbol{\delta} m_H$ and event classifier (S/B)

ℓ calibration from J/ψ or $Z \to \ell\ell$

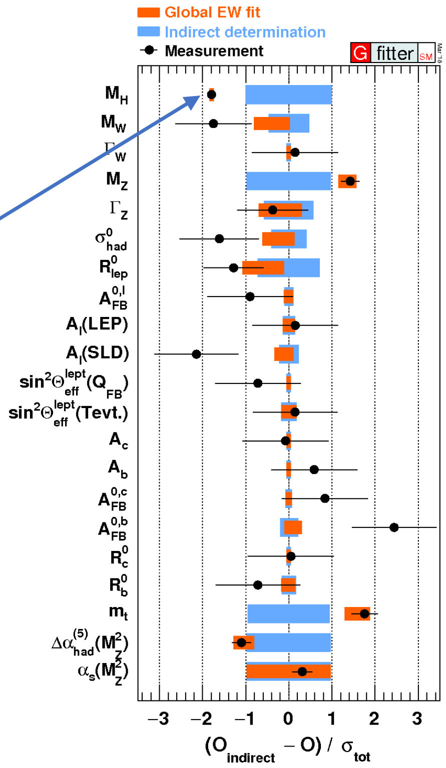
$\boldsymbol{\gamma}$ calibration from $Z \to ee$

$m_{ATLAS} < m_{CMS}$

- ATLAS: 4ℓ m_H=124.99 ± 0.18 ± 0.04 GeV (139/fb) arXiv:2207.00320
- CMS: $\boldsymbol{\gamma\gamma}$+$4\ell$ m_H= 125.46 ± 0.13 ± 0.13 GeV (36/fb) PLB 805 (2020) 135425
  - $\boldsymbol{\gamma\gamma}$ m_H= 125.78 ± 0.18 ± 0.18 GeV
  - 4ℓ m_H= 125.26 ± 0.20 ± 0.08 GeV JHEP 11 (2017) 047
- ATLAS: $\boldsymbol{\gamma\gamma}$+$4\ell$ m_H= 124.86 ± 0.18 ± 0.20 GeV (36/fb) PLB 784 (2018) 345
  - $\boldsymbol{\gamma\gamma}$ m_H= 124.93 ± 0.21 ± 0.34 GeV
  - 4ℓ m_H= 124.79 ± 0.36 ± 0.08 GeV
- ATLAS+CMS $\boldsymbol{\gamma\gamma}$+ 4ℓ m_H= 125.09 ± 0.21 ± 0.11 GeV (Run1) PRL 114 (2015) 191803

Run2 precision below the 0.1% level !

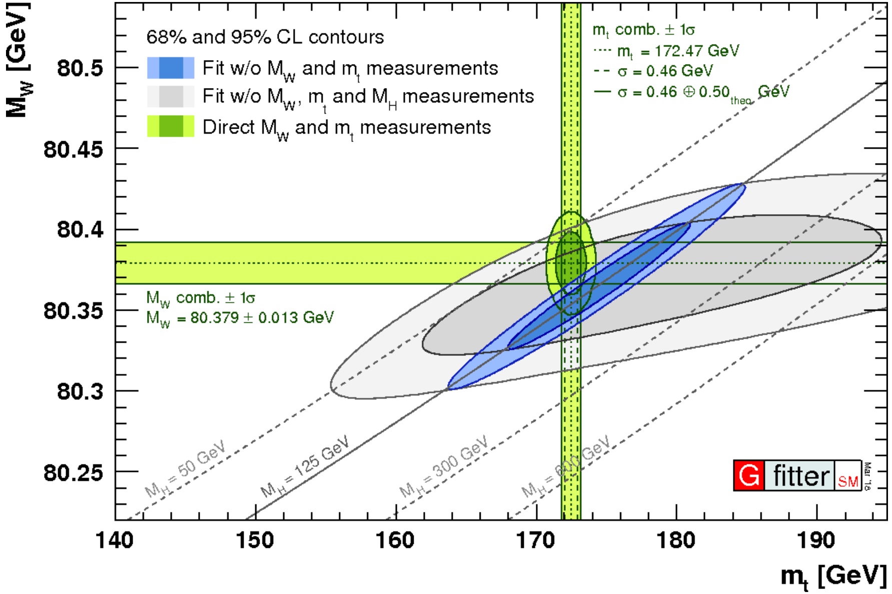
The Higgs Boson mass



can you see the measurement error bar ?

EPJ C78 (2018) 675

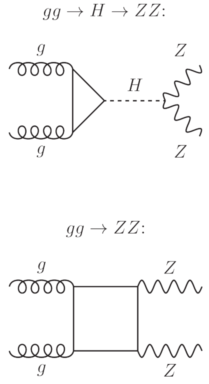
is ultra-precisely measured in the context of standard model precision fits

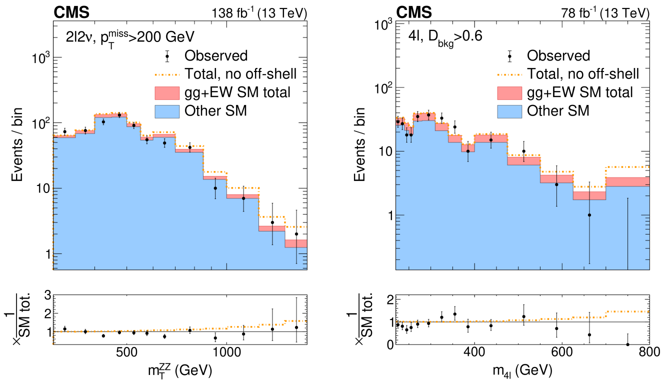


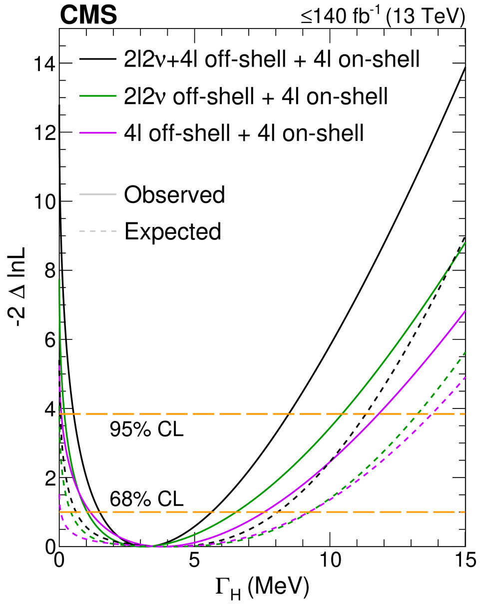
arXiv:2202.06923

The Higgs Boson width

4ℓ lineshape $\Rightarrow \Gamma_H < 1.1 \times 10^3$ MeV
4ℓ lifetime $\Rightarrow \Gamma_H > 3.5 \times 10^{-9}$ MeV







$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

assuming constant couplings in the range

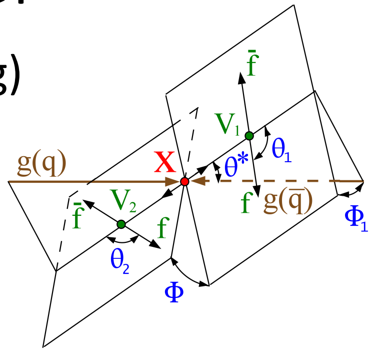
negative interference

3.6$\boldsymbol{\sigma}$ evidence for off-shell Higgs boson production

$$\Gamma_H = 3.2^{+2.4}_{-1.7} \text{ MeV}$$

Higgs Boson Spin and CP

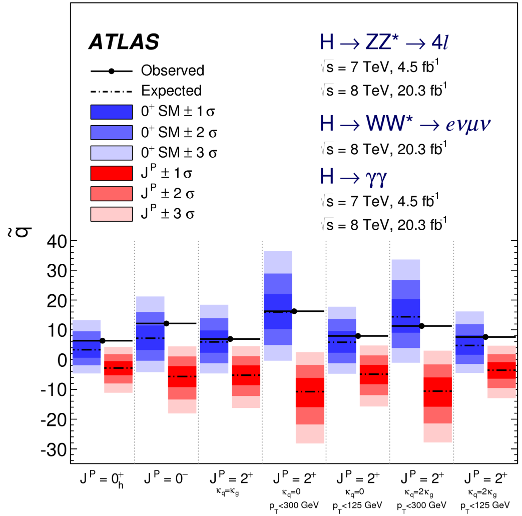
SM ($J^{PC} = 0^{++}$) $H \to \gamma\gamma \Rightarrow$ C=+1 and J=0,2 (Landau–Yang)



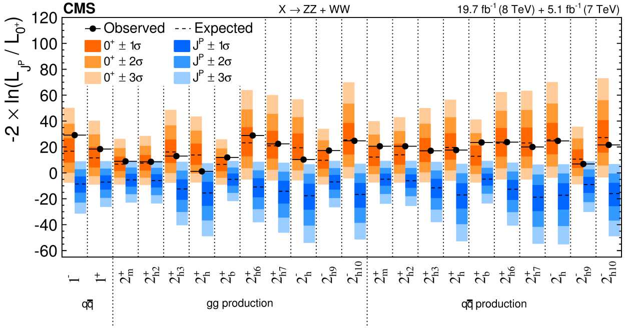
many non-SM hypothesis tested

study decay angles $H \to \gamma\gamma$, 4ℓ, $2\ell 2\nu$

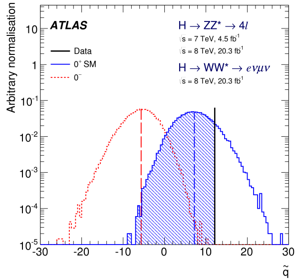
wide range of J=2 models excluded at CL > 99%

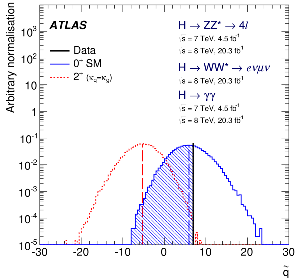


[EPJC 75 (2015) 476](#)



[PRD 92 (2015) 012004](#)





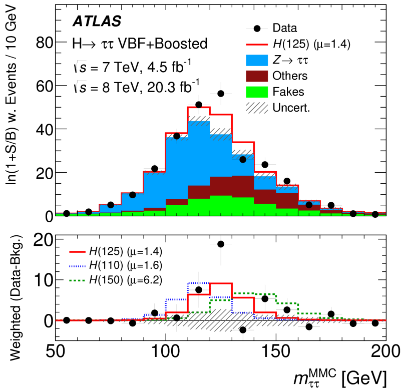
→ coupling anomalies / EFT

Higgs boson couplings

Direct observation of couplings to **Z, W bosons** with or soon after discovery
Coupling to **top quarks** extracted from resolving gg production and $\gamma\gamma$ decays

H→ττ Sensitivity mostly in the **VBF** channel

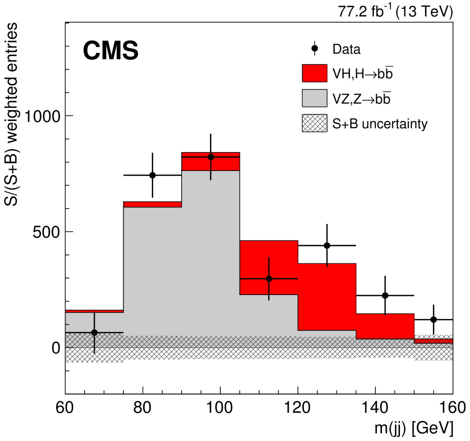
Separate evidences with Run1



JHEP 05 (2014) 104

JHEP 04 (2015) 117

H→bb
Sensitivity mostly in the **VH** channel



DY + jets backgrounds

25/fb(Run1) +80/fb(Run2)
Separate observations

PLB 786 (2018) 59

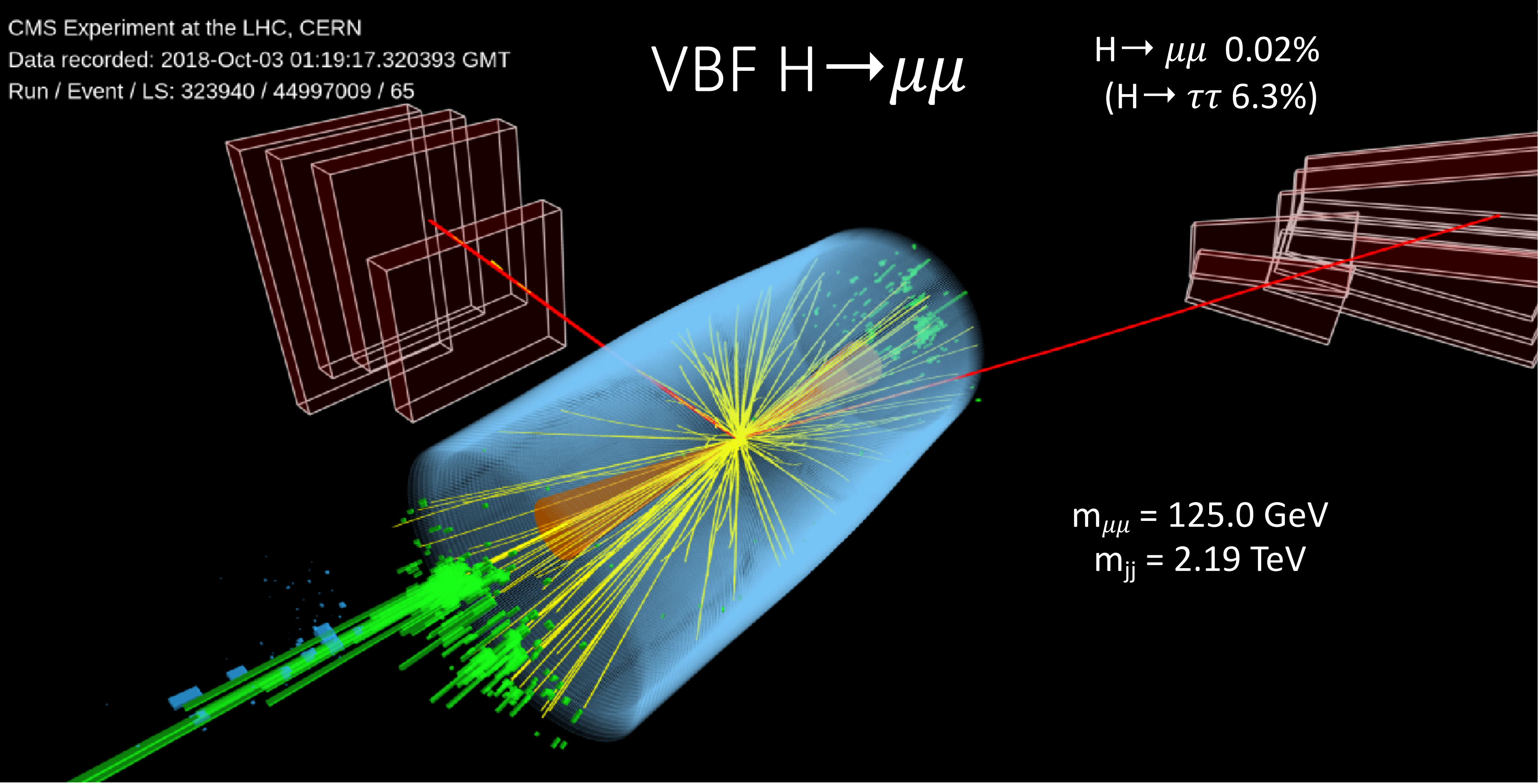
PRL 121 (2018) 121801

Run1-combined observation
JHEP 08 (2016) 045

3rd generation Yukawa settled

2nd generation and invisible

VBF H→$\mu\mu$



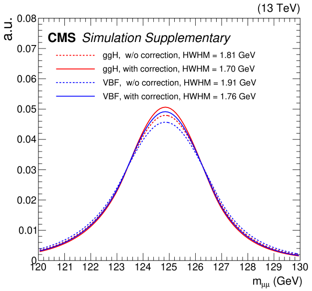
H→ $\mu\mu$ 0.02%
(H→ $\tau\tau$ 6.3%)

$m_{\mu\mu}$ = 125.0 GeV
m_{jj} = 2.19 TeV

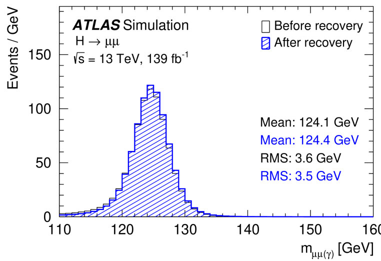
Higgs to muons

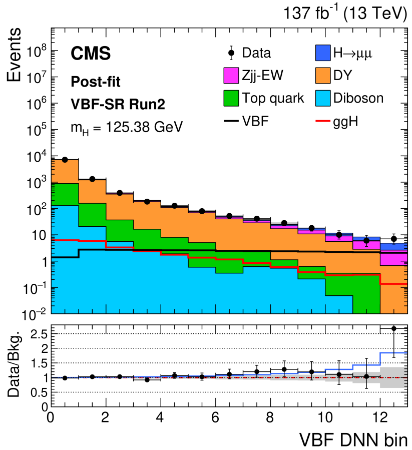
JHEP 01 (2021) 148

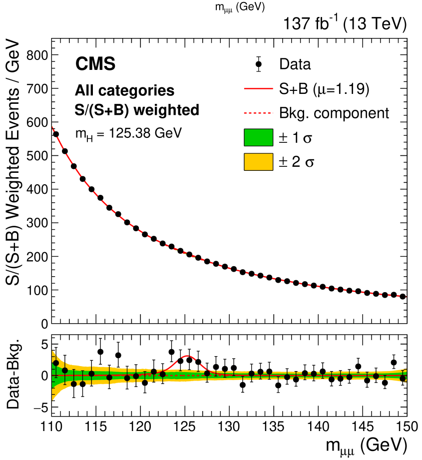
PLB 812 (2021) 135980

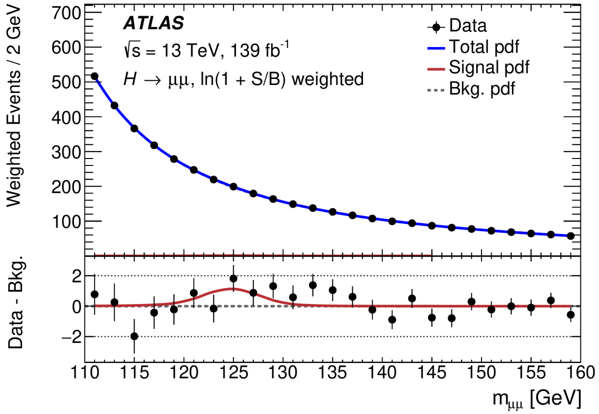


CMS has better $m_{\mu\mu}$ resolution wrt ATLAS





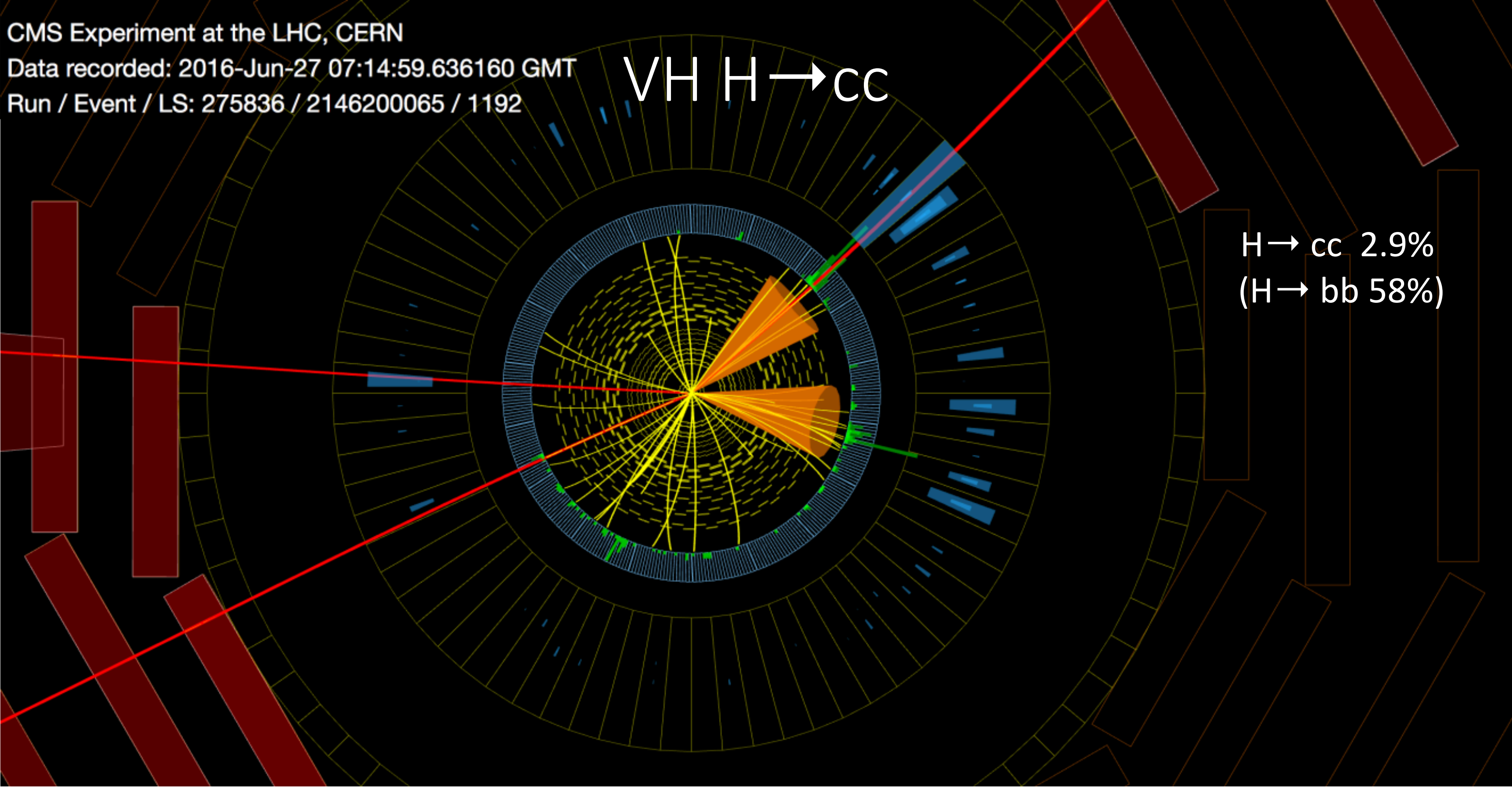




Signal presence in the VBF category extracted via direct fit to MVA output (includes $m_{\mu\mu}$) → MC backgrounds template

3.0σ - signal significance - 2.0σ

Fits to $m_{\mu\mu}$ distributions in 20 categories with varying purity → data-driven background



VH H→cc

H→ cc 2.9%
(H→ bb 58%)

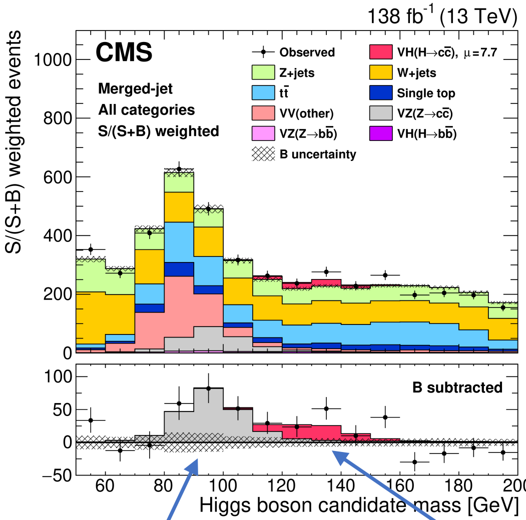
Higgs to charm

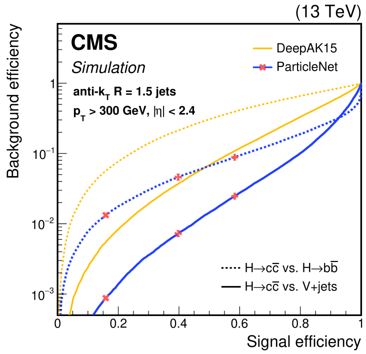
arXiv:2205.05550

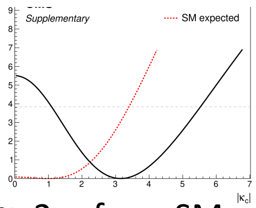
EPJC 82 (2022) 717

advancing with ML techniques

most sensitivity in merged-jet topology







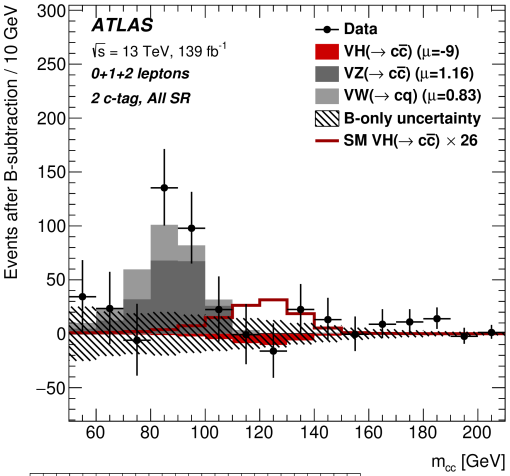
~>2σ from SM

$1.1<|\kappa_c| < 5.5$ @95%CL

VZ at 5.7σ significance

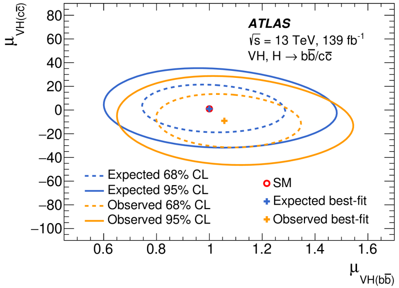
first observation of Z →cc at a hadronic collider.

VH signal $7.7^{+3.8}_{-3.5}$ SM



no merged-jet topologies

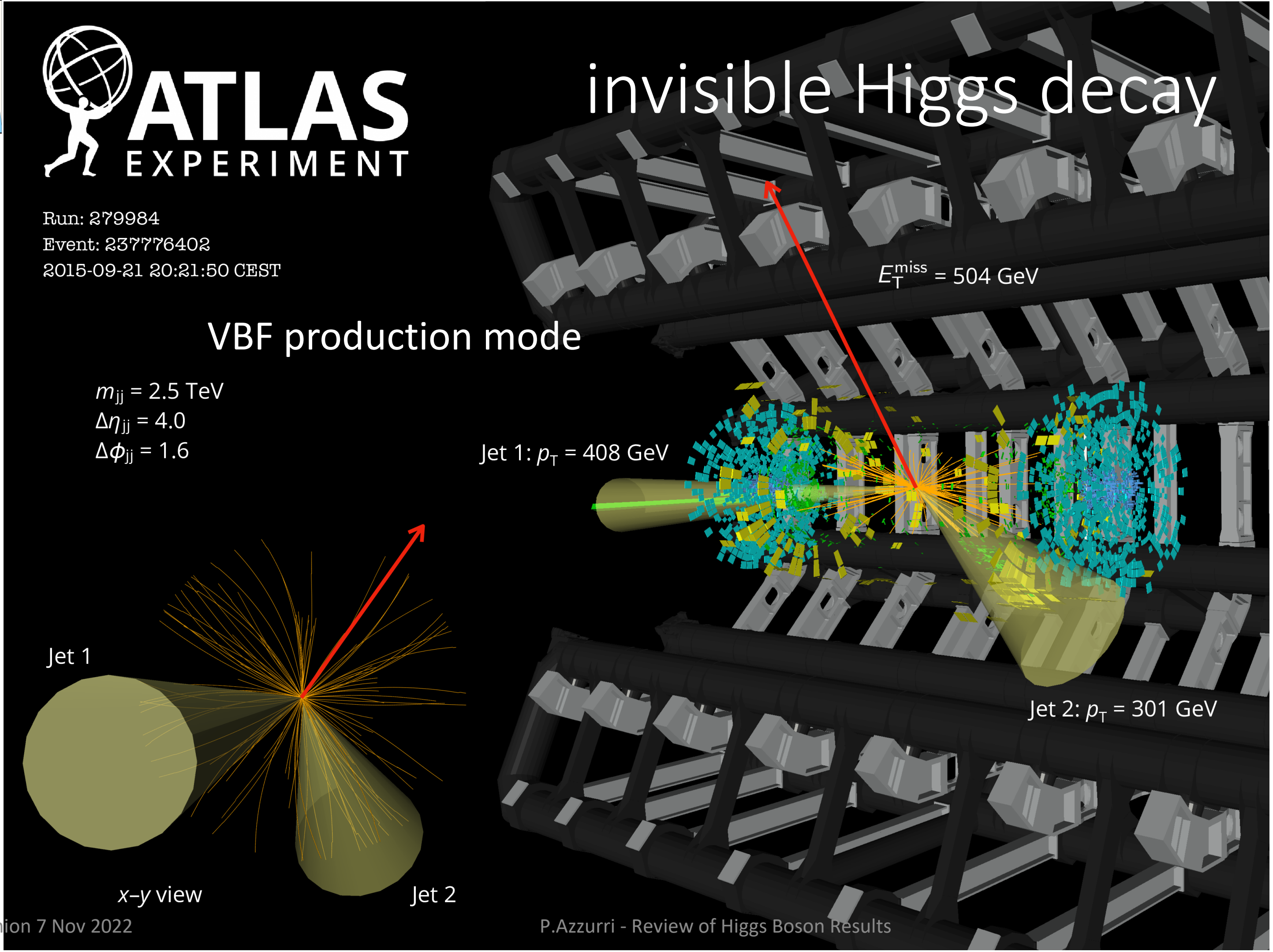
VH signal -9 ±16 SM



$|\kappa_c| < 8.5$ @95%CL

Simultaneous measurements of WW/WZ/ZZ and VH(bb)

invisible Higgs decay



invisible Higgs decays

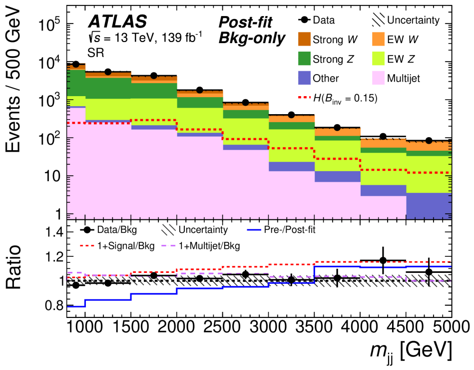
$B_{inv}^{SM} = 0.0012$

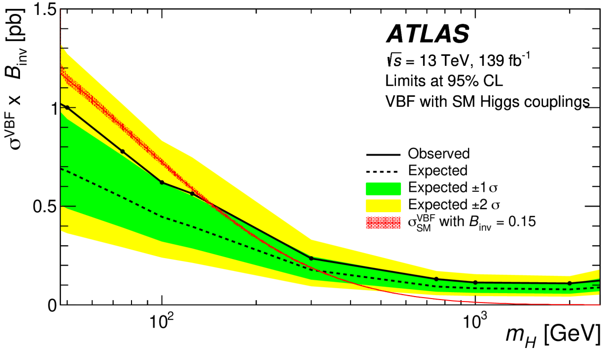
coupling to Dark Matter – Higgs boson portal

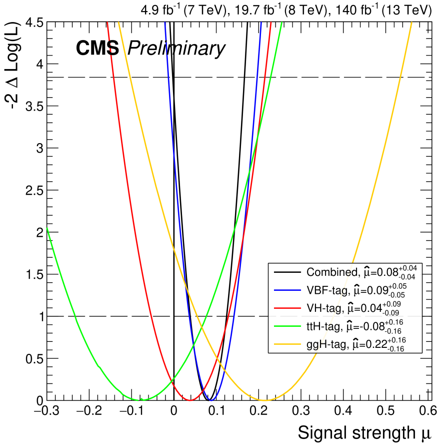
associated productions :
VBF most sensitive mode

dilepton, single lepton and single photon CRs

PRD 105 (2022) 092007 (VBF)
CMS-PAS-HIG-21-007 (comb)







JHEP 08 (2022) 104
PLB 829 (2022) 137066

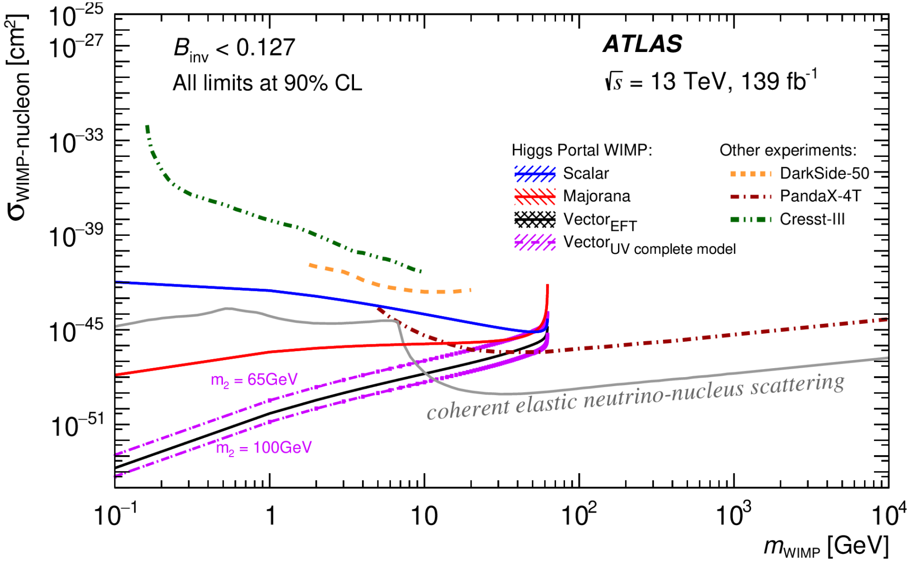
$B_{inv} < 0.14\ (0.10)$ @95% CL
$B_{inv} = 0.05 \pm 0.05$

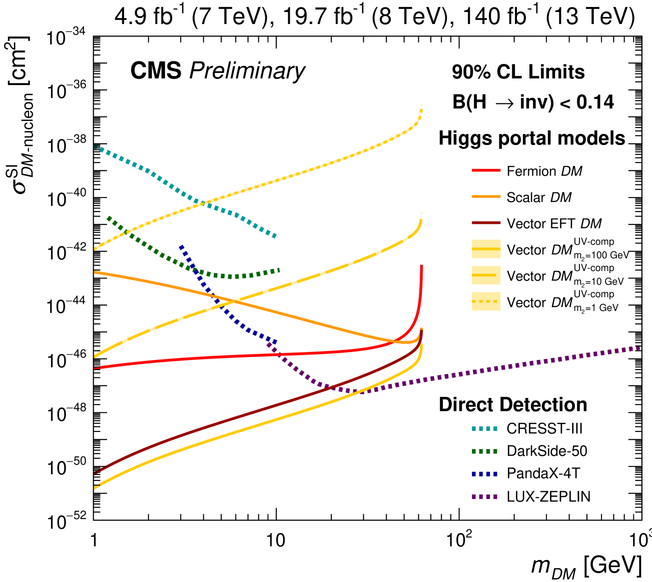
$B_{inv} < 0.15\ (0.08)$ @95% CL
$B_{inv} = 0.08 \pm 0.04$

invisible Higgs results & interpretations

	ATLAS (Run 1)	ATLAS (Run 2)	CMS (Run 1)	CMS (Run 2)
ggF (monojet); $H \to$ inv.	–	–	67 (71) %	66 (59)%
VBF; $H \to$ inv.	28 (31) %	13 (13) %	57 (40) %	33 (25) %
ZH; $Z \to \ell^+\ell^-$; $H \to$ inv.	75 (62)%	18 (18) %	75 (91) %	40 (42)%
VH; $Z, W \to jj$; $H \to$ inv.	78 (86)%	83 (58) %	–	50 (48)%
ZH; $Z \to b\bar{b}$; $H \to$ inv.	–	–	182 (189)%	–
$t\bar{t}H$; $H \to$ inv.	–	40 (36)%	–	46 (48)%
Combination	25 (27)%	13 (12)%	–	26 (20) %
Run 1 & 2 Combination	11 (11)%		19 (15)%	

many channels investigated

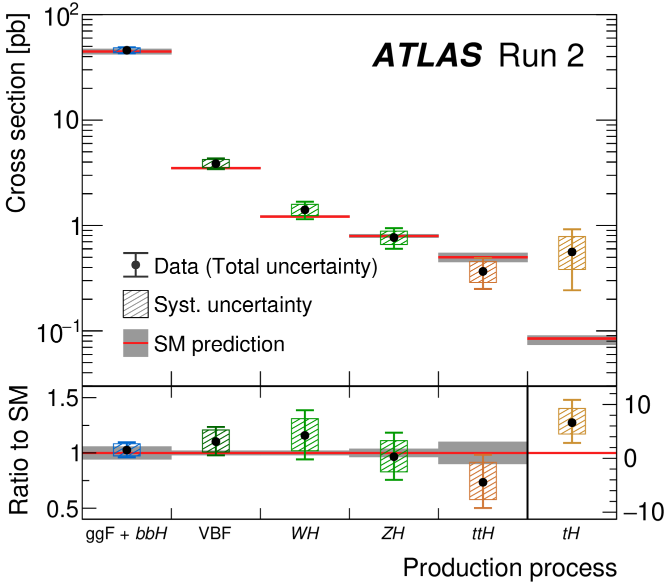


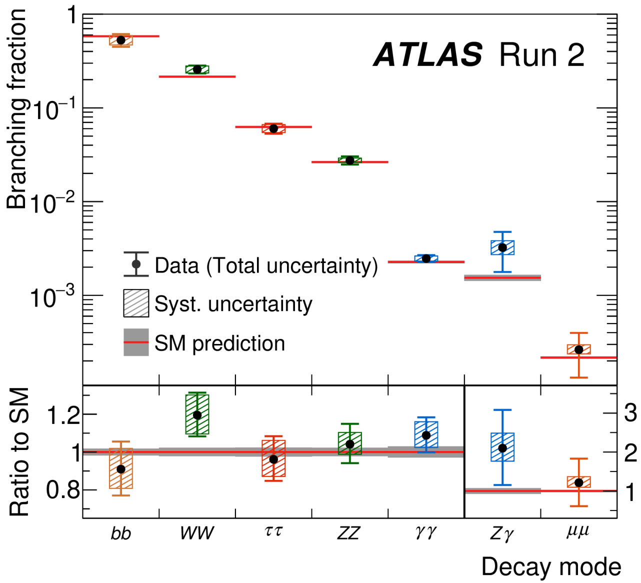


Higgs boson only mediator between the SM and DM

Run2 combined results

productions and decays





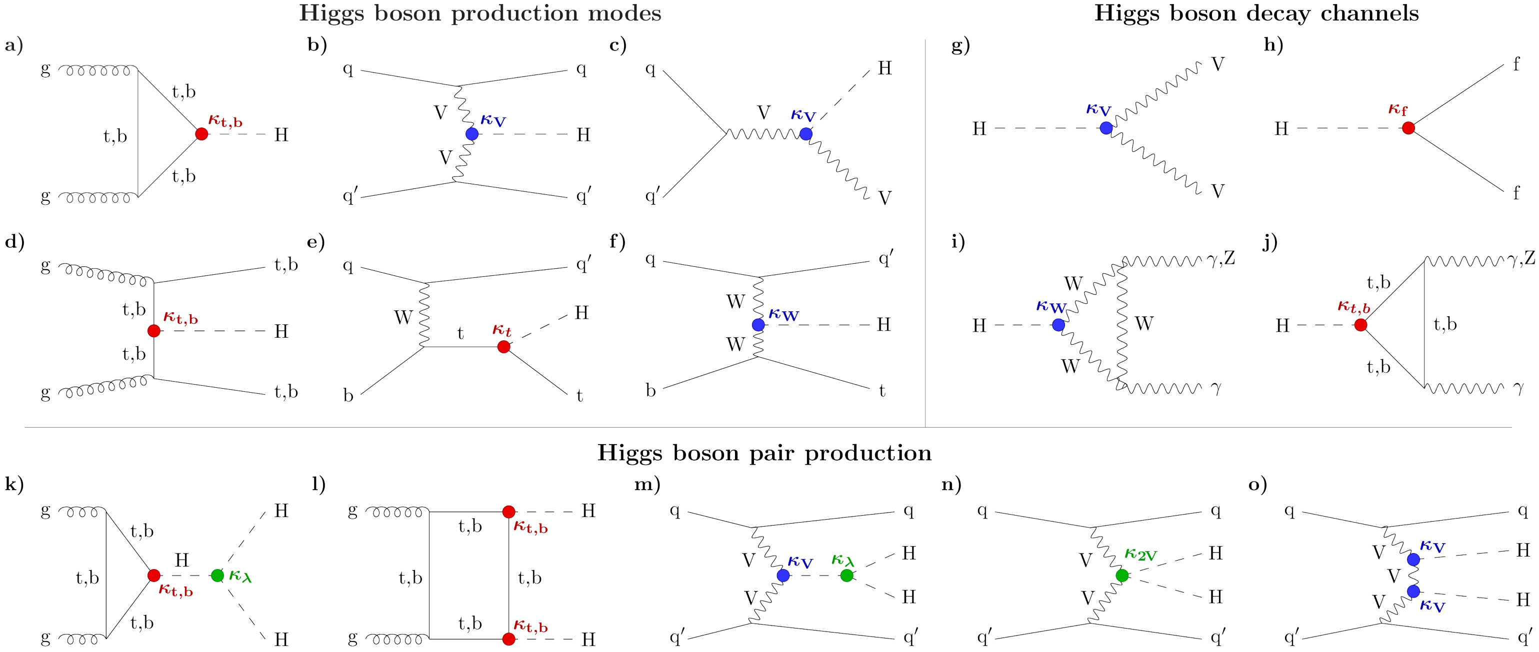
[Nature 607 (2022) 52-59]

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

ATLAS μ = 1.05 ± 0.04 (th) ± 0.03 (exp) ± 0.03 (stat)
CMS μ = 1.002 ± 0.036 (th) ± 0.033 (exp) ± 0.029 (stat)
similar th-exp-stat uncertainties : all improving wrt Run1 (≈1/2)

Combinations and interpretations

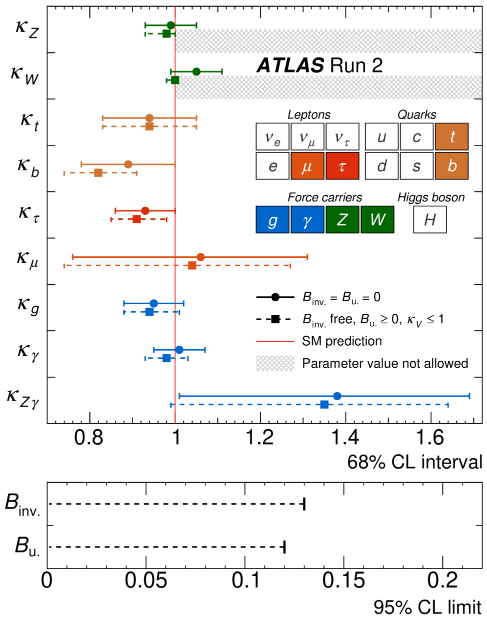
the *kappa* framework for couplings

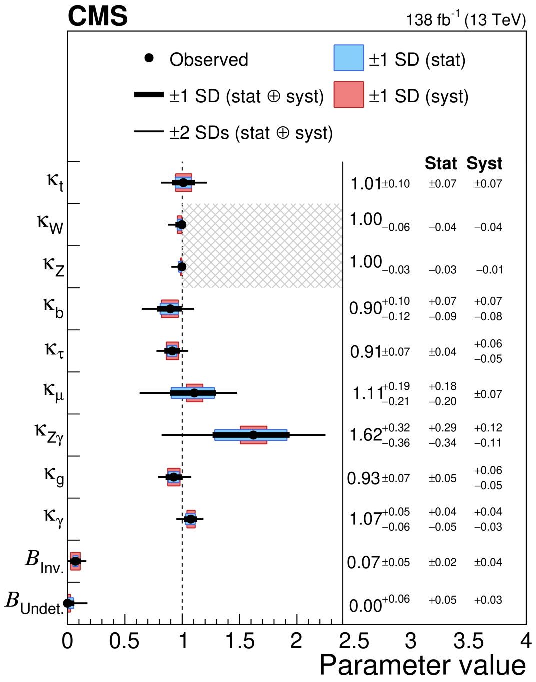


CERN-2013-004

can also account for invisible and undetected decays

Combinations and interpretations





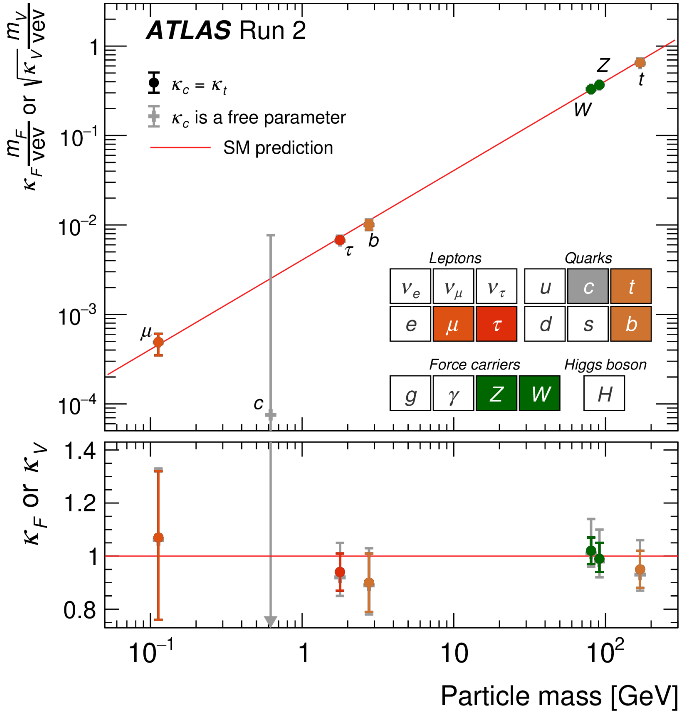
precision 3-10%

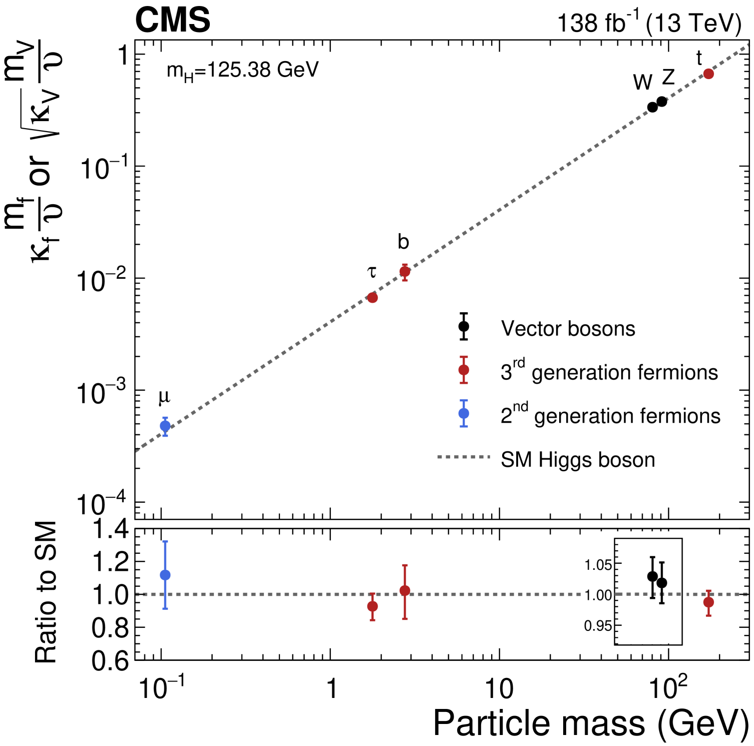
precision 5-10%
(BSM sensitivity)

Nature 607 (2022) 52-59

Nature 607 (2022) 60-68

Higgs boson couplings vs mass

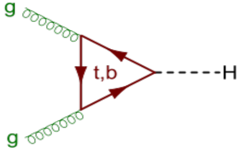


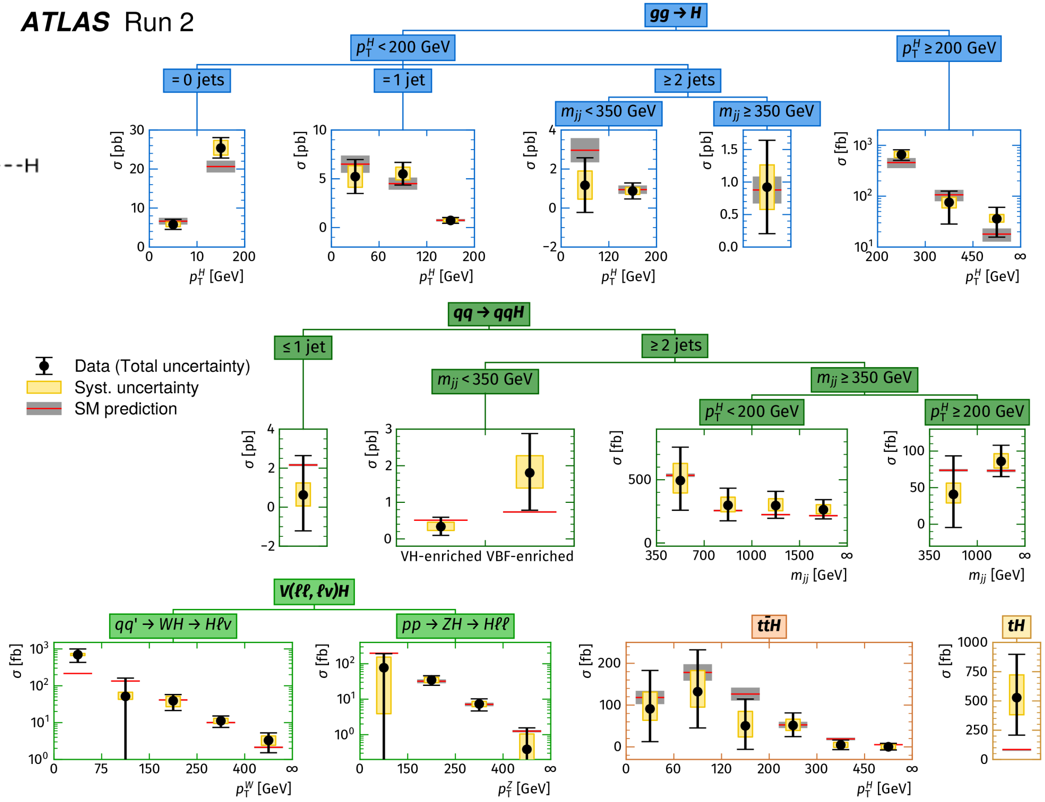


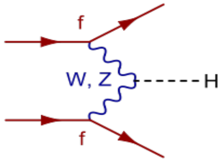
tested over four orders of magnitude

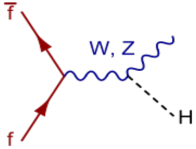
Differential measurements and interpretations

Simplified Template Cross Section



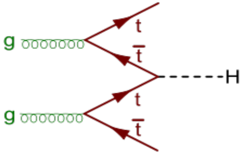






Higgs boson production in exclusive modes and phase space region.

Inclusive in decay modes



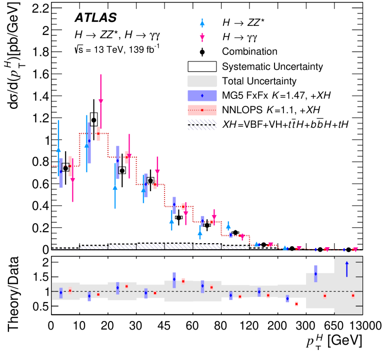
Nature 607, 52-59 (2022)

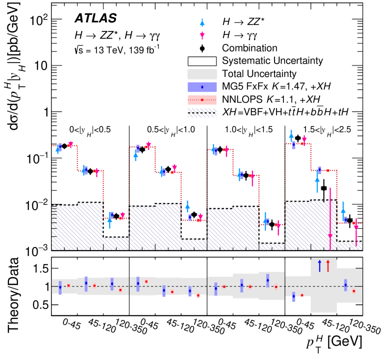
other differential measurements

H→$\gamma\gamma$+4ℓ

arXiv:2207.08615

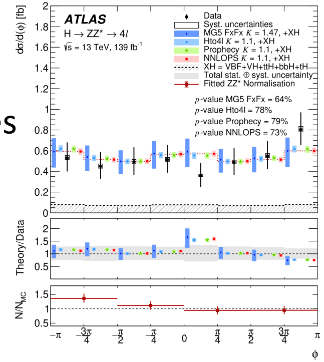
Double differential



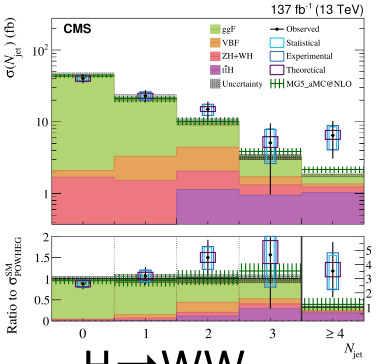


angle between ZZ* decay planes

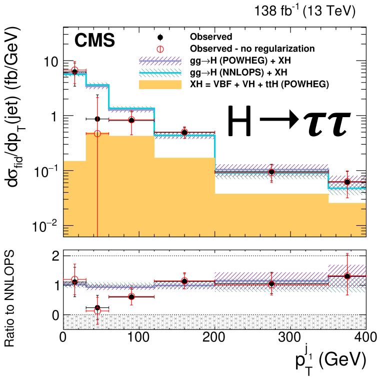
EPJC 80 (2020) 942



JHEP 03 (2021) 003



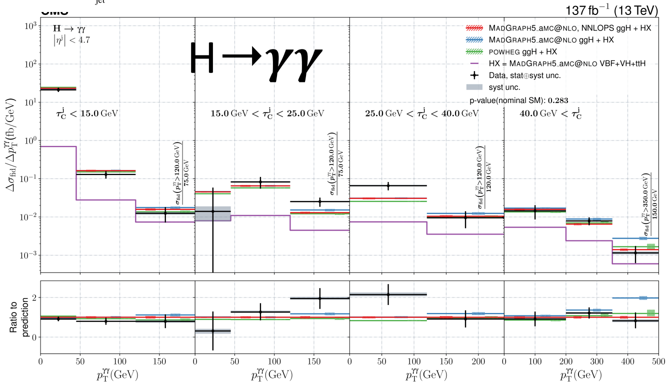
H→WW



H→$\tau\tau$

arXiv:2208.12279

JHEP 03 (2021) 003



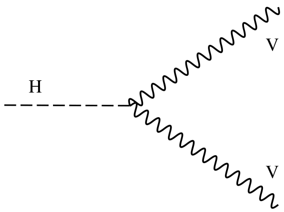
H→$\gamma\gamma$

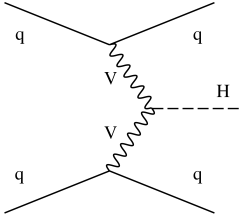
distinction between inclusive and associated (XH) productions

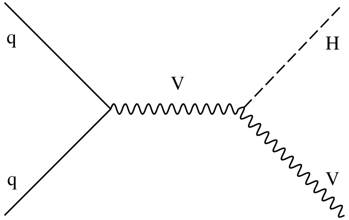
Double differential

τ_C event shape (correlated with p_T)

Anomalous couplings / EFT







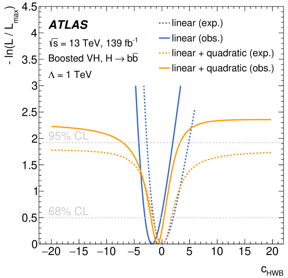
SMEFT

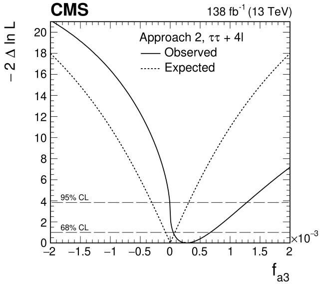
arXiv:2205.05120

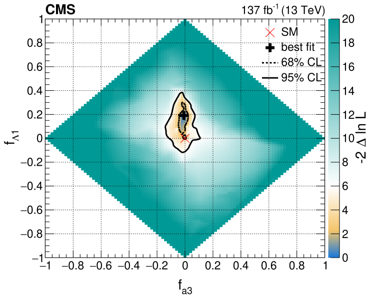
PRD 104 (2021) 052004

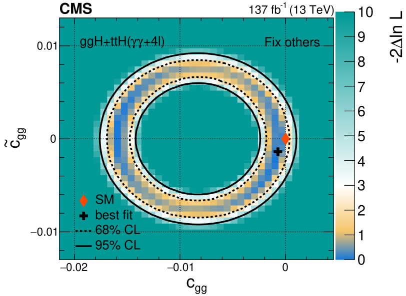
PLB 816 (2021) 136204

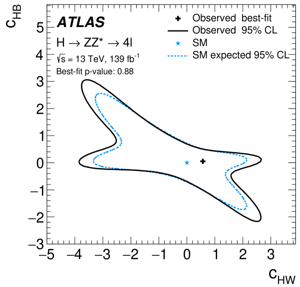
EPJC 80 (2020) 957

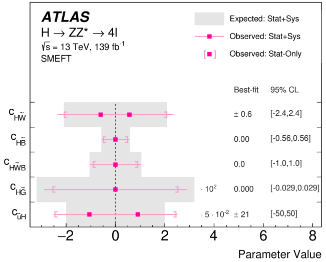










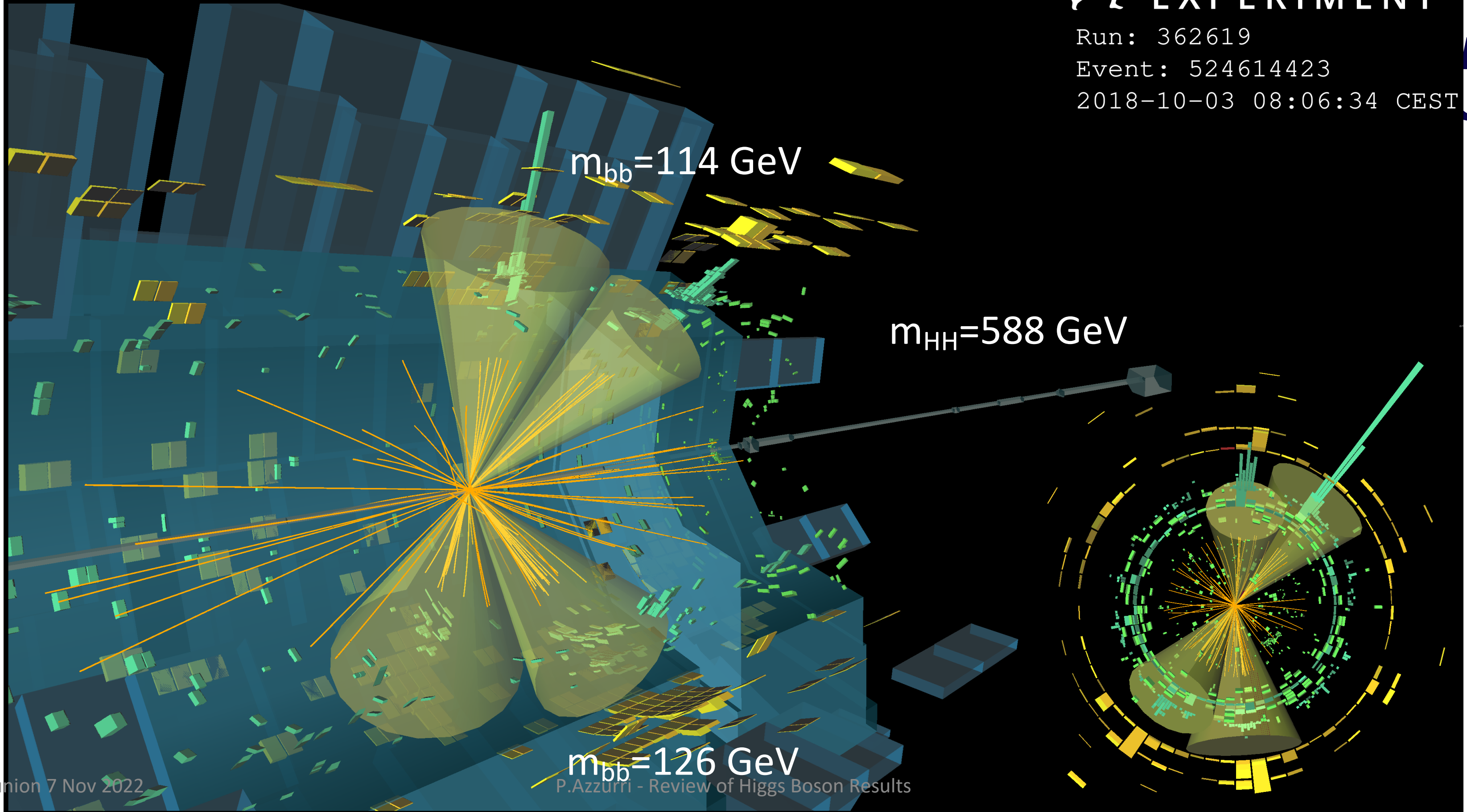


sensitivity to many other operators combined with EW measurements

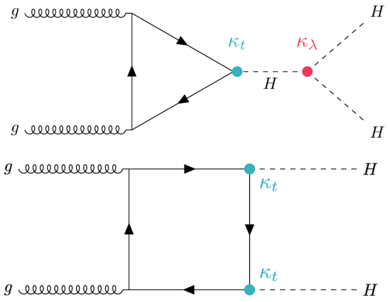
ATL-PHYS-PUB-2022-037

Double Higgs

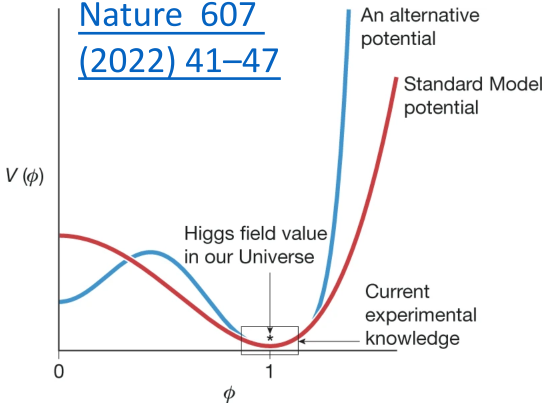
Double-Higgs HH→bbbb



Double-Higgs production & λ

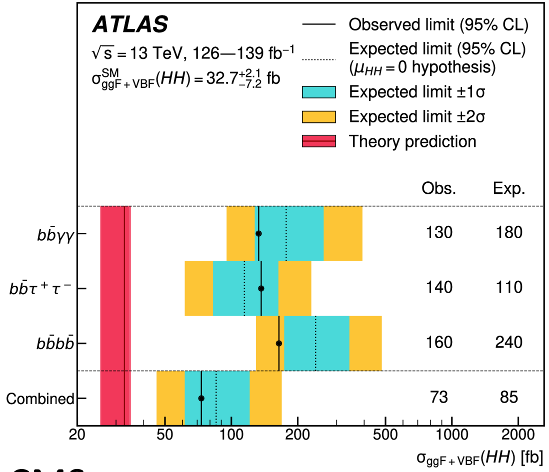


[Nature 607 (2022) 41–47]

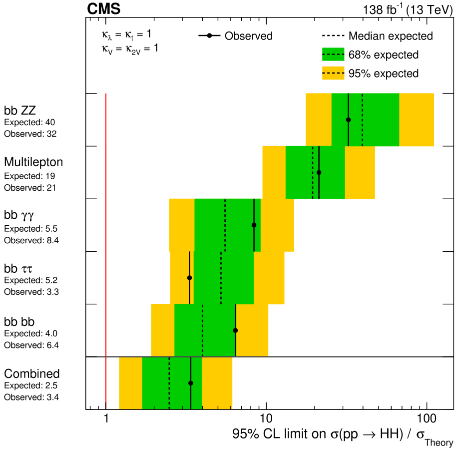


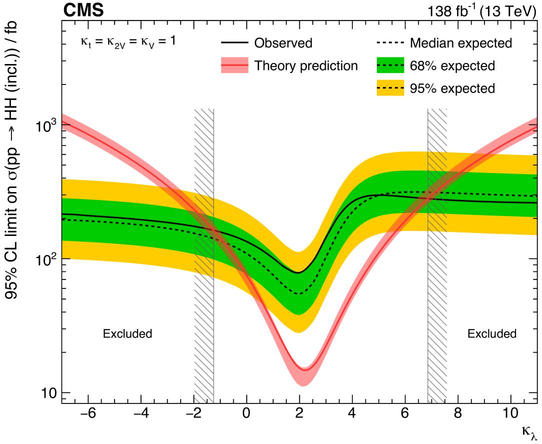
$$V(\phi) = \frac{1}{2} m_{\mathrm{H}}^2 \phi^2 + \sqrt{\lambda/2}\, m_{\mathrm{H}} \phi^3 + \frac{1}{4} \lambda \phi^4$$

[ATLAS-CONF-2022-050]



[Nature 607 (2022) 60-68]





CMS

μ_{HH} ~+1±1

$-1.2 < \kappa_\lambda < 6.5$ (95%CL)

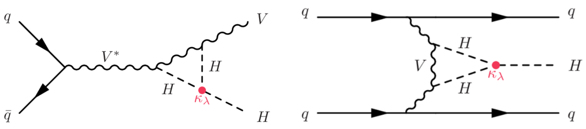
ATLAS

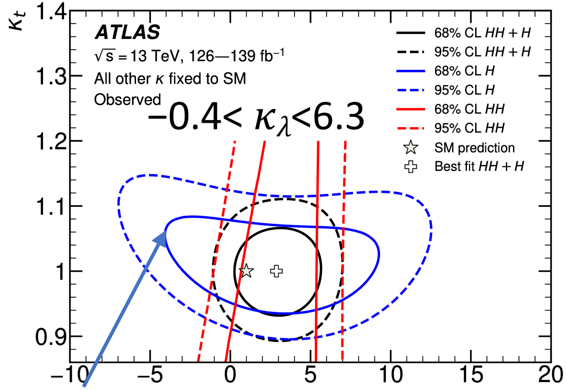
$\mu_{HH} = -0.73 \pm 1.25$

$-0.6 < \kappa_\lambda < 6.6$ (95%CL)

Double-Higgs production & λ

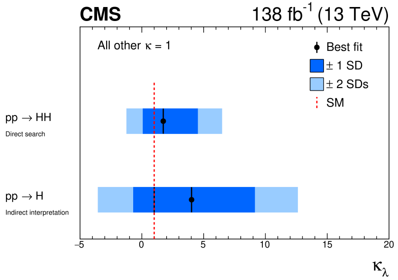
Higher order λ effects



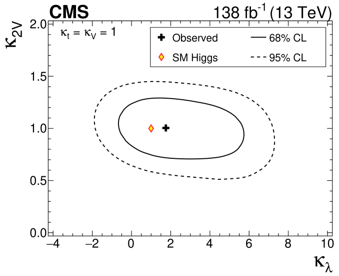


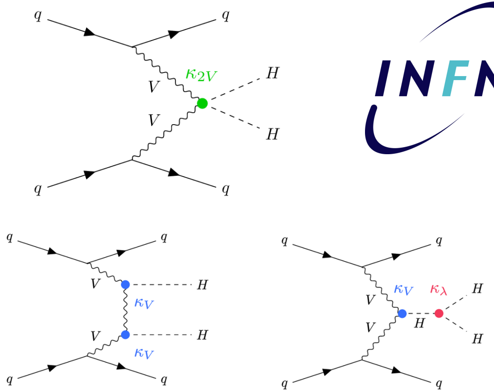
$-0.4 < \kappa_\lambda < 6.3$

indirect λ determinations (can be refined)

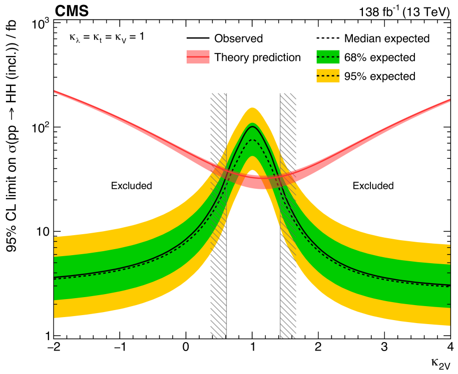


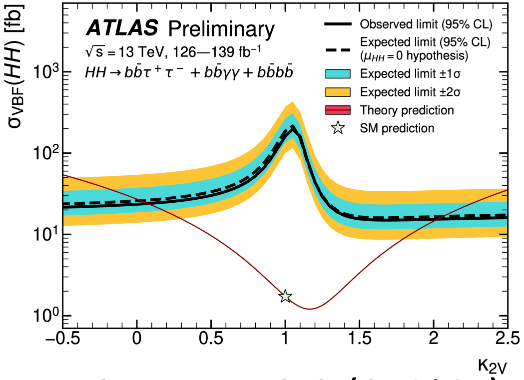
HH+2 jets





κ_{VV}=0 at 6.6σ



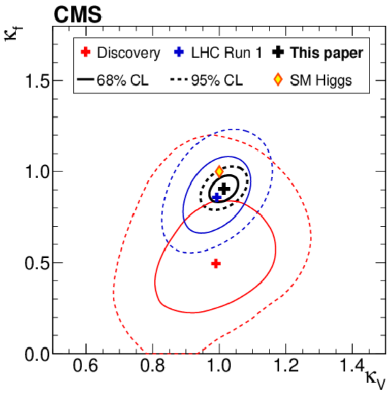


$0.67 < \kappa_{VV} < 1.38$ (95%CL)

$0.1 < \kappa_{VV} < 2.0$ (95%CL)

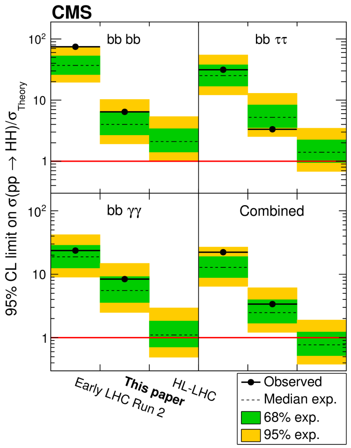
The Future

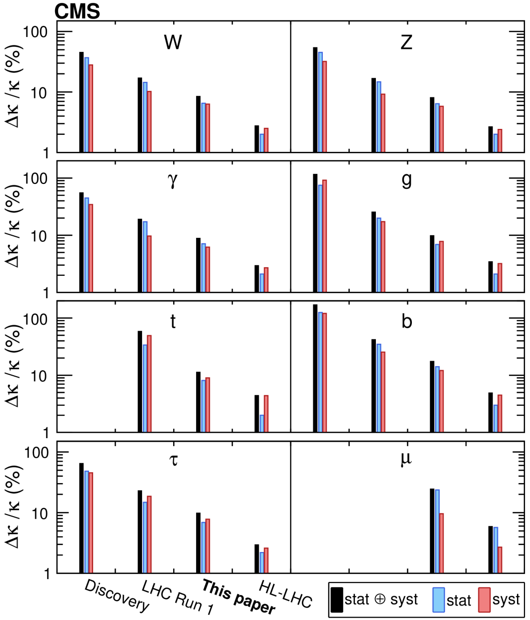
HL-LHC projections

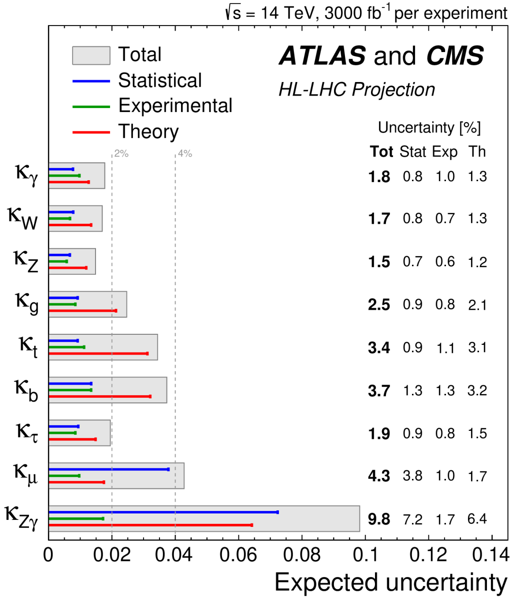


CERN-LPCC-2018-04

Snowmass White Paper
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001





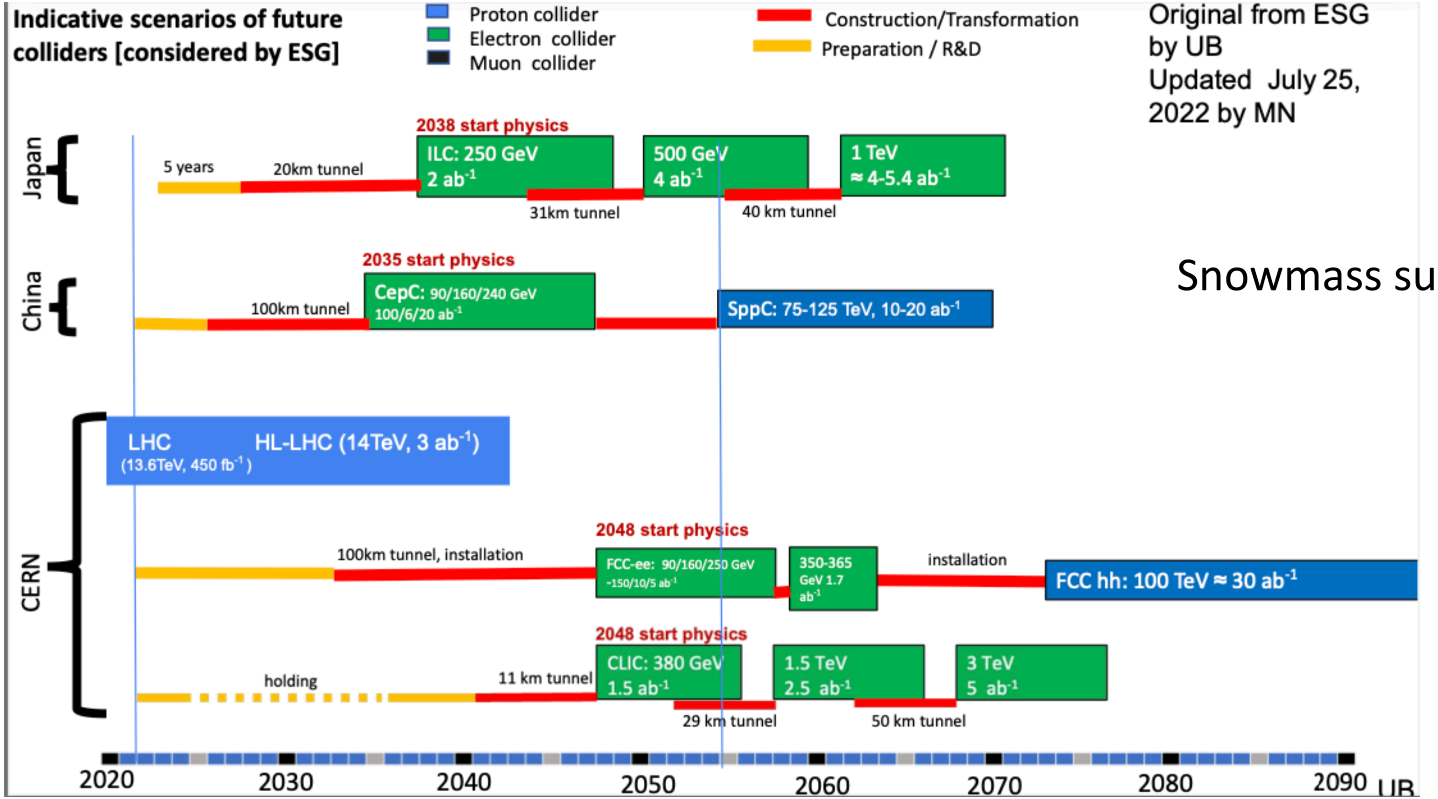


ATLAS + CMS could reach 5σ on SM λ

various scenarios are considered

dominant TH uncertainties expected

Higgs factories

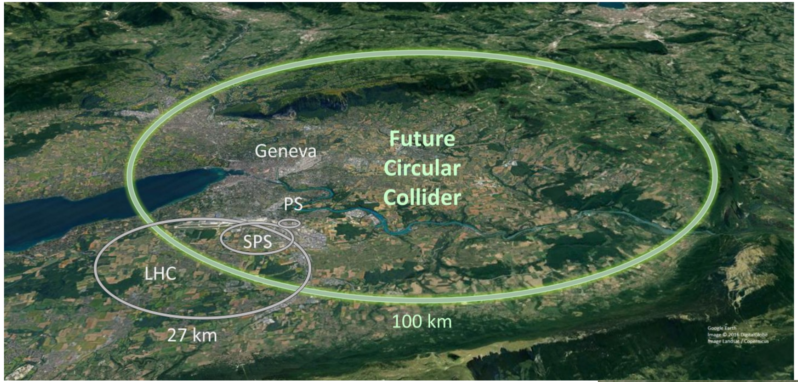


Original from ESG by UB
Updated July 25, 2022 by MN

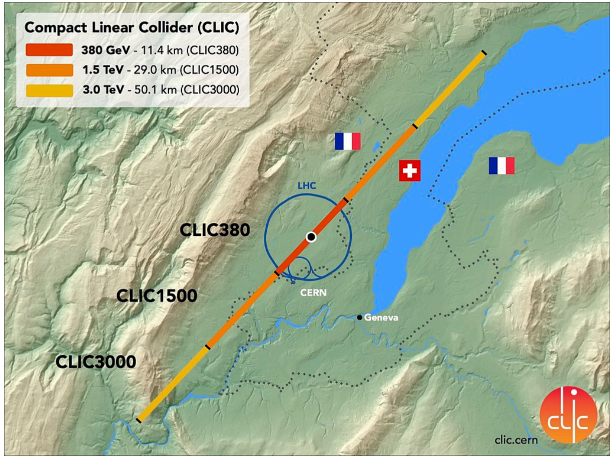
Snowmass summary

Higgs factories

L=30-50km



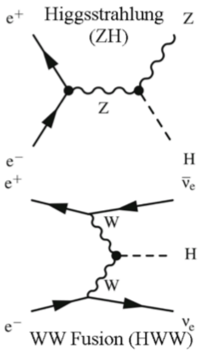
C=90-100Km

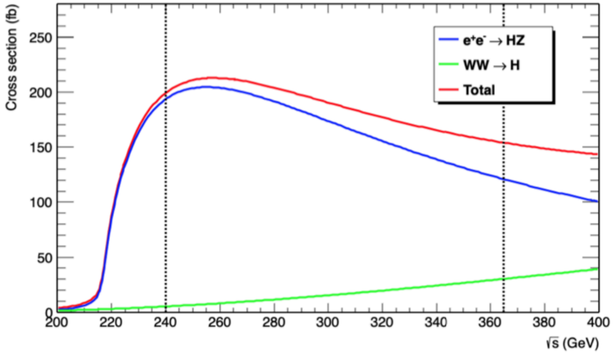


+ CCC & μ-collider options

Higgs factories

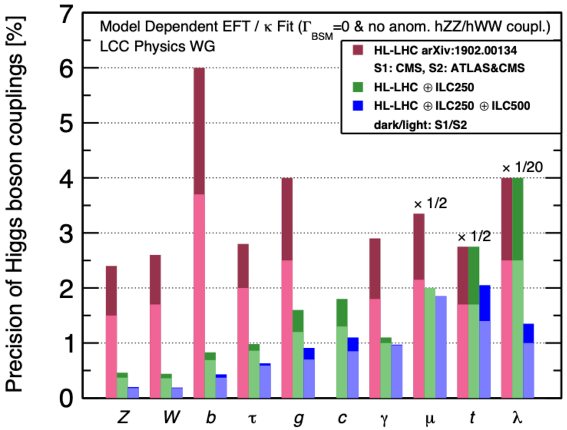
FCCee/CEPC





Collider	HL-LHC	FCC-ee$_{240\to365}$	FCC-INT
Lumi (ab^{-1})	3	5 + 0.2 + 1.5	30
Years	10	3 + 1 + 4	25
g_{HZZ} (%)	1.5	0.18 / 0.17	0.17/0.16
g_{HWW} (%)	1.7	0.44 / 0.41	0.20/0.19
g_{Hbb} (%)	5.1	0.69 / 0.64	0.48/0.48
g_{Hcc} (%)	SM	1.3 / 1.3	0.96/0.96
g_{Hgg} (%)	2.5	1.0 / 0.89	0.52/0.5
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74 / 0.66	0.49/0.46
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9 / 3.9	0.43/0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9 / 1.2	0.32/0.32
$g_{\mathrm{HZ}\gamma}$ (%)	11.	– / 10.	0.71/0.7
g_{Htt} (%)	3.4	10. / 3.1	1.0/0.95
g_{HHH} (%)	50.	44./33. 27./24.	3-4
Γ_{H} (%)	SM	1.1	0.91
$\mathrm{BR}_{\mathrm{inv}}$ (%)	1.9	0.19	0.024
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	SM (0.0)	1.1	1

ILC



improvements of 1-2 orders of magnitude for several Higgs properties determinations

$\boldsymbol{\lambda}$ from single-H corrections or $E_{CM}\gtrsim 500$ GeV

model independent access to couplings

Conclusions

- The discovery of the Higgs boson has been an fantastic event of incredible value : a great **success of a community** of thousands of physicists.
- In the following (last) 10 years the LHC evolved **to precision Higgs physics**
- Experiments have done **better than predicted**, both on analysis techniques and understanding detector uncertainties.
- Theory predictions have equally improved beyond expectations, enabling stringent comparisons. Overall **agreement with minimal SM predictions is excellent**.
- The **LHC** (Run3 + HL) will remain **at the forefront of future Higgs boson measurements**. An *e+e- Higgs factory* is the next highest priority for particle physics.
- Higgs physics remains as a vibrant field of particle physics, in which *many interesting results and surprises may lay ahead*

Thank you