Higgs results:
From the discovery to precision physics

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SPP2022 – Vienna

The BEH field

It permeates the entire universe

It gives mass to the elementary particles:

- EM and the weak interactions become distinct in their actions
- Without it, the universe would look very different

The Higgs boson

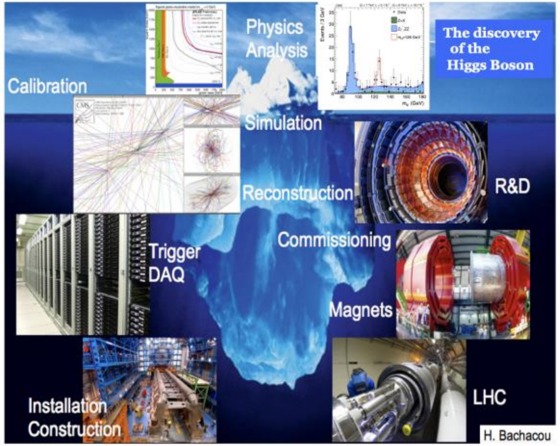
It is the only elementary particle that does not spin

It has zero electric charge

It is even under parity and charge conjugation

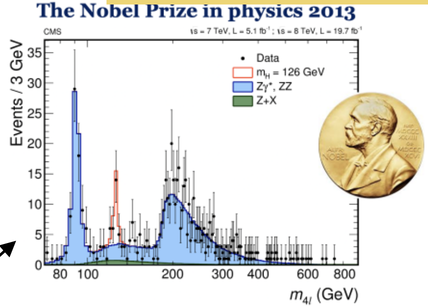
The long road of the Higgs boson: a worldwide effort

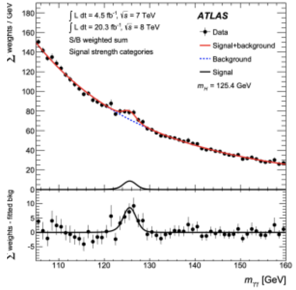
54 Yang & Mills
61 Glashow
64 Brout, Englert, Higgs et al
67-68 Weinberg and Salam
70 't Hooft and Veltman
73 Gargamelle : discovery of the weak neutral current
83: Ua1 & UA2: W and Z discovery
89-2000: LEP and HERA: the triumph of the SM
95: Tevatron: top quark discovery
2012: LHC: discovery of a Higgs like boson



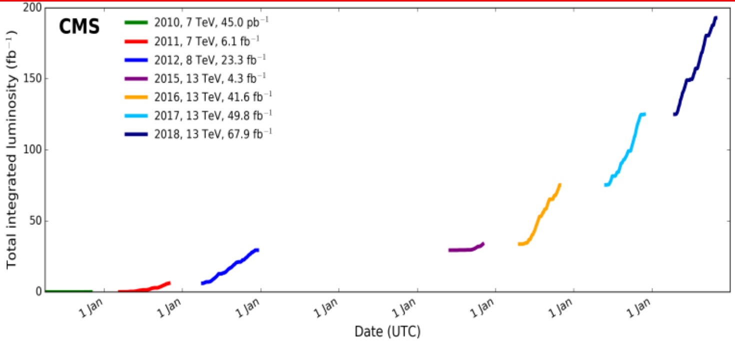
Superb detector performance

The Nobel Prize in physics 2013





Amazing **LHC**: from 7 to 13 TeV, L >140 fb^{-1}



The LHCHXSWG

The WLCG

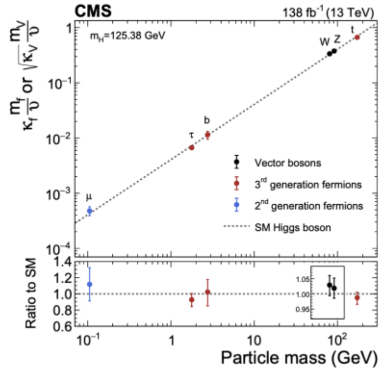
Run2 wrt Run1

Lumi ×10 more

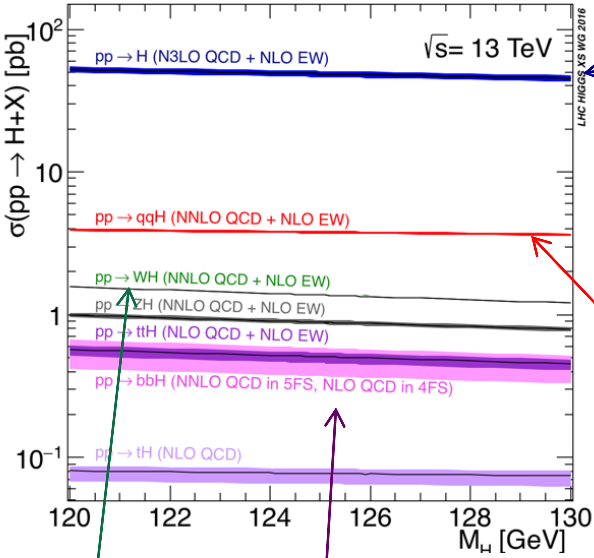
σ ×2−4 larger

Higgs ×30 more

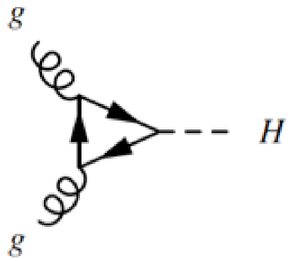
PRECISE MEASUREMENTS

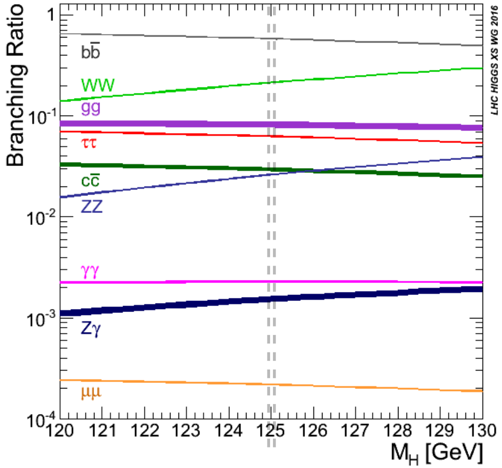


Cross Sections & BR: the LHCHXSWG results - 2017

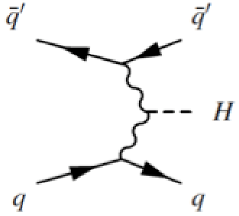


ggF: NNNLO+NNLL QCD + NLO EW



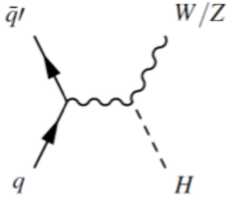


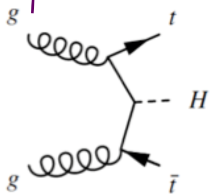
qqH: NNLO QCD + NLO EW



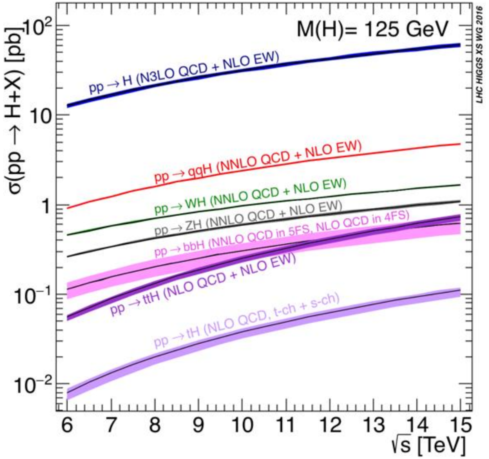
WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW





ttH: NLO QCD



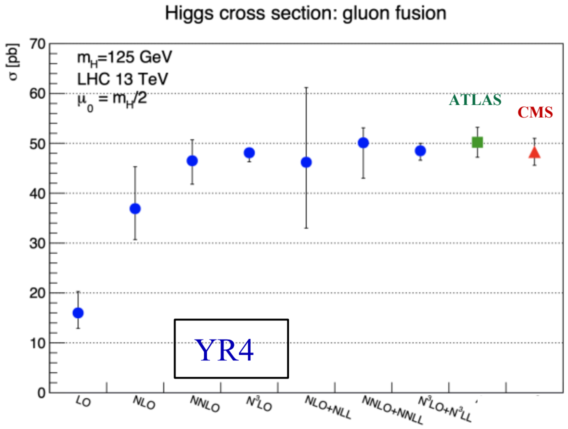
From 8 to 13 TeV

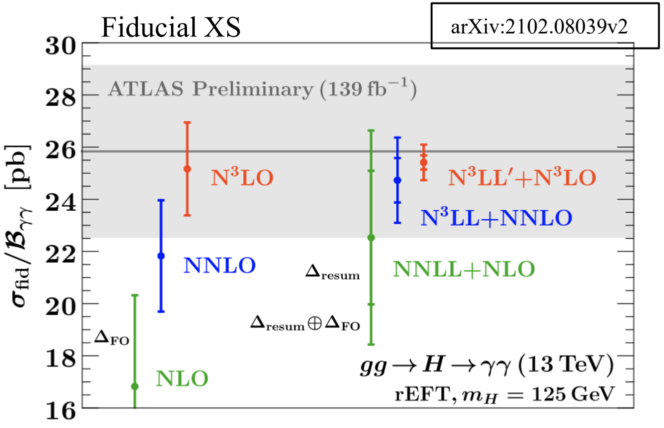
σ (ggF, VBF, VH) ~2 times larger

σ(ttH) ~4 times larger

The huge leap of theoretical calculations

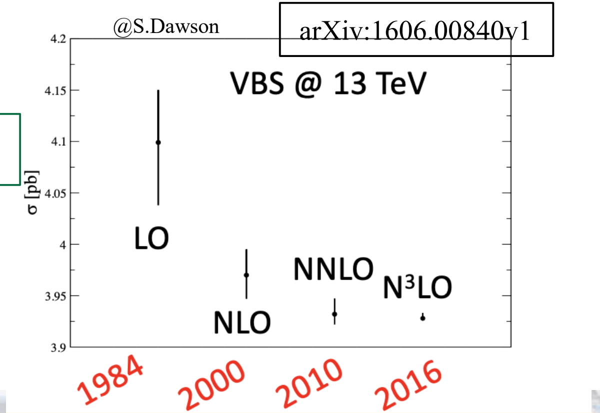
ggH





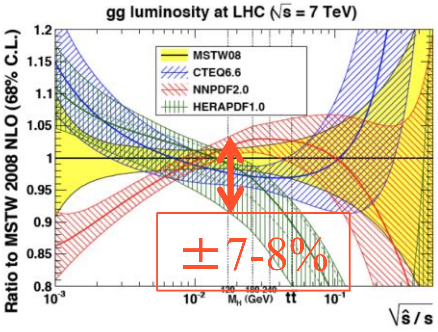
LHCHXSWG

qqH

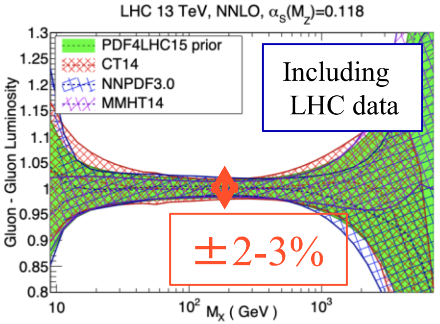


PDF

A huge improvement in the gluon PDF understanding

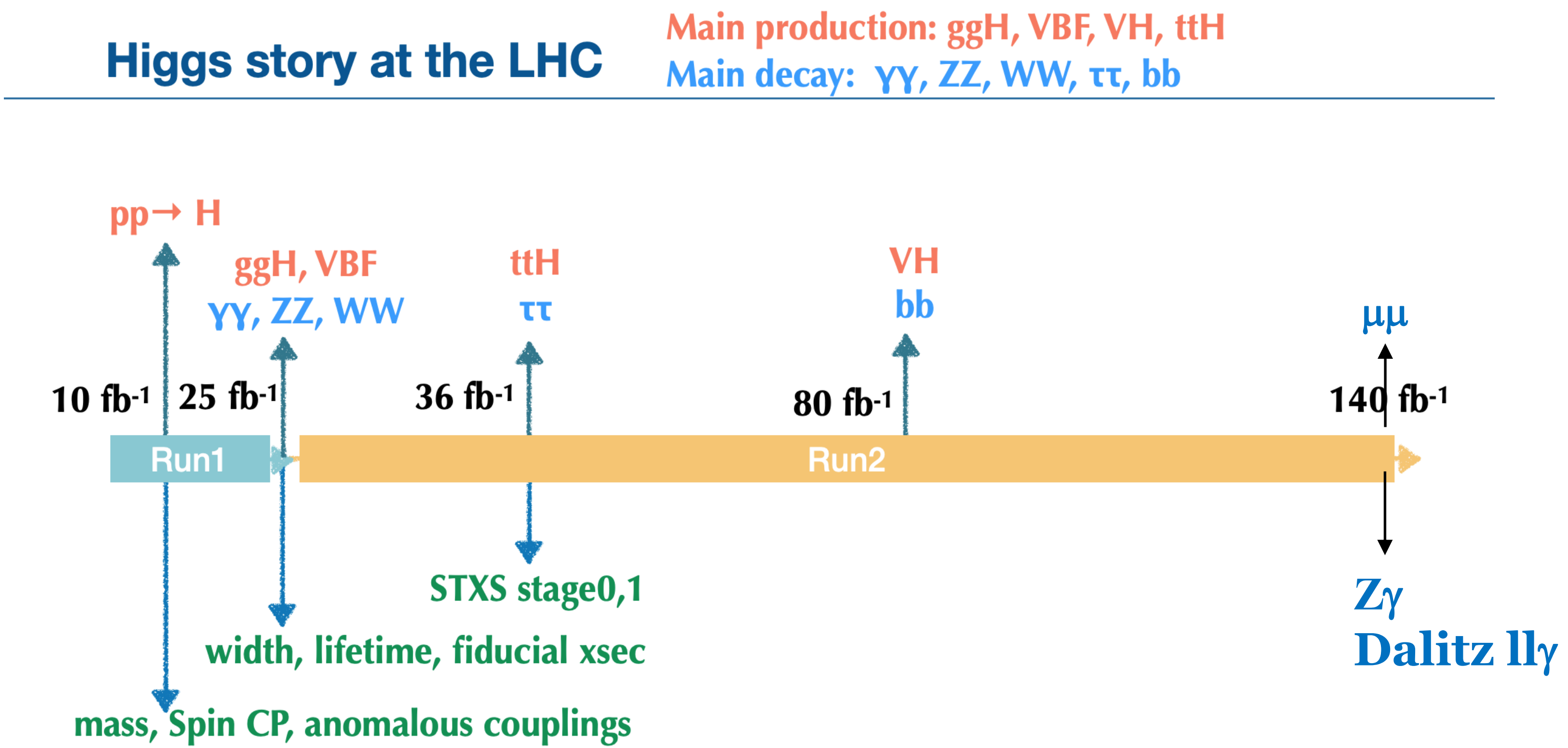


PDF4LHC-2011



PDF4LHC 2022

From the 4 of July 2012 to the end of Run2



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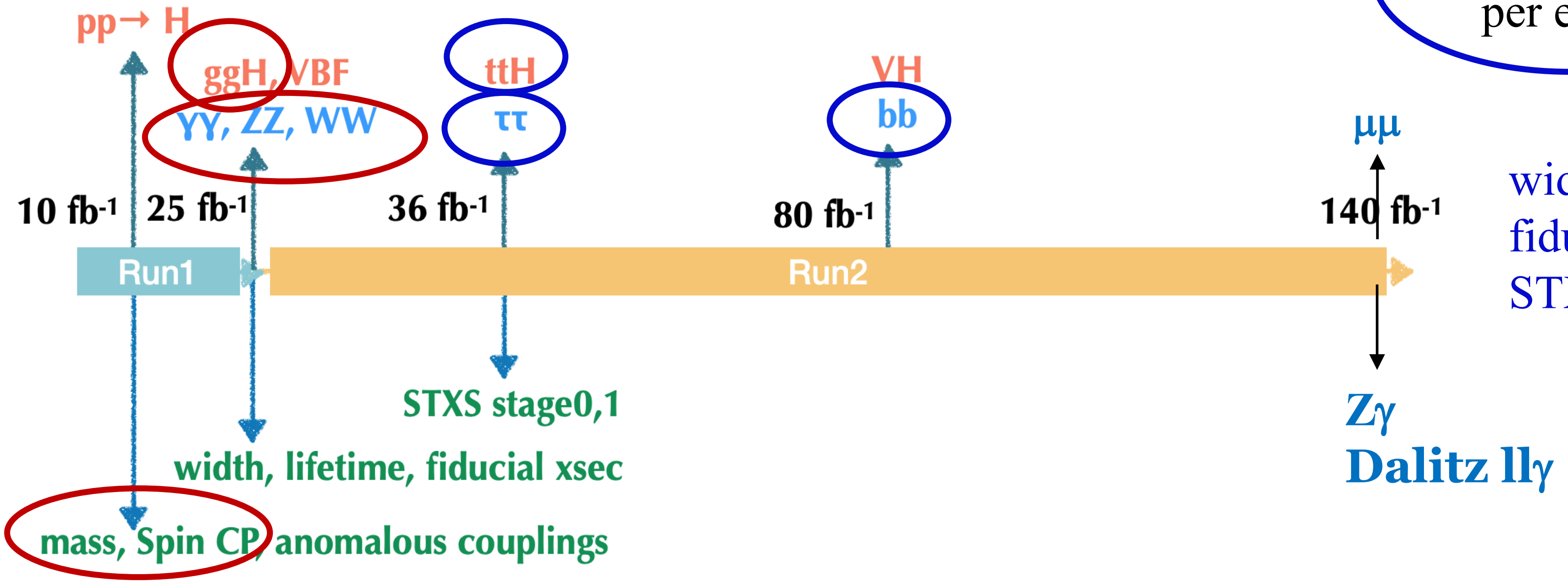
From the 4 of July 2012 to the end of Run2

~ 5% precision per exp.

Higgs story at the LHC

Main production: ggH, VBF, VH, ttH
Main decay: γγ, ZZ, WW, ττ, bb

~10% precision per exp.



width
fiducial xsec
STXS

The Higgs mass from $\gamma\gamma$ and 4l decay channels

Once the mass is known, all other properties are precisely defined.

$\gamma\gamma$

$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})$$

Choice of the primary vertex

Energy calibration

4 leptons: mass measurement performed with a 3D fit

- four –lepton invariant mass $\mathbf{m_{4l}}$
- associated per-event mass uncertainty $\delta \mathbf{m_{4l}}$
- kinematic discriminant MELA/NN

→ lepton momentum scale

ATLAS+CMS Run1	125.09 ± 0.24	(± 0.21 stat ± 0.11 syst) GeV
CMS Run1 + 2016	125.38 ± 0.14	(± 0.11 stat ± 0.08 syst) GeV
ATLAS *4l* Run1+Run2	124.94 ± 0.17	(± 0.17 stat ± 0.03 syst) GeV

1 per mille precision

The Higgs width from off-shell production

A real breakthrough after the discovery of the Higgs !

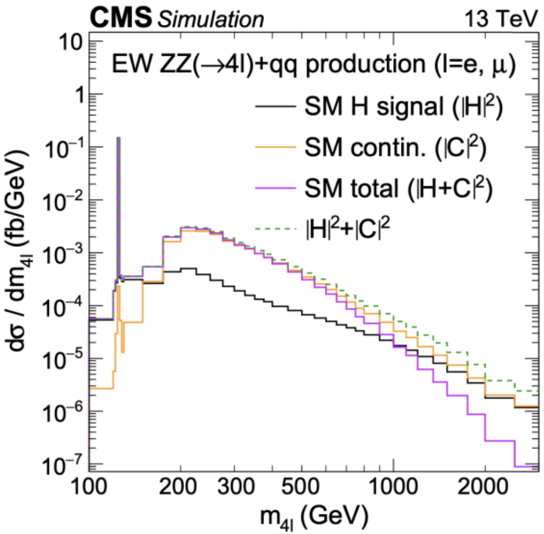
Kauer, Passarino: JHEP 1208 (2012) 116, Caola, Melnikov: Phys. Rev. D88 (2013) 054024

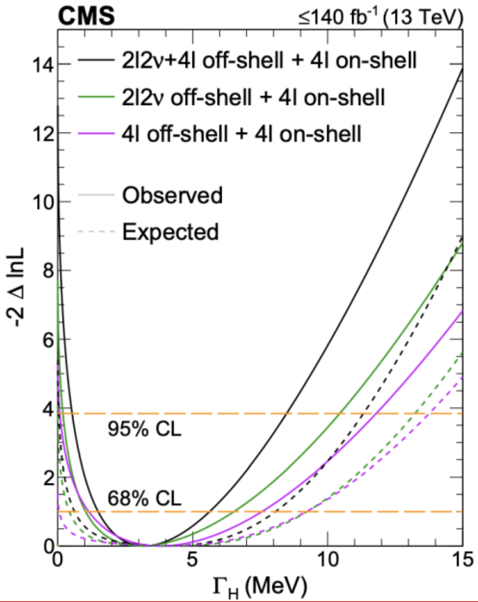
arXiv:2202.06923

Off-shell Higgs boson production is small but the BR to 2 real Z is large above $2m_Z$

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

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



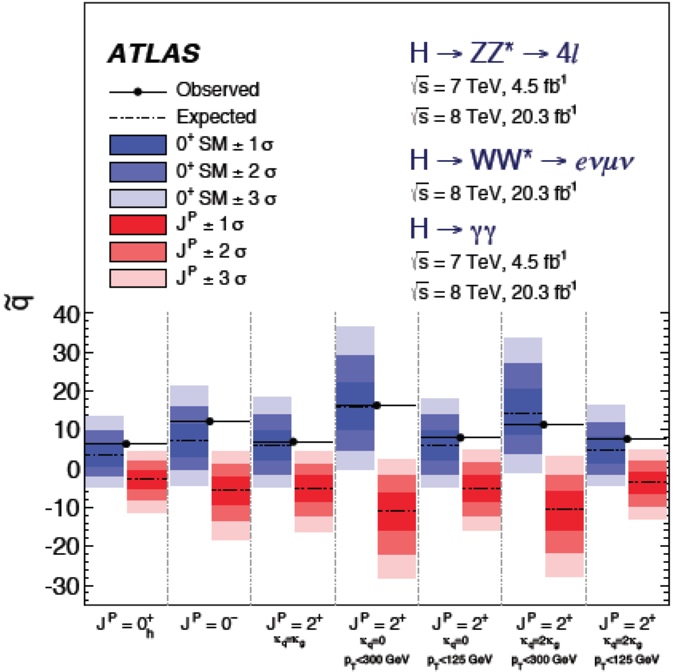


$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

This method assumes that the couplings at the pole and off-shell are the same

SM Higgs Spin and CP properties: J^{PC}

ATLAS and CMS many analyses, lots of results	→	**Spin 0 Positive parity at > 99.9% CL**

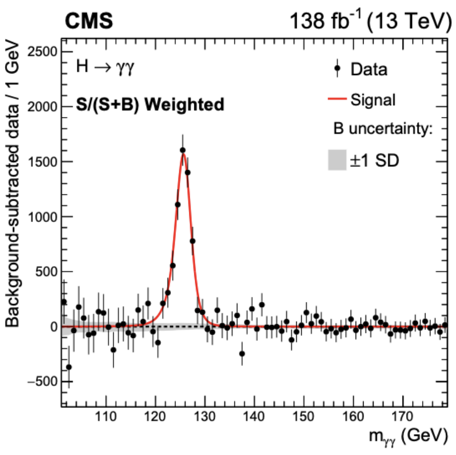


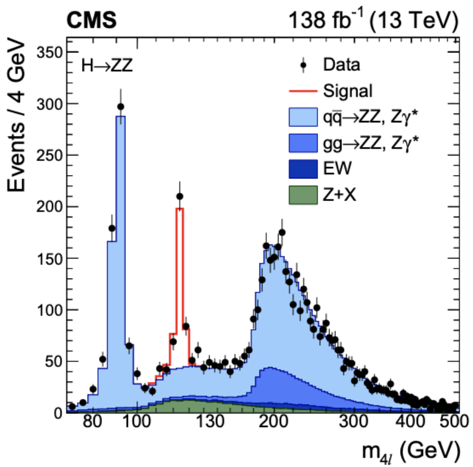
CP structure of various Higgs couplings probed for fermions (top, τ), gluons, EW vector bosons, with a variety of production and decay modes

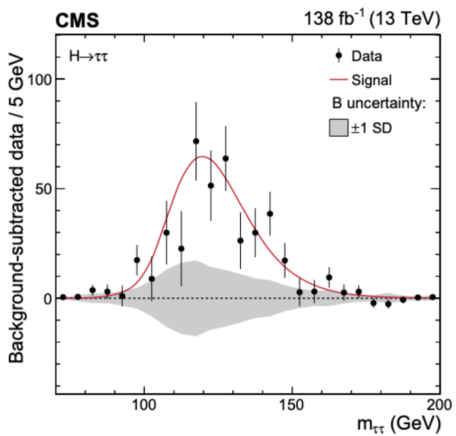
- Measurement globally in accord with SM CP-even hypothesis
- Pure CP-odd ttH coupling excluded 3.9 σ
- Pure CP-odd Hττ coupling excluded 3.4 σ

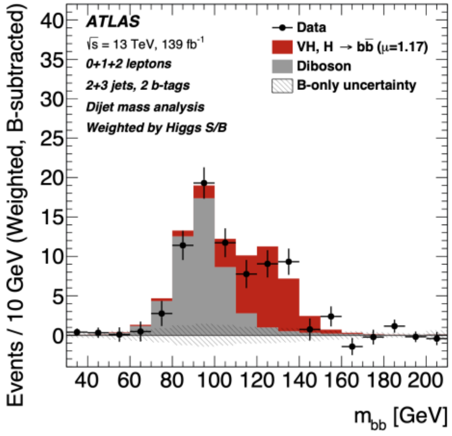
Bosonic channels

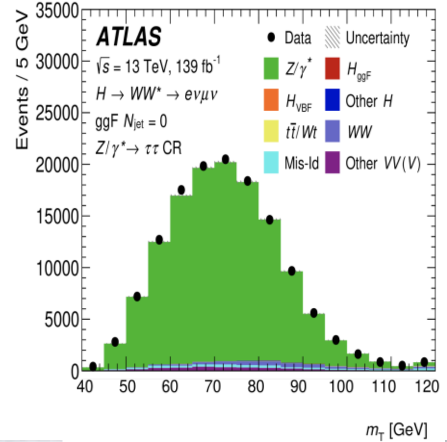
Fermionic channels

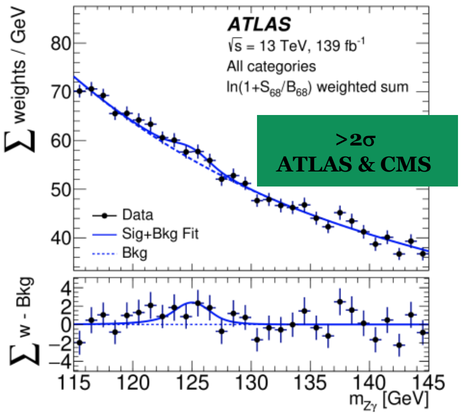


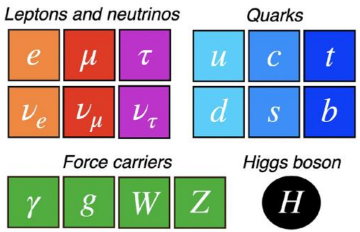


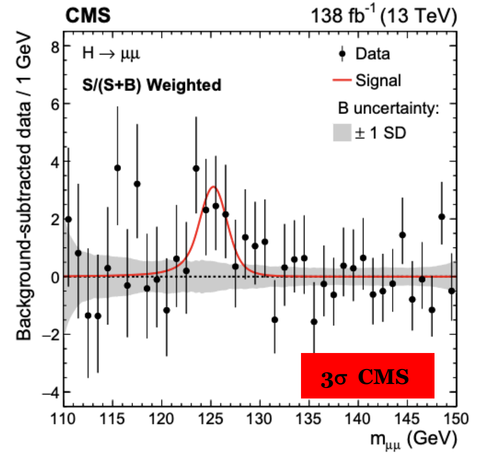




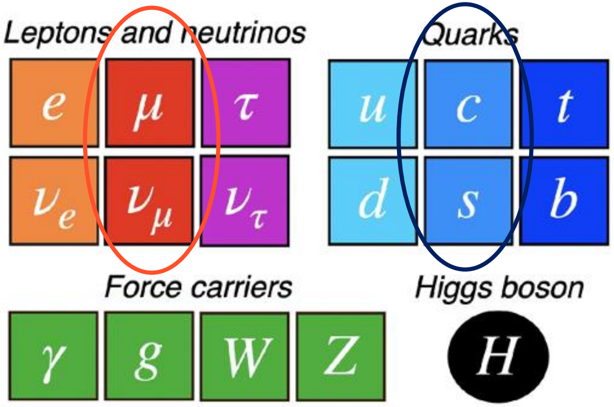








The coupling with the 2 generation

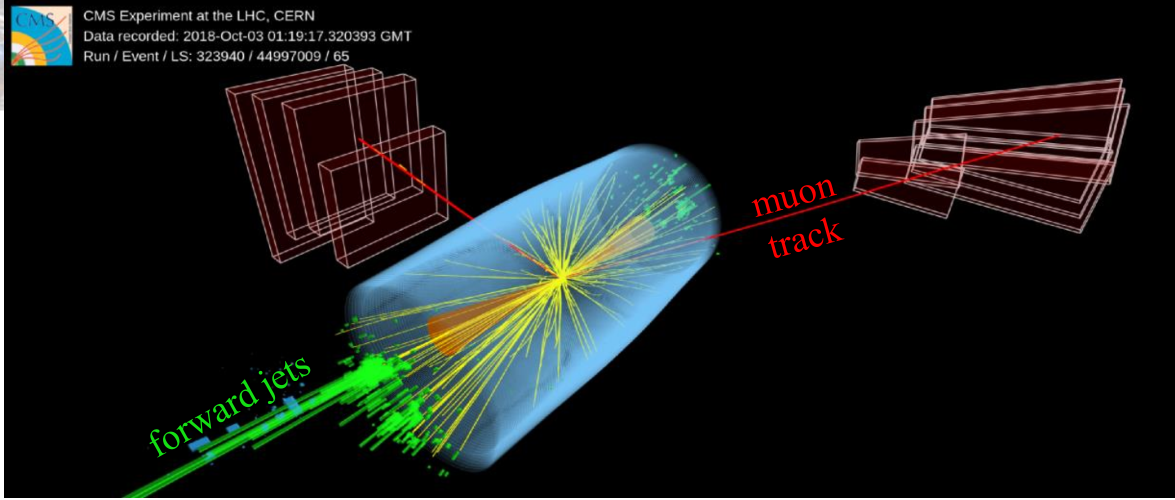


Boosted Decision Trees,
Deep Neural Network,
Advance Machine Learning …
improve
Efficiency and Purity

Ingenuity is giving us access at these *«exquisitely small signals »*

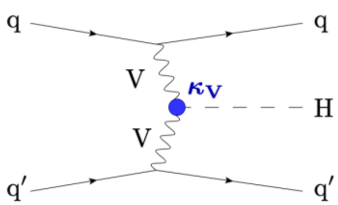
©Andre David

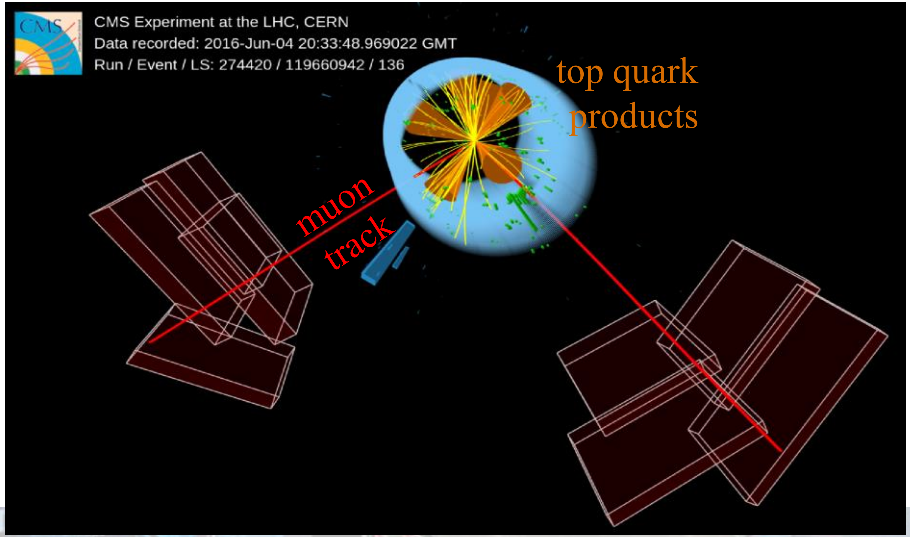
Higgs to muons



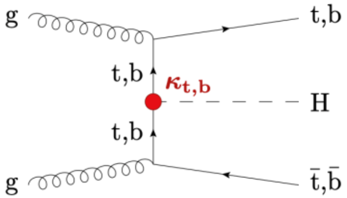
SM BR(H→ μμ) ~ 2.2×10^{-4}

Exploit all production modes.



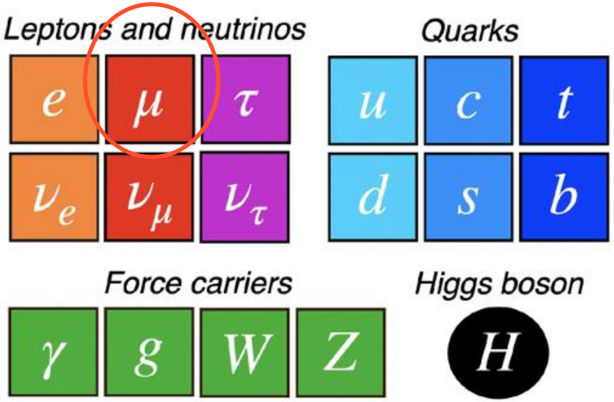


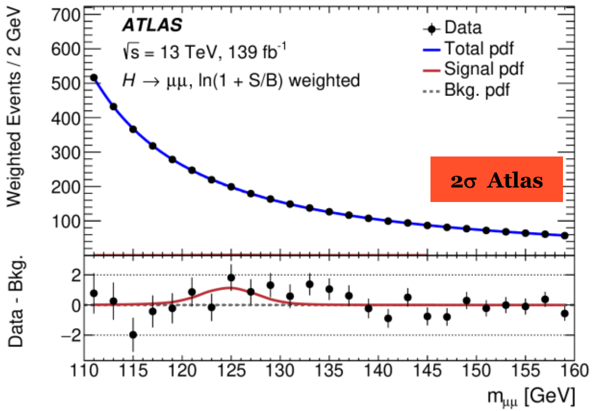
Candidate events compatible with different associated production modes and H⁰(125)→μμ decay.

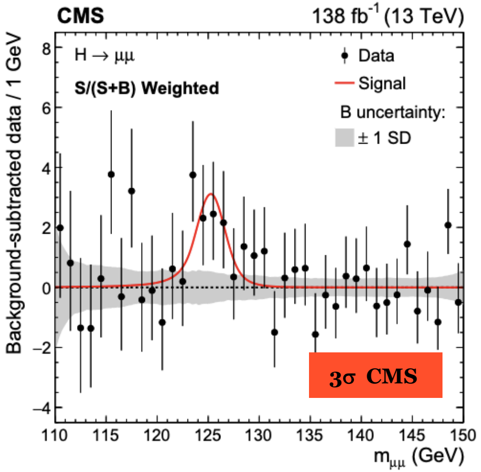


The coupling with the 2 generation

ATLAS: PLB 812 (2021) 135980
CMS: JHEP 01 (2021) 148





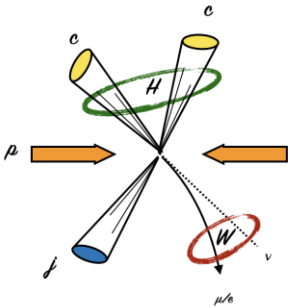


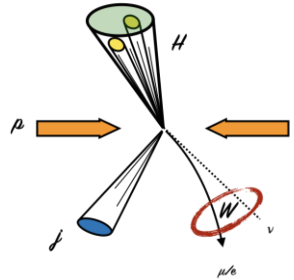
Higgs to charm

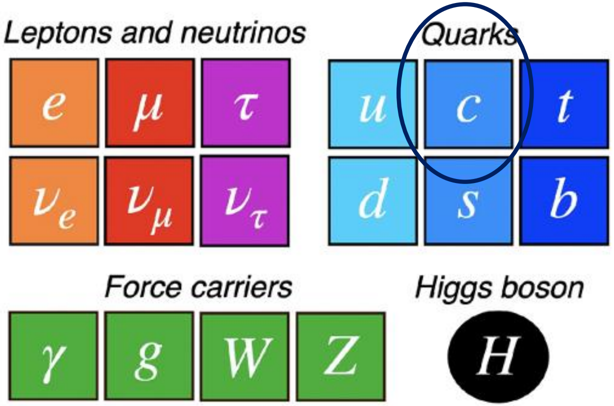
CMS: arxiv:2205.05550
ATLAS: arxiv:2201.11428

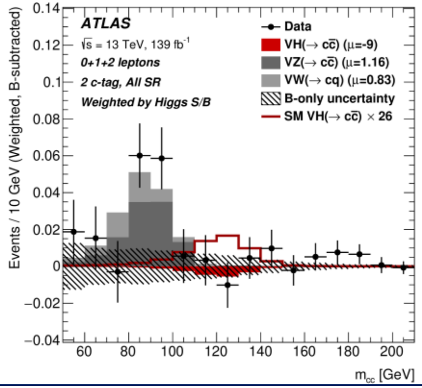
SM BR(H→cc) ~ 0.028

Search for H→cc
in VH events

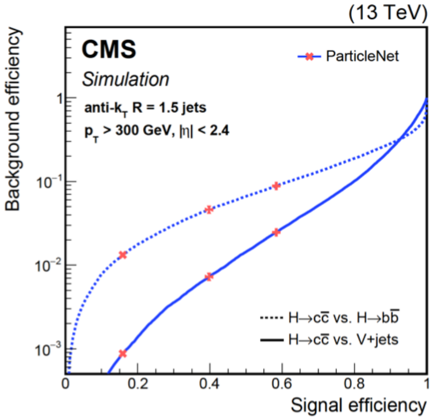


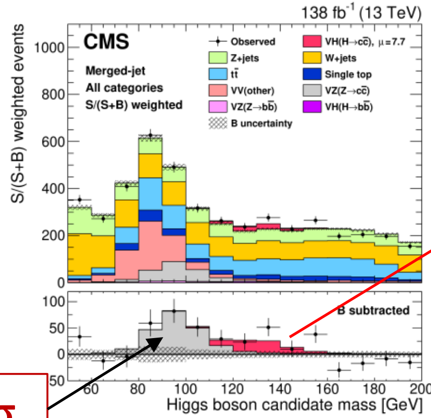


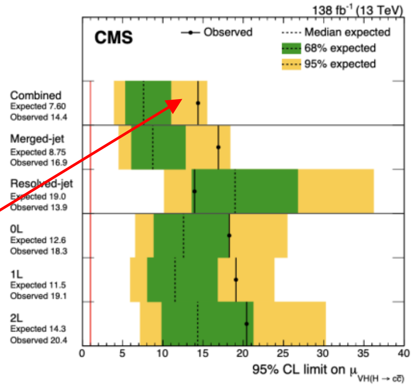




Sensitivity to **H→cc** ~ 8 × SM







Z→cc >> 5σ

Agreement with the SM: the signal strenght

fitting data from all production modes and decay channels with a common signal strength parameter

$$\mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}}$$

ATLAS

$\mu = 1.05 \pm 0.04\ (th) \pm 0.03\ (exp) \pm\ 0.03\ (stat)$

Nature 607, 52-59 (2022)

CMS

$\mu = 1.002 \pm 0.036\ (th) \pm 0.033\ (exp) \pm\ 0.029\ (stat)$

Nature 607, 60-68 (2022)

TOT: 14% Run1 → 6% Run2
TH : 7% → 4%

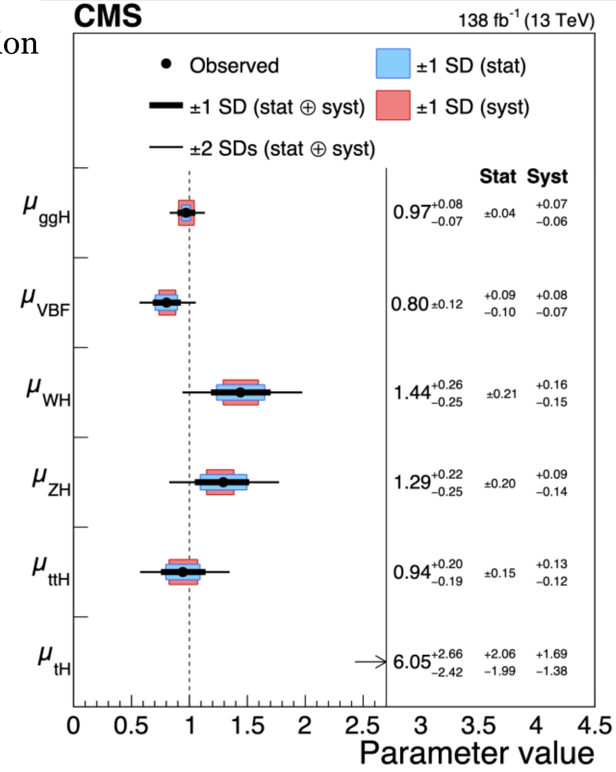
th – exp – stat uncertainties are of the same size

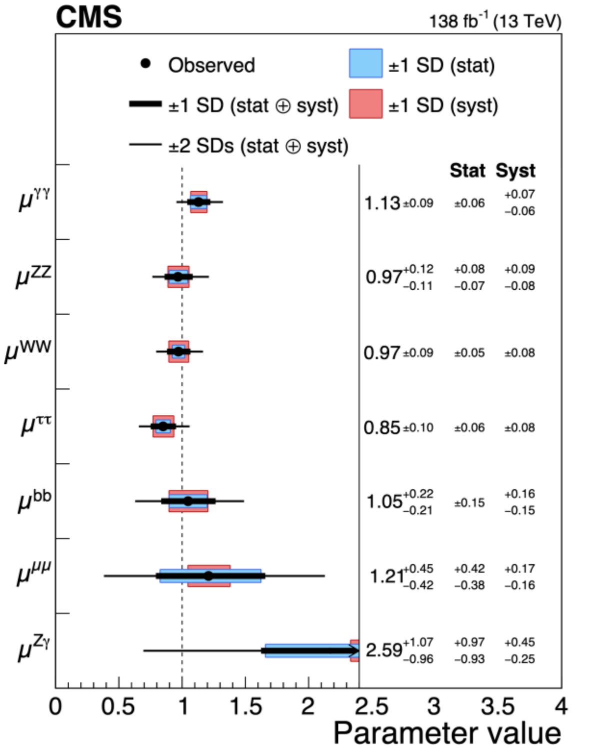
Higgs boson production modes and decay channels

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\rm SM}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{\rm SM}} \qquad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\rm SM}} = \mu_i \times \mu^f$$

Production

> 5 SD

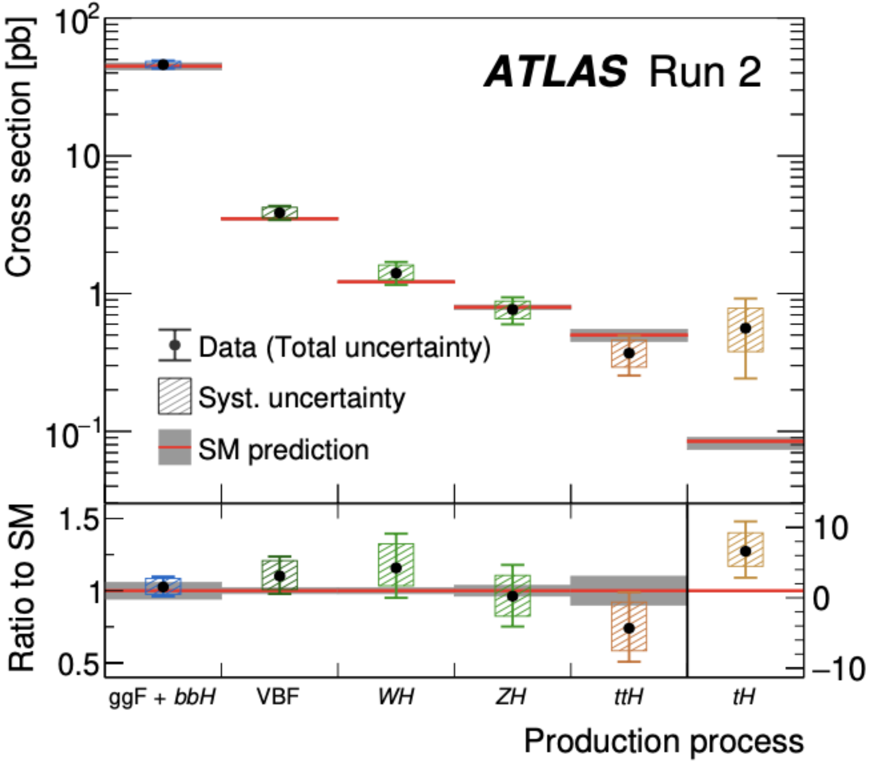




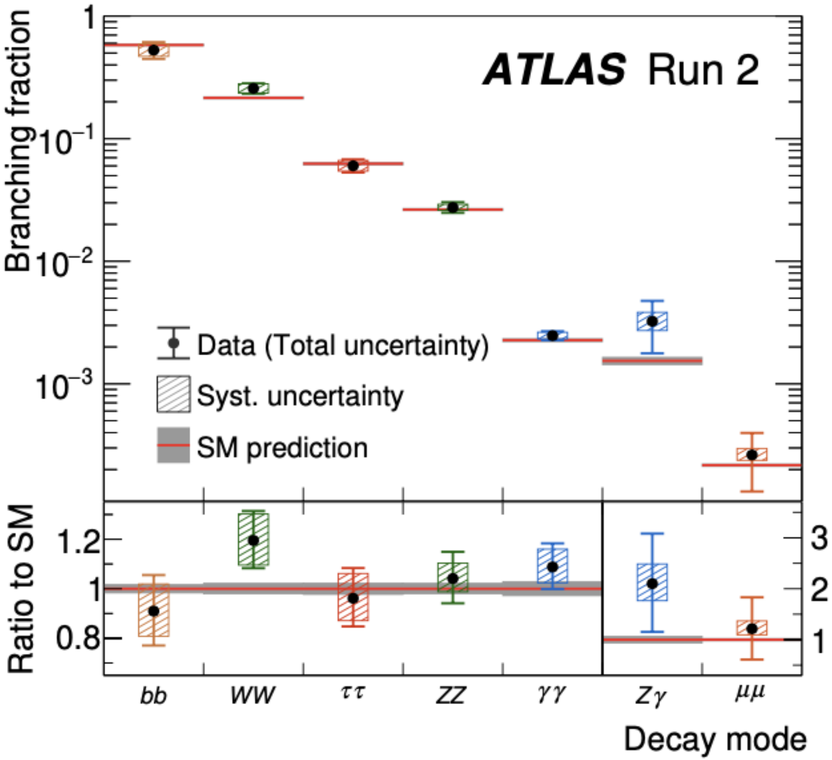
Decay

> 5 SD

XS and BR



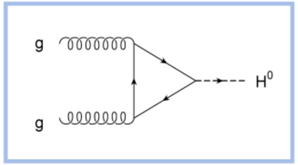
ATLAS Run 2
Cross section [pb]
Data (Total uncertainty)
Syst. uncertainty
SM prediction
Ratio to SM
ggF + bbH
VBF
WH
ZH
ttH
tH
Production process

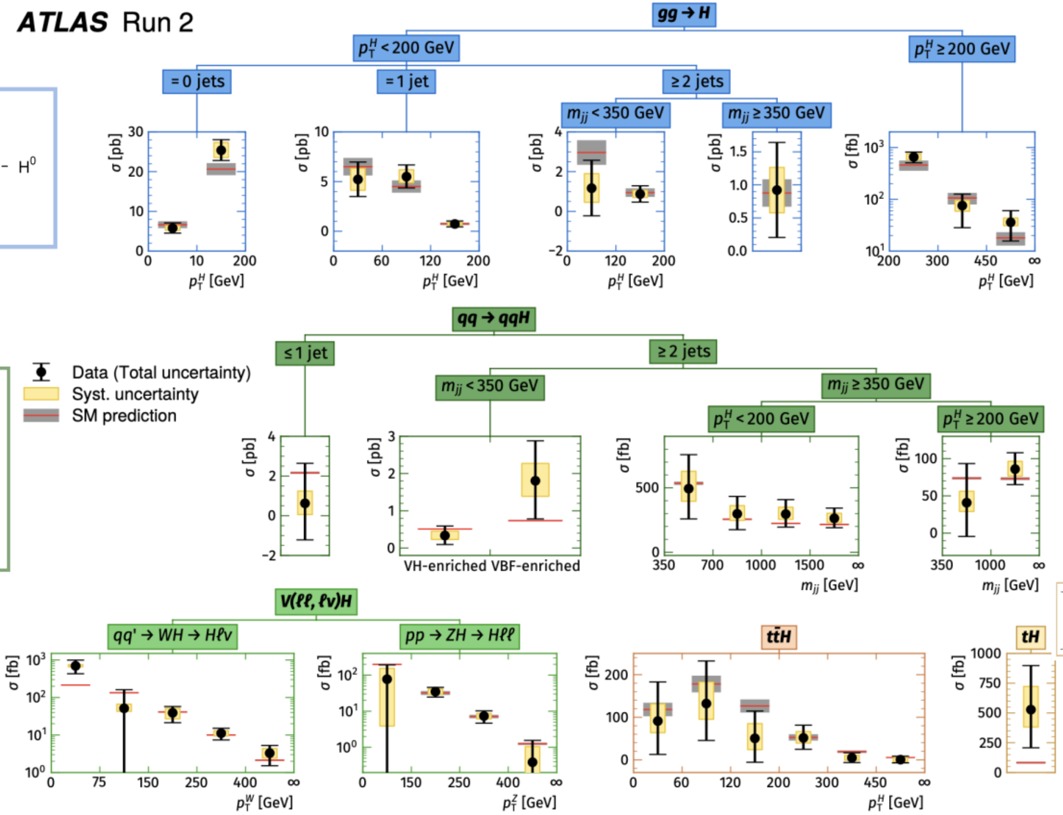


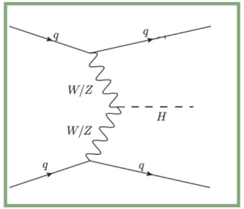
ATLAS Run 2
Branching fraction
Data (Total uncertainty)
Syst. uncertainty
SM prediction
Ratio to SM
bb
WW
ττ
ZZ
γγ
Zγ
μμ
Decay mode

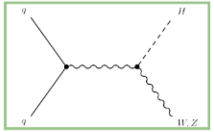
The Simplified Template Cross Section

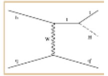
Maximise sensitivity to isolate BSM effects while reducing theory dependence

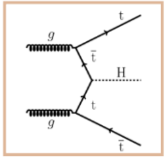












Inclusive over the Higgs decays

Measure cross sections in mutually exclusive regions of phase space

Measure cross sections separated into production modes (or more generally kinematic templates)

Non-Higgs backgrounds are subtracted

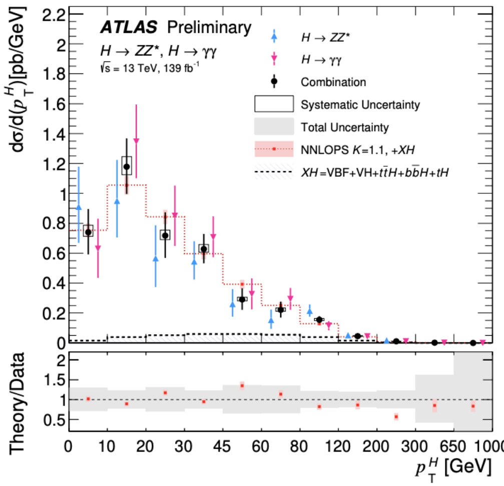
Differential distributions

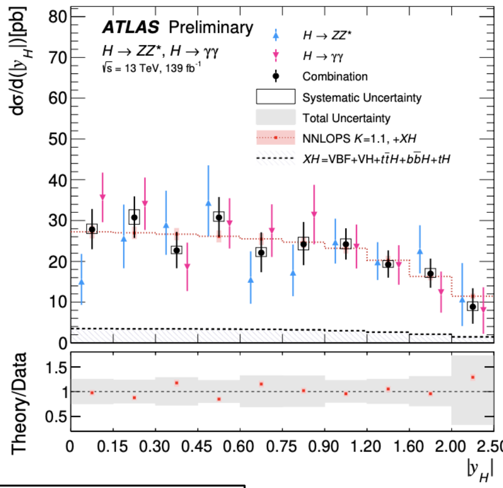
p_T , y, φ, n_{jet}... describe the Higgs production at LHC and help understanding QCD effects.

p_T → perturbative QCD

+ resummation of the leading logarithms,

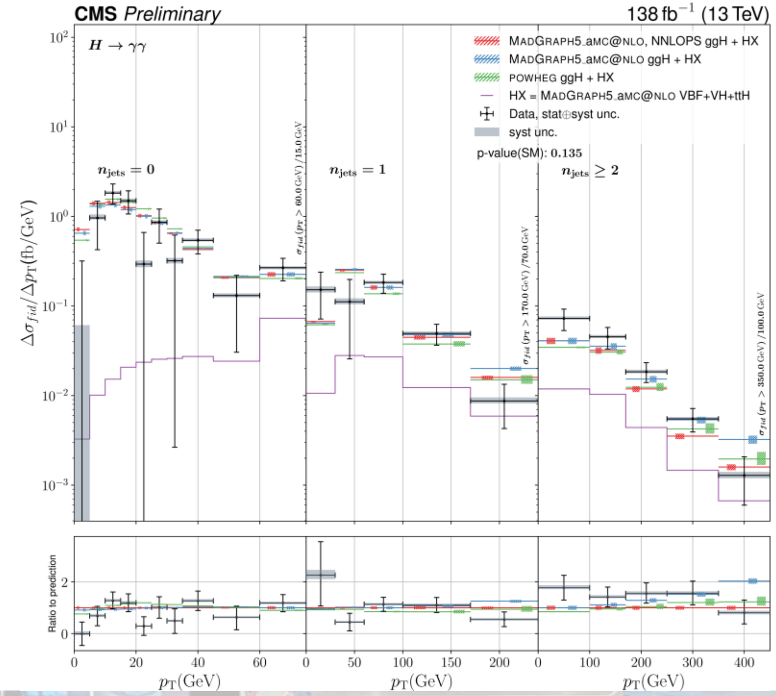
+ probe of new physics at high values.





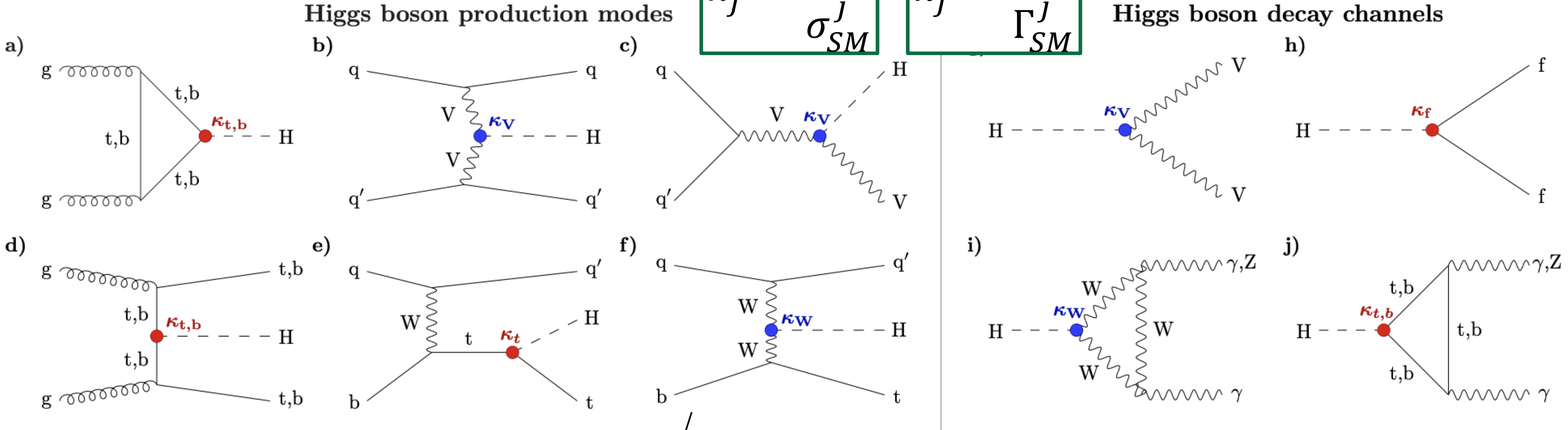
20-30% precision

Double differential XS

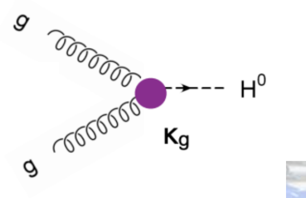


The couplings & the coupling modifiers: the κ framework.

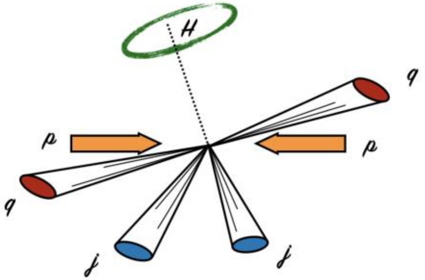
$$\kappa_j^2 = \frac{\sigma^j}{\sigma^j_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$



Alternatively, the loop could not be resolved and an effective coupling could be used:

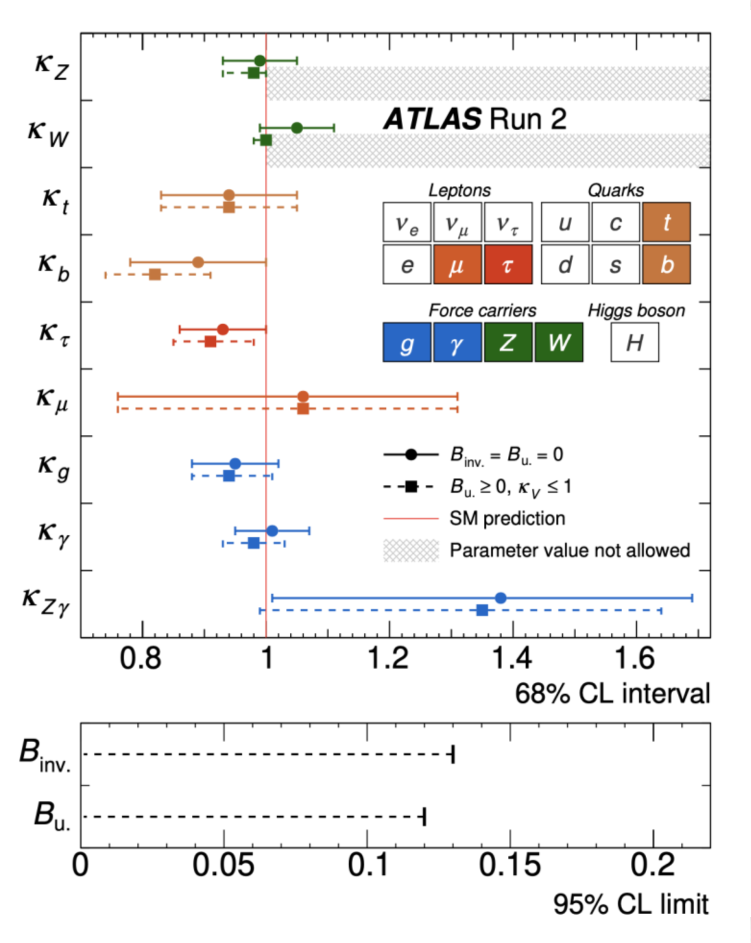


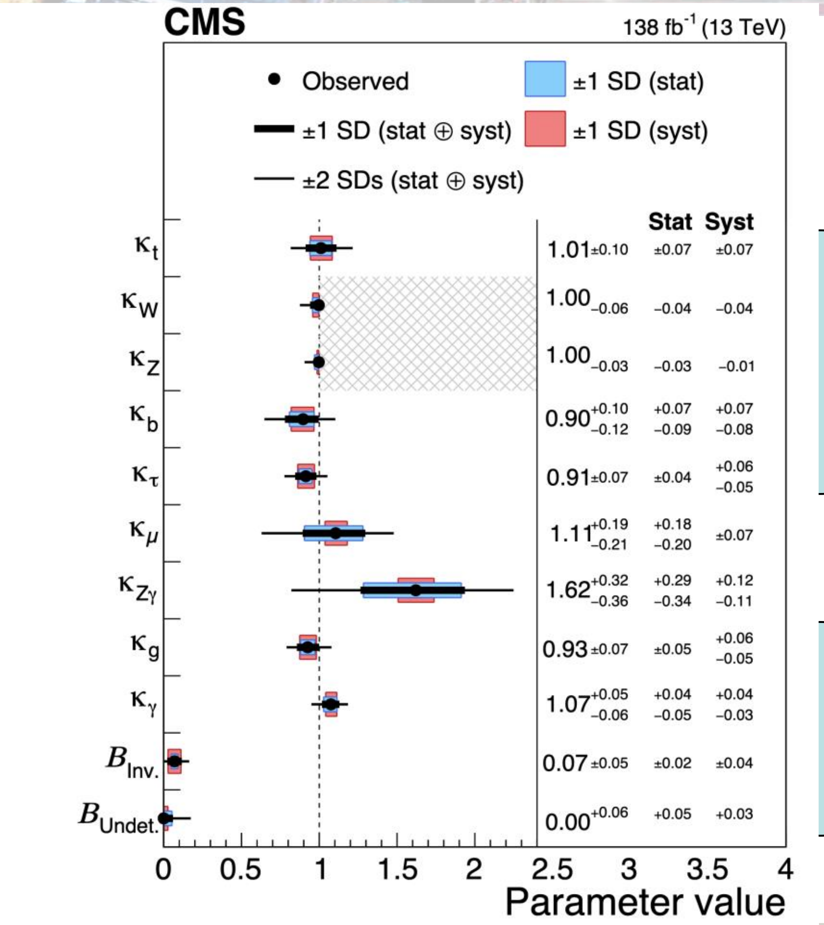
Invisible (ν, DM…) or Undetected decay



$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{(1 - \mathcal{B}_{inv} - \mathcal{B}_{undet})}$$

The κ framework

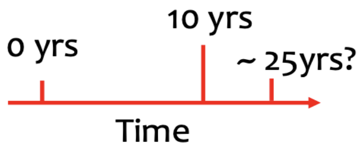


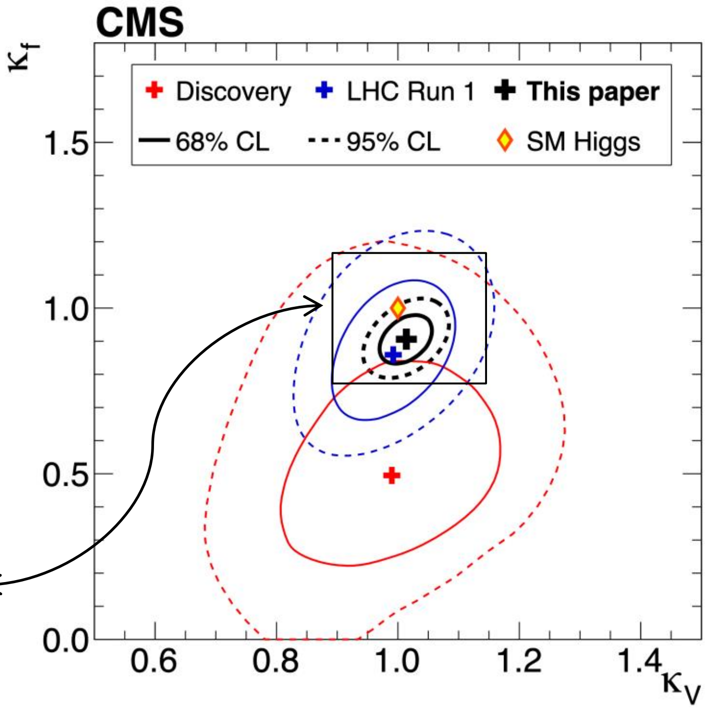


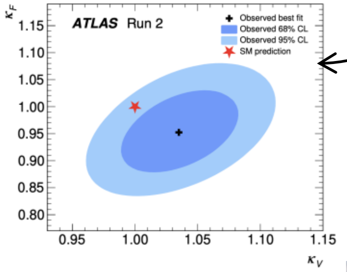
< 3 - 10%

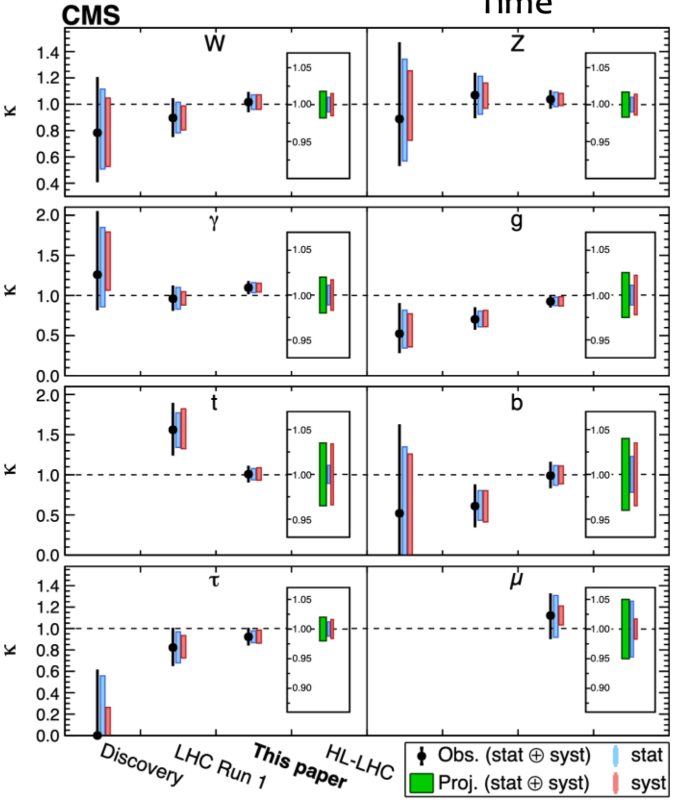
Luminosity, energy and …. ingenuity

~30 times more Higgs events in Run2



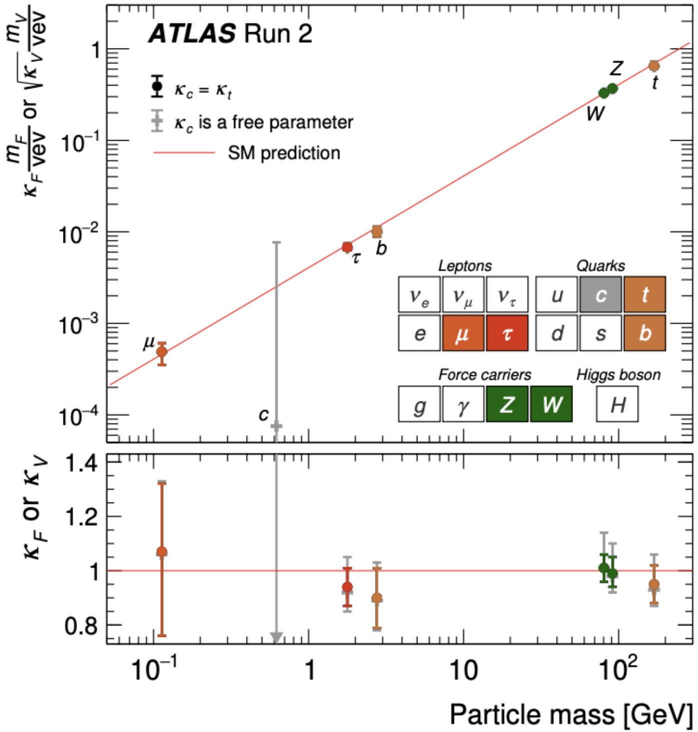


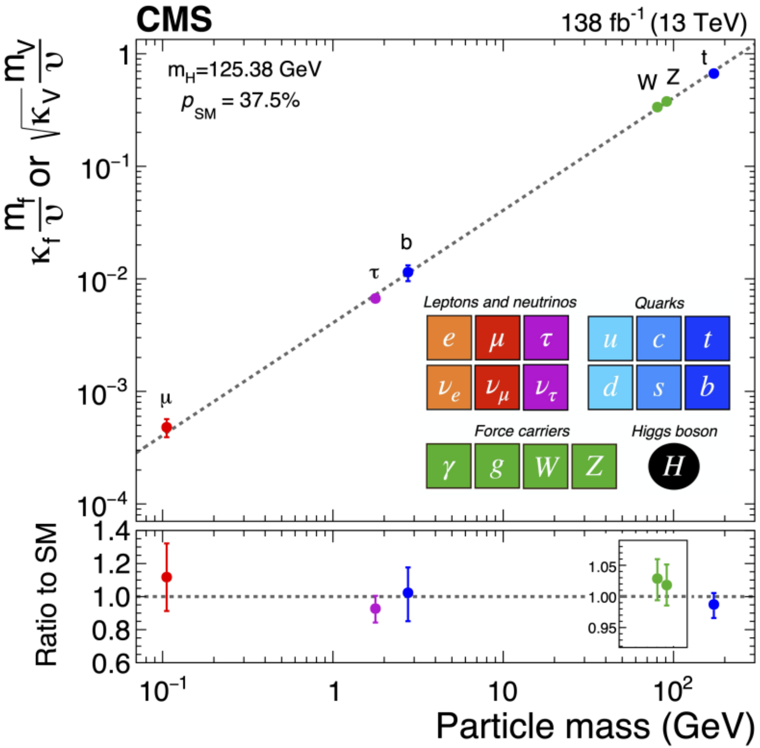




The portrait of the Higgs boson

SM test over many orders of magnitude





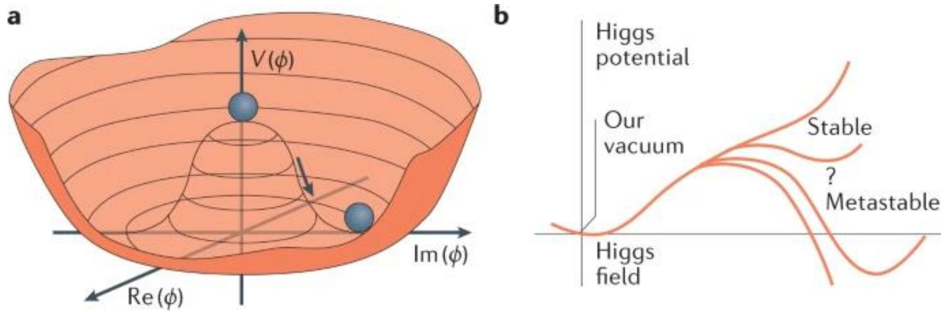
The Higgs couples with the particle mass !

The search for Higgs boson pair production

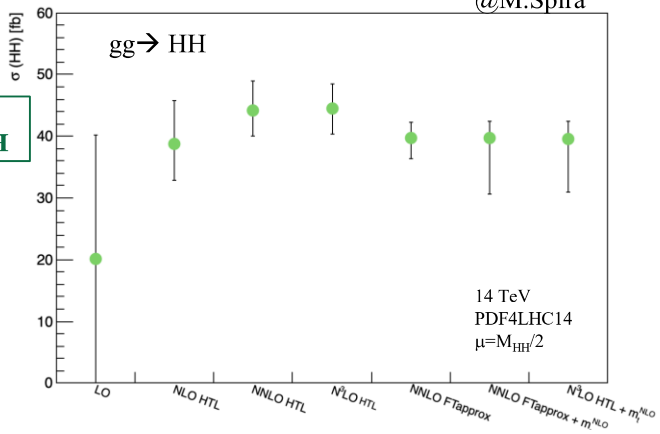
The Higgs potential
$$V(\phi) = \tfrac{1}{2} m_H^2 \phi^2 + \sqrt{\lambda/2}\, m_H \phi^3 + \tfrac{1}{4}\lambda\phi^4$$

$$\lambda = m_H^2/(2v^2)$$

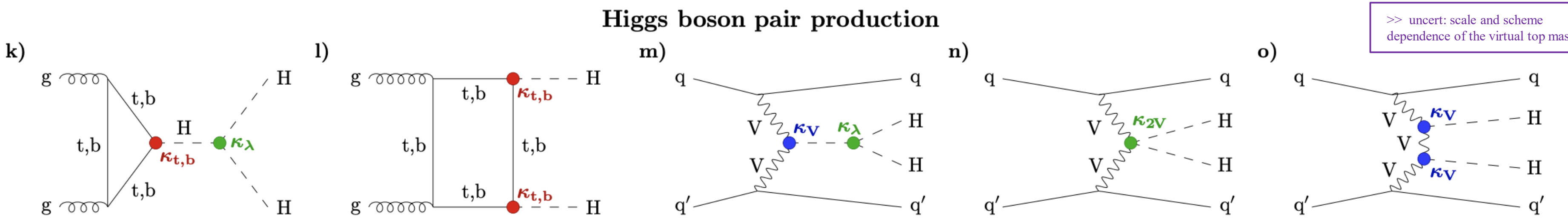
we measured the minimum, we should measure the curvature



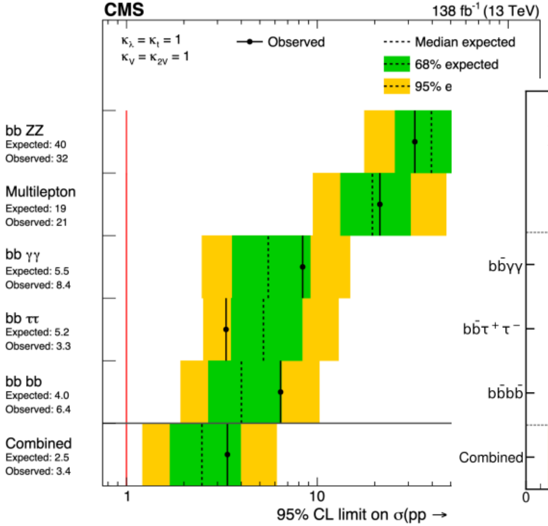
$\sigma_{HH} \sim 10^{-3}\, \sigma_H$

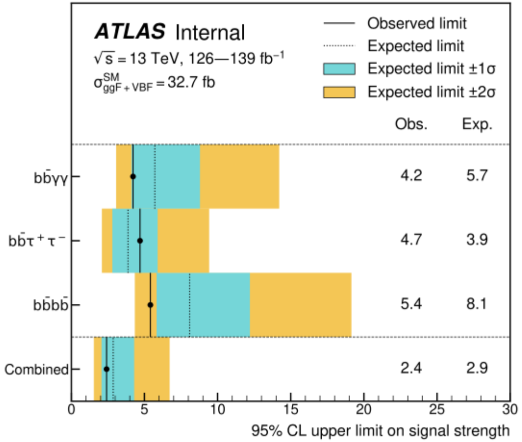


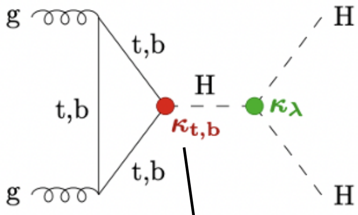
>> uncert: scale and scheme dependence of the virtual top mass



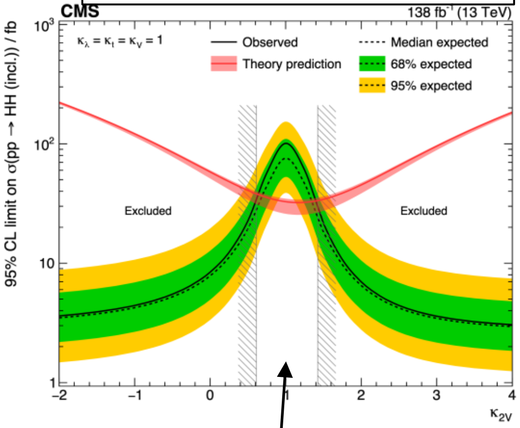
Results on HH production

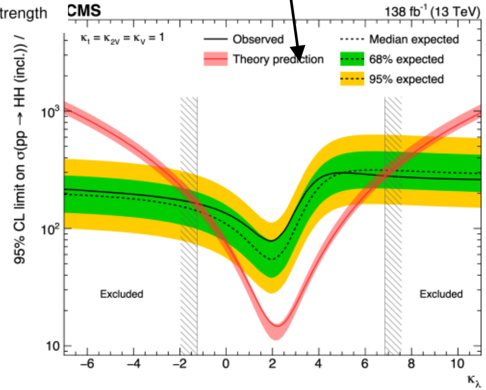


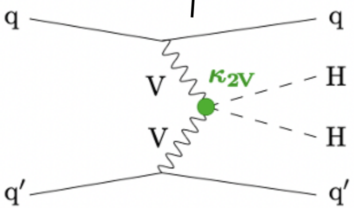




VVHH indeed exists







σ(HH) < 2. ÷ 3. SM

ATLAS +CMS will observe HH production at HL-LHC at 5 s.d.

This last 10 years

- Experiments have done much better than expected, both on the understanding of the detector and on analysis techniques

- Theoretical predictions have today reached a precision that was considered optimistic to reach for HL-LHC

- Theory & Experiments interaction has been a “game changer ” © F.Gianotti
  “We have learned that signal and backg cannot be separated on the basis of diagrams but only on the basis of cuts” © G. Passarino

- **LHC has gone from discovery to precision Higgs physics**

- “Precision Higgs physics is telescope to high scale physics” © S.Dawson

by the end of HL-LHC we will have ~180 M Higgs per Exp

Towards a new world

We have built huge and sophisticated accelerator and detectors "the cathedral of science", to find an elementary particle that explains how the elementary particles acquire mass.

The discovery of the Higgs Boson is of un-measurable value.

It is a great success of a community of thousands physicists: it is the result of a large group, where each of us has given its personal contribution.

Many thanks to

all the speakers of the 4-July-2022 event

all the speakers of the parallel session at ICHEP,

S. Forte, G Passarino, G. Ridolfi, M. Spira

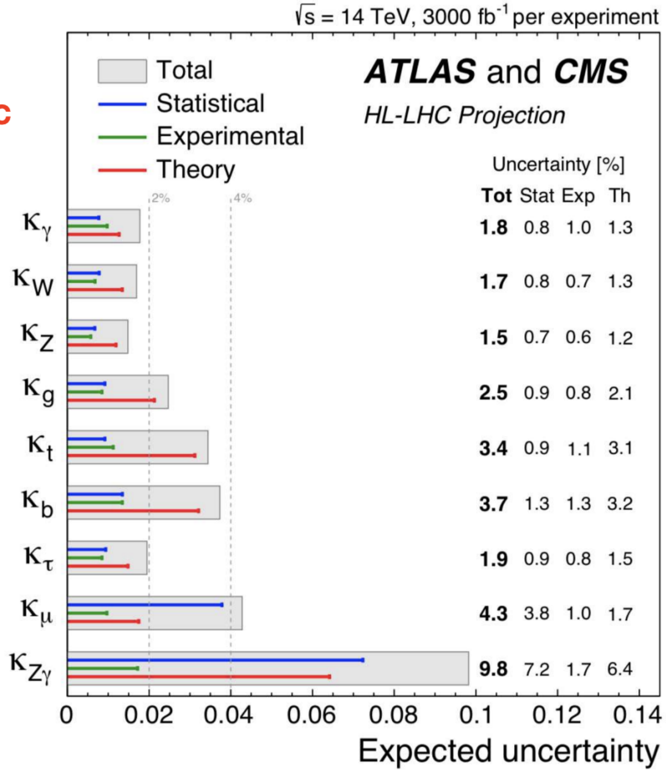
Backup

Precision Higgs couplings measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%

Nature 607, 52-59 (2022)

Nature 607, 60-68 (2022)



TH Uncertainties dominant (assumed to be 1/2 of Run 2)