Ten years of Higgs discovery: Looking back and ahead

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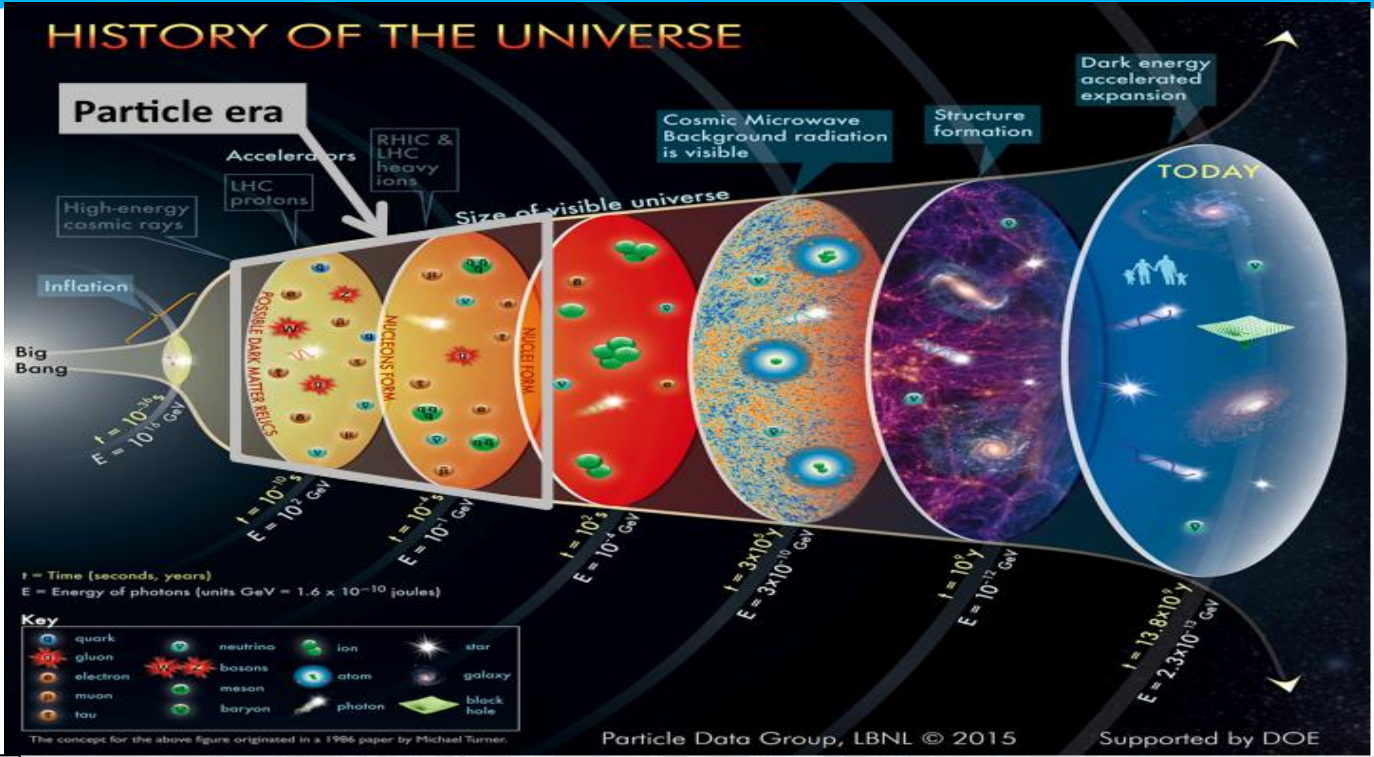
COMETA– 17 June 2024

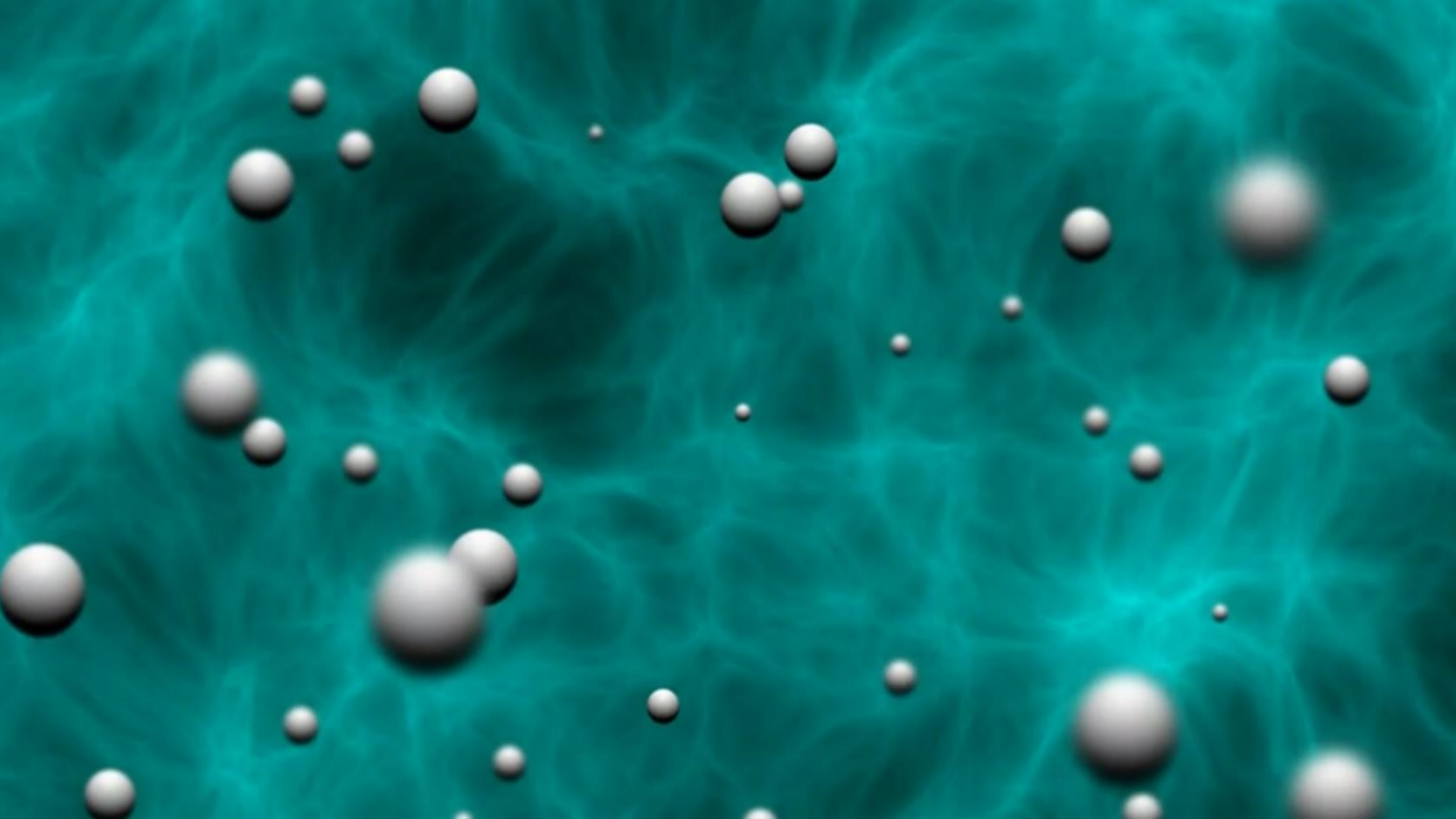
The Higgs field and the Higgs boson

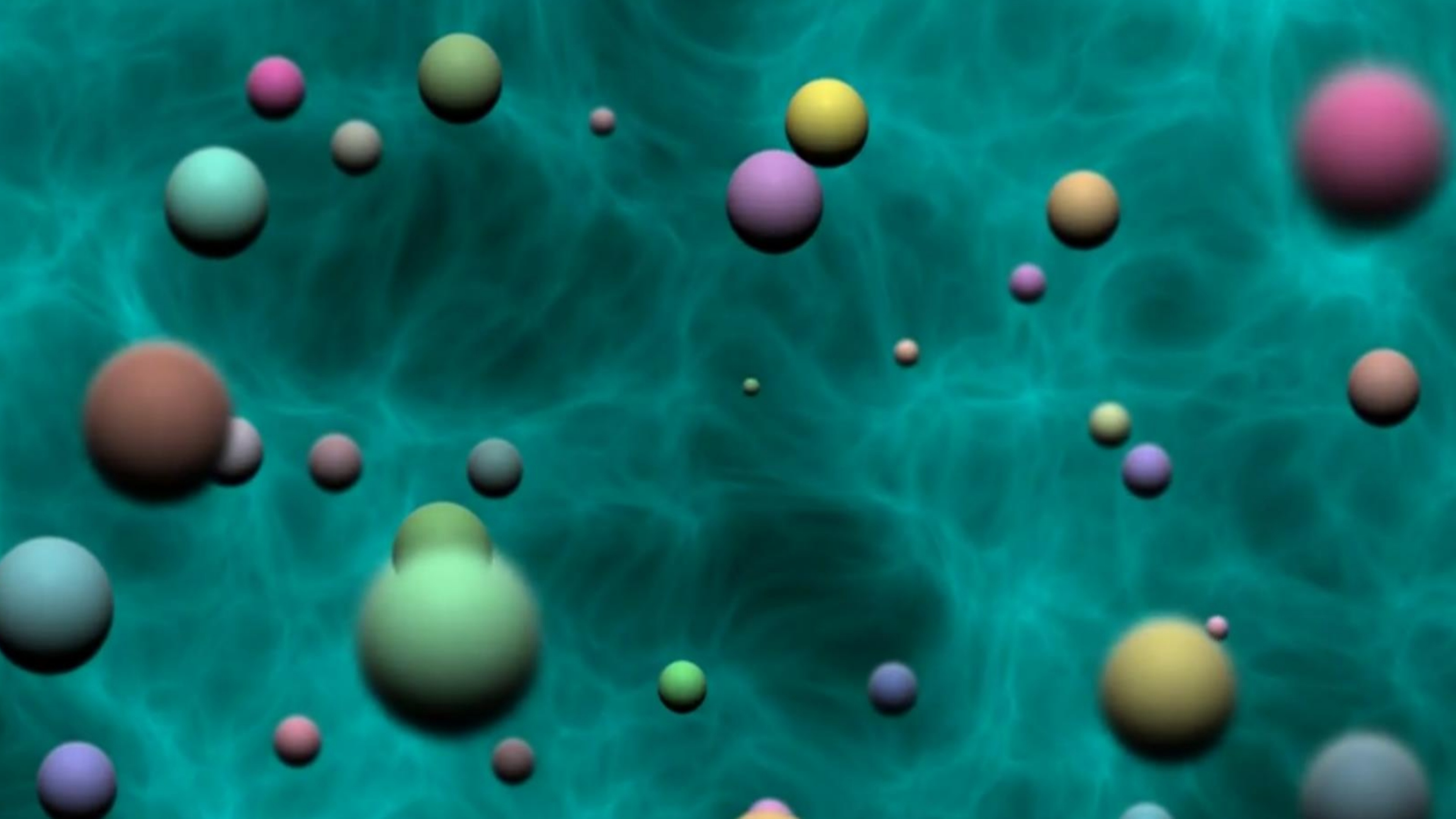
The Higgs boson

The Higgs boson is a prediction of a mechanism that took place in the early Universe, less than a picosecond after the Big Bang



Nature 607, (2022)





The Higgs boson

The Higgs boson is a prediction of a mechanism that took place in the early Universe, less than a picosecond after the Big Bang

The W and Z boson acquire mass, the photon remains massless

which led to the electromagnetic and the weak interactions becoming distinct in their actions.

“Thus, the elementary particles interacting with the BEH field acquire mass.
The impact is far reaching: for example, electrons become massive, allowing atoms to form, and endowing our Universe with the observed complexity.”

Nature 607, 60-8 (2022)

Special quantum numbers

In the SM, this mechanism, labelled as the Brout–Englert–Higgs (BEH) mechanism, introduces a complex scalar (spin-0) field that permeates the entire Universe. *Its quantum manifestation is known as the SM Higgs boson.*

$$J^{PC} = 0^{++}$$

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 to the Higgs boson

The Standard Model: a long journey

54 Yang & Mills

61 Glashow

64 Brout, Englert, Higgs et al

67-68 Glashow , Weinberg and Salam

70 ‘t Hooft et Veltman

73 J/Ψ (charm)

73 Gargamelle : discovery of the week neutral current

75 τ lepton

76 Υ (beauty)

83: Ua1 & UA2: W and Z discovery

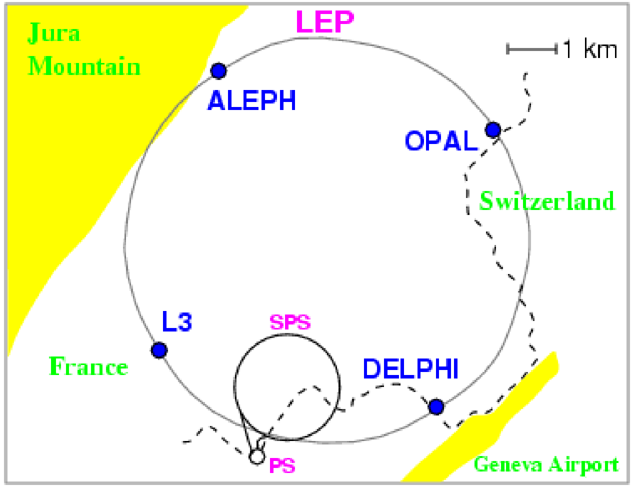
89-2000: LEP and HERA: the triumph of the SM

95: Tevatron: top quark discovery

2012: LHC: discovery of a Higgs like boson

The LEP journey

Large Electron Positron collider



the 27 Km circumference RING, 100 meters below ground

1983: the beginning of the excavations: the biggest European Eng. work

august 1989: first interaction at E=91 GeV

1995 - 2000: E=130 – 209 GeV

11 years for construction
12 years of data taking
~350 x 4 physics papers

LEP

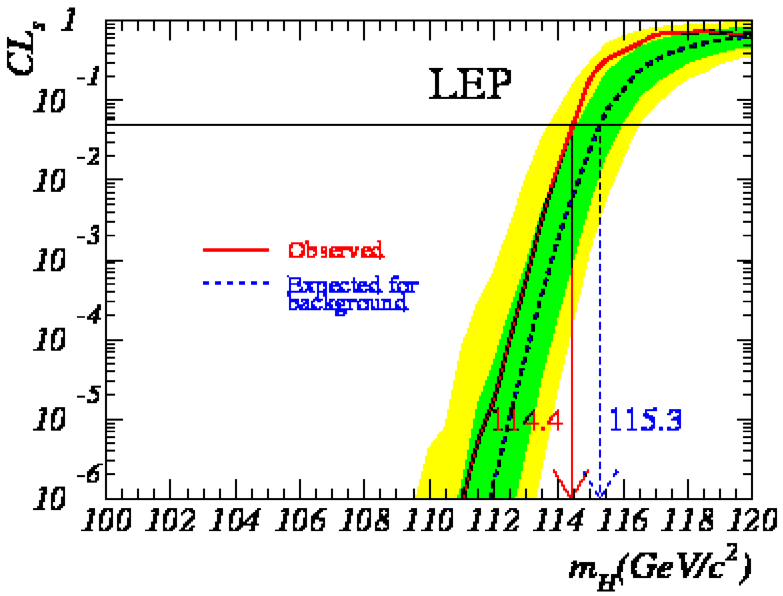
It is hard to remember how little we knew about the ElectroWeak physics and QCD before LEP started!

LEP did a gigantic leap

as an example:

- We did not know how many fermion families there are
- We measured quantities at the per mille or better precision
  (We could measure changes in the LEP circumference of less than 0.1 mm)
- We excluded many BSM models

The combined limit on the Higgs boson



	Exp	Obs
ALEPH	113.5	111.5
DELPHI	113.3	114.1
L3	112.4	112.0
OPAL	112.7	112.7
LEP	**115.3**	**114.4**
4-jets	114.5	113.3
$l+\nu+\tau$	114.2	114.2

At LEP2 : 1995-2000,
E_{cm} = 130 – 209 GeV
$\mathcal{L} > 2.5$ fb^{-1} @ $E_{cm} > 187$ GeV

Direct Searches:
LEP was the perfect machine to search for the Higgs
IF **$m(Higgs) < E_{cm} - M_Z$**

End of LEP

2000 last year of data taking at LEP

We insisted a lot to continue, but we failed.

1995 At the Research Board in June 95, Siemens proposed to produce
32 Superconducting RadioFrequency cavities for 32 MCH (they were producing the SC for LEP2, and after that they would have dismantled the production line)
With those cavities LEP could have reached Ecm=220 GeV

(thus **$m(Higgs) < E_{cm} - M_Z \sim 129 \quad (+ \Gamma_Z)$**)

The CERN management decided not to increase the energy to more than 200 GeV
(we went to 209 GeV anyway !)

An "historical" sentences from the 2000 « battle » :
Sam Ting: « At LEP every event is signal, at LHC every event is background »

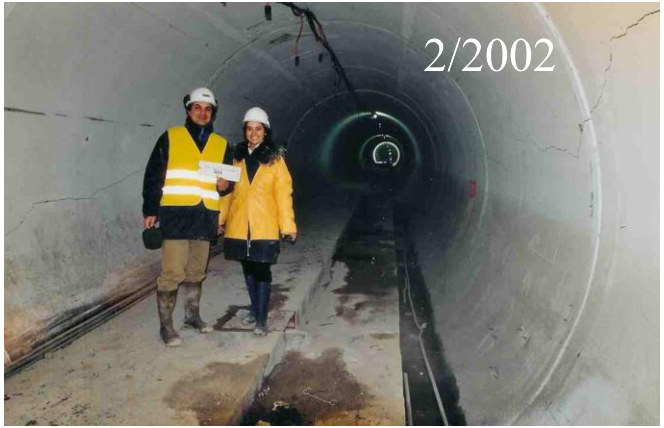
The end of LEP → Toward LHC

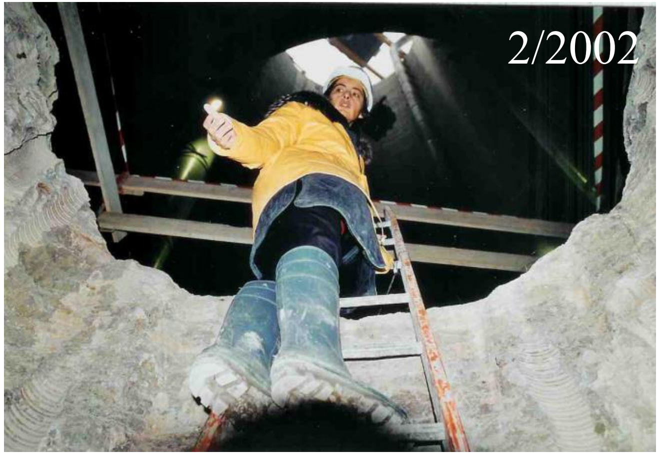
Dec 2000 LEP stops
and it is dismantled.

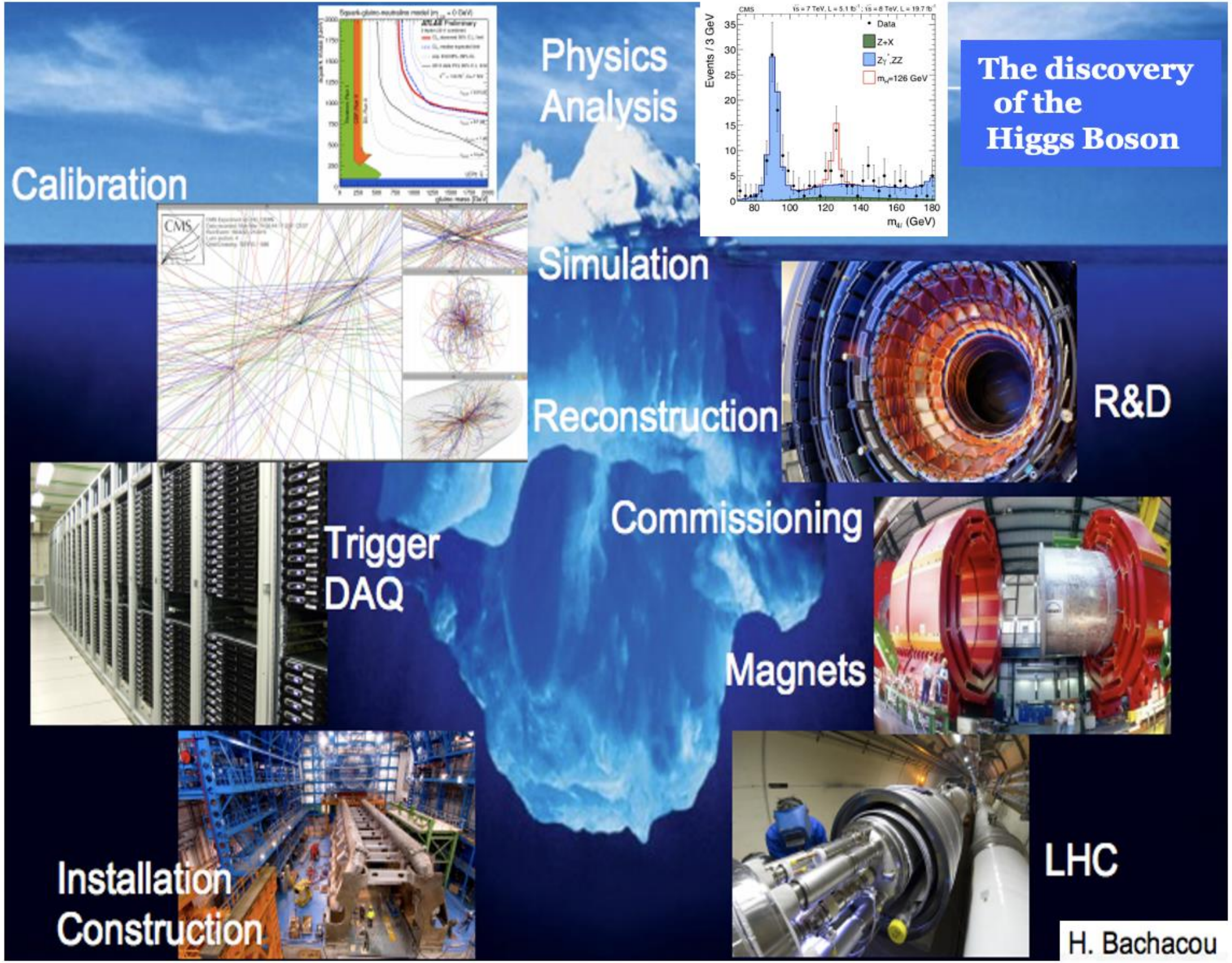
LHC starts engineering work

2009 first interactions

2010-2011-2012
LHC run at
7 TeV center-of-mass energy







The WLCG

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

The LHC Cross Section Working Group

In 2008 Giampiero Passarino had the idea of the group for the first time, underlying the urgency, since a discovery could come sooner than expected!

In August 2009 we met at the cafeteria of B40 (Passarino, Mariotti, Murray, Nisati, Qian and Stoeckli)

In Torino, in November 2009 (the exact day LHC delivered the very first pp interaction !) the group was formed and the program was discussed.

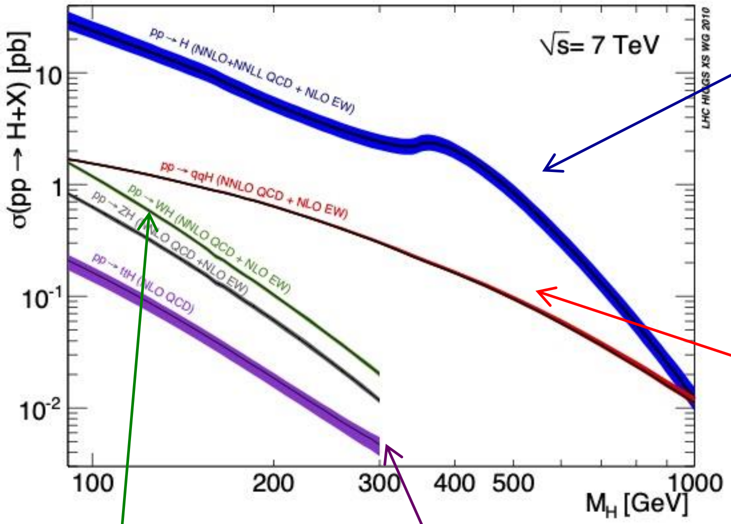
Jan 2010 the experiments formally recognize it.

17-Feb-2011 First Yellow Report:

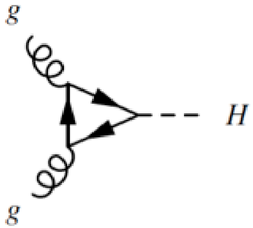
→ Since day-0 the Higgs analyses from Atlas and CMS have been using the LHCHXSWG prescriptions and results

Higgs production at LHC

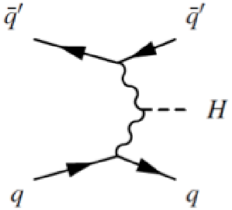
2010-2011



ggF: NNLO+NNLL QCD + NLO EW

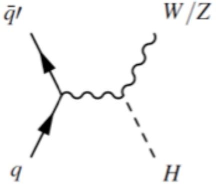


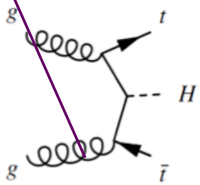
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW





ttH: NLO QCD

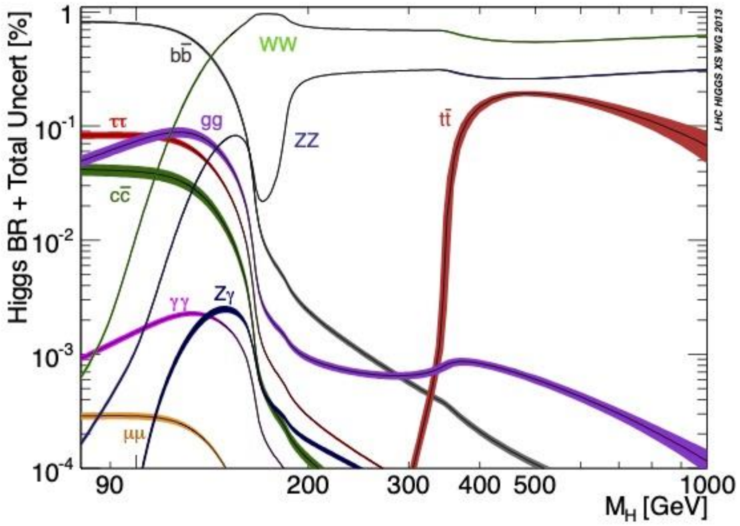
the
LHC H XS WG

	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+a_S	Total error
ggF	+25% (+100%)	+12% - 7%	±8%	+20 - 15%
VBF	<1% (+5-10%)	±1%	±4%	±5%
WH/ZH	+2-6% (+30%)	±1%	±4%	±5%
ttH	- (+5-20%)	+4% - 10%	±8%	+12 - 18%

Branching Ratios

2010-2011

$$\Gamma_H = \Gamma^{HD} - \Gamma^{HD}_{ZZ} - \Gamma^{HD}_{WW} + \Gamma^{Proph.}_{4f} + \Gamma^{HD}_{\gamma\gamma}\delta^{QED}_{\gamma ff}$$

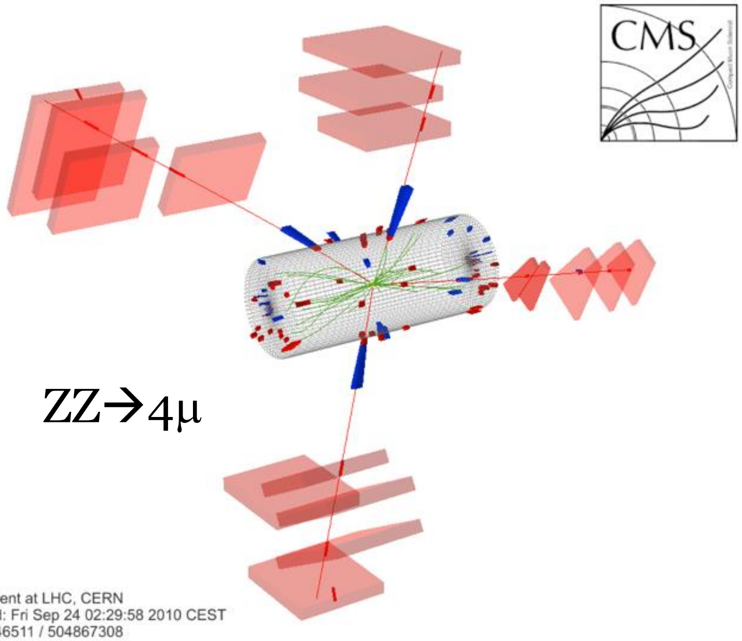


MH	Decay	THU	PU	Total
120 GeV	H→γγ	±2.9%	±2.5%	±5.4%
	H→bb	±1.3%	±1.5%	±2.8%
	H→ττ	±3.6%	±2.5%	±6.1%
150 GeV	H→WW	±0.3%	±0.6%	±0.9%
	H→ZZ	±0.3%	±0.6%	±0.9%

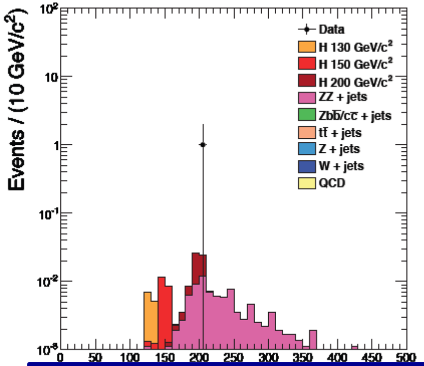
HD=HDecay NLO QCD +NLO EW

Proph = Prophecy4f NLO QCD+NLO EW

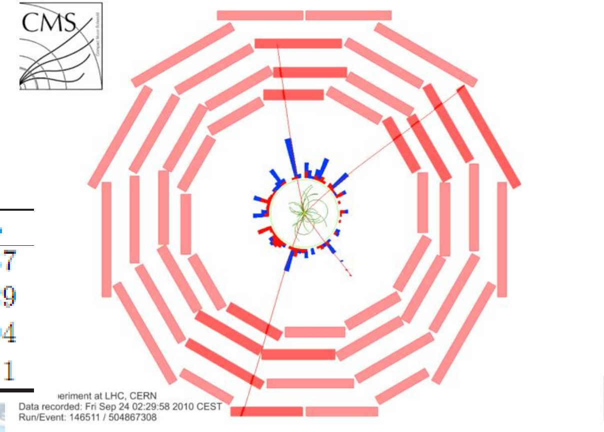
The first spectacular event, Sept 2010



ZZ→4μ

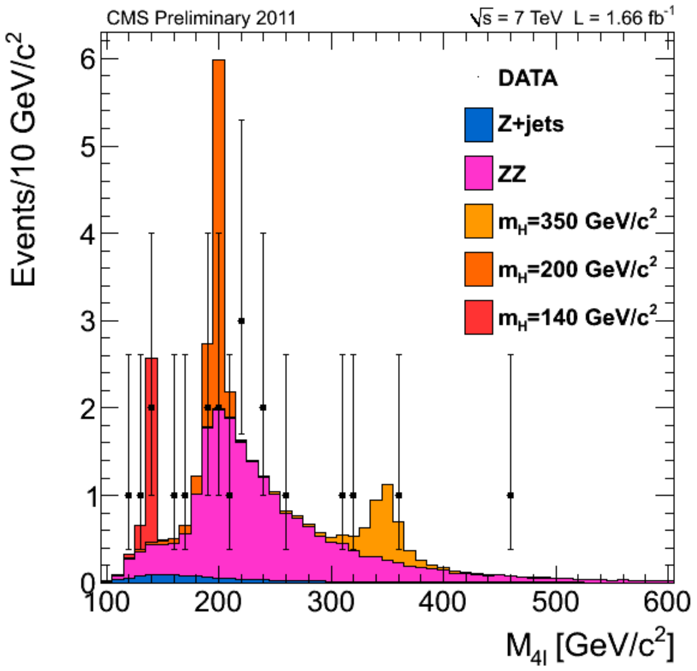


Prob = 23% to observe ZZ→4l in 35pb^{-1} at 7 TeV

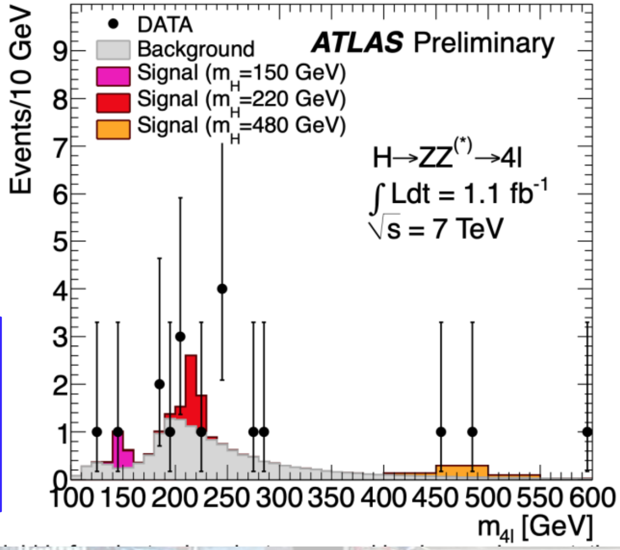


$m(4\ell)$ [GeV/c^2]	$m(2\ell)$ [GeV/c^2]	p_T (μ) [GeV/c]	μIso	S_{IP}
201.7	92.12	19.56	0	0.537
		25.88	0	1.029
	92.23	48.14	0	0.994
		43.44	0	0.411

Grenoble EPS Conference July 2011



We/HZZ4l went into « panic » mode
In July 2011: we had to defend all the events, one by one, we scrutinised all the backgrounds and their simulations



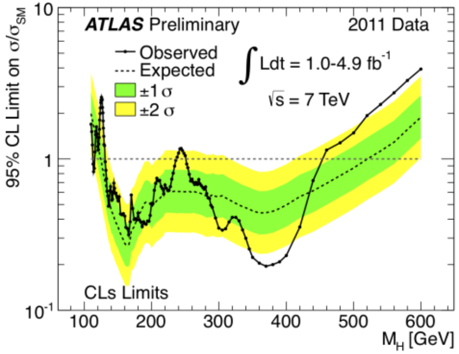
We/HZZ4l were under heavy review from the collaboration, to be finally approved and able to present the result at EPS-11

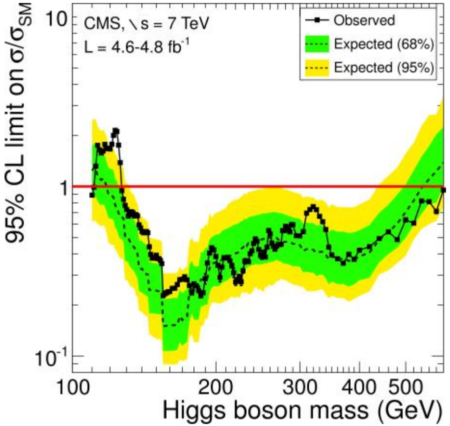
DEC 2011: Towards a discovery

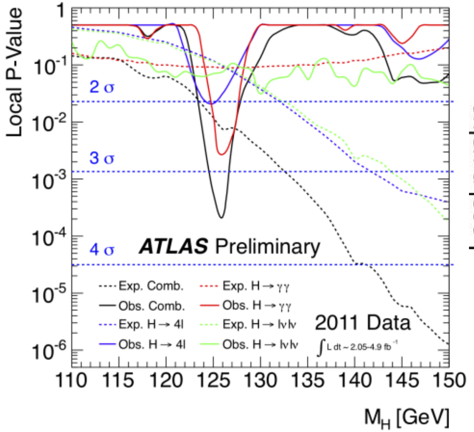
LHC: Dec 2011: very important results:

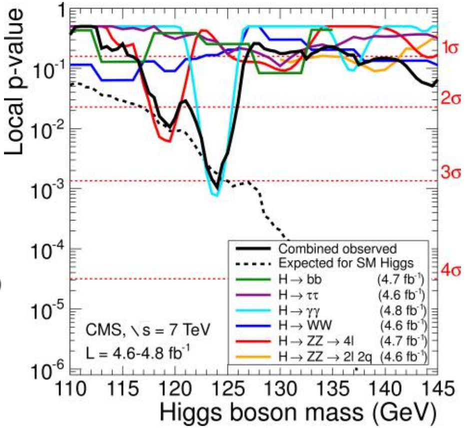
The Higgs boson is excluded in a large region of mass

and it is NOT excluded in a small interval









LHC 2012 blind analysis focused on m~115 - 130 GeV: Optimisation of the analyses with MonteCarlo, **without looking at the data**.

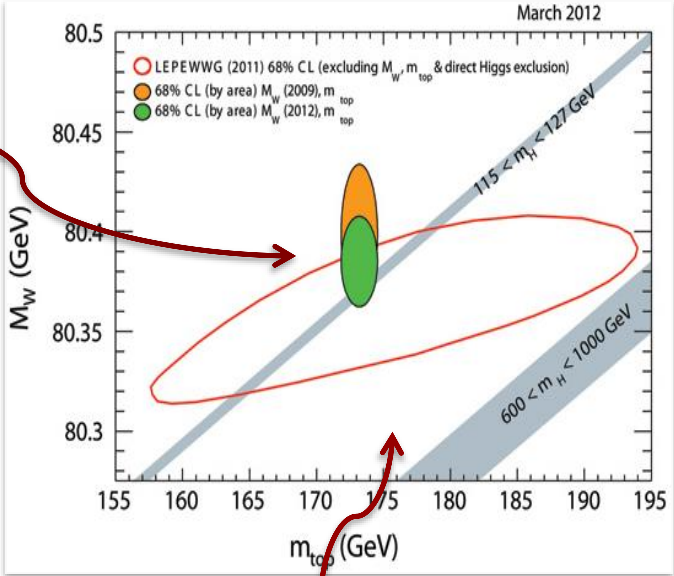
Where we stood 3 weeks before the 4 of July

1. M_{top} vs. M_W
   – Tevatron M_W *Tour de Force!!*
      • $m_W = 80385 \pm 15$ MeV
      (World Ave – Mar 2012)

2. Colliders leave little space

EW precision measurements

$$\Delta\rho = f(\sin^2\theta_W, G_F, m_t^2, \log m_H)$$



LHC Excluded a wide range of Higgs masses in 2011

This is the main story of the year 2011

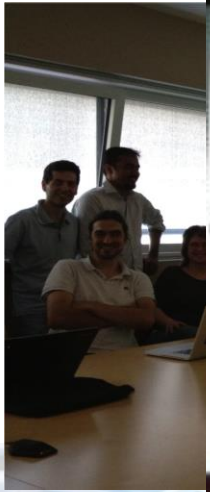
@Joe Incandela

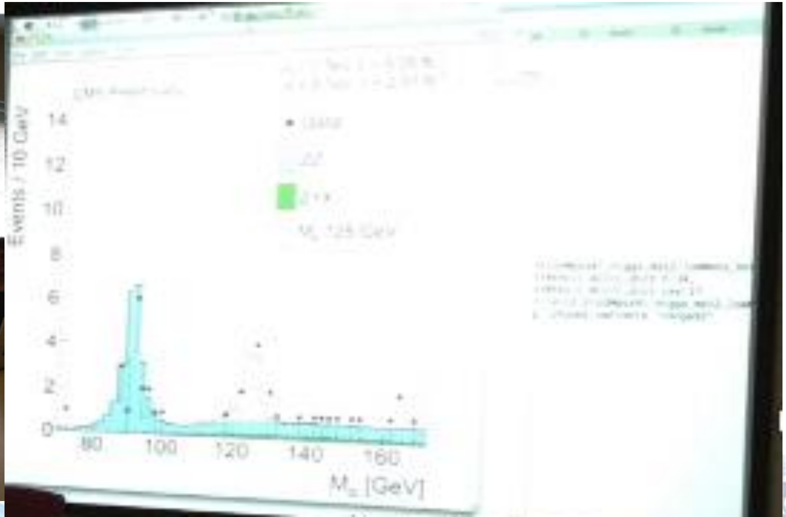
The D-day

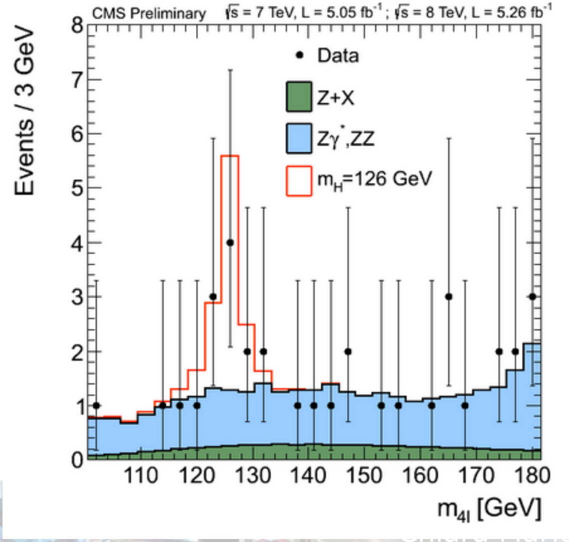
The 14 of June of 2012 at 19h00:

The analysis was ready. It could be no more optimised.
We could finally *«open the box»*, i.e. look at the DATA.

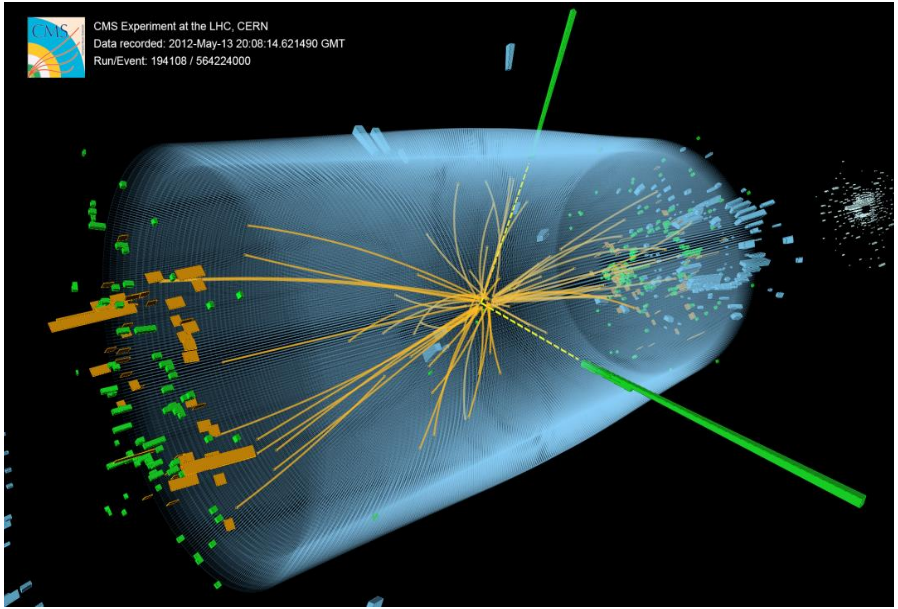
We did run the analysis on the data, and we projected on the screen:





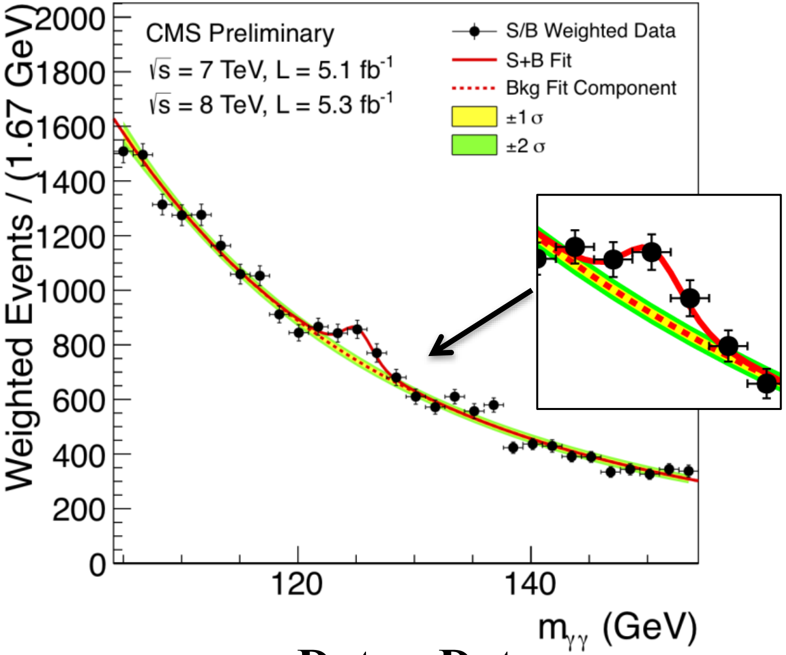


H→γγ, 14 June 2012



We look for an excess of events in the 2 photons mass spectra $m_{\gamma\gamma}$

$$pp \rightarrow H \rightarrow \gamma\gamma$$



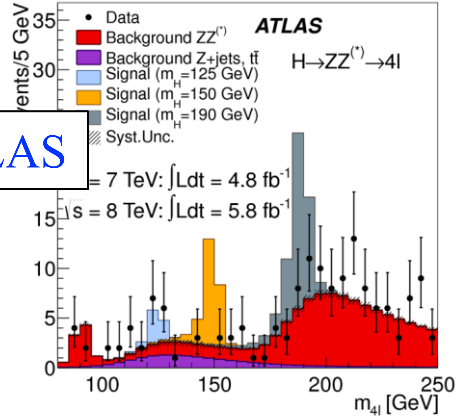
Dots – Data

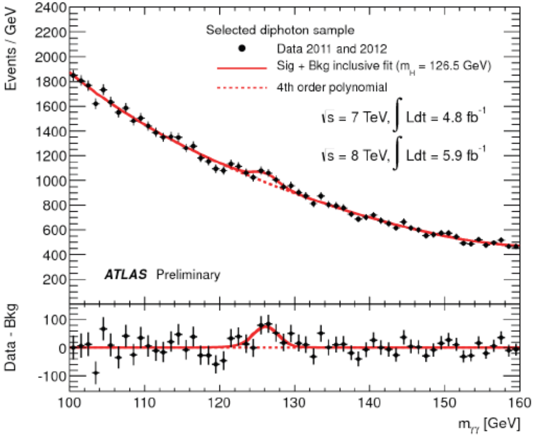
Lines - Simulation

4 July 2012

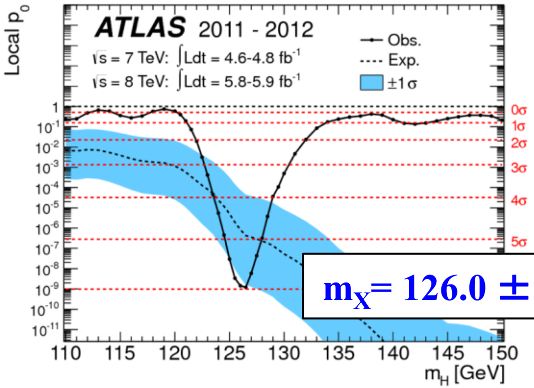
The 4th of July 2012

ATLAS



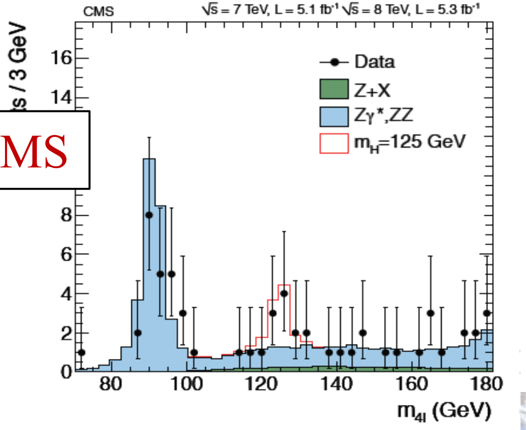


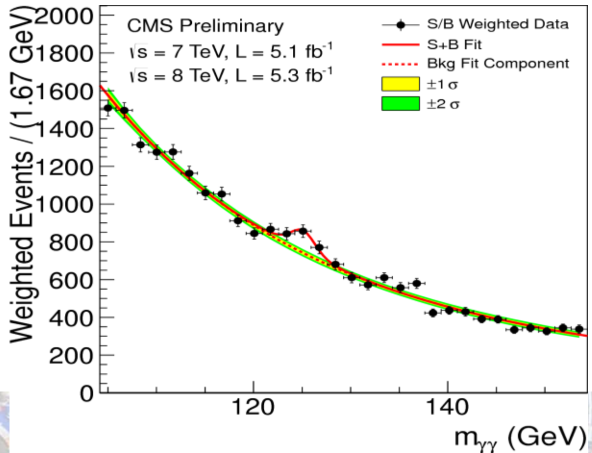
combination

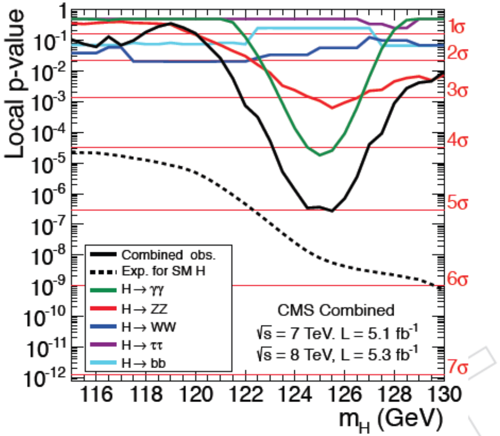


$m_X = 126.0 \pm 0.6$ GeV

CMS







$m_X = 125.3 \pm 0.6$ GeV

The Nobel Prize

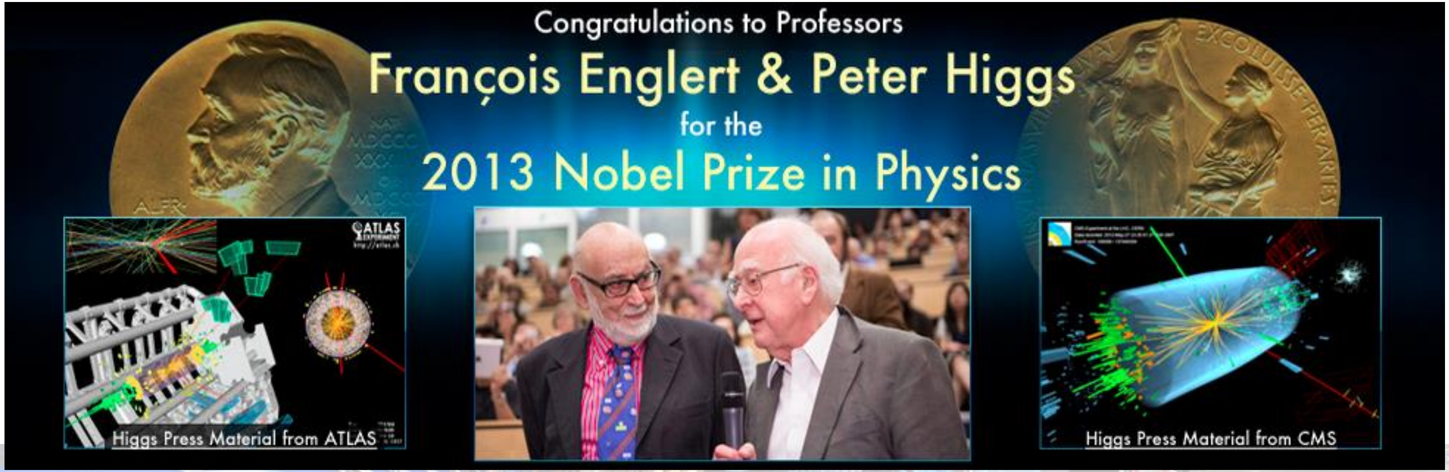
The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

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



A second big break-through (2013-2014)

- Following the work of

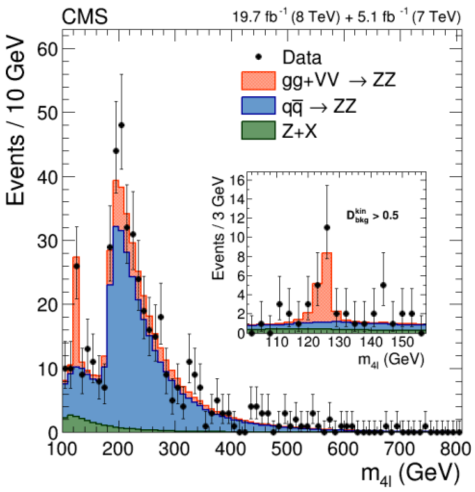
Kauer, Passarino: JHEP 1208 (2012) 116

Caola, Melnikov: Phys. Rev. D88 (2013) 054024

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

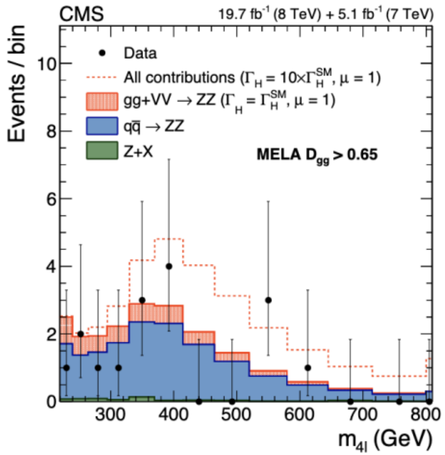
$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}$$

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



Γ_H(SM)= 4 MeV

Detector resolution ~ GeV

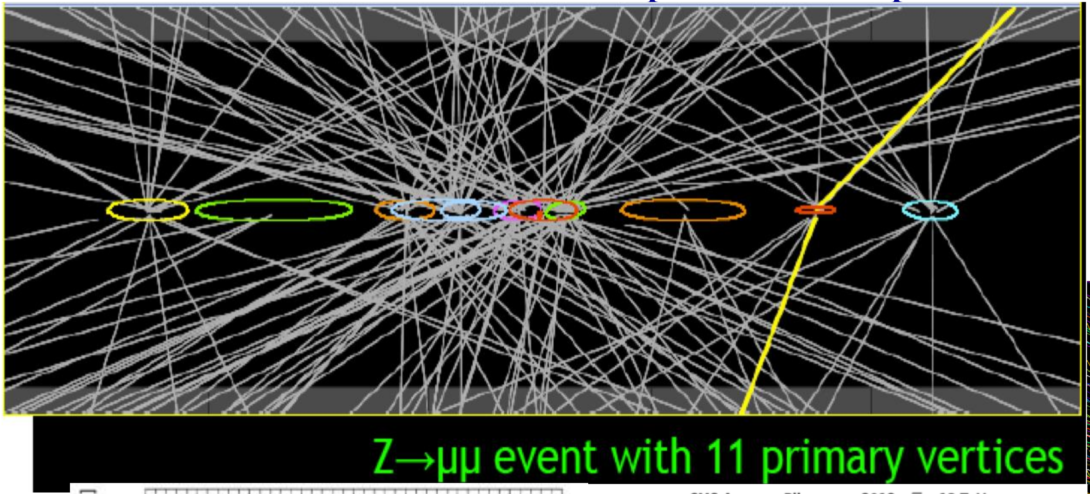


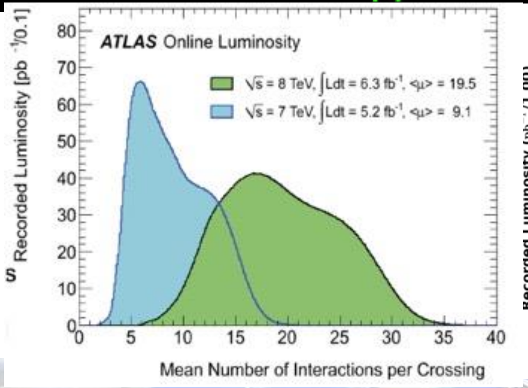
The Higgs width, Γ_H , can be constrained from off-shell production:
We can go from ***few GeV*** → ***tens of MeV*** using off-shell Higgs production

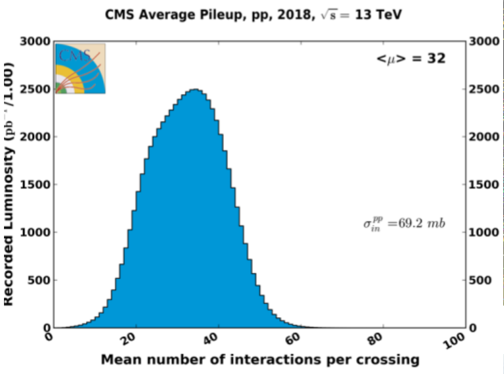
RUN1 : Γ_H < 13 MeV obs (26 MeV exp)

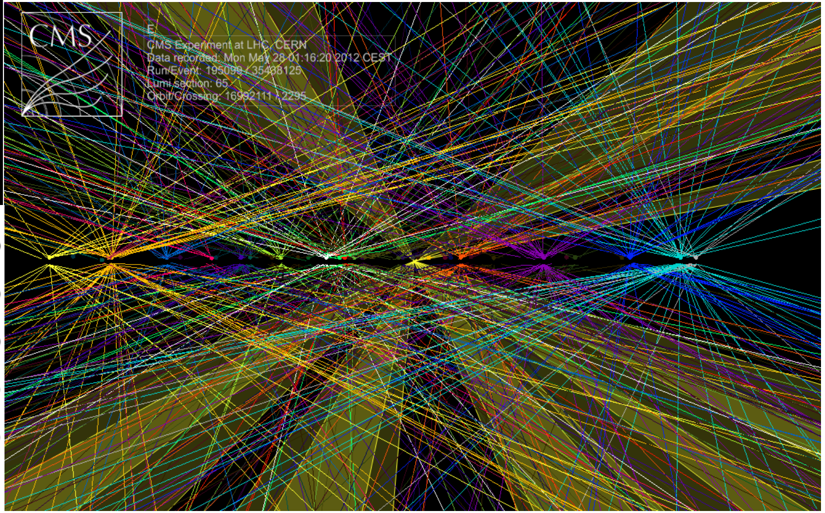
After 2012, towards RUN2

A lot of work from the experimental point of view:

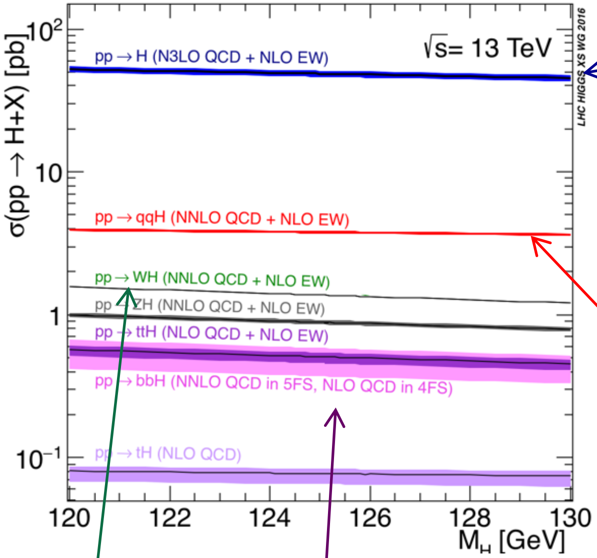




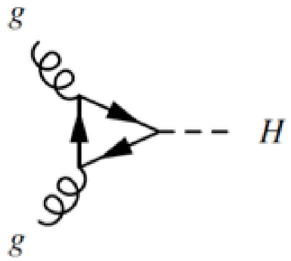


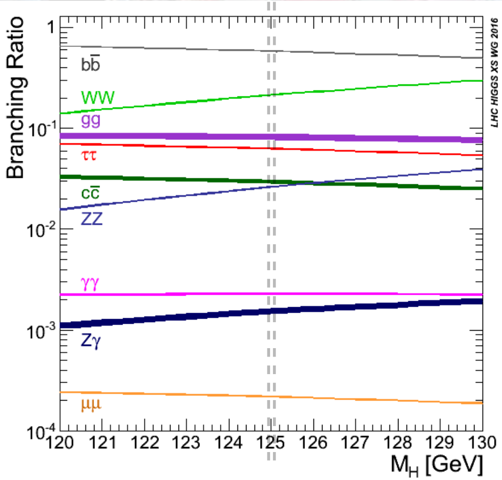


Cross Sections & BR: the LHCHXSWG results - 2017

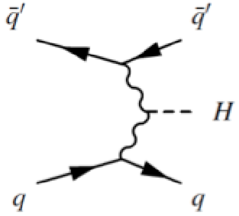


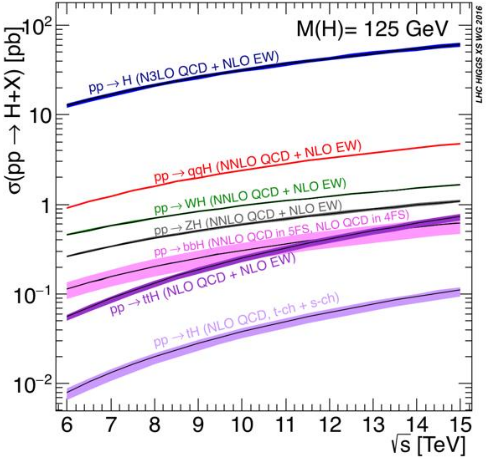
ggF: NNNLO+NNLL QCD + NLO EW





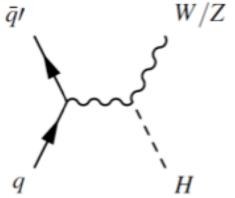
qqH: NNLO QCD + NLO EW

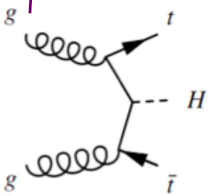




WH: NNLO QCD + NLO EW

ZH: NNLO QCD + NLO EW





ttH: NLO QCD

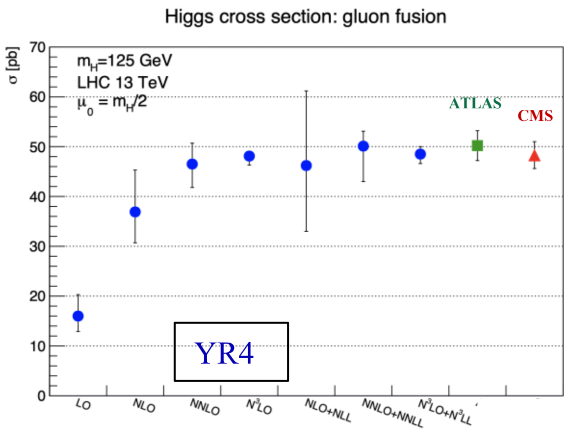
From 8 to 13 TeV

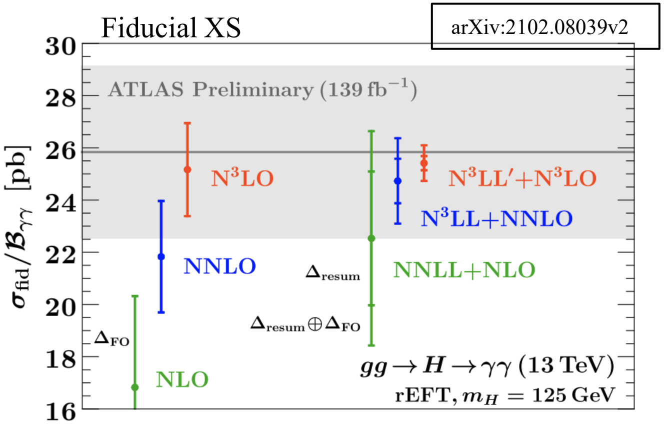
σ (ggF, VBF, VH) ~2 times larger

σ(ttH) ~4 times larger

The huge leap of theoretical calculations

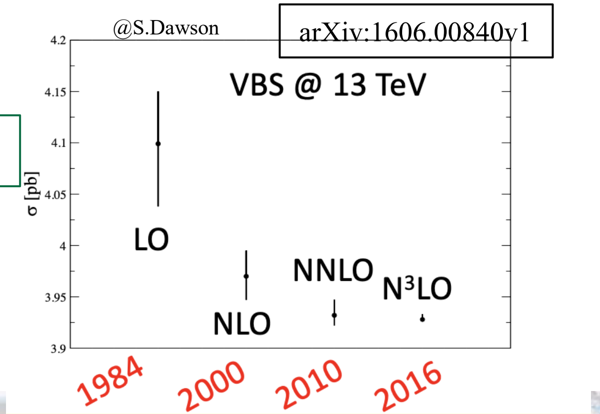
ggH





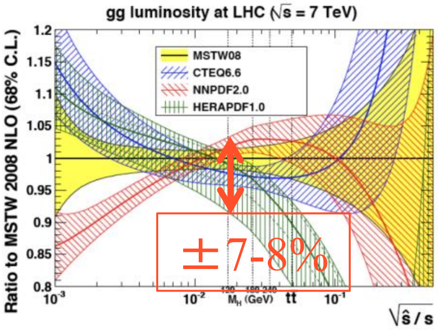
LHCHXSWG

qqH

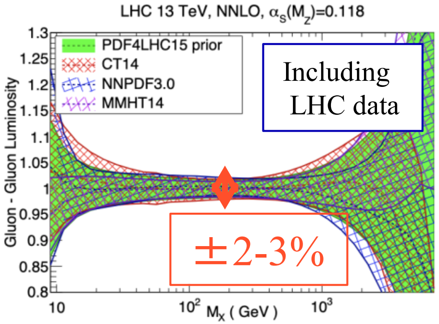


A huge improvement in the gluon PDF understanding

PDF

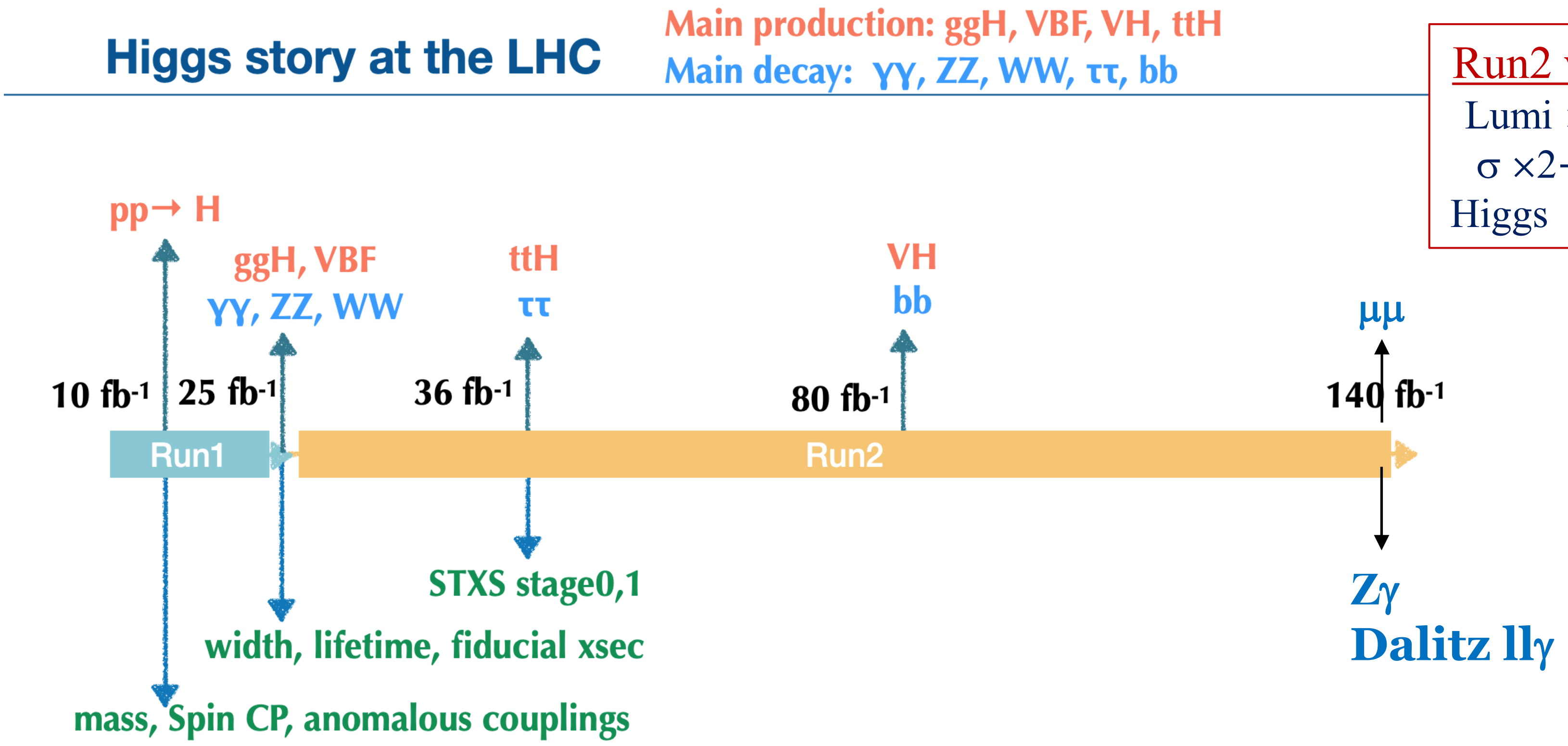


PDF4LHC-2011



PDF4LHC 2022

From the 4 of July 2012 to the end of Run2



Run2 wrt Run1

Lumi ×10 more

σ ×2−4 larger

Higgs ×30 more

©Meng Xiao

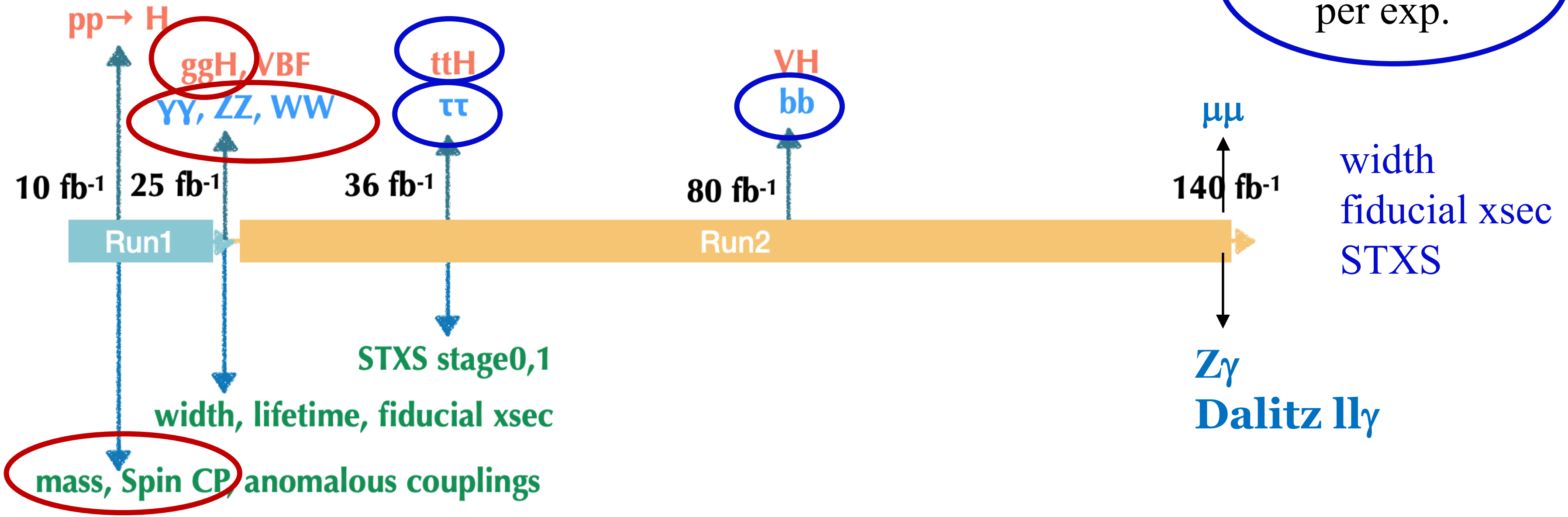
From the 4 of July 2012 to the end of Run2

~ 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.



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 $\mathbf{m_{4l}}$
- categories 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 4*l* Run1 + Run2	125.08 ± 0.12	(± 0.10 stat ± 0.05 syst) GeV
ATLAS 4*l*+γγ Run1+Run2	125.01 ± 0.11	(± 0.09 stat ± 0.06 syst) GeV

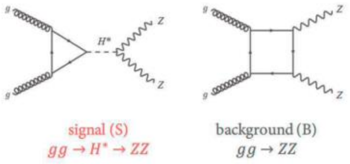
per mille precision

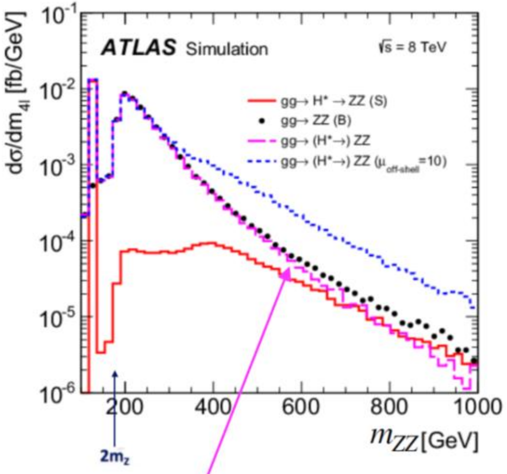
The Higgs width from off-shell production

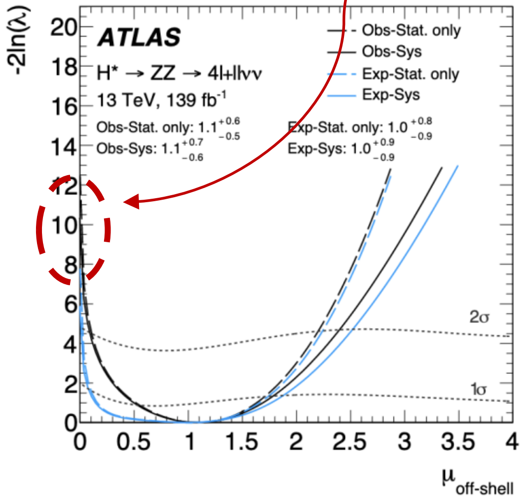
Both experiments observe Higgs off-shell production at > 3σ

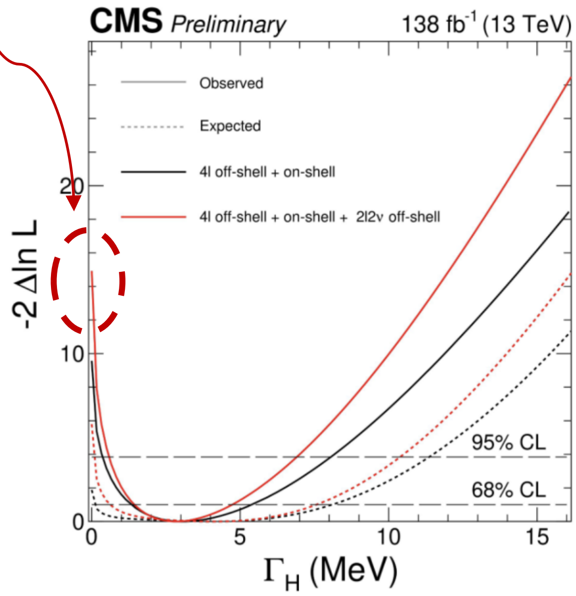
LHCP 2024

CMS-PAS-HIG-21-019









$\mathrm{SBI} = \mathrm{S} + \mathrm{B} + \mathrm{I}$

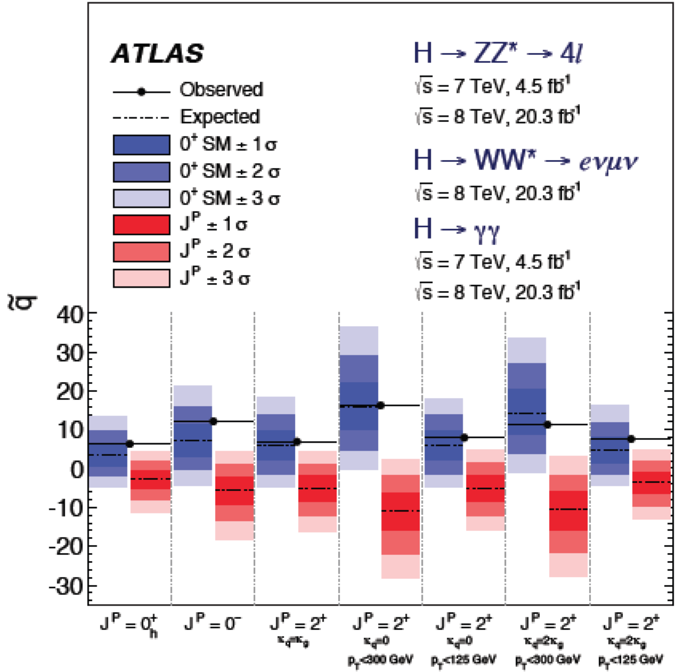
Known at NNnLO [Matrix]

$$\Gamma_H = 4.5^{+3.0}_{-2.5}\ \mathrm{MeV}$$

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ \mathrm{MeV}$$

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

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

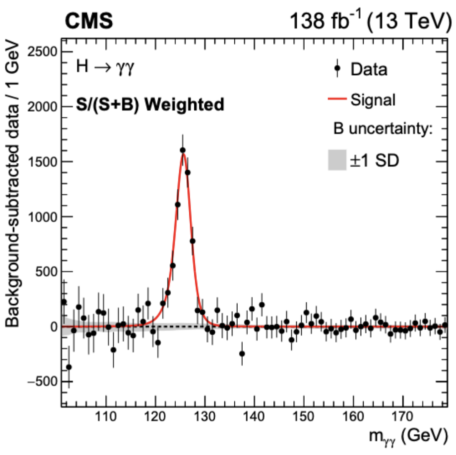


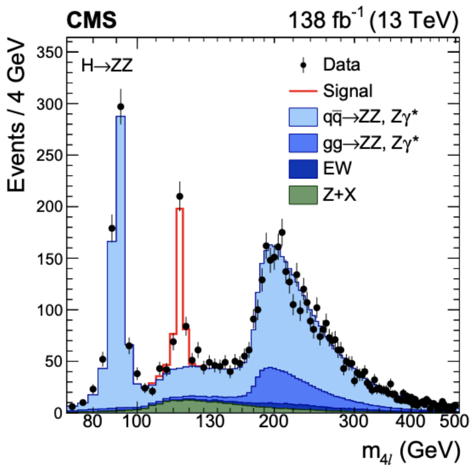
CP structure of various Higgs couplings probed for fermions (top, τ), gluons, EW vector bosons, with a variety of production and decay modes

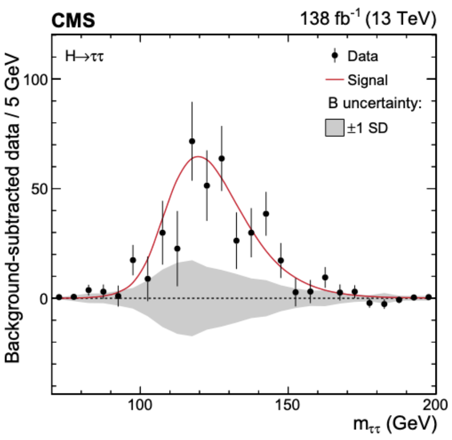
- Measurement globally in accord with SM CP-even hypothesis
- Pure CP-odd ttH coupling excluded 3.9 σ
- Pure CP-odd Hττ coupling excluded 3.4 σ

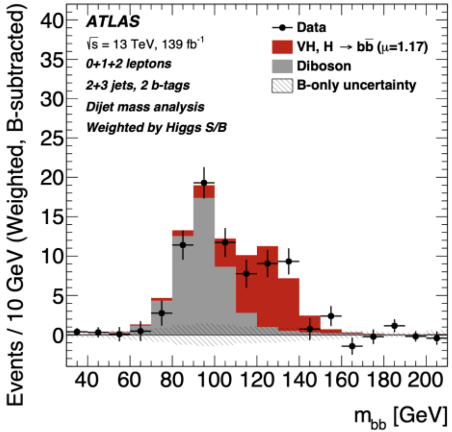
Bosonic channels

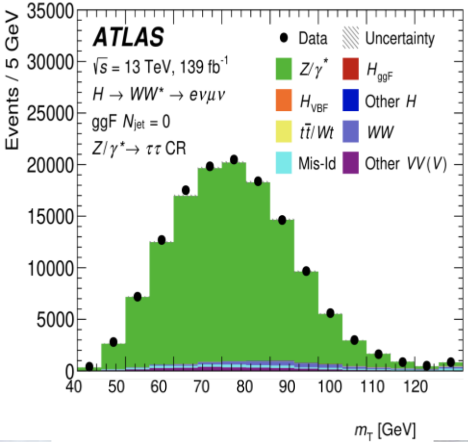
Fermionic channels

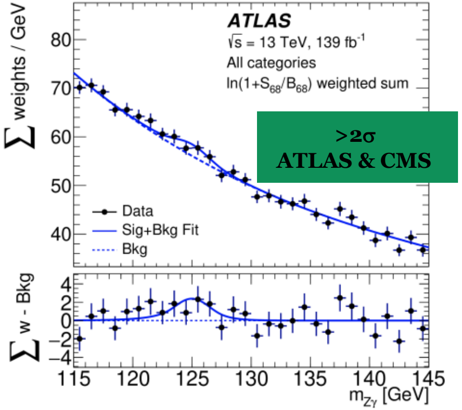




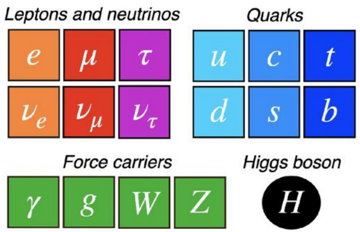


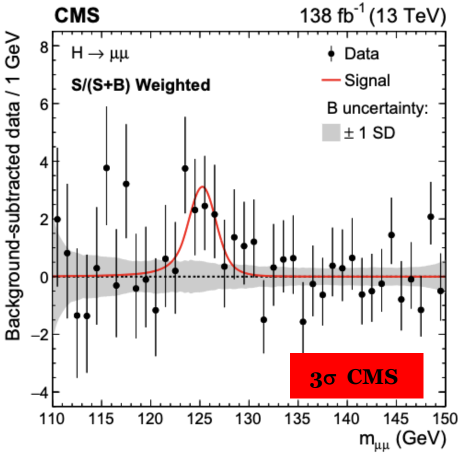






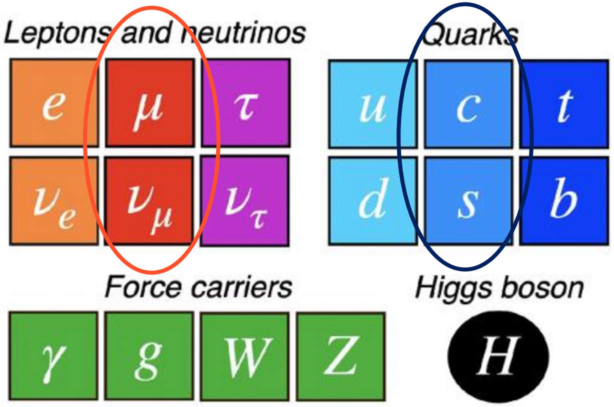
>2σ
ATLAS & CMS





3σ CMS

The coupling with the 2nd generation

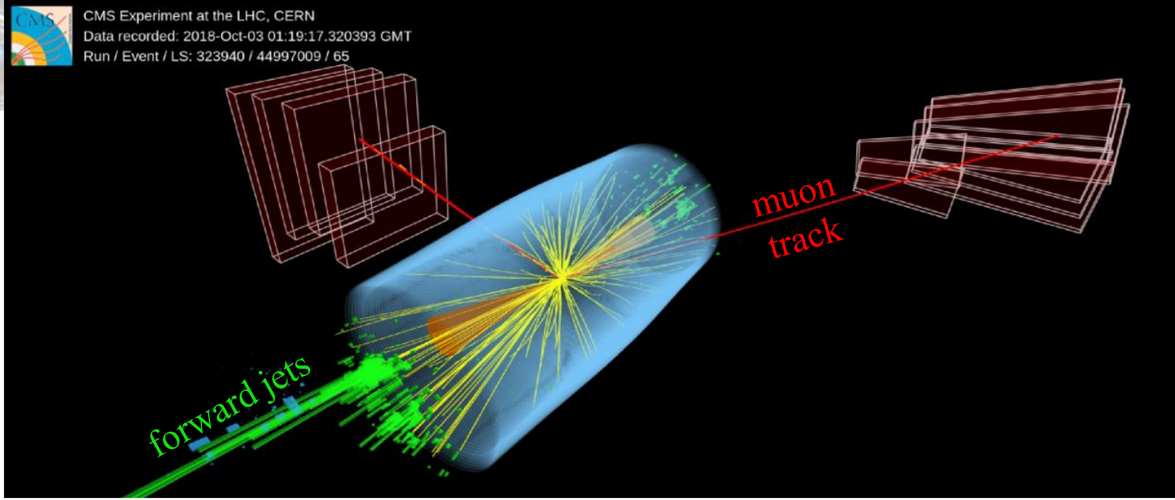


Boosted Decision Trees,
Deep Neural Network,
Advance Machine Learning …
improve
Efficiency and Purity

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

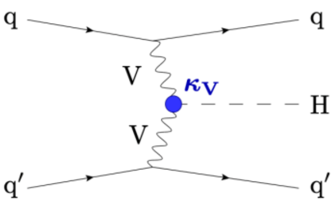
©Andre David

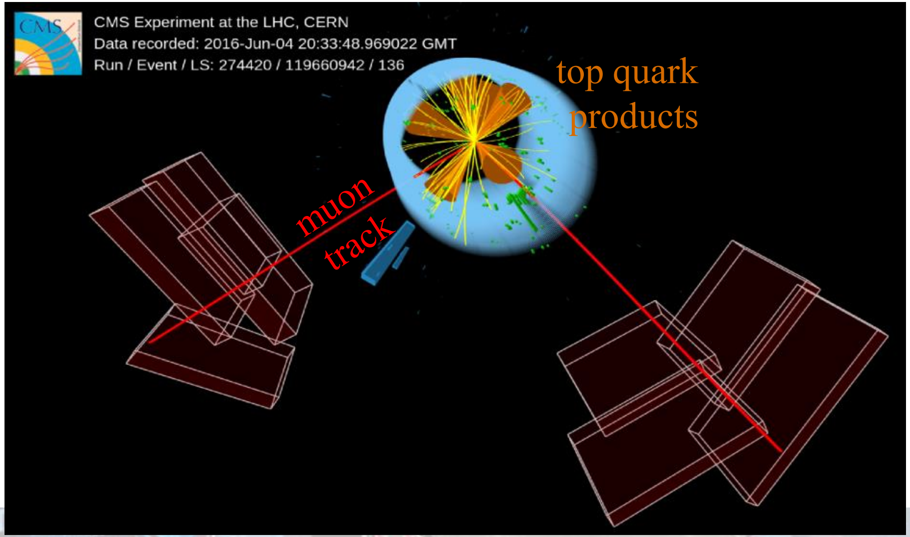
Higgs to muons



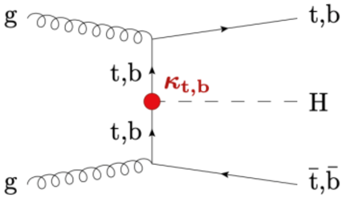
SM BR(H→ μμ) ~ 2.2 × 10^{-4}

Exploit all production modes.



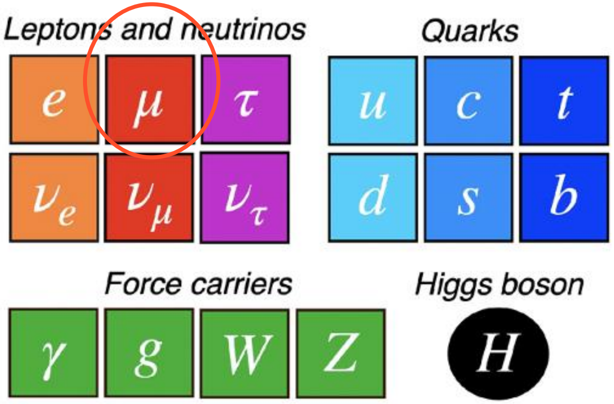


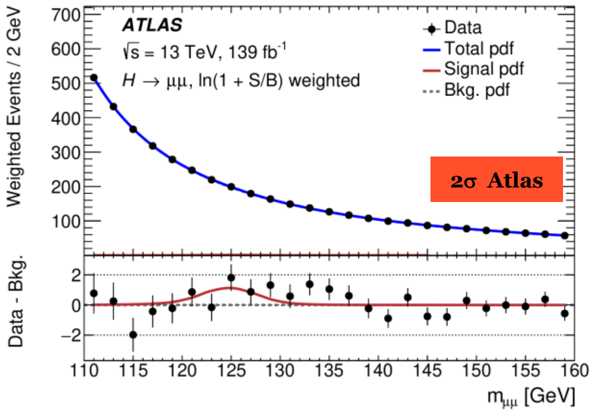
Candidate events compatible with different associated production modes and H⁰(125)→μμ decay.

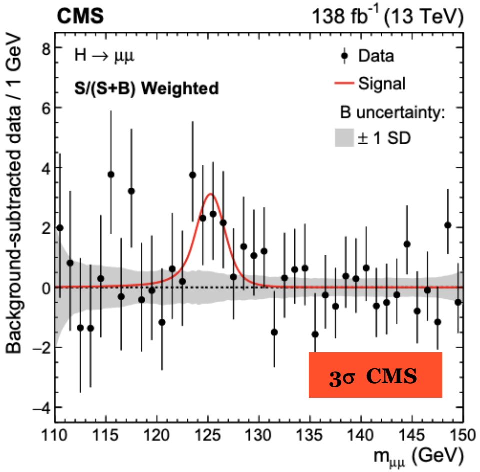


The coupling with the 2nd generation

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





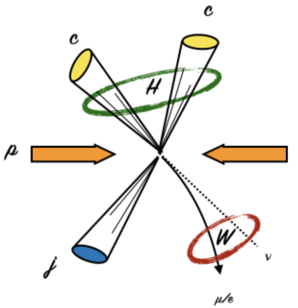


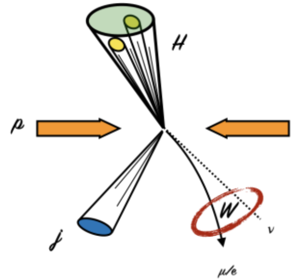
Higgs to charm

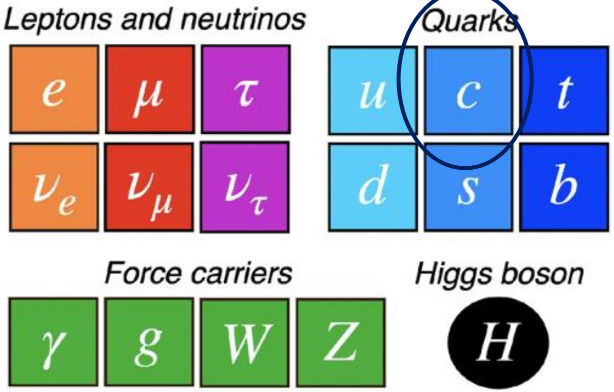
CMS: arxiv:2205.05550
ATLAS: arxiv:2201.11428

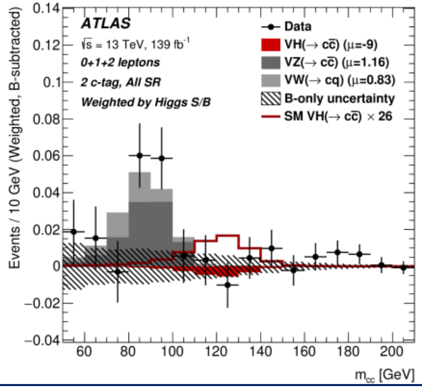
SM BR(H→cc) ~ 0.028

Search for H→cc
in VH events (and gg)

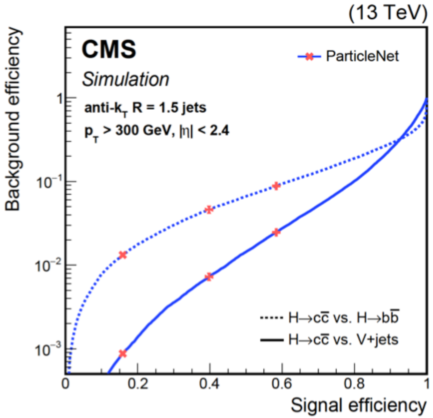


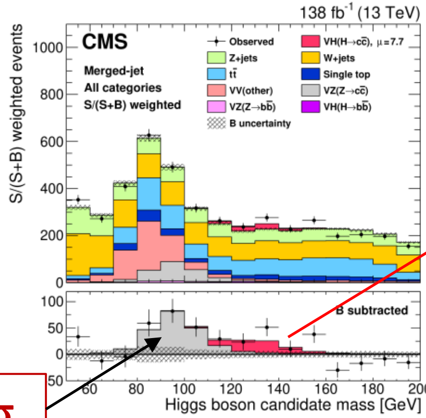


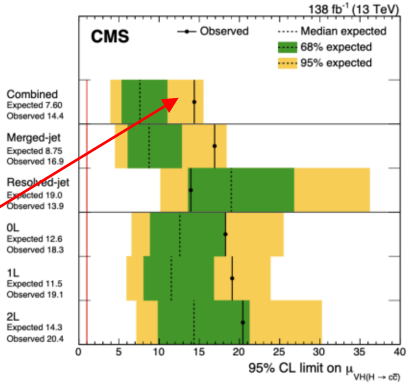




Sensitivity to **H→cc** ~ 8 × SM







Z→cc >> 5σ

Agreement with the SM: the signal strength

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%

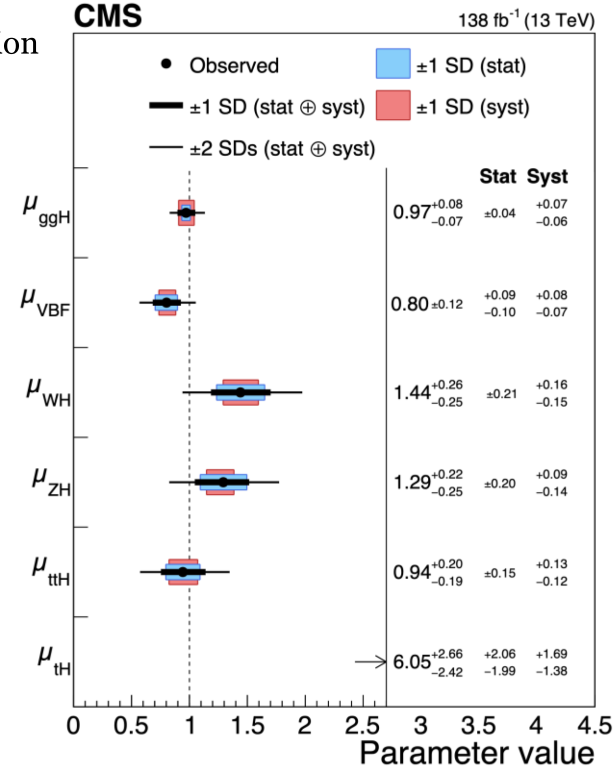
th – exp – stat uncertainties are of the same size

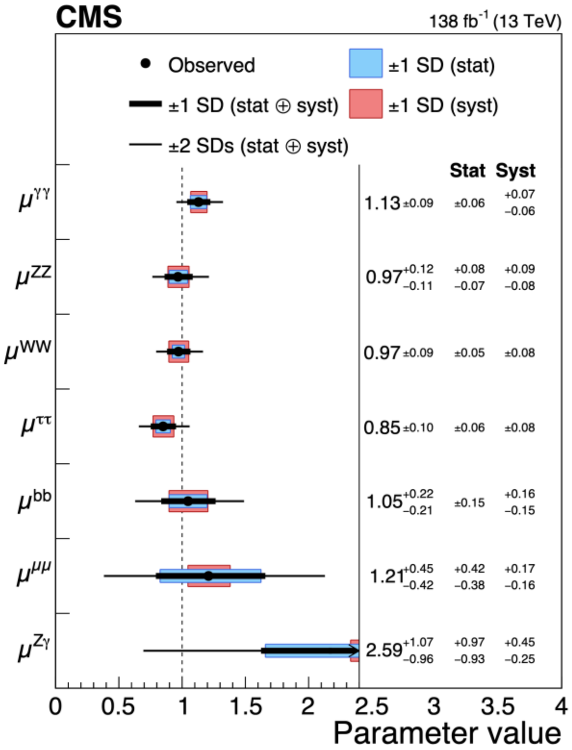
Higgs boson production modes and decay channels

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

Production

> 5 SD

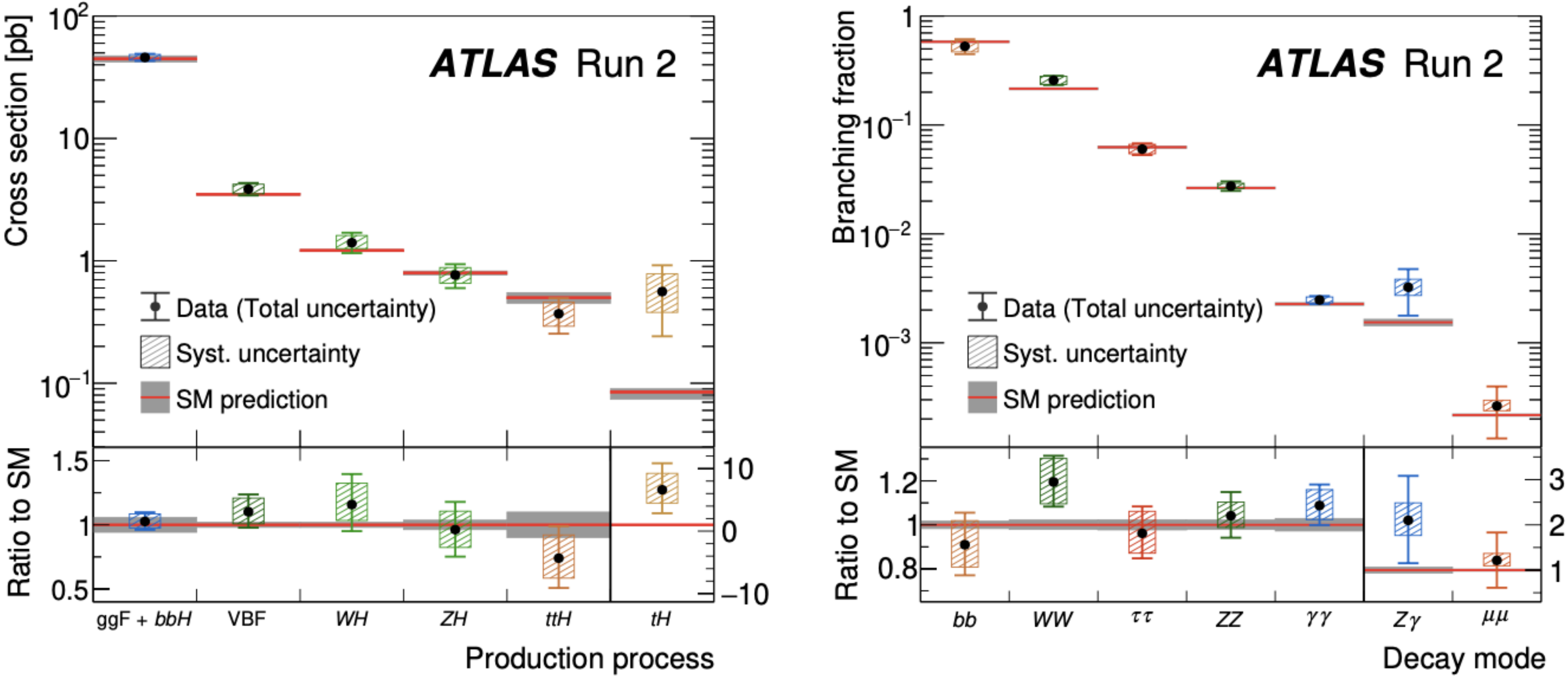




Decay

> 5 SD

Cross sections and Branching ratios



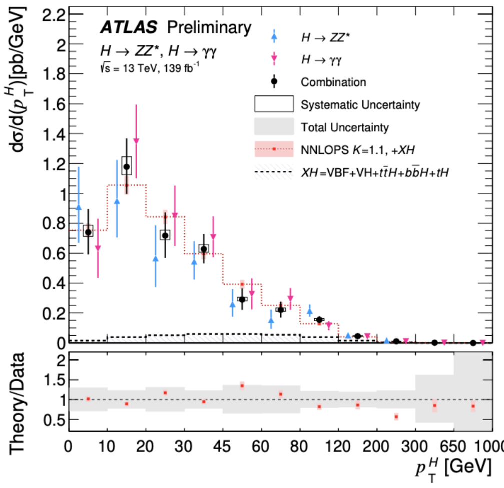
Differential distributions

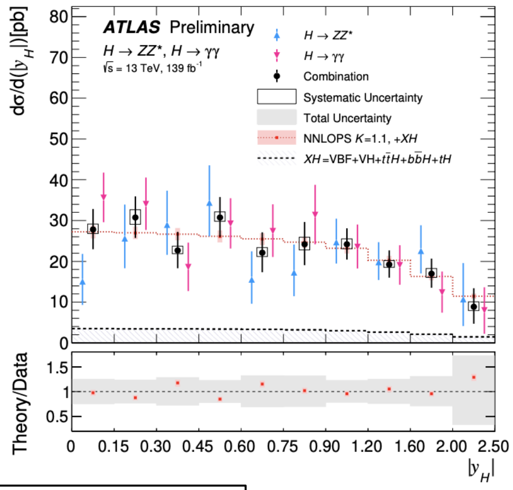
p_T , y, φ, n_{jet}… describe the Higgs production at LHC and help understanding QCD effects.

p_T → perturbative QCD

+ resummation of the leading logarithms,

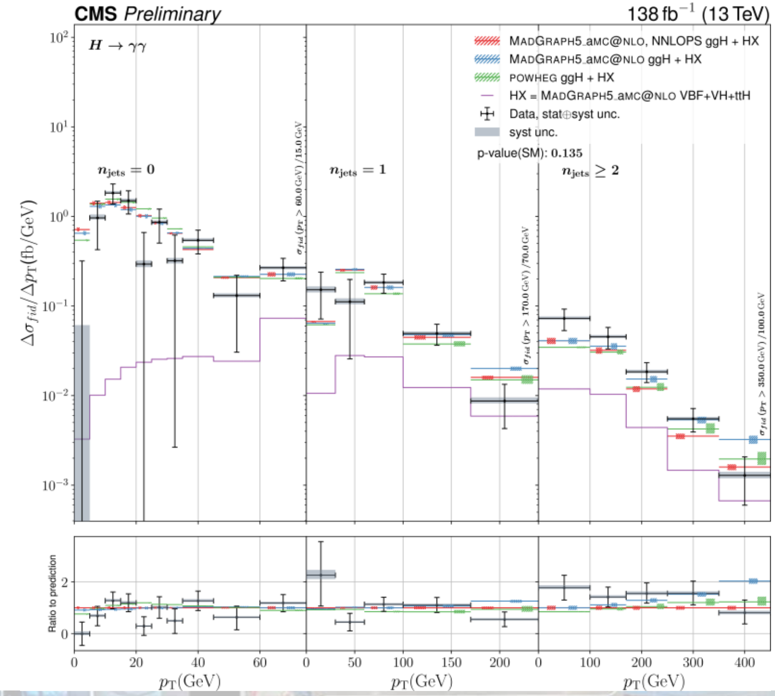
+ probe of new physics at high values.





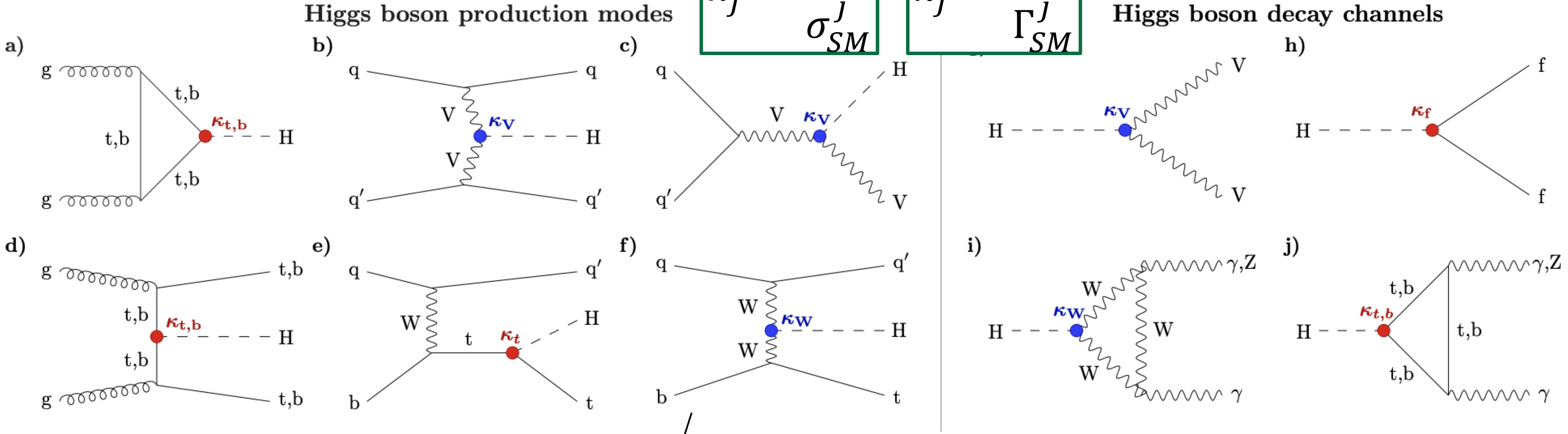
20-30% precision

Double differential XS

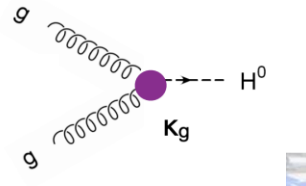


The couplings & the coupling modifiers: the κ framework.

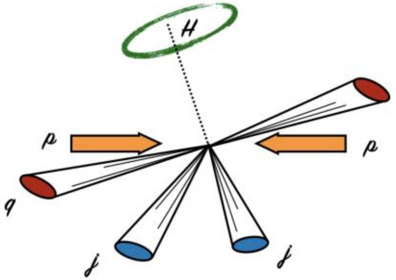
$$\kappa_j^2 = \frac{\sigma^j}{\sigma^j_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$



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

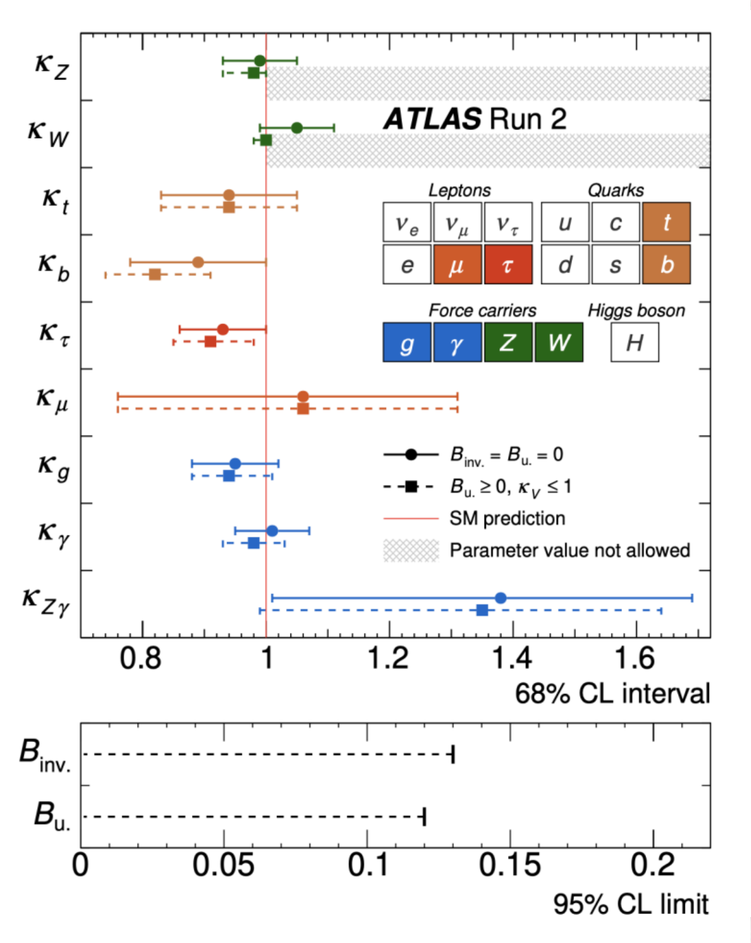


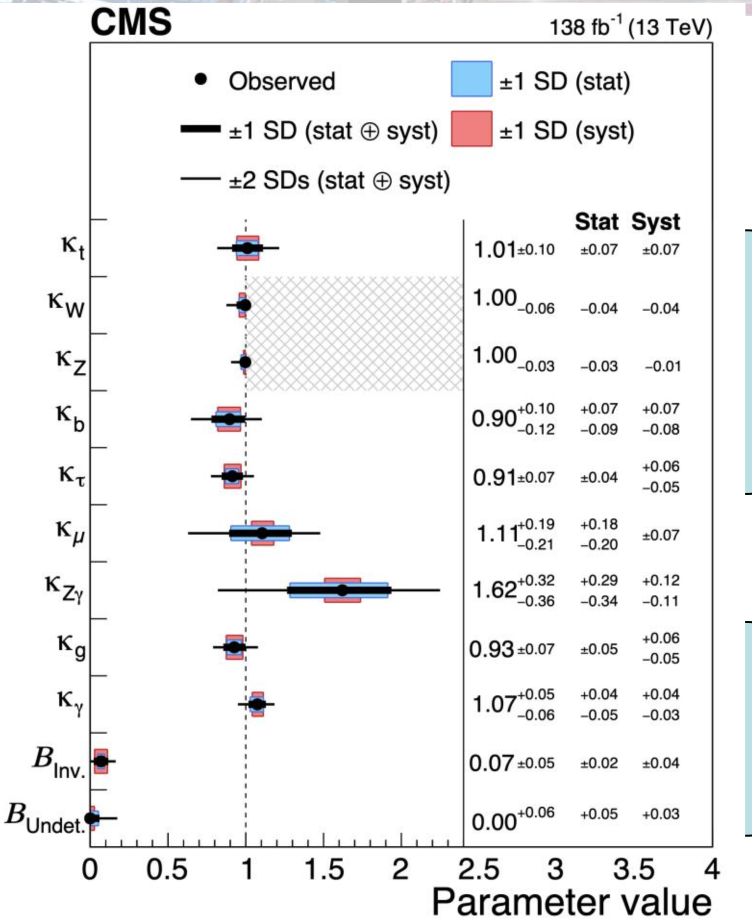
Invisible (ν, DM…) or Undetected decay



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

The κ framework





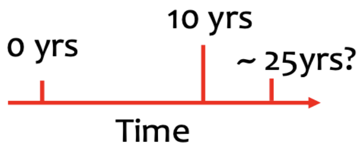
		Stat	Syst
κ_t	$1.01^{\pm0.10}$	±0.07	±0.07
κ_W	$1.00_{-0.06}$	−0.04	−0.04
κ_Z	$1.00_{-0.03}$	−0.03	−0.01
κ_b	$0.90^{+0.10}_{-0.12}$	+0.07 −0.09	+0.07 −0.08
κ_τ	$0.91^{\pm0.07}$	±0.04	+0.06 −0.05
κ_μ	$1.11^{+0.19}_{-0.21}$	+0.18 −0.20	±0.07
$\kappa_{Z\gamma}$	$1.62^{+0.32}_{-0.36}$	+0.29 −0.34	+0.12 −0.11
κ_g	$0.93^{\pm0.07}$	±0.05	+0.06 −0.05
κ_γ	$1.07^{+0.05}_{-0.06}$	+0.04 −0.05	+0.04 −0.03
$B_{Inv.}$	$0.07^{\pm0.05}$	±0.02	±0.04
$B_{Undet.}$	$0.00^{+0.06}$	+0.05	+0.03

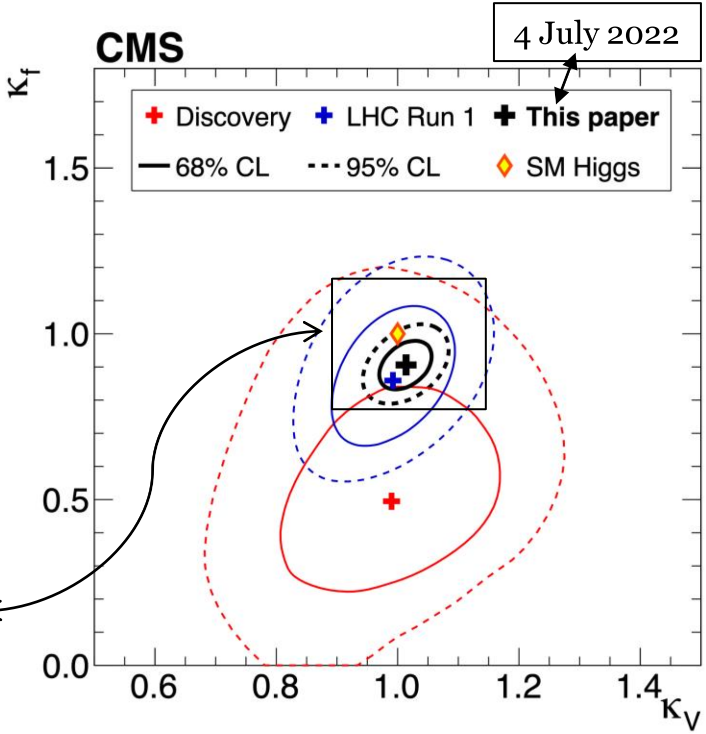
< 3 - 10%

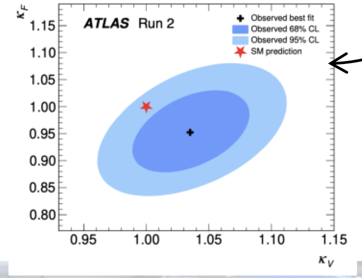
Chiara Mariotti

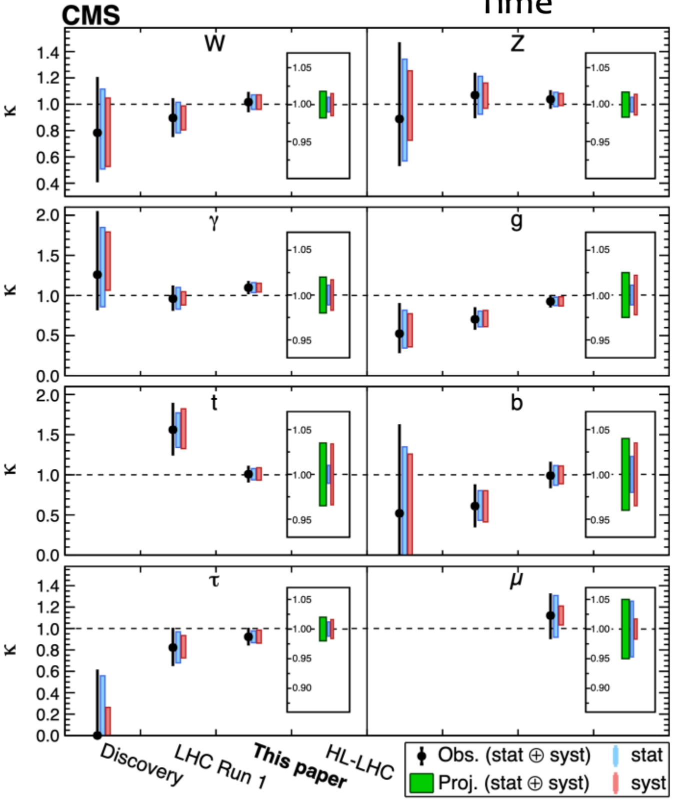
Luminosity, energy and …. ingenuity

~30 times more Higgs events in Run2



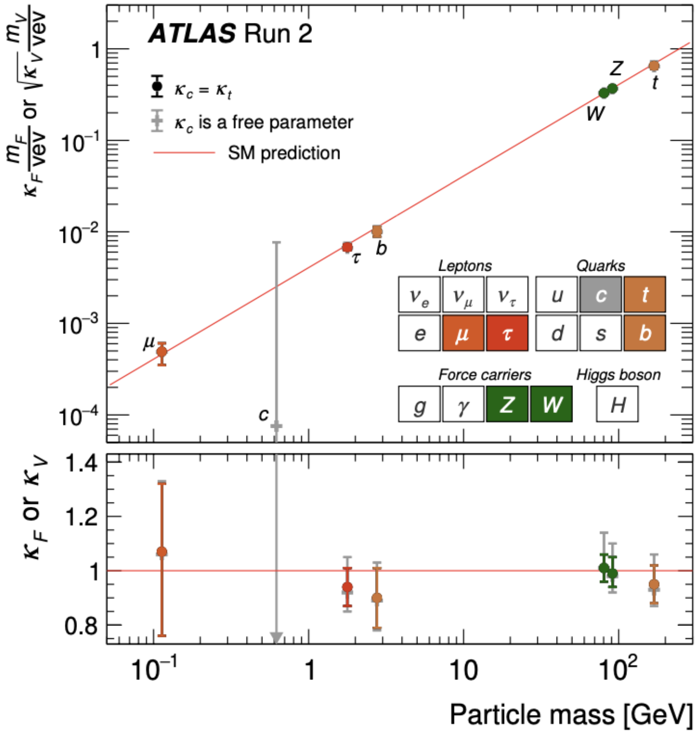


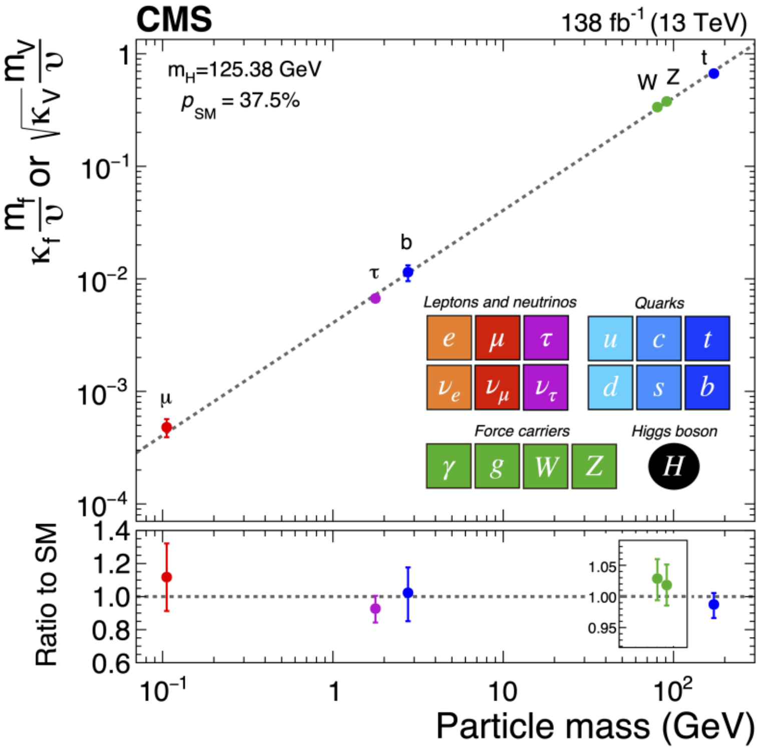




The portrait of the Higgs boson

SM test over many orders of magnitude





The Higgs couples with the particle mass !

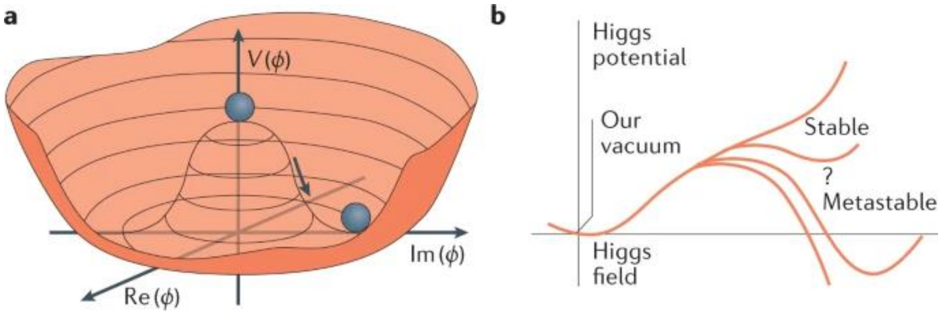
The search for Higgs boson pair production

The Higgs potential

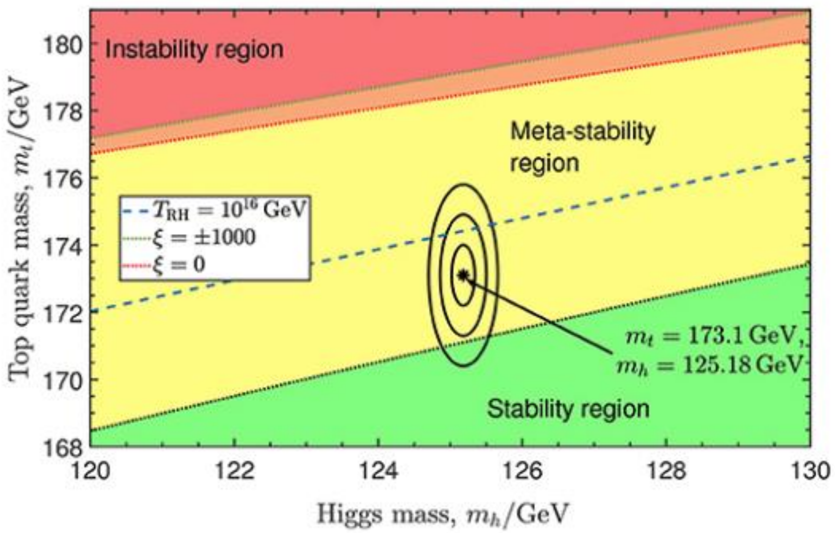
$$V(\phi) = \frac{1}{2}m_{\rm H}^2\phi^2 + \sqrt{\lambda/2}\,m_{\rm H}\phi^3 + \frac{1}{4}\lambda\phi^4$$

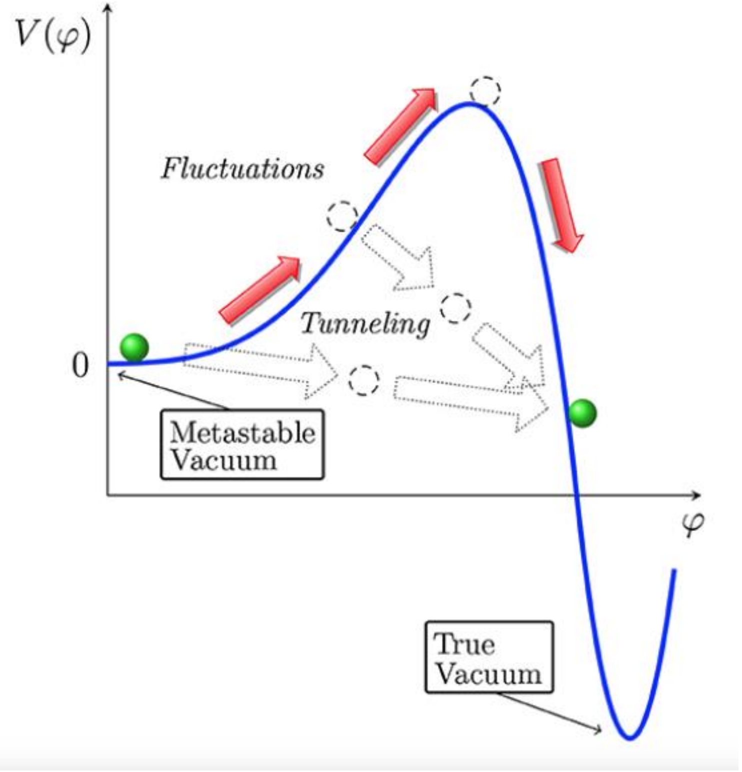
$$\lambda = m_{\rm H}^2/(2v^2)$$

we measured the minimum, we should measure the curvature



The future of our universe





The search for Higgs boson pair production

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

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

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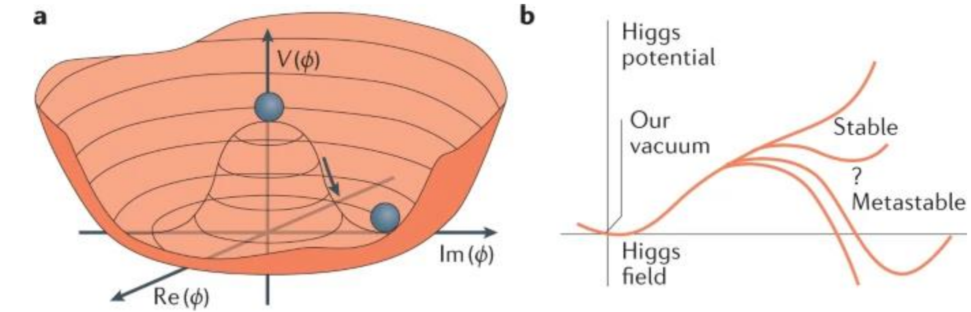
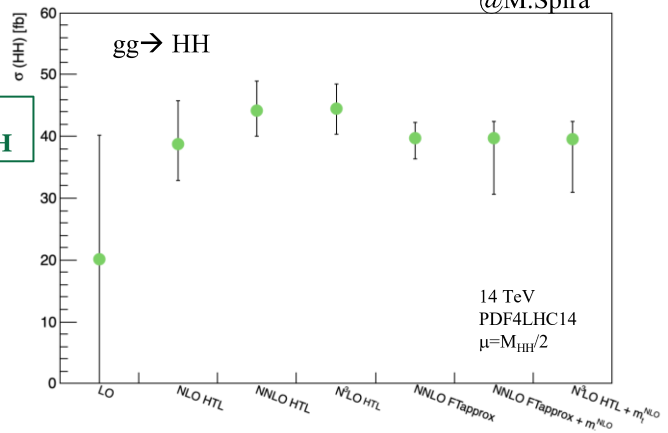


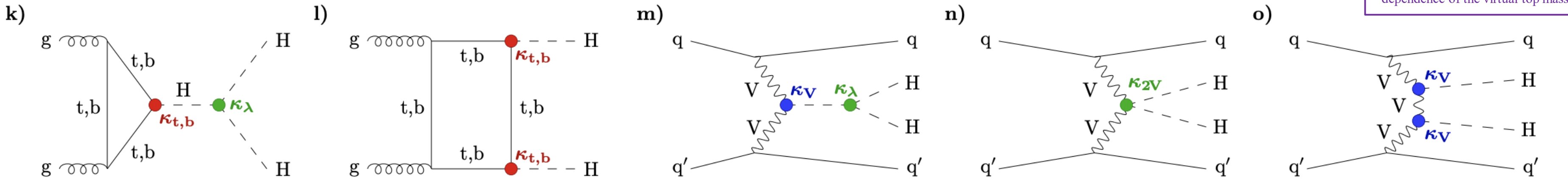
$\sigma_{HH} \sim 10^{-3}\, \sigma_H$

@M.Spira

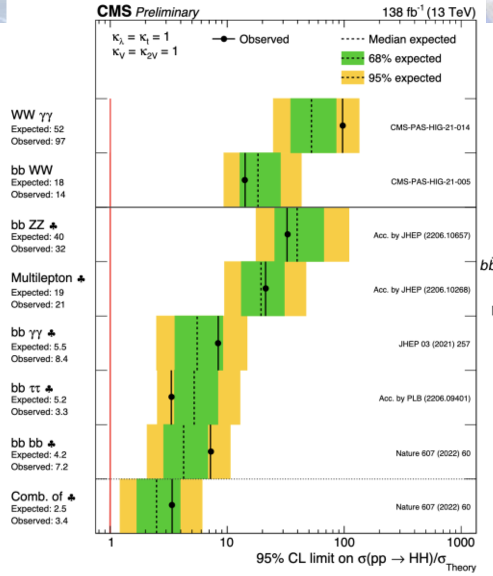


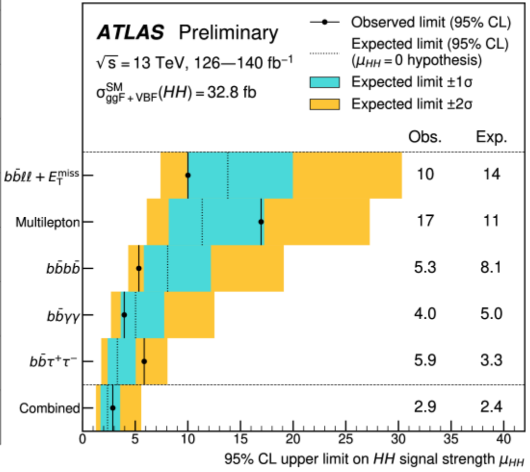
>> uncert: scale and scheme dependence of the virtual top mass

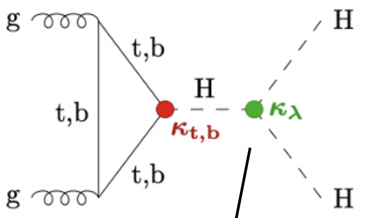
Higgs boson pair production



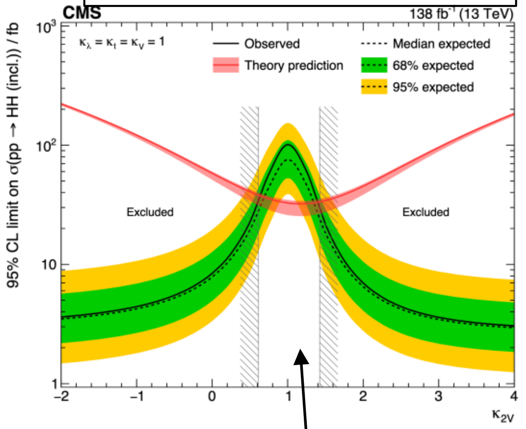
Results on HH production



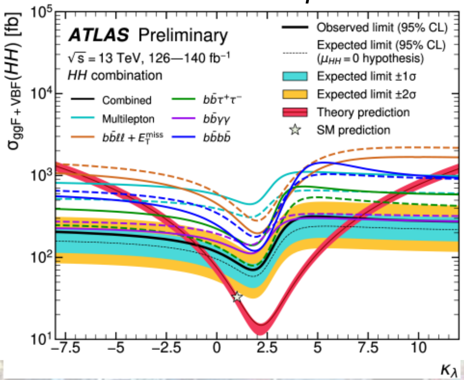


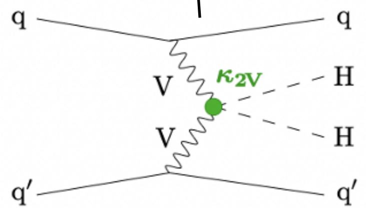


VVHH indeed exists



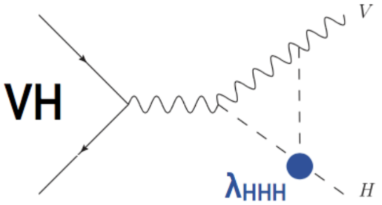
σ(HH) < 2. ÷ 3. SM

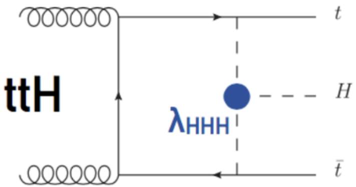




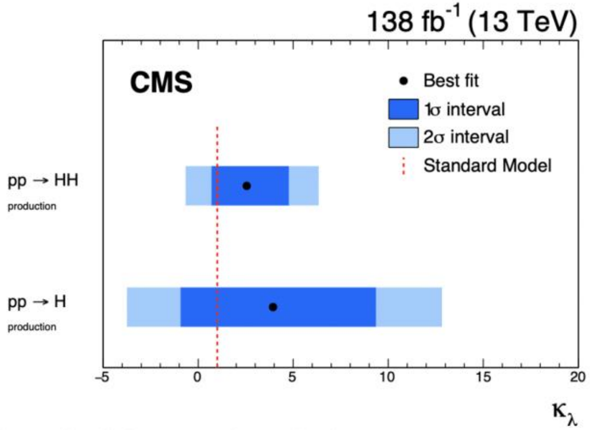
ATLAS +CMS will observe HH production at HL-LHC at 5 s.d.

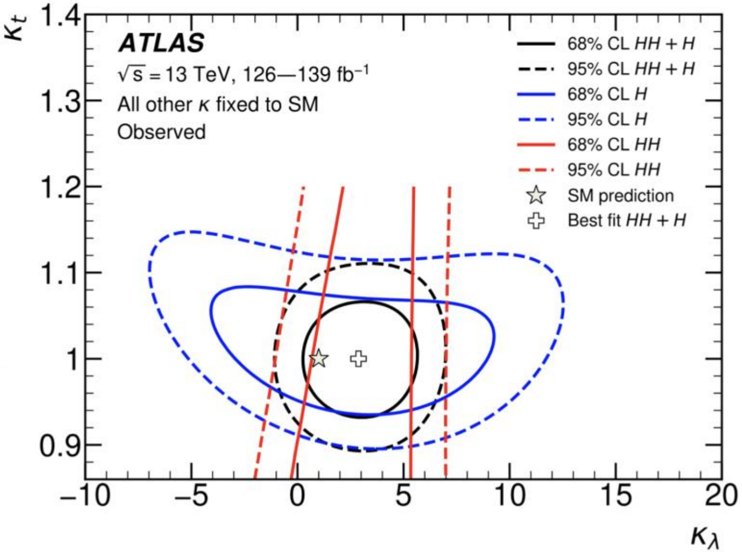
κ_λ from single Higgs production





Single Higgs production modes sensitive to self-coupling through loop corrections





The end of LHC

Extrapolation of the current measurements to 3 ab^{-1}

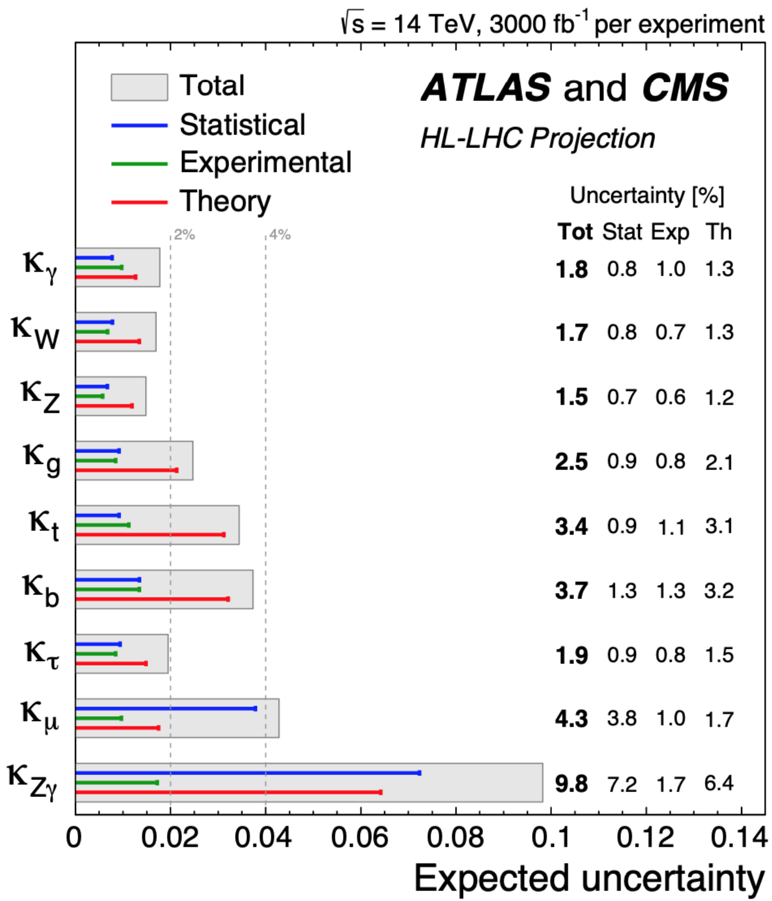
under assumptions on the evolution of the systematic uncertainties and detector performance as $\sqrt{L}$ and th-syst/2

Most couplings known at a precision of 2-4%

with theory uncertainties as the dominant ones

stat. uncertainties remaining relevant for very rare processes

- Run-3 goal: ~300fb^{-1} by 2025
- HL-LHC goal: ~3ab^{-1} by 2038



Current precision

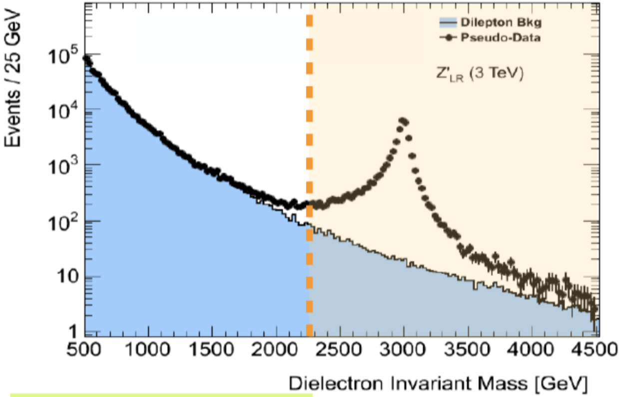
6%
6%
6%
7%
11%
11%
8%
20%
30%

B_{inv}	2.5%	<11%

Precision measurements

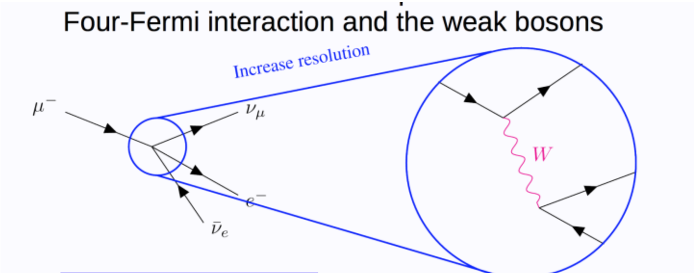
We are now measuring with high precisions all the characteristics of the Higgs bosons.
By measuring with high precision all the quantities related to the Standard Model we can observe deviations, if there is new physics.

effect of a Z’ in the dilepton spectrum

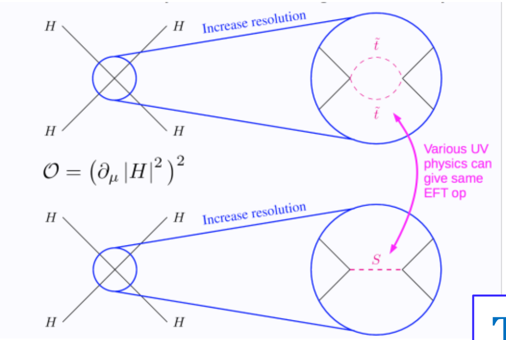


no resonance seen but *deviations* wrt SM

Increasing precisions is like observing with a magnifying glass:



Before 1960



The future

SMEFT

Effective Field Theory reveals high energy physics through precise measurements at low energy.
The validity is for $E \ll \Lambda$

from Lagrangian ...

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{n=1}^{N_8} \frac{b_j}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

SM — **EFT$_{d6}$** — **EFT$_{d8}$**

Linear EFT cross-sections: interference SM-EFT$_{d6}$

Quadratic EFT cross-sections: squares EFT$_{d6}$

to cross-sections ....

$$\sigma_{\mathrm{SMEFT}}(\boldsymbol{c}, \boldsymbol{\Lambda}) \simeq \sigma_{\mathrm{SM}} \times \left(1 + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \sigma_m^{(\mathrm{eft})} + \sum_{m,n=1}^{N_6} \frac{c_m c_n}{\Lambda^4} \sigma_{m,n}^{(\mathrm{eft})}\right)$$

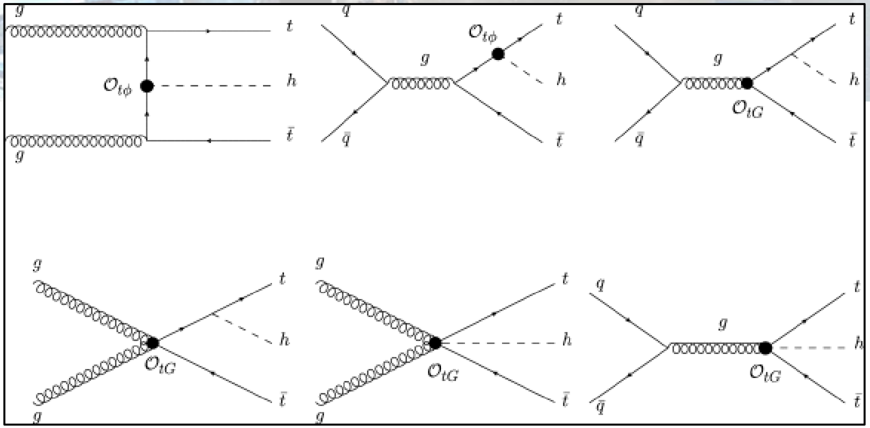
evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD with **SMEFT@NLO**

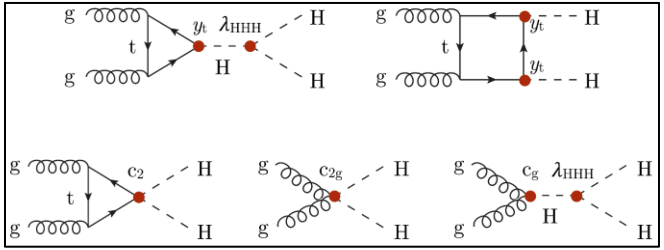
@Richard Ruiz

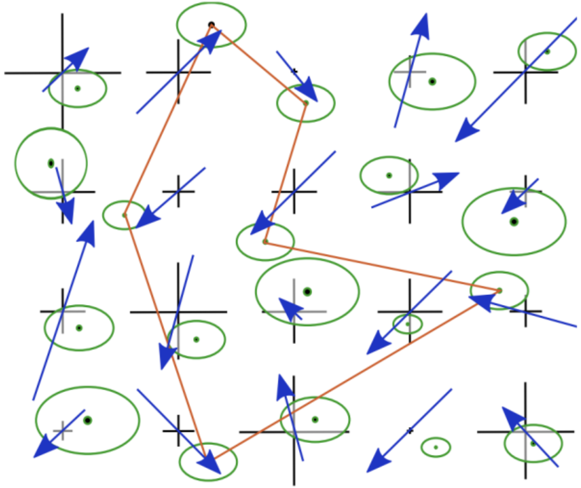
d5 → maiorana neutrino. The Weinberg operator can be probed at the LHC through the same-sign *WW VBS* channel, with $W_1 \rightarrow e,\mu,\tau$, but $W_2 \rightarrow \mu,\tau$

EFT a way to identify patterns of new physics



Identifying patterns of new physics





design sensitive observables

- precise SM predictions
- precise SMEFT predictions
- precise measurements

→ leverage correlations

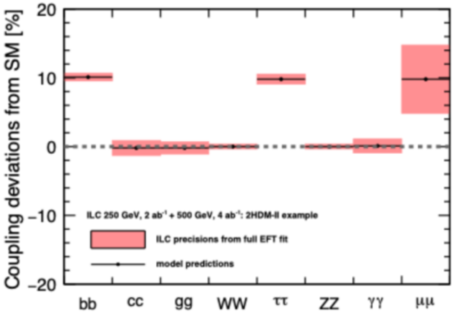
@Gautier Durieux

Patterns of deviations

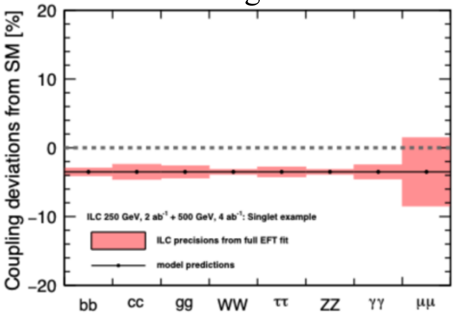
Different New Physics models lead to different patterns of deviations

The size of deviations depends on the NP scale.

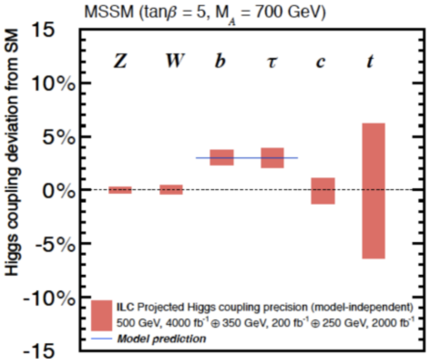
2HDM



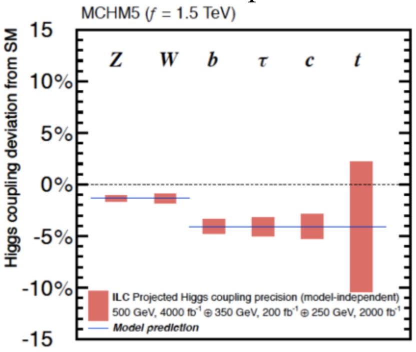
Singlet



MSSM

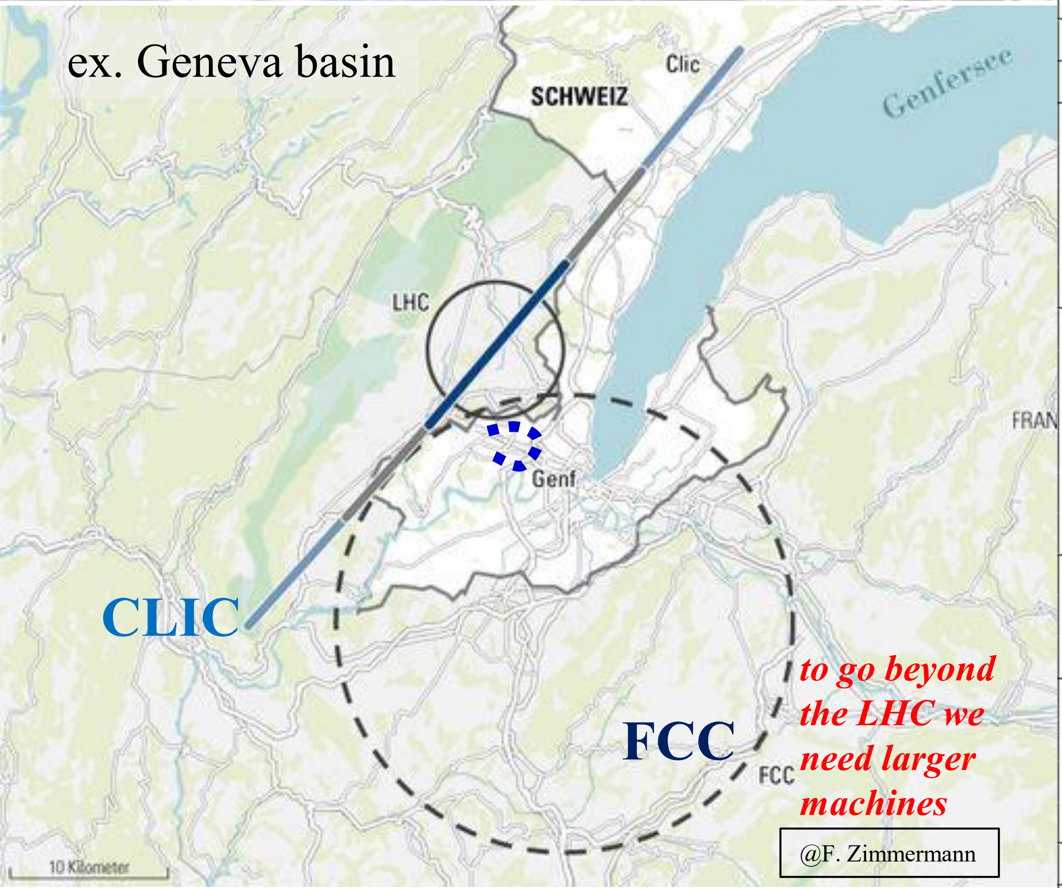


Composite H



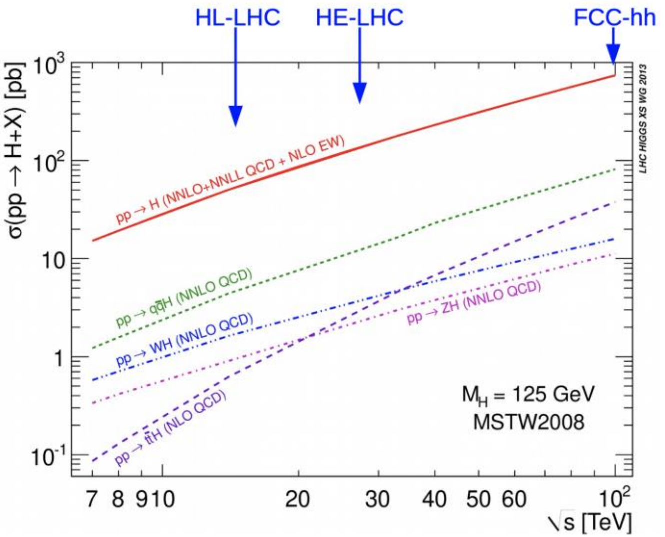
After full ILC running

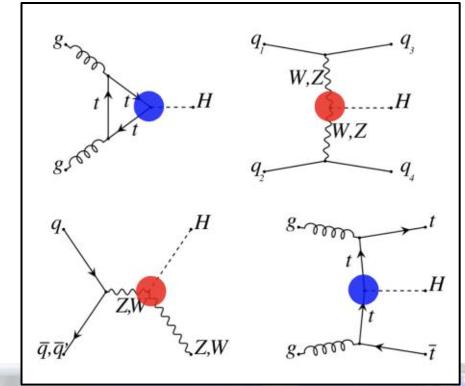
Proposed linear & circular colliders

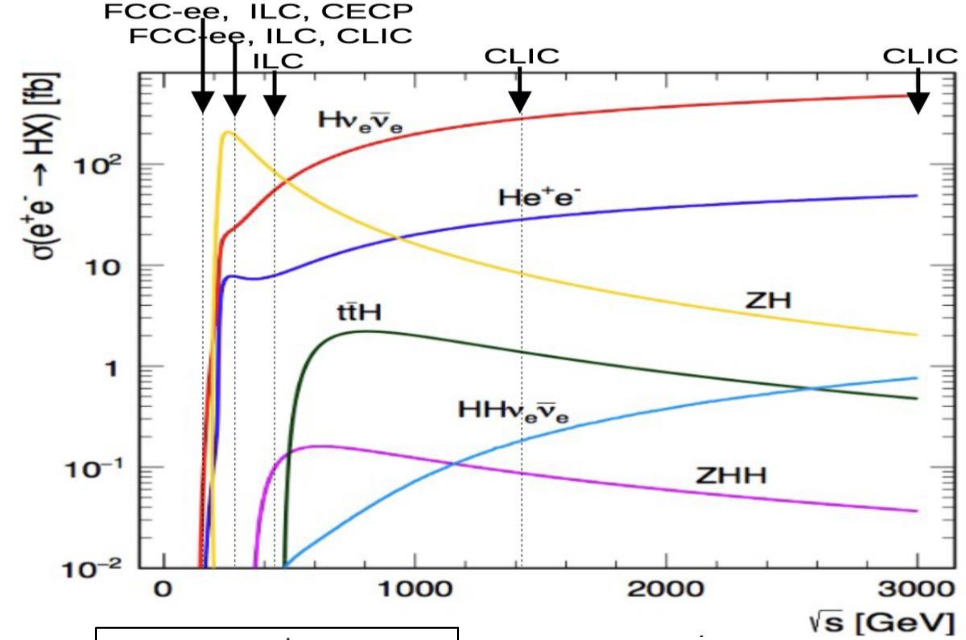


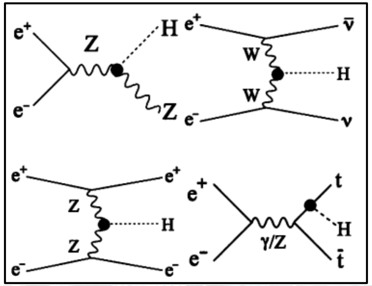
Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathcal{L}_{\text{inst}}$ $[10^{34}]$ $\text{cm}^{-2}\text{s}^{-1}$	$\mathcal{L}$ $[\text{ab}^{-1}]$	Time [years]
HL-LHC	pp	14 TeV	—	2	5	6.0	12
HE-LHC	pp	27 TeV	—	2	16	15.0	20
FCC-hh$^{(*)}$	pp	100 TeV	—	2	30	30.0	25
FCC-ee	ee	M_Z	0/0	2	100/200	150	4
		$2M_W$	0/0	2	25	10	1–2
		240 GeV	0/0	2	7	5	3
		$2m_{\text{top}}$	0/0	2	0.8/1.4	1.5	5 (+1)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5
		350 GeV	±80/±30	1	1.6	0.2	1
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5 (+1)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5 (+1-2)
CEPC	ee	M_Z	0/0	2	17/32	16	2
		$2M_W$	0/0	2	10	2.6	1
		240 GeV	0/0	2	3	5.6	7
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8
		1.5 TeV	±80/0	1	3.7	2.5	7
		3.0 TeV	±80/0	1	6.0	5.0	8 (+4)
LHeC	ep	1.3 TeV	—	1	0.8	1.0	15
HE-LHeC	ep	1.8 TeV	—	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	—	1	1.5	2.0	25

Hadron collider - σ(H) - Electron collider





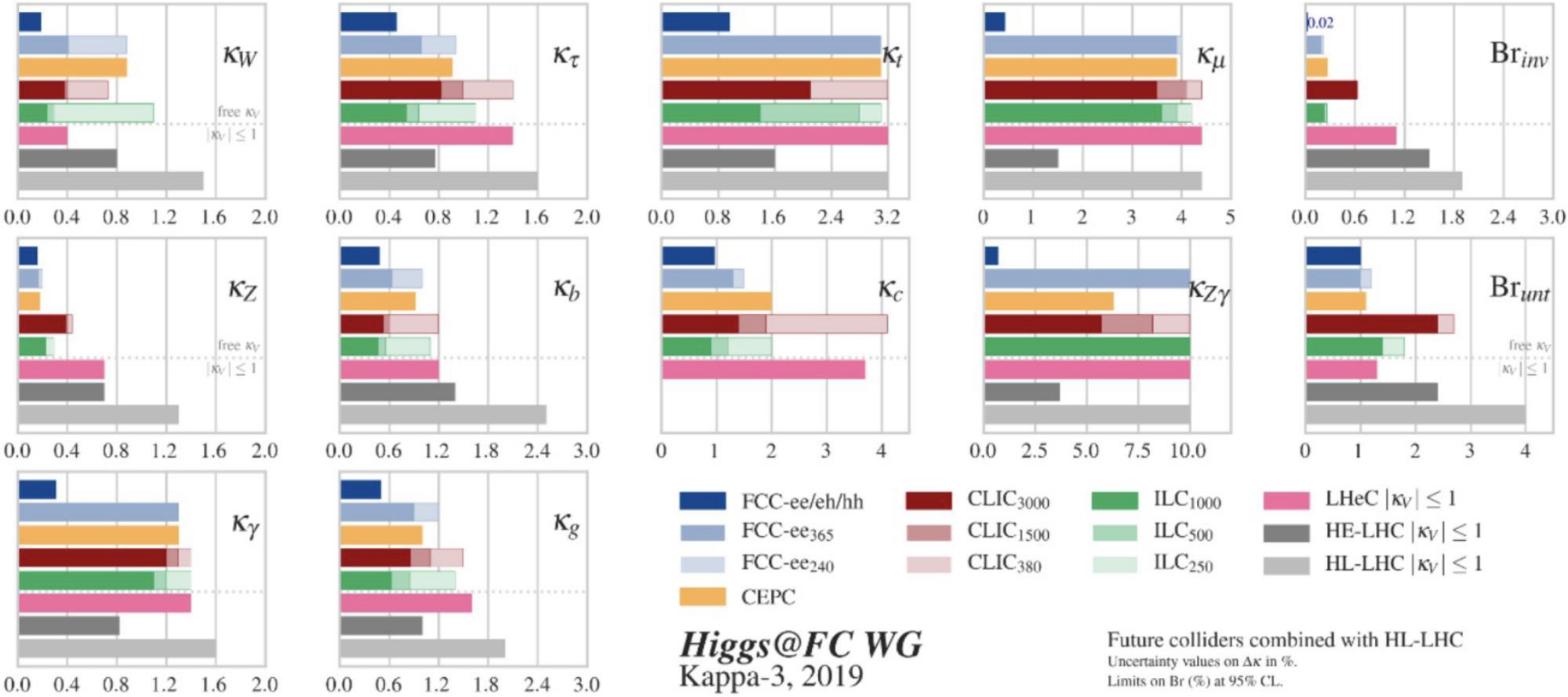




$$M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

@E. Petit

Higgs coupling at future colliders



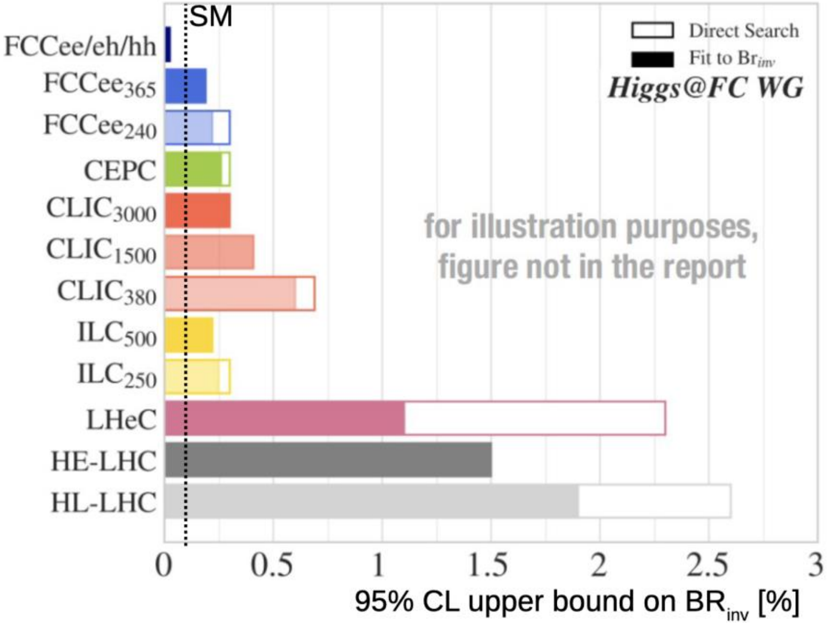
Invisible Higgs width

In the SM, $BR_{SM,inv}$ = BR(H→4ν) = 0.11%

Current limit: BRinv < 11% @95%CL. By the end of HL-LHC BRinv < 2.5%

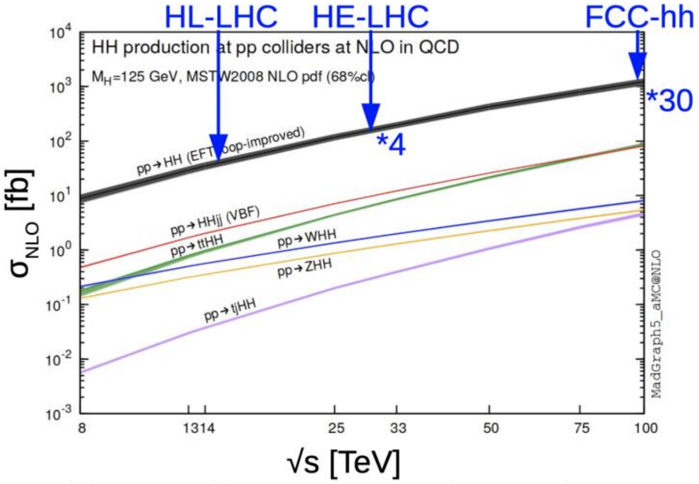
hh-coll: ET_{miss} uncertainties,

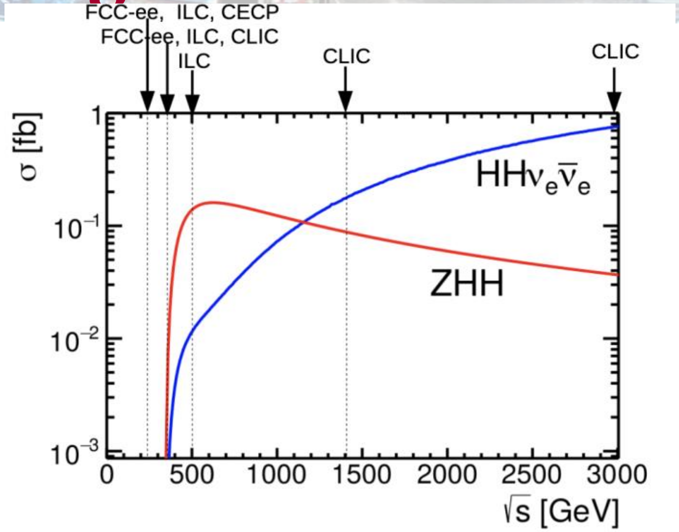
ee-coll: Z-recoil

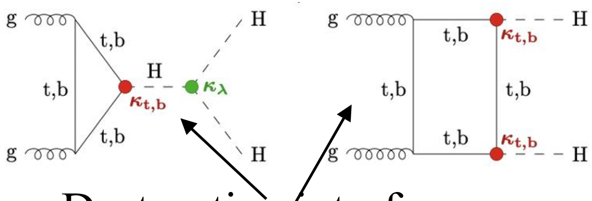


$$M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$$

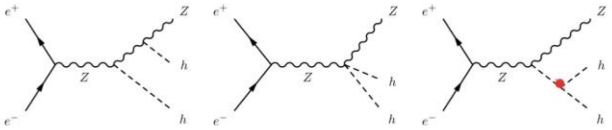
Di-Higgs production & self couplings



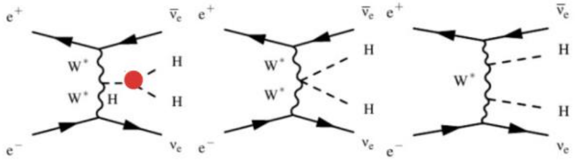




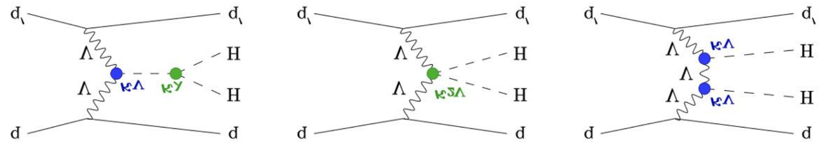
Destructive interference



– ZHH

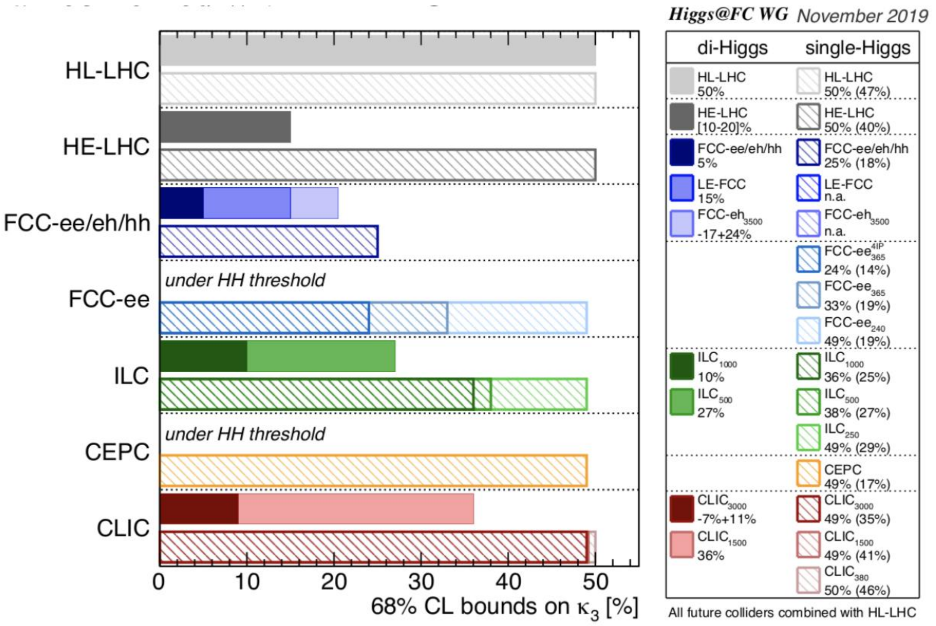


– VBF $\nu\bar{\nu}HH$



κ_λ at future colliders

68% CL uncertainties on κ_λ with di-Higgs and single-Higgs, combined with HL-HLC



HL-LHC will exclude the absence of Higgs self-interaction at 95% CL

FC will establish the existence of Higgs self-interaction at 5 σ

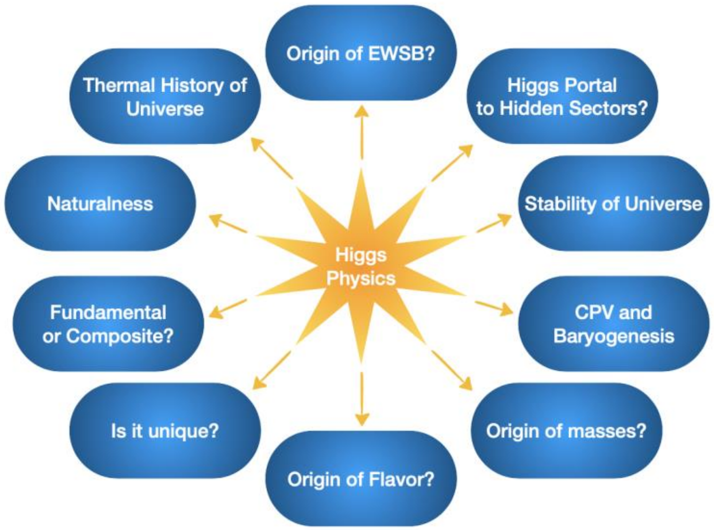
CLIC3000/FCC-hh can start probing the size of the quantum corrections to the Higgs potential directly.

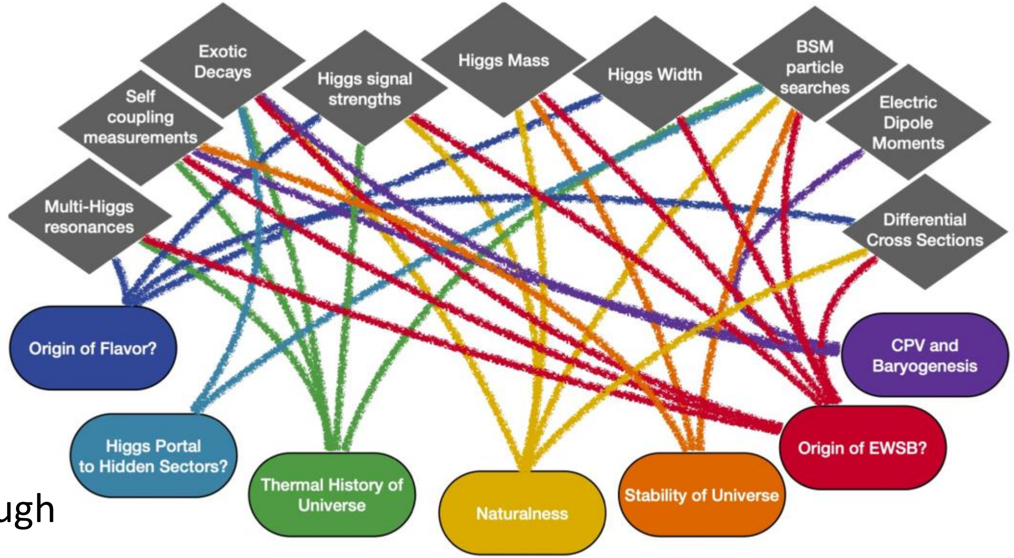
New colliders and the Higgs couplings

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge couplings	Higgs Width	ν couplings	λ_3	λ_4
	LHC/HL-LHC	✗	✗	✗	✓ (red)	✓ (yellow)	✓ (yellow)	✗	✓ (yellow)	✓ (yellow)	✓ (green)	✓ (yellow)	?	✓ (red)	✗
Higgs Factory	ILC/C^3	✗	✗	✗*	✓ (green)	✓ (green)	✓ (green)	✗	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✓ (yellow)	✗
Higgs Factory	CLIC	✗	✗	☐	✓ (green)	✓ (green)	✓ (green)	✗	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✓ (yellow)	✗
Higgs Factory	FCC-ee/CEPC	✗	✗	☐	✓ (green)	✓ (green)	✗	✓ (red)	✓ (yellow)	✓ (green)	✓ (green)	✓ (green)	?	✗	✗
High Energy	μ-Collider	✗	✗	☐	✓ (green)	✓ (green)	✓ (red)	✗	✓ (green)	✓ (green)	✓ (green)	✓ (green)	?	✓ (green)	✓ (red)
High Energy	FCC-hh/SPPC	☐	☐	☐	☐	✓ (green)	✓ (green)	☐	✓ (green)	✓ (green)	✓ (green)	☐	?	✓ (yellow)	✗

Order of Magnitude for Fractional Uncertainty ✓ (green) $\lesssim \mathcal{O}(.01)$ ✓ (yellow) $\mathcal{O}(.1)$ ✓ (red) $\mathcal{O}(1)$ ✗ $> \mathcal{O}(1)$ ☐ No data ? No target

@S.Dawson et al, Snowmass H report





"The SM will not be complete until we have enough precision in all its properties to verify that all SM predicted couplings exist. However, that is not the primary goal of precision Higgs physics program. If there is a deviation measured in a Higgs coupling it must have a cause, which is what we hope to find and understand. "

@S.Dawson et al, Snowmass H report

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 & Experiment 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 analysed up to now only 3% of the total number of Higgs boson that we will have at the end of LHC

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.

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.

Backup

It was not all roses and flowers !

The first hard moment was between Christmas 2010 and new years eve 2011 on the ggF results…

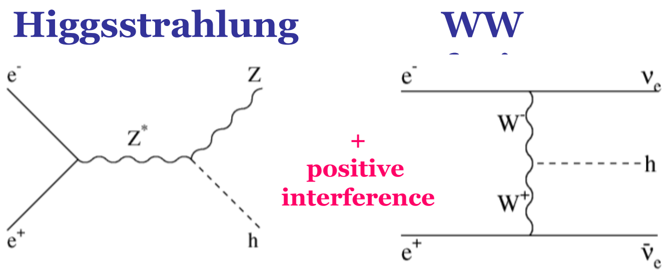
When we wanted to do the combination as well: VETO from Atlas…
« The white, the yellow and the black »….

The second hard moment was end of 2014. As J. Houston said:

« when the battle is won the generals are coming »

LEP: the ideal place.

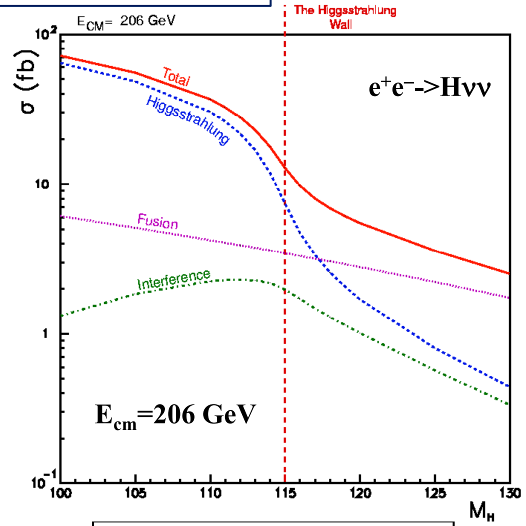
The simplicity of the initial states is transmitted to the final state



Dominant mode

m(H) ≤ √s-m(Z)

possibility to go beyond !



$\sigma_{tot}(m_H=115) \sim 40$ fb

Direct Searches:

LEP is the perfect machine to search for the Higgs

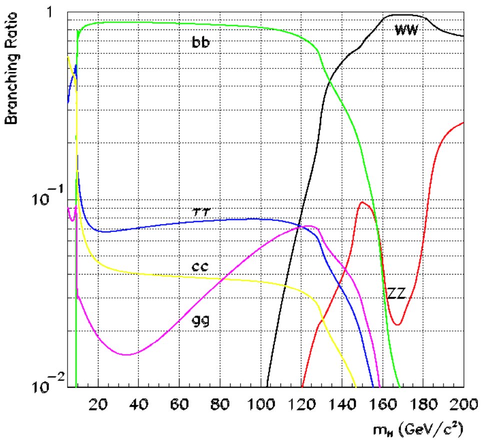
IF m(Higgs) < E_{cm} – Mz

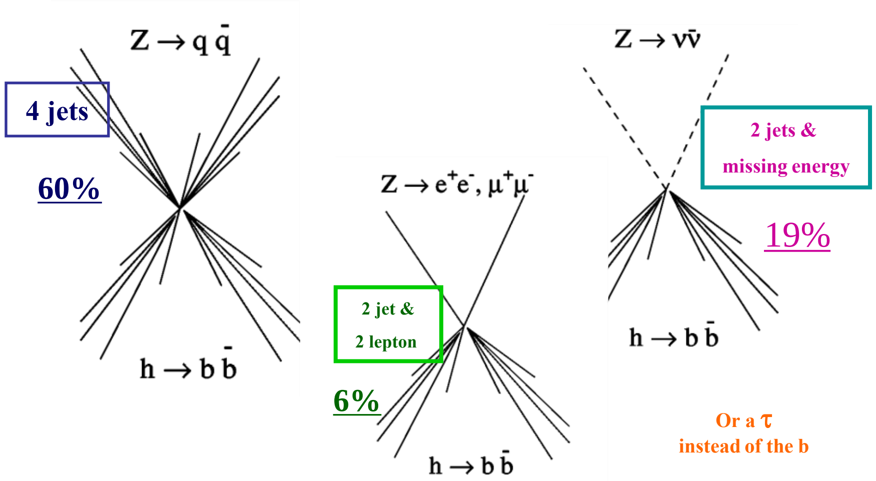
LEP2 : 1995-2000, E_{cm} = 130 – 209 GeV

$\mathcal{L}$ > 2.5 fb^{-1} @ E_{cm}> 187 GeV

LEP: the ideal place (2)

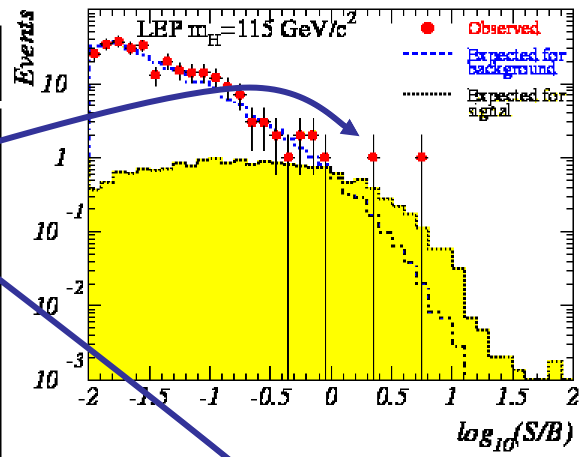
The simplicity of the initial states is transmitted to the final state

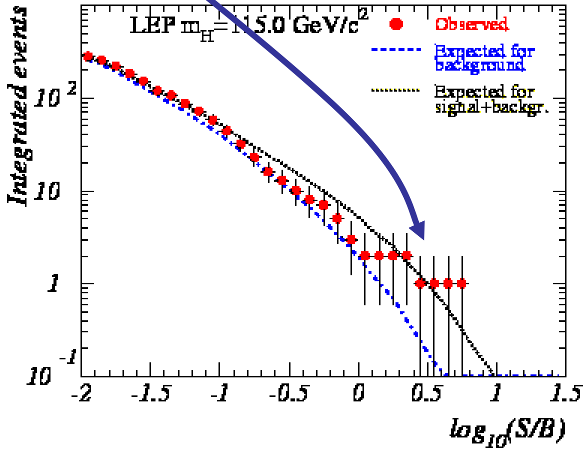




The events

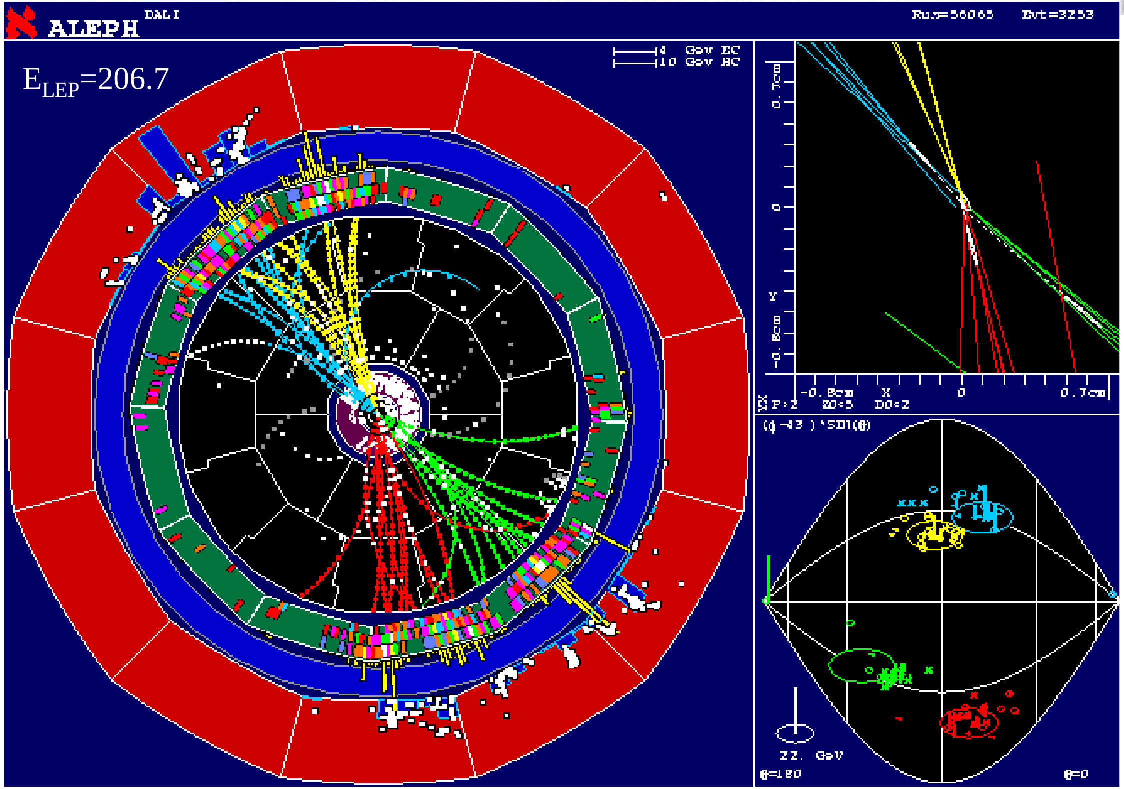
	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	207.0	4 jet	109.6	0.18	





The first 4 events maintain the highest weight in the final analyses

One of the 3 Aleph events



4 b cand.

HZ hyp.
m_H=114.4 GeV/c^2

NN = 0.997

jet b-tag:

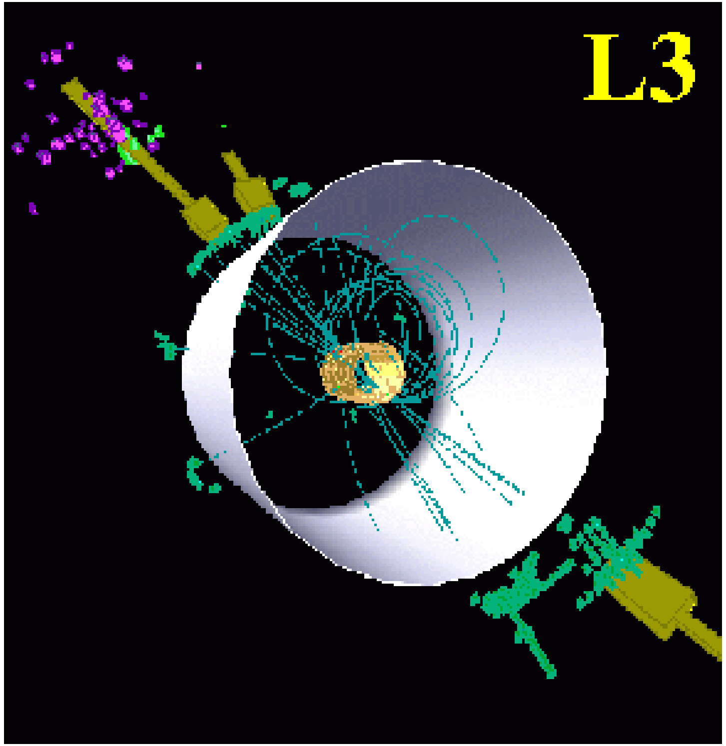
jet	b-tag
Z	
1	0.994
2	0.78
H	
3	0.993
4	0.999

ZZ hyp.
m_Z=97 GeV
m_Z=94 GeV

A 22 GeV shower in SICAL that was giving Evis = 252 GeV is rejected by a better algorithm : m_H= 112.8 –> m_H=114.4

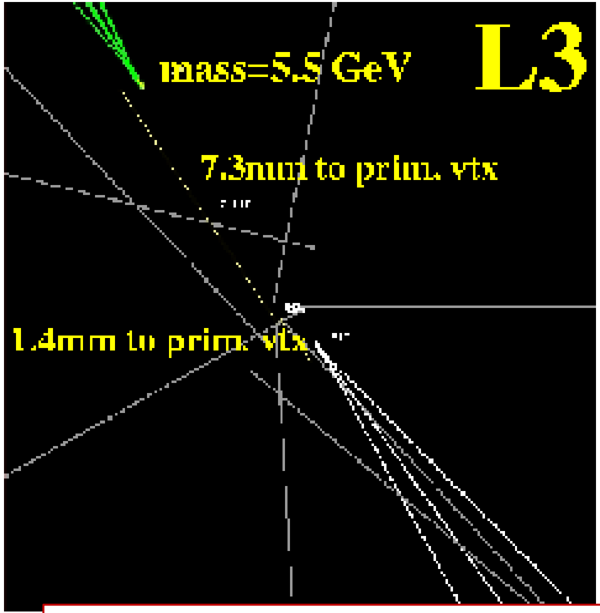
most significant Hνν candidate

The L3 event



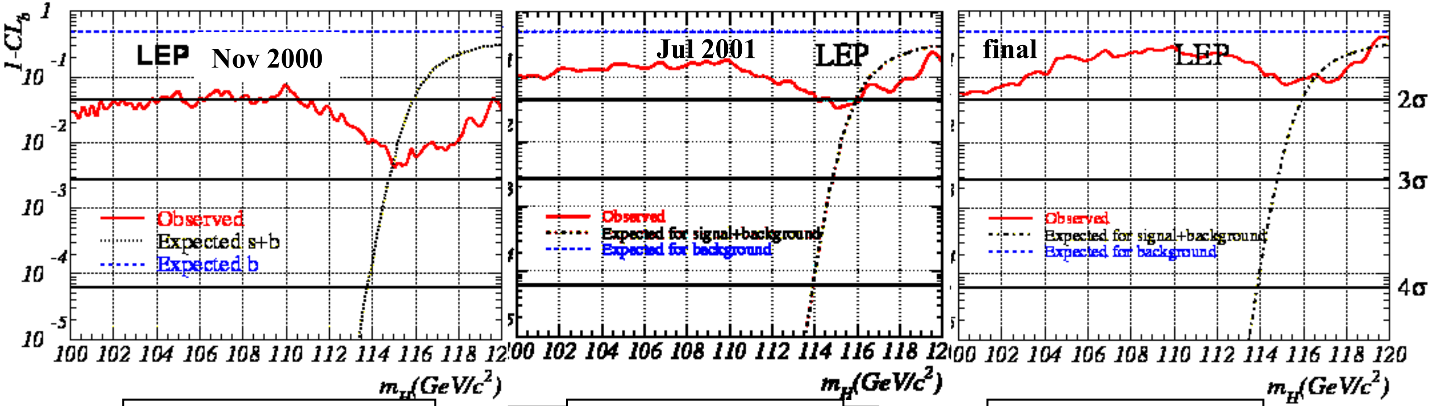
measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view



With Ballestrero WPHACT ...
Higgs events are not collinear !

Higgs discovery?
from end of 2000 to the final results…



Nov 2000	Jul 2001	final
4.2 x 10^{-3}	**~0.03**	**~ 0.09**
m_H>113.5	m_H>114.1	m_H>114.4
(115.3 expected)	(115.4 expected)	(115.3 expected)

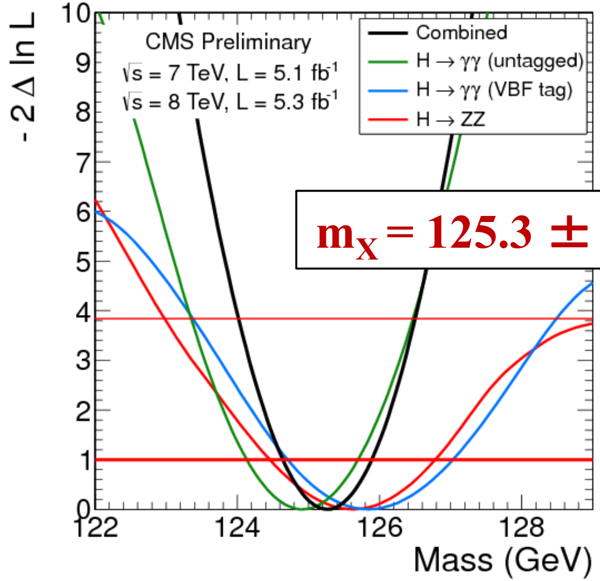
Changes:

Background Probabilities 1-CL_b (m_H=115)

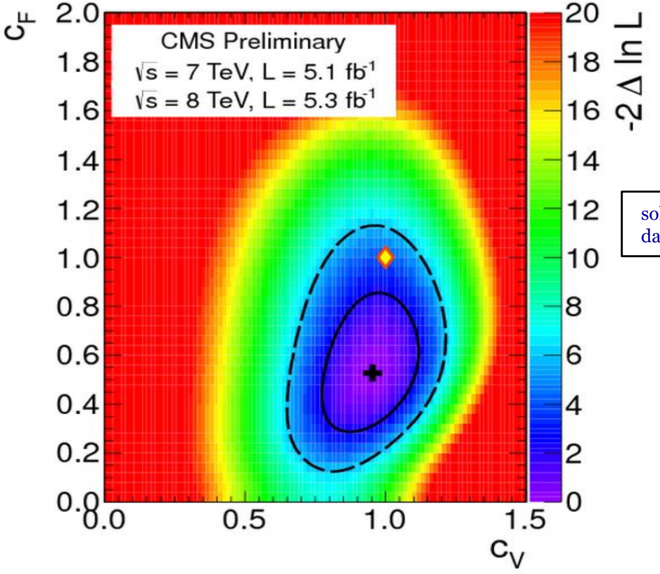
	Nov 2000	→	July 2001	→	final
LEPH:	0.00065 (to HWG) 0.0011 (publ.)	→	0.0015	→	0.0024
DELPHI:	0.68	→	0.77	→	0.73
L3:	0.068	→	0.32	→	0.32
OPAL:	0.19	→	0.20	→	0.50

The 4th of July 2012

We were ready to measure the characteristics of the boson in case we could reach the 5 sigmas: mass and couplings



$m_X = 125.3 \pm 0.6$ GeV

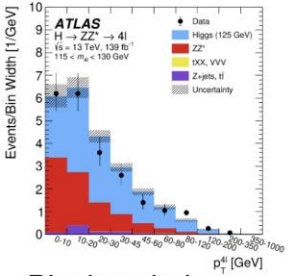


solid contour: 68% CL
dashed contour: 95% CL

Analysis Flow

Step #1

Reconstructed quantity

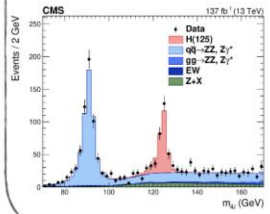


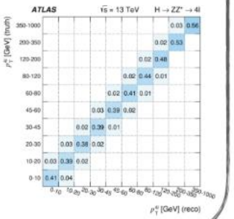
Binning choice: expected number of events, detector resolution, S/B, …..

Step #2

Observable: $m_{4\ell}$, $m_{\gamma\gamma}$, m_T, counting, …

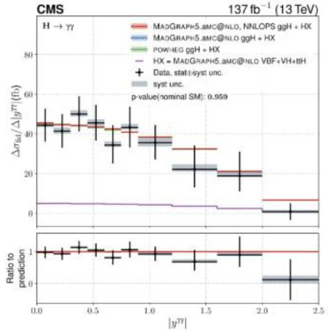
Unfolding method: matrix inversion, bin-by-bin correction, regularised, bayesian …



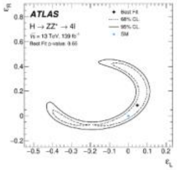


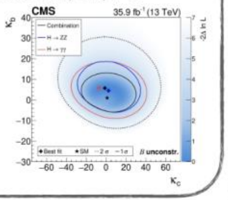
Step #3

Unfolded results



Interpretation: k-framework, eft, PO





Step #4

Haider Abidi

Precision Higgs couplings measurements at HL-LHC

	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)		

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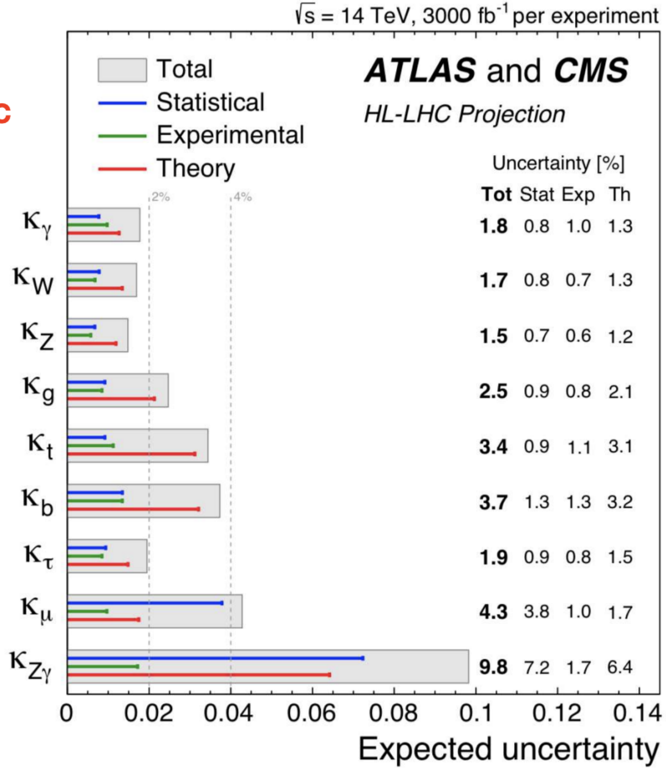

TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Higgs boson CP

$$\delta \mathcal{L}_{\rm CPV}^{hVV} = \frac{h}{v}\left[\tilde{c}_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{aa}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{za}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu} + \tilde{c}_{ww}\frac{g^2}{2}W^+_{\mu\nu}\tilde{W}^-_{\mu\nu}\right]$$

$$\mathcal{L}_{\rm CPV}^{hff} = -\bar{\kappa}_f m_f \frac{h}{v}\bar{\psi}_f(\cos\alpha + i\gamma_5\sin\alpha)\psi_f$$

- Sensitivity to the CP-odd hVV weak operators: studies both at the level of rates/distributions and via CP-sensitive observables
- CP violation in fermionic Higgs decays: ττ decay channel → measurement of the linear polarisations of both taus and the azimuthal angle between them
- CP violation in the top quark interactions: ttH and tH (rates and distributions):
  - HL-LHC: CP-odd Higgs excluded with 200fb^{-1}
  - CLIC 1.5 TeV : α_t (ttH) better than 15°
  - LHeC: Higgs interacting with the top quarks with CP-odd coupling excluded at 3σ with 3 ab^{-1}
  - FCC-eh: precision of 1.9% on α_t
  - current indirect limits from EDM bounds stronger than direct (though comparable for tau)

Name	α_τ	$\tilde{c}_{zz}$
HL-LHC	8°	0.45 (0.13)
HE-LHC	—	0.18
CEPC	—	0.11
FCC-ee$_{240}$	10°	—
ILC$_{250}$	4°	0.014

@E. Petit

Higgs boson width

- Three methods explored for HL-LHC
  - diphoton interference can only provide constraints ~8-22*SM
  - fits in the kappa framework: subjected to theoretical constraints (eg $|\kappa_V|<1$ and $B_{unt}=0$)
  - HZZ on-shell and off-shell: 20% precision, but very model-dependent
- Measurements in lepton colliders
  - mass recoil: measure the inclusive cross-section of ZH without assumption on the Higgs BR
  - mild model dependence

$$\frac{\sigma(ee\to ZH)}{BR(H\to ZZ^*)}=\frac{\sigma(ee\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H}\simeq\left[\frac{\sigma(ee\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{SM}\times\Gamma_H$$

Collider	$\delta\Gamma_H$ [%] from ref.	Extraction technique for standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	2.3	EFT fit [3, 4]	2.2
ILC_{500}	1.6	EFT fit [3, 4, 14]	1.1
ILC_{1000}	1.4	EFT fit [4]	1.0
$CLIC_{380}$	4.7	κ-framework [98]	2.5
$CLIC_{1500}$	2.6	κ-framework [98]	1.7
$CLIC_{3000}$	2.5	κ-framework [98]	1.6
CEPC	2.8	κ-framework [103, 104]	1.7
FCC-ee_{240}	2.7	κ-framework [1]	1.8
FCC-ee_{365}	1.3	κ-framework [1]	1.1

Higgs boson mass

- Current experimental precision ~0.1% (160 MeV)
- In lepton colliders m_H needs to be improved to around 10 MeV to avoid any limitation on ZZ/WW couplings
  - HL-LHC reach dependent on muon p_T calibration with high statistics: 10-20 MeV plausible (no formal study yet)
  - ZH recoil at lepton colliders: statistically limited

Collider	Strategy	δm_H (MeV)	Ref.	$\delta(\Gamma_{ZZ^*})$ [%]
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	[96]	1.9
HL-LHC	$m(ZZ)$	10-20	[13]	0.12-0.24
ILC_{250}	ZH recoil	14	[3]	0.17
$CLIC_{380}$	ZH recoil	78	[98]	0.94
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[20]	[98]	0.36
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	[98]	0.28
FCC-ee	ZH recoil	11	[99]	0.13
CEPC	ZH recoil	5.9	[2]	0.07