Higgs Boson: 10 Years and beyond

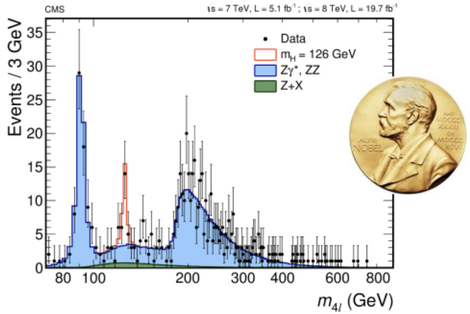
In honor of Tejinder Virdee

Chiara Mariotti, Royal Society
London, 13-14 October 2022

The long road of the Higgs boson: a worldwide effort

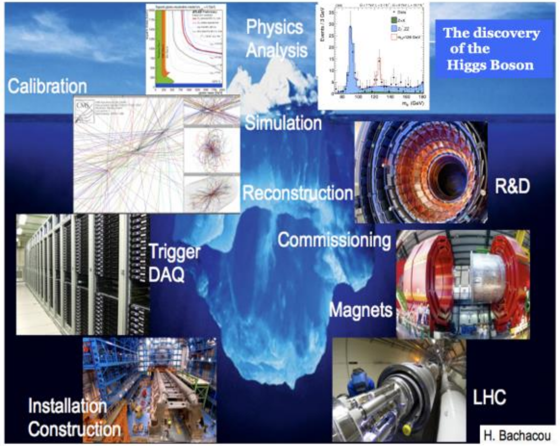
54 Yang & Mills
61 Glashow
64 Brout, Englert, Higgs et al
67-68 Weinberg and Salam
70 ‘t Hooft and Veltman
73 Gargamelle : discovery of the weak neutral current
83: Ua1 & UA2: W and Z discovery
89-2000: LEP and HERA: the triumph of the SM
95: Tevatron: top quark discovery
2012: LHC: discovery of a Higgs like boson

The Nobel Prize in physics 2013

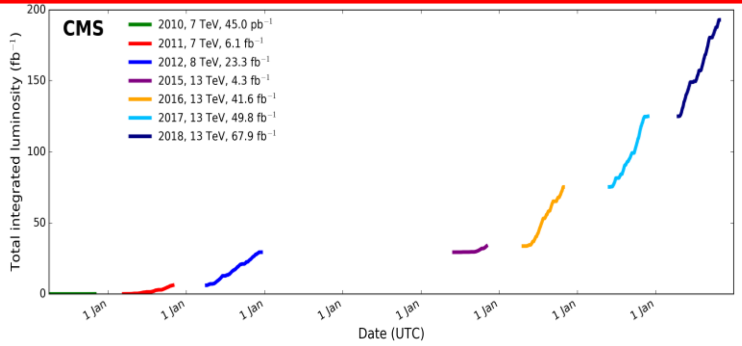


The WLCG

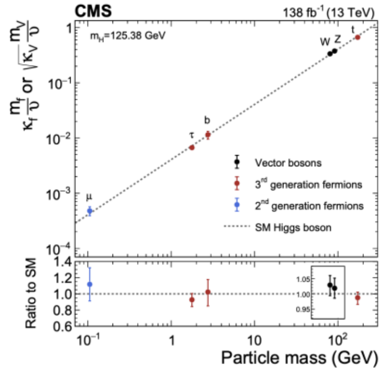
Run2 wrt Run1
Lumi ×10 more
σ ×2−4 larger
Higgs ×30 more



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



PRECISE MEASUREMENTS



Superb detector performance

The LHCHXSWG

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

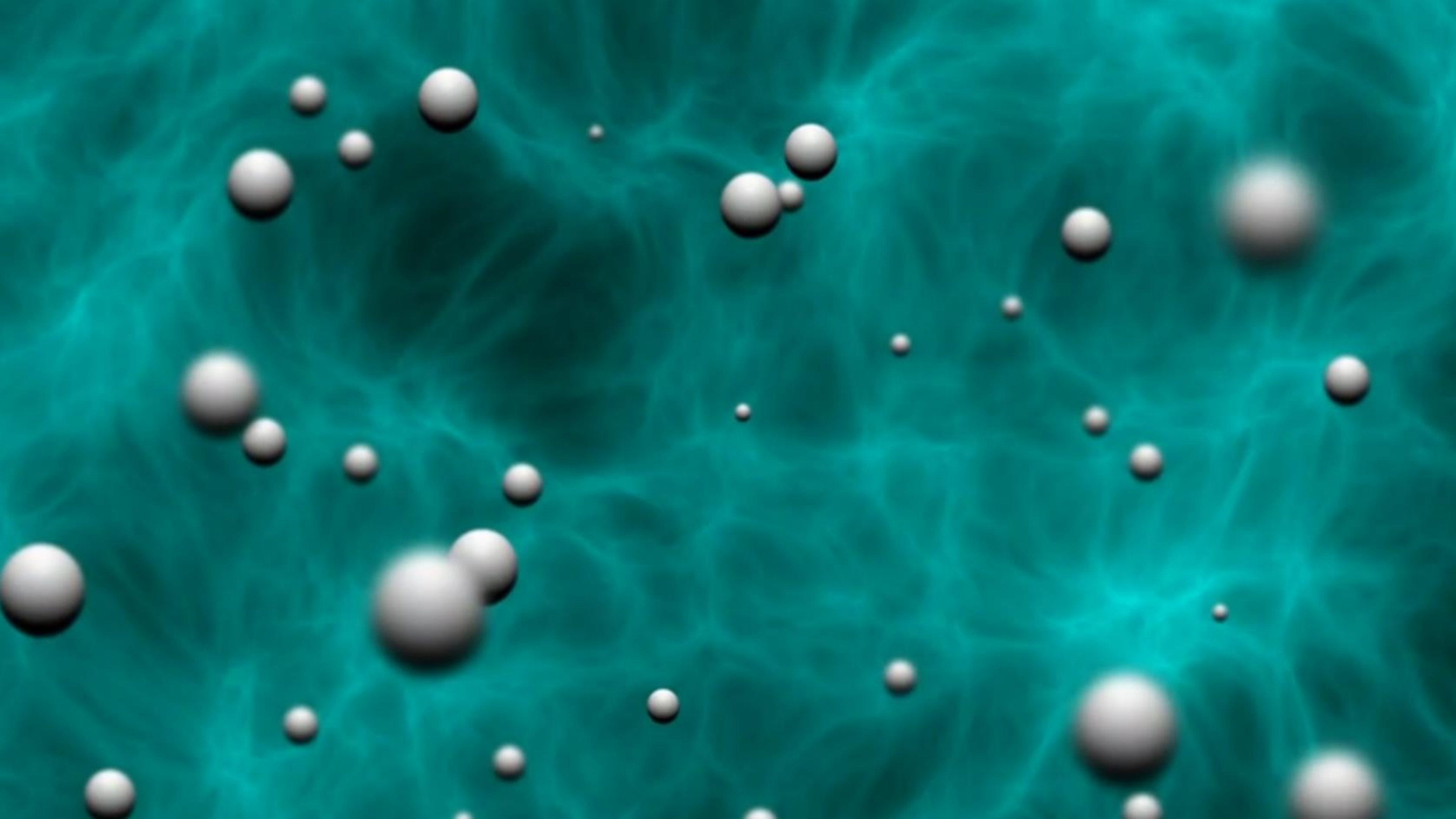
Nature 607, 60-68 (2022)

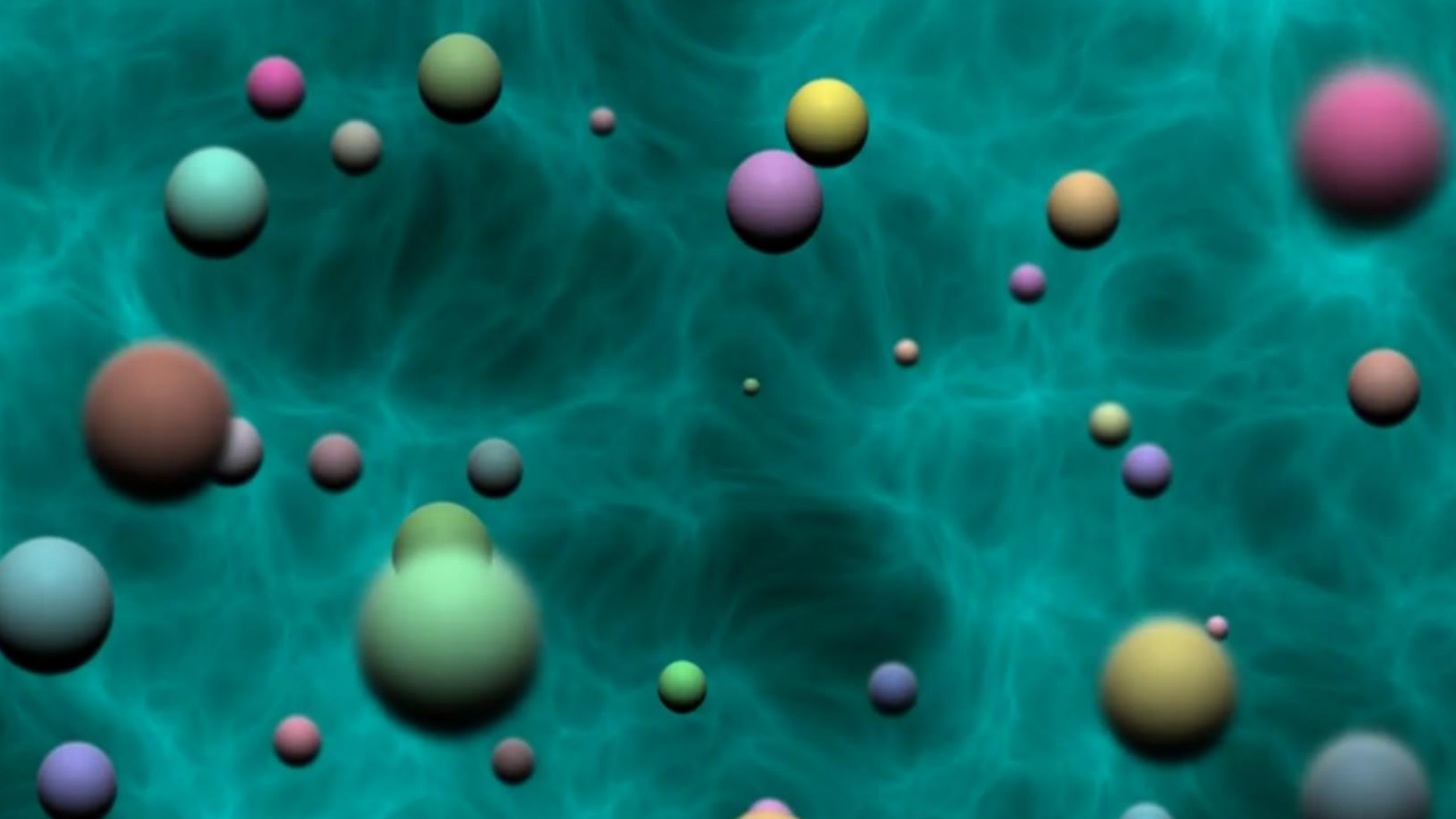
nature

Article | Open Access | Published: 04 July 2022

A portrait of the Higgs boson by the CMS experiment ten years after the discovery


10^{-10} SECONDS
AFTER BIG BANG





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.

Nature 607, 60-68 (2022)

Special quantum numbers

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

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.

Scalar fields are described only by a number at every point in space that is invariant under Lorentz transformations.
An analogy can be drawn of a map of an area where temperature is shown at various positions mimicking a scalar field. The same map, where instead the wind speed and direction are shown, would correspond to a vector field.

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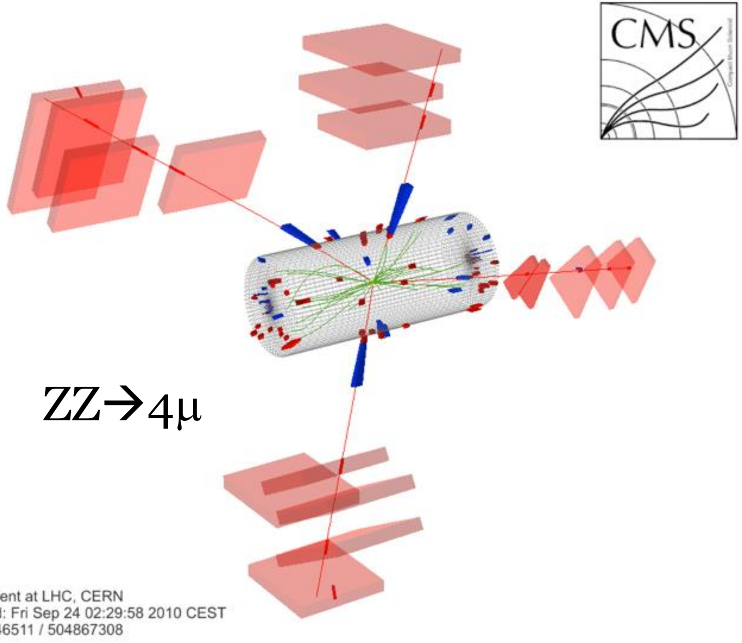
“Thus, the elementary particles interacting with the BEH field acquire mass.
The impact is far reaching: for example, electrons become massive, allowing atoms to form, and endowing our Universe with the observed complexity.”

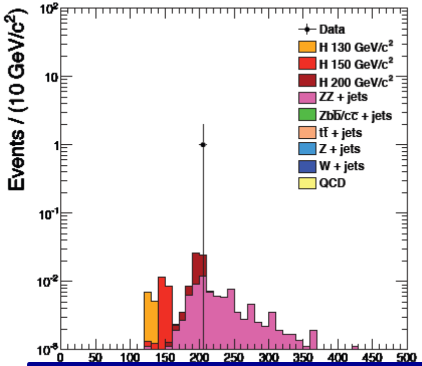
Nature 607, 60-68 (2022)

On the way to the discovery

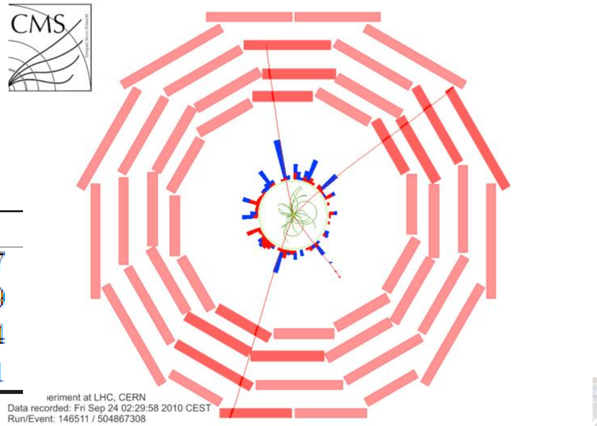
The first spectacular event, Sept 2010



ZZ→4μ

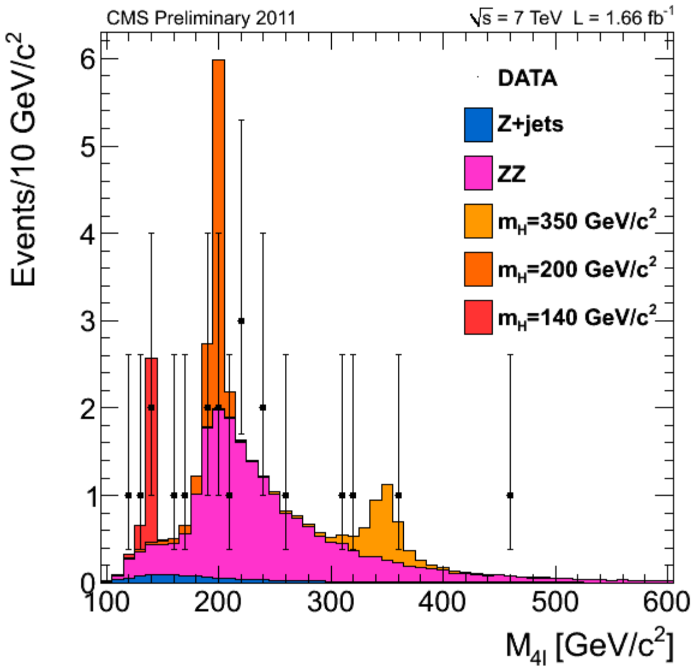


Prob = 23% to observe ZZ→4l in 35pb^{-1} at 7 TeV

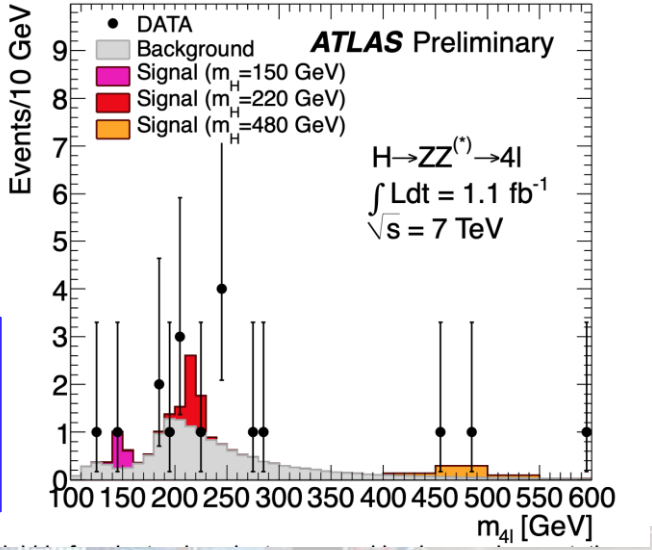


m(4ℓ) [GeV/c^2]	m(2ℓ) [GeV/c^2]	p_T (μ) [GeV/c]	μIso	S_{IP}
201.7	92.12	19.56	0	0.537
		25.88	0	1.029
	92.23	48.14	0	0.994
		43.44	0	0.411

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 MonteCarlo



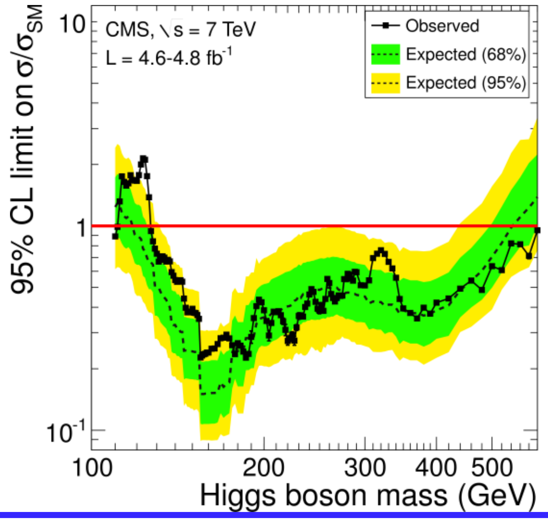
We/HZZ4l were under heavy review from the collaboration, to be finally approved and able to present the result at EPS-11

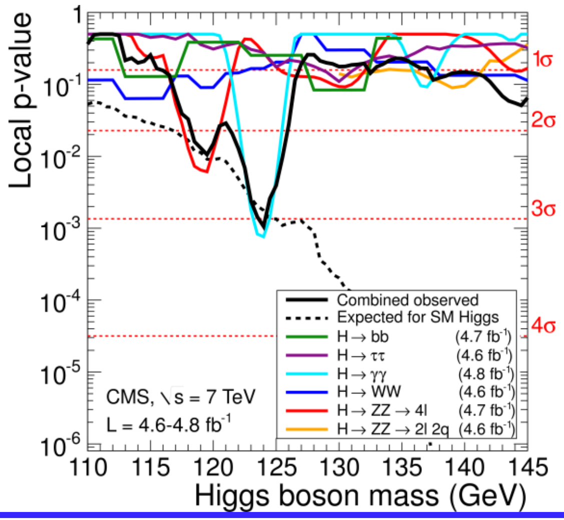
DEC 2011: Towards a discovery

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





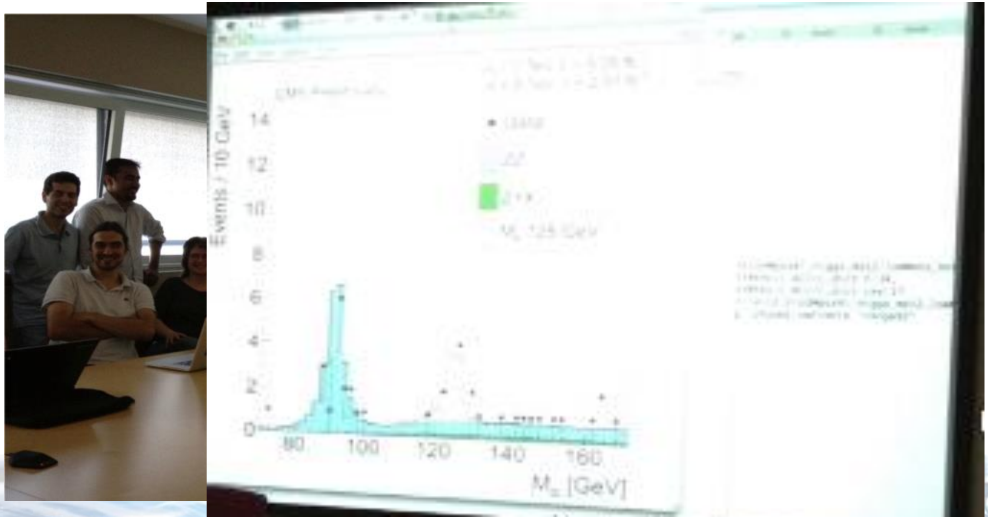
LHC 2012 blind analysis focused on m~115 - 130 GeV: Optimisation of the analyses with MonteCarlo, **without looking at the data**.

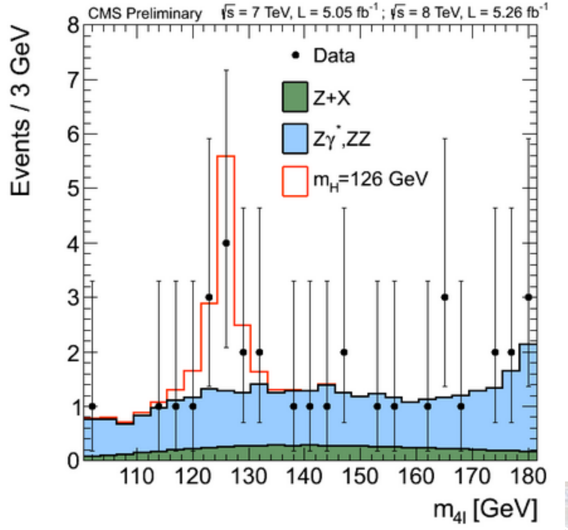
The D-day

The 14 of June of 2012 at 19h00:

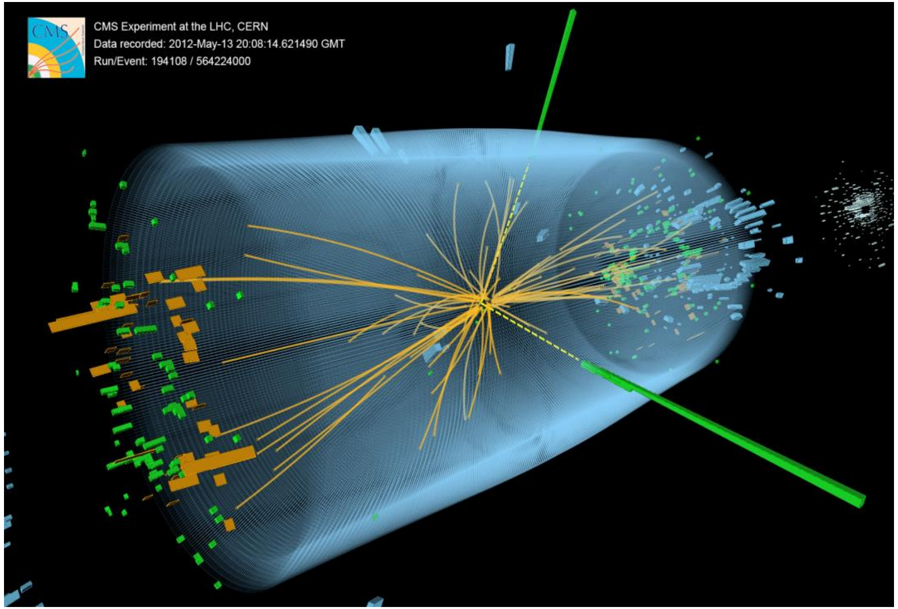
The analysis was ready. It could be no more optimised.
We could finally *«open the box»*, i.e. look at the DATA.

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



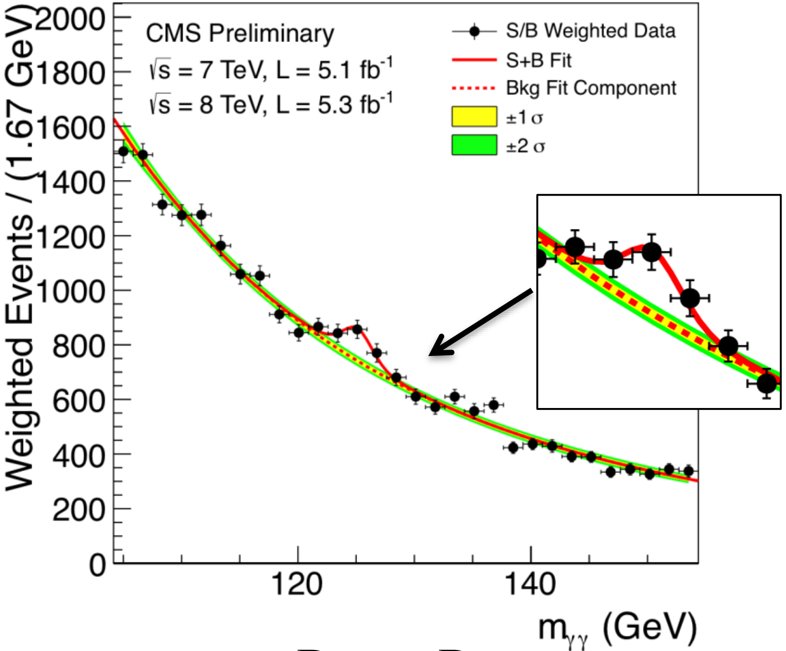


H→γγ, 14 June 2012



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

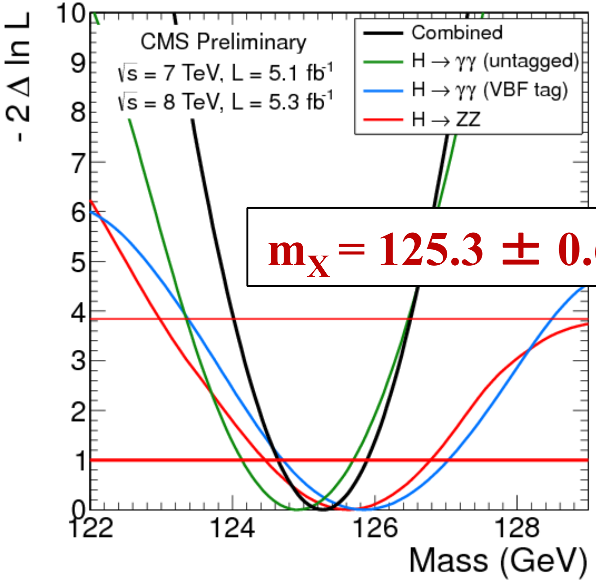
Towards the 4th of July

Jim was the ARC chair of the Higgs combination paper.

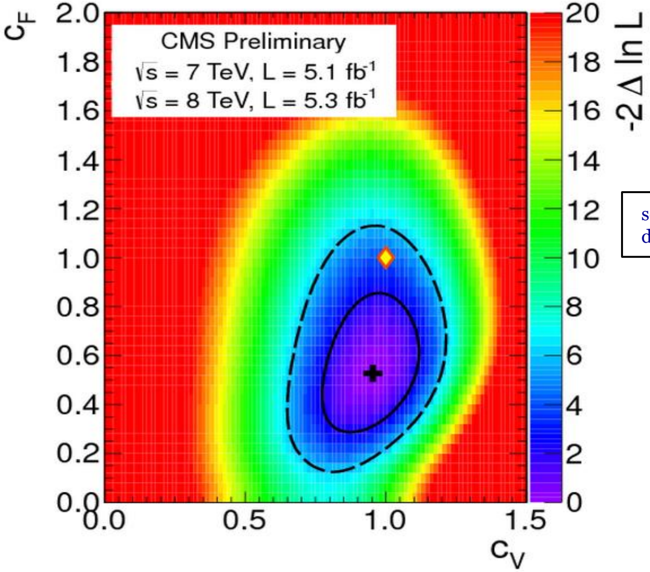
He was extremely cautious and wanted to understand all the details.

2 intense weeks: meeting every day at 9pm or 11pm or later (!!!!)   WHY !

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



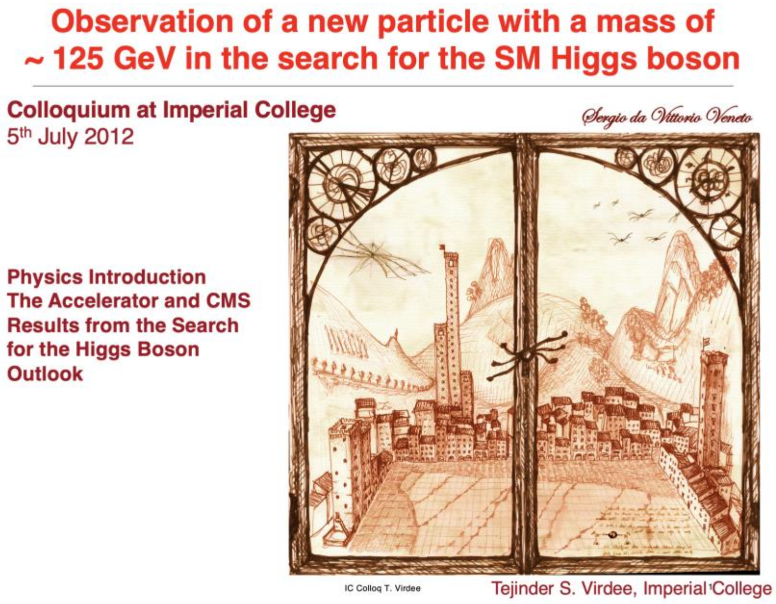
$m_X = 125.3 \pm 0.6$ GeV



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

4 July 2012

Jim was in IC that day…. with Tom Kibble



The « discovery » letter

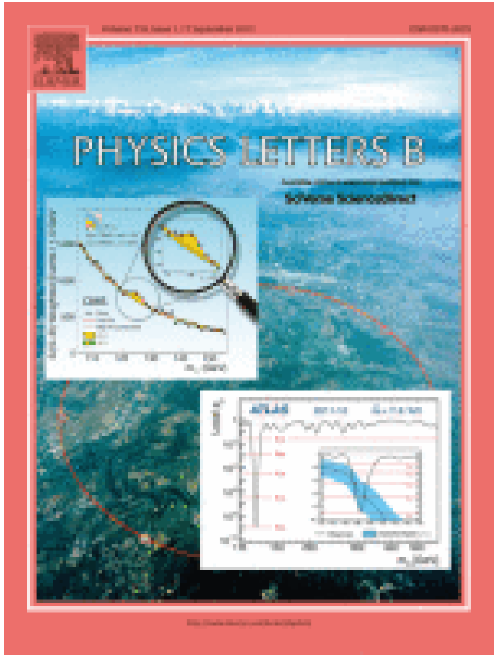
31 July 2012

Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC

CMS Collaboration • Serguei Chatrchyan (Yerevan Phys. Inst.) et al. (Jul, 2012)

Published in: *Phys.Lett.B* 716 (2012) 30-61 • e-Print: 1207.7235 [hep-ex]

13,242 citations

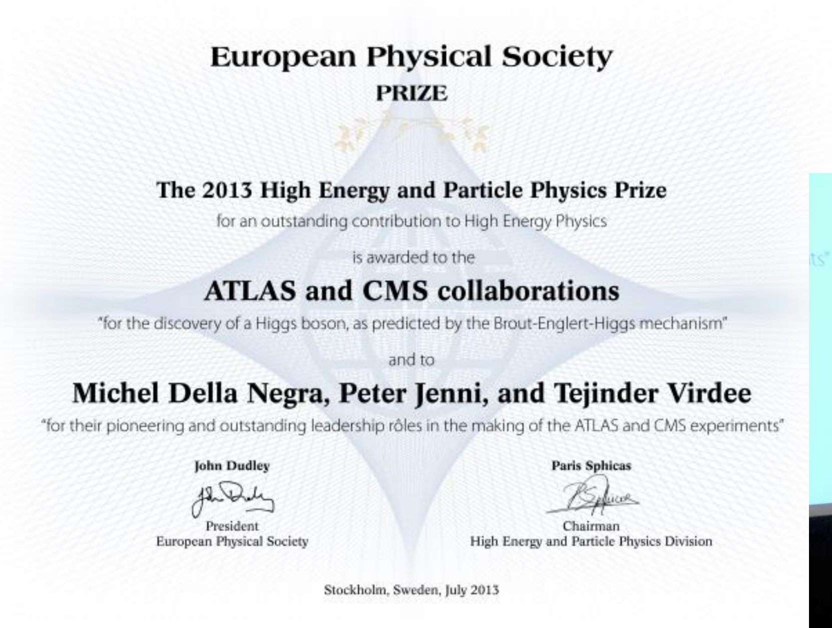


Prizes

Honoris Causa Lyon (Dec 2013)

Honoris Causa QMW 2013

EPS PRIZE - at the EPS conference



European Physical Society
PRIZE

The 2013 High Energy and Particle Physics Prize
for an outstanding contribution to High Energy Physics
is awarded to the
ATLAS and CMS collaborations
"for the discovery of a Higgs boson, as predicted by the Brout-Englert-Higgs mechanism"
and to
Michel Della Negra, Peter Jenni, and Tejinder Virdee
"for their pioneering and outstanding leadership rôles in the making of the ATLAS and CMS experiments"

John Dudley
President
European Physical Society

Paris Sphicas
Chairman
High Energy and Particle Physics Division

Stockholm, Sweden, July 2013


Michel Della Negra, Pet
for their pioneering and outstanding leadership
John Dudley
President
European

The Nobel Prize

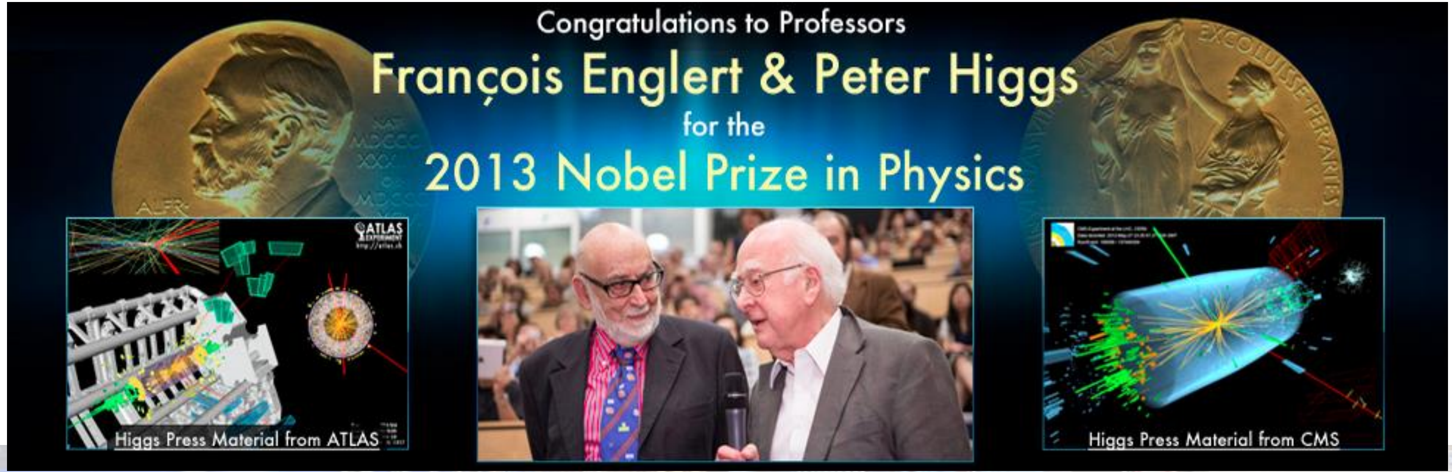
The Nobel Prize in Physics 2013

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

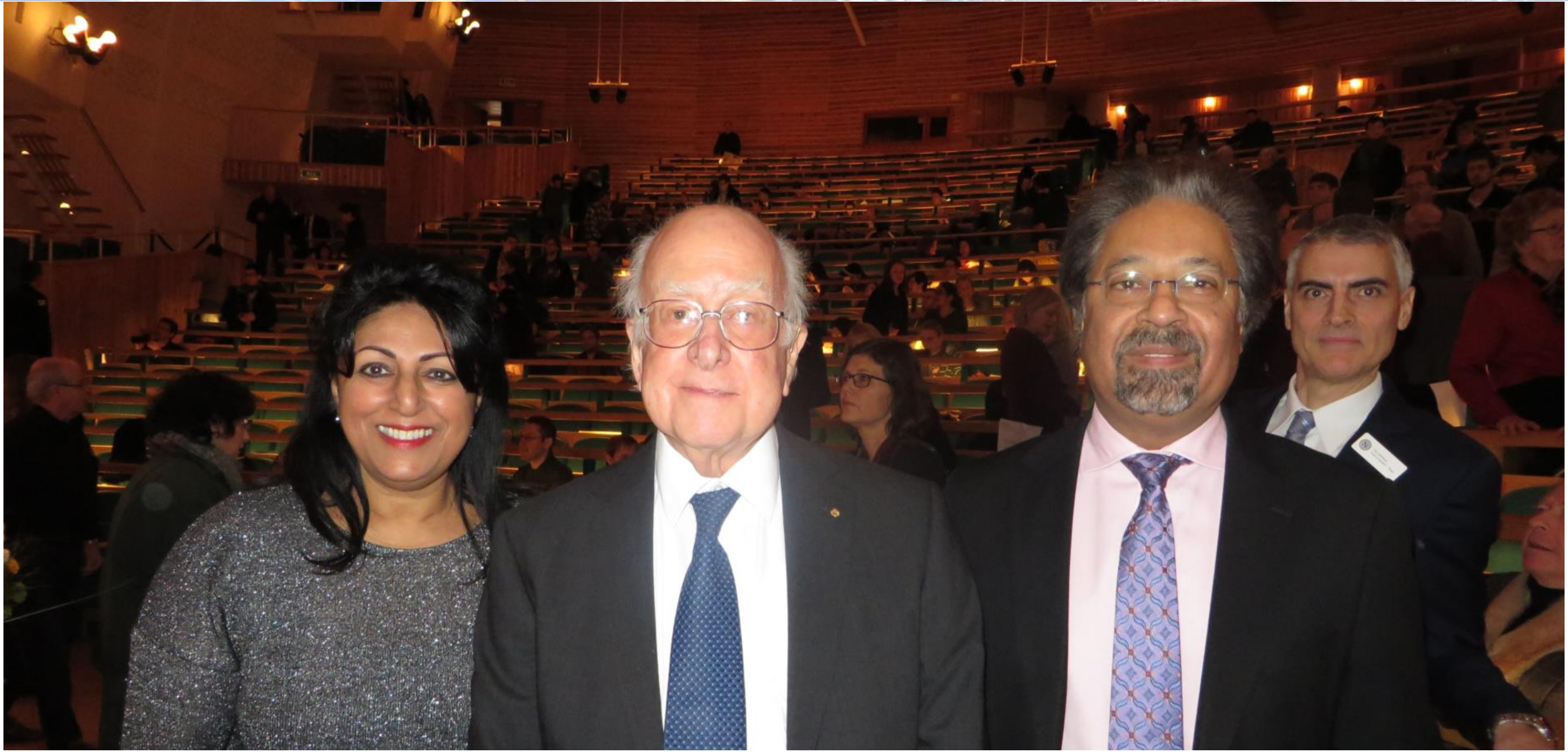
François Englert
Université Libre de Bruxelles, Brussels, Belgium

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"



Stockholm EPS Prize – Vatsala and Tejinder with Peter Higgs



In Stockholm, December 2013

2013 Breakthrough Prize Fundamental Physics

For their leadership role in the scientific endeavour that led to the discovery of the new Higgs-like particle by the ATLAS and CMS collaborations at CERN's Large Hadron Collider.

2014 Knight Bachelor : For services to science

Professor Virdee is one of the UK's most distinguished physicists and, as one of the creators of the Compact Muon Solenoid (CMS) Experiment he has made outstanding contributions to science. The CMS experiment, at the Large Hadron Collider, CERN, Geneva, has delivered seminal results in particle physics, including, and along with the ATLAS experiment, the groundbreaking discovery of the Higgs Boson. Beyond his innovative work in particle physics, he is also a great campaigner for science, and promoter of science and education in Africa and India.

Important moments

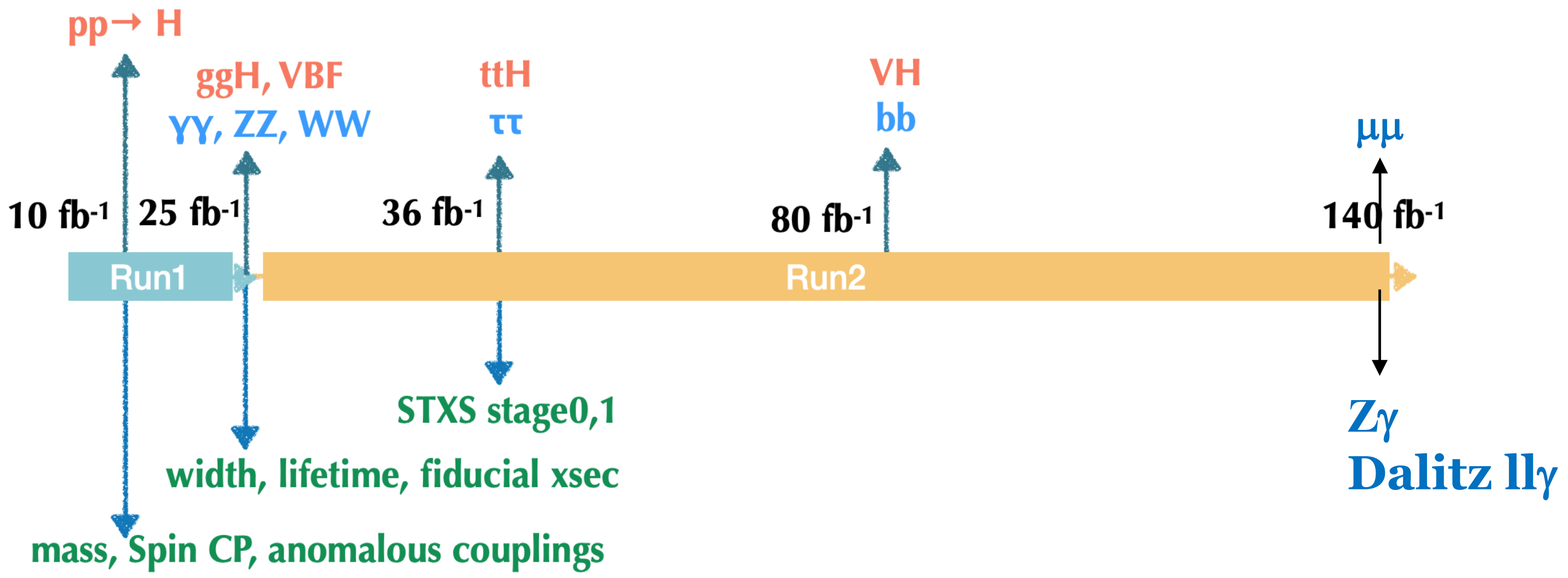
Jas' wedding in 2016

Towards precison measurements

From the 4 of July 2012 to the end of Run2

Higgs story at the LHC

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



©Meng Xiao

From the 4 of July 2012 to the end of Run2

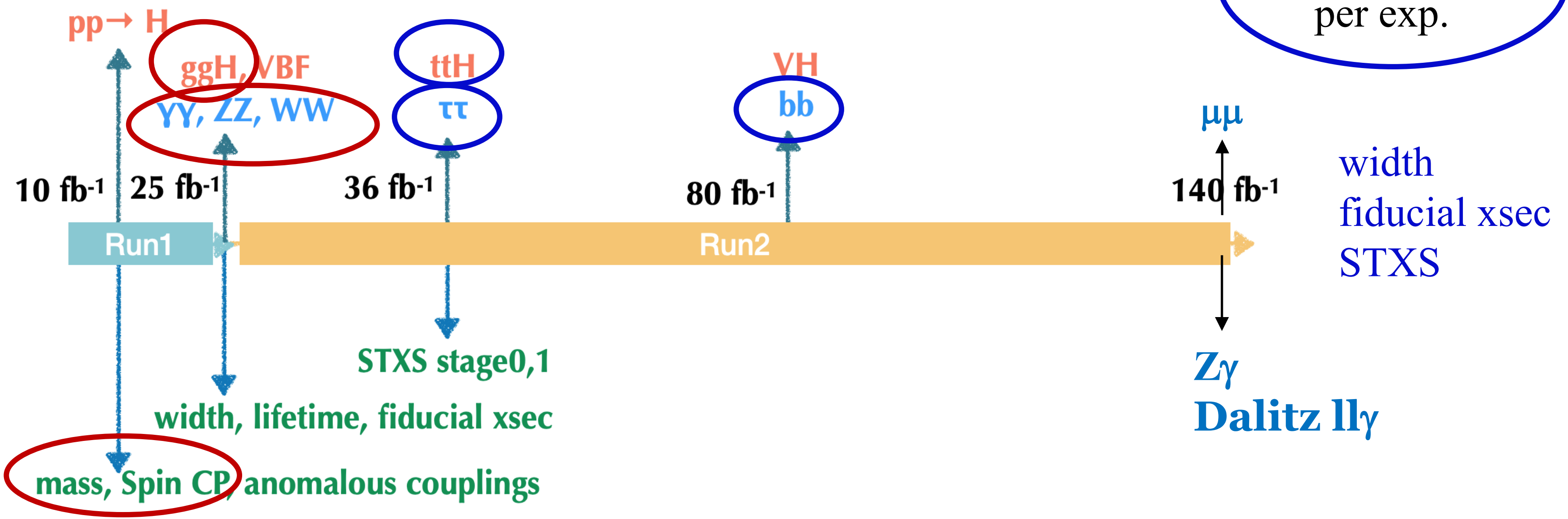
~ 5% precision per exp.

Higgs story at the LHC

Main production: ggH, VBF, VH, ttH

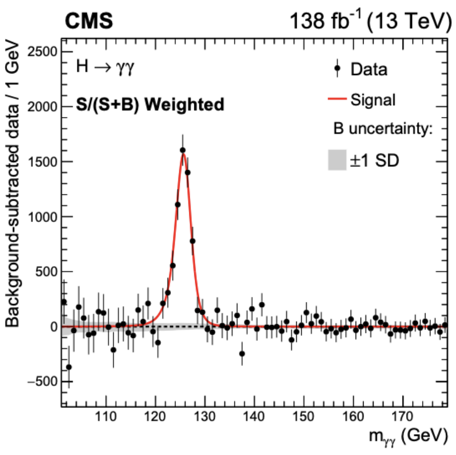
Main decay: γγ, ZZ, WW, ττ, bb

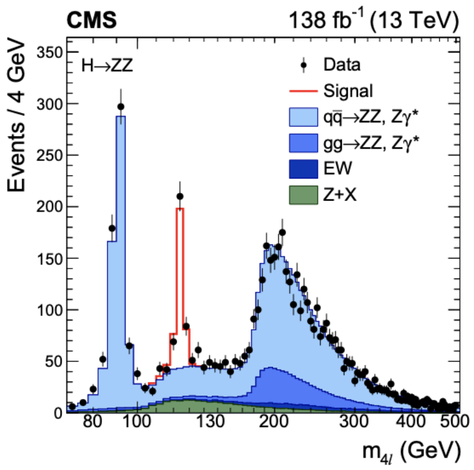
~10% precision per exp.

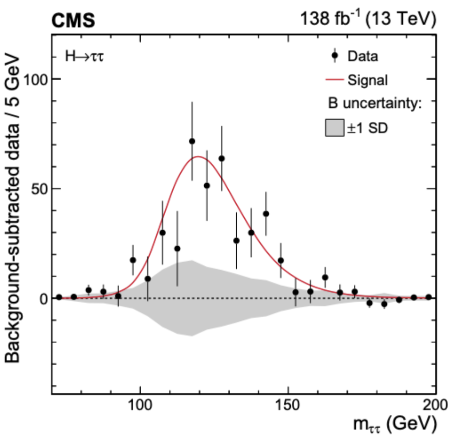


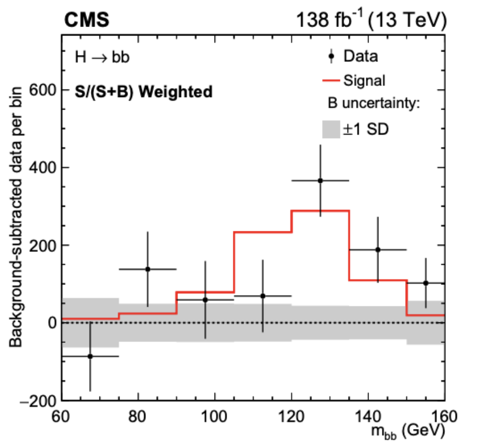
Bosonic channels

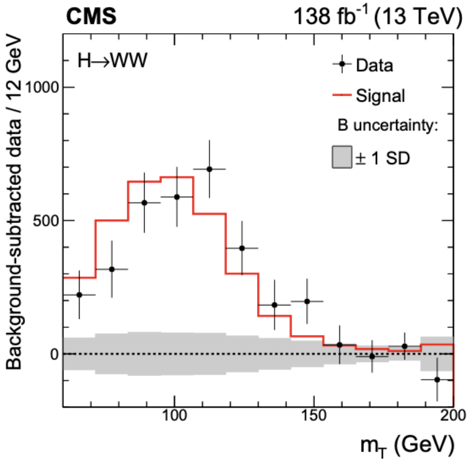
Fermionic channels

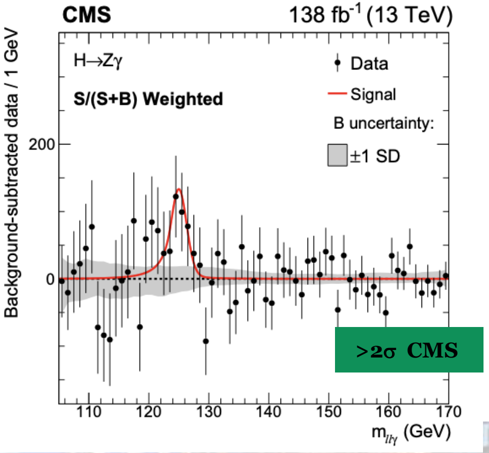


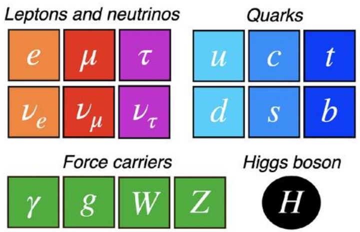












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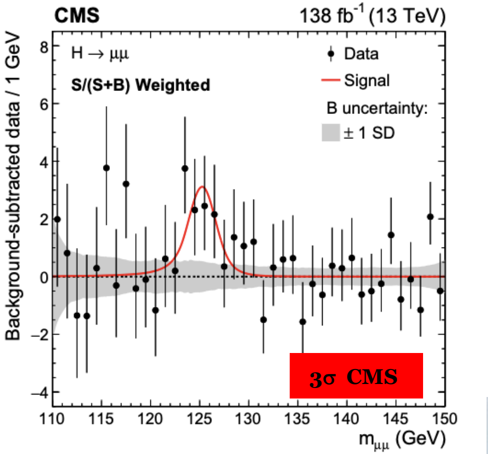
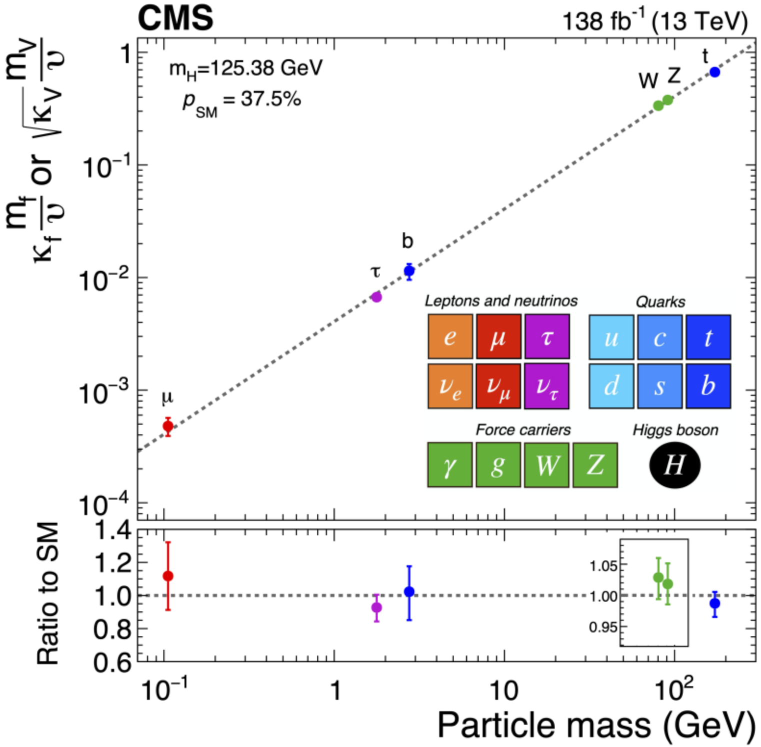


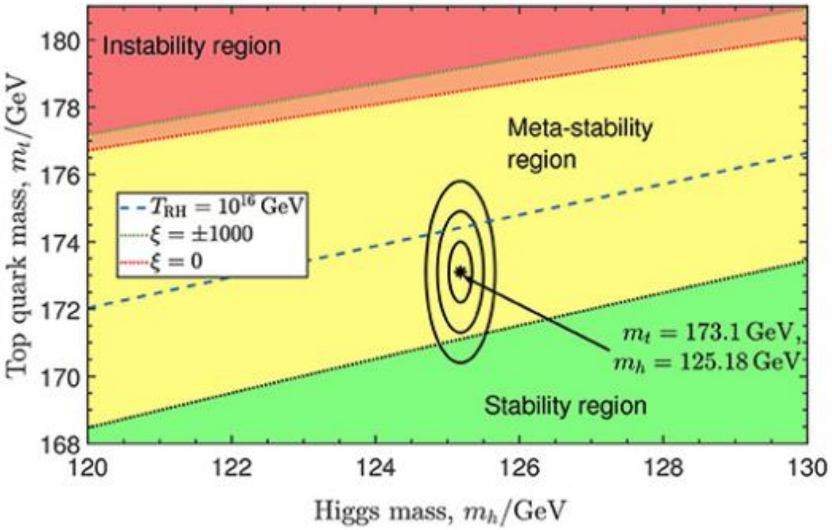
The portrait of the Higgs boson

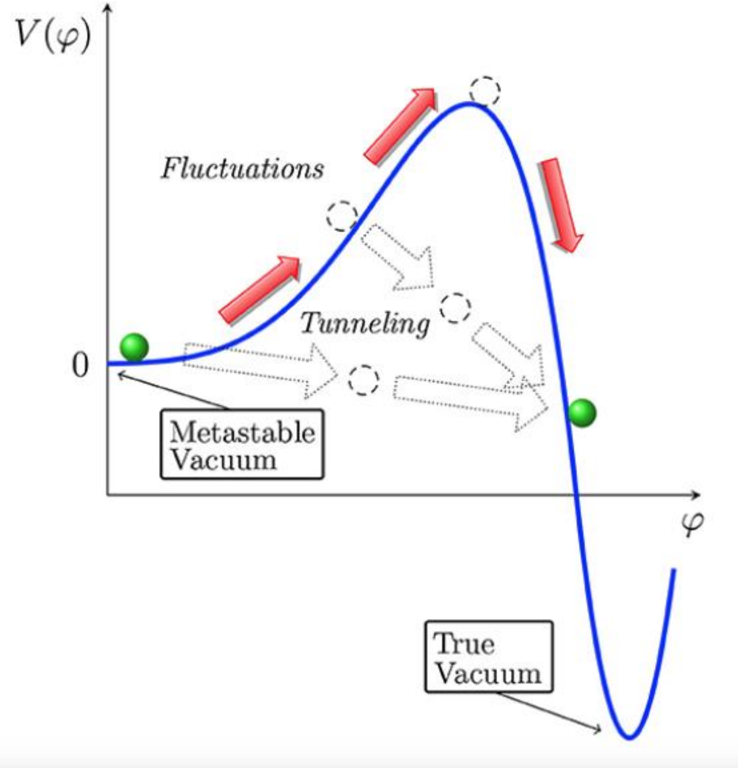
SM test over many orders of magnitude



The Higgs couples with the particle mass !

The future of our universe





The future of our universe

Much evidence points to the fact that the SM is a low-energy approximation of a more comprehensive theory. In connection with the mechanism of spontaneous symmetry breaking, several puzzles appear: the so-called naturalness, a technical issue related to the fact that the Higgs boson mass is close to the electroweak scale; in relation to cosmology, the metastability of the vacuum state of the SM and the conjectured period of inflation in the early Universe; the dynamics of the electroweak phase transition and its connection to the matter–antimatter asymmetry of our Universe. These issues motivate attempts at obtaining a deeper understanding of the physics of the Higgs boson.

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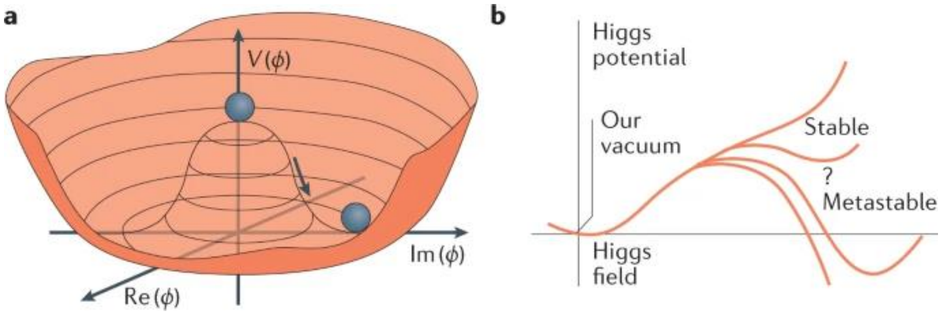
The search for Higgs boson pair production

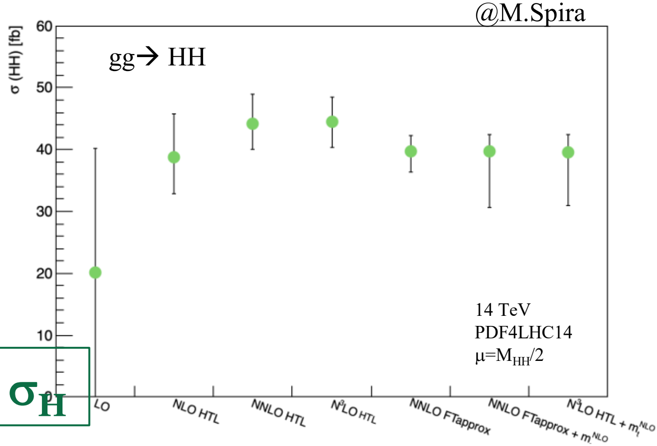
The Higgs potential

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

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

we measured the minimum, we should measure the curvature

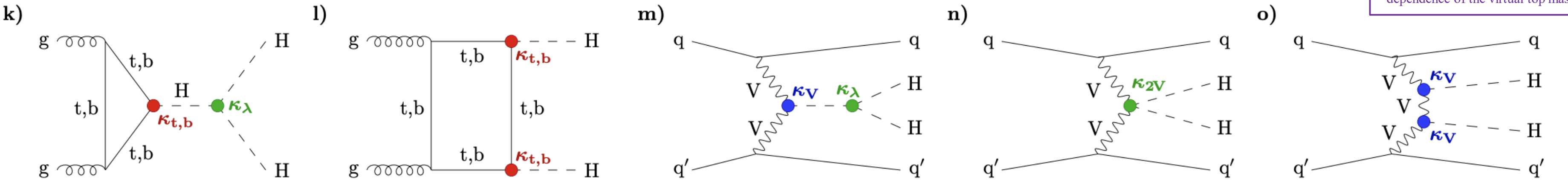




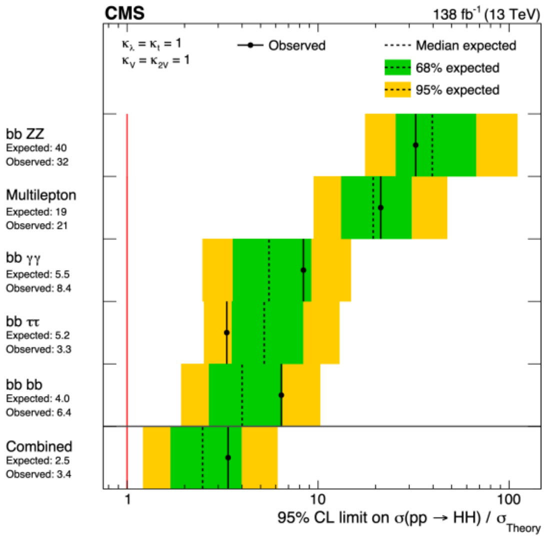
$\sigma_{HH} \sim 10^{-3}\, \sigma_H$

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

Higgs boson pair production

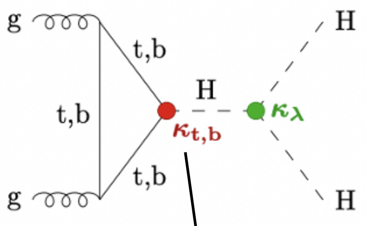


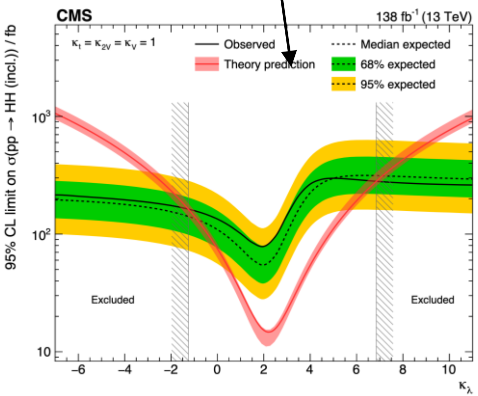
Results on HH production



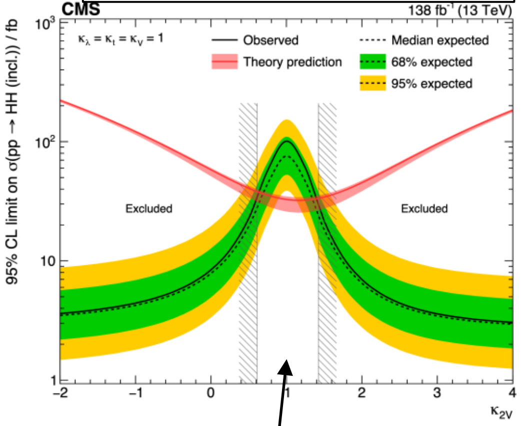
$\sigma(HH) < 2. \div 3.$ SM

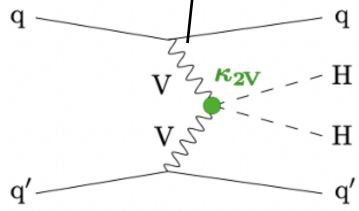
ATLAS +CMS will observe HH production at HL-LHC at 5 s.d.





VVHH indeed exists





The near future

The impressive progress made over the past decade is foreseen to continue into the next one. The current dataset is expected to be doubled in size by the middle of this decade, enabling the establishment of rare decays channels such as $H \to \mu\mu$ and $H \to Z\gamma$. Operation with the high-luminosity LHC is expected during the next decade and should yield ten times more data then originally foreseen. This should allow the ATLAS and CMS experiments to establish the SM **Higgs boson pair** production with a significance of 4 s.d., as well as the Higgs boson coupling to **charm quarks**, and to search for any exotic decays. Improvements in experimental techniques and theoretical calculations are also anticipated to continue. The CMS experiment is entering the era of precision Higgs physics that will shed light on BSM physics.

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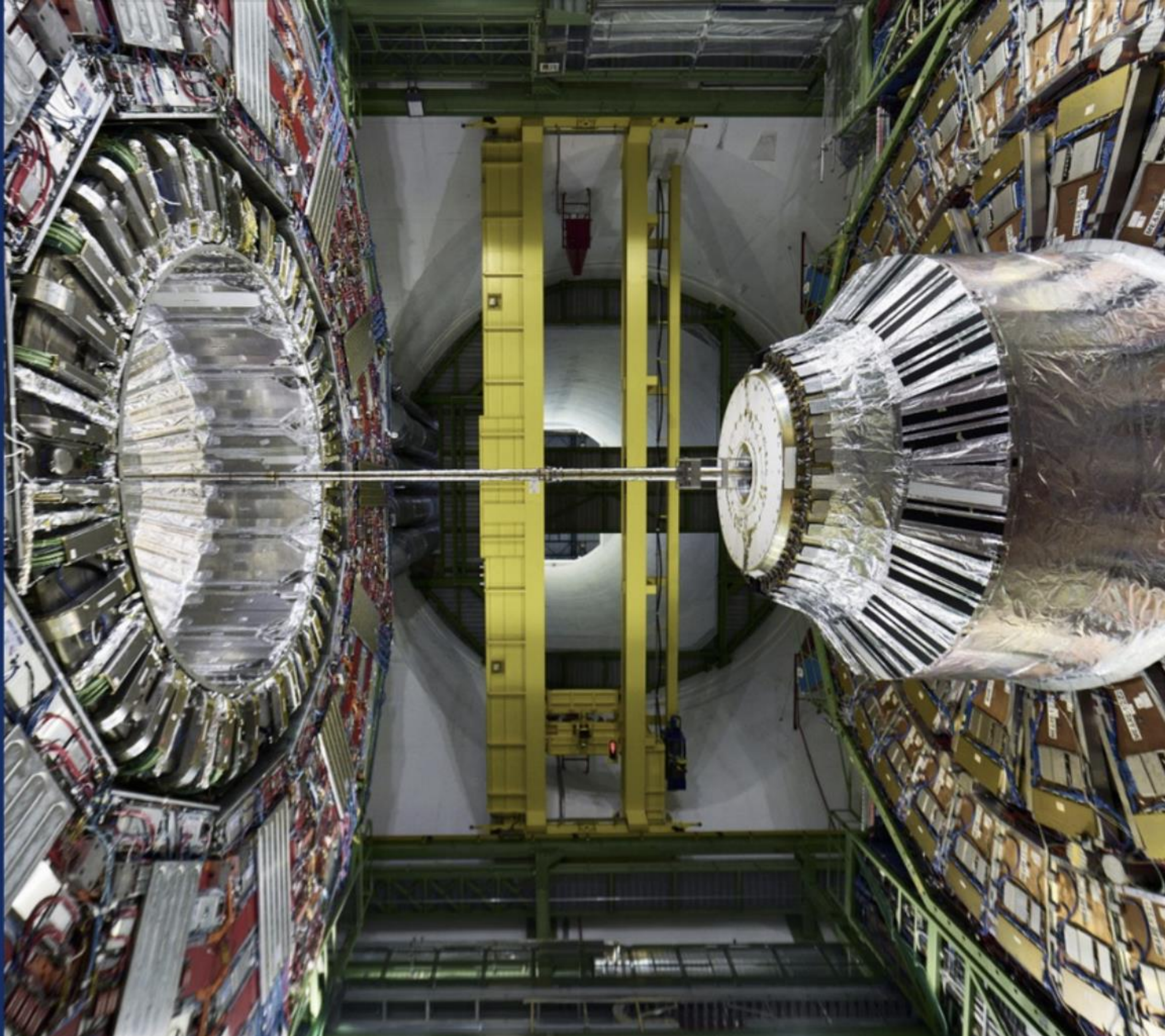
We have analysed up to now only 3% of the total number of Higgs boson that we will have at the end of LHC

Celebrating after the submission to Nature

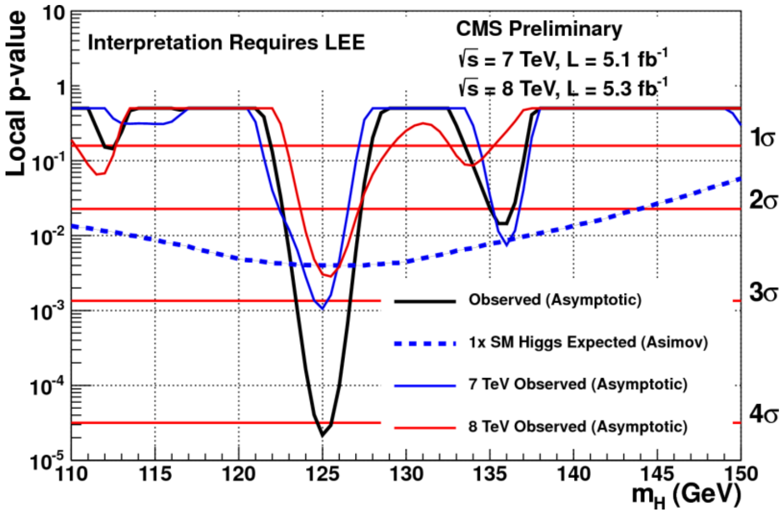
Happy birthday CMS +30!




Happy birthday
Tejinder !!!!!

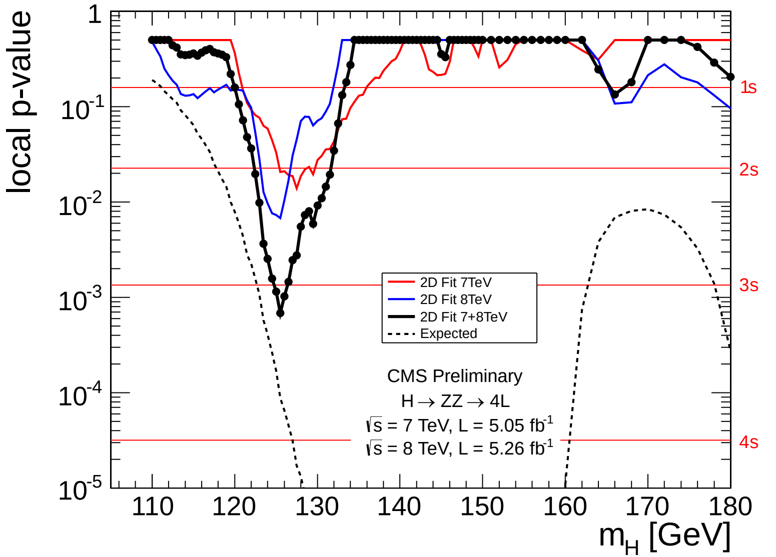
The p-value: the compatibility of the data with the background only hypotesys

H→γγ



- Minimum local p-value at 125 GeV with a local significance of **4.1 σ**

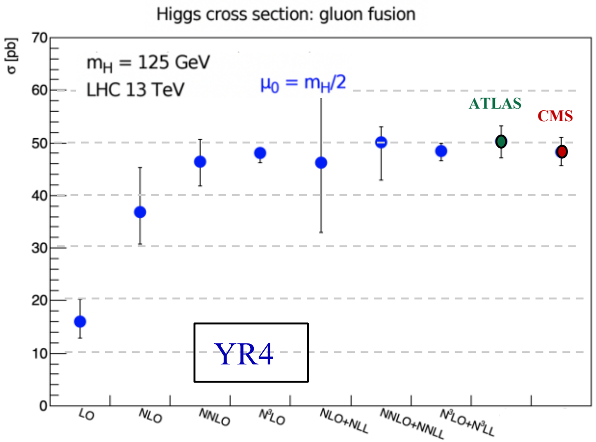
H→ZZ*→4*l*

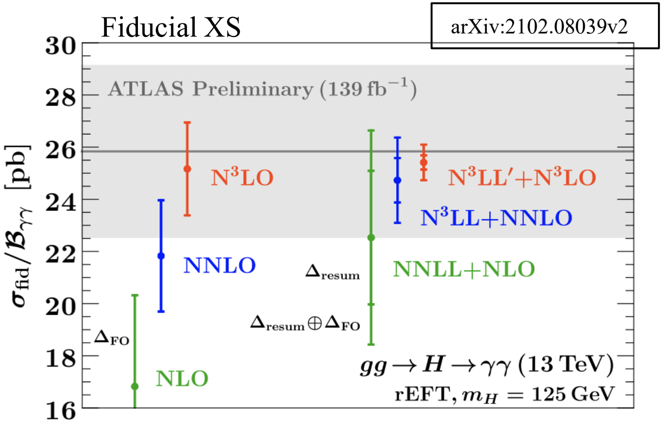


Expected significance at 125.5 GeV : **3.8 σ**
Observed significance at 125.5 GeV: 3.2 σ

The huge leap of theoretical calculations

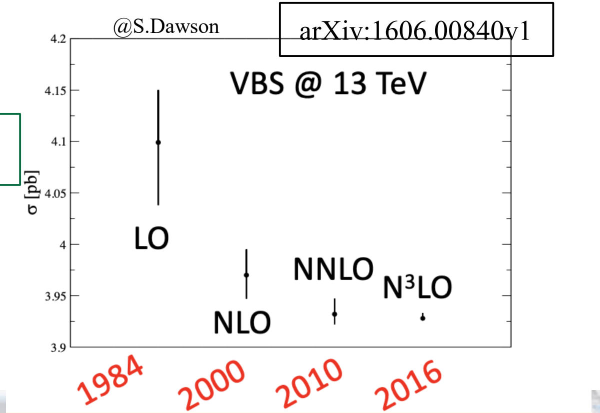
ggH





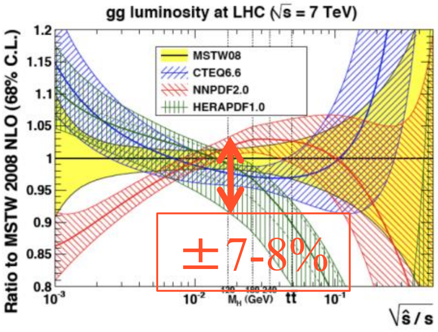
LHCHXSWG

qqH

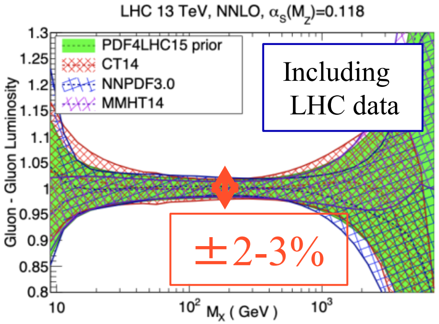


PDF

A huge improvement in the gluon PDF understanding

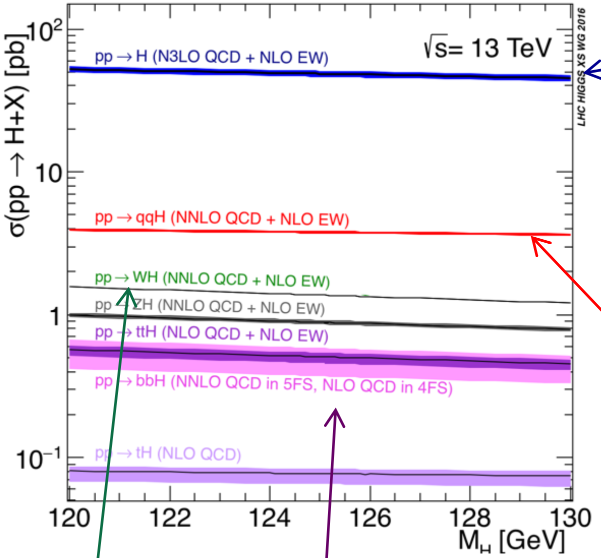


PDF4LHC-2011

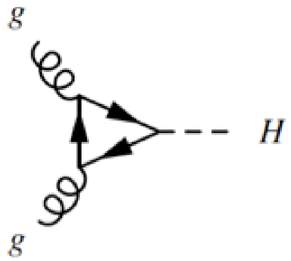


PDF4LHC 2022

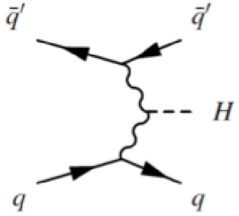
Cross Sections & BR: the LHCHXSWG results - 2017



ggF: NNNLO+NNLL QCD + NLO EW

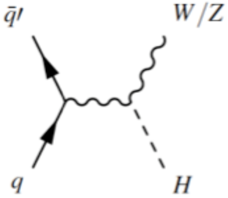


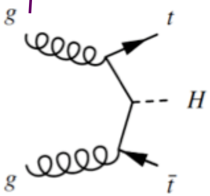
qqH: NNLO QCD + NLO EW



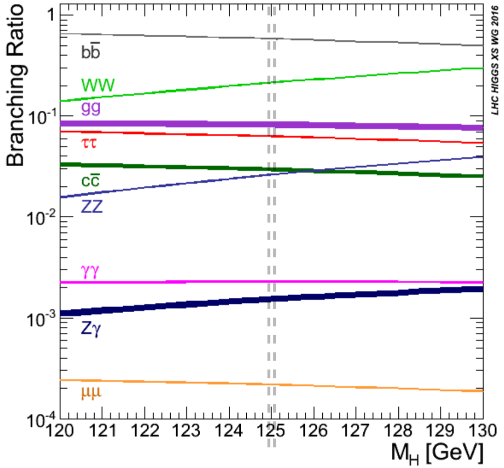
WH: NNLO QCD + NLO EW

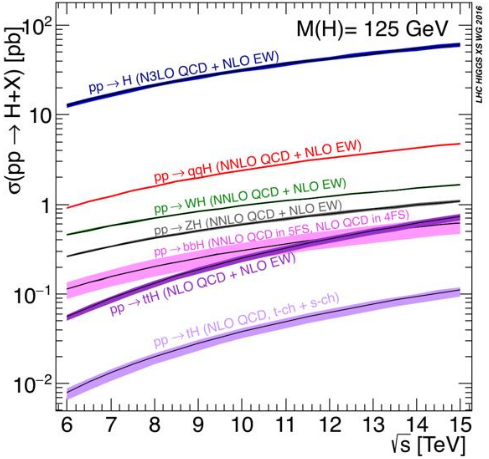
ZH: NNLO QCD + NLO EW





ttH: NLO QCD





From 8 to 13 TeV

σ (ggF, VBF, VH) ~2 times larger

σ(ttH) ~4 times larger

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

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

$\gamma\gamma$

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

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 Run1 + *4l* Run2	124.94 ± 0.17	(± 0.17 stat ± 0.03 syst) GeV

1 per mille precision

The Higgs width from off-shell production

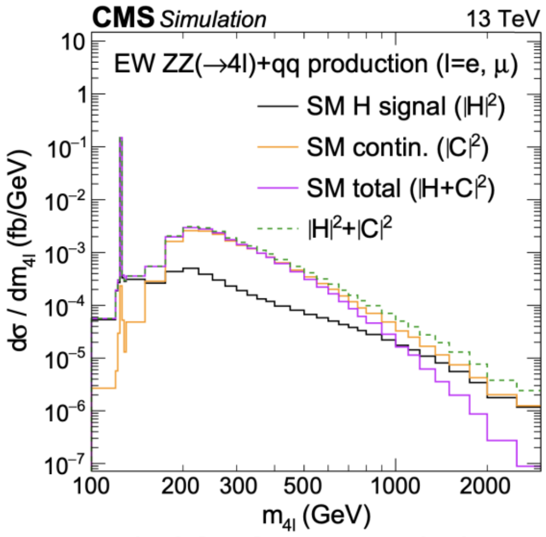
A real breakthrough after the discovery of the Higgs !

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

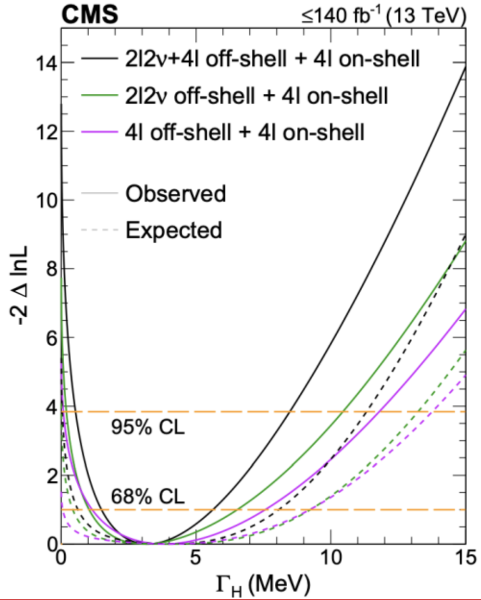
Off-shell Higgs boson production
is small but the BR to 2 real Z is large above $2m_Z$

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

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



arXiv:2202.06923

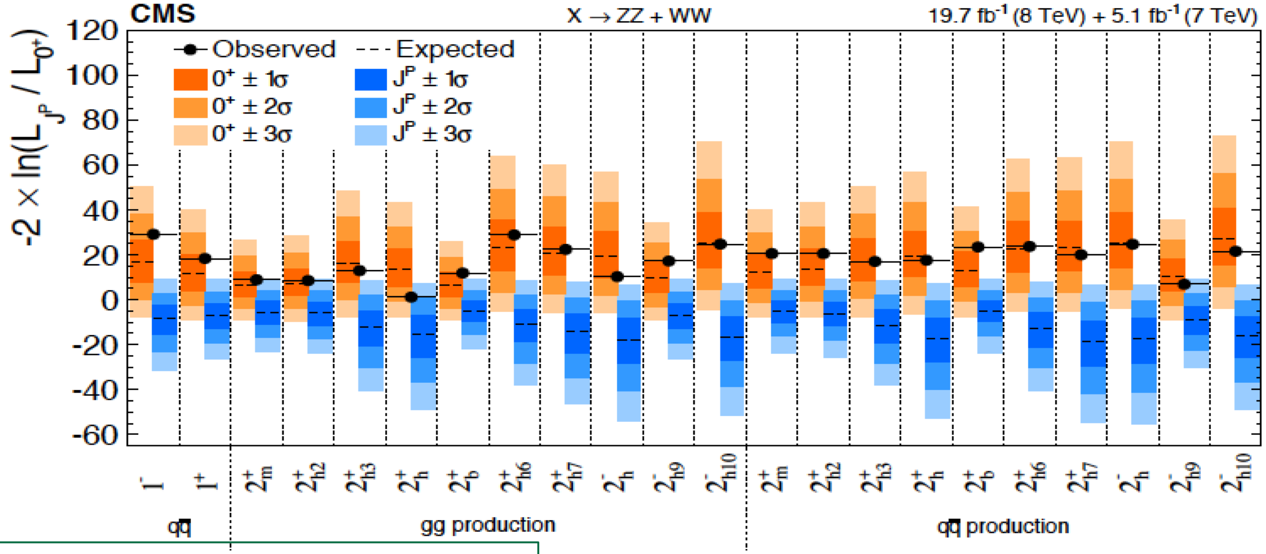


This method assumes that the couplings at the pole and off-shell are the same

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

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

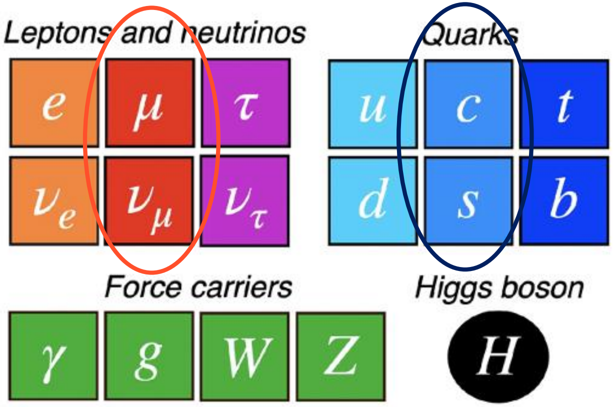
many analyses →
Spin 0
Positive parity
at > 99.9% CL



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

The coupling with the 2 generation



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

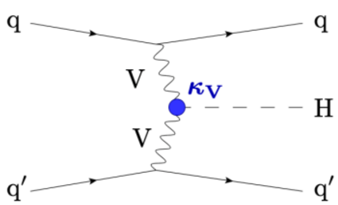
Ingenuity is giving us access at these *«exquisitely small signals »*

©Andre David

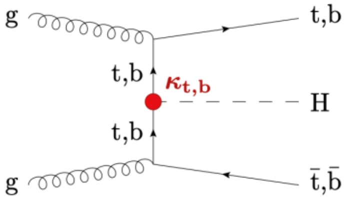
Higgs to muons

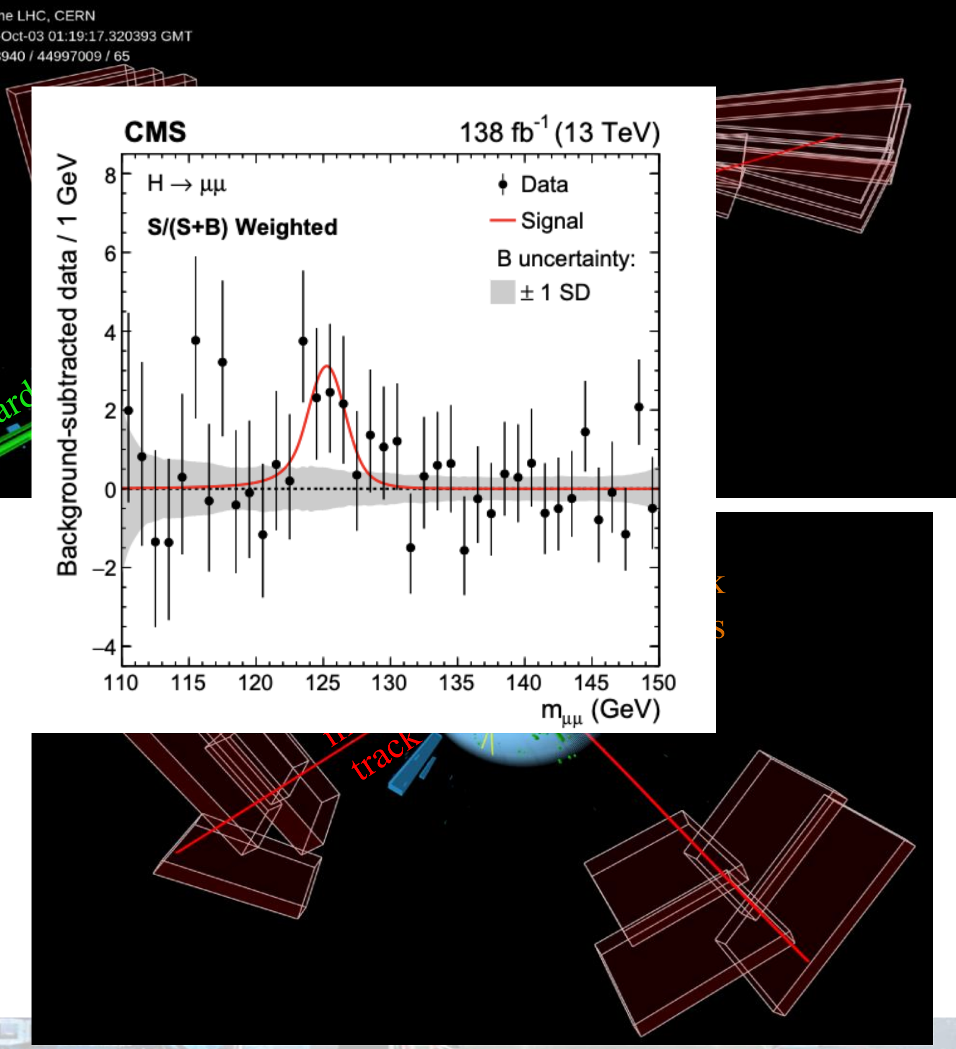
SM BR(H→ μμ) ~ 2.2 × 10^{-4}

Exploit all production modes.



Candidate events compatible with different associated production modes and $H^0(125) \to \mu\mu$ decay.



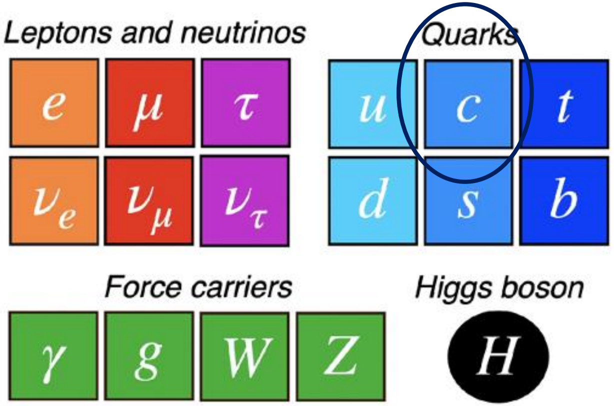


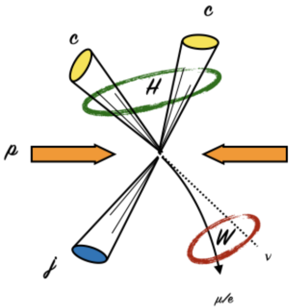
Higgs to charm

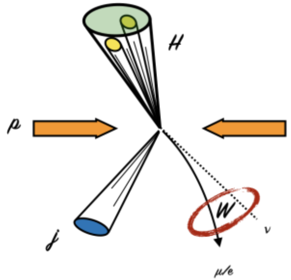
CMS: arxiv:2205.05550

SM BR(H→cc) ~ 0.028

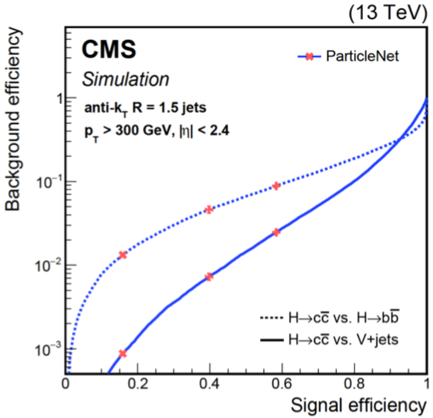
Search for H→cc
in VH events

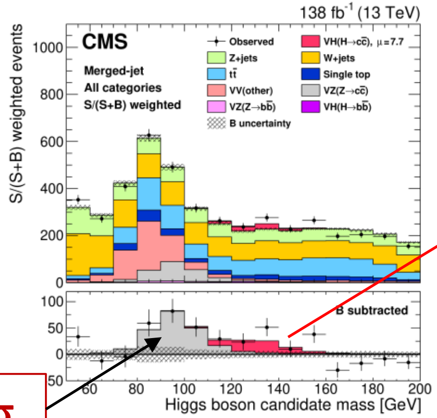


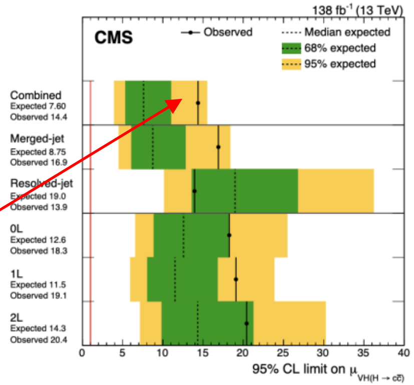




Sensitivity to **H→cc** ~ 8 × SM







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

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

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%

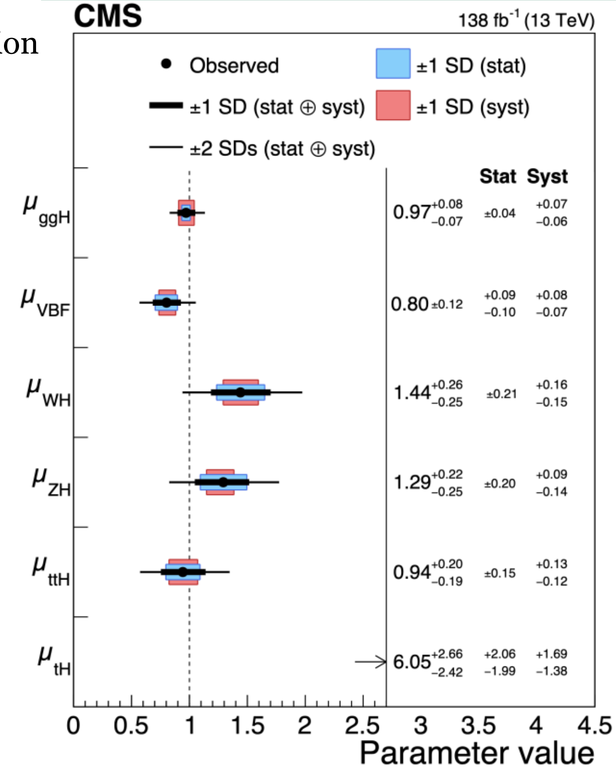
th – exp – stat uncertainties are of the same size

Higgs boson production modes and decay channels

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

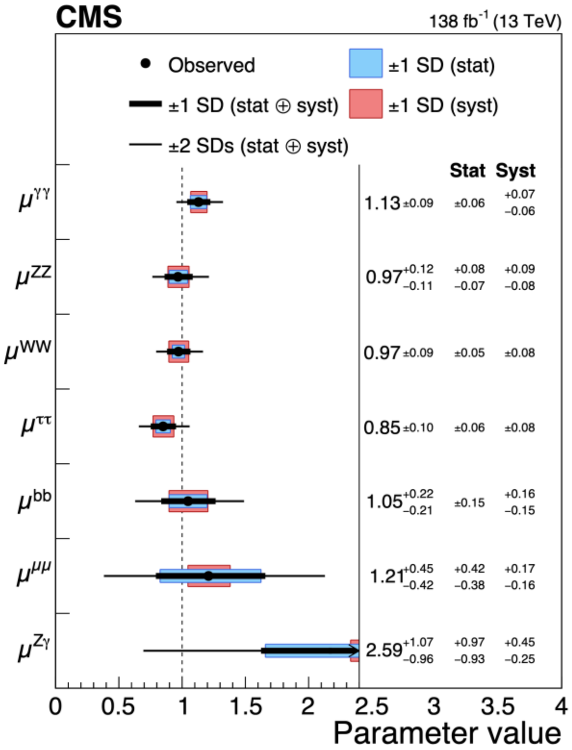
Production

> 5 SD



Decay

> 5 SD



Differential distributions

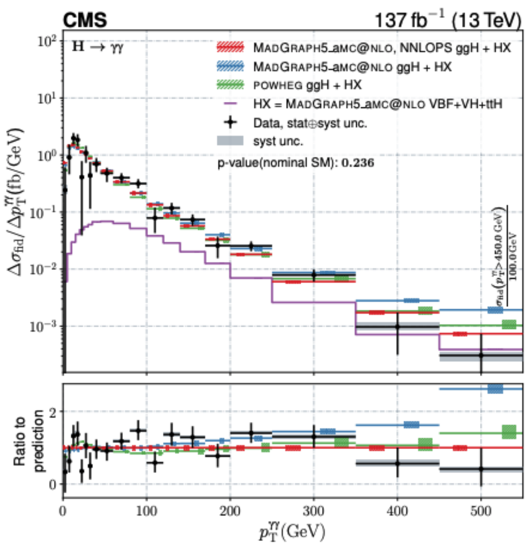
p_T , y, φ, n_{jet}… describe the Higgs production at LHC and help understanding QCD effects.

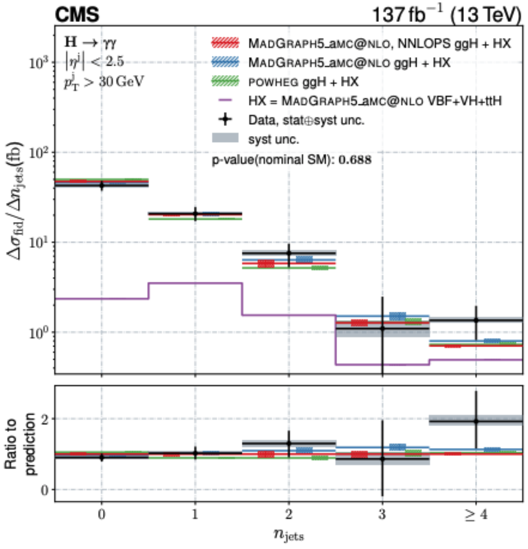
p_T → perturbative QCD

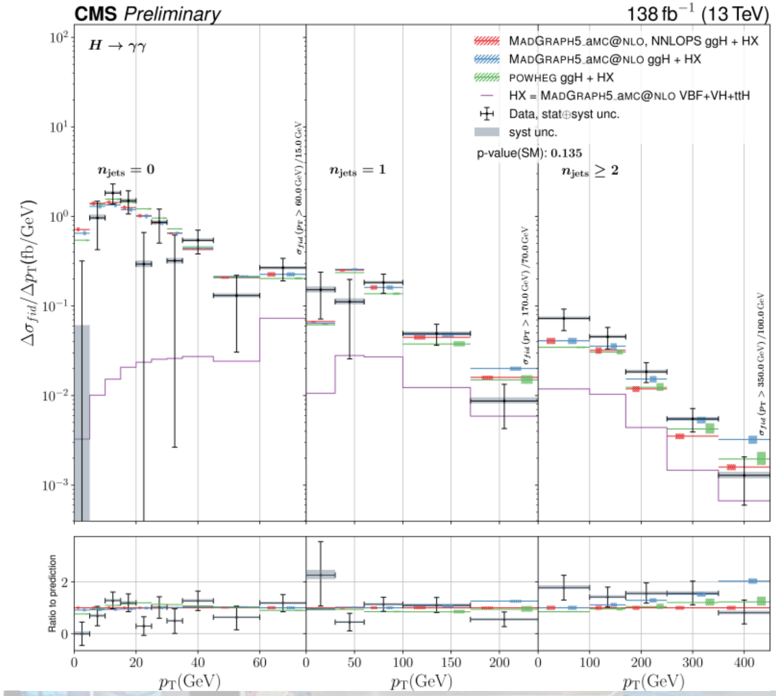
+ resummation of the leading logarithms,

+ probe of new physics at high values.

Double differential XS

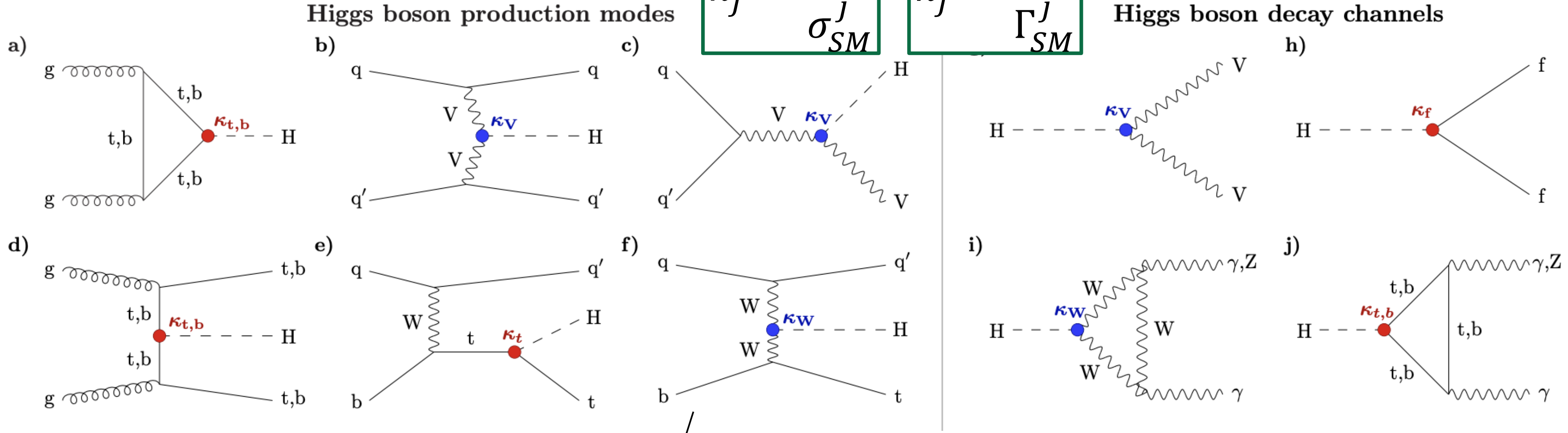




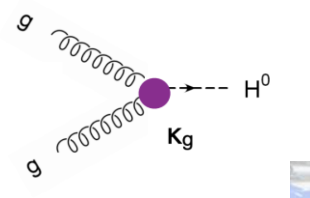


The couplings & the coupling modifiers: the κ framework.

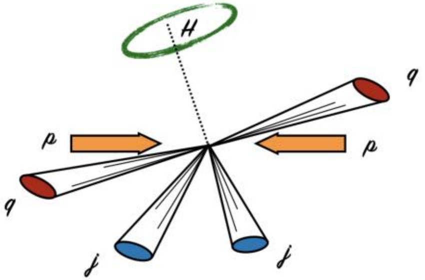
$$\kappa_j^2 = \frac{\sigma^j}{\sigma^j_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$



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

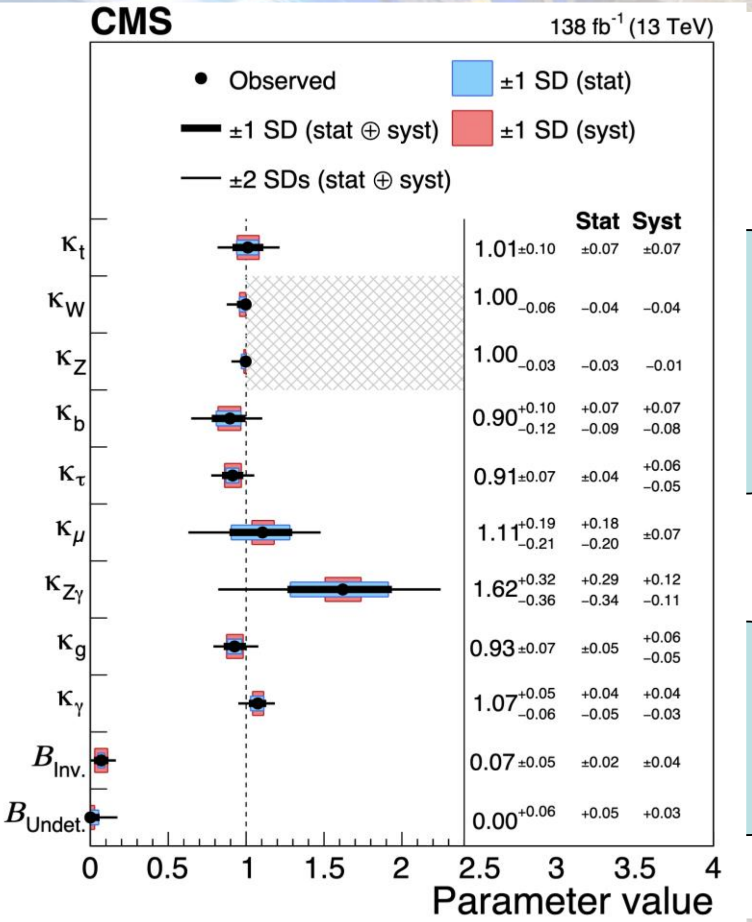


Invisible (ν, DM…) or Undetected decay

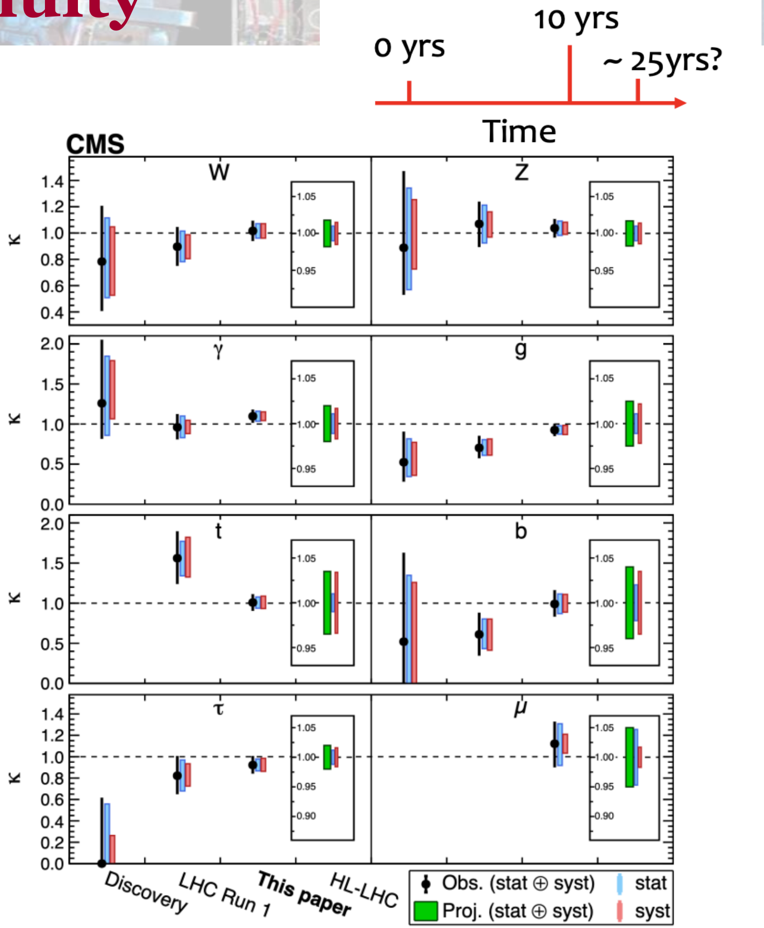


$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\kappa_H^2}{(1 - \mathcal{B}_{inv} - \mathcal{B}_{undet})}$$

Luminosity, energy and …. ingenuity

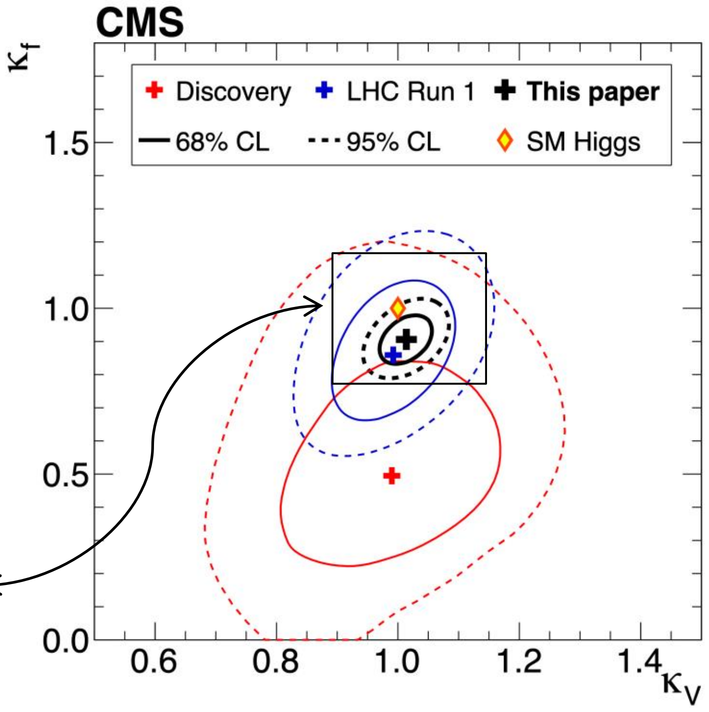


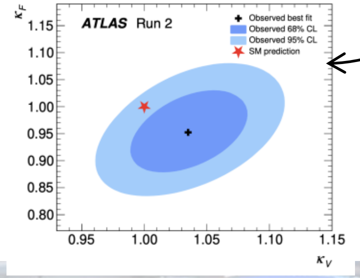
<3 - 10%

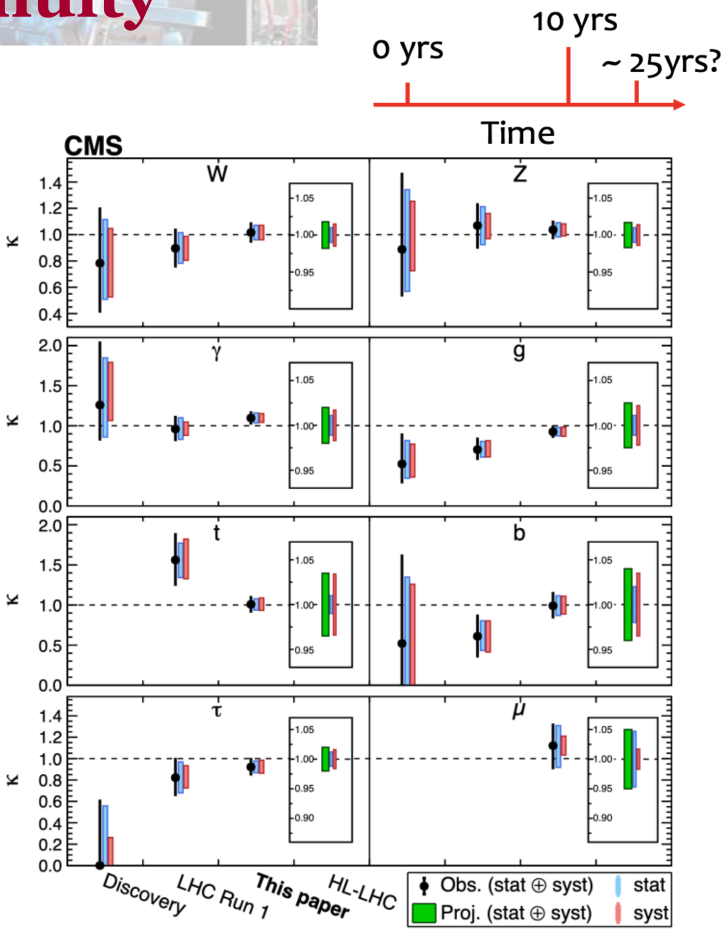


Luminosity, energy and …. ingenuity

~30 times more Higgs events in Run2

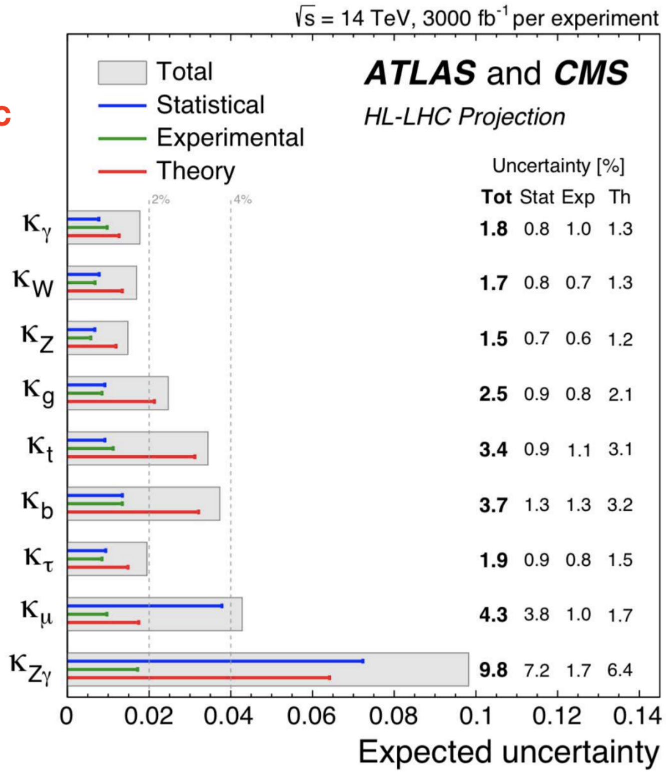






Precision Higgs couplings measurements

	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)