Stairways to heaven: precise measurements and searches at the CMS experiment

Chiara Mariotti

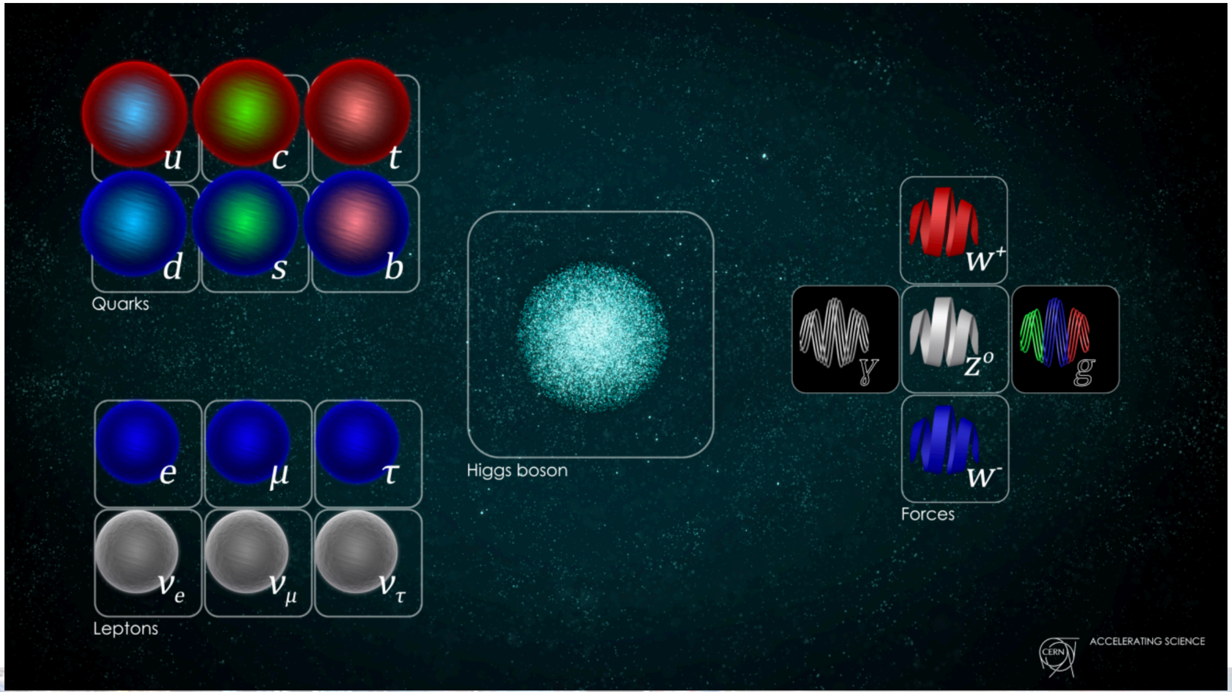
BU – November 2023

The discovery of the Higgs boson

The 4 July 2012 the ATLAS and CMS experiments announced the discovery of a new particle, that later was confirmed to be:

the Higgs boson

The last missing particle of the Standard Model

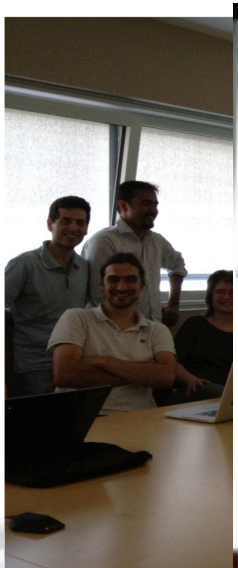


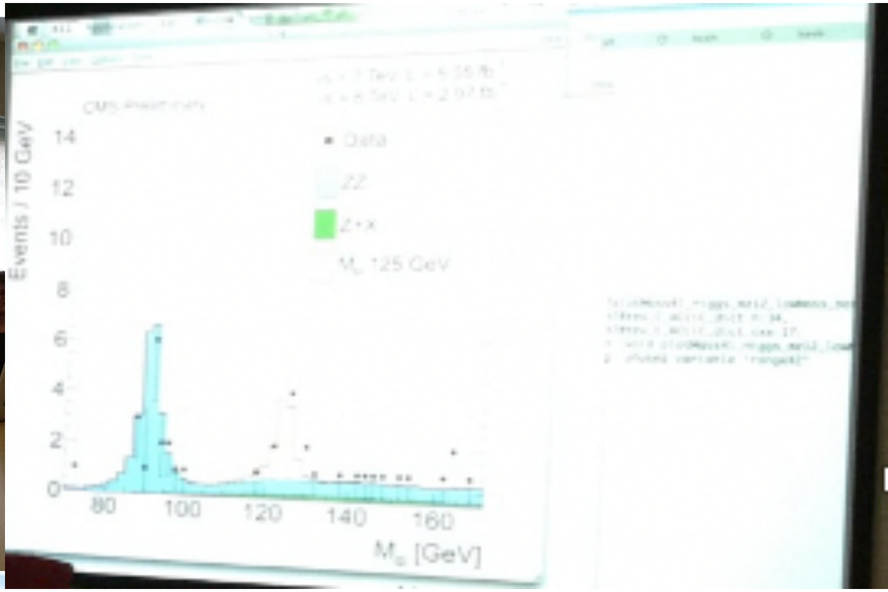
The D-day for CMS

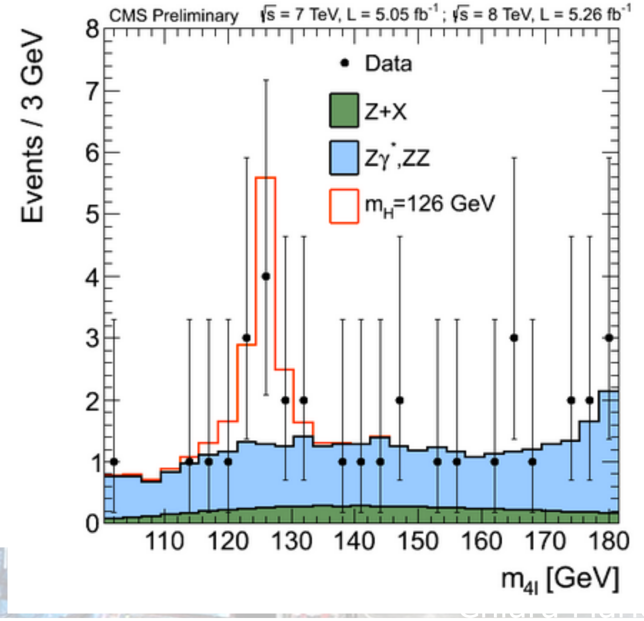
The 14 of June of 2012 at 19h00:

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:



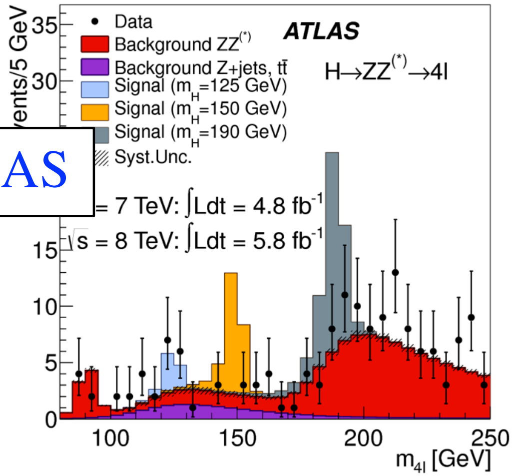


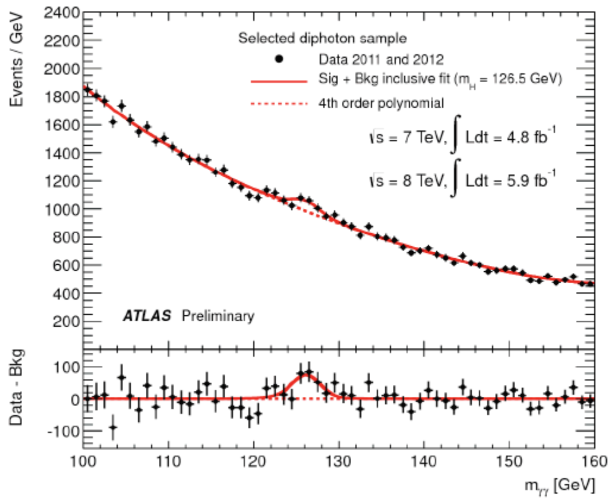


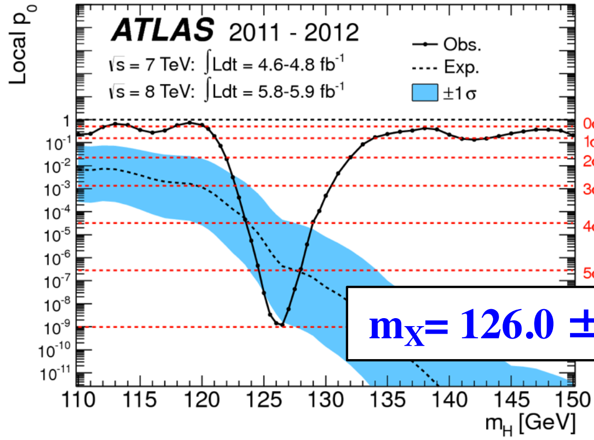
The 4th of July 2012

combination

ATLAS

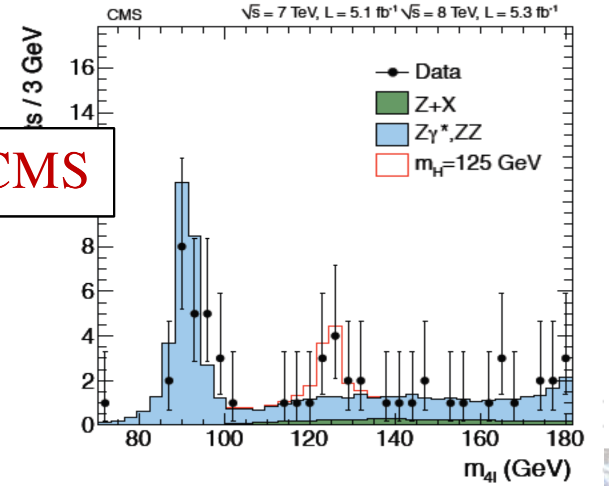


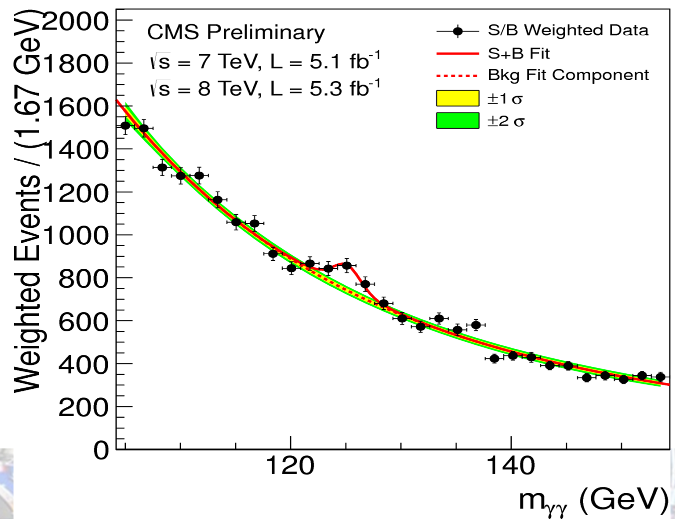


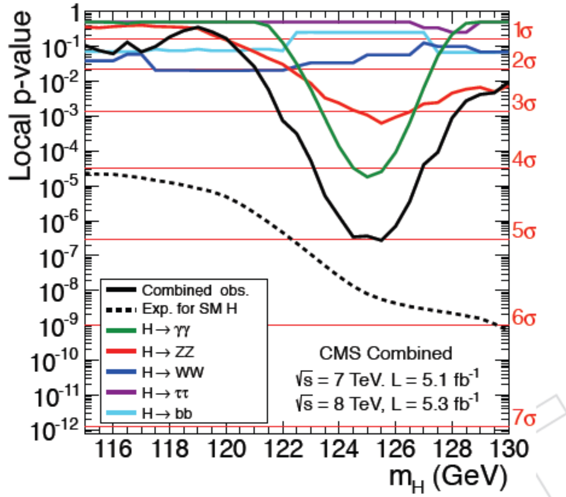


$m_X = 126.0 \pm 0.6$ GeV

CMS





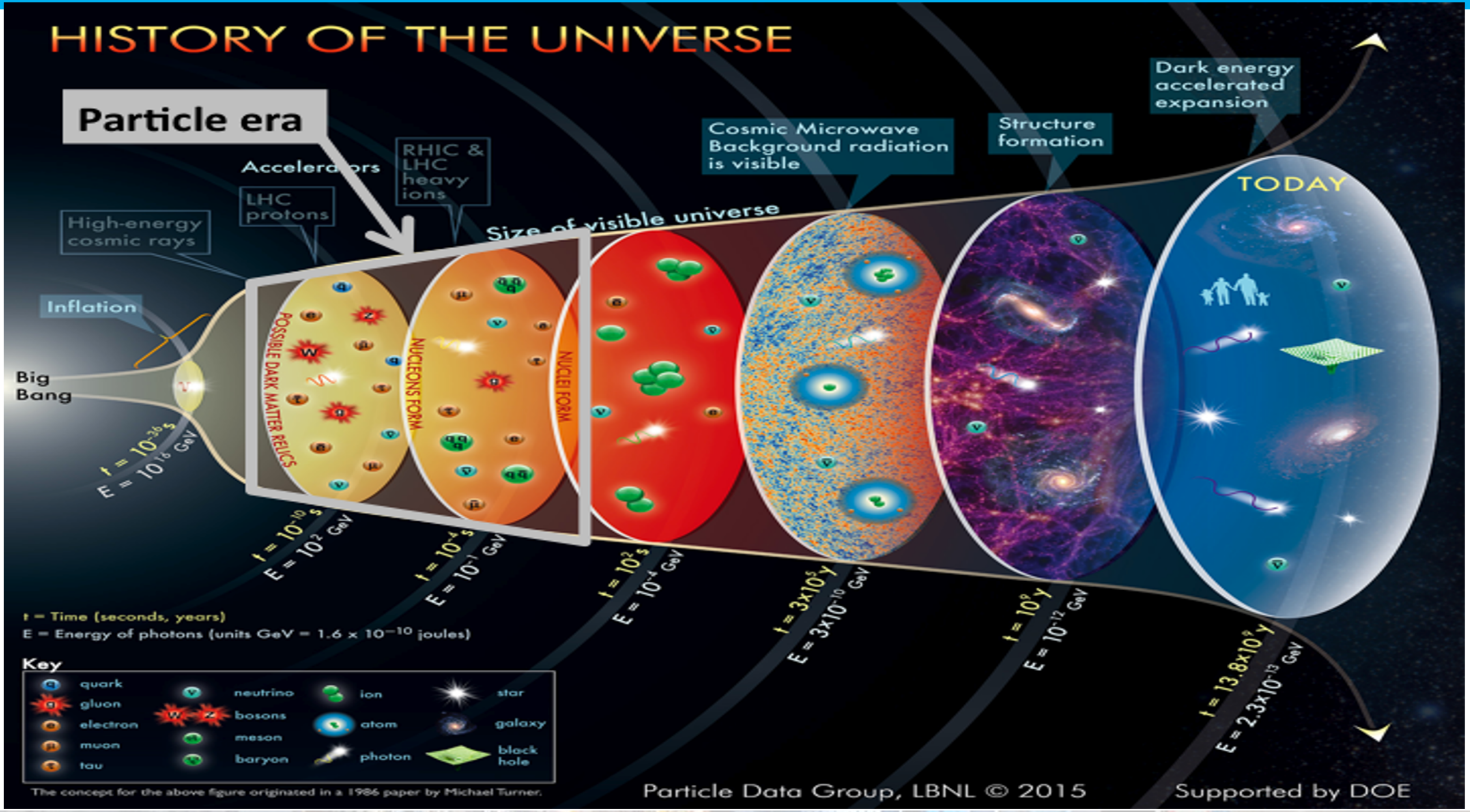


$m_X = 125.3 \pm 0.6$ GeV

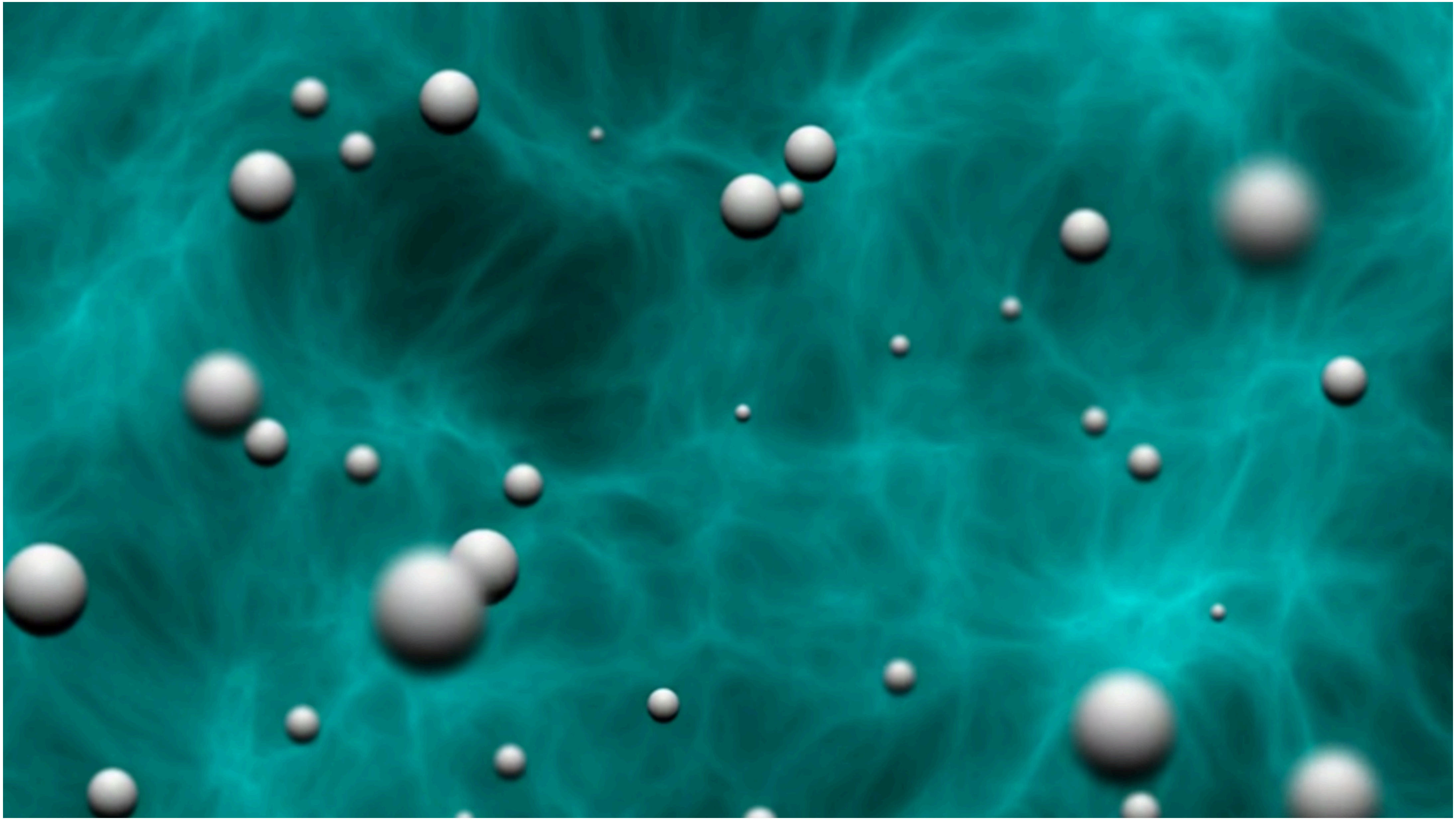

The Higgs field
and
the Higgs boson

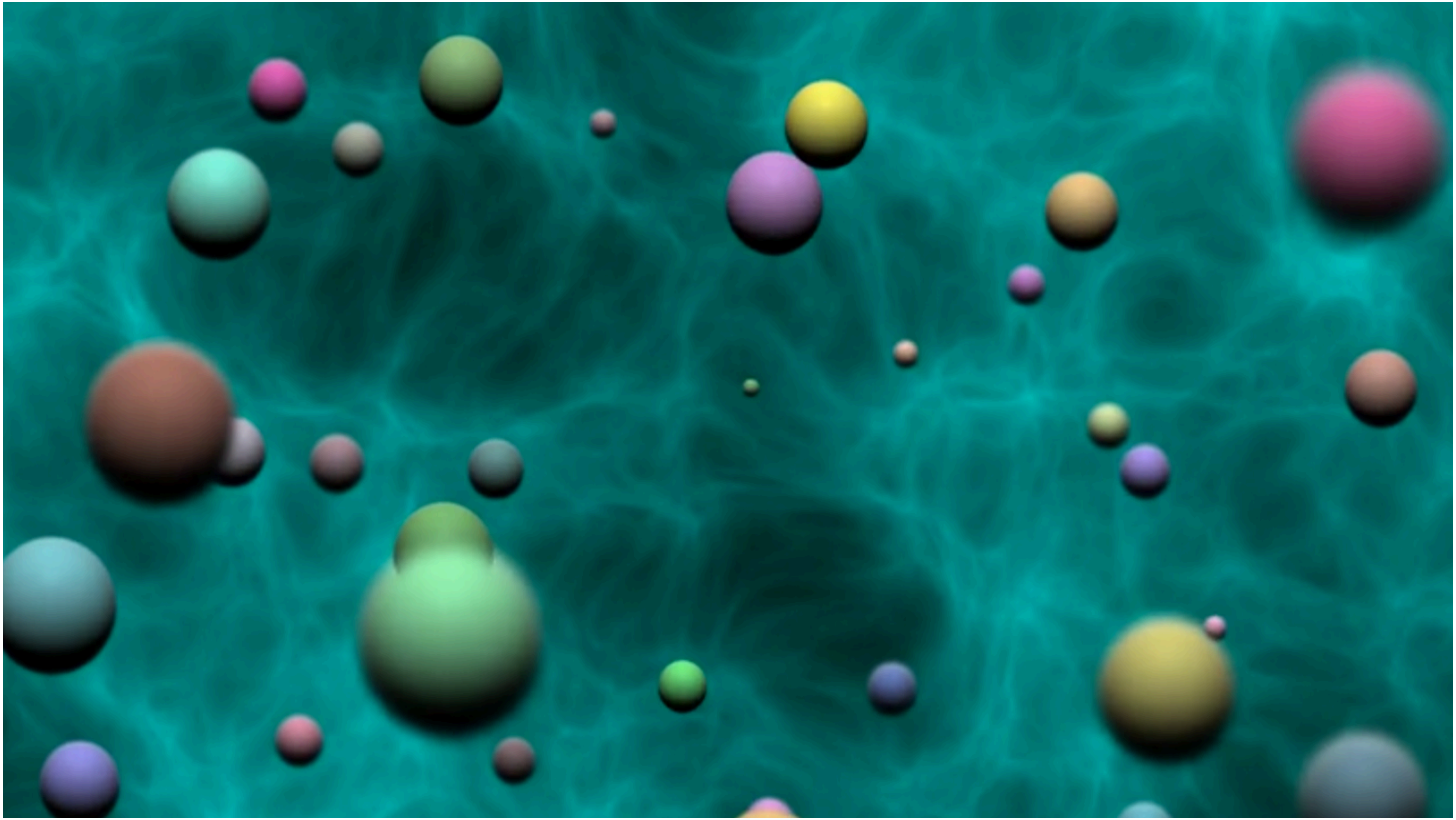
The Higgs boson

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)



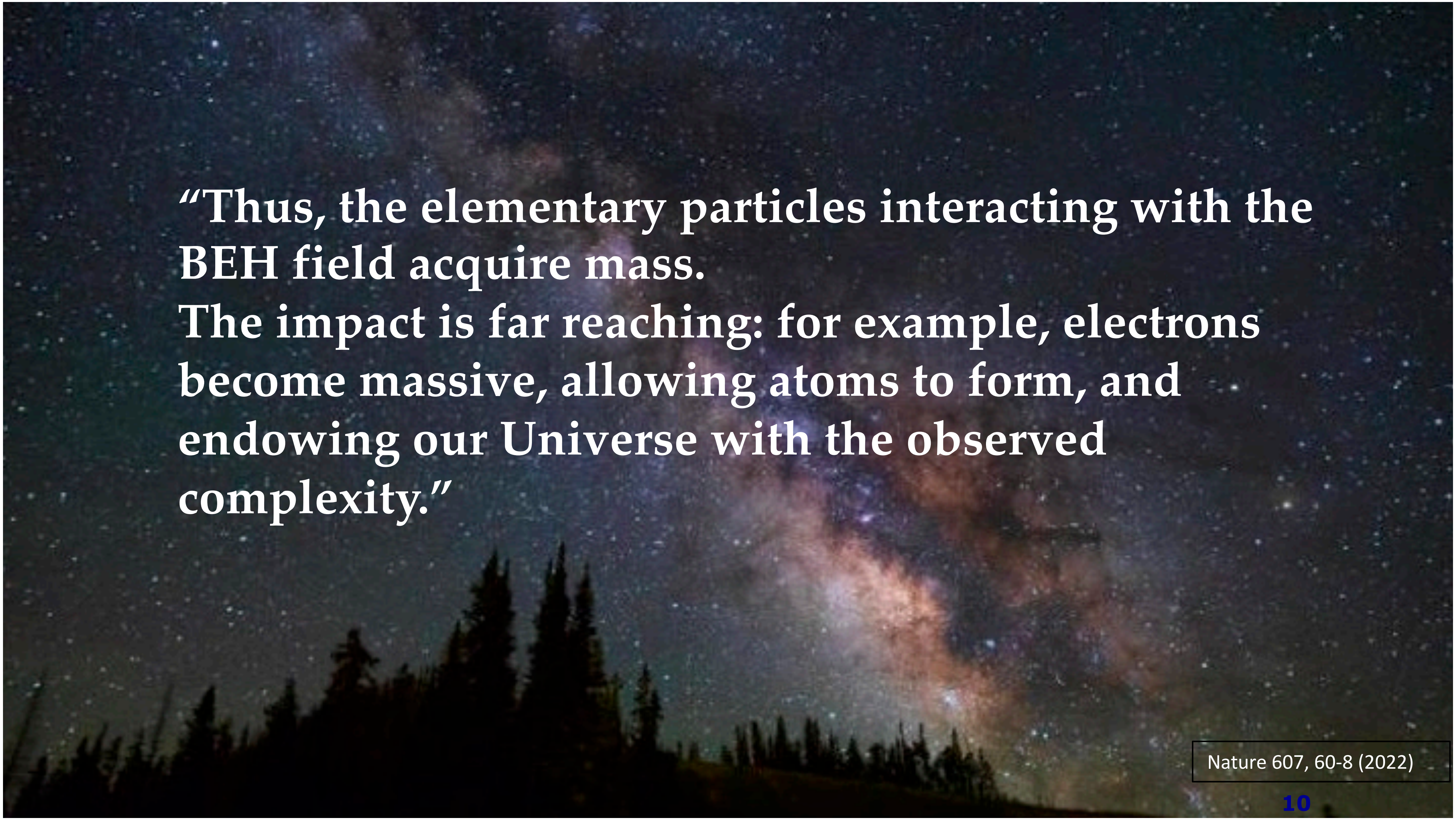


The Higgs boson

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.*

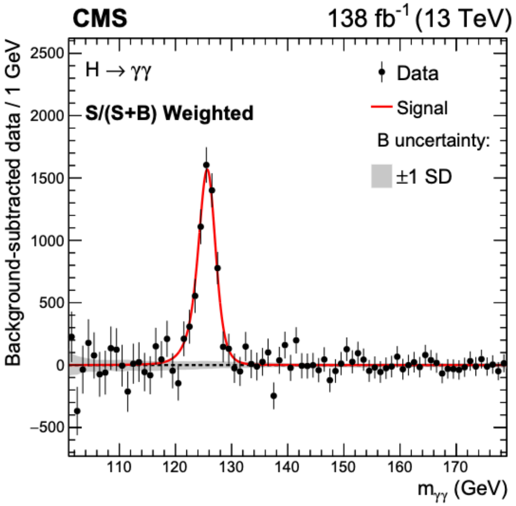
$$J^{PC} = 0^{++}$$

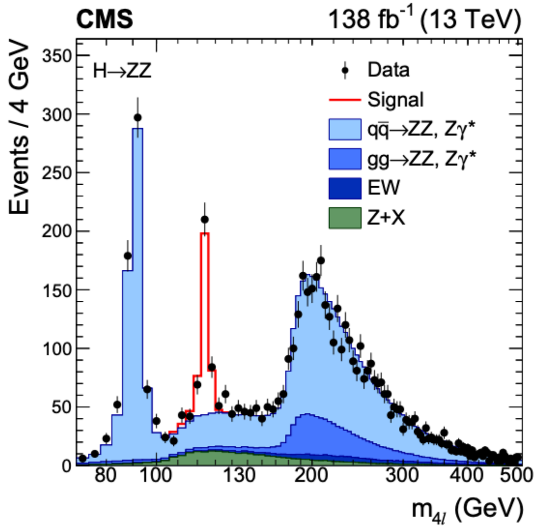
It is the only elementary particle that does not spin
It has zero electric charge
It is even under parity and charge conjugation

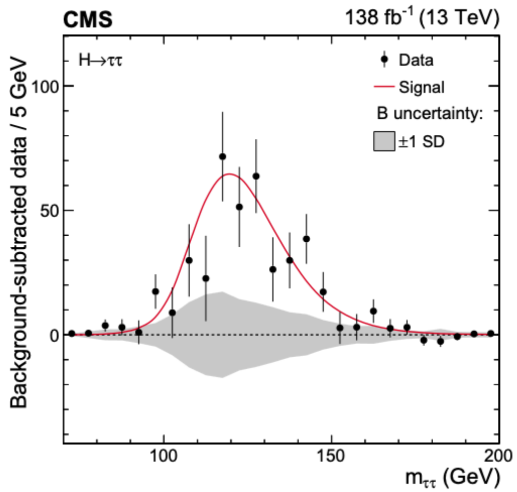
10 years after

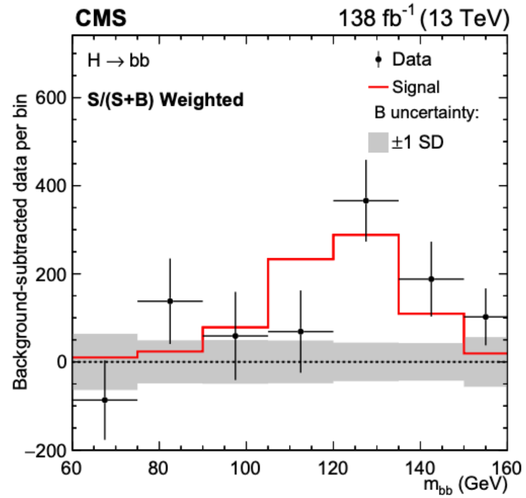
bosonic channels

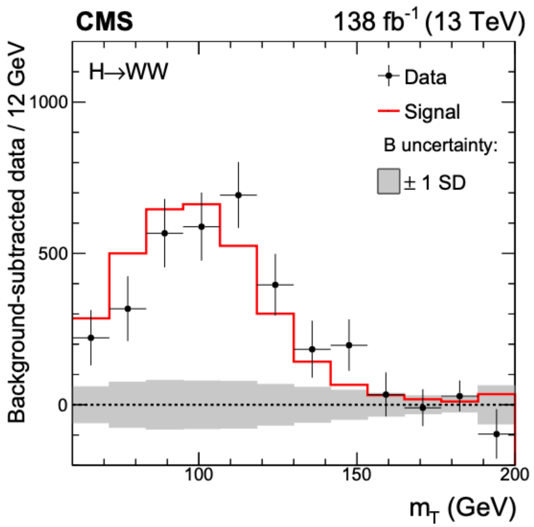
fermionic channels

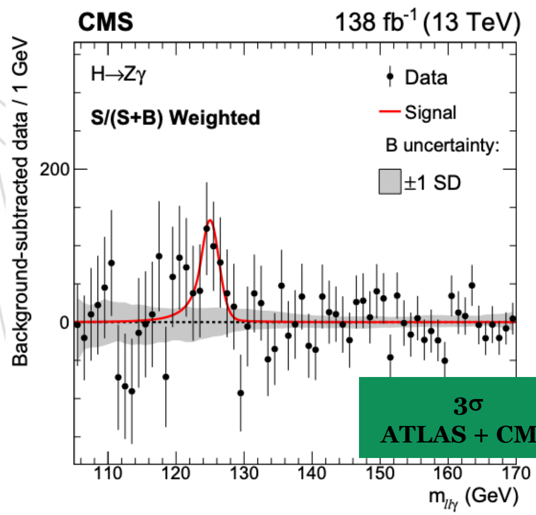




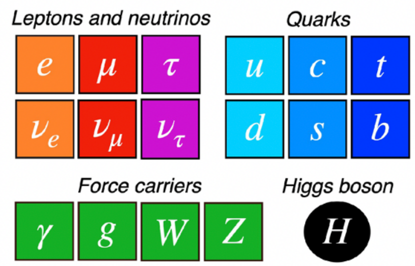




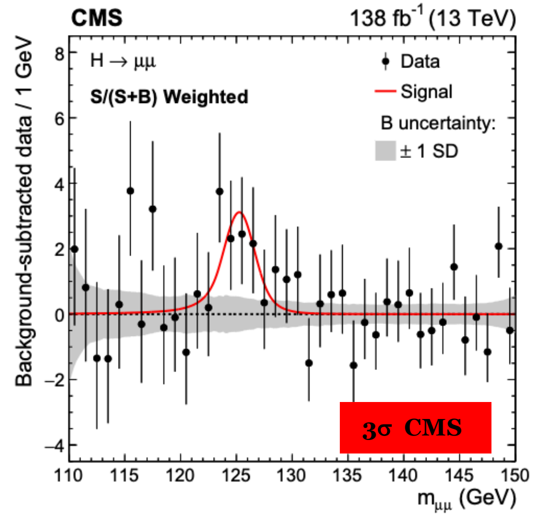




3σ
ATLAS + CMS



Nature 607, 60-68 (2022)



3σ CMS

The Higgs mass from γγ and 4l decay channels

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

γγ

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

Choice of the primary vertex

Energy calibration

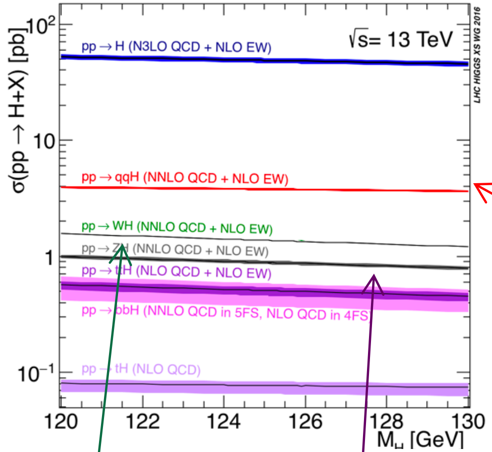
4 leptons: mass measurement performed with a 3D fit
- four –lepton invariant mass $\mathbf{m_{4l}}$
- associated per-event mass uncertainty δm_{4l}
- kinematic discriminant MELA/NN

→ lepton momentum scale

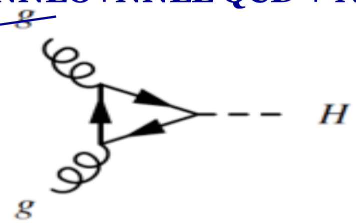
CMS Run1 + Run2 (4l only) 125.08 ± 0.12 (± 0.10 stat ±0.05 syst) GeV

1 per mille precision

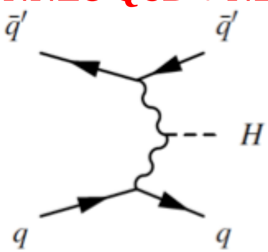
Higgs Cross Sections



ggF: NNNLO+NNLL QCD + NLO EW

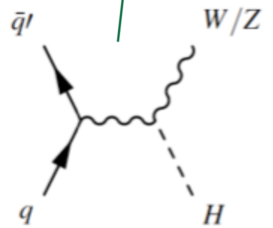


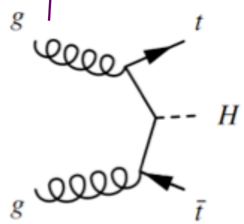
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW

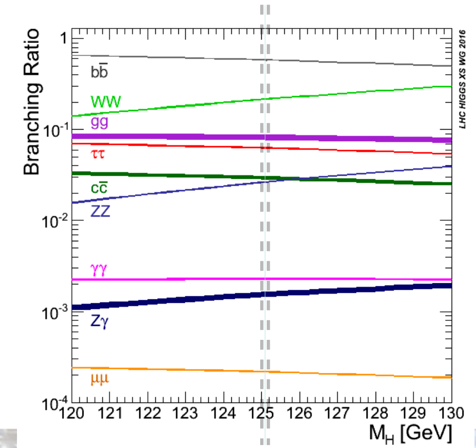
ZH: NNLO QCD + NLO EW



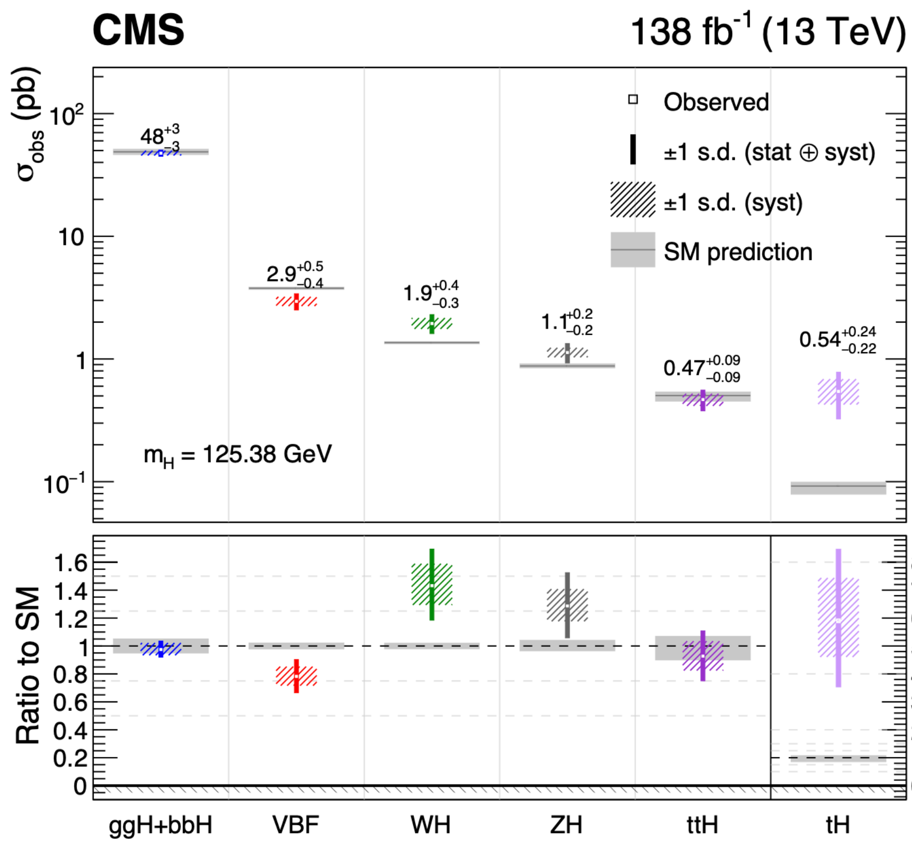


ttH: NLO QCD

Cross Sections & BR:
the LHCHXSWG results - 2017

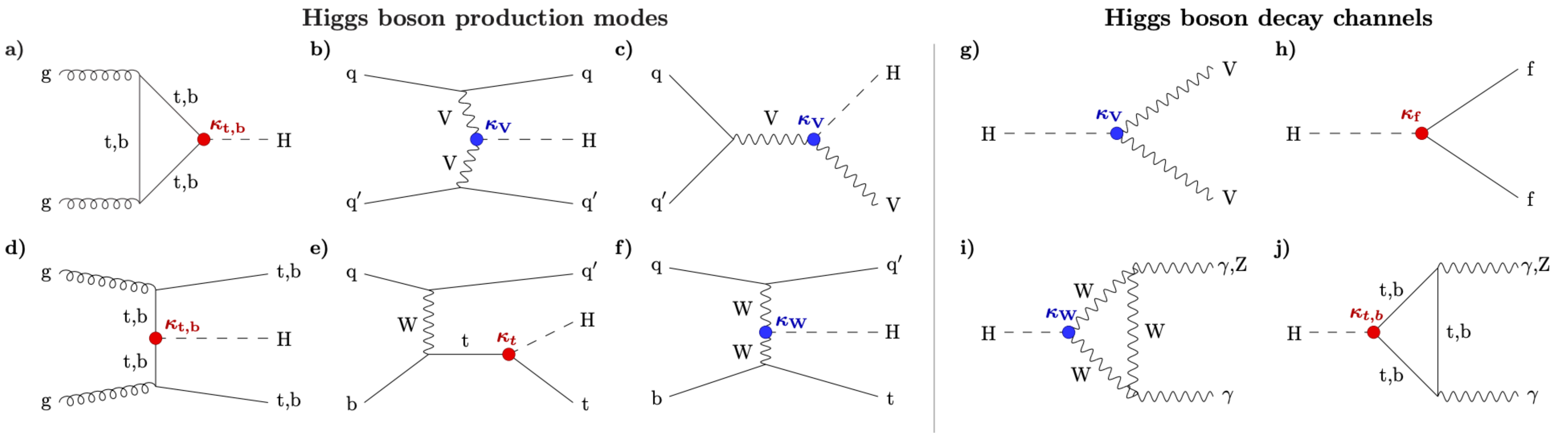


The Higgs steps in the stairway



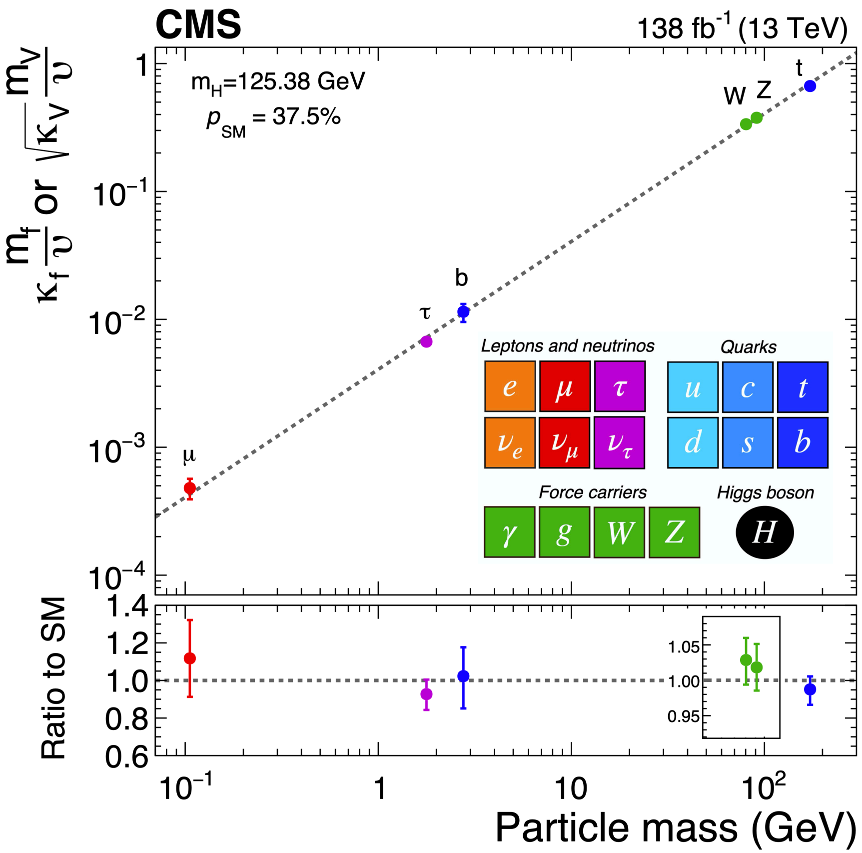
The couplings & the coupling modifiers: the κ framework.

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



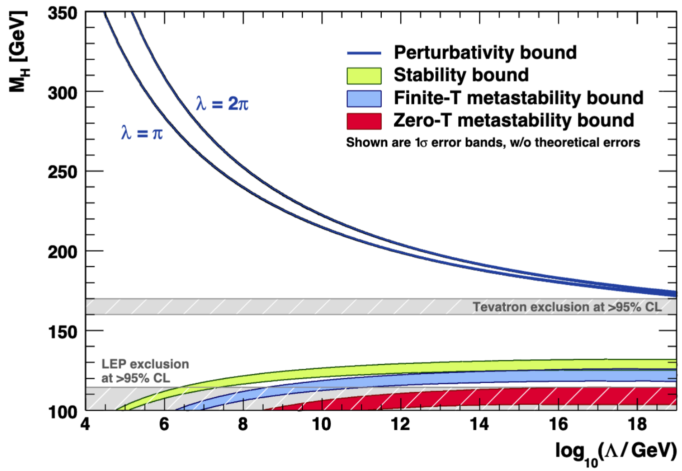
The portrait of the Higgs boson

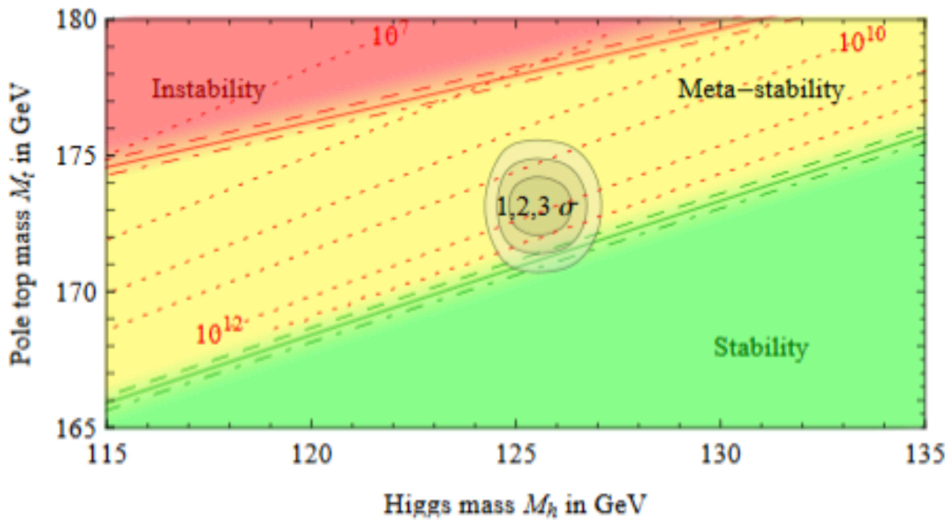
SM test over many orders of magnitude

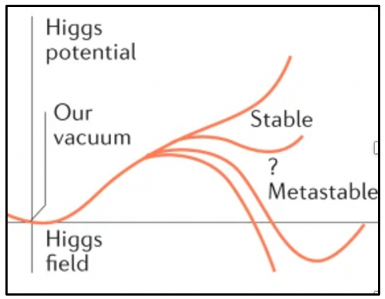


The Higgs couples with the particle mass !

The special value of the Higgs mass







"The measurements of the Higgs mass and top Yukawa coupling indicate that we live in a very special universe, at the edge of the absolute stability of the electroweak vacuum. [….] the Standard Model (SM) can be extended all the way up to the inflationary scale and the Higgs field, nonminimally coupled to gravity with strength ξ, can be responsible for inflation. "

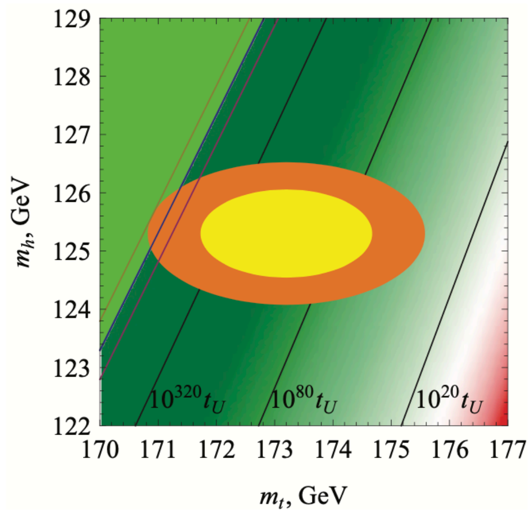
Mikhail Shaposhnikov

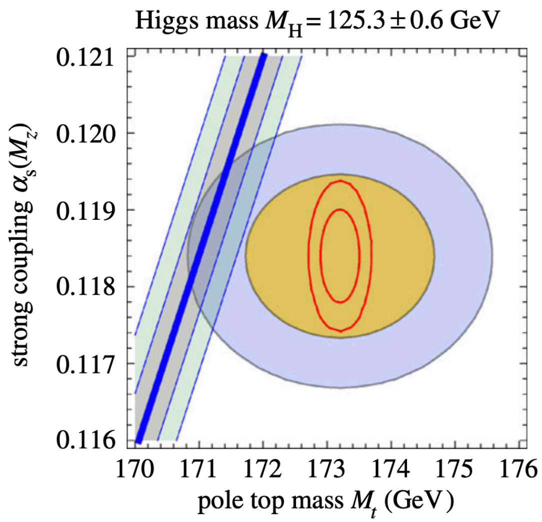
Higgs as inflaton

"The Higgs boson is a very special particle in the SM. It provides a mechanism for including *weakly interacting* massive vector bosons in the SM, and for 'giving' masses to quarks and leptons, […]the Higgs field may also have had an important role in cosmology: it could have made the Universe flat, homogeneous and isotropic, it could have produced the fluctuations that led to structure formation and it could also have enabled the radiation-dominated epoch of the hot Big Bang to occur. Moreover, in the modest extension of the SM by three relatively light Majorana fermions—heavy neutral leptons (HNLs)—the Higgs field is important for baryogenesis, leading to the charge asymmetric Universe, and for dark matter"

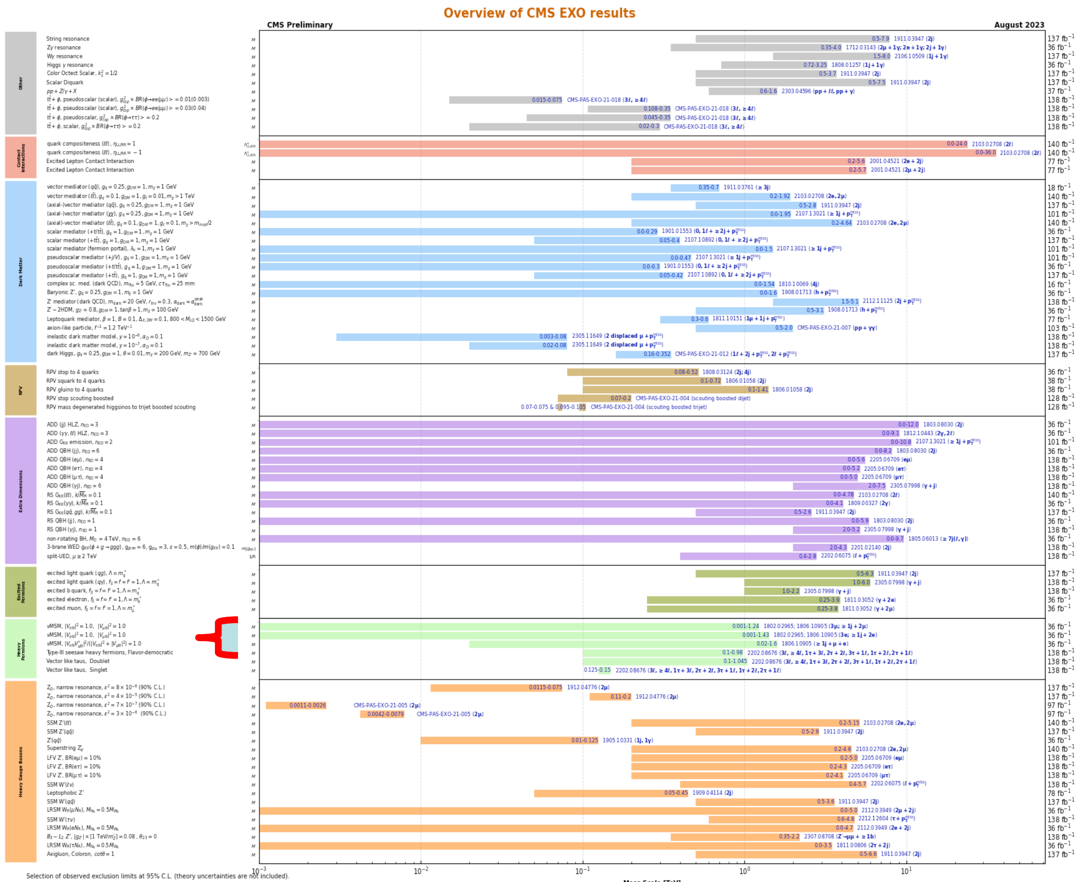
..the Higgs also determines the gravity interaction strength,
ξ , a new dimensionless coupling constant of the SM

The potential energy of the Higgs field leads to the exponential expansion of the Universe, which then becomes flat, homogeneous and isotropic.

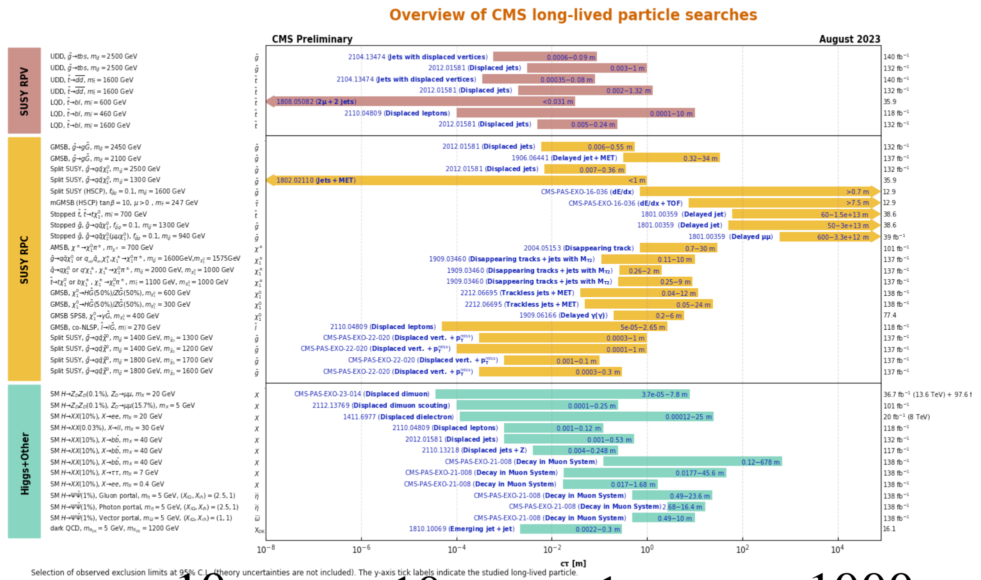




Nothing has been found up to now

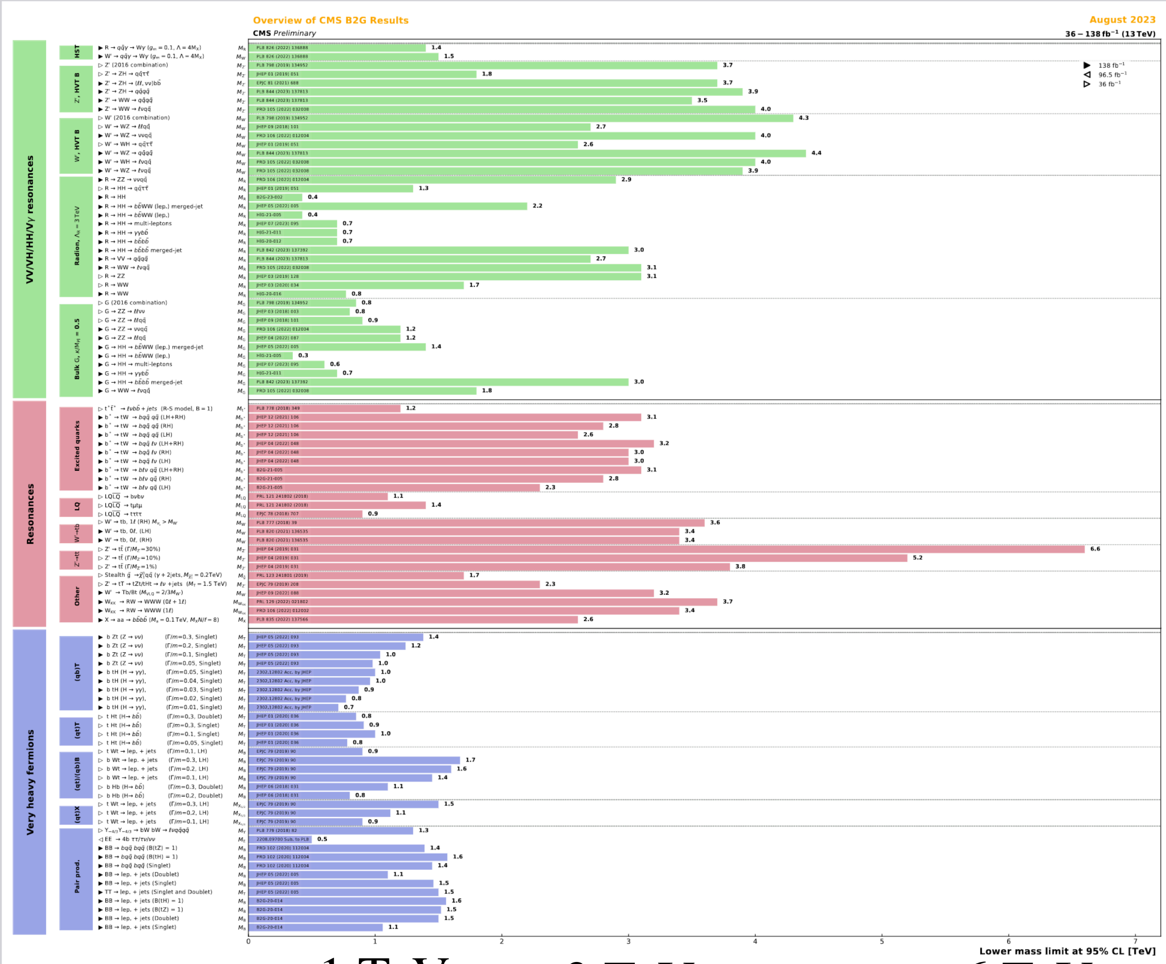


1 GeV 10 GeV 0.1 TeV 1 TeV 10 TeV



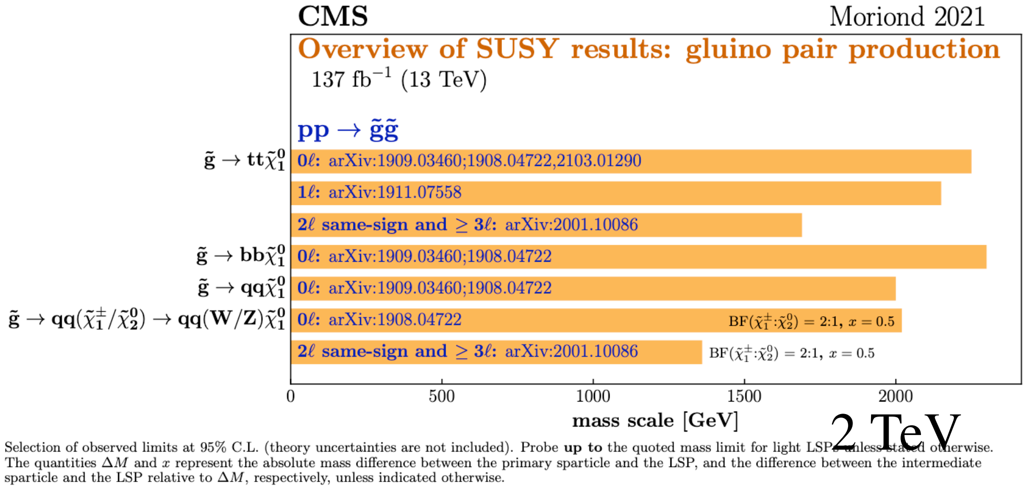
cτ 10 nm 10 mm 1m 1000 m 100 m

More searches

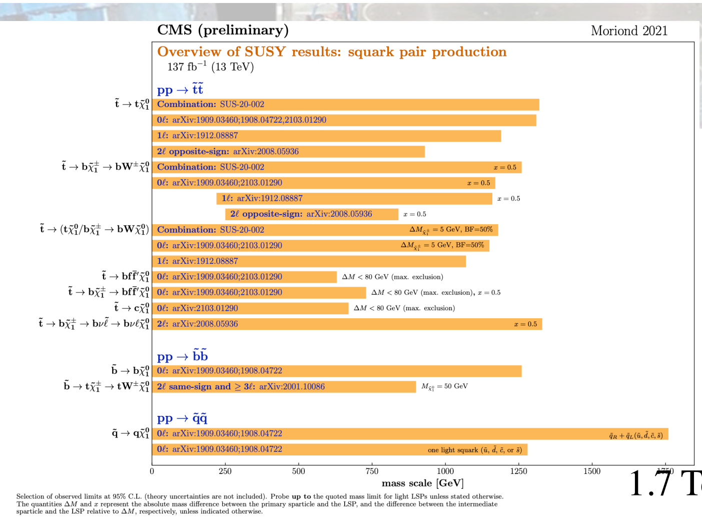


Lower mass limit 1 TeV 3 TeV 6 TeV

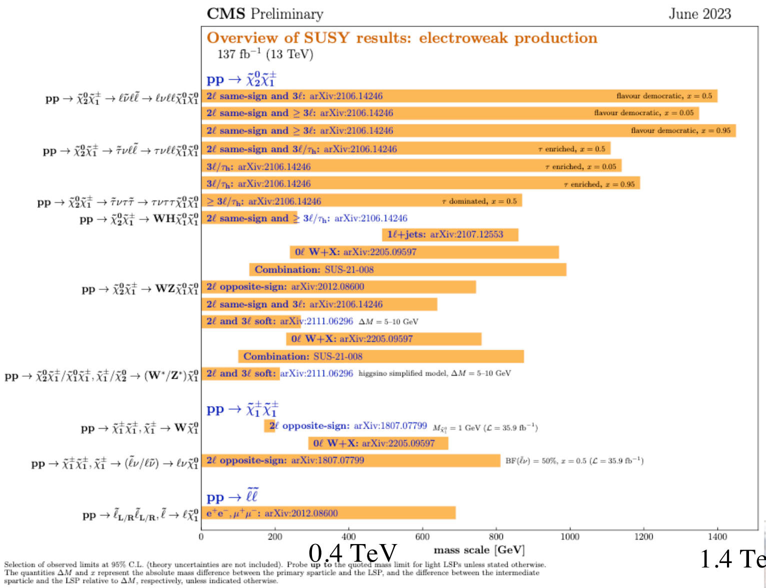
Searching for SUSY



2 TeV

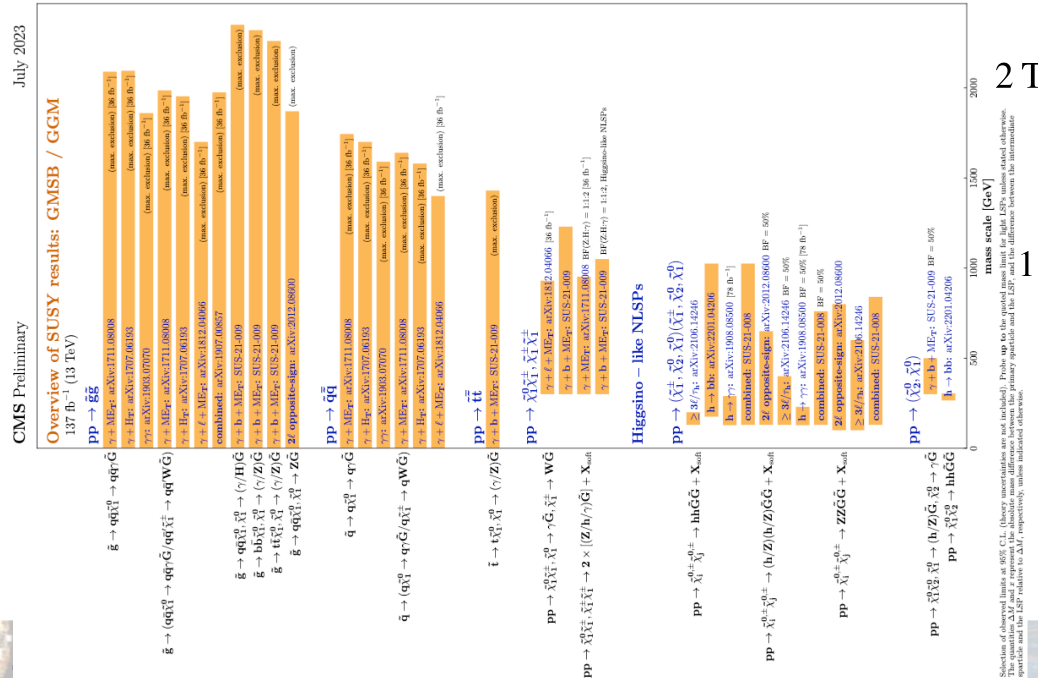


1.7 TeV



0.4 TeV

1.4 TeV



2 TeV

1 TeV

Precision

Hard to expect BSM from striking excess in a single process/observable: most probably, a consistent pattern of small deviations

- Precision theory: unique path to enhance sensitivity to potential deviations from the SM, increasing the LHC discovery reach

- Note: It is not just about finding New Physics.
  It's about describing Nature at unprecedented level!

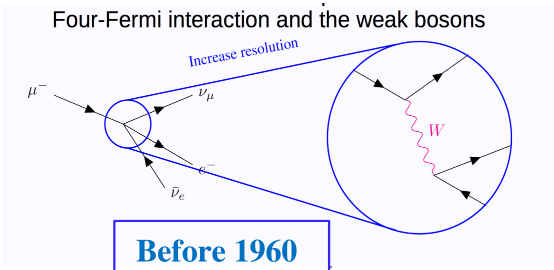
  - Every measurement/prediction that enhances our understanding in a non-obvious way has an immense value

  - The quest for precision has broad impact on the way we understand/measure fundamental interactions, the theo/expt techniques we develop

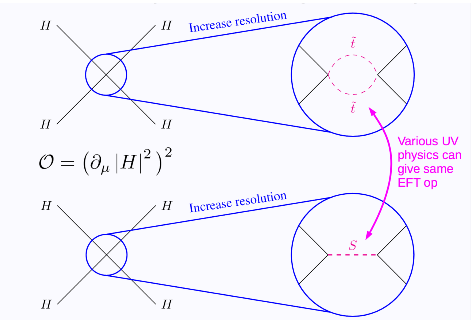
  - A wonderful community effort from maths to data science to technology

@Torrielli

Increasing precisions is like observing with a magnifying glass:



Before 1960



The future

H.Murayama

Is it possible at LHC?

Is it possible to measure observables with high precision in a very harsh hadronic environment?

Sam Ting (Nobel Prize laureate) said in 2000 at CERN (when we were discussing few interesting Higgs candidates, and if to stop LEP and move to LHC):

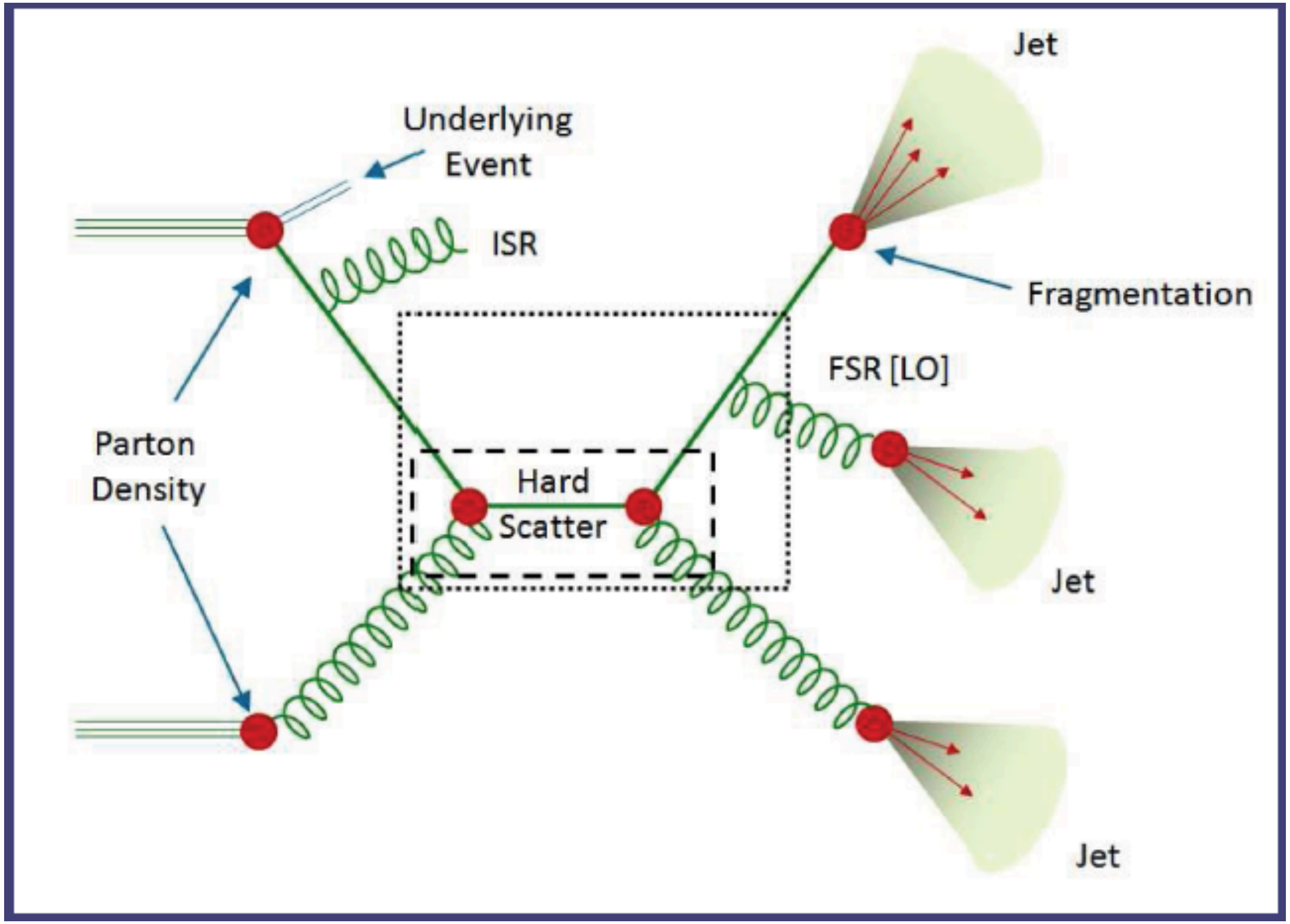
« At LEP every event is signal, at LHC every event is background »

Which observables ?

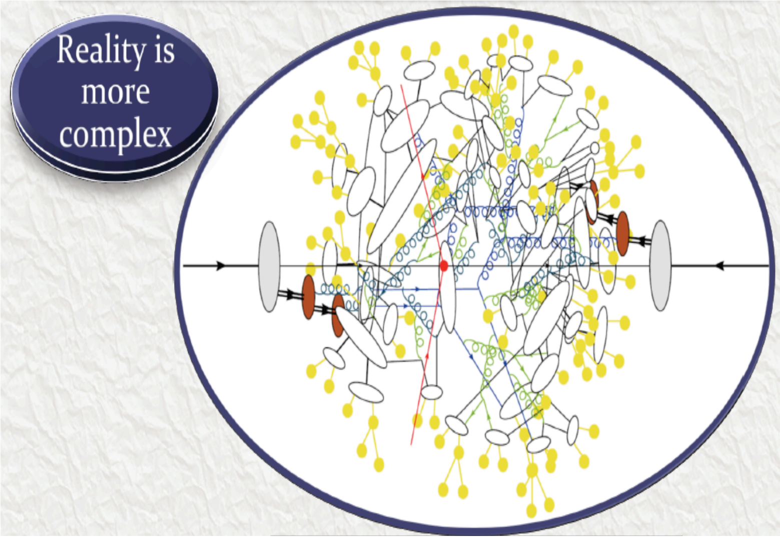
m_H, m_W, m_{top}, α_s + Cross-Sections and Differential Distributions

Precision in **Experimental measurements** and in **Theoretical Predictions**

Physics at LHC



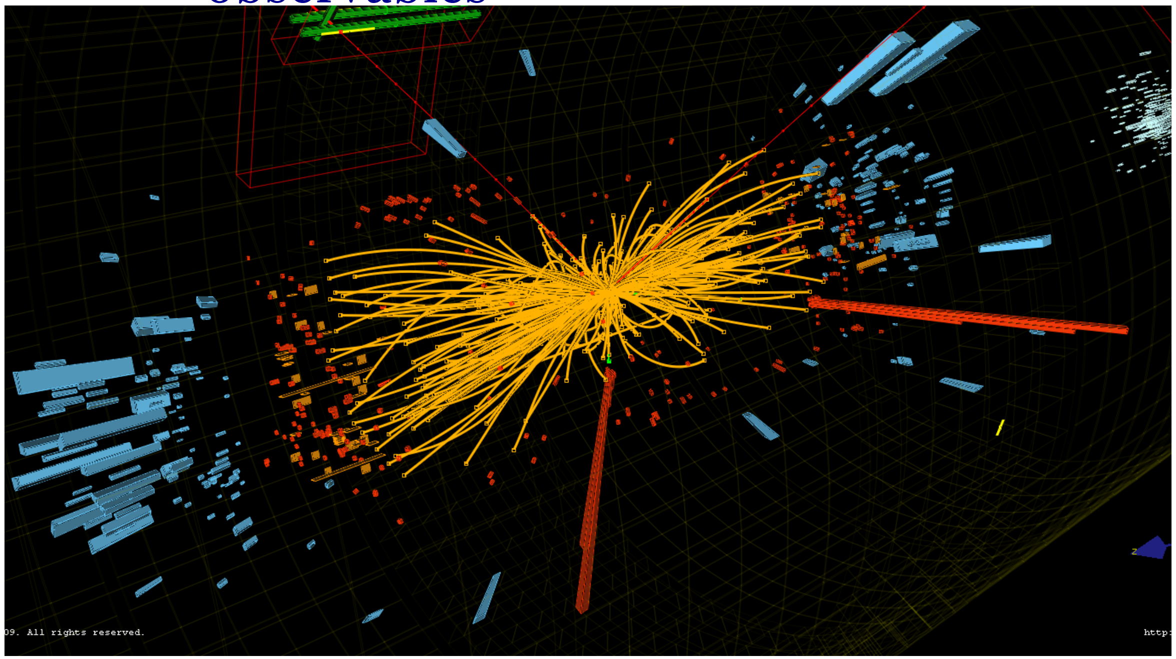
Reality is much more complex



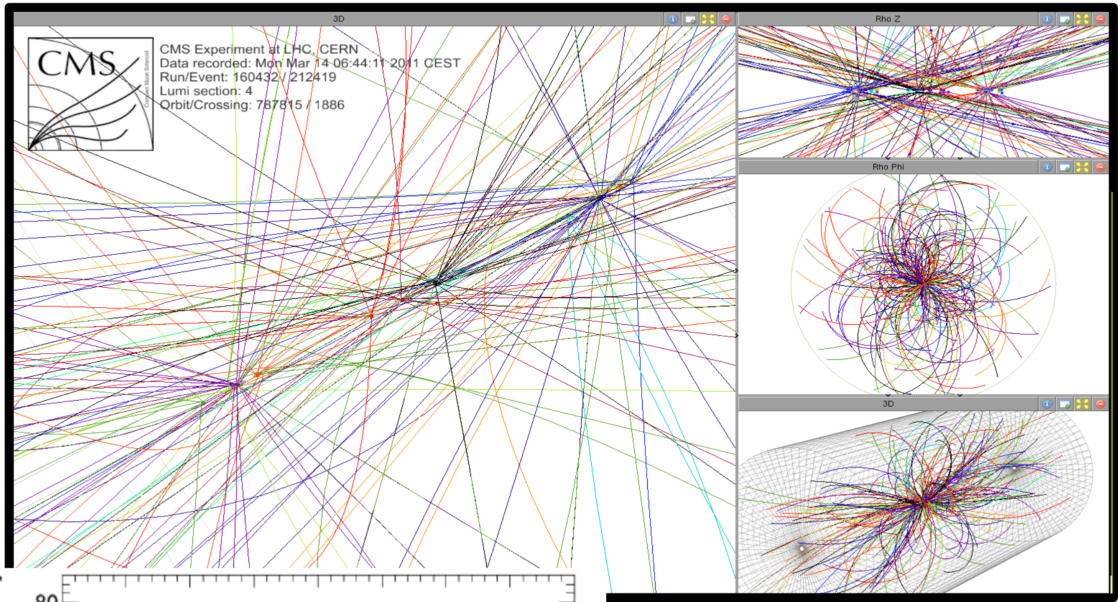
"ALL is QCD"

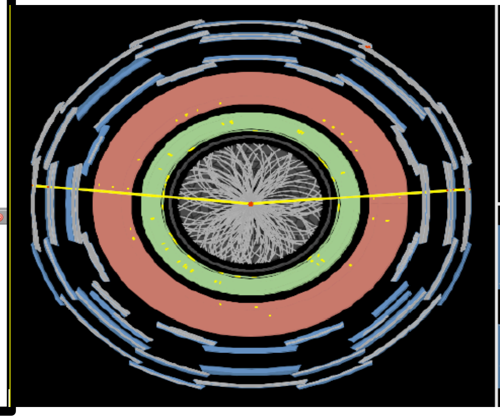
(Quanto Cromo Dinamic)

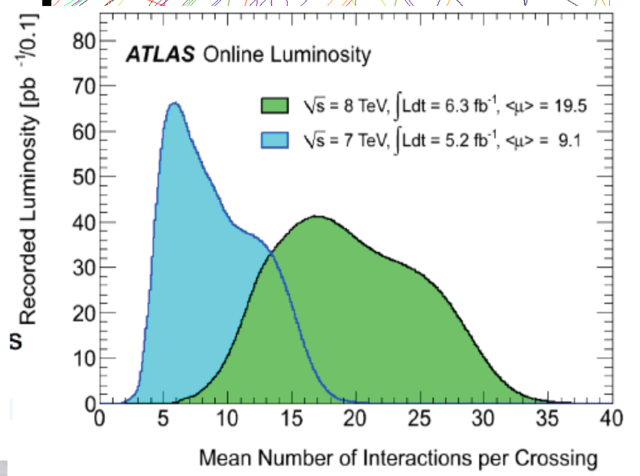
It should be known at the same precision or better of the interesting observables

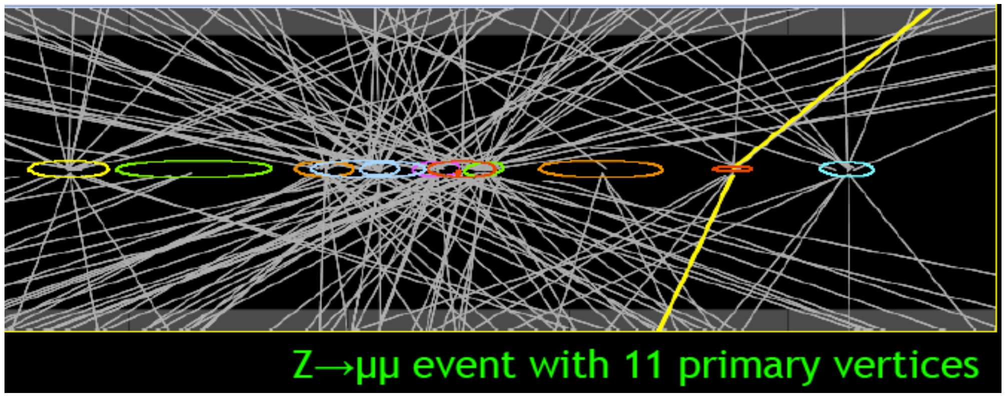


Pile-up

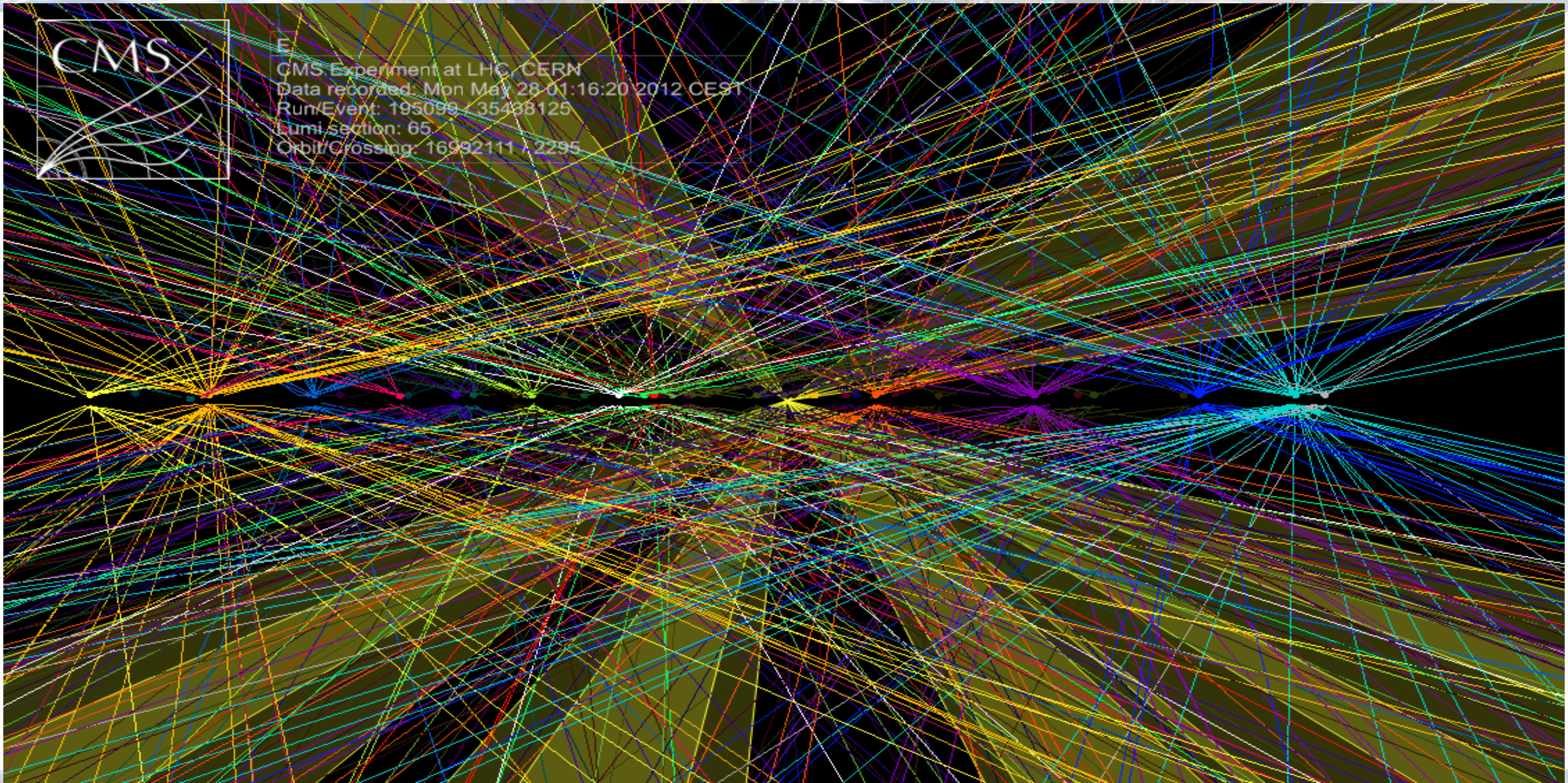

3D
Rho Z
Rho Phi
3D
CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Mar 14 06:44:11 2011 CEST
Run/Event: 160432 / 212419
Lumi section: 4
Orbit/Crossing: 787815 / 1886




ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 6.3 fb⁻¹, <μ> = 19.5
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40

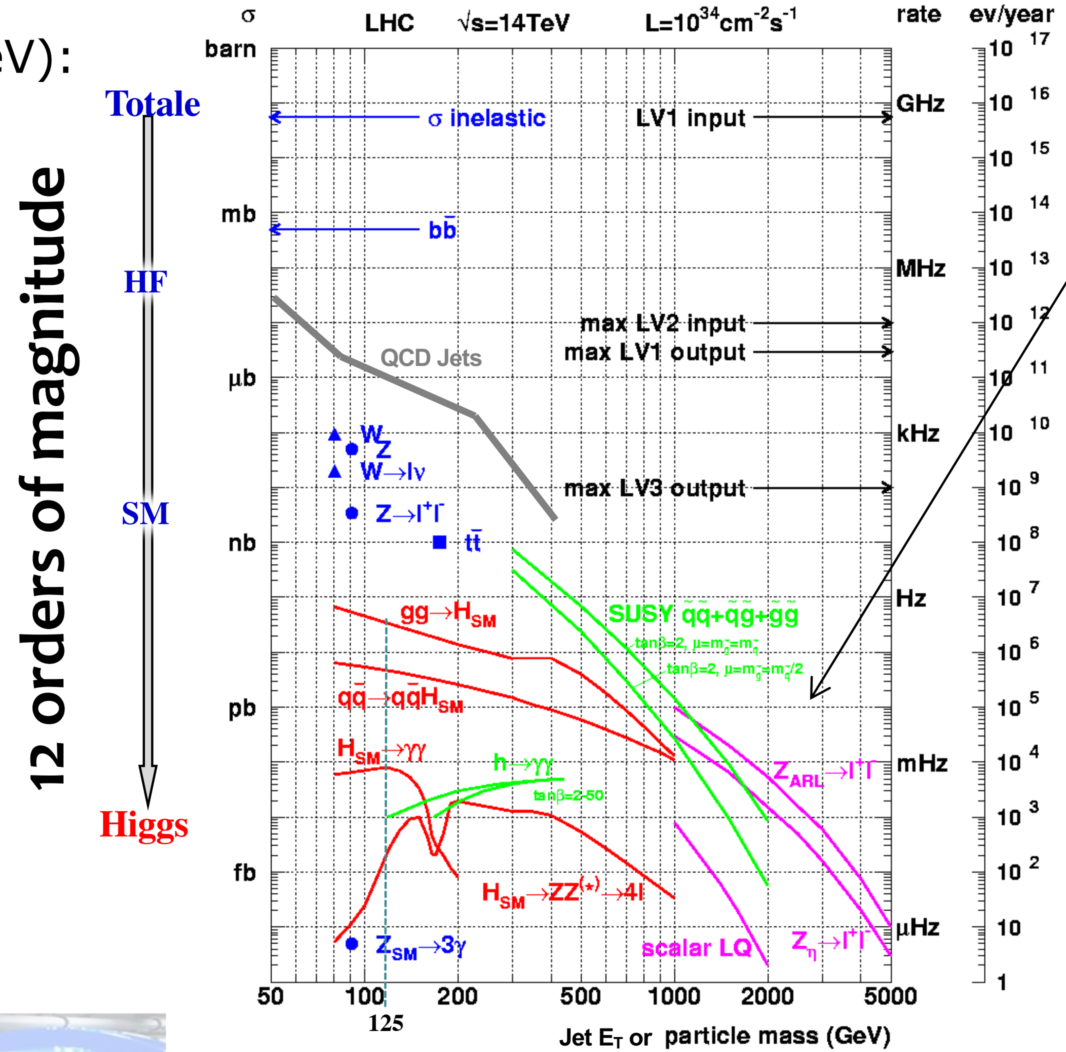

Z→μμ event with 11 primary vertices

Pile-up


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

Cross Sections

σ (at 14 TeV):



Very rare processes

$$R = \mathcal{L}\sigma$$

$$\mathcal{L} = f\frac{n_1 n_2}{A}$$

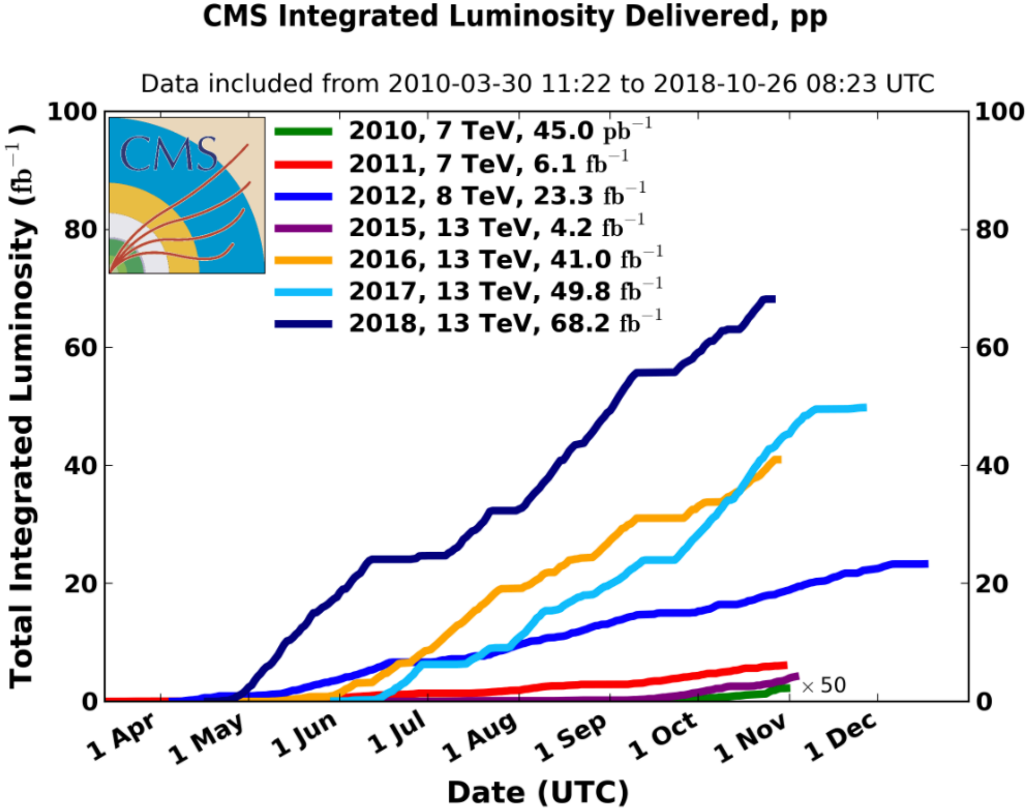
Number of proton in the beams

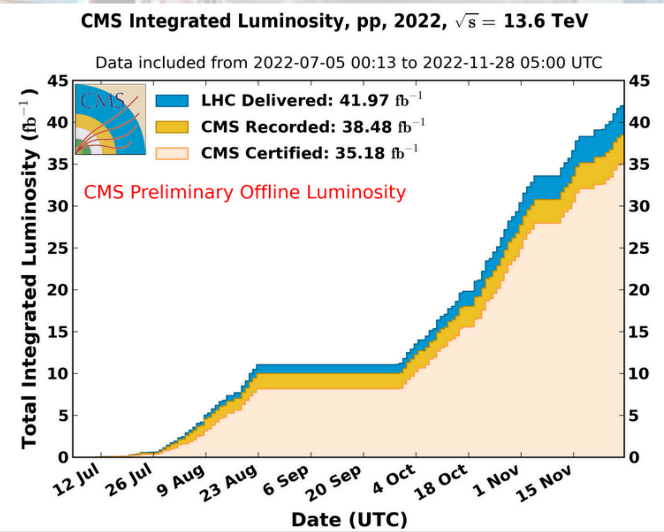
Collision frequency

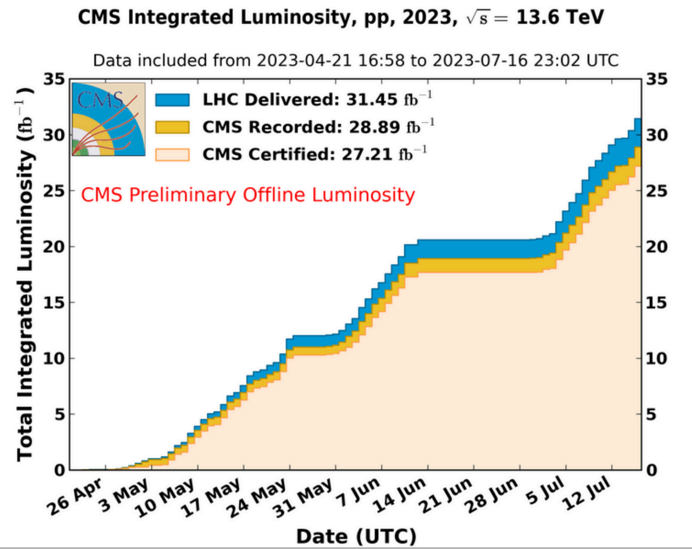
Collision surface

bb	10^5 events/sec
tt	0.8
W→ev	15
Z→ee	1.5
H	0.001

From $E_{cm} = 7$ to 13.6 TeV







At 7 TeV L= 5 fb^{-1}

At 8 TeV L=20 fb^{-1}

at 13 TeV L=138 fb^{-1}

at 13.6 TeV L= 70 fb^{-1}

QCD and Electroweak physics at LHC

QCD: In general combination of non-perturbative techniques, to describe the parton (quarks and gluons) distribution functions (PDFs) of the proton and the parton shower and hadronization process of scattered partons, and perturbative techniques to describe large momentum transfer parton scattering has been remarkably successful at describing QCD interactions at colliders and, with increasing sophistication, has reached a percent level accuracy at the LHC.

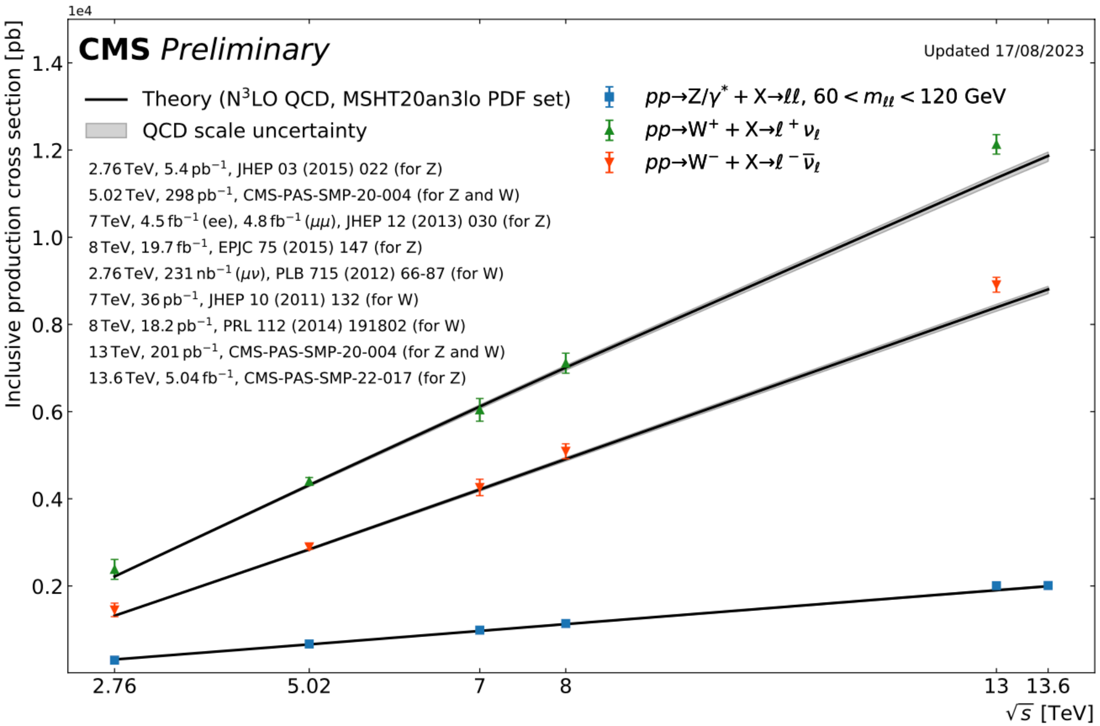
EW: EW physics tests the fundamental predictions of the SM. This includes the interactions predicted by the gauge structure of the SM and the nature of EW symmetry breaking via the Higgs mechanism, which leads to masses for the vector bosons.

EW bosons are copiously produced in LHC collisions and can be measured with high precision and low background by the CMS detector →
EW sector measurements test the limits of our ability to model SM interactions.

Vector Bosons: Z and W

Measurements of single boson production are among the most precise:

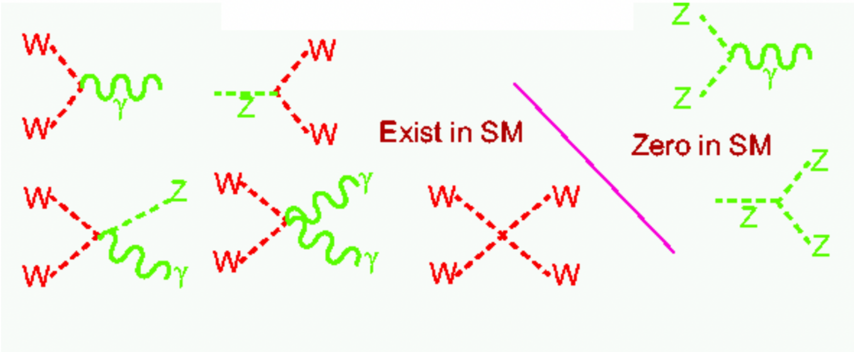
- constitute an essential test of SM physics
- allow to extract parton-parton cross sections using perturbative techniques.



2% precision
systematics limited (Lumi etc)

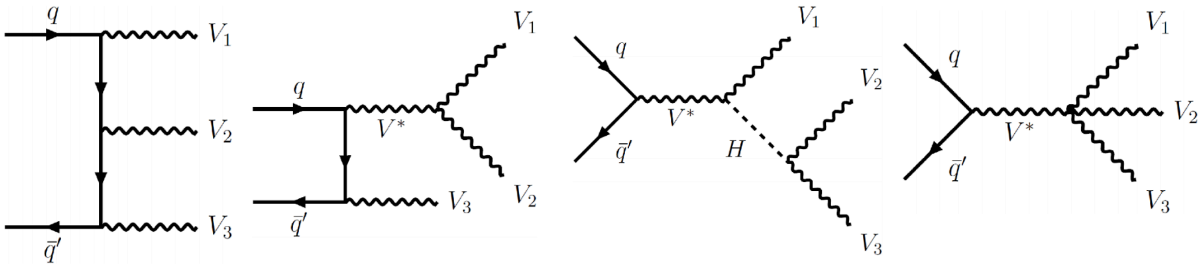
VV & VVV: Why multiboson ?

Validation of perturbative calculations



VV : Test of the non-abelian structure of Electroweak Theory
→ TGC and QGC

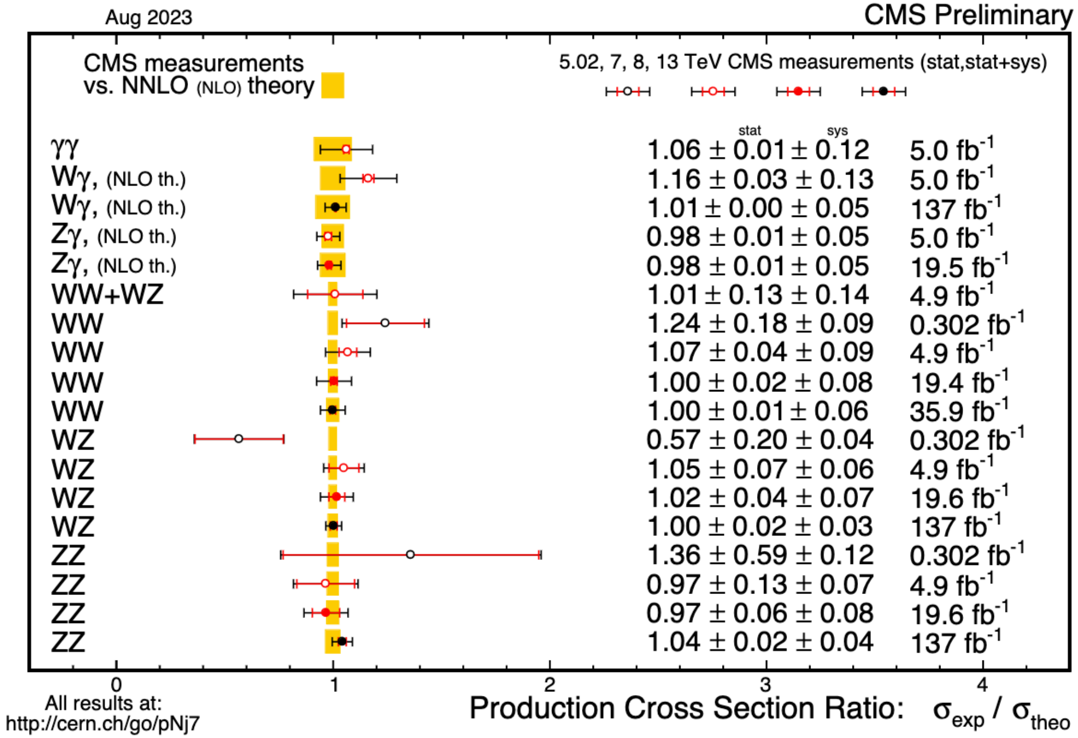
VVV:
- Direct measurement of gauge boson self-coupling and precision test of SM

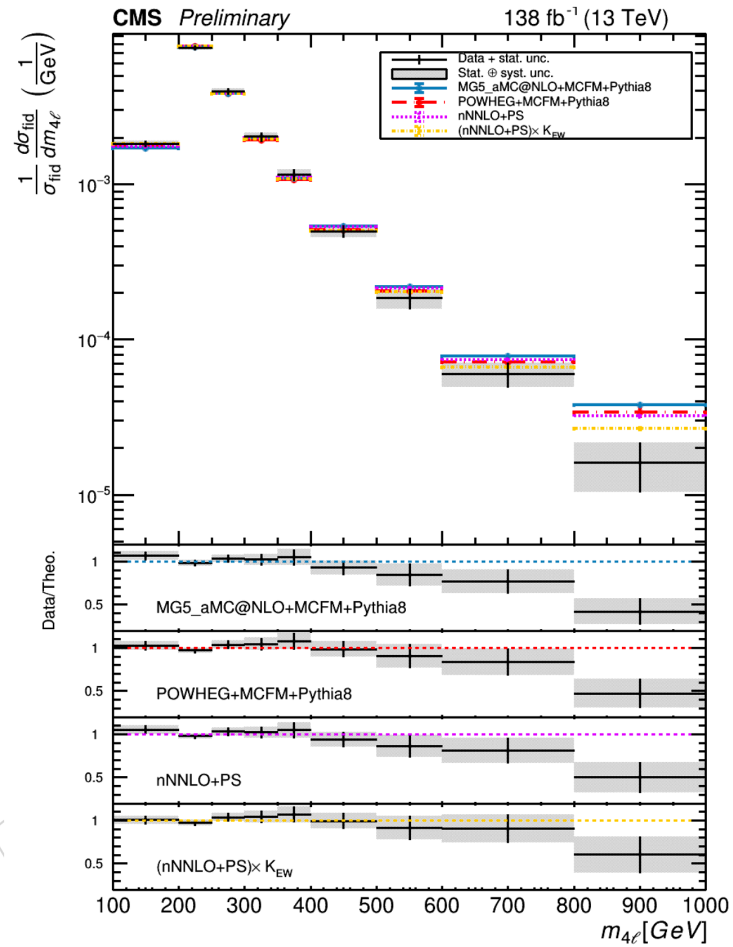


- Finely balanced cancellations between QGC, TGC, Higgs amplitudes is needed to preserve unitarity at high CM energies.
- Any anomalous HVV, QGC and TGC coupling can disturb the balance and create large cross-sections at high energies.

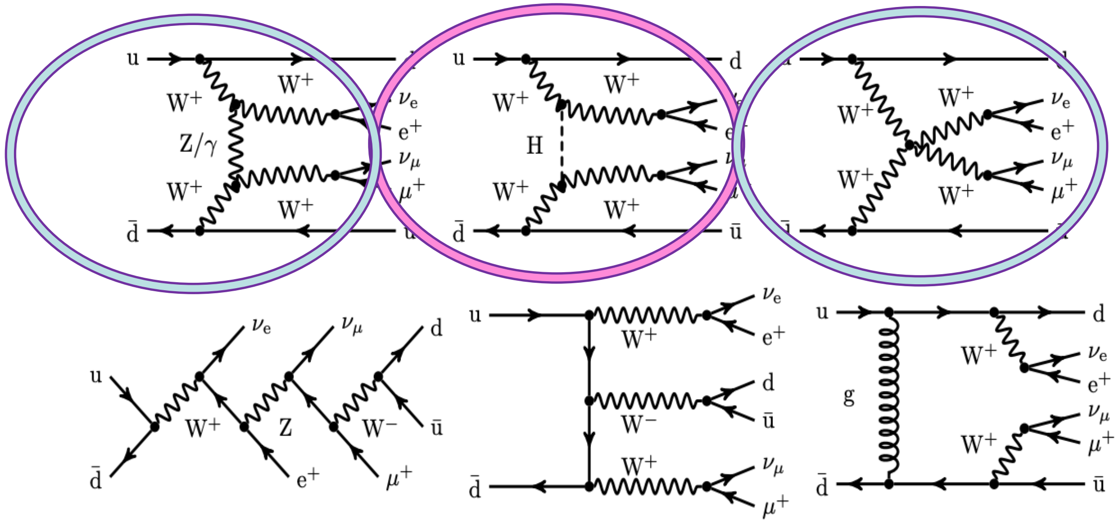
VV & VVV

Despite having the lowest available statistics of any di-boson production process the cross section for ZZ production is the second most accurately measured, thanks to the very low background.





Vector Boson scattering and V polarisation

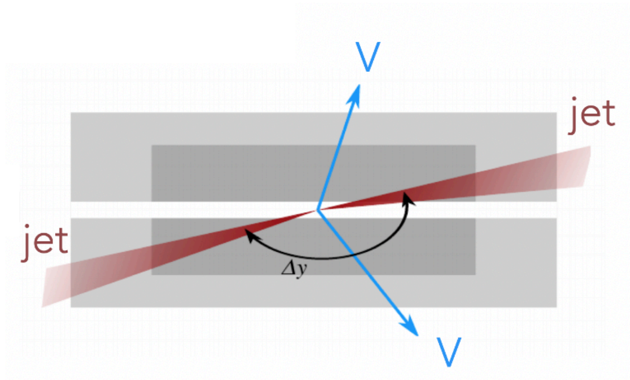


The Higgs mechanism explains how the elementary particles get mass. The W and Z acquire the longitudinal degree of freedom (W_L, Z_L).

→

Without the Higgs, $V_L V_L \rightarrow V_L V_L$ would break perturbative unitarity (for $\sqrt{s}$>~1.2 TeV).

Experimentally quite clean: two jets F&B and the 2 V in the barrel region.



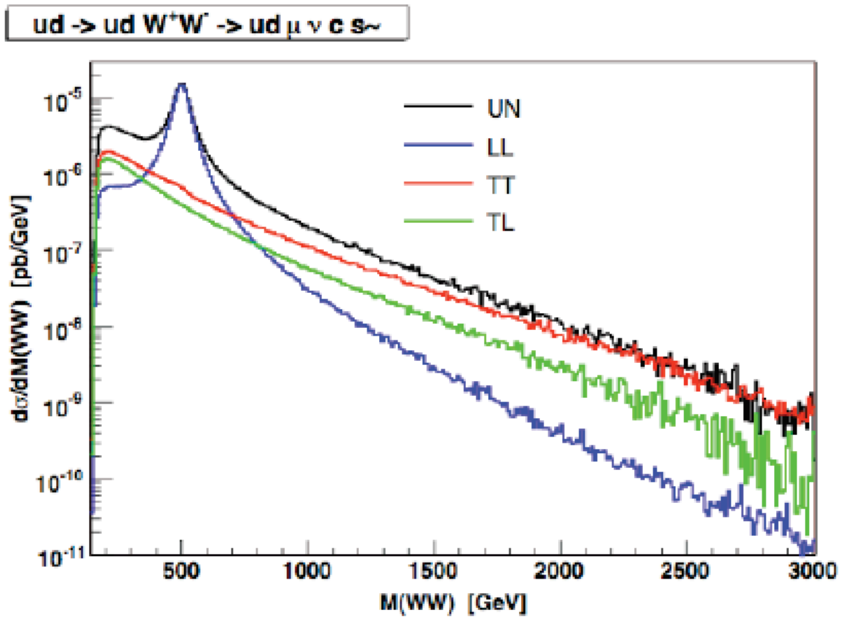
Theoretically not easy to compute: all the diagrams (6 fermions final state) must be computed all together, since the "VBS" alone are not gauge invariant and the interference with the other diagrams is huge and negative.

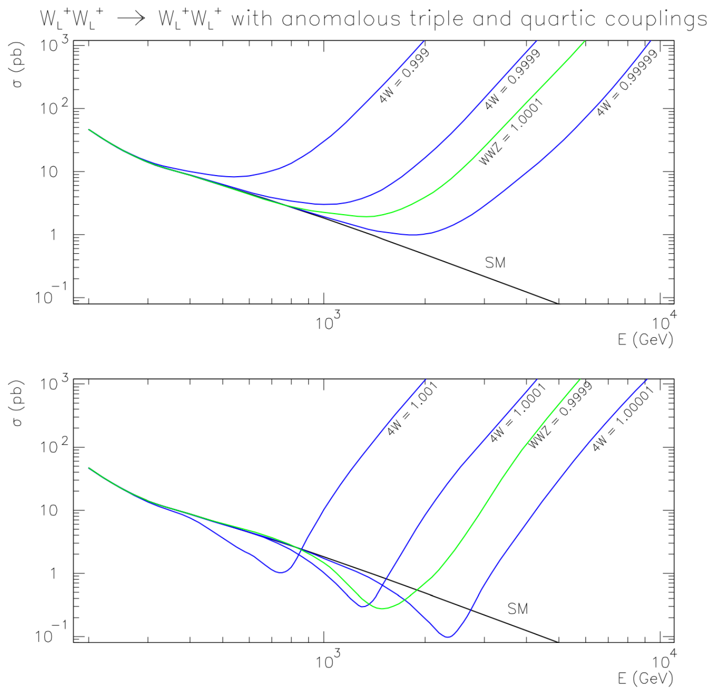
→ very small cross section for the EW process.

Vector Boson scattering and V polarisation

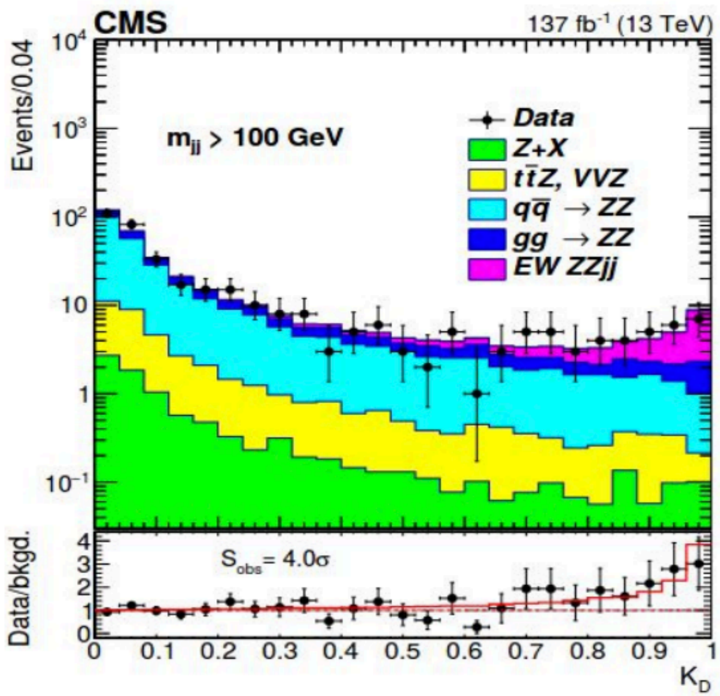
An essential test of the electroweak interactions and the nature of the massive electroweak W and Z bosons is a measurement of their polarization:

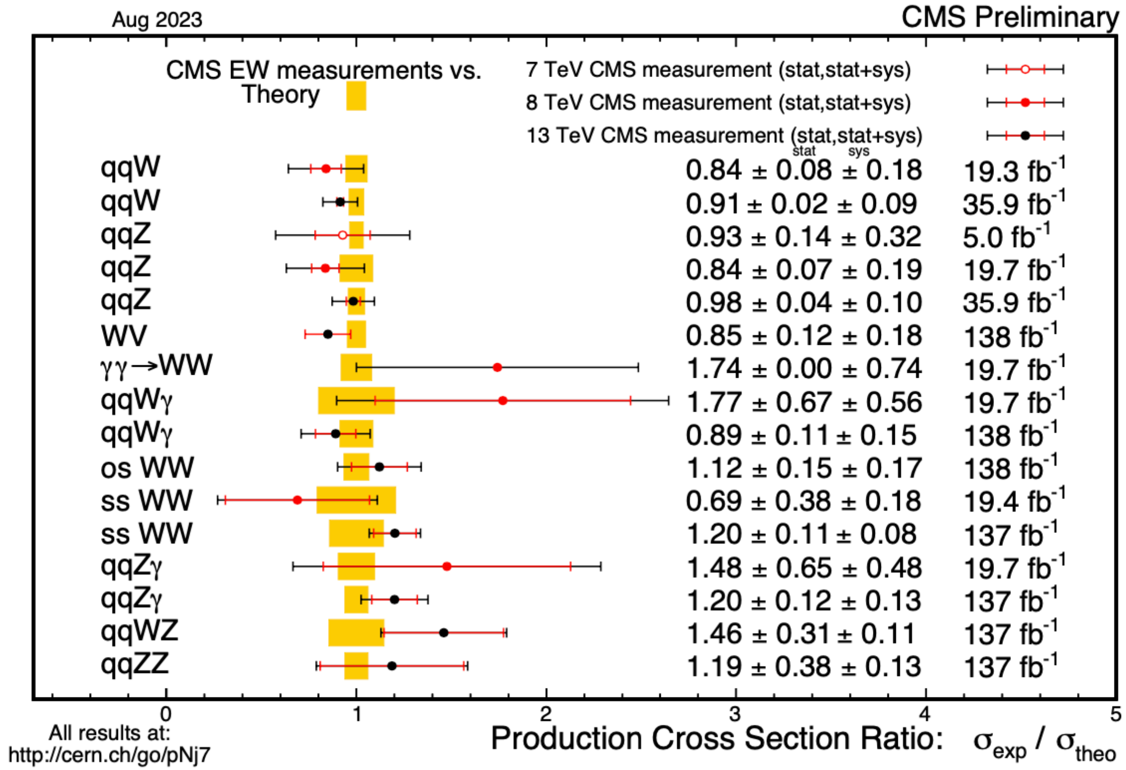
- Via the Higgs mechanism the W and Z acquire the longitudinal degree of freedom (W_L, Z_L).
- Without the Higgs, $V_L V_L \rightarrow V_L V_L$ would break perturbative unitarity (for $\sqrt{s}$>~1.2 TeV).





Vector Boson Scattering



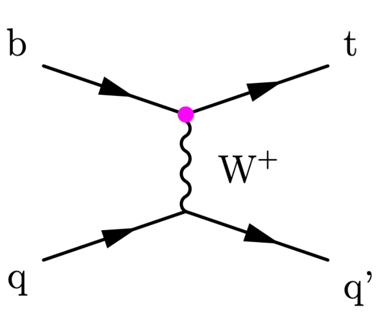


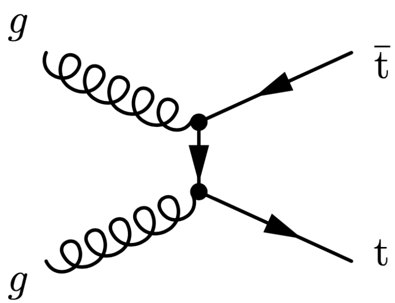
The observation of the scattering of longitudinal vector bosons would be a clear sign of the presence of the Higgs scattering interaction as a component of vector boson scattering and is considered one of the essential tests of the EWSB mechanism. A preliminary measurement has been made of longitudinal vector boson scattering in this mode using 13 TeV collision date finding a 2.3σ signal consistent with the SM expectation

Top mass

The mass of the top quark has strong significance in the context of vacuum stability and cosmological studies, as well as in BSM.

The top quark has an extremely short lifetime of about 0.5×10^{-24} s, causing it to decay before it undergoes hadronisation ($\sim 10^{-23}$ s) making it the only quark whose physical properties can be studied as if it were ”bare”, which, in turn, makes it a unique probe for constraining several extensions of the SM.





Dominant single-t and ttbar processes.

t→ Wb ; W→jj, lv

Many final states with many jets (b-tagged) and high-pt leptons

The top mass

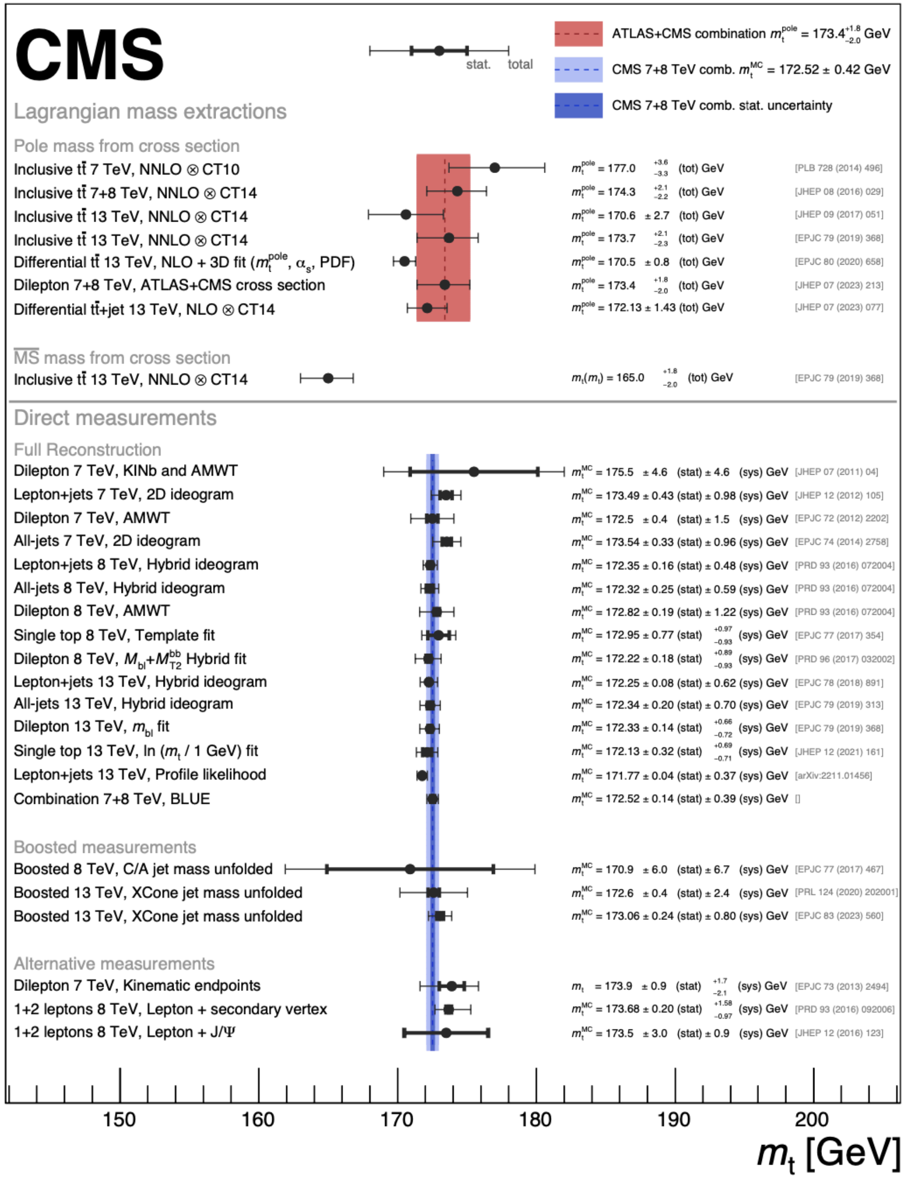
m_t =172.52±0.14(stat)± 0.30 (syst) GeV

ATLAS+CMS - 7+8 TeV

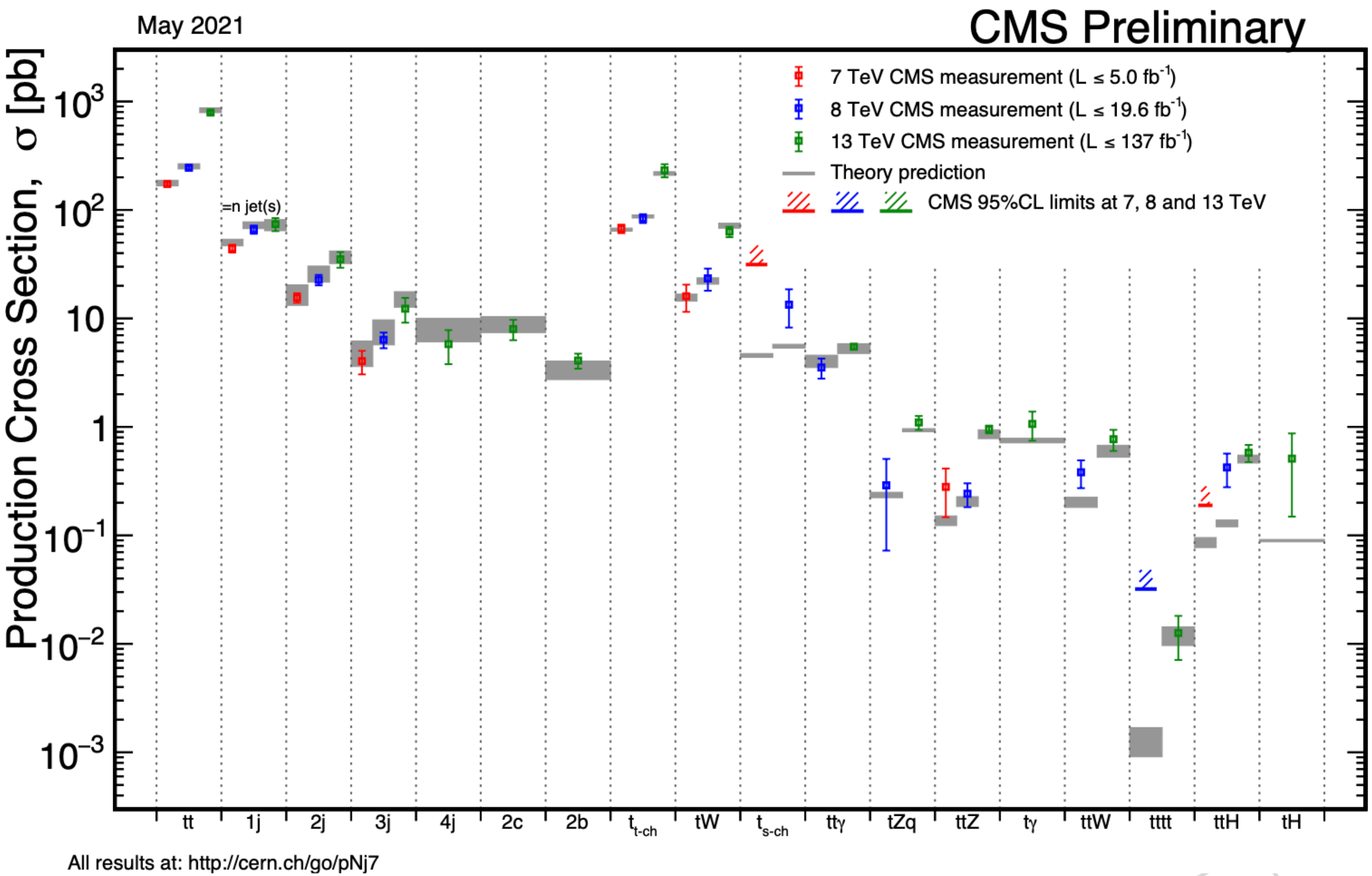
m_t =171.77±0.03(stat)± 0.37 (syst) GeV

best CMS single measurement - 13 TeV

Previous world average: m_T = 172.47 ±0.46 GeV (Tevatron+LHC)



The top quark steps in the stairway



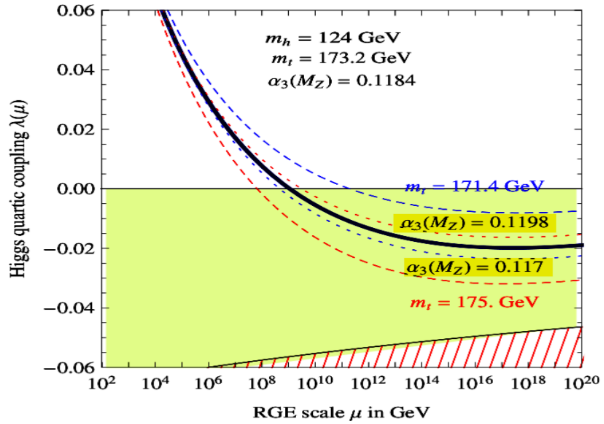
Alpha_strong

- Determines strength of the strong interaction between quarks & gluons.
- Single free parameter of QCD in the $m_q = 0$ limit.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \approx \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \approx 0.2$ GeV
- Least precisely known of all interaction couplings:

$$\delta\alpha \sim 10^{-10} \ll \delta G_F \ll 10^{-7} \ll \delta\alpha_s \sim 10^{-3}$$

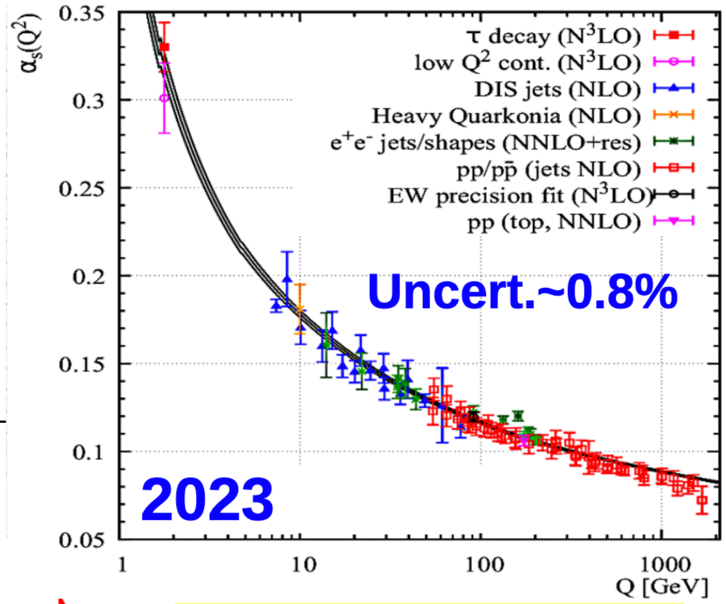
α_s impact beyond QCD

- Precision calculations of Higgs hadronic x-sections/decays, top mass, EWPO
- Impact physics approaching Planck scale: EW vacuumstability



CMS:
tt 0.1145 ± 0.0033 (±2.9%)
W,Z 0.1180 ± 0.0016 (±1.3%)
Jets 0.1166 ± 0.0017 (±1.5%)

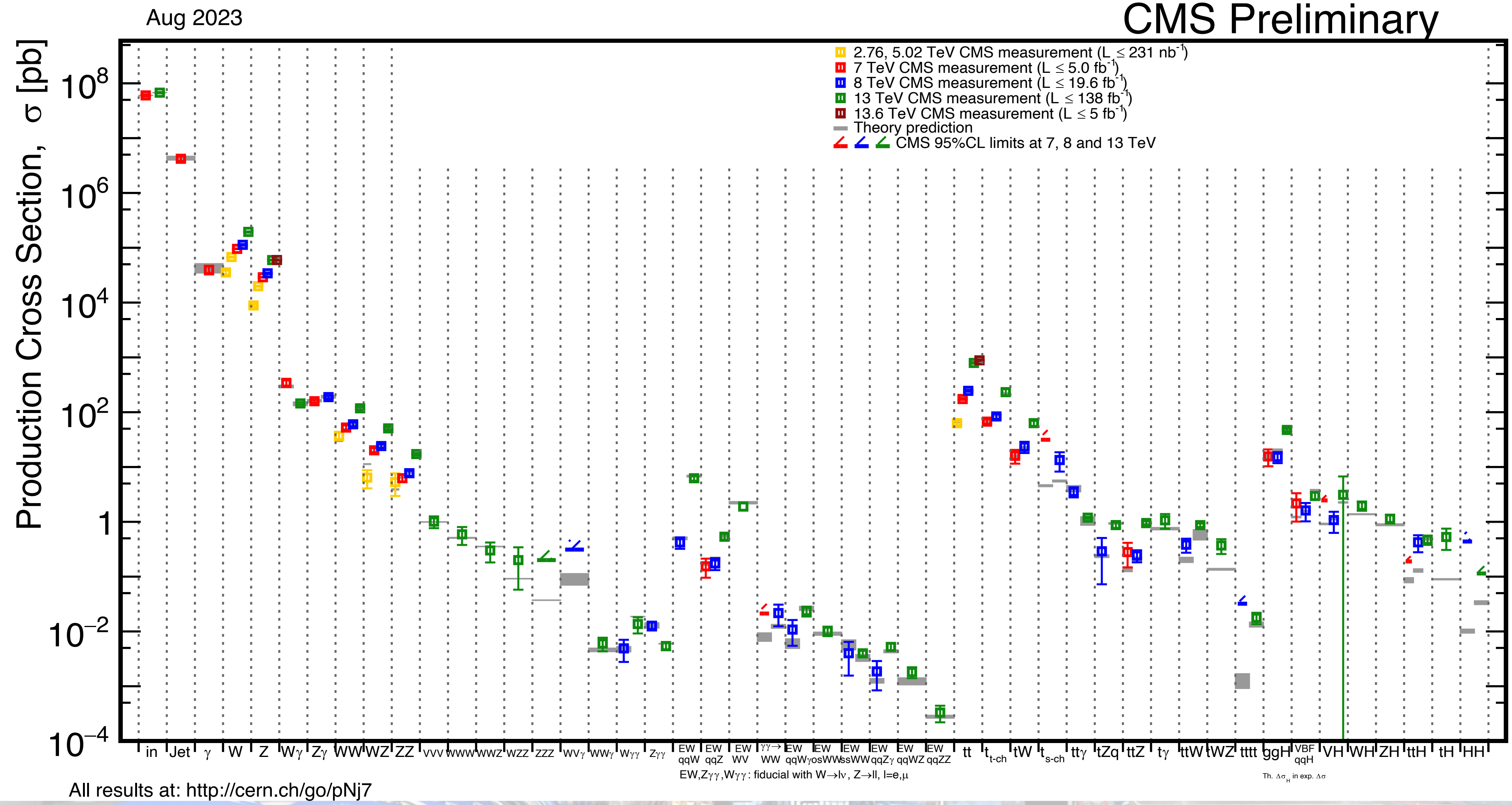
ATLAS
Z p_T 0.11828 ± 0.00088 (±0.75%)



$\alpha_s(M_Z^2) = 0.1179 \pm 0.0009$

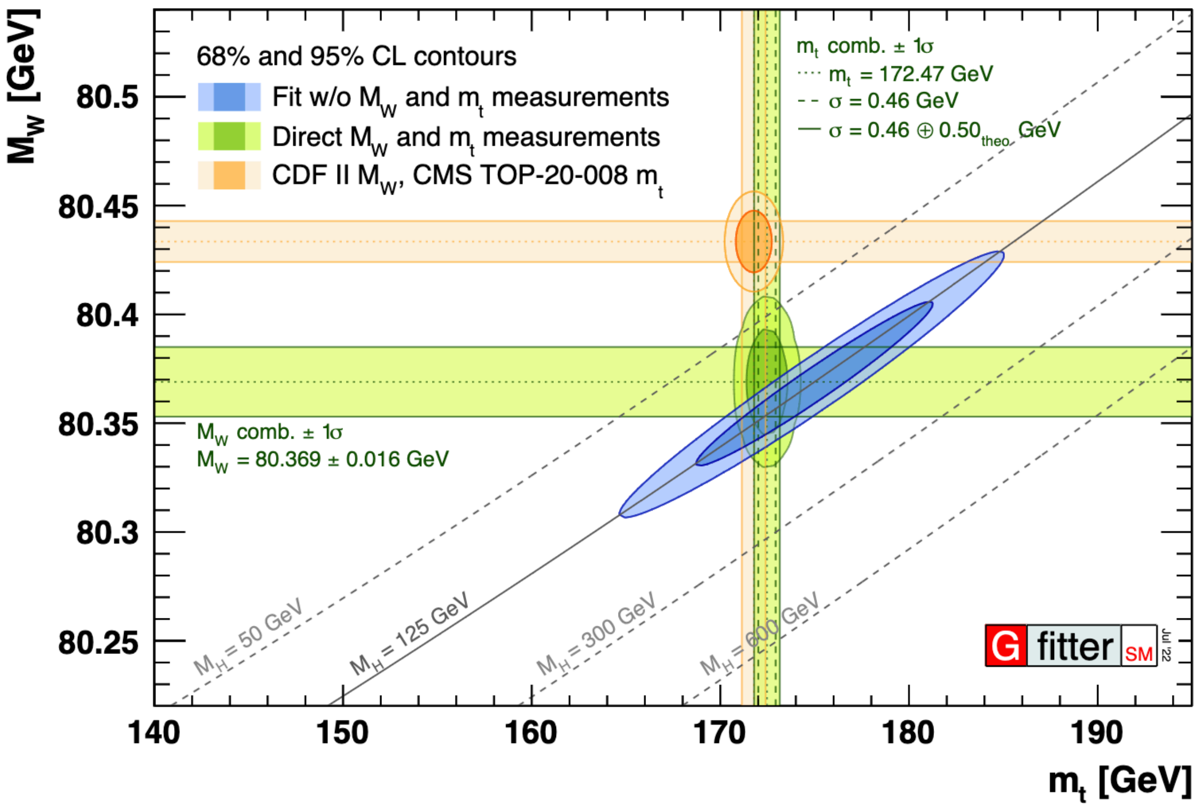
Stairway to heaven

12 orders of magnitude



EW fit

ATLAS latest
$m_W = 80360 \pm 5$ (stat.) $\pm$ 15 (syst.)
$= 80360 \pm 16$ MeV



The full set of electroweak data from LEP , the Tevatron and the LHC, including Higgs data, can be used to test the self consistency of the theory.

The most restrictive data points are the measurements of the Zbb coupling and the W boson mass.

When the experimental values of M_W , m_t, and M_H are omitted, the fit is in good agreement with the directly measured values of the masses.

Higgs physics
few more results

A second big break-through in 2013-2014

$\Gamma_H(SM) = 4$ MeV

Detector resolution ~ GeV

- Following the work of

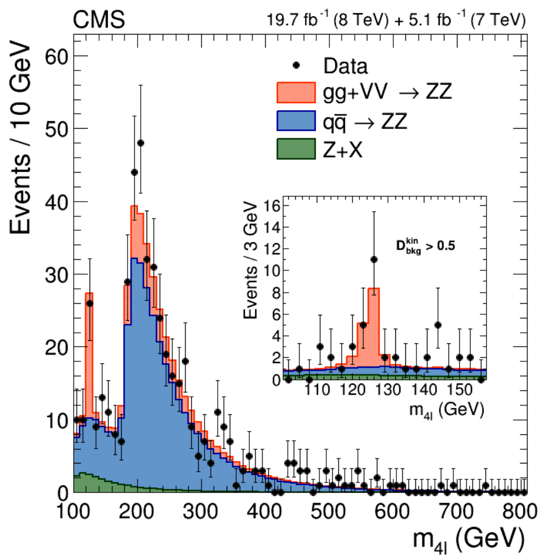
Kauer, Passarino: JHEP 1208 (2012) 116

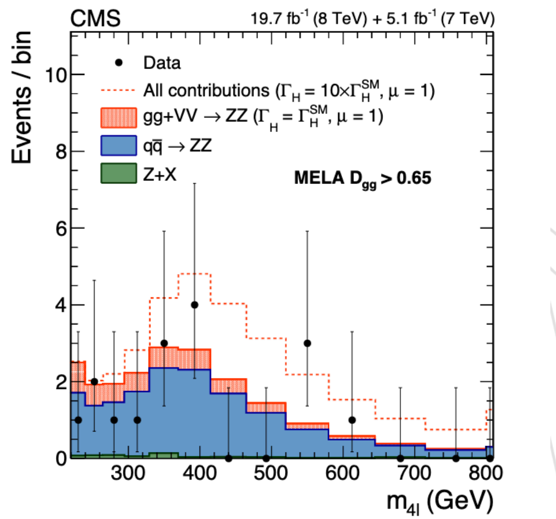
Caola, Melnikov: Phys. Rev. D88 (2013) 054024

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

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

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





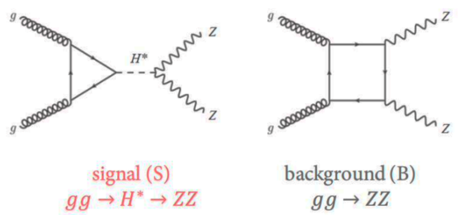
The Higgs width, Γ_H, can be constrained from off-shell production:

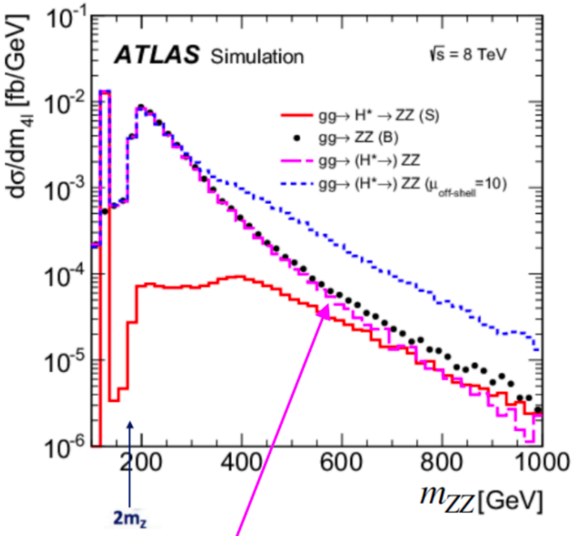
We can go from ***few GeV*** → ***tens of MeV*** using off-shell Higgs production

RUN1 : Γ_H < 13 MeV obs (26 MeV exp)

The Higgs width from off-shell production, 10 years after

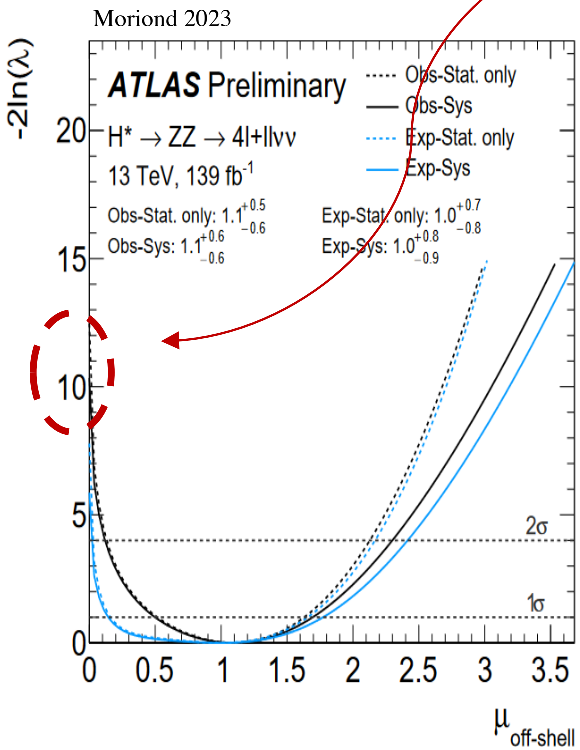
Both experiments observe Higgs off-shell production at > 3σ



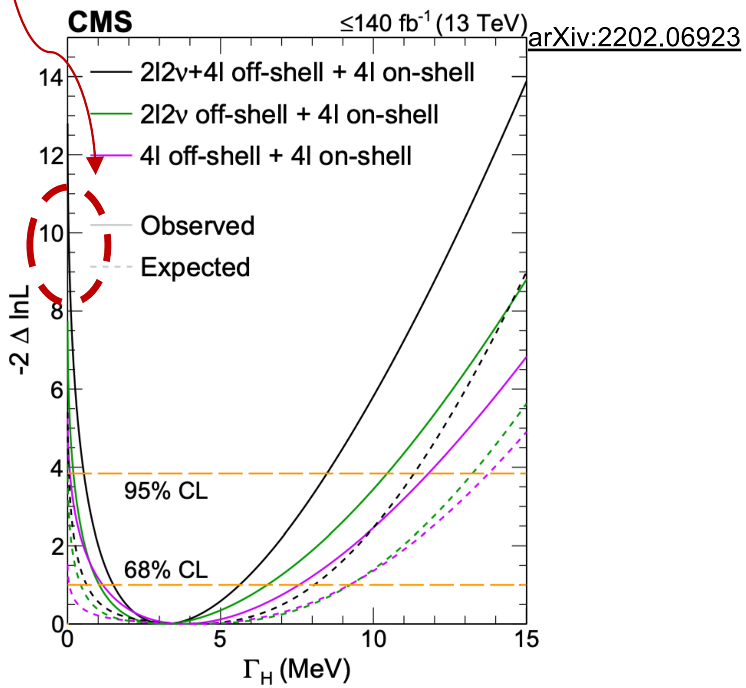


SBI = S + B + I

Known at NNnLO [Matrix]



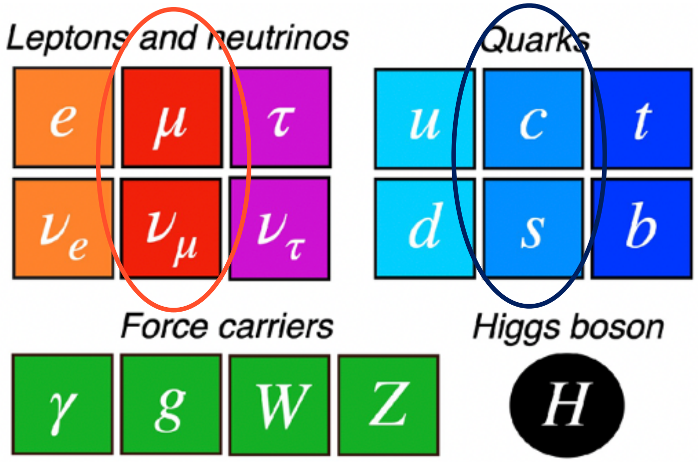
$\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV



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

with Run2 4l – CMS-HIG-21-019

The coupling with the 2nd generation



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

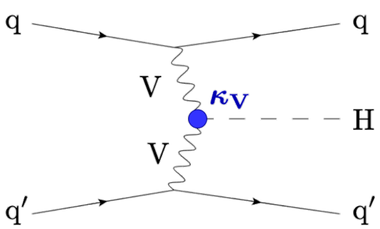
Ingenuity is giving us access at these *«exquisitely small signals »*

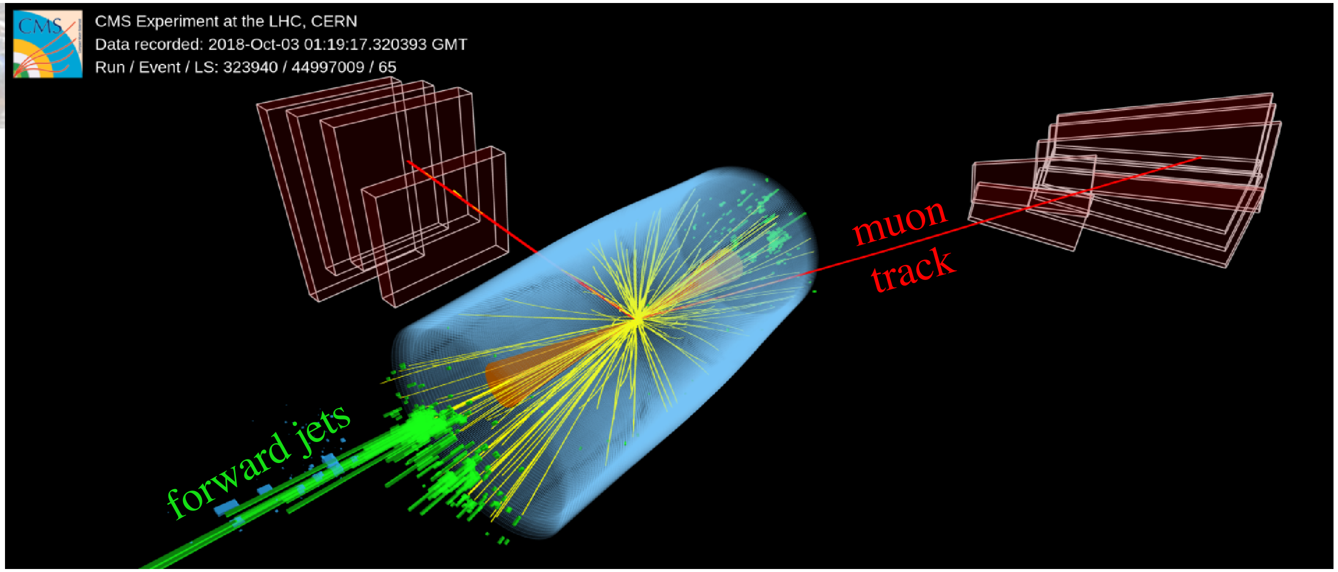
©Andre David

Higgs to muons

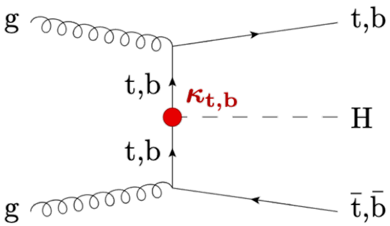
SM BR(H→ μμ) ~ 2.2 × 10^{-4}

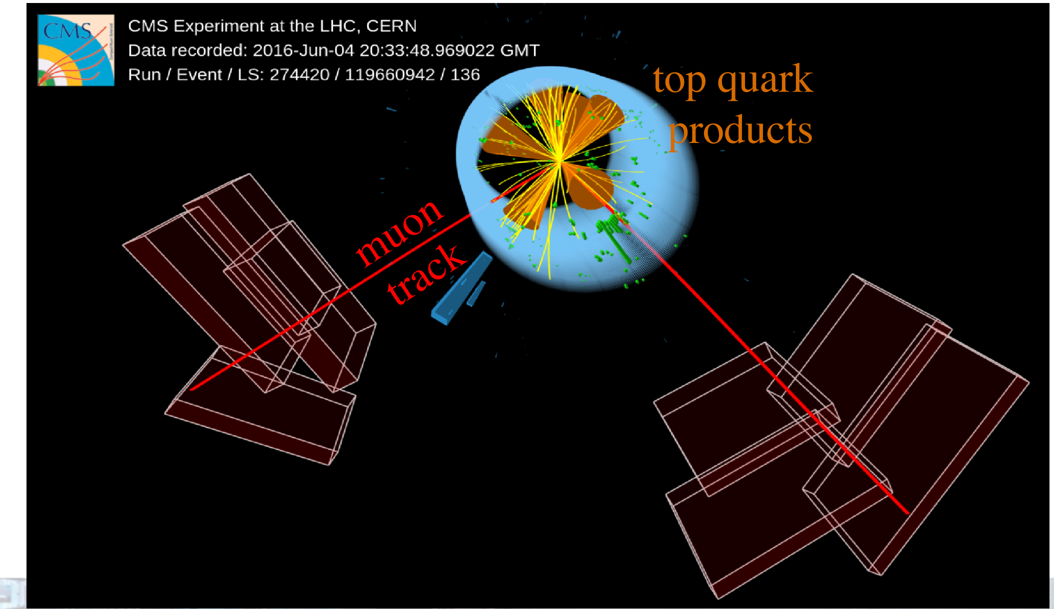
Exploit all production modes.





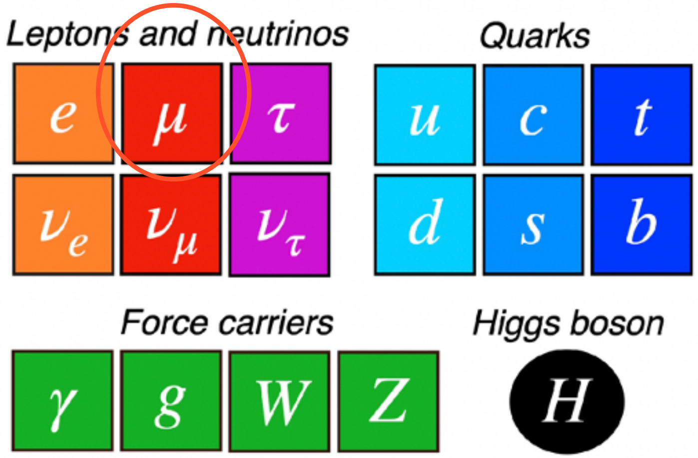
Candidate events compatible with different associated production modes and $H^0(125)\rightarrow\mu\mu$ decay.

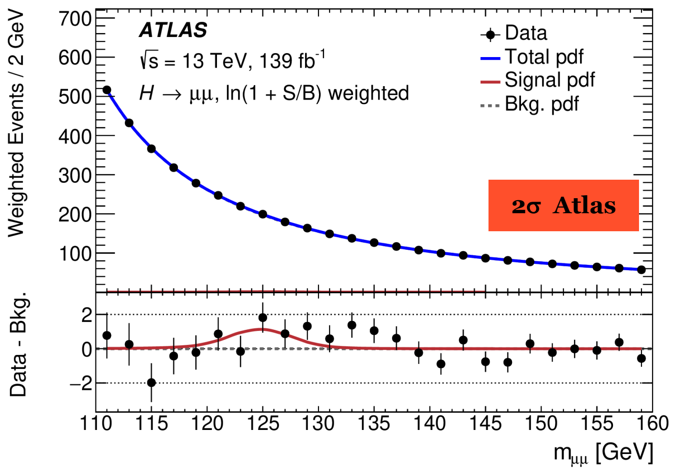


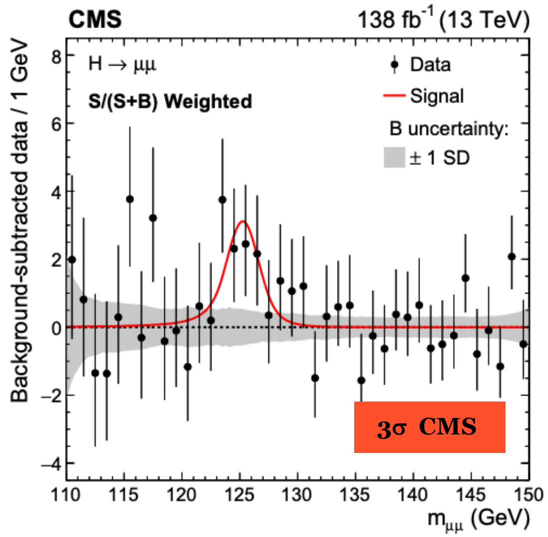


The coupling with the 2nd generation

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





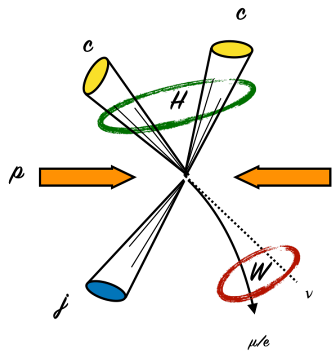


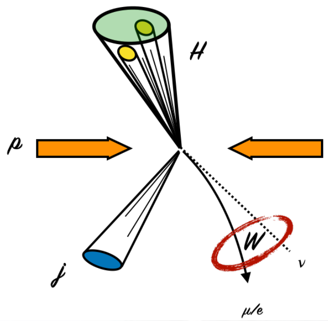
Higgs to charm

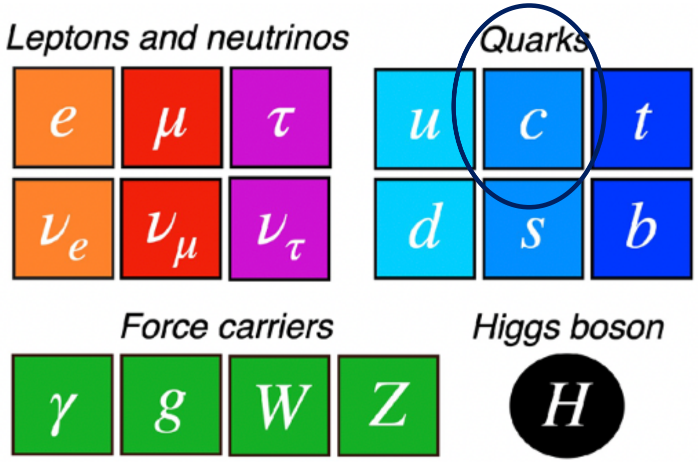
CMS: arxiv:2205.05550
ATLAS: arxiv:2201.11428

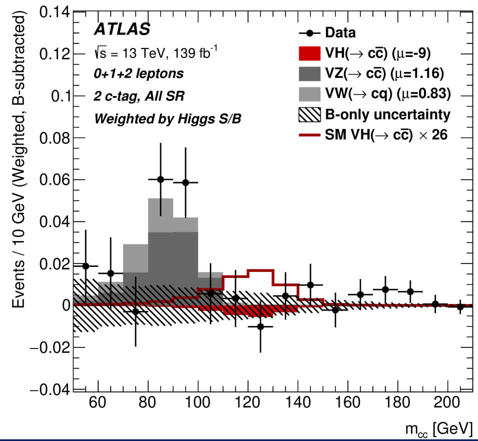
SM BR(H→cc) ~ 0.028

Search for H→cc
in VH events (and gg)

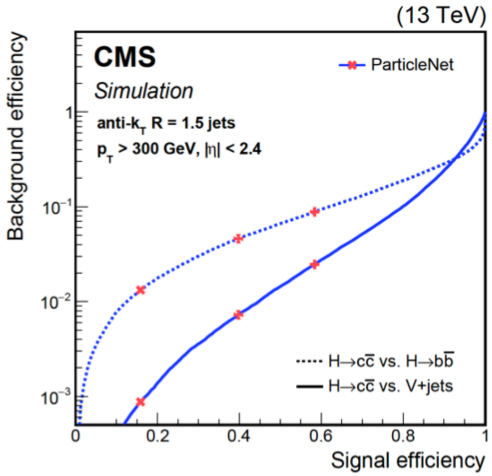


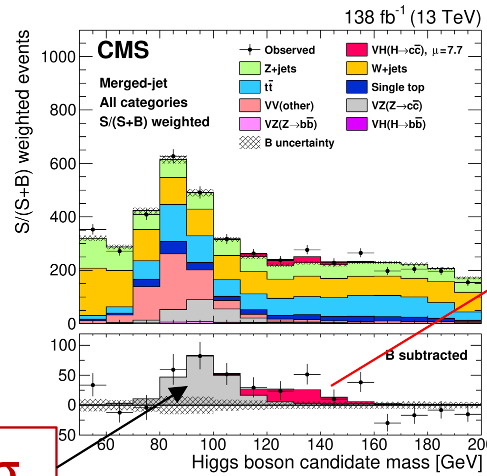


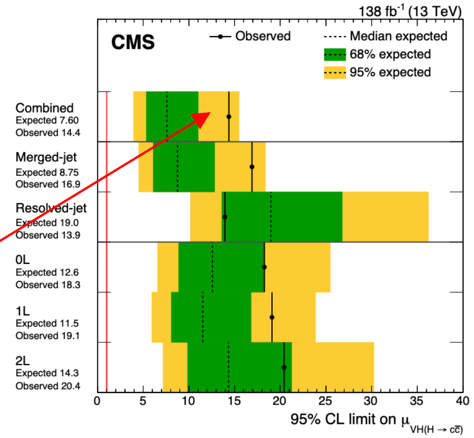




Sensitivity to **H→cc** ~ 8 × SM







Z→cc >> 5σ

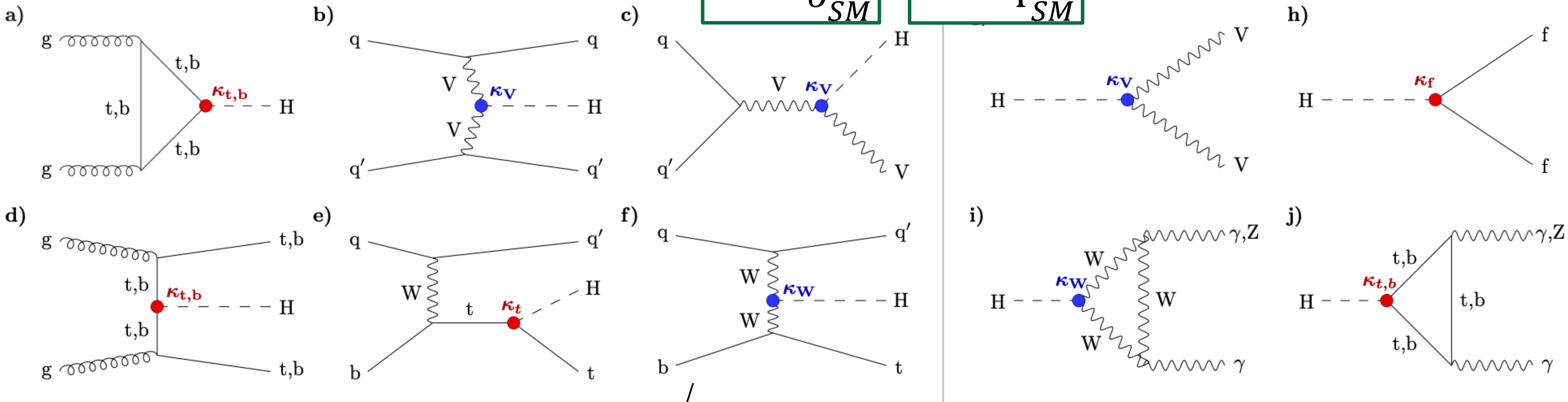
The couplings & the coupling modifiers: the κ framework.

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

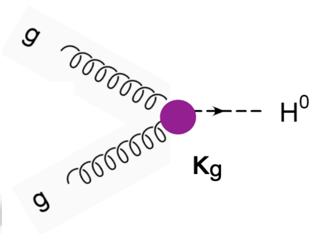
$$\kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{SM}}$$

Higgs boson production modes

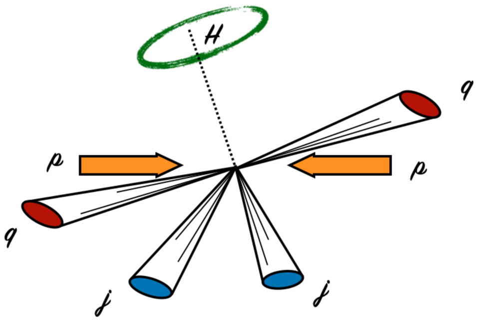
Higgs boson decay channels



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

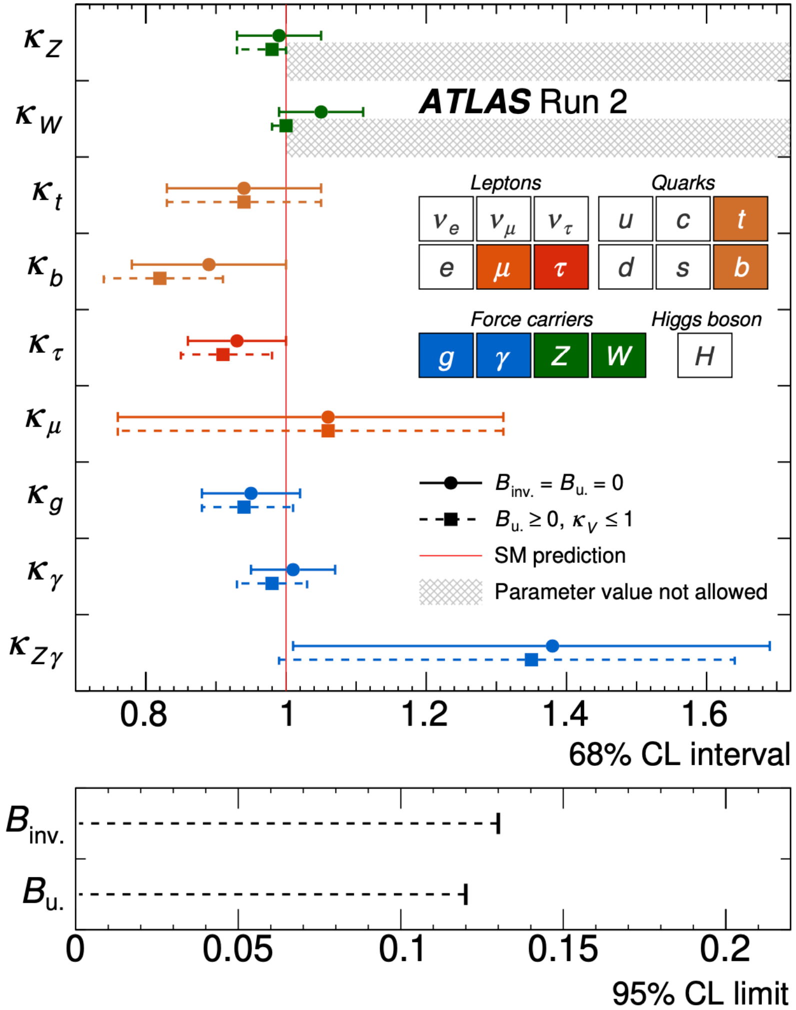


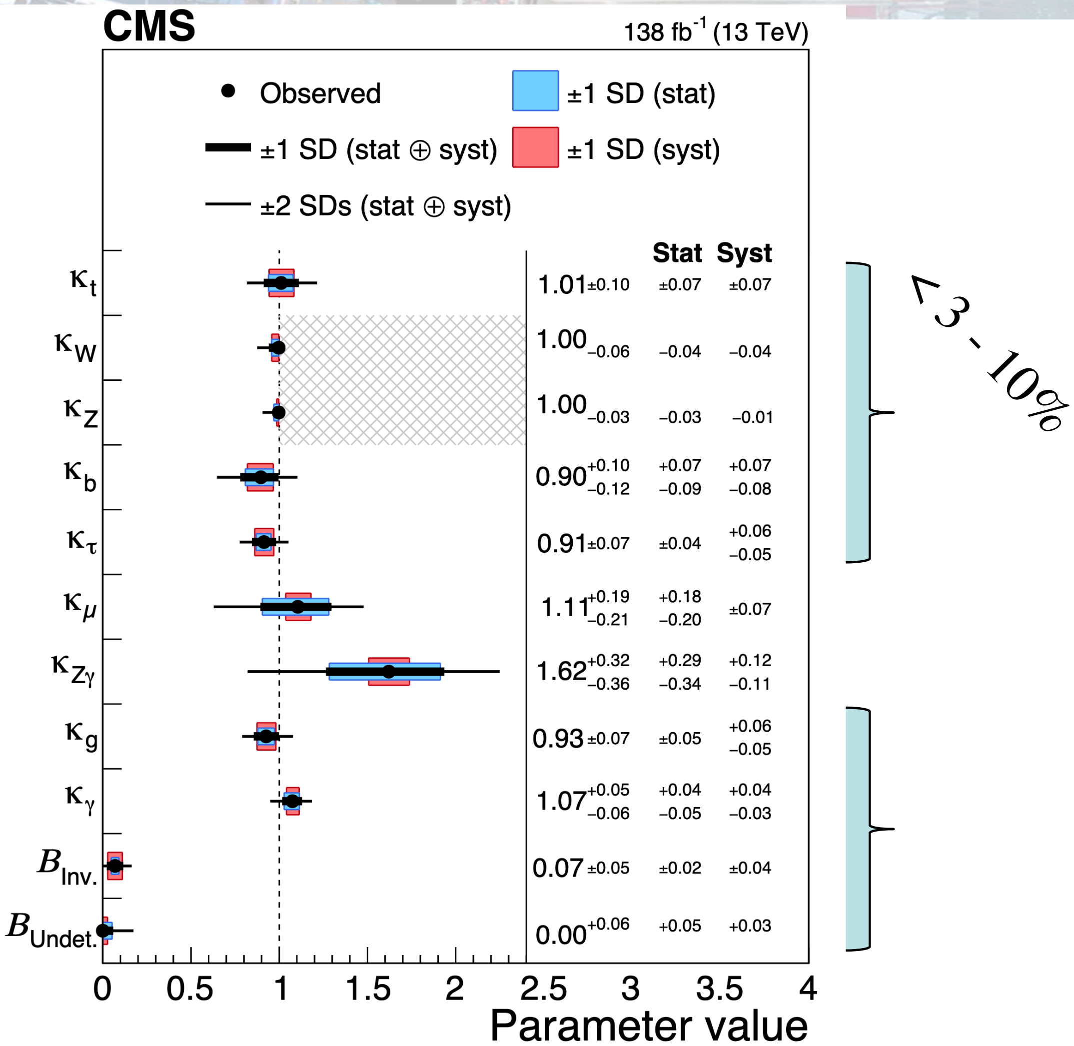
Invisible (ν, DM…) or Undetected decay



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

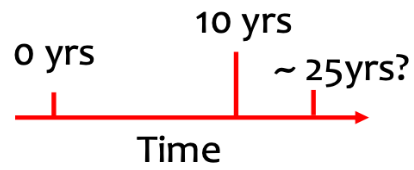
The κ framework

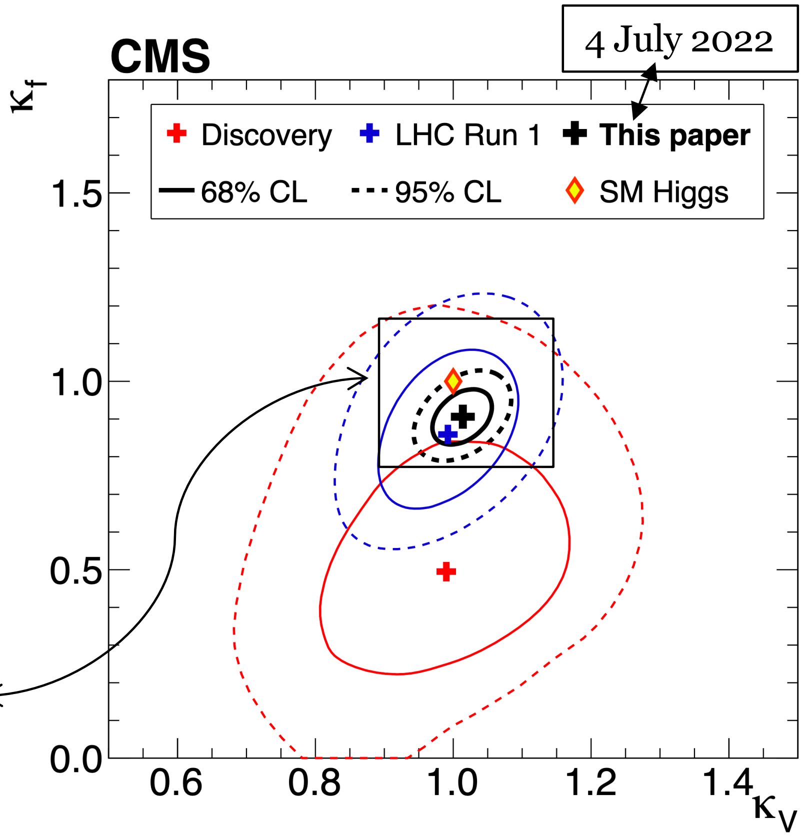


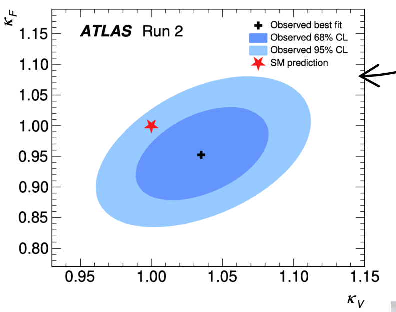


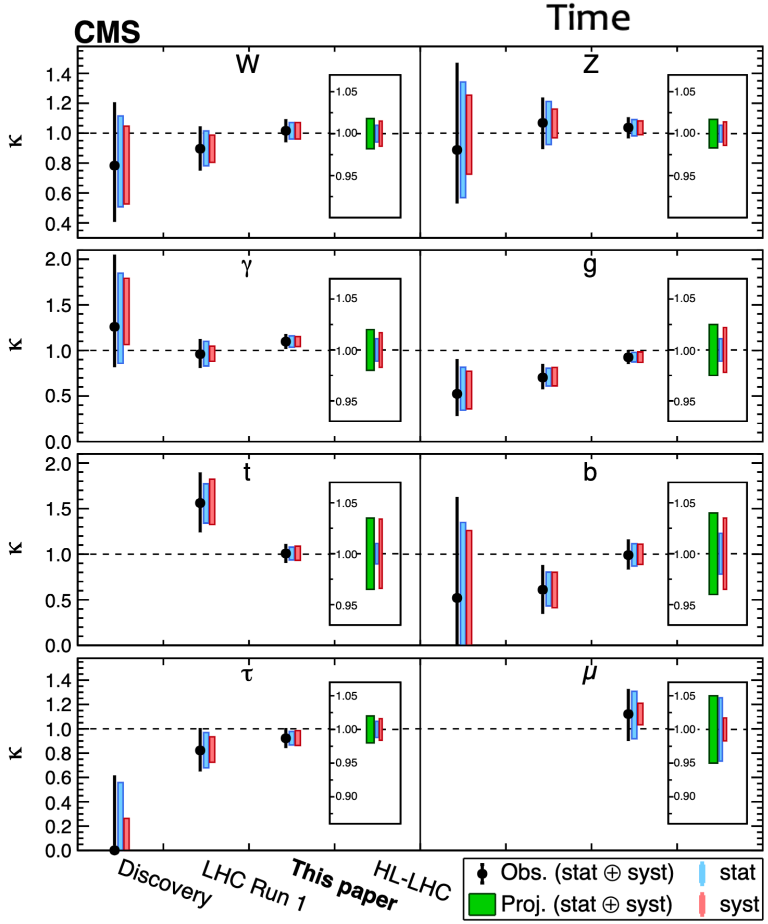
Luminosity, energy and …. ingenuity

~30 times more Higgs events in Run2







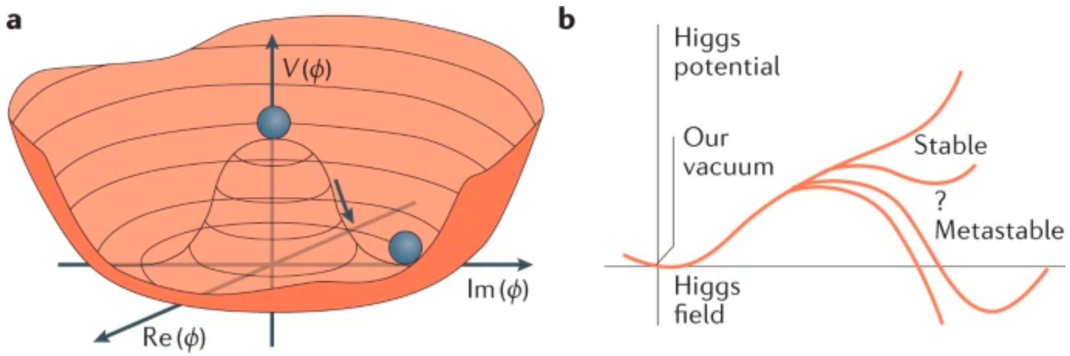


The search for Higgs boson pair production

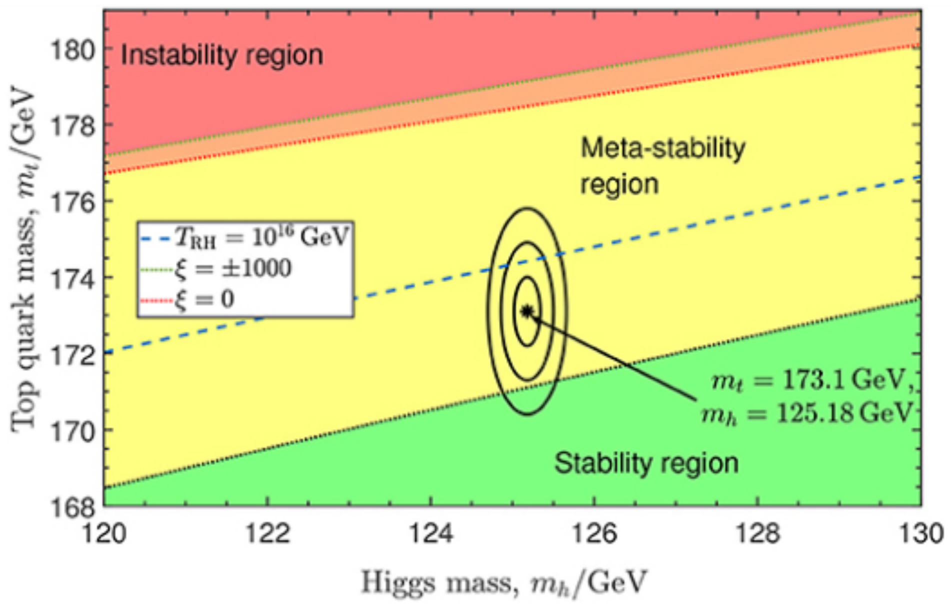
The Higgs potential $$V(\phi) = \frac{1}{2} m_{\mathrm{H}}^2 \phi^2 + \sqrt{\lambda/2}\, m_{\mathrm{H}} \phi^3 + \frac{1}{4} \lambda \phi^4$$

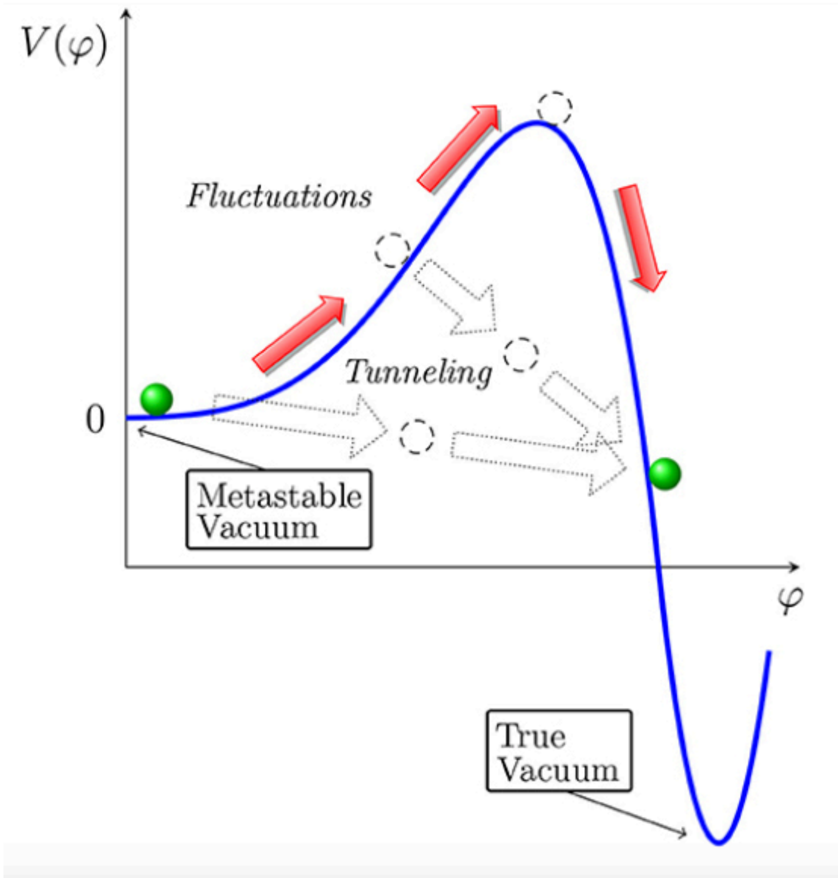
$$\lambda = m_{\mathrm{H}}^2 / (2v^2)$$

we measured the minimum, we should measure the curvature



The future of our universe





The search for Higgs boson pair production

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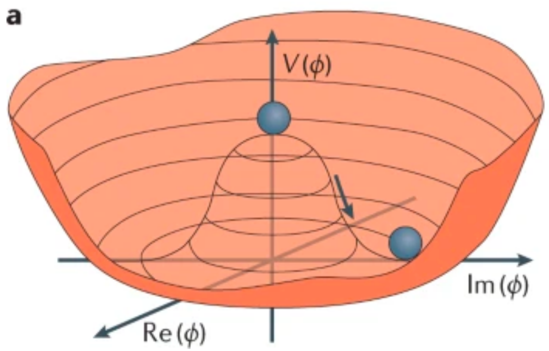
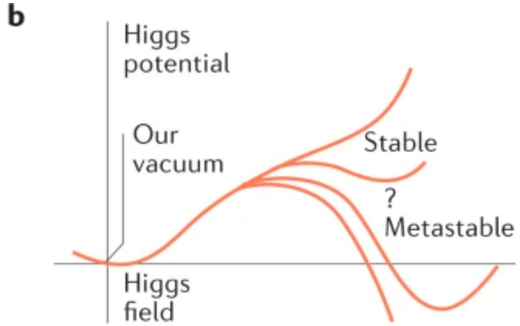
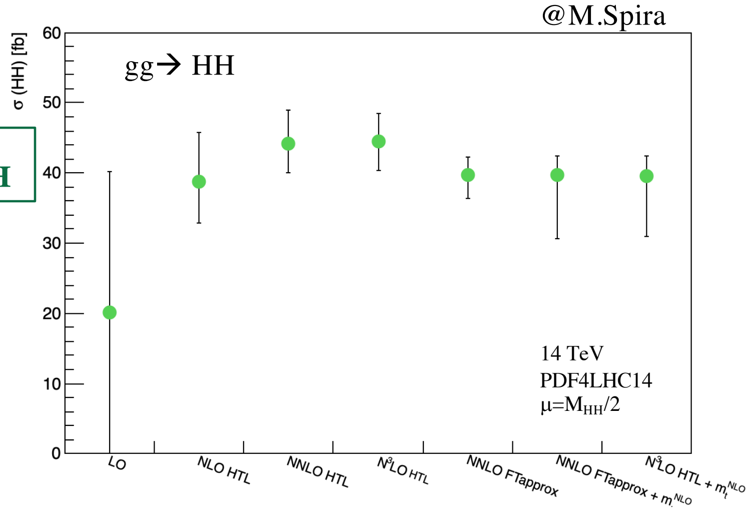
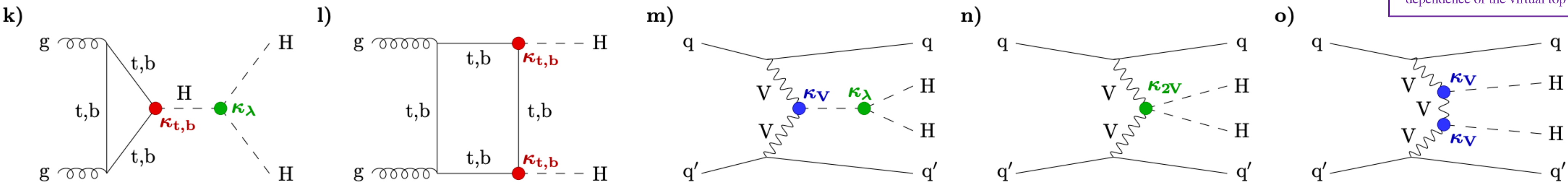




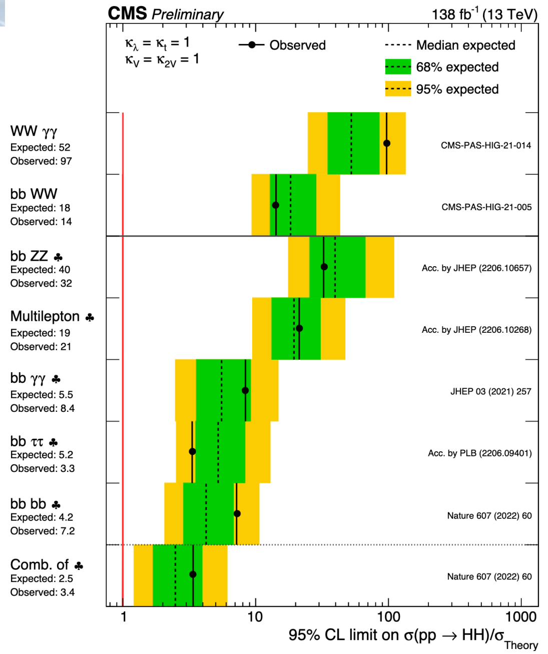
$\sigma_{HH} \sim 10^{-3}\,\sigma_{H}$

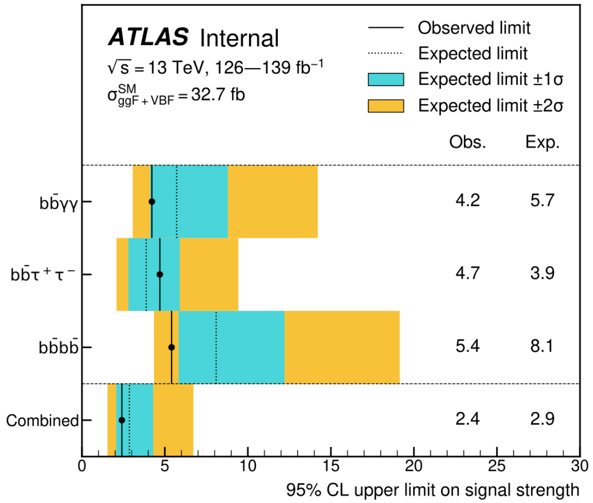


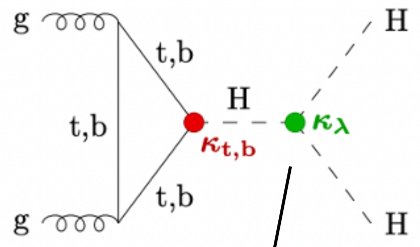
Higgs boson pair production

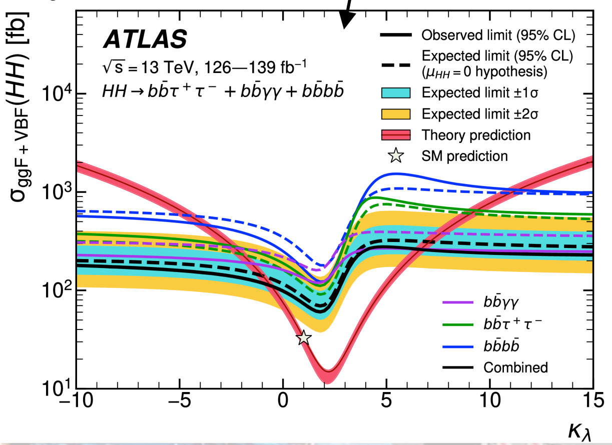


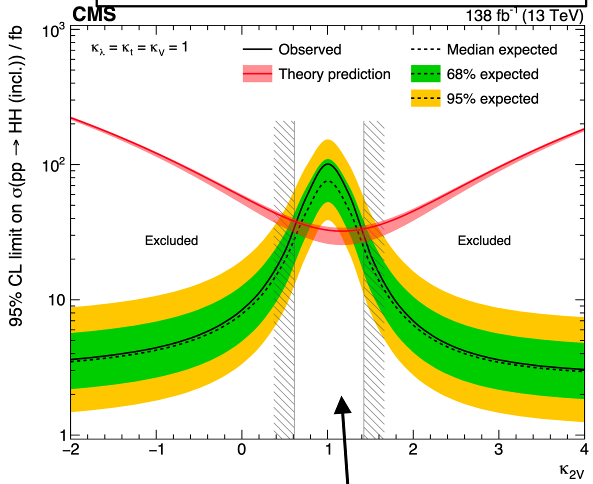
Results on HH production





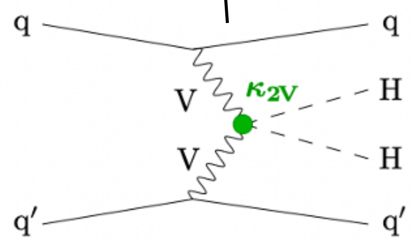




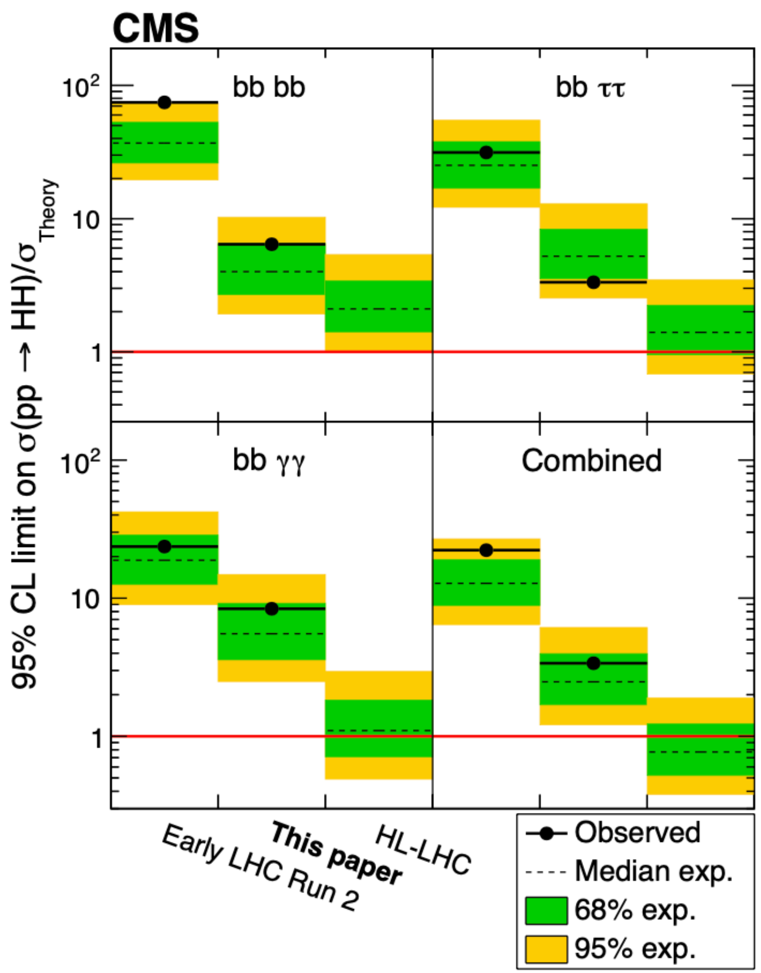


σ(HH) < 2. ÷ 3. SM

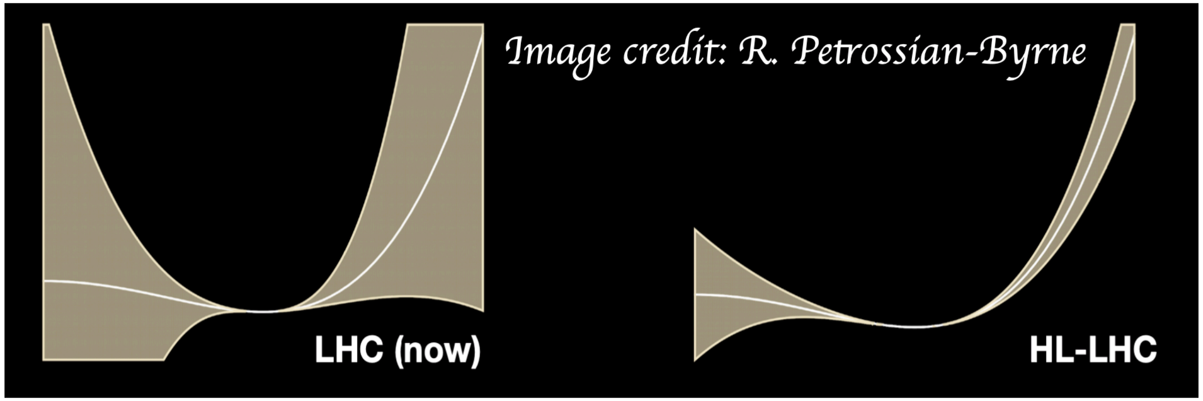
VVHH indeed exists



At the end HL-LHC



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



As of today

We have discovered the Higgs boson: 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.

We did not find up to now new physics, nor new particles.

The data agree well with the SM.

We will keep searching,

and doing precision measurements → they are our **stairway to heaven**

we have effectively entered an era of particle physics that is marked by its return to a measurement-driven character

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

*"Ooh, it makes me wonder
Ooh, really makes me wonder"*