The beauty of the Higgs boson

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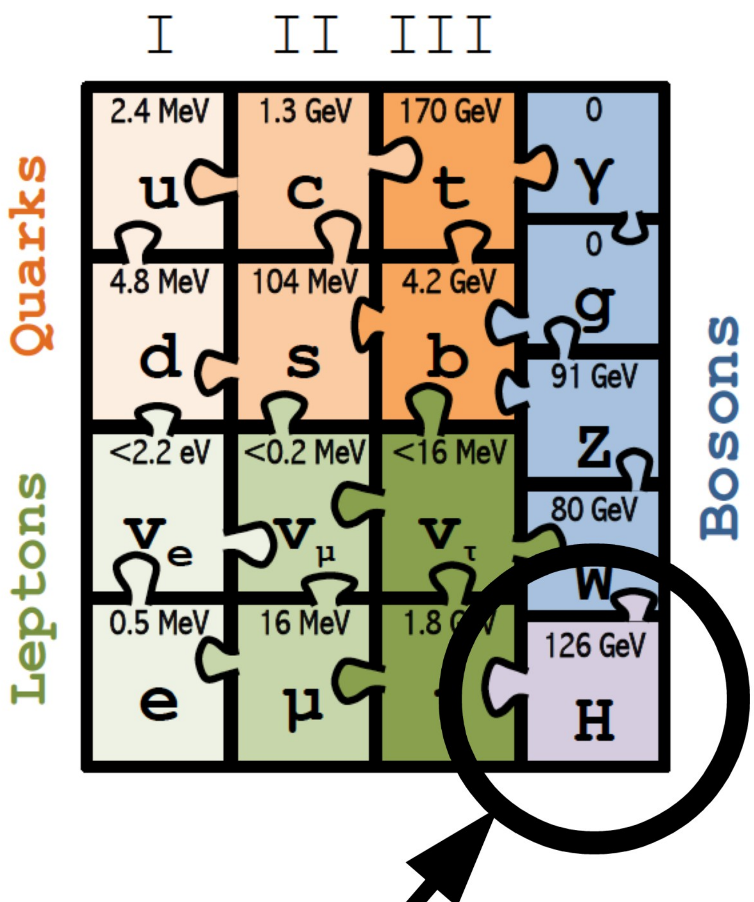
A biased personal view and selection of public results

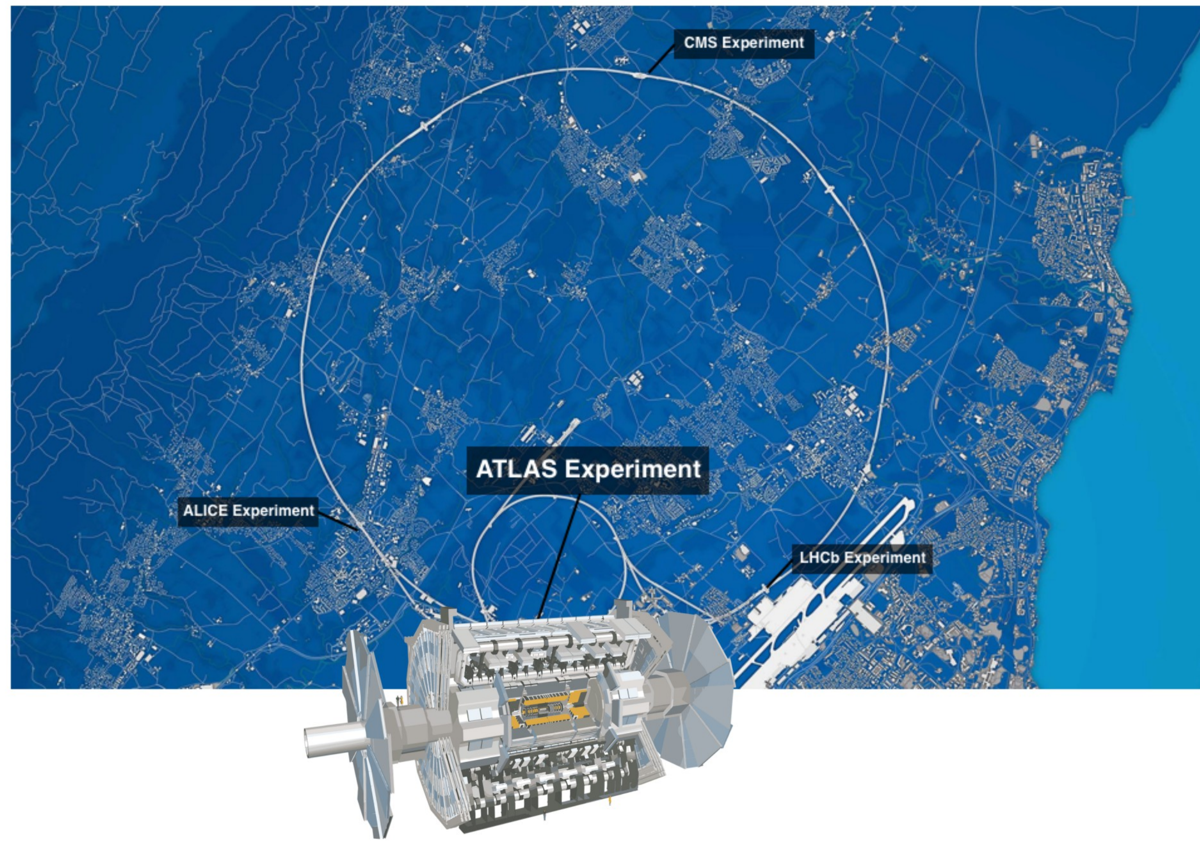
The 3rd African Conference on Fundamental and Applied Physics (ACP 2023)
George, South Africa
September 25-30, 2023

ATLAS EXPERIMENT LPNHE PARIS

In this talk



The main actor



The main stage will be the center of the ATLAS detector at the Large Hadron Collider (LHC) at CERN

Disclaimer: particle physics in the ATLAS Collaboration

In this talk

Known knowns *Things we are aware of and understand* E.g. The Standard Model (?)	**Known unknowns** *What we know we do not know* E.g. dark matter, dark energy, CP asymmetry, etc
Unknown knowns *Things we think we know* E.g. calculation of higher order	**Unknown unknown** *Information/gaps we are unaware of* E.g. physics beyond Standard Model/new physics

We will touch on the following topics

- The road to the discovery of the Higgs boson and why is this particle important?
- What do we know today about this particle? And how is it enriching our knowledge matrix?
- The future of the Higgs physics

The Standard Model (SM)
Quick reminder

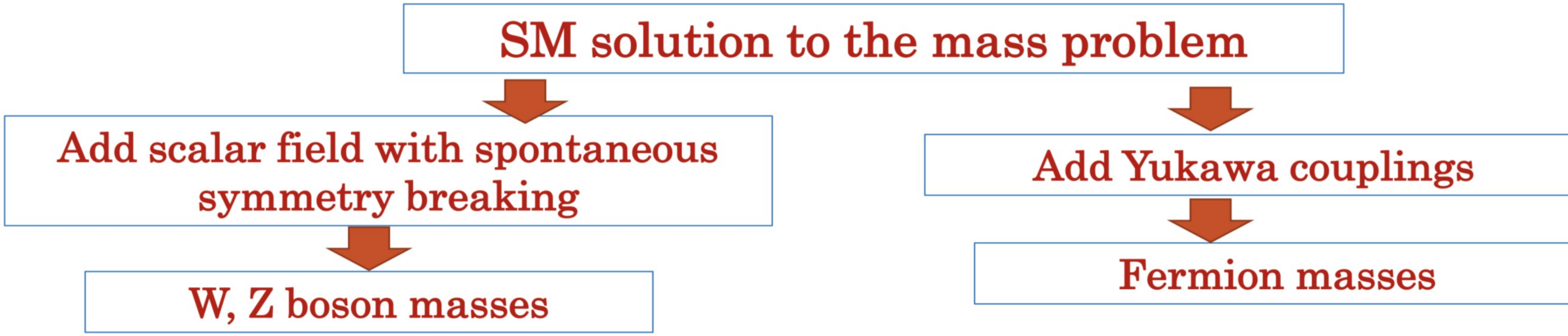
- The particle physics world in 1975
- The **local gauge symmetry** that defines the SM is

QCD → SU(3) x SU(2) x U(1) ← Electroweak

- The group representation determines the interaction form
  - Leptons: SU(3) singlets → do not interact strongly
  - Quarks: SU(3) triplets → interact with gluons
- Parity violation → Separation of the left and right SU(2) representations:
  - Left fermions: SU(2) doublets → interact weakly
  - Right fermions: SU(2) singlets → do not interact weakly
  - **No mass terms for fermions**
- Also, **no mass terms for bosons W and Z**
- In 1983 UA1 and UA2 announced the discovery of a massive W boson

The Standard Model (SM)

And the Higgs physics was born...



- Its discovery is an **important milestone for HEP**
  - Higgs = new forces of different nature than the gauge interactions known so far
  - **We want to know its most intimate secret**s: is the SM Lagrangian structure correct? Are the values of the coupling to the different zoo of particles as predicted by the SM? What is the shape of the Higgs potential?

- But **also for science in general**, as the knowledge of the values of the Higgs couplings is essential to our understanding of the deep structure of matter
  - Higgs **couples to W/Z boson via the BEH mechanism**
  - Higgs **couples to fermions via Yukawa**
    - Up- and down-quark Yukawa's related to the stability of nuclei
    - Electron Yukawa related to the size of the atoms
    - Top quark Yukawa decides (in part) the stability of the EW vacuum
  - Higgs couples to **itself via itself** and controls the (thermo)dynamics of the EW phase transition

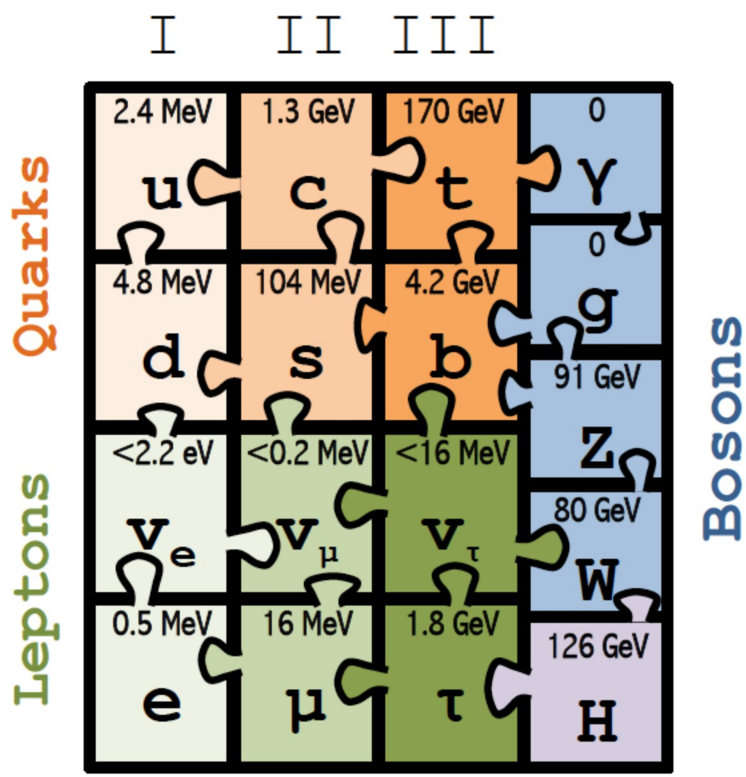
• *ABEGHHK'tH mechanism (known commonly as Higgs mechanism) proposed by three independent groups in 1964*
• *Yukawa interaction, was not formalized in first seminal papers (introduced by S. Weinberg)*

How well do we know the Standard Model?

$$
\begin{aligned}
&\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \\
&igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
&\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
&\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
&\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
&m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
&\tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2-1-\gamma^5)d^\lambda_j) + \\
&(\bar u^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2+\gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar e^\kappa U^{lep}{}^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep}{}^\dagger_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep}{}^\dagger_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \\
&\overline{\tfrac{1}{4}\,\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu + \\
&\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \\
&\partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \\
&\partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \\
&\partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \\
&\partial_\mu\bar X^-X^-) - \tfrac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
&\tfrac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).
\end{aligned}
$$

A very successful model

The Standard Model (SM) is a huge success from the experimental point of view



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

July 4th 2012: “Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC”

- The particle content of the SM is complete
- With the measurement of the Higgs mass, no more unmeasured parameters
- *Great introductions to the SM yesterday by Mu-chun Chen, Haifa Rejeb and Nausheen Shah!*

The Standard Model (SM)

And the Higgs physics was born...

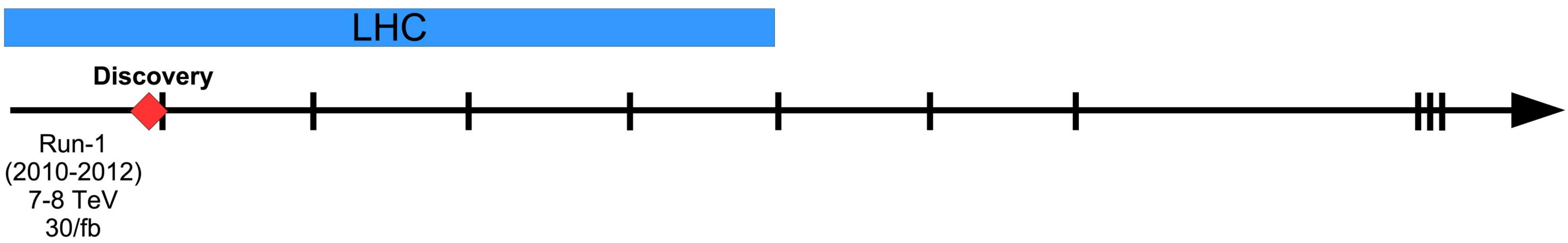
Standing ovation in the CERN auditorium at the end of the seminar announcing the discovery of the Higgs boson. (Image: Maximilien Brice, Laurent Egli/CERN)

The Standard Model (SM)

And the Higgs physics was born…

The buzz around the announcement was like that of a Lord of the Rings movie premiere, or the final Harry Potter book, with people queuing from the early hours to guarantee their seat to witness history. The queue wound its way from the auditorium on the first floor, down the main building staircase, through the cafeteria and out to the dining hall. (Image: Maximilien Brice/CERN)

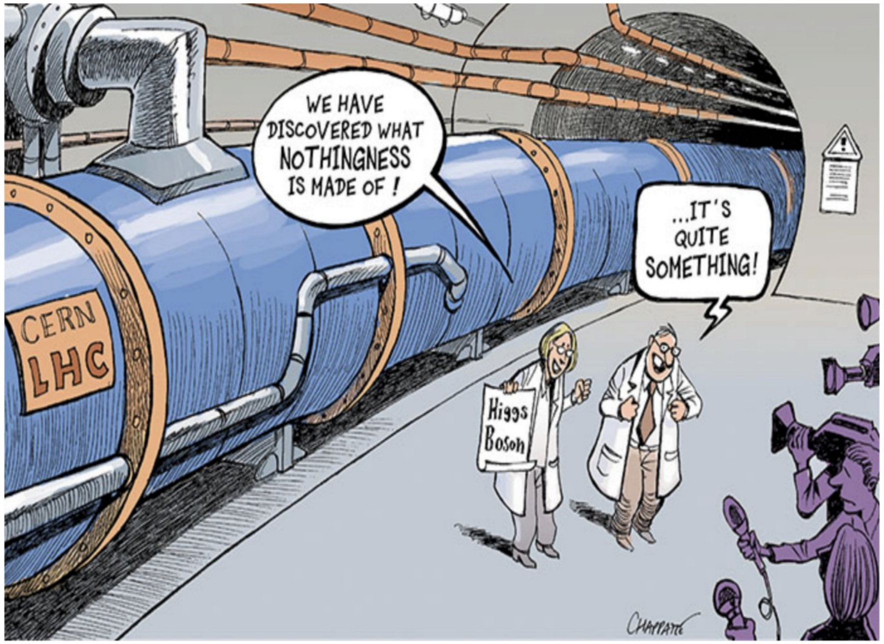
The road to discovery



- LHC approved by CERN council in 1994
- Started civil engineering in 1997 and commissioning in 2008

- September 2008, first beams but also accident to the superconducting dipoles
- Useful beams in 2010

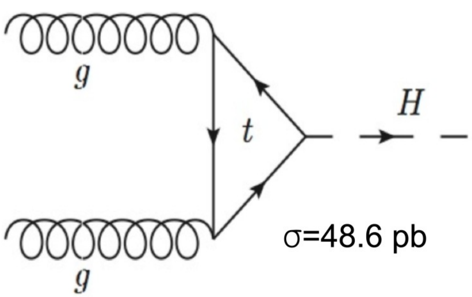
- Very quickly ATLAS and CMS excluded the existence of a SM Higgs in a very large mass range, spanning up to ~600 GeV... with the exception of a very narrow window ~125 GeV
- Discovery in 2012!



Identifying the Higgs boson at the LHC: production

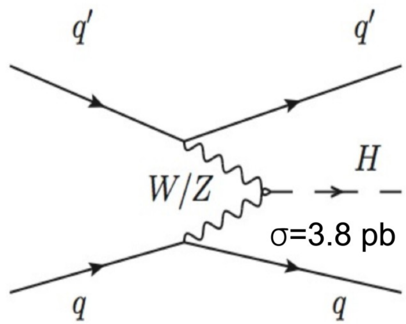
Different analyses performed by LHC experiments, depending on the Higgs production mode:

Gluon fusion (ggF)



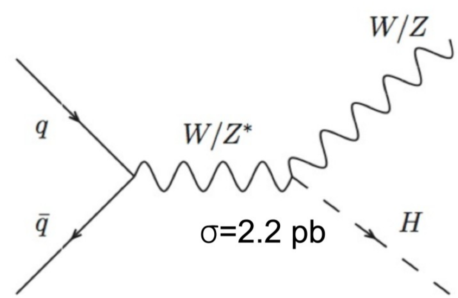
- Main production mode at the LHC
- Large backgrounds

Vector Boson Fusion (VBF)



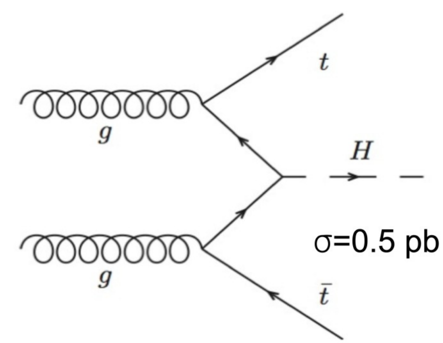
- The two jets with high rapidity separation improve triggering and bkg rejection

W/Z associated production (VH)



- Mostly triggered by leptonic decay of W/Z boson
- Accessibility to gauge coupling

tt associated production (ttH)



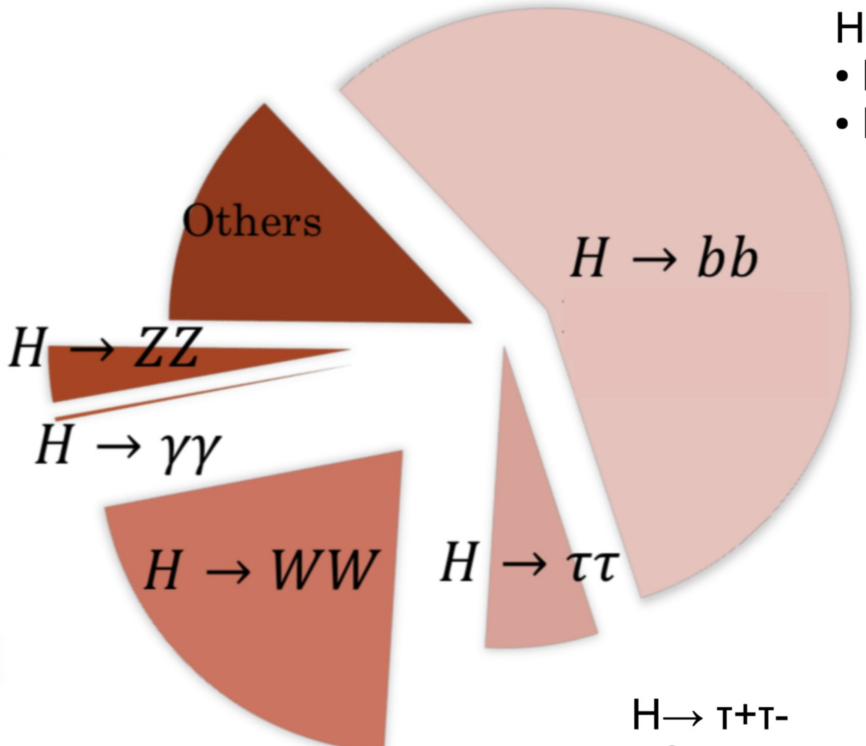
- Semileptonic and hadronic top decays
- Accessibility to the top Yukawa coupling

Identifying the Higgs boson at the LHC: decay

Which production mode or/and decay is the best?

H→ bb
- Dominant decay (~58% BR)
- Huge backgrounds from QCD jets

H→ Z(*)Z
- Penalty from Z→l+l-
- BR very clean, fully reconstructed



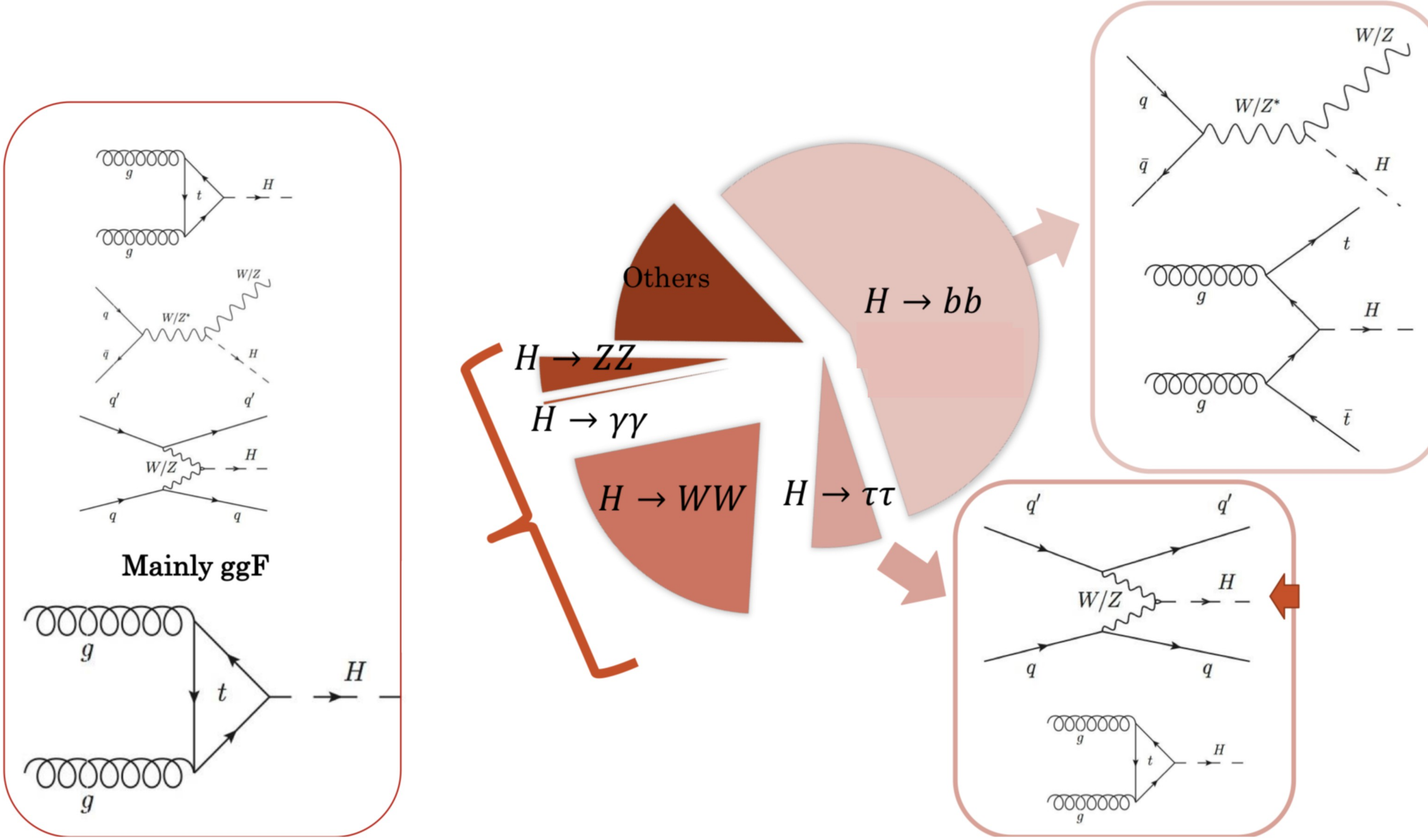
H→ γγ :
- Very small BR
- Huge bkgs. from QCD photons and jets
- Fully reconstructed, clean mass measurement

H→ W+W-
- Subdominant (~22%)
- Incomplete reconstruction

H→ τ+τ-
- Subdominant (~6%)
- Incomplete reconstruction

There is an interplay between production and decay based on the backgrounds

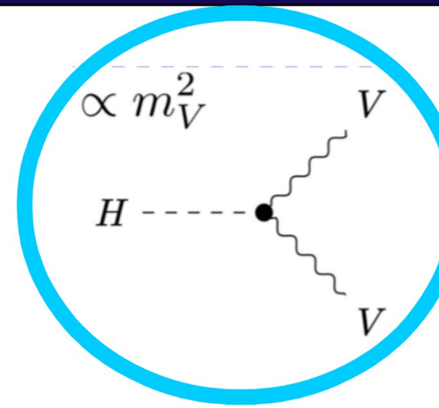
Identifying the Higgs boson at the LHC: Interplay between production and decay

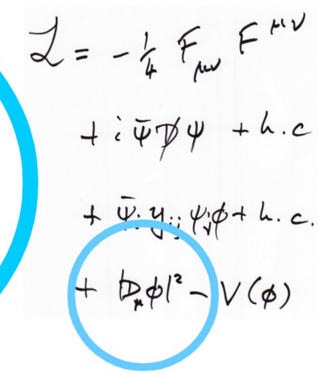


• *Slide from George Aad's JRJC 2014 talk*

Identifying the Higgs boson at the LHC: Interplay between production and decay

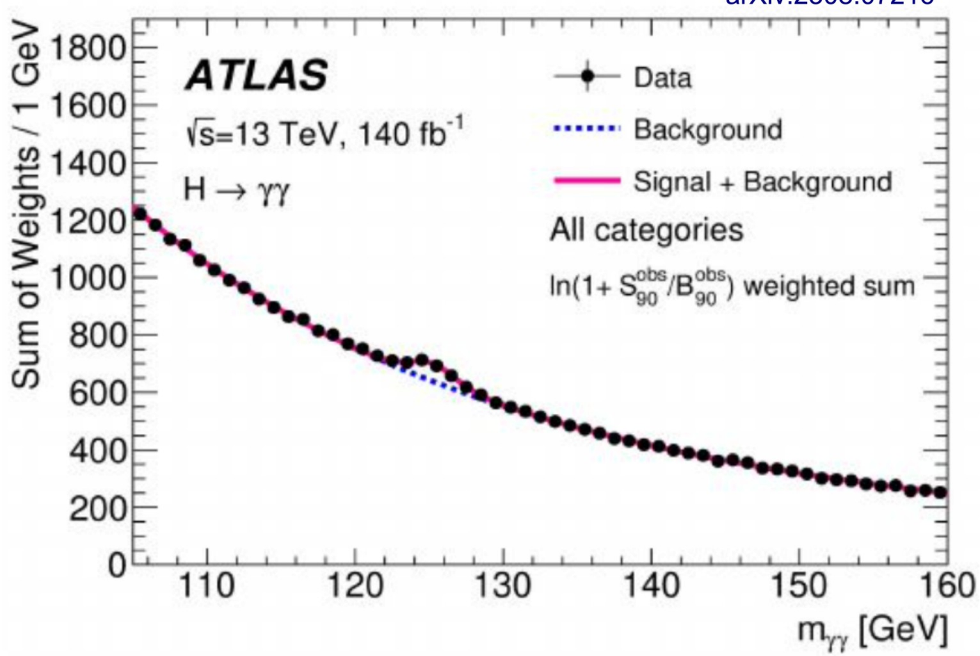
ZZ, WW and γγ were the first ones to be observed!
Now we are doing precision measurements with them!





Discovering a particle means being able to say that we see something different from the background noise, and that this cannot be explained by statistical fluctuation.

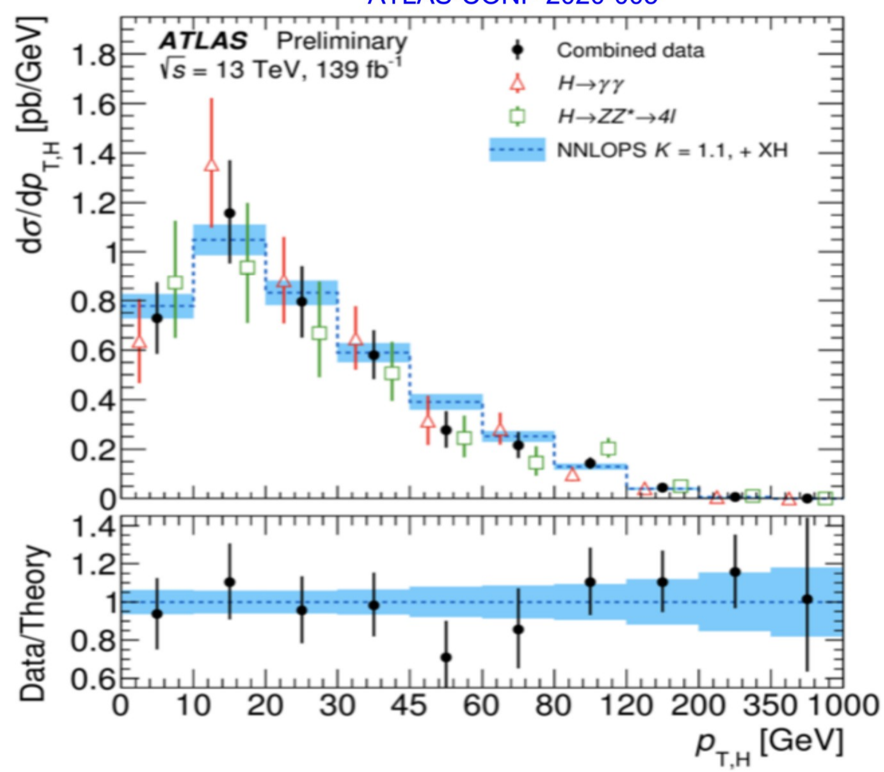
arXiv:2308.07216



Current ATLAS mass combined measurement:

125.11 +- 0.11 GeV (Less than 0.1% precision!)

ATLAS-CONF-2020-005

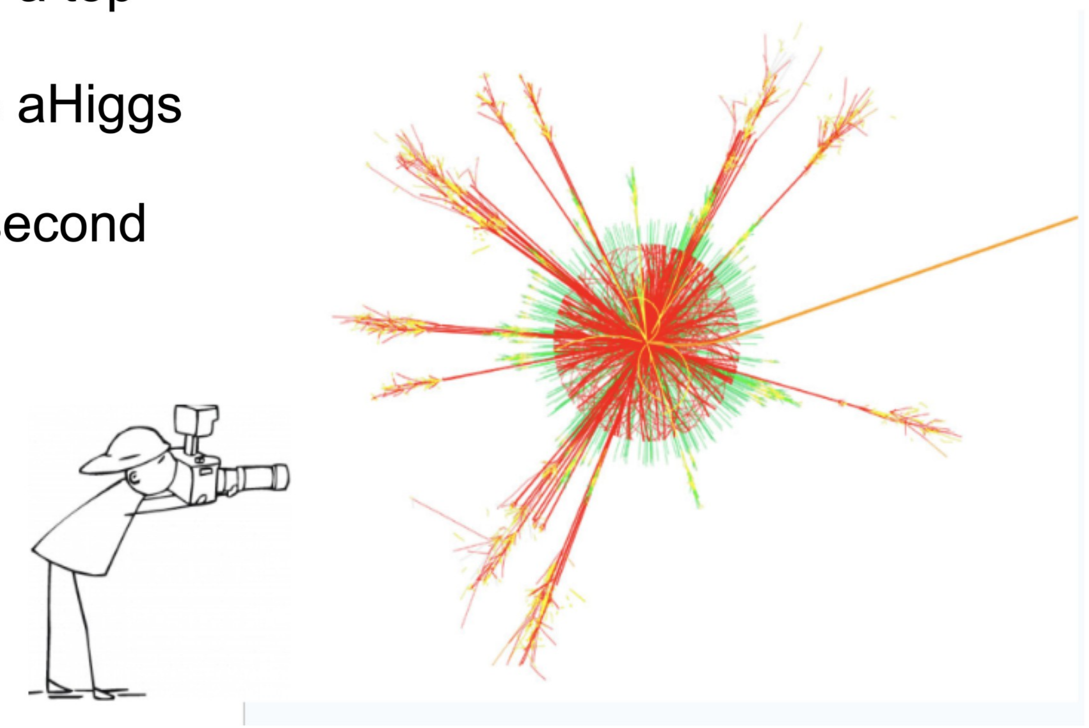


Measuring its transverse momentum spectra!

Identifying the Higgs boson at the LHC: Two main difficulties

- **First difficulty: Distinguishing the tiny fraction of interesting collisions**

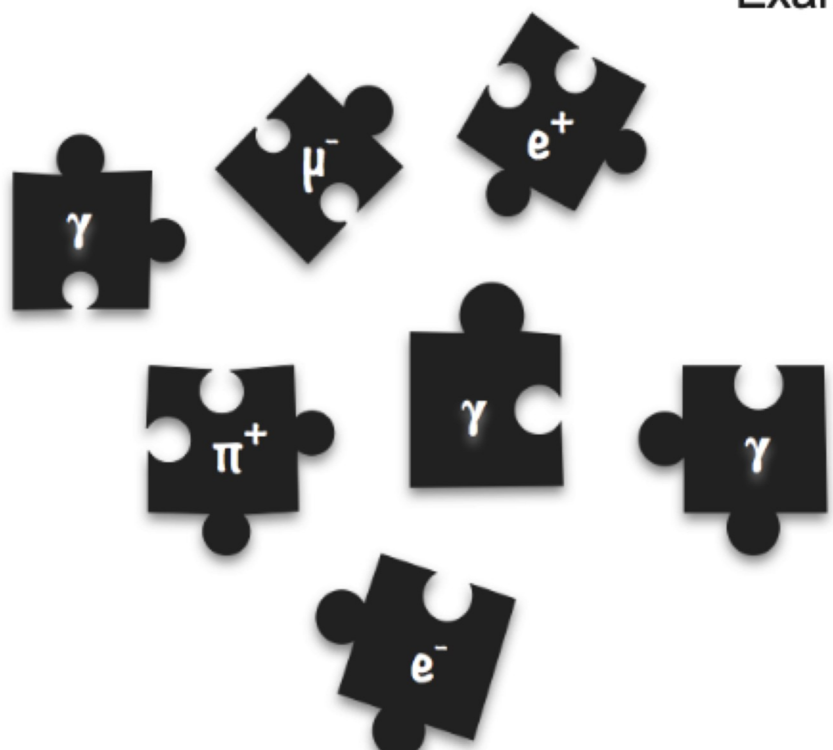
  - Ratio: Interesting collisions / Uninteresting collisions is 1 / 10 billion
    - It takes 10^{10} collisions to produce a b-quark
    - It takes 10^{12} collisions to produce a top quark
    - It takes 10^{14} collisions to produce aHiggs (one in a billion collisions!)
  - The LHC is 600 million collisions /second



Identifying the Higgs boson at the LHC: Two main difficulties

- **Second difficulty: Do these particles come from the same particle or not? Signa (minority) or background noise (majority)?**

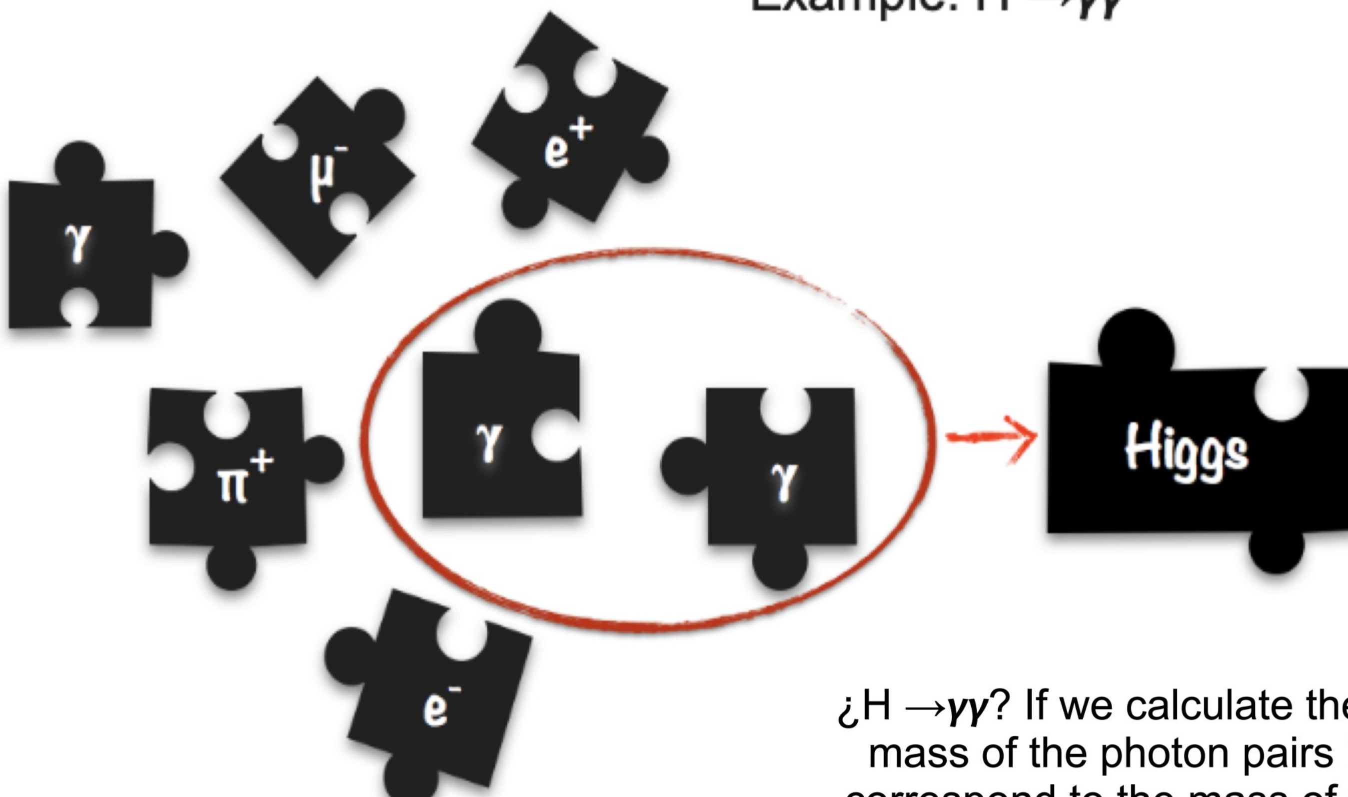
Example: H $\rightarrow \gamma\gamma$



Identifying the Higgs boson at the LHC: Two main difficulties

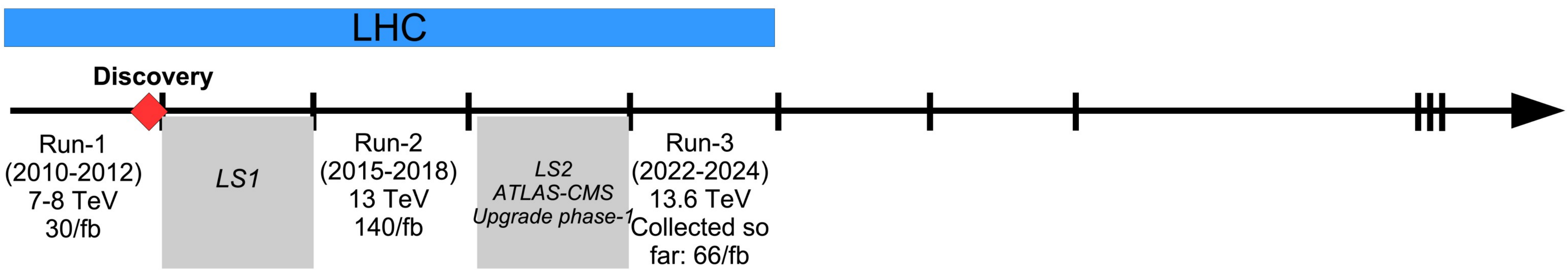
- **Second difficulty: Do these particles come from the same particle or not? Signa (minority) or background noise (majority)?**

Example: H →γγ



¿H →*γγ*? If we calculate the invariant mass of the photon pairs it should correspond to the mass of the Higgs

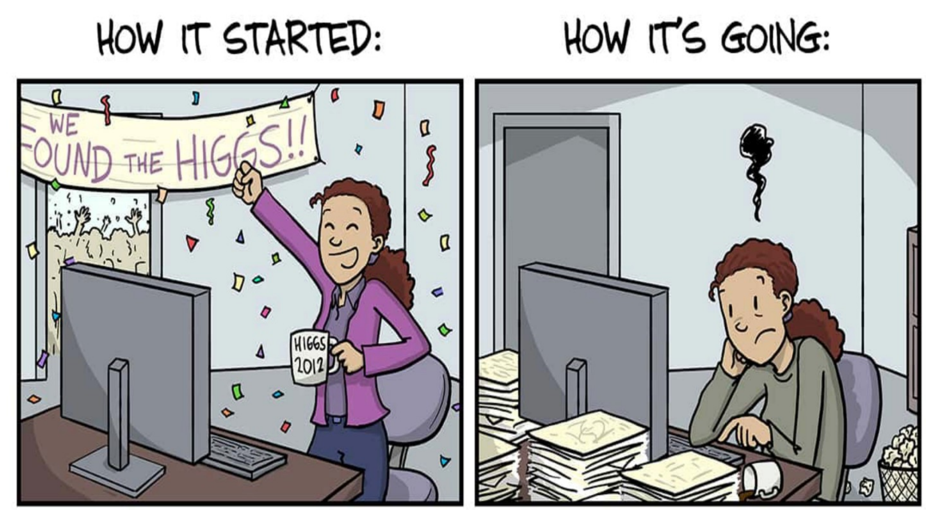
Where are we today?



- Large **increase in integrated luminosity** vs time: >15x the amount of data available at the moment of the discovery but conditions are more challenging!

- **Improvements in performance and analysis methodologies**! Large use of machine learning techniques to discriminate signal from background

- And a **good understanding of the detector** and data quality

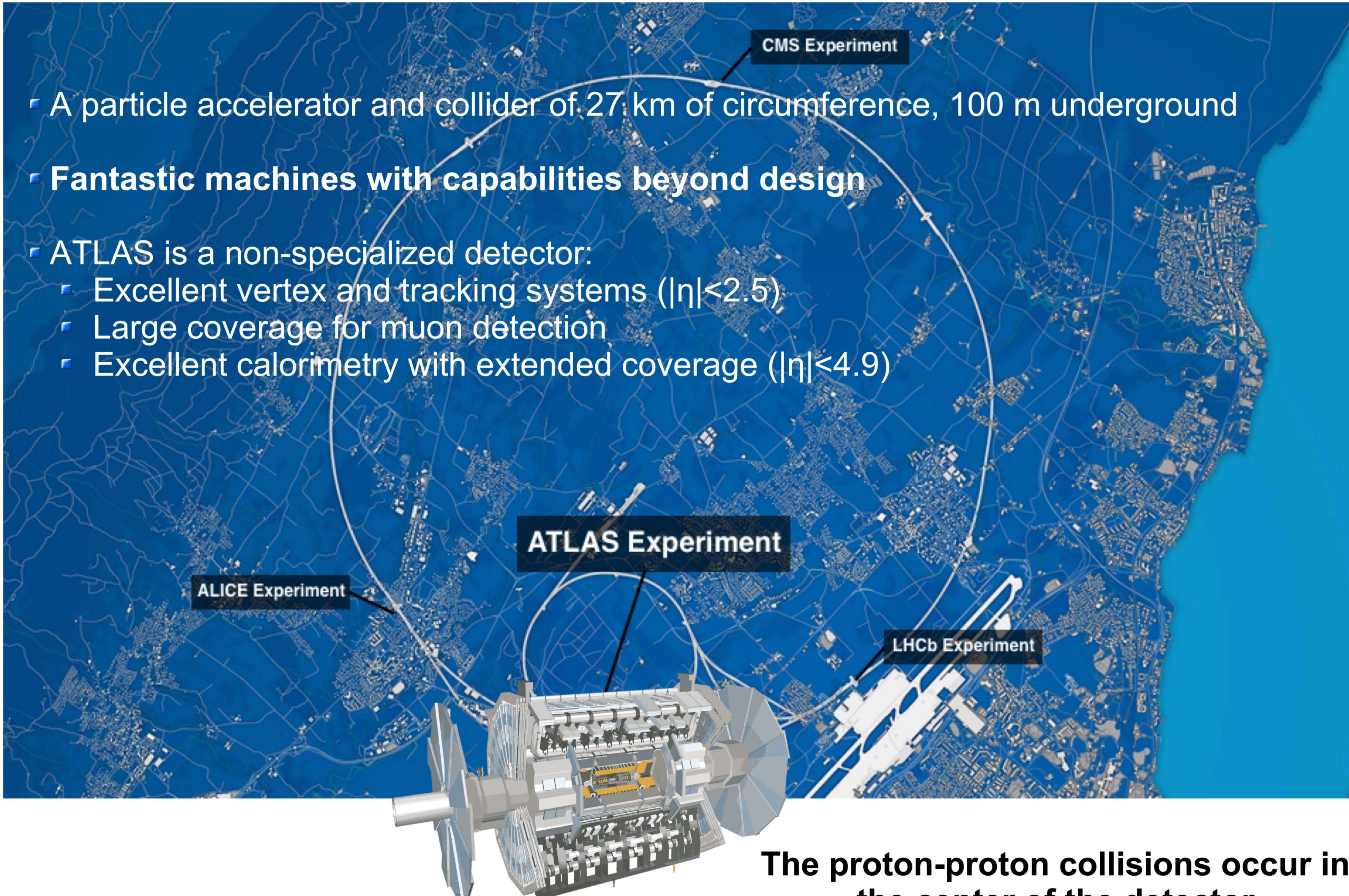


(Courtesy: Jorge Cham)

Our tools

The ATLAS experiment and the LHC

- A particle accelerator and collider of 27 km of circumference, 100 m underground
- **Fantastic machines with capabilities beyond design**
- ATLAS is a non-specialized detector:
  - Excellent vertex and tracking systems ($|\eta|<2.5$)
  - Large coverage for muon detection
  - Excellent calorimetry with extended coverage ($|\eta|<4.9$)



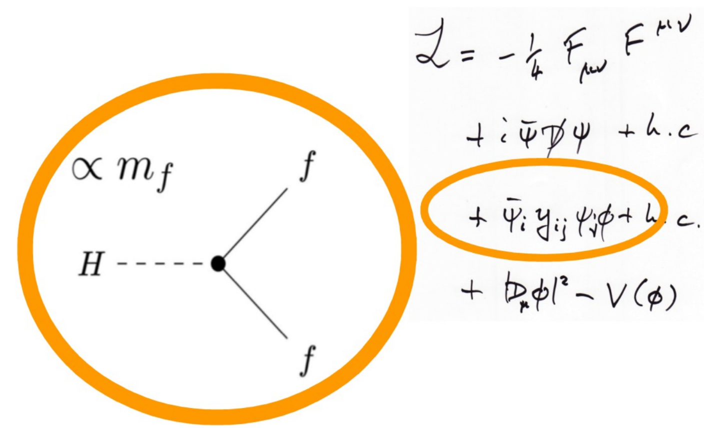
The proton-proton collisions occur in the center of the detector

Where are we today?

Analyses at different stages:
- Precision (e.g. YV, WW, ZZ)
- **Most recently observed and entering the precision era** (e.g. bb, $\tau\tau$)
- Searches (e.g. cc, u, ee, Zy, di-Higgs)

E.g. Observation of H→bb using 2018 data

- **Various production modes explored** ggF, VBF, ttH, VH
- Observation of H→bb in 2018 (VH, V→leptons), **now entering in differential and precision measurements mode** + exploiting new signatures VH → qqbb. Access to new corners, higher p_T spectra



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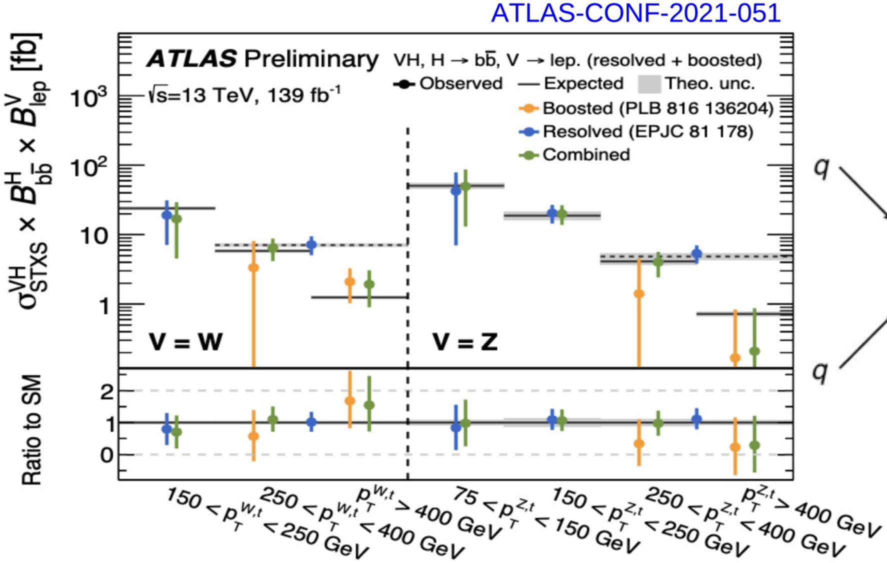
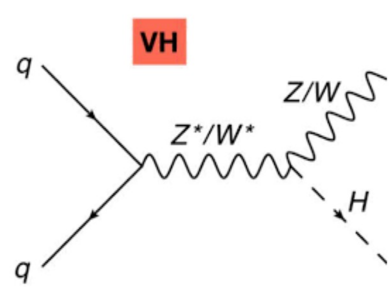
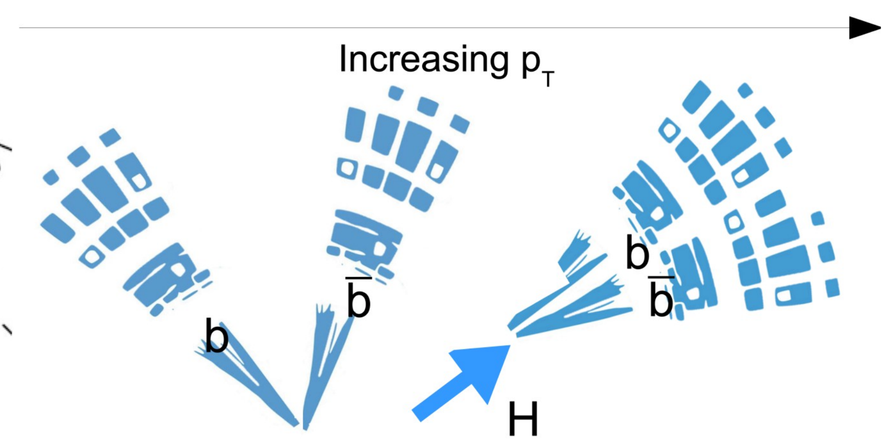


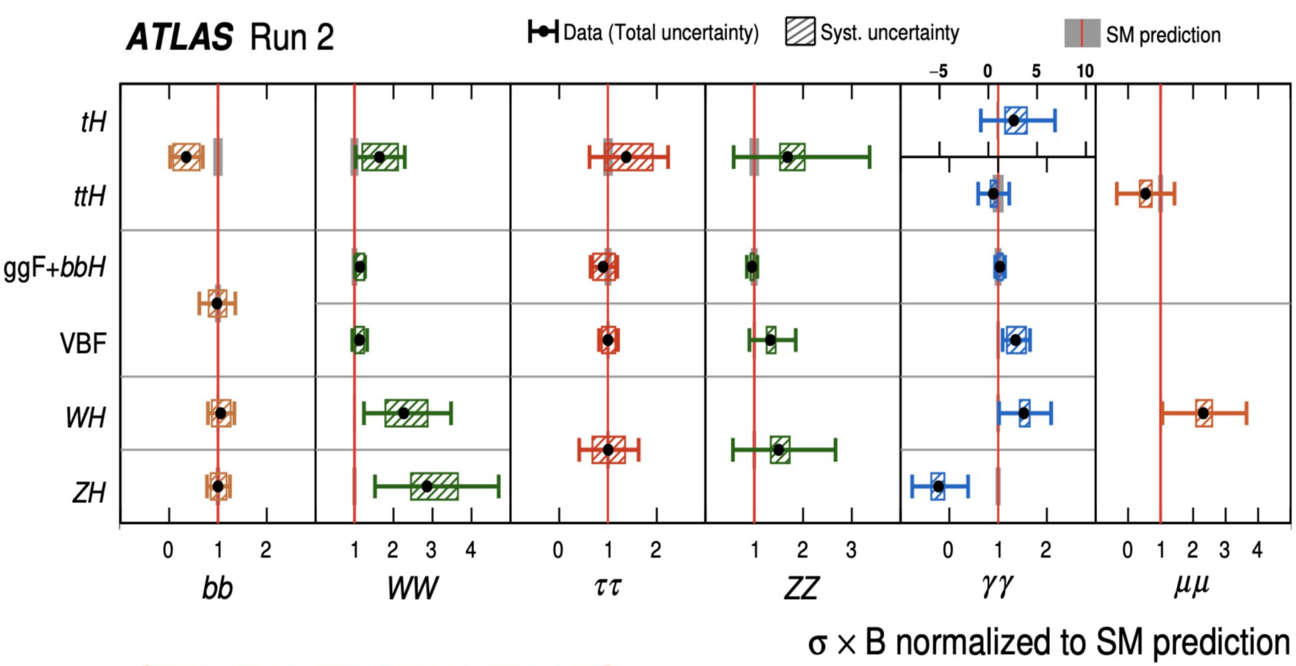




Signal-to-background ratio increases with Higgs boson p_T

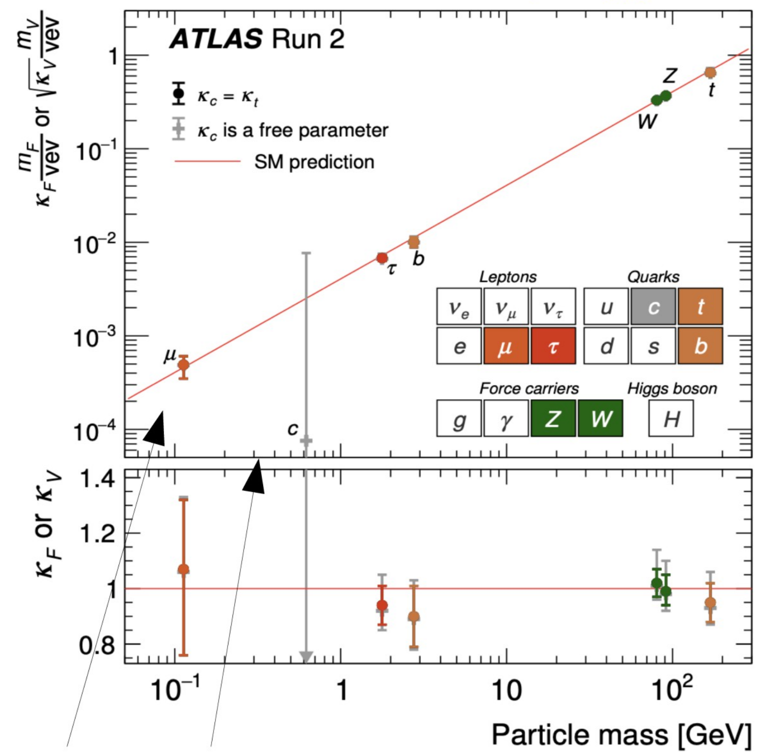
Where are we today?

- CMS and ATLAS have made big progress in the understanding of the Higgs sector and the EWSB mechanism since its discovery
  - **With increasing complexity of the analyses in terms of statistical model and analysis definition**



$\mu_{bb} = 0.91 \pm 0.14$

Nature 607.7917 (2022), pp. 52–59

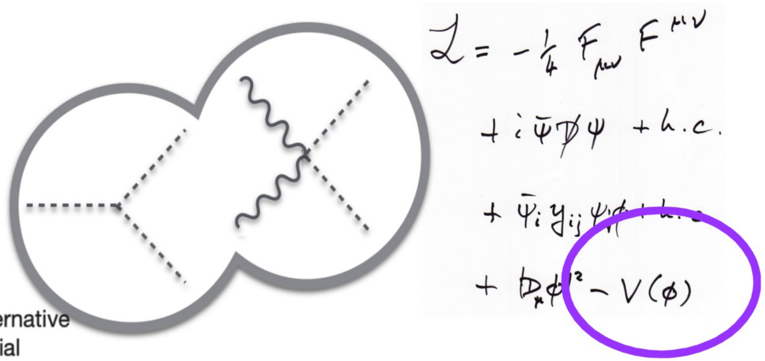


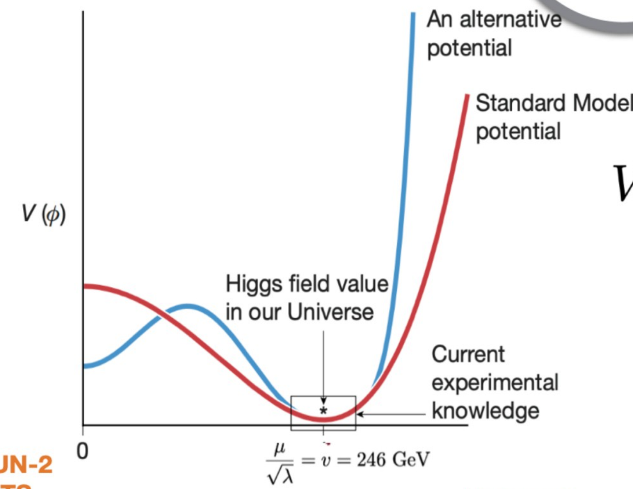
On the search side: the 2nd generation! Small couplings in the SM and large backgrounds: **H→ μμ and H→cc**

Also on the search side: HH production

- Another way of probing the EWSB mechanism: making progress towards **testing the shape of the Higgs potential through the Higgs self-coupling**
  - Rare process in SM: σ(gg→HH) ≈0.1%*σ(gg→H)

- Main channels studied so far: bbγγ, bbττ, bbbb
- Limits are around 3xSM now!

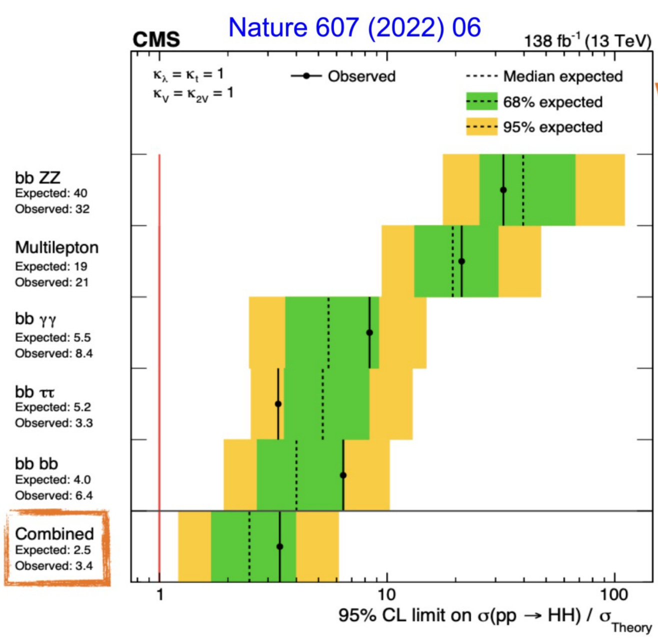




$$V = V_0 + \frac{1}{2} m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \ldots$$

Higgs boson mass: *know to 0.2%*

Higgs boson self interaction



WRT EARLY RUN-2 (2016) RESULTS

NEW

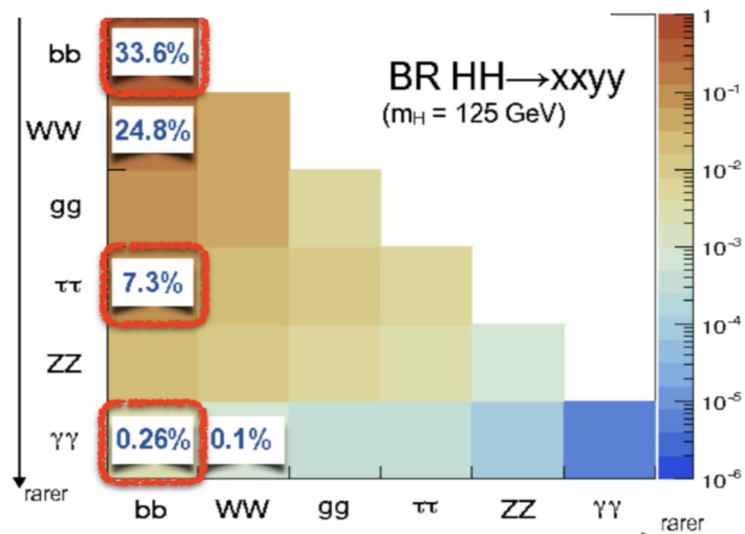
NEW

× 3 BETTER

× 5 BETTER

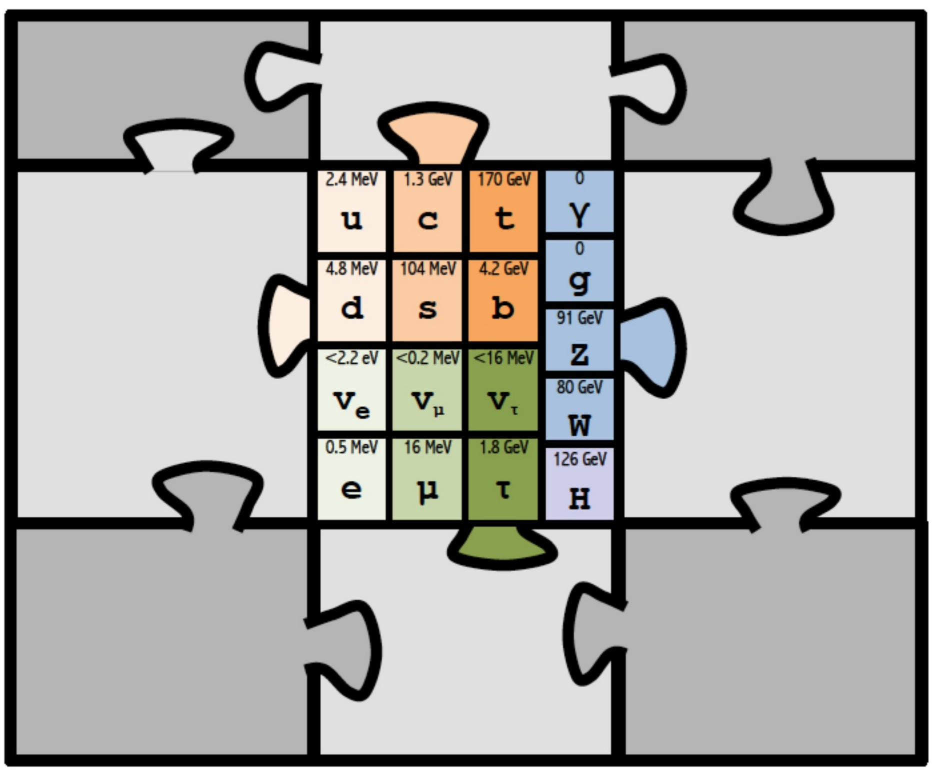
× 6 BETTER
× 30 in boosted analysis

× 5 BETTER



The Standard Model

One piece of the universe puzzle?



- **Present data compatible with a scalar particle with spin 0 and even parity (as predicted by the SM) of mass mH ~ 125.2 GeV**

- But the SM does not accommodate everything we need to know about nature:
  - Dark matter
  - Dark energy
  - Neutrino oscillation
  - Matter-antimatter asymmetry
  - Fermion mass hierarchy
  - Gravity
  - ...

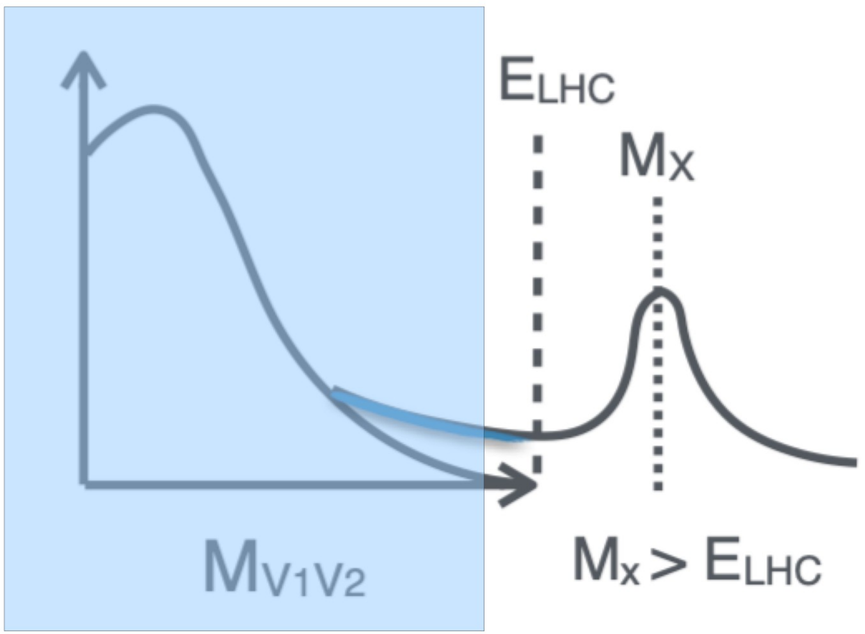
- There must be something more!

- Our work as scientists is to search for that something and understand what we have

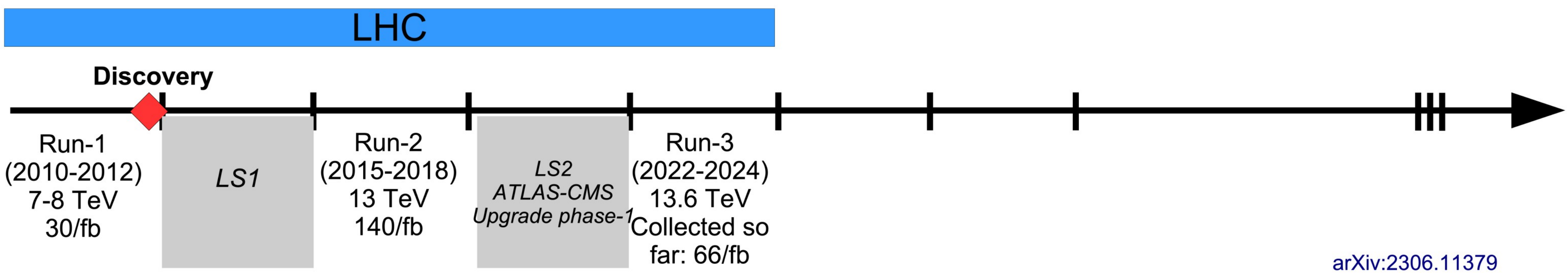
- **Could the Higgs be the tool to unlock new physics?**

The Higgs boson as a tool to search for new physics

- **The Higgs is still a tool for new physics:**
  - Measure its properties with better precision, in corners of the phase space
  - Search for Higgs decays to non-SM particles, e.g dark matter, long-lived particles, axion like particles, etc
  - Contributions of new physics to SM Higgs processes, e.g. BSM contributions can modify the Higgs boson coupling parameters and modify the di-Higgs cross section, i.e. extra dimensions, 2 Higgs doublets models, etc (see Nausheen Shah's talk)



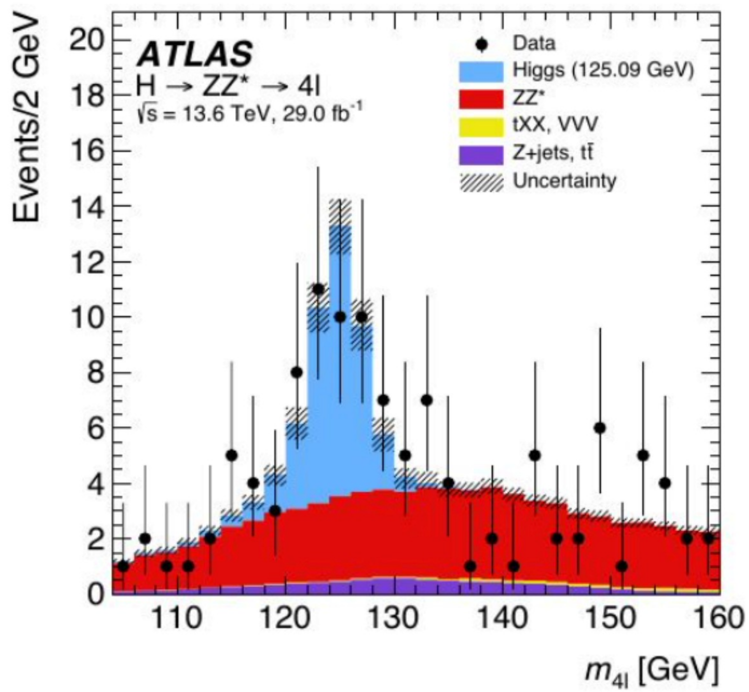
Towards Run-3



- **Full Run-2 and Run-3 initially expected to amount to 350-400/fb**! Some measurement wills clearly benefit from this:
  - H→μμ. We are within reach of observation by the end of Run 3, combining ATLAS and CMS
  - Gain stats in all high kinematic pt bins
  - Moving towards global LHC combinations
  - Accessing new phase space: BSM decays, long lived particles, etc

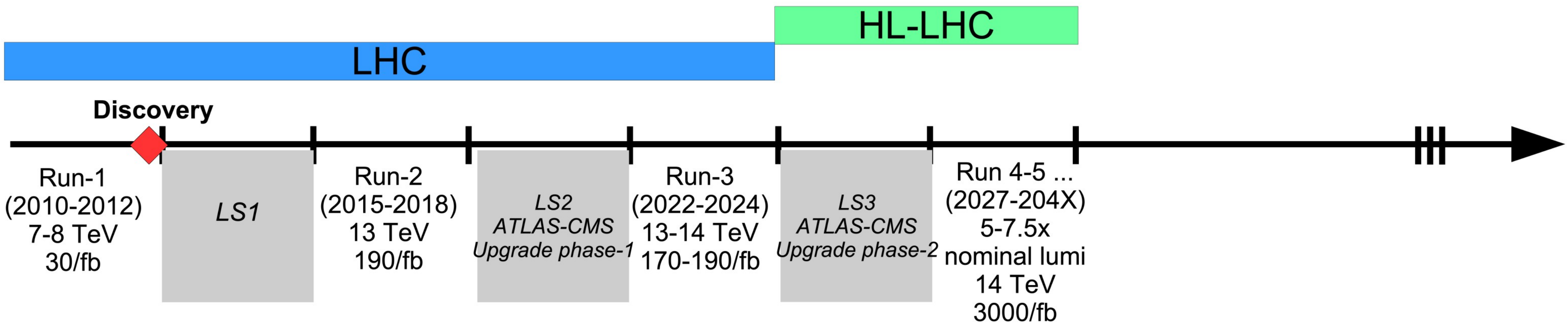
- **A lot of work for experimentalists (to understand the new data) and theorists (to provide better predictions and new models)**

arXiv:2306.11379



First measurement of H→ 4l cross section at 13.6 TeV

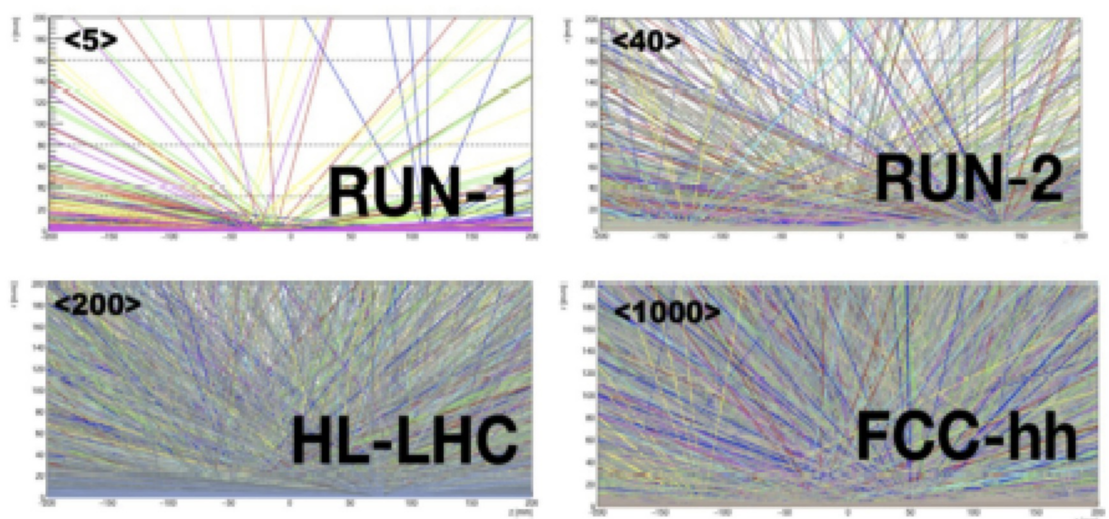
High Luminosity LHC (HL-LHC)



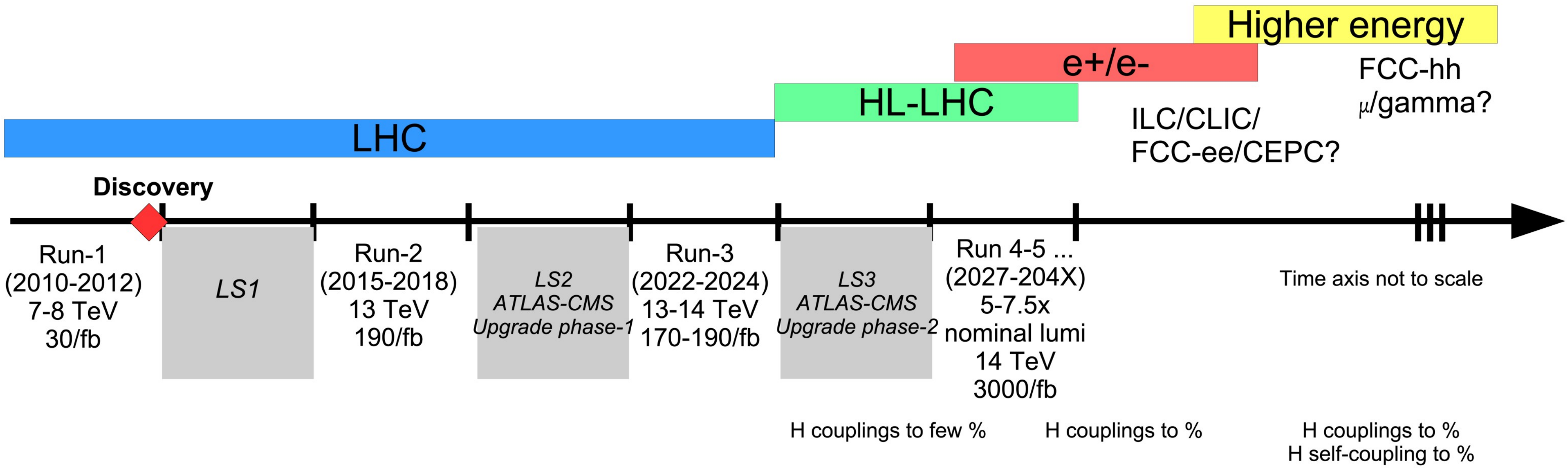
(some) Higgs boson couplings measured with O(5-10)% precision

- **HL-LHC will be a Higgs factory:** 170M Higgs bosons - 120k HH pairs for 3000/fb
  - Expected 2-4% precision for many of the Higgs couplings!
- Run-3 and HL-LHC means more data, hopefully a bit more energy (more reach for rare processed) but also a **more challenging environment**!

- **Phase-2 HL-LHC detector upgrades are being built to cope with the new challenging conditions**

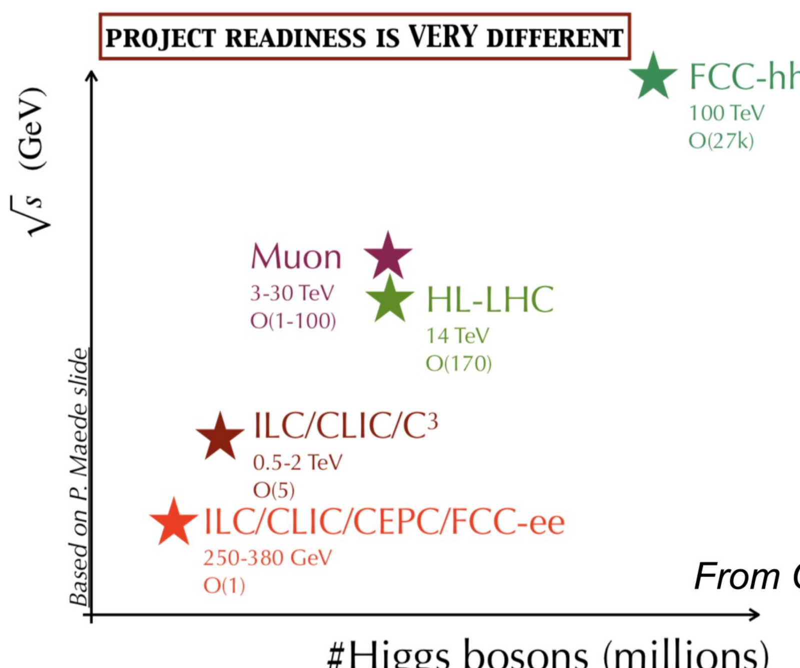


Beyond the HL-LHC



- **Wishlist beyond the HL-LHC:**
  - Establish Yukawa couplings to light flavor → needs precision
  - Establish self-coupling → needs high energy

- Different colliders probe different dominant processes, each with its own experimental challenges
- Complementarity among leptonic and hadronic colliders is the key



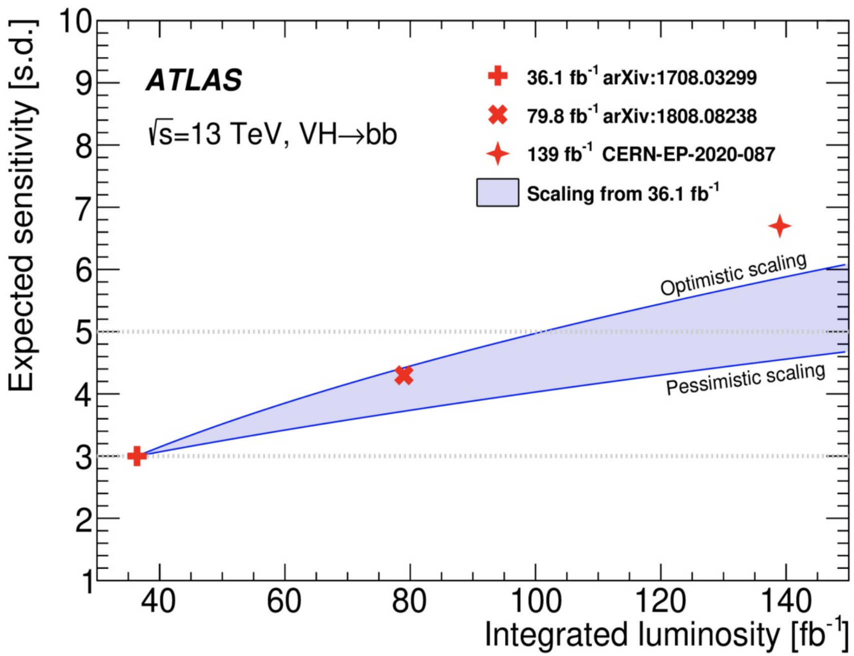
From C. Vernieri

To conclude

- Big progress in Higgs physics since its discovery. Impressive results due to **great teams, collaborations, technical improvements and available data**

- All the measurements are in **good agreement with SM prediction** given the current precision. But **still space for new physics!**
  - More combination measurements are also expected in the following months
  - Some local 3-4σ excesses in Run-2 that we will need to study further
  - **"We should not promise we discover something. We should not assume we will not discover anything. It is all about the tools we have". A. Rizzi (concluding talk at Higgs Hunting 2023)**

- **Huge effort to understand performance and potential of future machines**. Hopefully next LHC runs will provide new information about BSM existence and its scale!

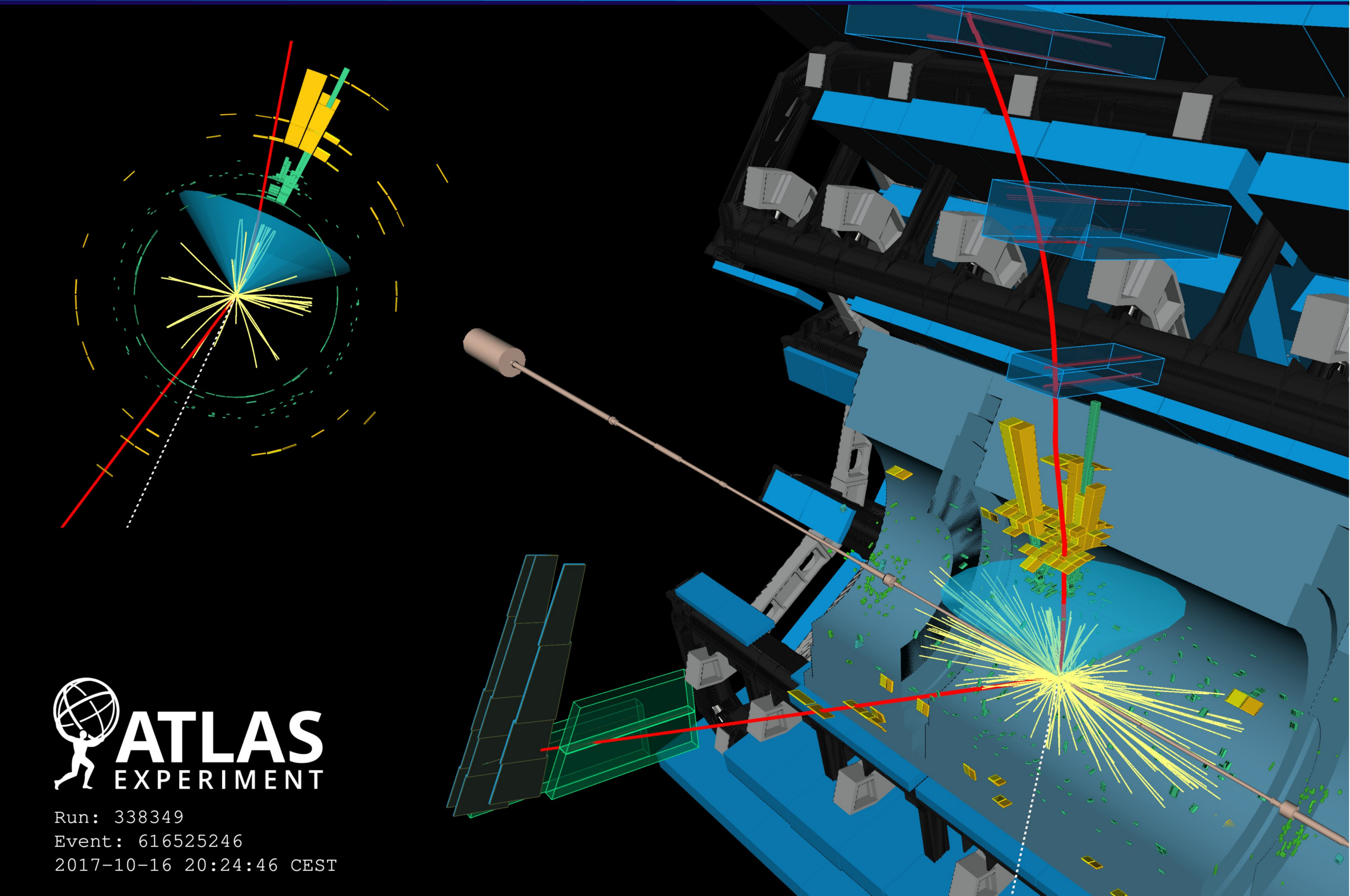


To conclude

Are we asking the right questions?

Known knowns *Things we are aware of and understand* E.g. The Standard Model (?)	**Known unknowns** *What we know we do not know* E.g. dark matter, dark energy, CP asymmetry, etc
Unknown knowns *Things we think we know* E.g. calculation of higher order	**Unknown unknown** *Information/gaps we are unaware of* E.g. physics beyond Standard Model/new physics

VH, H→bb, boosted regime



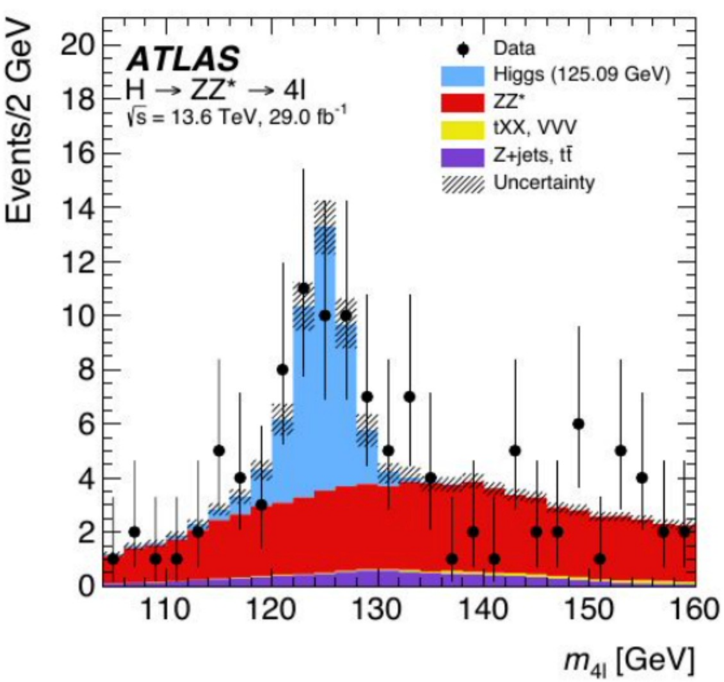
BACKUP

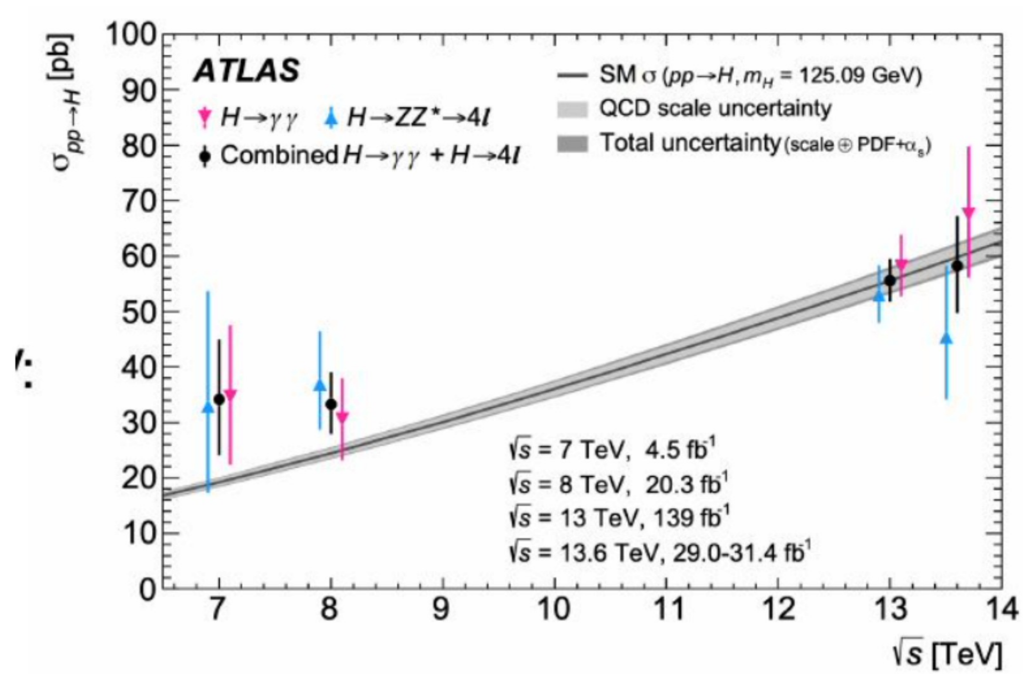
Looking at Run-3 data!

Run3 - New ATLAS measurement

- First measurement of H→ 4l cross section at 13.6 TeV
- Using 29/fb of Run3 data
- Combined with di-photon measurement

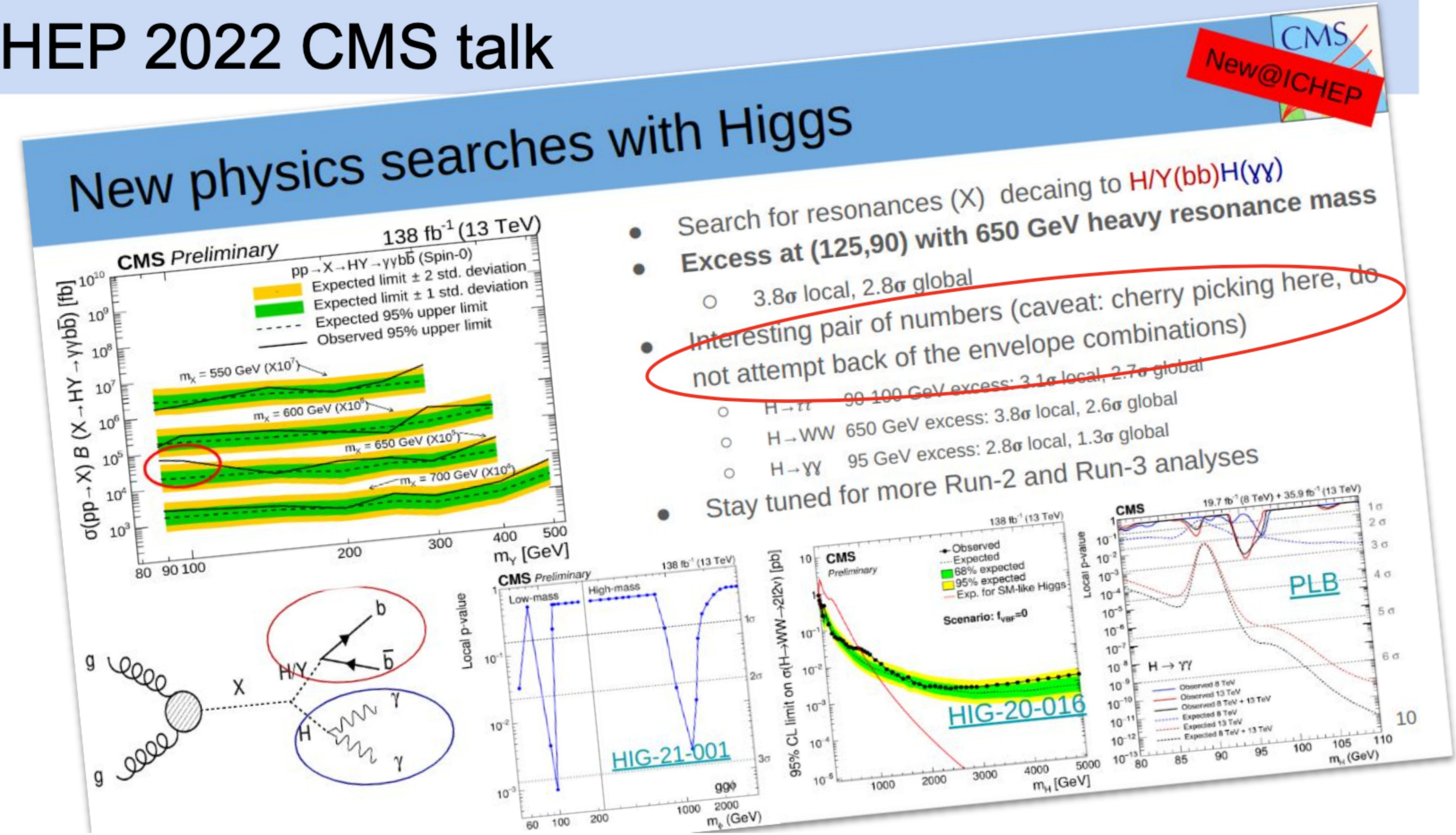
A. Reed





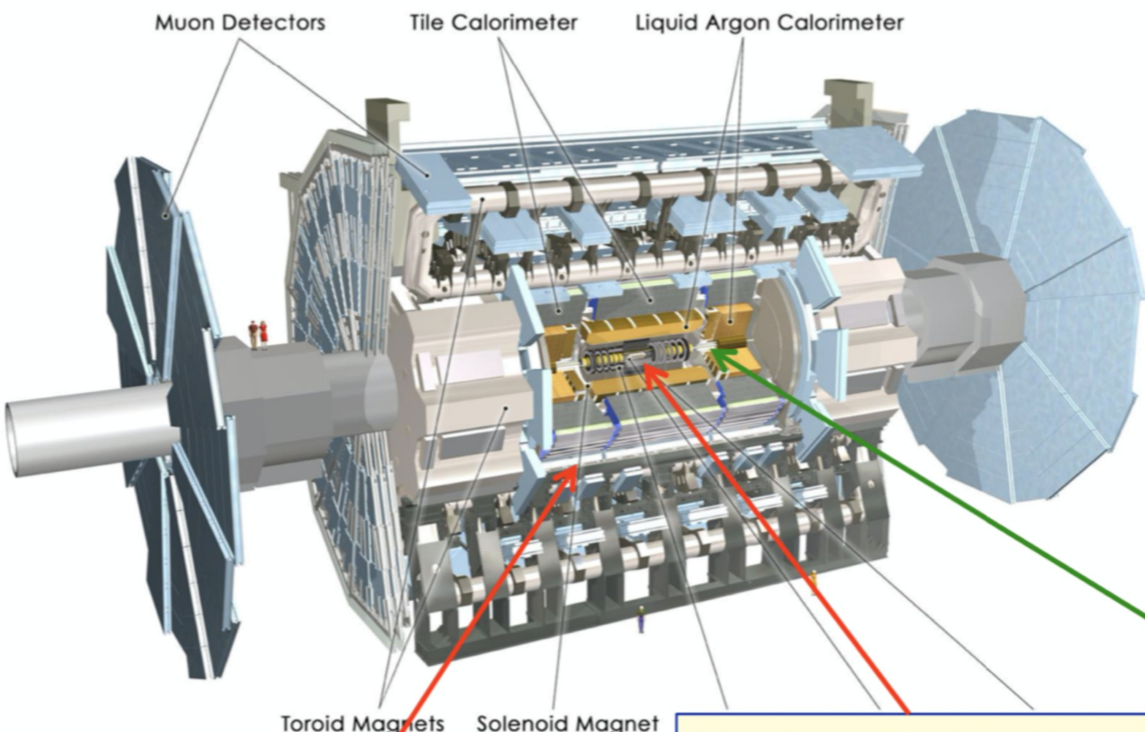
New physics searches with Higgs

ICHEP 2022 CMS talk



ATLAS Phase-II upgrade

From K. Jakobs



Upgraded Trigger and Data Acquisition System:

- L0: 1 MHz
- Improved High-Level Trigger

Electronics Upgrade :

- LAr Calorimeter
- Tile Calorimeter
- Muon system

New Inner Tracking Detector (all silicon tracker, up to $|\eta|$ =4)

New muon chambers in the inner barrel region

High granularity timing detector (forward region)

Approved by CERN Research Board (16th Sept.)

CMS Phase-II upgrade

From R. Carlin
ICHEP 2020

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ

https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters

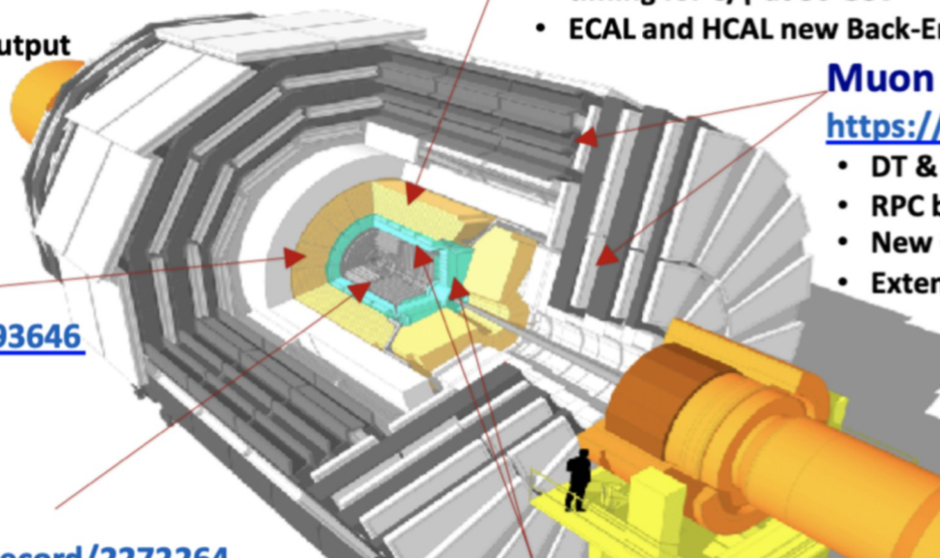
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/002706512

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector

https://cds.cern.ch/record/2296612

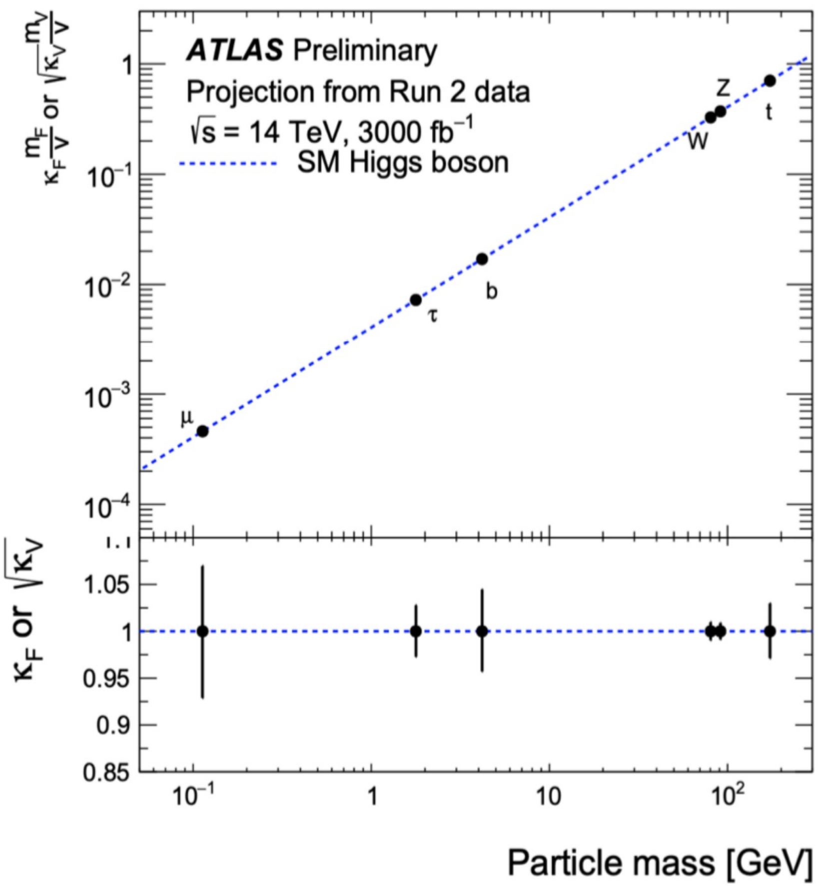
Precision timing with:

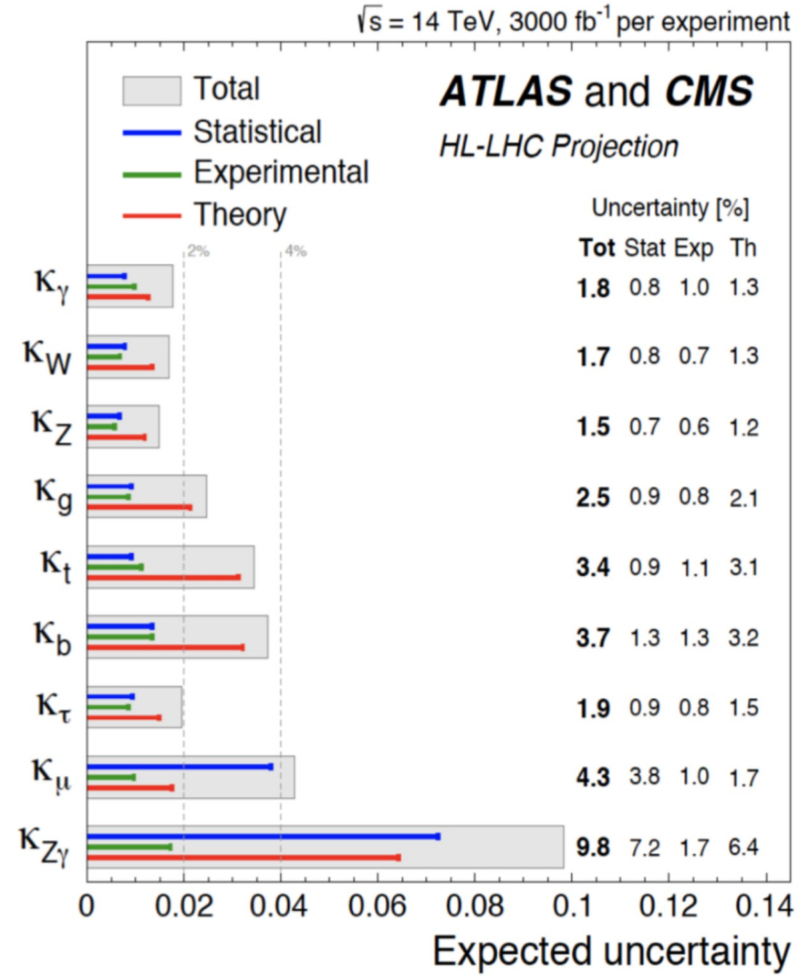
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

High Luminosity LHC (HL-LHC)

- **HL-LHC will dramatically expand the Higgs physics reach**

- Suggest to read Higgs Yellow Report CERN-LPCC-2018-04 submitted to the European Strategy in 2018!



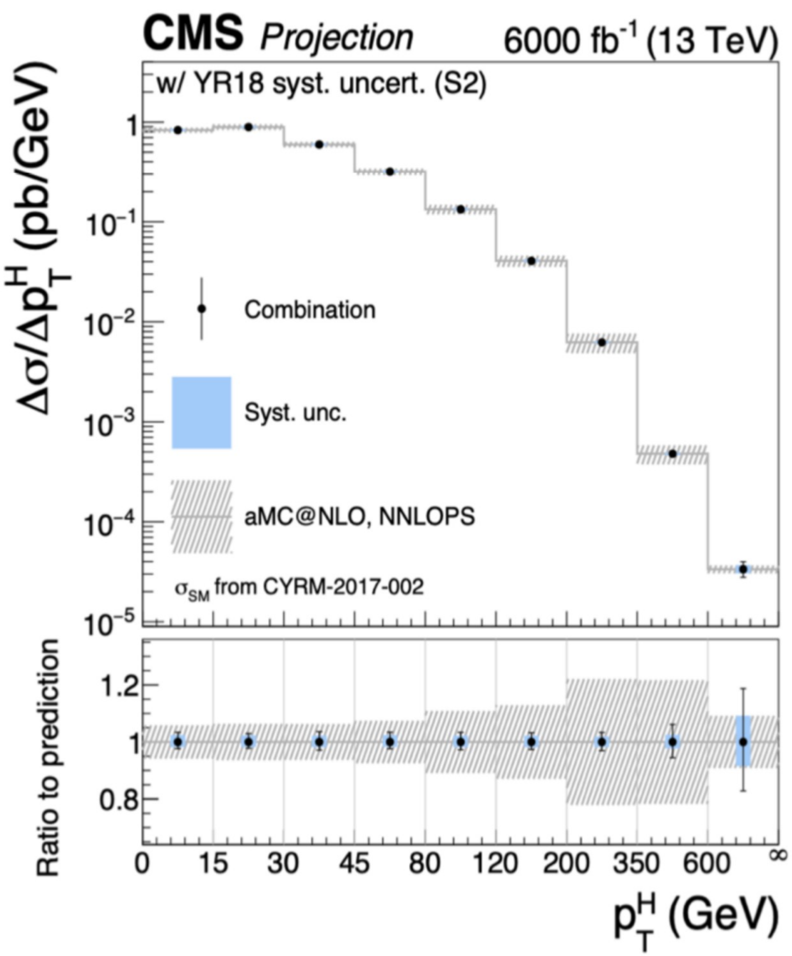


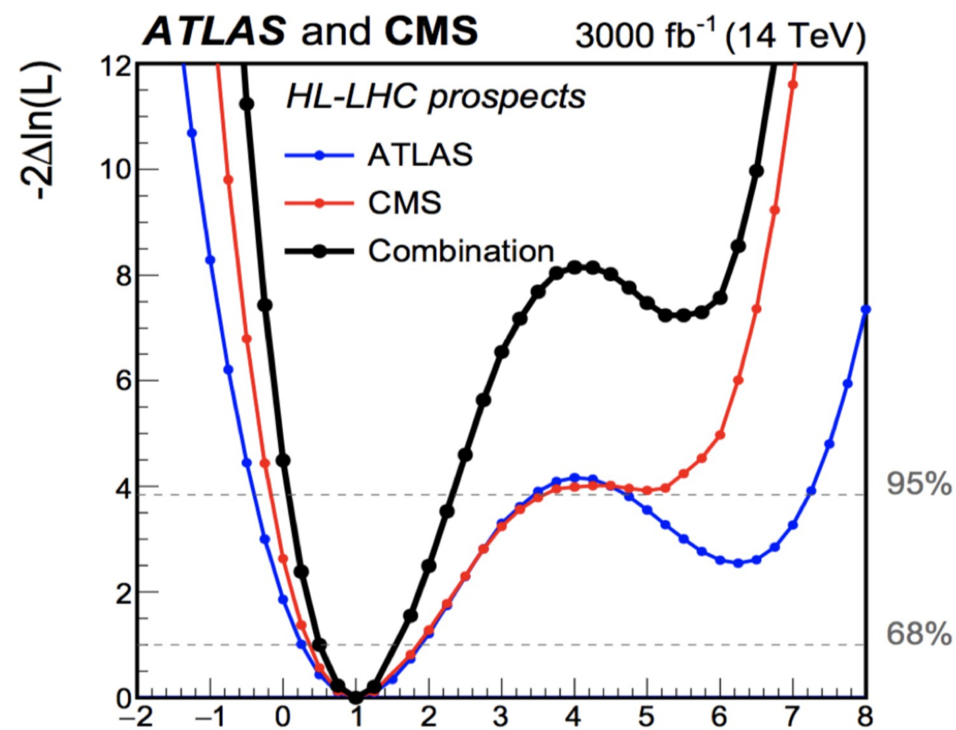
- 2-4% precision for many of the Higgs couplings. Theory uncertainty remains the largest component for most measurements
- Different uncertainties scenarios considered in these studies

High Luminosity LHC (HL-LHC)

- **HL-LHC will dramatically expand the Higgs physics reach**

- Differential cross-sections: theory uncertainty dominates in all bins except pT > 600 GeV





$$k_\lambda = \frac{\lambda}{\lambda_{SM}}$$

- Significance of HH signal at the 4σ level (both experiments)
- 50% uncertainty on the self-coupling

Beyond the HL-LHC

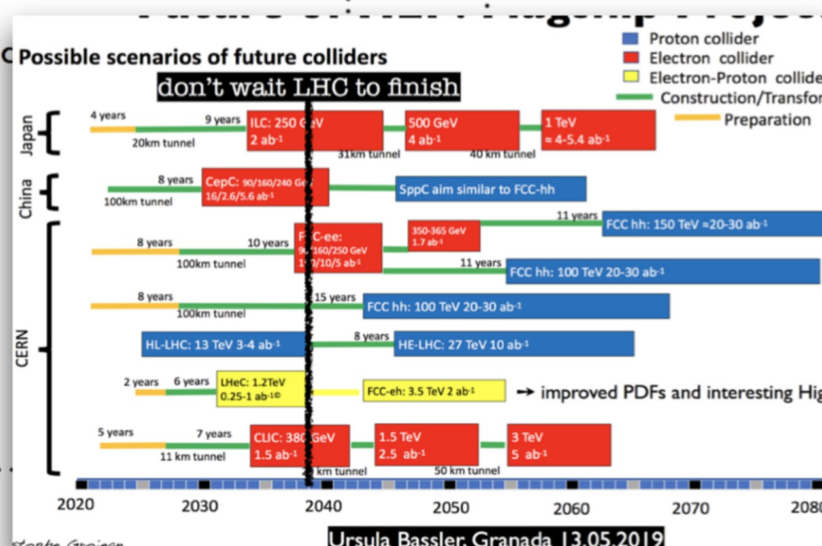
Which Machine(s)?

Hadrons

- o large mass reach ⇛ exploration?
- ▸ S/B ~ 10^{-10} (w/o trigger)
- o S/B ~ 0.1 (w/ trigger)
- o requires multiple detectors
  (w/ optimized design)
- ▸ only pdf access to $\sqrt{\hat{s}}$
- o ⇛ couplings to quarks anc

Leptons

- o S/B ~ 1 ⇛ measurement?
- o polarized beams
  (handle to chose the dominant process)
- o limited (direct) mass reach
- o identifiable final states
- ings



Circular

- o higher luminosity
- o several interaction points
- o precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)
- ▸ √s limited by synchroton radiation

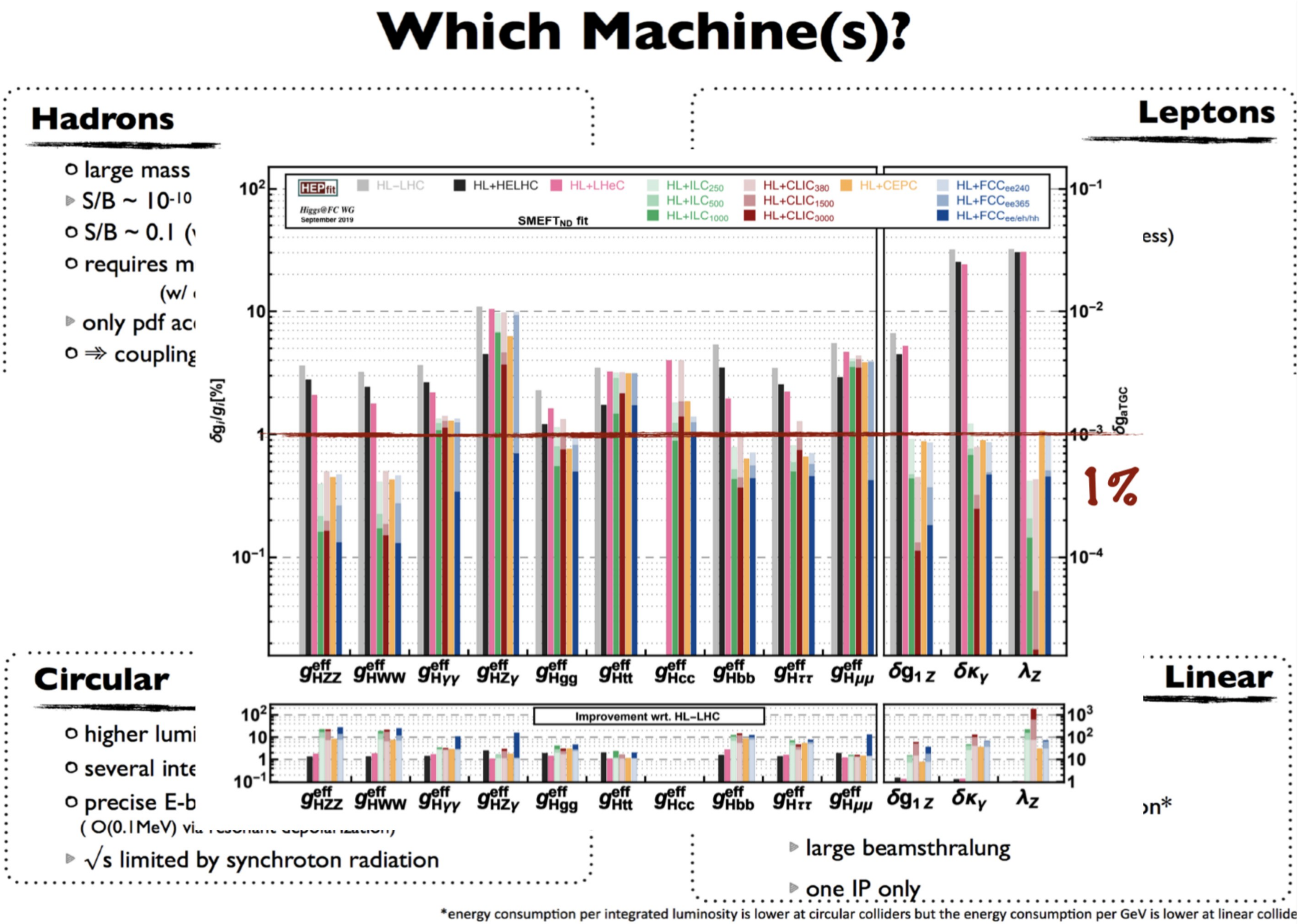
Linear

- o easier to upgrade in energy
- o easier to polarize beams
- o"greener": less power consumption*
- ▸ large beamsthralung
- ▸ one IP only

*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear collide

- *Slide from Christophe Grojean at Higgs2020 conference*

Beyond the HL-LHC



• *Slide from Christophe Grojean at Higgs2020 conference*