Higgs physics at the LHC: status and prospects

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A personal and biased selection of results. An experimentalist view.

5th ComHEP: Colombian Meeting on High Energy Physics
November 30th-December 4th, 2020

ATLAS EXPERIMENT LPNHE PARIS

Our tools

The LHC and its particle detectors

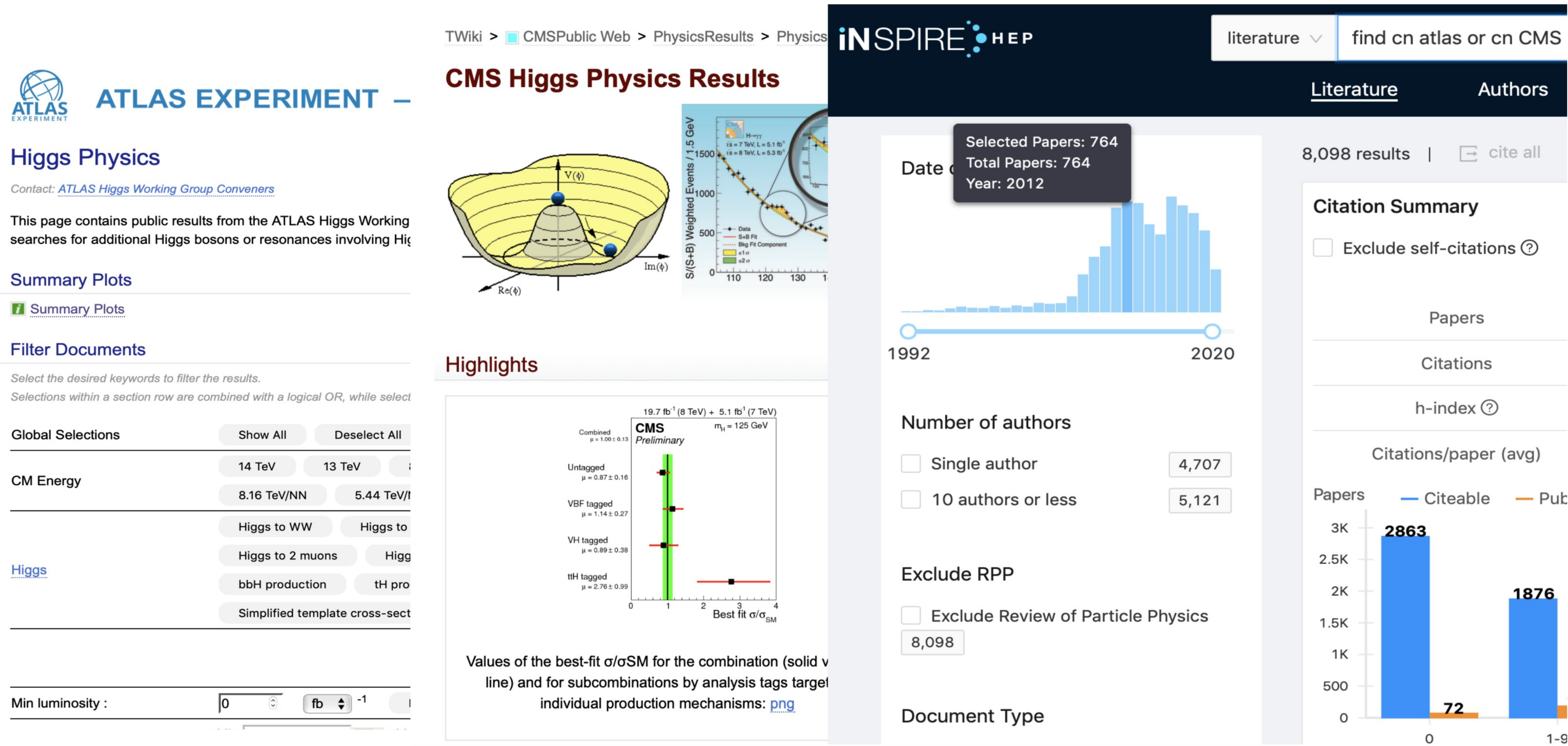
- A proton-proton collider of 27 Km circumference situated at CERN. Currently running at an center-of-mass energy of 13 TeV since 2015

- Non-specialized detectors*: broad range of physics, same concept, different technologies
  - Excellent vertex and tracking systems
  - Large coverage for muon detection
  - Excellent calorimetry with extended coverage

** There are more than two at LHC but will mainly hear in this talk about ATLAS and CMS*

A Higgs boson was discovered in 2012

A Higgs boson was discovered in 2012



- **Hundreds of papers since its discovery: ATLAS public, CMS public results**
- A Nobel prize in Physics 2013 for Francois Englert and Peter W. Higgs:
  - *"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"*
- **Why do we care?**

The Standard Model (SM)

Quick reminder

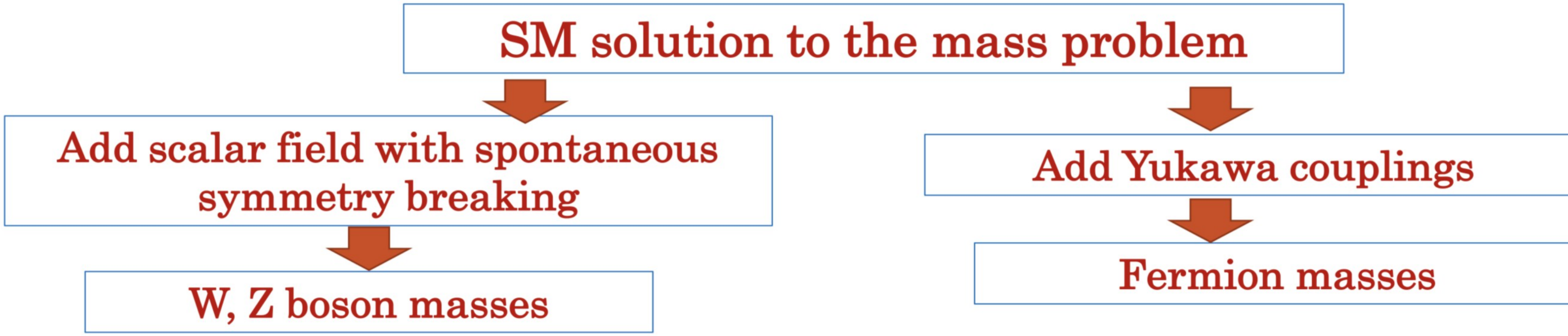
- The particle physics world in 1975
- The **local gauge symmetry** that defines the SM is

QCD → SU(3) x SU(2) x U(1) ← Electro weak

- 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 secrets: is the SM Lagrangian structure correct? Are the values of the coupling 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)

The Standard Model (SM)

And the Higgs physics was born...

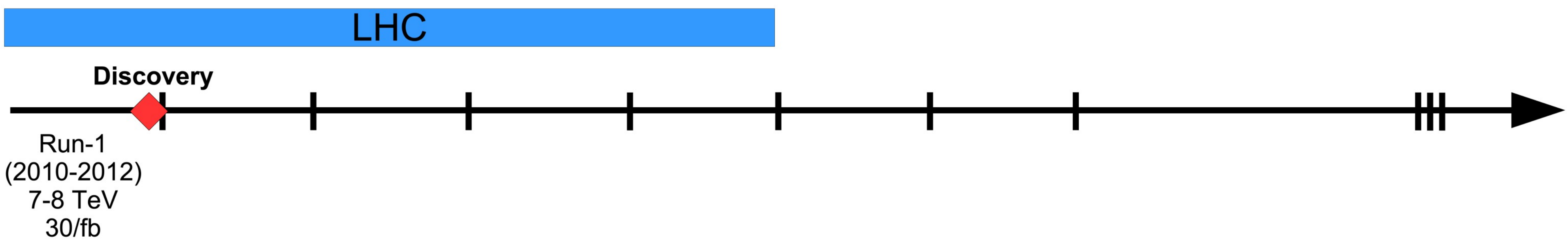
Standing ovation in the CERN auditorium at the end of the seminar announcing the discovery of the Higgs boson. (Image: Maximilien Brice, Laurent Egli/CERN)

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)

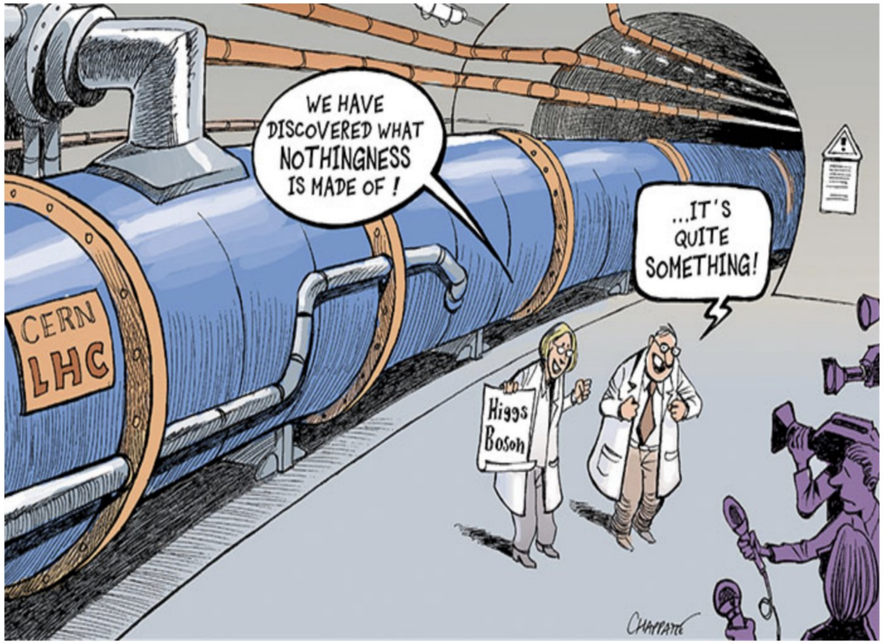
The road to discovery



- 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

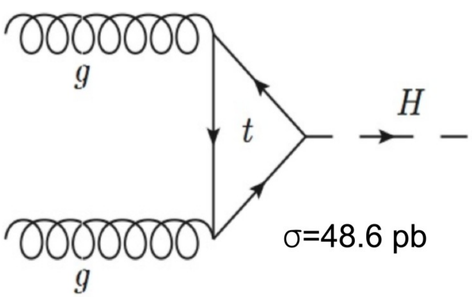
- Very quickly ATLAS and CMS excluded the existence of a SM Higgs in a very large mass range, spanning up to ~600 GeV... with the exception of a very narrow window ~125 GeV
- Discovery in 2012!



Identifying the Higgs boson at the LHC: production

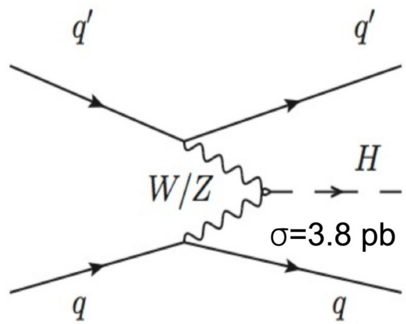
Different analyses performed by LHC experiments, depending on the Higgs production mode:

Gluon fusion (ggF)



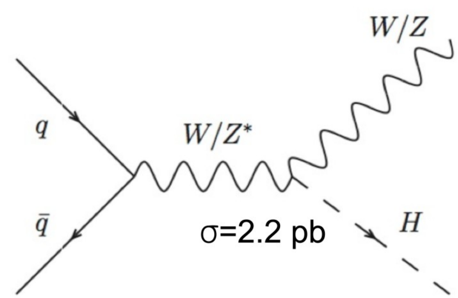
- Main production mode at the LHC
- Large backgrounds

Vector Boson Fusion (VBF)



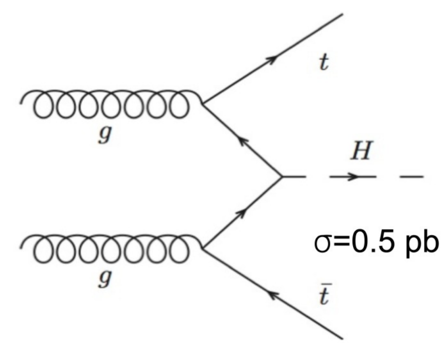
- The two jets with high rapidity separation improve triggering and bkg rejection

W/Z associated production (VH)



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

tt associated production (ttH)



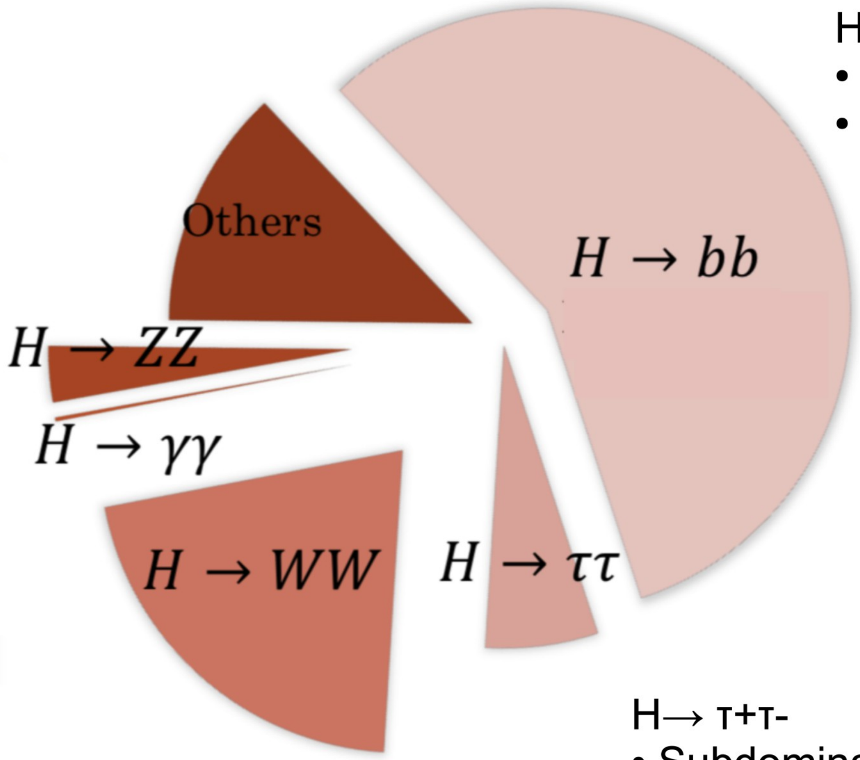
- Semileptonic and hadronic top decays
- Accessibility to the top Yukawa coupling

Identifying the Higgs boson at the LHC: decay

Which production mode or/and decay is the best?

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

$H \to Z^{(*)}Z$
- Penalty from $Z \to l^+l^-$
- BR very clean, fully reconstructed



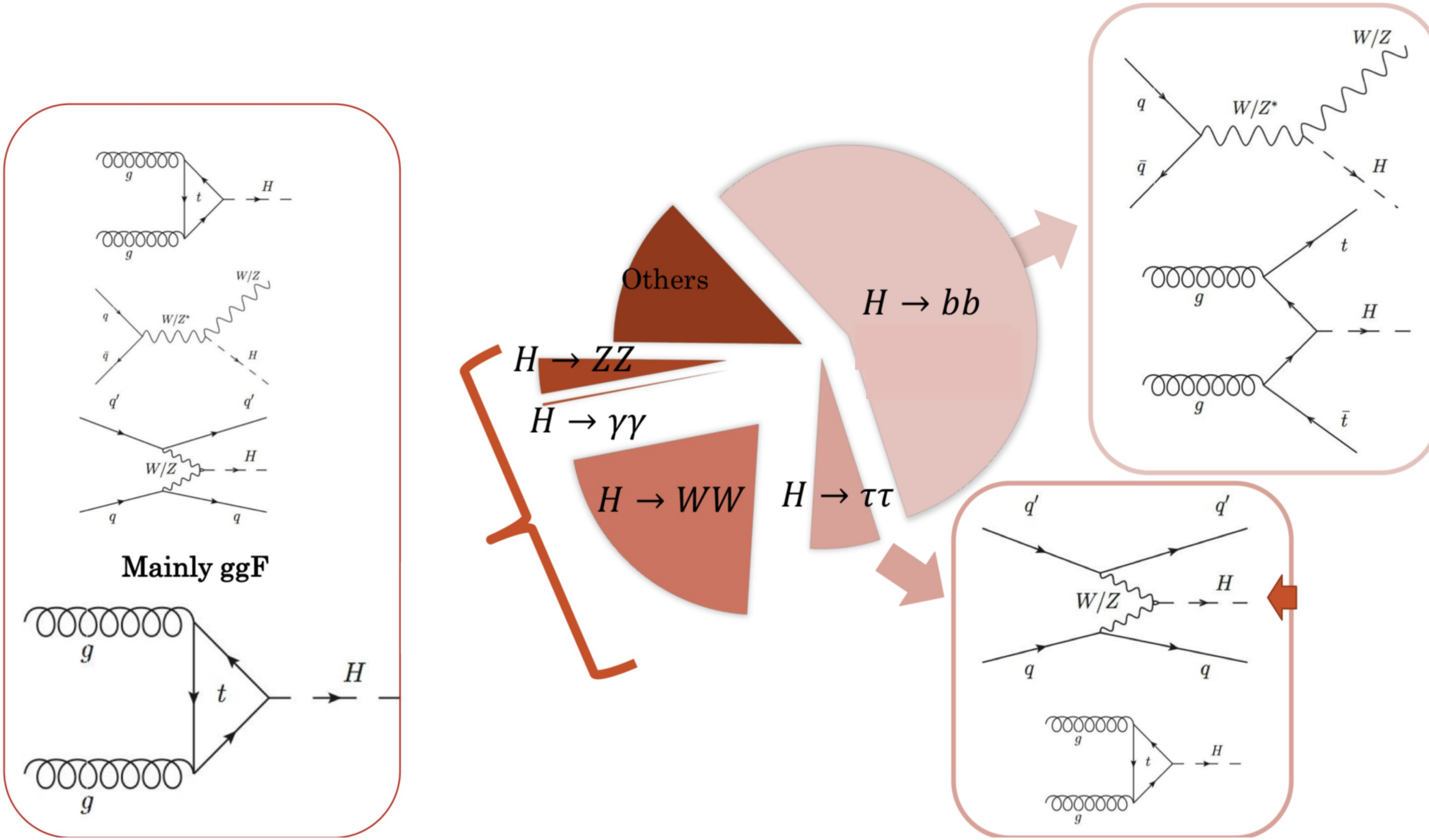
$H \to \gamma\gamma$:
- Very small BR
- Huge bkgs. from QCD photons and jets
- Fully reconstructed, clean mass measurement

$H \to W^+W^-$
- Subdominant (~22%)
- Incomplete reconstruction

$H \to \tau^+\tau^-$
- Subdominant (~6%)
- Incomplete reconstruction

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

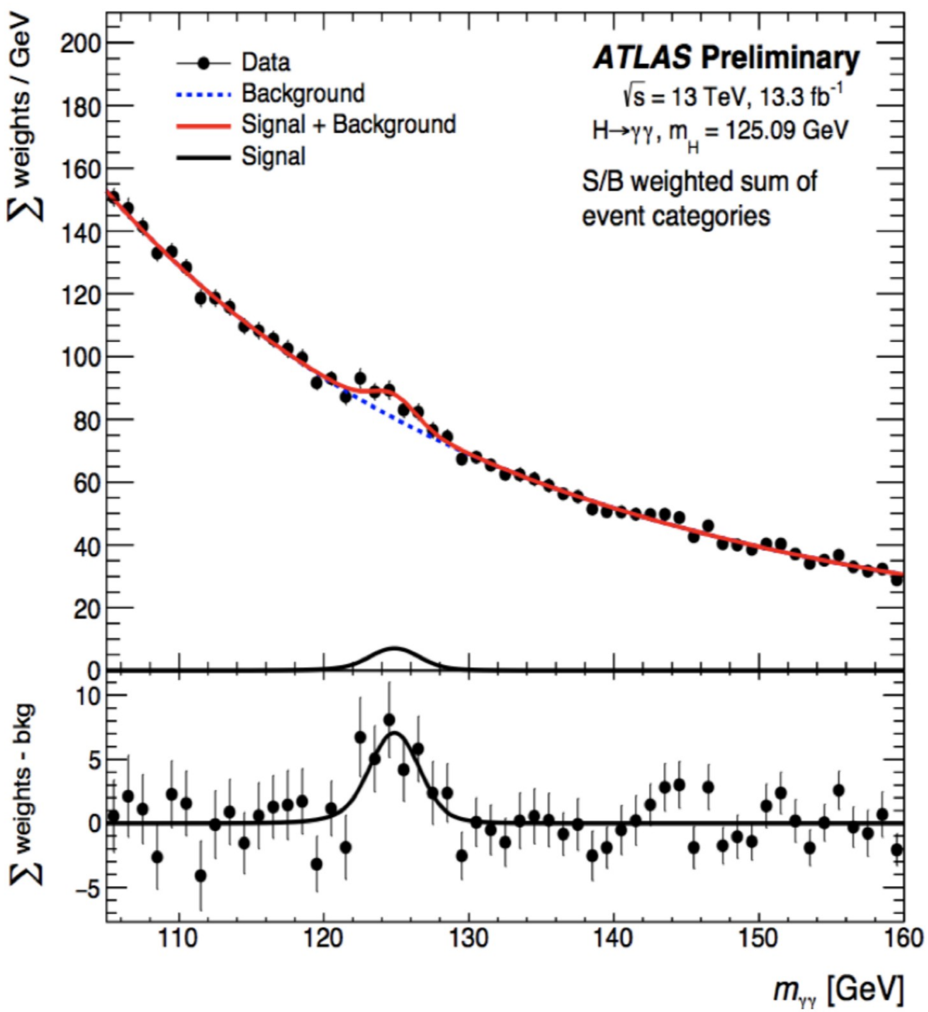
Identifying the Higgs boson at the LHC: Interplay between production and decay

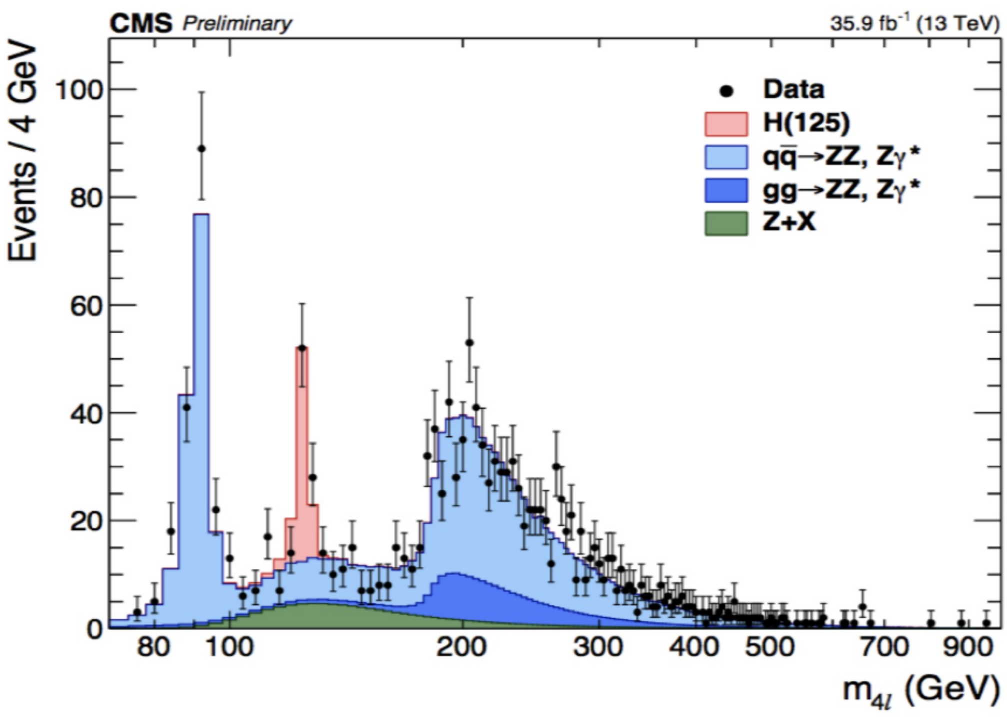


• *Slide from George Aad's JRJC 2014 talk*

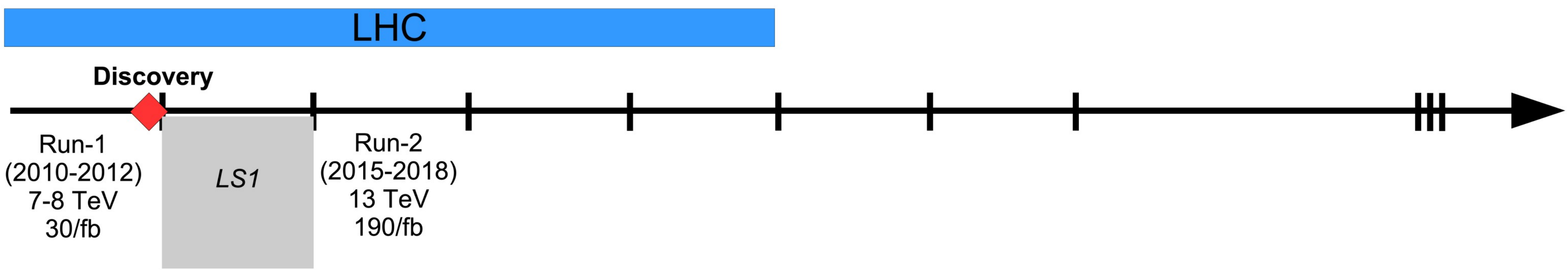
Identifying the Higgs boson at the LHC: Interplay between production and decay

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

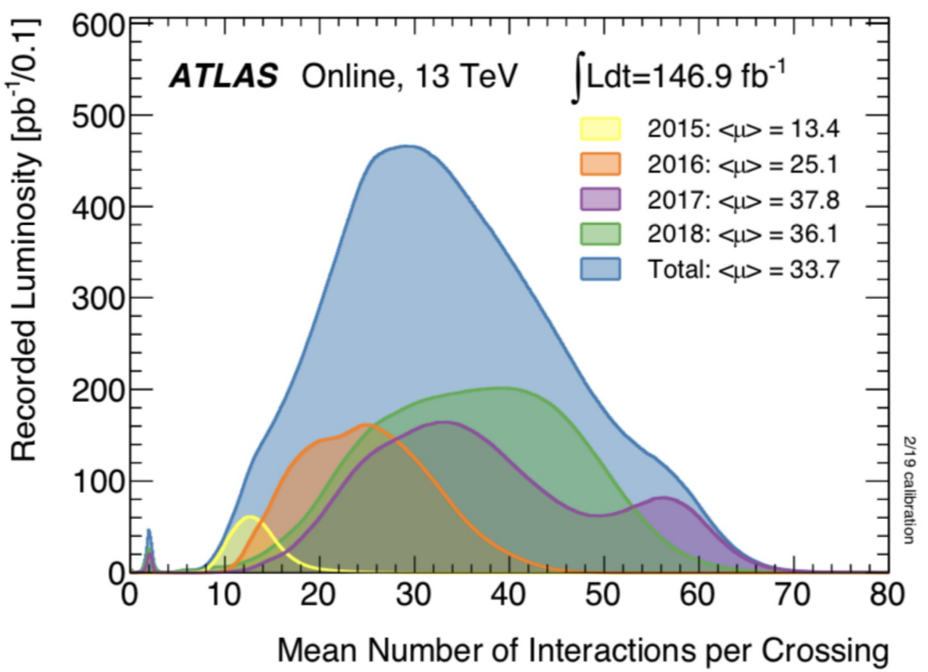




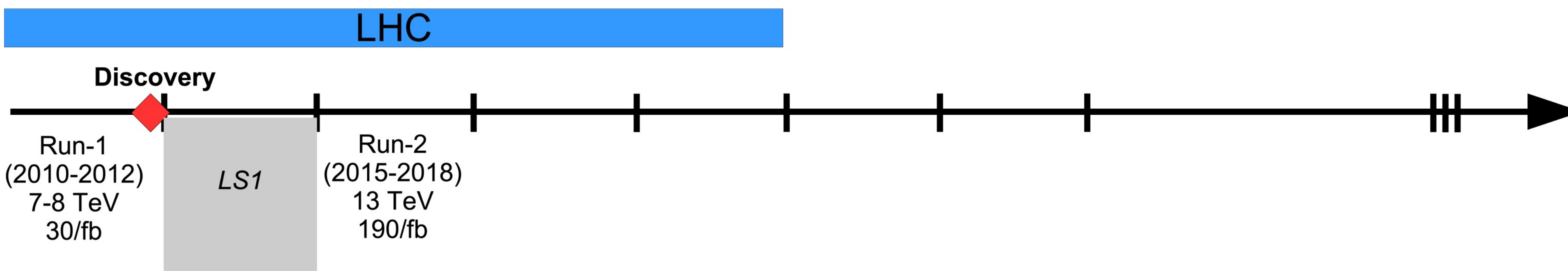
Where are we today?



- **~140/fb collected in Run-2 for physics analyses in ATLAS and CMS** → Large increase in integrated luminosity vs time
- Major improvements in performance and analysis methodologies
- **Major progress in last few years:**
  - Observation of H→ττ using 2016 data
  - Observation of H→bb decay in 2018
  - Observation of ttH production combining different decay modes
  - Evidence of H→μμ decay



Where are we today?



- **Analyses are in different stages:**
  - Precision (e.g. $\gamma\gamma$, WW, ZZ, $\tau\tau$)
  - Recently observed (e.g. bb)
  - Searches (e.g. cc, $\mu\mu$, di-Higgs)

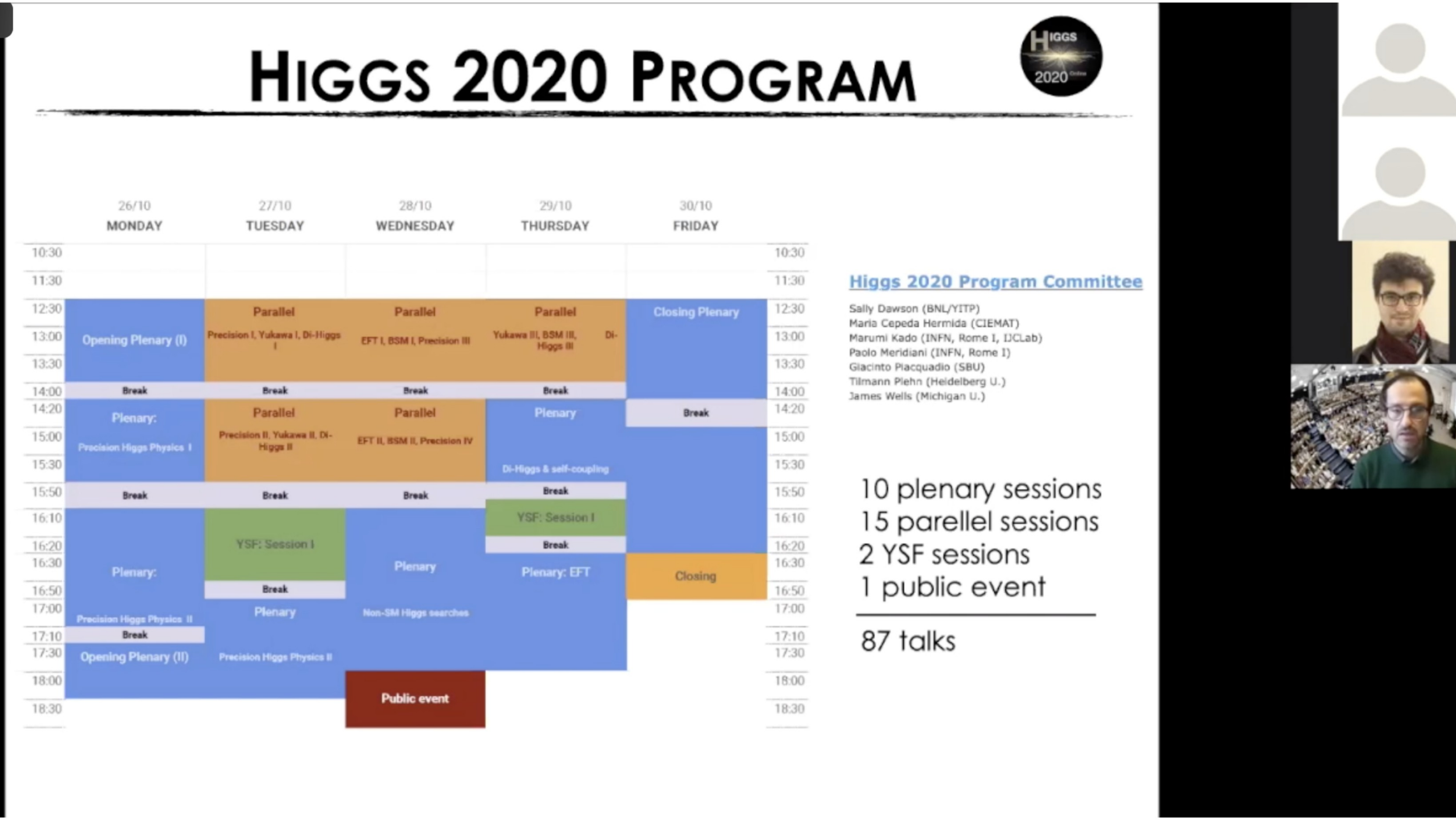
- I will highlight a few recent results, state of the art, mostly using full Run-2 results

- Many analyses being updated at the moment. Expecting many more new results in the next few months

Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$ 210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$ 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

Large sample of ~8M Higgs bosons (per experiment) produced in Run-2

In COVID times



On the precision side (1/2)

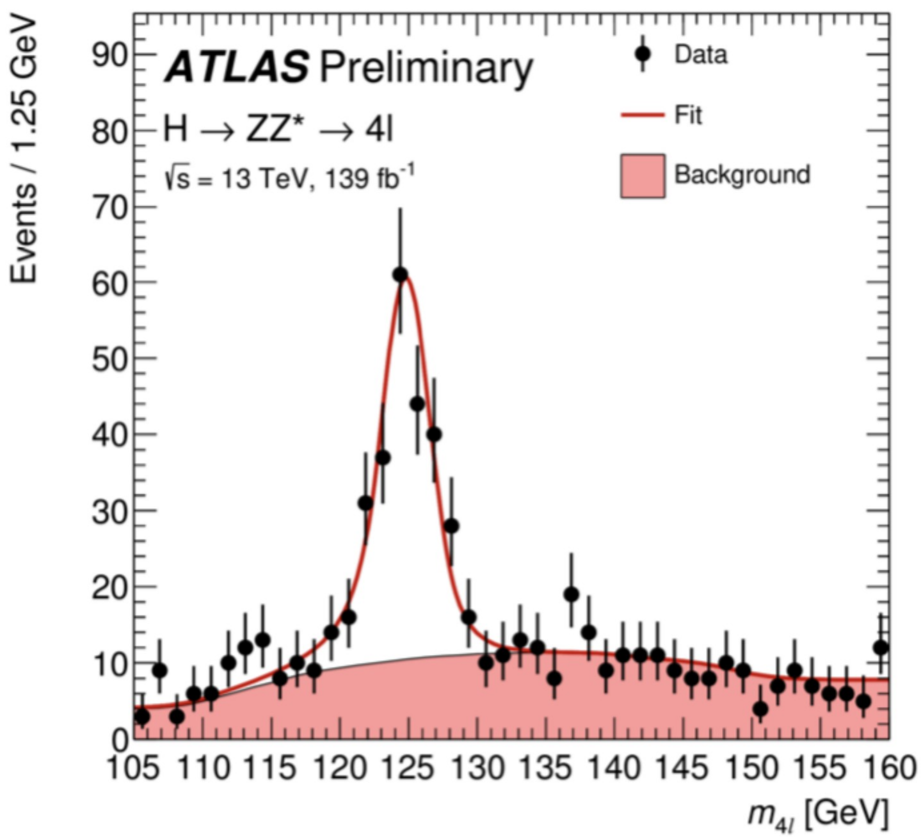
- **Mass measurement precision at the level of 0.1%** using ZZ events by ATLAS using full Run-2 dataset

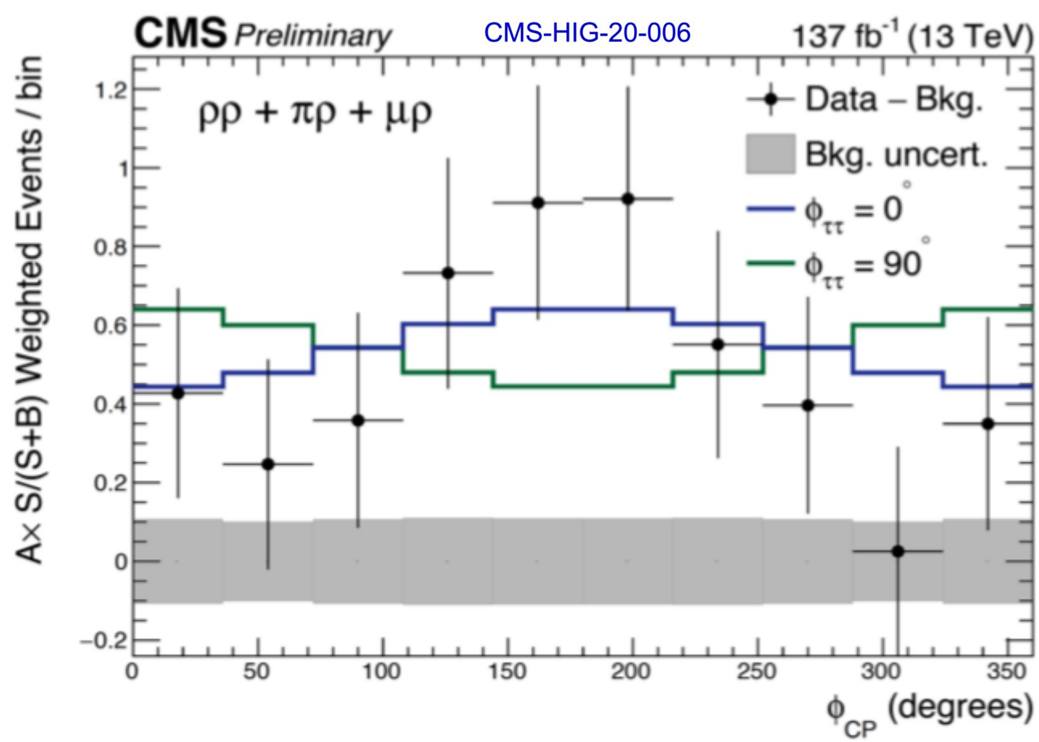
- Statistical uncert. leading. Systematics: μ momentum scale leading

- CMS first H→ττ CP-mixing angle measurement (using full Run-2 dataset)
- Constrained to $\phi_{\tau\tau}$=(4 +/- 17)° (68% CL)

- **Reject CP-odd component to couplings with fermions at more than 3σ**

ATLAS-CONF-2020-005

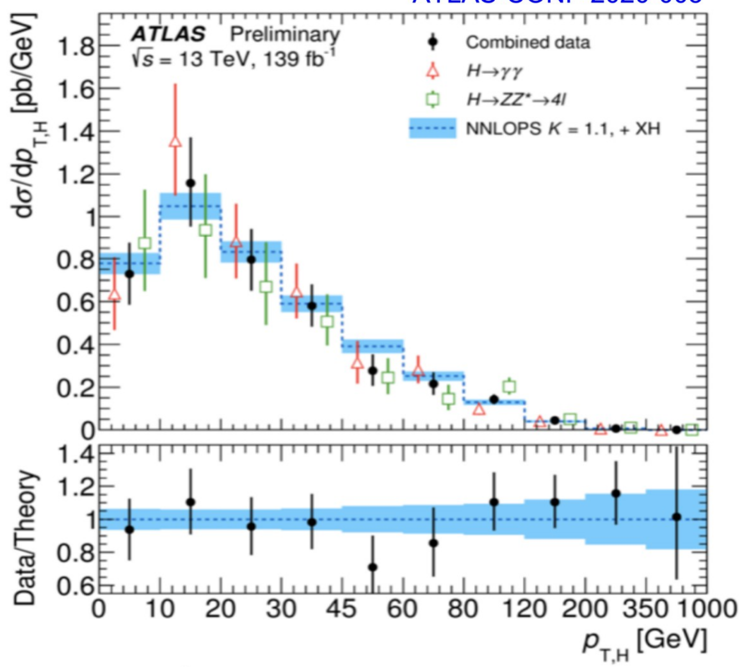


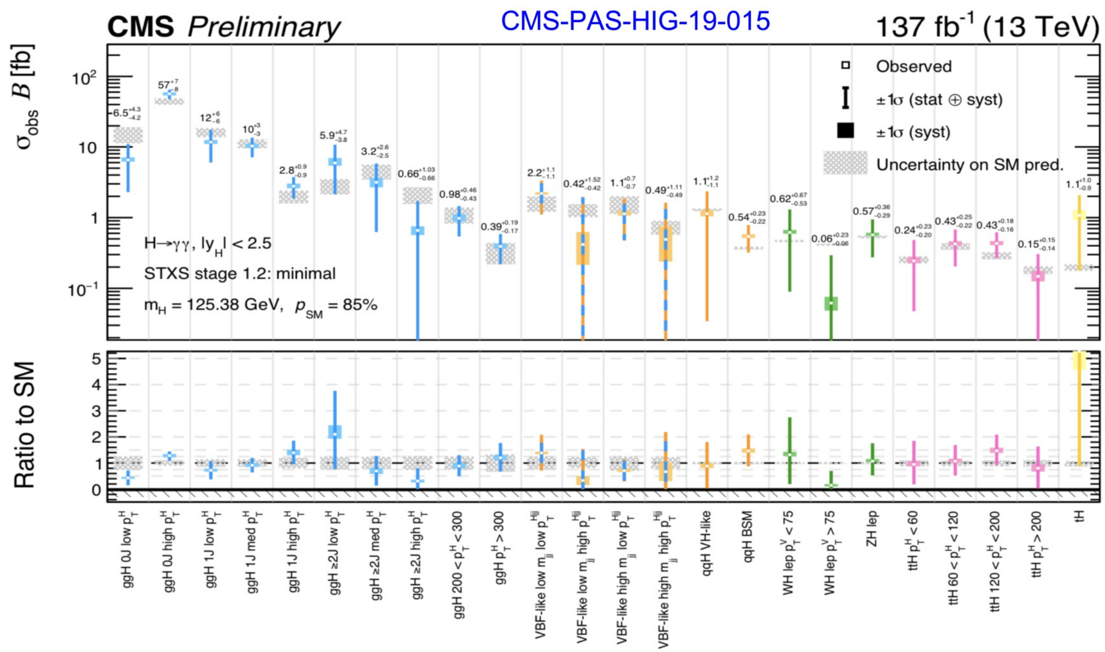


On the precision side (2/2)

- **Vast program of kinematic measurements:**
  - Inclusive Higgs production measured at <10% accuracy
  - all 5 main production modes observed
  - Differential cross-sections
  - Measurements by production mode in various kinematic regions (STXS)

ATLAS-CONF-2020-005

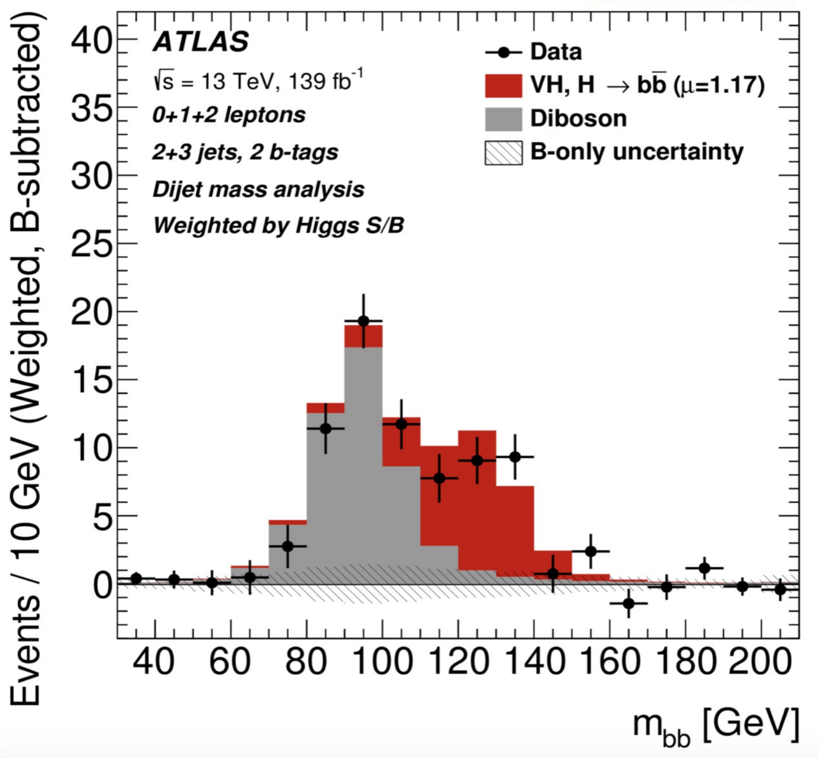




Recently observed

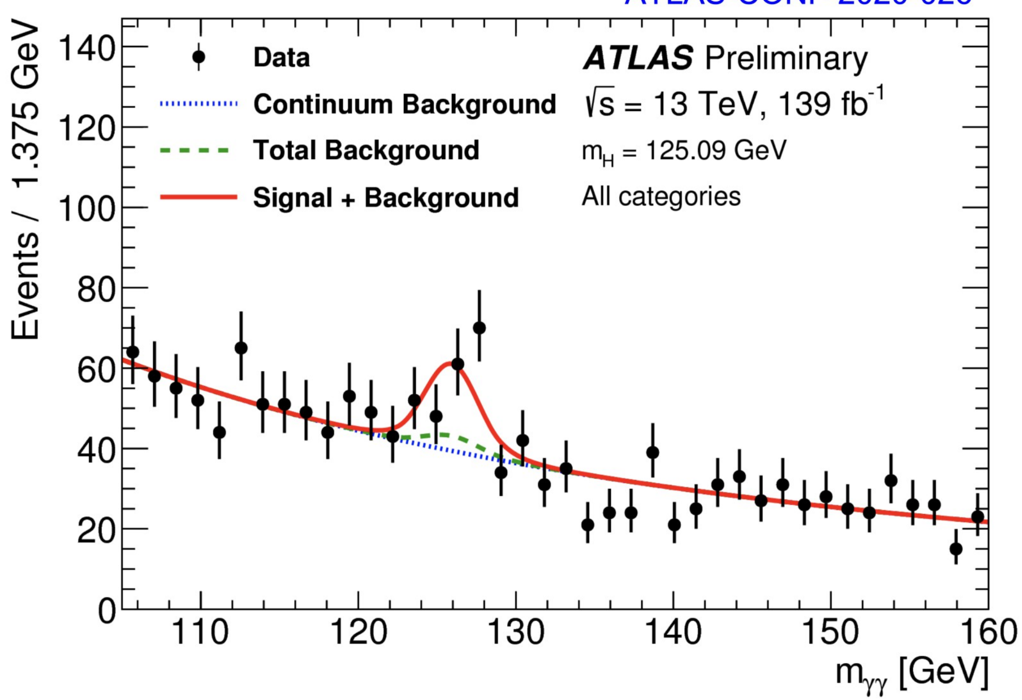
- **ATLAS VH, H→bb full Run-2 obtained a significance of 6.7σ**
- Main uncertainties: signal modelling, flavour tagging response, JER and JES, V+jets modelling
- **CMS observation combining Run-1 and partial 2017 dataset**

arXiv:2007.02873



- **ttH observation in 2018** by:
  - CMS: 5.2σ (4.2σ exp)
  - ATLAS: 6.3σ (5.1σ exp)
- Now observing some of the individual decays, e.g. ttH, H→γγ

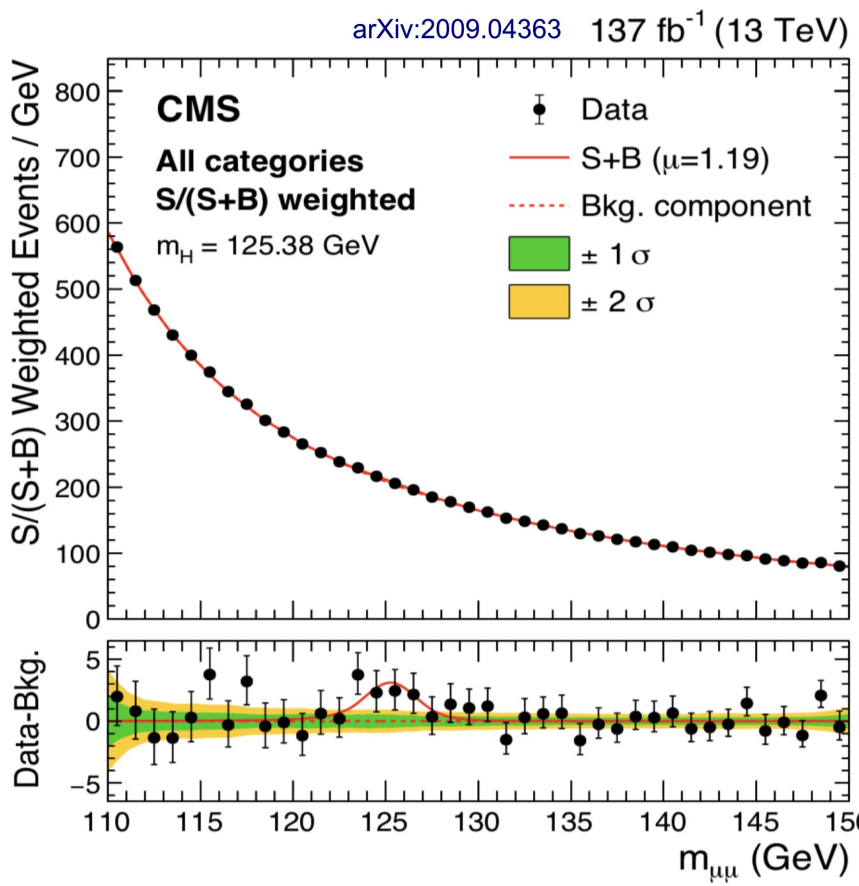
ATLAS-CONF-2020-026



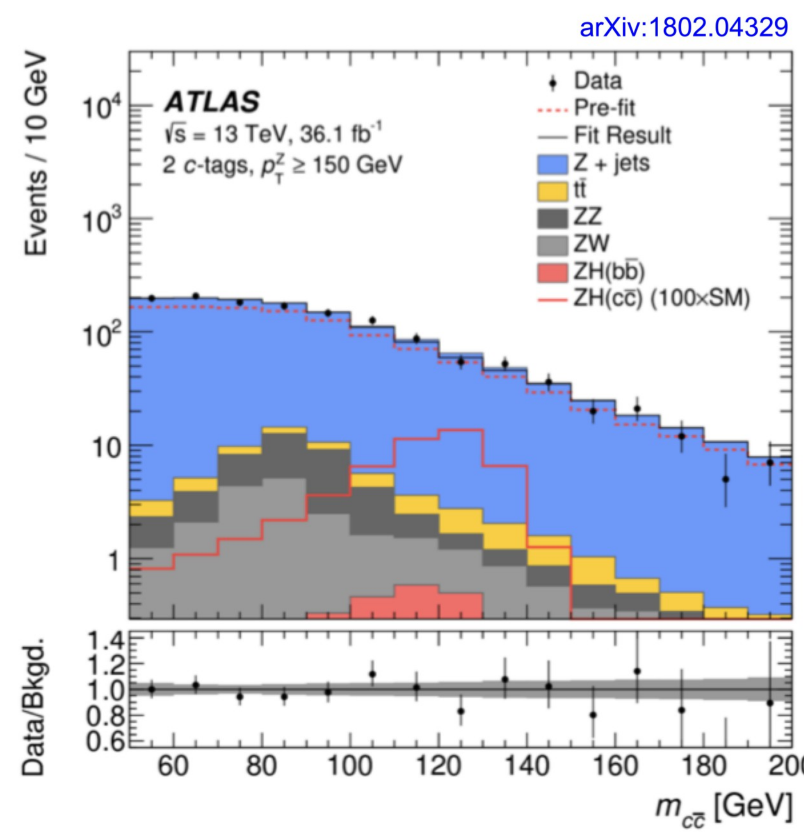
On the search side (1/2)

A new frontier: the 2nd generation! Small couplings in the SM and large backgrounds

- **Full Run 2 dataset search for H→ μμ**
- Results: CMS 3.0s (obs), 2.5s (exp), ATLAS: 2.0σ (obs), 1.7σ (exp)
- Consistent with SM prediction



- **CMS and ATLAS searching for H→cc**
- Make use of the VH production mode, machine learning based *c*-taggers
- Observed (expected) 95% CL upper limits on signal strength at 110 (150^{+81}_{-42}) by ATLAS and 70 (37^{+16}_{-11}) by CMS

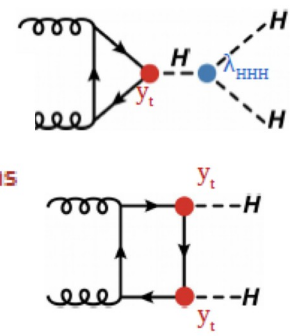


On the search side (2/2)

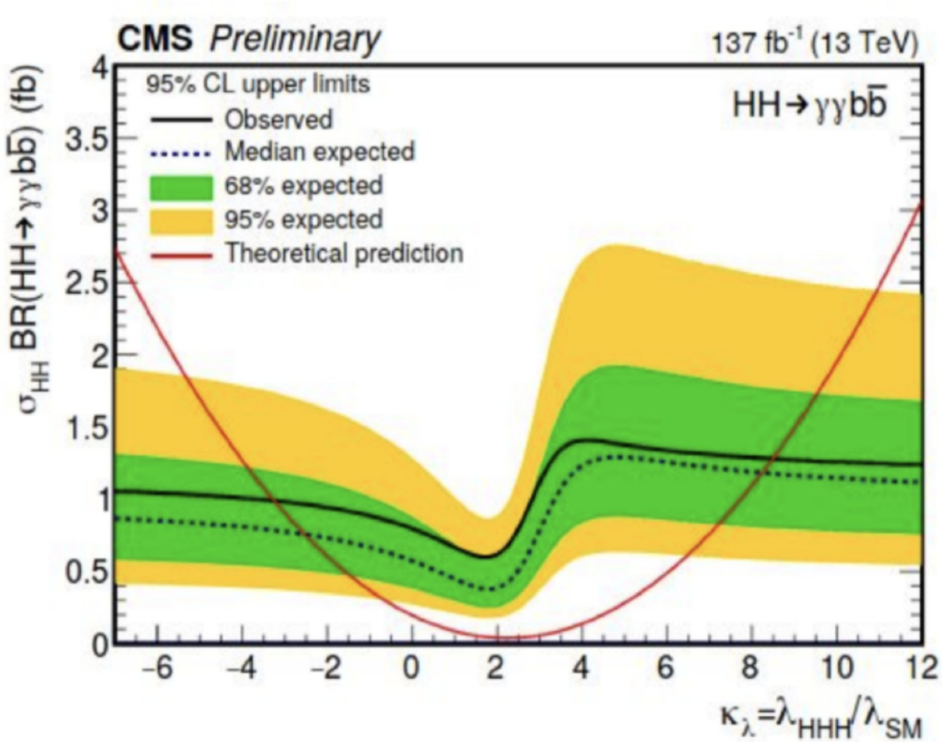
- Making progress towards **testing the shape of the Higgs potential through the Higgs self-coupling**
  - Rare process in SM: σ(gg→HH) ≈0.1%*σ(gg→H)

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

mass term self coupling terms



- Best 95% CL current limit on cross-section*BR on non-resonance production at 7.7x SM



HH decay branching ratios

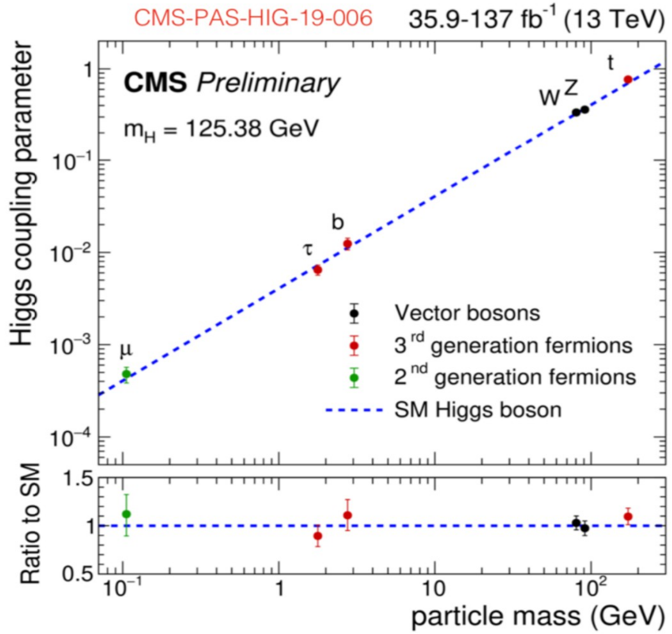
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

High BR

Precise mass reconstruction

The Higgs boson as a tool to search for new physics

- **So far, the 125 GeV Higgs boson has been shown to be very compatible with the SM**
  - Most recent ATLAS and CMS combined signal strengths:
    - ATLAS μ=1.06+/-0.07 (ATLAS-CONF-2019-037)
    - CMSμ=$1.02^{+0.06}_{-0.07}$(CMS-PAS-HIG-19-005)
  - Coupling to weak bosons (κ_V) consistent to within ~5% of the SM
  - Yukawa couplings observed for top, bottom, and tau fermions
  - Spin 0 confirmed during Run 1 with pure CP-odd state easily excluded in H→ZZ
  - Best fit to invisible BR compatible with SM: 0.00 +/- 0.06, with BR < 0.11 excluded at 95%



- **But 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
  - 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

• *From Pierre Savard at Higgs2020 conference*

The Higgs boson as a tool to search for new physics

B. Schuve

Direct searches for new physics: a snapshot

briefing

D. Curtin *et al.*, 1312.4992, PRD 90 (2014)

PROMPT DECAYS

- Many, MANY searches proposed in exotic Higgs decay paper. How do we do now, 7 years later?
- h to ss to 4 fermions: pretty good coverage of 4b, 2b+2lepton, 4 lepton (taus & muons)
  e.g., ATLAS 1806.07355; CMS 1812.06359; CMS 2005.08694
- h to ss to 4 gauge bosons: some searches for 2 photon + 2 gluon, 4 photons
  e.g., ATLAS 1509.05051; ATLAS 1803.11145
- h to two dark photons, Z + A': extensive searches with leptonic decays of dark photon
  e.g., ATLAS 1802.03388, CMS 1812.00380, ATLAS 2004.01678
- Flavour-violating decays: $h \to \bar{\ell}\ell'$
  e.g., ATLAS 1909.10235, CMS 1911.10267

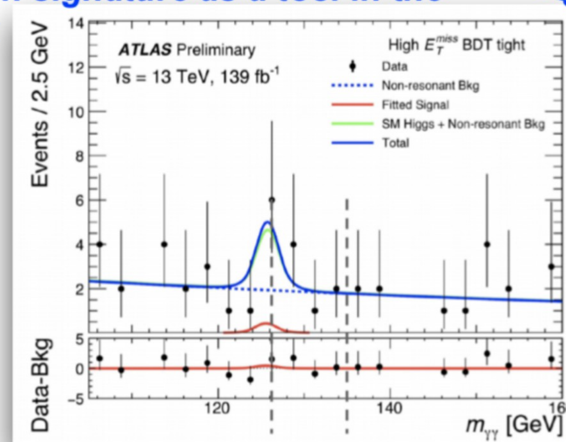
J. Alimena *et al.*, 1903.04497, J.Phys.G 47 (2020)

HIGGS + LONG-LIVED

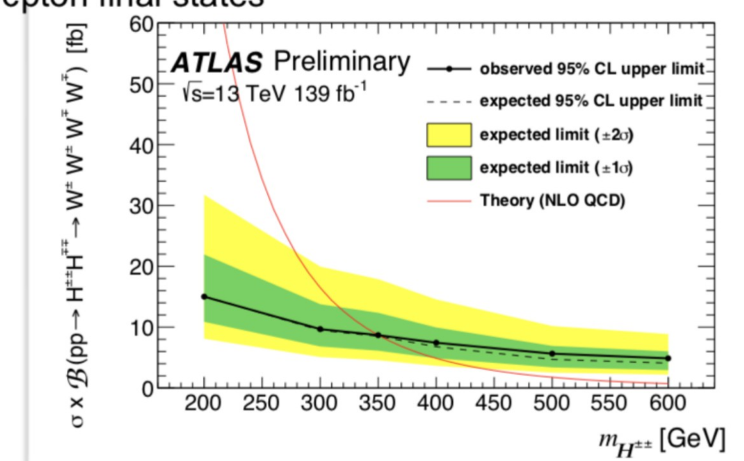
- Recently published LLP white paper takes a comprehensive look at (gaps in) coverage of LLP signatures, including from Higgs decays
- Where coverage is currently pretty solid:
  - LLP produced in Higgs decays & decaying to muons (some coverage of other flavour combinations too)
    ATLAS, 1808.03057, PRD 99 (2019); CMS, 1409.4789, PRL 114 (2015) ATLAS, 1504.05162, PRD 92 (2015)
  - Multiple lepton jets (collimated sprays of leptons + pions)
    ATLAS, 1909.01246, EPJC 80 (2020)
  - 1 or 2 LLPs produced in Higgs decays & decaying hadronically, **provided** they live long enough to reach

✦ ***SM Higgs boson signature as a tool in the questo for NP:***

✦ full Run2 H->γγ+MET search



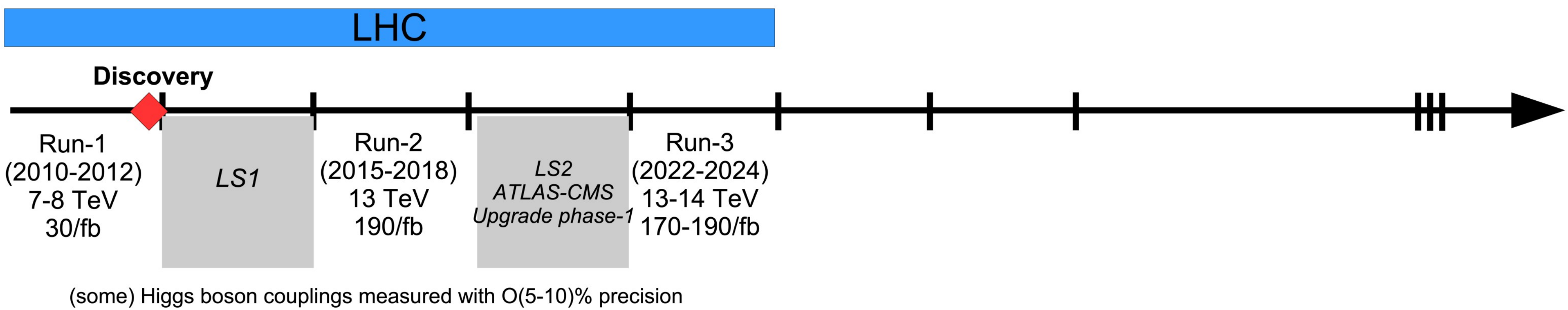
✦ ***Investigations ongoing also in extended Higgs sectors:*** $H^{\pm\pm}$ pair and single production in multi lepton final states



.... and many more ...

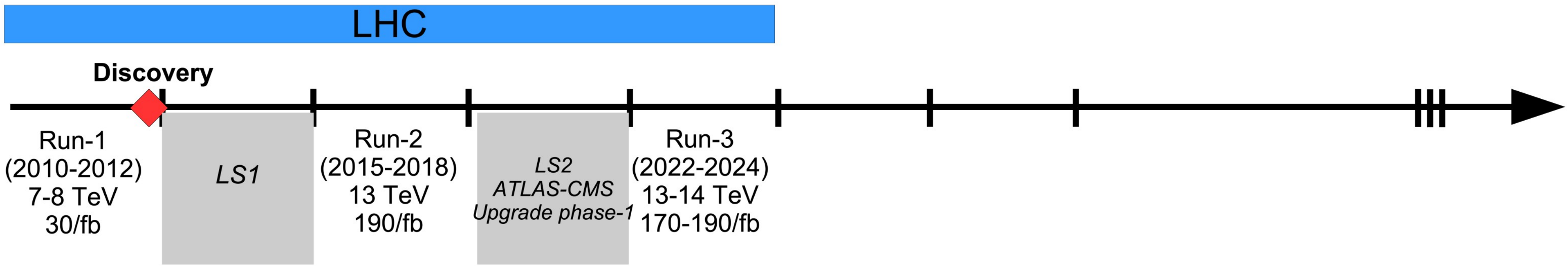
• *Summary slide from Valerio Dao from Higgs2020 conference*

Towards Run-3



- A 3-years run, plan to run at **2-2.5 times nominal luminosity** and modest increase in energy
- Start of Run-3 delayed due to COVID19
- A **lot of work for experimentalists and theorists:**
  - Need to reduce systematics (Theory, Modelling, PDFs), and improve our treatment of systematics as they become dominant for some analyses
  - Improving performance, analysis techniques

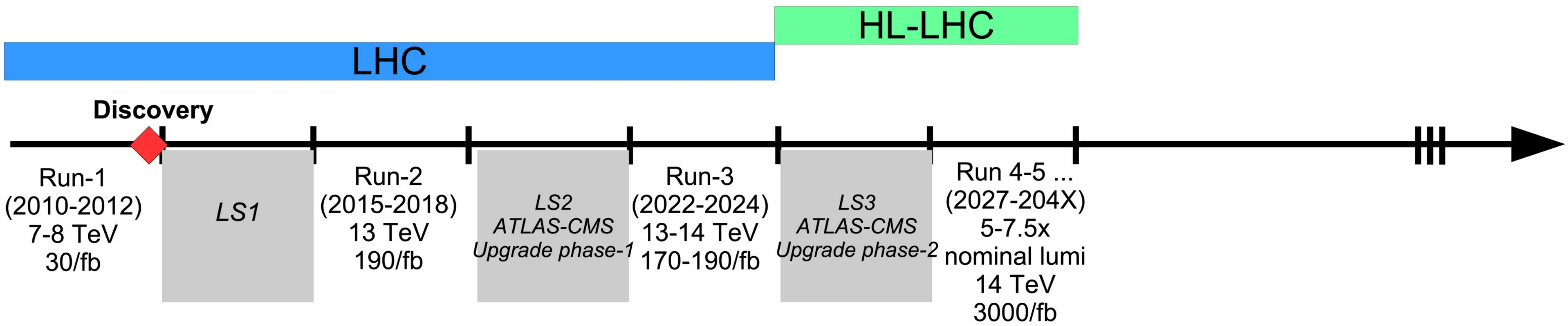
Towards Run-3



- **Full Run-2 and Run-3 will amount to 350-400/fb**! Some measurement will 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

- **Start of Run-3 delayed due to COVID19**

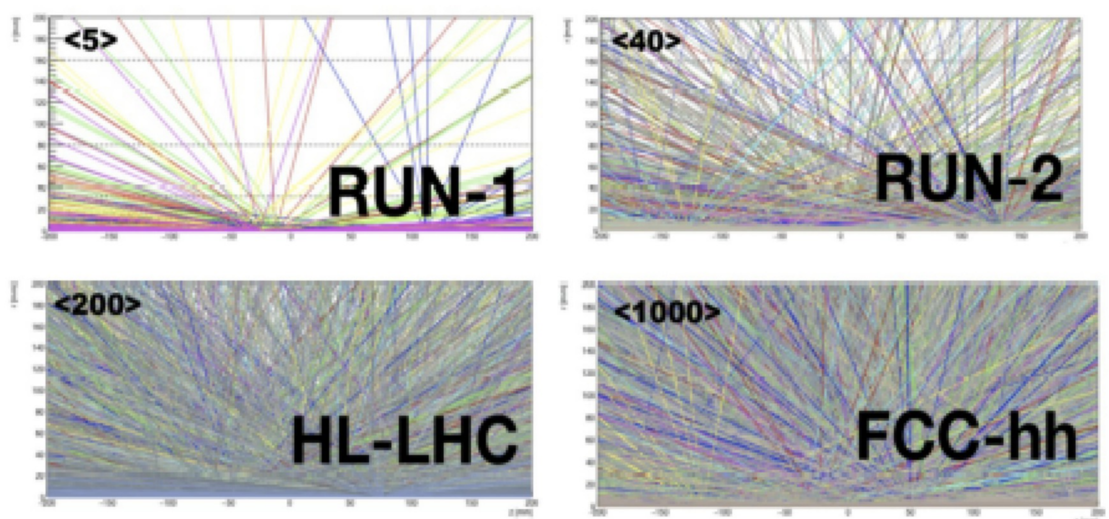
High Luminosity LHC (HL-LHC)



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

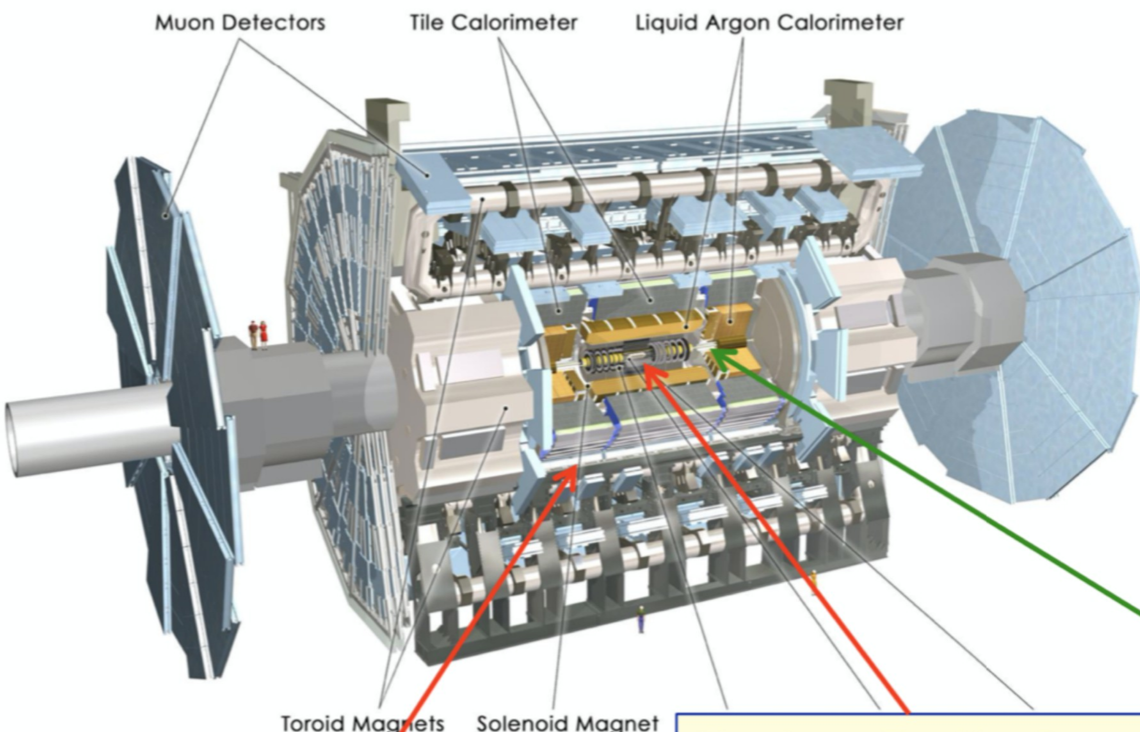
- **HL-LHC will be a Higgs factory:**
170M Higgs bosons - 120k HH pairs for 3000/fb
- Run-3 and HL-LHC means more data, hopefully a bit more energy (more reach for rare processed) but also a **more challenging environment**!

- **Phase-2 HL-LHC detector upgrades are being built**



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

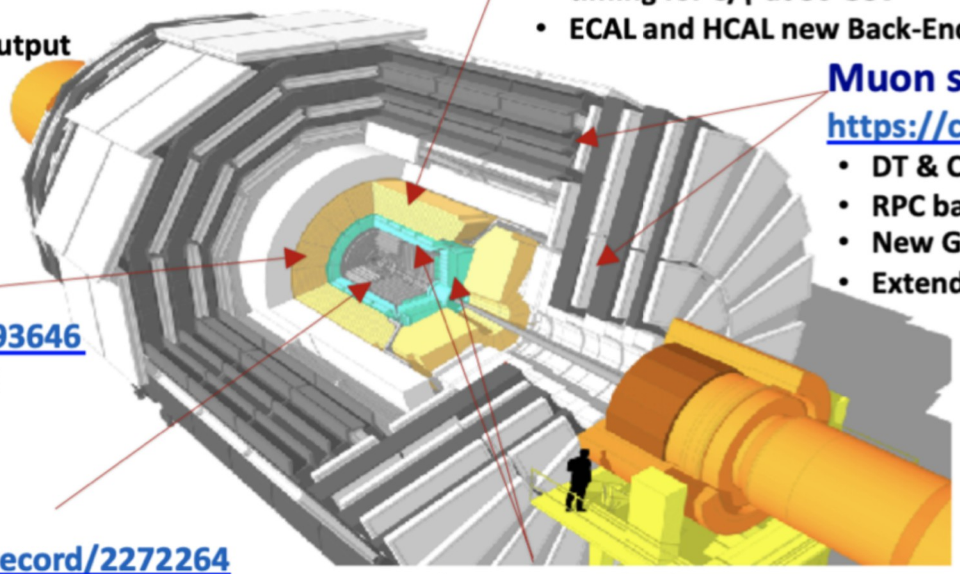
From R. Carlin
ICHEP 2020

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

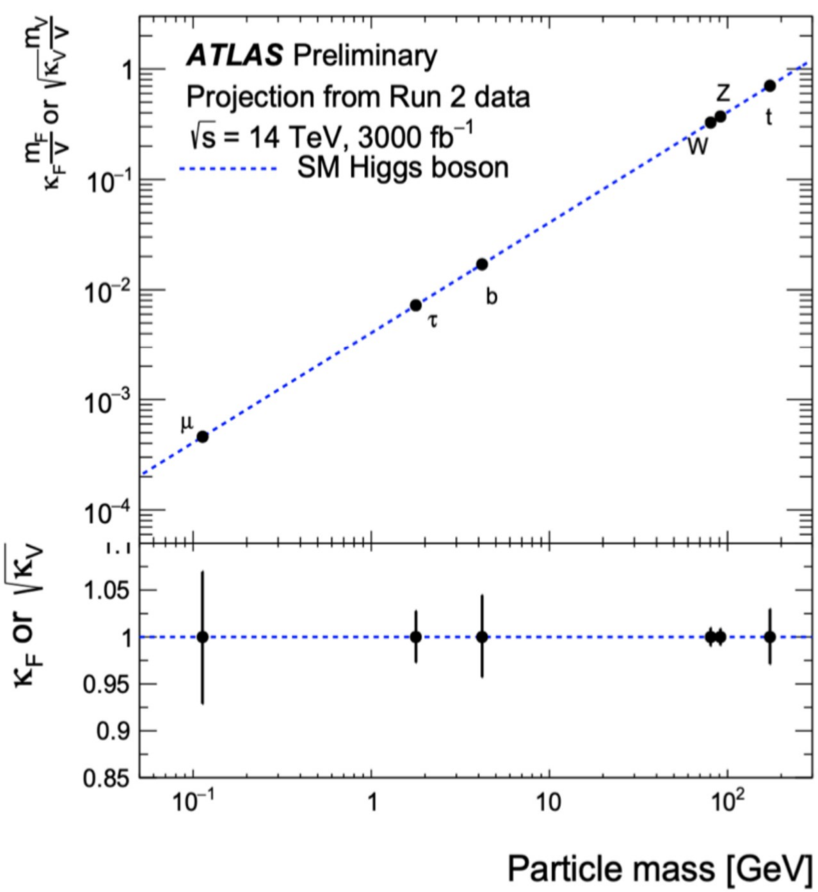
Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

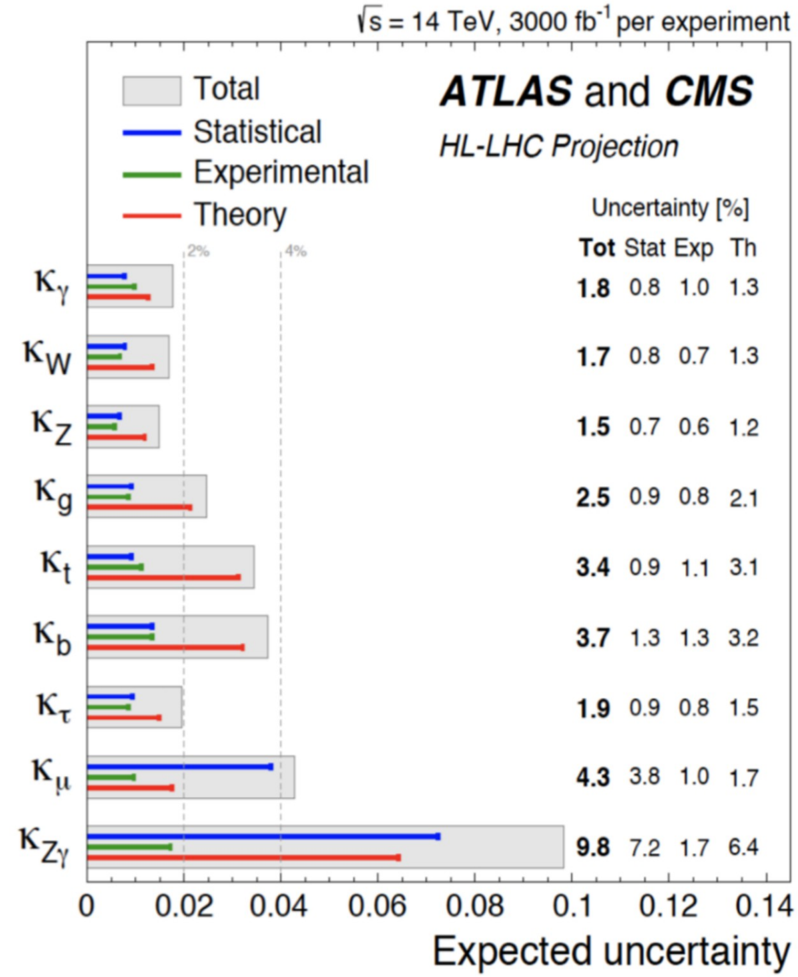
MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

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!



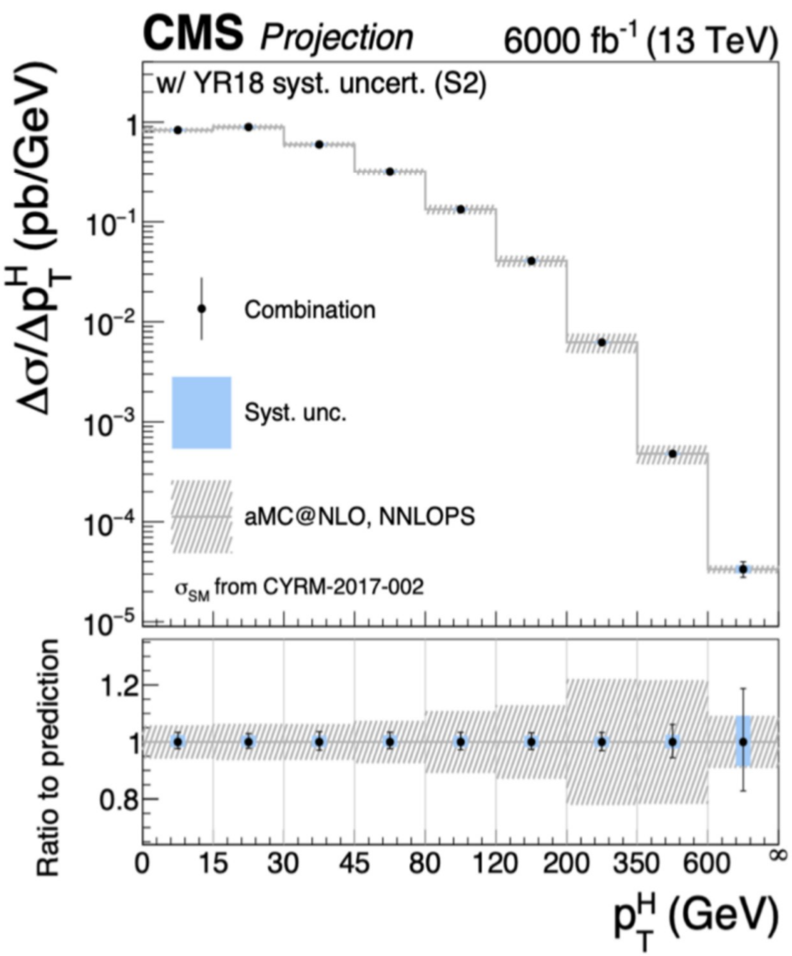


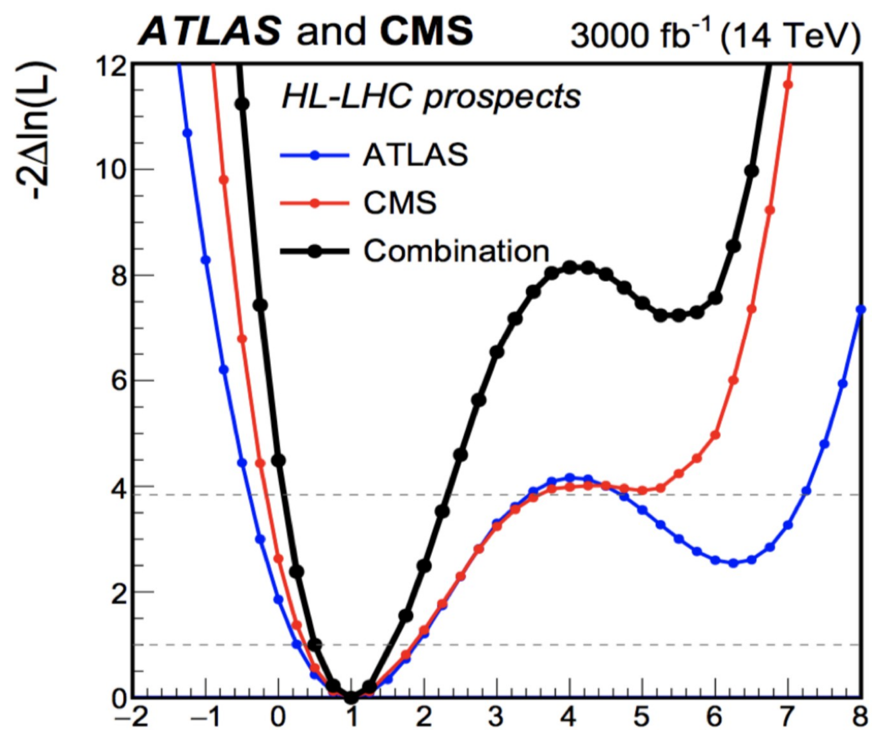
- 2-4% precision for many of the Higgs couplings. Theory uncertainty remains the largest component for most measurements
- Different uncertainties scenarios considered in these studies

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

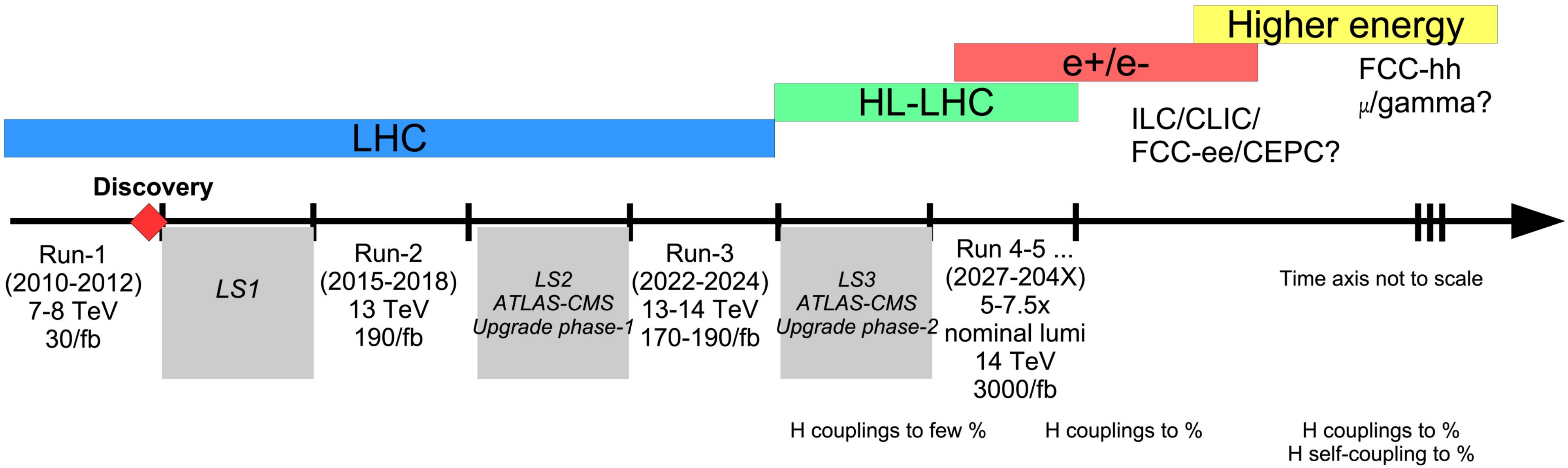




$$k_\lambda = \frac{\lambda}{\lambda_{SM}}$$

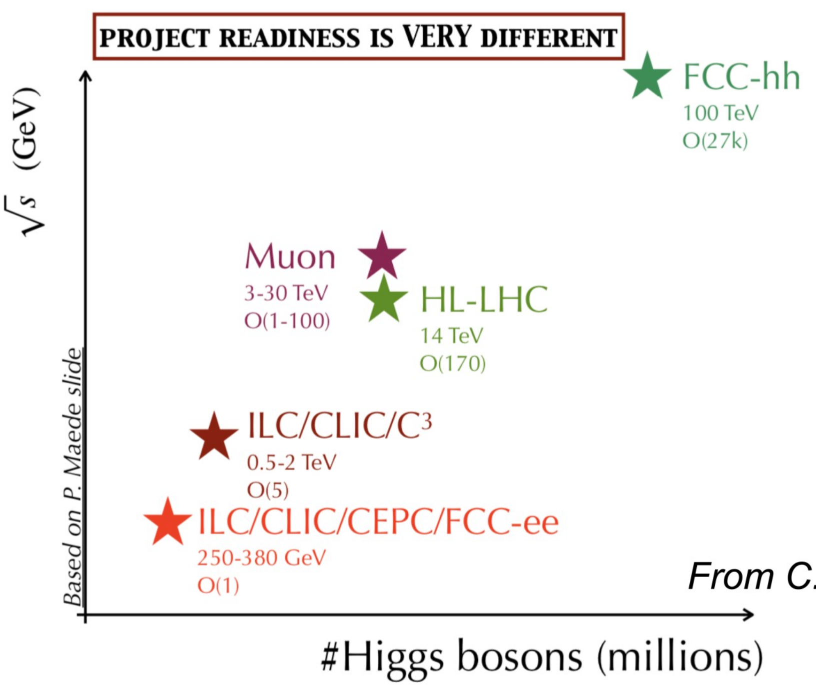
- Significance of HH signal at the 4σ level (both experiments)
- 50% uncertainty on the self-coupling

Beyond the HL-LHC



- **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

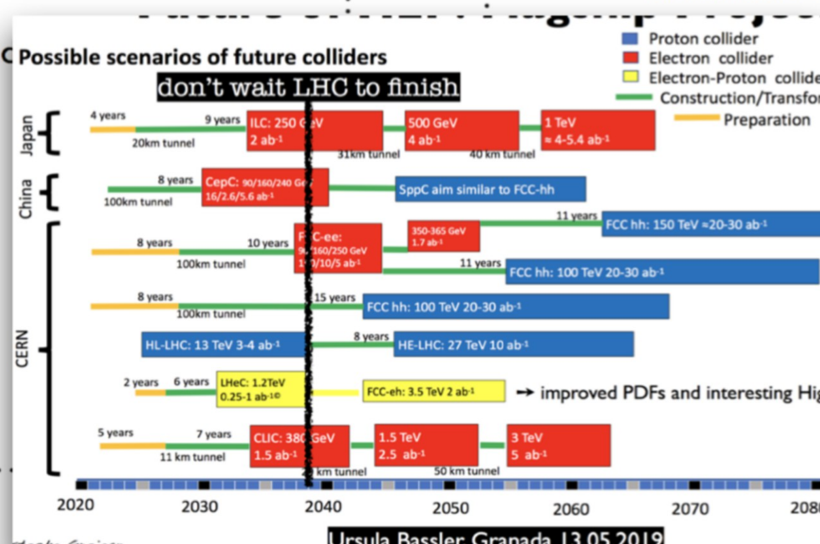
Which Machine(s)?

Hadrons

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

Leptons

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



Circular

- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
  - $\sqrt{s}$ limited by synchroton radiation

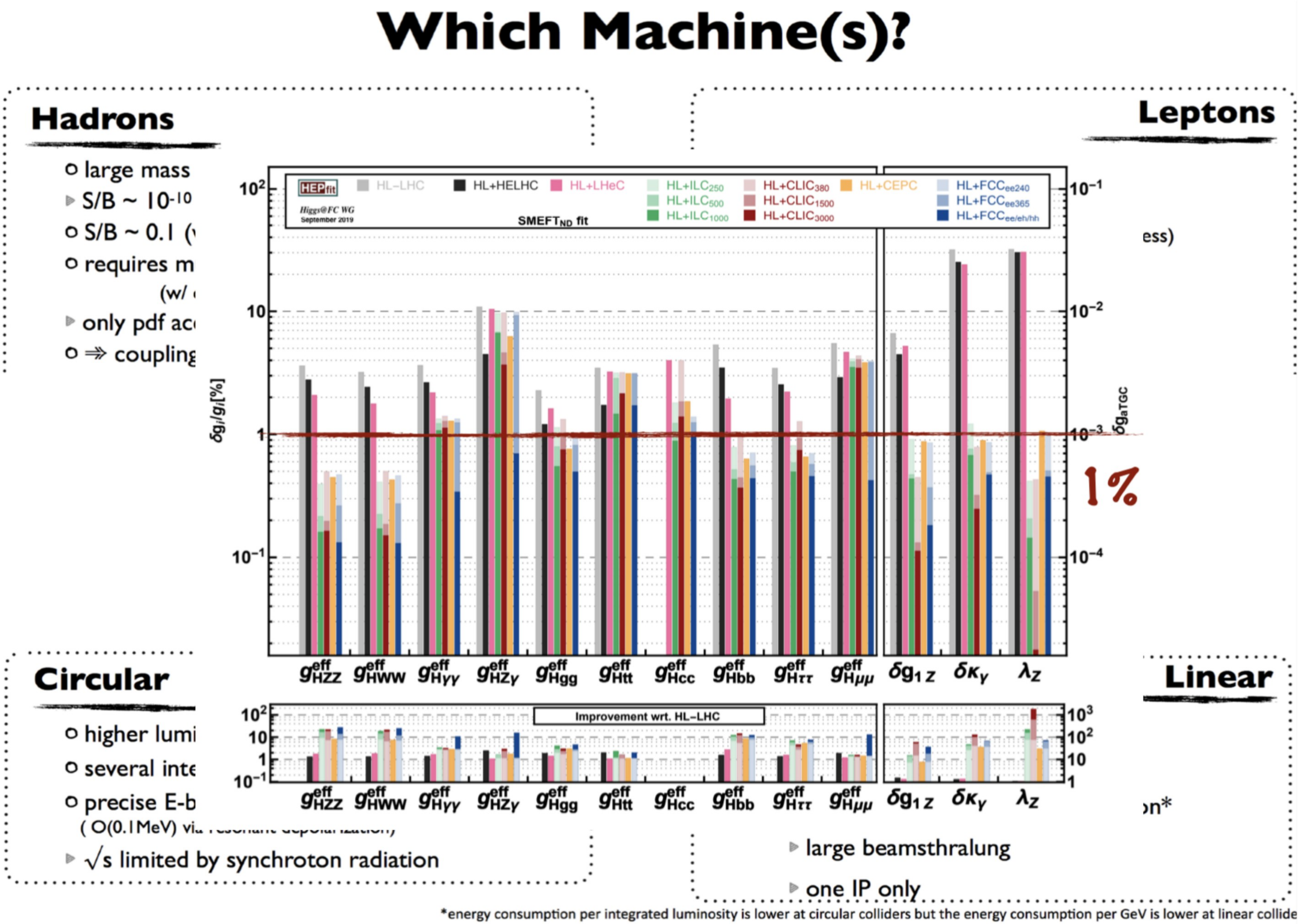
Linear

- easier to upgrade in energy
- easier to polarize beams
- "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*

To conclude

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

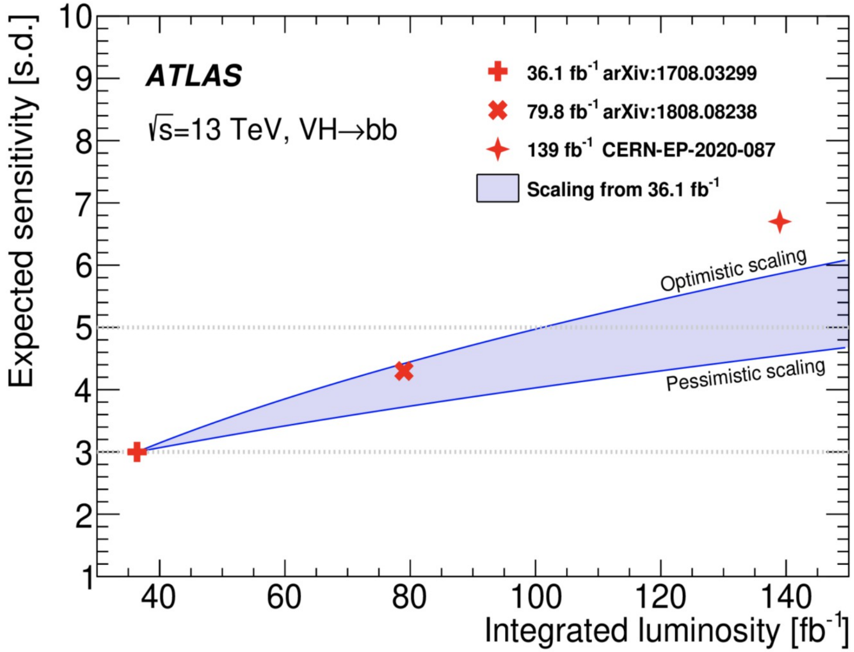
- All the measurements are in **good agreement with SM prediction** given the current precision. But **still space for new physics, unfortunately no roadmap available**

- **More analyses in progress using full Run-2 statistics!** More combination measurements are also expected in the following months and Run-3 will also start soon
  - The HL-LHC is a reality and we are evaluating updated scenario of proposed future colliders

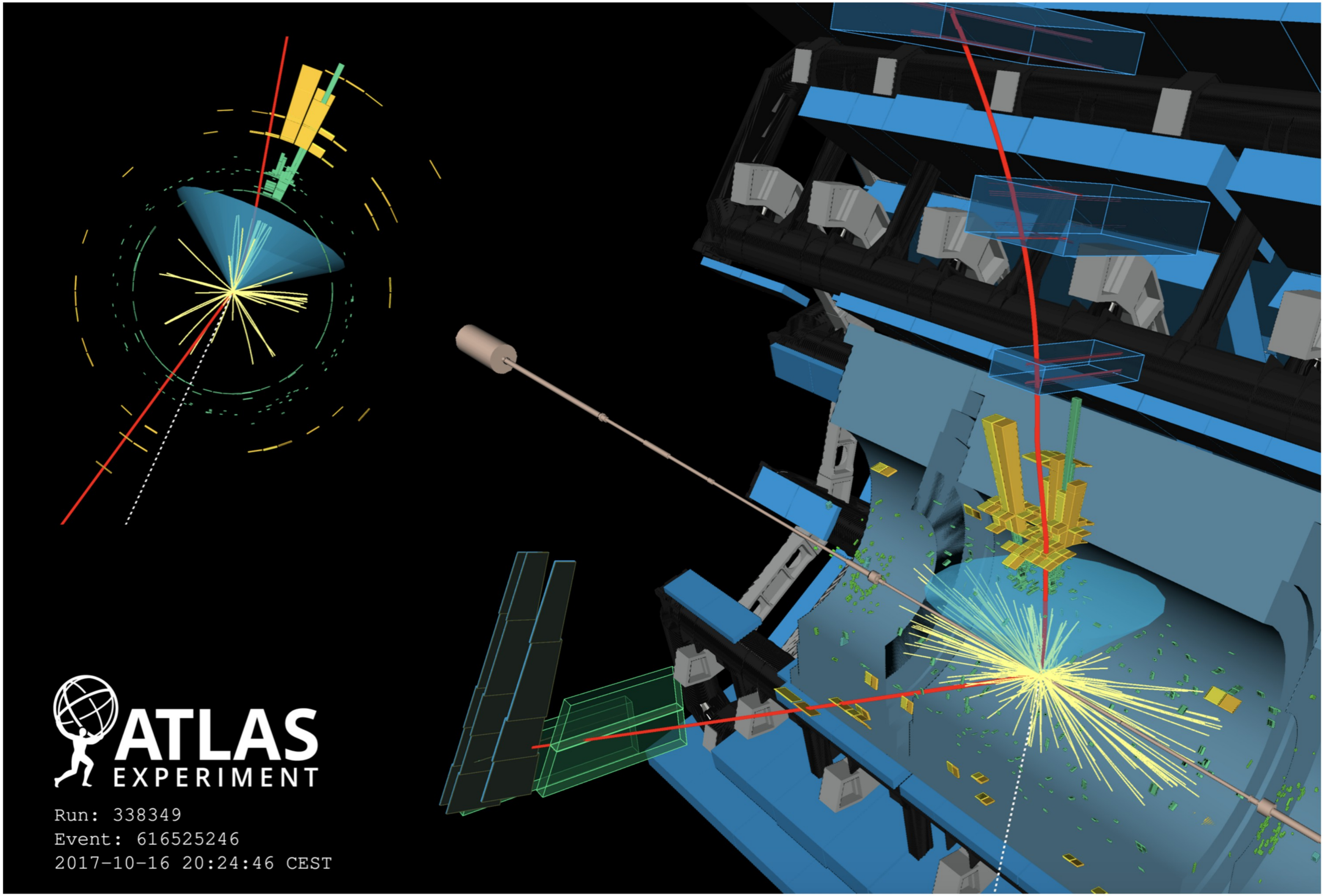
- **Huge effort to understand performance and potential of future machines**. Hopefully next LHC runs will provide new information about BSM existence and its scale!

- There is also a complementary and vibrant diversity program worldwide: MATHUSLA, FASER, etc

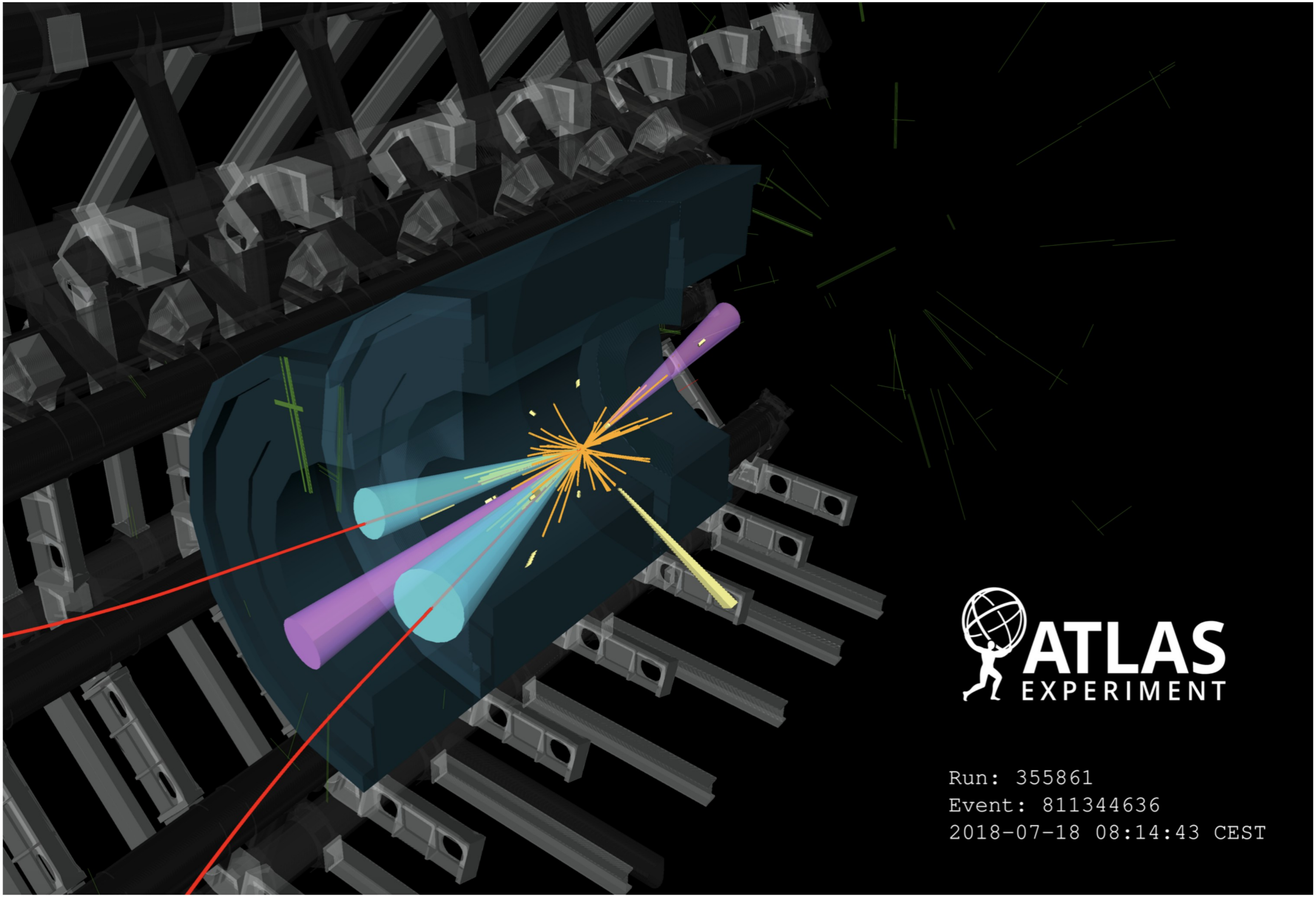
- Great to have these virtual spaces to bring the community together to discuss!



Boosted WH→μνbb candidate event



VBF H(→ bb)+γ candidate event



BACKUP