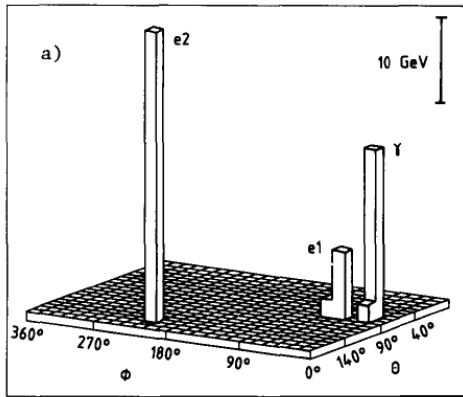


# From Z to Higgs, and beyond!

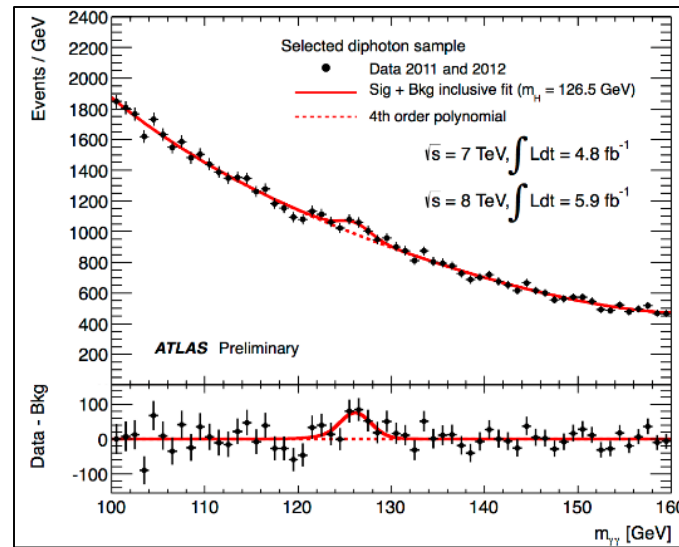
## Physics at hadron colliders

Bruno Mansoulié

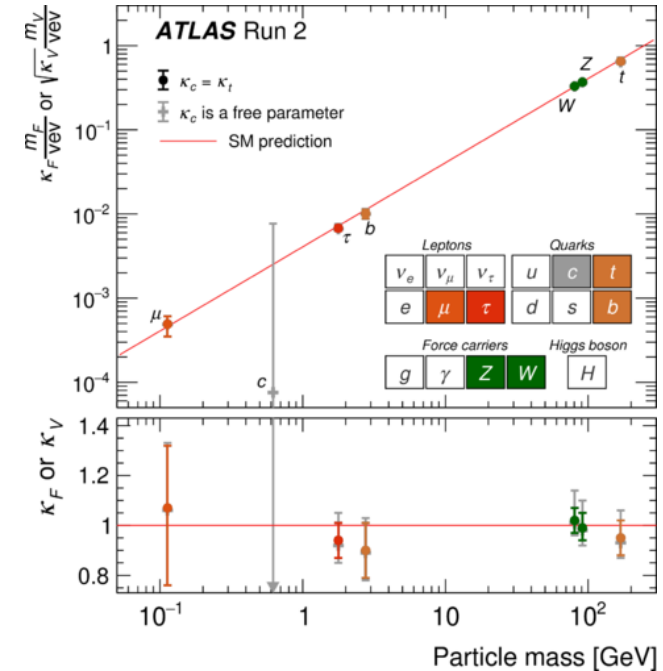
Département de Physique des Particules CEA, Université Paris-Saclay  
and CERN - Genève



UA2  $Z^0 \rightarrow e^+e^- \gamma$   
1983



ATLAS  $H \rightarrow \gamma \gamma$   
2012



2022

# Hadron colliders before the LHC

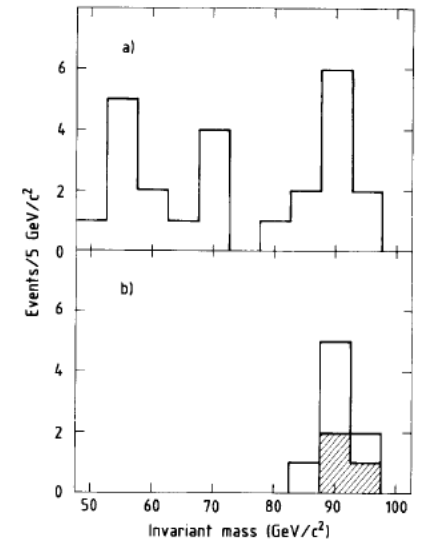
- **CERN ISR 1971 - 1984**
  - Proton-proton, two rings, 62 GeV center-of-mass energy
  - Tests of stochastic cooling (Rubbia, Van Der Meer)
- **CERN proton – antiproton collider 1981 - 1991**
  - 7 km circumference, underground
  - Re-use the SPS accelerator as a colliding ring for p and  $\bar{p}$ , 630 GeV c-o-m energy  
(thanks to stochastic cooling of  $\bar{p}$  's)
- **Fermilab (US) TeVatron 1985- 2011**
  - First large accelerator using superconducting magnets
  - 1.96 TeV c-o-m energy



# S p $\bar{p}$ S physics

- **UA1 and UA2 experiments**
  - Innovating detectors: UA1 (central detector) and UA2 (granular calorimeters)
  - Innovating analysis methods: Missing Transverse Energy, Calorimeter Jets...
  - Innovating theory approach: parton-to-collisions, Monte-Carlo generators...
- **Jets in UA2 (*P. Jenni et al.*)**
  - Parton model at work in hadron collisions. 2-to-2 QCD (Horgan & Jacob)
- **W and Z discovery (1983)**
  - Of course a major success for CERN.
  - *1984 Nobel prize to Rubbia and Van Der Meer*
- **Search for the top-quark :  $m(\text{top}) > 69 \text{ GeV}$  (1989)**
- ***Basis for the LEP physics programme***

UA2

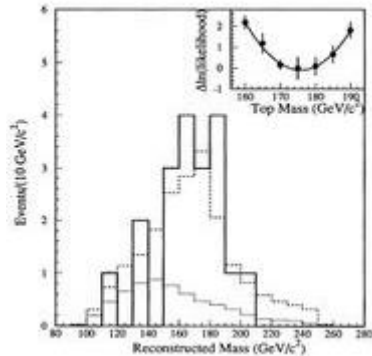


# Physics at the TeVatron

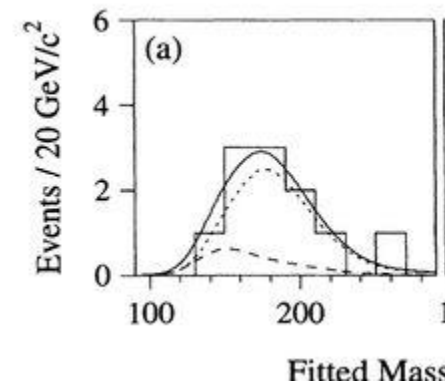
- **CDF and D0**
  - International collaborations : Saclay group in D0
  - Two large detectors with influences from UA1 and UA2 (resp.)
- **Much progress on W and Z, together with LEP**
  - Indirect prediction:  $110 \text{ GeV} < m(\text{top}) < 200 \text{ GeV}$  [1991]
- **Top quark discovery :  $m(\text{top}) \sim 175 \text{ GeV}$  [1995]**



– **CDF**



**D0**



– **Rather complex analyses (categories, etc.) open the way to LHC...**

# SSC, LHC, and the race for the Higgs boson

## • SSC in the US

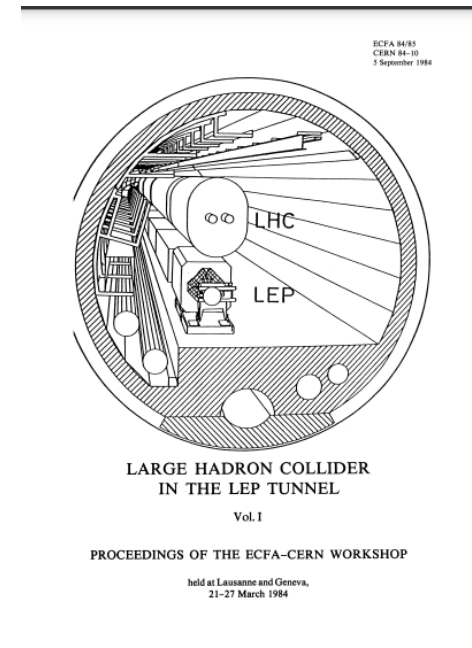
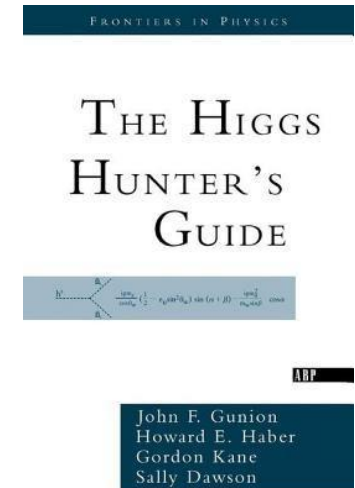
- Discussed from 1984, lab created 1989, cancelled 1993
- 87 km circumference, p-p, 20 + 20 TeV,  $10^{33} \text{ cm}^{-2}\text{s}^{-1}$  luminosity
- “No-Lose SSC corollary” ! => *find the Higgs, or sthg else*

## • LHC

- Envisioned in the LEP tunnel as soon as 1977 (*Van Hove, Adams*)
- *Foundation: Lausanne 1984 16-18 TeV,  $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$*
- 1984 – 1987: 15 TeV,  $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  lumi
  - *a good competitor to SSC*
- Full access to the Higgs, whatever its mass  
... if the high luminosity is manageable!

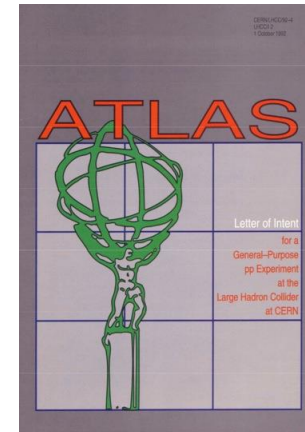
## • LEP and the Higgs Search

- *First accelerator to really attack the Higgs search*
- $m(H) > 114 \text{ GeV}$  (2000)



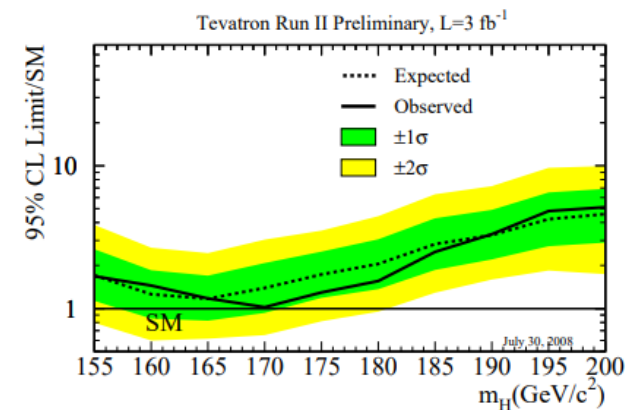
# Preparing for the LHC

- ATLAS and CMS [1992]
- Creation of the ATLAS collaboration
  - Merge of ASCOT and EAGLE proto-collaborations
    - *role of Saclay*
  - *P. Jenni 1st ATLAS spokesperson... for 14 years!*
- Detector R&D , design, and construction
- ATLAS Liquid Argon calorimeter (*D. Fournier*)
  - From prototype to full detector 1992-2004
- Monte-Carlo simulations
  - Progress in theory: NLO calculations...
  - Realistic simulations : detector optimization
    - *Higgs  $\rightarrow \gamma\gamma$  with Fabiola Gianotti...*



# LHC and the Higgs race

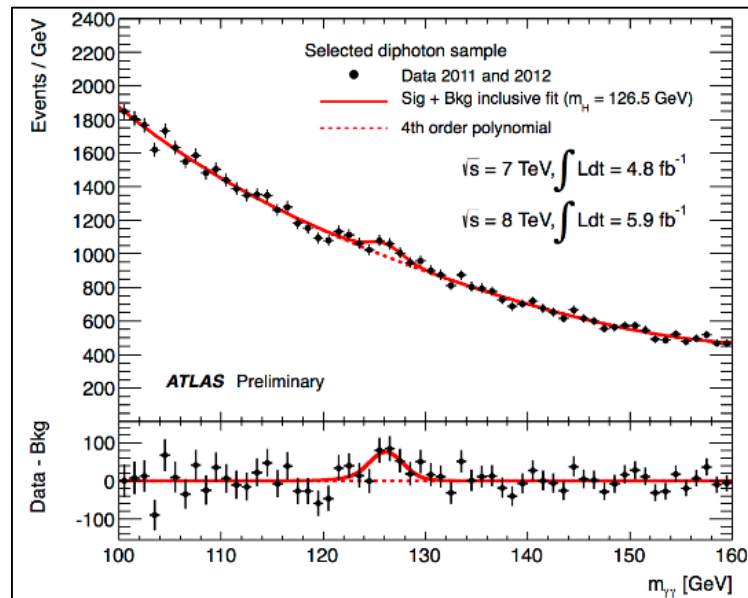
- Design (14 TeV) and construction
- Commissioning (2008)
  - First laps: beautiful!
  - The incident
- Competition from Fermilab for the Higgs?
  - TeVatron operating superbly now
  - Has an opportunity window on the Higgs!
- Hard decision:
  - repair to reach design energy or
  - *run at lower energy to lead the Higgs race ?*
    - 7 TeV, 8 TeV (2011, 2012)



J. Qian, Split, 2008

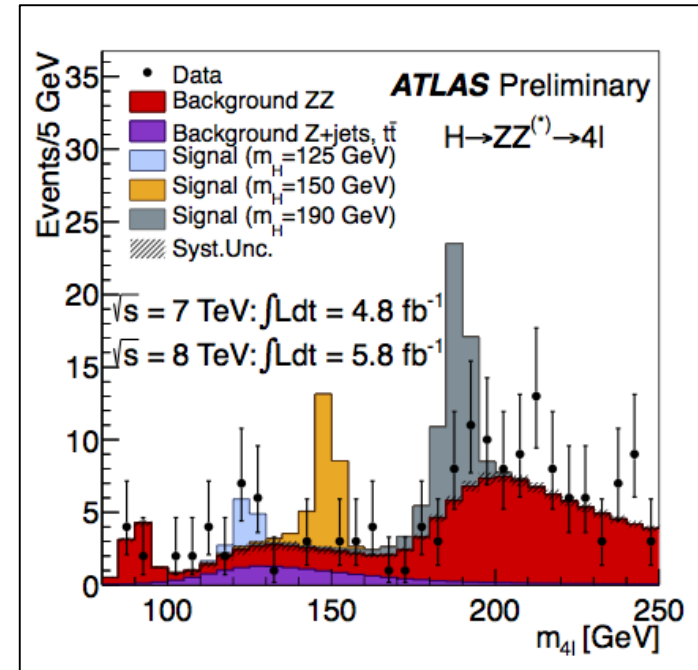
# Higgs search with the first LHC data (2011 and 2012)

- July 4th, 2012. ATLAS and CMS:  $m(H) = 125 \text{ GeV}$  !



$H \rightarrow \gamma \gamma$

- electromagnetic calorimeter
- several events on huge background

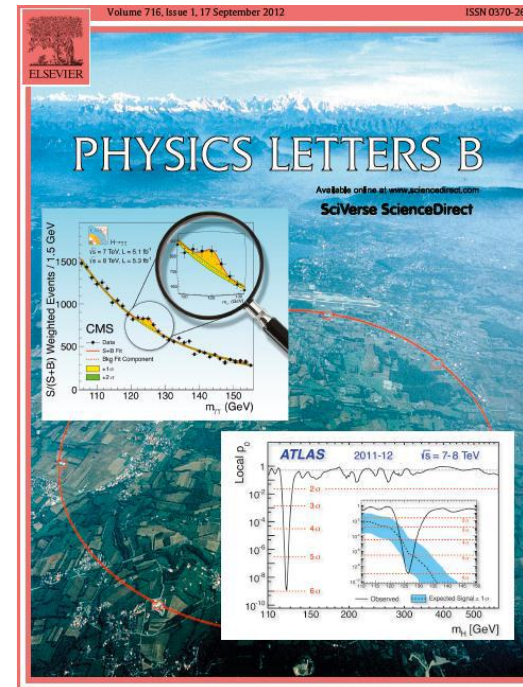


$H \rightarrow ZZ^* \rightarrow 4 \text{ leptons (e or } \mu)$

- central detector, muon spectrometer
- few events on low background



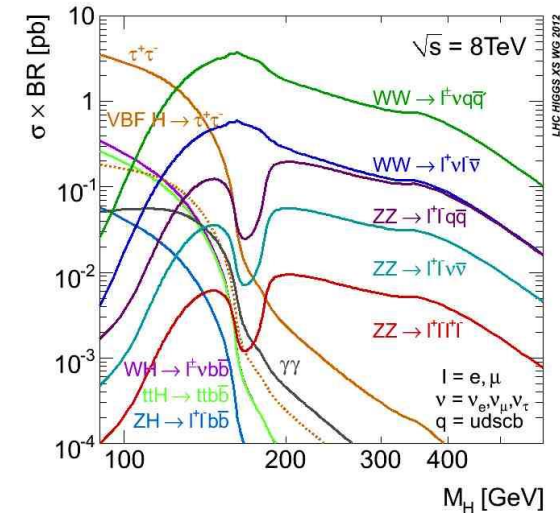
# Higgs boson discovery



Bruno Mansoulié, CEA/IRFU-SPP SSP Basel, 5 Sept 2023

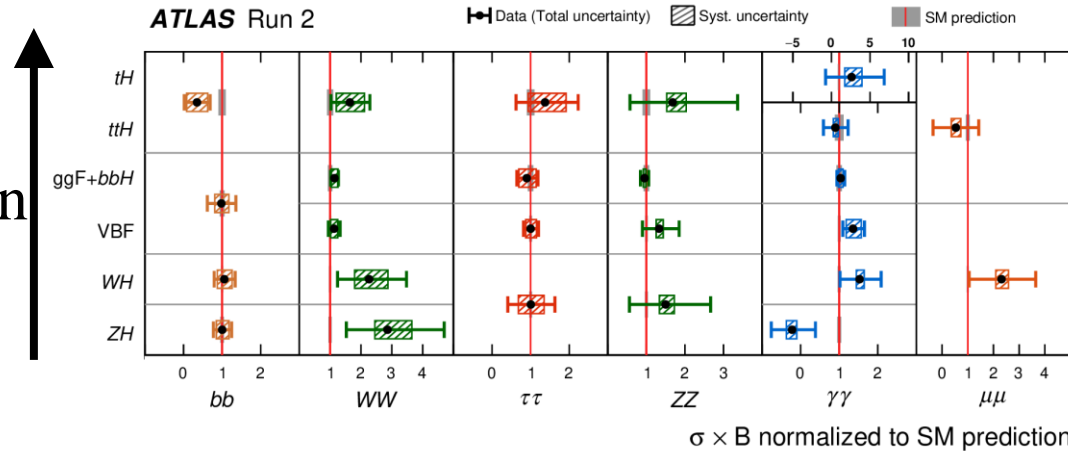
# Higgs after the discovery (2012 – today)

- Nature has been incredibly kind to us!
  - $m(H) = 125 \text{ GeV}$  gives many observable decay modes, and production modes



- Event yield

Production mode



Decay mode

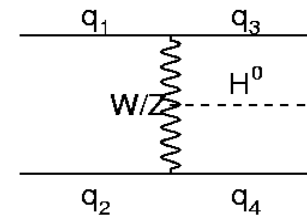
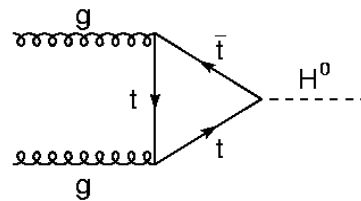
- Very large work from the “Higgs Group” over several years

# From the [production × decay] matrix to the Higgs couplings

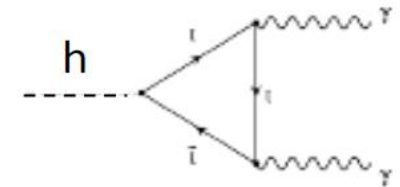
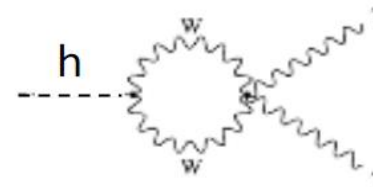
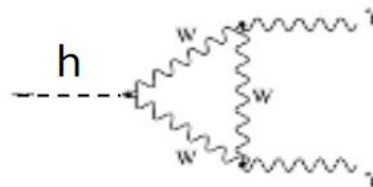
- Some channels involve several couplings of the Higgs

– Ex:  $H \rightarrow \gamma\gamma$

- Production



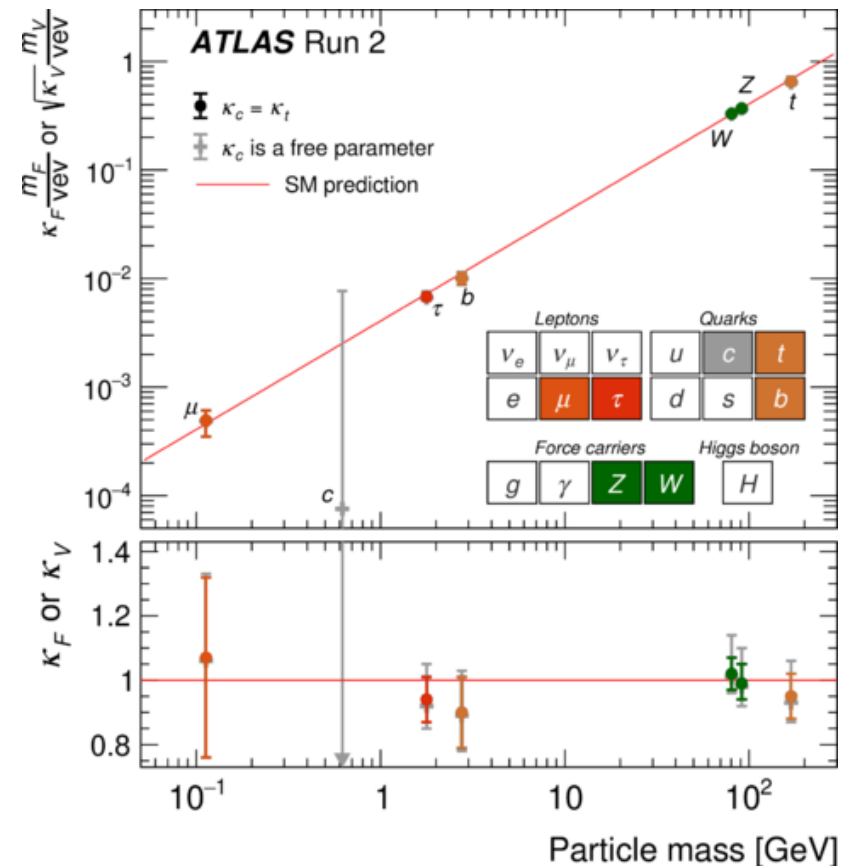
- Decay



- The game is now to go back from the measured 6x6 matrix to the elementary couplings of the Higgs (kind of a “diagonalization” )

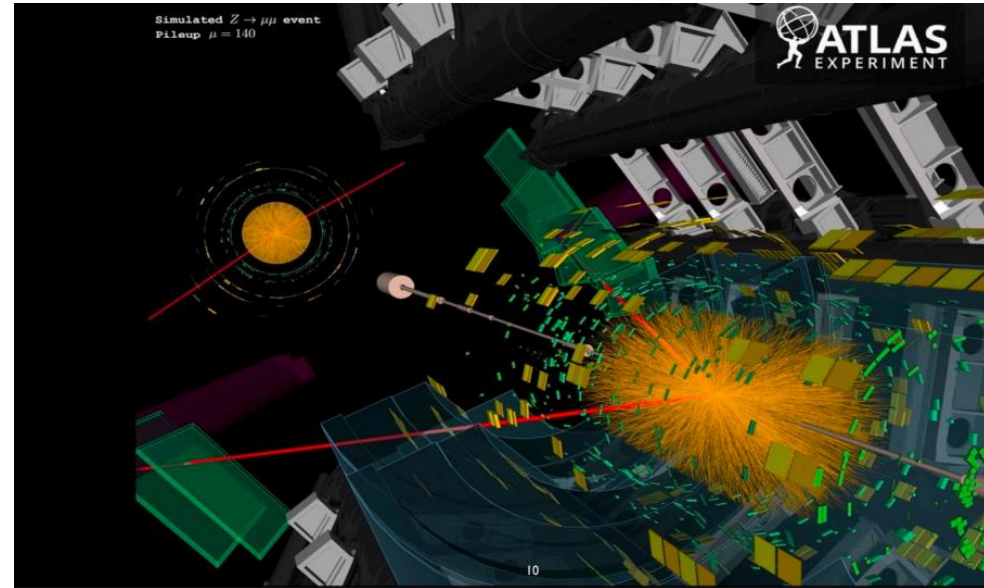
# Higgs analysis combinations

- Combine all Higgs searches into a large statistical model
  - Need to identify and homogenize all sources of systematic uncertainties
  - In the Nature paper of 2022: more than 2600 sources of syst uncertainties!
- Perform a huge fit
- Extract couplings under various hypothesis
- ATLAS Higgs combinations papers
  - Run-I ATLAS combination (2016)
  - Run-I ATLAS-CMS combination (2016)
    - *a nice adventure*
  - Run-I Run-II ATLAS combination (2022)



# The future studies at LHC, and beyond?

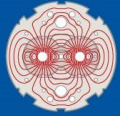
- Run-3 , then HL-LHC  
Important upgrades of LHC  
and experiments
- Higgs sector
  - HH production and the 3-H coupling
  - Searches for BSM Higgses
- All the BSM search programme
- After LHC: large projects : FCC (ee and hh)
  - FCC-hh 2070 : not for me to see!
  - *Could a muon collider be built and operated faster?*



## So many thank you's...

- **Of course to the SFP and SSP!**
- **To Swiss groups in ATLAS: Bern, Genève**
  - Anna Sfyrla, Hans Peter Beck, Allan Clark, Tobias Golling, Giuseppe Iacobucci...
  - *And now in GBAR experiment : ETHZ : Paolo Crivelli, Christian Regenfus...*
- **To my home lab: CEA-IRFU-Saclay**
  - Providing me with a strong work environment, nice colleagues, support
- **To CERN**
  - Amazing place: knowledge, exchanges, cooperation. All the young physicists around
- **To all those who showed me the way, whom I worked with, who helped, who supported... *Physicists, Engineers, Technicians, Admin...***
- **To my family and friends.**

## Additional slides



# LHC / HL-LHC Plan



We are here

LHC

HL-LHC

Run 1      Run 2      Run 3      Run 4 - 5...

LS1

13 TeV

EYETS

LS2

13.6 TeV

EYETS

LS3

13.6 - 14 TeV

energy

7 TeV

8 TeV

splice consolidation  
button collimators  
R2E project

cryolimit  
interaction  
regions

Diodes Consolidation  
LIU Installation  
Civil Eng. P1-P5

pilot beam

inner triplet  
radiation limit

HL-LHC  
installation

2011

2012

2013

2014

2015

2016

2017

2018

2019

2020

2021

2022

2023

2024

2025

2026

2027

2028

2029

2030

2031

2032

2033

2034

2035

2036

2037

2038

2039

2040

5 to 7.5 x nominal Lumi

75% nominal Lumi

nominal Lumi

2 x nominal Lumi

2 x nominal Lumi

30 fb<sup>-1</sup>

190 fb<sup>-1</sup>

450 fb<sup>-1</sup>

integrated  
luminosity  
3000 fb<sup>-1</sup>  
4000 fb<sup>-1</sup>

ATLAS - CMS  
upgrade phase 1

ALICE - LHCb  
upgrade

ATLAS - CMS  
HL upgrade

Run3 operation

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY



PROTOTYPES

CONSTRUCTION

INSTALLATION & COMM.

PHYSICS

LHC operation started in 2010 and is in its 3rd and last running period

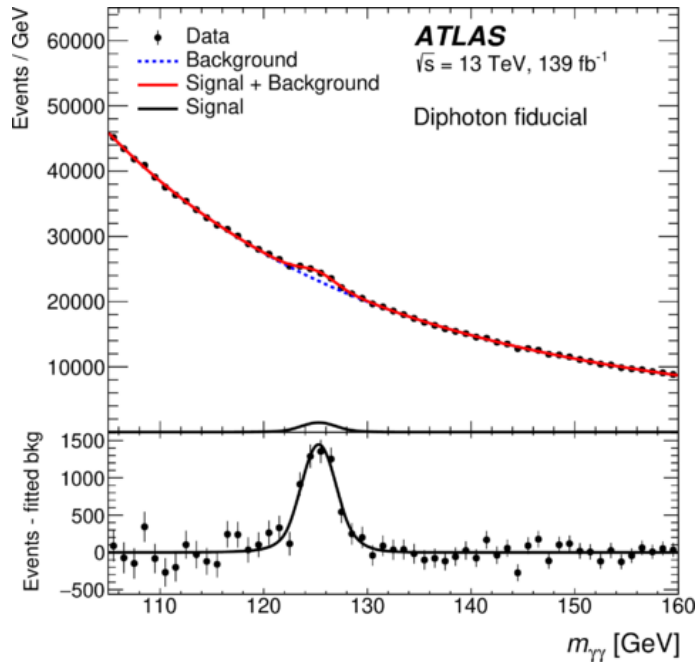
Operation exceeded the design luminosity but is still slightly short of the design energy

LHC Operation ends in 2025  
→ HL-LHC upgrade to take over as of 2029 after LS3

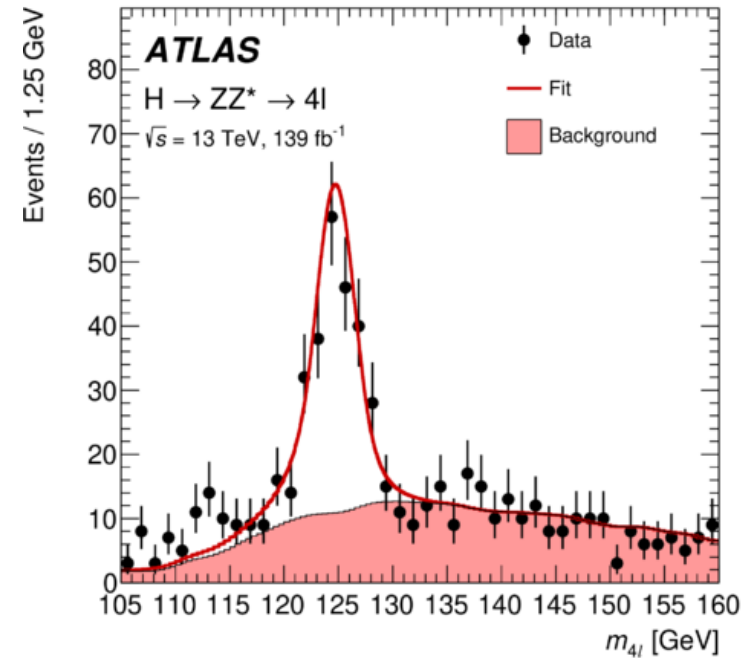


# Present status of SM Higgs studies: golden modes

## $H \rightarrow \gamma\gamma$



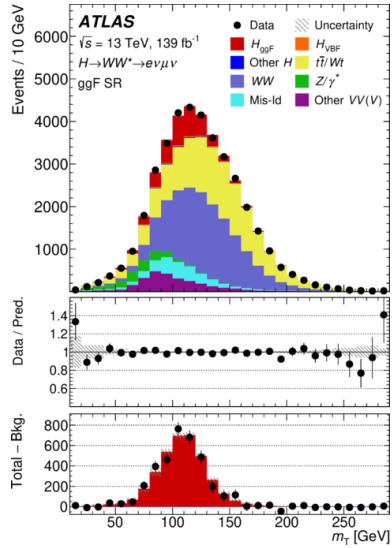
## $H \rightarrow ZZ^* \rightarrow 4 \text{ leptons}$



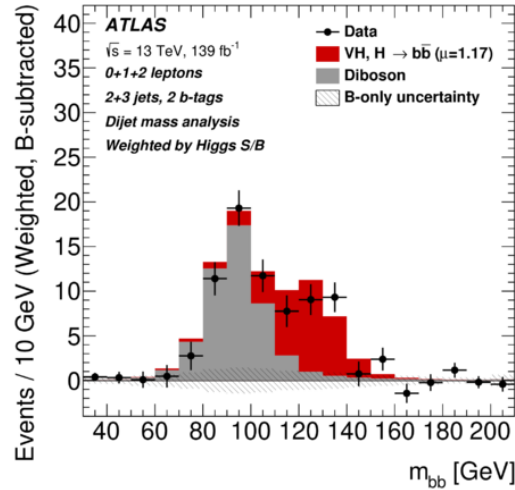
- Combine two channels (Run1+Run2):  $m(H) = 125.11 \pm 0.09(\text{stat}) \pm 0.06(\text{syst}) \text{ GeV}$  (ATLAS)

# Other decay modes

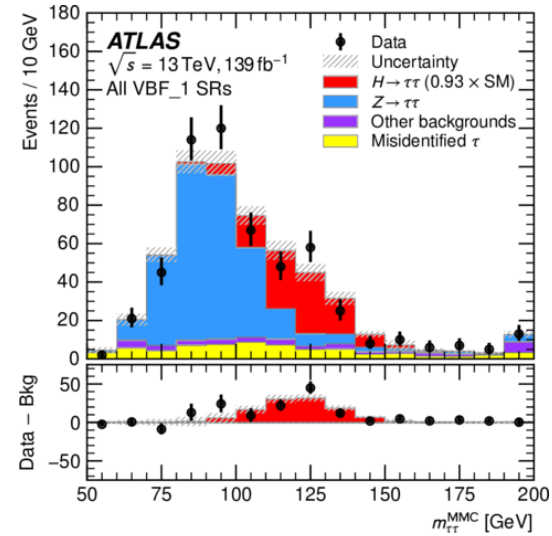
## • WW



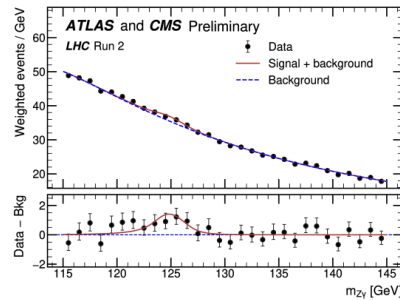
## b-bbar



## tau-tau



## Z-gamma



## mu-mu

