# Testing the Standard Model of Elementary Particle Physics I

First lecture

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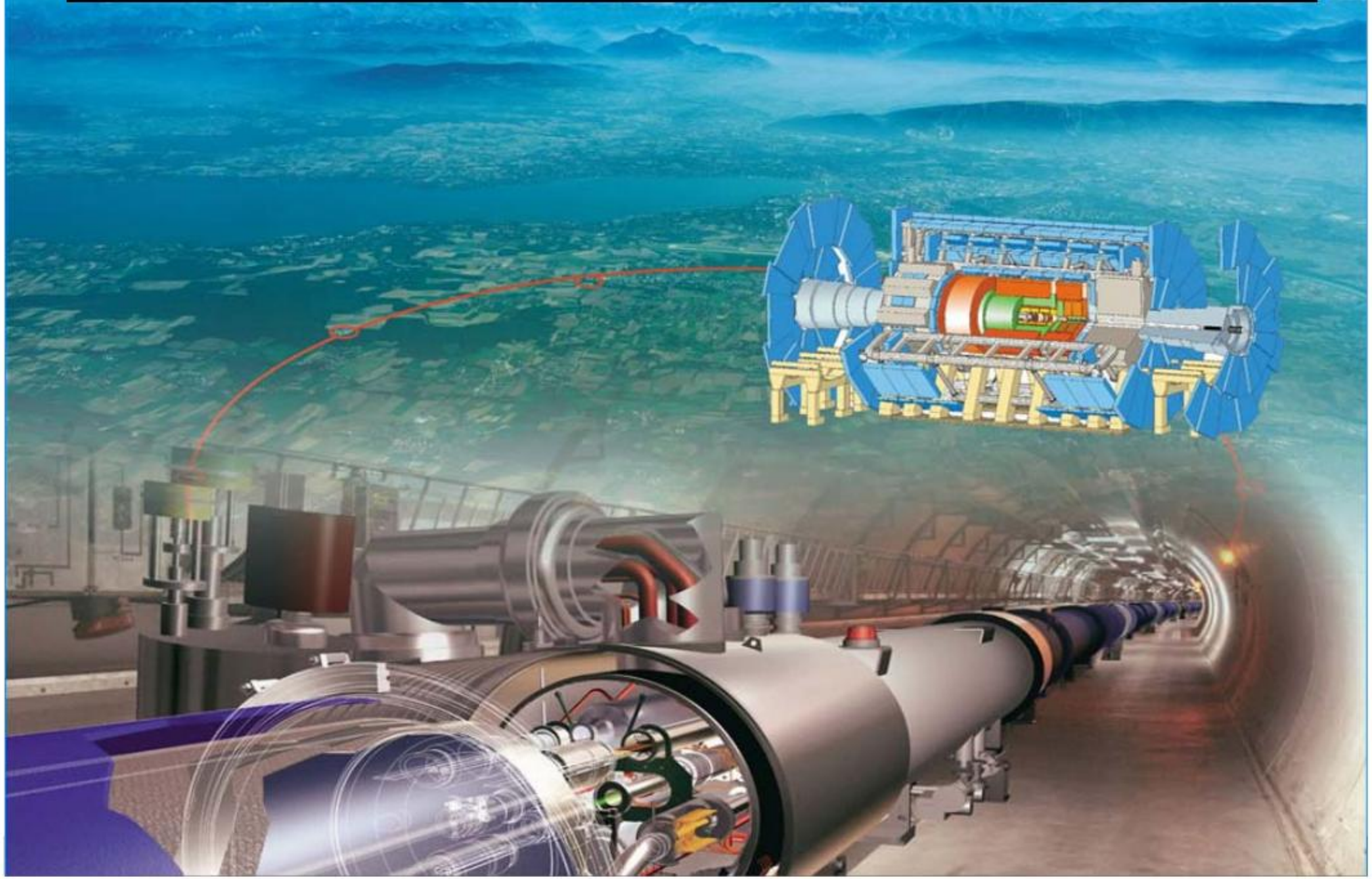
5th November 2020

# 1.1 Introduction to Elementary Particle Physics



# Introduction & Table of content

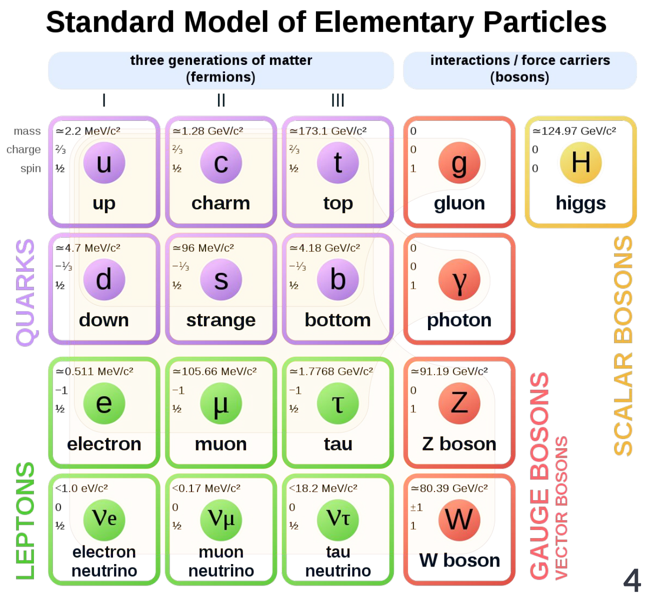
- This first lecture aims to give an overview of the various topics that we will discuss during this semester (some parts will be discussed in ***Testing the Standard Model of Elementary Particle Physics II***)
    - So we will not go into too much detail on the various topics
        - Will be more detailed starting from next week

- **Content:**
    - The Standard Model (SM) of particle physics in a nutshell:
        - Particle zoo (particle content of the SM)
        - Fundamental interactions
        - The Lagrangian of the SM
    - Experimental aspects:
        - The LHC
        - Modern particle detectors (ATLAS, CMS & LHCb)
        - Particle identification
        - Recent results on measurements and searches

# Standard model of particle physics in a nutshell

- The Standard Model (SM) describes the elementary constituents of nature, and the fundamental forces with which those particles interact with each other
- Over time and through many experiments, the Standard Model has become one of the most extensively tested theories in physics
- After the discovery of the Higgs boson in 2012, the particle content of the SM is finally complete

- However, the SM does not answer all phenomena seen in nature:
  - Gravity
  - Origin of the large asymmetry between matter and anti-matter
  - Neutrino masses
  - Dark matter
  - Naturalness problem




https://www.particlezoo.net

# Particle zoo (leptons):

| Symbol | Mass | Electric charge | Year of discovery |
|---|---|---|---|
| $\nu_e$ | < 2 eV | -- | 1956: by C. Cowan & F. Reines (inverse β decay) |
| $e^-$ | 0.511 MeV | -1 | 1897: by J.J. Thomson (cathode rays) |
| $\nu_\mu$ | < 0.19 MeV | -- | 1962: by L. Lederman & M. Schwartz |
| $\mu^-$ | 105.7 MeV | -1 | 1936: by C. D. Anderson & S. Neddermeyer (cosmic radiation) |
| $\nu_\tau$ | < 18.2 MeV | -- | 2000: DONUT Experiment |
| $\tau^-$ | 1.777 GeV | -1 | 1975: by Mark I at SLAC |


Masses are taken from the listings of the Particle Data Group (uncertainties are symmetrized)

# Particle zoo (quarks):


| Symbol | Mass | Electric charge | Year of discovery |
|---|---|---|---|
| u | 2.16±0.38 MeV | +2/3e | ~1964 |
| d | 4.67±0.32 MeV | -1/3e | ~1964 |
| s | 93±8 MeV | -1/3e | ~1964 |
| c | 1.27±0.02 GeV | +2/3e | 1974: at SLAC and BNL (via J/Ψ) |
| b | 4.18±0.03 GeV | -1/3e | 1977: by E288 experiment at Fermilab |
| t | 172.9±0.4 GeV | +2/3e | 1994: by CDF & D0 at the Tevatron |

**Masses are taken from the listings of the Particle Data Group (uncertainties are symmetrized)**


# Particle zoo (bosons):


| Symbol | Mass | Electric charge | Year of discovery |
|---|---|---|---|
| γ | -- | -- | 1900-1924: by e.g. Planck |
| g | -- | -- | 1979: by experiments at PETRA (DESY) |
| $W^+/W^-$ | 80.385±0.01 GeV | +1/-1 | 1983: by UA1 and UA2 at Super Proton Synchrotron |
| $Z^0$ | 91.1876±0.002 GeV | -- | 1983: by UA1 and UA2 at Super Proton Synchrotron |
| H | 125.09±0.4 GeV | -- | 2012: by ATLAS & CMS at the LHC |

**Masses are taken from the listings of the Particle Data Group (uncertainties are symmetrized)**

# Antiparticles

- **Every elementary particle is associated with an antiparticle**
  - **Particles & antiparticles:**
    - **Have the same mass and lifetime**
    - **Have opposite charge (e.g. electrical charge or colour charge)**
- **The electrically neutral bosons (Higgs and $Z^0$) are identical with their antiparticles**
- **It is not verified yet whether neutrinos are identical with their anti-particles or not**
  - **Majorana neutrino hypothesis vs Dirac neutrino hypothesis**

- **In the early universe (during the Baryogenesis), a surplus of matter over antimatter was produced.**
  - **Motivates searches for sources of CP symmetry violation**

# Fundamental interactions

| Interaction | EM | Weak | Strong |
|---|---|---|---|
| Gauge symmetry | $U(1)$ | $SU(2)$ | $SU(3)$ |
| Theory | QED | GSW | QCD |
| Gauge boson | Photon | $W^{\pm}$, $Z^0$ | 8 Gluons |
| Acts on | electric charge | flavour | colour charge |
| Range | $\infty$ | $10^{-18}\mathrm{m}$ | $10^{-15}\mathrm{m}$ |

Gravitation is not described by SM

# Lagrangian of the SM

The Standard Model of particle physics is based on a **quantum field theory.** A **Lagrangian** is used to describe the particle content of the theory via fields and their interactions:

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

**Kinematic term and self-interaction of the gauge boson fields**

$$+ i\bar{\psi}\not{D}\psi + h.c.$$

**Fermion kinematics and interaction**

$$+ \psi_i y_{ij}\psi_j\phi + h.c.$$

**Yukawa interaction (interaction between fermion fields and the Higgs field)**

$$+ |D_\mu\phi|^2 - V(\phi)$$

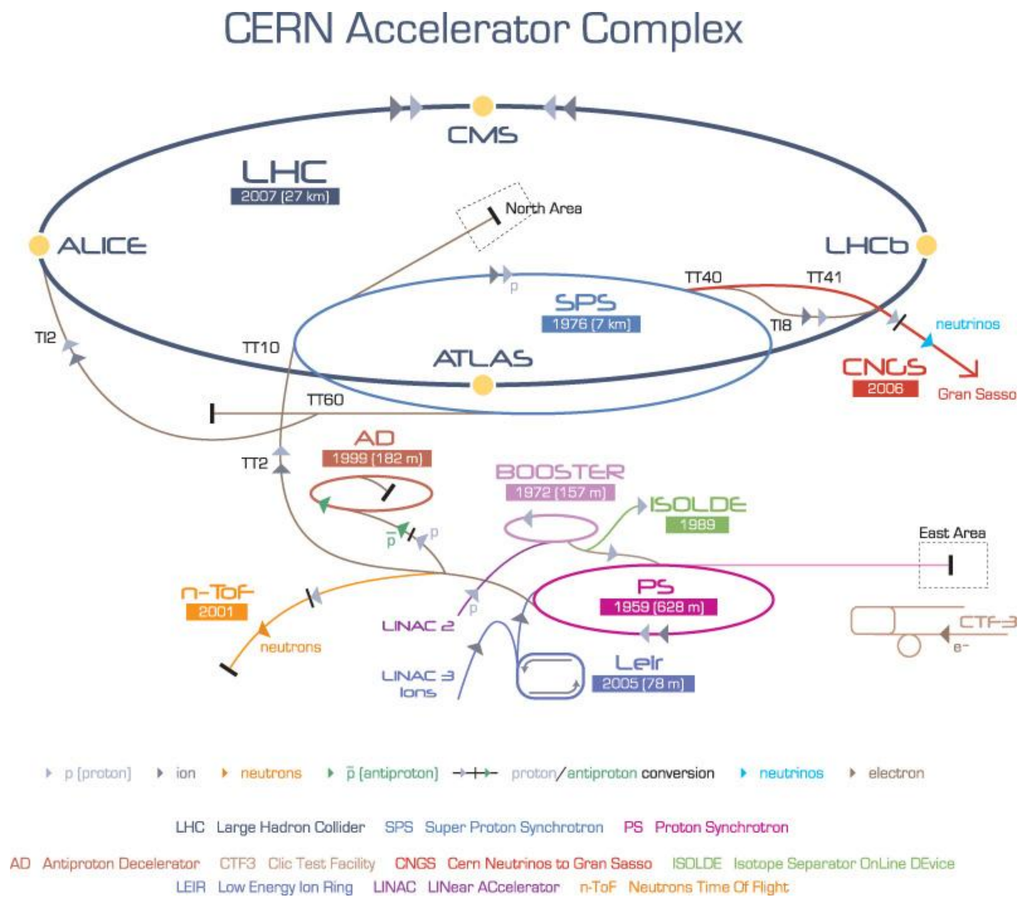
**Higgs field (potential, kinematics and interaction with gauge bosons)**

# Physics program at the LHC (and other collider experiments):

- **Measurements of particle properties:**
  - Cross sections
  - Branching ratios
  - Mass
  - Charge
  - Spin
  - CP state
- **Searches for so far unobserved processes or phenomena:**
  - Model dependent searches
  - Model independent searches

# Experimental setup

# The Large Hadron Collider




- Instantaneous luminosity

$$\mathcal{L} = fn\frac{N_1 N_2}{A}$$

$N_1$, $N_2$ = Number of hadrons per bunch

n = Number of bunches per beam

f = Resolution frequency

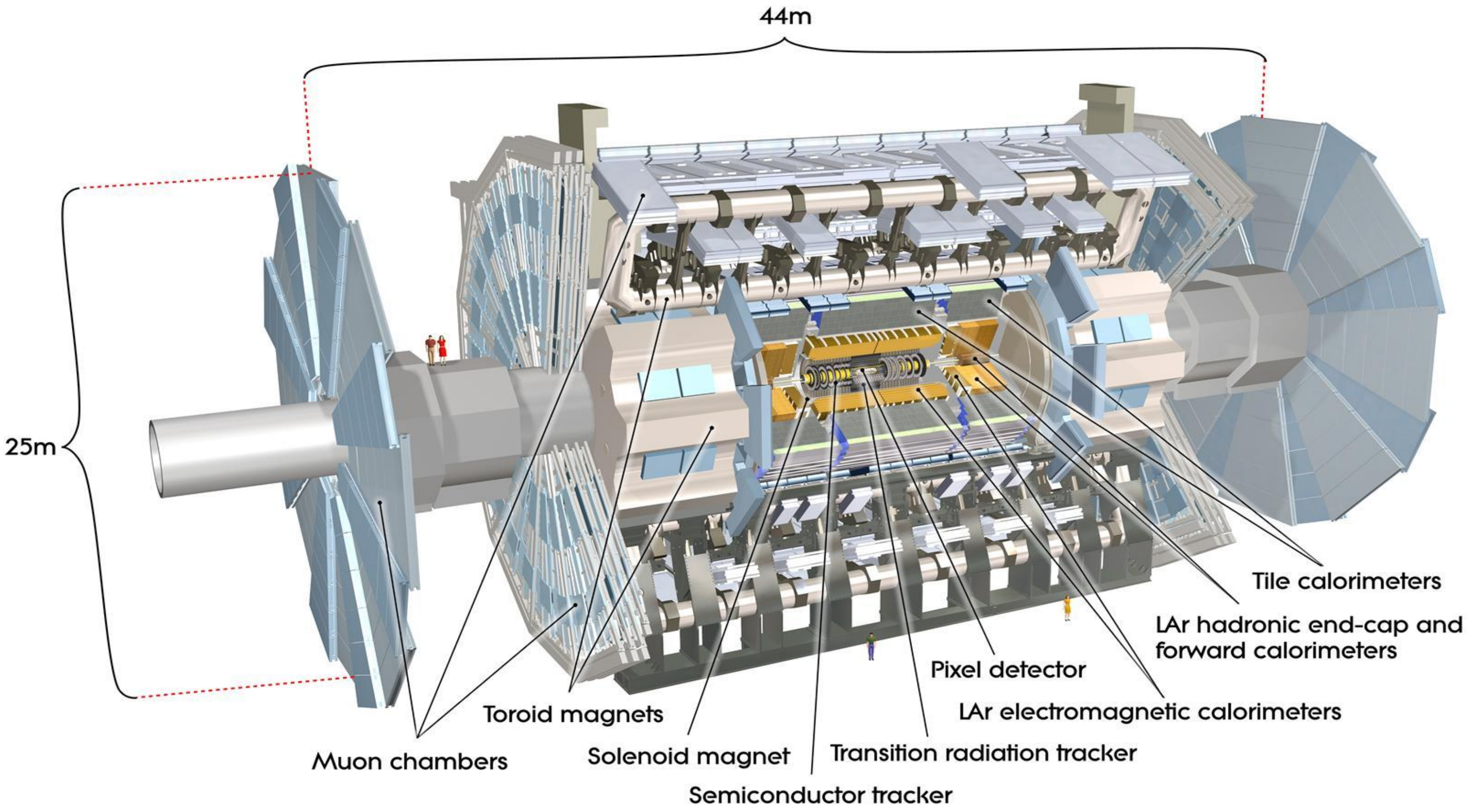
A = Beam cross section

- Integrated luminosity

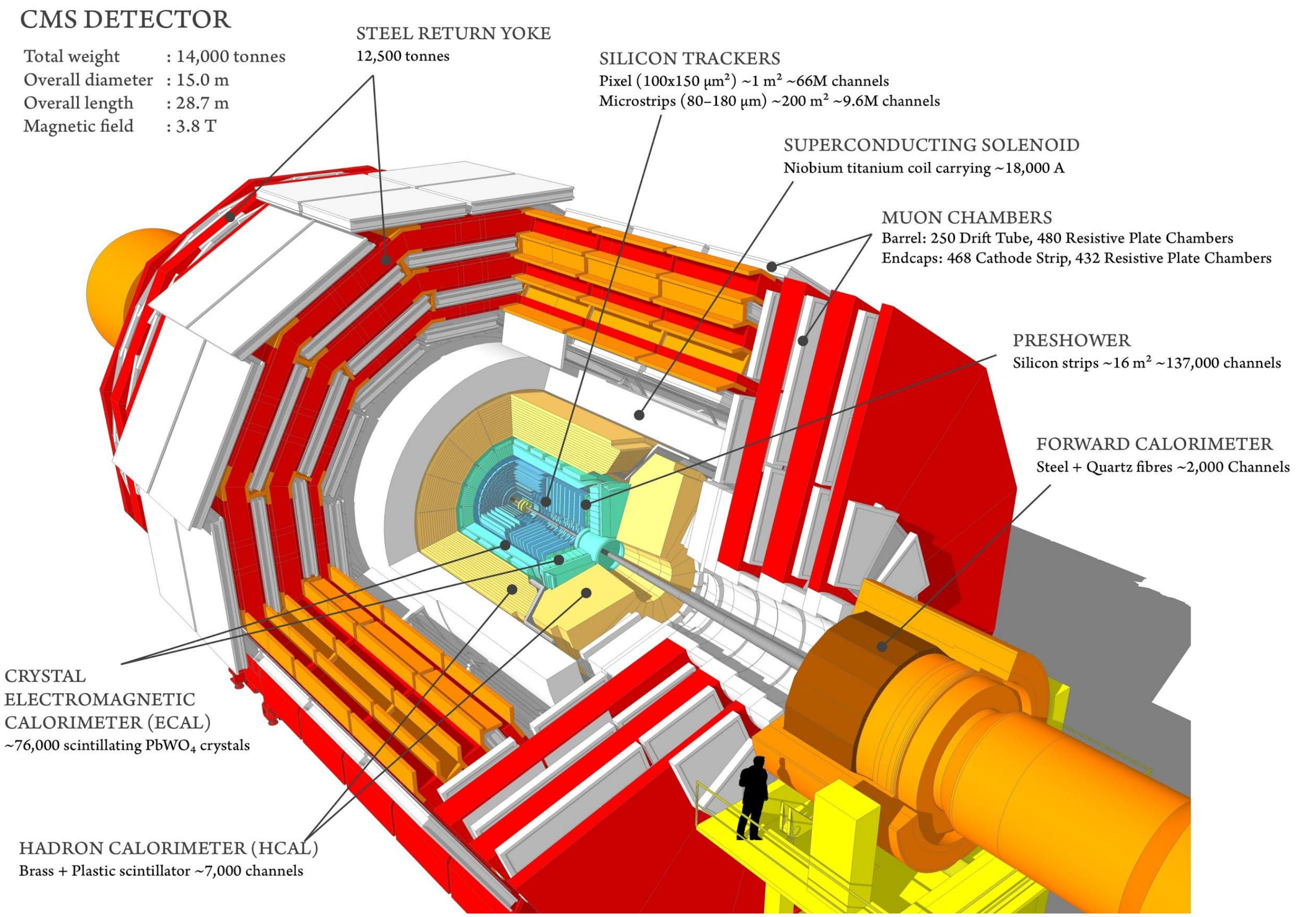
$$L = \int \mathcal{L}dt$$

- CoM energy: $\sqrt{s}$

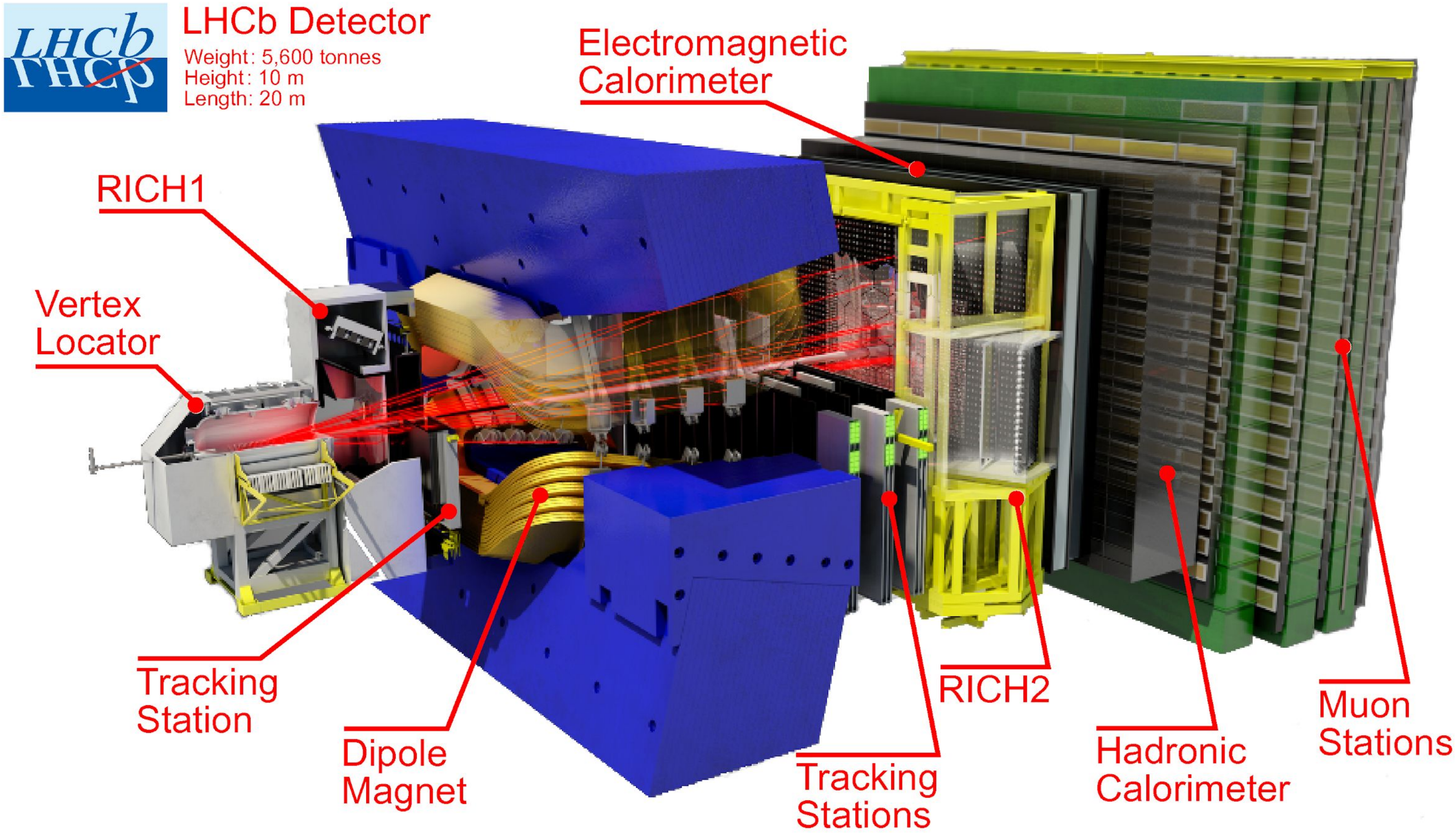
# The ATLAS Detector



# The CMS Detector



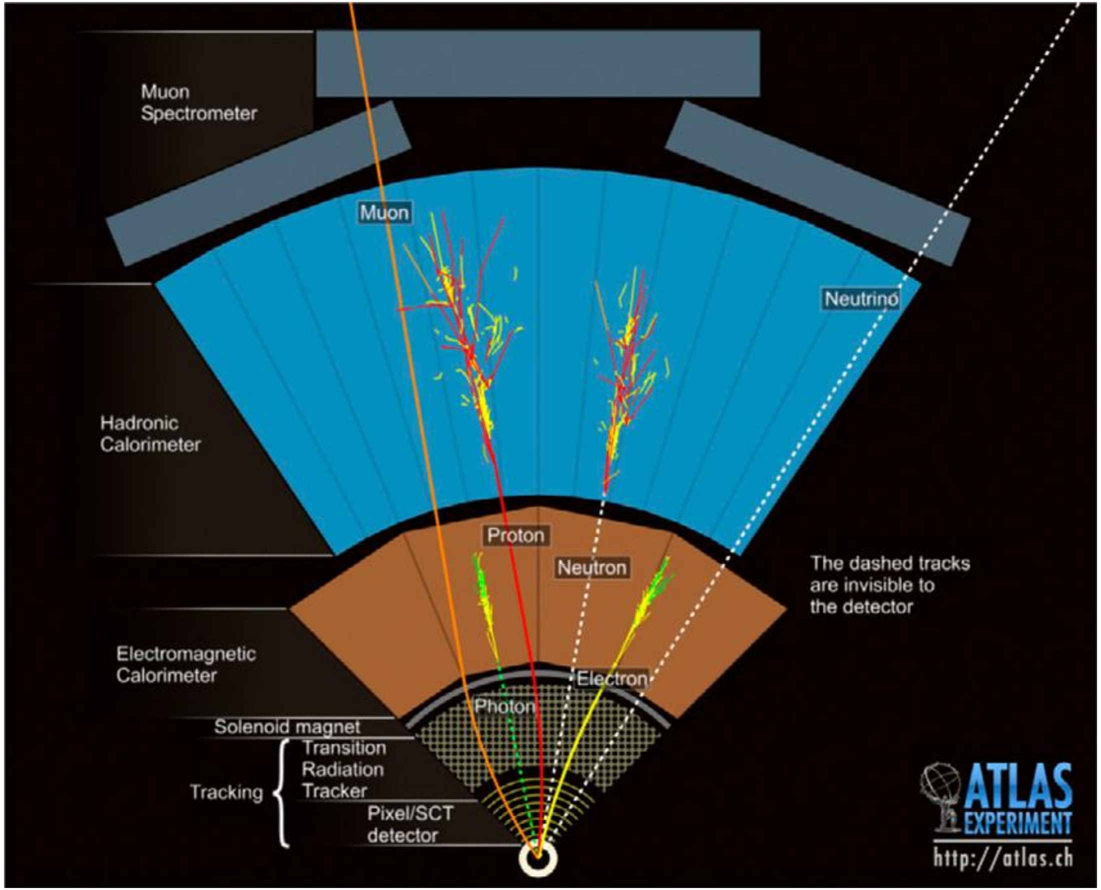
# The LHCb Detector



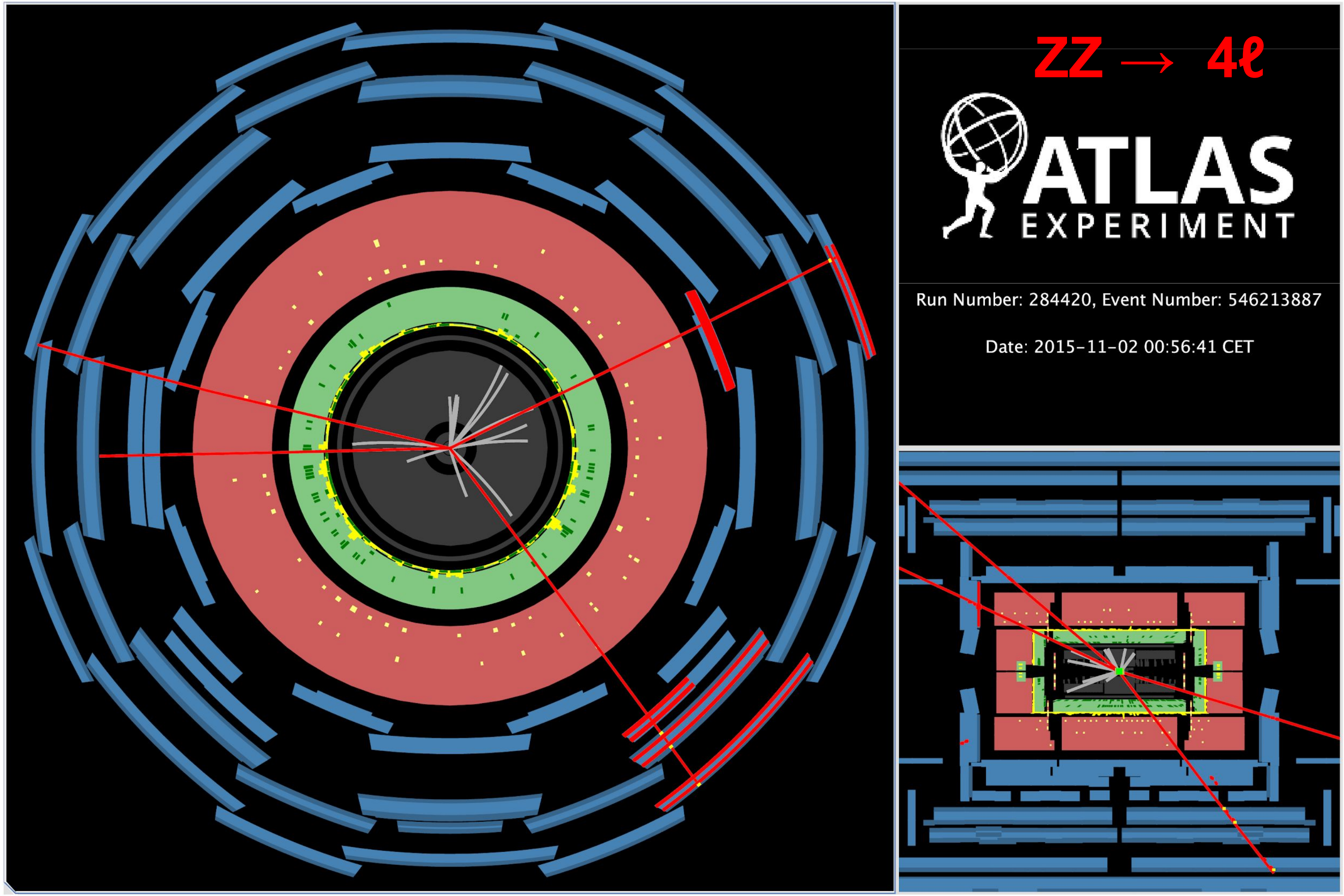
# Particle identification

- **Hadronic particle shower**
  - Cone shaped jets build from calorimeter clusters or tracks
- **Muons**
  - Combined tracks from Inner Detector and Spectrometer
- **Electrons**
  - Inner Detector (ID) track
  - Energy clusters in calorimeter system
- **Taus**
  - Jets with either 1 or 3 ID tracks
- **Neutrinos**
  - Pass through the detector without leaving any trace.
  - Estimated from energy balance:

$$E_{\mathrm{X,Y}}^{\mathrm{mis}} = -\sum E_{\mathrm{X,Y}}^{\mathrm{obj.}} + E_{\mathrm{X,Y}}^{\mathrm{soft}}$$



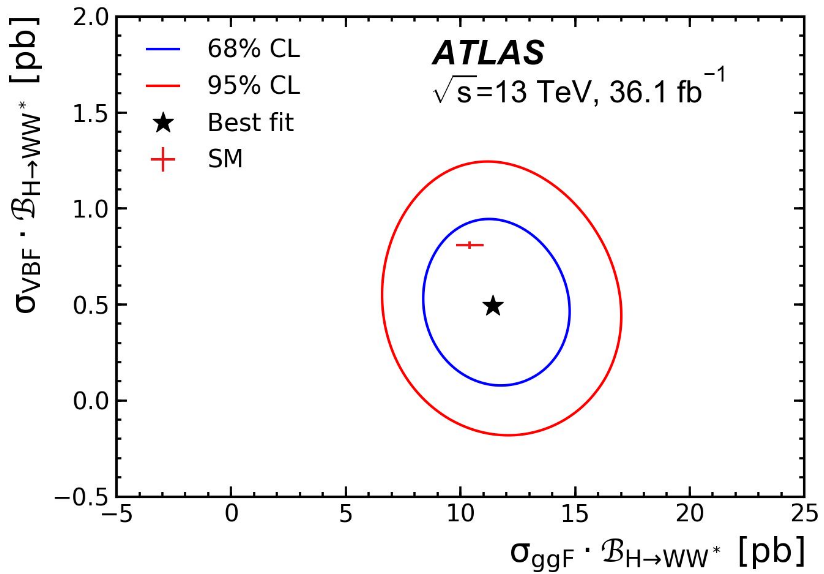
# $ZZ \rightarrow 4\ell$



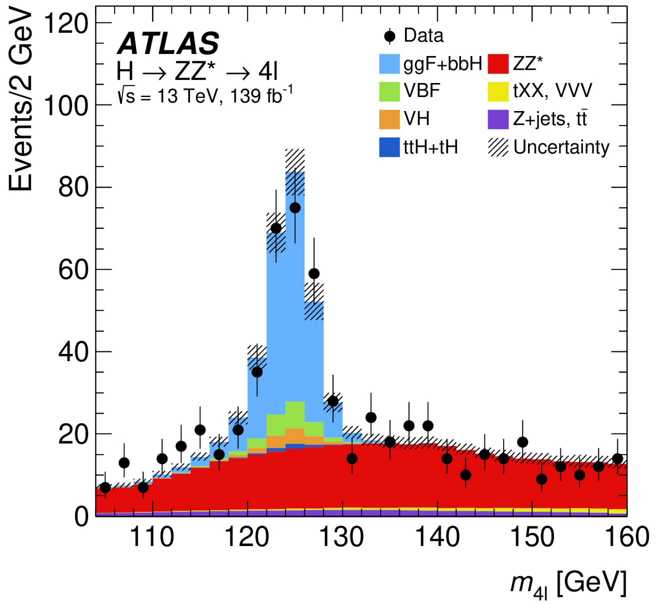
# Measurements

# Measurements

**Production cross section times branching ratio measurements of the two the two dominant production modes of the Higgs boson:**

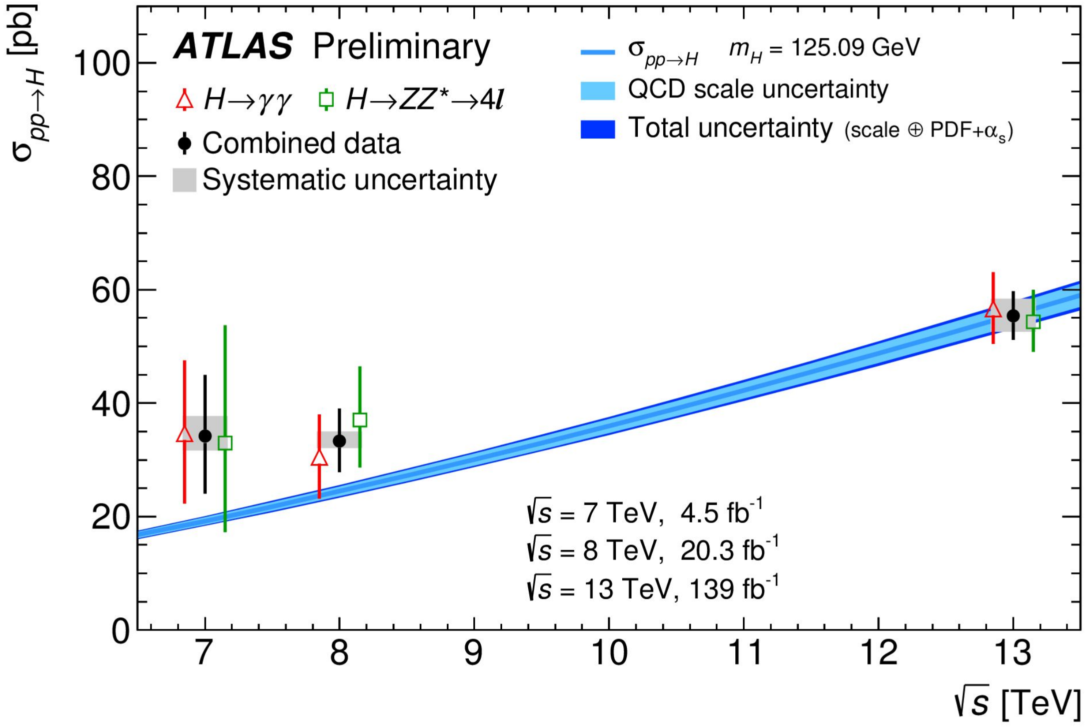


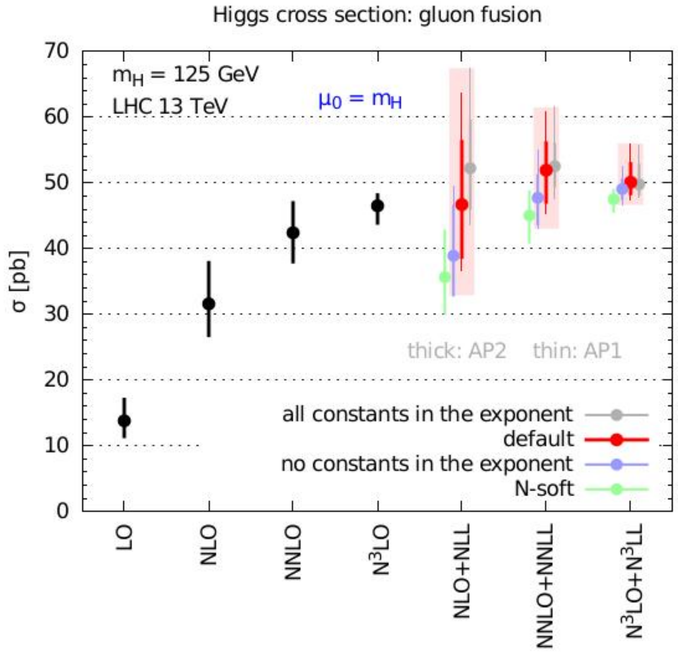

**Higgs boson mass measurement:**




- **Measurements of particle properties are essential to further our understanding of the Standard Model**
    - Used as inputs to theoretical calculations

# Interplay between theory and experiment

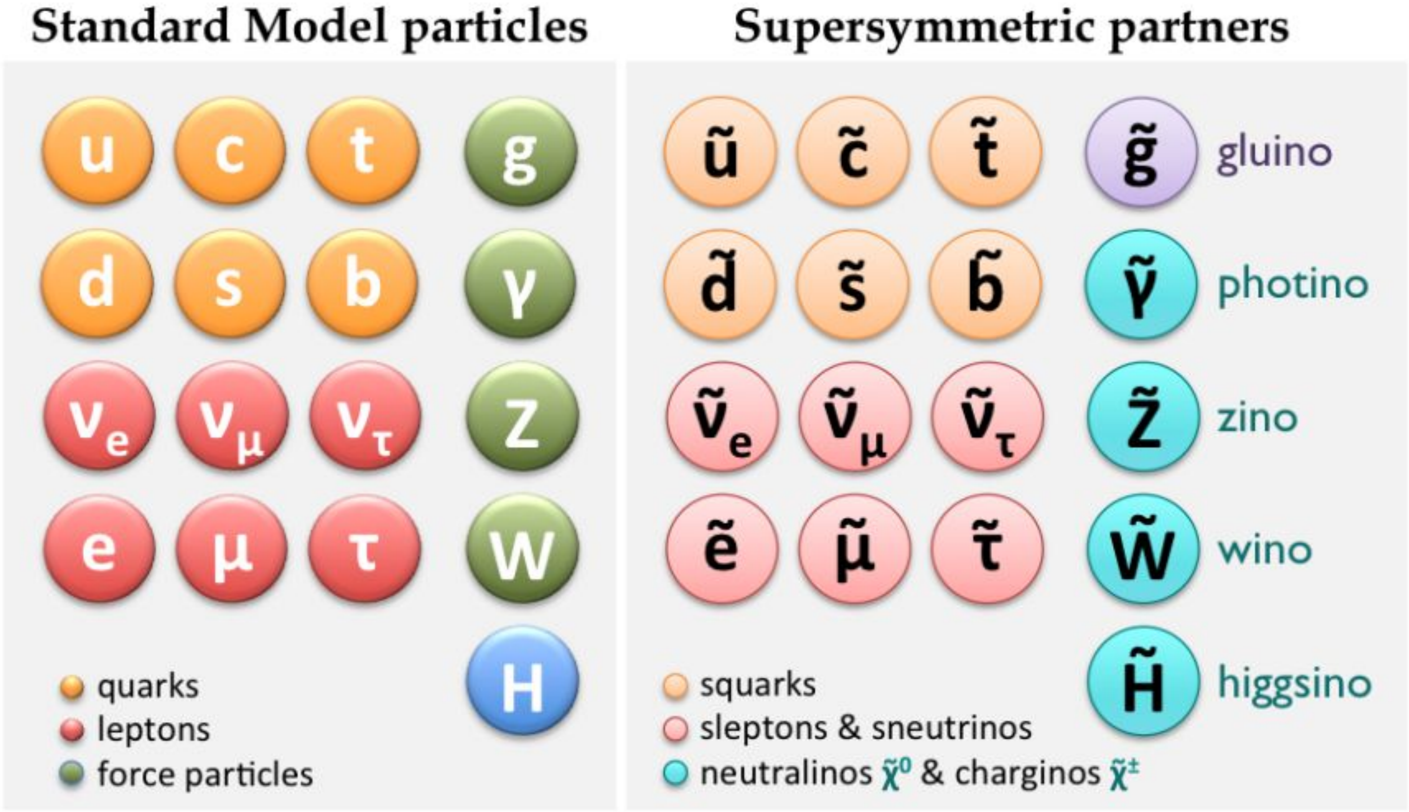



- **Experimental results depend strongly on the precision of theoretical predictions !!!**

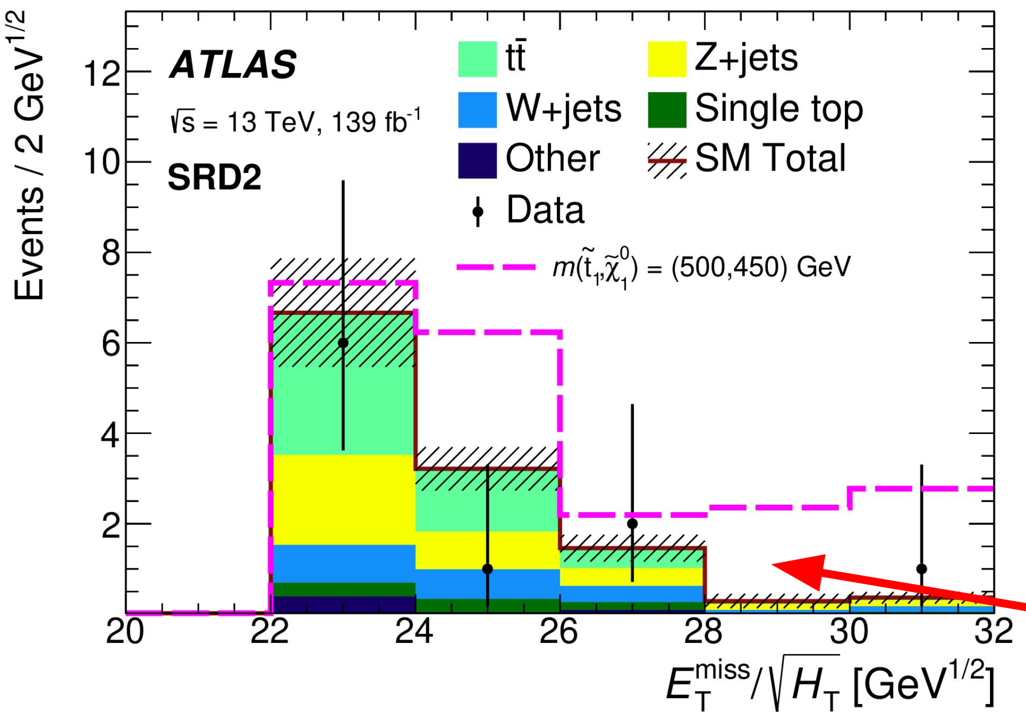
# Searches for physics beyond the Standard Model

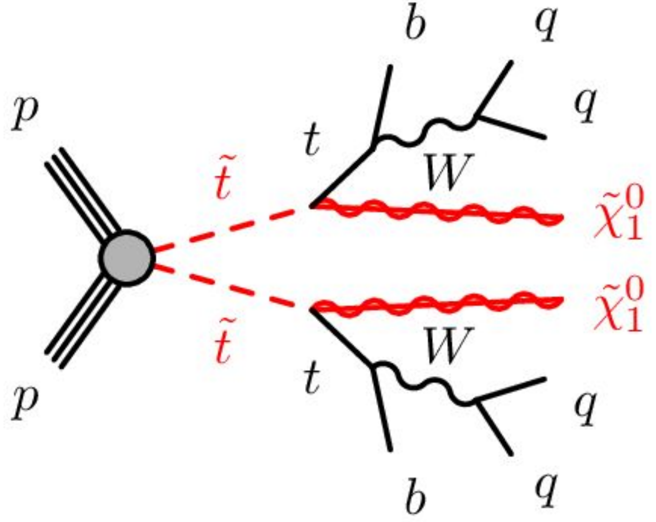
# Supersymmetry (SUSY)



# Search for Supersymmetry (SUSY)

- **Search for stop quark pair production**



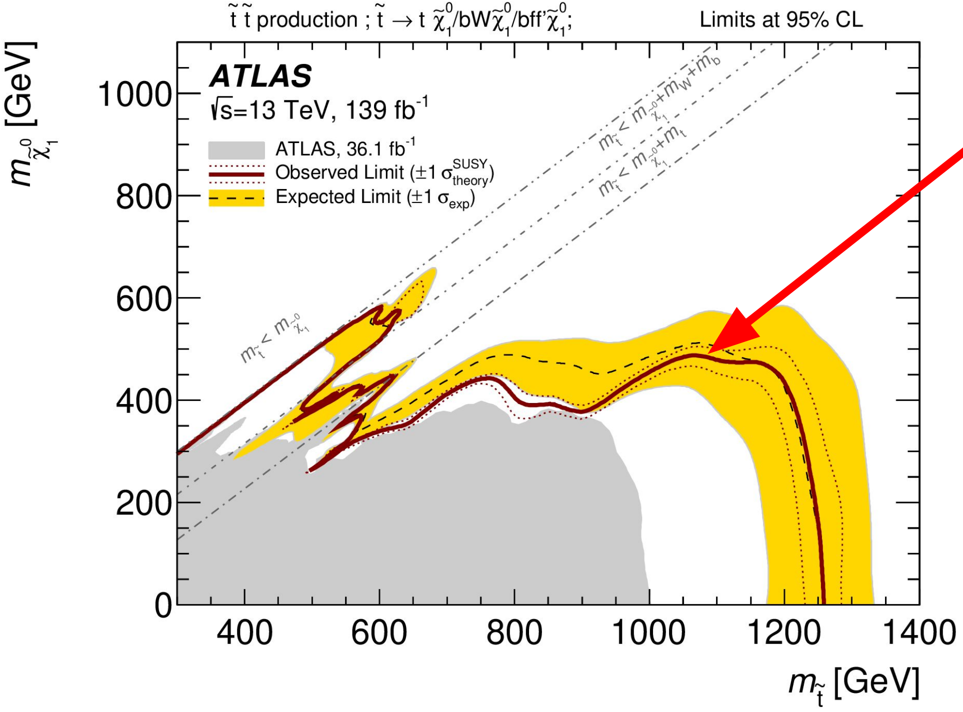

- **Search for multi-jet final state incl. large amount of missing $E_T$**

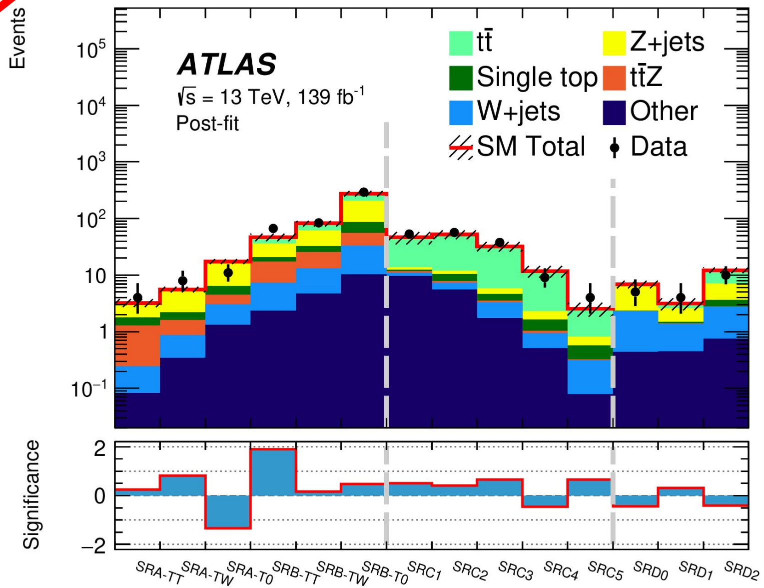
**Probe phase space regions sensitive to contributions from SUSY signal**

# Search for Supersymmetry (SUSY)

- **Search for stop quark pair production**

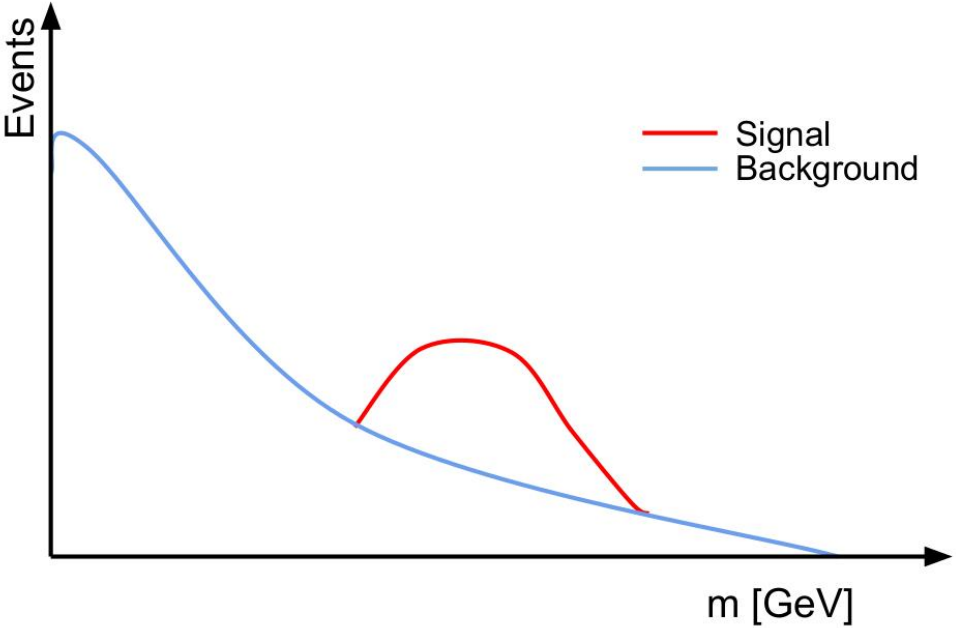
**Exclude stop masses up to ~ 1300 GeV for neutralino masses below 400 GeV**



# Direct Search for heavy Resonances

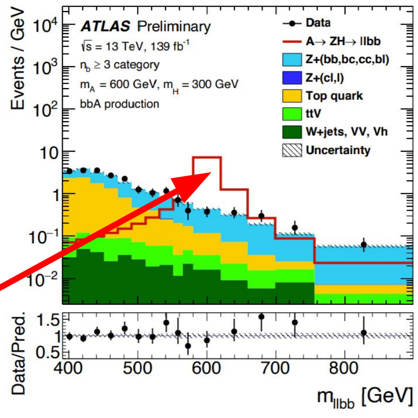
- Most searches for diboson resonances in ATLAS and CMS follow the same principle:
  - Perform (quasi) **model-independent search for a bump in a smoothly falling mass spectrum**

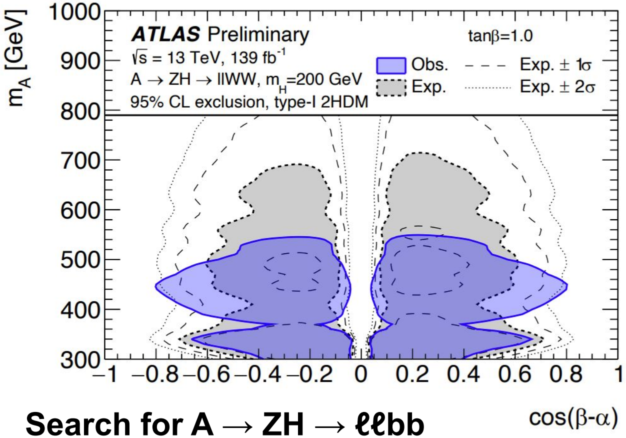



- **Interpretations in generic frameworks:**
  - Two Higgs Doublet Model (2HDM)
  - Higgs Triplet models
  - Heavy Vector Triplet (HVT) models
  - RS Extra-dimensional models

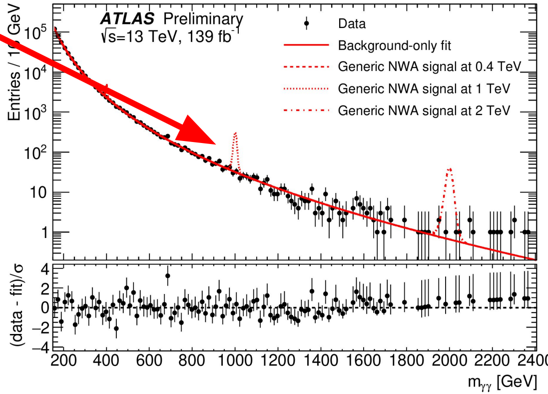
# Direct Search for heavy Resonances

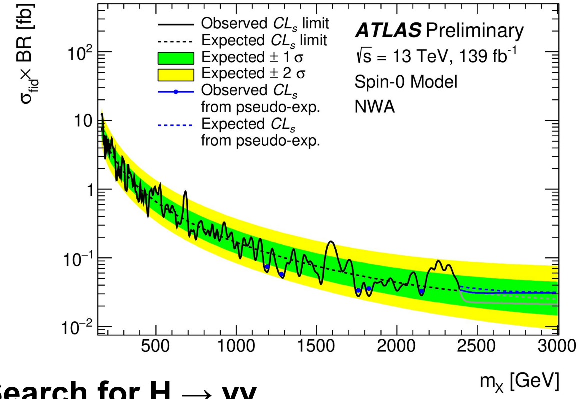
**Probe observables sensitive to contribution from signal process**




**Search for A → ZH → ℓℓbb**



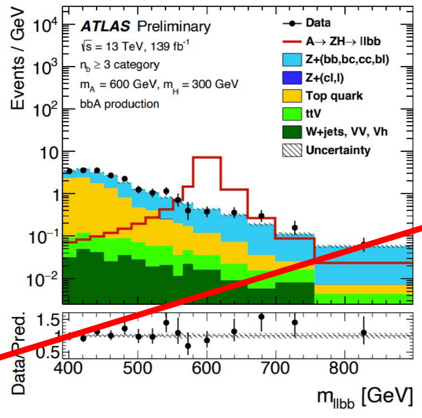



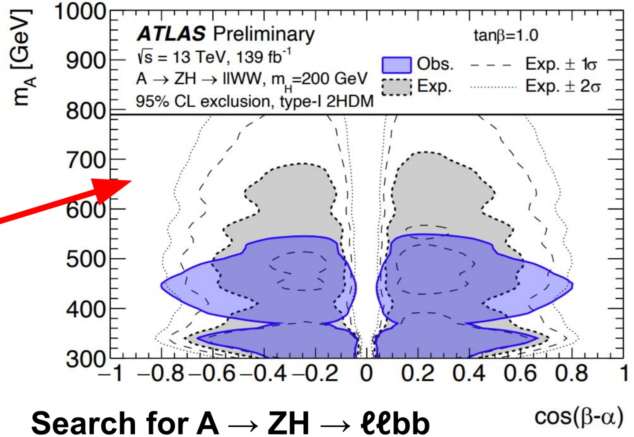

**Search for H → γγ**

# Direct Search for heavy Resonances

**In the absence of a signal:**

- Derive model dependent exclusion contours
- Set "model independent" limits on the production cross section times branching ratio

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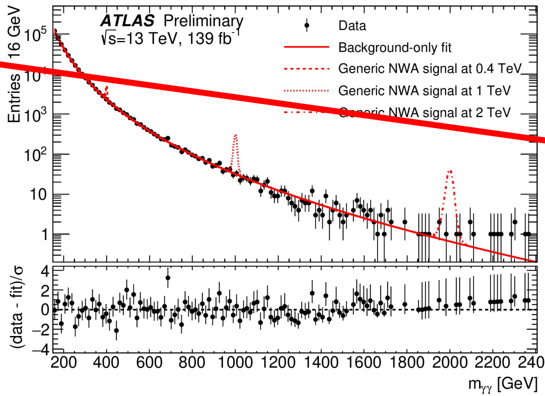
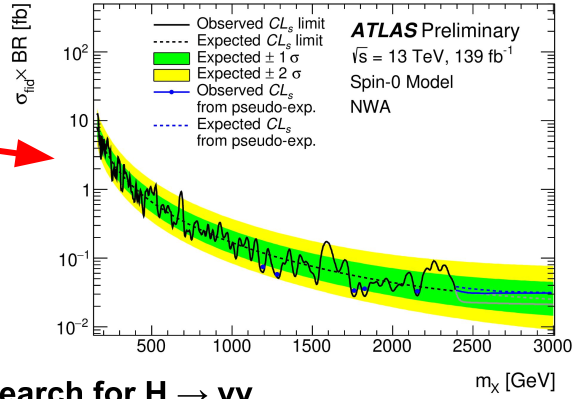
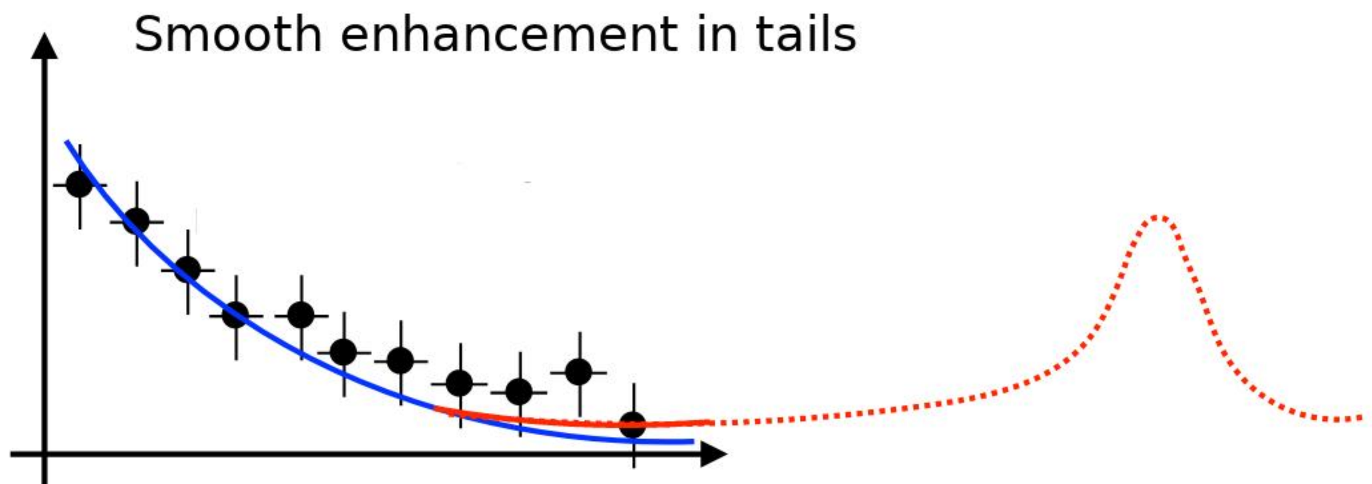



**Search for H → γγ**

# Effective field theories

- So far no hints for new physics in direct searches
- What if scale of new physics is outside the reach of the LHC?
    - **Search for smooth enhancements in the tails of our observables**
        - E.g. from resonances with masses beyond our reach
    - **Probing for shape modifications of our observables**
        - E.g. from anomalous couplings
- **Effective field theories (EFT) allow for model independent approaches to search for such new physics effects**

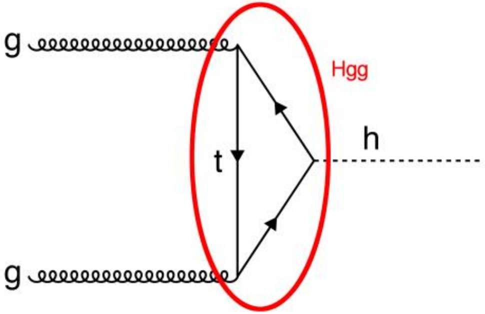


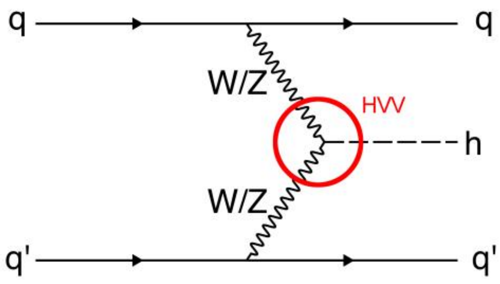
# Effective field theory (EFT)

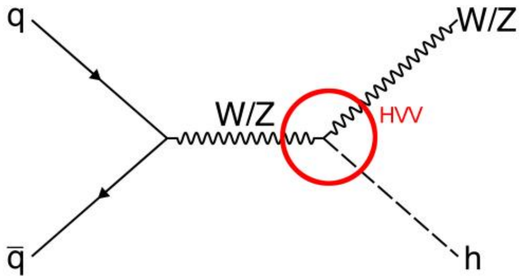
- **In EFTs, Lagrangian of the Standard Model of particle physics is supplemented with additional BSM terms:**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda} \mathcal{O}_i$$

- $\mathcal{O}_i$ are higher dimension operators
- $c_i$ are the so-called Wilson coefficients
  - Specify the strength of a new CP-even (or CP-odd) interaction (i.e. they describe deviation from SM)
- $\Lambda$ is mass scale for new particle

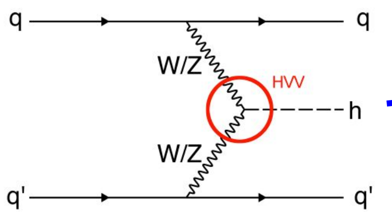


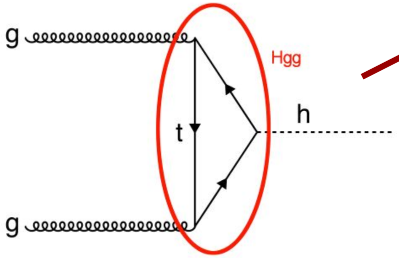



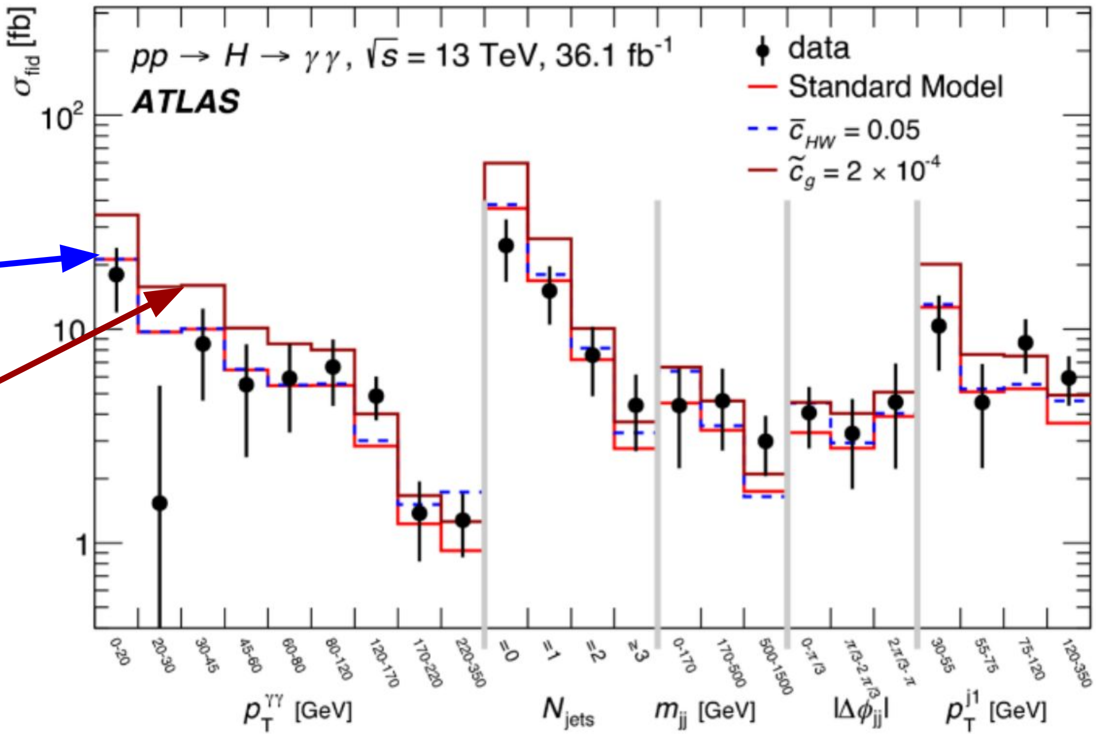



# Effective field theory (EFT)

**BSM physics contributions to the Higgs boson production process can modulate certain kinematical observables**




**Perform hypothesis tests to determine whether data fits better to SM predictions or BSM hypotheses**