The Higgs Boson:
from prediction to discovery
+
ATLAS data analysis and Monte Carlo simulation

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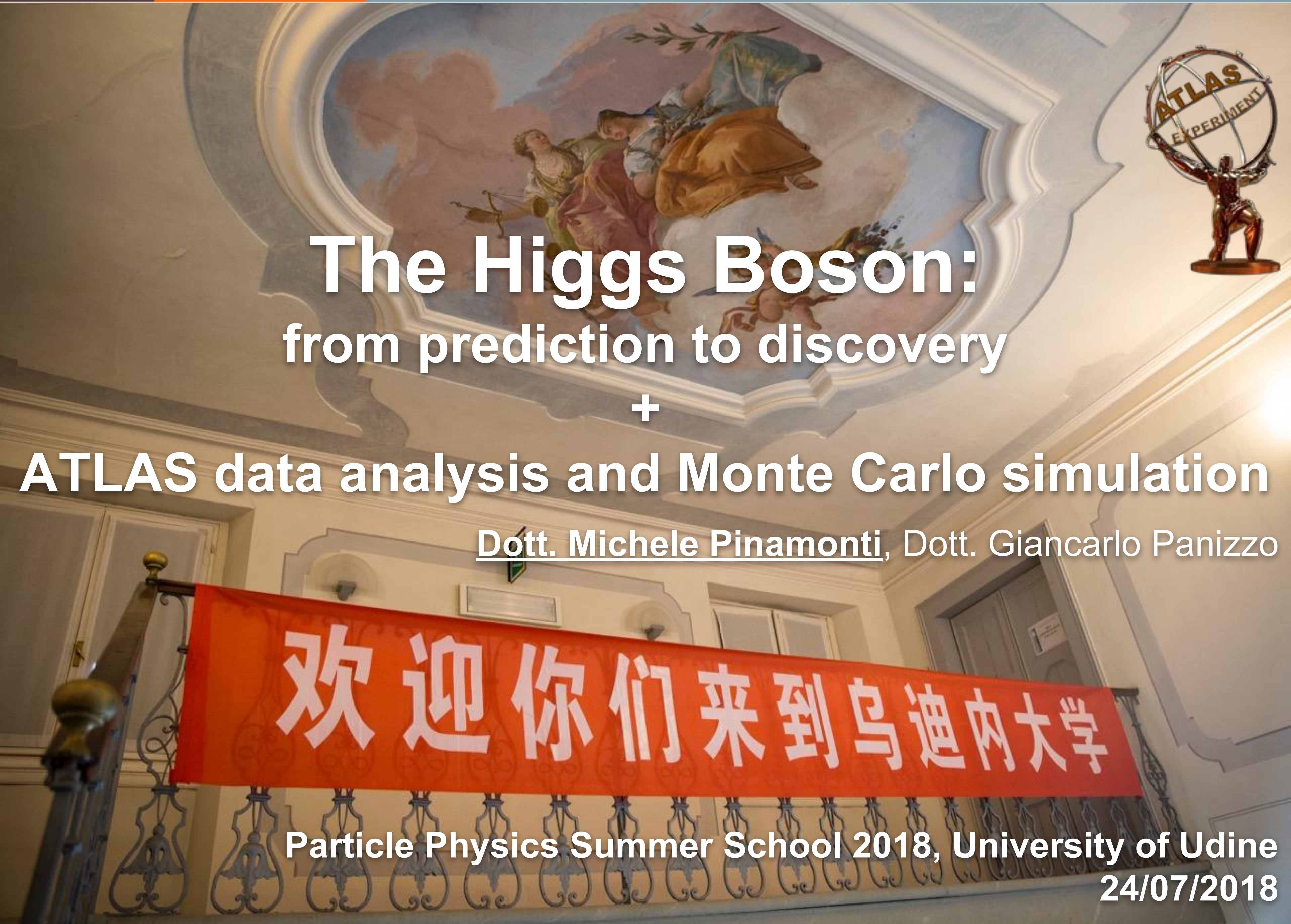

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24/07/2018

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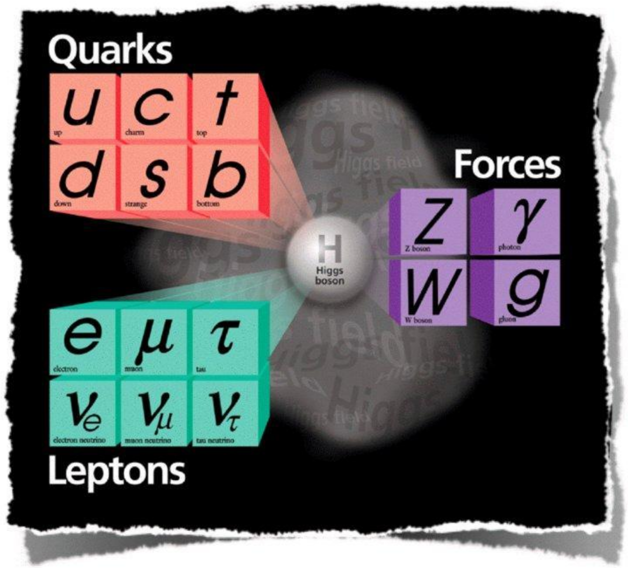
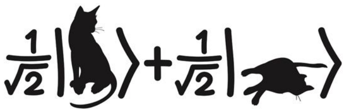
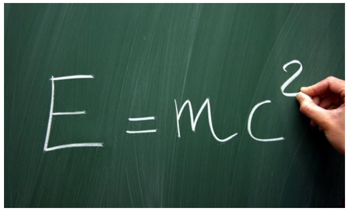
INTRODUCTION

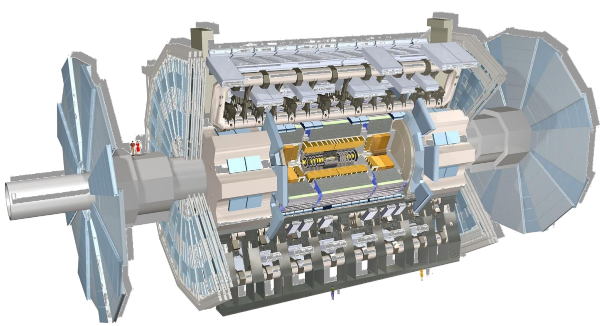


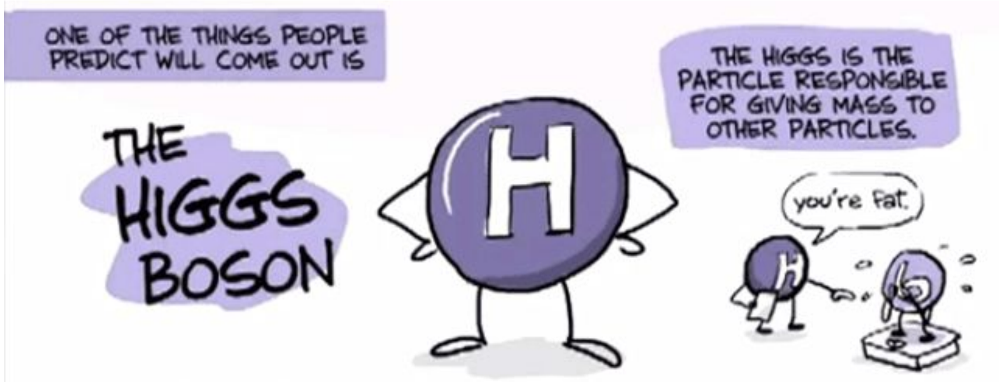
- What you should know:
  - ➜ Standard Model particles
  - ➜ Radiation-matter interaction
  - ➜ Quantum mechanics:
    - Energy quantisation
    - Indetermination and casuality
  - ➜ Special relativity / relativistic kinematics





- What will you learn:
  - ➜ What the Higgs is and what it is not
  - ➜ How ATLAS data analysis work





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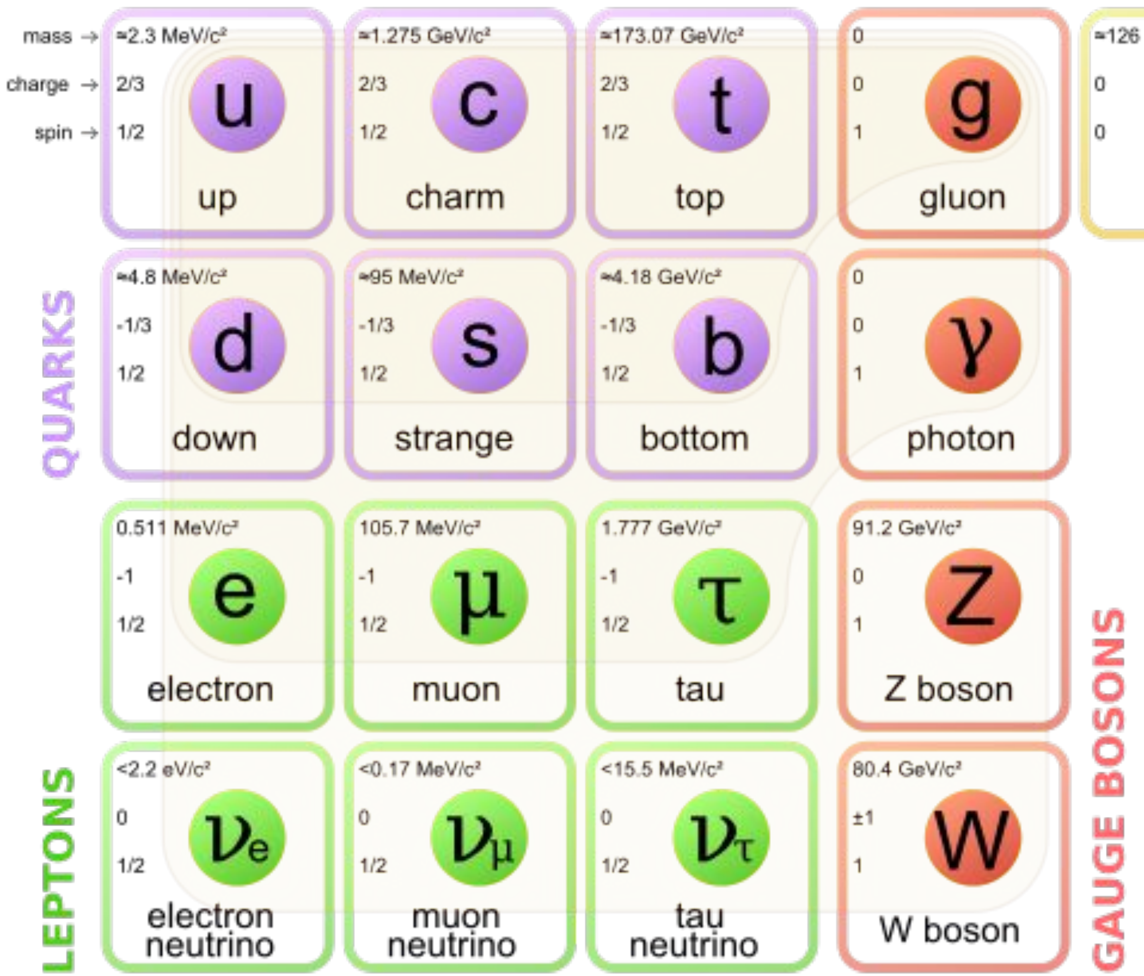
THE STANDARD MODEL



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

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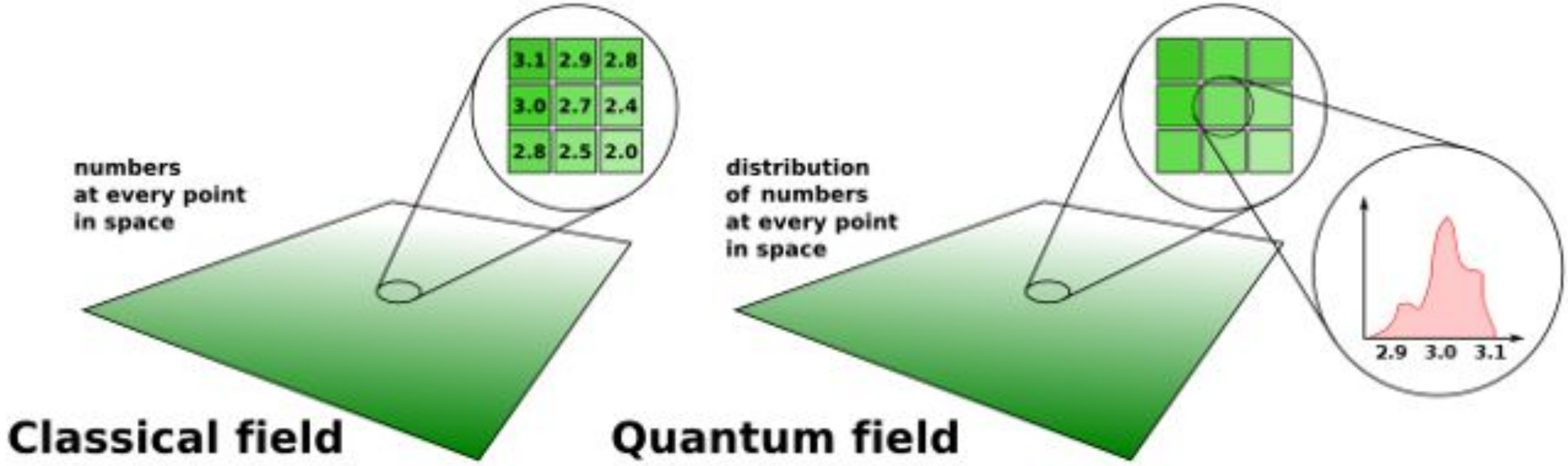
QUANTUM FIELD THEORY

- For each type of particle in the Standard Model, there's an associated field φ(x) = φ(x,y,z,t)



- Quantum fields are operators: they don't commute!
- φ can have several components:
  - ➜ scalars have one (complex) component
  - ➜ ...

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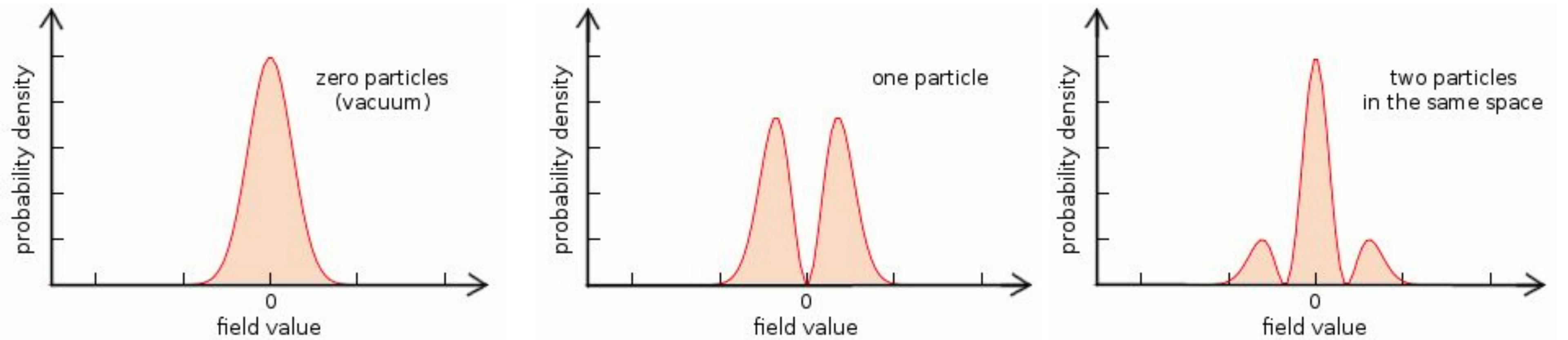
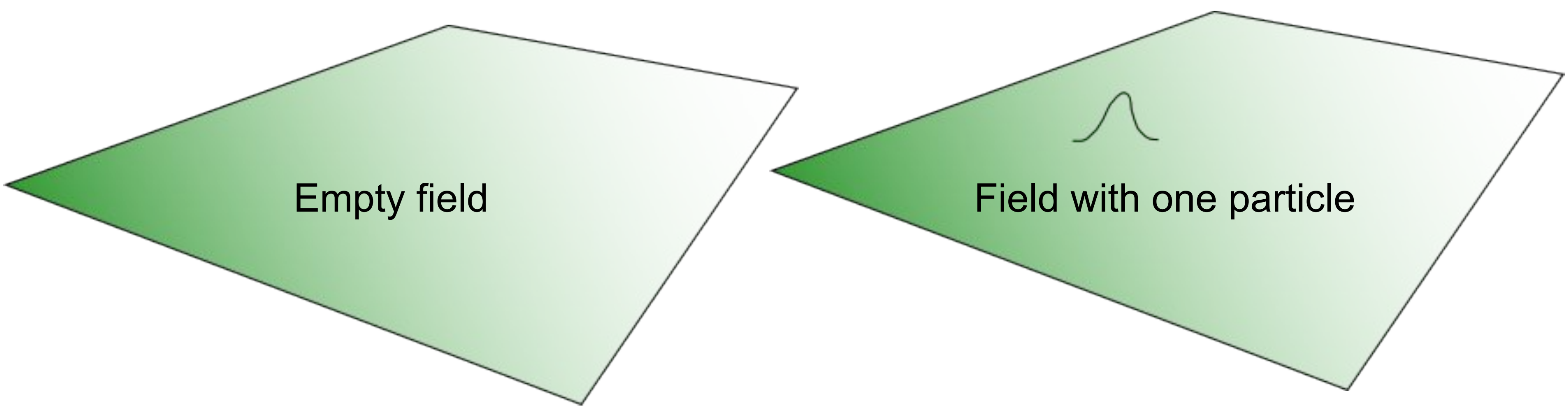
QUANTUM FIELD THEORY

- Excitations of φ correspond to creation of particles / anti-particles





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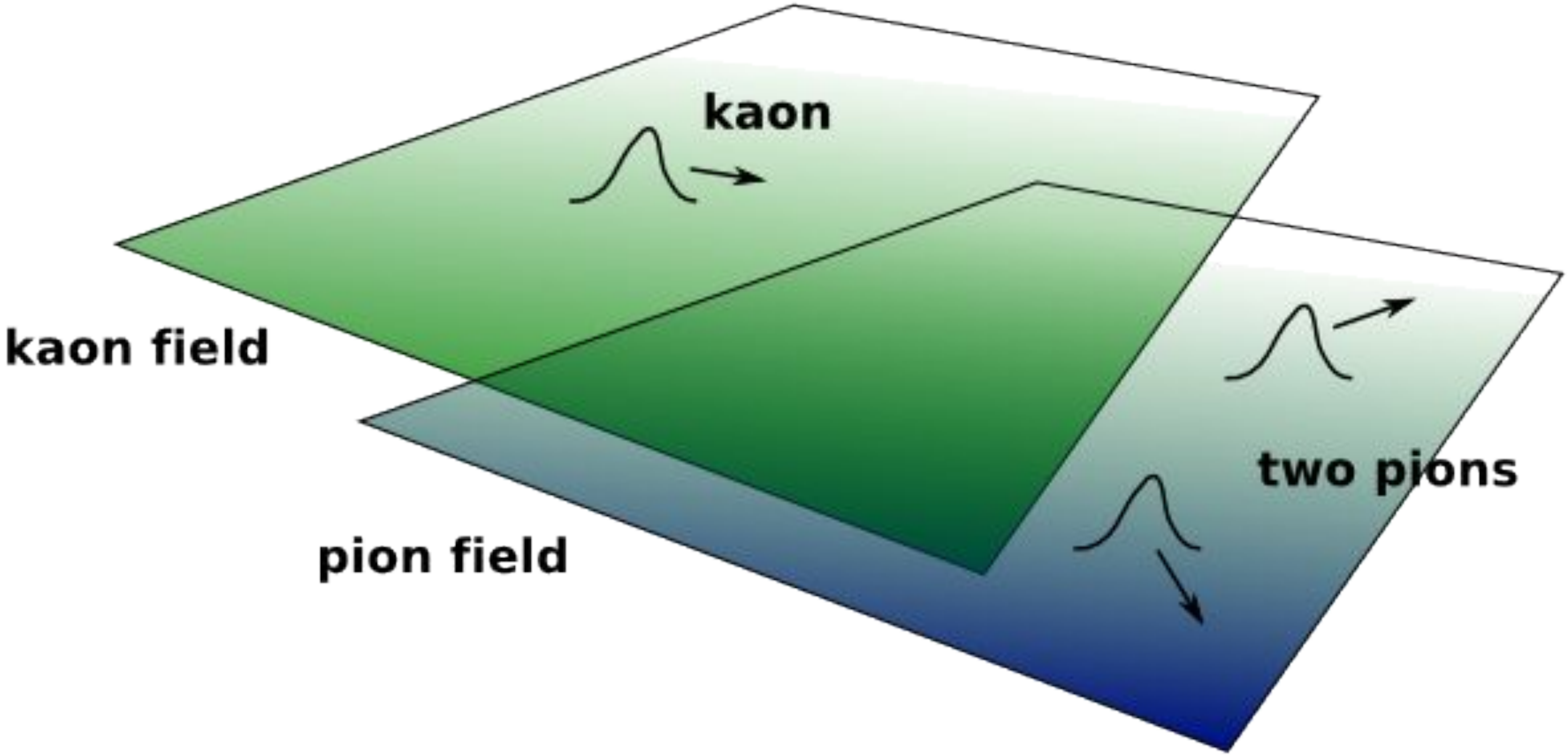
QUANTUM FIELD THEORY

- Some fields are connected to each other:
  - ➜ they interact, i.e. energy exchange between them is allowed
- Example:
  - ➜ decay K $\rightarrow$ π π



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THE LAGRANGIAN

- The Lagrangian (density) of the Standard Model:
  - ➜ a mathematical expression that contains the rules for particles and interactions between them

- Simple Lagrangians:
  - ➜ for a free fermion field:

space-time metrics operator

space-time derivative operator

hermitian conjugate of the fermion field

$$\mathcal{L} = \bar{\psi}(x)[\gamma^{\mu}\partial_{\mu} - m]\psi(x)$$

fermion field

  - ➜ for a fermion field with QED interaction:

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{int} = \bar{\psi}(x)[\gamma^{\mu}\partial_{\mu} - m]\psi(x) + ig\bar{\psi}(x)[iA_{\mu}(x)\gamma^{\mu}]\psi(x)$$

interaction term

electromagnetic field

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LAGRANGIAN AND SYMMETRIES

- Another, more elegant way to add the interaction with field A(x):
  ➜ impose **local symmetry** of the Lagrangian (gauge symmetry)

$$\varphi \rightarrow \varphi' \quad \Rightarrow \quad L \rightarrow L' = L$$

- Let's take L_0: $\mathcal{L} = \bar{\psi}(\gamma^\mu \partial_\mu - m)\psi$
  ➜ it's **invariant** for **global phase rotations**, i.e. $\psi \rightarrow e^{i\theta}\psi$ if θ doesn't depend on x
  ➜ but it's **NOT** if $\theta \rightarrow \theta(x)$ (**local** phase rotations)
- To make L invariant under local phase rotations, we need to move to the **covariant derivative**: $\partial_\mu \rightarrow D_\mu = \partial_\mu - igA_\mu(x)$
  ➜ interaction term comes from it!

(with A transforming as $A \rightarrow A - \partial\theta$)

- Adding kinetic term for the A field we have:

$$\mathcal{L} = \bar{\psi}(\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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QUANTUM-ELECTRO-DYNAMICS

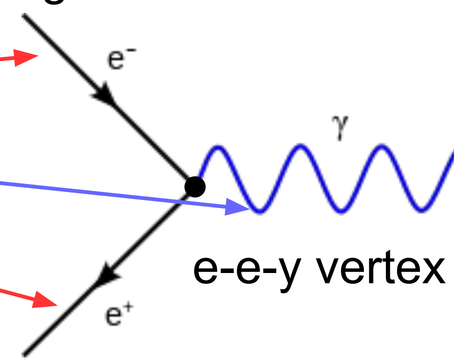
- The introduced field A(x) is the photon field (massless boson)
- Why massless?
  - ➜ A **mass term** would break the gauge symmetry!

(A → A - ∂θ)

$$\mathcal{L} = \bar{\psi}(\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + M^2 A_\mu A^\mu$$

$$\bar{\psi}\gamma^\mu \partial_\mu \psi - ig\bar{\psi}\gamma^\mu A_\mu \psi$$

Fermion-photon coupling



e-e-y vertex

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OTHER INTERACTIONS AND MASSES

- The QED example extends to other interactions:
  - ➜ **Weak** → W+, W- and Z bosons (mixed with QED into EW interaction)
  - ➜ **Strong** → 8 gluons (one for each combination of 2 of the 3 colours)

$$D_\mu = \partial_\mu - i\frac{g_1}{2} Y B_\mu - i\frac{g_2}{2}\sigma_j W^j_\mu - i\frac{g_3}{2}\lambda_\alpha G^\alpha_\mu$$

- As for the field A(x), **mass terms** **forbidden** **for all gauge bosons**
  - ➜ To satisfy EW gauge symmetry,
    mass terms are forbidden also **for fermions**

$$\mathcal{L} = \bar{\psi}(\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + M^2 A_\mu A^\mu$$

- But experimentally:
  - ➜ quarks and charged leptons have mass
  - ➜ the W and Z bosons have (large!) masses...
- We say the the **EW-symmetry** is **broken** by the mass terms in L

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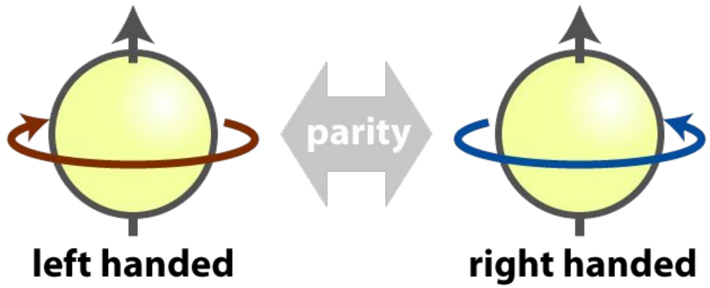
ELECTRO-WEAK SYMMETRY

- A simple way to understand how the EW gauge symmetry can forbid fermion mass terms:
  - ➜ the **EW interaction** is linked to the **helicity** (the **spin** projection on the motion axis)



  - ➜ The **distinction** between left-handed (L) and right-handed R) particles is **boost-invariant only if m=0**, *i.e. helicity is a Lorentz invariant only for mass-less particles*:
    - for massive particles we can consider a reference frame moving faster than the particle, where helicity is different!

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THE HIGGS MECHANISM

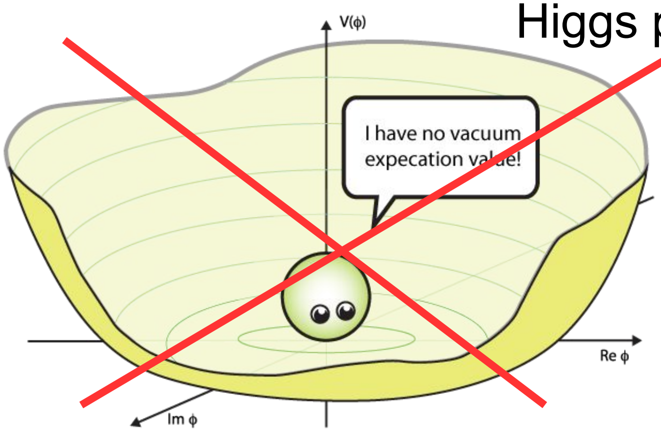
- Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism proposed in the '60s to explain the EW symmetry breaking:
  - ➜ through the introduction of a **new scalar field** (the **Higgs** field)
  - ➜ particles get mass by **interacting** with this field
  - ➜ EW symmetry is broken in a **dynamic way** (spontaneous symmetry breaking)

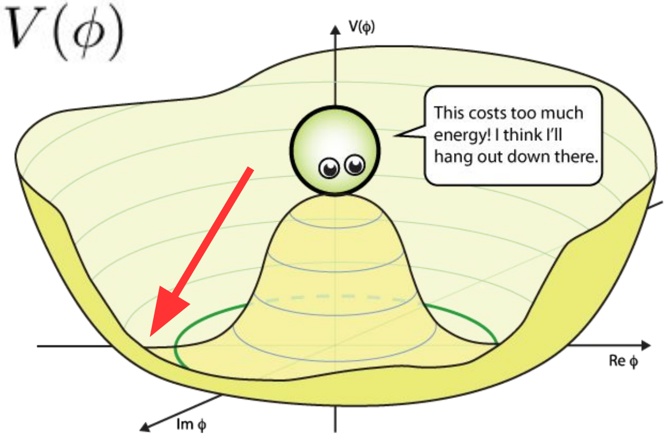
$$\mathcal{L} \to \mathcal{L} + (D_\mu \phi)^2 + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

THE HIGGS MECHANISM

$$\mathcal{L} \rightarrow \mathcal{L} + (D_\mu \phi)^2 + \boxed{\mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2}$$

Higgs potential $V(\phi)$





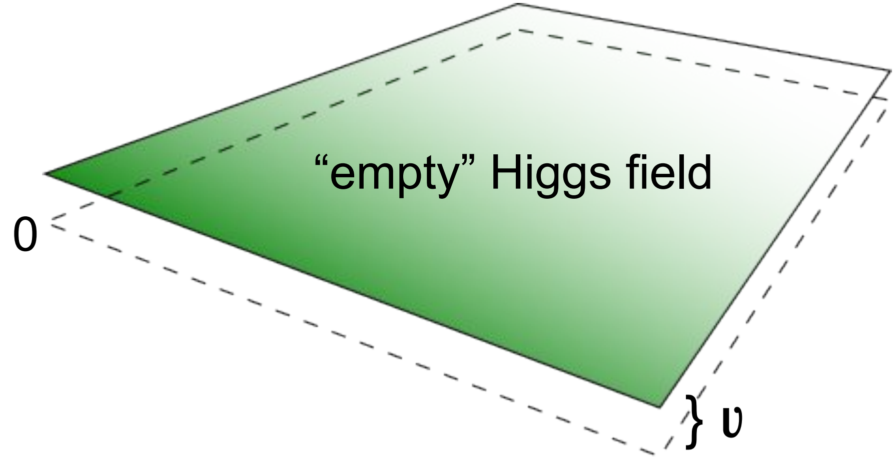
- Ground state (state with minimal energy) corresponds to a non-zero value, v

$\phi = v$

Vacuum expectation value

➜ The new field can be re-written as:

$$\phi(x) \simeq H(x) + v$$



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THE GENERATION OF THE MASSES

- In this way:

$$(D_\mu \phi)^2 \to (D_\mu (H(x) + v))^2$$
$$= \ldots - (igW_\mu (H(x) + v))^2$$
$$= \ldots + g^2 v^2 W_\mu W^\mu$$

…and one can have W and Z bosons getting masses (not g and γ)

➜ Moreover, adding "by hand" a new interaction term, the so-called Yukawa interaction (which is gauge-invariant):

$$\mathcal{L} \to \mathcal{L} - y_i \phi \bar{\psi}_i \psi_i \quad = \mathcal{L} - y_i H(x) \bar{\psi}_i \psi_i - y_i v \bar{\psi}_i \psi_i$$

… also the fermion mass terms are obtained

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THE SM LAGRANGIAN

- SM Lagrangian, invariant form:

$$\mathcal{L} = \bar{\psi}\gamma^{\mu} D_{\mu}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - y_i \phi \bar{\psi}_i \psi_i + (D_{\mu}\phi)^2 + \mu^2 \phi^{\dagger}\phi - \lambda(\phi^{\dagger}\phi)^2$$

$$\partial_{\mu} - igA_{\mu}(x)$$

$$H(x) + v$$

- After EM-symmetry breaking:

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{mass} + \mathcal{L}_{int} + \mathcal{L}_{H}$$

$$\bar{\psi}_i\gamma^{\mu}\partial_{\mu}\psi_i - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$m_i\bar{\psi}_i\psi_i + M^2 A_{\mu}A^{\mu} + \ldots$$

$$(\partial_{\mu}H)^2 + \mu^2 H^{\dagger}H - \lambda(H^{\dagger}H)^2$$

$$-ig\bar{\psi}_i\gamma^{\mu}A_{\mu}\psi_i - y_i H\bar{\psi}_i\psi_i - gvHA_{\mu}A^{\mu} + \ldots$$

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THE HIGGS BOSON

- **Notice**: until now we didn't talk about Higgs "boson" or "particle"
  - ➜ particles **don't** get mass thanks to the **Higgs boson**!!!
  - ➜ particles get mass through the ***interaction*** with the Higgs ***field***
    - and actually through the interaction with the part of the field which is NOT associated with the Higgs boson, the **v.e.v.**

$$\phi(x) \simeq H(x) + v$$

- The Higgs boson is a **side-effect** of the Higgs mechanism
  - ➜ but allows to prove the validity of the theory experimentally:
    - a **new neutral scalar boson** is **predicted**,
      with unknown mass but known couplings with massive particles (coupling with H and v is the same, and coupling with v is know thanks to the particle mass)

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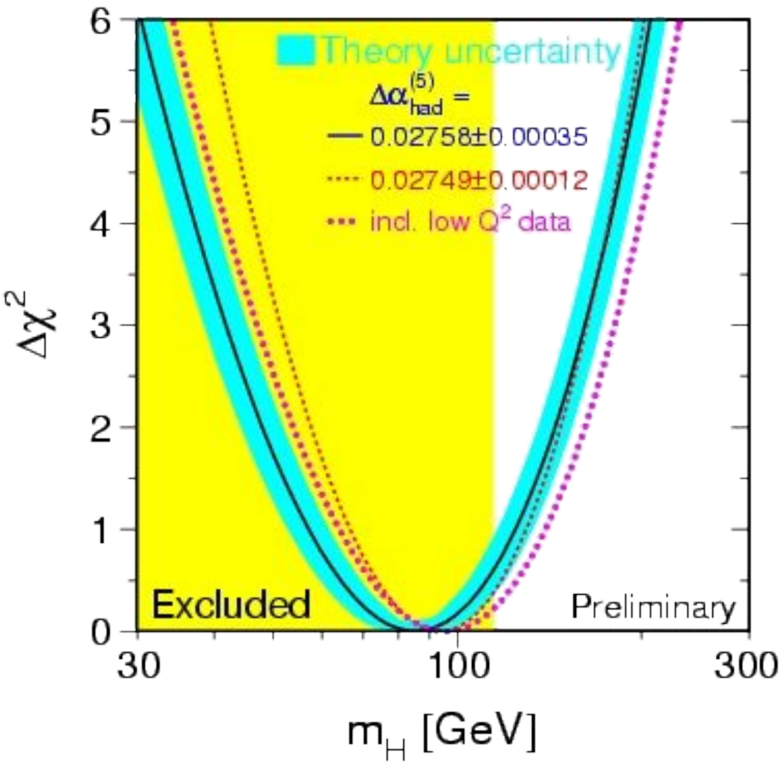
THE HIGGS BOSON BEFORE LHC

- What did we know about it **before LHC**?
  - ➜ **coupling strength** with other particles proportional to mass:
    - H prefers to decay into heavy particles
    - H can be produced preferentially from interaction between heavy particles
  - ➜ its **mass** should be:
    - higher than ~115 GeV from searches at previous colliders (LEP)
    - not too high, in agreement with its indirect determination from a fit to other SM observables



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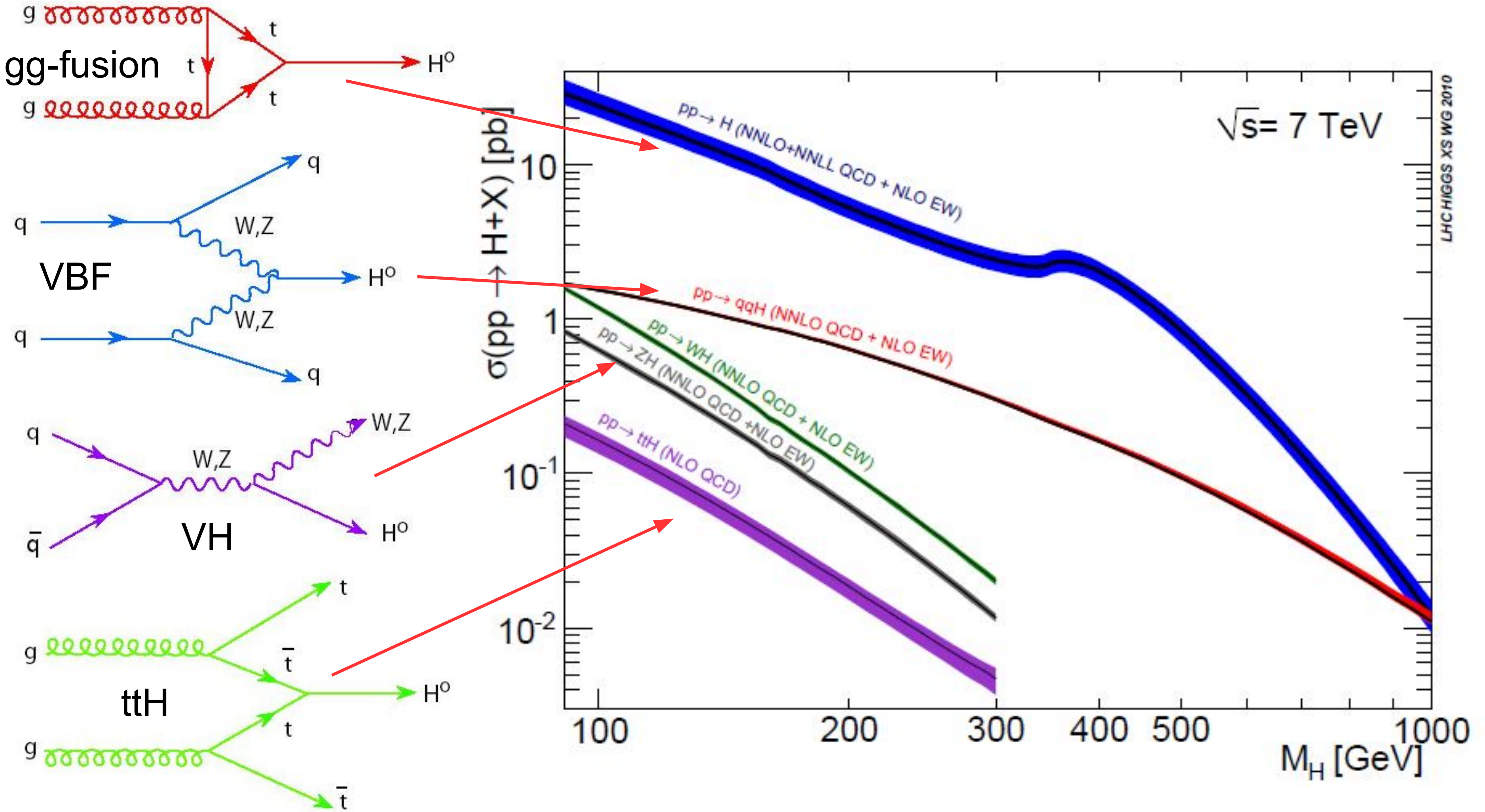
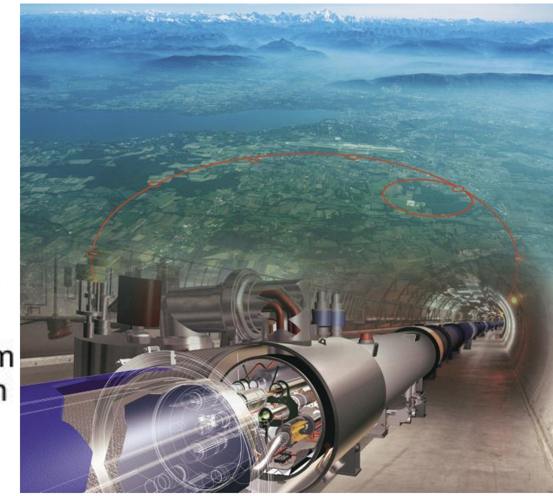
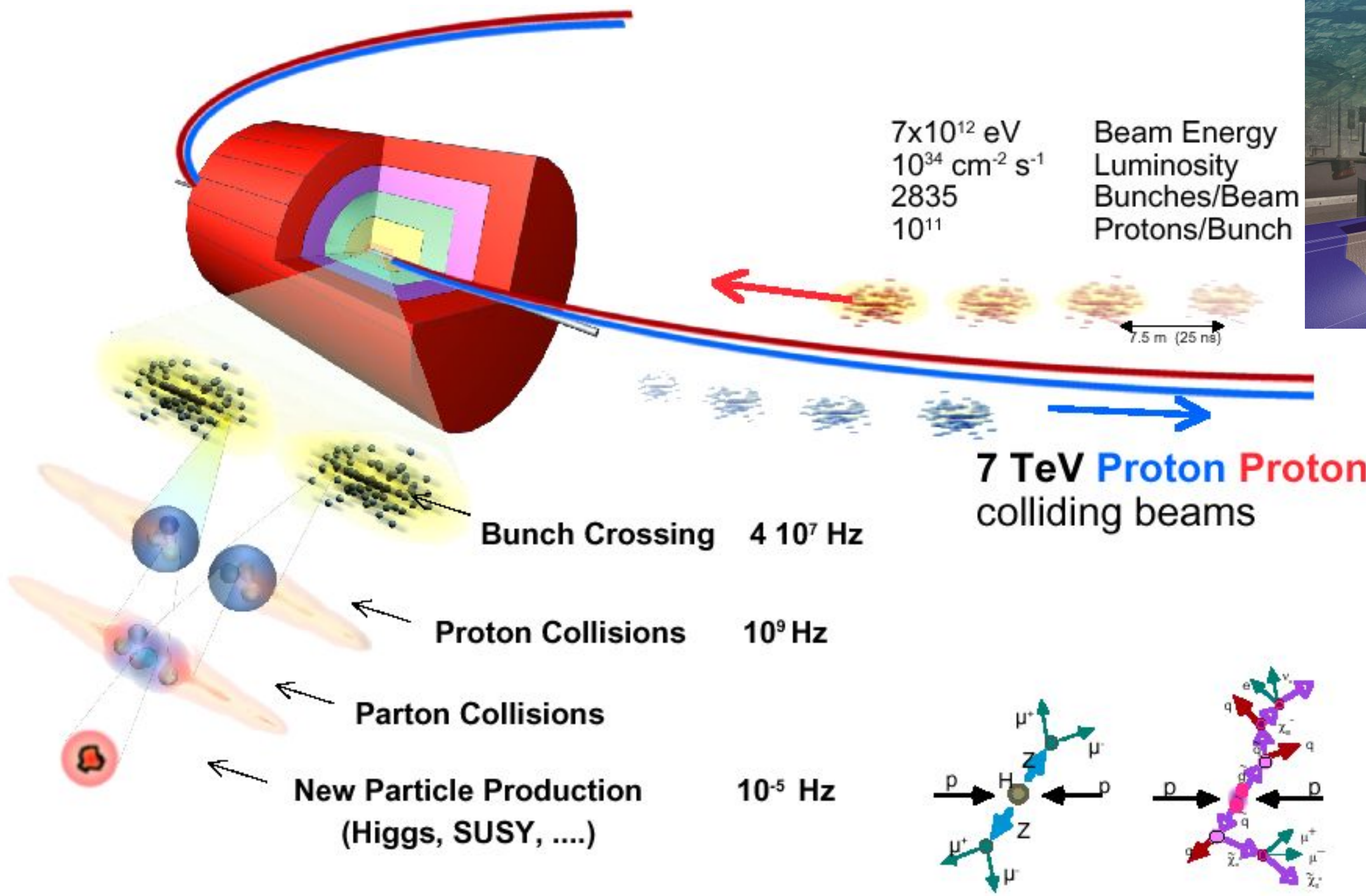
HIGGS BOSON PRODUCTION



THE LARGE HADRON COLLIDER





Selection of 1 event in 10,000,000,000,000

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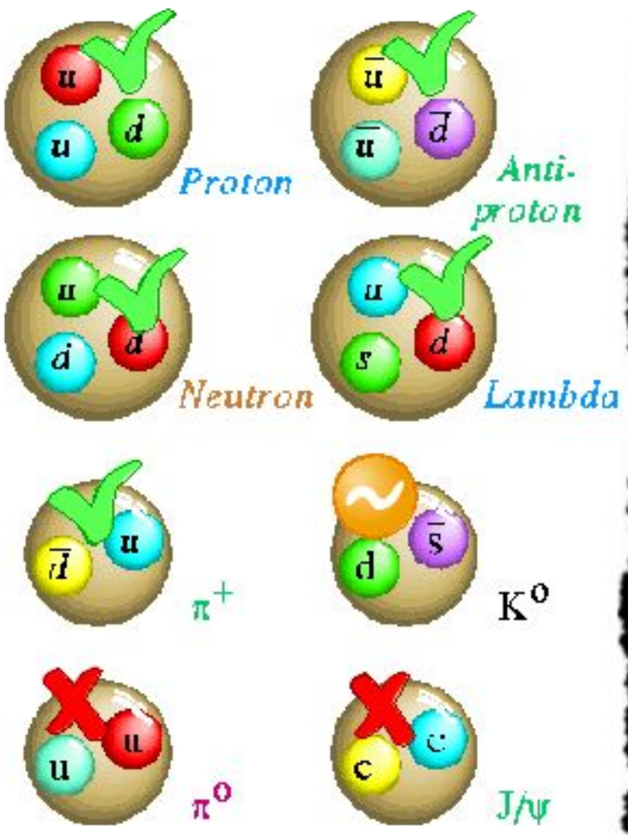
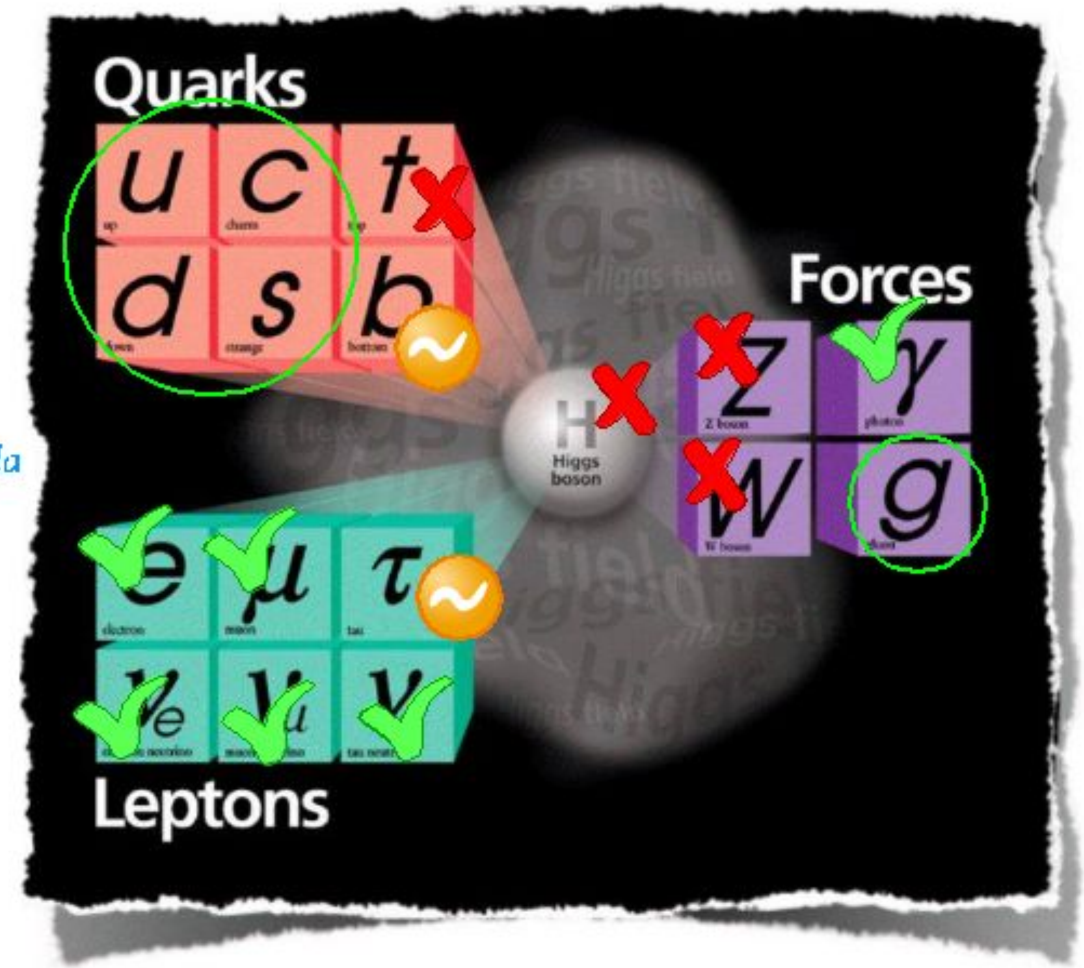
SEEING THE HIGGS BOSON

- The Higgs boson can only be seen via its decay products
  - ➜ "Stable" and "unstable" particles:





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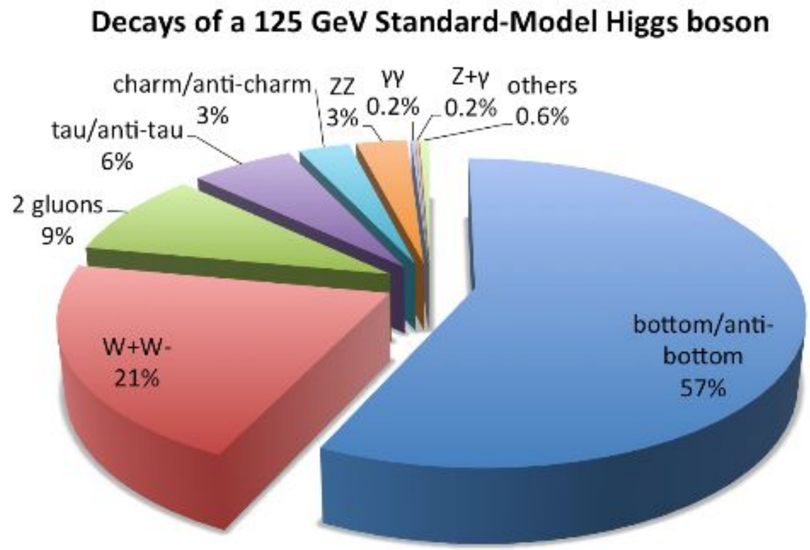
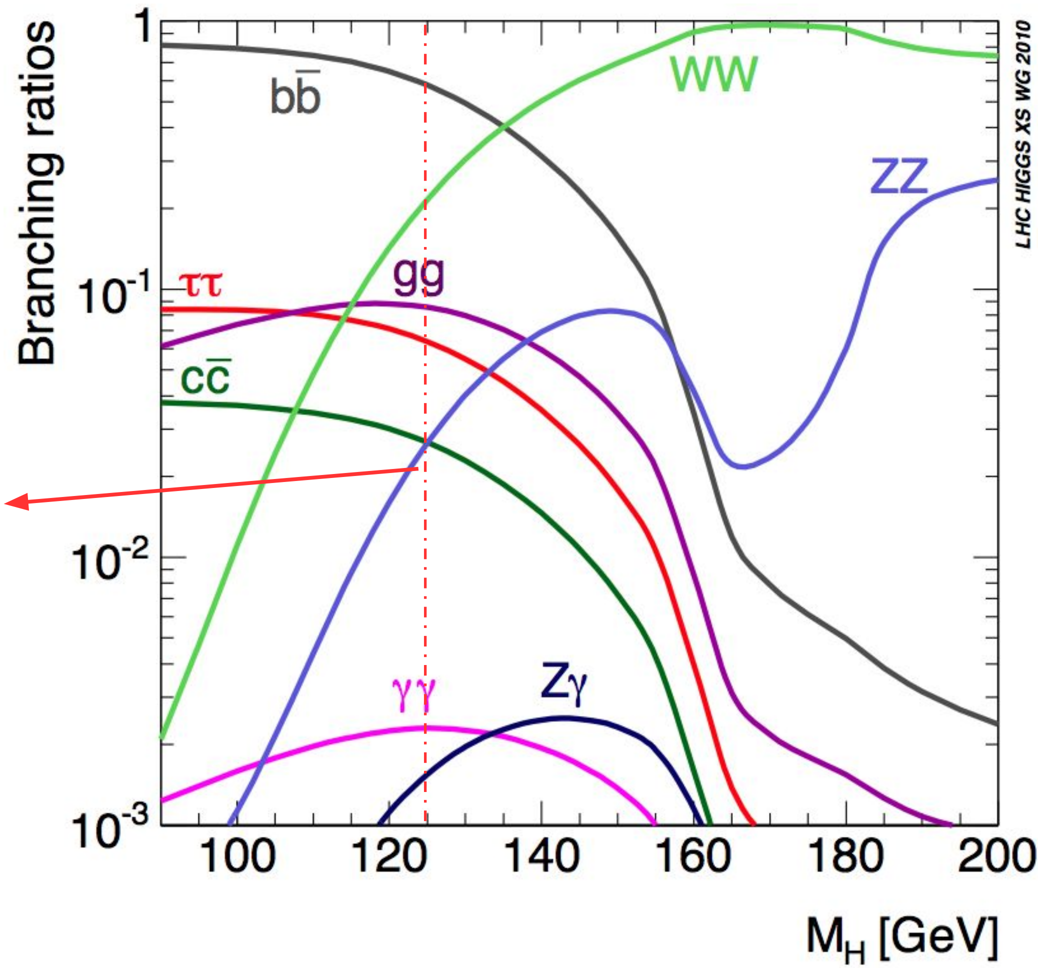
HIGGS BOSON DECAY





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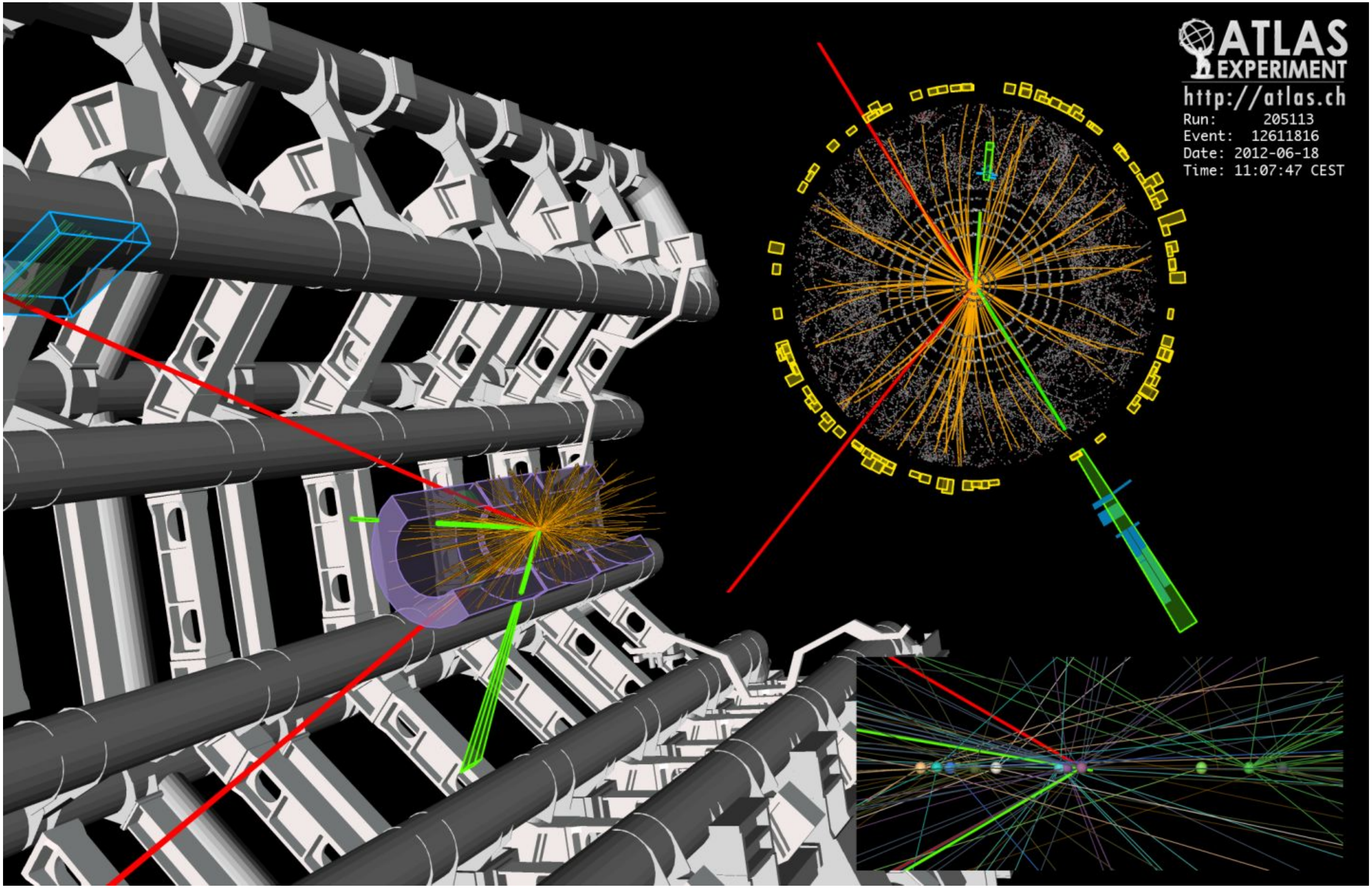
A HIGGS BOSON CANDIDATE IN ATLAS



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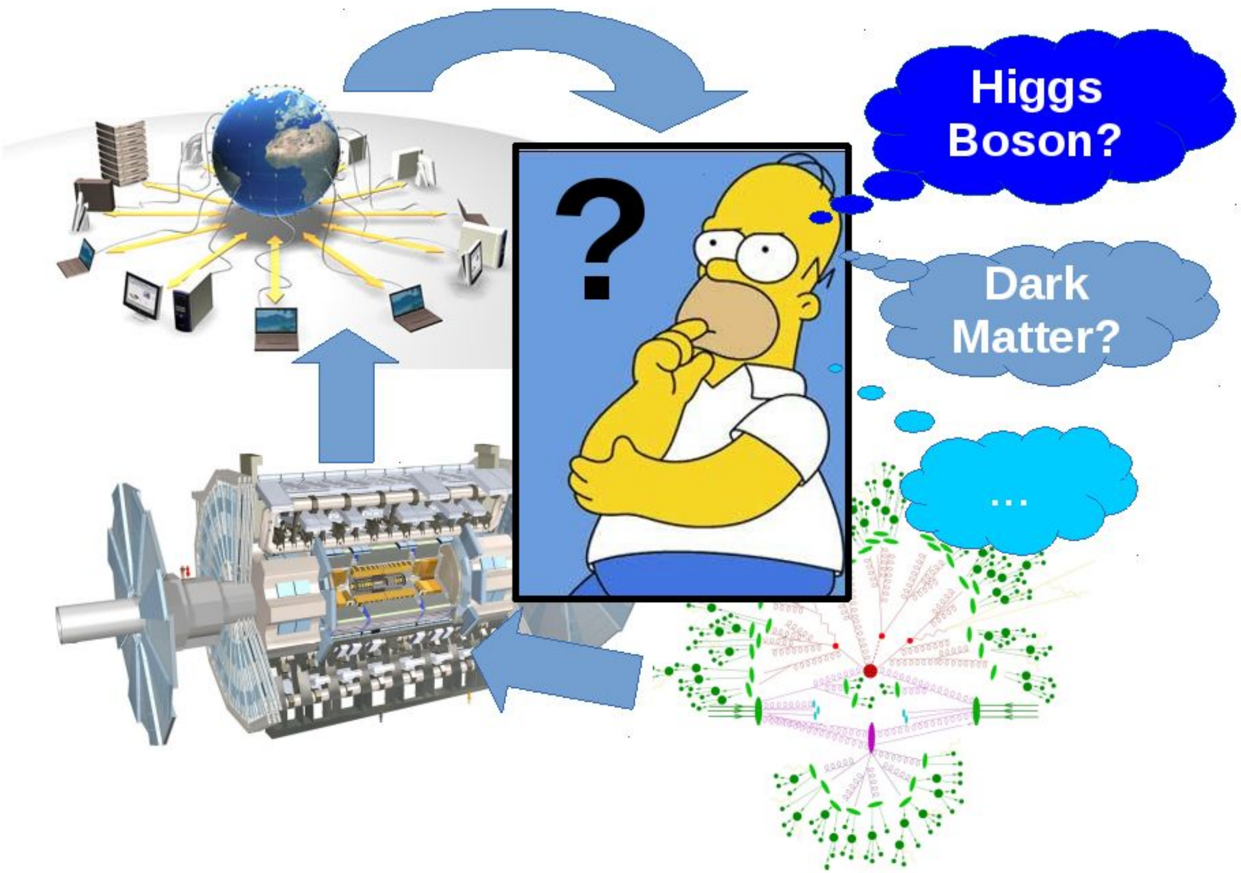
ATLAS DATA ANALYSIS

- What does it mean "analyse ATLAS data"?



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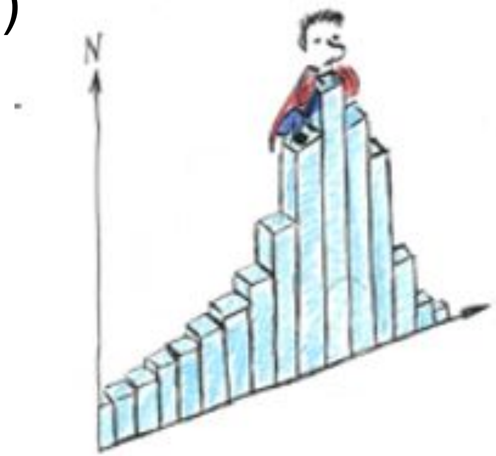
ATLAS DATA ANALYSIS

1. Define **what** we want to measure
2. Choose a “**final state**” or “channel”
3. Identification of **background** processes
4. Define an “**event selection**” (and an “object selection”)
5. Look at the “**observable**”:
   number of events, invariant mass, asymmetry...
   ➜ usually build histogram(s)
6. **Extract** the measurement & it's uncertainty
   ➜ from the comparison of data histograms with a model (built from theory, assumptions, simulation...)
   ➜ statistical interpretation



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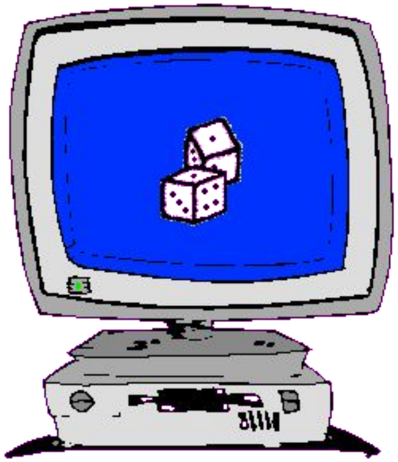
REAL DATA AND SIMULATION

- Detector system
- Trigger
- Data-acquisition
- Data distribution
- Reconstruction
- Calibration

- "In parallel", the analyser should:
  - ➜ get and read the Data from the detector
  - ➜ compare with Simulated Data



- Monte Carlo (MC) generator development
- Simulated event production

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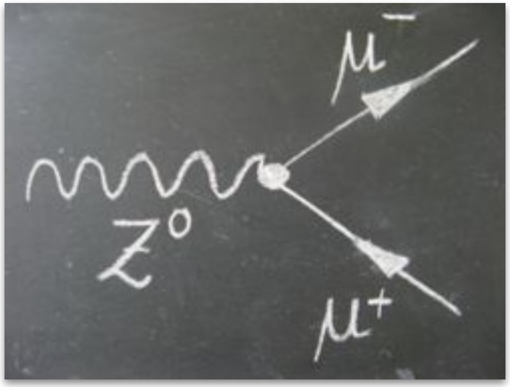
SIMPLE EXAMPLE



1. What?
   - ➜ Measure the production cross-section of the Z boson in pp collisions at 7 TeV
2. Final state?
   - ➜ Use the final state with two opposite sign electrons / muons (from Z decay)
3. Background?
   - ➜ Events from tt → Wb Wb → lvb lvb, events with "fake" lepton(s)...
4. Selection?
   - ➜ 2 electrons or muons with pT > 25 GeV, $|\eta|<2.5$, isolated (energy around lepton below a given threshold)
5. Observable?
   - ➜ Build a histogram with the dilepton invariant mass

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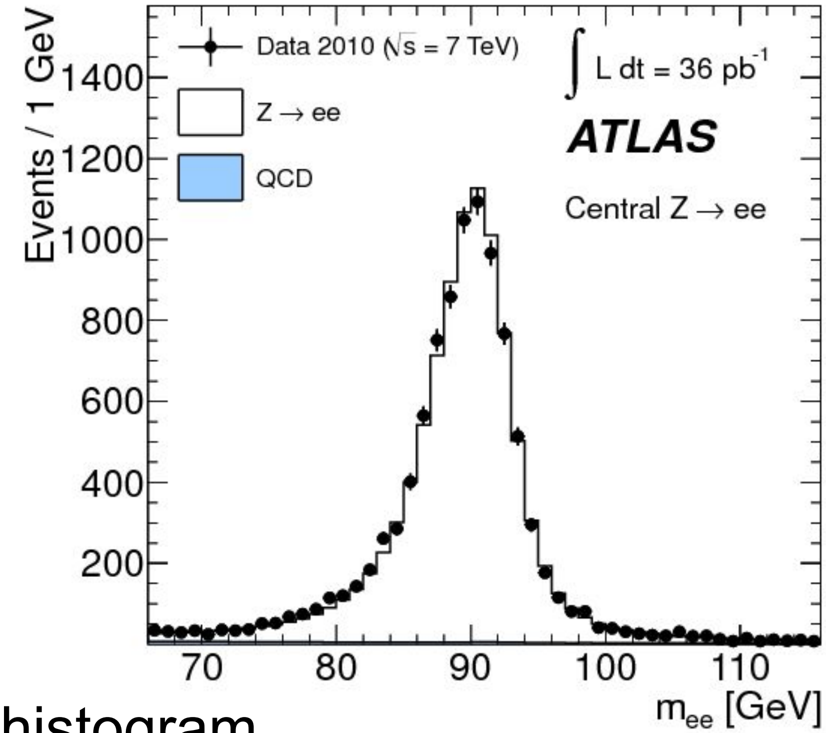
SIMPLE EXAMPLE



6. Extract measurement!
   - ➜ compare two histograms:
     - data histogram
     - MC-simulation events, scaled according to predicted cross-section and amount of data (integrated luminosity)
   - ➜ Scale signal component in MC histogram by a factor *μ* which maximises the agreement with data
   - ➜ Fit procedure:

     $N_i = \mu * S_i + B_i$

     $X^2 = \Sigma_i (D_i - N_i)^2 / \sigma^2_{Di} = \Sigma_i (D_i - \mu * S_i - B_i)^2 / D_i$
   - ➜ Value of μ minimizing this X^2 is used to extract measurement:

     $\sigma_Z^{measured} = \mu * \sigma_Z^{prediction}$

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MONTE CARLO SIMULATION

- Monte Carlo simulation used to predict what we expect to see under certain conditions:
  - ➜ to perform studies before having the data
  - ➜ to compute event selection efficiency / acceptance
  - ➜ to predict the amount of background events
  - ➜ to distinguish different signals

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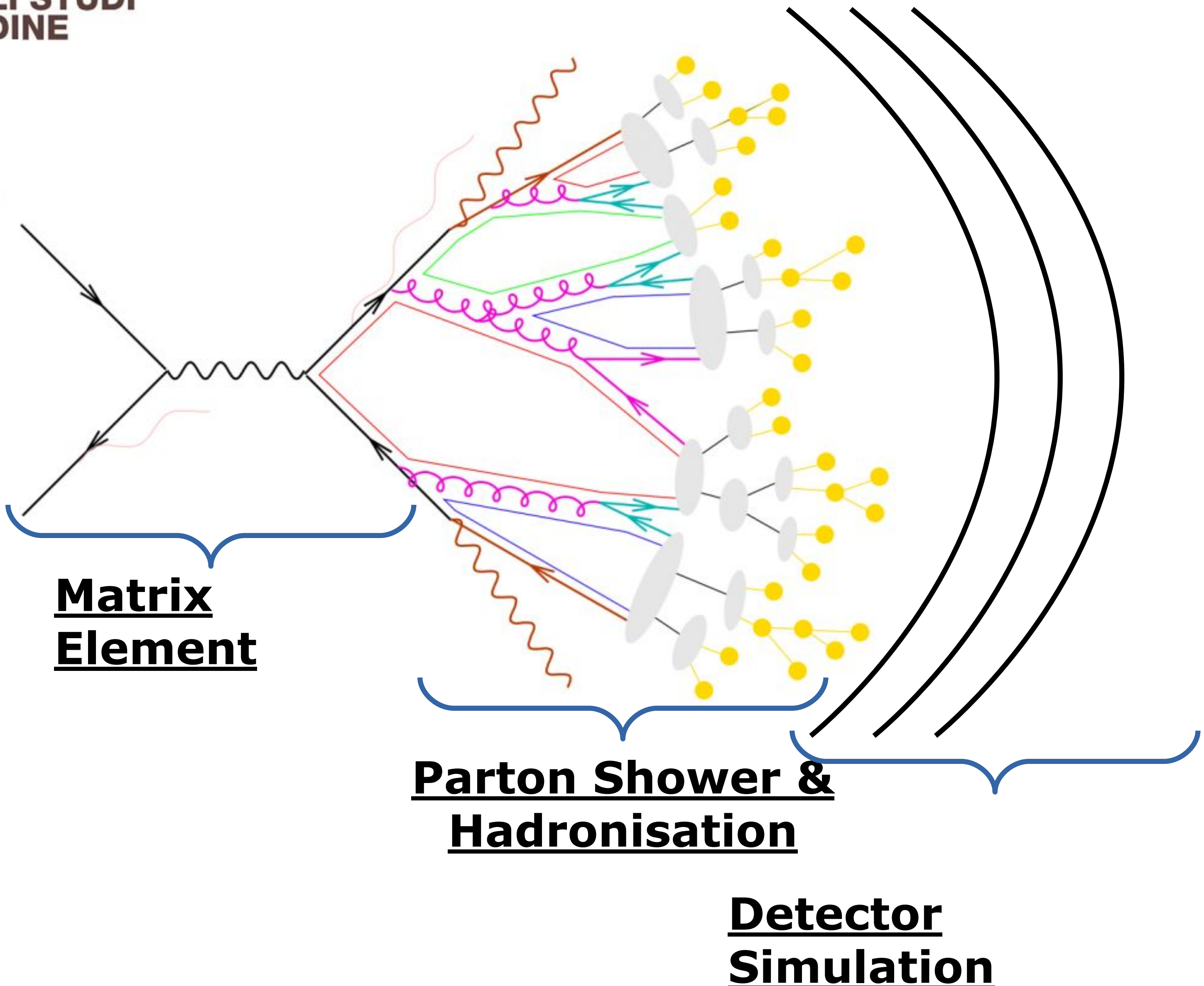
“Matrix Element”
- → Generation of the central process
- → At “parton level”
- → Usually no decays
- → No hadrons
- → No time-evolution

“Parton Shower & Hadronisation”
- → Evolution of the final (and initial!) states
- → Simulation non-perturbative QCD: gluon emission and gluon splitting
- → From partons to parton-jets and hadrons
- → Unstable particle decays

“Detector Simulation”
- → Simulation of the particle-detector material interaction
- → Full simulation very computationally expensive
- → Often “fast simulation“ used

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays



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"Matrix Element"

- ➔ MadGraph
- ➔ Multi-leg LO processes (i.e. 2→N processes)
- ➔ Any process, at any order in QCD and EW
- ➔ QCD-NLO functionality added with aMCatNLO
- ➔ Any new model: useful for new physics studies!

"Parton Shower & Hadronisation"

- ➔ Pythia
- ➔ Most standard complete MC generator (ME+PS+Had)
- ➔ Automatically interfaced with MadGraph

"Detector Simulation"

- ➔ Delphes
- ➔ Fast simulation of the detector response through parametric simulation (not full simulation)

DELPHES
fast simulation

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MADGRAPH INPUTS AND OUTPUTS

- When running MG5, different cards (text files containing options)
- The most important ones:
  - ➜ run_card.dat
  - ➜ param_card.dat
- delphes_card.dat

```
#*********************************************************************
# Number of events and rnd seed                                      *
# Warning: Do not generate more than 1M events in a single run       *
# If you want to run Pythia, avoid more than 50k events in a run.    *
#*********************************************************************
  10000 = nevents ! Number of unweighted events requested
      0       = iseed    ! rnd seed (0=assigned automatically=default))
#*********************************************************************
# Collider type and energy                                           *
# lpp: 0=No PDF, 1=proton, -1=antiproton, 2=photon from proton,      *
#                                        3=photon from electron      *
#*********************************************************************
        1     = lpp1    ! beam 1 type
        1     = lpp2    ! beam 2 type
     6500     = ebeam1  ! beam 1 total energy in GeV
     6500     = ebeam2  ! beam 2 total energy in GeV
```

```
Block MASS      #  Mass spectrum (kinematic masses)
#        PDG       Mass
          5     4.70000000E+00   # bottom    pole mass
          6     1.74300000E+02   # top       pole mass
         15     1.77700000E+00   # tau       mass
         23     9.11880000E+01   # Z         mass
         24     8.04190000E+01   # W         mass
         25     1.20000000E+02   # H         mass
#             PDG        Width
DECAY          6     1.50833649E+00   # top width
DECAY         23     2.44140351E+00   # Z   width
DECAY         24     2.04759951E+00   # W   width
DECAY         25     5.75308848E-03   # H   width
```

Output (from Delphes):

Jet[0] → PT, Eta, Phi, Mass, Btag, ...

TTree

Electron[x]	Muon[x]	Jet[x]	…
Electron[x]	Muon[x]	Jet[x]	…
Electron[x]	Muon[x]	Jet[x]	…

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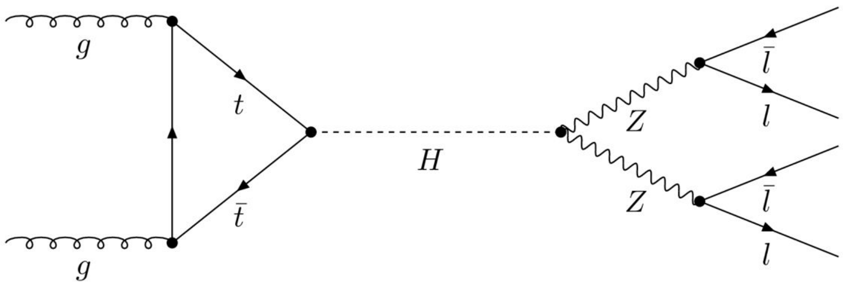
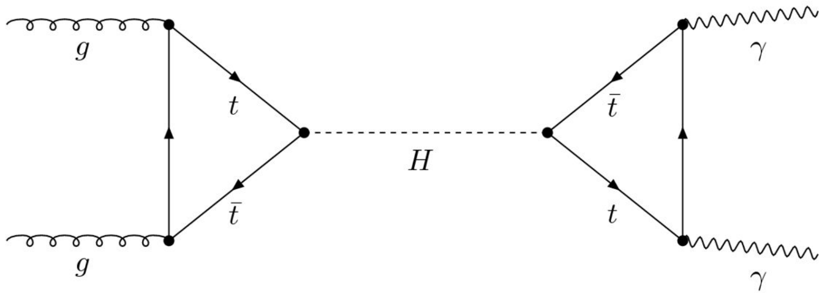
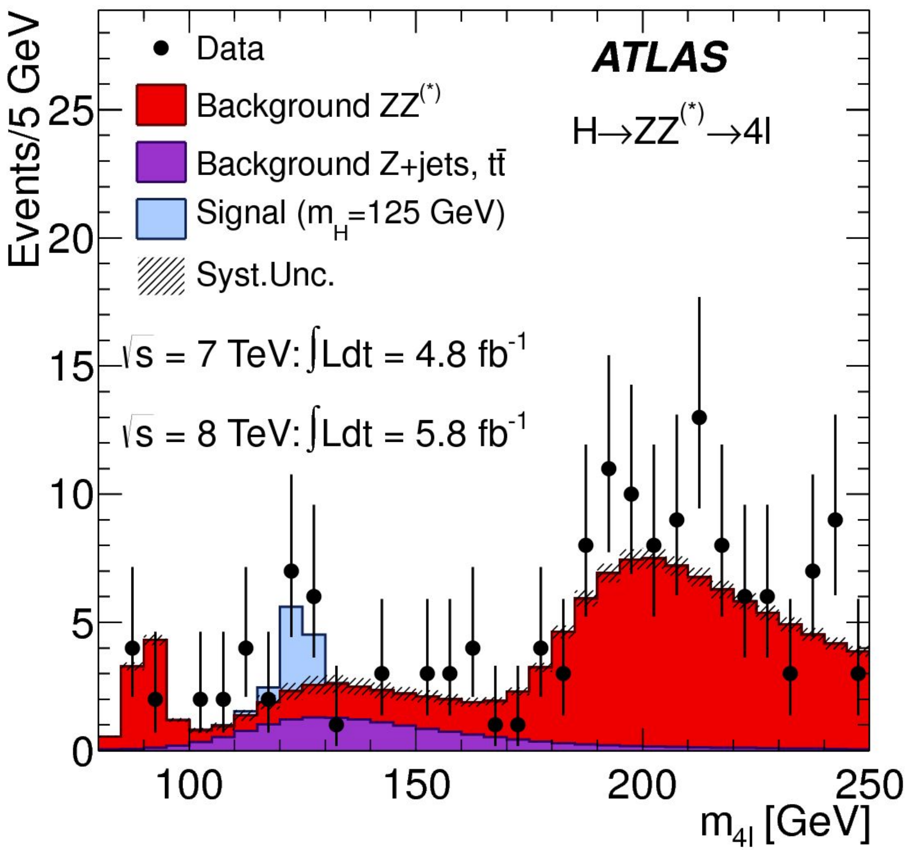
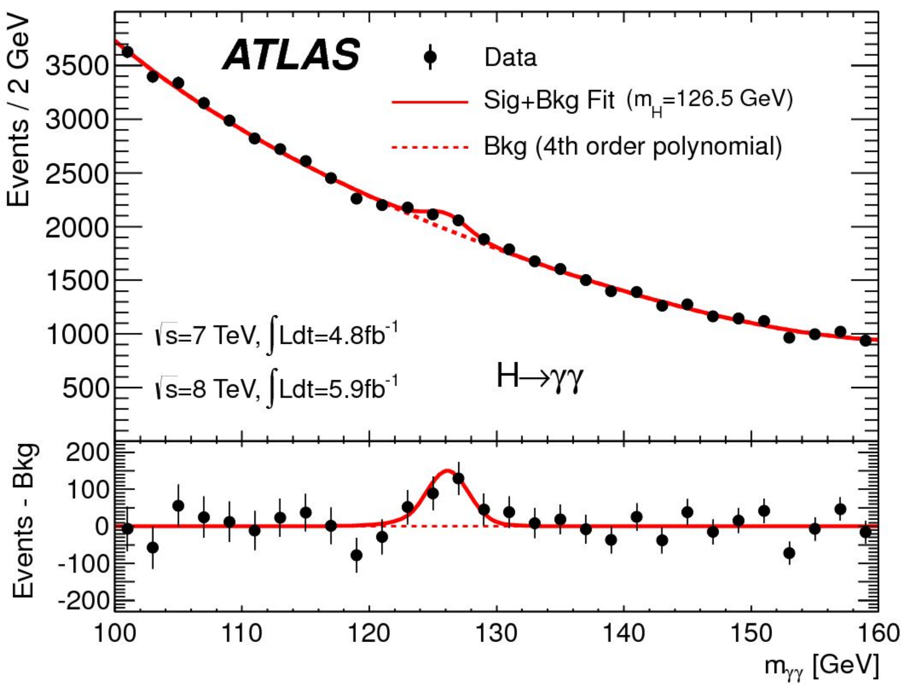
THE GOLDEN CHANNELS









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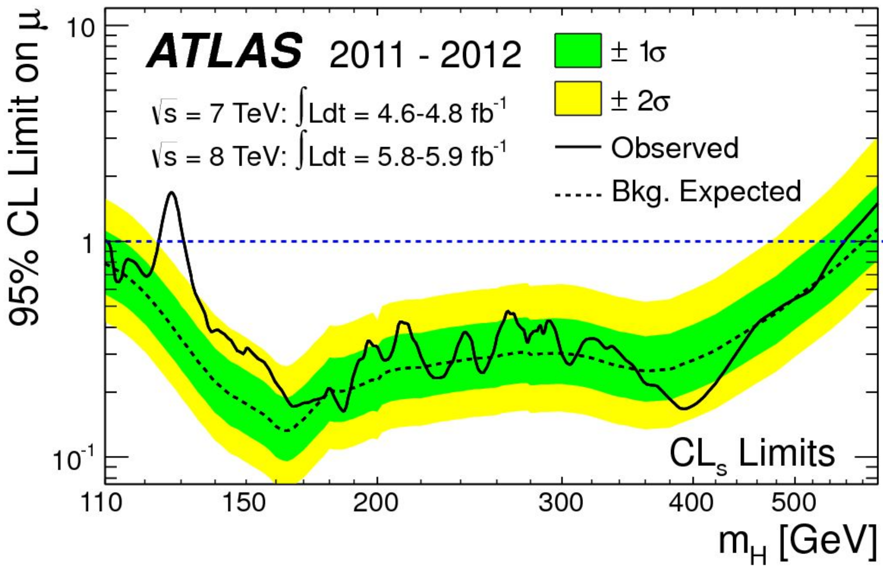
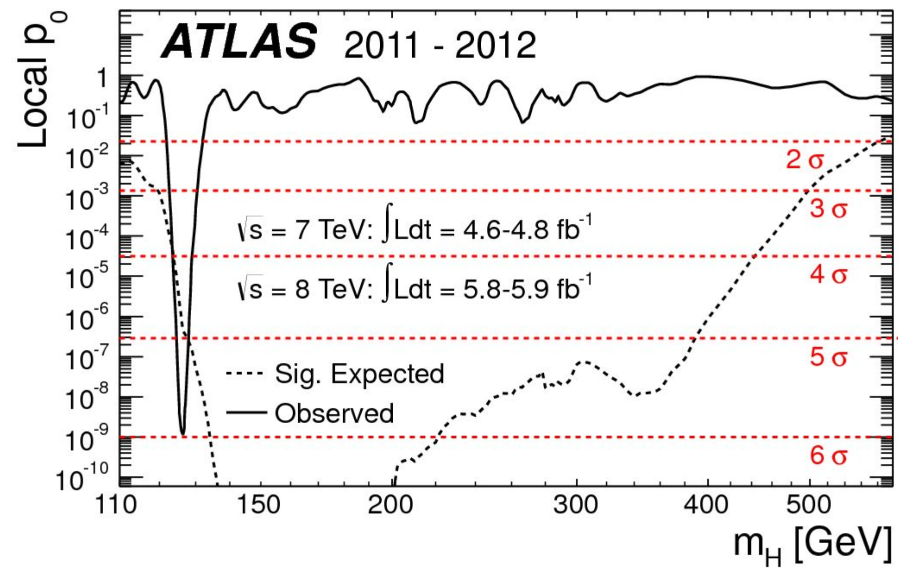
OBSERVATION





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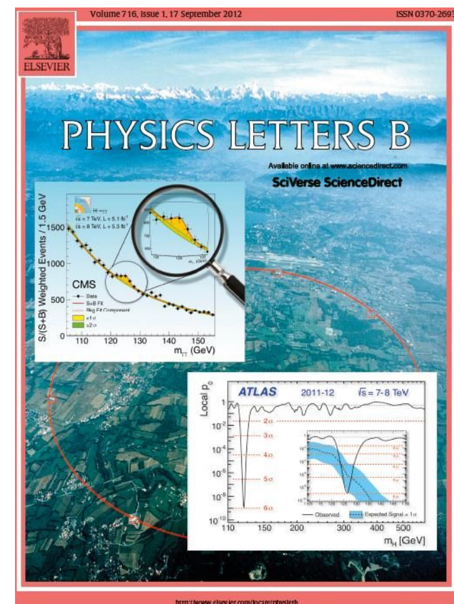
DISCOVERY

Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

CERN, 4th July 2012



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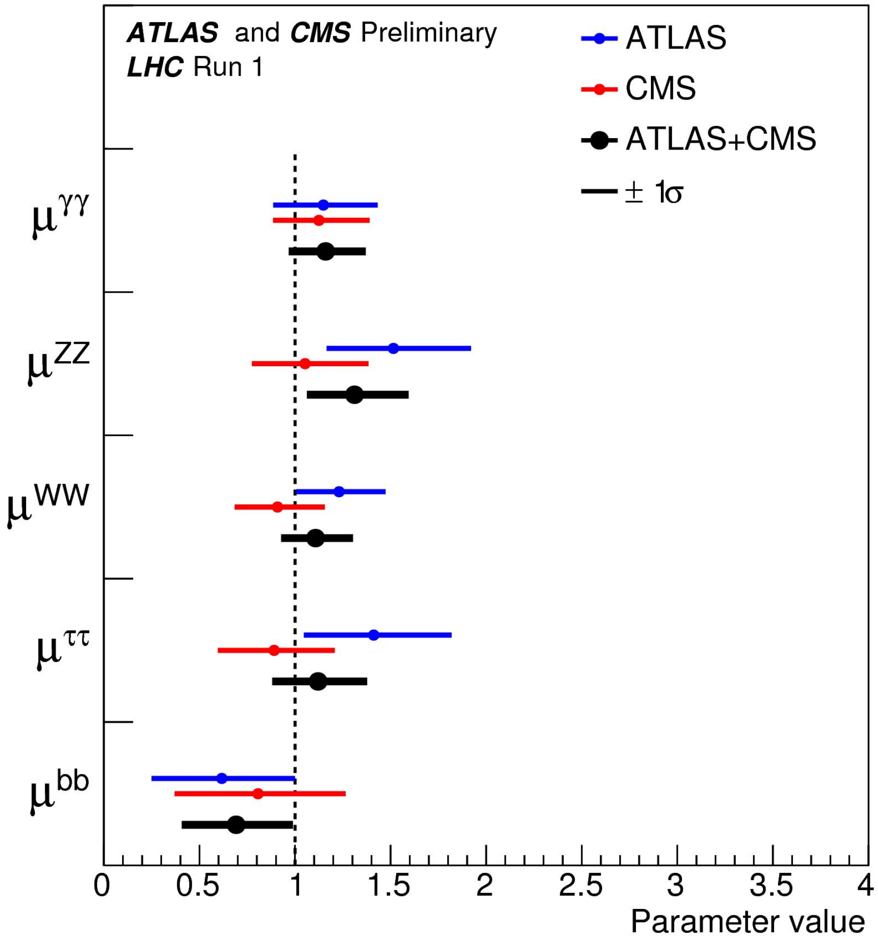
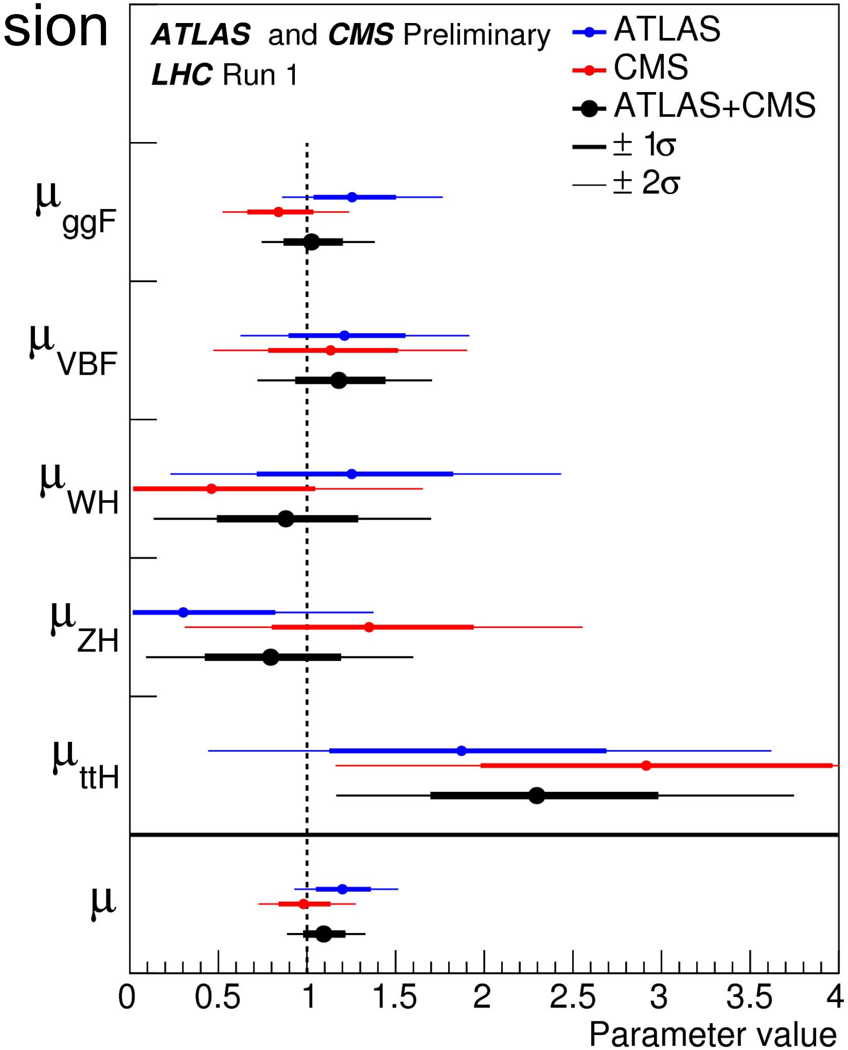
THE SITUATION AT THE END OF LHC RUN I

- All the production and decay channels are measured, with increasing precision





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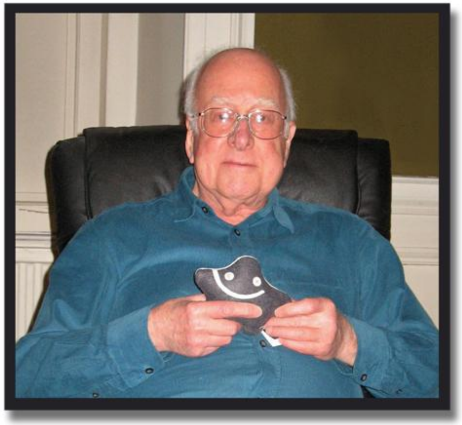
AND IN THE FUTURE?

Higgs Boson Discovery:

First success of the LHC,

Last success of the Standard Model



- As of today, all the measurements of the Higgs boson production, decay and properties are in agreement with the SM predictions
- The precision is increasing further in the LHC Run 2:
  - ➜ Deviations from SM predictions might open the way to New Physics, beyond the Standard Model

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TO WORK!

- Exercise and instructions can be found here:
  - ➜ https://twiki.cern.ch/twiki/bin/view/Main/UniudHiggsTutorial2018

- What we will do:
  - ➜ use Madgraph + Pythia + Delphes to generate simulated events
    - for H $\rightarrow$ ZZ* $\rightarrow$ 4 lepton signal
    - and for ZZ $\rightarrow$ 4 lepton non-Higgs background
  - ➜ use ROOT to analyse the data (both “real data” and simulated events):
    - reading each event
    - applying a selection
    - filling a histogram
  - ➜ combine the histograms to make a nice plot