Searching for New Physics at the Large Hadron Collider

the discovery of a Higgs particle and beyond

Laura Reina (FSU, Physics Department)

Quarknet at FSU, July 2015

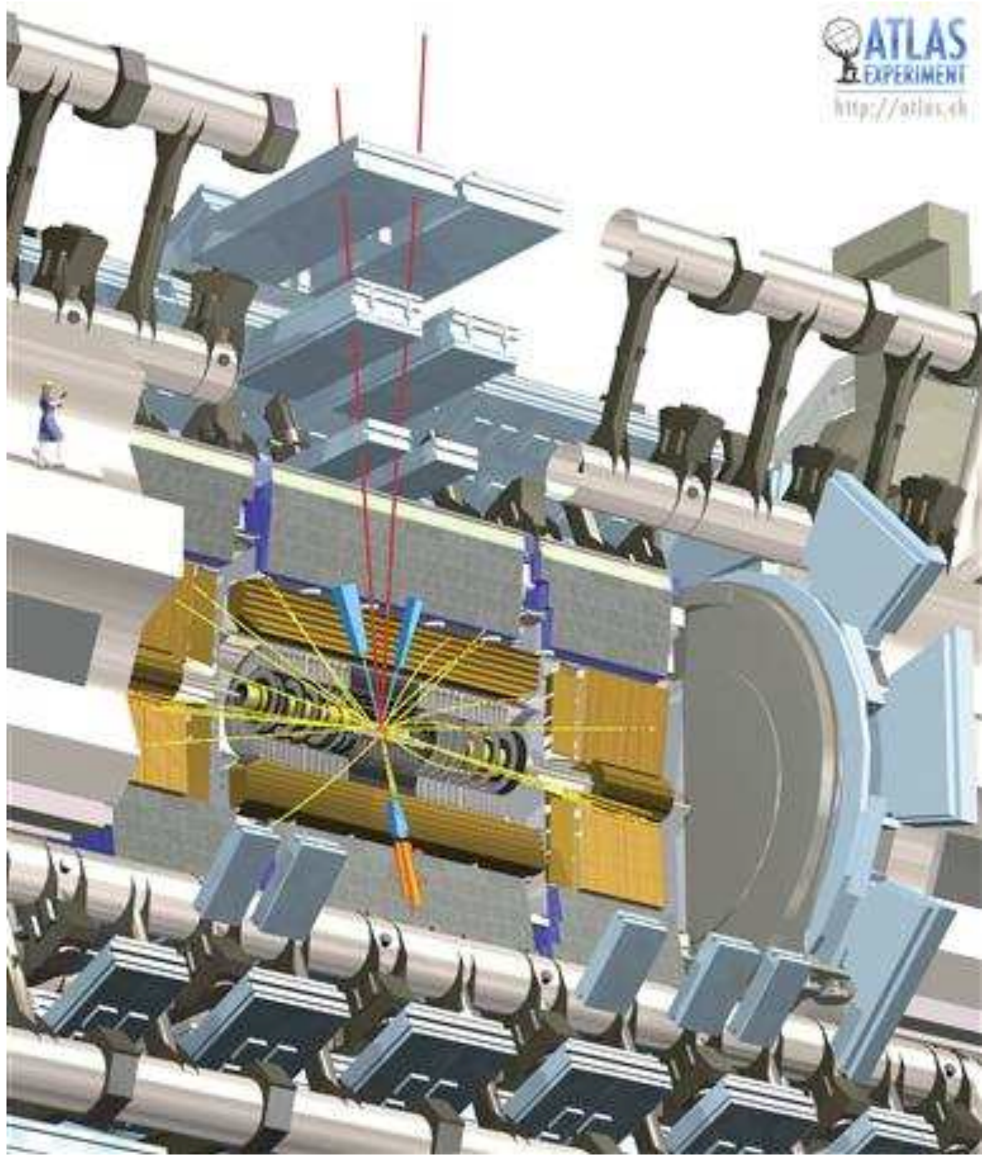
Very special time for particle physics

Two hadron colliders teamed in the discovery of new physics:

- the Tevatron collected high quality data at $\sqrt{s} = 1.96$ TeV;
- the Large Hadron Collider (LHC) very successfully operated at $\sqrt{s} = 7, 8$ TeV, will reach the designed $\sqrt{s} = 13 - 14$ TeV starting in 2015, eventually collecting more than 100 times the data of the Tevatron.

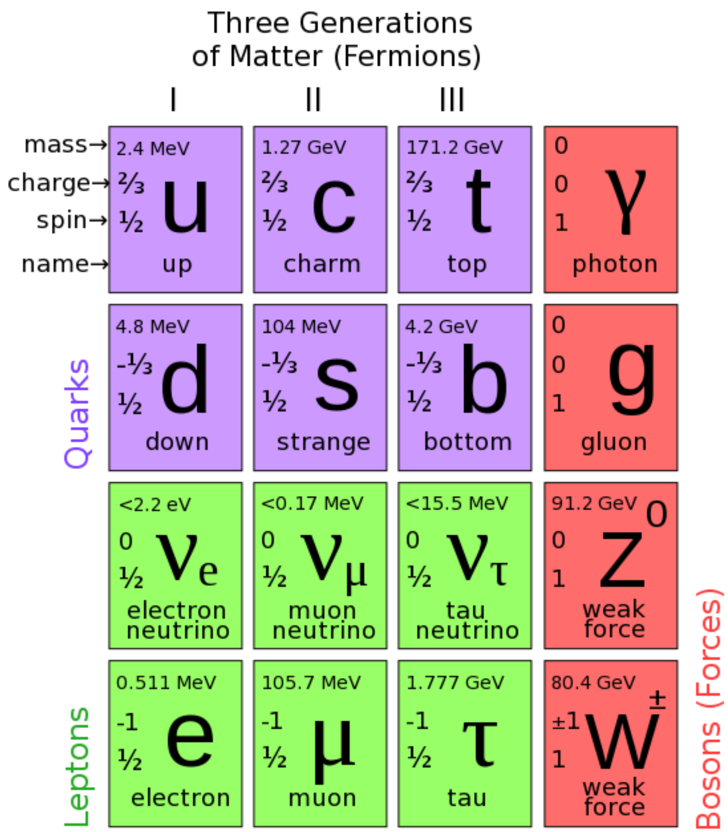
Because ..... $E = mc^2$ (!) we do expect to see new particles and to be able to identify them with reasonable accuracy.


LHCb
ATLAS
CERN
CERN
ALICE
CMS
SUISSE
FRANCE
SPS 7 km
LHC 27 km


ATLAS
EXPERIMENT
http://atlas.ch

The Standard Model of particle physics

"*The Standard Model is a quantum field theory based on the local symmetry group* $SU(3) \times SU(2) \times U(1)$."



$SU(3)_c \to$ strong force (g)

$SU(2)_L \times U(1)_Y$ electroweak force (W, Z, γ)

particle multiplets:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} u \\ d \end{pmatrix}_L \leftrightarrow \underbrace{\begin{pmatrix} \color{red}{u} & \color{blue}{u} & \color{green}{u} \\ \color{red}{d} & \color{blue}{d} & \color{green}{d} \end{pmatrix}_L}_{SU(3)} \Big\} SU(2)$$

$$e_R \ , \ u_R = (\color{red}{u}\ \color{blue}{u}\ \color{green}{u})_R \ , \ d_R = (\color{red}{d}\ \color{blue}{d}\ \color{green}{d})_R$$

Masses induced by coupling to the Higgs particle(?)

The story begins in 1964 . . .

with Englert and Brout; Higgs; Hagen, Guralnik and Kibble

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

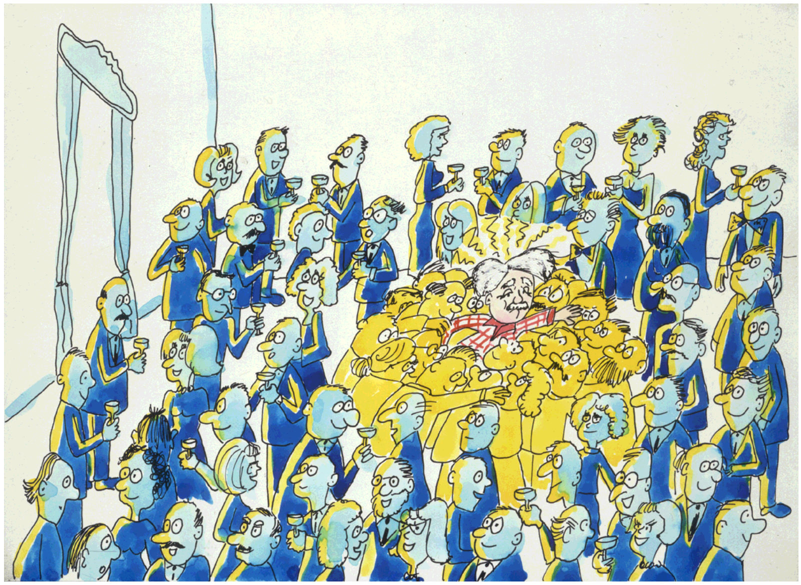
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

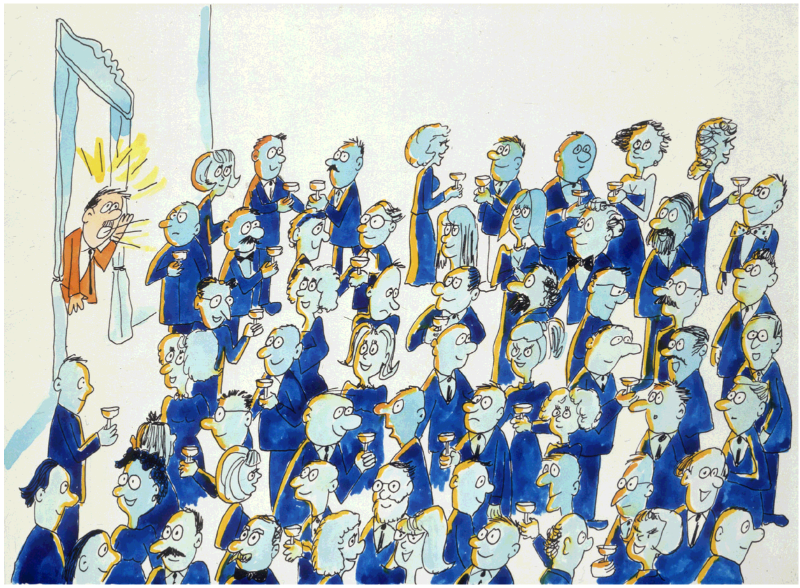
The Higgs Field and Mass

To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled with the Higgs field ...

... a well known physicist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step ...

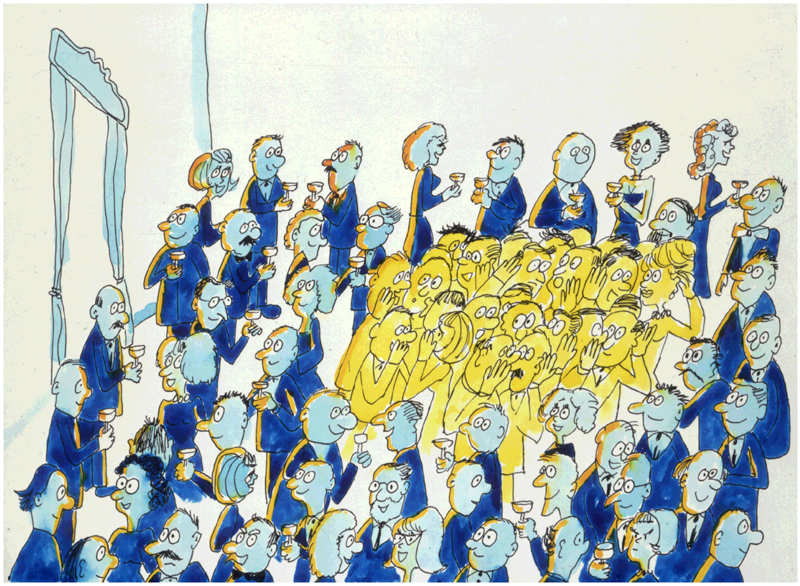
... this increases his resistance to movement, in other words ... he acquires mass! ... just like a particle moving through the Higgs field ...





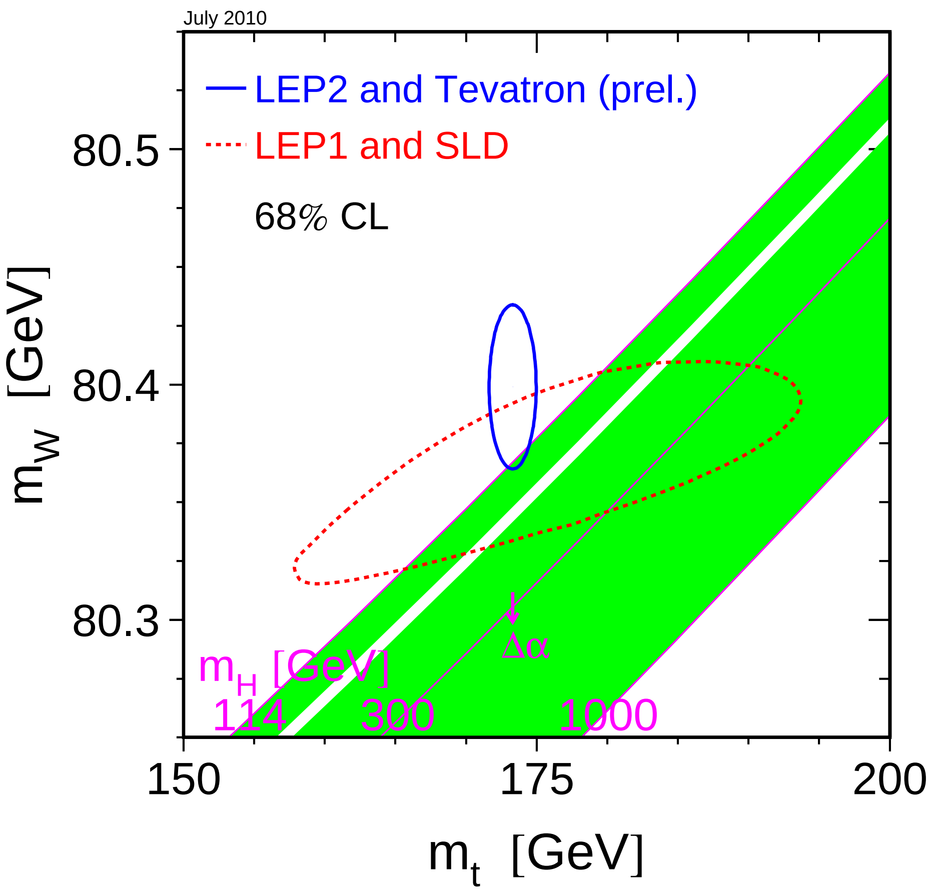
... if now a rumor crosses the room, ...

... it creates the same kind of clustering, but this time among the scientists themselves. In this analogy the Higgs field has materialized and acquired a mass itself!



Light SM Higgs boson strongly favored

Precision measurement provides an invaluable tool to test the consistency of the SM.



$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$m_t = 173.2 \pm 0.90 \text{ GeV}$$

$$\Downarrow$$

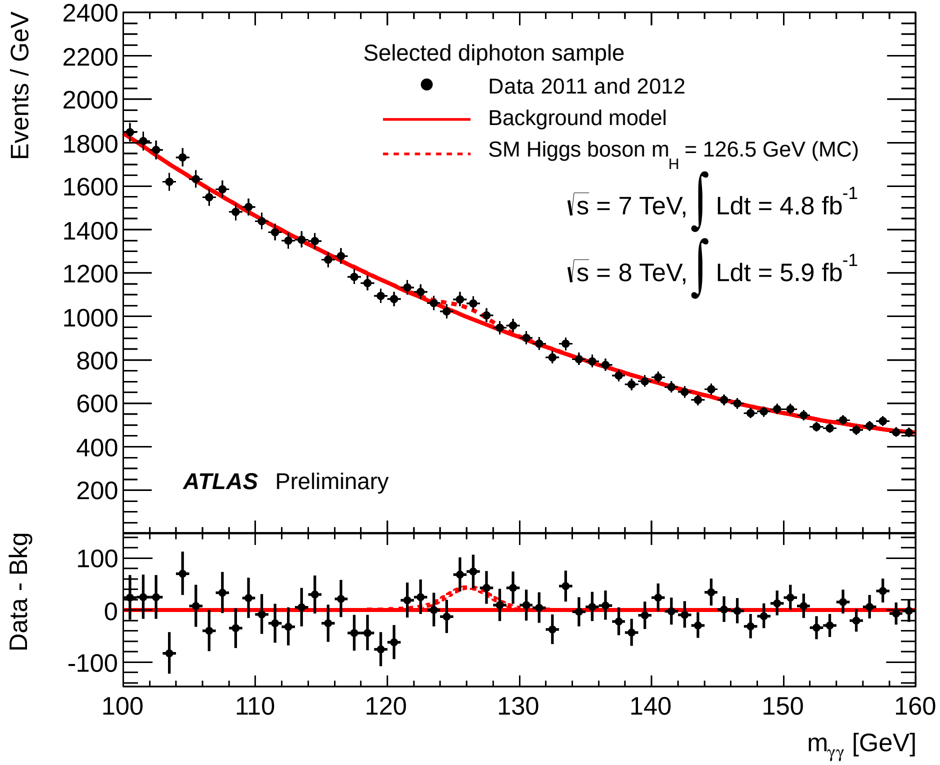
$$M_H = 94^{+29}_{-24} \text{ GeV}$$

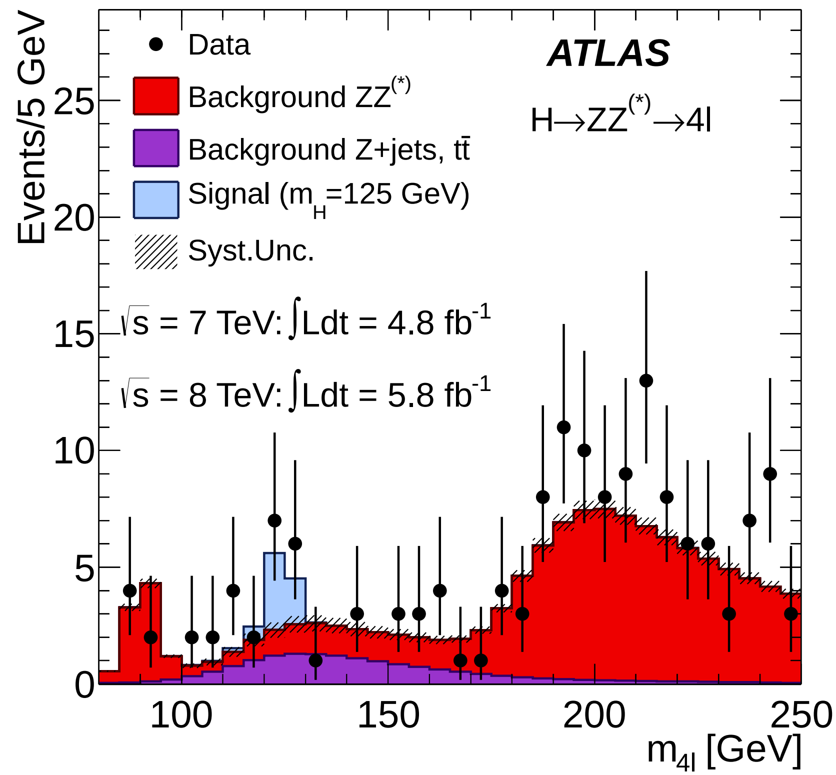
$$M_H < 152\,(171) \text{ GeV}$$

plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

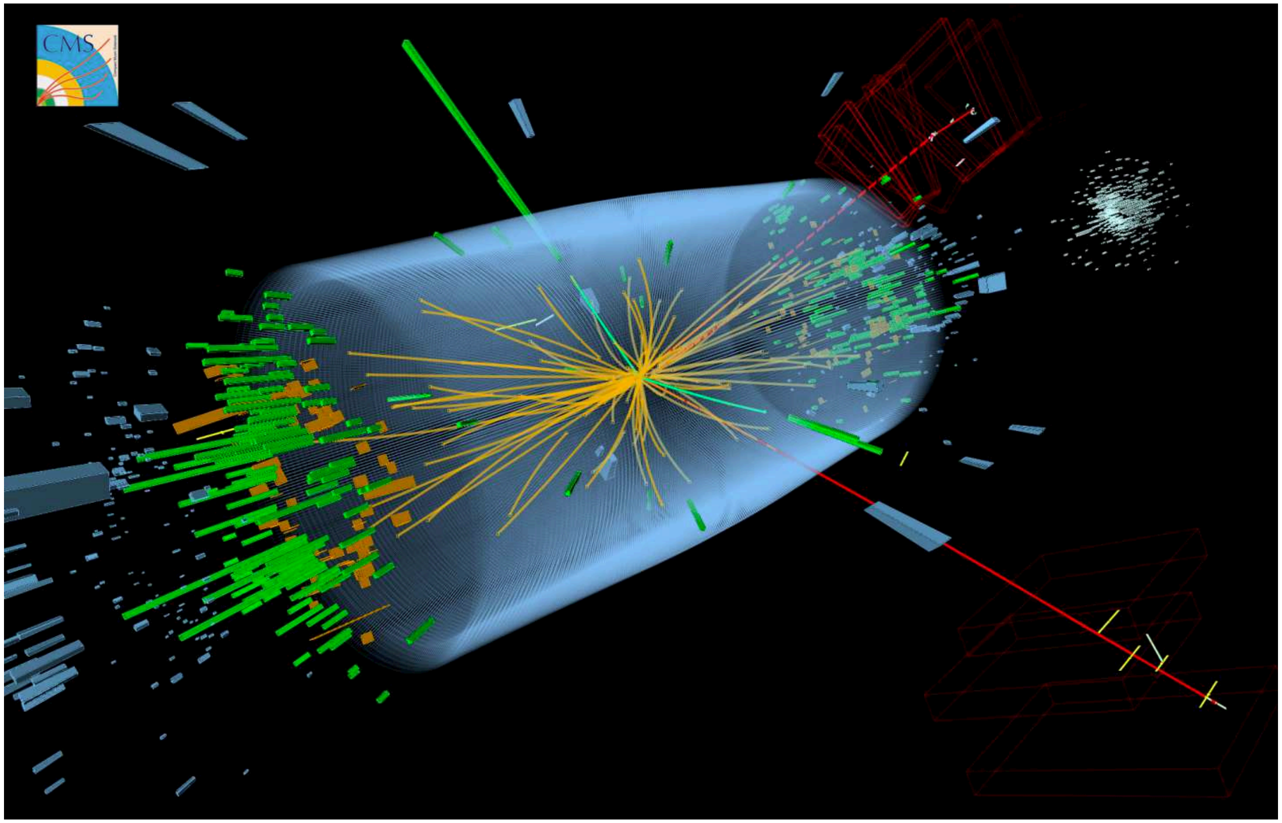
Confirmed by direct searches! SM Higgs-like particle discovered at the LHC with $M_H = 125 - 126$ GeV





plus exclusion limits (95 % c.l.) extended to:

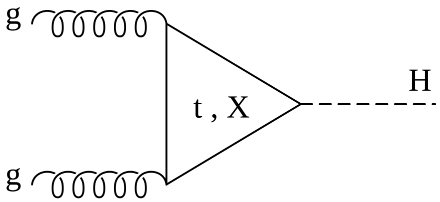
- ▷ 110 GeV $< M_H <$ 122.5 GeV , 127 GeV $< M_H <$ 600 GeV (CMS)
- ▷ 111.4 GeV $< M_H <$ 122.1 GeV , 129.2 GeV $< M_H <$ 541 GeV (ATLAS)


CMS

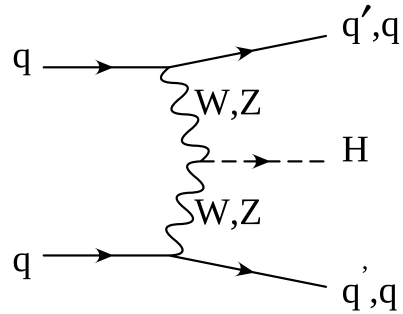
How can we read these events? How can we tell signal from background?

Higgs boson production at hadron colliders

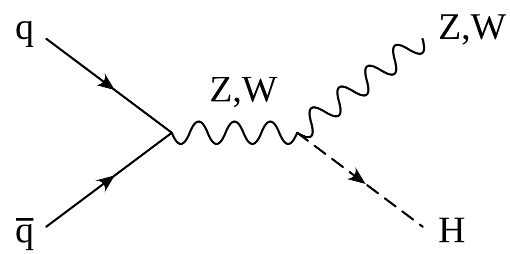
$gg \to H$



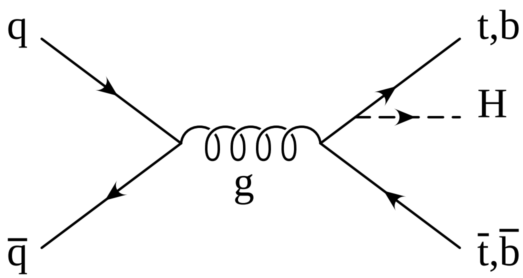
$qq \to qqH$

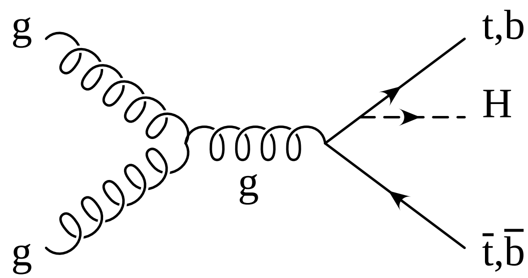


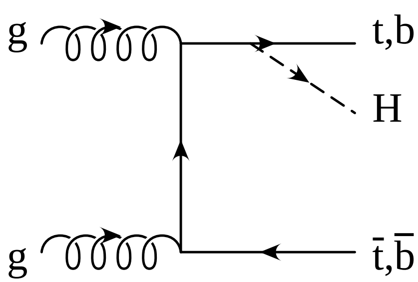
$qq \to WH, ZH$

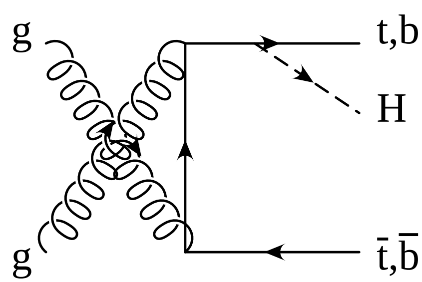


$q\bar{q}, gg \to t\bar{t}H, b\bar{b}H$

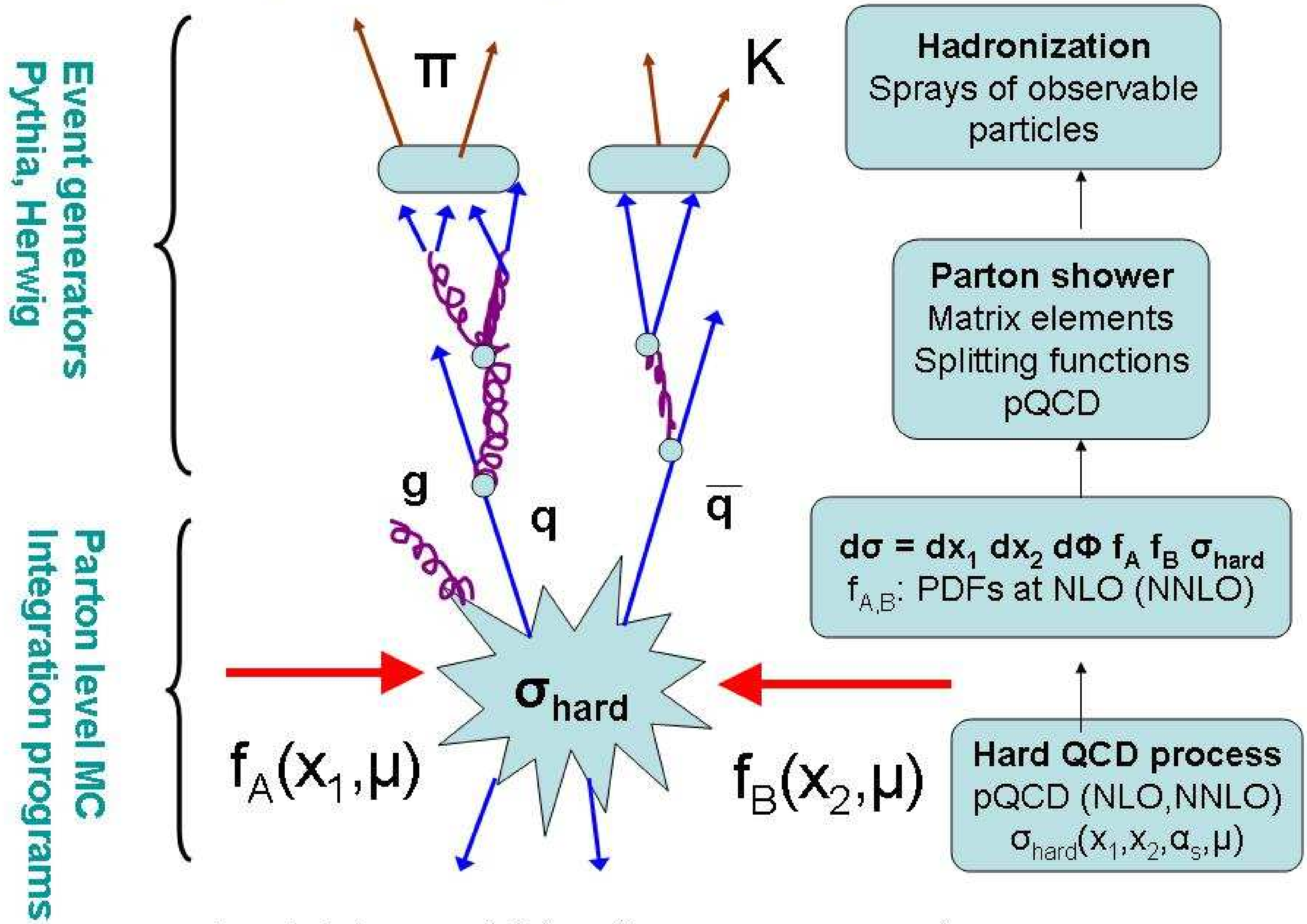






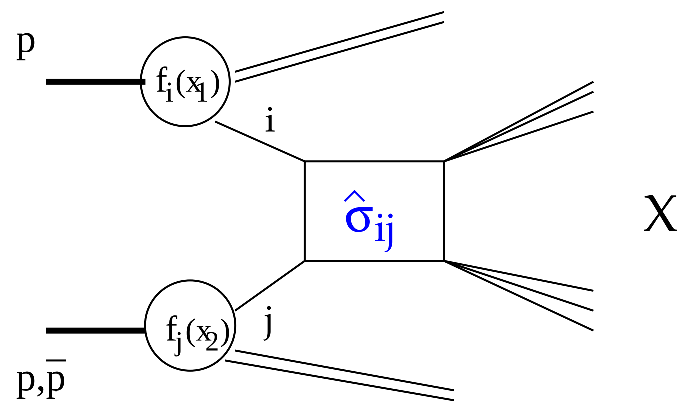


Anatomy of a QCD prediction at hadron colliders



+ underlying event, interactions among remnants

The basic picture of a $p\bar{p}, pp \rightarrow X$ high energy process ...



where the <u>short</u> and <u>long distance</u> part of the QCD interactions can be factorized and the cross section for $pp, p\bar{p} \rightarrow X$ can be calculated as:

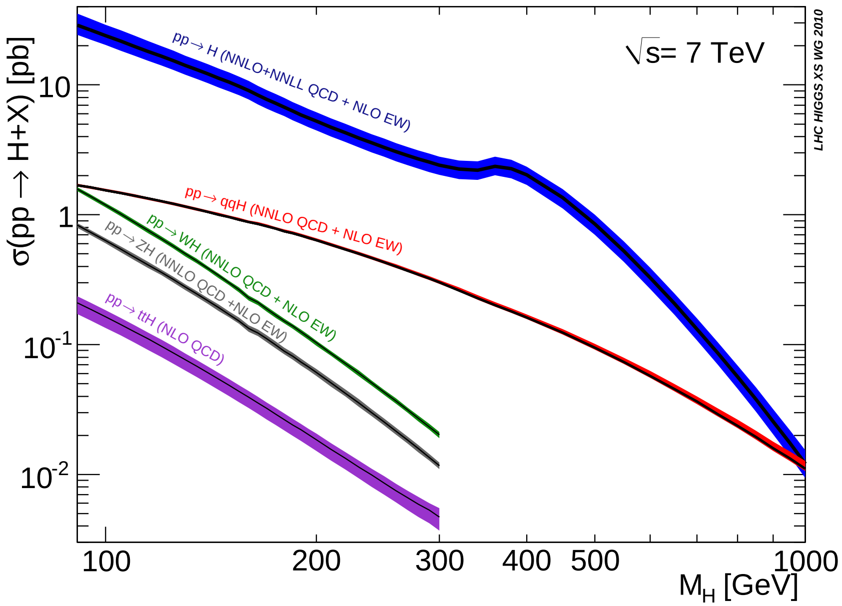
$$\sigma(pp, p\bar{p} \rightarrow X) = \sum_{ij} \int dx_1 dx_2 f_i{}^p(x_1) f_j{}^{p,\bar{p}}(x_2) \hat{\sigma}(ij \rightarrow X)$$

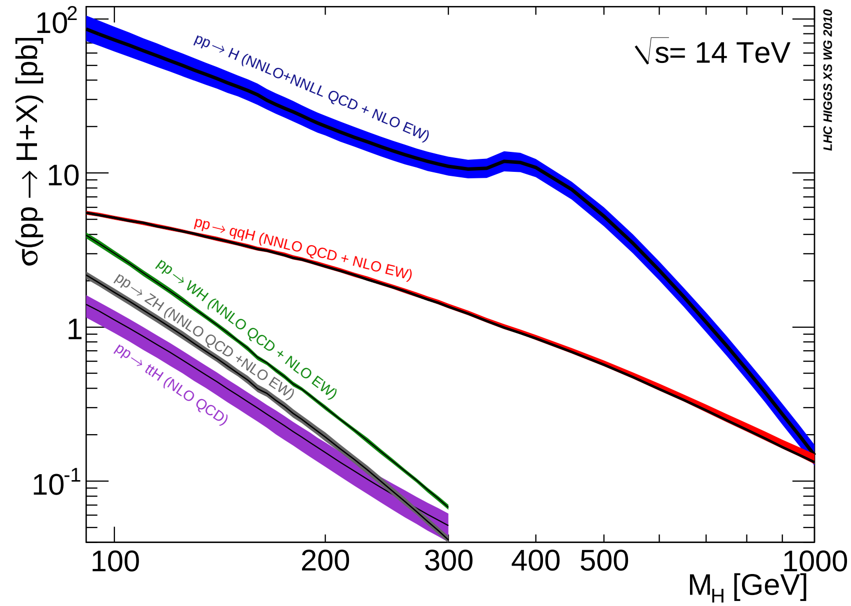
$\longrightarrow$ $ij \rightarrow$ quarks or gluons (partons)

$\longrightarrow$ $f_i^p(x)$, $f_i^{p,\bar{p}}(x)$: Parton Distributions Functions: probability densities (probability of finding parton i in p or $\bar{p}$ with a fraction x of the original hadron momentum)

$\longrightarrow$ $\hat{\sigma}(ij \rightarrow X)$: partonic cross section

Theoretical predictions of SM Higgs production have been crucial to discovery: synergy between theory and experiments.





LHC Higgs Cross Sections Working Group

- ▷ highly refined predictions including all known QCD and EW effects on total and differential cross sections available for all production modes;
- ▷ directly used to compare with data at discovery time;
- ▷ now used to study properties of discovered particle and identify it unambiguously.

Summary: some important facts

- The discovery of a Higgs particle has been an incredible adventure that has seen the joint effort of decades of theoretical and experimental work coalesce and give amazing results.

- It has shown the impact of precise theoretical predictions when compared with experimental measurements for
  - ▷ discovery of new physics (Higgs boson, Supersymmetry, . . .)
  - ▷ precision measurements of masses, coupling . . .

- Further developments in QCD and EW calculations are under way to face the challenges of Run II of the LHC, aiming at
  - ▷ testing existing techniques on new problems;
  - ▷ developing new techniques and new algorithms;
  - ▷ understanding the comparison with data.