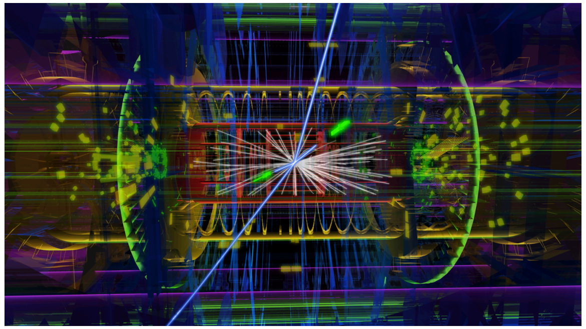
CERN

European Organization for Nuclear Research

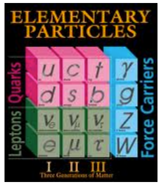
Organisation Européenne pour la Recherche Nucléaire

Particle physics today



Giulia Zanderighi (CERN & University of Oxford)

Status of particle physics



- Standard Model (SM): successful theory of strong (QCD), weak and electromagnetic (EW) elementary interactions
- Yet, no fundamental theory:
theoretical issues + unexplained phenomena (e.g. gravity, matter anti-matter asymmetry, dark matter, dark energy, ...)
- The LHC is designed to
  - ☑ test origin of mass (through the Higgs mechanism)
  - ☐ find physics beyond the SM (still to be done)

BUT

Do we know what this really means?

What is the problem with particles having a mass?

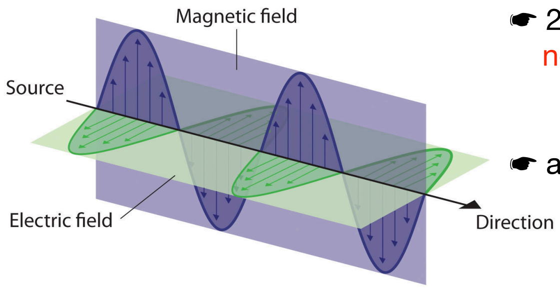
What is the Higgs mechanism & how does it solve the problem?

Why should there be New Physics at the TeV scale?

Step back

Duality in quantum field theory: wave ⇔ particle

electromagnetic wave ⇔ photon

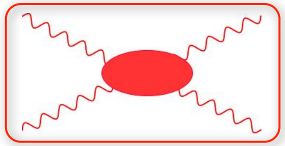


☛ 2 transverse polarisations, no longitudinal polarisation

☛ an empirical but crucial fact

Gauge symmetry

If a 3rd longitudinal polarization existed

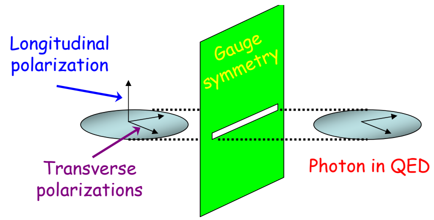


⇒ scattering probability grows with energy

Violation of unitarity (probability > 1) ⇒ field theory breaks down

<u>In QED:</u>

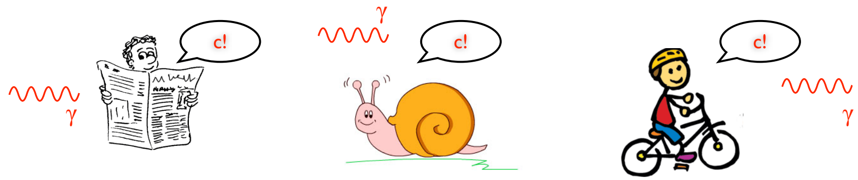
3rd polarization does not exist ↔ gauge symmetry



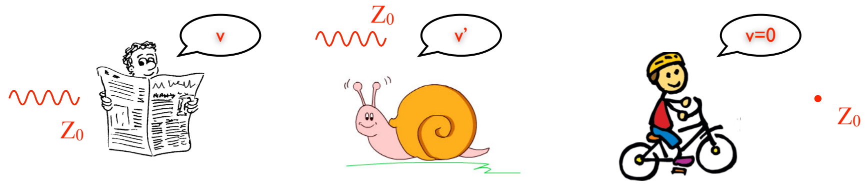
Gauge symmetry crucial to keep theory sensible at high energy

Gauge filter and masses

From relativity: the speed of light is the same in all frames



For massive particle can choose a frame where the particle is at rest



In that frame, the distinction between transverse and longitudinal polarizations breaks rotational invariance

Gauge trick does not work with massive particles

EW symmetry breaking

$Sp\bar{p}S$ (1983-1985) $p\bar{p}$ collider at CERN, Geneva, running at E_{beam} = 450 GeV

LEP-II (1990-2001) e^+e^- collider at CERN, Geneva, running at E = 91.2 ➠ 206 GeV

Z/W interactions are described by a EW gauge theory
But Z/W masses break EW symmetry ⇒ theory breaks down at high E

gauge symmetry ↔ massless states ↔ sensible field theory

At what energy does this happen?

E > 1 TeV

That's why the LHC was designed to investigate
- the mechanisms of mass generation
- how to keep the theory sensible at higher energy

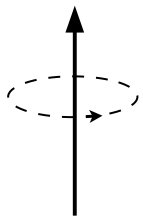
Spontaneous symmetry breaking

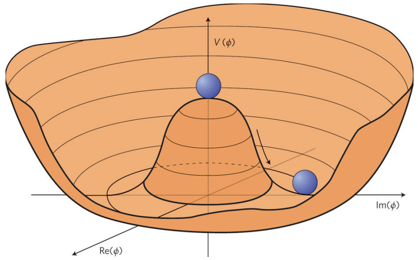
<u>Most popular solution:</u>

Higgs mechanism, i.e. EW symmetry spontaneously broken

<u>Spontaneous symmetry breaking (SSB):</u> symmetry of equations but not of solutions

What does this mean ?





configuration breaks rotational invariance, laws do not

Spontaneous symmetry breaking

With SSB relations implied by the exact symmetry can be modified

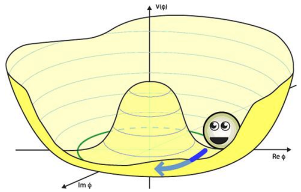
e.g. laws invariant under $d \leftrightarrow u$ with solutions $m_d = m_u$

but also solutions with $m_d > m_u$ are possible

as long as $m_d < m_u$ also exists

Typical of SSB is degeneracy of solutions. Quantum interpretation: zero energy excitation, i.e. massless particle

Goldstone '61



Problem: in Nature there is *no* massless Goldstone boson

EW symmetry breaking

<u>Higgs mechanism</u>

with gauge interactions, zero-energy excitation absorbed by the gauge field ⇒ massive gauge particles and no Goldstone boson

Brout, Englert, Higgs ’64; Weinberg and Salam ’67

<u>Higgs field</u>

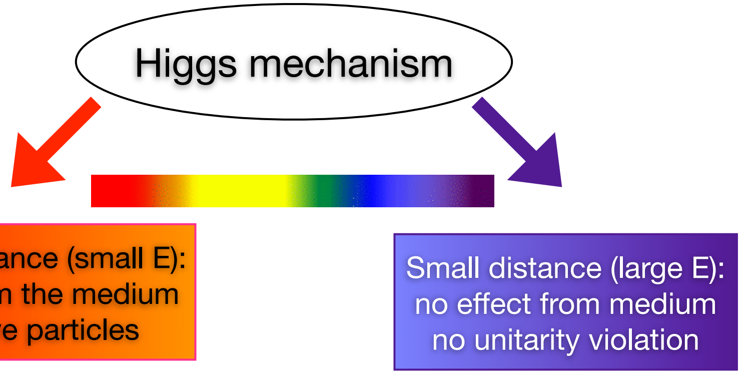
continuum medium pervading the whole universe. Particles interacting undergo a slow-down just as particles propagating in any medium do

slow down ⇒ inertia ⇒ mass

vacuum *Higgs filled vacuum*

EW symmetry breaking

The problem was
- massless particles ↔ gauge invariance
- massive particles ↔ unitarity violation

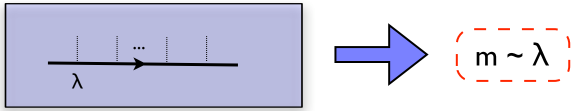


NB: EW charge distribution carries no electric charge ⟹ photon remains massless even after EWSB

Higgs mechanism in EW

- If the Higgs field exists, then quanta of the field must exist too
  ⇒ Higgs boson

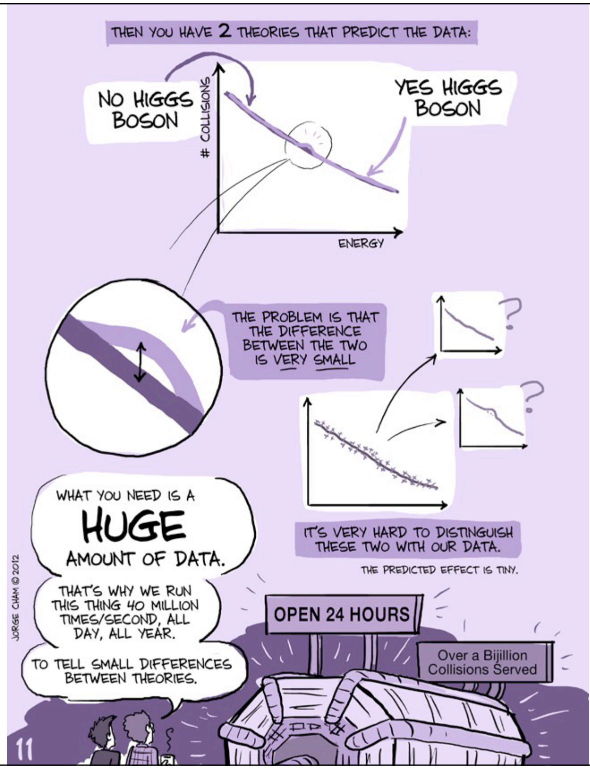
- Coupling of a particle to Higgs is proportional to the particle's mass



Higgs filled vacuum

- The Higgs boson will have a mass too ... because the Higgs slows itself down as it propagates in the (Higgs) vacuum

- In the SM the Higgs mass is a free parameter, but once its value is determined everything else (couplings/masses) is fixed

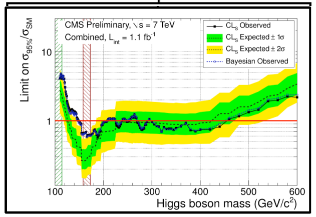


Before the discovery

A brief history

First combined exclusion limits

2011 2012 2013 2014

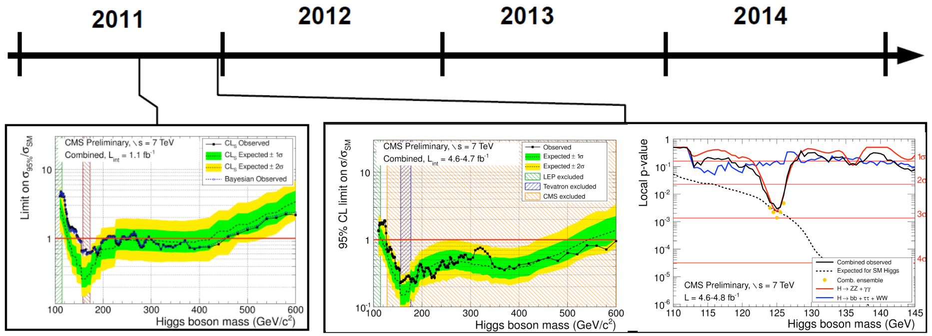


First $1fb^{-1}$ (7TeV):
no Higgs boson between 160 and 500GeV

EPS-HEP '11
Lepton-Photon '11

A brief history

First hints



First 5fb^{-1} (7TeV):

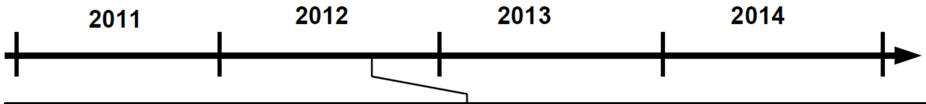
SM Higgs boson excluded for 127 < m_H < 600GeV

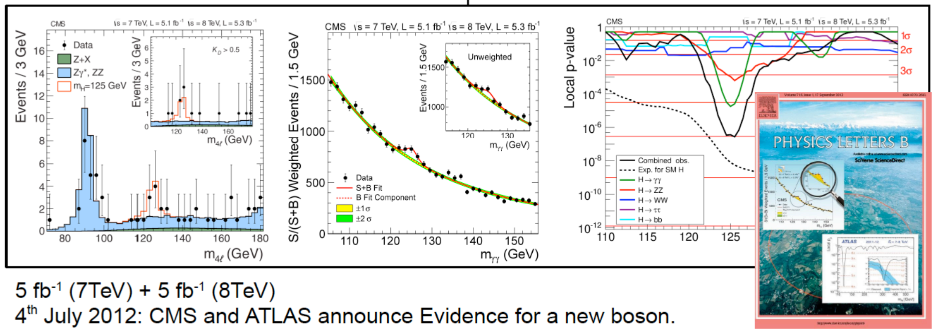
Excess (local significance 2.8σ) for m_H~125GeV

CMS/ATLAS Higgs Jamboree
Moriond 2012

A brief history

Evidence of a new boson





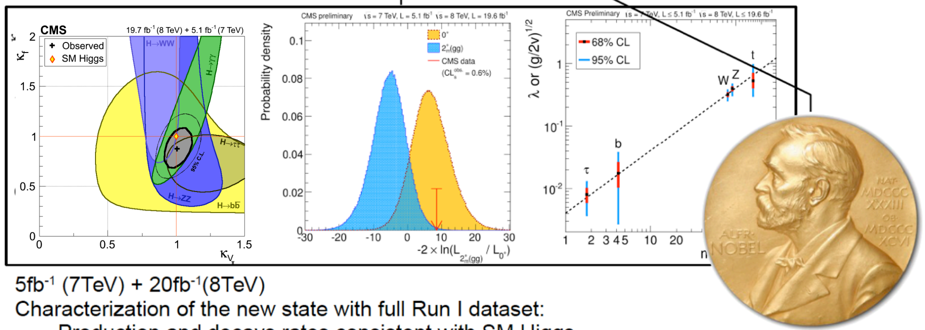
5 fb^{-1} (7TeV) + 5 fb^{-1} (8TeV)

4th July 2012: CMS and ATLAS announce Evidence for a new boson.

A brief history

Identification of the Higgs boson

2011 2012 2013 2014



5fb^{-1} (7TeV) + 20fb^{-1}(8TeV)

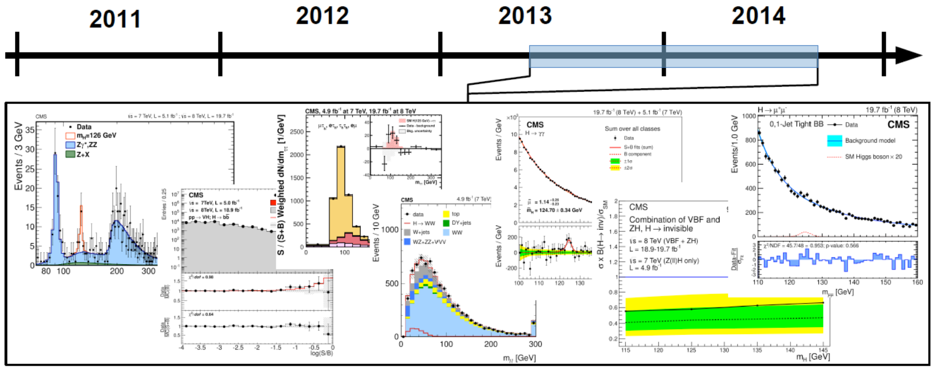
Characterization of the new state with full Run I dataset:

- Production and decays rates consistent with SM Higgs
- 0^+ spin parity favoured by data.

8th October 2013: Nobel Prize for Physics awarded to prof. Higgs and Englert.

A brief history

The Run I legacy



$5fb^{-1}$ (7TeV) + $20fb^{-1}$(8TeV)

Final results on Run I full dataset published 1-2 years after the discovery of the new boson.

Ultimate precision for this dataset attained.

Preliminary combined analysis of all channels presented in July 2014.

A brief history

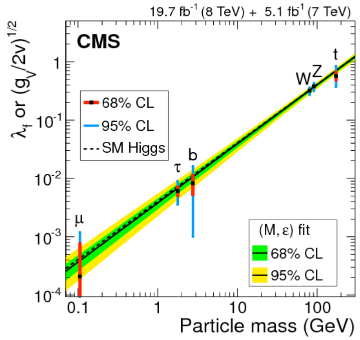
2012-2014 remarkably intense and exciting years for particle physics

Current studies of the Higgs

First studies of Higgs properties in LHC Run I:

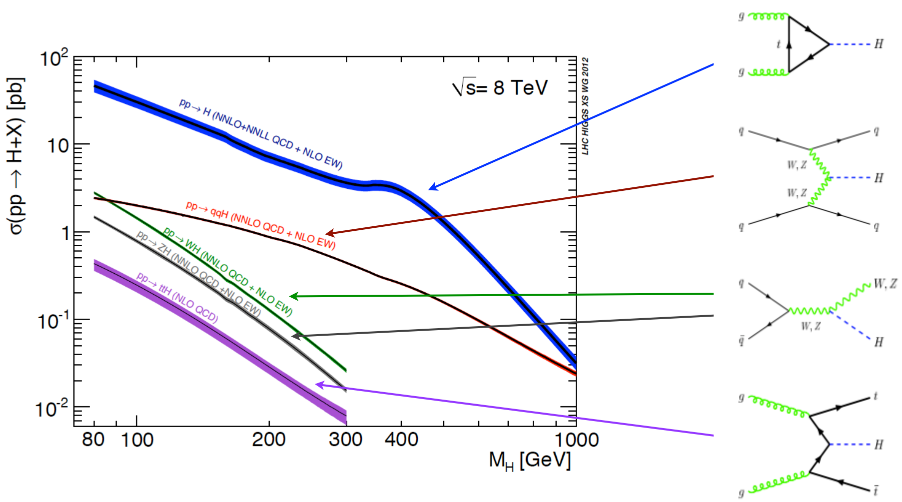
- consistent with $J^{CP}=0^{++}$
- SM Yukawa couplings
- m_H=125.09±0.21(stat.)±0.11(syst.) GeV

Looks very much like SM Higgs



Era of precision Higgs physics just started in Run II. Aim is to reduce the error bars above and establish deviations from the SM pattern, or at least to exclude all New Physics models that predict deviations from the proportionality between a particle mass and it’s coupling to the Higgs

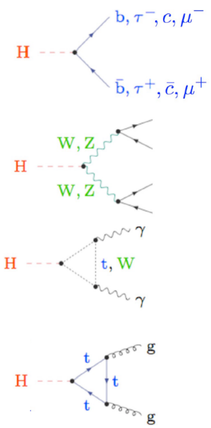
Higgs production at the LHC

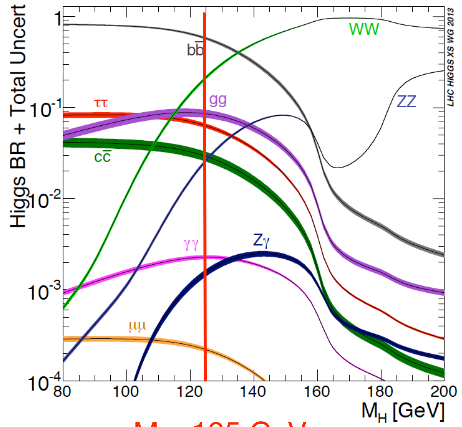


Higgs decays at the LHC

i.e. what is actually seen in detectors

Higgs decays very very quickly.... fortunately, its mass lies in a sweet spot (M_H ~125 GeV) where many decay modes are available





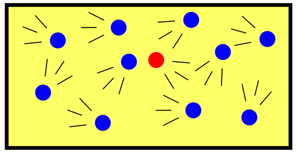
M_H=125 GeV

The hierarchy problem

- the Higgs mass receives corrections from vacuum fluctuations
- the size of the correction should be proportional to the maximum allowed energy M_{Planck} , M_{GUT}, . . .
- $M_H \ll M_{Planck}$ requires fine-tuning up to 17 digits or New Physics!

<u>Analogy with thermal fluctuations</u>

t = 0



thermalisation

At large t expect to have

$$E_{\color{red}\bullet} \sim E_{\color{blue}\bullet}$$

While the observation is

$$E_{\color{red}\bullet} \sim 10^{-17} E_{\color{blue}\bullet}$$

While there is no inconsistency, it just seems hard to believe!

Explanations for gauge hierarchy

- ☛ <u>In the analogy:</u> natural explanation could be that red does not really interact with blue because the interaction is screened

- ☛ <u>In the Higgs case:</u> similarly, the interaction could be screened by new forces/particles

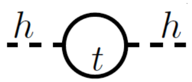
A variety of possible explanations exist to protect the Higgs mass from having a sensitivity to high-energy scales

(supersymmetry, technicolour, Randall-Sundrum warped space, pseudo-Goldstone Higgs, Little Higgs, ...)

Currently these are all speculations. Only experimental data can discriminate between the predictions of various models

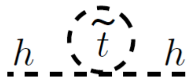
SUSY solution to hierarchy problem

More concretely: from LHC data we know that $m_H \approx 125$ GeV.
The Higgs mass receives so-called loop corrections, for instance



Problem: the loop correction above gives $\Delta m_H \approx 10^{19}$ GeV

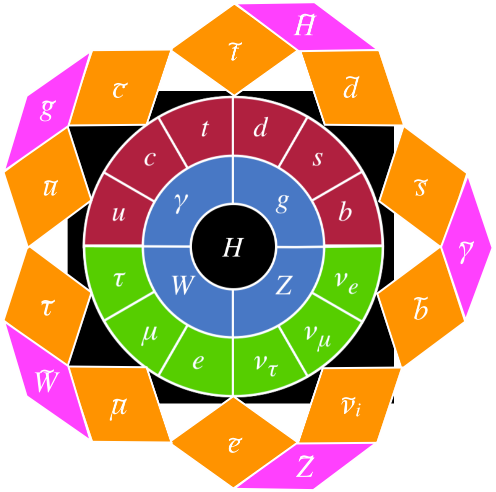
In supersymmetric models the solution is very simple, one needs to add a correction from the super-symmetric partner of the top



And this gives $\Delta m_H \approx -10^{19}$ GeV, making it “natural” to have a light Higgs boson

The MSSM

- In the MSSM each SM particle gets its own superpartner
- Fermions (bosons) have supersymmetric bosonic (fermionic) partners
- We will see later that the MSSM provides a natural candidate for Dark Matter



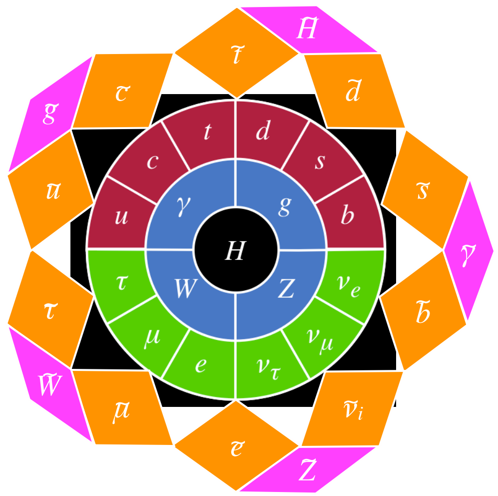
Minimal supersymmetric SM (MSSM)

The MSSM

The three BIG arguments in support of supersymmetry (SUSY)

- gauge coupling unification
- naturalness, i.e. solution to the hierarchy problem
- natural Dark Matter candidate

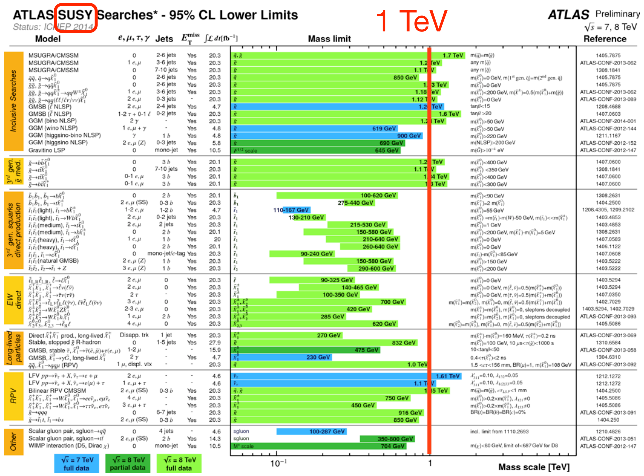
Problem with SUSY: not seen yet



Minimal supersymmetric SM (MSSM)

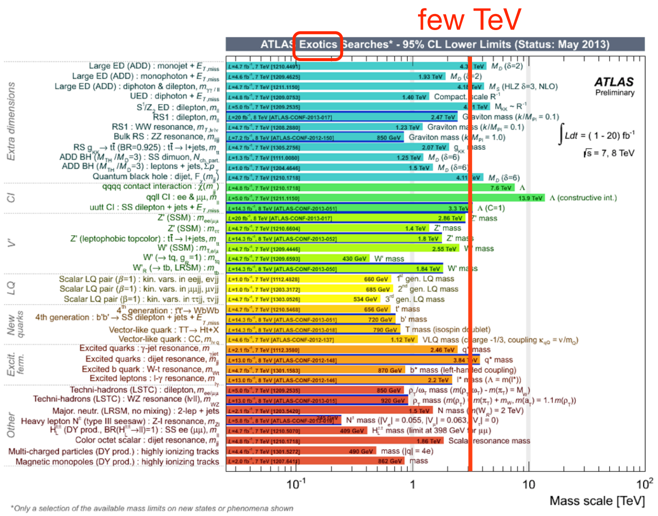
Status of New Physics searches

Unfortunately, SUSY searches are so far not successful



Status of New Physics searches

Also other Beyond the SM searches are so far not successful



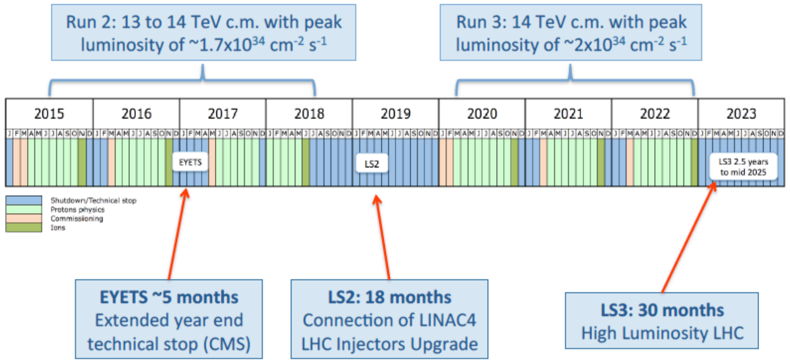
Status of New Physics searches

- Fantastic data available and expected from LHC (first results from Run II being analyzed now)
- Higgs discovery was a true milestone for particle physics, but also leaves many questions open (hierarchy problem, naturalness, ...)
- Run II will focus on precision studies: what does the future hold?

Future directions

- with the discovery of the Higgs boson the SM is complete
- we have many the theories beyond the Standard Model, but possibly none that stands out now
- the near future will focus on direct and indirect searches for deviations from the SM (and on ruling out BSM models)
- first the first time, we do not have a clear indication of where to look (i.e. on the mass-scale of New Physics)
- this means that currently no experiment can guarantee a discovery
- still many open questions to address, exploring a new frontier

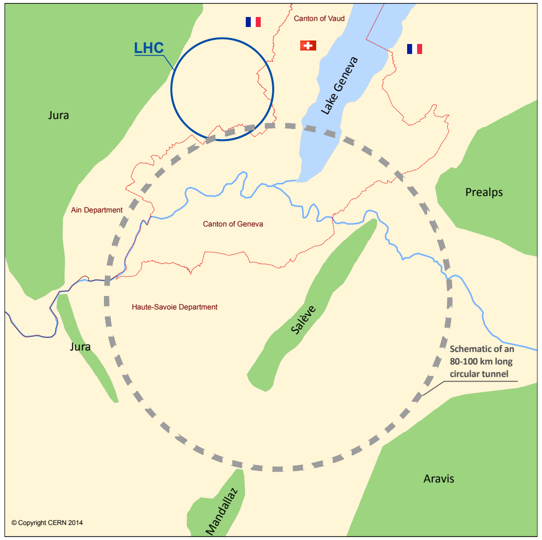
LHC's near future



Afterwards?

- hopefully results from the LHC will guide us in choice of the next colliders
- the time scale design and build a new collier is about 30 ys
- we have to starting thinking now about what should come after the LHC
- possibilities include FCC-e^+e^- circular colliders (at energies up to ttbar threshold), electron-proton machine, or 100 TeV proton-proton collider (FCC-hh)
- machine type, site (CERN, China, ...?), etc. still all to be decided

Afterwards?



Canton of Vaud
LHC
Lake Geneva
Jura
Prealps
Ain Department
Canton of Geneva
Haute-Savoie Department
Salève
Jura
Schematic of an 80-100 km long circular tunnel
Aravis
Mandallaz
© Copyright CERN 2014