Elementary Particle Physics: Theory

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Santander, 06/2012

1. What is Elementary Particle Physics?
2. What do we know about our world?
3. Theoretical Elementary Particle Physics
4. Outlook: Beyond the Standard Model

1. What is Elementary Particle Physics?

Elementary Particle Physics investigates:

– the inner structure of matter, its smallest building blocks
– the fundamental forces acting among the fundamental particles

$\Rightarrow$ Goal: find smallest structure of matter
find the most basic laws of nature

19th century:

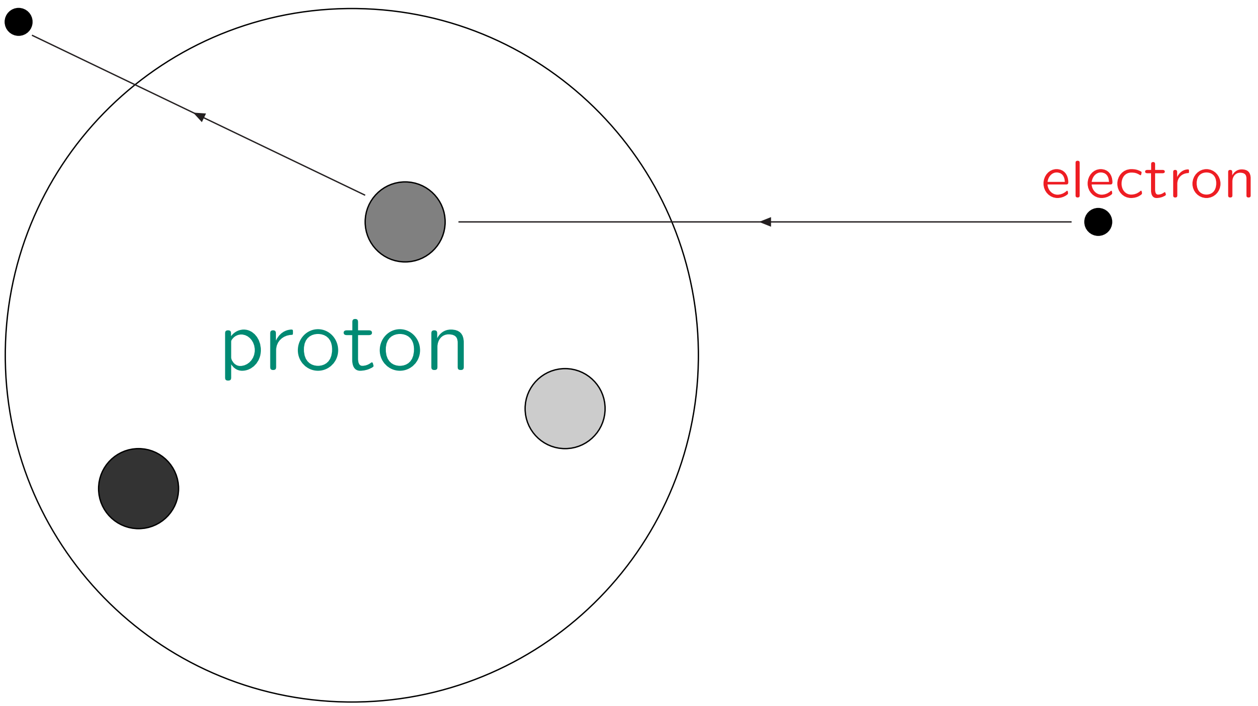
chemical bindings $\rightarrow$ elements
christals, molecules $\rightarrow$ atoms

$\Rightarrow$ periodic system of elements

20th century:

atoms $\rightarrow$ nucleus + shell (elektrons)
nucleus $\rightarrow$ protons + neutrons
protons, neutrons $\rightarrow$ quarks

How to find a substructure:



- the to be investigated object (proton) is shot at with small projectiles (electrons)
- the substructure (quarks) leads to a deviation of the projectiles
- the deviation is measured
- the measurement is compared with predictions to reconstruct the underlying structure

Elementary particle physics consist of two areas:

theory and experiment

Theory:

– search for models (master formula) that describe our world (model = mathematical formulation of laws of nature)
– calculation of predictions within a model (predictions: “deviations”, masses of elementary particles, . . .)

Experiment:

– to do experiments to find new particles or “substructure”

To find the basic laws of nature and the most fundamental structure of matter:

Comparison of theoretical predictions of a model with experimental results

Theory and Experiment have to work hand in hand!

2. What do we know about our world?

A) matter particles

- our world consist of about 100 elements
- the elements consist of atomic nuclei and a shell of electrons (electrically negatively charged)
- the atomic nucleus consist of protons (positively charged) and neutrons (neutral)
- protons and neutrons consist of quarks:
  u quarks (charge +2/3) and d quarks (charge -1/3)
  proton: $u\,u\,d$ (2/3 + 2/3 - 1/3 = +1)
  neutron: $u\,d\,d$ (2/2 - 1/3 - 1/3 = 0)

$\Rightarrow$ our world consists of 3 matter particles: u quark, d quark, electron (e^-)

But there is more:
B) additional (instable) matter particles
C) force particles (responsible for the forces between the matter particles)
D) the Higgs particle

B) Additional (instable) matter particles

1. family: quarks: d, u leptons: e^-, ν_e (neutrino)

2. family: quarks: s, c leptons: μ^-, ν_μ (neutrino)

3. family: quarks: b, t leptons: τ^-, ν_τ (neutrino)

In total:

6 quarks and 6 leptons

The heavier particles (2. and 3. family) decay in very short time into the lighter particles (1. family)

Example:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

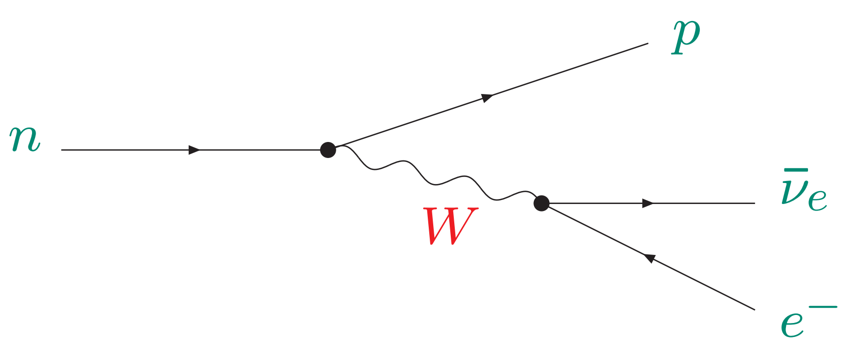
C) Force particles

Experimental results: $\Rightarrow$ 4 fundamental forces

1. electromagnetic force (light)
2. weak force (decay of nucleus: $n \to p + e^- + \bar{\nu}_e$)
3. strong force (keeps atomic nucleus together)
4. gravitational force (apple falls, earth circles sun)

force = exchange of force particles between matter particles

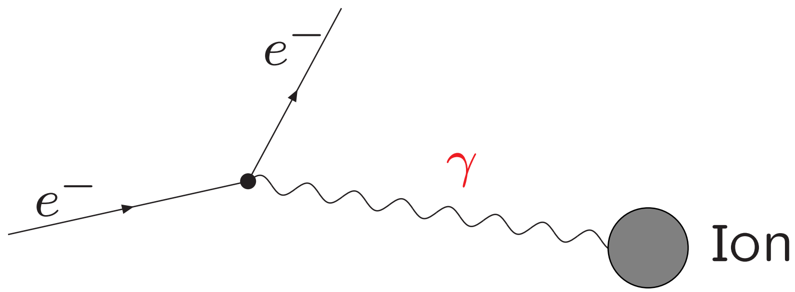
Example: decay of atomic nucleus:



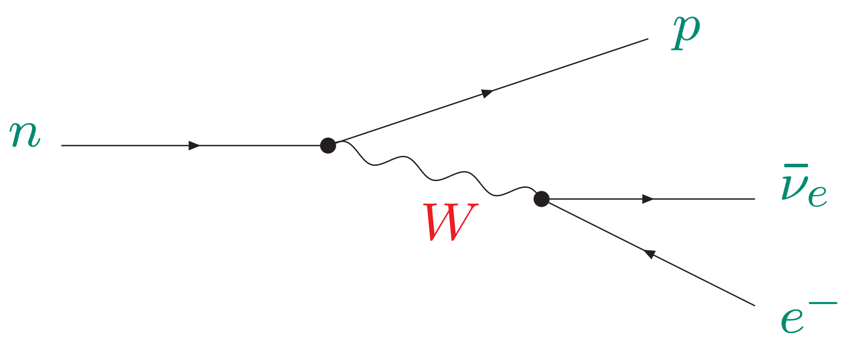
$\Rightarrow$ force is carried by the W particle

Forces and force particles (I):

1. electromagnetic force: photon: γ

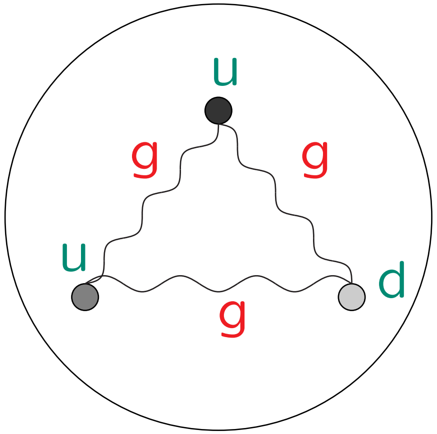


2. weak force: W^+, W^-, Z^0

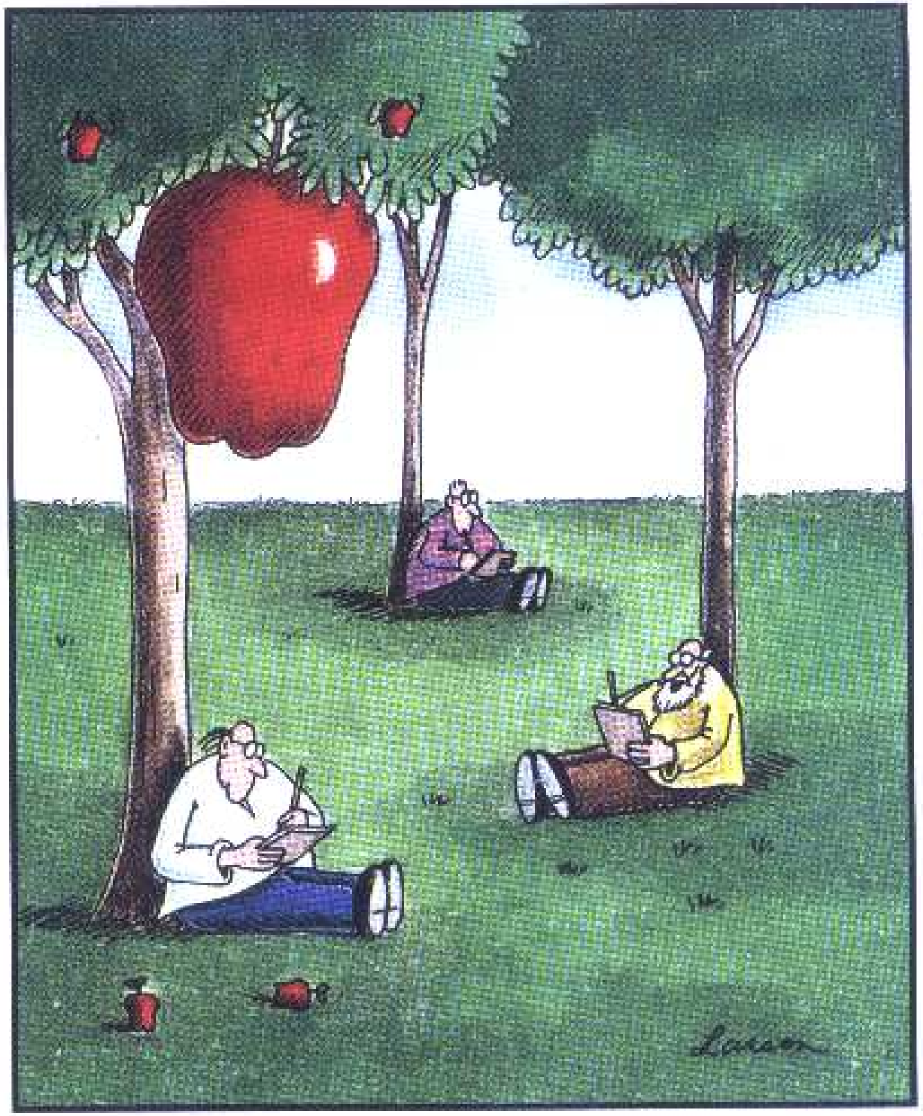


Forces and force particles (II):

3. strong force: gluon: g

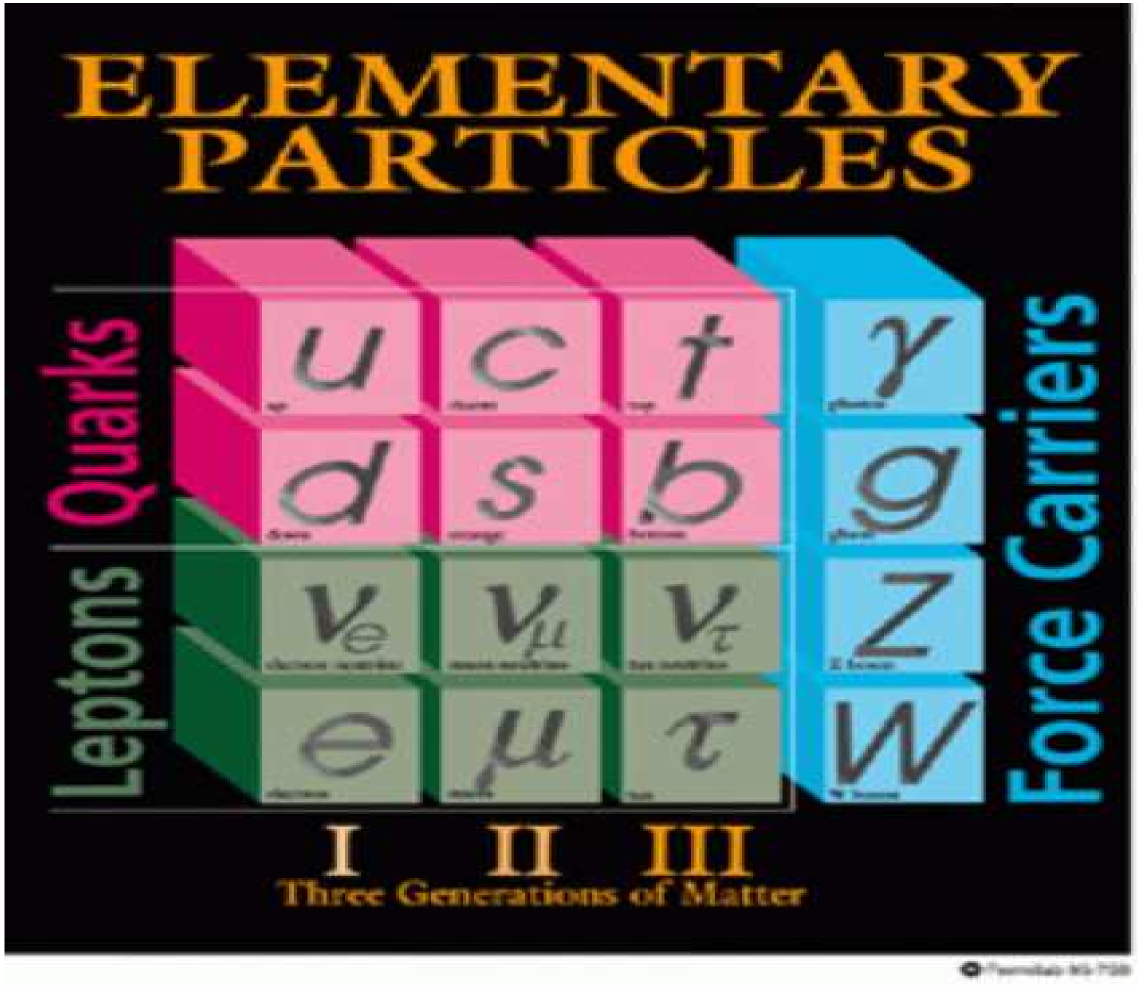


4. gravitational force: graviton(?)



"Nothing yet. ... How about you, Newton?"

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

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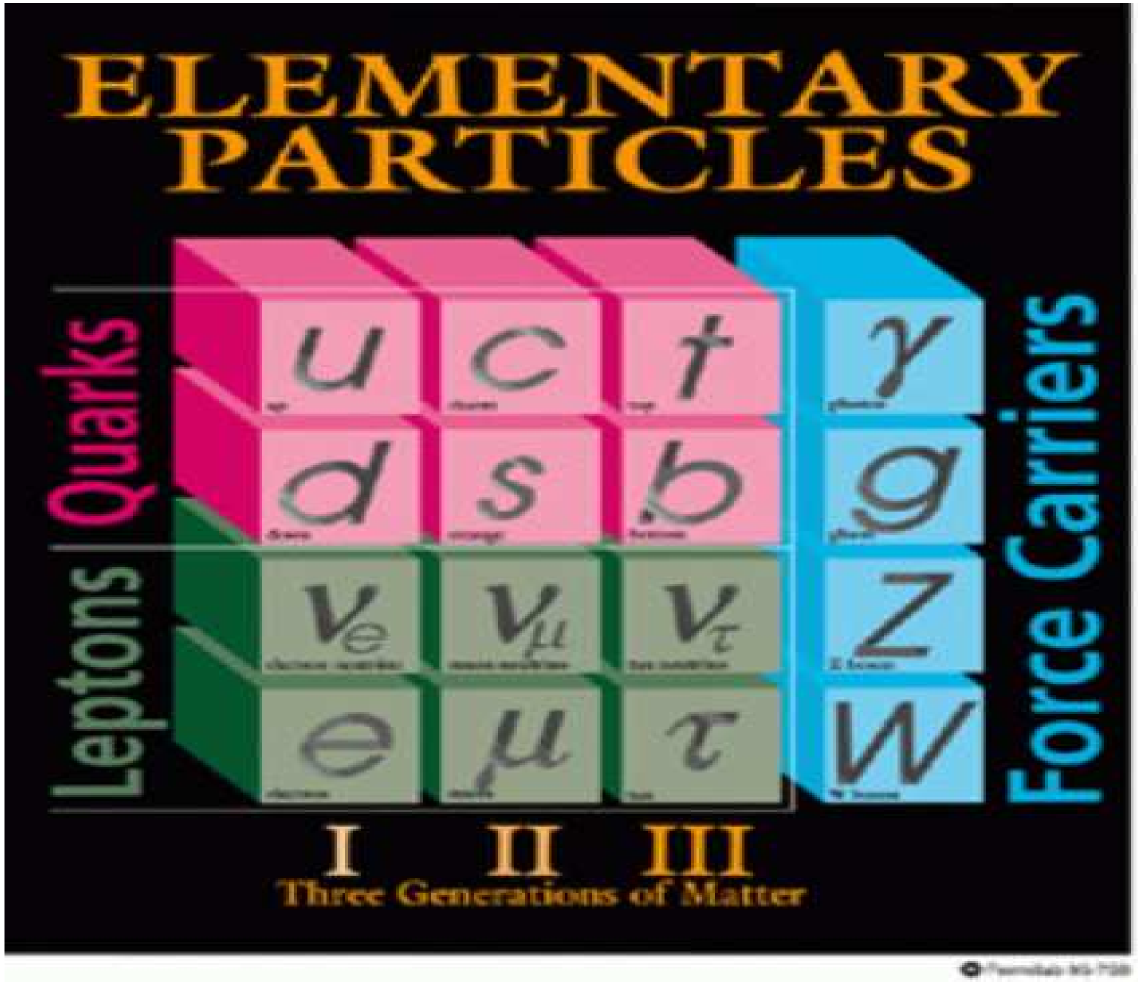


⇒ all particles experimentally seen

⇒ but one particle is missing . . .

D) The Higgs particle

The model requires one more particle, the Higgs particle
(named after one of its "discoverers", Peter Higgs)

Only if the Higgs particle is included the "SM works"
without it the SM is mathematically inconsistent!

The Higgs mechanism gives masses to all elementary particles

In total:

6 quarks and 6 leptons

force carriers: γ, W^+, W^-, Z, g

+Higgs particle

⇒ Standard Model of elementary particle physics

agrees (nearly) perfectly with experimental results

The "tool" to search for the Higgs particle:

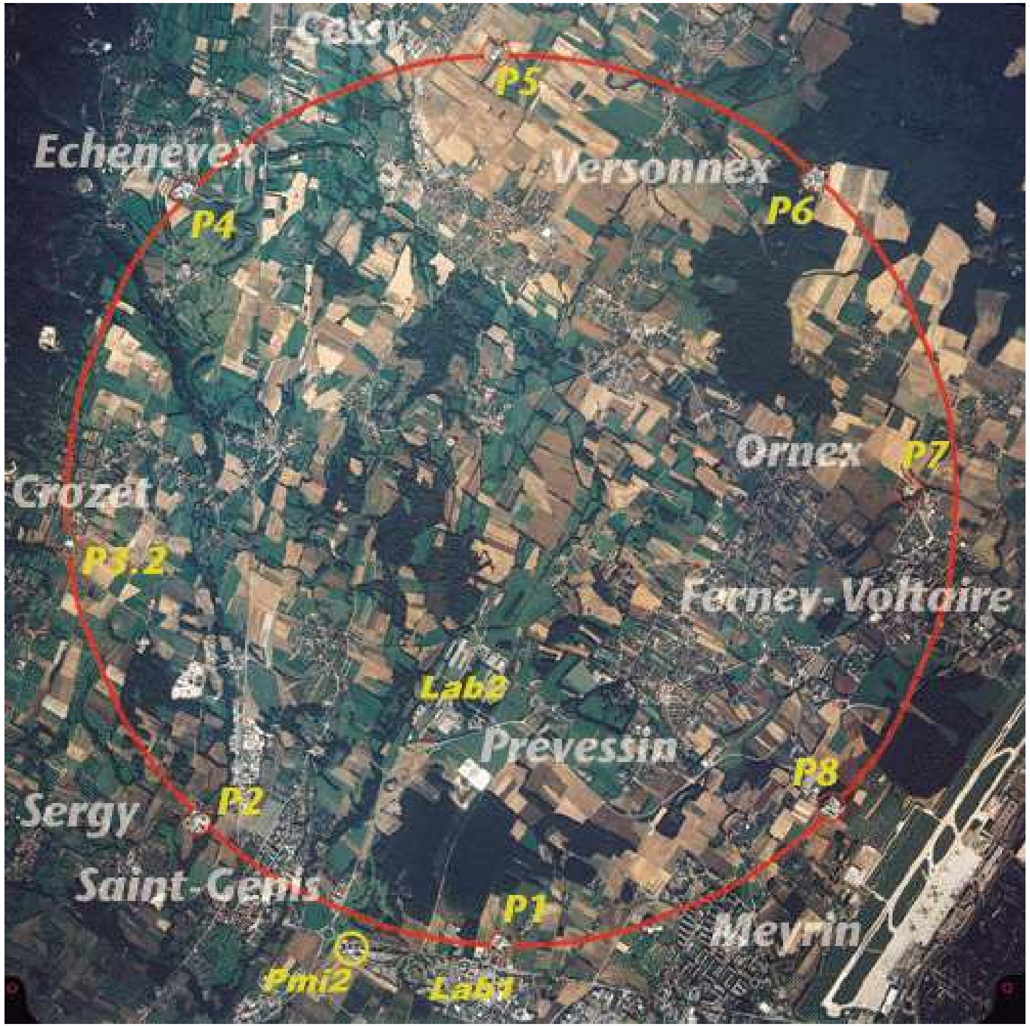
LHC:

$p \rightarrow\leftarrow p$ collisions at

$\sqrt{s} = 7, 8, 14(?)$ TeV

– 27 km circumference
– two general purpose detectors: ATLAS and CMS
– one B physics detector: LHCb
– one heavy ion detector: Alice

⇒ next talk



What can we learn from the LHC?

- How do elementary particles obtain the property of mass:
  Is there a Higgs particle? Are there several Higgs particles?

- Do all the forces of nature arise from a single fundamental interaction?

- Are there more than three dimensions of space?

- Are space and time embedded into a "superspace"?

- Can dark matter be produced in the laboratory?

- . . .

$\Rightarrow$ the LHC might answer all those questions!

3. Theoretical Elementary Particle Physics

Theory:

– search for models (master formula) that describe our world
  (model = mathematical formulation of laws of nature)
– calculation of predictions within a model

predictions:
- masses of elementary particles
- production cross sections (Higgs at the LHC, . . .)
- decay probabilities
- . . .

Experiment:

– perform experiments to
  - find new particles
  - measure the masses of elementary particles
  - measure other properties
  - . . .

Comparison between theory predictions and experimental results
⇒ "true" theory of nature

A theory is based on a "master formula": Lagrangian

⇒ describes content: particles, interactions, . . .

A Lagrangian is constructed/guessed based on:

– symmetry principles
– necessity: experimental data should be described
– simplicity
– experience/intuition

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Current “best” Lagrangian: SM

(over)simplified version:

$$\mathcal{L}_{\mathrm{SM}} = g_{\gamma f \bar{f}}\, \gamma f \bar{f} + g_{Z f \bar{f}}\, Z f \bar{f} + g_{W f' \bar{f}}\, W f' \bar{f} + g_{g q \bar{q}}\, g q \bar{q}$$
$$+ g_{H f \bar{f}}\, (v + H) f \bar{f} + g_{HZZ}\, (v^2 + H) ZZ + g_{HWW}\, (v^2 + H) WW$$
$$+ \ldots$$

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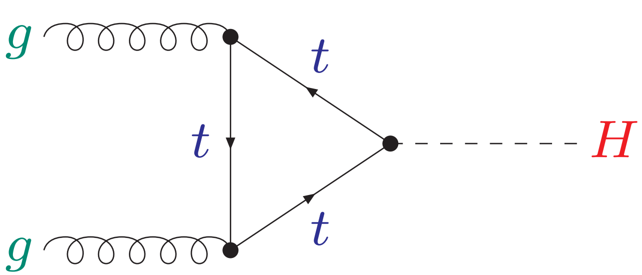
$$+ g_{H f \bar{f}}\, (v + H) f \bar{f} + g_{HZZ}\, (v^2 + H) ZZ + g_{HWW}\, (v^2 + H) WW$$
$$+ \ldots$$

Full version: ⇒ see my T-Shirt!

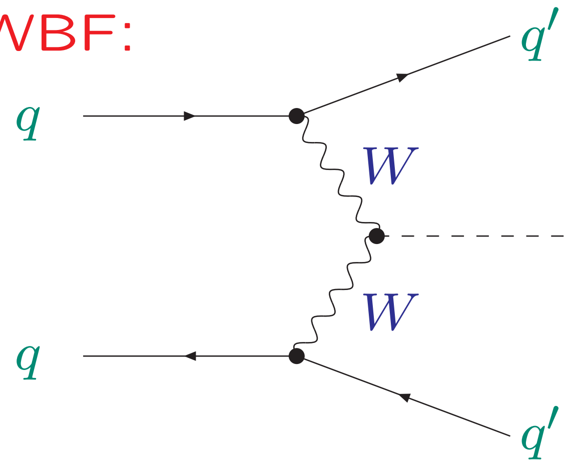
The Lagrangian can be translated into Particle Physics Processes:

Important SM production channel at the LHC:

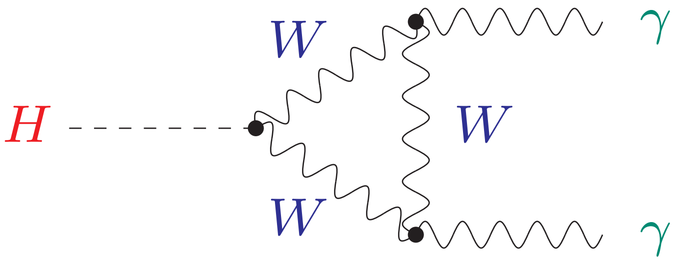
Gluon-Fusion:

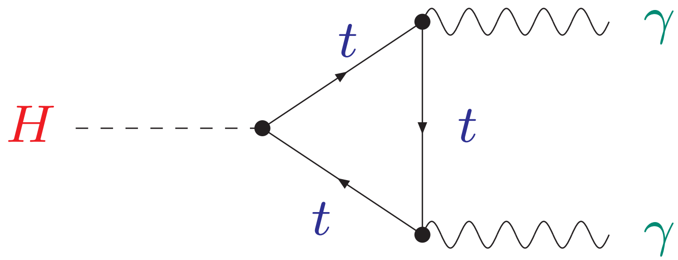


WBF:



Important decay for Higgs mass measurement:



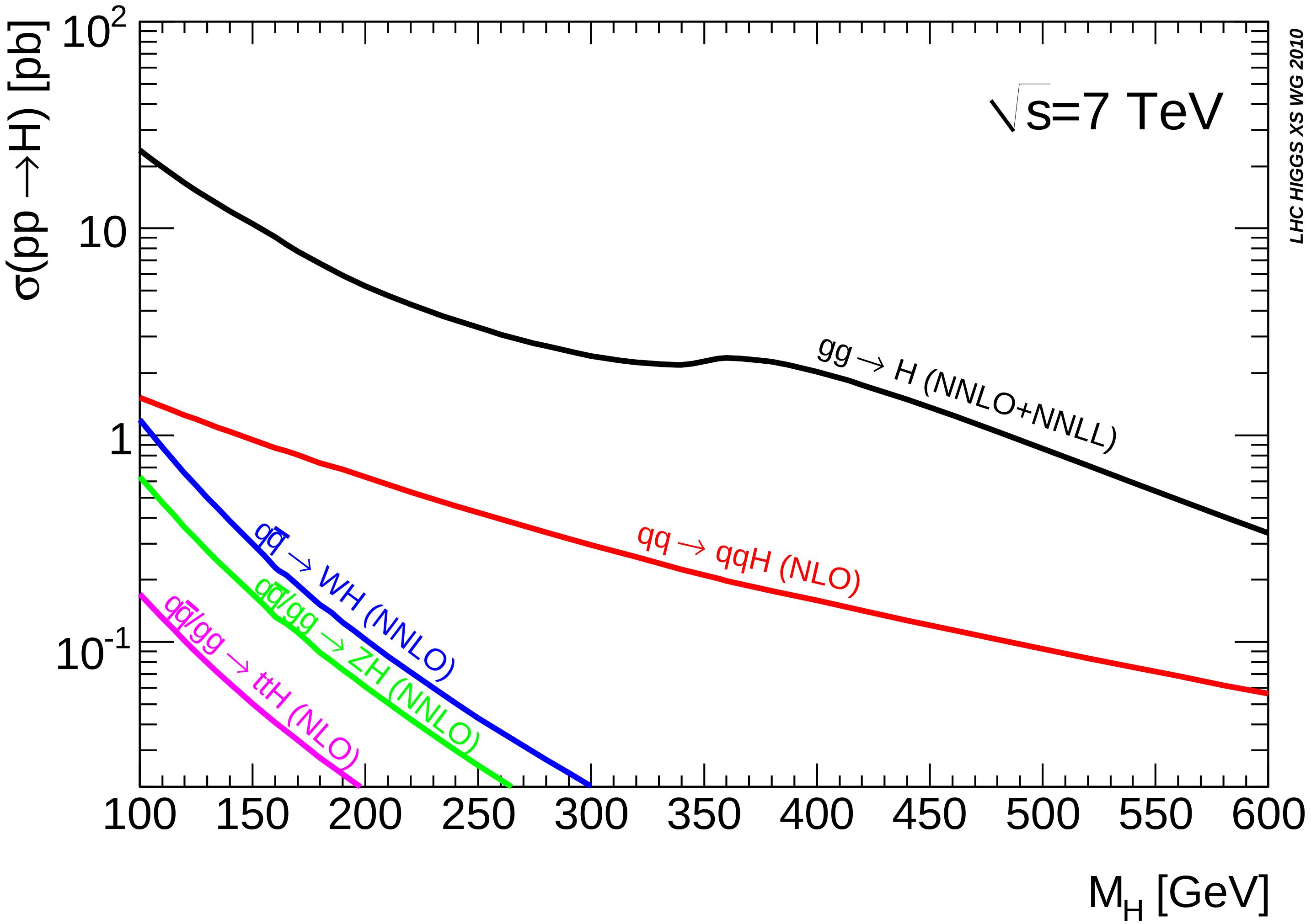


The "Pictures" (Feynman diagrams) are equivalent to mathematical formulas:

⇒ they can be "calculated"

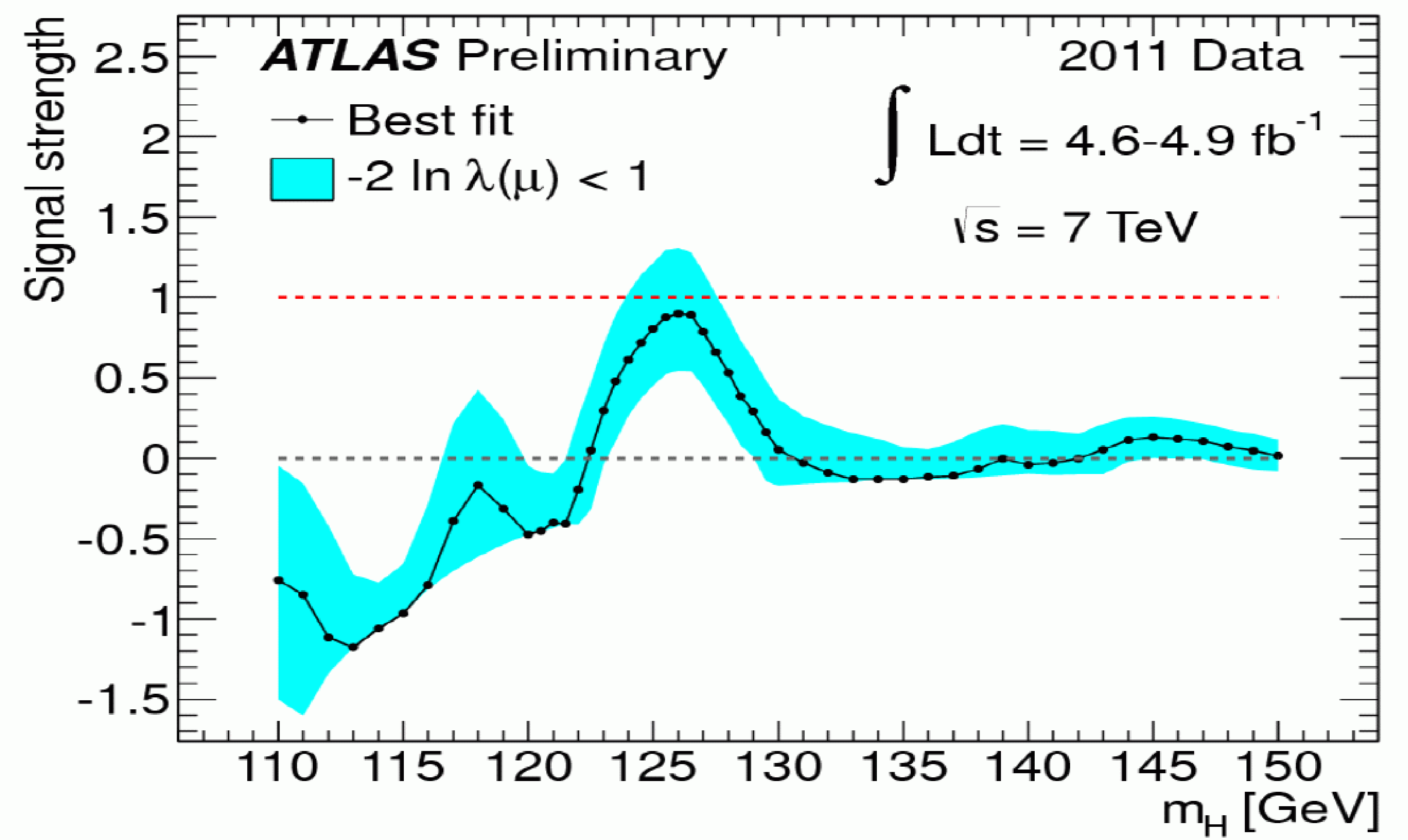
"Probability" to produce a Higgs boson at the LHC (if it exists):

[*LHC Higgs XS WG '11*]



Comparison of theory and experiment:

⇒ compare calculated (theory) probabilities for Higgs production with measured (experimental) data (here divided by SM theory):



⇒ there could be a Higgs particle . . .

4. Outlook: Beyond the SM

Status: SM agrees with nearly all experimental results to highest precision

"Failures" of the SM:

- gravitation is not included
- no unification of other three forces
- no Dark Matter candidate
- Mass of the Higgs particle "unstable" wrt. to quantum corrections
- some data (e.g. the anomalous magnetic moment of the muon) do not agree well

$\Rightarrow$ go to extended theories to resolve these problems

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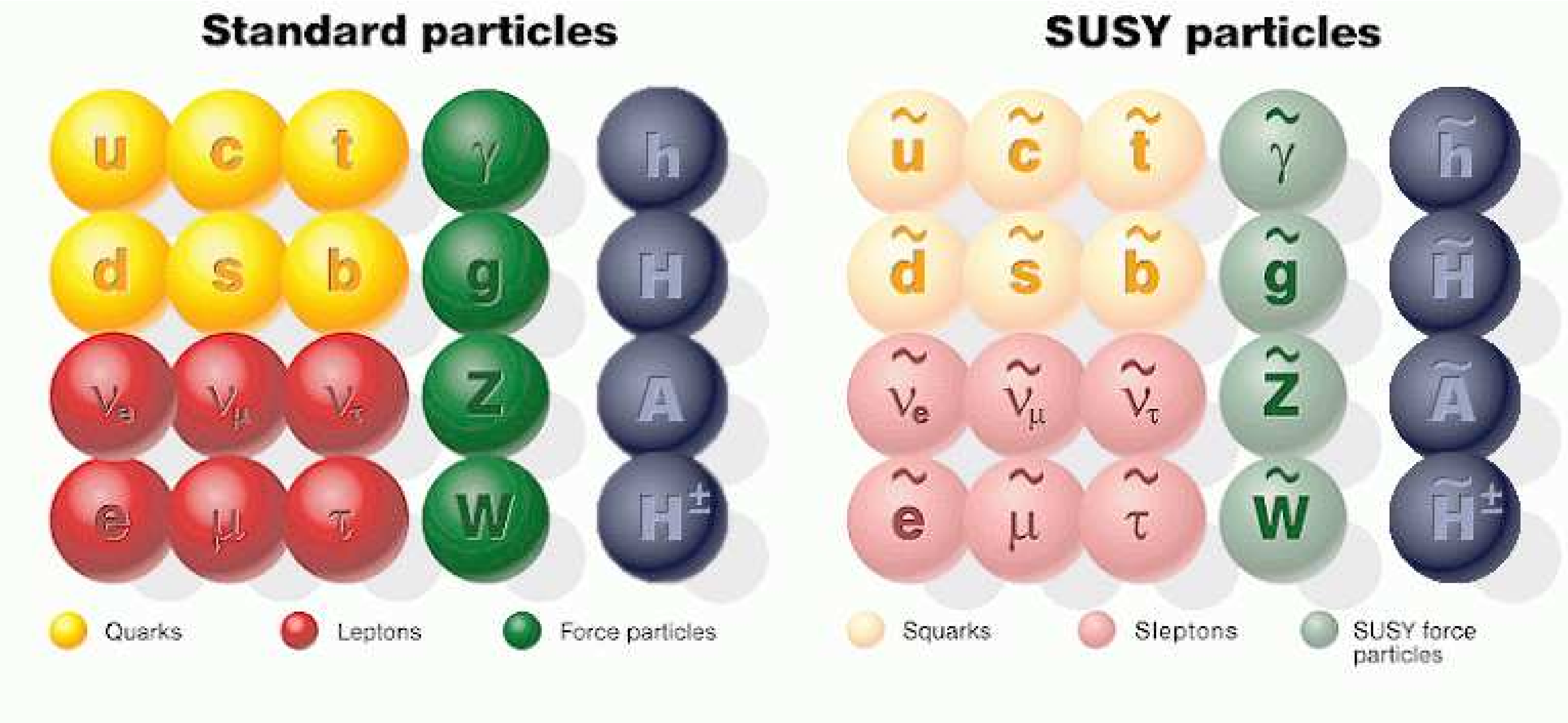
"Popular" solution:
The Minimal Supersymmetric Standard Model (MSSM)

⇒ theory group at IFCA works on SM and SUSY

The particle content of the MSSM

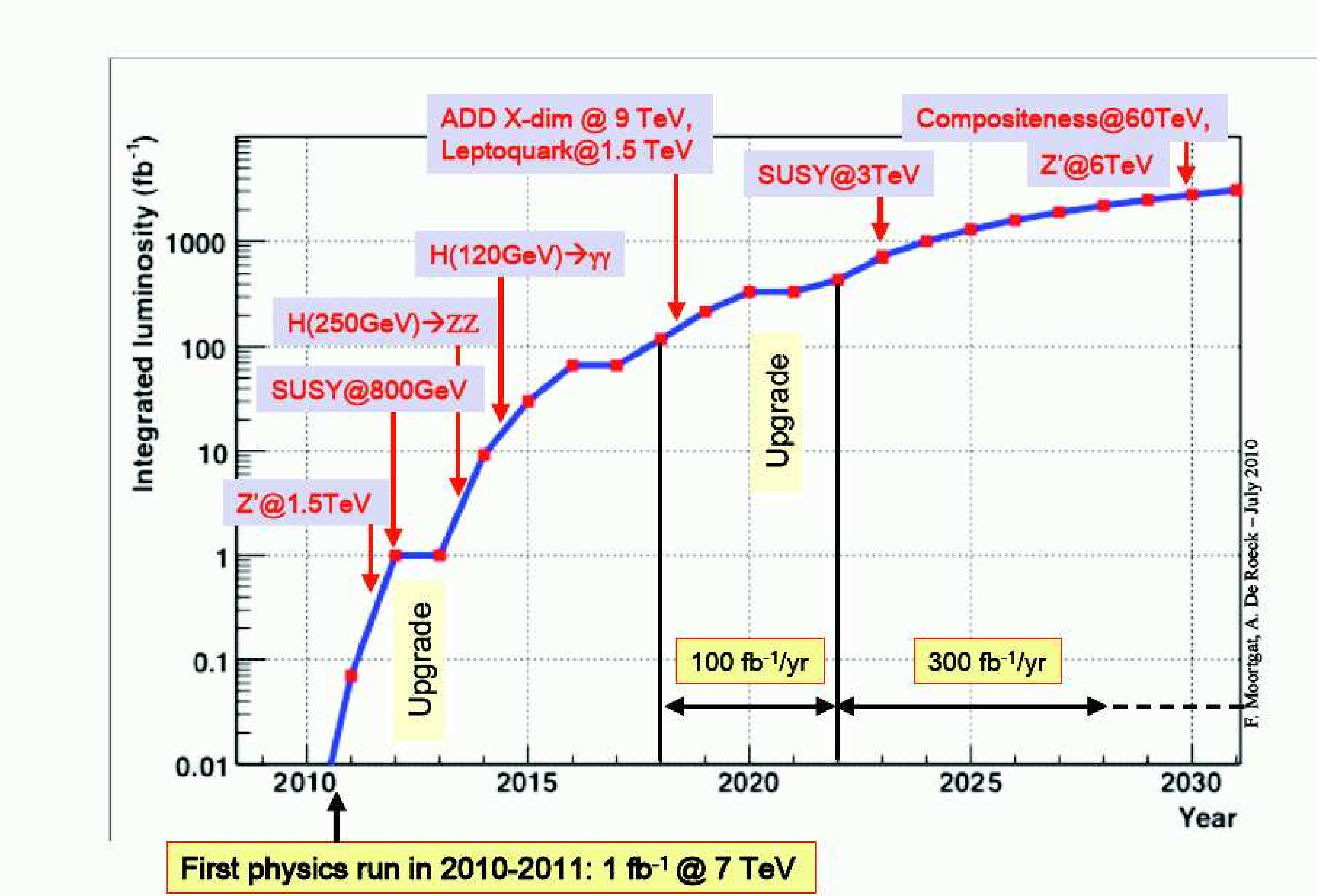
Superpartners for Standard Model particles



$\Rightarrow$ the MSSM has five Higgs particles: h, H, A, H^+, H^- $+$ DM particle: $\tilde{\gamma}$

Back-up

Overview: [*A. De Roeck et al. '10*]



CERN TH institute 02/09: LHC2FC: From the LHC to Future Colliders