The Standard Model and LHC phenomenology

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Particle Physics in the headlines

- ☑ **Higgs Boson: most important discovery in particle physics** in 25 years
- ☑ Completes the **extremely successful Standard Model of particle physics ….**
- ☑ … but at the same time **opens a number of crucial questions**
- ☑ The **LHC** will play a central role in **exploring the high-energy frontier in the next 20 years**


El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs

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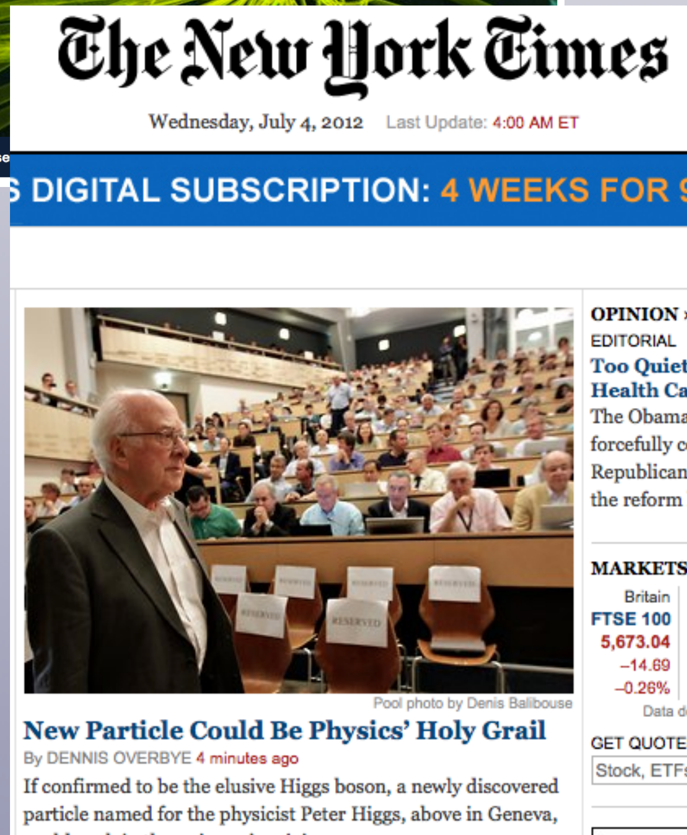
Ciencia | 04/07/2012 - 09:46h | Actualizado el 04/07/2012 - 11:27h

El bosón de Higgs podría se


The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

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Pool photo by Denis Balibouse

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva,

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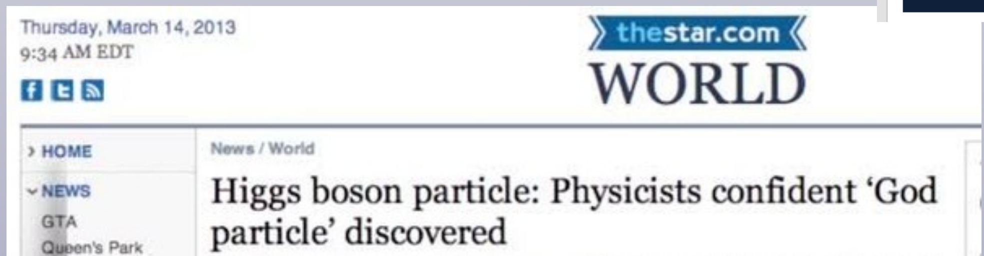
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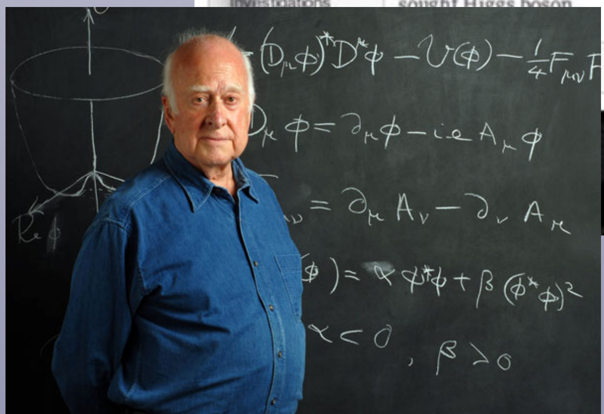
Higgs boson particle: Physicists confident 'God particle' discovered

Scientists announced Thursday that the parti
CMS experiments at the Large Hadron Collid
sought Higgs boson



High-Energy Physics in the Higgs Boson Era

- Higgs Boson: last missing ingredient of successful **Standard Model** of particle physics

- The Standard Model is **not a complete theory of nature**: a substantial amount of experimental data and theoretical arguments require **New Physics Beyond the Standard Model**:

  - Dark Matter and Dark Energy
  - Huge gap (10^{16}) between Higgs mass and Plank scale
  - Unification of Gravity and Quantum Mechanics
  - Inflation
  - Flavor physics and Neutrino masses and mixings

- The LHC program for the coming decade is based on the **detailed characterisation of the properties of the Higgs Boson** and the **search of Physics Beyond the Standard Model**:

  - **Direct searches**: new heavy particle production, supersymmetry, extra dimensions
  - **Indirect searches**: Higgs couplings and branching ratios, Higgs compositeness
  - **Consistency tests**: precision electroweak data

Precision SM: Toolbox for Discoveries at the LHC

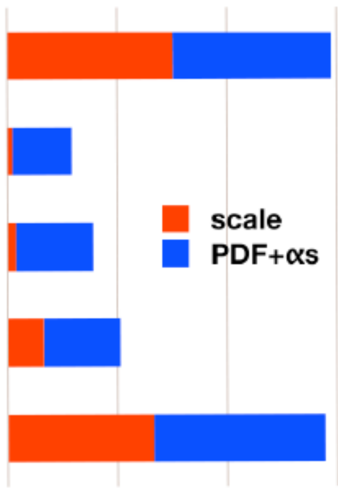
The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....

.... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)   Mangano, Aspen14

This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Improving our **quantitative understanding of the Standard Model** is essential in this new era for HEP, where we need to hunt, unbiased, **for answers to the big questions of our field**
Now, more than ever, **sharpening our SM tools** could be the **key for new discoveries at the LHC**

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Campbell, ICHEP12

Prime example: **extraction of Higgs couplings** from LHC data soon to be **limited by QCD uncertainties**

Better **QCD predictions**

Improved indirect **sensitivity to New Physics** via deviations of Higgs couplings from SM expectations

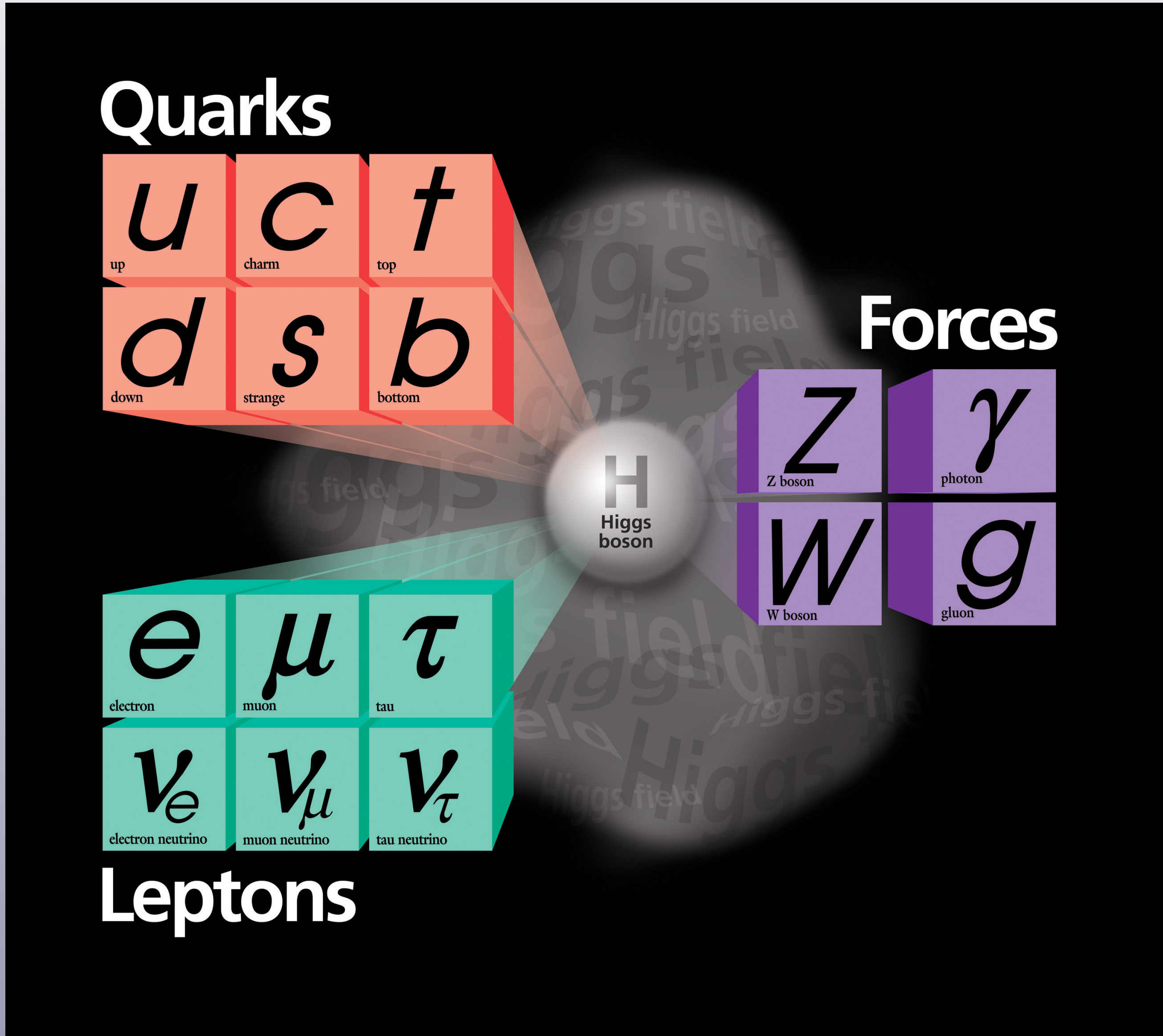
The Standard Model: a history of success

- The **Standard Model (SM) of particle physics** explains a wide variety of microscopic phenomena in a unified framework: **Quantum Field Theory**

- **Matter content** composed by **six quarks** and **six leptons,** organised in **three families**

- Interactions **between matter particles** are governed by **gauge bosons: photons** (electromagnetism), **W and Z bosons** (weak force), and **gluons** (strong interaction)

- The last ingredient is the **Higgs Boson,** provides mechanism by which **particles acquire mass**



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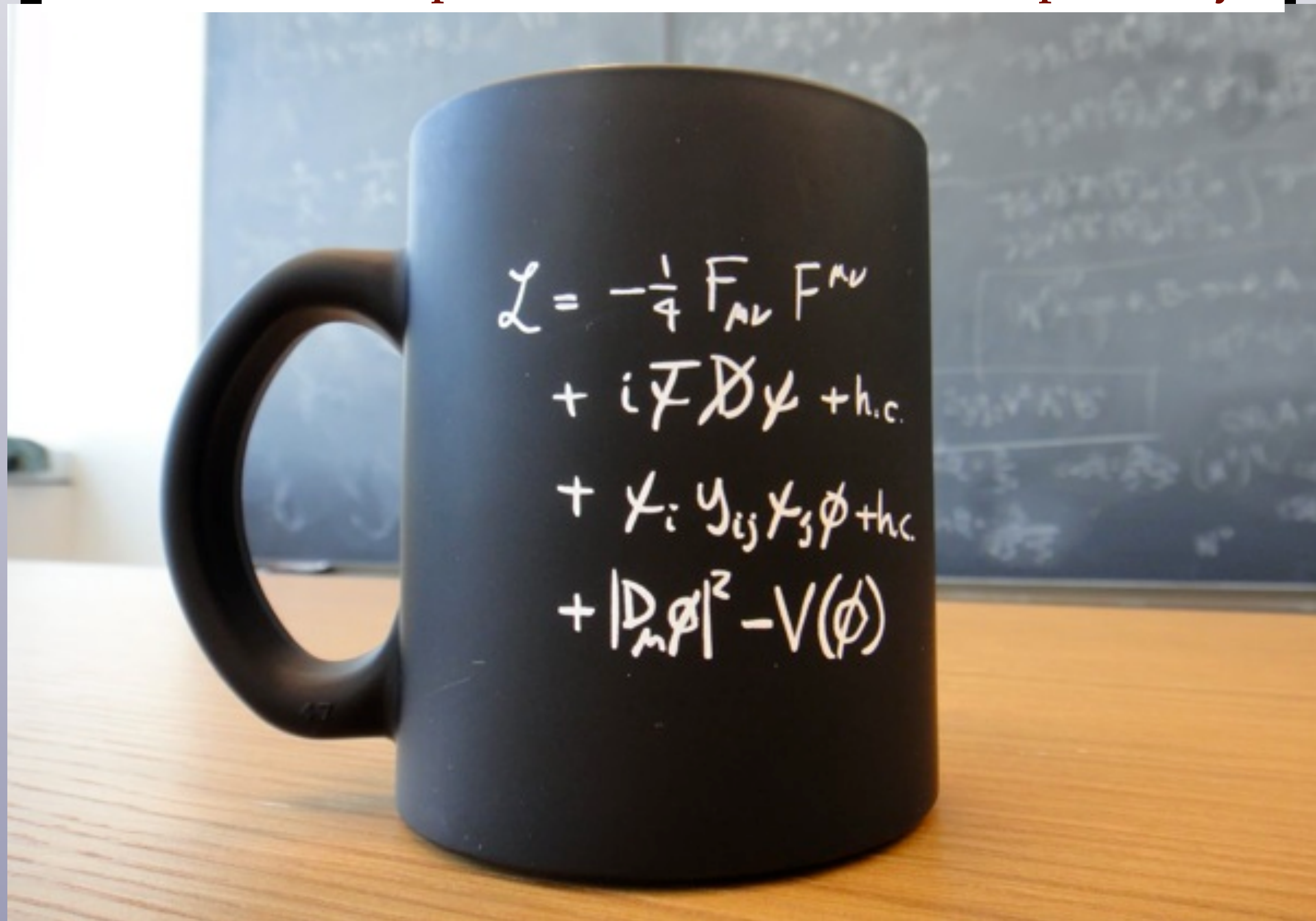
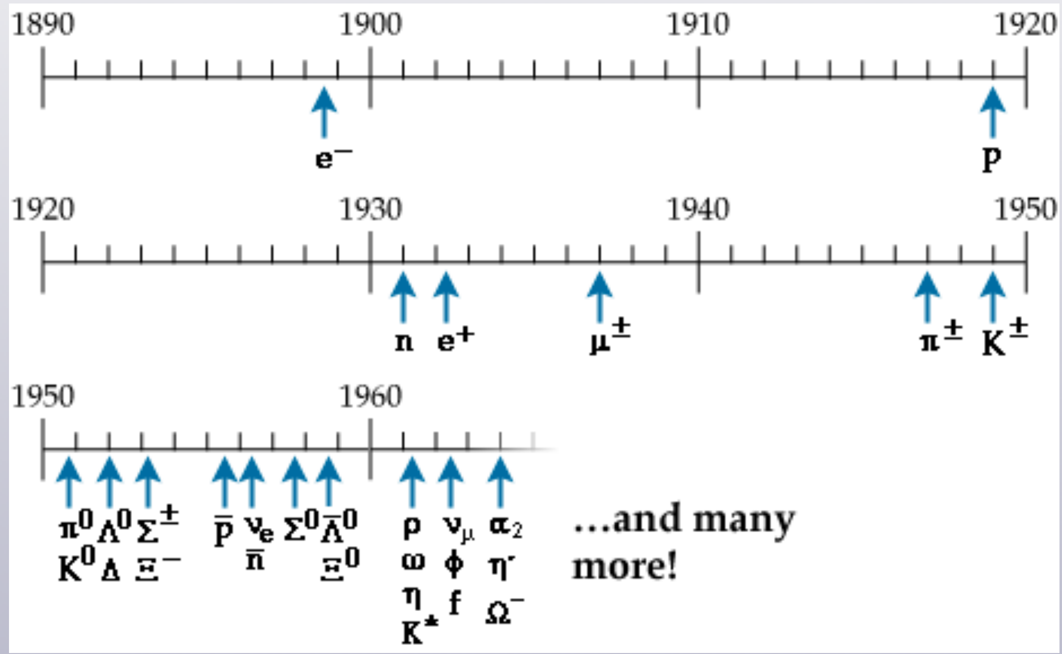
Quantum Field Theory provides a consistent framework to describe all known particles and interactions (except Gravity)

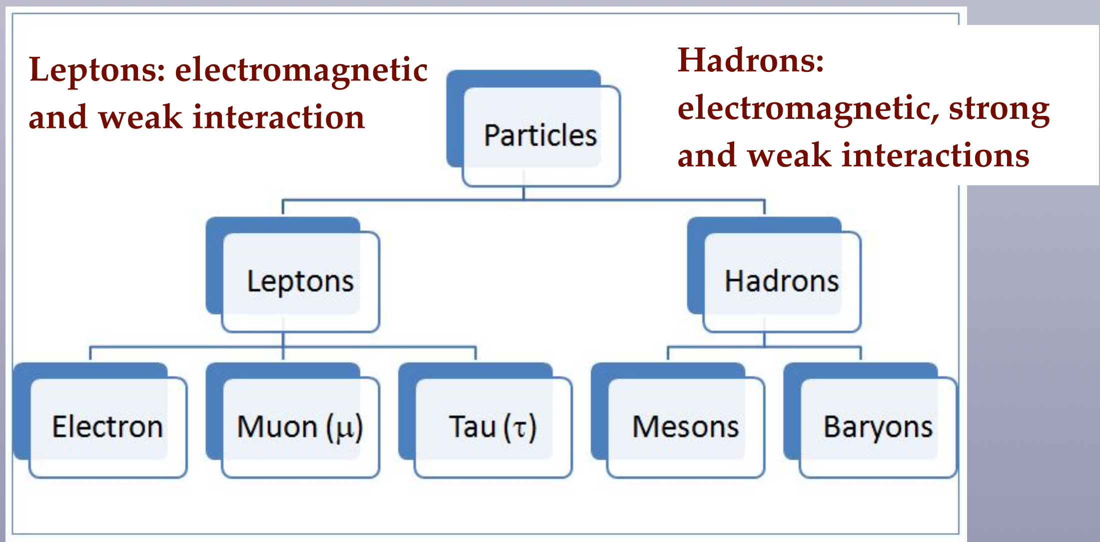


The Dawn of the Standard Model

- By early 30s, after discovery of electron, proton, neutron, and positron, we had a reasonable **description of particle physics**
- The discovery of the **muon** (37) was **completely unexpected**: this new particle, a *heavier electron*, did not fit in!
- To make things worse, a **plethora of new strongly interacting particles** (pions, kaons) with no role in Nature, was soon discovered
- How to **make sense** of this chaos?

Status of high-energy physics in the early 60s:





- Many **conceptual questions** unanswered:
  - How are **atomic nuclei bound together**?
  - What is the origin of the **weak interaction**?
  - Are **hadrons fundamental particles** or composite states?
  - What is the **mathematical language** to describe particle physics?

Quantum Electrodynamics (QED)

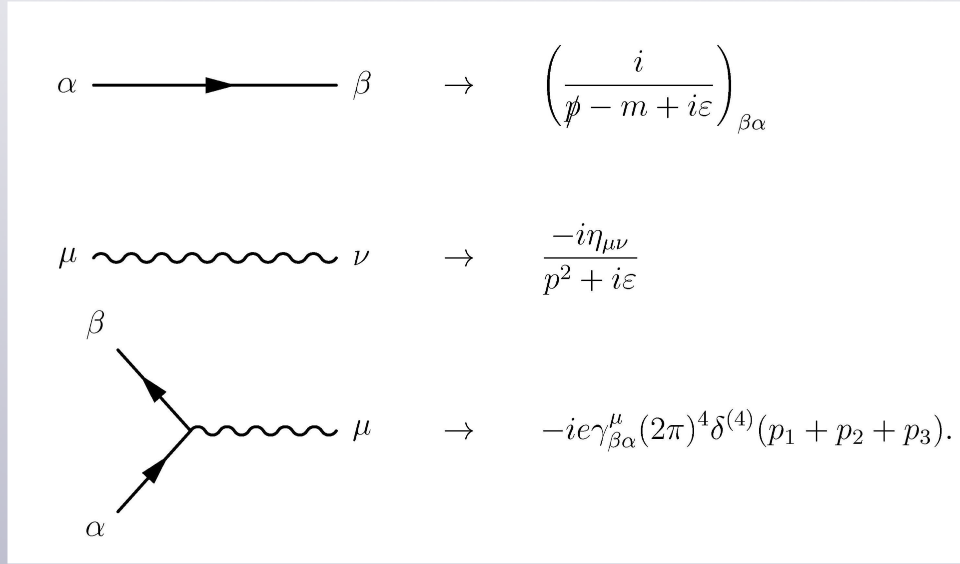
- ☑ The interactions of electrically charged particles are governed by **electromagnetism** (EM)

- ☑ Making sense of EM once **quantum corrections are accounted** for was a theoretical *tour de force* that ended in formulation of **Quantum Electrodynamics (QED)**

- ☑ Starting from **simple rules** (Feynman diagrams), compute terms at any order in the **perturbative expansion in the QED coupling**

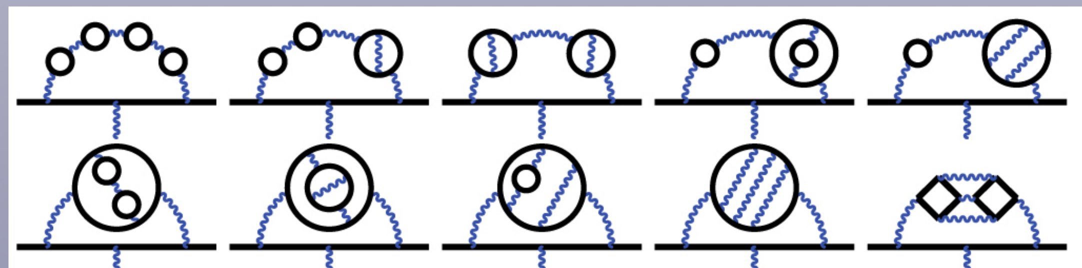
- ☑ Some of the **most precise calculations ever done** have been obtained in QED: for instance, the **muon anomalous magnetic moment known better than one part in one billion!**

QED Feynman rules



Feynman diagrams for muon anomalous magnetic moment

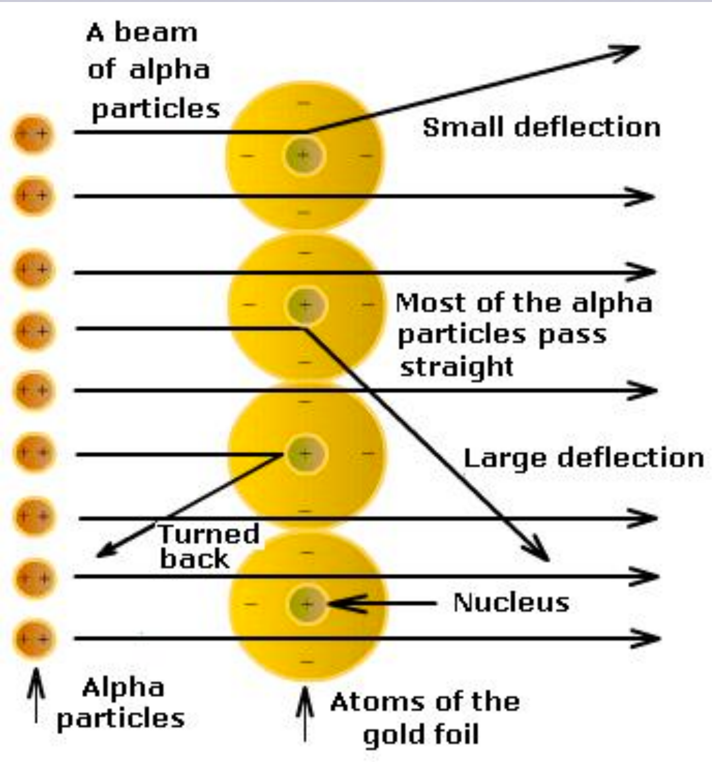
$$a_\mu^{\rm QED} = 116\,584\,718.09(0.15) \times 10^{-11}$$



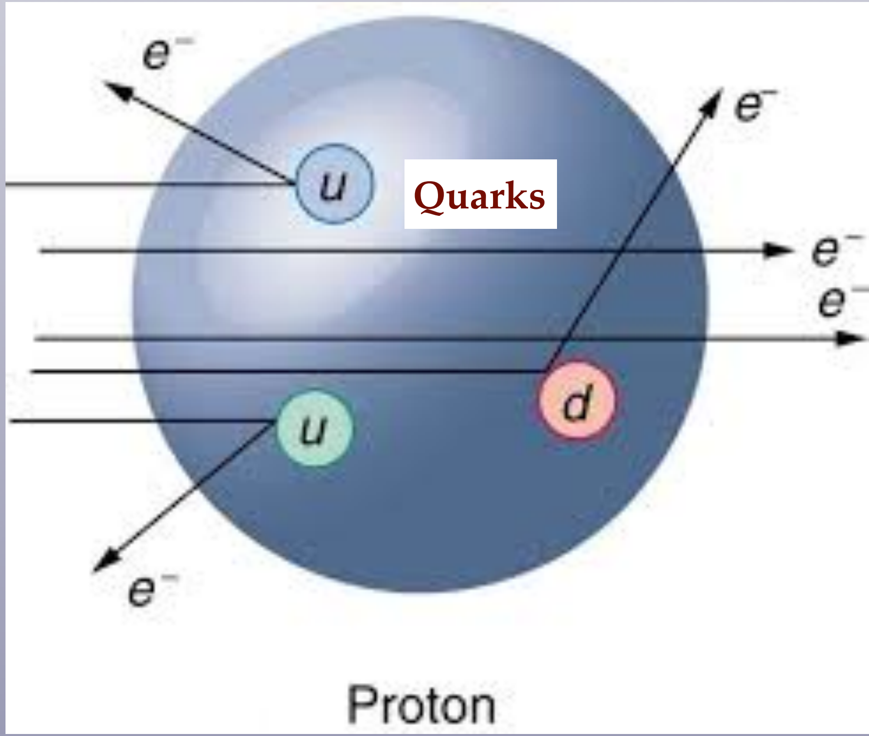
Quarks: the inner life of protons

- Scattering of **α particles (He nuclei) off atoms** lead in 1911 Rutherford to **discovery of internal structure of atoms**: a **point-like nucleus** and layers of electrons
- 70 years later, the **scattering of energetic electrons off protons** lead to equally surprising result: the **internal structure of protons**, composed by point-like **quarks**

Rutherford experiment:
Atoms have internal structure!



Electron-proton collisions at Stanford Linear Accelerator:
Protons have internal structure!



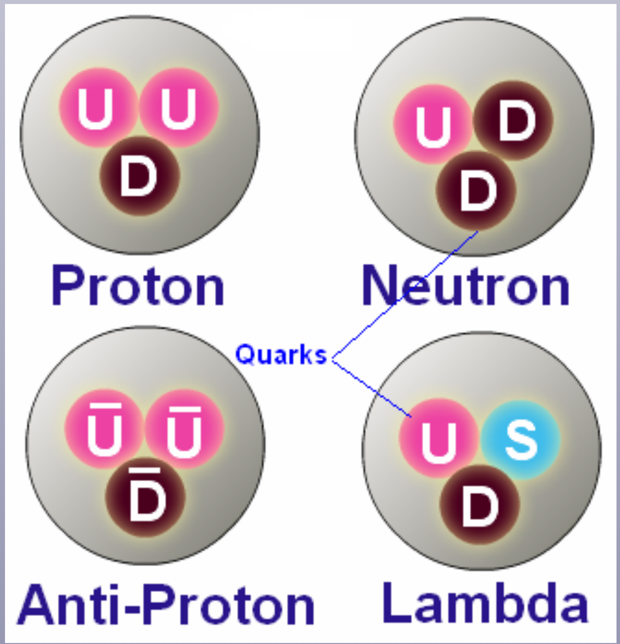
Quarks: charming, beautiful and top

- The **Constituent Quark Model** allowed to **describe all known hadrons** as composite states of only three types of quarks: up, down and strange, with **fractional electric charge**

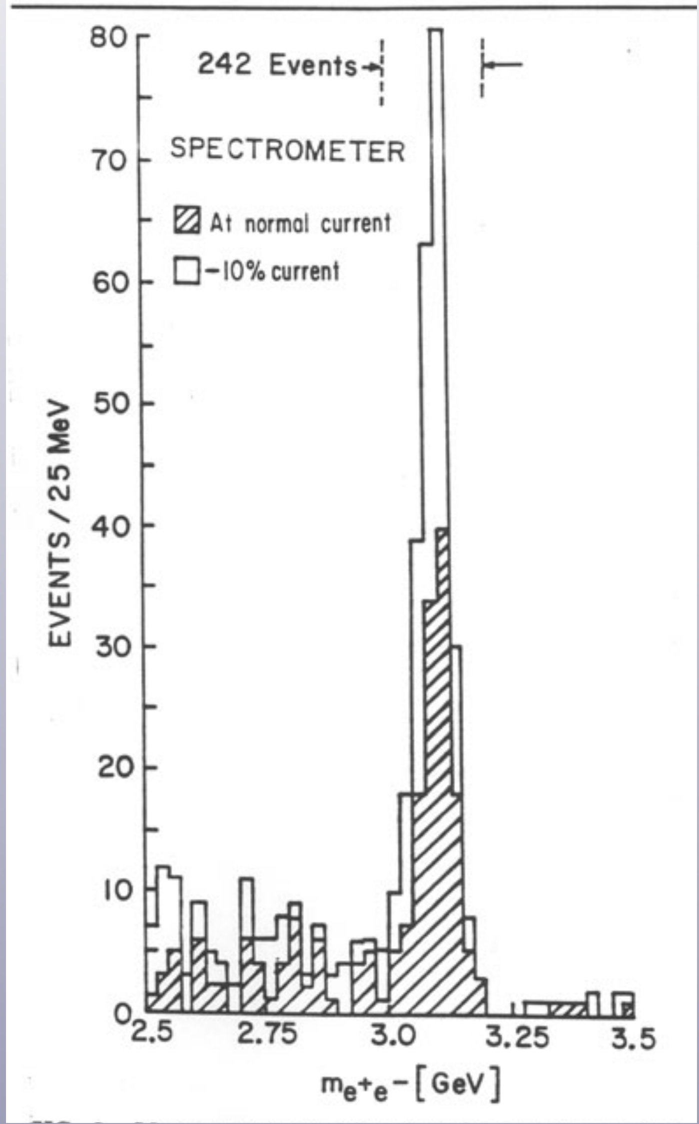
- Considered as a **mathematical trick** to organise hadrons, **real existence confirmed** only after SLAC experiments

- Much to everyone's surprised, **two new, heavier quarks were soon discovered**: the **charm** quark (73) and the **bottom** quark (77). Much heavier **top quark** had to wait until **1995** to be discovered

Quark Constituent Model:
Hadrons composed by quarks



Discovery of charm quark

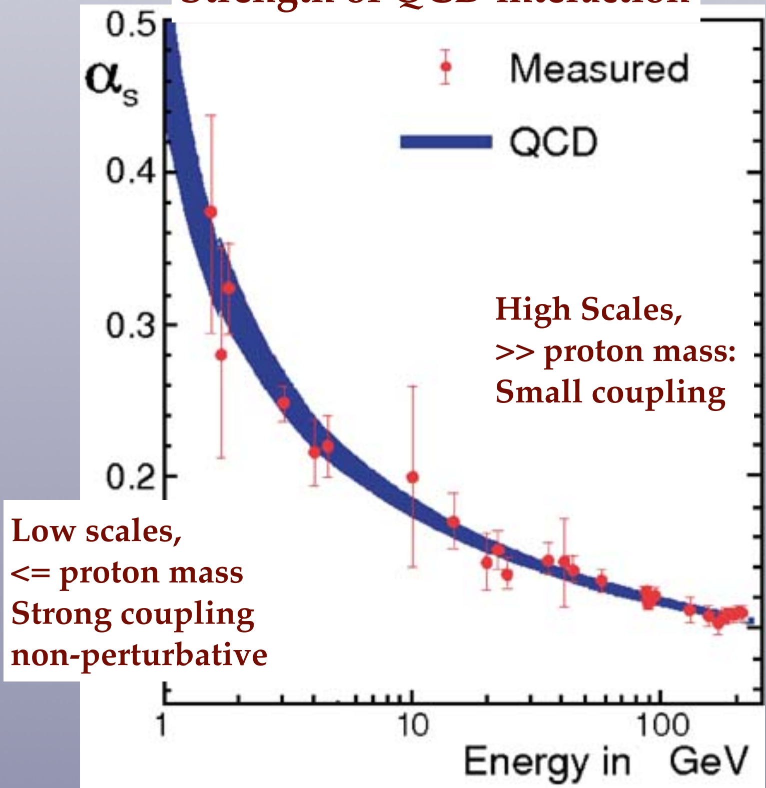


Evidence of new particle with mass 3 GeV: the J/Psi, charm/anti-charm pair

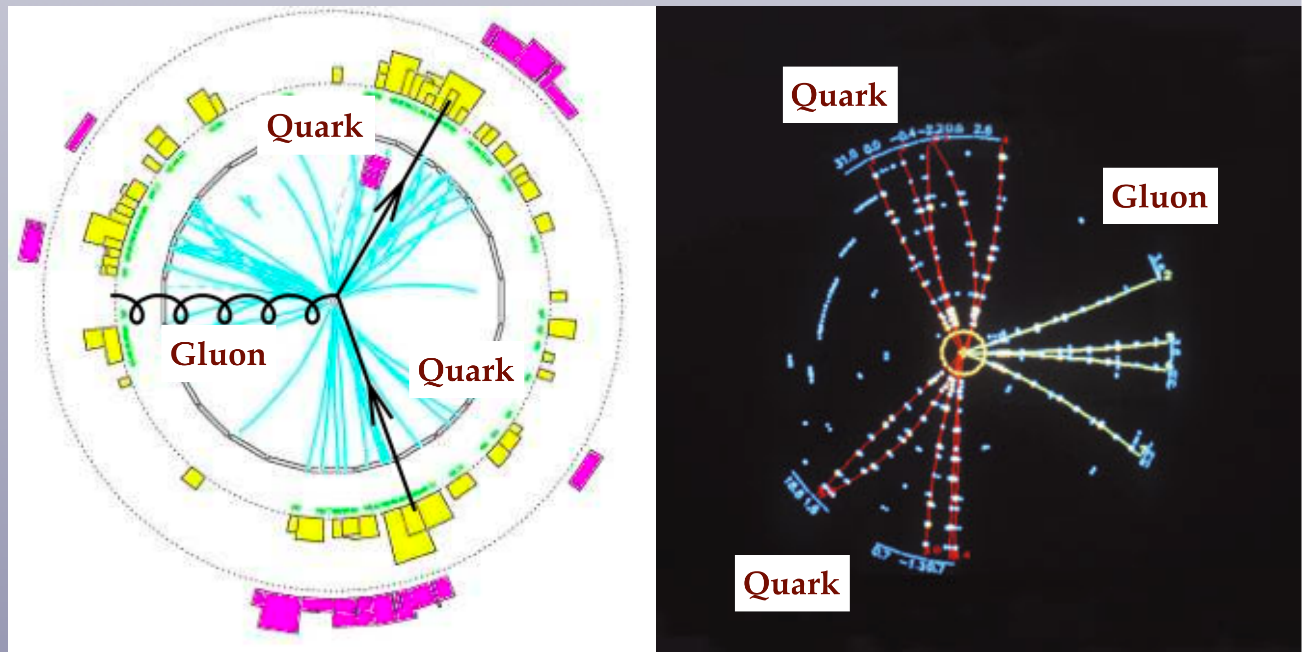
Eight Gluons to Bind Them All

- **Electromagnetism** can be understood as a **renormalizable Quantum Field Theory (QFT), Quantum Electrodynamics** (QED). Compute scattering amplitudes as **perturbative expansion in small coupling**
- **Hadrons interact strongly**: QED model cannot be applied to **nuclear strong force**?
- In fact, strong force is also a renormalizable QFT but with **asymptotic freedom:** it looks like QED, but only at **very high energies**
- The **mediator of the strong force** is the **gluon** (analog of the photon), responsible for **binding the quarks together in the proton**

Strength of QCD interaction



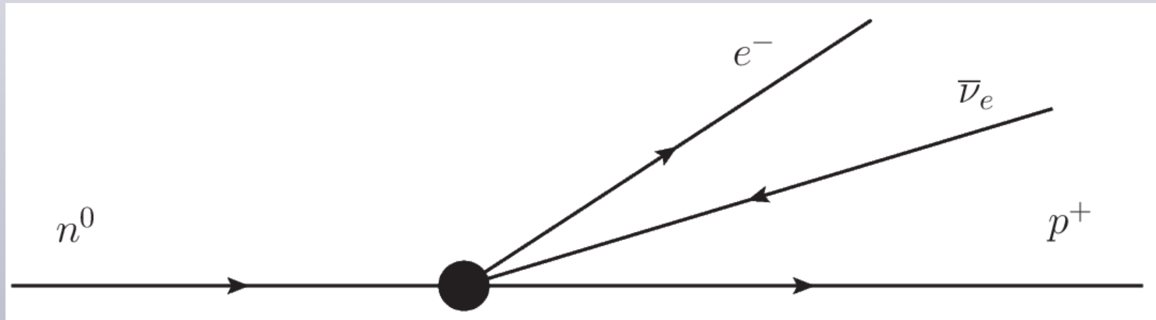
Discovery of the Gluon (77): Three-Jet events in electron-positron collisions

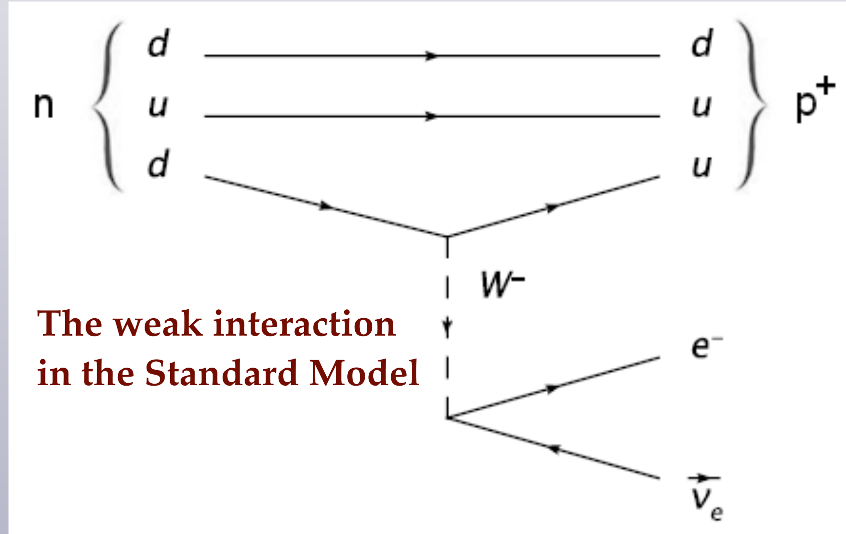


Weak vector bosons

- Fermi (30s) explained **beta-decay of nuclei** by a **four-body interaction** between neutrons, protons, electrons and neutrinos: the **weak nuclear interaction**
- Weak interaction also similar to electromagnetism, but with **massive vector bosons, the W and Z particles.** Due to **large masses** (80 and 91 GeV) their interactions are **point-like at low energies**
- Evidence for **Neutral Currents** (73) followed by the **discovery of the W and Z** bosons at the CERN (83)

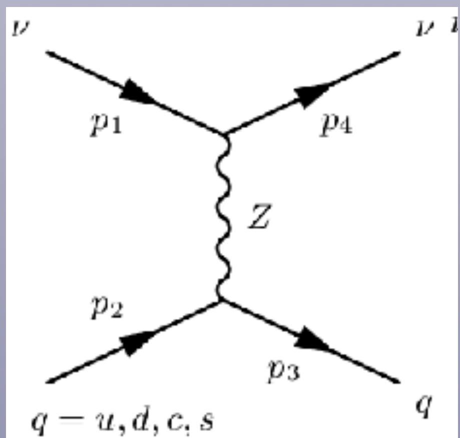
Fermi picture of the weak interaction

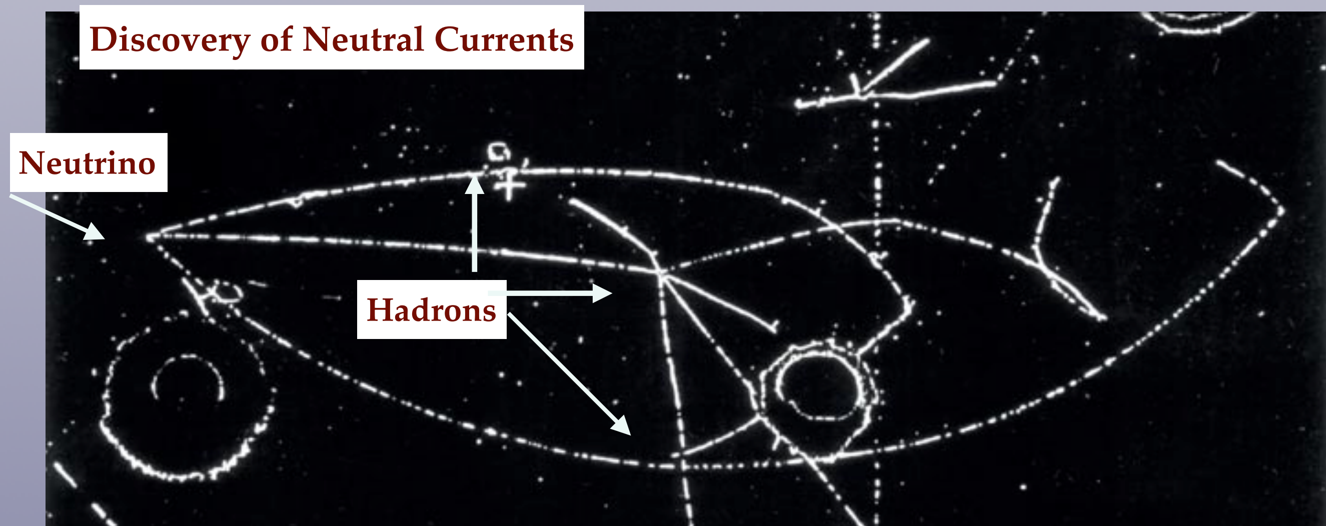




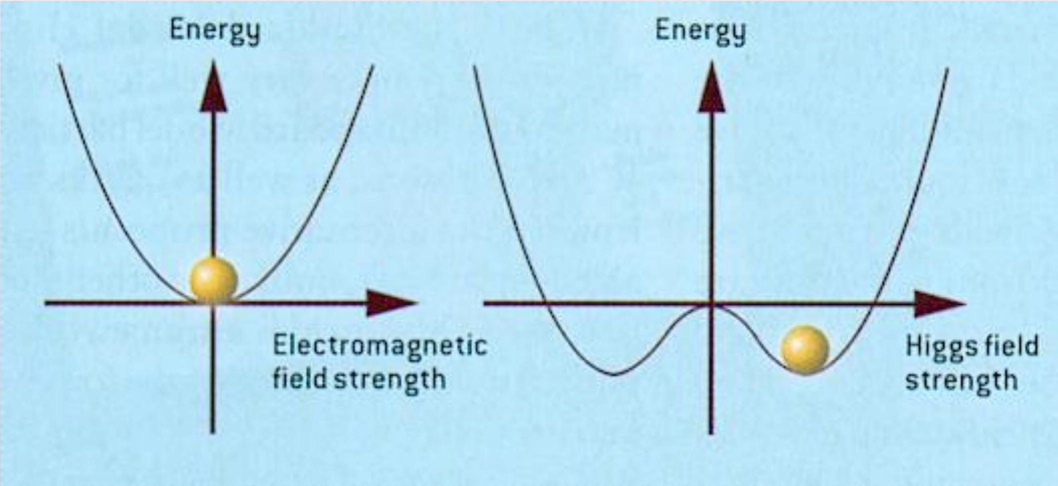
The weak interaction in the Standard Model

Neutral currents in neutrino scattering: indirect evidence for the Z boson



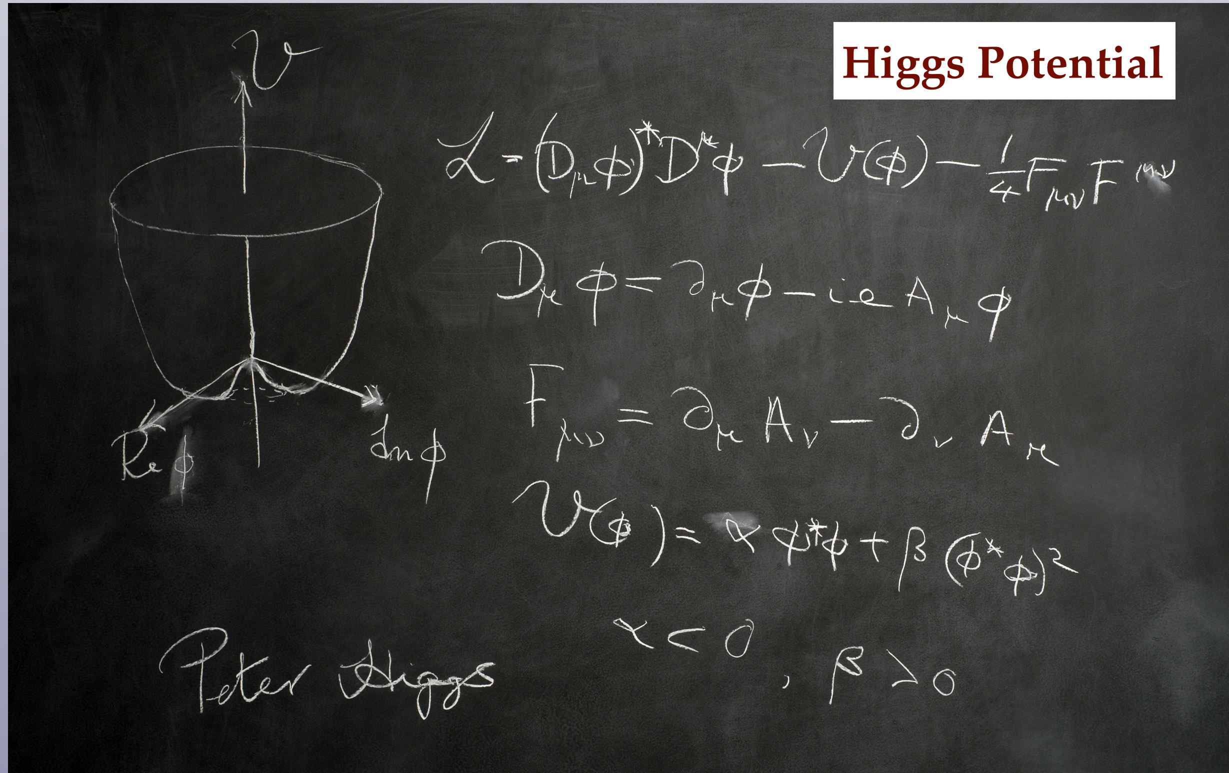


The Higgs Mechanism



- In the SM, symmetries **do not allow mass terms** in the Lagrangian
- The Higgs **mechanism** bypasses this restriction: laws are still symmetric, but the **specific configuration** chosen by Nature (Higgs potential) is not**: Spontaneous Symmetry Breaking**

- Thanks to the Higgs mechanism, **SM particles can acquire a mass**
- As a byproduct, the **Higgs particle, excitation of the Higgs field** can also be produced if energy high enough
- Predicted more than 50 years ago, it was finally **discovered in 2012 at LHC**

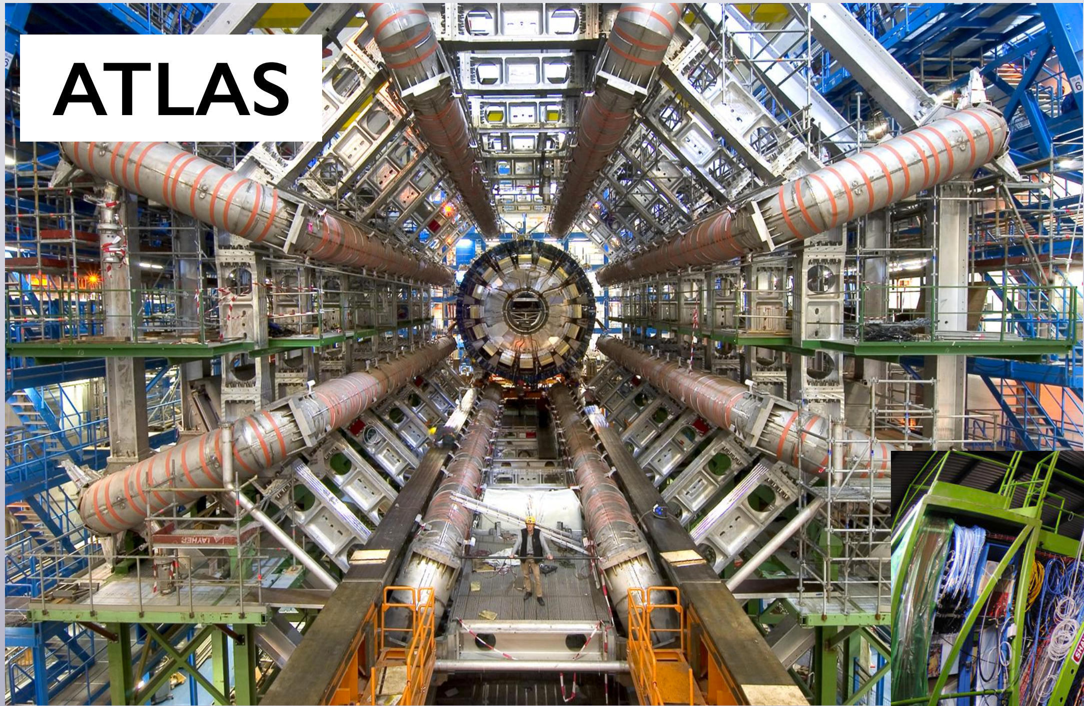


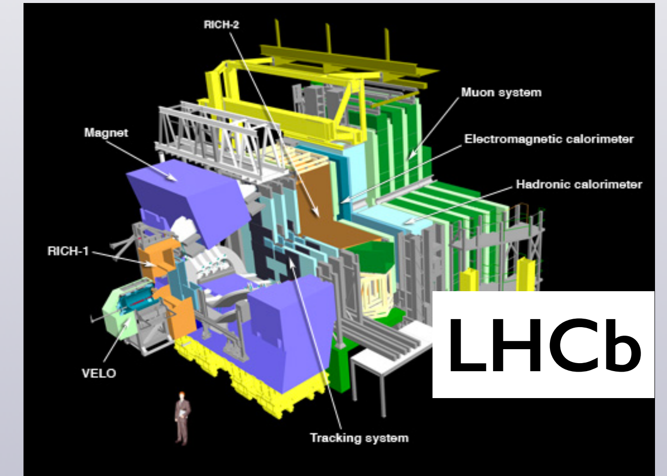
The Large Hadron Collider

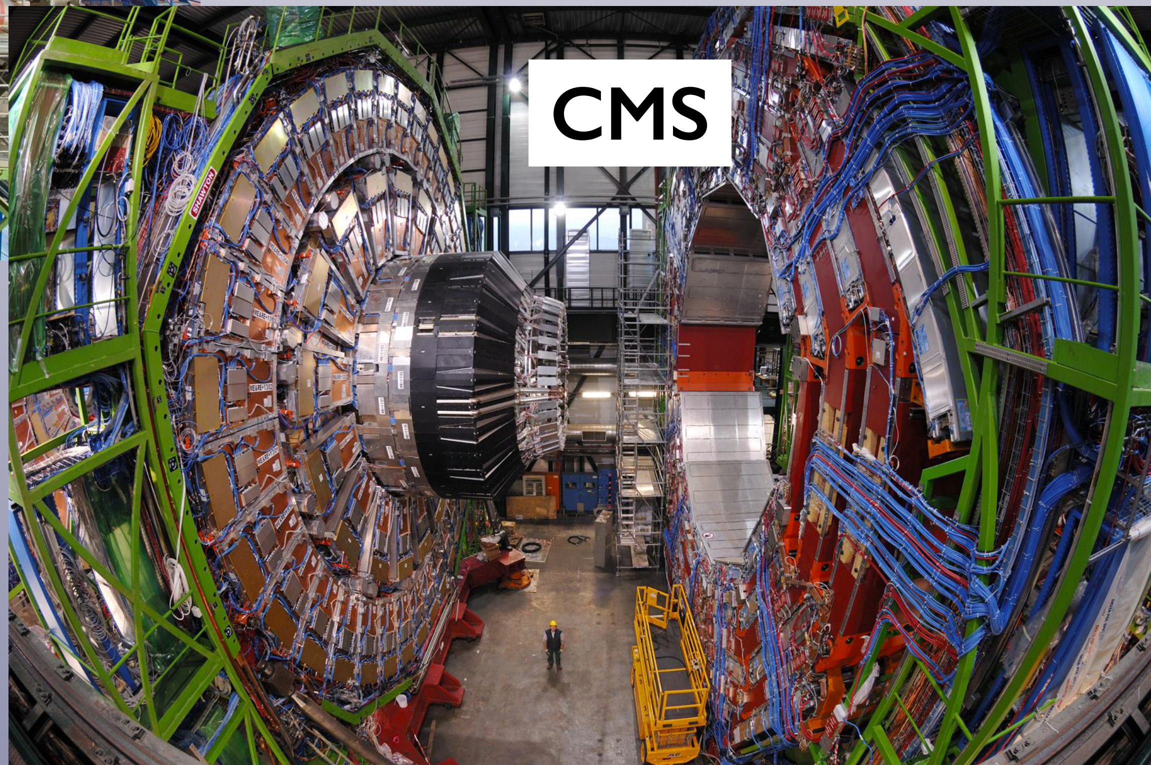
- The LHC is the **most powerful particle accelerator ever build by mankind**
- Hosted by CERN, the LHC is composed by a **massive 27 km long tunnel** with **four gigantic detectors: ATLAS, CMS, LHCb** and **ALICE**
- At the LHC protons **collide at the highest energies ever achieved**: unique probe of the **fundamental laws of Nature**

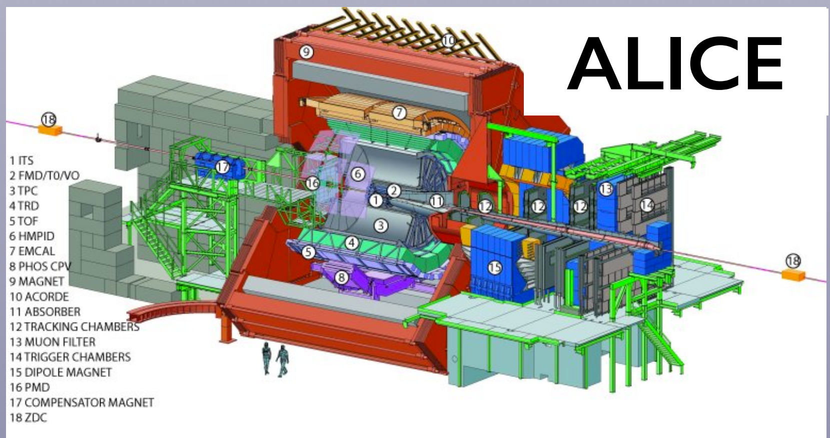
The LHC Detectors

Where proton beams cross and **collisions take place**, huge detectors measure the products of the collision in an attempt to understand **the laws of Nature at the smallest distances**









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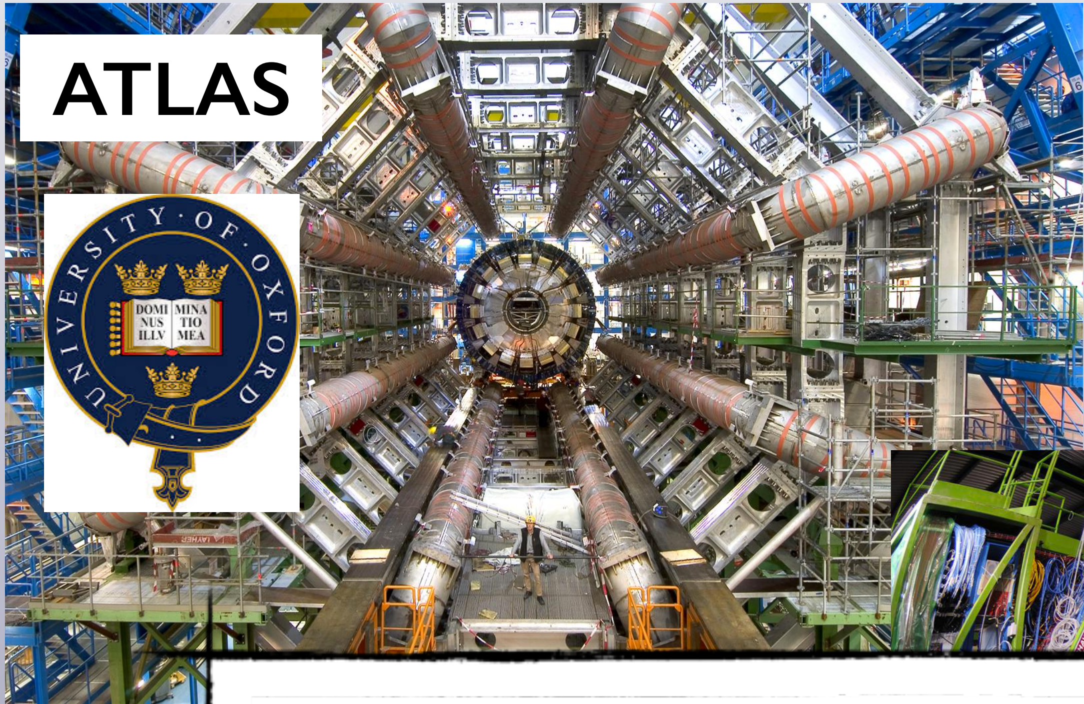
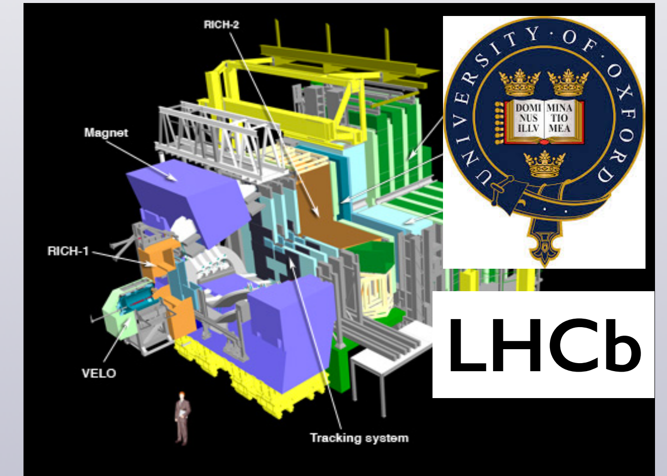
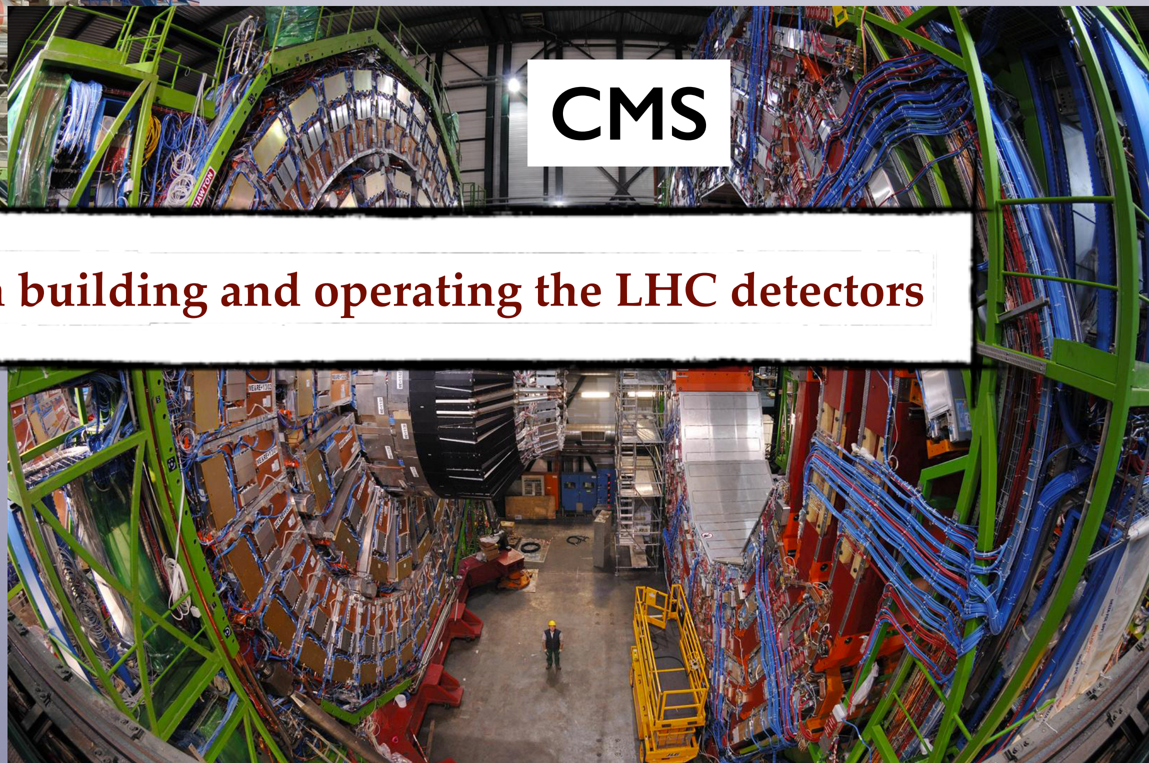
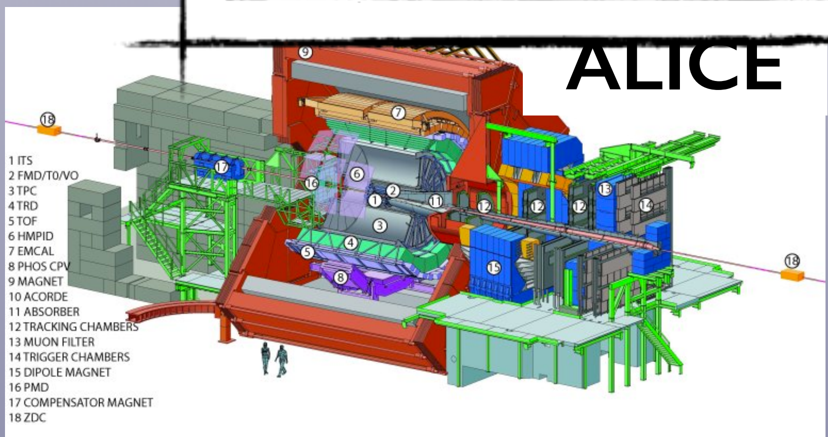


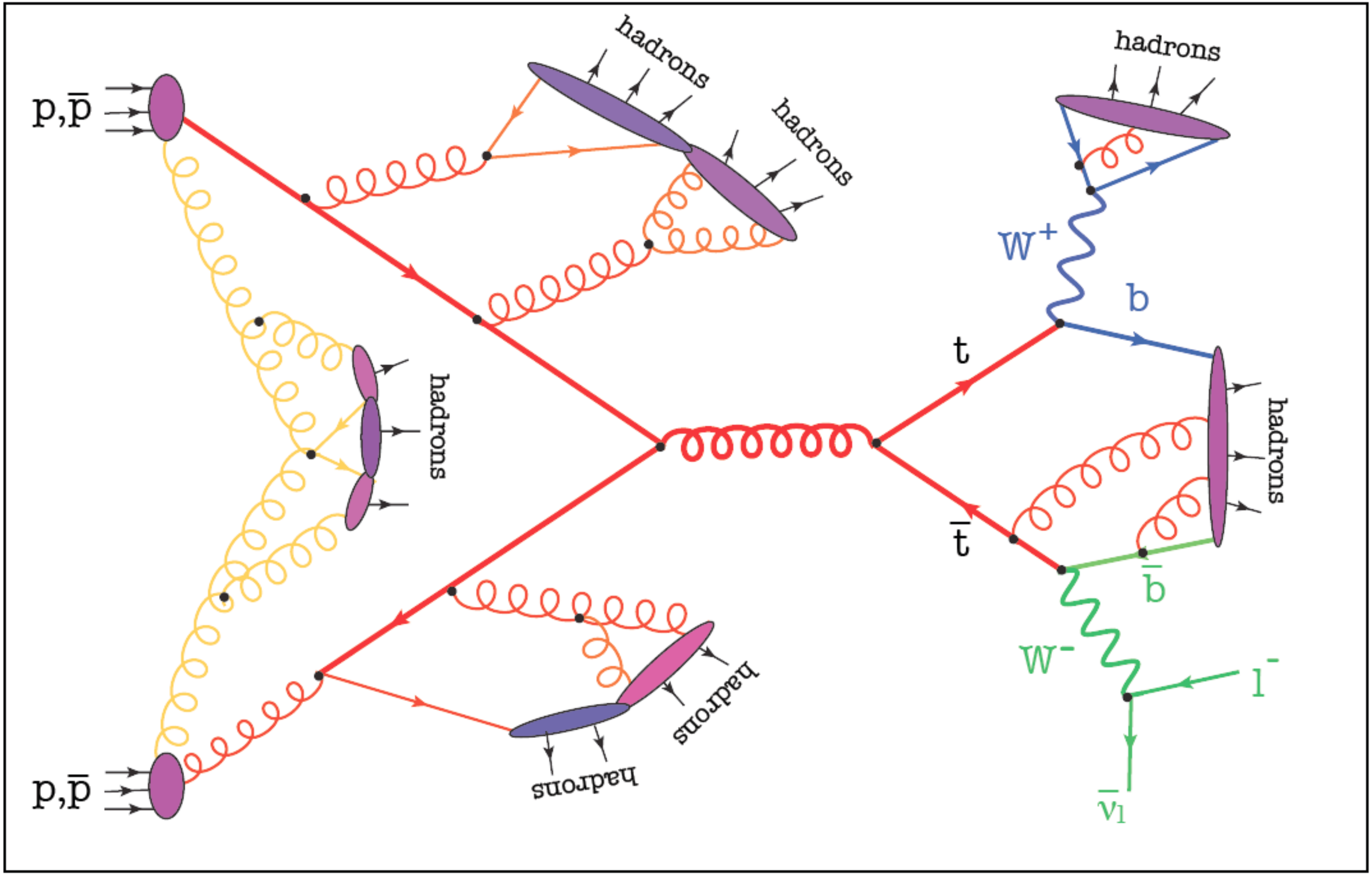




Oxford plays a central role in building and operating the LHC detectors

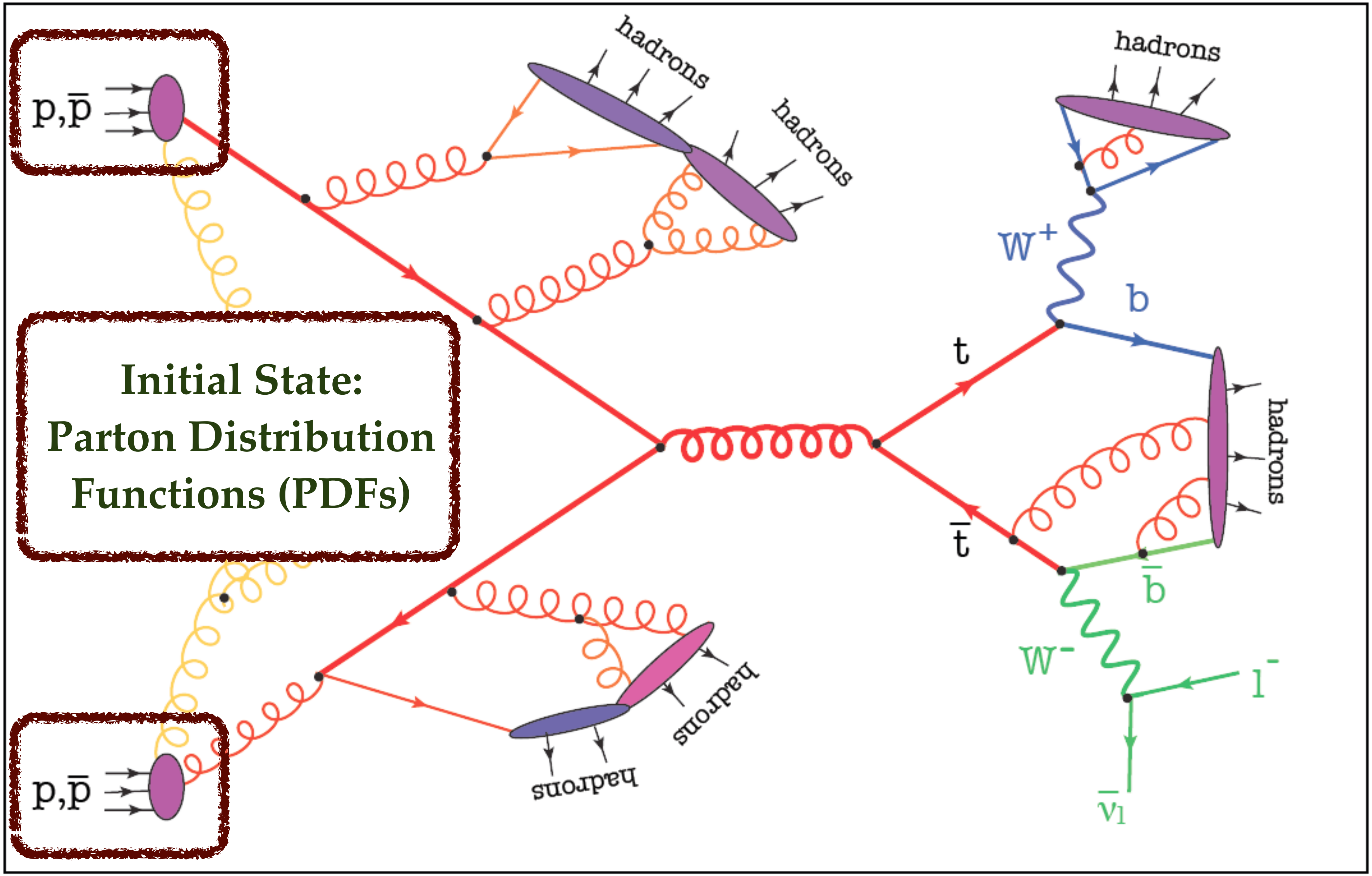


Anatomy of LHC collisions



Drawing by K. Hamilton

Anatomy of LHC collisions



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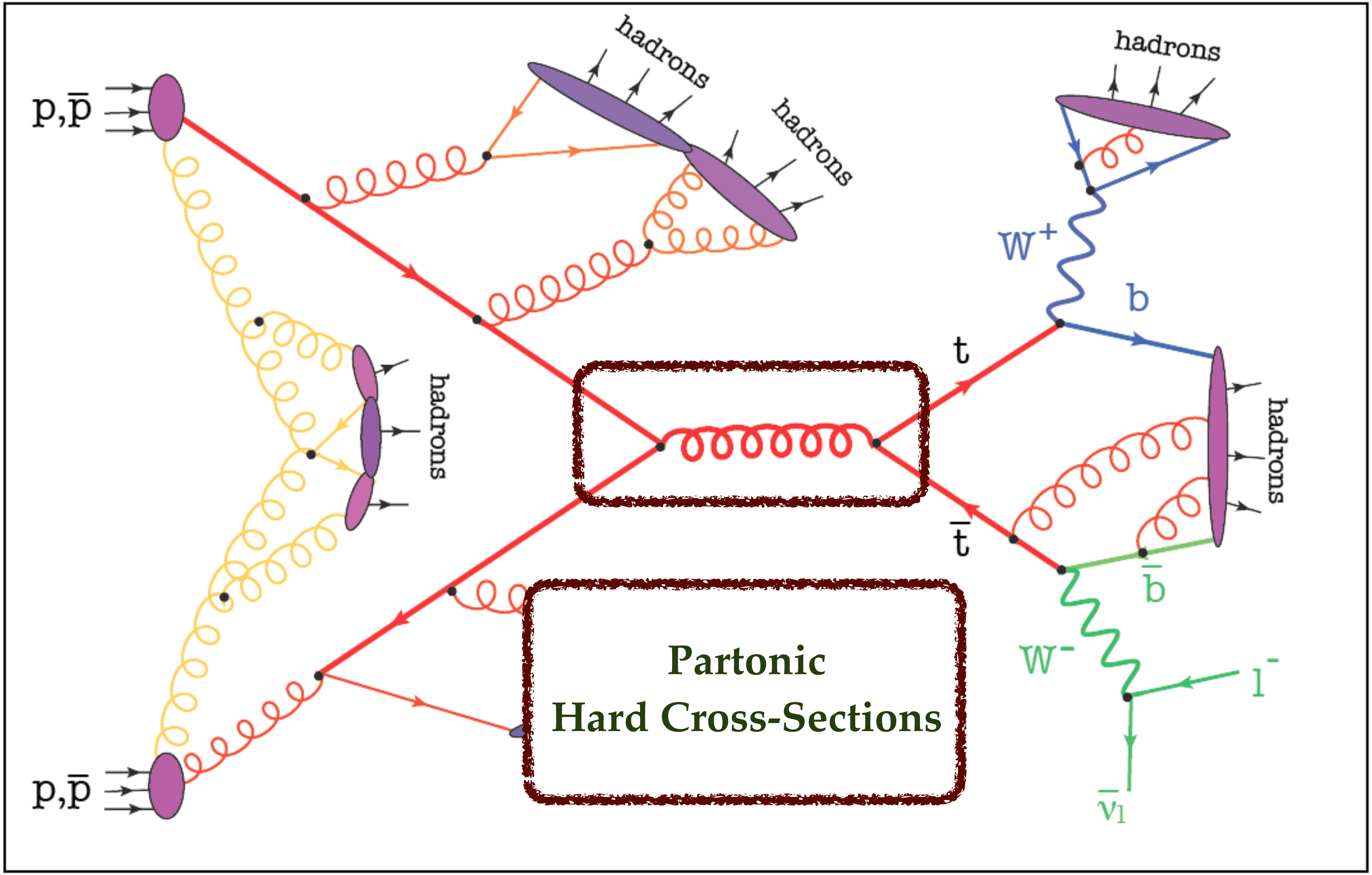

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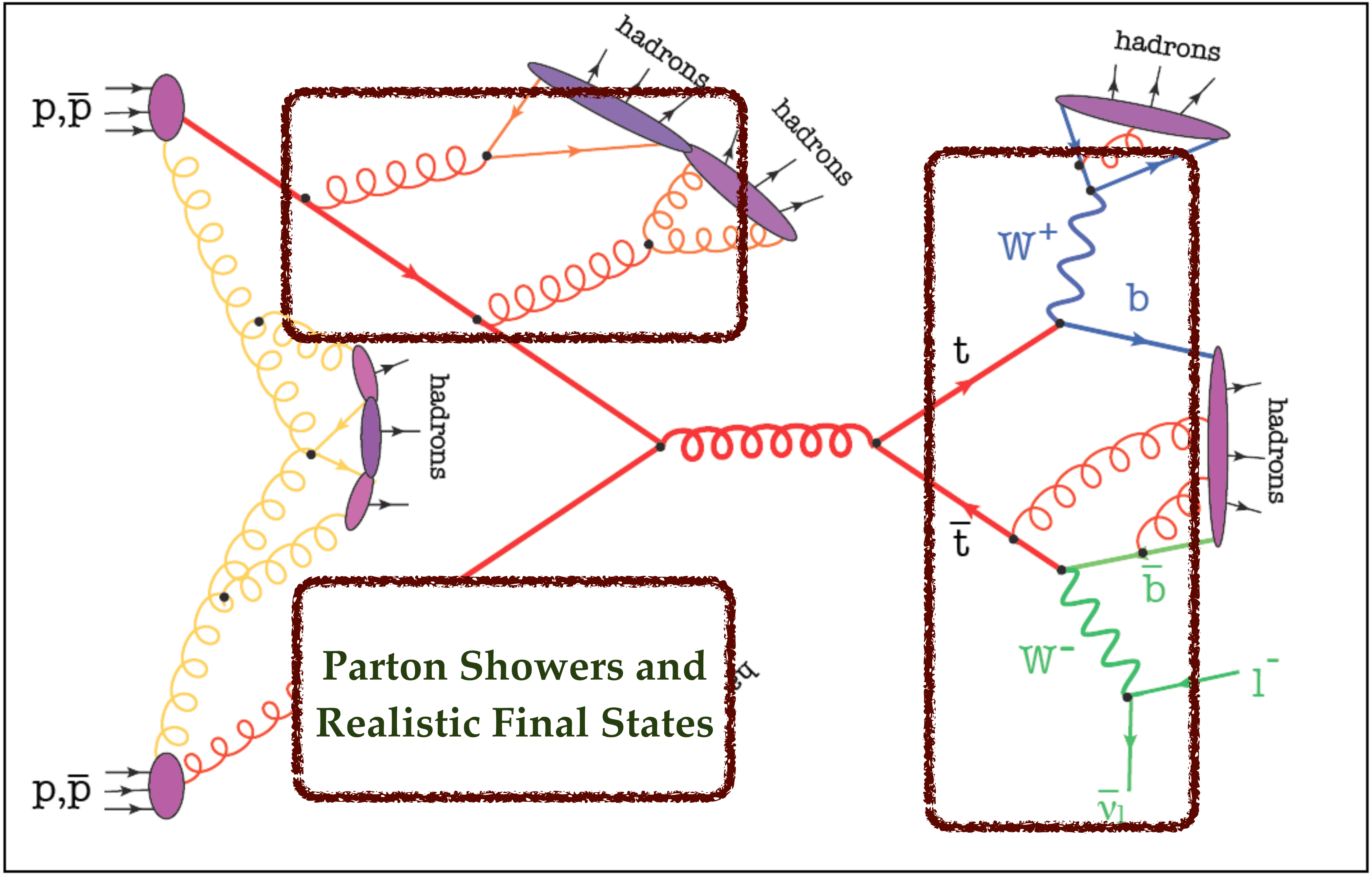

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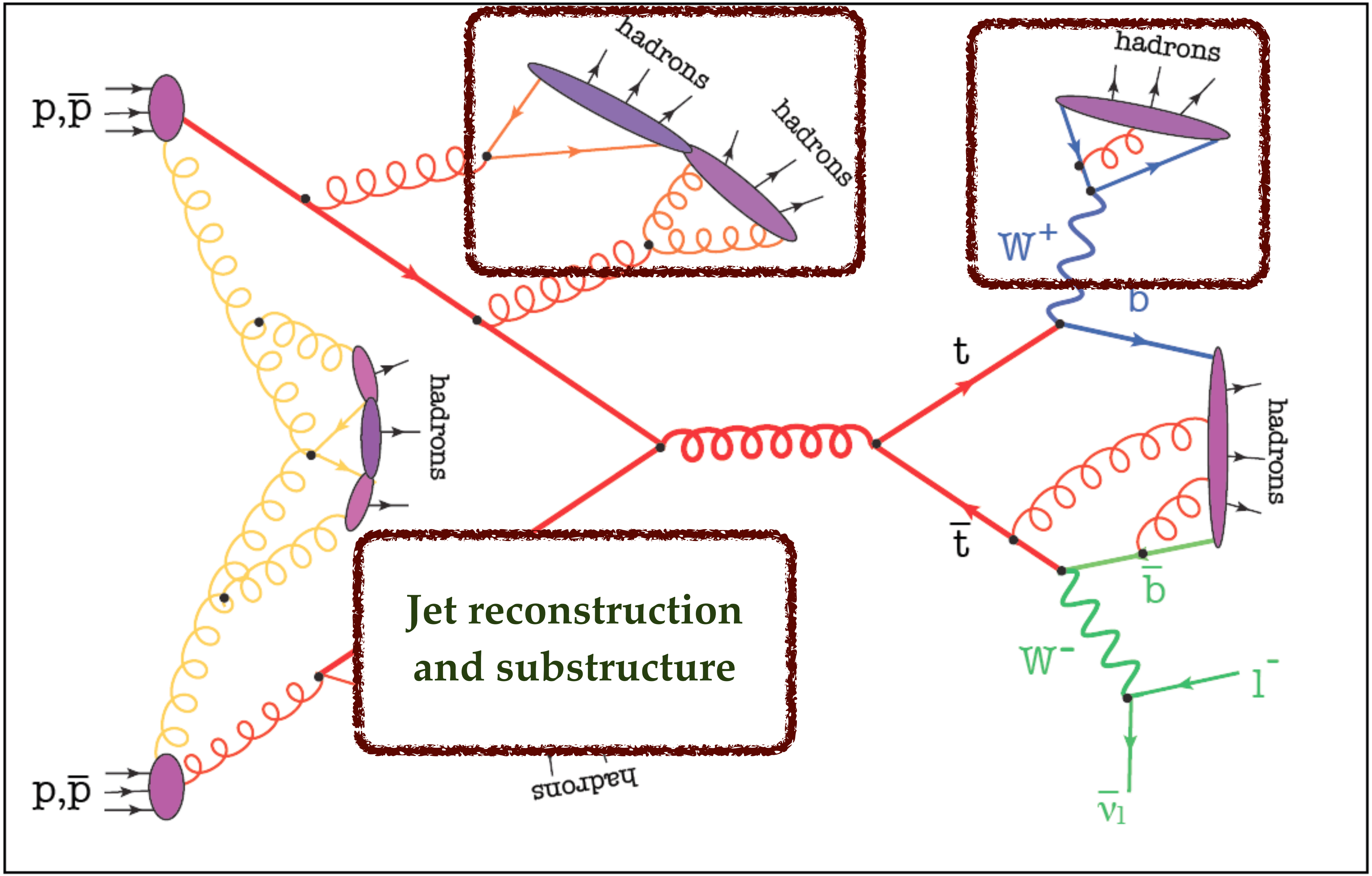

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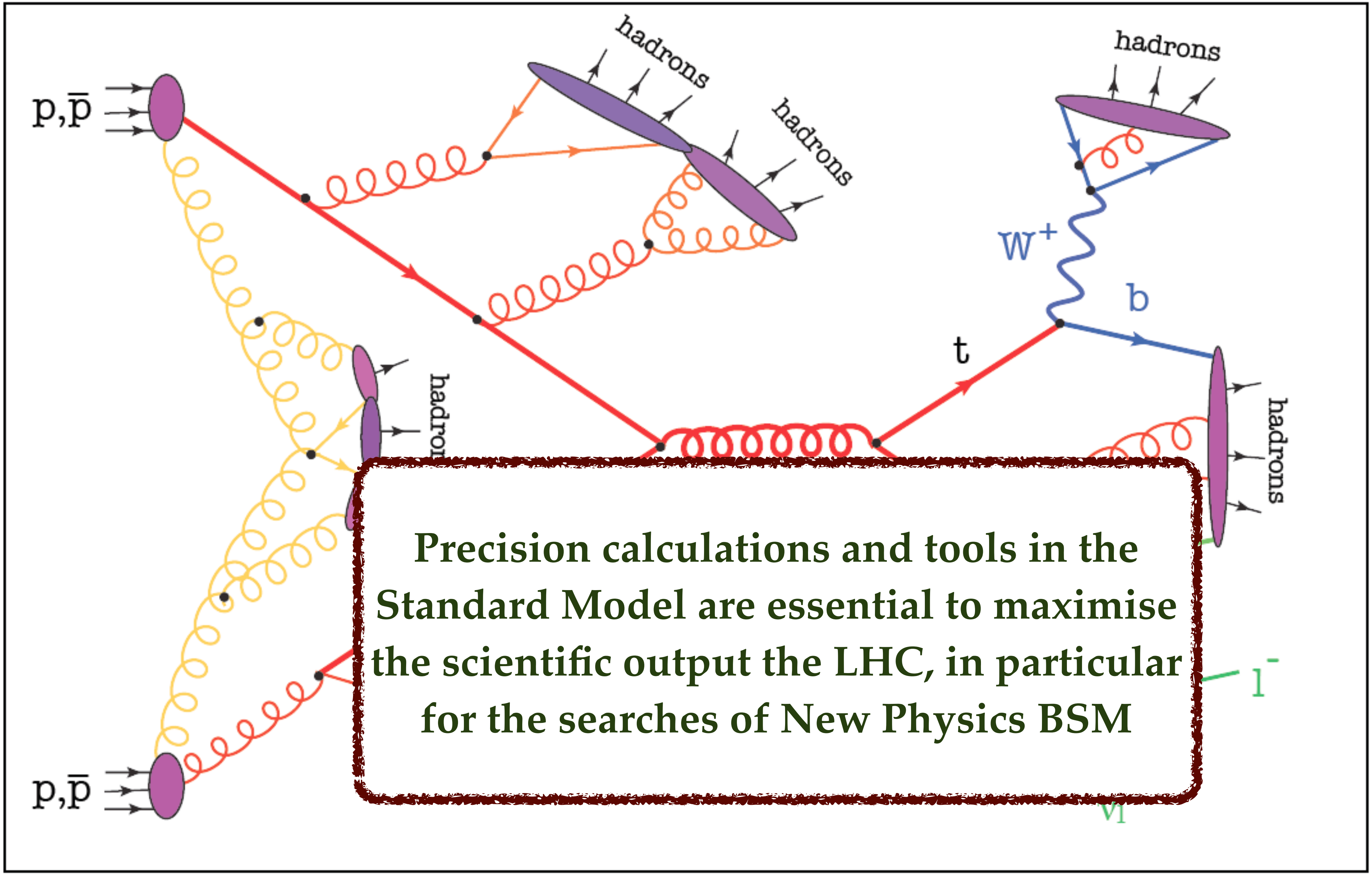
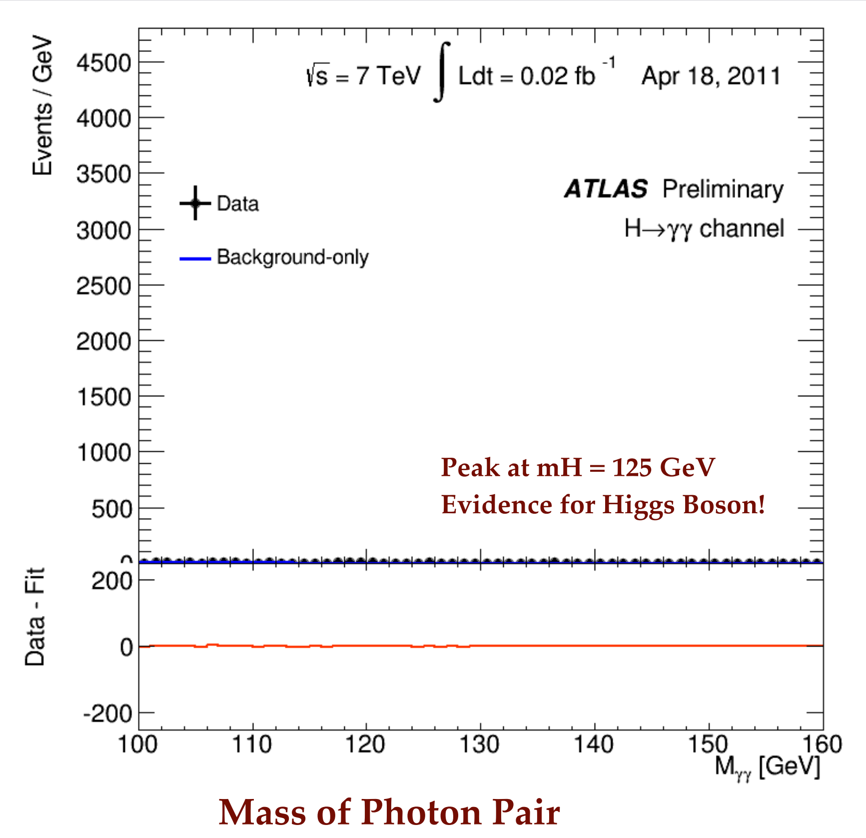


Precision calculations and tools in the Standard Model are essential to maximise the scientific output the LHC, in particular for the searches of New Physics BSM

Drawing by K. Hamilton

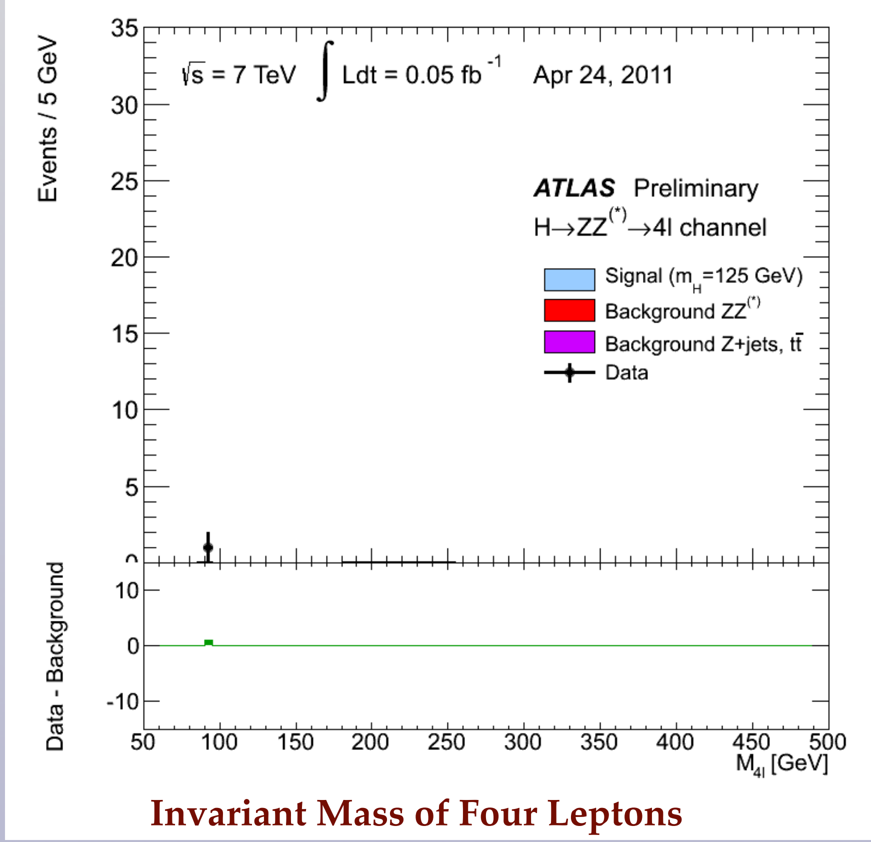
The Higgs discovered - 4th of July Fireworks

Higgs Decays into Two Photons

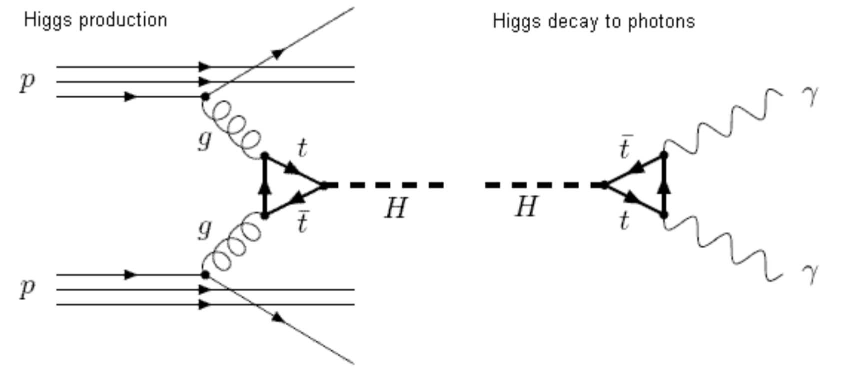


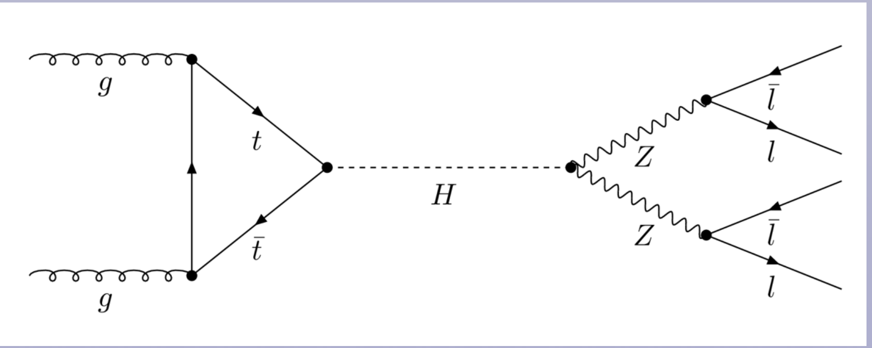
Mass of Photon Pair

Higgs Decays into Four Leptons



Invariant Mass of Four Leptons





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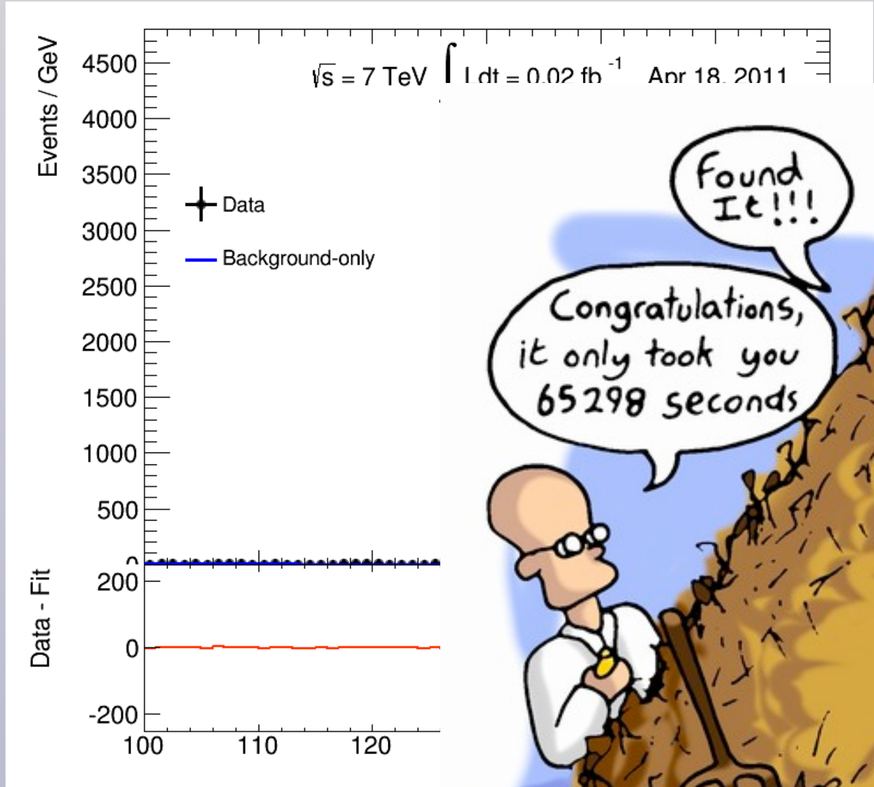
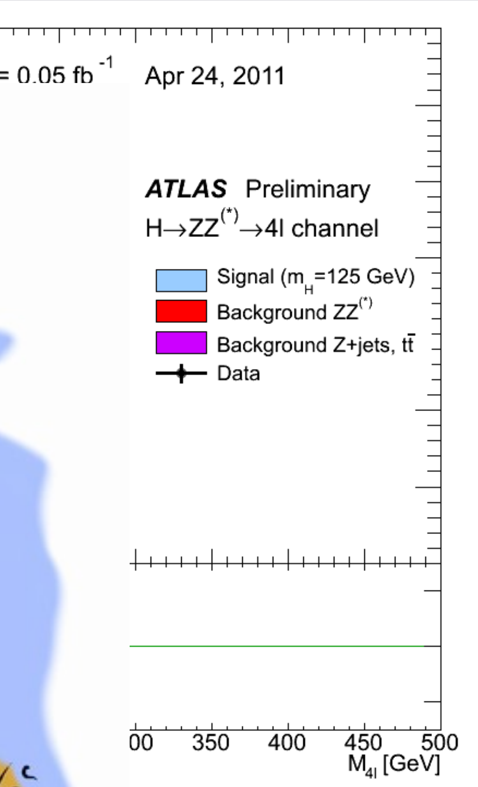
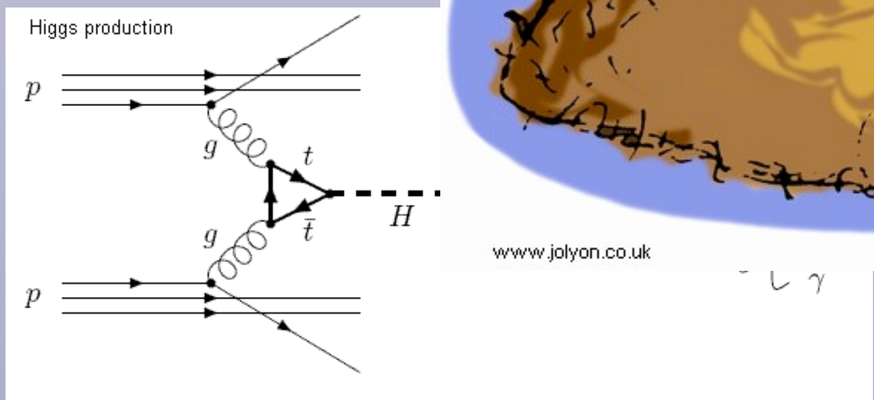


Mass of Phot

Higgs Decays into Four Leptons

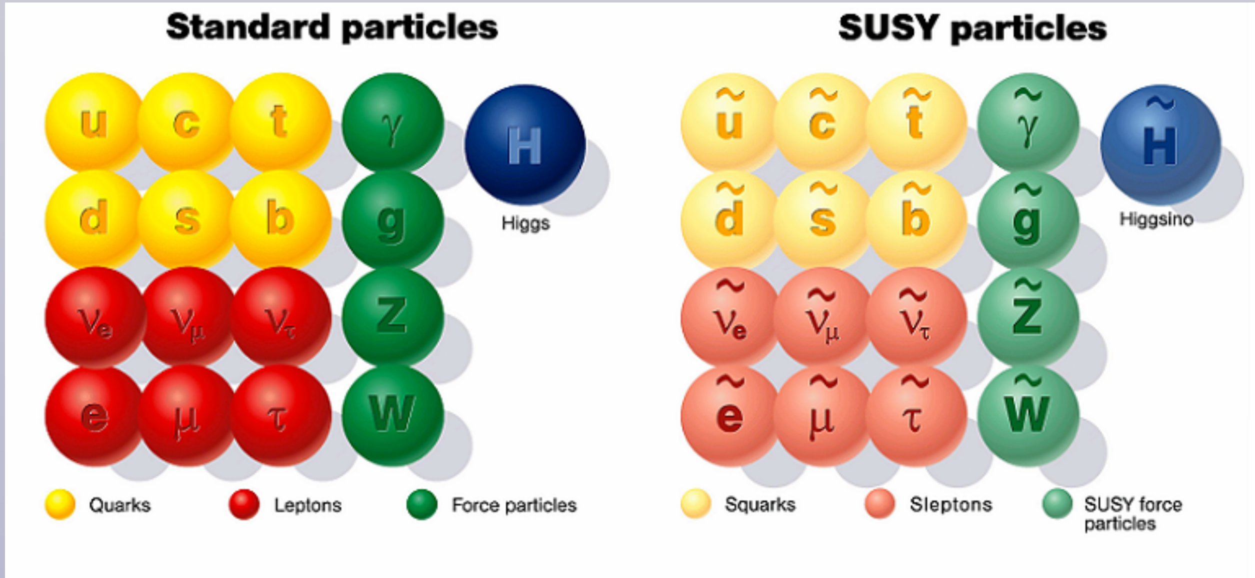


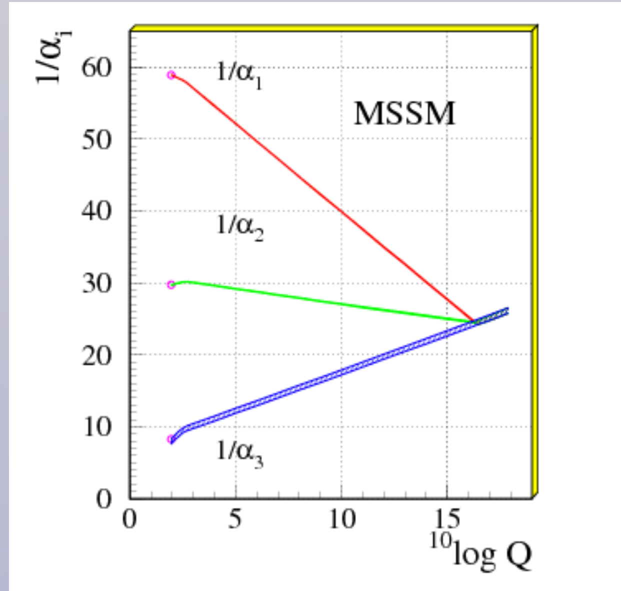
r Leptons



Beyond the SM: searching for the unknown

- **Despite the Higgs discovery, crucial questions** are left open: **stability of Higgs mass**, nature of **Dark Matter**, the possible **unification of forces**, the role of **gravity**, origin of matter-anti-matter asymmetry
- Motivation to develop theories **beyond the Standard Model (BSM)** to improve on its limitations, theories that can be **scrutinised at the LHC**
- *e.g*. **Supersymmetry:** each SM particle has a **superpartner** with spin differing by 1/2. SUSY predicts **unification of all forces** (but gravity) at very high scales





No hints of BSM physics at the LHC yet, though the **upcoming Run II with increased energy** opens a completely new region of the parameter space

New discoveries could be around the corner! But these may very well require an improved understanding of **precision calculations in the SM**, and the development of **new suitable tools for LHC phenomenology**

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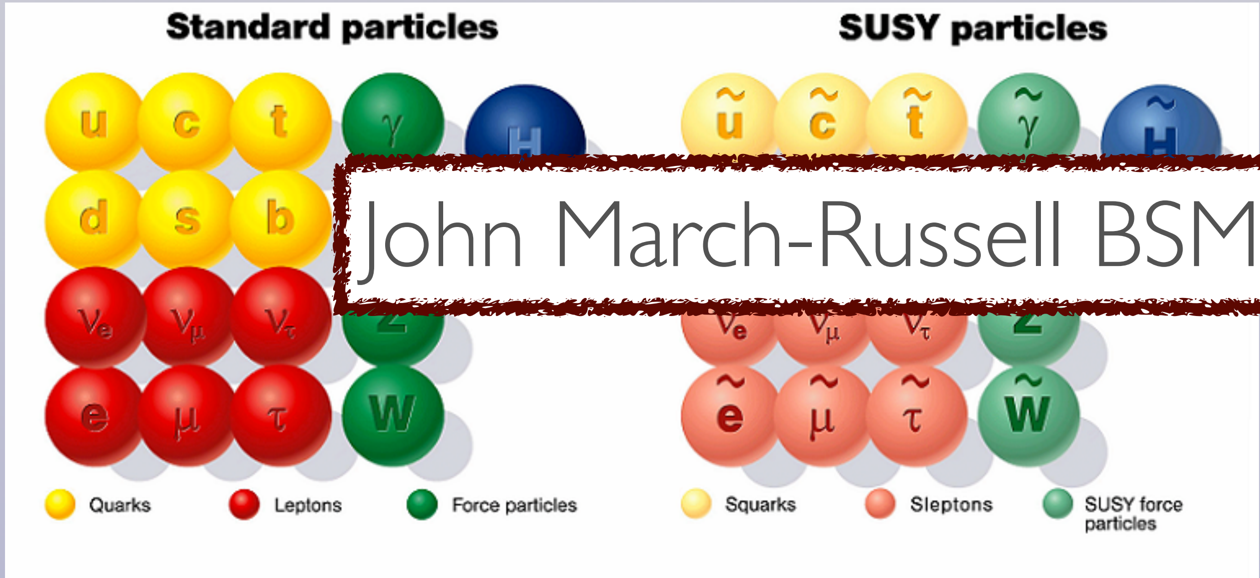
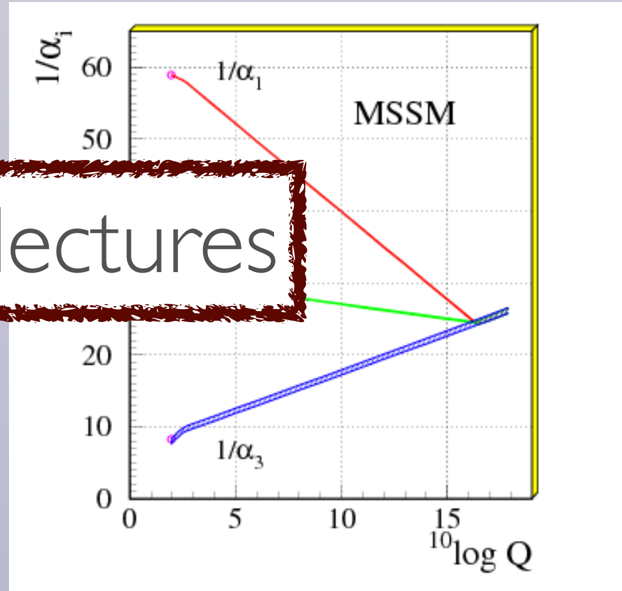
- *e.g.* **Supersymmetry:** each SM particle has a **superpartner** with spin differing by 1/2. SUSY predicts **unification of all forces** (but gravity) at very high scales





John March-Russell BSM lectures

No hints of BSM physics at the LHC yet, though the **upcoming Run II with increased energy** opens a completely new region of the parameter space

New discoveries could be around the corner! But these may very well require an improved understanding of **precision calculations in the SM**, and the development of **new suitable tools for LHC phenomenology**

Outline of the course

- This course aims of providing a first introduction of the building blocks of the Standard Model: **Quantum Chromodynamics**, **Electroweak interactions**, and the **Higgs sector**
- The emphasis will be on applications of the Standard Model to **LHC phenomenology**: high-precision tests of the SM, tools like PDFs and Monte Carlo generators, backgrounds for searches, jet substructure ….
- Familiarity with the **QED Lagrangian**, the mathematical methods of **Quantum Field Theory** and **Feynman diagram calculations** will help in following the lectures
- We have started with an **historical introduction** and then we will move into the basic formalism of Quantum Chromodynamics

- The Standard Model: an historical introduction.
- The strong interaction. Motivation for QCD. The hadron spectrum. Evidence for a new quantum degree of freedom: color. Evidence for a new gauge boson: the gluon. Scaling in deep-inelastic scattering.
- The QCD Lagrangian. Similarities and differences with QED Feynman rules. Color algebra and color flow. Symmetries of QCD.

Outline of the course

- Then we move to perturbative QCD in **electron-positron**, **electron-hadron**, **hadron-hadron** collisions
- We will introduce essential concepts such as **asymptotic freedom**, cancellation of **soft and collinear divergences**, **parton distributions** and the **factorization theorem**
- Here we will explore how QCD provides the **toolbox for every virtually LHC analysis**, from PDFs to higher-order calculations, Monte Carlo generators and jet substructure

- Asymptotic freedom. QCD in electron-positron annihilation. Renormalization group equations. The running of the strong coupling constant. Sterman-Weinberg jets and radiative corrections. Soft and collinear singularities in NLO matrix elements. Infrared and collinear safe observables.
- Perturbative QCD in processes with hadrons in the initial state. QCD factorization and the parton model. Parton Distribution Functions. The parton model and radiative corrections. Factorization of initial state divergences and DGLAP evolution of parton distributions.
- State-of-the-art perturbative QCD at the LHC. Collider kinematics. Jet production at hadron colliders. Drell-Yan production and impact on PDFs. Theoretical uncertainties in perturbative QCD. Searches for New Physics at the LHC.
- Parton fragmentation in perturbative QCD. Parton evolution as a semi-classical branching process. Monte Carlo event generators and realistic simulation of hadronic final states. Jet reconstruction in hadronic collisions. Jet algorithms and jet substructure methods.

Outline of the course

- Then in the second part of the lectures we present the **electroweak sector, electroweak symmetry breaking and the Higgs mechanism**

- We also study the **phenomenology of Higgs production and decay at the LHC**

- Electroweak interactions. Historical introduction. Weak decays, Fermi theory, violations of unitarity. Symmetries of the weak interaction. Neutral and charged currents. Experimental evidence for the W and Z bosons.

- $SU(2) \times U_Y(1)$ gauge symmetry and spontaneous symmetry breaking. Mass generation for gauge bosons. The Higgs mechanism. Custodial symmetry and Yukawa masses. Anomaly cancellation. Feynman rules in electroweak theory.

- Higgs phenomenology at hadron colliders. Production channels and decay modes. Comparison with LHC measurements. Unitarization of vector-boson scattering. Higgs pair production. Prospects for Higgs physics at the LHC.

References

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[4] C. P. Burgess and G. D. Moore, "The standard model: A primer," Cambridge, UK: Cambridge Univ. Press (2007).

[5] R. K. Ellis, W. J. Stirling and B. R. Webber, "QCD and collider physics," Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. **8**, 1 (1996).

[6] G. Dissertori, I. G. Knowles and M. Schmelling, "Quantum Chromodynamics: High energy experiments and theory," International series of monographs on physics, 115, Oxford Science Publications.

[7] J. Rojo, "The Strong Interactions and LHC phenomenology", lecture notes available online at `http://juanrojo.com/teaching`

[8] G. Zanderighi, "QCD and collider physics", lecture notes available online at `http://www2.physics.ox.ac.uk/sites/default/files/QCDLectures.pdf`

[9] P. Nason, "Introduction to QCD", lecture notes available online at `http://moby.mib.infn.it/~nason/misc/QCD-intro.ps.gz`

- All the material of the course (including lecture notes) will be available from

http://juanrojo.com/teaching