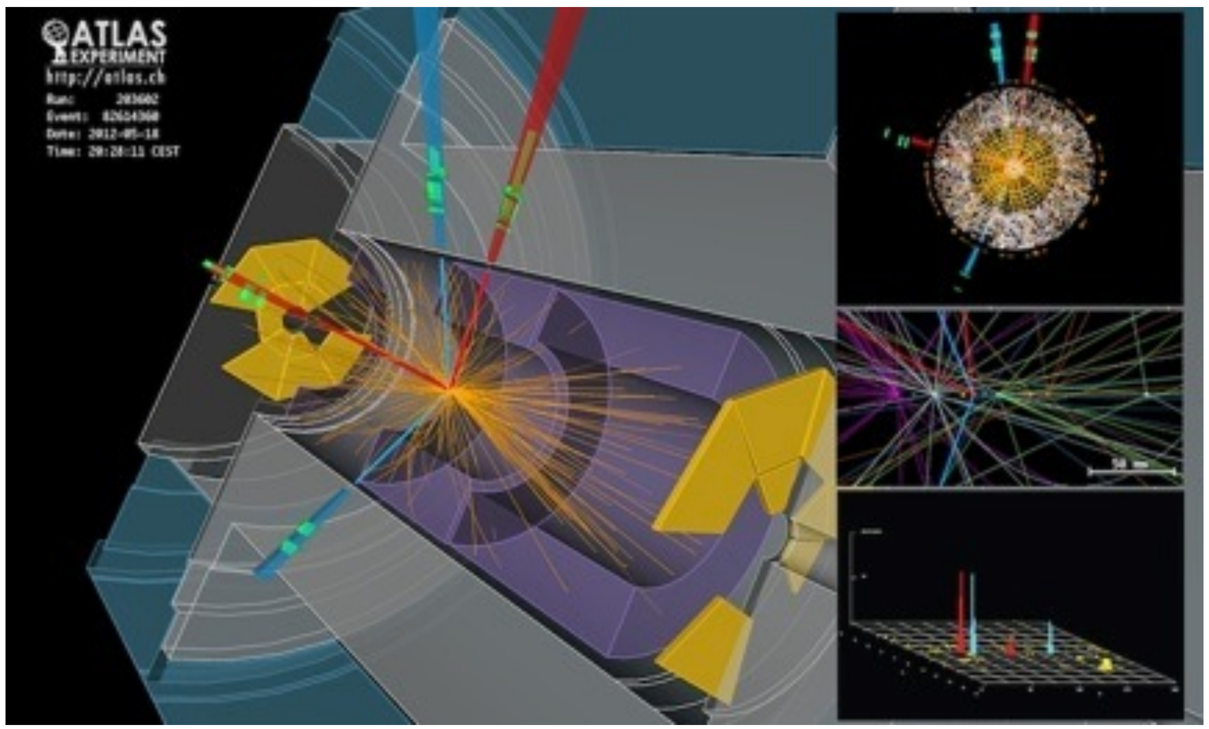
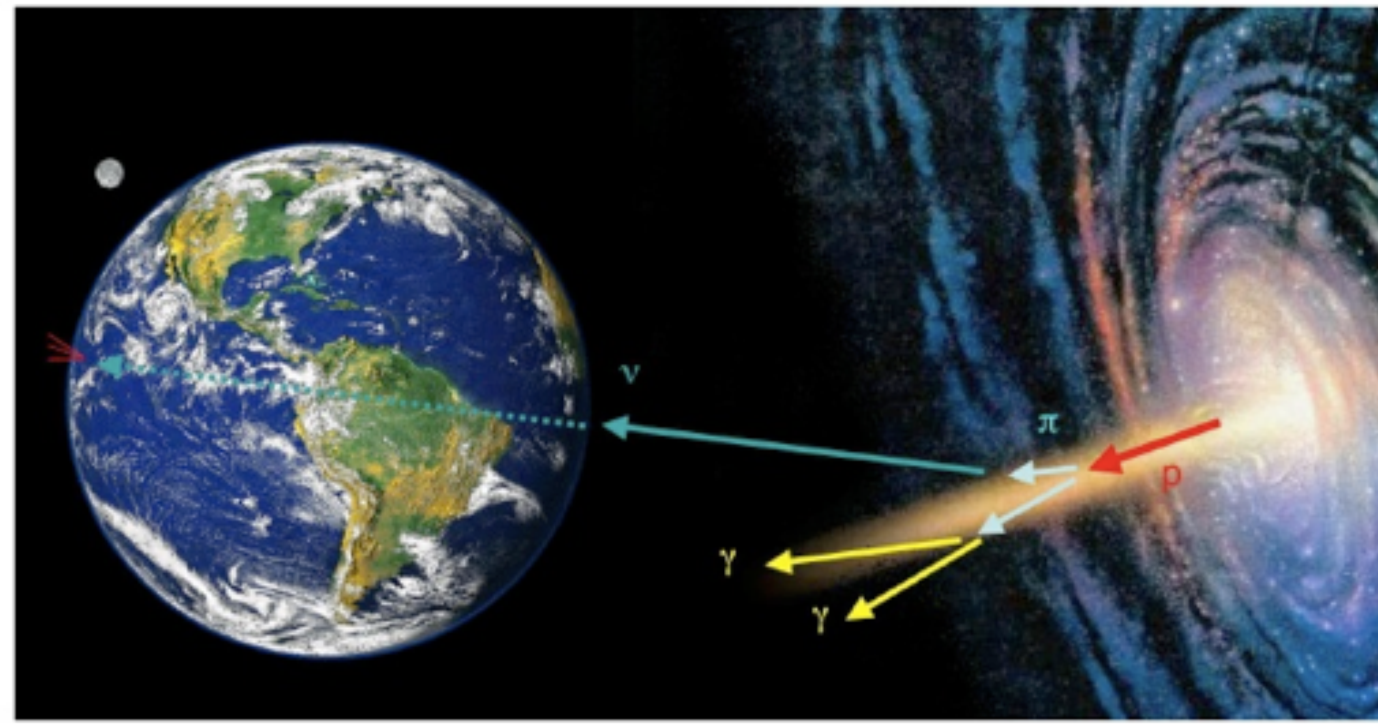
Particle Physics at Colliders and in the High Energy Universe





1. Introduction & Particle Physics Refresher

14.10.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon
Dr. Bela Majorovits

Overview

- Goal of the Course
- Organisation

- Overall Motivation & Open Questions

- Particle Physics Refresher: Key Concepts, Experimental Techniques

Goal of the Course

- Introduction to modern particle physics at the interface of accelerator-based experiments and astro-particle physics:
    - Current topics in particle physics at the highest energy with a thorough discussion of the experimental methods, including: The Standard Model, the Higgs Boson, Physics beyond the Standard Model and a general introduction to high-energy proton-proton collisions
    - An introduction to cosmology
    - High-energy processes in the early Universe from thermal freeze-out to the cosmic microwave background
    - Design and technology of the Large Hadron Collider and the corresponding experiments
    - Particle acceleration in the Universe

In general:
Focus on latest results, general overview over the fields of High Energy Physics (HEP) and Astroparticle Physics from an experimental perspective

- Continued in the Summer: Precision measurements at lower energies, rare processes: Electroweak & Flavor Physics, Neutrinos, Dark Matter

Organisation

- Time and place:
  - Mondays, 15:00 - 16:30
  - Physik II, Seminarraum PH 227
- Prerequisites:
  - Introductory lecture to Particle, Nuclear & Astrophysics
- Exercise Classes: A “Journal Club” - see next slide
- Exams: Oral, on request
- Slides (FS) / Lecture Notes (BM): Available on-line at the moment accessible via our indico system - link from main webpage will come soon: https://indico.mpp.mpg.de/category/137/

Organisation - Journal Club

- Time and place:
  - Mondays, starting at 16:30 directly after lecture (probably with a short break…)
  - Physik II, Seminarraum PH 227

- The concept:
  - During a lecture, you will be given a related scientific publication, together with a few questions. Read the paper, and try to answer the questions as preparation for the Journal Club in the following week
  - In the Journal Club, we will discuss the topic of the paper, taking the questions as starting points
  - *Question to you:* Do you prefer printed copies of the paper, or a pdf available for download?

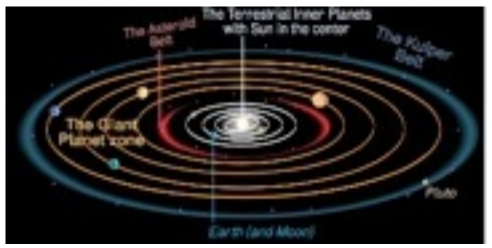
Plan to honor regular, active participation in the Journal Club by a "grade bonus" for the module exam

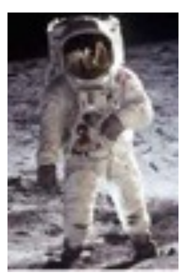
Lecture Overview - Preliminary Time Plan

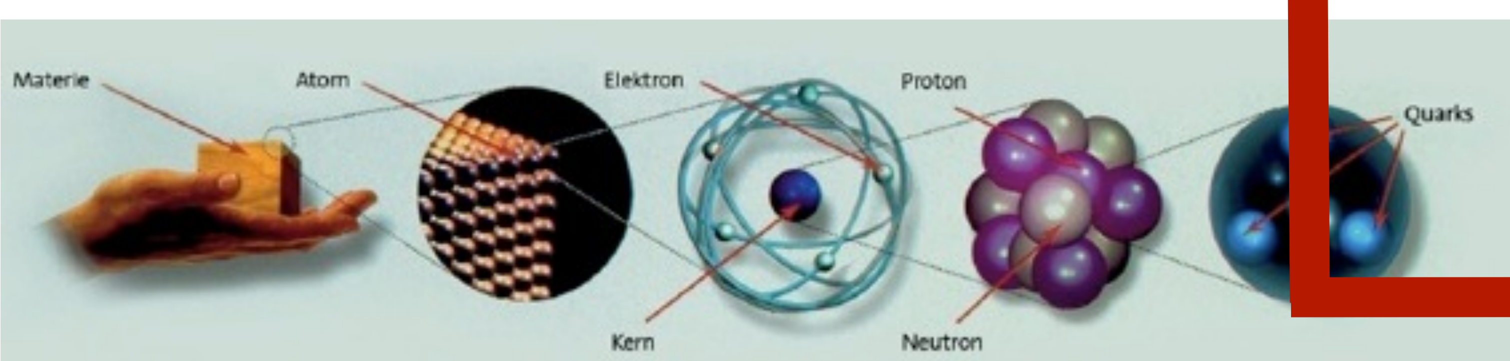
14.10.	Introduction, Particle Physics Refresher	*F. Simon*
21.10.	Introduction to Cosmology I	*B. Majorovits*
28.10.	Introduction to Cosmology II	*B. Majorovits*
04.11.	Particle Collisions at High Energy	*F. Simon*
11.11.	The Higgs Boson	*F. Simon*
18.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
25.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
02.12.	Particle Colliders	*F. Simon*
09.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
16.12.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
	Christmas Break	
13.01.	Detectors for Particle Colliders	*F. Simon*
20.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
27.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
03.02.	Physics beyond the Standard Model in the Early Universe	*B. Majorovits*

Overview, Open Questions

Connecting the Smallest and Largest Structures





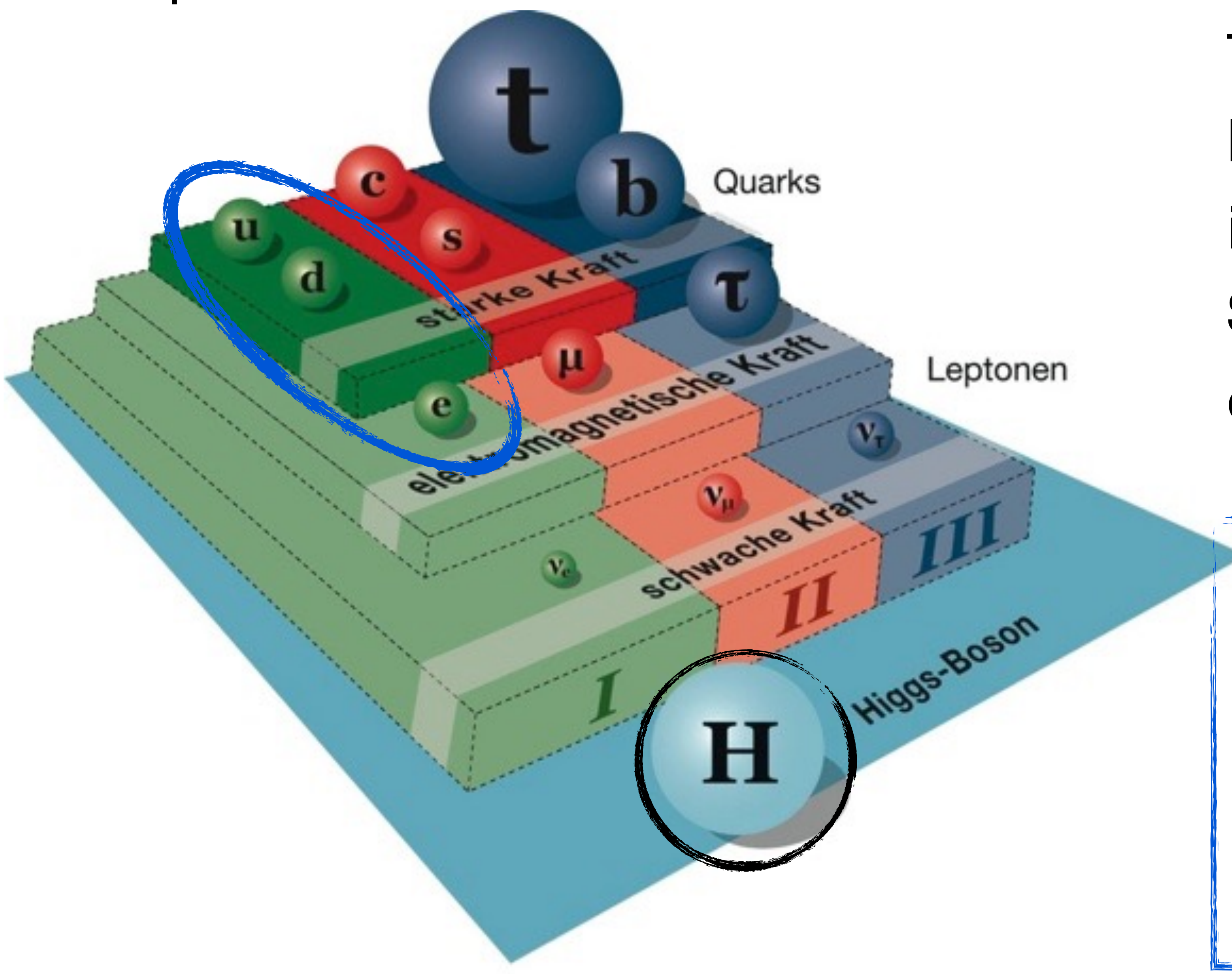


	Size	Mass
Universe	10^{26} m	10^{52} kg
Galaxy	10^{21} m	10^{41} kg
Solar System	10^{13} m	10^{30} kg
Earth	10^{7} m	10^{24} kg
Man	10^{0} m	10^{2} kg
Atom	10^{-10} m	10^{-26} kg
Nucleus	10^{-14} m	10^{-26} kg
Nucleon	10^{-15} m	10^{-27} kg
Quarks, Leptons	$<10^{-18}$ m	10^{-30} kg

“Astroteilchenphysik in Deutschland”, http://www.astroteilchenphysik.de/, und darin angegebene Referenzen

Particle Physics: The Standard Model

- detailed knowledge about the structure of matter based on decades of experimental and theoretical work



The fundamental building blocks of matter and their interactions form the **Standard Model** of particle physics

The stuff we are made of:

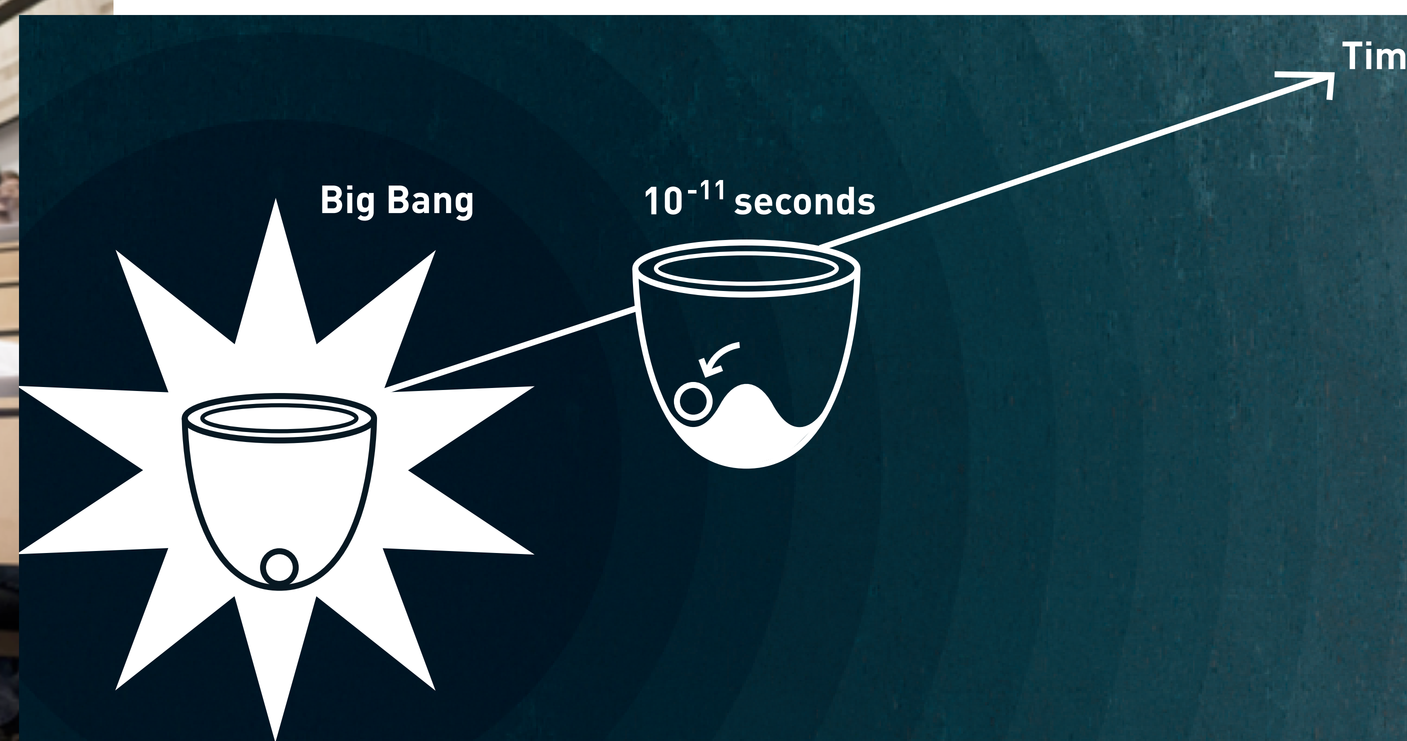
- Protons and Neutrons consist (mainly) of *u* and *d* Quarks
- Atoms have an “electron cloud”

Discovered 2012: Generation of mass via the Higgs field

Generation of Mass - Nobel Prize 2013

The Nobel Prize in Physics 2013 - François Englert, Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



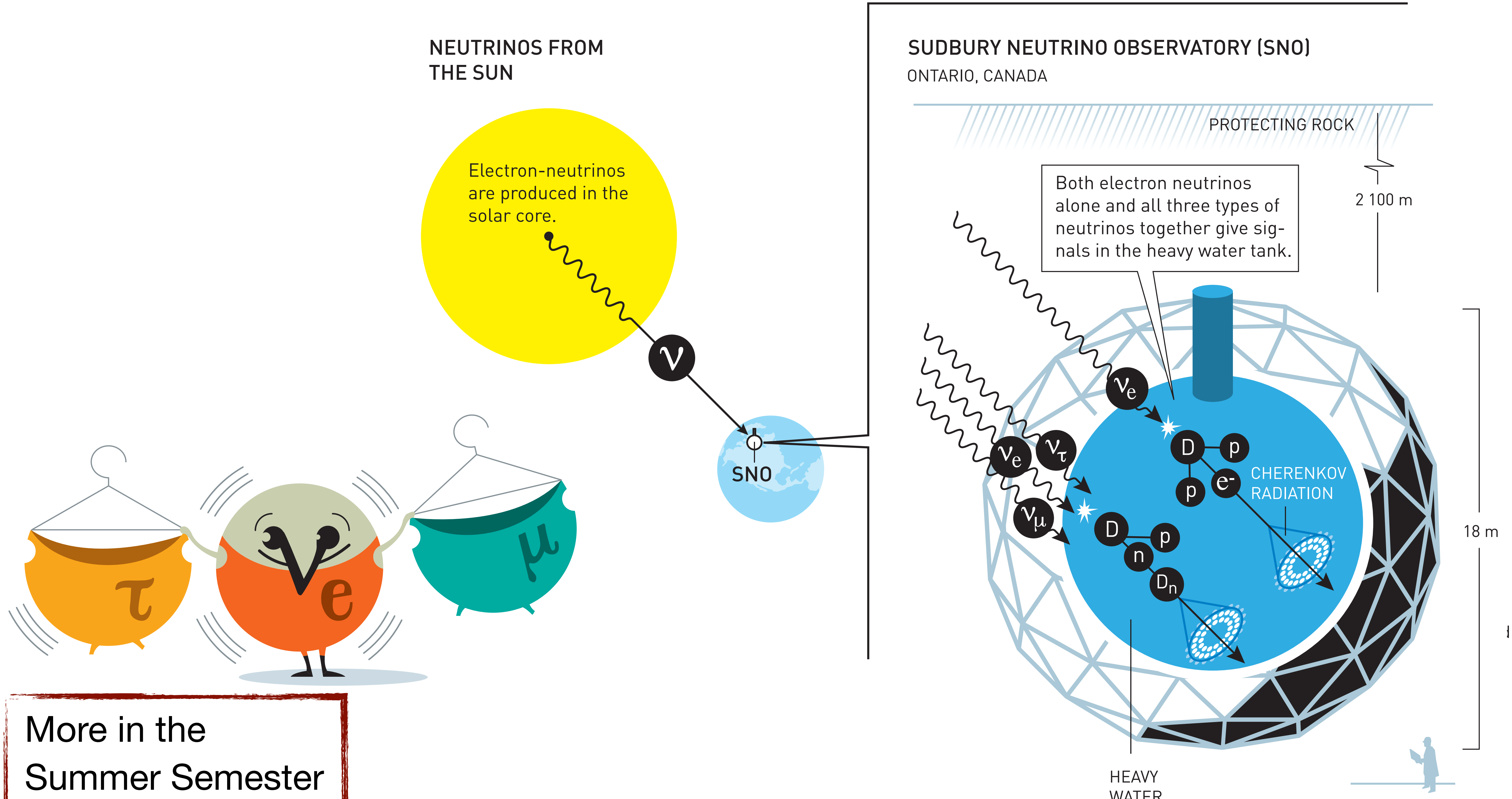
CERN, July 4, 2012

More next month

Neutrino Masses - Nobel Prize 2015

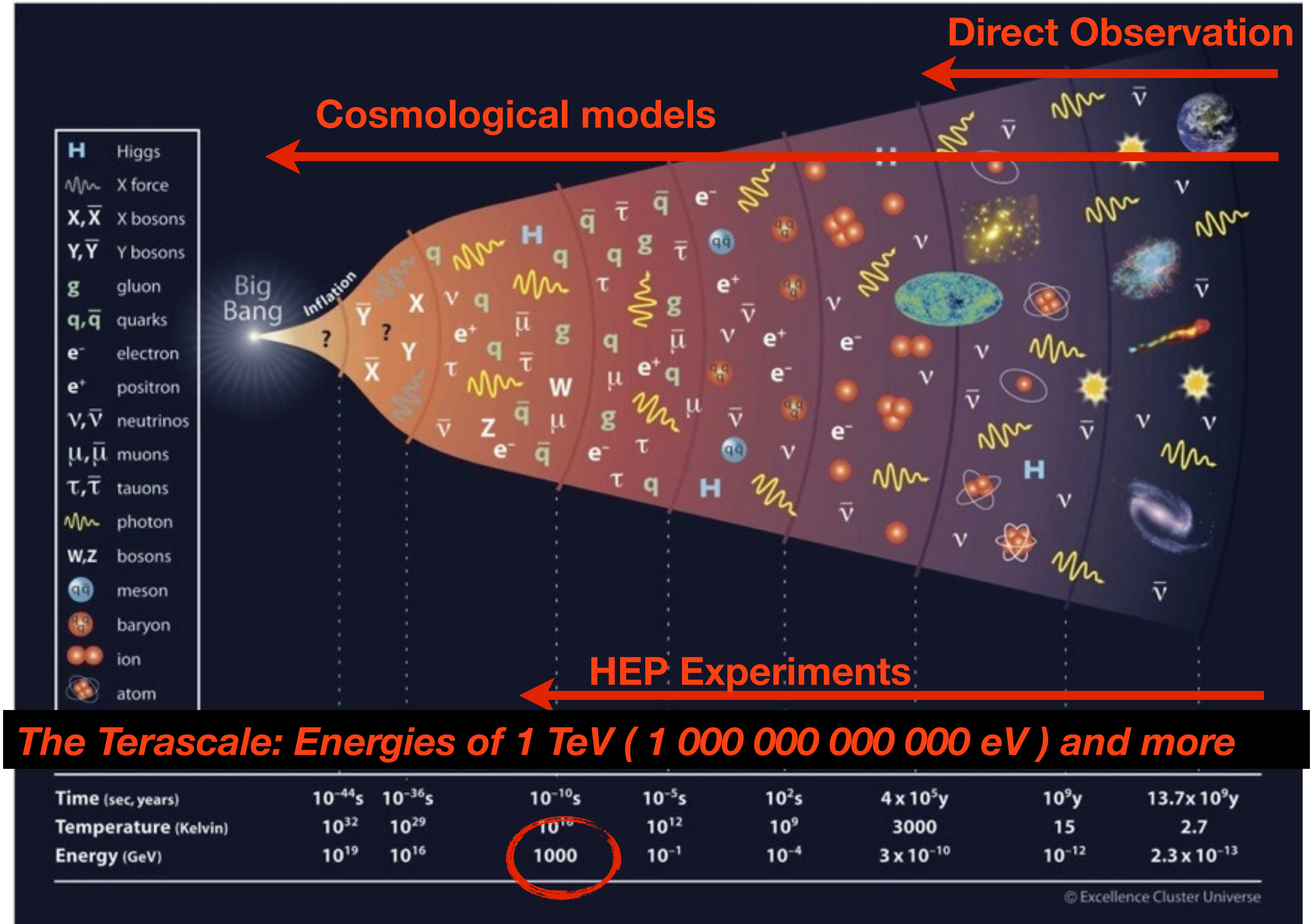
The Nobel Prize in Physics 2015 - Takaaki Kajita, Arthur McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



More in the Summer Semester

Understanding the Universe

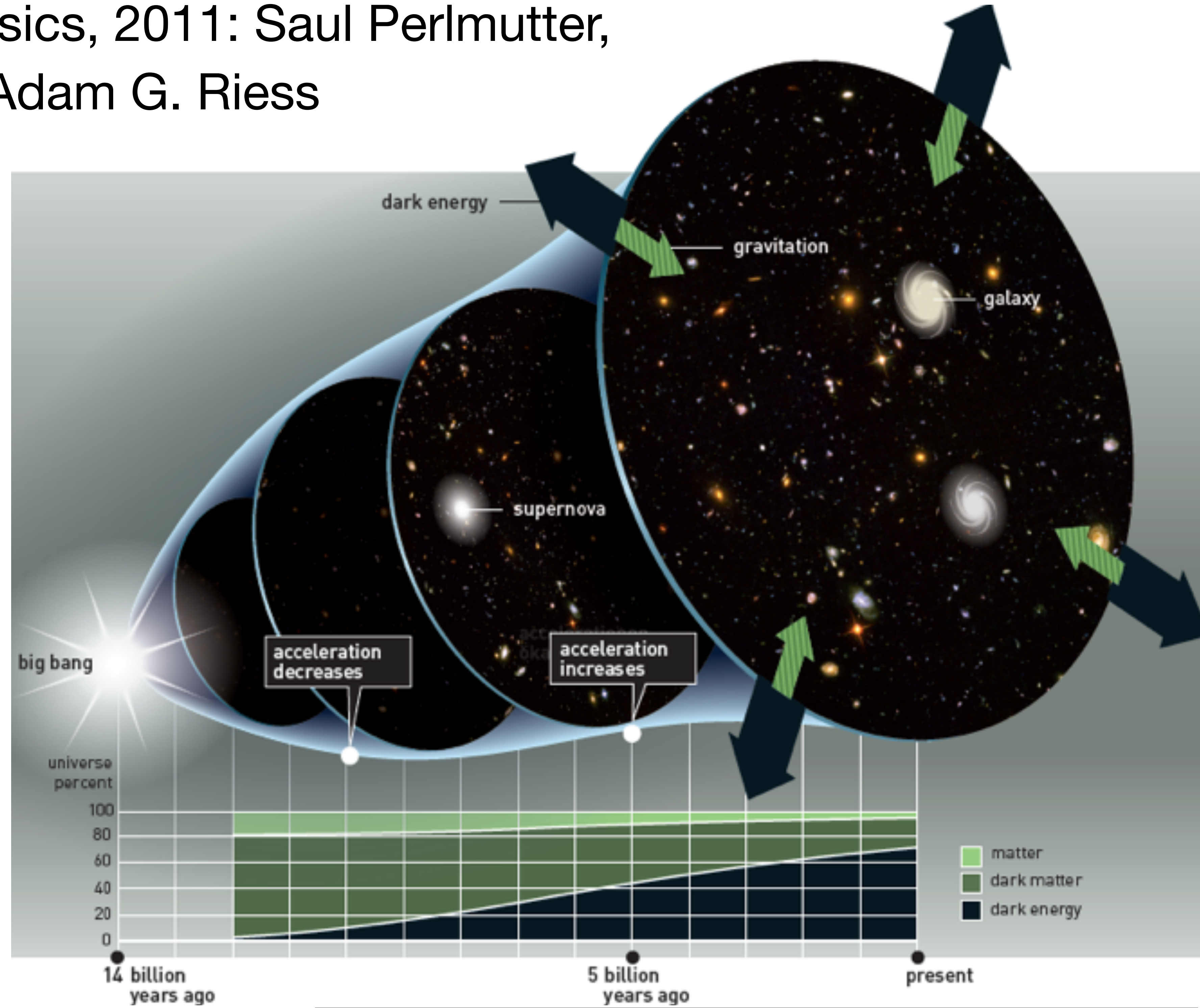


Accelerated Expansion of the Universe: Dark Energy

Nobel Prize in Physics, 2011: Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

- Discovery of the accelerated expansion of the Universe, discovery of Dark Energy:

  Observation of special distant supernova-explosions

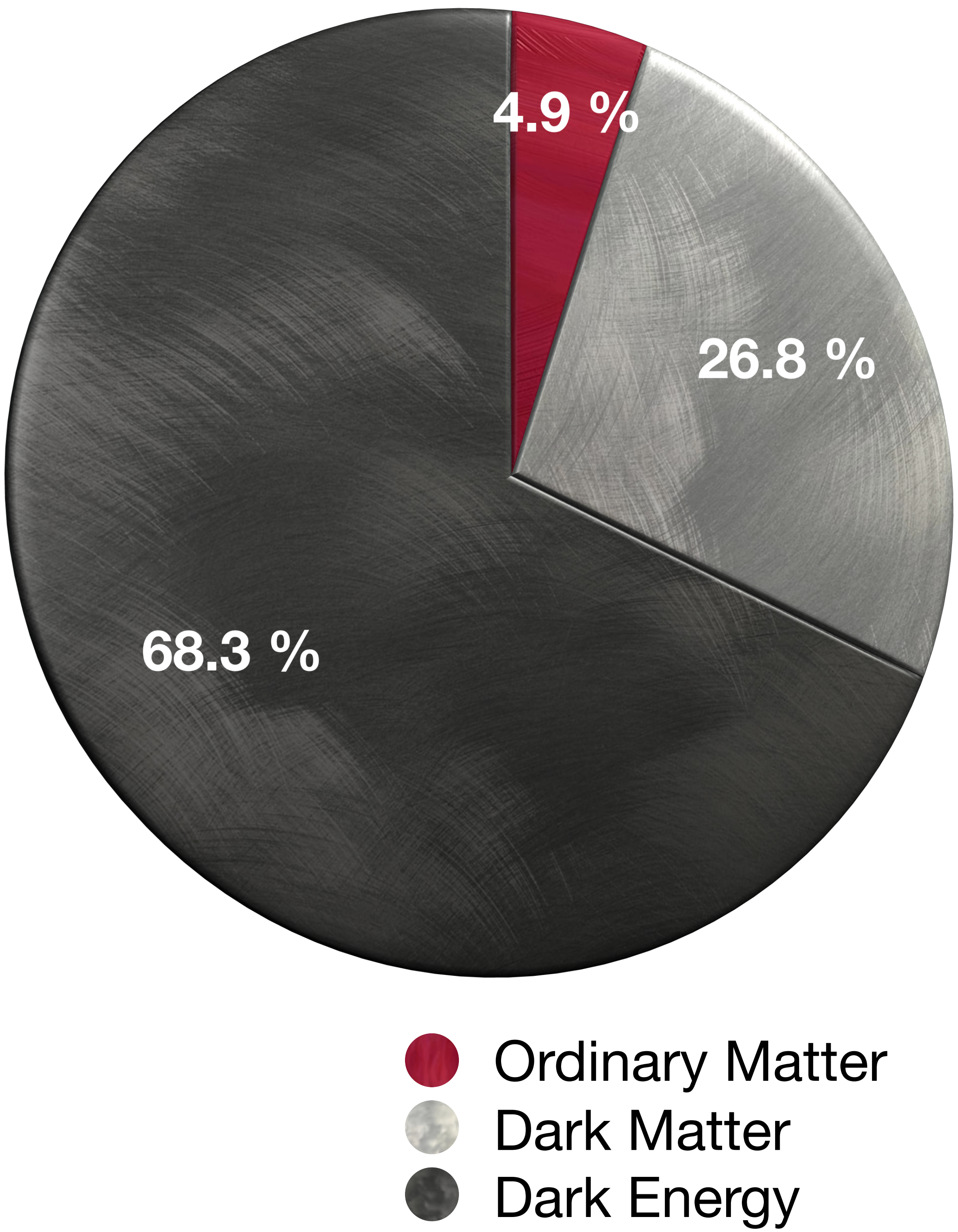


"The Nobel Prize in Physics 2011 - Popular Information". Nobelprize.org. 12 Oct 2011

More next week

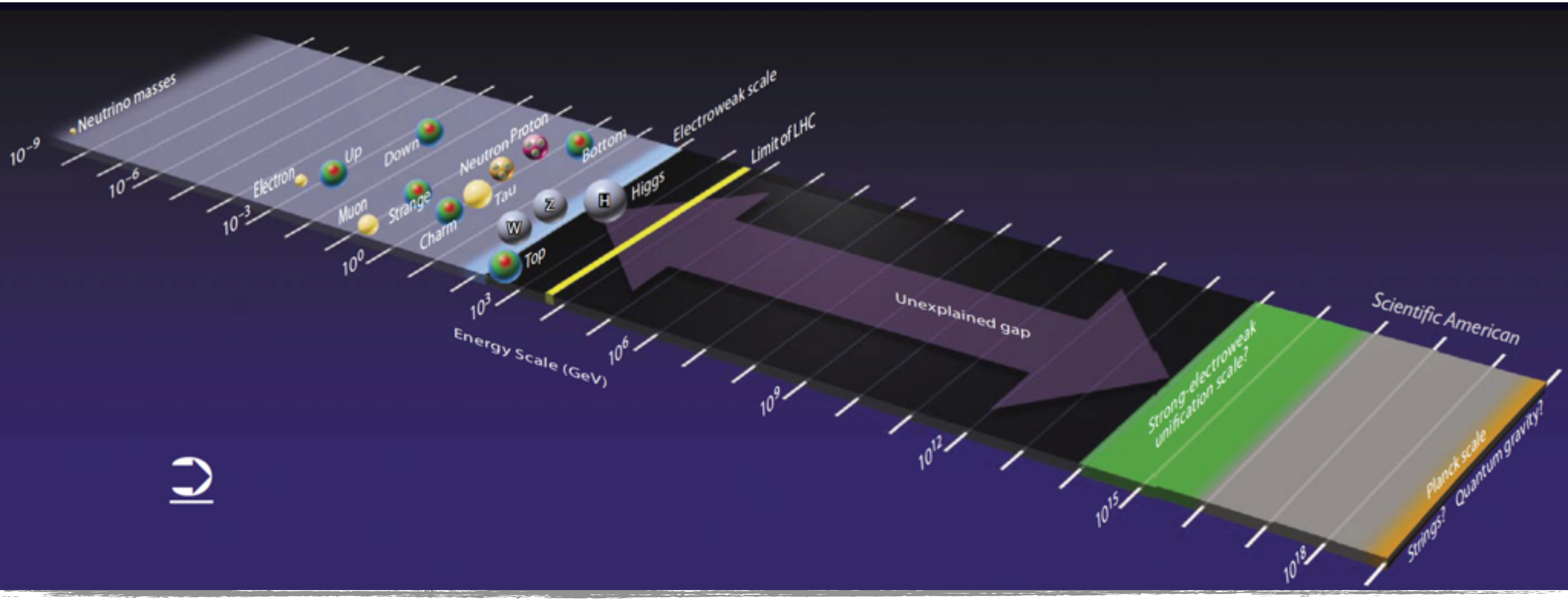
Open Questions: Energy Content of the Universe

- Long known from the observed rotation curves of galaxies: galaxies contain much more mass than would be expected by the number of their stars
- Substantially improved understanding in the last ~ 15 years: Today we know that only 5% of the energy content of the universe is in Standard Model particles
    - 1/4: Dark Matter - A new particle? Could be produced at accelerators!
    - 3/4: Dark Energy - Up to now no good explanation!



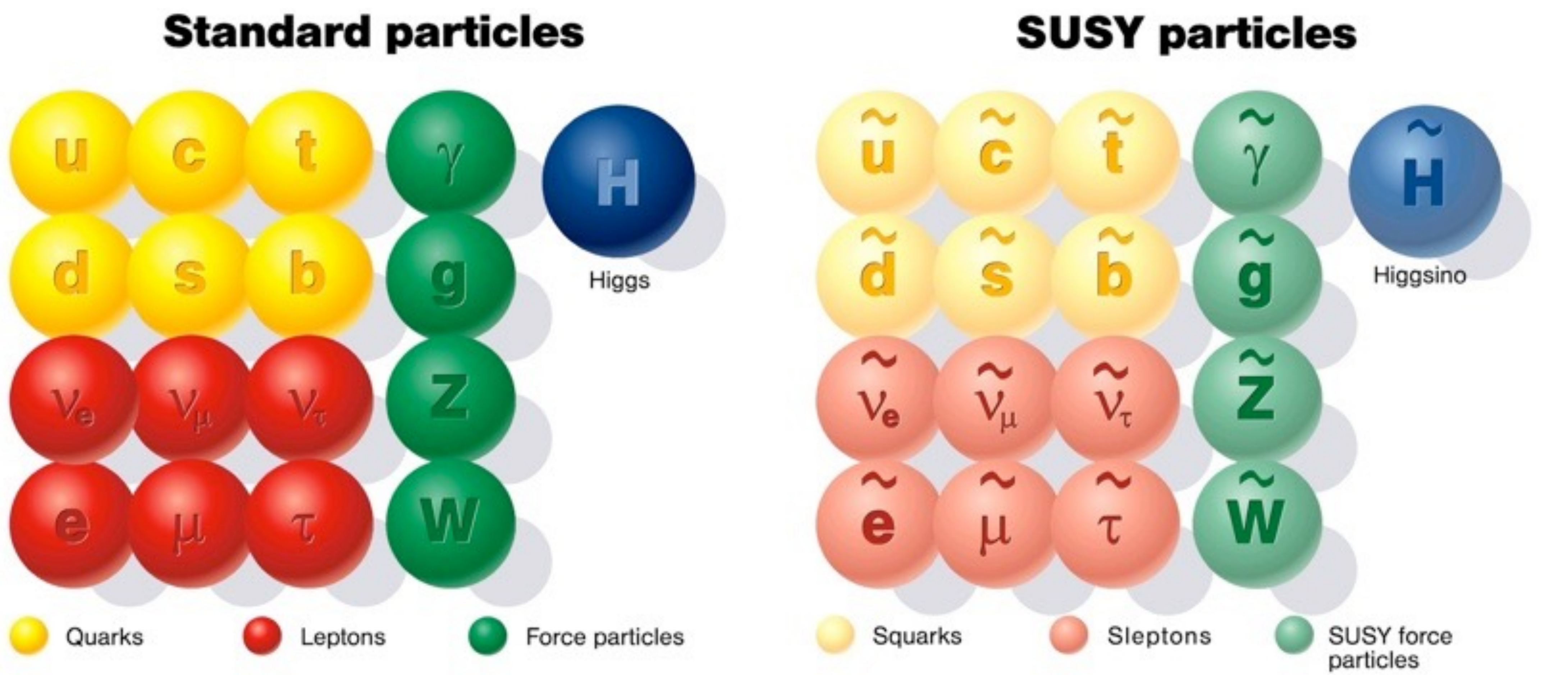
Fundamental Questions: Particle Masses

- How are the particle masses generated?
  In the Standard Model: The Higgs mechanism
  - But: Why are particle masses so different, and why are particles so light?
  - Two very different energy scales: The electroweak scale, and the scale of gravity: “Hierarchy Problem”



Ideas for Solutions

- New symmetries and new particles at higher energies:
  Protection for the SM particles by cancelations in higher order loop contributions



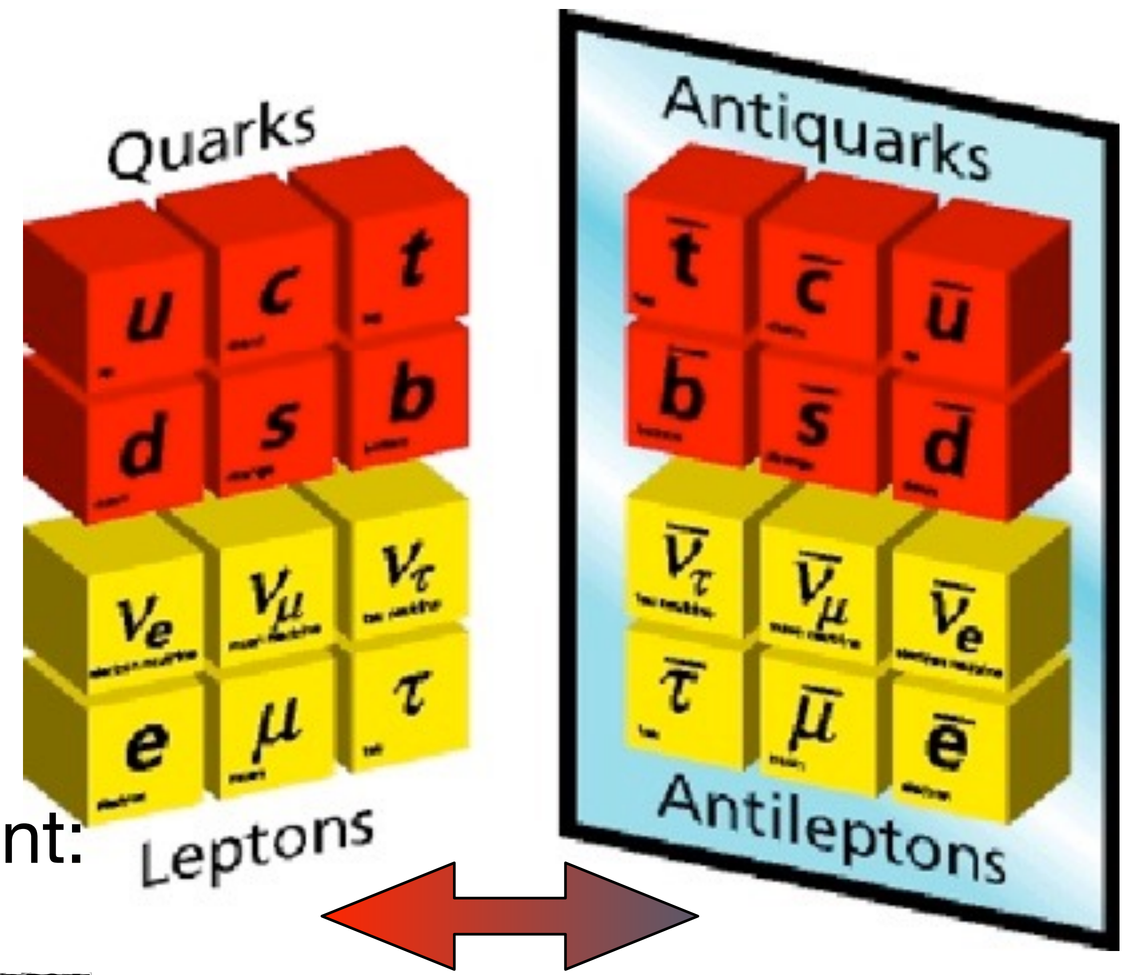
- The most popular scenario: Supersymmetry - A rich phenomenology to discover - and provides dark matter candidate!
- Many other possibilities: Large extra dimensions particularly attractive

Fundamental Questions: Matter Dominance

- Today, the whole Universe consists of Matter:
  What happened to the anti-matter that was created in the Big Bang?

- A slight preference (on the 10^{-9} level) for matter over anti-matter is needed to explain cosmological observations
  - CP violation can provide such an asymmetry...

... but the SM effect is by far not sufficient:



an imperfect symmetry!

New CP violating processes are required at higher energy scales!

More next month and in the Summer

Open Questions

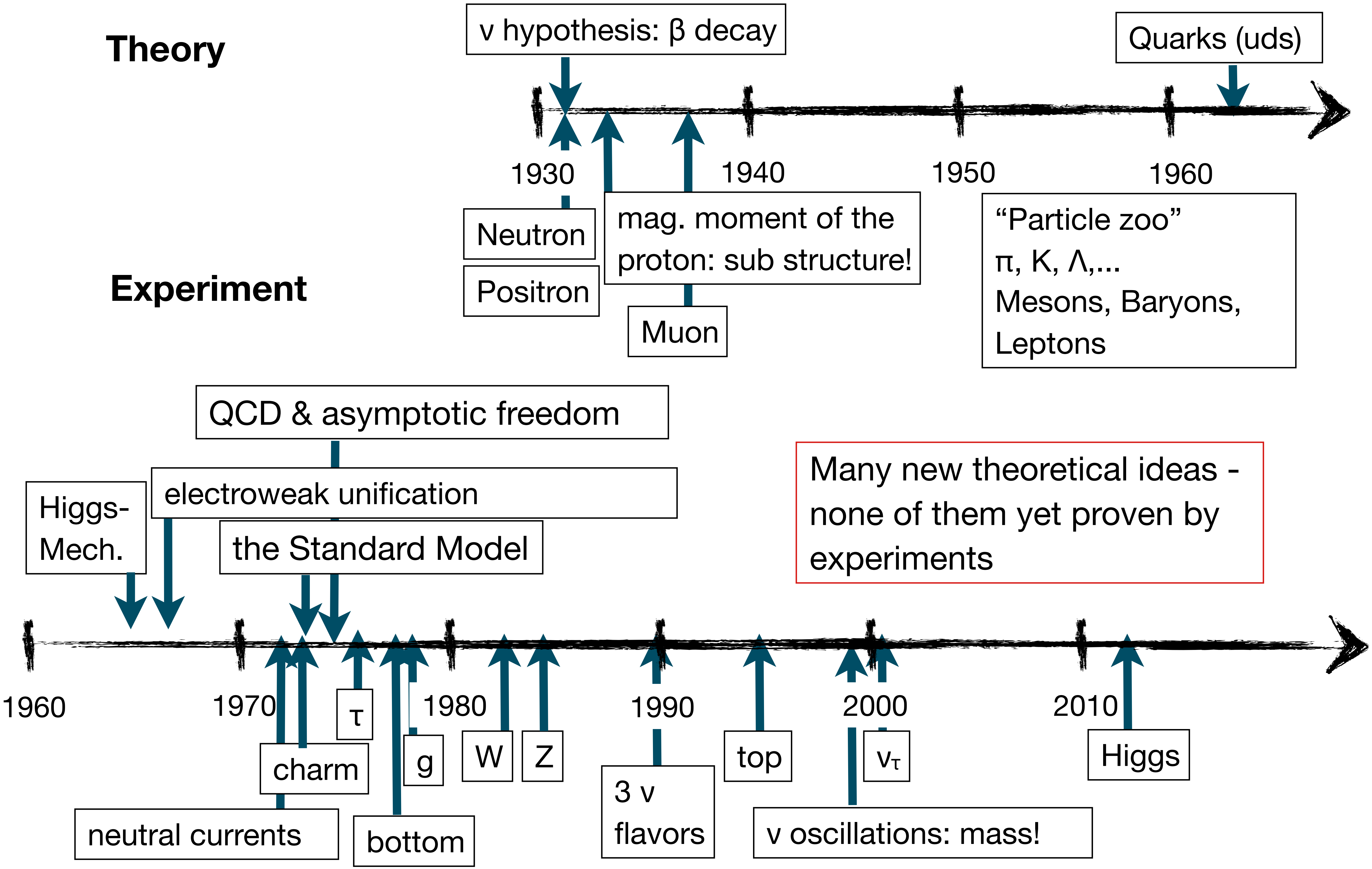
- Short Summary:

  We expect New Physics beyond the Standard Model to get answers for at least some of these questions

  High expectations for experiments at colliders and astroparticle experiments !

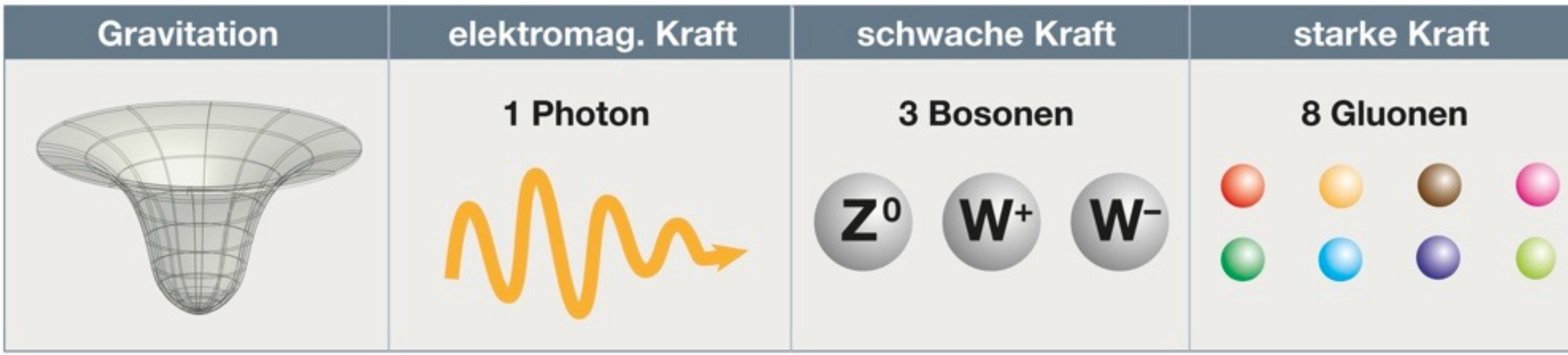
Particle Physics Refresher:
Standard Model, Experimental Strategies

History of Particle Physics



Fundamental Forces

- Four known Forces
  - Gravitation governs our every-day life, evolution of the Universe
  - ‣ It is irrelevant on the scales of particle physics



couples to mass	couples to charge	couples to weak isospin	couples to color

Relative strength at low energies

$\sim 10^{-40}$	1/137	10^{-13}	~1

due to the high mass of W, Z:
W: ~ 80 GeV , Z: ~ 91 GeV

The Standard Model of Particle Physics

- The SM describes our visible Universe by a (reasonably small) set of particles:
  - The particles that make up matter: Spin 1/2 Fermions
  - … and the force carriers: Spin 1 Vector bosons

Elementary Particles				Elementary Forces		
	Generation				exchange boson	relative strength
	1	2	3			
Quarks	u	c	t	Strong	g	1
	d	s	b	el.-magn.	γ	1/137
Leptons	ν_e	ν_μ	ν_τ	Weak	$W^\pm$, Z^0	10^{-14}
	e	μ	τ	*Gravitation*	*G*	10^{-40}

… plus the Higgs particle as a consequence of the mechanism to generate mass

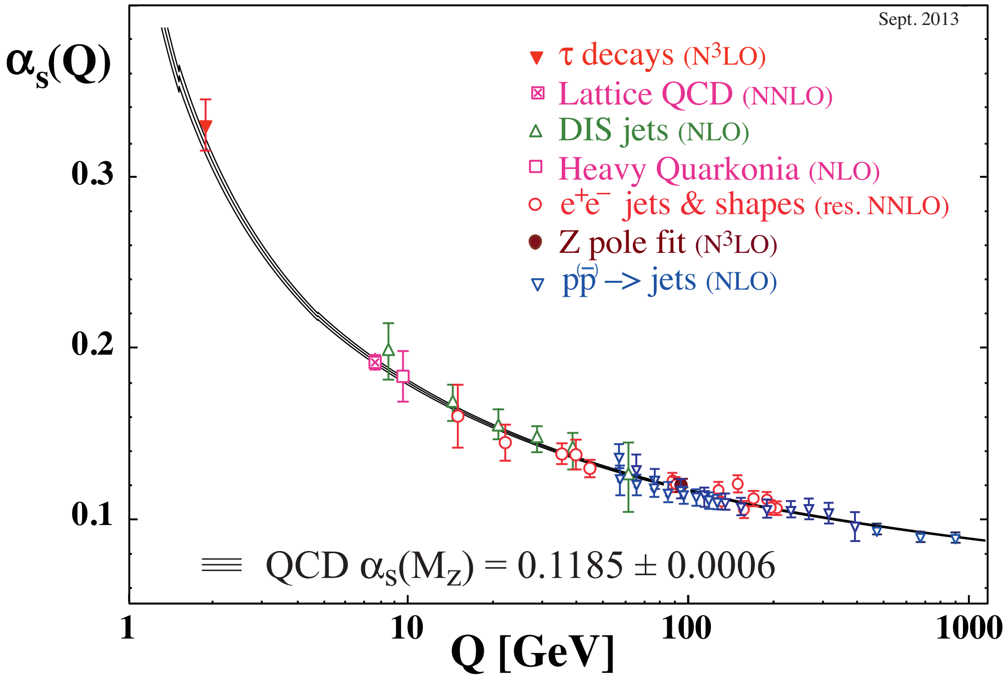
Underlying theories: QCD; QED / weak interaction ➯ electroweak unification (GSW)

Key Elements of the Standard Model: Electroweak

- The electroweak part of the SM is based on the gauge group SU(2) x U(1)
- This gives rise to the gauge bosons W^+, W^-, Z for SU(2) and γ for U(1)
- Left-handed fermion fields transform as doublets under SU(2) - right handed fermions as singlets (no coupling of right-handed fermions to W; **V-A structure of the weak interaction** (maximum parity violation))
- There are three fermion families
- A complex scalar Higgs field is added for mass generation through spontaneous symmetry breaking to give mass to the gauge bosons and fermions -> Gives rise to one physical neutral scalar particle, the Higgs boson
- The electroweak SM describes in lowest order ("Born approximation") processes such as $f_1 f_2 \rightarrow f_3 f_4$ with only 3 free parameters: α, G_f, $\sin^2\theta_W$

Key Elements of the Standard Model: Strong

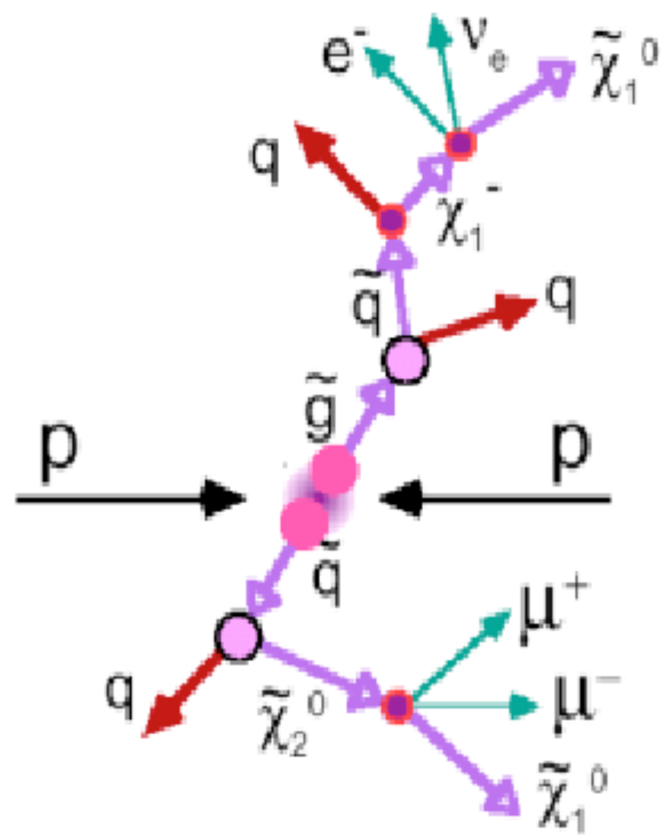
- Described by **Quantum Chromodynamics (QCD),** gauge group SU(3)
- Gluons as exchange bosons, couple to “color”, a “charge” carried by quarks
- Gluons themselves carry color charge: can self-interact
- The coupling constant of the strong interaction (α_s) decreases with increasing momentum transfer: In the limit of very short distances, the coupling vanishes: **asymptotic freedom**



- On the other hand: coupling tends to infinity for large distances: It is impossible to separate color charges, at large distance new particle / anti-particle pairs are created from the increasing field energy. Only color-neutral objects can exist as free particles: **Confinement**
- Gives rise to the rich structure of hadrons, the complexity of the proton and of final states in particle collisions

Strategies for Discovery in Particle Physics

- Two complementary approaches:



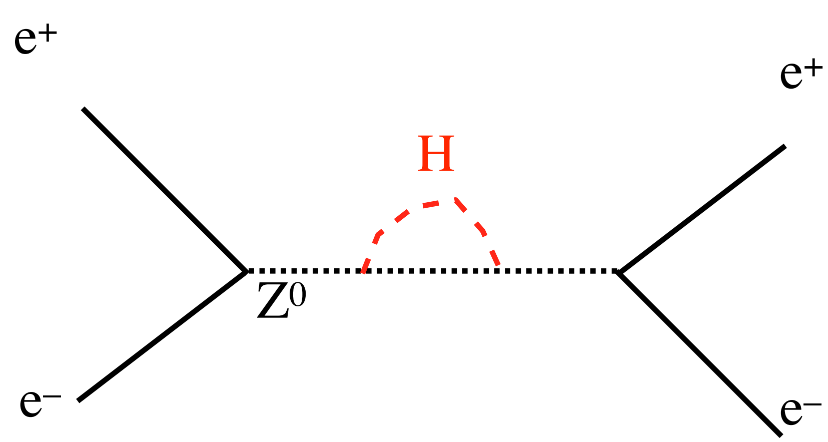
Direct searches at highest energies:

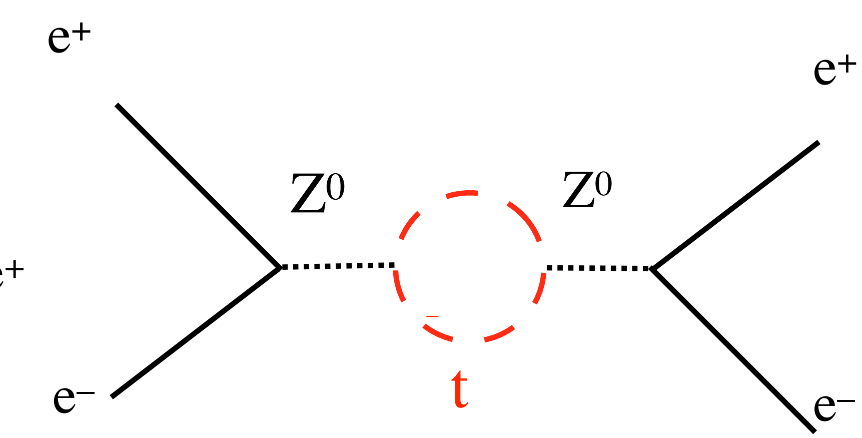
Production and detection of new particles

The Emphasis in this semester

Precision measurements:

Indirect evidence for new particles in virtual quantum loops





The Tools: Accelerators & Detectors

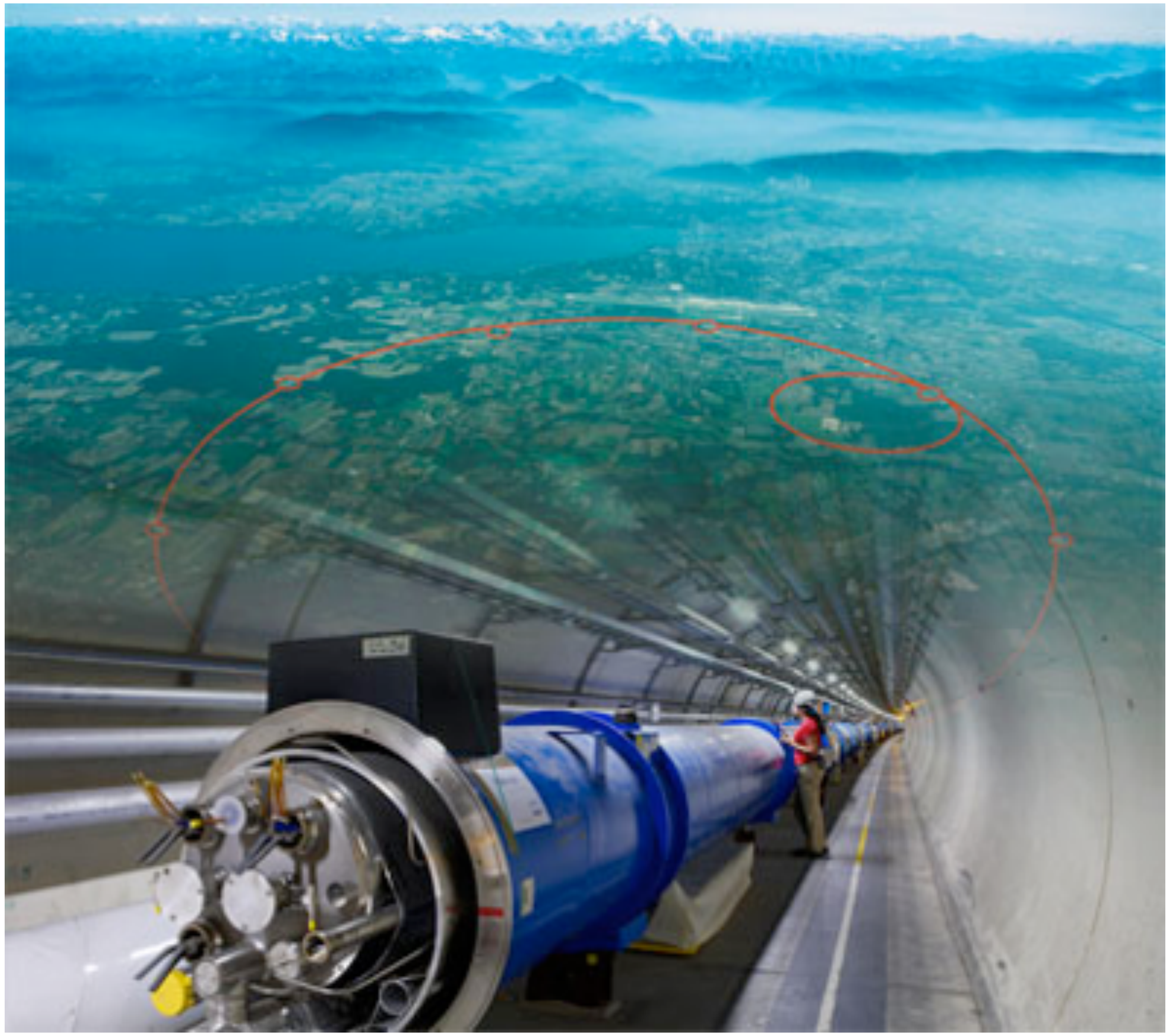
- To study the smallest structures very high energies are necessary: Energy ⇔ distance (de Broglie - wavelength)
  - Resolution d[fm] ~ 0.197/E [GeV]

Accelerators for highest energies, collisions in the lab frame: Colliders!

The biggest collider:
Large Hadron Collider (LHC)

The “Weltmaschine”:
10 000 scientists and engineers from more than 100 countries

Recently completed “Run 2”:
Second phase of LHC running, energies of 13 TeV (6.5 TeV + 6.5 TeV)
Currently: Shutdown for maintenance and upgrades



Detectors / HEP Experiments

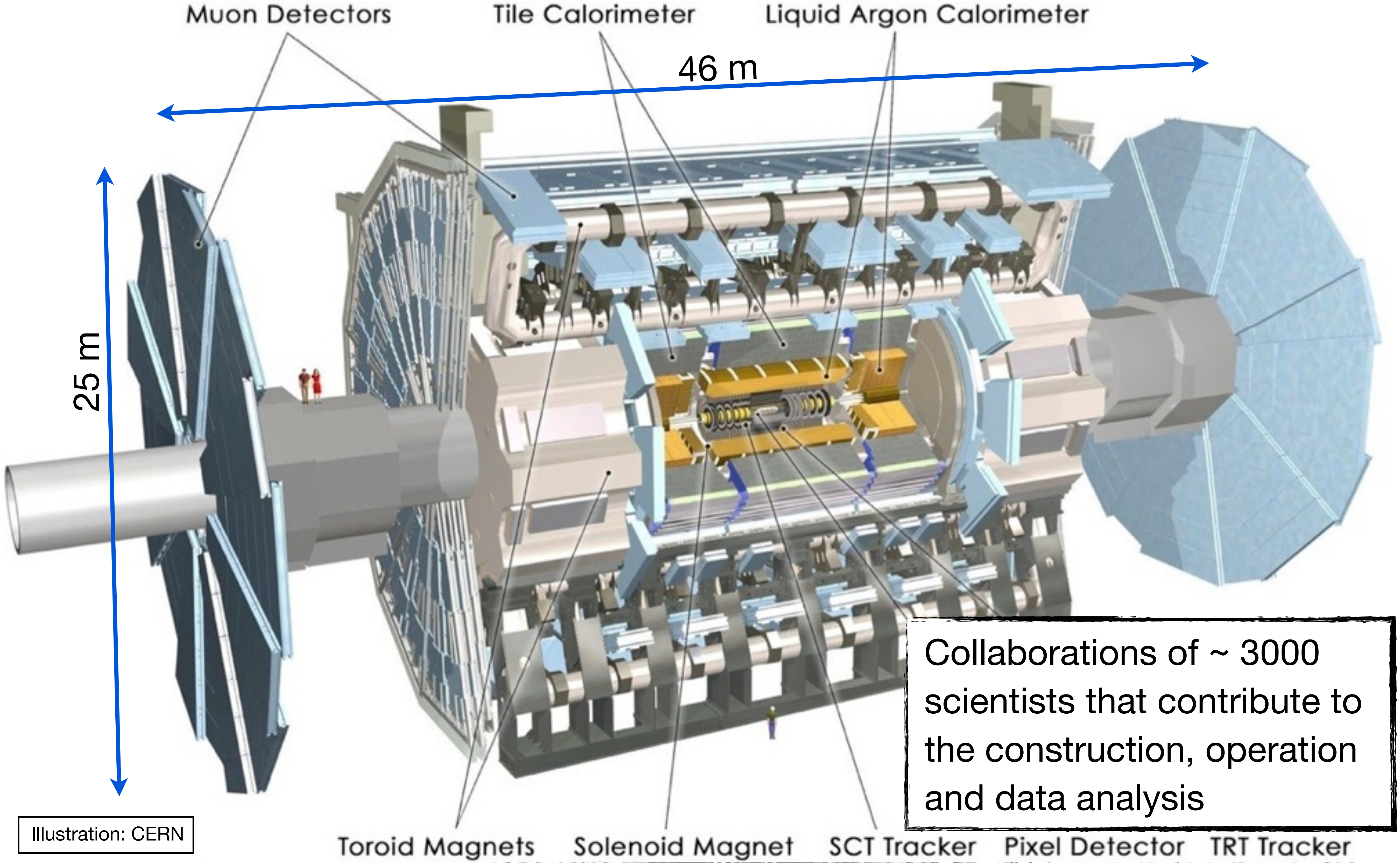
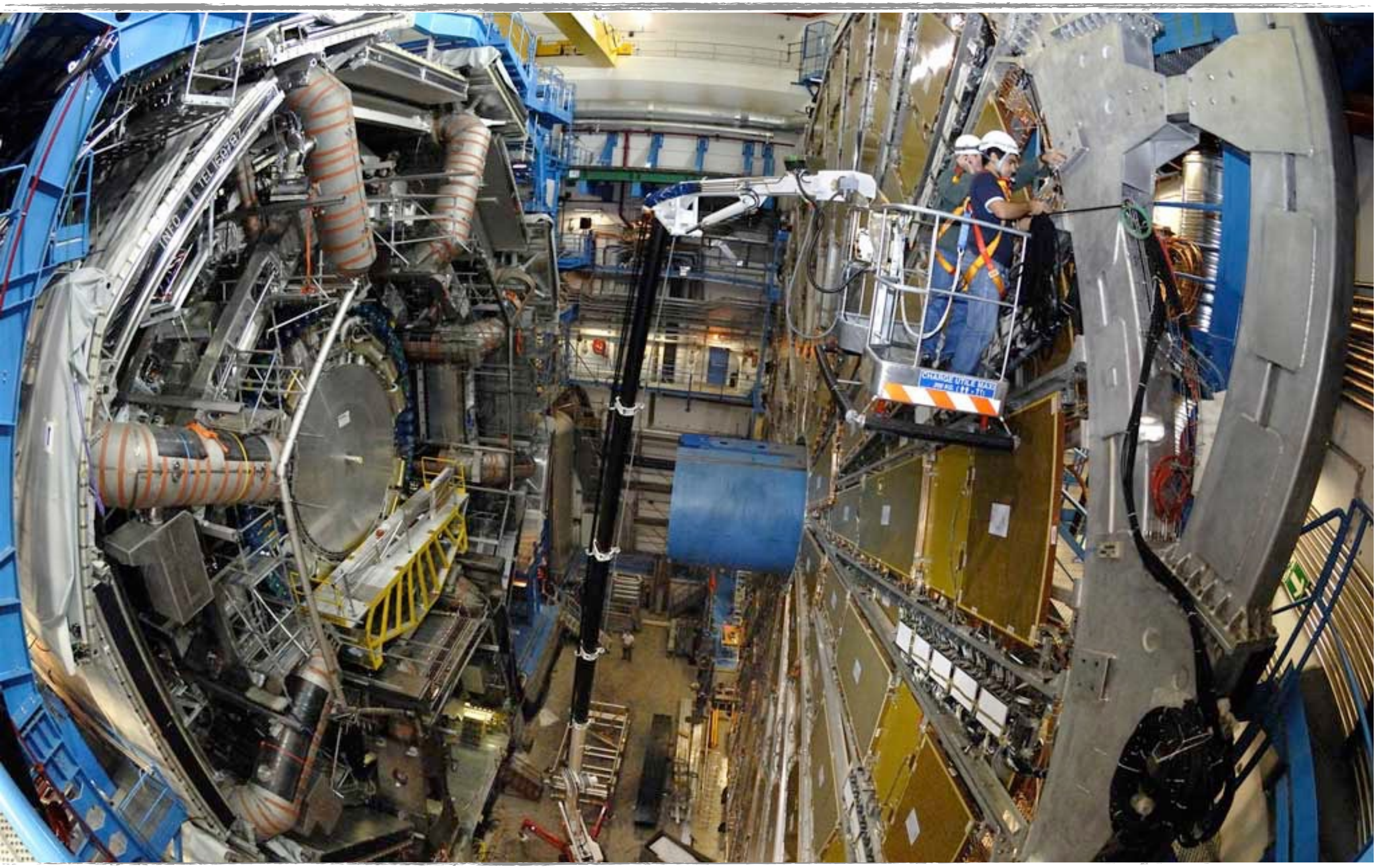


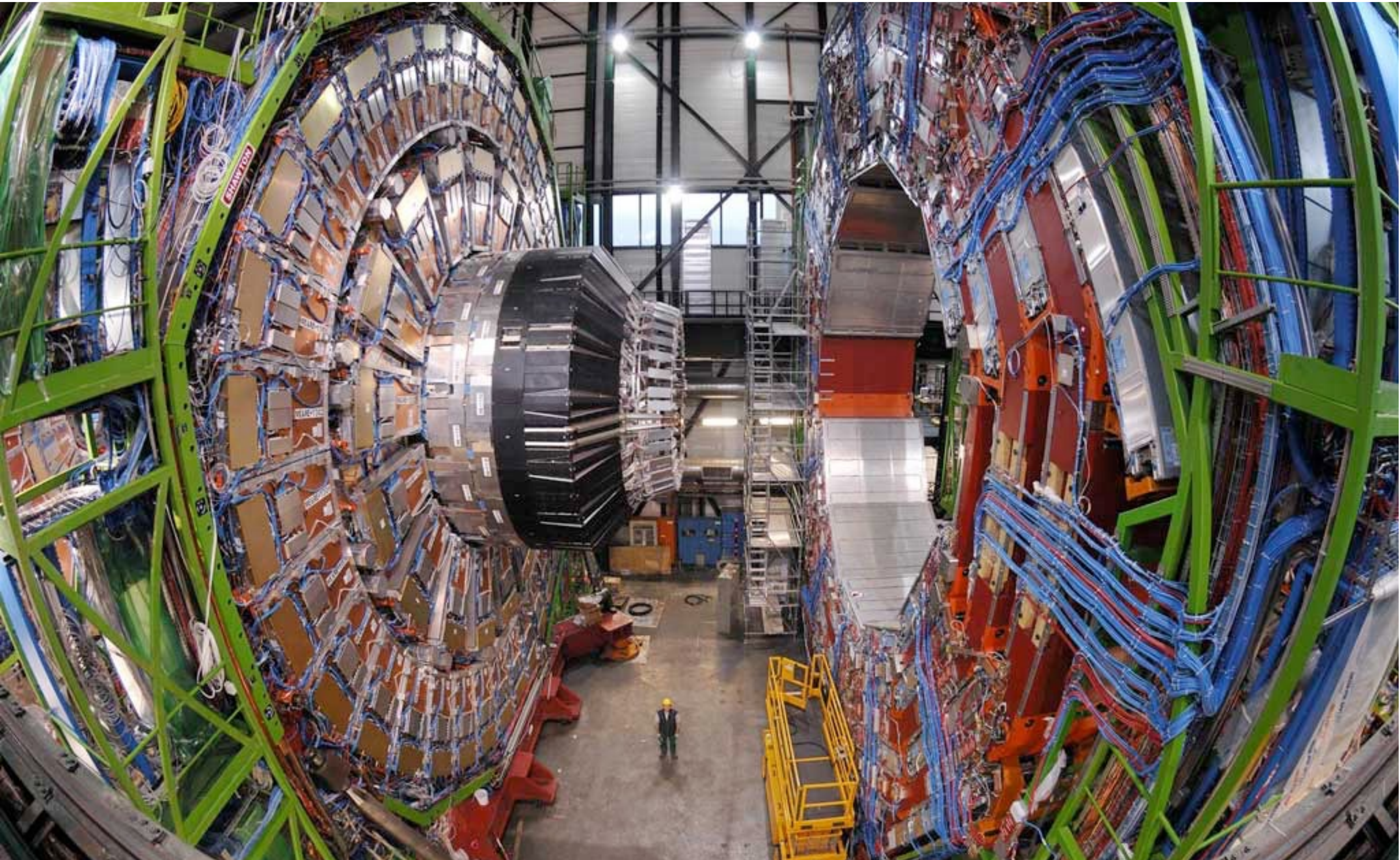
Illustration: CERN

Collaborations of ~ 3000 scientists that contribute to the construction, operation and data analysis

Detectors: ATLAS

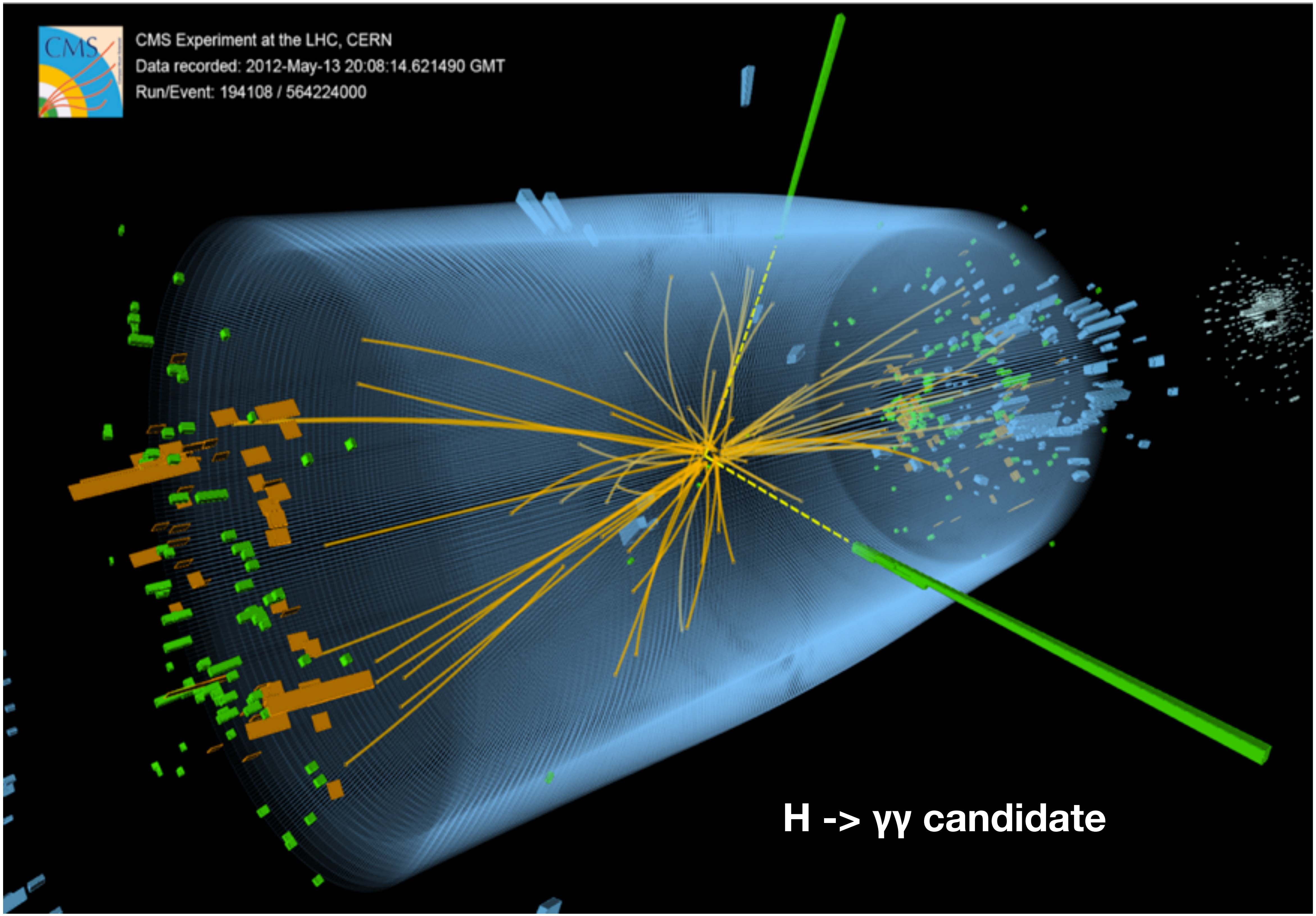


Detectors: CMS



4th of July 2012: Long awaited...

A possible Higgs Event



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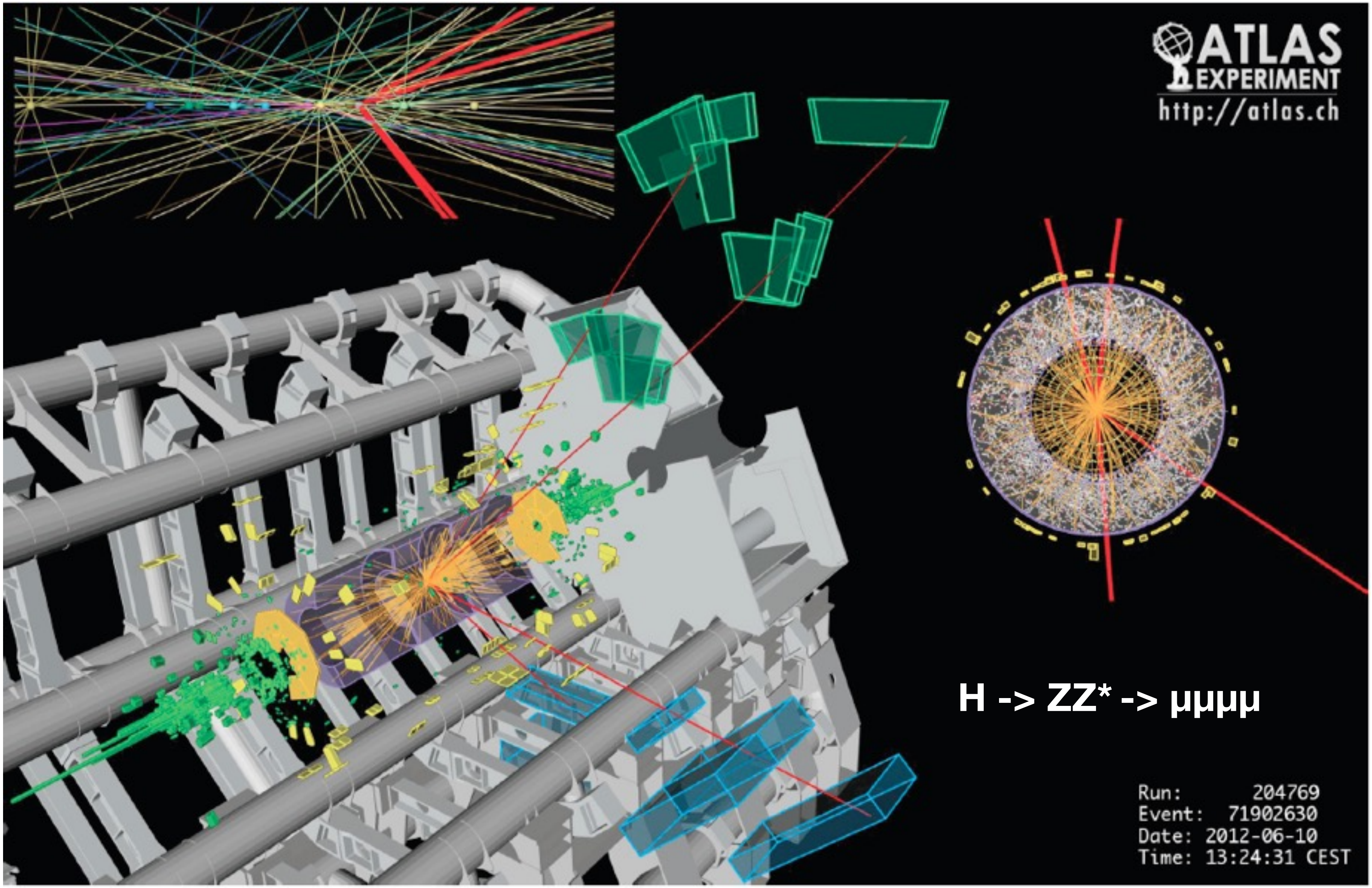
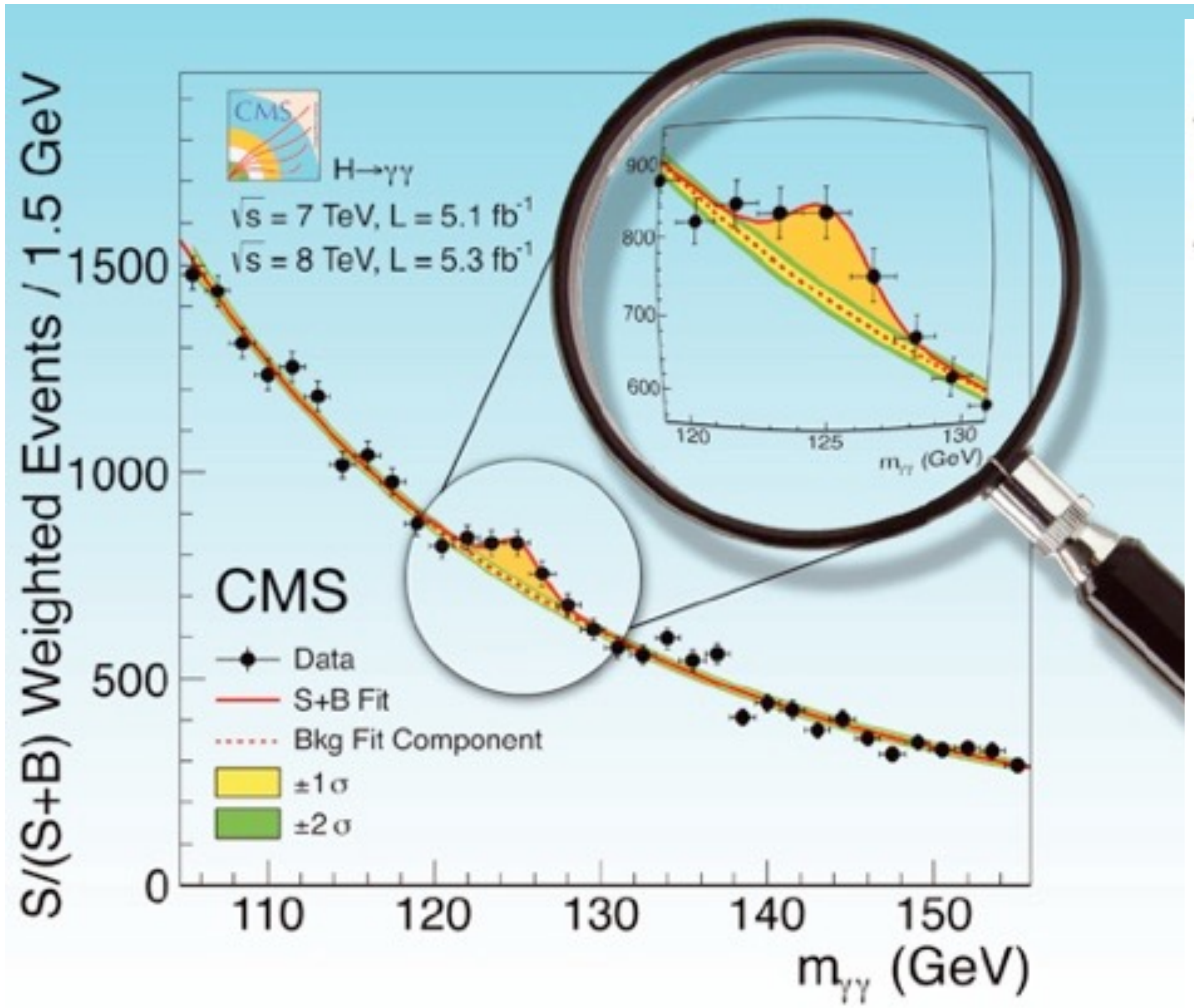
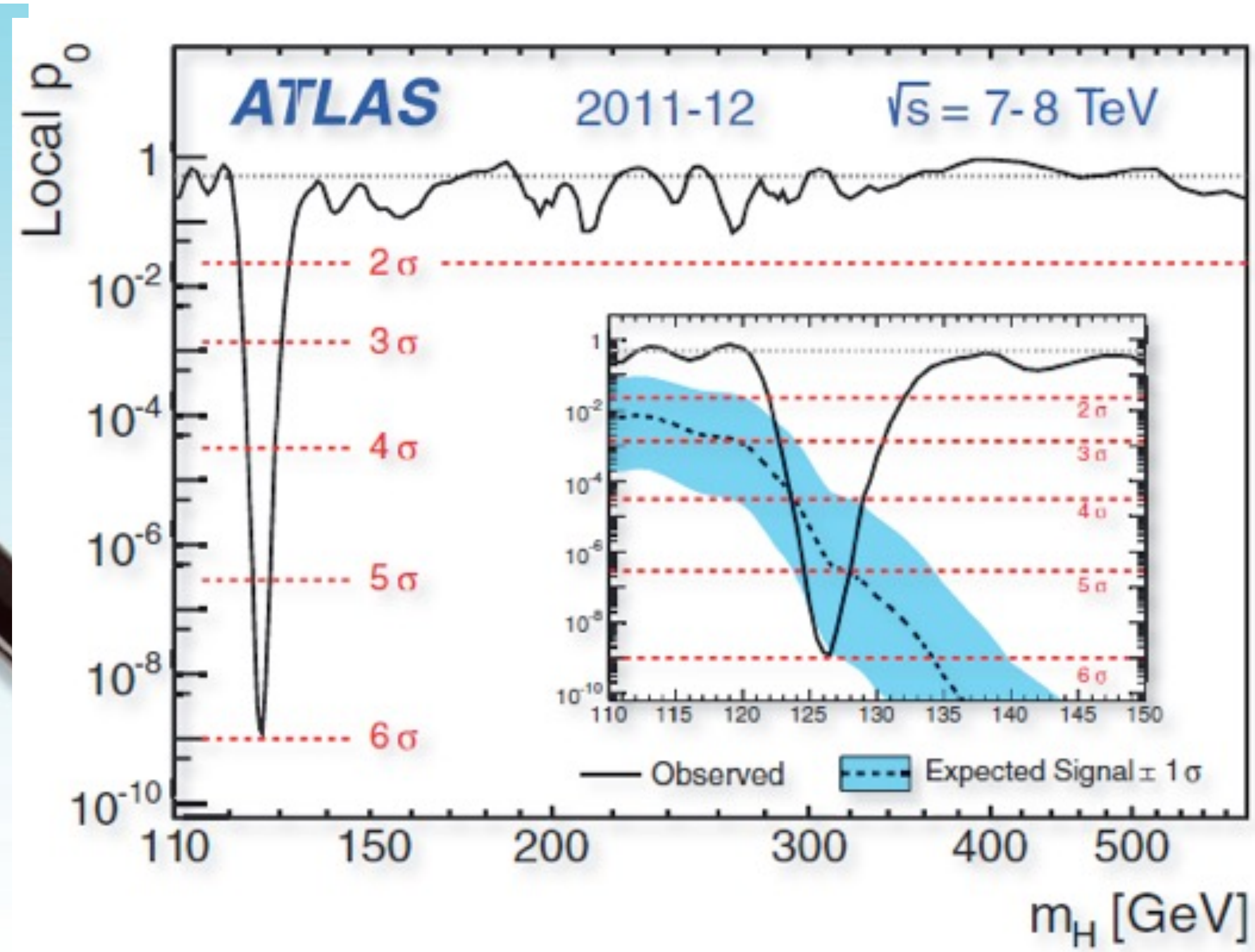


Successful Higgs Search





- Fully confirmed signal, at a mass of 125.1 GeV - up to now perfectly consistent with the expectations for the SM Higgs

... but despite the striking shortcomings of the Standard Model, no signs of “New Physics” in collider experiments (yet)!

Outlook

Next Lecture: October 21

Introduction to Cosmology I, B. Majorovits

Lecture Overview - Preliminary

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