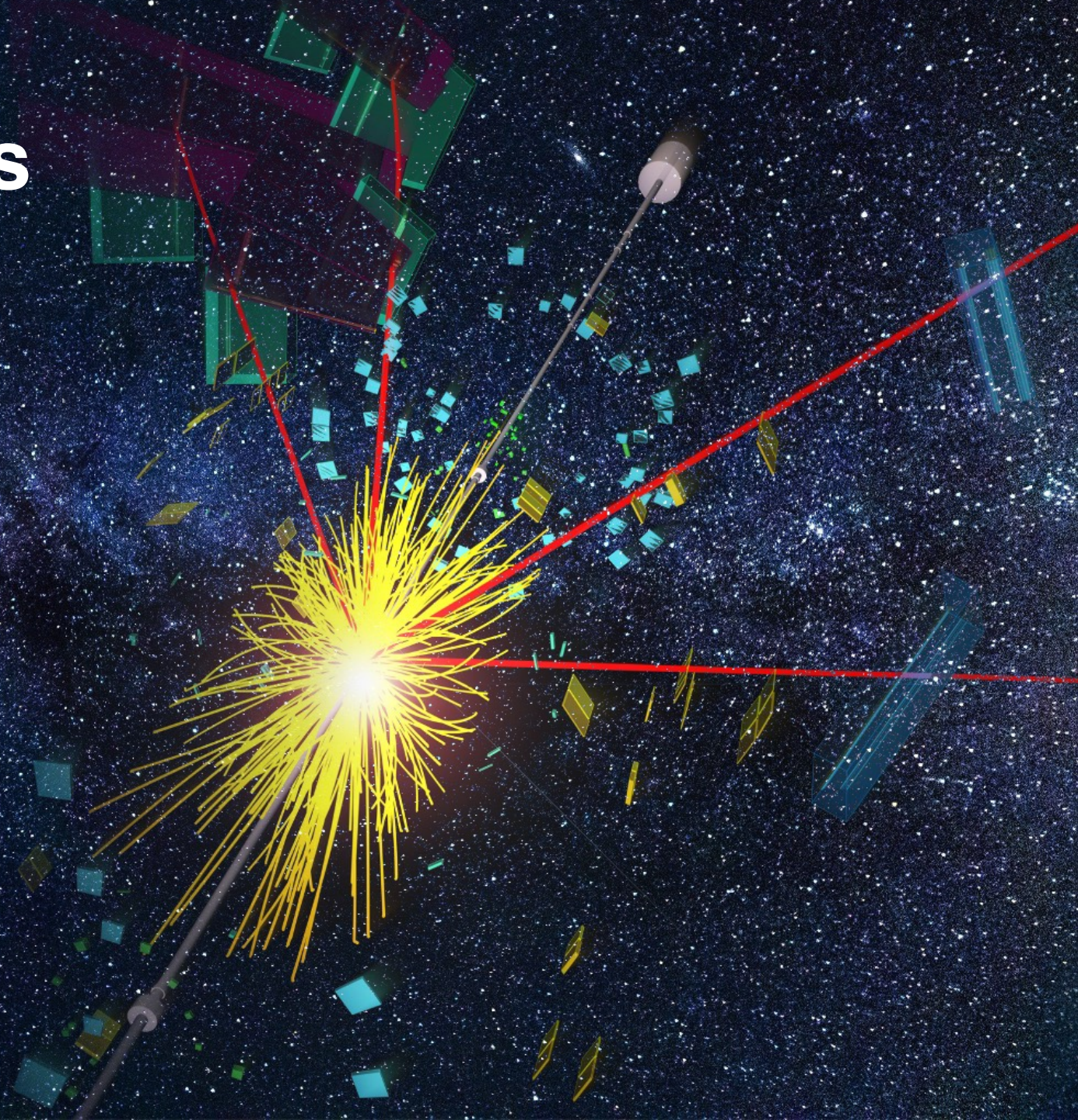


Experimental Physics at the LHC (1)

Andreas Hoecker (CERN)

57. Herbstschule HEP

1–11 September 2026, Bad Honnef, Germany

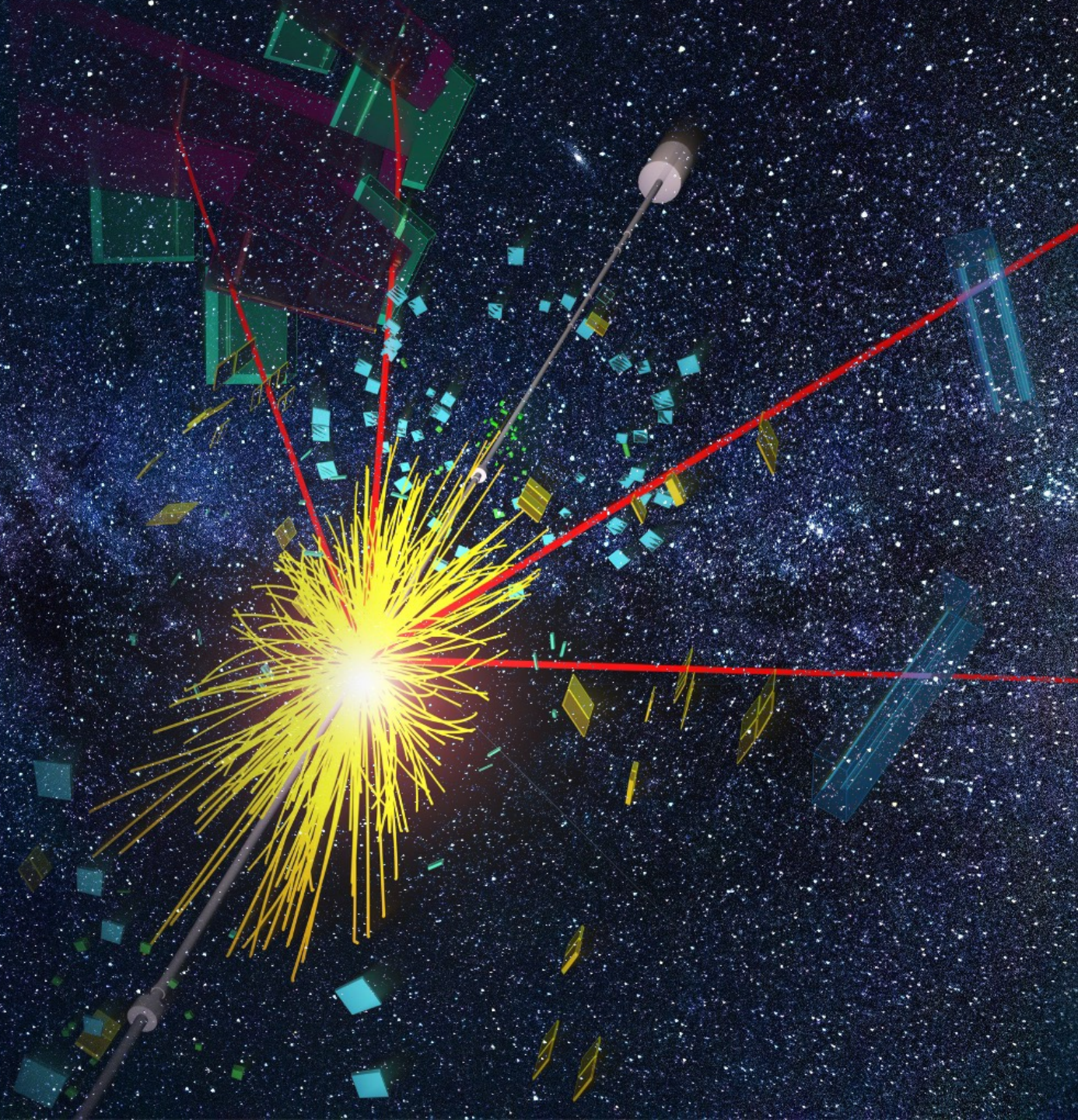


Today's lecture:

- **A brief conceptual introduction**
 - certainly overlap with other lectures, but hopefully highlighting different perspectives
- **Historical collider milestones**
- **Introduction to the LHC**

Next lectures:

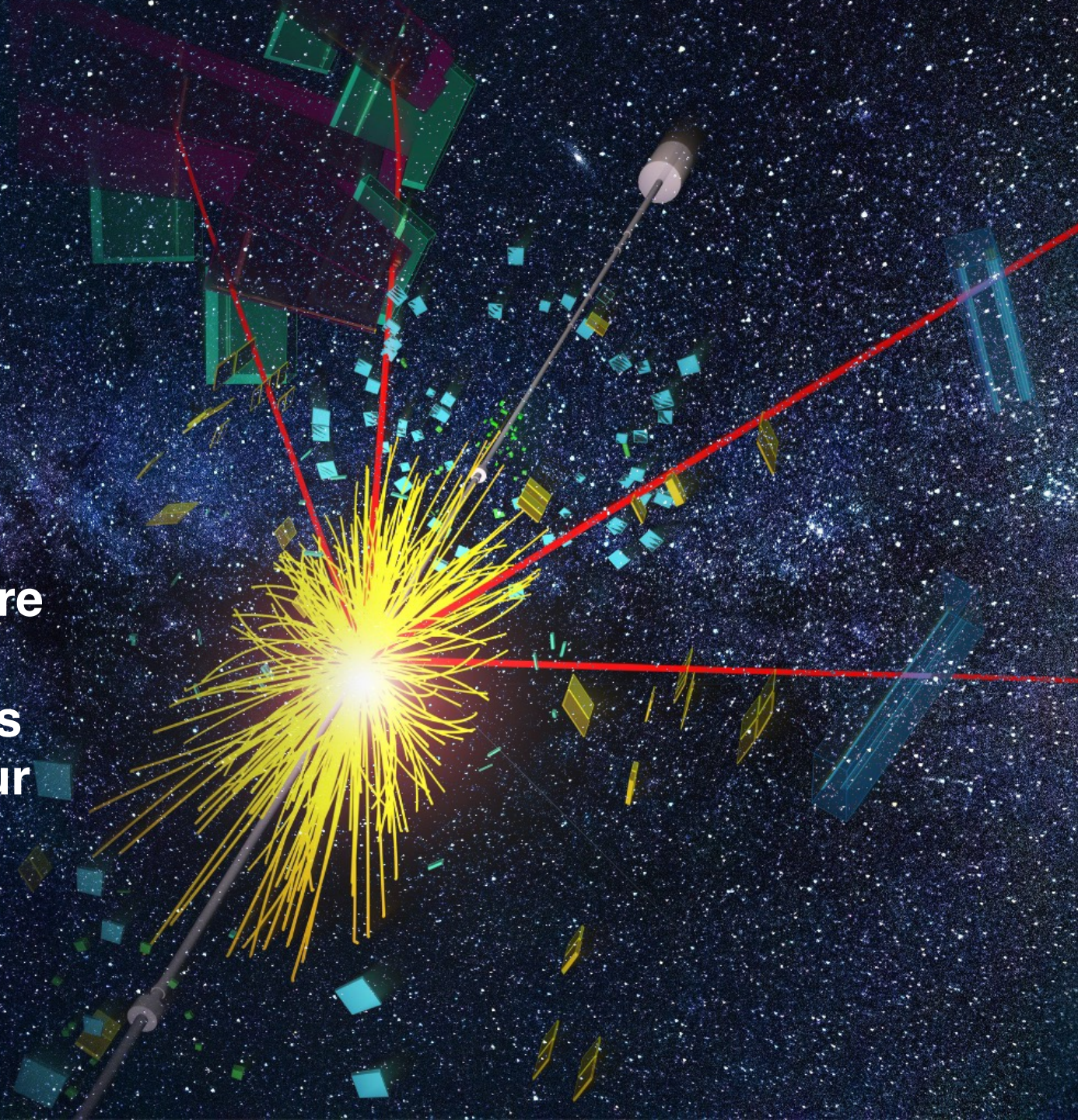
- Particle detection at the LHC
- Data reconstruction and analysis
- Selected physics topics
- Upgrade to the High-Luminosity LHC
- New physics opportunities



A big apology for showing more ATLAS examples in this lecture, simply because I know better how to find them

In all cases, there exist equivalent CMS examples

I further apologise for focusing more on the high- p_T LHC experiments, assuming many of the LHCb results are featured in the dedicated flavour lecture



The time will come when diligent research over long periods will bring to light things which now lie hidden. A single lifetime, even though entirely devoted to the sky, would not be enough for the investigation of so vast a subject ...

And so this knowledge will be unfolded only through long successive ages. There will come a time when our descendants will be amazed that we did not know things that are so plain to them ...

Many discoveries are reserved for ages still to come, when memory of us will have been effaced. Our universe is a sorry little affair, unless it has in it something for every age to investigate. Nature does not reveal her mysteries once and for all.

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Seneca the Younger (Stoic philosopher of Ancient Rome) in *Naturales Quaestiones*, 1st century AD

Steven Weinberg's four golden lessons: start before you feel ready;
tackle the messy problems; accept wasting time*; know your field's history**

<https://www.nature.com/articles/426389a> (2003)

* *"If you want to be creative, then you will have to get used to spending most of your time not being creative"*

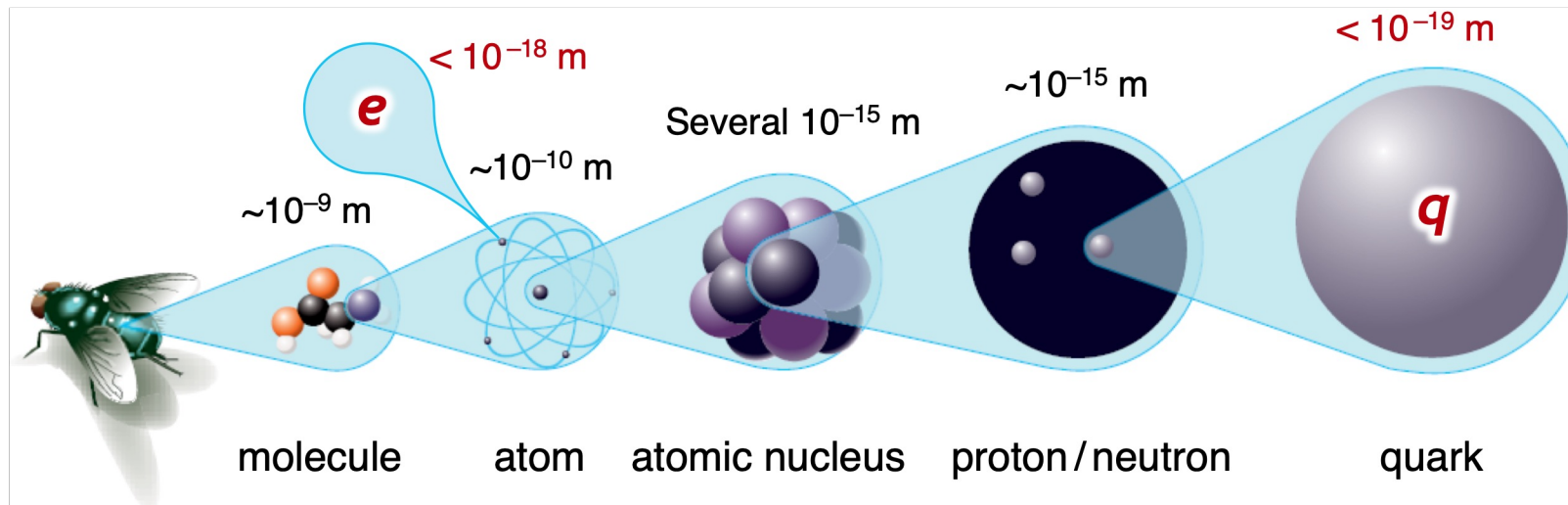
** *"The best antidote to the philosophy of science is a knowledge of the history of science", "Science is civilizing work, of which scientists are able to feel proud"*

No single insight in this search is sacred,
only the searching

Paraphrased from Ann Druyan's introduction to Carl Sagan's *The Varieties of Scientific Experience*

It's all made of a handful of particles and forces

The sub-atomic structure of matter and its interactions are elegantly simple (a very simplified picture)



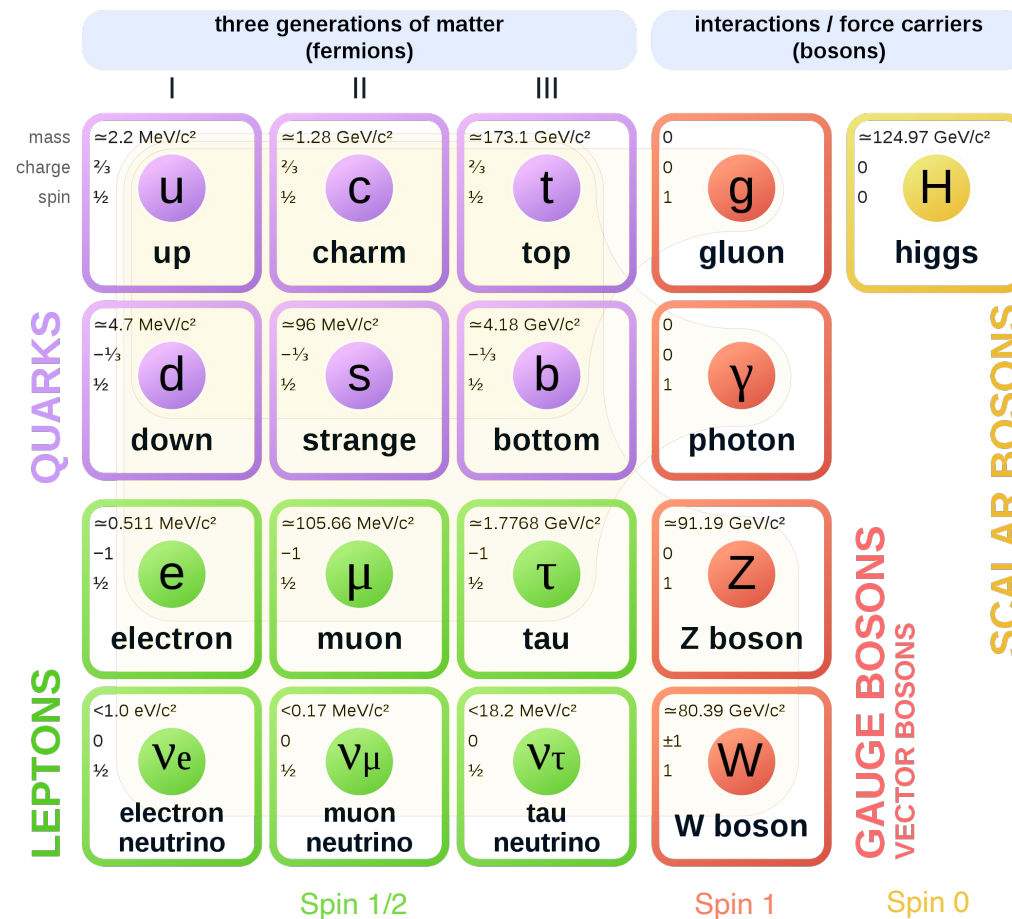
The universe is a strange place

- Elementary particles are point-like — with no spatial extent at all
- Without some remarkable mechanism at play, elementary particles would have no mass (except for spin-zero particles)
- Bare fermion masses are forbidden by the chiral structure of weak interaction

It's all made of a handful of particles and forces

The sub-atomic structure of matter and its interactions are described by the **Standard Model**

Standard Model of Elementary Particles



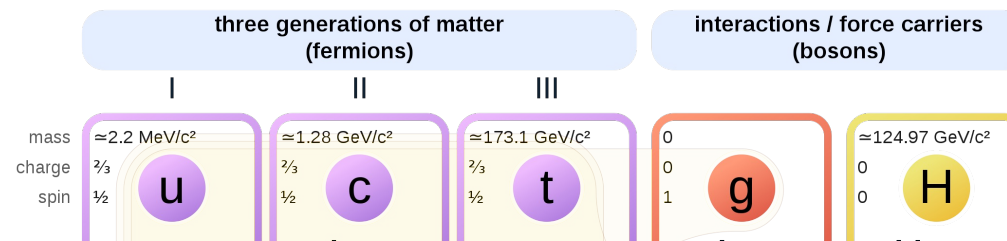
In mathematical terms, **particles are local excitations of quantum fields**. There are matter fields (fermions) and force fields (bosons)

Completely new type of force, very different from the other known forces

It's all made of a handful of particles and forces

The sub-atomic structure of matter and its interactions are described by the **Standard Model**

Standard Model of Elementary Particles

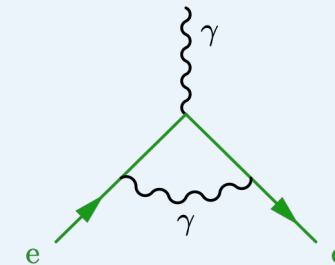


The Standard Model is a highly predictive theory

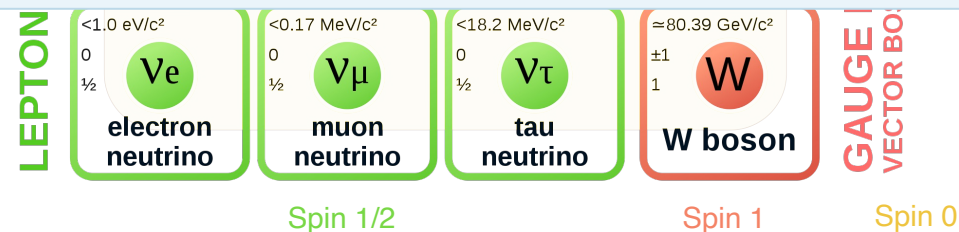
For example, prediction of the magnetic dipole moment of the electron:

$$a_e \equiv \frac{g_e - 2}{2} = 0.001\,159\,652\,180\,59 \pm 0.000\,000\,000\,000\,13$$

In agreement with experiment within a precision of 10^{-10} !



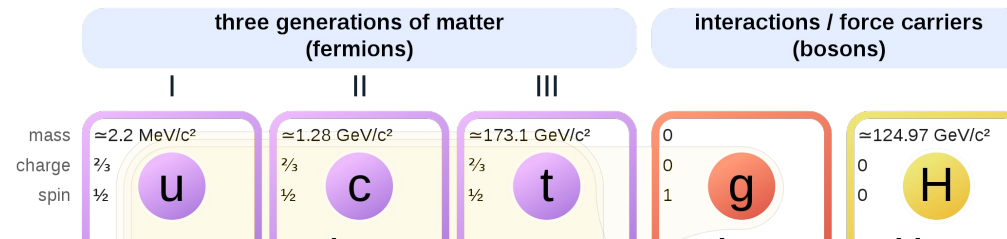
“Schwinger” term:
 $a_e = \alpha/(2\pi)$



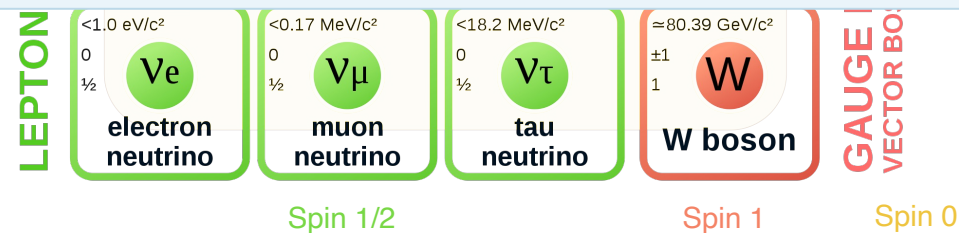
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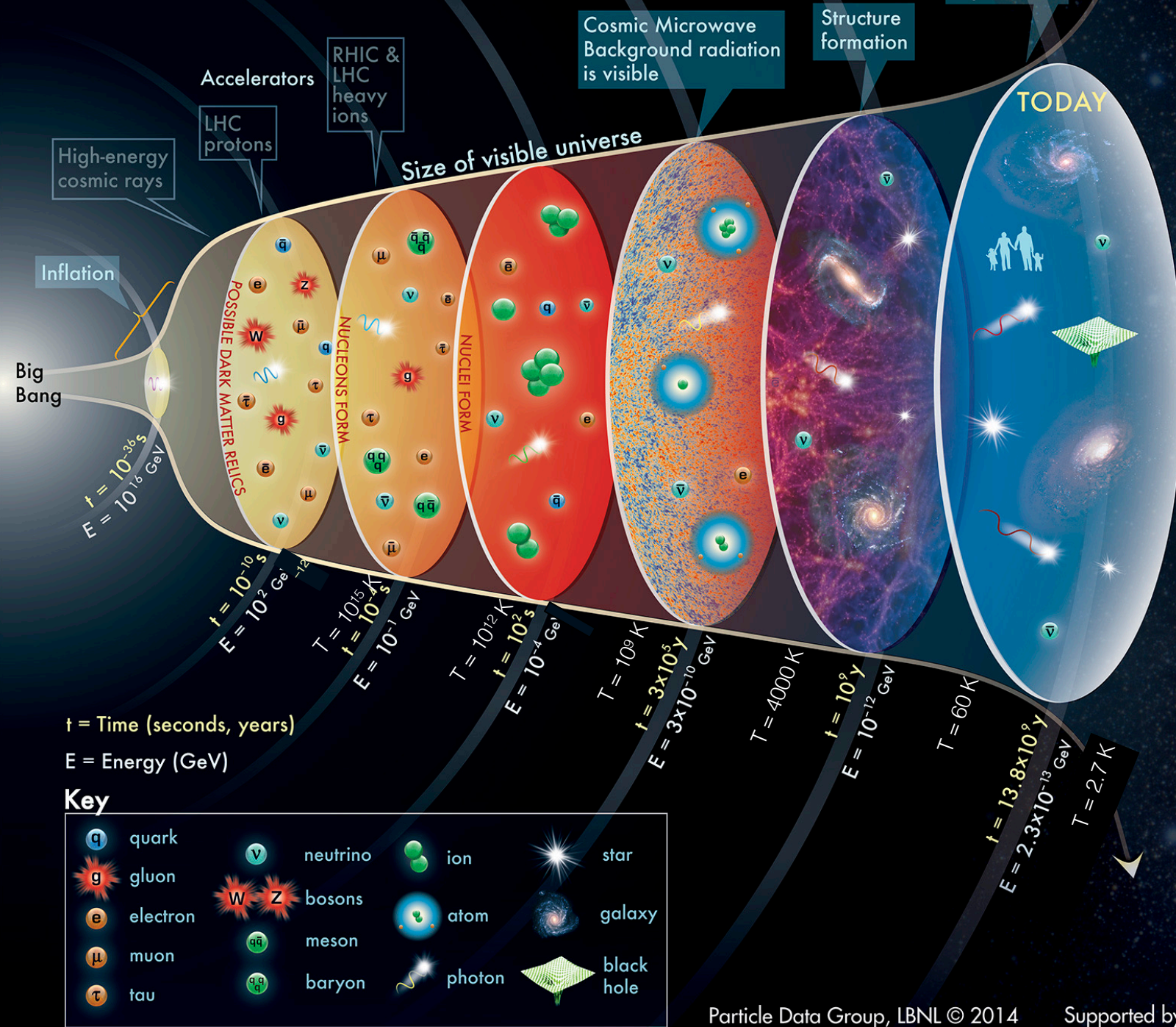
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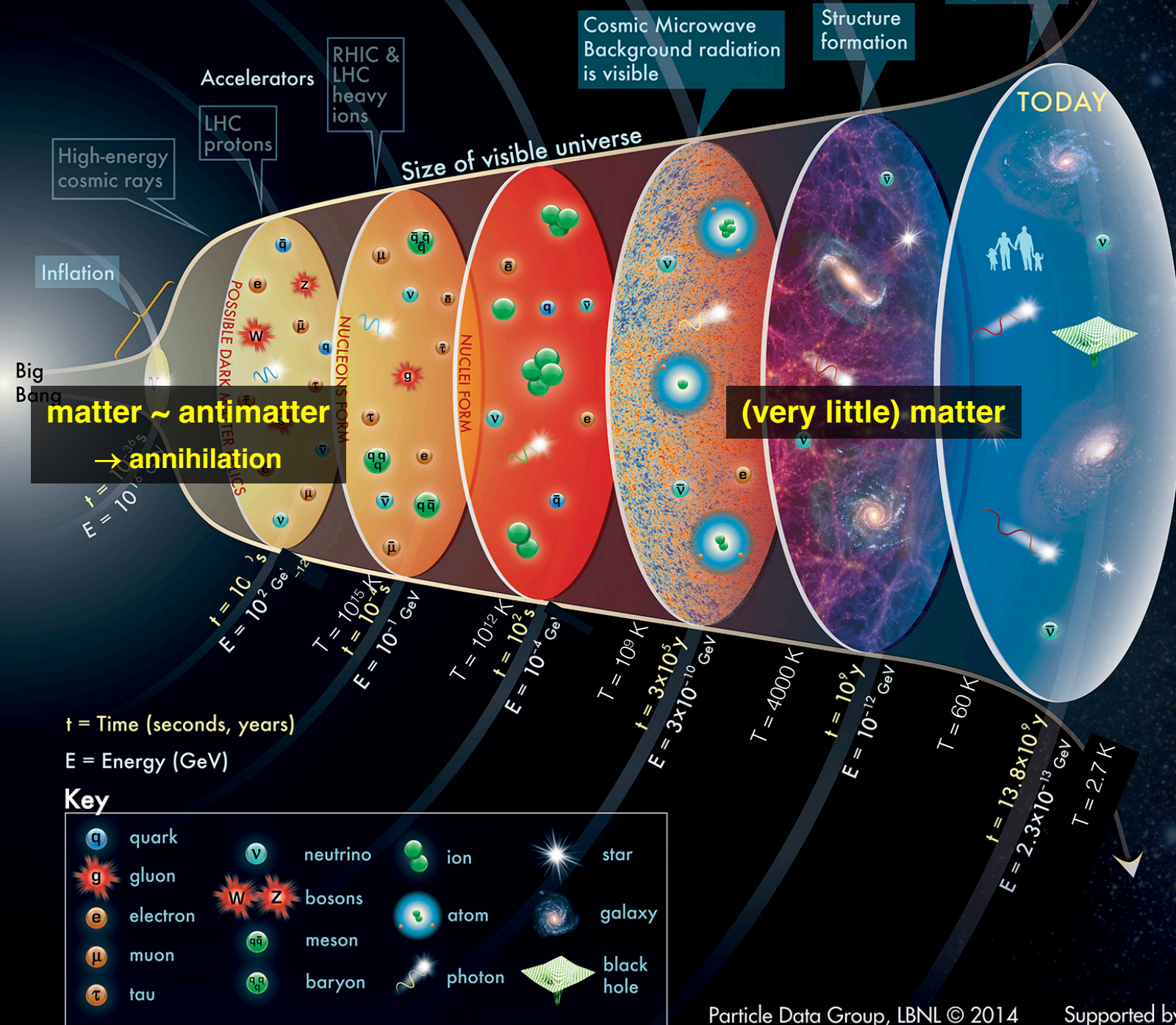
The strong force is particular, the world is made of non-perturbative objects: hadrons. How do we know that hadrons obey the laws of QCD?





The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago



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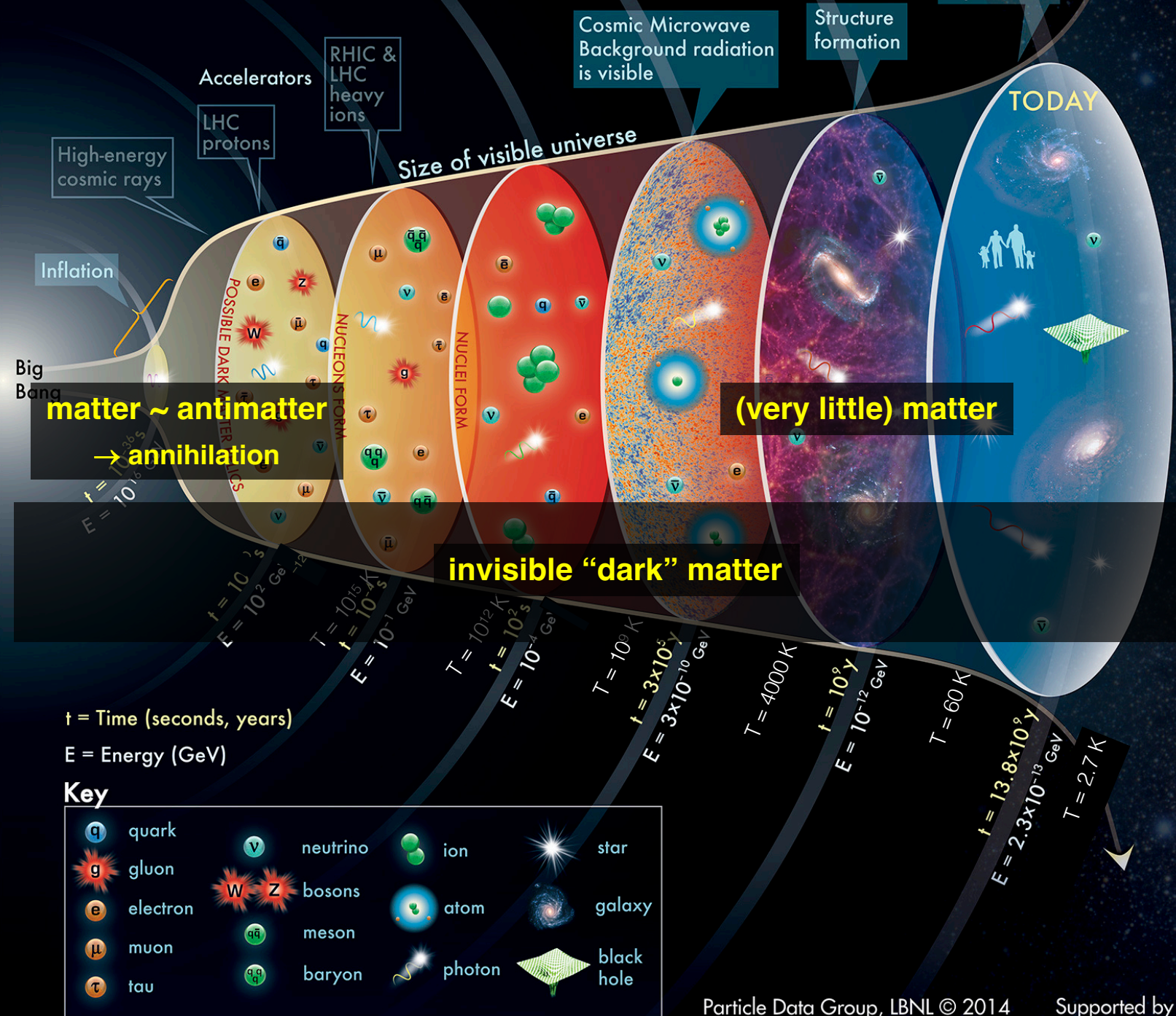
But why is there (only) matter left in the universe?

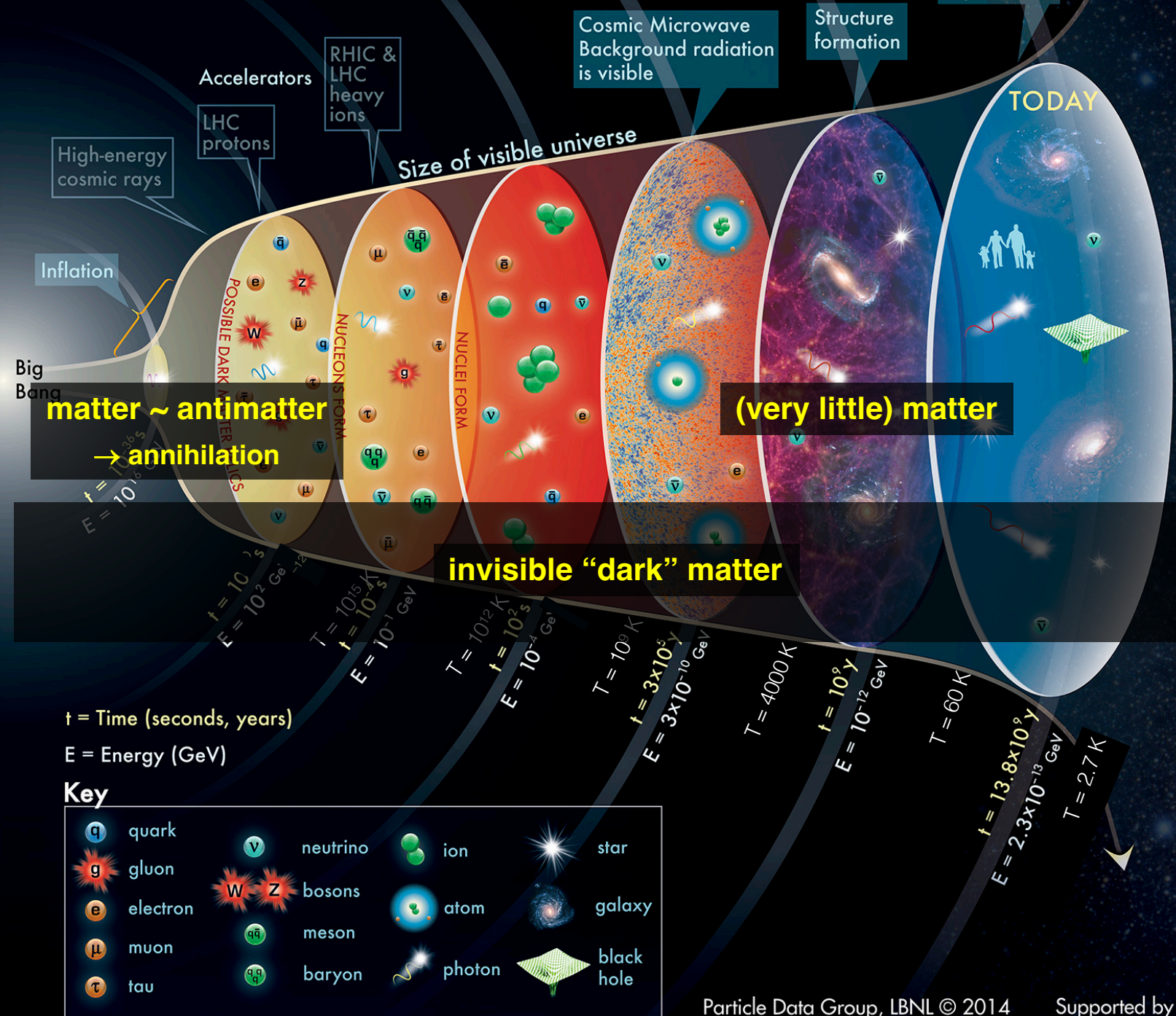
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And what is the origin of the huge quantity of *dark matter* (5 times more than the baryonic matter)?





The Standard Model

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But why is there (only) matter left in the universe?

And what is the origin of the huge quantity of *dark matter* (5 times more than the baryonic matter)?

And why do elementary particles have mass at all?
(Simply sticking masses onto particles breaks gauge symmetry)

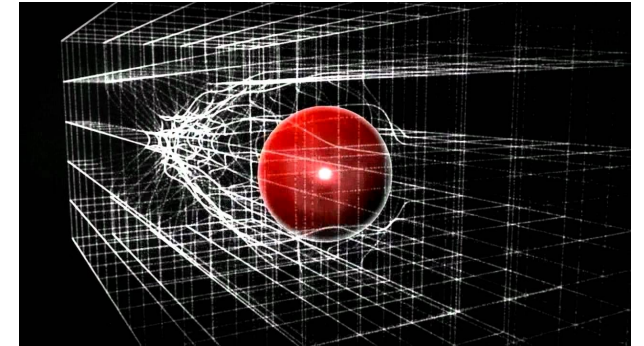
Gauge symmetry and the Brout-Englert-Higgs mechanism

A solution to the mass problem is to introduce a new complex scalar field ϕ , which couples to the weak bosons and fermions, and whose energy potential is such that the field condensates below a critical temperature T_{EW} with a non-zero vacuum expectation value $\langle 0|\phi|0\rangle = v \neq 0$, thus spontaneously breaking the symmetry of the vacuum

The field pervades all space. The interaction of a particle with the Higgs field gives the particle mass. The stronger the interaction the greater the mass.

The fermion “Dirac” mass term $-m_f(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ couples the left- and right-chiral fermion fields, enabling chirality-changing processes

A local excitation of the Higgs field ϕ around its ground state is the **Higgs boson**



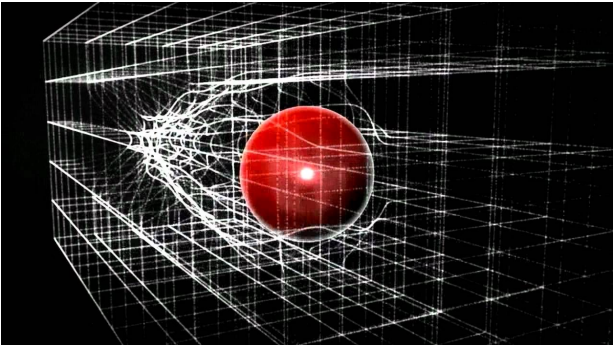
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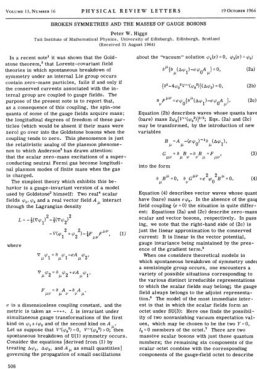
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Peter Ware Higgs (1929 – 2024)



[Broken Symmetries and the Masses of Gauge Bosons](#), PRL 13, 508, (1964) — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

Superconductivity (BCS theory) was key in the development of the BEH mechanism [[My life as a boson](#), 2010]

François Englert (1932 – 2026)

Robert Brout (1928 – 2011)

[Broken Symmetry and the Mass of Gauge Vector Mesons](#), PRL 13, 321, (1964)



The Brout-Englert-Higgs (BEH) mechanism

*Note that in the SM, this phase transition is a smooth crossover, ie, of 2nd order with no Higgs bubble creation

The BEH potential energy:

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

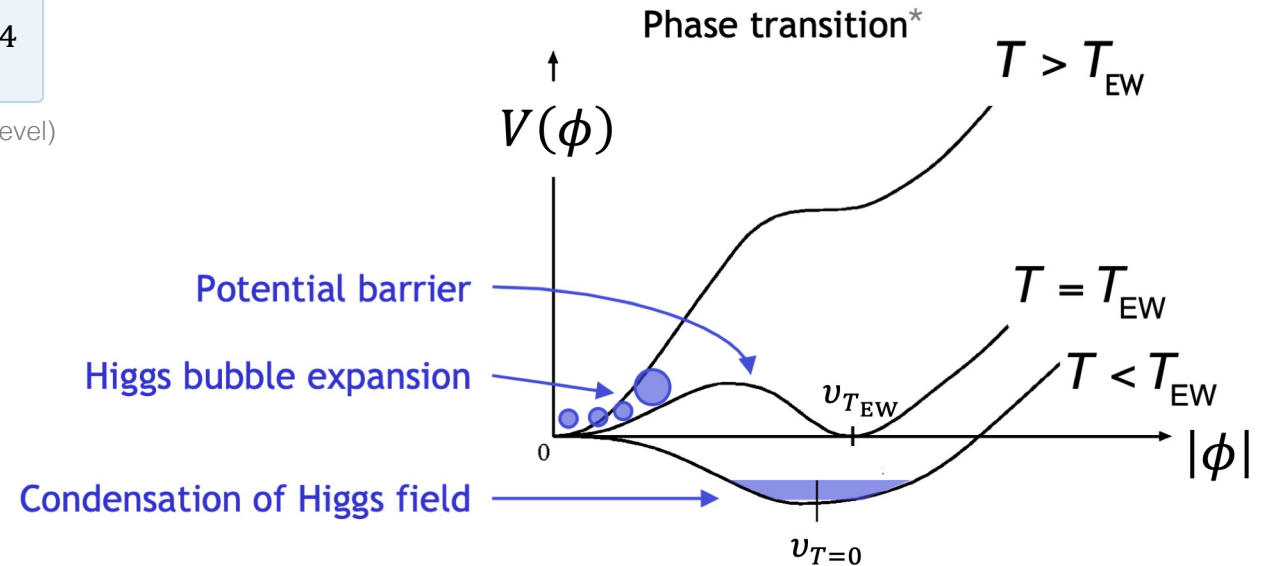
At lowest order (tree level)

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = v_T = 0$), a phase transition at $\sim T_{EW}$ ($\sim 10^{15}$ K, 10^{-12} s after the big bang) led to $|\phi_{min}| = v_{T_{EW}} > 0$

At $T = 0$, $V(\phi)$ has a minimum at:

$$v = v_{T=0} = \sqrt{\frac{\mu^2}{2\lambda}} \quad (v = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246 \text{ GeV})$$

where was used: $g/m_W \propto \sqrt{G_F}$



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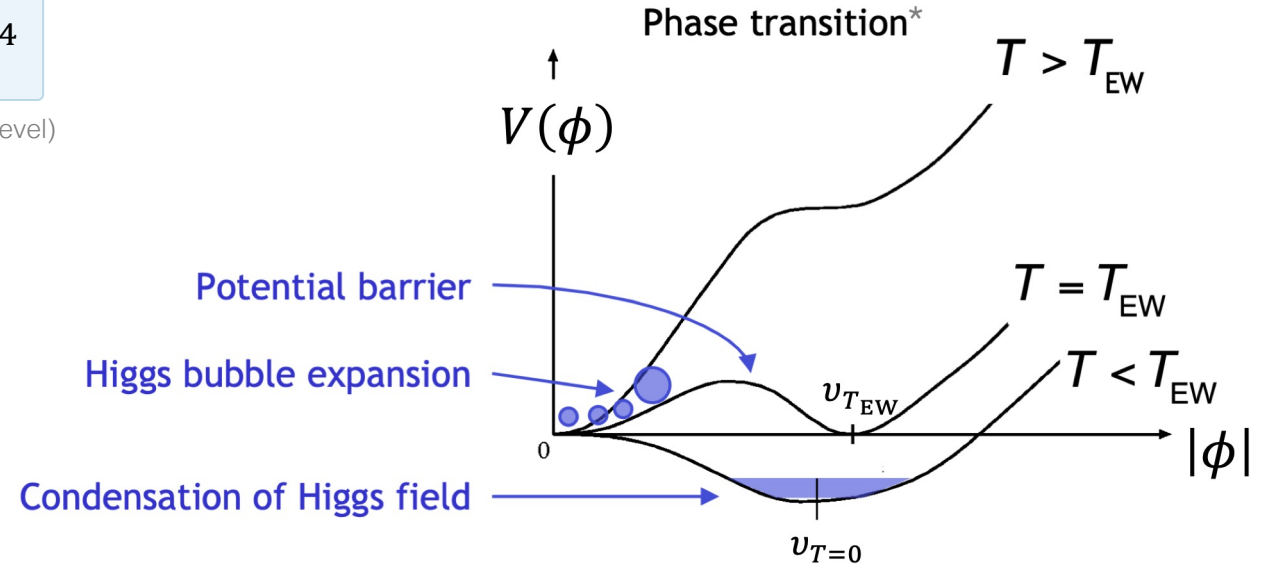
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Developing $\phi(x) \propto (0, v + H(x))$ around the minimum and inserting it into the SM Lagrangian expanded by particle interactions with $\phi(x)$, determines the particle spectrum

- $m_\gamma = 0$, $m_W = \frac{1}{2}gv$, $m_Z = \frac{1}{2}\sqrt{g^2 + g'^2} \cdot v$, $m_W/m_Z = \cos \theta_W$
- $m_f = \frac{1}{\sqrt{2}}y_f v$, (y_f = Yukawa couplings, not predicted by Higgs mechanism, note that $y_{\text{top}} \approx 1$, but $y_e \approx 3 \cdot 10^{-6}$)
- $m_H = \sqrt{2} \cdot \mu = v\sqrt{2\lambda} + \Delta\lambda$ (energy-dependent quantum corrections)



The Brout-Englert-Higgs mechanism

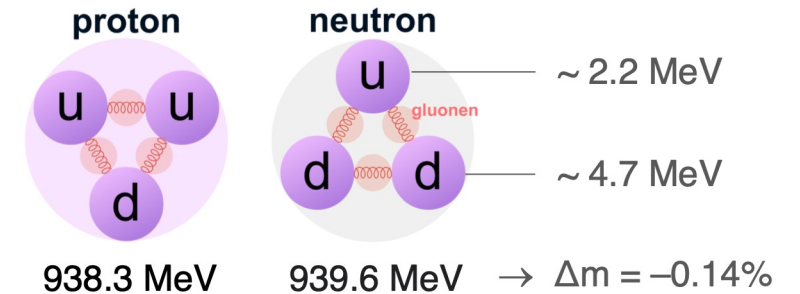
A few remarks:

- The left-right asymmetric (chiral, V–A) gauge structure of weak interaction forbids “bare” fermion masses; they arise only via the BEH mechanism $m_f = \frac{1}{\sqrt{2}} y_f v$, making SM fermions naturally light
- The SM fermion structure may suggest that there are (many?) super-heavy left-right gauge symmetric fermions (beyond our reach) in a grand-unified framework, and the SM fermions only survived down to the EW scale because they cannot have bare masses. This may also explain the very light neutrinos (lepton-number violation has at least D=5, suppressed by super-heavy M)
- The Higgs boson can have bare mass, so why is it (and with it the W and Z bosons) not super heavy?
- **This is the core conceptual challenge of the SM, calling for in-depth study of the scalar sector and potential TeV-scale extensions**

The Brout-Englert-Higgs mechanism

A few further comments:

- BEH mechanism is a new origin of mass via spontaneous symmetry breaking. Other forms: binding energy in composite objects (emergent property of interactions), mass from classical inertia (mass is just a fixed property with no explanation — it's “given”), or the bare Higgs boson mass itself, which comes from the curvature of the BEH potential at the minimum ($m_H = v\sqrt{2\lambda}$), and is a gauge invariant parameter of the Lagrangian
- The BEH mechanism is required because we assume the bosons and fermions to be elementary. It would be different had they substructure: binding energy could give mass
- The resulting mass values govern the history of the universe (incl. complex chemistry and life) → what would happen had we (or nature) a dial to change the particle masses?
- *Quiz: What would happen, had the electron the mass of a muon?* [see [R. Cahn, 1996](#)] *Are there other indications of an apparently “designed” or “anthropically selected” universe (m_u , m_d , m_e , α , v , ...)?* [see [J. Donoghue, 2016](#)]



A remarkable analogy — Superconductivity

The universe as a superconductor for weak interactions

SC (BCS*) theory

Cooper pair Bose condensate

Condensate charge ($-2e$)

Effective photon mass

$T_{\text{crit}} \sim \text{mK}$ to several tens of K

Higgs mechanism

Higgs VEV (condensed Higgs field)

Higgs doublet carries weak charge

W & Z bosons acquire mass

EW crossover: $T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$



A superconductor is locked mid-air in different orientations above a permanent magnet — superconductive levitation due to the expulsion of the static magnetic field (Meissner effect) [[Source](#)]

In response to an externally applied magnetic field, perpetual eddy currents circulate in the superconductor, producing an internal magnetic field that exactly cancels the externally applied one

*Bardeen, Cooper, Schrieffer theory – mid 1950s

Further reading, eg: [L. Dixon, "From superconductors to supercolliders"](#), 1996

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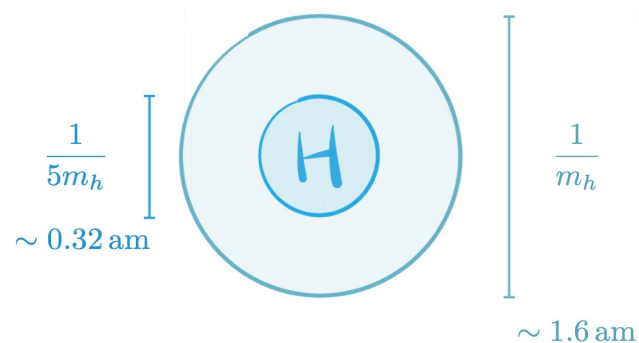
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→ Is the Higgs boson elementary or composite?



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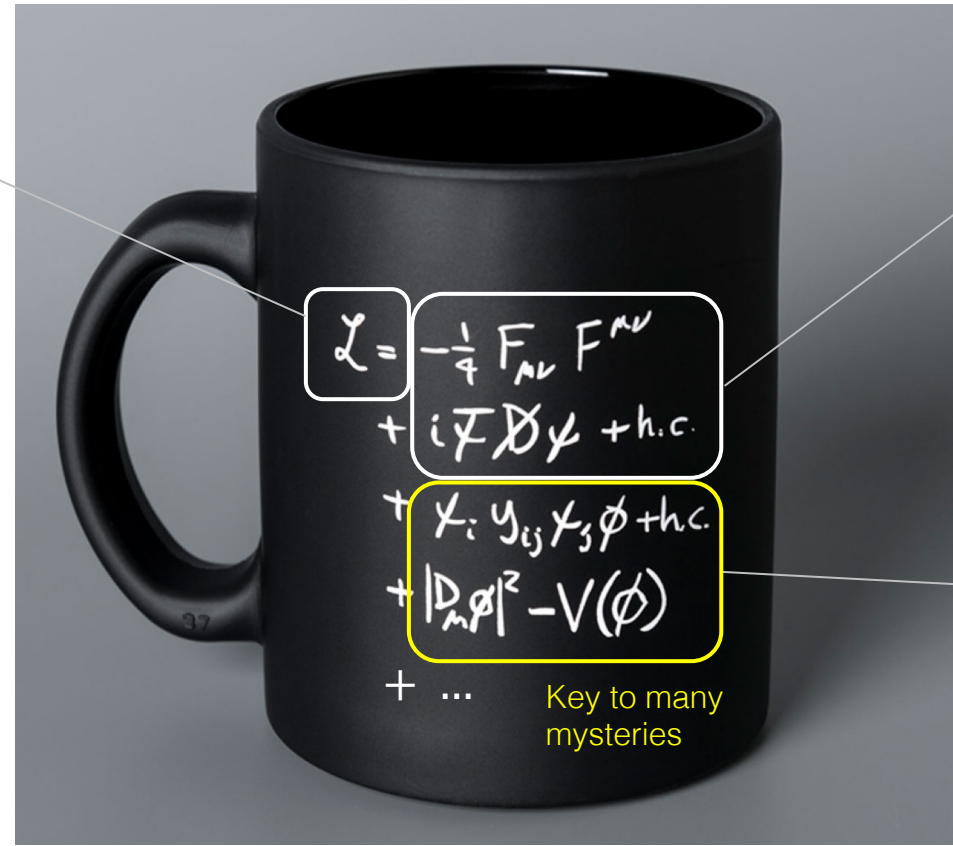
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Completing the Standard Model

The scalar Higgs sector completes the Standard Model

The **SM Lagrangian**



These terms describe **interactions among force particles (top) and among matter and force particles (bottom)**

Beauty: interactions governed by gauge symmetries with only 3 (EW) and 2 (QCD, θ_{strong} tiny $\rightarrow$ strong CP problem) parameters

This term is related to the **Higgs sector**

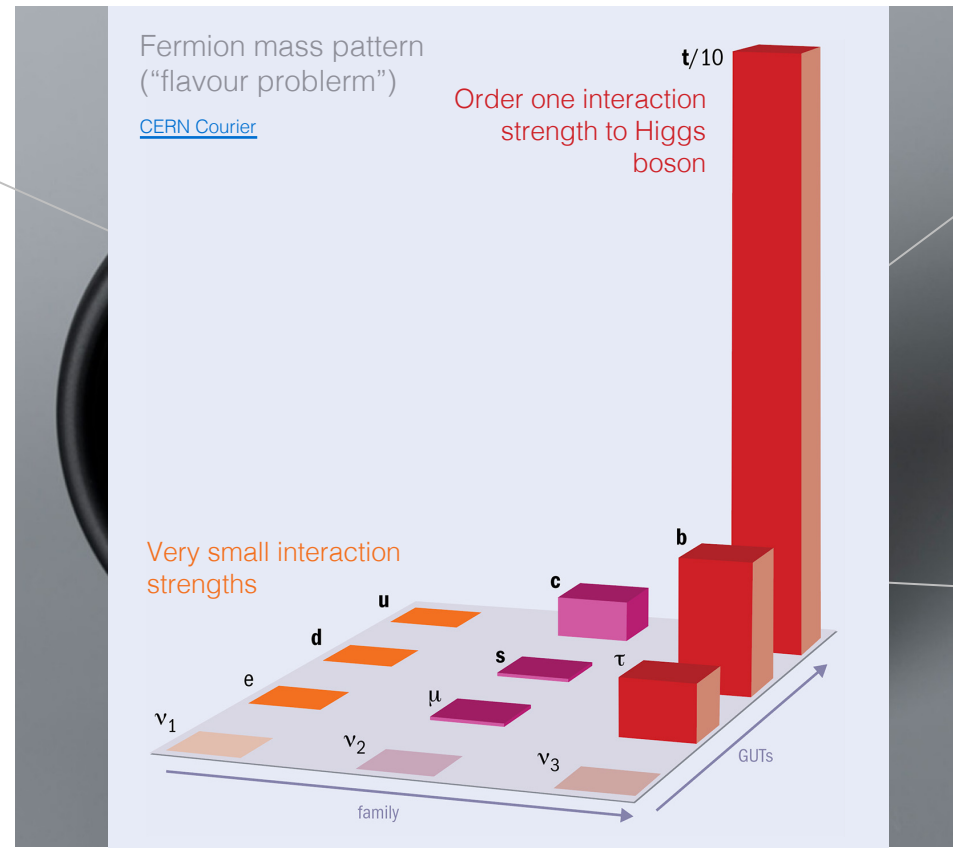
Unpleasant: not governed by symmetries, 23 free parameters*, large hierarchy among masses

*Assuming neutrinos are Majorana particles (total of 9 neutrino related parameters)

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Producing the Higgs boson and pushing the boundaries of our understanding requires a huge accelerator

This accelerator has been built at CERN

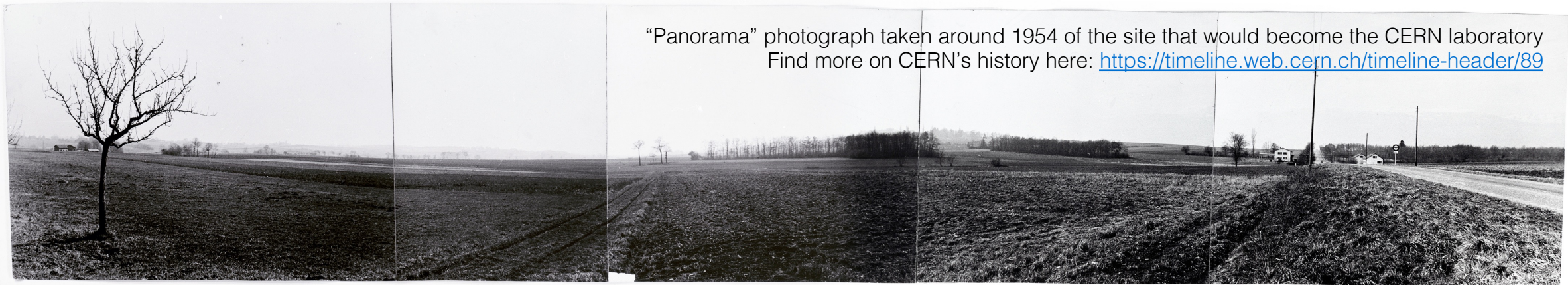


Objective: Creation of a powerful and competitive infrastructure for fundamental research in nuclear / particle physics in Europe

1952: Creation of a Council: "Conseil Européen pour la Recherche Nucléaire"

Belgium, Denmark, France, West Germany, Greece, Italy, The Netherlands, Norway, Sweden, Switzerland, United Kingdom, Yugoslavia

Coming into force of the convention on 29 September 1954: Foundation as "Organisation Européenne pour la Recherche Nucléaire"



Objective: Creation of a powerful and competitive infrastructure for fundamental research in nuclear / particle physics in Europe

The first steps towards CERN's creation were taken in the United States between 1947 and 1949. François de Rose, a French diplomat who was involved in that process, remembers Robert Oppenheimer saying to him: "We have learnt all we know in Europe. But in the future, fundamental physics research is going to require substantial resources which will be beyond the means of individual European countries. You will need to pool your efforts to build these big machines that are going to be needed. It would be unhealthy if the Europeans were obliged to go the United States or the Soviet Union to conduct their fundamental research."

Source: <https://home.cern/news/series/cern70/cern70-foundations-european-science>



tory
r/89



On 17 May 1954, the first shovel of earth was dug on the Meyrin site in Switzerland under the eyes of Geneva officials and members of CERN staff



Aerial view of the 25 GeV Proton Synchrotron at CERN in 1965

CERN today — the world's largest centre for particle physics



CERN – Meyrin Campus next to Geneva, Switzerland

CERN today

ATLAS Experiment



CERN today: 25 Member States



A laboratory for people around the world

25 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Estonia – Finland – France – Germany
Greece – Hungary – Israel – Italy – Netherlands
Norway – Poland – Portugal – Romania – Serbia
Slovakia – Slovenia – Spain – Sweden – Switzerland
United Kingdom

10 Associate Member States

Brazil – Croatia – Cyprus – India – Ireland – Latvia
Lithuania – Pakistan – Türkiye – Ukraine

4 Observers

Japan – USA – European Union – UNESCO

Data as of 31 December 2024

~ 50 Cooperation Agreements

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bahrain
Bangladesh – Bolivia – Bosnia and Herzegovina – Canada – Chile – Colombia
Costa Rica – Ecuador – Egypt – Georgia – Guatemala – Honduras – Iceland
Iran – Jordan – Kazakhstan – Lebanon – Malta – Mexico – Mongolia – Montenegro
Morocco – Nepal – New Zealand – North Macedonia – Paraguay – Palestine
People's Republic of China – Peru – Philippines – Qatar – Saudi Arabia
South Africa – Sri Lanka – Thailand – Republic of Korea – Tunisia
United Arab Emirates – Uruguay – Vietnam

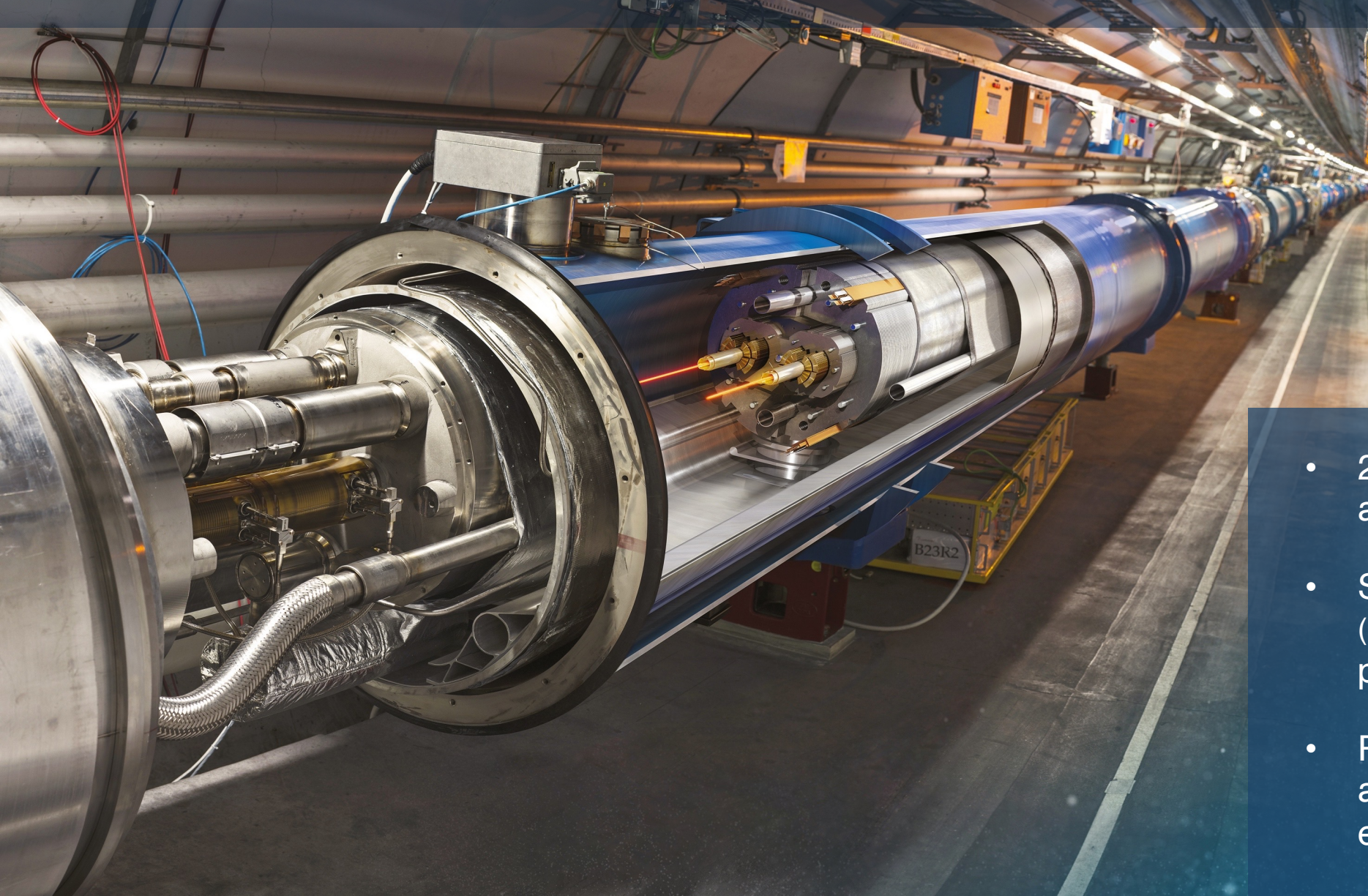
CERN members:

- 2'700 staff
- 1'200 graduates and fellows
- 13'000 users (3'000 Ph.D. students)



Education & training is one
of CERN's core mission

Large Hadron Collider (LHC) — the world's largest accelerator reaching unprecedented energies



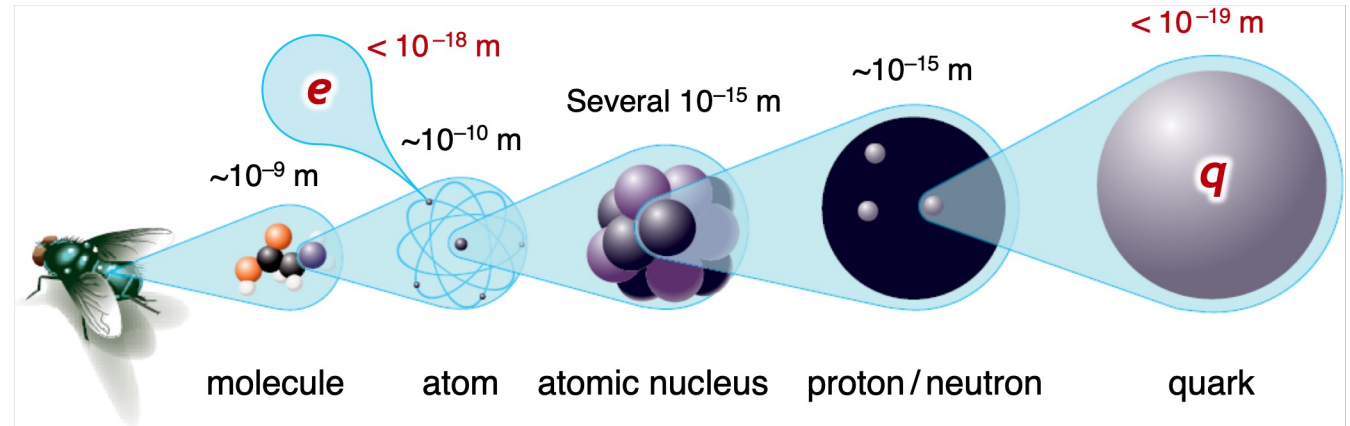
- 27 km underground accelerator and collider
- Superconducting magnets ($1.9\text{ K} = -271.3\text{ }^{\circ}\text{C}$) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

A few accelerator and collider basics (example: LHC)

A particle collider can **create new particles**, higher energy $\rightarrow$ heavier particles: $E = mc^2$

It is (also) a **microscope**,
higher energy $\rightarrow$ better space resolution:

$$\lambda[\text{nm}] = \frac{hc}{E} \approx \frac{1240 \text{ eV} \cdot \text{nm}}{E [\text{eV}]}, \quad \lambda_{\text{de Broglie}} = \frac{h}{p}$$



Visible light microscope



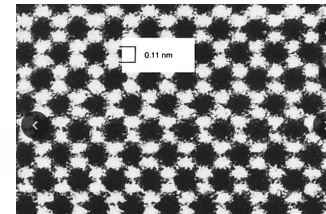

 $\lambda \approx 400\text{--}700 \text{ nm}$



Electron microscopes



$\lambda < 0.1 \text{ nm}$



Atomic structure of diamond surface

LHC

$\lambda_{\text{de B.}} \sim 2 \cdot 10^{-19} \text{ m (at 10 TeV)}$



Particle collider versus fixed target

Central collisions vs. hitting a stationary (“fixed”) target?

$$E_{\text{CM}}^2 = s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2E_1E_2 - 2\mathbf{p}_1\mathbf{p}_2$$



$$E_1 = E_2 = E_{\text{beam}}, \mathbf{p}_1 = -\mathbf{p}_2$$

$$\rightarrow E_{\text{CM}} = \sqrt{s} \approx 2E_{\text{beam}}$$



$$E_1 = E_{\text{beam}}, E_2 = m_2, \mathbf{p}_2 = 0$$

$$\rightarrow E_{\text{CM}} \approx \sqrt{2m_2E_{\text{beam}}}$$

Huge advantage of colliders over fixed target; for protons: $E_{\text{CM}} = 1.4\sqrt{\text{GeV}}\sqrt{E_{\text{beam}}}$

$\rightarrow E_{\text{CM}} = 14 \text{ TeV}$ would require a $100'000 \text{ TeV} = 100 \text{ PeV}$ beam in fixed target mode

Collider reaches much higher E_{CM} , so why are fixed target collisions still useful?

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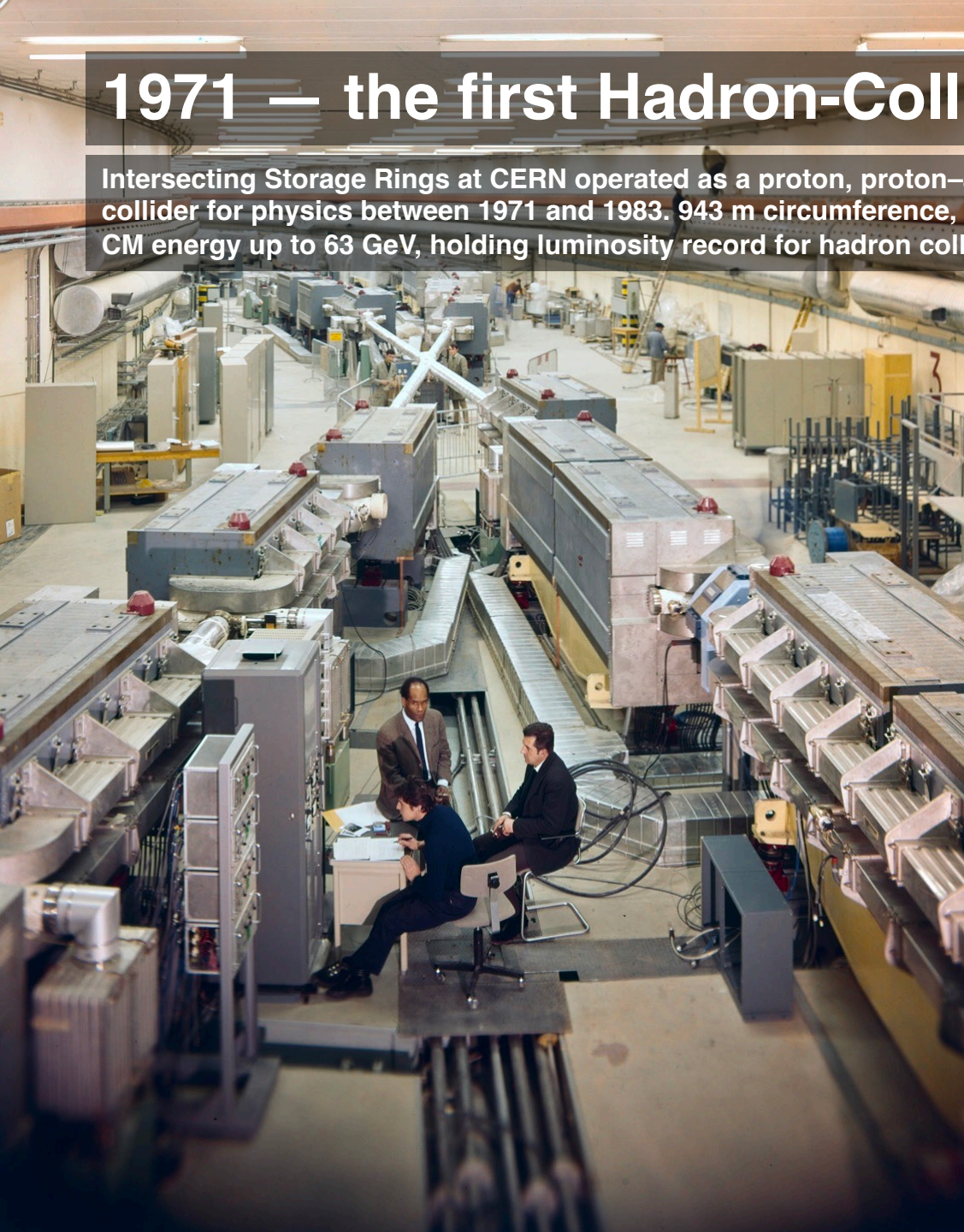
$$\rightarrow E_{\text{CM}} \approx \sqrt{2m_2E_{\text{beam}}}$$

The second quantity that characterises particle collisions is **luminosity** L ($N_{\text{events of given process}} = \sigma_{\text{process}} \cdot L$)

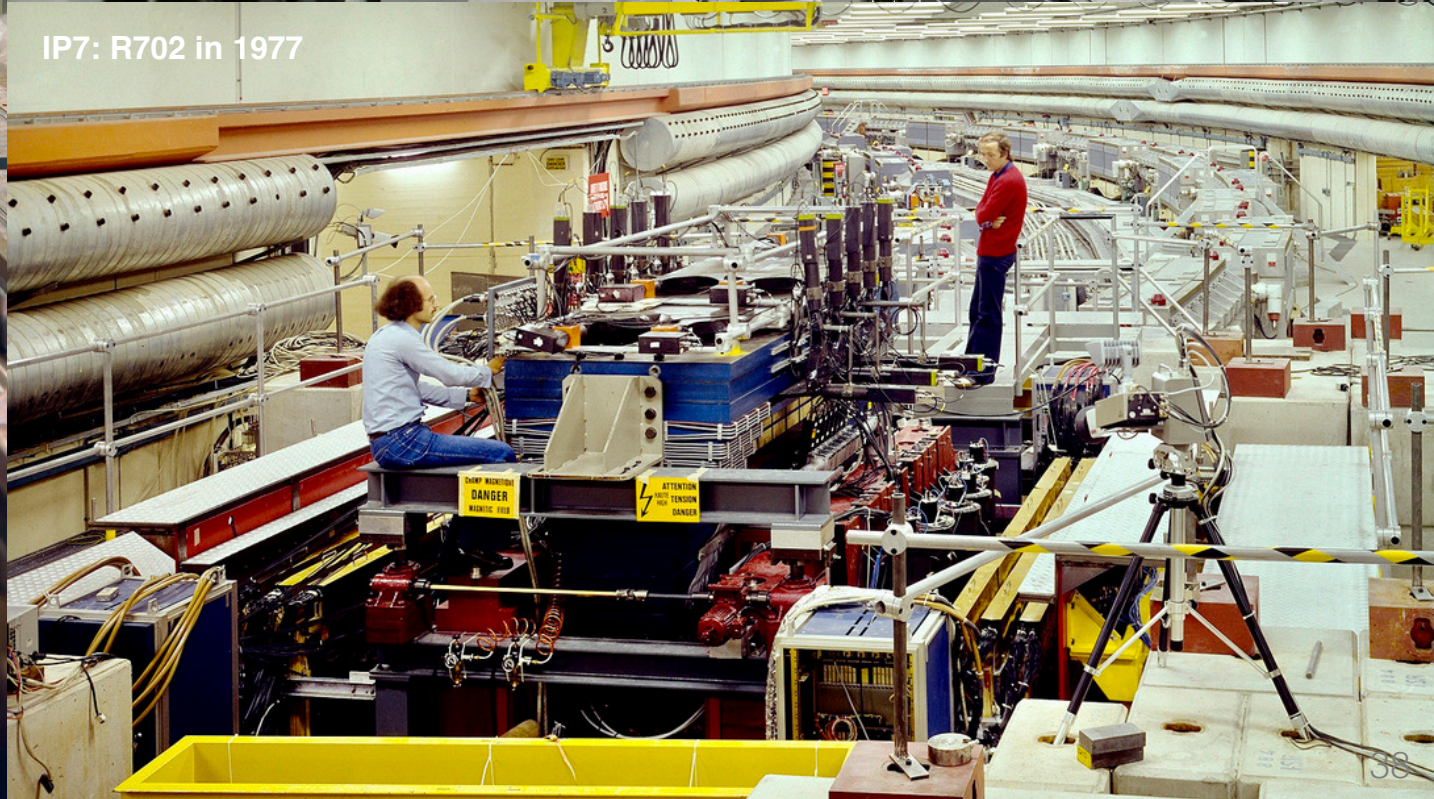
- At a collider $L = n_1 n_2 f / A$. LHC: $n_1 \sim n_2 \sim 1.6 \cdot 10^{11}$ protons, $f \approx 28$ MHz, $A \sim 4\pi(0.016 \mu\text{m})^2 \rightarrow L \sim 2.2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- At a fixed-target experiment like NA62 at CERN's SPS, a proton beam hits a Be target of 40 cm length $\rightarrow 4.4 \cdot 10^{25}$ nucleons/cm² !), reaching an effective luminosity of $L = \phi_{\text{beam}} [\text{protons/s}] \cdot n_{\text{target}} [\text{nucleons/cm}^2] \sim 10^{37} \text{ cm}^{-2}\text{s}^{-1}$
- Fixed-target experiments are also way easier to build and have less stringent precision / alignment requirements
- Nevertheless, to reach the energy frontier, a collider is best!

1971 — the first Hadron-Collider

Intersecting Storage Rings at CERN operated as a proton, proton-antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron colliders until 2004



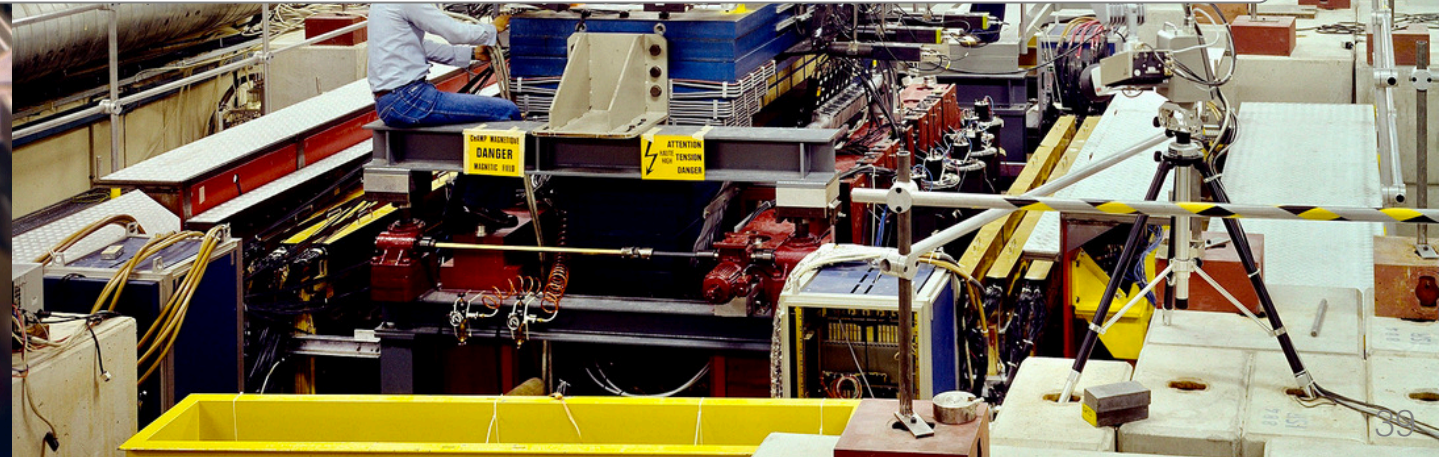
IP7: R702 in 1977



1971 — the first Hadron-Collider

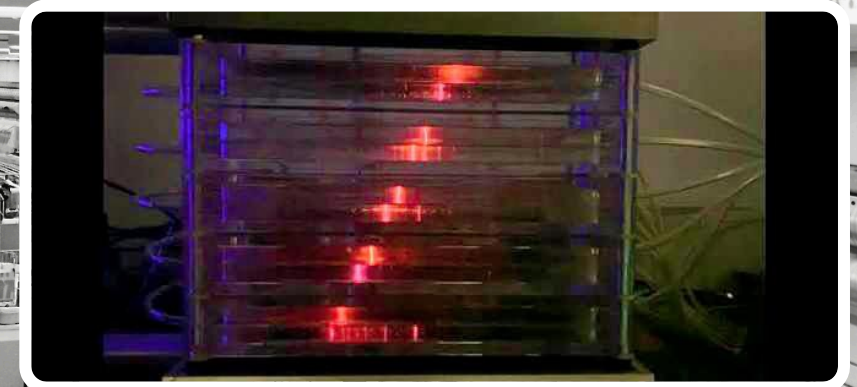
Intersecting Storage Rings at CERN operated as a proton, proton-antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron machines until 2004

The ISR missed the 1974 'November revolution' and also the bottom quark discovery in 1977 because of an initial lack of low-mass triggers, slow DAQ, and insufficient acceptance. However, its legacy enabled the next generation collider experiments: proton stacking, space charge compensation, beam diagnostics, stochastic cooling, van-der-Meer luminosity scans, importance of efficient triggers and large-angle coverage, jets, etc.



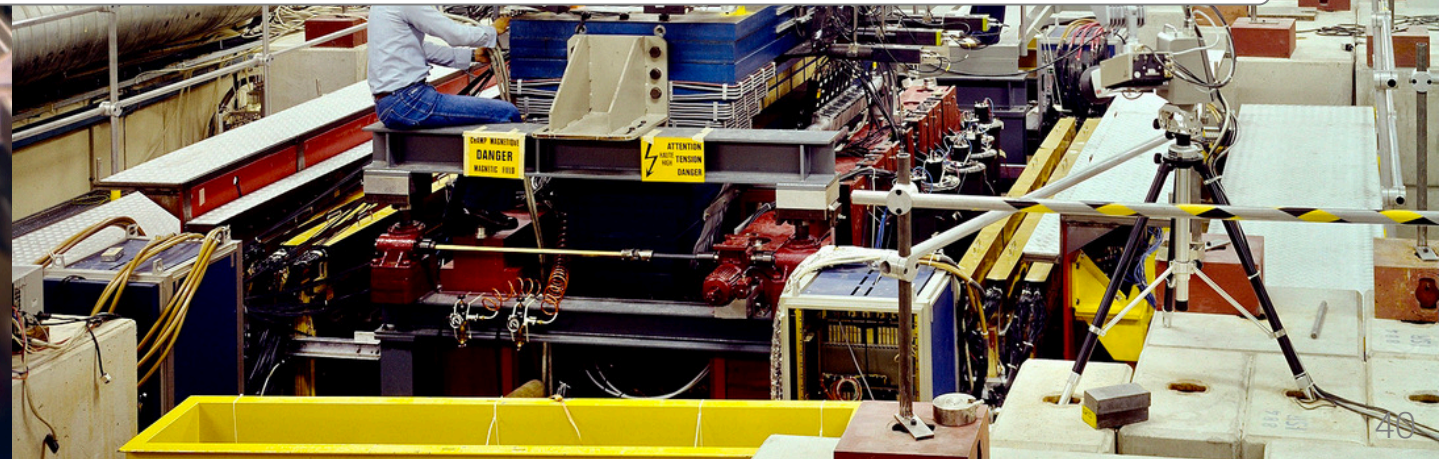
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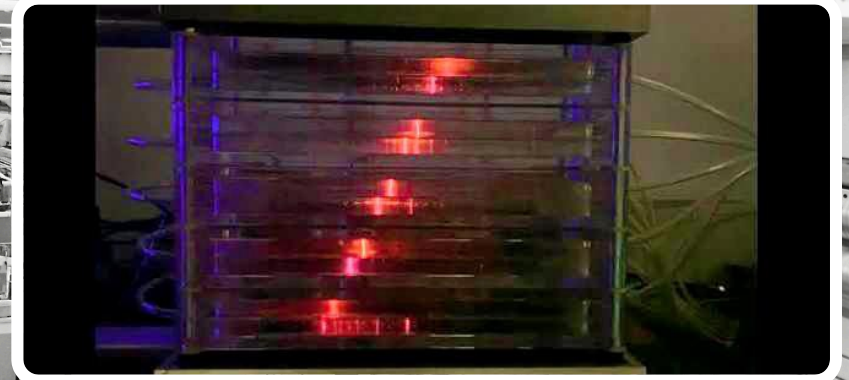
Particle detectors also went through revolutions from the low-rate visual (eg, cloud chambers) and high-rate counting devices (eg, scintillators with PMTs) in the late 1950s, early 1960s, to spark chambers in the 1960s, allowing to visualise charged tracks at relatively high rate

Cylindrical spark chambers were at the heart of the SLAC-LBL Magnetic Detector (Mark-I) at SPEAR enabling the November 1974 revolution (charm), and also the discovery of ψ' , open charm, tau-lepton, quark spin, ...)



1971 — the first Hadron-Collider

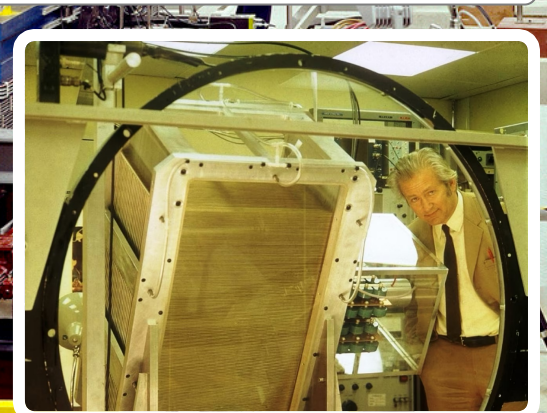
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The development of MWPC in 1968 by G. Charpak rapidly superseded spark chambers during the 1970s, ...



ISR Control Room (early 70s)



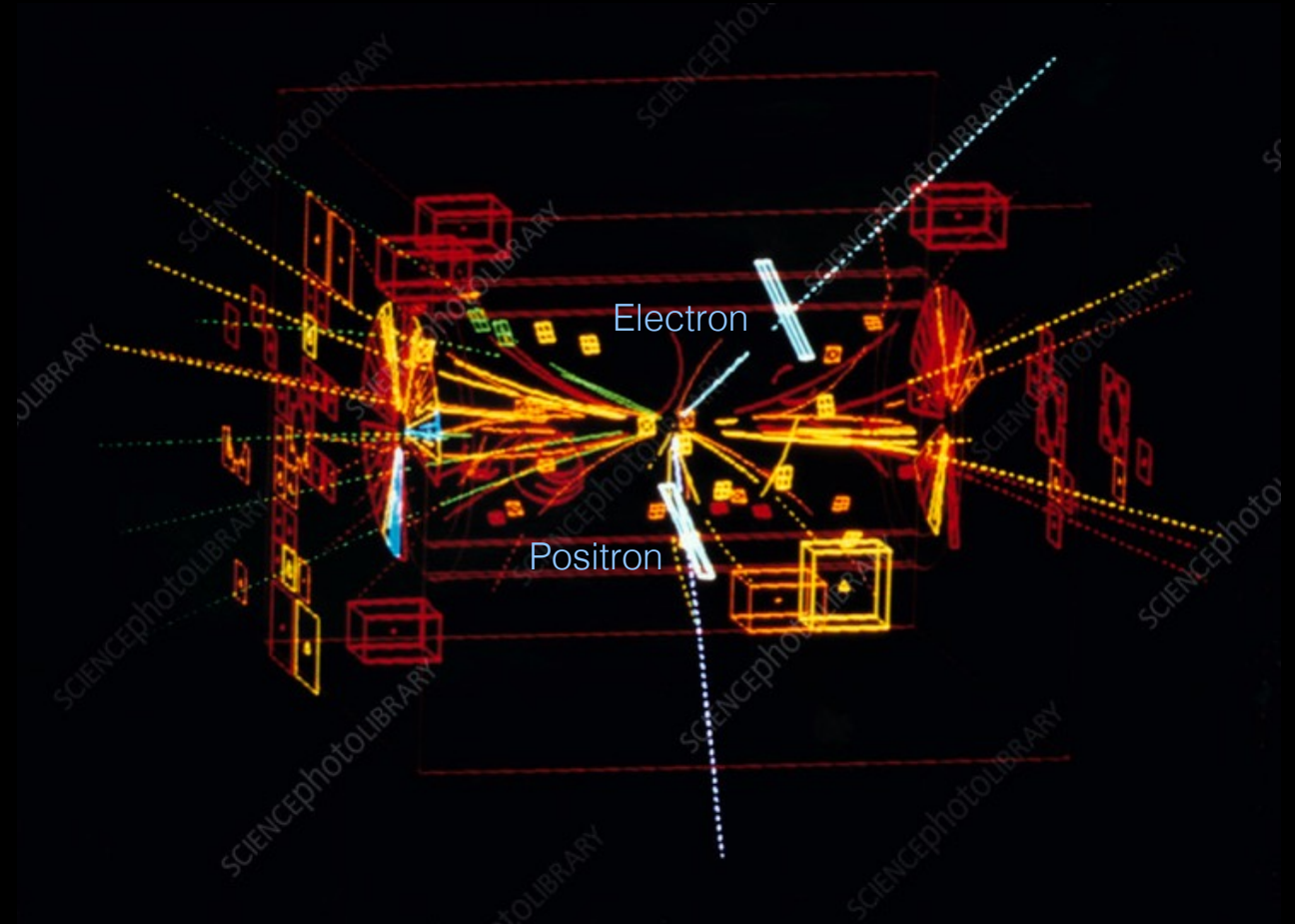
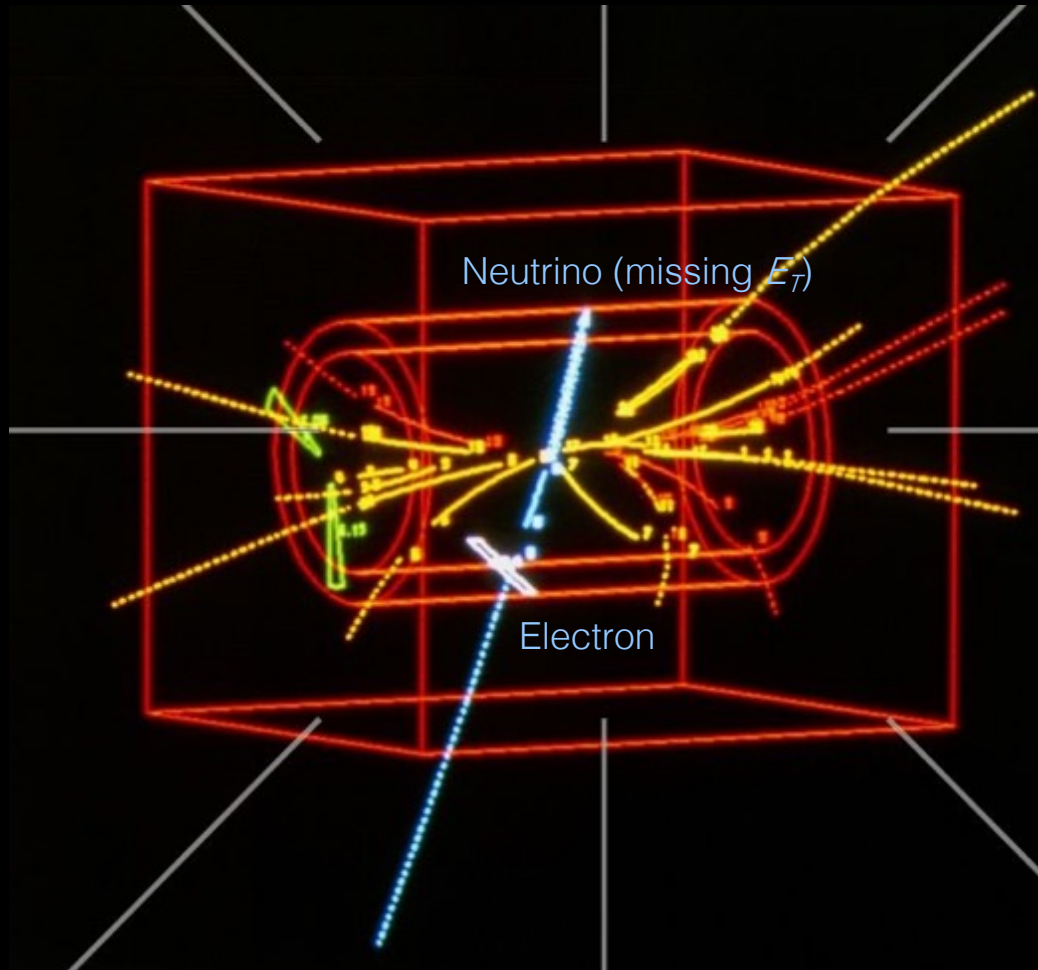
LHC Control Room (July 2022)





SPS: 6.9-km proton synchrotron and ppbar collider, (900 GeV) with UA1 and UA2 detectors
Both experiments were approved in 1978, first data taking in 1981

Discovery of the W and Z bosons by UA1 and UA2 at CERN's SPS collider in 1983

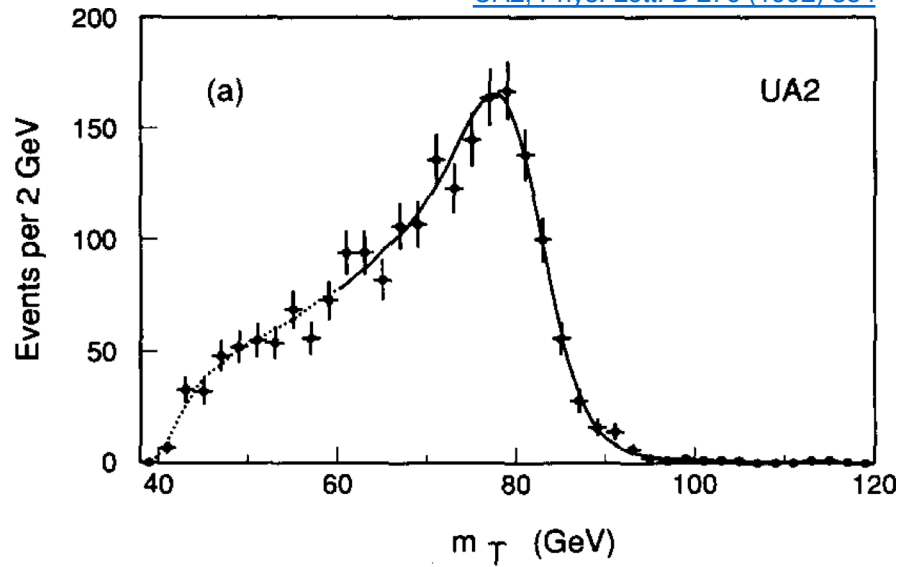


Displays show W (left) and Z (right) boson candidates from proton–antiproton collisions measured in the UA1 detector (1982/83)

Nobel Prize 1984 to Carlo Rubbia and Simon van der Meer *for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction* [[Link](#)]

Discovery of the W and Z bosons by UA1 and UA2 at CERN's SPS collider in 1983

UA2, Phys. Lett. B 276 (1992) 354

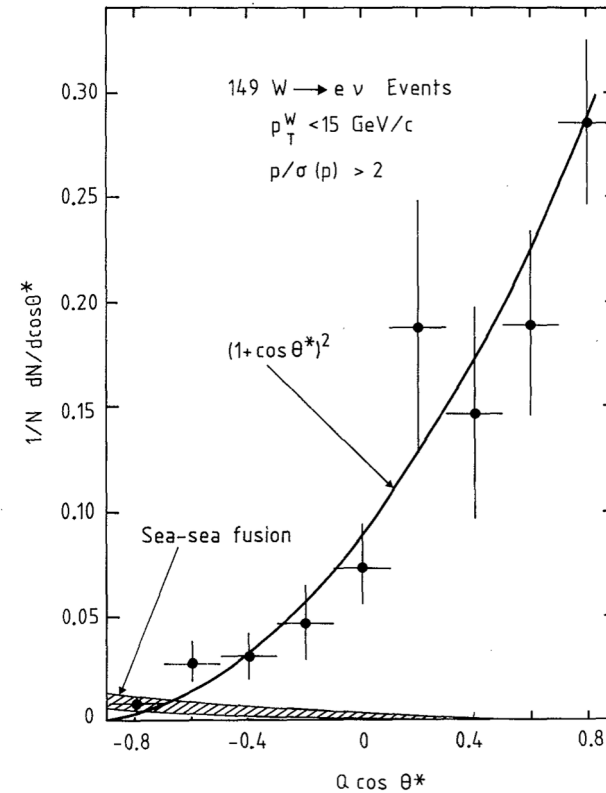


Transverse mass with full UA2 dataset (1992):
 $m_W = 80.84 \pm 0.22 \pm 0.81$ (calibration) GeV

Together with Z-mass measurement allowed to determine the weak mixing angle and to test the "custodial" symmetry relation:

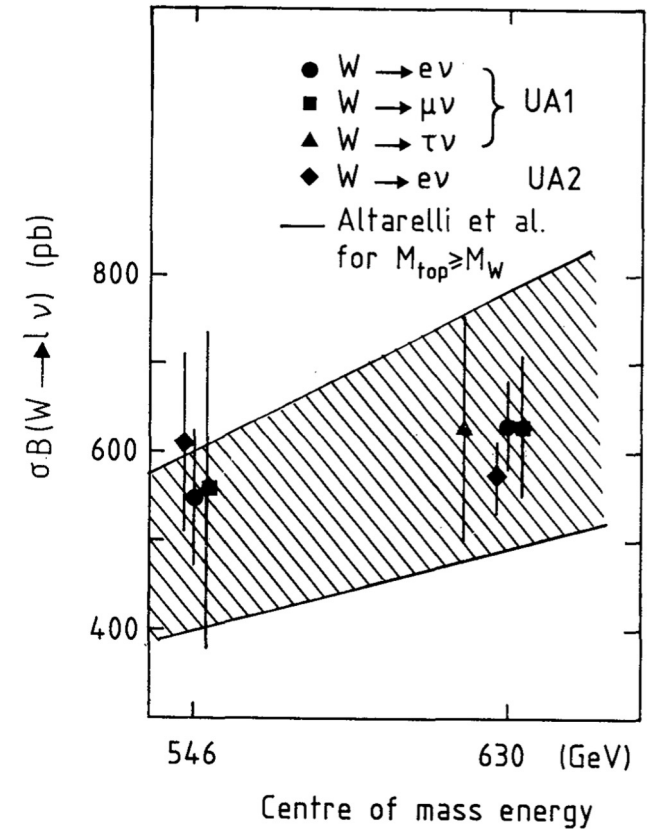
$$\rho \equiv m_W^2 / (m_Z^2 \cdot \cos^2 \theta_W) \approx 1$$

UA1, Z. Phys. C 44 (1989) 15



Charge asymmetry in the $W \rightarrow e \nu$ decay: W production polarised along anti-p beam due to V-A coupling

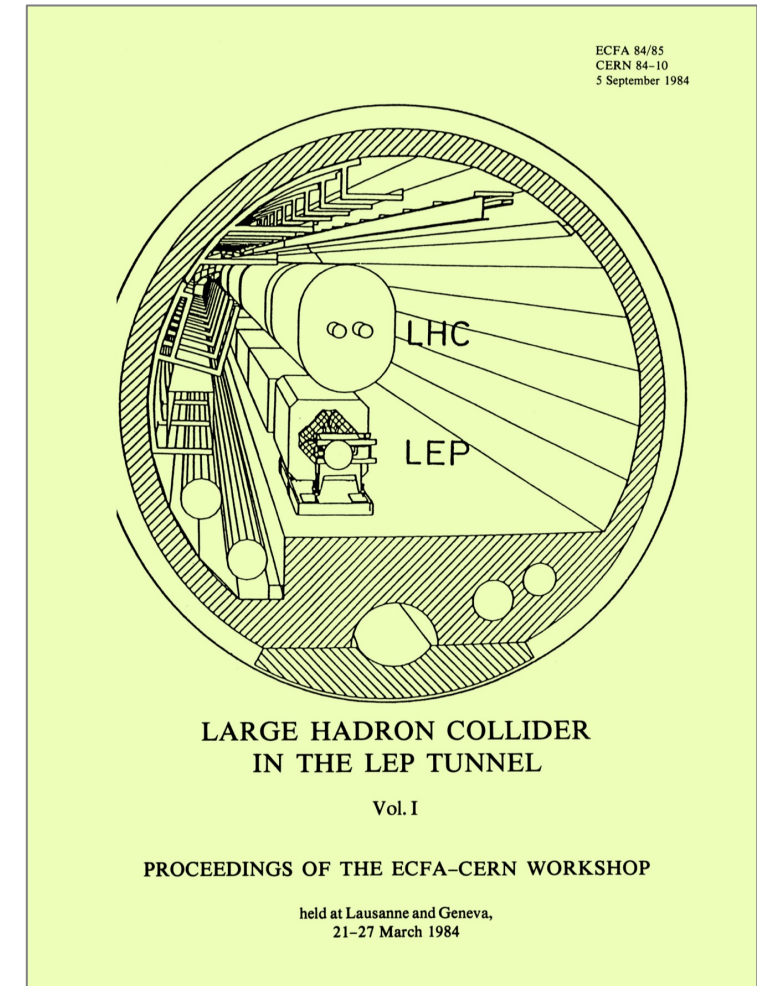
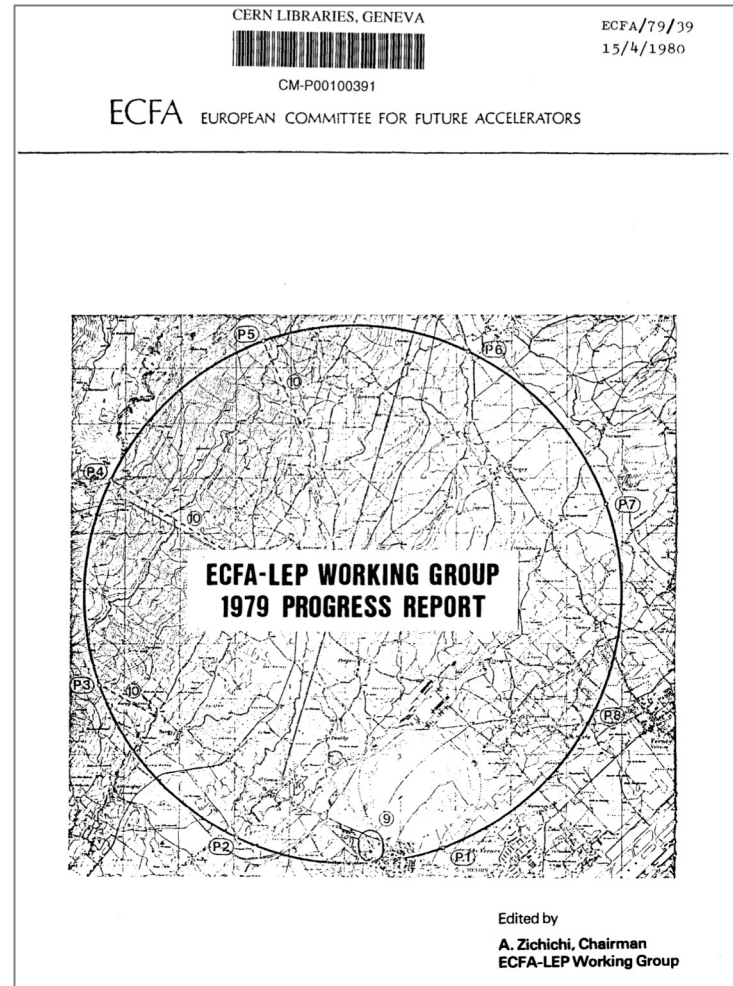
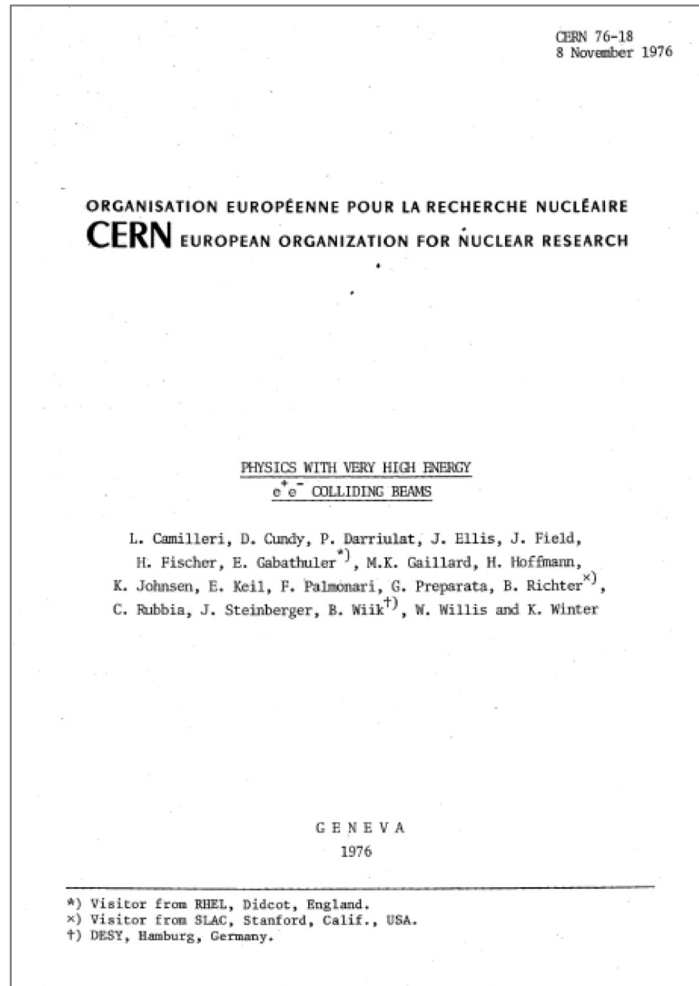
UA1, Z. Phys. C 44 (1989) 15



Universality of weak currents

A new Circular Collider at CERN

The birth of LEP and the LHC: a 26.7 km tunnel facility

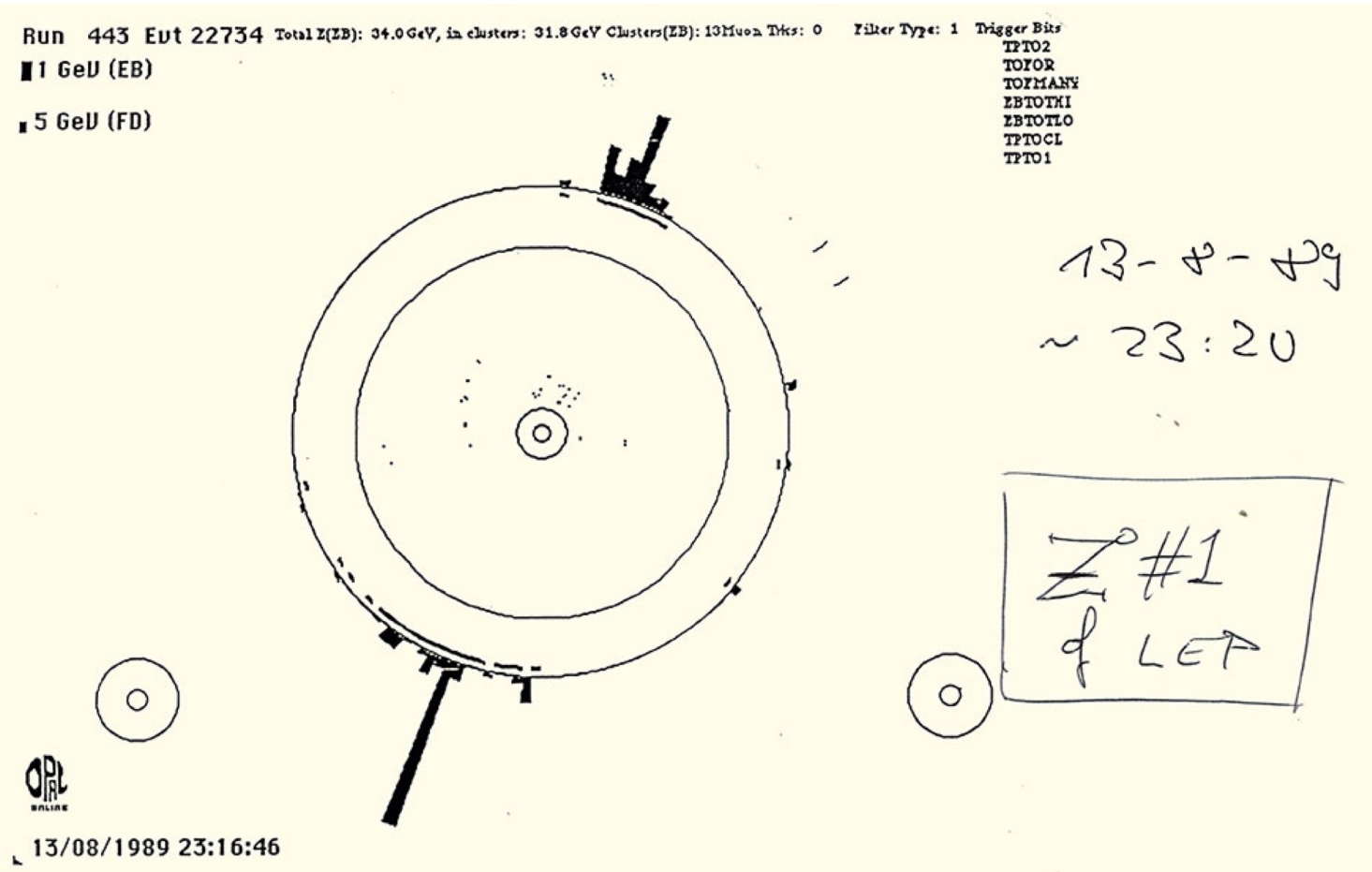


The Large Electron–Positron Collider

LEP was formally approved in 1981, tunnel construction 1983–1988, first beam on 14 July 1989



LEP tunnel before installation of bending magnets

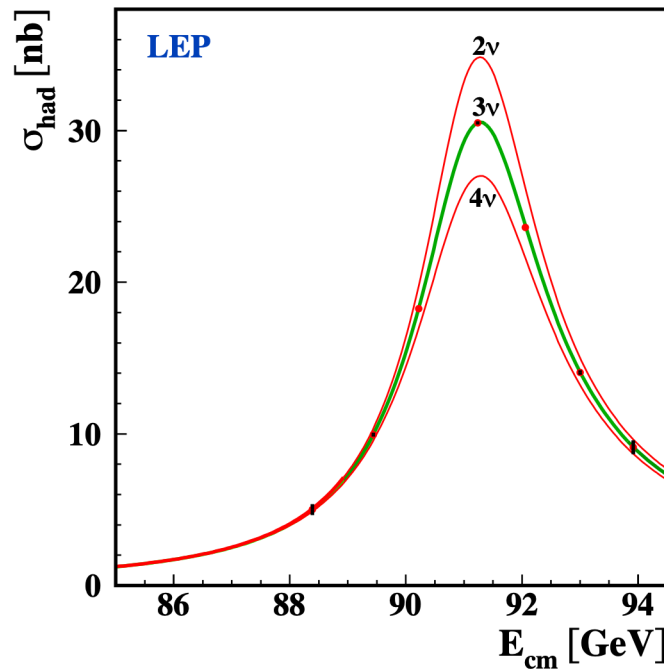


OPAL logbook entry on 13 Aug 1989 with the first Z-boson candidate

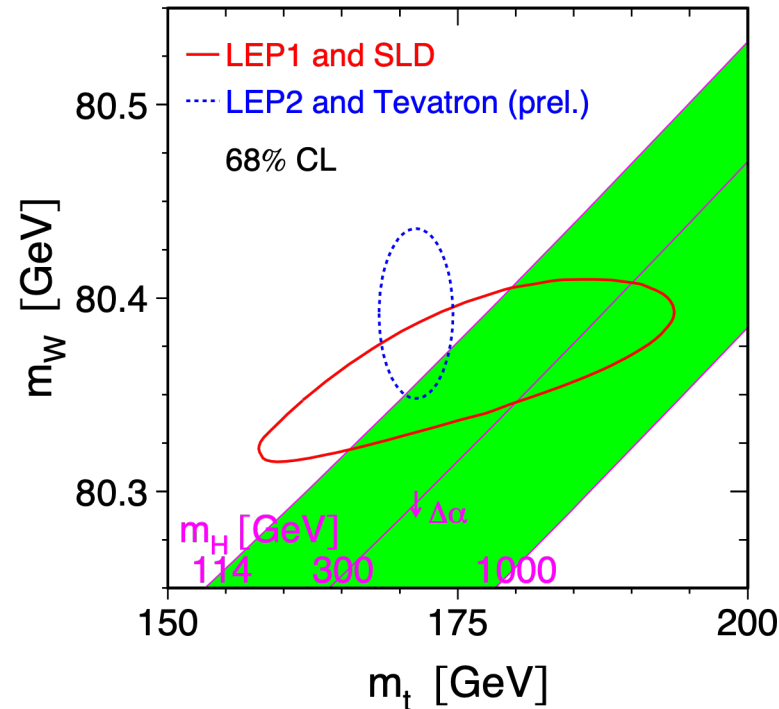
With LEP and SLC, the Standard Model entered the precision era

Huge amount of experimental and theoretical developments during LEP and SLC (SLAC) years, pioneering era of high-precision physics in HEP, **constraints on yet unseen heavy particles through quantum loops**

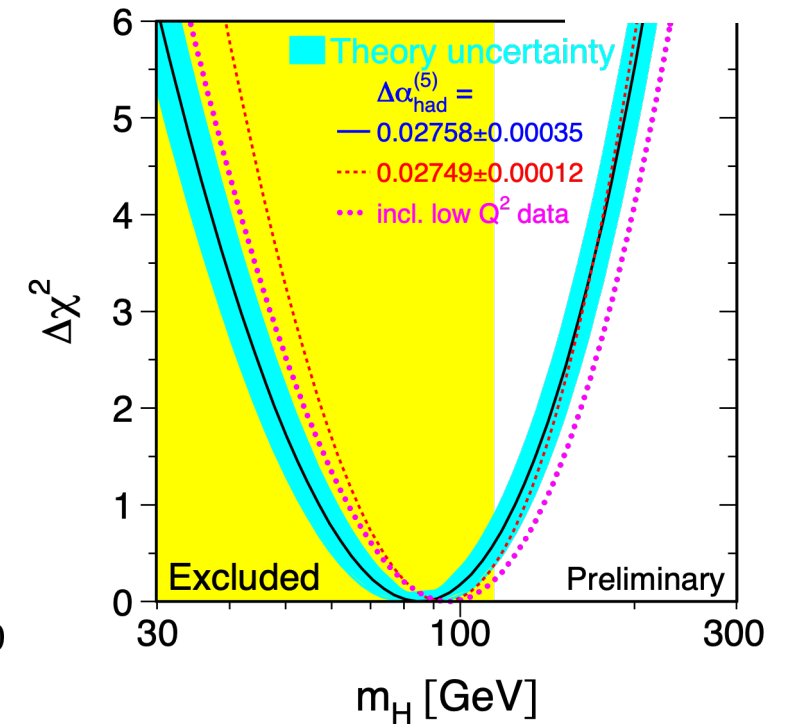
There are 3 light neutrino families



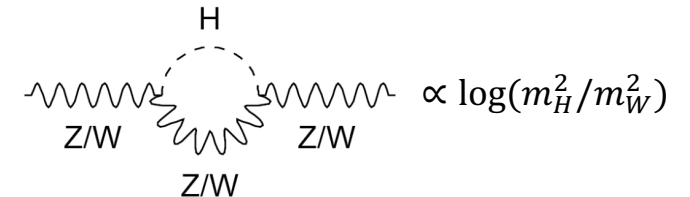
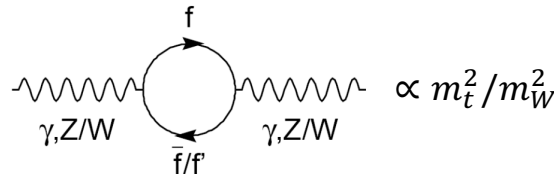
The top quark is heavy



The Higgs boson is light, but $> m_Z$

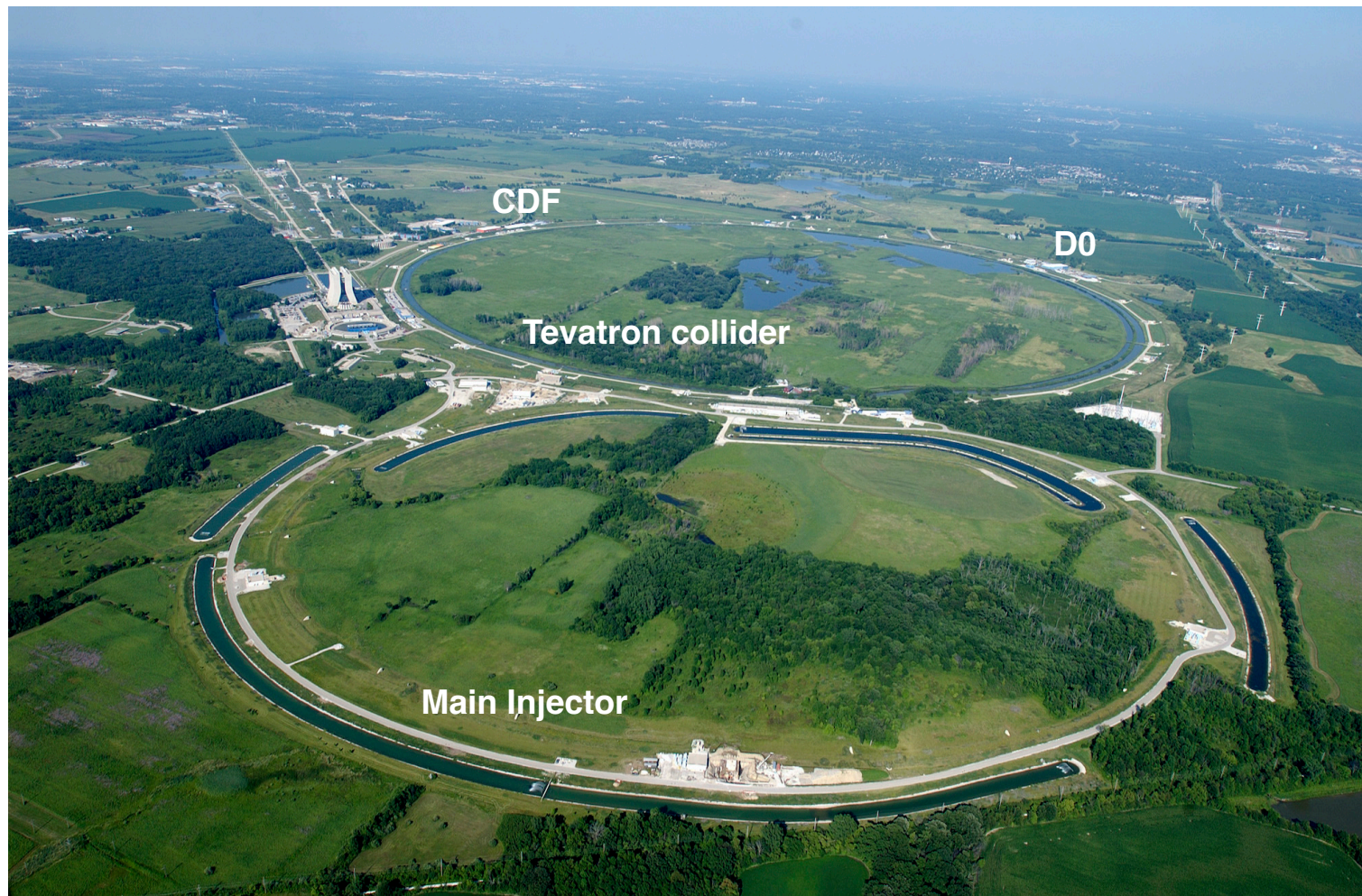


- m_Z measured to 2.1 MeV (0.0023%) precision via beam-energy calibration
- Per-mil tests of lepton universality, QCD, and tau-lepton properties



Late 1980s: the Tevatron at Fermilab climbed at the energy frontier

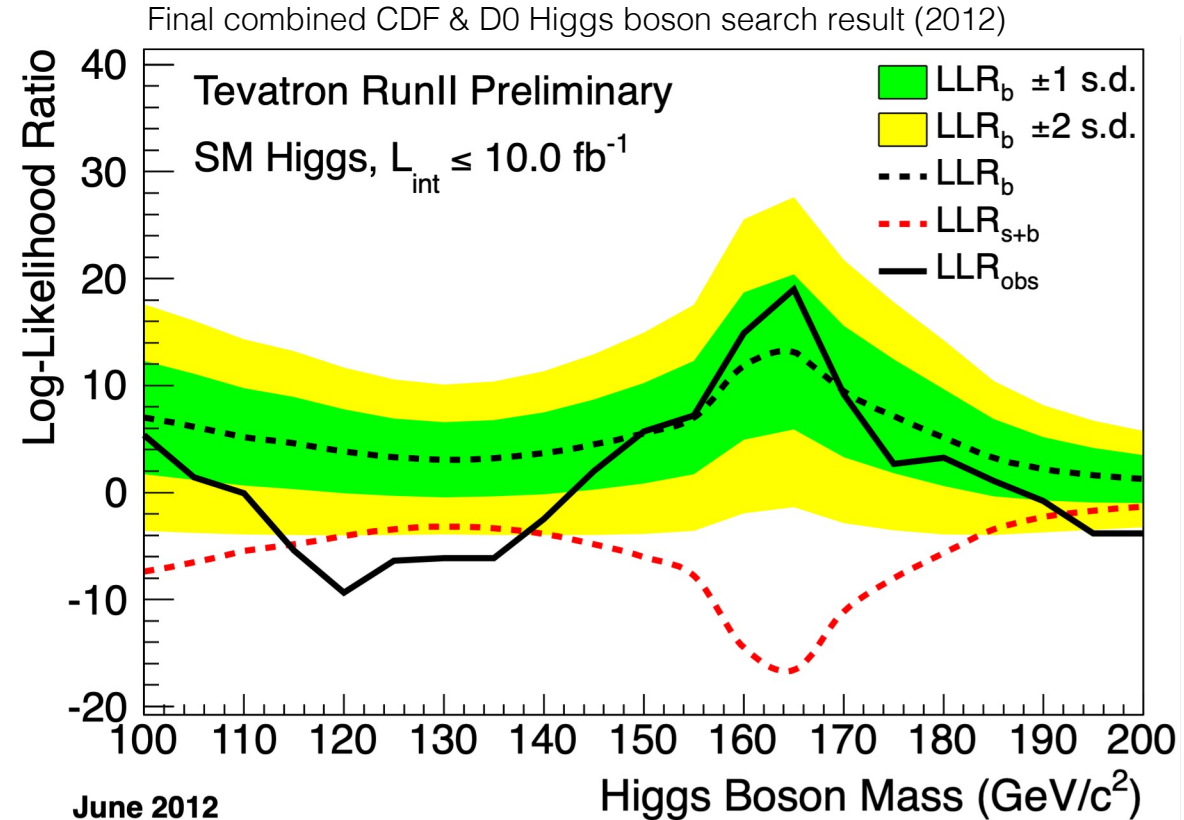
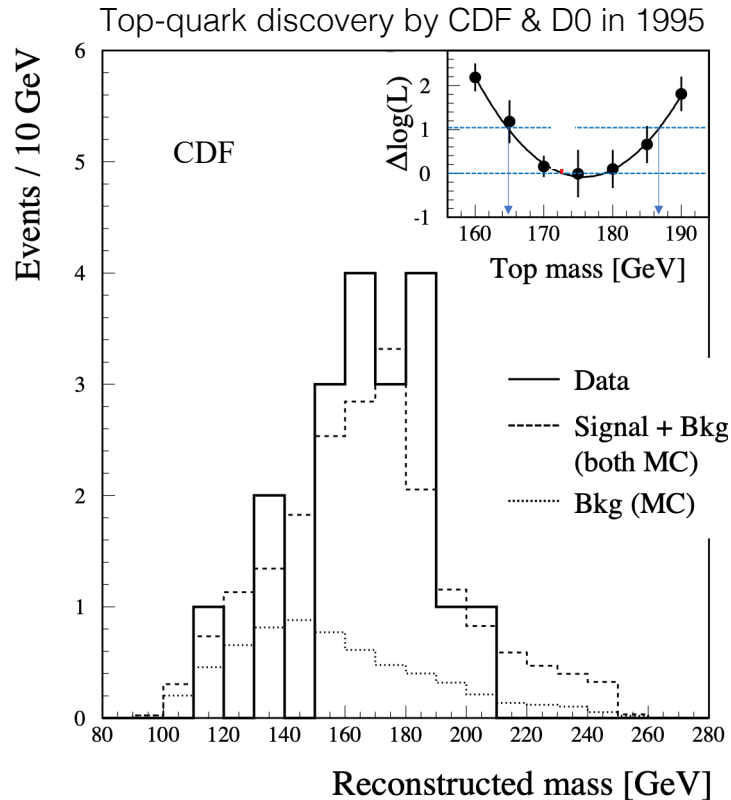
Thanks to 4.4 T superconducting dipole magnets, the 6.3-km circumference Tevatron reached 1.8 TeV proton–antiproton collision energy (later up to 1.98 TeV) and quickly overtook the SppS after physics operation started in 1987 (the antiproton cooling was based on Gersh Budker’s electron cooling method during Run 2) and ended in 2011



Aerial view of Fermilab's proton--antiproton accelerator and collider complex in 2011. The Main Injector and Recycler ring is seen in front and the 6.3-kilometre circumference Tevatron collider ring in the background. On the left the iconic Wilson Hall, Fermilab's central laboratory building. Close-by are the proton source and the Booster. Tevatron's main detectors CDF and D0 are placed to the left and right along the ring, respectively.

Late 1980s: the Tevatron at Fermilab climbed at the energy frontier

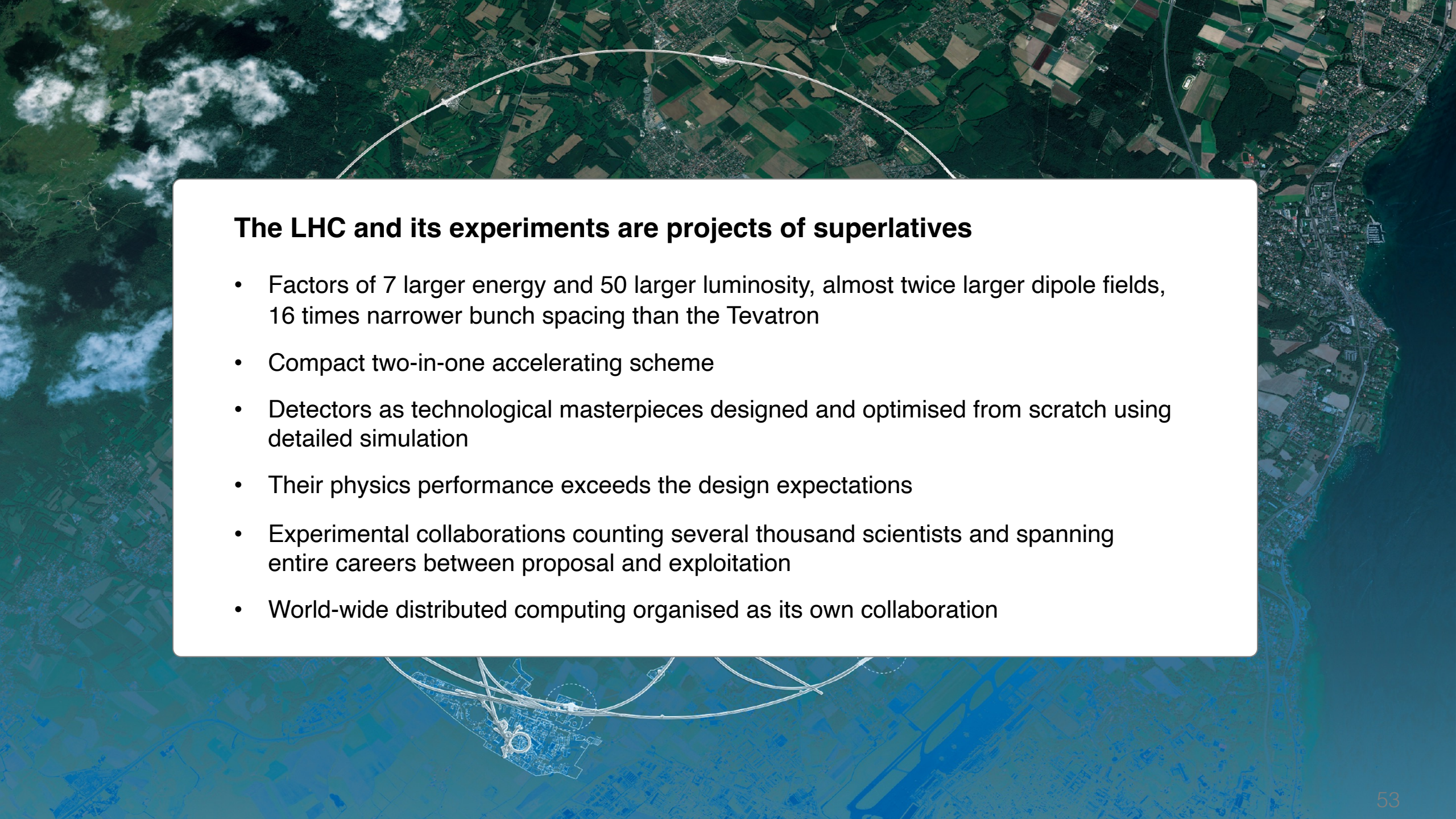
Among the Tevatron legacies:



- High-precision top and W mass measurements, $\sigma(m_{\text{top}}) = 0.65 \text{ GeV}$ (0.4%), $\sigma(m_W) = 16 \text{ MeV}$ (0.02%)
- Also: first observation of neutral B_s oscillation by CDF in 2006

The Large Hadron Collider

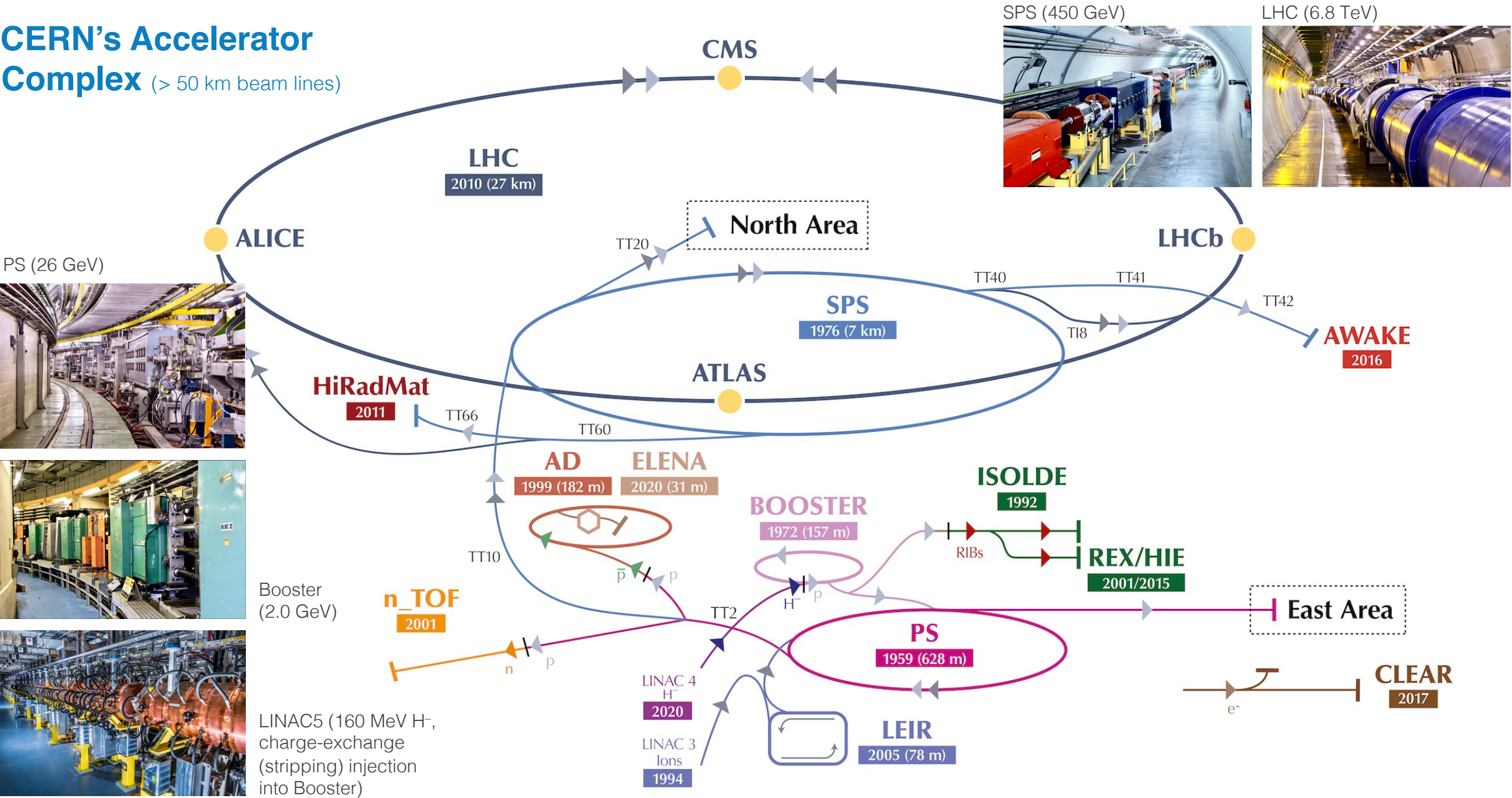
An aerial photograph of the landscape around Geneva, Switzerland, showing the patchwork of green and brown agricultural fields. Overlaid on this image is a white line representing the circular path of the Large Hadron Collider (LHC) tunnel. The tunnel forms a large circle with a diameter of approximately 27 kilometers. Several smaller circular and linear structures are also visible, representing the various experiments and service tunnels connected to the main ring. The title 'The Large Hadron Collider' is written in a large, white, sans-serif font across the center of the image.

An aerial photograph of the LHC tunnel, which is a long, straight line cutting through a green, hilly landscape. The tunnel is highlighted in white, and the surrounding area is covered in dense green vegetation. The sky is blue with some white clouds. The overall image has a blue tint.

The LHC and its experiments are projects of superlatives

- Factors of 7 larger energy and 50 larger luminosity, almost twice larger dipole fields, 16 times narrower bunch spacing than the Tevatron
- Compact two-in-one accelerating scheme
- Detectors as technological masterpieces designed and optimised from scratch using detailed simulation
- Their physics performance exceeds the design expectations
- Experimental collaborations counting several thousand scientists and spanning entire careers between proposal and exploitation
- World-wide distributed computing organised as its own collaboration

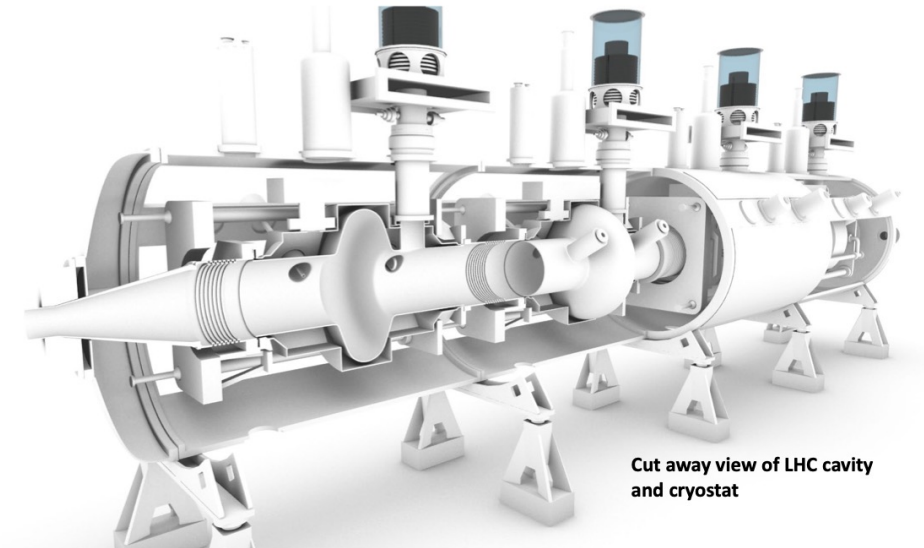
CERN's Accelerator Complex (> 50 km beam lines)



Accelerating protons in the LHC

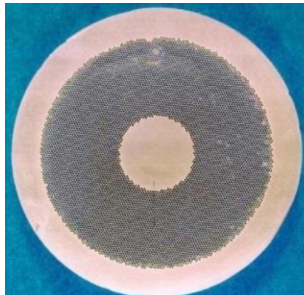
Oscillating microwave fields accelerate the protons in the LHC

- 16 400 MHz superconducting RF cavities (8 per beam in 4 cryomodules) each provide up to 2 MV (16 MV per beam). During energy ramp, only a small phase component of this voltage accelerates the protons; most provides longitudinal focusing and keeps the bunches stable
- Each cavity is driven by a high-power klystron, a tube containing electron beams, intensity-modulated to a frequency of 400.8 MHz
- Acceleration rate is limited by synchronous ramping of dipole fields with the beam momentum



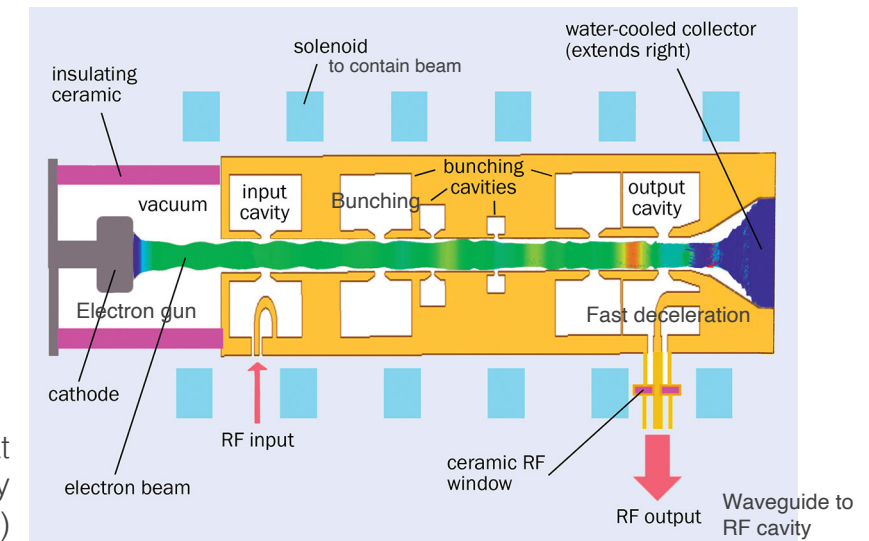
What limits their energy?

- Bending power of dipole magnets for given bending radius:
 $E_{\text{beam}} [\text{TeV}] \approx 0.3 \cdot B [\text{T}] \cdot \varrho [\text{km}] \approx 0.3 \cdot 8.3 \text{ T} \cdot 2.8 \text{ km} \approx 7 \text{ TeV}$
- High-field magnets are key for hadron colliders



LHC: multifilament NbTi alloy superconducting wire ("strand", 0.85 mm) surrounded by copper stabiliser, 11,800 A

Operating principle of a klystron (at LHC: 3–4 m height, power efficiency ~62%, becoming 70% at HL-LHC)



Cross section and luminosity

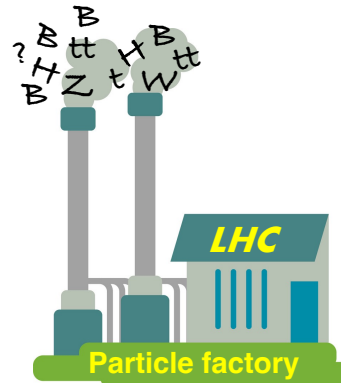
Cross section and luminosity drive the number of events produced of a given process

$$N_{\text{events}}^{\text{obs}} = \text{cross section} \times \text{acceptance} \times \int L \cdot dt$$

“Cross section” given by Nature

“Acceptance” of detection optimised by experimentalist

Integrated luminosity delivered by LHC



The **cross section**, σ , measures the probability of a particle reaction. It can be pictured as the effective target area presented by one particle to another: the larger the cross-section, the more frequently the reaction occurs

Cross-sections have units of area. Particle physicists use the barn: $1 \text{ barn} = 10^{-24} \text{ cm}^2 = 100 \text{ fm}^2$

Cross section and luminosity

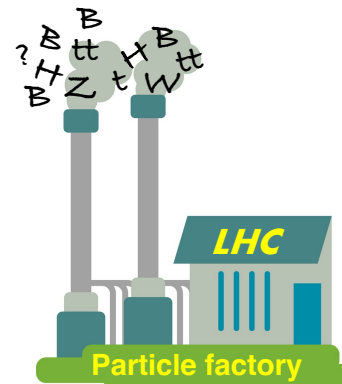
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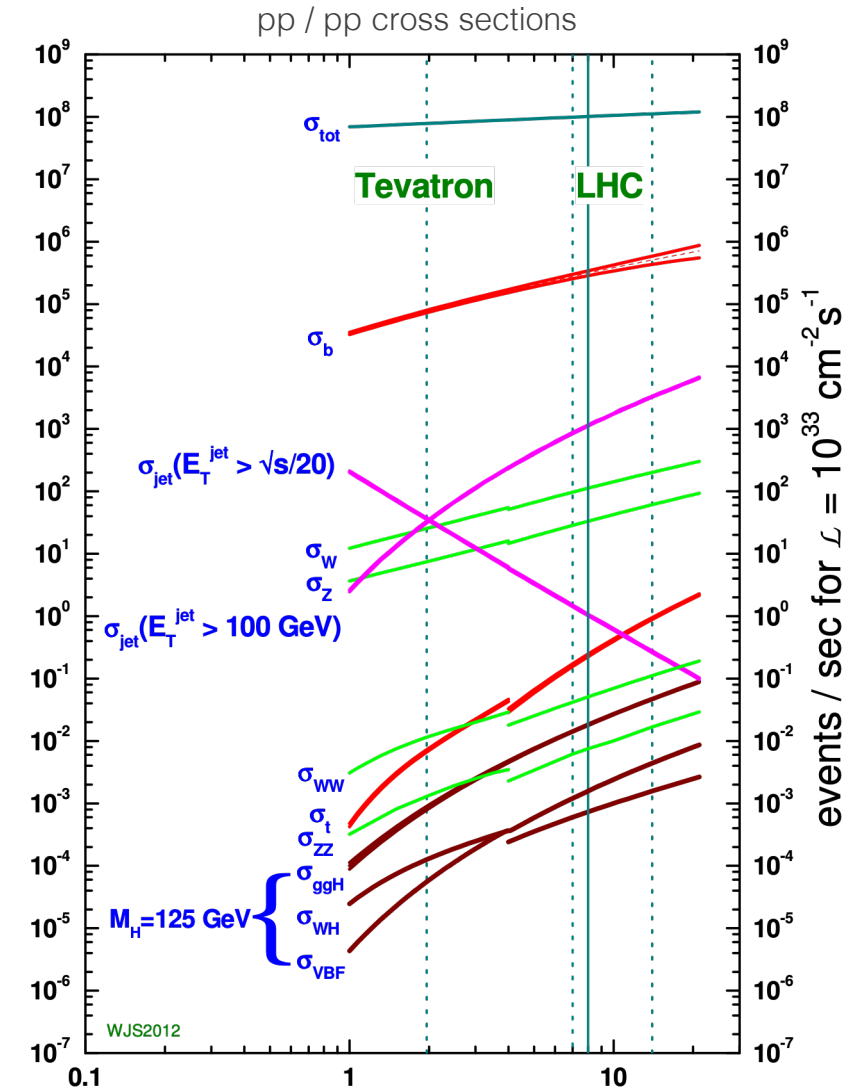
“Acceptance” of detection optimised by experimentalist

Integrated luminosity delivered by LHC



Cross sections at LHC (13 TeV) [N_{events} in 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ — Run 2]

- Total: 100 mb, inelastic: 80 mb (remaining diffractive)
- b-quarks: 400 μb , jets with $E_T > 100 \text{ GeV}$: 3 μb
- W and Z: 200 / 60 nb | [26 / 8 B events] ($\rightarrow \ell\nu / \ell\ell$: 20 / 2 nb [2.8 / 0.27 B] per flavour)
- WW / ZZ / WWW: 125 / 28 pb / 0.5 pb [17.5 / 3.9 M / 70 k]
- Top quark pair: 830 pb [116 M]
- H: 56 pb [7.8 M]
- HH: 33 fb [4.6 k]



Cross section and luminosity

Cross section and luminosity drive the number of events produced of a given process

$$N_{\text{events}}^{\text{obs}} = \text{cross section} \times \text{acceptance} \times \int L \cdot dt$$

Luminosity is a function of the LHC beam parameters $[L] = \frac{1}{\text{s} \cdot \text{cm}^2} = \frac{10^{-33}}{\text{s} \cdot \text{nb}}$

$$L = \frac{f_r n_{\text{bunch}} N_p^2}{4\pi\sigma_x\sigma_y} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

- f_r = 11245.5 Hz is the bunch revolution frequency
- n_{bunch} ~ 2500 is the number of bunches in the machine
- N_p $\sim 1.6 \times 10^{11}$ is the number of protons per bunch (“bunch intensity”)
- $\sigma_{x/y}$ $\sim 16 \mu\text{m}$ is the transverse beam width characterising beam optics of the final focusing system (60-m long “inner triplet” assembly)

Reduction factor R

Crossing angle (0.3 mrad, to avoid parasitic collisions) and small “hourglass effect” ($\sigma_z \sim 4\text{--}6 \text{ cm}$, β^* varies along z)



Crossing angle (approx. factor $1/\sqrt{1 + (\theta_c\sigma_z/2\sigma_x)^2} = 1/\sqrt{1 + \phi^2} \approx 0.82$)

Hourglass (varying β^* along IP in z , factor decreases with increasing σ_z/β^*)

$$L_{\text{peak}} \sim 2.2 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$$

$$\text{Interaction rate: } R = L_{\text{peak}} \sigma \sim 1.8 \text{ GHz}$$

18 nb⁻¹ was the dataset used by UA1 for the W discovery (run of Nov/Dec 1982) → 0.8 seconds at the LHC

Piwiński angle

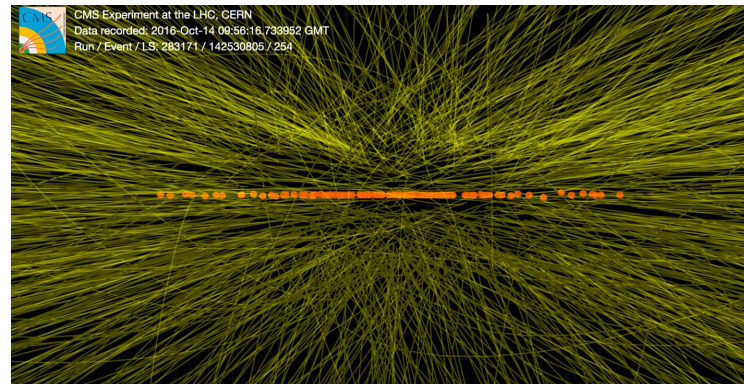
Maximising luminosity

High luminosity requires: many protons per bunch, many bunches, low transverse beam emittance, strong focusing

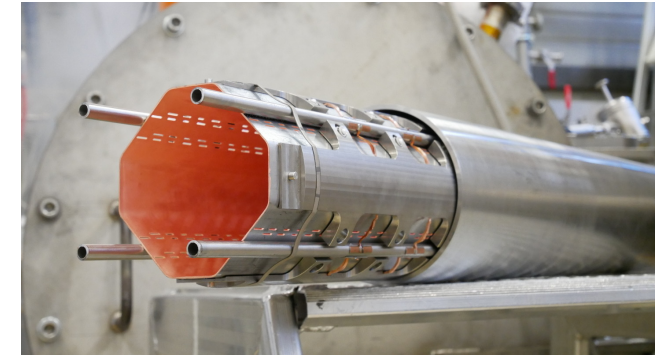
What limits the luminosity?

- **Beam intensity** limited by available cooling to mitigate heat load from synchrotron radiation & beam coupling impedance*: $\Delta E_{\text{loss}} \propto E_p^4 / (m_p^4 \cdot \rho) \sim 18 \text{ keV / turn}$, or a power of 6 kW / beam / turn, intercepted by *beamscreen* at higher temperature (5–20 K) to evacuate heat
- **Beam focusing**: beamspot $\sigma = \sqrt{\varepsilon \beta^* / \gamma}$, LHC: $\varepsilon \sim 2.5 \text{ } \mu\text{m}$, $\beta^* \sim 30 \text{ cm}$, limited by strength and aperture (available clearance) of focusing quadrupole magnets in inner triplet
- High peak luminosity also challenges experiments due to **simultaneous pp collisions**, **pileup background**, affecting trigger and event reconstruction

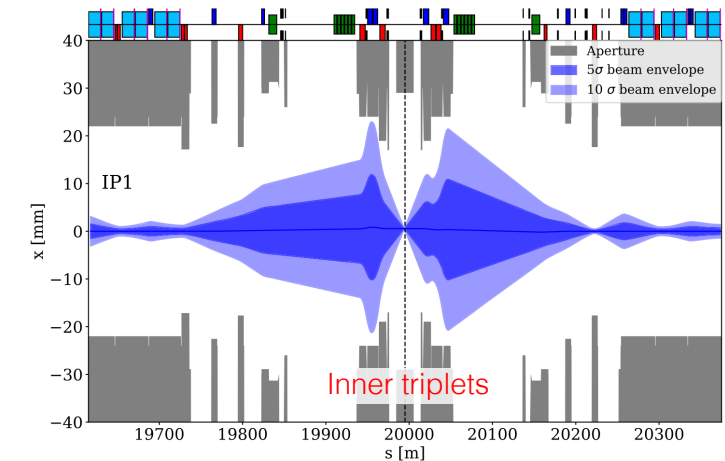
$$\mu = \frac{\sigma_{\text{inel}} \cdot L}{n_b \cdot f_r} \approx \frac{80 \text{ mb} \cdot 2.2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}}{2448 \cdot 11,246 \text{ Hz}}$$
$$\approx \frac{1.76 \text{ GHz}}{2448 \cdot 11,246 \text{ Hz}} \approx 64$$



~100 pileup pp interactions in CMS detector



Helium cooled LHC beamscreen within beam pipe

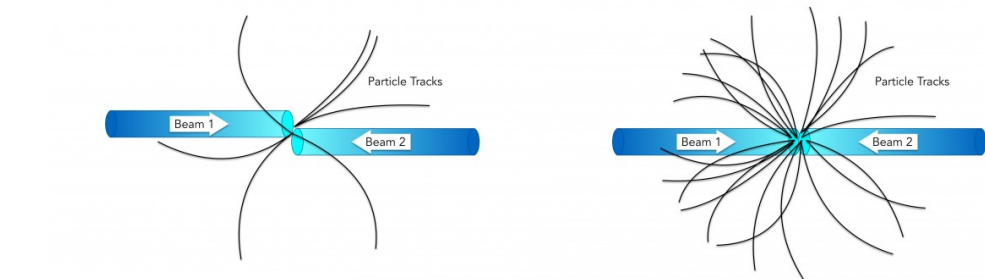


Horizontal beam envelopes around IP1 of 5 and 10 σ for the 2018 optics with a β^* of 25 cm

[*Impedance: beam induces EM fields in surroundings (cavities, vacuum chamber walls, collimators, etc) quantified by “impedance”]

Cross-section measurements require precise luminosity value

Any detector with a linear luminosity response can be used to measure the luminosity. Its “visible cross section” is calibrated in situ using van der Meer beam-separation scans.

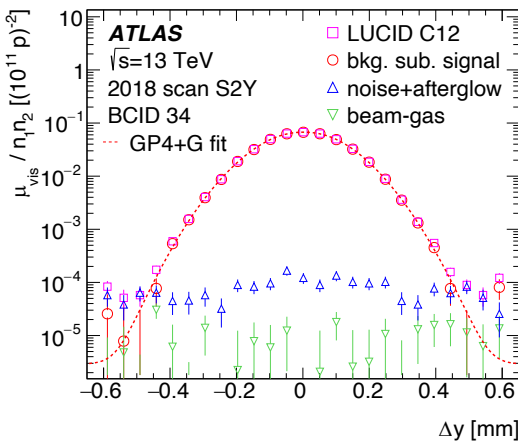
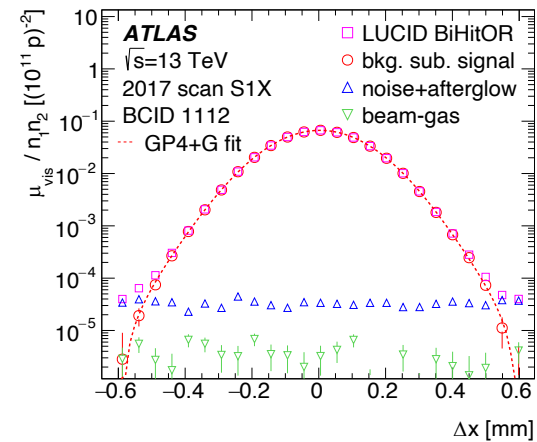


Peak visible interaction rate per bunch crossing

Convolved beam sizes

$$\sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{max}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2} \quad \text{and then:} \quad L_b = \mu_{\text{vis}} f_r / \sigma_{\text{vis}}$$

Bunch intensities



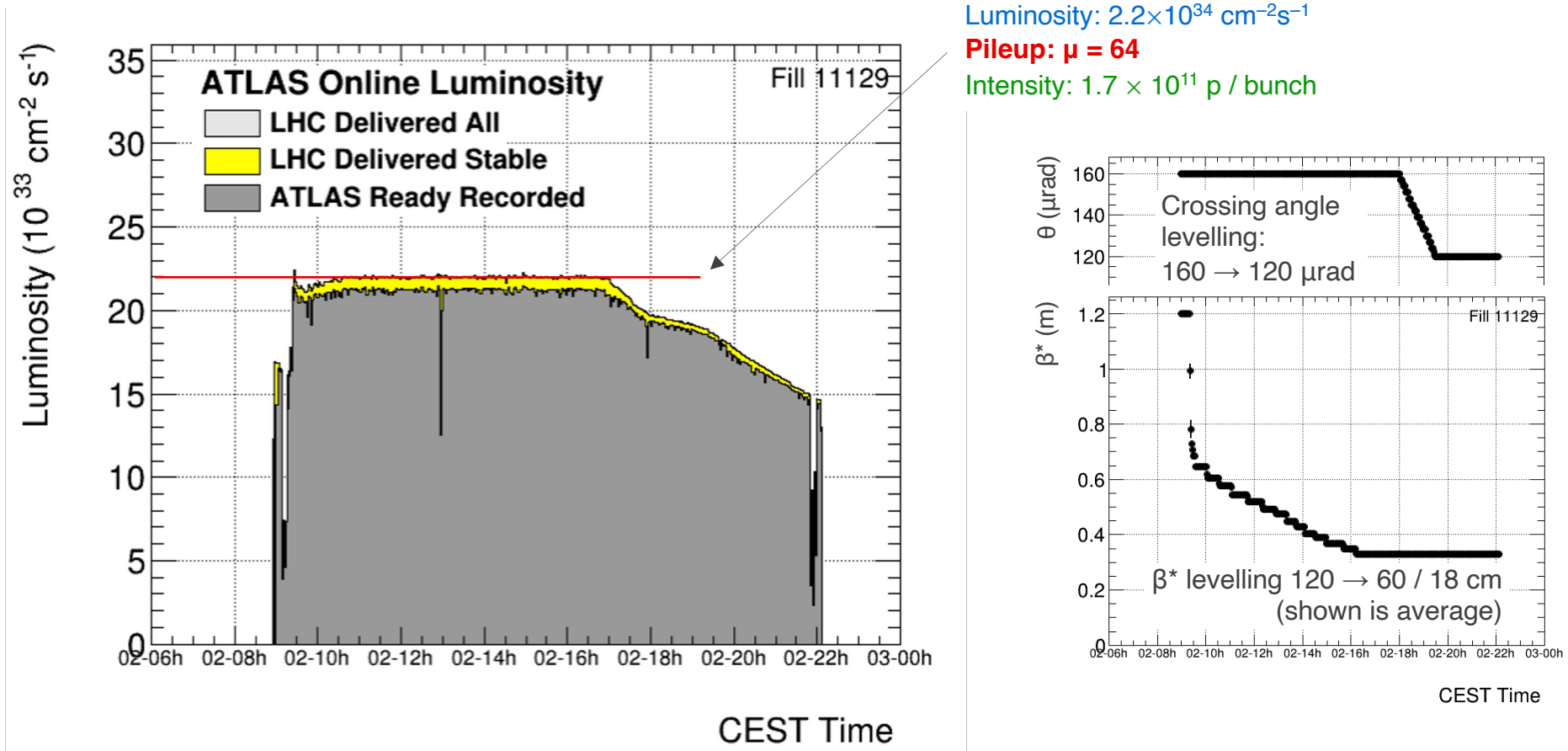
Very challenging to achieve sub-percent precision (Tevatron exps: ~6%)

Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity [fb ⁻¹]	3.24	33.40	44.63	58.79	140.07
Total uncertainty [fb ⁻¹]	0.04	0.30	0.50	0.64	1.17
Uncertainty contributions [%]:					
Statistical uncertainty	0.07	0.02	0.02	0.03	0.01
Fit model*	0.14	0.08	0.09	0.17	0.12
Background subtraction*	0.06	0.11	0.19	0.11	0.13
FBCT bunch-by-bunch fractions*	0.07	0.09	0.07	0.07	0.07
Ghost-charge and satellite bunches*	0.04	0.04	0.02	0.09	0.05
DCCT calibration*	0.20	0.20	0.20	0.20	0.20
Orbit-drift correction	0.05	0.02	0.02	0.01	0.01
Beam position jitter	0.20	0.22	0.20	0.23	0.13
Non-factorisation effects*	0.60	0.30	0.10	0.30	0.24
Beam-beam effects*	0.27	0.25	0.26	0.26	0.26
Emittance growth correction*	0.04	0.02	0.09	0.02	0.04
Length scale calibration	0.03	0.06	0.04	0.04	0.03
Inner detector length scale*	0.12	0.12	0.12	0.12	0.12
Magnetic non-linearity	0.37	0.07	0.34	0.60	0.27
Bunch-by-bunch σ_{vis} consistency	0.44	0.28	0.19	0.00	0.09
Scan-to-scan reproducibility	0.09	0.18	0.71	0.30	0.26
Reference specific luminosity	0.13	0.29	0.30	0.31	0.18
Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65
Calibration transfer*	0.50	0.50	0.50	0.50	0.50
Calibration anchoring	0.22	0.18	0.14	0.26	0.13
Long-term stability	0.23	0.12	0.16	0.12	0.08
Total uncertainty [%]	1.13	0.89	1.13	1.10	0.83

Table from: [ATLAS: arXiv:2212.09379](#), See also: [CMS: arXiv:2606.26832](#)

A typical LHC fill during Run 3

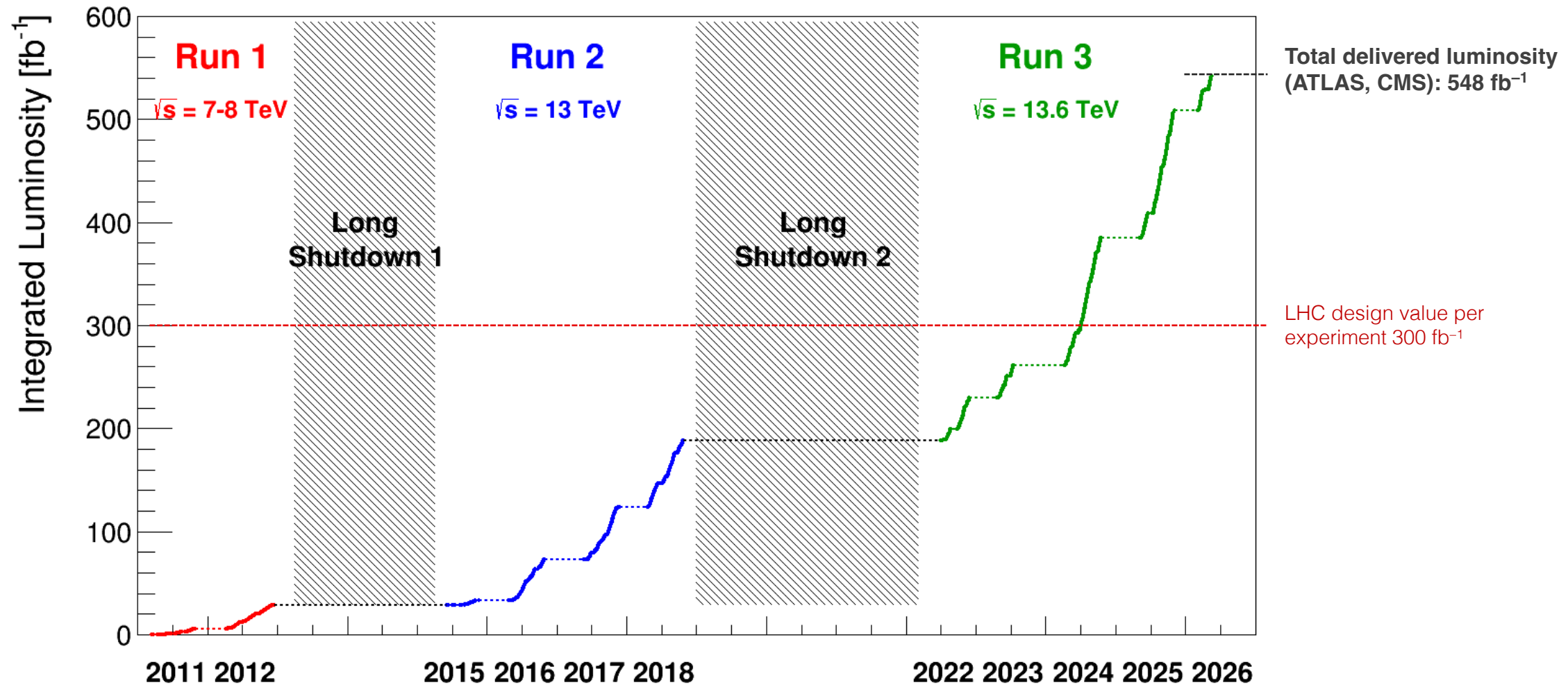
Luminosity profile during a 15h28 fill (13h07 in stable beams), 2 Oct 2025



Delivered integrated luminosity in this fill: 947 pb^{-1}
ATLAS recorded luminosity : 917 pb^{-1} (96.9%)

Delivered luminosity

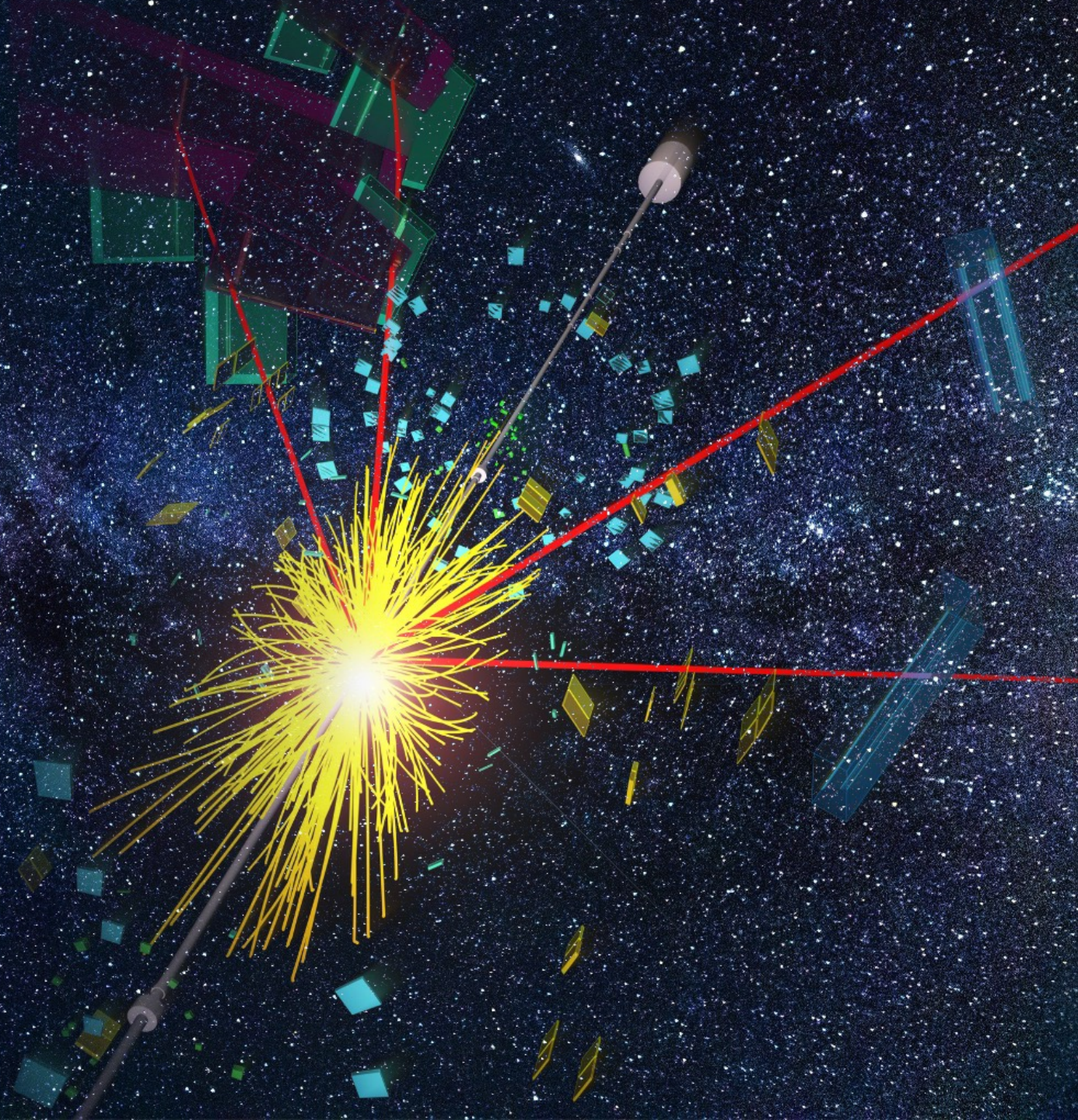
Superb LHC performance in 2024 through 2026 — Run 2+3 > 3 × Run 2; > 450 fb⁻¹ good physics data at 13 & 13.6 TeV



Some conclusions from today's lecture

- The universe is a strange place
- The gauge sector is tightly constrained by symmetry, new physics effects are typically suppressed by v^2/Λ^2
- The Yukawa sector is far less constrained: gauge symmetry permits the Yukawa couplings but does not explain their values, hierarchy, flavour structure, or CP phases. Many BSM scenarios therefore predict modified Yukawa interactions
- The Higgs is the only elementary scalar in the SM. It is subject to large radiative corrections, making it particularly susceptible to heavy new degrees of freedom — the essence of the hierarchy or naturalness problem
- High-energy and luminosity colliders are essential: they are the telescopes of particle physics
- At a hadron collider, the collision energy is limited by the ring circumference and the strength of the bending magnets, while the luminosity is driven by the beam intensity and the focusing strength

Extra slides

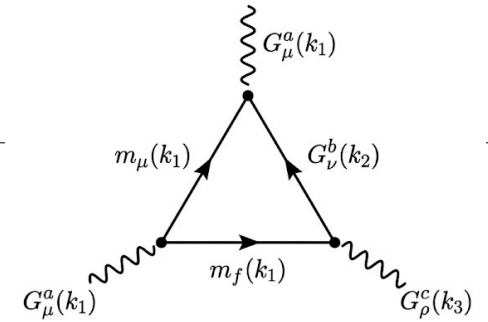


(Digression) Gauge anomaly cancellation and GUT

A chiral gauge theory is consistent only if all gauge anomalies cancel

In the SM, quark and lepton contributions cancel precisely, generation by generation — by design?

- SM is chiral: left- and right-handed fermions carry different electroweak quantum numbers
- Fermion triangle diagrams can make gauge currents non-conserved



Chiral gauge anomalies cancel when summing all SM contributions

LH Fields	$(SU(3)_C, SU(2)_L)_Y$
Q_L	$(3, 2)_{+1/6}$
u_R^c	$(\bar{3}, 1)_{-2/3}$
d_R^c	$(\bar{3}, 1)_{+1/3}$
L_L	$(1, 2)_{-1/2}$
e_R^c	$(1, 1)_{+1}$



$$U(1)_Y^3 \text{ anomaly: } \sum_{\psi_L} Y^3 = 6 \left(\frac{1}{6}\right)^3 + 3 \left(-\frac{2}{3}\right)^3 + 3 \left(\frac{1}{3}\right)^3 + 2 \left(-\frac{1}{2}\right)^3 + 1^3 = 0$$

$SU(3)_C^3$ anomaly: cancels because Q_L balanced by u_R^c and d_R^c

$$SU(2)_L^2 U(1)_Y \text{ anomaly: } 3Y_{Q_L} + Y_{L_L} = 3 \left(\frac{1}{6}\right) - \frac{1}{2} = 0$$

$$SU(3)_C^2 U(1)_Y \text{ anomaly: } 2Y_{Q_L} + Y_{u_R^c} + Y_{d_R^c} = 2 \left(\frac{1}{6}\right) - \frac{2}{3} + \frac{1}{3} = 0$$

Quantum contributions from chiral quarks and leptons cancel

Gauge anomaly cancellation hints at grand unification (GUT)

- $SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$, with fermion multiplets for each generation: $\bar{\mathbf{5}}_F \oplus \mathbf{10}_F$ with $A(\mathbf{10}) + A(\bar{\mathbf{5}}) = 1 - 1 = 0$
- $SO(10) \rightarrow \dots \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$, with $\mathbf{16}_F = Q_L + u_R^c + d_R^c + L_L + e_R^c + \nu_R^c$, single multiplet, built-in anomaly cancellation
- GUTs unify quarks and leptons, explaining anomaly cancellation and quantising hypercharge, *but it is not a prove for GUT!*

GUT scalar sector is tricky: coloured Higgs partners must be superheavy to suppress proton decay; GUT-scale states destabilise Higgs mass (μ); and breaking the GUT to exactly the SM often requires large scalar multiplets with carefully aligned VEVs

(Digression) Vacuum energy: where QFT meets gravity

Quantum field theory describes the fabric of empty space

- In QFT, the vacuum is not an empty void but a dynamic and structured entity with **quantum fluctuations, zero-point energy** (*Nullpunktsenergie*)
- Zero-point energy: quantum fields have vacuum energy even in absence of real particles
($\rho_{\text{QFT}} \propto M_{\text{Pl}}^4 \sim (2 \cdot 10^{18} \text{ GeV})^4 \rightarrow 10^{110} \text{ eV}^4 \gg \rho_{\Lambda} \sim (2 \cdot 10^{-3} \text{ eV})^4 \sim 10^{-11} \text{ eV}^4$)

Electroweak theory and Brout-Englert-Higgs mechanism

- Higgs field has vacuum expectation value $\langle 0|\phi|0\rangle = v \approx 246 \text{ GeV}$
($|\Delta\rho_{\text{EW}}| \sim V(v) - V(0) = m_{\text{H}}^2 v^2 / 8 \sim 10^{44} \text{ eV}^4$)

QCD vacuum

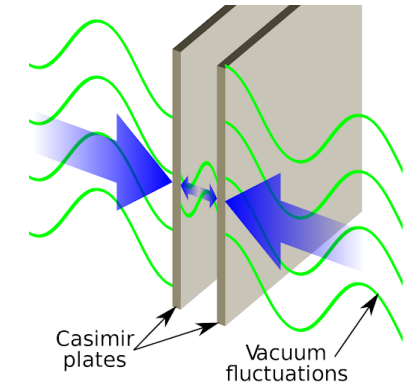
- The quark condensate signals spontaneous chiral-symmetry breaking; quark and gluon condensates contribute to the nonperturbative QCD vacuum energy
($|\Delta\rho_{\text{QCD}}| \sim \Lambda_{\text{QCD}}^4 \sim 10^{32} \text{ eV}^4$)

General relativity

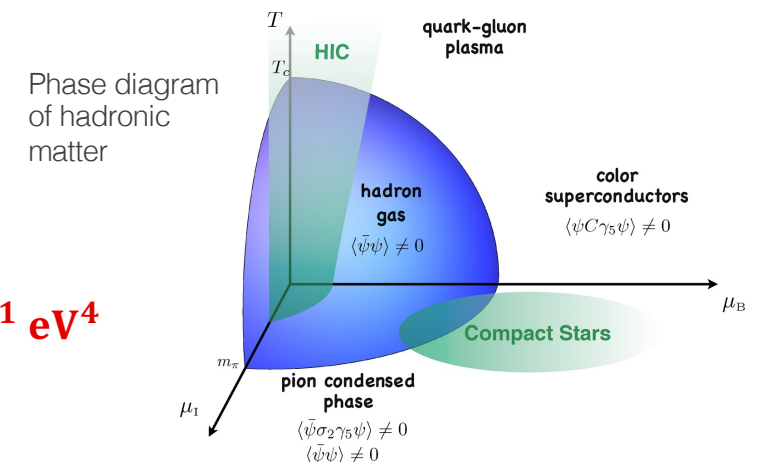
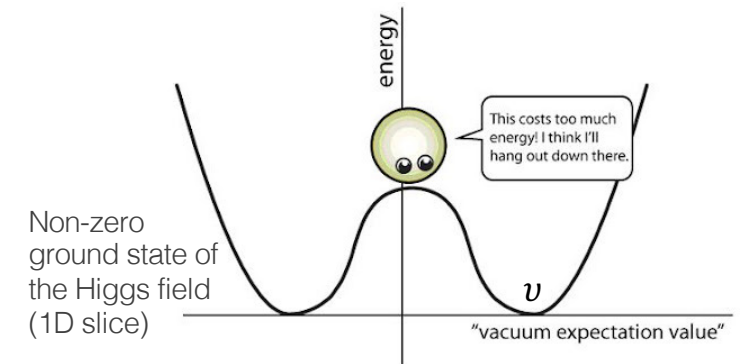
- In General Relativity, the cosmological constant (Λ) which can be interpreted as a form of (dark) vacuum energy, drives the accelerated expansion of the universe

$$\Rightarrow \rho_{\Lambda}^{\text{obs}} = \Lambda/8\pi G = \rho_{\text{bare}} + \rho_{\text{QFT}}^{\text{ren.}} + \Delta\rho_{\text{EW}} + \Delta\rho_{\text{QCD}} + \dots \simeq (2.3 \text{ meV})^4 \simeq 2.8 \cdot 10^{-11} \text{ eV}^4$$

Why is this renormalised sum extraordinarily small and radiatively stable?



Casimir force: an observable quantum-field boundary effect, sensitive to energy differences, not absolute vacuum energy



Delivered luminosity

Superb LHC performance in 2024 through 2026 — Run 2+3 > 3 × Run 2; > 450 fb⁻¹ good physics data at 13 & 13.6 TeV

