Welcome to

Subatomic Smash:

The Quest for the Higgs Boson

University of Victoria | 50 YEARS

Gregor Craigie,

Host of *On The Island*,

CBC Radio One's weekday morning show in Victoria

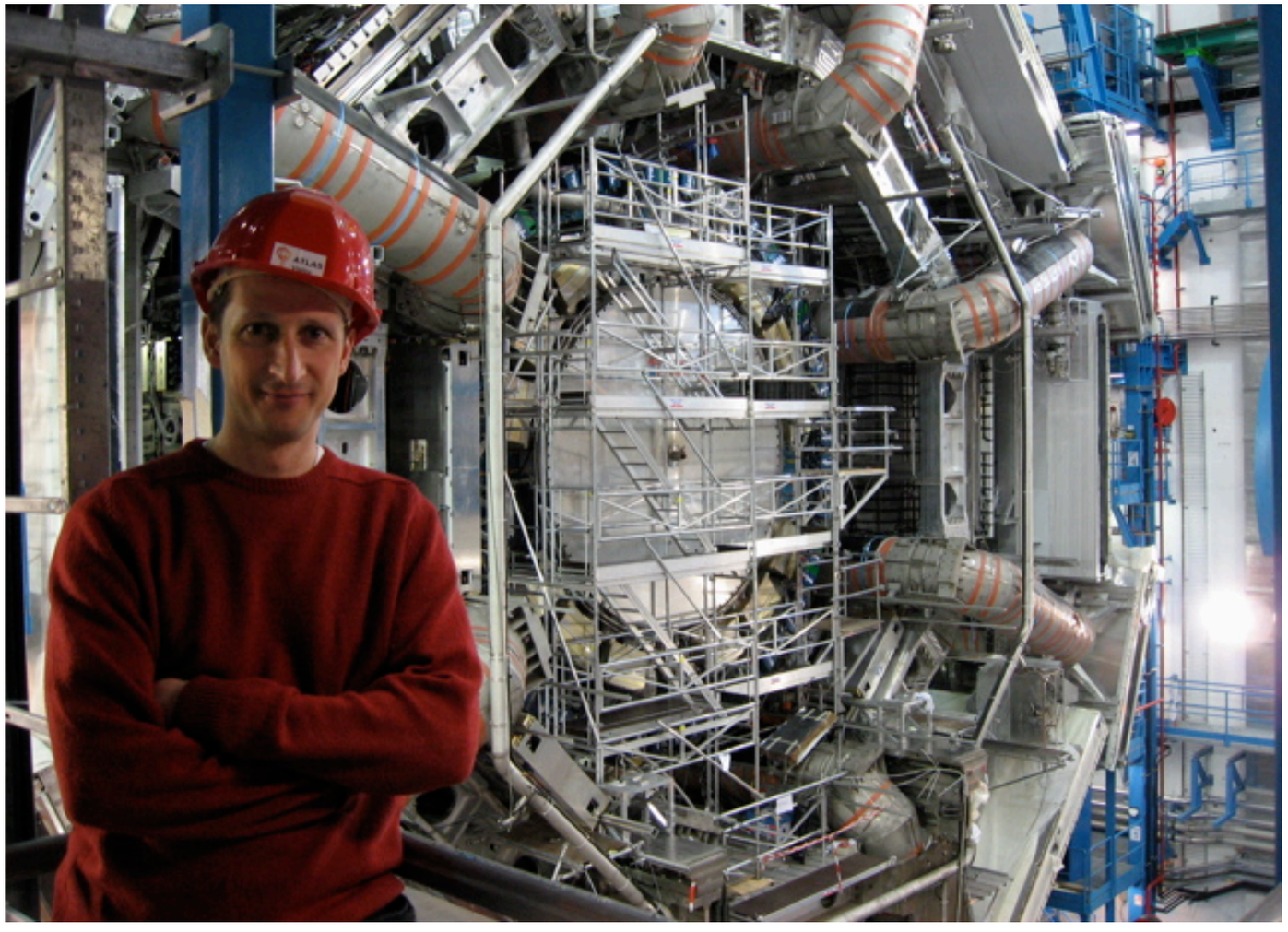
University of Victoria | 50 YEARS

Professor Emeritus

Alan Astbury

University of Victoria | 50 YEARS

Dr. Michel Lefebvre



University of Victoria | 50 YEARS

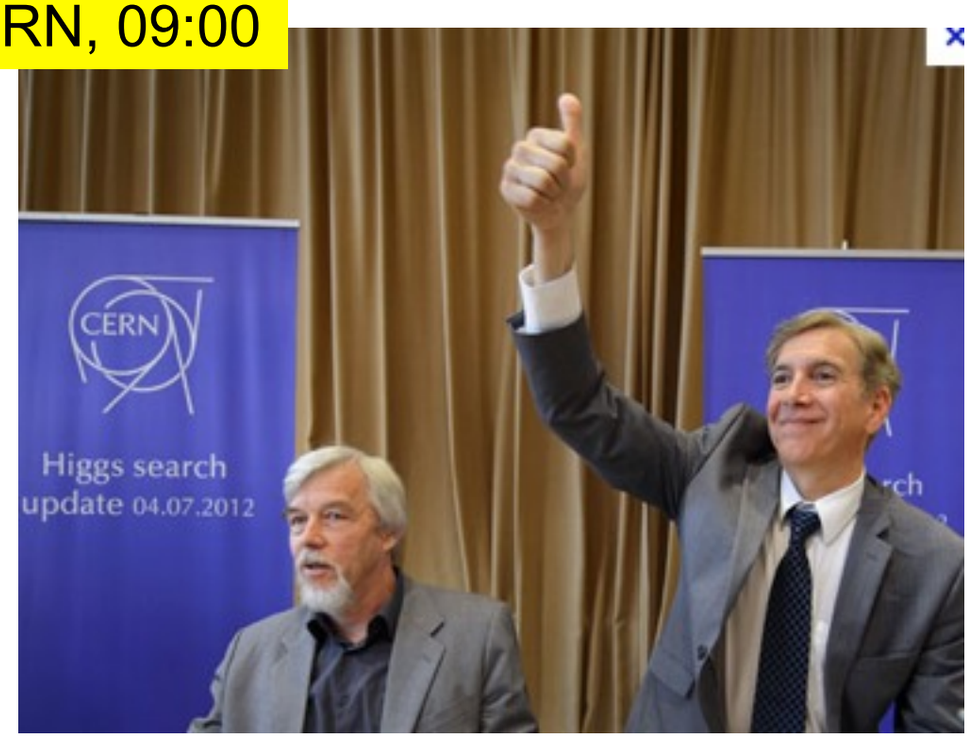
Subatomic Smash
The Quest for the Higgs Boson

Michel Lefebvre
Physics and Astronomy

9 April 2013

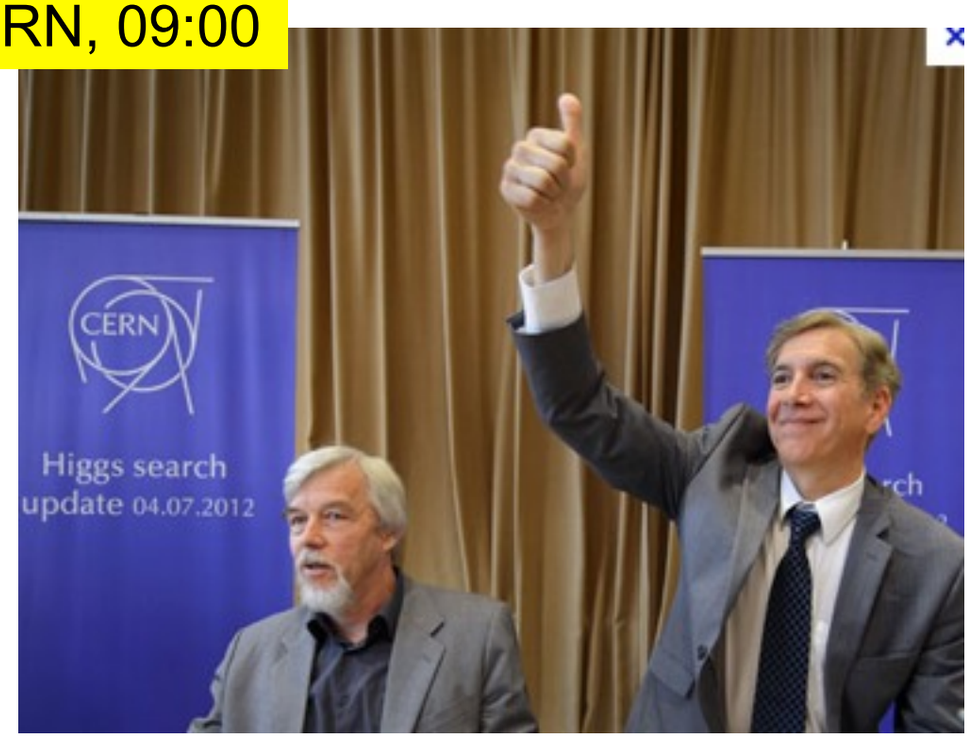
4 July 2012 CERN and Melbourne

CERN, 09:00



4 July 2012 CERN and Melbourne

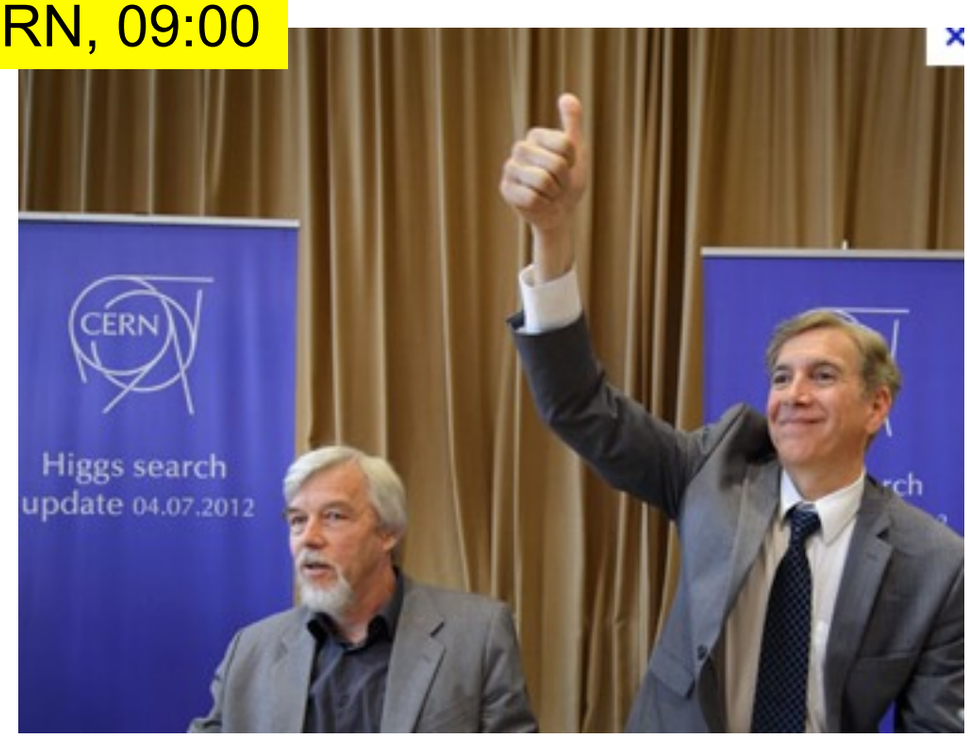
CERN, 09:00



ICHEP 2012, Melbourne, 19:00

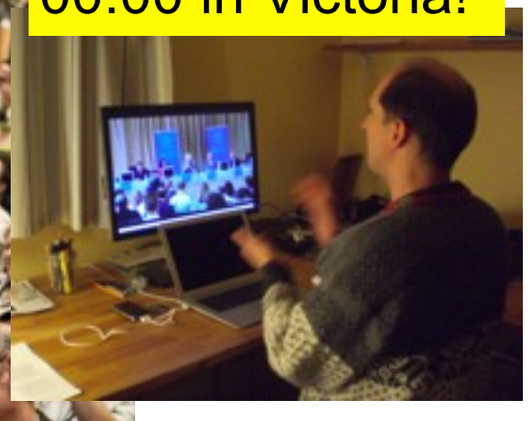
4 July 2012 CERN and Melbourne

CERN, 09:00



ICHEP 2012, Melbourne, 19:00

00:00 in Victoria!



What is the world made of?

What holds it together?

Understanding nature's fundamental constituents and forces

Search for the fundamental

Why do so many things in this world share the same characteristics?

Matter is made from a few fundamental building blocks of nature

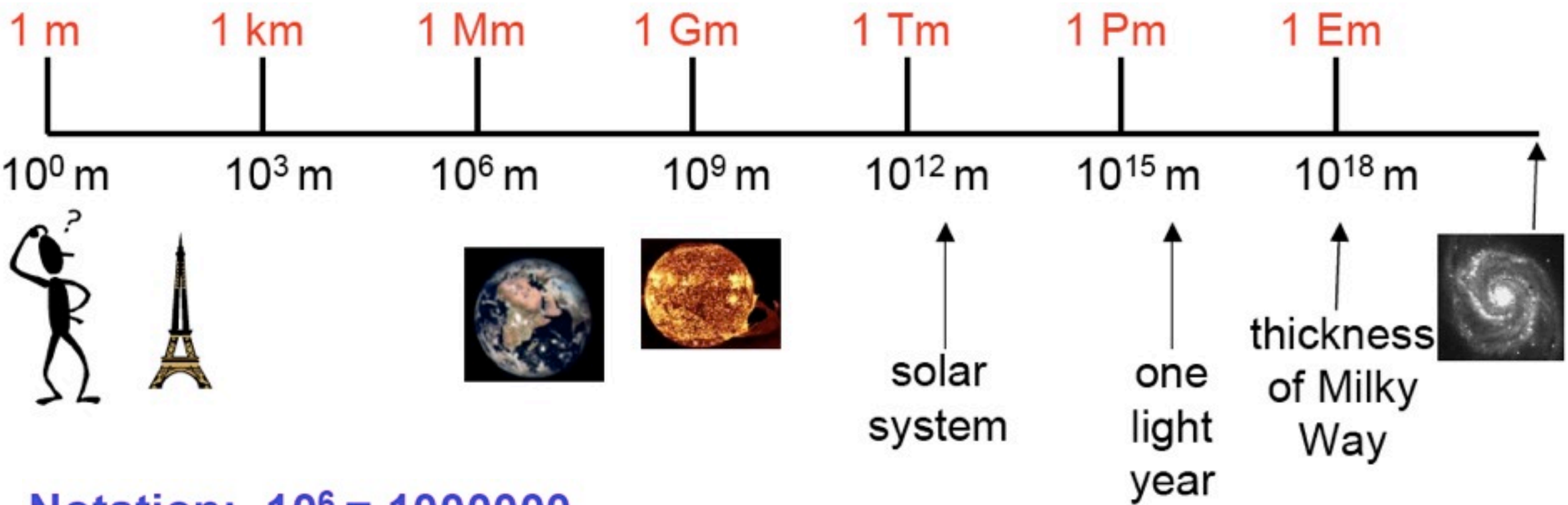
Fundamental: simple and structureless
not made of anything smaller

Even in ancient times, people sought to organize the world around them into fundamental elements, such as earth, air, fire, and water.

“Nothing exists except atoms and empty space; everything else is opinion.”

Democritus (ca. 460 BC - ca. 370 BC)

Length Scales



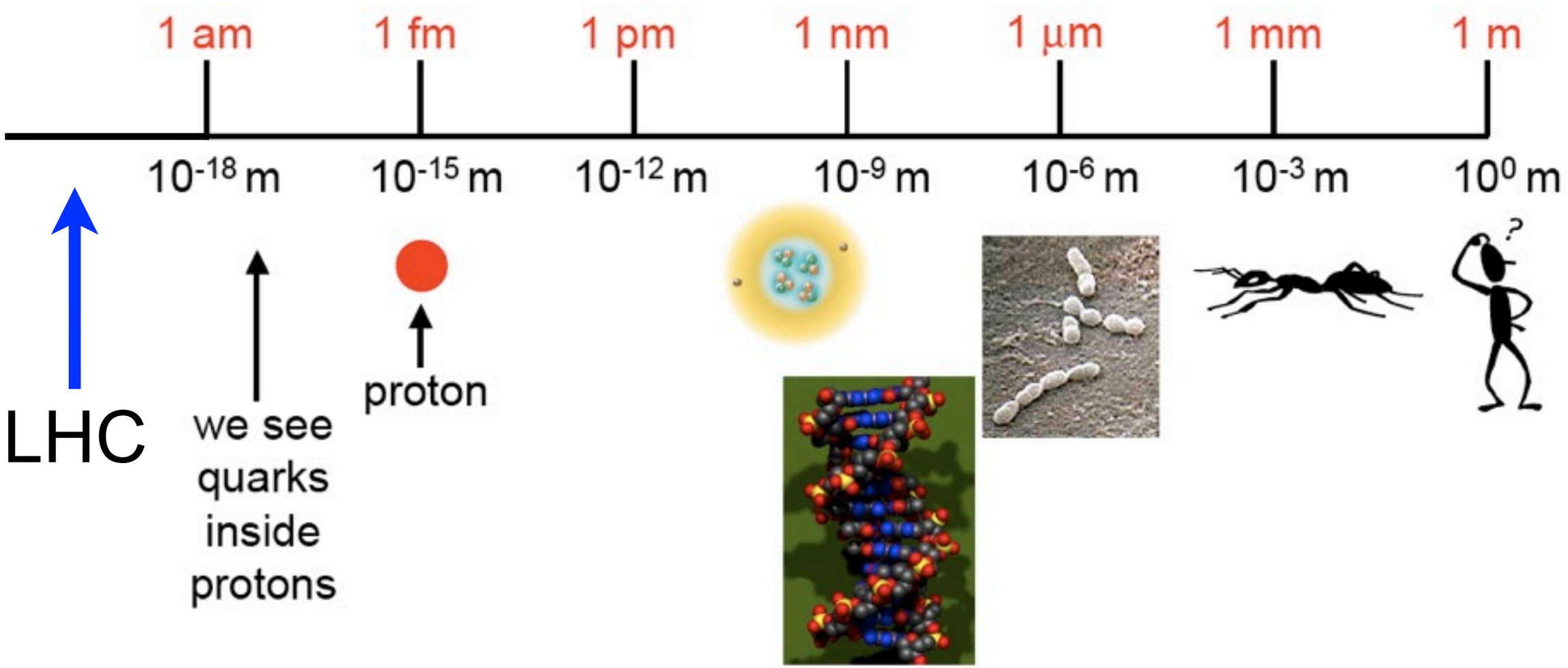
Notation: $10^6 = 1000000$

6 zeros!

Astrophysics explores matter and space in its largest dimensions

Gravitational force

Length Scales



Notation: $10^{-6} = 0.000001$

6^{th} decimal place!

Particle Physics explores matter and space in its smallest dimensions

The Elements

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr			

The Elements

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$_2$He

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79Au

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92 U

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Seeing atoms

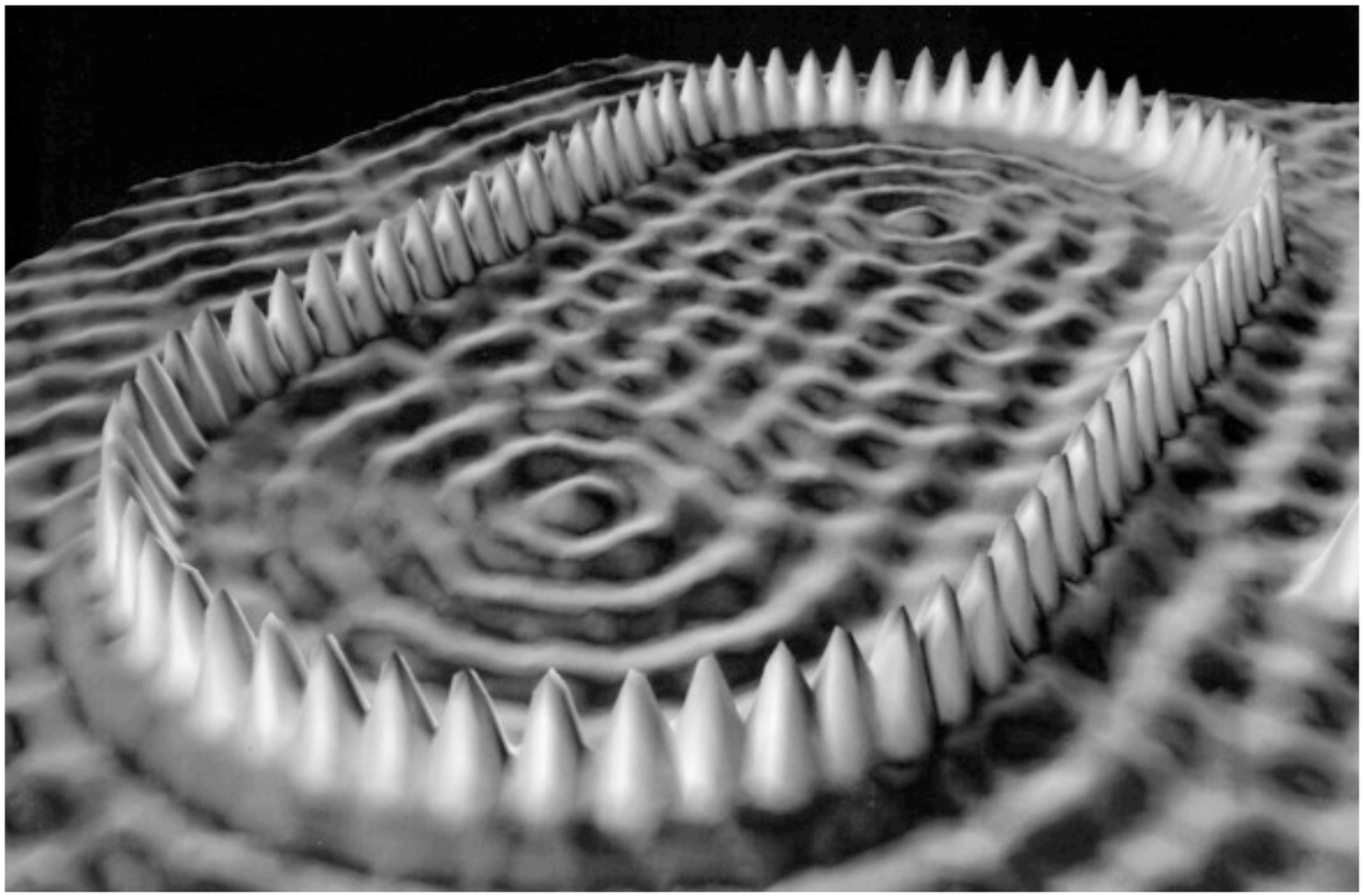


Photo credit: Copyright © IBM

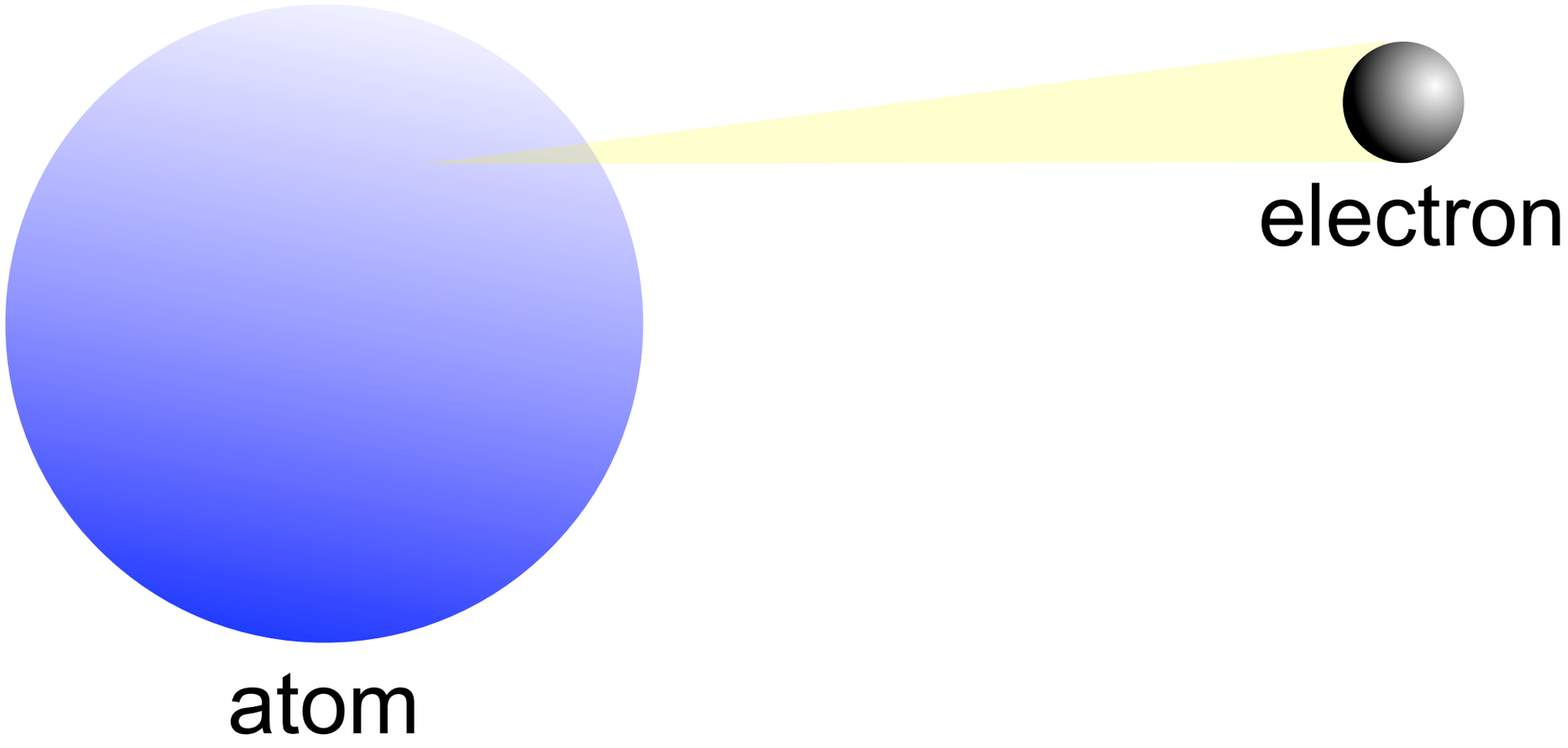
76 individually placed iron atoms on a copper surface revealed by a scanning tunneling microscope

We can now “see” atoms!

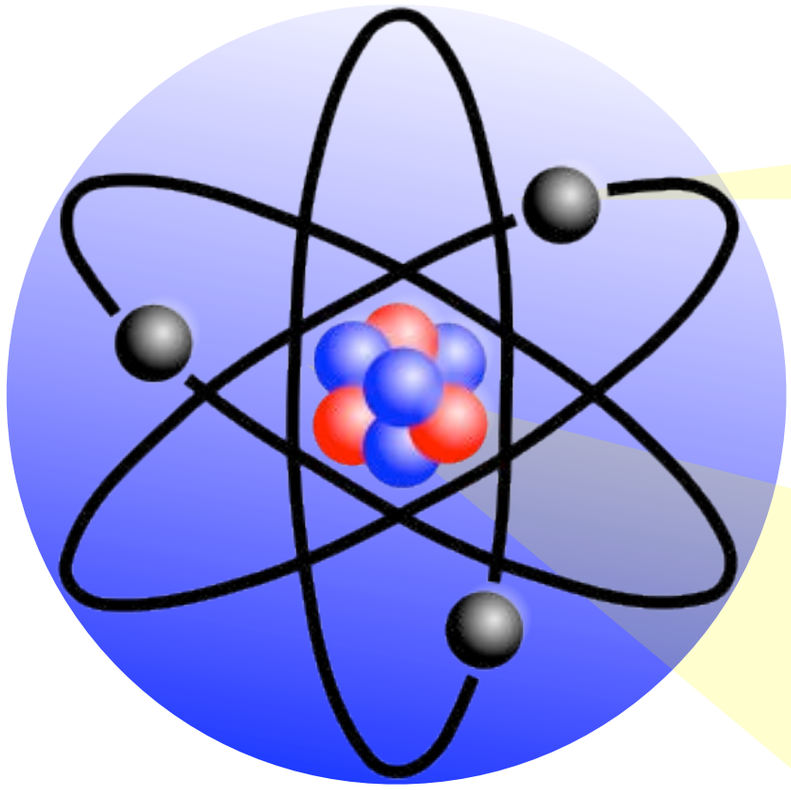
Inside the atom

atom

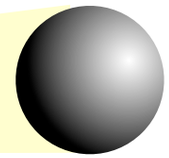
Inside the atom



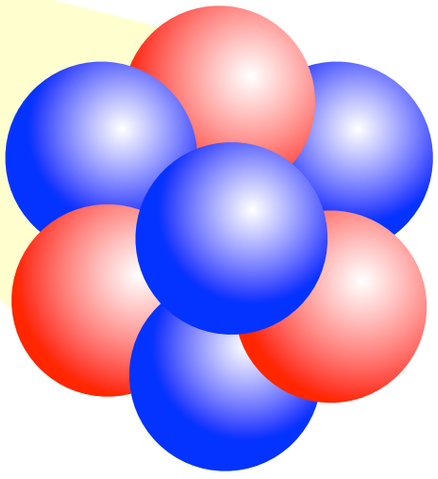
Inside the atom



atom



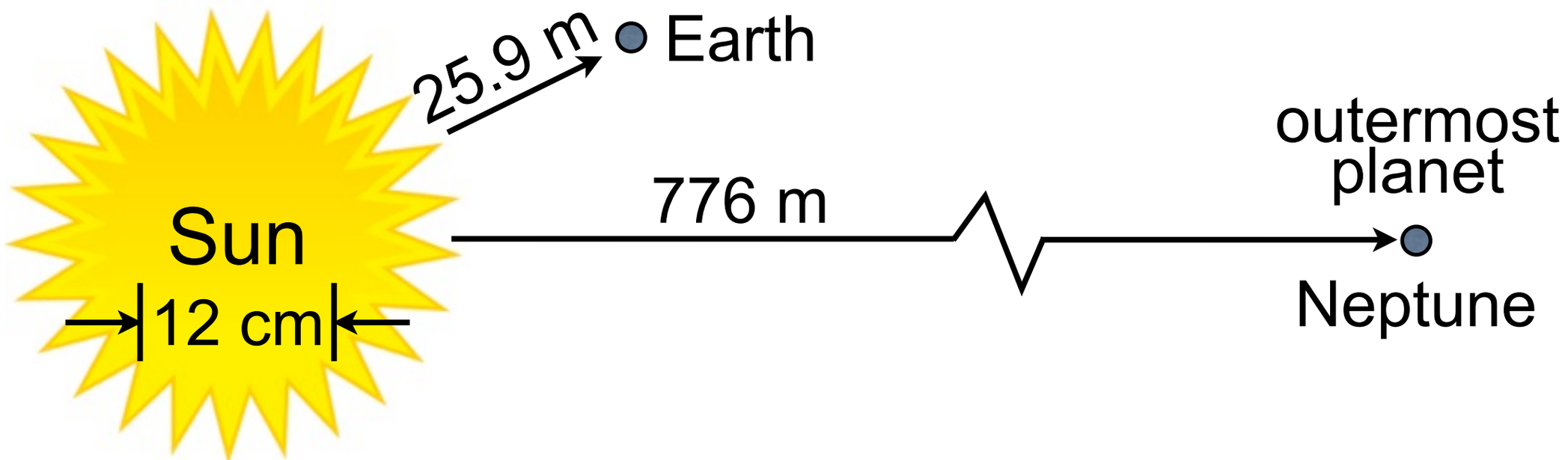
electron



nucleus

Length Scales

Sun scaled to the size of a basket ball



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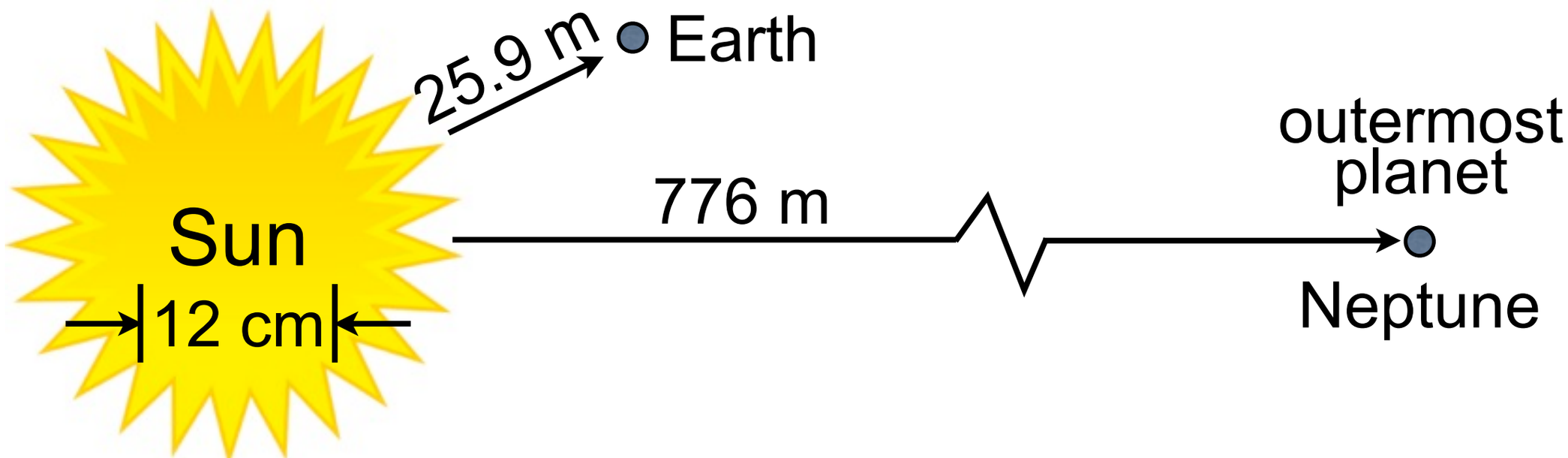
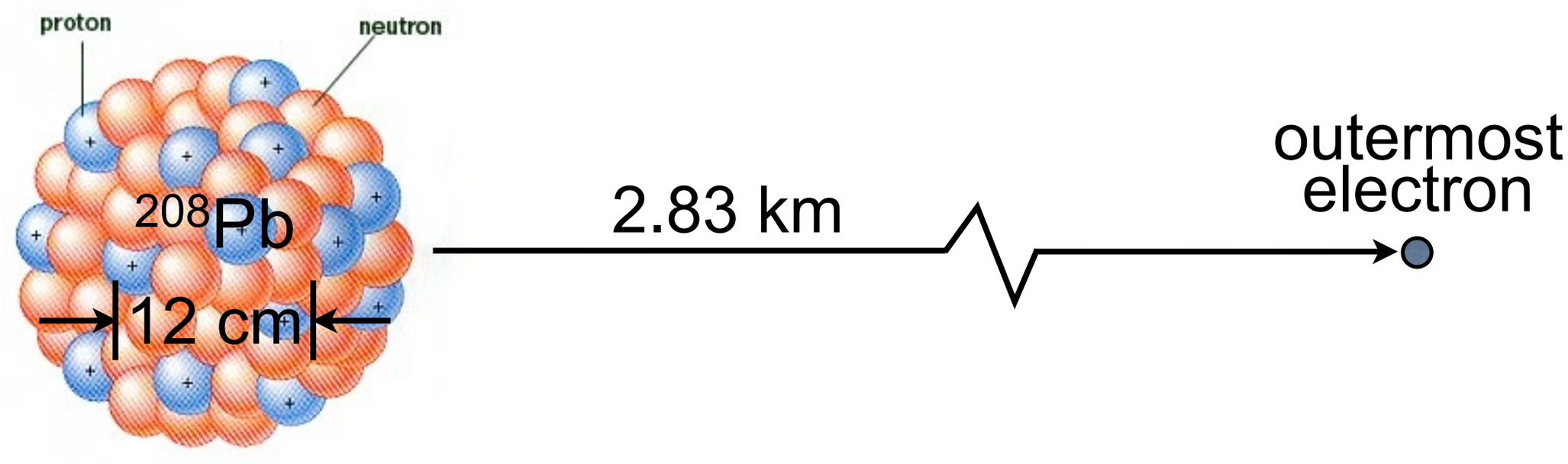
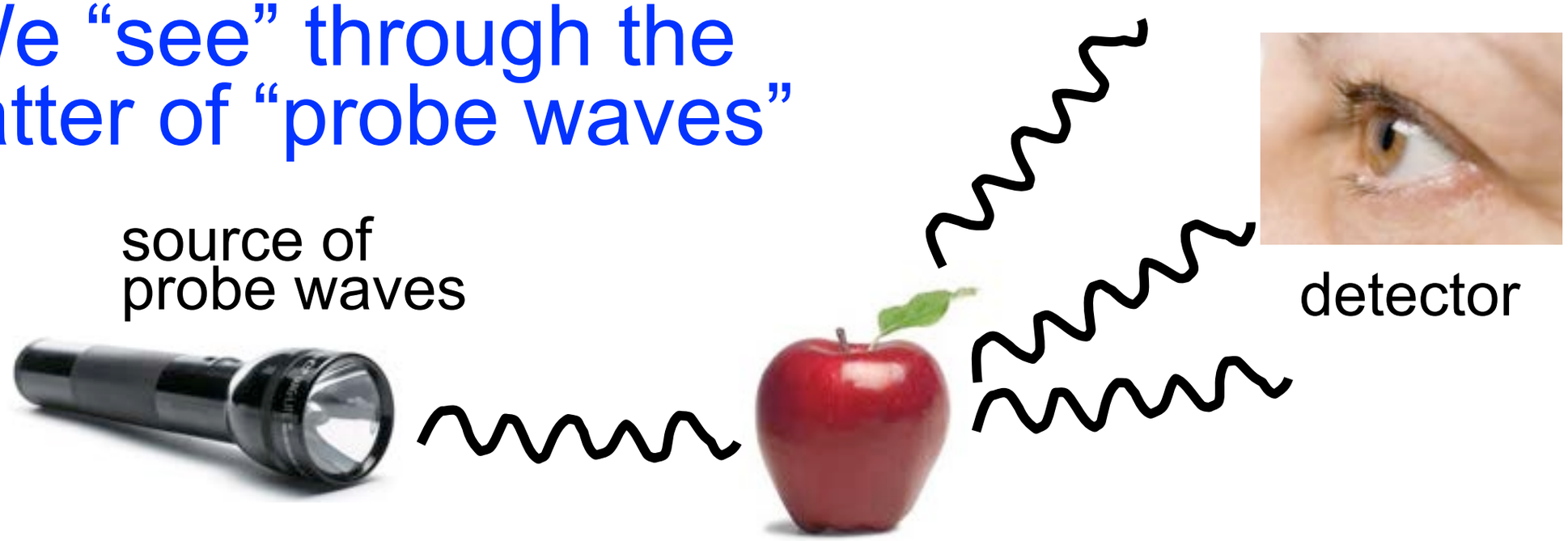


Lead nucleus scaled to the size of a basket ball



Scattering Experiments

We “see” through the scatter of “probe waves”



The wave can resolve features about the size of its wavelength

Light as waves

Light as waves

Light as particles
the photon

Light as waves

Light as particles

the photon

the electron

Matter as particles

Light as waves

Light as particles

the photon

the electron

Matter as waves

Matter as particles

Quantum Mechanics

Light as waves

Light as particles

the photon

the electron

Matter as waves

Matter as particles

Scattering Experiments

We “see” through the scatter of “probe waves”

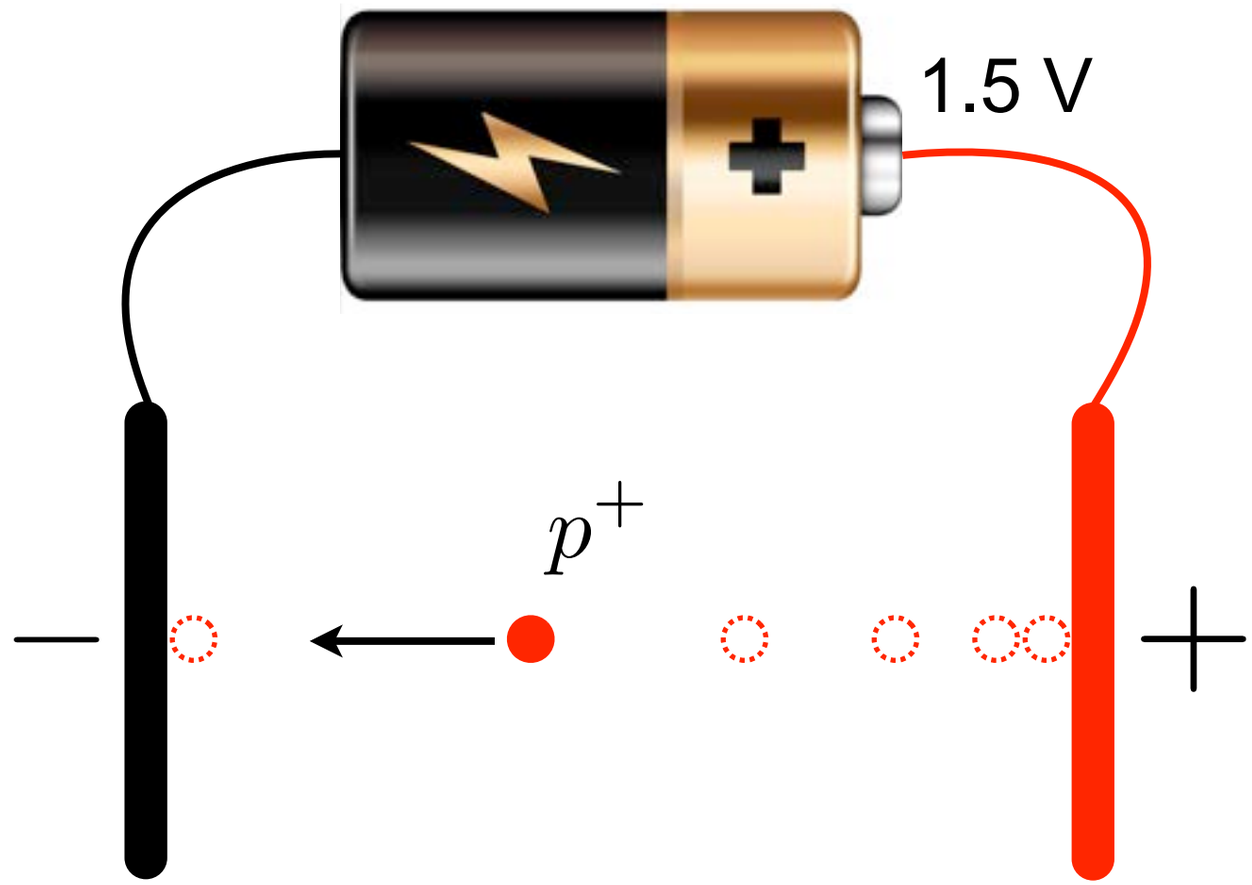
source of probe waves

detector

use particle “matter waves”

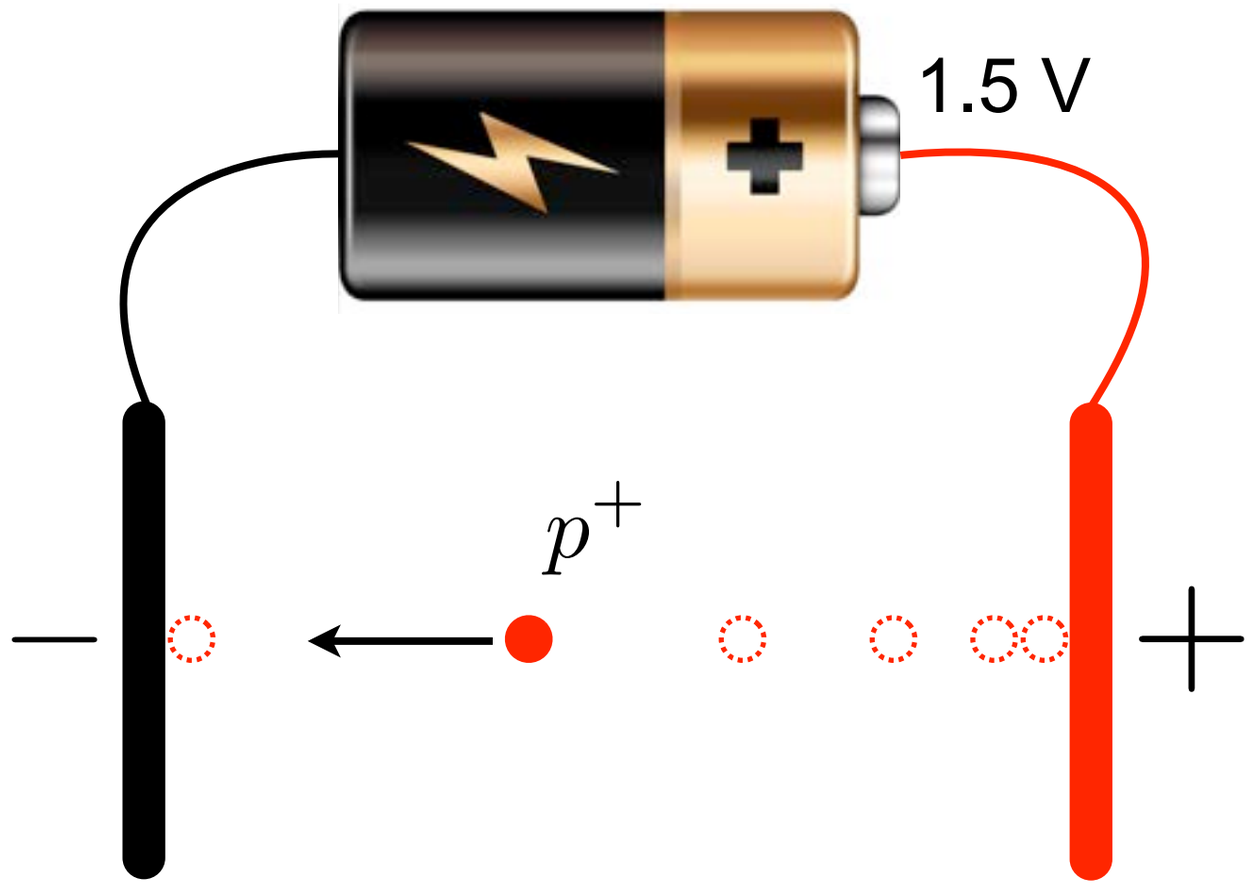
High energy particle means small matter wavelength!

Accelerating



Here the proton gains an energy of 1.5 “electron-Volt” or 1.5 eV

Accelerating



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- Charged particles can also be accelerated using electromagnetic waves to reach much higher energies
  - 1 MeV = 1,000,000 eV
  - 1 GeV = 1,000,000,000 eV ~ mc^2 for proton!
  - 1 TeV = 1,000,000,000,000 eV

Special Relativity

Space and Time are not absolute

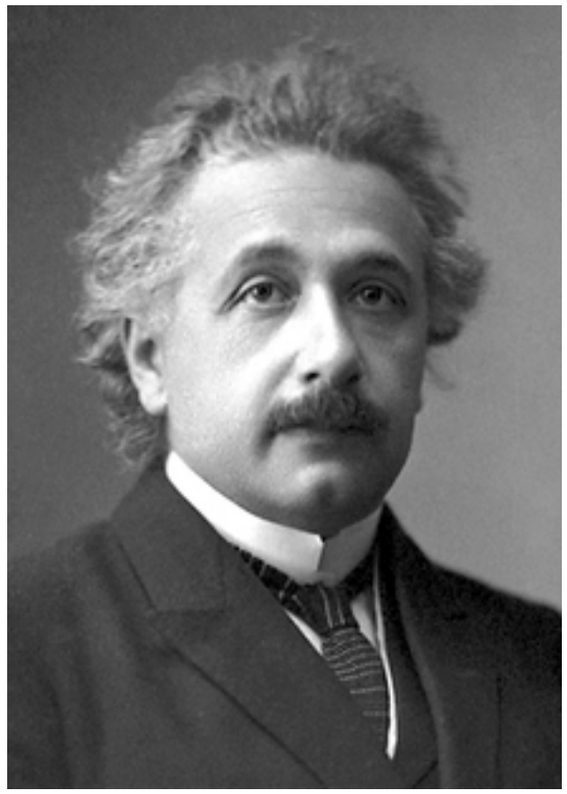
Space-Time

Newton's dynamics no longer valid for fast moving particles

speed of light is a limit speed

$$c = 299\,792\,458 \text{ m/s}$$

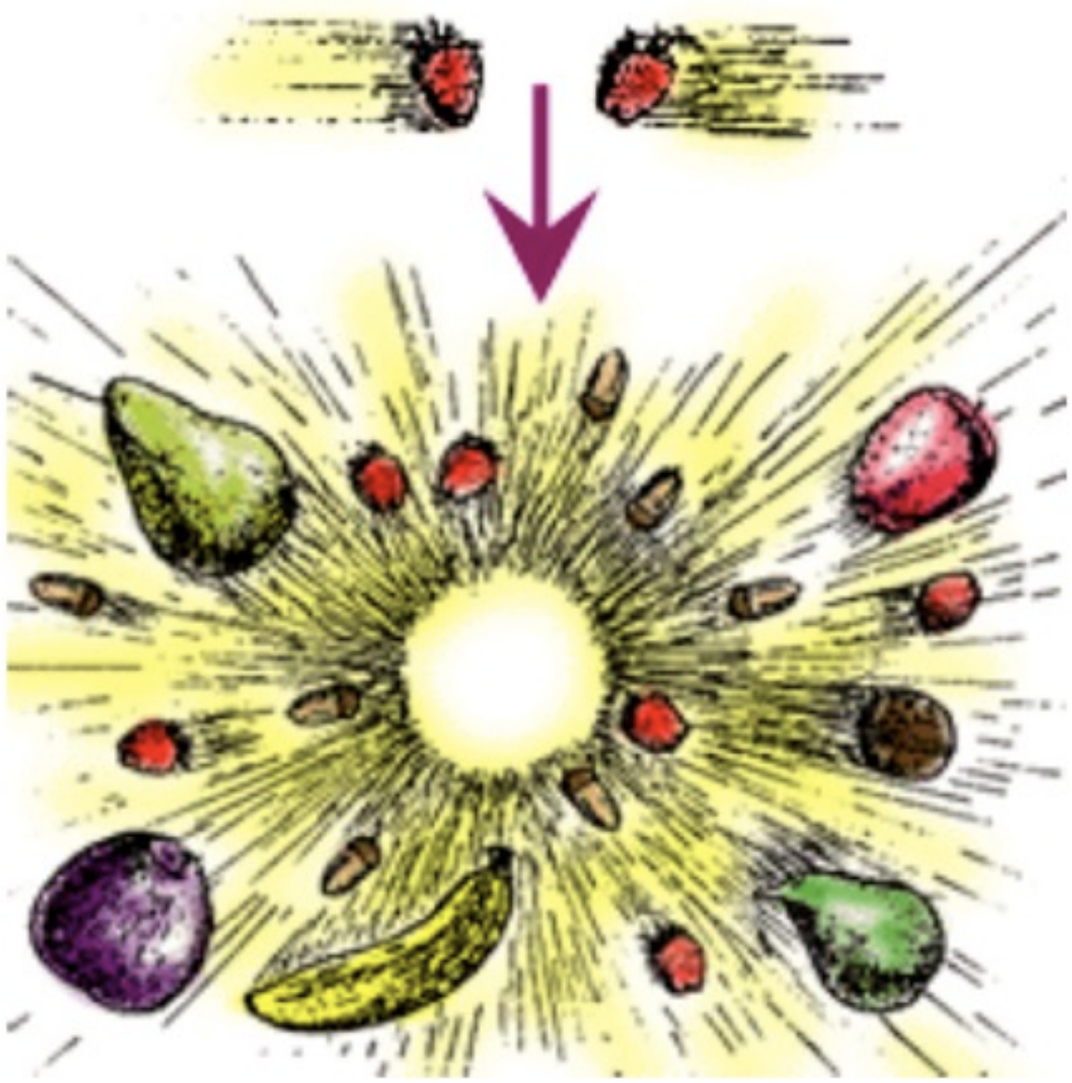
Nobel Prize
1921



Albert Einstein
(1879-1955)

Equivalence of mass and energy $E = mc^2$

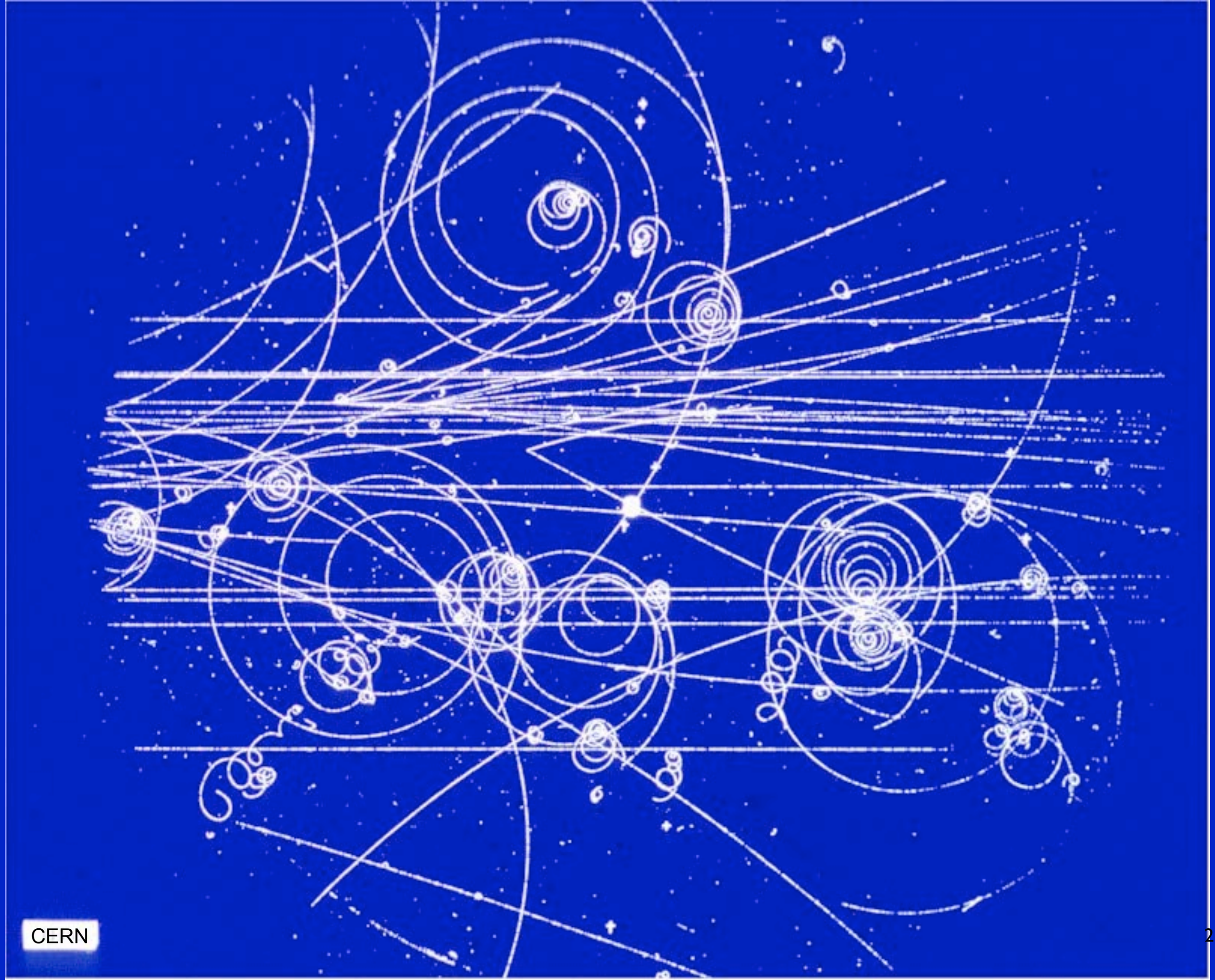
Colliding



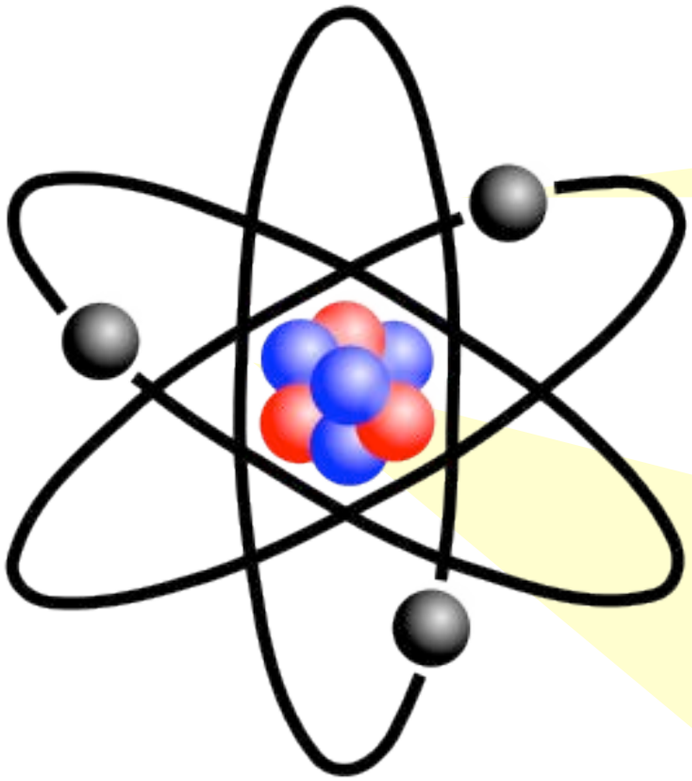
Can produce new particles

$$E = mc^2$$

New particles signal new physical laws!



Inside the atom



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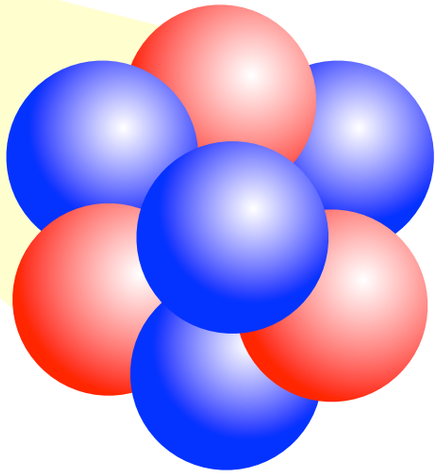
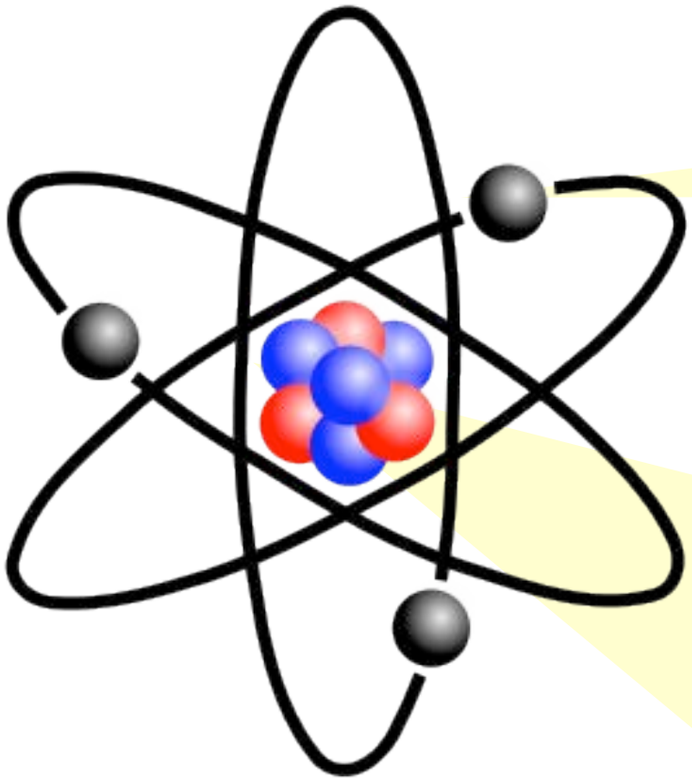
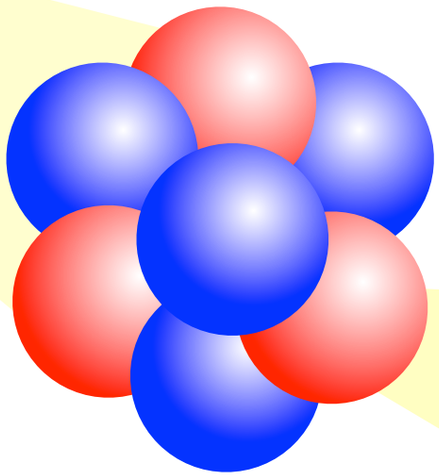


nucleus

Inside the atom

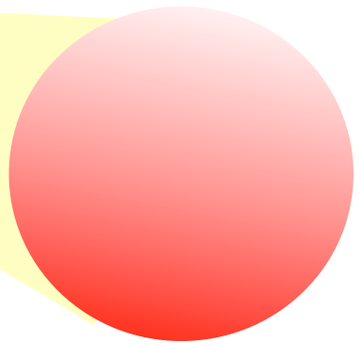


atom



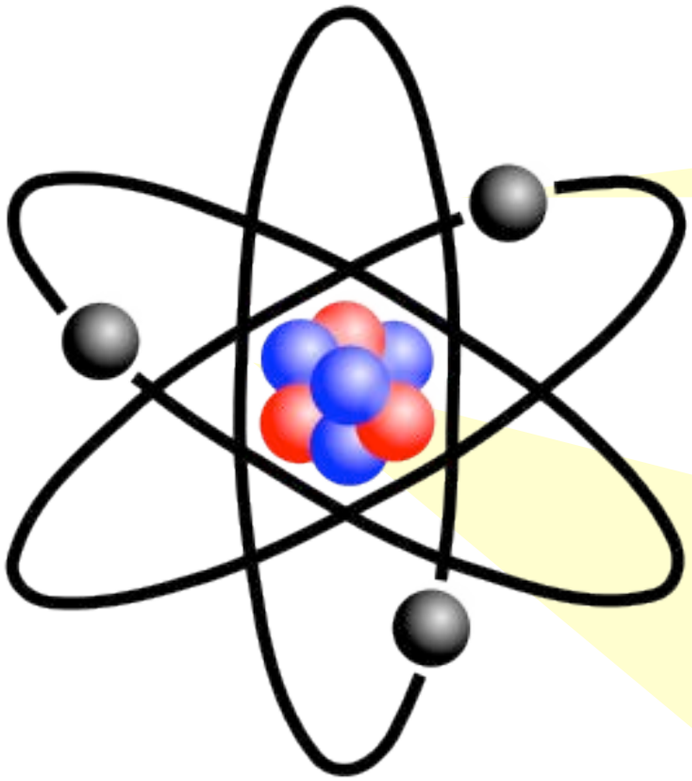
nucleus

electron

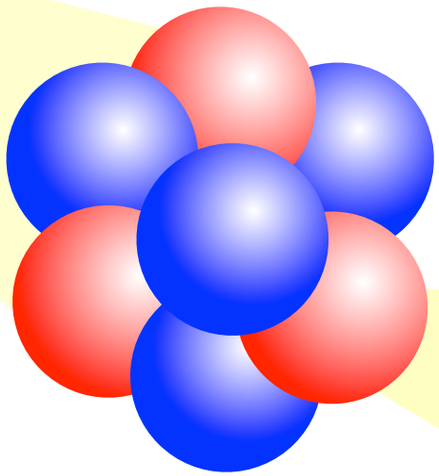


proton

Inside the atom



atom



nucleus

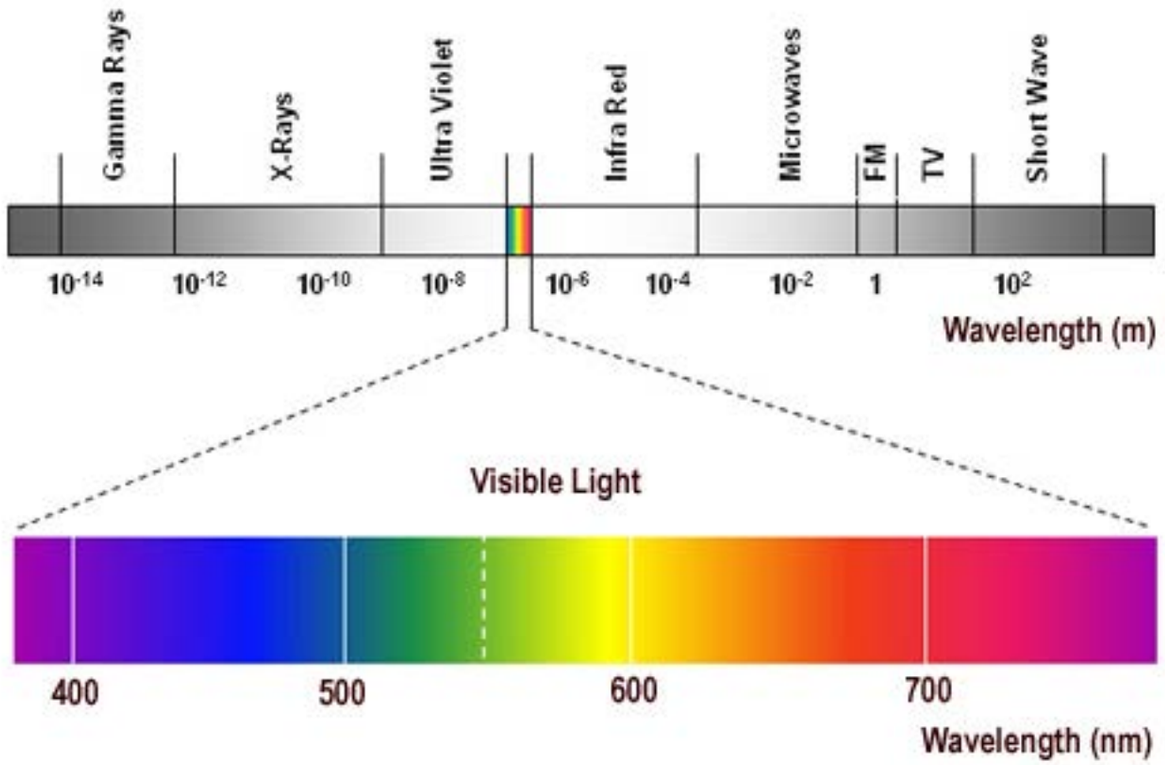
proton

quark

Electromagnetic force

Force between charged particles

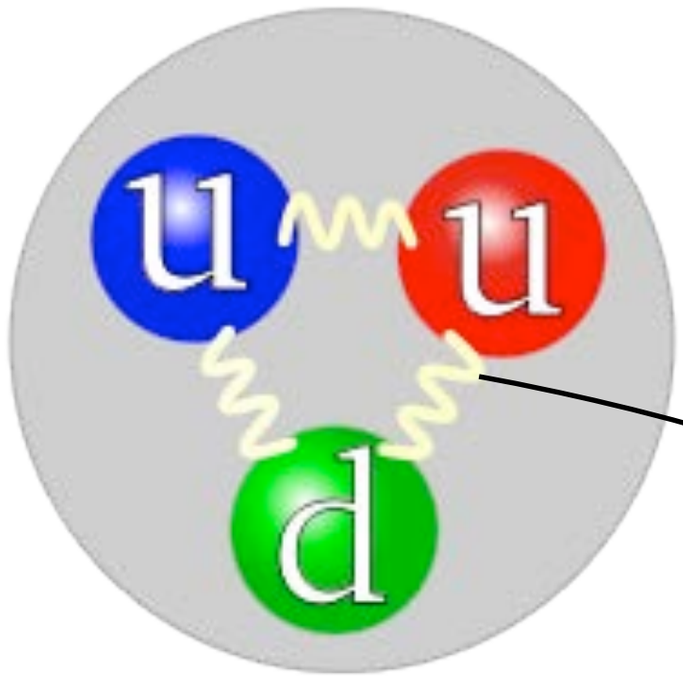
Carried by photons



Electromagnetic spectrum

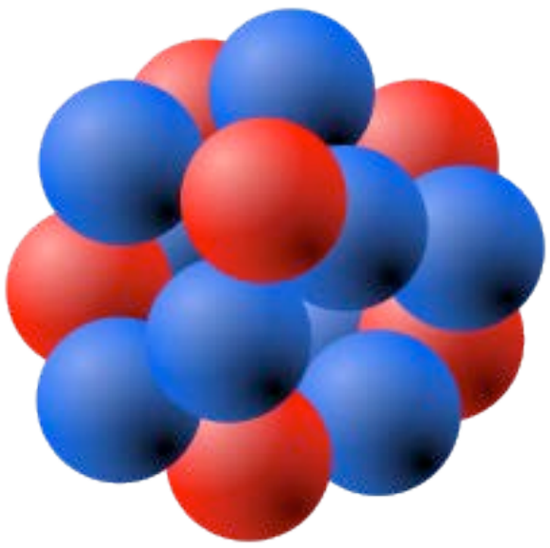
Strong force

Force between quarks carried by gluons



Proton

gluons

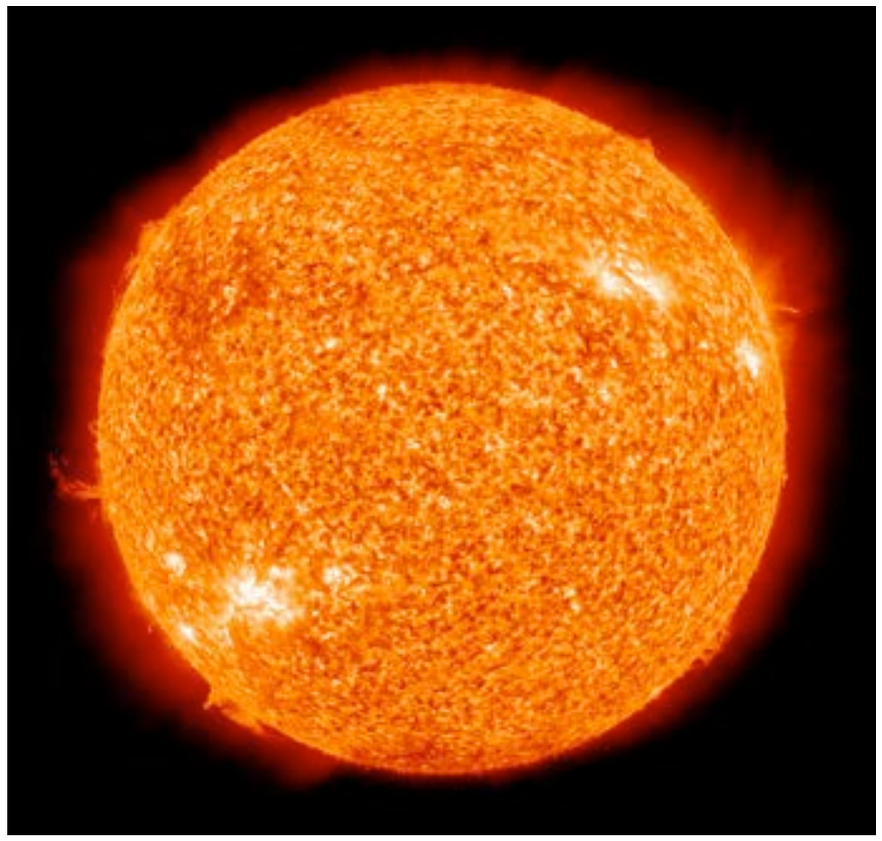


Binds protons and neutrons to form atomic nuclei

Weak force

neutron decay $n \rightarrow p + e^- + \bar{\nu}_{\mathrm{e}}$

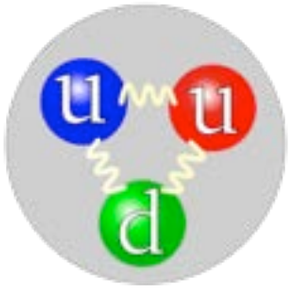
force carried by
W and Z bosons



controls the burning rate of the Sun

$$p + p \rightarrow e^+ + \nu_{\mathrm{e}} + pn$$

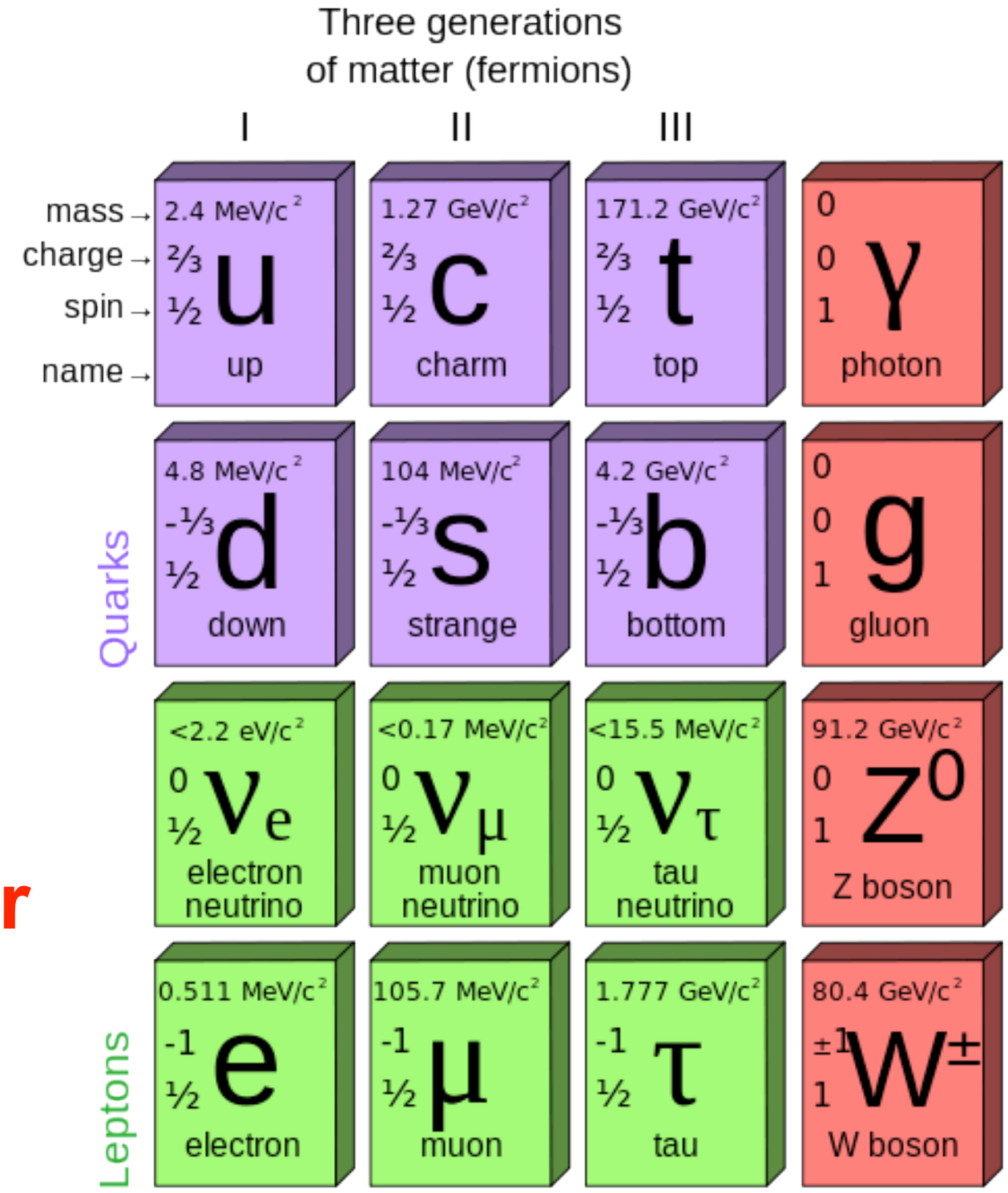
Matter and Forces



the **proton**: three bound quarks

Matter: spin 1/2 fermions

and Antimatter



Forces: mediated by spin 1 bosons

Fields and particles

Electromagnetic field → Photons

Waves ⟷ particles

Fields and particles

Electromagnetic field → Photons

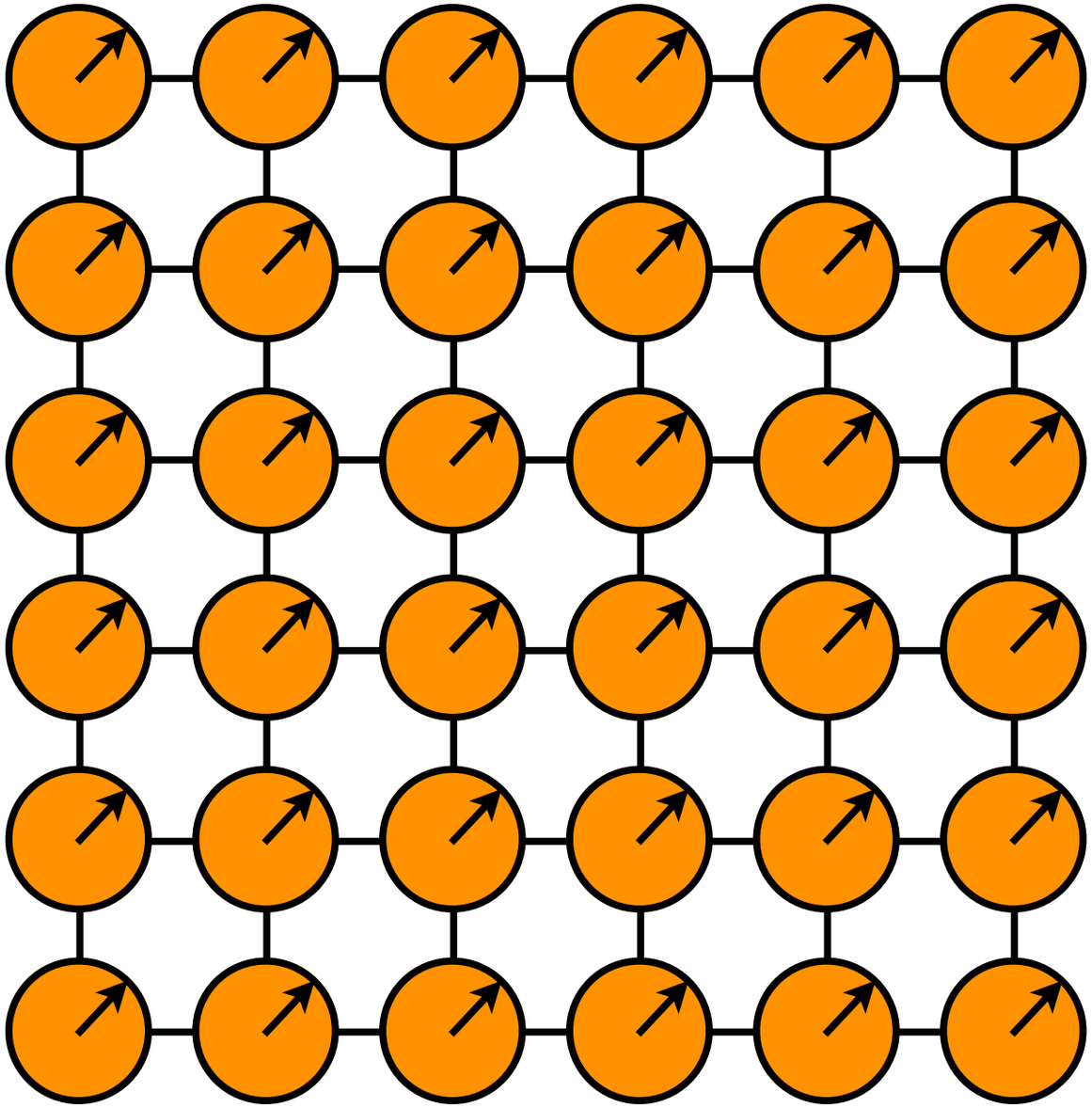
Waves ⟺ particles

Fundamental particles
are quanta of excitation
of fundamental fields

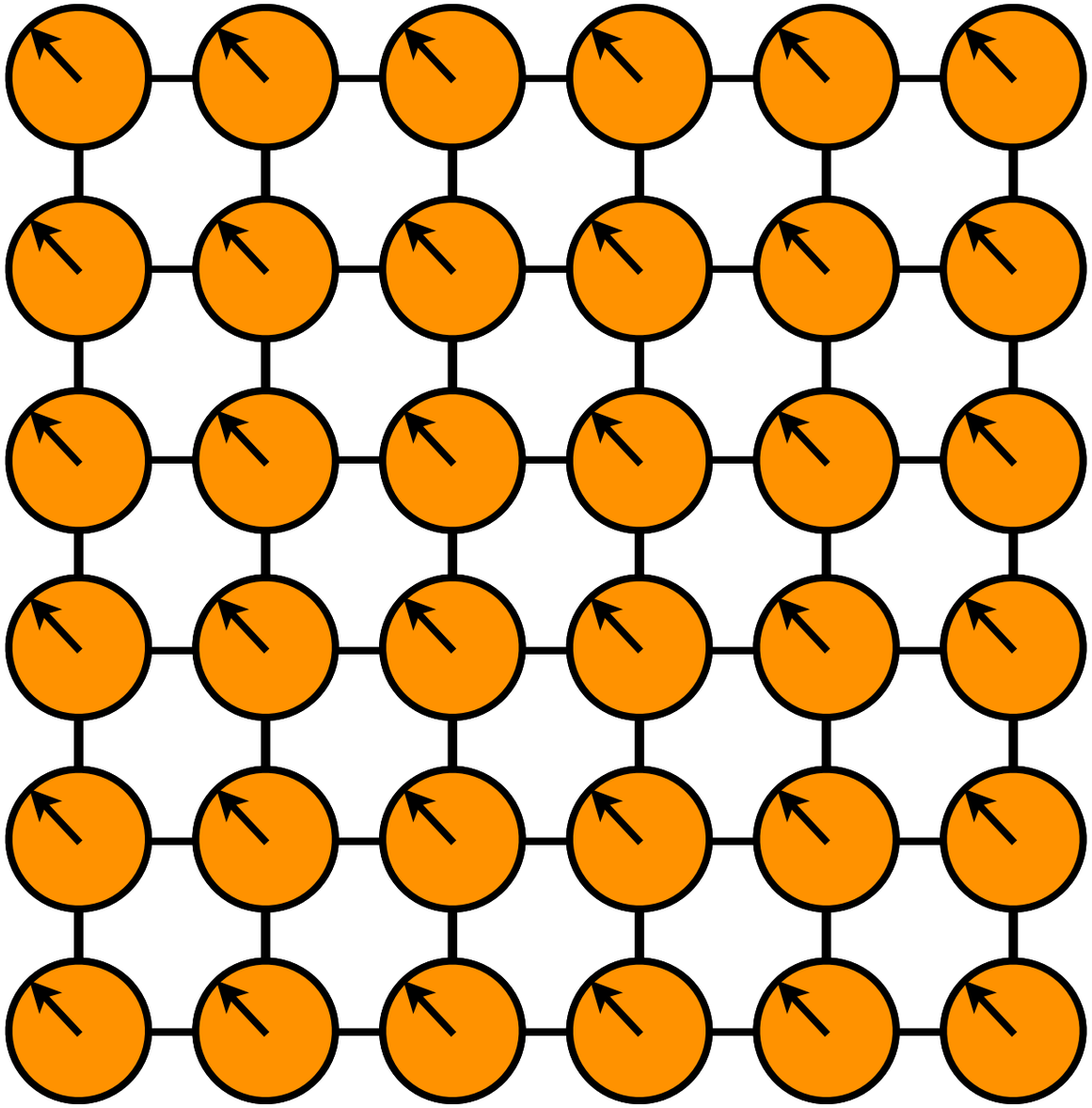
Symmetries

Symmetries are related to conservation laws

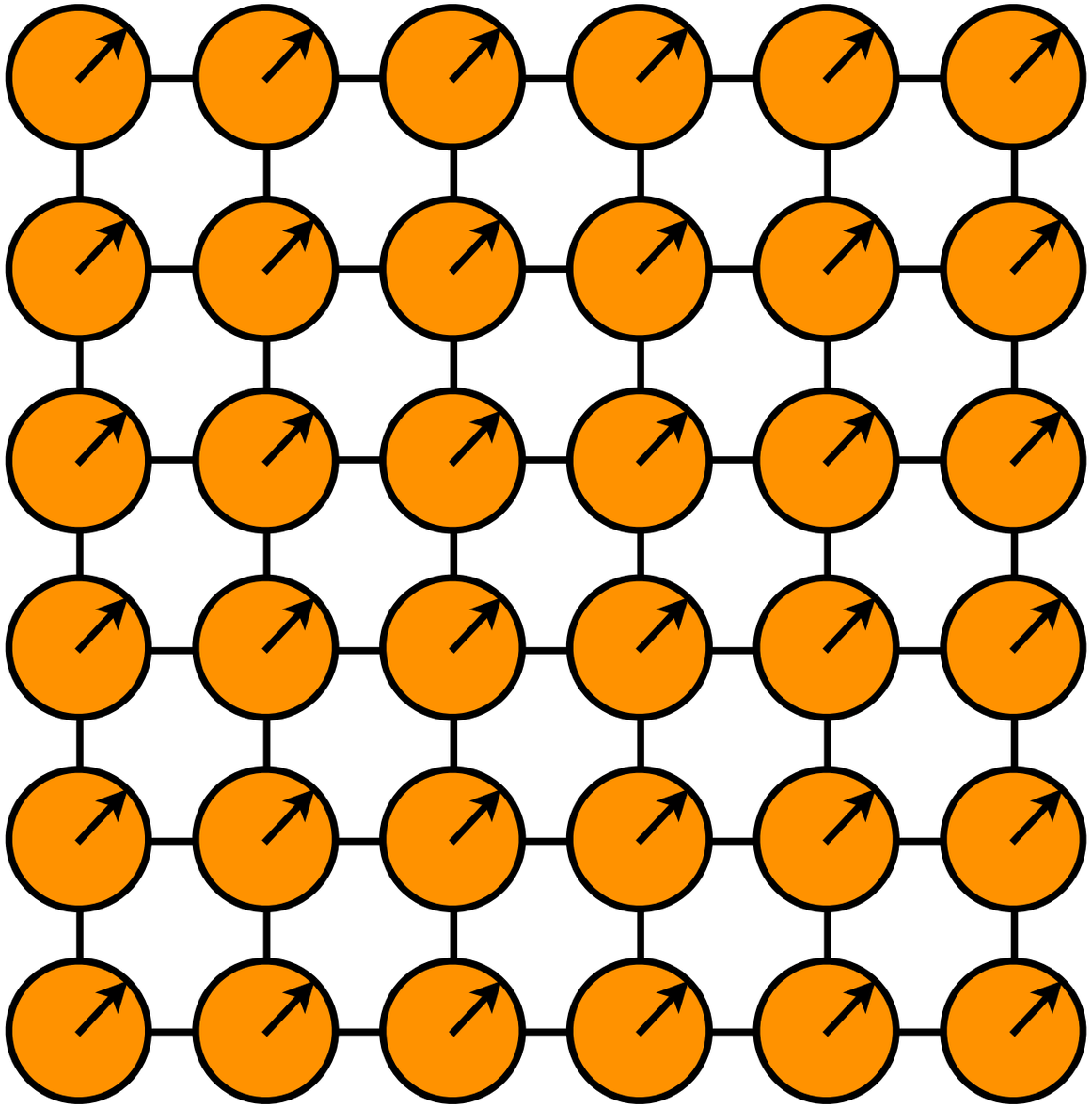
Symmetries and Forces



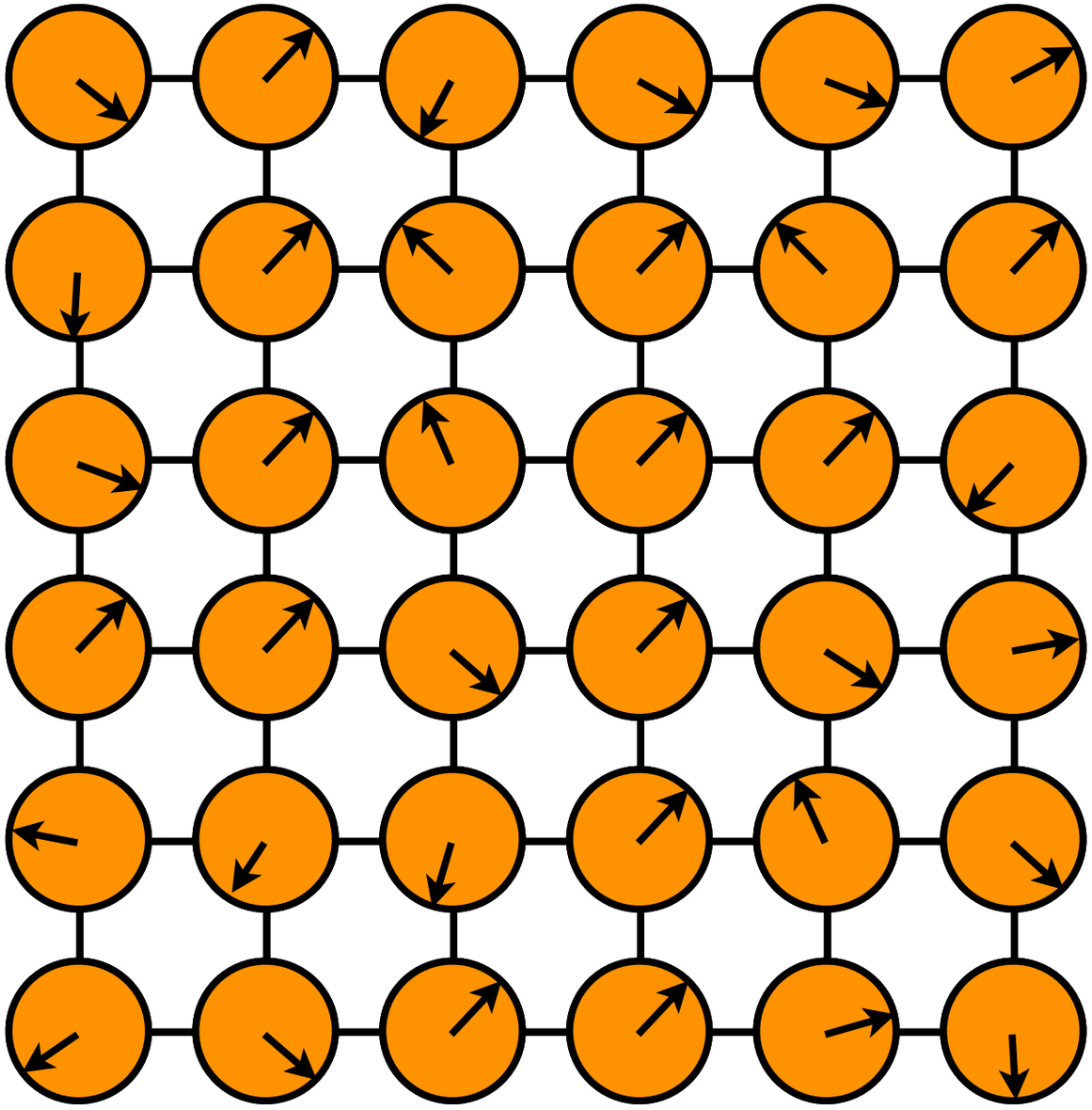
Symmetries and Forces



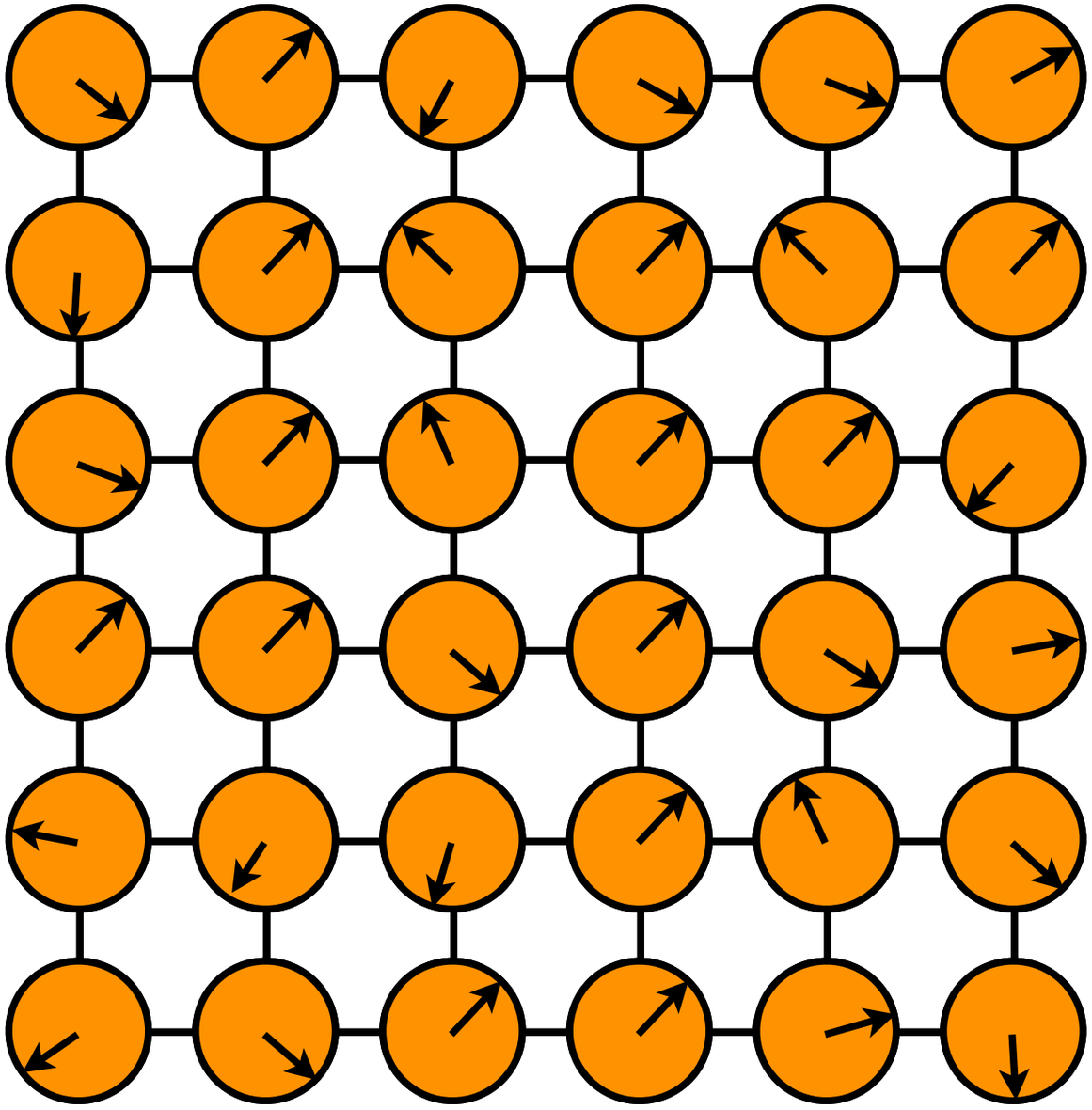
Symmetries and Forces



Symmetries and Forces



Symmetries and Forces



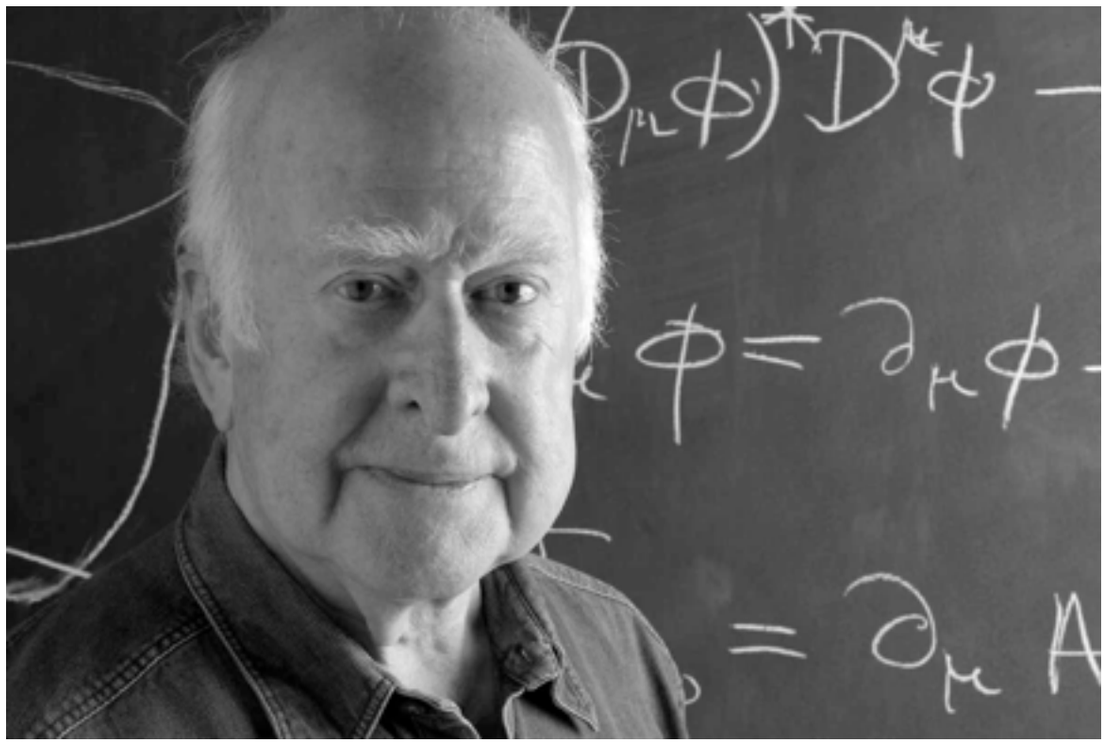
Local symmetry

Force!

All known forces are consequences of local symmetries...
but this only works for massless particles!!

The Higgs mechanism

Mathematical construct that allows all particles to have mass while allowing the theory the keep powerful symmetries that predict all forces

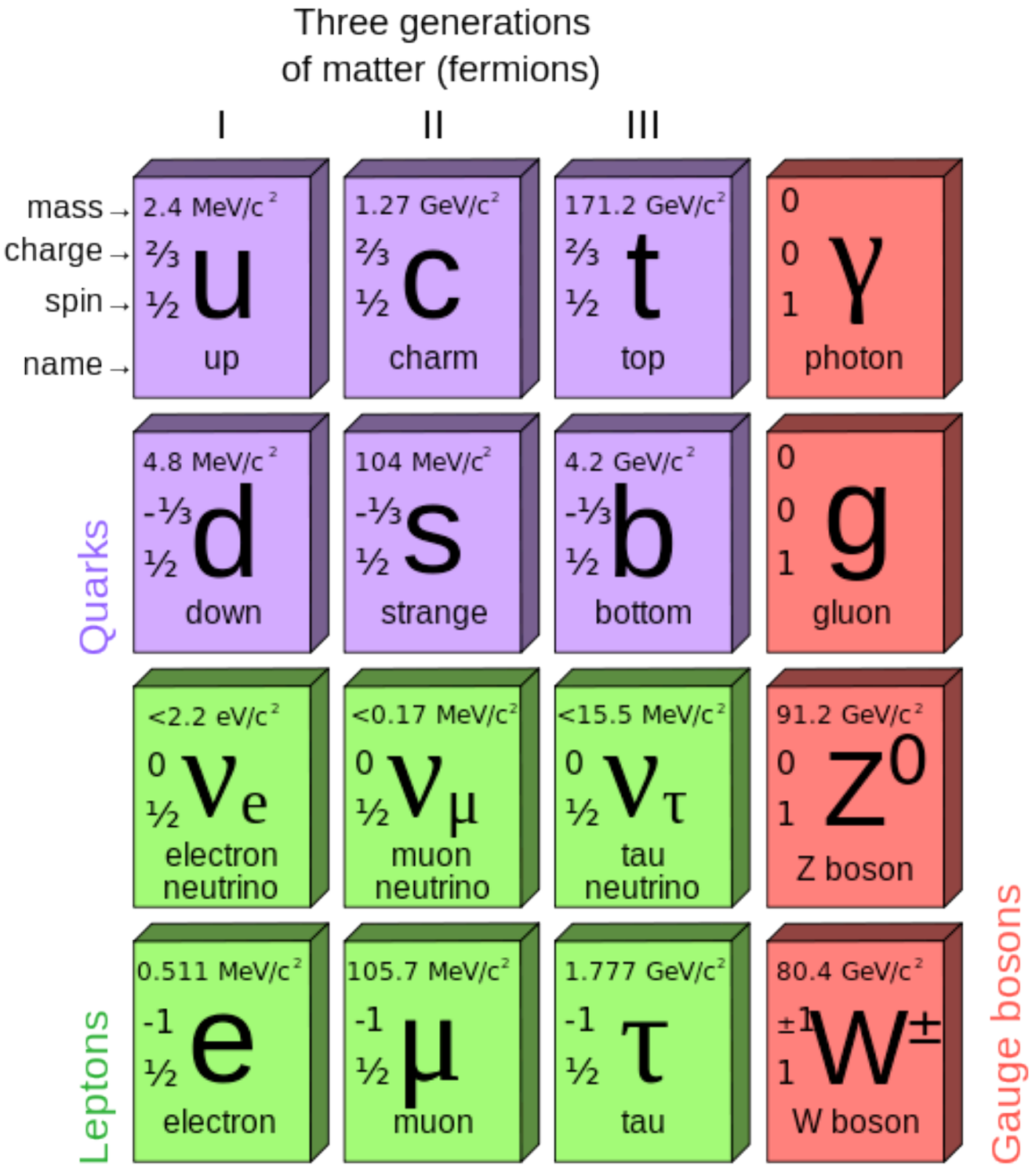


Peter Higgs
1929-

R. Brout, F. Englert, P. Higgs, G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble

→ Higgs Field →

The Standard Model



Higgs boson: the missing piece

H^0

- Very successful theory
  - relativistic quantum fields
  - All experimental measurements at the subatomic level agree with the SM to date!
- But it does not predict the mass of the Higgs boson!

The Standard Model

Standard Model Lagrangian Density

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - ig c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
&\tfrac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
&W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2}g[W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H\partial_\mu \phi^+ - \\
&\phi^+ \partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
&igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
&igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
&\tfrac{1}{4}g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \tfrac{1}{2}g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
&g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + \\
&m^\lambda_d) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
&\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - 1 - \gamma^5) u^\lambda_j) + \\
&(\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
&\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u^\lambda_j)] + \\
&\tfrac{ig}{2\sqrt{2}} \tfrac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M} [H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \\
&\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j] - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
&\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
&igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
&igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
&igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
&\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \phi^+ - \\
&\bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} igM[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w [\bar{X}^0 X^- \phi^+ - \\
&\bar{X}^0 X^+ \phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

The Standard Model

Standard Model Lagrangian Density

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w} Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w} Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + \\
&m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \\
&\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + \\
&(\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 + \\
&\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] + \\
&\tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \\
&\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \\
&\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
&igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
&igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
&igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \\
&\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0\phi^+ - \\
&\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w} igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \\
&\bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

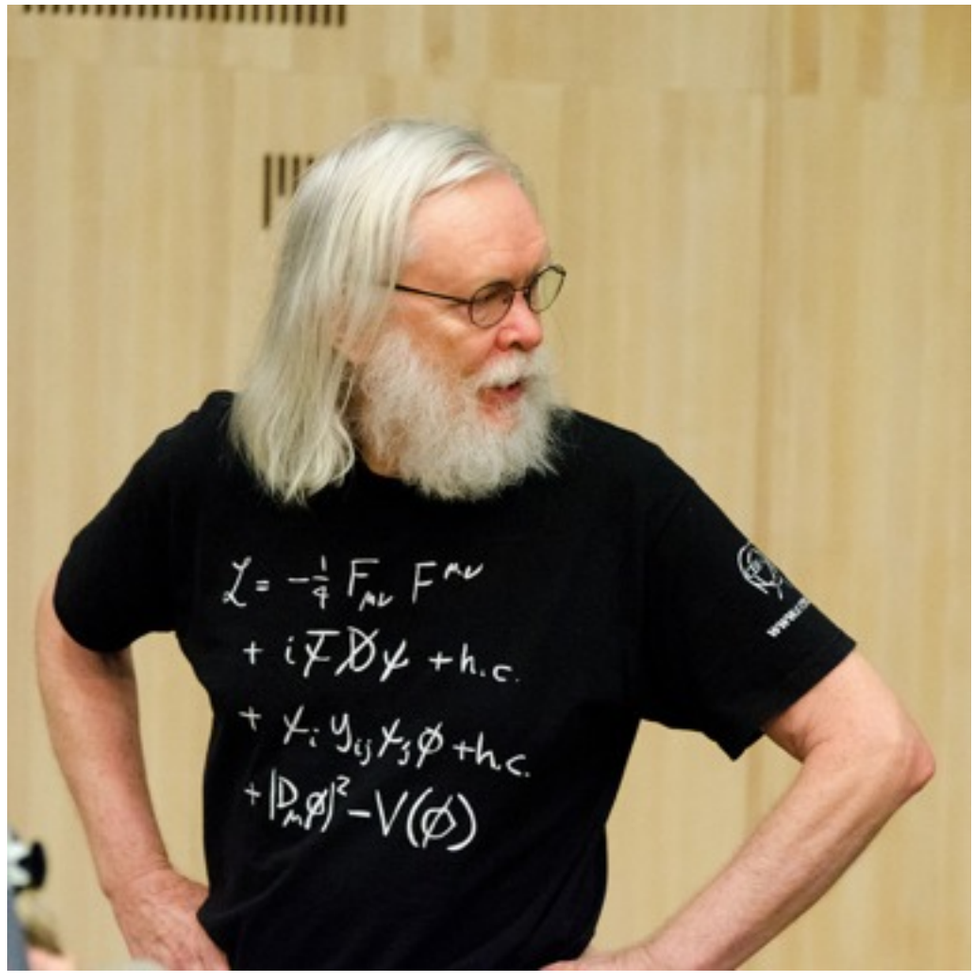
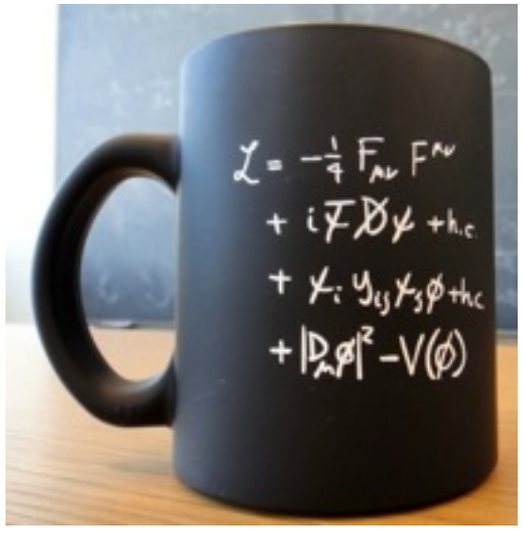


Photo: Josh Thompson



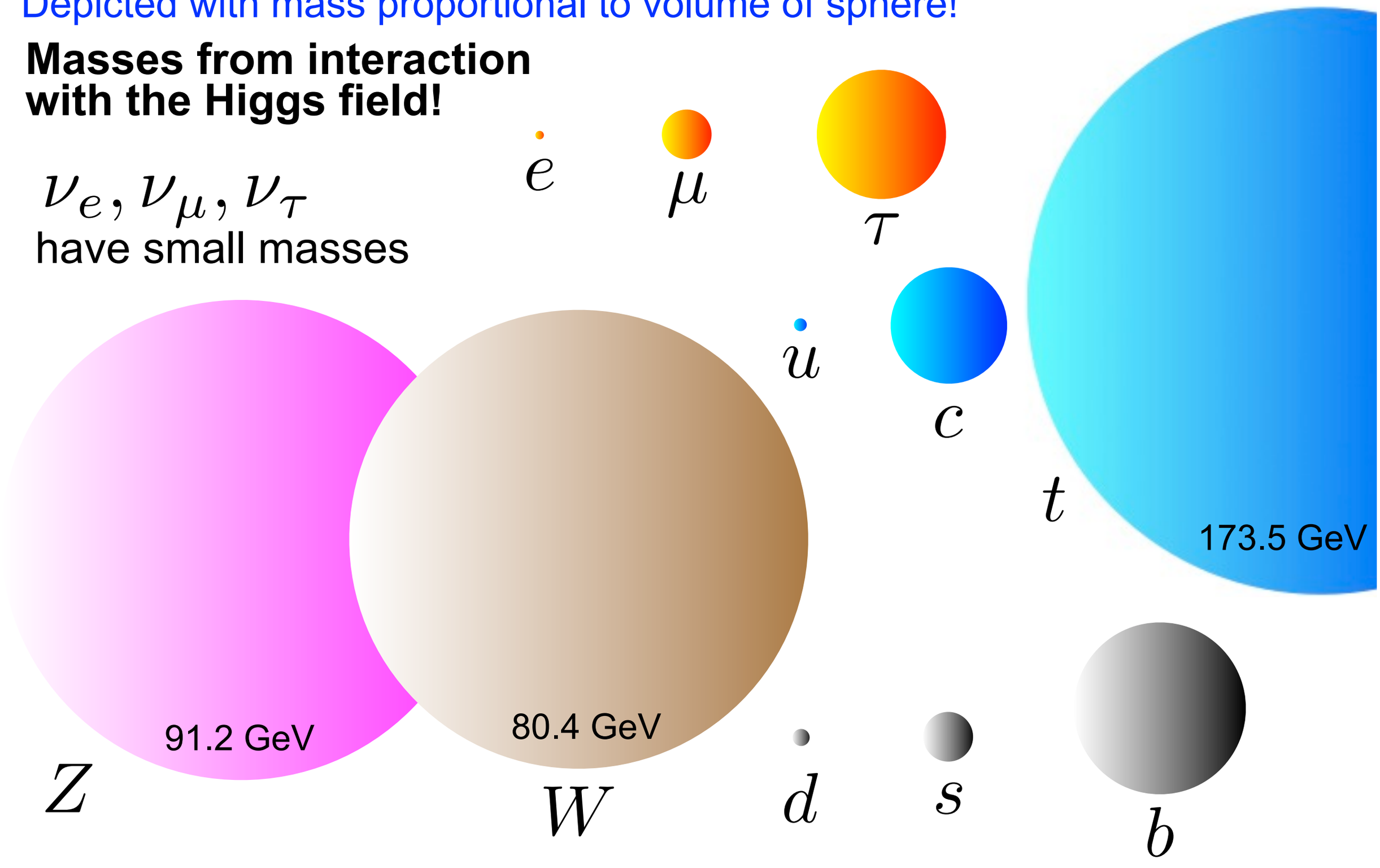
Fundamental Masses

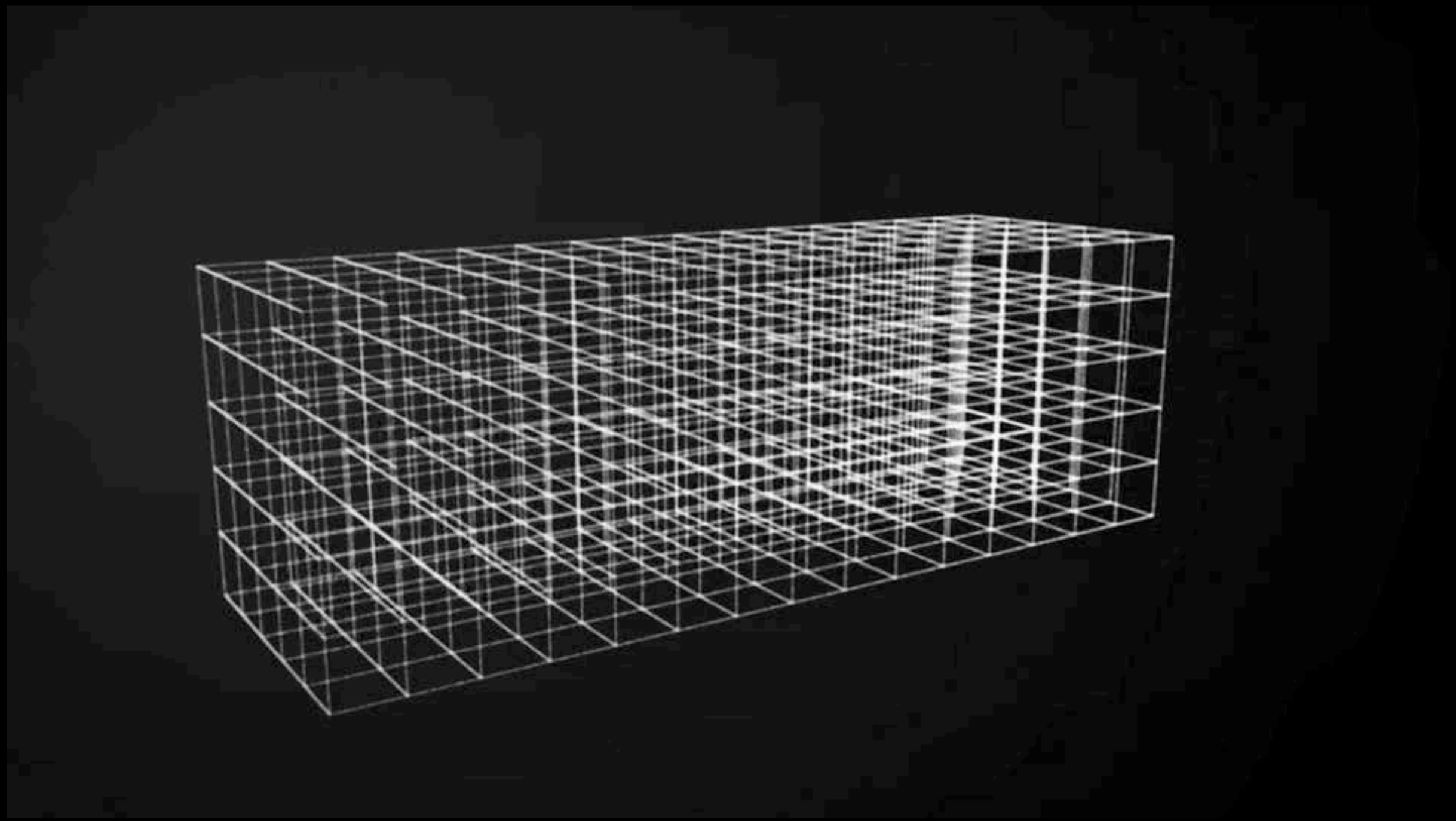
γ, g
massless

Depicted with mass proportional to volume of sphere!

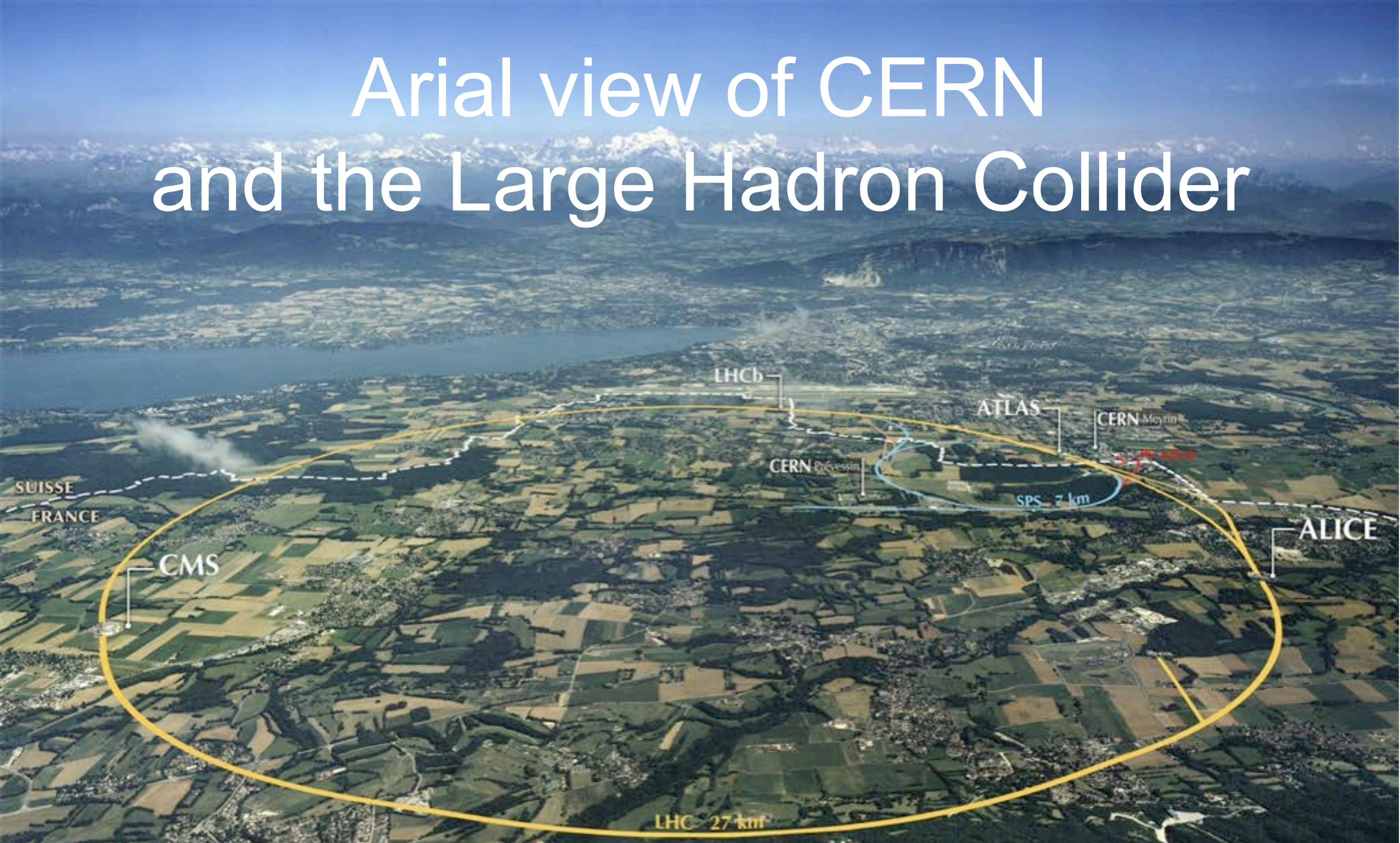
Masses from interaction with the Higgs field!

ν_e, ν_μ, ν_τ
have small masses





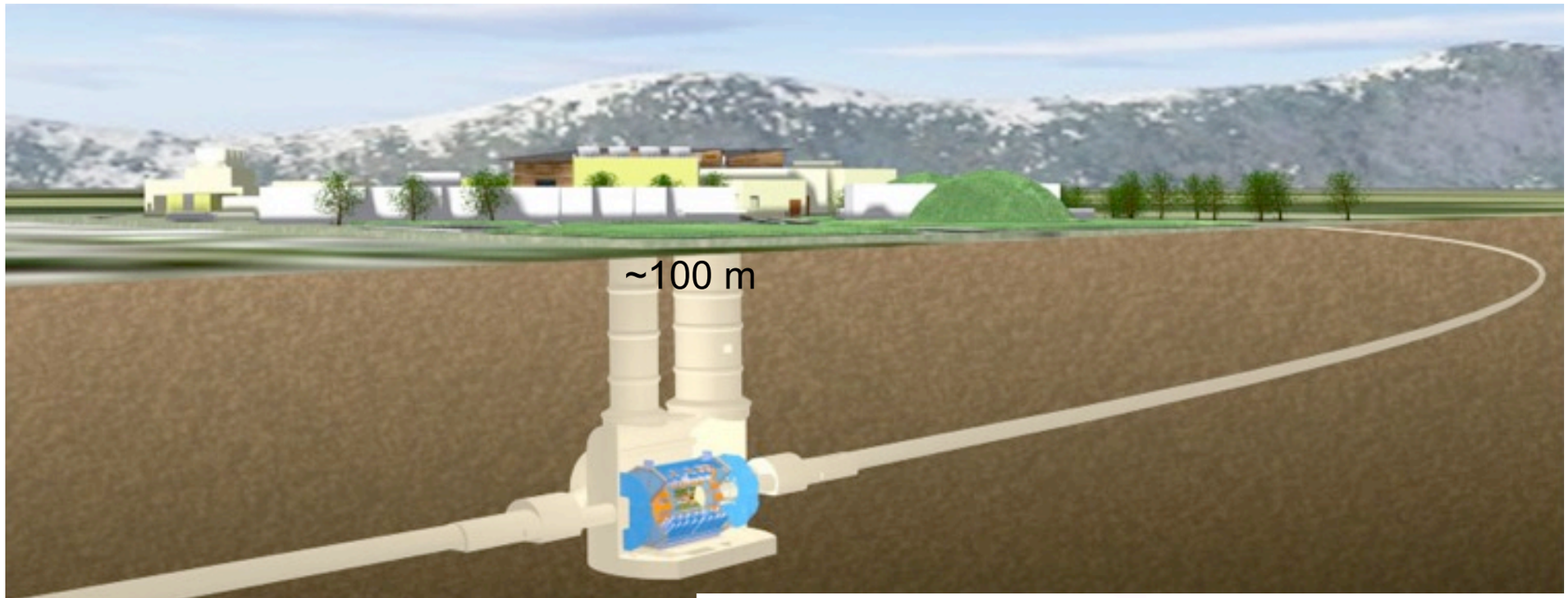
Arial view of CERN and the Large Hadron Collider



CERN now has Observer Status in the General Assembly of the UN

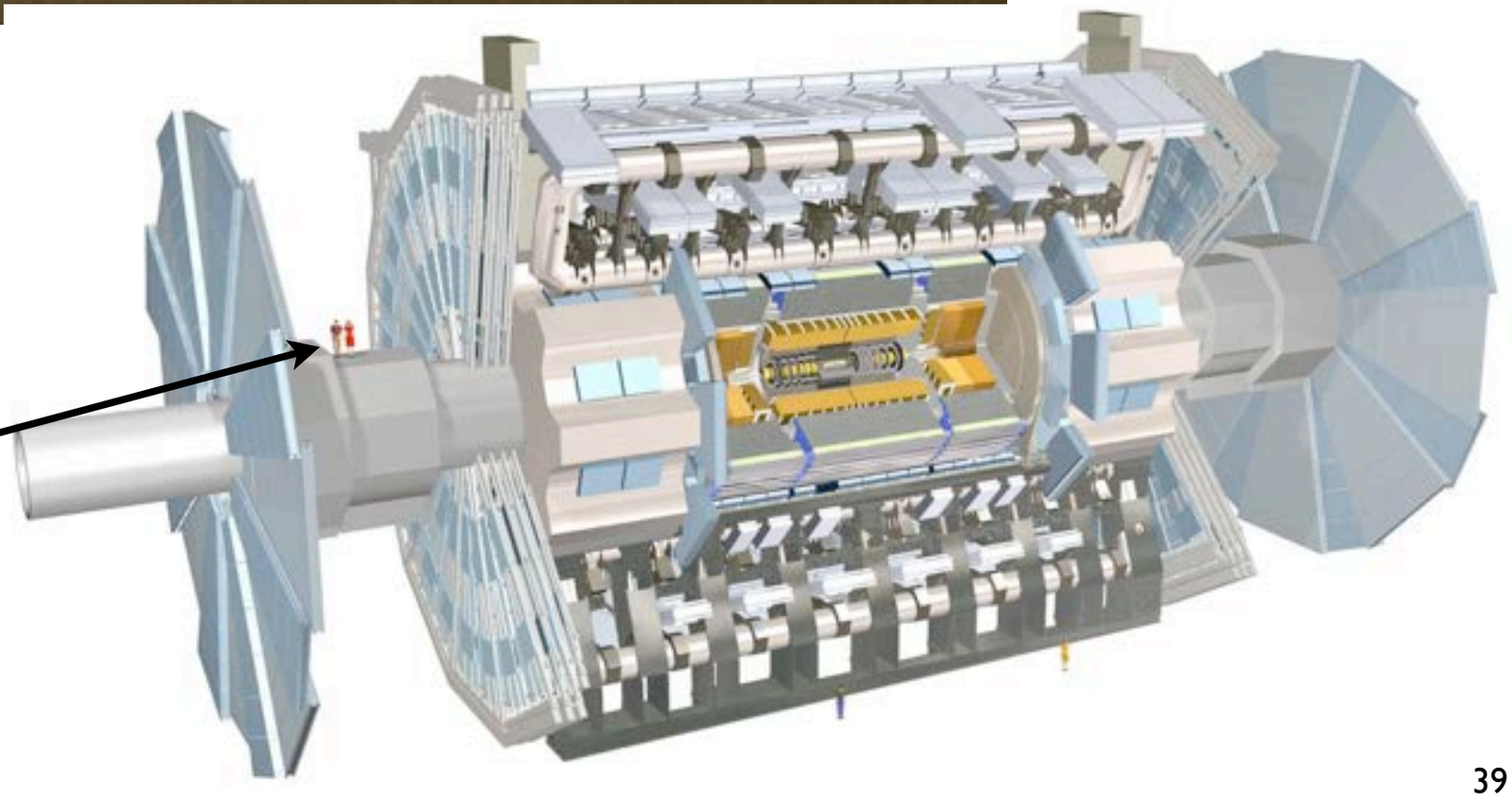
Getting around in the Large Hadron Collider

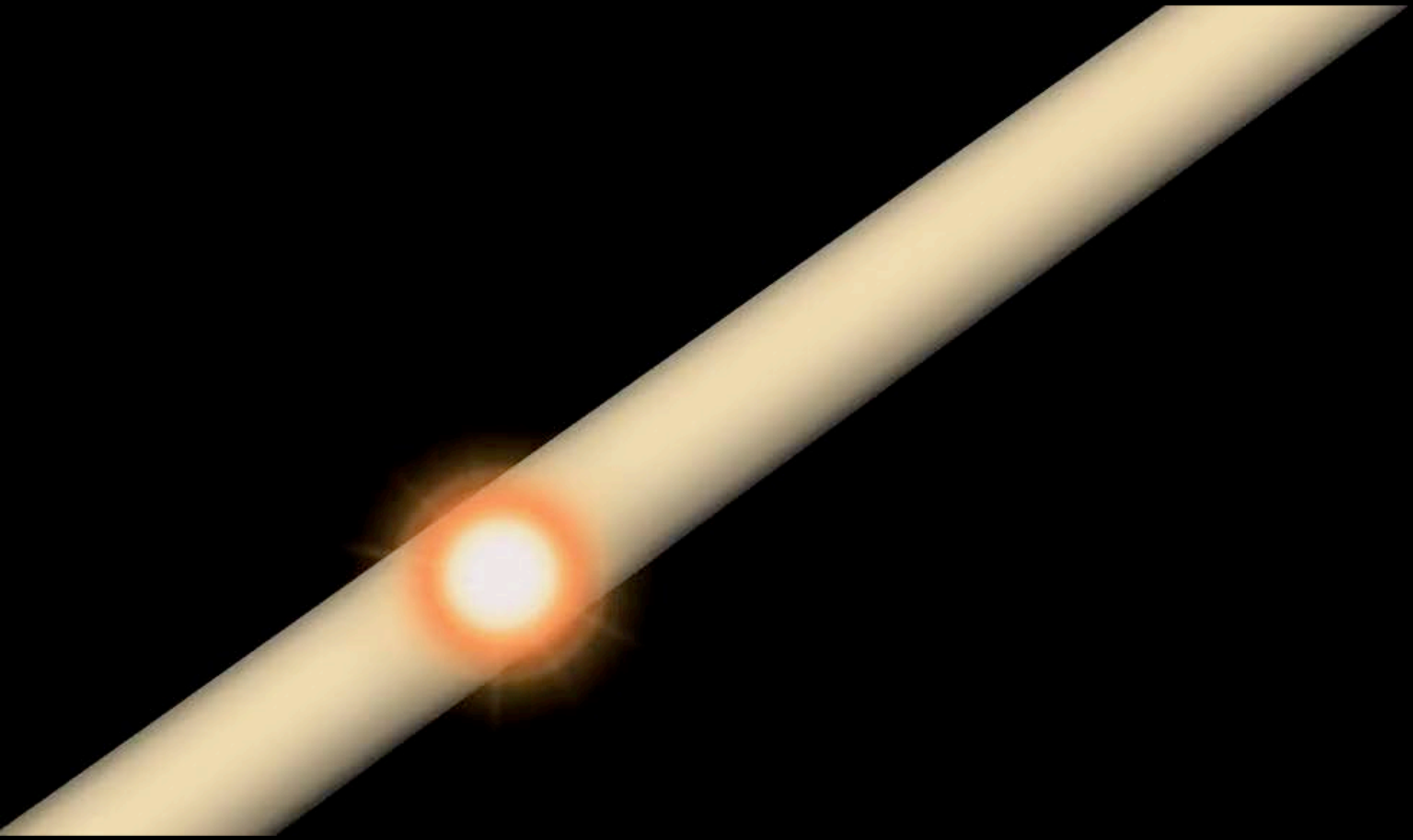
The ATLAS detector at the LHC



The ATLAS Experiment at CERN, http://atlas.ch

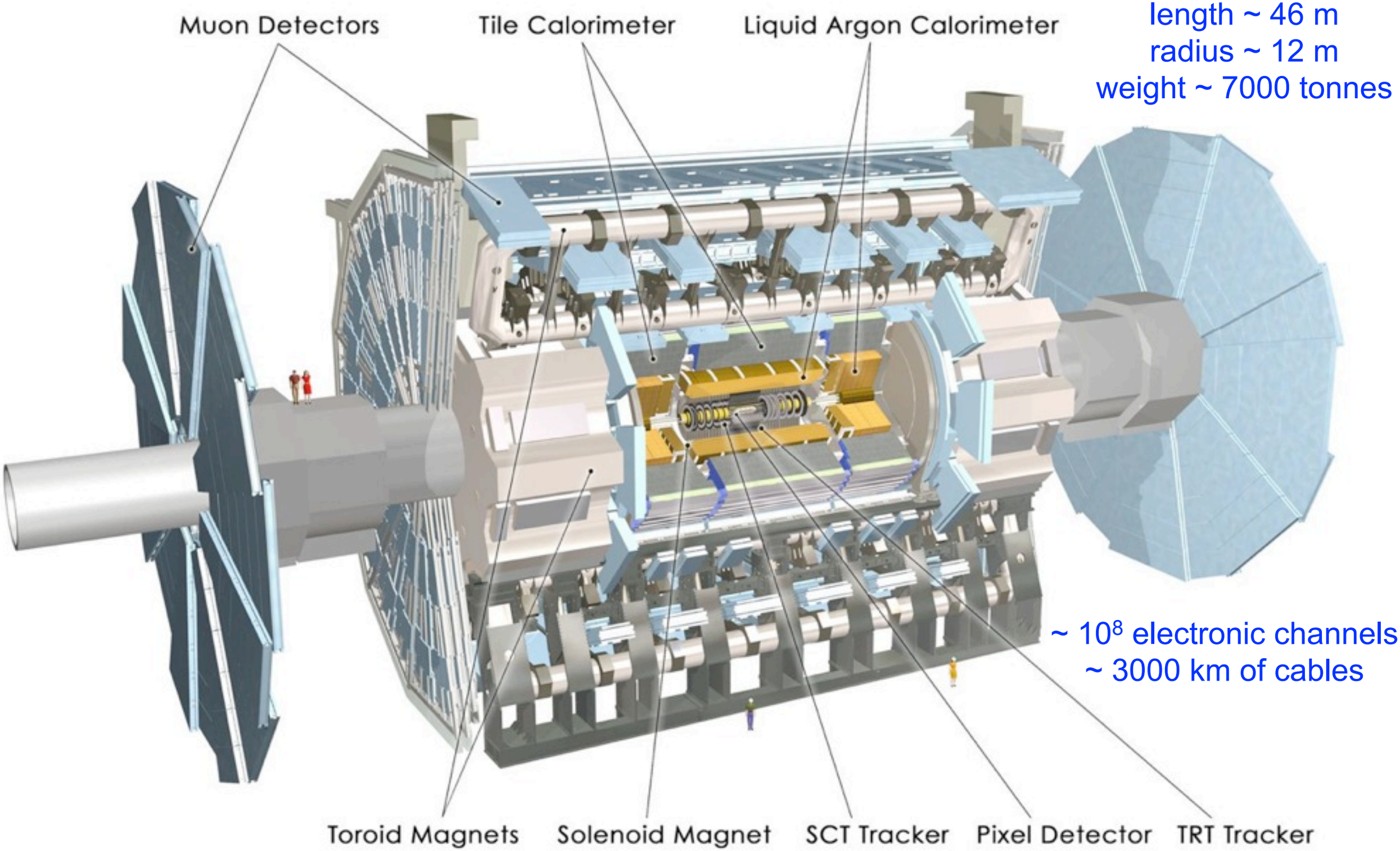
a person!





http://www.atlas.ch/multimedia/4-muon-event.html

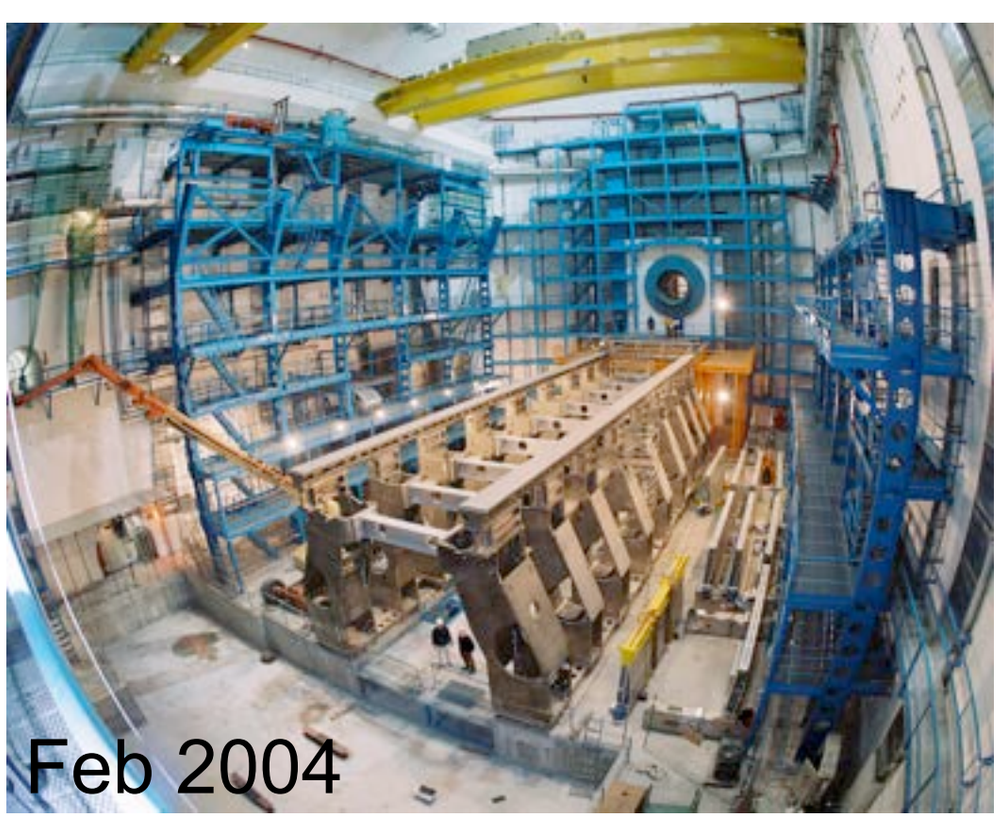
The ATLAS detector



length ~ 46 m
radius ~ 12 m
weight ~ 7000 tonnes

~ 10^8 electronic channels
~ 3000 km of cables

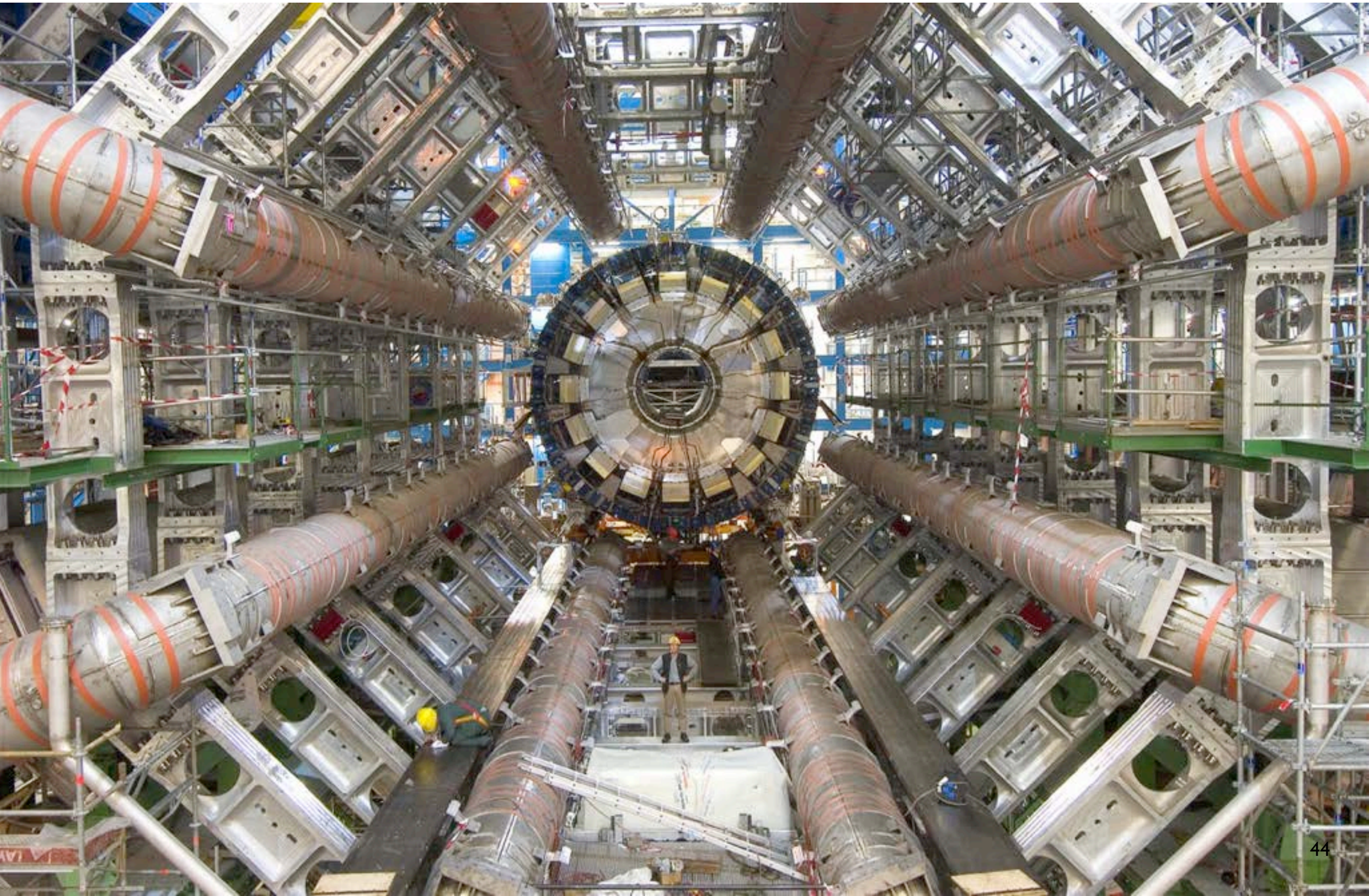
ATLAS cavern



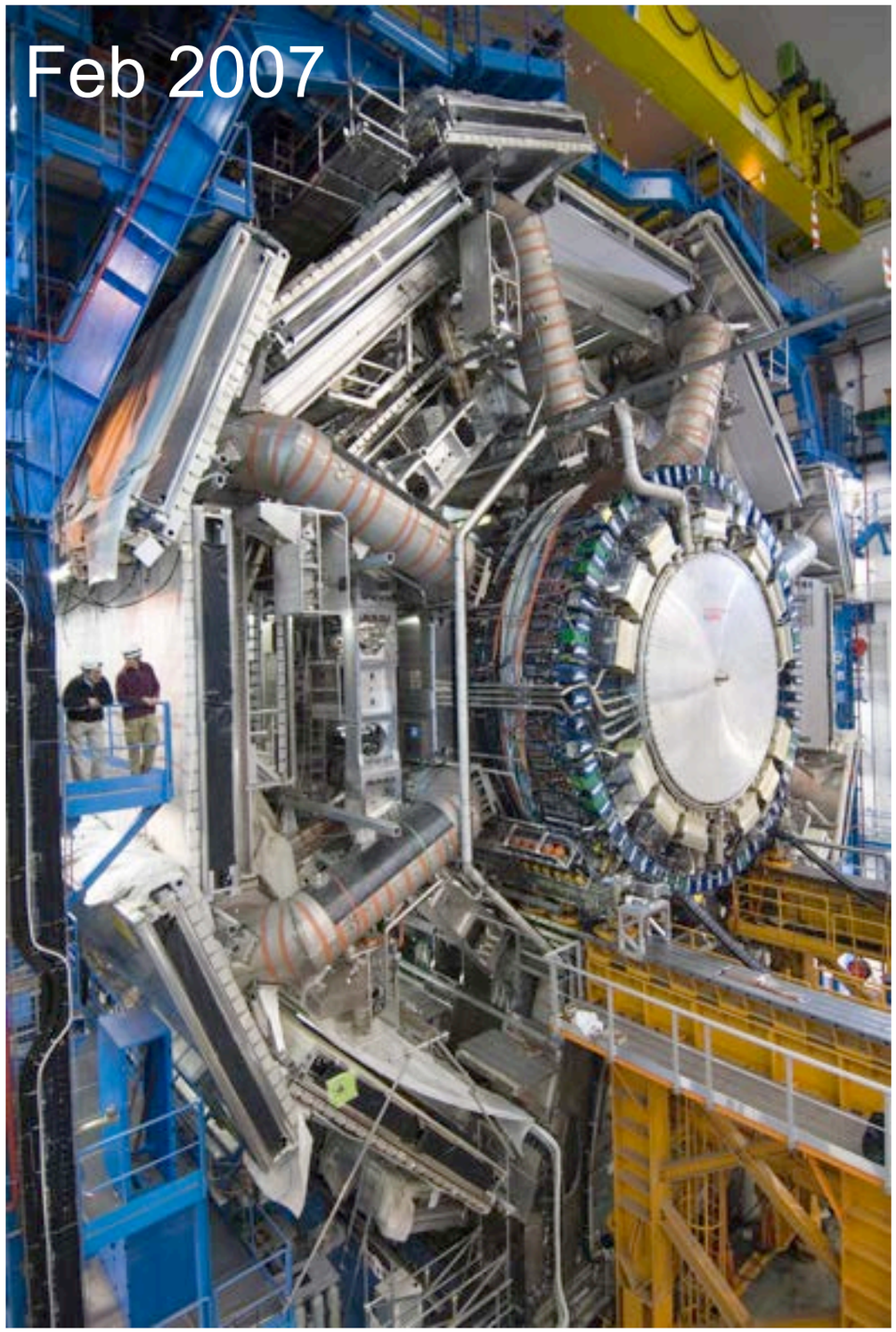
The ATLAS Experiment at CERN, http://atlas.ch

CERN

Barrel Toroids all installed (Nov 2005)



Moving the calorimeters in place

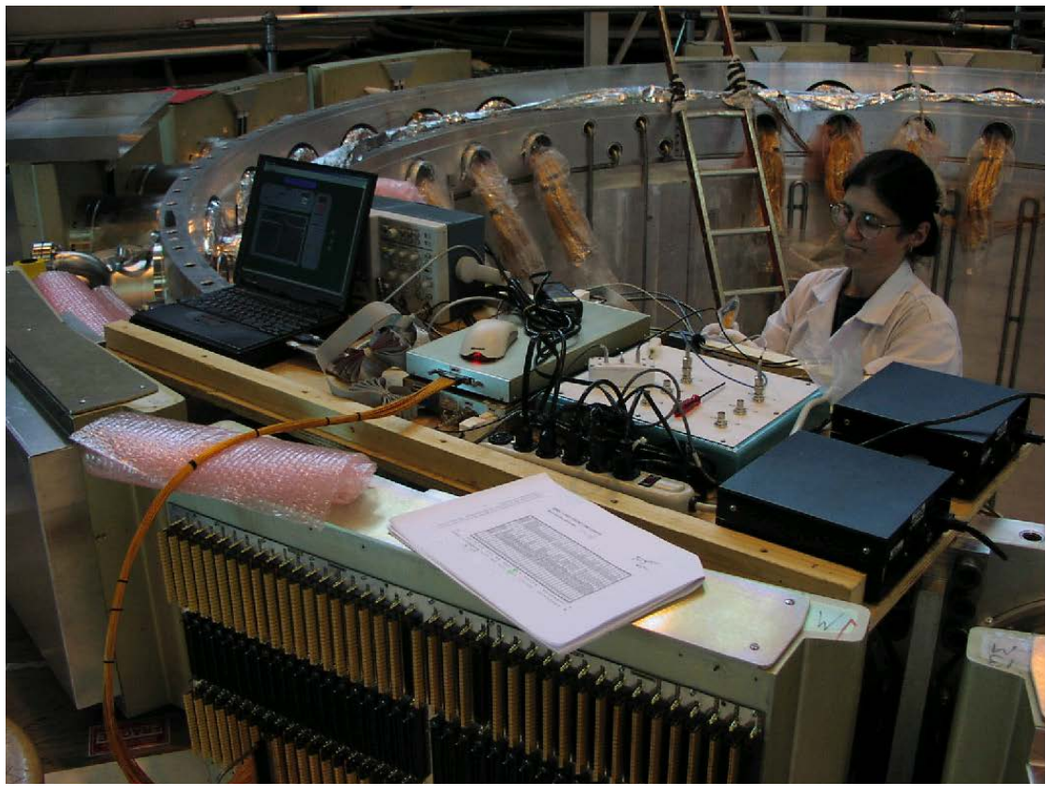


Closing of LHC beam pipe (16 June 2008)

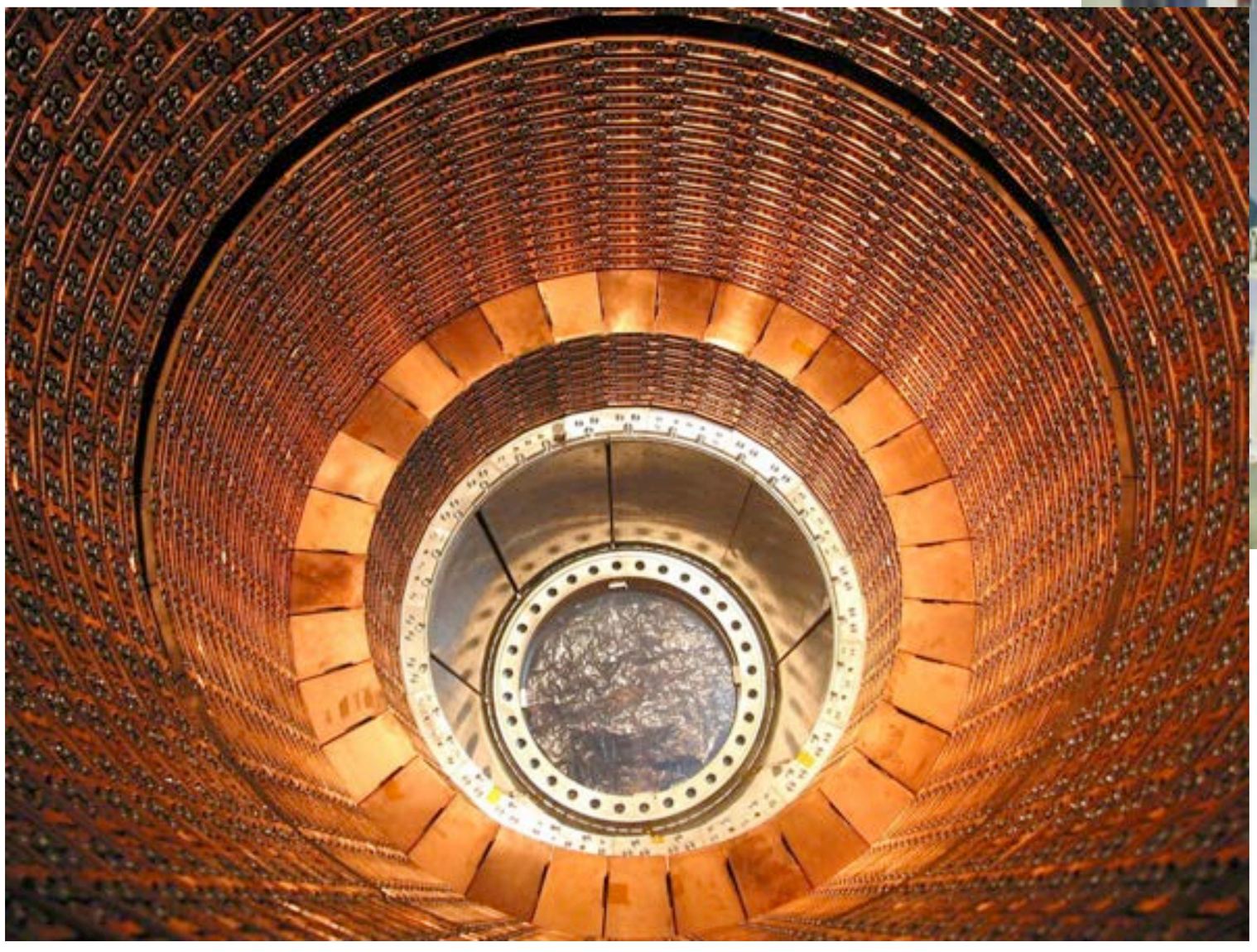
ATLAS components and Canada

ATLAS lab at UVic during construction

Feedthrough tests at CERN

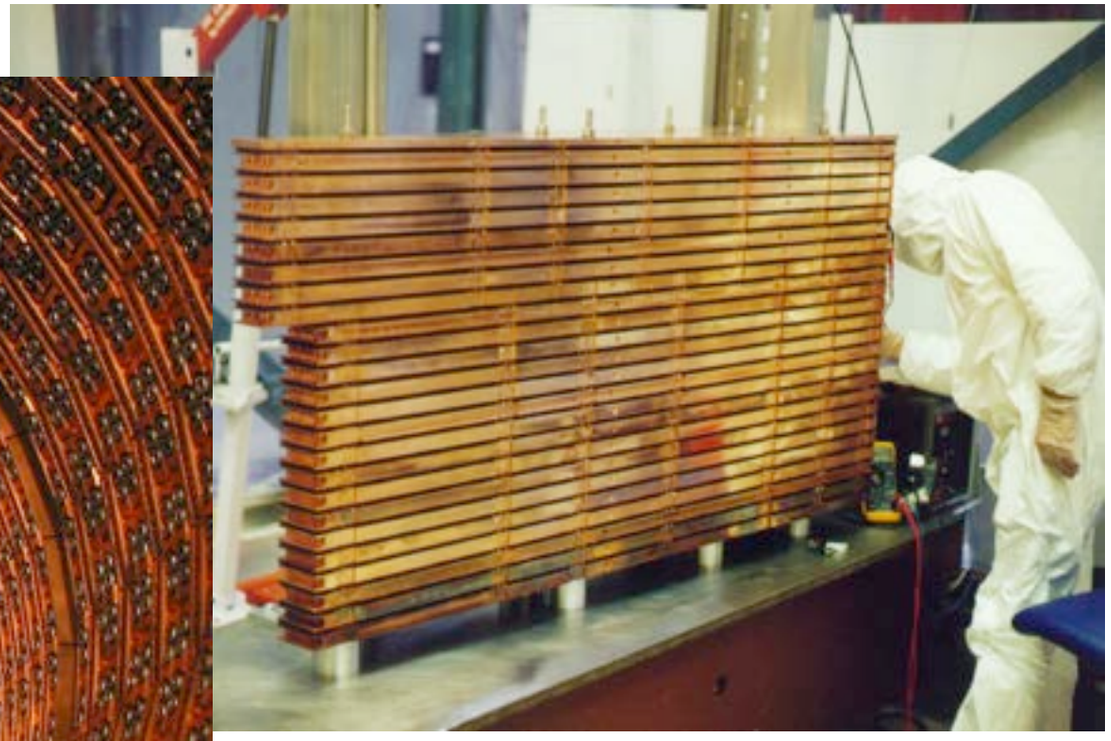


ATLAS components and Canada

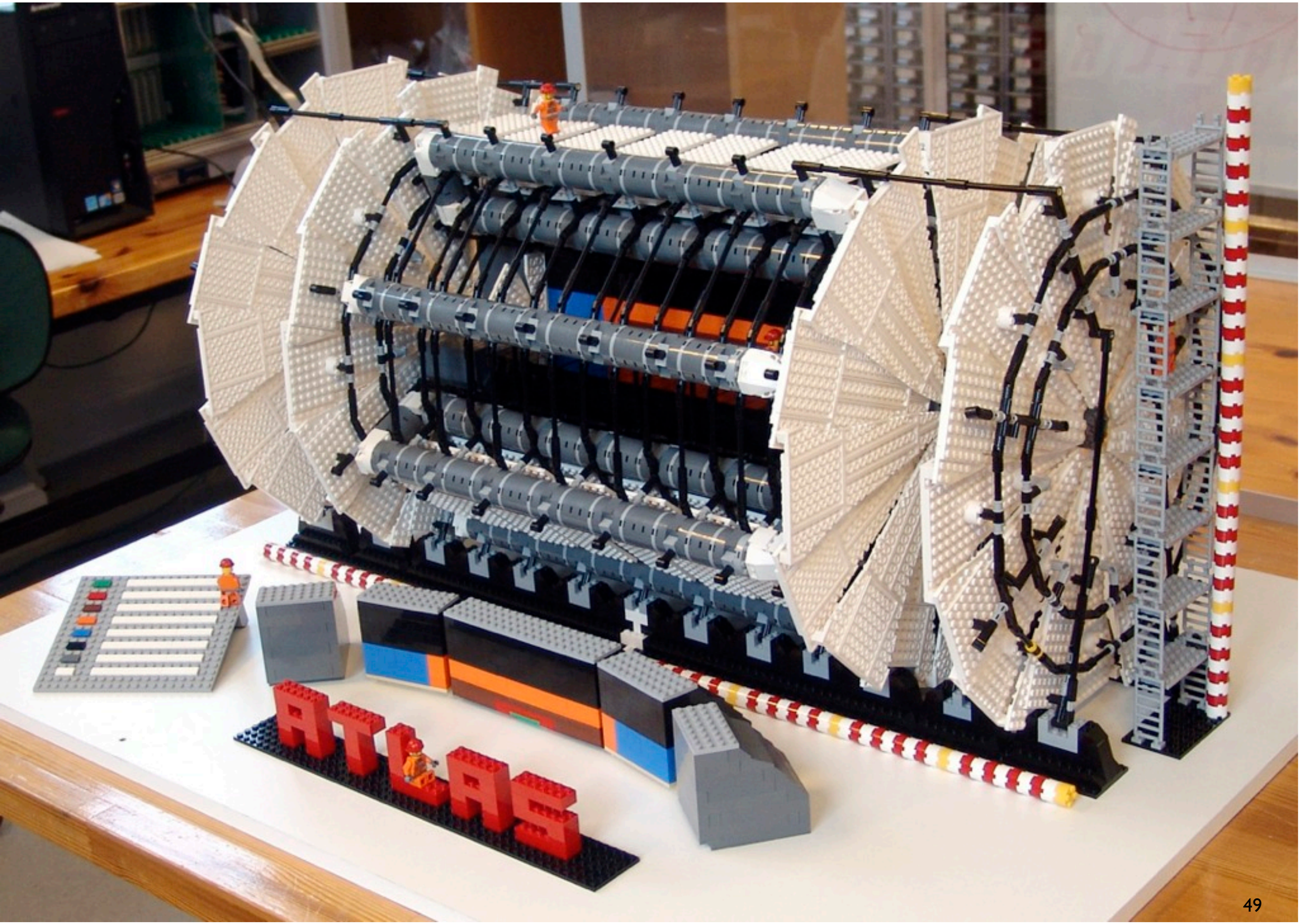


The ATLAS Experiment at CERN, http://atlas.ch

A view inside the liquid-argon calorimeter endcap. The circular inner bore of the EMEC, front and rear HEC wheels.

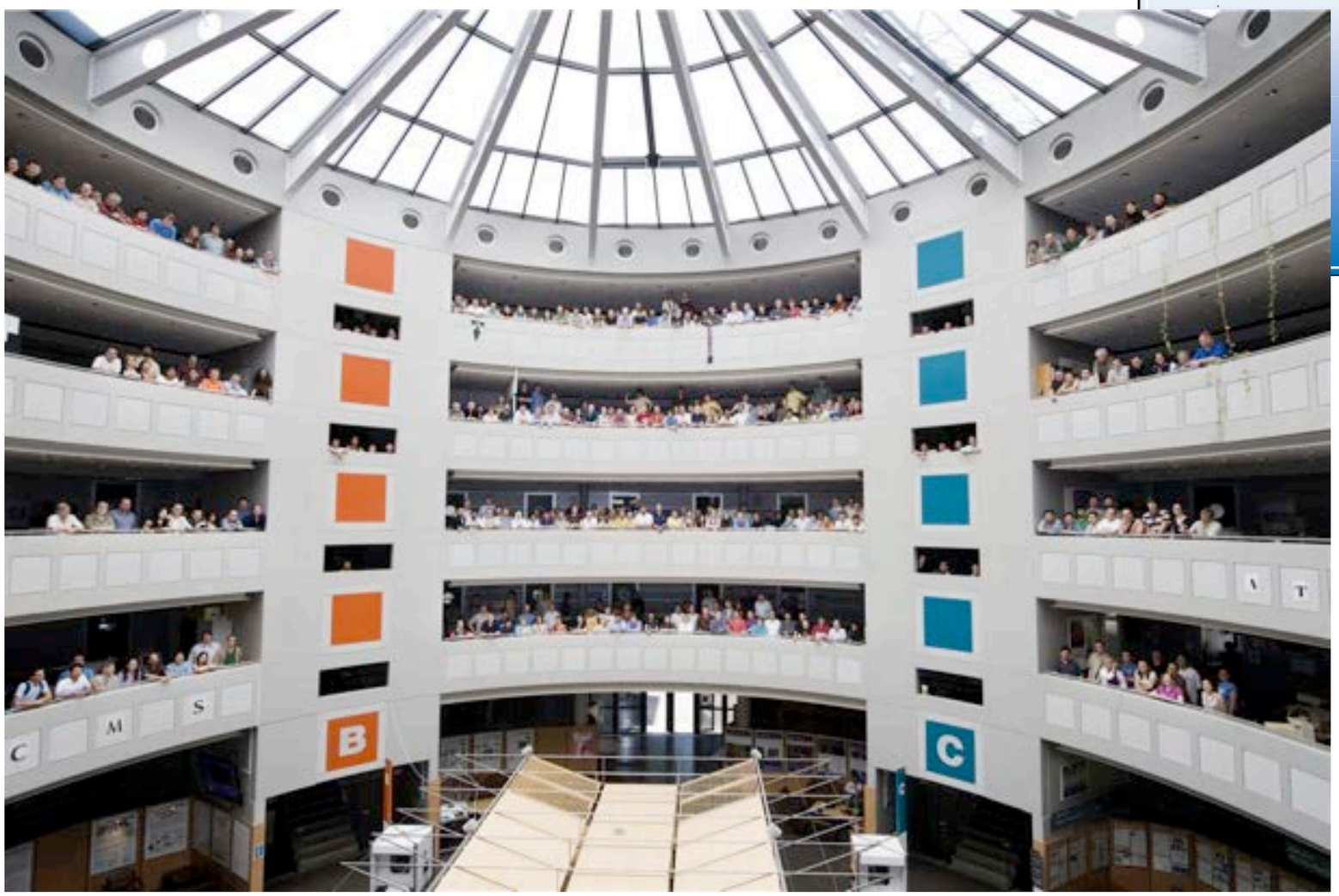


Encap calorimeter module under construction at TRIUMF


ATLAS

The ATLAS Collaboration

- 38 countries
- 174 institutions
- 3000 scientific participants
  - about 1000 students



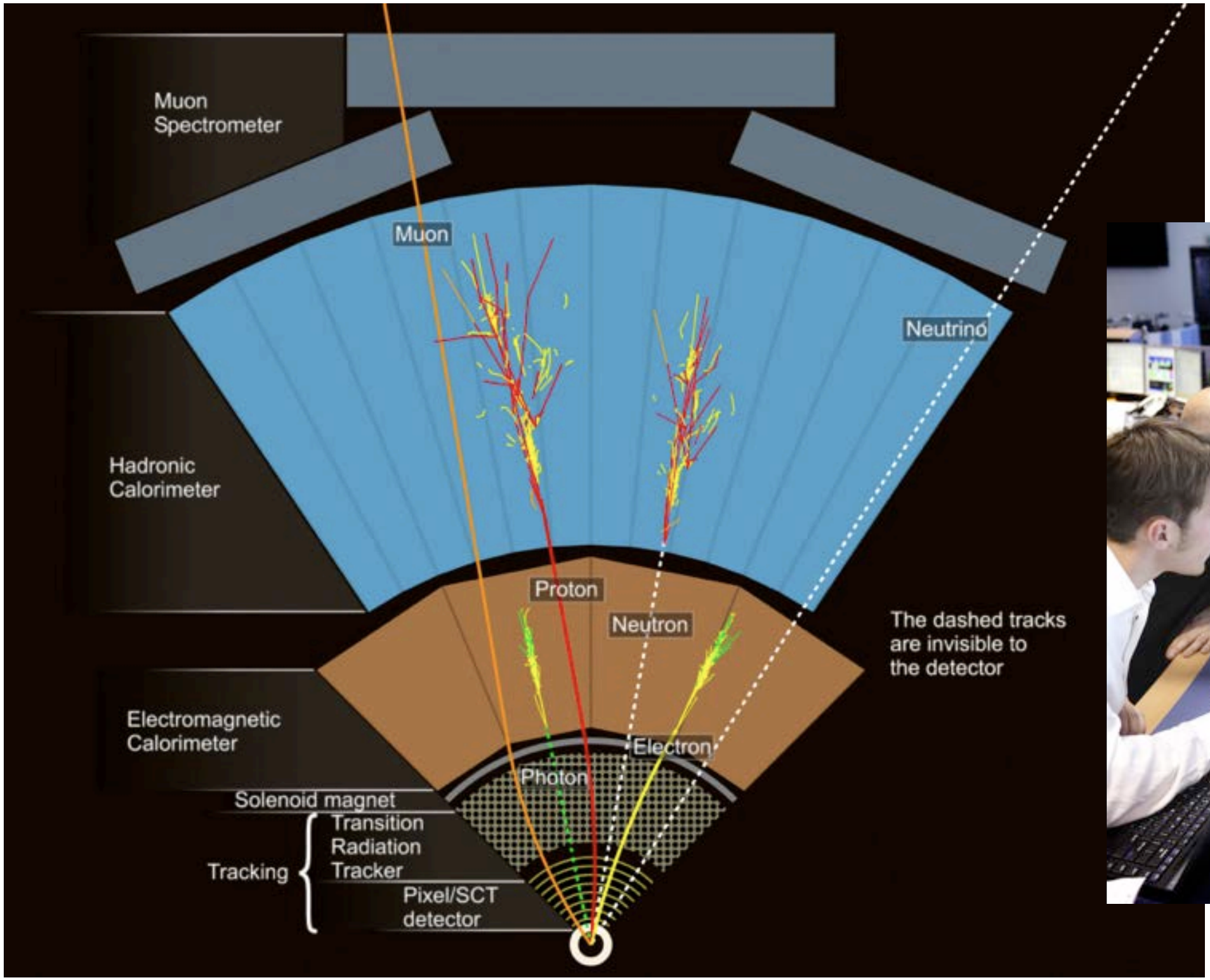
ATLAS EXPERIMENT
http://atlas.ch

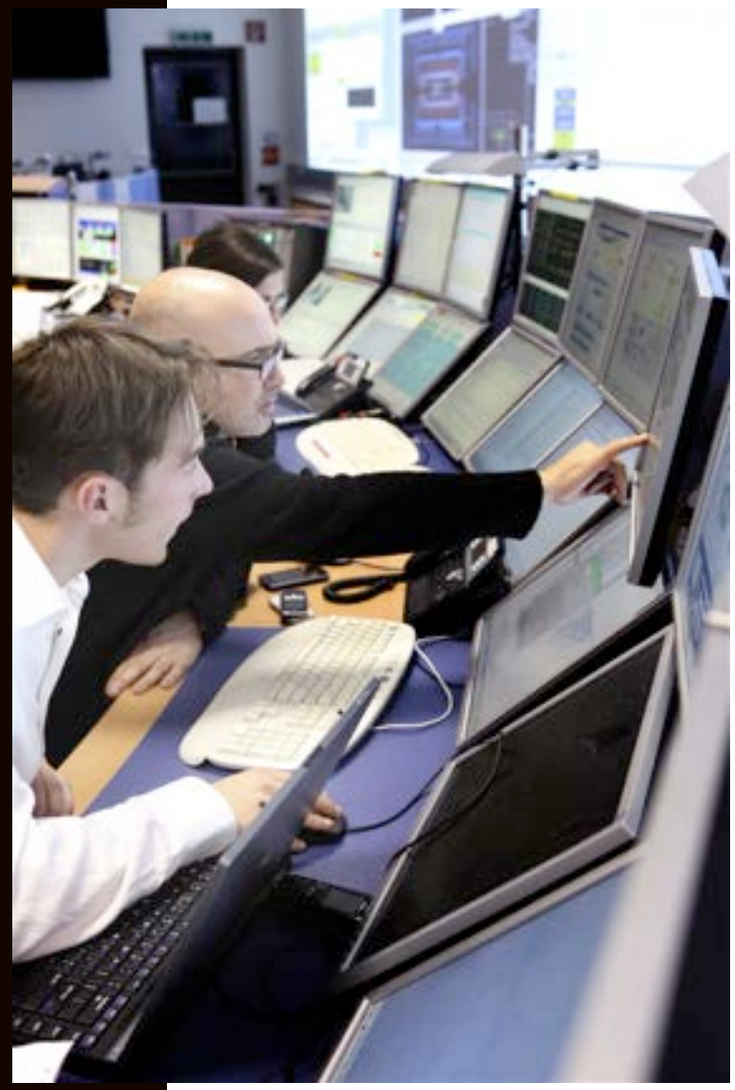
ATLAS and Canada

Alberta
Carleton
McGill
Montréal
SFU
Toronto
TRIUMF
UBC
Victoria
York

- ATLAS celebrated its 20th anniversary on Oct 1st 2012
- Over 150 Canadian scientists participate in the ATLAS experiment
- ATLAS Canada Collaboration
  - Founded in 1992 — ML, UVic
  - Spokesperson (07-) — Rob McPherson, UVic/IPP
  - Deputy — Richard Teuscher, UofT/IPP
  - Physics Coordination — Bernd Stelzer, SFU
  - Computing Coordination — Reda Tafirout, TRIUMF
- Contributions to the ATLAS detector construction
  - Calorimetry, cryogenics, electronics, trigger, ...
- Contributions to the LHC construction (TRIUMF)
- TRIUMF, Canada's nuclear and particle physics laboratory located in Vancouver
  - http://www.triumf.ca/

Particle identification in ATLAS





Historical Picture

The WWW was invented at CERN in March 1989

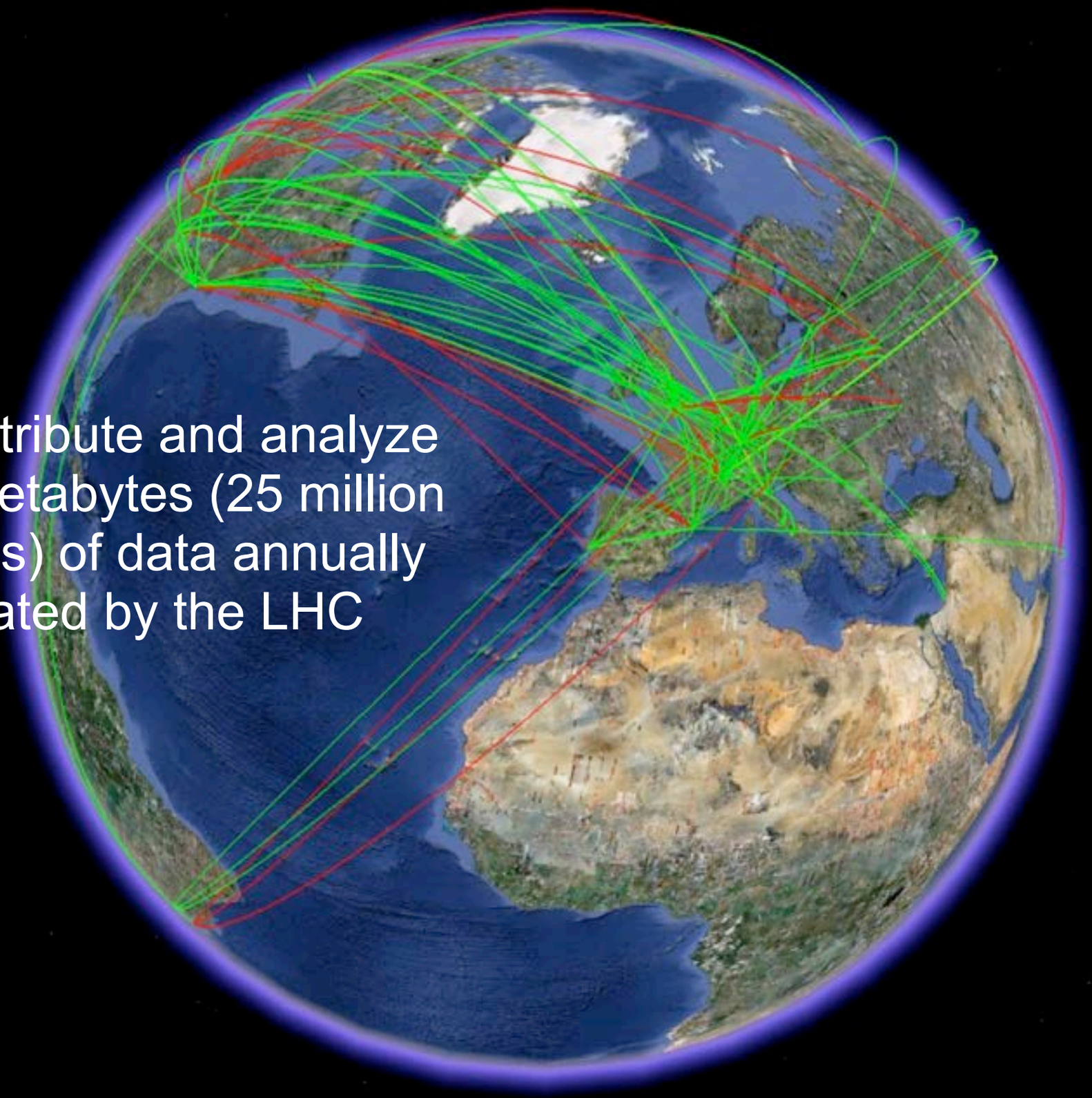
Historical Picture

The WWW was invented at CERN in March 1989

The LHC was already a hot topic!

The first photographic image on the Web in 1992!

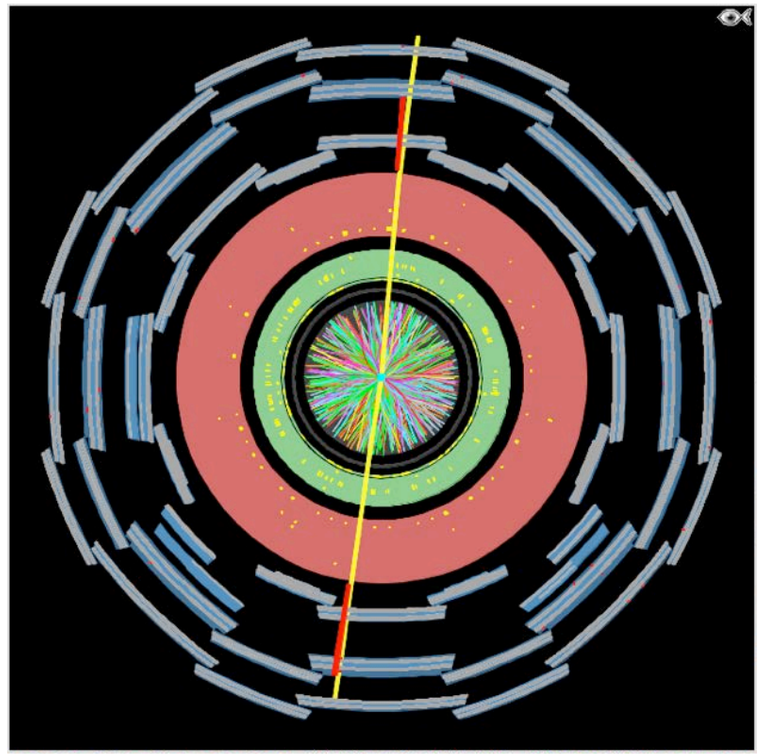
Worldwide LHC Computing Grid



Store, distribute and analyze the ~25 Petabytes (25 million Gigabytes) of data annually generated by the LHC

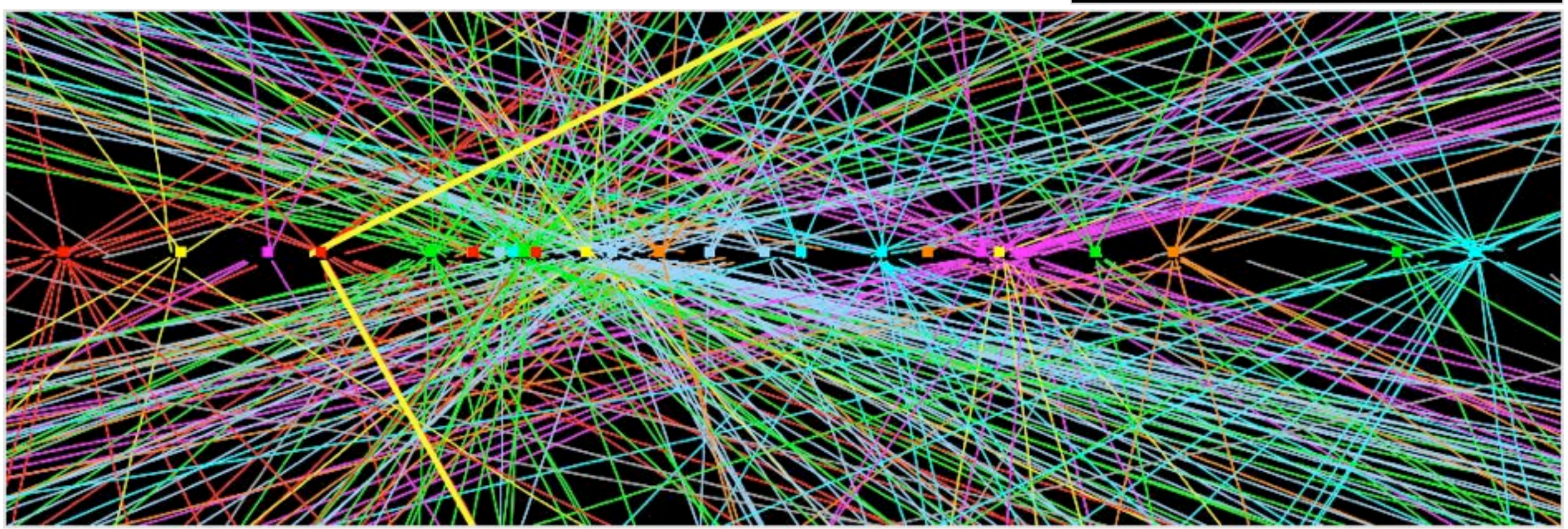
Experimental challenges

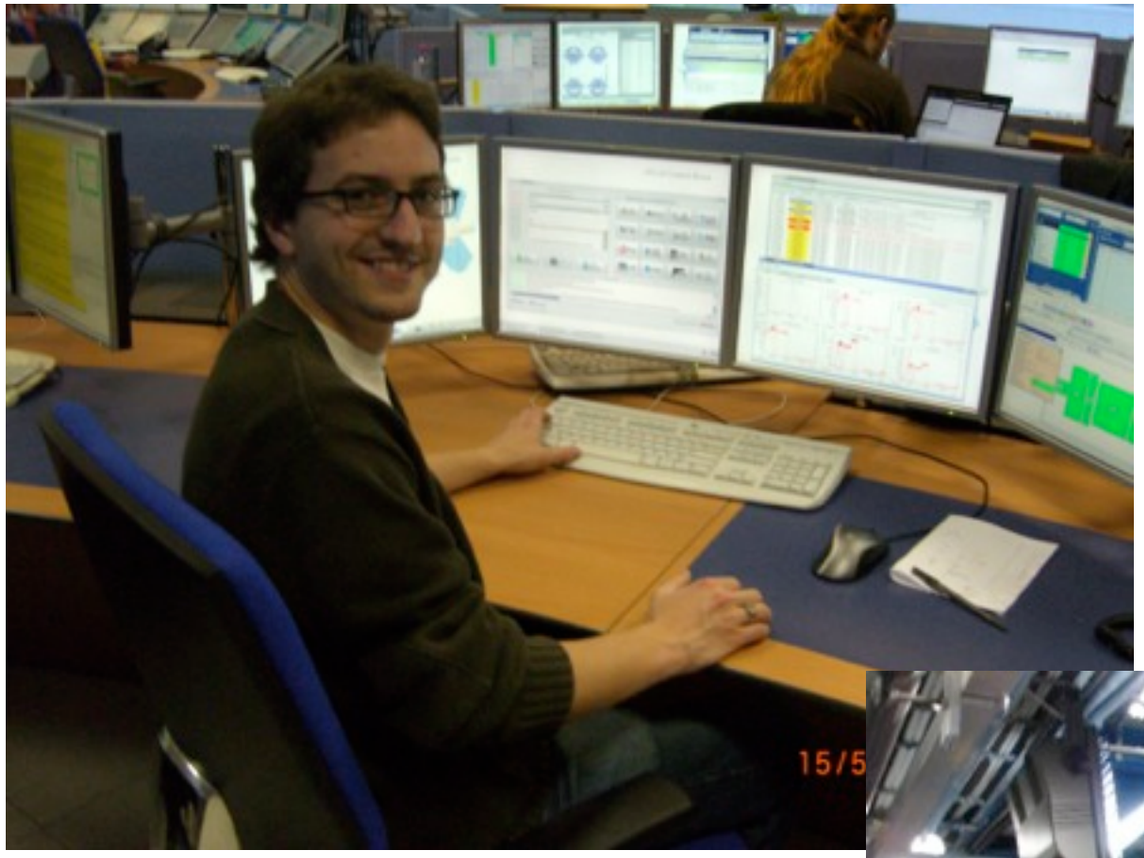
- 20 million beam crossings per second!
- many collisions per beam crossing!



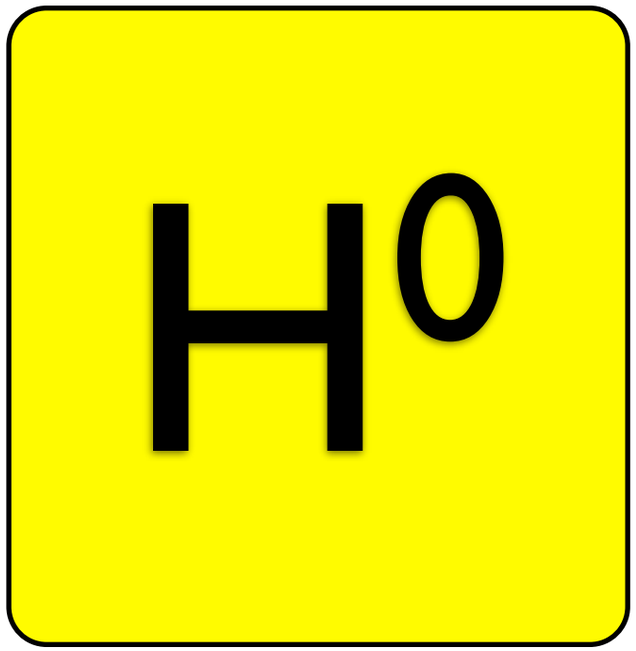
$Z \rightarrow \mu^+\mu^-$ event with 25 vertices

~1cm





the **Higgs boson**: the missing piece



Spin 0

A new type of particle!

A new force of nature!

Proton-proton Collision in the ATLAS Experiment

Production of the Higgs particle decaying to two Photons

http://www.atlas.ch/multimedia/a-higgs-particle-decaying-2-photons.html

Higgs decays

The Higgs particle is predicted to decay in different ways

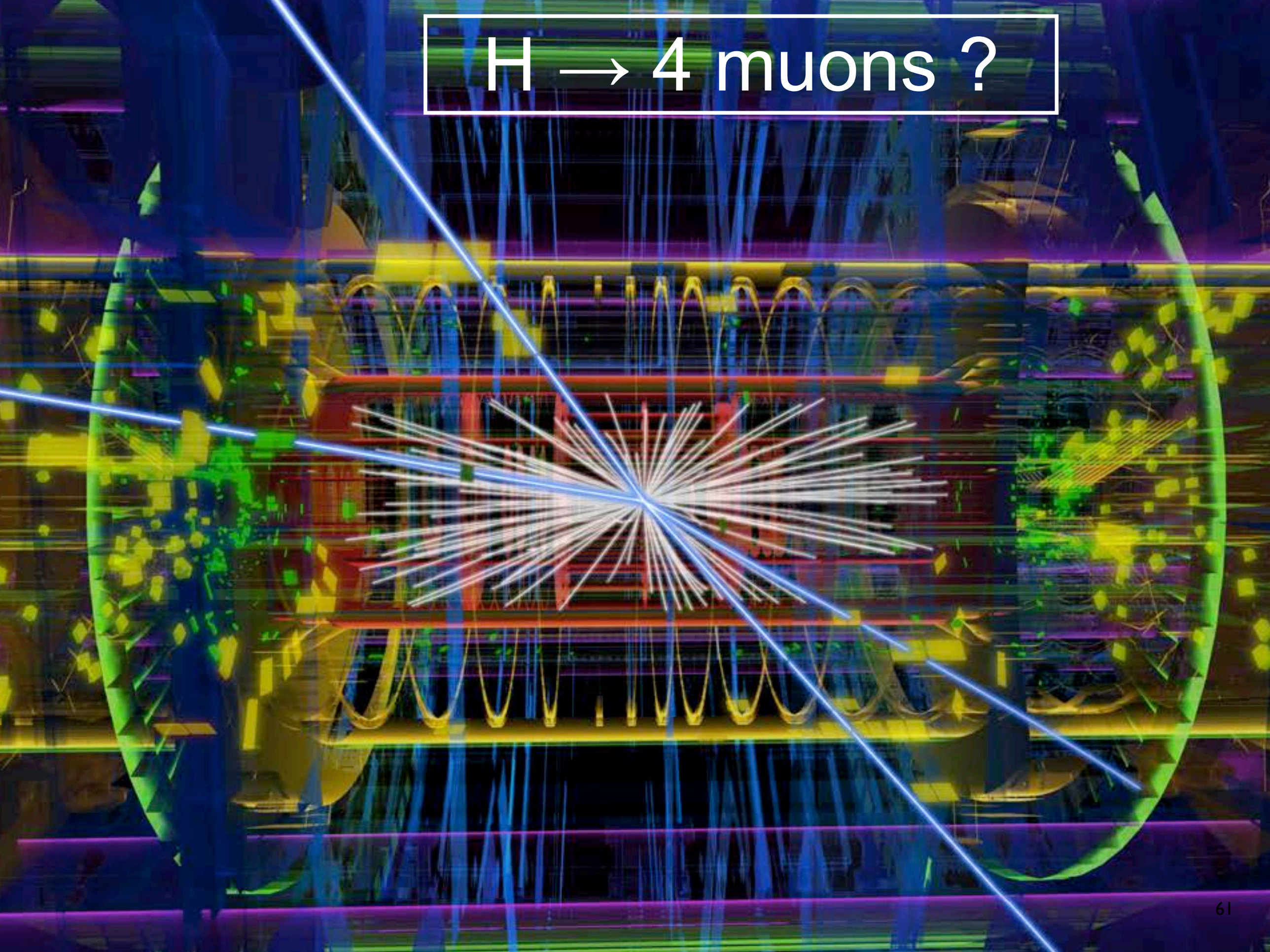
Promising signatures:

~0.23% $\mathrm{H} \to \gamma\,\gamma$

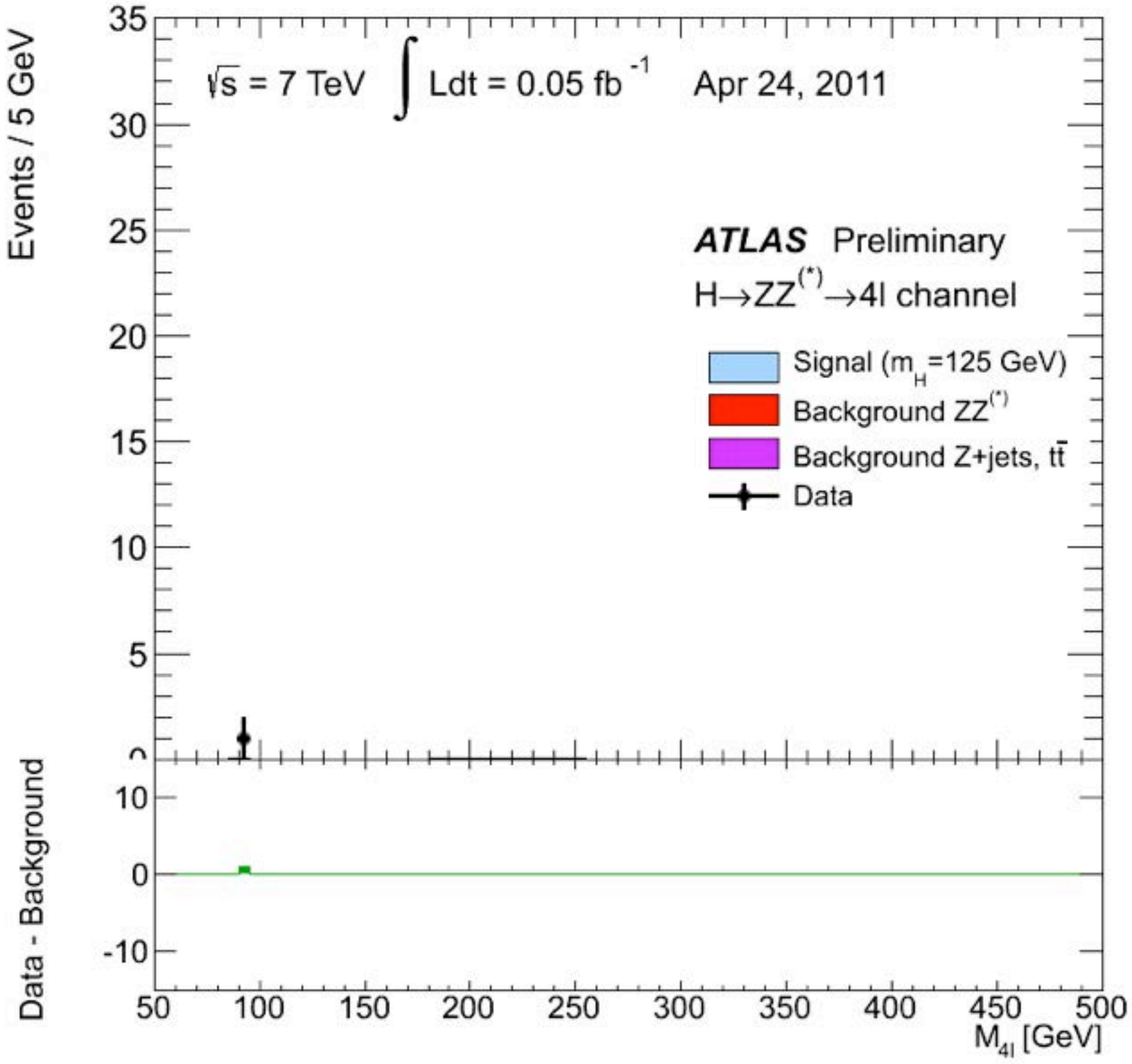
~0.02% $\mathrm{H} \to \mathrm{Z}\,\mathrm{Z}^{(*)} \to 4\ell$ *e* or *μ* pairs

The mass of the Higgs particle can be obtained from the measurement of its decay products

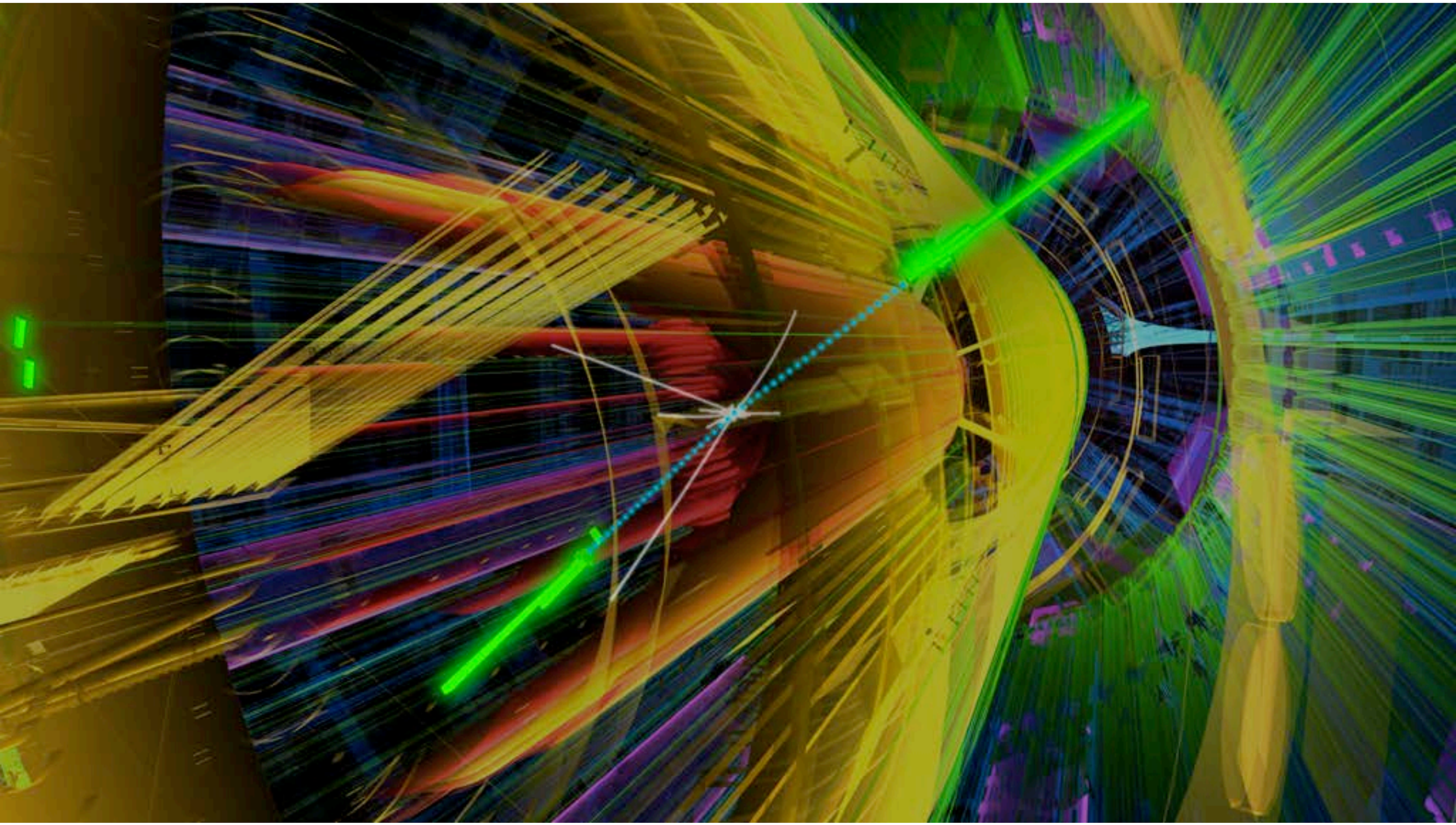
$H \rightarrow 4$ muons ?



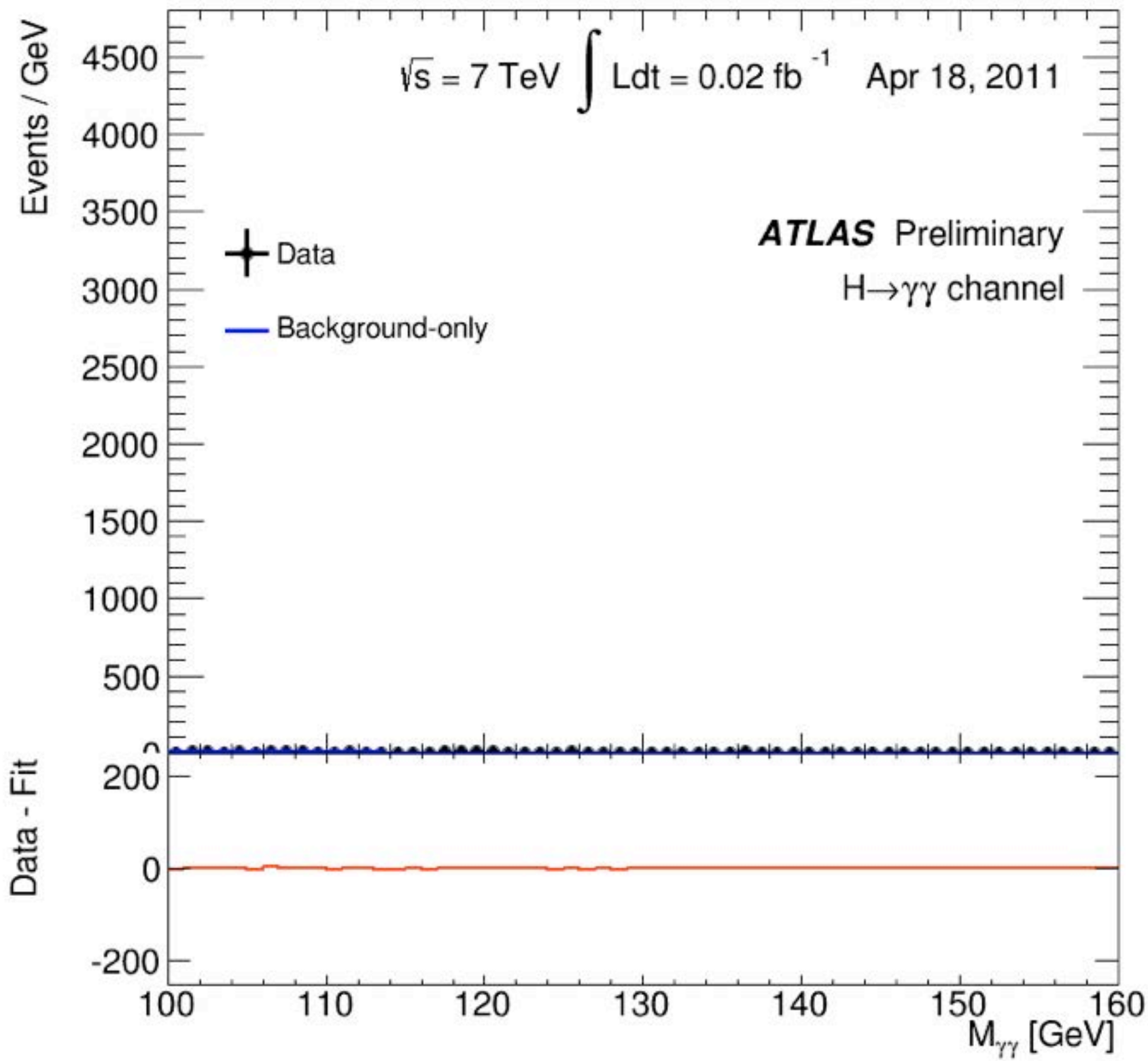
H → 4 leptons


√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

$H \rightarrow \gamma\ \gamma$?

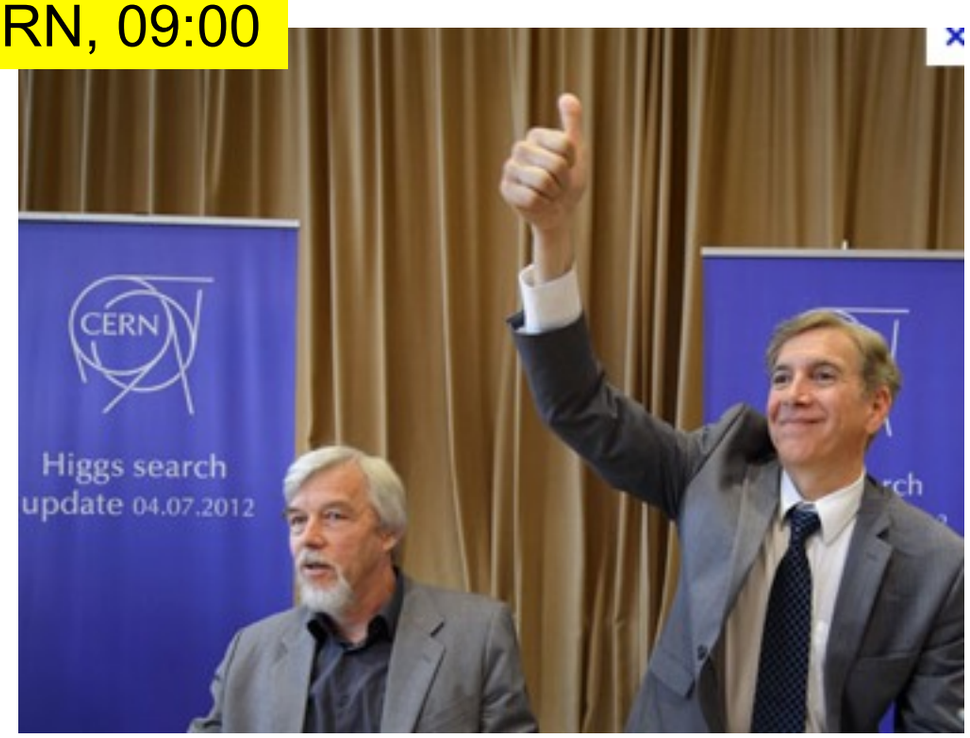


$H \rightarrow \gamma\ \gamma$



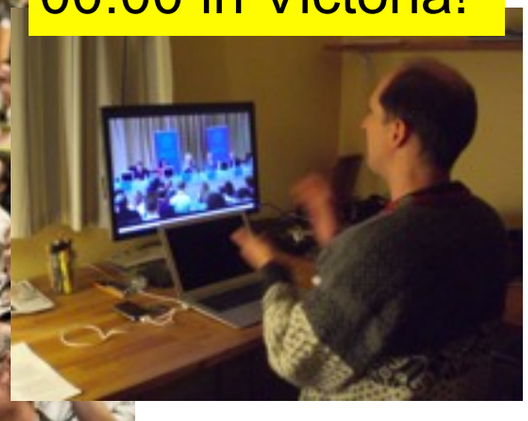
4 July 2012 CERN and Melbourne

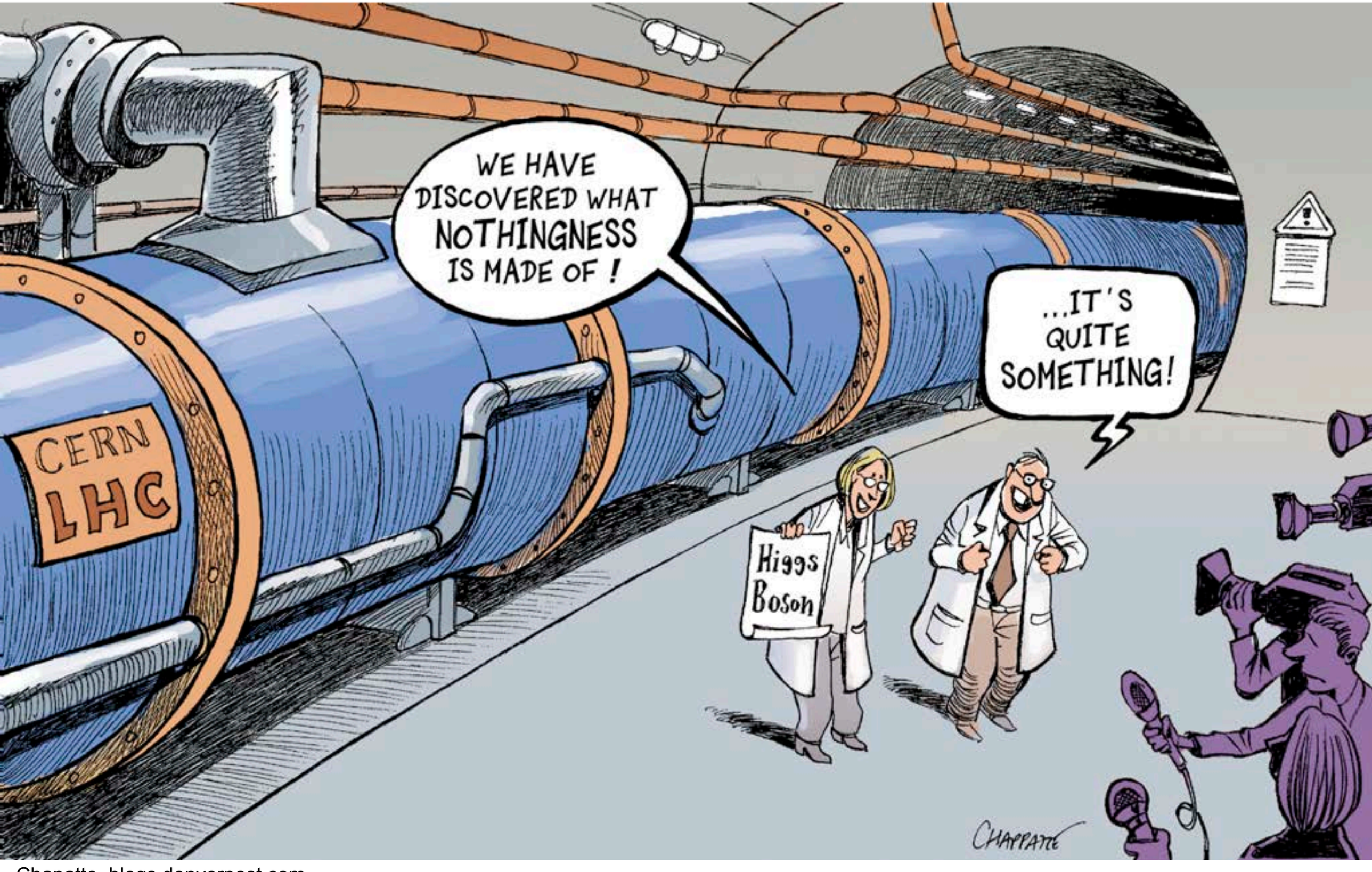
CERN, 09:00



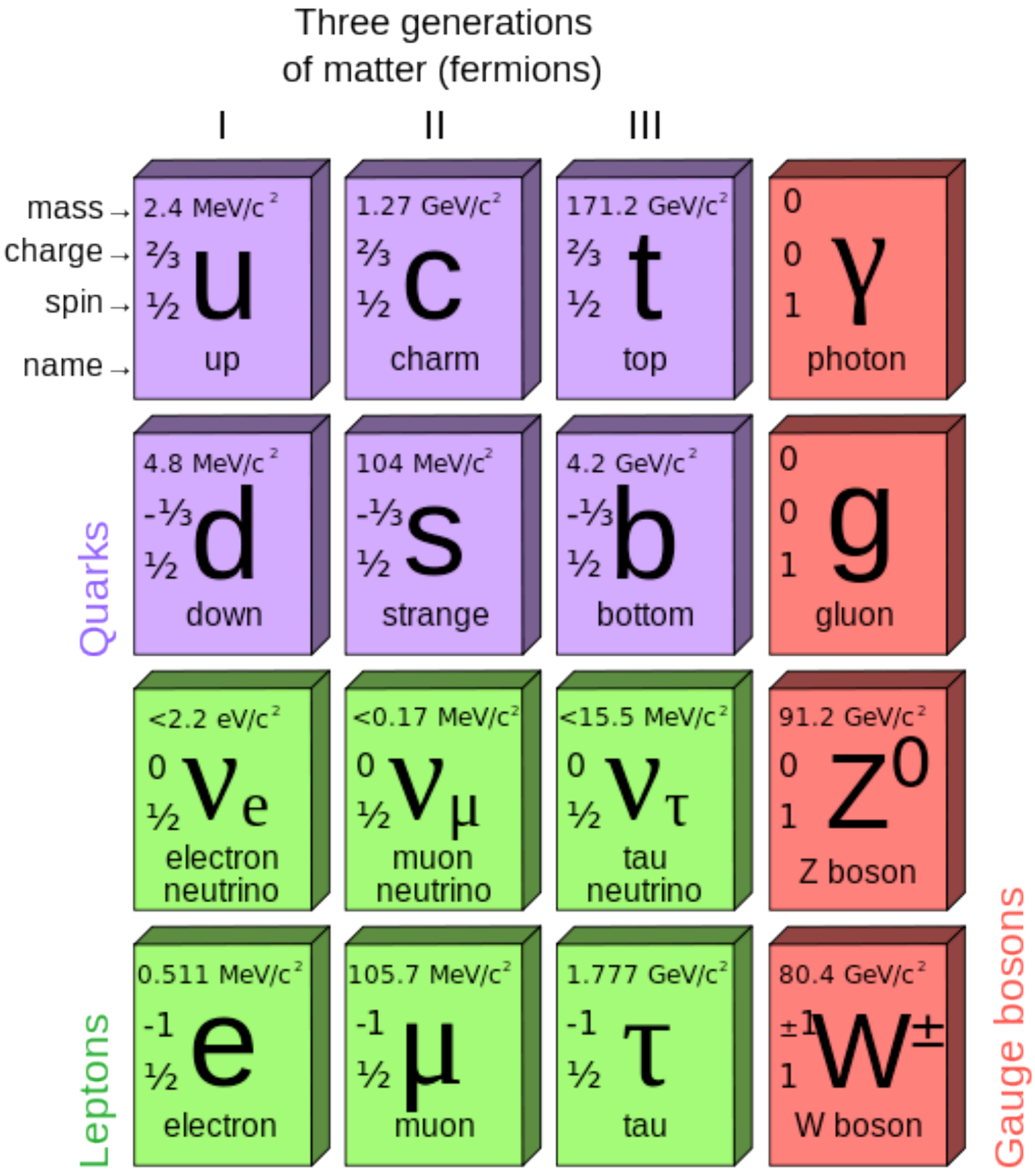
ICHEP 2012, Melbourne, 19:00

00:00 in Victoria!





Chapatte, blogs.denverpost.com



the **Higgs boson**:
the missing piece

H^0 ?

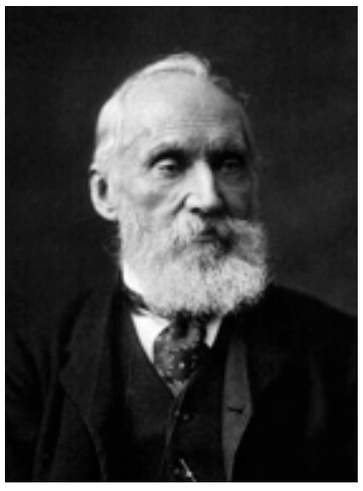
the new particle appears to be a Higgs Boson

A new force of nature!!!

If it's the Higgs, is that it?

"*Our future discoveries must be looked for in the 6th place of decimals.*"
Albert A. Michelson, 1894

"*There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.*"
William Thomson (Lord Kelvin), 1900



The Higgs Boson?

Supersymmetry?

Where is the antimatter?

Dark Matter?

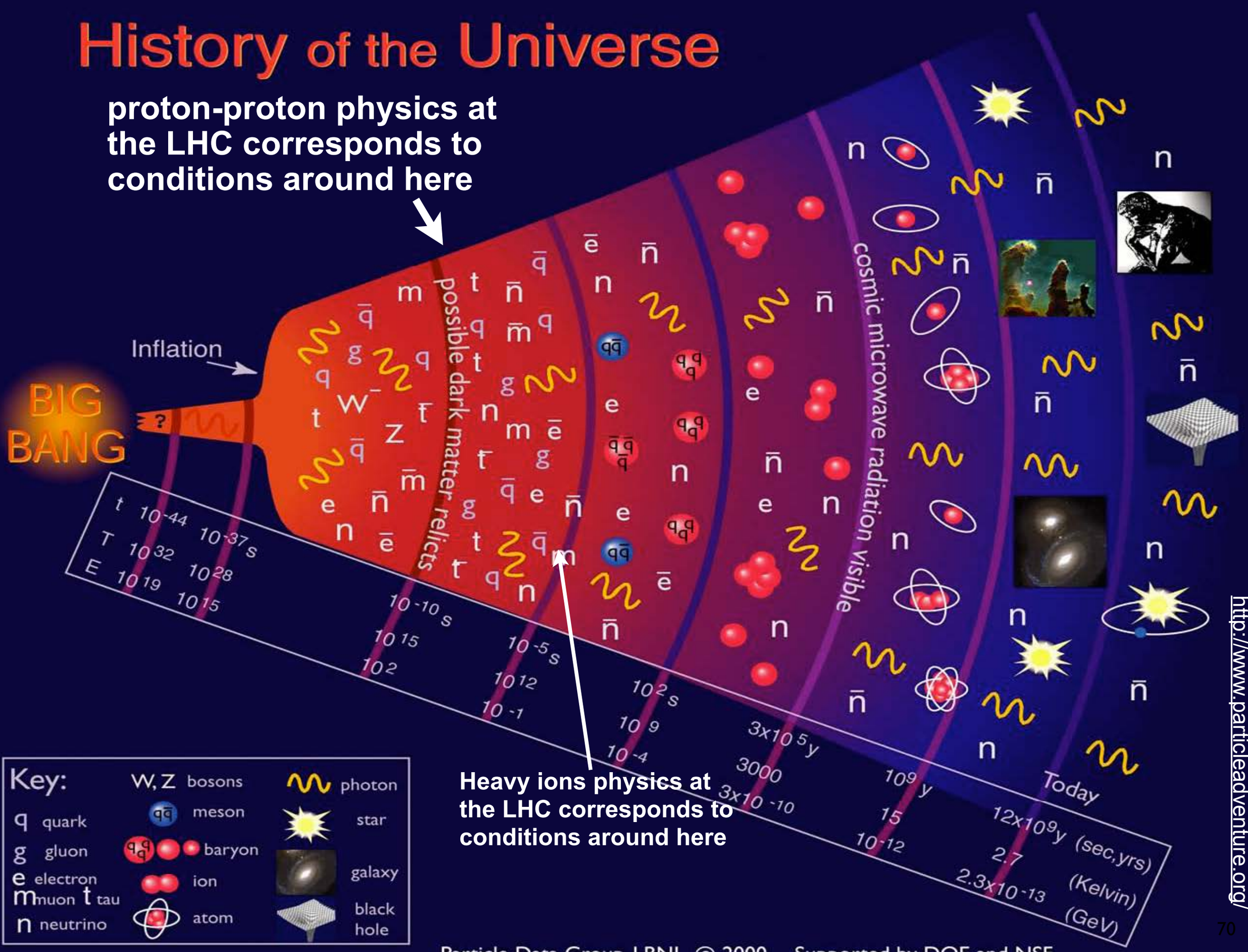
Inside the electron?

Dark Energy?

Extra Dimensions?

History of the Universe

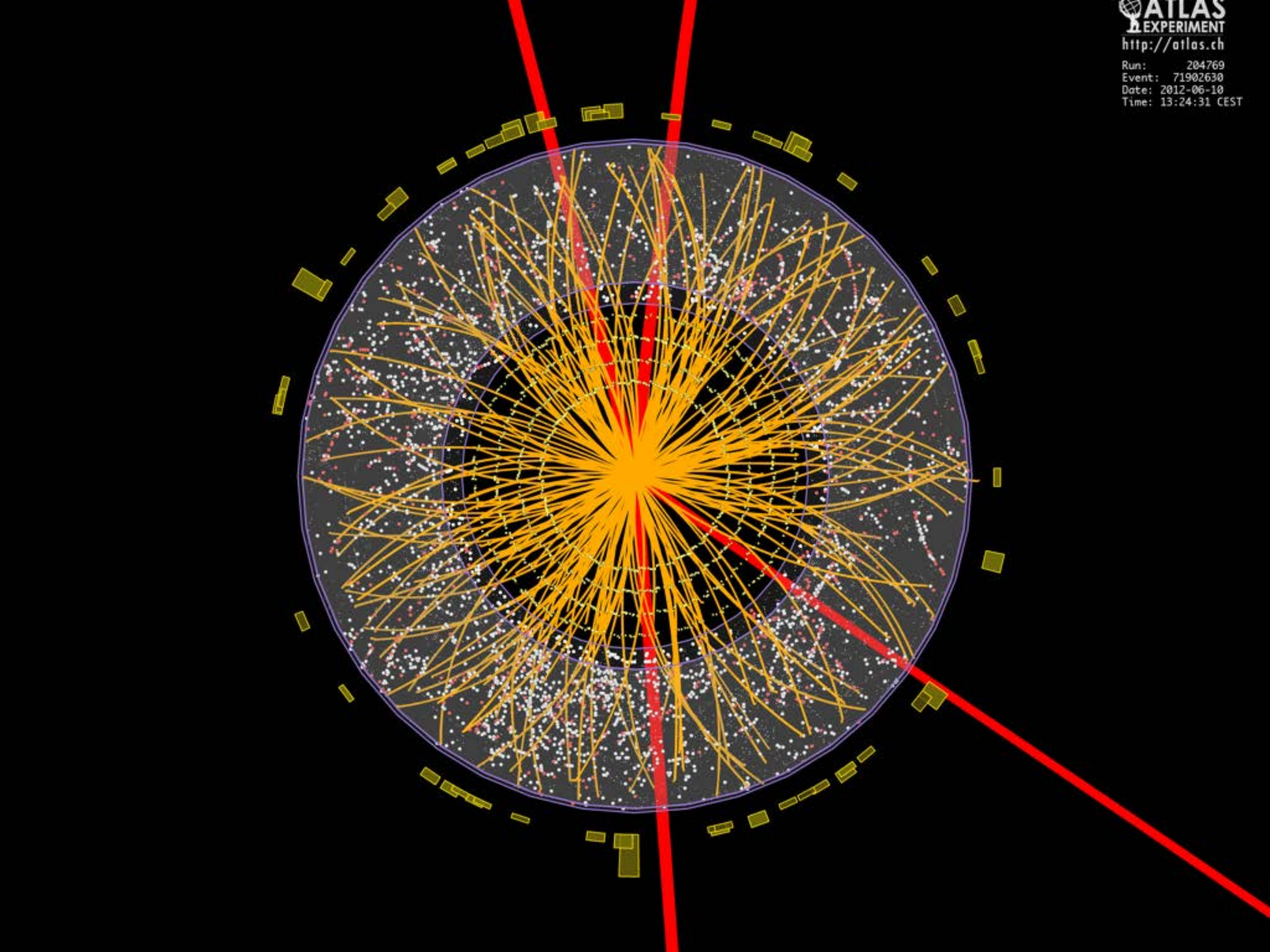
proton-proton physics at the LHC corresponds to conditions around here



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

http://www.particleadventure.org/

M101, European Space Agency & NASA


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Subatomic Smash:
The Quest for the Higgs Boson

University of Victoria | 50 YEARS