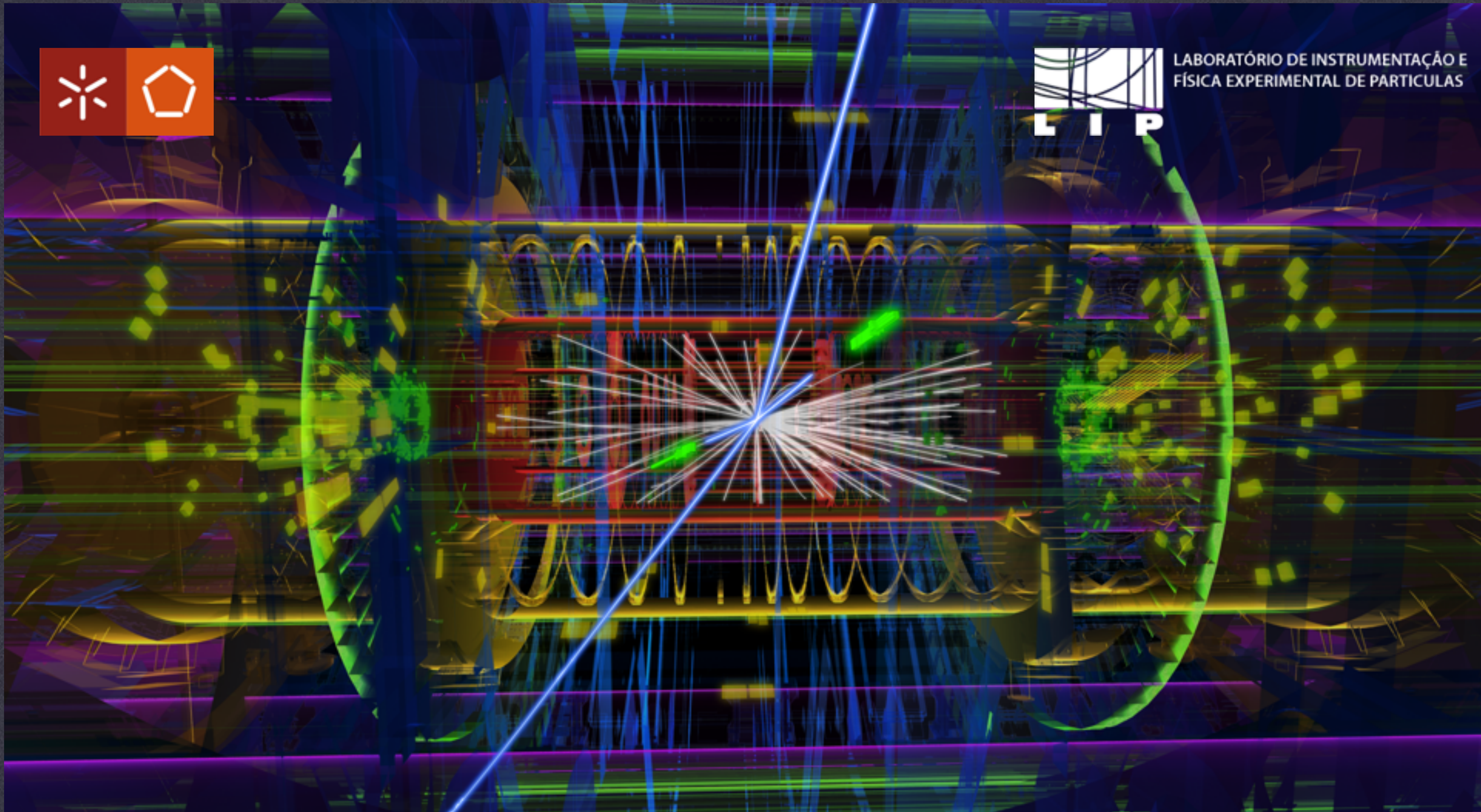


PROJECT

COMPUTATIONAL PARTICLE PHYSICS

2015/2016

INTEGRATED PROJECT

ADVISOR

ANDRÉ PEREIRA

Agenda

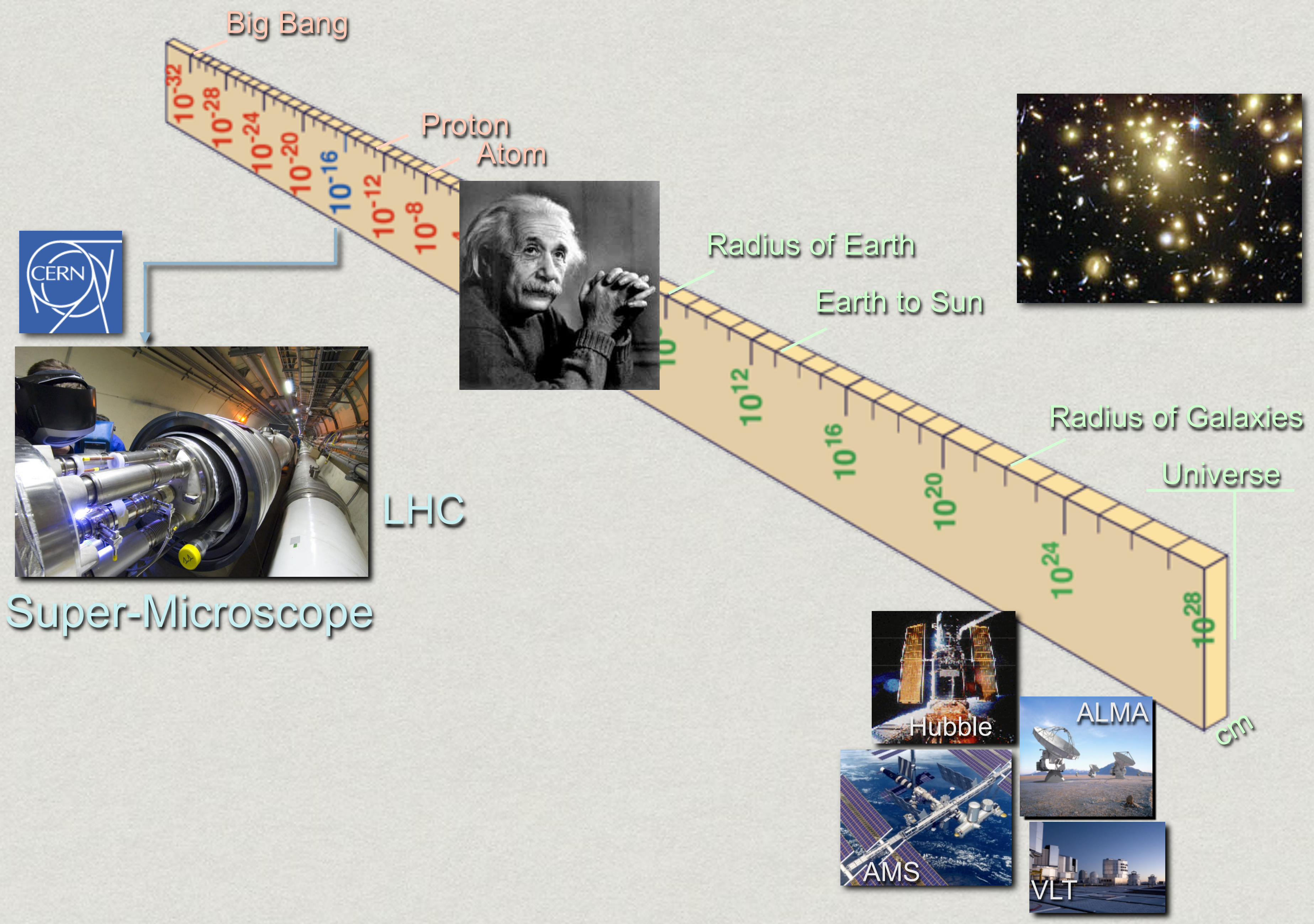
* Background
* Standard Model
* Particle Collisions and Analysis
* Integrated Project Proposals

BACKGROUND

CERN

- European Organisation for Nuclear Research
- Formed in 1954
- 21 member states and 7 observers
- Human resources at the end of 2013
  - 2513 staff members
  - 12313 fellows, associates, and engineers
  - 608 universities and research centres
  - 113 nationalities

CERN

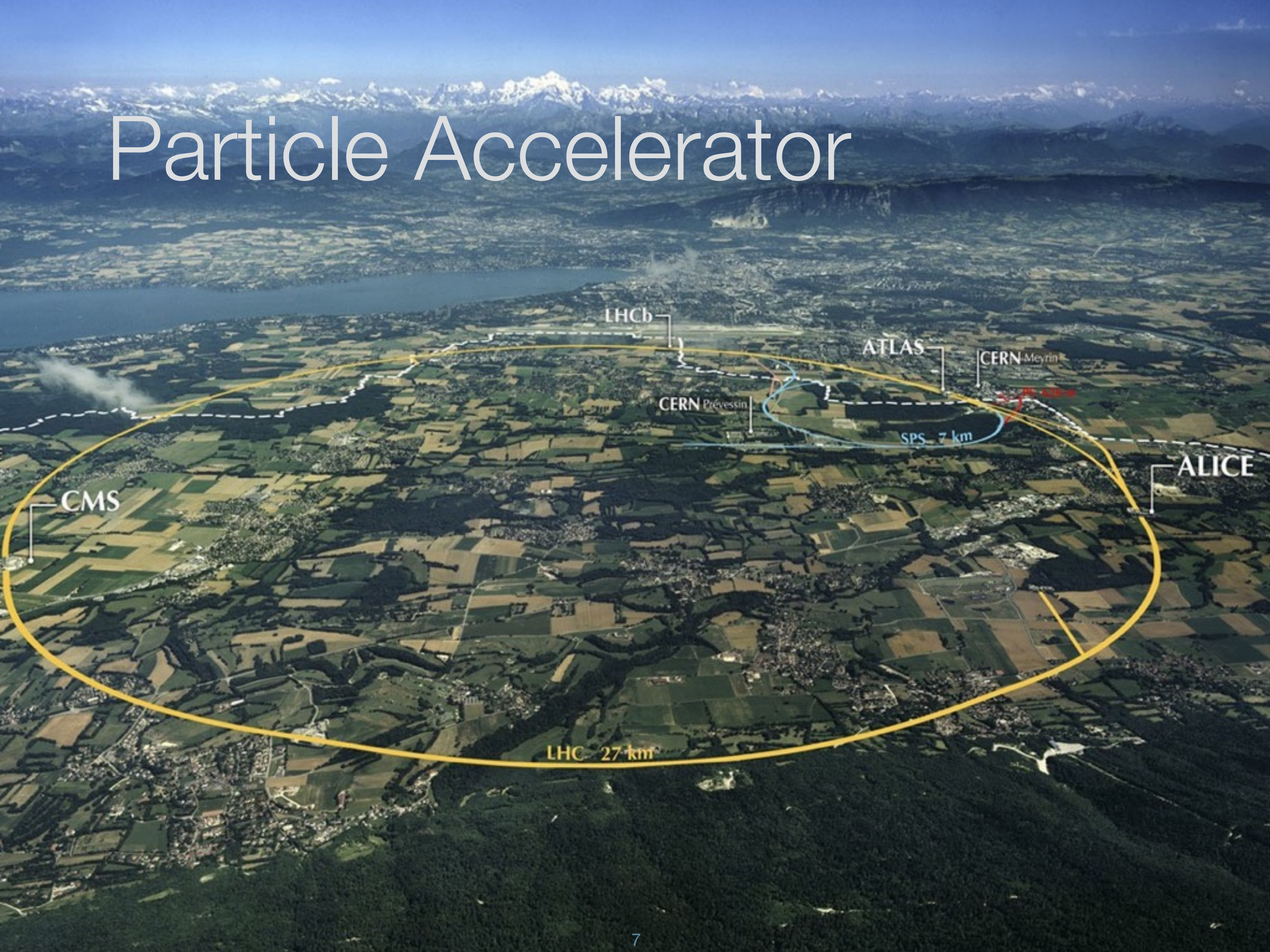


Big Bang
Proton
Atom
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
Radius of Earth
Earth to Sun
10^{12}
10^{16}
10^{20}
Radius of Galaxies
Universe
10^{24}
10^{28}
cm
CERN
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT

CERN

- Research focus on High Energy Physics
  - Interactions at the quantum level
- Some scientific contributions
  - 1973 - discovery of neutral currents
  - 1983 - discovery of W and Z bosons
  - 1989 - number of light neutrino families determination
  - 1995 - first creation of antihydrogen atom
  - 1999 - discovery of direct CP violation
  - 2012 - discovery of the Higgs boson

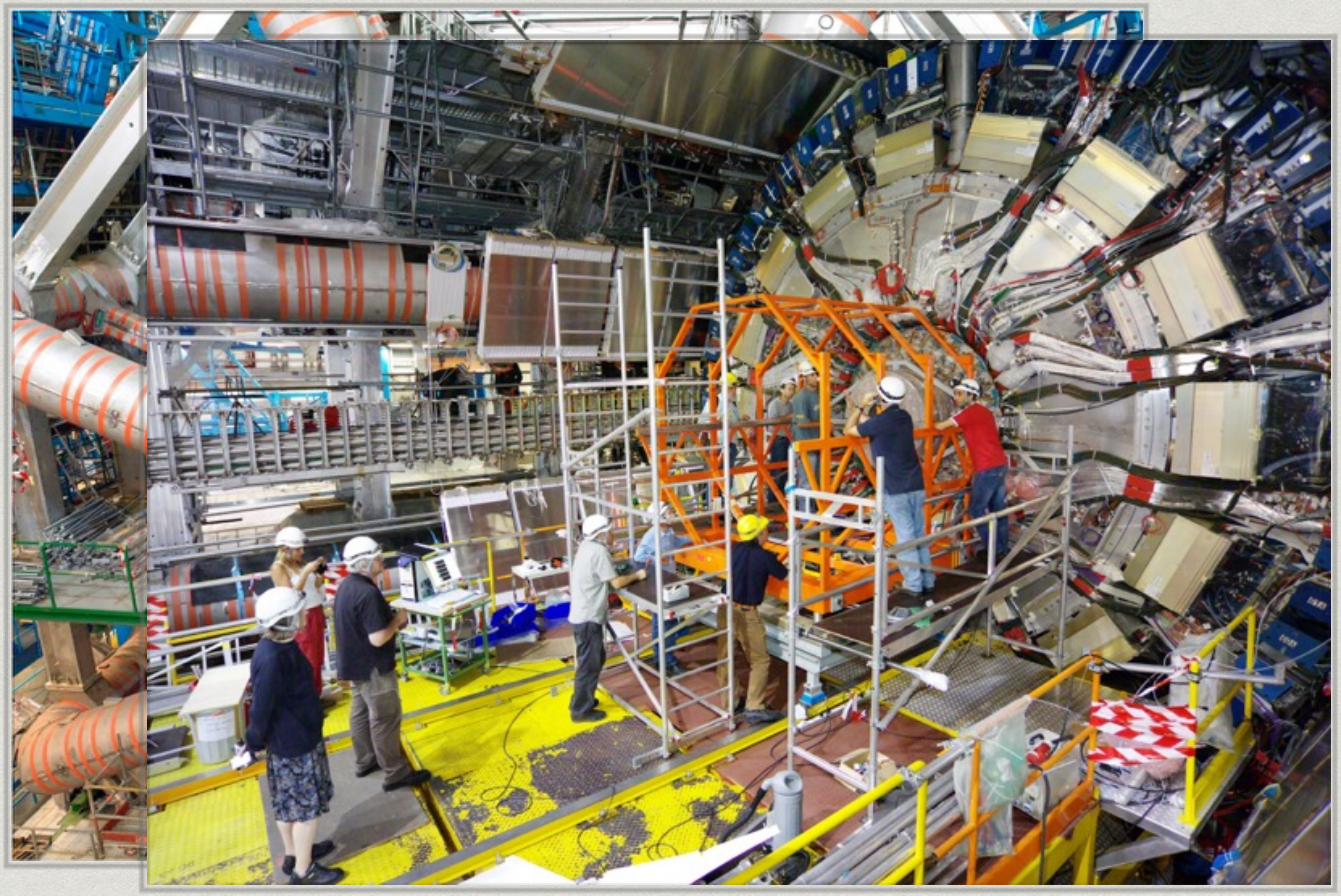
Particle Accelerator



Large Hadron Collider

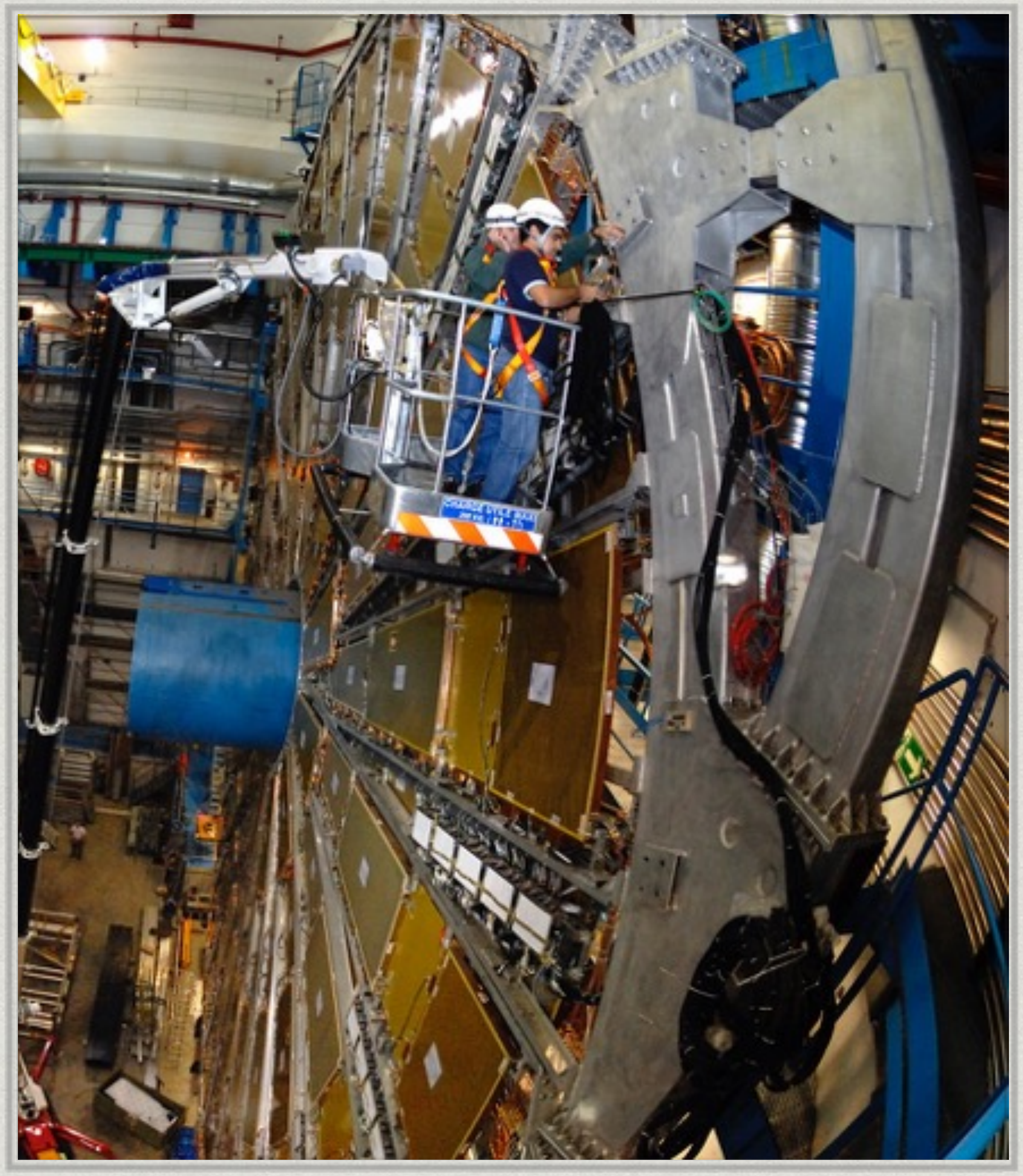
- 27 km perimeter, 100m underground
- Energy of 7 TeV
- 4 major experiments
  - different approaches to solve similar problems
- Operating temperature of -271ºC
- A 3k million € facility

ATLAS Particle Detector



Atlas Particle Detector

- 25m diameter per 45m length
- 800 million collisions/sec
  - only 200/sec are interesting
- 3.2 petabytes of data per year



THE STANDARD MODEL

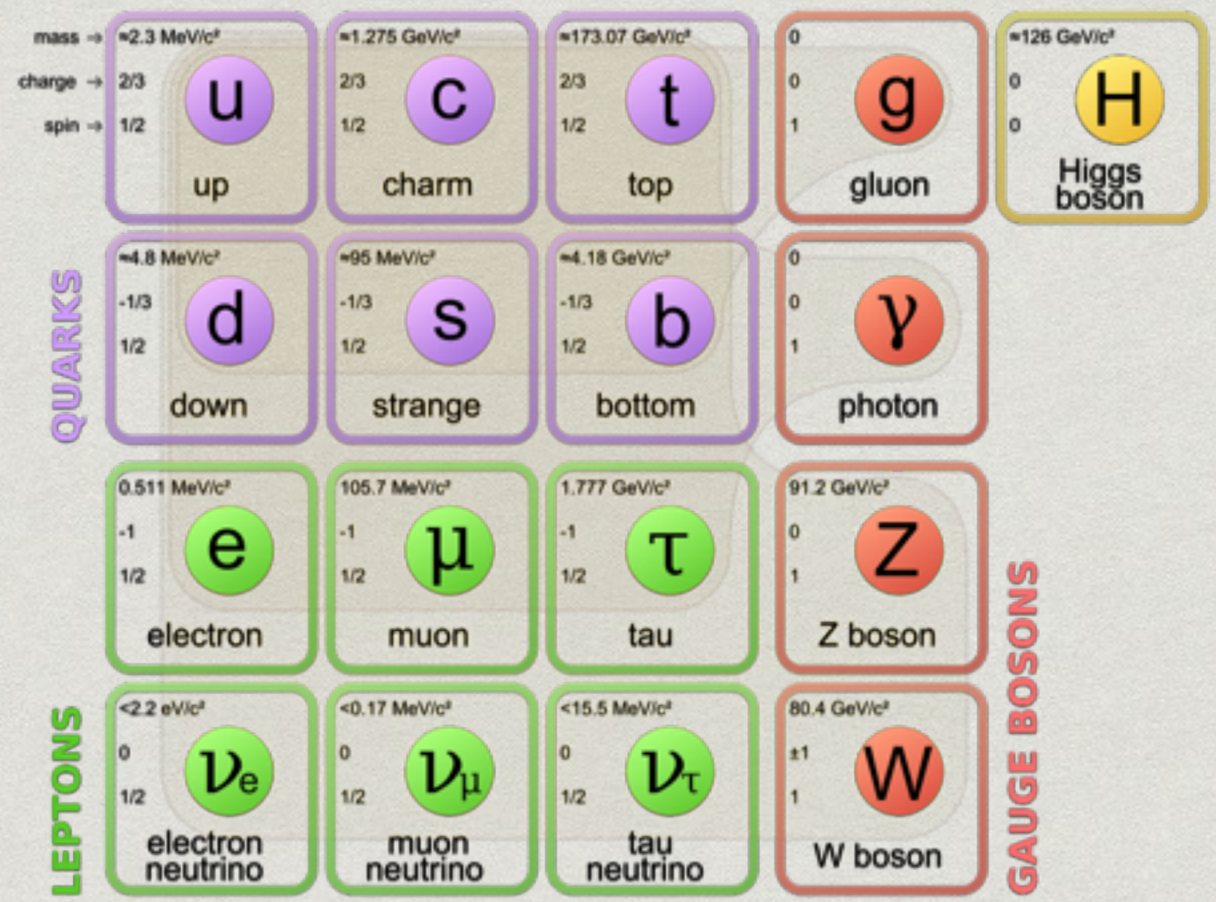
$$\begin{gathered}
-\tfrac12\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac14 g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac12 i g_s^2(\bar q^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac12\partial_\mu H\partial_\mu H - \\
\tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac12\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 + \tfrac12(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)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac12 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^-] - \\
\tfrac18 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)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 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)] + \tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac12 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}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\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_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac14 g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\tfrac14 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^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac12 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_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \\
\bar d_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac13(\bar d_j^\lambda\gamma^\mu d_j^\lambda)] + \\
\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_j^\lambda\gamma^\mu(\tfrac43 s_w^2 - \\
1-\gamma^5)u_j^\lambda) + (\bar d_j^\lambda\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar u_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\
\gamma^5)u_j^\lambda)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\tfrac g2\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + \\
m_u^\lambda(\bar u_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1- \\
\gamma^5)u_j^\kappa] - \tfrac g2\tfrac{m_u^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda) - \tfrac g2\tfrac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) - \\
\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar d_j^\lambda\gamma^5 d_j^\lambda) + \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_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \\
\partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \\
\partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \\
\partial_\mu\bar X^-X^-) - \tfrac12 gM[\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c_w^2}\bar X^0X^0H] + \\
\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^0X^-\phi^+ - \bar X^0X^+\phi^-] + \\
igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \tfrac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]
\end{gathered}$$

The Standard Model (SM)

- Theory that explains the fundamental particles and forces
  - Proposed in the mid 70’s
  - Has several limitations
- Often regarded as the “theory of almost everything”
  - It explains almost 5% of the universe!

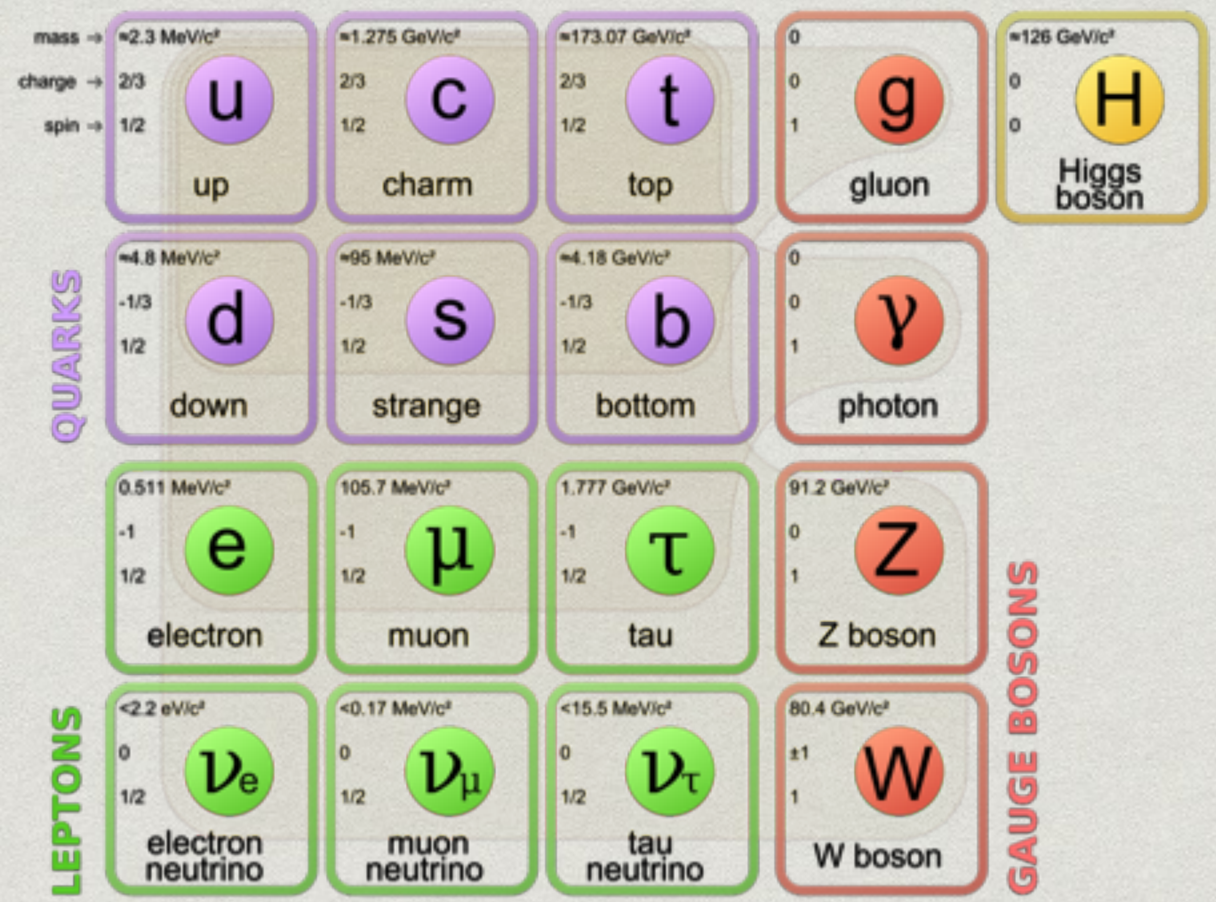
Fundamental Particles

- Particles divided according to specific properties
  - Fermions
    - Quarks
    - Leptons
  - Gauge bosons
  - Higgs Boson



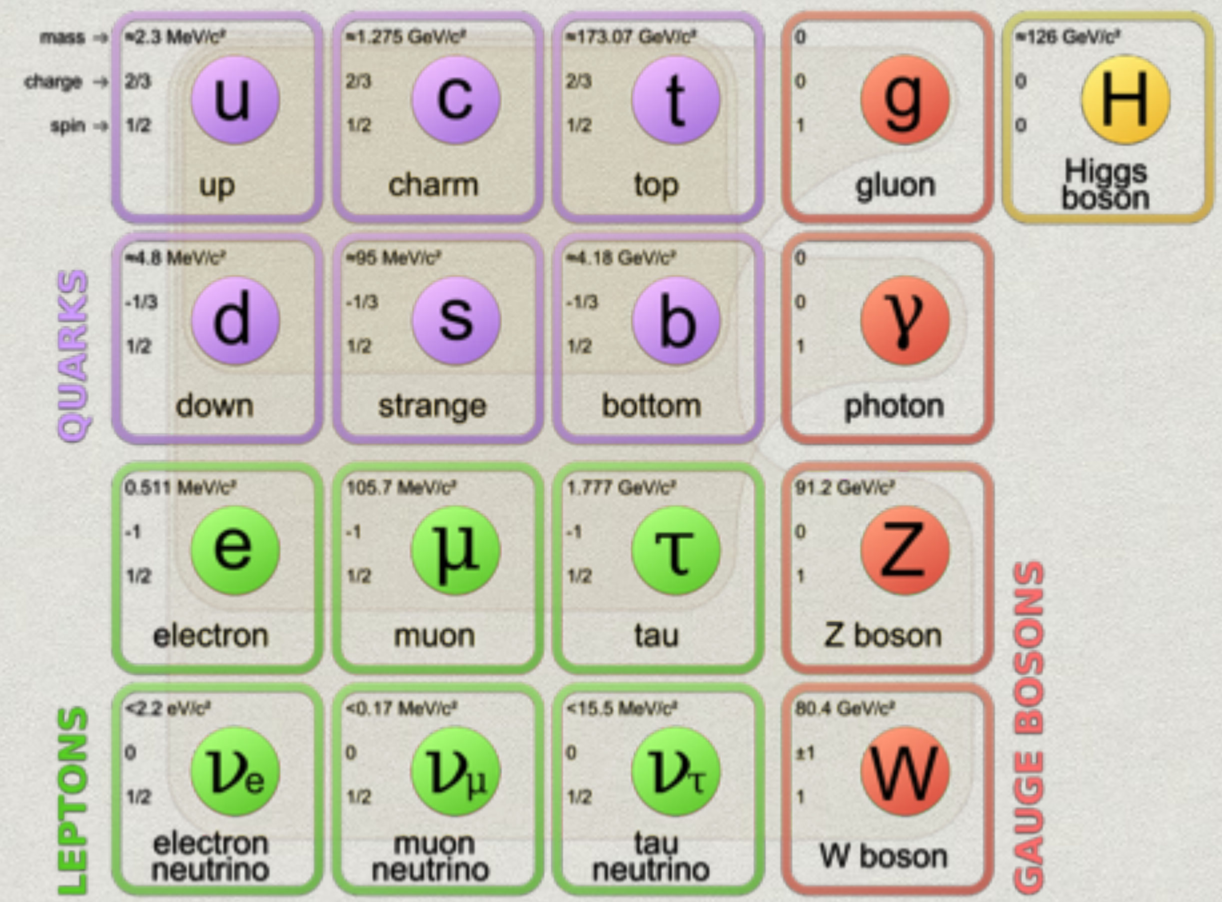
Fundamental Particles

- Fermions
  - Have antiparticles
  - Matter particles
  - Grouped by Pauli exclusion principle
  - Instability increases from left to right
    - Higher probability of decaying
    - Quarks hadronize



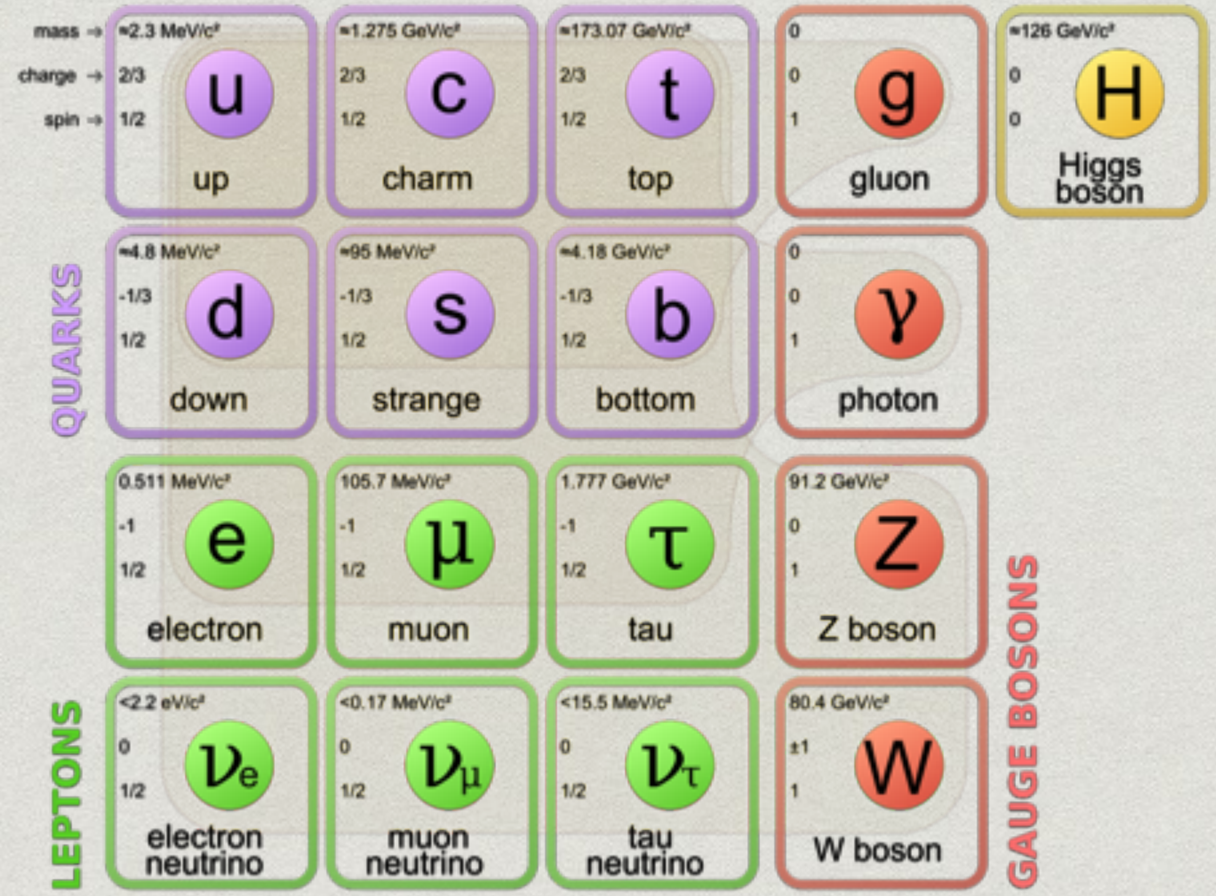
Fundamental Forces

- Gauge bosons
  - Mediate interactions among the fundamental particles
  - Each one is responsible for a single force
  - Particles exchange gauge bosons to interact



Fundamental Forces*

- Gluon
  - Strong interactions among coloured particles
- Photon
  - Electromagnetic force interactions among charged fermions
- W and Z bosons
  - Weak force interactions among fermions
- Electroweak interactions mediated by a combination of W, Z, and photons

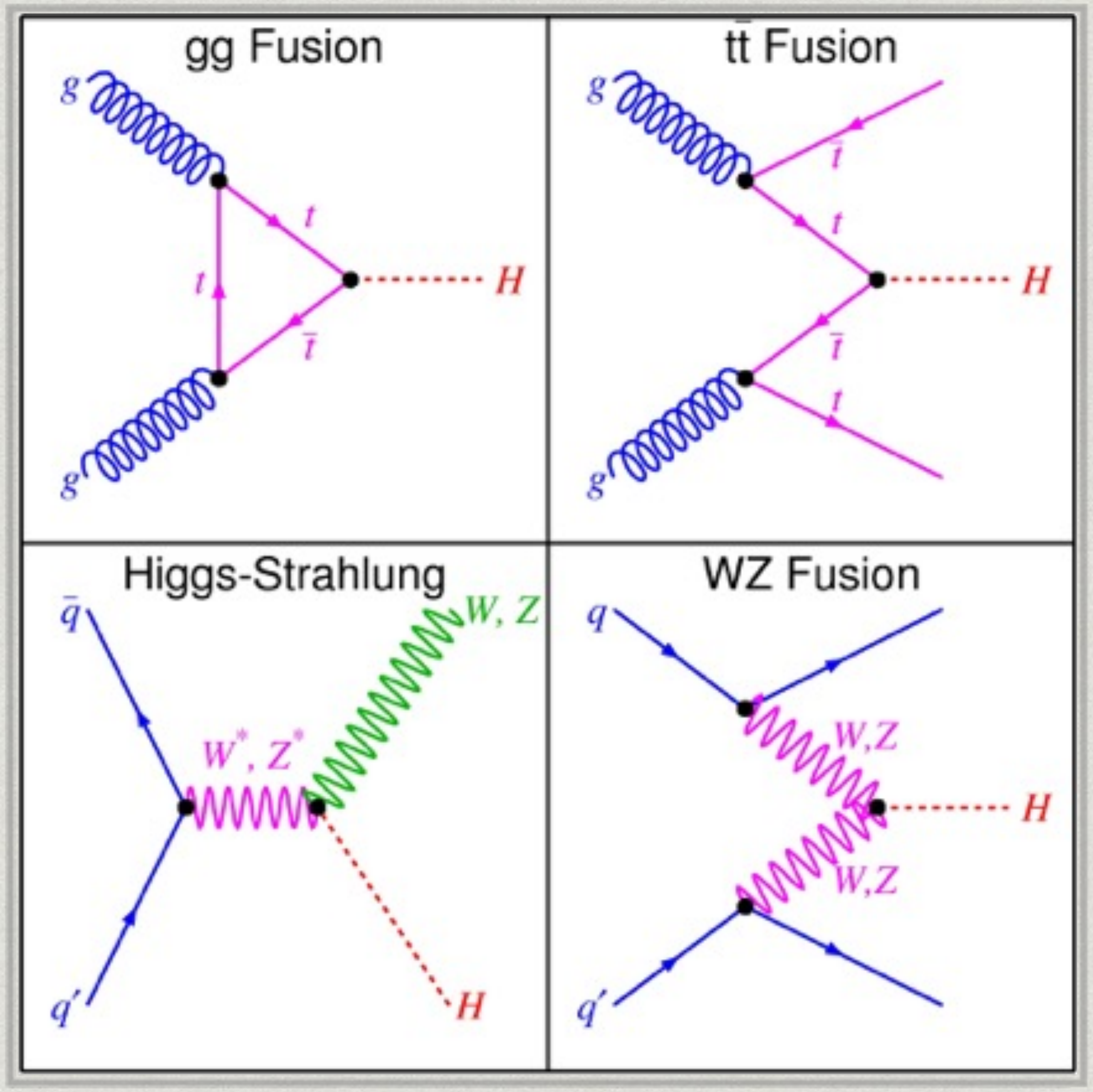


* *where is gravity?*

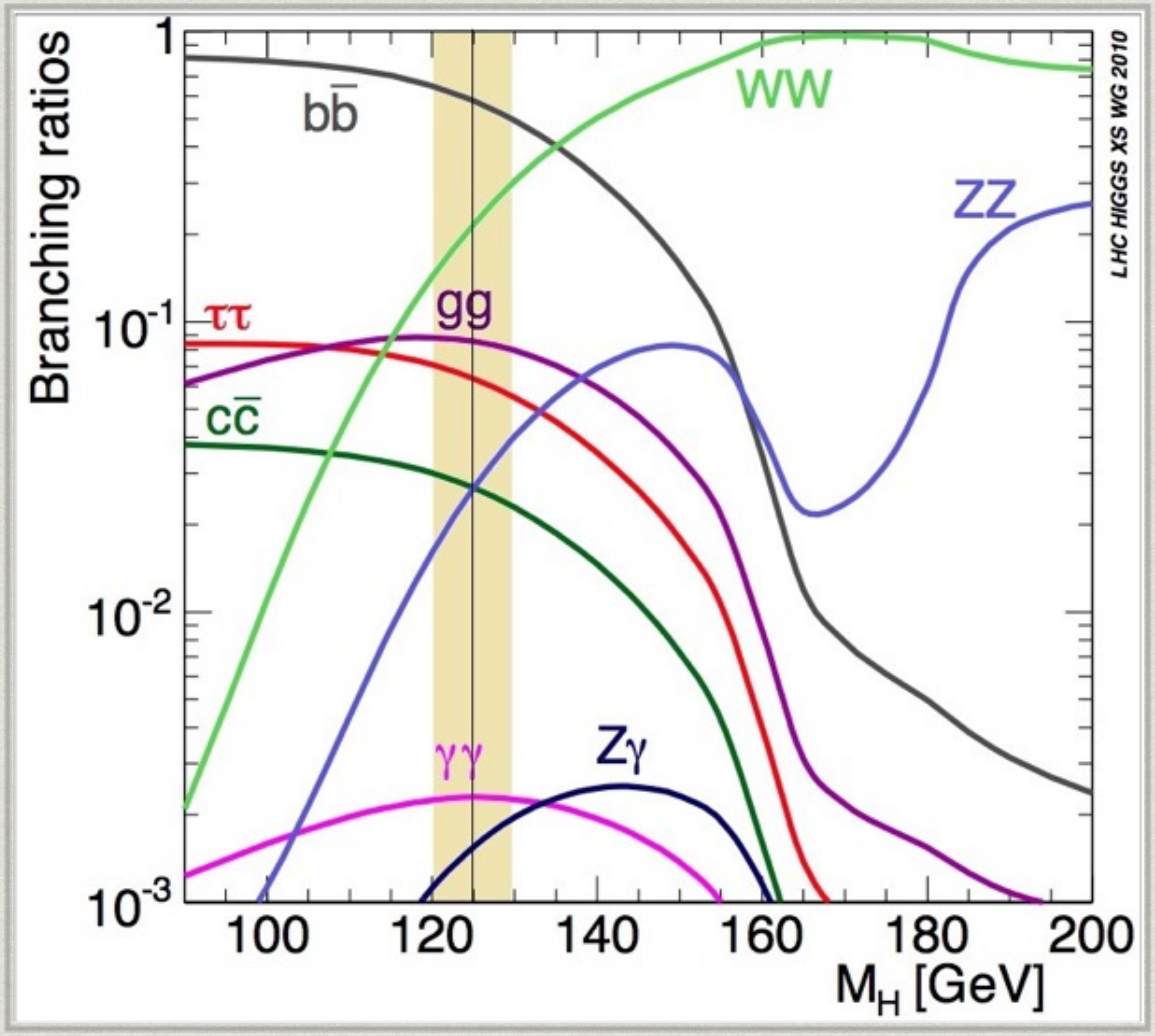
The Higgs Boson

- Higgs mechanism proposed in 1964
  - A field that is present everywhere
  - Breaks the symmetry of gauge bosons fields
    - Gives mass to the fundamental particles!
  - Excitations of the field originate Higgs bosons
    - Very unstable (lifetime of 10^{-22} seconds)

Higgs Boson Production



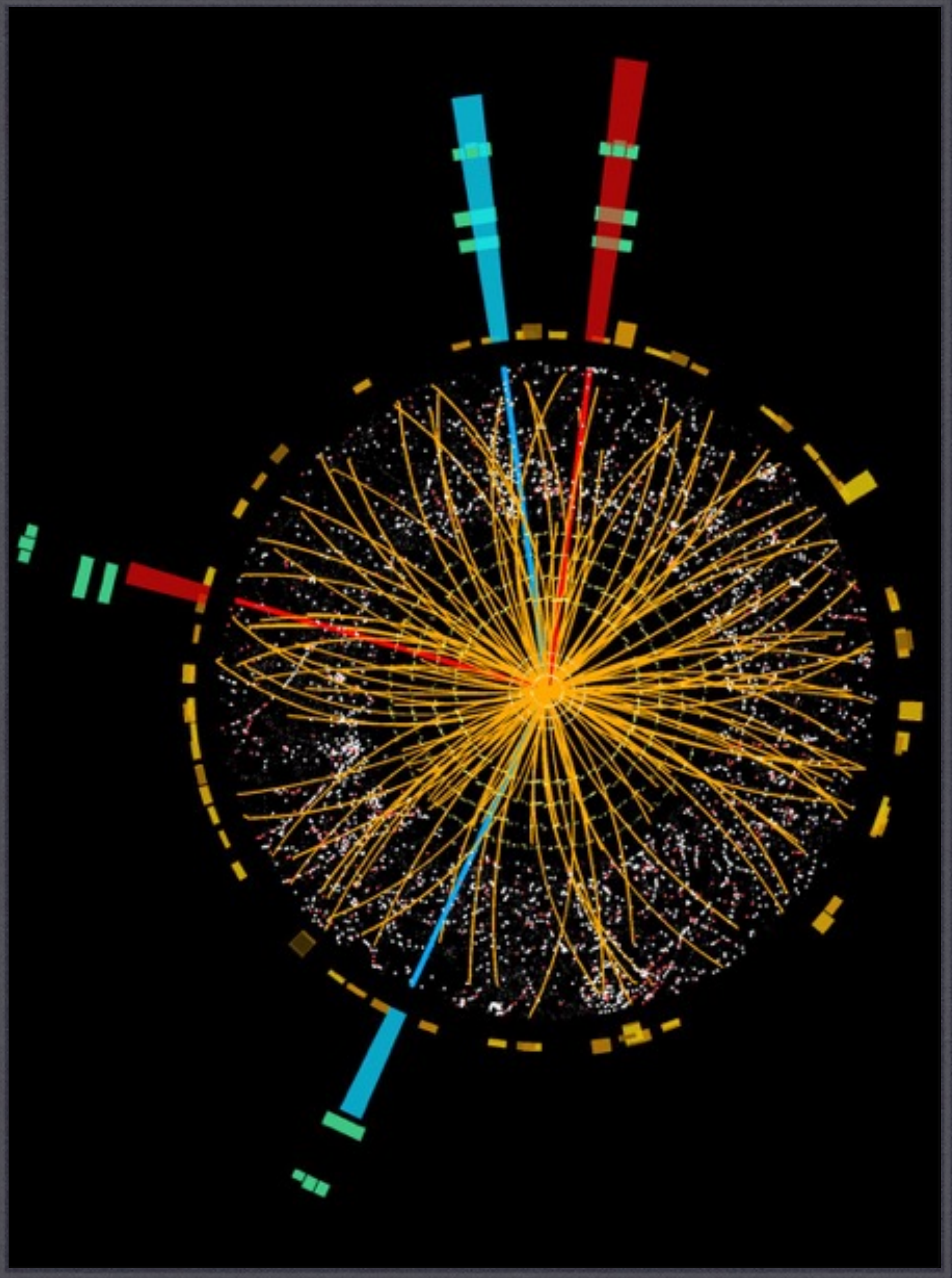
Higgs Boson Decay



SM Challenges

- Where is gravity?
  - Attempts of adding a graviton do not fit with what is measured experimentally
- Dark matter (28% of the universe energy) is not modelled by the SM
- SM predicts that neutrinos should be massless
- The universe has more matter than antimatter
- …

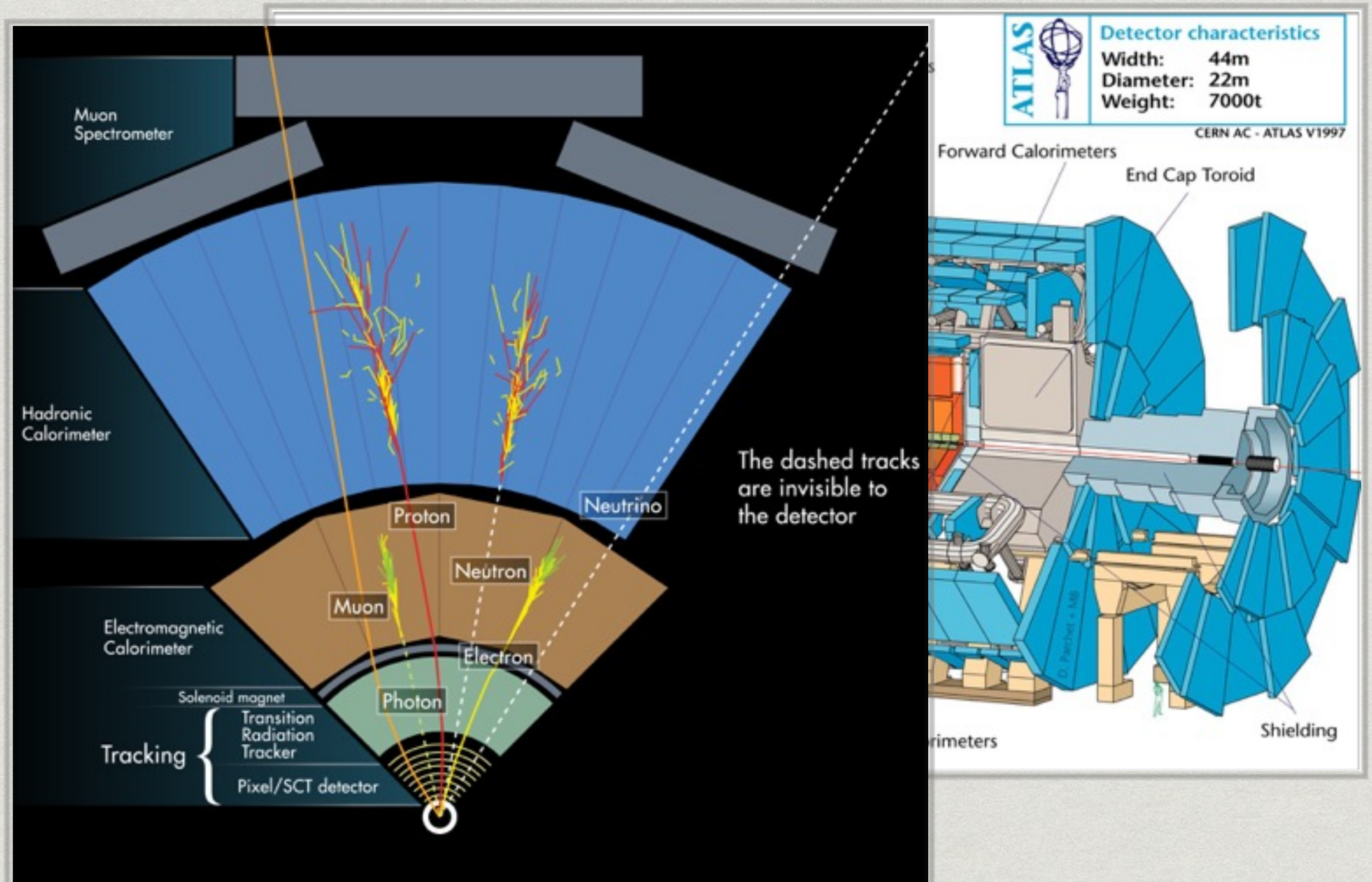
PARTICLE COLLISIONS AND ANALYSIS



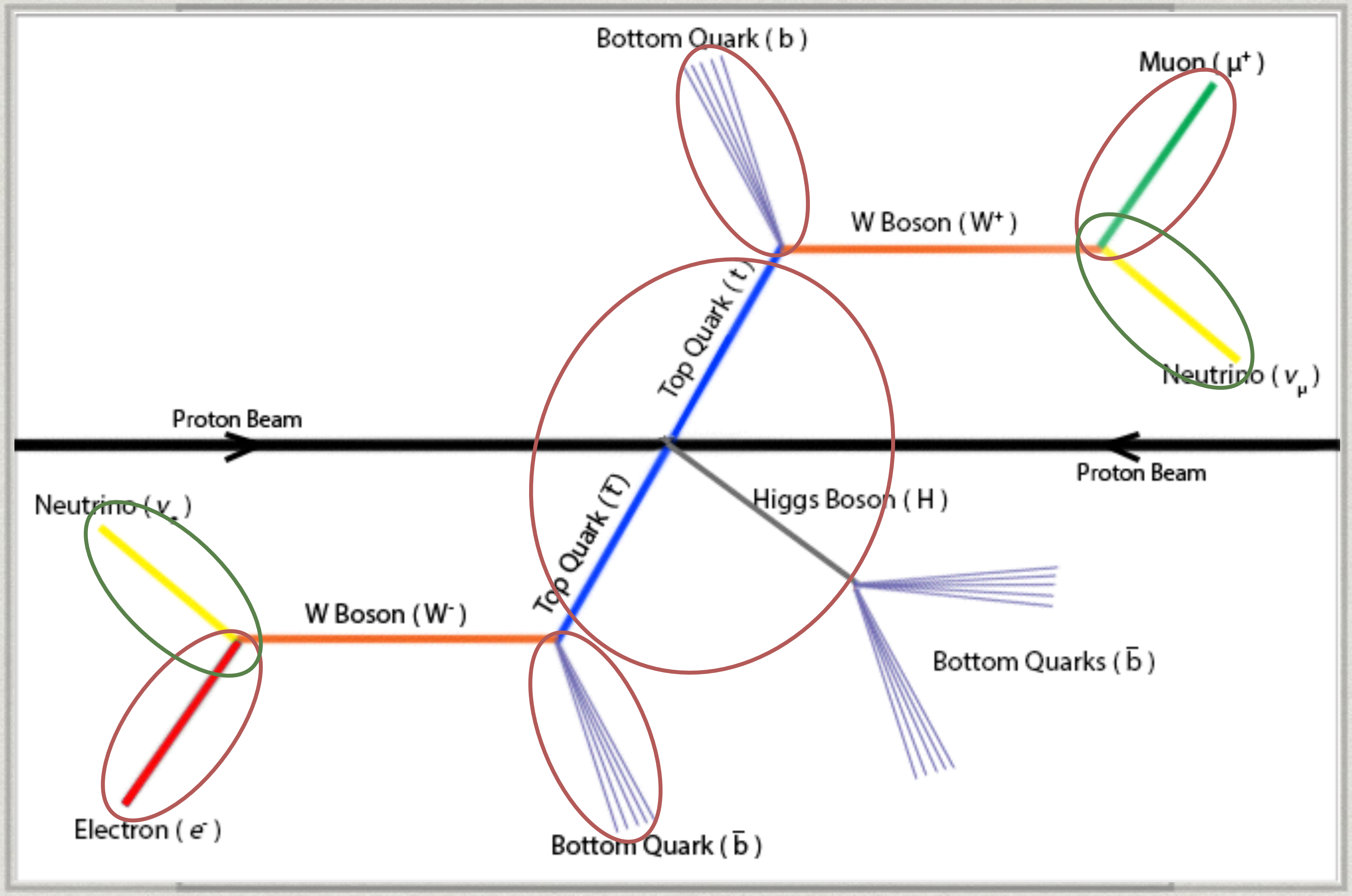
The Collision

- Bunch of particles accelerated by the LHC close to the speed of light in opposite directions
- Set to collide at a specific detector core
- Technically, in high energies, particles do not collide…
  - The particles mediating the fundamental forces interact

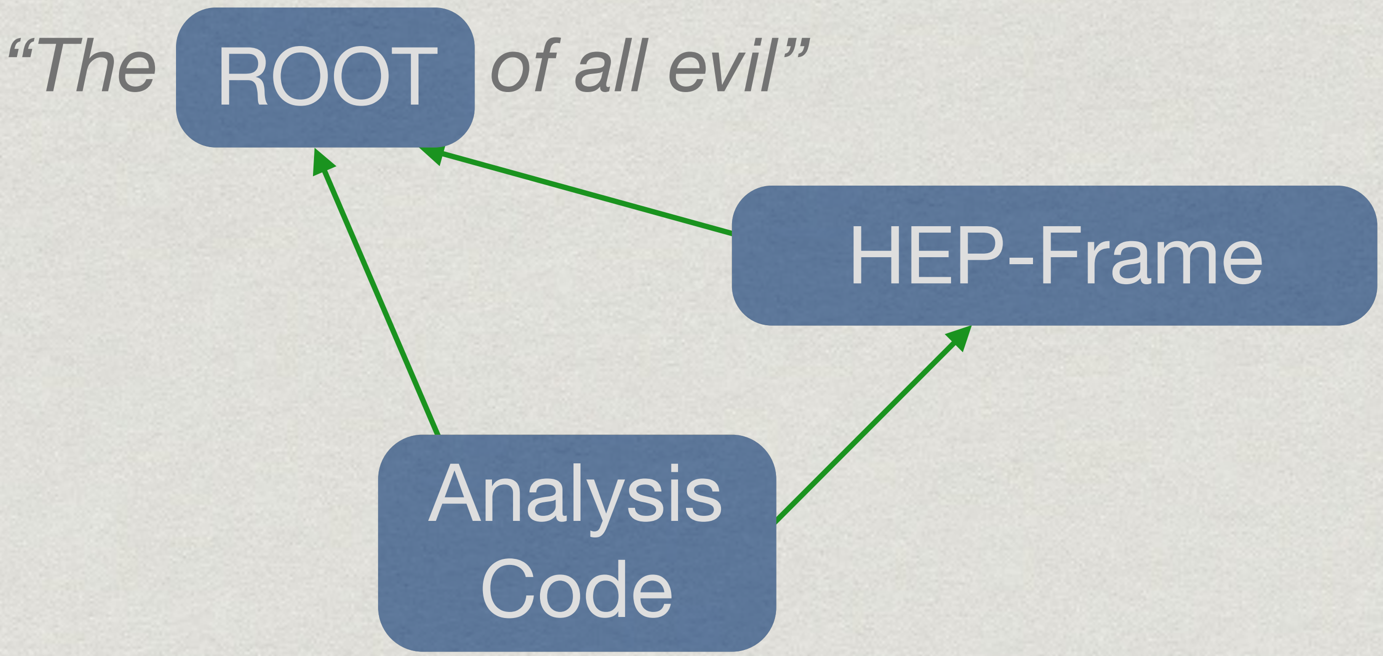
Inside the ATLAS Detector



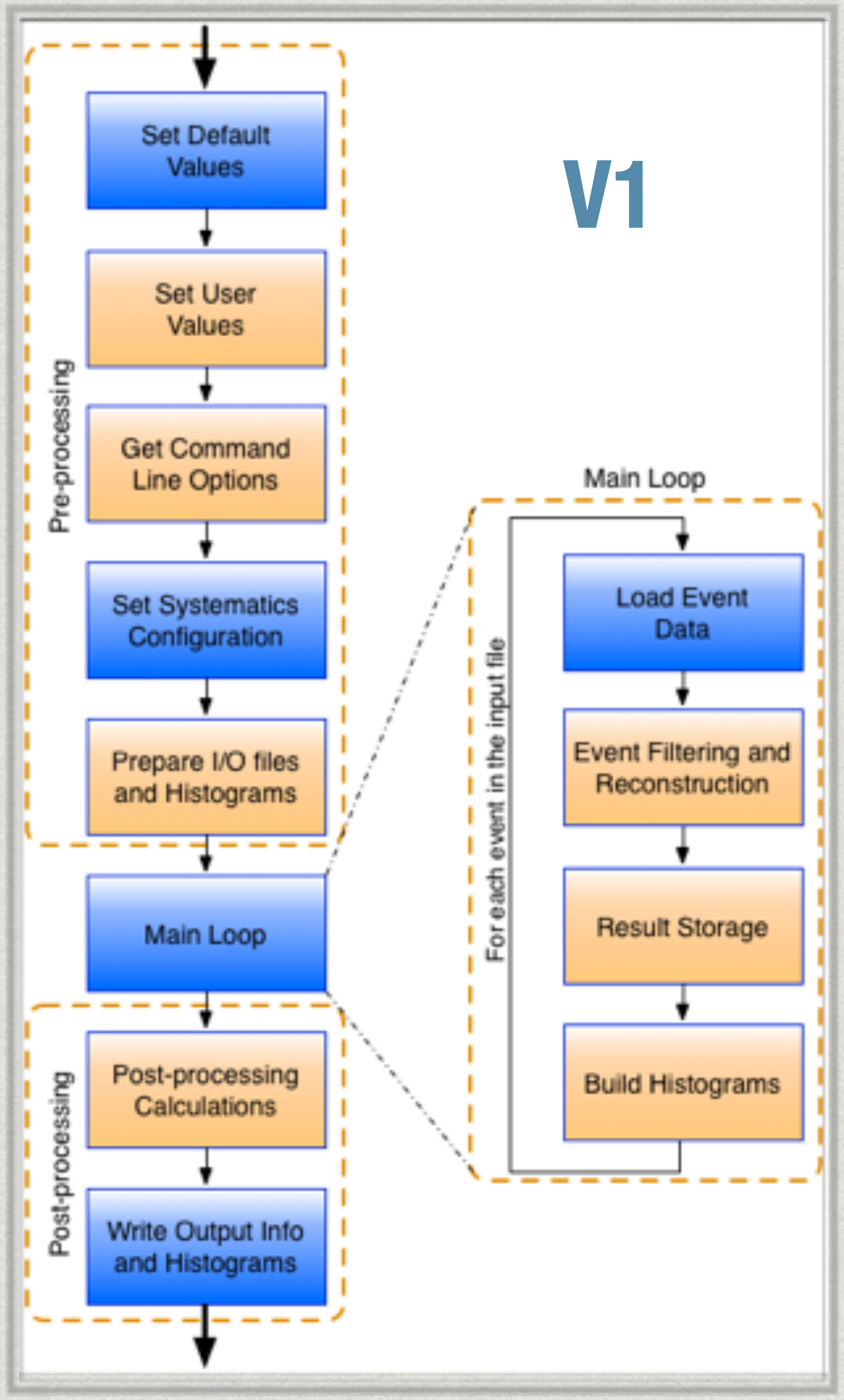
Higgs Boson Couplings to Top Quarks

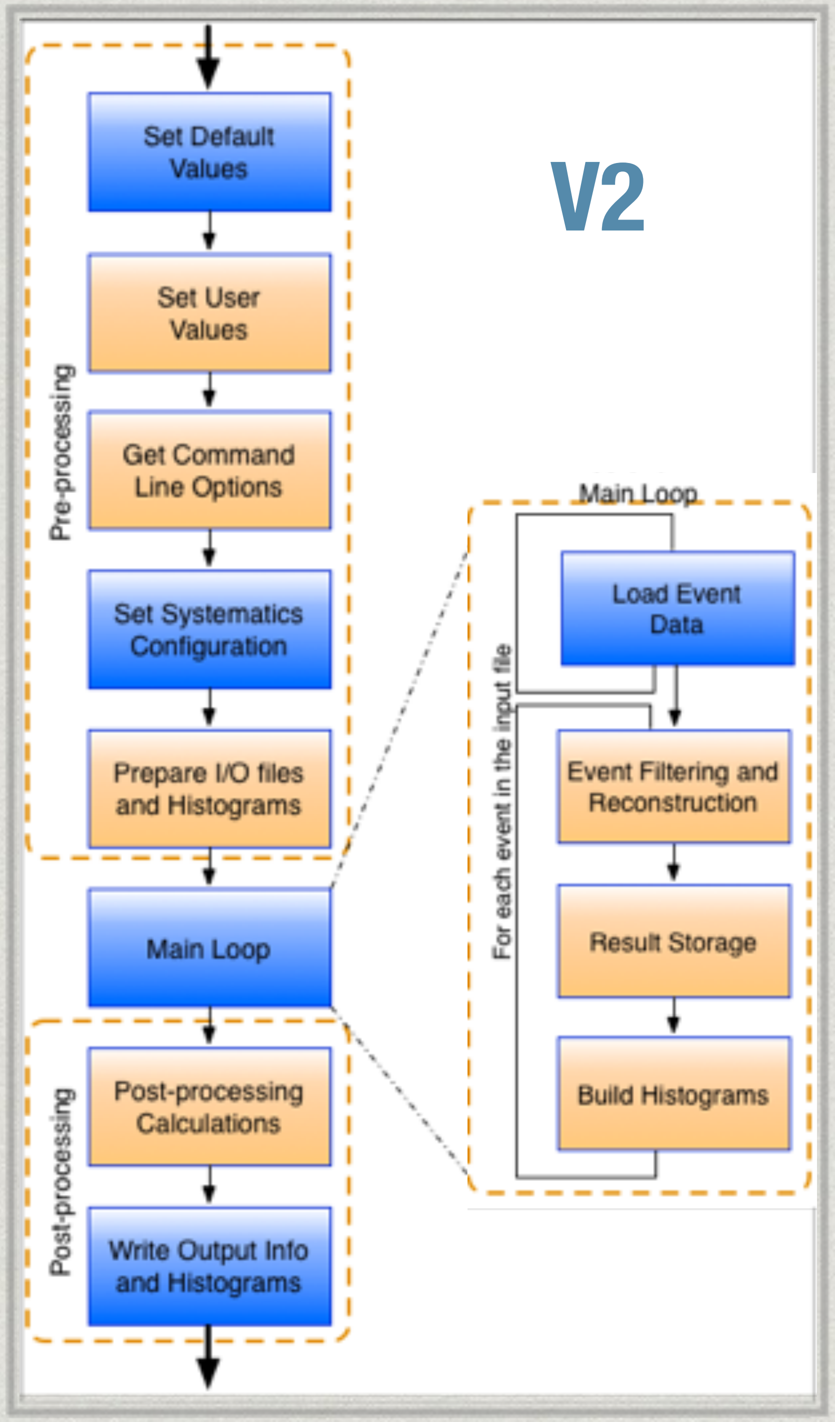


Code Dependencies



Code Structure

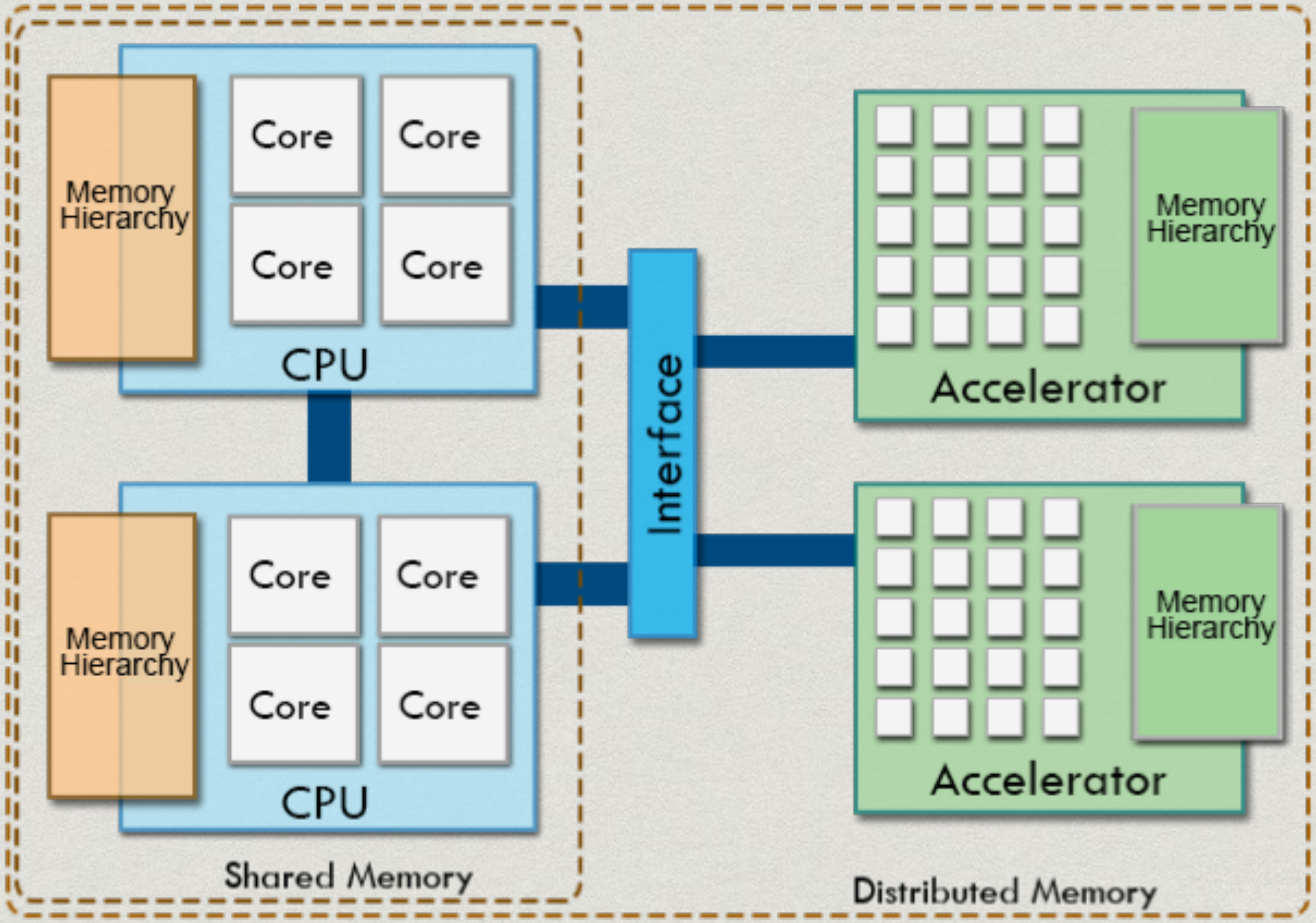




Challenges (i)

- The latest version of HEP-Frame has inefficiencies… Where?
  - File I/O
  - Parallelisation mechanisms
  - Underuse of available resources (such as memory)
- Profile, identify bottlenecks, improve the code
  - And perhaps propose alternatives?

Heterogeneous Platforms (HetPlats)



HetPlats Challenges

- Different architectures
  - Distinct designs of parallelism
  - Distinct memory hierarchies
- Different programming paradigms
  - Distinct code for efficient algorithms among devices
- Workload management
  - High latency communication between CPU and device
  - Different throughputs among devices

HetPlats Frameworks

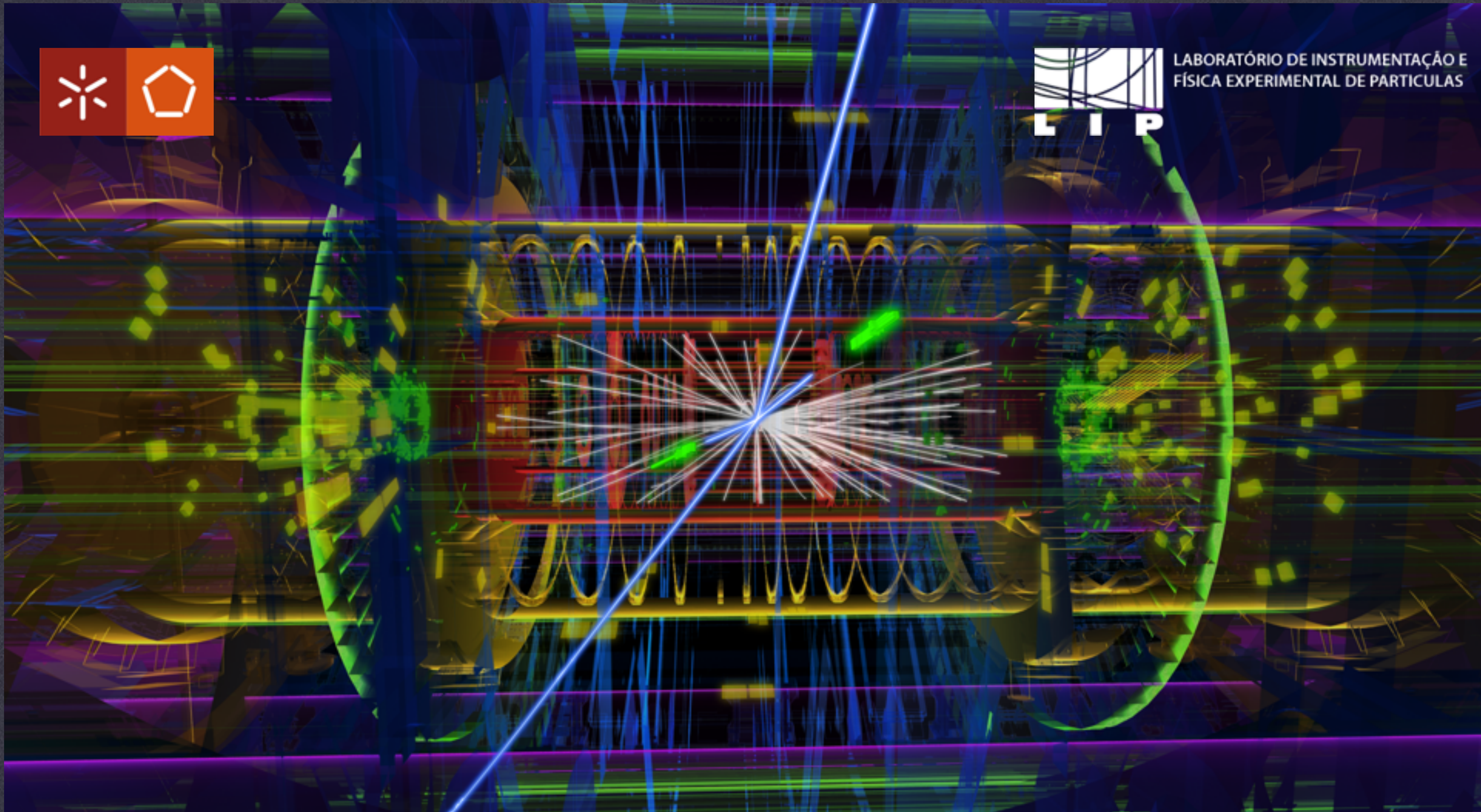
- StarPU
  - Task based
  - Minimisation of memory transfer costs
- Legion
  - Dynamic partitioning of the workload
  - Relies on properties added to the data structures
- DICE
  - Dynamic partitioning of the workload
  - Specific data structures provided
  - In-house development

Challenges (ii)

- Porting HEP-Frame with these frameworks to
  - Improve the code efficiency in
    - Multiple multicore CPUs
    - Multiple multicore CPUs + NVidia GPUs
    - Multiple multicore CPUs + Intel Xeon Phi?
  - Port the efficiency across different architectures

Resources

* The code (duh)
* A PhD pre-thesis
* A MSc thesis
* One publication
* Me!



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