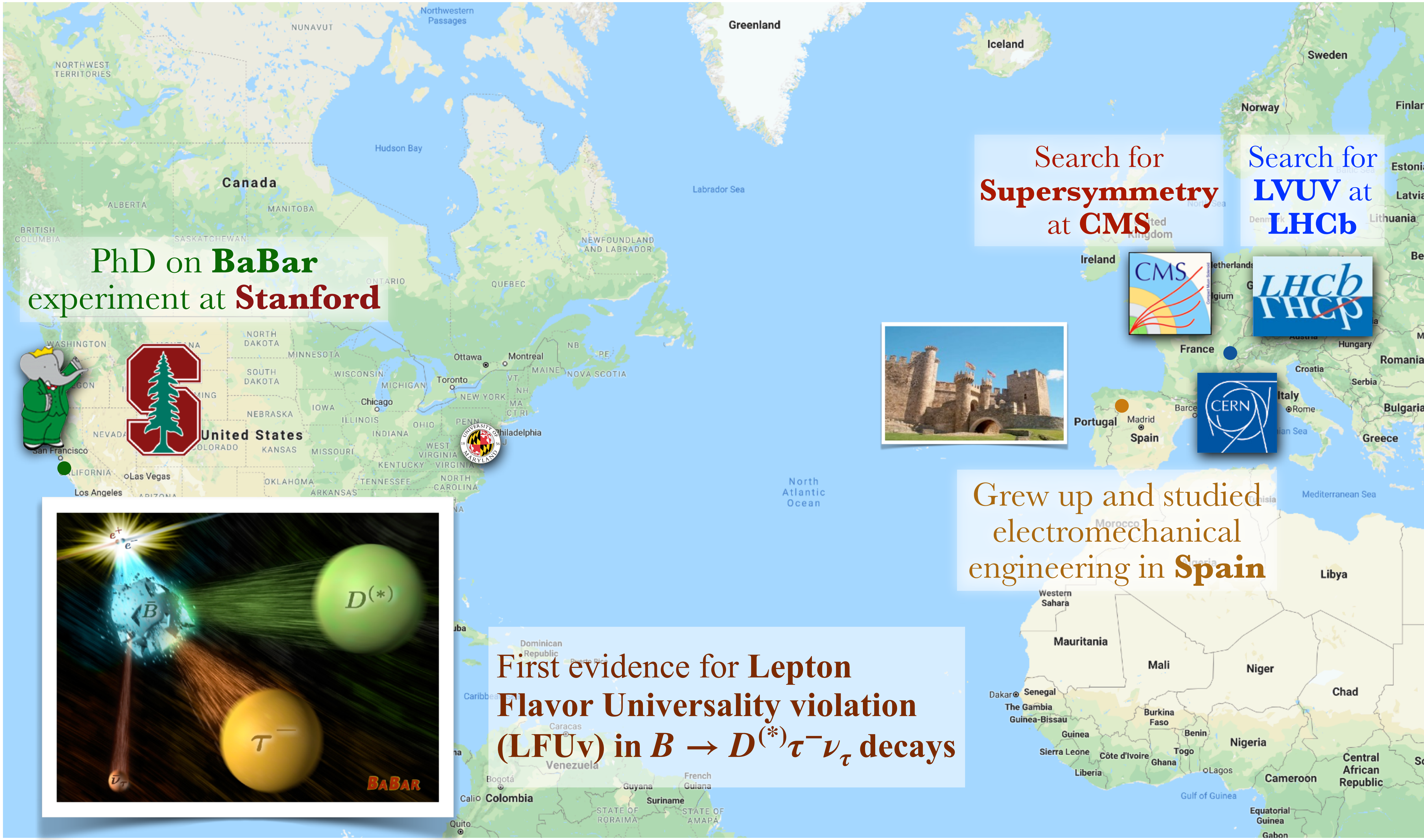
Introduction to Special Relativity and LHCb

UNIVERSITY OF MARYLAND 1856

LHCb

7th July 2022

Manuel Franco Sevilla



PhD on **BaBar** experiment at **Stanford**

Search for **Supersymmetry** at **CMS**

Search for **LVUV** at **LHCb**

Grew up and studied electromechanical engineering in **Spain**

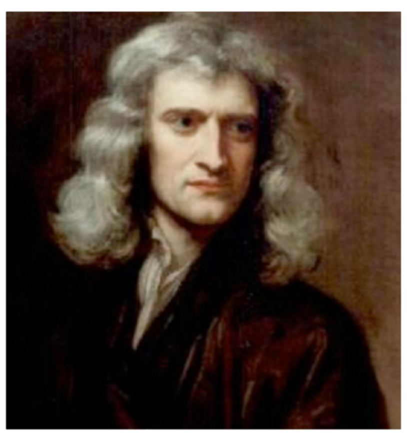
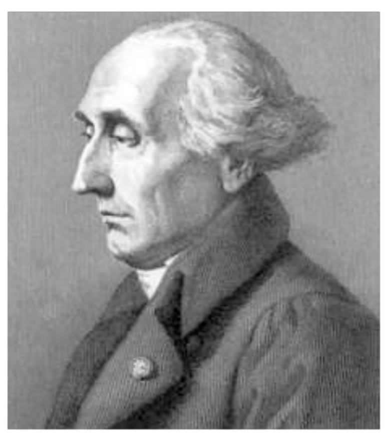
First evidence for **Lepton Flavor Universality violation (LFUv) in $B \rightarrow D^{(*)}\tau^-\nu_\tau$ decays**

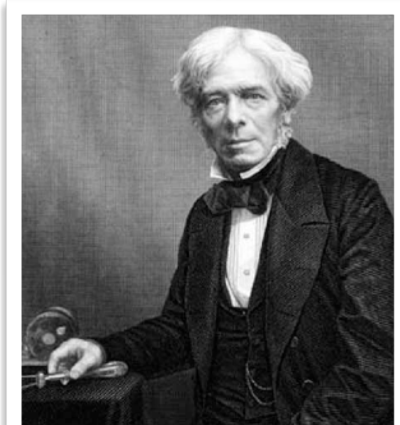
Outline

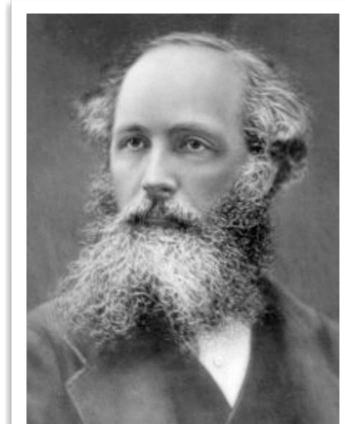
- Overview of **Modern physics**
- Introduction to **Special Relativity**
- Introduction to **LHCb**

Physics complete in the XIX century?

- From the **XVII to the XIX centuries, extraordinary progress** in our fundamental understanding of the universe
  - ➡ Newton's Gravitation, Classical and Statistical Mechanics, Thermodynamics, Electromagnetism





$$F = G\frac{Mm}{R^2}$$

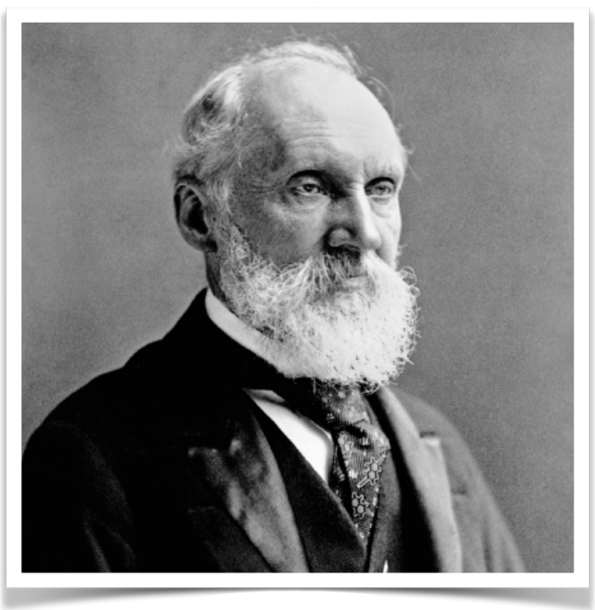
$$\boldsymbol{\nabla}\cdot\boldsymbol{E} = \frac{\rho}{\epsilon_0} \qquad \boldsymbol{\nabla}\cdot\boldsymbol{B} = 0 \qquad \boldsymbol{\nabla}\times\boldsymbol{E} = -\frac{\partial\boldsymbol{B}}{\partial t} \qquad \boldsymbol{\nabla}\times\boldsymbol{B} = \mu_0\left(\boldsymbol{J} + \frac{\partial\boldsymbol{E}}{\partial t}\right)$$

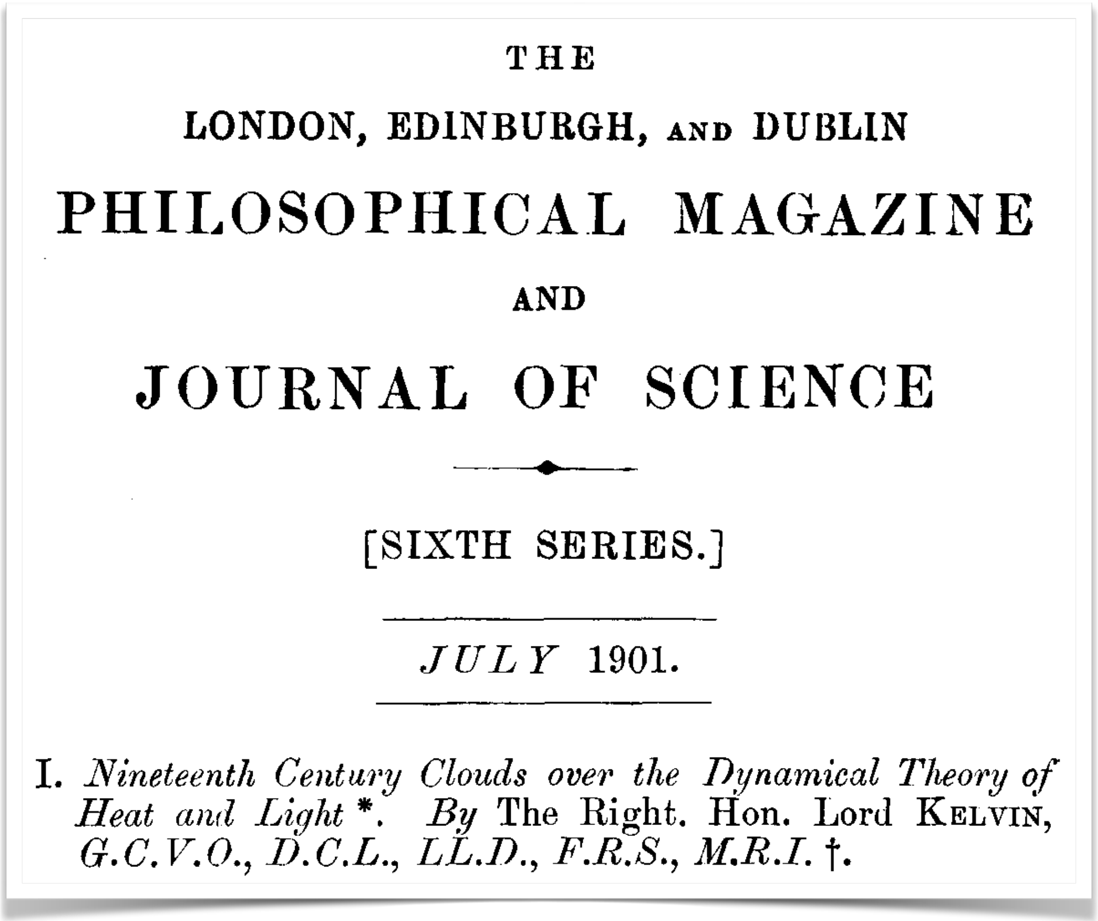
Feeling at the end of the XIX century

"There is nothing new to be discovered in physics now, All that remains is more and more precise measurements."

Lord Kelvin's clouds

"The beauty and clearness of the dynamical theory, which asserts heat and light to be modes of motion, is at present obscured by two clouds"





THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE

[SIXTH SERIES.]

JULY 1901.

I. *Nineteenth Century Clouds over the Dynamical Theory of Heat and Light* *. *By* The Right. Hon. Lord KELVIN, *G.C.V.O., D.C.L., LL.D., F.R.S., M.R.I.* †.

Michelson-Morley

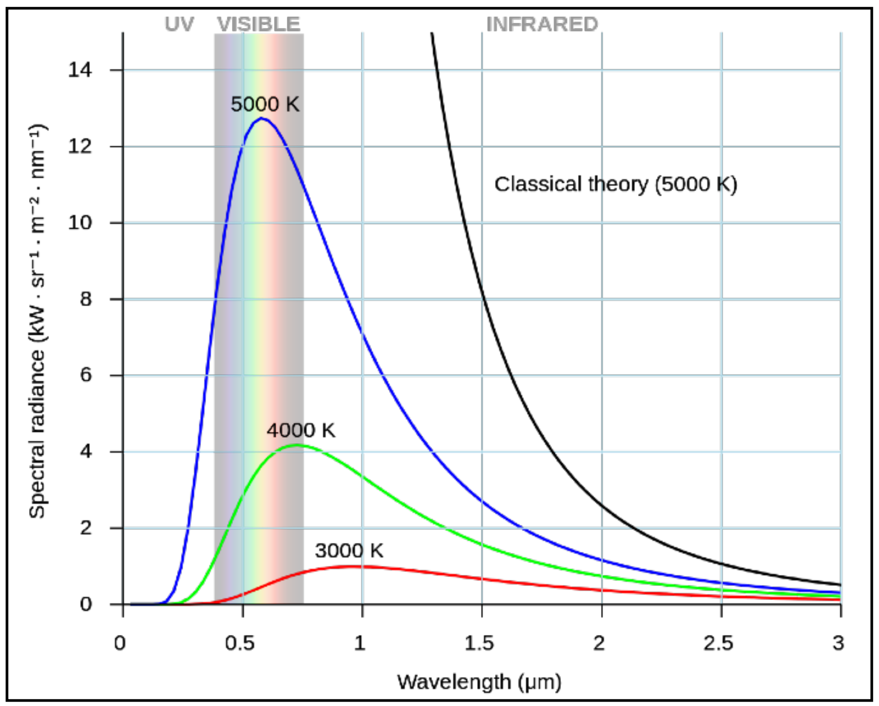
Black-body spectrum

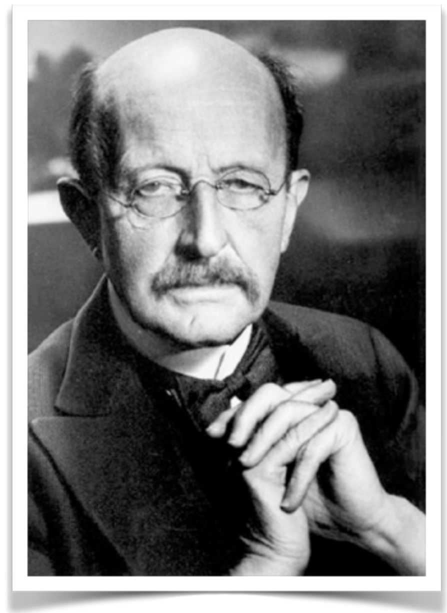
Quantum mechanics in a nutshell

Black body radiation
Ultraviolet catastrophe

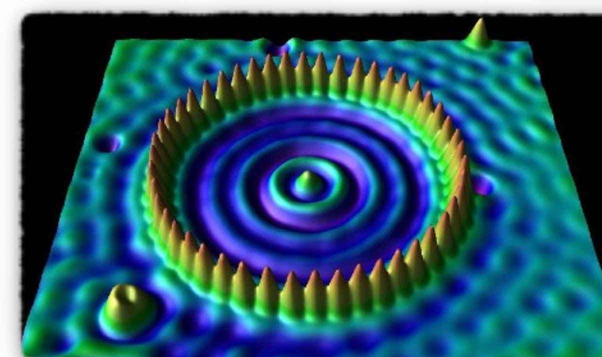
→ **Energy quantization** →

Deeper understanding of the Universe's fundamental constituents





$$E = h\nu$$



+ many other experiments (photoelectric effect…)

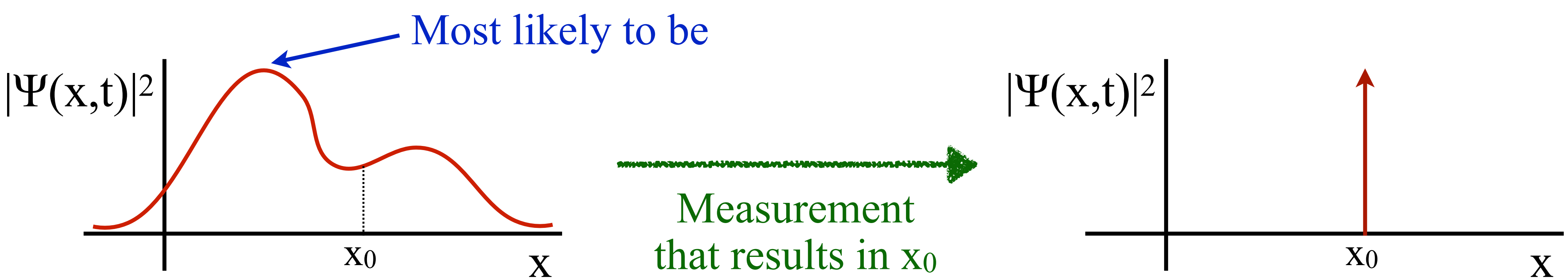
+ work from many others (Einstein, Schrödinger, Heisenberg…)

Quantum mechanics

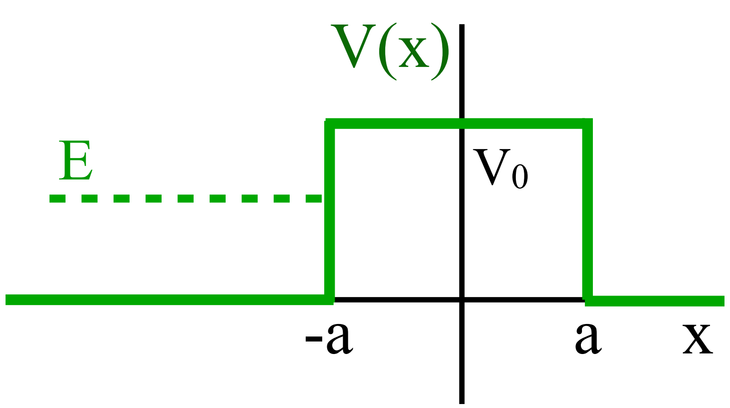
Particles have a wavefunction Ψ found by solving Schrödinger equation

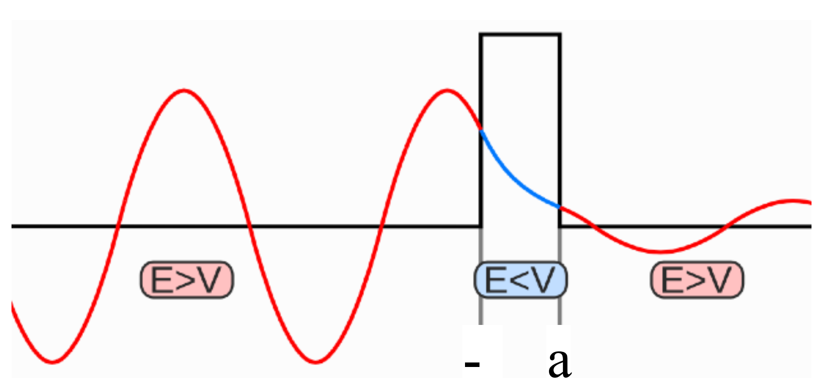
$$i\hbar\frac{\partial}{\partial t}\Psi(x,y,z,t) = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(x,y,z,t)\right)\Psi(x,y,z,t)$$

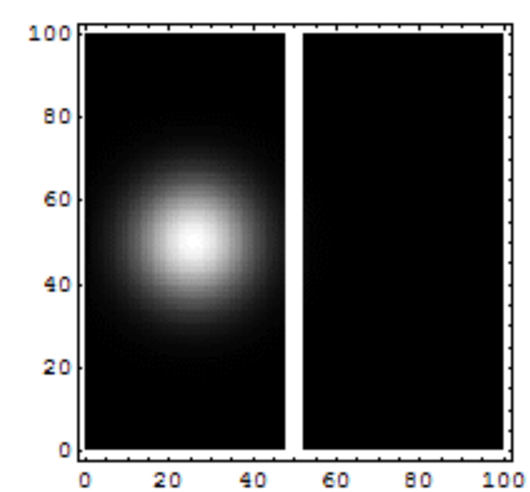
$\left|\Psi(x,t)\right|^2 = \Psi^*\Psi$ is the probability of finding the particle between x and x+dx at time t



Tunneling of particle coming from left

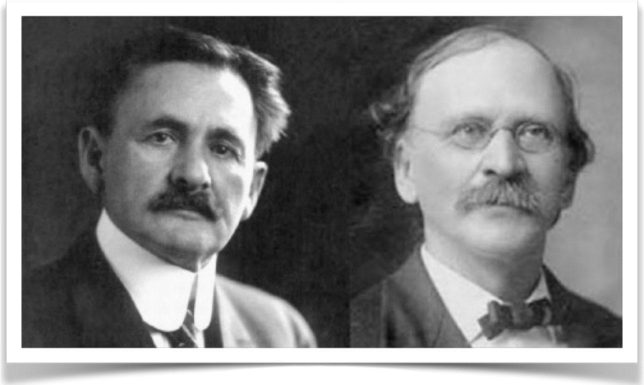


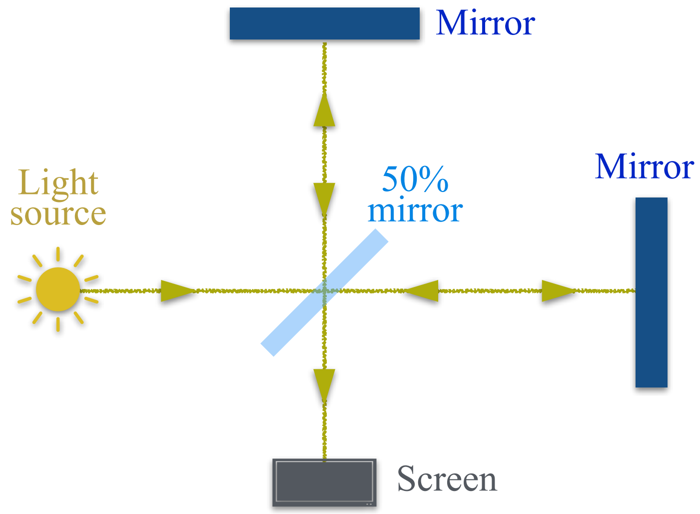




Relativity in a nutshell

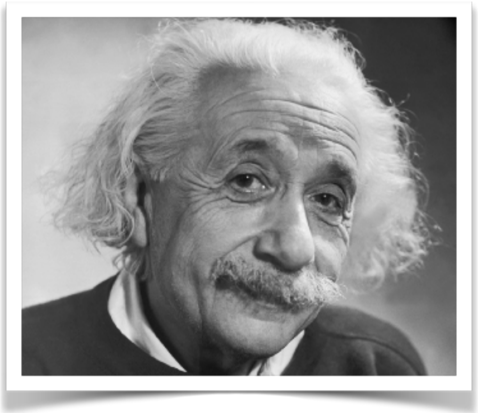
Michelson-Morley experiment





+ experiments from many others (ether dragging…)

Einstein's postulates



The laws of Physics have the same form in all inertial frames of reference

The speed of light in vacuum has the same value c in every direction in all inertial frames of reference

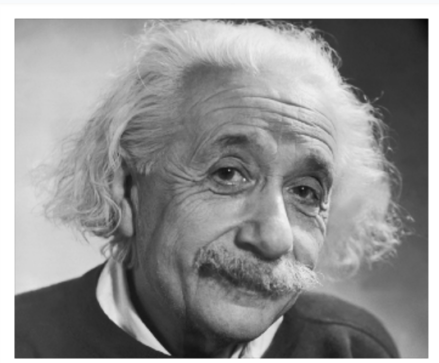
+ work from many others (Poincaré, Lorentz…)

Deeper understanding of the Universe's spacetime, mass, and energy

$$E = mc^2$$

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

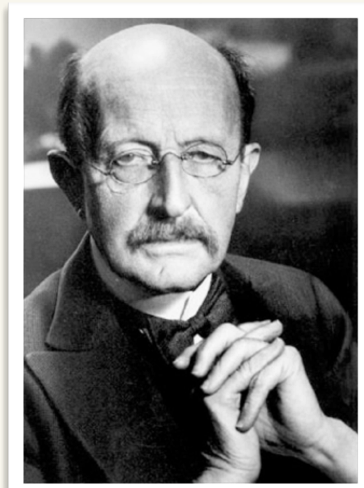
- Break-neck pace of discovery in the XX century

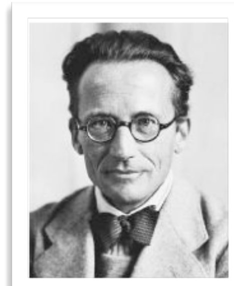


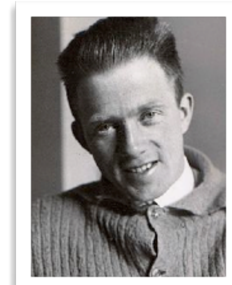
$$E = mc^2$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

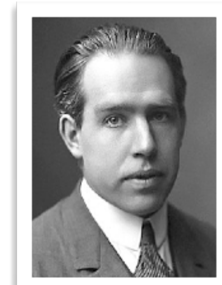
$$E = h\nu$$

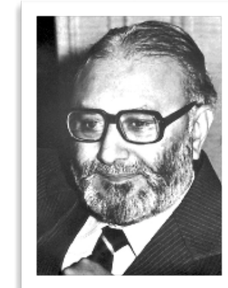


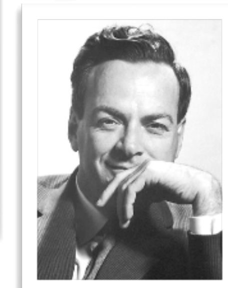




Quantum mechanics



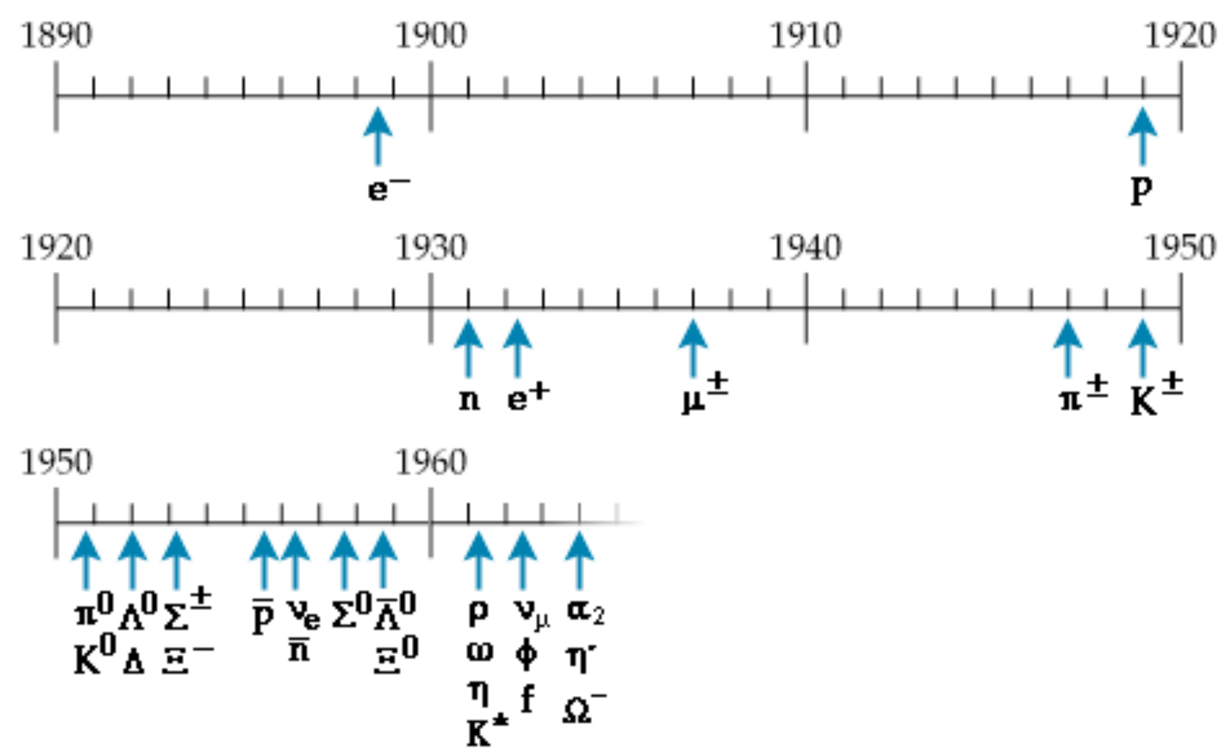




QED

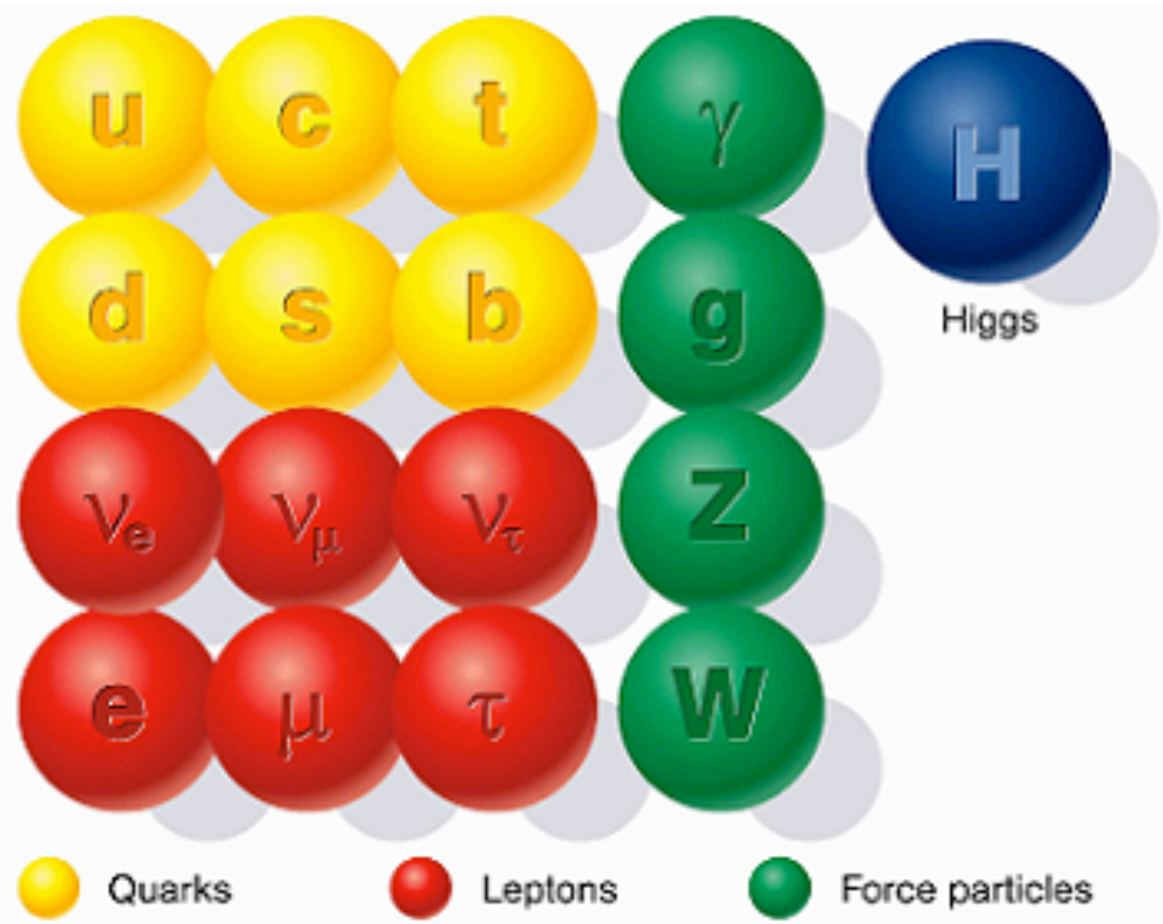
Higgs mechanism

QCD



- XX century **theoretical advances culminate** in the 70's with **SM of particle physics**

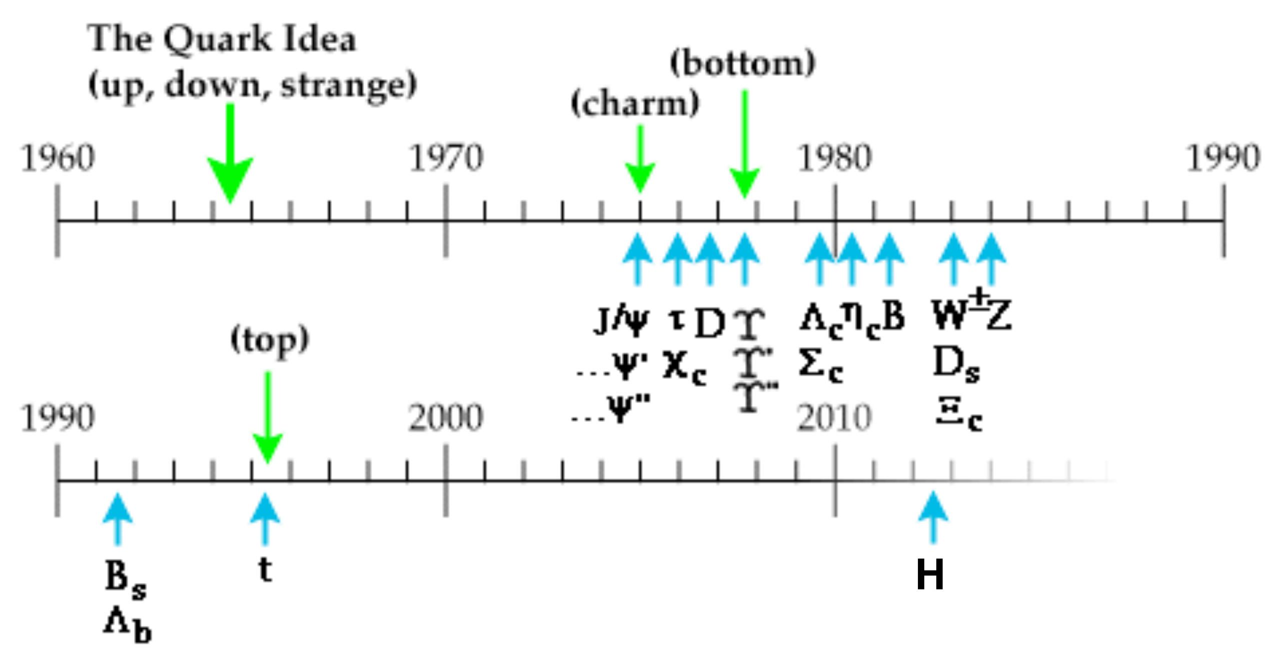
$$\boxed{\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)}$$



Anomalous magnetic dipole moment

$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{SM}} = 0.001\ 159\ 652\ 181\ 643(764)$$

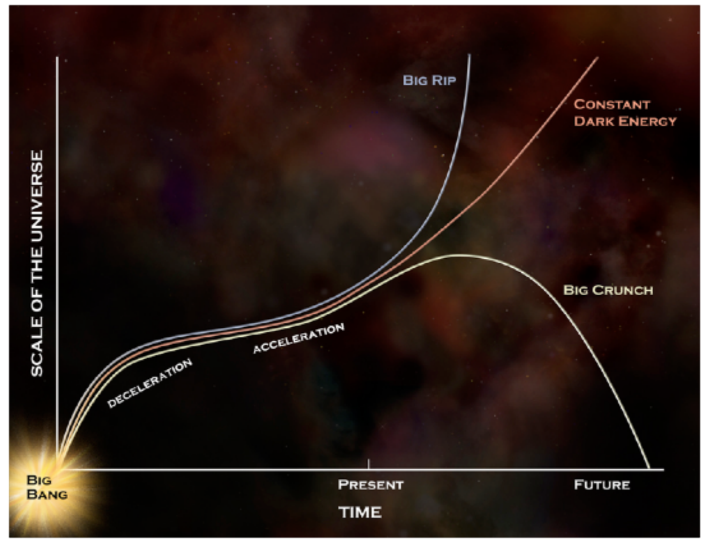
$$\left.\frac{g_e - 2}{2}\right|_{\mathrm{exp}} = 0.001\ 159\ 652\ 180\ 73(28)$$



Anything left to discover?

Clouds today

NASA/CXC/M. Weiss



Hierarchy problem

Dark matter

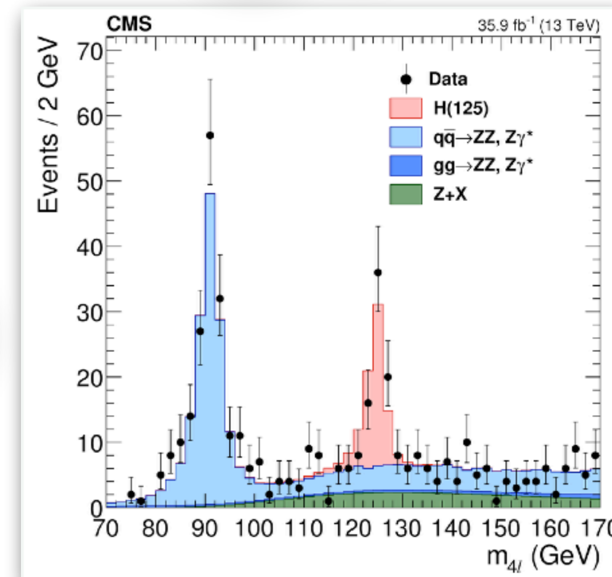
NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.

Dark energy

GR-SM unification

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

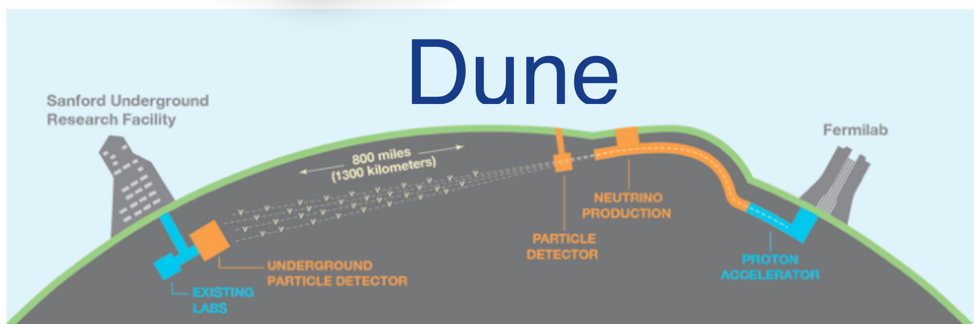
$$\mathrm{SU(3)} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}$$

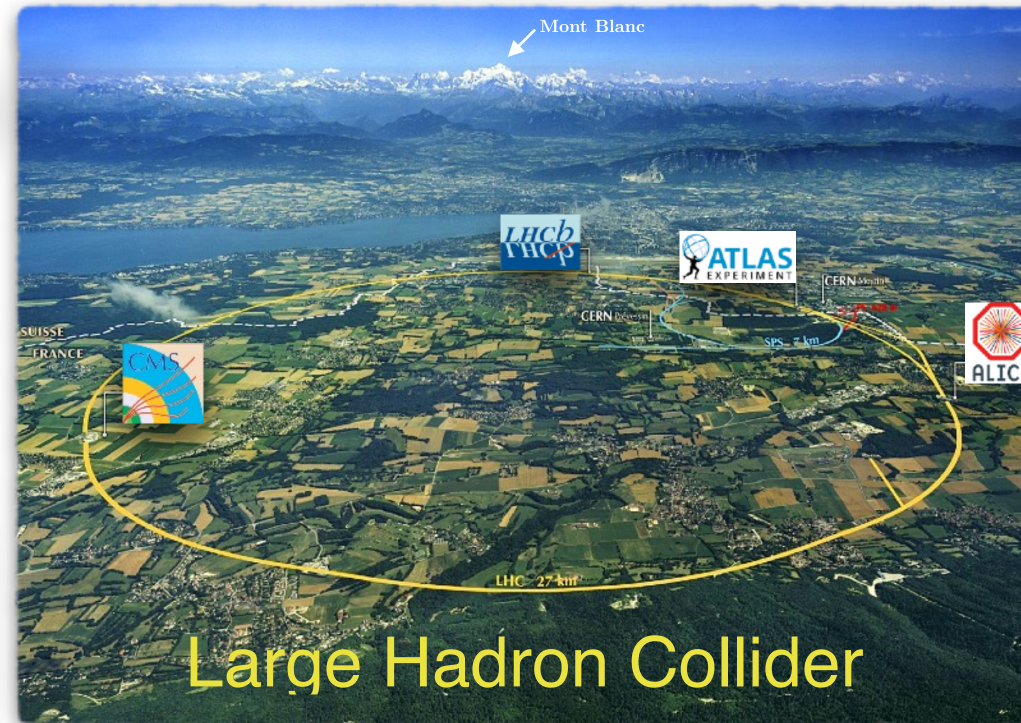


JHEP **11** (2017) 047

Hierarchy problem

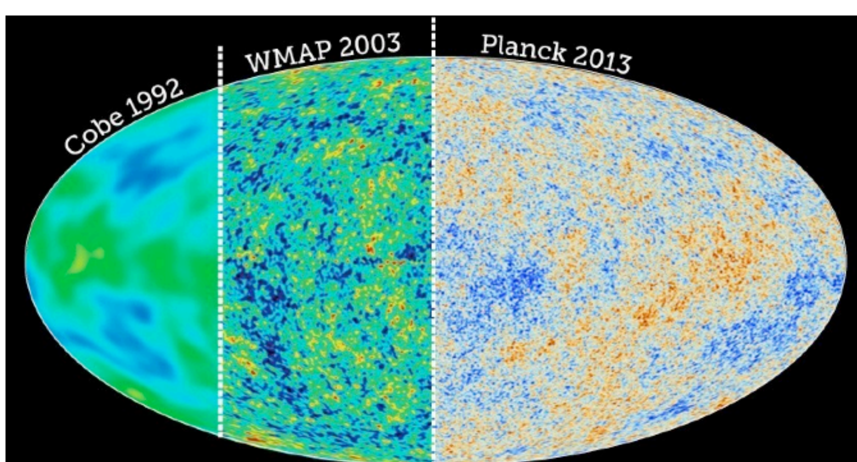
Dark matter

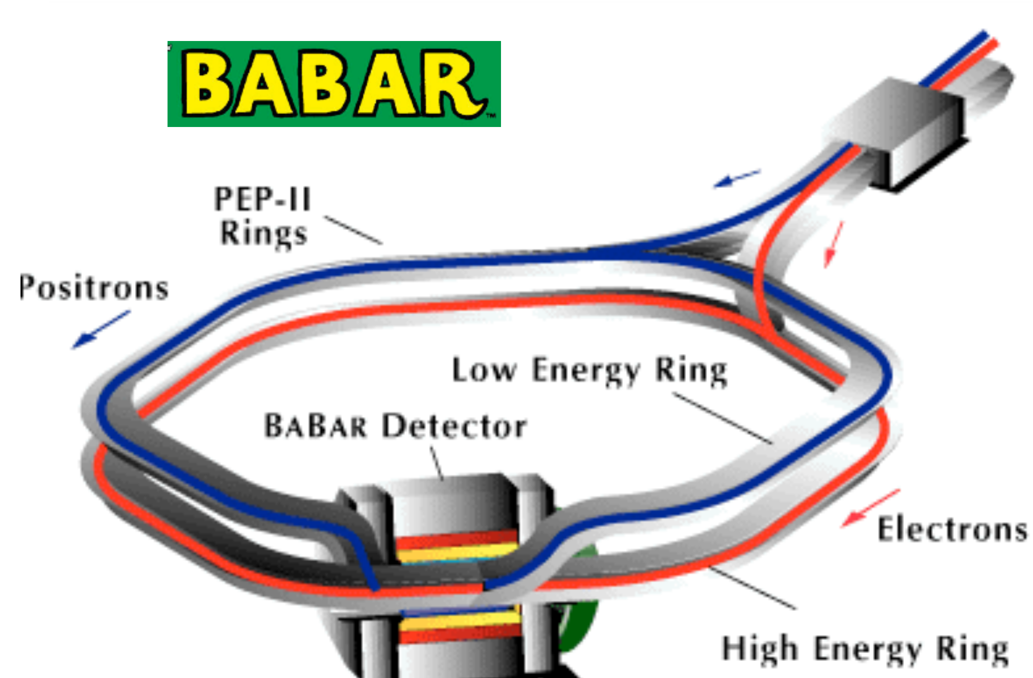




Matter ≠ antimatter

GR-SM unification





Modern physics timeline

Electron discovery

Ultraviolet catastrophe *Energy quantization* *General Relativity* *Positron discovery* *Particle zoo*

Michelson-Morley experiment

Maxwell equations *Special Relativity* *Schrödinger equation* *QED* *Higgs mechanism* *QCD* *Neutrino masses* *Higgs discovery*

XIX century	XX century	XXI
Classical	Modern Physics	

	Low speeds	High speeds
Large sizes	*Classical physics*	*Relativity*
Small sizes	*Quantum mechanics*	***Relativistic quantum***

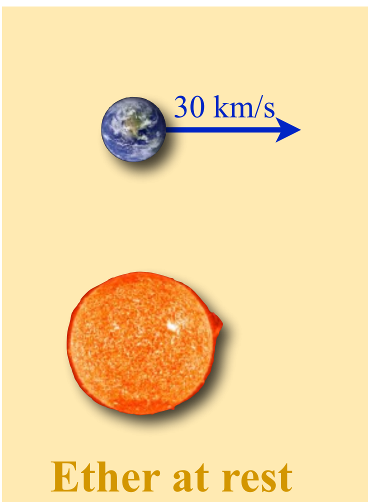
In **particle physics** we deal with small sizes and high energies (speeds), so we use a **relativistic quantum** framework called **Quantum Field Theory (QFT)**

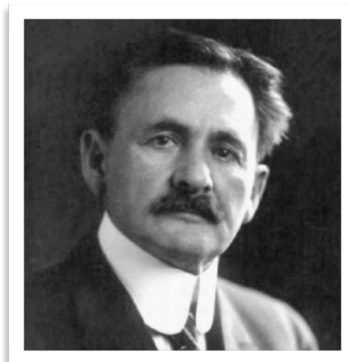
Special Relativity

Einstein's postulates

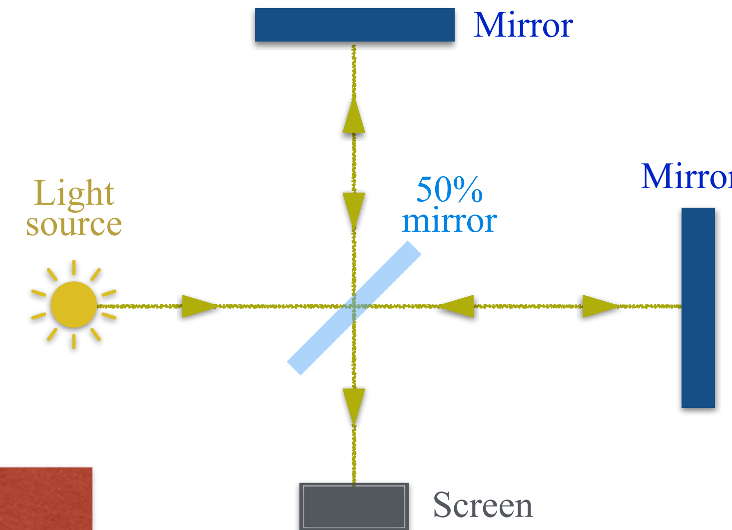
Hypothesis was that **Earth** was **moving at least at 30 km/s with respect to Ether**

If light moved at c with respect to Ether, **beam** would take **different times when aligned with Earth's speed versus transverse to it**

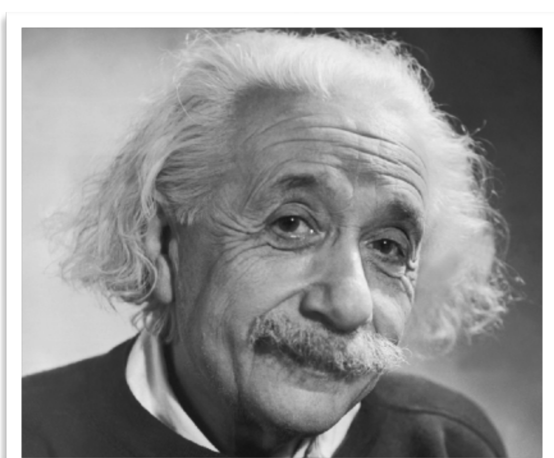




With an **interferometer**, **invented** by **Michelson** in **1881** (Naval academy, Annapolis).



No evidence for light traveling at different speeds in different directions



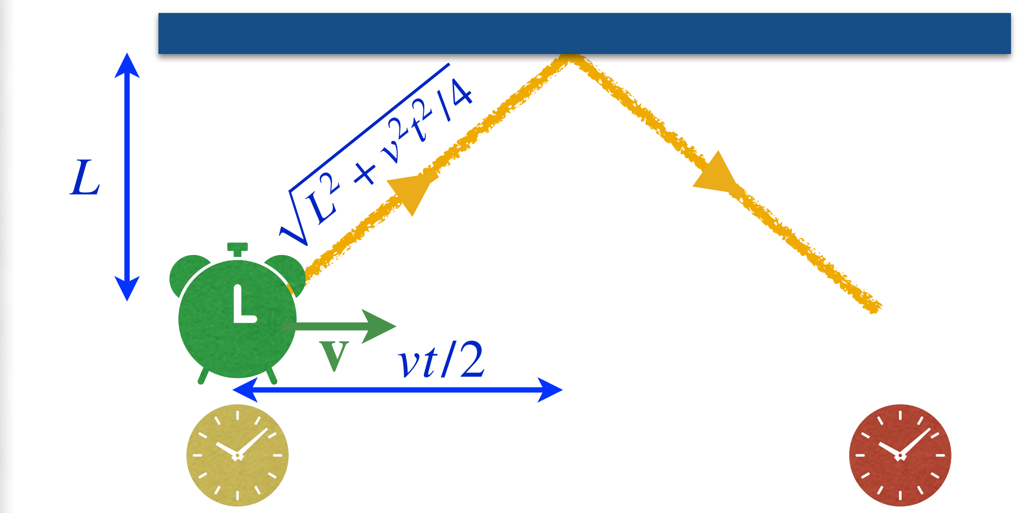
Relativity principle: all laws of Physics *have the* ***same form*** *in all* ***inertial*** *(no acceleration)* ***frames of reference***

The ***speed of light in vacuum*** *has the* ***same value c*** *in every direction in all* ***inertial frames of reference***

Time dilation

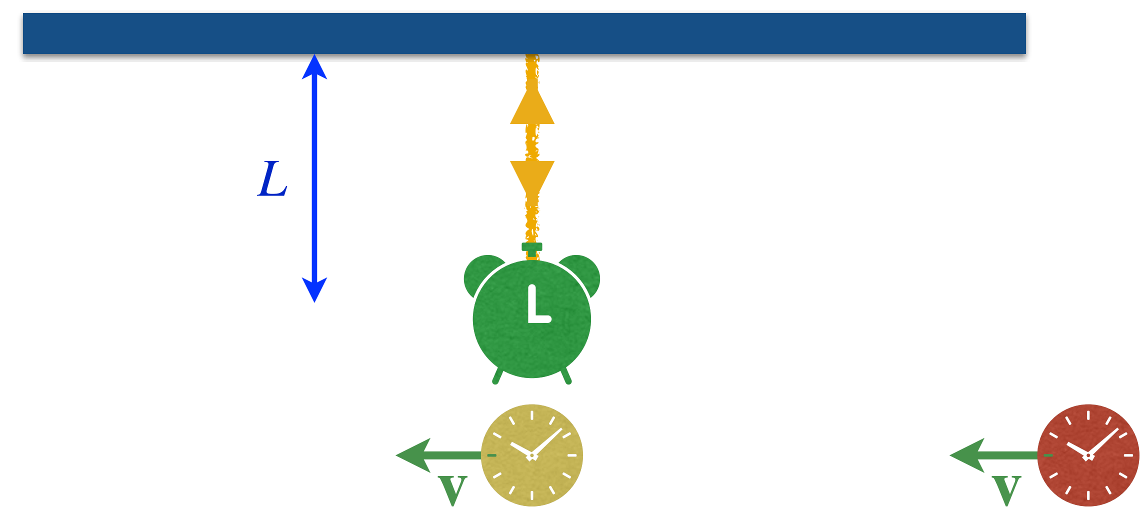
~ What's the **time** passed **between light is emitted** and **absorbed** by the green clock?

Rest frame



$$t = 2\frac{\sqrt{L^2+v^2t^2/4}}{c} \Rightarrow t = \frac{2L}{c}\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Green clock frame



Total time between events is simply **total distance** covered by light **divided by speed**

$$t' = \frac{2L}{c}$$

We define a new quantity γ

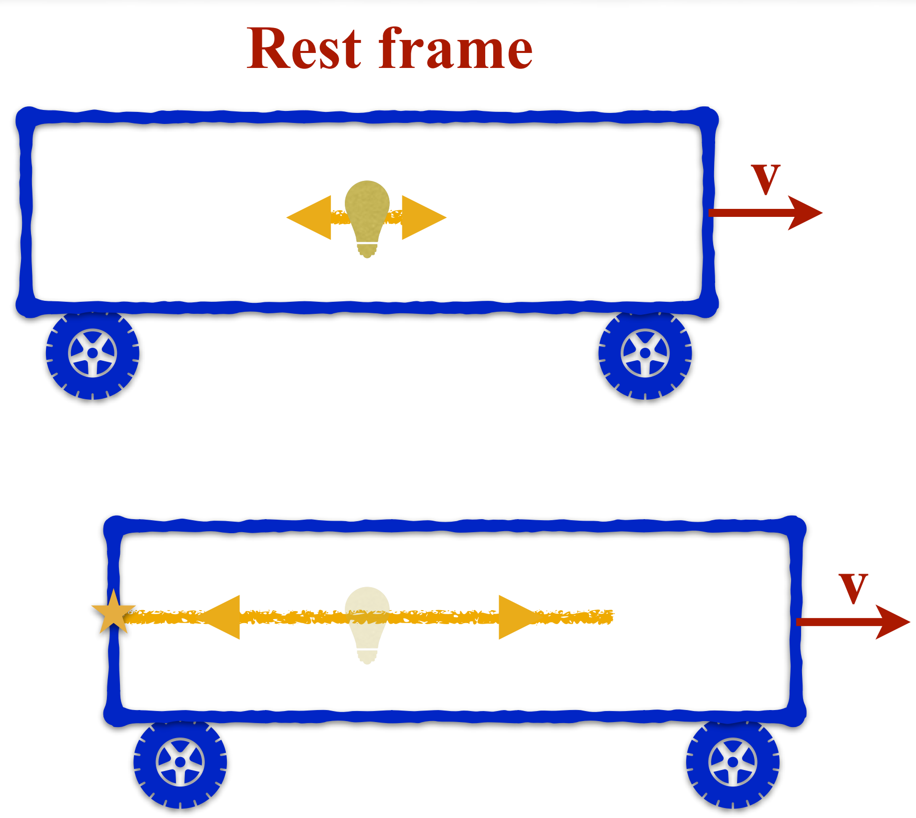
$$\boxed{\gamma \equiv \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}}$$

$$\boxed{t = t'\gamma}$$

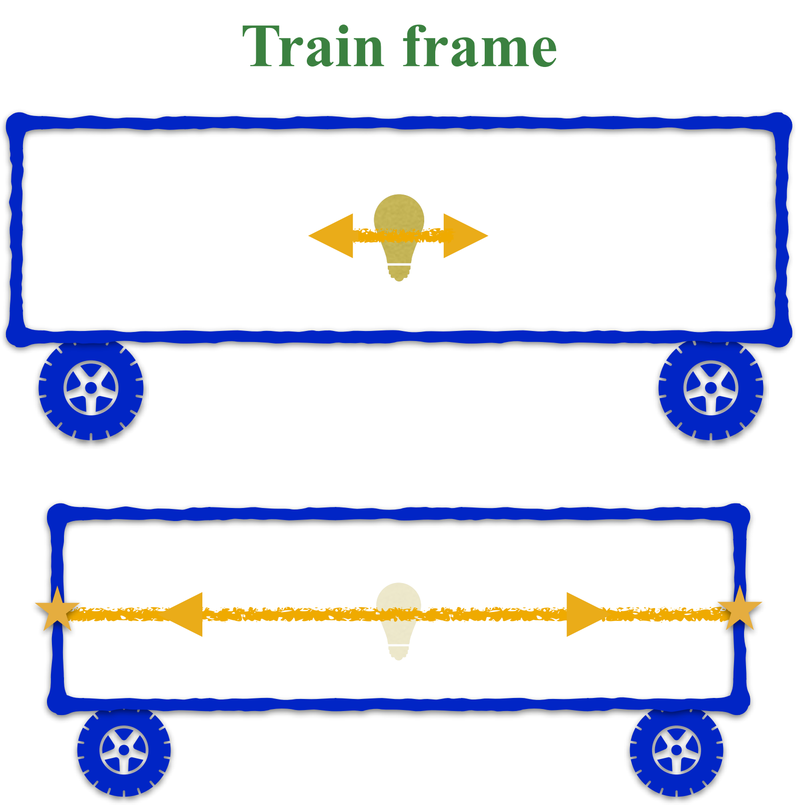
Based on Einstein postulates alone, **time passes more slowly when moving**

Simultaneity is frame dependent

- A light goes off in the middle of a moving train
  - ➡ Do the light rays **reach** the **front/back of the train at the same time?**



Light reaches the **back** of the train **earlier than the front**

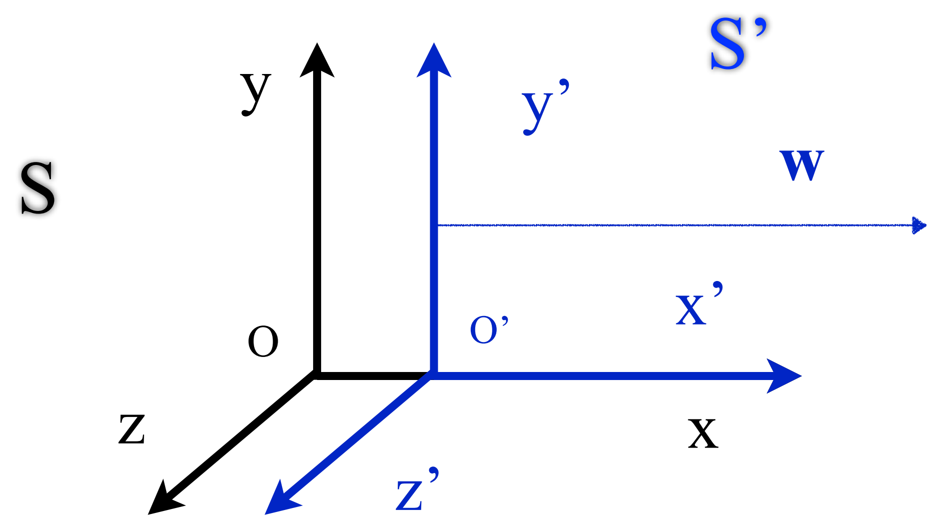


Light reaches **back** and **front** **simultaneously**

Whether two events that occurred far apart are simultaneous or not depends on the frame of reference

Lorentz transformation

- **Lorentz boost** for
  - Two inertial frames
  - Same origin at t=0 and S′
  - Moving at speed v **along the x axis**



$$\boxed{\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}}$$

Often we use this 2x2 matrix as nothing interesting may be happening in y and z

$$\begin{bmatrix} ct' \\ x' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma \\ -\beta\gamma & \gamma \end{bmatrix} \begin{bmatrix} ct \\ x \end{bmatrix}$$

$$\beta \equiv \frac{v}{c} \qquad \gamma \equiv \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \beta^2}}$$

4-momentum

- Similar to space-time, **energy and momentum** are **intrinsically connected**
  - Represent with 4-component vector called **4-momentum**
    - Classical momentum is $\vec{p} = m\vec{v}$, while relativistic is $\vec{p} = m\gamma\vec{v}$

Important

$$\begin{bmatrix} p'_0 \\ p'_1 \\ p'_2 \\ p'_3 \end{bmatrix} = \begin{bmatrix} E'/c \\ p'_x \\ p'_y \\ p'_z \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E/c \\ p_x \\ p_y \\ p_z \end{bmatrix}$$

  - Energy and momentum ($p^2 = p_x^2 + p_y^2 + p_z^2$) of a particle of mass m are related as

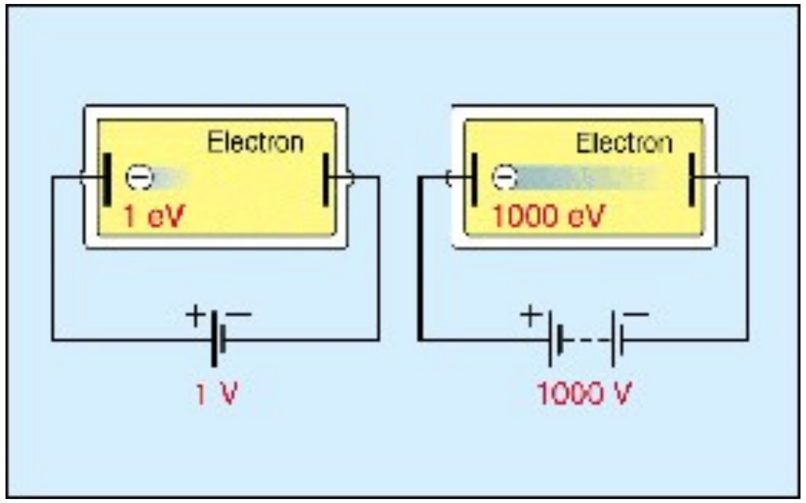
$$E^2 = p^2c^2 + m^2c^4 \quad \Rightarrow \quad p = \sqrt{E^2/c^2 - m^2c^2} \quad \Rightarrow \quad m = \sqrt{E^2/c^4 - p^2/c^2}$$

$$\boxed{p^\nu = \begin{bmatrix} m\gamma c \\ m\gamma\vec{v} \end{bmatrix}_\nu = \begin{bmatrix} \frac{E}{c} \\ \vec{p} \end{bmatrix}_\nu = \begin{bmatrix} \sqrt{p^2 + m^2c^2} \\ \vec{p} \end{bmatrix}_\nu}$$

Total 4-momentum is **always conserved**

Units in particle physics

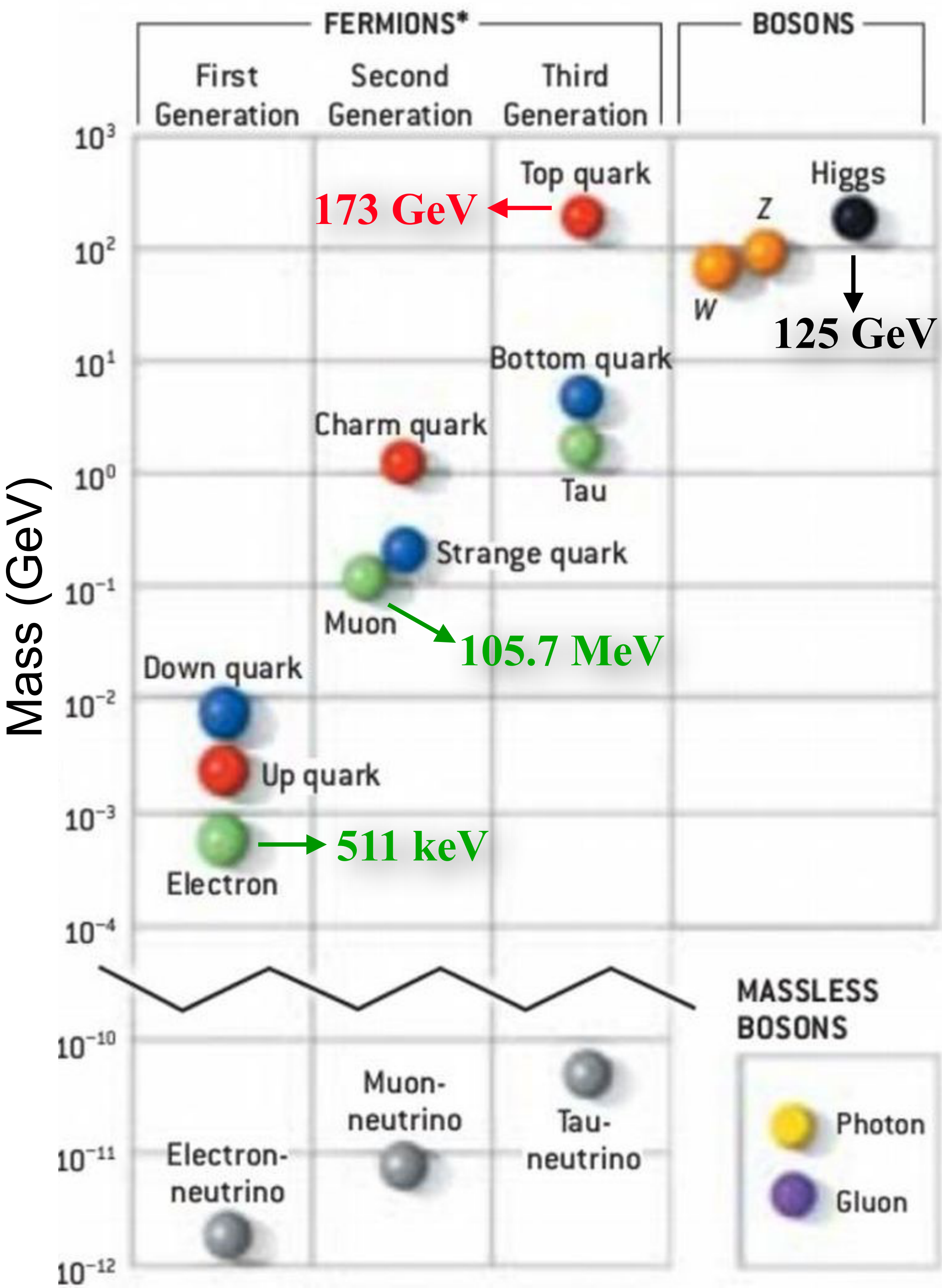
- Typically use ***electronvolts*** **(eV)** to **measure energy**
  - ➡ Energy of an electron accelerated by a 1 V potential
  - ➡ Very useful in the original experiments
  - ➡ 1 eV = 1.602×10^{-19} J



- Use **eV/c** for **momentum**
- Use **eV/c²** for **mass**
- What is the energy of an **electron** ($\mathbf{m_e}$ **= 511 keV/c²**) that has a **momentum of 1 MeV/c**?

$$E_e = \sqrt{p_e^2c^2 + m_e^2c^4} = \sqrt{(1\ \mathrm{MeV}/c)^2c^2 + \left(0.511\ \mathrm{MeV}/\mathrm{c}^2\right)^2c^4} = 1.12\ \mathrm{MeV}$$

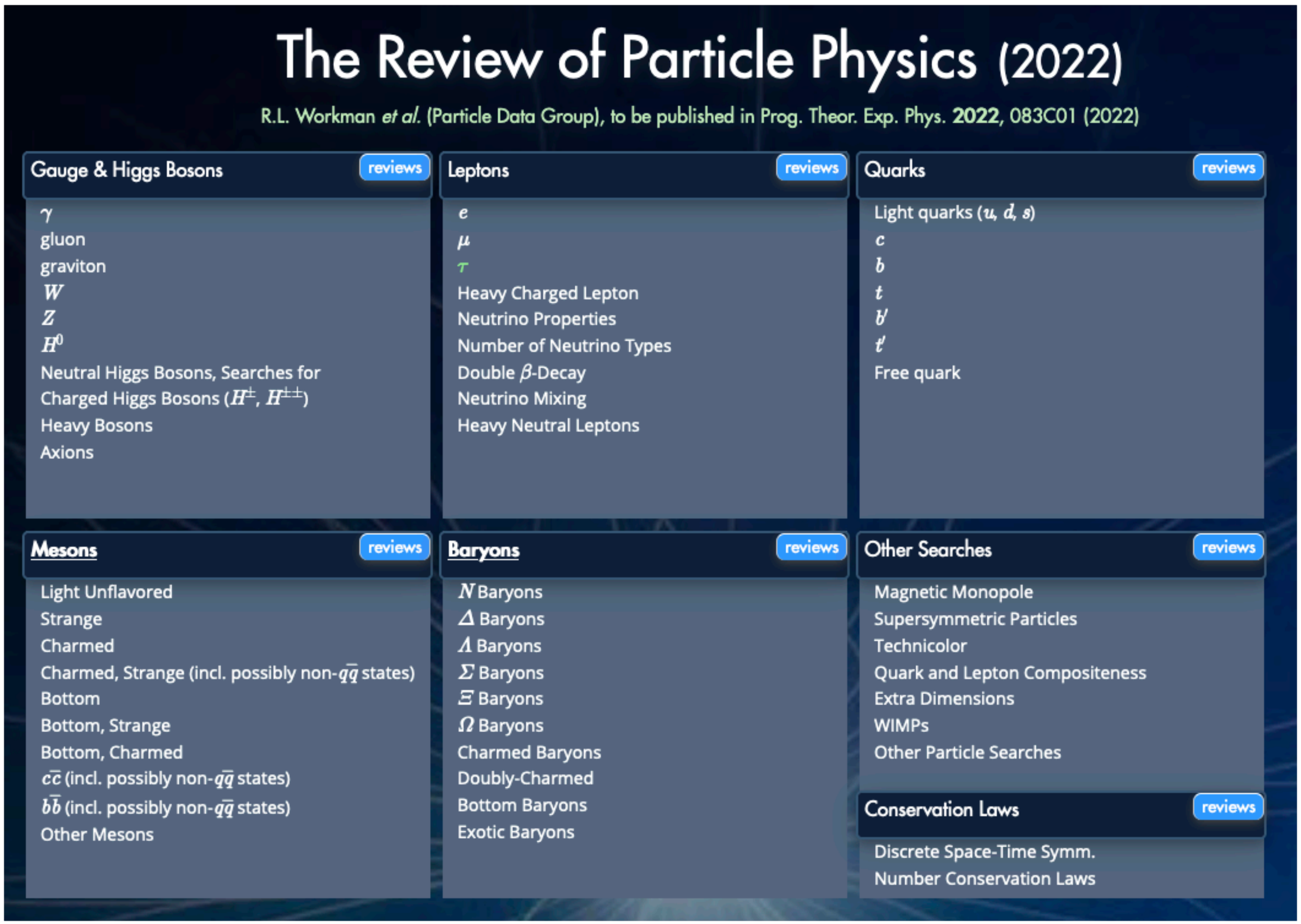
- Very often, we just set **c = 1**, so ***energy, mass,*** *and* ***momentum*** *are* ***measured in eV***



- Elementary particles masses cover a large range
  - Photon/gluon are massless
  - Neutrinos ~ meV
  - 1st generation fermions ~1 MeV
  - 2nd generation fermions ~ 0.1 - 1 GeV
  - 3rd generation fermions ~ 1 - 173 GeV
  - W, Z bosons ~ 90 GeV
  - Higgs boson ~ 125 GeV
- Masses of non-elementary particles heavily determined by binding energy
  - eg, m(u) = 2.3 MeV, m(d) = 4.8 MeV
    - **Mass of proton (uud) is 938 MeV**

PDG (Particle Data Group)

- Find all particle properties at https://pdglive.lbl.gov/Viewer.action



Important

Particle decays

∼ A particle α decays into two other particles λ and ω: **α → λ ω**

General conservation of 4-momentum

$$\begin{bmatrix} \sqrt{p_\alpha^2 + m_\alpha^2 c^2} \\ p_{\alpha,x} \\ p_{\alpha,y} \\ p_{\alpha,z} \end{bmatrix} = \begin{bmatrix} \sqrt{p_\lambda^2 + m_\lambda^2 c^2} \\ p_{\lambda,x} \\ p_{\lambda,y} \\ p_{\lambda,z} \end{bmatrix} + \begin{bmatrix} \sqrt{p_\omega^2 + m_\omega^2 c^2} \\ p_{\omega,x} \\ p_{\omega,y} \\ p_{\omega,z} \end{bmatrix}$$

Conservation of 4-momentum in two-body decay

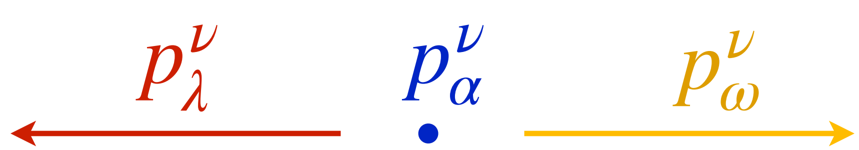
$$\begin{bmatrix} m_\alpha c \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{p_\lambda^2 + m_\lambda^2 c^2} \\ p_\lambda \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \sqrt{p_\omega^2 + m_\omega^2 c^2} \\ p_\omega \\ 0 \\ 0 \end{bmatrix}$$

$$p_\alpha = \sqrt{p_{\alpha,x}^2 + p_{\alpha,y}^2 + p_{\alpha,z}^2}$$

$$p_\lambda = \sqrt{p_{\lambda,x}^2 + p_{\lambda,y}^2 + p_{\lambda,z}^2}$$

$$p_\omega = \sqrt{p_{\omega,x}^2 + p_{\omega,y}^2 + p_{\omega,z}^2}$$

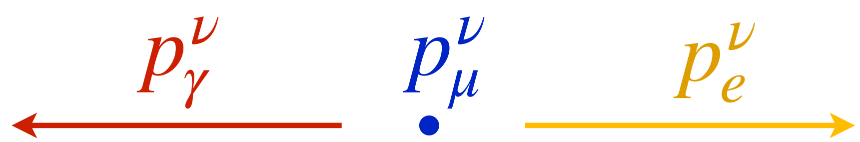
	Degrees of freedom				Equations
	α	**λ**	**ω**	**Total**	(constraints)
Original	4	4	4	**12**	**4**
Masses	3	3	3	**9**	**4**
α at rest	0	3	3	**6**	**4**
Symmetry	0	1	1	**2**	**2**



Cannot know λ and ω direction (isotropic decay), but we know that they will **both travel along the same line** in **opposite directions** by **conservation of momentum**
→ **Choose x axis along the direction of the decay**

Particle decay

- A muon **μ⁻** is a particle very similar to an electron **e⁻** but with a higher mass $\mathbf{m_\mu > m_e}$. What is the **energy** of the (**massless**) photon γ emitted in the decay $\mu^- \rightarrow e^- + \gamma$ assuming the **muon is initially at rest**?



Conservation of 4-momentum

$$\begin{bmatrix} \sqrt{p_\mu^2 + m_\mu^2 c^2} \\ p_\mu \end{bmatrix} = \begin{bmatrix} \sqrt{p_e^2 + m_e^2 c^2} \\ p_e \end{bmatrix} + \begin{bmatrix} \sqrt{p_\gamma^2 + m_\gamma^2 c^2} \\ p_\gamma \end{bmatrix}$$

Cannot know γ and e⁻ direction (isotropic decay), but we know that they will **both travel along the same line** in **opposite directions** by **conservation of momentum**

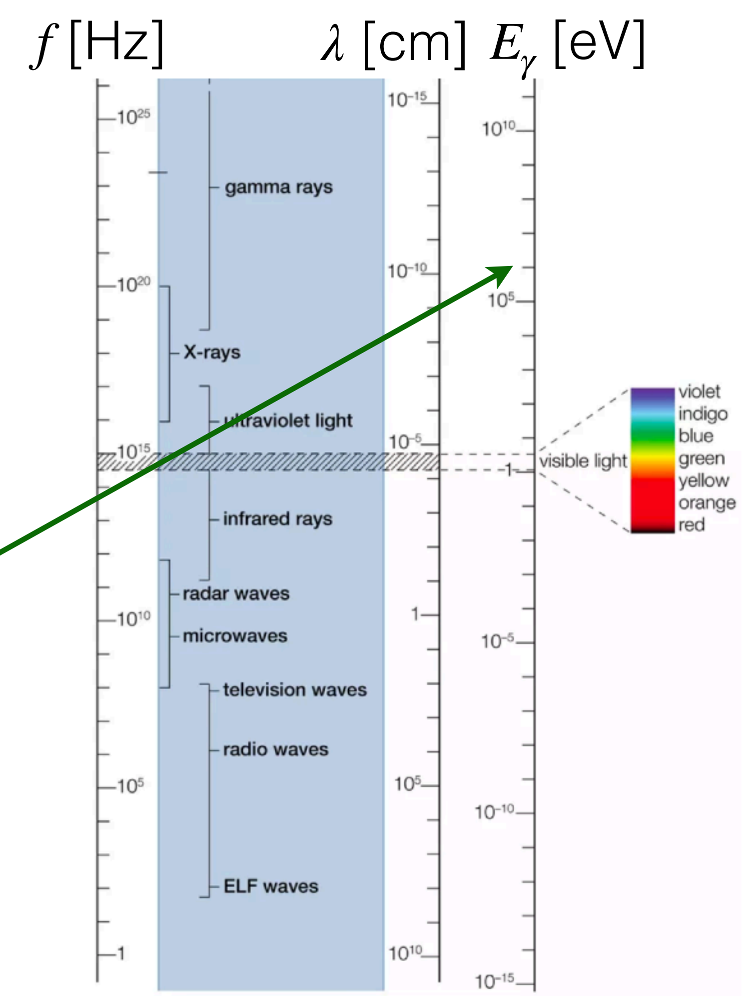
Since the muon is at rest, $\mathbf{p_\mu = 0}$, the photon is massless, $\mathbf{m_\gamma = 0}$

$$\begin{bmatrix} m_\mu c \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{p_e^2 + m_e^2 c^2} \\ p_e \end{bmatrix} + \begin{bmatrix} |p_\gamma| \\ p_\gamma \end{bmatrix} \Rightarrow \begin{array}{c} \sqrt{p_e^2 + m_e^2 c^2} = m_\mu c - |p_\gamma| \\ 0 = p_e + p_\gamma \end{array}$$

Solve for positive $\mathbf{p_\gamma}$

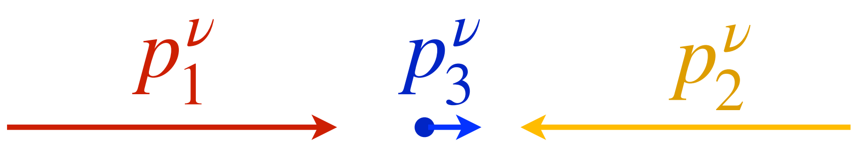
$$p_\gamma^2 + m_e^2 c^2 = m_\mu^2 c^2 - 2 m_\mu c p_\gamma + p_\gamma^2 \Rightarrow p_\gamma = \frac{m_\mu^2 c - m_e^2 c}{2 m_\mu}$$

$$E_\gamma = p_\gamma c = \frac{m_\mu^2 c^2 - m_e^2 c^2}{2 m_\mu} = 52.83 \text{ MeV}$$



Particle collisions

- Two particles of mass **m_1** and **m_2** collide each carrying momentum **p_1** and **p_2** what is the **mass and momentum of the particle they produce**?



Conservation of 4-momentum

$$\begin{bmatrix}\sqrt{p_1^2+m_1^2c^2}\\ p_1\end{bmatrix}+\begin{bmatrix}\sqrt{p_2^2+m_2^2c^2}\\ p_2\end{bmatrix}=\begin{bmatrix}\sqrt{p_3^2+m_3^2c^2}\\ p_3\end{bmatrix}$$

$$p_3=p_2+p_1 \quad \Rightarrow \quad \boxed{m_3=\sqrt{\left(\sqrt{p_1^2/c^2+m_1^2}+\sqrt{p_2^2/c^2+m_2^2}\right)^2-\left(p_1+p_2\right)^2/c^2}}$$

For instance, at the **LHC** we collide **two protons** (mass ~ 1 GeV/c^2) of energy **7 TeV each**

$$\left|p_1\right|=\left|p_2\right|=\sqrt{E^2/c^2-m_p^2c^2}\approx E/c=7\ \mathrm{TeV/c}$$

$$p_3=p_1+p_2=\left(7\ \mathrm{TeV/c}\right)+\left(-7\ \mathrm{TeV/c}\right)=0$$

$$m_3=\sqrt{(7\ \mathrm{TeV/c^2})^2+(1\ \mathrm{GeV/c^2})^2}+\sqrt{(-7\ \mathrm{TeV/c^2})^2+(1\ \mathrm{GeV/c^2})^2}\approx 14\ \mathrm{TeV/c^2}$$

Because protons are not elementary, the highest mass that can be produced is smaller than this

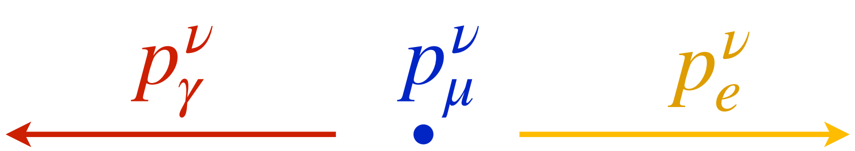
Dynamics summary

- **Relationship between γ(β), m, E, and p in Relativity**

$$\boxed{p^\nu = \begin{bmatrix} m\gamma c \\ m\gamma\vec{v} \end{bmatrix} = \begin{bmatrix} \frac{E}{c} \\ \vec{p} \end{bmatrix} = \begin{bmatrix} \sqrt{p^2 + m^2c^2} \\ \vec{p} \end{bmatrix} \quad \text{with} \quad \vec{p} = m\gamma\vec{v}}$$

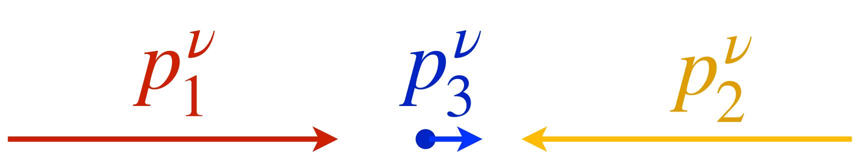
For particles with m = 0, the first expression is not useful, but the other two are still valid

- **Particle decay**



$$\begin{bmatrix} m_\mu c \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{p_e^2 + m_e^2c^2} \\ p_e \end{bmatrix} + \begin{bmatrix} \sqrt{p_\gamma^2 + m_\gamma^2c^2} \\ p_\gamma \end{bmatrix}$$

- **Particles collide to create a third particle**



$$\begin{bmatrix} \sqrt{p_1^2 + m_1^2c^2} \\ p_1 \end{bmatrix} + \begin{bmatrix} \sqrt{p_2^2 + m_2^2c^2} \\ p_2 \end{bmatrix} = \begin{bmatrix} \sqrt{p_3^2 + m_3^2c^2} \\ p_3 \end{bmatrix}$$

4-momentum practice

- **Relationship between γ(β), m, E, and p in Relativity**

$$p^\nu = \begin{bmatrix} m\gamma c \\ m\gamma \vec{v} \end{bmatrix} = \begin{bmatrix} \frac{E}{c} \\ \vec{p} \end{bmatrix} = \begin{bmatrix} \sqrt{p^2 + m^2c^2} \\ \vec{p} \end{bmatrix} \quad \text{with} \quad \vec{p} = m\gamma\vec{v}$$

- A proton ($m_p = 1$ GeV/c²) has a momentum of 10 GeV/c
  - ➡ What is its energy?

$$E = \sqrt{p^2c^2 + m^2c^4} = \sqrt{(10\text{ GeV})^2 + (1\text{ GeV})^2} = 10.05\text{ GeV}$$

  - ➡ How would you calculate its speed?

$$\gamma = \frac{E}{mc^2} = 10.05 = \frac{1}{\sqrt{1-\beta^2}} \quad \rightarrow \quad \beta = \sqrt{1 - \frac{1}{\gamma^2}} = 0.995$$

- A proton ($m_p = 1$ GeV/c²) has an energy of 7 TeV/c
  - ➡ What is its speed and momentum? $\gamma = 7{,}000 \quad \rightarrow \quad \beta = 0.9999999898$

$$p = \sqrt{E^2/c^2 - m^2c^4} = \sqrt{(7\text{ TeV})^2 + (0.001\text{ TeV})^2} = 7\text{ TeV/c}$$

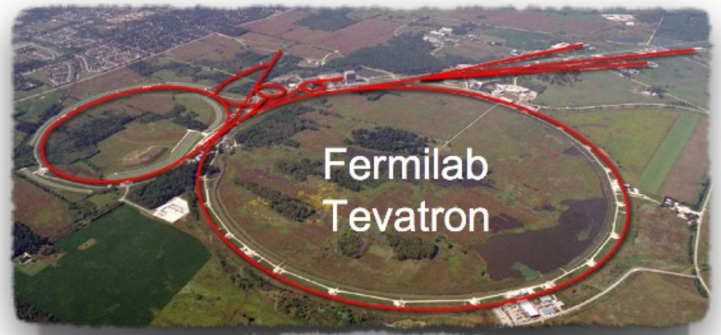
Particle colliders

Particle accelerator types

Type of collision

Fixed target
NA62

vs



Collider
Tevatron

Geometry

Linear collider
Stanford Linear Collider (SLC)

vs

Circular collider
Large Electron-Positron collider (LEP)

Type of particle

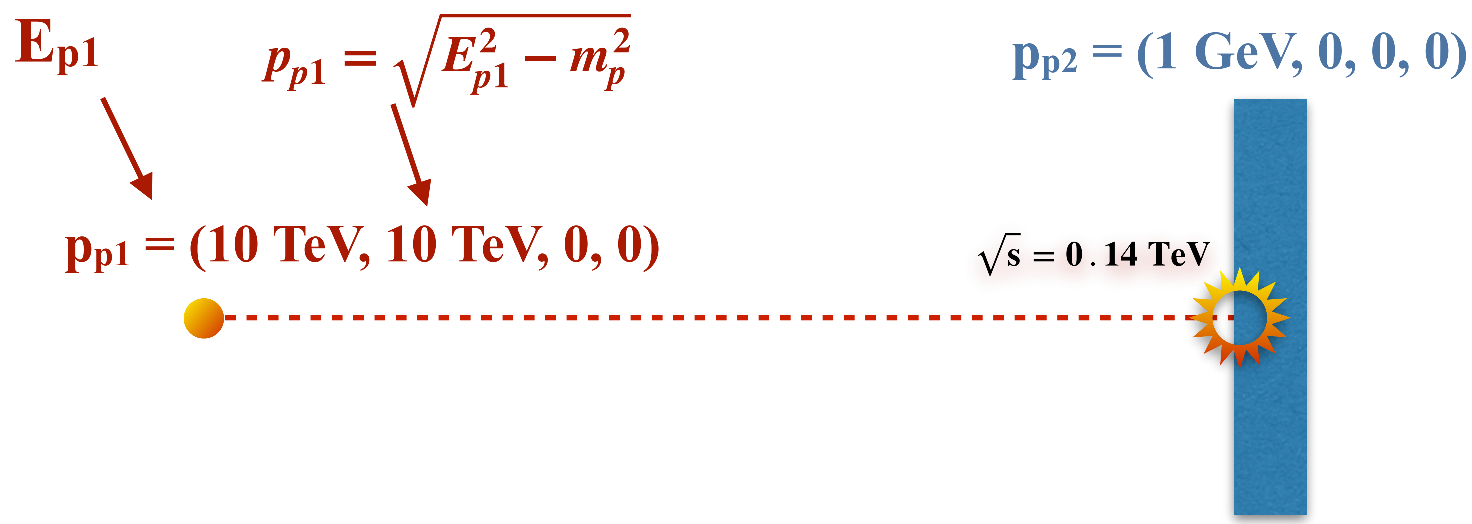
Lepton collider
Positron-Electron Project II (PEP-II)

vs

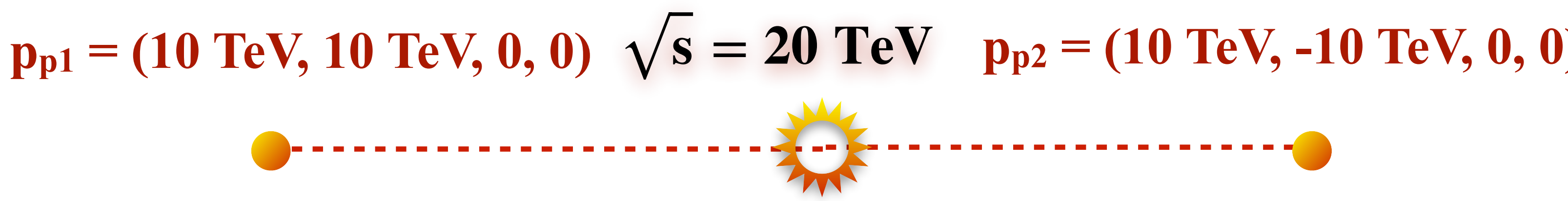
Hadron collider
Large Hadron Collider (LHC)

Fixed target vs Colliders

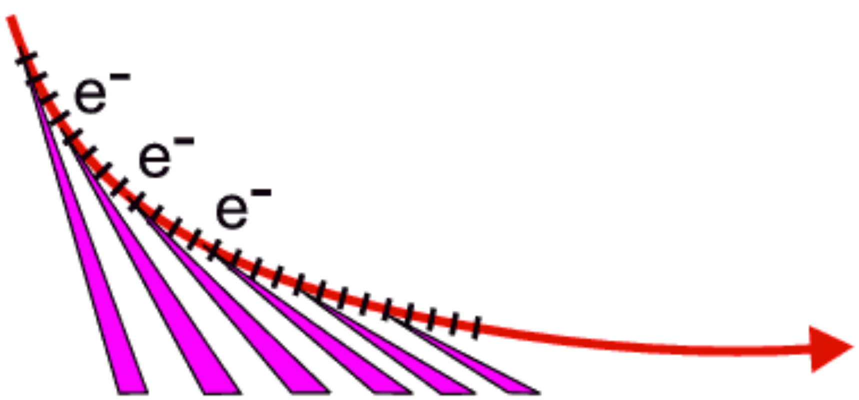
- In **Fixed target experiments** a **beam of high-energy particles** collides against a **large** and **stationary target**
  - ➡ Easy, cheap
  - ➡ Inefficient → difficult to reach high energies



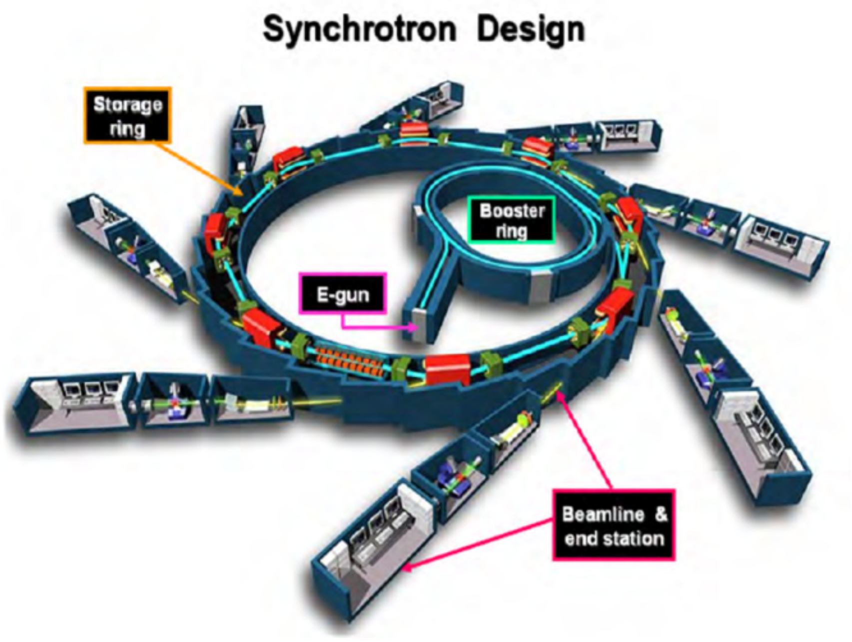
- **Colliders** crash **two narrow beams of particles**
  - ➡ Difficult but efficient



- **Circular** geometry has **key advantages** as particles circle around
  - ➡ Can have **higher energies** as particles are accelerated at each cycle
  - ➡ Can have **higher collision rates** as particle bunches have more opportunities to collide
- However, charged particles emit **synchrotron radiation when changing direction**
  - ➡ **Power loss** grows very **quickly with energy**
  - ➡ Circular geometry **not feasible for light particles** (eg, electrons) for $\sqrt{s} \geq \sim 250$ GeV
    - ✦ Use protons ($m_p \sim 2000 m_e$) for higher energies



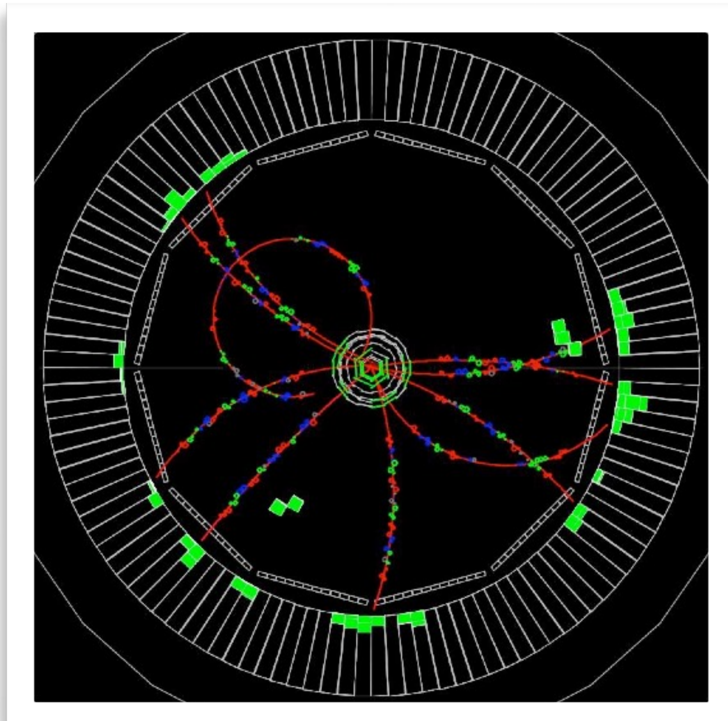
$$P^{\mathrm{loss}}_{\mathrm{sync}} \propto \frac{E^4}{m^4 R^2}$$

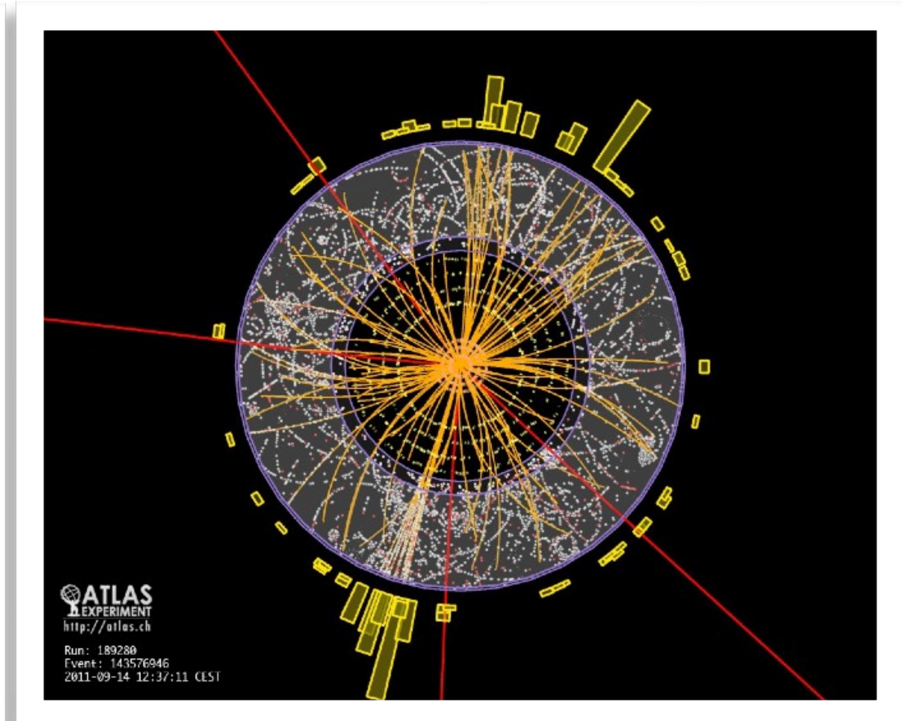


Lepton vs Hadron colliders

- Easier to make **precision measurements in lepton colliders**
  - ➡ **Known collision energy** because leptons are elementary particles
  - ➡ **Cleaner environment**

Clean lepton-lepton collision
BaBar at SLAC PEP-II



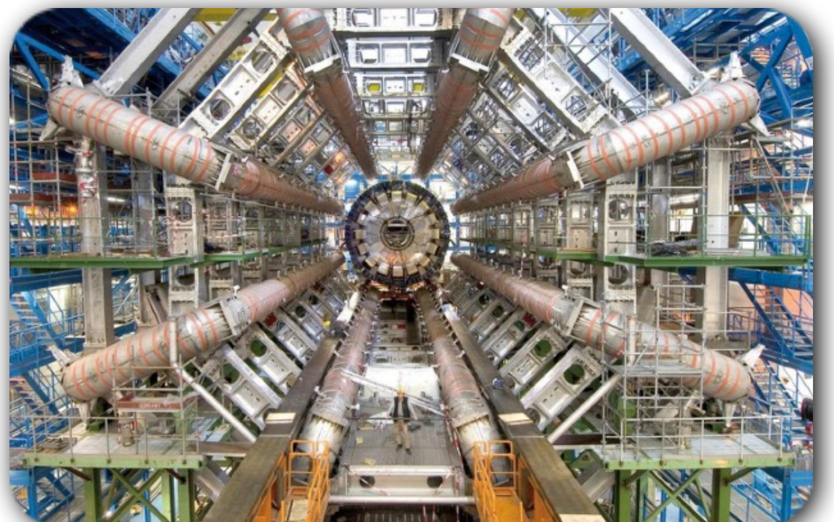


Messy hadron-hadron collision
ATLAS at CERN LHC

- However, **hadron** colliders can achieve **higher energies**
  - ➡ **Higher statistics too** due to higher production *cross sections*

The Large Hadron Collider (LHC)

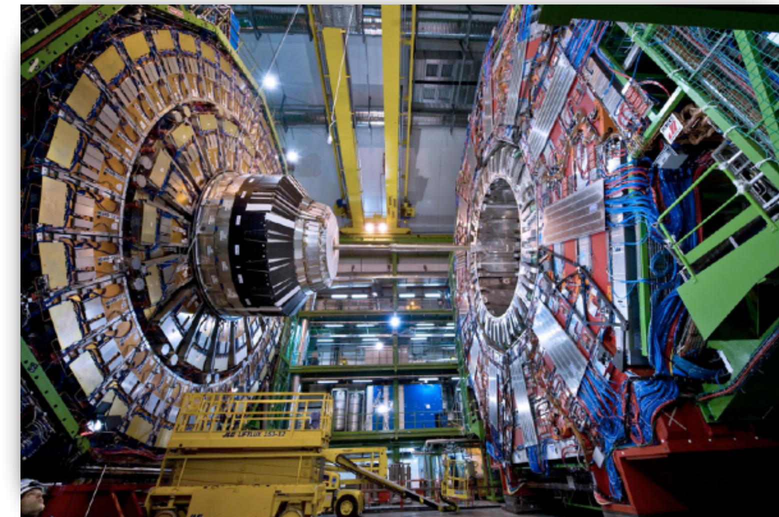
Overview of the LHC experiments



General purpose

Discovered Higgs boson in 2012

Direct searches for new physics



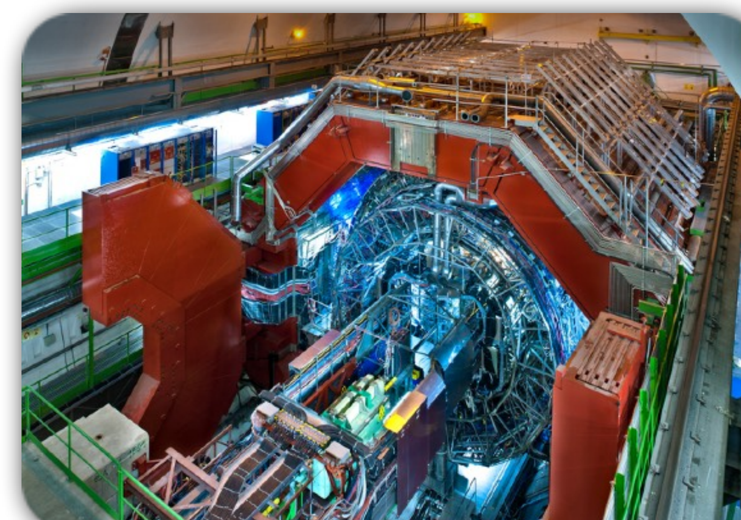
Precision flavor measurements

Covers 4% solid angle (25% of b decays)

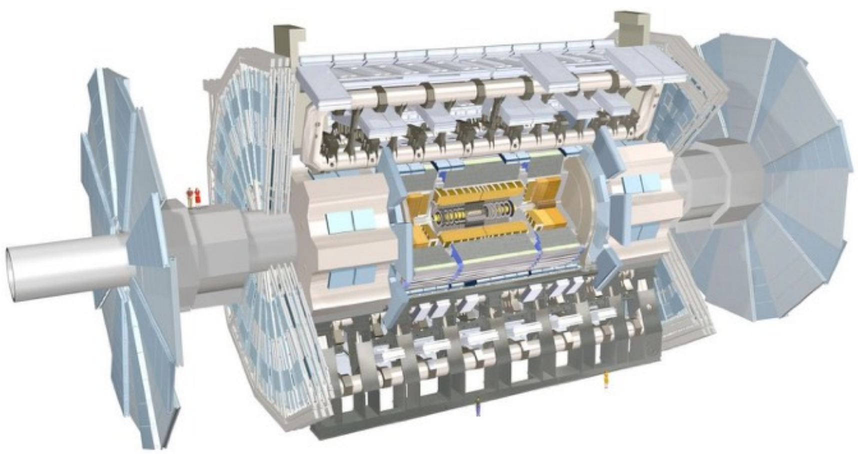
Indirect searches for new physics

Heavy ion measurements

Focus on quark-gluon plasma

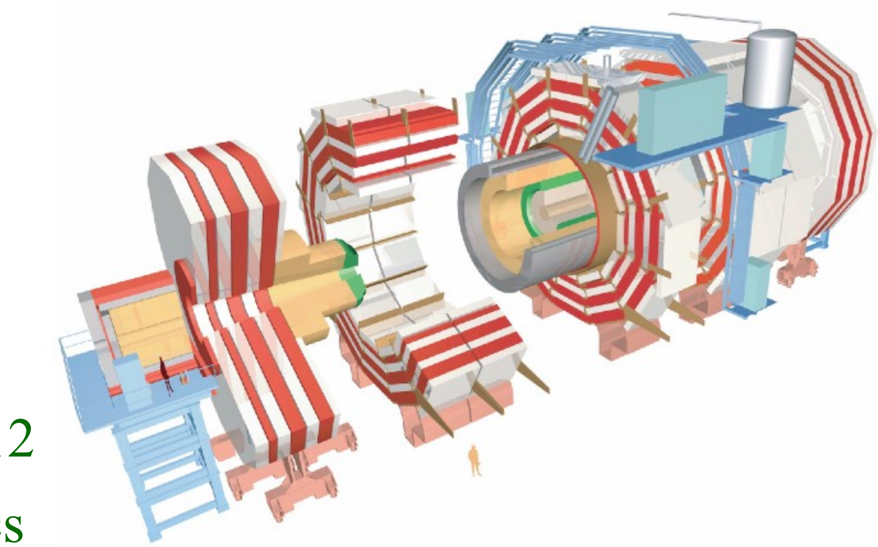


Overview of the LHC experiments



ATLAS EXPERIMENT

CMS



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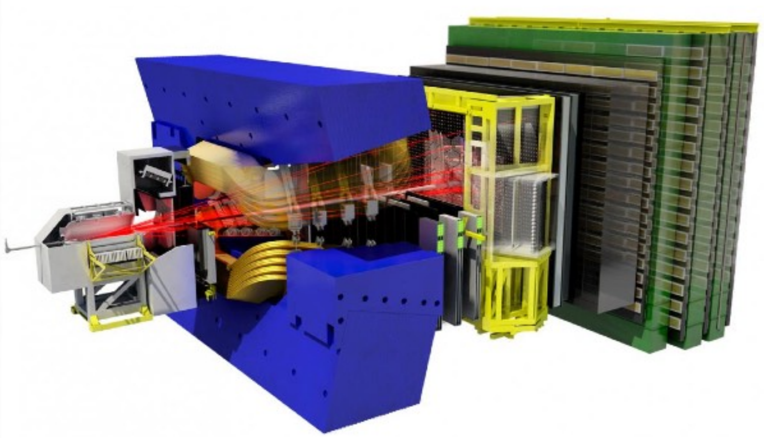


LHCb

Precision flavor measurements

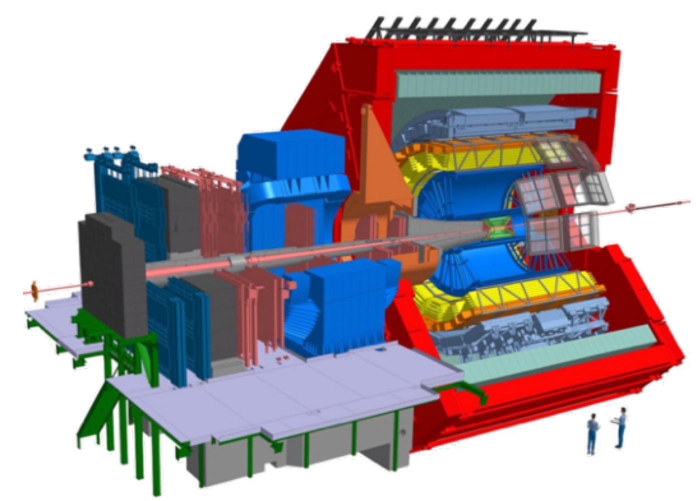
Covers 4% solid angle (25% of b decays)

Indirect searches for new physics

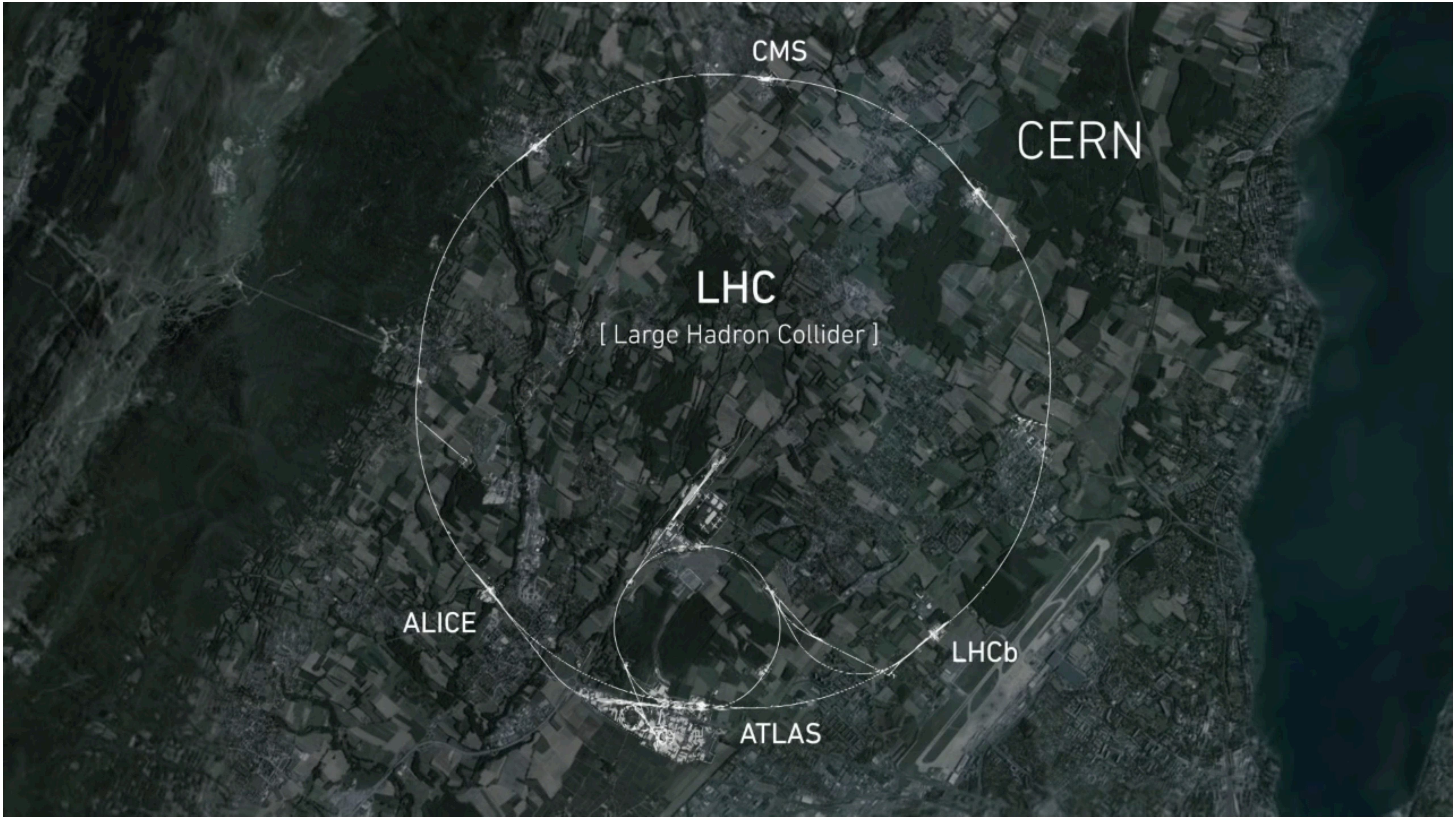
ALICE

Heavy ion measurements

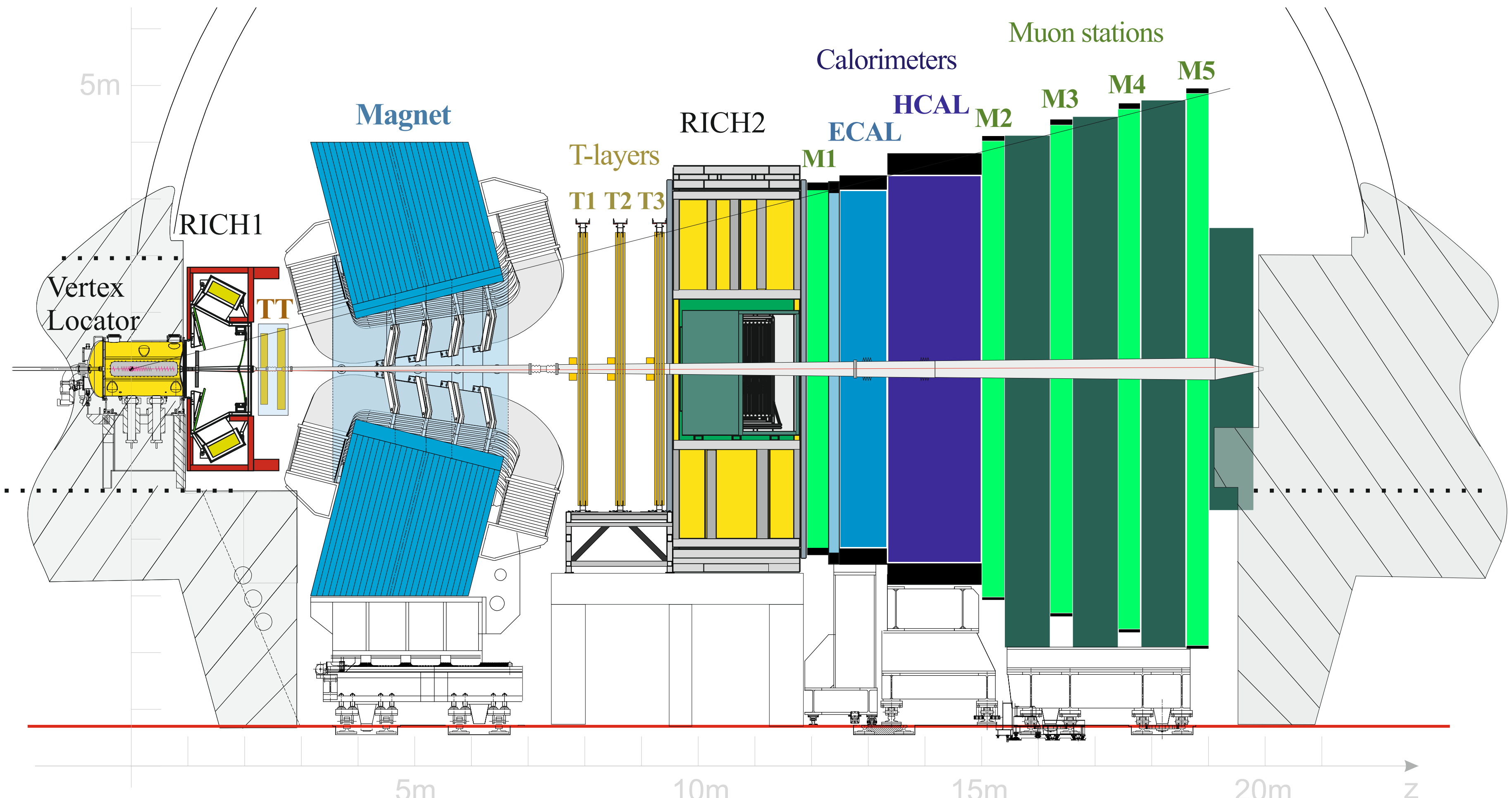
Focus on quark-gluon plasma

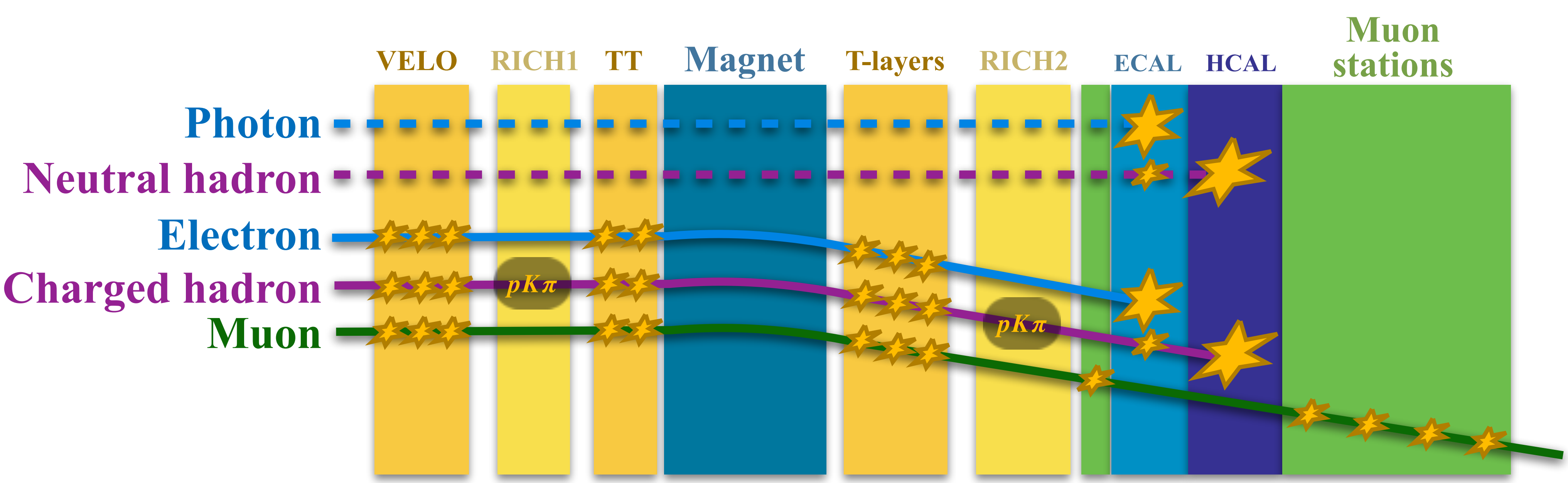


Path of the protons



LHCb subdetectors

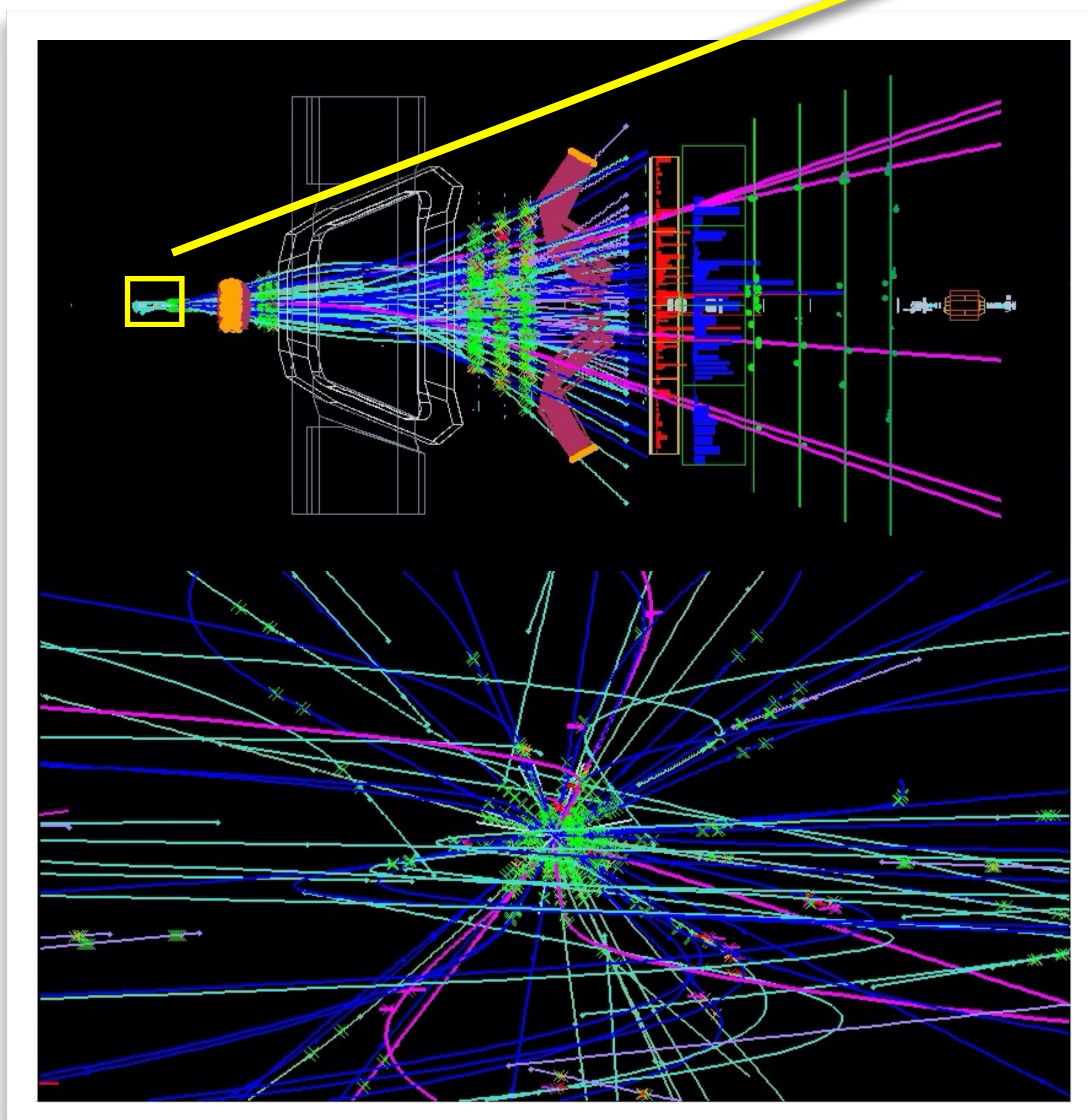




Measure momentum of charged particles from bending of the tracks in magnetic field

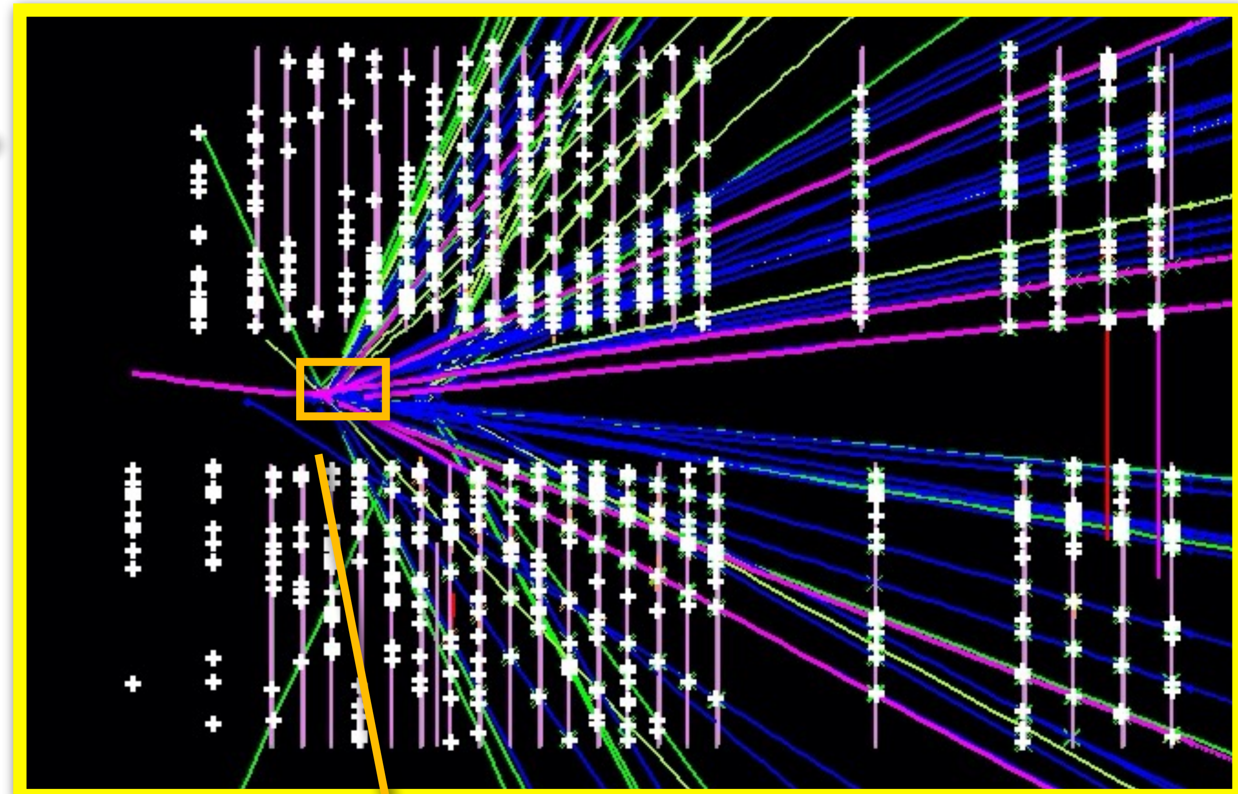
Vertexing is key

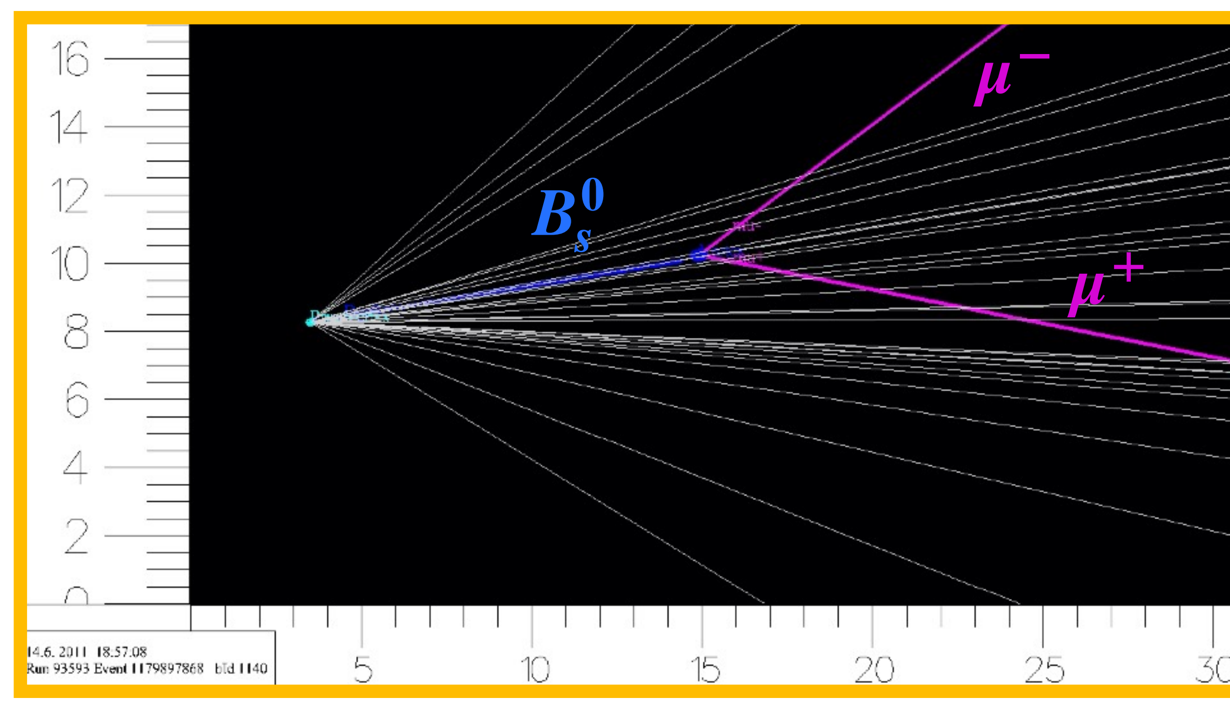
B mesons fly a **few cm**
thanks to LHC boost →
reconstruct decay vertex



$pp \to X_b B_s^0 X$

$B_s^0 \to \mu^+\mu^-$





Invariant mass reconstruction

Important

Find momenta of **two muon candidates**

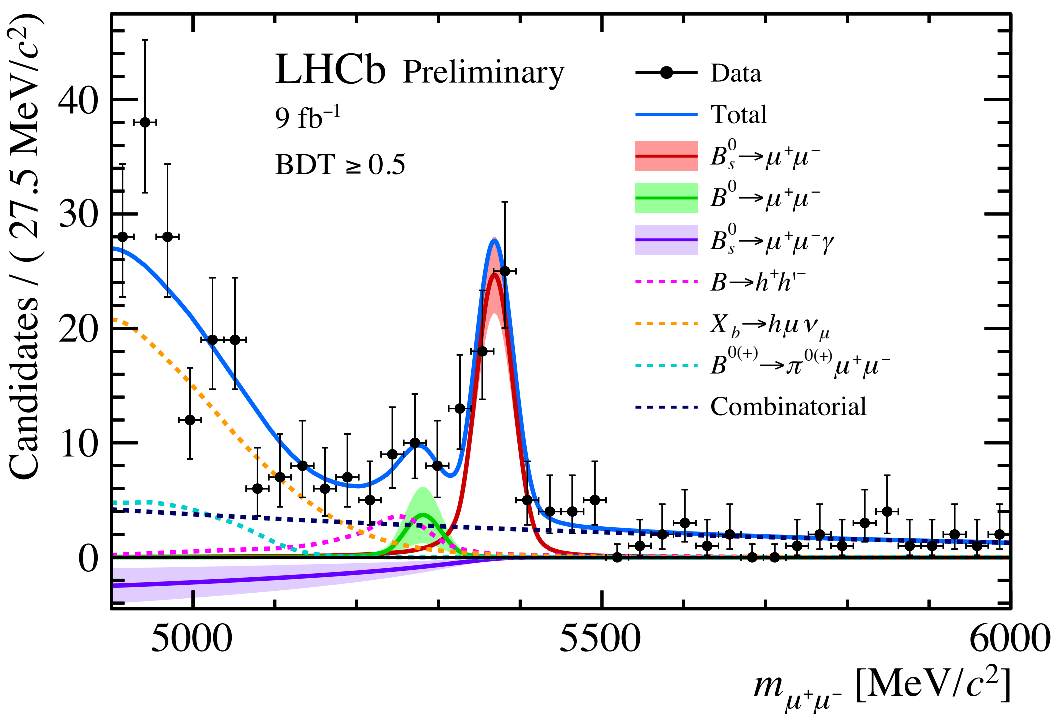
$\overrightarrow{p}^{\mu 1} = (p_x^{\mu 1}, p_y^{\mu 1}, p_z^{\mu 1})$ and $\overrightarrow{p}^{\mu 2} = (p_x^{\mu 2}, p_y^{\mu 2}, p_z^{\mu 2})$

Calculate **invariant mass** $m(\mu^+\mu^-)$ assuming they are muons

($m_\mu = 105.658$ MeV from **PDG**)

$$m(\mu^+\mu^-) = \sqrt{\left(E^{\mu 1} + E^{\mu 2}\right)^2 - \left(\overrightarrow{p}^{\mu 1} + \overrightarrow{p}^{\mu 2}\right)^2} =$$

$$\sqrt{\left(\sqrt{\left(p^{\mu 1}\right)^2 + m_\mu^2} + \sqrt{\left(p^{\mu 2}\right)^2 + m_\mu^2}\right)^2 - \left(p_x^{\mu 1} + p_x^{\mu 2}\right)^2 - \left(p_y^{\mu 1} + p_y^{\mu 2}\right)^2 - \left(p_z^{\mu 1} + p_z^{\mu 2}\right)^2}$$



Signal events coming from $B_s^0 \to \mu^+\mu^-$ **peak** at B_s^0 mass, **background events** have different shapes