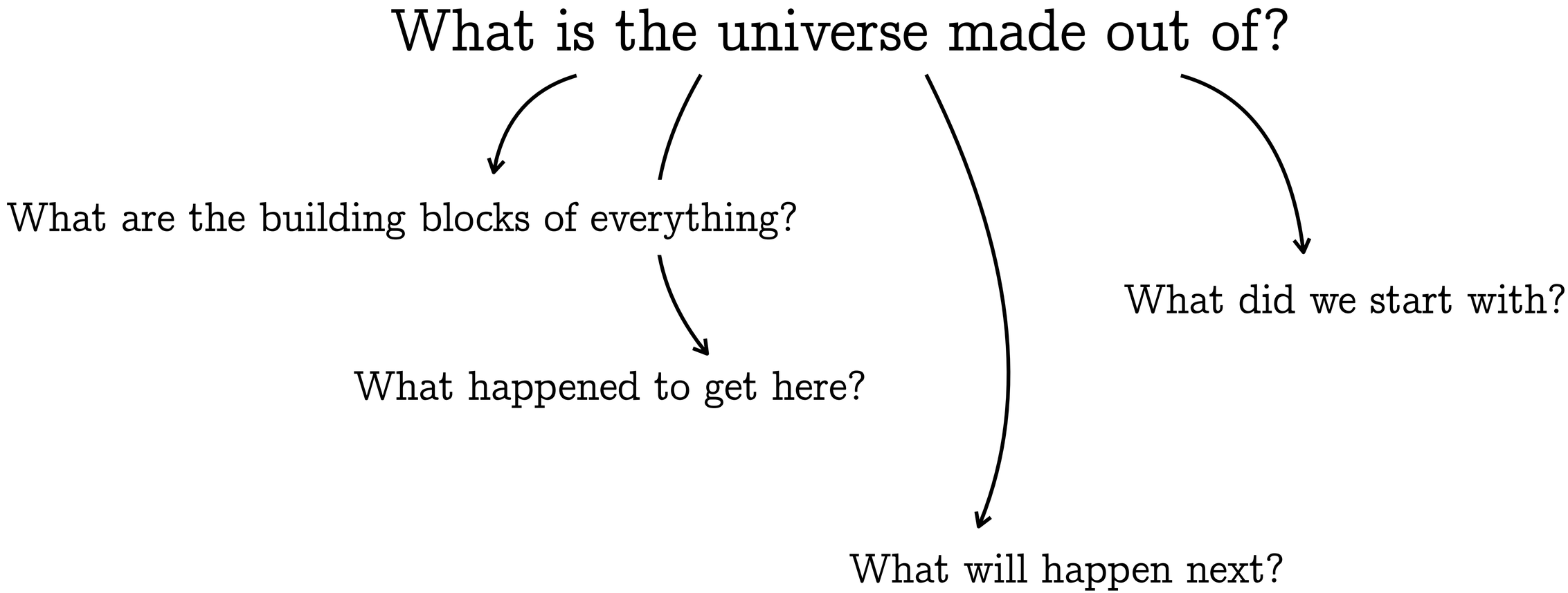
Introduction to Particle Physics

Cari Cesarotti - CERN Fellow

International High School Teacher Program

July 6, 2026

What are we trying to learn?



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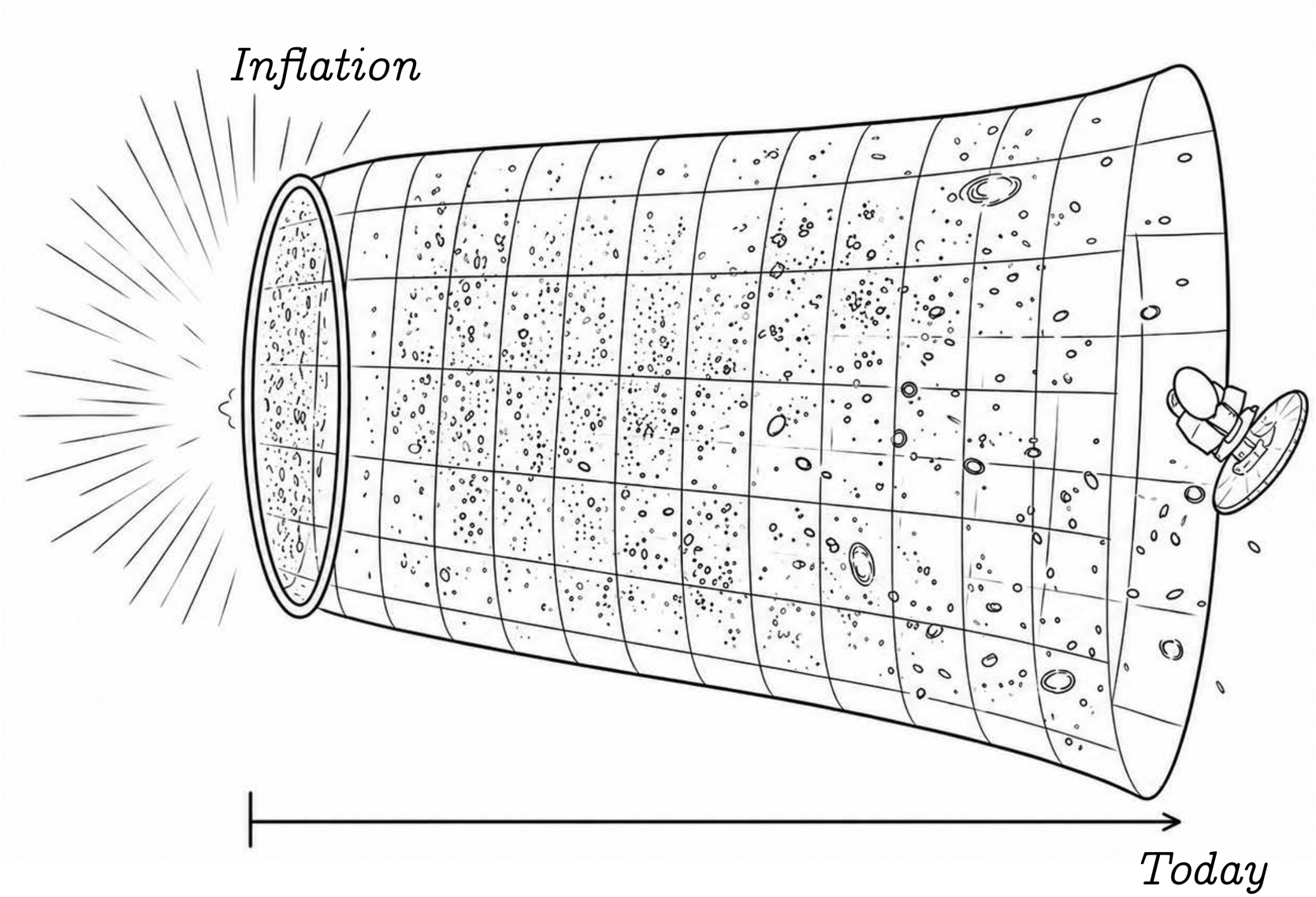

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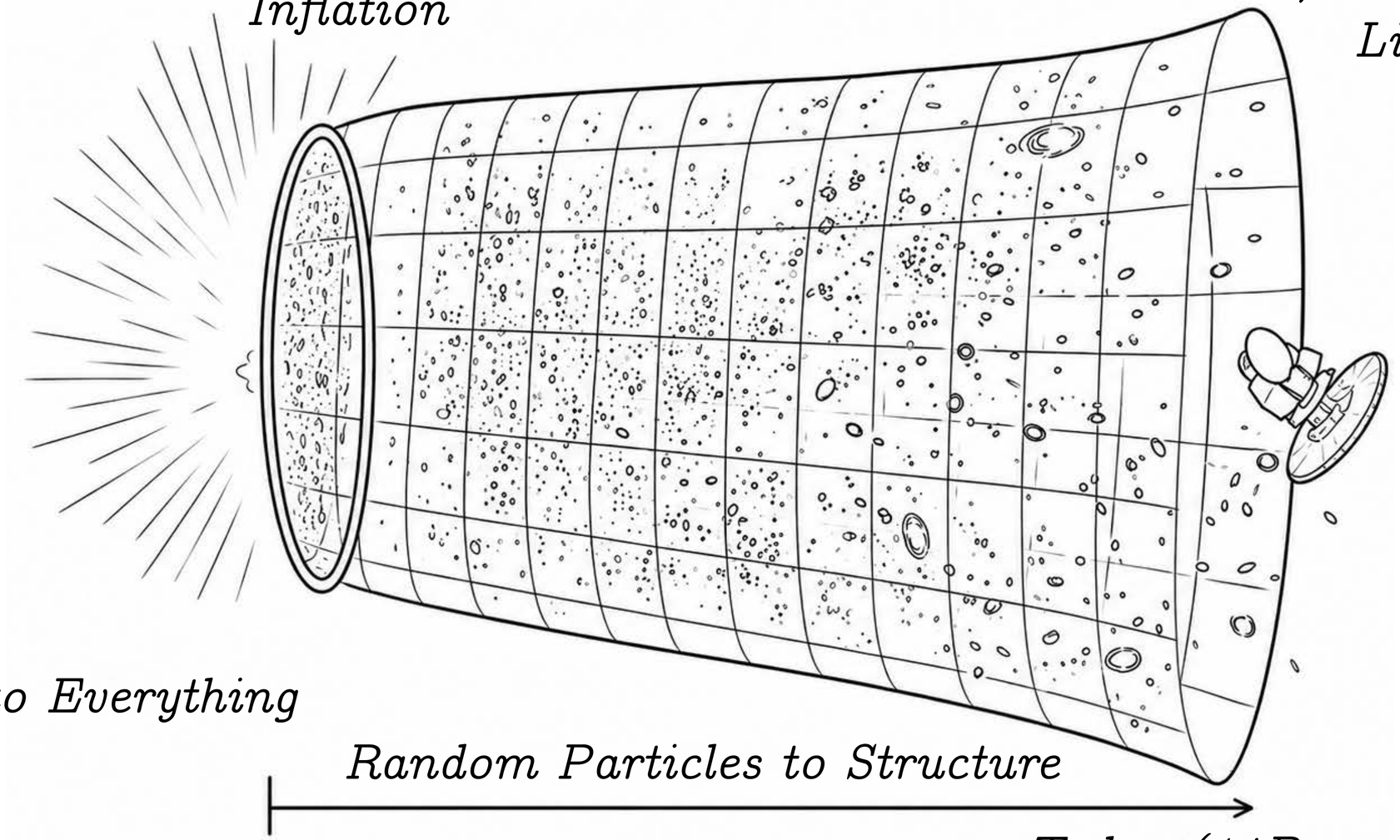

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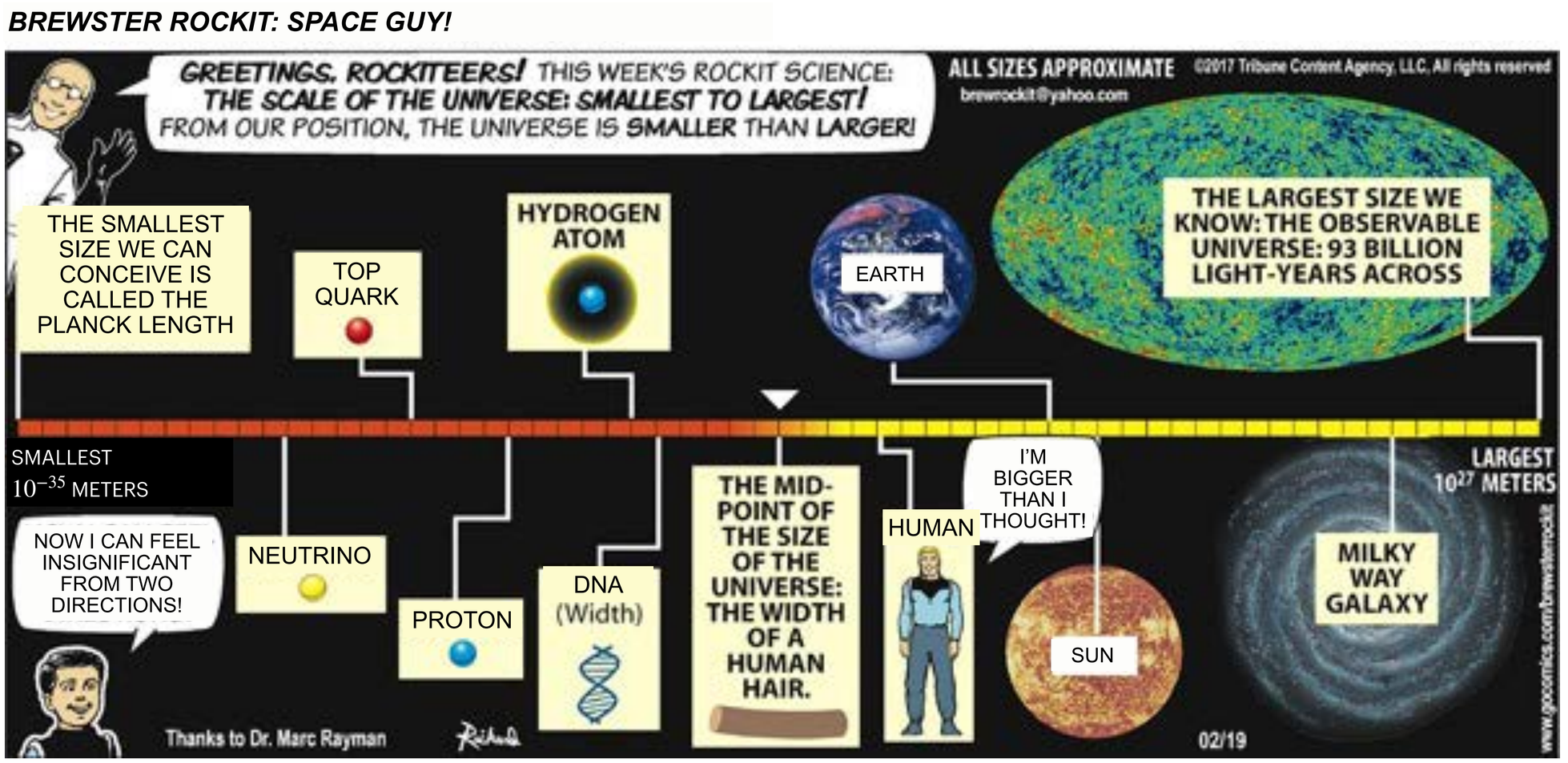

We want to study the small stuff

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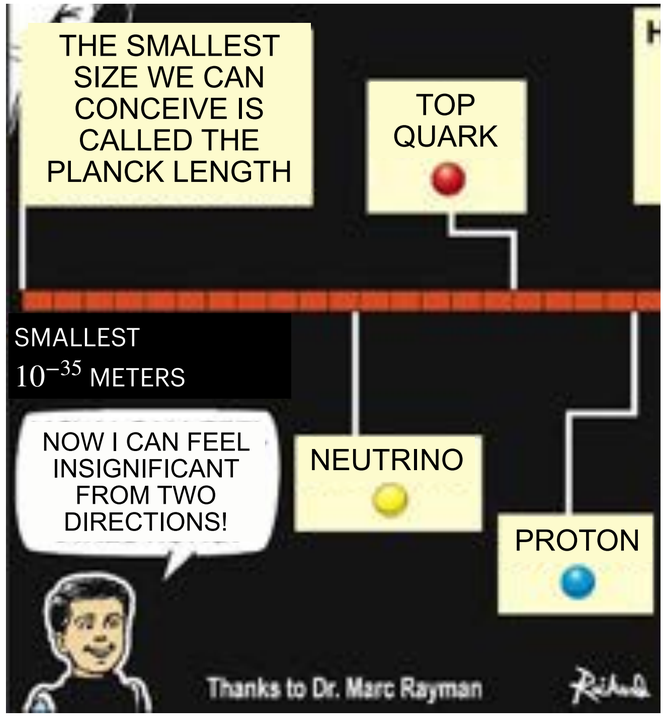
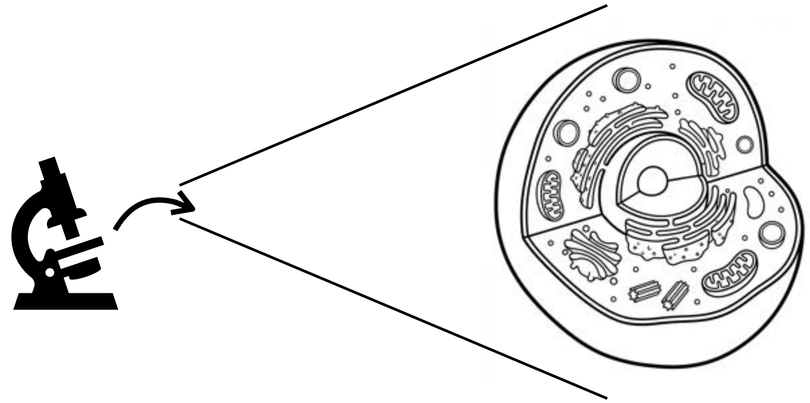
What are we trying to learn?

BREWSTER ROCKIT: SPACE GUY!



To see small, we need to build big



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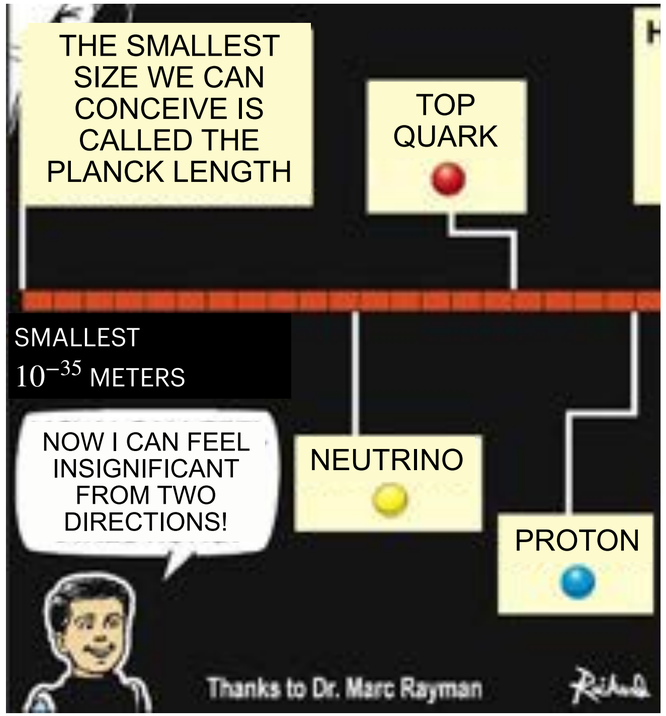

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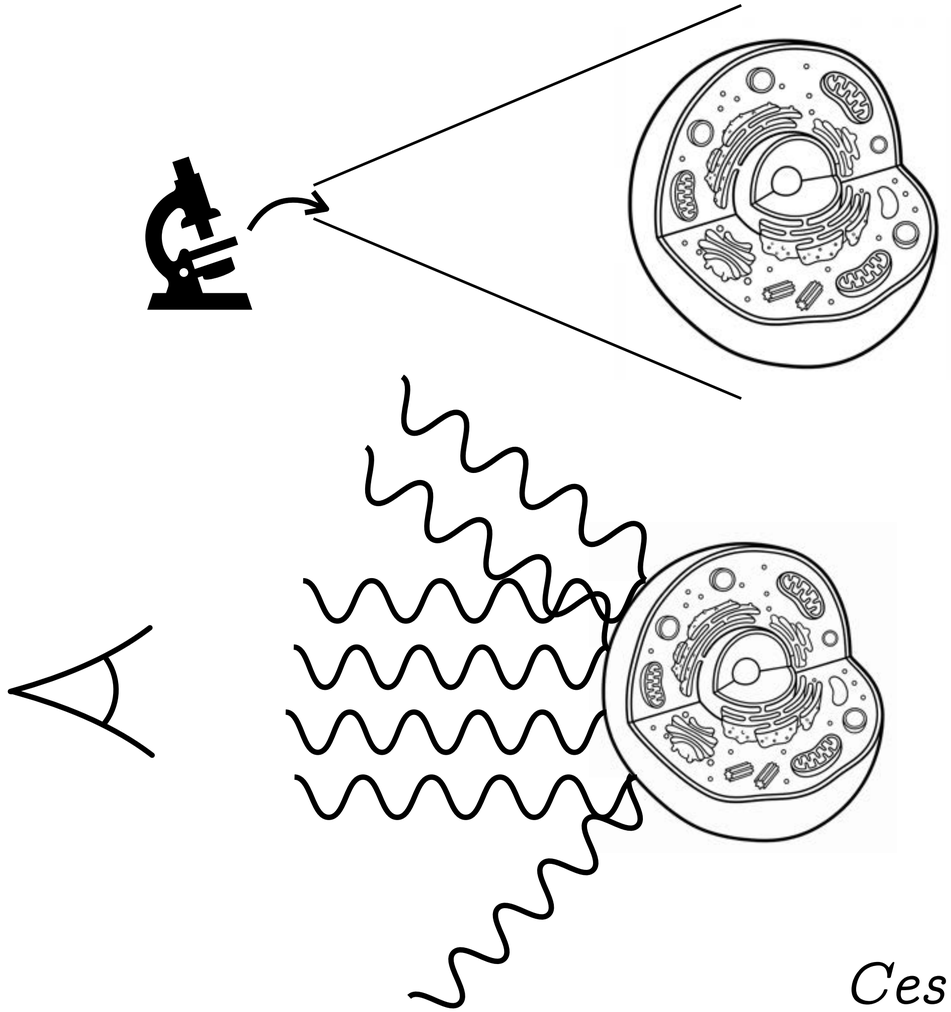

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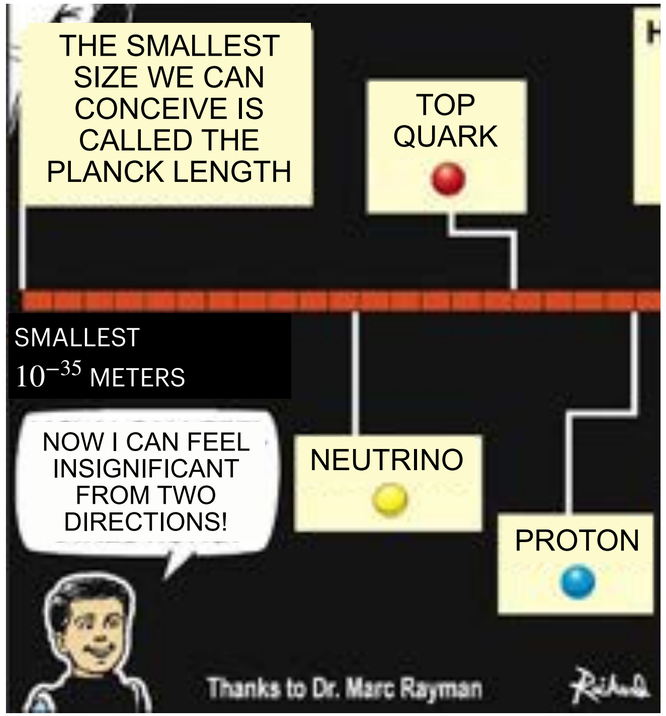

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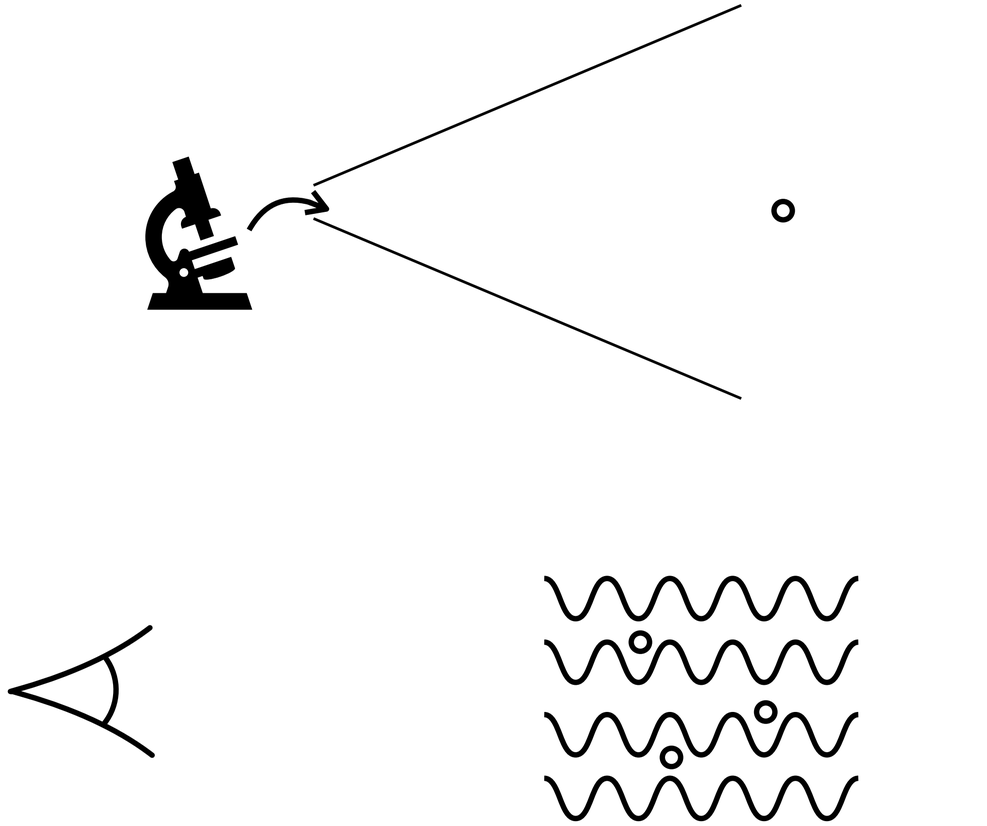

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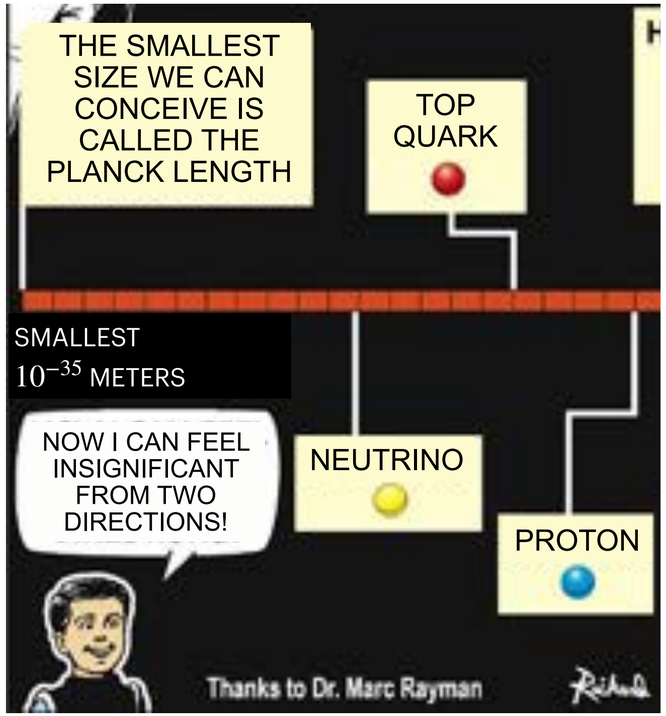

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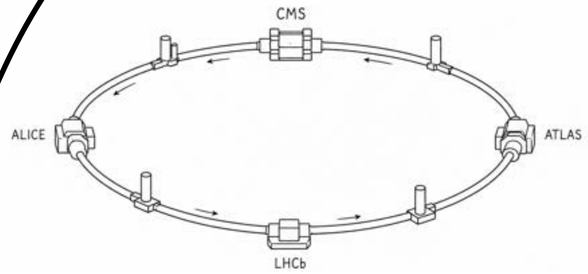
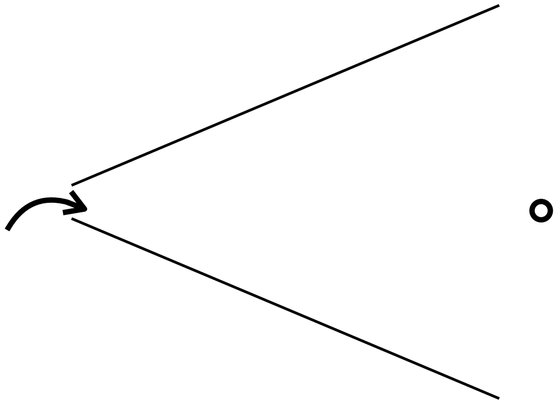
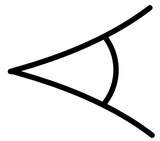
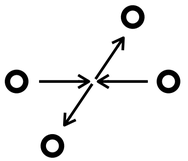




Large Hadron Collider at CERN





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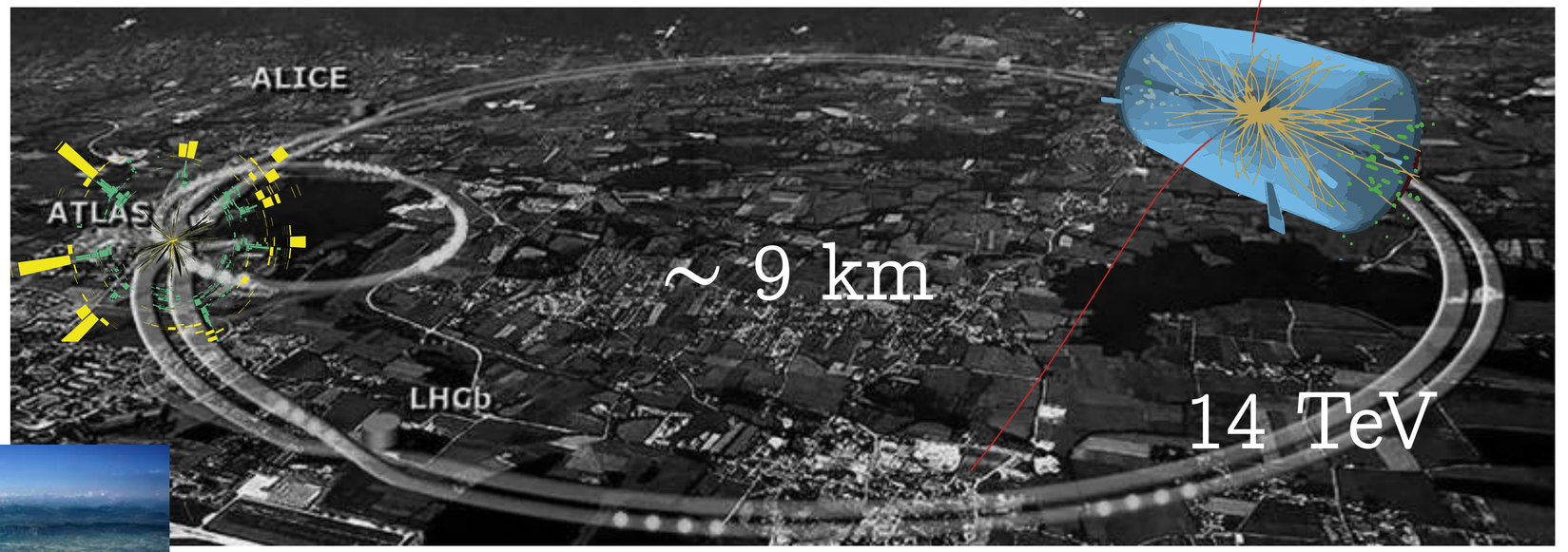
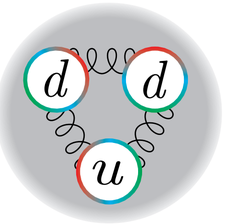
How do we see particles?

Colliders are the observation tools for the very small & energetic





Proton on proton collisions (pp)

Bunches of protons: 10^{11} protons/bunch

2.5×10^7 times per second!

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How do we see particles?

Colliders are the observation tools for the very small & energetic

Conceptual Point 1:

$$E = mc^2$$

Mass is Energy

How do we see particles?

Colliders are the observation tools for the very small & energetic

Conceptual Point 1:

$$E = mc^2$$

Mass is Energy

$$E^2 = m^2c^4 + p^2c^2$$

Mass *and* momentum is Energy

How do we see particles?

Colliders are the observation tools for the very small & energetic

Conceptual Point 2:

Small lengths $\leftrightarrow$ High Energies

$$\lambda = \frac{h}{mc}$$

$$\hbar = 6.58 \times 10^{-16} \text{eV} \cdot \text{s}$$

$$\hbar = \frac{h}{2\pi}$$

$$c = 3 \times 10^{8} \text{ m/s}$$

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Conceptual Point 2:

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$$\hbar = 6.58 \times 10^{-16} \text{eV} \cdot \text{s}$$

$$\hbar = \frac{h}{2\pi}$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$14 \text{ TeV} \sim 10^{-19} \text{ m}$$

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What are particles?

Cartoon of particles is perfect, hard ball

e

But where do these come from?

Particles are *excitations of a field*

Fundamental object *everywhere in space* is **electron field**

Dump energy into field → get e

Example: The ocean is a field

Excitation is a wave

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What particles are there?

We haven't always had colliders to find particles

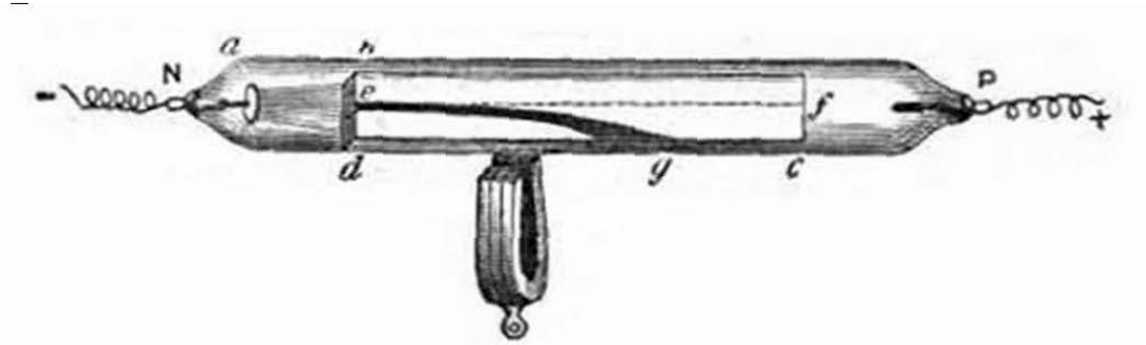
e^-

Electron

Discovery by J.J. Thomson

Cathode Rays deflected by magnet/electric field

Mass-to-charge ratio measured



1897

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Electron

Mass confirmed by Millikin's oil drop experiment

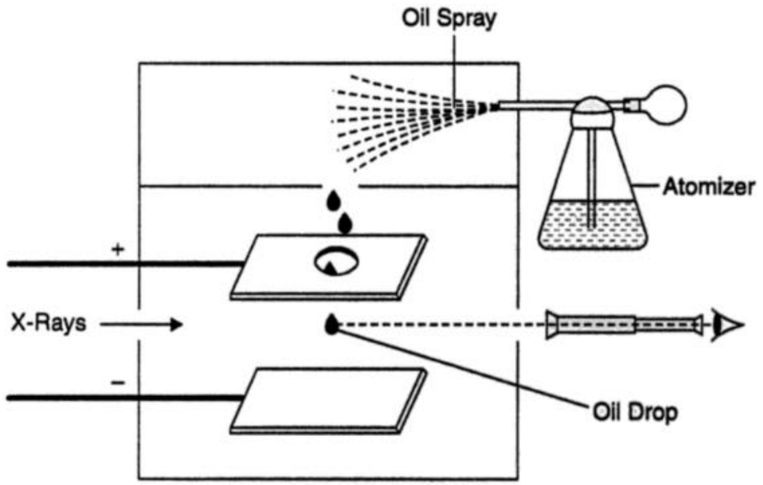

Fig: Millikan's oil drop experiment for the determination of charge on an electron.

1897

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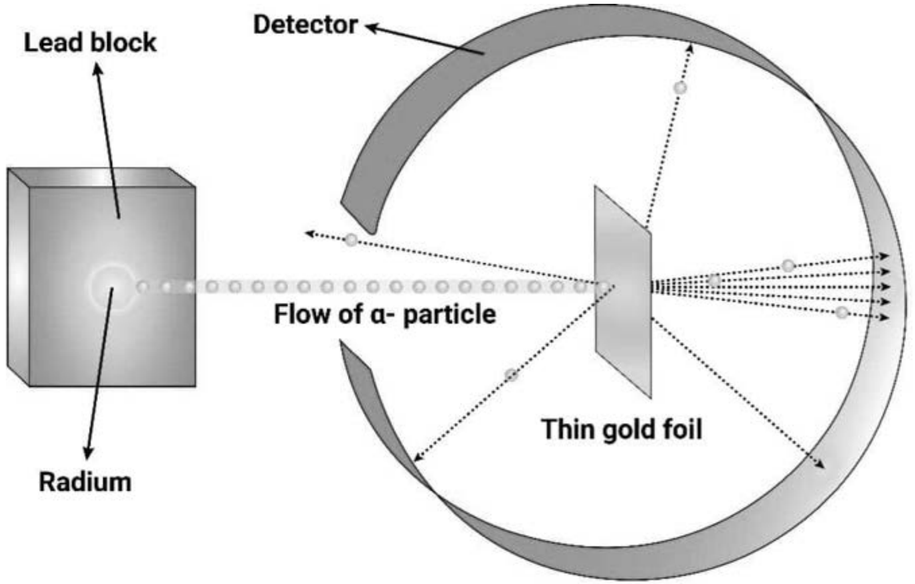
Electron

e^-

N

Nucleus*



Rutherford gold foil / alpha particle

1897

1909

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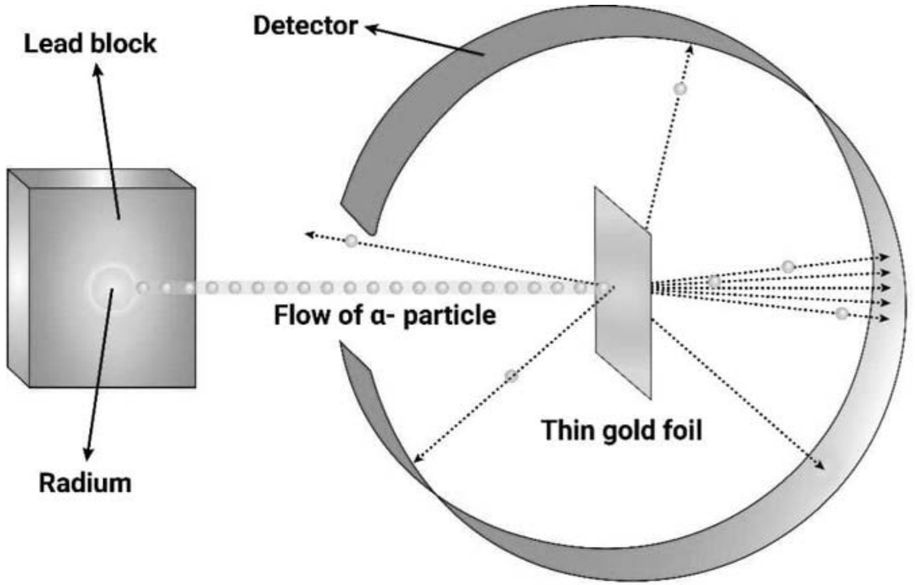
Electron

e^-

Proton

p^+



Rutherford gold foil / alpha particle

1897 1909 1917

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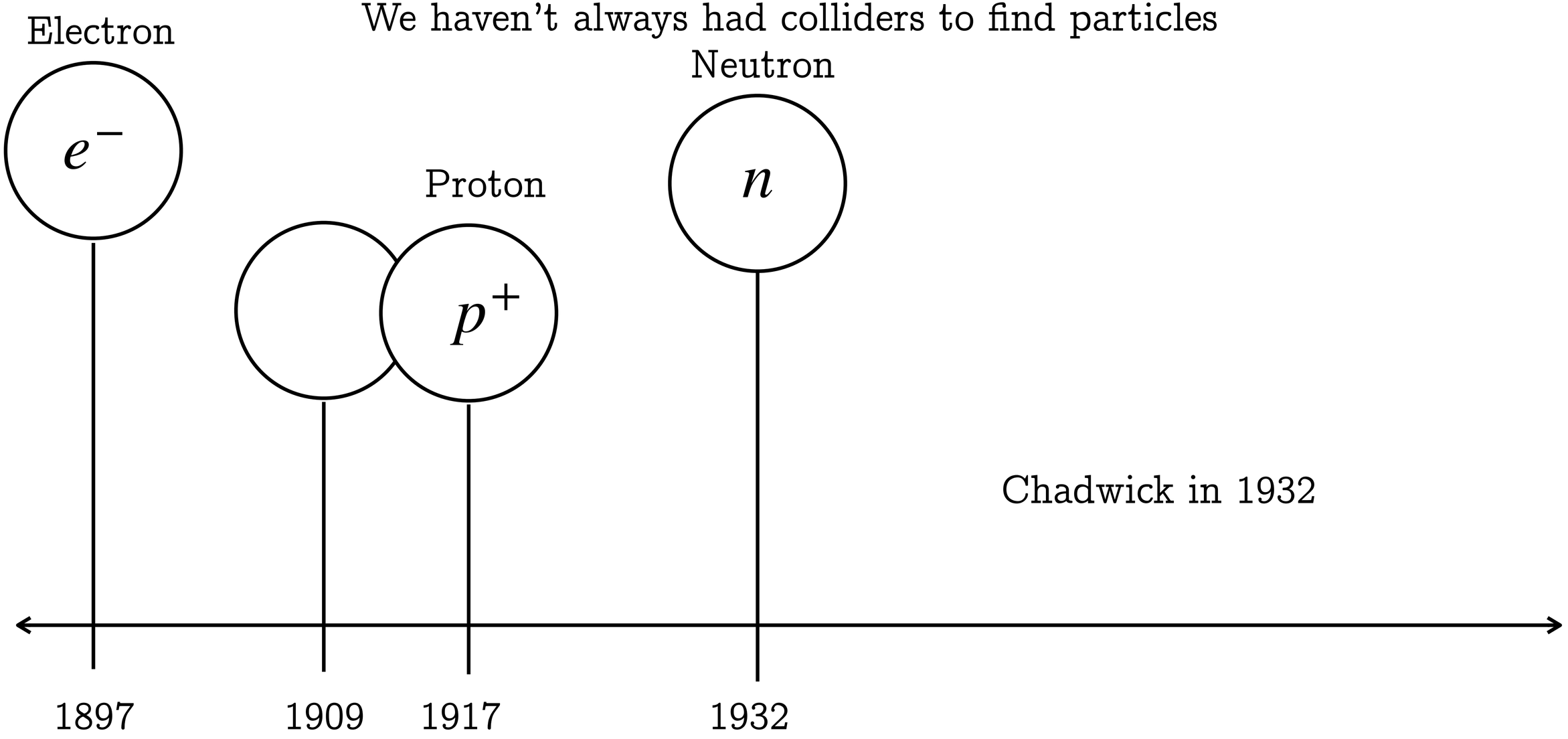

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What particles are there?

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Electron

e^-

Proton

p^+

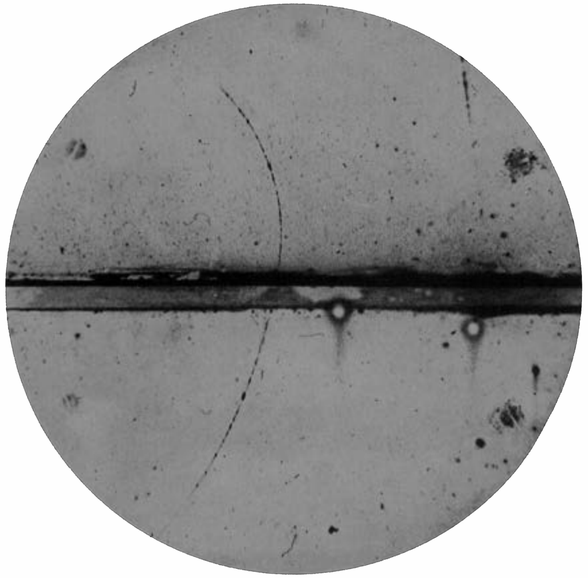
Neutron

n

Positron

e^+

Carl Anderson in cloud chamber



1897 1909 1917 1932

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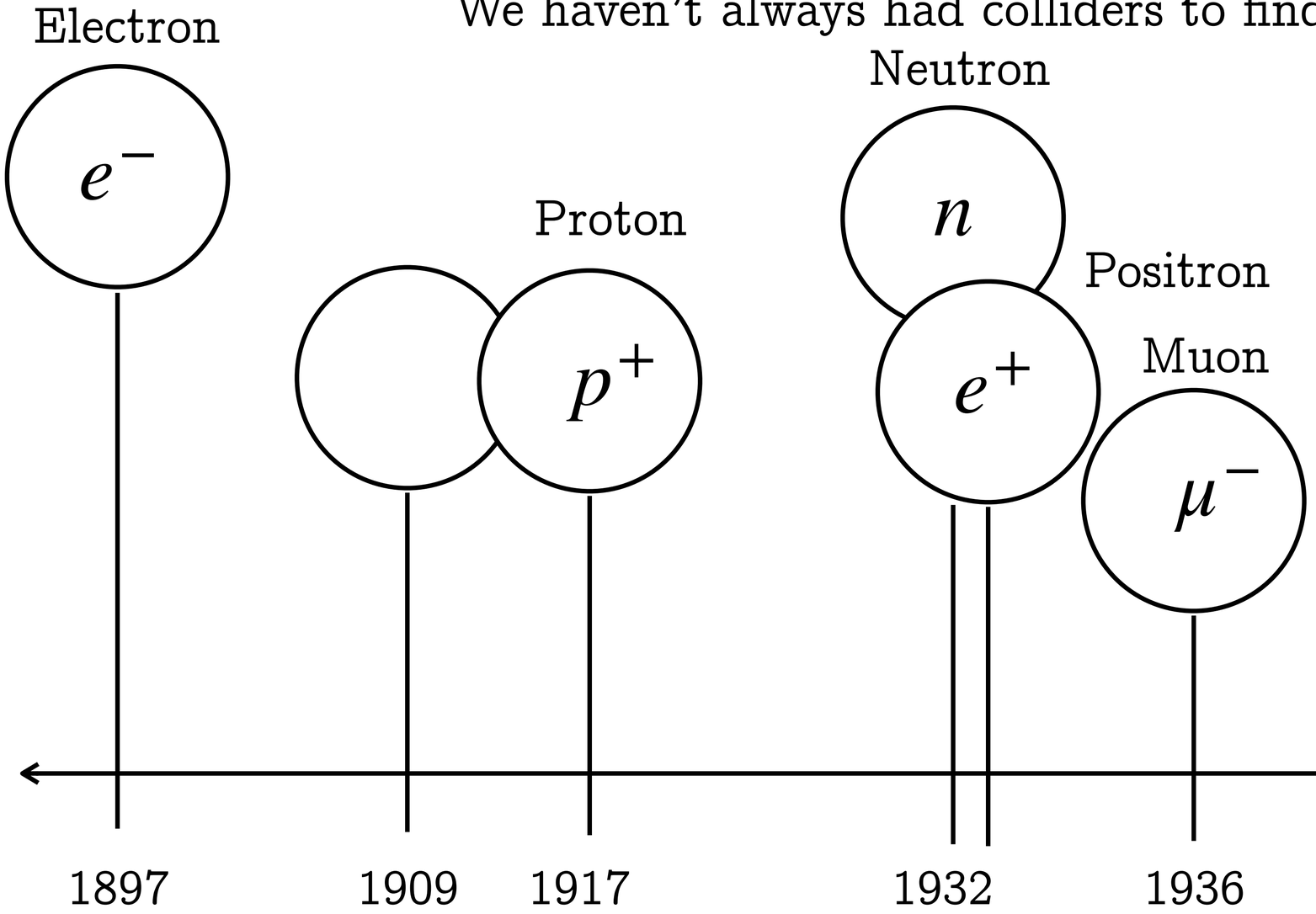
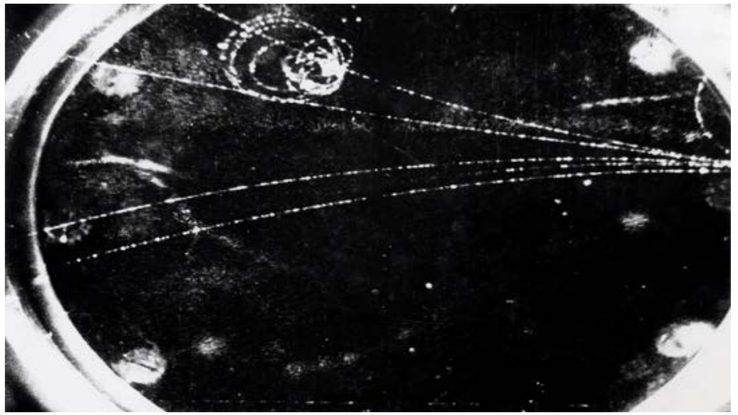


Carl Anderson, again



Cesarotti

What particles are there?

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Electron

e^-

Proton

p^+

Neutron

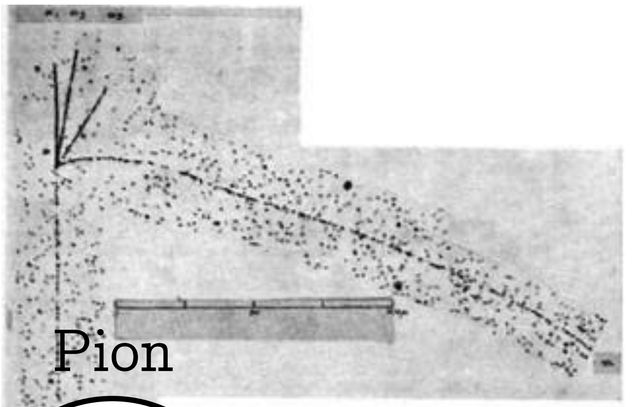
n

Positron

e^+

Muon

μ^-



Pion

π

Era of colliders

...

1897 1909 1917 1932 1936 1947

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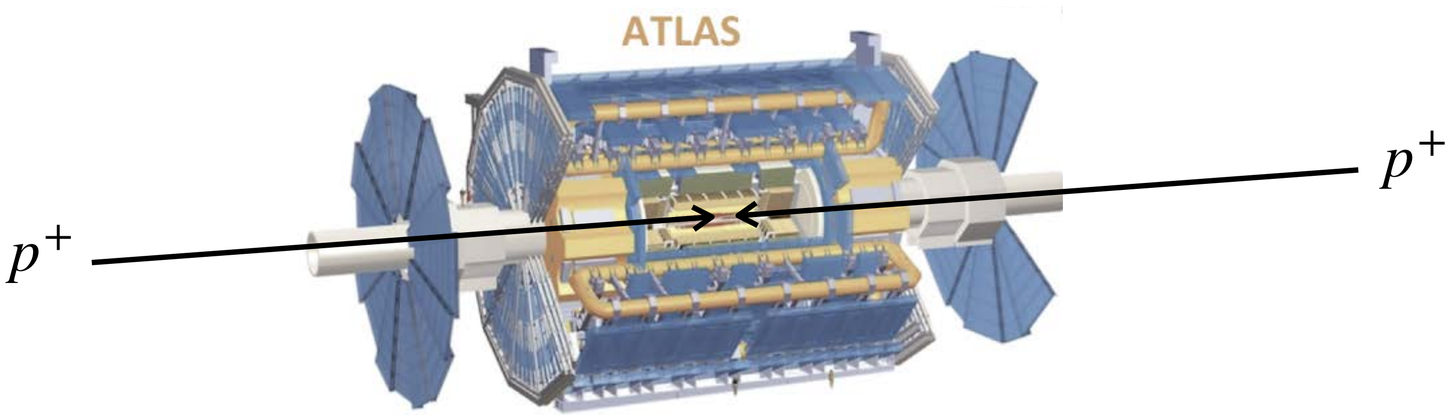
How do we see particles at colliders?

Not a direct microscope, we must interpret!

$$E^2 = m^2c^4 + p^2c^2$$



High energy proton ↔ many lower energy particles

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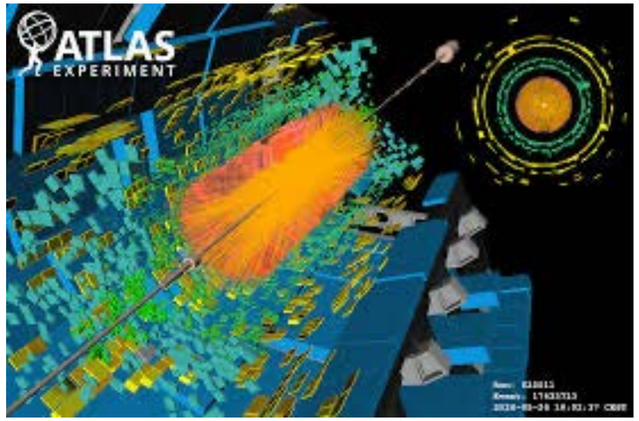

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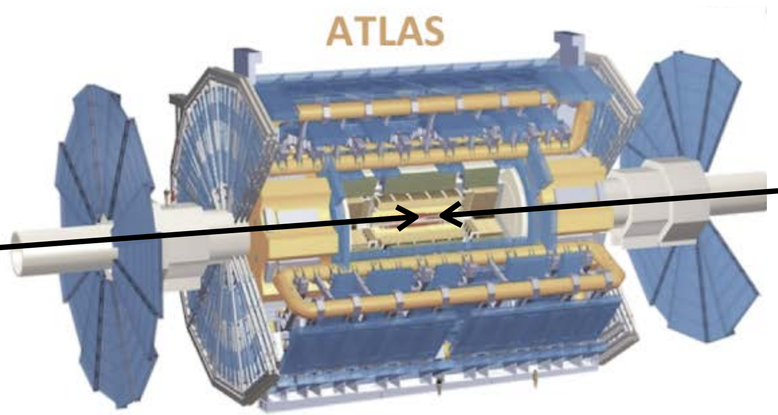
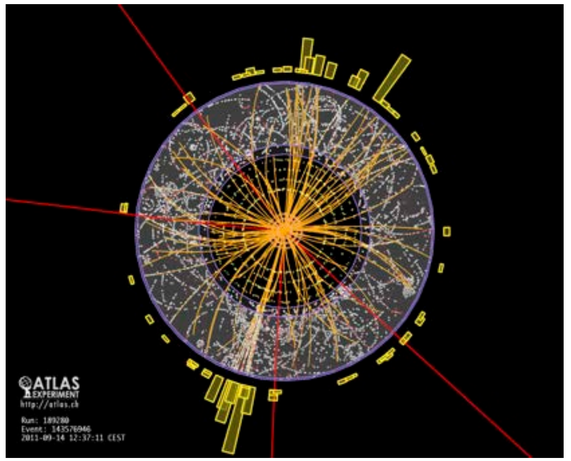


p^+

p^+



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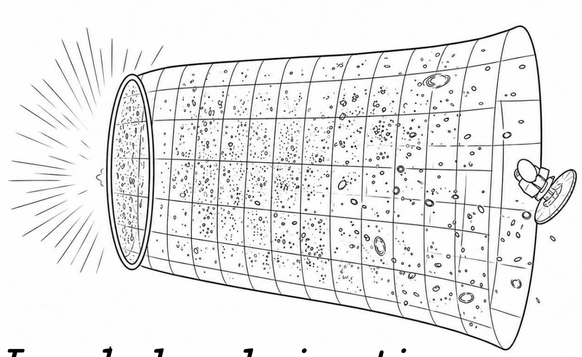
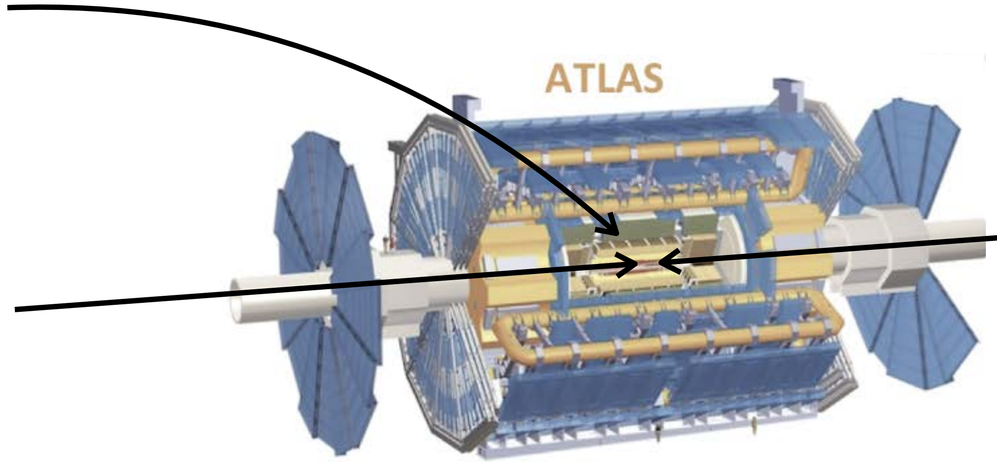
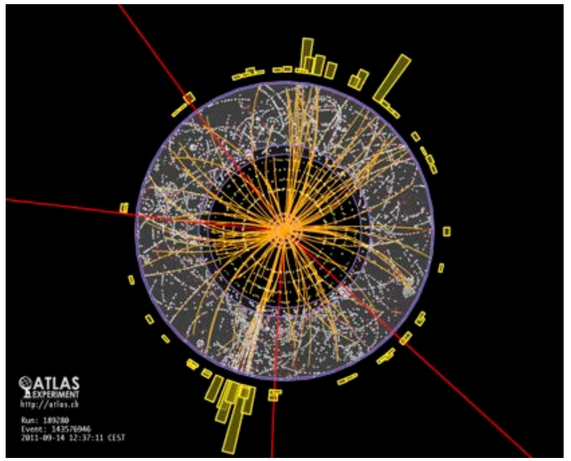


Look back in time



p^+

p^+ "Event"



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What do we measure at colliders?

We look at number of *signal* events produced

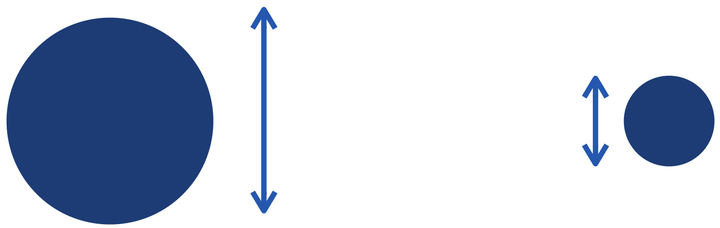
Number of events = Probability of event × number of collisions × sensitivity of detection

Cross section σ

Theorists' calculation

Detectors & Analysis

Collider parameters



Quantum mechanics is *probabilistic* whereas Classical mechanics is *deterministic*

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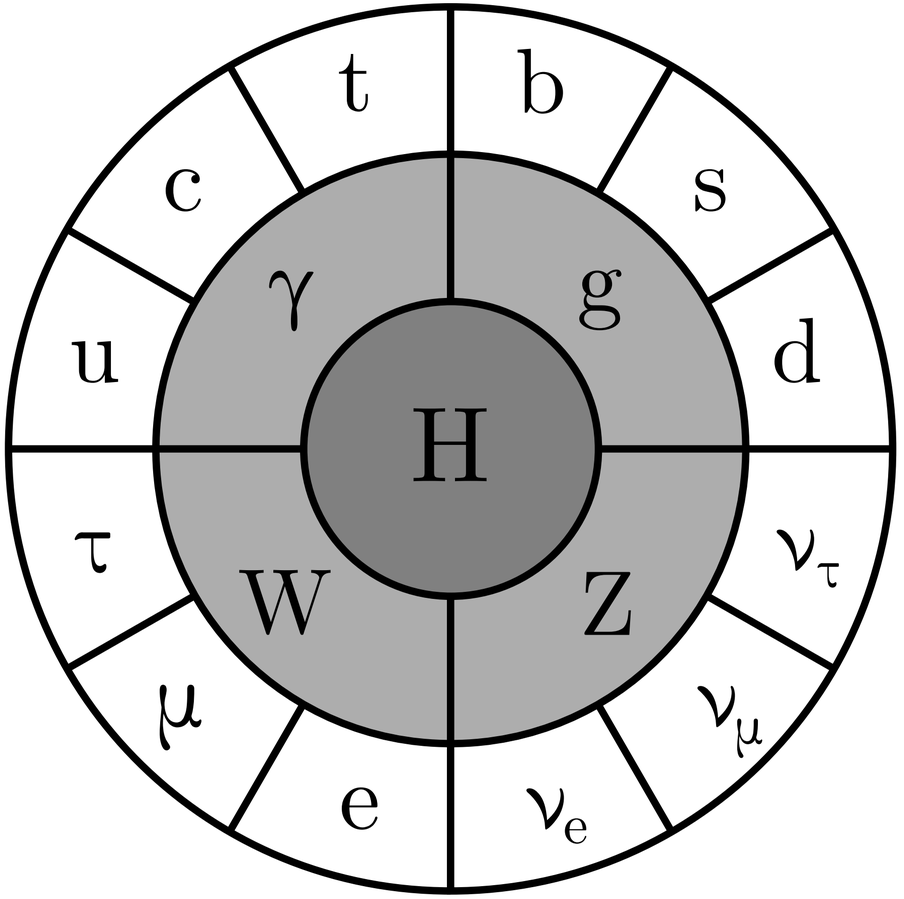
What particles have we found?

The catalog of known particles & forces is the *Standard Model* (SM)



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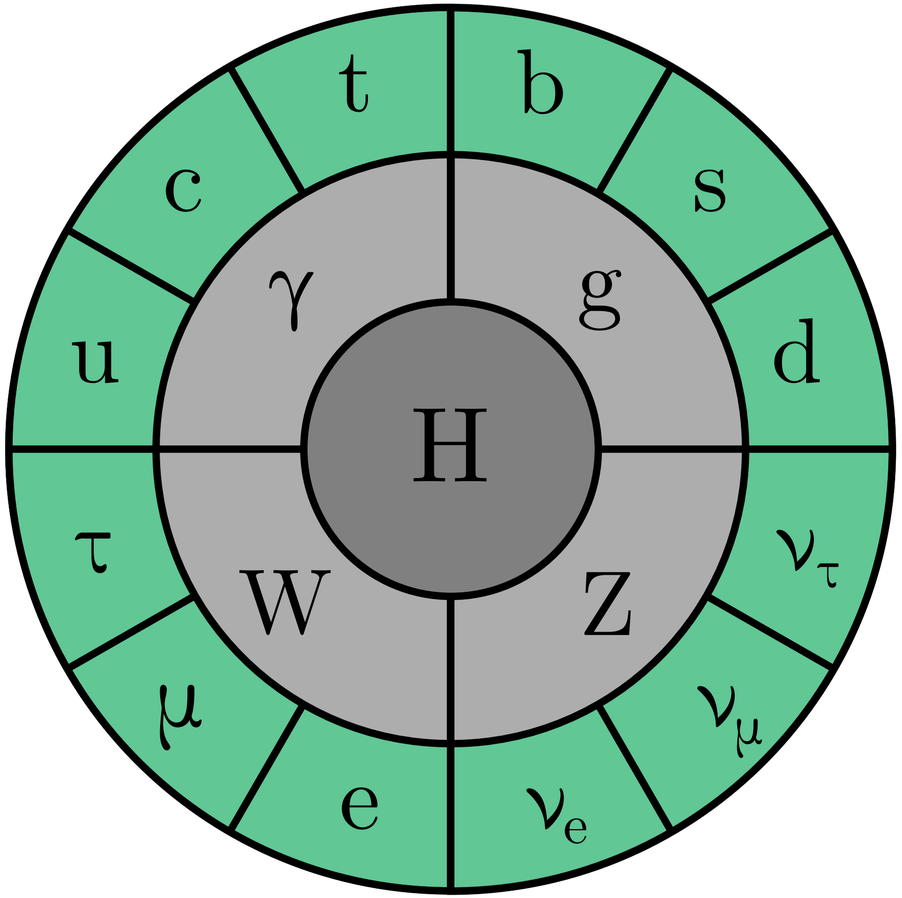

Fermions → Matter

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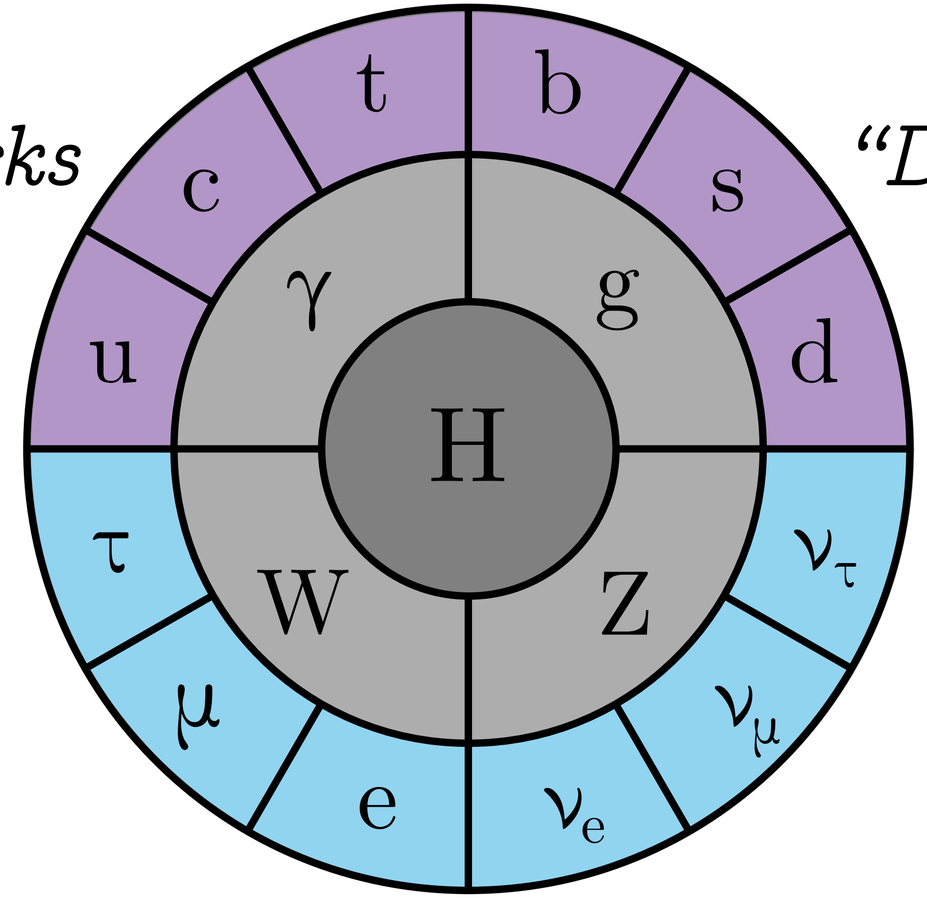
"Up-type" Quarks

"Down-type" Quarks



Leptons

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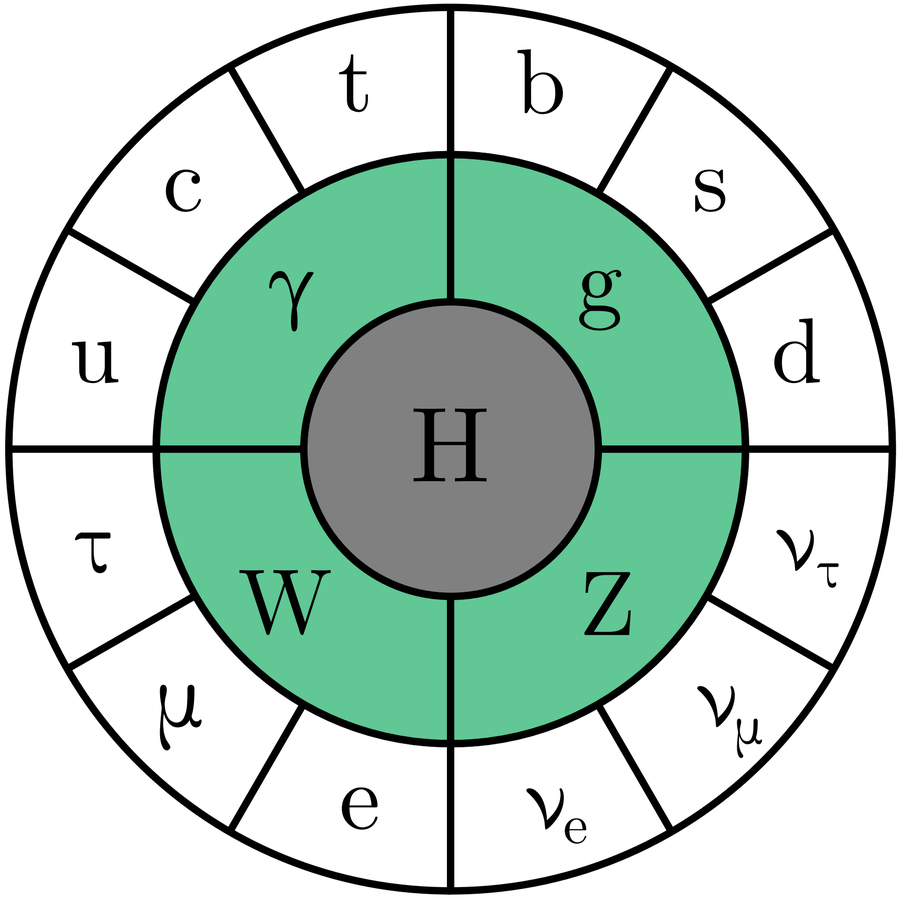

Gauge Bosons → Forces

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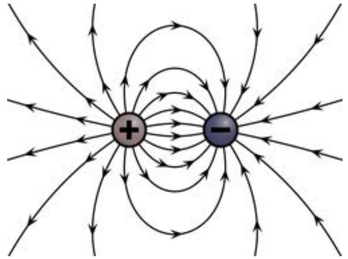
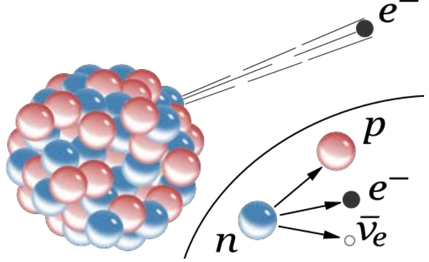
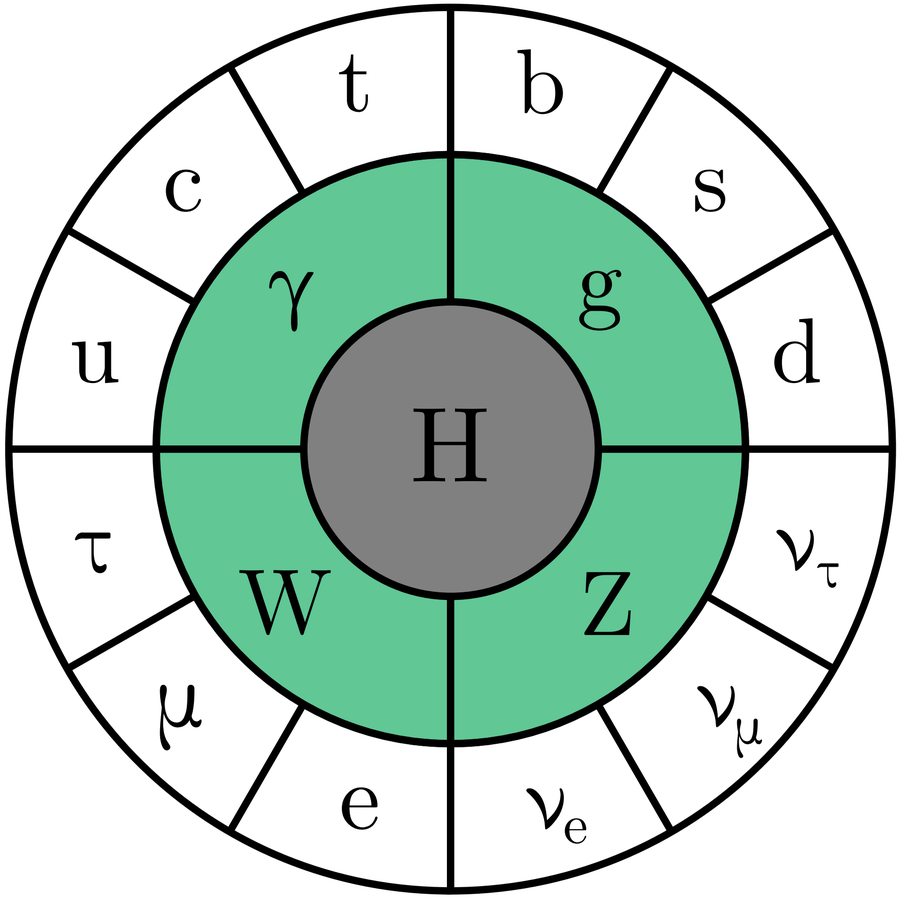
Photon γ*:*
Electromagnetism

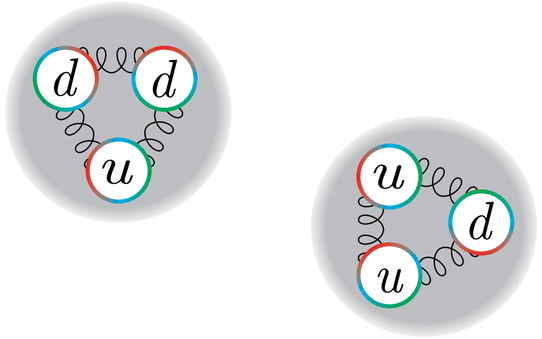


W/Z:
Weak Force





Gluon: Strong Force
(QCD)



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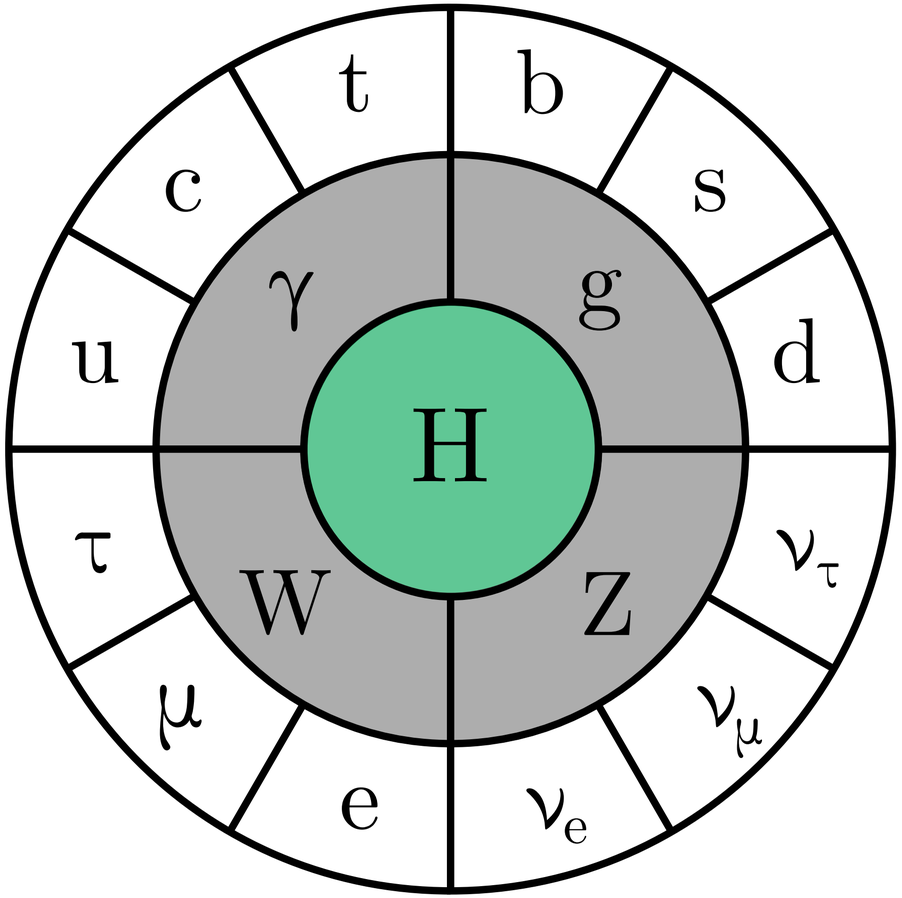

Discovered in 2012

Higgs Bosons → Particle Mass

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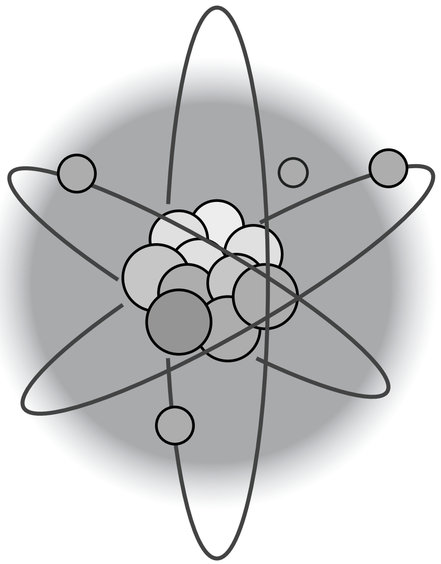
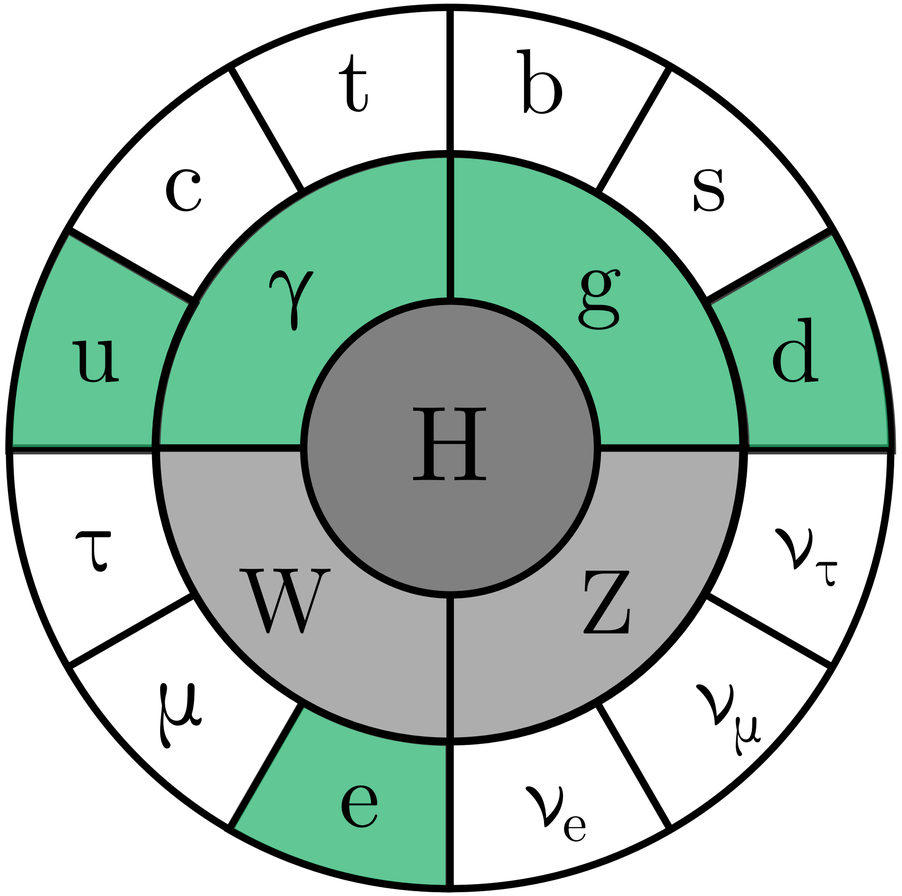
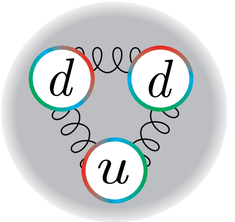
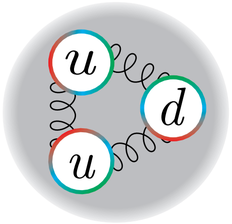






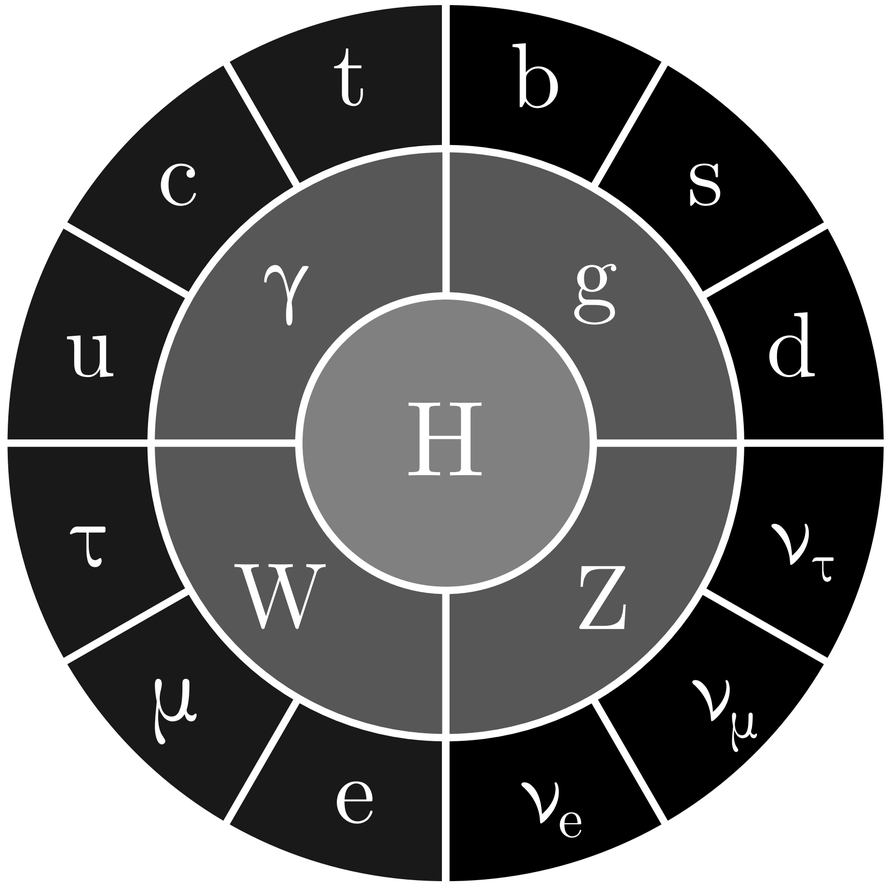


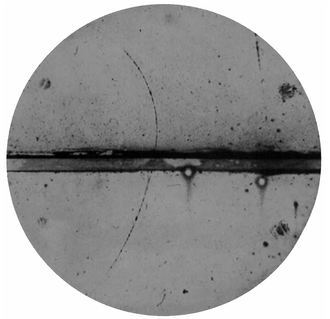
Particles that make up “our” universe

Cesarotti

What particles have we found?

The catalog of known particles & forces is the *Standard Model* (SM)



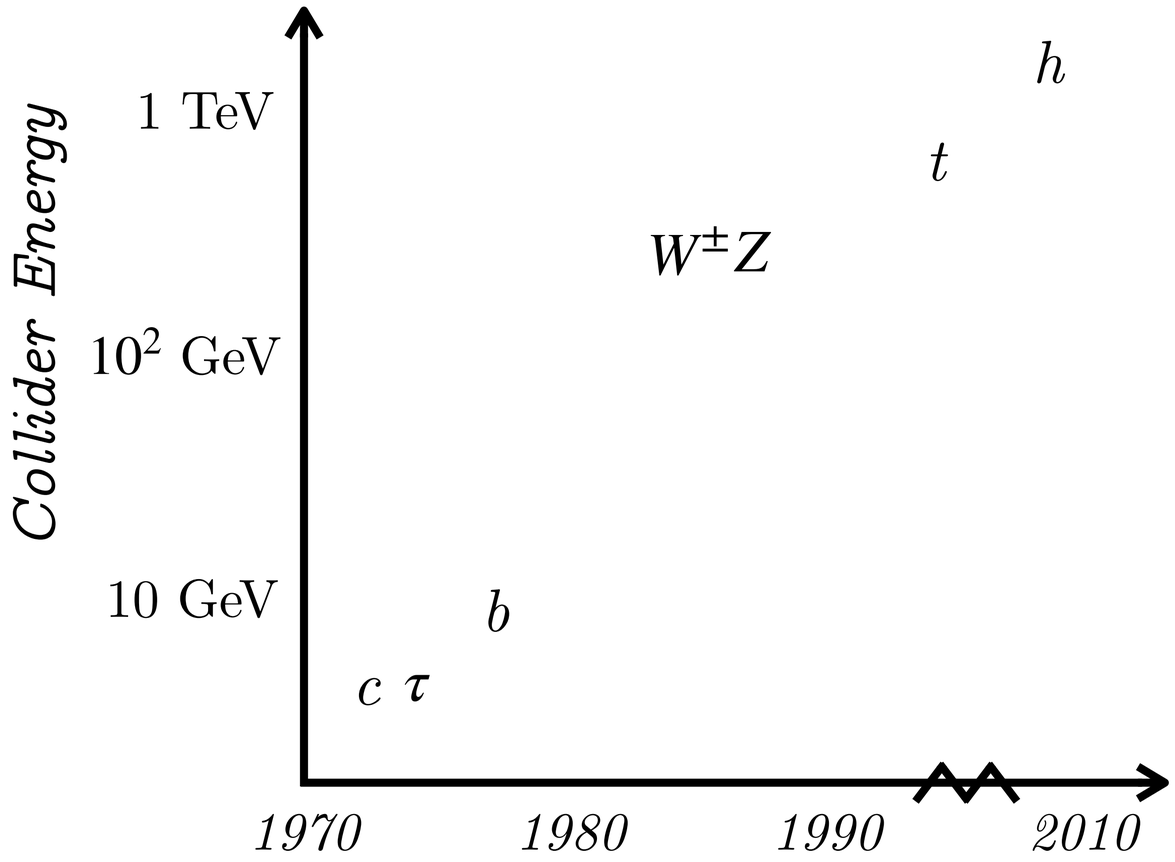


Electron ↔ positron!

Anti-matter (*not* dark matter!)

Cesarotti

What particles have we found?



Higher energies at colliders give more particle discoveries

	I	II	III	Bosons	
Quarks	u	c	t	g	H
	d	s	b	γ	
Leptons	e	μ	τ	Z	
	ν_e	ν_μ	ν_τ	$W^{\pm}$	

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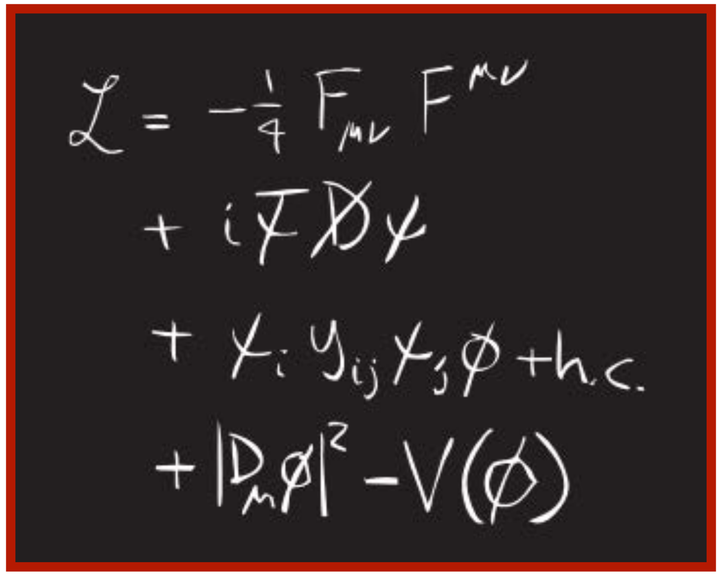
What do we calculate?

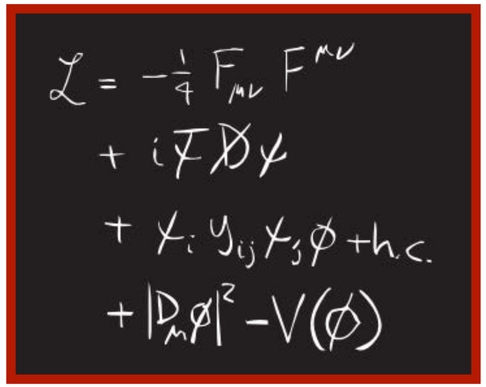
Standard Model Lagrangian: Rules of particle interactions



Probability with which particles interact

What do we calculate?

Standard Model Lagrangian: Rules of particle interactions



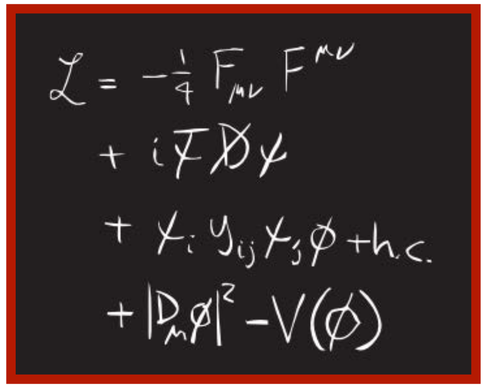
$$\mathscr{L}_{\rm SM} = -\frac{1}{4} G_a^{\mu\nu} G_{a\mu\nu} - \frac{1}{4} W_b^{\mu\nu} W_{b\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - (D^\mu \phi)^\dagger (D_\mu \phi)$$
$$+ i \overline{Q_{Li}} \not{D} Q_{Li} + i \overline{U_{Ri}} \not{D} U_{Ri} + i \overline{D_{Ri}} \not{D} D_{Ri} + i \overline{L_{Li}} \not{D} L_{Li} + i \overline{E_{Ri}} \not{D} E_{Ri}$$
$$- \left(Y_{ij}^u \overline{Q_{Li}} U_{Rj} \widetilde{\phi} + Y_{ij}^d \overline{Q_{Li}} D_{Rj} \phi + Y_{ij}^e \overline{L_{Li}} E_{Rj} \phi + h.c. \right)$$
$$- \lambda \left(\phi^\dagger \phi - v^2/2 \right)^2 .$$

Looks scary but don't worry

Cesarotti

What do we calculate?

Standard Model Lagrangian: Rules of particle interactions



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$$- \left(Y^u_{ij}\,\overline{Q_{Li}}\, U_{Rj}\, \widetilde{\phi} + Y^d_{ij}\,\overline{Q_{Li}}\, D_{Rj}\, \phi + Y^e_{ij}\,\overline{L_{Li}}\, E_{Rj}\, \phi + h.c. \right)$$
$$- \lambda \left(\phi^\dagger \phi - v^2/2 \right)^2 .$$

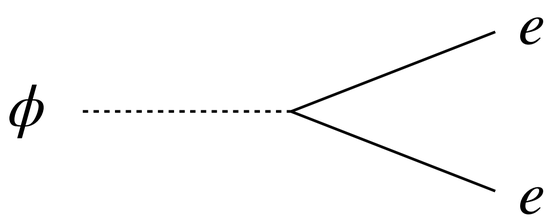
Looks scary but don't worry

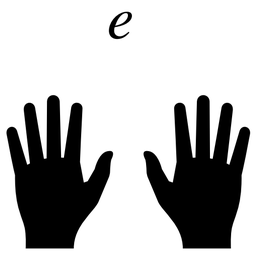
$Y^e =$ *Probability of interaction*

$\phi =$ *Higgs*

$E =$ *right electron*

$L =$ *left electron*





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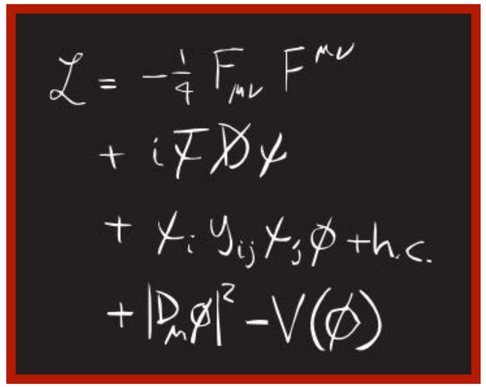
What do we calculate?

Standard Model Lagrangian: Rules of particle interactions



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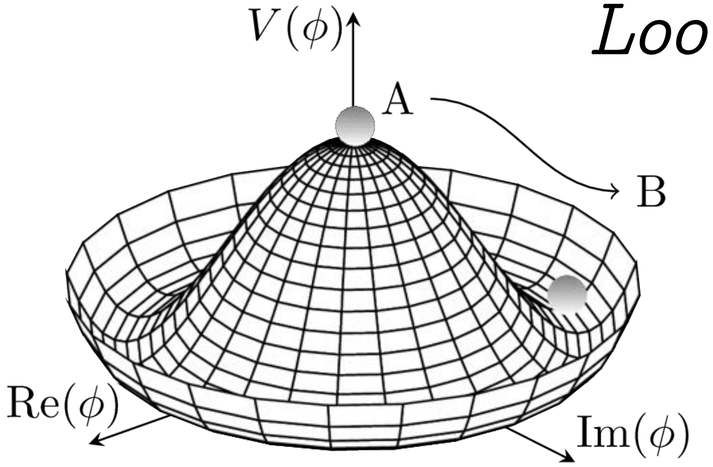
Looks scary but don't worry



Intuition with gravity!

"Rocking" energy → mass energy

Higgs Potential

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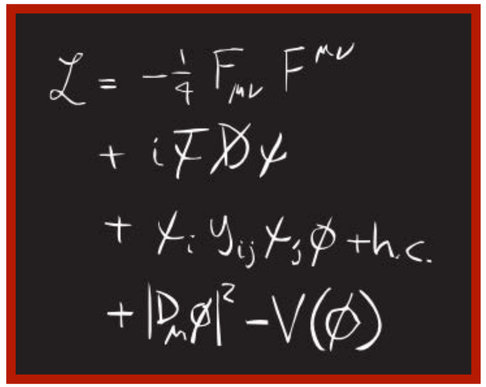
What do we calculate?

Standard Model Lagrangian: Rules of particle interactions



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$$+ i \overline{Q_{Li}} \not{D} Q_{Li} + i \overline{U_{Ri}} \not{D} U_{Ri} + i \overline{D_{Ri}} \not{D} D_{Ri} + i \overline{L_{Li}} \not{D} L_{Li} + i \overline{E_{Ri}} \not{D} E_{Ri}$$
$$- \left(Y_{ij}^u \overline{Q_{Li}} U_{Rj} \widetilde{\phi} + Y_{ij}^d \overline{Q_{Li}} D_{Rj} \phi + Y_{ij}^e \overline{L_{Li}} E_{Rj} \phi + h.c. \right)$$
$$- \lambda \left(\phi^\dagger \phi - v^2/2 \right)^2 .$$

Just a cookbook:

Particles are ingredients, couplings are amounts

Everything we've observed follows the recipe

Cesarotti

What particles have we found?

Example of analysis

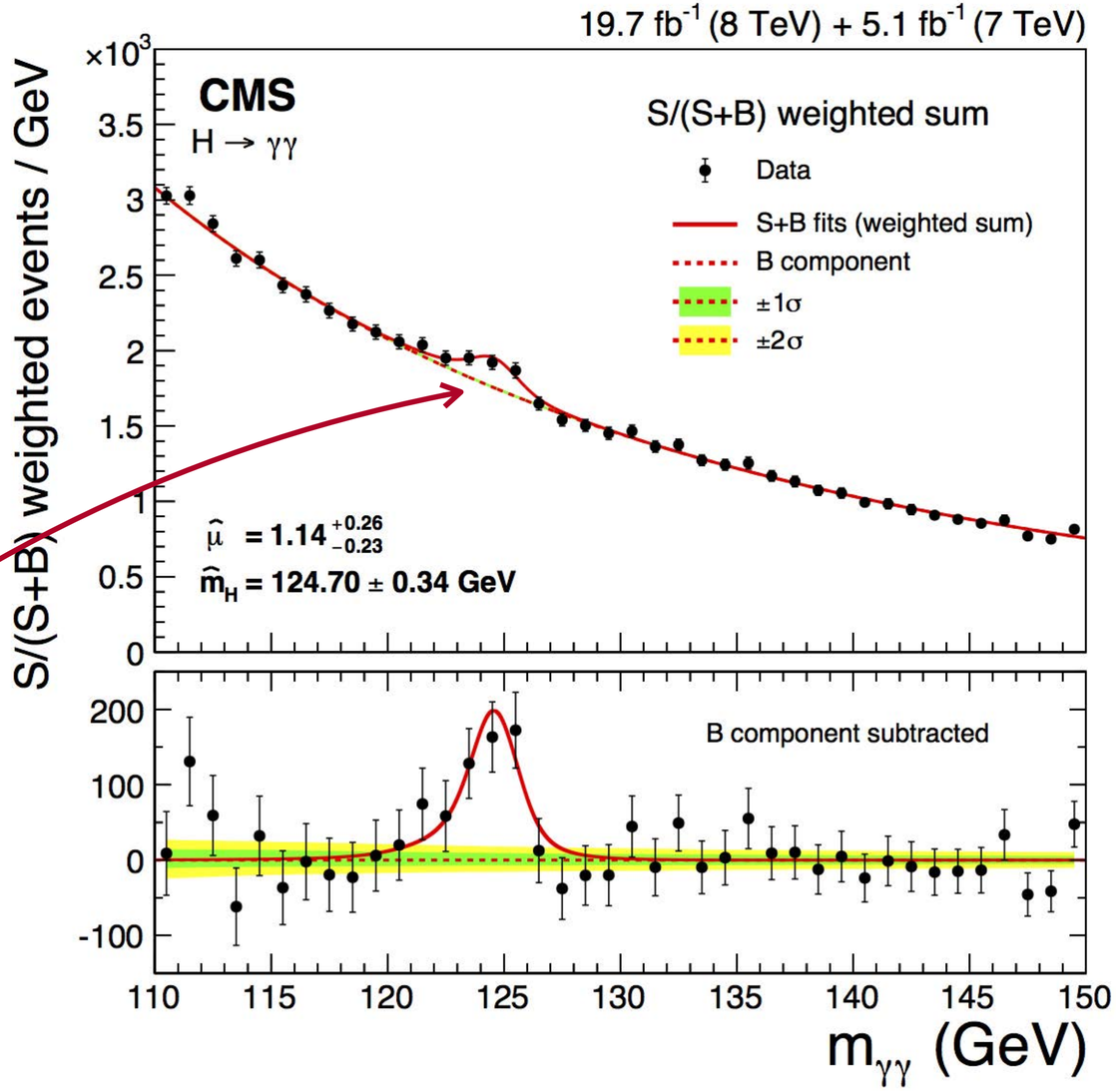
Higgs doesn't live long: $\sim 10^{-22}$ s

$$h \to \gamma\gamma$$

Detectors see $\gamma\gamma$

$$E^2 = m^2c^4 + m^2p^2$$

"Bump hunt"



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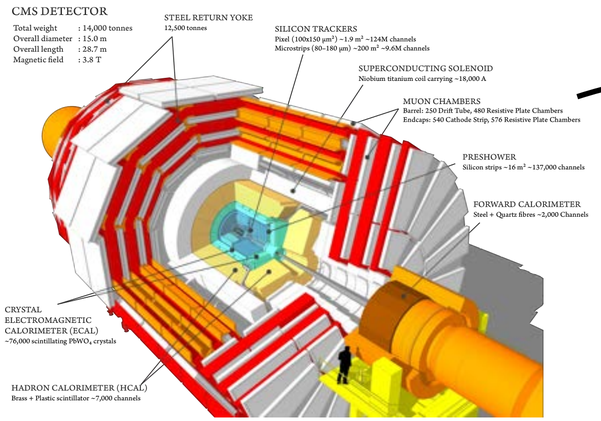
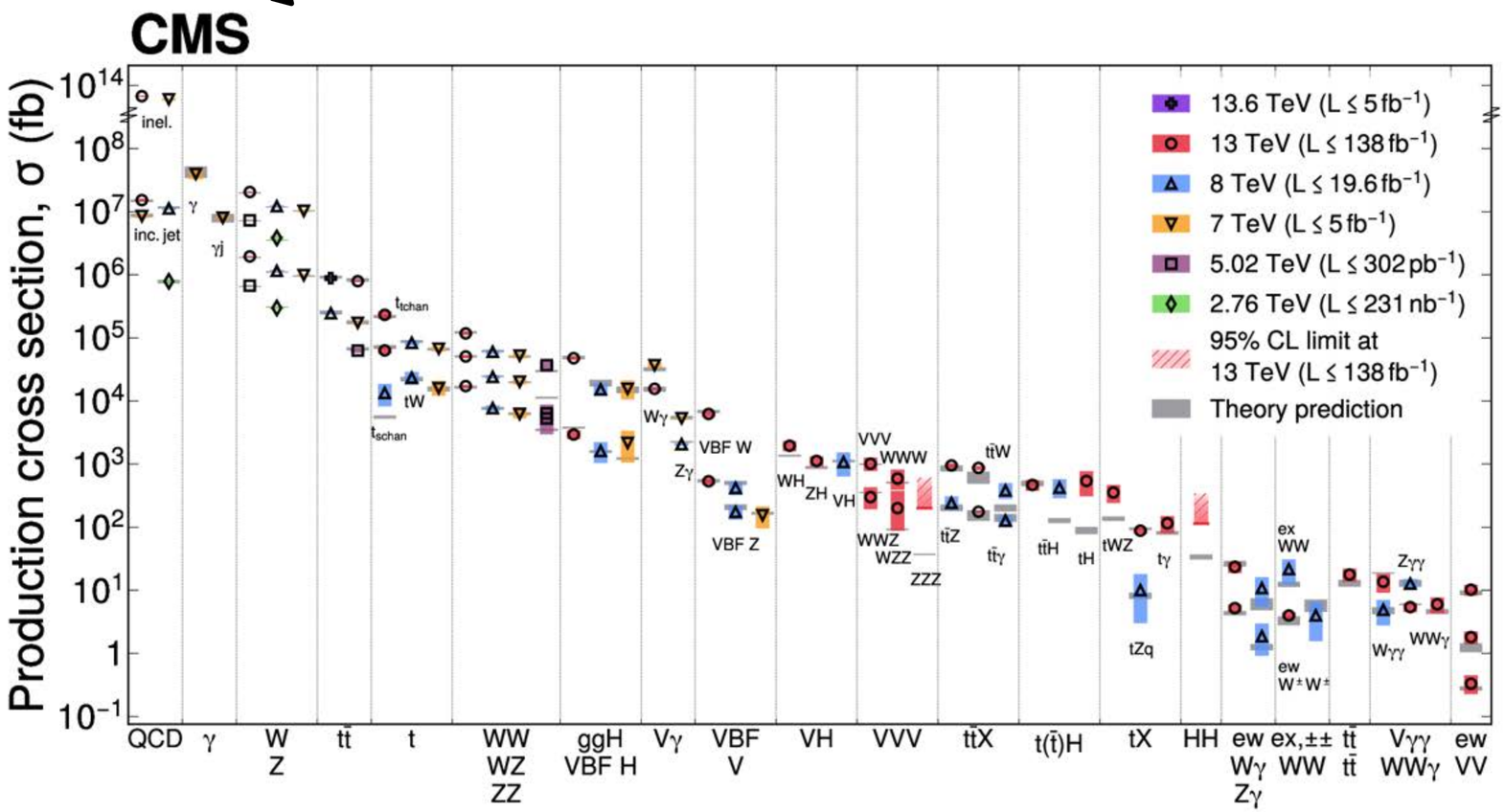
What else do we measure?



$$1\ femtobarn\ (fb) = 10^{-39}\ cm^2$$

Frequency



Physics process

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What don't we know?

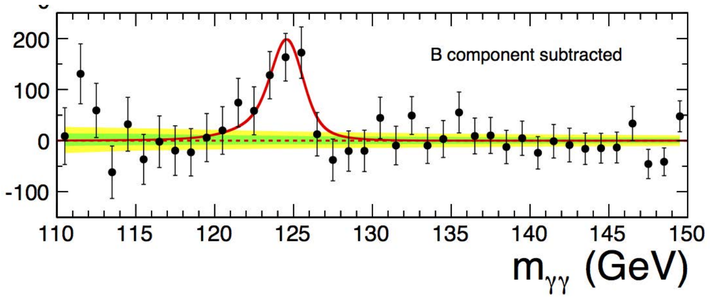
Physics is dynamic — we still have many questions yet to solve

Why does the SM look this way?

	I	II	III	Bosons	
Quarks	u	c	t	g	H
	d	s	b	γ	
Leptons	e	μ	τ	Z	
	ν_e	ν_μ	ν_τ	$W^\pm$	

What is gravity?

Why is the Higgs so light?



What is at higher energy?

What is dark matter?

Why is there matter but no anti-matter?

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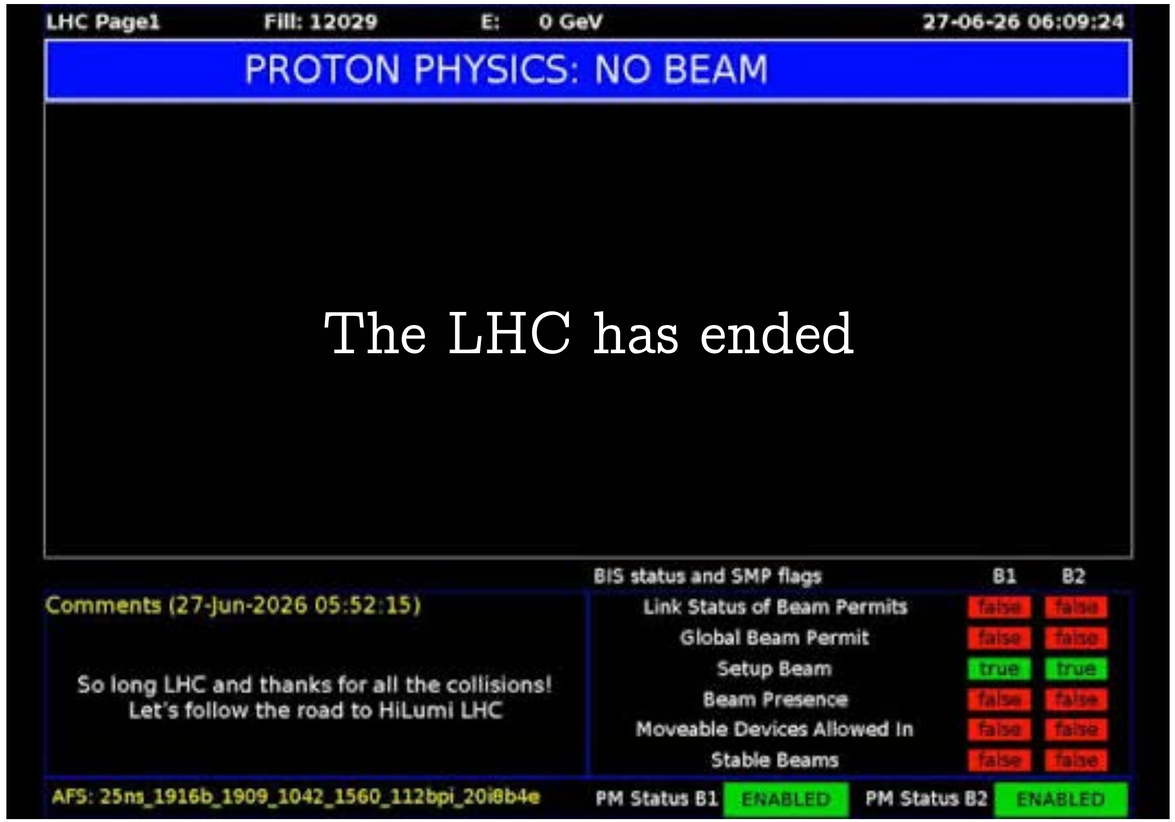
What is the future of particle physics?



Future options to be considered

Do we build on what we've already done? Or do we try something totally new?

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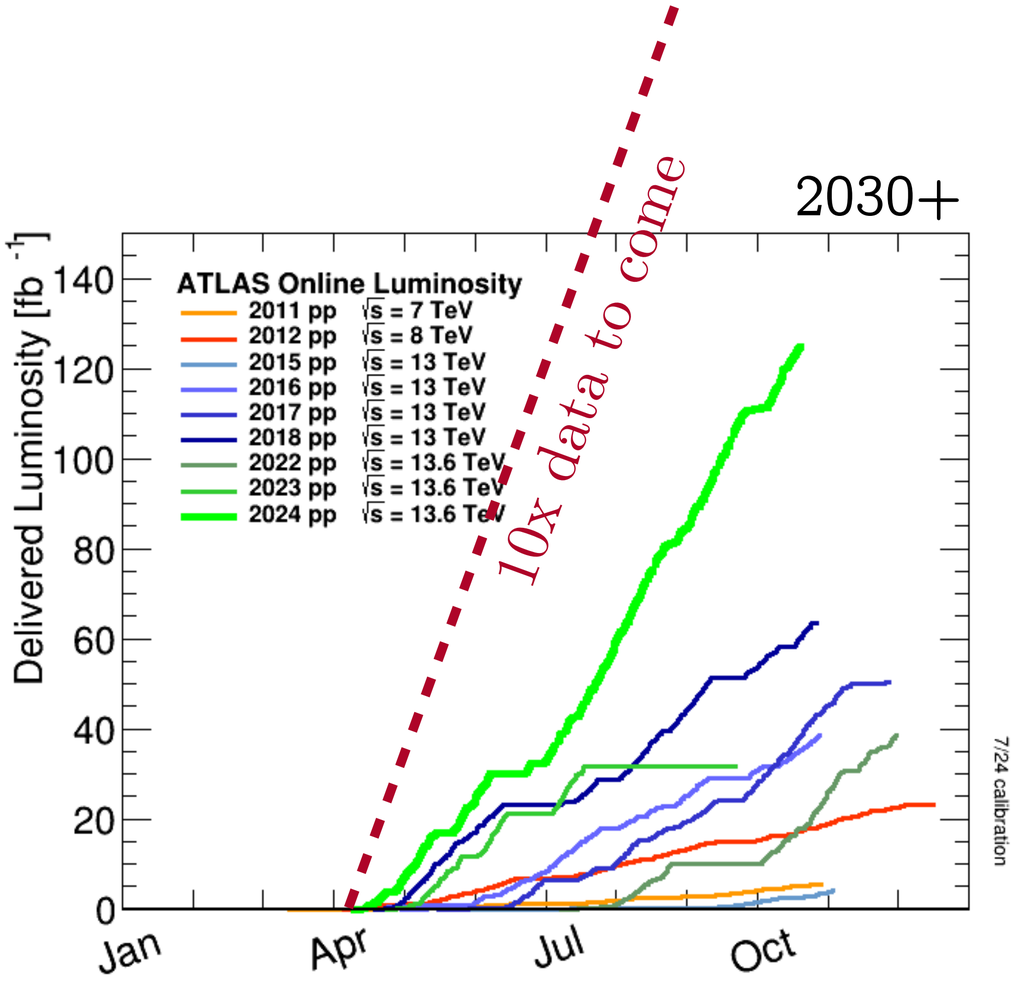
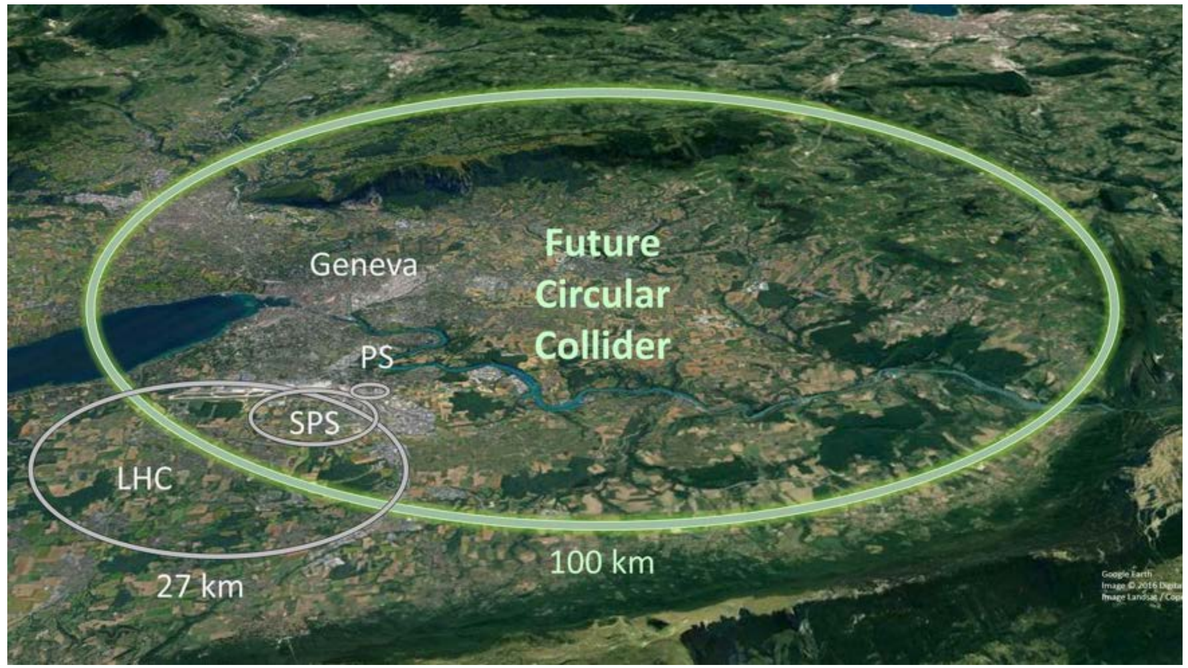
What is the future of particle physics?

Step 1: LHC comes back with more protons (High-Luminosity LHC)



Step 2: (at CERN?) Likely FCC-ee

Many more electrons at much lower energy



Idea: improve statistics

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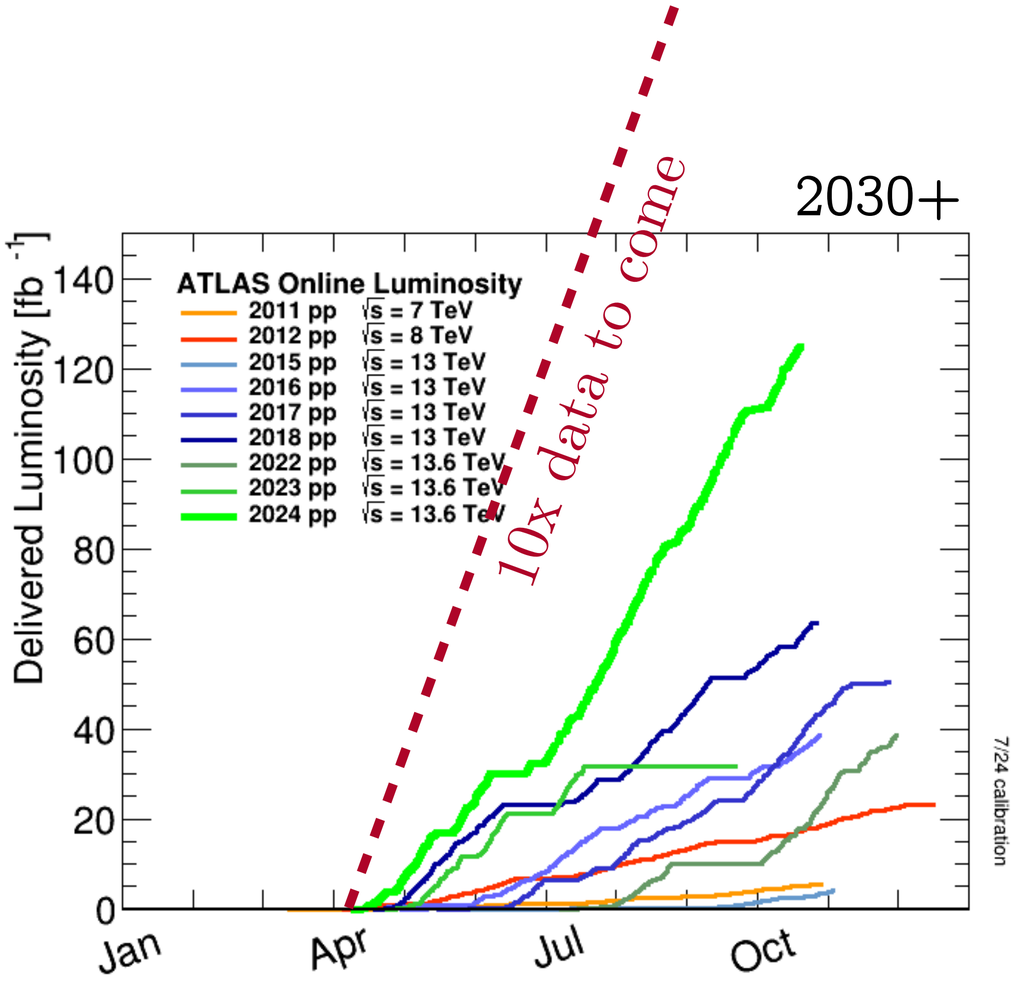
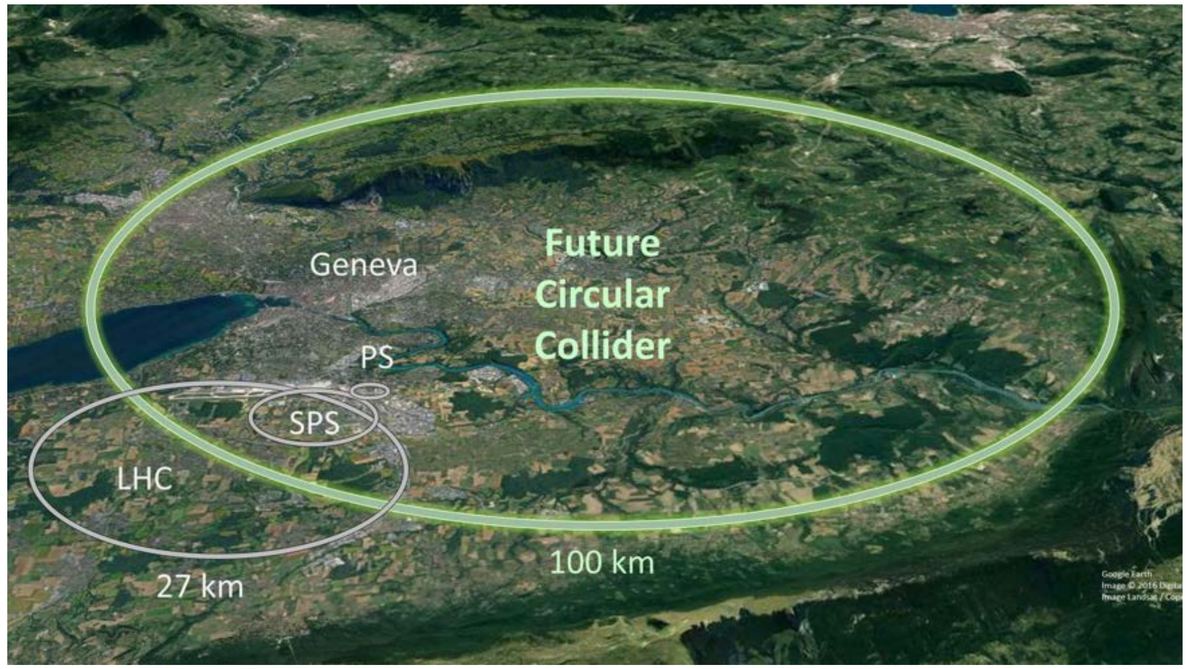
What is the future of particle physics?

Step 1: LHC comes back with more protons (High-Luminosity LHC)



Step 2: (at CERN?) Likely FCC-ee

Step 3: (same tunnel) Likely FCC-hh



Idea: higher energy to go back further in time

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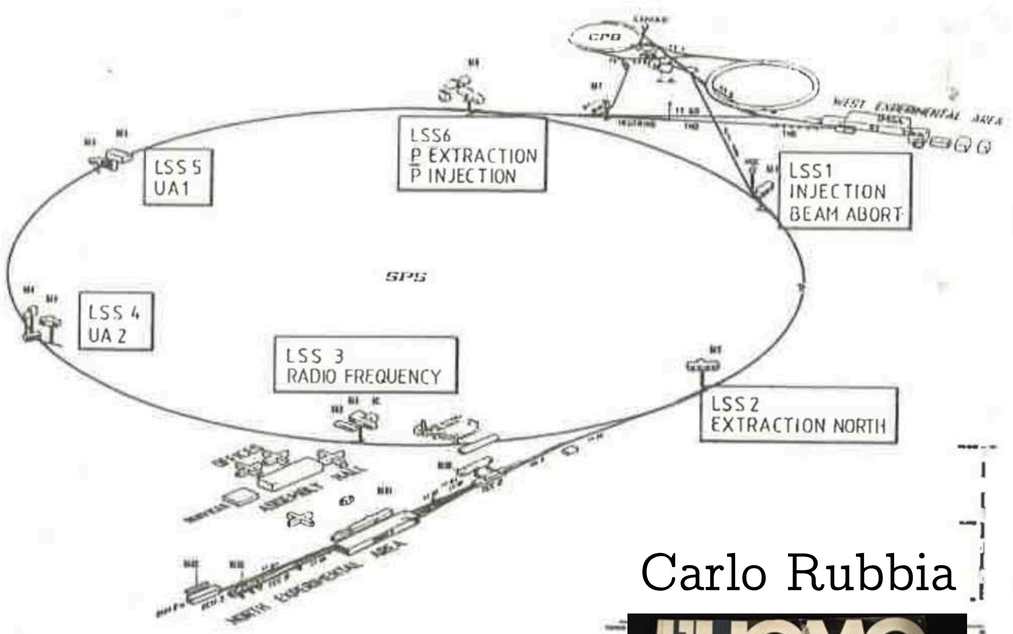
What if we tried something totally new?

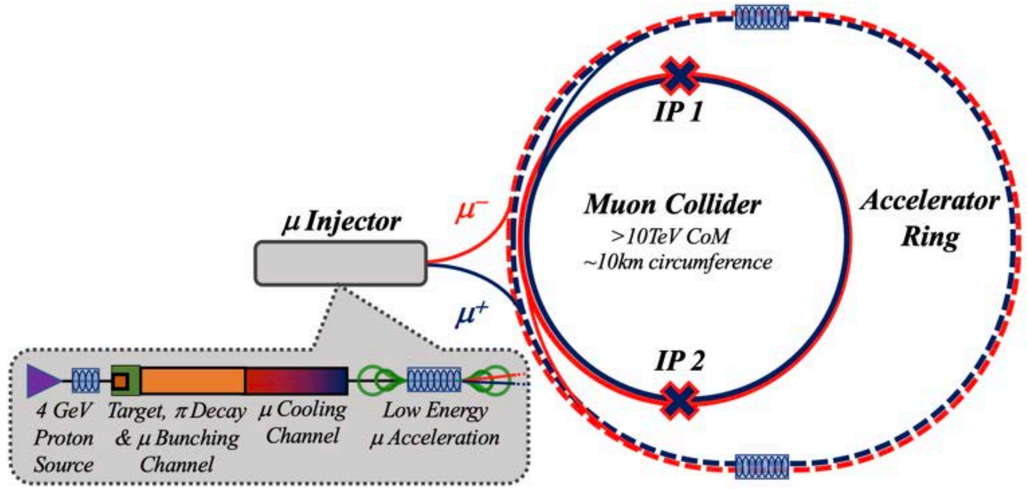
Historical Example: UA1 ($p\bar{p}$)



Discovery of W, Z, jets

Carlo Rubbia

Today's analogy: Muon Collider ($\mu^+\mu^-$)



High energy and precision,
Like electron and proton colliders combined

Cesarotti

*Not to Scale

Comparison of Future Circular Colliders

pp

FCC-hh

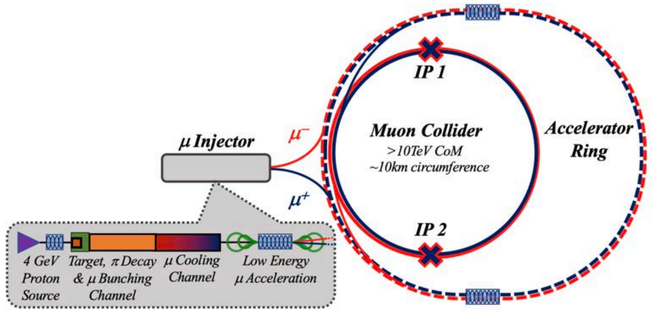
$\mathcal{O}(91$ km$)$

$\sqrt{s} = 85+$ TeV

$\mu^+\mu^-$

MuC

$\mathcal{O}(10$ km$)$



$\sqrt{s} = 3$ TeV (energy stage)

$\sqrt{s} = 10$ TeV

e^+e^-

FCC-ee

$\mathcal{O}(91$ km$)$

$\sqrt{s} \sim m_Z - 350$ GeV

Cesarotti

*Not to Scale

Comparison of Future Circular Colliders

pp | $\mu^+\mu^-$ | e^+e^-

MuC

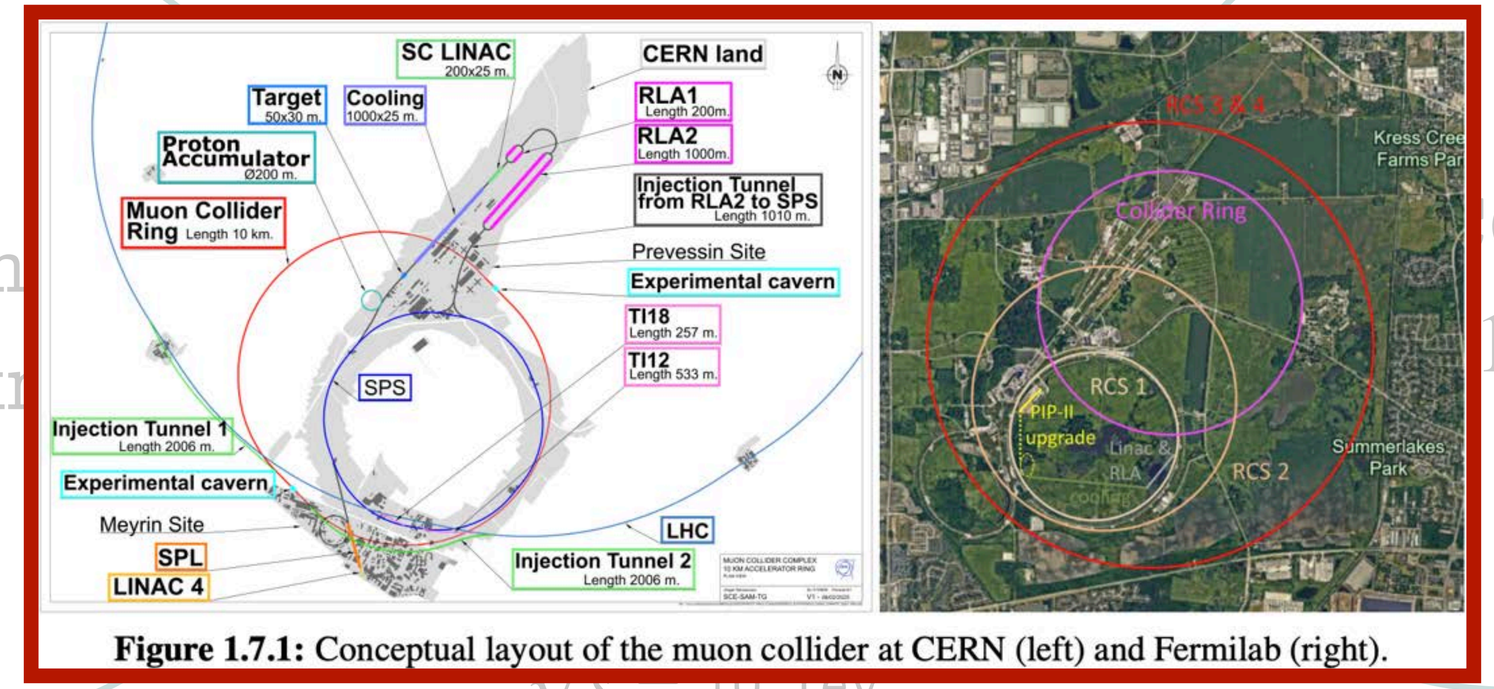


Figure 1.7.1: Conceptual layout of the muon collider at CERN (left) and Fermilab (right).

FCC-h

$\mathcal{O}$(91 km

C-ee

1 km)

$\sqrt{s} = 10$ TeV

$\sqrt{s} = 85+$ TeV

$\sqrt{s} \sim m_Z - 350$ GeV

Cesarotti

And so what comes next?

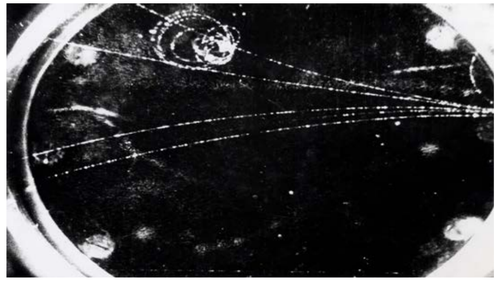
We keep trying to answer the big questions

What is the universe made out of?

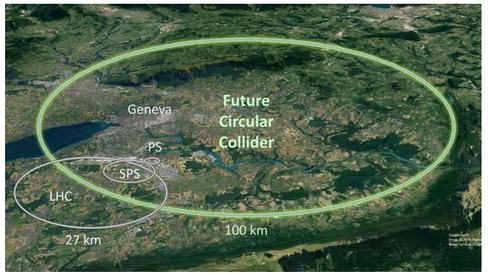
What are the building blocks of everything?

	I	II	III	Bosons	
Quarks	u	c	t	g	H
	d	s	b	γ	
Leptons	e	μ	τ	Z	
	ν_e	ν_μ	ν_τ	$W^\pm$	

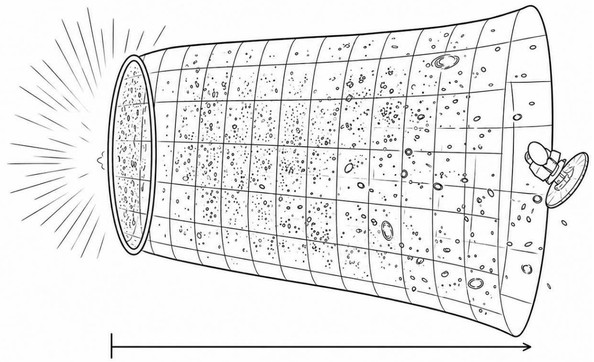
What happened to get here?



What will happen next



What did we start with?



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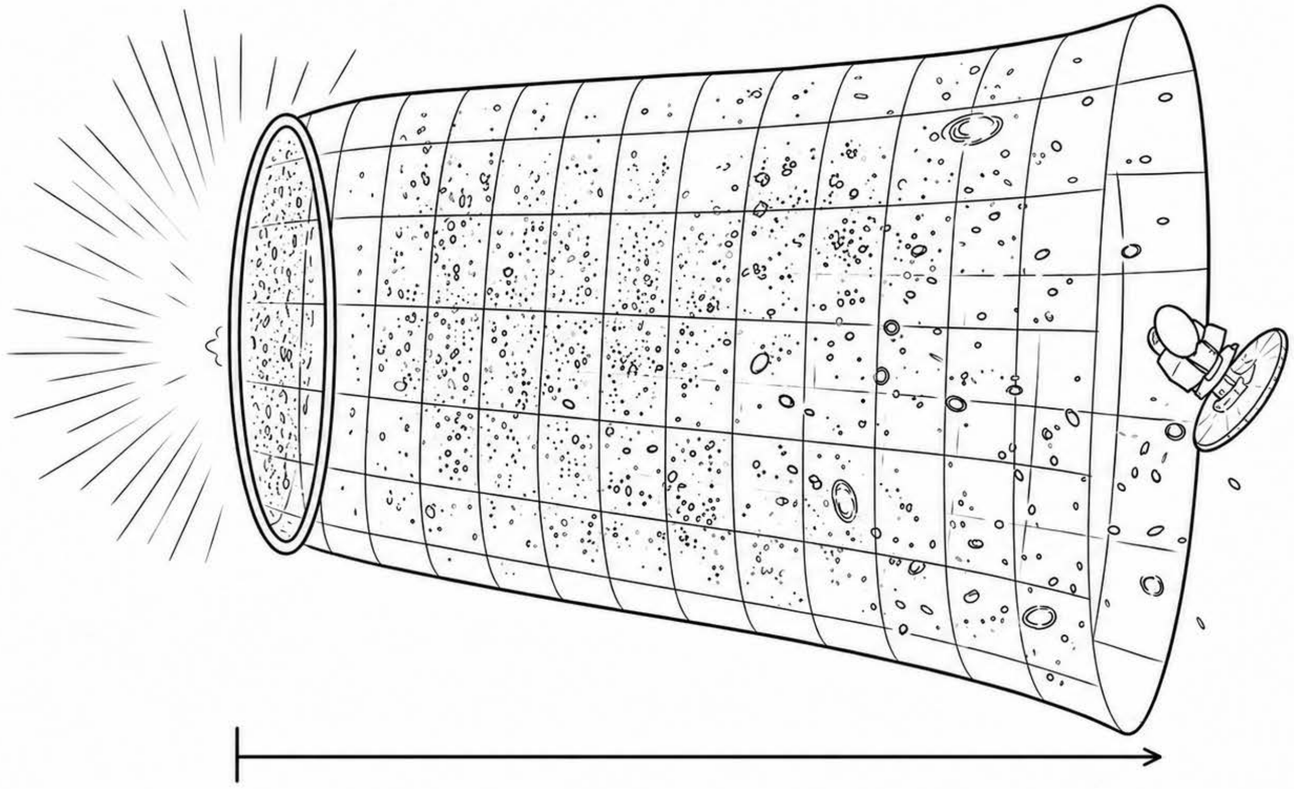
And so what comes next?

We are never finished with the story of discovery

Every time we've found a new particle, we thought we completed the story

...and every time, we find something new we don't understand!



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