Universität Zürich[UZH]

Antrittsvorlesung

March 20, 2017

The Eyes of the Particle Physicist

Olaf Steinkamp

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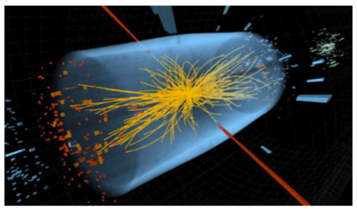

Registro del CMS que pudiera ser la firma de la partícula de Higgs. / CERN

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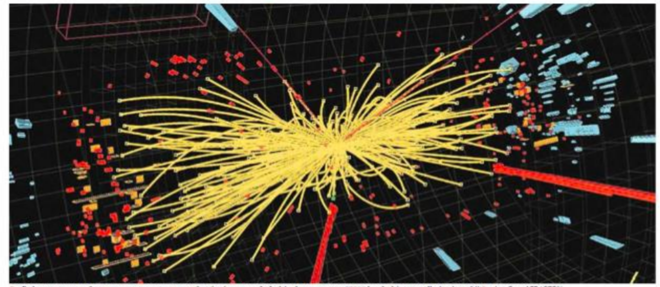

Grafische weergave van de sporen van een proton-protonbotsing in een van de deeltjesdetectoren van CERN, het deeltjesversnellerinstituut bij Genève. Foto AFP / CERN

Historische stap in het onderzoek naar de bouwstenen waaruit heelal is opgebouwd

Higgsdeeltje ‘vrijwel zeker’ ontdekt

Door BRUNO VAN WAYENBURG

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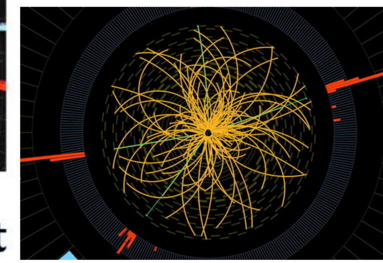

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Higgs of niet, het is een spectaculaire ontdekking

Door: Pieter Sabel – 04/07/12, 11:29

© EPA. Foto uit 2007 van de supergeleidende magneetkern van de deeltjesversneller van CERN in Genève.

'I think we have it', zei de president-directeur van het Zwitserse onderzoeksinstituut CERN vandaag na afloop van een persconferentie over de zoektocht naar het zogenoemde Higgs-deeltje. Hij sprak van een 'historische mijlpaal'. Maar met zekerheid omgeven - er is meer onderzoek nodig. Wat is er nu ontdekt?

Wat we in elk geval met voldoende zekerheid kunnen zeggen, is dat er een deeltje is gevonden met een massa, waarvan het bestaan in de natuurkunde nog niet eerder bekend was. En dat deeltje lijkt op het Higgs-deeltje of Higgs-boson, zegt Martijn van Calmthout van de wetenschapsredactie van de Volkskrant.

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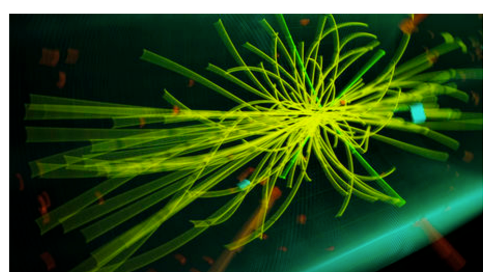

Une nouvelle particule a été découverte par des chercheurs du CERN lancés sur la trace du boson de Higgs. Plus...

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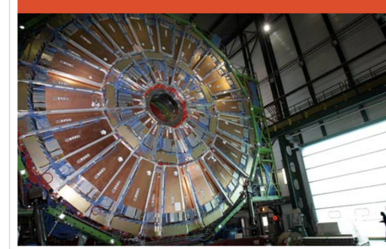

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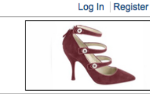

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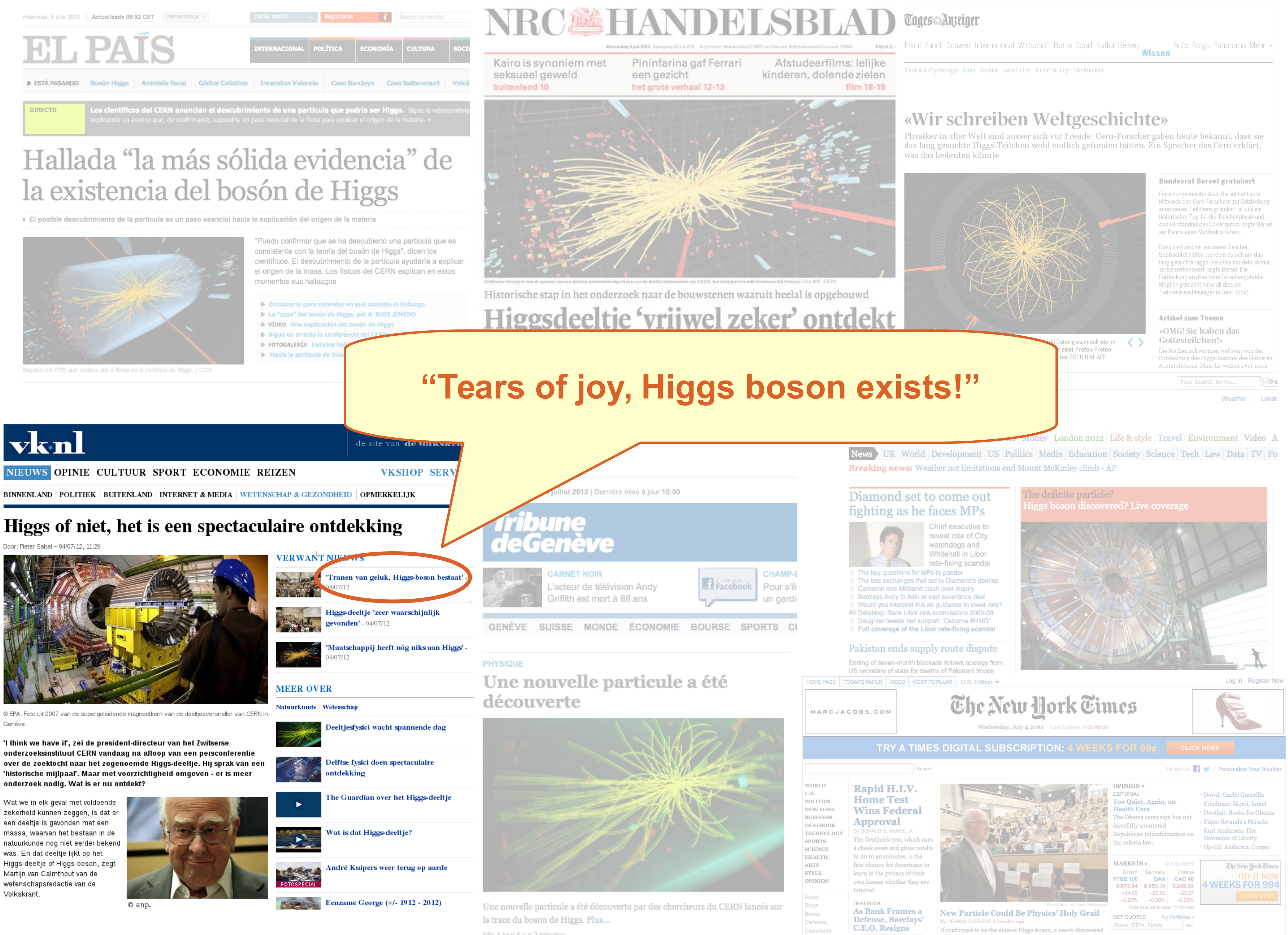

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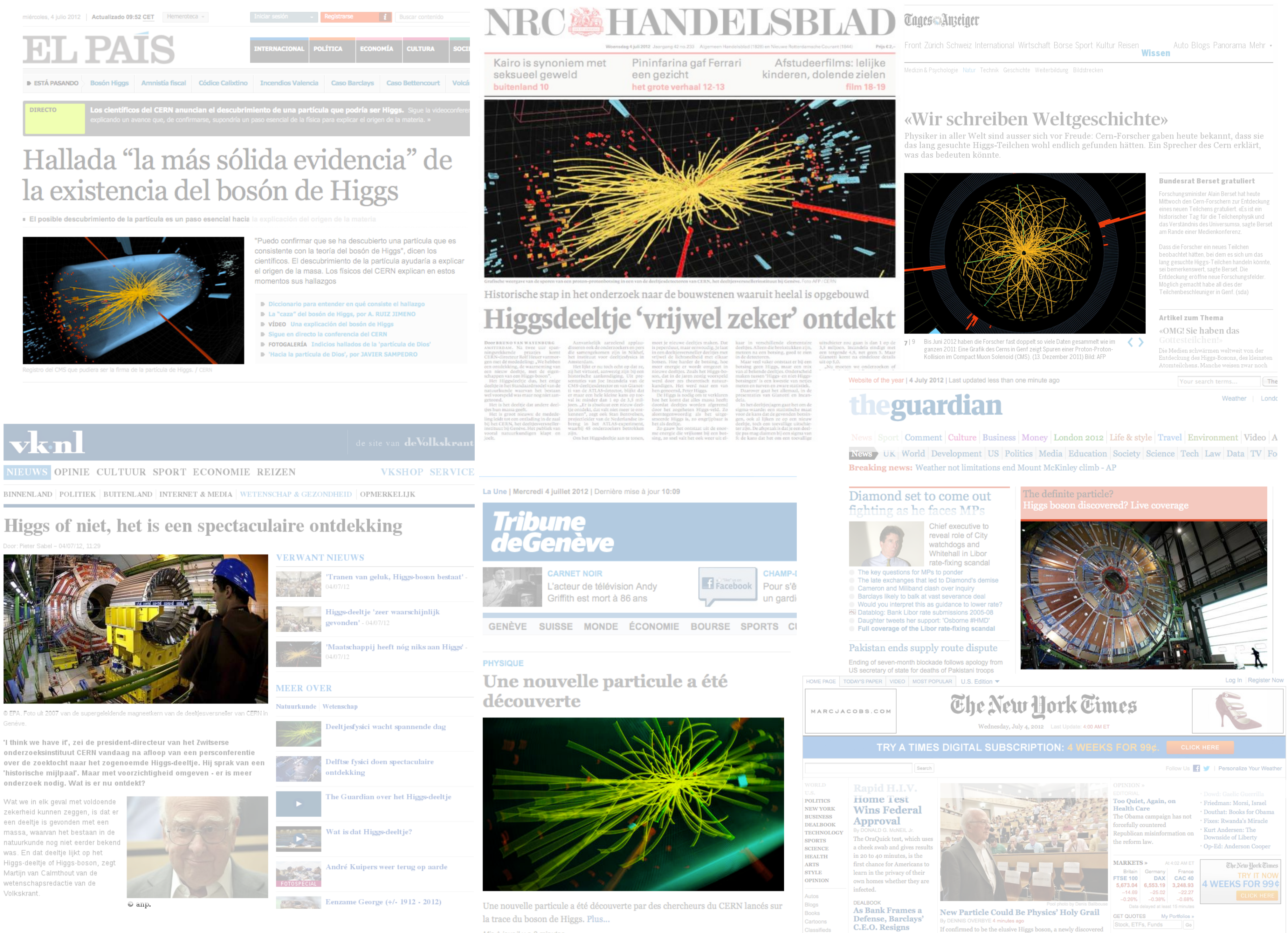

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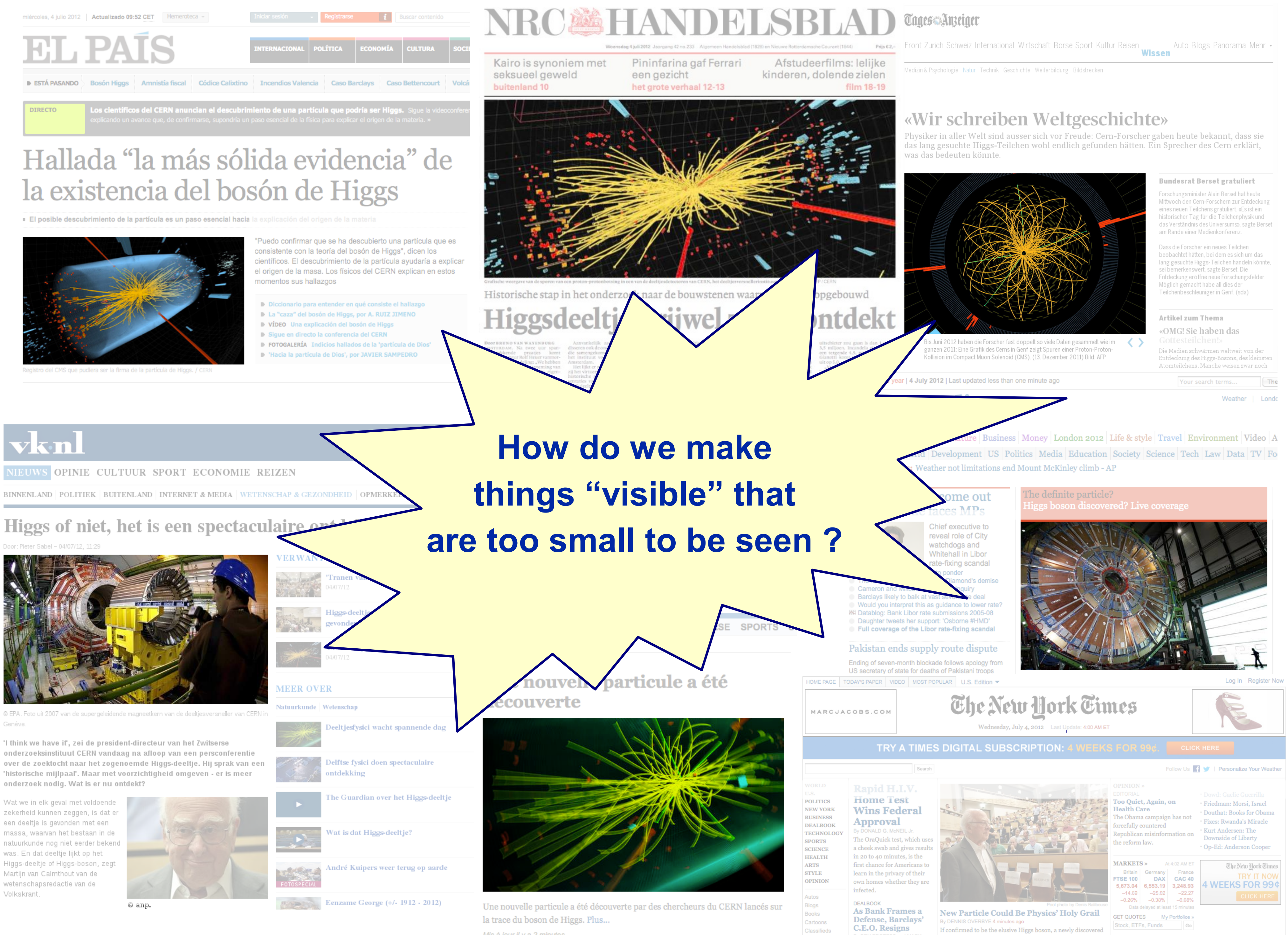

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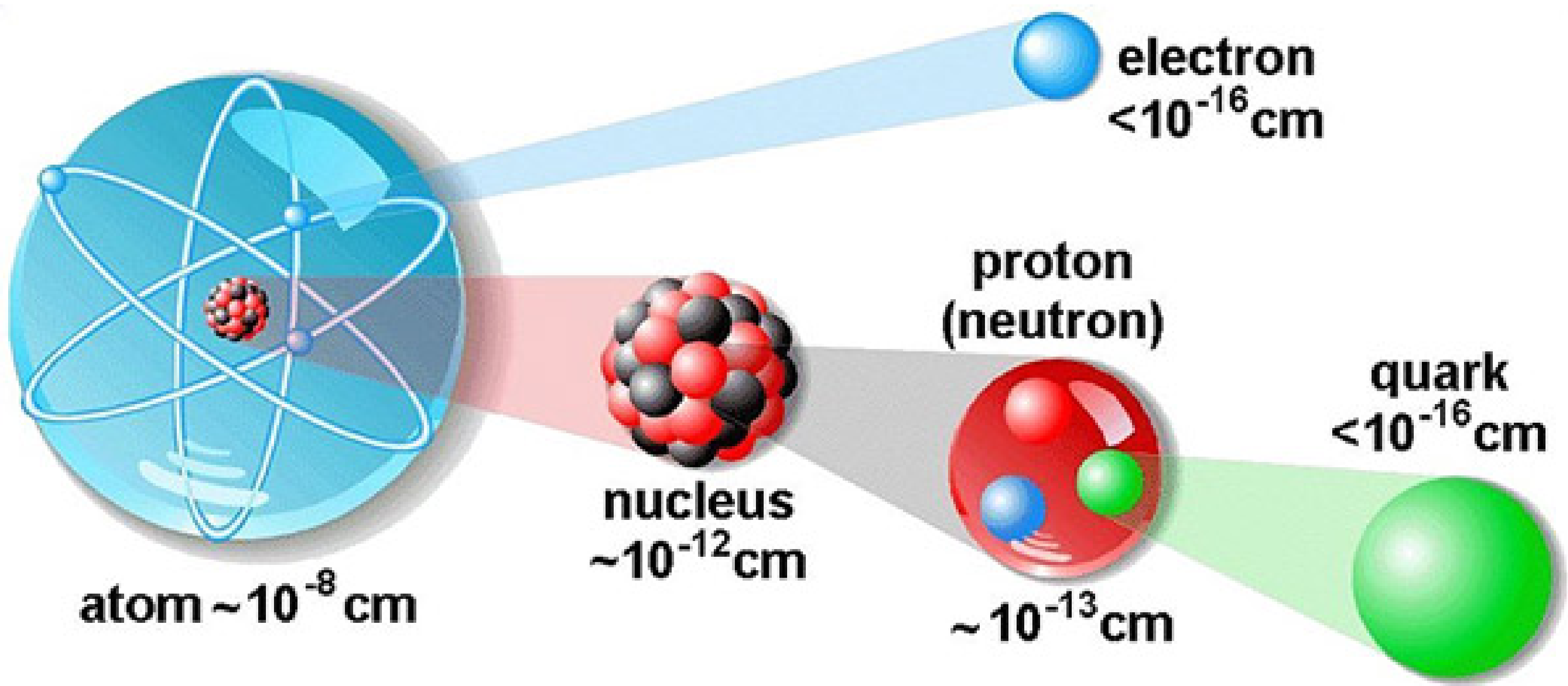
Standard Model of Particle Physics



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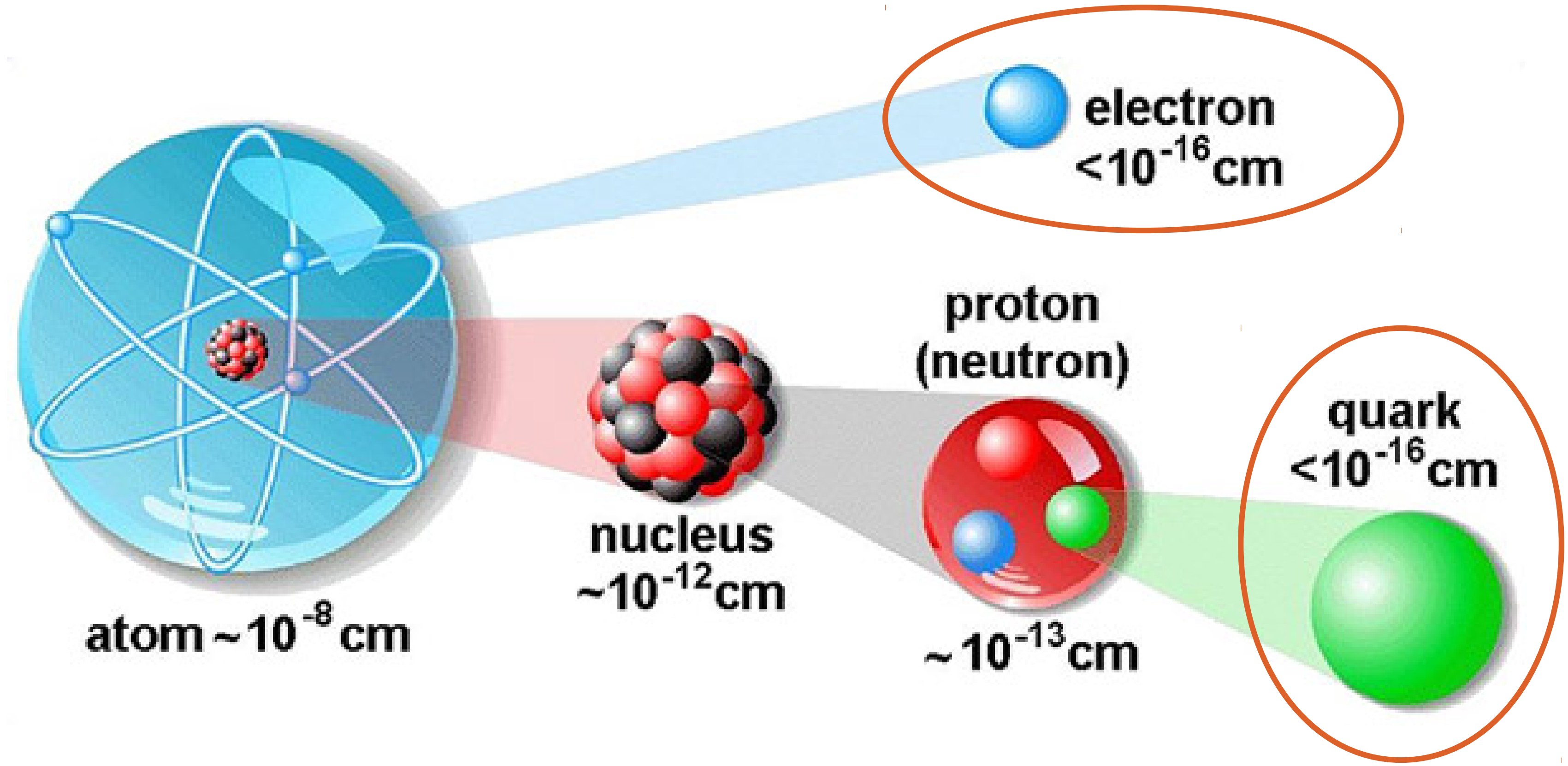

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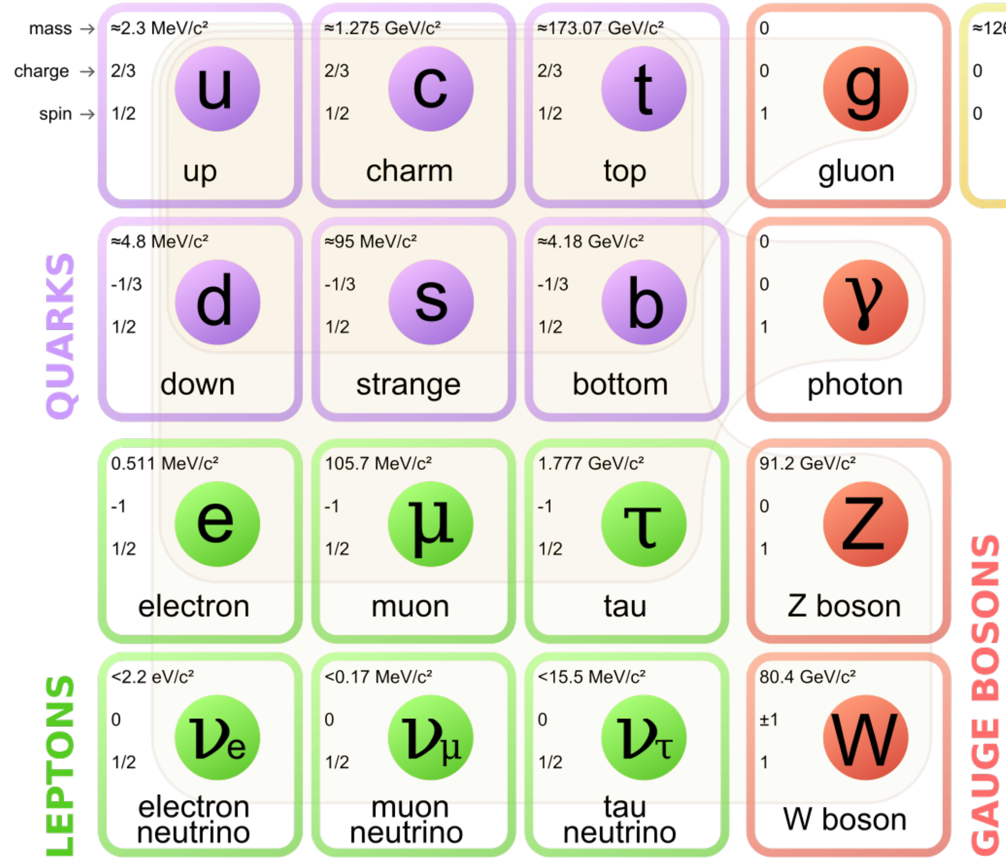

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Elementary particles

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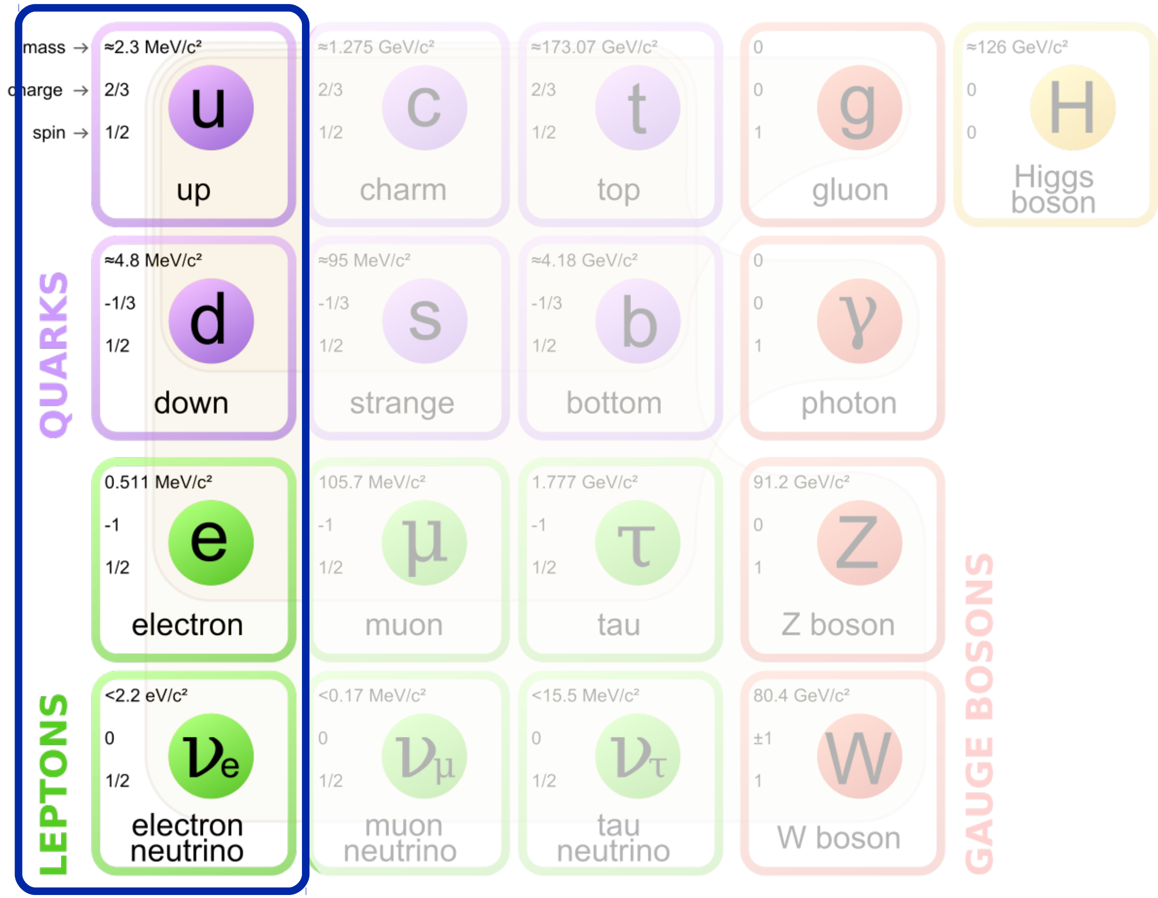
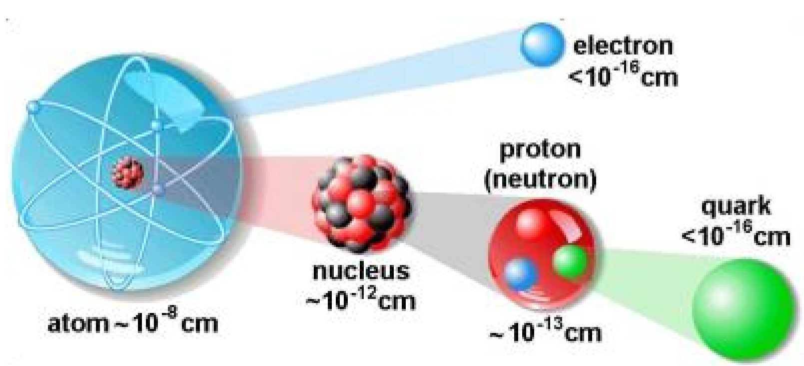


Quarks, electron → matter



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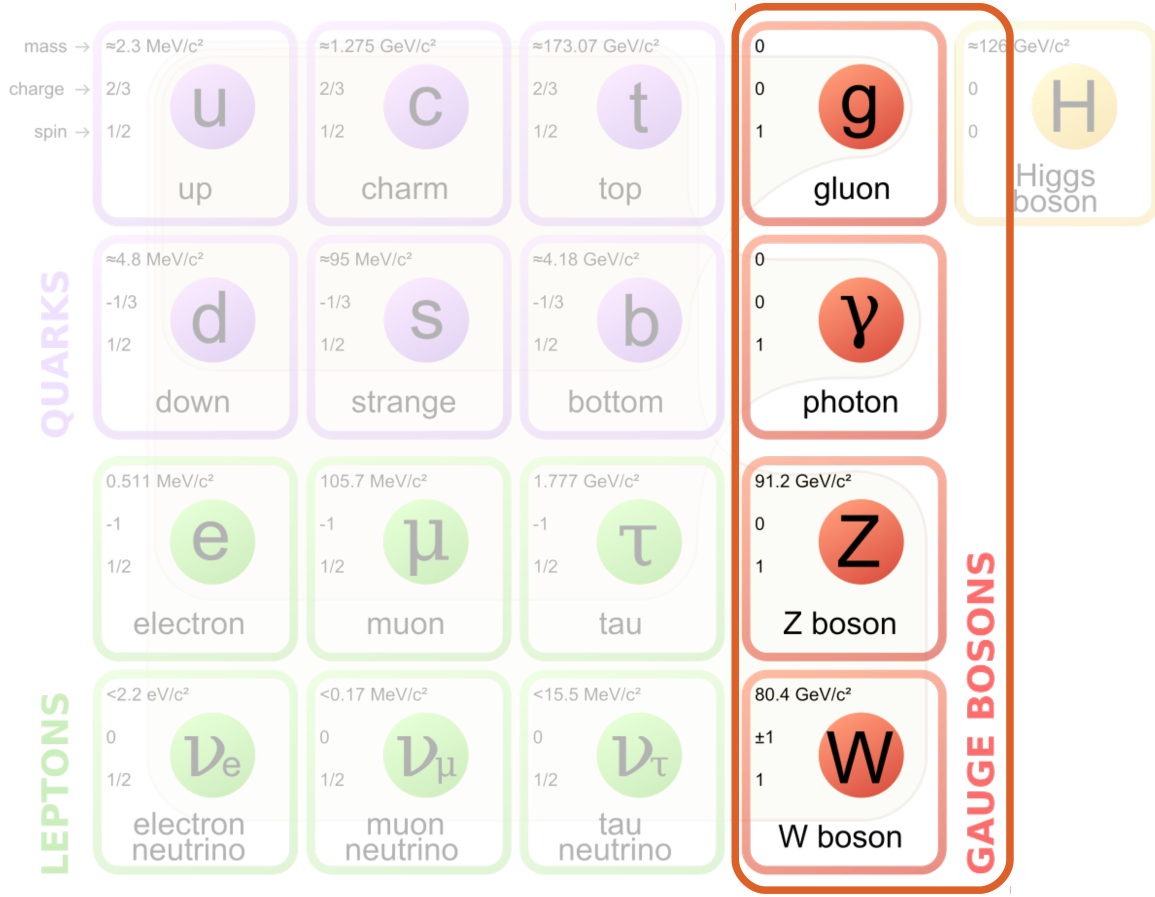
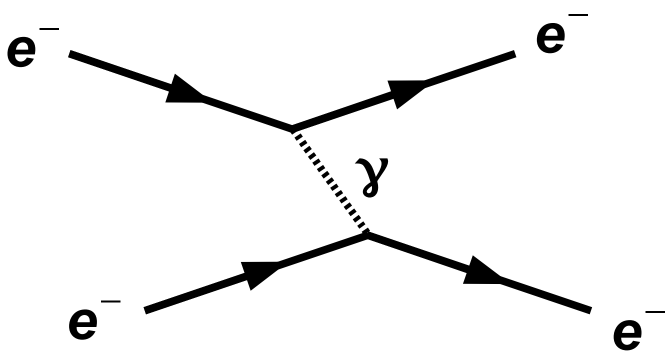


Gauge Bosons → interactions



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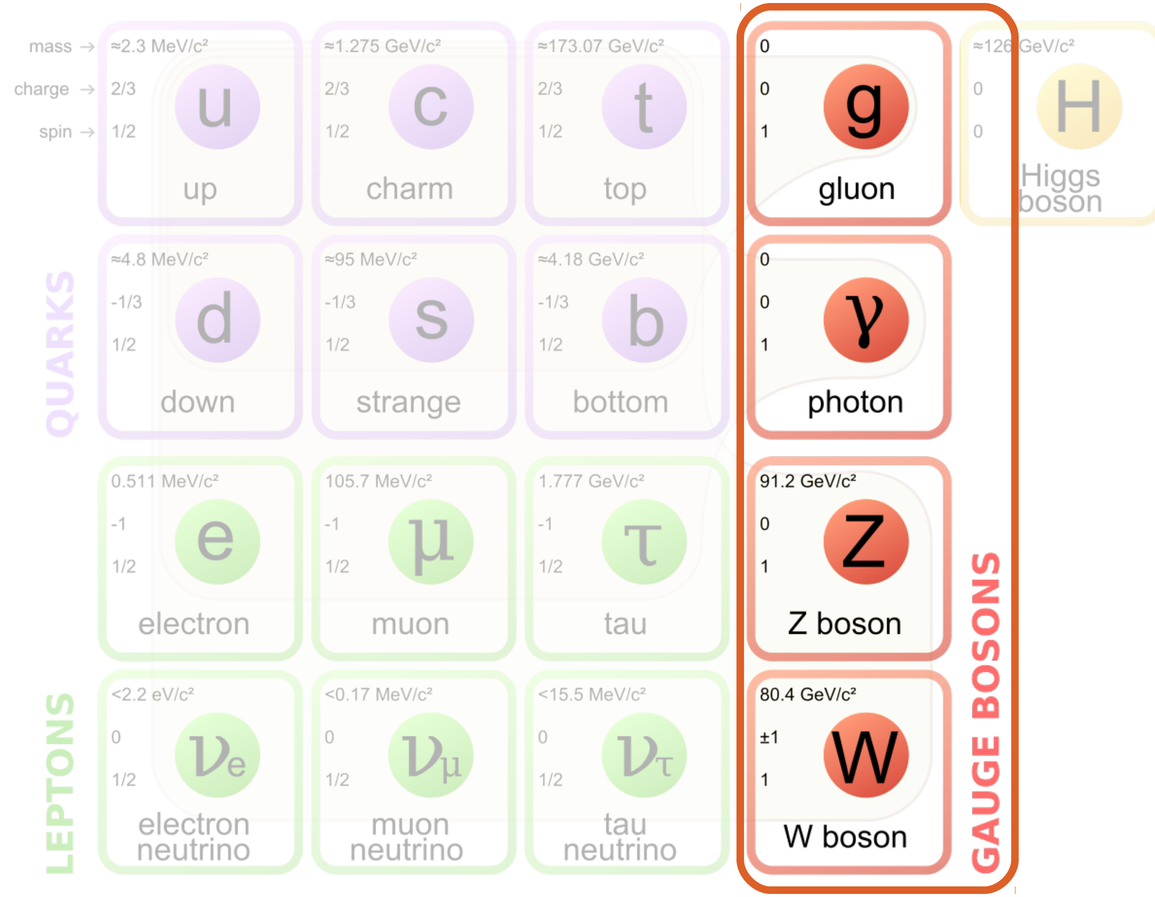

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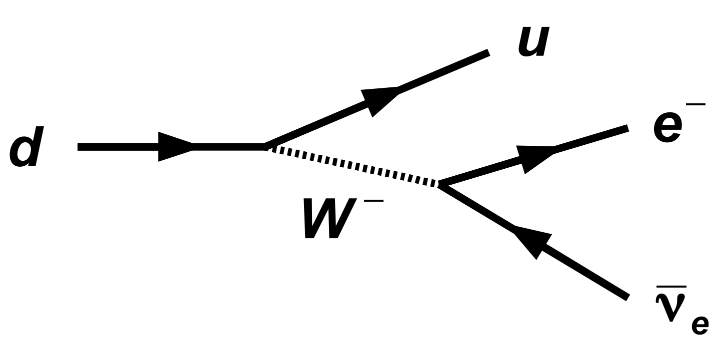

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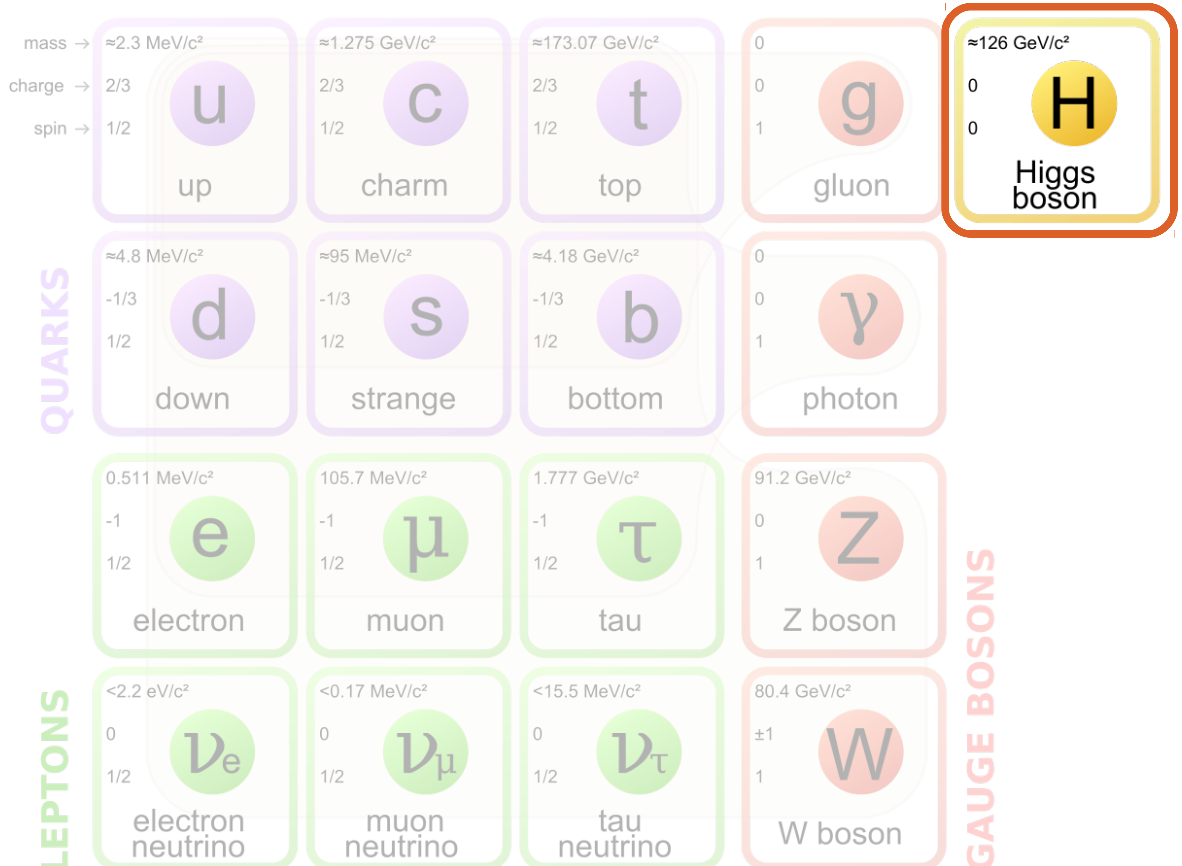

Higgs Boson → mass

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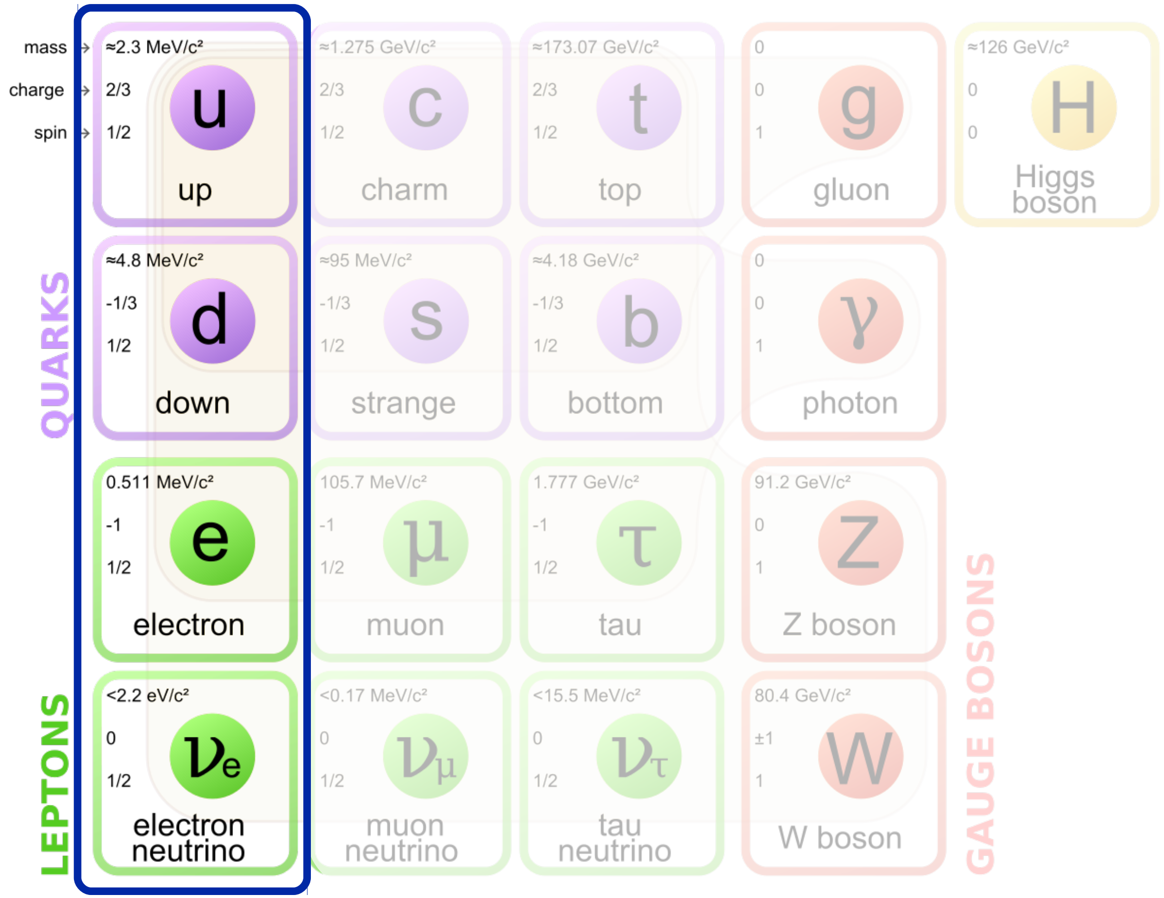
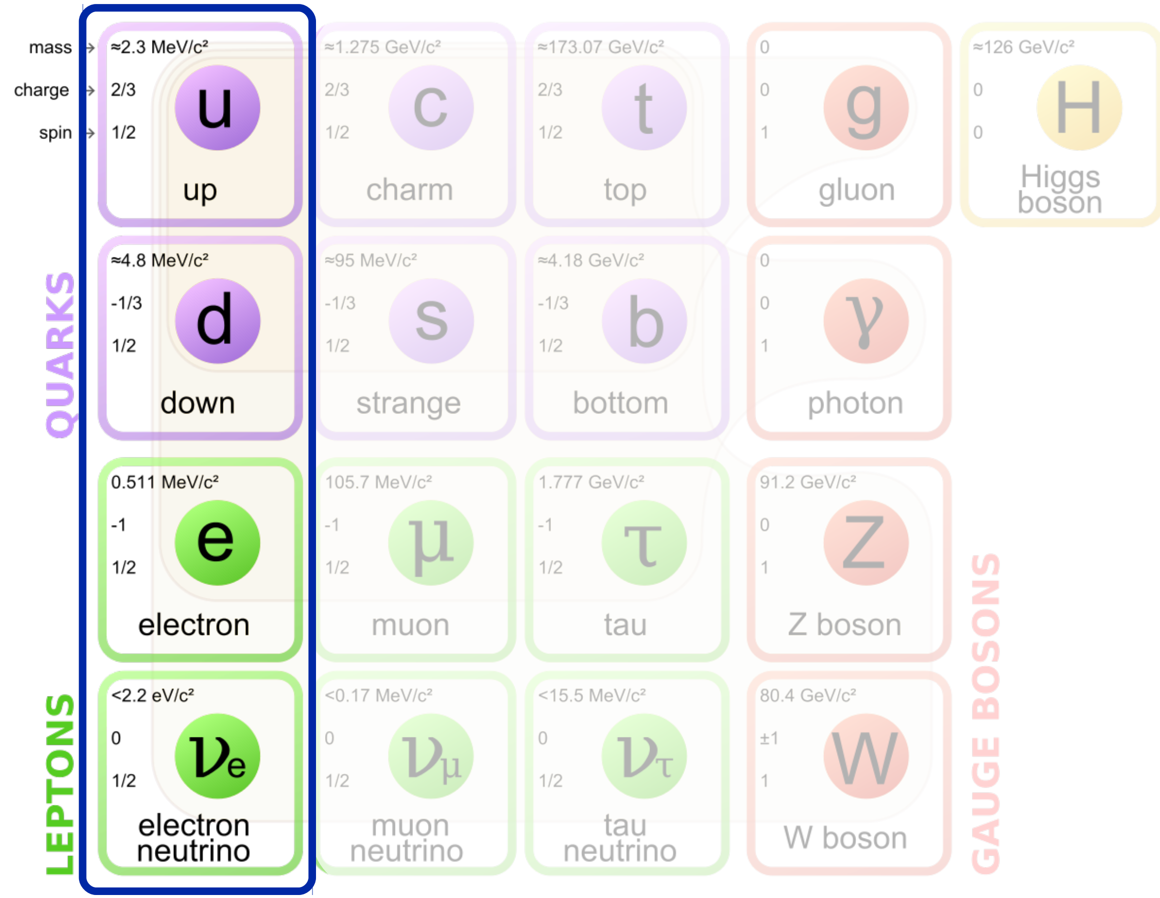


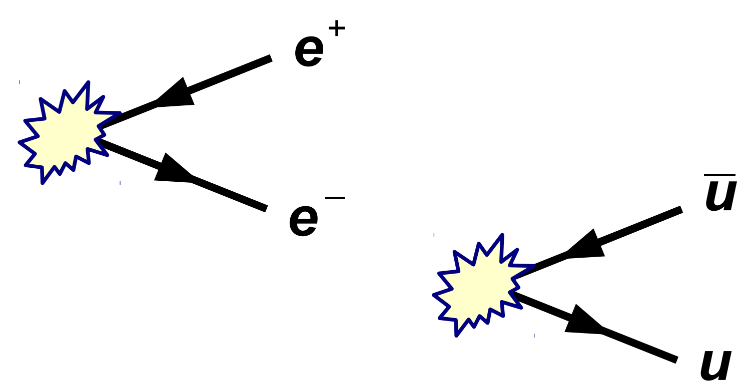
For each matter particle there is a corresponding antiparticle

- **Same mass as the particle, but opposite charge**

Standard Model of Particle Physics



Particle – antiparticle pairs can be produced out of energy



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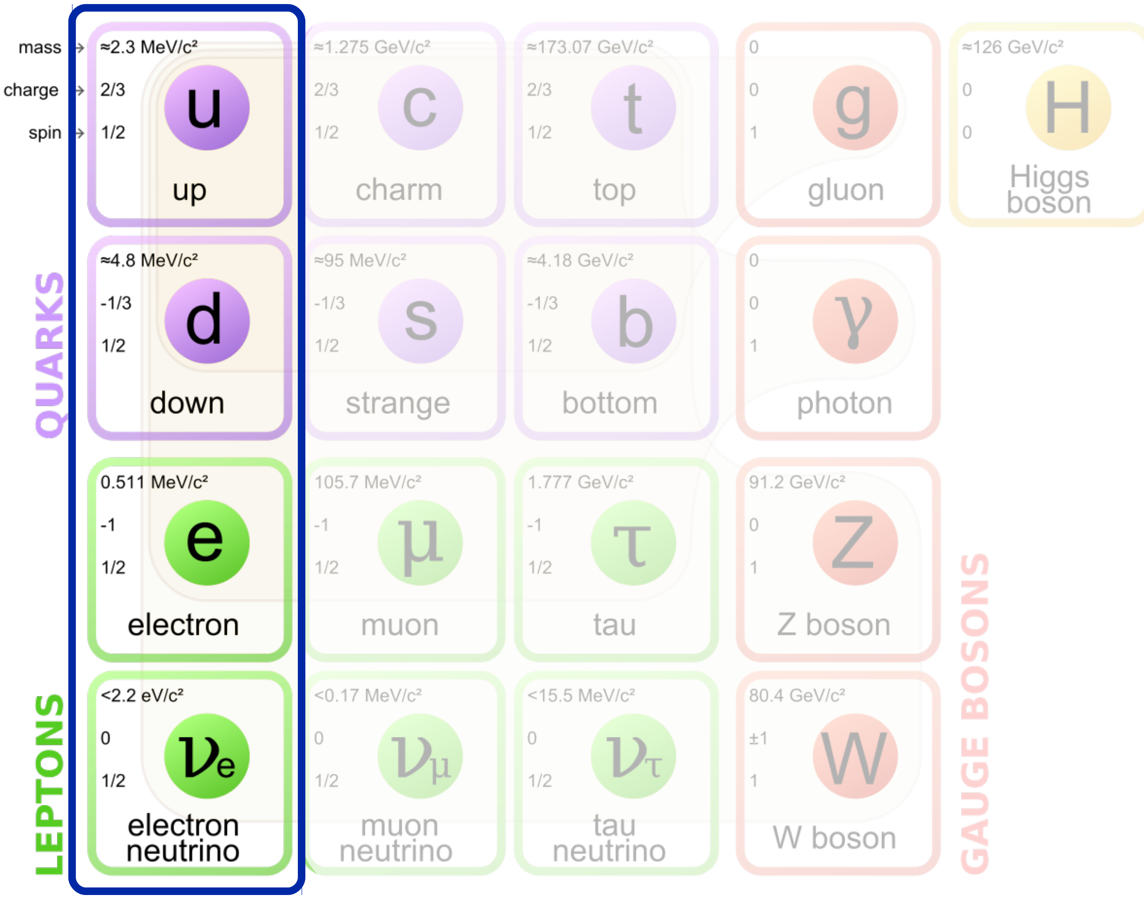
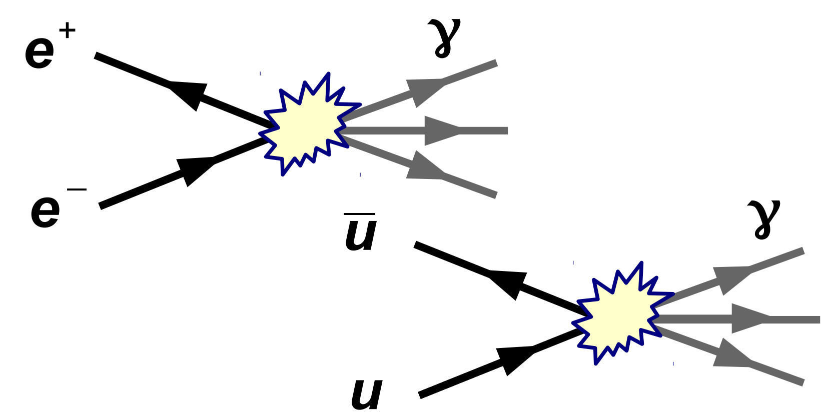
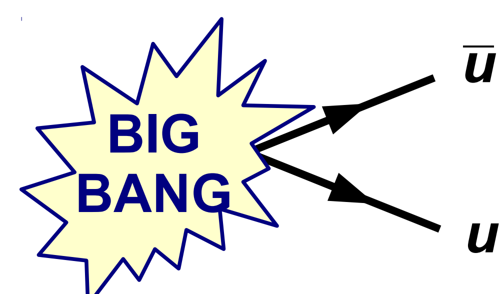


Particle – antiparticle pairs annihilate into energy (e.g. gamma rays)



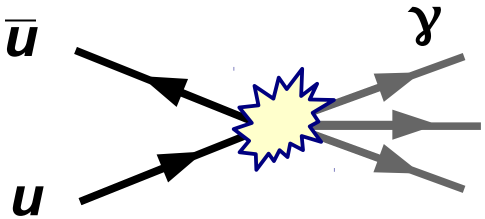
Fundamental Questions

WHY DO WE SEE SO MUCH MORE MATTER THAN ANTIMATTER IN THE UNIVERSE ?

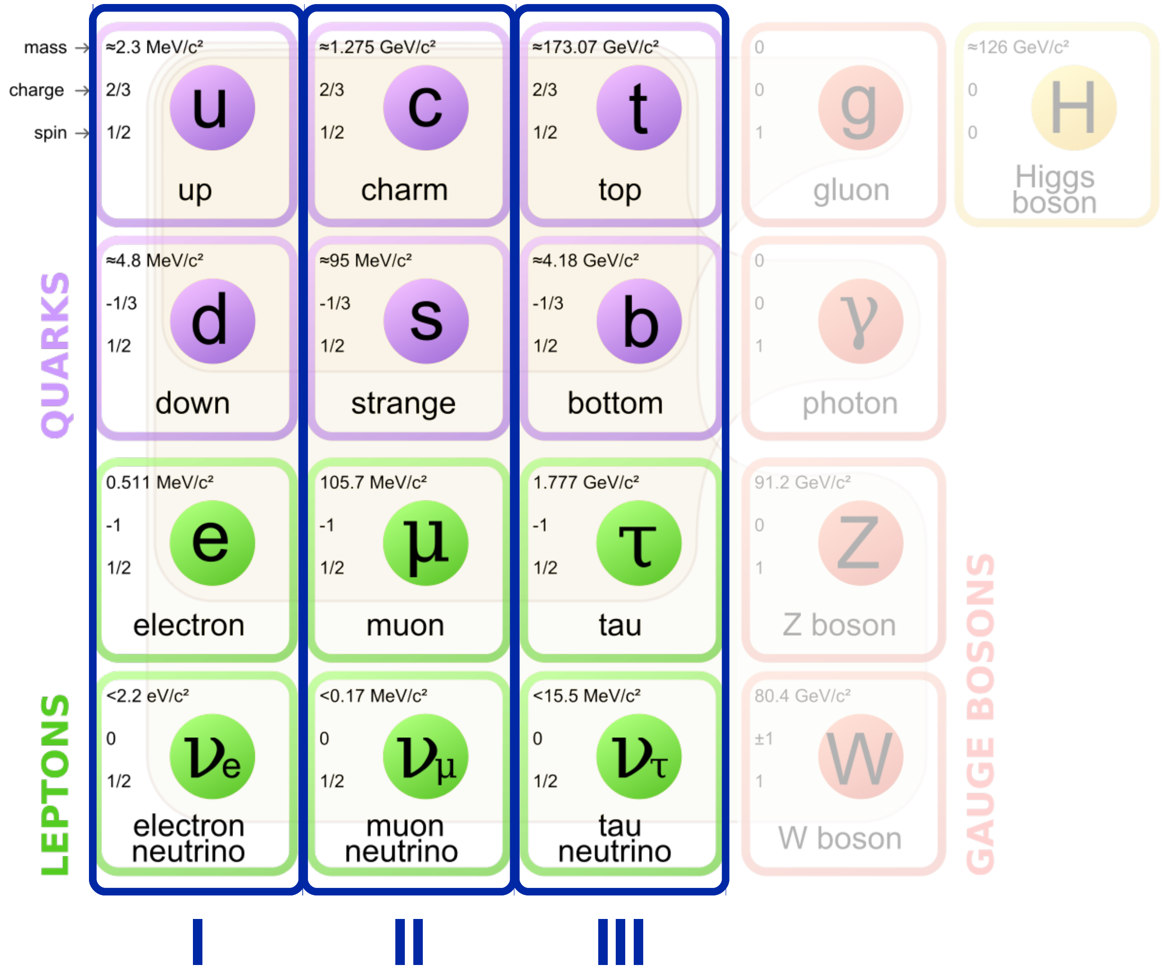


Fundamental Questions

WHY DOES ANYTHING EXIST AT ALL ?



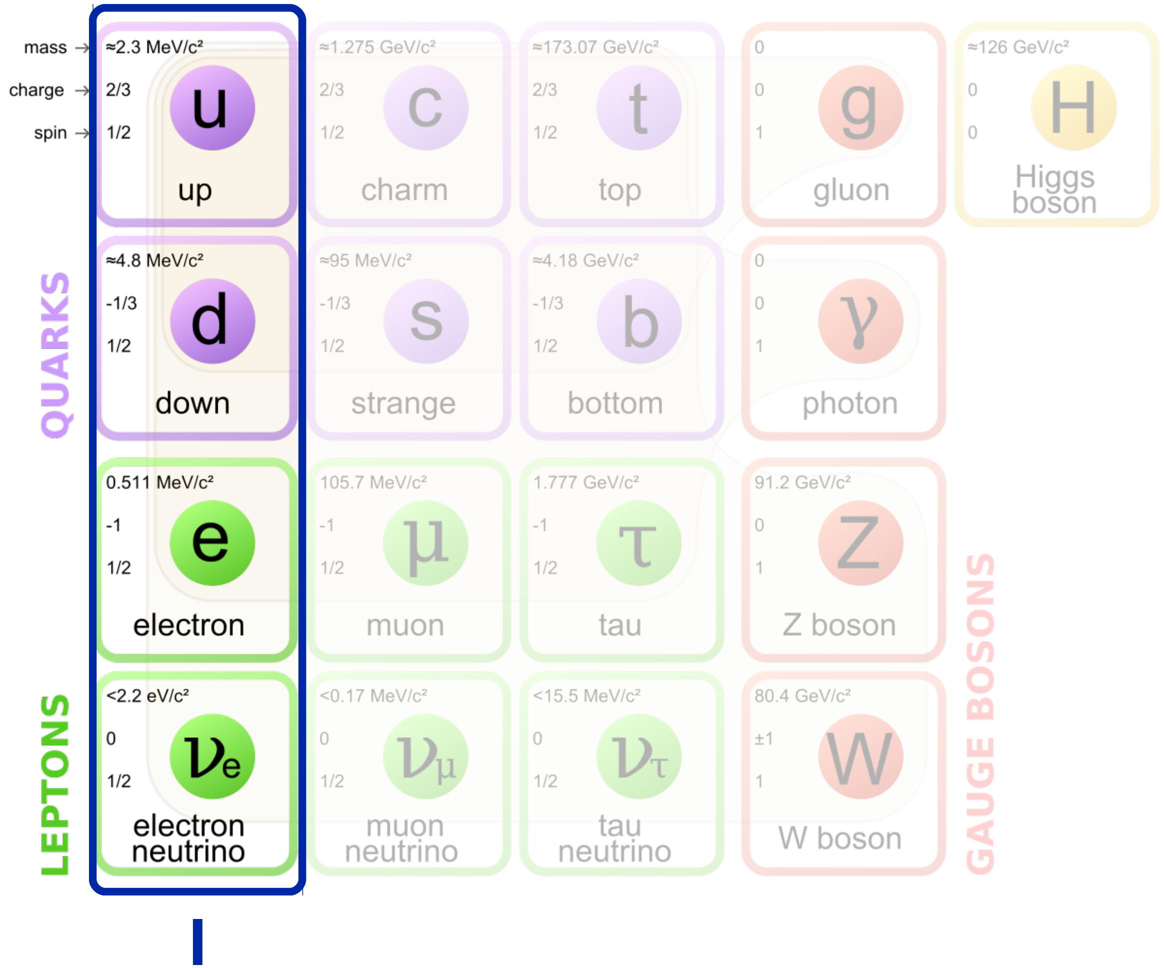
Standard Model of Particle Physics



Three "generations" of matter particles

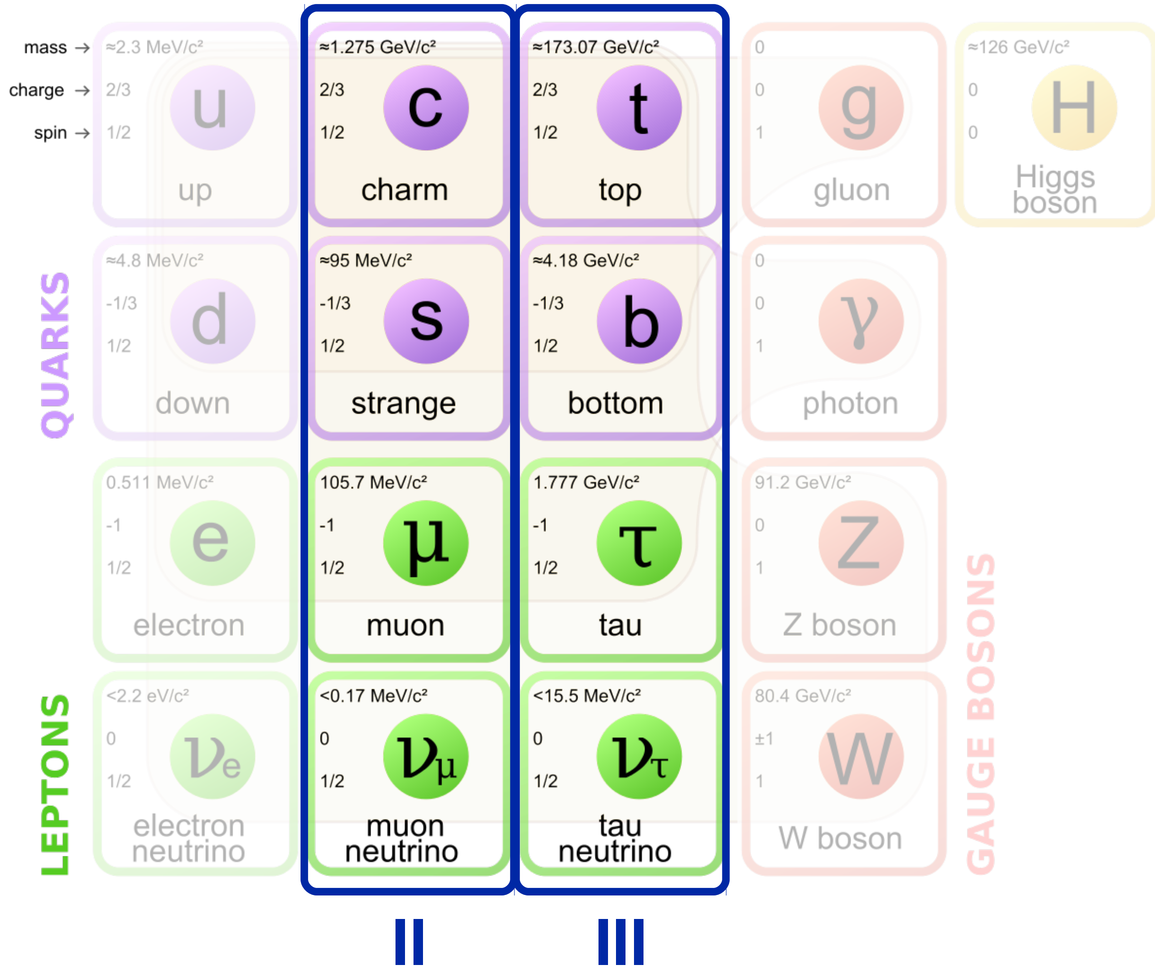
2nd and 3rd generation are heavier siblings of 1st generation

Standard Model of Particle Physics

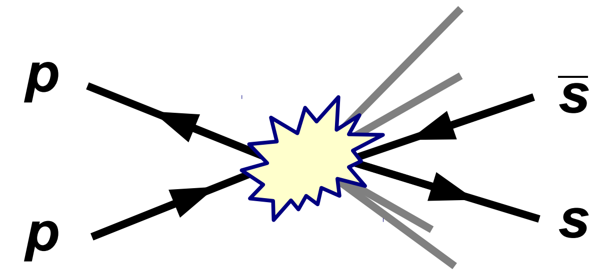


All ordinary matter (you, me, …) is made up from particles of the 1st generation

Standard Model of Particle Physics



Particles of 2nd and 3rd generation can be produced in high-energy collisions (cosmic rays, particle accelerators)



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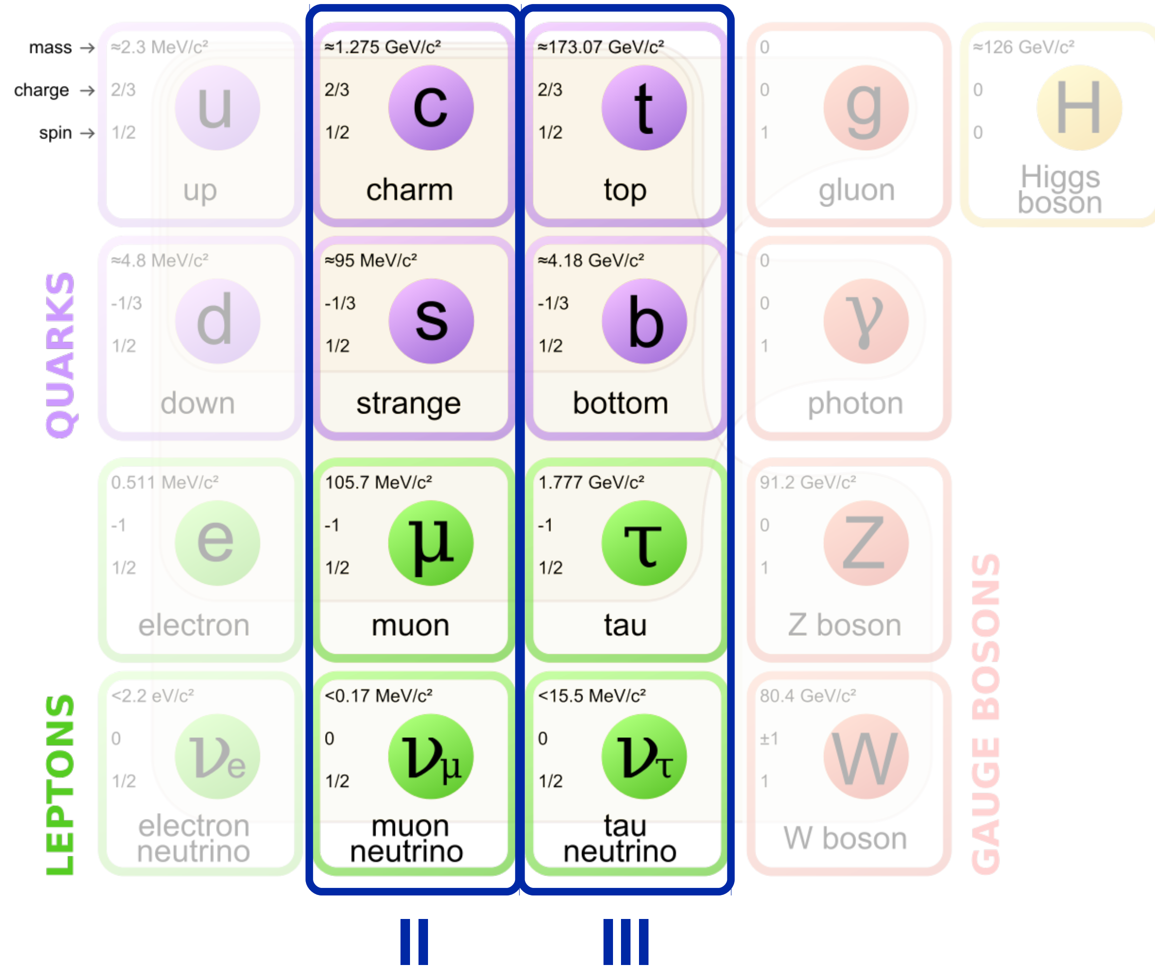
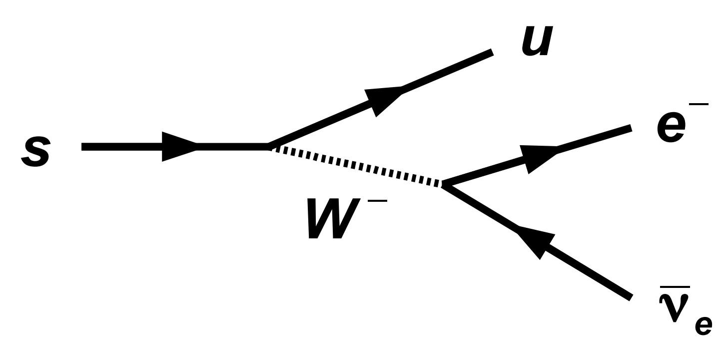


… but they are very short-lived and decay to particles of the 1st generation



Fundamental Questions

Who ordered THAT ?

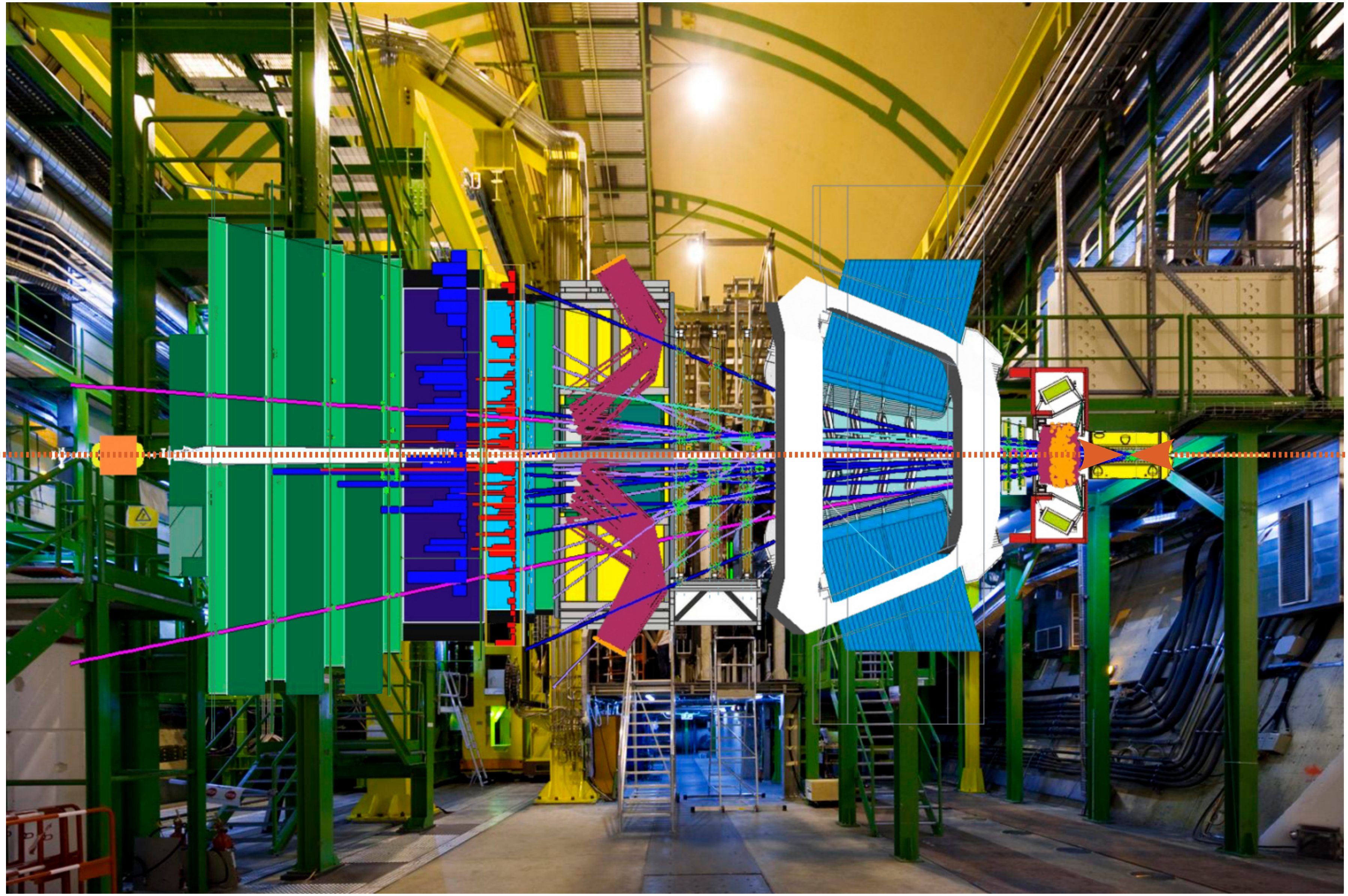
(Isidor Isaac Rabi on the discovery of the muon)

photo source: <https://en.wikipedia.org/wiki/Isidor_Isaac_Rabi>

WHY THREE GENERATIONS ?

LHCb Experiment

p



p

source: <https://cds.cern.ch/record/1463546>

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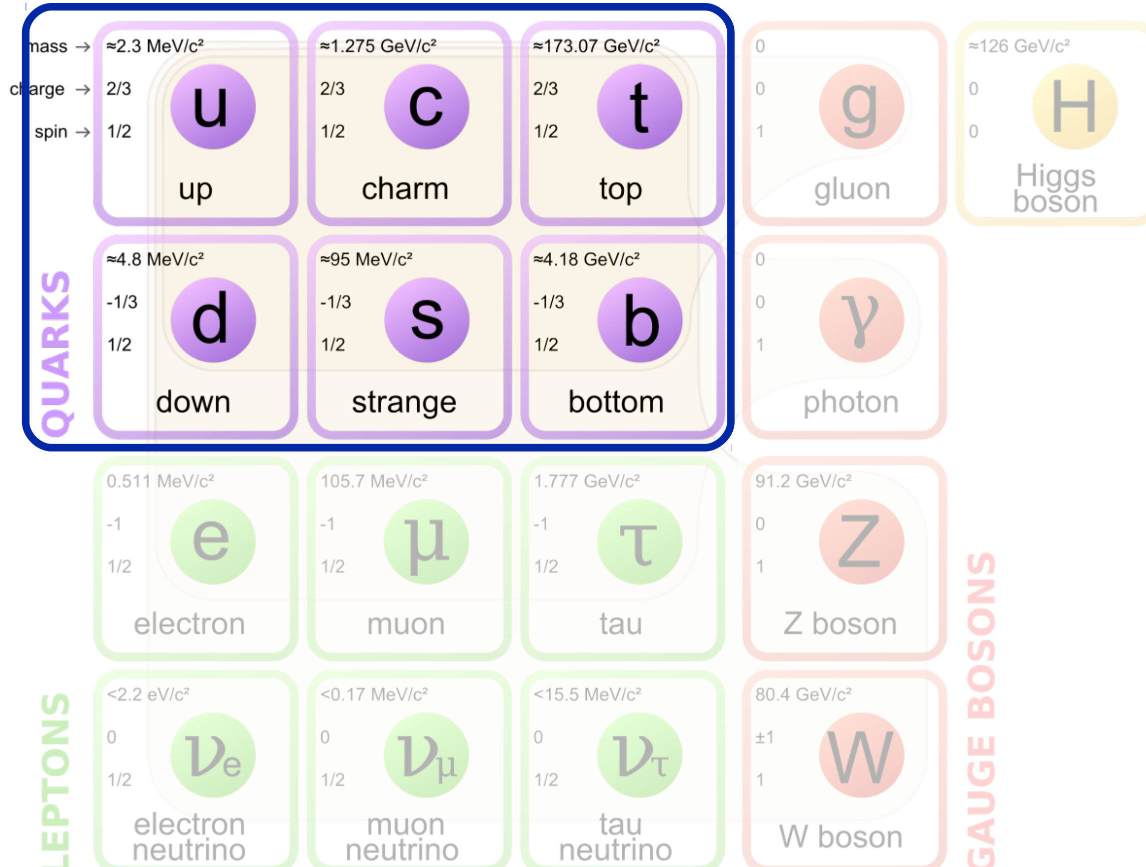
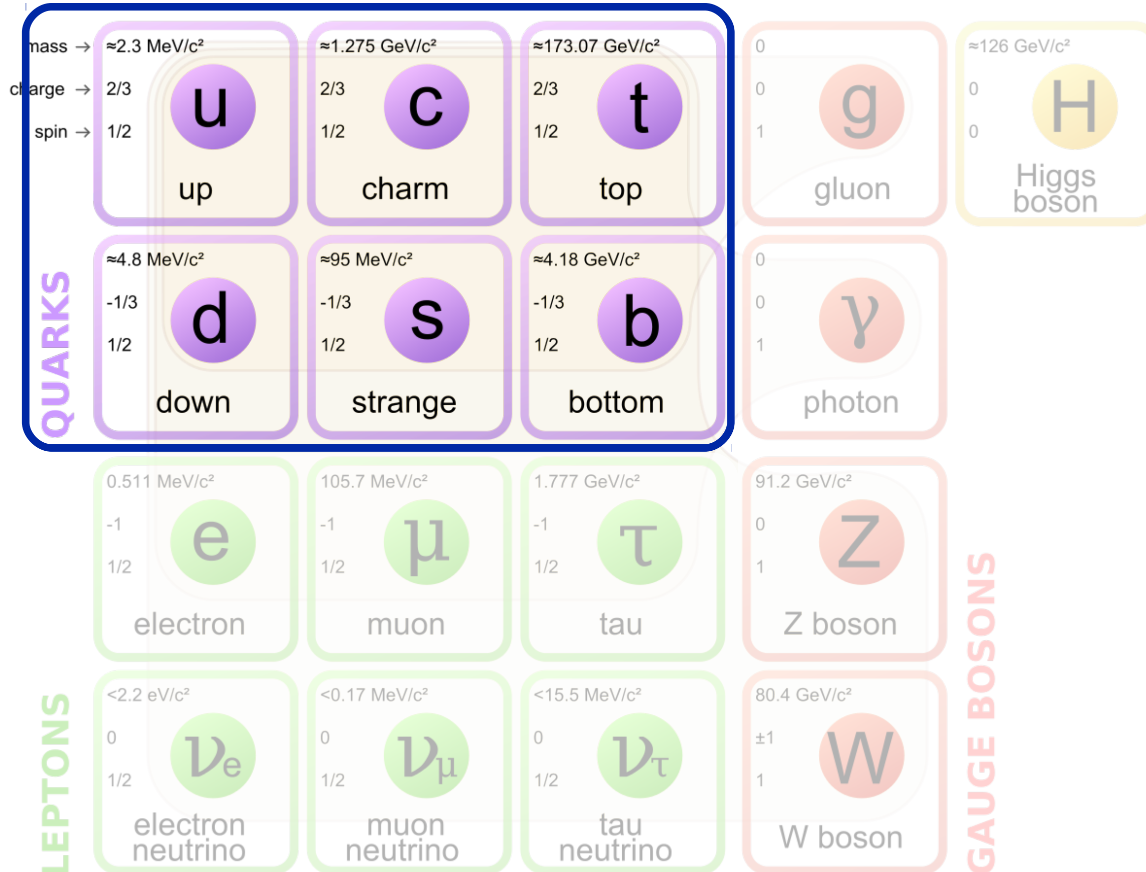


Quarks are not observed as free particles

Standard Model of Particle Physics

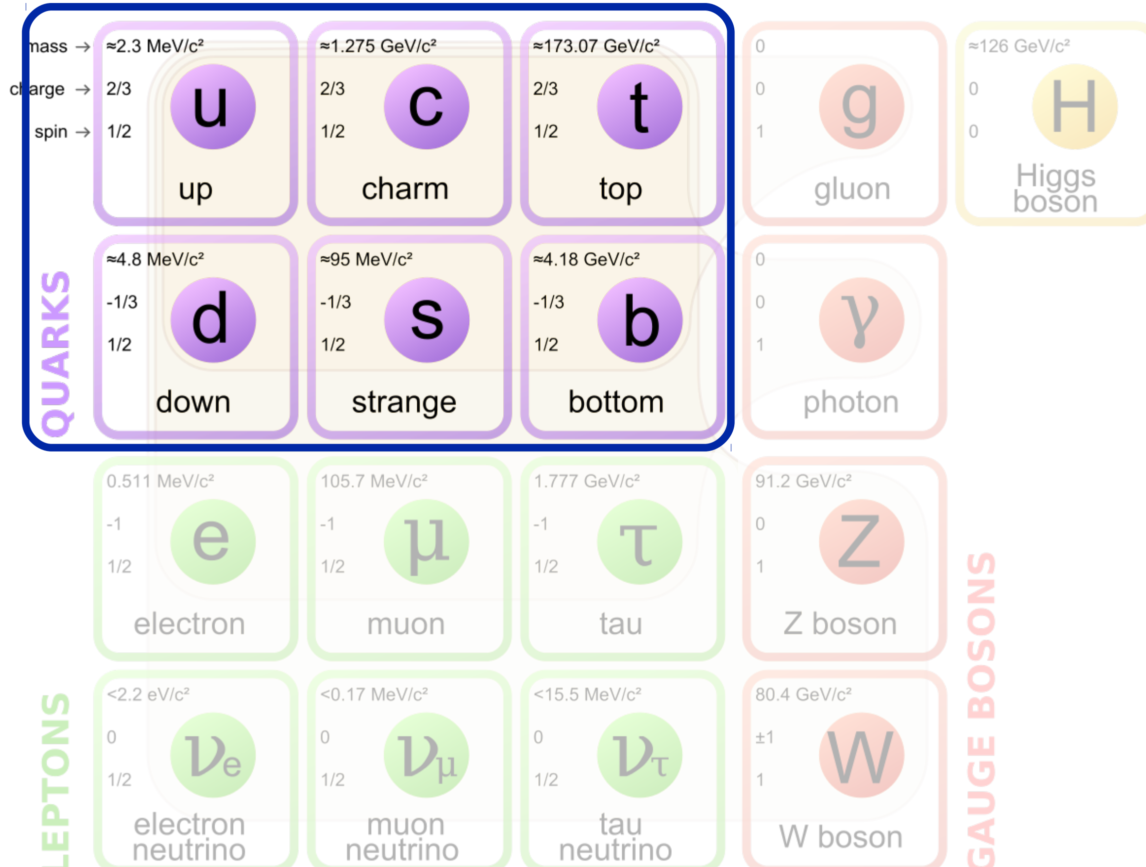


Particles that are observed consist of

- **three quarks (e.g. proton), or**
  - **a quark and an antiquark**

("exotic" combinations: Tetraquarks, Pentaquarks)

Standard Model of Particle Physics



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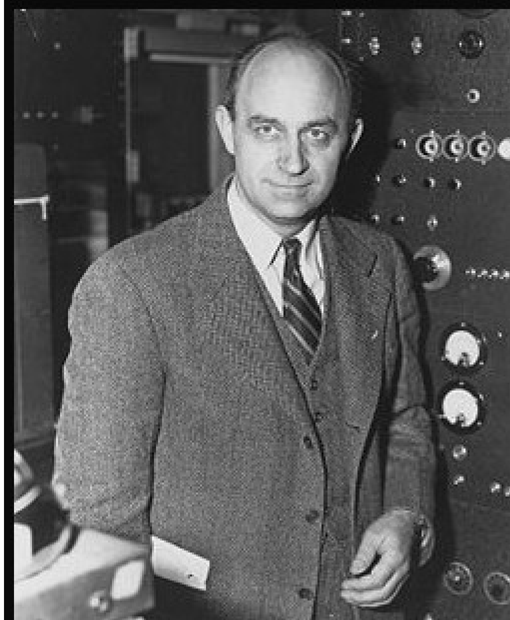
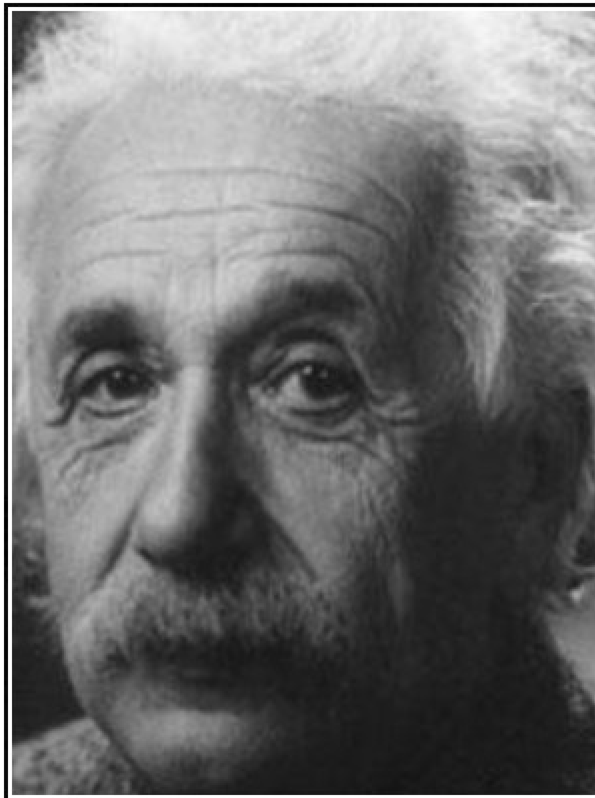
Many possible combinations: "particle zoo"



If I could remember the names of all these particles, I would have been a botanist.

(Enrico Fermi)



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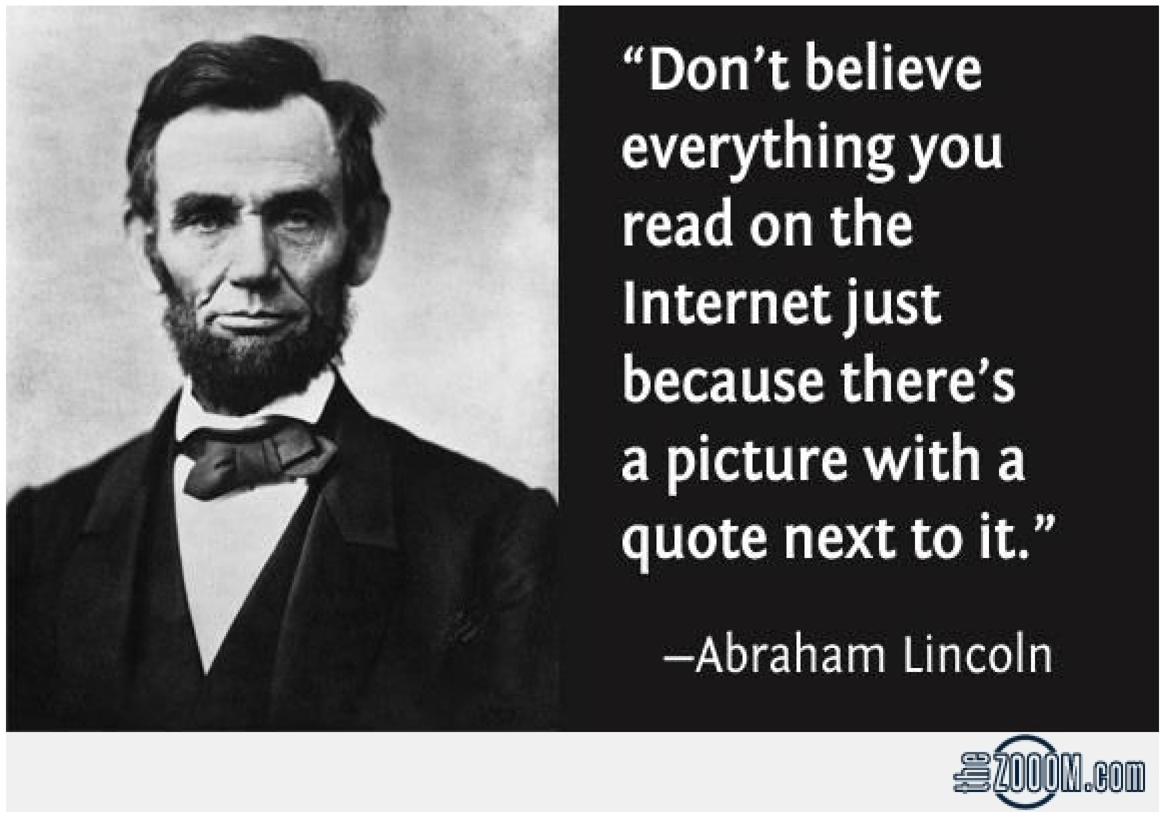
— *Albert Einstein* —

AZ QUOTES

source: <http://www.azquotes.com/quote/582126>



source: <http://www.thezooom.com/2012/07/3962/>

Reconstructing an Event

Most particles in the particle zoo are very short-lived

Very few are stable or live long enough to leave a trace in a particle detector

electrons and muons

protons (*uud*)

pions ($u\bar{d}$) and kaons ($u\bar{s}$)

} **charged**

photons

neutrons (*udd*)

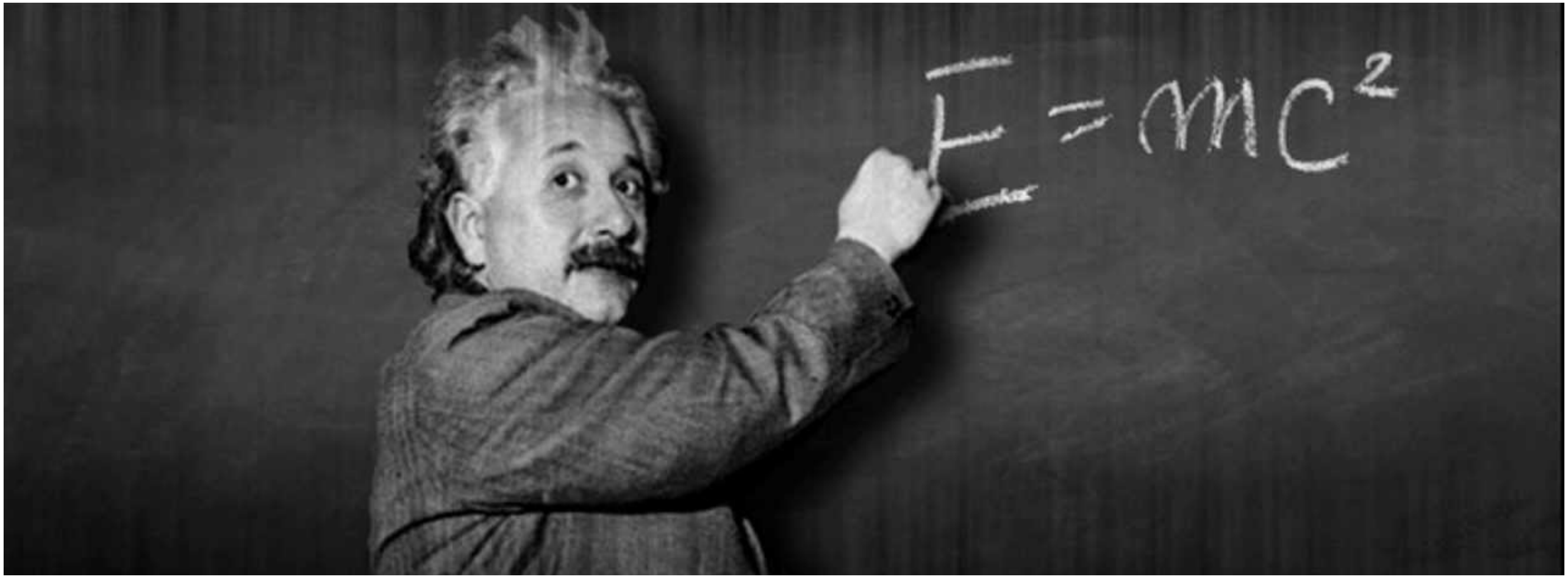
} **neutral**

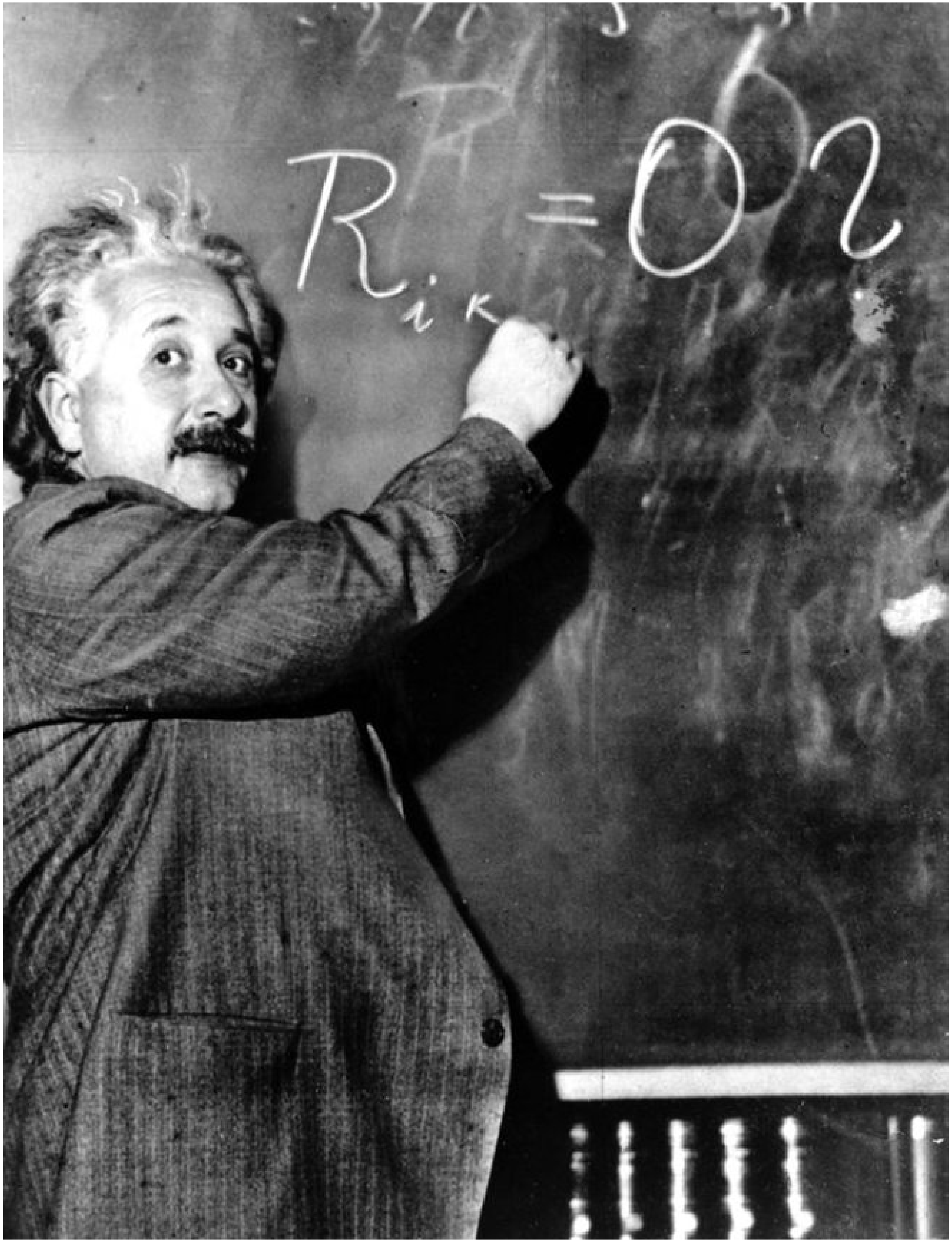
... and their antiparticles

Reconstructing an Event

Short-lived particles can be reconstructed indirectly by measuring their long-lived decay products

→ Relativistic kinematics





source: <http://www.gettyimages.ch/fotos/einstein-e=mc2>

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→ Relativistic kinematics

$$E = m \cdot c^2$$

Reconstructing an Event

Short-lived particles can be reconstructed indirectly by measuring their long-lived decay products

→ Relativistic kinematics

$$E = m$$

"natural units": $c = 1$

Reconstructing an Event

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

Reconstructing an Event

Short-lived particles can be reconstructed indirectly by measuring their long-lived decay products

→ Relativistic kinematics

$$m^2 = E^2 - p^2$$

Reconstructing an Event

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→ Energy and momentum conserved in the decay

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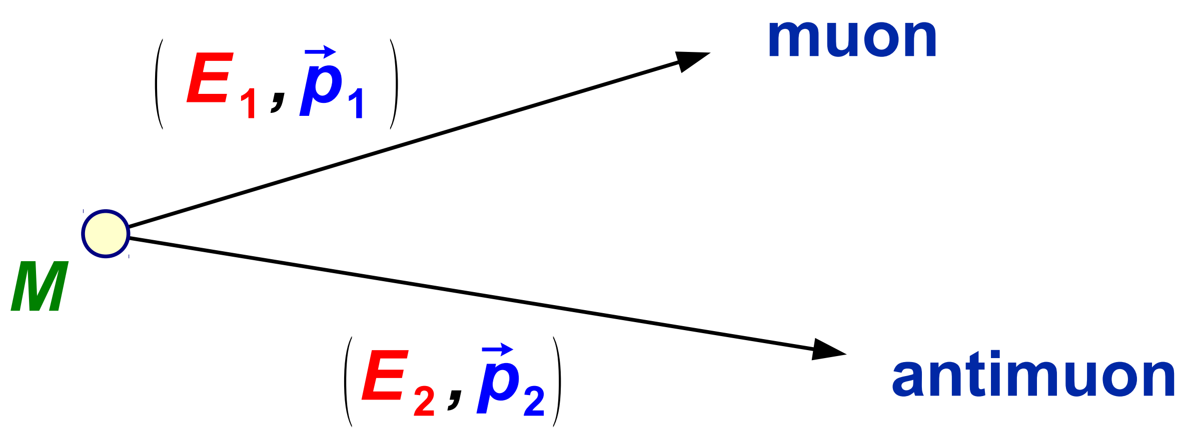
- M^2: mass of decaying particle
- $\sum_i$: sum over decay products
- E_i: energies of decay products
- $\vec{p}_i$: momenta of decay products

Reconstructing an Event

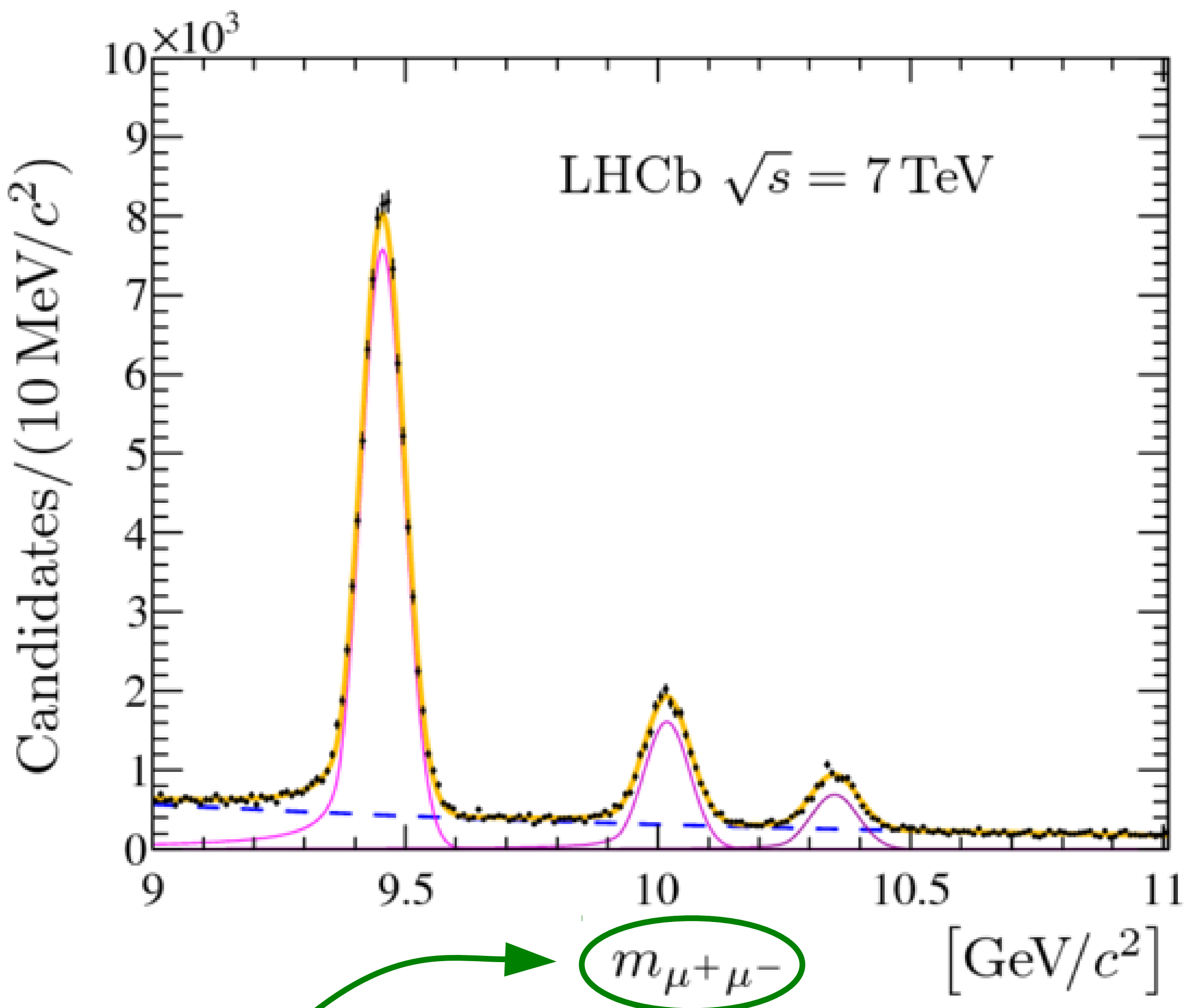


Simple example: particle decays to a muon and an antimuon

- Measure the momenta of the muon and the antimuon
- Determine their energies
- Calculate the mass of the decaying particle:

$$M^2 = \left(E_1 + E_2 \right)^2 - \left| \vec{p}_1 + \vec{p}_2 \right|^2$$

Reconstructing an Event

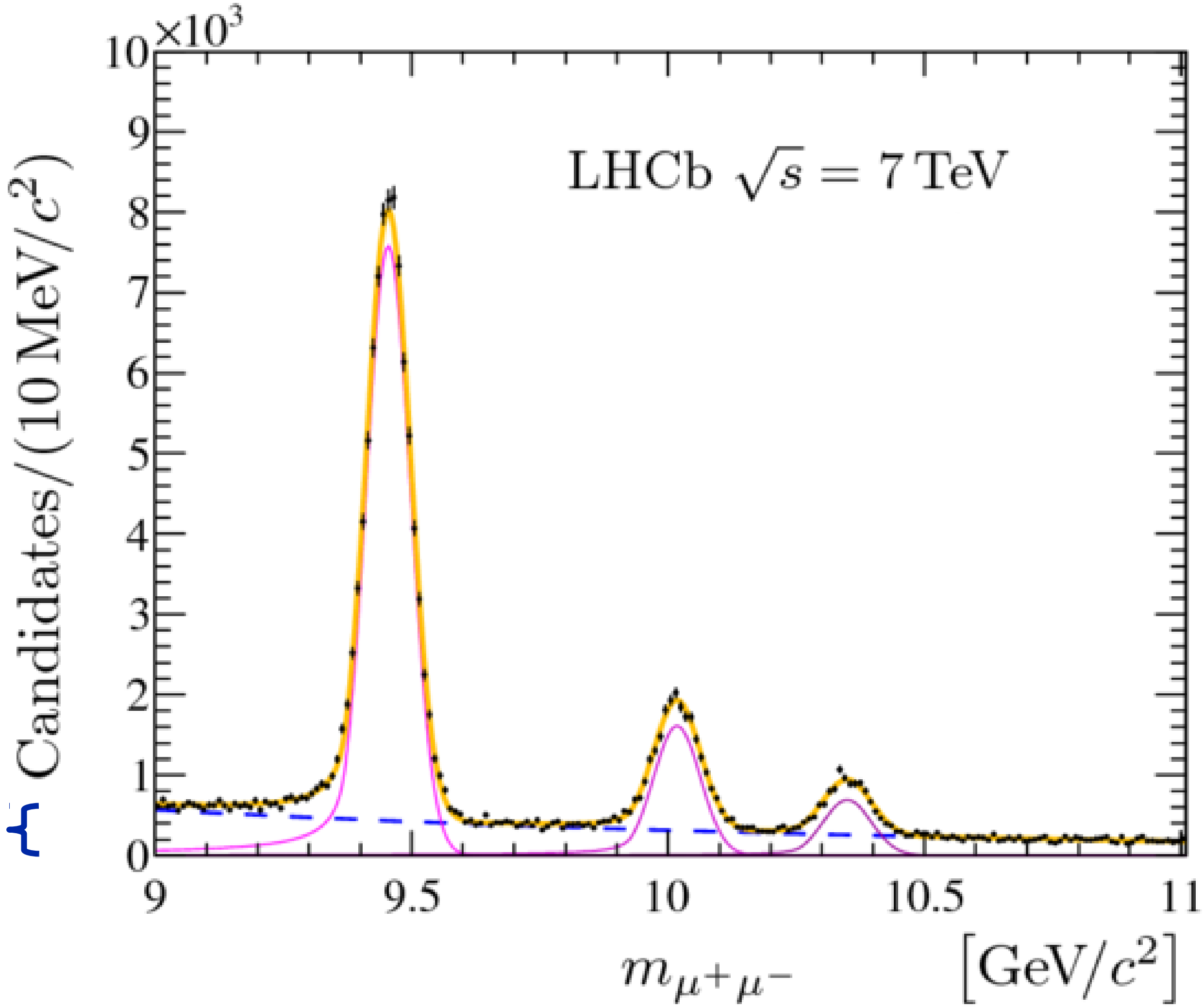


$$M^2 = \left(E_1 + E_2\right)^2 - \left|\vec{p}_1 + \vec{p}_2\right|^2$$

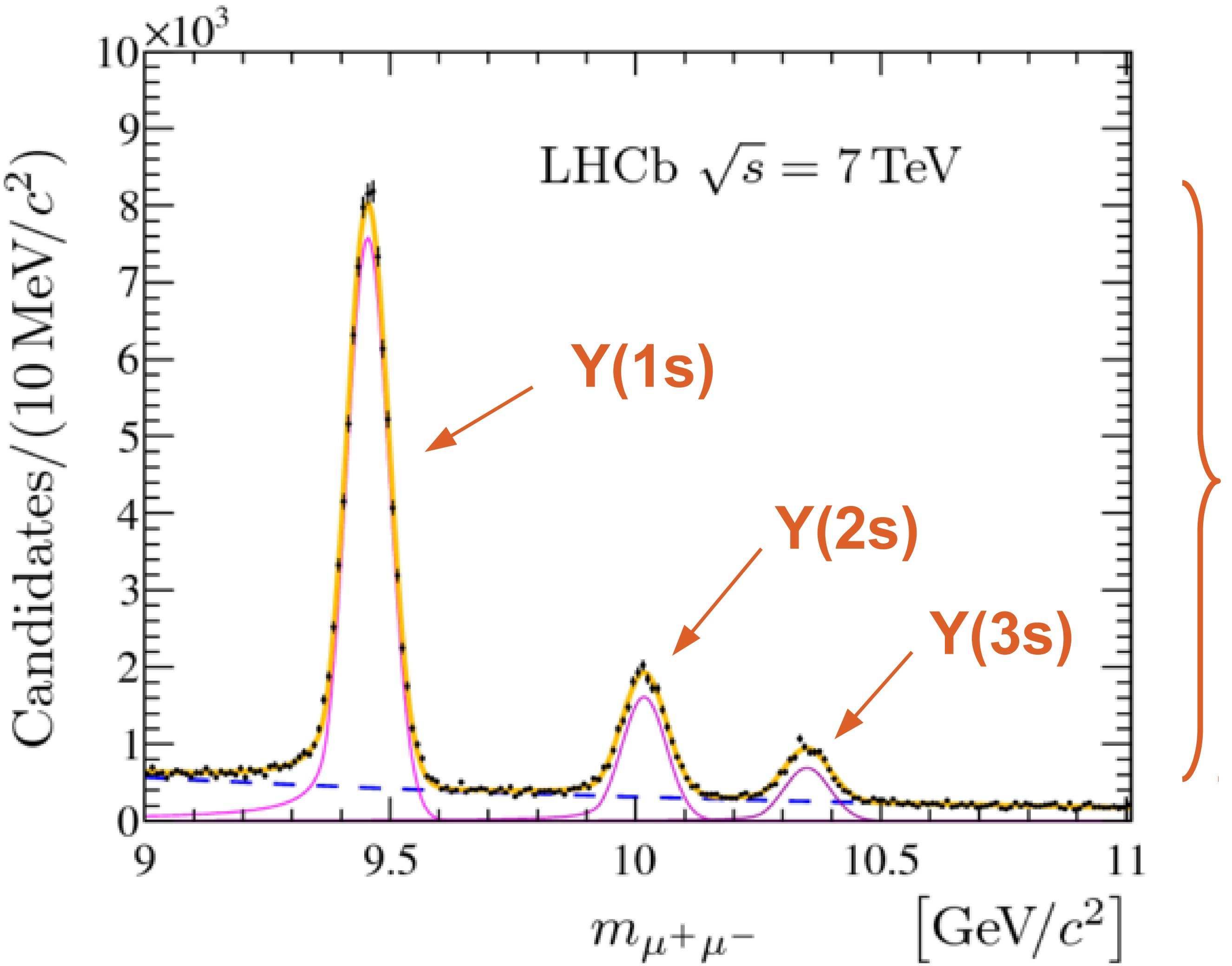
[The LHCb collaboration, R.Aaij et al., J.High Energy Phys.(2015) 103]

Reconstructing an Event

Random combinations of a muon and an antimuon

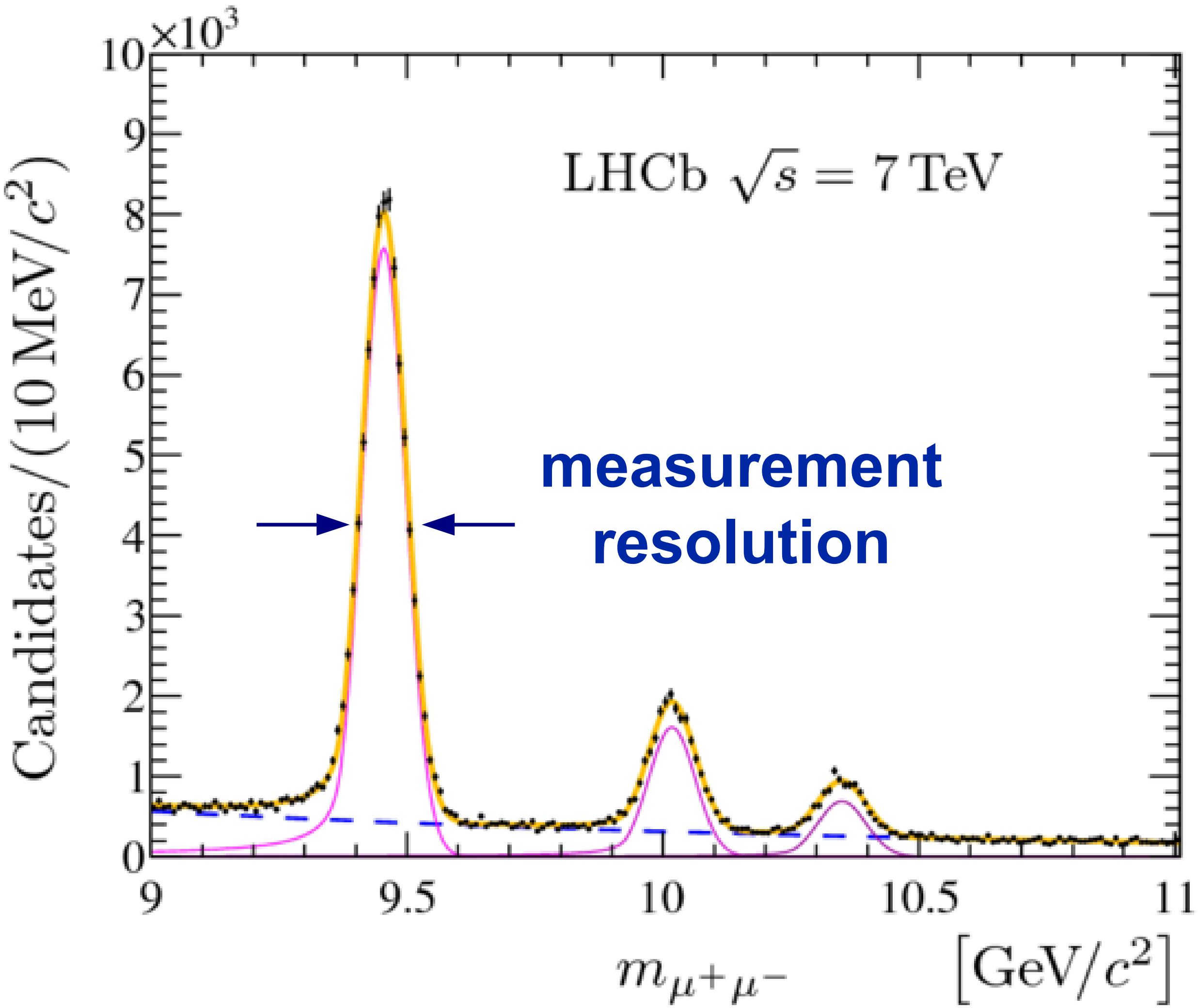


Reconstructing an Event



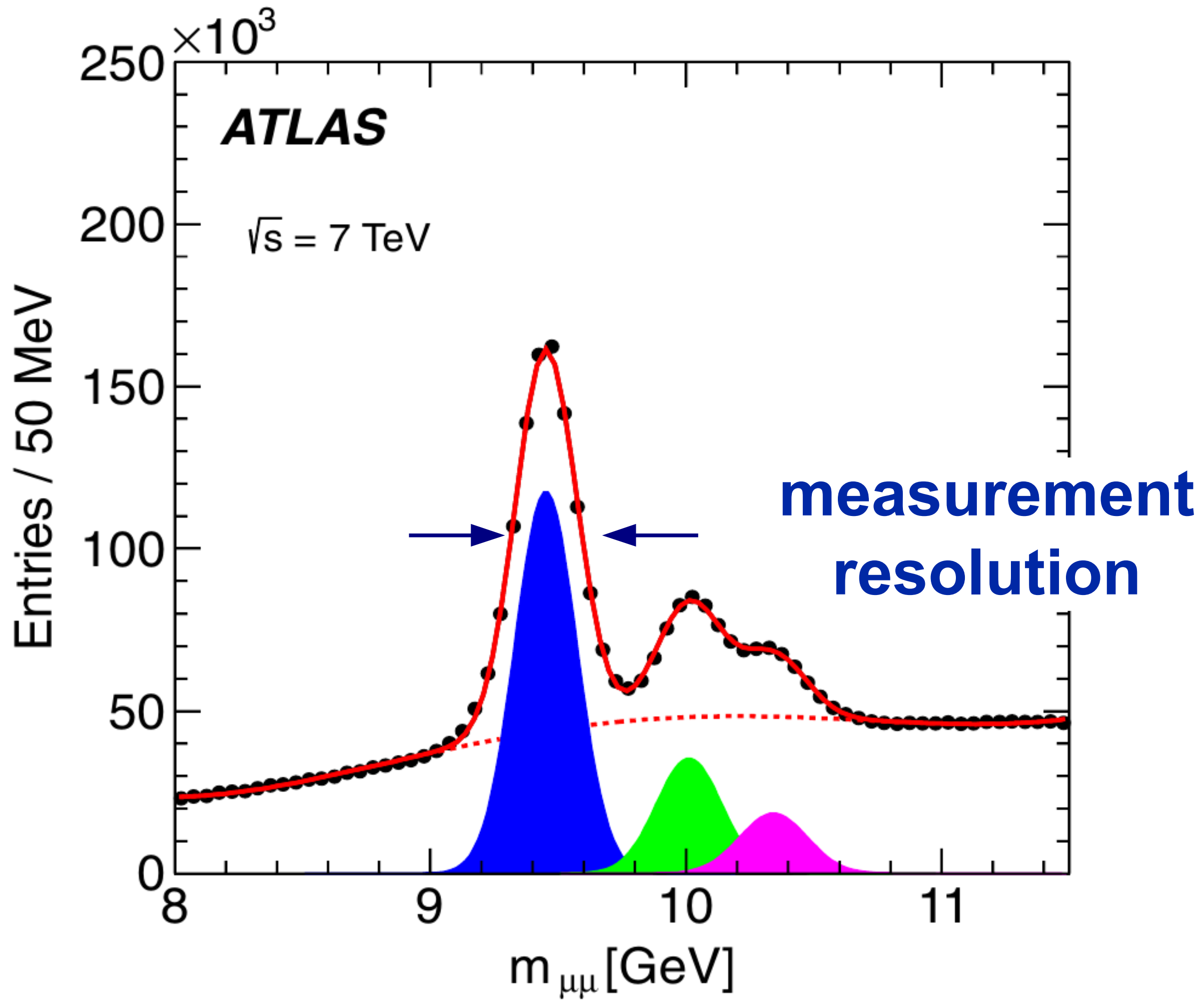
Short-lived particles decaying to a muon and an antimuon

Reconstructing an Event



Spread in reconstructed mass values due to finite precision of momentum measurements

Reconstructing an Event



[G.Aad et al. (ATLAS Collaboration), Phys.Rev.D 87 (2013) 052004]

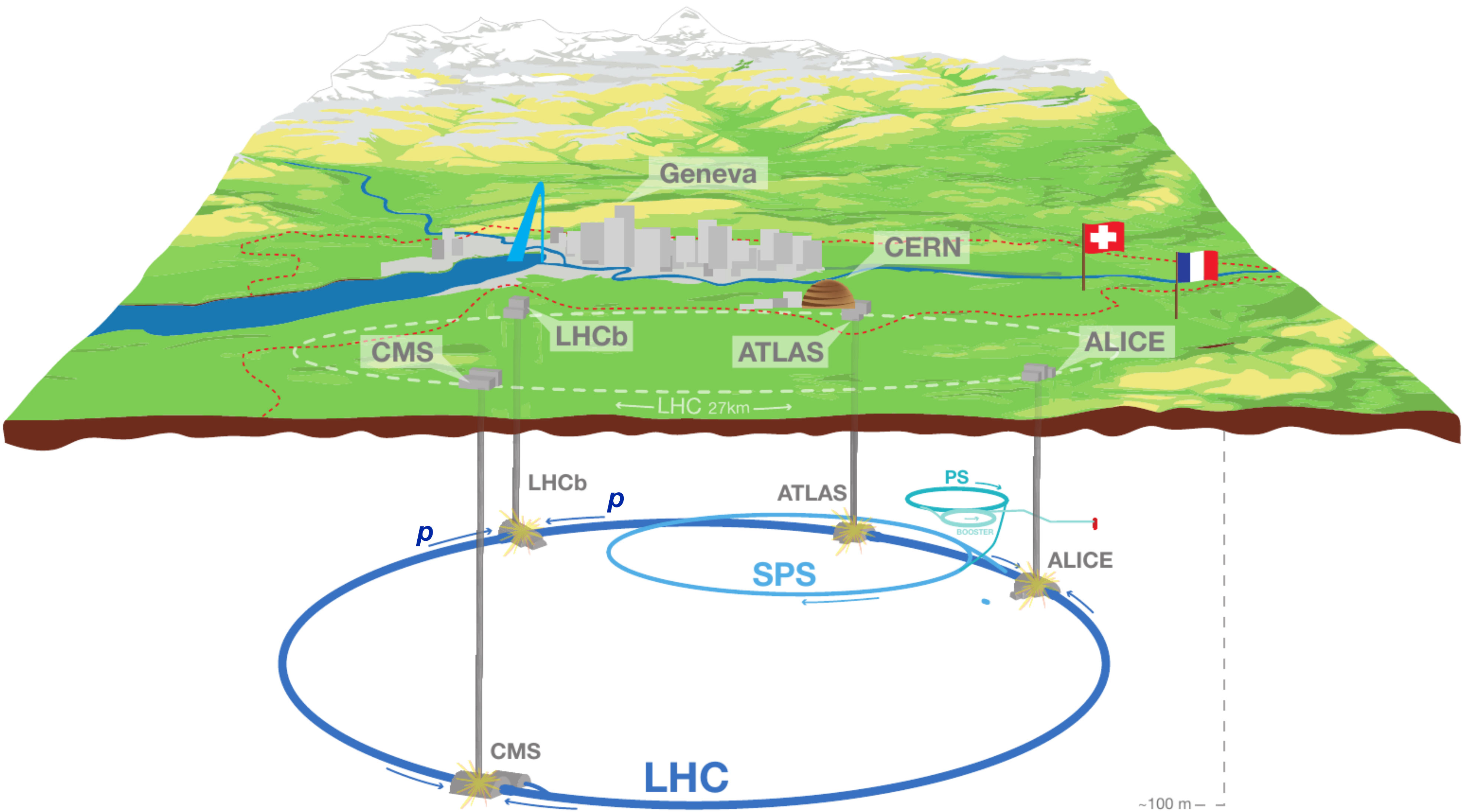
Spread in reconstructed mass values due to finite precision of momentum measurements

Reconstructing an Event

i.e. need to

- Measure the flight directions of long-lived particles
- Measure the magnitudes of their momenta
- Determine which type of particle they are
(to know their mass and energy)

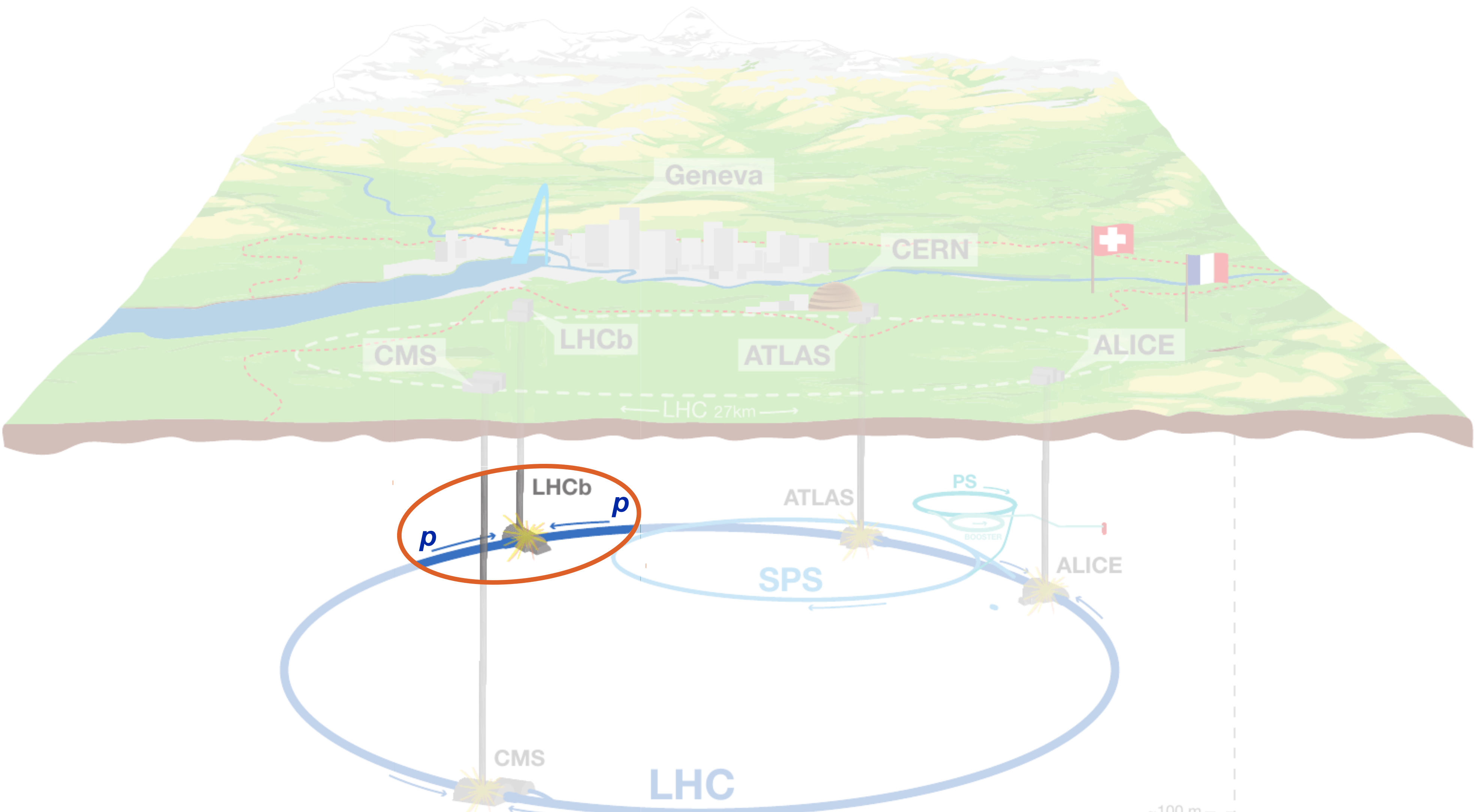
LHCb Experiment



source: <http://cds.cern.ch/record/1708849>

Collision energy = 13'000 × the mass of the proton

LHCb Experiment



LHCb Experiment

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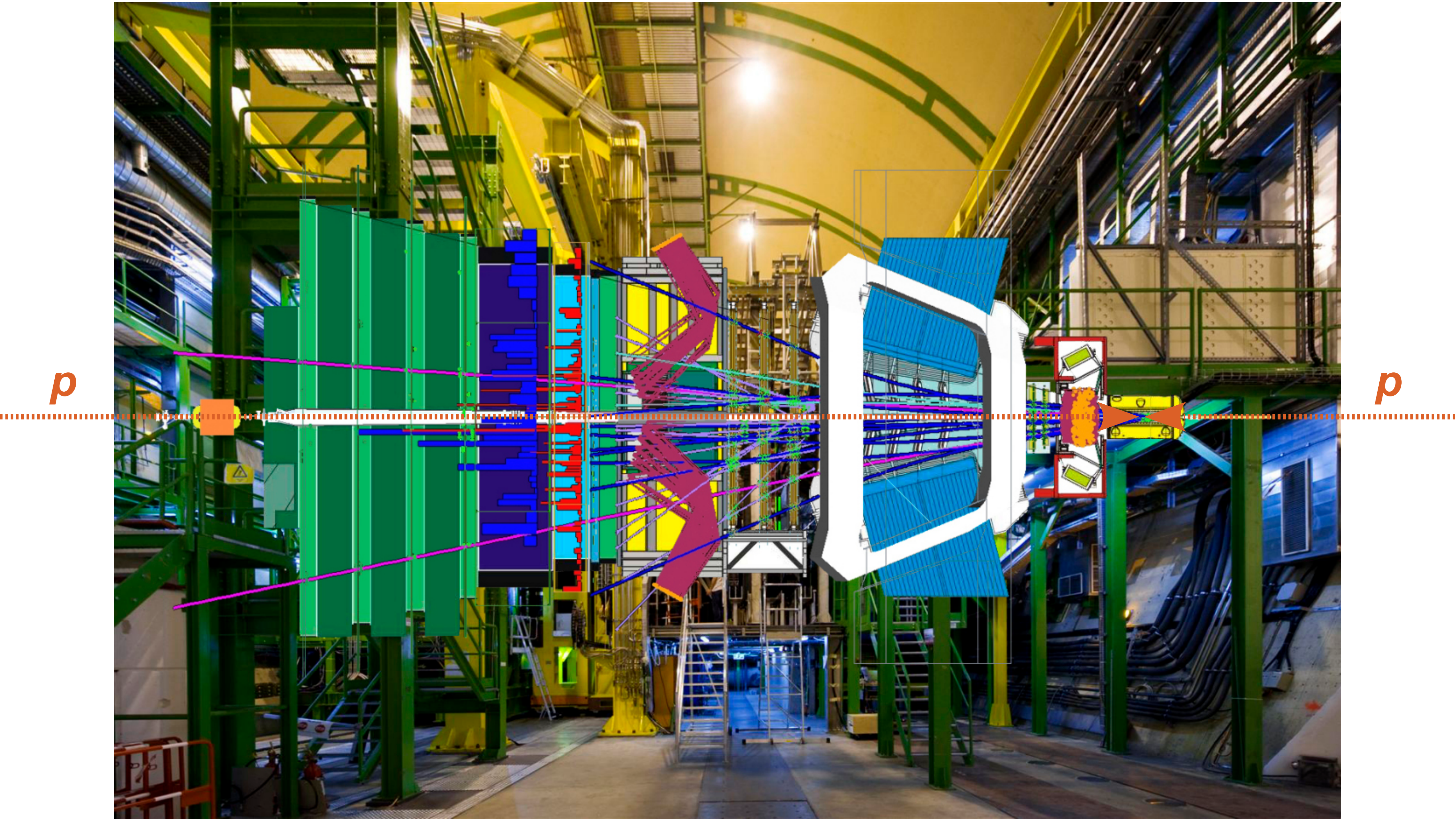

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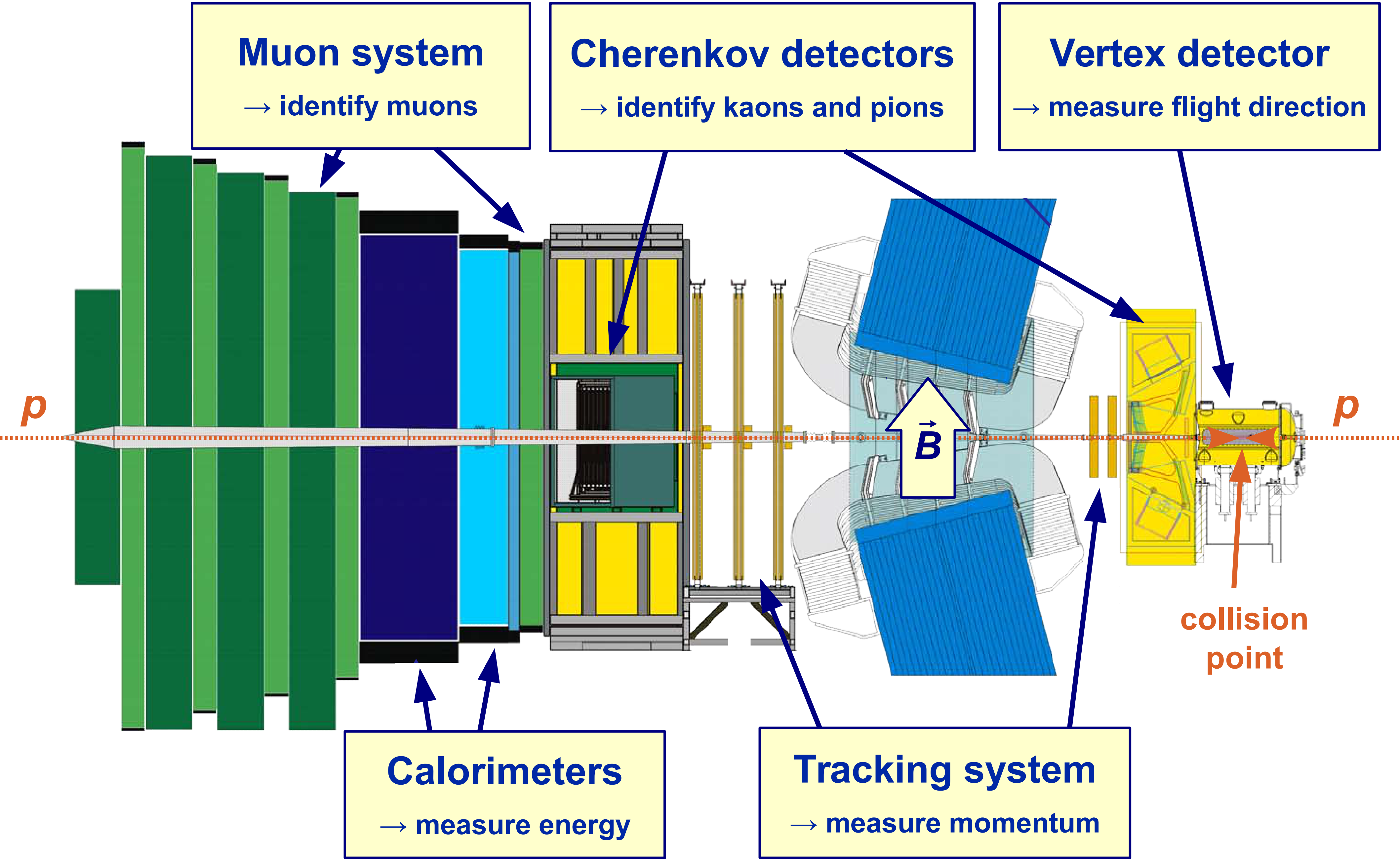

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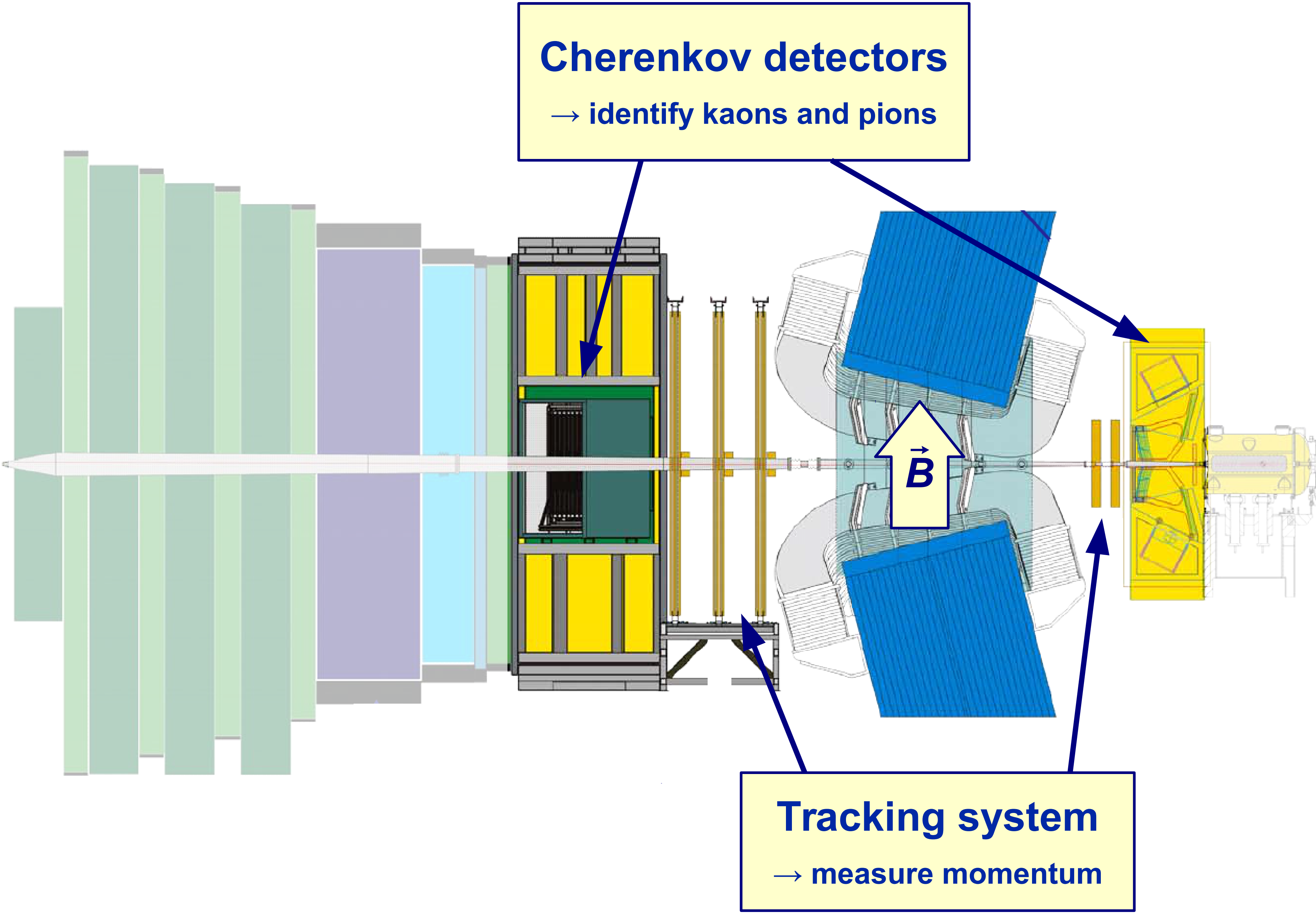

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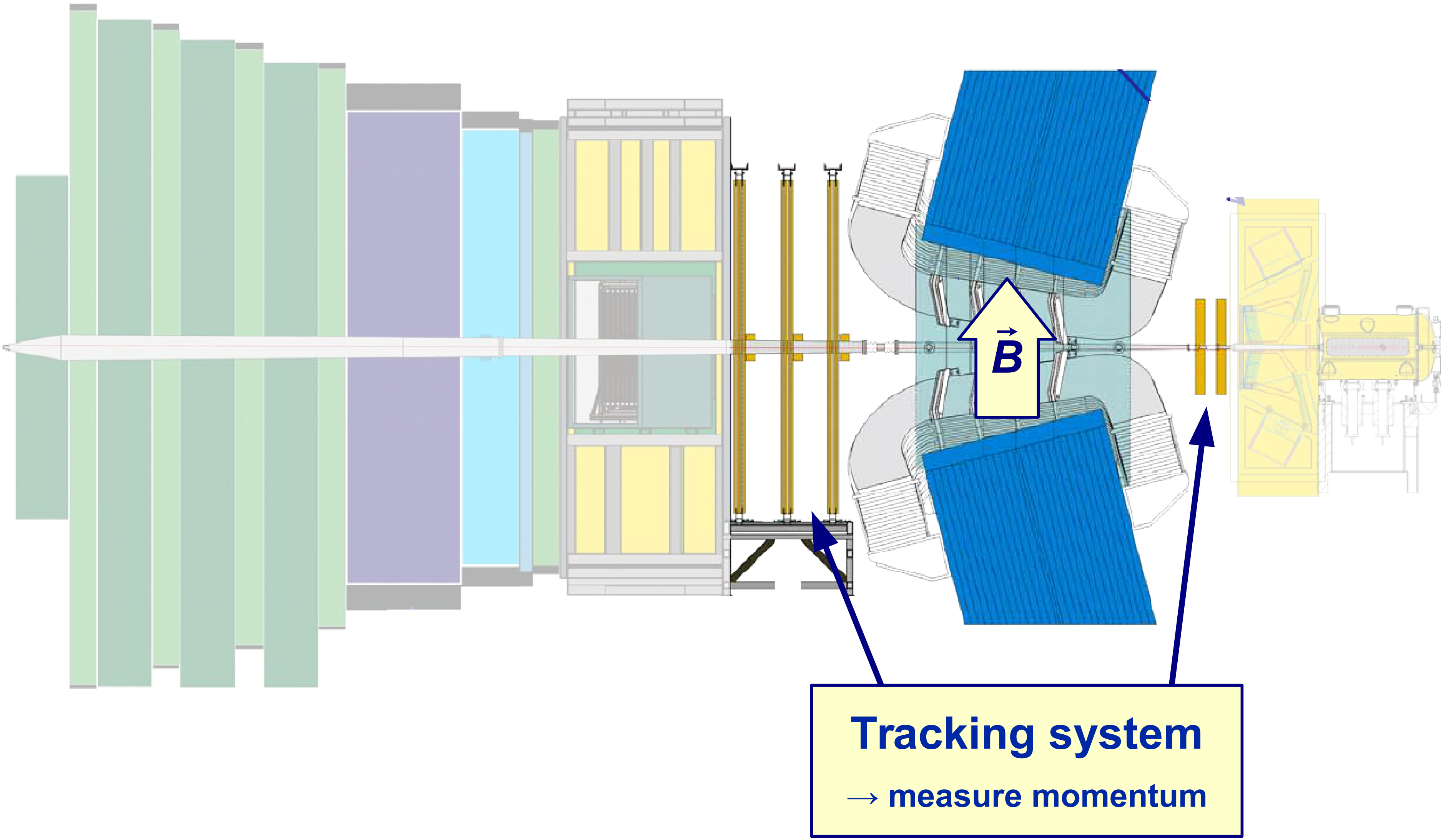

Lorentz Force

Moving charge in a magnetic field → Lorentz force

$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

- charge: q
- velocity: $\vec{v}$
- magnetic field: $\vec{B}$

Lorentz Force

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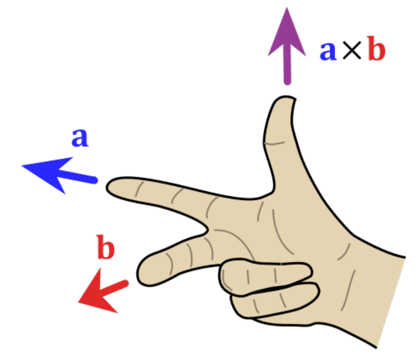
charge — velocity — magnetic field

Remember the famous "right hand rule" for the vector product ?



source: <https://en.wikipedia.org/wiki/Cross_product>

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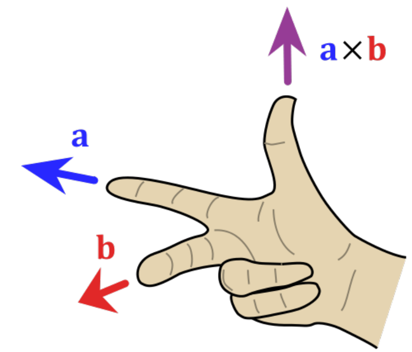
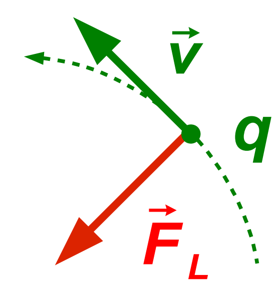


→ Force always perpendicular
to field lines AND to direction of motion

→ Particle forced onto a circular trajectory



Measure Momentum

Some really simple calculation shows that

$$p = q \cdot B \cdot r$$

momentum → p

curvature of the trajectory → r

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But how do we measure

the trajectory of an object

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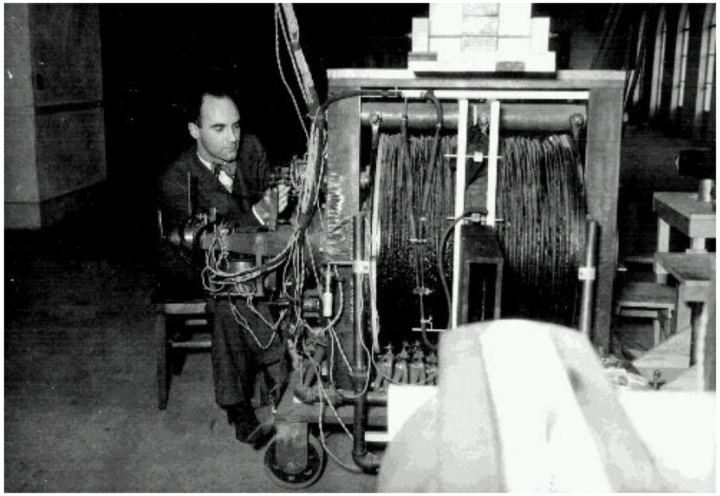
Cloud Chamber

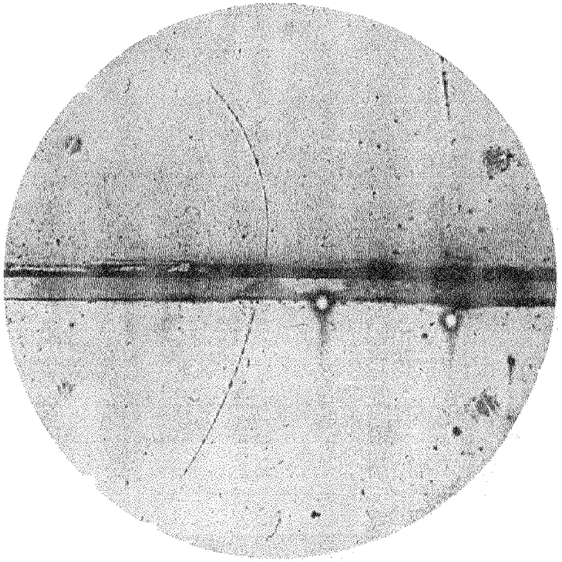
Create a volume of clear,
super-saturated vapour

Charged particle passing through
interacts with atoms in the gas
→ Creates clusters of ionized atoms

Ionization clusters cause condensation
→ Formation of droplets
along the particle trajectory

Take a photograph,
take a ruler and analyse





discovery of the antielectron
(Anderson, 1932)

photo credit: Carl D. Anderson, Physical Review Vol.43, p491 (1933)

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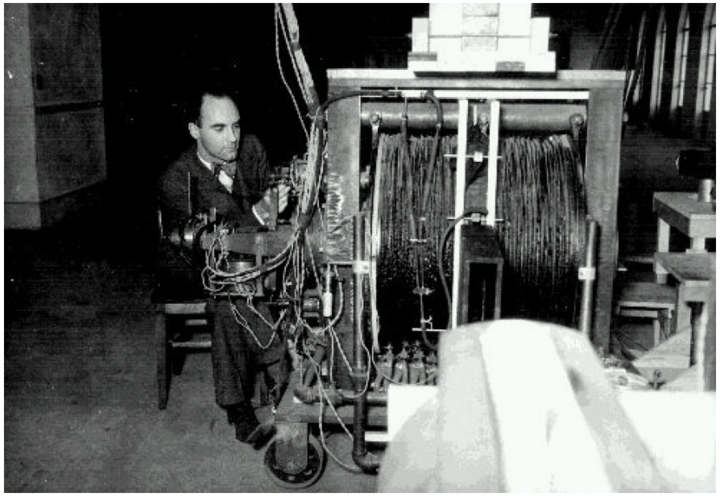

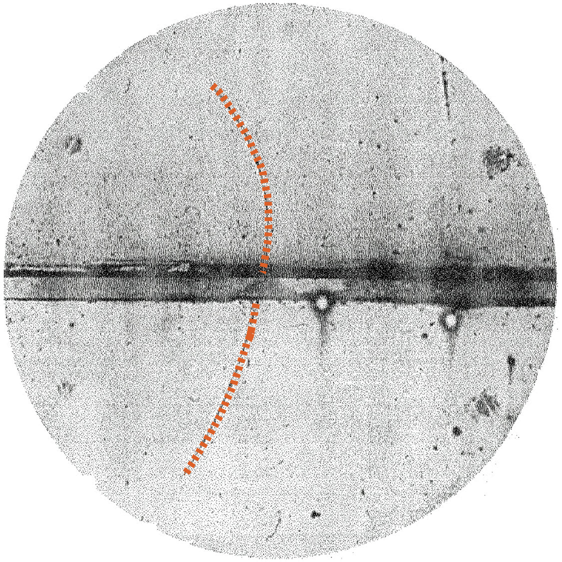

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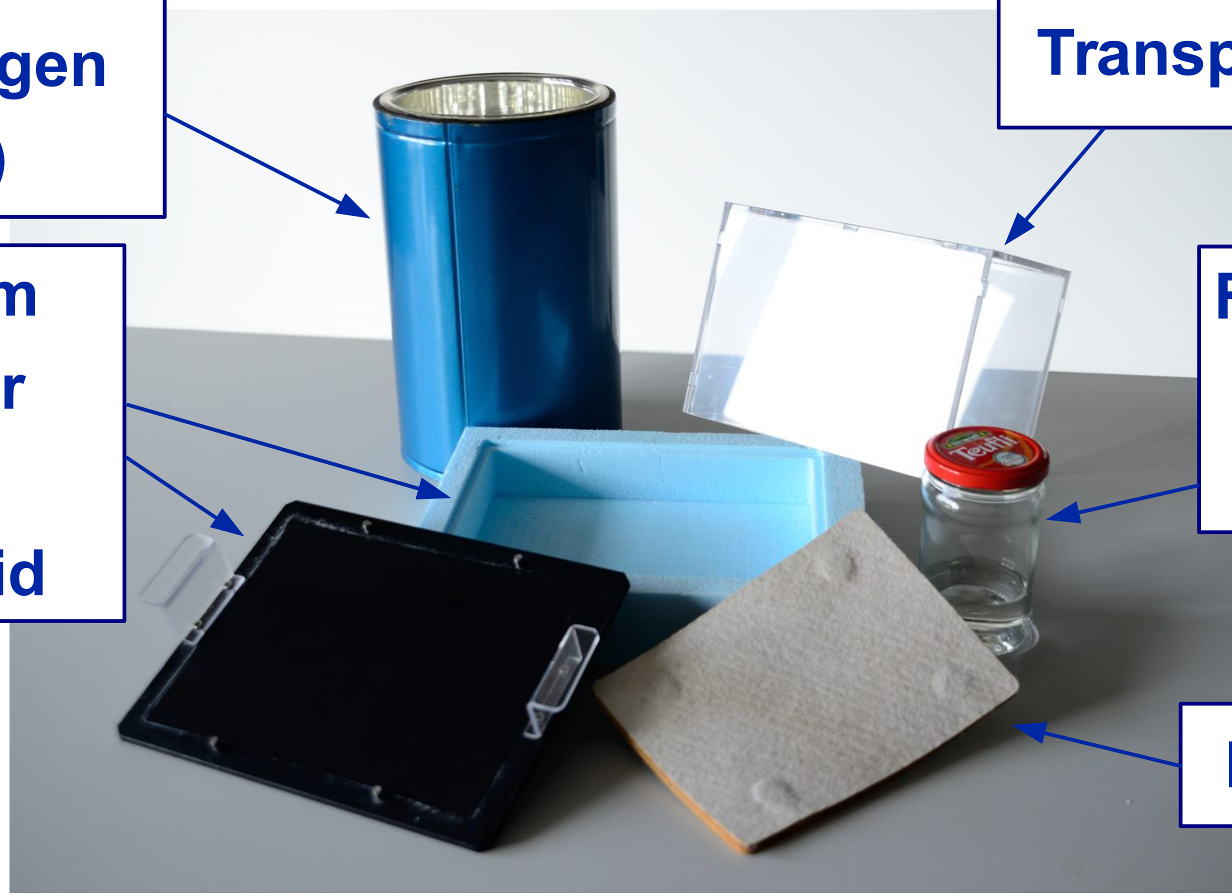
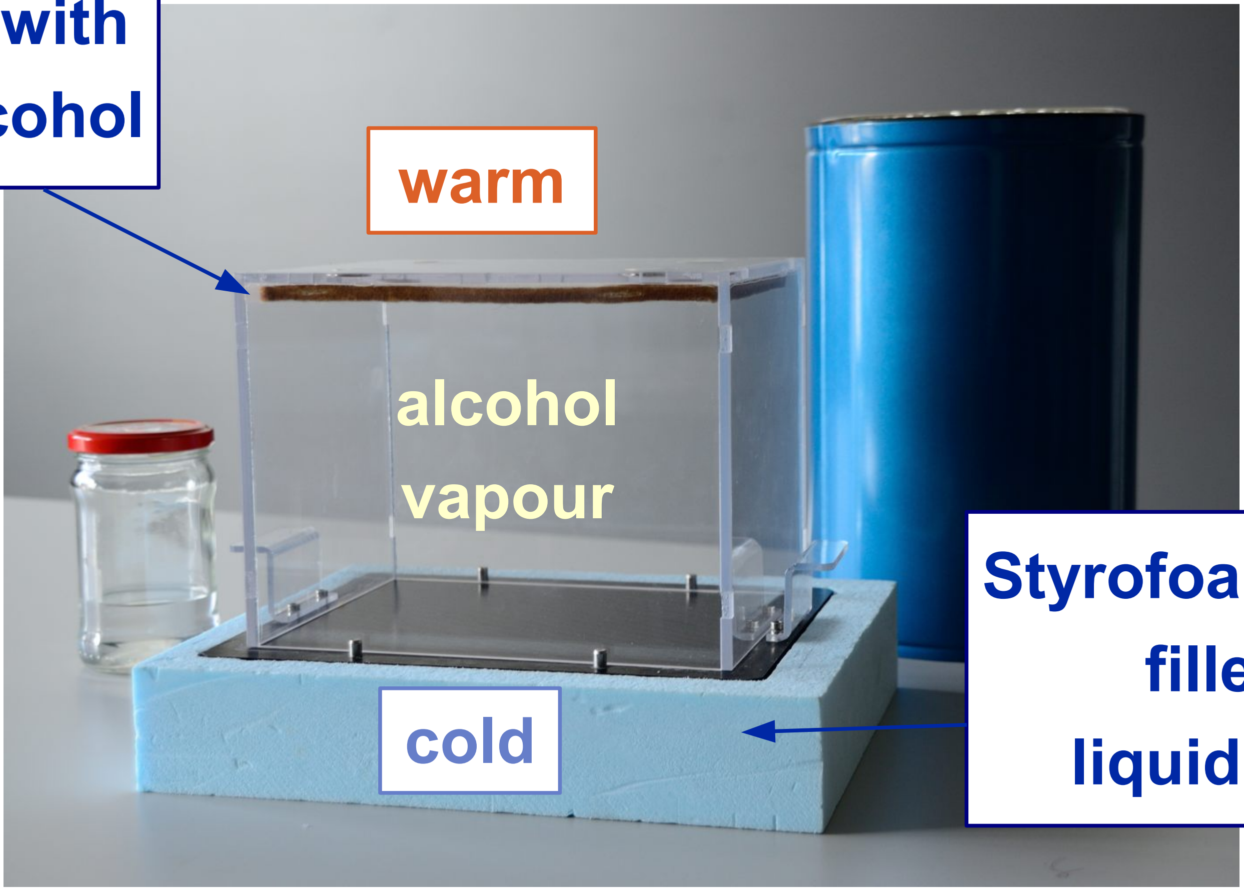
Build your own Cloud Chamber



+ Insulating gloves, safety glasses, bright flashlight

Build your own Cloud Chamber



Setup: Katharina Müller, UZH Science Lab
(katharina.mueller@sciencelab.uzh.ch)

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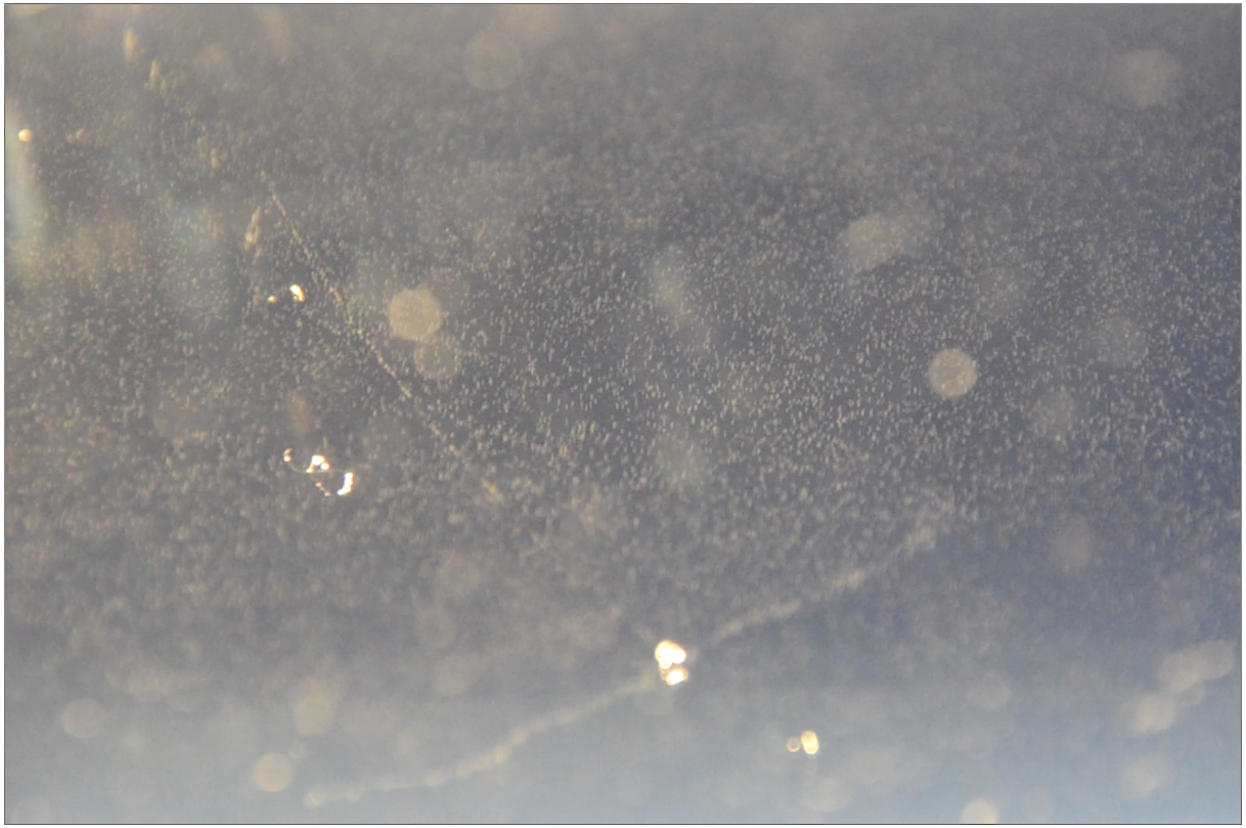

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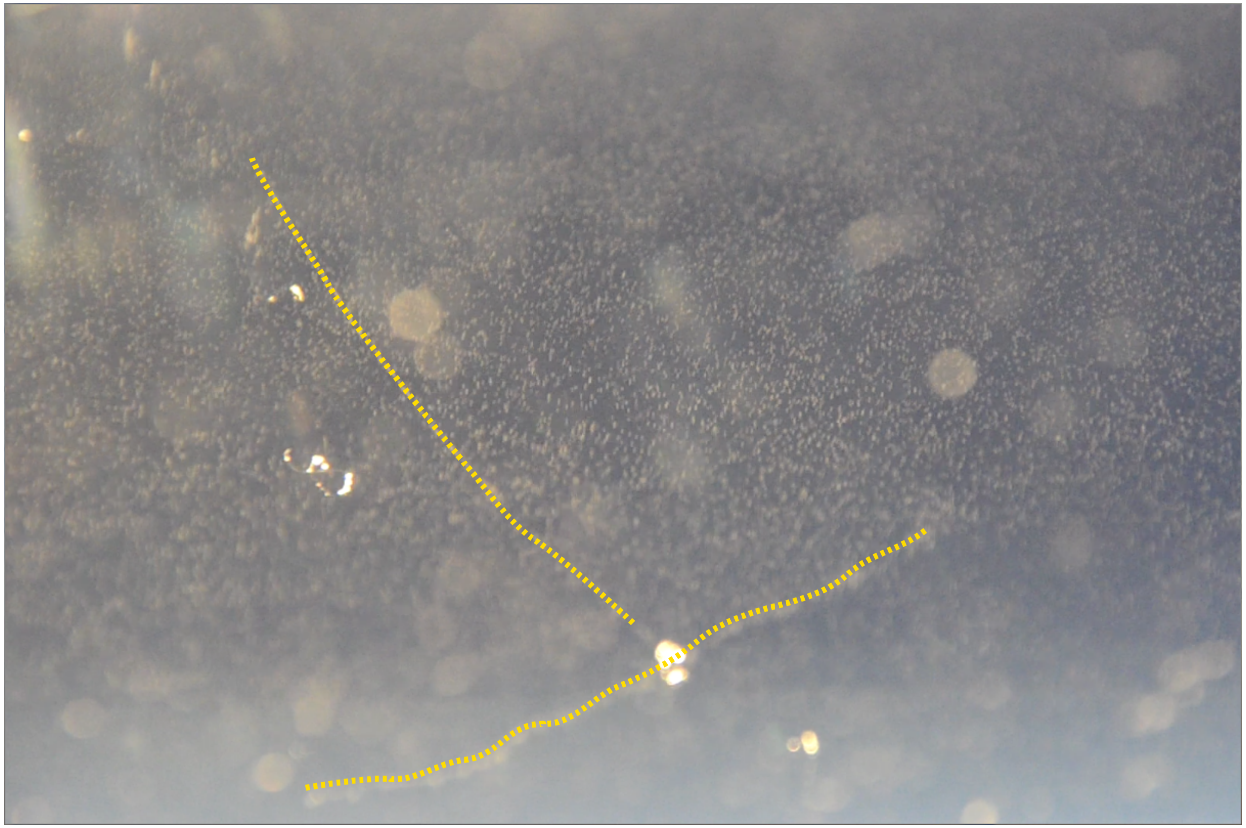

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Modern Tracking Detectors

Searching for increasingly rare processes

→ Have to deal with higher and higher event rates

(LHC: 40 million events per second**)**

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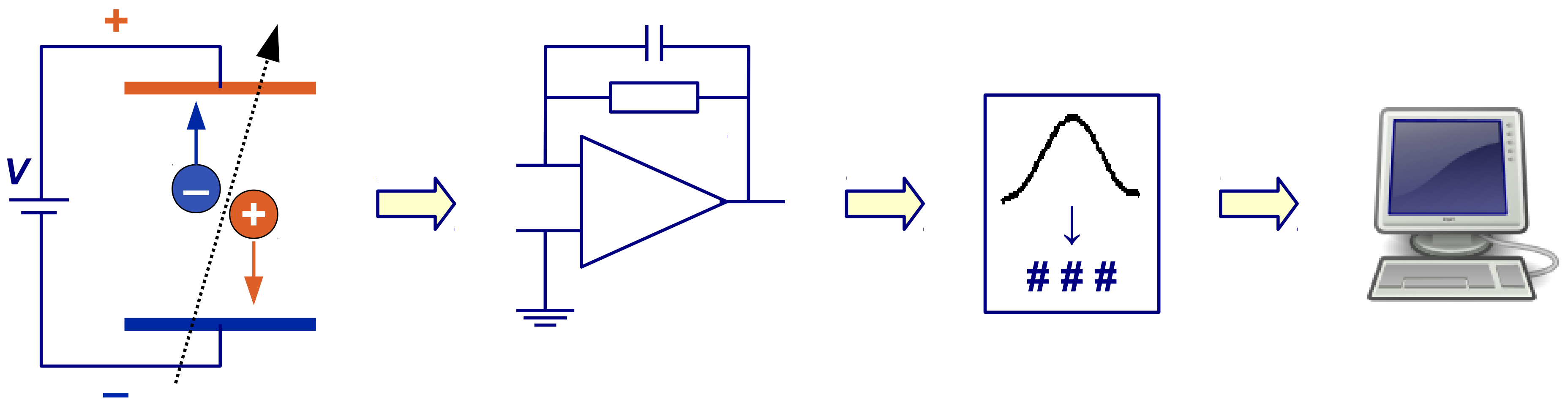

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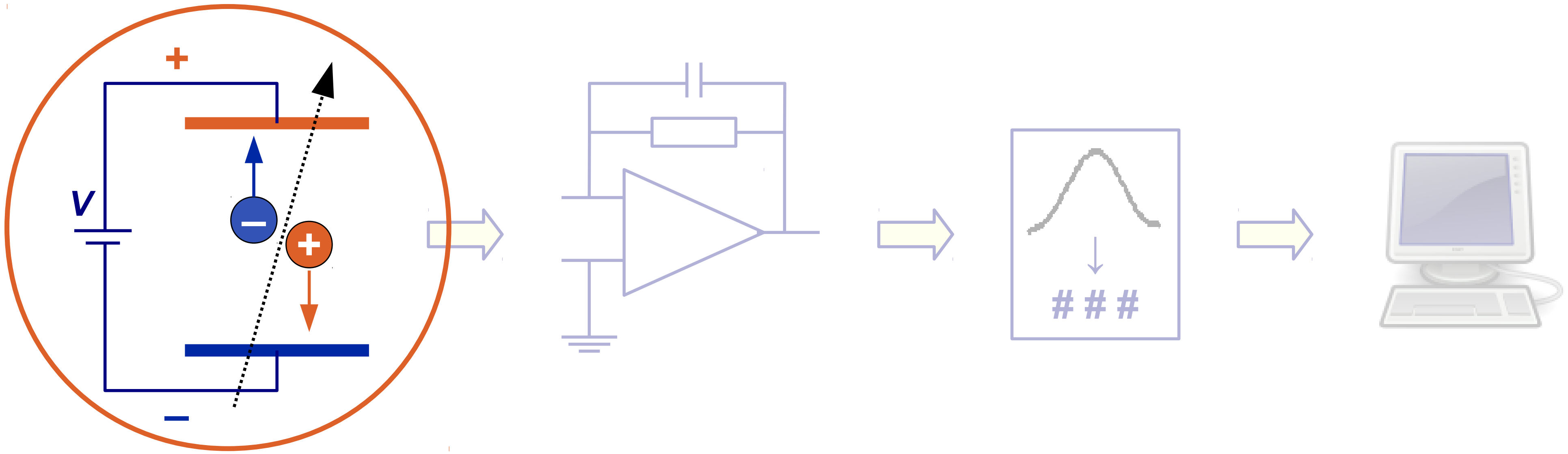
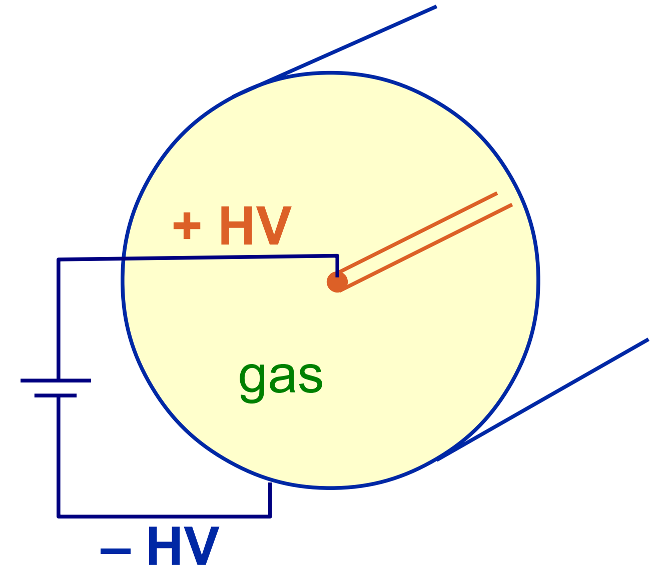


Gaseous Tracking Detectors

Cylindrical metallized tube,
filled with a gas mixture

Thin wire along the centre of this tube

High Voltage (typically a few kV**)**
between the wire and the outer wall



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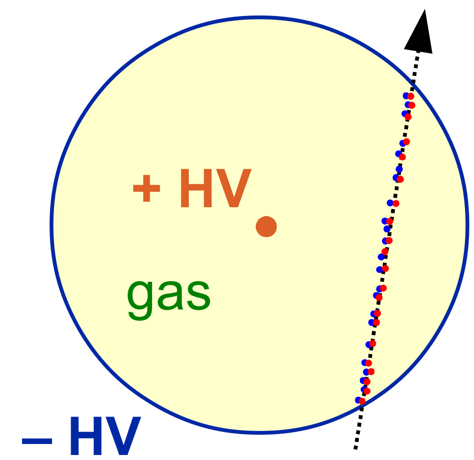

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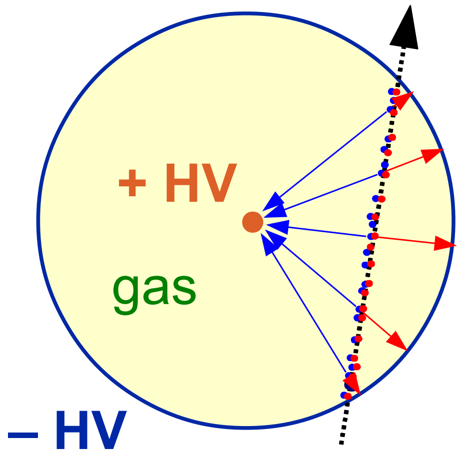

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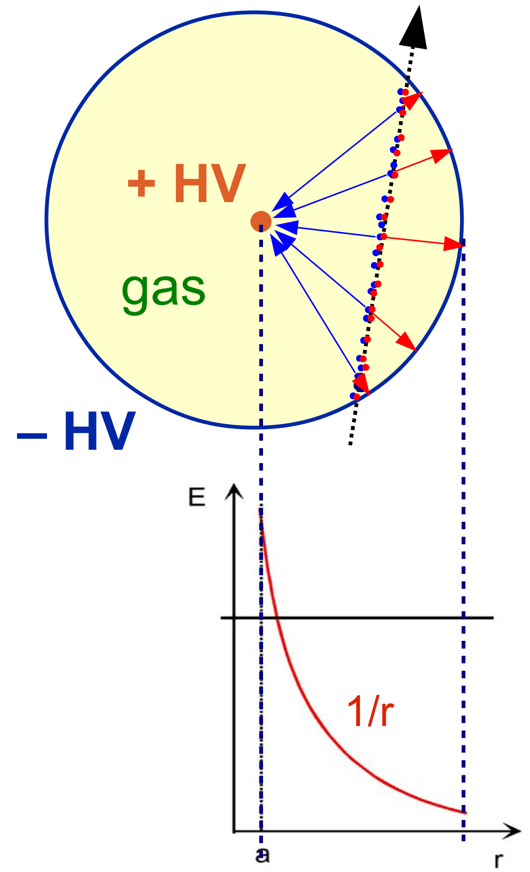

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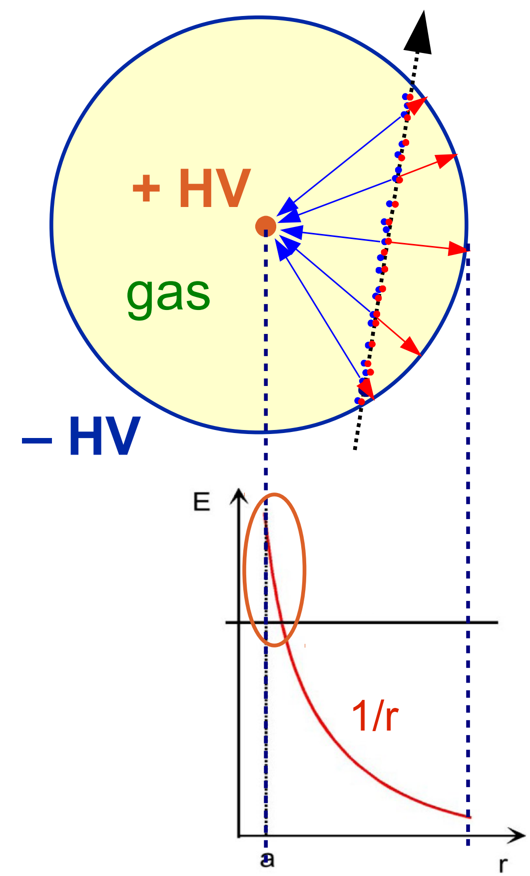
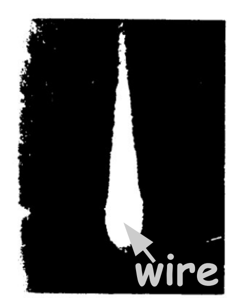
Very high electric field close to the wire
electrons gain energy → ionize atoms
→ charge avalanche (typically 1'000'000 e^-)
→ voltage pulse on the wire

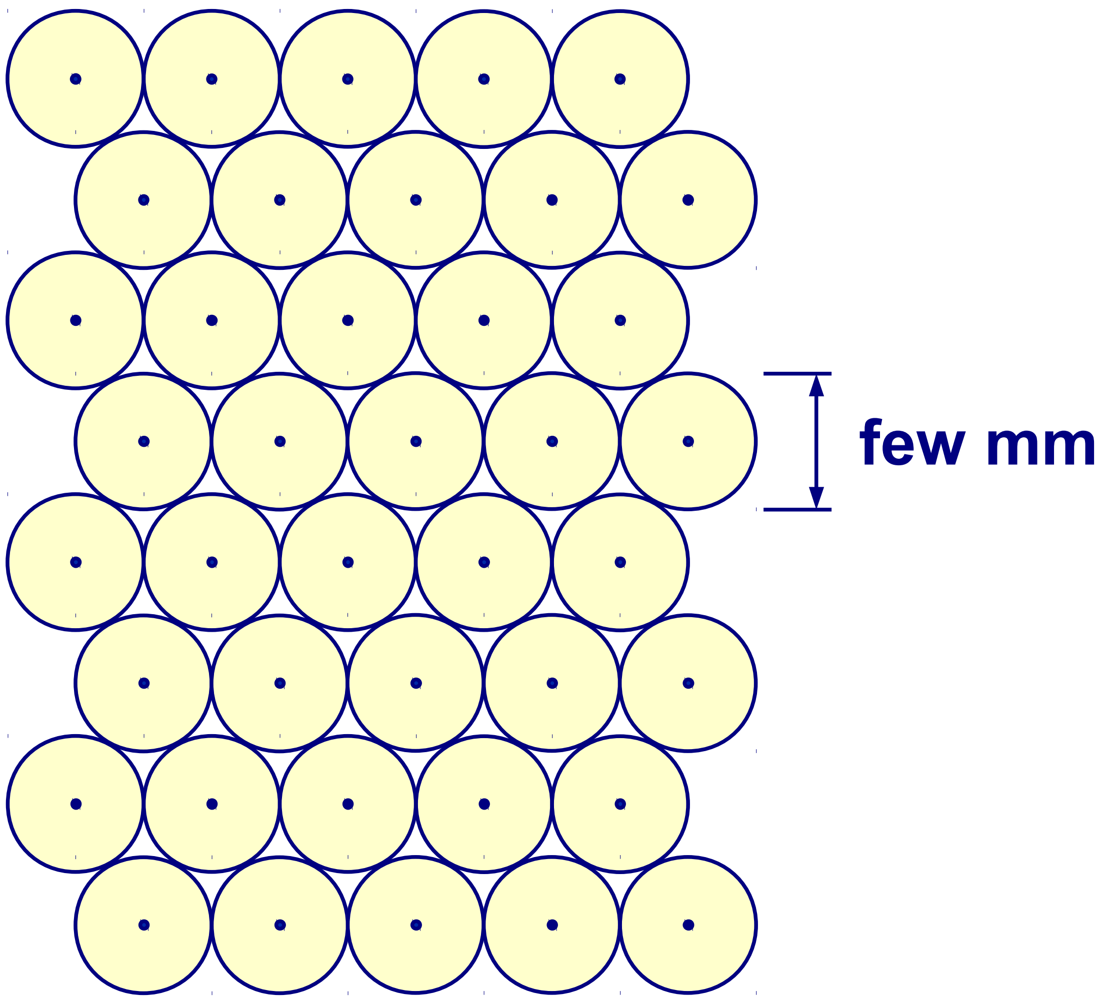




photograph of charge avalanche, taken in a cloud chamber

Gaseous Tracking Detectors

Build arrays of such drift tubes to follow the trajectories of particles



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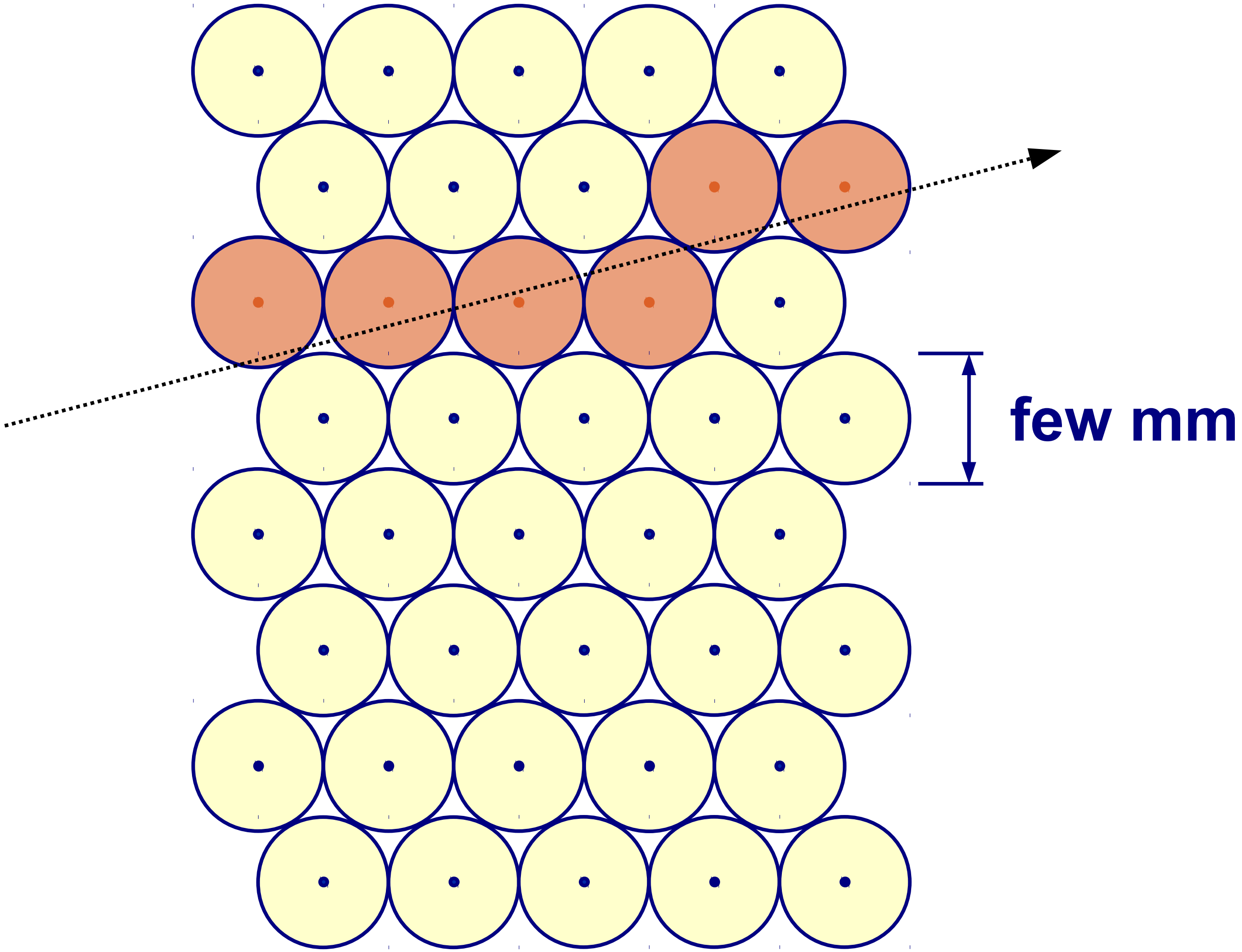

Gaseous Tracking Detectors

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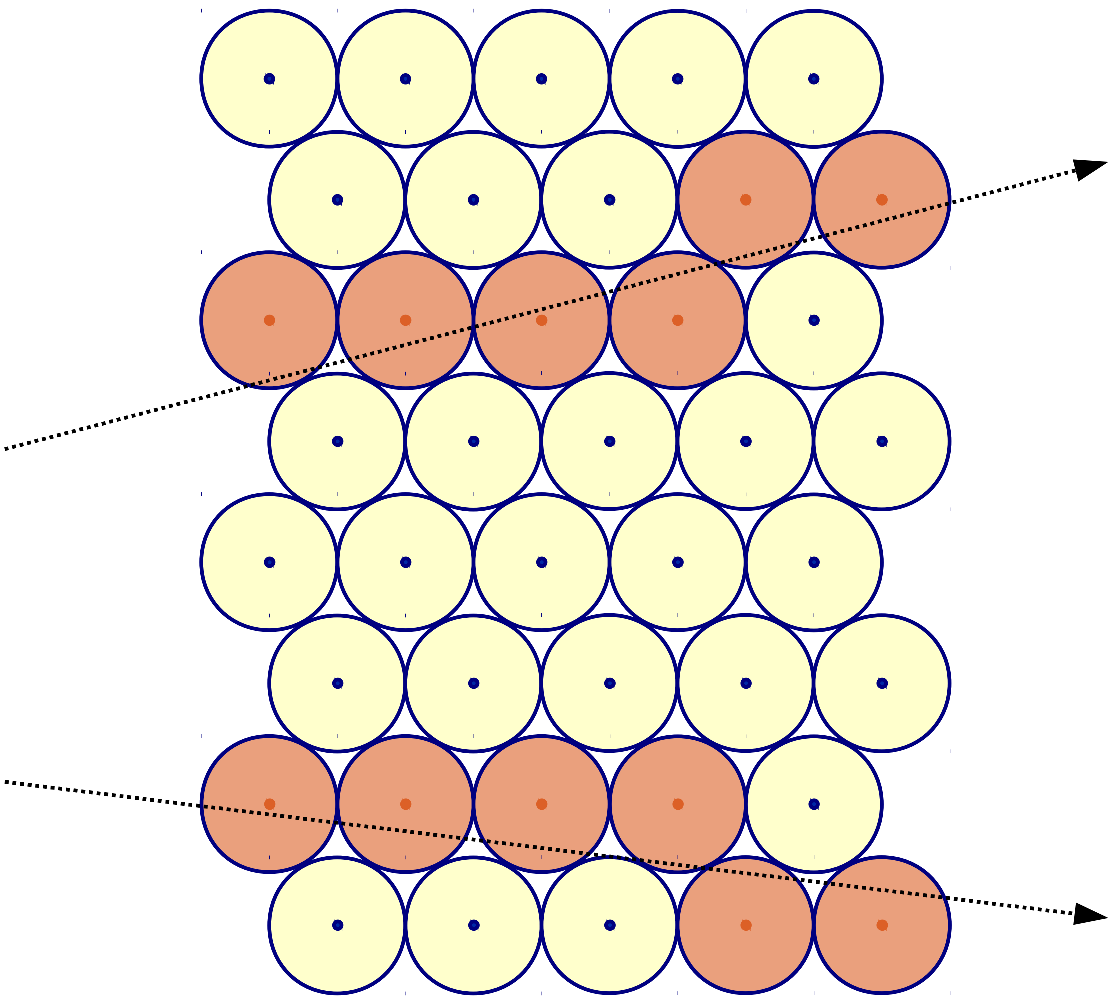
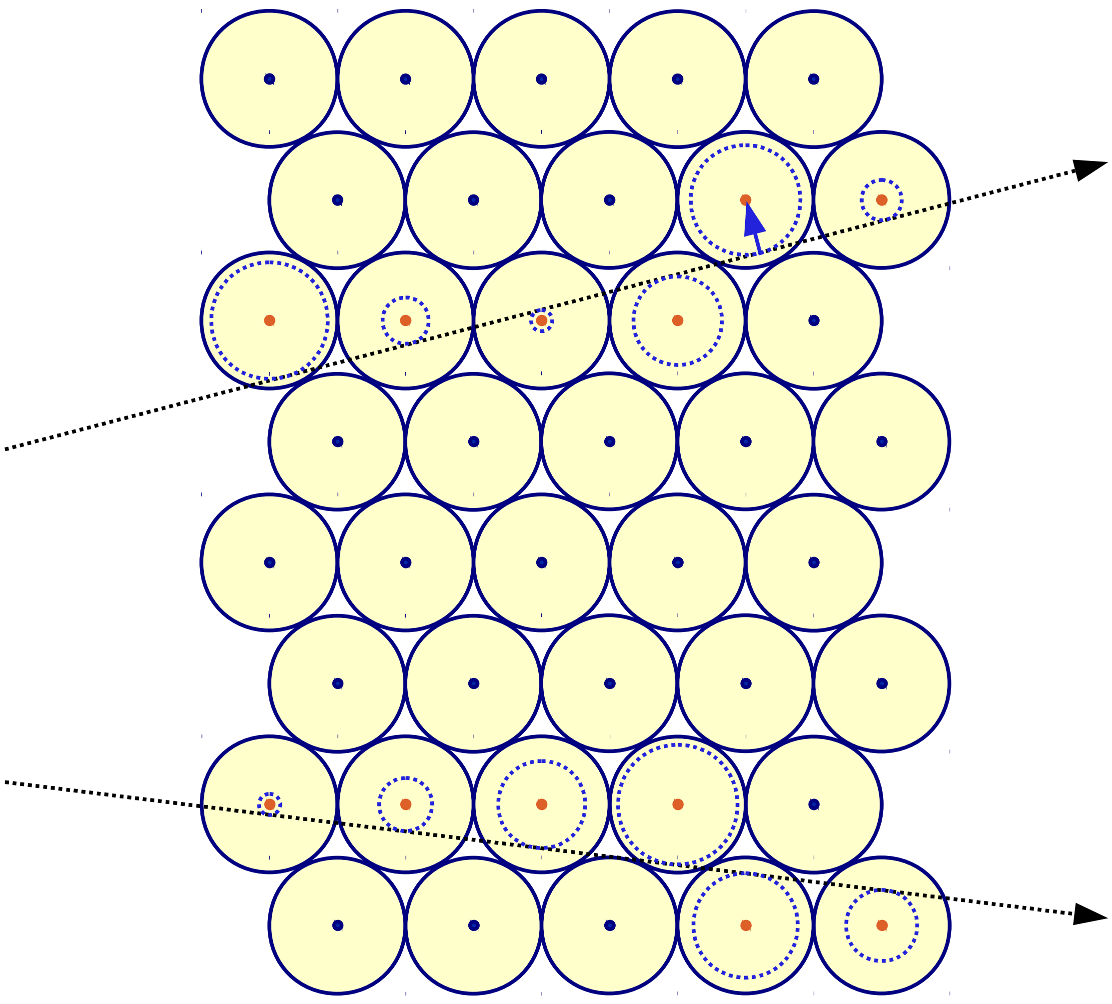


Gaseous Tracking Detectors

Can do better than a simple yes / no:

Measure the time it takes the electrons to reach the wire

→ calculate drift radius → more precise measurement



Gaseous Tracking Detectors

Easy to cover large surfaces

Quite cheap

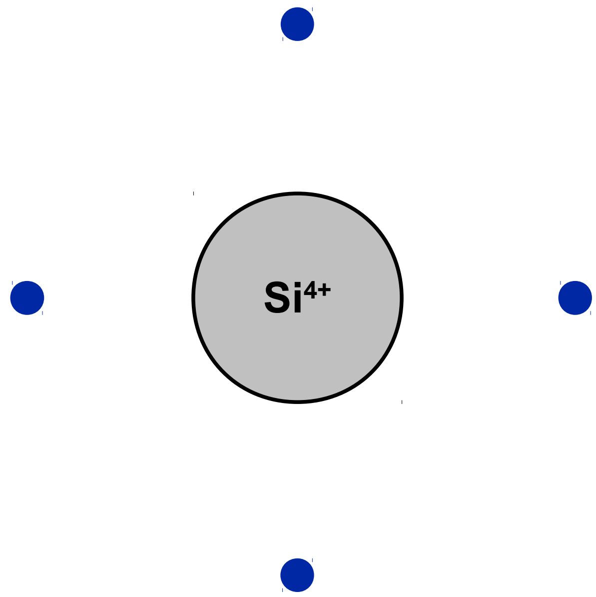
Spatial resolution ~ 0.1 mm

Limited performance at very high rates

→ e.g. Electrons take ~ 100 ns = 0.0000001 s to reach the wire

(LHC: a new collision every 25 ns)

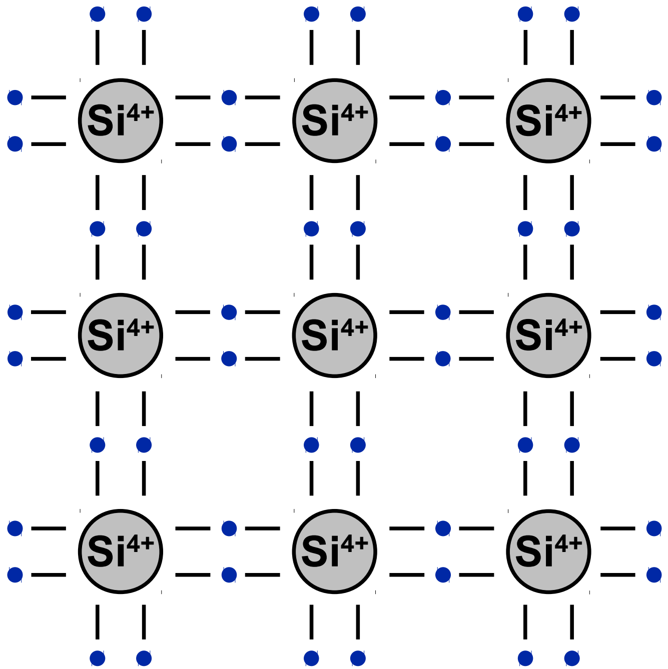
Silicon Detectors



Silicon Detectors

Silicon is the 2nd most abundant chemical element in Earth's crust

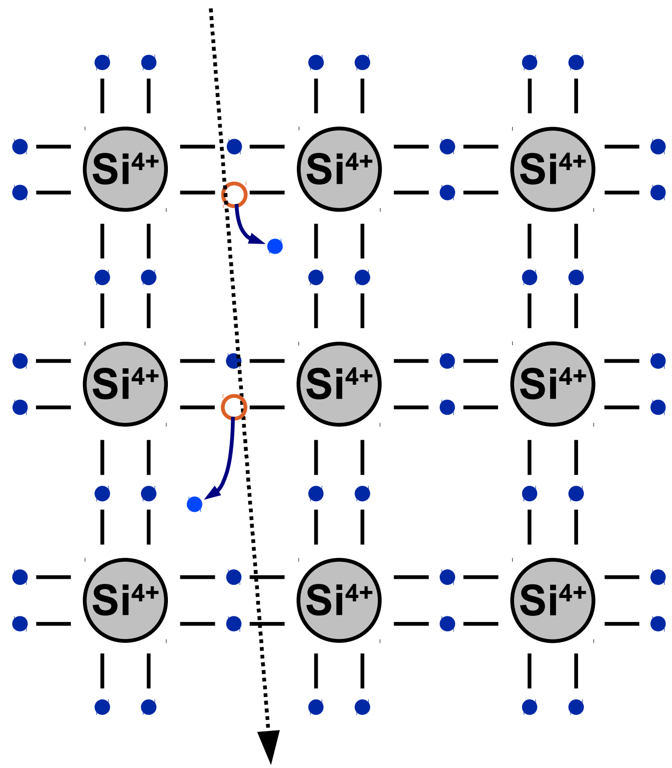
Silicon Detectors



Silicon crystal is a semi-conductor:

Electrons are bound to nuclei in the lattice of the crystal, but only weakly

Silicon Detectors

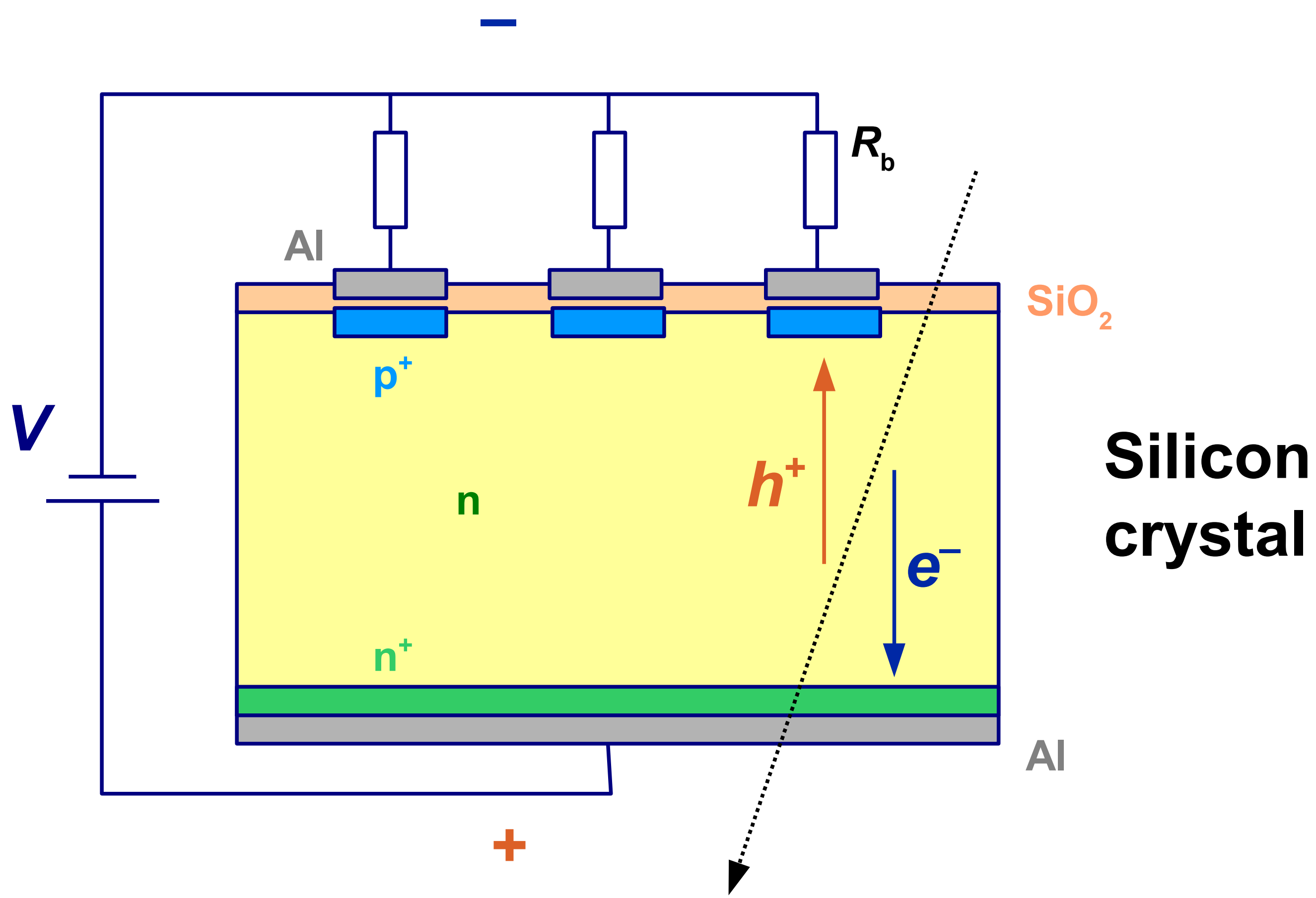


A charged particle can kick electrons out of the lattice, leaving behind "holes"

(~ 30'000 electron/hole pairs in ½ mm of silicon)

These electrons and holes can move through the lattice

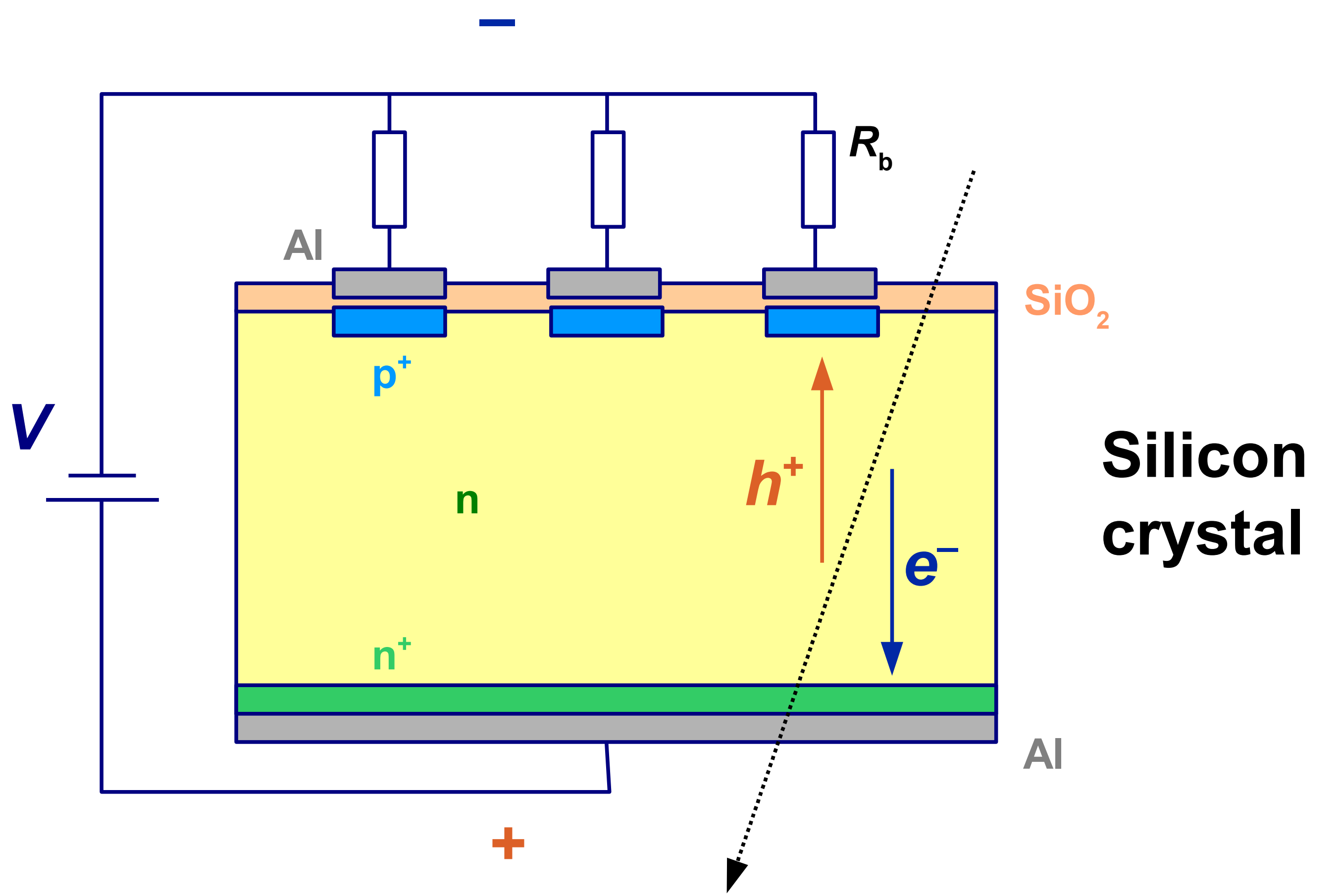
Silicon Detectors



Apply an electric field across the crystal

→ Collect electrons and holes on electrodes at the surface

Silicon Detectors



→ For details, sign up for my lecture in autumn ;-)

Silicon Detectors

Better resolution than gaseous detectors

0.01 mm ↔ 0.1 mm

Faster than gaseous detectors

10 ns ↔ 100 ns

+ Other advantages

Silicon Detectors

Better resolution than gaseous detectors
0.01 mm ↔ 0.1 mm

Faster than gaseous detectors
10 ns ↔ 100 ns

+ Other advantages

More difficult to cover large areas

More expensive than gaseous detectors

Silicon Detectors

Better resolution than gaseou detectors

0.01 mm 0.1

Fa

USE SILICON DETECTORS

WHERE THEIR

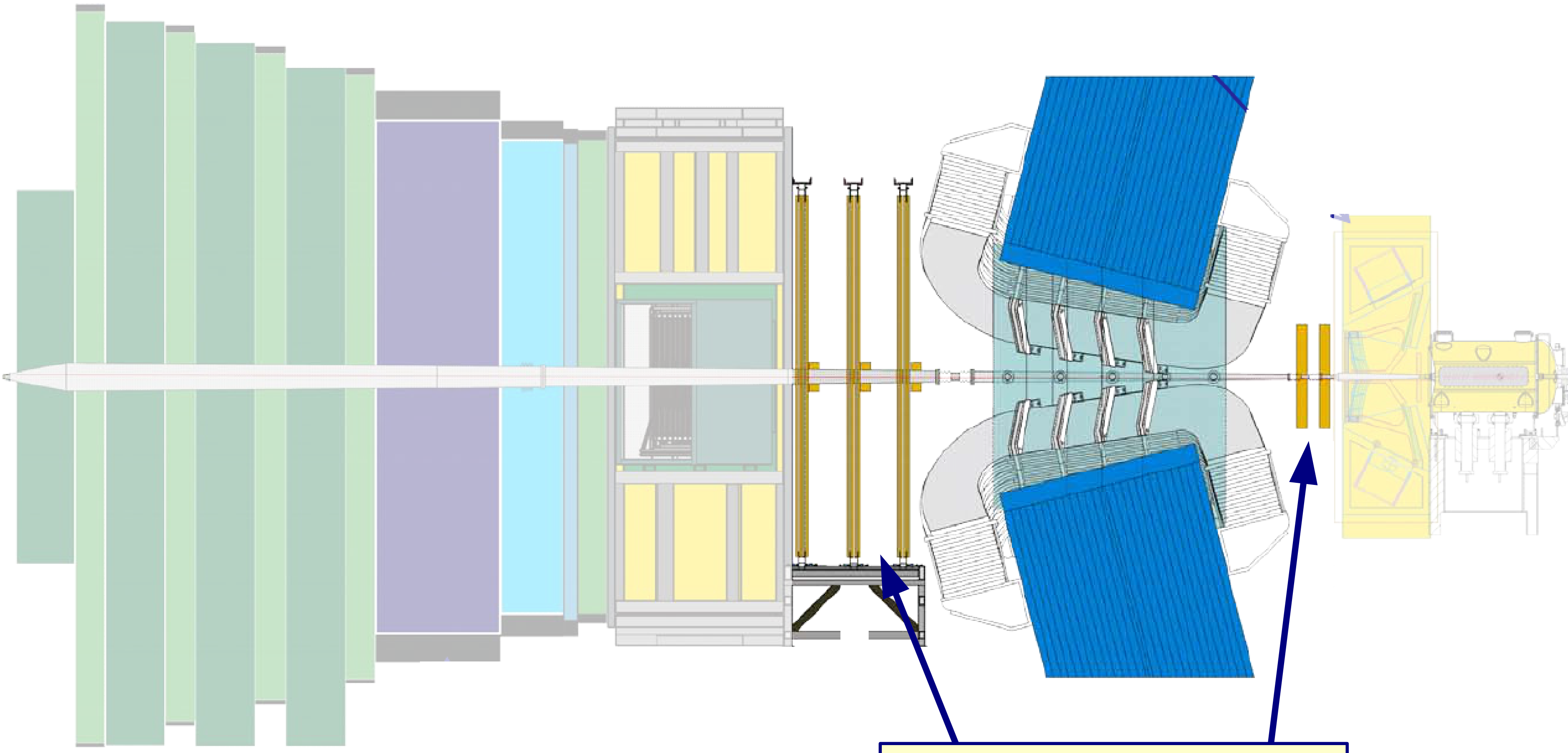
SUPERIOR PERFORMANCE

IS NEEDED

reas

More e siv han gaseous detectors

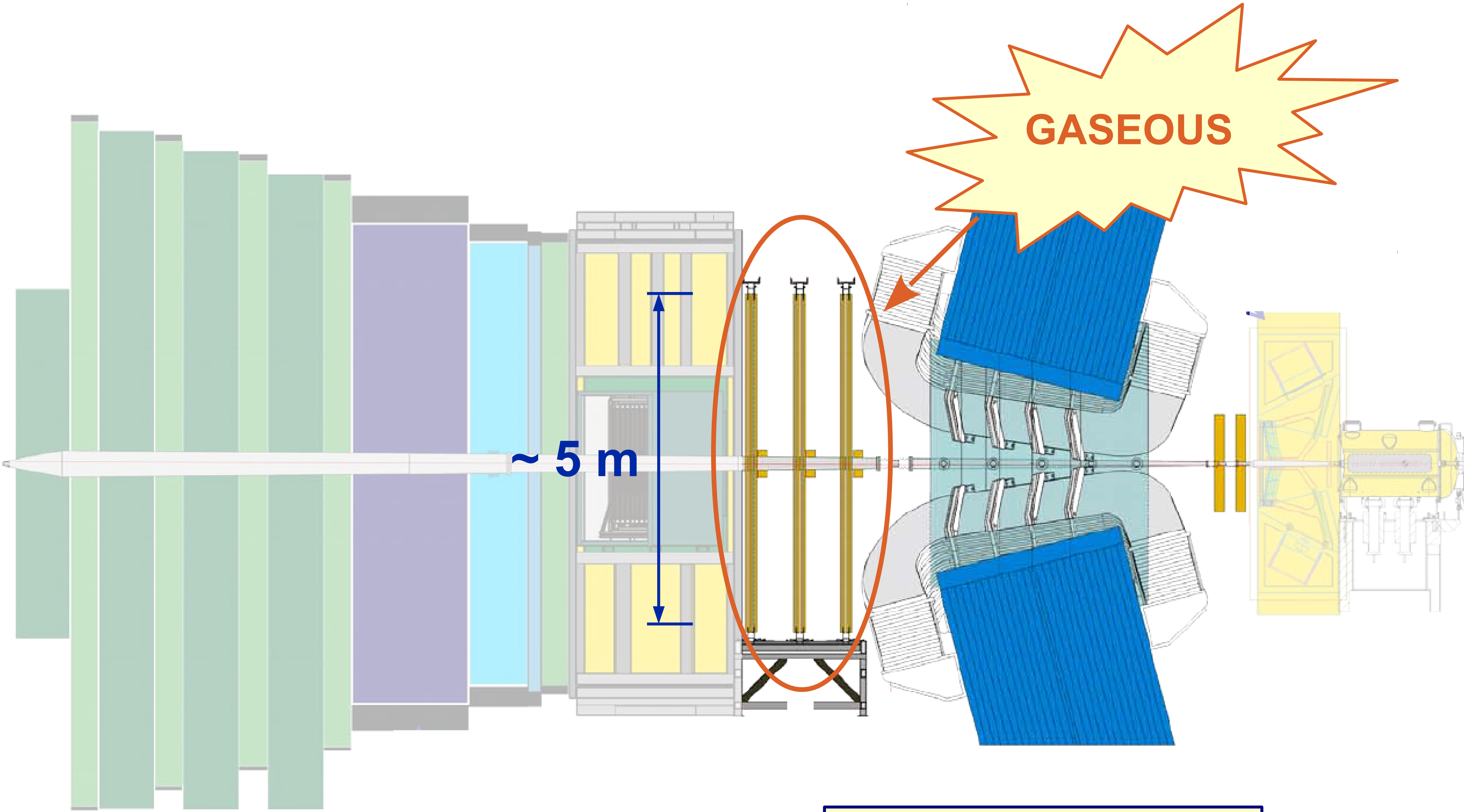
LHCb Experiment



Tracking system

→ measure momentum

LHCb Experiment



Tracking system

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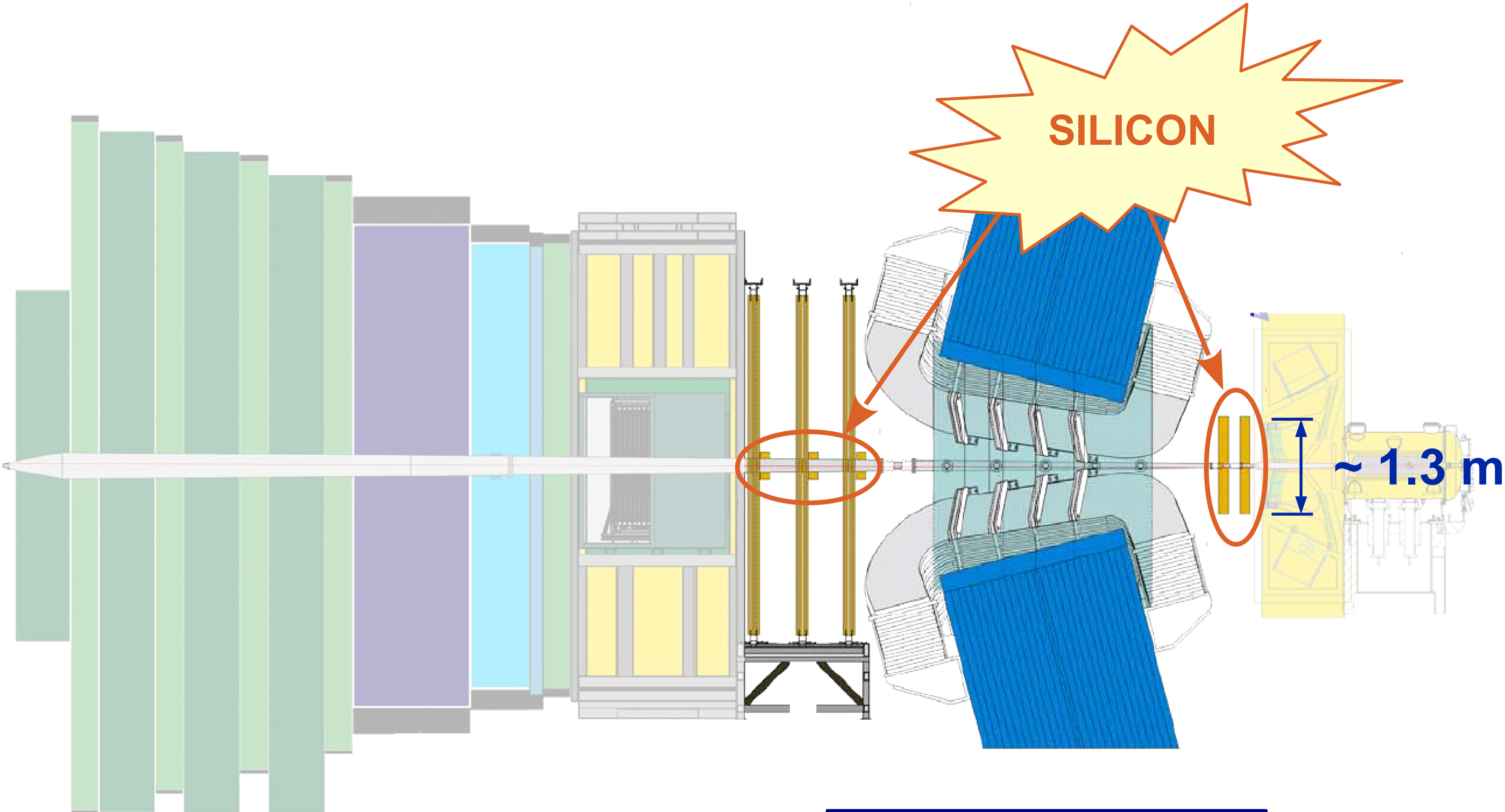
LHCb Experiment



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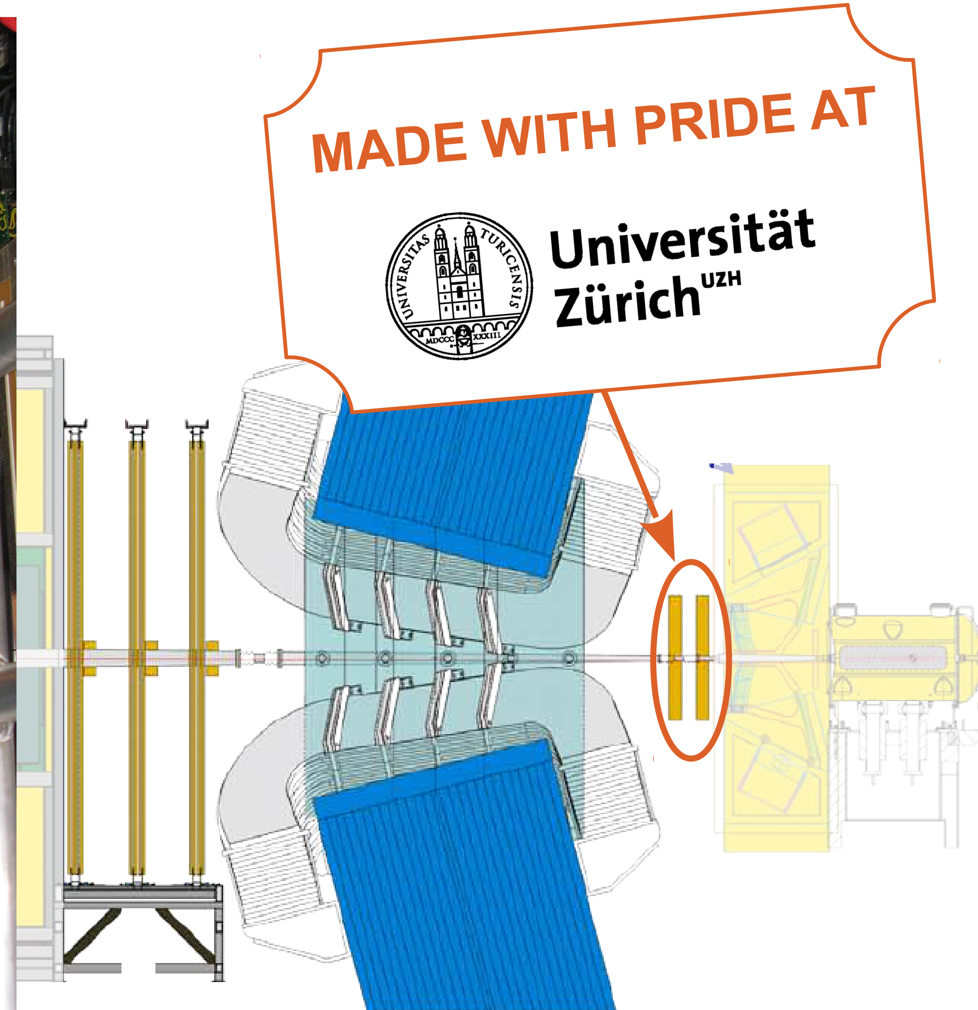
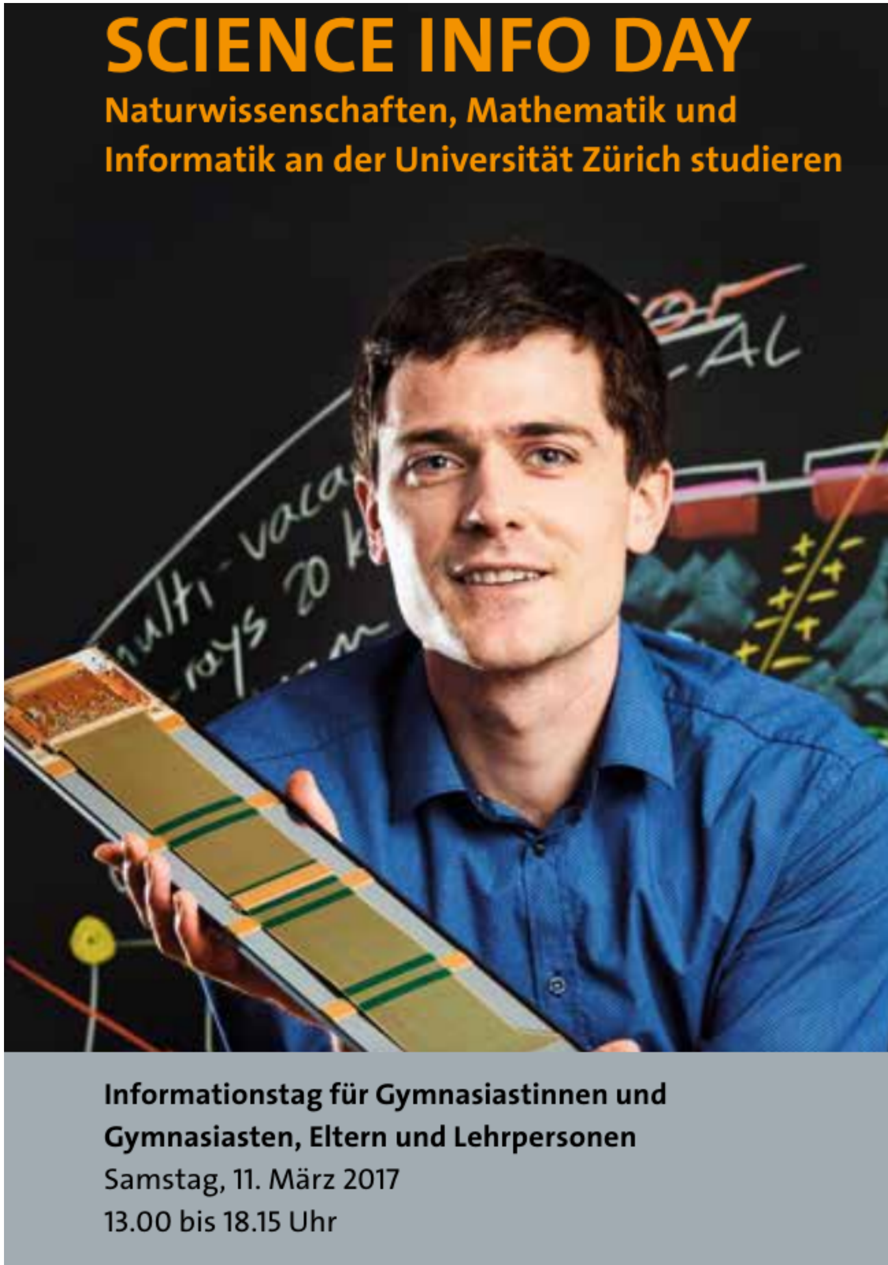
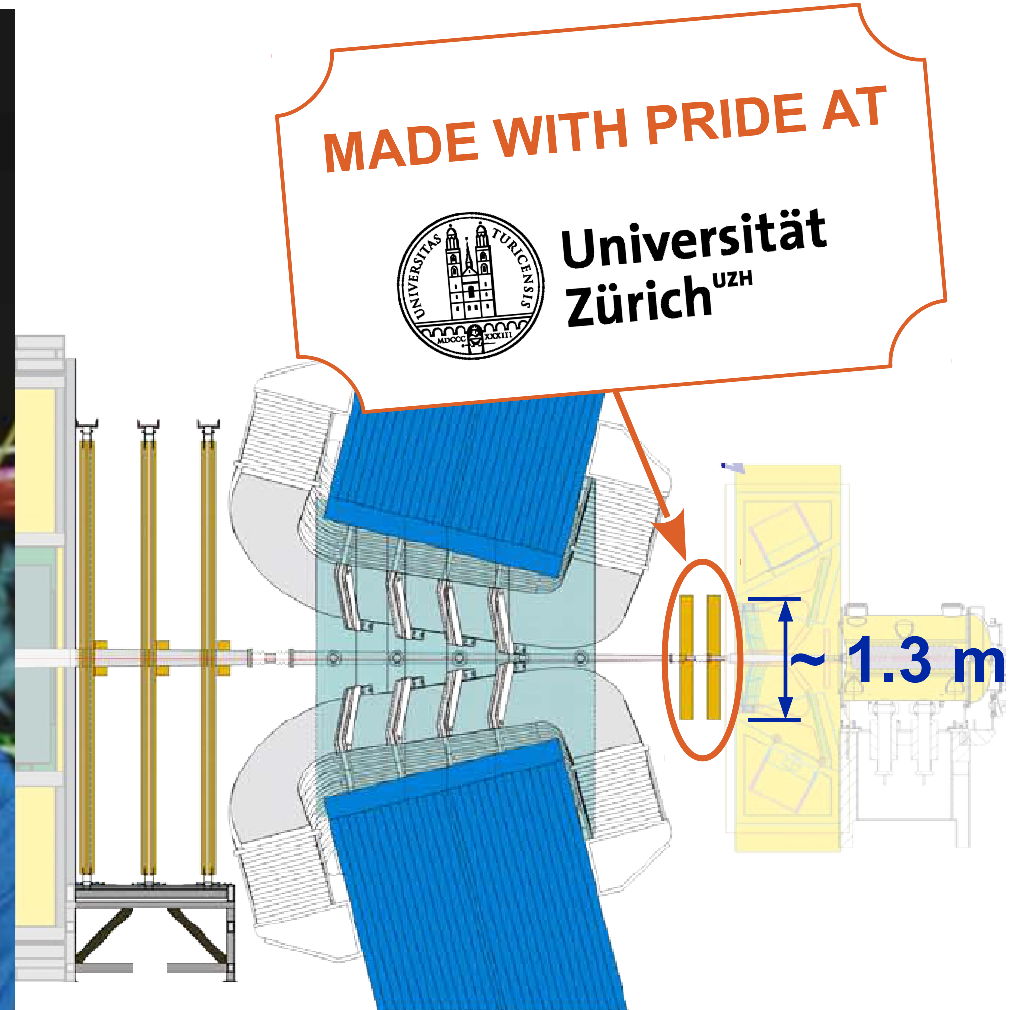
LHCb Experiment



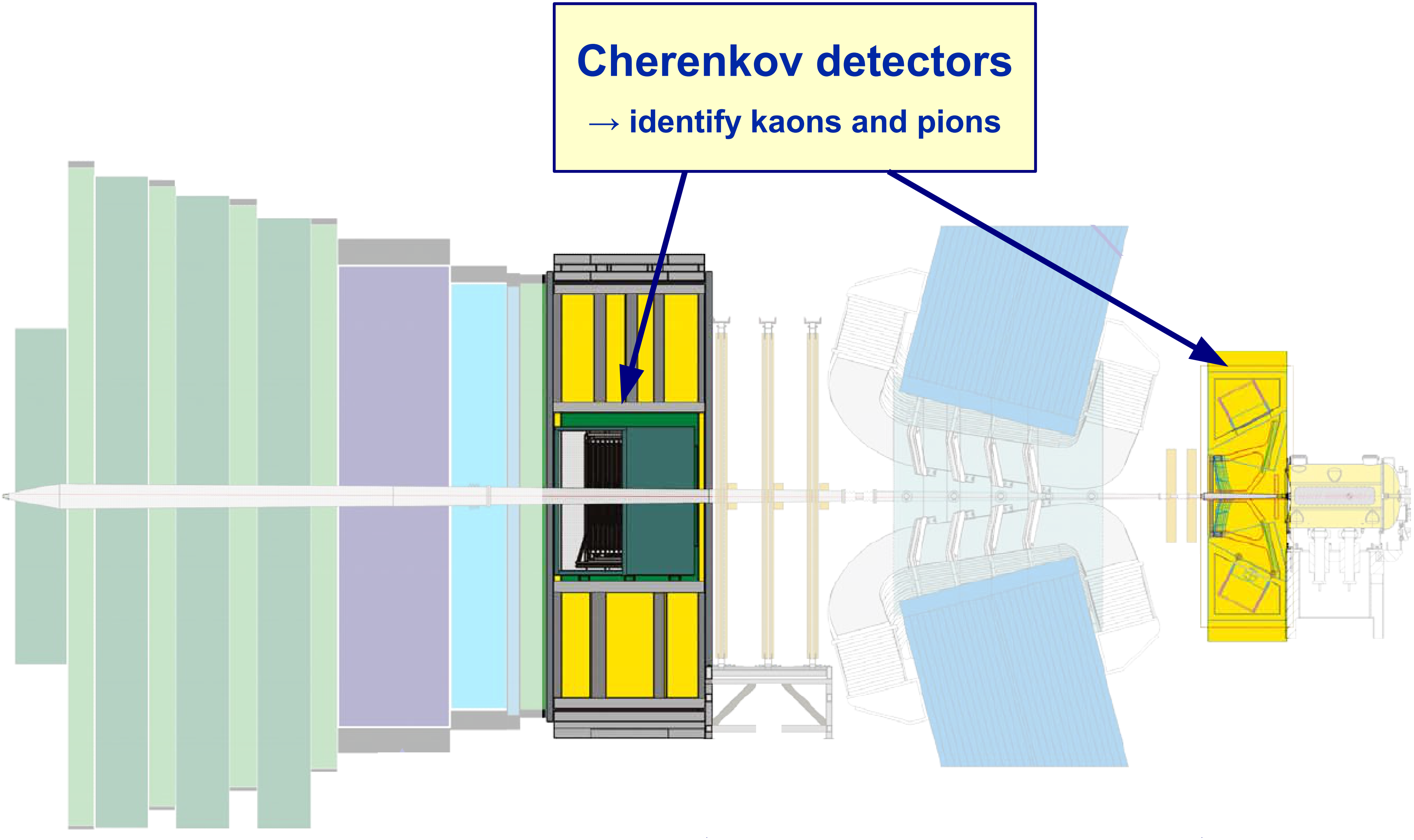
LHCb Experiment





source: <http://www.mnf.uzh.ch/de/oeffentlichkeit/science-info-day.html>

LHCb Experiment



Particle Identification

Each type of particle has a characteristic mass

→ Measure the mass to determine of which type a particle is

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

→ Measure momentum ✓ and energy

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or ...

Particle Identification

Each type of particle has a characteristic mass

→ Measure the mass to determine of which type a particle is

$$p = m \cdot v$$

speed

→ Measure momentum ✓ and speed

→ Cherenkov detectors

Particle Identification

Each type of particle has a characteristic mass

→ Measure the mass to determine of which type a particle is

$$p = \gamma \cdot m \cdot v$$

speed

→ Measure momentum ✓ and speed

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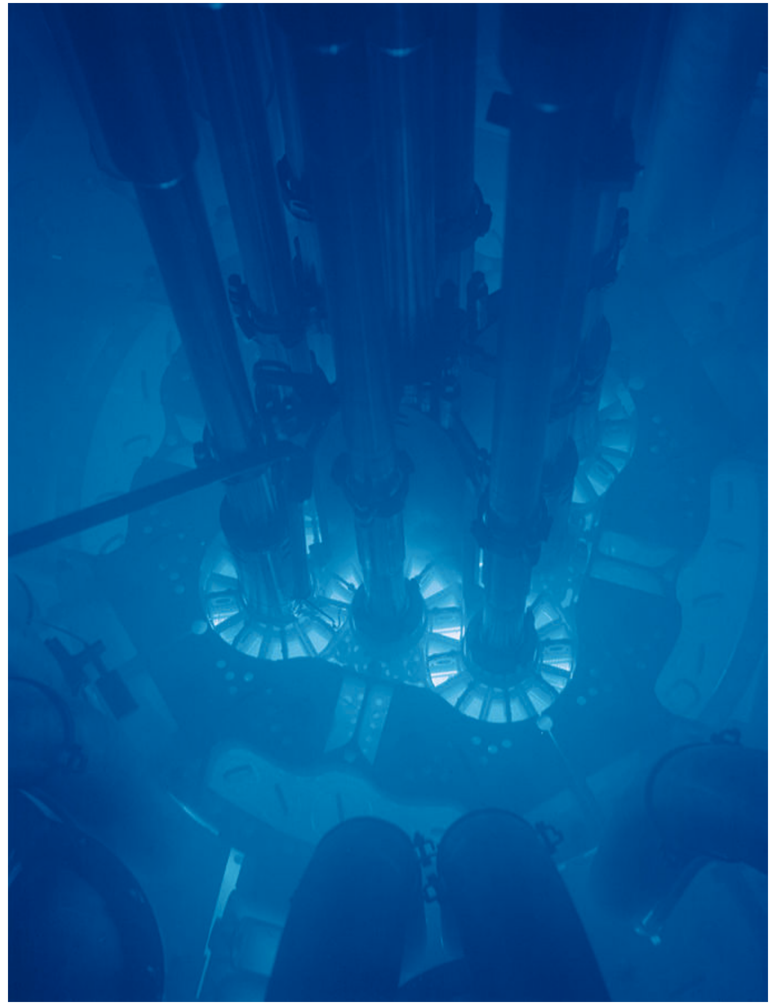
Cherenkov Effect



source: <https://en.wikipedia.org/wiki/Cherenkov_radiation>

Cherenkov light is emitted when a charged particle moves through a medium at a speed faster than that of light

Cherenkov Effect

source: <http://www.cartoonsidrew.com/2011/05/einsteins-speed-limit.html>

Moving faster than light ???

Cherenkov Effect

Speed of light in a medium
is smaller than
“the” speed of light in vacuum

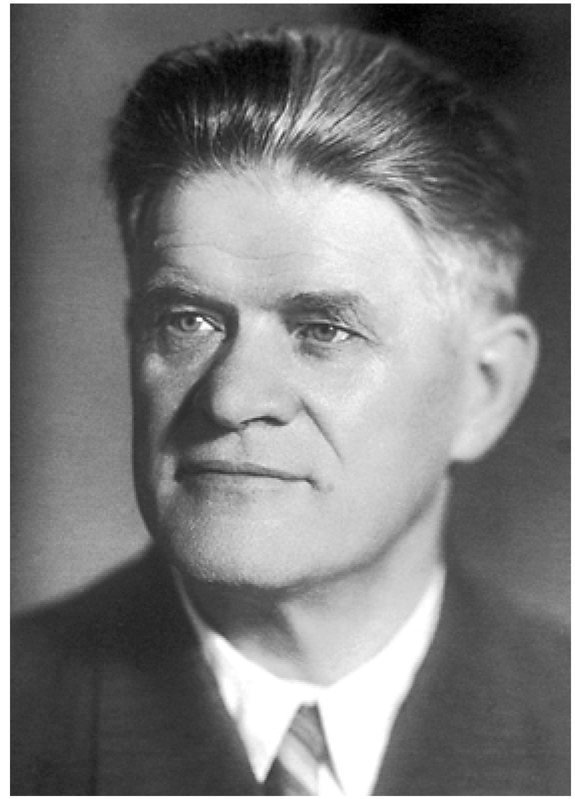
e.g. Speed of light in water is only 226’000 km/s

→ Charged particles can move through a medium
faster than the speed of light in that medium

When that happens, an electromagnetic shock wave is created

→ Emission of Cherenkov light

Cherenkov Effect



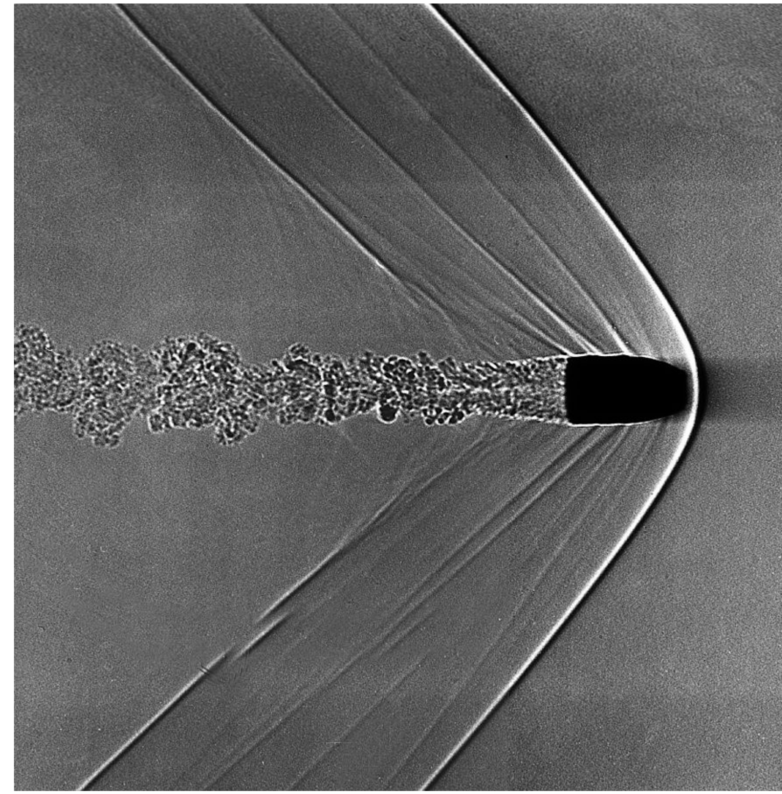
Pavel Alekseyevich Cherenkov

Nobel Prize in Physics (1958)

source: <https://en.wikipedia.org/wiki/Pavel_Cherenkov>

Cherenkov Effect

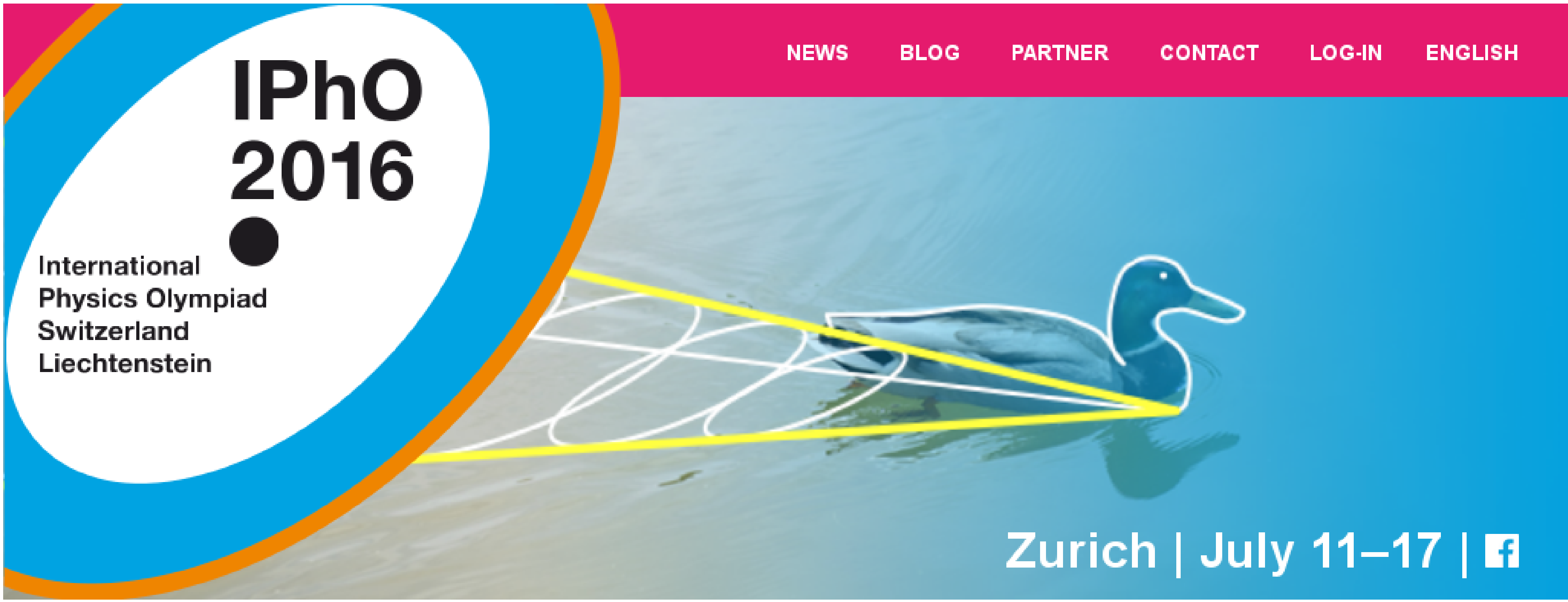
source: <https://en.wikipedia.org/wiki/Sound_barrier>



source: <https://en.wikipedia.org/wiki/Bullet_bow_shockwave>

Equivalent to the "sonic boom" emitted by a body moving faster than the speed of sound

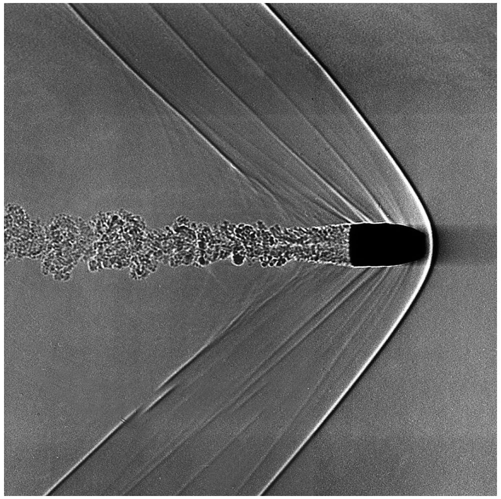
Cherenkov Effect

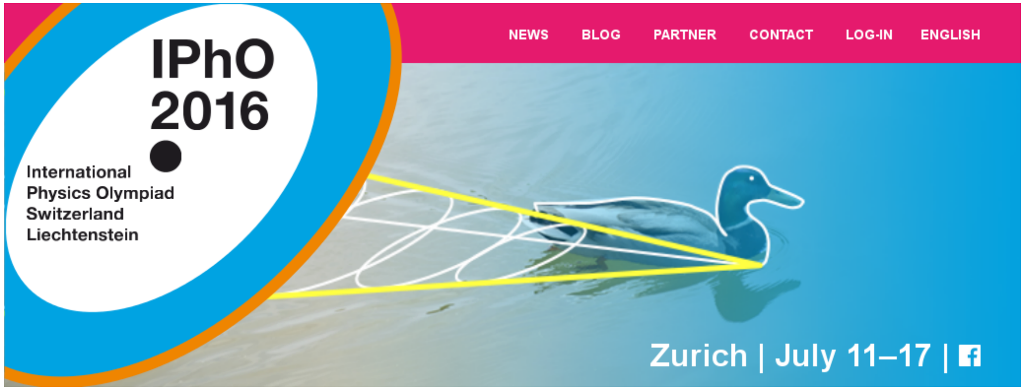


source: <http://www.ipho2016.org/>

… or the wake created by a duck swimming faster than the speed of water waves

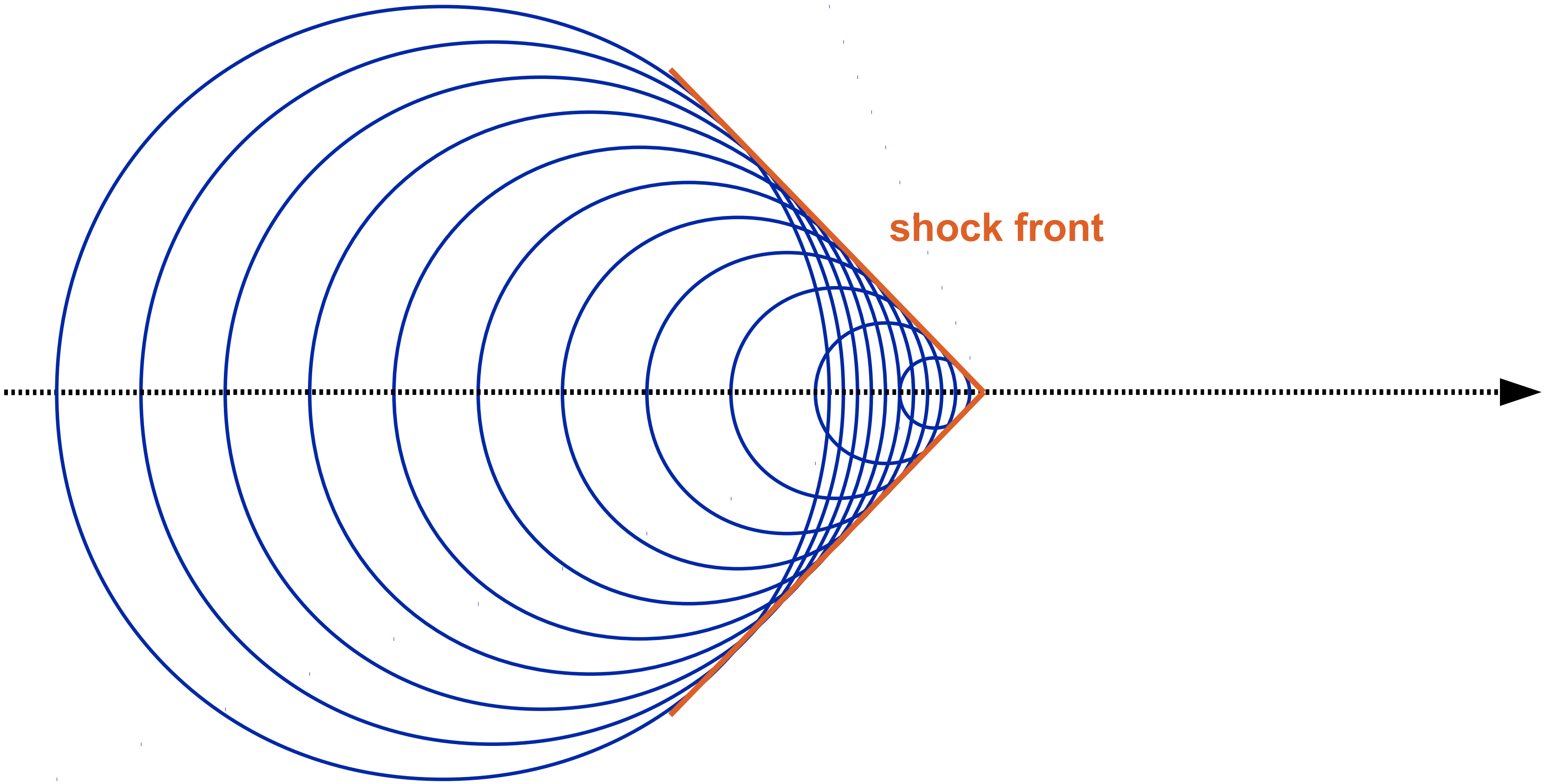
Cherenkov Angle





The shock wave is emitted under an angle with respect to the direction of motion

Cherenkov Angle

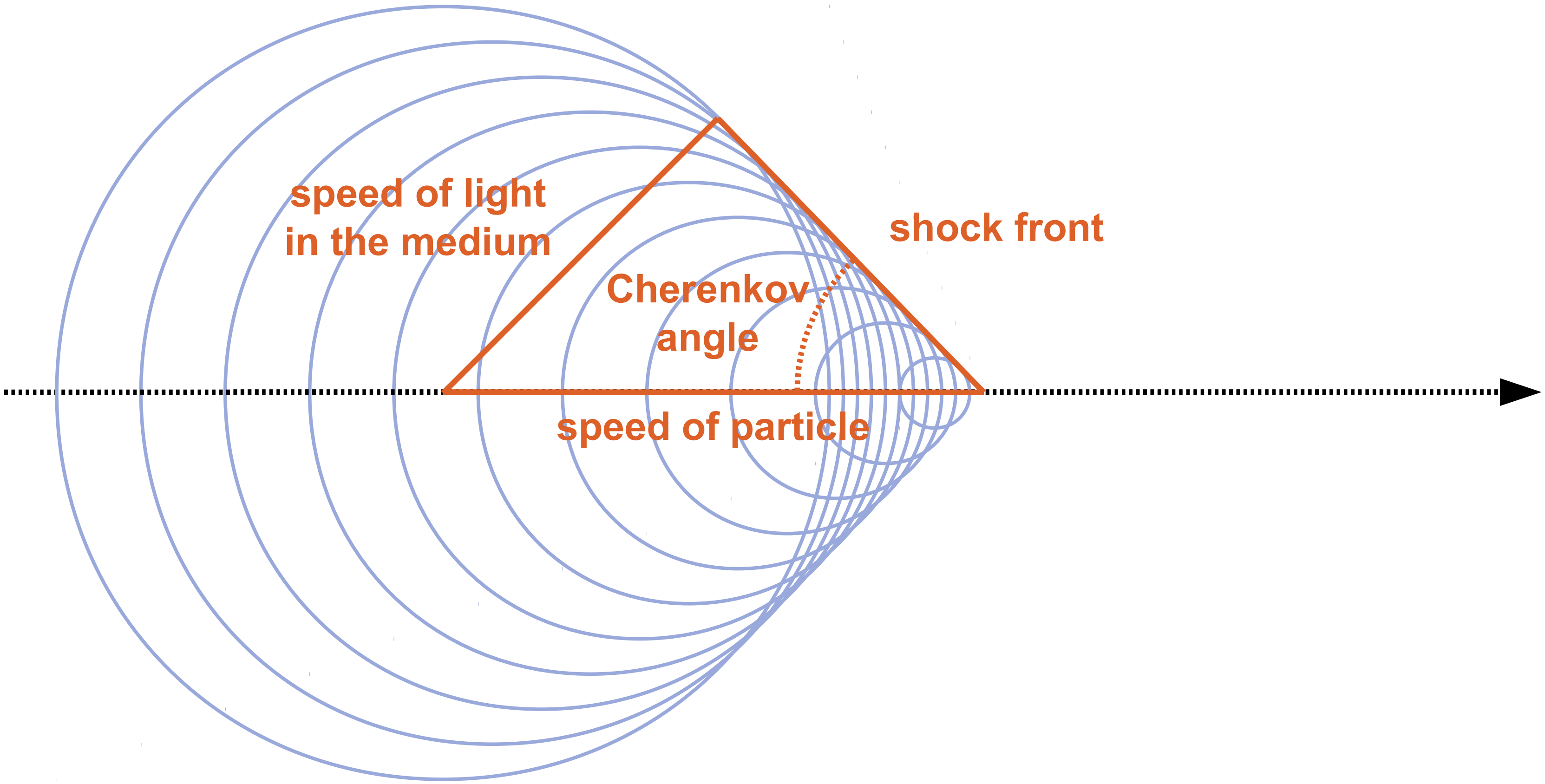


source: <https://en.wikipedia.org/wiki/Cherenkov_radiation>

The shock wave is emitted under an angle with respect to the direction of motion

That angle depends on the speed of the object / particle

Cherenkov Angle



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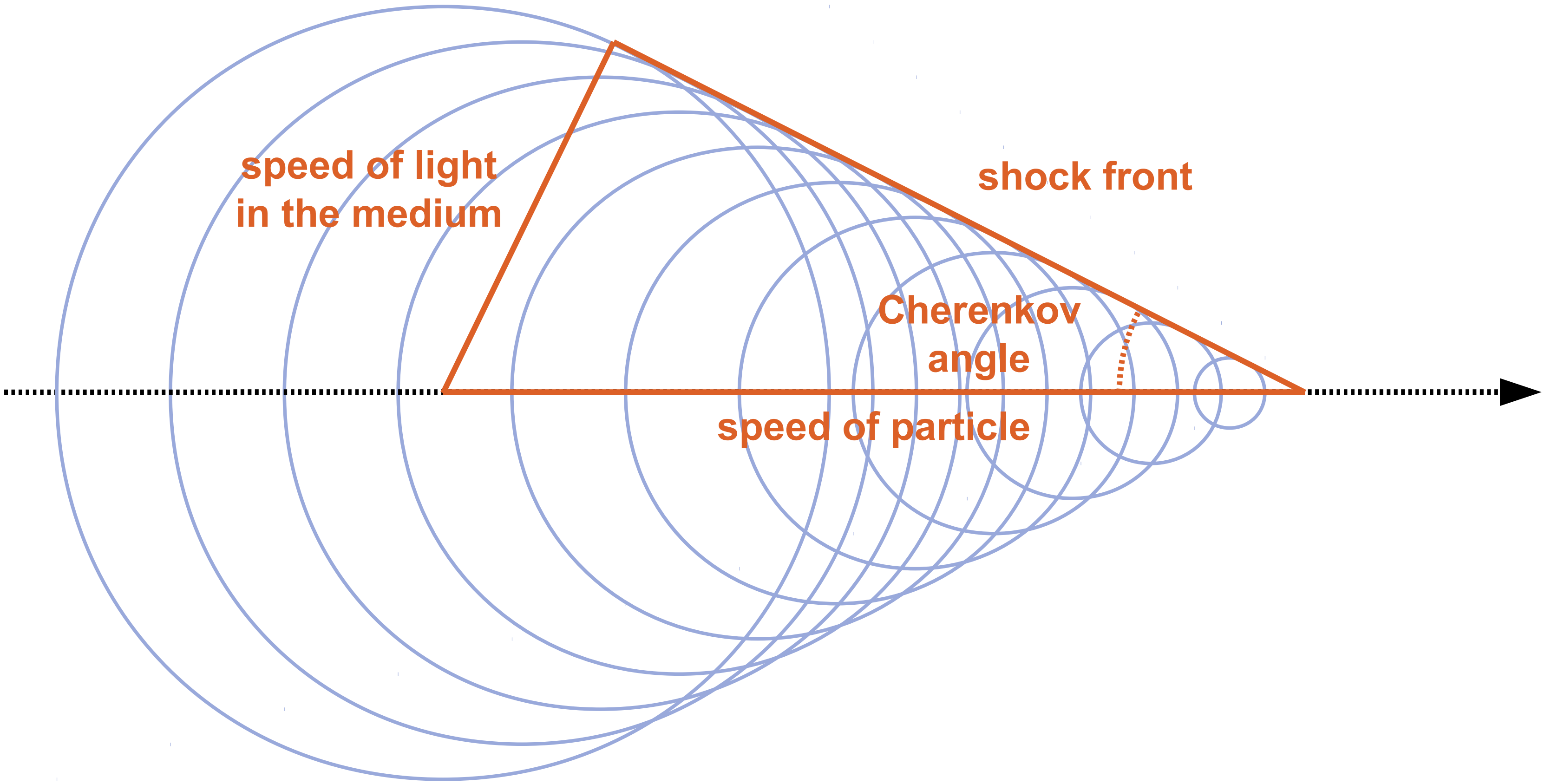

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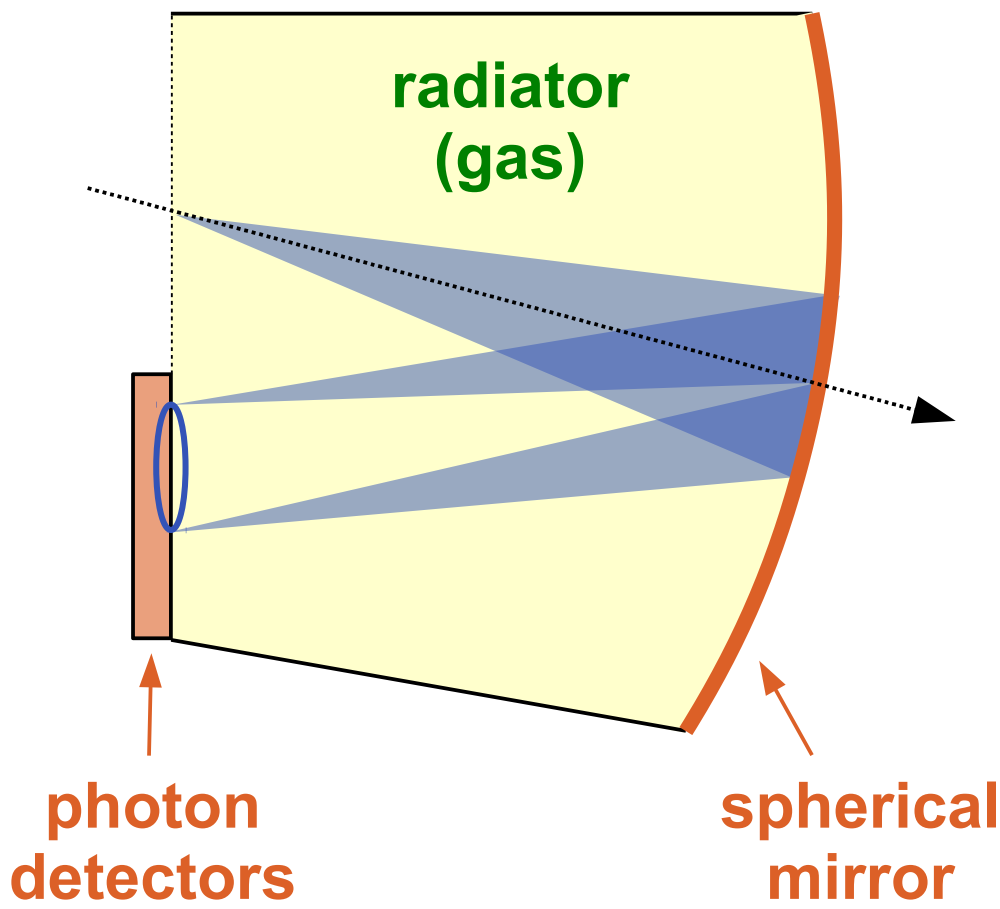
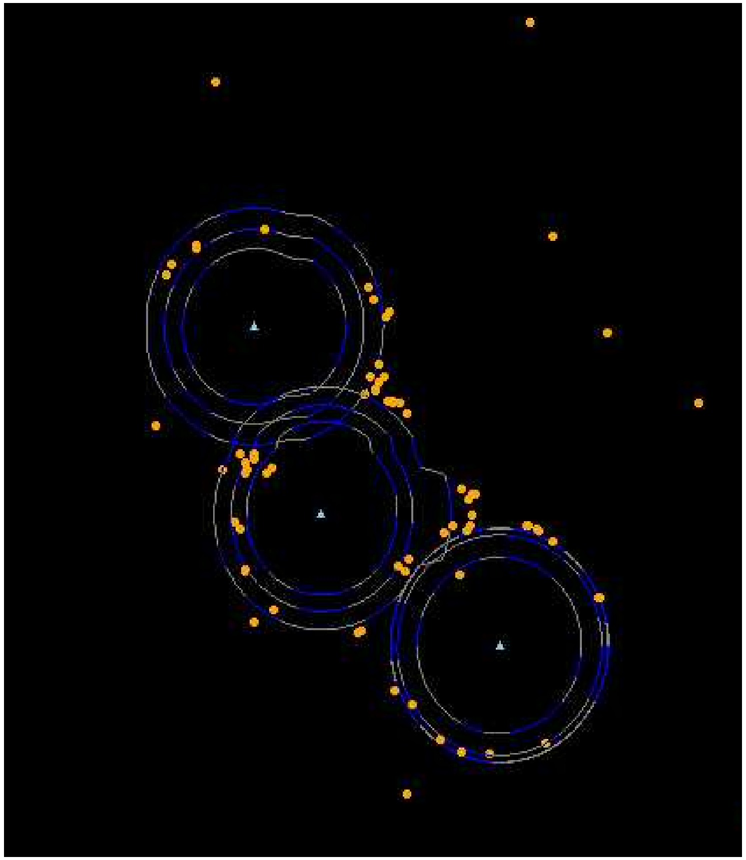
RICH



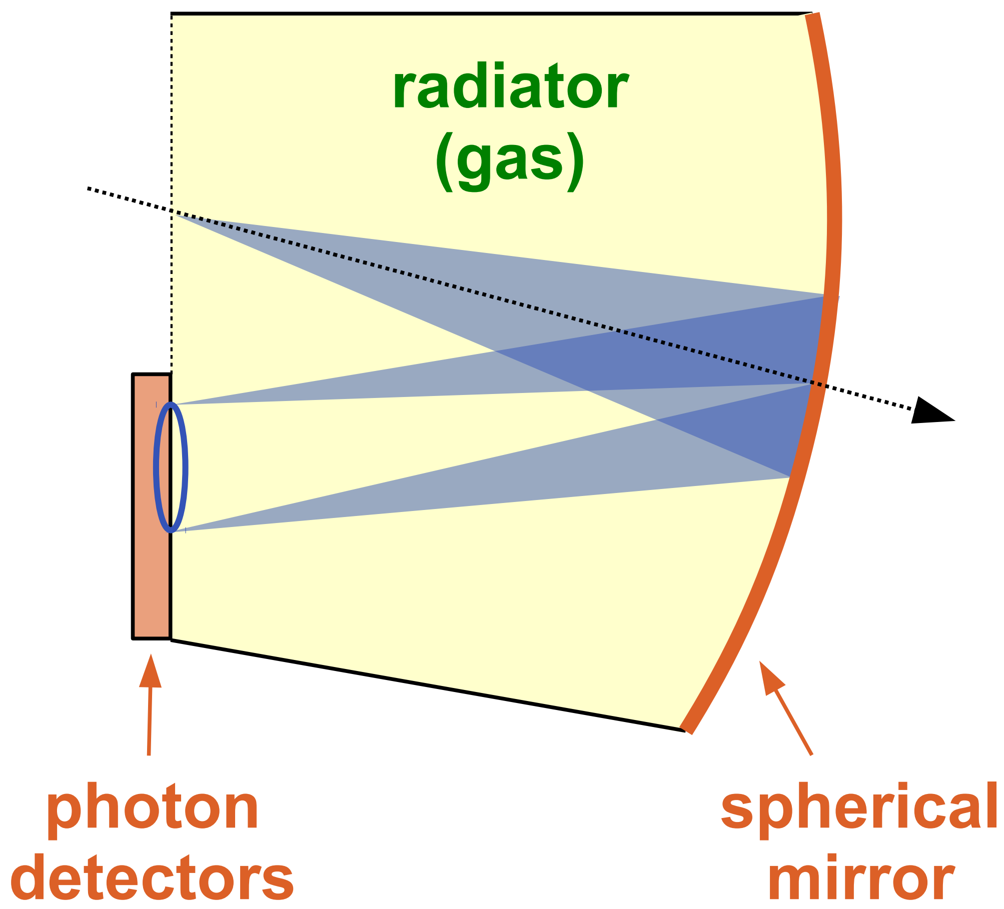


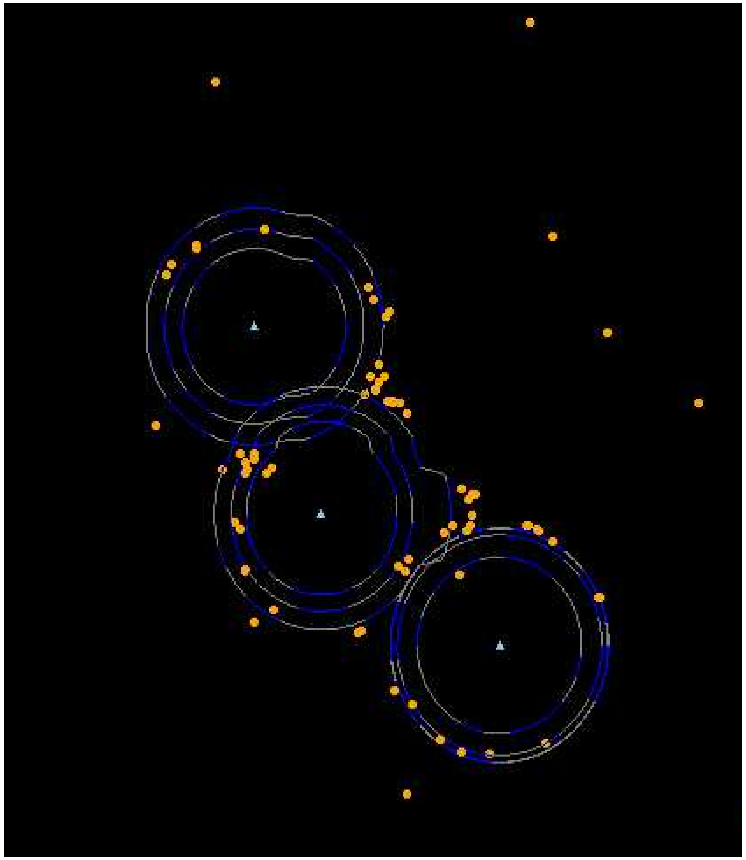
source: <lhcb-public.web.cern.ch/lhcb-public/>

“Ring Imaging CHerenkov detector”:

Focus the emitted light onto a detection plane → rings

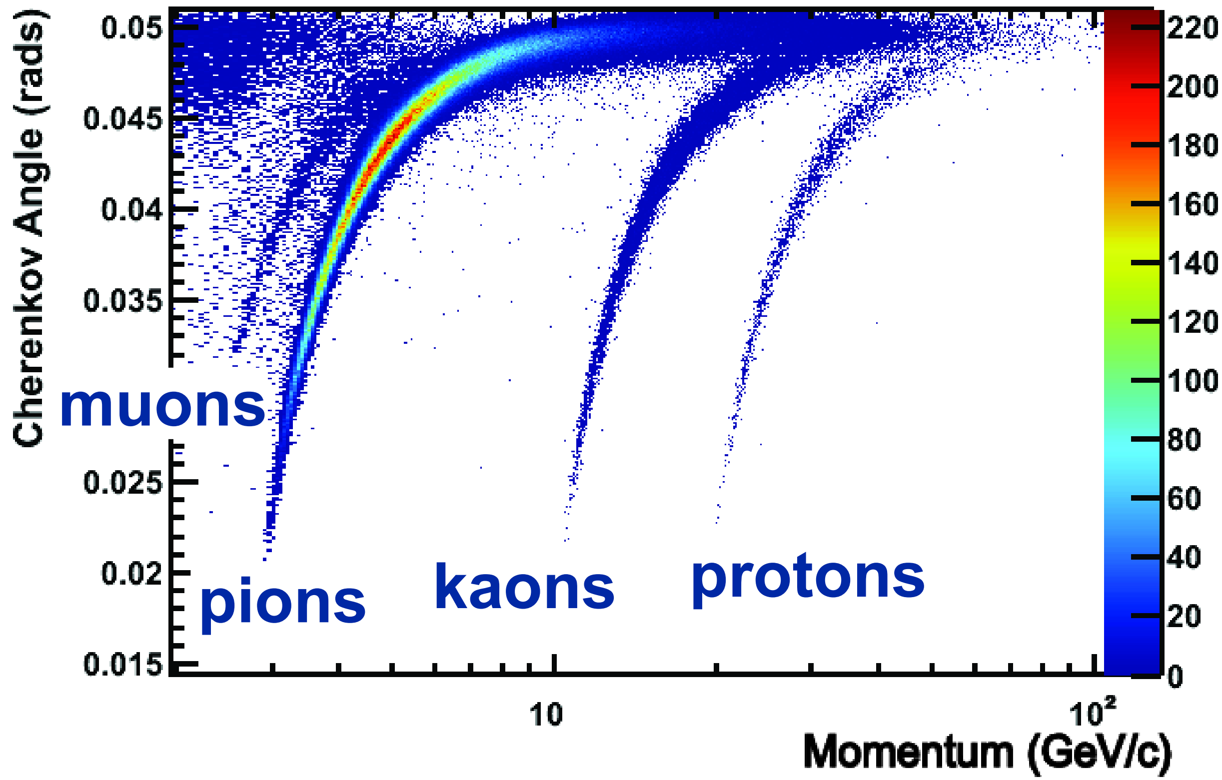
RICH Detectors





Radius of the ring → Cherenkov angle → Speed of the particle

Particle Identification



Momentum (tracking system)
&
Cherenkov angle (RICH)

→ Particle type

[The LHCb RICH Collaboration, M.Adinolfi et al., Eur.Phys.J. C (2013) 73:2431]

Many more ingredients …

Other detector elements

→ e.g. Calorimeters to measure the energy of the particles

Trigger

→ Fast electronics to decide whether something interesting happened

Data Acquisition

→ Fast network to transfer the detector information to computers

Reconstruction Software

→ Algorithms to interpret the raw data and reconstruct what happened

…

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…

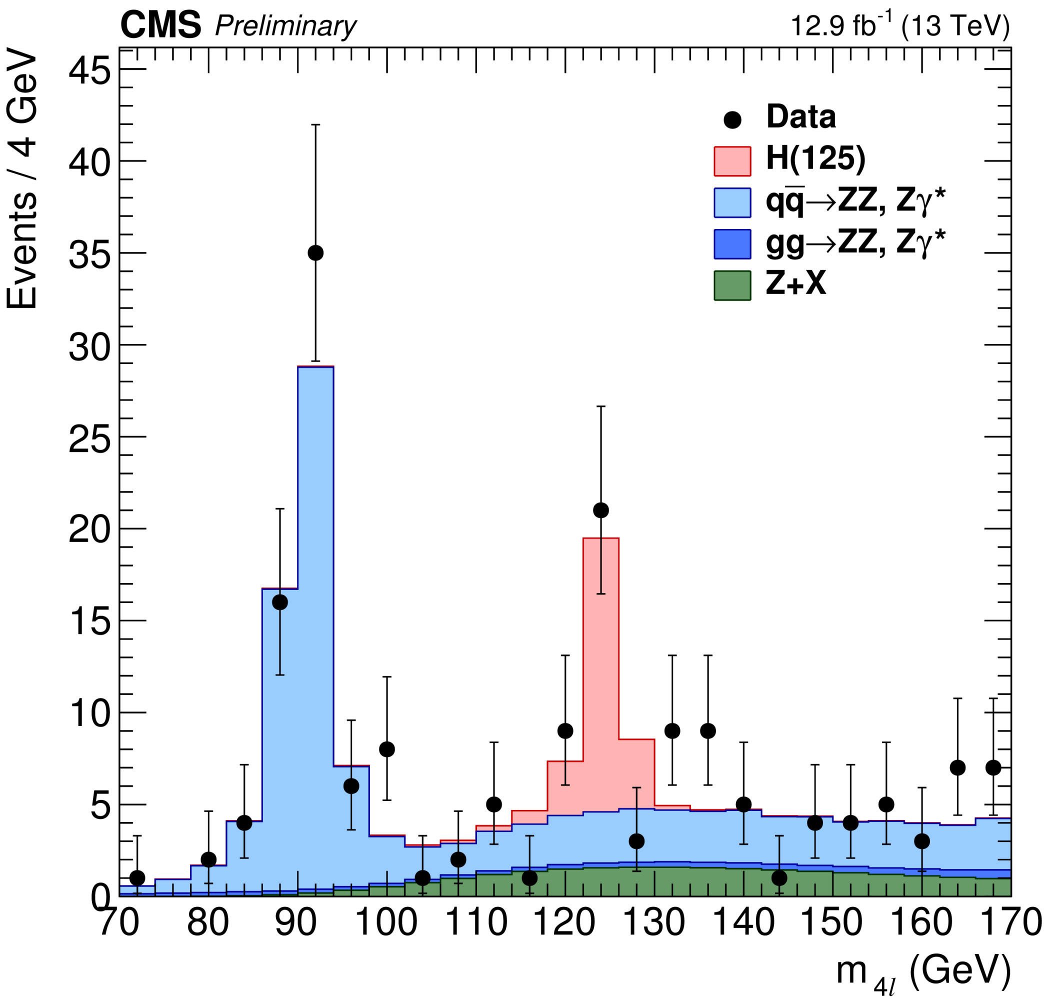
People

(physicists, but also engineers and technicians)

→ Who develop, build and commission all this

→ Who ensure efficient and precise operation over many years

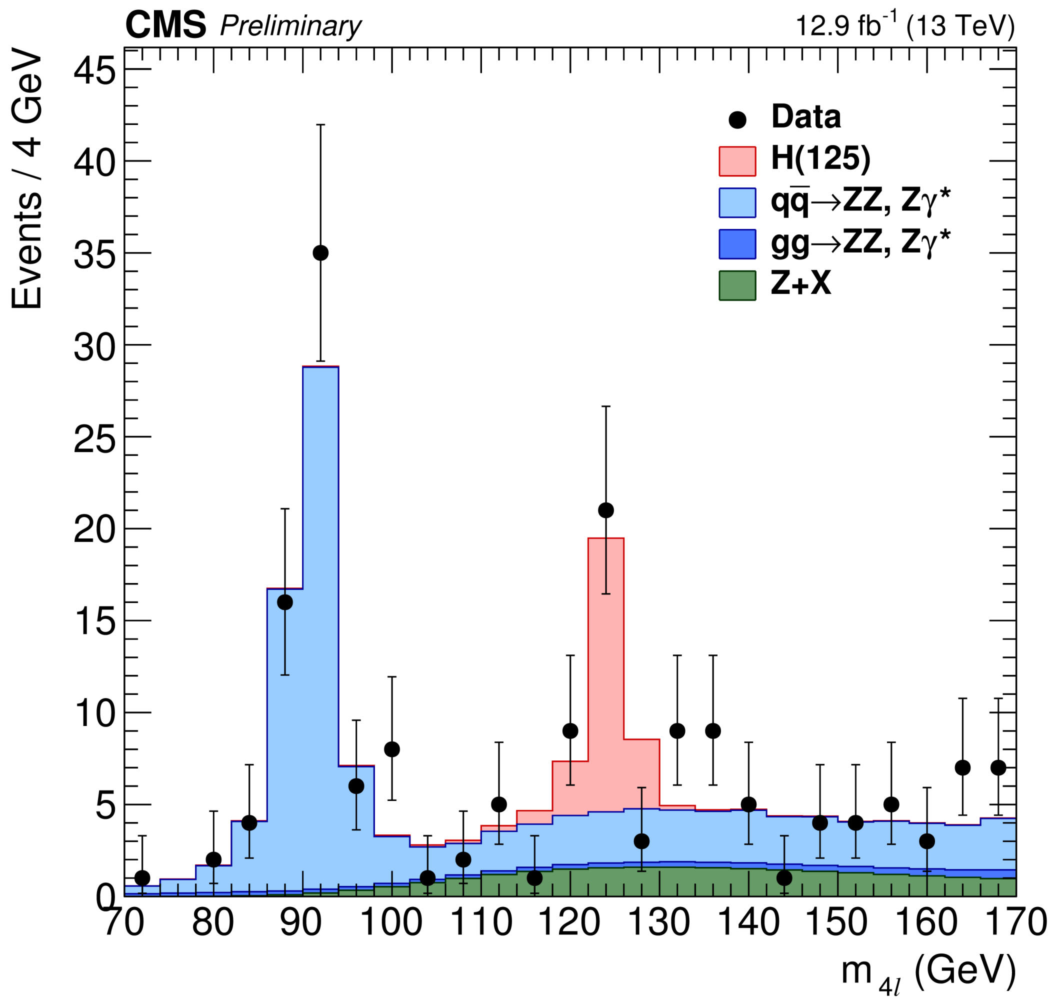
Seeing the Invisible



Higgs signal

in the CMS experiment

Seeing the Invisible



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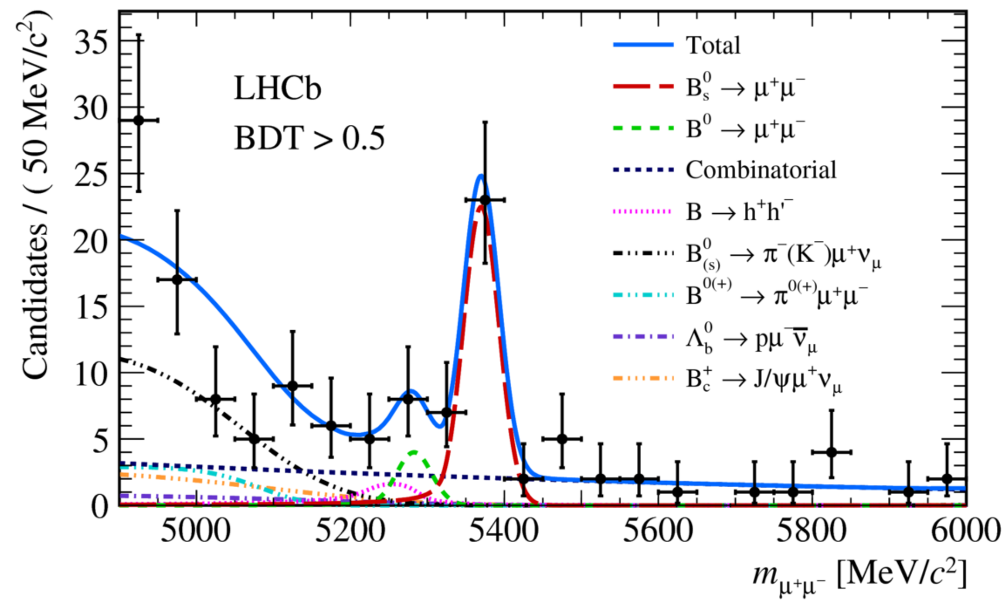

Observation of an

extremely rare decay

in the LHCb experiment