Lecture 6, Nov 6, 2019

Introduction to detectors

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Olaf Steinkamp

Born in Bremen (Germany)

Studied physics in Bonn (D)

PhD thesis work at CERN (GE)

1st PostDoc at CEA Saclay (F)

- NA48 experiment at CERN

2nd PostDoc at NIKHEF Amsterdam (NL)

- HERA-B experiment at DESY (Hamburg)

Since 2000 at University of Zurich:

- LHCb experiment at CERN
- Lectures on particle physics, data analysis, experimental techniques

FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

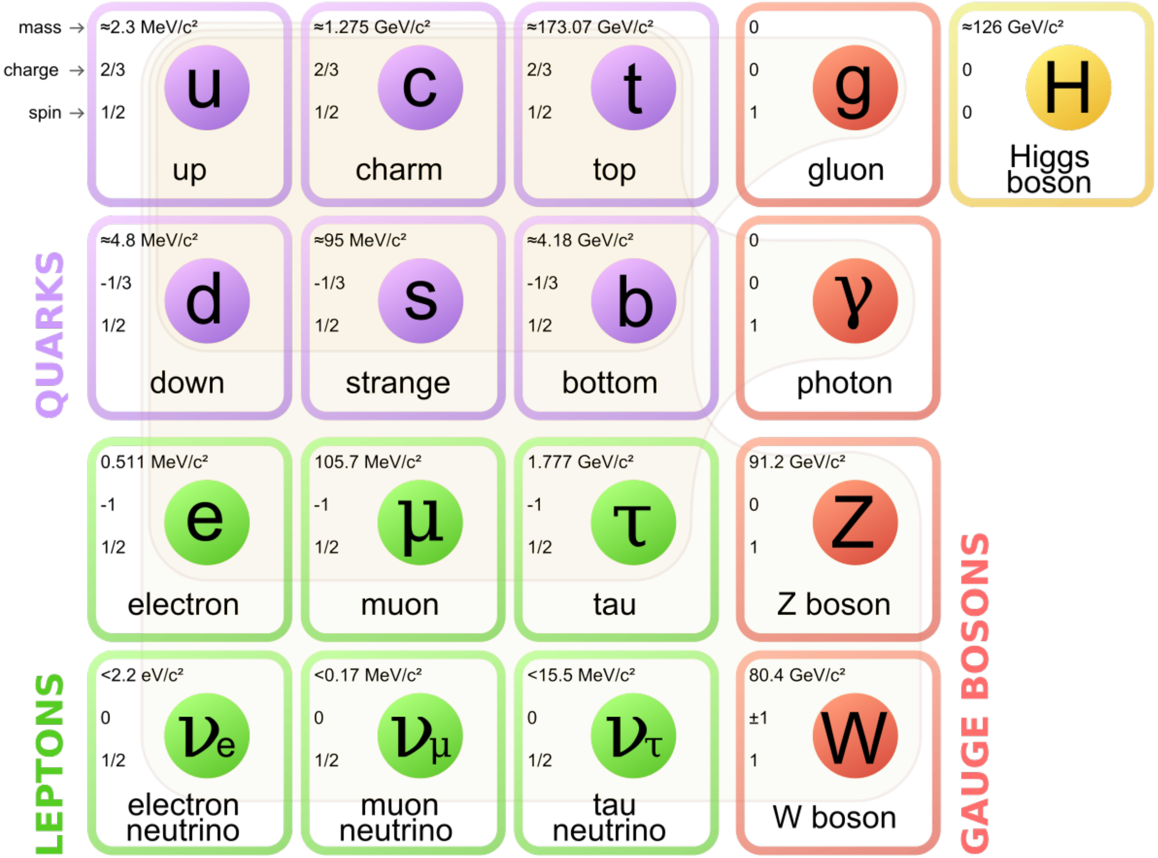
MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

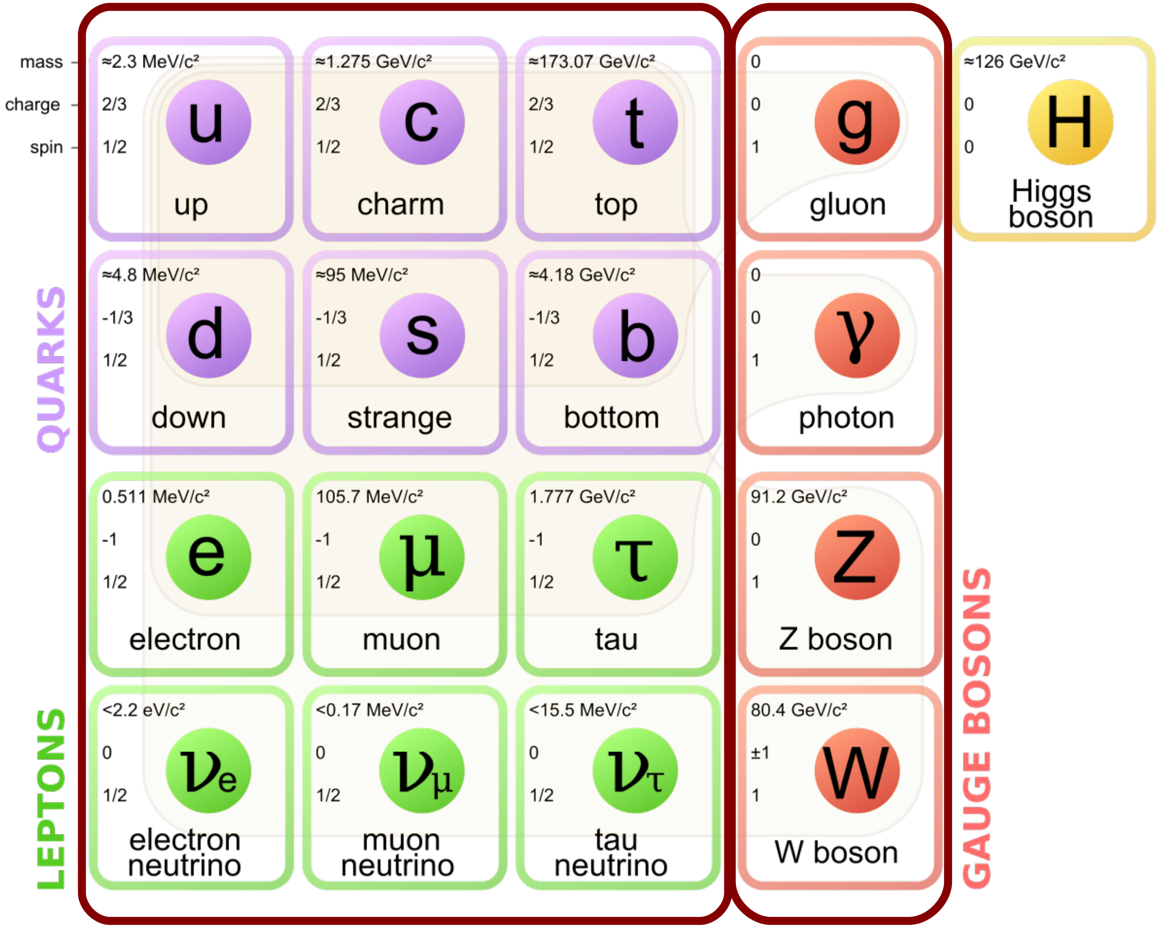
University of Zurich UZH

Elementary Particles



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

Elementary Particles



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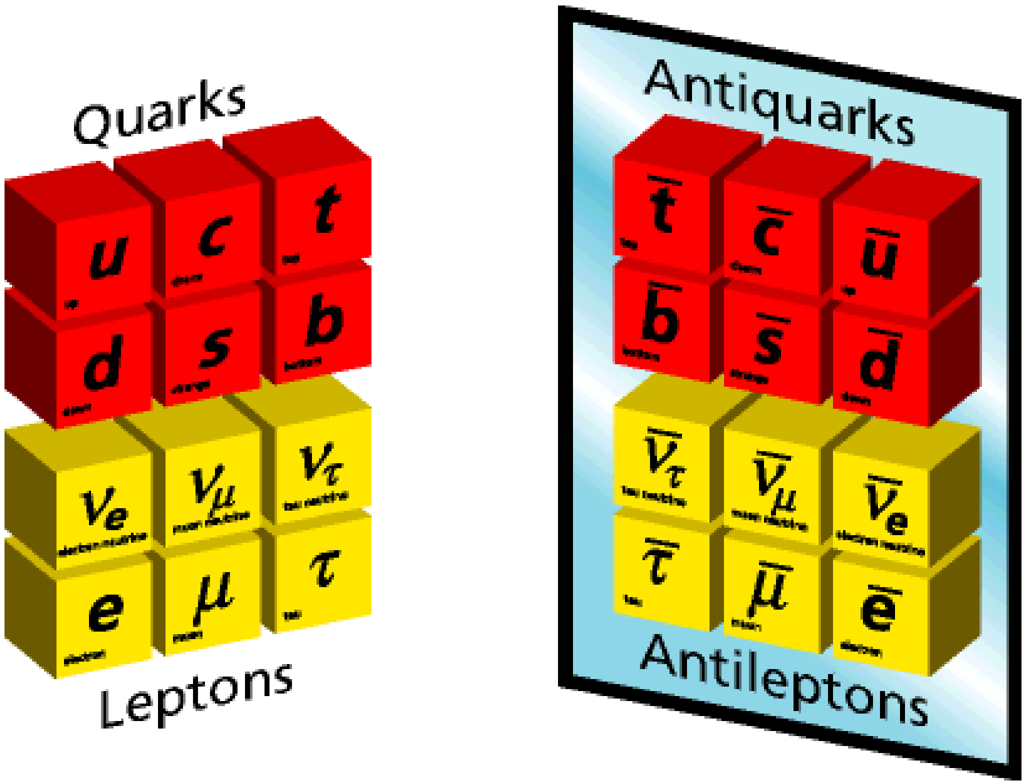
matter **interactions**

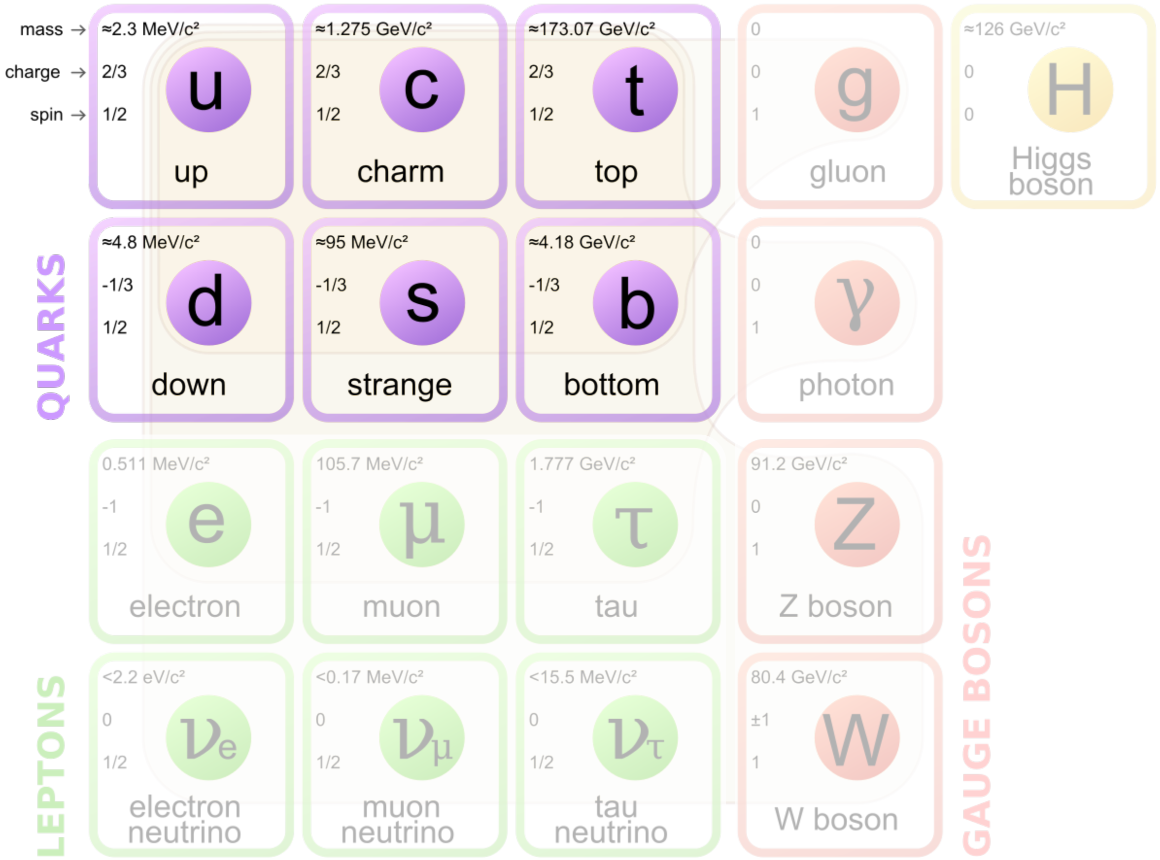
Elementary Particles



+ matter antiparticles: same mass, same lifetime, opposite charge

(anti-electron ≡ positron)

Particle Zoo



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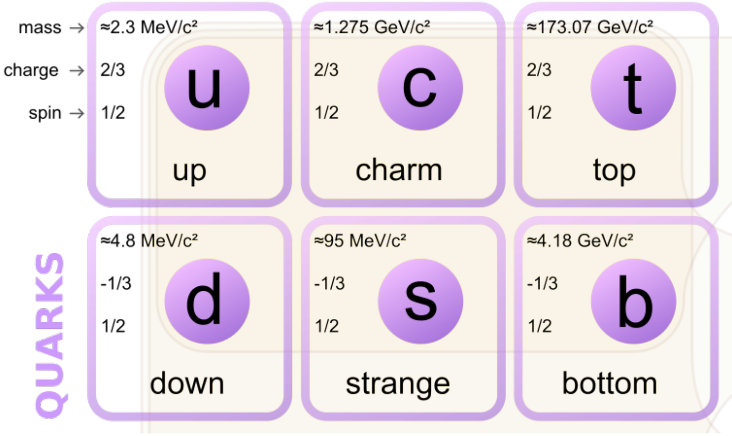
Quarks / antiquarks are not observed as free particles

Particle Zoo

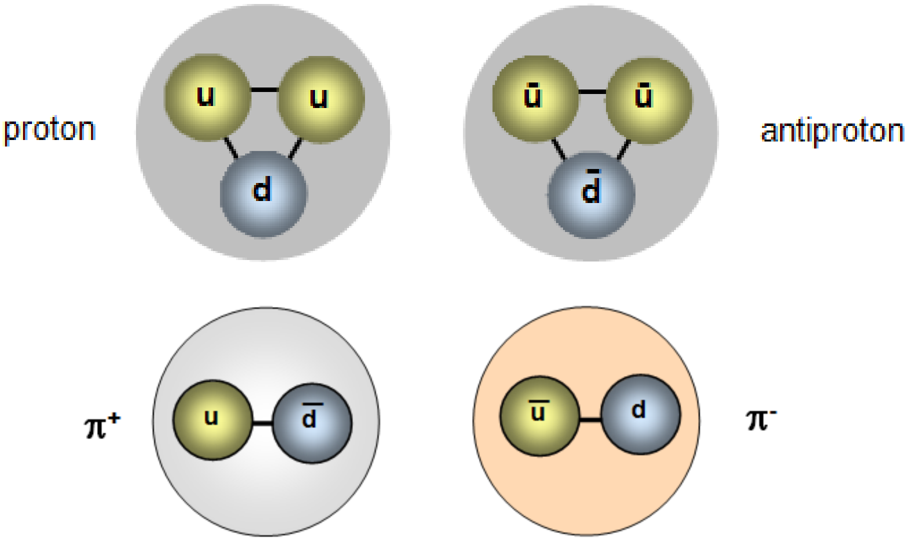


QUARKS

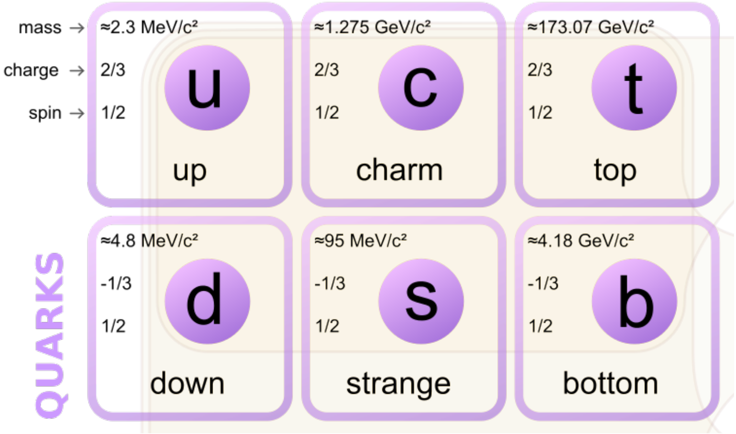
mass →	≈2.3 MeV/c^2	≈1.275 GeV/c^2	≈173.07 GeV/c^2
charge →	2/3	2/3	2/3
spin →	1/2	1/2	1/2
	u	c	t
	up	charm	top
	≈4.8 MeV/c^2	≈95 MeV/c^2	≈4.18 GeV/c^2
	-1/3	-1/3	-1/3
	1/2	1/2	1/2
	d	s	b
	down	strange	bottom

Observed particles consist of

- **three quarks (**“baryons”**), or**
- **quark and antiquark (**“mesons”**)**



Particle Zoo



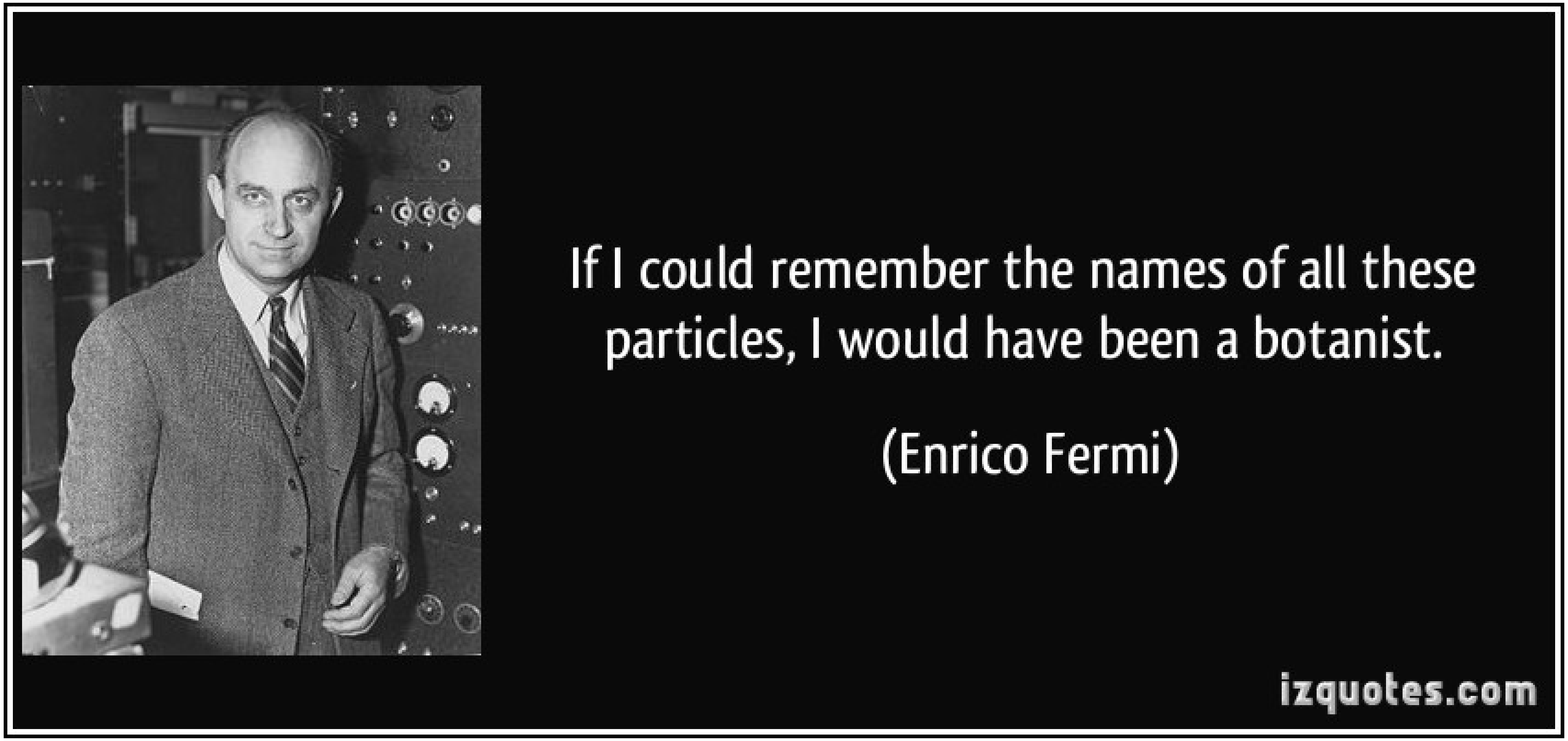
Observed particles consist of

- **three quarks (“baryons”), or**
- **quark and antiquark (“mesons”)**

}

many possible combinations: “particle zoo”

Particle Zoo



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

(Enrico Fermi)

izquotes.com

source: <http://izquotes.com/quote/389467>

Long-lived Particles

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

Short-lived Particles

Reconstruct short-lived particles indirectly,
by measuring their long-lived decay products

Relativistic kinematics

$$\boxed{E^2 = m^2 + p^2}$$

using “natural units”
with $c \equiv 1$

Energy and momentum conservation in the decay

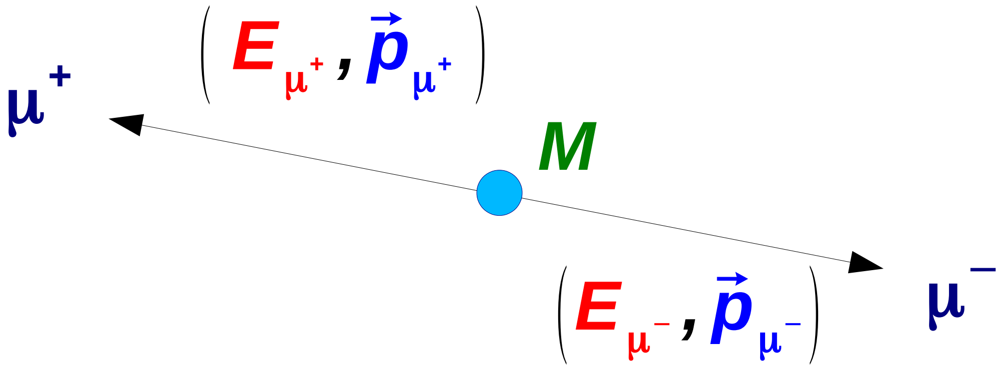
$$\boxed{M^2 = \left(\sum E_i\right)^2 - \left|\sum \vec{p}_i\right|^2}$$

Mass of decaying particle

Energies and momenta of
the particles produced in the decay

Short-lived Particles

Example: particle with mass $M > 2m_\mu$ decays to muon and antimuon



μ^+

$(E_{\mu^+}, \vec{p}_{\mu^+})$

M

$(E_{\mu^-}, \vec{p}_{\mu^-})$

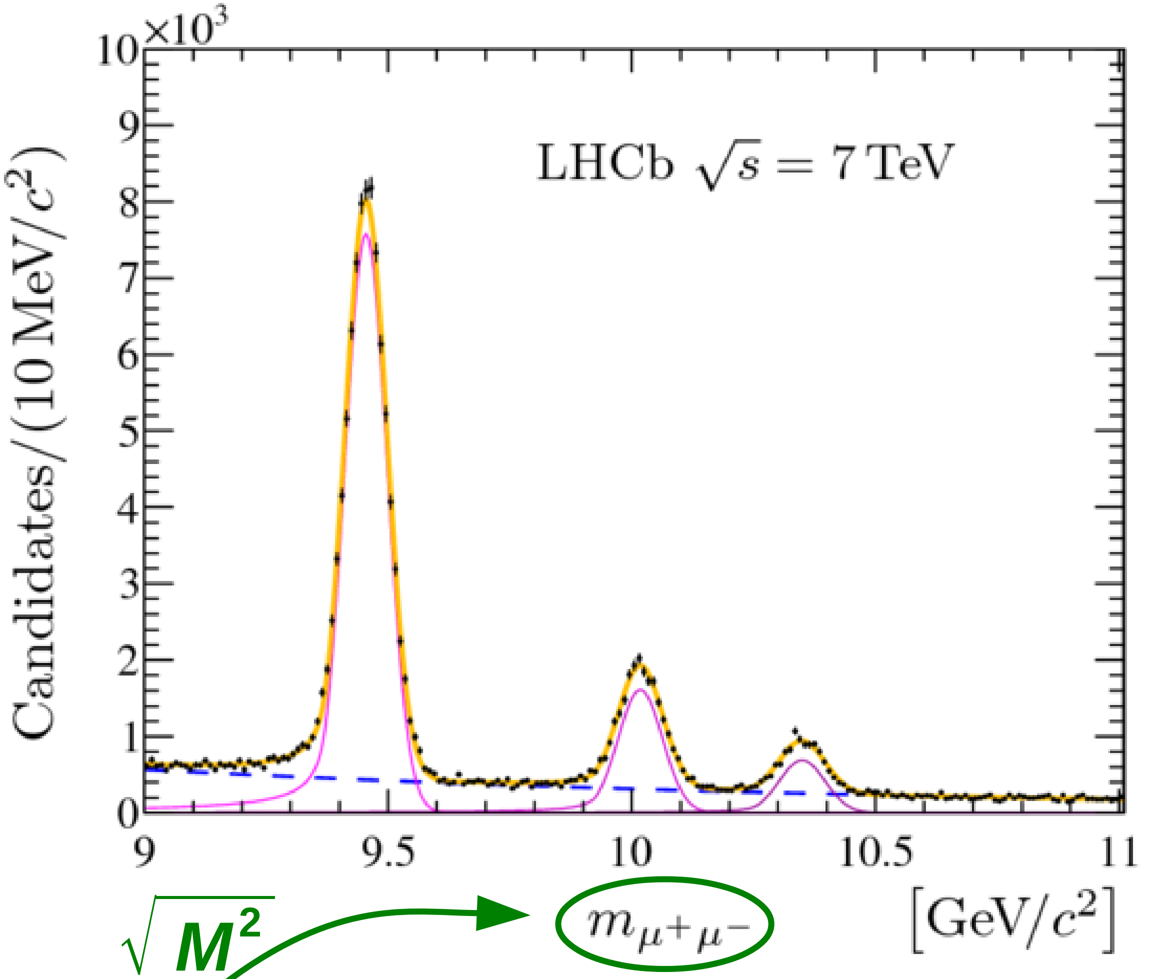
μ^-

Measure the momenta of muon and antimuon

- **determine their energies ($E_{\mu^\pm}^2 = m_\mu^2 + p_{\mu^\pm}^2$)**
- **calculate the mass of the decaying particle:**

$$\boxed{M^2 = \left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2}$$

Short-lived Particles

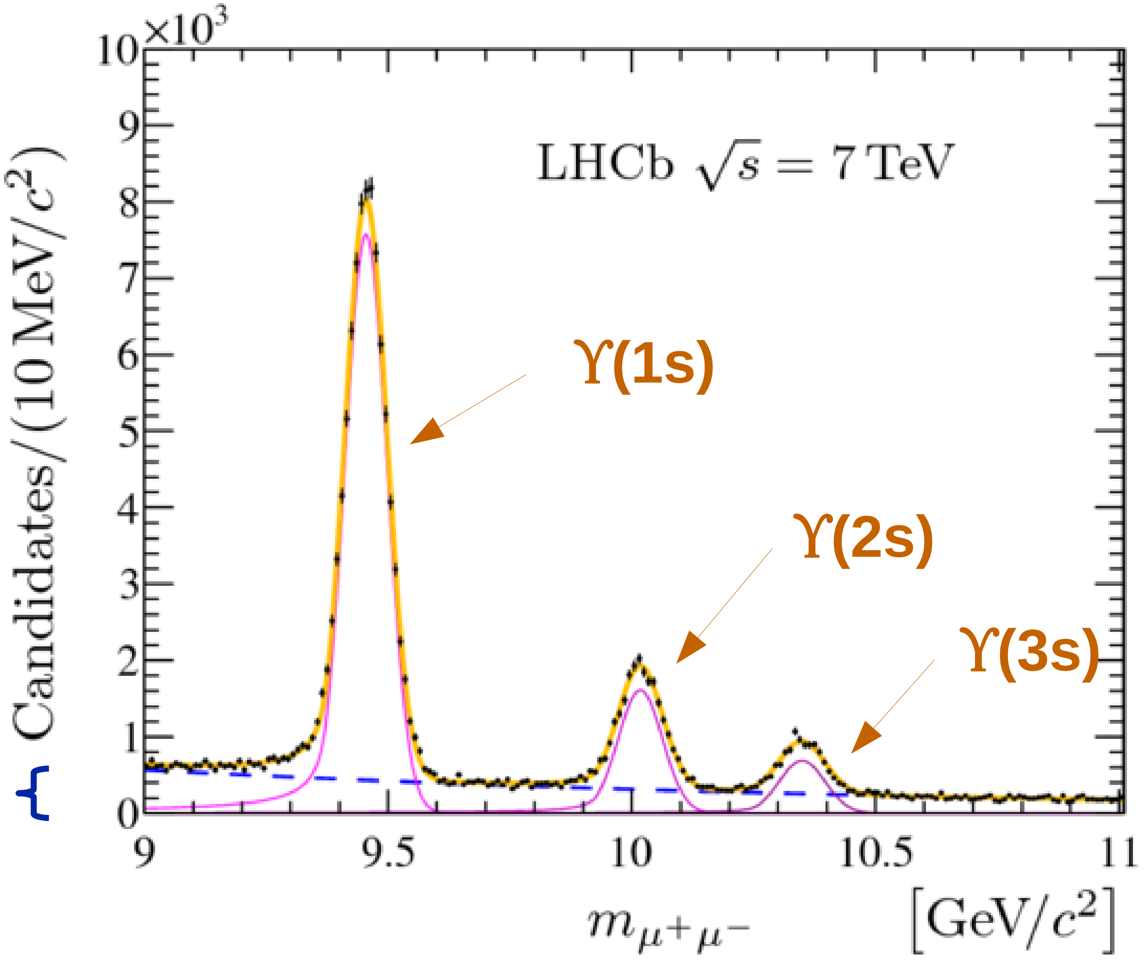


$\sqrt{M^2}$

$$M^2 = \left(E_{\mu^+} + E_{\mu^-}\right)^2 - \left|\vec{p}_{\mu^+} + \vec{p}_{\mu^-}\right|^2$$

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

Short-lived Particles

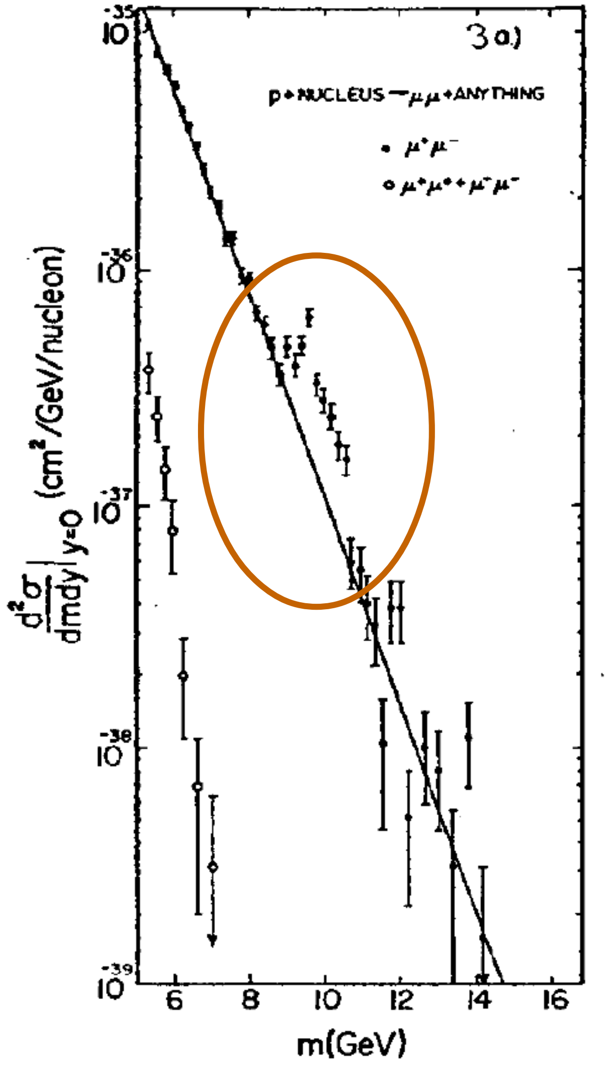


signal: short-lived particles decaying into $\mu^+ \mu^-$

background: random combinations of μ^+ and μ^-

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

Discovery of ϒ particles in 1977



OBSERVATION OF A DIMUON RESONANCE AT 9.5 GeV
IN 400 GeV PROTON-NUCLEUS COLLISIONS

S. W. Herb, D. C. Hom, L. M. Lederman,
J. C. Sens, H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown
W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

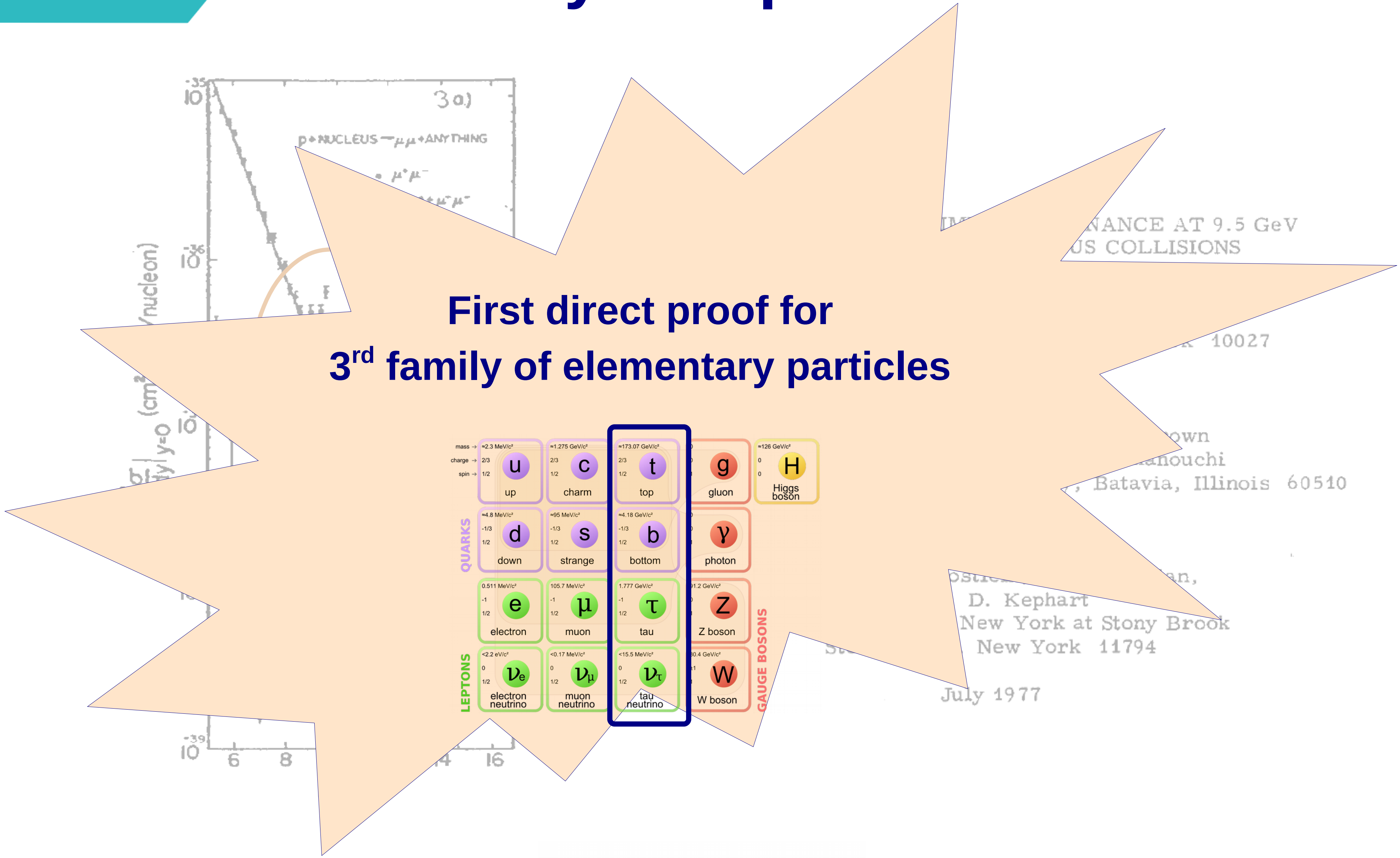
and

A. S. Ito, H. Jöstlein, D. M. Kaplan,
and R. D. Kephart
State University of New York at Stony Brook
Stony Brook, New York 11794

July 1977

[S.W.Herb et al., Fermilab-Pub-77/58-EXP]

Discovery of ϒ particles in 1977

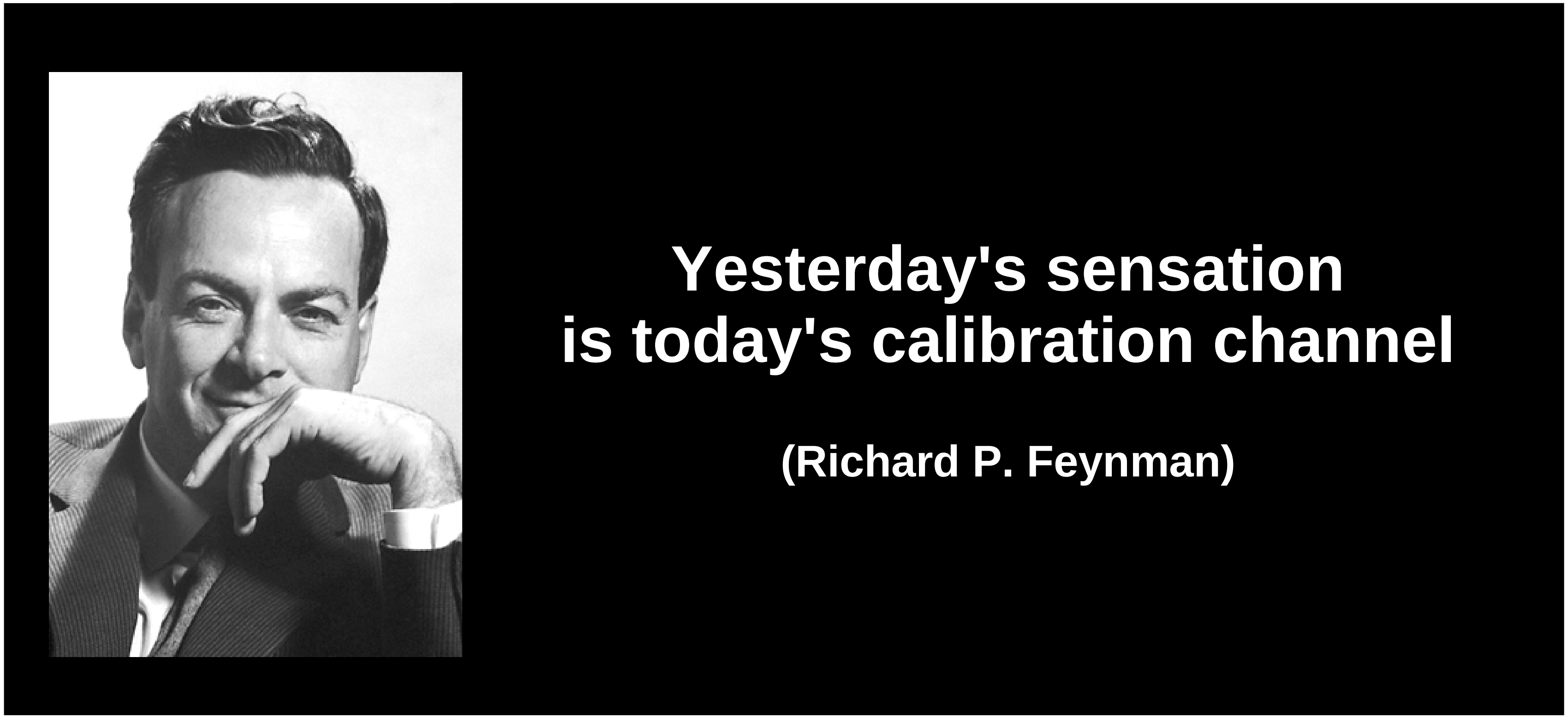


First direct proof for

3rd family of elementary particles

[S.W.Herb et al., Fermilab-Pub-77/58-EXP]

“Yesterday’s sensation …“

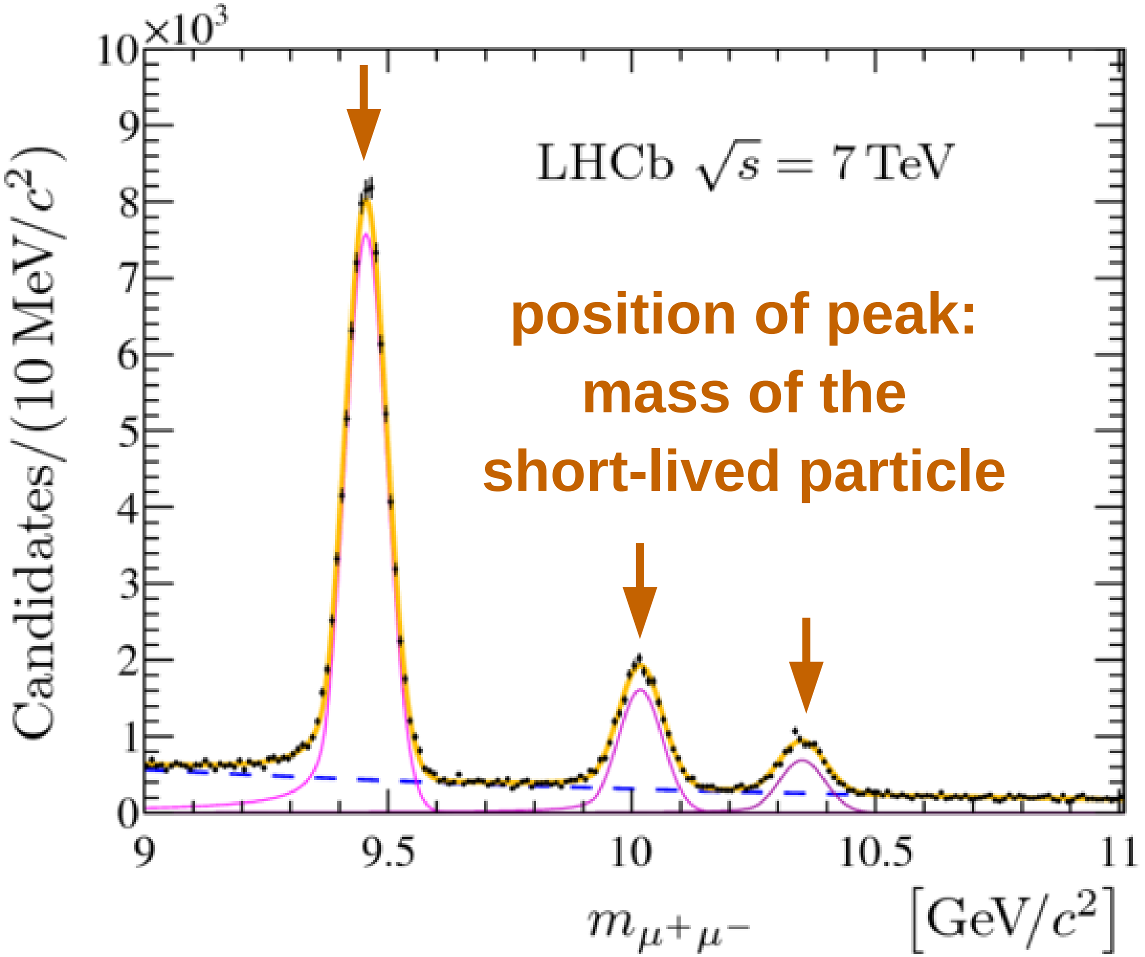


Yesterday's sensation
is today's calibration channel

(Richard P. Feynman)

photo source: [https://en.wikipedia.org/wiki/Richard_Feynman]

“… today’s calibration channel“



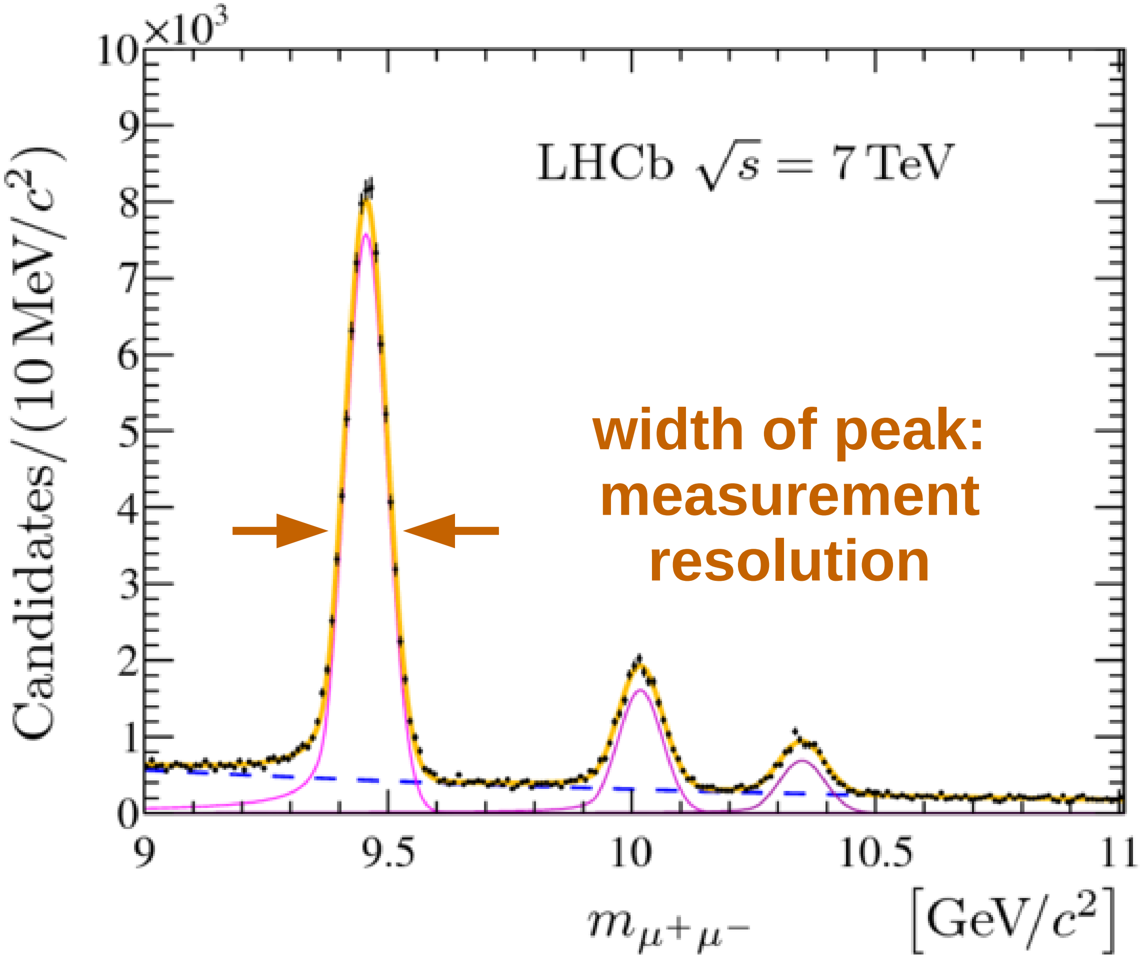
position of peak:
mass of the
short-lived particle

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

Compare position of peak with known mass of the particle

→ calibrate momentum measurement

“... today’s calibration channel“



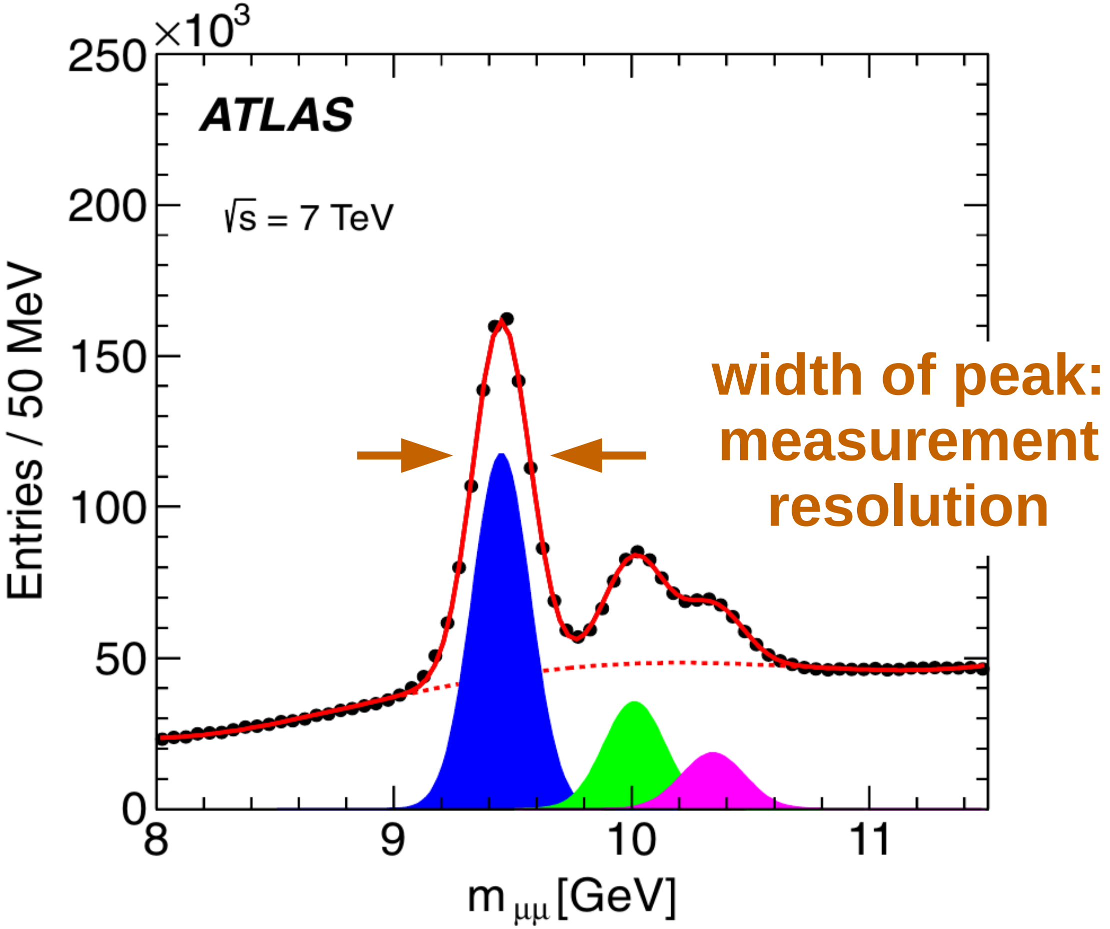
width of peak: measurement resolution

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

Width of signal due to finite precision of momentum measurement

→ determine momentum resolution of the detector

“… today’s calibration channel“



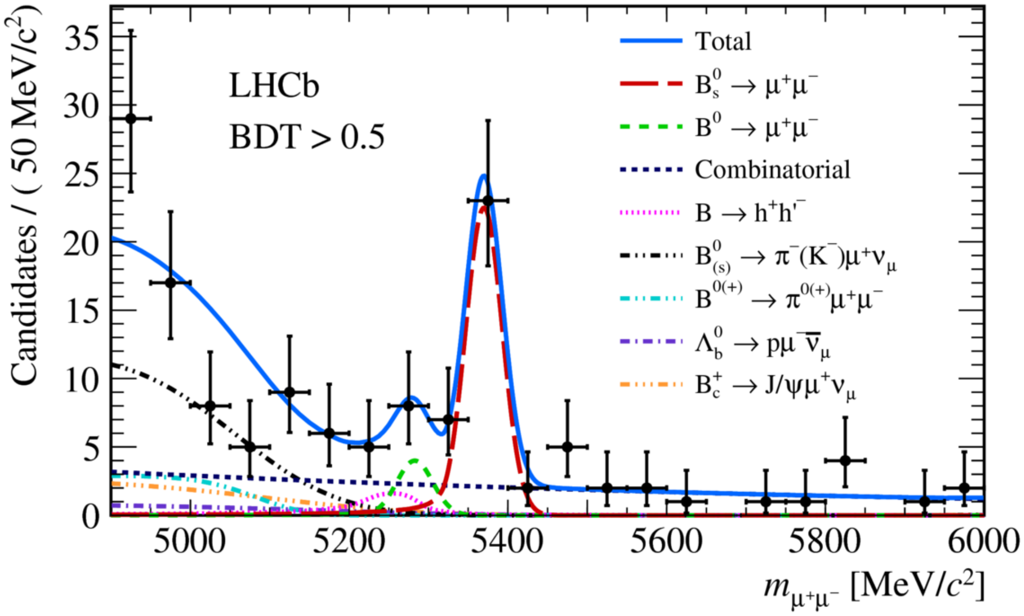
width of peak:
measurement
resolution

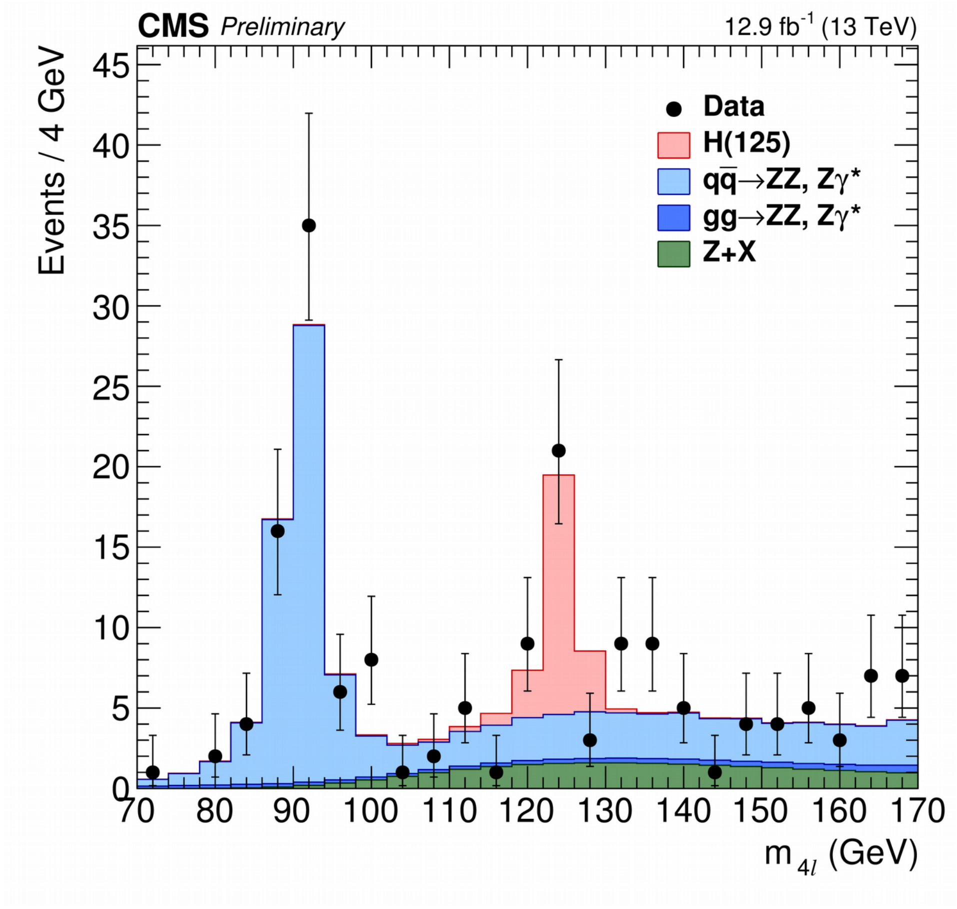
[G.Aad et al. (ATLAS Collaboration), Phys.Rev.D 87 (2013) 052004]

Width of signal due to finite precision of momentum measurement

→ determine momentum resolution of the detector

Today’s sensations





First measurement of the very rare decay

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

in LHCb and CMS

Discovery of the Higgs-boson

in ATLAS and CMS

Experiments

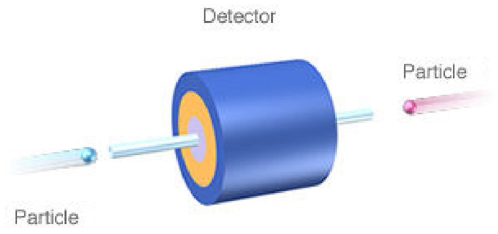
Accelerate a beam of (stable & charged) particles to high energies

- electrons/positrons, protons/antiprotons, heavy ions

Bring them into collision with

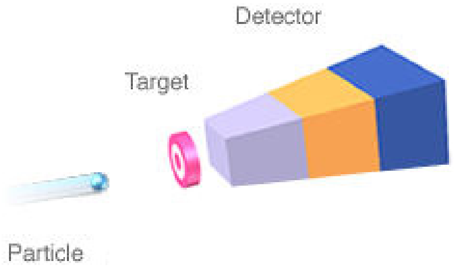
- **another beam of particles ("collider experiment")**

e.g. ATLAS, CMS

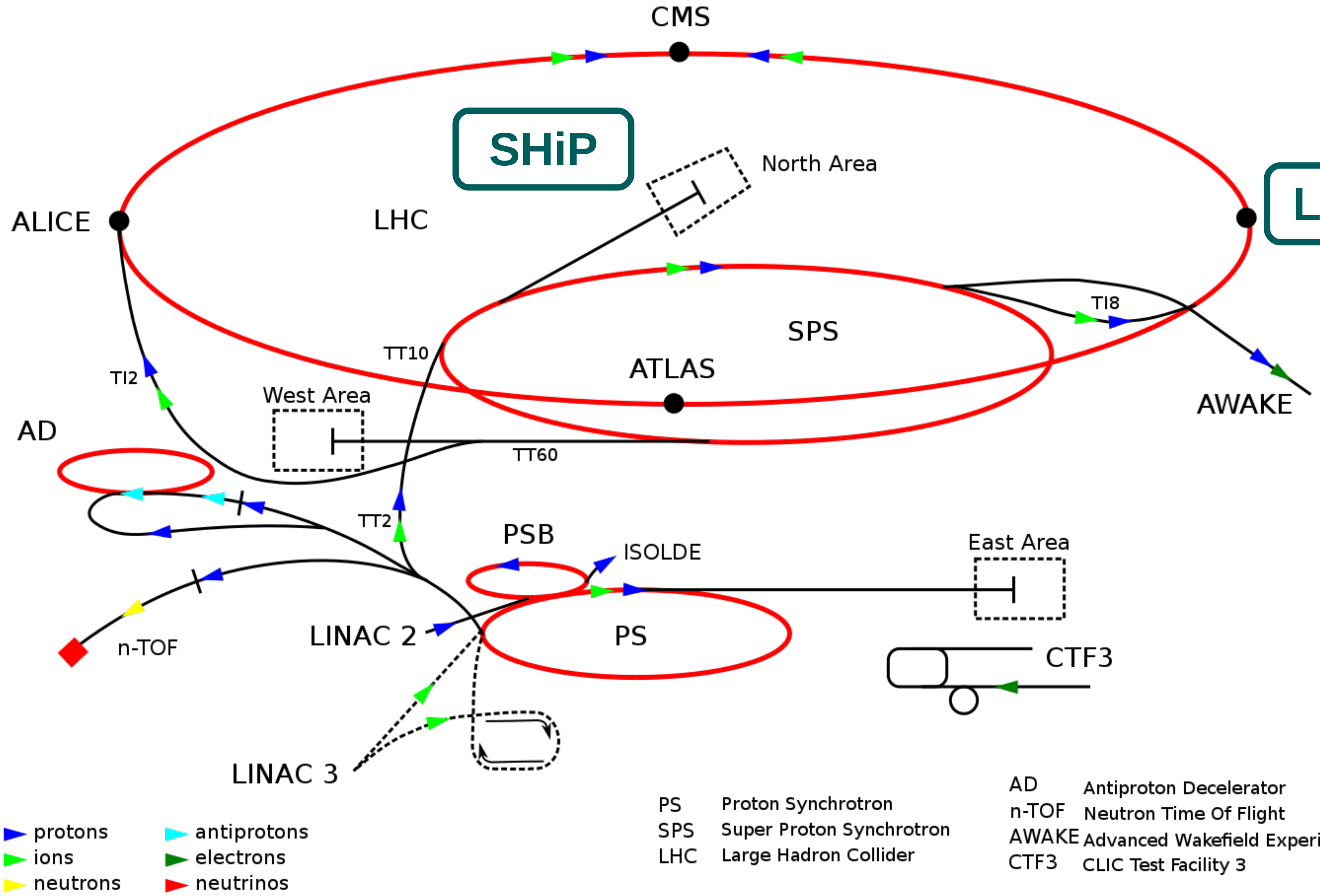


- **a target at rest ("fixed-target experiment")**

e.g. SHiP



Experiments



PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider

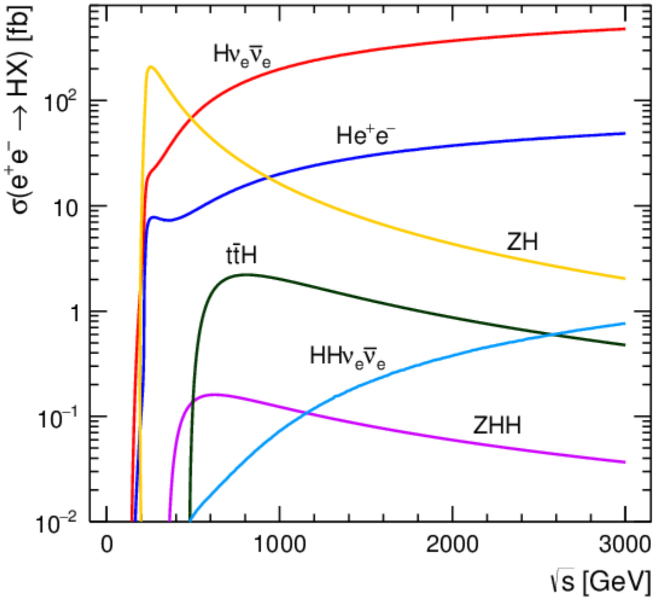
AD	Antiproton Decelerator
n-TOF	Neutron Time Of Flight
AWAKE	Advanced Wakefield Experiment
CTF3	CLIC Test Facility 3

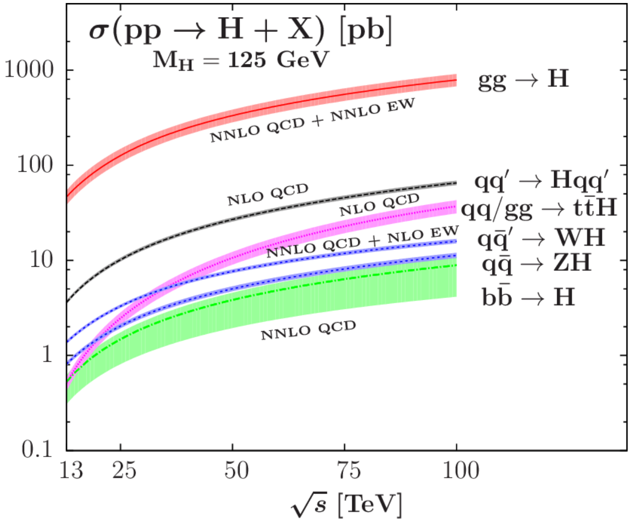
Experiments

Collide particles
at the highest possible energy

→ to probe high masses

$$E = mc^2$$





Experiments

Collide particles at the highest possible energy

→ to probe high masses

$$E = mc^2$$

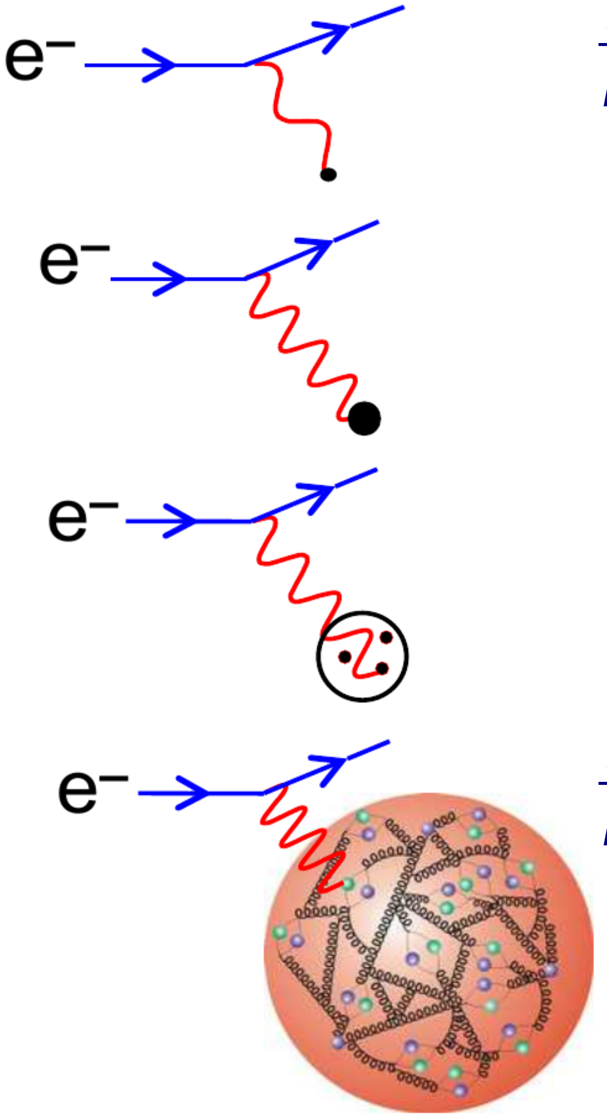
→ to probe small distances

Heisenberg
uncertainty principle:

$$\Delta p \cdot \Delta x \geq \hbar$$

De Broglie wavelength

$$\lambda = \frac{\hbar}{p}$$



$$\frac{\hbar}{p} \gg r_p$$

$$\frac{\hbar}{p} \approx r_p$$

$$\frac{\hbar}{p} < r_p$$

$$\frac{\hbar}{p} \ll r_p$$

Experiments

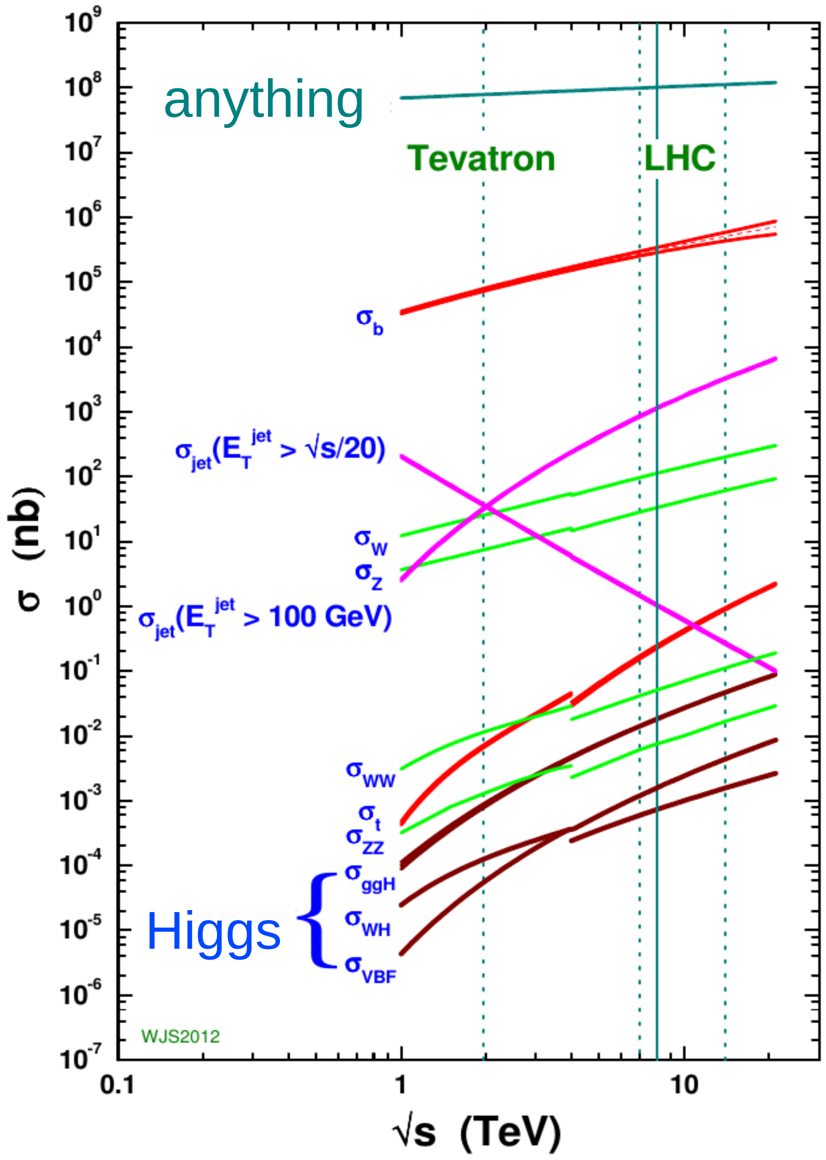
Collide particles
at the highest possible energy

and the at highest possible rate

→ to probe rare processes

e.g. LHC at 13 TeV:

only about 1 in 10^9 *pp* collisions produces a Higgs boson



Experiments

Particle physics experiments use different “subdetectors” to

→ measure the trajectories of long-lived particles

→ measure their momentum and energy

→ determine their type

If we know the particle type, we know its mass
→ measure energy directly or calculate it from momentum

$$\boxed{E^2 = m^2 + p^2}$$

Experiments

Components of a particle-physics experiment

- production & decay vertices
- flight paths
- momenta

} **position-sensitive detectors (in magnetic field)**

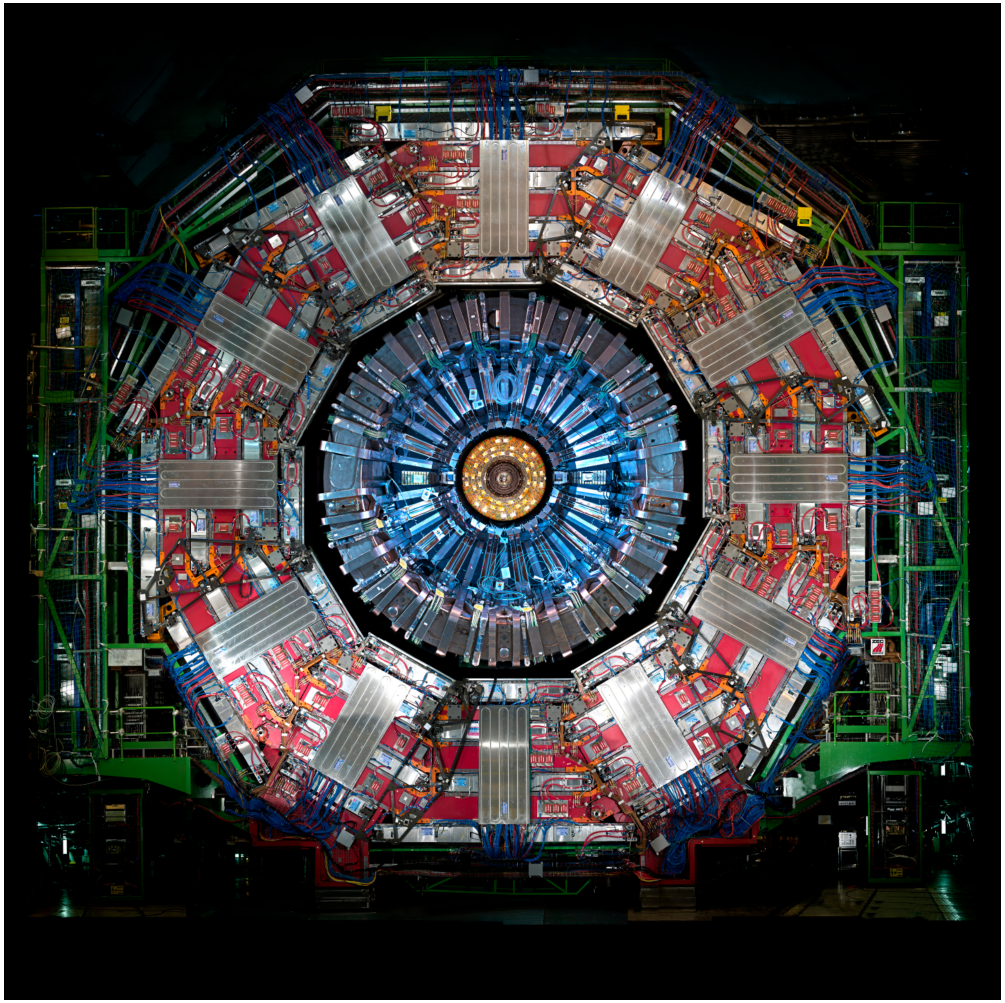
- speed – **Cherenkov counters**

} charged particles only

- energy – **calorimeters** | charged and neutral

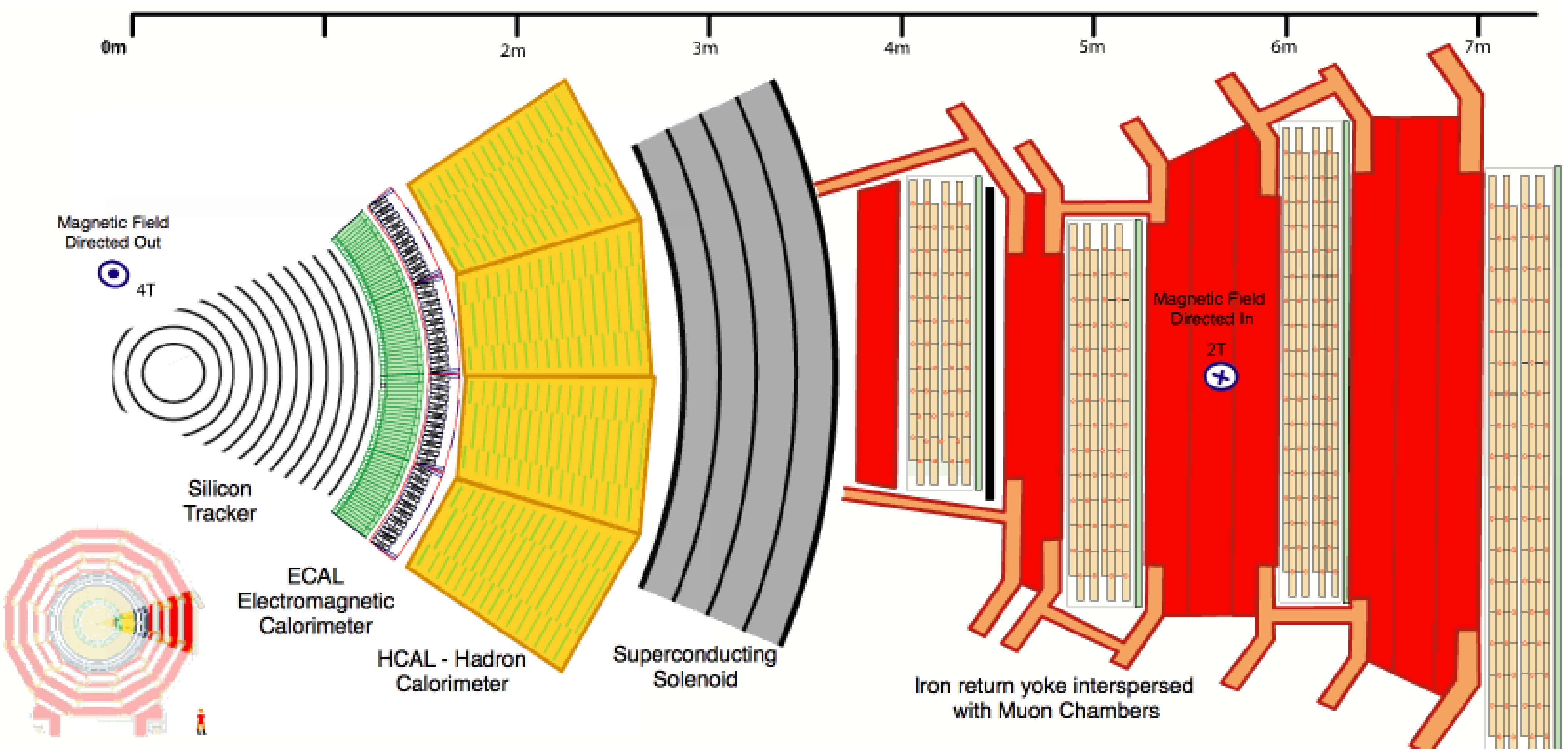
(momentum + speed → mass → particle type)

Example: CMS at the LHC

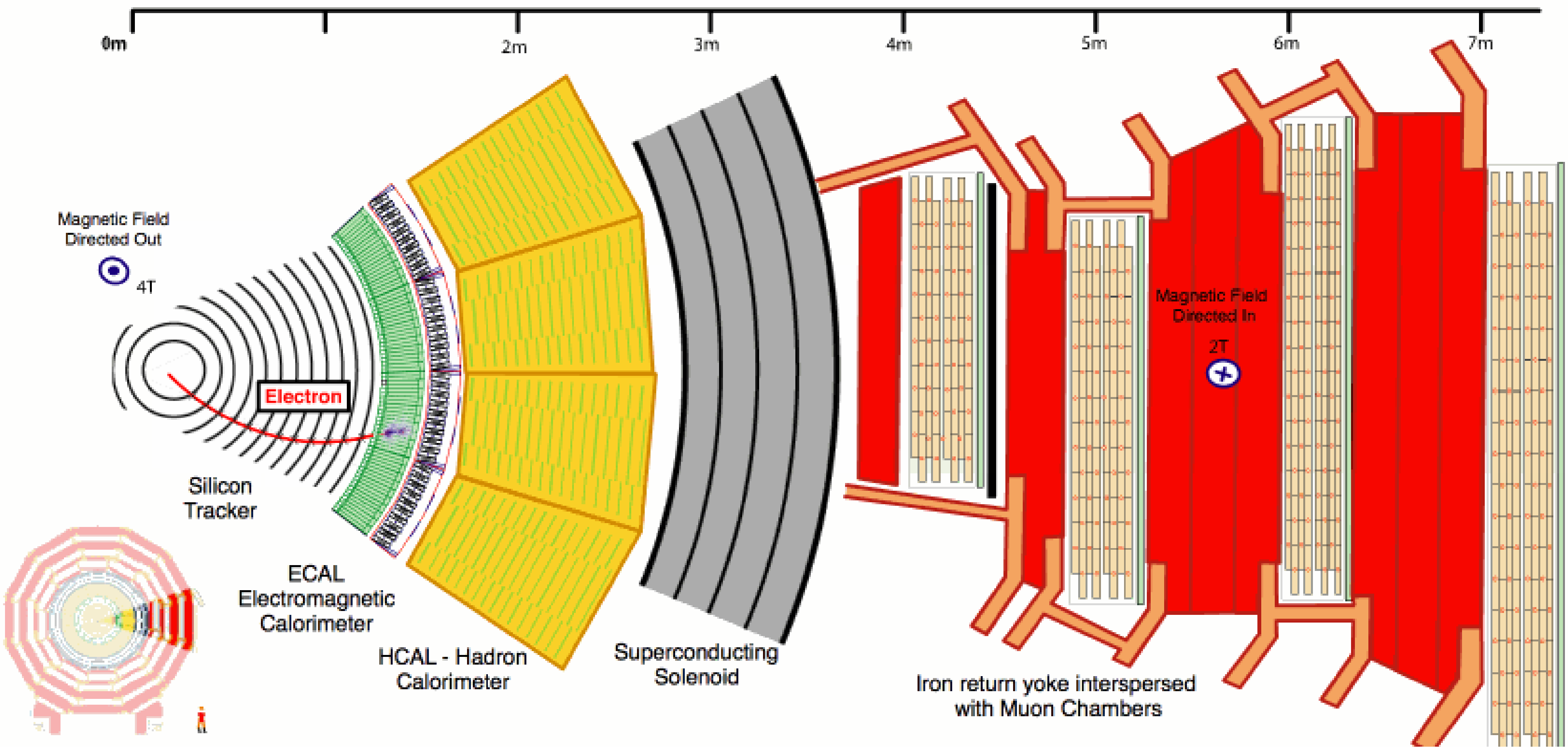


source: <http://cds.cern.ch/record/1474902>

Example: CMS at the LHC

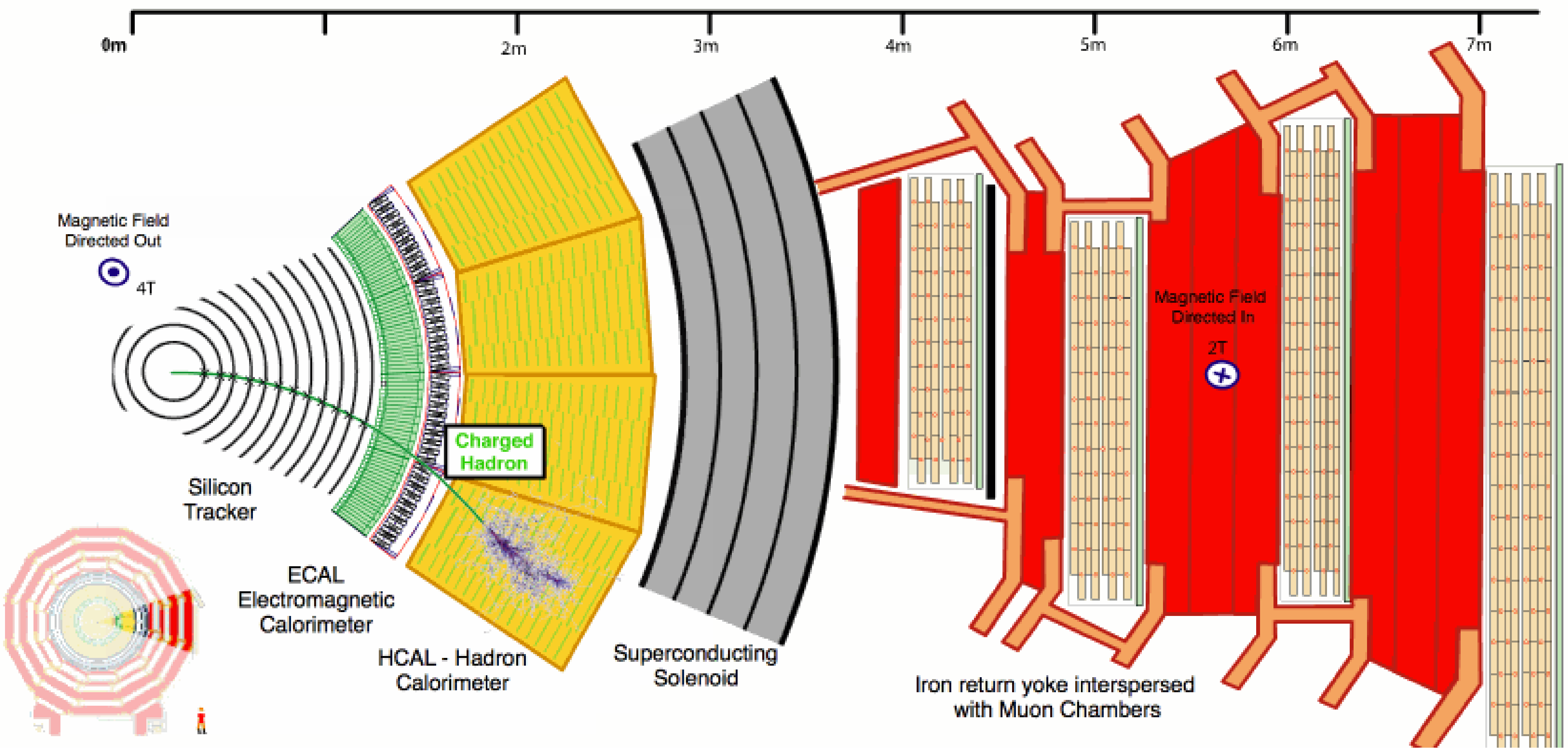


Example: CMS at the LHC



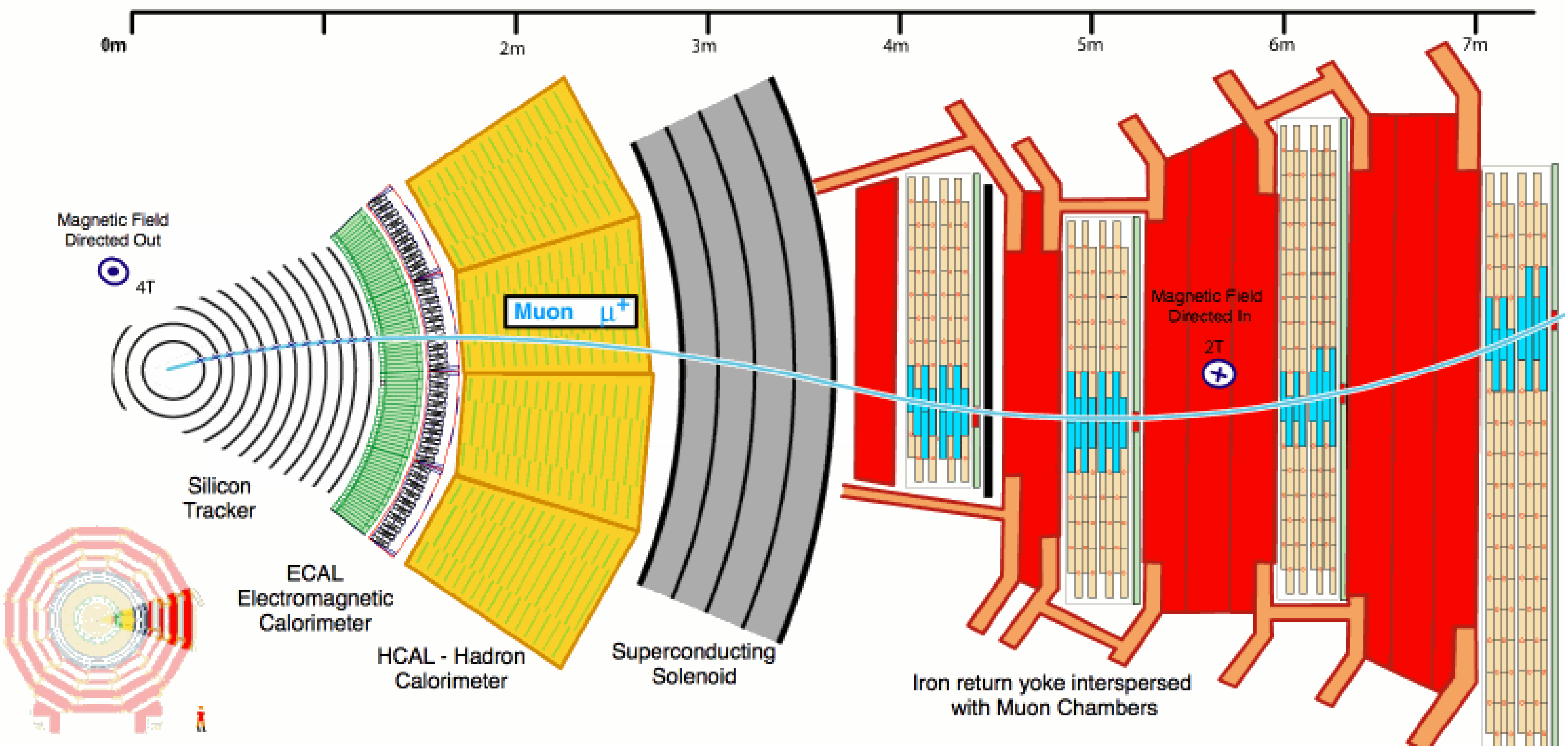
Electron/positron

Example: CMS at the LHC



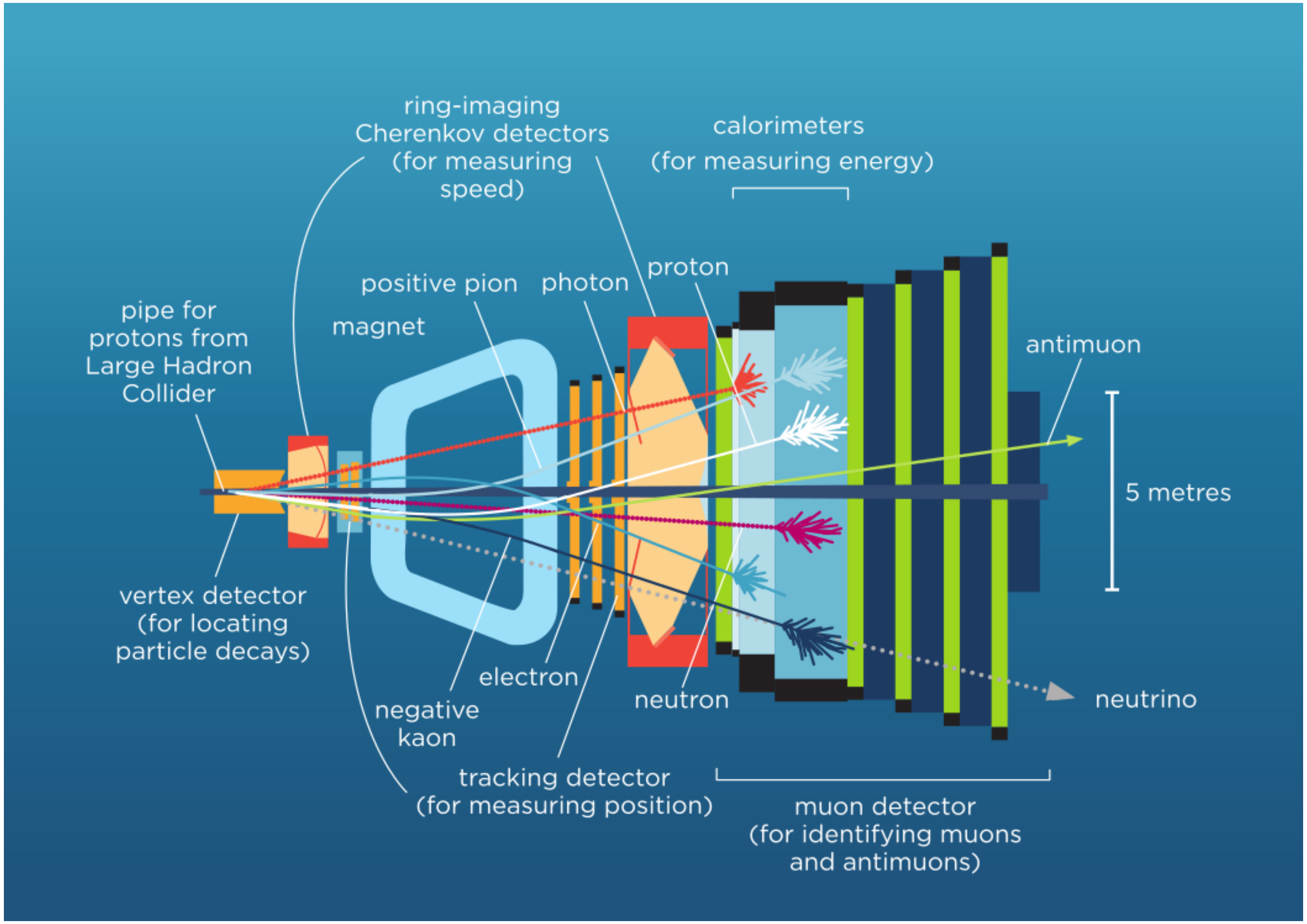
Proton, charged pion or kaon

Example: CMS at the LHC



Muon

LHCb at the LHC



Different geometry, but similar components

(+ Ring-Imaging Cherenkov detectors to distinguish proton / pion / kaon **)**

LHCb at the LHC

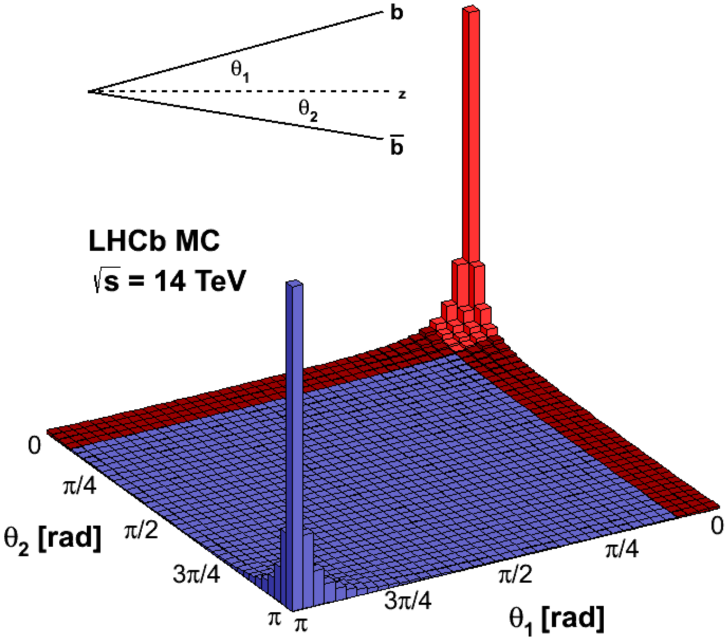
LHCb: collider experiment that looks like a fixed-target experiment

Main goal is to study decays of mesons and baryons that contain a b or $\bar{b}$ quark

These particles are produced mostly under small angles with respect to the proton beam axis

→ more cost efficient to build a detector that covers only the relevant angles

Experiments are optimized for the physics processes they are meant to study !



Momentum measurement

Moving charge in magnetic field → Lorentz force

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

→ forces particle onto circular trajectory around field lines

$$\frac{m \cdot v^2}{r} = q \cdot v \cdot B$$

$$\boxed{p = q \cdot B \cdot r}$$

In common units and for $q = \pm 1$

$$p\,[\mathrm{GeV}] \approx \pm 0.3 \cdot B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

Momentum measurement

Typical collider experiment

- **solenoid/toroid magnet**

→ field lines parallel to beam axis

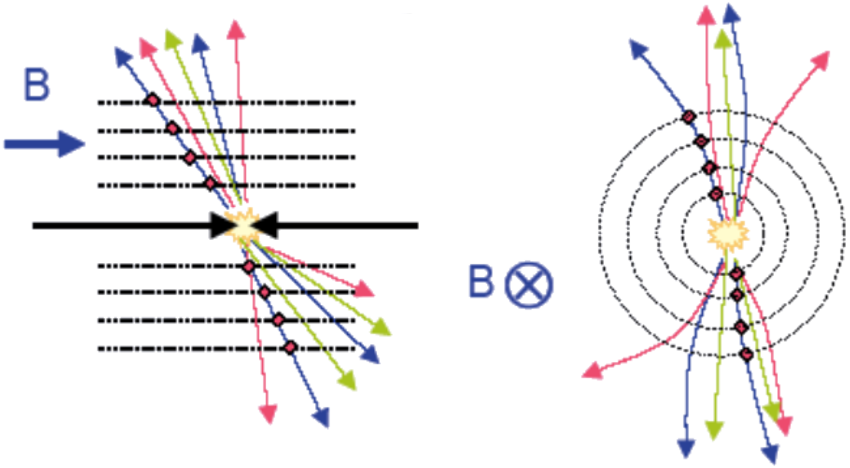
- **cylindrical tracking layers inside the magnet**

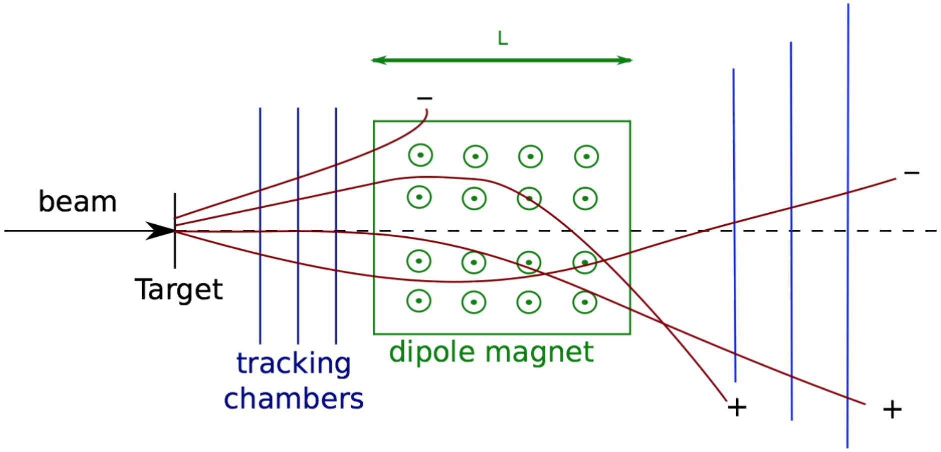
Typical fixed-target experiment

- **dipole magnet**

→ field lines orthogonal to beam axis

- **planar tracking detectors before and after the magnet**

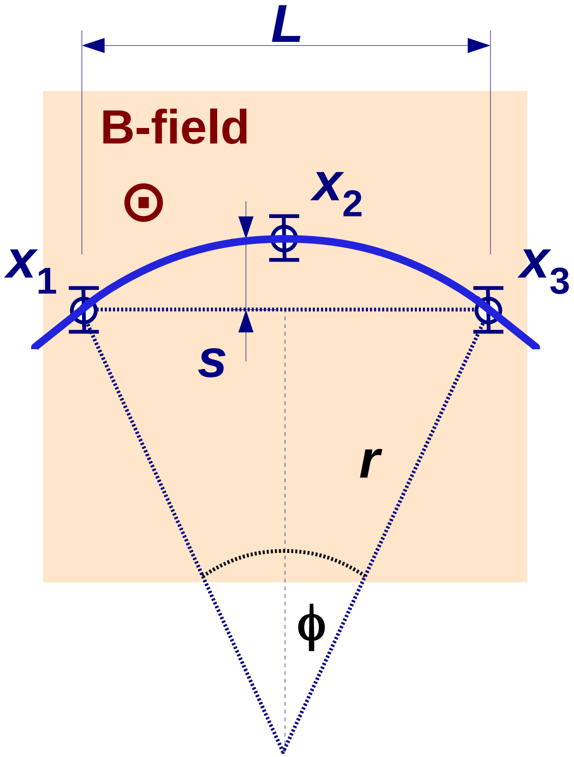




More on magnets and magnet design in the tutorial by Михаил Горшенков and Павел Дергачев

Momentum resolution

Determine sagitta of the trajectory from three position measurements



- from geometry:

$$\frac{L/2}{r} = \sin\frac{\phi}{2} \approx \frac{\phi}{2} \qquad (\text{for } \phi \text{ not too large})$$

$$s = r\cdot\left(1-\cos\frac{\phi}{2}\right) \approx r\cdot\left[1-\left(1-\frac{1}{2}\left(\frac{\phi}{2}\right)^2\right)\right] = r\cdot\frac{\phi^2}{8}$$

- deflection in magnetic field (for $q = +1$):

$$r = \frac{p}{0.3\,B} \Rightarrow \phi = \frac{L}{r} = \frac{0.3\,B\cdot L}{p} \Rightarrow s = \frac{0.3}{8}\cdot\frac{L^2\cdot B}{p}$$

- position measurements with resolution σ_x:

$$s = x_2 - \frac{x_1+x_3}{2} \Rightarrow \sigma_s^2 = \frac{3}{2}\sigma_x^2 \longrightarrow \boxed{\frac{\sigma(p)}{p} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\,\sigma_x\cdot\frac{8\,p}{0.3\,B\,L^2}}$$

Momentum resolution

“Gluckstern equation” for *N* equidistant measurements

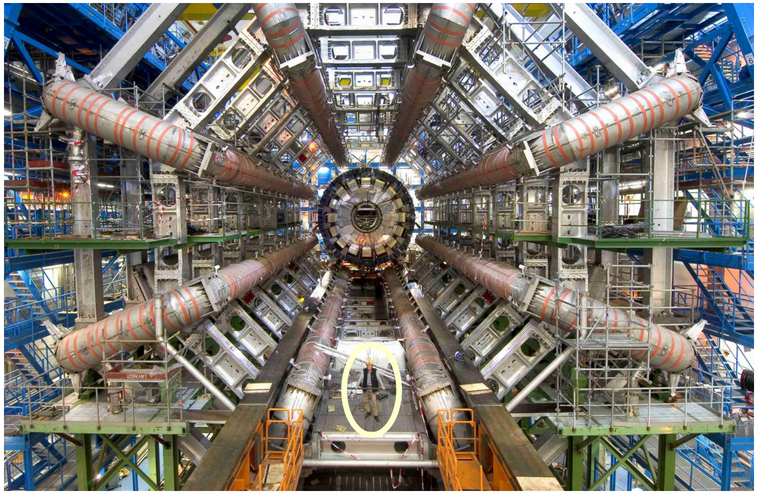
$$\frac{\sigma(p_T)}{p_T} \approx \sqrt{\frac{720}{N+4}} \cdot \sigma_x \cdot \frac{p_T}{0.3\, B\, L^2}$$

(p_T = “transverse momentum” = component orthogonal to magnetic field)

[Gluckstern, NIM 24 (1963) 381]

Relative momentum resolution

- **deteriorates linearly with increasing momentum**
- **improves linearly with the strength of magnetic field**
- **improves quadratically with the length of the measured track segment**



⇒ main reason for the large size of high-energy particle physics experiments

Interaction in material

Detection based on interaction of particles in detector material

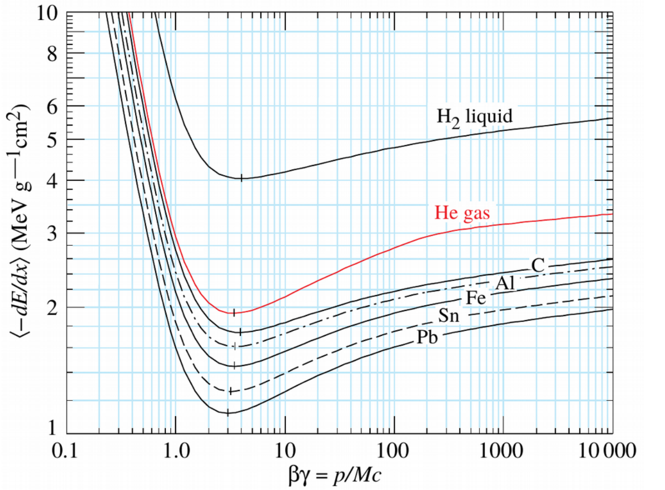
Ionization or excitation of atoms
→ creation of free electric charge carriers
or scintillation light

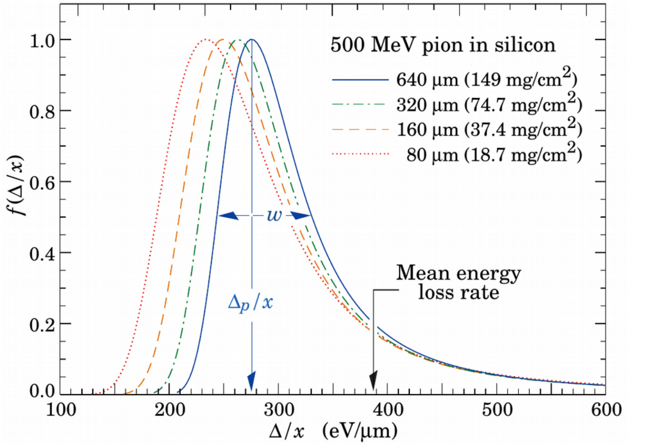
Mean energy loss of charged particles
described by Bethe-Bloch equation

$$-\frac{dE}{dx} \propto \frac{Z}{A}\cdot\frac{1}{\beta^2}\cdot\left(\frac{1}{2}\cdot\ln\frac{2\,m_e c^2\beta^2\gamma^2 T_{max}}{I^2}-\beta^2\right)$$

Energy-loss distribution in thin layer of material
described by Ландау distribution

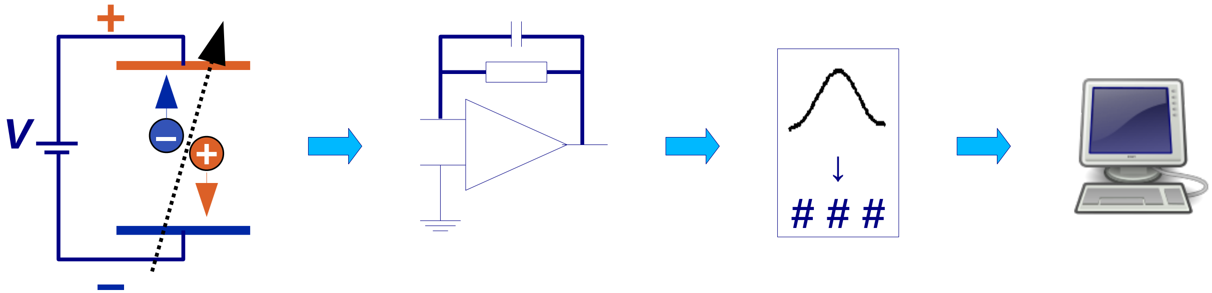
(→ Richard Jacobsson, lecture 8)





Electronic Readout

apply electric field across detector volume, collect charges on electrodes



- **electronically integrate & amplify signal pulse**
- **digitize the signal:**
  - discriminator ⇒ binary information (hit / no hit)
  - analog-to-digital converter (ADC) ⇒ encode pulse height
  - time-to-digital converter (TDC) ⇒ encode signal arrival time
- **transfer digital data to a computer farm for processing and storage**

need to know WHEN to read out the detector → trigger
(→ Lea Caminada’s lecture in spring**)**

Gaseous tracking detectors

Thin-walled cylindrical tube, filled with a gas
(e.g. 80% Ar / 20% CO_2**)**

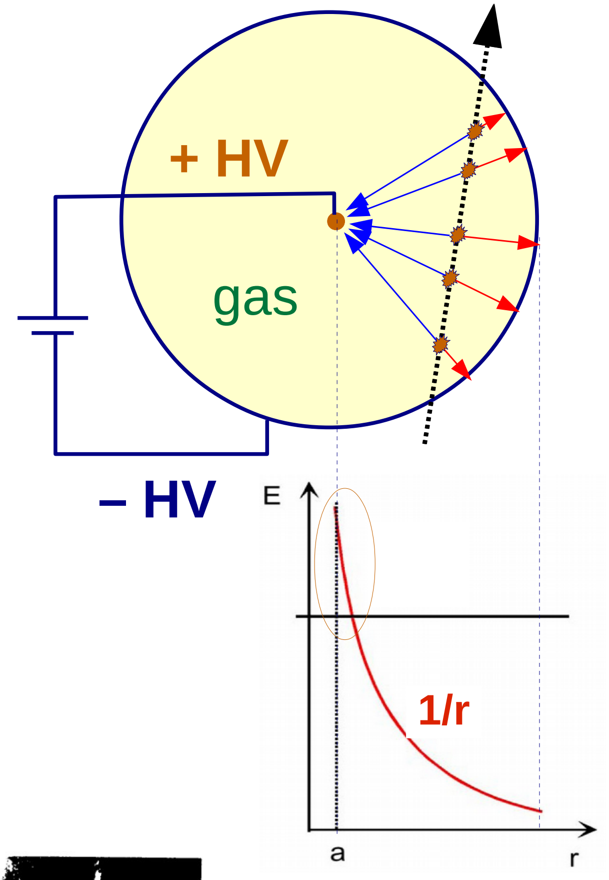
Thin wire along the centre of this tube

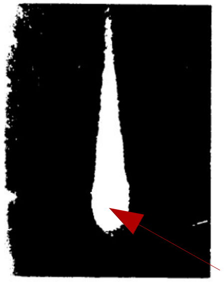
Apply a high voltage (typically 1– 2 kV**)**
between wire and outer wall of the tube

Charged particle ionizes atoms in the gas
electric field: electrons drift towards the wire

Very high electric field close to the wire
electrons gain enough energy
to ionize secondary atoms

→ **Charge avalanche, voltage pulse on wire**

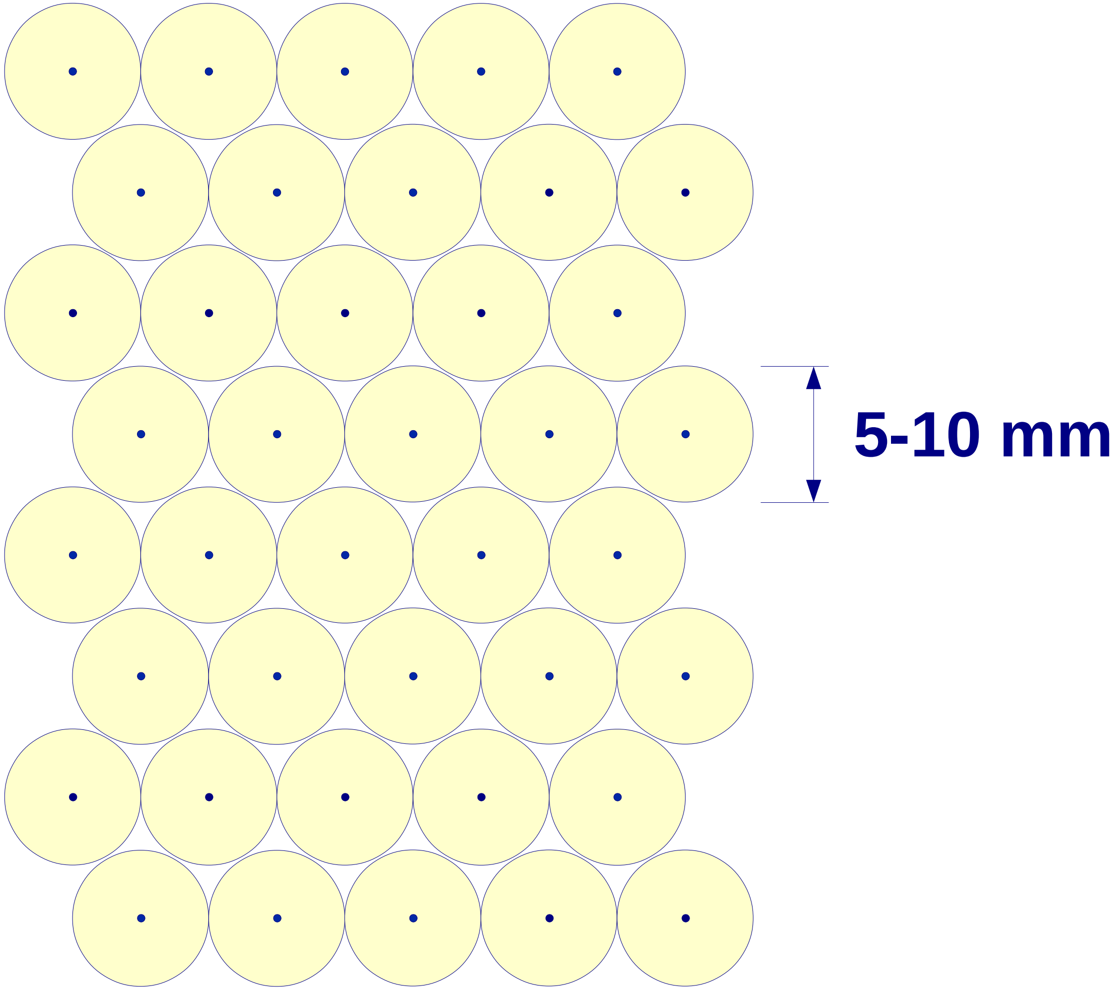




photograph of a charge avalanche

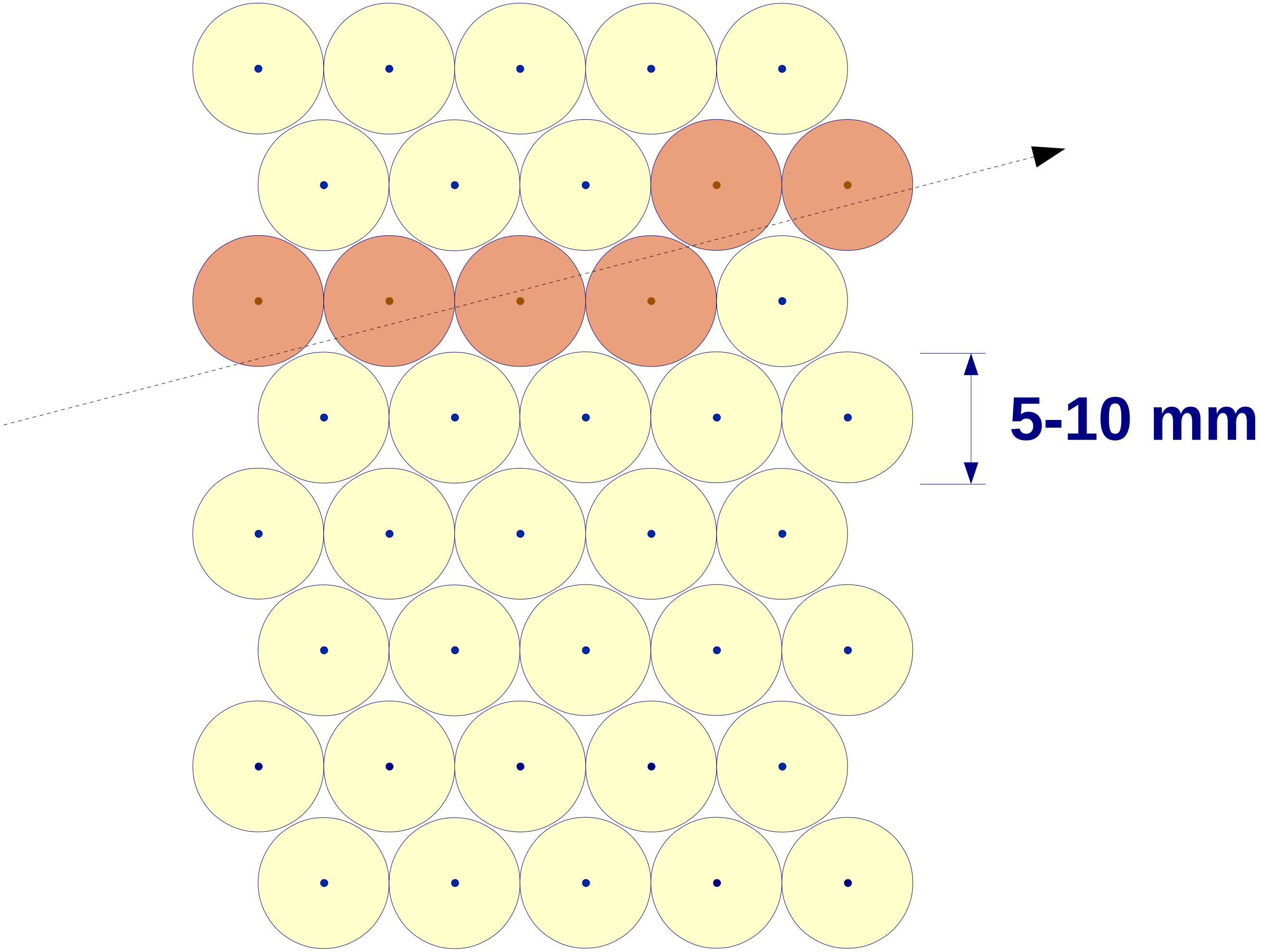
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



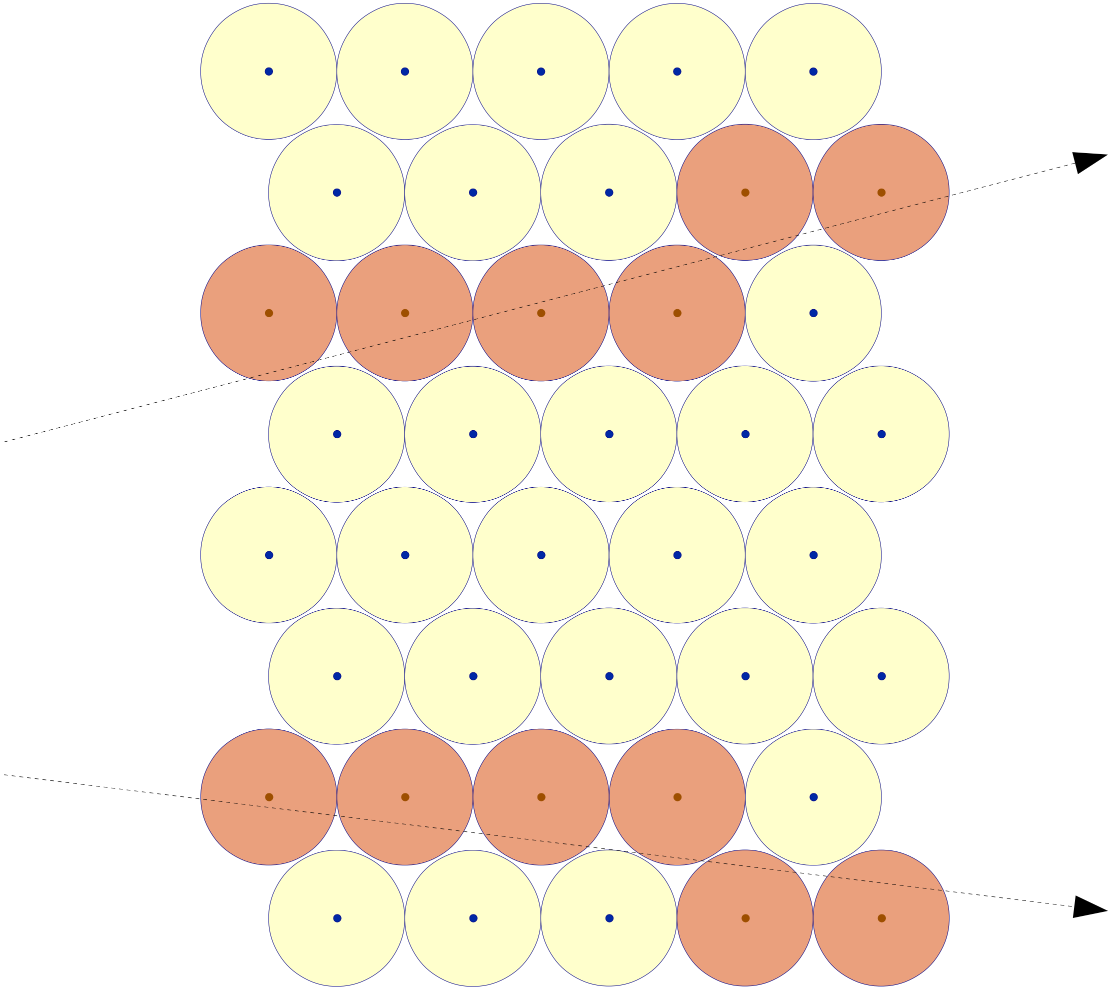
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



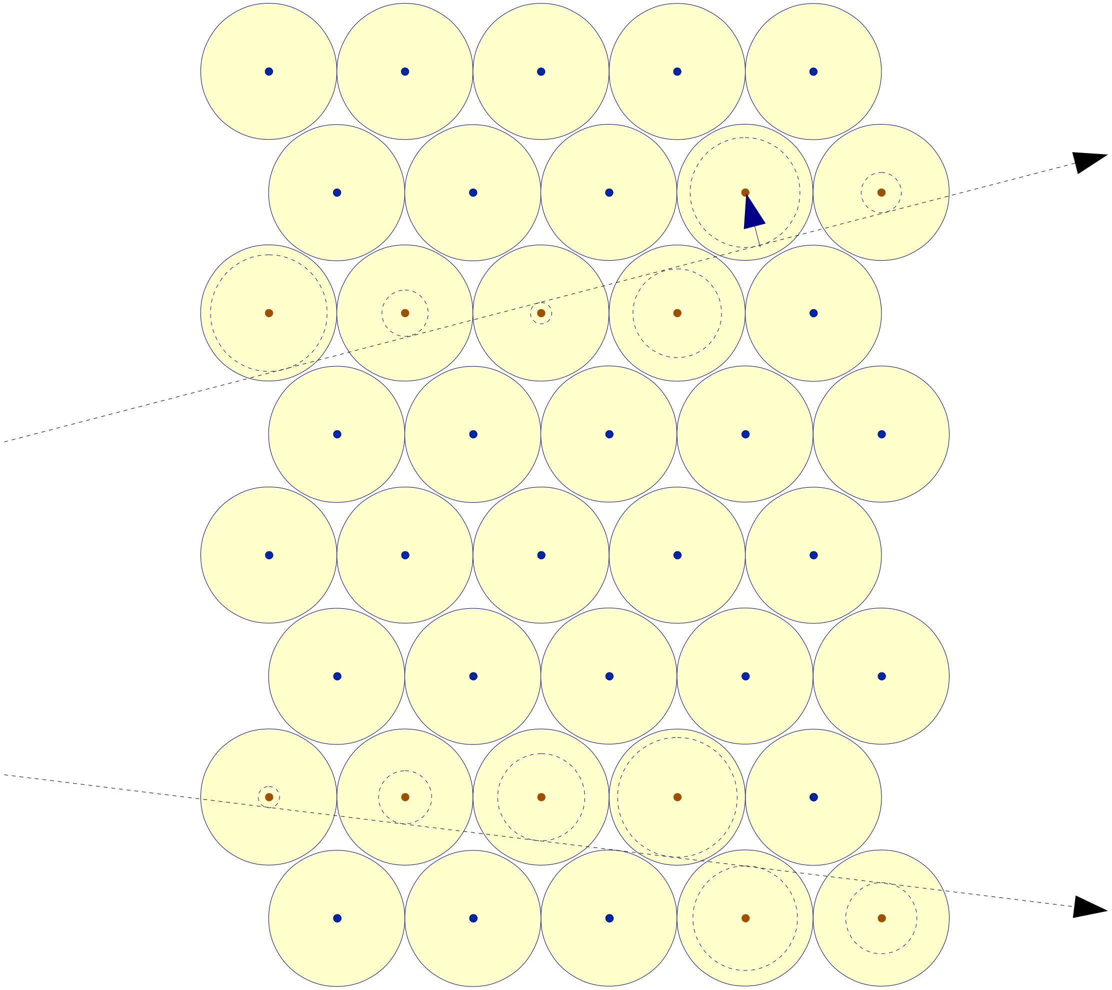
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



Gaseous tracking detectors

To improve spatial resolution: measure drift time of electrons



Gaseous tracking detectors

**+ spatial resolution < 200 µm,
appropriate for many applications**

+ easy to cover large surfaces

+ cost effective

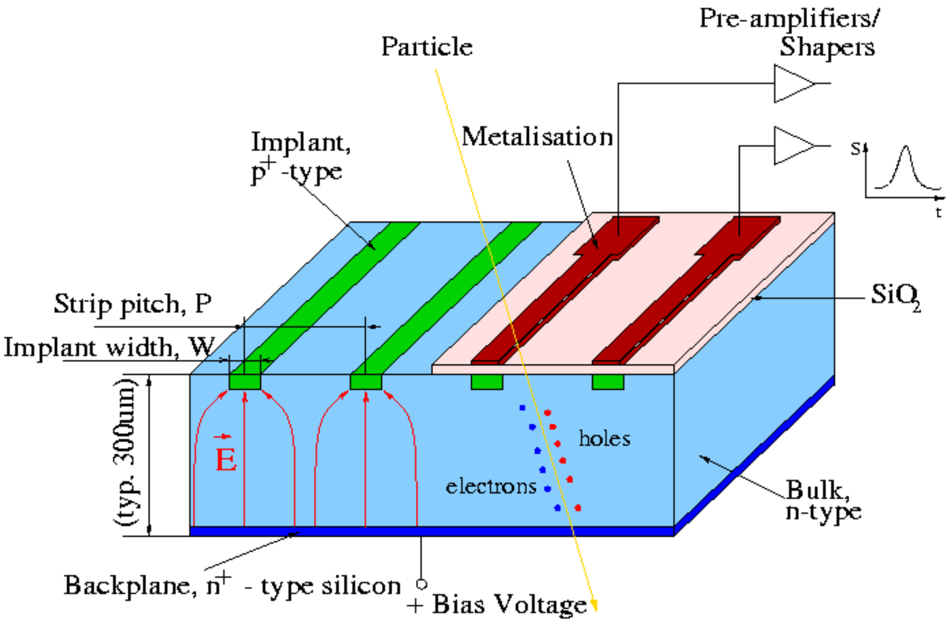
**but: granularity, rate capability
and radiation hardness
reaching their limits at the LHC**

drift time for electrons typically 100 ns,
bunch crossings at LHC every 25 ns

Silicon tracking detectors

Segmented reverse biased *p–n* junction (diode)

- ***n*–doped silicon wafer with segmented *p*–doped implants**
  - strips with pitch 250 – 20 μm
    ⇒ spatial resolution 50 to a few μm
  - or pixels for even finer granularity
- **apply reverse bias voltage**
  - fully deplete bulk, create electric field
- **ionizing particle creates electron-hole pairs in silicon lattice**
  - electrons and holes drift in electric field, induce signal on *p*-doped implants



Silicon tracking detectors

+ spatial resolution down to few μm, much better than gaseous detectors

+ faster signal collection, higher rate capability

+ much better radiation hardness

but: much more expensive than gaseous

→ use silicon detectors where needed, gaseous where you can afford it

More on gaseous and silicon tracking detectors in my lecture next year

Nuclear Emulsions

Similar to photographic film:
silver bromide crystals suspended in gelatine

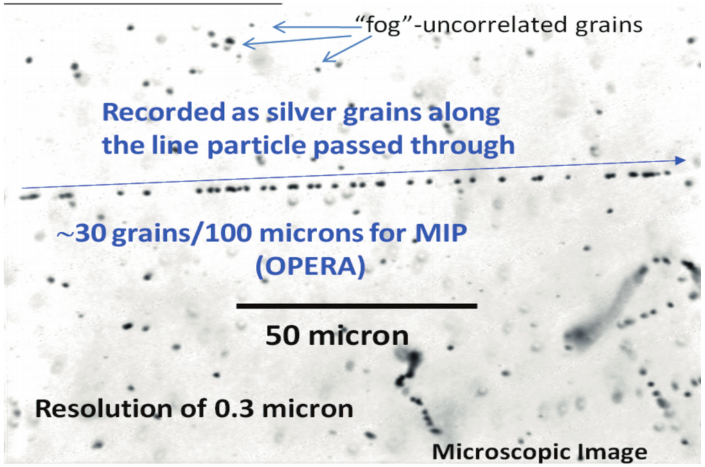
Charged particles create silver grains
→ latent image, made visible through chemical processing

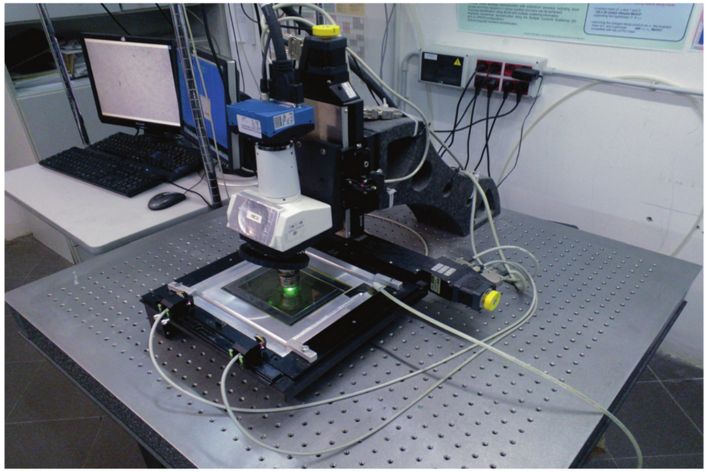
Low rate capability but sub-μm resolution

“Old” technology, e.g. employed in discovery of charged pions in 1947

Renaissance, e.g. in tau neutrino physics, thanks to development of fast and fully automated film scanning techniques

(→ Giovanni de Lelli, lecture 7)





Energy measurement

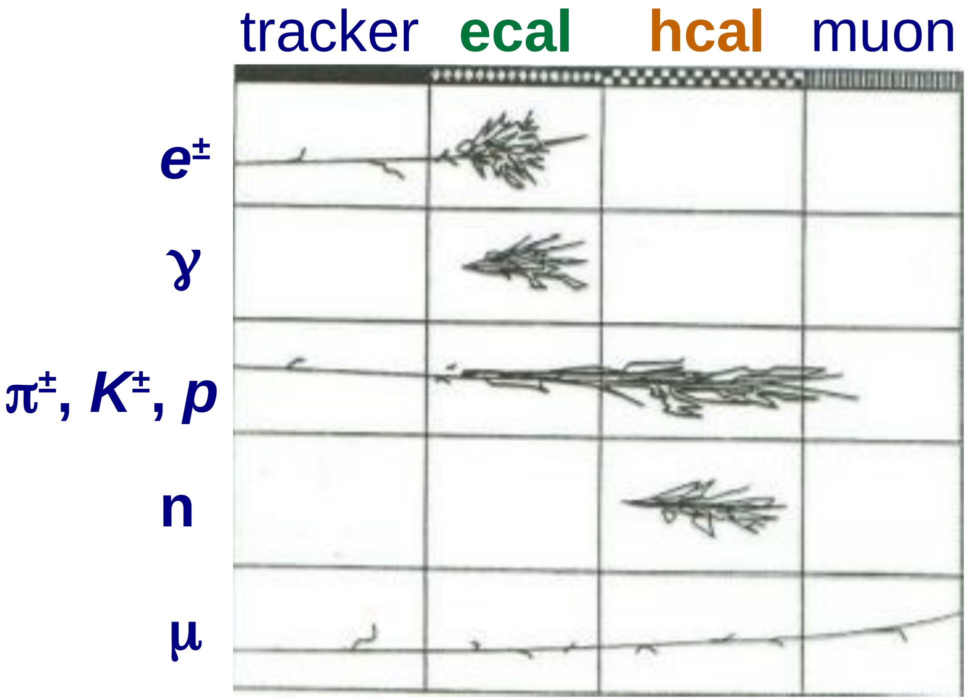
Calorimeter: high-density material with large *Z*
→ incident particle initiates cascade (“shower”) of secondary particles

Measure total signal amplitude: proportional to the number of particles in the shower → proportional to the energy of the incident particle

Electromagnetic calorimeter:
electromagnetic cascade
induced by electrons or photons

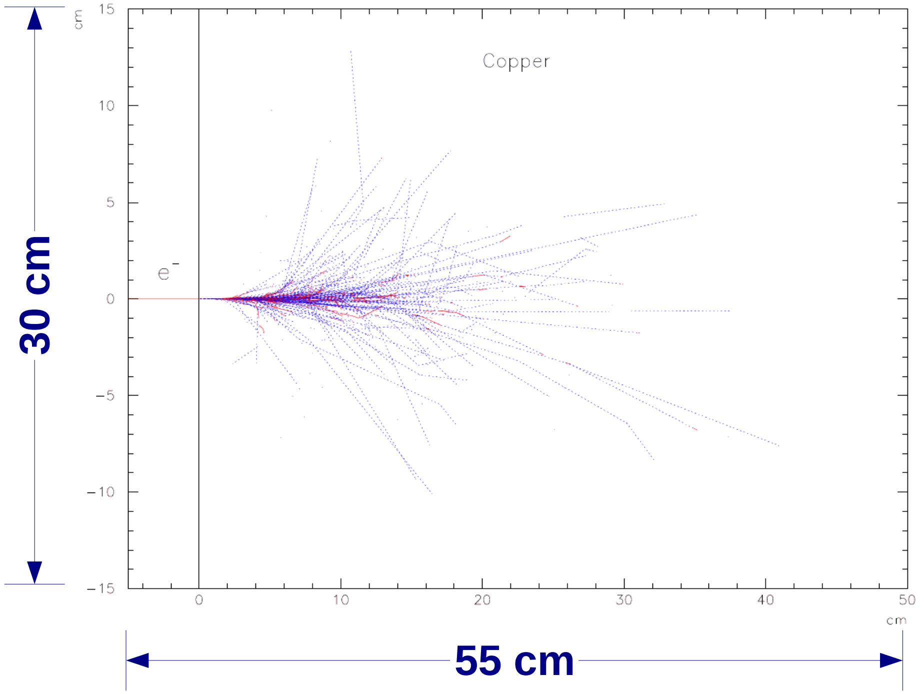
Hadronic calorimeters:
hadronic cascade
induced by pions, kaons, protons

Destructive measurement
→ calorimeters after tracking

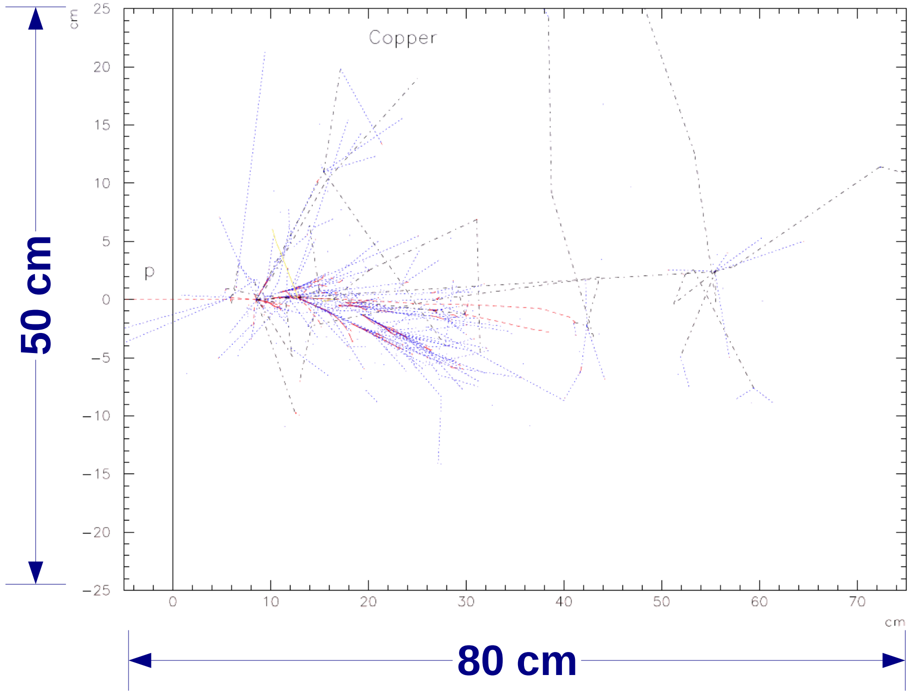


Energy measurement

Simulation of **electromagnetic shower** (8 GeV electron in Copper)

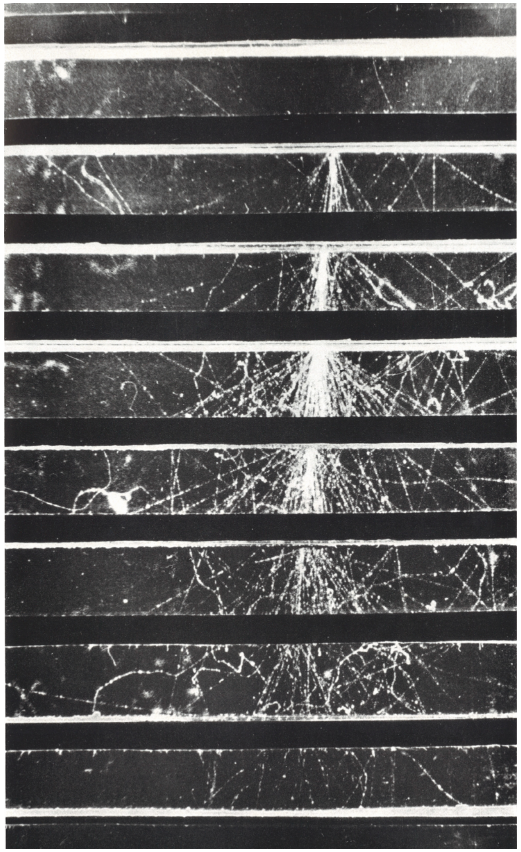


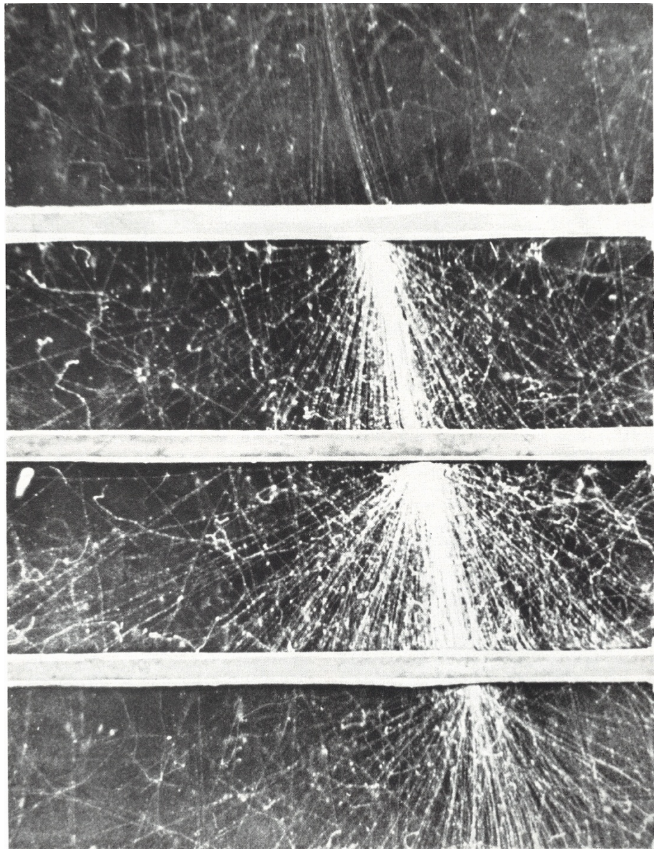
Simulation of **hadronic shower** (8 GeV proton in Copper)



Electromagnetic Calorimeters

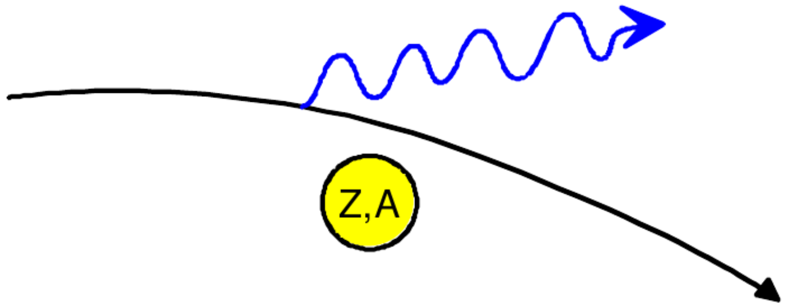
Electromagnetic showers (probably induced by photons**), observed in bubble chambers with lead absorber plates**



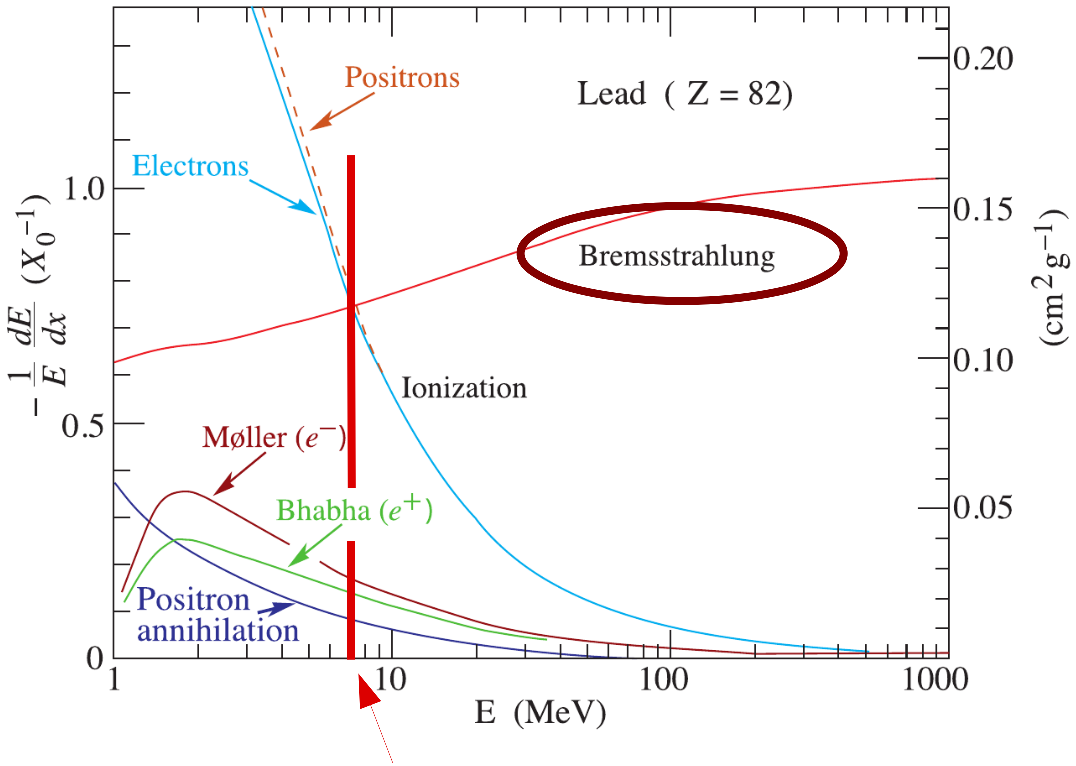


Electromagnetic Calorimeters

High-energy $e^{\pm}$ lose energy mostly through Bremsstrahlung
→ creation of a high-energy photon



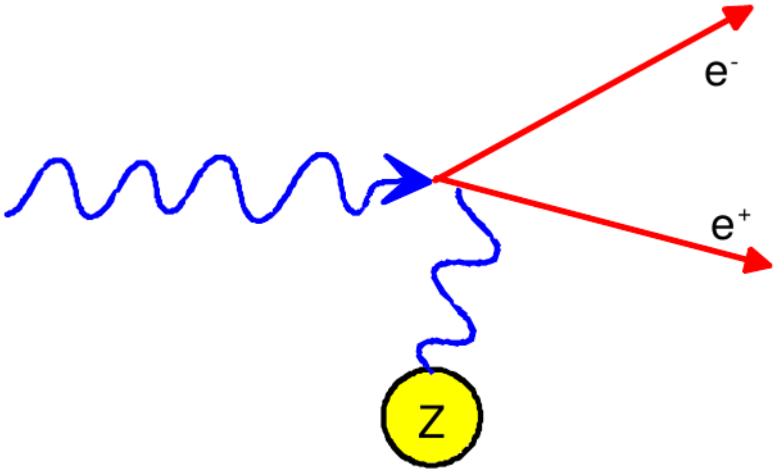
Radiation length X_0:
amount of material after which electron energy has reduced to 1/e
(depends on *Z*, *A*, density**)**

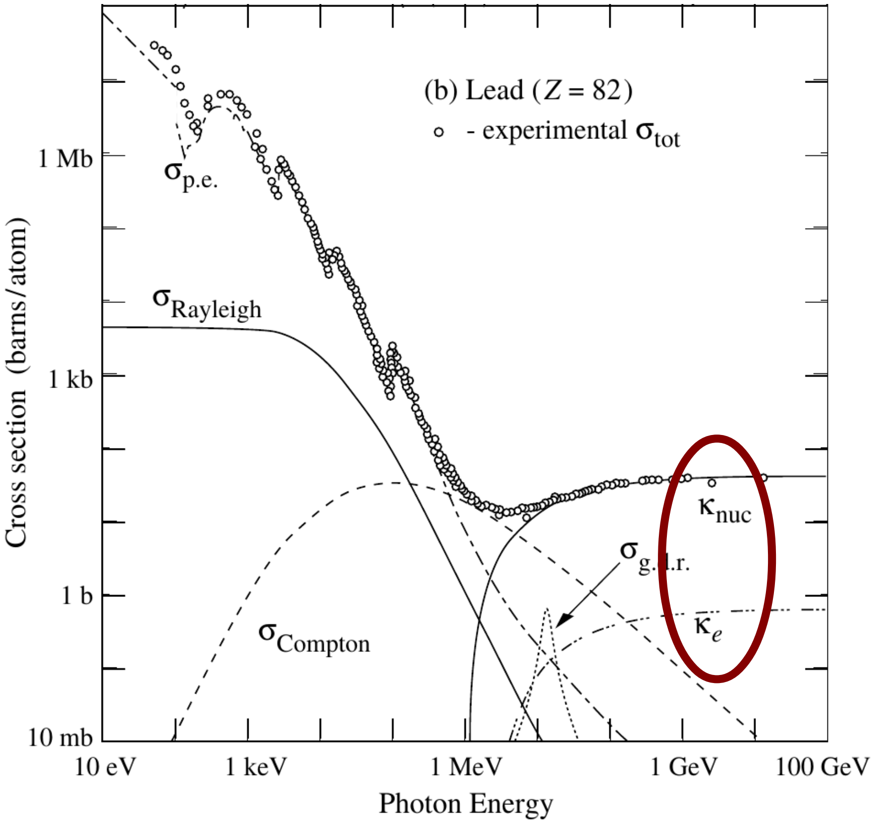


critical energy, E_c

Electromagnetic Calorimeters

High-energy γ lose energy predominantly through pair production
→ creation of a high-energy electron/positron pair





Mean free path for pair production also determined by X_0

(→ Richard Jacobsson, lecture 8)

Electromagnetic Calorimeters

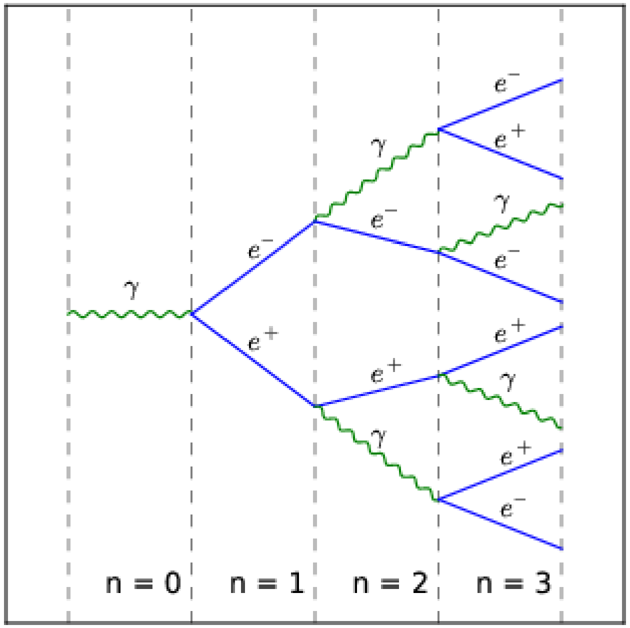
Simple model of the electromagnetic cascade:

(1) γ creates an e^+/e^- pair after $1 \cdot X_{0,}$
energy is split equally between e^+ and e^-

(2) e^+ and e^- radiate a γ after $1 \cdot X_{0,}$
energy is split equally between e^+/e^- and γ

⇒ after $n \cdot X_0$: 2^n particles with energy $E / 2^n$

(3) cascade stops when e^+/e^- energy
drops below critical energy E_c



⇒ shower depth (in X_0)

$$n_{\max} = \frac{1}{\ln 2} \cdot \ln \frac{E}{E_c}$$

total number of particles produced

$$N_{\text{tot}} = \sum_{n=0}^{n_{\max}} 2^n \approx 2 \cdot \frac{E}{E_c}$$

Electromagnetic Calorimeters

This simple model illustrates two important features of calorimeters:

$$n_{max} \propto \ln E$$

⇒ thickness of material required to contain the cascade increases logarithmically with the energy of the incident particle

$$N_{tot} \propto E \quad \Rightarrow \quad \frac{\sigma(E)}{E} = \frac{\sigma(N_{tot})}{N_{tot}} = \frac{\sqrt{N_{tot}}}{N_{tot}} = \frac{1}{\sqrt{N_{tot}}} \propto \frac{1}{\sqrt{E}}$$

⇒ relative energy resolution improves with increasing energy

Compare relative momentum resolution:

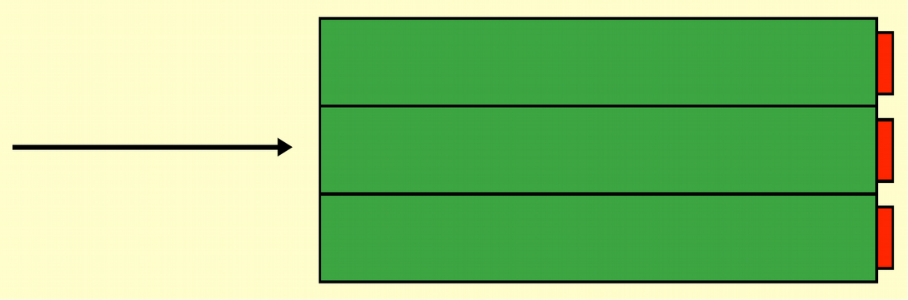
$$\frac{\sigma(p)}{p} \propto p$$

⇒ at very high energies, energy measurement more precise than momentum measurement

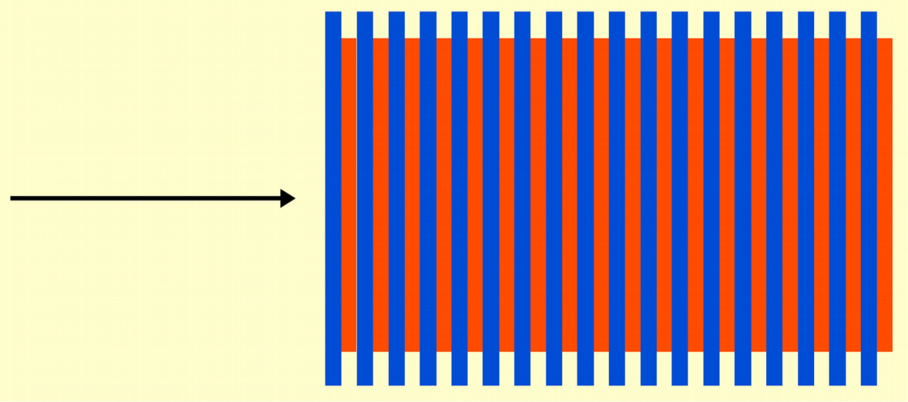
Calorimeters

Two basic types of calorimeters:

Homogeneous calorimeters:
single medium serves as
absorber and detector
(e.g. lead-loaded glass, $PbWO_4$ crystals)



Sampling calorimeters:
alternate layers of absorber
and active medium
(e.g. lead/iron + scintillators)



Sampling calorimeters: do not see full signal → loss in resolution
But less expensive + ability to reconstruct longitudinal shower profile

Calorimeters

Long-standing and important contributions to calorimetry from Russia

E.g., idea of a sampling calorimeter first put forward in 1954 by Н. Л. Григоров
for an experiment to study cosmic-rays in the Pamir mountains

→ more on calorimetry in Giovanni di Lella's lecture in spring

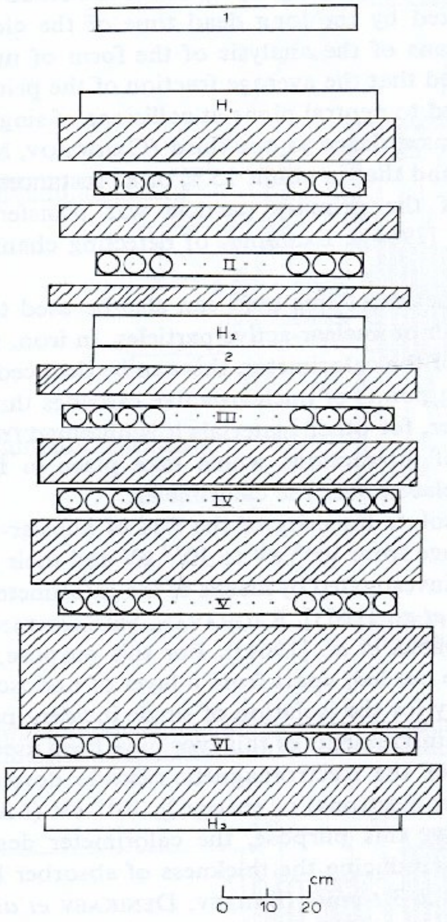


Fig. 14. Schematic diagram of the first ionization calorimeter (GRIGOROV, MURZIN and RAPOPORT [1958]). The shaded areas represent absorber. Layers 1 and 2 are the rows of counters forming the controlling telescope. Layers H_1, H_2, H_3 are hodoscoped counters, while layers I, . . ., VI are the detectors (ionization chambers) of the calorimeter.

Particle Identification

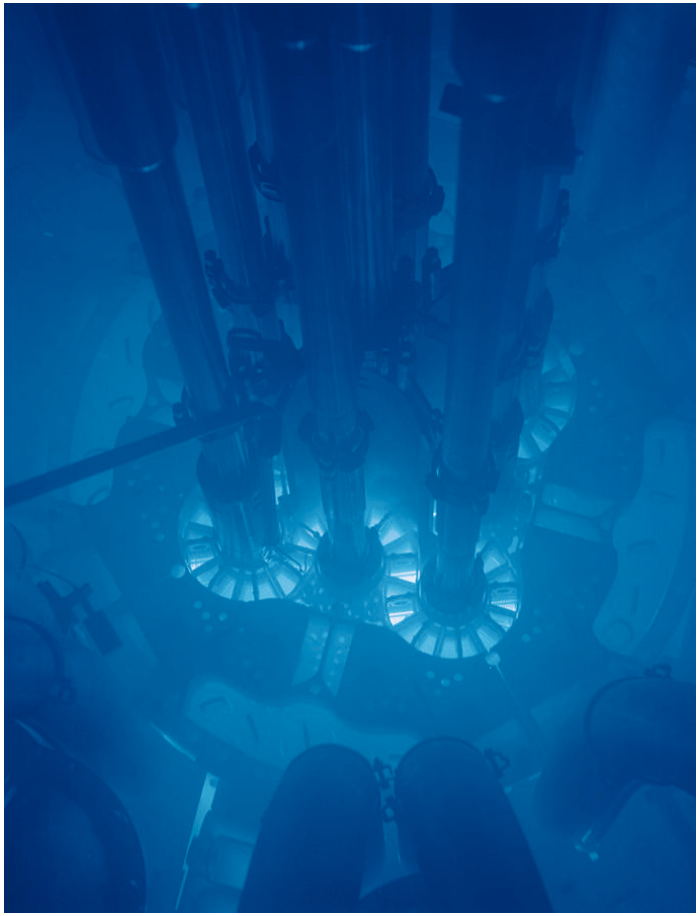
Various means for particle identification

- **shower shape in calorimeters**
  (electron/photon/hadrons/muons**)**
- **muon detectors after a shielding wall**
  (makes muons the easiest to identify**)**
- **or effects that depend on the speed of the particle:**

→ energy loss in gaseous or silicon detectors (Bethe Bloch)
→ time of flight between two scintillator counters
→ Cherenkov light

(→ Андрей Голутвин, lecture 4 **)**

Ring Imaging Cherenkov Detectors



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

Ring Imaging Cherenkov Detectors

Special relativity tells us that nothing propagates faster than speed of light in vacuum

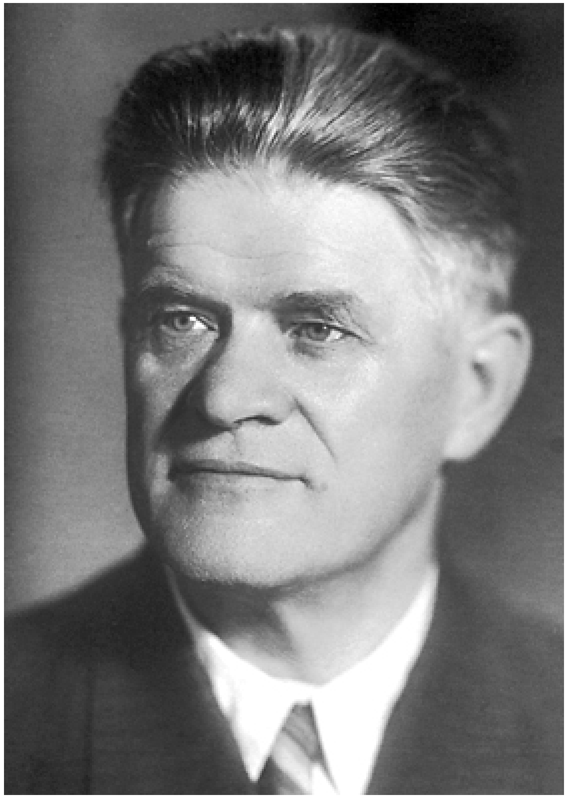
But: speed of light in a medium is smaller than speed of light in vacuum:

$$c_{\text{medium}} = c_{\text{vacuum}} / n_{\text{medium}}$$

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



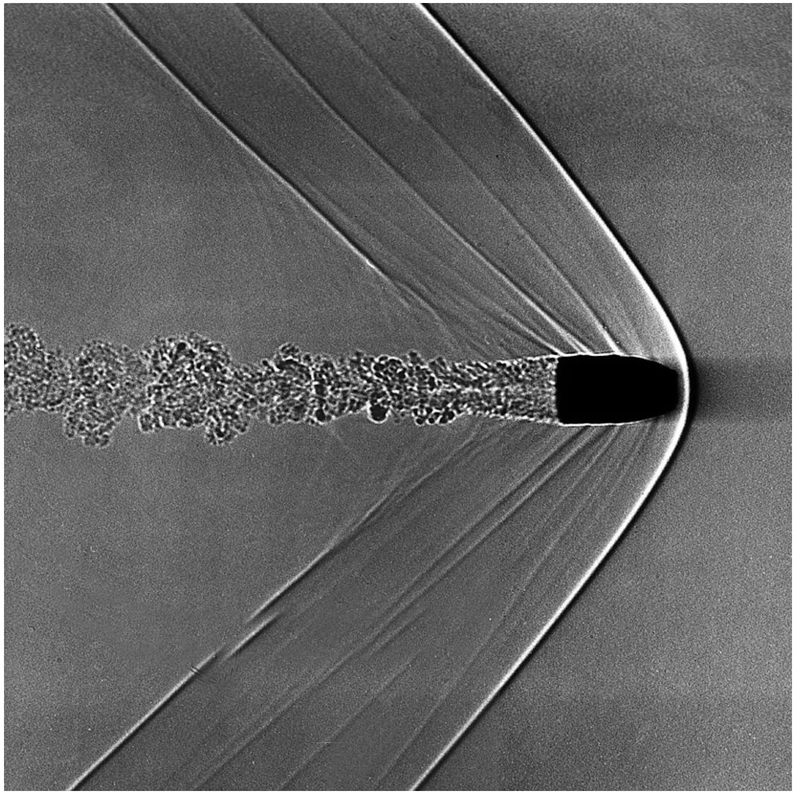
Павел Алексеевич Черенков

Nobel Prize in Physics (1958)

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

Ring Imaging Cherenkov Detectors

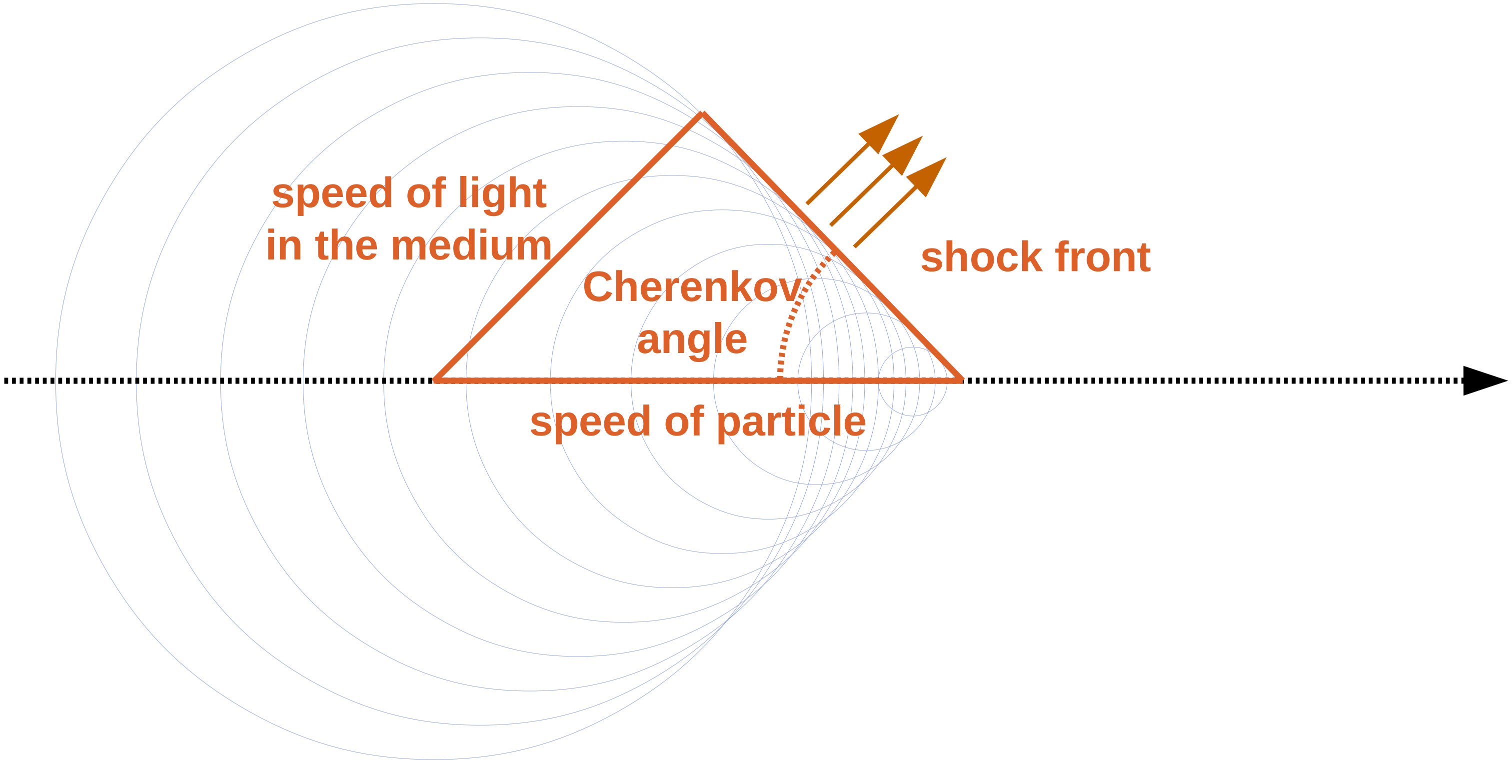
source: <https://en.wikipedia.org/wiki/Sound_barrier>



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

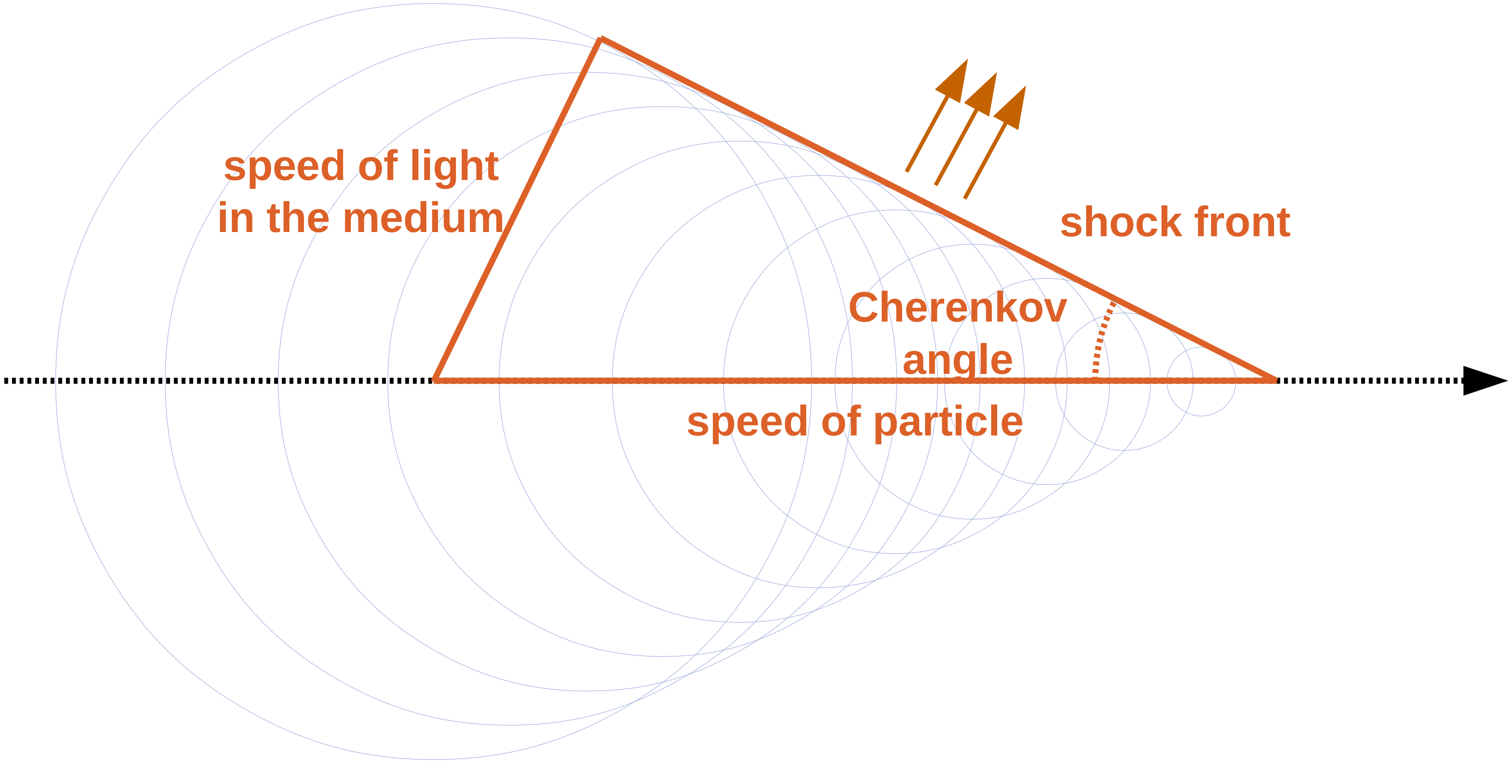
Equivalent to the “sonic boom” emitted by an object moving faster than the speed of sound

Ring Imaging Cherenkov Detectors



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

Ring Imaging Cherenkov Detectors



That angle depends on the speed of the object / particle

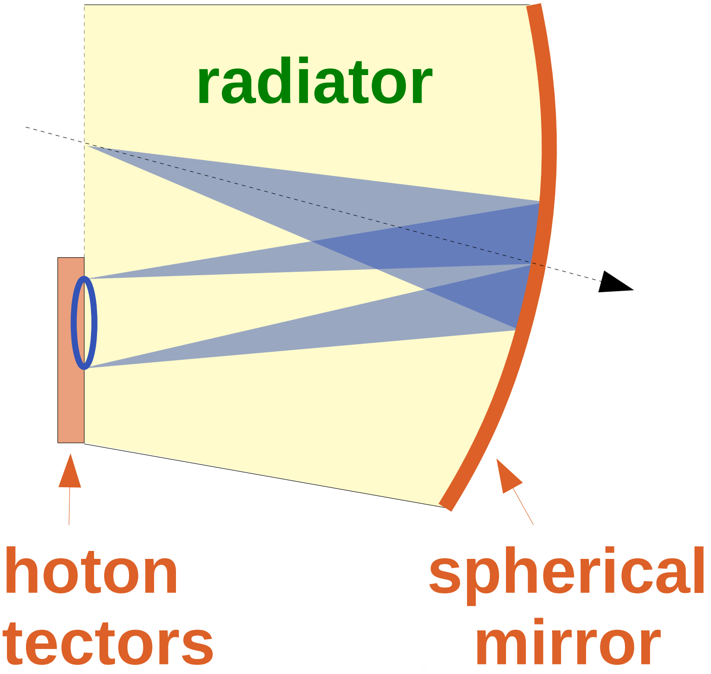
Ring Imaging Cherenkov Detectors

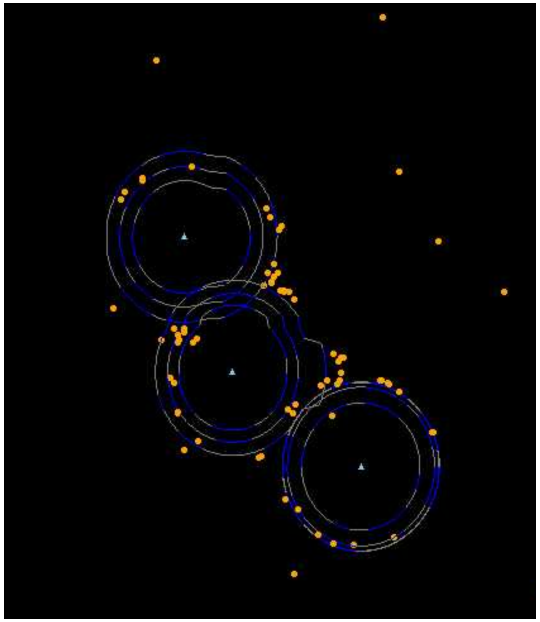
E.g. LHCb: use C_4F_{10} and CF_4 gas as radiator

→ correct refractive index

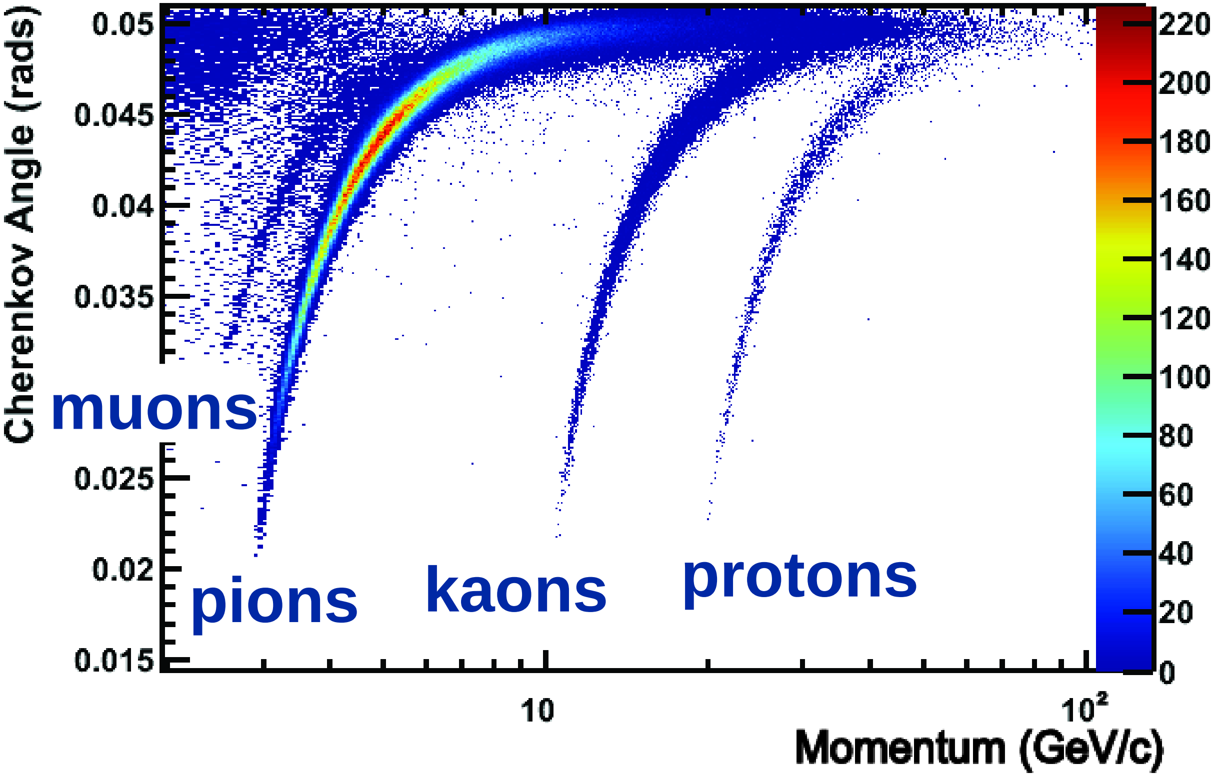
→ transparent for the produced photons

focus the emitted light onto a plane of photon detectors → rings





Ring Imaging Cherenkov Detectors



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

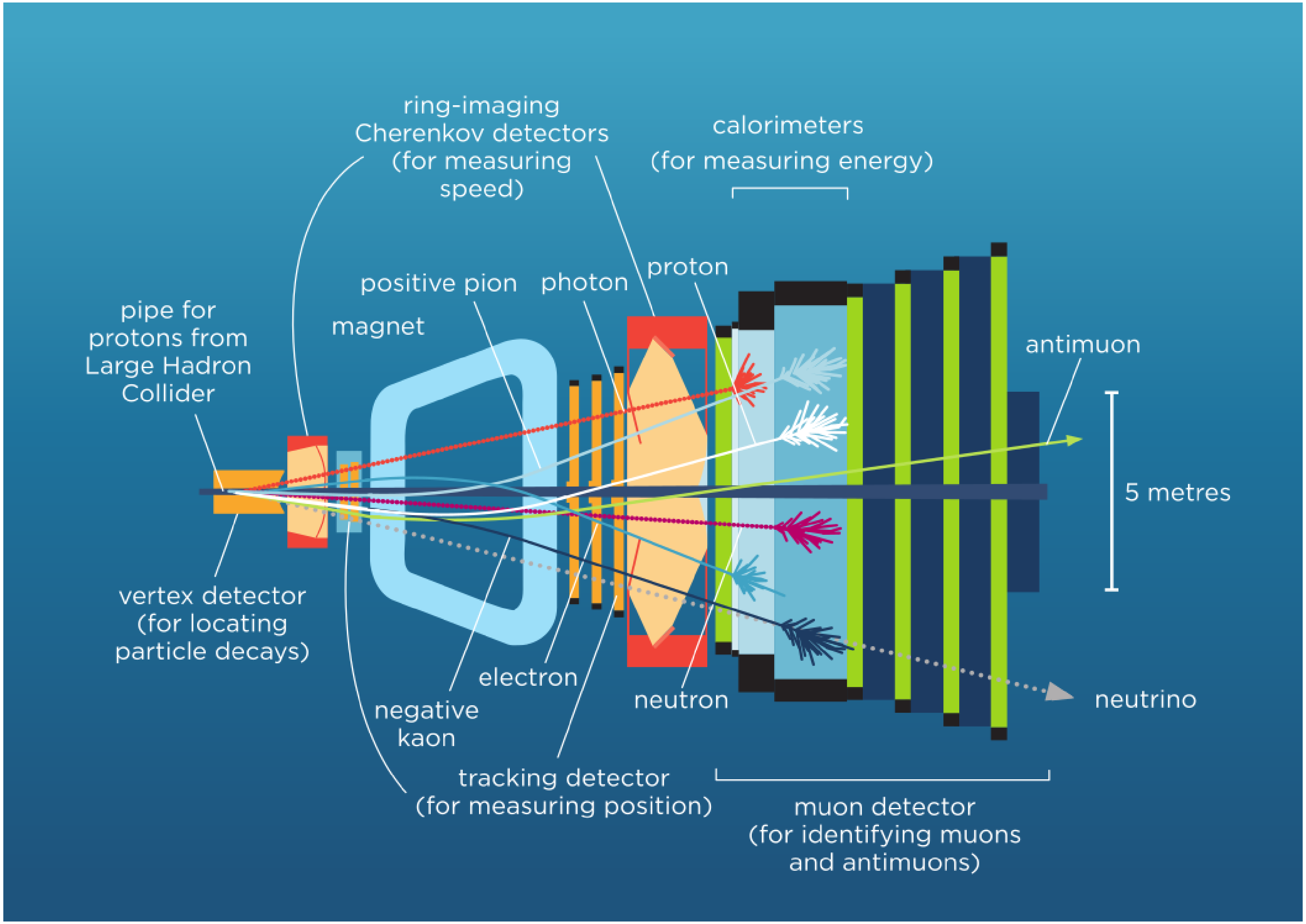
Momentum (from tracking system**)**

&

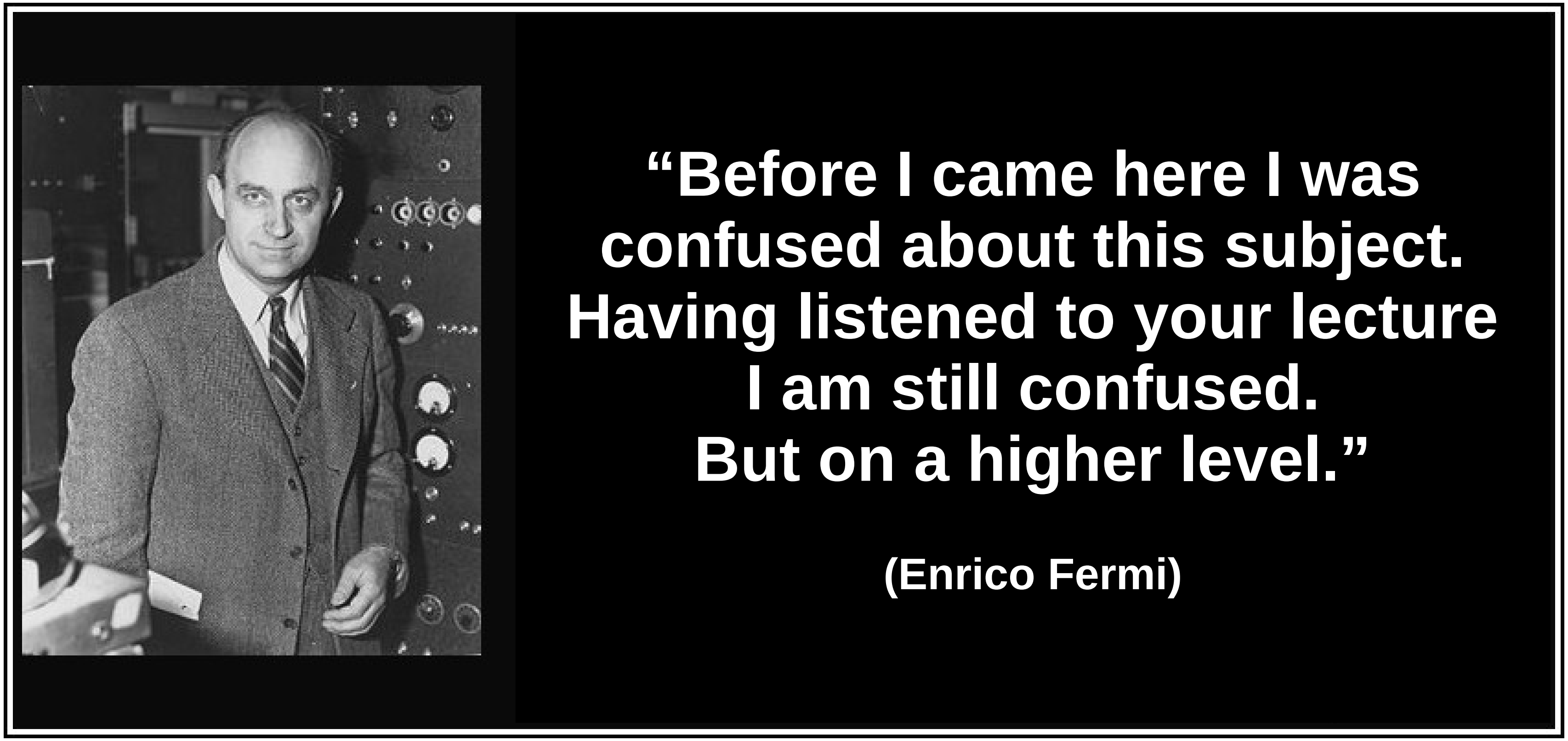
Cherenkov angle (from RICH detector**)**

type of particle

LHCb at the LHC



Summary



“Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level.”

(Enrico Fermi)

picture from [http://izquotes.com/quote/389467]

Outlook

Brief overview of the main components of a particle physics detector, many more details in dedicated lectures:

Interaction of charged particles in material

(Richard Jacobsson**)**

Particle Identification (RICH etc)

(Андрей Голутвин**)**

Tracking detectors

(Giovanni de Lellis next week; myself in spring**)**

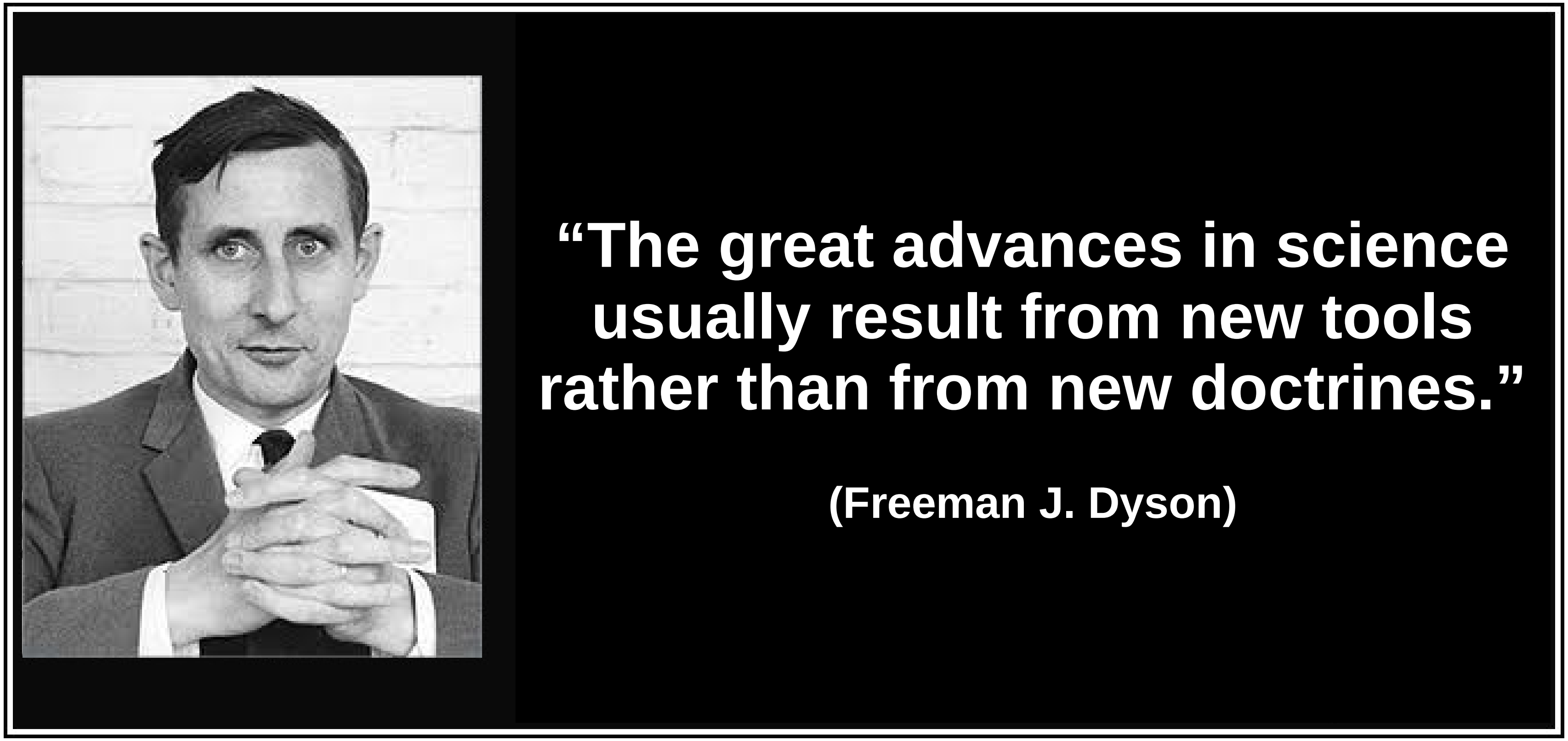
Calorimeters

(Giovanni de Lellis**)**

Trigger and readout electronics

(Lea Caminada**)**

Final word ...



“The great advances in science usually result from new tools rather than from new doctrines.”

(Freeman J. Dyson)

The slides of this lecture are available at

http://www.physik.uzh.ch/~olafs/pdf/191106_MISIS.pdf