Closing lecture

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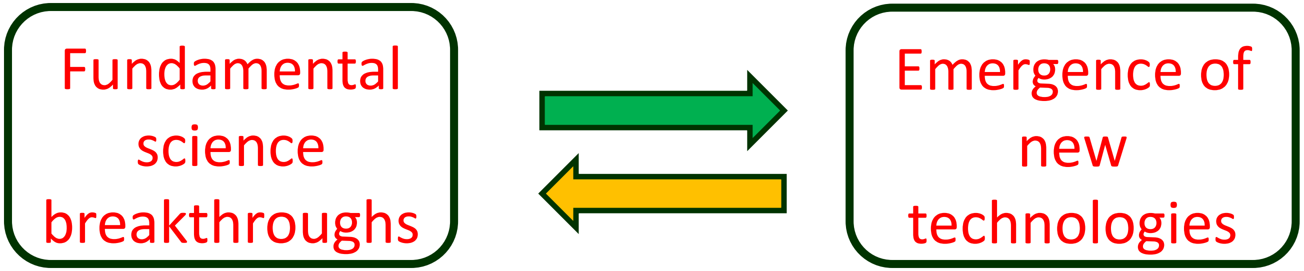
22 April 2020

The course **«New technologies to search for new phenomena in particle physics»**
has been getting around a few main topics:

- Introduction into particle physics
- Interaction of particles and radiation with matter
- Physics and technology of particle detectors
- Modern methods of data analysis



Fundamental science breakthroughs

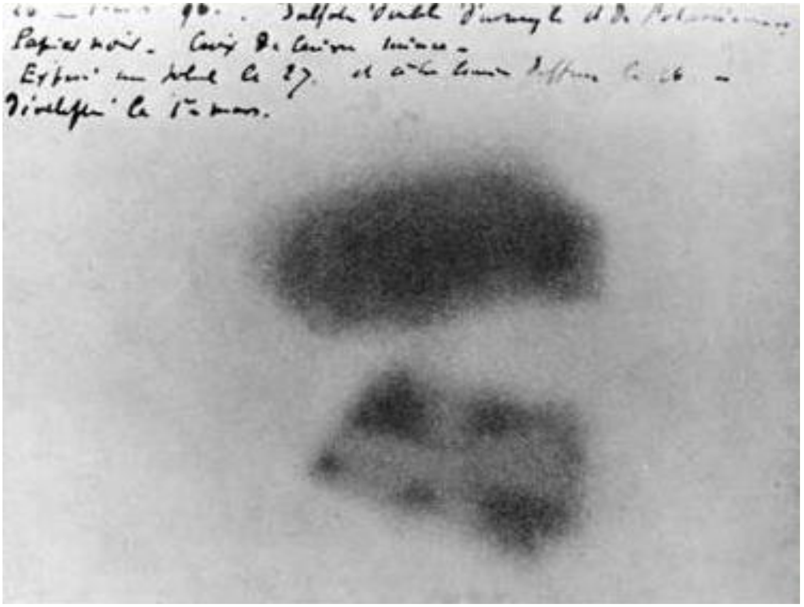
Emergence of new technologies

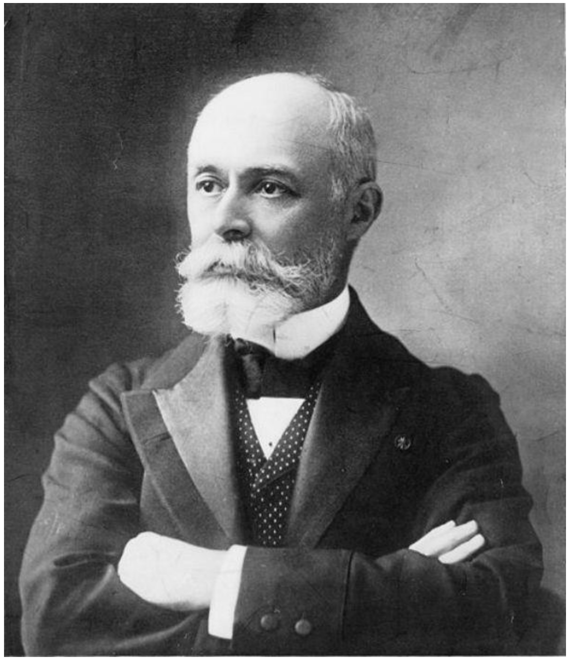
19 lectures by Andrey Golutvin, Richard Jacobsson, Olaf Steinkamp, Giovanni De Lellis, Andrey Ustyuzhanin, Nico Serra, Natalia Polukhina, Mitesh Patel, Lesya Schutska, Mikhail Dubinin, Kostas Petridis and VS.

Most of my slides have been borrowed from their presentations

1896 – …

The phenomenon of radioactivity was discovered by Antoine Henri Becquerel in 1896.

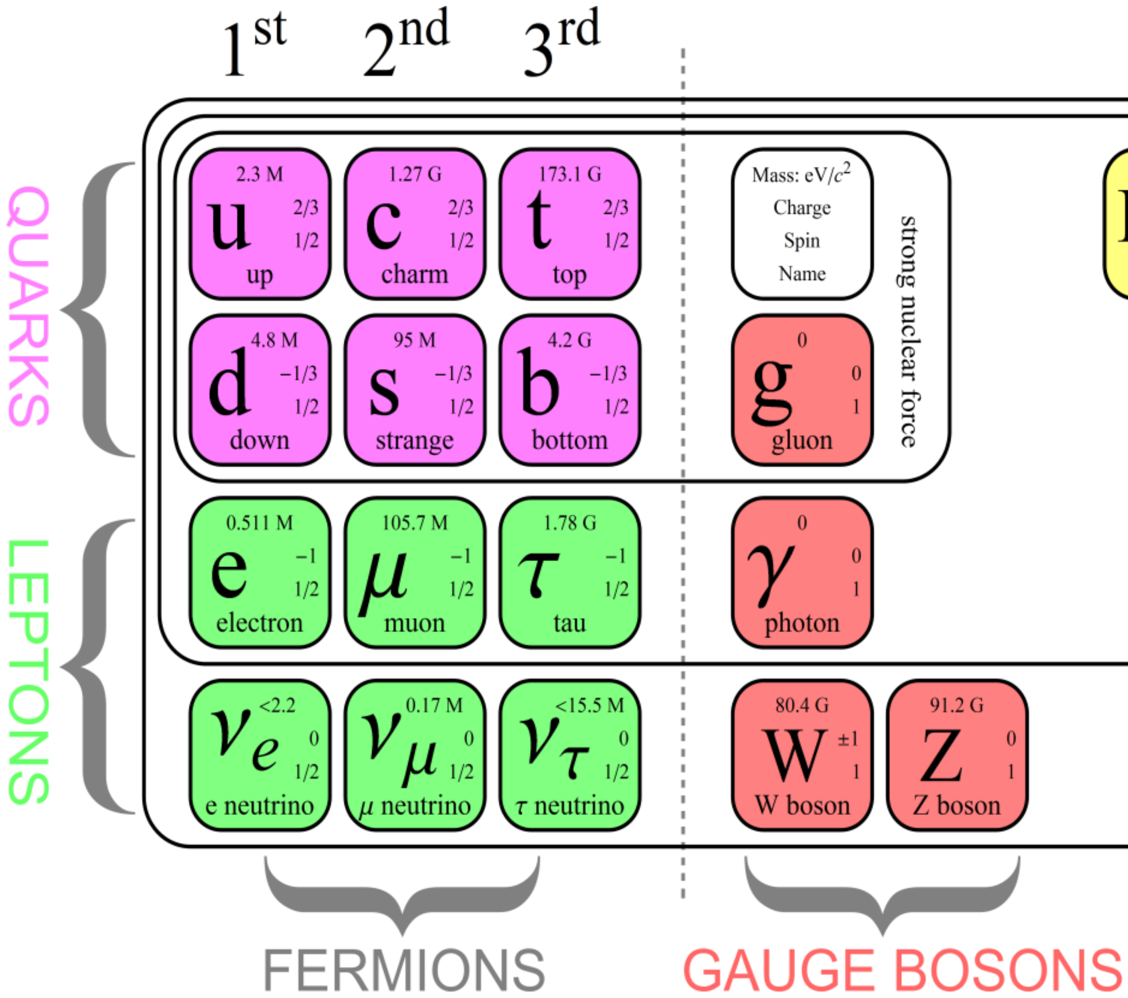




A.H. Becquerel
(1852-1908)

Image of Becquerel photographic plate, which was illuminated by the radiation of uranium salts. Clearly visible is the shadow of a metallic Maltese cross placed between the plate and the uranium salt.

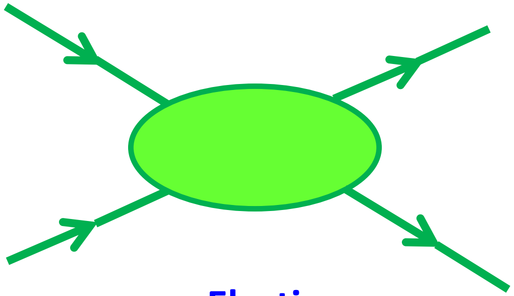
… – 2020


1st
2nd
3rd
QUARKS
LEPTONS
2.3 M u 2/3 1/2 up
1.27 G c 2/3 1/2 charm
173.1 G t 2/3 1/2 top
4.8 M d −1/3 1/2 down
95 M s −1/3 1/2 strange
4.2 G b −1/3 1/2 bottom
0.511 M e −1 1/2 electron
105.7 M μ −1 1/2 muon
1.78 G τ −1 1/2 tau
<2.2 νe 0 1/2 e neutrino
0.17 M νμ 0 1/2 μ neutrino
<15.5 M ντ 0 1/2 τ neutrino
Mass: eV/c2
Charge
Spin
Name
0 g 0 1 gluon
0 γ 0 1 photon
80.4 G W ±1 1 W boson
91.2 G Z 0 1 Z boson
126 G H 0 0 higgs
strong nuclear force
electromagnetic force
weak nuclear force
FERMIONS
GAUGE BOSONS

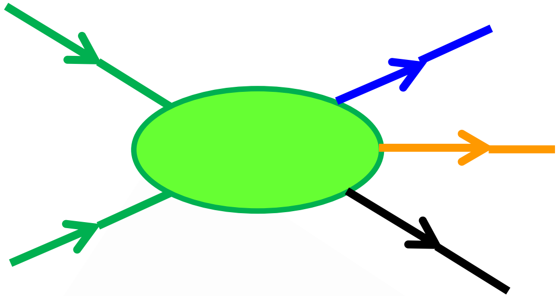
Main quantities of interest in particle physics are probabilities:

- Scattering

Probabilities are
measured in units
of area

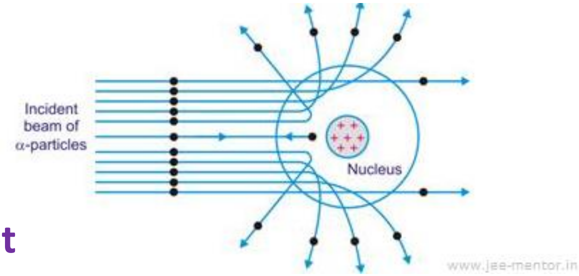


Elastic

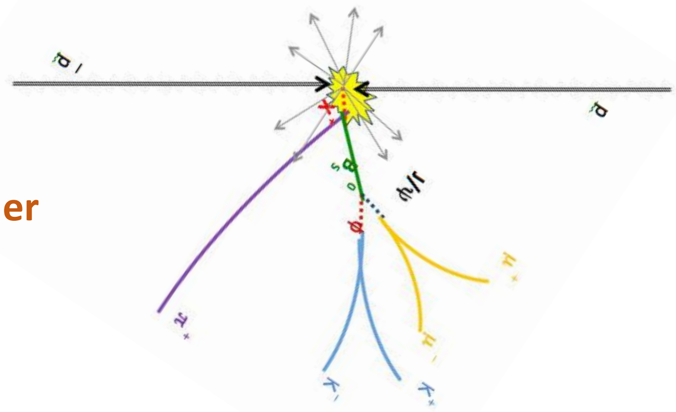


Inelastic

Fixed target

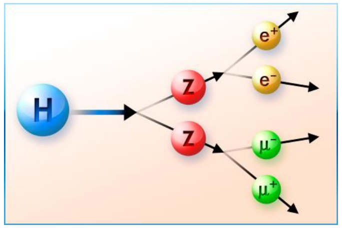


Collider



- Decays

Probabilities are
measured in units
of inverse time



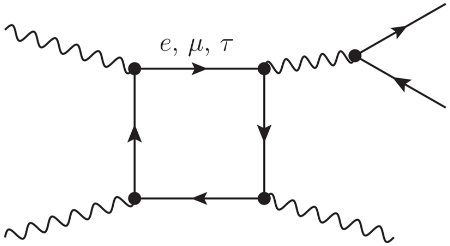
$$-\Delta N \propto N \cdot \Delta t$$

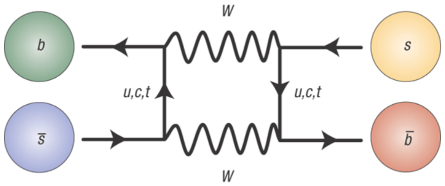
Particles do not age

Probabilities are complex amplitudes squared:

$$\boxed{P \propto |A|^2}$$

$$A(p_{in}, p_{out}) = \int dq\, V_1[q,p] \cdot D_2[q,p] \cdot \ldots \Longleftrightarrow$$

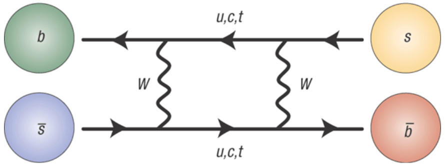




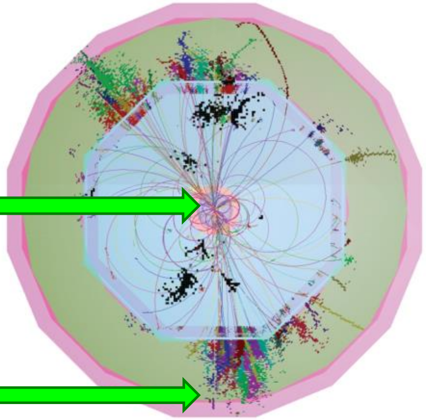
$$= A_1$$

$$\Rightarrow P = |A_1 + A_2|^2$$

Interference



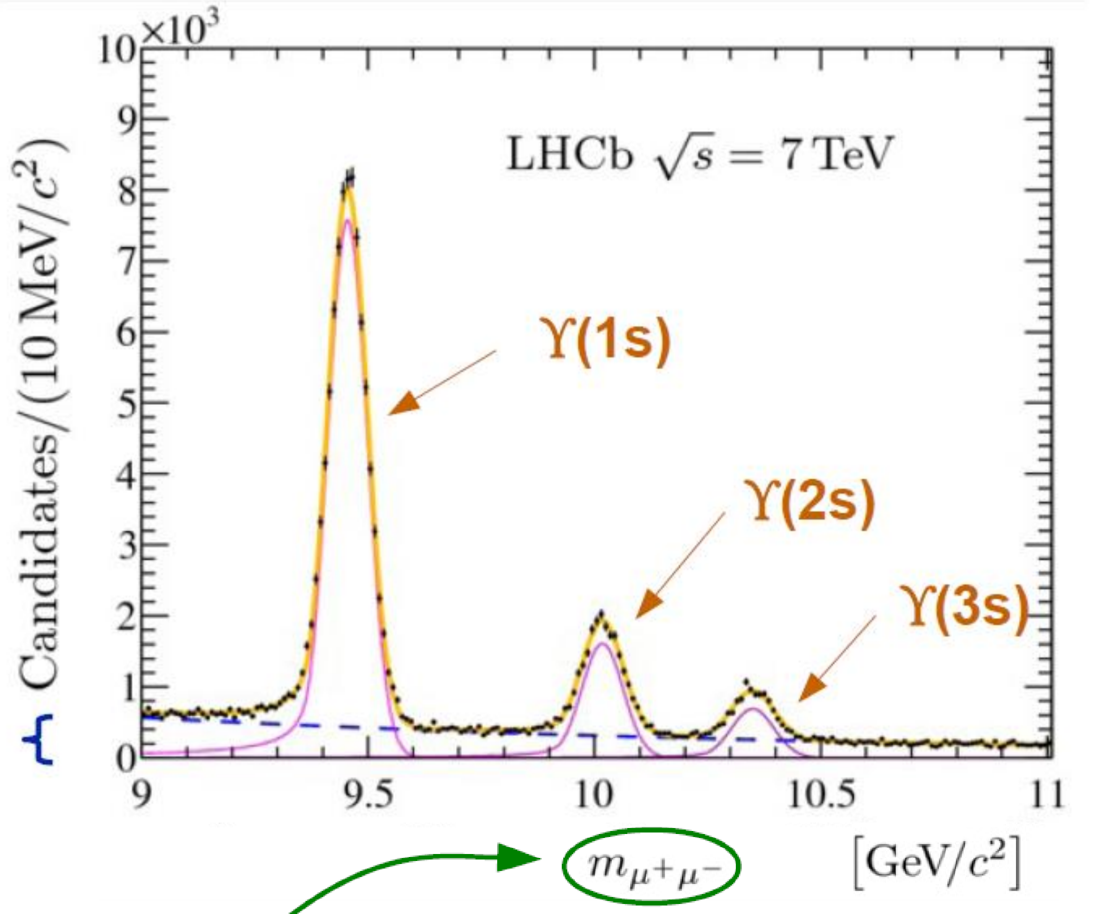
$$= A_2$$



Final result = QFT part × detector part

SM

Short-lived Particles



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

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

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

The SM has many built in small parameters

Each one gives a chance to construct perturbation theory

Some are related to symmetry breaking.

1. Dimensionless interaction constants $\alpha_{em}^{-1} = 137 \quad \alpha_s^{-1}(M_Z) = 8.5$
2. Rank of color gauge group **SU(3)** $1/9 = 1/3^2$
3. Quark masses in strong interaction scale units $\frac{m_{u,d}}{\Lambda} = (0.5 \div 2)\%$
4. Strong to weak scales ratio $G_F m_p^2 = 1 \cdot 10^{-5}$
5. Yukawa constants $\frac{m_e}{m_t} = 3 \cdot 10^{-6}$
6. Quark mixing parameters $\lambda = |V_{us}| = 0.22$
7. …

Some important small parameters are beyond the SM:

$$G_N m_p^2 = 6 \cdot 10^{-39} \qquad m_\nu$$

We have compelling evidence (not from LHC) that ***there is physics*** beyond the **SM**:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

Besides that, there are many «why» and «how» in the **SM**:

- How is EW scale so smaller than UV scale?
- Why hierarchy between **SM** scales?
- Why are lefts doublets and rights singlets?
- Why 3 generations? Why CKM hierarchy & CP?
- ...

Baryon asymmetry problem

In the early Universe at the temperature of the order of 100 MeV−1 intensive processes of quark (positive baryon number) – antiquark (negative baryon number) creation and annihilation took place. Qualitative thermodynamics estimate

$$\frac{N_q - N_{\bar{q}}}{N_q + N_{\bar{q}}} \approx \frac{N_{baryons}}{N_{photons}} \approx 10^{-10}$$

In the process of expansion quarks annihilate with antiquarks to photons but some redundant quarks form the existing baryonic matter plus relic photons. What is the mechanism to form redundant quarks? SM does not provide sufficient CP violation to form baryon asymmetry.

So, SM is definitely not a closed theory. But is it a consistent theory?

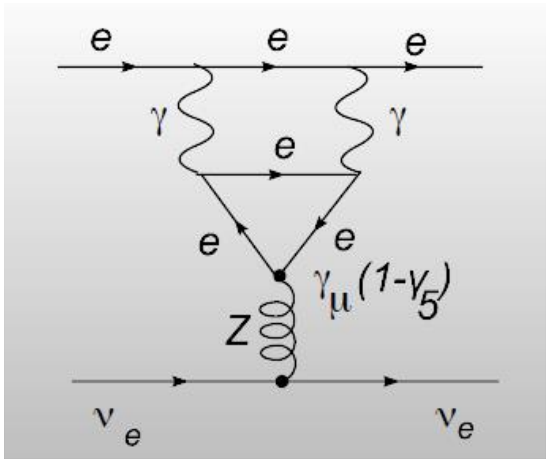
Generally, NO →

- Landau pole
- Anomalies
- Naturalness

but the things are arranged in such a tricky way, that (almost) all is cured…

Example: cancellation of anomalies.

Links quarks and leptons!



$$TrY^3 = \;= 3\left[(\frac{1}{3})^3+(\frac{1}{3})^3-(\frac{4}{3})^3-(-\frac{2}{3})^3\right]+(-1)^3+(-1)^3-(-2)^3=0$$

$$\begin{array}{cccccccc}\uparrow&\uparrow&\uparrow&\uparrow&\uparrow&\uparrow&\uparrow&\uparrow\\ colour & u_L & d_L & u_R & d_R & \nu_L & e_L & e_R.\end{array}$$

Model independent searches. SM effective field theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \cdots$$

$$L_{eff}^{(n)} = L_{SM} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_k C_{nk} O_{nk}$$

c_i – dimensionless coefficients
Λ – dimensionful scale of new physics
O_i – operators constructed from SM fields preserving SM gauge invariance, and other symmetries

W. Buchmuller, D.Wyler, Nucl.Phys. B268, 621(1986)
S.Weinberg, Phys.Rev.Lett. 43, 1566 (1979)

also the "decoupling theorem"

T.Appelquist, J.Carazzone, Phys.Rev. D11, 2856 (1975)):

Properties of Hidden Particles

$$L = L_{SM} + L_{mediator} + L_{HS}$$

Visible Sector

Mediators or portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

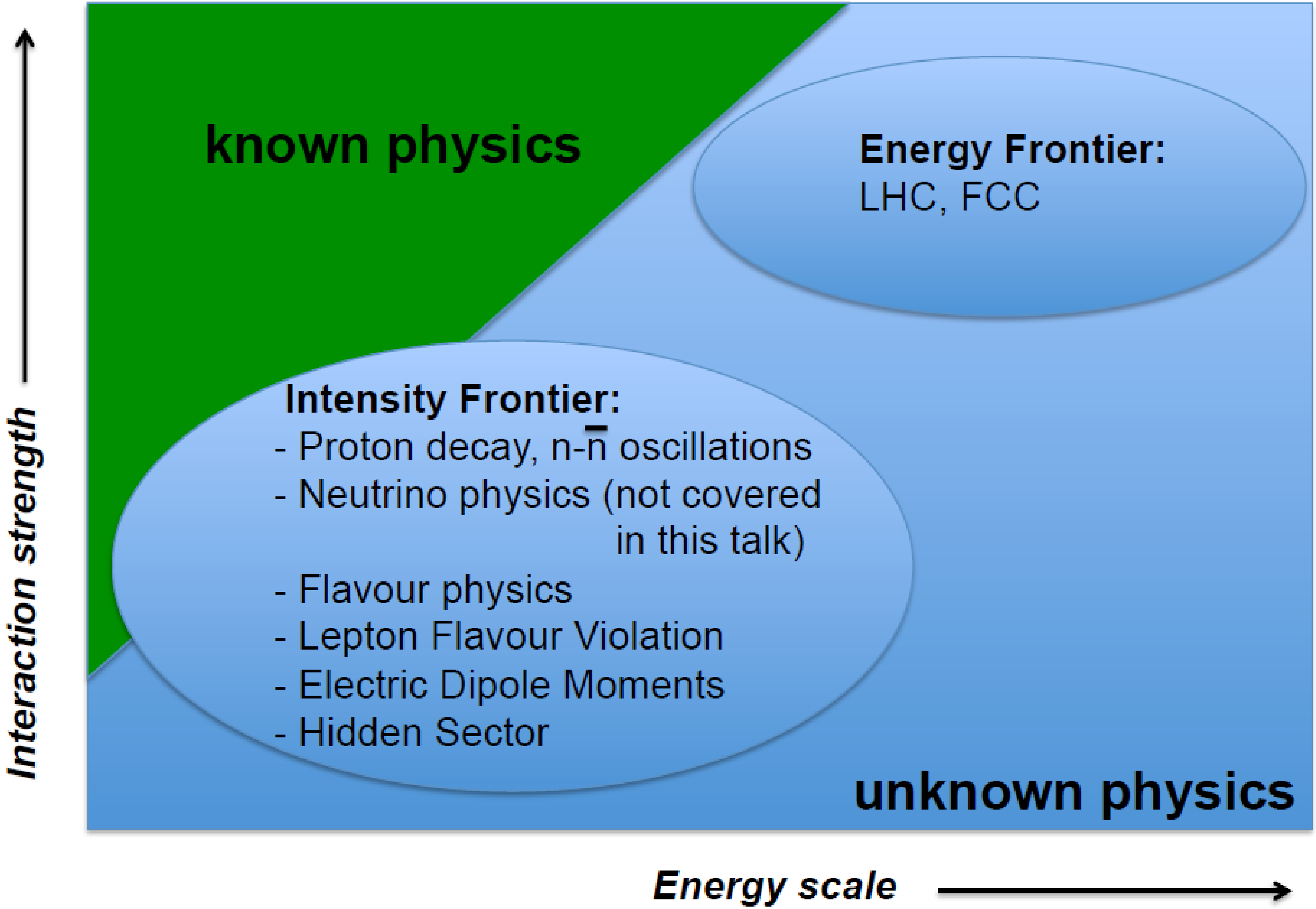
Naturally accommodates Dark Matter (may have rich structure)

✓ *HS production and decay rates are strongly suppressed relative to SM*
  - *Production branching ratios O(10^{-10})*
  - *Long-lived objects*
  - *Interact very weakly with matter*
  - *May decay to various final states*

Portal models	*Final states*
HNL	$l^+\pi^-$, l^+K^-, $l^+\rho^-$
Vector, scalar, axion portals	l^+l^-
HNL	$l^+l^-\nu$
Axion portal	$\gamma\gamma$

Full reconstruction and PID are essential to minimize model dependence

$$\boxed{\text{effect} \sim \frac{g^2}{M^2}}$$



known physics

Energy Frontier:
LHC, FCC

Intensity Frontier:
- Proton decay, n-$\bar{n}$ oscillations
- Neutrino physics (not covered in this talk)
- Flavour physics
- Lepton Flavour Violation
- Electric Dipole Moments
- Hidden Sector

unknown physics

Interaction strength

Energy scale

Particle Physics Experiments

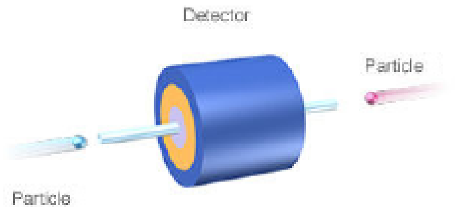
Accelerate a beam of (stable & charged) particles to high energies

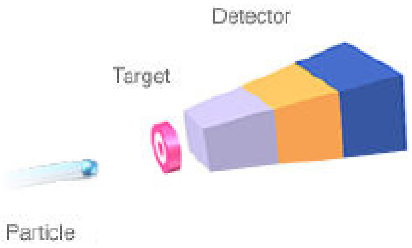
→ electrons/positrons, protons/antiprotons, heavy ions

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



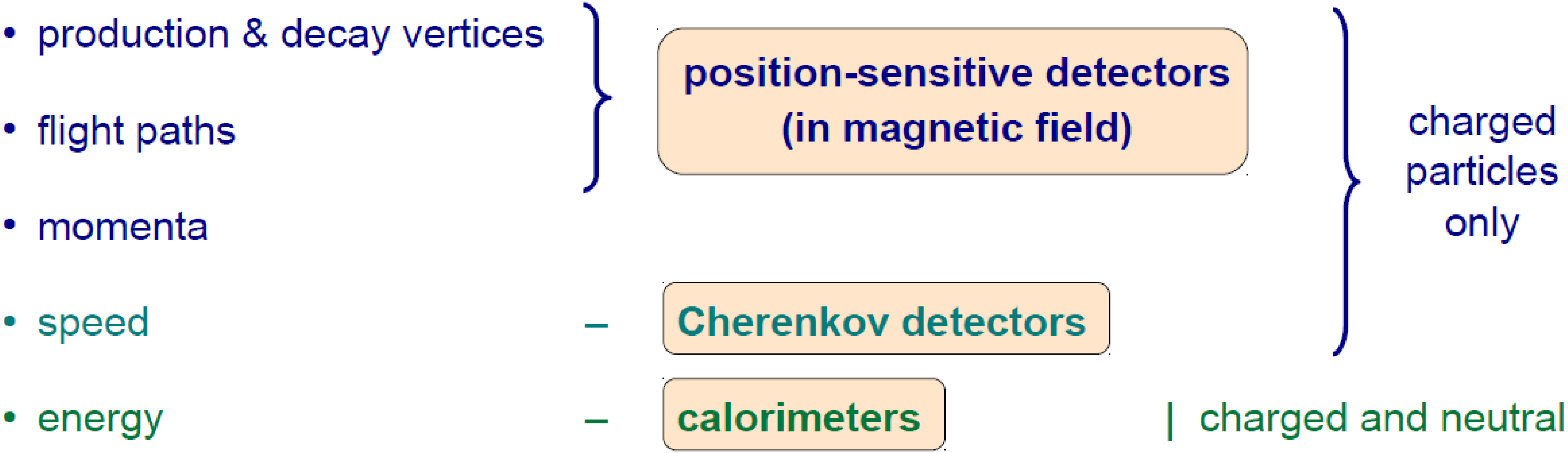


Measure the properties of the long-lived particles that are created in the collision

Reconstruct short-lived particles using relativistic kinematics

Experiments

Detector-components of a particle-physics experiment



- production & decay vertices
- flight paths
- momenta
- speed – **Cherenkov detectors**
- energy – **calorimeters** | charged and neutral

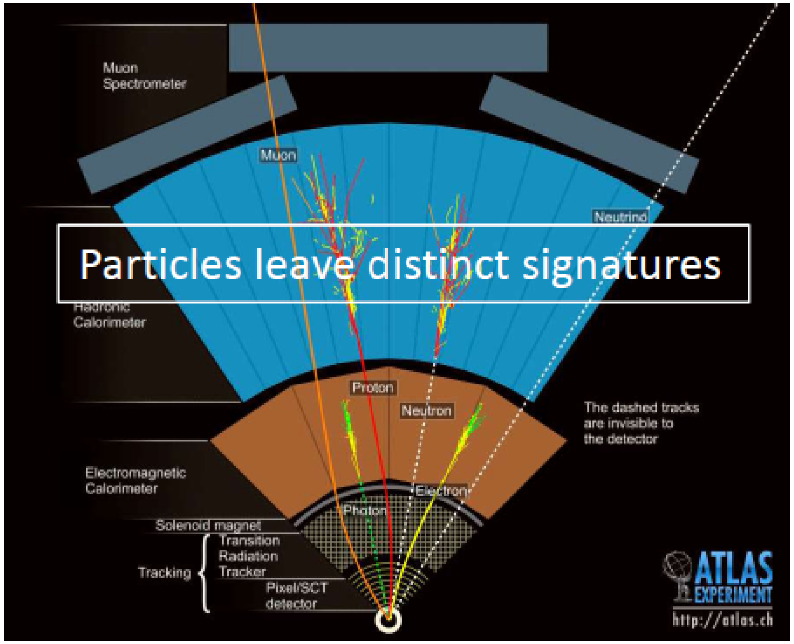
position-sensitive detectors (in magnetic field)

charged particles only

(momentum + speed → mass → particle type)

Detection of particles

- Effect on the medium and on the stable/semi-stable particles emitted from the collision
  - Remember: The interesting stuff takes place in the collision point in a volume the size of a proton!
  - ➔ Measuring the emitted particles allow us to infer the underlying physics event
  - No discussion on detection/identification of short-lived particles
  - ➔ In short, they are detected by the stable/semi-stable products!
- Particles of interest
  - Photons – stable
  - Hadrons (anti-hadrons)
    - Protons – stable
    - Neutrons – lifetime 886s
    - Charged pions – lifetime 2.6×10^{-8}s ($c\tau\sim7.8$m)
    - Charged kaons – lifetime 1.2×10^{-8}s ($c\tau\sim3.6$m)
    - Neutral kaon K_L – lifetime 5.1×10^{-8} ($c\tau\sim15.3$m)
    - K_S, Λ, Σ, Ξ – lifetime $O(10^{-10}$s) ($c\tau\sim O(0.1$m))
  - Charged leptons (anti-leptons)
    - Electrons – stable
    - Muons – lifetime 2.2×10^{-6} ($c\tau\sim687$m)
  - Neutrino – stable
  - ➔ “Life distance” in lab-system $L = \gamma\beta c\tau$ Beneficial!



Particles leave distinct signatures

The dashed tracks are invisible to the detector

See detector lectures by Steinkamp, Golutvin

Detector Components

Position-sensitive detectors

→ production vertices and flight path of charged particles

→ decay vertices of short-lived particles

Position sensitive detectors in a magnetic field

→ momenta of charged particles

Calorimeters

→ energy of charged and neutral particles

Cherenkov counters, Transition radiation counters, Time-of-flight counters, …

→ speed of charged particles

(momentum + speed → mass → particle type)

Requirements

Spatial hit resolution

→ vertex resolution, momentum resolution, …

Granularity

→ ability to separate two particles that pass the detector close in space

Rate capability

→ ability to separate two particles that pass the detector close in time

Material budget

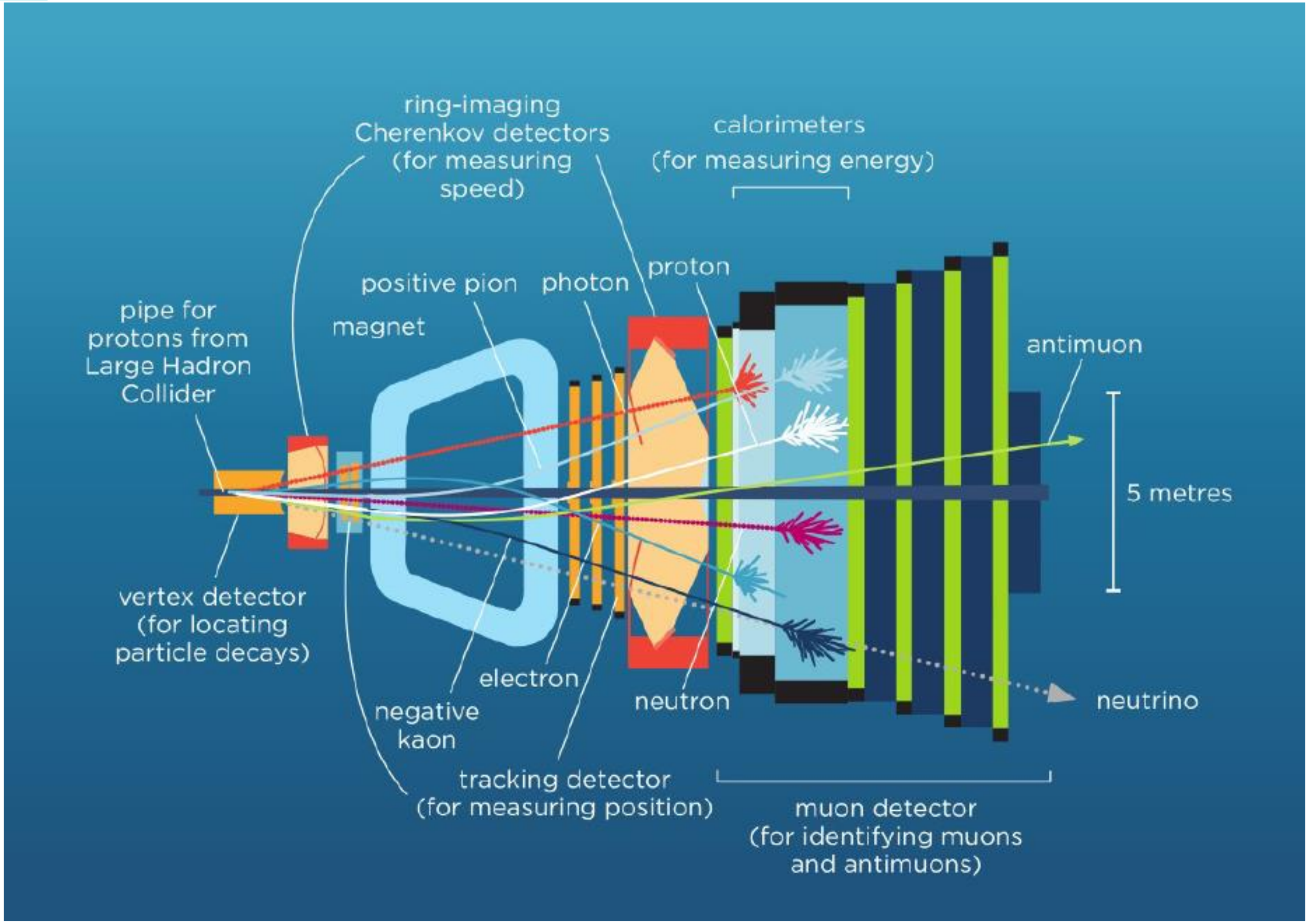
→ minimize multiple scattering, hadronic interactions

Radiation hardness

→ performance degradation from degradation of detector material

Cost !!!

→ often dominated by readout electronics
(number of channels, amount of information per channel)


ring-imaging Cherenkov detectors (for measuring speed)
calorimeters (for measuring energy)
pipe for protons from Large Hadron Collider
positive pion
photon
proton
magnet
antimuon
5 metres
vertex detector (for locating particle decays)
electron
negative kaon
neutron
neutrino
tracking detector (for measuring position)
muon detector (for identifying muons and antimuons)

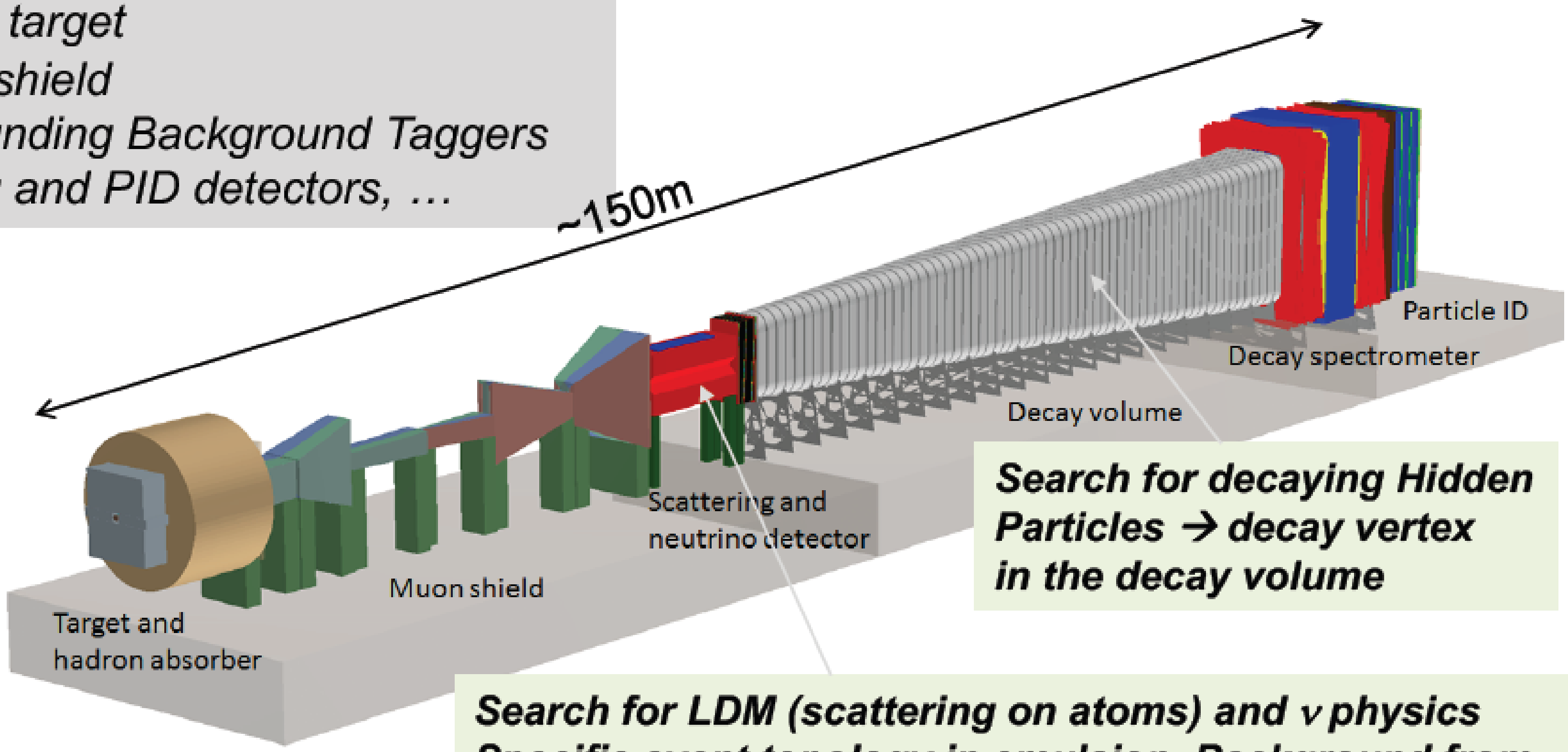
SHiP detector at BDF/CERN

SHiP Technical Proposal:
1504.04956

$>10^{18}$ D, $>10^{16}$ τ, $>10^{20}$ γ
for 2×10^{20} pot (in 5 years)

"Zero background" experiment

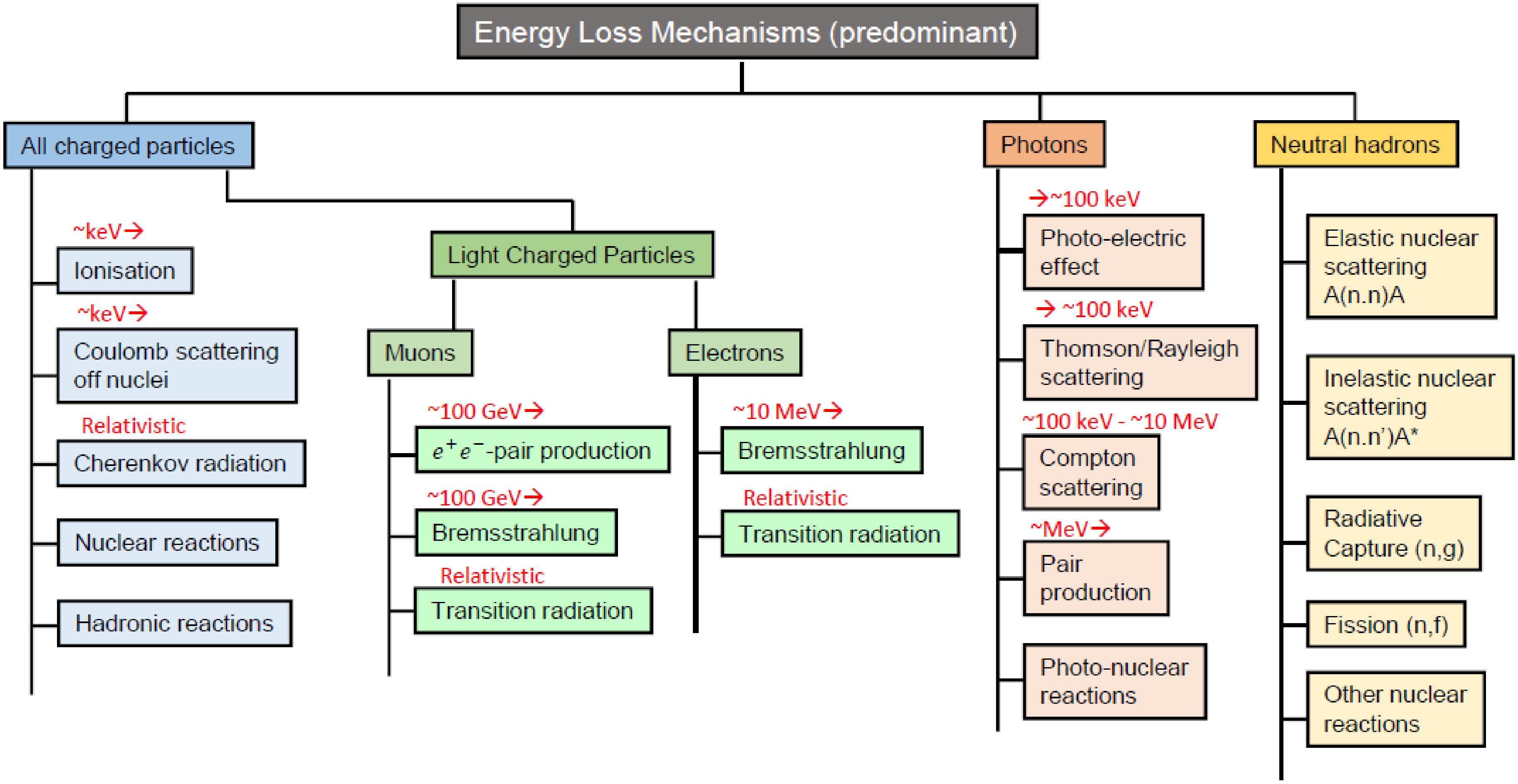
- *Heavy target*
- *Muon shield*
- *Surrounding Background Taggers*
- *Timing and PID detectors, …*



Search for decaying Hidden Particles → decay vertex in the decay volume

Search for LDM (scattering on atoms) and ν physics Specific event topology in emulsion. Background from neutrino interaction for LDM searches can be reduced to a manageable level

Overview of interactions with matter – “energy thresholds”

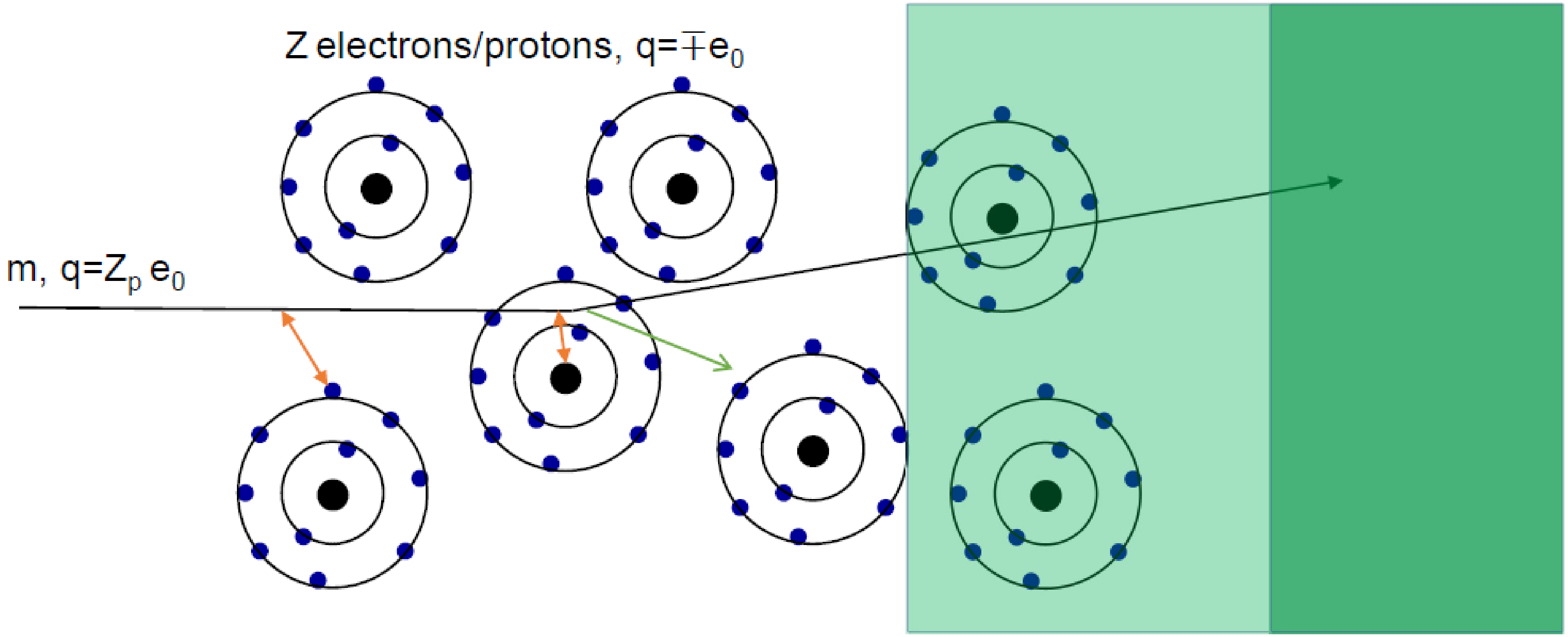


Energy Loss Mechanisms (predominant)

- All charged particles
  - ~keV→ Ionisation
  - ~keV→ Coulomb scattering off nuclei
  - Relativistic Cherenkov radiation
  - Nuclear reactions
  - Hadronic reactions
  - Light Charged Particles
    - Muons
      - ~100 GeV→ e^+e^--pair production
      - ~100 GeV→ Bremsstrahlung
      - Relativistic Transition radiation
    - Electrons
      - ~10 MeV→ Bremsstrahlung
      - Relativistic Transition radiation
- Photons
  - →~100 keV Photo-electric effect
  - → ~100 keV Thomson/Rayleigh scattering
  - ~100 keV - ~10 MeV Compton scattering
  - ~MeV→ Pair production
  - Photo-nuclear reactions
- Neutral hadrons
  - Elastic nuclear scattering A(n.n)A
  - Inelastic nuclear scattering A(n.n')A*
  - Radiative Capture (n,g)
  - Fission (n,f)
  - Other nuclear reactions

Charged particle energy loss by e.m. interactions

Medium: electrons and protons in nucleus



Atomic electrons

- Excitation
- Ionisation

Atomic nuclei

- Coulomb scattering
- Bremsstrahlung

Medium if $v > \frac{c}{\eta_{refractive}}$

- Cherenkov radiation
- Transition radiation

Energy loss by heavy charged particle, cont'd

- Full extended formula

$$-\frac{dE}{dx}=4\pi N_A r_e^2 m_e c^2 \rho \boxed{\frac{Z}{A}}\frac{z^2}{\beta^2}\left[\boxed{\frac{1}{2}\ln\frac{2\beta^2\gamma^2 m_e c^2(\Delta E)_{max}}{I^2}}-\beta^2+\boxed{\frac{1}{8}\frac{(\Delta E)_{max}^2}{((\Delta E)_0+Mc^2)^2}}+\boxed{zL_1(\beta)}+\boxed{z^2L_2(\beta)}-\frac{C}{Z}-\frac{\delta}{2}\right]$$

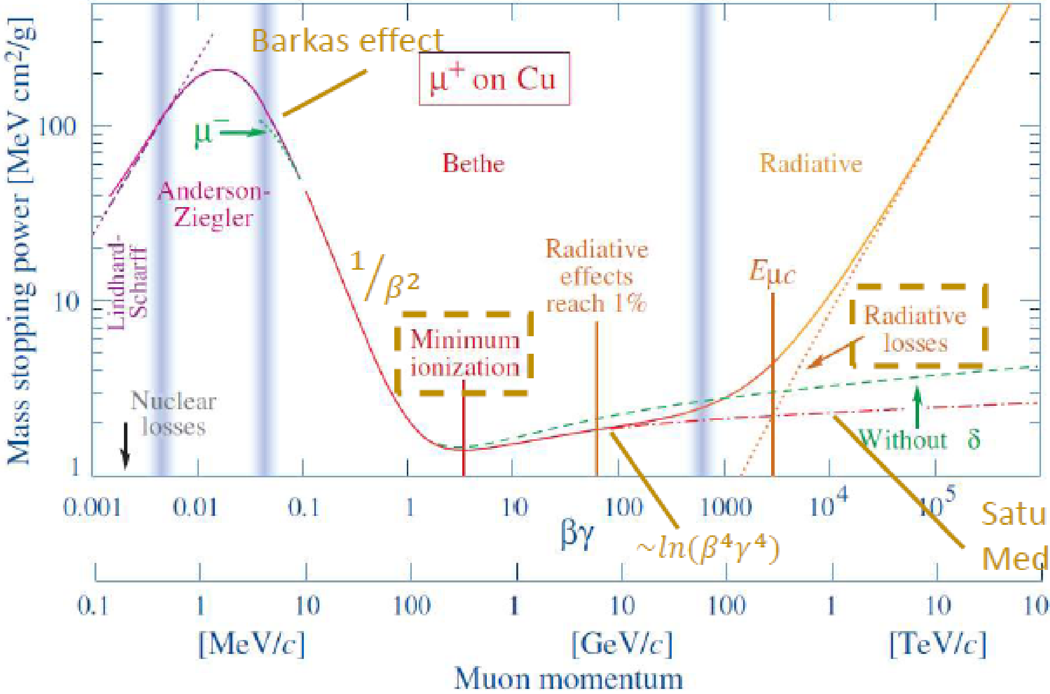
For spin $\frac{1}{2}$ only

Weak dependence on material

Relativistic rise $\sim ln(\beta^4\gamma^4)$ (hard losses)

Barkas-Andersen z^3term (neg/pos particles)

F. Bloch z^4term



Saturation (δ)
Medium polarized

Often dE/dx is given as $\frac{[MeV]}{[g/c\ \ ^2]}$, i. e. $\frac{1}{\rho}\frac{dE}{dx}$

Plotted as function of $\beta\gamma=\frac{p}{mc}$

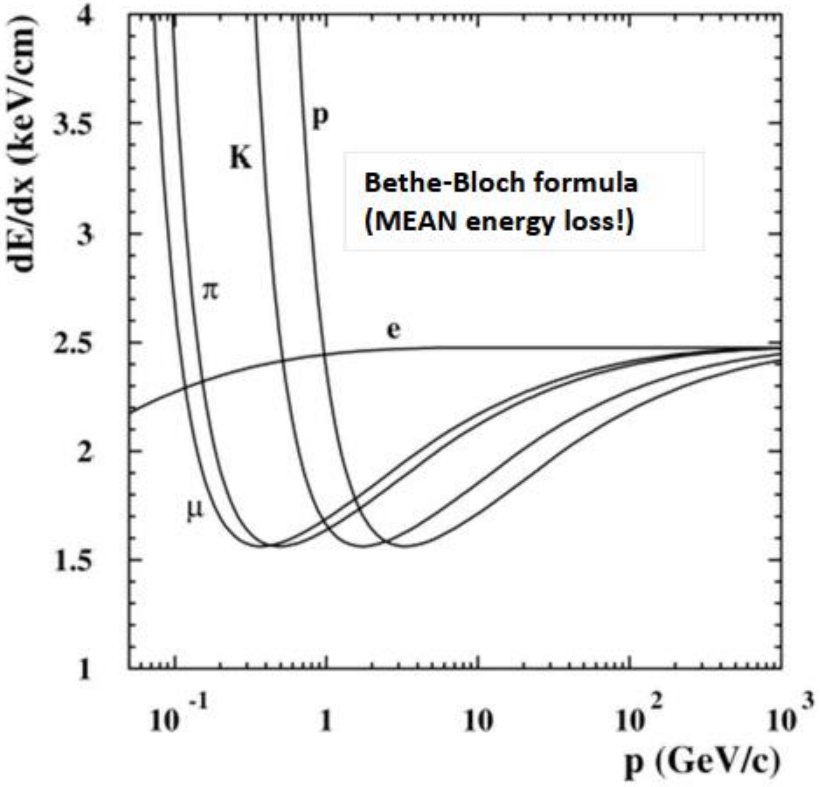
Broad minimum ~3-3.5 for $Z>7$

Most particles in HEP experiments are in the minimum :

➔ Min. Ionizing Particles (MIPs) ~13 MeV/cm

Energy loss as particle signature

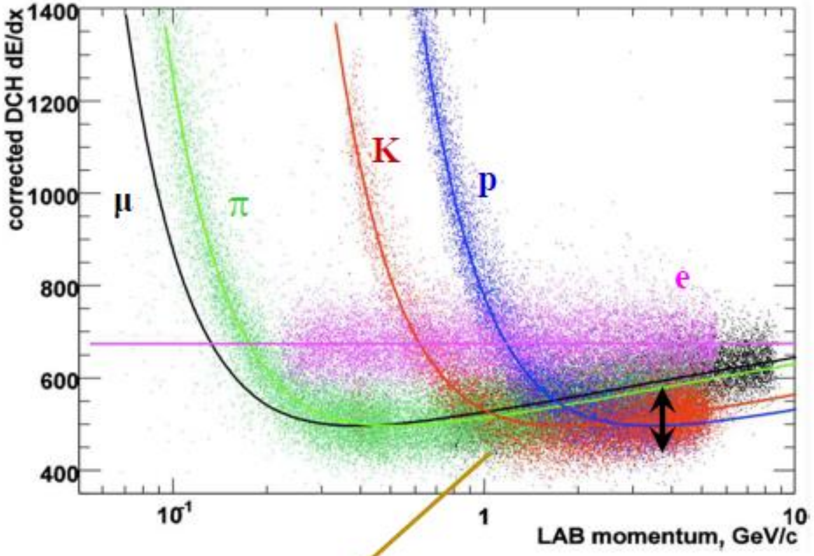
Particle identification by measuring ${}^{dE}/_{dx}$ and p!



Bethe-Bloch formula (MEAN energy loss!)

$$-\frac{dE}{dx} \propto \frac{Z}{A}\frac{z^2}{\beta^2} \sim \frac{Z}{A}\boxed{\frac{z^2 m}{E}}$$

Of course it is not that clean…

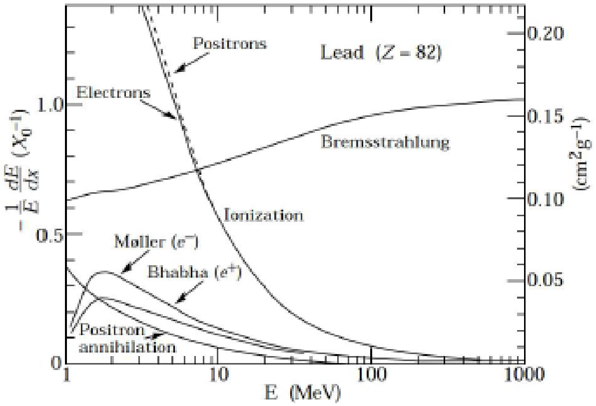


Relativistic rise
$\sim ln(\beta^4\gamma^4)$ (hard losses)
→ stochastic

Bremsstrahlung – Critical energy and Radiation length

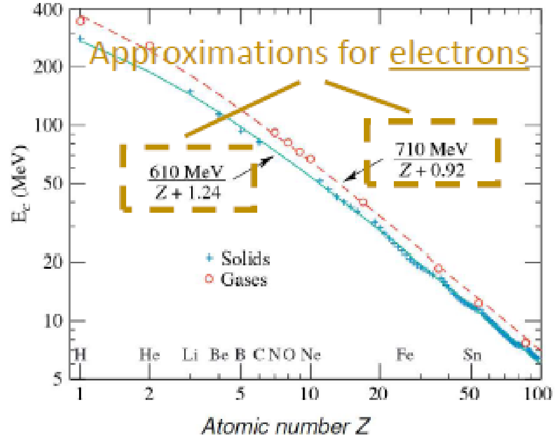
- Total energy loss

$$\left\langle\frac{dE}{dx}\right\rangle_{tot} = \left\langle\frac{dE}{dx}\right\rangle_{ion} + \left\langle\frac{dE}{dx}\right\rangle_{brems}$$



- Critical energy (definition)

$$\frac{\left\langle\frac{dE}{dx}\right\rangle_{brems}(E_{crit})}{\left\langle\frac{dE}{dx}\right\rangle_{ion}(E_{crit})} = 1 \Rightarrow E_{crit} \approx \frac{3\pi}{4}\left(\frac{m}{M}\right)\left(\frac{mc^2}{Z\alpha}\right)$$



- Radiation length (definition)

$$-\left\langle\frac{dE}{dx}\right\rangle_{brems} \equiv \frac{E}{X_0} \Rightarrow E(x) = E_o e^{-x/X_0} \Rightarrow \frac{1}{X_0} = 4\alpha r_e^2 N_A \rho \frac{Z^2}{A}\left[ln\frac{183}{Z^{1/3}}\right]$$

- $1 \times X_0 \Rightarrow \frac{1}{e} \times E_0 = 63\% E_0$

Common approximation (Dahl):

$$X_0\rho\,[g/cm^2] = \frac{716.4 g/cm^2 A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Momentum measurement

Typical collider experiment:
solenoid or toroid magnet

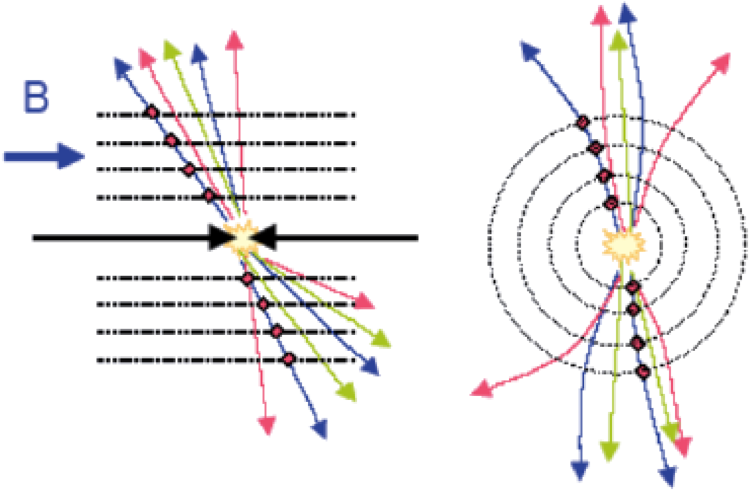
→ field lines parallel to beam

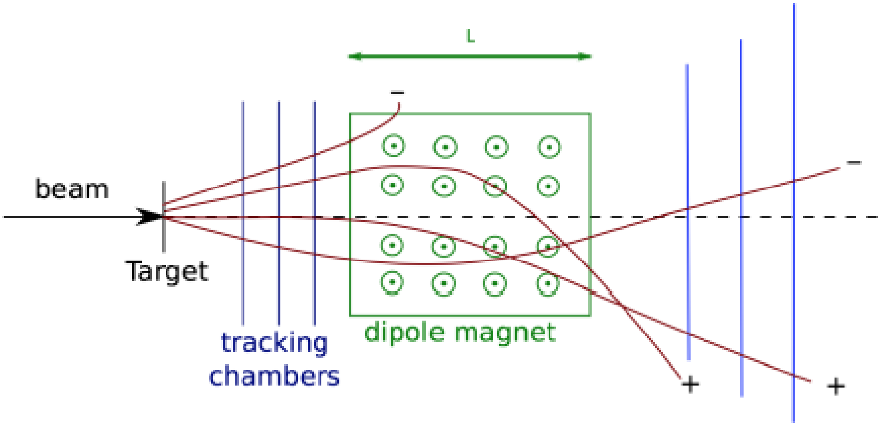
cylindrical tracking layers
inside the magnet

Typical fixed-target experiment:
dipole magnet

→ field lines orthogonal to beam

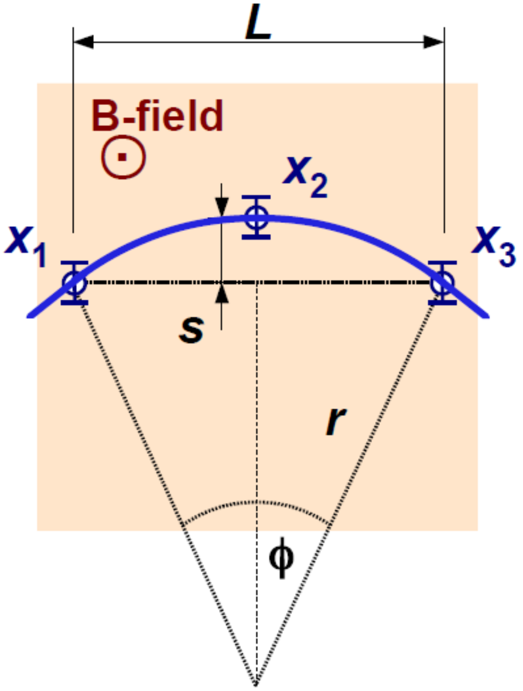
planar tracking detectors
before and after the magnet





Momentum resolution (I)

Determine sagitta of the trajectory from three position measurements



- from geometry:

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

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

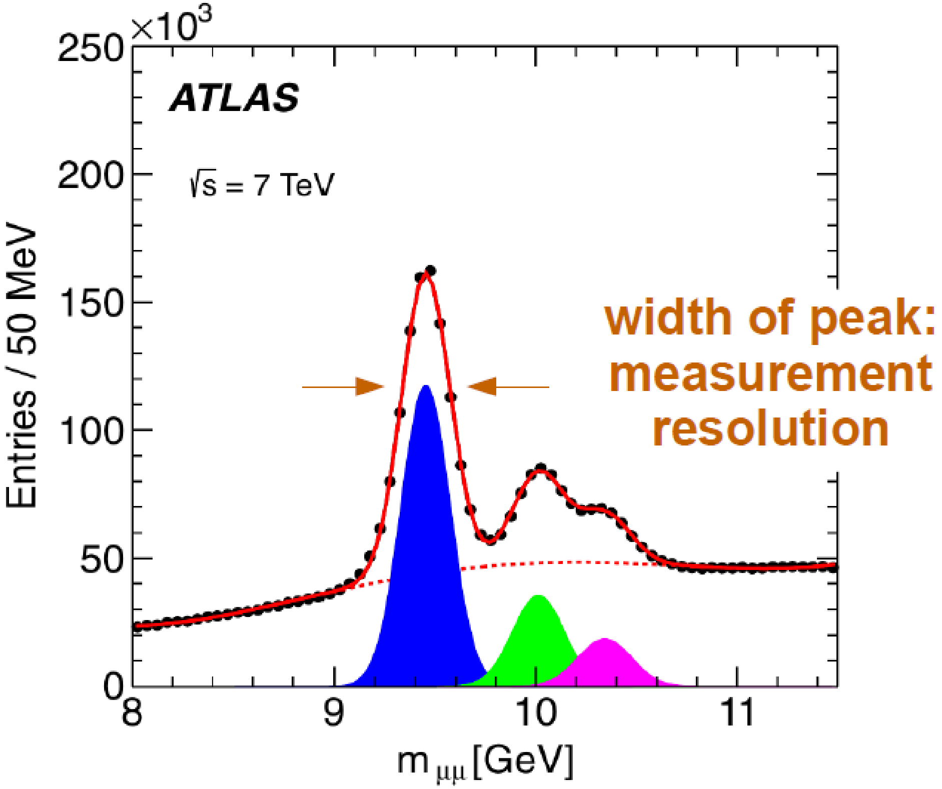
- deflection in magnetic field (for $q = 1$):

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

- position measurements with resolution σ_x:

$$s = x_2 - \frac{x_1 + x_3}{2} \;\Rightarrow\; \sigma_s^2 = \frac{3}{2}\sigma_x^2$$

$$\boxed{\frac{\sigma(p)}{p} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\,\sigma_x \cdot \frac{8\,p}{0.3\,B\,L^2}}$$



width of peak: measurement resolution

Width of signal due to finite precision of momentum measurement
→ determine momentum resolution of the detector

Silicon tracking detectors

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

Simplest device: *n*–doped monocrystalline silicon wafer, *p*–doped implants at surface

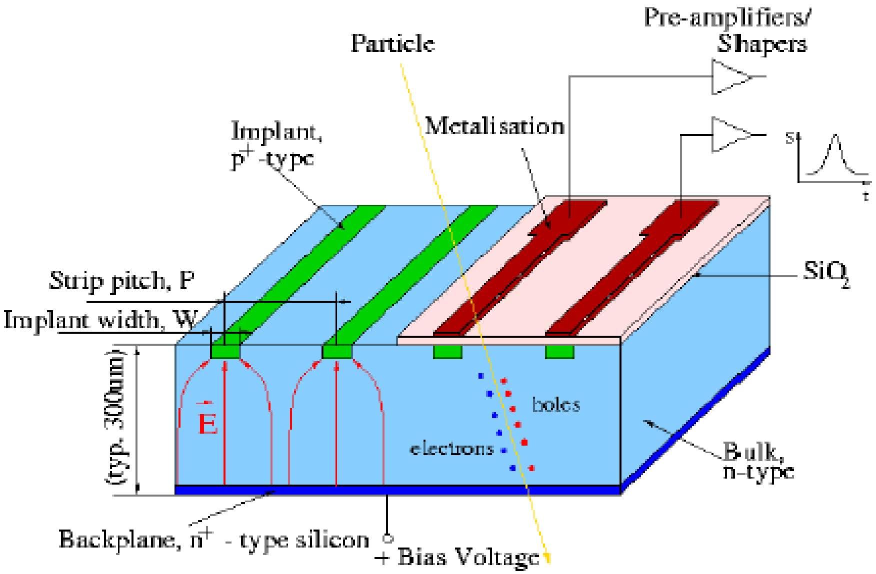
→ strips with pitch 250 – 20 µm

→ resolution 50 to a few µm

→ or pixels for even finer granularity

Apply reverse bias voltage

→ electric field through the wafer



Ionizing particle creates electron-hole pairs in the silicon lattice

→ electrons and holes drift to surface

→ induce signals on the *p*-doped implants

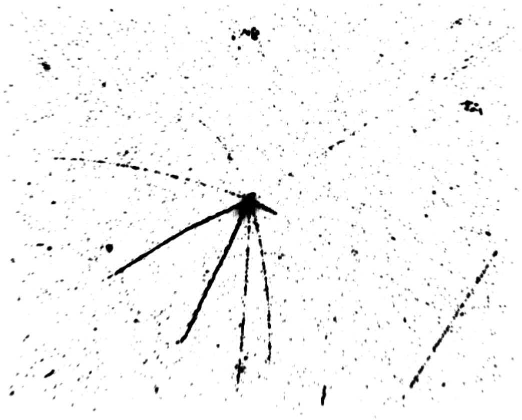
Emulsion technology

Hardware

- Detector production
- Development

Scanning

- Microscope readout
- Reconstruction



Physics experiments

- OPERA
- T2K
- AEgIS
- SHiP

Accelerator

- Beam monitoring

Medical application

- Neutron dosimetry
- Proton radiography
- Beam characterization in proton therapy

Geosciences

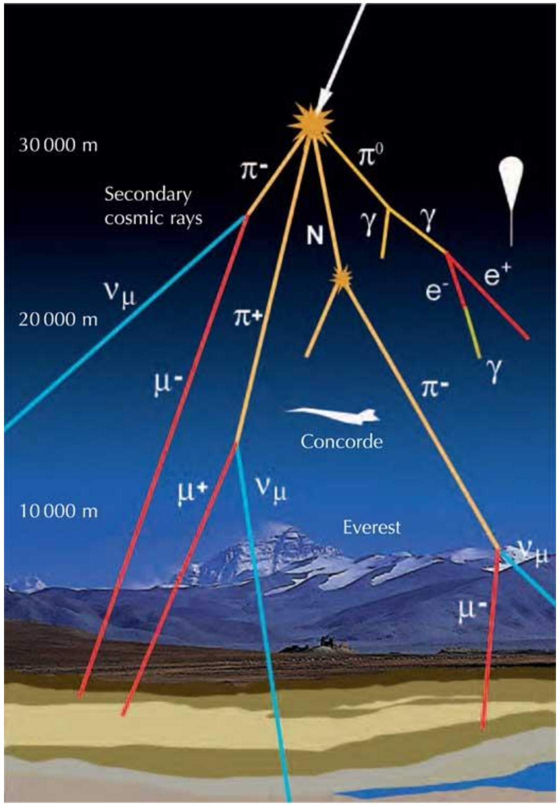
- Muon radiography

Cosmic Ray Physics

- Balloon

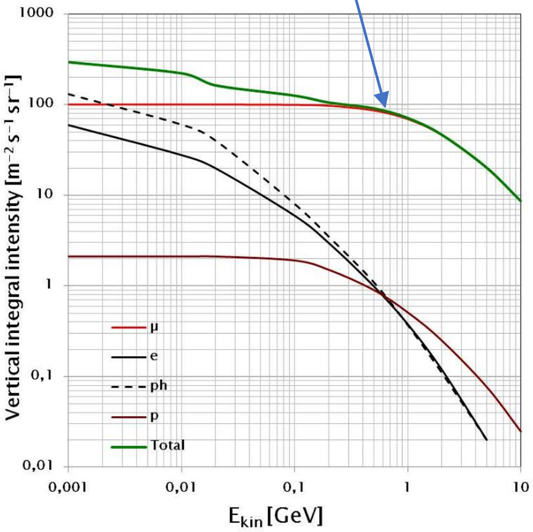
Atmospheric muons

Muons produced by protons coming from space in the upper layers of atmosphere

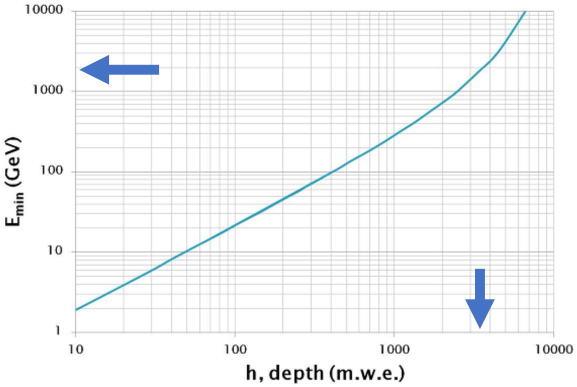


Muons flux is well studied and quite stable in time at the energies exceeding 1 GeV

Them are dominating ionizing particles at sea level

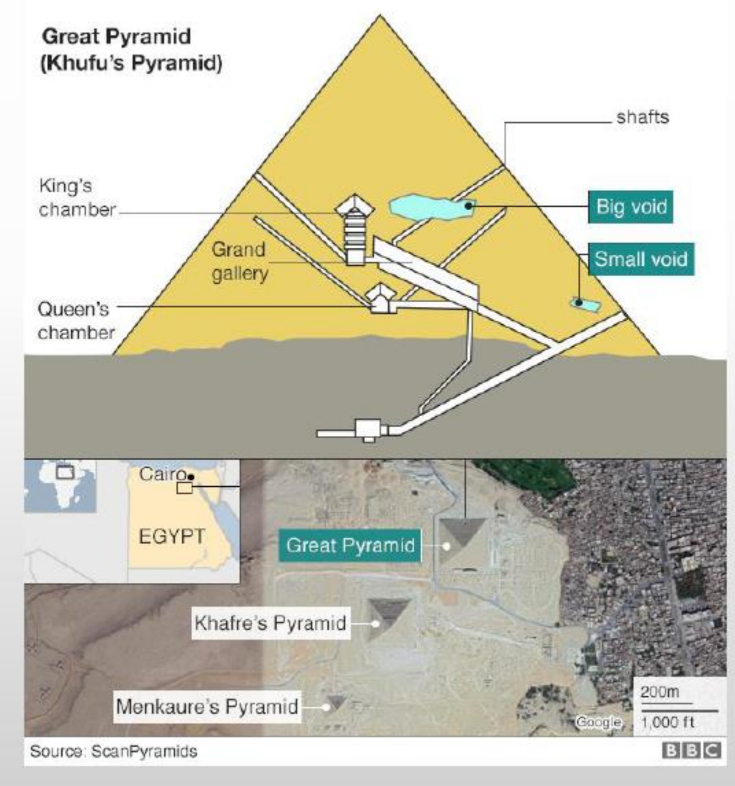


Muons are highly penetrating and cross thick layers of material if have enough initial energy: 2TeV -> 3 km w.e.

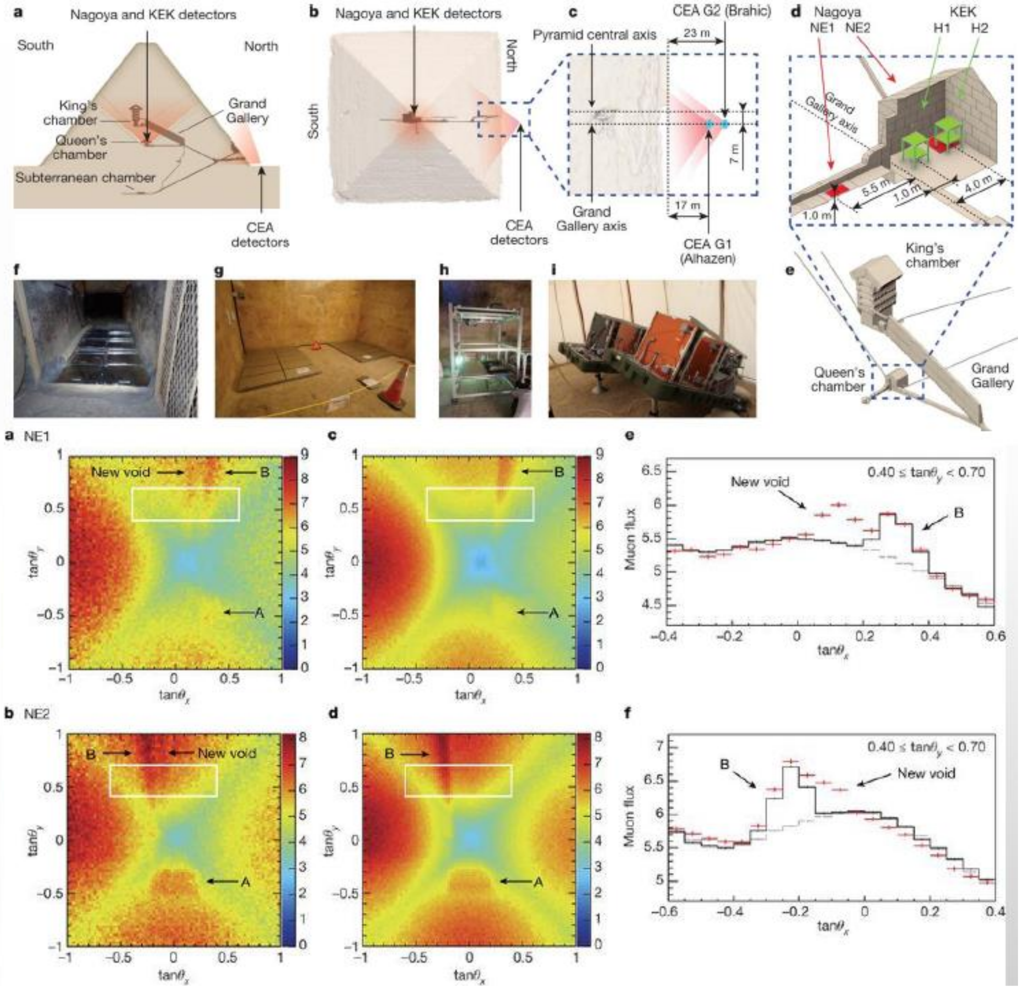


Can be used for radiography of bulky objects

2017: The hidden void in Great Pyramid was found by the emulsion detector!



Source: ScanPyramids



Summary

Efficient and precise tracking of charged particles is a crucial ingredient for almost all particle physics experiments

→ to determine production and decay vertices
→ to measure momenta

Detection based on interaction of particle with detector material, e.g.

→ ionisation of a gas
→ creation of electron/pair holes in a semiconductor

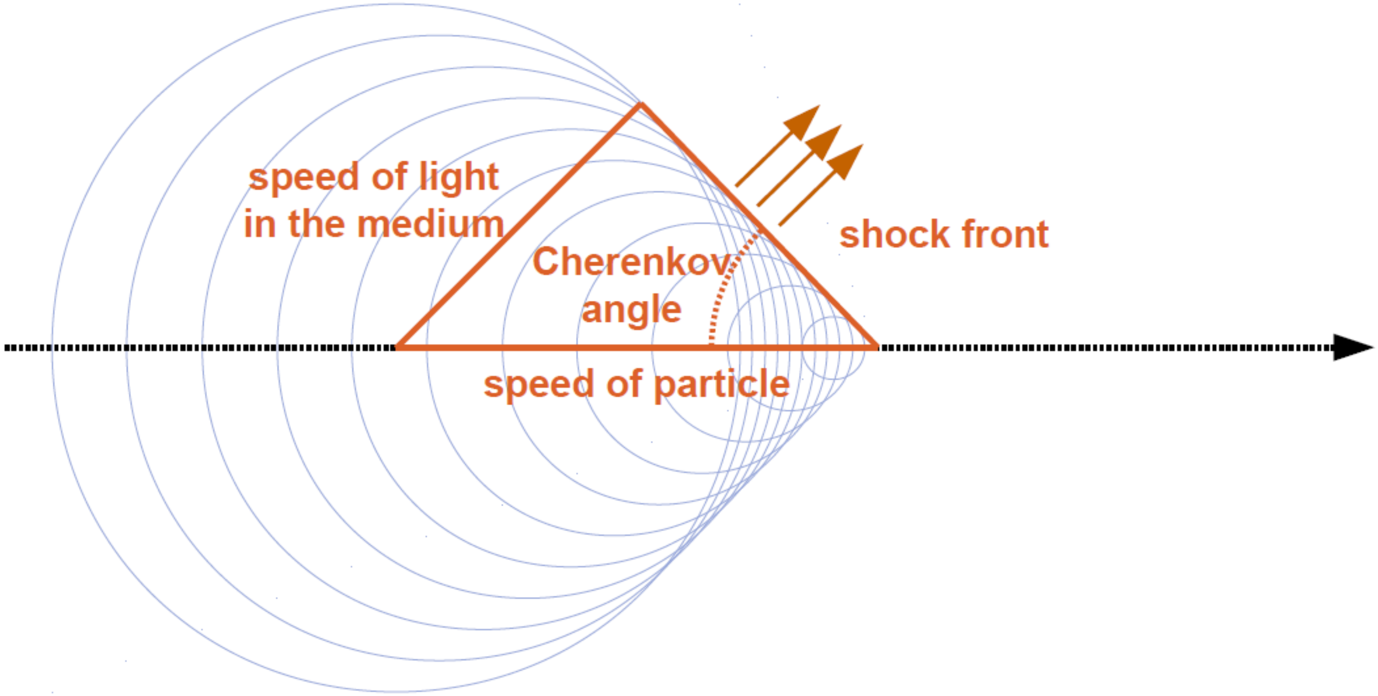
Apply electric field across detector volume, read out the signals induced by drifting charges on segmented electrodes

→ wires, strips, pixels

Many (sometimes conflicting) performance requirements
→ granularity, spatial resolution, rate capability, radiation hardness, material budget, cost

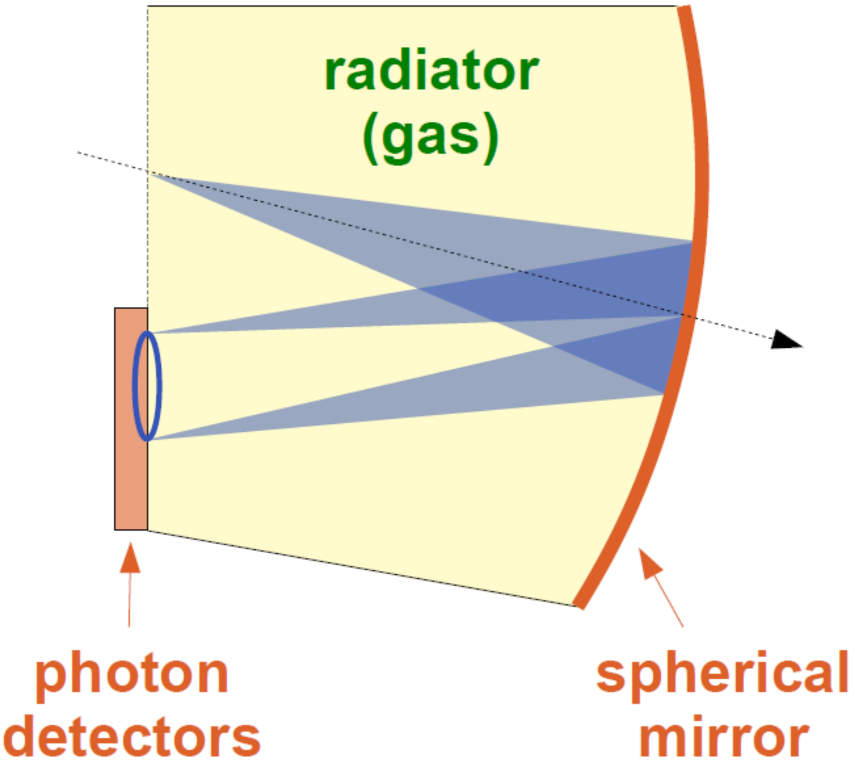
New detector technologies to face new challenges

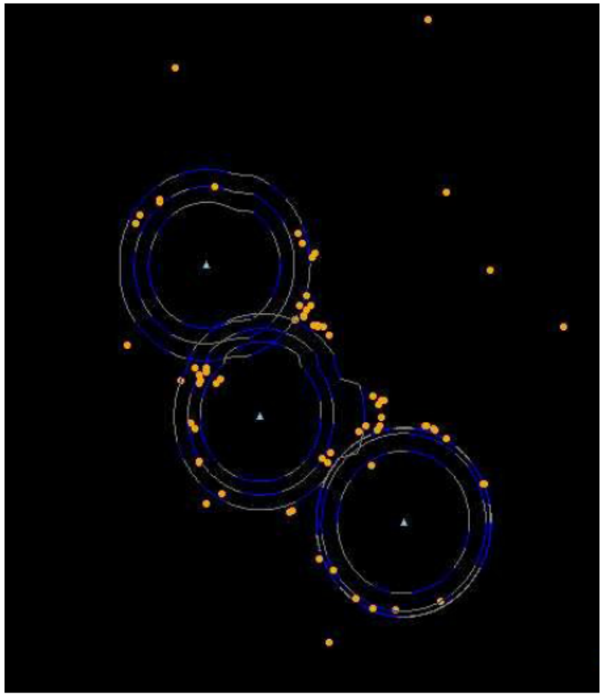
Ring Imaging Cherenkov Detectors



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

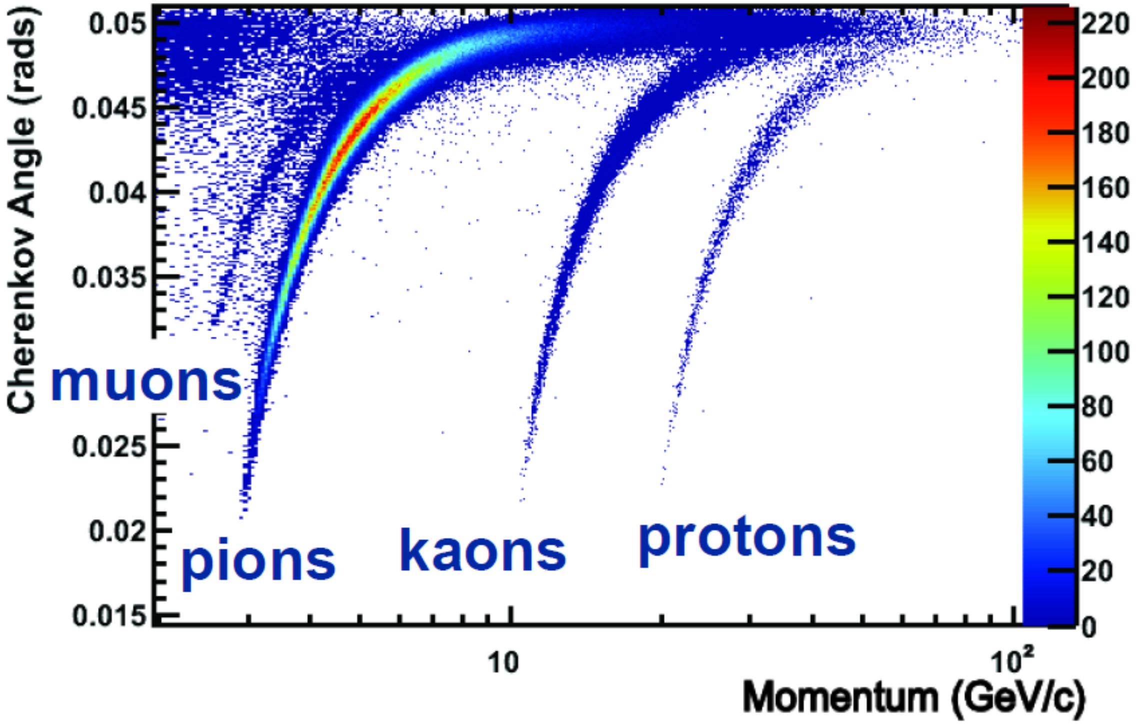
Ring Imaging Cherenkov Detectors





“Ring Imaging CHerenkov detector” (RICH):
focus the emitted light onto a detection plane → rings

Ring Imaging Cherenkov Detectors



Momentum (from tracking system)

&

Cherenkov angle (from RICH detector)

} **particle identification**

Energy measurement

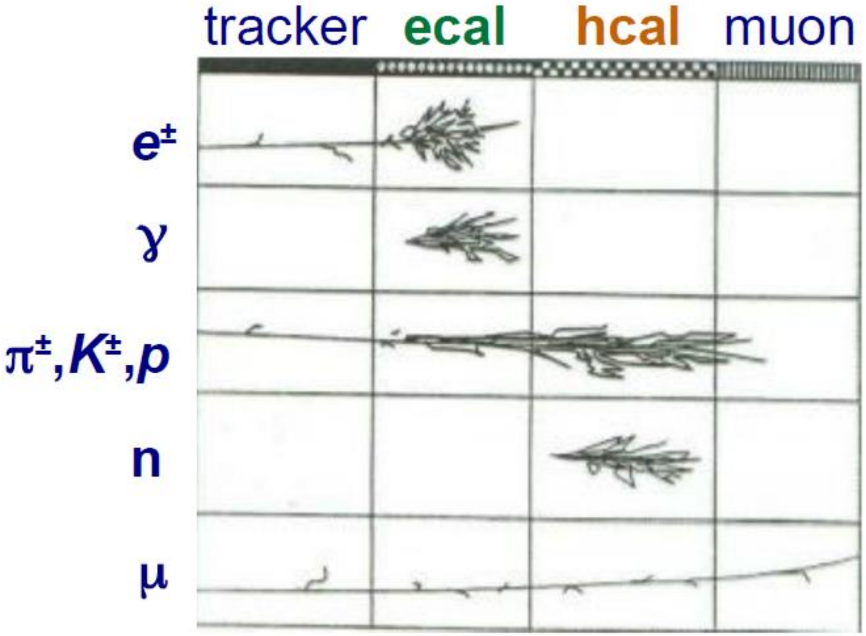
Calorimeter: high-density material with large *Z*
→ incident particle initiates cascade (“shower”) of secondary particles

Signal created in active detector material
is 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

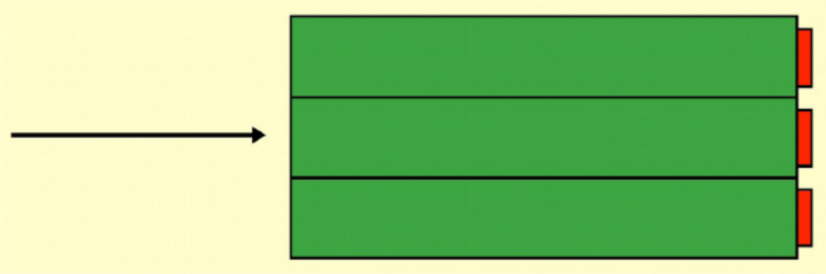
Destructive measurement
→ calorimeters after tracking



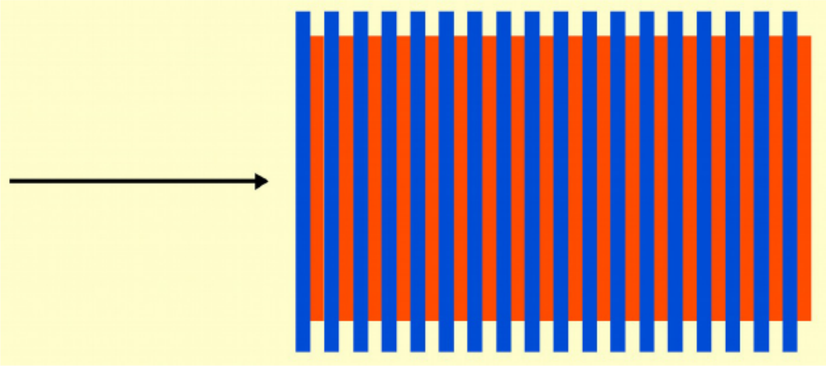
Calorimeters

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 all signal, but cheaper + ability to reconstruct longitudinal shower profile

Calorimetry

Calorimeters are attractive in our field for various reasons:

In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as 1/Sqrt(E), where E is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

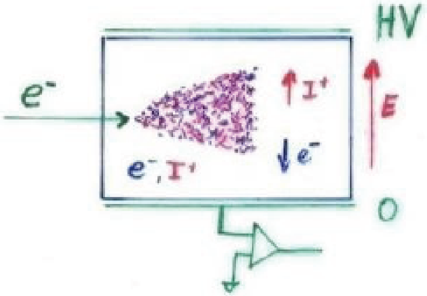
Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. On the contrary, for a fixed momentum resolution, the bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum.

Calorimetry: Energy Measurement by total Absorption of Particles

The measurement is destructive. The particle cannot be studied further

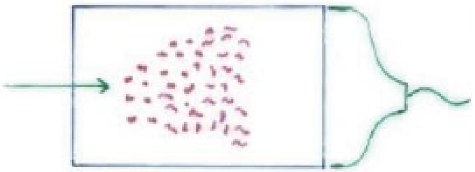
Energy measurement by:



Collecting the produced charge

Liquid Noble Gas

(Noble Liquids)



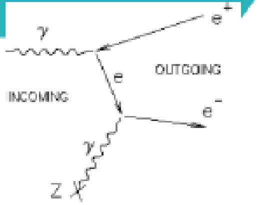
Measuring the photons produced by the collisions of the e± with the atom electrons of the material

Scintillating Crystals,

Plastic Scintillators

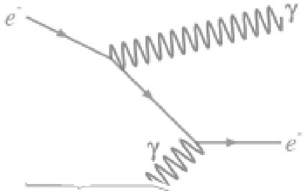
Total amount of pairs or photons is proportional to the total track length and is proportional to the particle energy

Pair Production: Quantum Mechanics



$$\gamma + \text{Nucl.} \rightarrow e^+ + e^- + \text{Nucl.}$$

The diagram is very similar to Bremsstrahlung



$$e^- + \text{Nucl.} \rightarrow \gamma + e^- + \text{Nucl.}$$

Crossing Symmetry:
same cross-section

$$\frac{d\sigma(E,E')}{dE'} = 4\alpha Z^2 r_e^2 \frac{1}{E} \cdot G(E,E') \qquad E >> 137 m_e c^2 Z^{-\frac{1}{3}}$$

$$G(E,E') = \left[\left(\frac{E'+m_ec^2}{E}\right)^2 r \left(1 - \frac{E'+m_ec^2}{E}\right)^2 + \frac{2}{3}\frac{E'+m_ec^2}{E}\left(1\frac{E'+m_ec^2}{E}\right)\ln Z^{-\frac{1}{3}} - \frac{1}{9}\left(\frac{E'+m_ec^2}{E}\right)\left(1 - \frac{E'+m_ec^2}{E}\right)\right]$$

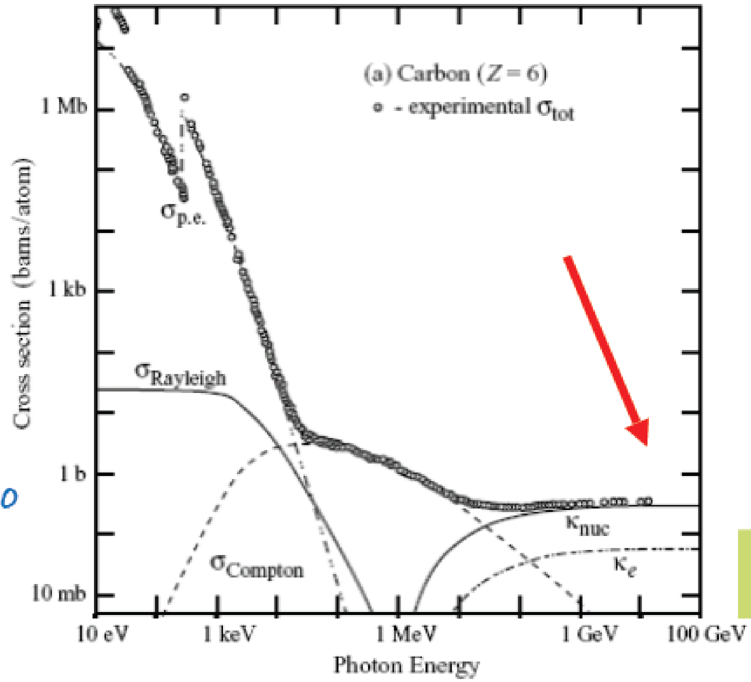
$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma'}{dE'} dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{9} \ln 183 Z^{-\frac{1}{3}}$$

$$P(x) = \frac{1}{\lambda} e^{-\frac{x}{\lambda}} \qquad \lambda = \frac{A}{\rho N_A \sigma} = \frac{9}{7} X_0$$

Probability that Photon converts to e^+e^- after a distance x

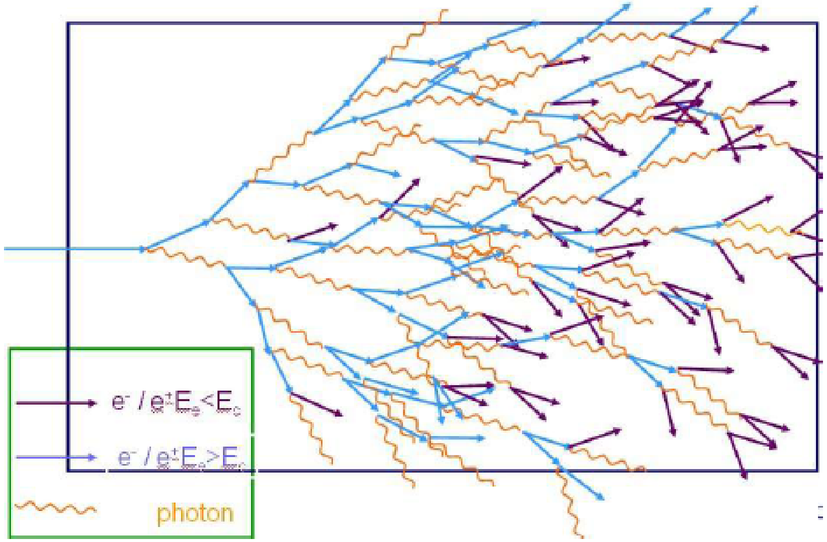
For $E\gamma >> m_e c^2 = 0.5\text{MeV} : \lambda = 9/7 X_0$

Average distance a high energy photon has to travel before it converts into an e^+e^- pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing its energy from E_0 to $E_0 * e^{-1}$ by photon radiation.



Electromagnetic showers

- Combined effect of bremsstrahlung and pair-production
  - e^+/e^-: starts with bremsstrahlung $\left\langle \frac{dE}{dx} \right\rangle_{brems} = \frac{E}{X_0}$
  - γ: starts with pair-production $\sigma_{pp} \propto \frac{7}{9}\frac{1}{X_0}$



"Heitler model"

- Shower multiplicity and average energy per particle

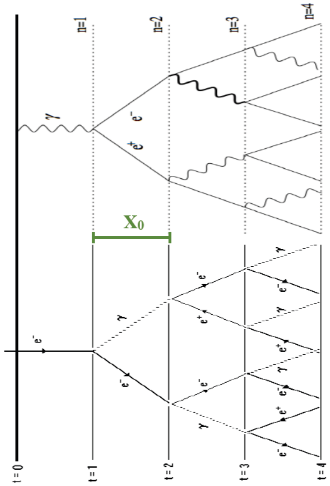
$$N \cong 2^t \quad \Rightarrow \quad \langle E(t) \rangle \cong \frac{E_0}{2^t}$$

$t = \frac{x}{X_0}$, number of X_0 traversed

- Maximum penetration depth defined by E_{Crit} ($E < E_{Crit}$: only energy loss by ionization/excitation)

$$\langle E(t_{max}) \rangle = \frac{E_0}{2^{t_{max}}} = E_{Crit} \quad \Rightarrow \quad t_{max} = \frac{1}{ln\,2}\,ln\frac{E_0}{E_{Crit}} \quad \Rightarrow \quad N_{max} = \frac{E_o}{E_{Crit}}$$

Electro-Magnetic Shower of High Energy Electrons and Photons



$$N(n) = 2^n$$

Number of particles ($e^{\pm}$,γ) after nX_0

$$E(n) = \frac{E_0}{2^n}$$

Average Energy of particles after nX_0

Shower stops if $E(n) = E_c$

$$n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$$

Shower length rises with $\ln E_0$

$$N_{tr}(n) = 2^n$$

Number of $e^{\pm}$ track segments of length X_0 after nX_0

$$L = \sum_{n=0}^{n_{max}} 2^n X_0 = \left(2\frac{E_0}{E_c} - 1\right) X_0 \sim 2\frac{E_0}{E_c} X_0 = c_1 \cdot E_0$$

Total (charged) track length is proportional to the Energy of the particle

→ Calorimeter Principle

Energy Resolution of Calorimeters

Stochastic term:
Fluctuations related to the physics development of the shower.

Noise term:
From electronics noise of the readout chain. For constant electronics noise → double signal = double S/N

Constant term:
Instrumental effects that cause variations of the calorimeter response with the particle impact point.

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Add in squares

For homogeneous calorimeters the noise term and constant term become dominant.

For sampling calorimeters the stochastic term, then called 'sampling' term becomes dominant.

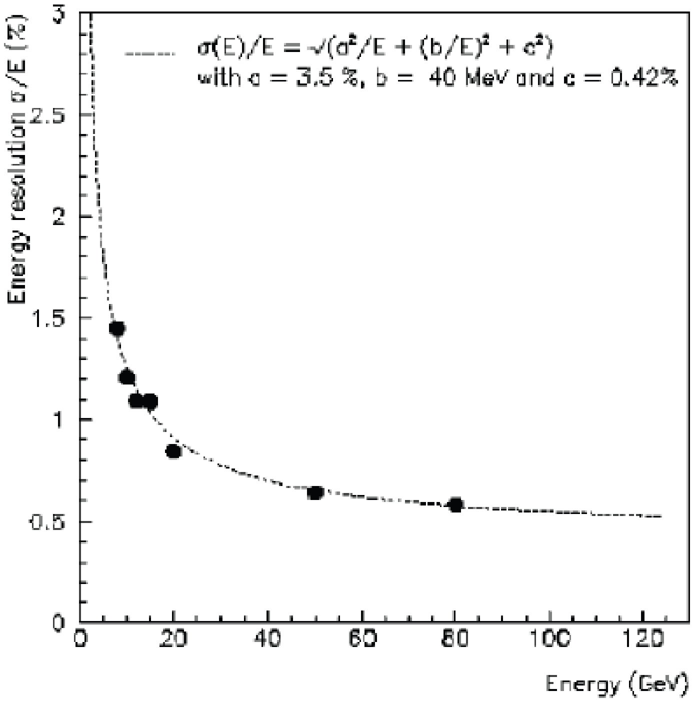
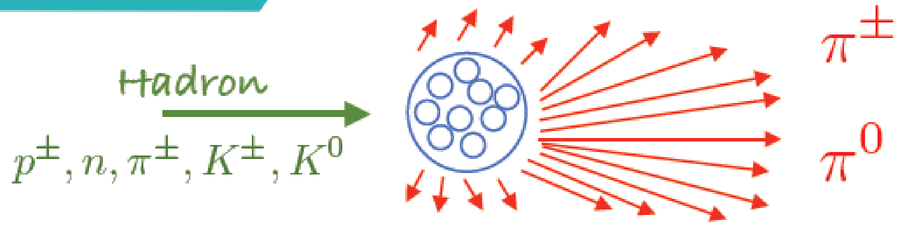


FIG. 3. Fractional electron energy resolution as a function of energy measured with a prototype of the NA48 liquid krypton electromagnetic calorimeter (NA48 Collaboration, 1995). The line is a fit to the experimental points with the form and the parameters indicated in the figure.

Hadronic Calorimetry



Hadron

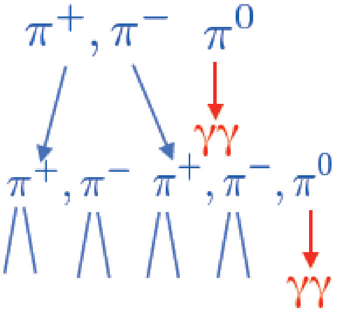
$p^\pm, n, \pi^\pm, K^\pm, K^0$

$\pi^\pm$

π^0

Strong Interaction

Approximate Energy Distribution

~50%	~20%	~30%
 π^+, π^- π^0 γγ π^+, π^- π^+, π^-, π^0 γγ Hadron Cascade	Nuclear Excitation 5-30 MeV p, n, γ	Slow Nucleons

$\pi^0 \rightarrow \gamma\gamma \rightarrow$ Electromagnetic Component

In Hadronic Cascades the longitudinal Shower is given by the Absorption Length λ_a

$$I \sim \exp^{-\frac{x}{\lambda_a}}$$

In typical Detector materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{9} \cdot 35 A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7,87	1.76cm	~17cm
Pb	11,35	0.56cm	~17cm

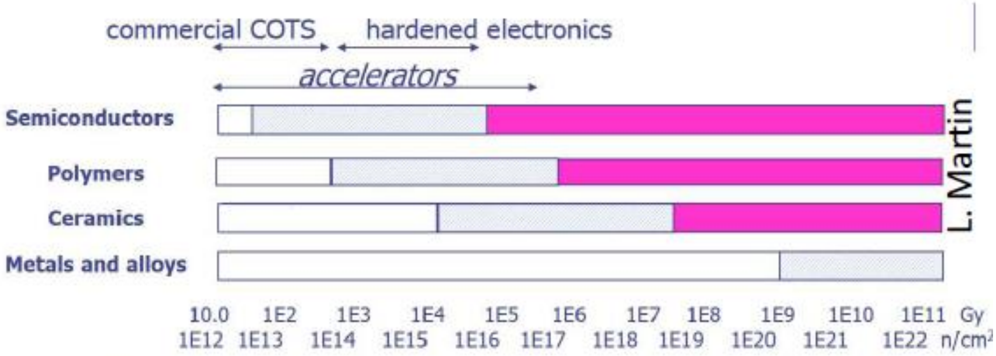
Energy Resolution:

- A large fraction of the Energy "disappears" into:
  - Binding Energy of the emitted Nucleons
  - $\pi \to \mu + \nu$ which are not absorbed
- π^0's decaying into γγ start EM Cascade ($\tau \sim 10^{-16}$s)

Energy resolution is worse than for EM Calorimeters

Characteristics and consequences

- Characteristics
  - Cumulative effects (material and electronics)
    - Effects increase with fluence
    - Reaches stable effect
    - Annealing may be possible
    - General failure will appear after integrated dose
  - Single event effects (electronics)
    - Stochastic – caused by single particle
    - Effects observed immediately
    - Frequency of effects proportional to fluence

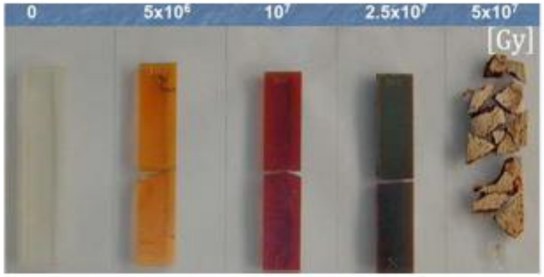


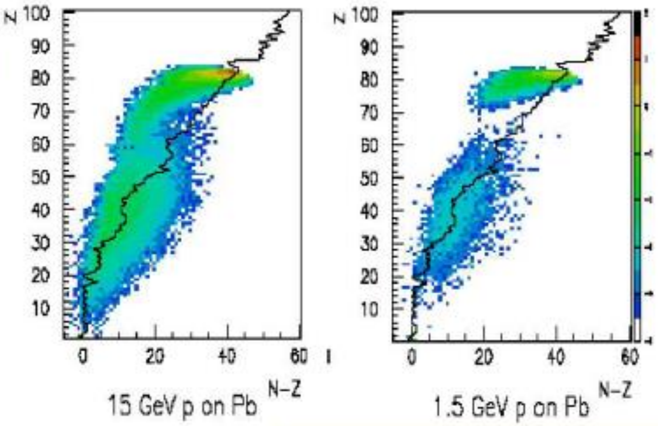
L. Martin

☐ - no damage
▨ - mild to severe damage
🟥 - destruction

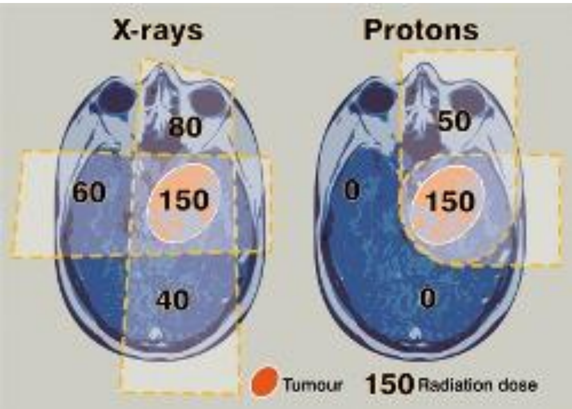
!!! Assumption !!!
(depends on particle energy spectra)
1 neutron (1MeV) /cm² ~ 3.3E-11 Gy

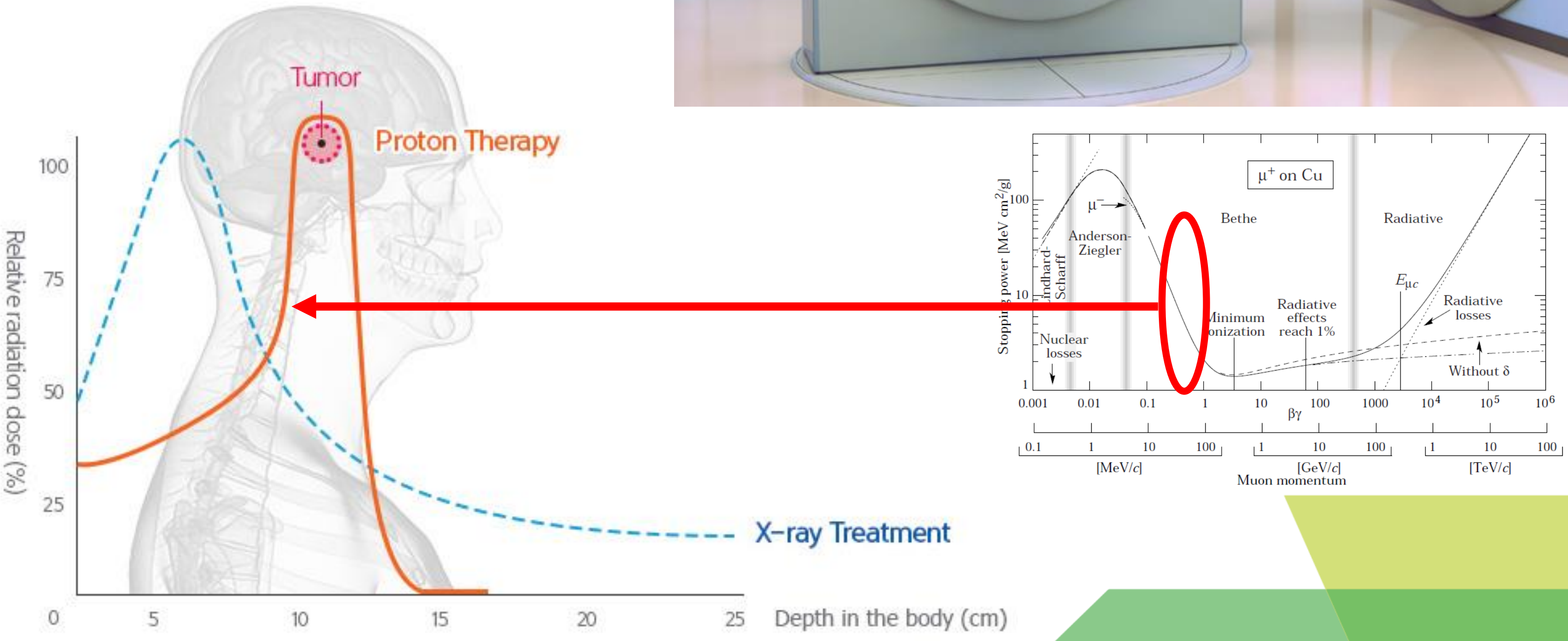
- Global consequences
  - Detector performance
  - Equipment ageing/distruction
  - Operational challenges
  - Radiation Safety
  - Environmental Hazards





Hadron therapy for oncology treatment





Modern methods of data analysis: references

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Reviews of Modern Physics, 91 (2019) 045002

2. Lectures and demonstrations on

https://machine-learning-for-physicists.org/

3. Lectures on *The Machine Learning in High Energy Physics* schools

6th in 2020, https://indico.cern.ch/event/838377/

4. Lectures by Andrey Ustyuzhanin and Nico Serra, 2018-2020

http://research.misis.ru/megascience

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

— Freeman J. Dyson, The American Mathematical Monthly 103 (1996) 800