Interactions of particles and matter, from the detector point of view

NNV visit,
September 26th 2017,
CERN, Switzerland

Collisions

- At CERN we make tiny particles such as protons, pions, ions and electrons, collide with each other;
- we observe what emerges;
- and thus get a glimpse of:
    - what is inside;
    - how strong the particles were bound together.

Collisions

- 50 km/h: superficial damage, repairable
- 90 km/h: distortion, wheel detached, injury
- 180 km/h: car disintegrated, no survivors

Energies that concern us

- The *physics* of current experiments may play in the TeV-EeV energy range,
- but the *particles* to be tracked typically have an energy of GeV to MeV,
- and *detection* relies on processes from the particle energy down to the eV, the energy of visible light.

[Top: LHC, 6.5+6.5 TeV,
Bottom: Auger Observatory 10^{17}-10^{20} eV]

Lifetime vs detector size

- Particle speed ≈ $3\ 10^8$ m/s (*c*, speed of light). On average they travel before decay: lifetime × *c* × energy/mass.

  $c\,\tau$ Lorentz factor γ

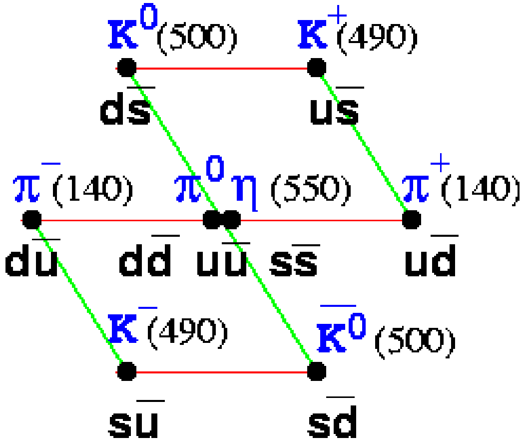
- Lifetime of a few common particles:

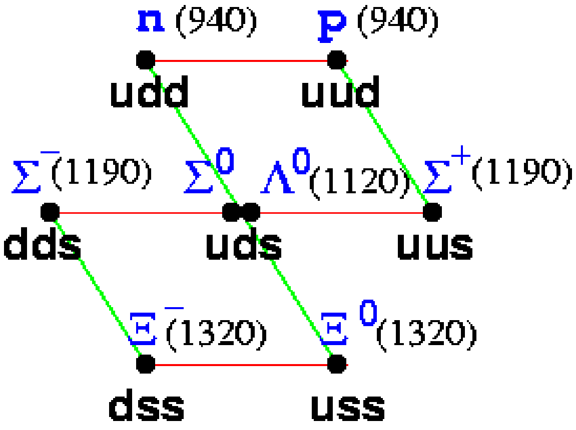
p	$> 2.1\ 10^{29}$ a	
$e^\pm$	$> 4.6\ 10^{26}$ a	
n	890 s	
$\mu^\pm$	2.2 μs	$c\tau = 660$ m (at 1 GeV: 6.3 km)
K_{long}	52 ns	
$\pi^\pm$	26 ns	
$K^\pm$	12 ns	
K_{short}	90 ps	
$D^\pm$	1.0 ps	$c\tau = 300\ \mu$m
D^0	0.41 ps	
π^0	$84\ 10^{-18}$s	

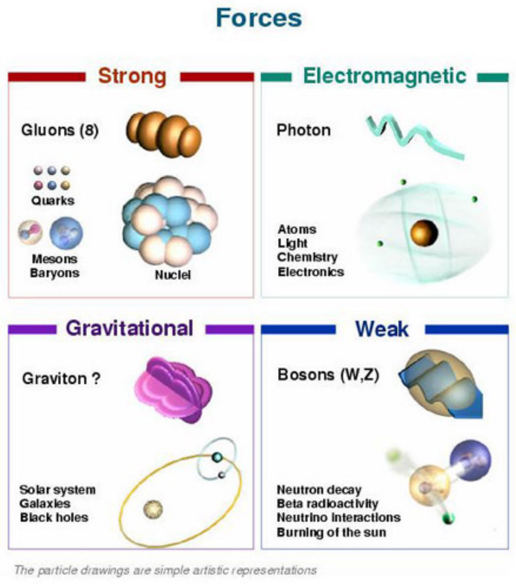
[PDG 2004]

Particles HEP tries to see

- Many decay before they can be detected.
- Remain a handful of long-lived particles:
  - gauge bosons: γ
  - leptons: $e^\pm$, $\mu^\pm$, ν_e, ν_μ
  - hadrons: p, n, π, K, ...
- Most are subject to electro-magnetic interactions, some interact also through the strong force, a few only feel the weak force.
- The gravitational force is barely detectable.







[Drawings: Mark Alford (0^- mesons, ½$^+$ baryons), ETHZ (bottom)]

Tracking ↔ interactions

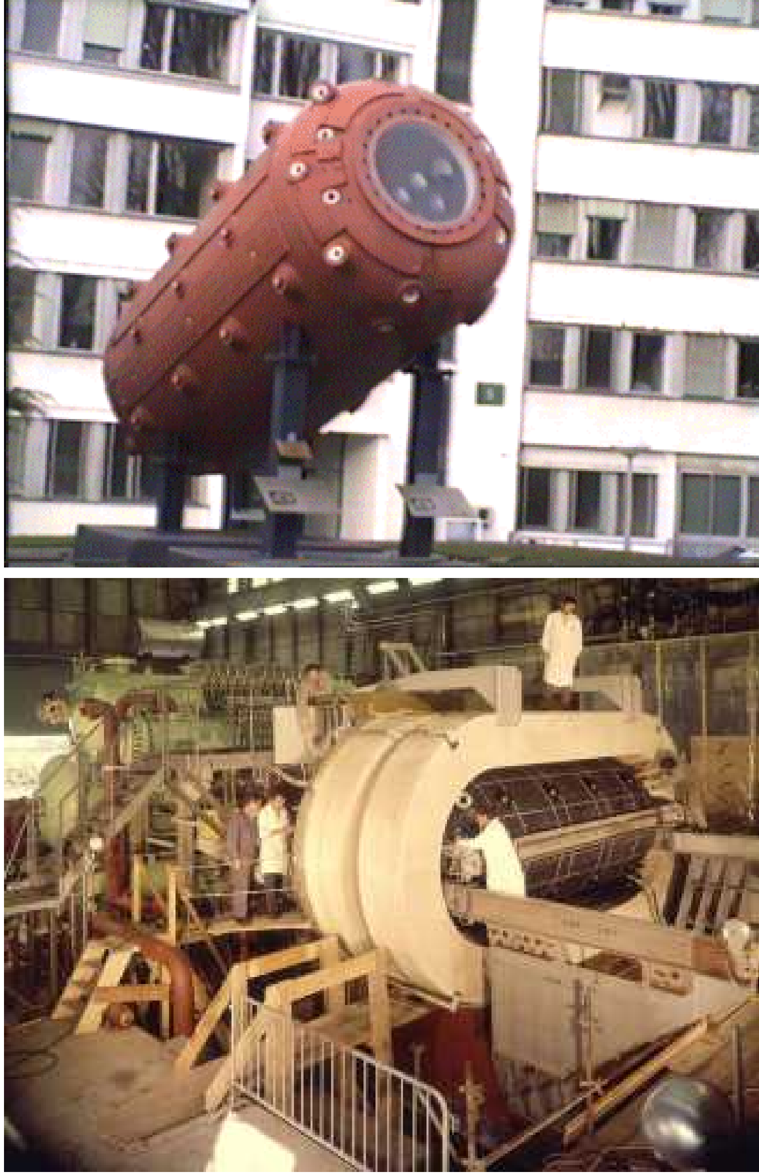
- Particles interact with the detector material they traverse.

- The interactions depend on the type and energy of the particle as well as on the matter traversed.

- These interactions
  - blur the trajectory and cause energy loss, but ...
  - they are the basis for tracking and identification.

- In this presentation, we review a few of the mechanisms.

Gargamelle



Neutrinos

- Neutrino interactions with matter are exceedingly rare.
- Interactions come in 2 kinds:
  - $W^\pm$ exchange: “charged current”
  - Z exchange: “neutral current”
- Typical reactions:

$\nu_e\, n \rightarrow p\, e^-$

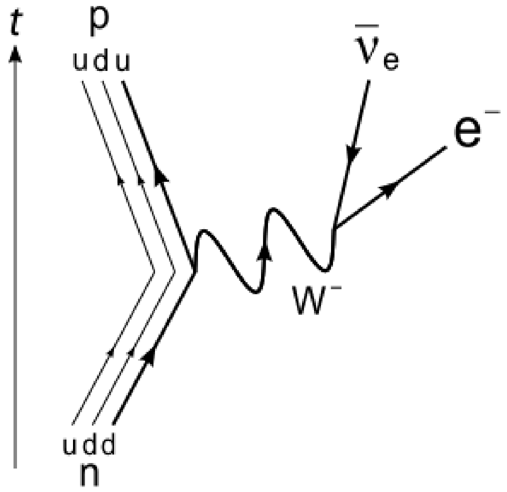
$\overline{\nu_e}\, p \rightarrow n\, e^+$ (ν proof of existence: Reines and Cowan, 1956)

$\nu_\mu \rightarrow \nu_\mu\, \mu^-\mu^+$ (in the vicinity of a nucleus, $W^\pm$ or Z)

$\overline{\nu_\mu}\, e^- \rightarrow \overline{\nu_\mu}\, e^-$ (neutral current discovery channel, 1973)

β^- decay

- How to transform a neutron into a proton ?
  - charges   d: $-\frac{1}{3}$,   u: $\frac{2}{3}$, $\nu : 0$
  - W mediates the weak force



- Check the charge balance and other conservation laws.
- Which particles can you easily detect ?
- How do you know a neutrino was there ?

Gargamelle

- Neutral current search with the Gargamelle bubble chamber:

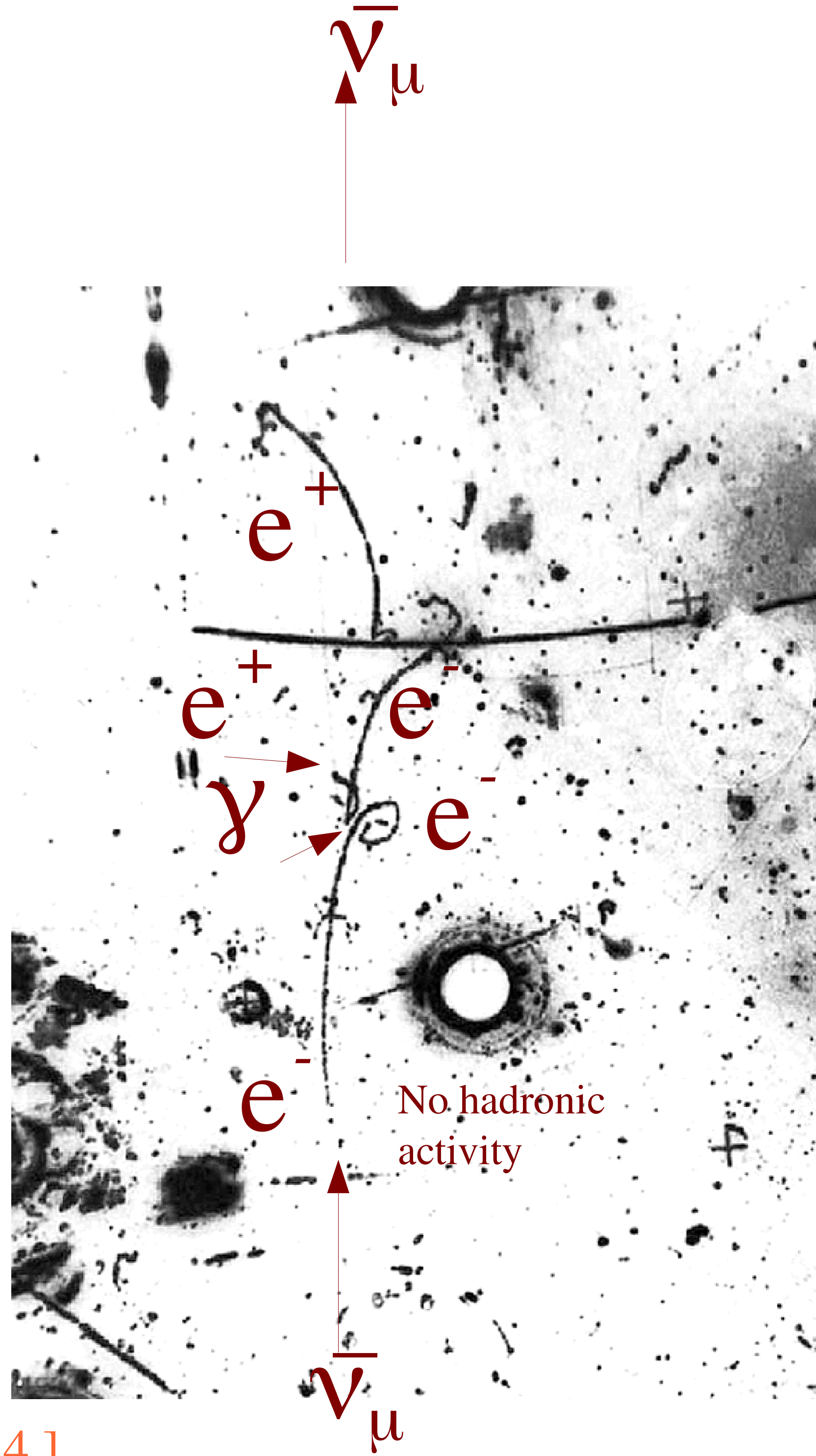
  NC: $\nu_\mu/\bar{\nu}_\mu + N \rightarrow \nu_\mu/\bar{\nu}_\mu + \text{hadrons}$

  CC: $\nu_\mu/\bar{\nu}_\mu + N \rightarrow \mu^-/\mu^+ + \text{hadrons}$

- Shown is a ν-e scattering event:

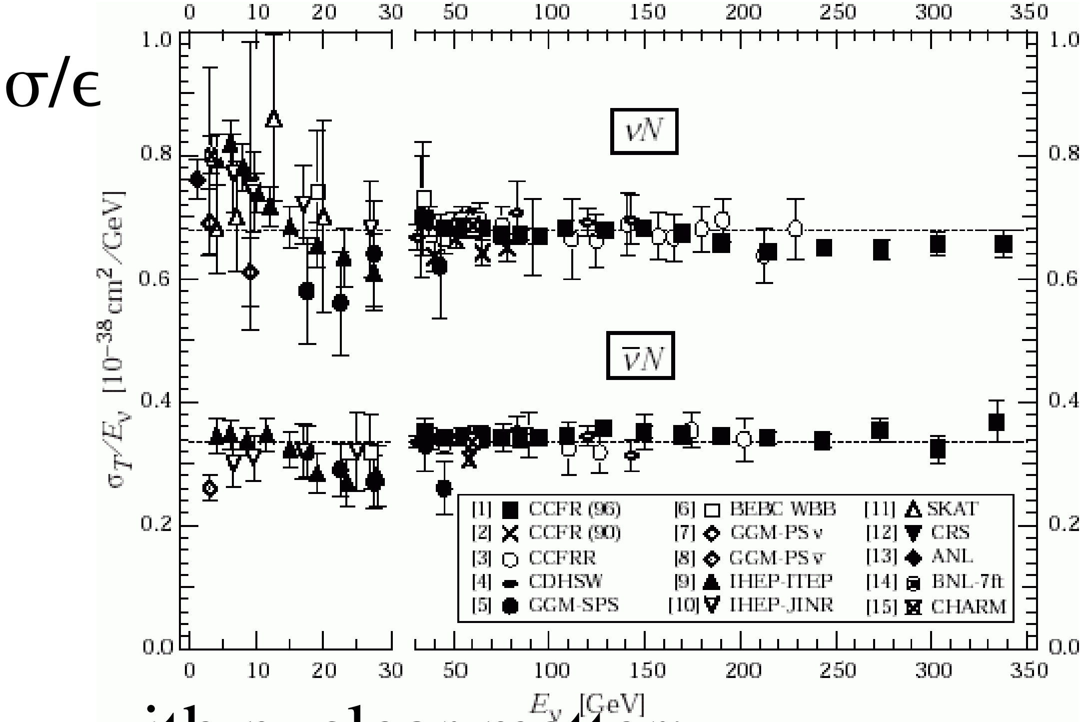
  $\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$

- One candidate found in 360,000 anti-neutrino events.



[F.J. Hasert *et al.*, Phys. Lett. **46B** (1973) 121-124.]

Cross sections ...

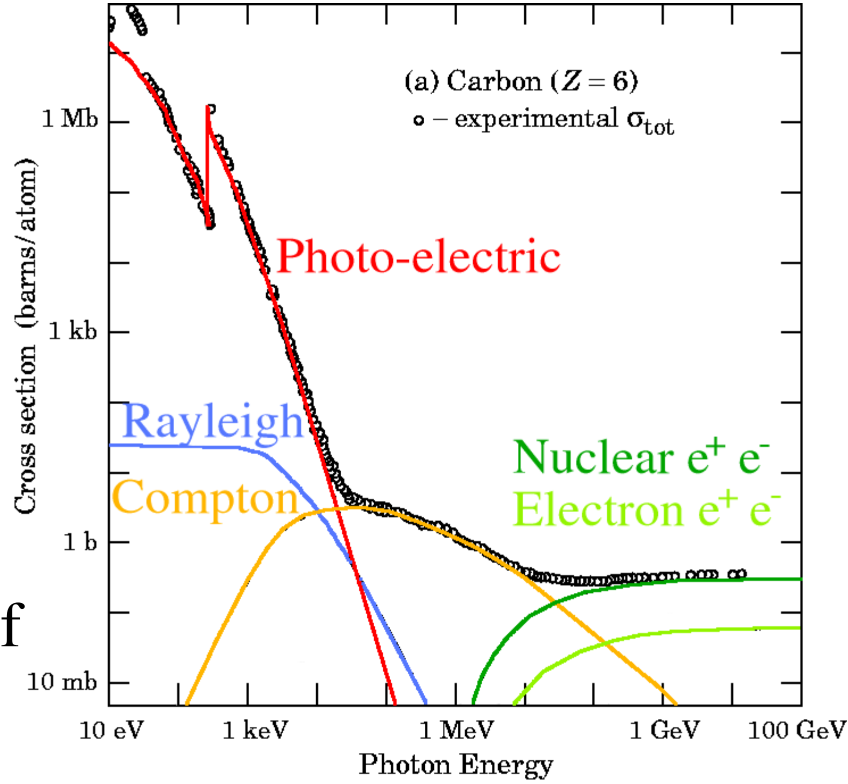


- Quantifies how easily particles hit a target.
- Example: cross section of ν_μ with nuclear matter:
  $\sigma \sim \epsilon \times 0.7 \cdot 10^{-38}\ \text{cm}^2$ (energy ϵ in GeV).
- For a ν_μ with energy $\varepsilon = 100$ GeV, a nucleon has an equivalent surface of $0.7 \cdot 10^{-36}\ \text{cm}^2$,
- Only ~0.3 % of these neutrinos is expected to scatter when going through the centre of the Earth. It takes PeV energies to make the Earth opaque.

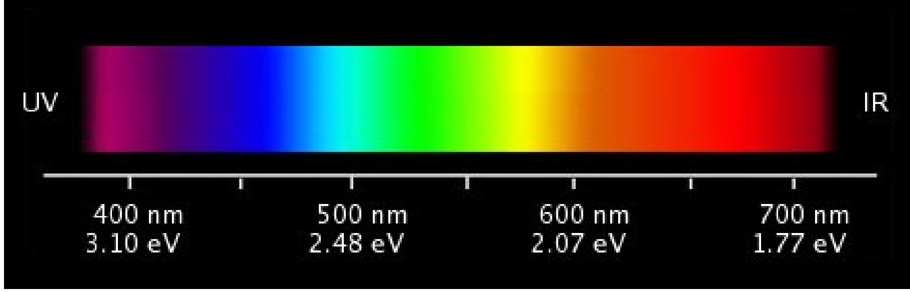
Photons

- Many photon interaction mechanisms:
  - ϵ < few eV: molecular interactions;
  - ϵ < 1 MeV: photo-electric effect;
  - ϵ < 1 MeV: Rayleigh scattering;
  - ϵ ~ 1 MeV: Compton scattering;
  - ϵ > 1 MeV: pair production;
  - ϵ > 1 MeV: nuclear interactions.

- Photons play a key role in the tracking of charged particles, even if in many cases, eventually e^- and ions produce the signal.

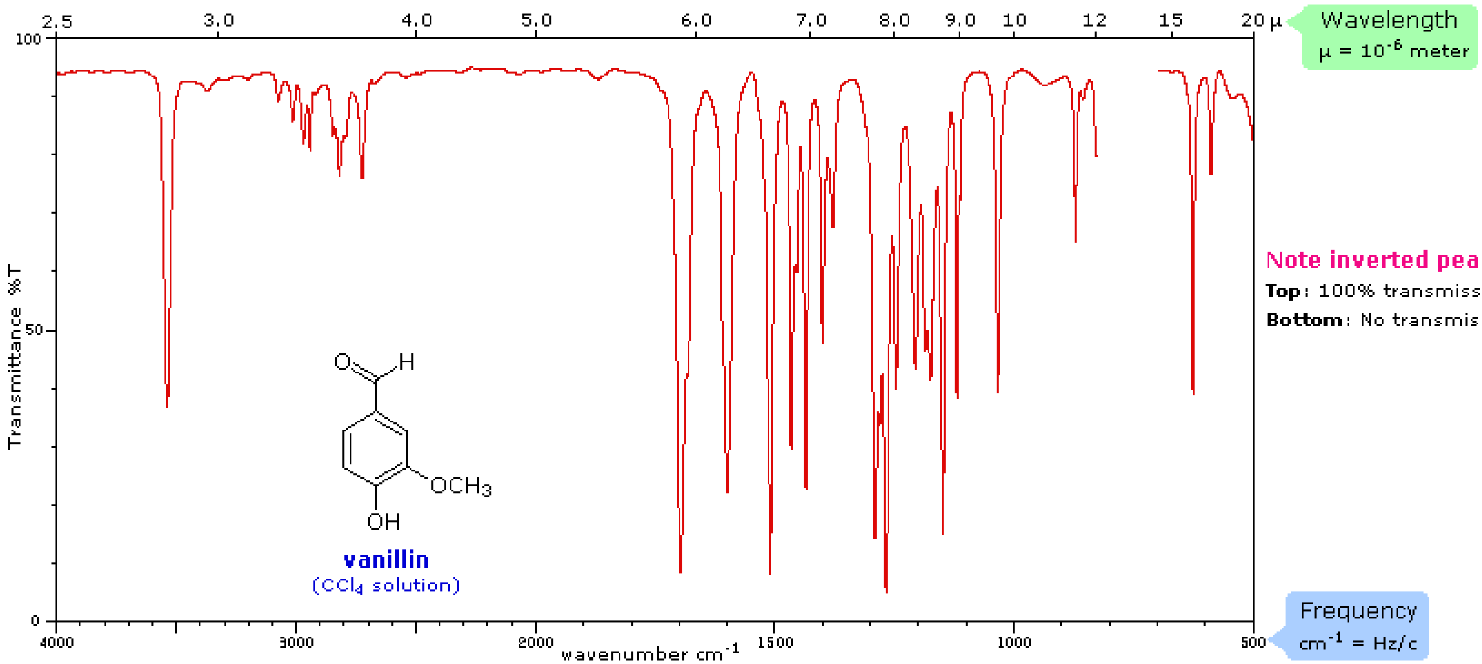


[Adapted from the PDG, 2004 edition]



Sub-eV γ's

- ϵ < 1 meV: Microwaves, molecular rotations of substances with a dipole moment (e.g. water), in a microwave oven
- ϵ < 1.8 eV: Infrared, molecular vibrations are excited



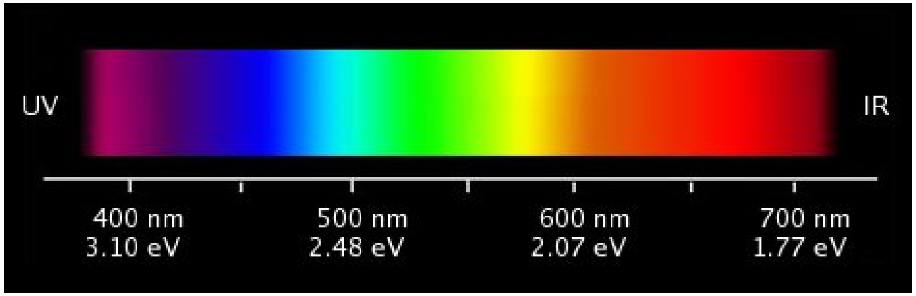
Note inverted peaks

Top: 100% transmission

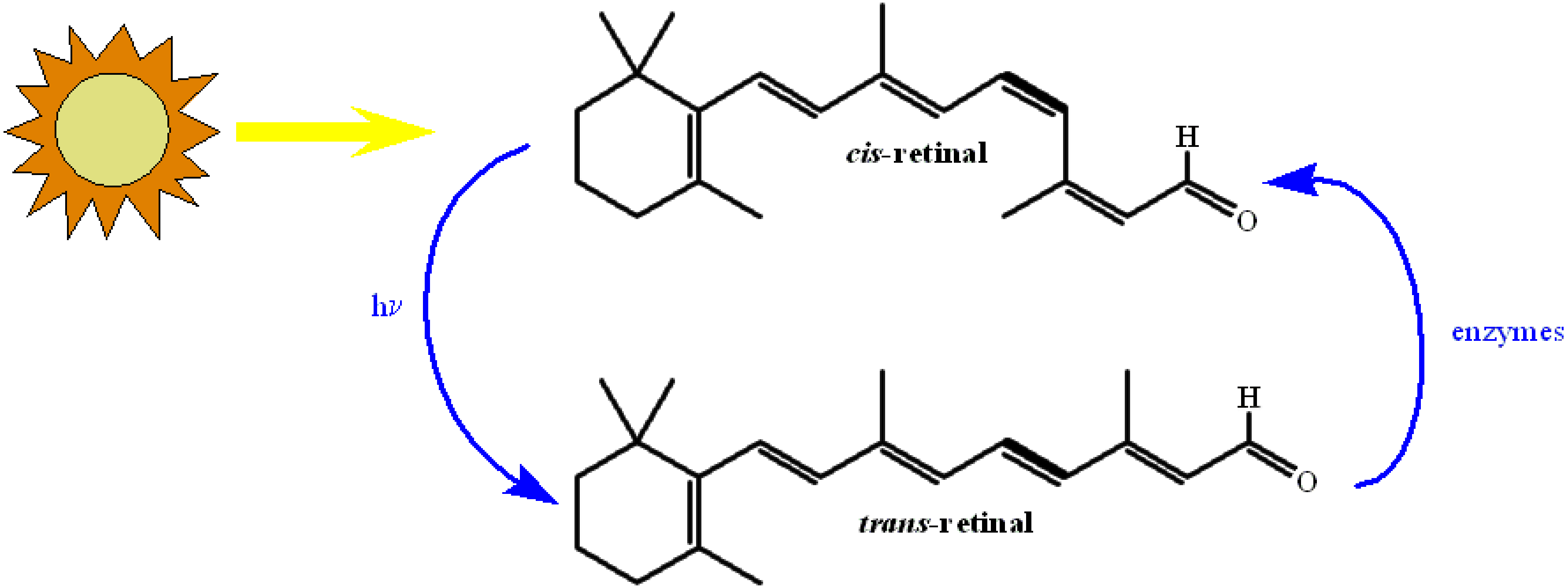
Bottom: No transmission

[From William Reusch, MSU]

eV γ's



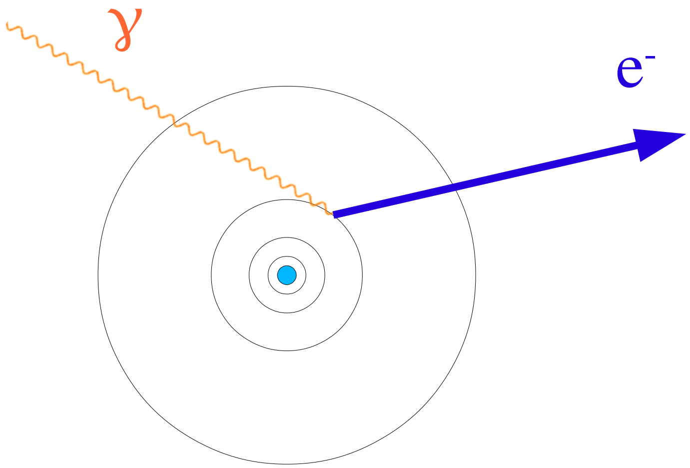
- $1.8 < \epsilon < 3$ eV: Visible light
- $\epsilon > 3$ eV: Ultraviolet: approaching excitations & ionisations



[From Kevin A. Boudreaux]

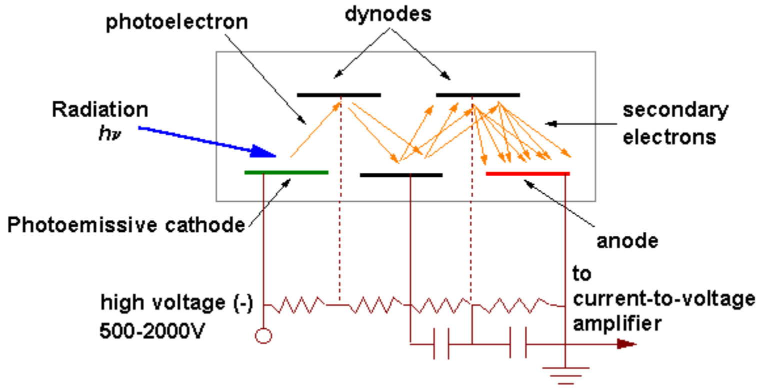
Photo-electric effect

- *The reactions up to here are of limited use for HEP purposes.*
- A γ is absorbed and a photo-electron is ejected.



- Dominant process for $\epsilon_\gamma < 10$ keV.

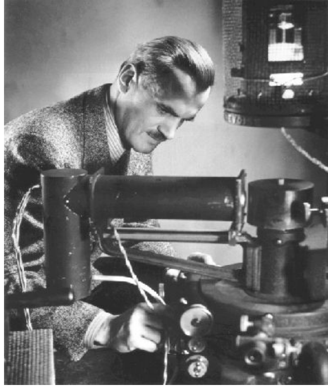
Photo-multipliers



- Photo-multipliers rely on the photo-electric effect. The cathode could be any metal, but would more likely be an alkali coating or perhaps a “p-doped GaAs with negative electron affinity through adsorption of Cs/O”.
- Such layers can have a work-function as low as 1.1 eV for multi-alkali, and 1 eV for GaAs. To be compared with Pt: 6.35 eV, Al: 4.1 eV, Cs: 2.1 eV (alkali).

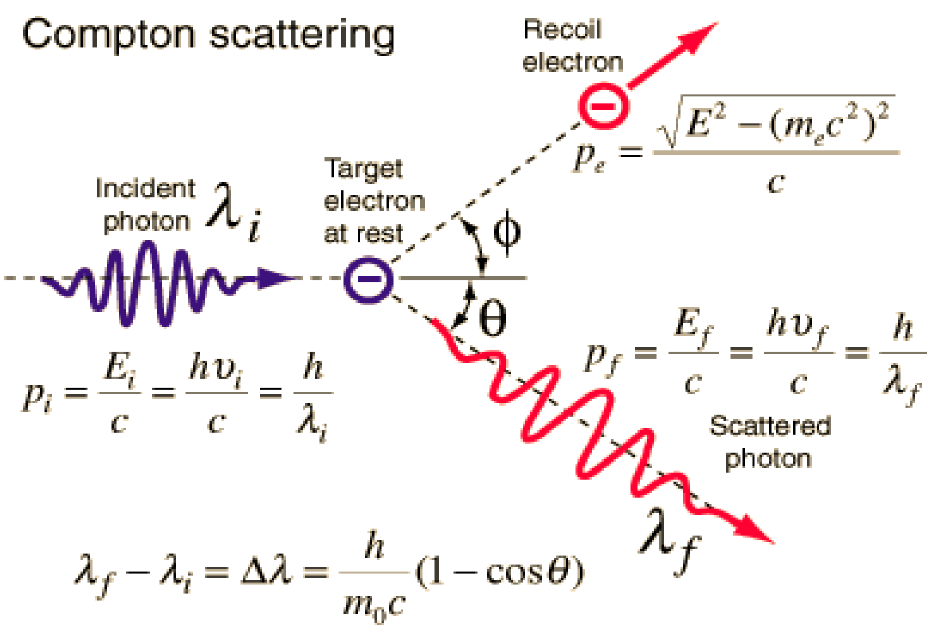
[Diagram: Brian Tissue]

Compton scattering



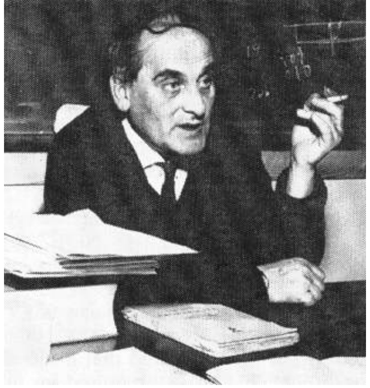
Arthur Holly Compton
(1892-1962)

- Scattering of a **γ** on an e$^-$ with transfer of *part* of the energy from the **γ** to the e$^-$.
- Sometimes called “incoherent scattering”.
- Dominant around $\epsilon_\gamma \approx 1$ MeV
- Ref: Arthur H. Compton, Phys. Rev. **21** (1923) 483 and **22** (1923) 409.



[Sketch: hyperphysics]

Pair production



Beppo Occhialini (1907-1993)

Patrick Maynard Stuart Blackett, baron Blackett (1897-1974)

- Production of an e^+e^- pair by a $\boldsymbol{\gamma}$ in the nuclear or electronic field of an atom.
- Only possible if $\epsilon_\gamma > 2\ m_e \approx 1$ MeV.
- Dominant at high energy, when the photo-electric effect and Compton scattering are small.
- Of major importance to calorimetry.

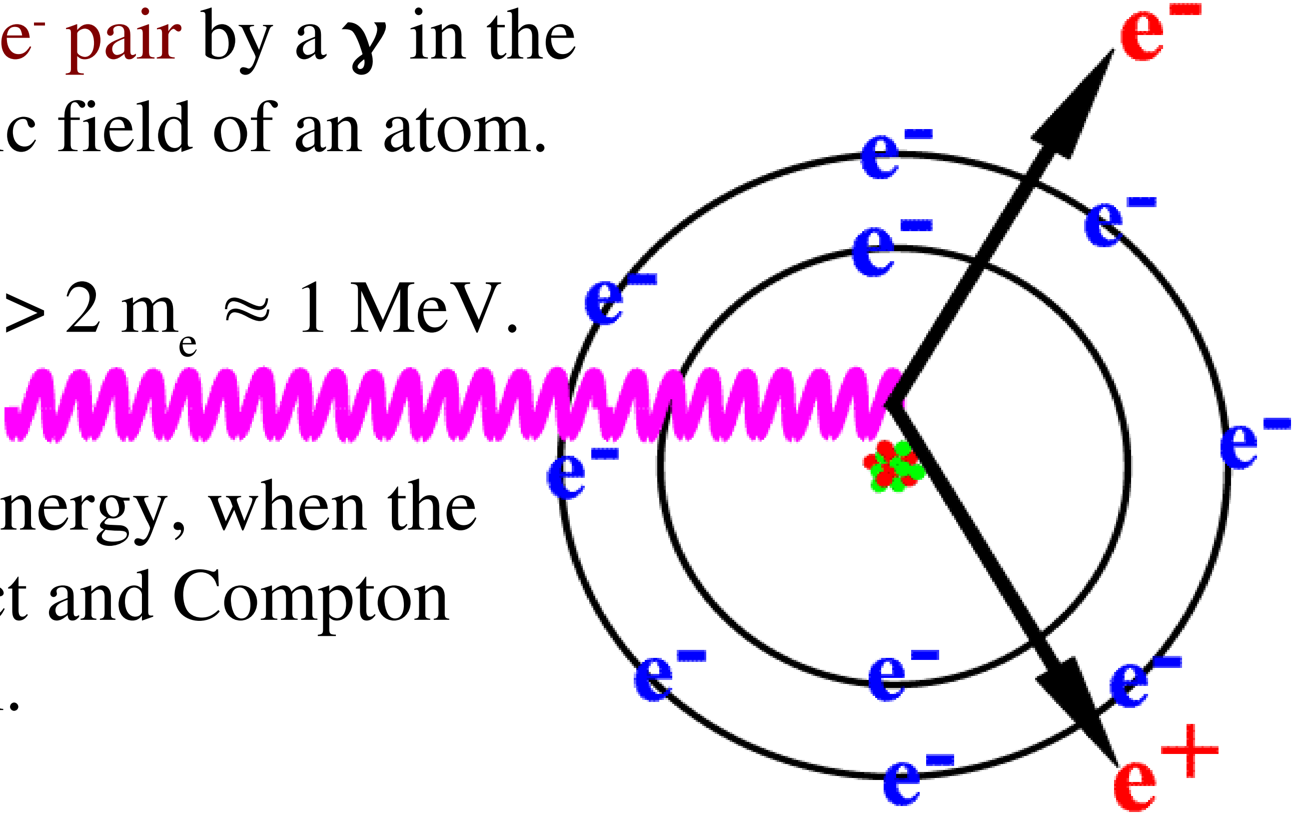
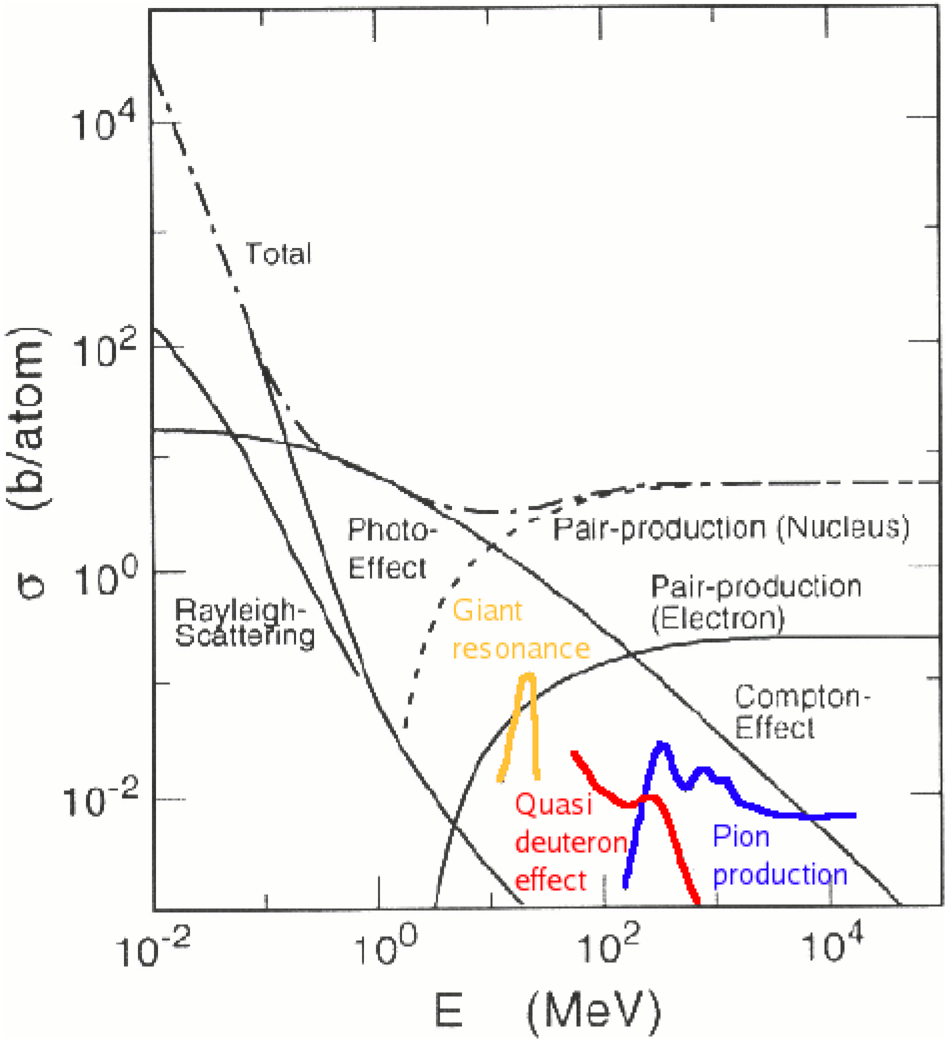


Photo-nuclear interactions

- Main nuclear terms in Cu:
  - $10 < \epsilon_\gamma < 30$ MeV:
    - giant dipole resonance
    - fission, n and γ emission
  - $30 < \epsilon_\gamma < 150$ MeV:
    - quasi-deuteron process,
    - emission of 2 nucleons
  - $\epsilon_\gamma > 150$ MeV:
    - production of *e.g.* pions
- Detection not based on e^-.



[Diagram: ANL/APS]

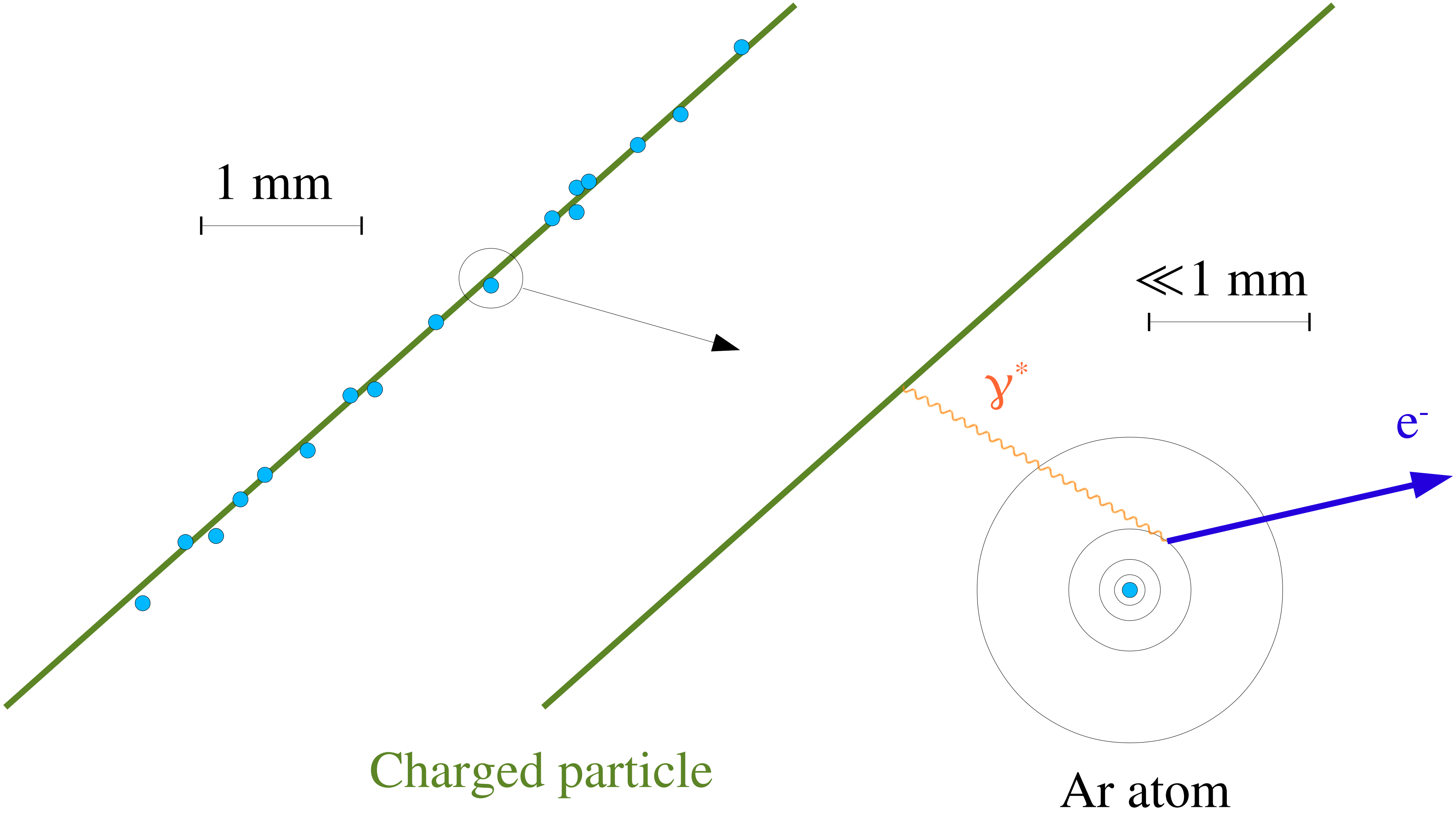
Charged particles

- Measured by tracking detectors.

- We'll discuss peculiarities of $e^\pm$ and $\mu^\pm$ separately.
- Most of the mechanisms listed here apply to $\mu^\pm$, less often to $e^\pm$.

- Principal reactions:
  - low energy: nuclear scattering effects
  - all energy: ionisations and excitations
  - $\beta > 1/n$: Черенков radiation
  - $\epsilon > 1$ GeV: inelastic nuclear interactions

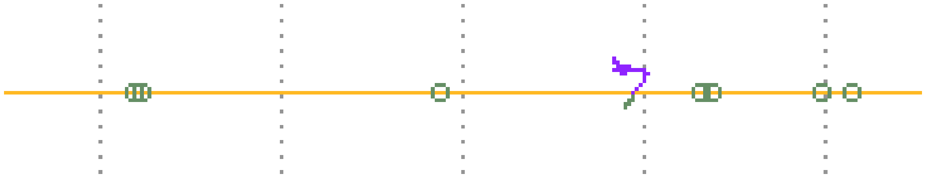
Ionisation by photon exchange (gas)



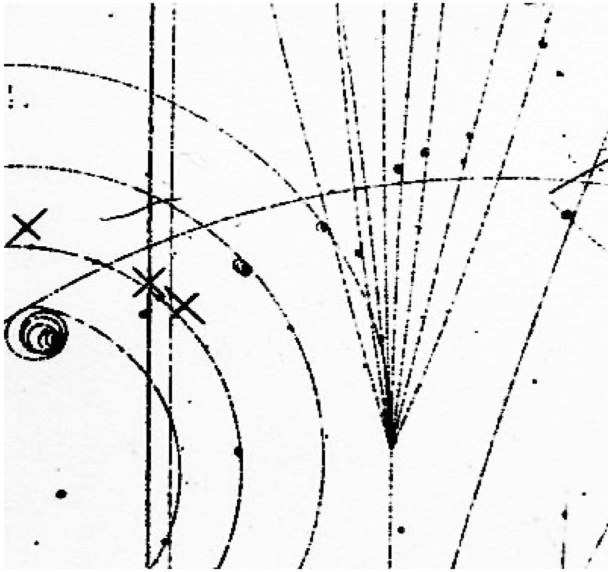
Ionisation traces

- One of the beauties of ionisation is the high density of ionising interactions – which is excellent for tracking.

- Detectors that rely on ionisation losses:
  - gas-based detectors: ~70 e^-/ion^+ pairs/cm;



Ar 93 % CO_2 7 %, 3 atm, 10 GeV μ, 1 mm of track

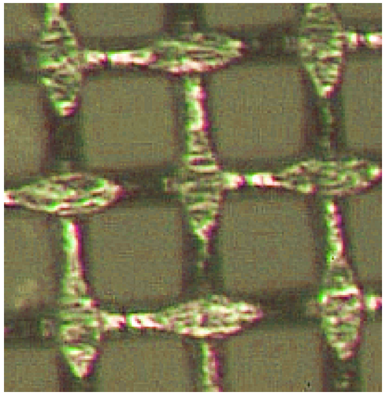


24 GeV protons on lH_2 in the 2m CERN bubble chamber (~1970)

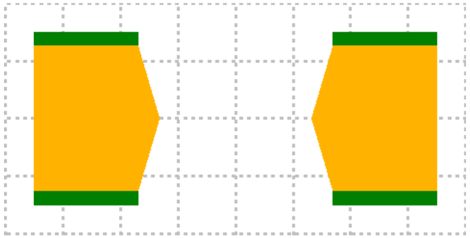
  - semiconductors: ~70 $e^-/hole^+$ pairs / μm;
  - lH_2 bubble chamber: ~100 bubbles/cm.

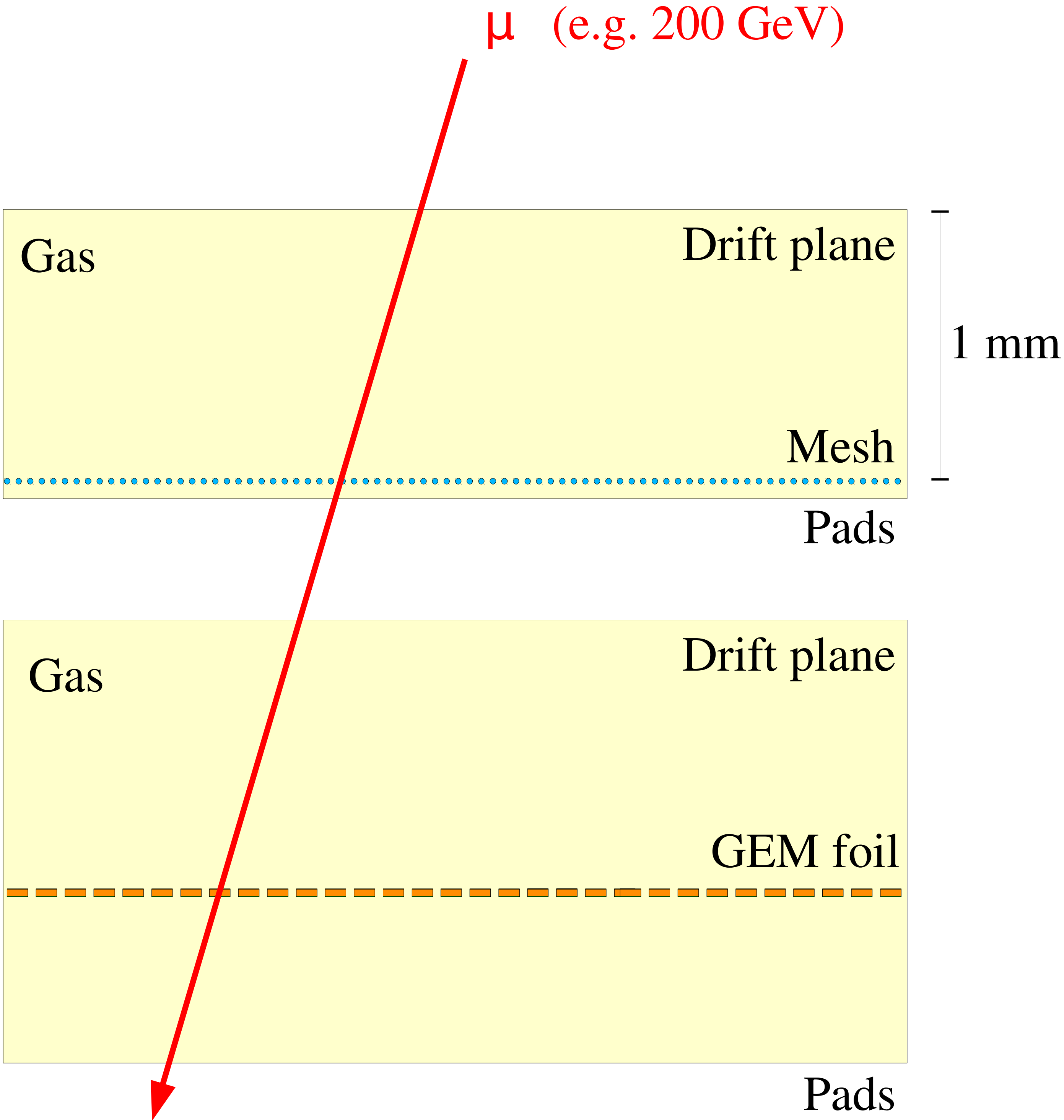
MPGDs

- Micromegas



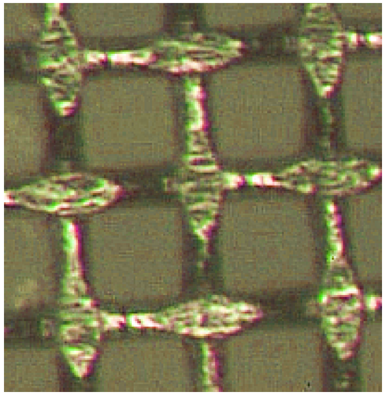
- GEM

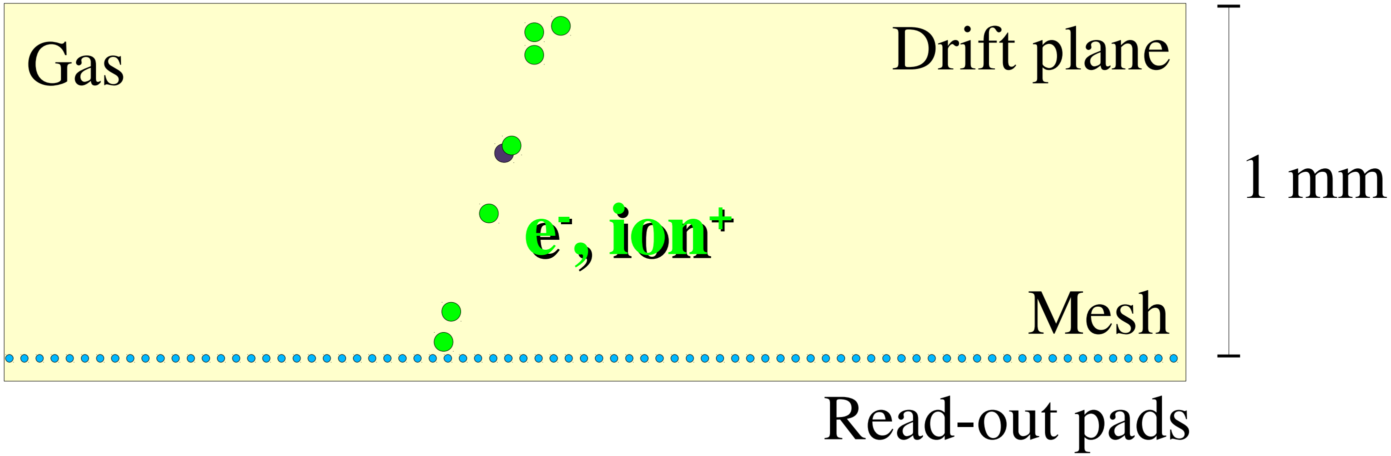




Ionisation trace

- Micromegas





Gas

Drift plane

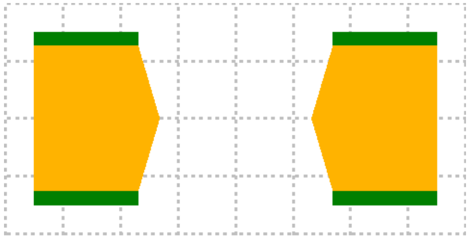
e^-, ion$^+$

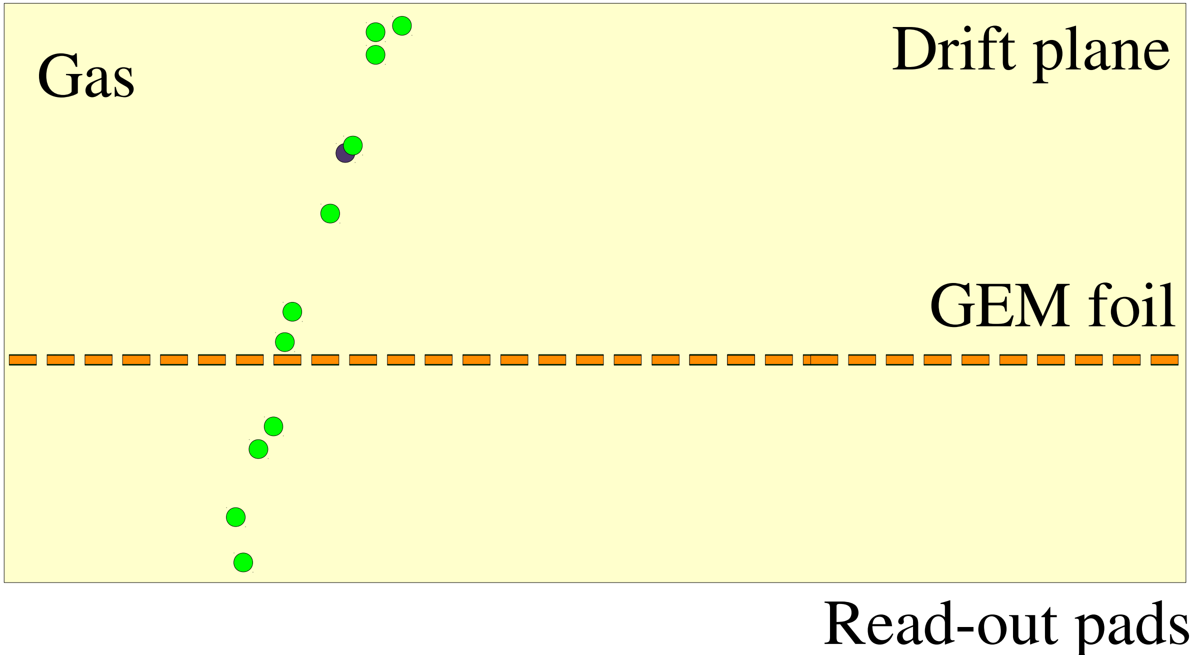
Mesh

1 mm

Read-out pads

- GEM





Gas

Drift plane

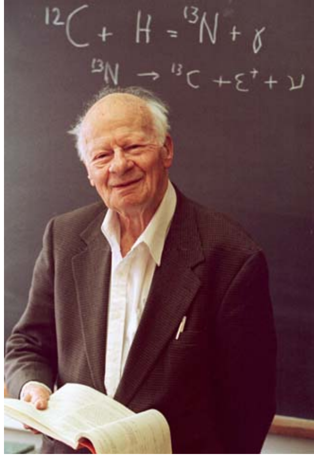
GEM foil

Read-out pads

Semiconductors

- Differences between semiconductors and gases:
  - electrons jump from the valence band (bound to an individual atom) to the conduction band (not attached to any individual atom, but still in the semiconductor);
  - energy consumed per e^-/ion$^+$ pair is larger in a gas;
  - much higher ionisation density;
  - more compact and higher resolution.

Hans Bethe
(1906-2005)



Ionisation losses: Bethe formula

- If we make the assumptions:
  - projectile mass $M \gg m$, the e$^-$ mass,
  - only Coulomb energy transfer to free e$^-$, not to the nuclei;
  - *effective* ionisation energy I < energy transfer < kinematics.

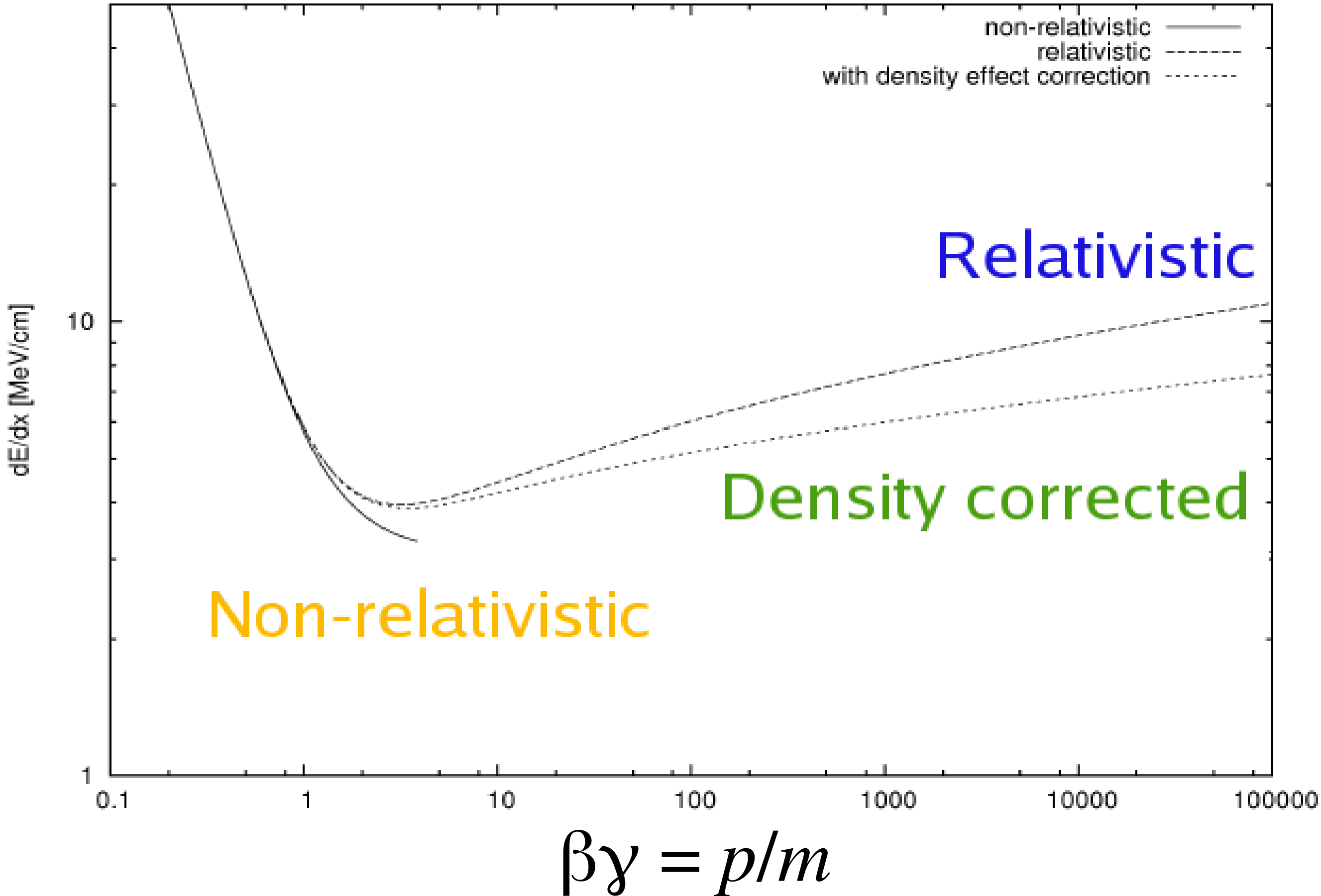
- The ionisation losses are given by (Hans Bethe formula):

$$\frac{\mathrm{d}E}{\mathrm{d}x} \propto -\frac{Z^2}{m\beta^2}\frac{z}{A}\left(\log\left(\frac{2m\beta^2\gamma^2 T_{\max}}{I}\right) - \beta^2 - \text{corrections}\right)$$

  - β, γ: velocity of projectile;
  - Z^2: projectile charge squared (i.e. independent of sign);
  - no dependence of projectile mass;
  - z and A of target (linear: number of e$^-$ encountered);
  - $T_{\max}$: highest energy that can be transferred to the target.

The Bethe formula

- Example for Si



[Diagram: Heinrich Schindler]

Features of ionisation: small losses

- A good thing with ionisation is that losses are small for high-energy particles.
  - The energy loss at the $\gamma \approx 3$ dip can be approximated by $\mathrm{d}E/\mathrm{d}x \approx 1.5$ [MeV cm^2/g] ρ [g/cm^3]
  - At higher energies, losses can be up to 50 % larger.

- Examples:
  - TPC filled with Ne gas: $\mathrm{d}E/\mathrm{d}x \approx 145$ keV/m
  - semi-conductor: $\mathrm{d}E/\mathrm{d}x \approx 25$ keV/100 μm

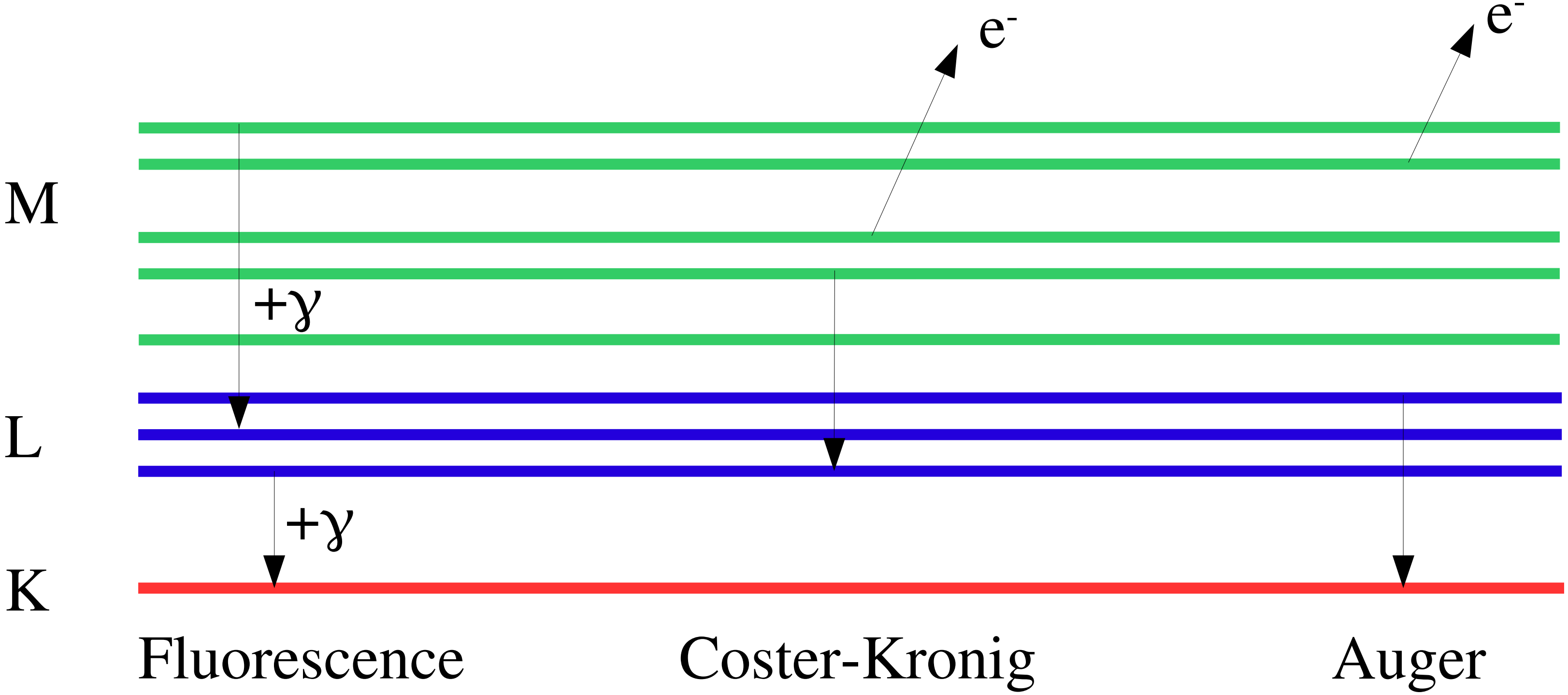
De-excitation

Ralph de Laer Kronig
(1904-1995)

Dirk Coster
(1889-1950)

Lise Meitner
(1878-1968)

Pierre Victor Auger
(1899-1993)



References:

D. Coster and R. de L. Kronig, Physica **2** (1935) 13-24.

Lise Meitner, *Über die β-Strahl-Spektra und ihren Zusammenhang mit der γ-Strahlung*, Z. Phys. **11** (1922) 35-54.

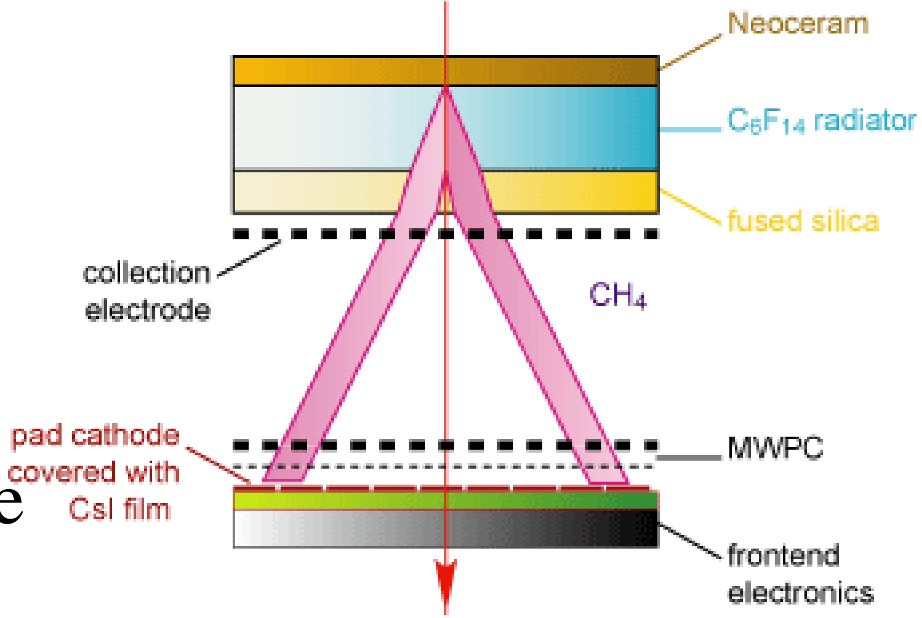
L. Meitner, *Das β-Strahlenspektrum von* UX_1 *und seine Deutung*, Z. Phys. **17** (1923) 54-66.

P. Auger, J. Phys. Radium **6** (1925) 205.

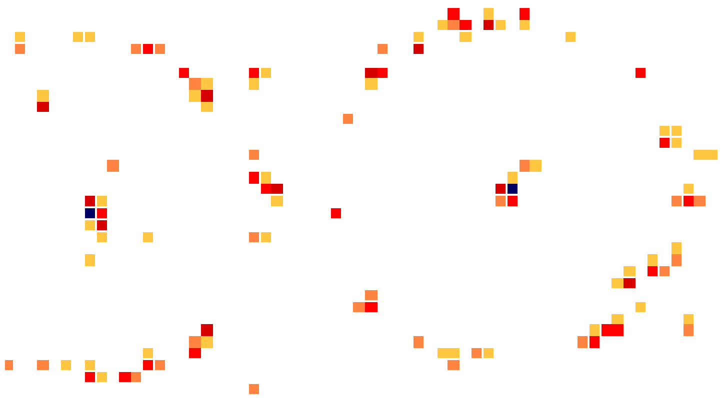
Павел Алексеевич Черенков
(1904–1990)

Черенков radiation

- Photon emission by charged particles exceeding the local phase velocity of light: $\beta n > 1$.
- *Velocity* threshold: suitable for particle identification purposes.
- Peaks at $\cos(\theta) = \beta n$, light in the blue/UV.
- A few 100 γ's/cm, energy loss is minor, smaller than ionisation, larger than transition radiation.



[Alice HMPID]



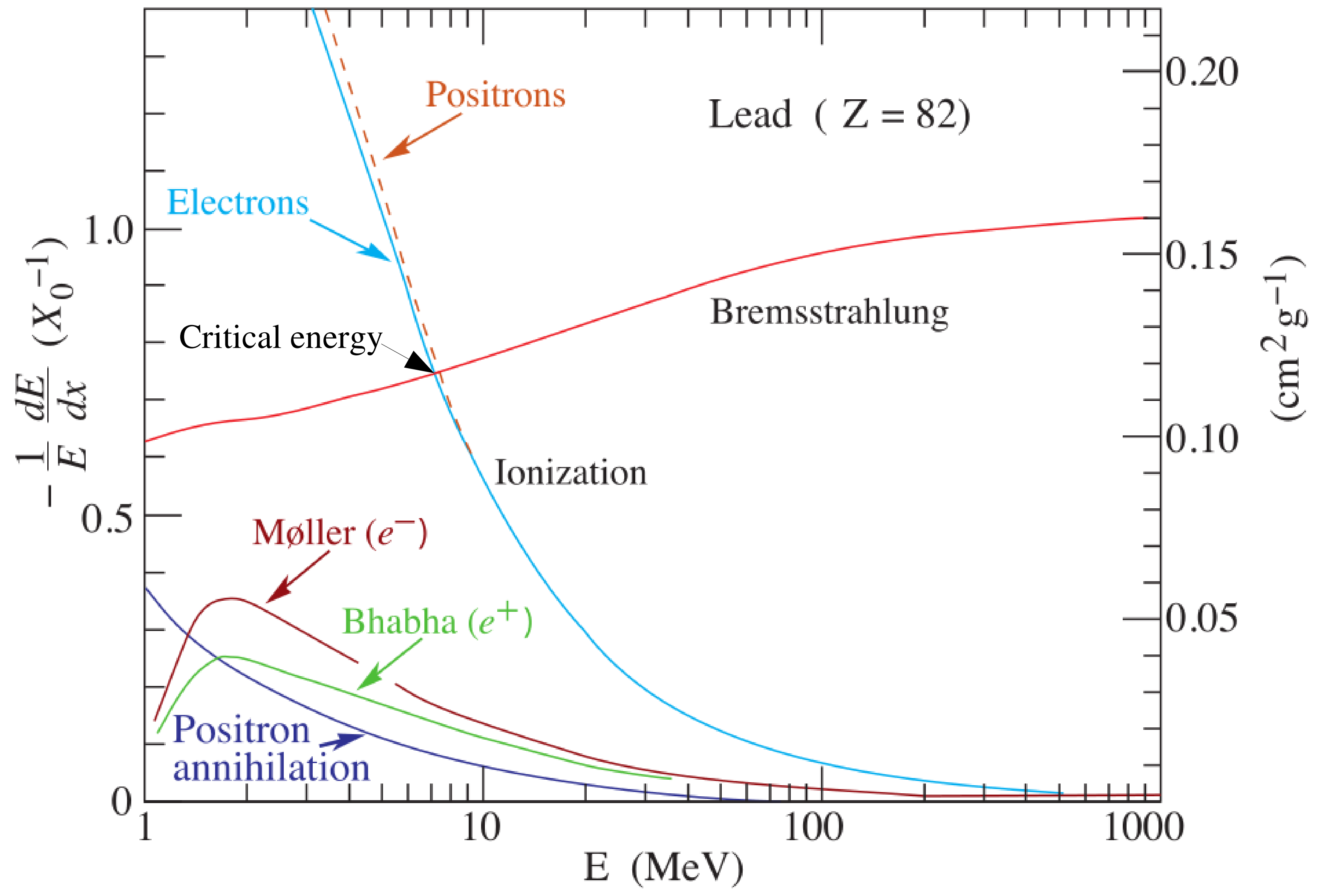
Electrons and muons

- Electrons:
  - $\epsilon < 5$ eV: elastic scattering;
  - 5 - 10 eV: elastic + inelastic scattering, excitations;
  - 10 eV-10 MeV: attachment, excitation, ionisation;
  - > 10-100 MeV: Bremsstrahlung dominates (showers !);
  - from ~1 GeV: transition radiation becomes practical.

- Muons:
  - all ϵ: multiple scattering;
  - $\epsilon < 400$ GeV: muons easily traverse material;
  - $\epsilon > 400$ GeV: Bremsstrahlung and e^+e^- pair production, EM showers, nuclear interactions.

- Note: also some generic charged particle processes apply.

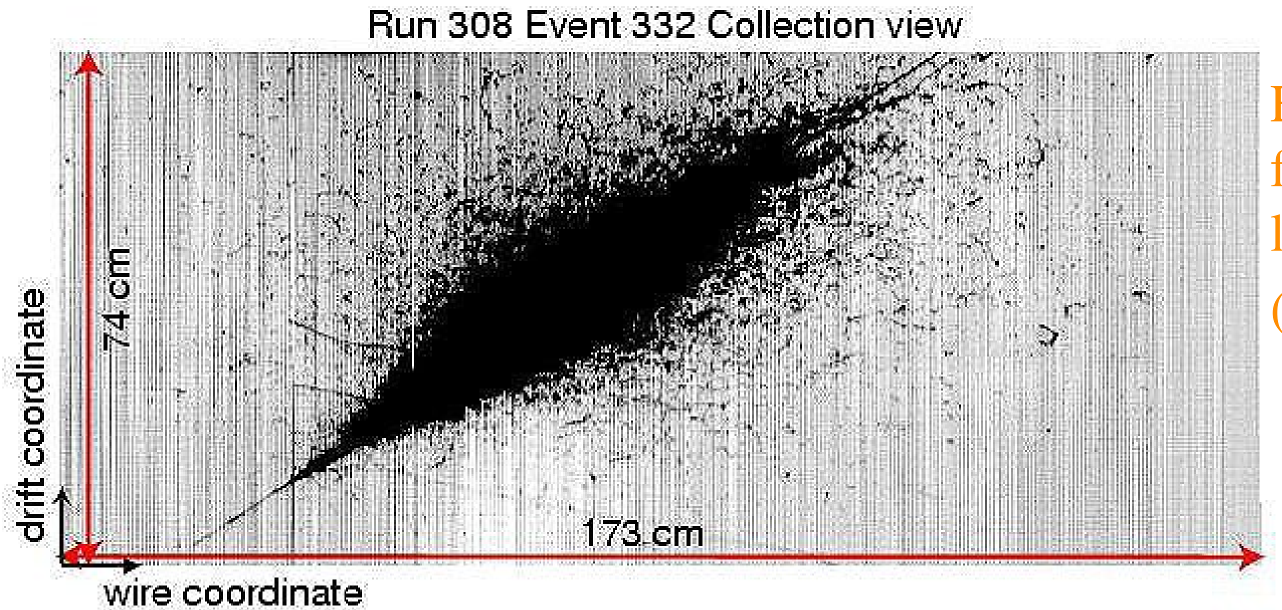
Electron (positron) energy loss



- [From PDG]

Electromagnetic showers

- At energies where Bremsstrahlung and pair production have become important, and in thick layers of material, secondary e$^-$'s and γ's re-interact, thus leading to the production of showers.
- This is a destructive detection mechanism.



Electromagnetic shower from a cosmic. Absorber: liquid Ar, $X_0 = 14$ cm. (Icarus, 2001)

Transition radiation

- 1946: Effect predicted
  [Ginzburg and Frank, Zh. Eksp. Teor. Fiz. 16 (1946) 15]
- 1956: First observed in visible light
  [P. Goldsmith and J.V. Jelley, Philos. Mag. 4 (1959) 836]
- 1957: X-ray TR predicted for high-γ particles
  [G.M. Garibian, Zh. Eksp. Teor. Fiz. 33 (1957) 1043]
- 1960s and 1970s: X-ray TR observed with e^-
- 1970s: First practical use
  [e.g. J. Cobb *et al.*, NIM 140 (1977) 413-427]

Mikael Leonovich
Ter-Mikaelian
(1923–2004)

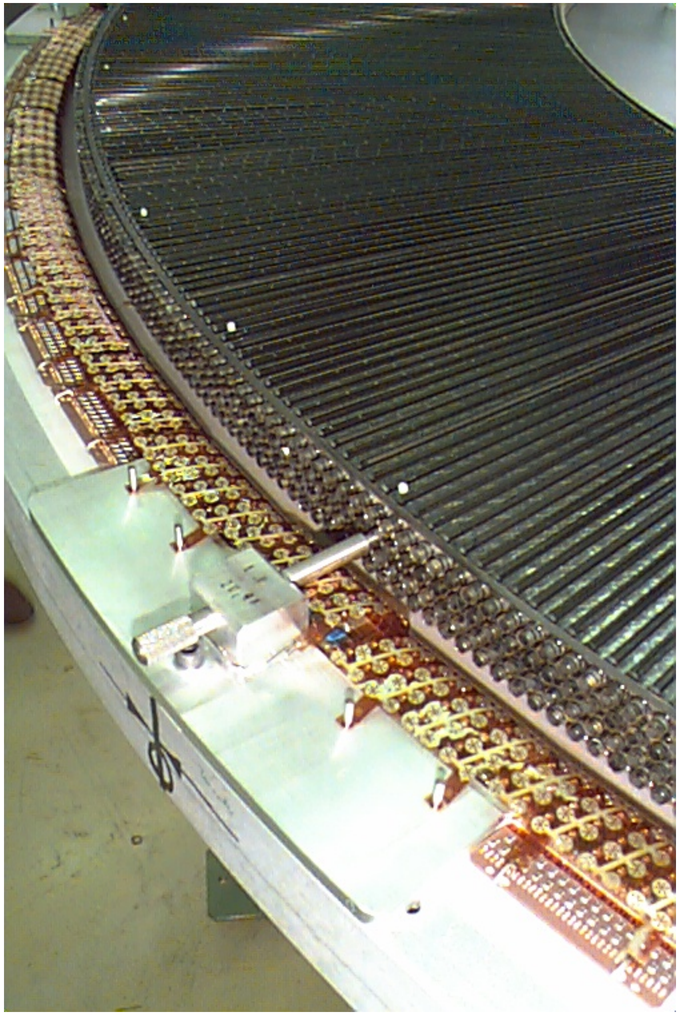
Борис Долгошеин
(1930 – 2010)

Transition radiation: e^- identification

- Transition radiation is emitted by charged particles crossing boundaries between materials with different ϵ.

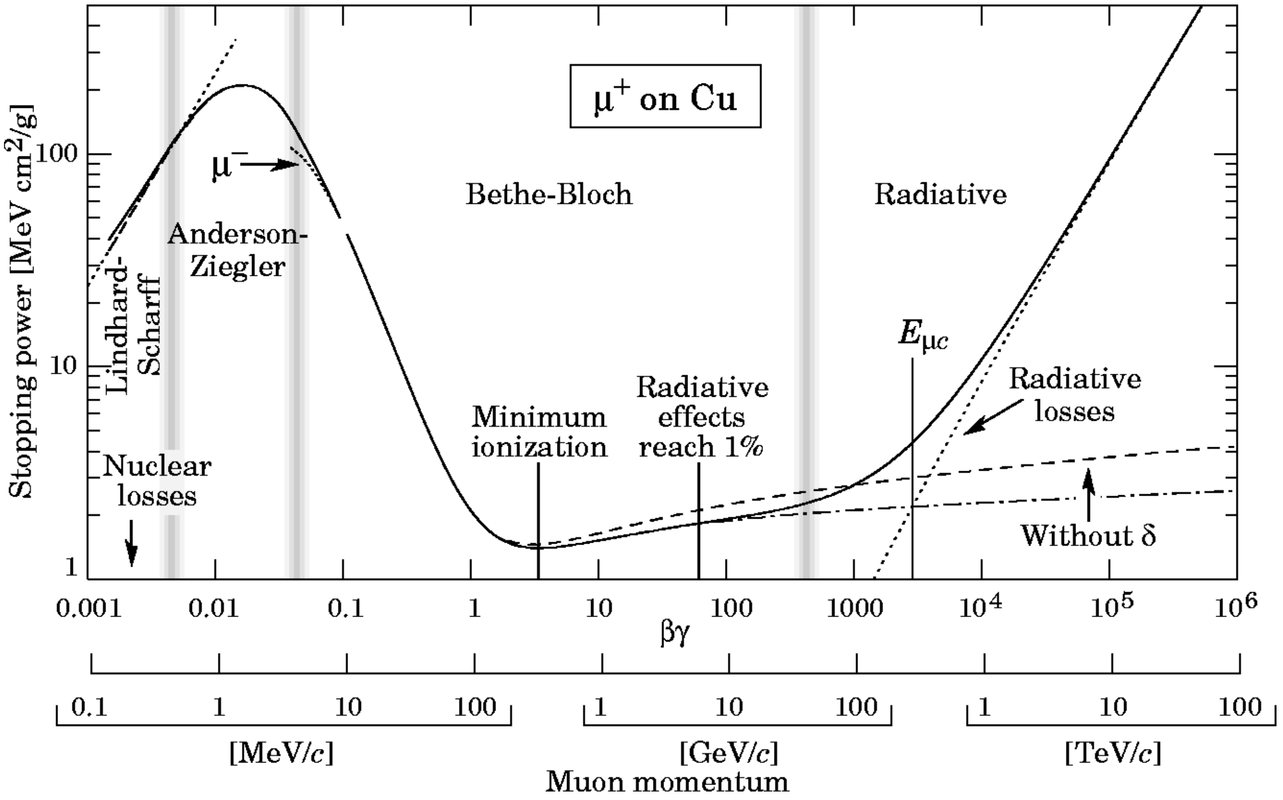
- A particularly subtle effect: very low photon yield, which moreover tends to be concentrated at low (keV) energies.

- The energy loss is $\propto \gamma = \log E/m$, e^- are distinguished from hadrons at equal E, up to ~100 GeV.



$\mu^{\pm}$ energy losses

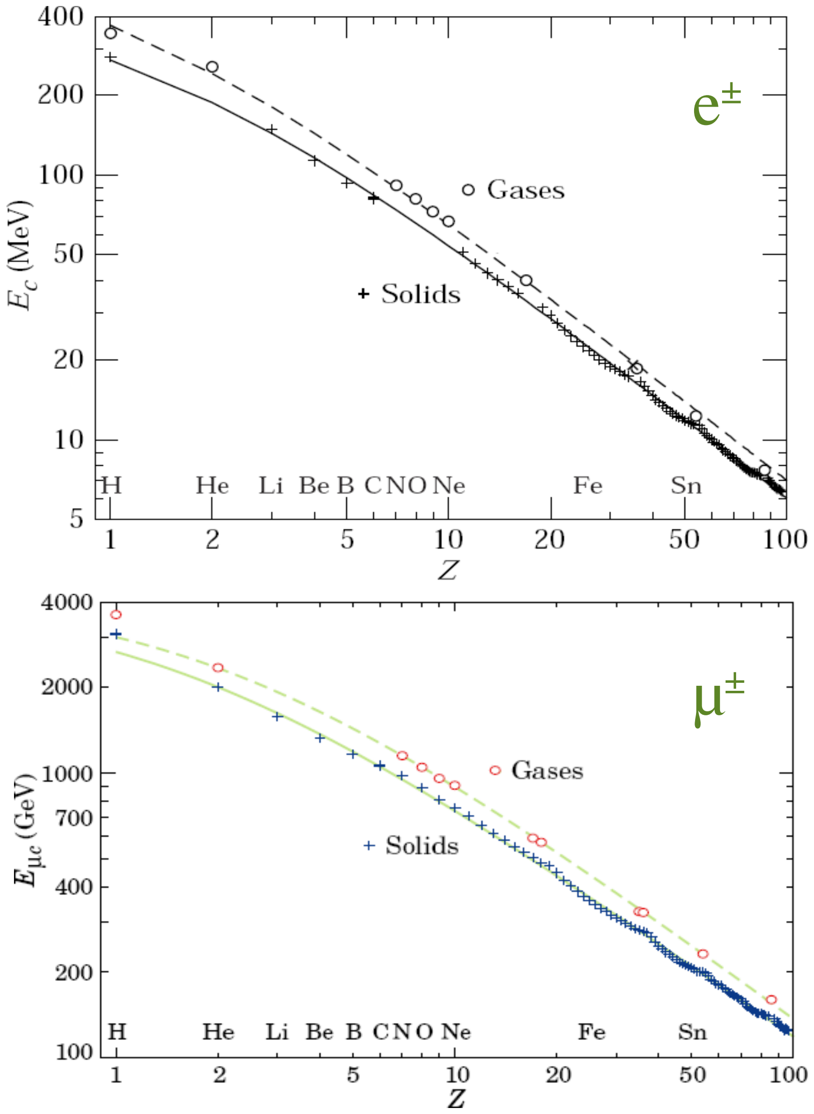
- Muons behave like other charged particles, except that they do not like hadronic interactions.
- We're usually concerned with MeV-GeV energies for which ionisation losses dominate.



[Reproduced from the PDG, 2004 edition]

Why do μ± penetrate so easily ?

- Few nuclear interactions (*cf.* π±).
- μ± Bremsstrahlung starts at a few 100 GeV, much higher than e± and losses proportional to ~~ $1/m^4$ and $m_\mu \sim 200\, m_e$;
- observed in cosmic showers; until recently, of minor importance for laboratory generated μ± but occurs at LHC.

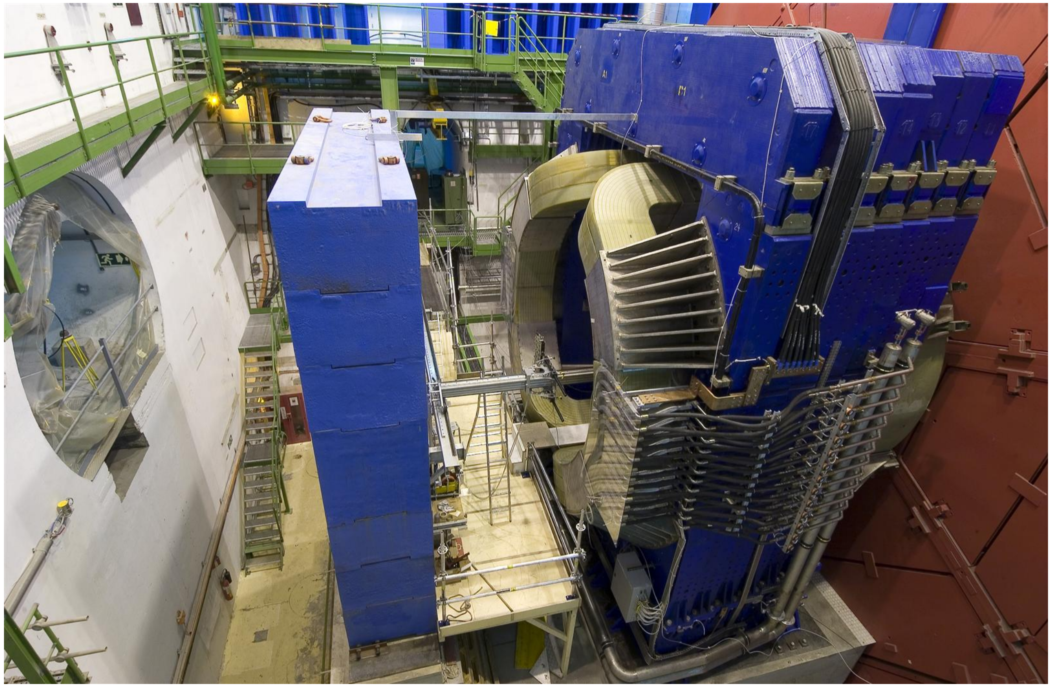


[Plots based on data computed by A. Fassò]

Identifying $\mu^{\pm}$

- Thick walls of material are used to separate $\pi^{\pm}$ and $\mu^{\pm}$.
- At the LHC, the highest energy $\mu^{\pm}$ no longer penetrate as easily !

Dipole magnet

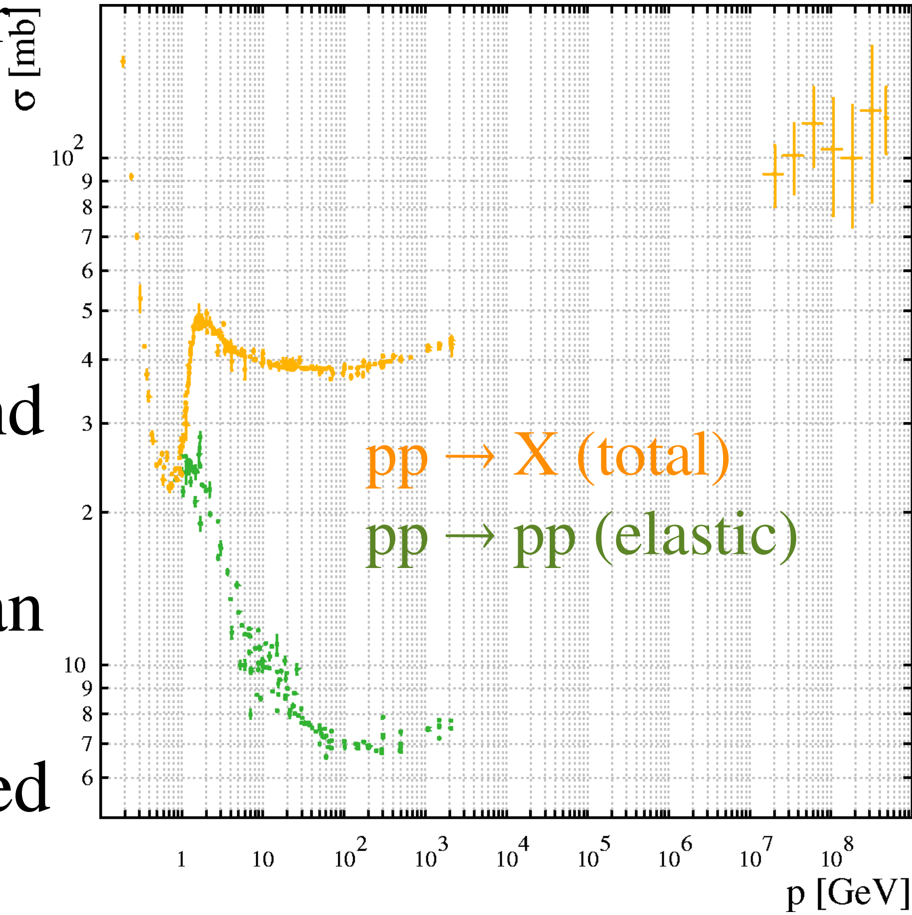


Muon wall

[Part of the Alice muon system]

Hadronic interactions

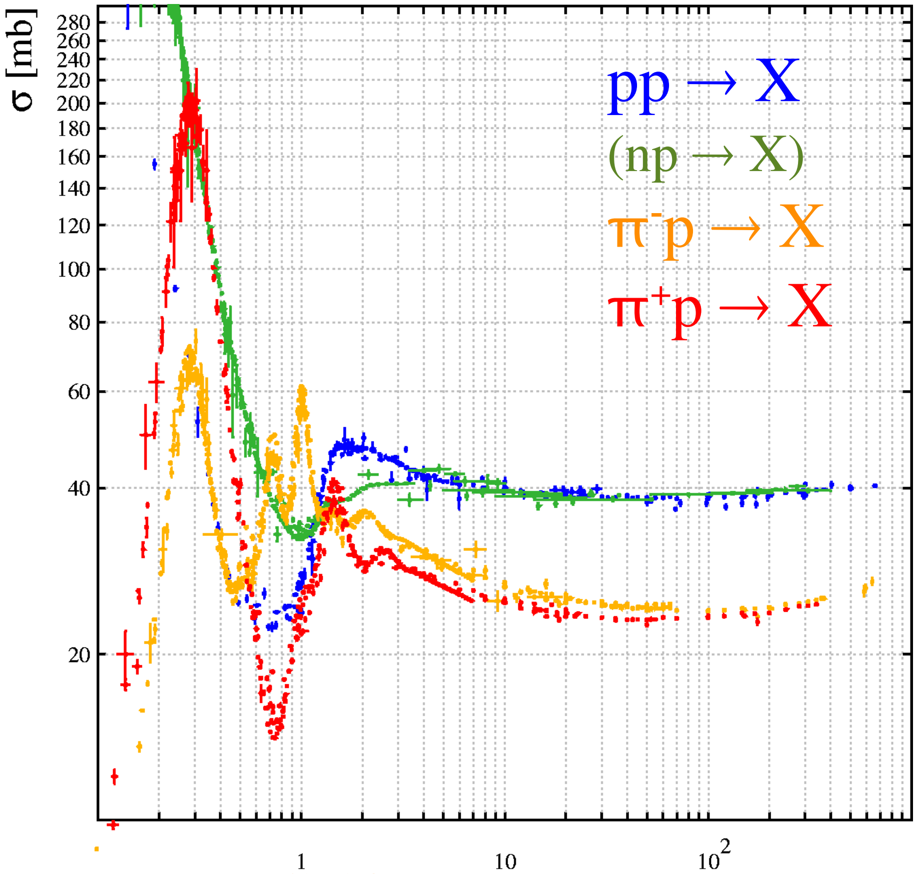
- $p_{\text{lab}} <$ few MeV: Coulomb barrier preventing inelastic p collisions;
- $p_{\text{lab}} \sim$ 1 GeV: pp cross section largely elastic;
- $p_{\text{lab}} \sim$ few GeV: fragmentation and isotope production;
- higher momenta: inelastic with an elastic part ~10-20 % in pp;
- elastic scattering is not much used for tracking.



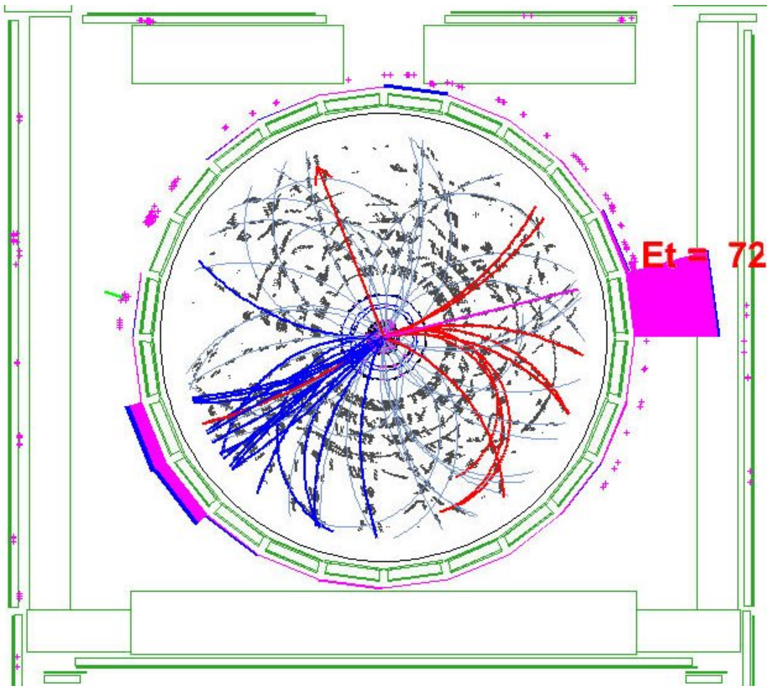
Data compiled from numerous sources by the COMPAS group, IHEP (2003).

Hadronic interactions: inelastic part

- $p_{\mathrm{lab}} > 1$ GeV: inelastic + elastic, quasi-elastic and coherent
- Compare: $r_{\mathrm{proton}} \sim 0.85\ 10^{-15}$ m with $\sigma_{pp} \sim 40$ mb



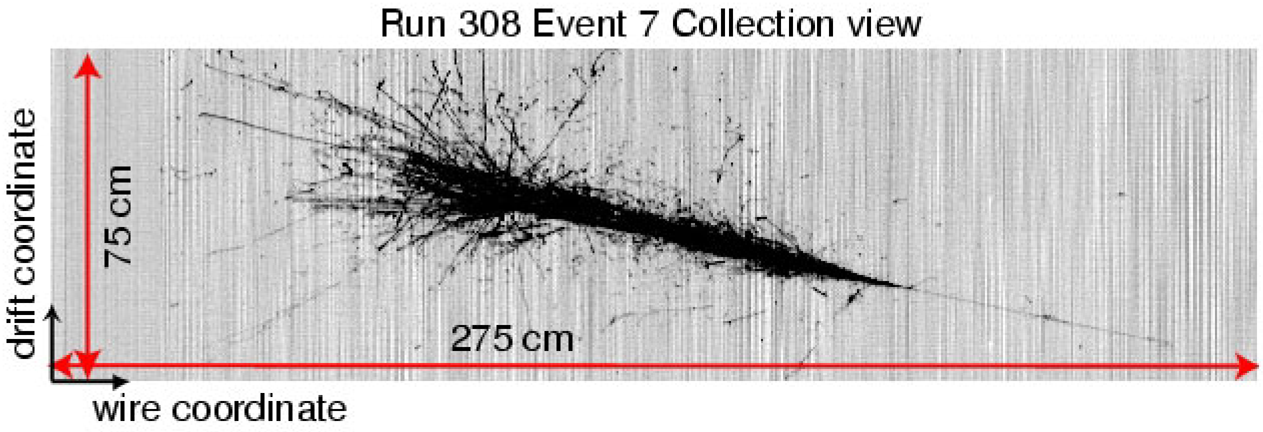
Data compiled from numerous sources by the COMPAS group, IHEP (2003).



Single top quark event candidate
$\sqrt{s}$ = 1.96 TeV (CDF, 2009)

Hadronic showers

- Hadrons traversing a thick layer of material, may start a shower – the basis of hadronic calorimetry.
- Calorimetry is a prime example of a destructive tracking technique.



Hadronic shower from a cosmic observed in Icarus.
Absorber: liquid Ar, $\lambda = 84$ cm (2001)

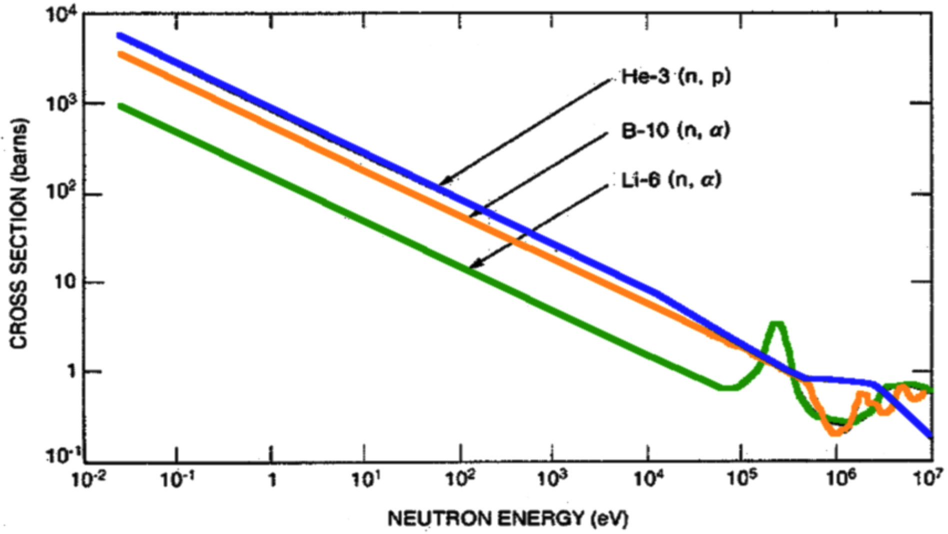
Neutrons

- $\epsilon < 0.1$ MeV: (n,p), (n,α), capture, fission in suitable materials; unlike p, no Coulomb barrier;
- $\epsilon \sim 1$ GeV: elastic scattering, in suitable materials recoils and charged particle-production;
- $\epsilon > 1$ GeV: mainly nuclear interactions.

Neutron detection – MeV range

- Neutrons are neutral – only nuclear interactions.
- Penetrate deep into materials, excellent for diagnostics.

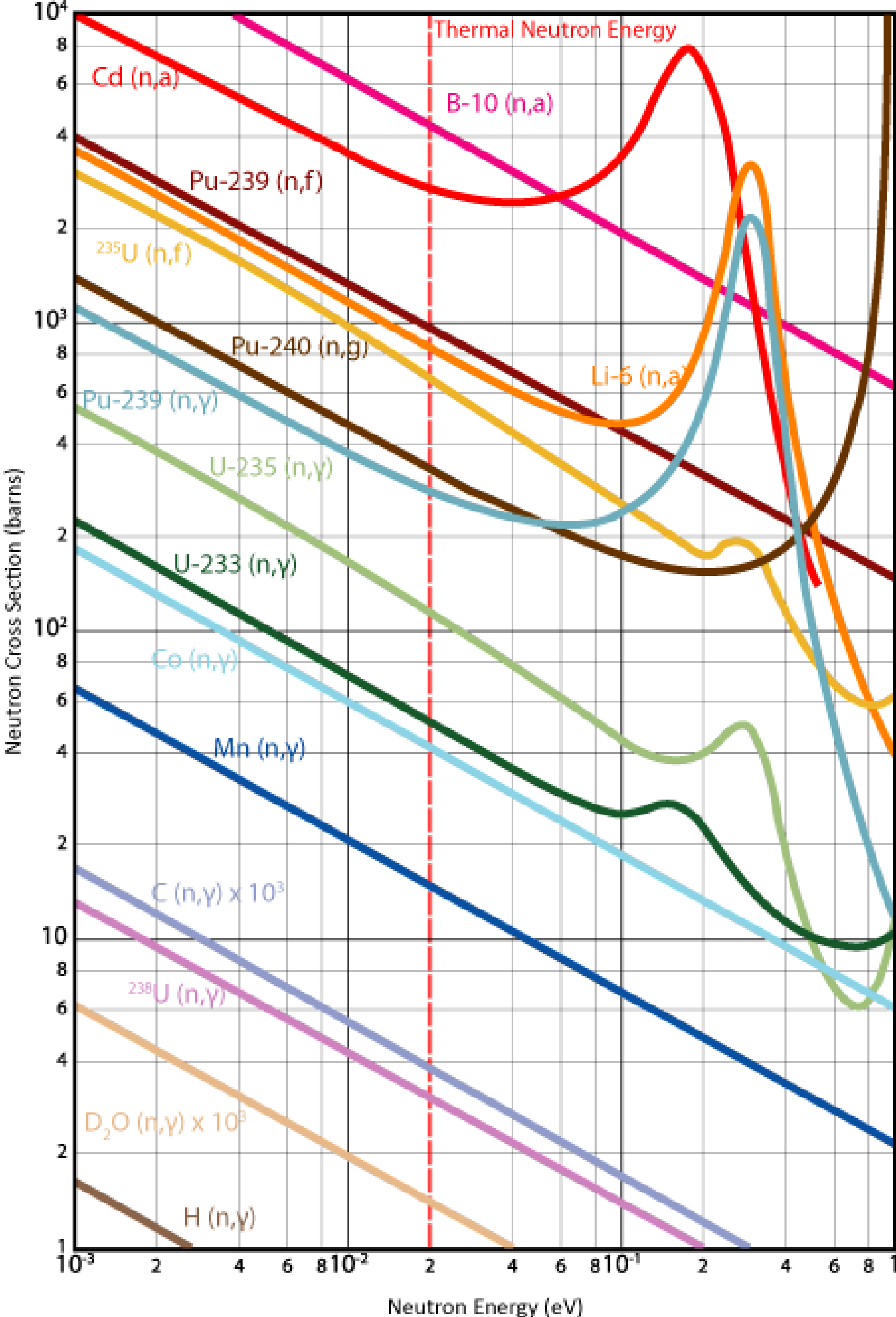
- Detection options use reactions producing charge. Reactions used up to the MeV energy range include:
  - detection of recoil protons
    - $n\ {}^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H}\ p + 765\ \mathrm{keV}$
  - nuclear reaction
    - $n\ {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li}^{*}\ {}^{4}\mathrm{He} + 2310\ \mathrm{keV}$,
    - ${}^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + 480\ \mathrm{keV}$



[Adapted from TW Crane and MP Baker, Neutron detectors]

Neutron capture

- ^{108}Cd: used in the Reines and Cowan experiment.
- This isotope reacts as $^{108}\mathrm{Cd}\,(n,\gamma)^{109}\mathrm{Cd}^{*}$



Summary

- Neutrinos
  - Charged and Neutral current
- Photons:
  - Photo-electric – Compton scattering – Pair production
- Charged particles:
  - Ionisation – Čerenkov radiation – Nuclear interactions
- Electrons
  - + Bremsstrahlung – Transition radiation
- Muons
  - + Multiple scattering & Energy loss – Bremsstrahlung
- Neutrons
  - capture (n,p), (n,α), fission