Interactions of particles and matter, with a view to tracking

3rd EIROforum School on Instrumentation,
May 27th – 31st 2013,
CERN, Switzerland

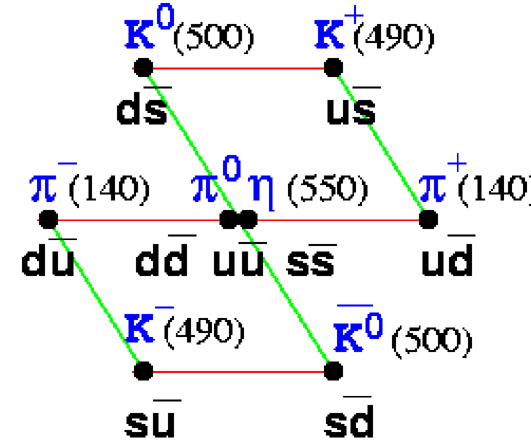
The importance of interactions

- Particles interact with matter they traverse according to their nature and energy, and according to the properties of the matter being traversed.

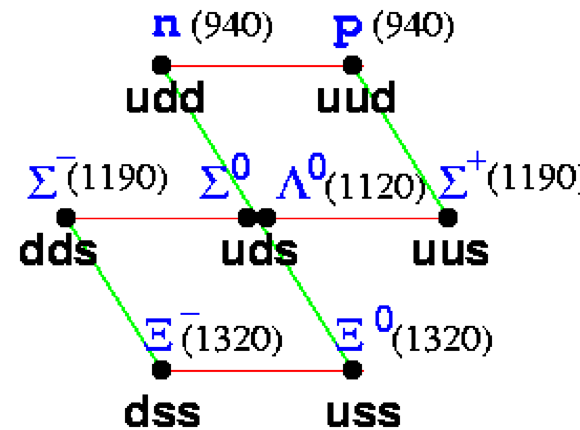
- These interactions
  - blur the trajectory and cause energy loss, but ...
  - they are the basis for tracking and identification.

- In this presentation, we review the mechanisms that are relevant to present particle physics experiments.

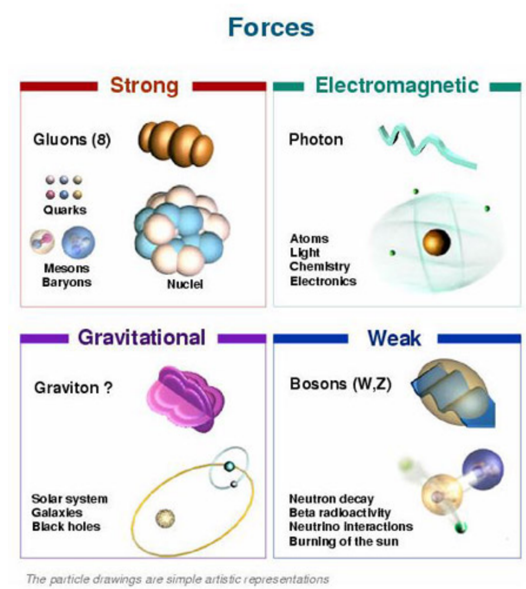
Particles HEP is interested in



- Common, long-lived particles that high-energy experiments track and identify:
  - 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 through the strong force, a few only feel the weak force. The effect of the gravitational force is only just detectable.



[Drawings: Mark Alford (0^- mesons, $\frac{1}{2}^+$ baryons), ETHZ (bottom)]

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.

[Top: LHC, 3.5+3.5 TeV,
Bottom: Auger Observatory > EeV]

Interactions of neutrinos

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

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

$\bar{\nu}_e p \rightarrow n\, e^+$ (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)

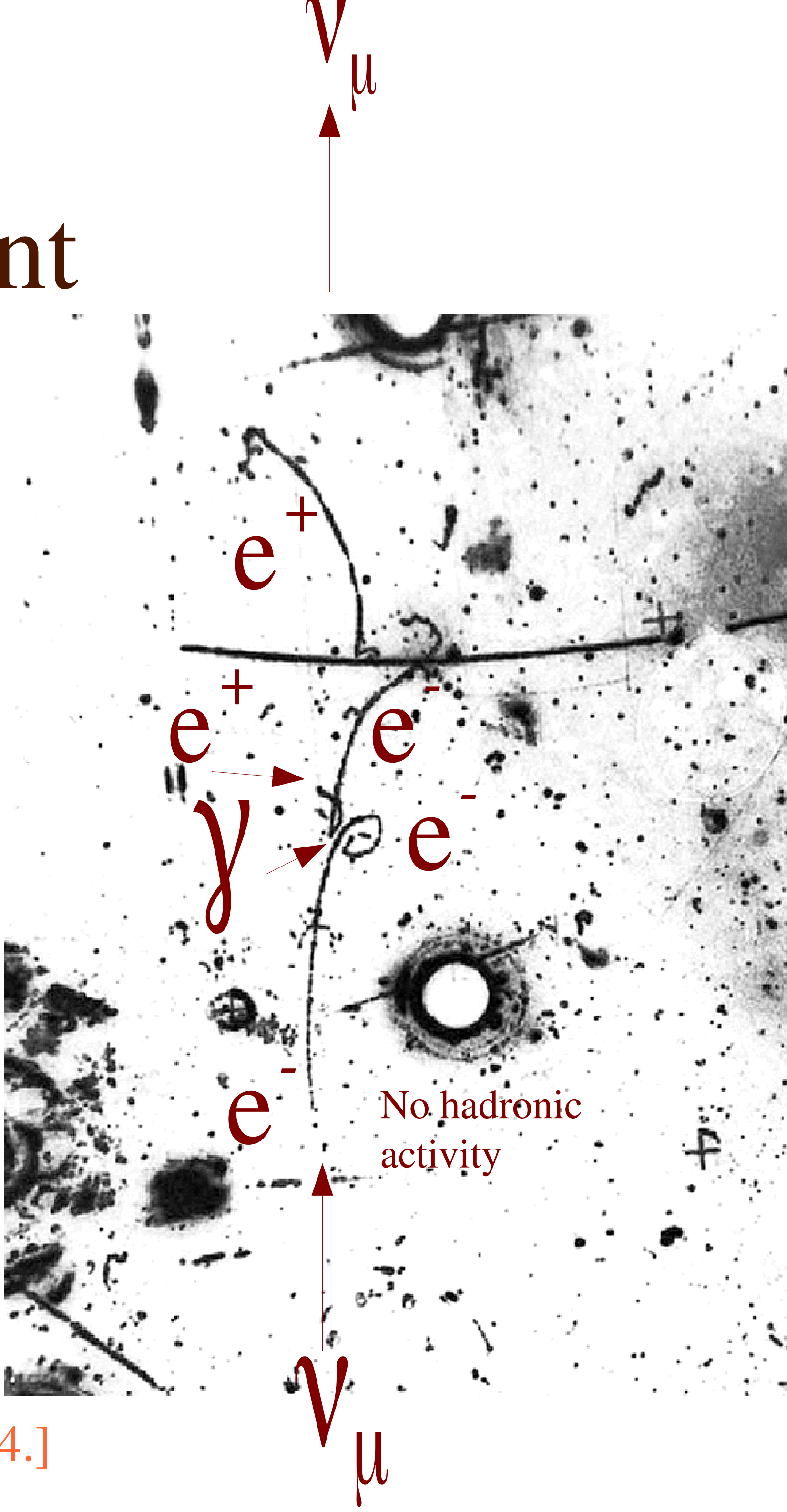
$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ (a neutral current discovery channel, 1973)

First neutral current event

- First neutral current eν event (elastic scattering) seen in the Gargamelle bubble chamber:

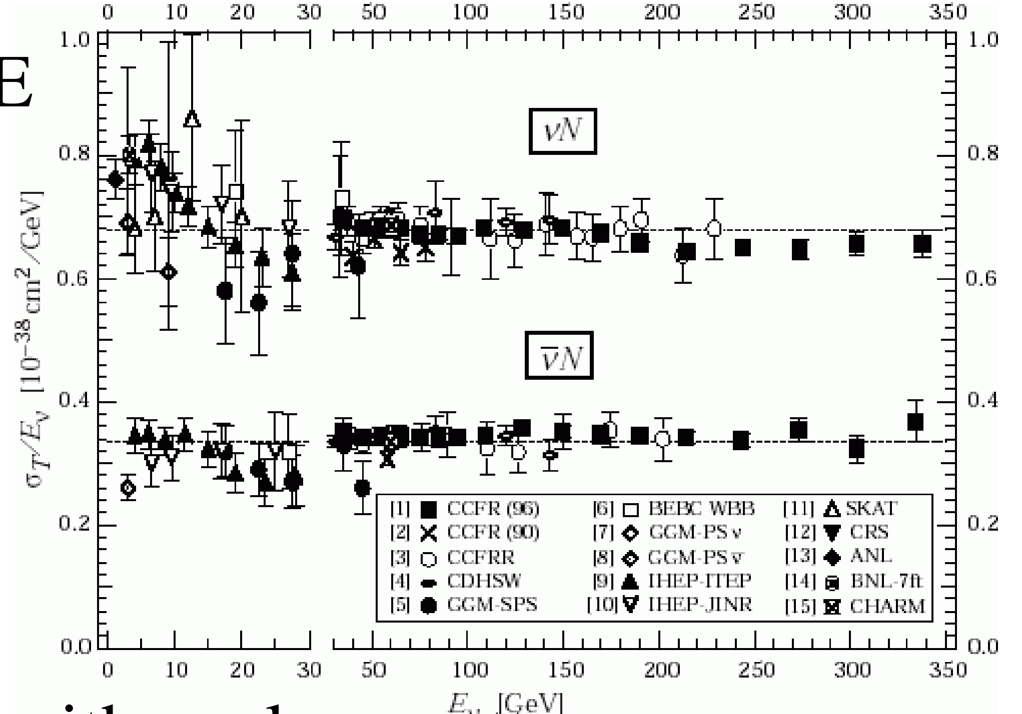
$$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$$

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



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

σ/E



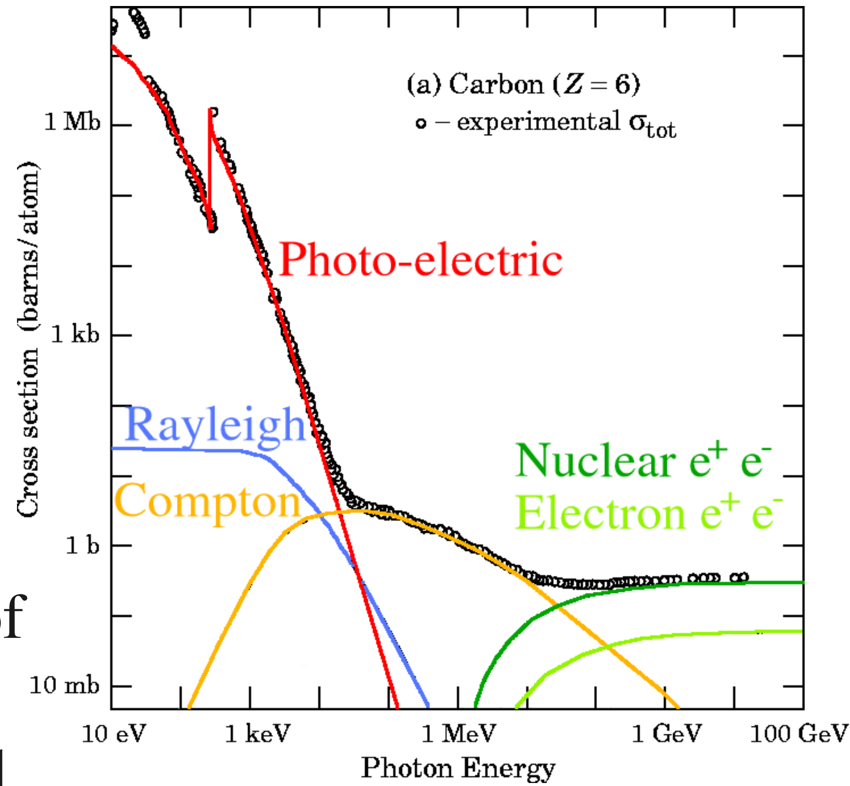
Cross sections ...

- Quantifies how easily particles hit a target.
- Example: cross section of ν_μ with nuclear matter: $\sigma \sim \epsilon\ 10^{-38}\ \mathrm{cm}^2 = \epsilon\ 10^{-14}$ barn (ϵ in GeV).
- Thus, for a ν_μ with energy $\epsilon = 100$ GeV, a nucleon has an equivalent surface area of 10^{-36} cm^2, i.e. $r \sim 6\ 10^{-19}$ cm, much smaller than a proton ($r \sim 1.2\ 10^{-13}$ cm).
- A 1 cm^2 Earth core contains $< 4\ 10^{33}$ nucleons and only ~0.4 % of these neutrinos is expected to scatter.
- At PeV energies, the Earth is opaque.

Interactions of photons

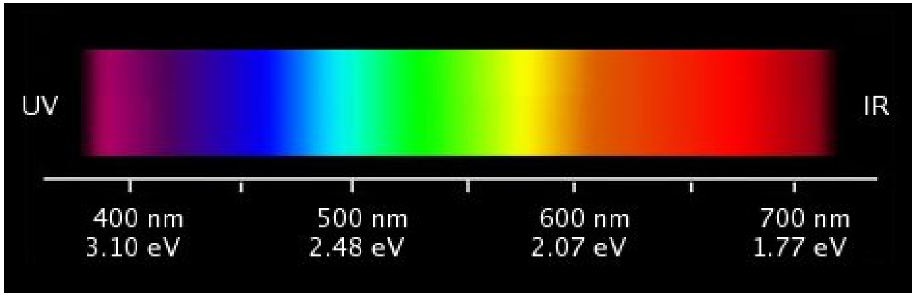
- Many photon interaction mechanisms:
  - ϵ < few eV: molecular interactions;
  - ϵ < 1 MeV: photo-electric effect;
  - ϵ < 1 MeV: Rayleigh scattering;
  - ϵ ~ 1 MeV: Compton scattering;
  - ϵ > 1 MeV: pair production;
  - ϵ > 1 MeV: nuclear interactions.

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

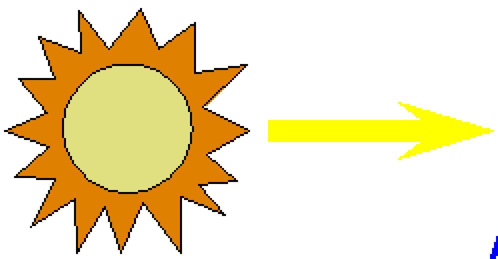


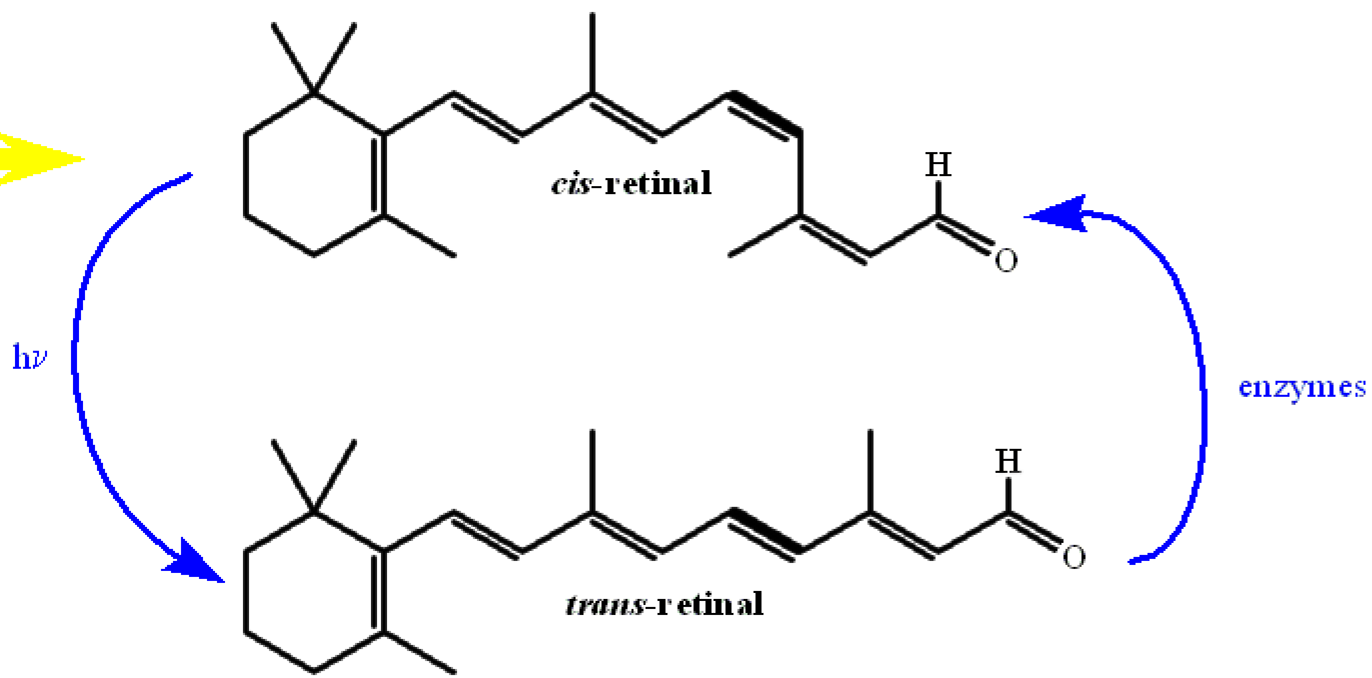
[Adapted from the PDG, 2004 edition]

eV γ's



- 1.8 < ϵ < 3 eV: Visible light
- ϵ > 3 eV: Ultraviolet: approaching excitations & ionisations





[From Kevin A. Boudreaux]

Photo-electric effect

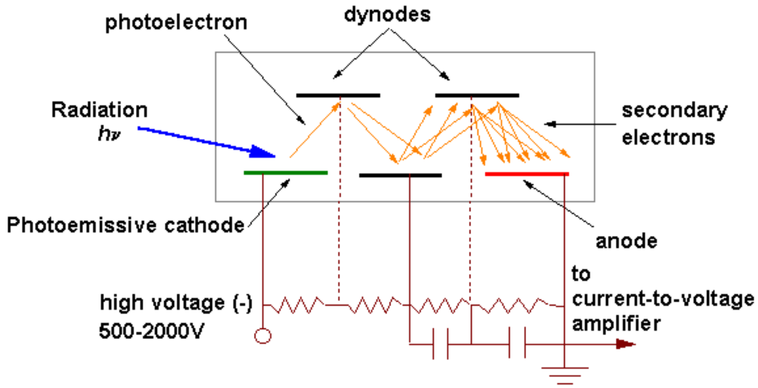
- *The reactions up to here are of limited use for HEP purposes.*

- A γ is absorbed and a photo-electron is ejected
  - the γ disappears,
  - the photo-e^- gets an energy $\epsilon_{pe} = \epsilon_{\gamma} - \epsilon_{binding}$.

- This can happen at all atomic energy levels:
  - outer shell: the photo-e^- sometimes ionises further;
  - inner shell: atom is left excited; followed by Auger-e^- or fluorescence; photo-e^-, Auger-e^- and fluorescence-γ may be able to ionise.
  - more on this later ...

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

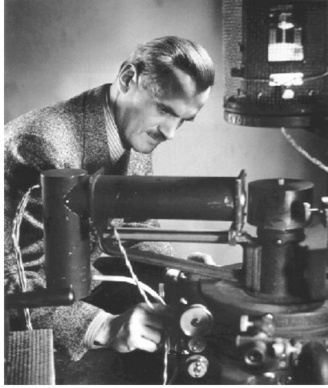
Photo-multipliers



- 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).
- Some photocathodes have a sensitive range that extends into the infrared ($\lambda > 1000$ nm).

[Diagram: Brian Tissue]

Arthur Holly Compton
(1892-1962)



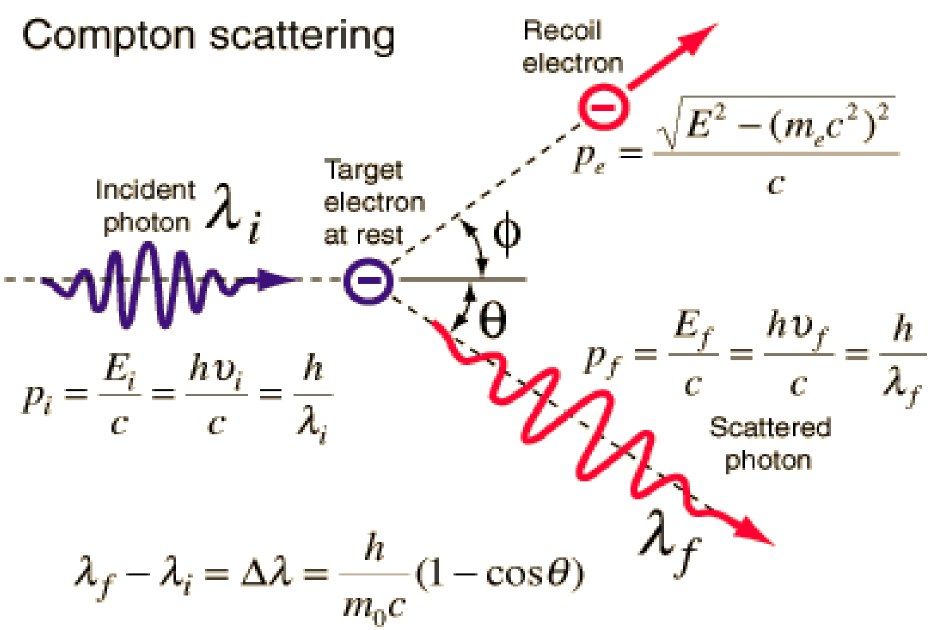
Compton scattering

- 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

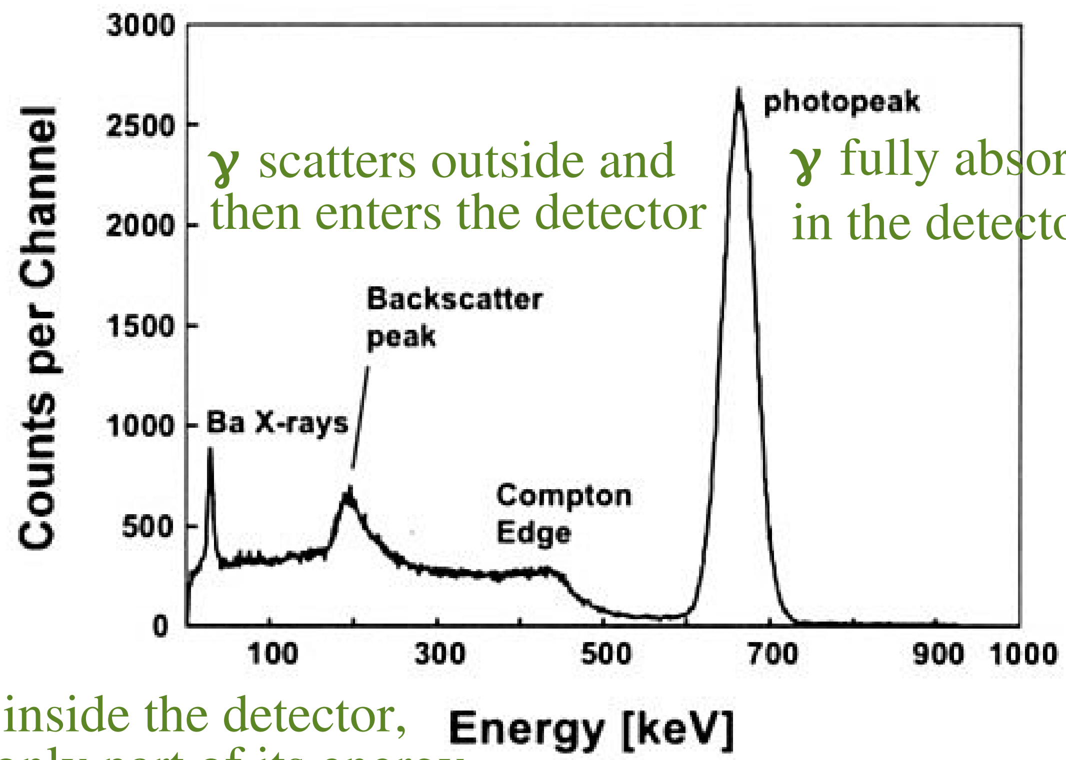
- Ref: Arthur H. Compton, Phys. Rev. **21** (1923) 483 and **22** (1923) 409.



[Sketch: hyperphysics]

Compton edge

- Compton scattering somewhat favours the maximal (and minimal) energy transfers, which leads to the presence of an “edge” a bit below full absorption.



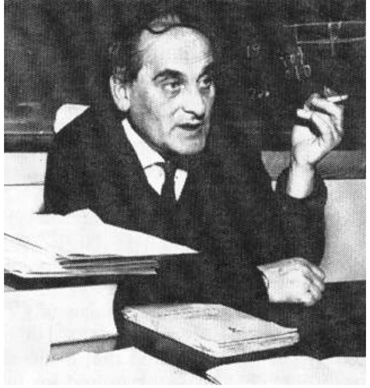
γ scatters outside and
then enters the detector

γ fully absorbed
in the detector

γ scatters inside the detector,
and loses only part of its energy

[Diagram: Scionix]

Pair production



Beppo Occhialini (1907-1993)

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

- Production of an e^+e^- pair by a γ 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.

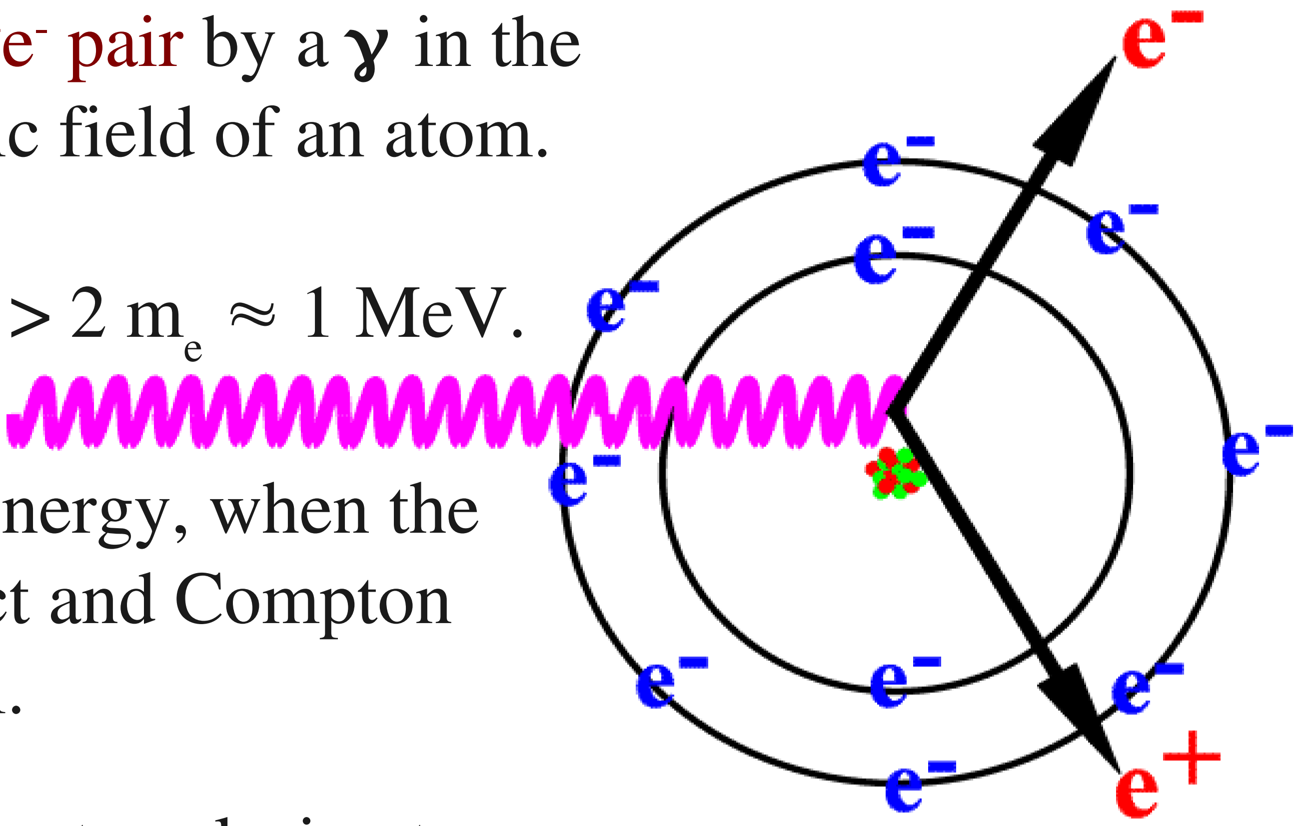
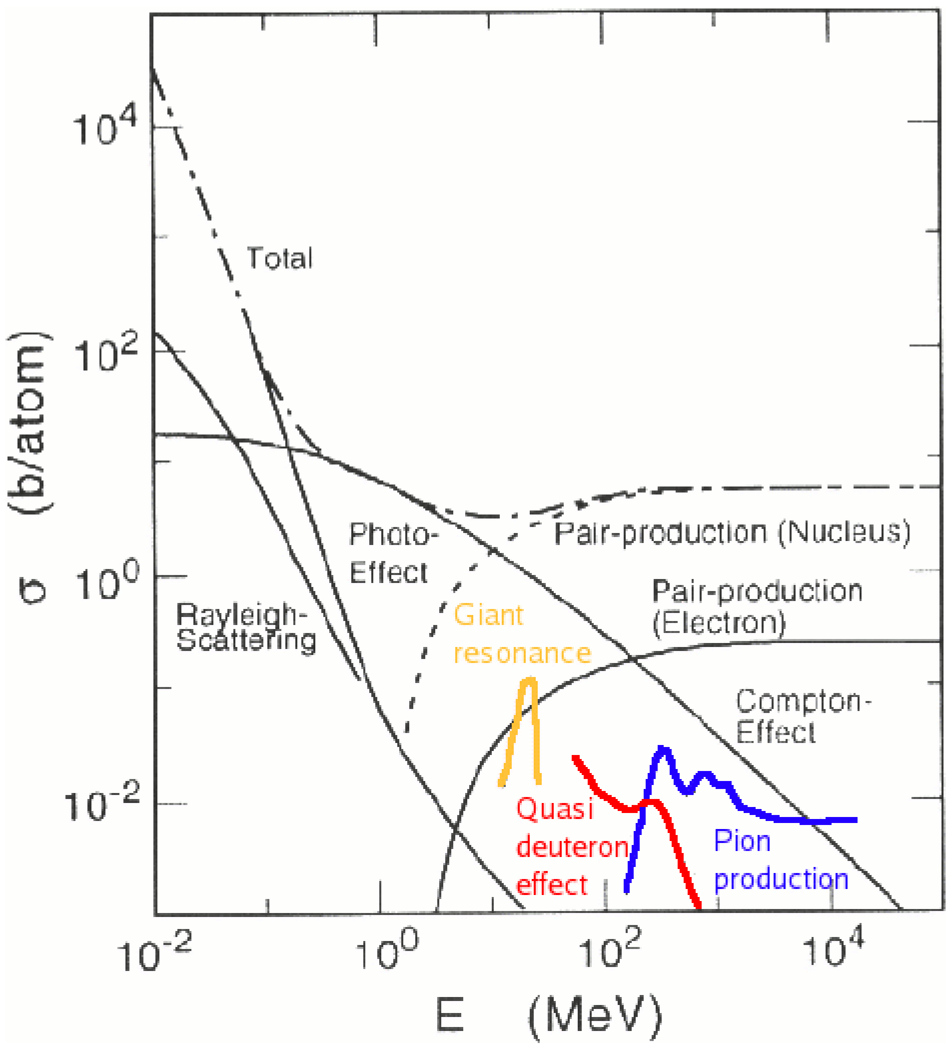


Photo-nuclear interactions

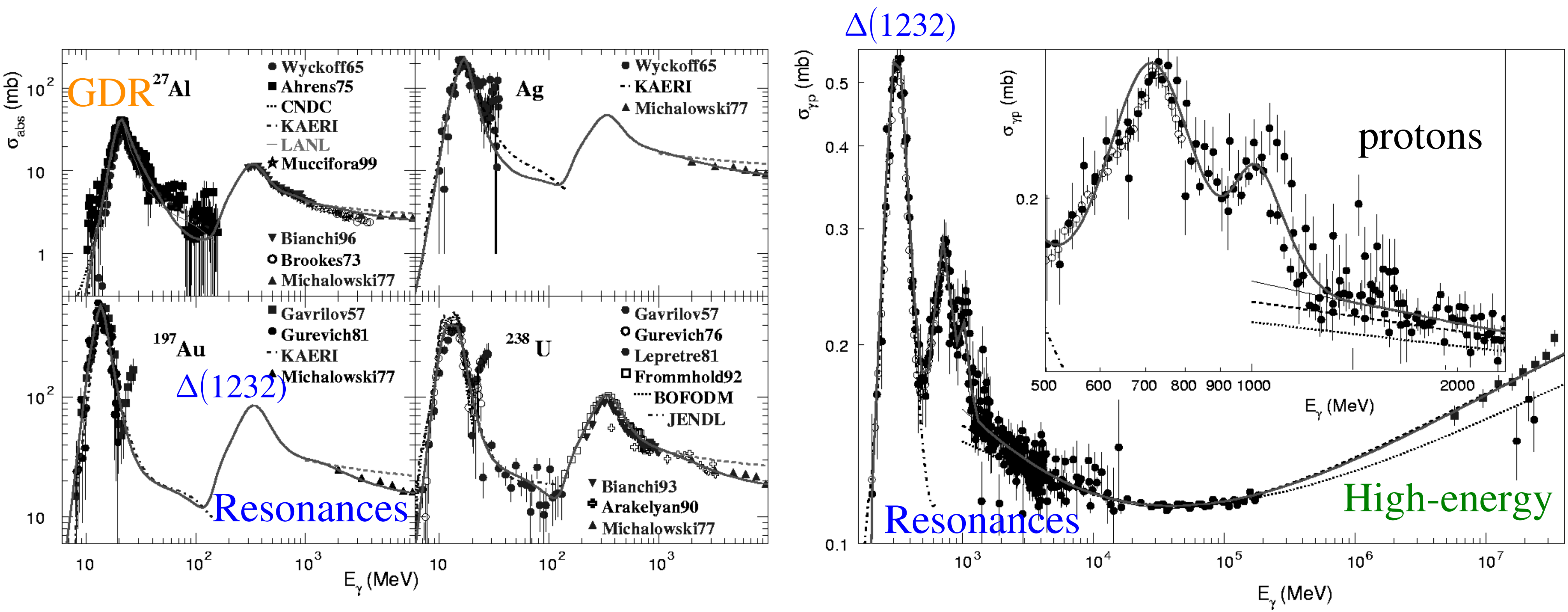
- Main nuclear terms in Cu:
  - $10 < \epsilon_\gamma < 30$ MeV:
    - giant dipole resonance
  - $30 < \epsilon_\gamma < 150$ MeV:
    - quasi-deuteron process,
  - $\epsilon_\gamma > 150$ MeV:
    - production of *e.g.* pions



[Diagram: ANL/APS]

Photo-nuclear interactions (cont'd)

- Cross-section for a wide range of nuclei and energies have been compiled and parametrised for use within Geant 4.



- Ref: M.V. Kossov, Eur. Phys. J. A **14**, 377–392 (2002)

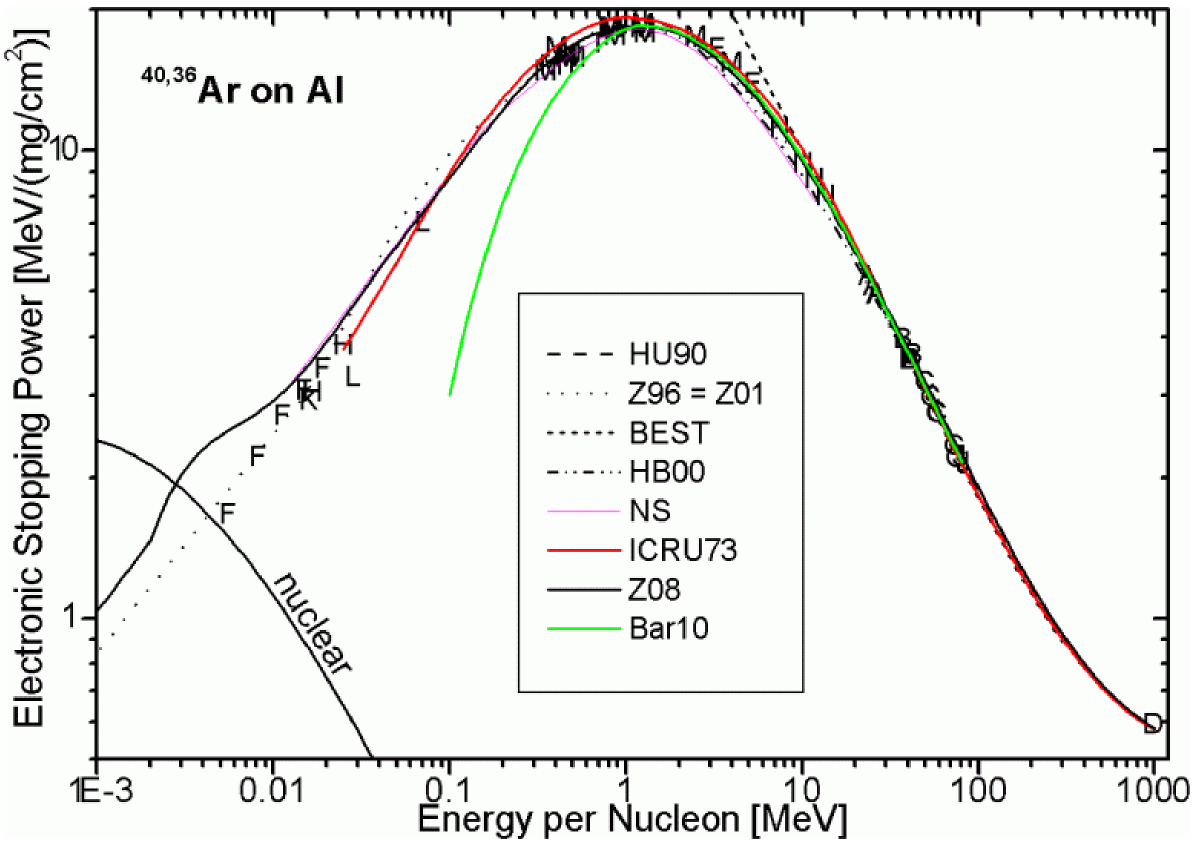
Interactions of charged particles

- 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 $\beta\gamma$: nuclear effects
  - all $\beta\gamma$: ionisations and excitations
  - $\beta > 1/n$: Čerenkov radiation
  - $\epsilon > 1$ GeV: inelastic nuclear interactions

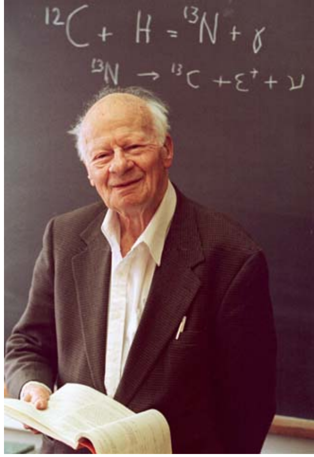
Electromagnetic losses at low energy

- Nuclear effects abound at low energy.
- Numerous models: SRIM, MSTAR, CasP, PASS ...



- Ref: Helmut Paul, http://www.exphys.uni-linz.ac.at/Stopping/

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.

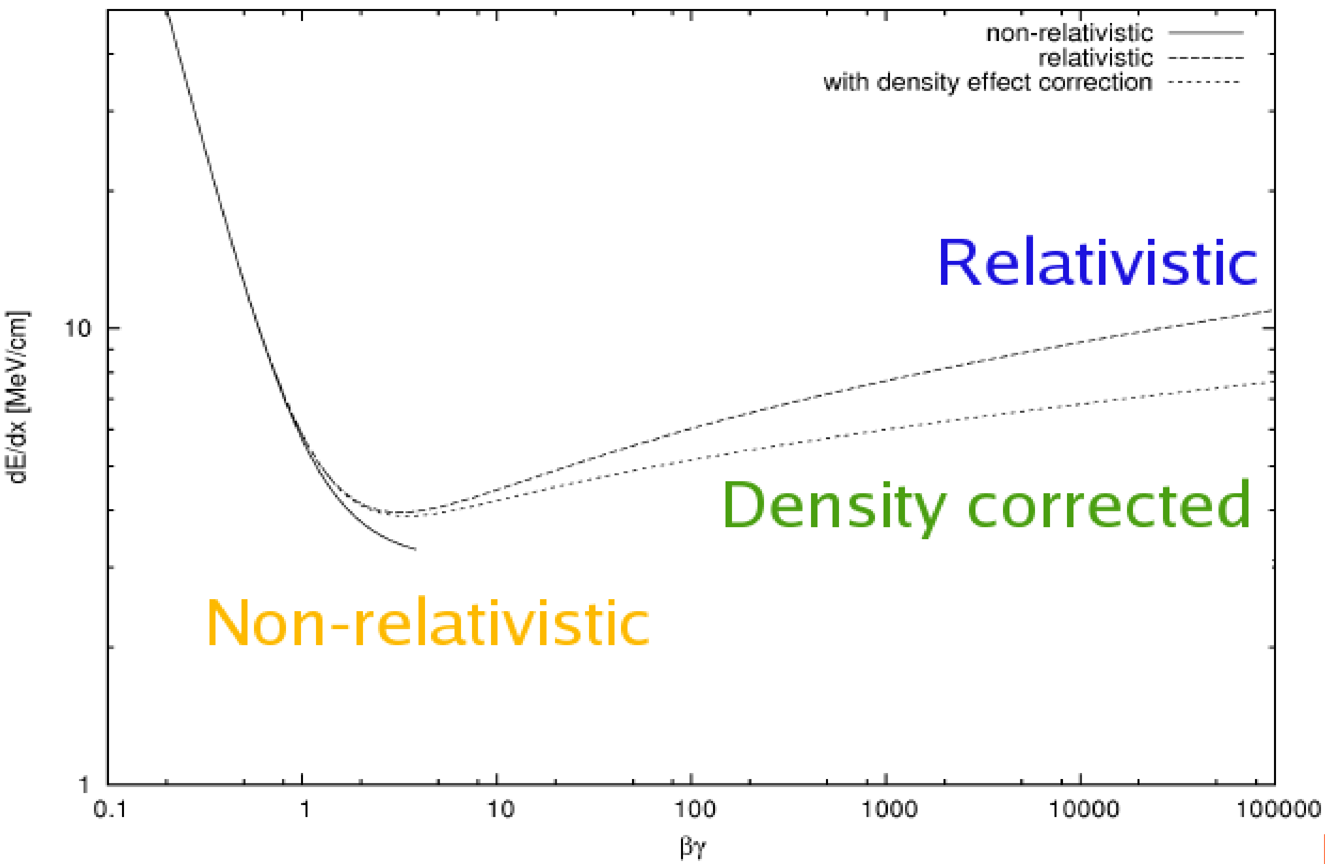
- The ionisation losses are given by (Hans Bethe formula):

$$\frac{dE}{dx} \propto -\frac{Z^2 z}{m\beta^2}\left(\log\left(\frac{2m\beta^2\gamma^2}{I}\right) - \beta^2 - \textit{corrections}\right)$$

  - β, γ: velocity of projectile;
  - Z^2: projectile charge (squared: Mott);
  - z: target atomic number (linear: number of e$^-$ encountered).

The Bethe formula: high energies

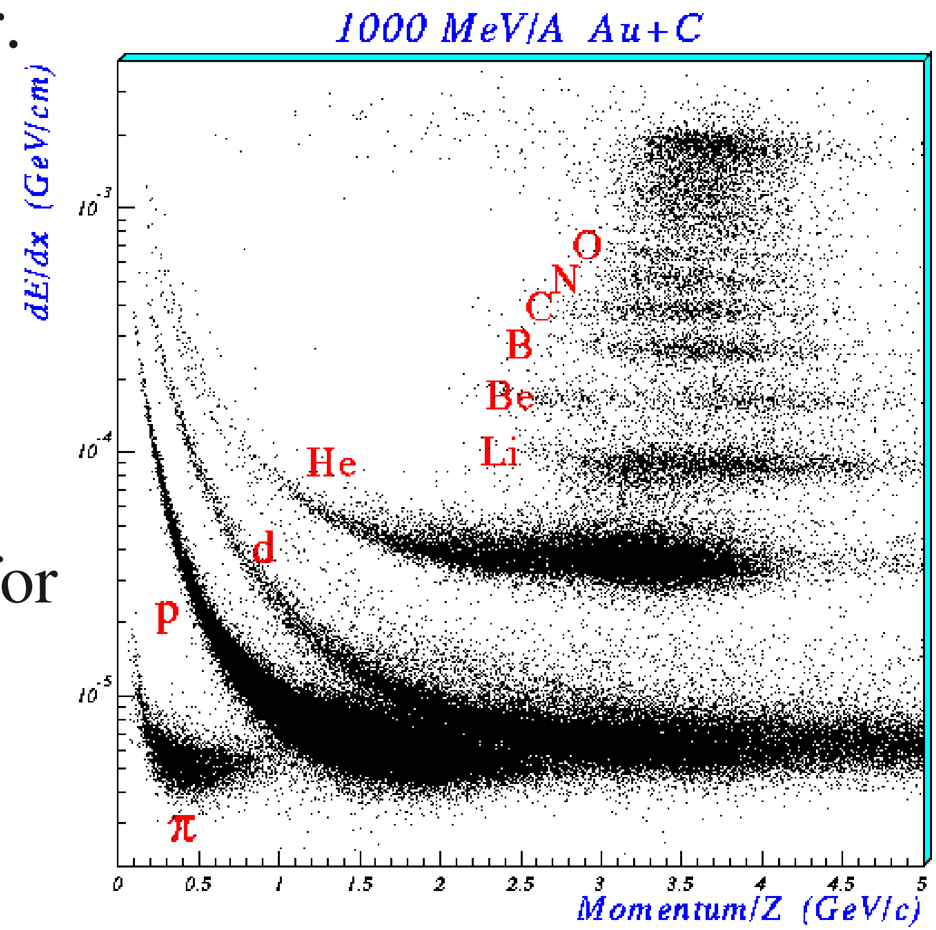
- Example for Si, assuming $I = 173$ eV (!), and using Sternheimer's parametrisation for the density effect.



[Diagram: Heinrich Schindler]

Bethe formula and particle identification

- The formula holds in the high projectile mass limit – the projectile mass does not appear.
  - only the projectile velocity β and charge Z remain;
  - at equal charge (± 1): particle identification below the $\gamma \approx 3$ "minimum ionising" dip;
  - differentiation by energy loss for particles of higher charge.



[Diagram: EOS collaboration]

Лев Давидович Ландау
(1908-1968)

Energy loss fluctuations

- Given a single-collision energy loss distribution $w(\epsilon)$, the distribution $f(\epsilon)$ of the energy loss ϵ after many collisions is *schematically* given by the Laplace transform:

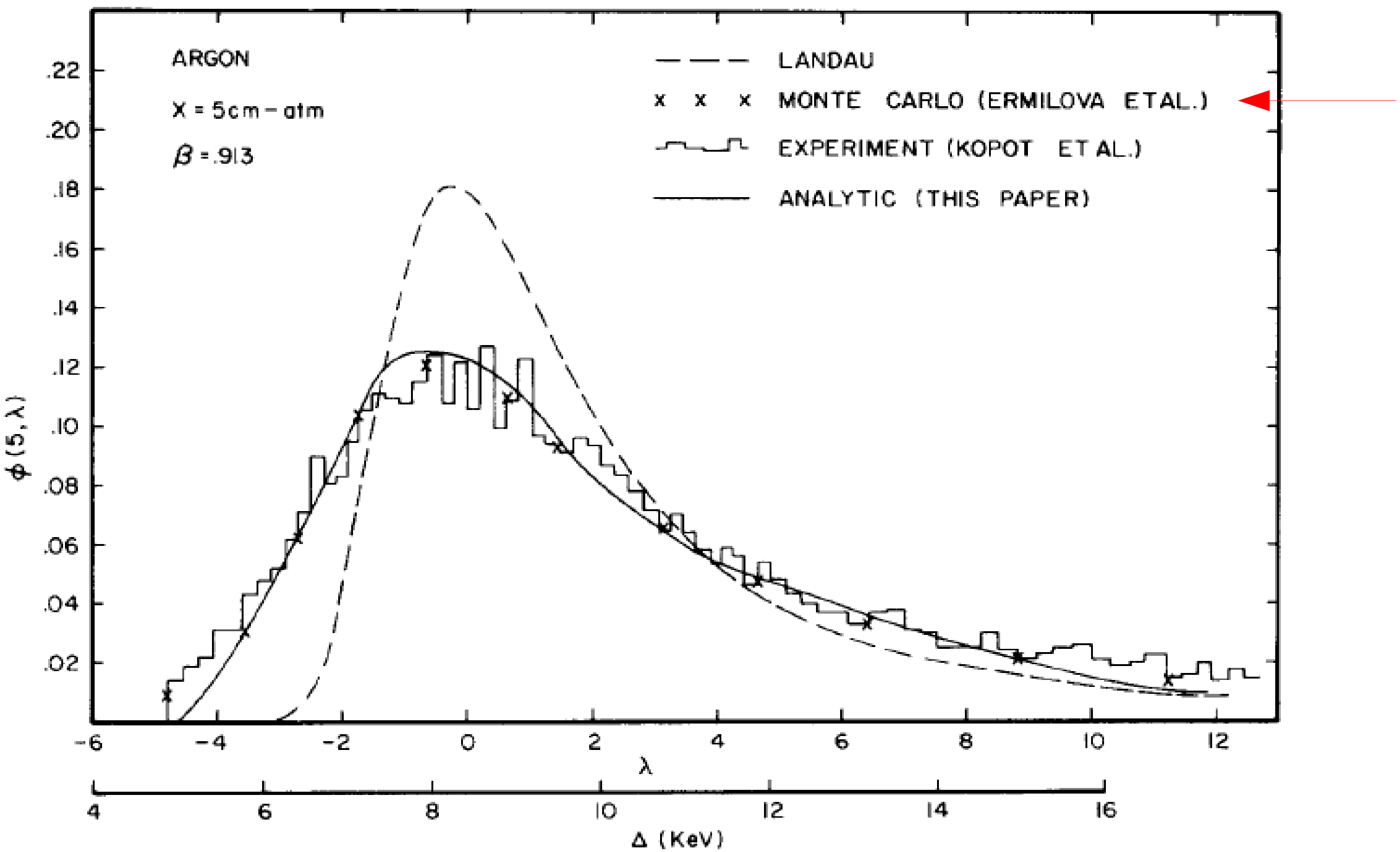
$$L f(x,s) = e^{-x\int_0^\infty (1-e^{-s\epsilon}) w(\epsilon) d\epsilon}$$

- Ландау showed (1944), assuming in particular:
  - thick layers: numerous small energy losses;
  - Rutherford-inspired energy loss distribution $w(\epsilon) \sim 1/\epsilon^2$;
  - neglect of the atomic structure:

$$L f(s) \approx s^s$$

Is the Landau distribution appropriate ?

- 2 GeV protons on an (only !) 5 cm thick Ar gas layer:



[Diagram: Richard Talman, NIM A **159** (1979) 189-211]

Ionisation process in detail

Igor Smirnov

- PAI model or absorption of real photons:

  $\text{Atom} + \pi^- \rightarrow \text{Ion}^{+*} + \pi^- + e^-$
  $\text{Atom} + \gamma \rightarrow \text{Ion}^{+*} + e^-$ (photo-electric effect)

- Decay of excited states:

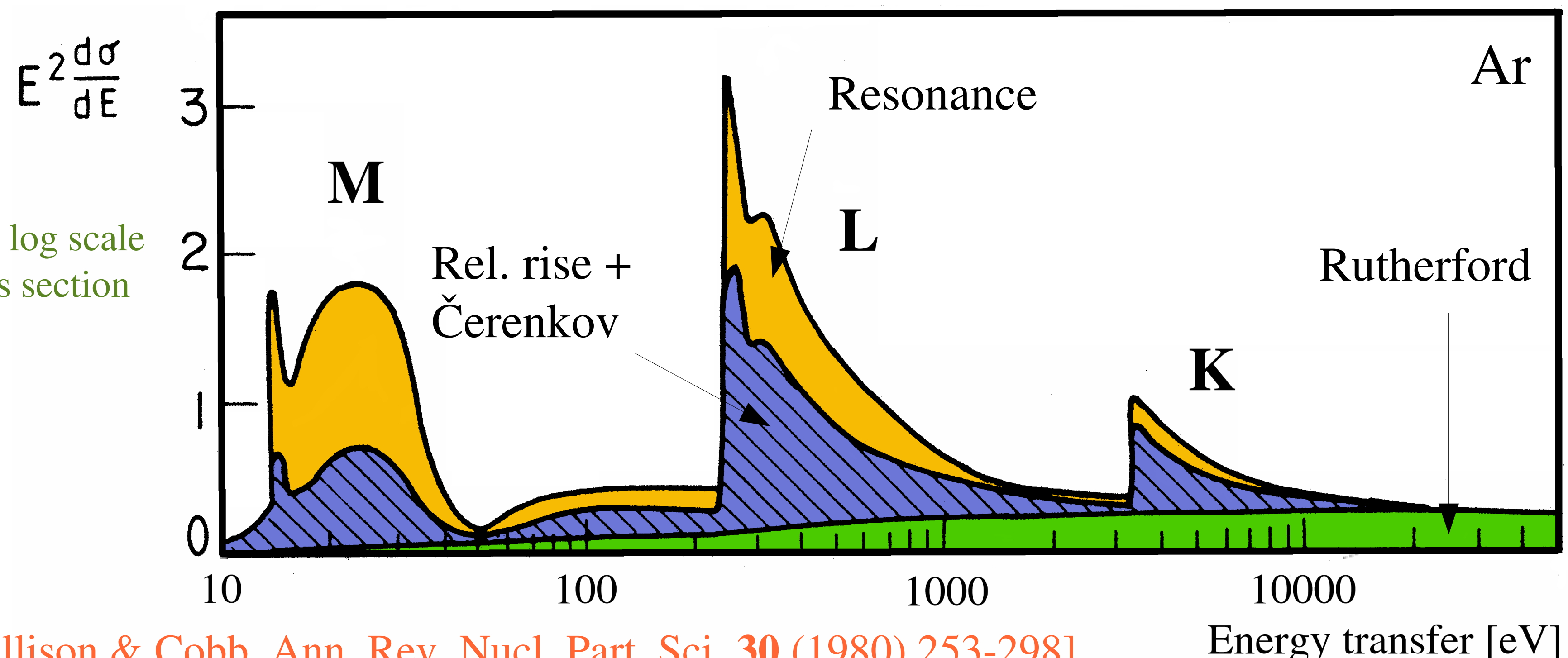
  $\text{Ion}^{+*} \rightarrow \text{Ion}^{++} + e^-$ (Auger)
  $\text{Ion}^{+*} \rightarrow \text{Ion}^{+} + \gamma$ (fluorescence)
  $\text{Ion}^{+*} \rightarrow \text{Ion}^{+*}$ (Coster-Kronig)

- Treatment of:
  - secondary photons, returning to the PAI model,
  - ionising photo-electrons and Auger-electrons, collectively known as δ-electrons:

  $e^- + \text{Atom} \rightarrow \text{Ion}^{+} + 2\,e^-$ (absorption of high-energy electrons)

Importance of inner shells

- All electron orbitals (shells) participate:
  - outer shells: frequent interactions, few electrons;
  - inner shells: few interactions, many electrons.
- All terms in the formula are important.



Scaling with E^2:
equal areas on log scale
weighing cross section

[Adapted from Allison & Cobb, Ann. Rev. Nucl. Part. Sci. **30** (1980) 253-298]

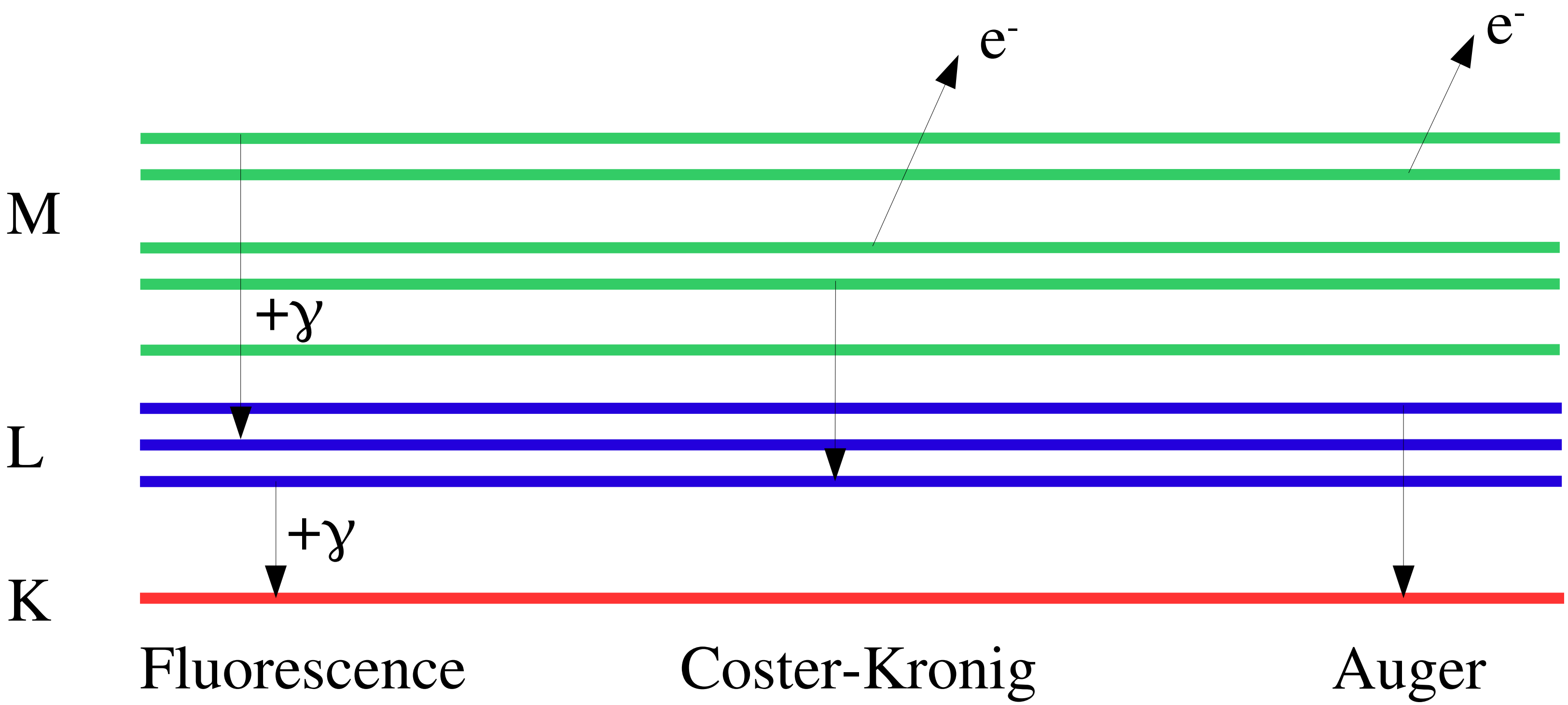
De-excitation

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.

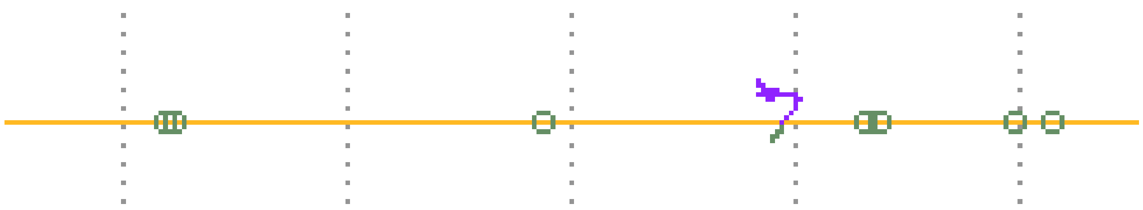
L. Meitner, *Das β-Strahlenspektrum von UX_1 und seine Deutung*, Z. Phys. **17** (1923) 54-66.

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

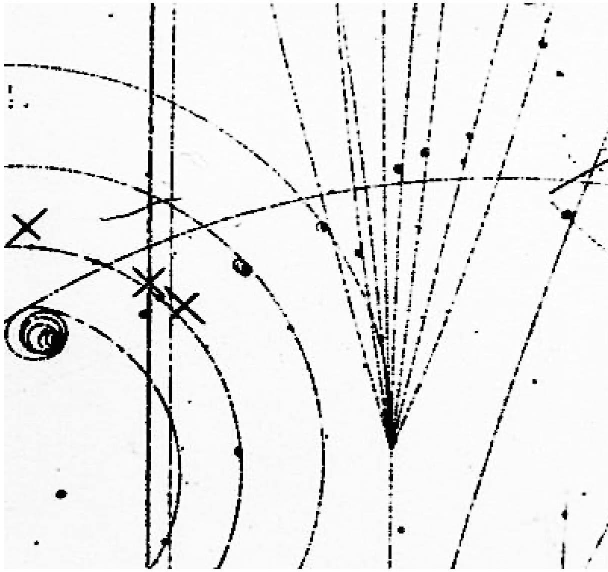
Features of ionisation: high density

- 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: ~50 e^--ion$^+$ pairs/cm;
  - lH_2 bubble chamber: ~100 bubbles/cm;
  - semi-conductor: ~10^6 e^-/h pairs/cm



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



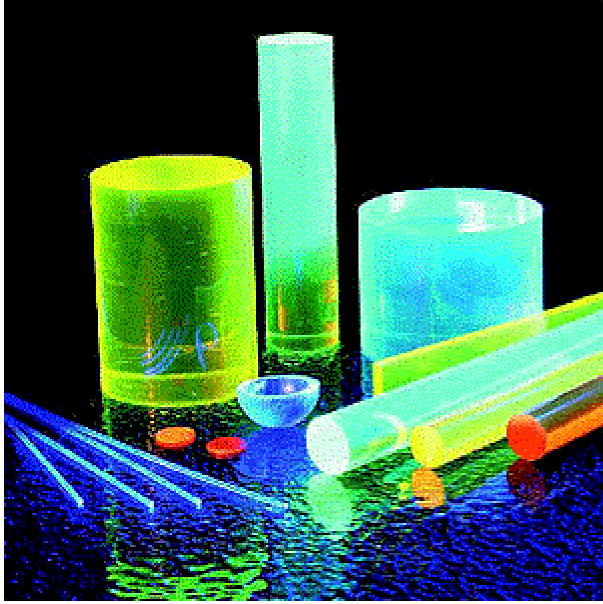
24 GeV protons on lH_2 in the 2m CERN bubble chamber (~1970)

Features of ionisation: small losses

- Another good thing is that ionisation 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: $\mathrm{d}E \approx 145$ keV/m
  - semi-conductor: $\mathrm{d}E \approx 38$ keV/100 μm

Plastic scintillators,
image: Amcrys (Ukraine)



Ionisation & Excitation

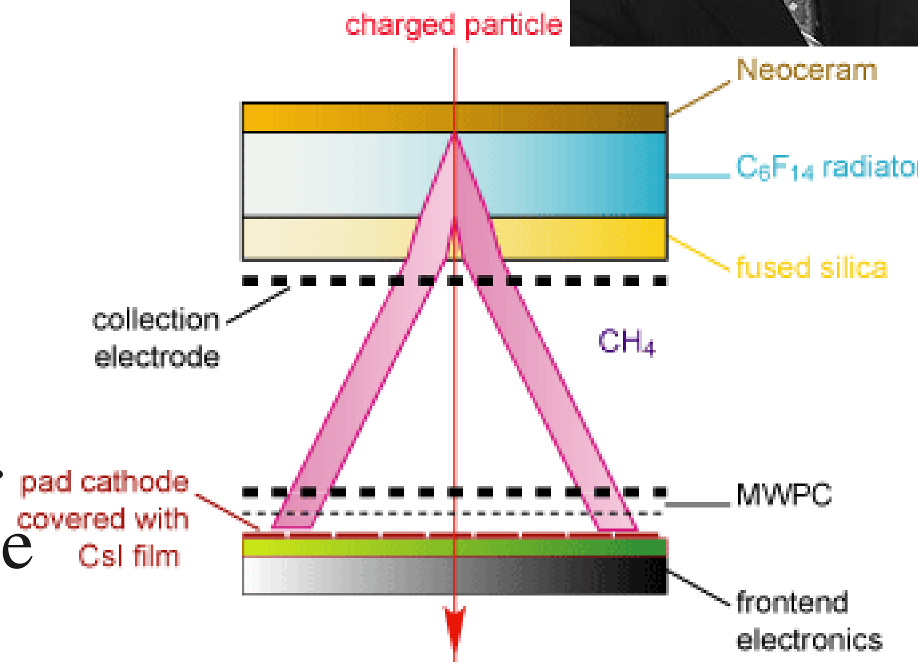
- Ionisation as a source of electrons is used in precision tracking devices:
  - semi-conductor,
  - gas-based.

- Excitation (atomic and molecular) accompanies ionisation, at slightly lower energy.
- De-excitation light spans the entire spectrum.
- In suitable materials, excited states decay via visible light emission. Scintillation is used in:
  - calorimetry (*e.g.* CsI crystals),
  - trigger systems, hodoscopes ...

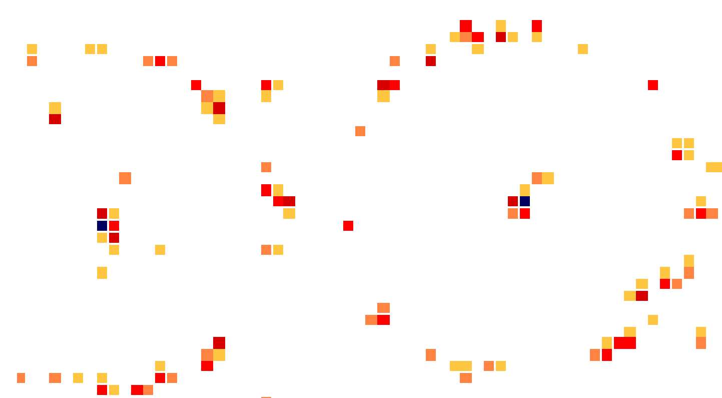
Павел Алексеевич Черенков
(1904–1990)

Čerenkov 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.

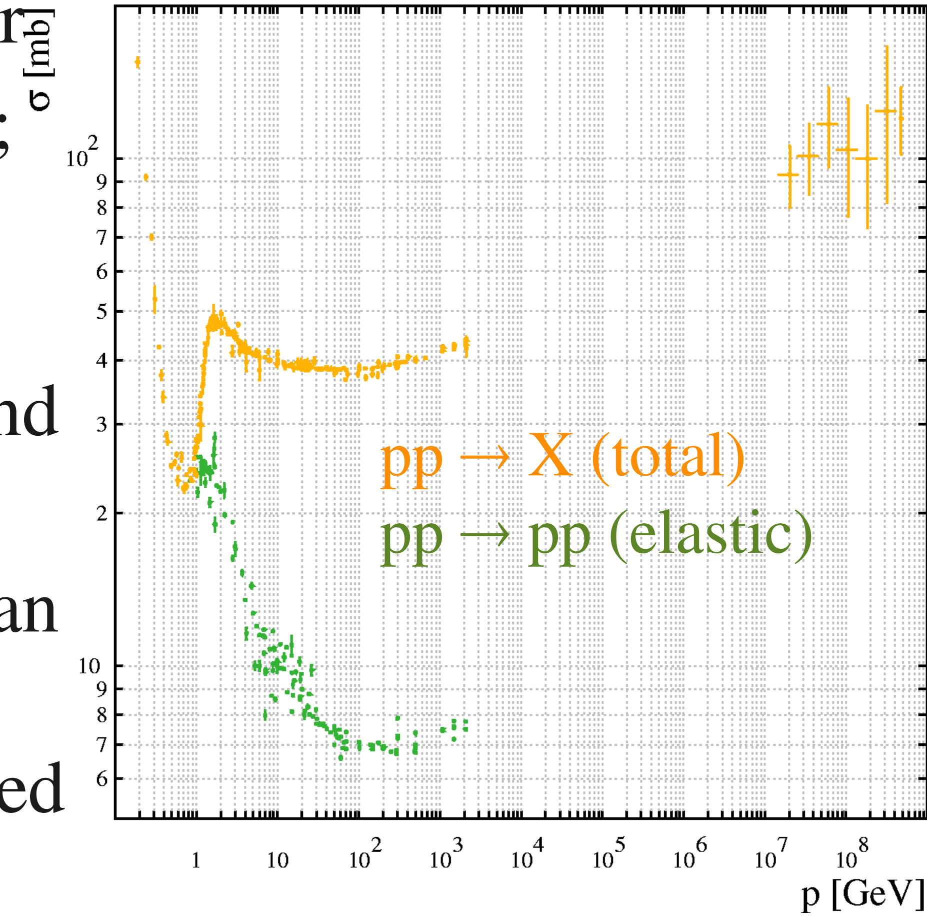


[Alice HMPID]



Hadronic interactions: elastic part

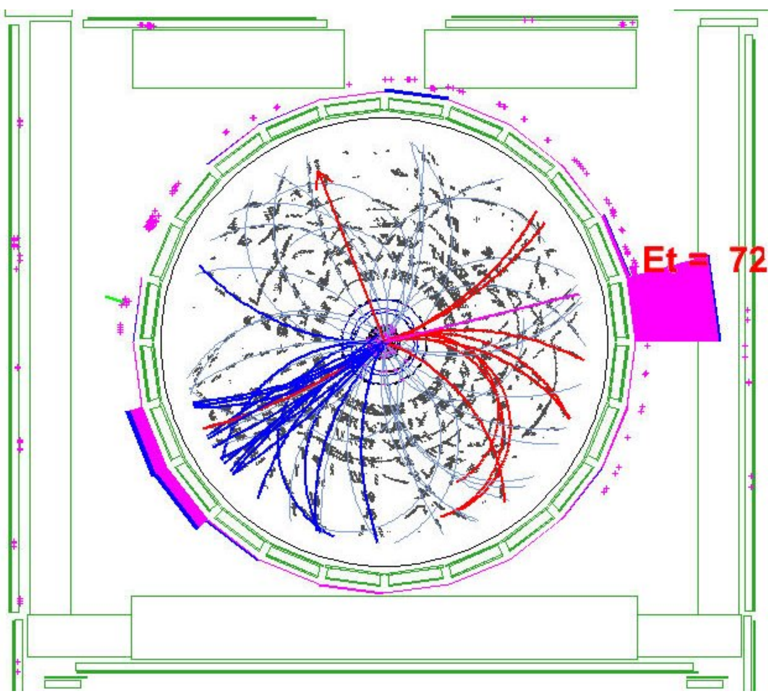
- p_{lab} < few MeV: Coulomb barrier preventing inelastic p collisions;
- p_{lab} ~ 1 GeV: pp cross section largely elastic;
- p_{lab} ~ few GeV: fragmentation and isotope production;
- higher momenta: inelastic with an elastic part ~10-20 % in pp;
- elastic scattering is not much used for tracking.



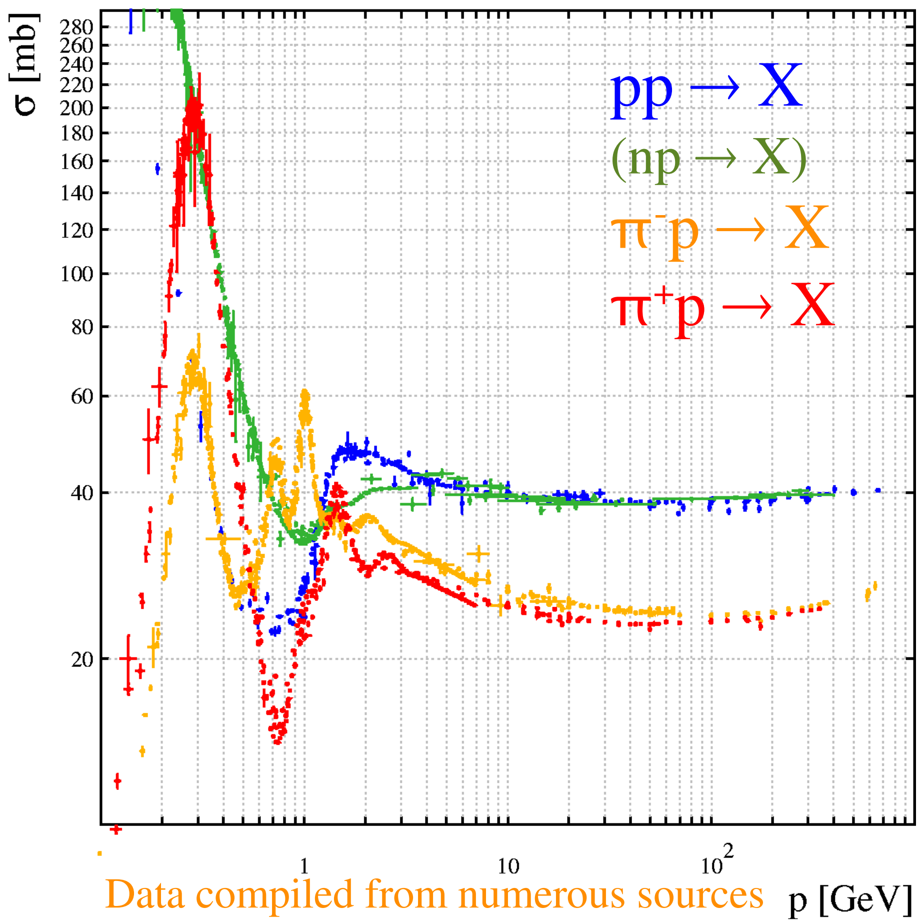
Data compiled from numerous sources by the COMPAS group, IHEP (2003).

Hadronic interactions: inelastic part

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



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



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

Nuclear interaction length

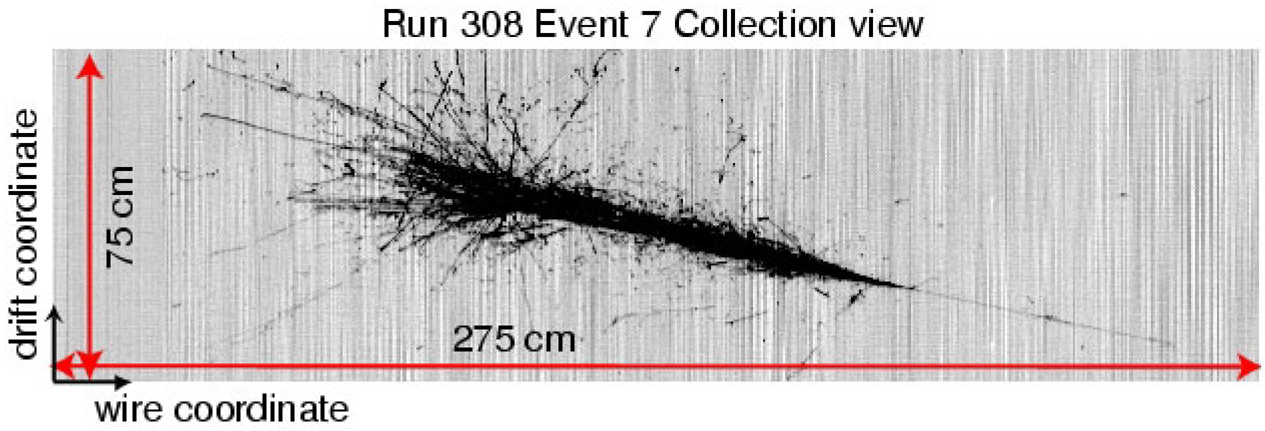
- Mean free path before undergoing a nuclear interaction.
- Natural unit to measure longitudinal shower development.

- One can make an estimate from:
  - definition: $\lambda = A \,/\, (N \rho \, \sigma_{pA})$ $\quad N \sim 6.022 \; 10^{23}$
  - if A is large: $\sigma_{pA} \sim \sigma_{pp} A^{2/3}$ $\quad A$: atomic weight

- Examples:
  - air: 770 m
  - Al: 39 cm
  - Pb: 17 cm

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.



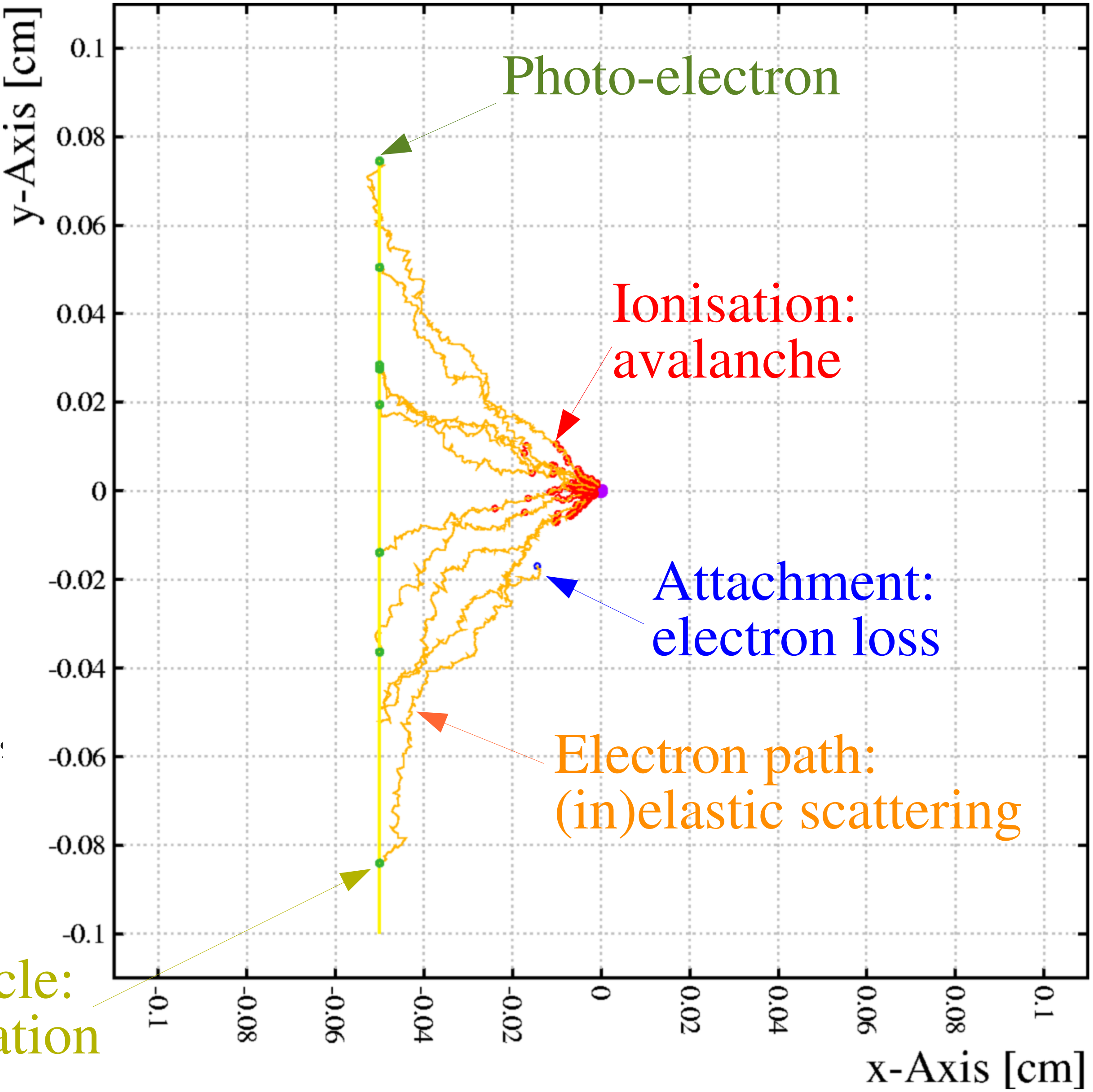
Hadronic shower from a cosmic observed in Icarus.
Absorber: liquid Ar, λ = 84 cm (2001)

Interactions of $e^{\pm}$ and $\mu^{\pm}$

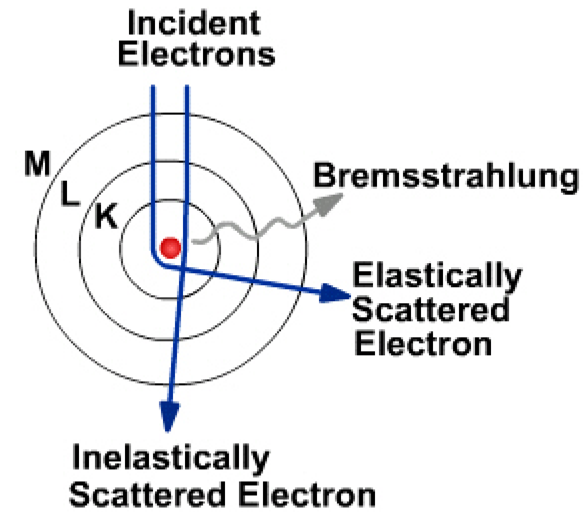
- Electrons:
  - $\epsilon < 5$ eV: elastic scattering;
  - 5 - 10 eV: elastic + inelastic scattering, excitations;
  - 10 eV-10 MeV: attachment, excitation, ionisation;
  - > 10-100 MeV: Bremsstrahlung dominates;
  - from ~1 GeV: transition radiation becomes practical.
- Muons:
  - all ϵ: multiple scattering;
  - $\epsilon < 400$ 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.

eV-energy electrons in a gas

- Ionisation e^- produced by a 10 GeV μ in Ar 80 % CO_2 20 %
- CSC-like structure, E-field to move the electrons to a wire.
- Excitations also occur, but are not shown.



Bremsstrahlung



- Deflection of a charge in a strong nuclear E-field, resulting in the emission of a γ.

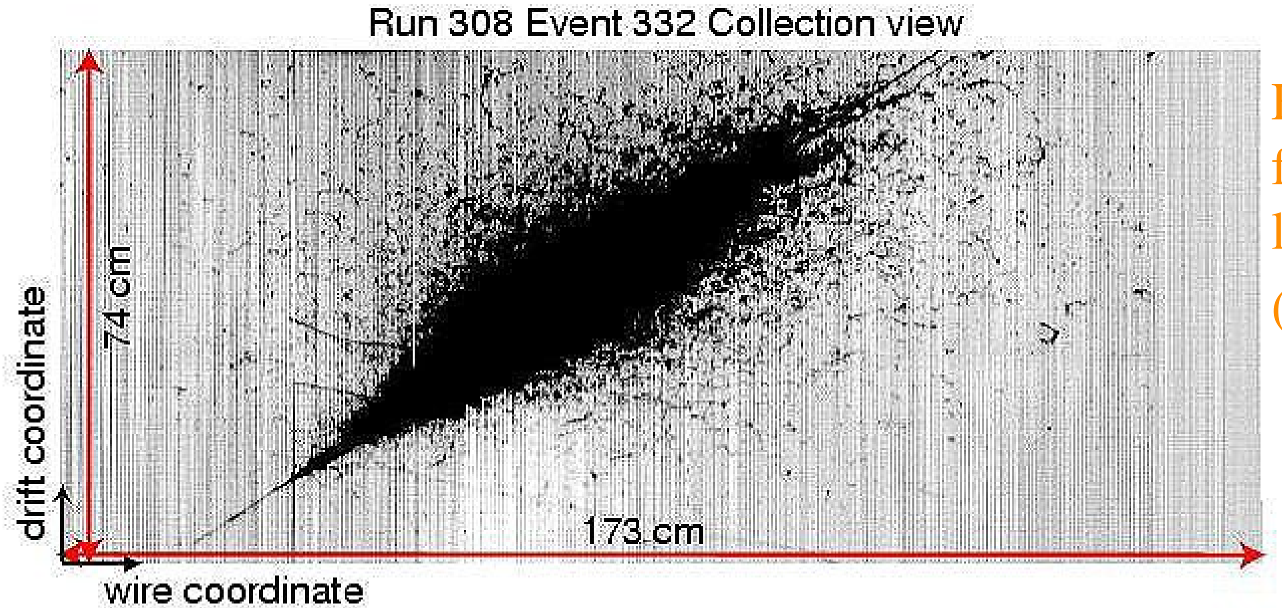
- One (of two) common mechanisms to produce X-rays.
- Major role in calorimetry.

- Dominant process for $e^{\pm}$ at high energies (> 10 MeV).
- Scales with $1/M^2$ and relevant for $\mu^{\pm}$ at LHC energies (a few 100 GeV, depending on the medium).
- Losses are proportional to the energy of the particle.
- Scales with z^2 of the medium (just z for the e^- term).

[Diagram: NDT]

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)

Radiation length X_0

- Distance after which Bremsstrahlung has reduced the energy of an high-energy e^- to $1/e$ of the original.
- Usually expressed in g/cm^2 to eliminate the dependence on the density of the material.
- Scales in $\sim 1/z^2$.

- Examples:
  - air: 300 m
  - Fe: 1.76 cm
  - Pb: 0.56 cm

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)

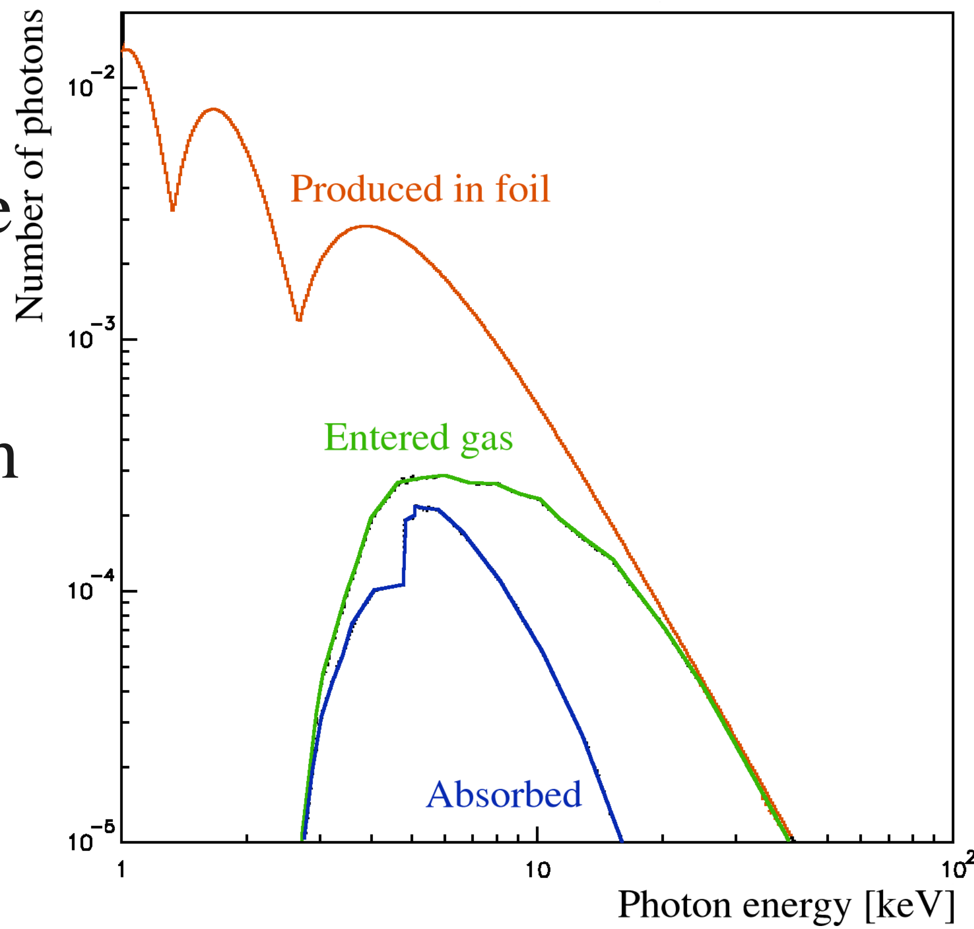
Борис Долгошеин (1930 – 2010)

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

Transition radiation photons

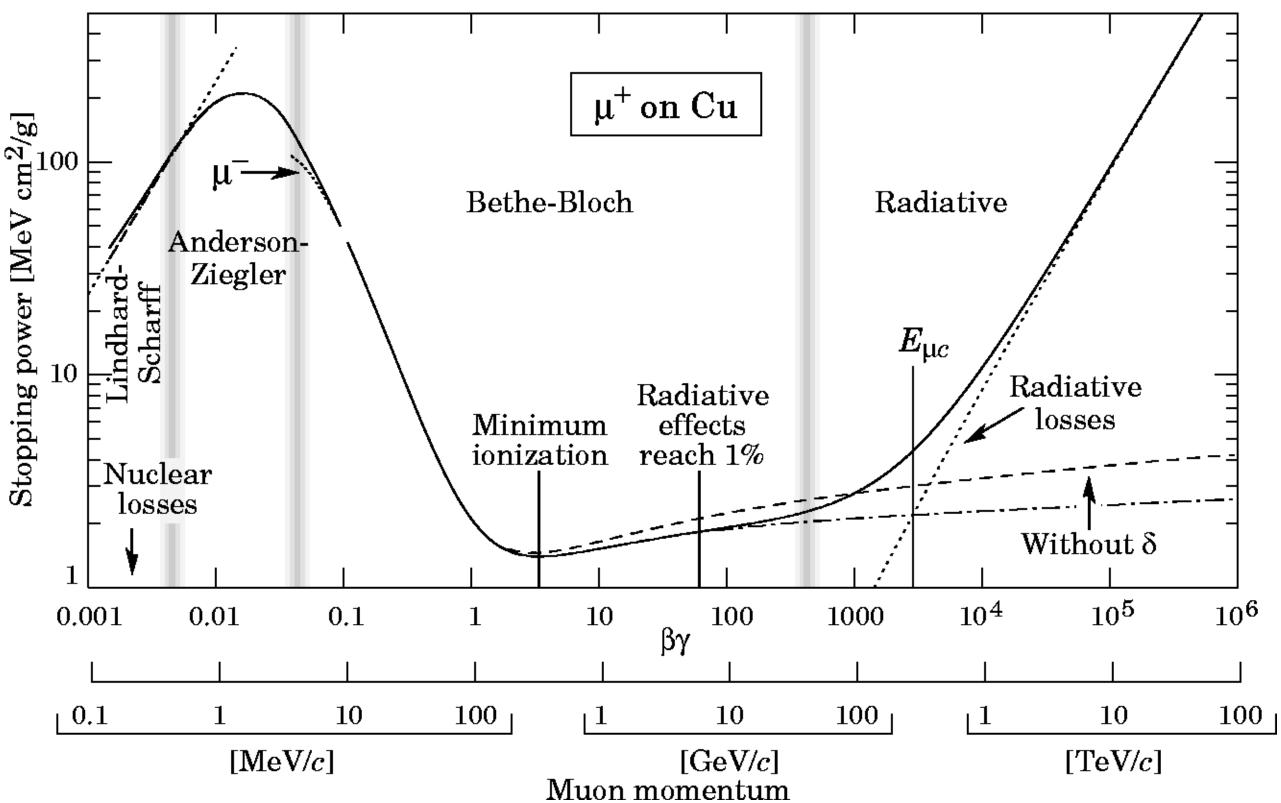
- TR photons have mainly low energies, but below a few keV they are usually stopped before they reach the gas.
- We're therefore concerned with γ-energies of 1-50 keV.
- Such γ's are detectable by photo-ionisation in e.g. Xe.



[Plot from Pavel Nevski]

Overview of $\mu^{\pm}$ energy losses

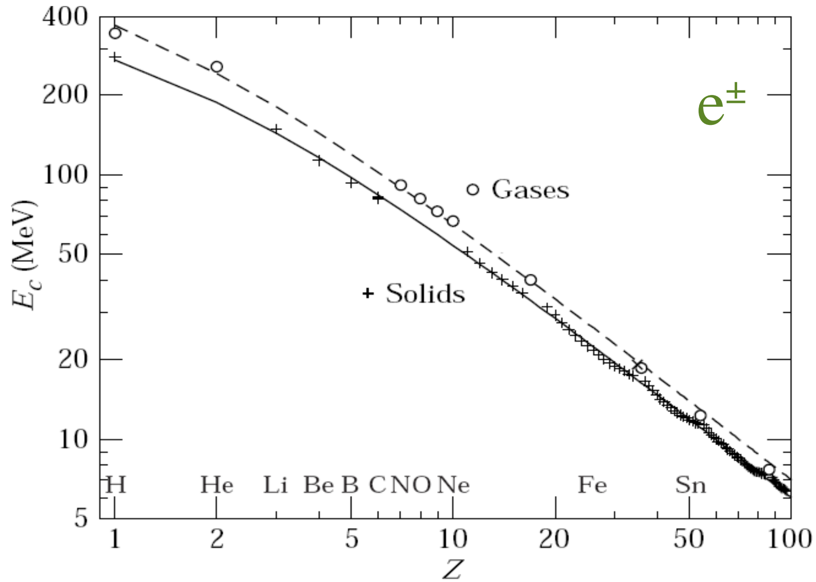
- We're usually concerned with MeV-GeV energies for which ionisation losses dominate.
- At high energy, Bremsstrahlung takes over.

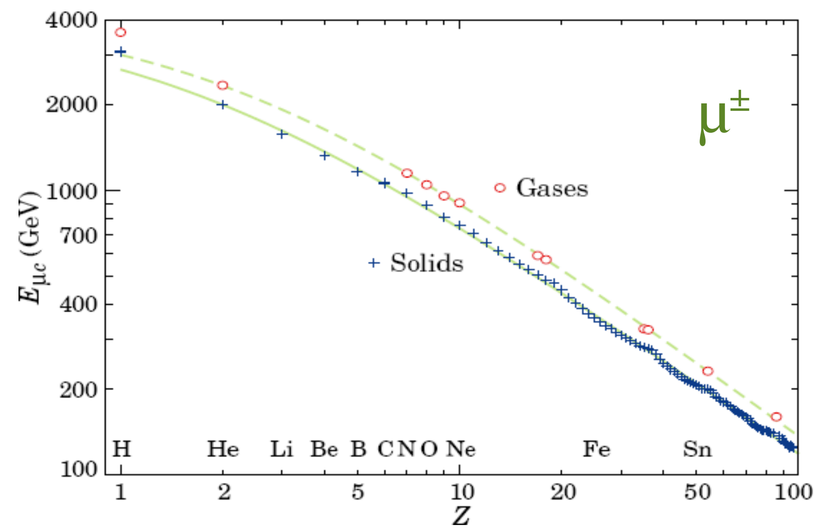


[Reproduced from the PDG, 2004 edition]

Why do $\mu^{\pm}$ penetrate so easily ?

- Few nuclear interactions (*cf.* $\pi^{\pm}$).
- Bremsstrahlung from $\mu^{\pm}$ starts at much higher energy than from $e^{\pm}$:
  - critical energy for $e^{\pm}$ is ~20 MeV but for $\mu^{\pm}$ it is ~ 400 GeV (depending on the materials)
  - observed in cosmic showers;
  - until recently, of minor importance for laboratory generated $\mu^{\pm}$ but occurs at LHC.



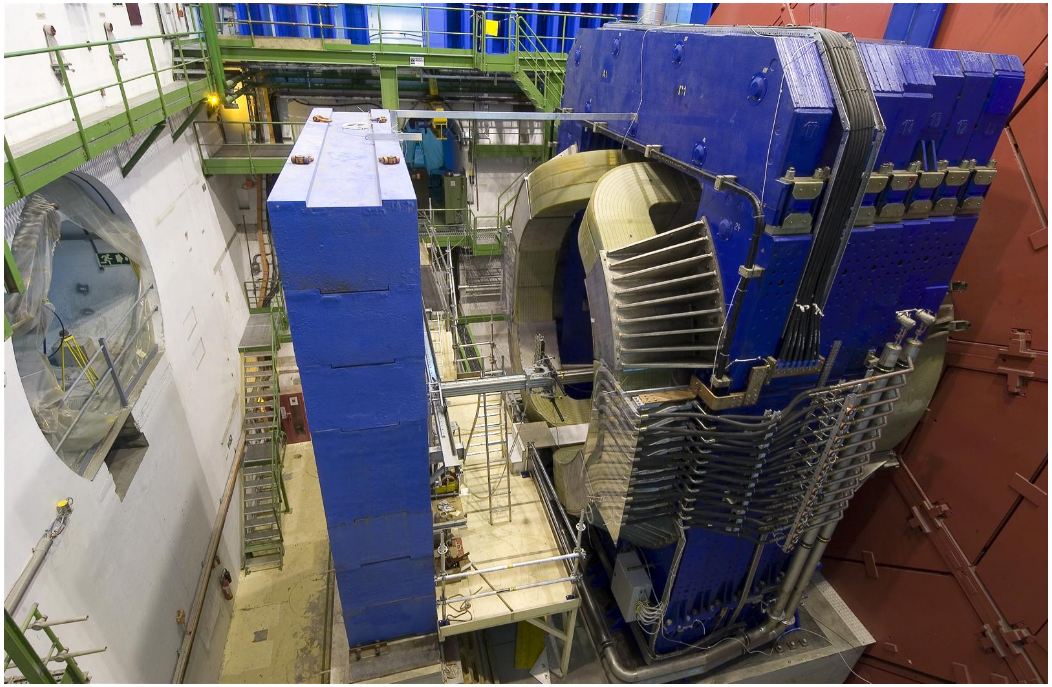


[Plots based on data computed by A. Fassò]

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

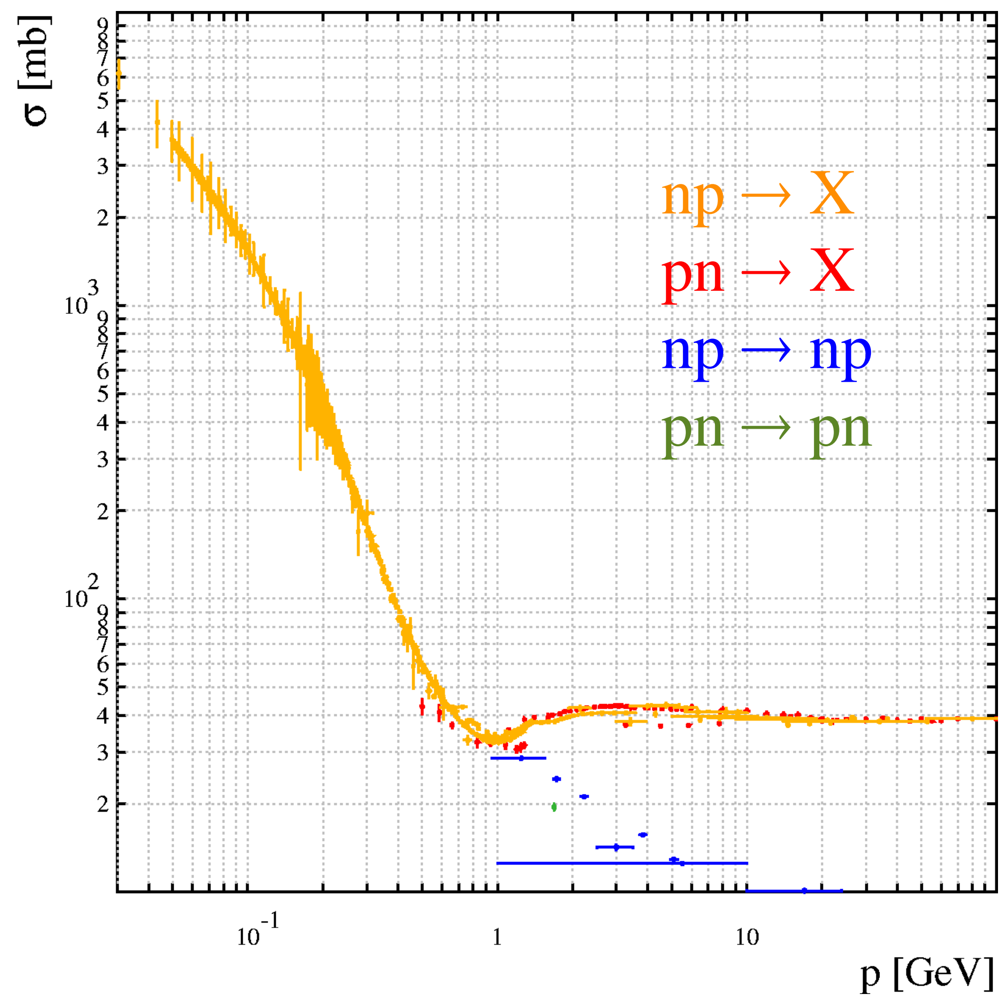
[Part of the Alice muon system]

Interactions of 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 – proton collisions

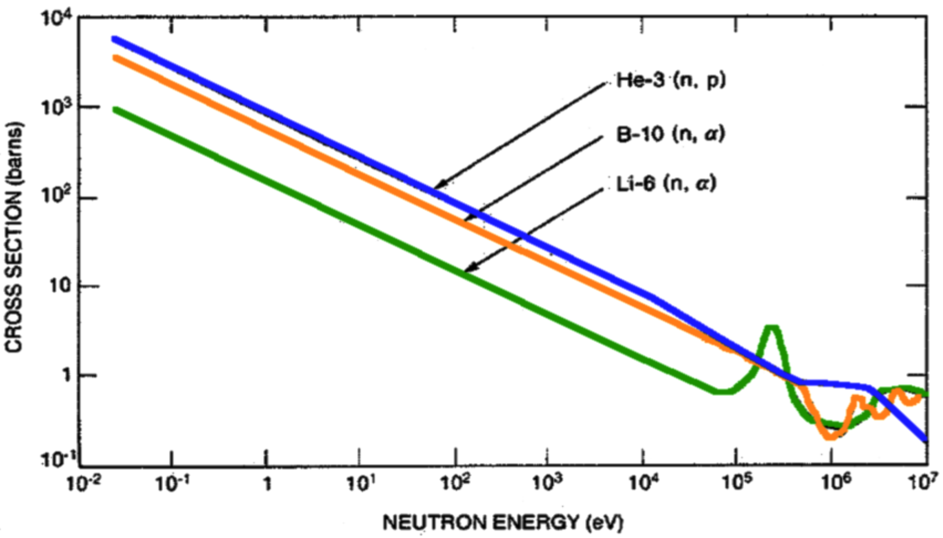
- Around 1 GeV, pn collisions are mainly elastic.
- Neutron cross sections at low energy are *very* large and complex.
- At higher energies, they are mainly nuclear with a cross section similar to pp.



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}He $\rightarrow$ ^{3}H p + 765 keV
  - nuclear reaction
    - n ^{10}B $\rightarrow$ ^{7}Li* ^{4}He + 2310 keV,
    - ^{7}Li* $\rightarrow$ ^{7}Li + 480 keV



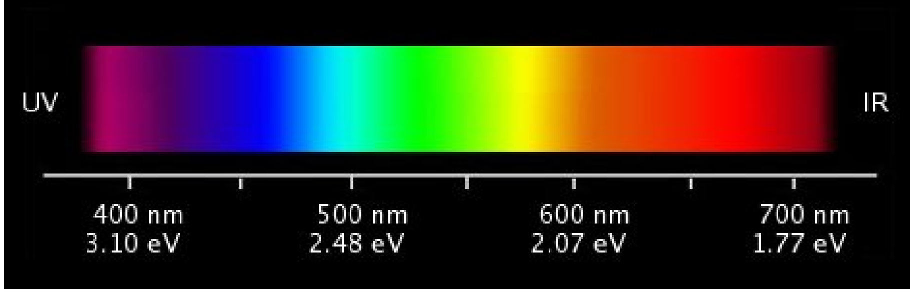
[Adapted from TW Crane and MP Baker, Neutron detectors]

Summary

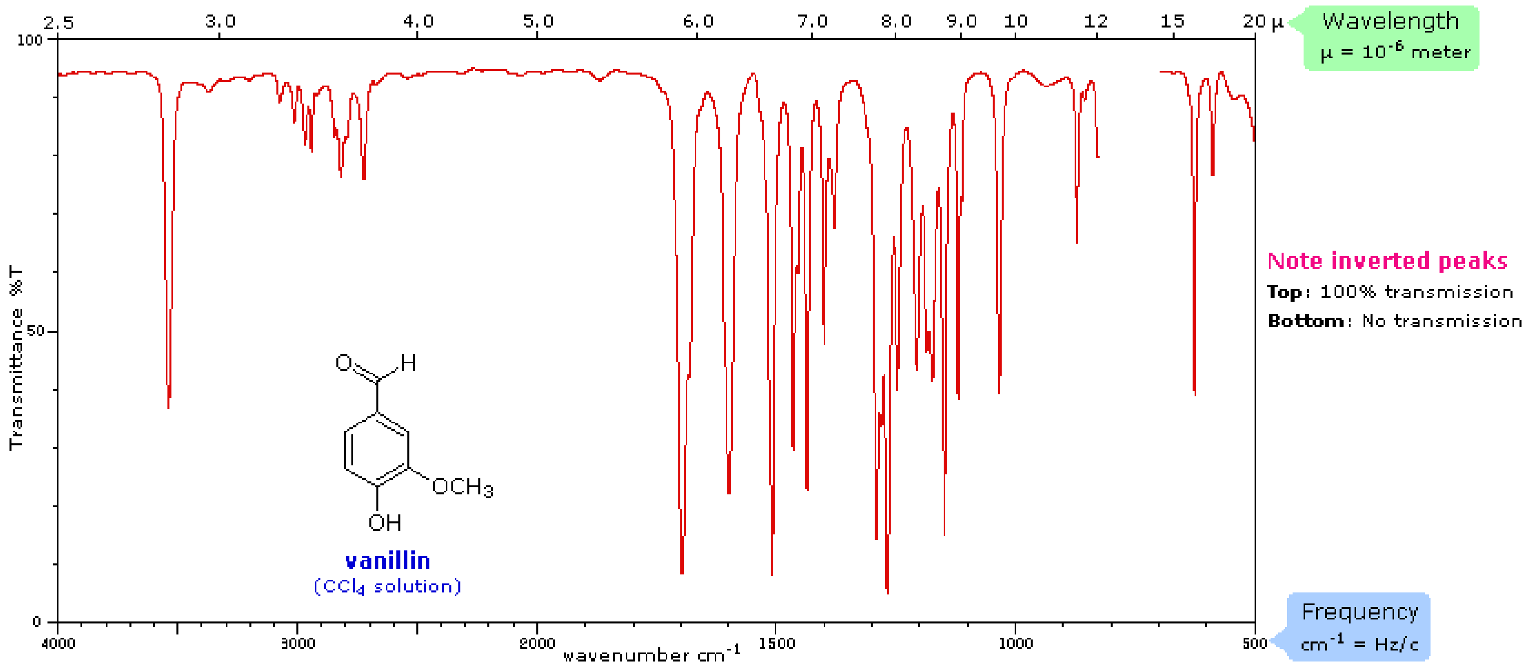
- Neutrinos
  - Charged and Neutral current
- Photons:
  - Photo-electric – Compton scattering – Pair production
- Charged particles:
  - Ionisation – Čerenkov radiation – Nuclear interactions
- Electrons
  - + Bremsstrahlung – Transition radiation
- Muons
  - + Multiple scattering & Energy loss – Bremsstrahlung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

Unused slides

Sub-eV γ's



- $\epsilon < 1$ meV: Microwaves, molecular rotations of materials with a dipole moment (water), used in a microwave oven
- $\epsilon < 1.8$ eV: Infrared, molecular vibrations are excited



[From William Reusch, MSU]

Materials we use

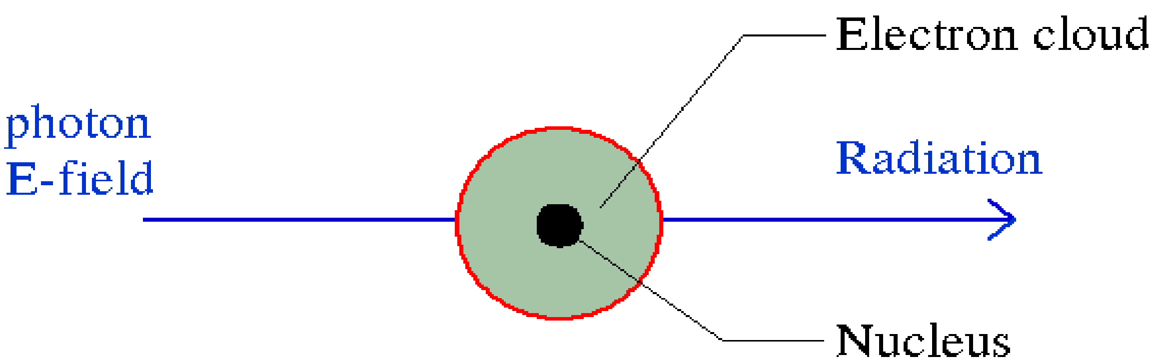
- The physics pursued may be exotic, and the energies high, but the materials used are relatively common.

- Commonly used:
  - calorimeters: Pb, Fe, Cu, U ...
  - scintillators: crystals, plastics,
  - semi-conductor trackers: Si, Ge, ...
  - gas-based tracking: Ar, Ne, Xe, CO_2 ... + W, Be, ...
  - construction: Al, steel, carbon-fibre, glass-fibre, epoxy
  - electronics,
  - cooling fluids: CO_2, freons, ...

JohnWilliam Strutt,
3rd Baron Rayleigh of
Terling Place
(1842-1919)

Rayleigh scattering

- Photon scatters elastically on (quasi) free electrons, inducing dipole radiation, without loss of energy.
- Larger at high energy (short wavelength): $P \propto \cos^2\theta/\lambda^4$ probably best known for making the sky appear blue.
- Almost never the dominant contribution.
- *Not a source of electrons*, but affects shower shapes.



[Animation: ENS Lyon]

Basics of the PAI model


Wade Allison


John Cobb

- Key ingredient: photo-absorption cross section $\sigma_\gamma(E)$

$$\frac{\beta^2\pi}{\alpha}\frac{d\sigma}{dE} = \frac{\sigma_\gamma(E)}{E}\log\left(\frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2}}\right)+$$

Relativistic rise

$$\frac{1}{N\hbar c}\left(\beta^2-\frac{\epsilon_1}{|\epsilon|^2}\right)\theta+$$

Čerenkov radiation

$$\frac{\sigma_\gamma(E)}{E}\log\left(\frac{2m_e c^2\beta^2}{E}\right)+$$

Resonance region

$$\frac{1}{E^2}\int_0^E \sigma_\gamma(E_1)\,dE_1$$

Rutherford scattering

Cross section to transfer energy E

With:

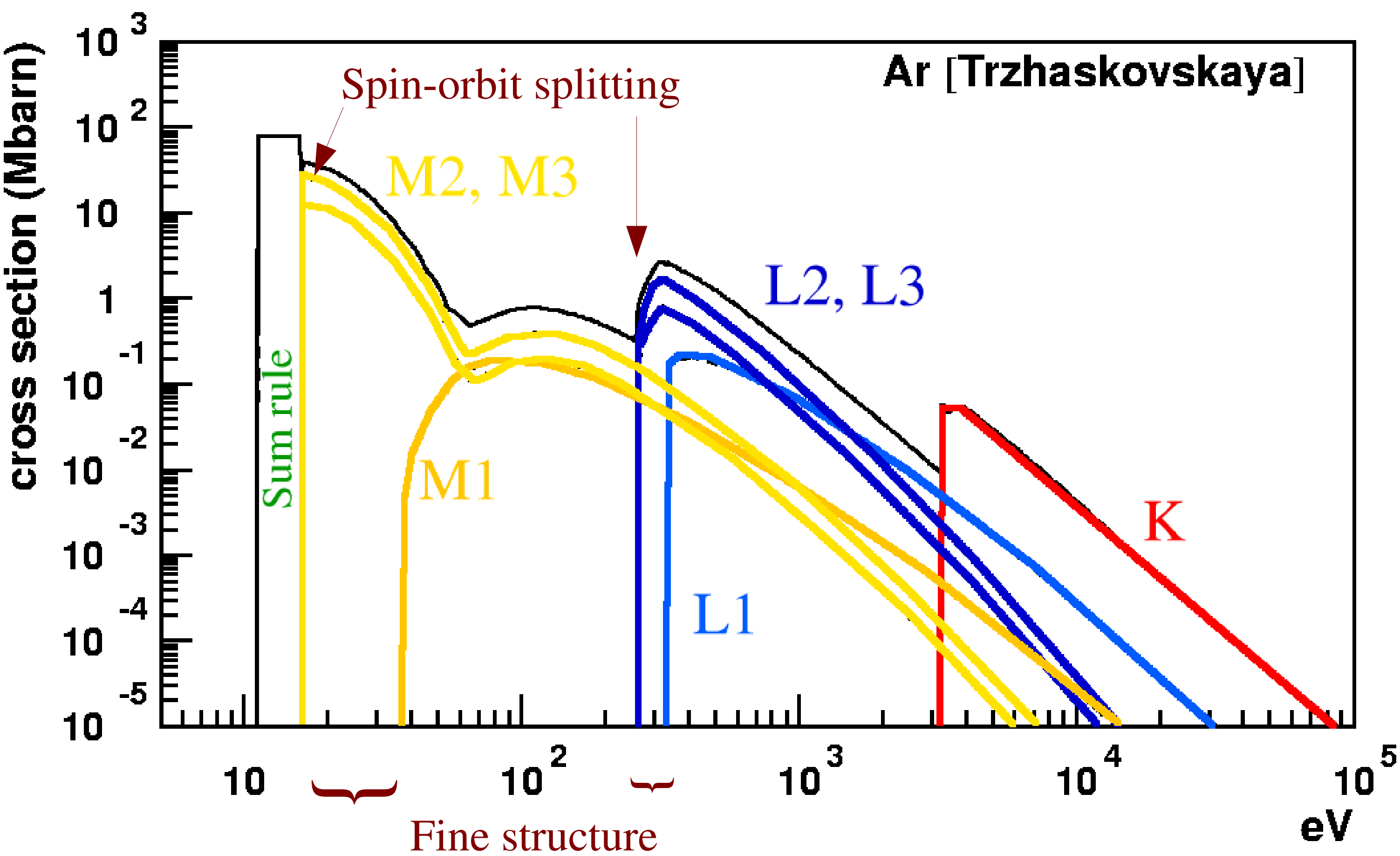
$$\epsilon_2(E) = \frac{N_e\hbar c}{EZ}\sigma_\gamma(E)$$

$$\epsilon_1(E) = 1+\frac{2}{\pi}\mathrm{P}\int_0^\infty \frac{x\,\epsilon_2(x)}{x^2-E^2}\,dx$$

$$\theta = \arg(1-\epsilon_1\beta^2+i\,\epsilon_2\beta^2) = \frac{\pi}{2}-\arctan\frac{1-\epsilon_1\beta^2}{\epsilon_2\beta^2}$$

Photo-absorption in argon

- Argon has 3 shells, hence 3 groups of lines:



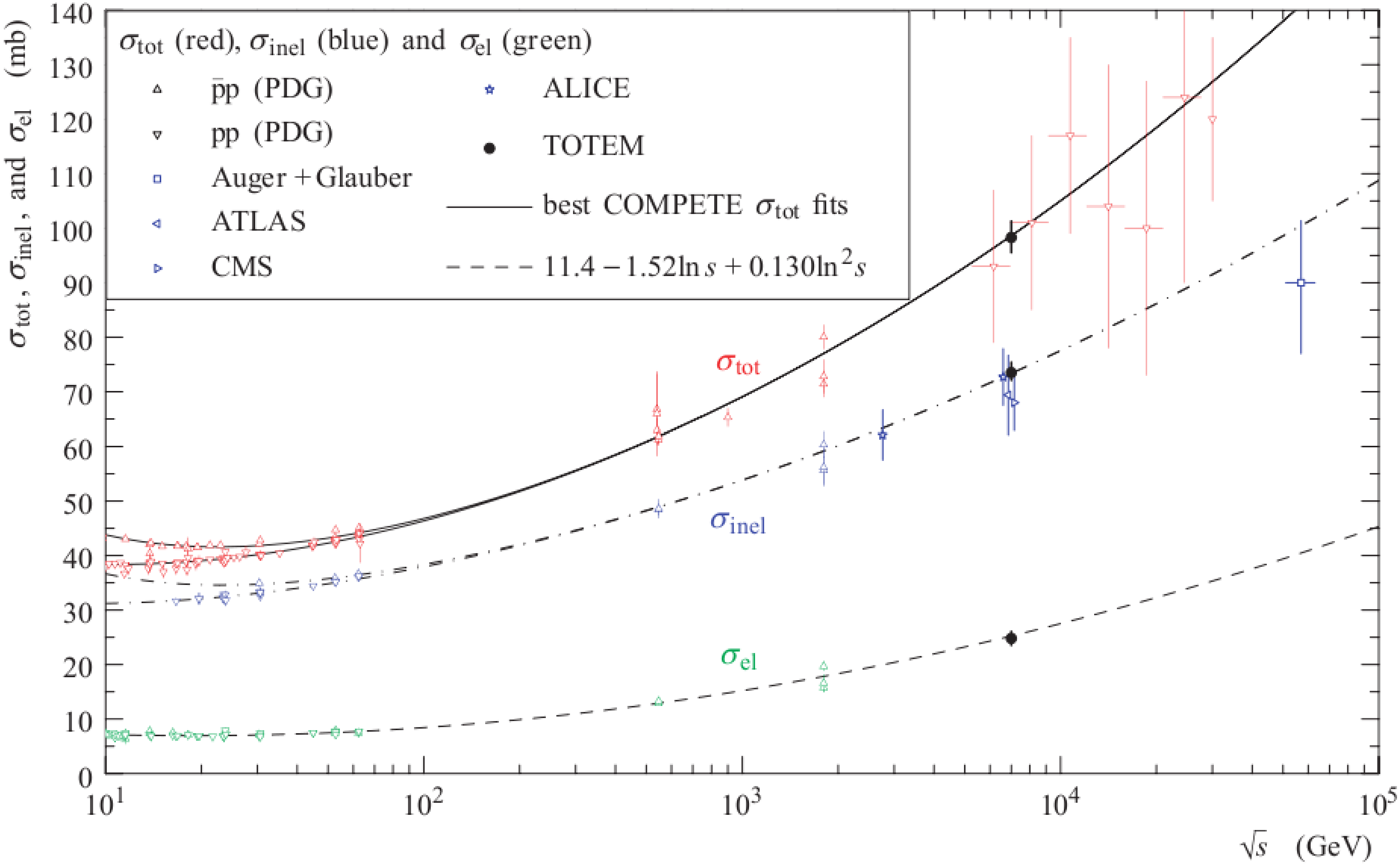
K = 1s

L1 = 2s
L2 = 2p 1/2
L3 = 2p 3/2

M1 = 3s
M2 = 3p 1/2
M3 = 3p 3/2

[Plot from Igor Smirnov]

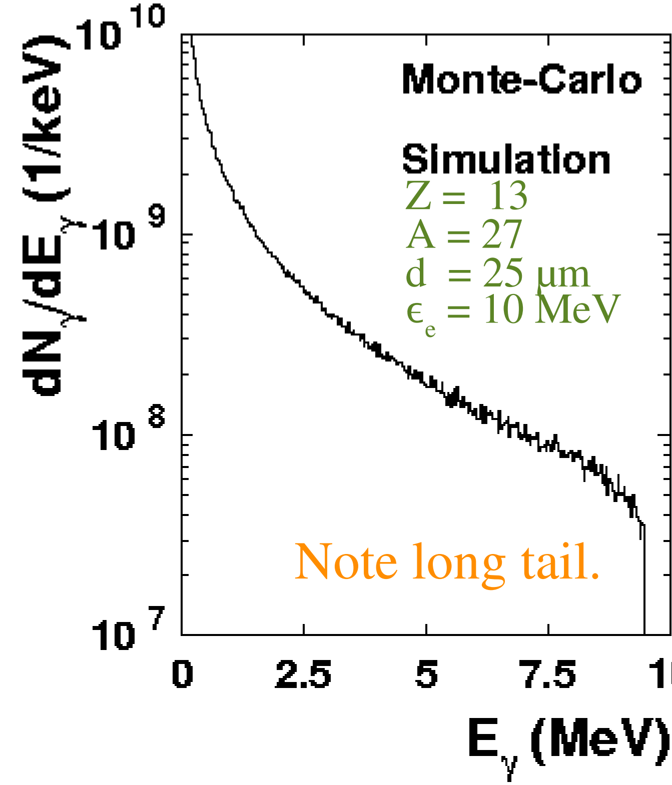
Cosmic ray experiments vs LHC

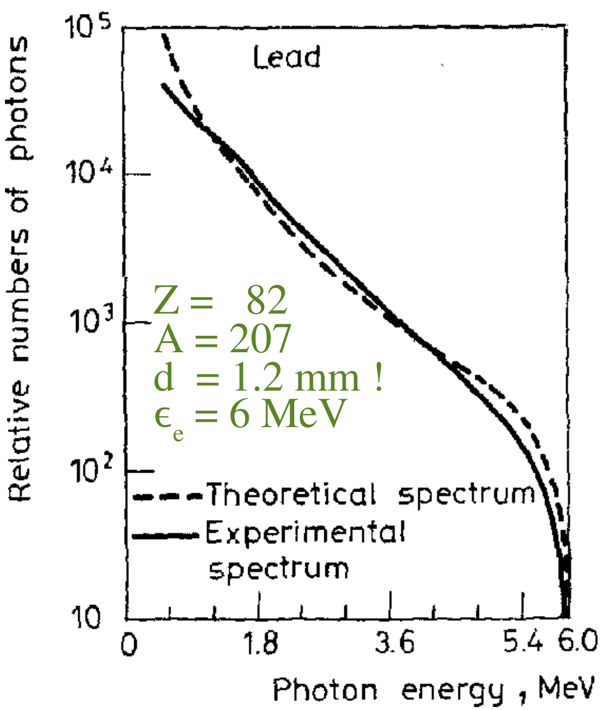


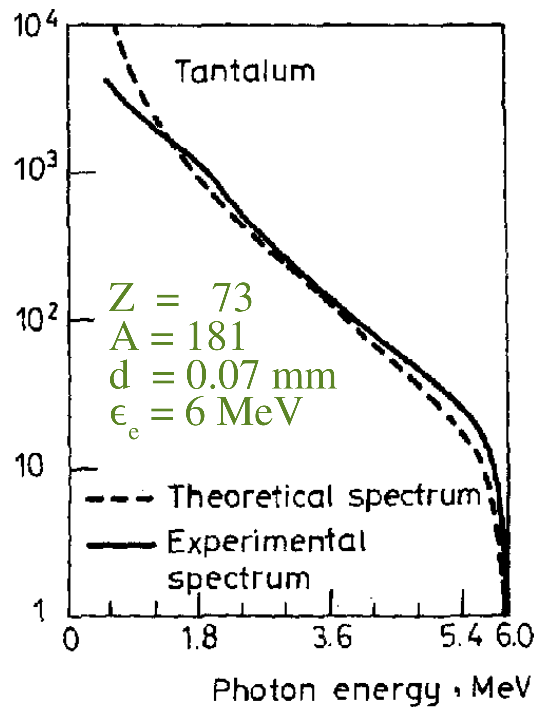
[TOTEM Collaboration, EPL (2011) 96 21002.]

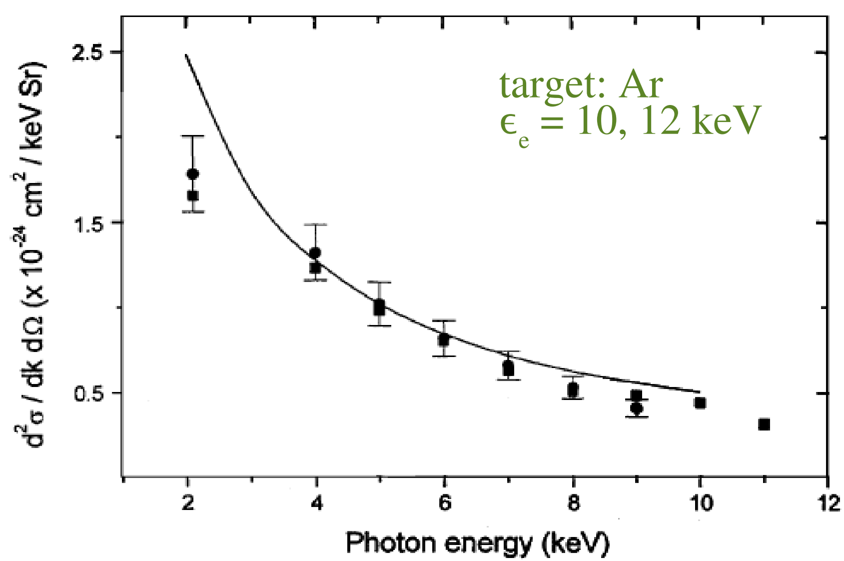
Bremsstrahlung spectra

- The *shape* does not depend much on the target material, but does depend on the thickness and the energy.





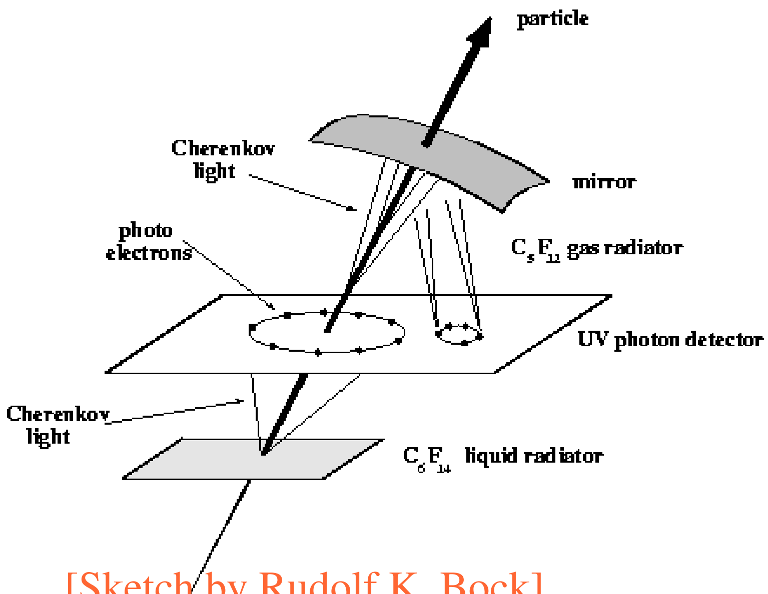




[Left: V.S. Deshmukh, V.N. Bhoraskar, J. Radioanal. Nucl. Chem., Letters **103(2)** (1986) 87-94; Right: R. Shanker, Rad. Phys. and Chem. **75** (2006) 1176–1186; Top: FZD.]

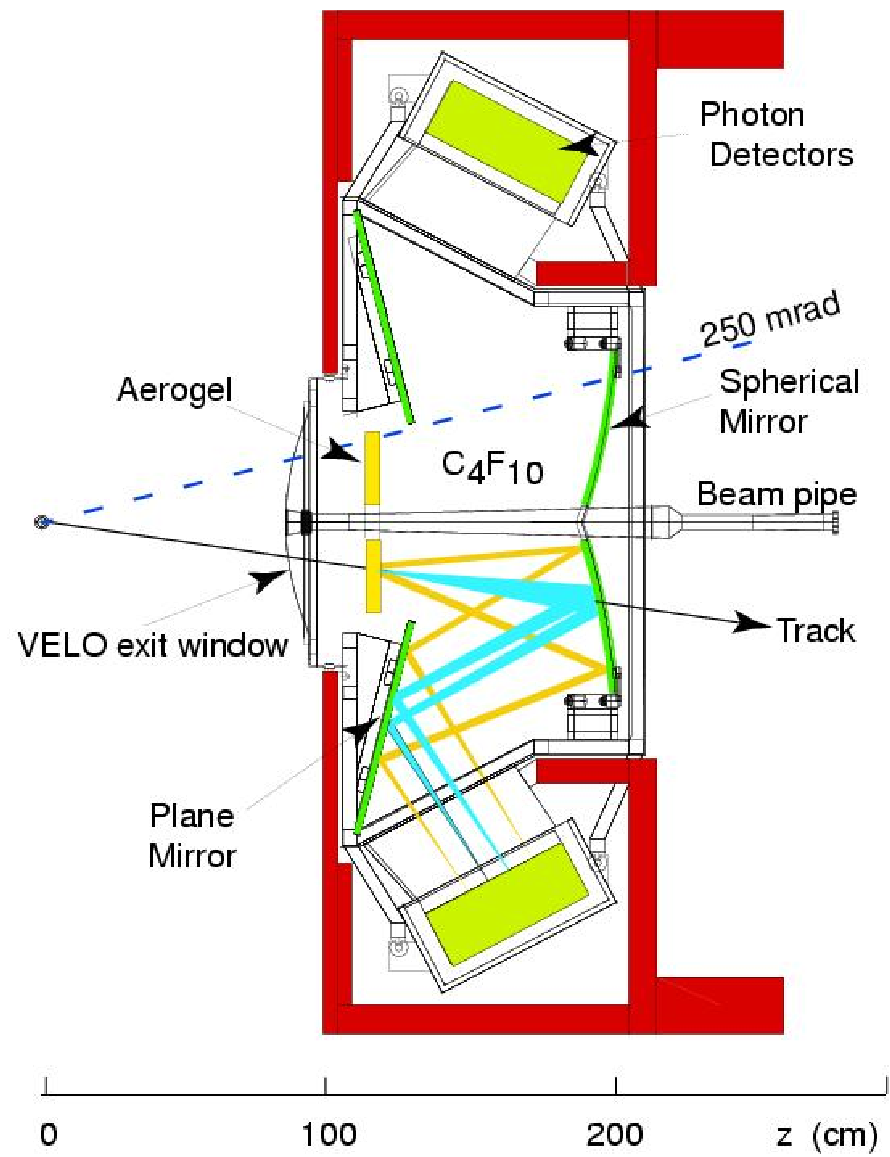
Čerenkov detectors: examples

- To see the ring, 2 options:
  - direct focusing: thin, usually liquid radiator
  - mirror focusing: also thick radiators, e.g. a gas

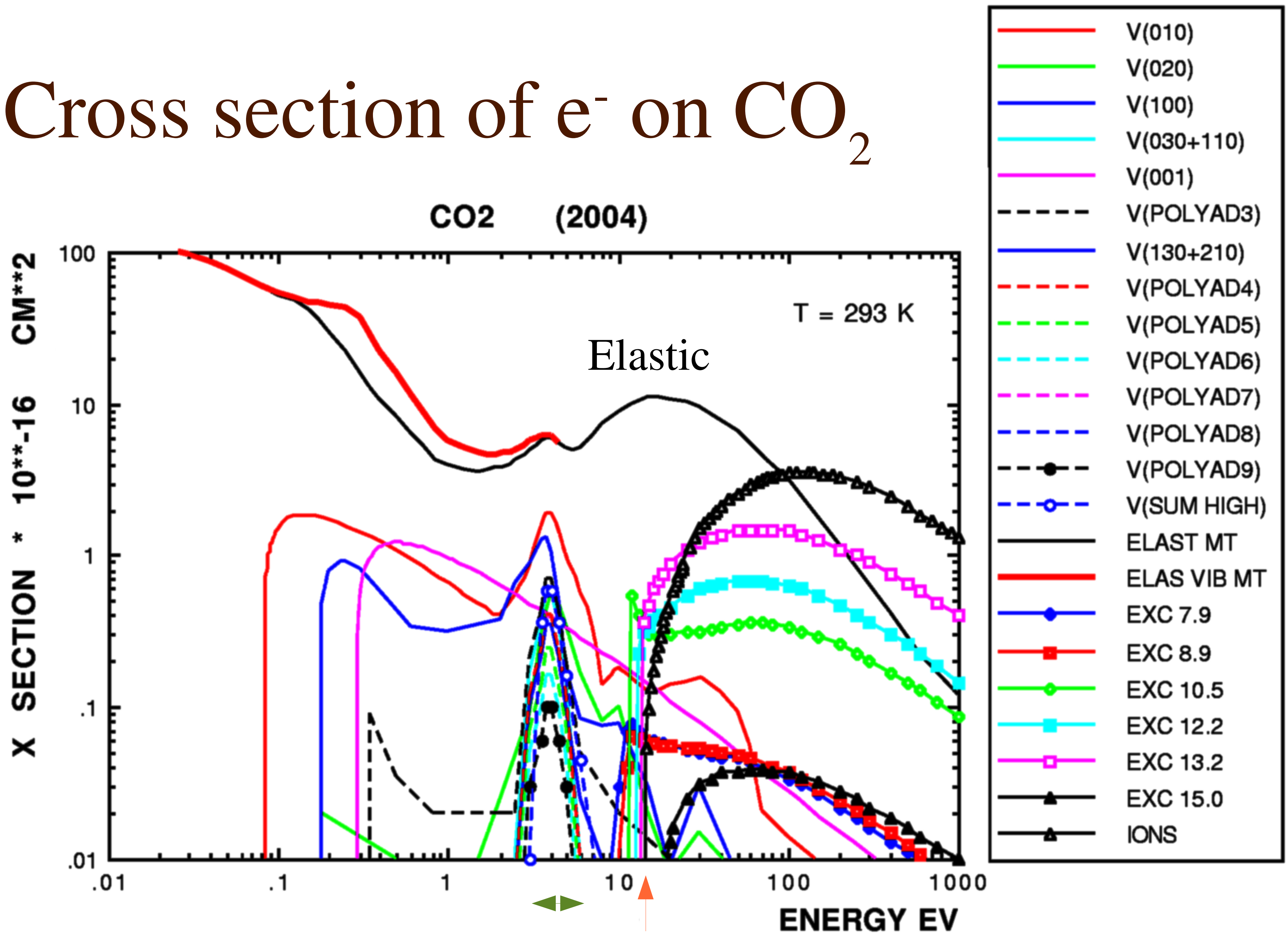


[Sketch by Rudolf K. Bock]

[LHCb RICH1]



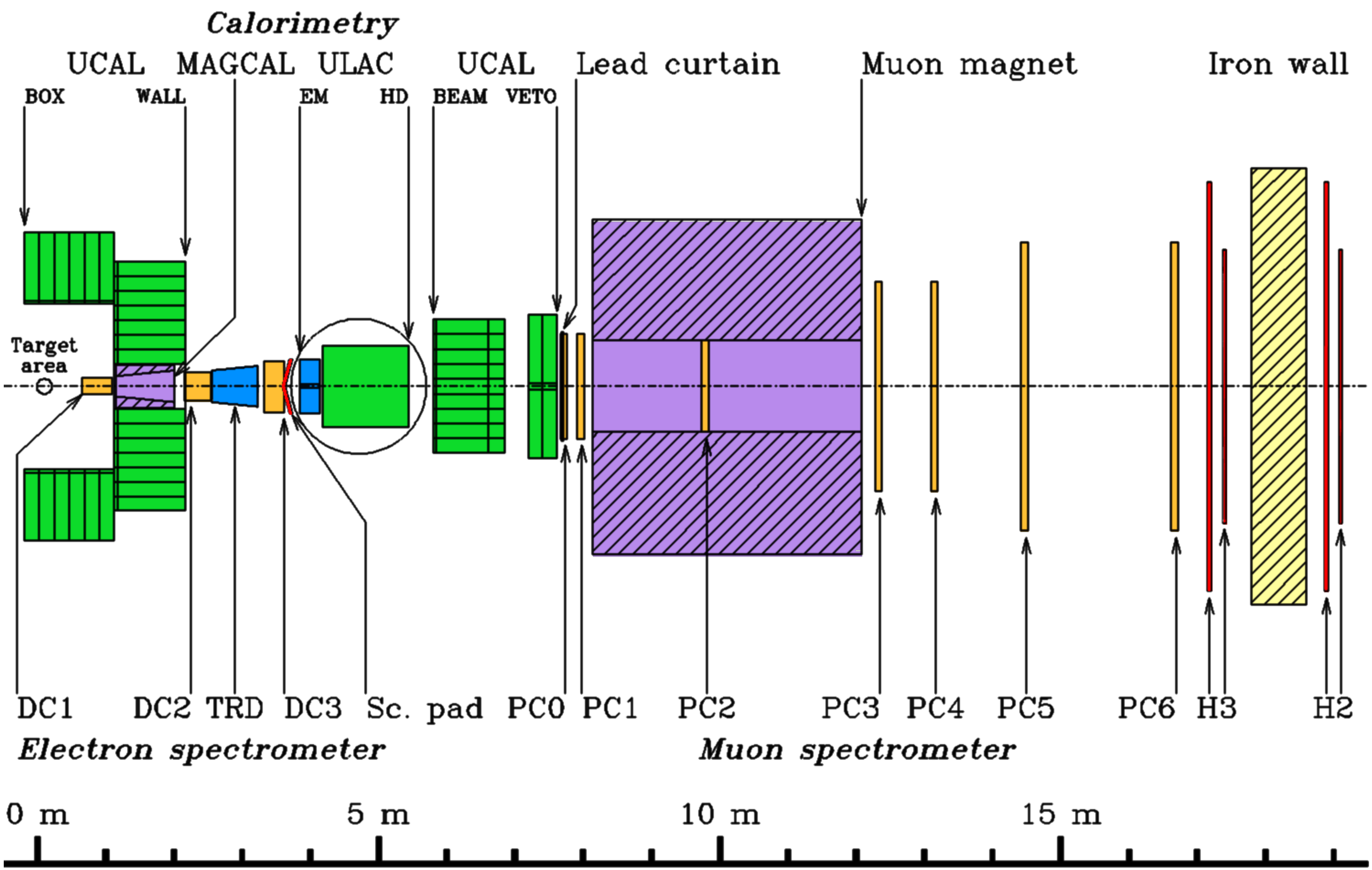
Cross section of e^- on CO_2



Attachment range:
4 eV < ϵ < 8 eV

Ionisation threshold:
ϵ = 13.8 eV

Helios/I layout (1989)



Multiple scattering & Energy loss

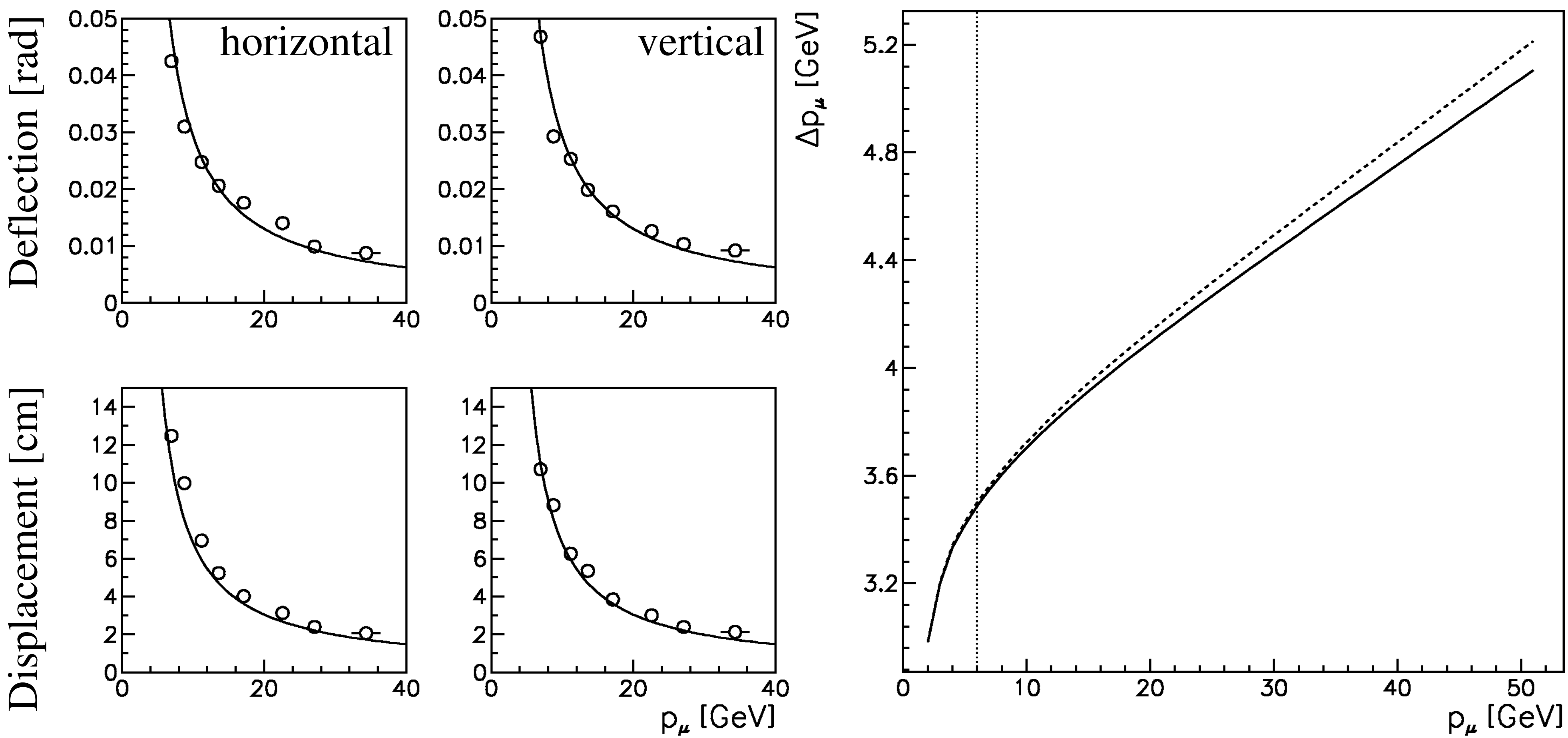
- Caused by repeated elastic EM scattering by charged particles that traverse thick layers of material.

- Particularly relevant for $\mu^{\pm}$ in high-energy physics, but also common for low-energy $e^{\pm}$.

- Hadrons generally undergo nuclear interactions before multiple scattering and energy loss become significant.

Multiple scattering and Energy loss

- Muons before and after 320 radiation lengths and 13 interaction lengths, mostly U.



Neutron capture

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