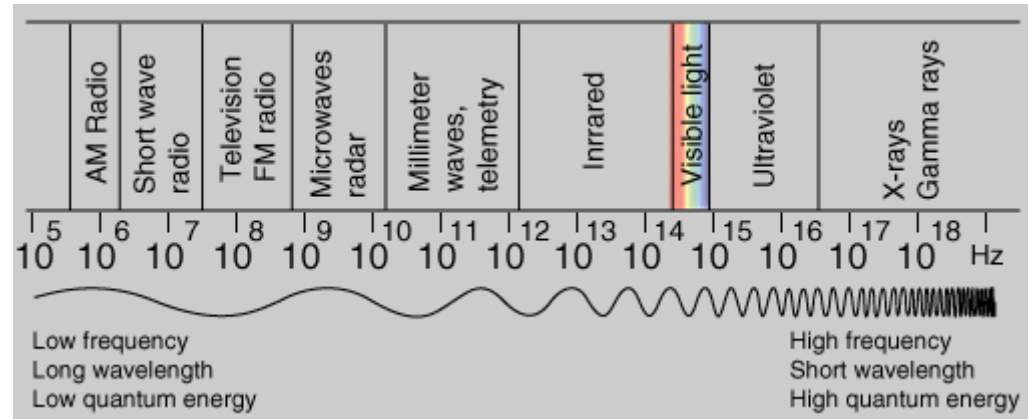


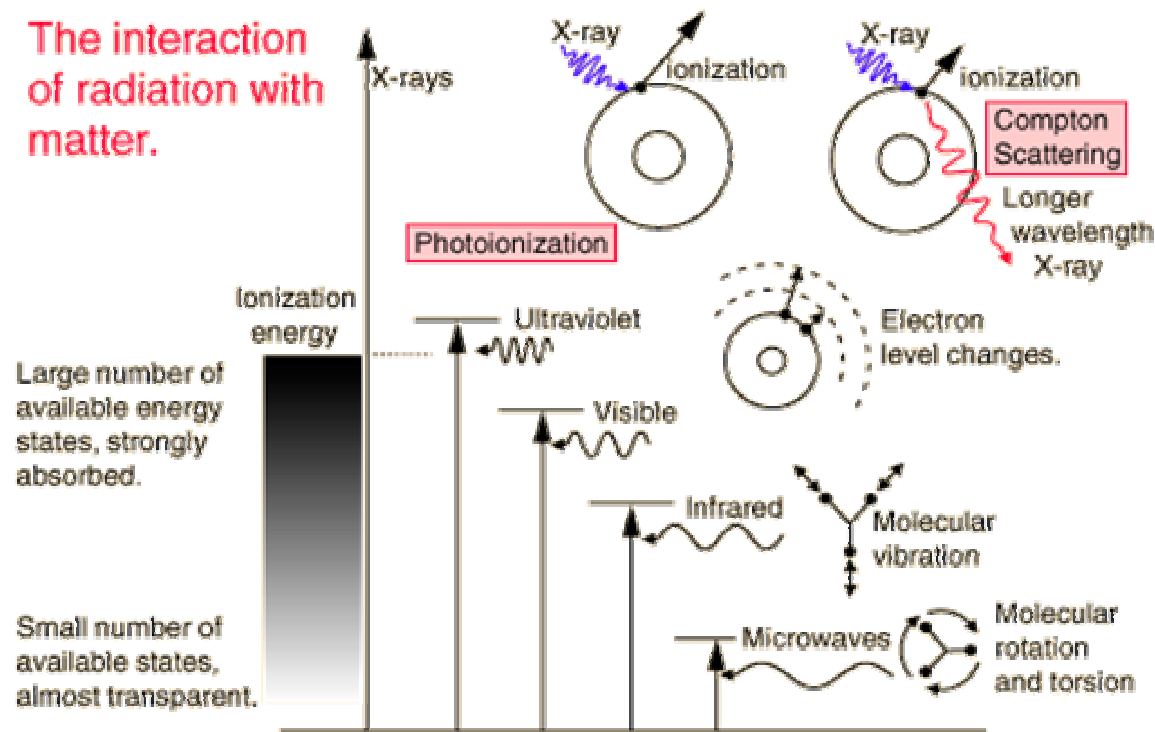
Interazioni di fotoni ed elettroni



Interazioni di fotoni (1)



The interaction of radiation with matter.



Interazioni di fotoni (2)

Effetto fotoelettrico

$$\sigma = \sqrt{\frac{32}{\varepsilon^7}} \alpha^4 Z^5 \left(\frac{8}{3} \pi r_e^2 \right)$$

$$\varepsilon = E/m_e c^2$$

Effetto Compton

$$\sigma = 2\pi r_e^2 Z \left\{ \frac{1+\varepsilon}{\varepsilon^2} \left[\frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{\ln(1+2\varepsilon)}{\varepsilon} \right] + \frac{\ln(1+2\varepsilon)}{2\varepsilon} - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right\} \text{ cm}^2/\text{elettrone}$$

Klein-Nishina

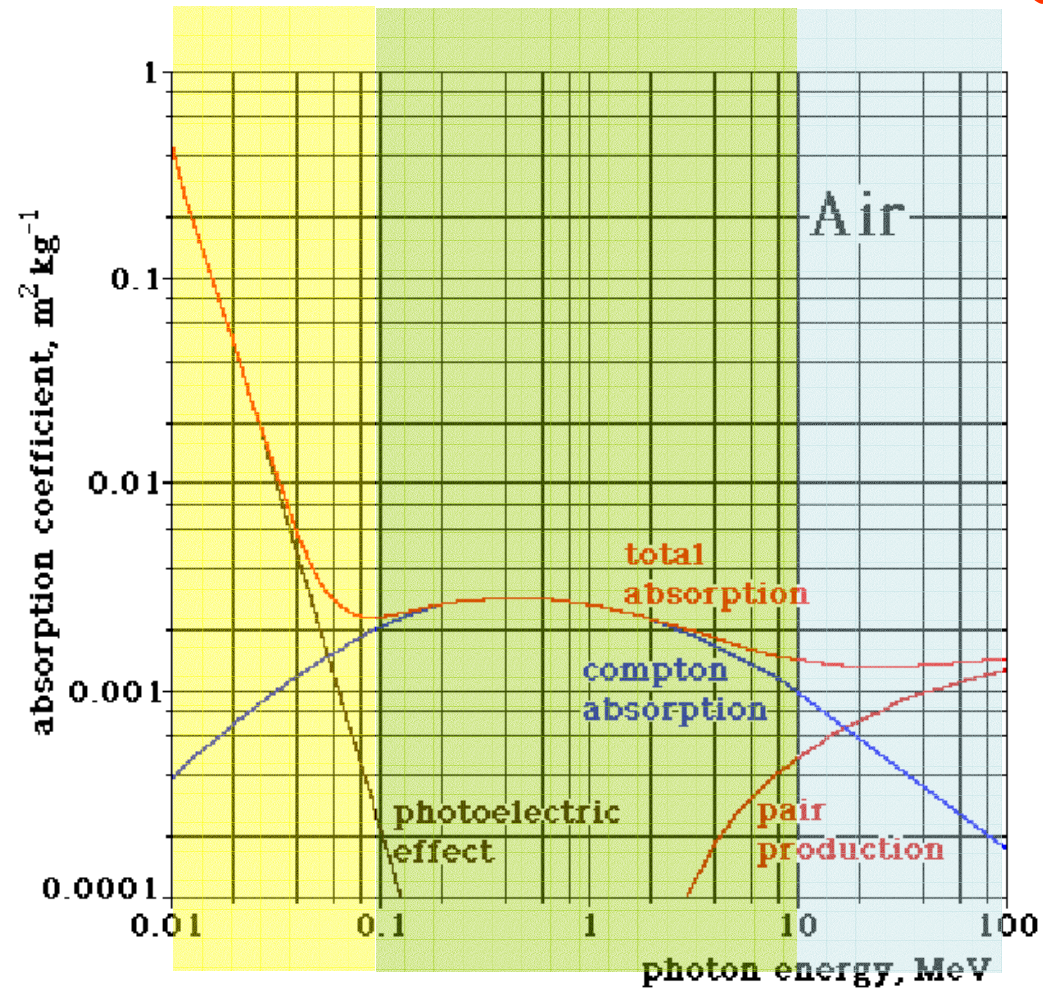
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'}{E} \right)^2 \left(\frac{E}{E'} + \frac{E'}{E} - \sin^2 \theta \right)$$

Produzione di coppie

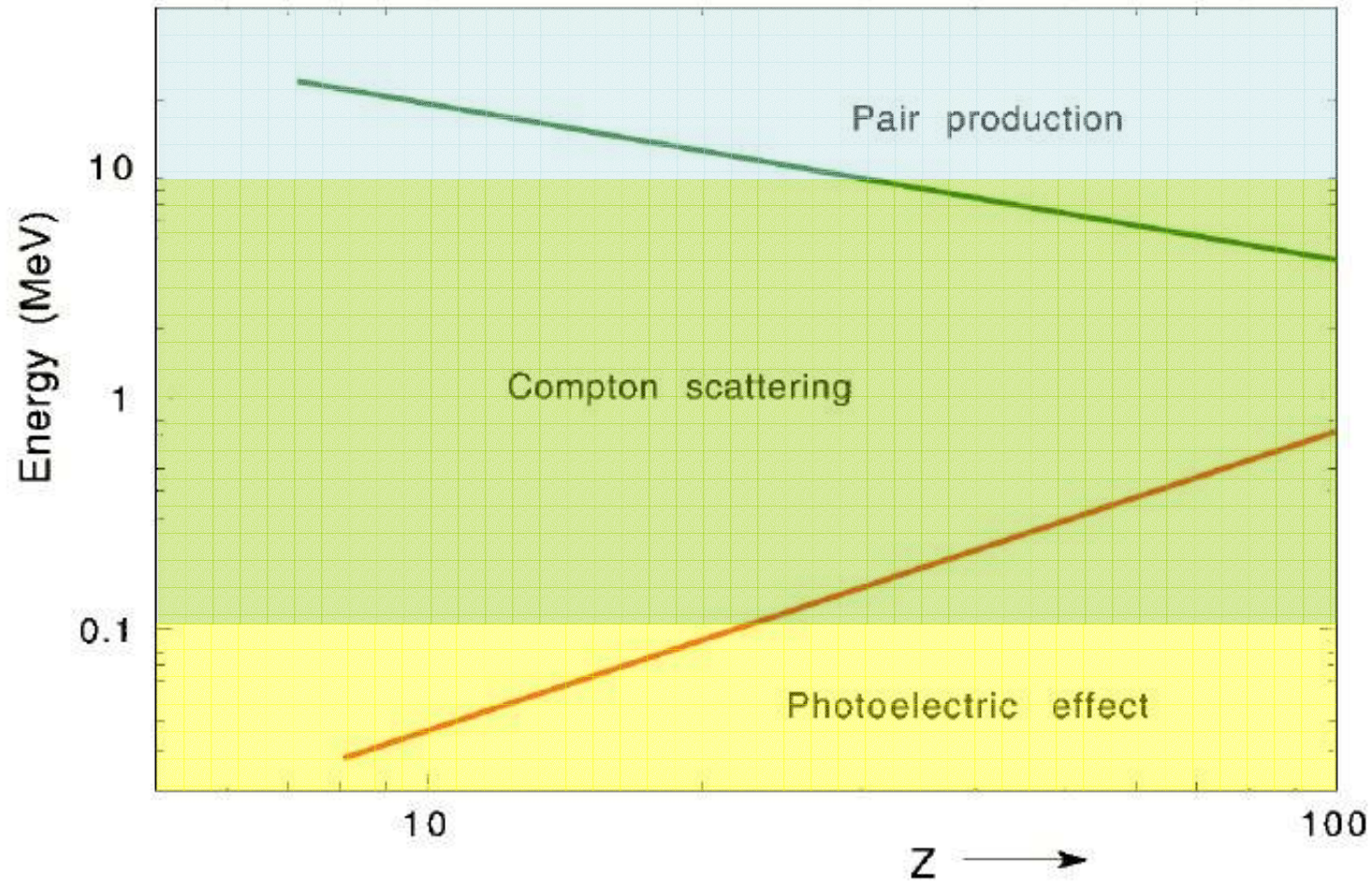
$$\sigma = 4\alpha r_e^2 Z^2 \left[\frac{7}{9} \ln \left(\frac{183}{Z^{1/3}} \right) - \frac{1}{54} \right] \text{ cm}^2/\text{atomo}$$

Alte energie
($\varepsilon \gg 1/\alpha Z^{1/3}$)

Interazioni di fotoni (3)



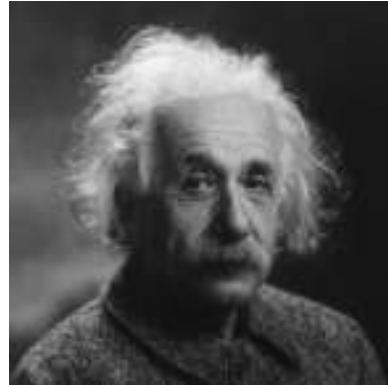
Interazioni di fotoni (4)



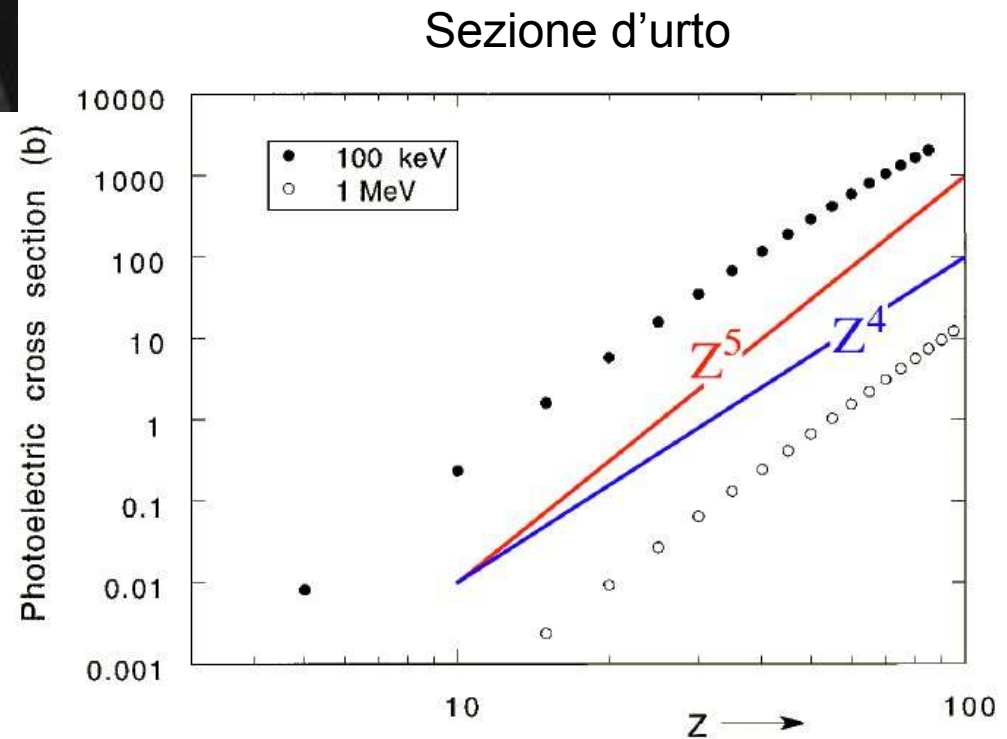
Effetto fotoelettrico (1)



Joseph John Thomson
(1856-1940)
Nobel 1906

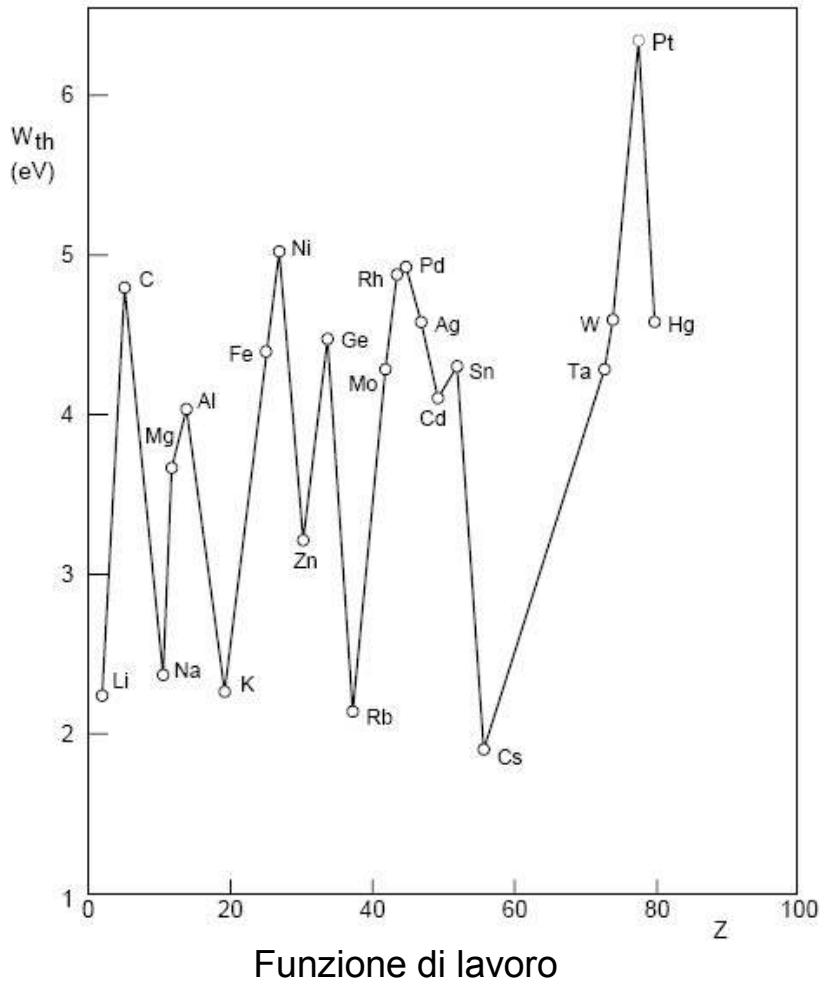


Albert Einstein
(1879-1955)
Nobel 1921



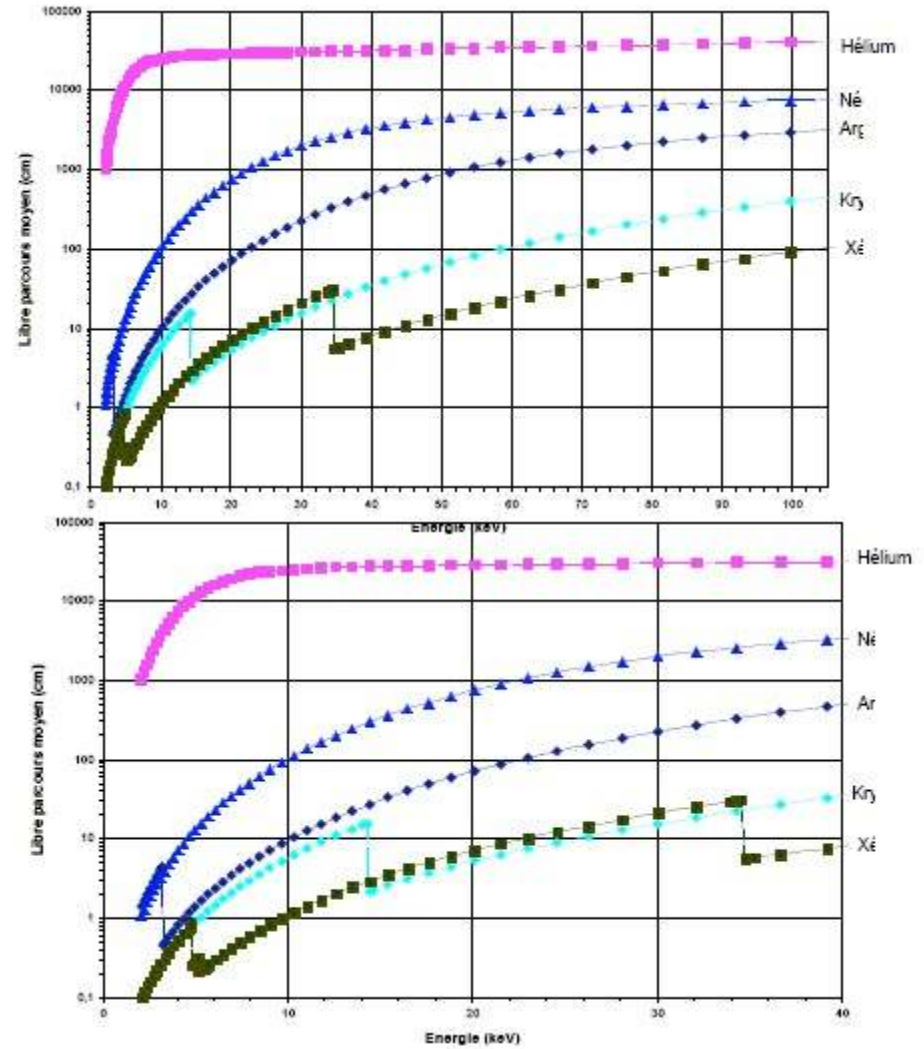
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Effetto fotoelettrico (2)



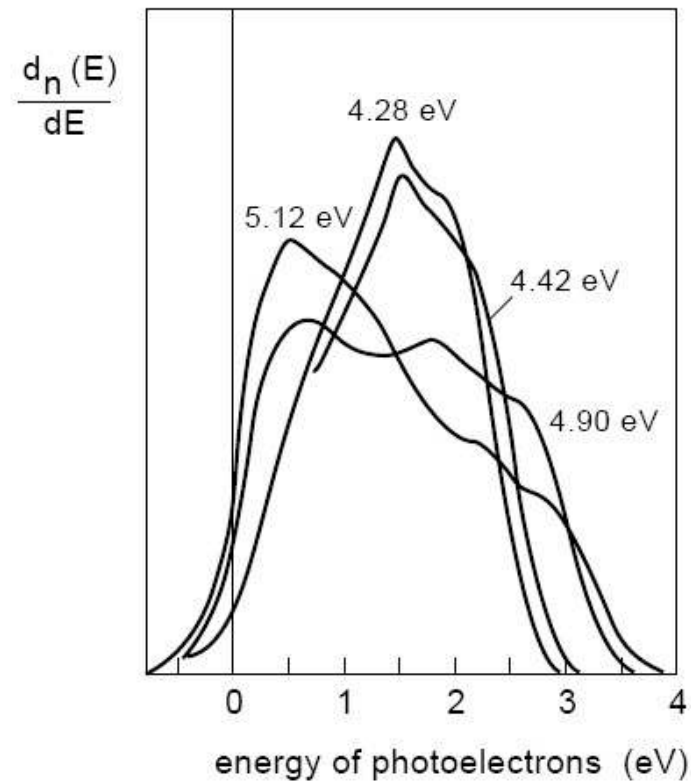
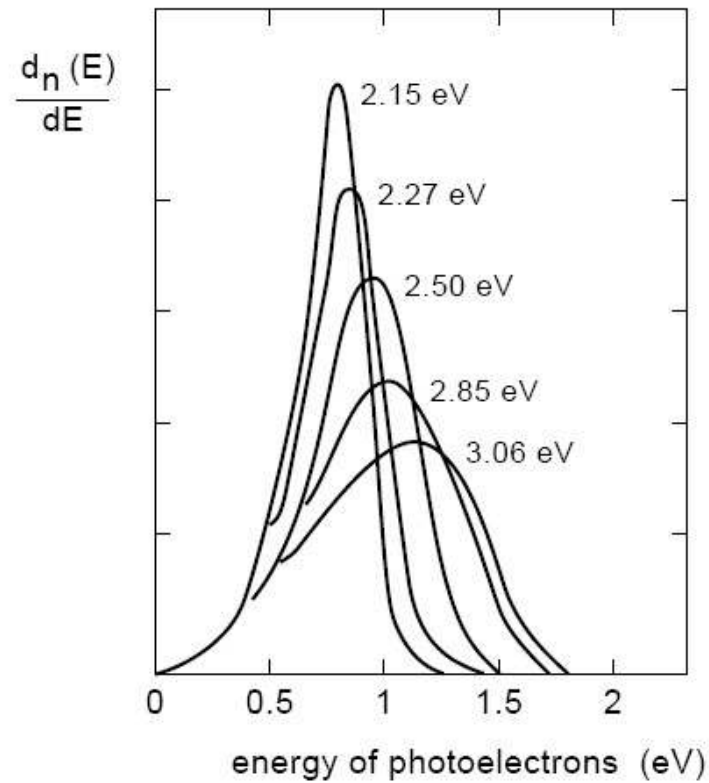
M. Sozzi

Cammino libero medio



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Effetto fotoelettrico (3)

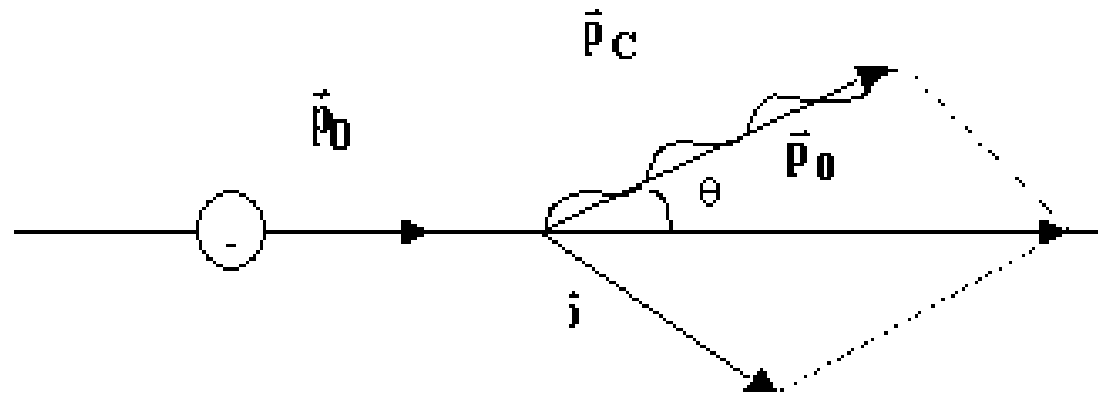


Spettro energetico dei foto-elettroni

Effetto Compton (1)



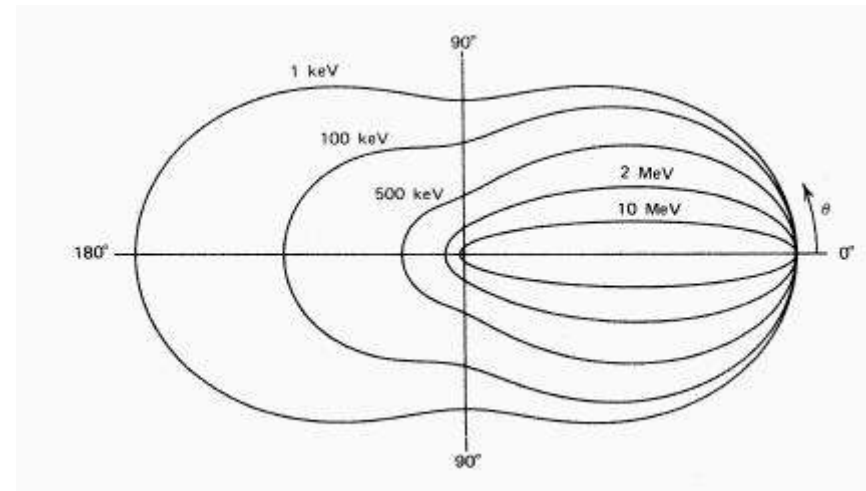
Arthur Holly Compton
(1892-1962)
Nobel 1927



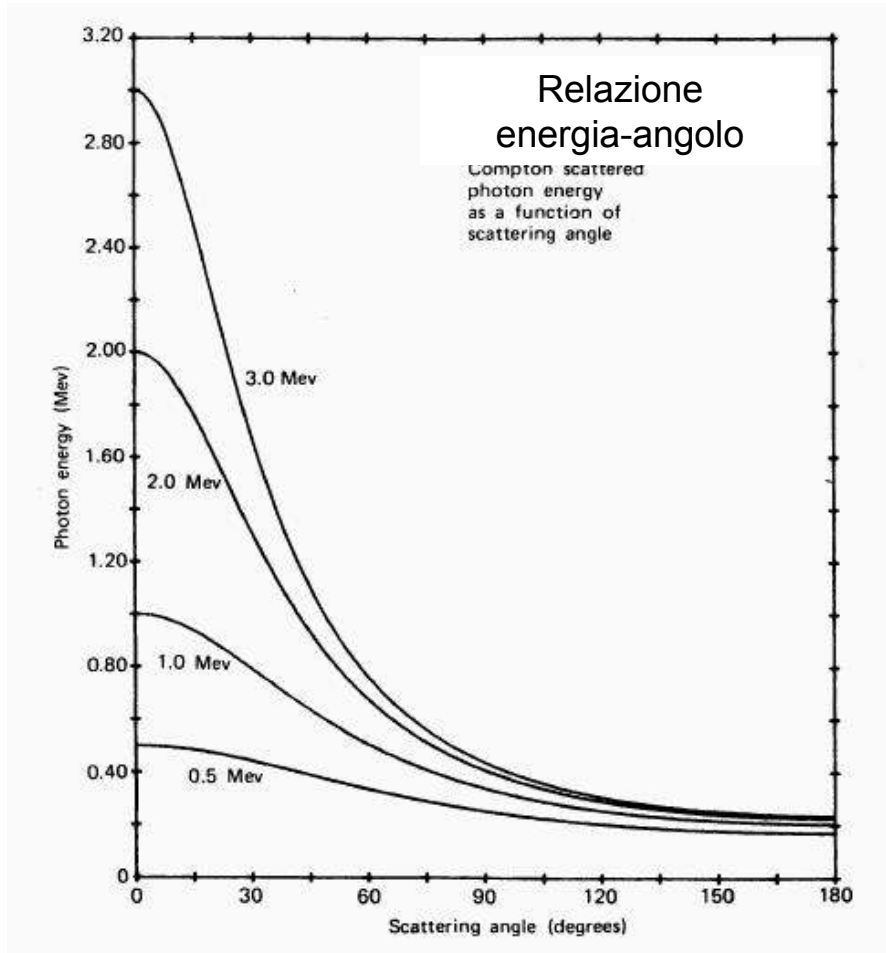
Oskar Klein
(1894-1977)



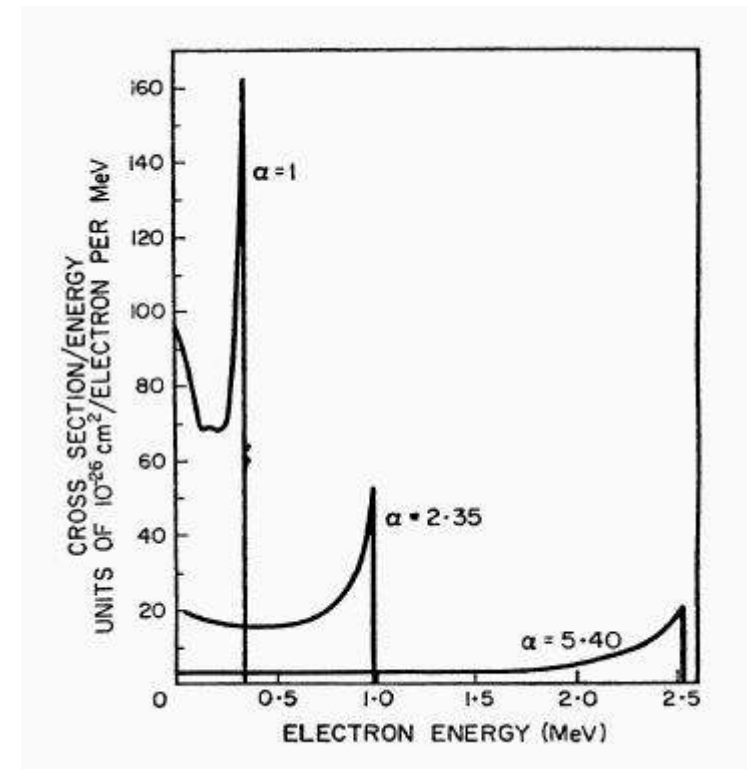
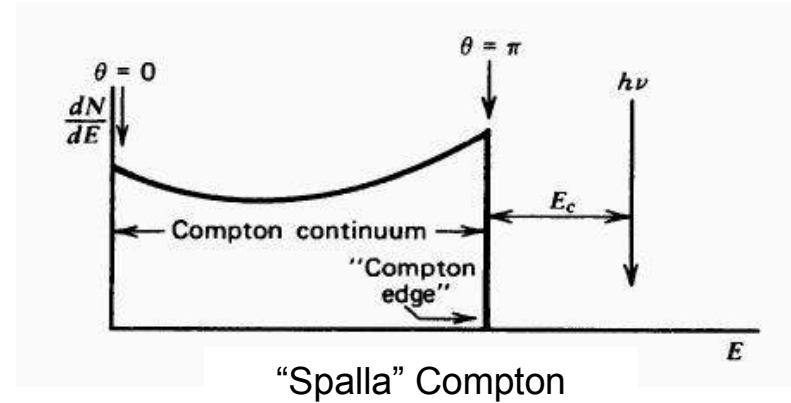
Yoshio Nishina
(1890-1951)]



Effetto Compton (2)

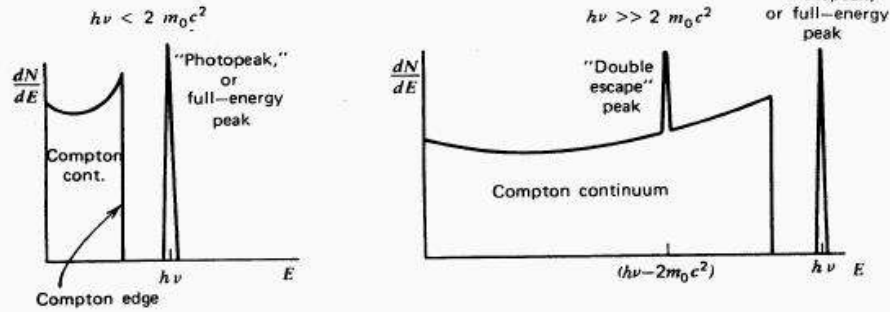


M. Sozzi



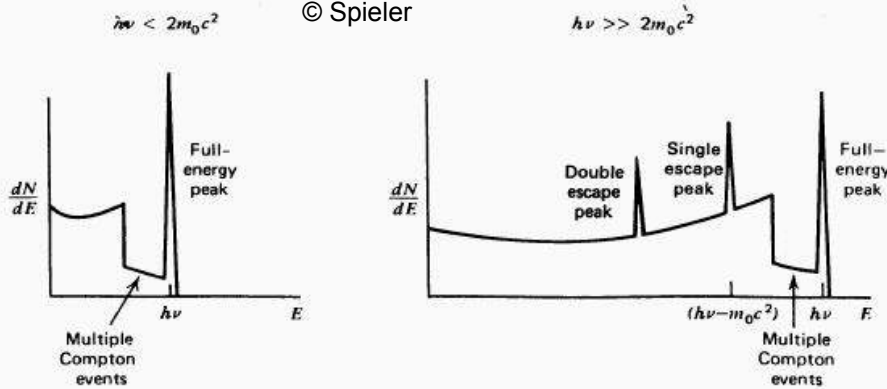
Effetto Compton (3)

© Spieler



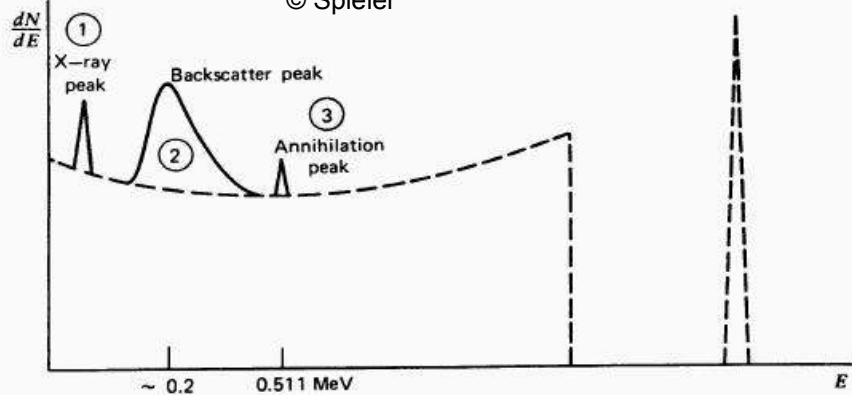
Rivelatore piccolo

© Spieler



Rivelatore medio

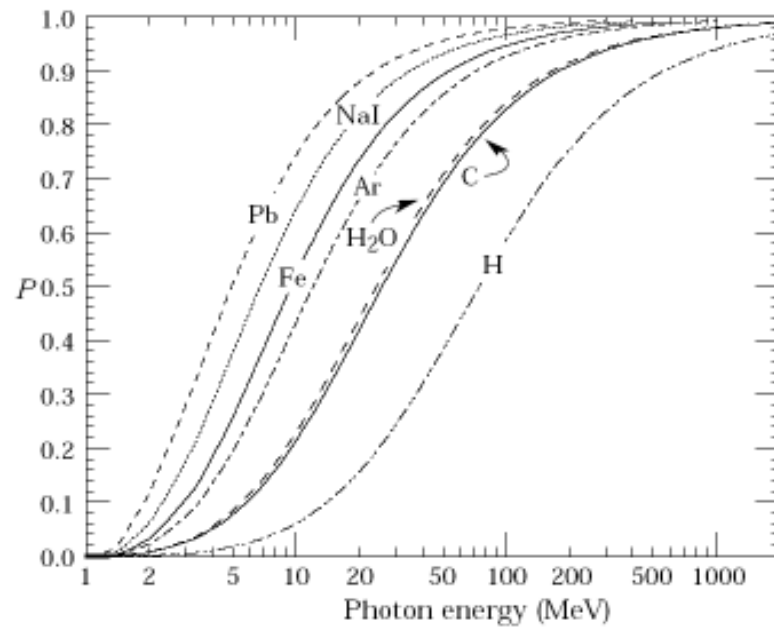
© Spieler



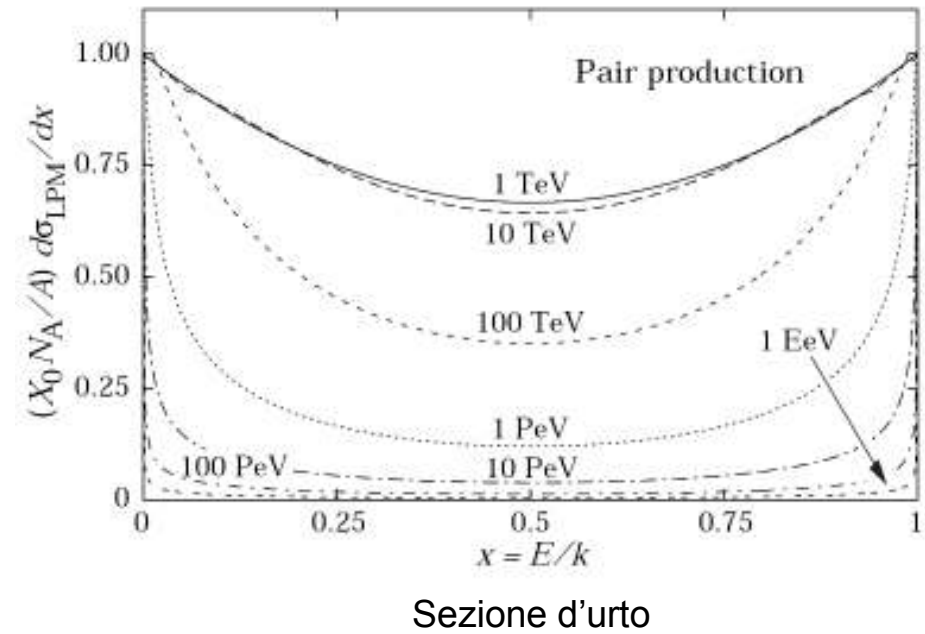
Rivelatore con schermatura

Produzione di coppie

Probabilità di creazione di coppie
in un'interazione



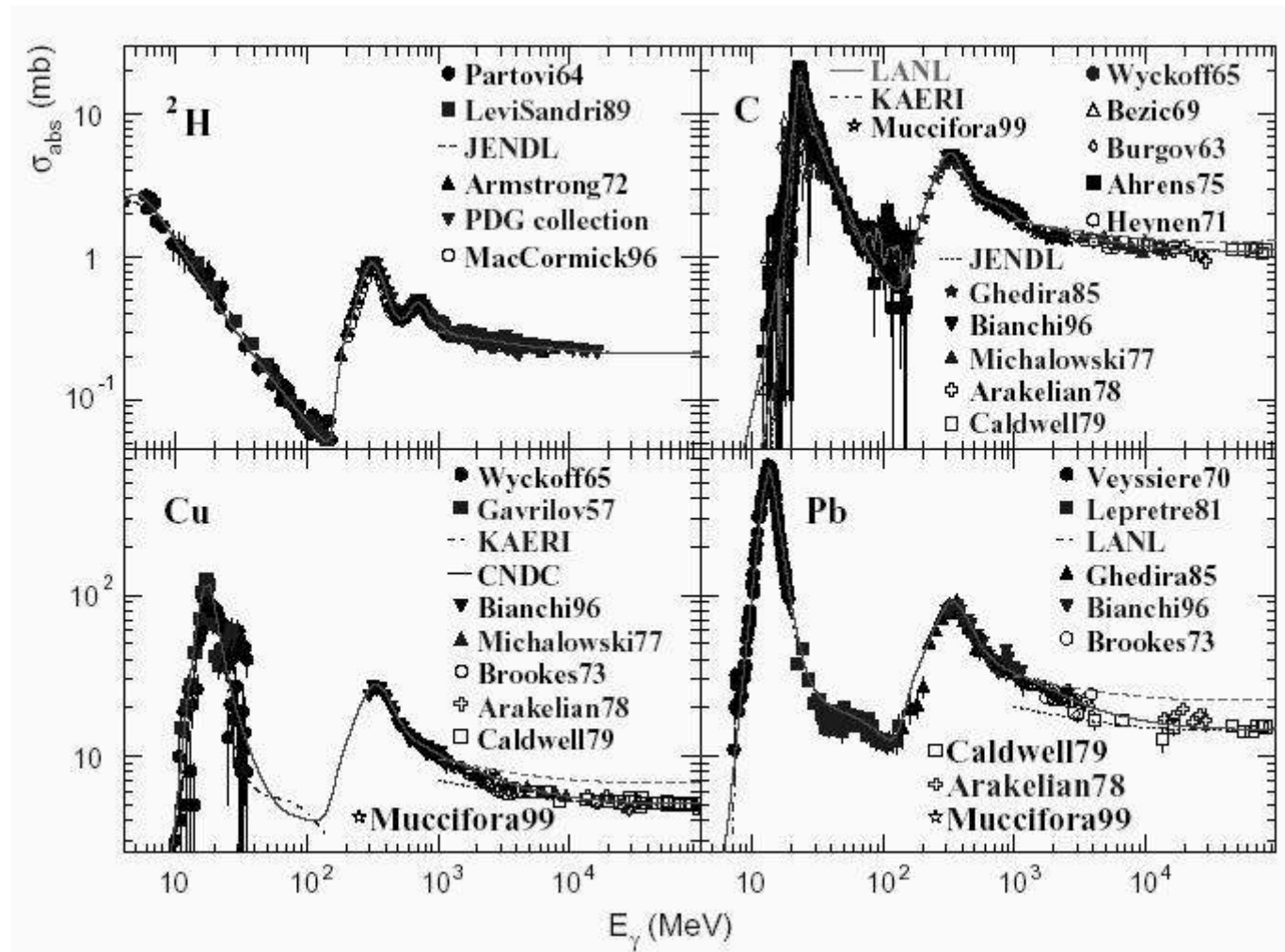
M. Sozzi



Sezione d'urto

Lab. Fisica Interaz. Fondamentali

Reazioni foto-nucleari

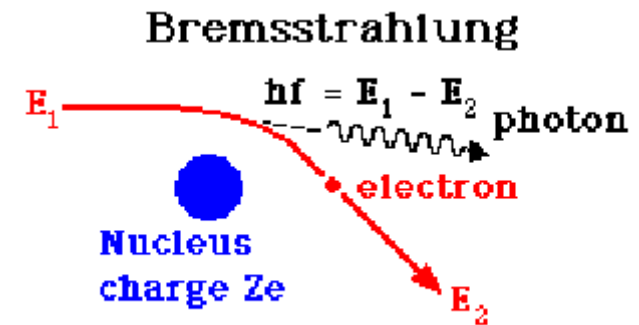


Bremsstrahlung (1)

In presenza del campo EM di un nucleo: emissione di radiazione di frenamento

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{e^2}{Mc^2} \right)^2 E \ln \left(\frac{183}{Z^{1/3}} \right)$$

Bethe-Heitler



Hans Albrecht Bethe
(1906-2005)
Nobel 1967



Walter Heinrich Heitler
(1904-1981)

Lunghezza di radiazione

$$X_0 = \frac{A}{4\alpha N_A Z(Z+1) r_e^2 \ln(183 / Z^{1/3})} \quad \text{g/cm}^2$$

$$\begin{aligned} X_0/\rho(\text{C}) &= 19 \text{ cm} \\ X_0/\rho(\text{aria}) &= 300 \text{ m} \\ X_0/\rho(\text{Fe}) &= 1.8 \text{ cm} \end{aligned}$$

$$X_0 = \frac{716.4 A \text{ g cm}^{-2}}{Z(Z+1) \ln(287 / \sqrt{Z})}$$

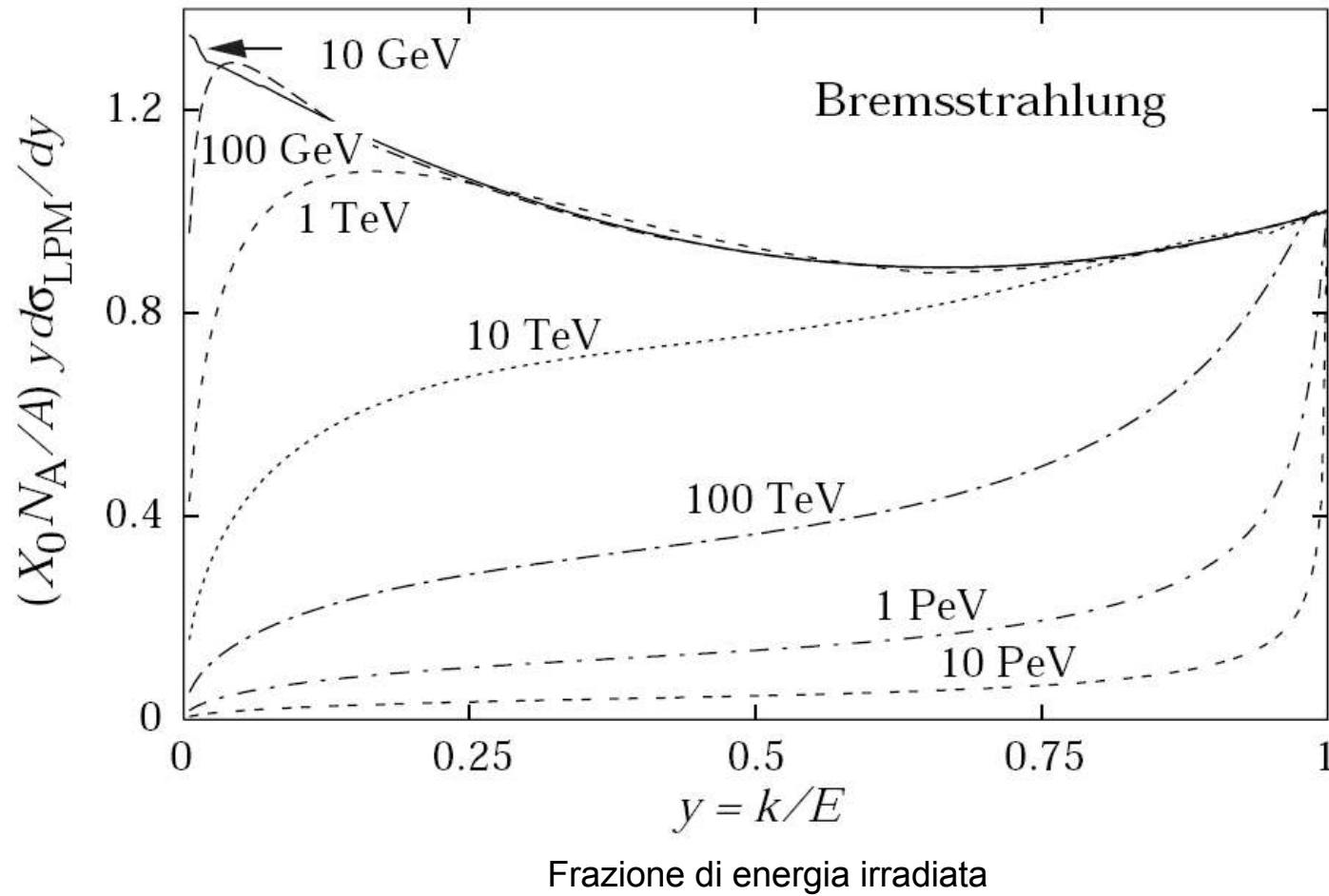
(fit ai dati)

Composti:

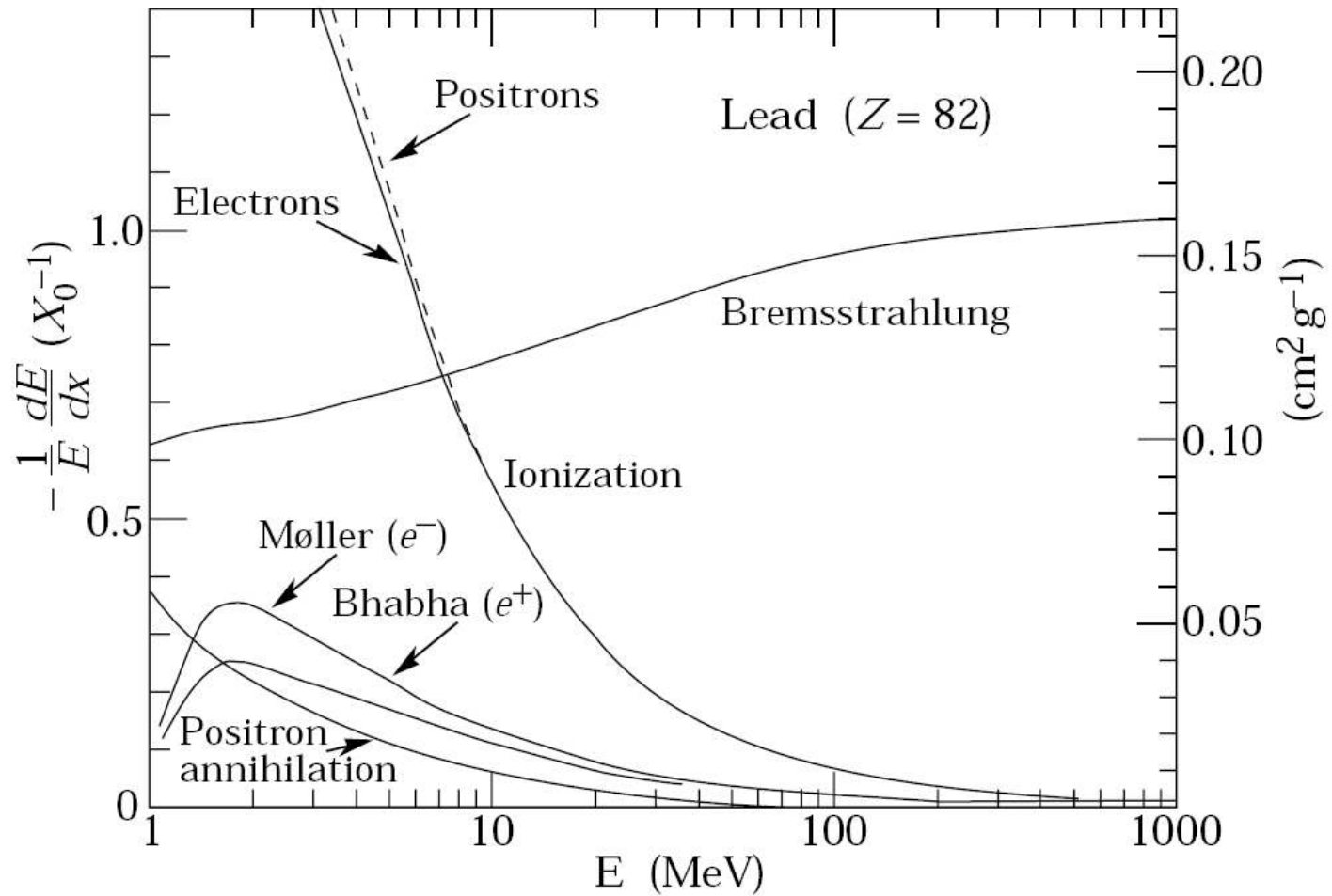
$$\frac{1}{X_0} = \sum_i \frac{w_i}{X_{0i}}$$

w_i = frazione in peso

Bremsstrahlung (2)



Perdita di energia di elettroni

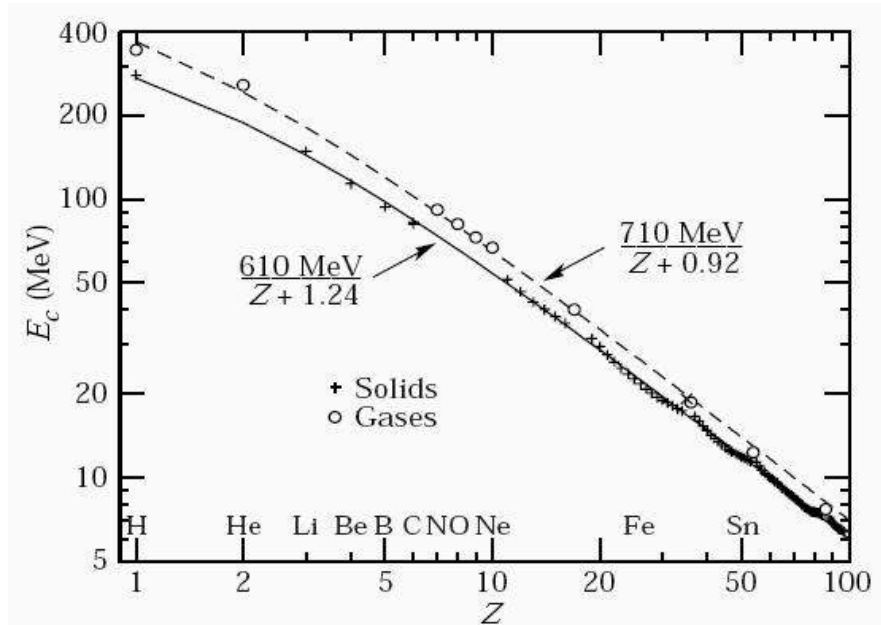
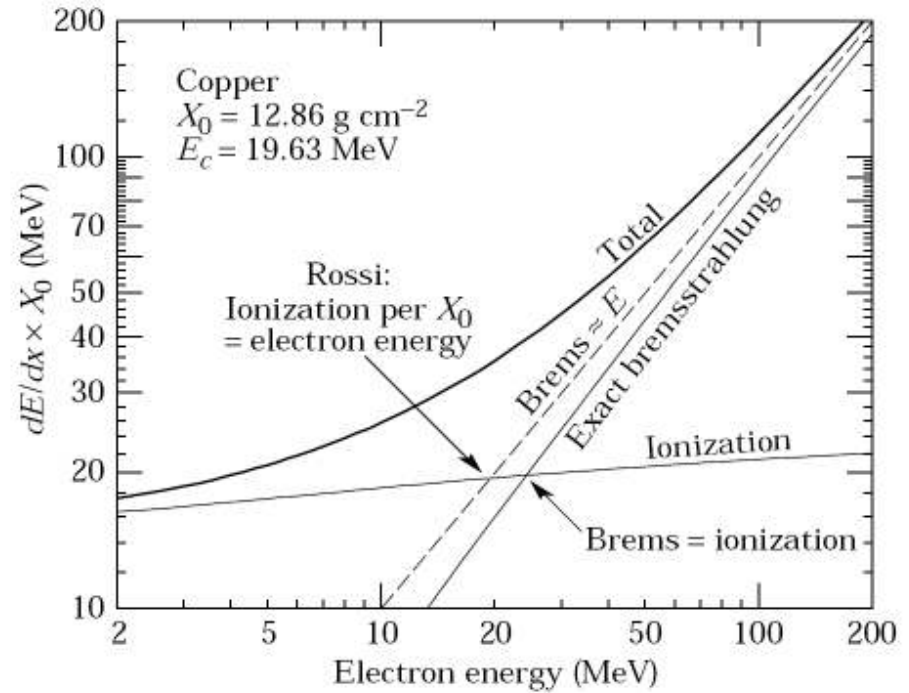


Energia critica

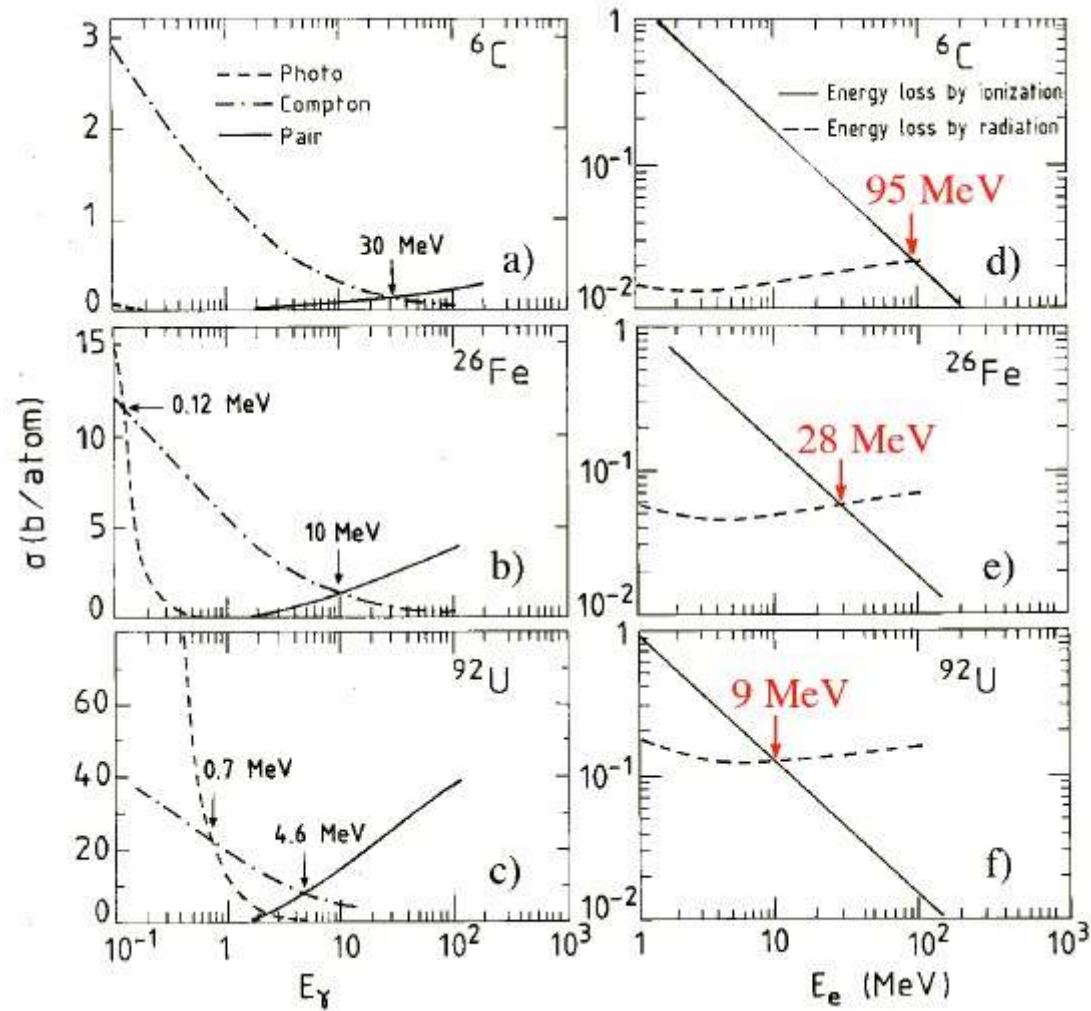
- (1) Energia a cui la perdita di energia per *bremstrahlung* e per ionizzazione sono uguali
- (2) Energia a cui un elettrone perderebbe tutta la sua energia per ionizzazione in una lunghezza di radiazione

$$E_c \approx \frac{800 \text{ MeV}}{Z+1.2}$$

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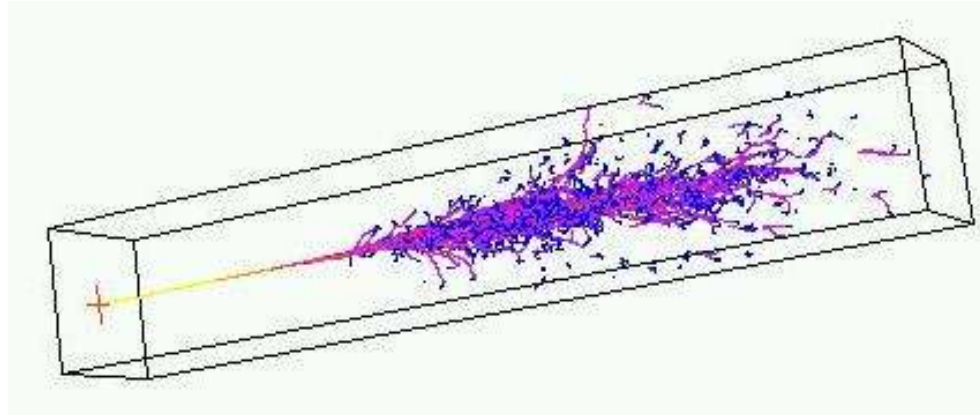
Fotoni ed elettroni



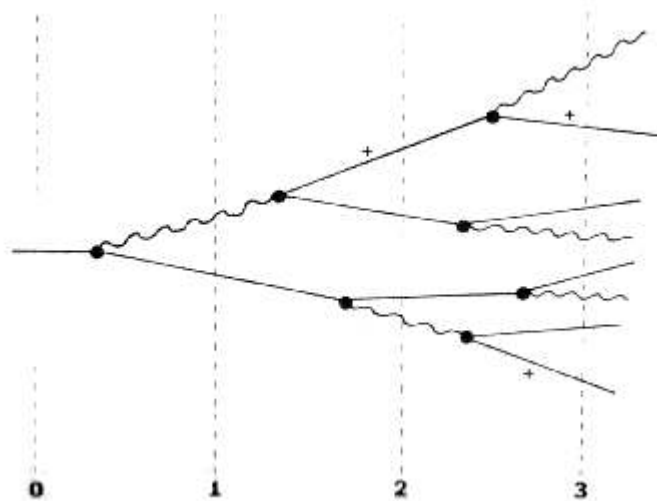
Sciame elettromagnetici (1)



Bruno Benedetto Rossi
(1905-1993)

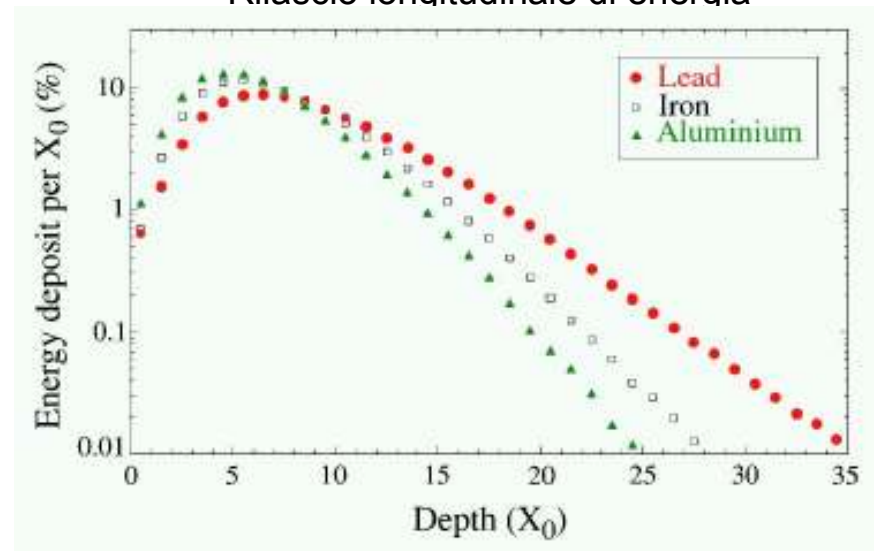


Modello empirico



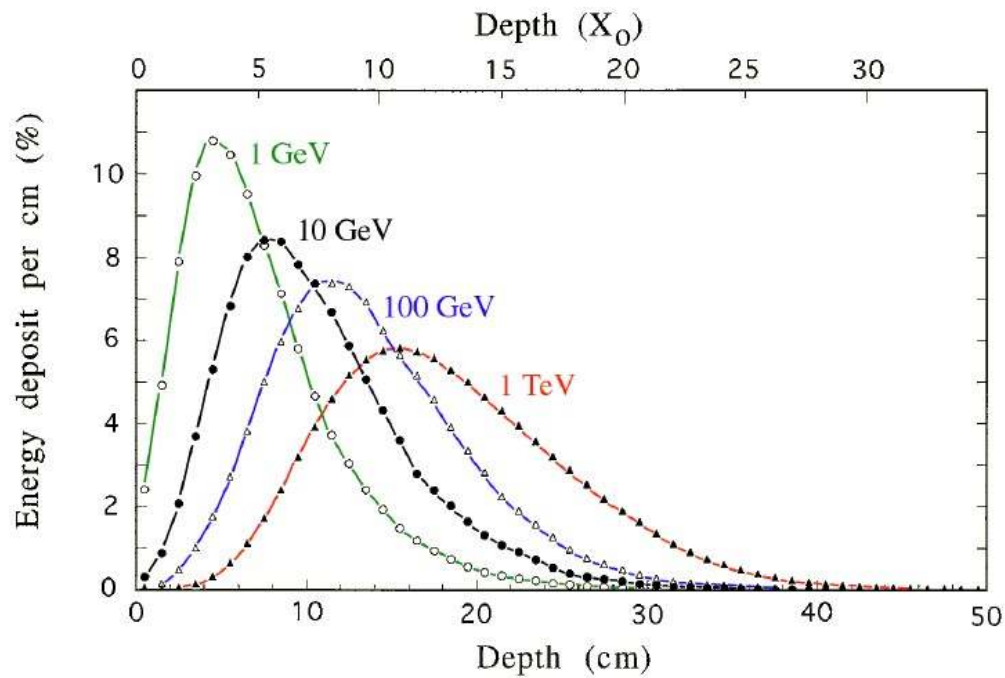
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Rilascio longitudinale di energia

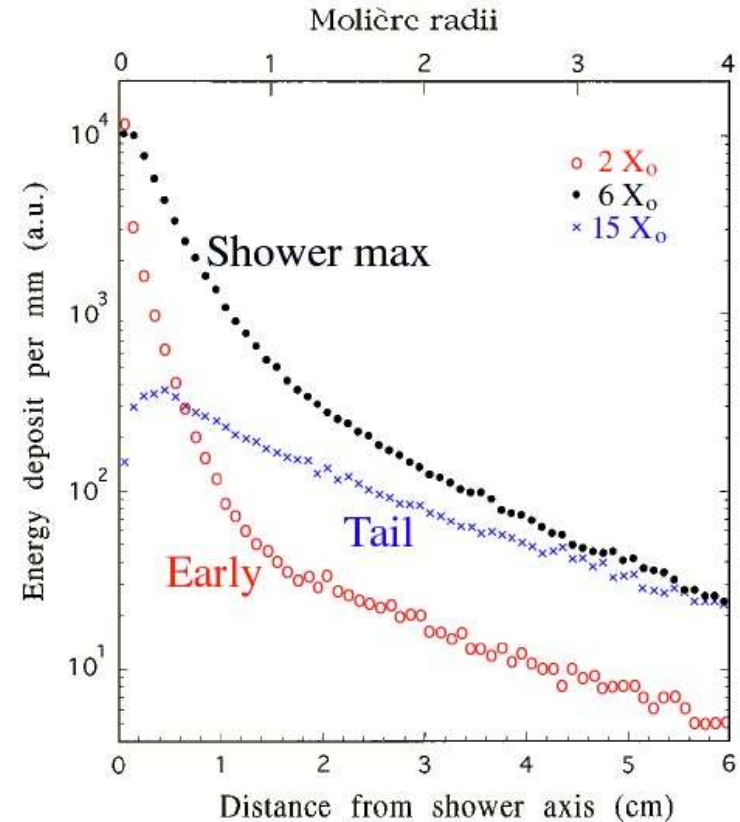


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Sciami elettromagnetici (2)



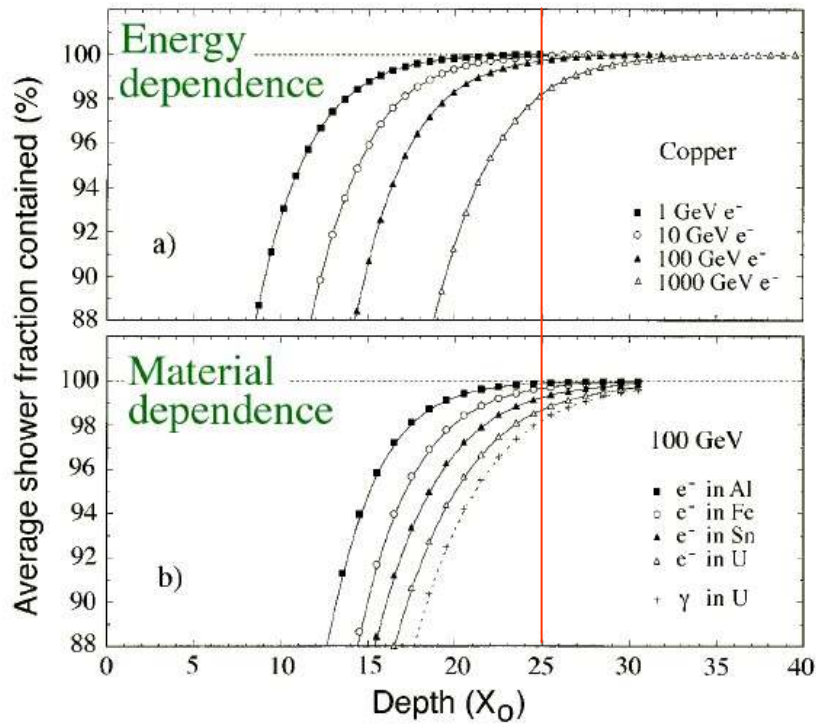
Distribuzione longitudinale del deposito di energia



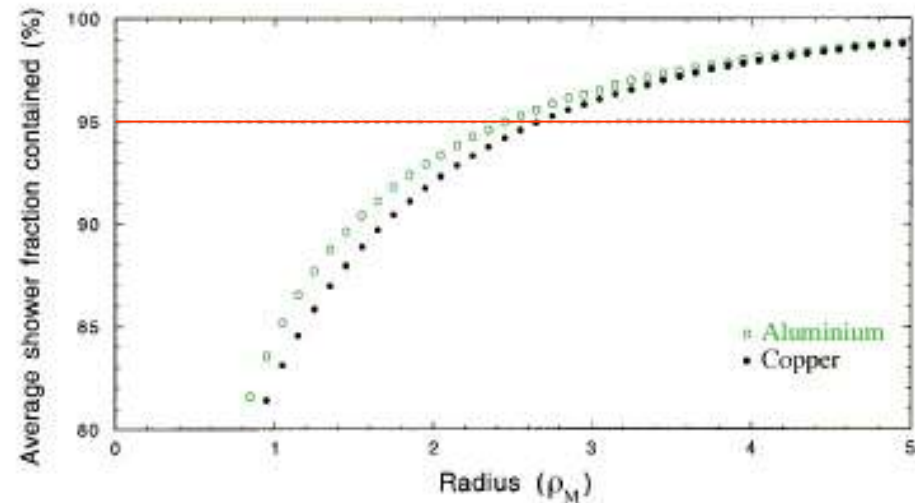
Distribuzione trasversale del deposito di energia

Sciami elettromagnetici (3)

Contenimento longitudinale

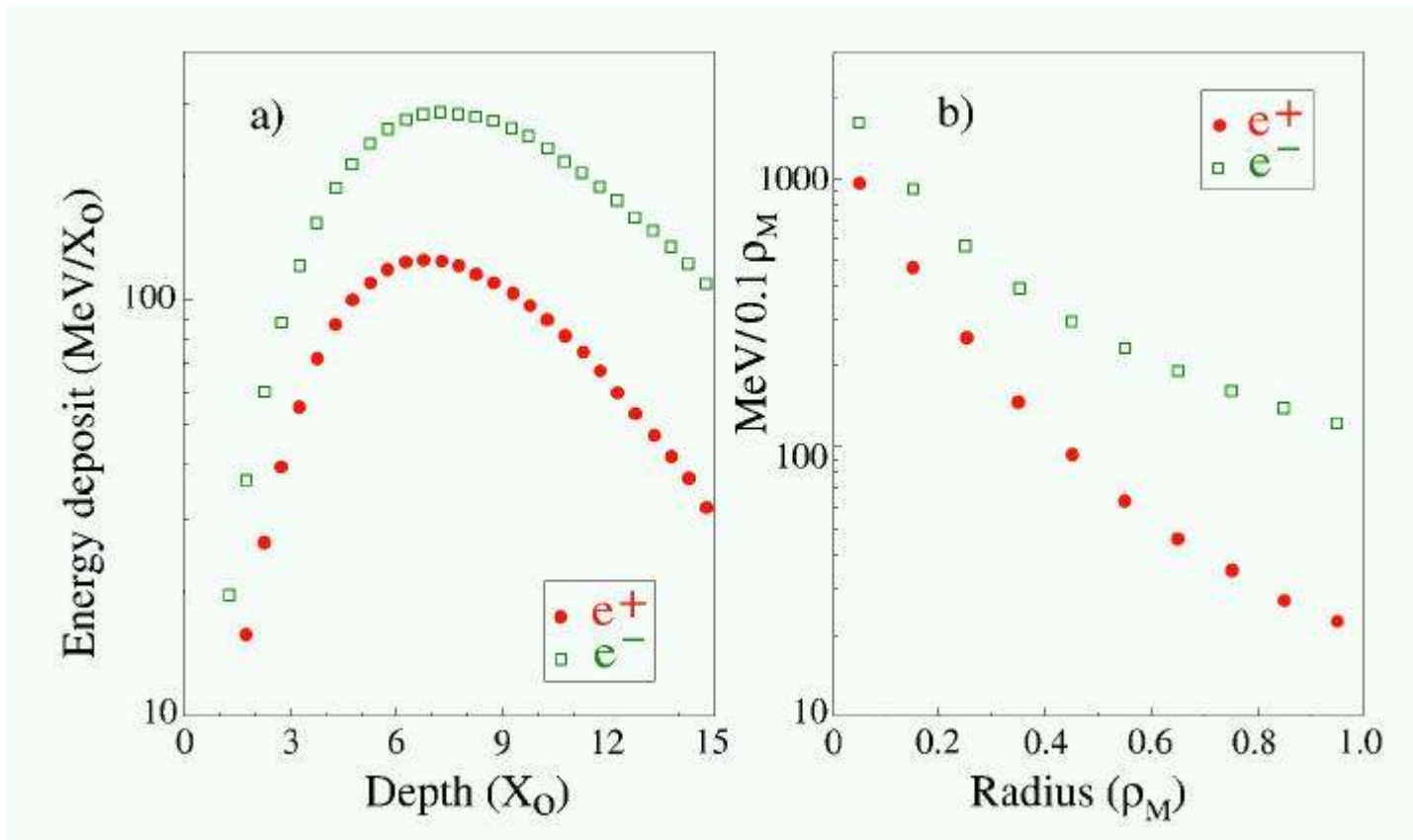


Contenimento trasversale



$$25X_0 \quad 2.5R_M$$

Sciame elettromagnetici (4)



Confronto elettroni e positroni

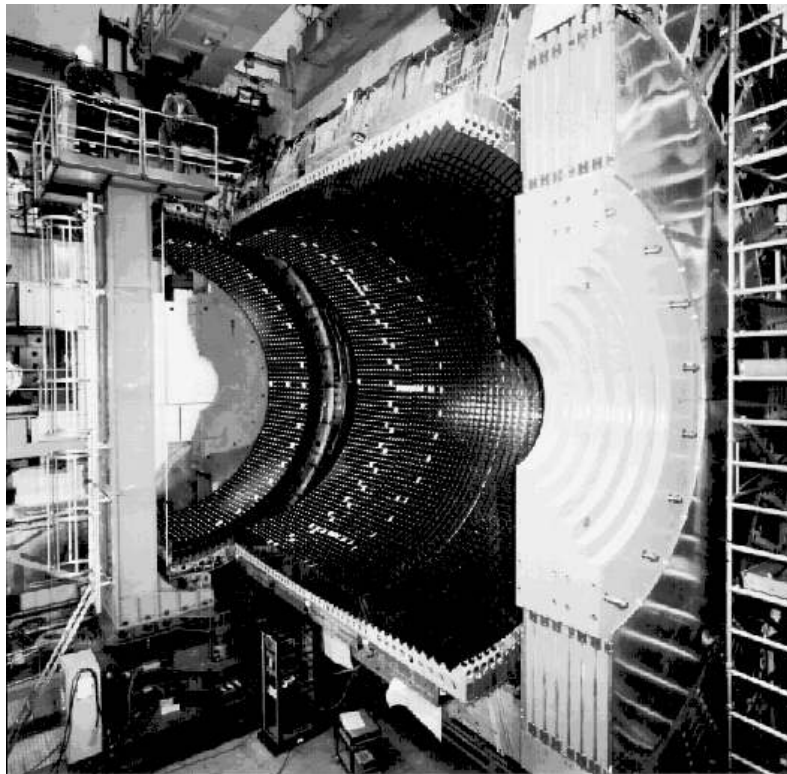
Calorimetri elettromagnetici

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
Bi ₄ Ge ₃ O ₁₂ (BGO) (L3)	$22X_0$	$2\%/ \sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/ \sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
PbWO ₄ (PWO) (CMS)	$25X_0$	$3\%/ \sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/ \sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/ \sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	$20-30X_0$	$18\%/ \sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/ \sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/ \sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/ \sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/ \sqrt{E}$	1993
Liquid Ar/Pb (H1)	$20-30X_0$	$12\%/ \sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/ \sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/ \sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

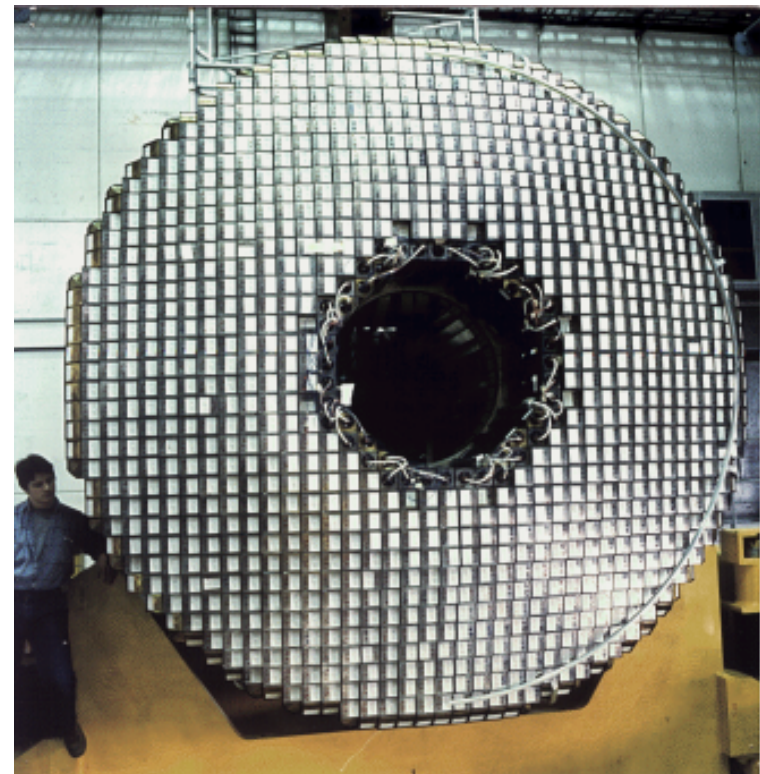
(E in GeV)

Calorimetri a vetro al piombo (OPAL)

Sciame elettromagnetico + effetto Cerenkov



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Calorimetro a LAr (ATLAS)

Sciame elettromagnetico + camera a ionizzazione (campionamento)



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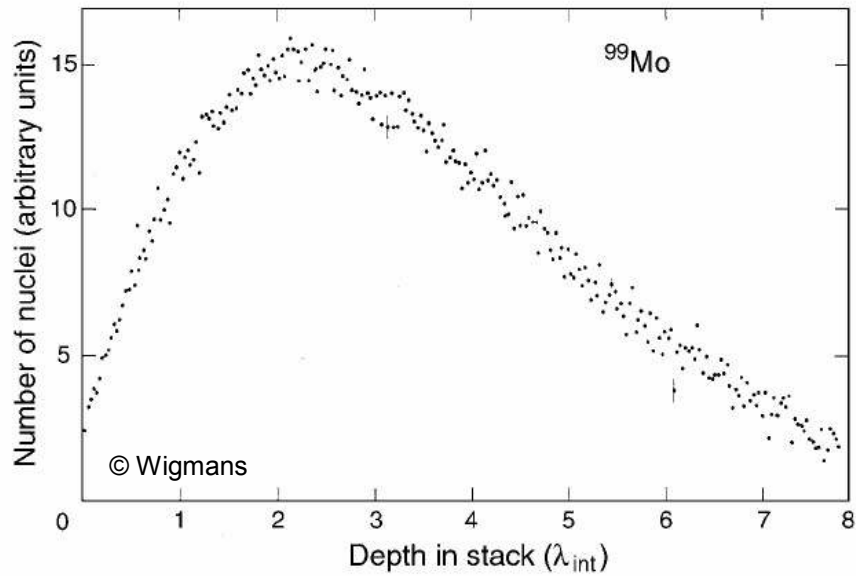
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Calorimetro a LKr (NA48)



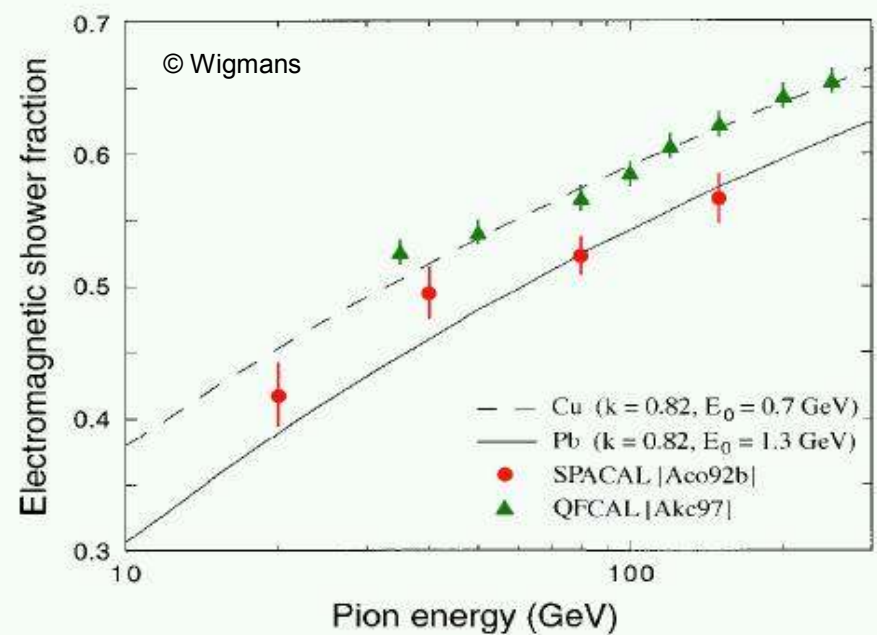
Sciame elettromagnetico +
camera a ionizzazione (omogeneo)

Sciami adronici



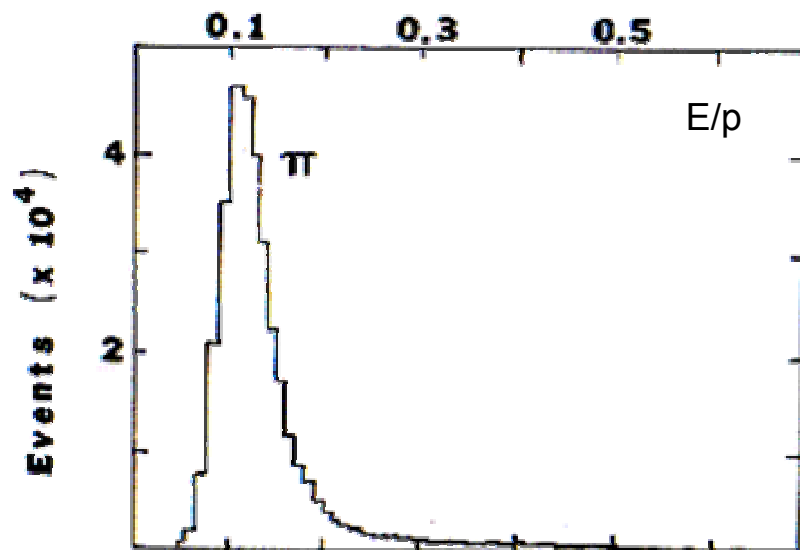
Distribuzione longitudinale
del numero di nuclei

Frazione di energia “elettromagnetica”



Calorimetri adronici

© Wigmans



	<i>Lead</i>	<i>Iron</i>
Ionization by pions	19%	21%
Ionization by protons	37%	53%
<i>Total ionization</i>	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
<i>Total invisible energy</i>	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

Per 1 GeV di energia non-EM depositata

Perdita di energia di muoni

