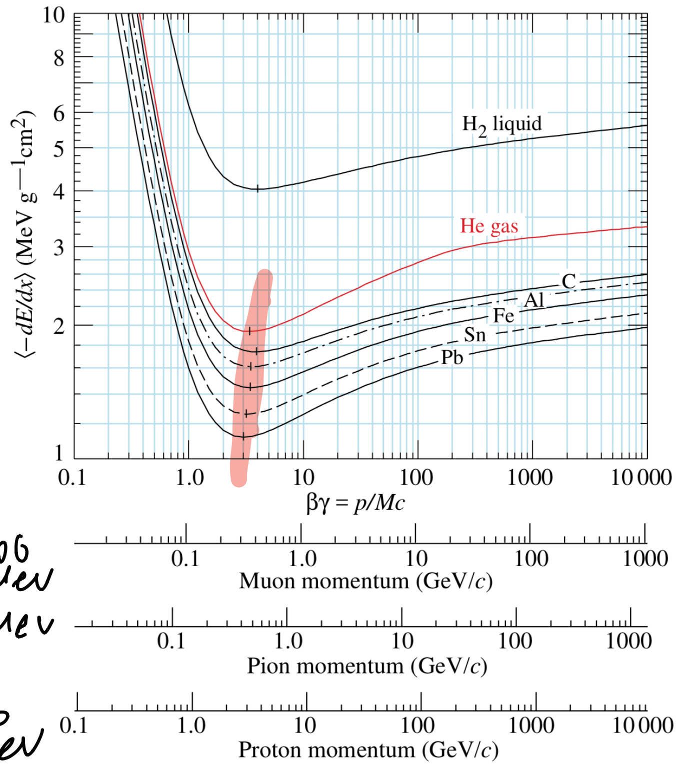
minimum ionizing particle

mip

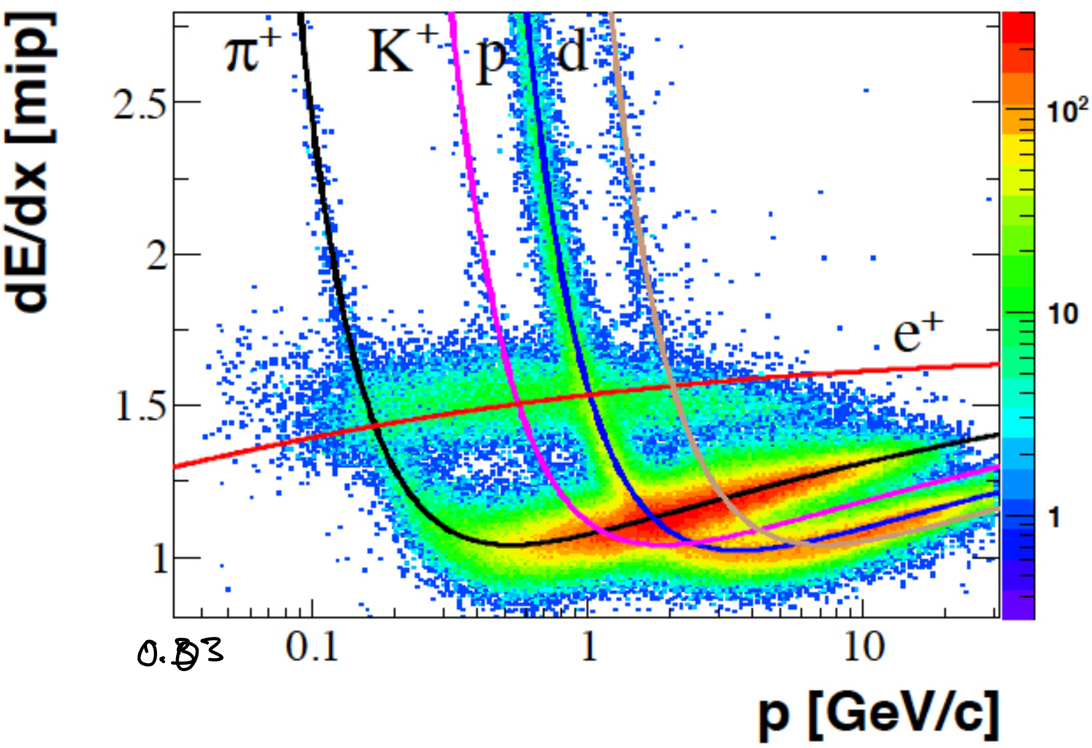
$$\beta\gamma = \frac{p}{m}$$



$m_\mu = 106$ MeV

140 MeV

1000 MeV



0.03

$$M_e = 0.5 \text{ MeV} \qquad \beta\gamma = \frac{p}{m}$$

$$\text{mip} \quad \beta\gamma = 3 \implies P_e \simeq 1.5 \text{ MeV}$$

$$ma = \frac{1}{4\pi\varepsilon_0}\frac{(Z_p \cdot Z_N)e^2}{r} \Rightarrow a \propto \frac{1}{m}$$

Effetto Larmor, Irraggiamento.

Potenza di irraggiamento $P = \frac{2}{3}\frac{e^2}{m^2c^3}|\dot{v}|^2$

per particelle non relativistiche

Potenza irraggiata relativistica

$p_\mu = \left(\frac{E}{c}, \vec{P}\right)$

$$P = -\frac{2}{3}\frac{e^2}{m^2c^3}\frac{dp_\mu}{d\tau}\frac{dp^\mu}{d\tau}$$

$$\frac{dp_\mu}{d\tau}\frac{dp^\mu}{d\tau} = \left|\frac{dE}{d\tau}\right|^2 - \left|\frac{d\vec{P}}{d\tau}\right|^2$$

$\frac{E}{c} = \gamma mc$ $\quad \vec{P} = \gamma m\vec{v} = \gamma mc\vec{\beta}$

$\gamma = \frac{1}{\sqrt{1-\beta^2}}$ $\quad \vec{\beta} = \frac{\vec{P}}{E}$

$\frac{dE}{d\tau}$ $\quad \frac{d\beta}{d\tau}$

$u_\mu = (\gamma c, \gamma\vec{\beta}c)$
$= (\gamma, \gamma\vec{\beta})$

$$P = \frac{2}{3}\frac{e^2}{c}\gamma^6\left[\dot{\beta}^2 - (\vec{\beta}\times\dot{\vec{\beta}})^2\right]$$

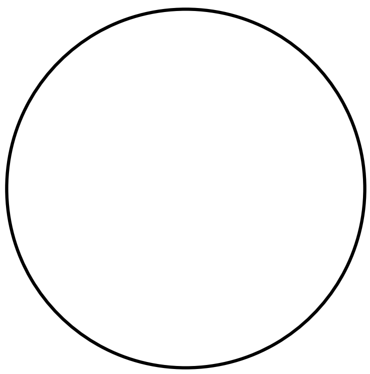
accel. lineare. $P = \frac{2}{3} \frac{e^2}{c} \gamma^6 \dot{\beta}^2$ $\quad \vec{\beta} \parallel \dot{\vec{\beta}}$

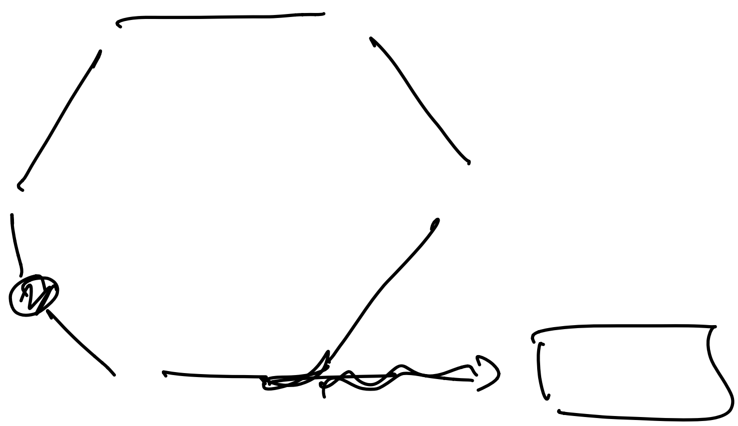
accel. circolare / curvilinea. $\quad \vec{\beta} \perp \dot{\vec{\beta}}$

circolare $\quad \dot{\vec{\beta}}^2 - (\vec{\beta} \times \dot{\vec{\beta}})^2 = \dot{\beta}^2 - \dot{\beta}^2 \beta^2$

$$= \dot{\beta}^2 (1-\beta^2) \quad \frac{1}{\gamma^2} \dot{\beta}^2$$

$$P = \frac{2}{3} \frac{e^2}{c} \gamma^6 \frac{\dot{\beta}^2}{\gamma^2} \quad \propto \quad \gamma^4 \dot{\beta}^2$$





$$P \propto \gamma^4 \dot{\beta}^2 \qquad \gamma = \frac{E}{m}$$

$$P \propto \left(\frac{E}{m}\right)^4 \dot{\beta}^2$$

$$\frac{P_p}{P_e} \simeq \left(\frac{m_e}{m_p}\right)^4 = \left(\frac{0.5 \text{ MeV}}{1000 \text{ MeV}}\right)^4$$

$$\left(\frac{1}{2000}\right)^4 \qquad \left(\frac{1}{2}\right)^4 10^{-12} \simeq 10^{-13}$$

LHC $\quad P \simeq E = 6.5$ TeV per particella.

TeV $= 10^{12}$ eV

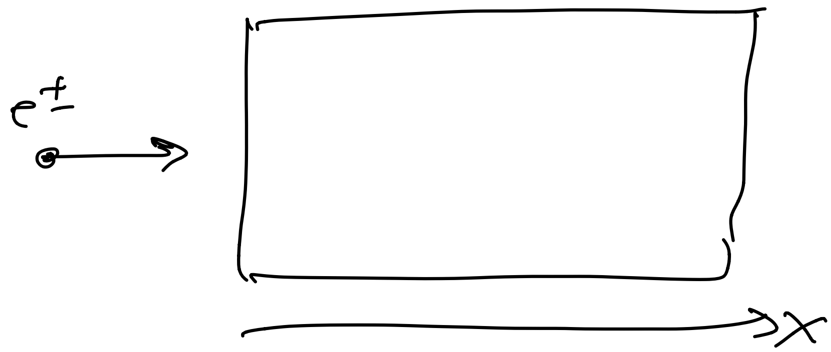
Irraggiamento di $e^{\pm}$: Bremsstrahlung

$$\left.\frac{dE}{dx}\right|_{Brems.} \simeq \frac{E}{X_0}$$

fatto osservato

$$\frac{1}{X_0} \propto \rho \frac{N_A}{A} Z^2_{mezzo} \ln\left(183\, Z^{-1/3}\right)$$

lunghezza di radiazione.



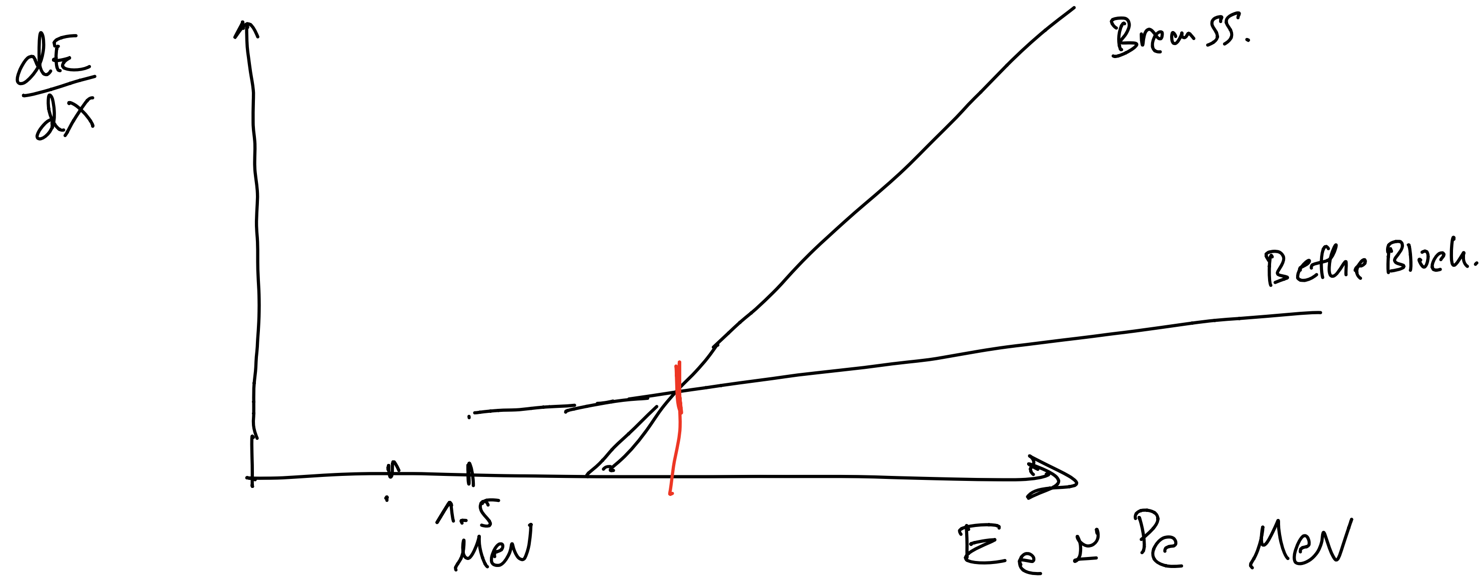
$$E(x) = E_0\, e^{-x/X_0}$$

$$\frac{1}{\rho}\frac{1}{X_0} \propto \frac{N_A}{A} Z^2 \ln\left(183\, Z^{-1/3}\right)$$

$$\rho X_0 \simeq 170 \frac{A}{Z^2}\ g/cm^2$$

$$\dot{N}_r = \sigma \cdot \dot{N}_p\, n\, d$$

$$\frac{\dot{N}_r}{\dot{N}_p} = Prob(\text{interazione})$$



$$\left.\frac{dE}{dx}\right|_{e^{\mp}} = \left.\frac{dE}{dx}\right|_{ion} + \left.\frac{dE}{dx}\right|_{Brem}$$

$$\frac{\left.\frac{1}{\rho}\frac{dE}{dx}\right|_{Brem}}{\left.\frac{1}{\rho}\frac{dE}{dx}\right|_{ion}} \simeq \frac{K_e\, Z}{1200\, m_e} \qquad K_e = E_e - m_e \simeq E_c$$

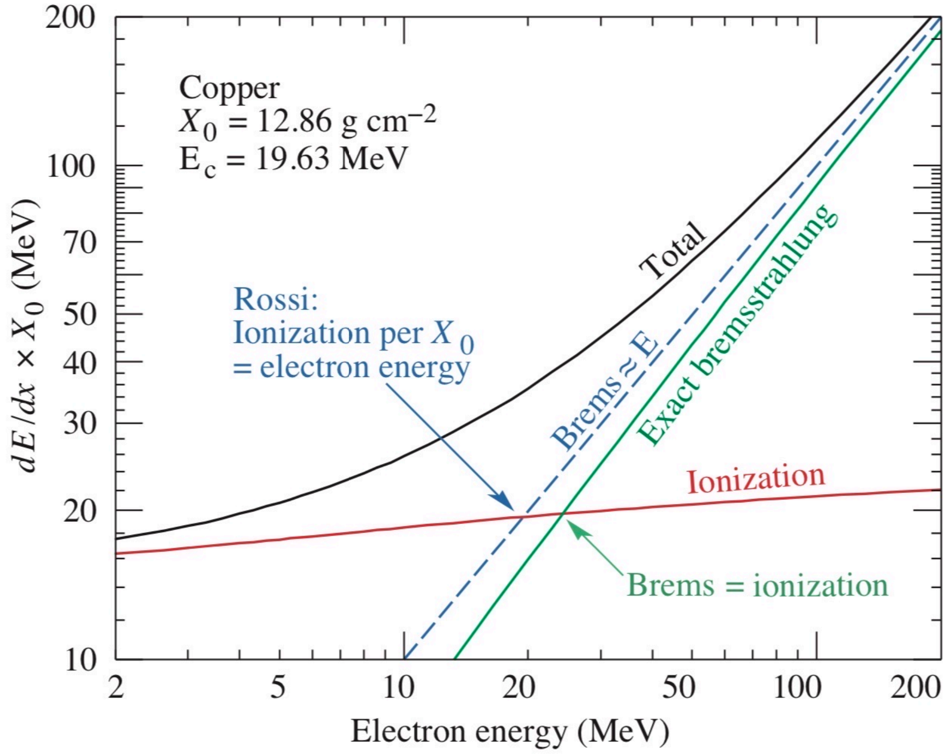
sperimentale
fenomenologico.

$$1 = \frac{E_c\, Z}{1200\, m_e} \Rightarrow E_c = \frac{600\ \text{MeV}}{Z}$$

prop. del mezzo.

Pb, $Z = 82$ $\qquad E_c \simeq 7$ MeV

Per $\quad E \gtrsim E_c \quad$ domina irraggiamento



al minimo di ionizzazione.

$$\left.\frac{dE}{dx}\right|_{ion} \approx \left.\frac{dE}{dx}\right|_{Brem} \simeq \frac{E_c}{X_0}$$

$$\simeq \frac{600\,MeV}{\cancel{Z}} \quad \frac{1}{170} \quad \frac{Z^{\cancel{2}}}{A} \; g^{-1}\,cm^2 \qquad \frac{1}{\rho}$$

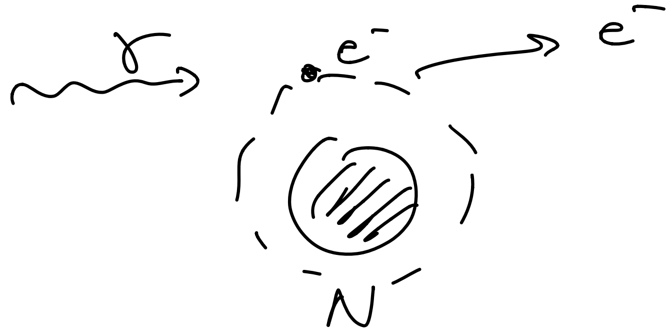
$$\simeq \frac{600}{170 \times 2} \simeq 1.7 \; MeV\, g^{-1}\, cm^2$$

Fotoni nella materia

- Effetto foto elettrico.

$$\gamma + e^- \to e^- + A$$

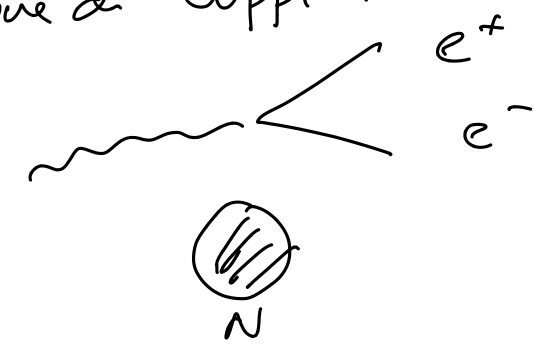
$$m_e^2 + 2 m_e E_\gamma \neq m_e^2$$ senza il nucleo



- Effetto Compton $\qquad \gamma + e^- \to \gamma + e^-$

$$\frac{E_\gamma'}{E_\gamma} = \frac{1}{1+\frac{E_\gamma}{m_e}(1-\cos\theta)}$$

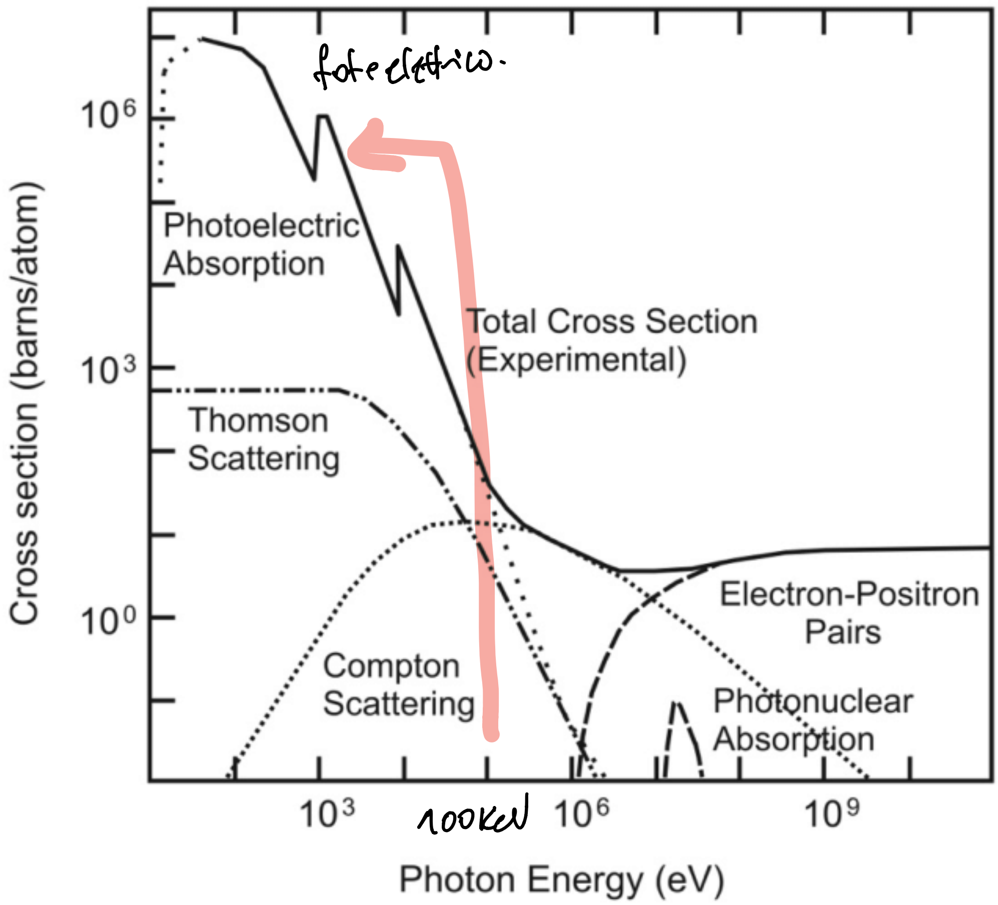
- produzione di Coppia.



$\cancel{\gamma \to e^+ e^-}$ $\qquad \gamma + N \to e^+ e^- + N.$

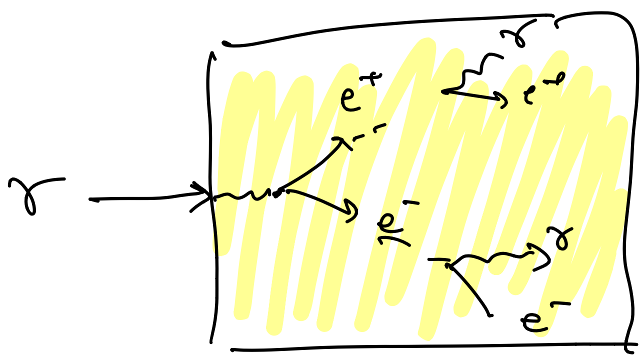
soglia $\qquad E_\gamma \geq 2 m_e = 1.022$ MeV.

sezione d'urto



Fotone alta energia $E_\gamma \simeq 100$ MeV.

$E_c \simeq 10$ MeV. del mezzo.



$E_{e^\pm} \simeq \frac{1}{2} E_\gamma \simeq 50$ MeV.

$e^- \longrightarrow e^- + \gamma$.

sviluppo dello sciame EM.

continua finché $E_i \leq E_c$.

N iteration: $2^N \Rightarrow E_N \simeq \frac{E_0}{2^N}$

Finche $e^{\pm}, \gamma$ sopra soglia $\Rightarrow$ aumento di particelle.

quando sotto soglia.

$E_{e^{\pm}} < E_C \Rightarrow$ ionizzazione.

$e^+ + e^- \longrightarrow \gamma + \gamma$ $E_\gamma \simeq m_e$

γ con $E < 1.022$