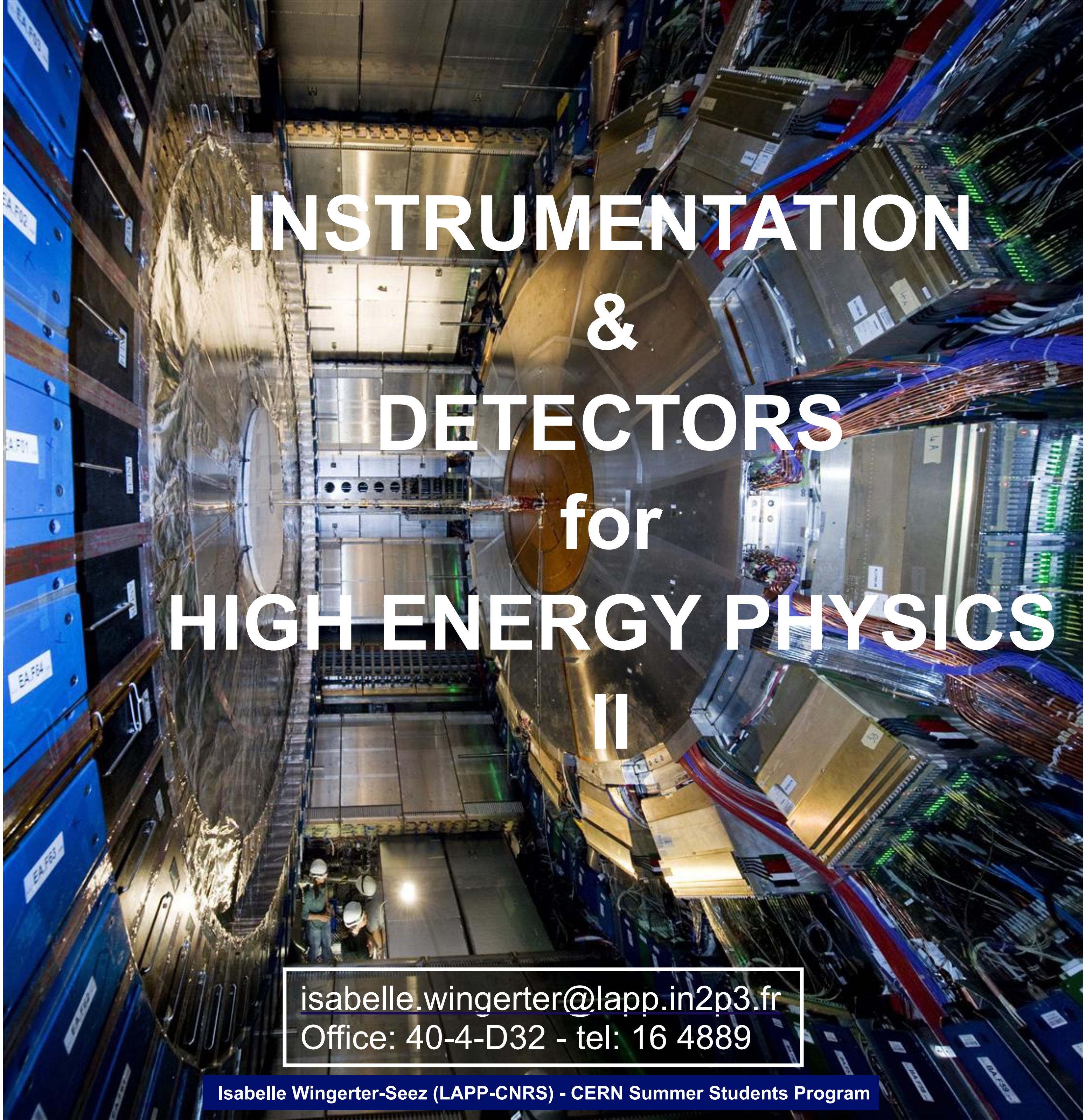


INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS II

isabelle.wingerter@lapp.in2p3.fr
Office: 40-4-D32 - tel: 16 4889

DETECTOR: INTRODUCTION QUIZZ

What is a detector ?

What does a detector measure ?

(How is a detector designed ?)

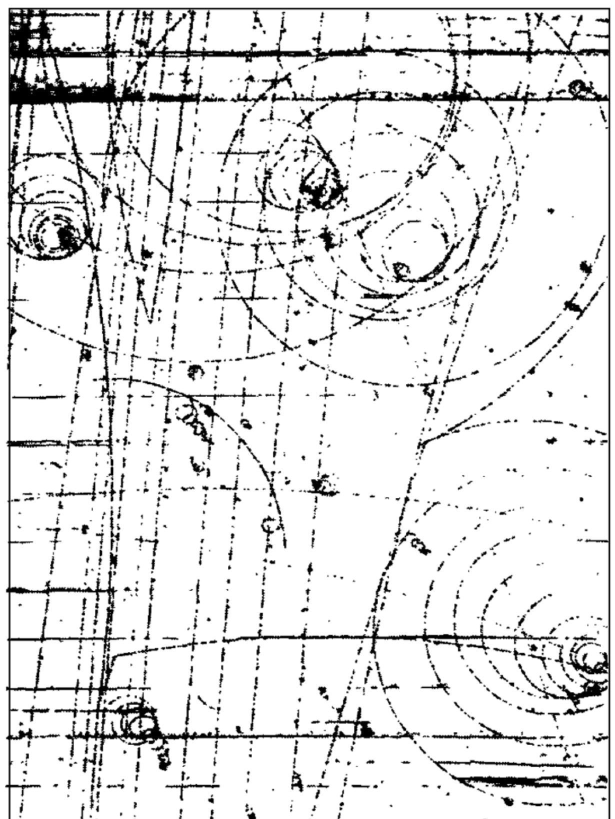
Compare a digital camera with the ATLAS detector

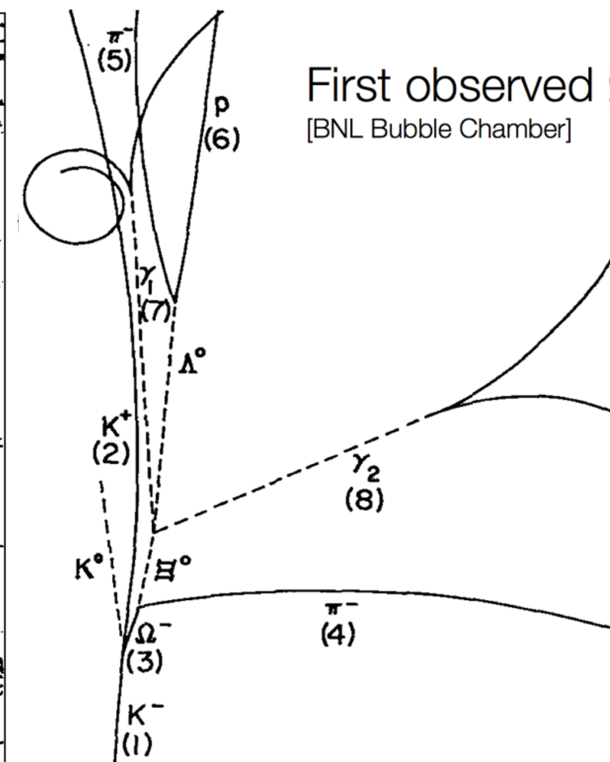
Would you join an experiment where the calorimeter is in front of the tracking system ?

WHAT IS A PARTICLE DETECTOR ?

An apparatus able to

- detect the passage of a particle
- and/or localise it
- and/or measure its momentum or energy
- and/or identify its nature
- and/or measure its time of arrival
- …..

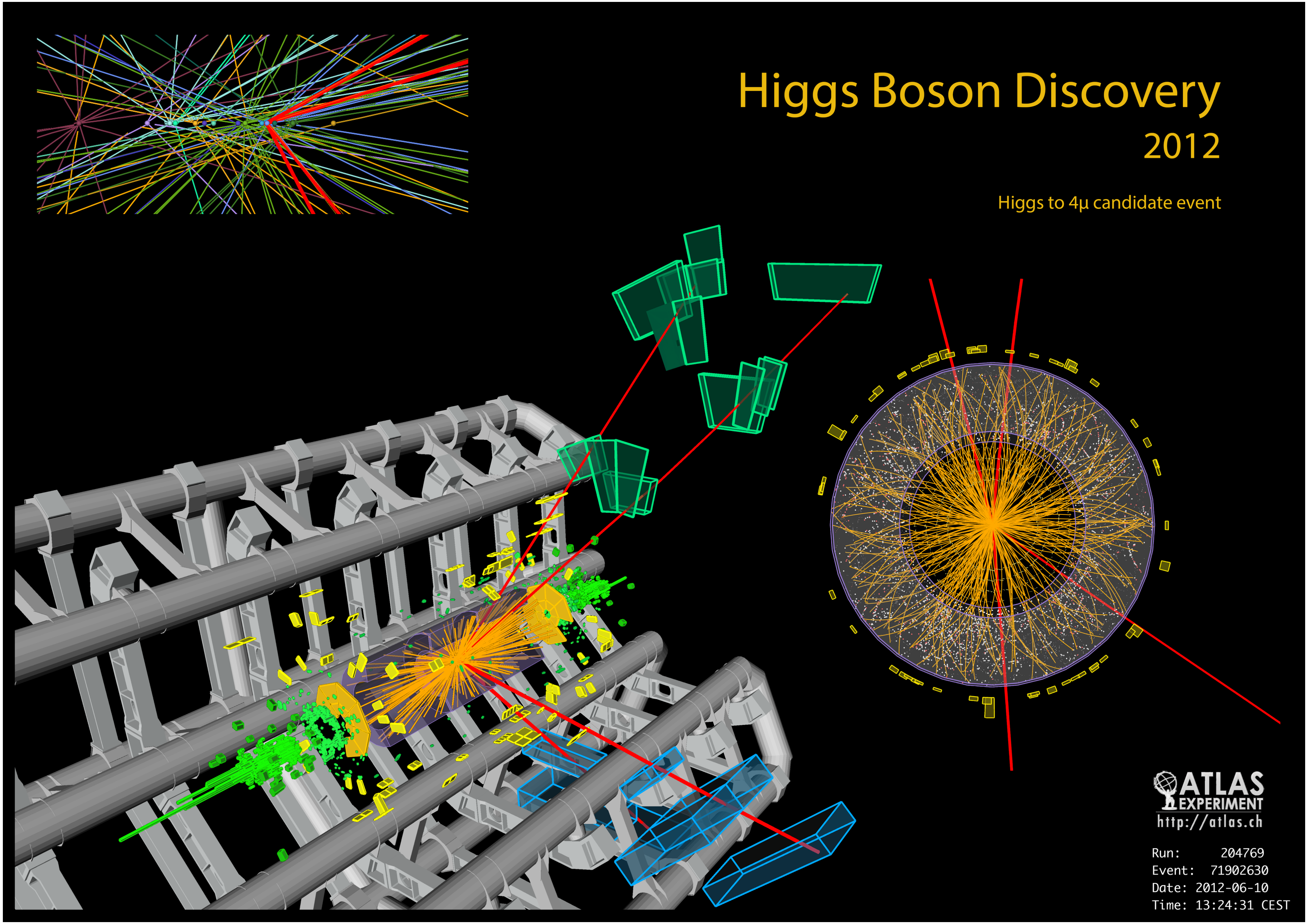




First observed Ω^- event

[BNL Bubble Chamber]

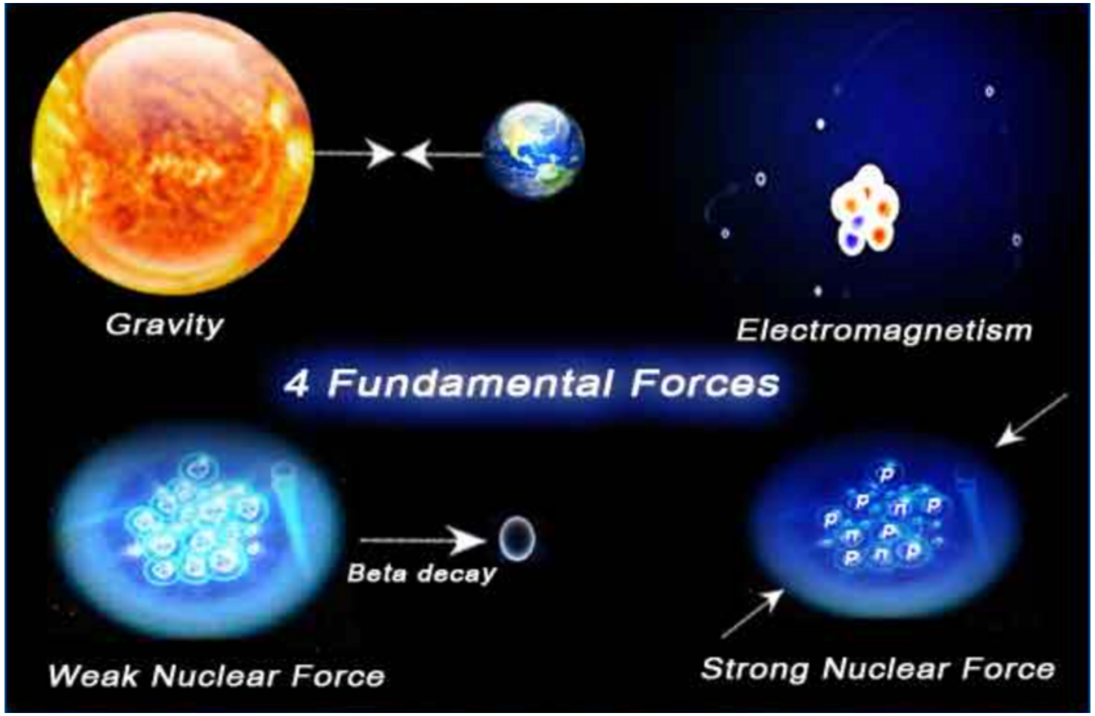
ATLAS 4 μ event: LHC collision event



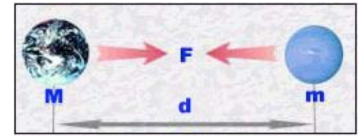
TODAY

INTERACTIONS

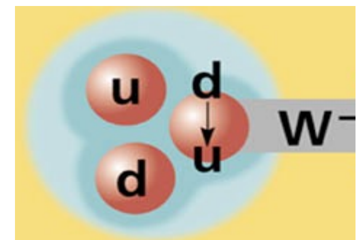
INTERACTIONS



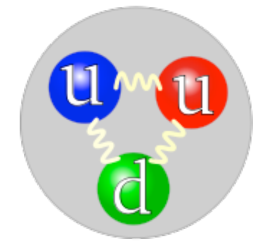
Gravity
Graviton ?



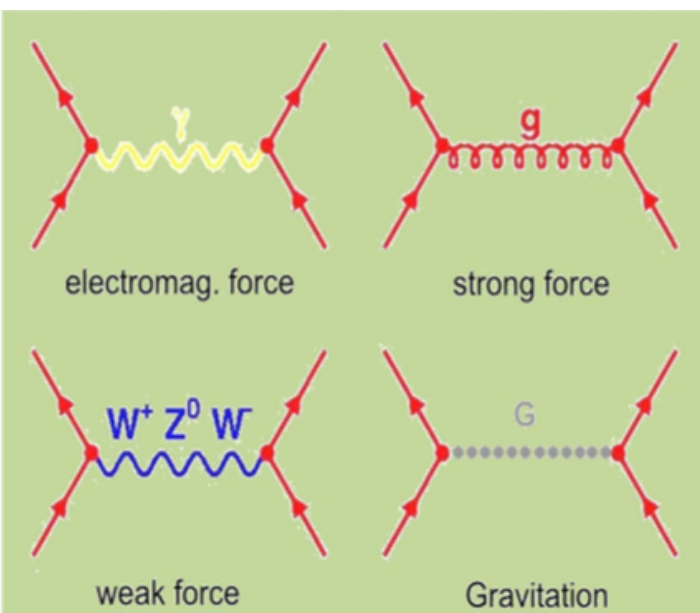
Electromagntism
Photon



Weak interaction
W & Z bosons

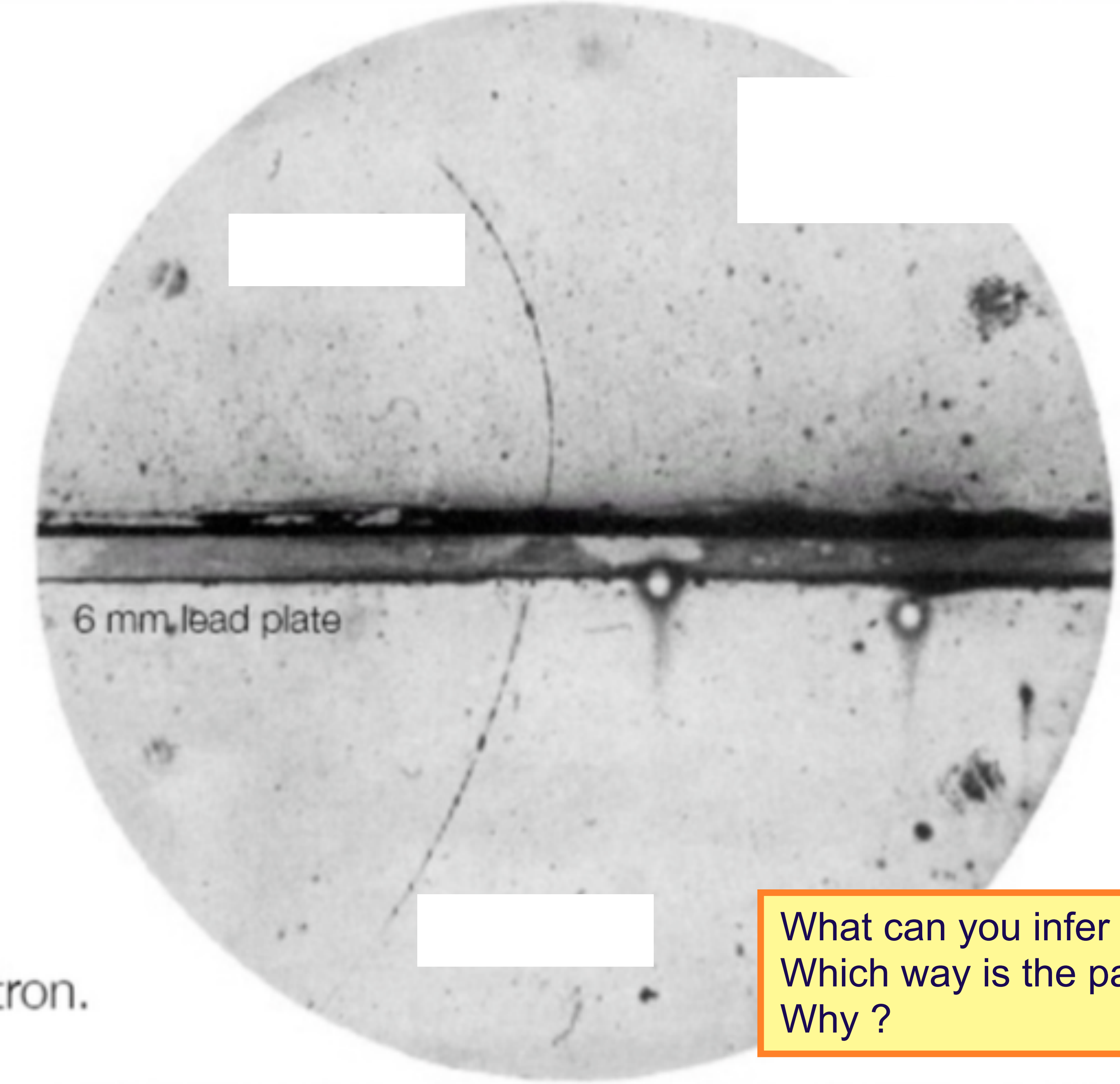


Strong interaction
Gluons



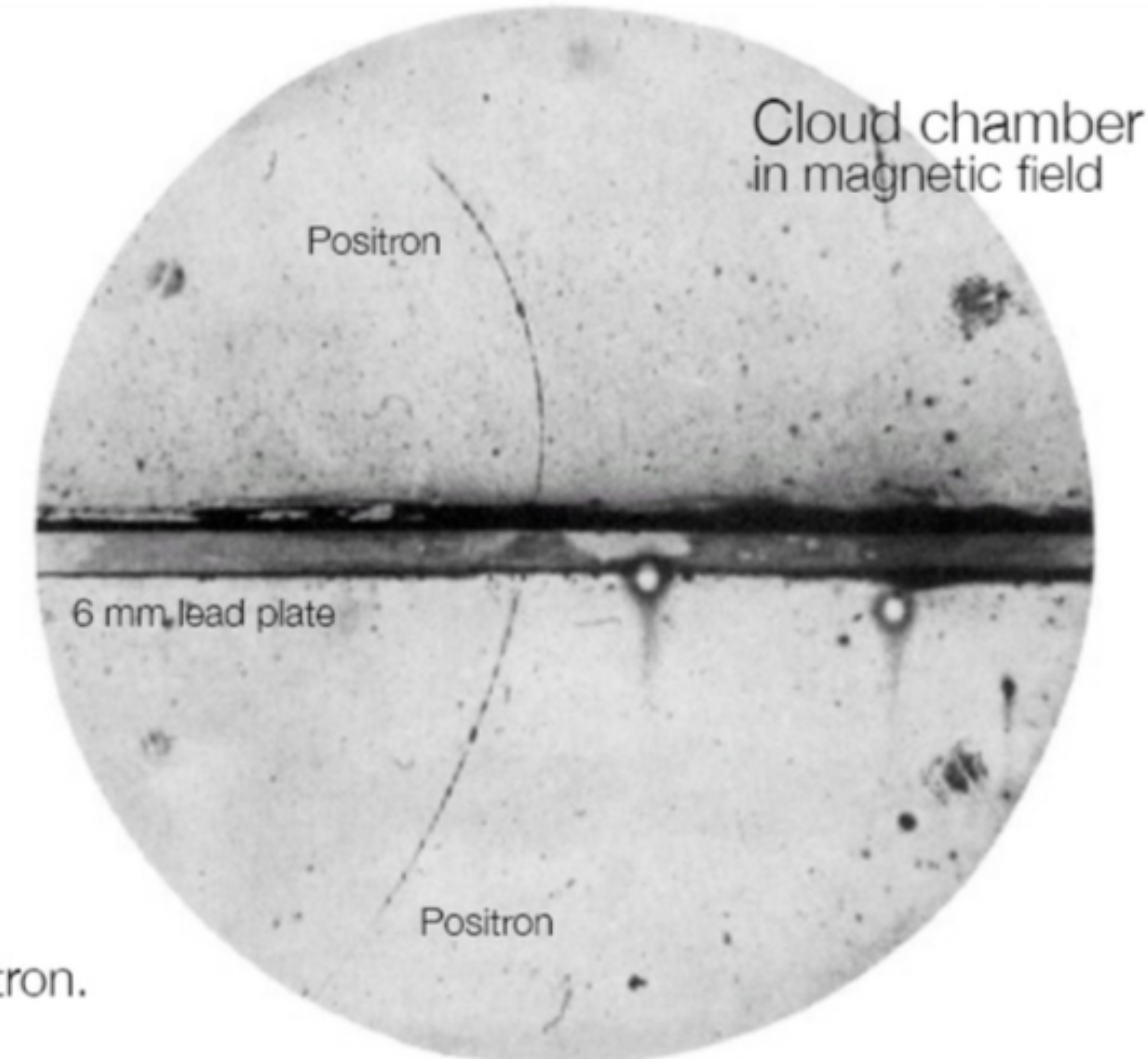
In the Standard Model (SM) of particle physics, the electromagnetic and the weak forces are unified: electroweak interaction.

HOW to DETECT and IDENTIFY a PARTICLE?



What can you infer from this picture about the setup ?
Which way is the particle traversing the photograph ?
Why ?

POSITRON DISCOVERY in 1933



Positron discovery in 1933 by Carl Andersen

HOW ARE PARTICLES DETECTED ?

In order to detect a particle it must

- interact with the material of the detector
- transfer energy in some recognisable way and leave a *signal.*

Detection of particles happens via their energy loss in the material they traverse.

Charged particles	Ionization, Bremsstrahlung, Cherenkov, …	multiple interactions
Photons	Photo/Compton effect, pair production	single interactions…
Hadrons	Nuclear interactions	multiple interactions
Neutrinos	Weak interactions	

THE 13 PARTICLES A DETECTOR MUST BE ABLE TO MEASURE AND IDENTIFY

$e^\pm$ $m_e = 0.511$ MeV
$\mu^\pm$ $m_\mu = 105.7$ MeV $\sim 200\, m_e$
γ $m_\gamma = 0$, $Q = 0$

} EM

$\pi^\pm$ $m_\pi = 139.6$ MeV $\sim 270\, m_e$
$K^\pm$ $m_K = 493.7$ MeV $\sim 1000\, m_e$ ($\sim 3.5\, m_\pi$)
$p^\pm$ $m_p = 938.3$ MeV $\sim 2000\, m_e$

} EM, Strong

K^0 $m_{K^0} = 497.7$ MeV $Q = 0$
n $m_n = 939.6$ MeV $Q = 0$

} Strong

The Difference in

Mass, Charge, Interaction

is the key to the Identification

W. Riegler/CERN

MEASURING PARTICLES

$eV = 1.6 \cdot 10^{-19}$ J
c = 299 792 458 m/s
e = $1.602176487(40) \cdot 10^{-19}$ C

Particles are characterized by

- Mass [Unit: eV/c^2 or eV]
- Momentum [Unit: eV/c or eV]
- Energy [Unit: eV]
- Charge [Unit: e]

[+ Spin, Lifetime ...]

Particle Identification via measurement of

e.g. $(E, \vec{p}, Q)$ or $(\vec{p}, \beta, Q)$
$(\vec{p}, m, Q)$ ...

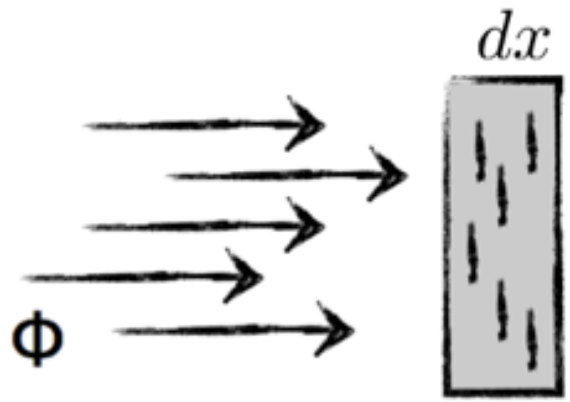
Relativistic kinematics:

$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}} \qquad \vec{p} = m\gamma\vec{\beta}c \qquad \vec{\beta} = \frac{\vec{p}c}{E}$$

INTERACTION CROSS-SECTION



Flux $\Phi = \frac{1}{S}\frac{dN_i}{dt}$ [$L^{-2}t^{-1}$]

area obscured by target particle

Reactions per unit of time $\frac{dN_{\rm reac}}{dt} = \Phi \sigma N_{\rm target} dx$ [t^{-1}]

[$L^{-2}t^{-1}$] [?] [L^{-1}] [L]

Reaction rate per target particle $W_{if} = \Phi\sigma$ [t^{-1}]

Cross section per target particle $\sigma = \frac{W_{if}}{\Phi}$ [L^2] = reaction rate per unit of flux

1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

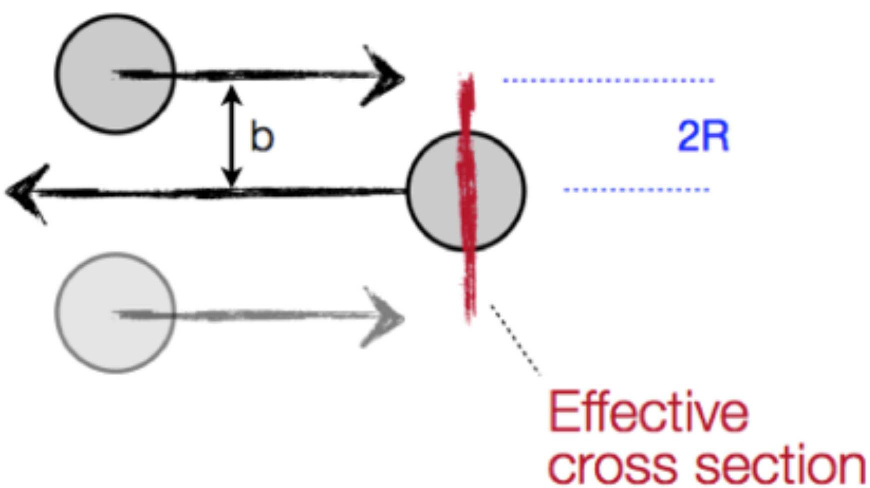
CROSS-SECTION: ORDER OF MAGNITUDE

Standard
cross section unit: $[\sigma]$ = mb with 1 mb = 10^{-27} cm^2

or in
natural units: $[\sigma] = \mathrm{GeV}^{-2}$ with 1 GeV^{-2} = 0.389 mb
1 mb = 2.57 GeV^{-2}

using: $\hbar c$ = 0.1973 GeV fm
$(\hbar c)^2$ = 0.389 GeV^2 mb

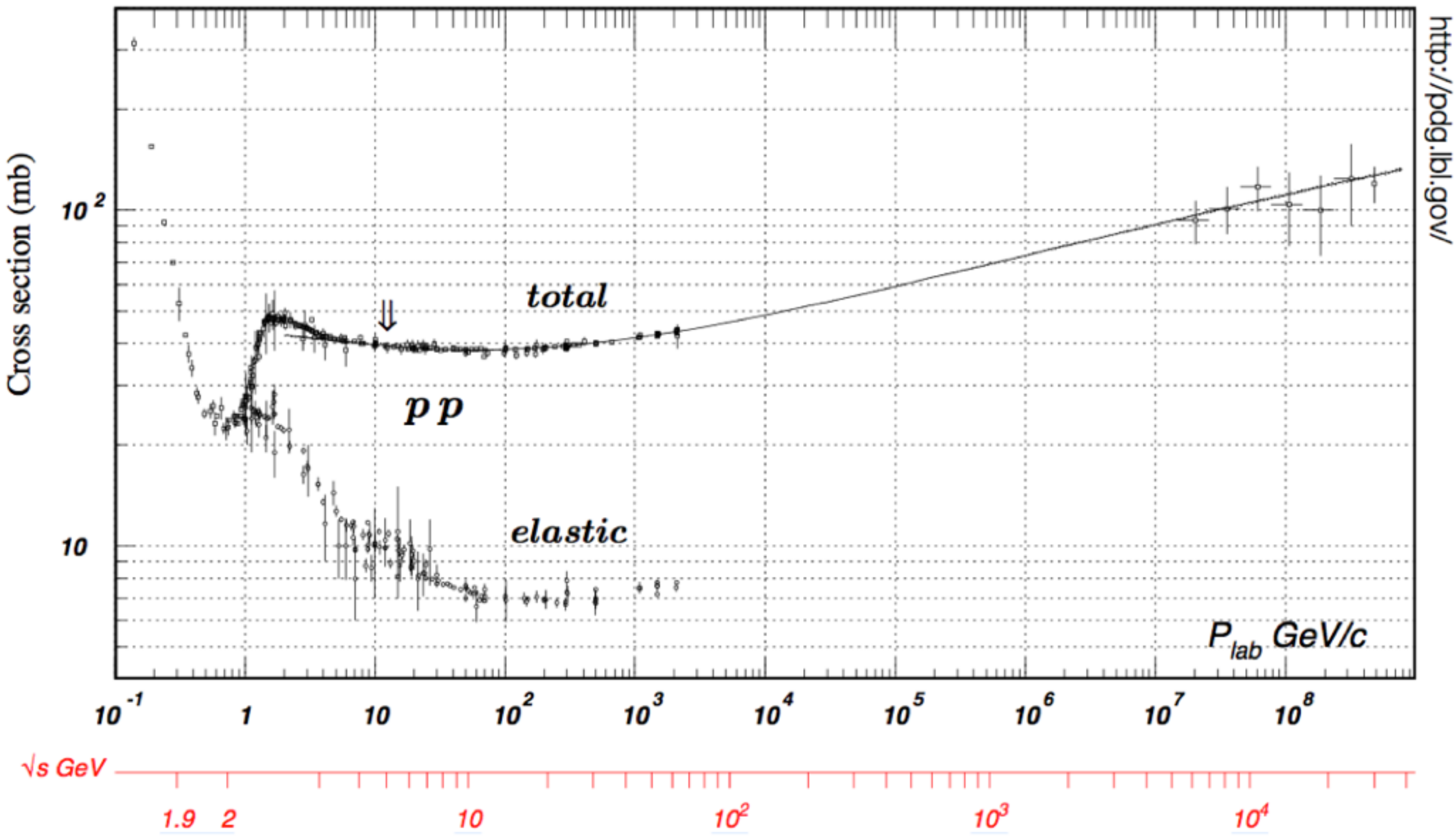
Estimating the
proton-proton cross section:



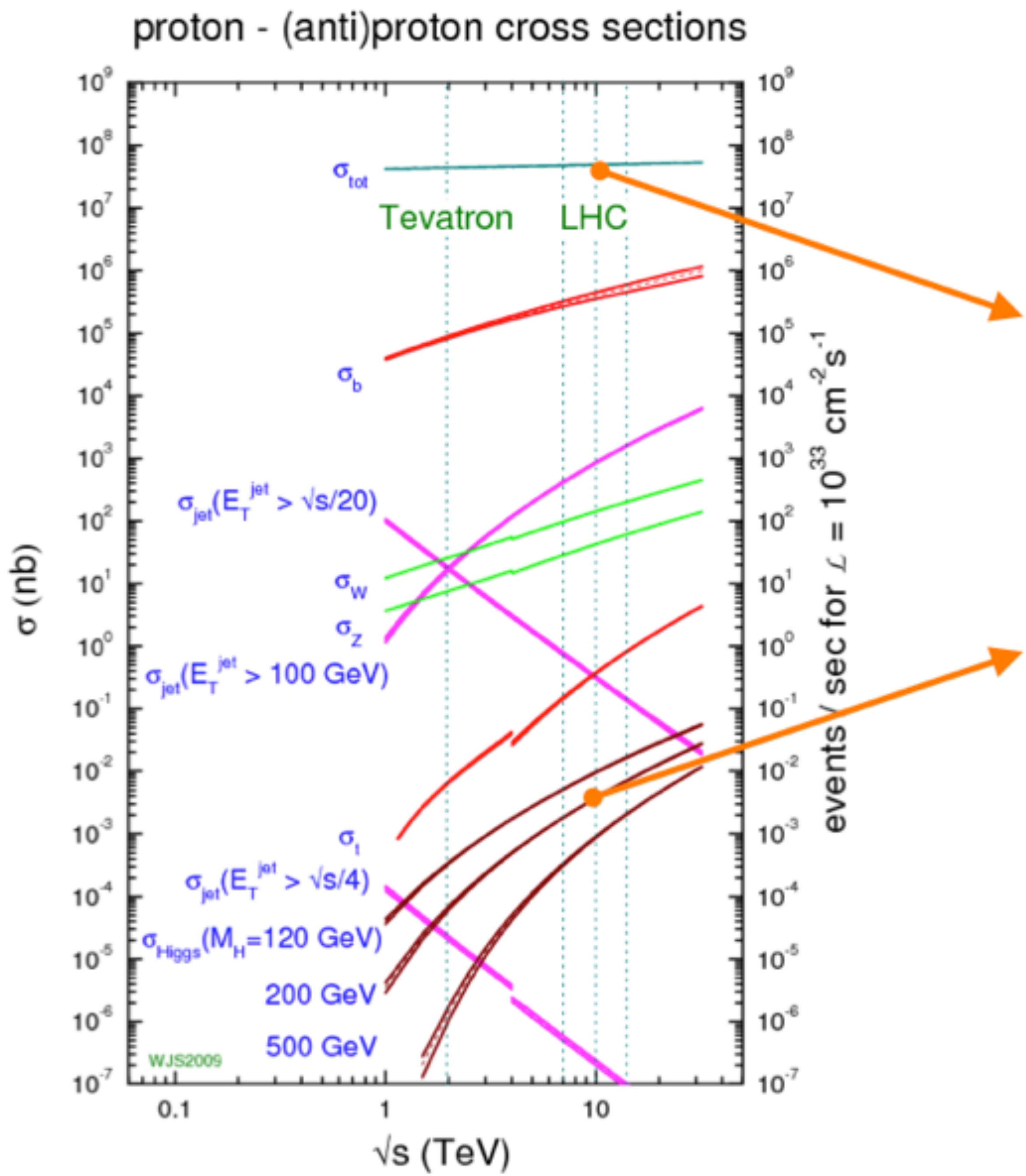
Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

$$\sigma = \pi(2R)^2 = \pi\cdot 1.6^2\ \mathrm{fm}^2$$
$$= \pi\cdot 1.6^2\ 10^{-26}\ \mathrm{cm}^2$$
$$= \pi\cdot 1.6^2\ 10\ \mathrm{mb}$$
$$= 80\ \mathrm{mb}$$

PROTON-PROTON SCATTERING CROSS-SECTION



CROSS-SECTIONS AT THE LHC



10^8 events/s

$\sim 10^{10}$

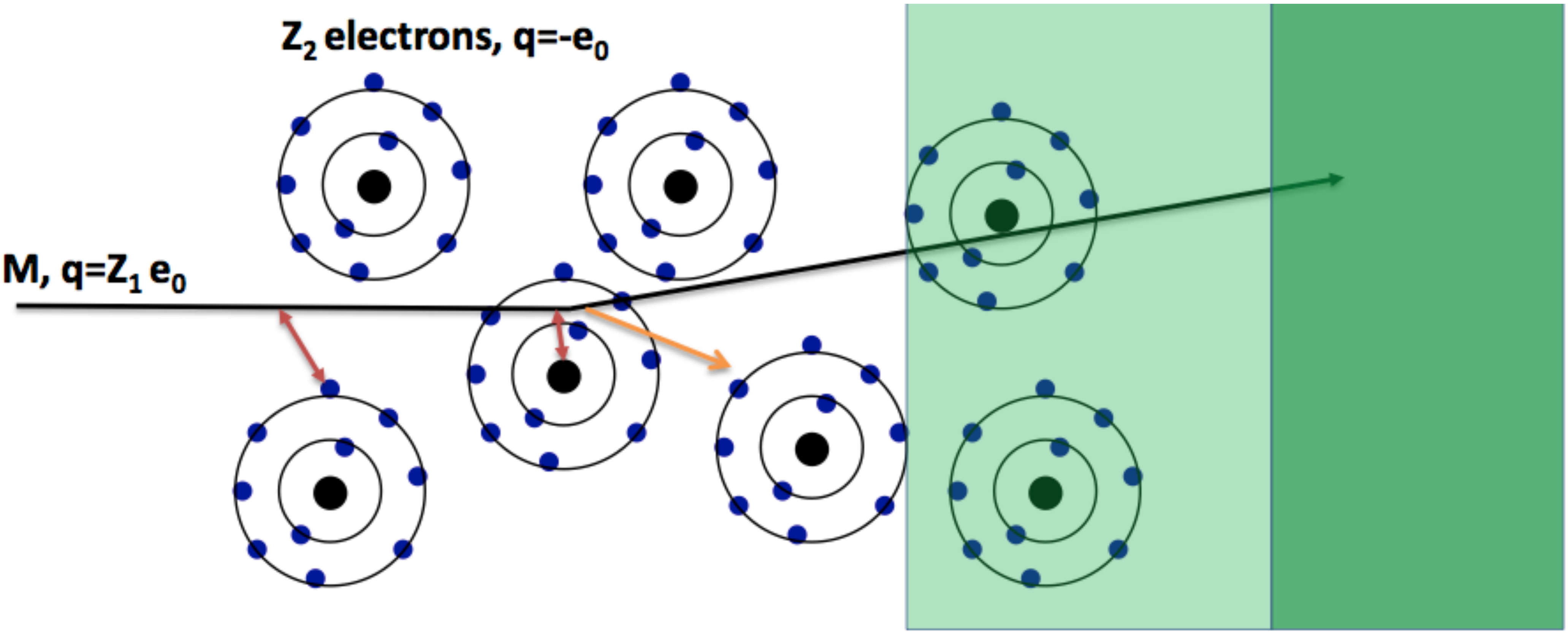
10^{-2} events/s ~ 10 events/min

[m_H ~ 120 GeV]

0.2% H → γγ
1.5% H → ZZ

TRIGGER !

ELECTROMAGNETIC INTERACTION
PARTICLE - MATTER



Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

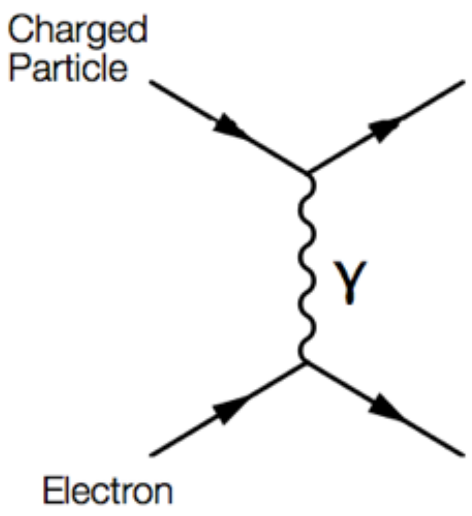
Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung photon** can be emitted

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as **Cherenkov radiation.** When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

ENERGY LOSS BY IONISATION: BETHE-BLOCH FORMULA

For now assume: $Mc^2 \gg m_e c^2$

i.e. energy loss for heavy charged particles
[dE/dx for electrons more difficult ...]



Interaction dominated
by elastic collisions with electrons ...

Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$\propto 1/\beta^2 \cdot \ln(\mathrm{const} \cdot \beta^2 \gamma^2)$

BETHE-BLOCH FORMULA

[see e.g. PDG 2010]

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] [\cdot \rho]$$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307\ \text{MeV g}^{-1}\ \text{cm}^2$

$T_{max} = 2m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle

M : Mass of incident particle

Z : Charge number of medium

A : Atomic mass of medium

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$

[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm

[Classical electron radius]

$m_e = 511$ keV

[Electron mass]

$\beta = v/c$

[Velocity]

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

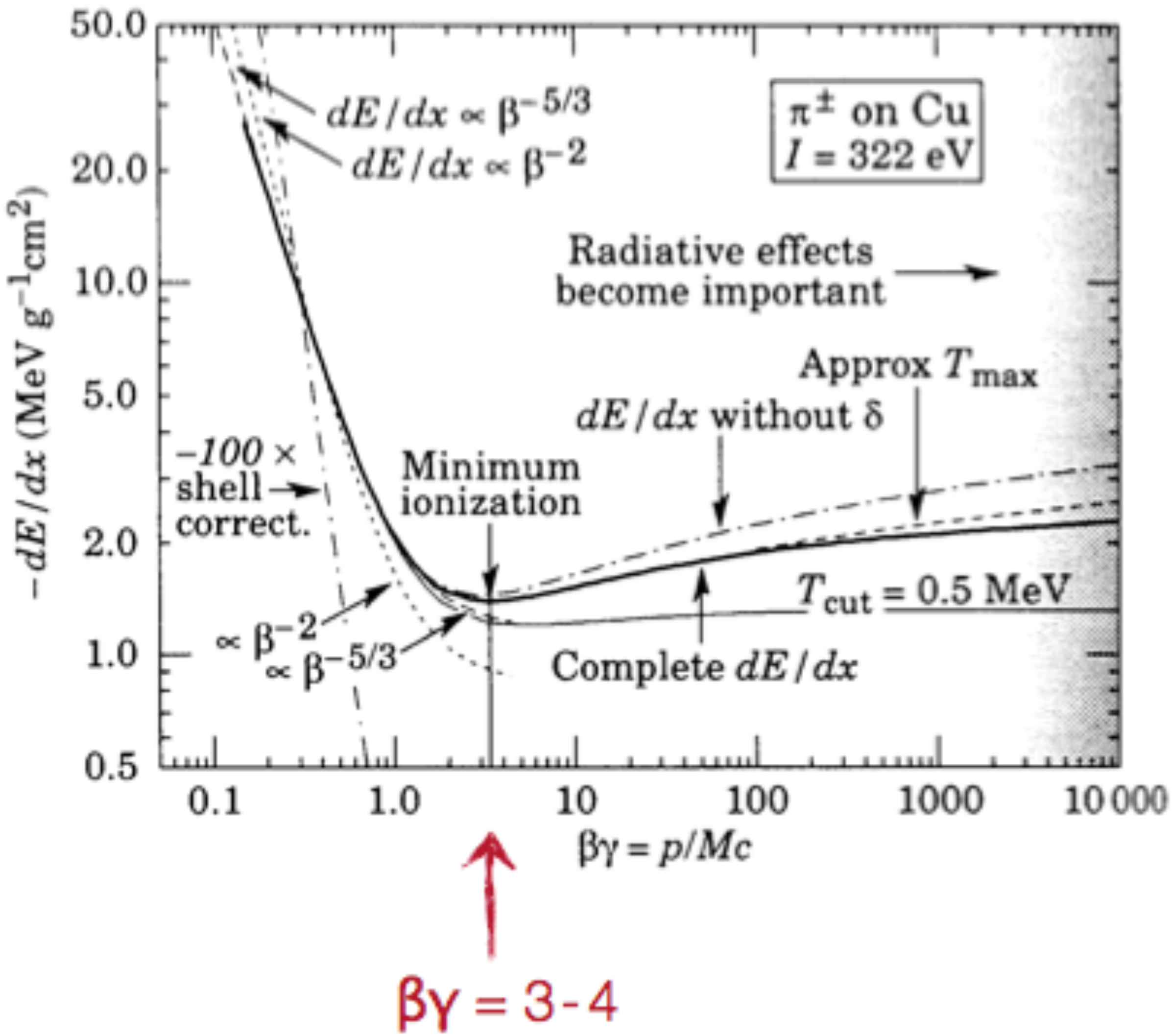
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$

$M > m_\mu$

ENERGY LOSS of PIONS in Cu



Minimum
ionizing particles (MIP): **βγ** = 3-4

dE/dx falls ~ β^{-2}; kinematic factor
[precise dependence: ~ $\beta^{-5/3}$]

dE/dx rises ~ ln$(\beta\gamma)^2$; relativistic rise
[rel. extension of transversal E-field]

Saturation at large (**βγ**) due to density effect (correction **δ**)
[polarization of medium]

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

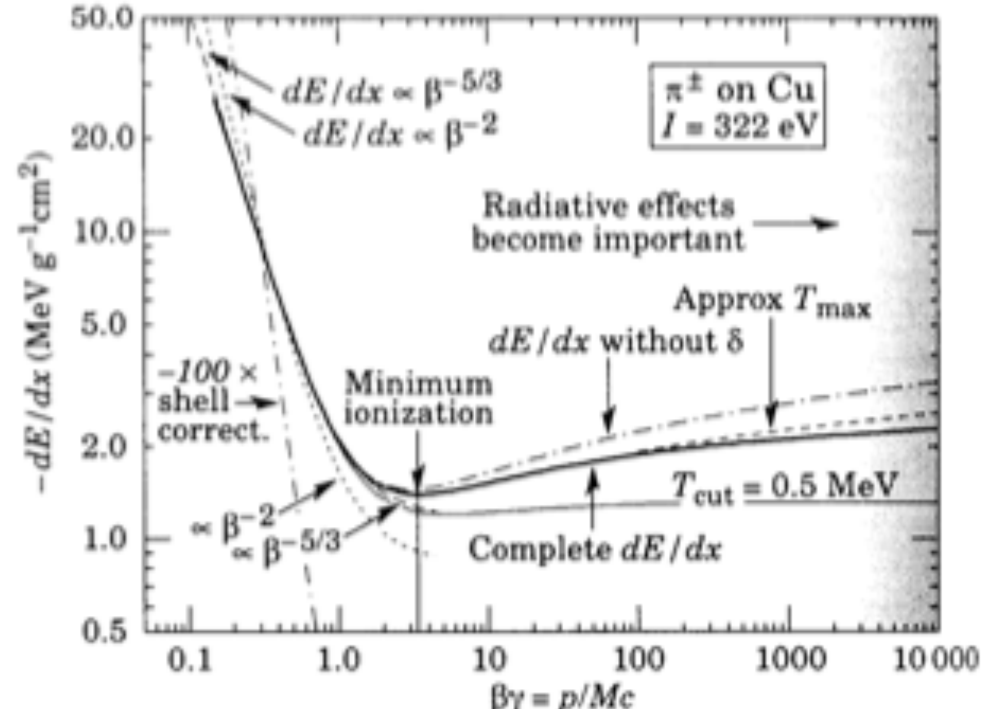
UNDERSTANDING BETHE-BLOCH

$1/\beta^2$-dependence:

Remember:

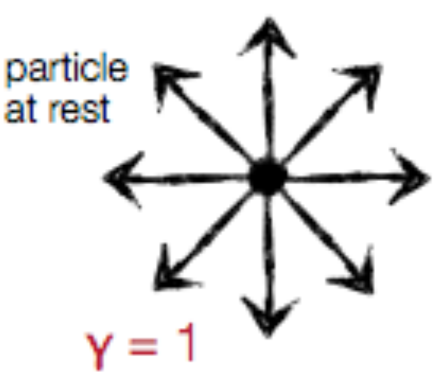
$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

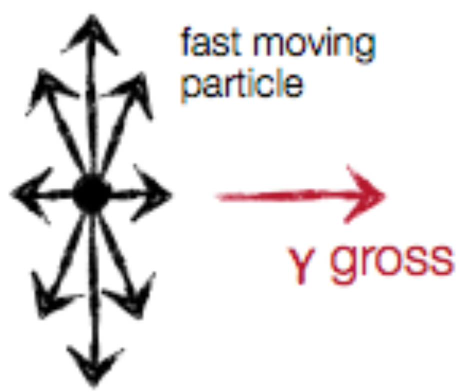
i.e. slower particles feel electric force of atomic electron for longer time ...



Relativistic rise for $\beta\gamma > 4$:

High energy particle: transversal electric field increases due to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...





Corrections:

low energy : shell corrections

high energy : density corrections

UNDERSTANDING BETHE-BLOCH

Density correction:

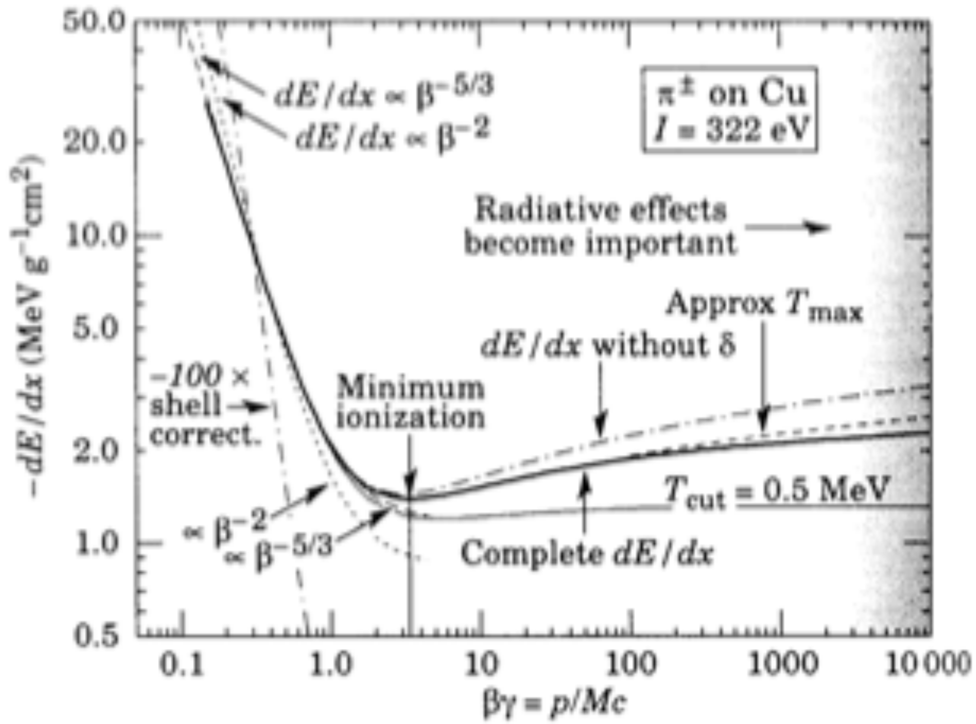
Polarization effect ...
[density dependent]

→ Shielding of electrical field far from particle path; effectively cuts of the long range contribution ...

More relevant at high γ ...
[Increased range of electric field; larger b_{max}; ...]

For high energies:

$$\delta/2 \rightarrow \ln(\hbar\omega/I) + \ln\beta\gamma - 1/2$$



Density effect leads to saturation at high energy ...

Shell correction:

Arises if particle velocity is close to orbital velocity of electrons, i.e. $\beta c \sim v_e$.

Assumption that electron is at rest breaks down ...
Capture process is possible ...

Shell correction are in general small ...

CHARGED PARTICLE ENERGY LOSS in MATERIALS

Dependance on target element

Mass A

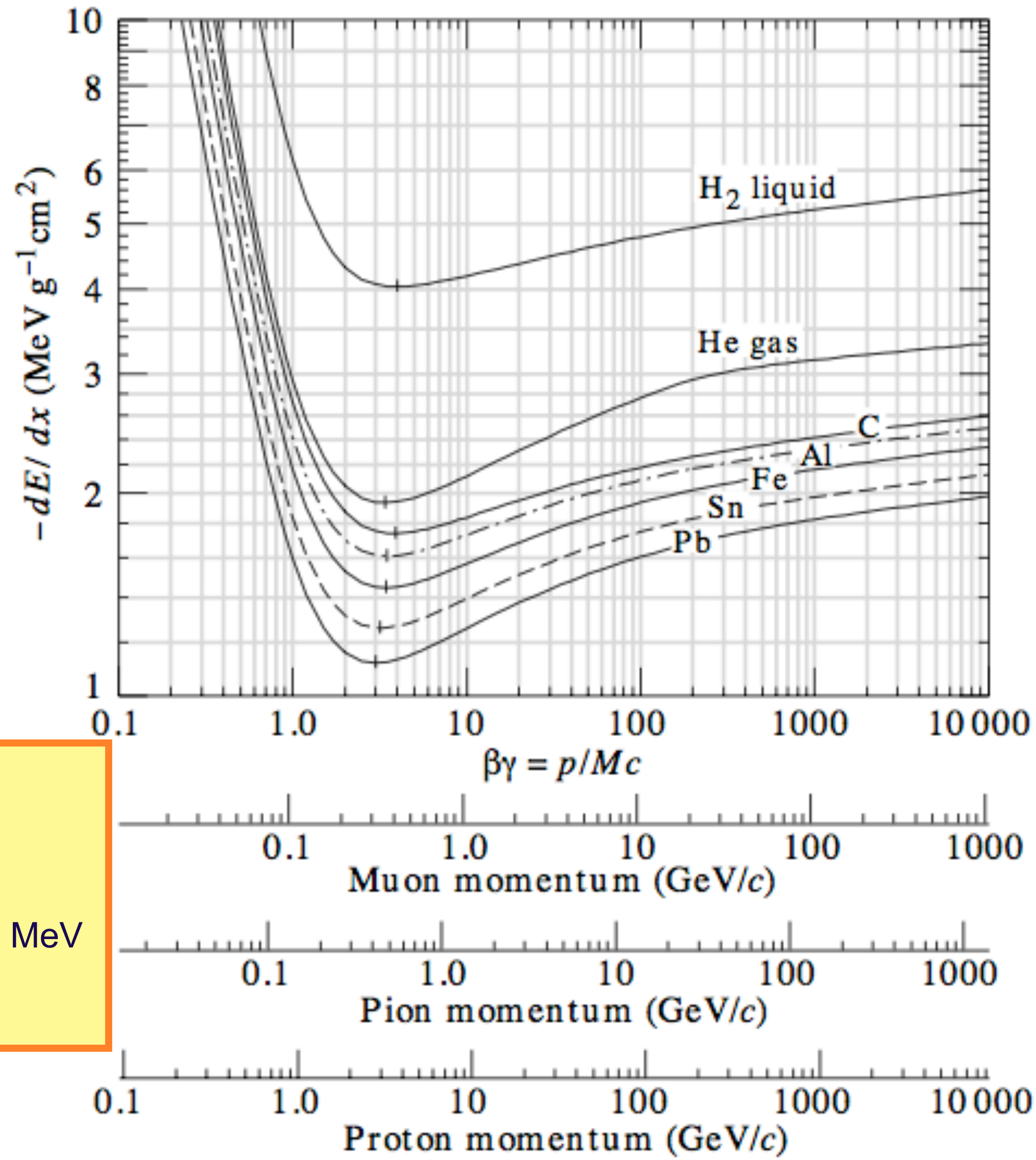
Charge Z

Minimum Ionisation

$-dE/dx \sim 1\text{-}2$ MeV $g^{-1}cm^2$

e.g. for Pb with ρ=11.35 g/cm^3:

$-dE/dx \sim 13$ MeV/cm



Can a 1 GeV muon traverse 1 meter of iron ?

ρ_{Fe} = 7.87 g/cm^3

dE/dx ~1.4 MeV cm^2/g (p=1 GeV)

ΔE = 7.87 g/cm^3 x 100cm x 1.4 MeV cm^2/g = 1102 MeV

For a 1 TeV muon ? ΔE ~2 GeV

MATERIAL PROPERTIES

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T $\{g/cm^2\}$	Nuclear [a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\|_{min}$ [b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length [c] X_0 $\{g/cm^2\}$	Radiation length [c] X_0 $\{cm\}$	Density $\{g/cm^3\}$ ($\{g/\ell\}$ for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\min}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [h]	184.5	(1.038) [h]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [i]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [j]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [k]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [l]			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) [m]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [n]			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator [o]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [p]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [q]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al_2O_3)			0.49038	67.0	98.9	1.647	27.94	7.04	3.97		1.761
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [r]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [s]			0.50093	66.3	96.9	1.740	27.25	136@ρ=0.2	0.04–0.6		1.0+0.21ρ
NEMA G10 plate [t]				62.6	90.2	1.87	33.0	19.4	1.7		—

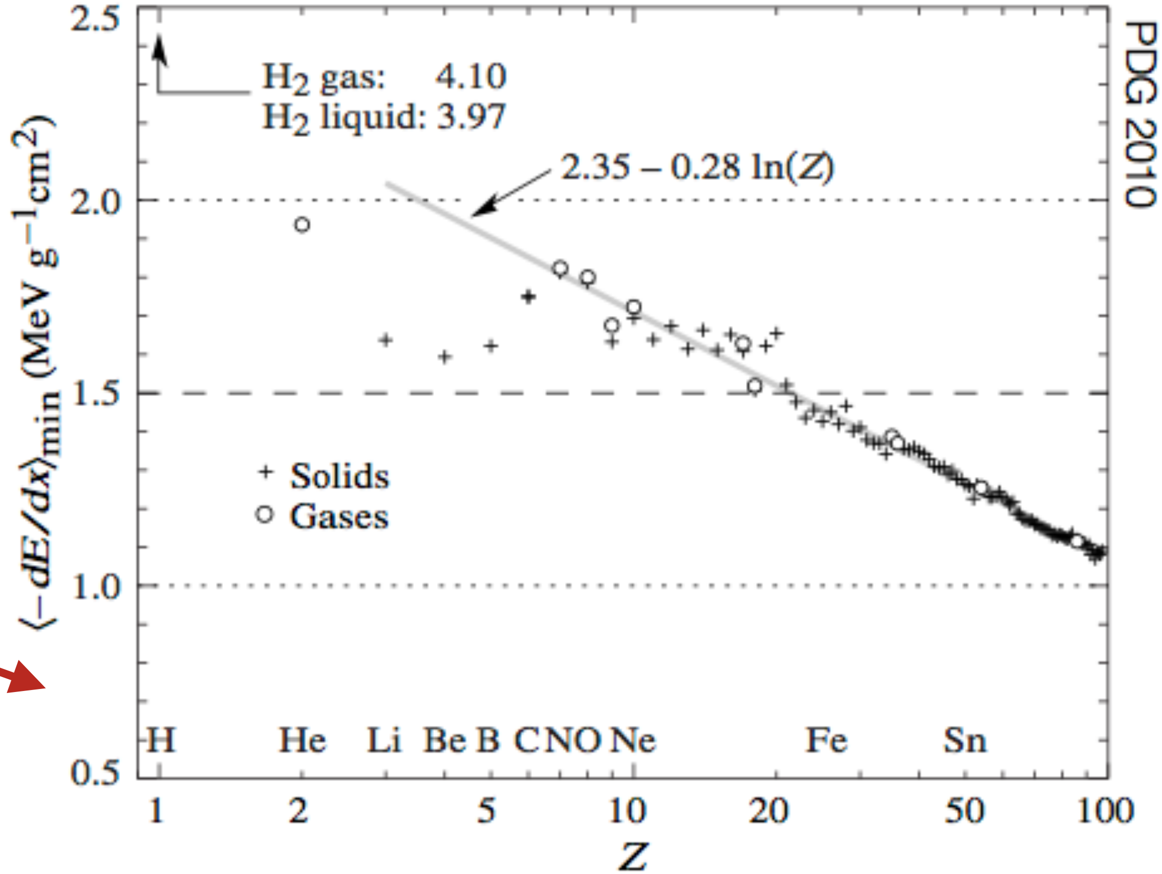
STOPPING POWER AT MINIMUM IONISATION

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] [\cdot \rho]$$

density

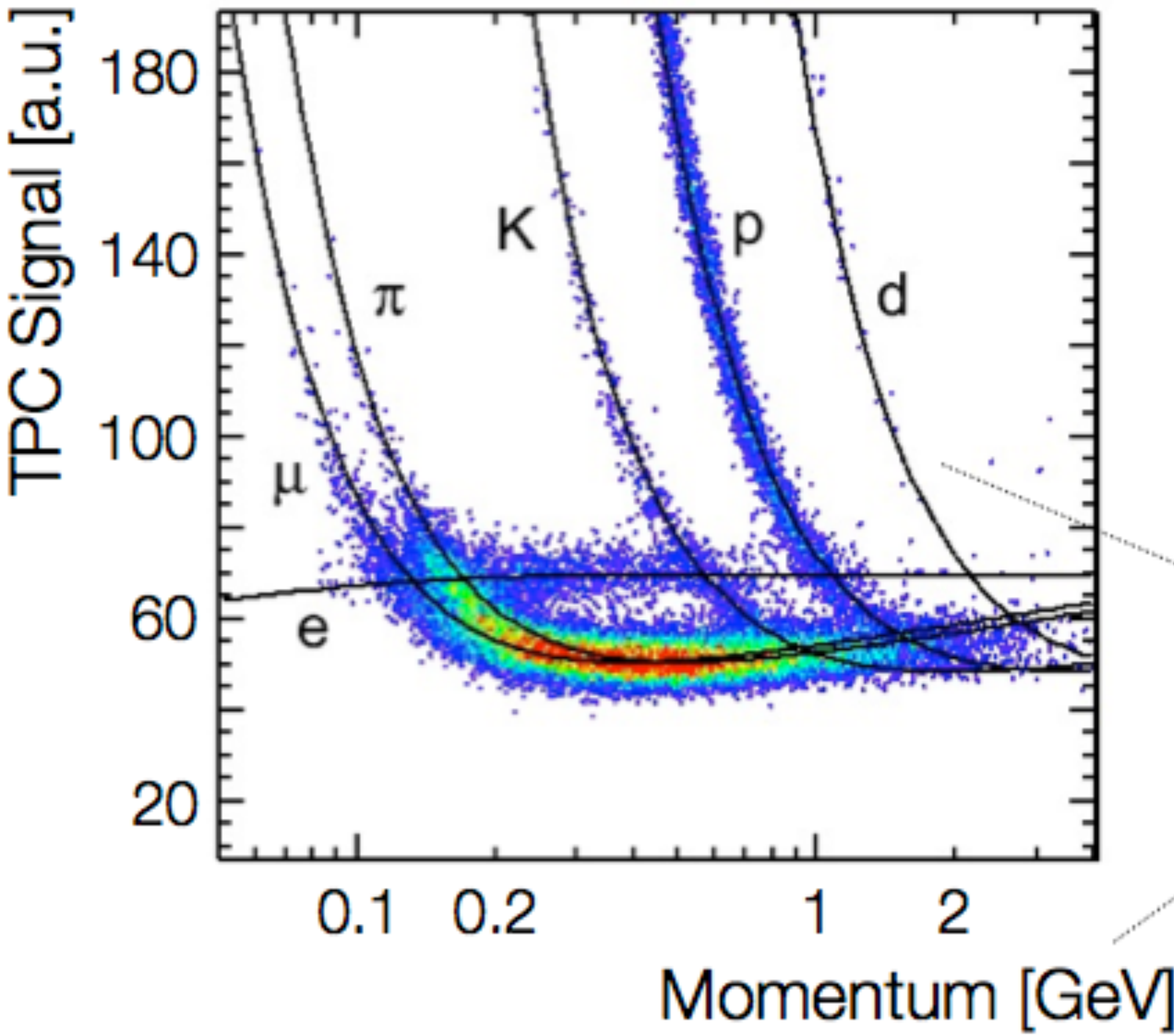
material dependance on Z/A ~ 1/2

Small dependance with Z



Stopping power at minimum ionization for the chemical elements. The straight line is fitted for Z > 6.
A simple functional dependence on Z is not to be expected, since <–dE/dx> also depends on other variables.

dE/dX and PARTICLE IDENTIFICATION



Measured
energy loss

[ALICE TPC, 2009]

Bethe-Bloch

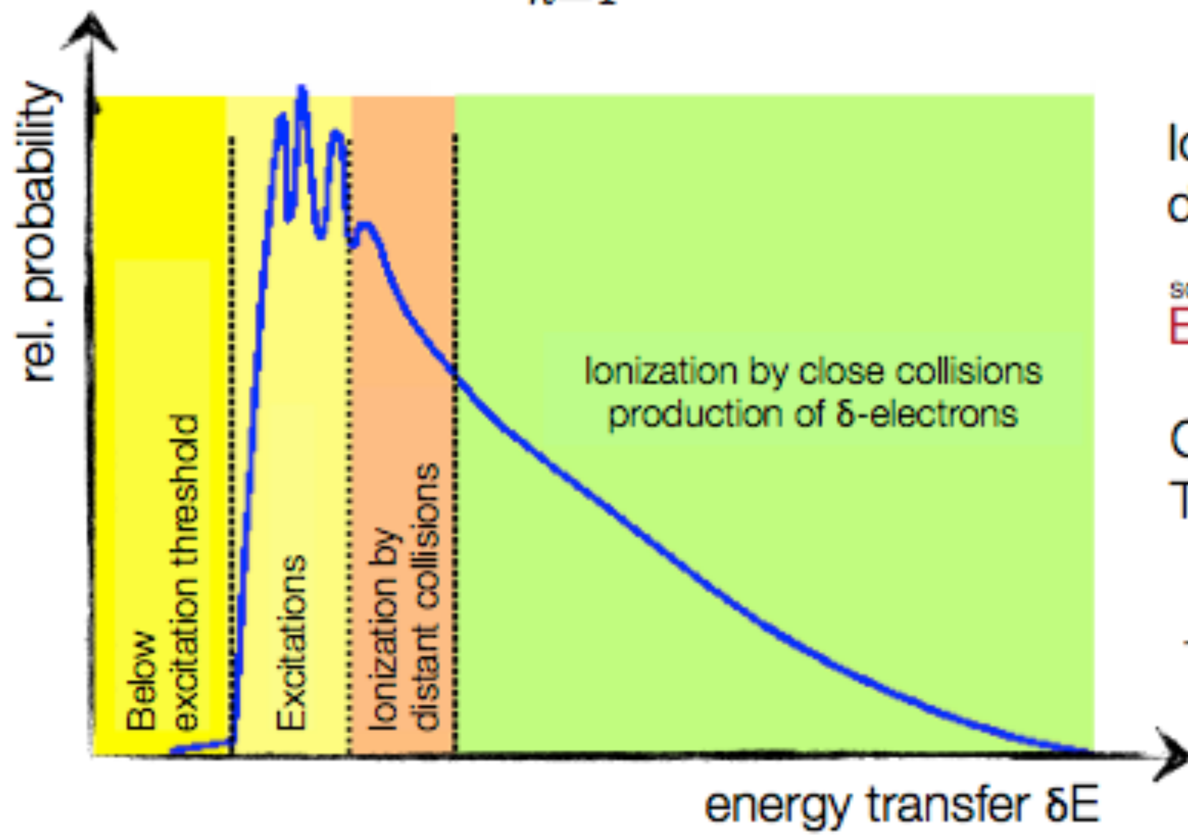
Remember:
dE/dx depends on β!

dE/dx FLUCTUATIONS

Bethe-Bloch describes mean energy loss; measurement via energy loss ΔE in a material of thickness Δx with

$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

N : number of collisions
δE : energy loss in a single collision



Ionization loss δE distributed statistically ...

so-called
Energy loss 'straggling'

Complicated problem ...
Thin absorbers: Landau distribution

Standard Gauss with mean energy loss E_0
\+ tail towards high energies due to δ-electrons

see also Allison & Cobb
[Ann. Rev. Nucl. Part. Sci. 30 (1980) 253.]

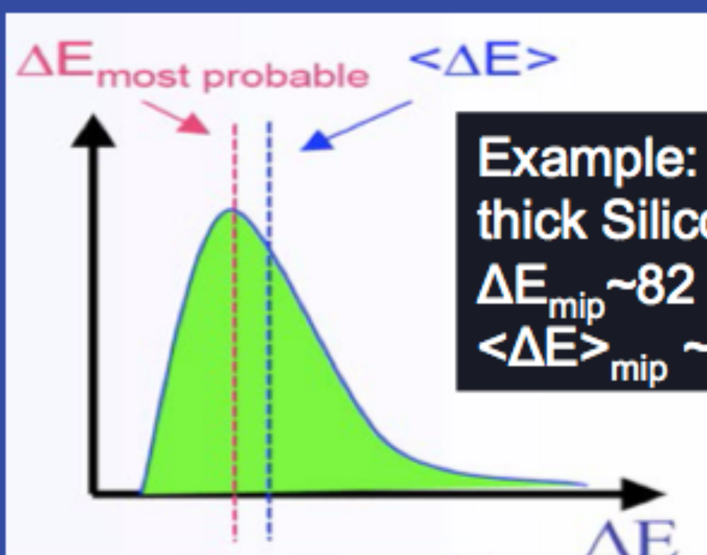
dE/dx FLUCTUATIONS

In a detector, with limited granularity, one measures $\Delta E/\Delta x$, and not $\langle dE/dx \rangle$

i.e. the energy deposit in a thickness of material

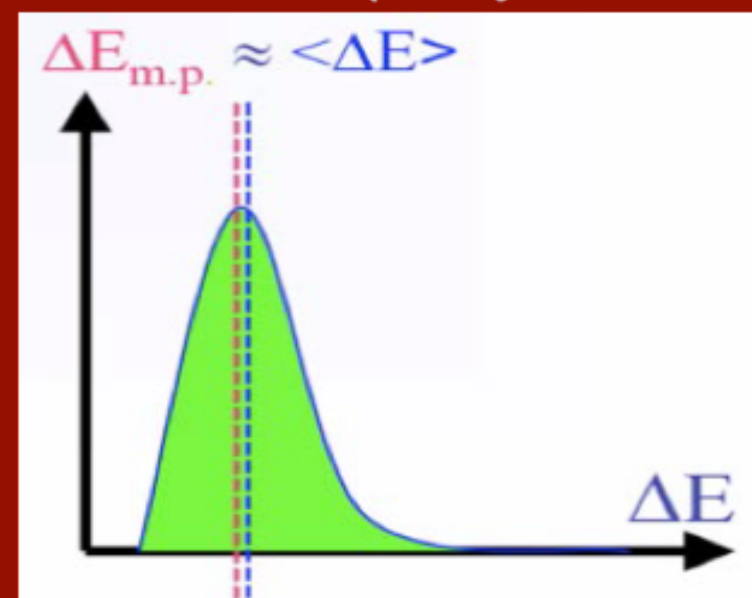
therefore multi-measurements are needed.

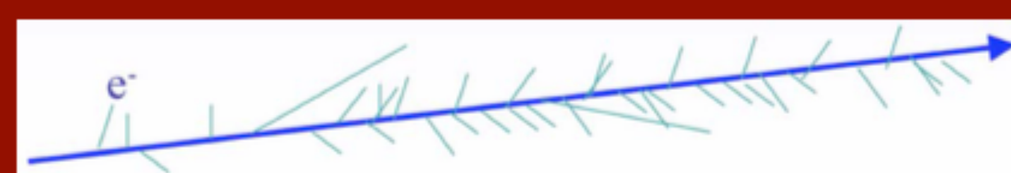
- Thin layers or low density materials: dE/dx has large fluctuations towards high losses (Landau)



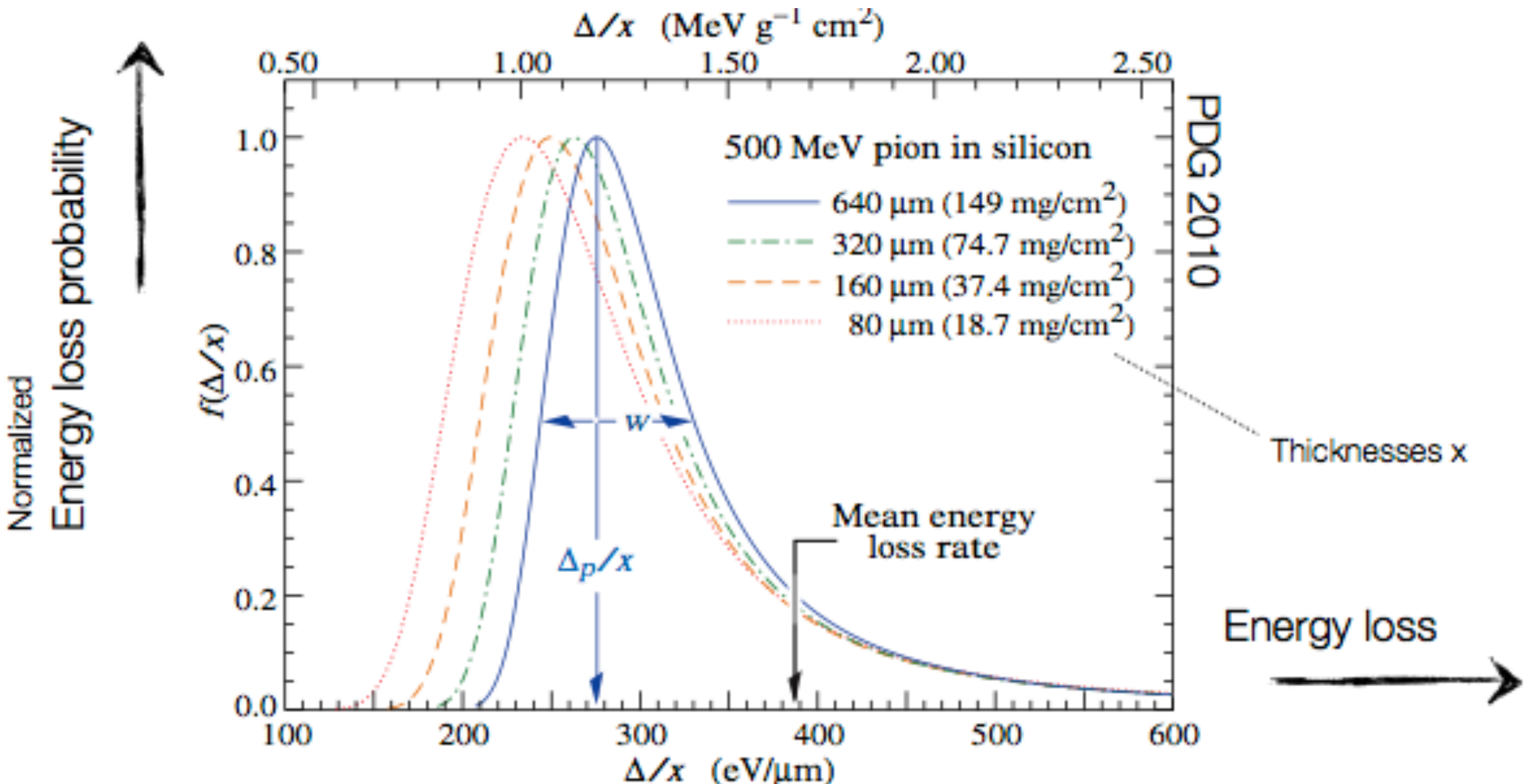
Example: 300 µm thick Silicon ΔE_{mip} ~82 keV, $\langle \Delta E \rangle_{mip}$ ~115 keV

- Thick layers and high density materials: the dE/dx is a more Gaussian-like (many collisions





dE/dx FLUCTUATIONS - LANDAU DISTRIBUTION



Approximation:

$$f(\Delta/x) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\Delta/x - a(\Delta/x)_{\mathrm{mip}}}{\xi}\right) + e^{-\left(\frac{\Delta/x - a(\Delta/x)_{\mathrm{mip}}}{\xi}\right)}\right]$$

for full form see e.g. Leo

ξ: material constant

ENERGY LOSS of ELECTRONS

Bethe-Bloch formula needs modification

Incident and target electron have same mass m_e
Scattering of identical, undistinguishable particles

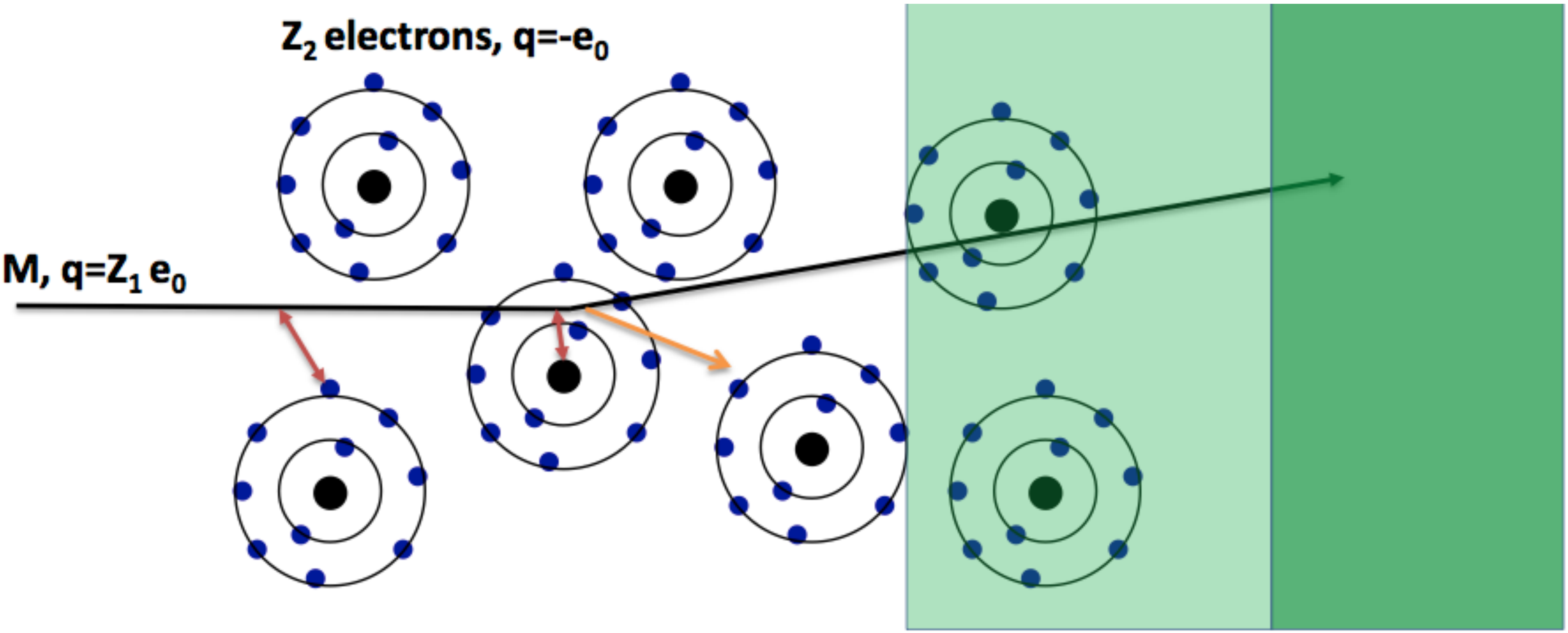
$$-\left\langle \frac{dE}{dx} \right\rangle_{\text{el.}} = K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e \beta^2 c^2 \gamma^2 T}{2I^2} + F(\gamma) \right]$$

[T: kinetic energy of electron]

$W_{max} = ½T$

Remark: different energy loss for electrons and positrons at low energy as positrons are not identical with electrons; different treatment ...

ELECTROMAGNETIC INTERACTION
PARTICLE - MATTER



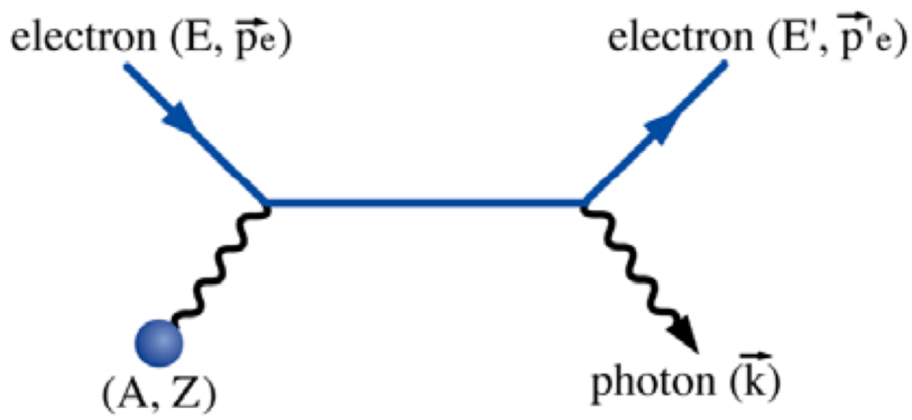
Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung photon** can be emitted

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as **Cherenkov radiation.** When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

BREMSSTRAHLUNG

Real photon emission in the electromagnetic field of the atomic nucleus



Electric field of the nucleus + of the electrons Z(Z+1)

At large radius, electrons screen the nucleus $\ln(183Z^{-1/3})$

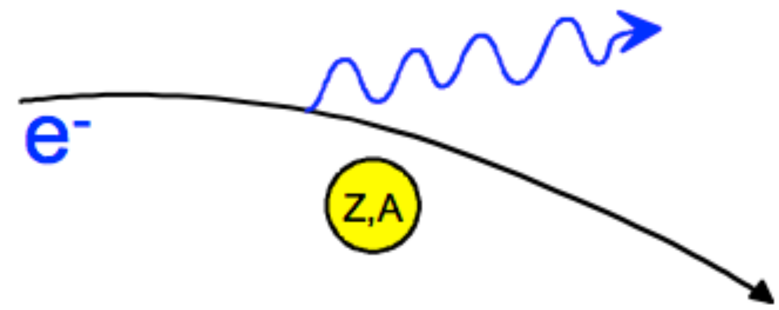
$$d\sigma/dk = 4\,\alpha\,Z(Z+1)r_e^2\ln(183Z^{-1/3})(4/3-4/3y+y^2)/k$$ [D.F.]

where y=k/E and $r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2} = 2.818\ 10^{-15}$ m classical radius of the electron

For a given E, the average energy lost by radiation, dE, is obtained by integrating over y.

BREMSSTRAHLUNG & RADIATION LENGTH

Bremsstrahlung arises if particles are accelerated in Coulomb field of nucleus



$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A} \left(\frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} \right)^2 E \ \ln \frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}$$

i.e. energy loss proportional to $1/m^2$ ➞ main relevance for electrons ...

... or ultra-relativistic muons

Consider electrons:

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 \cdot E \ \ln \frac{183}{Z^{\frac{1}{3}}}$$

$$\frac{dE}{dx} = \frac{E}{X_0} \qquad \text{with} \quad X_0 = \frac{A}{4\alpha N_A \ Z^2 r_e^2 \ \ln \frac{183}{Z^{\frac{1}{3}}}}$$

[Radiation length in g/cm²]

➞ $E = E_0 e^{-x/X_0}$

After passage of one X_0 electron has lost all but $(1/e)^{th}$ of its energy

[i.e. 63%]

RADIATION LENGTH

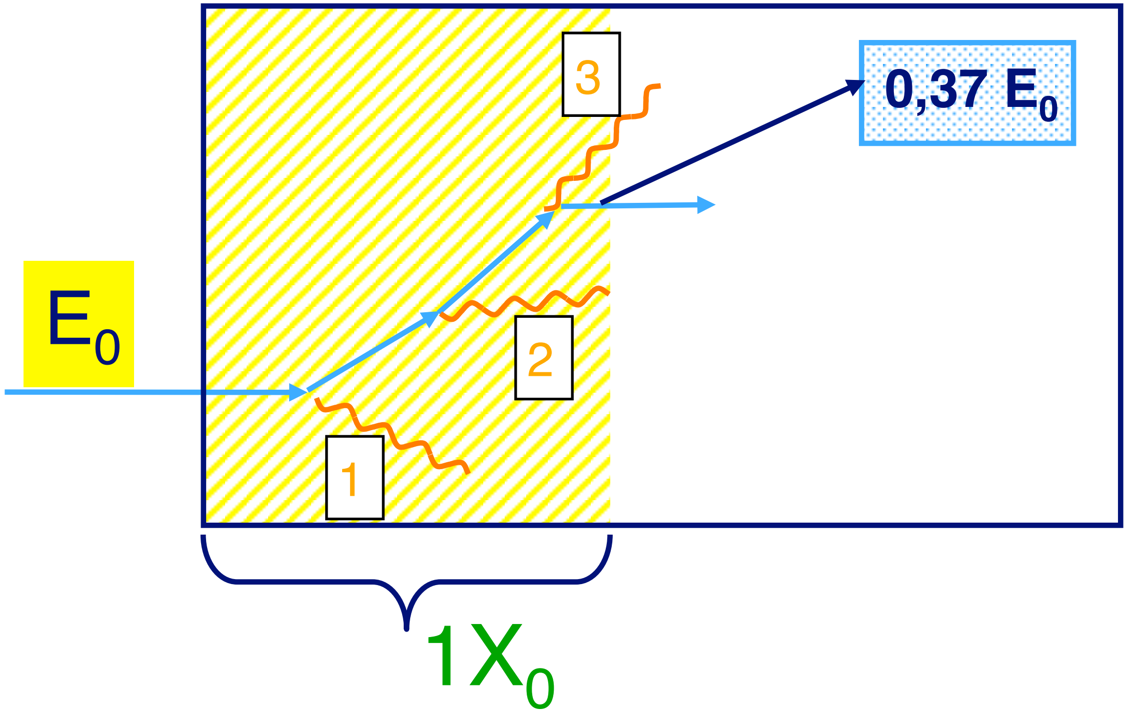
The radiation length is a "universal" distance, very useful to describe electromagnetic showers (electrons & photons)

X_0 is the distance after which the incident electron has radiated (1-1/e) 63% of its incident energy

$dE/dx = E/X_0$

$dE/E = dx/X_0$

$E = E_0 e^{-x/X_0}$



	Air	Eau	Al	LAr	Fe	Pb	$PbWO_4$	LAr/Pb
Z	-	-	13	18	26	82	-	-
X_0 (cm)	30420	36	8,9	14	1,76	0.56	0.89	1.9

CRITICAL ENERGY

Critical energy:

$$\frac{dE}{dx}(E_c)\Big|_{\text{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\text{Ion}}$$

Approximation:

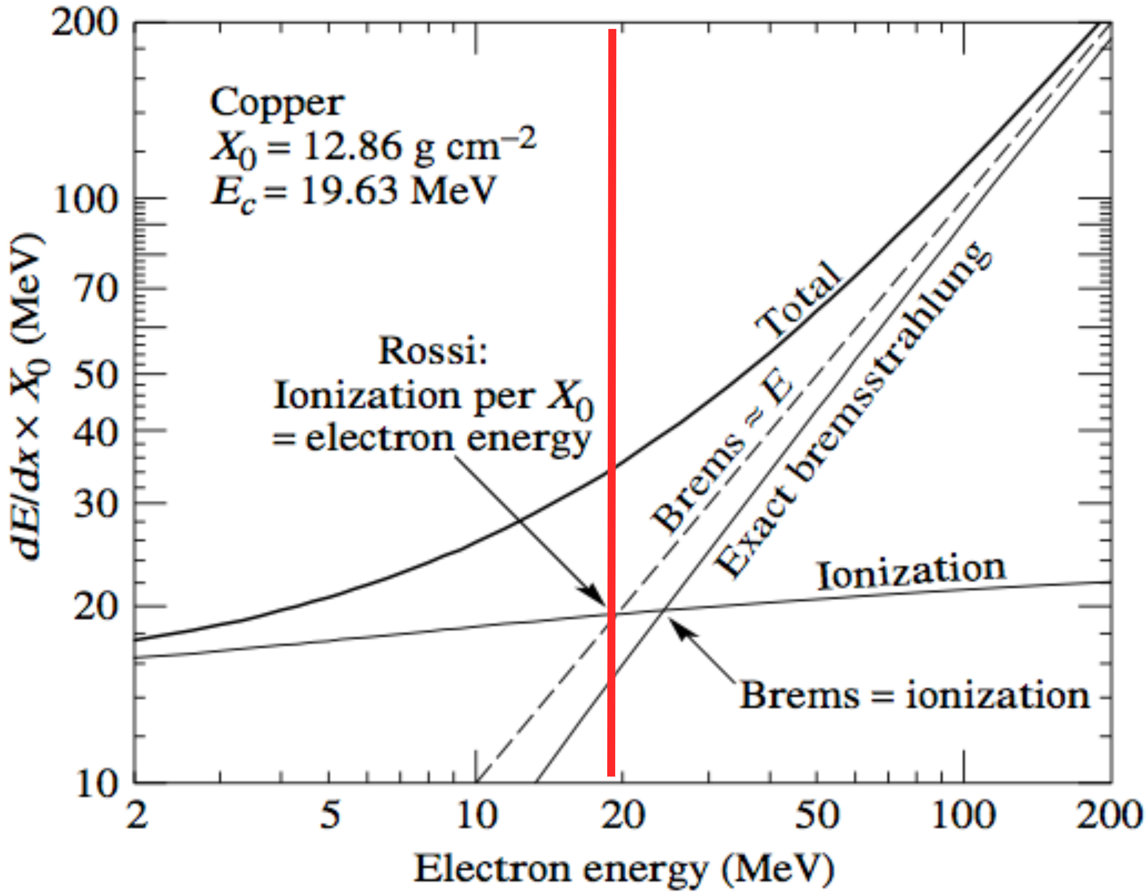
$$E_c^{\text{Gas}} = \frac{710\ \text{MeV}}{Z+0.92}$$

$$E_c^{\text{Sol/Liq}} = \frac{610\ \text{MeV}}{Z+1.24}$$

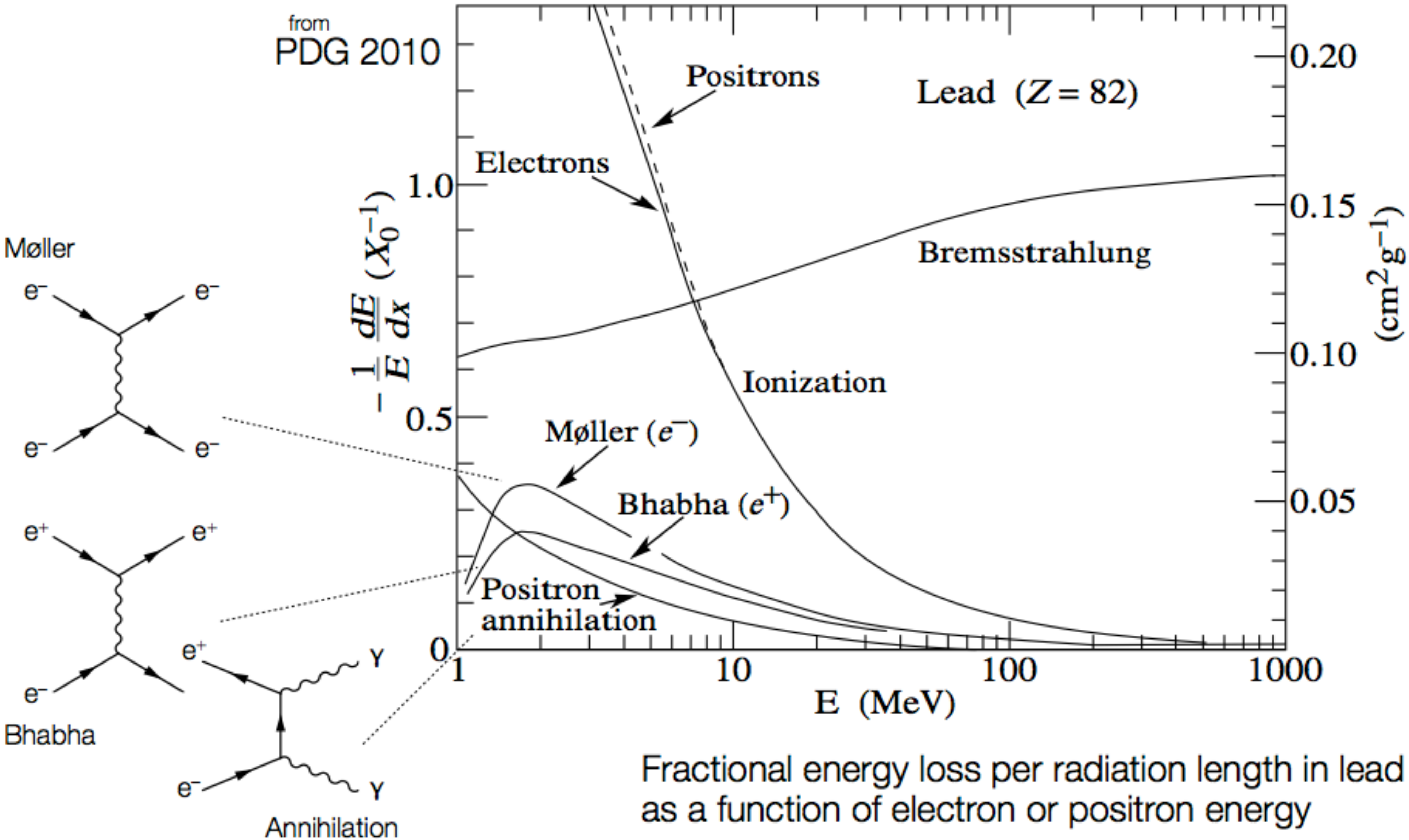
Example Copper:

$E_c \approx 610/30$ MeV ≈ 20 MeV

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$

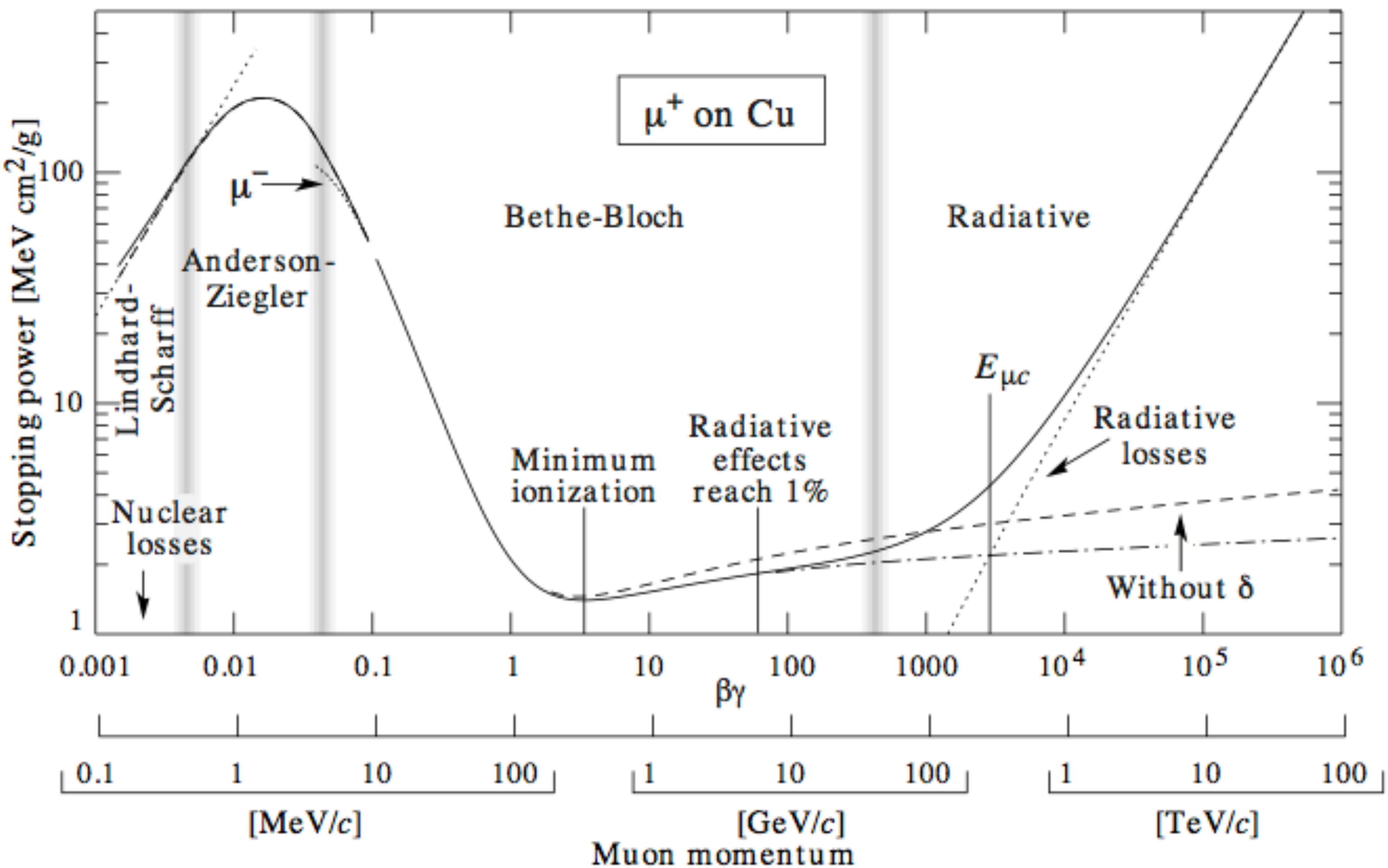


TOTAL ENERGY LOSS FOR ELECTRONS



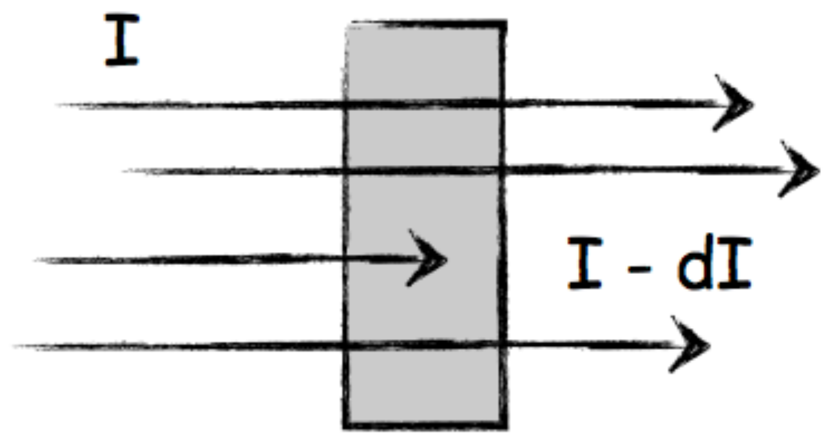
Fractional energy loss per radiation length in lead as a function of electron or positron energy

μ^+ in COPPER



μ+ on Cu
Stopping power [MeV cm2/g]
Bethe-Bloch
Radiative
Anderson-Ziegler
Lindhard-Scharff
μ−
Eμc
Minimum ionization
Radiative effects reach 1%
Radiative losses
Nuclear losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

INTERACTION OF PHOTONS WITH MATTER



Characteristic for interactions of photons with matter:

A single interaction removes photon from beam !

Possible Interactions

Photoelectric Effect
Compton Scattering
Pair Production

Rayleigh Scattering (γA → γA; A = atom; coherent)
Thomson Scattering (γe → γe; elastic scattering)
Photo Nuclear Absorption (γK → pK/nK)
Nuclear Resonance Scattering (γK → K* → γK)
Delbruck Scattering (γK → γK)
Hadron Pair production (γK → h^+h^- K)

$$dI = -\mu\, I\, dx$$

[μ : absorption coefficient]

depends on E, Z, ρ

→ Beer-Lambert law:

$$I(x) = I_0 e^{-\mu x}$$

with $\lambda = 1/\mu = 1/n\sigma$

[mean free path]

PHOTO-ELECTRIC EFFECT

Energy of
outgoing electron:

$$E_e = h\nu - I_b$$

Photon energy

Binding energy
[strongly Z dependent]

Typical energy dependence:

$$\sigma_{\rm ph} = 2\pi r_e^2\, \alpha^4\, Z^5\, (mc^2)/E_\gamma$$

[for $E_\gamma \gg mc^2$]

$$\sigma_{\rm ph} = \alpha\pi\, a_{\rm B}\, Z^5\, (I_0/E_\gamma)^{7/2}$$

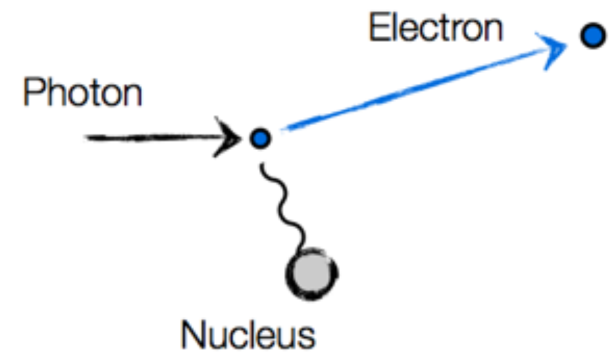
[for $I_0 \ll E_\gamma \ll mc^2$]

Example values:

$a_B = 0.53 \cdot 10^{-10}$ m; I_0 =13.6 eV; α =1/137; 1 b = 10^{-24} m
use E_γ = 100 keV

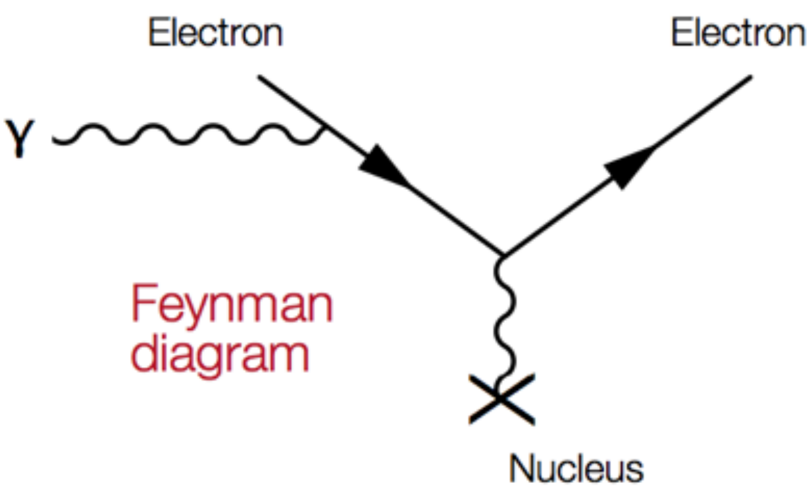
→ σ_{ph}(Fe) = 29 barn
σ_{ph}(Pb) = 5000 barn

Naive picture



γ + atom → e^- + atom$^+$

Feynman diagram



PAIR PRODUCTION

Cross Section:
[for $E_\gamma \gg m_e c^2$]

$$\sigma_{pair} \approx \frac{7}{9} \underbrace{\left(4\,\alpha r_e^2 Z^2 \ln \frac{183}{Z^{\frac{1}{3}}}\right)}_{A/N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm²]

Absorption coefficient:

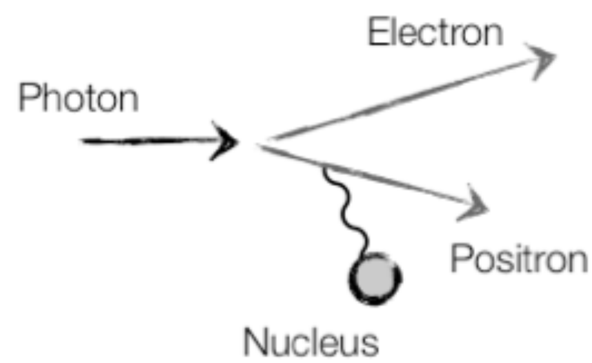
$\mu = n\sigma$ [with n: particle density]

$\mu = \rho \cdot N_A/A\ \sigma_{pair}$

$= 7/9\ \frac{1}{X_0}$

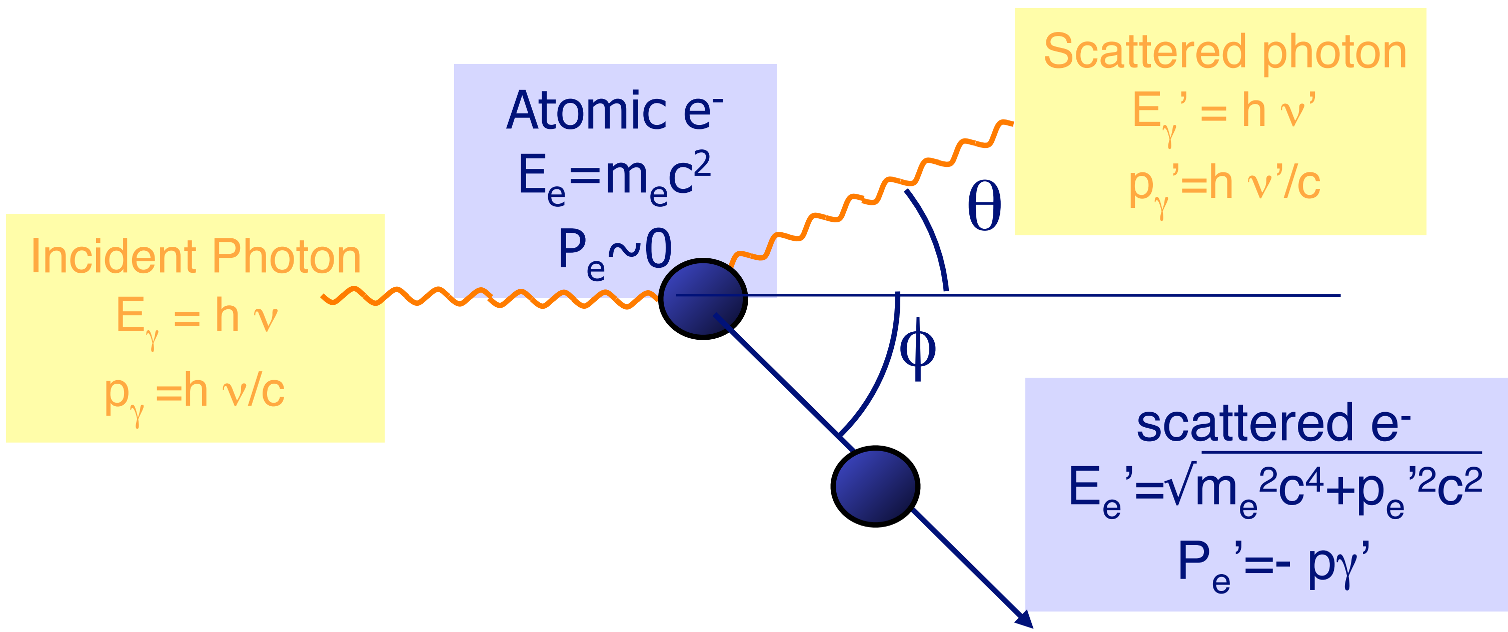
[where now X_0 is in cm]

$$I(x) = I_0 e^{-\mu x}$$



	ρ [g/cm³]	X_0 [cm]
H_2 [fl.]	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Air	$1.2 \cdot 10^{-3}$	$30 \cdot 10^{3}$

COMPTON SCATTERING

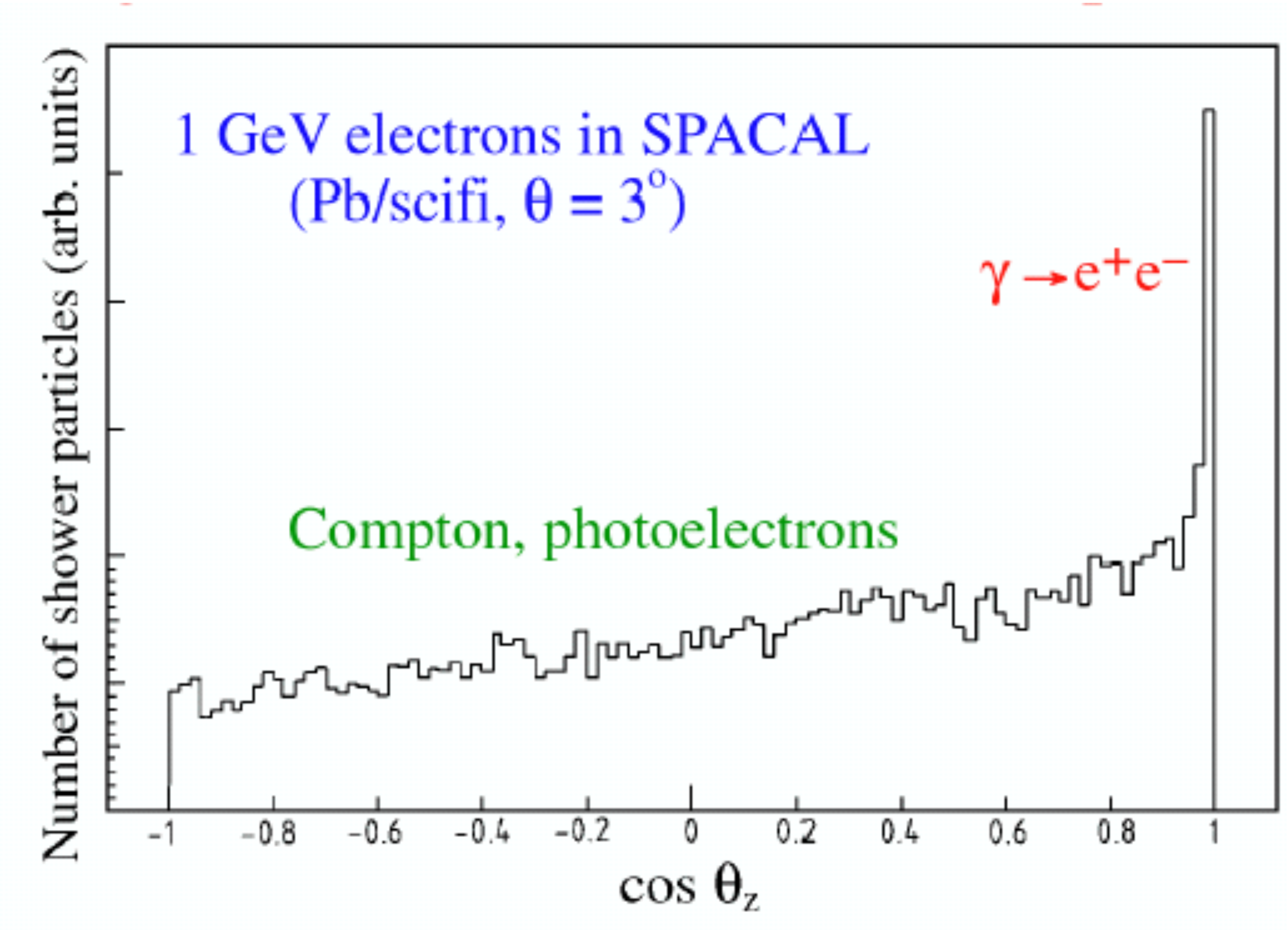


QED cross-section for γ-e scattering

$\sigma_{compton} \sim Z \,.\, \ln(E_\gamma)/E_\gamma$

Process dominant at $E\gamma \simeq$ 100 keV - 5 GeV

ANGULAR DISTRIBUTION

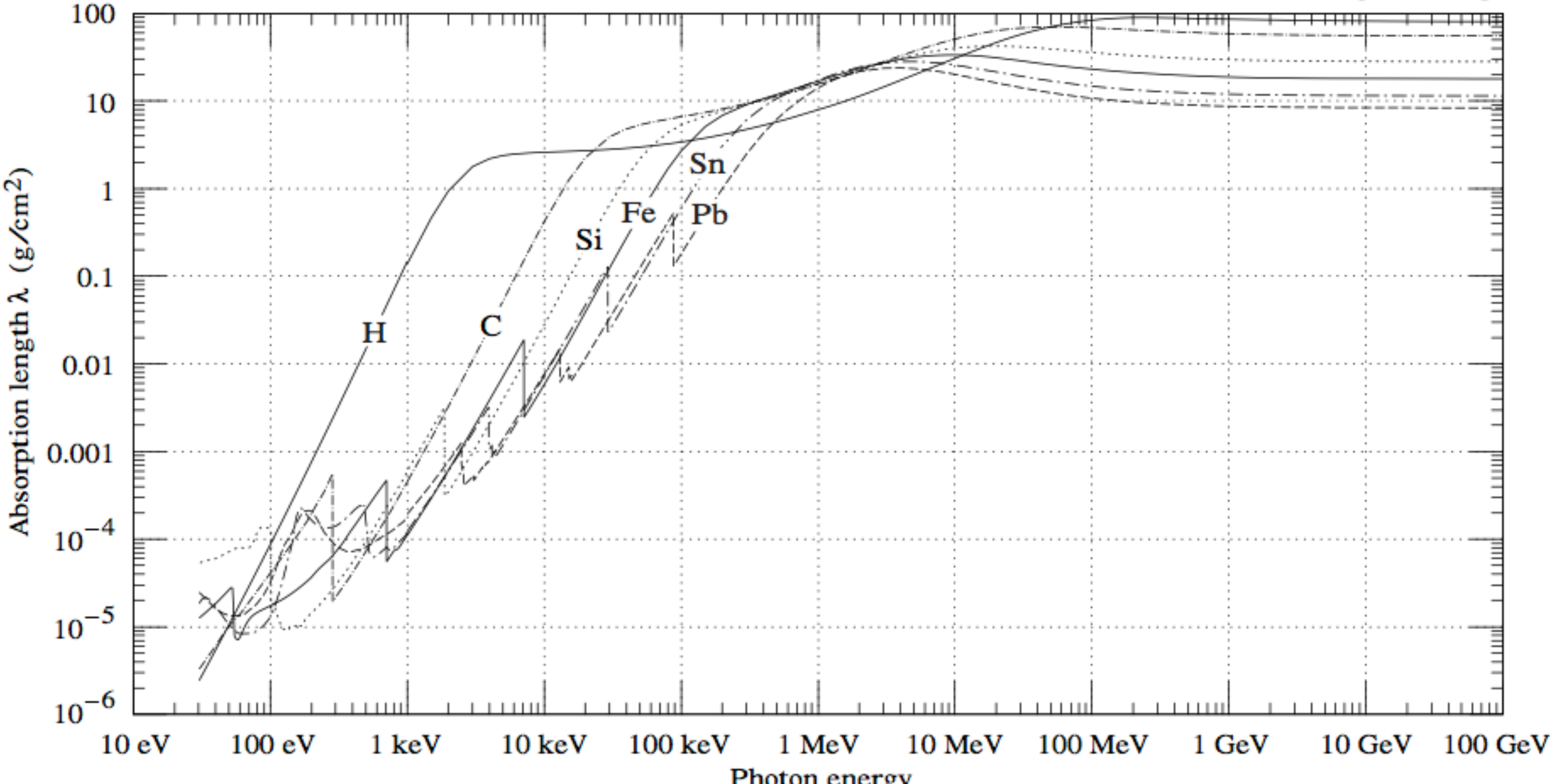


INTERACTION OF PHOTONS WITH MATTER

Mass absorption coefficient $\lambda = 1/(\mu/\rho)$ [g.cm^2] with $\mu = N_A.\sigma/A$

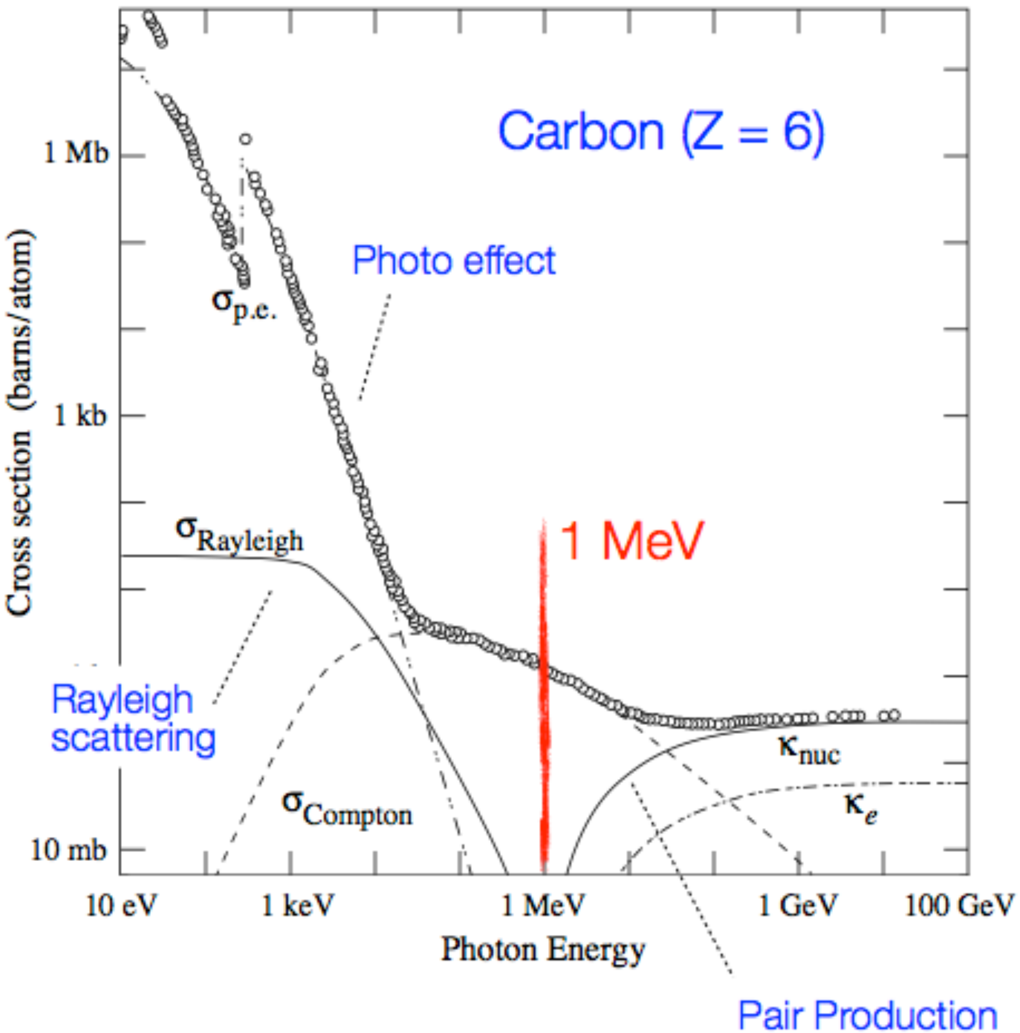
$\sigma_{Ph} \propto \frac{Z^5}{E^{3.5}}$ $\sigma_{Compton} \propto \frac{\ln E}{E} \cdot Z$ $\sigma_{Pair} \propto Z^2$

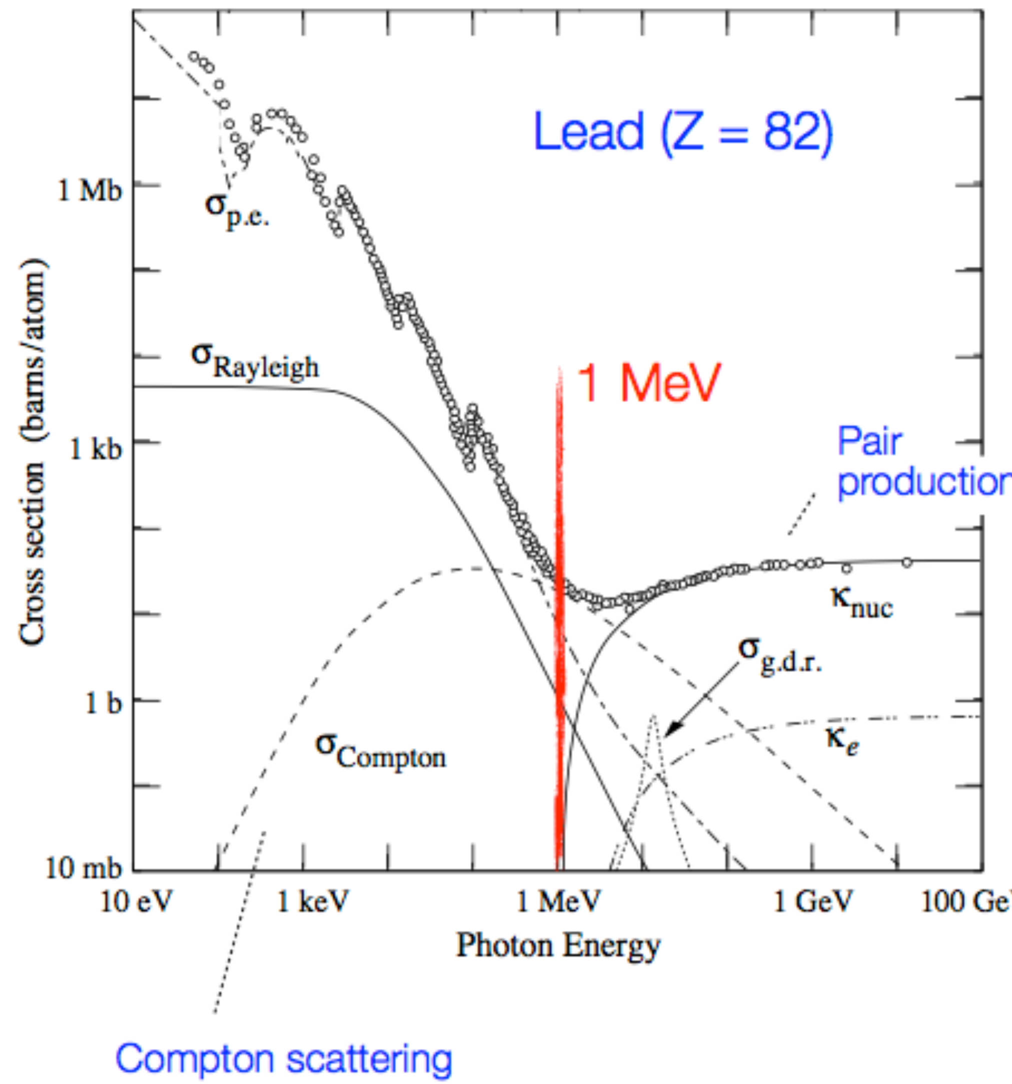
from PDG



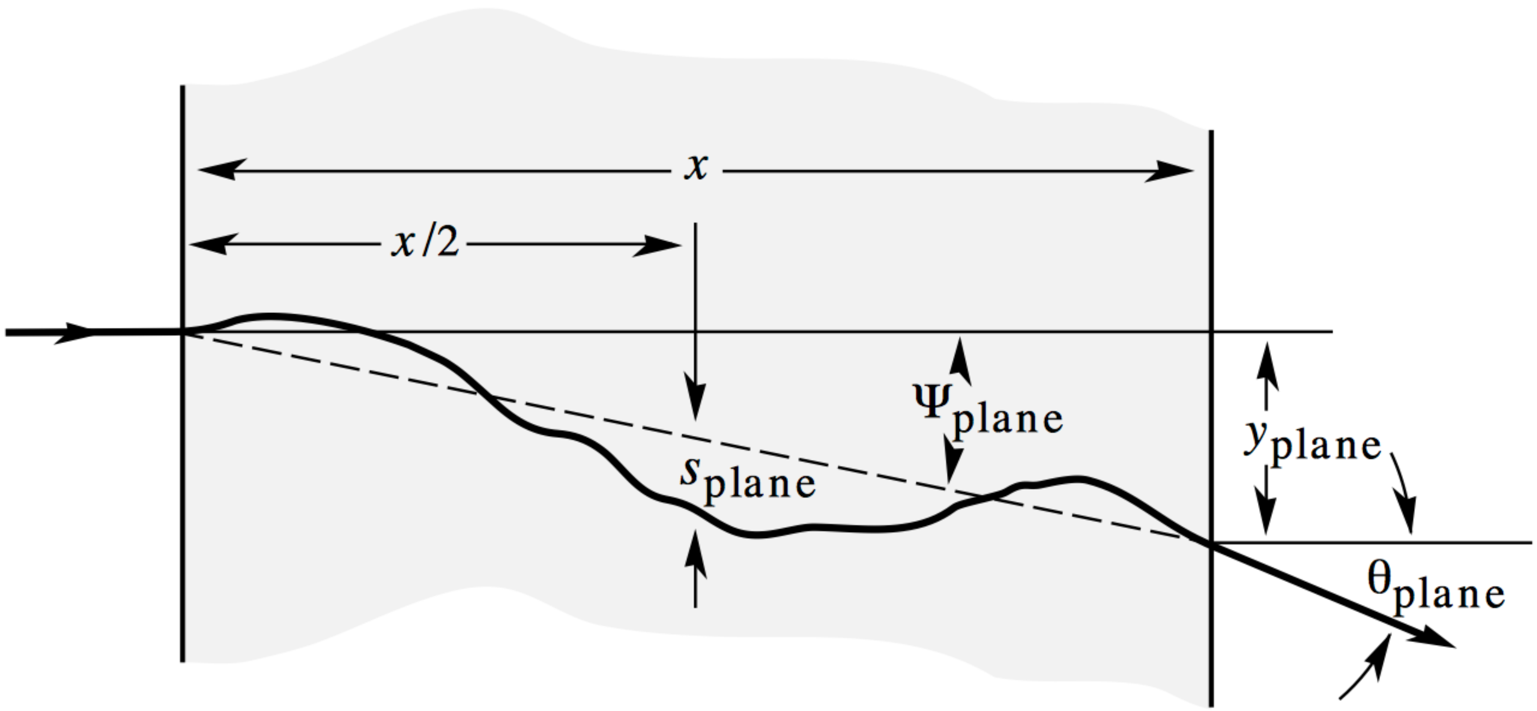
INTERACTION OF PHOTONS WITH MATTER

Photon Total Cross Sections





MULTIPLE SCATTERING



Scattering of charged particles off the atoms in the medium causes a change of direction

The statistical sum of many such small angle scattering results in a gaussian angular distribution with a width given by

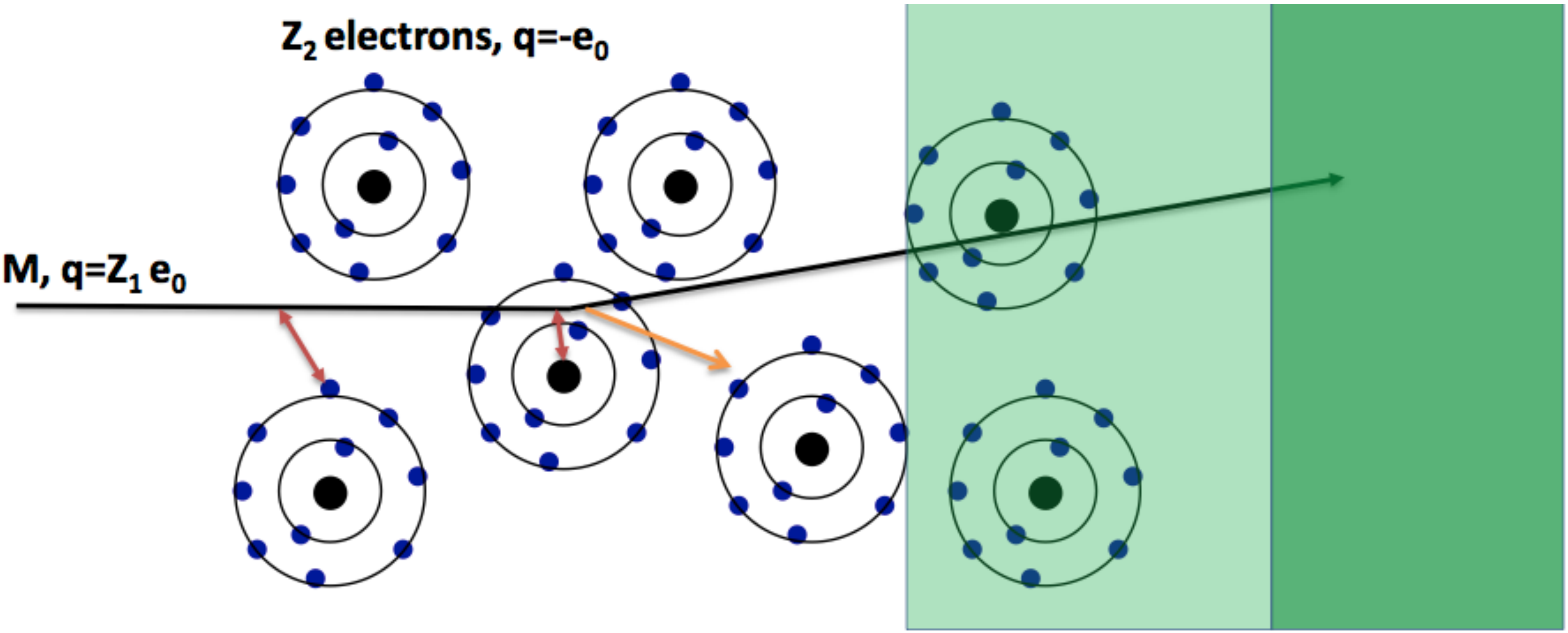
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

Example

p=1 GeV, x=300µm, Si X_0=9.4 cm → θ_0=0.8 mrad

For a distance of 10 cm this corresponds to 80 µm, which is significantly larger than typical resolution of Si-strip detector.

ELECTROMAGNETIC INTERACTION
PARTICLE - MATTER



Interaction with the atomic electrons.
The incoming particle loses energy and the atoms are **exited** or **ionised**.

Interaction with the atomic nucleus.
The incoming particle is deflected causing **multiple scattering** of the particle in the material.
During this scattering a **Bremsstrahlung photon** can be emitted

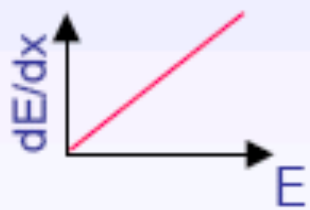
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as **Cherenkov radiation.** When the particle crosses the boundary between two media, there is a probability of 1% to produce an Xray photon called **Transition radiation.**

Reminder: basic electromagnetic interactions

e^+ / e^-

- Ionisation

- Bremsstrahlung



γ

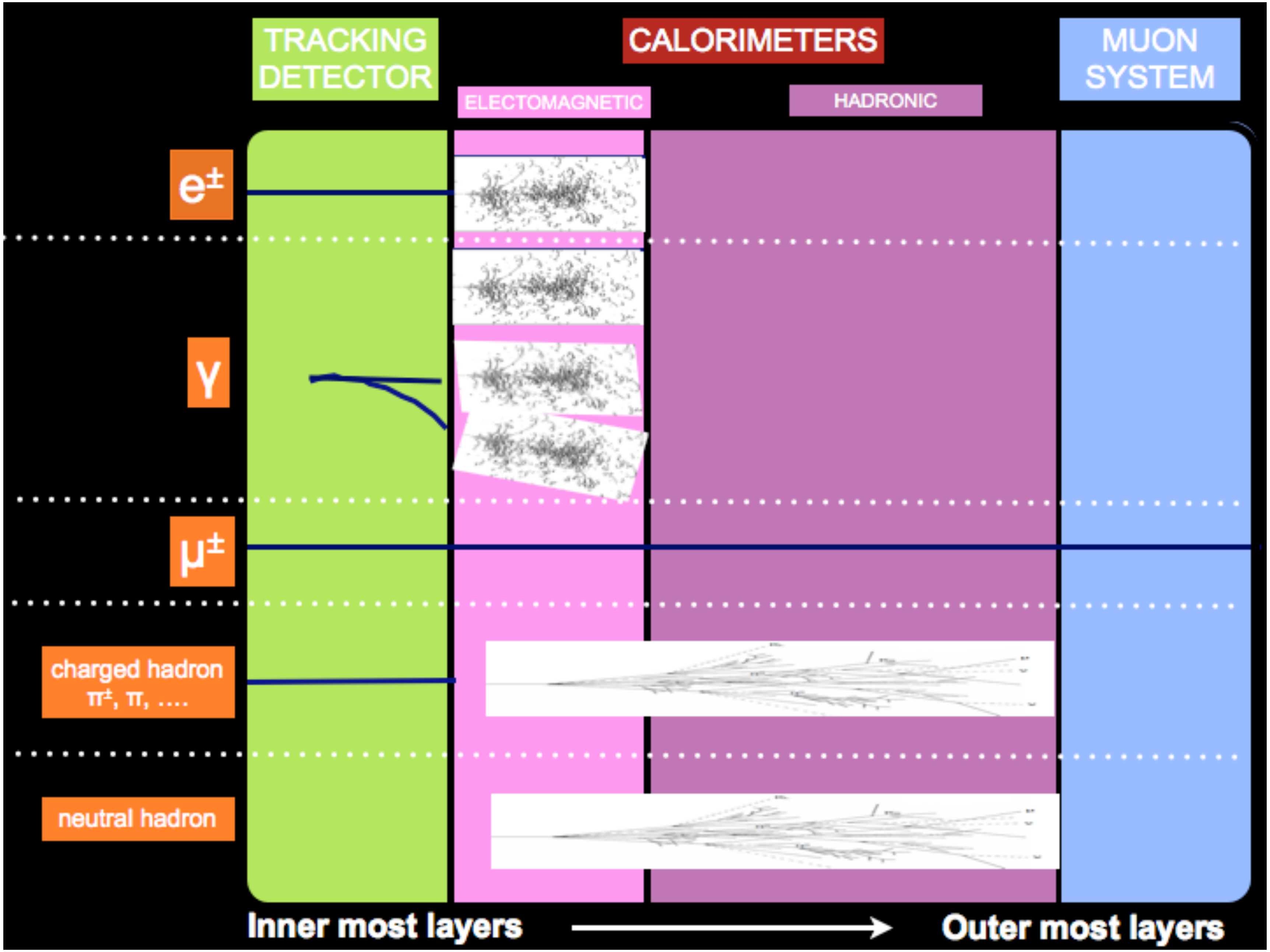
- Photoelectric effect

- Compton effect

- Pair production

DETECTOR QUIZZ II : explain this schematic

INTERACTIONS → DETECTORS

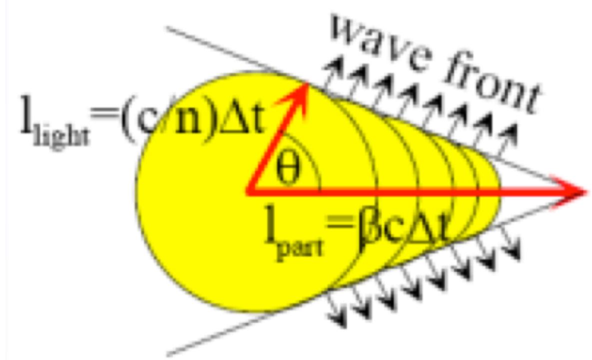


EXTRA

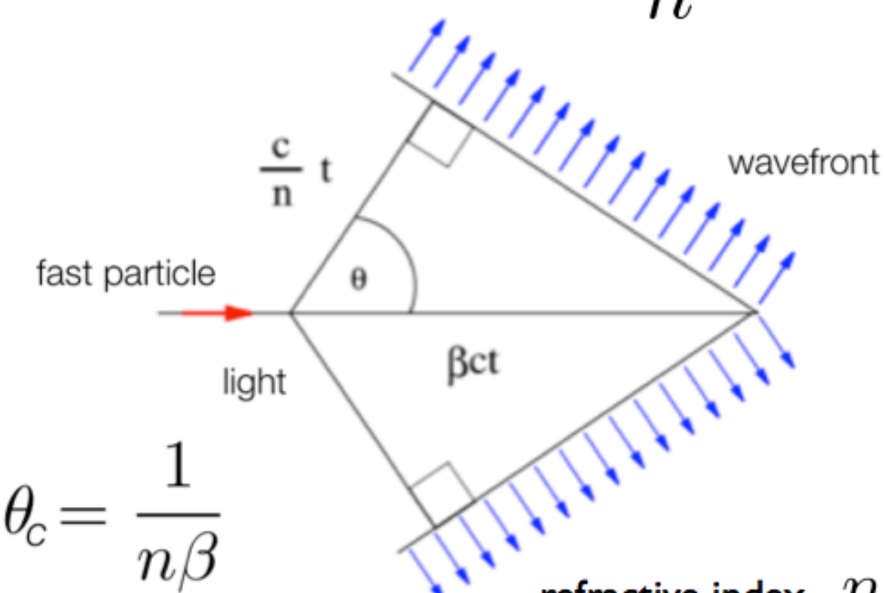
CERENKOV RADIATION

Particles moving in a medium with **speed larger than speed of light in that medium** loose energy by emitting electromagnetic radiation

- Charged particles polarise the medium generating an electrical dipole varying with time
- Every point in the trajectory emits a spherical EM wave; waves constructively interfere



$$\beta > \frac{1}{n}$$



$$\cos\theta_c = \frac{1}{n\beta}$$

refractive index $n = \sqrt{\varepsilon}$ dielectric constant

CERENKOV RADIATION

Parameters of Typical Radiator

Medium	n	β_{thr}	θ_{max} [β=1]	N_{ph} [eV^{-1} cm^{-1}]
Air	1.000283	0.9997	1.36	0.208
Isobutan	1.00127	0.9987	2.89	0.941
Water	1.33	0.752	41.2	160.8
Quartz	1.46	0.685	46.7	196.4

Note: Energy loss by Cherenkov radiation very small w.r.t. ionization (< 1%).

Example:
[Proton with E_{kin} =1 GeV passing through 1 cm water]

$\beta = p/E \approx 0.875$; $\cos\theta_C = 1/n\beta = 0.859$ ➛ $\theta_C = 30.8°$
$d^2N/(dEdx) = 370 \sin^2\theta_C\ eV^{-1}\ cm^{-1} \approx 100\ eV^{-1}\ cm^{-1}$

➛ $\Delta E_{loss} = \langle E \rangle\, d^2N/(dEdx)\, \Delta E\, \Delta x$
$= 2.5\ eV \cdot 100\ eV^{-1}\ cm^{-1} \cdot 5\ eV \cdot 1\ cm = 1.25\ keV$

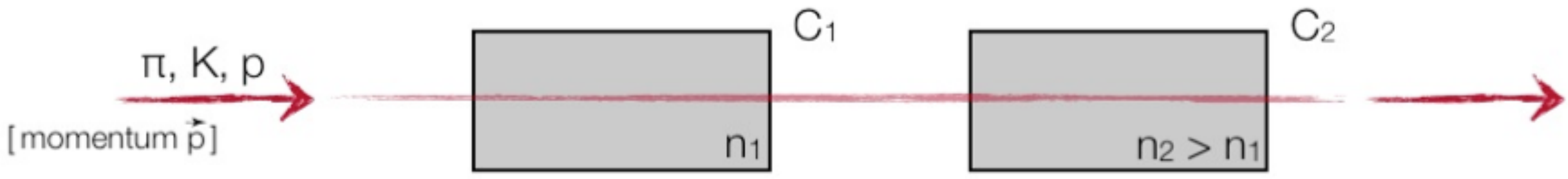
Visible light only!
[E = 1 - 5 eV; λ = 300 - 600 nm]

$\Delta E_{loss} < 1.25$ keV

IDENTIFYING PARTICLES with CERENKOV RADIATION

Threshold detection:

Observation of Cherenkov radiation → $\beta > \beta_{thr}$



Choose n_1, n_2 in such a way that for:

n_2 : $\beta_\pi, \beta_K > 1/n_2$ and $\beta_p < 1/n_2$

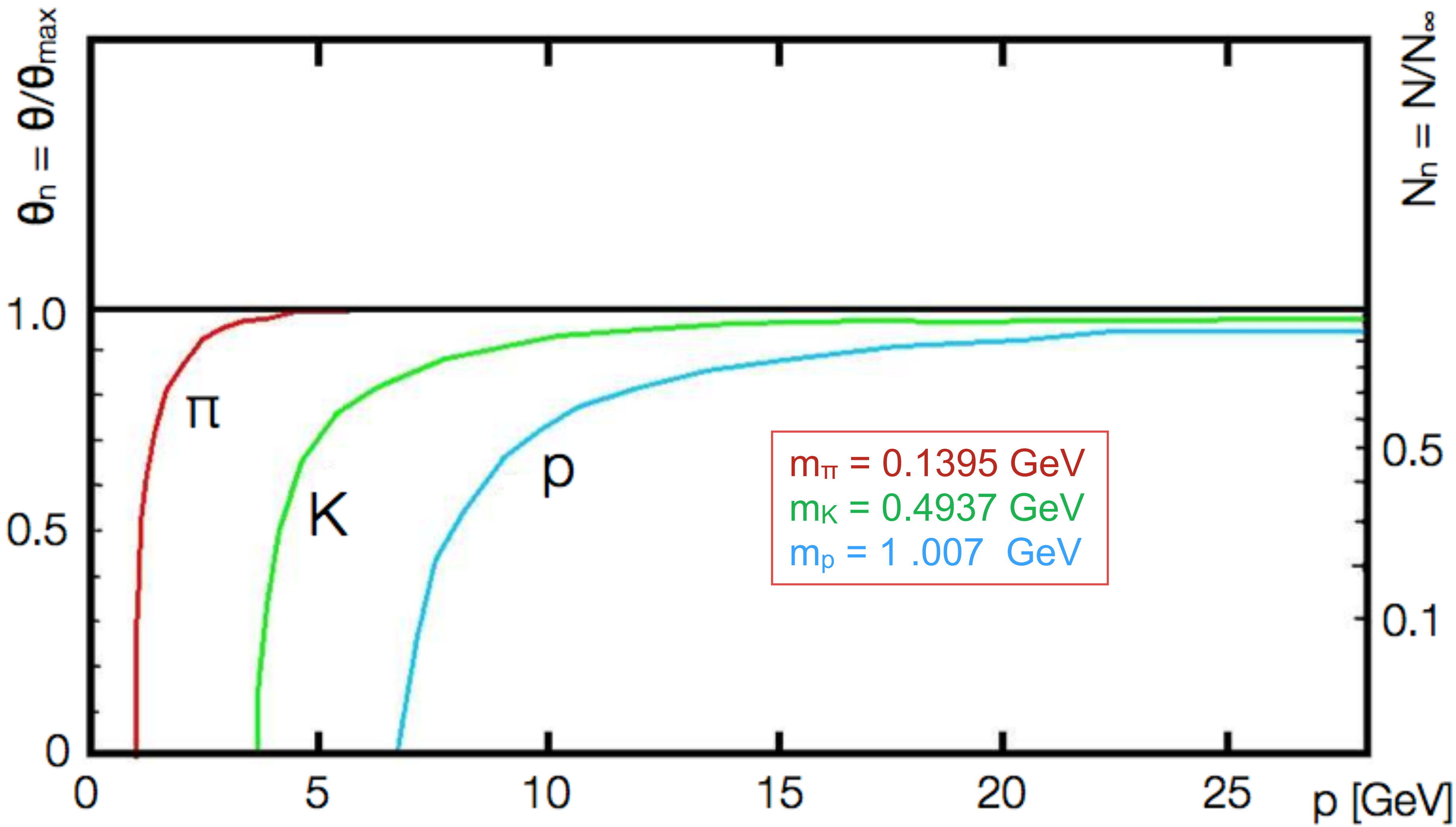
n_1 : $\beta_\pi > 1/n_1$ and $\beta_K, \beta_p < 1/n_1$

Light in C_1 and C_2 → identified pion

Light in C_2 and not in C_1 → identified kaon

Light neither in C_1 and C_2 → identified proton

CERENKOV RADIATION: MOMENTUM DEPENDENCE

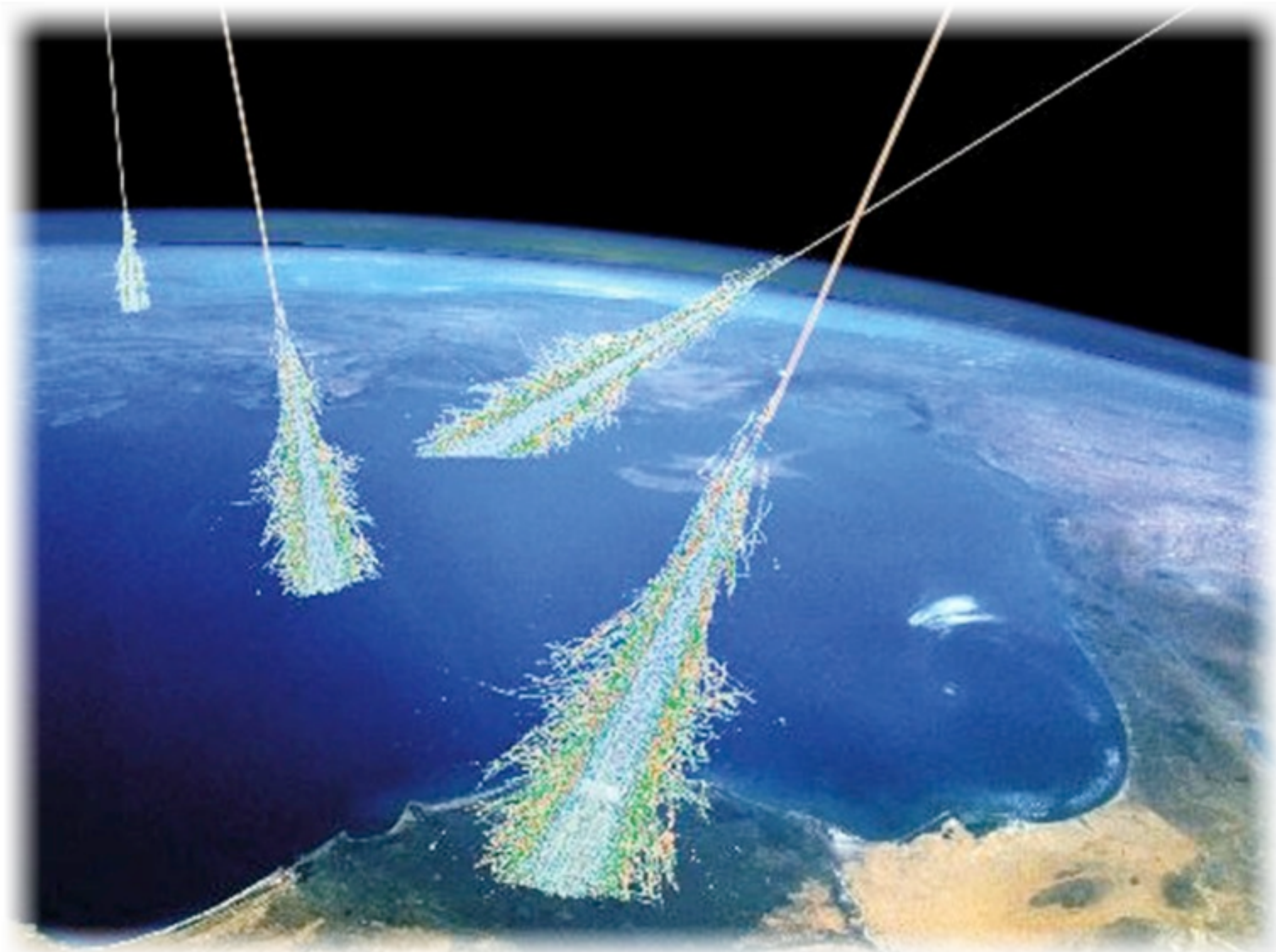


Cherenkov angle
Number of photons

] grows with **β** and reaches asymptotic value for **β** = 1

[θ_{max} = arccos (1/n); N_∞ = x·370/cm (1-1/n²)]

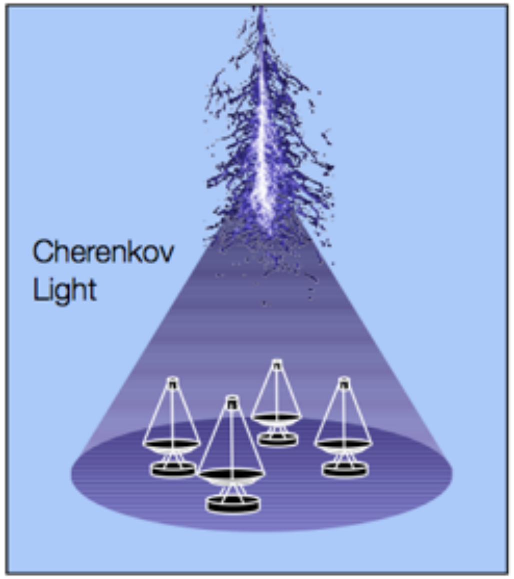
COSMIC RAYS



HESS EXPERIMENT

Hess Telescopes
Namibia

γ-ray detection



Transition radiation

Transition radiation occurs if a relativistic particle (**large γ**) passes the **boundaries between two media with different refraction indices.**

Intensity of radiation is **logarithmically proportional to γ**

Angular distribution strongly forward peaked
[Interference; coherence condition]

$$\theta \leq 1/\gamma$$

Coherent radiation is generated only over a very small formation length

$$D = \gamma c/\omega_p$$

Plasma frequency
[from Drude model]

Volume element from which coherent radiation is emitted ...

$$V = \pi D \rho_{max}^2$$

$\rho_{max} = \gamma v/\omega$
[transversal range ... ... with large polarization]

Maximum energy of radiated photons limited by plasma frequency ...
[results from requiring $V \neq 0 \rightarrow \omega = \gamma\omega_p$]

$$E_{max} = \gamma\hbar\omega_p$$

[X-Rays → large γ!!]

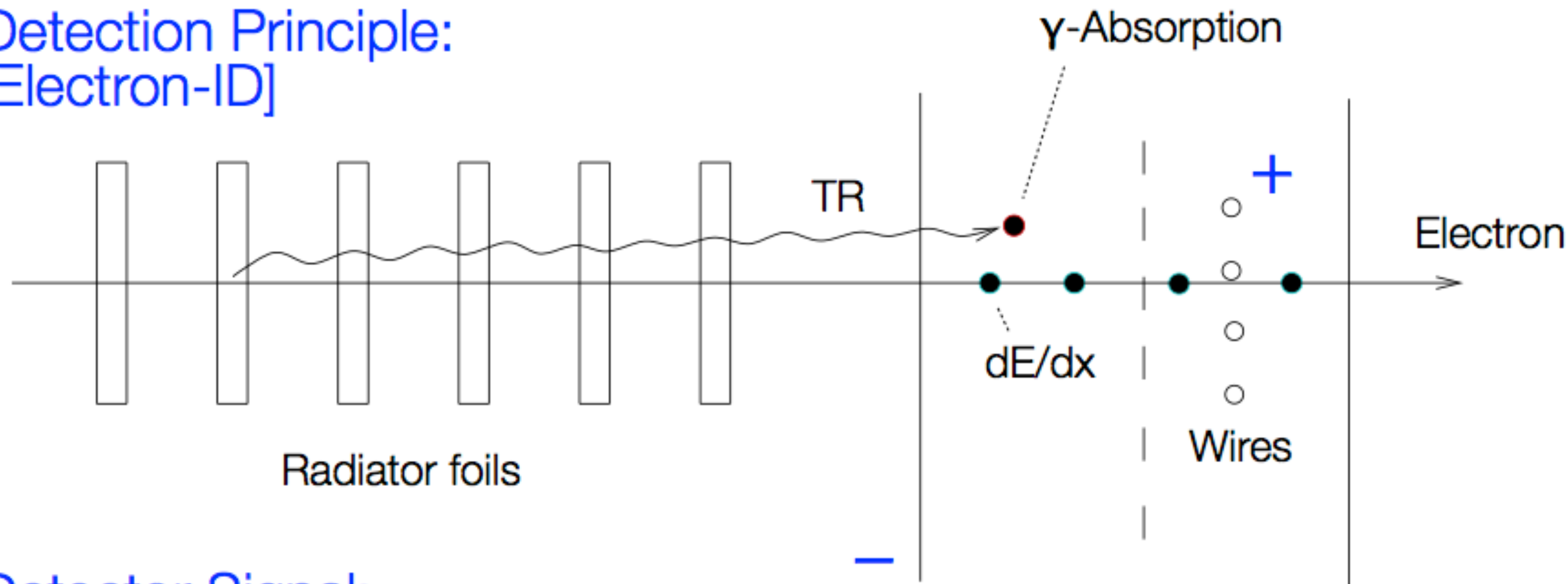
Typical values: CH_2: $\hbar\omega_p = 20$ eV; $\gamma = 10^3$
[Air: $\hbar\omega_p = 0.7$ eV]

$$D = 10\ \mu m$$

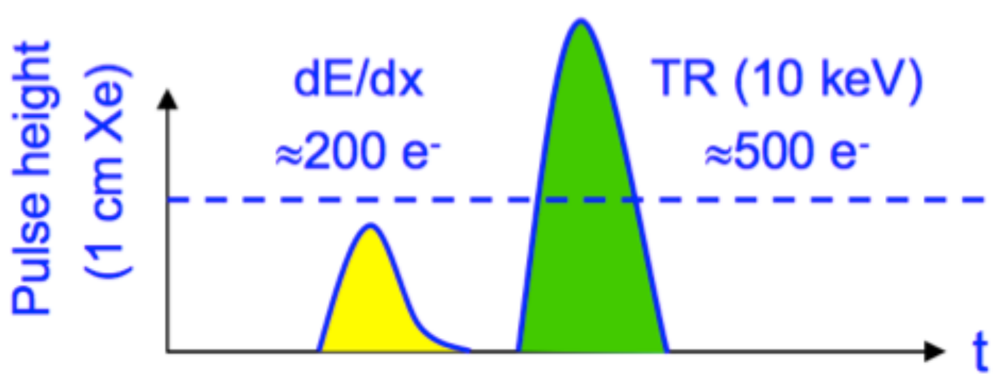
[d > D: absorption dominates]

IDENTIFYING PARTICLES WITH TRANSITION RADIATION

Detection Principle:
[Electron-ID]



Detector Signal:

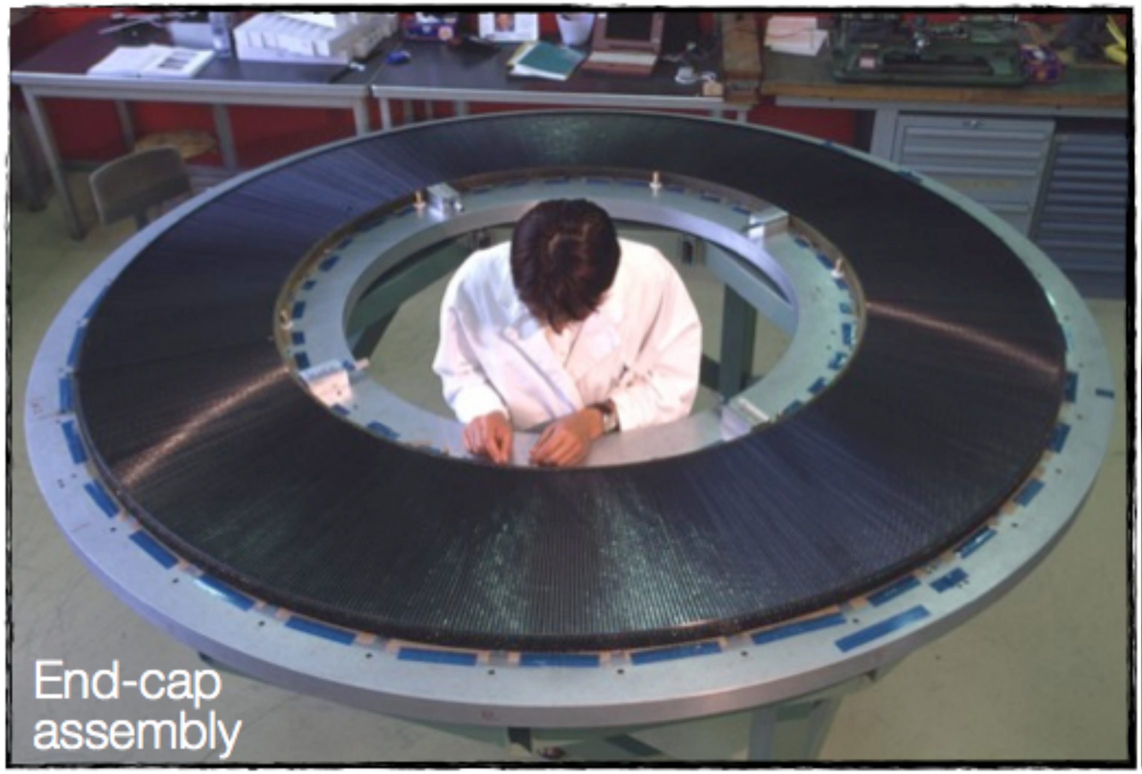


- Detector should be sensitive to $3 \lesssim E_{\gamma} \lesssim 30$ keV.
  - ✓ Gaseous detectors
- In gas $\sigma_{\text{photo effect}} \propto Z^5$
- Gases with high Z are required
  - ✓ e.g. Xenon (Z=54)

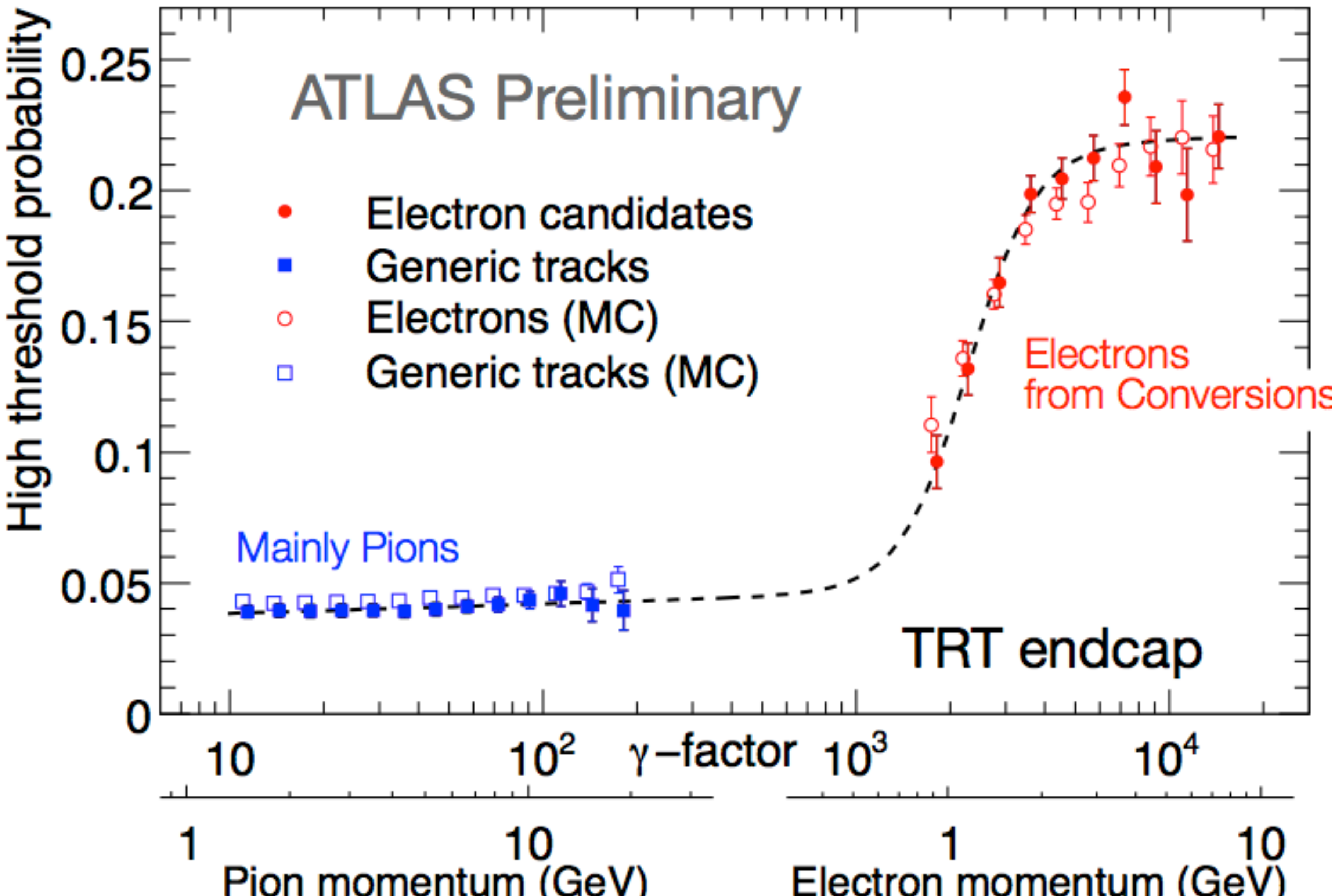
ATLAS TRANSITION RADIATION TRACKER

Straw Tube Tracker
with interspace filled with foam

➛ Tracking & transition radiation



IDENTIFYING PARTICLES WITH TRANSITION RADIATION

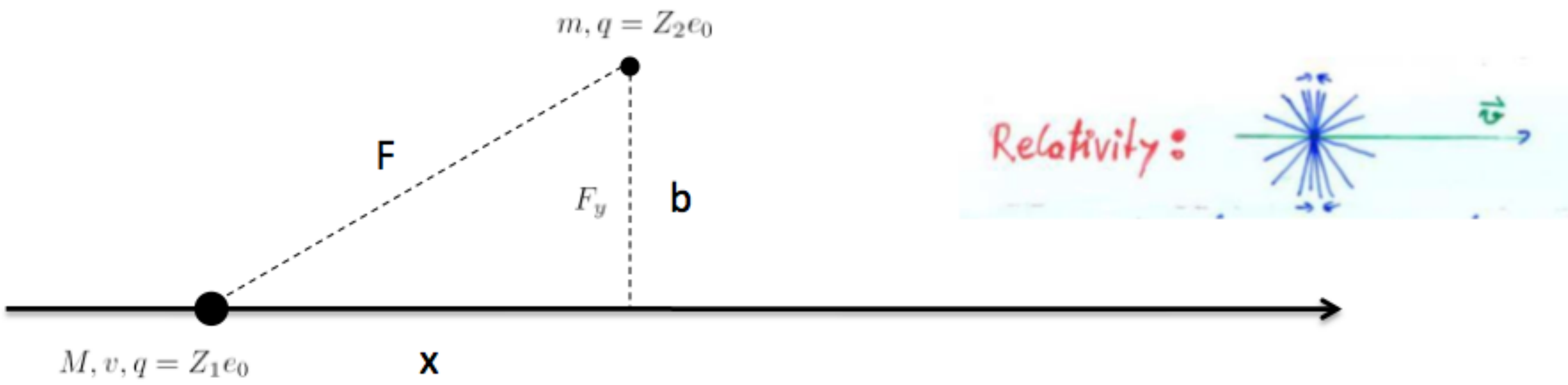


CREDIT and BIBLIOGRAPHY

A lot of material in these lectures are from:

- Daniel Fournier @ EDIT2011
- Marco Delmastro @ ESIPAP 2014
- Weiner Raigler @ AEPSHEP2013
  - Hans Christian Schultz-Coulon's lectures
- Carsten Niebuhr's lectures [1][2][3]
- Georg Streinbrueck's lecture
- Pippa Wells @ EDIT2011
- Jérôme Baudot @ ESIPAP2014

IONISATION & EXCITATION



While the charged particle is passing another charged particle the Coulomb force is acting, resulting in momentum transfer.

$$F_y = \frac{Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 (b^2 + v^2 t^2)} \frac{b}{\sqrt{b^2 + v^2 t^2}}$$

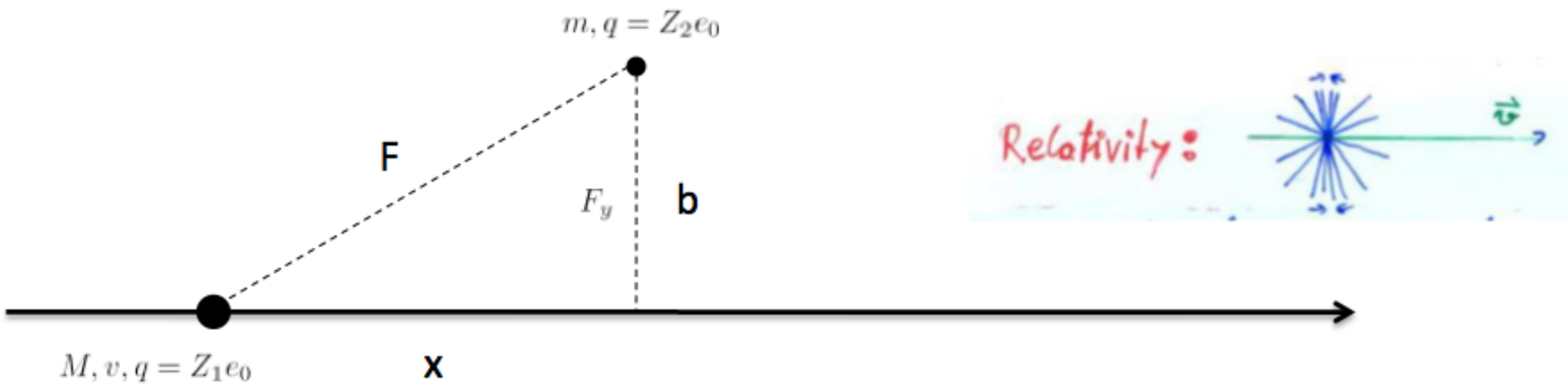
$$\Delta p = \int_{-\infty}^{\infty} F_y(t) dt = \frac{2 Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 v b}$$

The relativistic form of the transverse electric field does not change the momentum transfer. The transverse field is stronger, but the time of action is shorter.

$$F_y = \frac{\gamma Z_1 Z_2 e_0^2 b}{4\pi\varepsilon_0 (b^2 + \gamma^2 v^2 t^2)^{3/2}}$$

$$\Delta p = \int_{-\infty}^{\infty} F_y(t) dt = \frac{2 Z_1 Z_2 e_0^2}{4\pi\varepsilon_0 v b}$$

IONISATION & EXCITATION



The transferred energy

$$\Delta E = \frac{(\Delta p)^2}{2m} = \frac{Z_2^2}{m} \frac{2Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2}$$

$$\Delta E(electrons) = Z_2 \frac{1}{m_e} \frac{2Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2}$$

$$\Delta E(nucleus) = \frac{Z_2^2}{2Z_2 m_p} \frac{2Z_1^2 e_0^4}{(4\pi\varepsilon_0)^2 v^2 b^2}$$

The incoming particle transfers energy mainly/only to the atomic electrons.

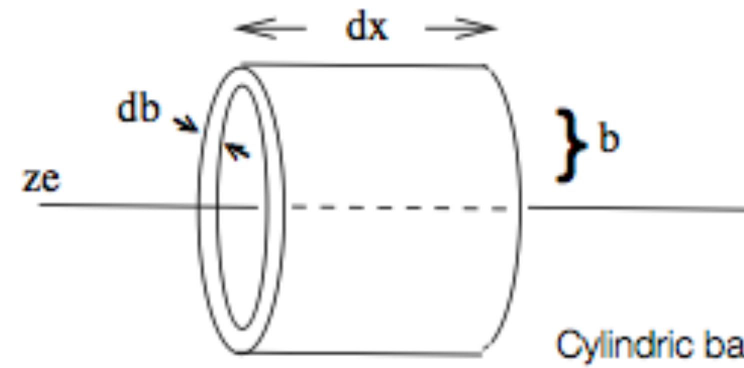
$$\frac{\Delta E(electrons)}{\Delta E(nucleus)} = \frac{2m_p}{m_e} \approx 4000$$

BETHE-BLOCH FORMULA - CLASSICAL DERIVATION

Bohr 1913

Energy transfer onto single electron
for impact parameter b:

$$\Delta E(b) = \frac{\Delta p^2}{2m_e}$$



Cylindric barrel
with N_e electrons

Consider cylindric barrel ➛ $N_e = n \cdot (2\pi b) \cdot db dx$

Energy loss per path length dx for
distance between b and b+db in medium with electron density n:

Energy loss!

$$-dE(b) = \frac{\Delta p^2}{2m_e} \cdot 2\pi nb\, db\, dx = \frac{4z^2e^4}{2b^2v^2m_e} \cdot 2\pi nb\, db\, dx = \frac{4\pi\, n\, z^2e^4}{m_ev^2}\frac{db}{b}dx$$

Diverges for b ➛ 0; integration only
for relevant range [b_{min}, b_{max}]:

Bohr 1913

$$-\frac{dE}{dx} = \frac{4\pi\, n\, z^2e^4}{m_ev^2} \cdot \int_{b_{min}}^{b_{max}} \frac{db}{b} = \frac{4\pi\, n\, z^2e^4}{m_ev^2} \ln\frac{b_{max}}{b_{min}}$$

BETHE-BLOCH FORMULA - CLASSICAL DERIVATION

Determination of relevant range [b_{min}, b_{max}]: Bohr 1913

[Arguments: $b_{min} > \lambda_e$, i.e. de Broglie wavelength; $b_{max} < \infty$ due to screening ...]

$$b_{\rm min} = \lambda_{\rm e} = \frac{h}{p} = \frac{2\pi\hbar}{\gamma m_{\rm e} v}$$

Use Heisenberg uncertainty principle or that electron is located within de Broglie wavelength ...

$$b_{\rm max} = \frac{\gamma v}{\langle \nu_{\rm e} \rangle} \; ; \quad \left[\gamma = \frac{1}{\sqrt{1-\beta^2}} \right]$$

Interaction time (b/v) must be much shorter than period of the electron (γ/ν_e) to guarantee relevant energy transfer ...

[adiabatic invariance]

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_{\rm e}\, c^2 \beta^2}\, n \cdot \ln \frac{m_{\rm e}\, c^2 \beta^2 \gamma^2}{2\pi\hbar \,\langle \nu_{\rm e} \rangle}$$

Deviates by factor 2 from QM derivation

Electron density: $n = N_A \cdot \rho \cdot Z/A$!!

Effective Ionization potential: $I \sim h\langle\nu_e\rangle$