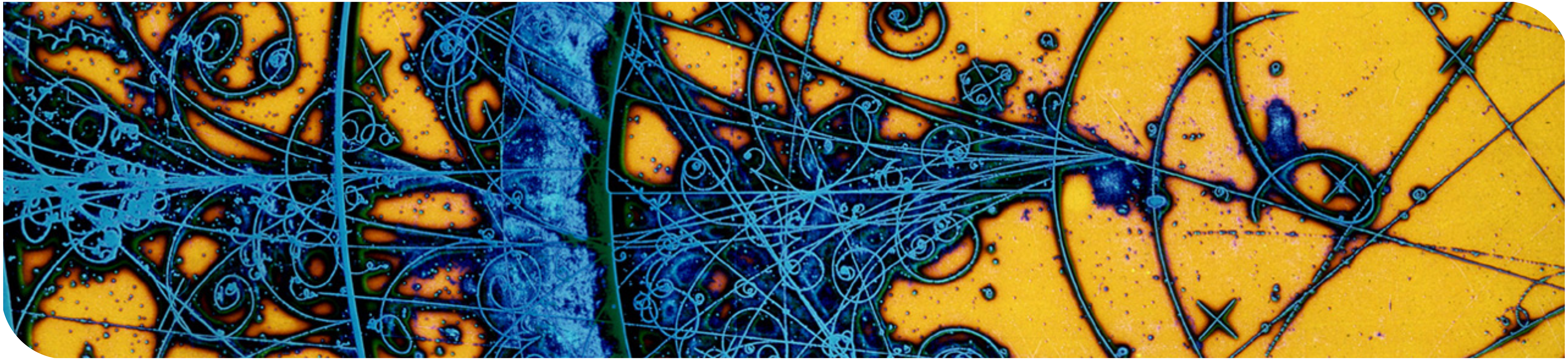
Karlsruhe Institute of Technology

Particle Physics 1
Lecture 3: Interactions with matter

Prof. Dr. Torben FERBER (torben.ferber@kit.edu, he/him), Institute of Experimental Particle Physics (ETP)
Winter 2023/2024



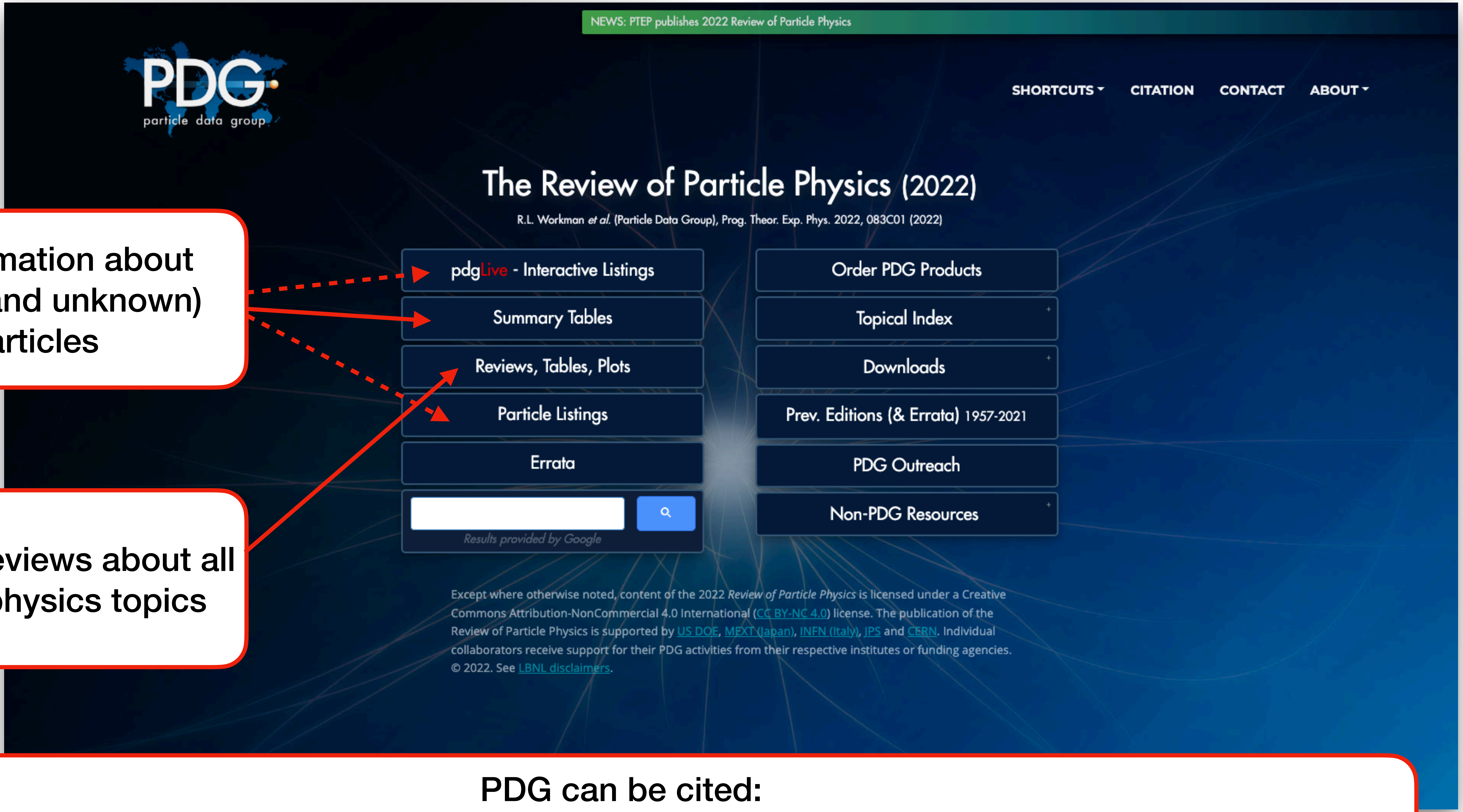
Credit: CERN

Questions from past lectures

Learning goals

- Usage of the Particle Data Group (PDG) website
- Theoretical background of all main particle interactions
- Understanding of energy- and material-dependency of all these interactions
- Understanding of electromagnetic and hadronic shower development

How to use the PDG

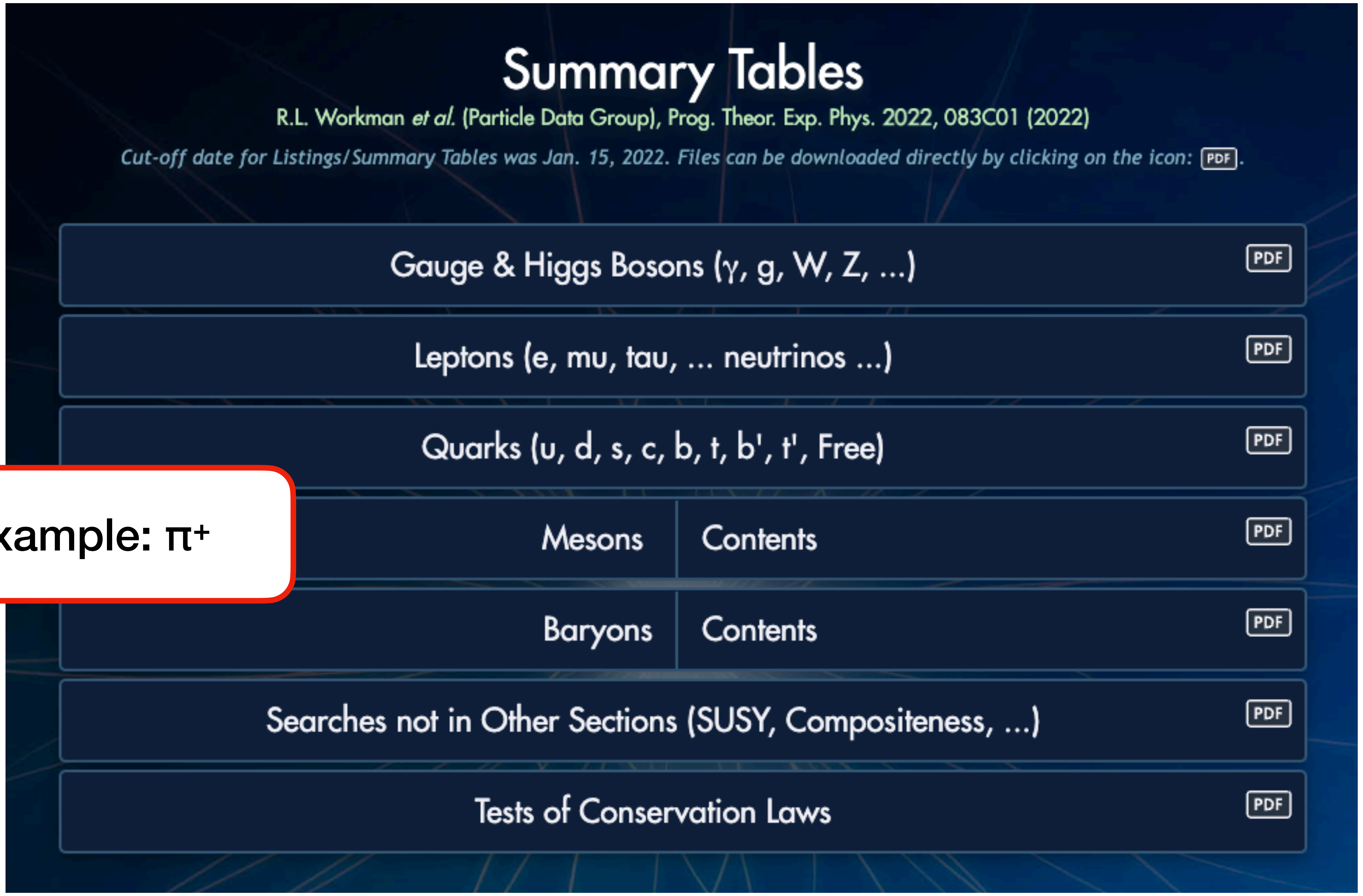


All information about known (and unknown) particles

Brief(ish) reviews about all particle physics topics

PDG can be cited:
R. L. Workman et al. (Particle Data Group), Prof. Theor. Exp. Phys. 2022, Issue 8, (2022), 083C01
https://doi.org/10.1093/ptep/ptac097

How to use the PDG: “Particle Listing”



Example: π^+

How to use the PDG: “Particle Listing”

Name
(sometimes multiple names)

$\pi^{\pm}$

$I^G(J^P) = 1^-(0^-)$

Quantum numbers

Mass and lifetime

Mass $m = 139.57039 \pm 0.00018$ MeV (S = 1.8)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

S are scale factors used in a statistical analysis.
Values != 1 indicate inconsistent data

$\pi^{\pm} \to \ell^{\pm}\nu\gamma$ form factors [a]

$F_V = 0.0254 \pm 0.0017$
$F_A = 0.0119 \pm 0.0001$
F_V slope parameter $a = 0.10 \pm 0.06$
$R = 0.059^{+0.009}_{-0.008}$

We have never observed charge violation, so all decays are identical for the opposite charge.

π^- modes are charge conjugates of the modes below.

There are some BSM decays…

For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\quad\mu^+\nu_\mu\gamma$		[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$\quad e^+\nu_e\gamma$		[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$		70
$\mu^+\nu_\mu\nu\overline{\nu}$			$< 9 \times 10^{-6}$	90%	30
$e^+\nu_e\nu\overline{\nu}$			$< 1.6 \times 10^{-7}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\overline{\nu}_e$	*L*	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*		$< 1.6 \times 10^{-6}$	90%	30

Indented decays are a subset of the decay group.

Fraction of all possible decays (ideally they sum to 1).

Upper limit! This decay has not been observed, but is smaller than the given value.

Decay forbidden in the SM, but decay products are SM particles
(here: only upper limits!)

PINGO

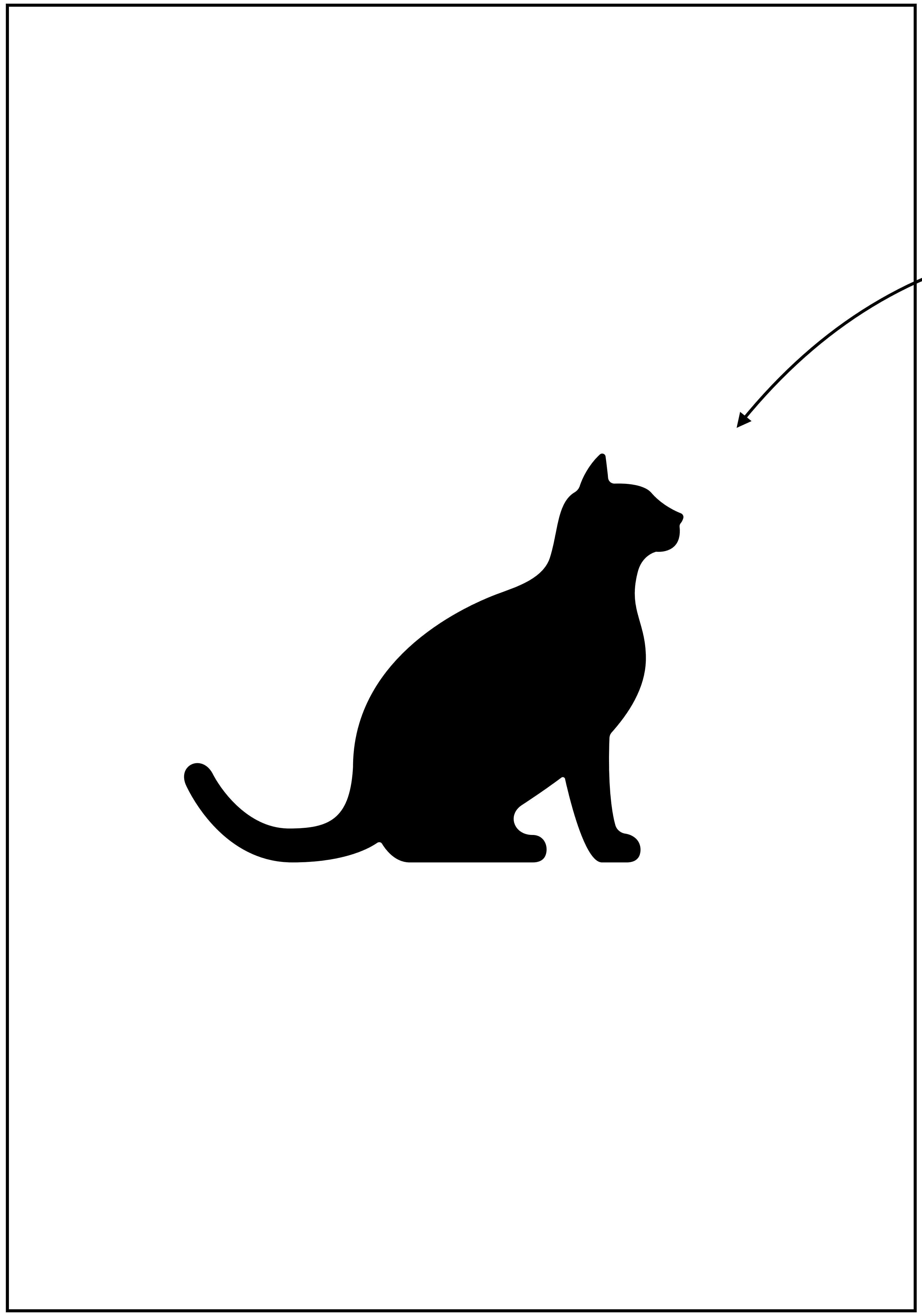
- **PINGO:**
  - Umfrage: Teilchenphysik 1 (WS 23/24)
  - Zugangsnummer: 434521
  - Link: https://pingo.coactum.de/events/434521

PINGO: J/Ψ

- How likely does a J/ψ decay into a pair of charged pions?
  - About 0.88 of all decays
  - About 3.6×10^{-3} of all decays
  - About 1.5×10^{-4} of all decays

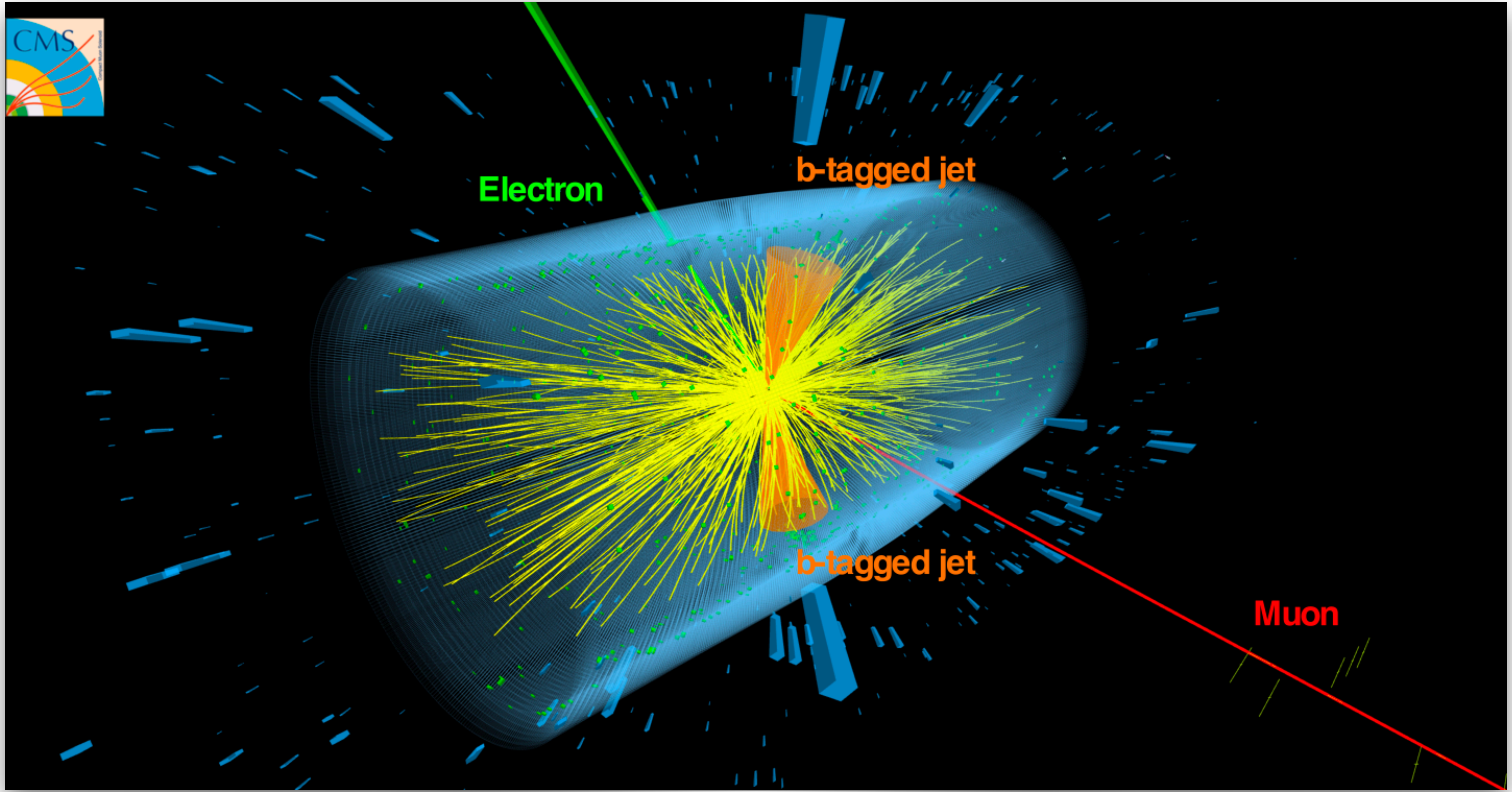
PINGO: J/Ψ

- How likely does a J/Ψ decay into a pair of charged pions?
  - About 0.88 of all decays
  - About 3.6×10^{-3} of all decays
  - **About 1.5×10^{-4} of all decays**



Your cat picture!

Particle interactions in particle physics



Credit: CMS collaboration

Stable Particles

- In particle physics detectors, we detect stable particles
  - photons
  - electrons (and positrons)
  - muons* (and anti-muons)
  - charged pions* (and anti-pions)
  - charged kaons* (and anti-kaons)
  - protons (and anti-protons)
  - heavy nuclei or ions (e.g. deuteron, α-particles, …)
  - neutrons and neutral kaons* (K_L^0)
  - neutrinos and dark matter (we actually do not detect them in collider experiments)

* Those particle are (almost) stable in particle detectors, meaning that they usually interact before they decay.

Unstable Particles

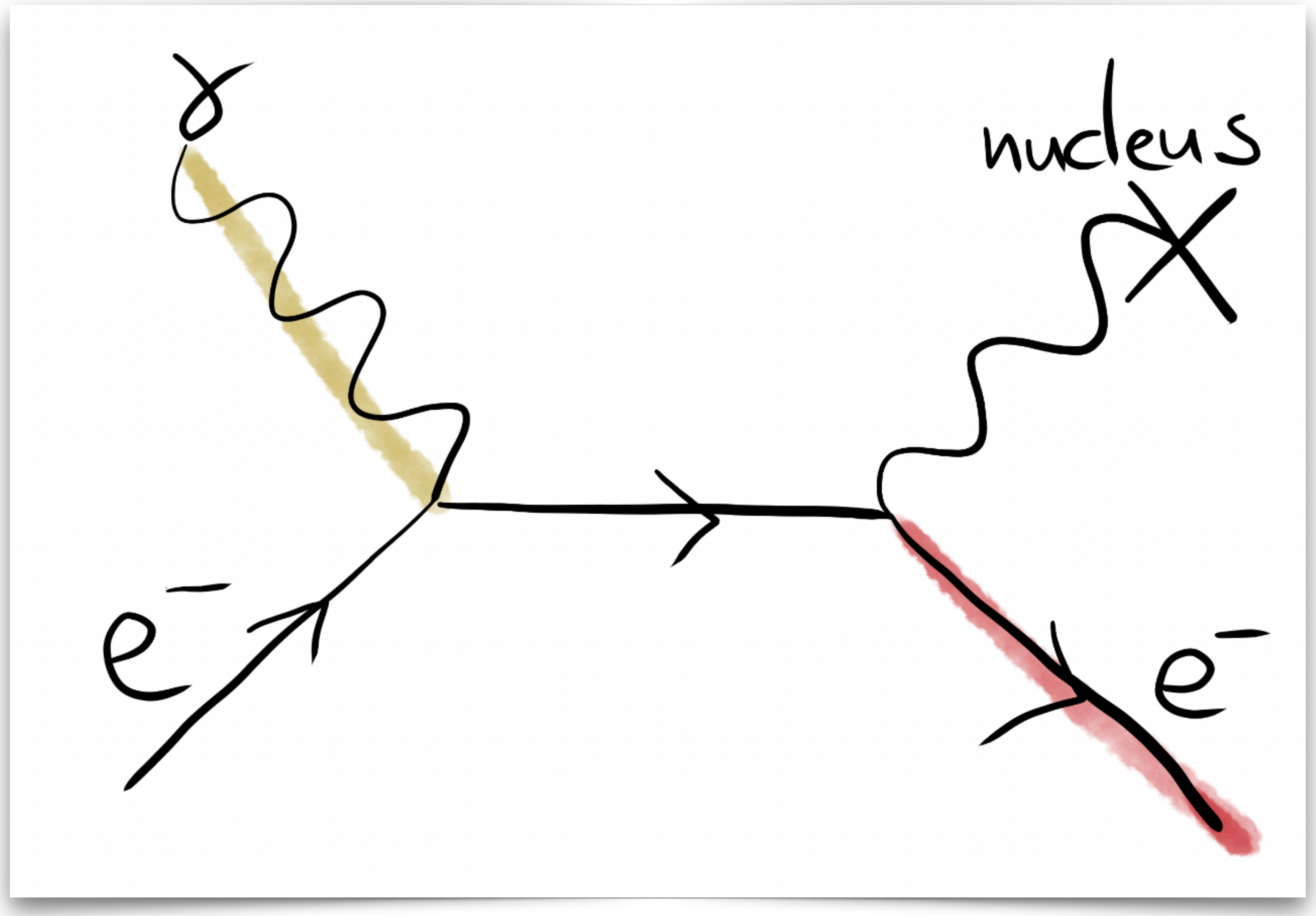
- most mesons, most baryons, Z/W/H-bosons
  - can decay into stable neutral particles, e.g. $\pi^0 \rightarrow \gamma\gamma$
  - can decay into stable charged particles, e.g. $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$
  - can decay into invisible particles, e.g. $Z^0 \rightarrow \nu\bar{\nu}$
- tau leptons
  - always involve neutrino(s), e.g. $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$
- **careful**: unstable particles can first decay into other unstable particles
  - e.g. $B^+ \rightarrow \bar{D}*\tau^+\nu_\tau \rightarrow D^0\pi^0\mu^+\nu_\mu\bar{\nu}_\tau\nu_\tau \rightarrow K_S^0K^+K^-\gamma\gamma\mu^+\nu_\mu\bar{\nu}_\tau\nu_\tau \rightarrow \pi^+\pi^-K^+K^-\gamma\gamma\mu^+\nu_\mu\bar{\nu}_\tau\nu_\tau$
- quarks do not exist as free particle but they hadronize and form hadrons: detected as jets or by detecting individual hadrons

Photons: Photoelectric effect

- Atomic photoelectric effect that ionizes an atom

$$\sigma_{\text{p.e.}} = \frac{8\pi}{3} r_e^2 Z^5 \alpha^4 \left(\frac{1}{\epsilon}\right)^{\delta}$$

  - $\delta = \begin{cases} 3.5 & \text{for} \quad \epsilon \ll 1 \\ 1 & \text{for} \quad \epsilon \gg 1 \end{cases}$ with $\epsilon = \frac{E_\gamma}{m_e}$ (reduced energy)
  - classical electron radius $r_e = 2.7$ fm
  - fine-structure constant $\alpha = \alpha(0) \approx \frac{1}{137}$
- Photon looses all its energy
- Absorption edges due to atomic energy levels



$$\sigma_{\text{p.e.}} \propto Z^5 E^{-3.5}$$

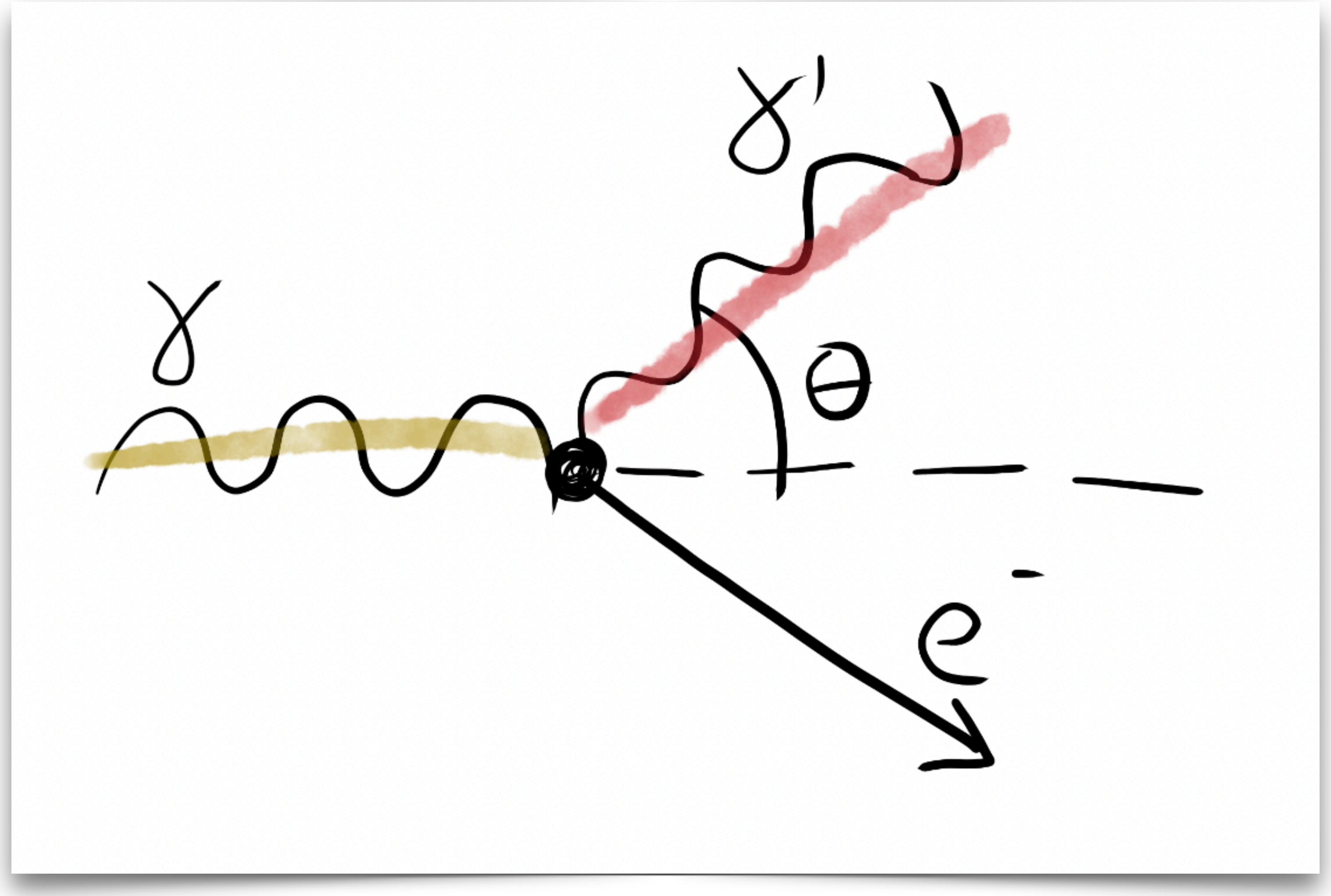
Photons: Compton scattering

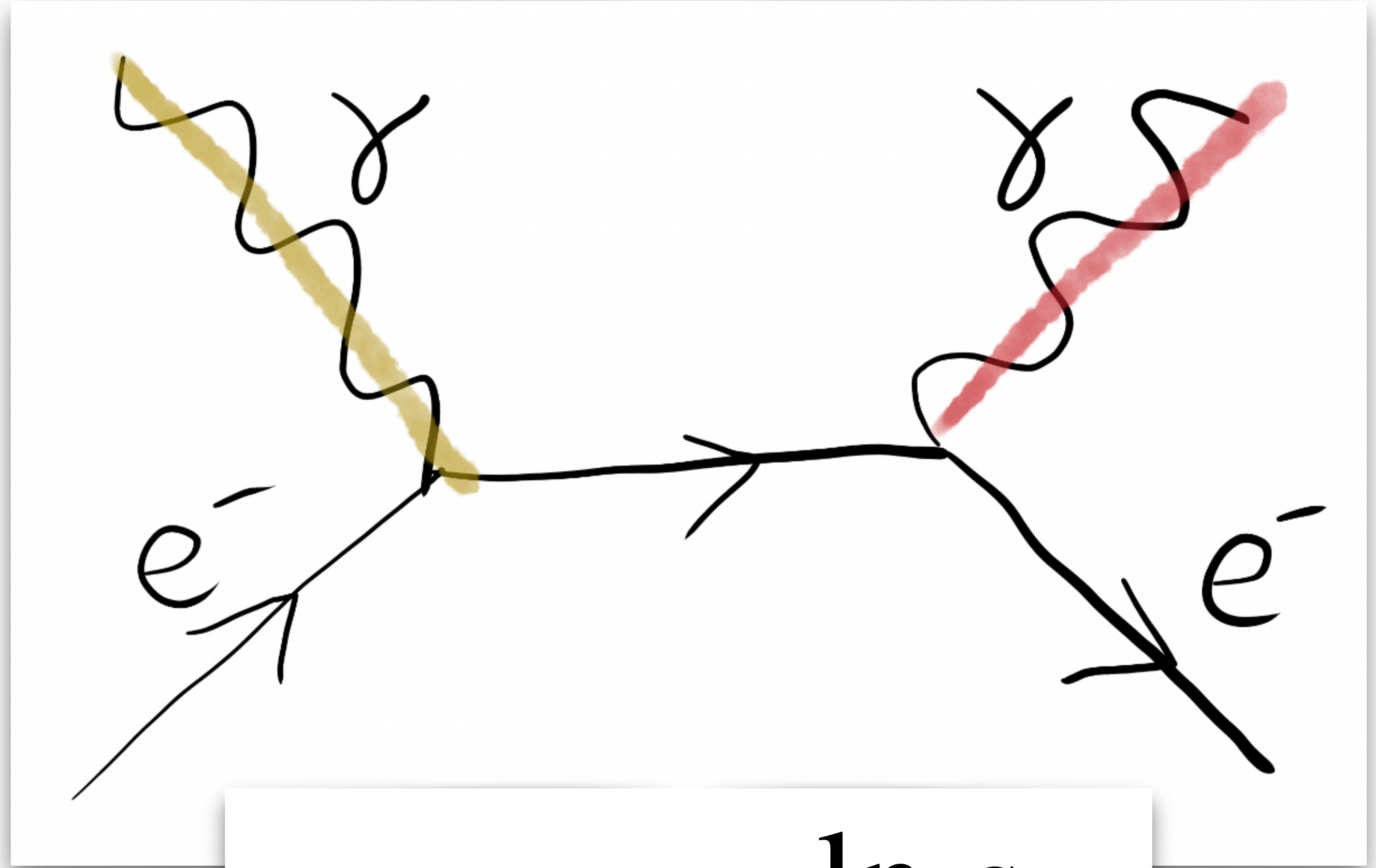
- Photon looses a part of its energy due to inelastic scattering with an electron

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

- Cross section for $\epsilon \gg 1$ given by Klein-Nishina-Equation for free electrons:

$$\sigma_C = \pi r_e^2 \frac{1}{\epsilon}\left(\frac{1}{2} + \ln(2\epsilon) + \mathcal{O}\left(\frac{1}{\epsilon}\right)\right)$$





$$\sigma_C \propto Z\frac{\ln\epsilon}{\epsilon}$$

Photons: Compton scattering

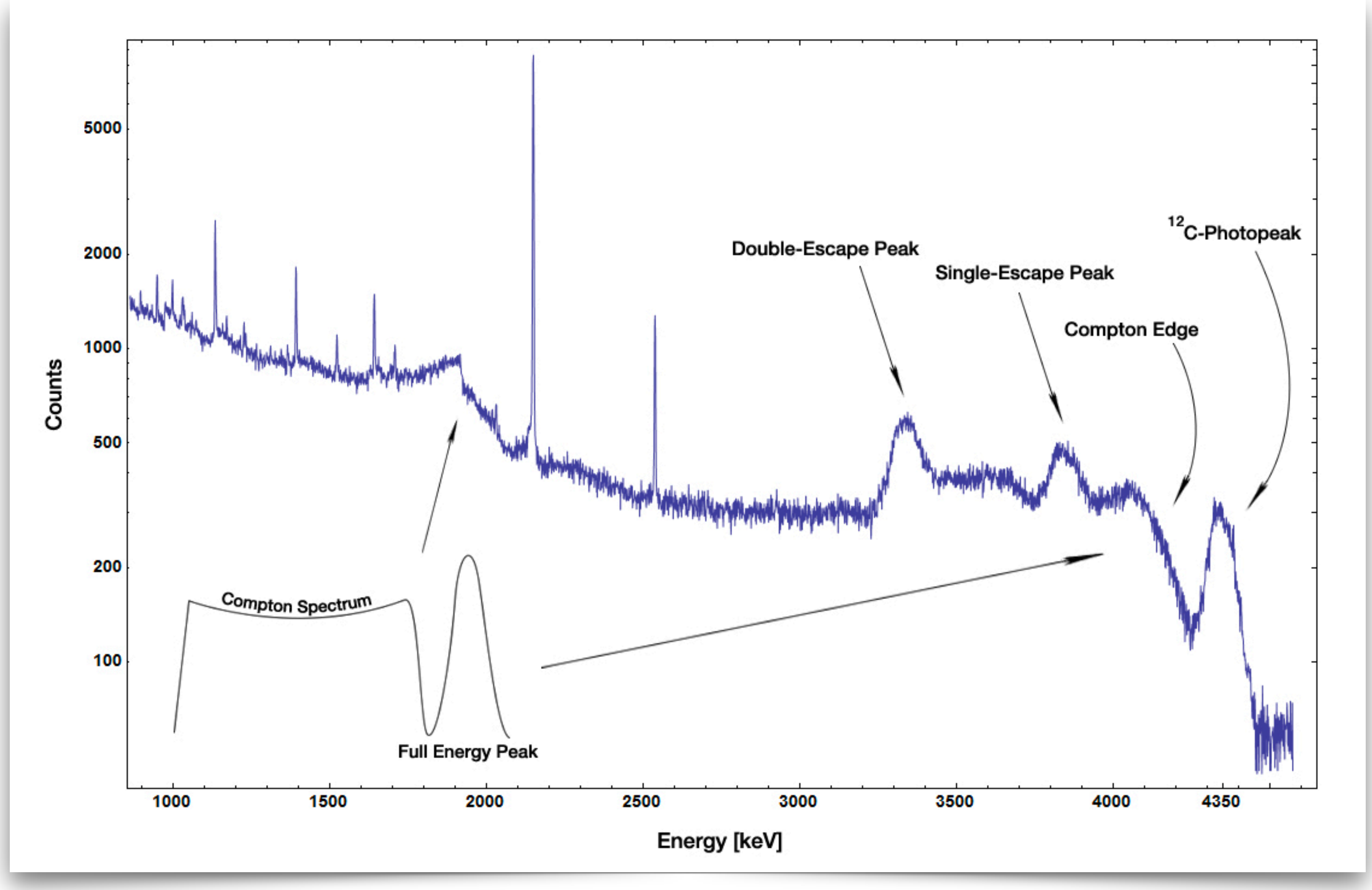
- Kinetic energy of the electron:

$$T_e = E_\gamma - E'_\gamma = E_\gamma \frac{\epsilon(1-\cos\theta)}{1+(\epsilon-\cos\theta)}$$

- Maximum energy transfer to electron for θ=180°:

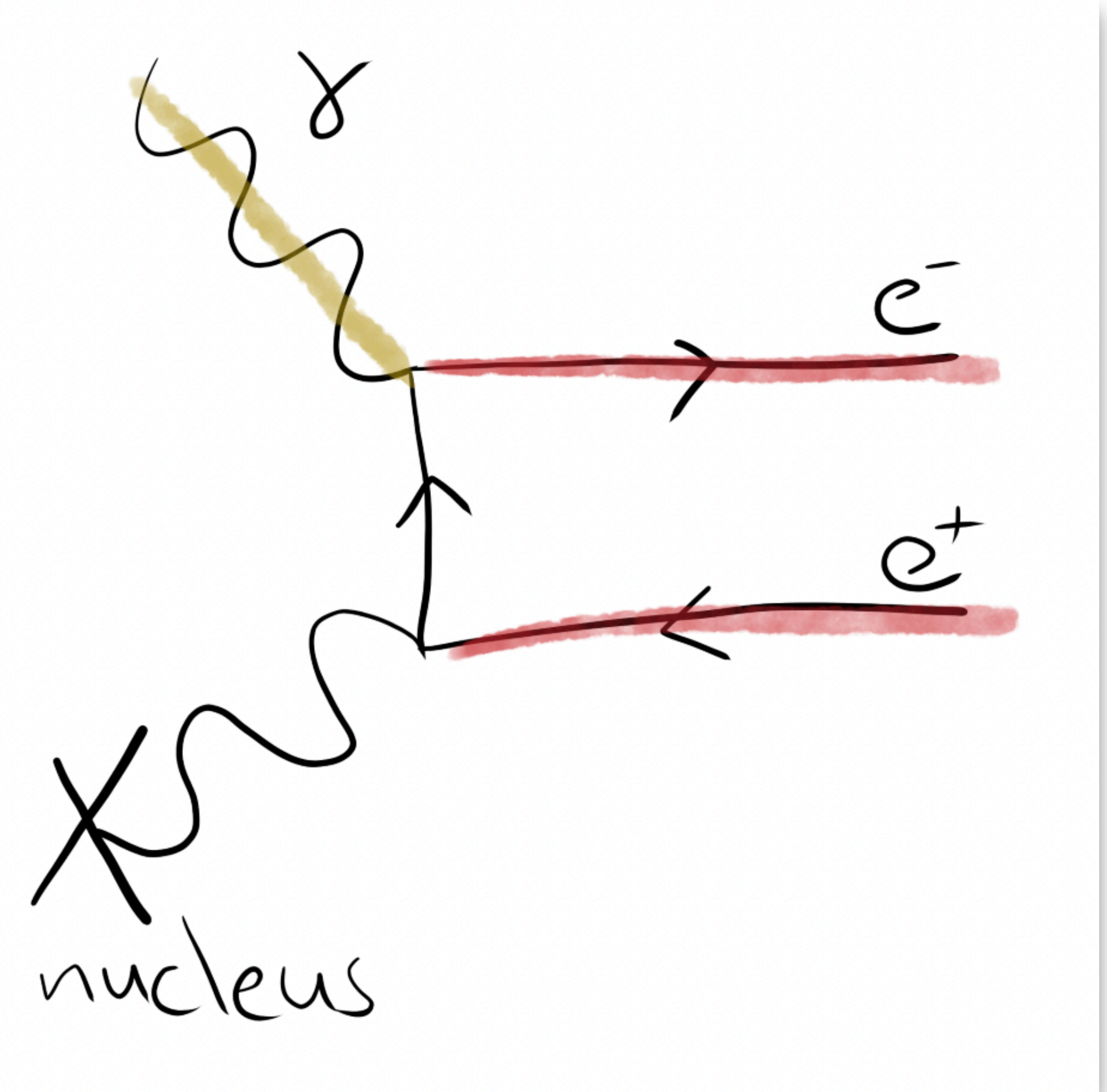
$$T_{\max} = E_\gamma \frac{2\epsilon}{1+2\epsilon} < E_\gamma$$

- It is not possible to transfer the whole photon energy via Compton scattering
- Compton edge position is a property of the photon and not of the material!



Photons: Pair production

- Kinematic constraints
  - Threshold effect only possible for ε > 2
  - 4-momentum conservation only within electric field of nucleus (nucleus receives recoil)



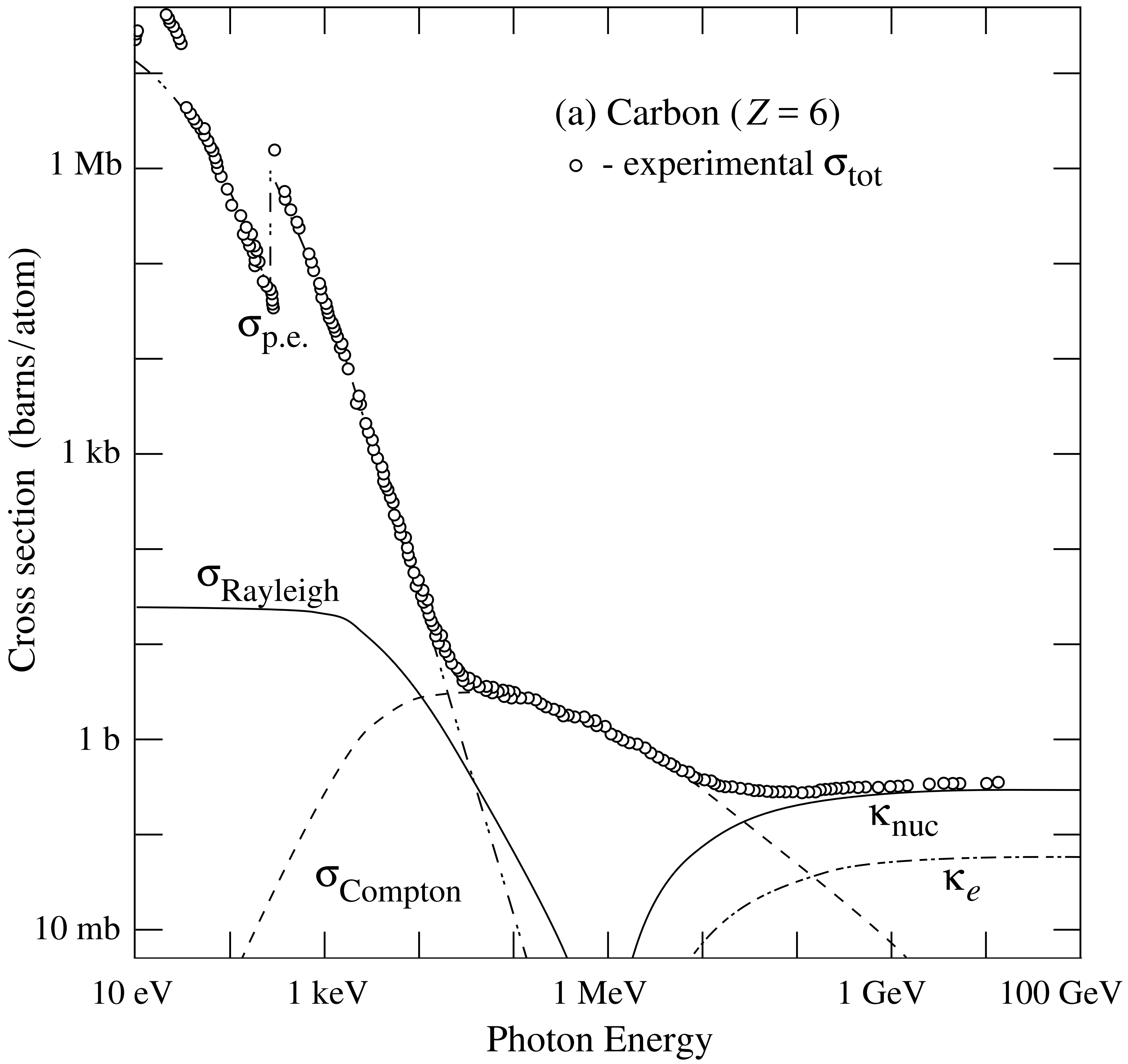
- Cross section (ε≫1, Z>4):

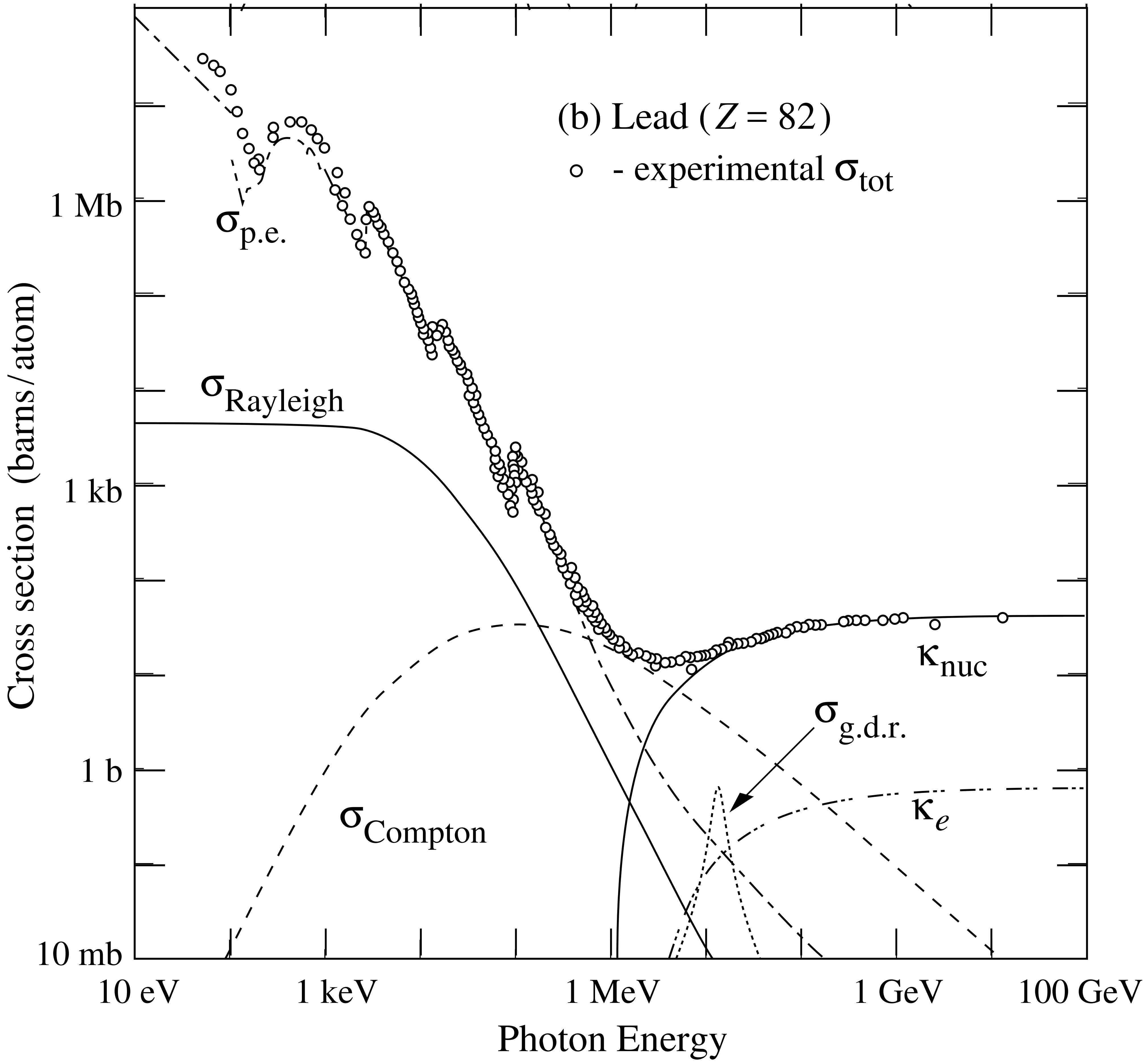
$$\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln\left(\frac{183}{Z^{1/3}} \right) - \frac{1}{54} \right)$$

  - [σ] = cm²/atom
  - independent of γ energy for ε≫1

$$\sigma_{\text{pair}} \propto Z^2 \ln(Z^{-1/3})$$

Photons: Summary





Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

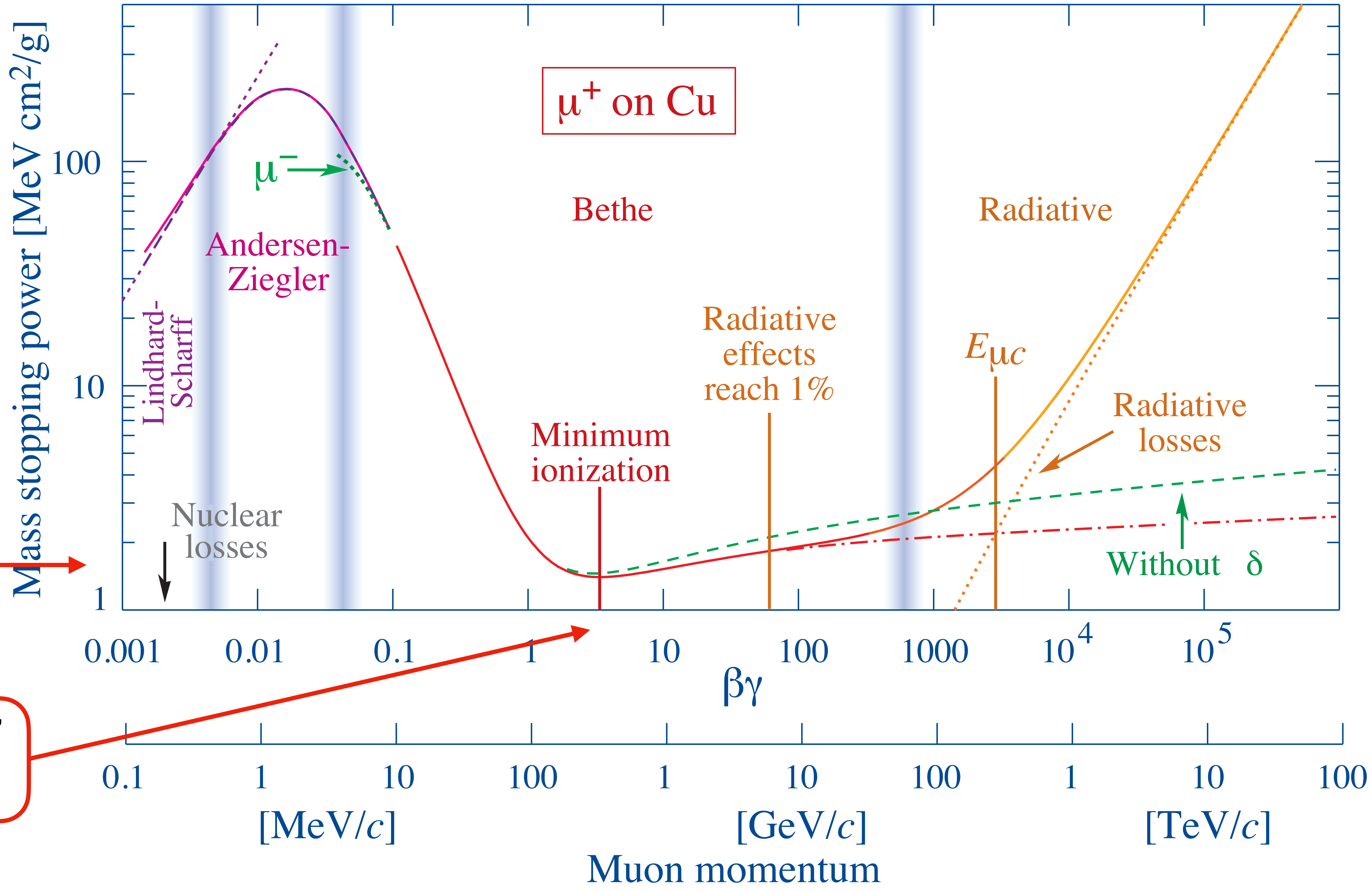
Charged Particles: Ionization

- Fast charged particles lose energy by inelastic collisions with electrons via ionization and atomic excitation
- Bethe-formula or so called “mass stopping power” (in units of MeV cm² / g), valid for $0.1 \lesssim \beta\gamma \lesssim 1000$:

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

K: $4\pi N_A r_e^2 m_e c^2 \approx 0.307$ MeV cm² / mol
Z: atomic number
A: atomic mass
β: Lorentz-boost
W_{max}: Maximum possible energy transfer to an electron in one collision in MeV
I: mean excitation energy in eV (!)
δ: density effect correction

Charged Particles: Ionization



energy loss:
1-2 MeV cm²/g

“minimum ionization”
for βγ≈3-4, a few
hundert MeV for μ

Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

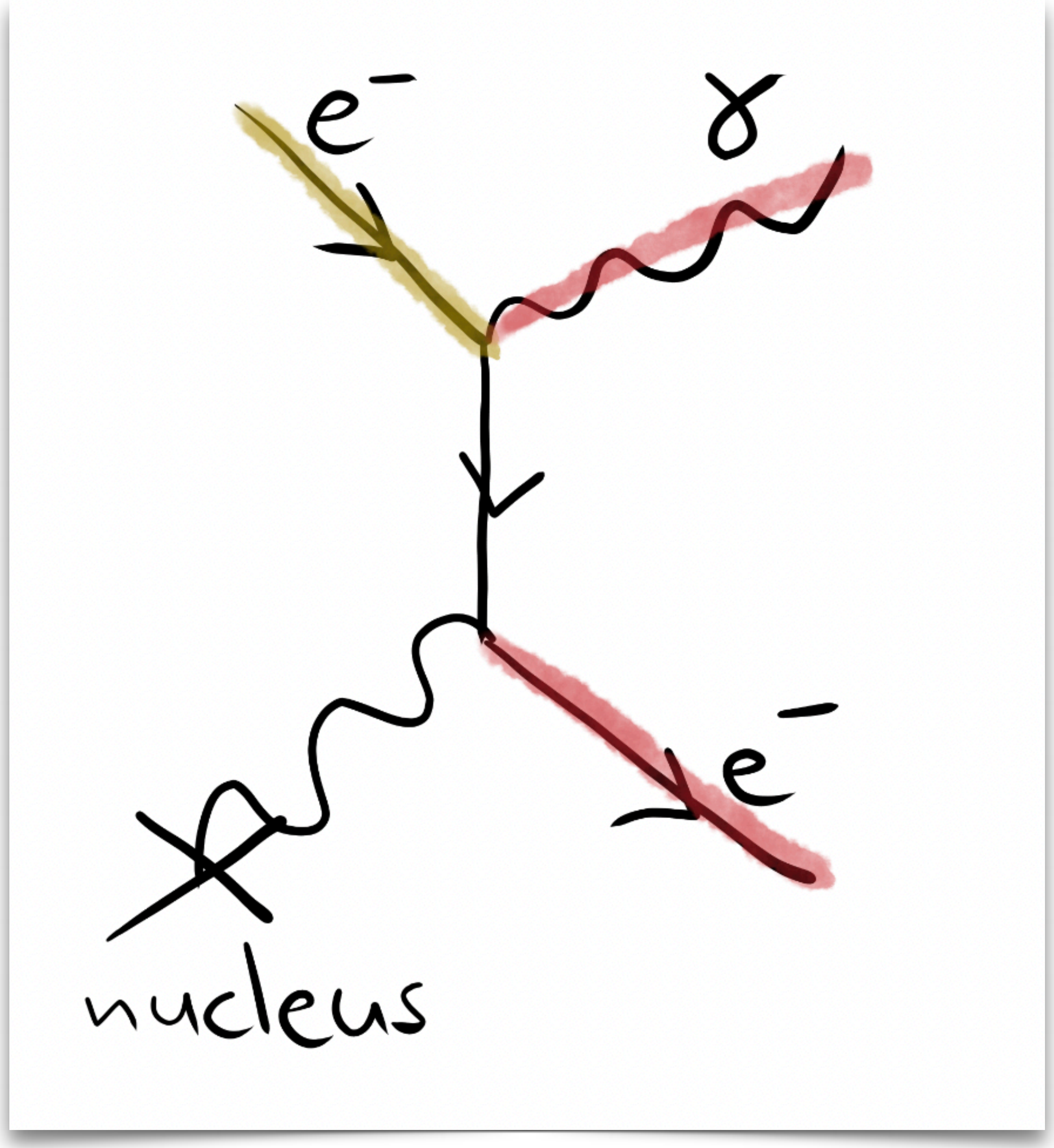
Charged Particles: Bremsstrahlung for electrons

- Energy loss via photon emission in the Coulomb field of a nucleus

$$-\frac{dE}{dX} = 4\alpha r_e^2 Z^2 \frac{N_A}{A} E \ln\left(\frac{183}{Z^{1/3}}\right) \equiv \frac{E}{X_0}$$

with radiation length

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\left(\frac{183}{Z^{1/3}}\right)}$$, unit: $[X_0] = \mathrm{g/cm^2}$



- For other particles, Bremsstrahlung is much smaller

Critical energy

- Critical energy is defined as energy where ionization energy loss and Bremsstrahlung energy loss are identical:

$$\left(\frac{dE}{dX}(E_C)\right)\Bigg|_{\text{brems}} = \left(\frac{dE}{dX}(E_C)\right)\Bigg|_{\text{ionisation}}$$

- $E<E_C$: ionization dominates, $E>E_C$: bremsstrahlung dominates
- Approximate values for electrons:
  - $E_{\text{C}}^{\text{gas}} = \frac{710\text{MeV}}{Z+0.92}$
  - $E_{\text{C}}^{\text{solid or liquid}} = \frac{610\text{MeV}}{Z+1.24}$

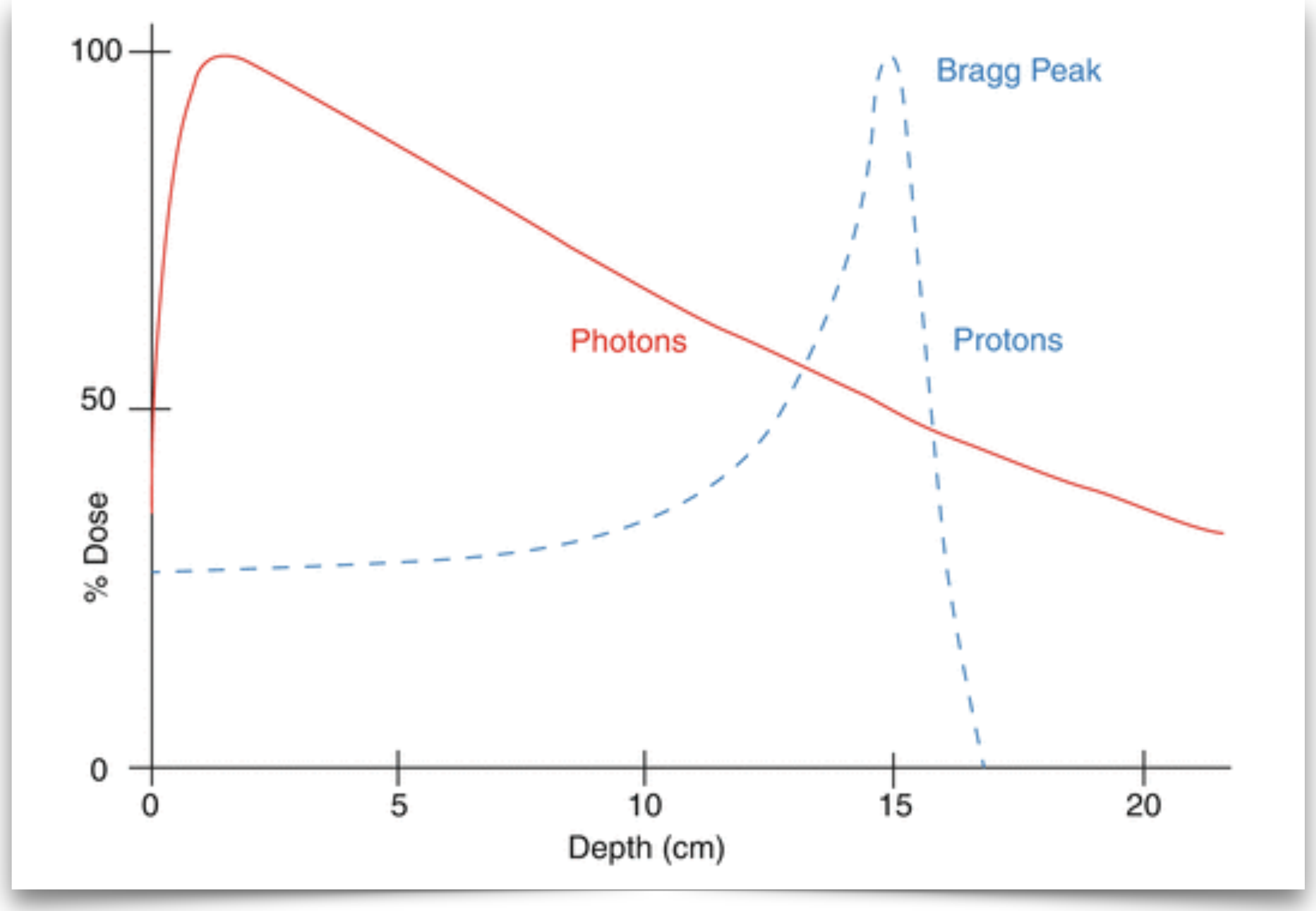
Radiation length

- Reduction of **electron** energy to a factor $e^{-1} \approx 63\,\%$ after the particle travelled $1X_0$

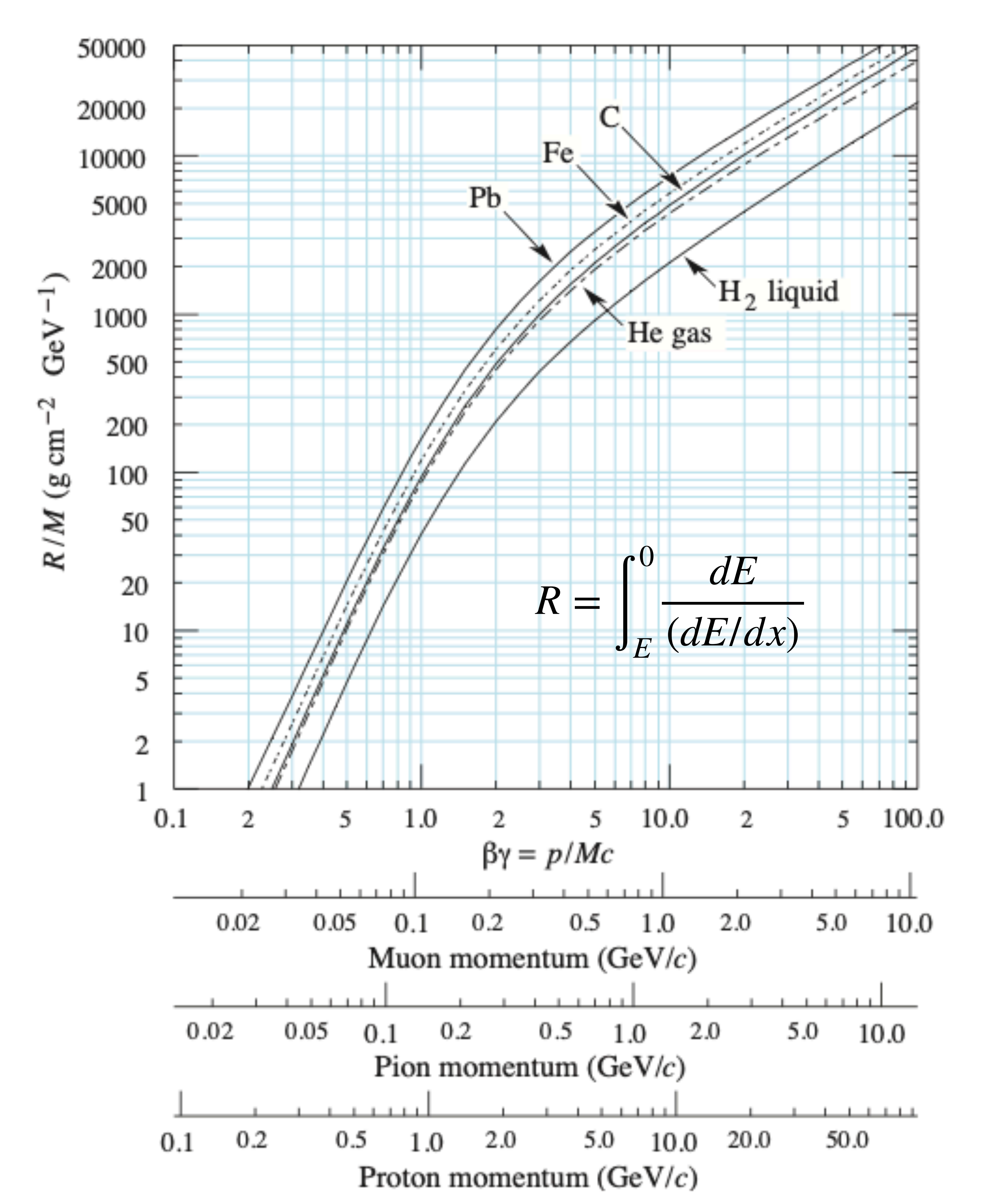
- Compare with pair production for **photons**: $\sigma_\text{pair} \approx \frac{7}{9}\frac{N_A}{A}\frac{1}{X_0}$
  - reduction of photon intensity (the photons are destroyed in the process) to $e^{-7/9} \approx 46\,\%$
  - after $1X_0$, 54% of all photons have turned into a pair of electron and positron

Charged Particles: Range in matter

- Range is given by integrating all energy loss processes ("continous slowing down approximation", CSDA)
- If the (heavy) particle has lost most of it's energy, the energy loss becomes very large: Bragg-peak



Credit: https://radiologykey.com/



Credit: https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/gallery/gal2_12.htm

Properties of materials

- https://pdg.lbl.gov/2022/AtomicNuclearProperties/index.html

Iron

Atomic and nuclear properties of iron (Fe)

Quantity	Value	Units	Value	Units
Atomic number	26			
Atomic mass	55.845(2)	g mol^{-1}		
Density	7.874	g cm^{-3}		
Mean excitation energy	286.0	eV		
Minimum ionization	1.451	MeV g^{-1}cm^{2}	11.43	MeV cm^{-1}
Nuclear interaction length	132.1	g cm^{-2}	16.77	cm
Nuclear collision length	81.7	g cm^{-2}	10.37	cm
Pion interaction length	160.7	g cm^{-2}	20.41	cm
Pion collision length	107.0	g cm^{-2}	13.59	cm
Radiation length	13.84	g cm^{-2}	1.757	cm
Critical energy	21.68	MeV (for e^-)	21.00	MeV (for e^+)
Muon critical energy	347.	GeV		
Molière radius	13.53	g cm^{-2}	1.719	cm
Plasma energy $\hbar\omega_p$	55.17	eV		
Melting point	1811.	K	1538.	C
Boiling point @ 1 atm	3134.	K	2861.	C

CsI

Atomic and nuclear properties of cesium iodide (CsI)

Quantity	Value	Units	Value	Units
<Z/A>	0.41569	mol g^{-1}		
Density	4.510	g cm^{-3}		
Mean excitation energy	553.1	eV		
Minimum ionization	1.243	MeV g^{-1}cm^{2}	5.605	MeV cm^{-1}
Nuclear interaction length	171.5	g cm^{-2}	38.04	cm
Nuclear collision length	100.6	g cm^{-2}	22.30	cm
Pion interaction length	198.7	g cm^{-2}	44.06	cm
Pion collision length	124.7	g cm^{-2}	27.65	cm
Radiation length	8.39	g cm^{-2}	1.860	cm
Critical energy	11.17	MeV (for e^-)	10.80	MeV (for e^+)
Muon critical energy	198.	GeV		
Molière radius	15.92	g cm^{-2}	3.531	cm
Plasma energy $\hbar\omega_p$	39.46	eV		
Melting point	894.2	K	621.0	C
Boiling point @ 1 atm	1553.	K	1280.	C
Index of refraction (Na D)	1.787			

Composition:

Elem	Z	Atomic frac*	A	Mass frac
I	53	1.00	126.9045	0.488451
Cs	55	1.00	132.9055	0.511549

* calculated from mass fraction data

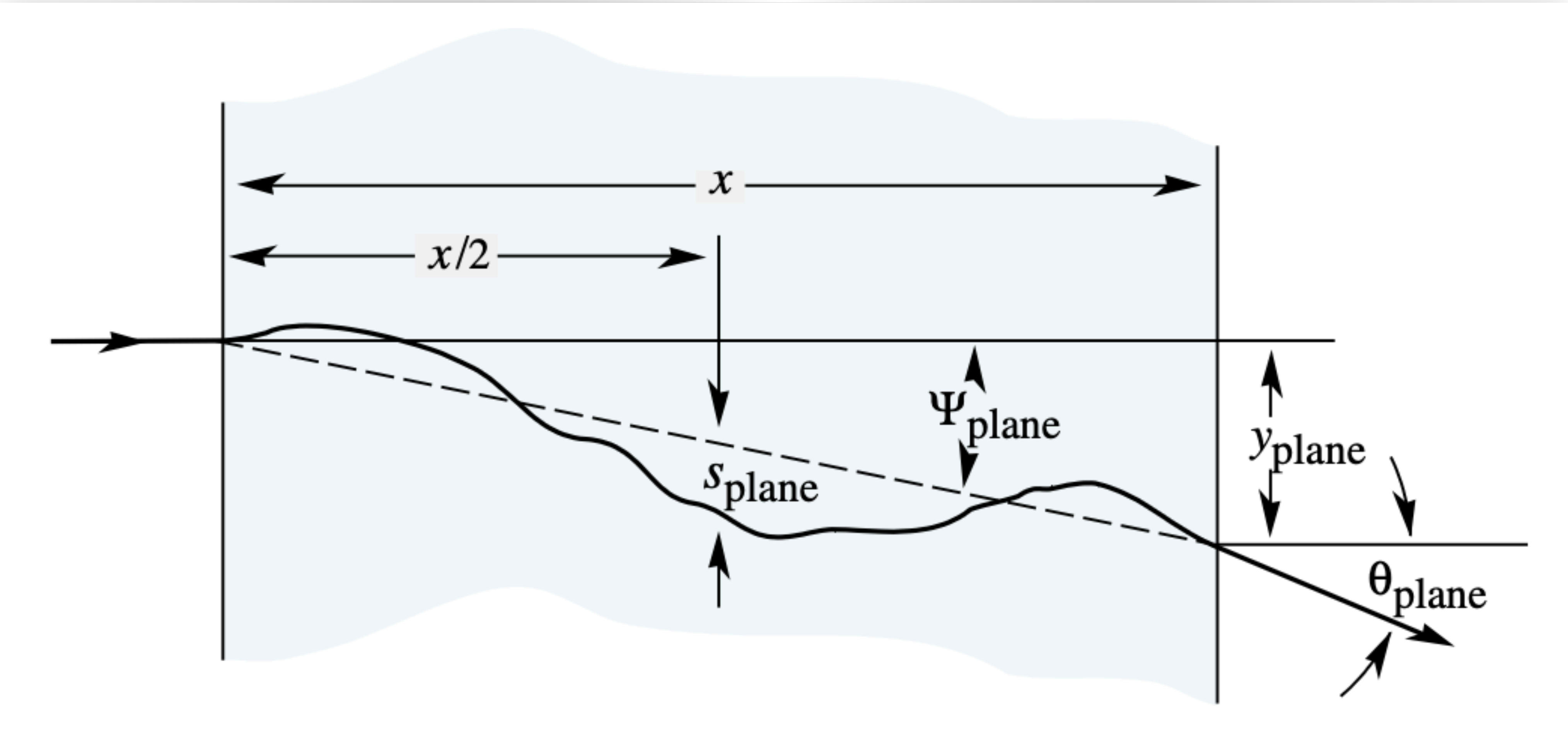
Charged Particles: Multiple scattering

- Charged particles in a medium dont only loose energy… they are deflected by many small Coulomb-scatters: multiple scattering

- Central-limit theorem: After many random scatters, the net scattering angle is approximately Gaussian

- Standard deviation after distance x:

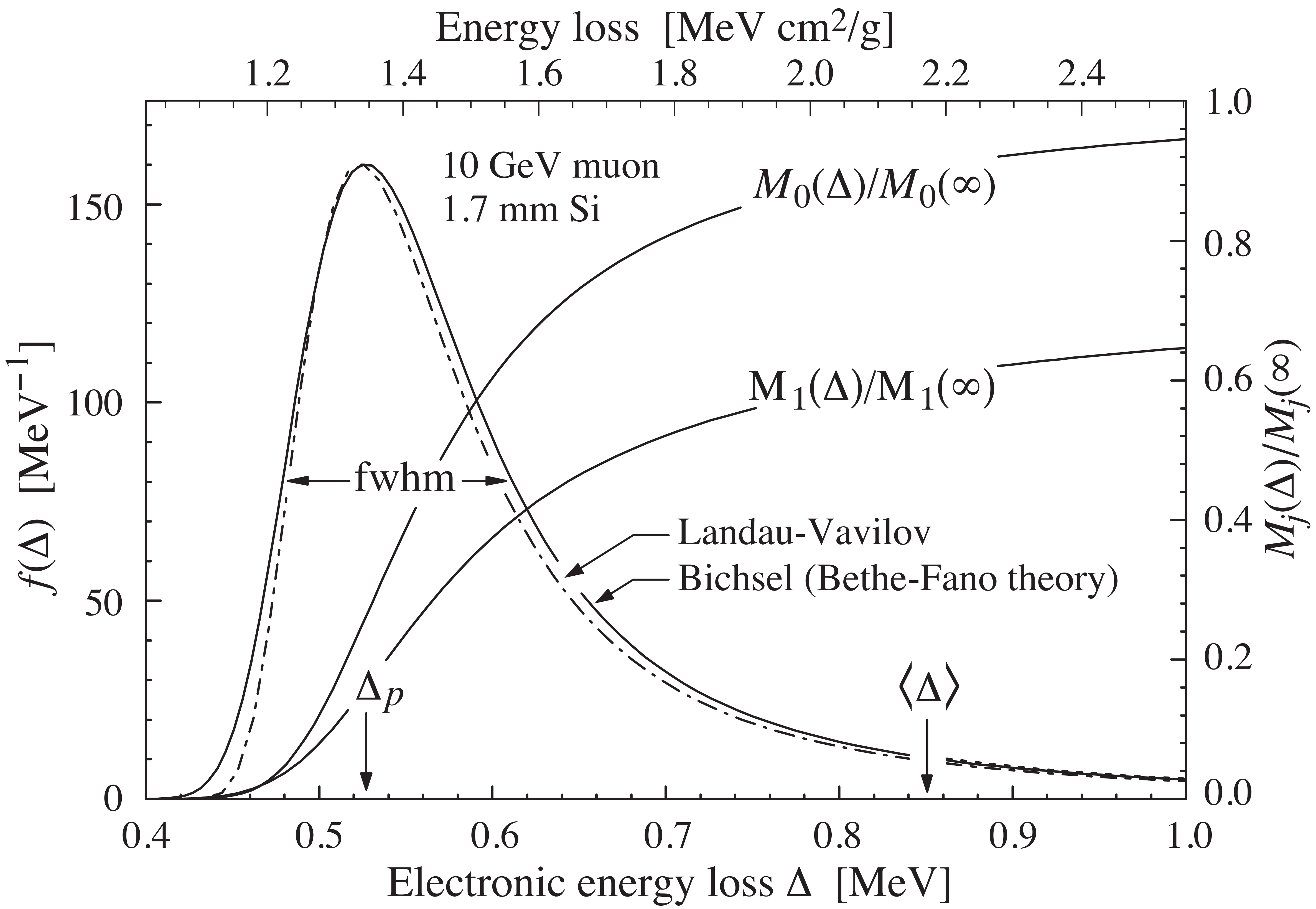
$$\sqrt{\langle \theta^2_{\text{plane}} \rangle} = \theta_0 \approx 13.6\,\text{MeV}\frac{q}{p\beta}\sqrt{\frac{x}{X_0}}$$



Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

Charged Particles: Energy loss fluctuations

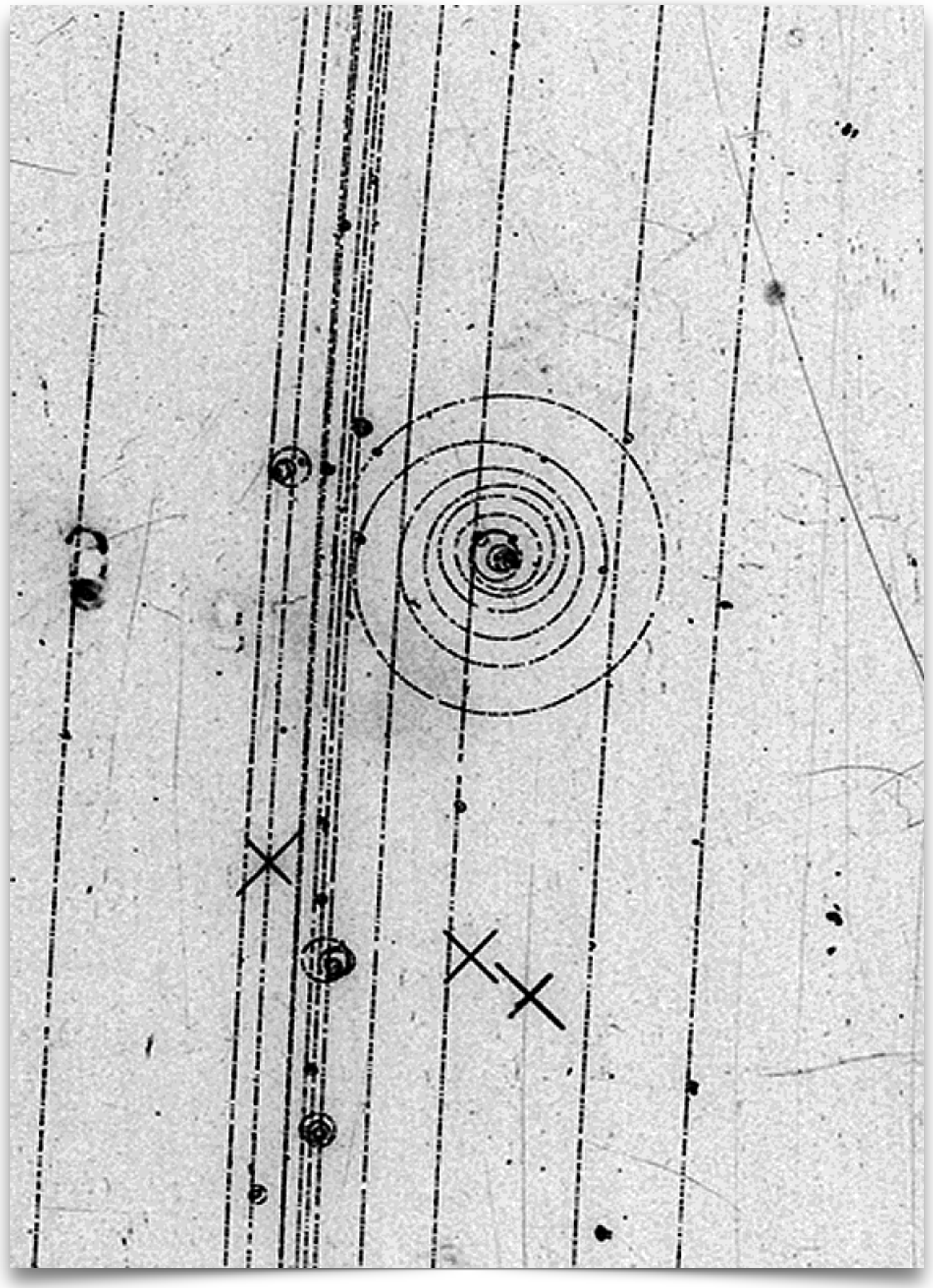
- Bethe-formulate describe the mean energy loss
- There are sizeable fluctuations in energy loss
  - strongly asymmetric distribution around most probable value described by Landau-Vavilov-distribution
  - too make things worse: mean of the Landau distribution is not defined (see CgDA lecture)

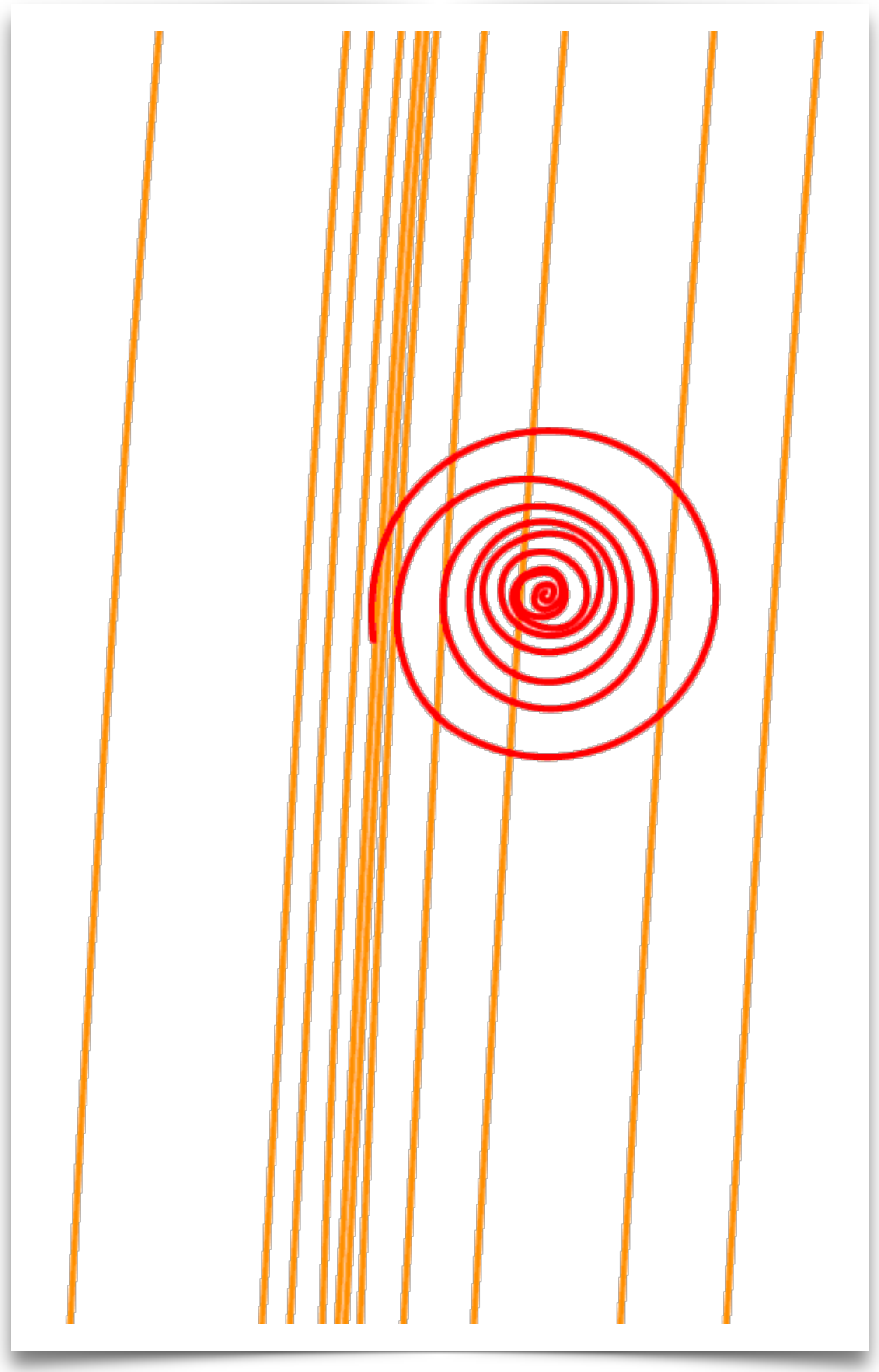


Credit: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

Charged Particles: δ-rays

- Close to maximal energy transfer to a single electron (tail of Landau distribution)
  - called δ-electrons or “knock-on”-electrons that have enough energy to ionize material on their own…

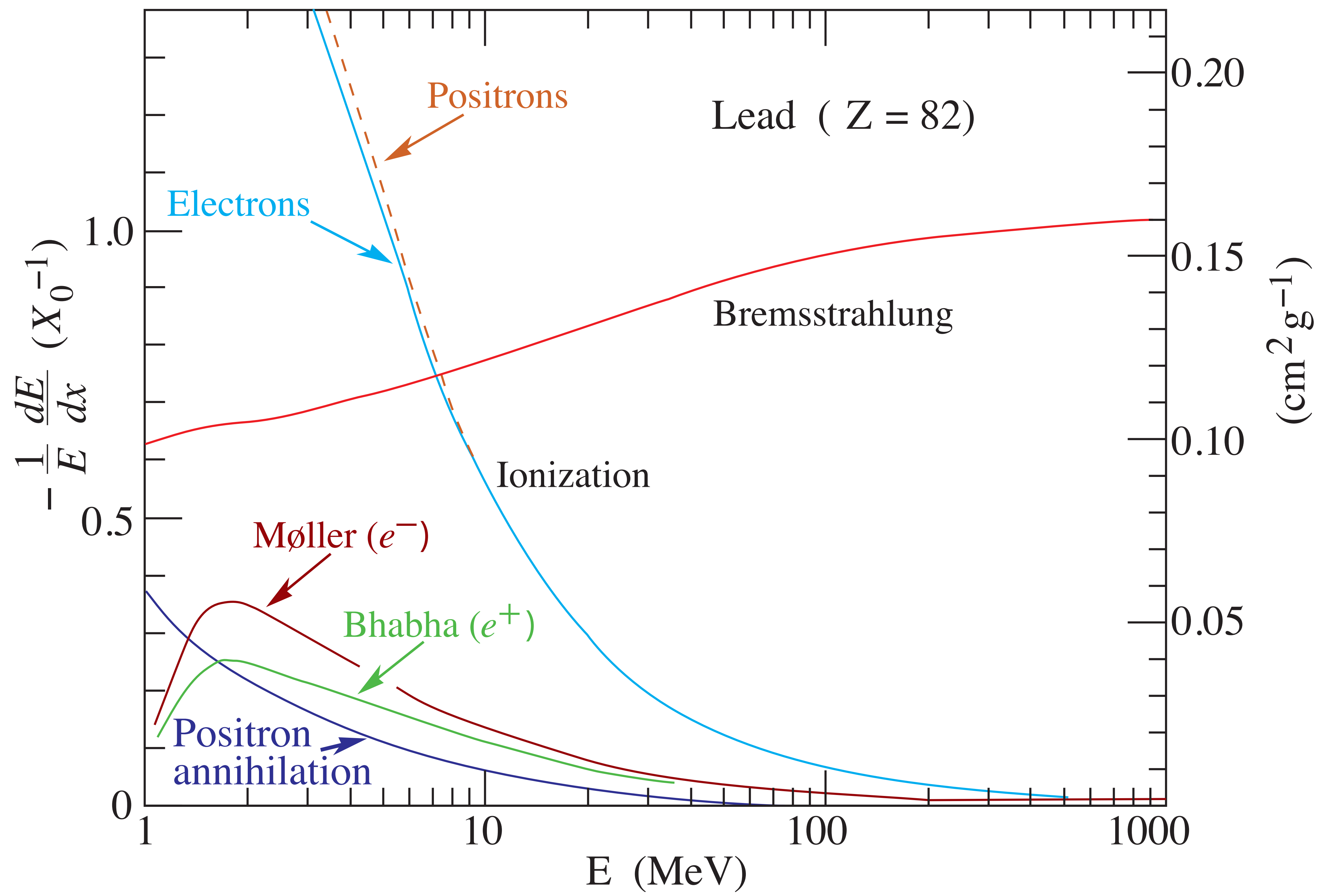


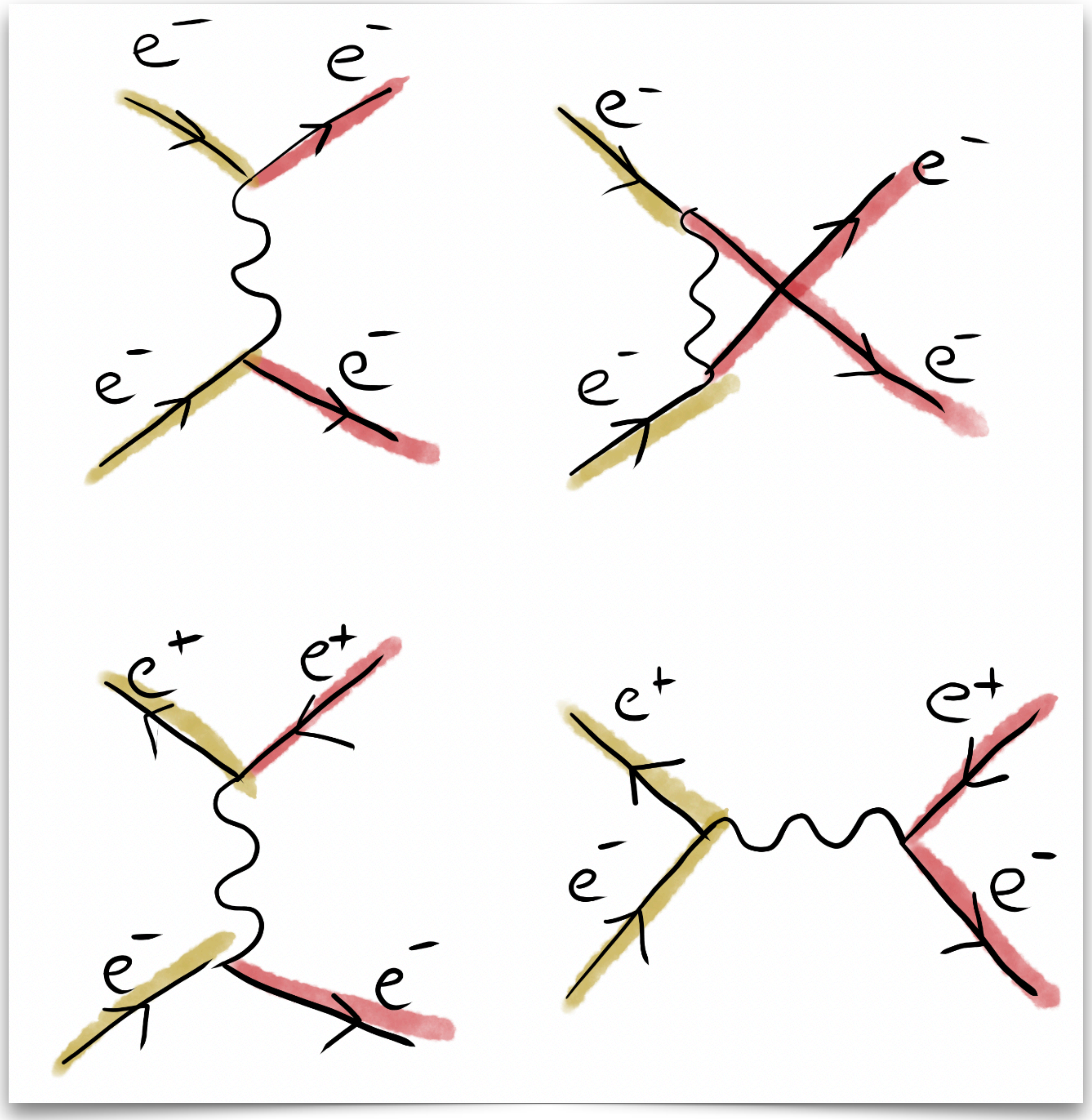


Credit: https://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/gallery/gal2_12.htm

Charged Particles: energy loss for electrons

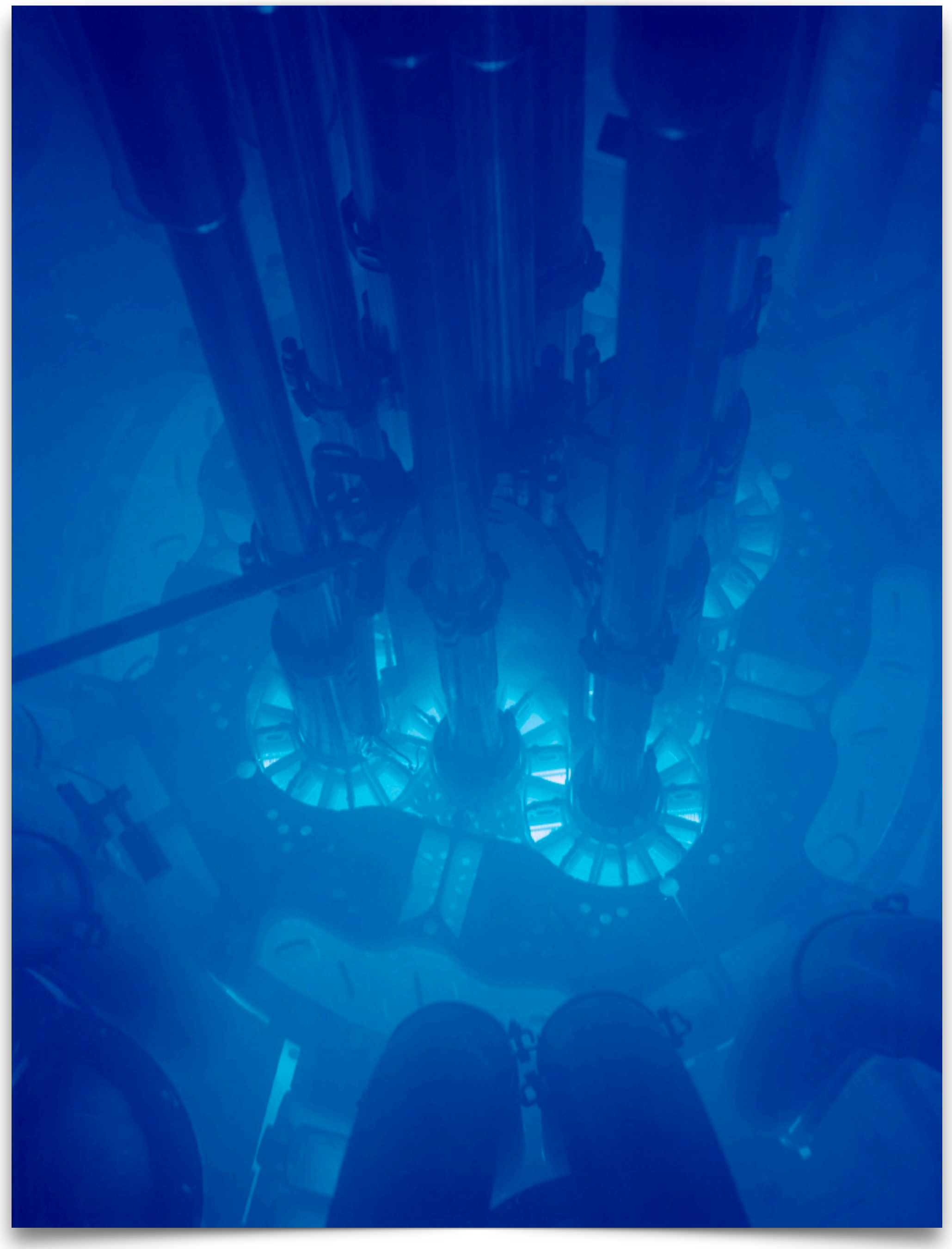
- At low energies in addition to Bremsstrahlung and ionization:
  - electrons: Møller scattering
  - positrons: Bhabha scattering, pair annihilation





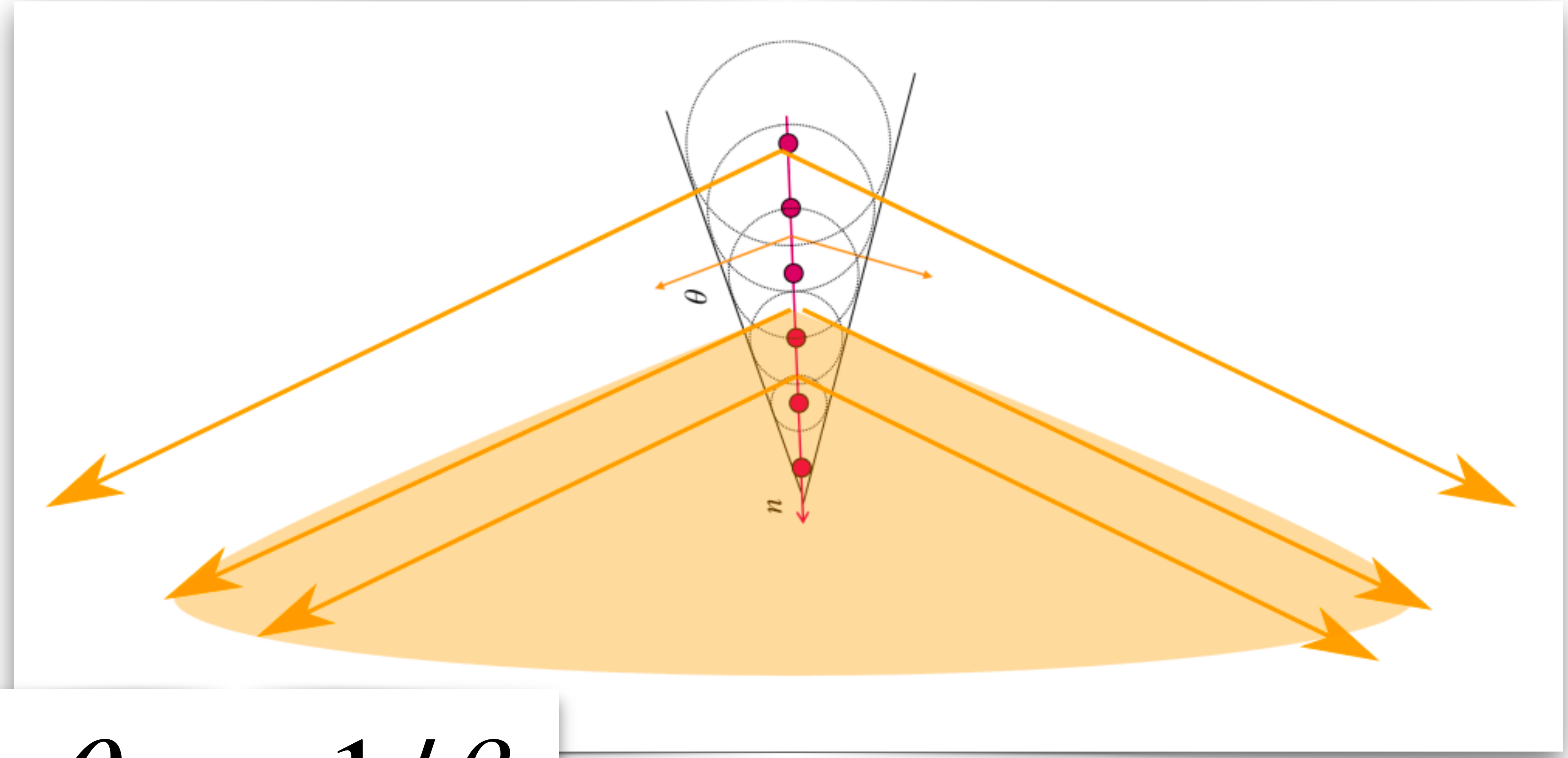
Charged Particles: Cerenkov radiation

- Radiation emitted by charged particles when passing a **homogenous** dielectric medium at a speed β greater than the phase velocity of light in that medium ($\beta > 1/n$).
  - caused by polarization of material and subsequent photon emission
  - if particle is slow, destructive interference destroys macroscopic light emission
  - visible if medium is transparent to ~blue light
- Cerenkov angle θ_C depends on material and particle speed: $\cos\theta_C = 1/(n\beta)$.



Cerenkov radiation in cooling water of the Idaho nuclear test reactor

Credit: Argonne National Laboratory, CC BY-SA 2.0



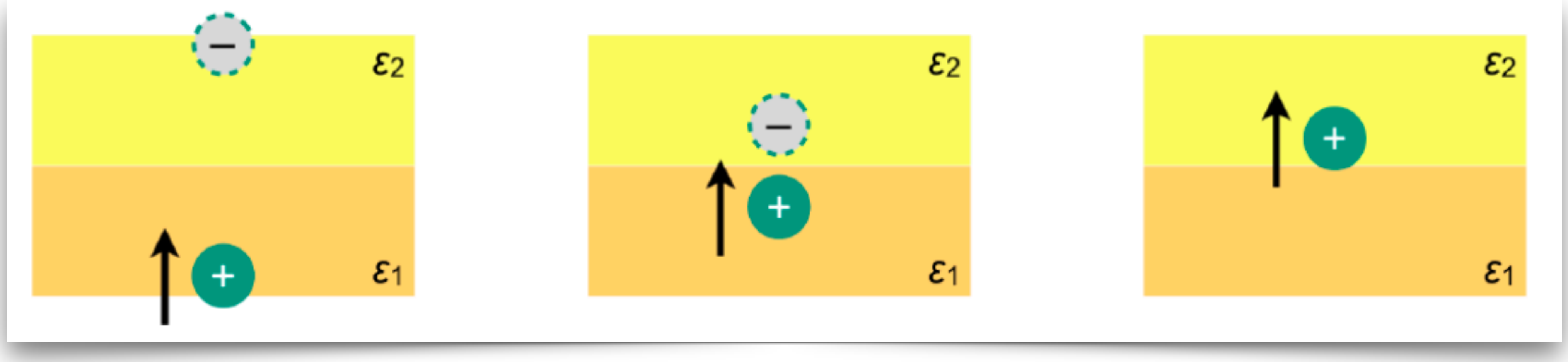
Credit: https://physics.stackexchange.com/

$$\theta_c \propto 1/\beta$$

Charged Particles: Transition radiation

- Radiation emitted when a charged particle passes through the boundary between two homogenous media with different permittivity ε.

- Classical explanation: Radiation of a time-dependent dipole between the charge and its mirror charge

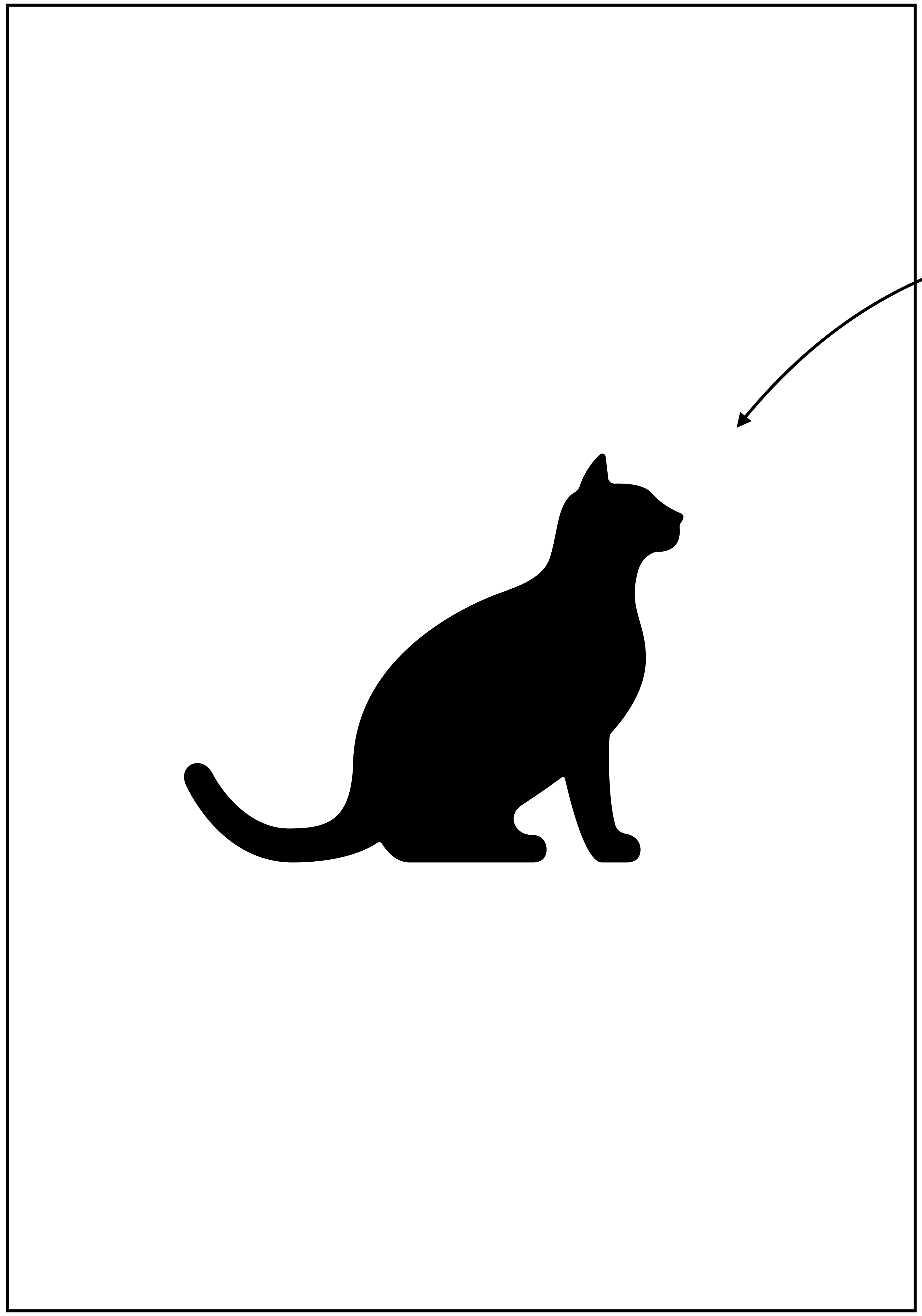


- Intensity:

$$I = \alpha q^2 \gamma \frac{\omega_p}{3} \text{ with } \omega_p^2 = \frac{n_e e^2}{\epsilon_r \epsilon_o m_e} \text{ of the}$$

medium with larger ω

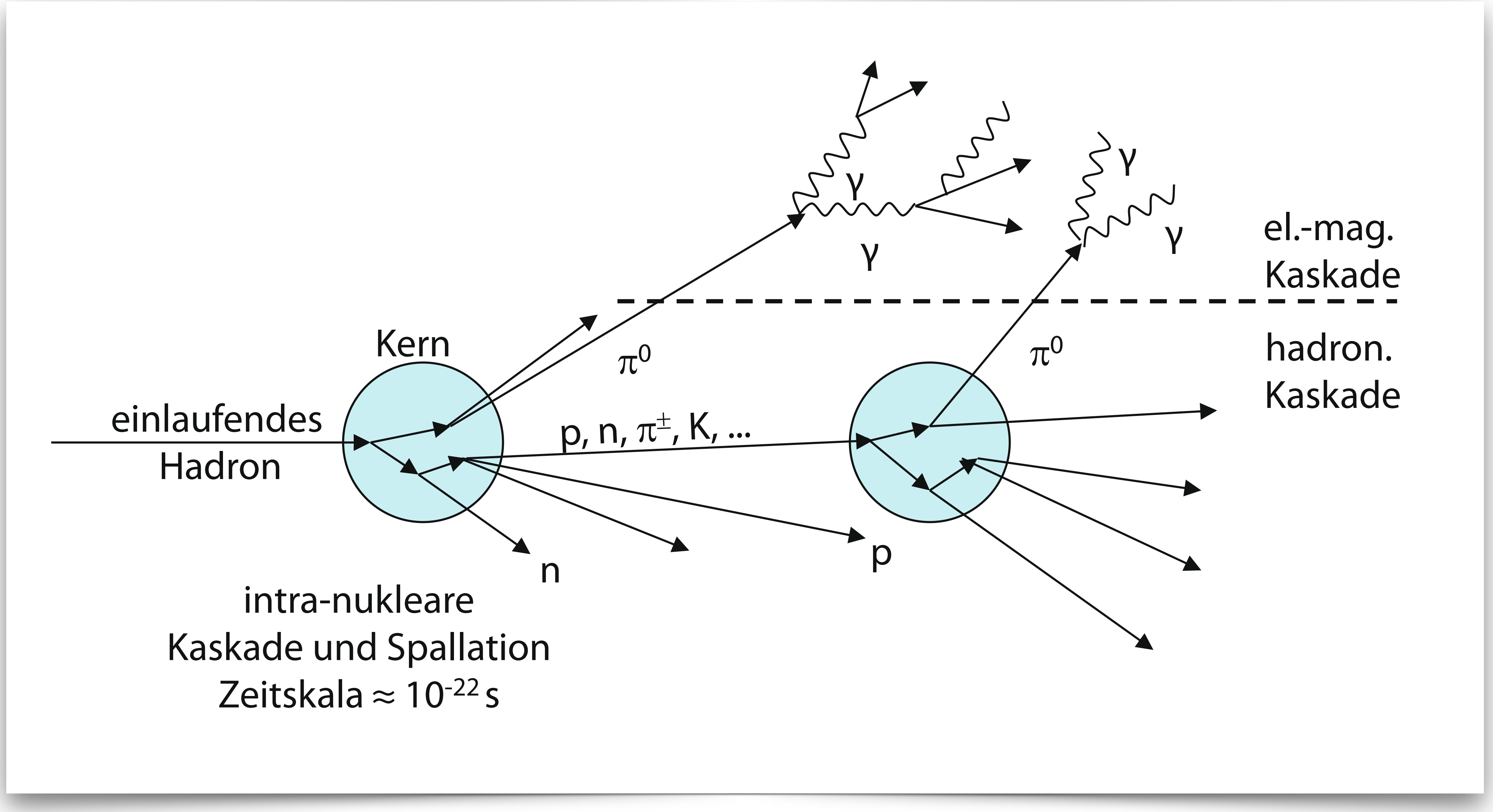
$$I \propto \gamma$$



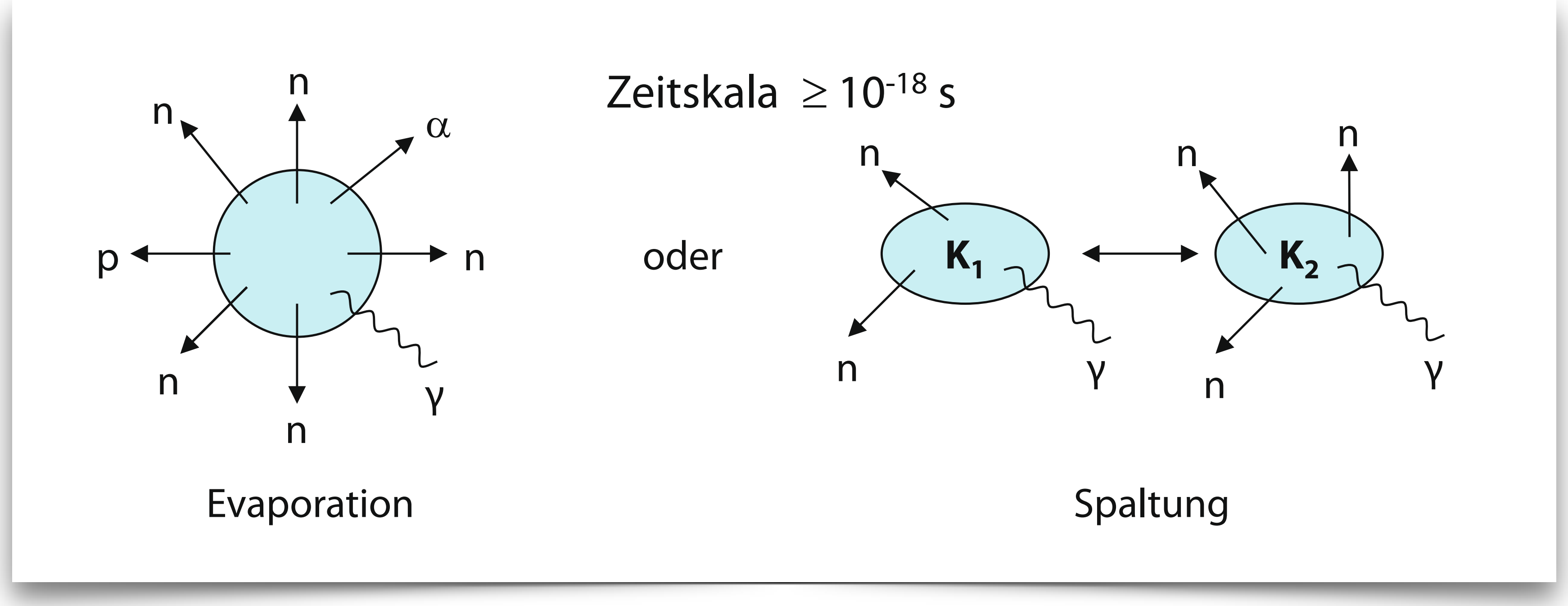
Your cat picture!

Charged Particles: Hadronic Interactions

- Strong interactions between hadrons and nuclei
  - production of secondary hadrons (mostly pions), about 1/3 of those will be neutral pions decaying to two photons*
  - delayed nuclear evaporation and spallation
  - production of "invisible" neutrinos in hadron decays
  - production of long lived hadrons carry energy away ("split-offs" or "satellites")
- Huge fluctuations, "missing" energy (from neutrinos) and "extra" energy (e.g. from nuclear fission and evaporation)
- This is a mess!



Credit: Wermes & Kolanoski, 2016



* This is a good chance to practice how to use the Particle Data Group website

Charged Particles: Hadronic Interactions

- Absorption of hadrons in matter is parametrized by hadronic interaction length λ:

$$I(x) = I_0 \exp\left(\frac{x}{\lambda}\right) \text{ with } \lambda = \left(\sigma_{\text{inel.}} \frac{N_A}{A} \rho\right)^{-1}$$

- λ is material dependent and typically 20-30× larger than the radiation length X_0
- λ is tabulated for most used materials

Atomic and nuclear properties of iron (Fe)

Quantity	Value	Units	Value	Units
Atomic number	26			
Atomic mass	55.845(2)	g mol^{-1}		
Density	7.874	g cm^{-3}		
Mean excitation energy	286.0	eV		
Minimum ionization	1.451	MeV g^{-1}cm^{2}	11.43	MeV cm^{-1}
Nuclear interaction length	132.1	g cm^{-2}	16.77	cm
Nuclear collision length	81.7	g cm^{-2}	10.37	cm
Pion interaction length	160.7	g cm^{-2}	20.41	cm
Pion collision length	107.0	g cm^{-2}	13.59	cm
Radiation length	13.84	g cm^{-2}	1.757	cm
Critical energy	21.68	MeV (for e^-)	21.00	MeV (for e^+)
Muon critical energy	347.	GeV		
Molière radius	13.53	g cm^{-2}	1.719	cm
Plasma energy $\hbar\omega_p$	55.17	eV		
Melting point	1811.	K	1538.	C
Boiling point @ 1 atm	3134.	K	2861.	C

Charged Particles: Kaons are special

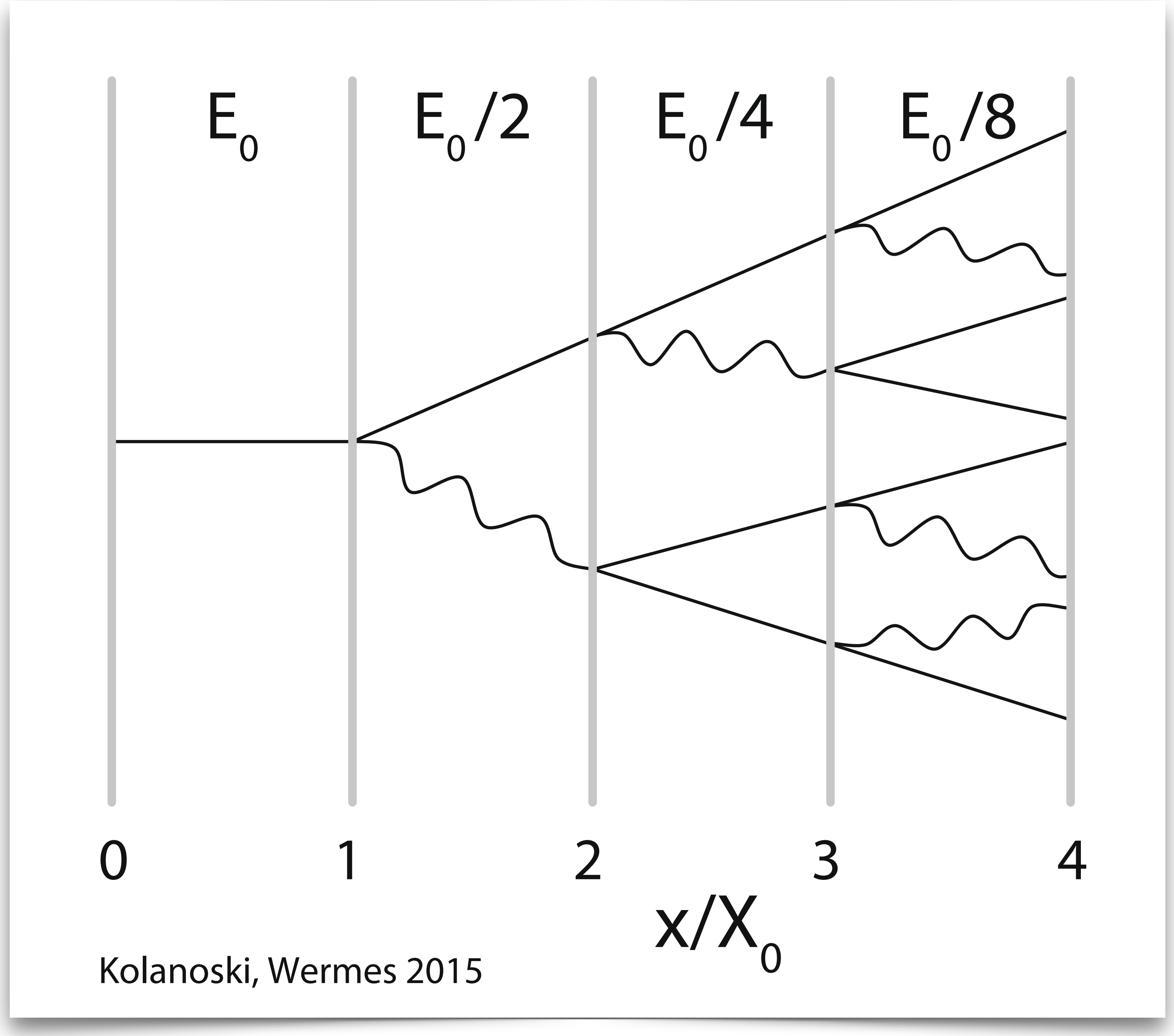
- Interactions of charged low energy (~GeV) Kaons show a strong charge asymmetry:
  - The detector medium typically only contains protons (and neutrons) but not anti-protons
  - Strangeness is a conserved quantum number
  - Flavour hypercharge Y = B + S must be conserved
- e.g. $K^-(\bar{u}s) + p(uud) \rightarrow \pi^0(u\bar{u}) + \Lambda(uds)$ allows hyperon*

  production, but $K^+(u\bar{s}) + p(uud) \rightarrow \Delta^{++}(uuu) + K^0(d\bar{s})$ does not!

* Hyperons are baryons that contain strange quarks

Photons, electrons and positrons: Electromagnetic showers

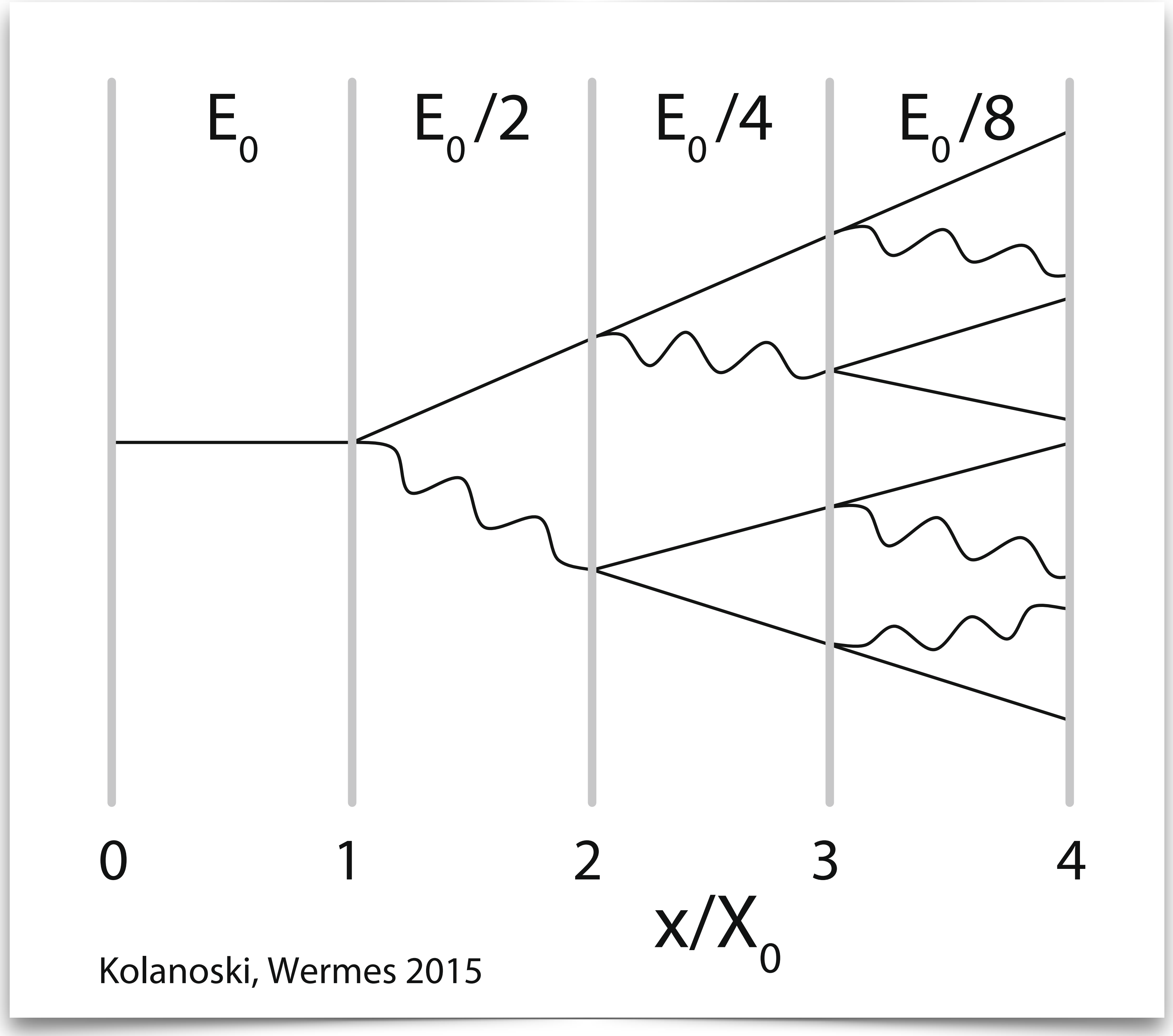
- High energetic photons and electrons (and positrons) can be described by the (very) simplified Heitler model
  - using only two processes: pair production (photons) and bremsstrahlung (electrons), until the energy of the particle is below the critical energy E_C (after which ionization dominates)
  - assume that one of these processes happens after one radiation length X_0



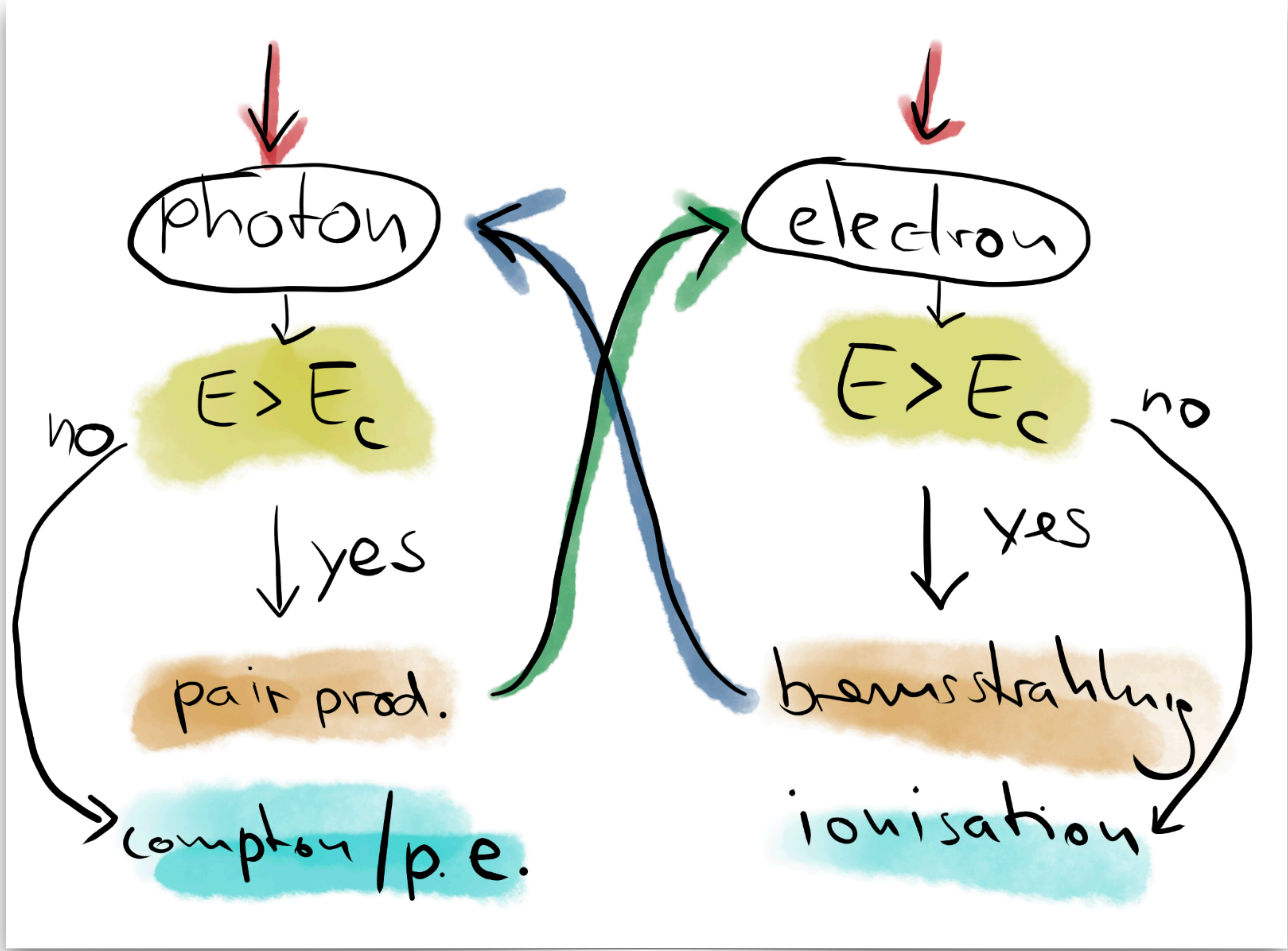
Photons, electrons and positrons: Electromagnetic showers

- Total number of particles: $n = \frac{E_0}{E_C} \propto E_0$
  - Sum of all distances by all particles: $s = \frac{E_0}{E_C} X_0$
  - Particles after t steps: $n(t) = 2^t$
  - Maximum number of steps for $E = E_C = \frac{E_0}{2^{t_{max}}}$
- Maximum number of steps

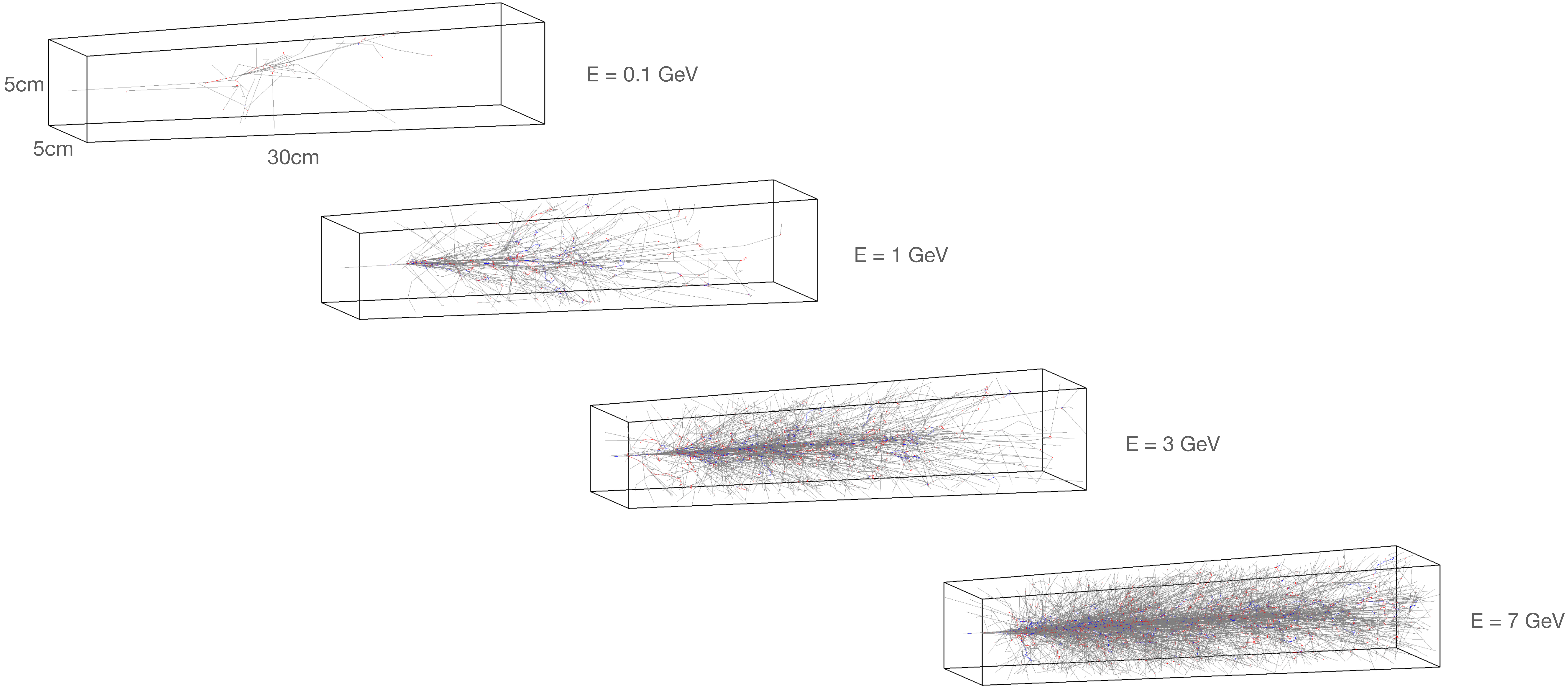
$$t_{\text{max}} = \frac{\ln(E_0/E_C)}{\ln 2} \propto \ln E_0$$



Photons and electrons: Electromagnetic showers



Photons and electrons: Electromagnetic showers



GEANT4 simulation, Belle II crystals, photons

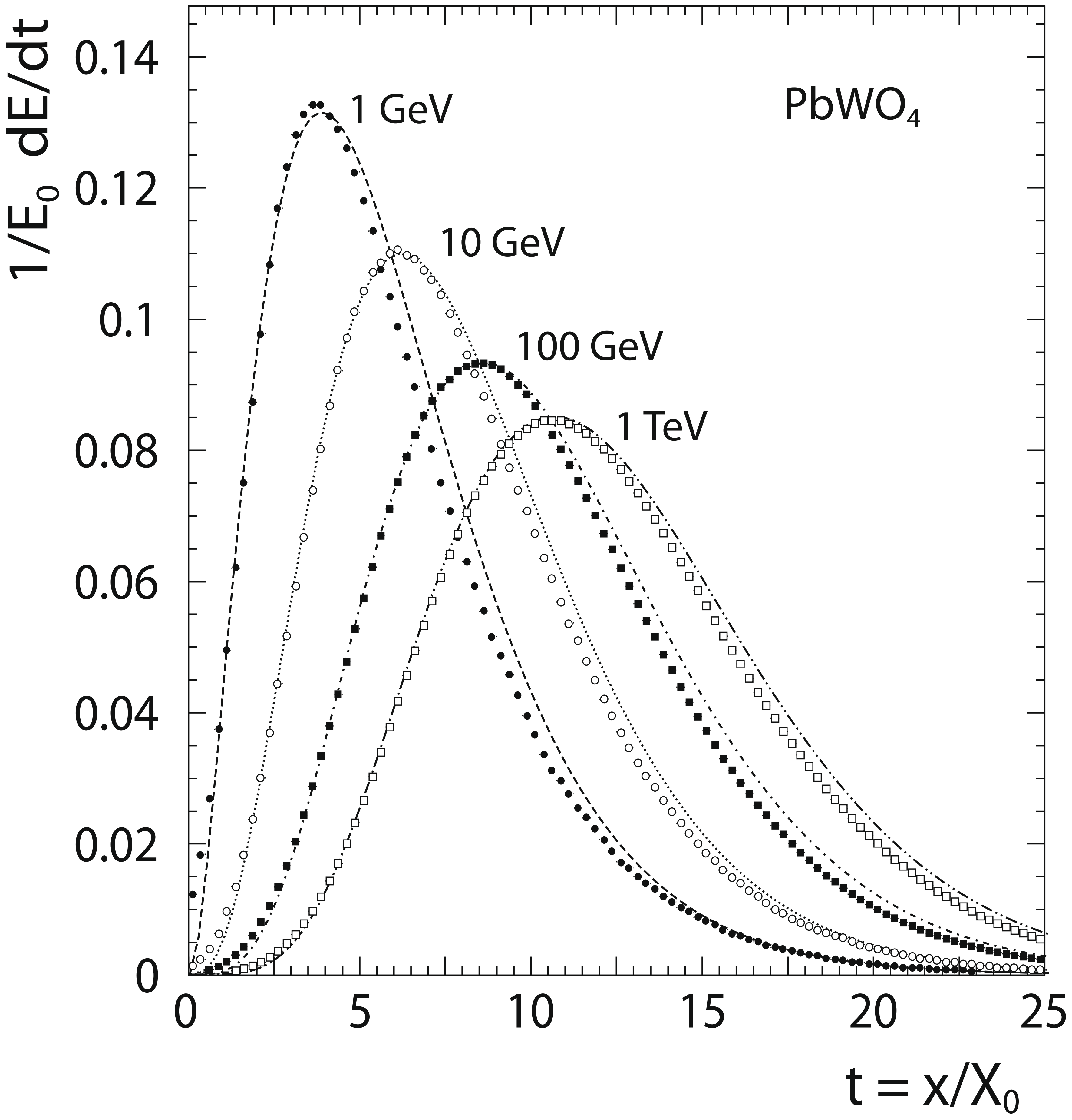
Photons and electrons: Electromagnetic showers

- Longitudinal shower profile parametrization:

$$\frac{dE}{dt} = E_0 \frac{b^a}{\Gamma(a)} t^{a-1} \exp(-bt)$$

  - Maximum: $t_{\text{max}} = \ln\left(\frac{E_0}{E_C}\right) + \begin{cases} -0.5 & \text{(electrons)} \\ 0.5 & \text{(photons)} \end{cases}$
  - Containment: $t_{98\%} \approx t_{\text{max}} + 13.6 \pm 2.0$
    - Example for a 5 GeV photon in CsI:

$$t_{98\%} \approx \left(\ln(5000/11.17) - 0.5 + 13.6\right) X_0 \approx 19.2\, X_0 \approx 36\,\text{cm}$$



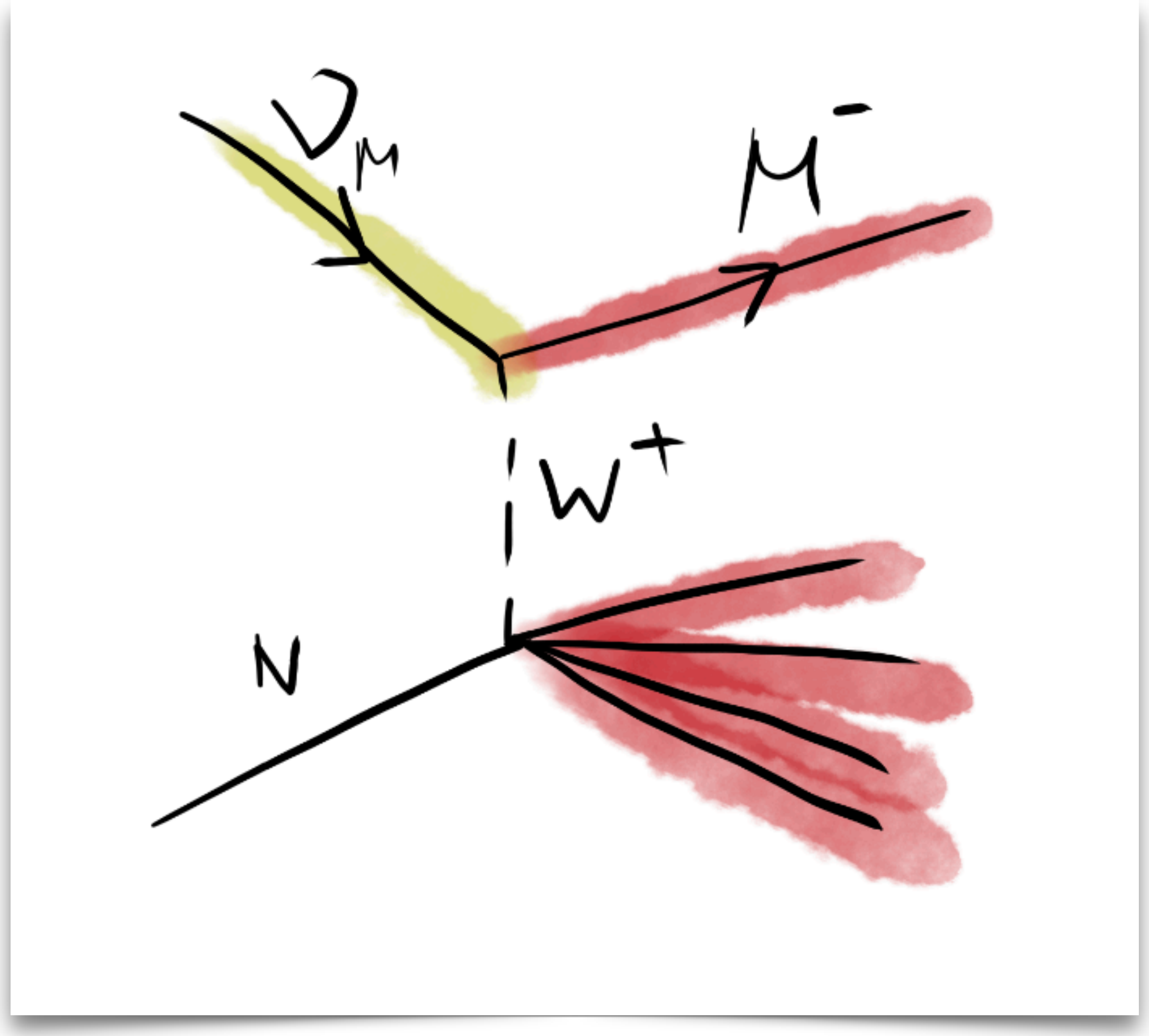
Credit: Wermes & Kolanoski, 2016

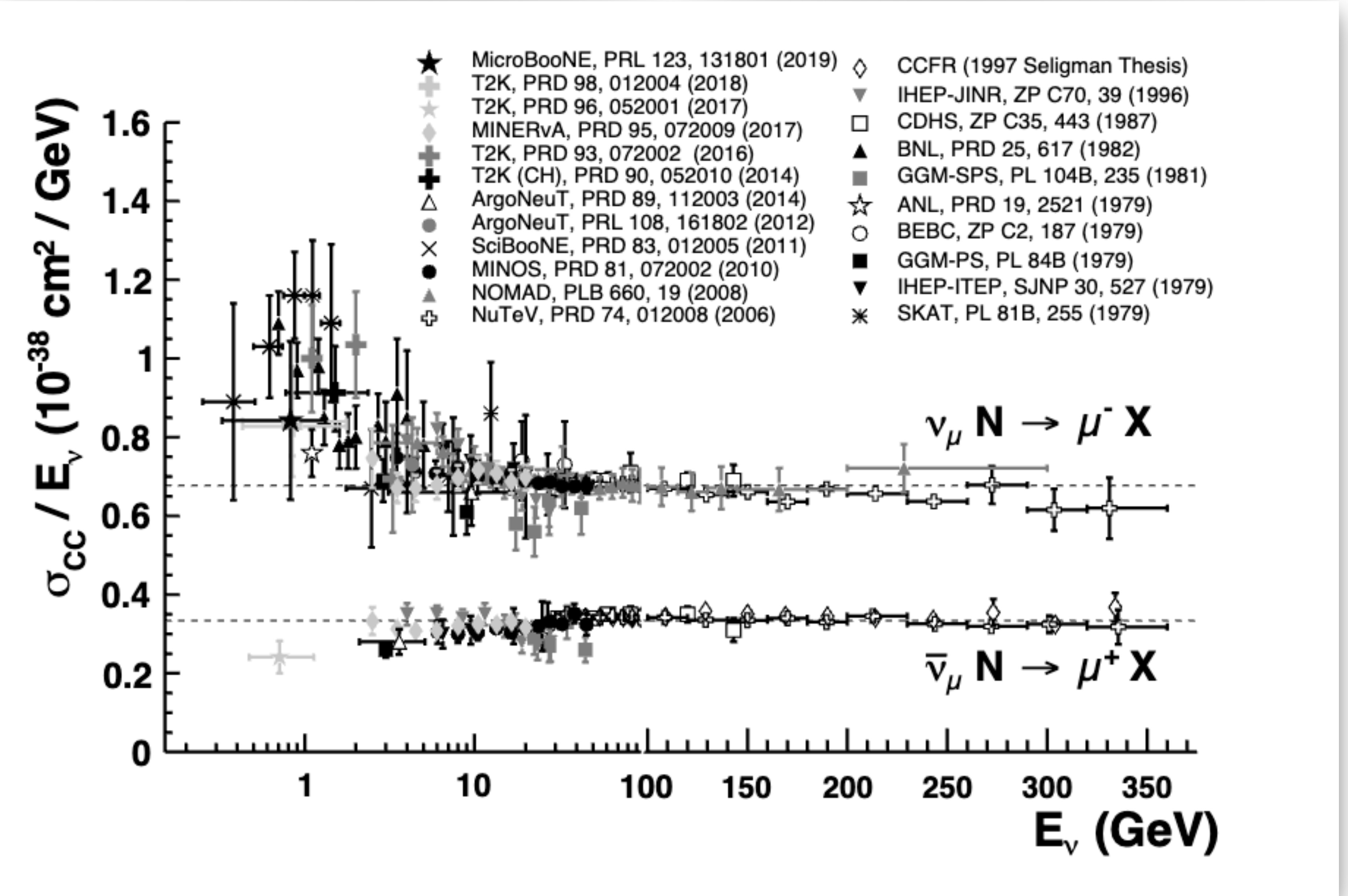
Intermediate summary particle interactions

- Many different processes contribute to the energy loss depending on energy range, material, and particle
  - **Photons**: Photoelectric effect, Compton-scatterung, pair production
  - **Charged particles**: Ionization and to much less extend Cerenkov and transition radiation
    - special case **electrons**: Bremsstrahlung dominates over ionization at high energies
    - special case **positrons**: Bhabha scattering, pair annihilation
  - **Hadrons**: Nuclear reaction resulting in complicated hadron showers
- Parametrization:
  - Photons and electrons: Radiation length X_0
  - Hadrons: Nuclear interaction length λ

Neutrinos

- Neutrinos can interact only via the weak force
- Cross section are very small (but they increase with energy)
- Typical absorption length for a a MeV neutrino in lead is ~1 lightyear
- For all collider experiments, the probability to see a neutrino interaction, is zero*



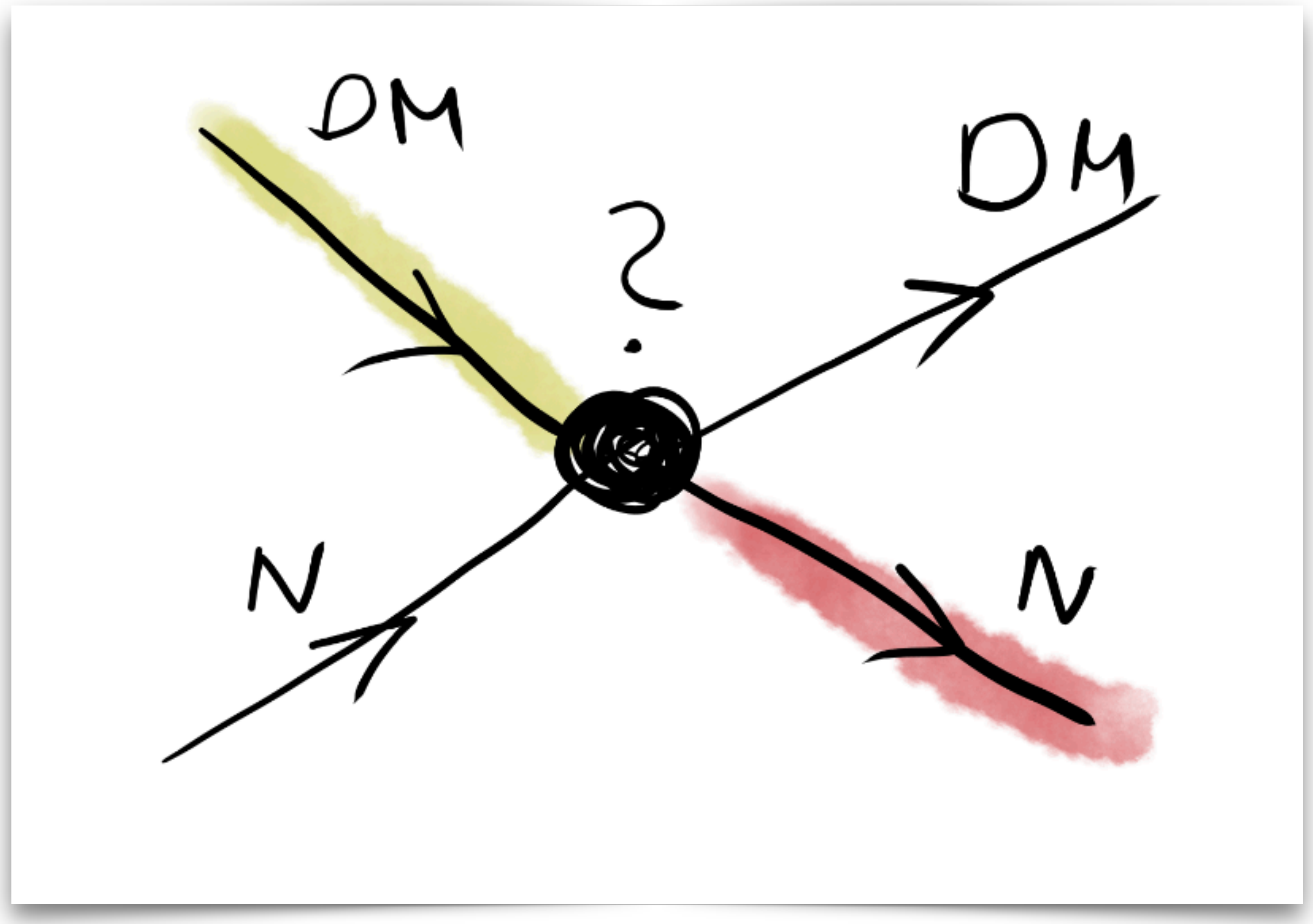


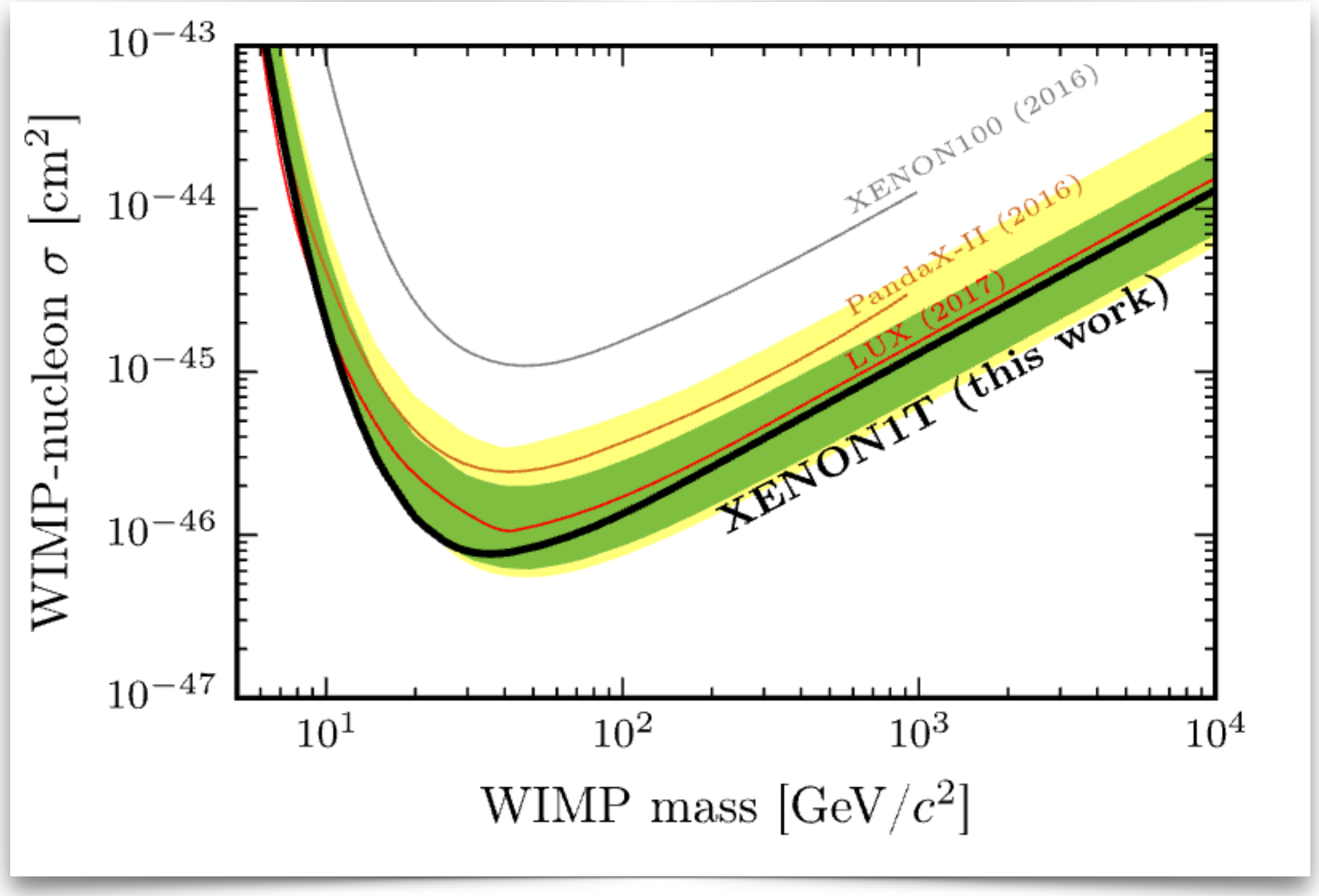
Credit: /https://pdg.lbl.gov/2022/reviews/rpp2022-rev-nu-cross-sections.pdf

* We will have lectures in TP1 on neutrino physics later.

Dark Matter

- Dark matter are hypothetical particles, we do not know the cross section
- From cosmological evidence, we know that the cross section with normal matter must be very small
- We have determined upper limits for cross sections, i.e. maximal values, that are even smaller than for neutrinos
- For all collider experiments, the probability to see a dark matter interaction, can safely be assumed to be zero*





Credit: Phys. Rev. Lett. **119**, 181301 (2017)

* We will have lectures in TP1 on dark matter physics later.

What questions do you have?