Fundamentalne interakcije

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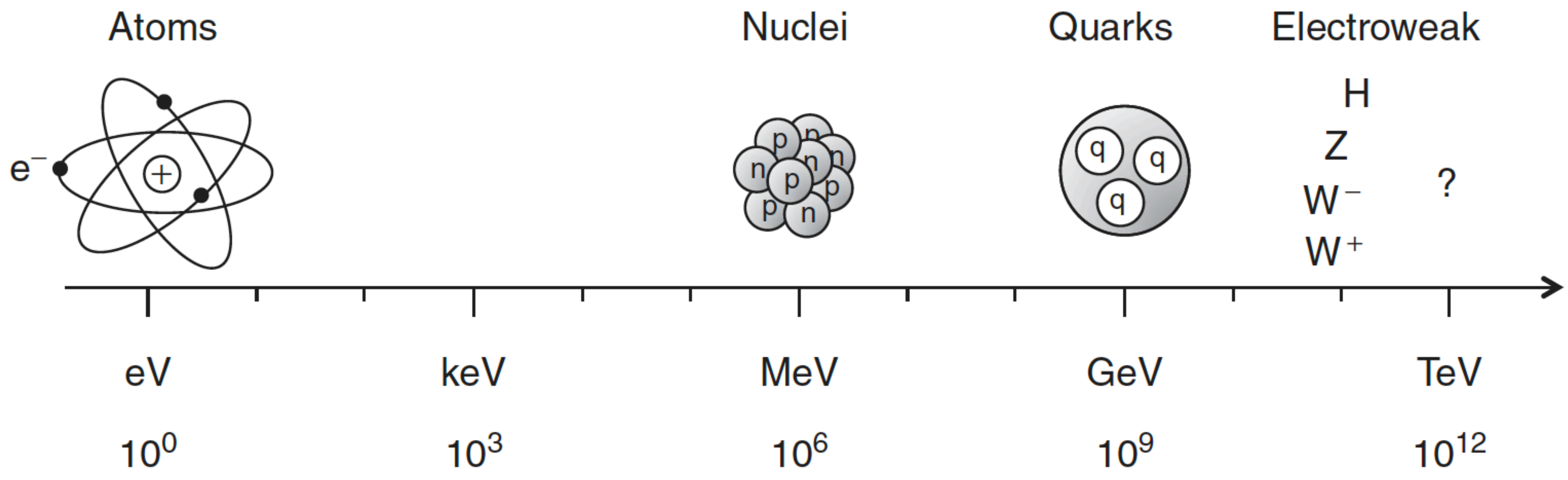
- TEXT

STANDARDNI MODEL

- Standardni model elementarnih čestica objedinjuje sva naša trenutna znanja o elementarnim česticama i fundamentalnim interakcijama medju njima. Fundamentalne interakcije se opisuju izmenom čestica prenosilaca interakcije.
- Zadivljuće SM uspešno upside sve dosadašnje eksperimentalne podatke
- Često se ističe da SM predsravlja trijumf moderne fizike.

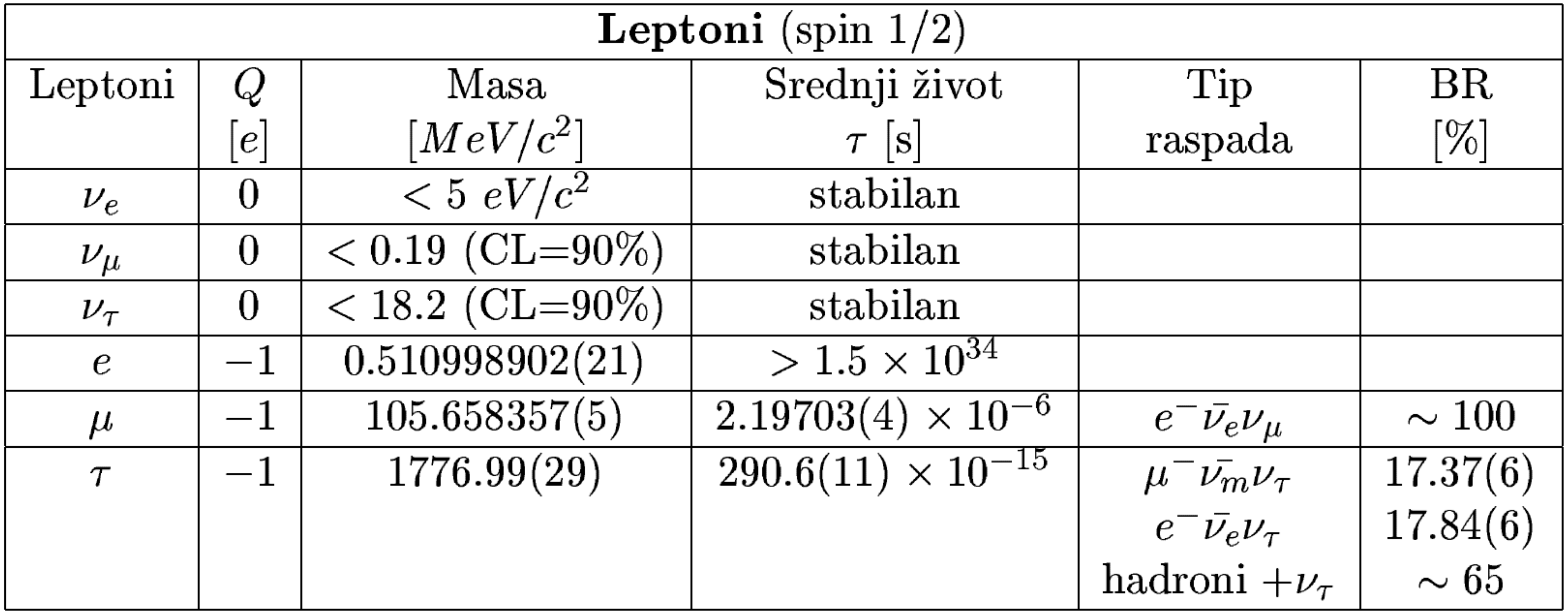
STANDARDNI MODEL KAO EFEKTIVNA TEORIJA



The Universe at different energy scales, from atomic physics to modern particle physics at the TeV scale.

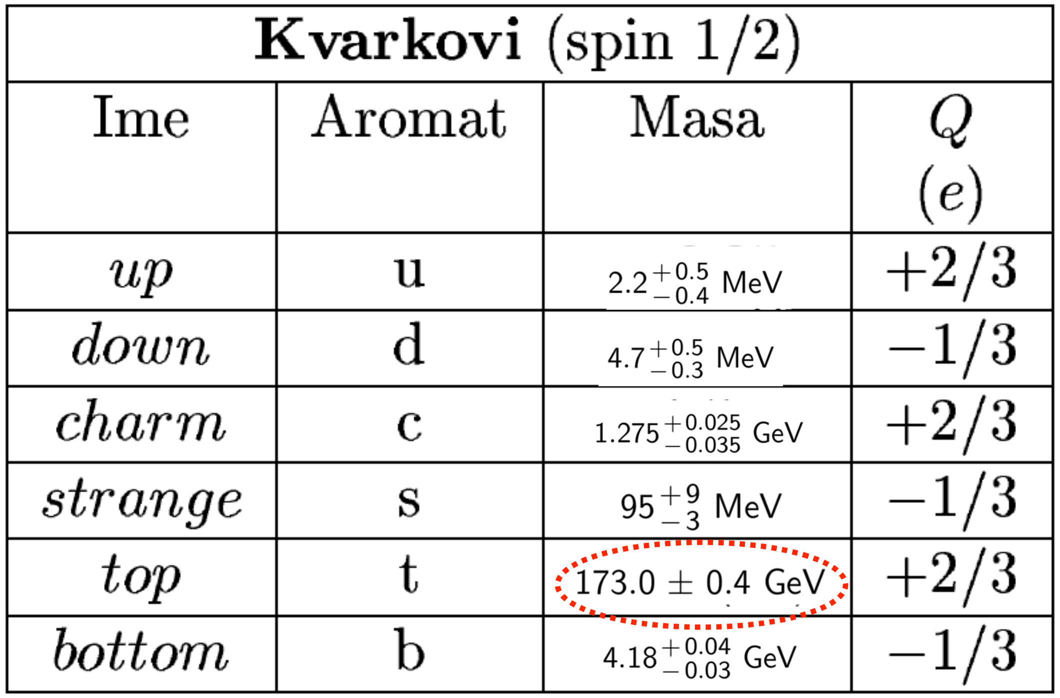
- U principopu zadatak fizzle je da obezbedi efektivan matametički opis fizičkog sistema za odgovarajuću energetsku skalu koja se razmatra (*energy scale*)
  - Fundamentalnma teorija elektromagnetizma je kvantna elektrodinamika (*Quantum Electrodynamics, QED*).
  - Fundamentalna teorija jakih interkazija je kvantna hromodinamika (*Quantum Chromodynamics, QCD*).
  - Fundamentalne interakcije upotpunjuje opis slabih interakcija
  - Gravitacviona interakcija je veoma slaba, ali uvek privlačna, nema značaja u mikrosvetu

FERMIONI (ČESTICE MATERIJE)



Leptoni (spin 1/2)

Leptoni	Q [e]	Masa $[MeV/c^2]$	Srednji život τ [s]	Tip raspada	BR [%]
ν_e	0	$< 5\ eV/c^2$	stabilan		
ν_μ	0	$<$ 0.19 (CL=90%)	stabilan		
ν_τ	0	$<$ 18.2 (CL=90%)	stabilan		
e	-1	0.510998902(21)	$> 1.5 \times 10^{34}$		
μ	-1	105.658357(5)	$2.19703(4) \times 10^{-6}$	$e^- \bar{\nu}_e \nu_\mu$	~ 100
τ	-1	1776.99(29)	$290.6(11) \times 10^{-15}$	$\mu^- \bar{\nu}_m \nu_\tau$	17.37(6)
				$e^- \bar{\nu}_e \nu_\tau$	17.84(6)
				hadroni $+\nu_\tau$	~ 65



Kvarkovi (spin 1/2)

Ime	Aromat	Masa	Q (e)
up	u	$2.2^{+0.5}_{-0.4}$ MeV	$+2/3$
down	d	$4.7^{+0.5}_{-0.3}$ MeV	$-1/3$
charm	c	$1.275^{+0.025}_{-0.035}$ GeV	$+2/3$
strange	s	95^{+9}_{-3} MeV	$-1/3$
top	t	173.0 ± 0.4 GeV	$+2/3$
bottom	b	$4.18^{+0.04}_{-0.03}$ GeV	$-1/3$

FERMIONI (ČESTICE MATERIJE, 2)

I familija	II familija	III familija
ν_e	ν_μ	ν_τ
e	μ	τ
u	c	t
d	s	b

- Postoje jaki eksperimentalni dokazi da postoje samo tri generacije fermiona. Sva materija u univerzumu se sastioji od 12 čestica spina 1/2

- Jako se zna da neutrino nisu bezmasena, njihiove mase su toliko male da ih je teško eksperimtalno utvrditi

- Mase čestica u okviru jedne familije su bliske, ali *hijerarhija masa* nije objašnjenja do danas.

- Dinamika fundamentalnih fermions je opisana relativističkom Dirakovom jenačinom, jedna od posledica Dirakove jednačine da svaki od 12 fermions ima soju antičesticu kola ima identičnu masu, Ali suprotan zany naelektrisanja.

FERMIONI (ČESTICE MATERIJE, 3)

- Čestice interaguju jedna sa drugom kroz četiri interakcije: ***gravity***, ***electromagnetism***, the ***strong force*** and the ***weak force***.
  - Gravitaciona sila je toliko slaba da može biti zanemarne u SM.
- Svih 12 fudamentalnih fermiona nosi naboj ***weak isospin*** te stoiga interaguju ***slabom interakcijom.***
- See neutrina, ski fermions su ***naelektrisani*** te podležu elektromagnetnim interkcijama prema ***QED.***
- Same kvarkovi image ***naboj bone (colour)*** te stog interaguju ***jakom interakcijom***
- Used osobina ***QCD*** interakcija, kvarkovi ne postoje kao slobodne čestice, veće se javljaun u svojim veznaim stanjima ***hadronima***.

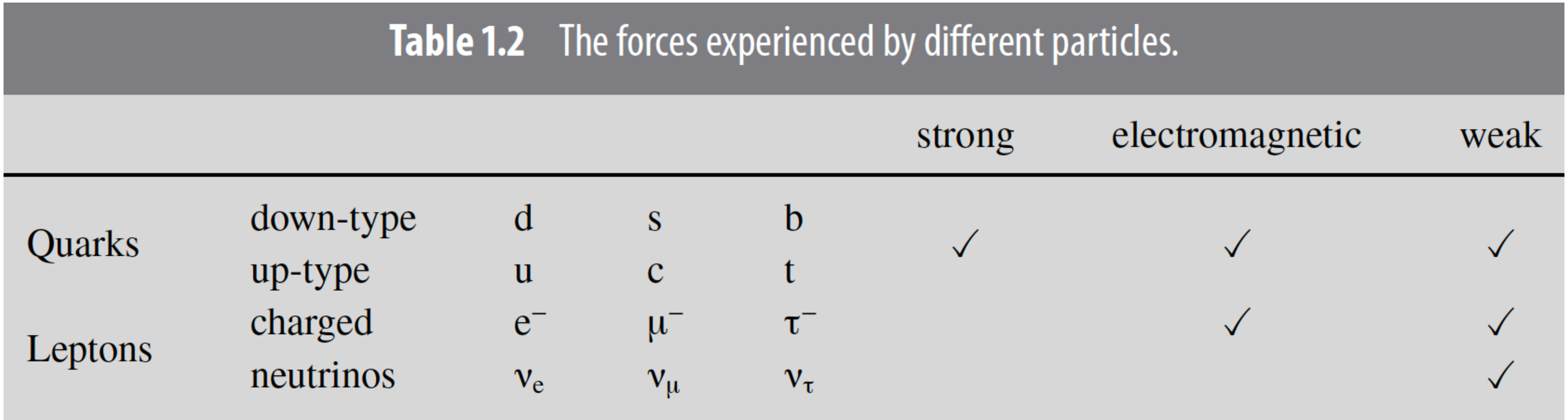
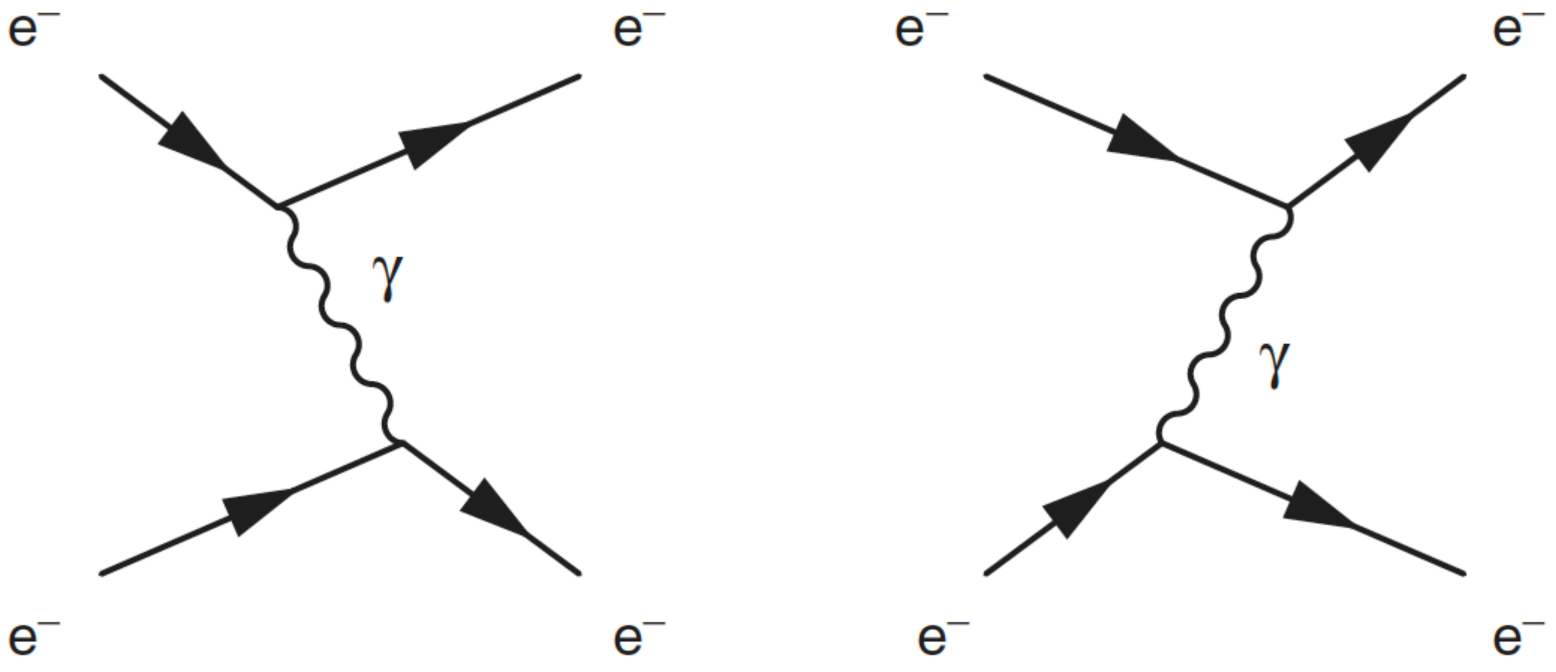


Table 1.2 The forces experienced by different particles.

					strong	electromagnetic	weak
Quarks	down-type	d	s	b	✓	✓	✓
	up-type	u	c	t			
Leptons	charged	e^-	μ^-	τ^-		✓	✓
	neutrinos	ν_e	ν_μ	ν_τ			✓

FUNDAMENTALNE INTERAKCIJE

- U modernoj teoriji čestica interakcije se opisuju formalizmom kvantne teorije polja (*Quantum Field Theory, QFT*).
- U QED interakcije izmedju naelektrsanih čestica se obavlja izmenom ***virtuelnih*** fotona.



- Na dijagramu levo gornji elektron emituje foton a donji ga apsorbuje. Impuls se transferiše sa jednog na drugi elektron i taj transfer se manifestuje kao sila -- interakcija. Na dijagramu desno je vremenski redosled drugačiji: donji elektron emituje a gornji apsorbuje foton. <u>Pošto nema nikakve oservorane razmen čestica kombinacija oba dijagrama ima fizičkog smisla.</u>

FUNDAMENTALNE INTERAKCIJE

- QFT opsiuje tri interakcije kroz ***izmenu bozona spina 1 koji su prenosici interakcija***, gradijnetni *gauge* bozoni.
    - ***photon*** je *gauge* bozon u ***QED***.
    - U ***jakim interakcijama***, prenosioci interakcije su ***gluonkoji*** su kao i fotoni bezmaseni. ***Postoji 8 gluona!***
    - Slabe naelektrisane interakcije (***weak charged-current interaction),*** prepose se izmenom naelektrsanih ***W bozona (W^+ and W^-)***, koji su 8 puta teži od protina. Postoje I ***weak neutral-current interaction,*** koje prenose neutralni ***Z^0 bozoni***.
- Jačina interakcija zavisi od rastojanja i energetske skale koja se razmatra.

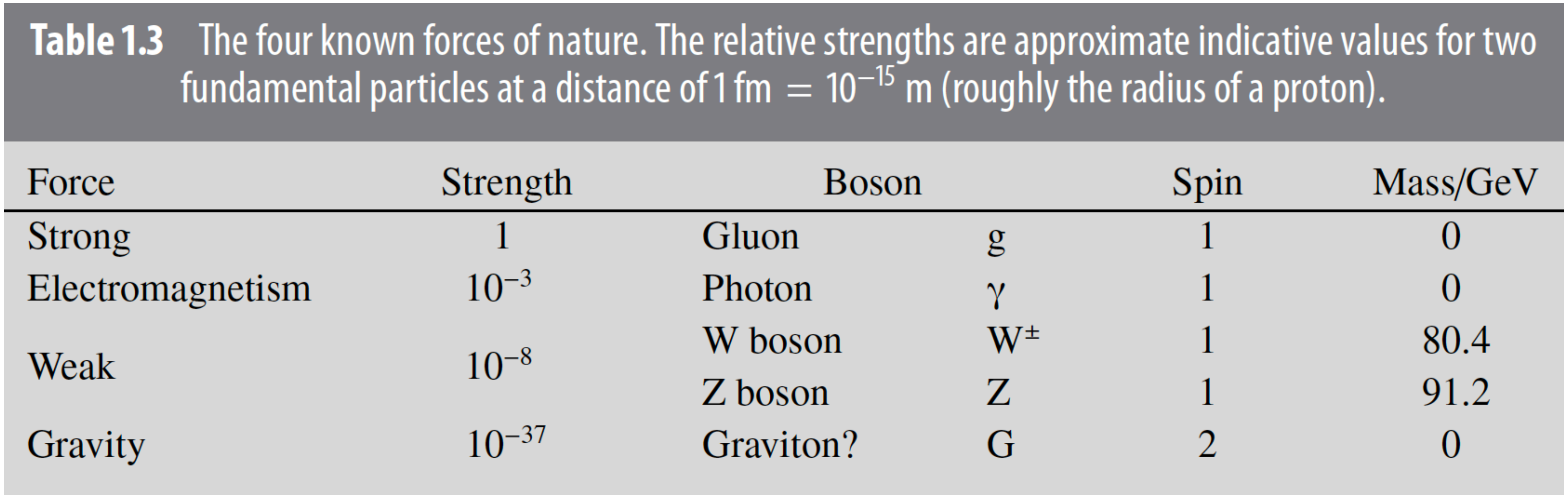
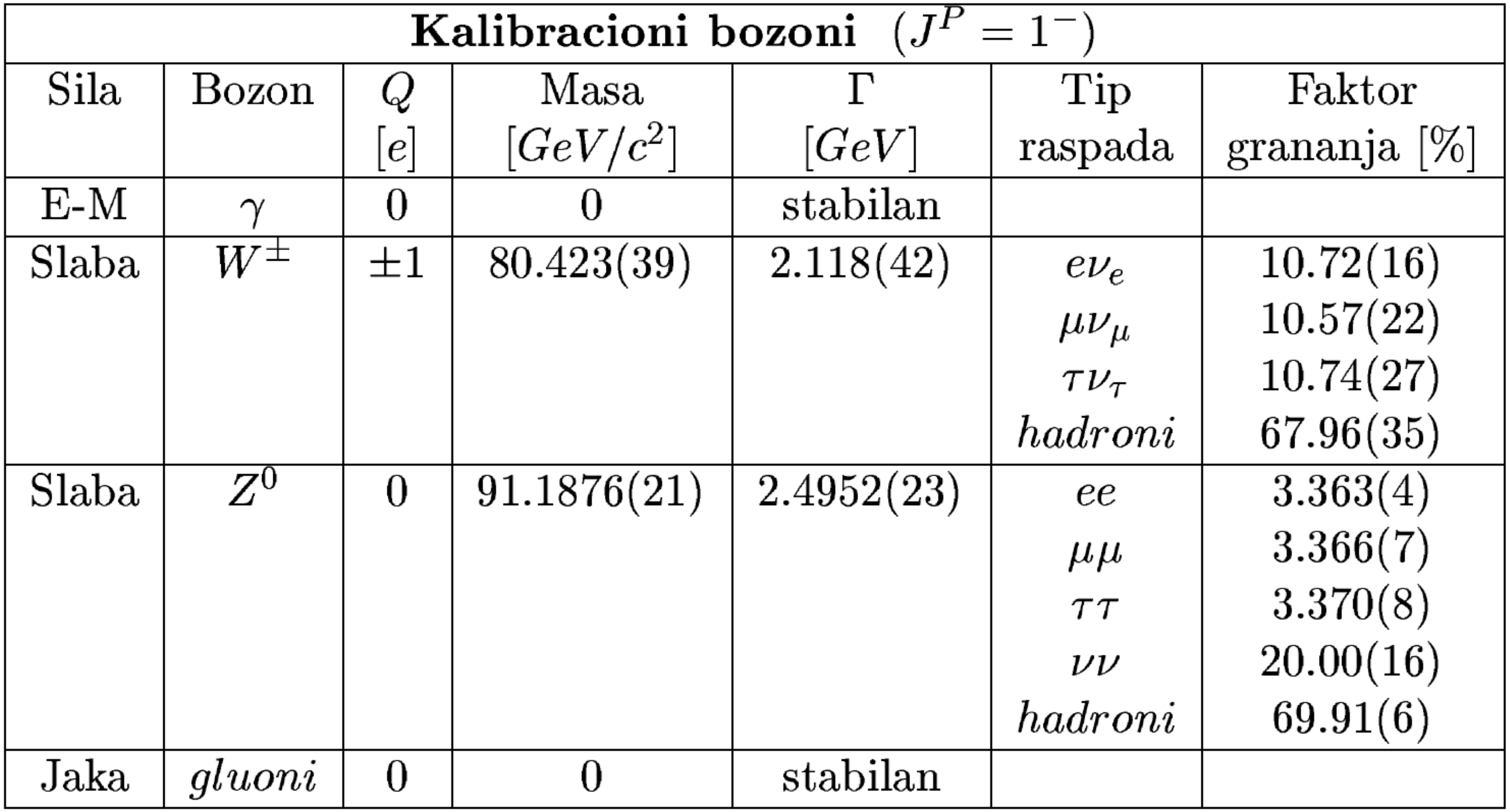


Table 1.3 The four known forces of nature. The relative strengths are approximate indicative values for two fundamental particles at a distance of 1 fm $= 10^{-15}$ m (roughly the radius of a proton).

Force	Strength	Boson		Spin	Mass/GeV
Strong	1	Gluon	g	1	0
Electromagnetism	10^{-3}	Photon	γ	1	0
Weak	10^{-8}	W boson	$W^\pm$	1	80.4
		Z boson	Z	1	91.2
Gravity	10^{-37}	Graviton?	G	2	0

GRADIJENTNI BOZONI



Kalibracioni bozoni ($J^P = 1^-$)

Sila	Bozon	Q [e]	Masa [GeV/c^2]	Γ [GeV]	Tip raspada	Faktor grananja [%]
E-M	γ	0	0	stabilan		
Slaba	$W^\pm$	± 1	80.423(39)	2.118(42)	$e\nu_e$	10.72(16)
					$\mu\nu_\mu$	10.57(22)
					$\tau\nu_\tau$	10.74(27)
					hadroni	67.96(35)
Slaba	Z^0	0	91.1876(21)	2.4952(23)	ee	3.363(4)
					$\mu\mu$	3.366(7)
					$\tau\tau$	3.370(8)
					$\nu\nu$	20.00(16)
					hadroni	69.91(6)
Jaka	*gluoni*	0	0	stabilan		

- Gradijetni, kalibracioni, ***gauge*** bozoni

HIGGS BOZON

- Poslednji element Standardnog modela je Higsov bozon, koji je otkriven eksperimentima ATLAS i CMS na Velikom Hadronskom Kolajderu (LHC) 2012. godine. Higgsov bozon, koji ima masu ***mH ≈ 125 GeV,*** razlikuje se od svih ostalih Standardnih Model čestice. Za razliku od, fundamentalni fermioni i kalibarski bozoni, koji su pojedinačno spin-pol i spin-1 čestice, Higsov bozon je spin-0 skalarna čestica.

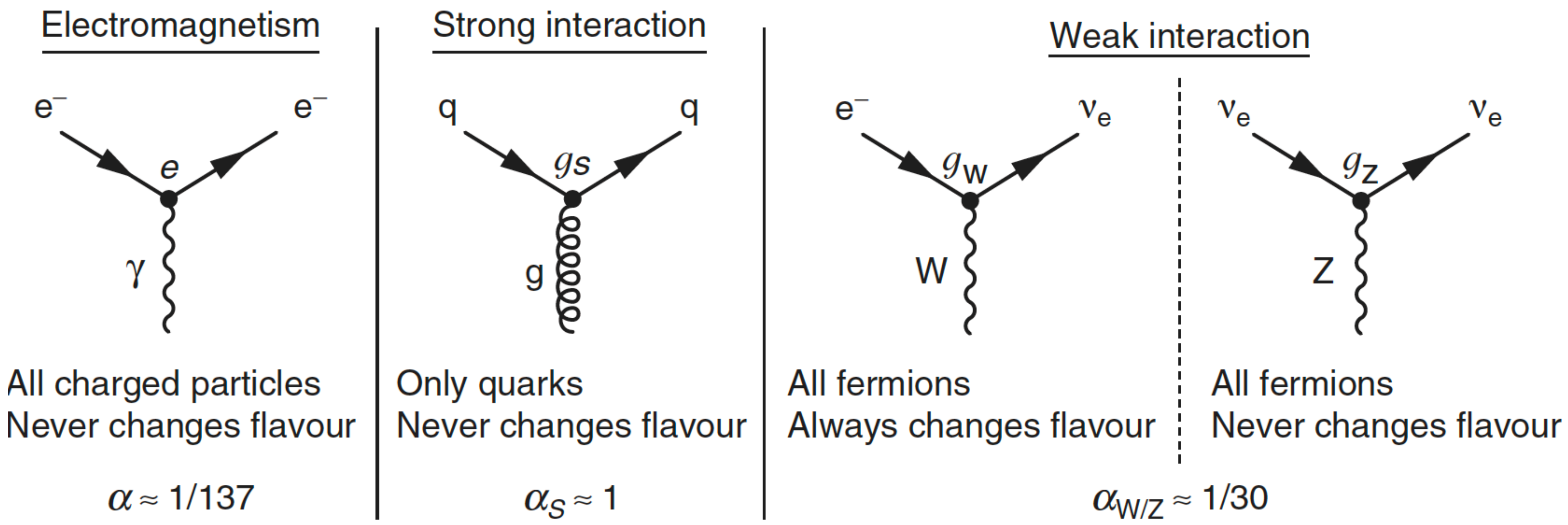
- Kako je zamišljeno u Standardnom modelu, Higsov bozon je jedini fundamentalni skalar koji je do sada otkriven.

- Higsov bozon igra posebnu ulogu u SM; on obezbeđuje mehanizam kojim sve druge čestice stiču masu. Bez nje bi Univerzum bio veoma različit, sve čestice bi bile bez mase i širile bi se brzinom svetlosti! U QFT Higsov bozon se može smatrati ekscitacijom Higsovog polja. Za razliku od polja koja su povezana sa fundamentalnim fermionima i bozonima, koji imaju nultu *ocekivanu vakumsku vrednost*, veruje se da Higsovo polje ima vrednost ne-nultu ocekivanu vev.

- To je interakcija inicijalno bezmasnih čestica sa ovim ne-nultim Higsovim poljem koje im daje svoje mase. Otkriće Higsove čestice na LHC-u predstavljalo je izuzetnu validaciju teorijskih ideja koje čine standardni model.

- Sve mase W^+ ,W^-, Z^0 i H bozona su reda veličine od 100 GeV, što je poznato kao ***elektroslaba energetska skala***. Ovo se ne događa slučajno; u Standardnom modelu, mase slabih mernih bozona su blisko povezane sa Higsovim mehanizmom.

INTERAKCIJE U SM



- Jacina fundamentalne interakcije između kalibarskog bozona i fermiona određena je konstantom spajanja g, koja se može posmatrati kao mera verovatnoće spin-half fermiona koji emituje ili apsorbuje bozon interakcije.

- Preciznije rečeno, kvantno-mehanički element matrice prelaza za proces interakcije uključuje faktor konstante sprege g za svaki interakcijski vertex.

$$\mathcal{M} \propto g^2 \qquad |\mathcal{M}|^2 \propto g^4$$

- U parks se Kristi bezdimenziona kosntatntna, $\alpha \propto g^2$, u elektromagmnetrizmu to je. konstanta fine strukture.

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

QED

INTERAKCIJE U SM

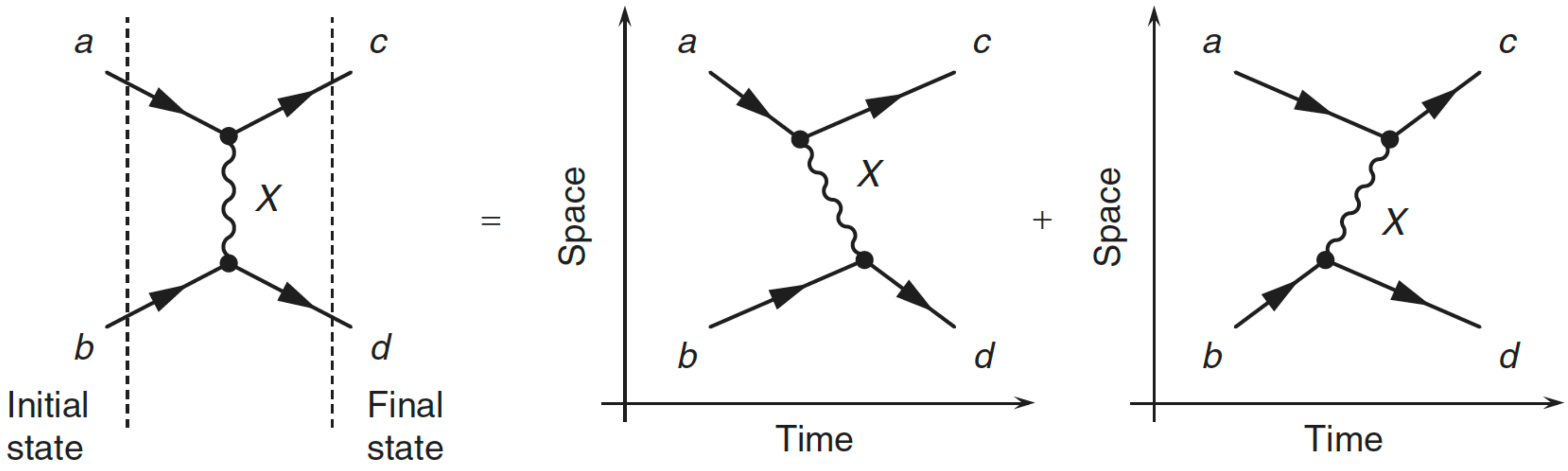
- The nature of the strong, electromagnetic and weak forces are determined by the properties of the bosons of the associated quantum field theory, and the way in which the gauge bosons couple to the spin-half fermions.

- A particle couples to a force-carrying boson only if it carries the charge of the interaction.

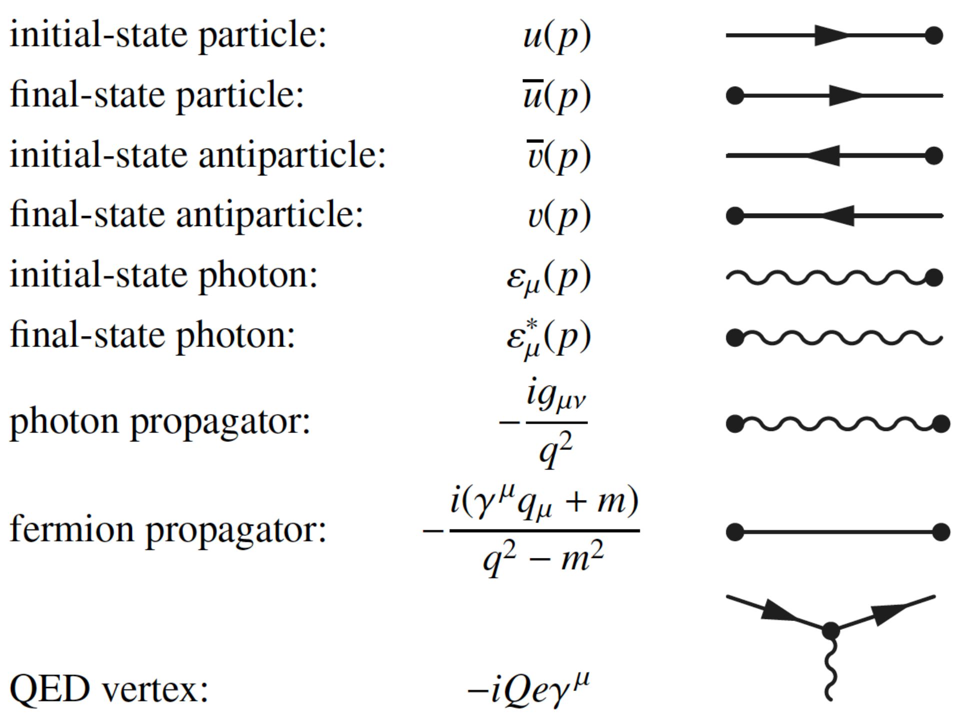
- All twelve fundamental fermions carry the charge of the weak interaction, known as weak isospin, and therefore they all participate in the weak interaction. The weak charged-current interaction does not correspond to the usual concept of a force as it couples together different flavour fermions. Since the W_+ and W_- bosons have charges of +e and –e respectively, in order to conserve electric charge, the weak charged-current interaction only couples together pairs of fundamental fermions that differ by one unit of electric charge. In the case of the leptons, by definition, the weak interaction couples a charged lepton with its corresponding neutrino. Since the weak interaction is the only known force for which the incoming and outgoing fermions are different, the weak charged current interaction is particularly important when considering particle decays as it introduces a change of flavour.

- The intrinsic strength of the electromagnetic interaction is given by the size of fine-structure constant $\alpha = 1/137$. The QCD interaction is intrinsically stronger with $\alpha_s \sim 1$. The intrinsic strength of the weak interaction, with $\alpha_W \sim 1/30$, is in fact greater than that of QED. However, the large mass of the associated W boson means that at relatively low-energy scales, such as those encountered in particle decays, the weak interaction is (as its name suggests) very much weaker than QED.

FEJNMANOVI DIJAGRAMI

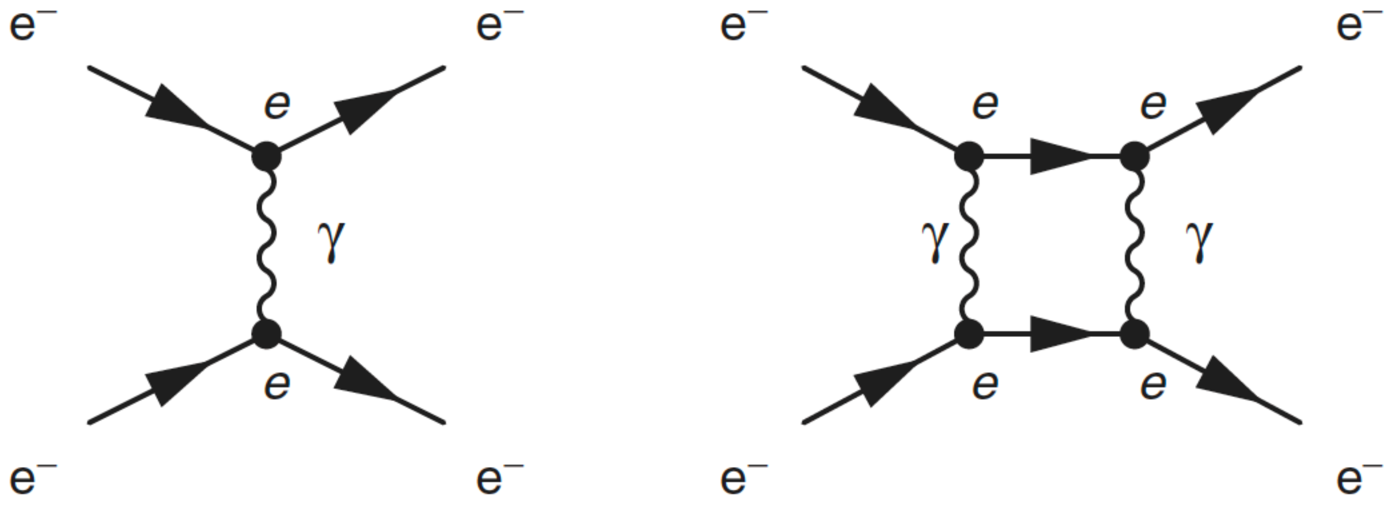


- Feynman diagrams are much more than a pictorial representation of the fundamental physics underlying a particular process. From QFT it is possible to derive simple Feynman rules associated with the vertices and virtual particles in a Feynman diagram. Once the Feynman diagram has been drawn, it is straightforward to write down the quantum-mechanical transition matrix element using the relevant Feynman rules.



initial-state particle:	$u(p)$
final-state particle:	$\overline{u}(p)$
initial-state antiparticle:	$\overline{v}(p)$
final-state antiparticle:	$v(p)$
initial-state photon:	$\varepsilon_\mu(p)$
final-state photon:	$\varepsilon^*_\mu(p)$
photon propagator:	$-\frac{ig_{\mu\nu}}{q^2}$
fermion propagator:	$-\frac{i(\gamma^\mu q_\mu + m)}{q^2 - m^2}$
QED vertex:	$-iQe\gamma^\mu$

FEJNMANOVI DIJAGRAMI



$$|\mathcal{M}_{\gamma}^{2}| \propto \alpha^{2} \quad \text{and} \quad |\mathcal{M}_{\gamma\gamma}^{2}| \propto \alpha^{4}$$

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar} |\ M\ |^{2} \rho(E)$$

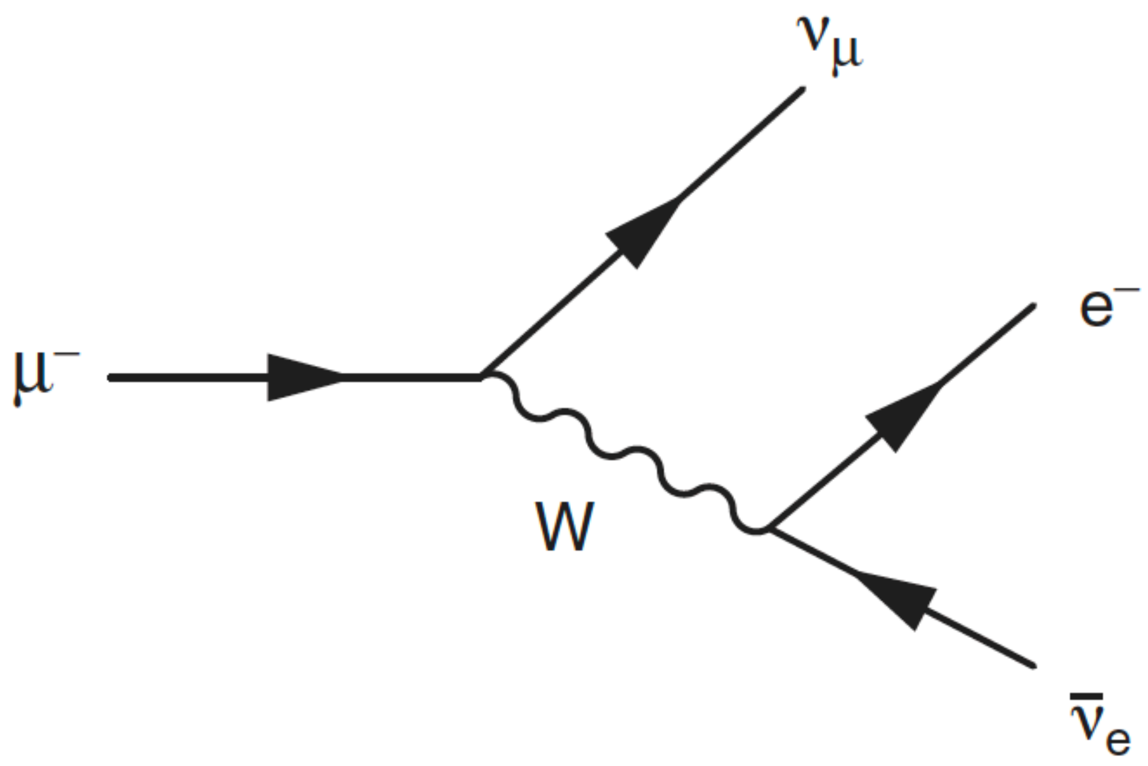
$$\sigma_{i\to f} = \frac{\Gamma_{i\to f}}{v}$$

- In general, for each process considered, there will be an infinite number of Feynman diagrams that can be drawn. Both diagrams have the same initial and final state, and therefore correspond to the same physical process, ee→ee. Each interaction vertex is associated with a factor e in the matrix element, or equivalently a factor of α in the matrix element.

- Because the coupling strength of the electromagnetic interaction is relatively small, α ~ 1/137, the diagram with four vertices is suppressed by a factor $O(10^4)$ relative to the diagram with two vertices. In the language of perturbation theory, only the lowest-order (Leading Order - LO) term is significant.

RASPADI ČESTICA (I)

- Most particles decay with a very short lifetime. Consequently, only the relatively few stable and long-lived types of particle are detected in particle physics experiments.
- There are twelve fundamental spin-half particles (and the twelve corresponding antiparticles), but they are not **all** stable. For a particle to decay there must be a final state with lower total rest mass that can be reached by a process with a Feynman diagram constructed from the Standard Model vertices. Decays of the fundamental particles all involve the weak charged current which has the only interaction vertex that allows for a change in flavour.



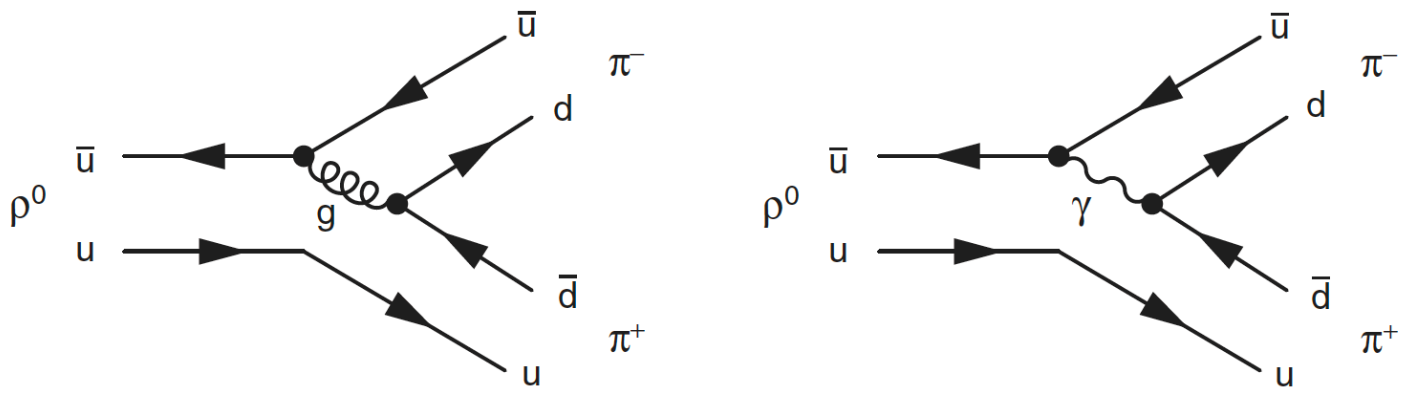
RASPADI ČESTICA (2)

- Because of the nature of the QCD interaction, quarks are never observed as free particles but are always found confined in bound states, known as hadrons. Consequently their decays need to be considered in the context of these bound states. The only hadronic states that have been observed to date, are the mesons which consist of a quark and an antiquark (qq), the baryons which consist of three quarks (qqq), and the antibaryons consisting of three antiquarks (q q q).

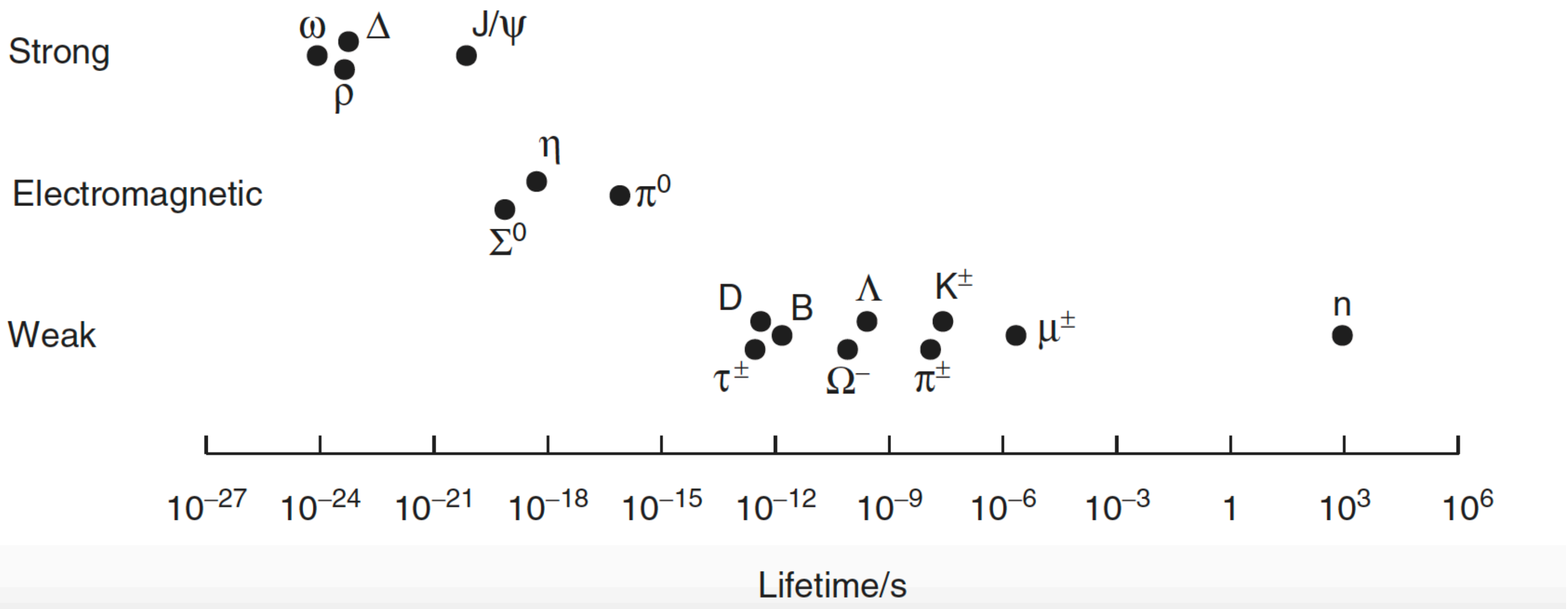
- Many hadronic states have been observed. The only stable hadron is the proton, which is the lightest system of three quarks with m_p = 938.3MeV. As a free particle, the neutron with mass m_n = 939.6MeV, decays with a lifetime of about 15 min via the weak interaction process n→p $e_- \nu_e$. Although a free neutron can decay, when bound within a nucleus, the change in nuclear binding energy is usually larger than the proton– neutron mass difference, and under these circumstances the neutron behaves as a stable particle. All other hadronic states decay, usually very rapidly.

RASPADI ČESTICA (3)

- Whilst particle decay rates depend on a number of factors, the most important is the type of fundamental interaction involved in the decay. For example, Feynman diagrams for the decay of the ρ_0 meson, $\rho_0 \to \pi_+\pi_-$. The first diagram is a strong decay involving the exchange of a gluon. The second diagram is an electromagnetic process. Because α_s is two orders of magnitude greater than α, the contribution from the strong decay Feynman diagram dominates.
- Because many particles have very short lifetimes, only their decay products are observed in particle physics experiments.



Two possible Feynman diagrams for the decay $\rho^0 \to \pi^+\pi^-$.



RASPADI ČESTICA (4)

- U uzorku od N čestica nekog tipa, broj koji se raspada u atom vremenu δt je dat sumom raspadnutih čestica u svakom *kanalu rasapada (decay channel)*:

$$\delta N = -N\Gamma_1 \delta t - N\Gamma_2 \delta t - \cdots = -N \sum_j \Gamma_j \delta t = -N\Gamma \delta t,$$

- Totalna brzina raspada Γ je suma individualnih bzrina raspada (za svaki kanal rasapada),

$$\Gamma = \sum_j \Gamma_j.$$

- Brij preostalih čestica dat je dobro poznatim eksponencijalnim zakonom:

$$N(t) = N(0)\, e^{-\Gamma t} = N(0)\, \exp\left(-\frac{t}{\tau}\right)$$

- Gde je τ vreme raspada u system mirovanja čestice (proper lifetime) i povezano je sa totalnom brzin raspada:

$$\tau = \frac{1}{\Gamma}.$$

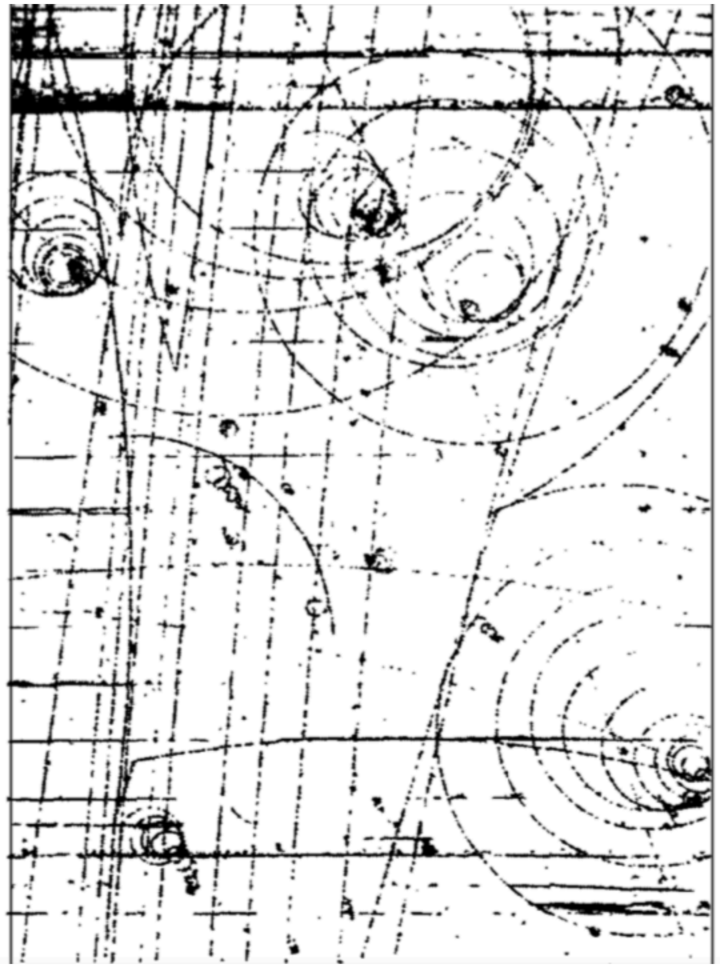
- Relativna frekvenca odvijanja konkretnog kanala raspada naziva se factor granjanja *(branching ratio ,branching fraction)*. Factor granjanja kanala raspada *j*, BR(j) je onda:

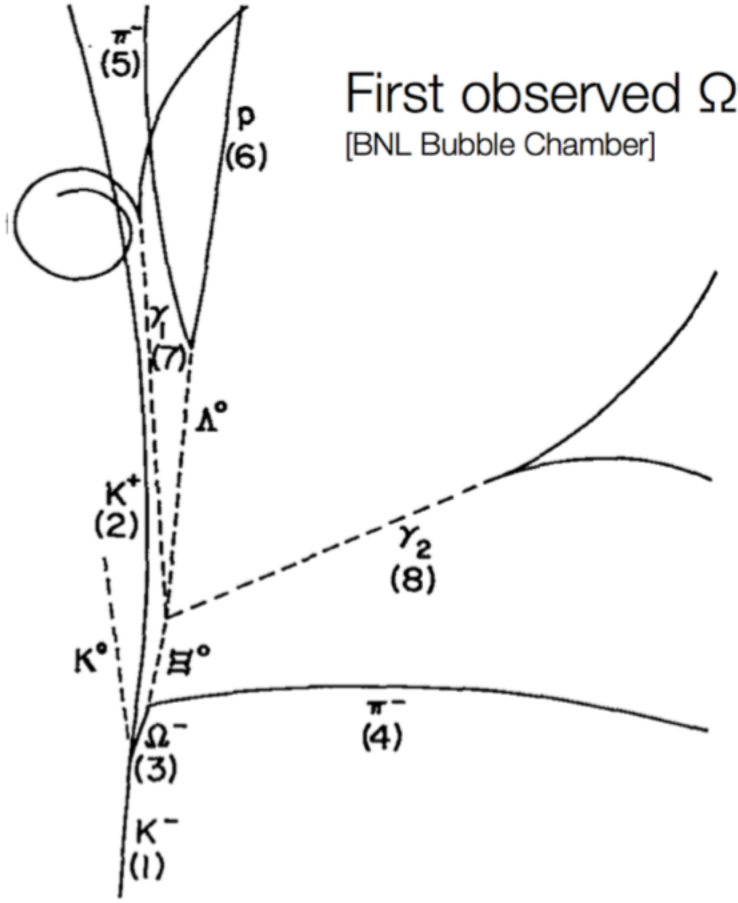
$$BR(j) = \frac{\Gamma_j}{\Gamma}.$$

DETEKCIJA

DETEKTOR ČESTICA

- Uredjaj koji:
  - Detektuje čestice koje prolaze kroz materijal detektora
  - i/ili lokalizuju te čestice u prostor-veremenu
  - i/ili izmeri impulse ili energije tih čestica
  - i/ili identifikuju čestice (na osnovu raznih tehnika: vreme preleta, skretanja u mag, polju …)

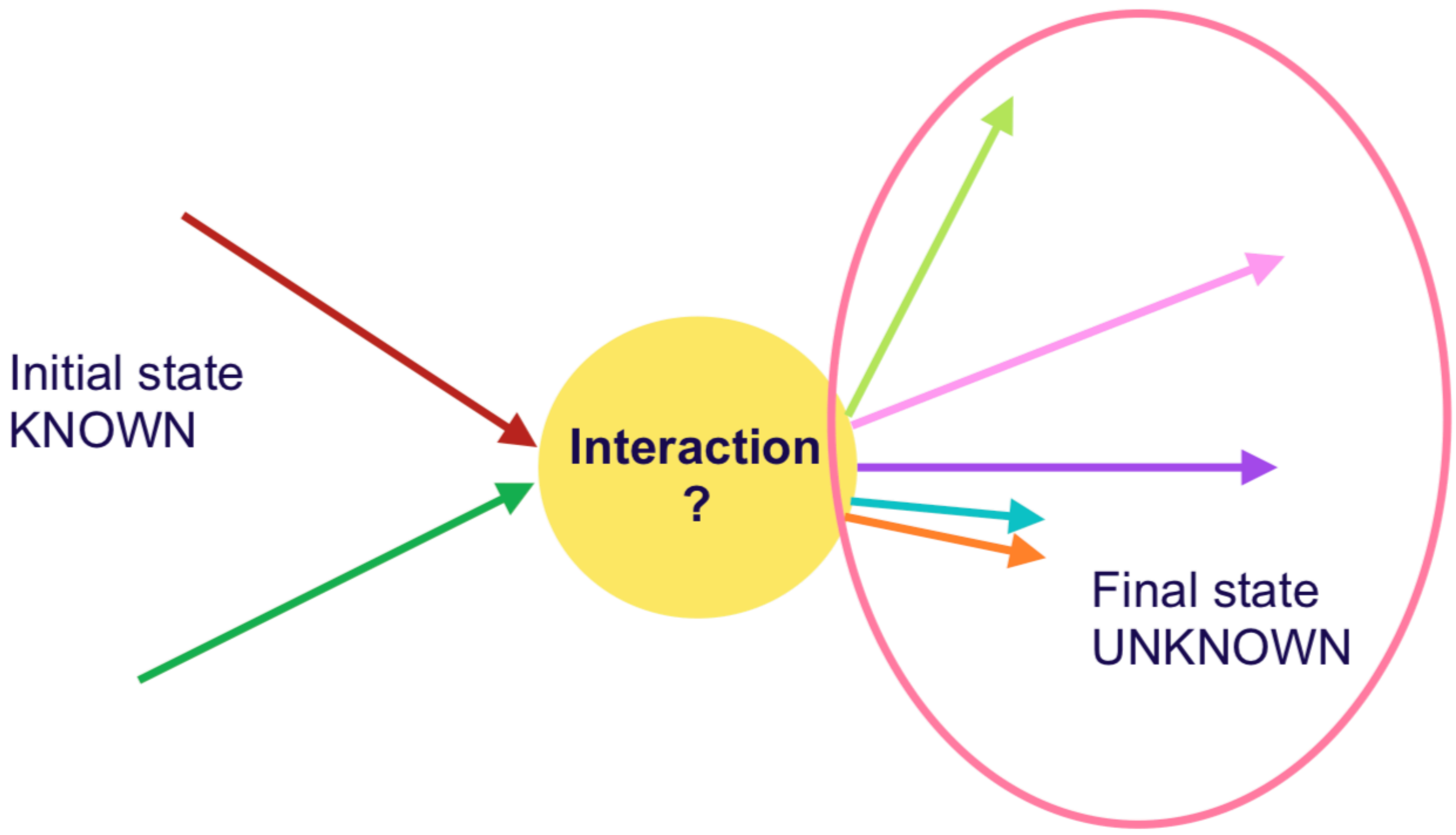




First observed Ω^- event

[BNL Bubble Chamber]

DETEKTOR ČESTICA (2)



- Zadatak detektora je da ***zabeleže*** tj. ***izmere konačna stanja*** kako bi fizičari interpretirali ***prirodu inetrakcije***

- Mali broj čestica je stabilan: elektron, proton, fotoni i efektivni nedetktabilni neutrini.
  - Nestabilne čestice putuju $\gamma v \tau$, τ srednje vreme života.
  - Relativističke čestice sa $\tau > 10^{-10}$s propagiraju ~ nekoliko metara: mioni μ, neutron n(ddu), naelektrisani pioni i kaoni.
  - Ostale čestice se mogu identfikovati samo kroz identifikaciju njihovih produkata raspada.

KAKO IZMERITI OSOBINE ČESTICA

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 ...]

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

Particle Identification via measurement of

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

Relativistic kinematics:

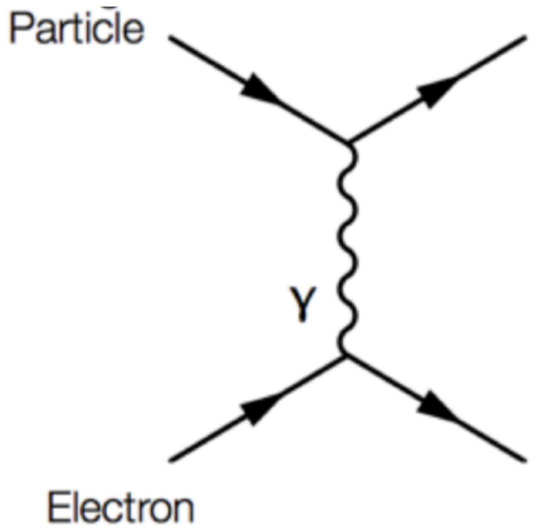
$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

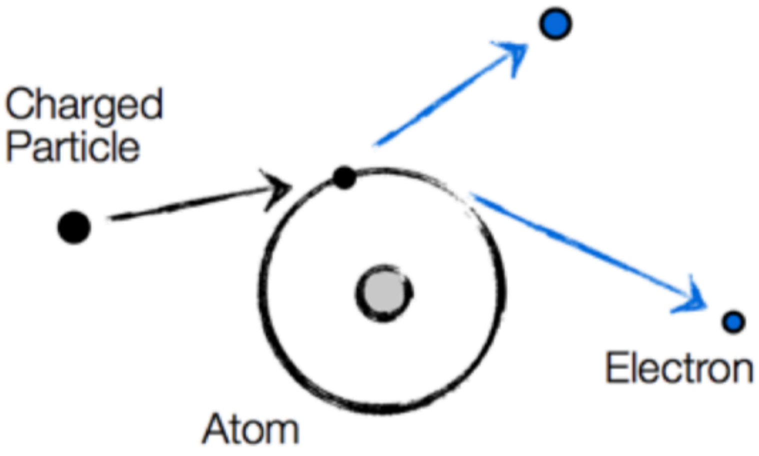
$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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

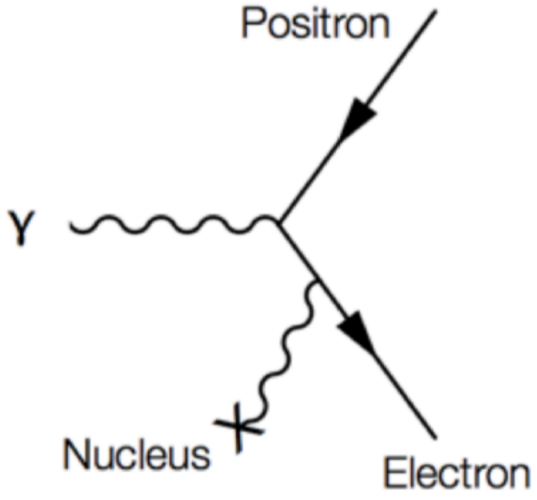
PRIMERI INTERAKCIJA ČESTICA SA MATERIJOM

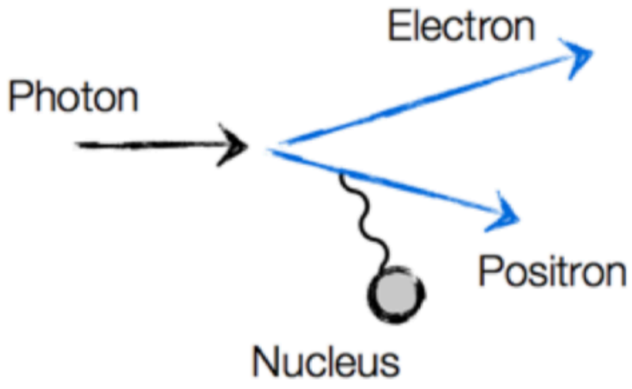
Jonizacija



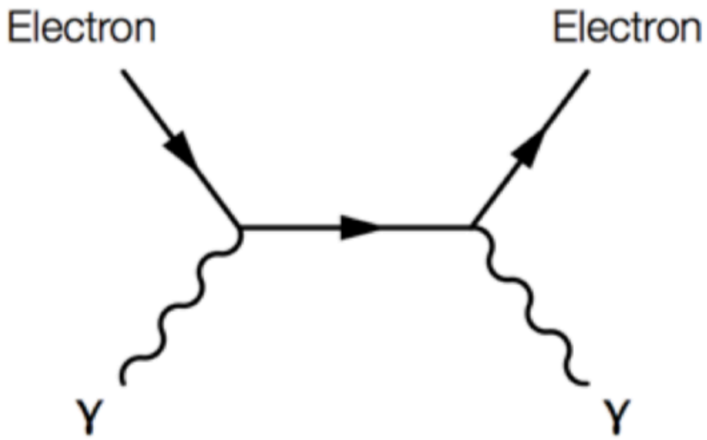


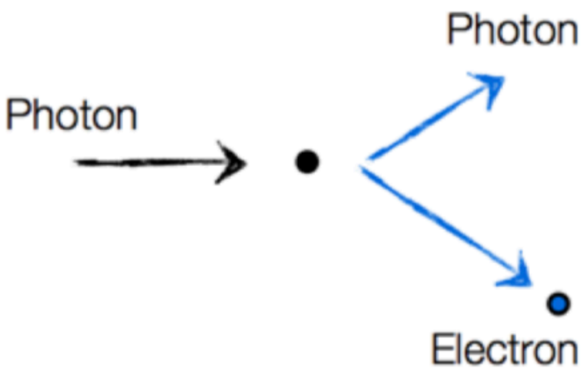
Zakočno zračenje





Komptonovo rasejanje





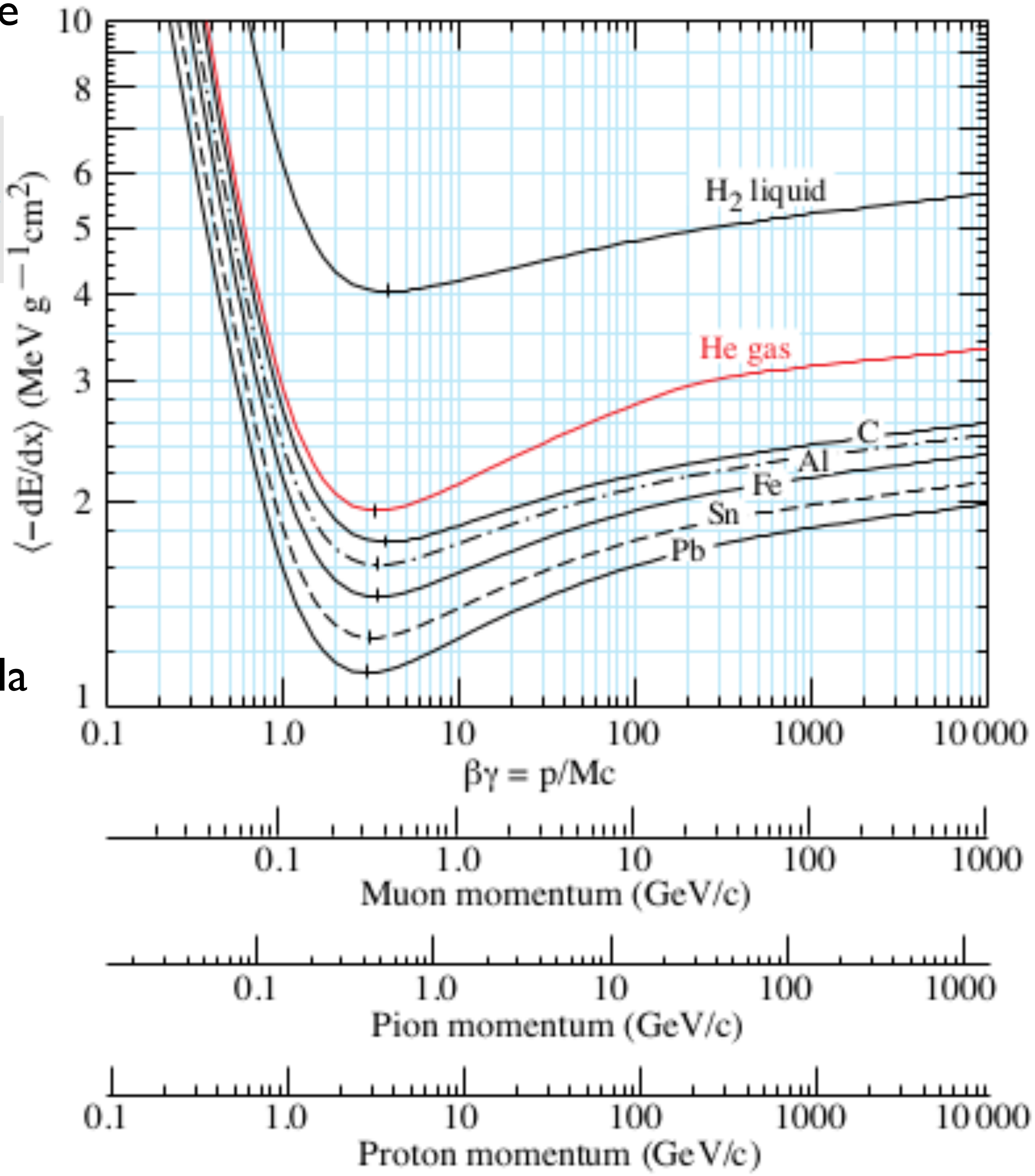
INTERAKCIJA I DETEKCIJA NAELEKTRISANIH Č.

- Bete-Blohova formula za jonizacione gubitke naelektrisanih čestica kroz materiju

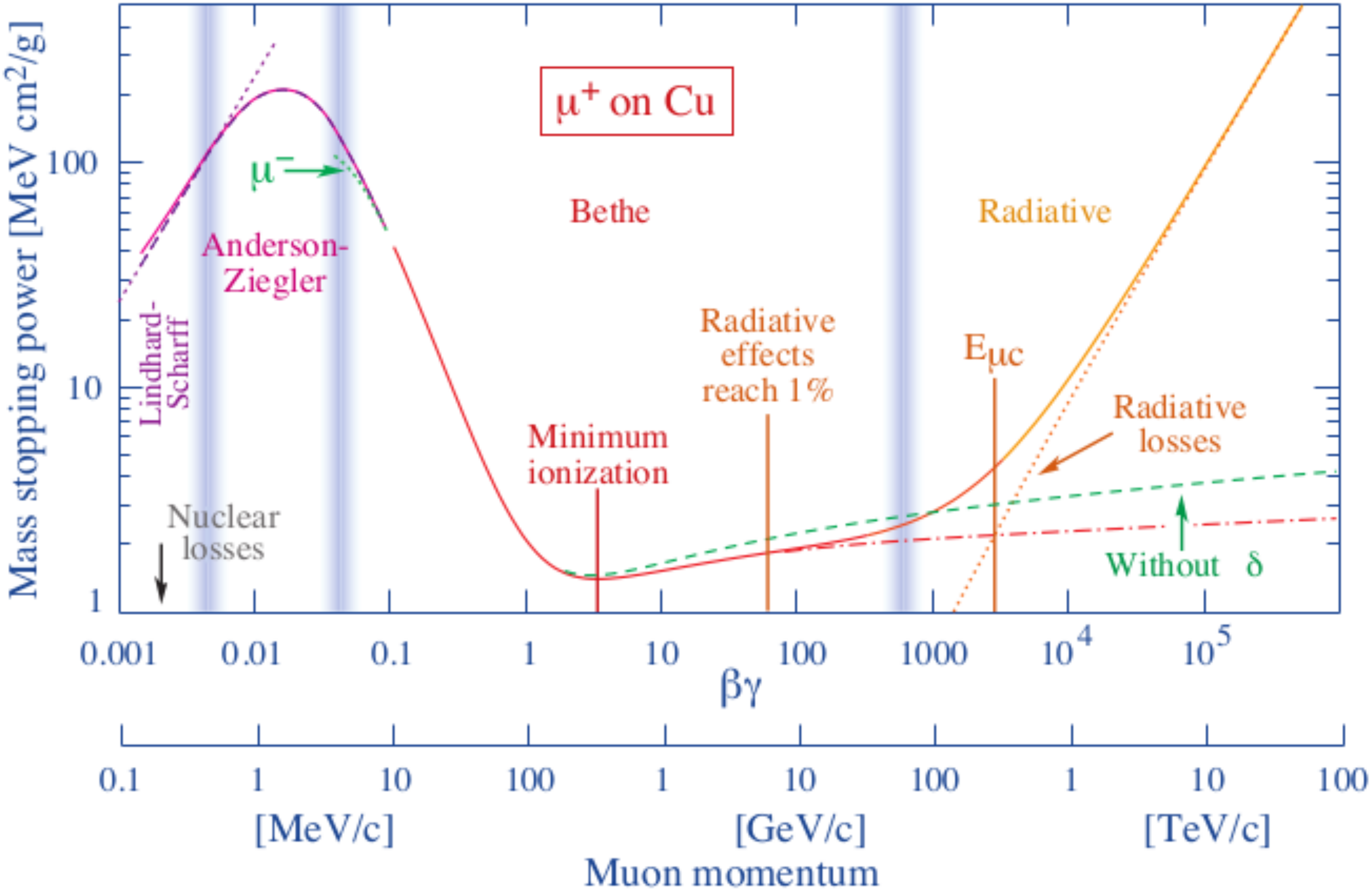
$$\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} \approx -\frac{4\pi\hbar^2c^2\alpha^2}{m_e v^2 m_u}\frac{Z}{A}\left\{\ln\left[\frac{2\beta^2\gamma^2 m_e c^2}{I_e}\right]-\beta^2\right\}$$

$n=\rho/(Am_u)$, $I_e \sim 10\,Z\,\mathrm{eV}$

- Spore čestice gebe najviše energije
- Moderni deteriori uglavnom rade sa relativističkim česticama
- Z/A ~konstantno, slaba zavisnost od materijala
- Minimum Ionising particles (MIP) p~3M
- Gubitak energije je srednja vrednost za dati materijal
  - U osnovi stohastički proces, fluktuacije mogu biti opisane različitim raspodelama
  - Mali transferi verovatniji.



INTERAKCIJA I DETEKCIJA MIONA

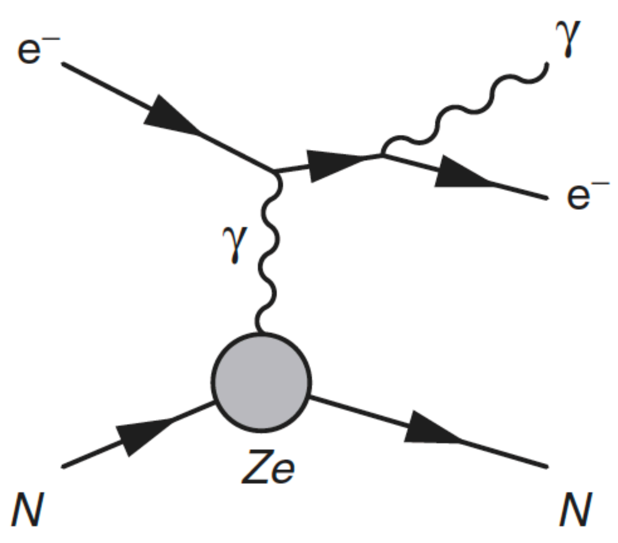


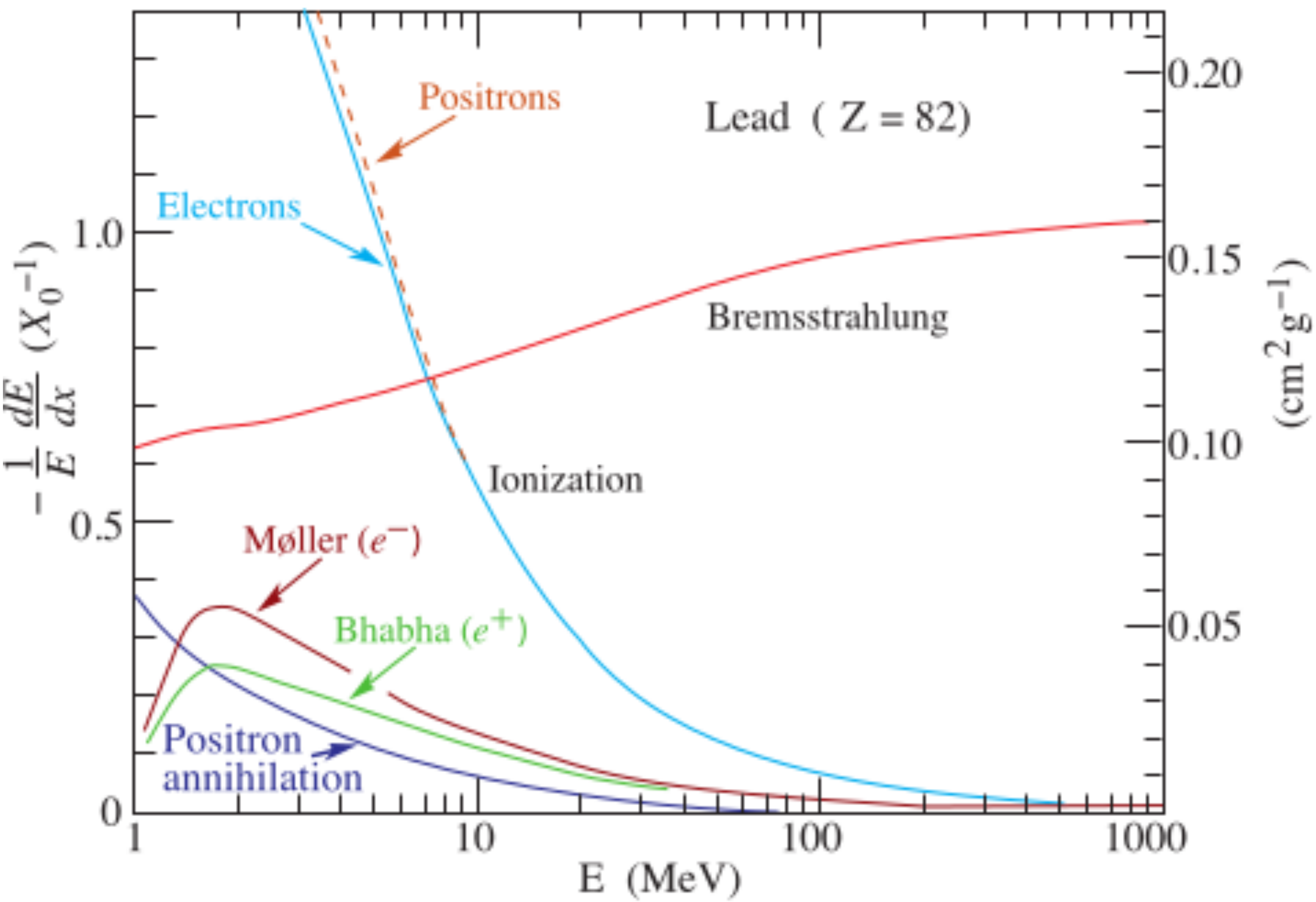
- Mioni do 100 GeV dominant gube energiju kroz jonizaciju
- Posledični mioni proizvedeni na akecelarorskim ekesperimetima prelaze ceo detektor uz male gubitke kroz proces jonizaciju.

INTERAKCIJA I DETEKCIJA ELEKTRONA

- Iznad kritične energuje glavni mehanizam gubitaka je *bremsstrahlung*

$$E_c \sim \frac{800}{Z}\,\mathrm{MeV}$$



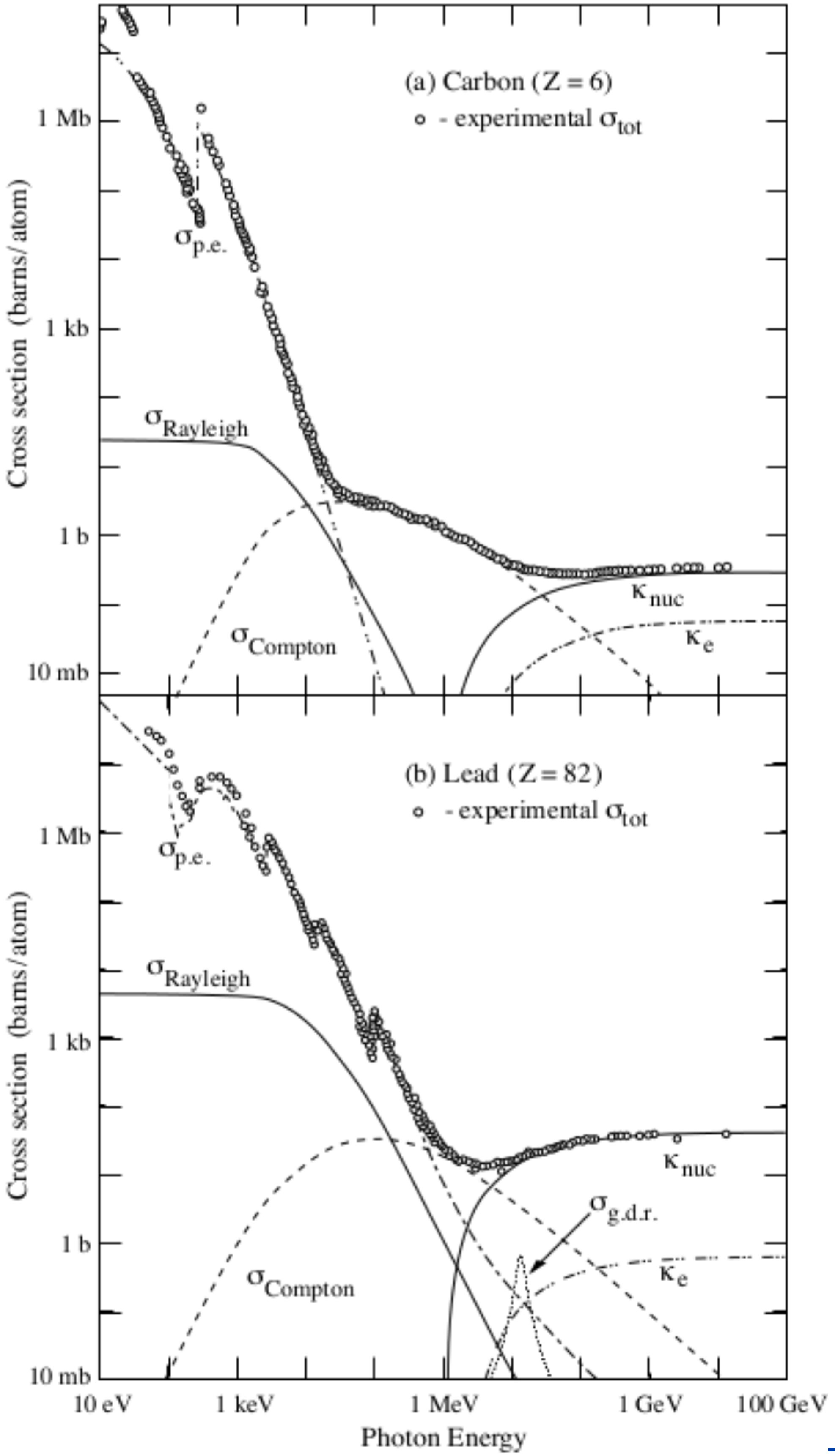


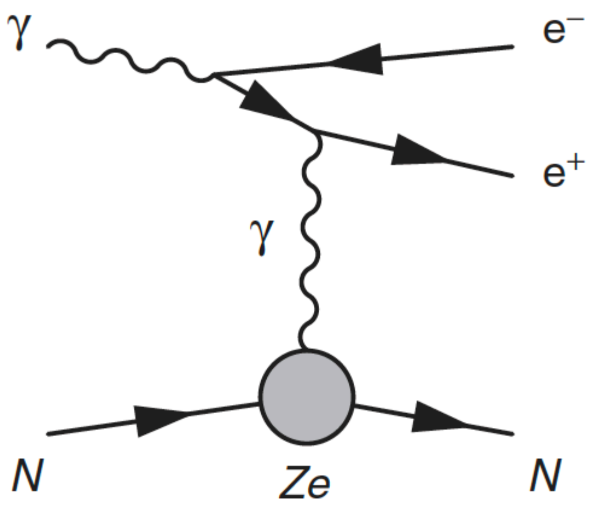
- Interakciona dužina, X_0, karakteriše gubitke elektrona usled elektromagnetnih inetrakcija: ona predstavlja rastojanje nakon koga elektron izgubi svu energiju osim 1/e.

$$X_0 \approx \frac{1}{4\alpha n Z^2 r_e^2 \ln\left(287/Z^{1/2}\right)}$$

- Molijerov radijus opisuje prosečno radijalno odstupanje elektrona kritične energije nakon predjenog puta X_0

INTERAKCIJA I DETEKCIJA FOTONA



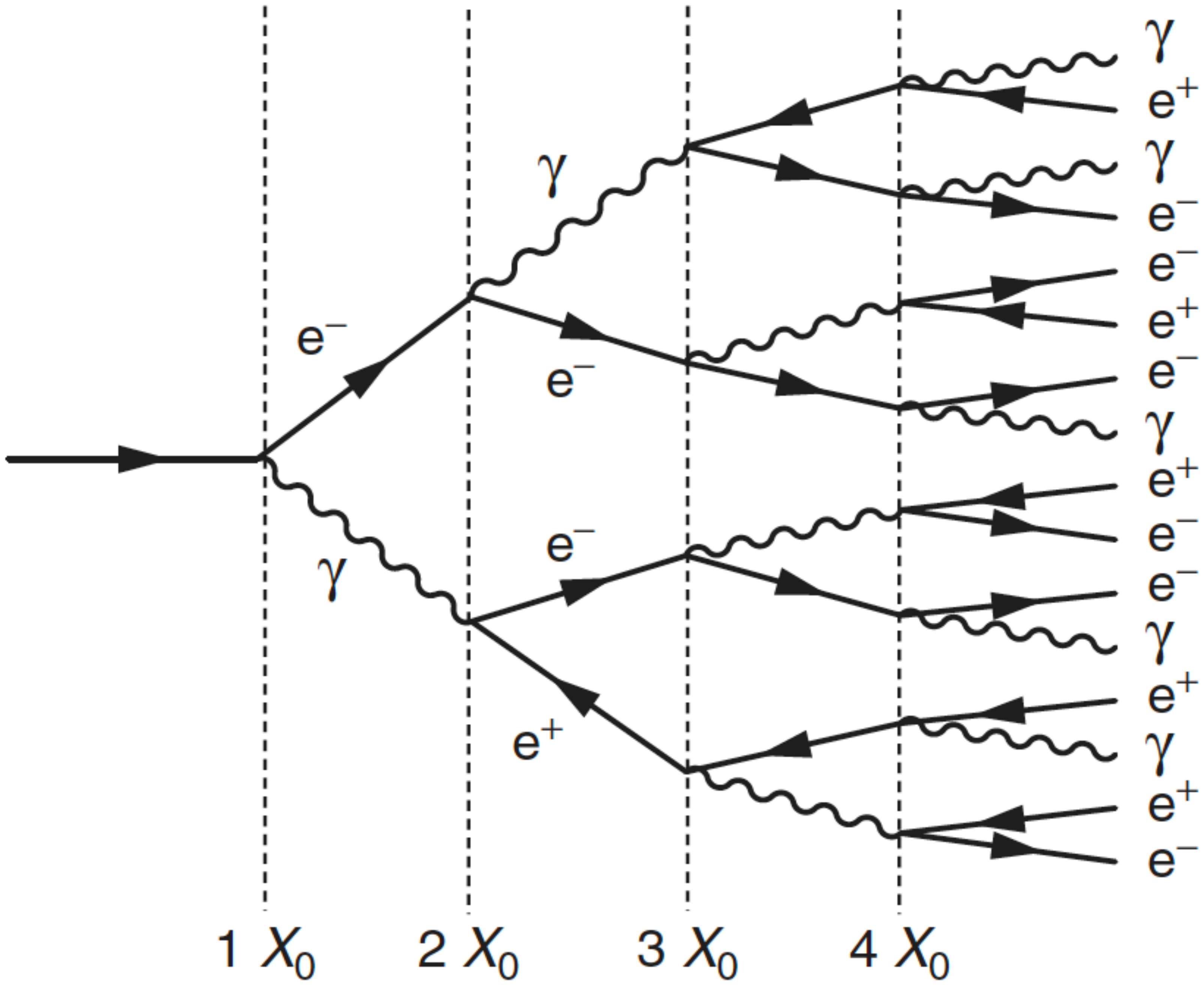


- Fotoni niskih energija uglavnom gube energiju kroz Komptonovo rasejanje i fotoefekat
- Na akceleratorima dominira produckija e^+e^- prova
- Totalni opresek za produkciju parova

$$\sigma_{par} = \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

- Verovatnoća za produkciju para iznosi na putu X_0 iznosi $e^{-7/9}$
  - *Ne zavisi od materiajala.*

ELEKTROMAGNETNI PLJUSAK



- Elektron i fotoni proizvode kaskadu (pjusak) lektrona, pozitrona i fotona u materijalu
- Srednja energija zavisi od broja radijacionih dužina

$$\langle E\rangle \approx \frac{E}{2^x}.$$

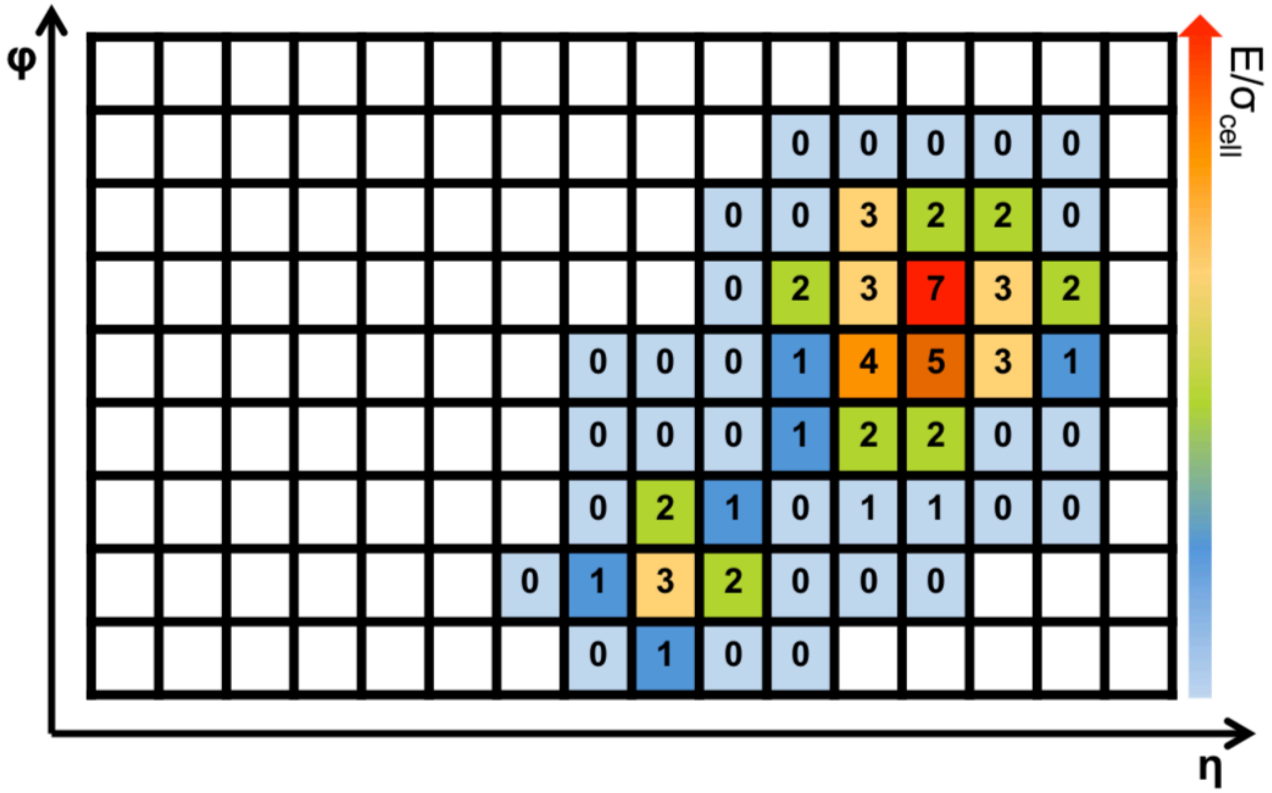
- Maksimalni broj čestica iznosi:

$$x_{max} = \frac{\ln(E/E_c)}{\ln 2}$$

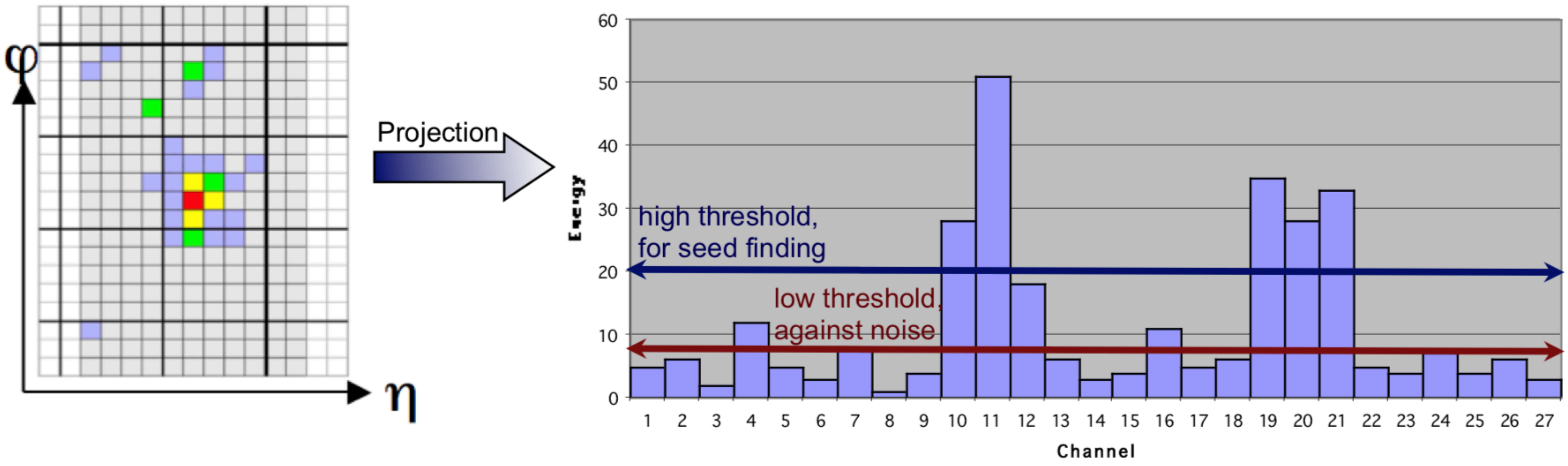
  - Gvoždje: E_c~10 MeV, za $E_{e/gamma}$ ~100 GeV, x_{max} ~13 X_0 (~10 cm)
- Elektroni kritične energije prelaze < X0
- Stohastičkoi proces, fluktuacije su male usled velikog broja čestica

ELEKTROMAGNETNI KALORIMETRI

- Elektromagnentni kalorometri
  - Mere energiju elektrona i fotona
  - Poziciju deponovanog siognala
  - Pravac upadnih čestica
- Podeljeni na ćelije koje formiraju klastere
- Različite tehnologije PbWO4 neorganski scintilator (CMS), tečni argon (ATLAS)



										0	0	0	0	0	
									0	0	3	2	2	0	
									0	2	3	7	3	2	
							0	0	0	1	4	5	3	1	
							0	0	0	1	2	2	0	0	
							0	2	1	0	1	1	0	0	
						0	1	3	2	0	0	0			
							0	1	0	0					



ELEKTROMAGNETNI KALORIMETRI (2)

- Elektromagnentni kalorometri se još dele na
  - Homogene
  - Sendvič (*Sampling*) koji se sastoje od slojeva aktivnog materijala i apsorbera
- Energetska rezolucija EM kalorimetera

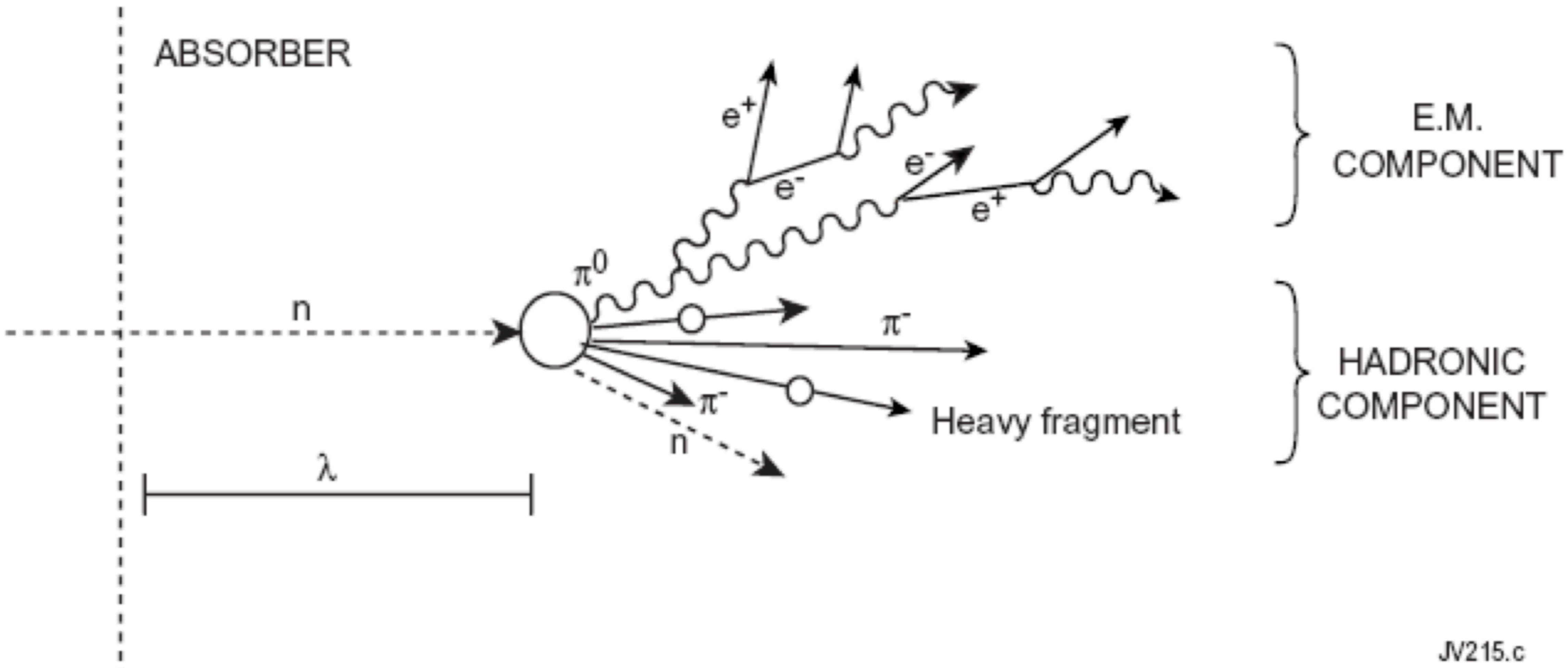
$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \otimes \frac{b}{E} \otimes c$$

$$a \otimes b = \sqrt{a^2 + b^2}.$$

- Gde prvi član opisuje Poasonovske fluktuacije, drugi šum, a treći nesavršenost u konstrukciji kalorimetra, neuniformnost ćelija, interkalibraciju, curenje energije itd.,
- Homogeni kalorimetre imaju bolju energetsku rezoluciju (malo c), dok sampling kalorimetri imaju bolju protsornu rezoluciju (preczinije merenje pozicije pljuska)
- Tipična rezolucija EM kalorimetara je:

$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/\mathrm{GeV}}}$$

INETARKCIJA I DETEKCIJA HADRONA



- Visoko - energetski hadroni pri prolasku kroz materiju interaguju sa jezgrima produkujuči sekundarne hadrone
- Najčešće su u pitanju pioni (π^0,$\pi^{+/-}$), kaoni, i u manjioj meri barioni; π^0 čine 30% produkcije
- U odnosu na elektromagnetrnu kaskadu hadronske imaju veći domet i veće fluktuacije

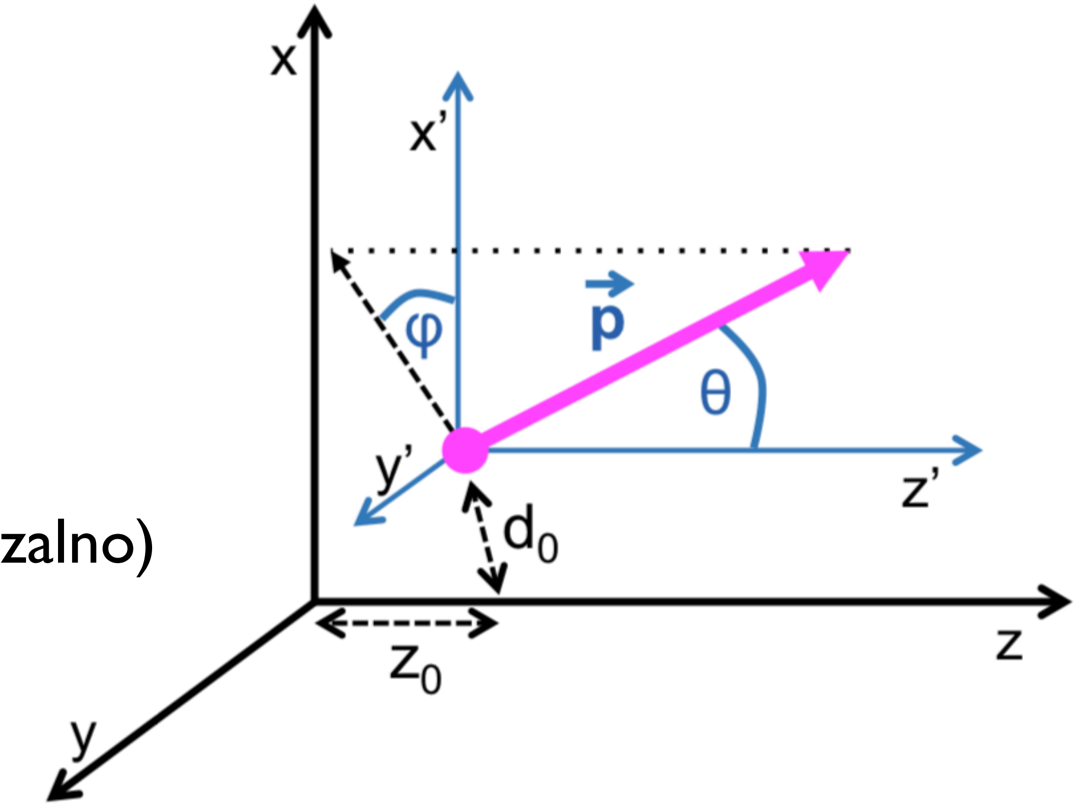
INETARKCIJA I DETEKCIJA HADRONA

- Razvoj hadronske kaskade se parametrizuje interakcionom dužinom λ_I (pandan X_0)
  - Srednje rastojanje između dve interakcije relativističkih hadrona
  - U proseku 10 puta veća od radijacione dužine
- Hadronske kaskade su mnogo više varijabilne u odnosu na elektromagnetne
  - Veliki broj različitih tipova čestica
  - Velki deo energije se gubi kroz nuklearne ekscitacije i raspade jezgara
- Hadronski kalorimetri su veliki (upadni hadon od 100 GeV ima zaustavni put od 2m u olovi)
- Hadronski kalorimetri su uvek sampling kalorimetri (zbog debljine)
- Hadronski kalorimetri se uvek postavljaju iza EM kalorimetara
- Tipična rezolucija hadronskih kalorimetara je:

$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/\mathrm{GeV}}}$$

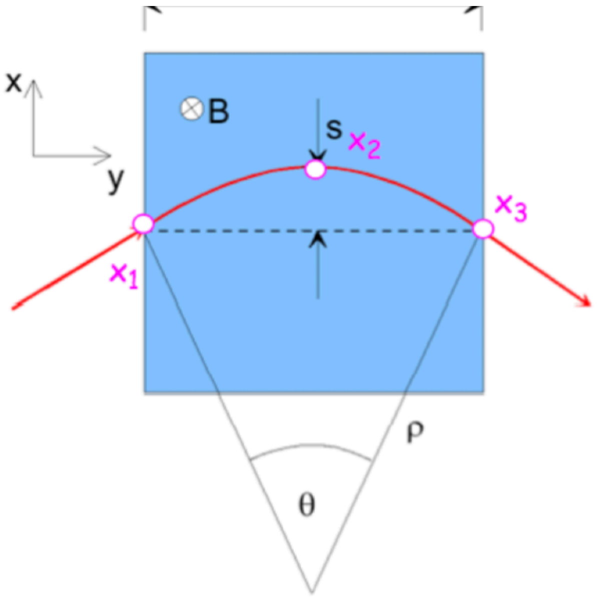
DETEKTORI TRAGOVA

- Detektori tragova
  - Mere impuls čestica
  - Pravac naelektrisane čestice
  - Naelektrisanje
  - Rastojanje (longitudinalno i transverzalno) od date ose (sudara)



$$\boxed{\frac{d\vec{p}}{dt} = q\vec{\beta} \times \vec{B}}$$

$$\boxed{p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]}$$



s = sagitta

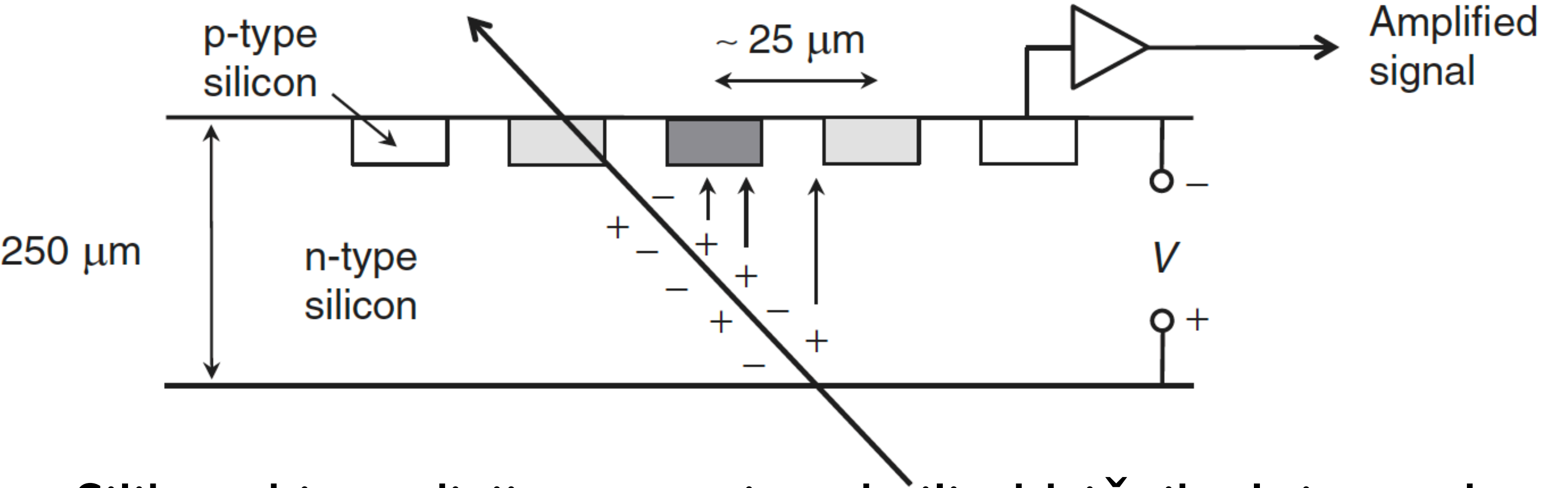
l = chord

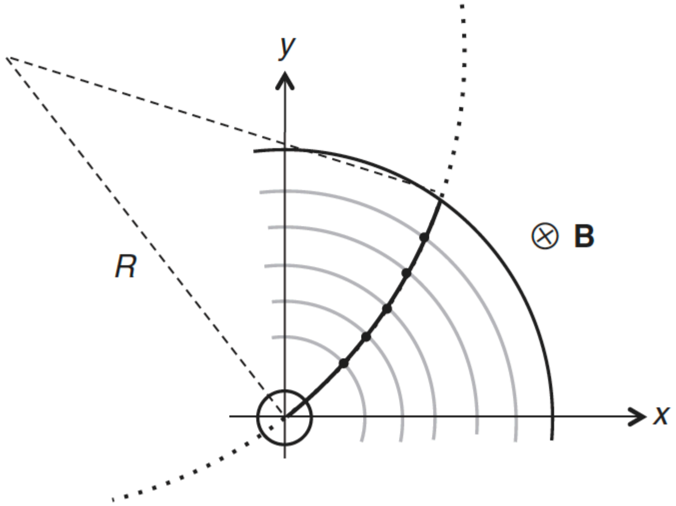
ρ = radius

$$\rho \simeq \frac{l^2}{8s} \qquad p = 0.3\frac{Bl^2}{8s} \qquad \left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

DETEKTORI TRAGOVA (=NAELEKTRISANIH Č.)

- Detektori tragova su zasnovani na jonizaciji atoma koju vrše naelektrsane čestice, na osnovu koje se vrši detekcija ***trajektorije*** te naelektrisane čestice
- Dva osnovna tipa detektora tragova:
  - Drift jonizovanih elektrona u prisustvu jakog električnog polja u gasu velike zapremine **- *gasni detektori***
  - Moderniji poluporovodnički detektori - ***silikonske trake i pixeli***
- Nalektrsane čestice formairaju parove elektron-šupljine (~10k !), a razlika potencija vodi driftu šupljina gde se kolektuju na p–n spojevim. Senzori formirju trake (*strips*) razdvojene O(25 μm), ili pixele sa 2D slikom.

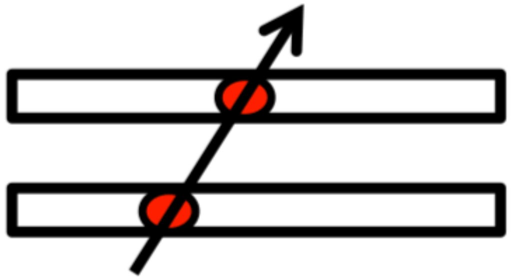




- Silikonski uredjaji se sastoje od cilinddričnih slojeva gde naelektrsana šestica ostavlja *hit*-ove na osnovu koje se može rekonstruisati njena trajektorija. Sistem se obično nalazi u jakom *homogenom magnetnom polju.*

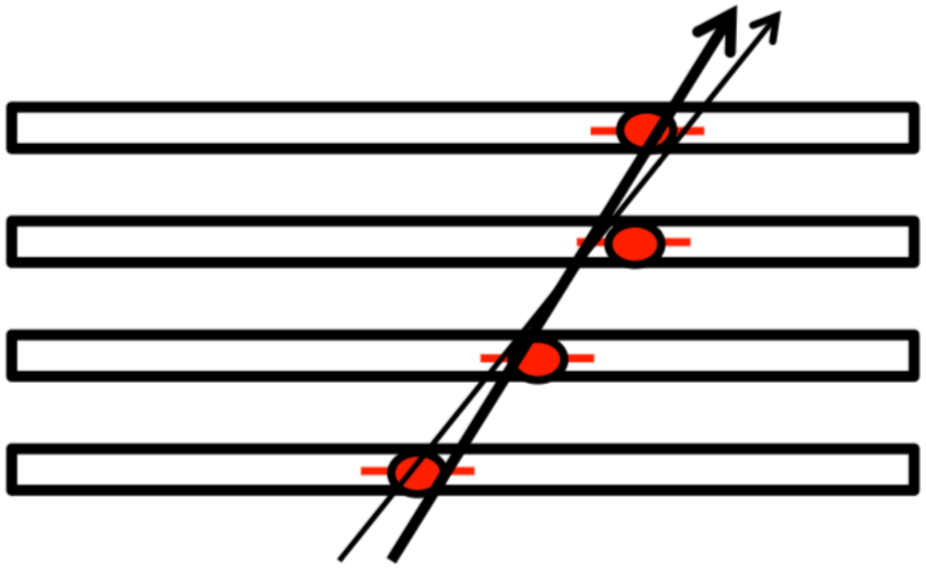
DETEKTORI TRAGOVA

- **Perfect measurement – ideal**



- **Imperfect measurement – reality**

- **Small errors and more points help to constrain the possibilities**



$$\frac{dp_T}{p_T} = \frac{\sqrt{3}}{2}\sigma_x \frac{8p_T}{0.3BL^2}$$

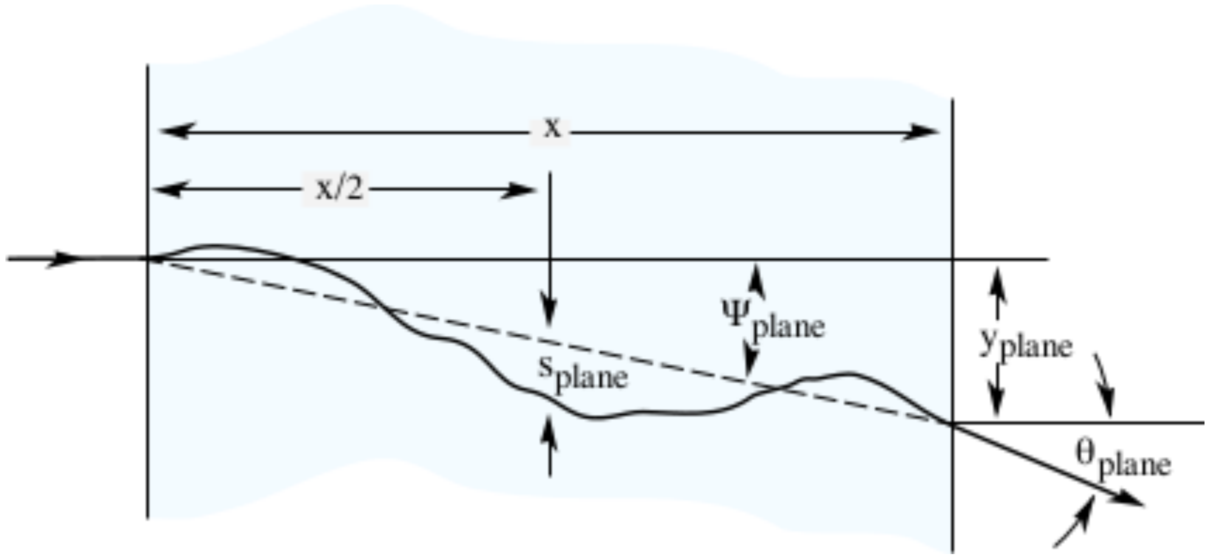
- Rezolucija (transverzalnog) impulsa zavisi od:

jačine magnetnog polja

L (square), the lever arm

Broja merenja

Pozicione rezolucije (poravnjanja) σ_x

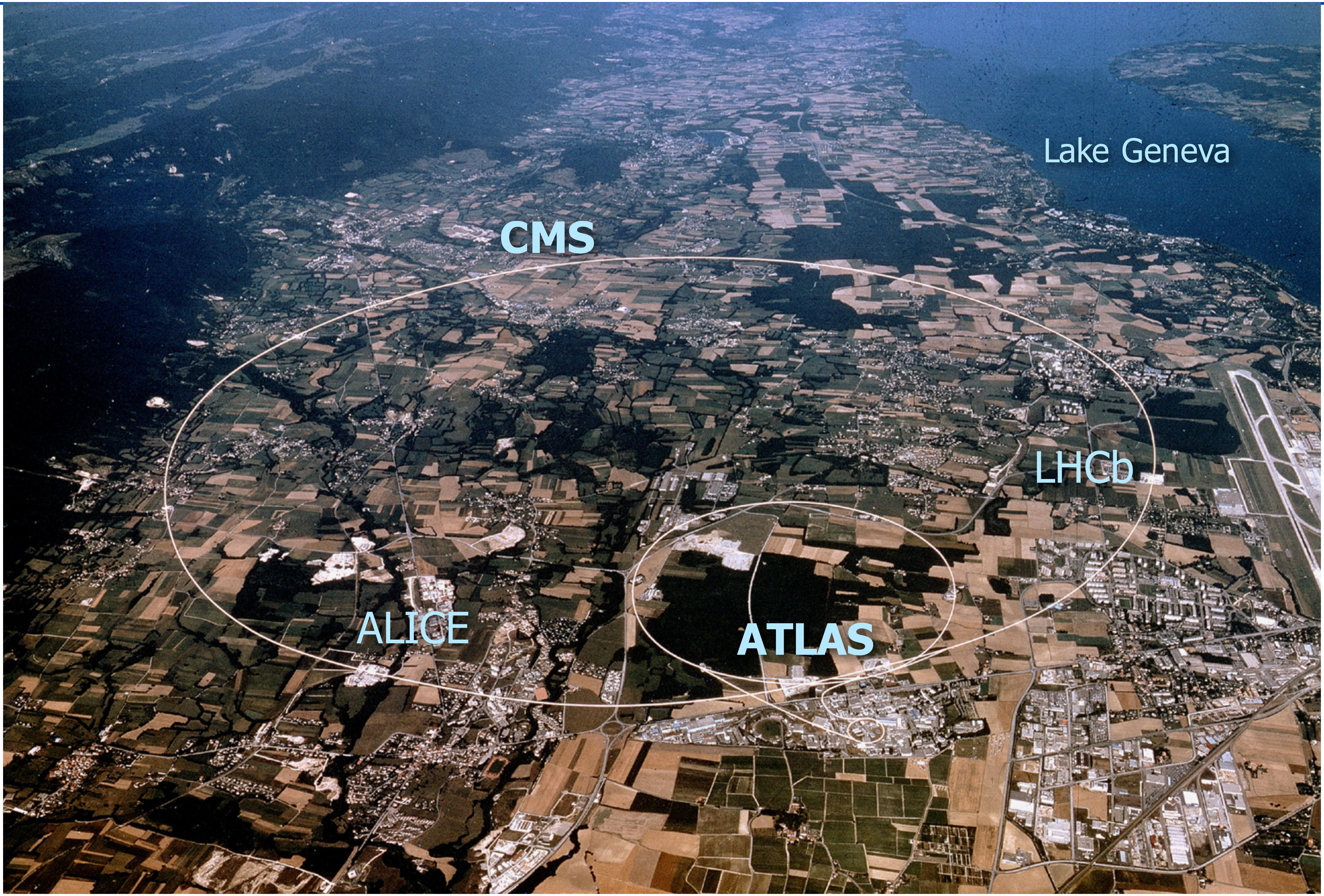


KOLAJDERSKI EKSPERIMENTI

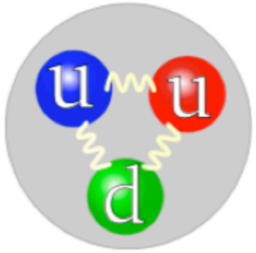
KOLAJDERI (=SUDARAČI)

Collider	Laboratory	Type	Date	$\sqrt{s}$/GeV	Luminosity/$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
PEP-II	SLAC	e^+e^-	1999–2008	10.5	1.2×10^{34}
KEKB	KEK	e^+e^-	1999–2010	10.6	2.1×10^{34}
LEP	CERN	e^+e^-	1989–2000	90–209	10^{32}
HERA	DESY	e^-p/ e^+p	1992–2007	320	8×10^{31}
Tevatron	Fermilab	$p\overline{p}$	1987–2012	1960	4×10^{32}
LHC	CERN	pp	2009–	14 000	10^{34}

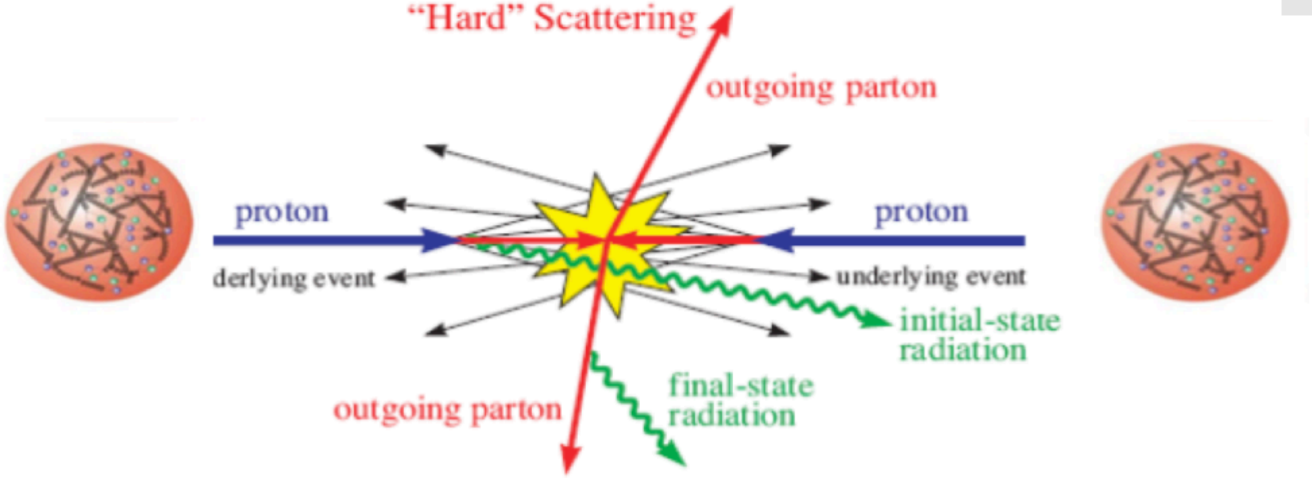
LHC

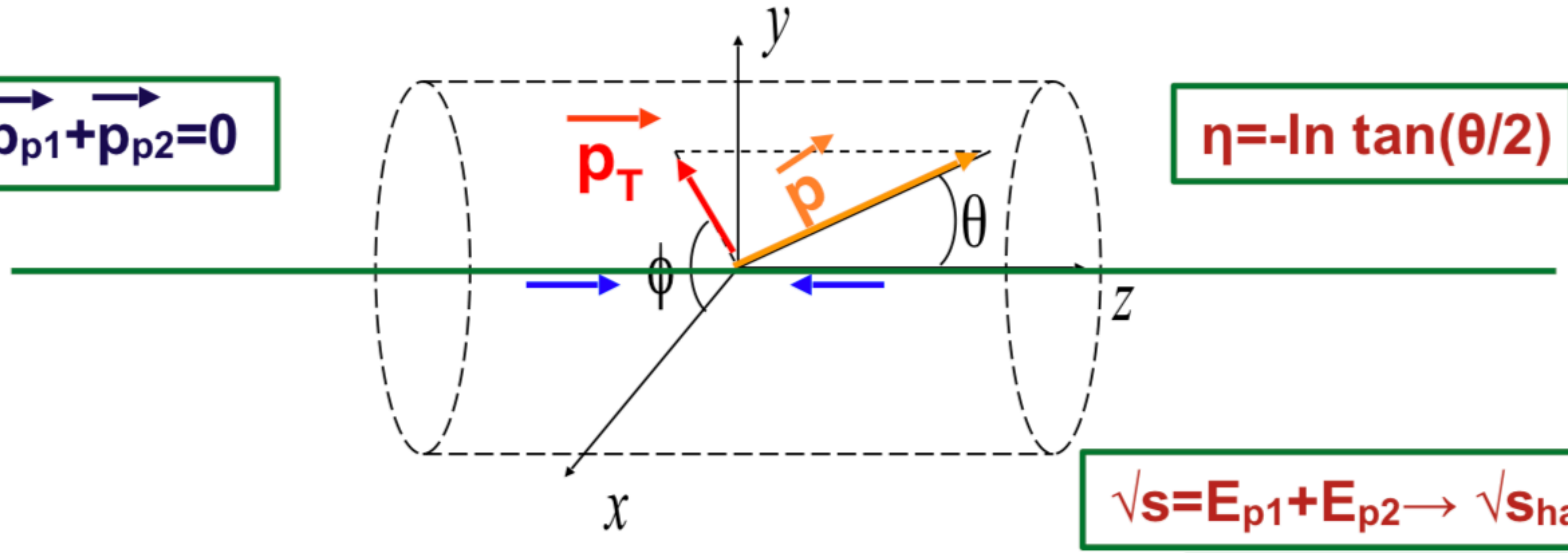


PROTON-PROTON INTERAKCIJE NA LHC-U



$$s = \left(\sum_{i=1}^{2} E_i\right)^2 - \left(\sum_{i=1}^{2} \mathbf{p}_i\right)^2$$





proton₁

proton₂

$\vec{p}_{p1}+\vec{p}_{p2}=0$

$\eta=-\ln\tan(\theta/2)$

$\sqrt{s}=E_{p1}+E_{p2} \rightarrow \sqrt{s_{hard}}=E_{parton1}+E_{parton2}$

$M_{12}=\sqrt{[2E_1.E_2(1-\cos\alpha_{12})]}$

LUMINOZNOST

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

k = number of bunches = 2808
N = no. protons per bunch = 1.15×10^{11}
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y = beam sizes at collision point (hor./vert.) = 16 μm

$N = \sigma \times \mathcal{L}$ gde je $\mathcal{L} = \int L\,dt$, ili jednostavnije $\mathcal{L} = L \times t$

σ = presek, odnosno verovatnoća da se neki proces dogodi

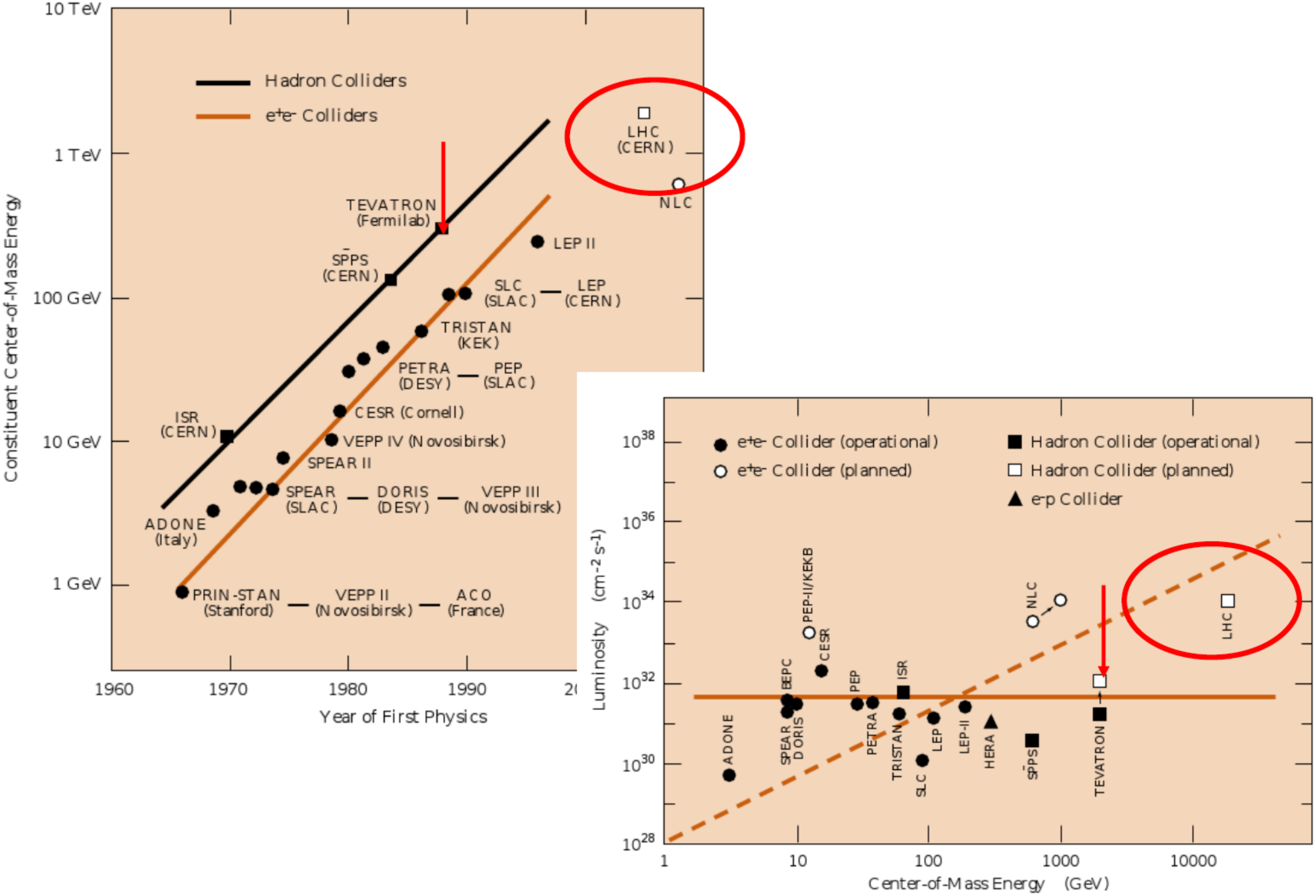
$\mathcal{L}$ = integralna luminoznost

N = broj OČEKIVANIH DOGAĐAJA nekog procesa

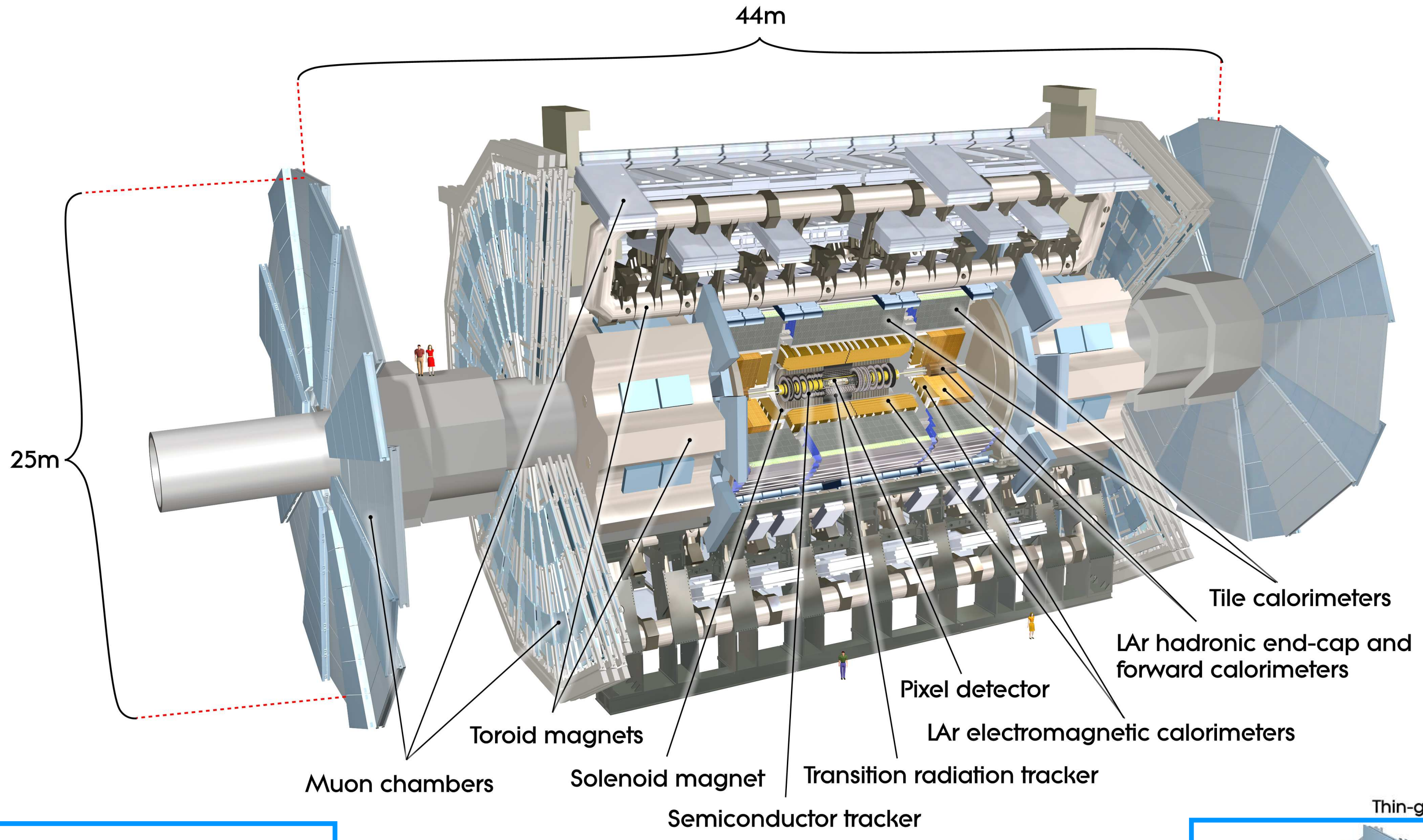
Uzmimo ovakav primer:
proces produkcije W bozona koji se raspada na mion i njegov neutrino, ima presek σ≈20000 pb, znači za integralnu luminoznost od $\mathcal{L}$ =10 fb^-1

(~1 godina rada) biće proizvedeno 200M W->μν!

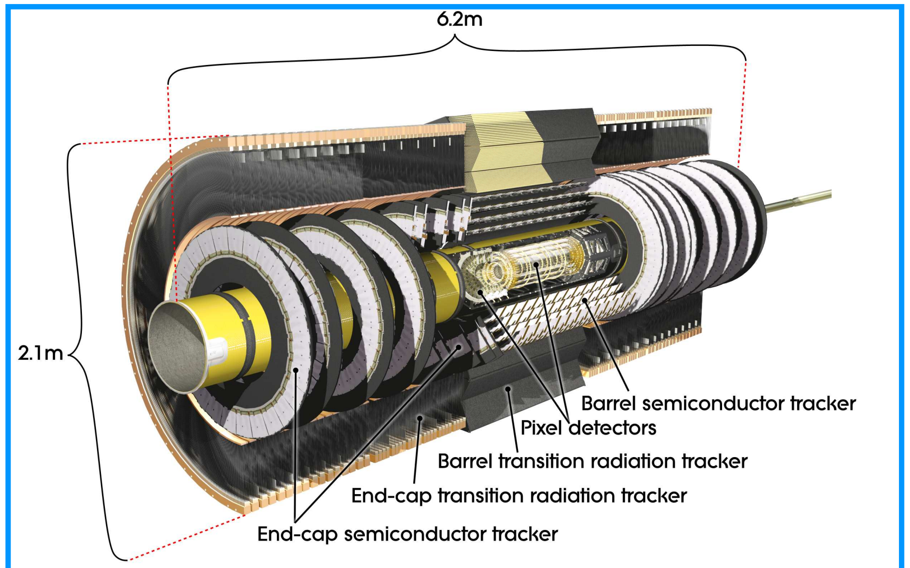
ENERGIJA I LUMINOZNOST NA AKCELERATORIMA



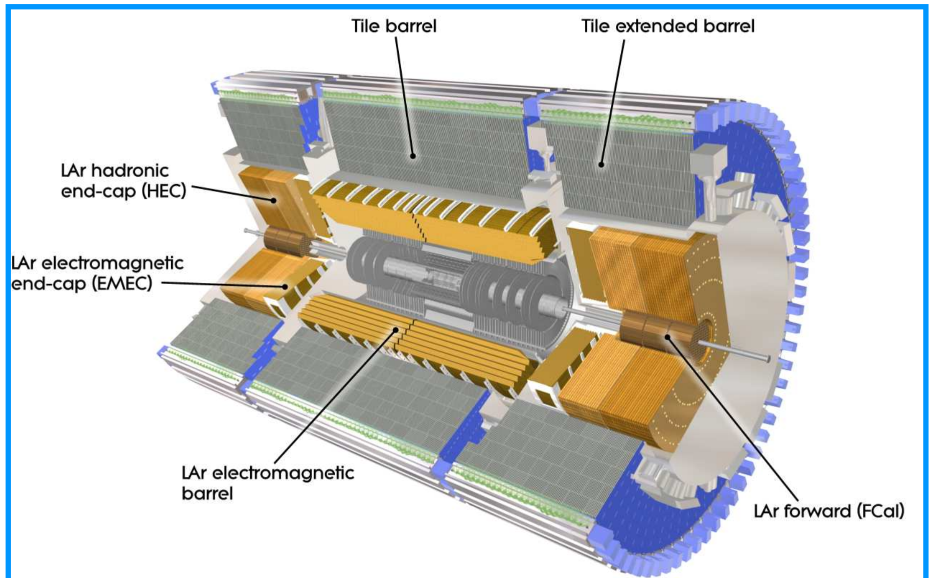
ATLAS DETEKTOR



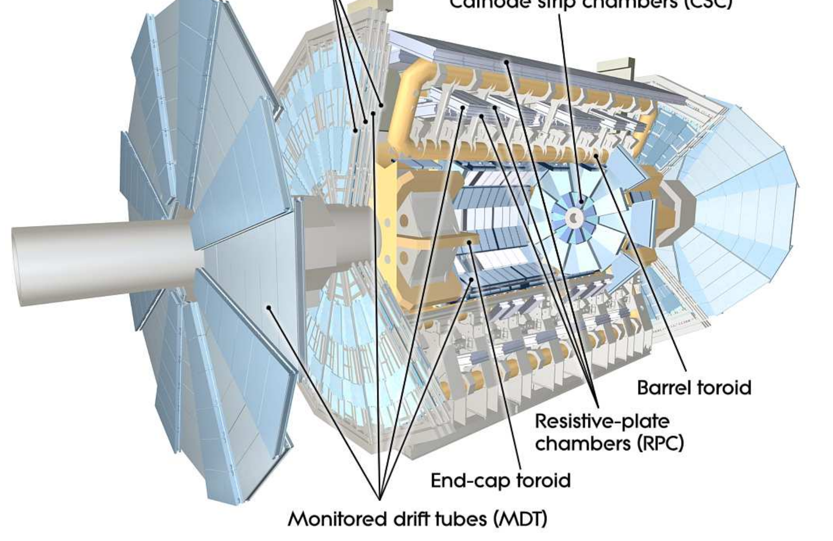
+ Trigger, computing resources, software infrastructure…



- **Inner detector: electrons, muons (kinematics)**

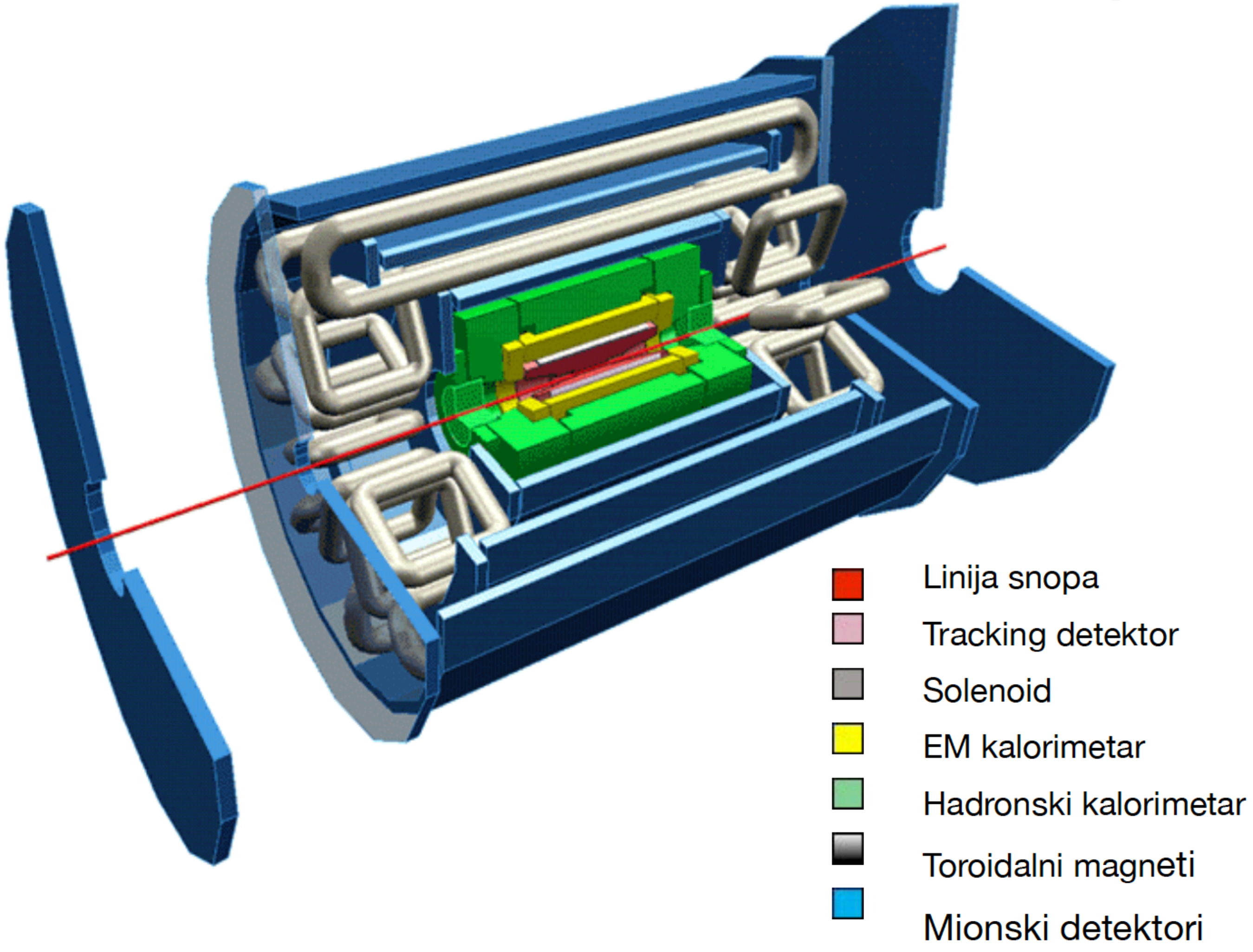


- **ECAL, HCAL: electrons, hadronic recoil**

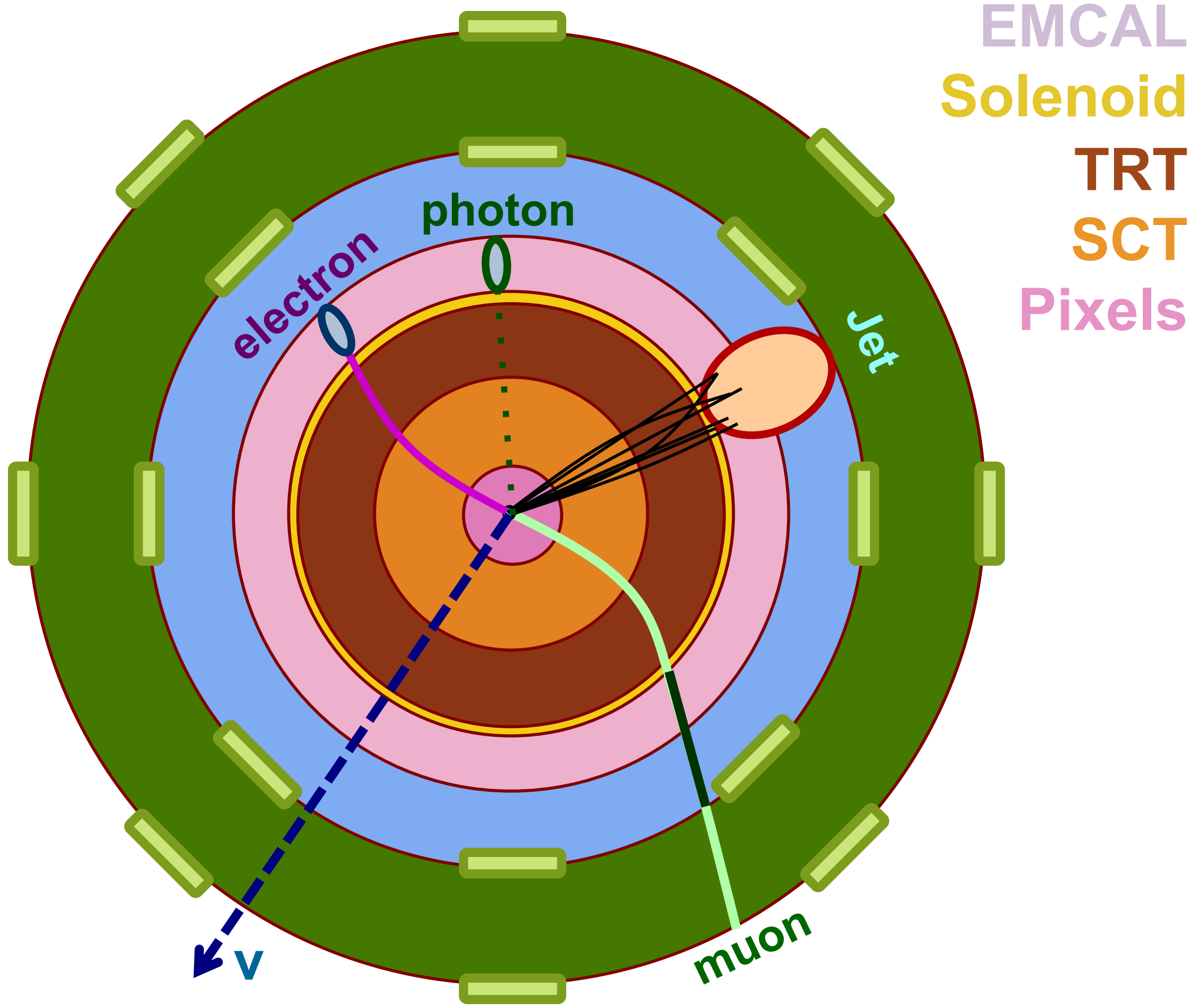


- **Muon Systems: muons (identif.)**

ATLAS DETEKTOR (2)

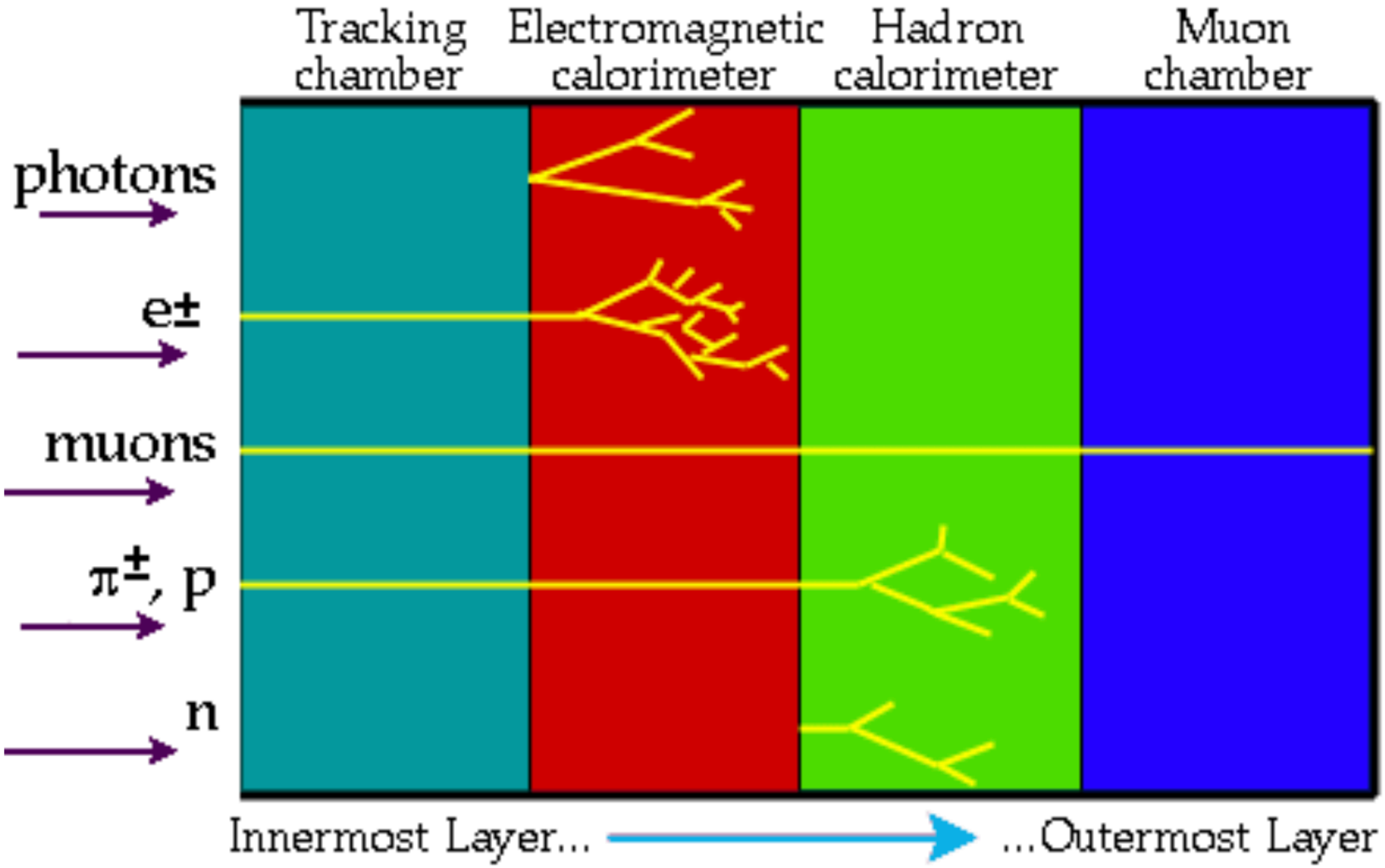


Simplified Detector Transverse View

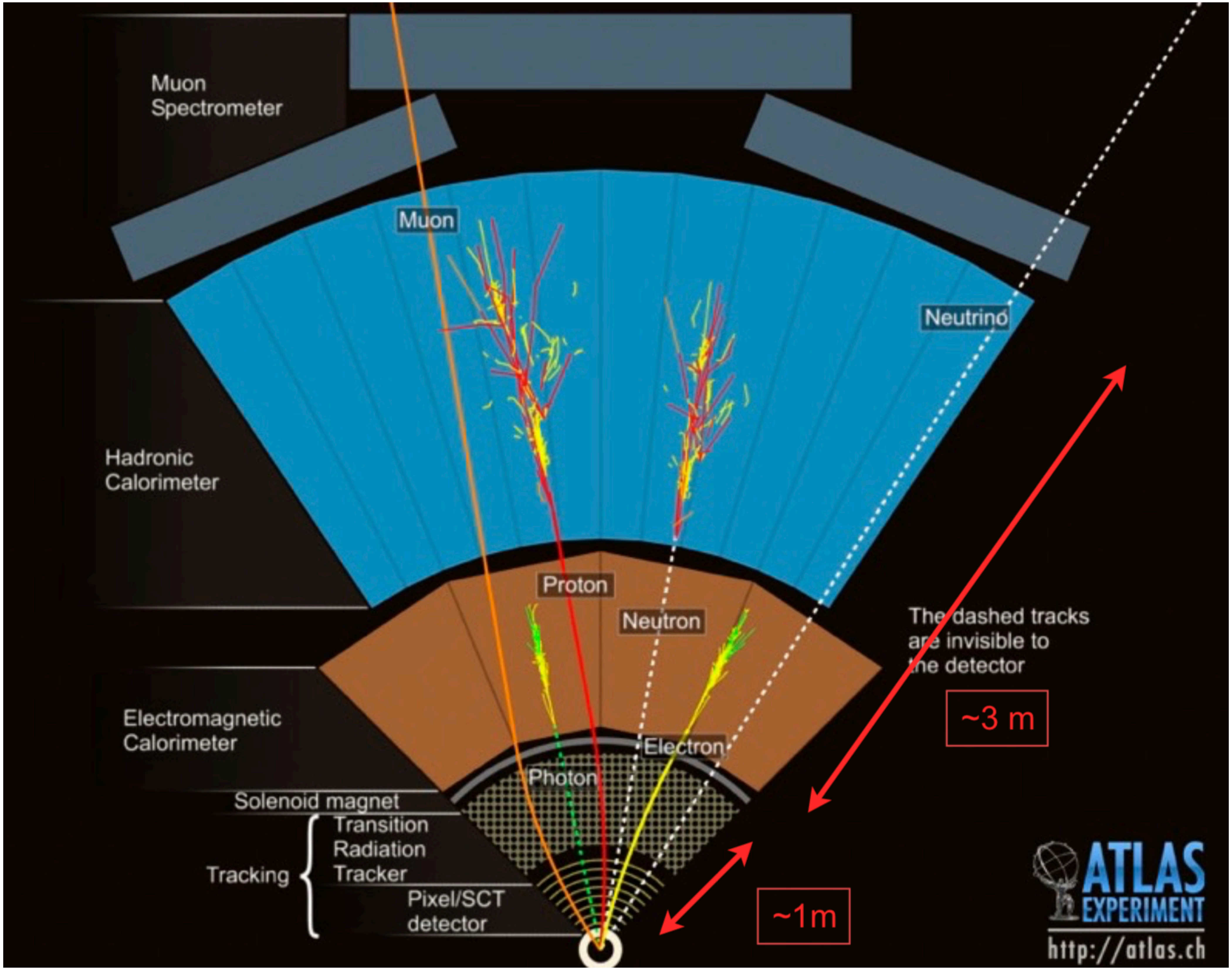


INTERAKCIJA SA DETEKTORIMA

Interakcija čestica sa različitim delovima detektora



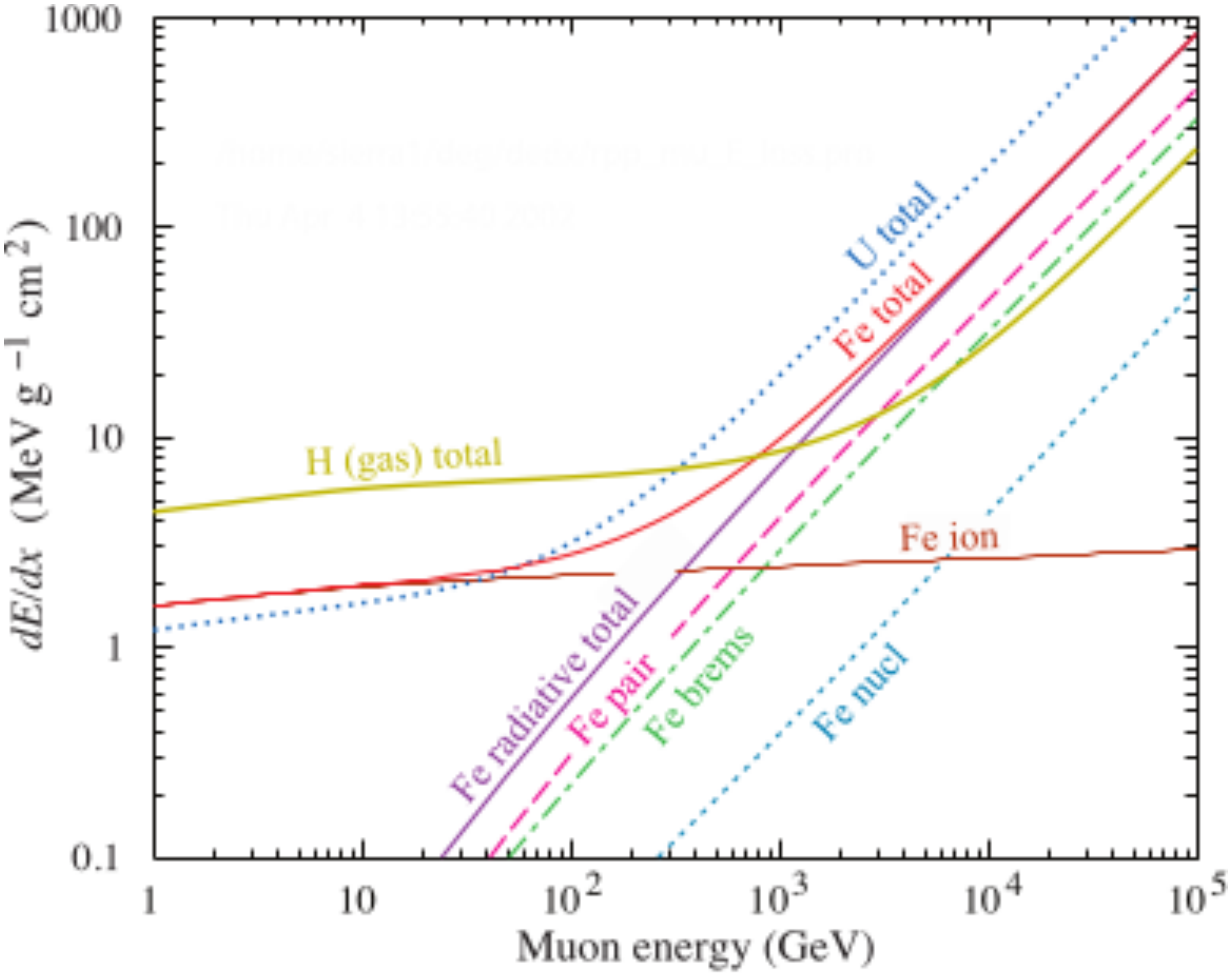
REKONSTRUKCIJA ČESTICA



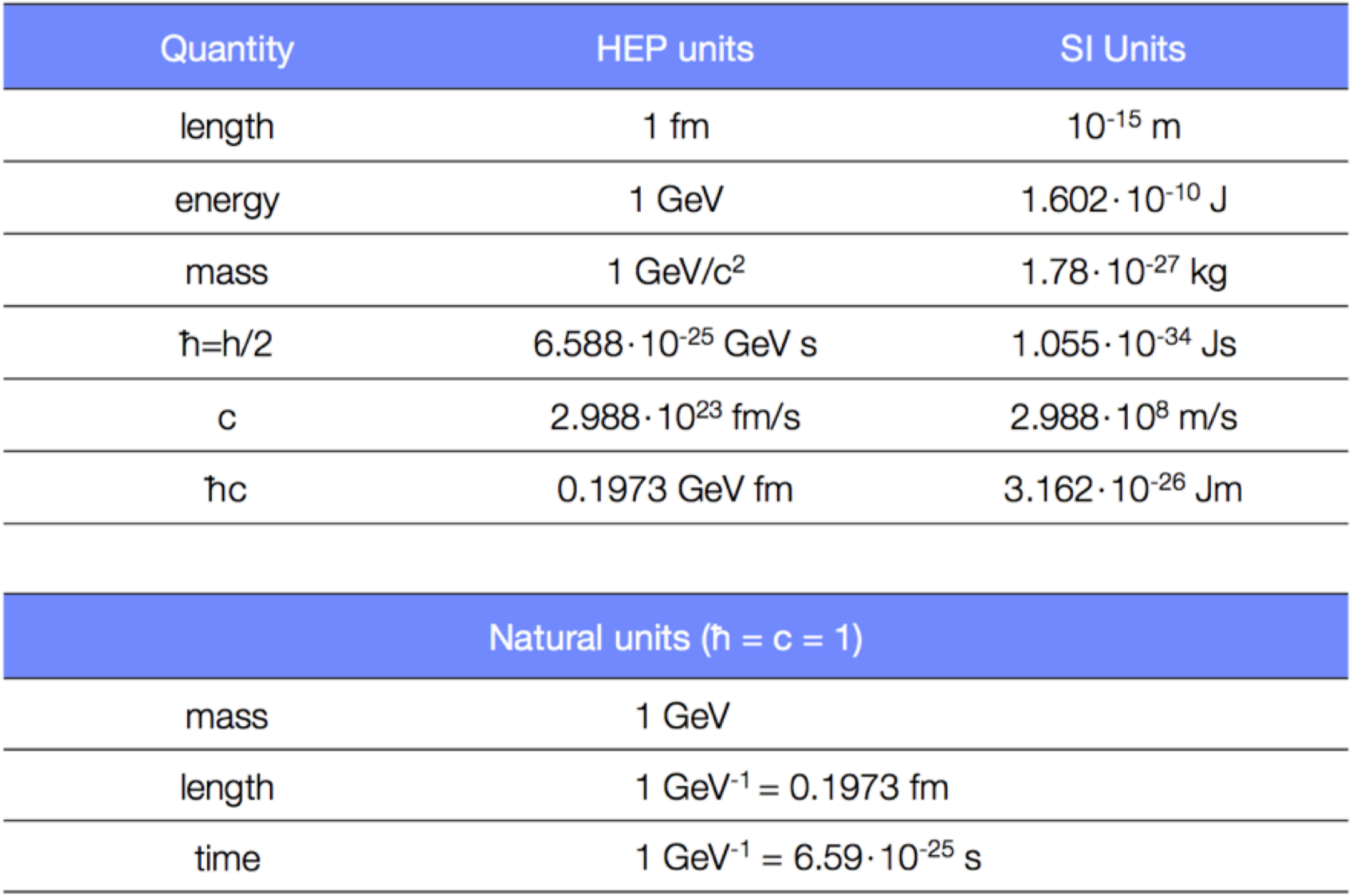
The dashed tracks are invisible to the detector

APENDIKS

INTERAKCIJA I DETEKCIJA MIONA



NEKE OSNOVNE JEDINICE



Quantity	HEP units	SI Units
length	1 fm	10^{-15} m
energy	1 GeV	$1.602 \cdot 10^{-10}$ J
mass	1 GeV/c^2	$1.78 \cdot 10^{-27}$ kg
$\hbar = h/2$	$6.588 \cdot 10^{-25}$ GeV s	$1.055 \cdot 10^{-34}$ Js
c	$2.988 \cdot 10^{23}$ fm/s	$2.988 \cdot 10^{8}$ m/s
$\hbar c$	0.1973 GeV fm	$3.162 \cdot 10^{-26}$ Jm

Natural units ($\hbar = c = 1$)	
mass	1 GeV
length	$1\ \text{GeV}^{-1} = 0.1973$ fm
time	$1\ \text{GeV}^{-1} = 6.59 \cdot 10^{-25}$ s

EM KALORIMETRI

a the stochastic term accounts for Poisson-like fluctuations

- naturally small for homogeneous calorimeters
- takes into account sampling fluctuations for sampling calorimeters

b the noise term (hits at low energy)

- mainly the energy equivalent of the electronics noise
- at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

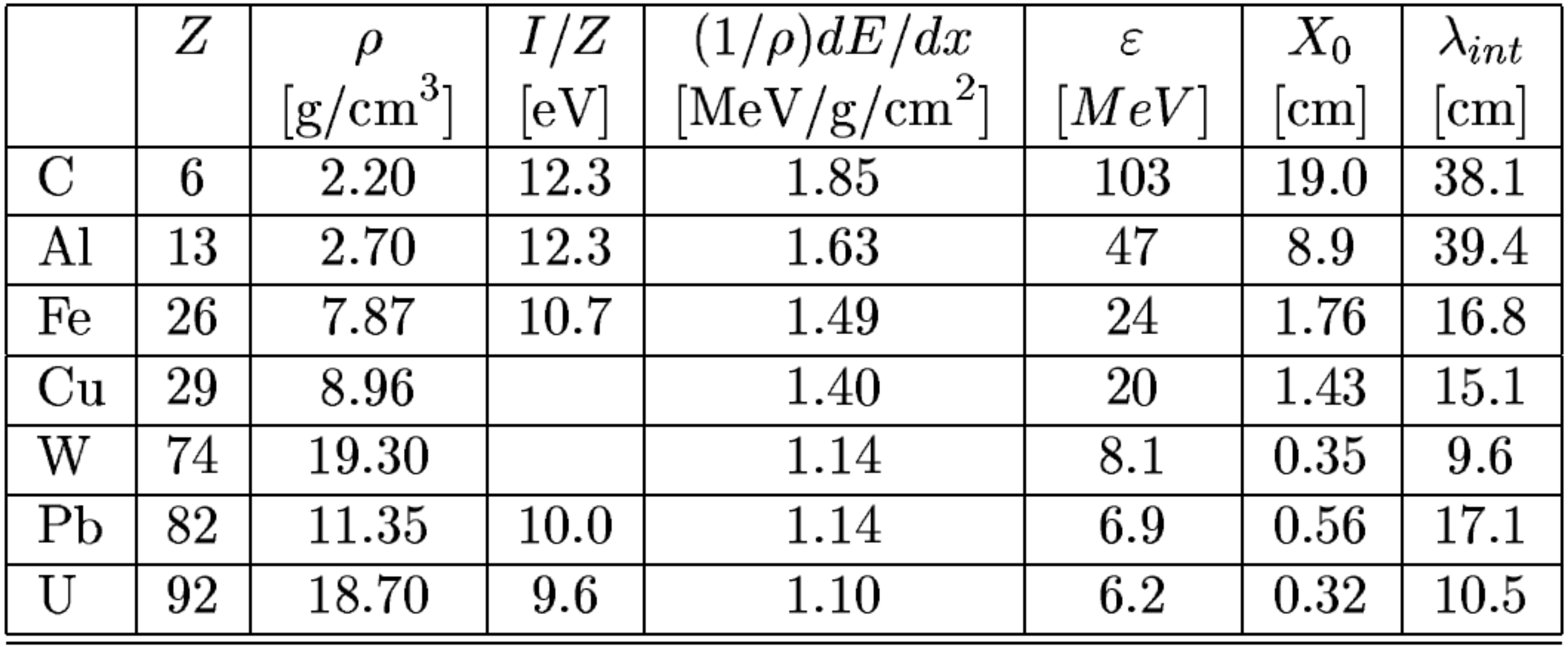
c the constant term (hits at high energy)

- Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

$$\boxed{\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

HAD KALORIMETRI

$$\lambda_{int} \approx 35 A^{1/3} [g/cm^2].$$



	Z	ρ [g/cm^3]	I/Z [eV]	$(1/\rho)dE/dx$ [MeV/g/cm^2]	ε $[MeV]$	X_0 [cm]	λ_{int} [cm]
C	6	2.20	12.3	1.85	103	19.0	38.1
Al	13	2.70	12.3	1.63	47	8.9	39.4
Fe	26	7.87	10.7	1.49	24	1.76	16.8
Cu	29	8.96		1.40	20	1.43	15.1
W	74	19.30		1.14	8.1	0.35	9.6
Pb	82	11.35	10.0	1.14	6.9	0.56	17.1
U	92	18.70	9.6	1.10	6.2	0.32	10.5

INTRODUCTION

Fundamental Theorem of Particle Physics Research:

- ***Standard Model is not complete***
  - *The Standard Model of particle physics is not complete, and it is this incompleteness that motivates almost all particle physicists to do particle physics. (J.Wells)*
  - ***How is the Standard Model incomplete? Indirectly, the Standard Model is incomplete because we do not know several important why questions that cannot be answered within the theory.***
    - ***Why three generations?***
    - ***What is the dark matter?***
    - ***Why is matter so much more copious than anti-matter?***
    - ***Why is the strong CP violating angle so small?***
    - ***Why is the electroweak scale so much smaller than the Planck scale?***
    - ***Why are there three spatial dimensions and one time dimension?***
    - ***Why do the gauge couplings have their values, and appear to merge at high energy?***
    - ***Why are there large hierarchies in the quark and lepton masses and mixings?***
    - ***Why are neutrino masses so much smaller?***
    - ***Why does electroweak symmetry break?***
    - **…**

INSTEAD OF SUMMARY…

… PARTICIPATE IN THE CENTURIES OLD EFFORT OF UNDERSTANDING FUNDAMENTAL LAWS OF NATURE