Das letzte Elementarteilchen?
Bilanz zum Standardmodell der Teilchenphysik

Robert Harlander

RWTH Aachen University

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

What should we work on?

Create a file or build a site

Research and plan next steps

Get a briefing on recent work

Automate routine and recurring work

Choose project

Plugins

Do anything

Ask for approval

5.6 Terra Medium

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5.6 Terra Medium

ELEMENTARTEILCHENPHYSIK

Das Standardmodell auf dem Prüfstand

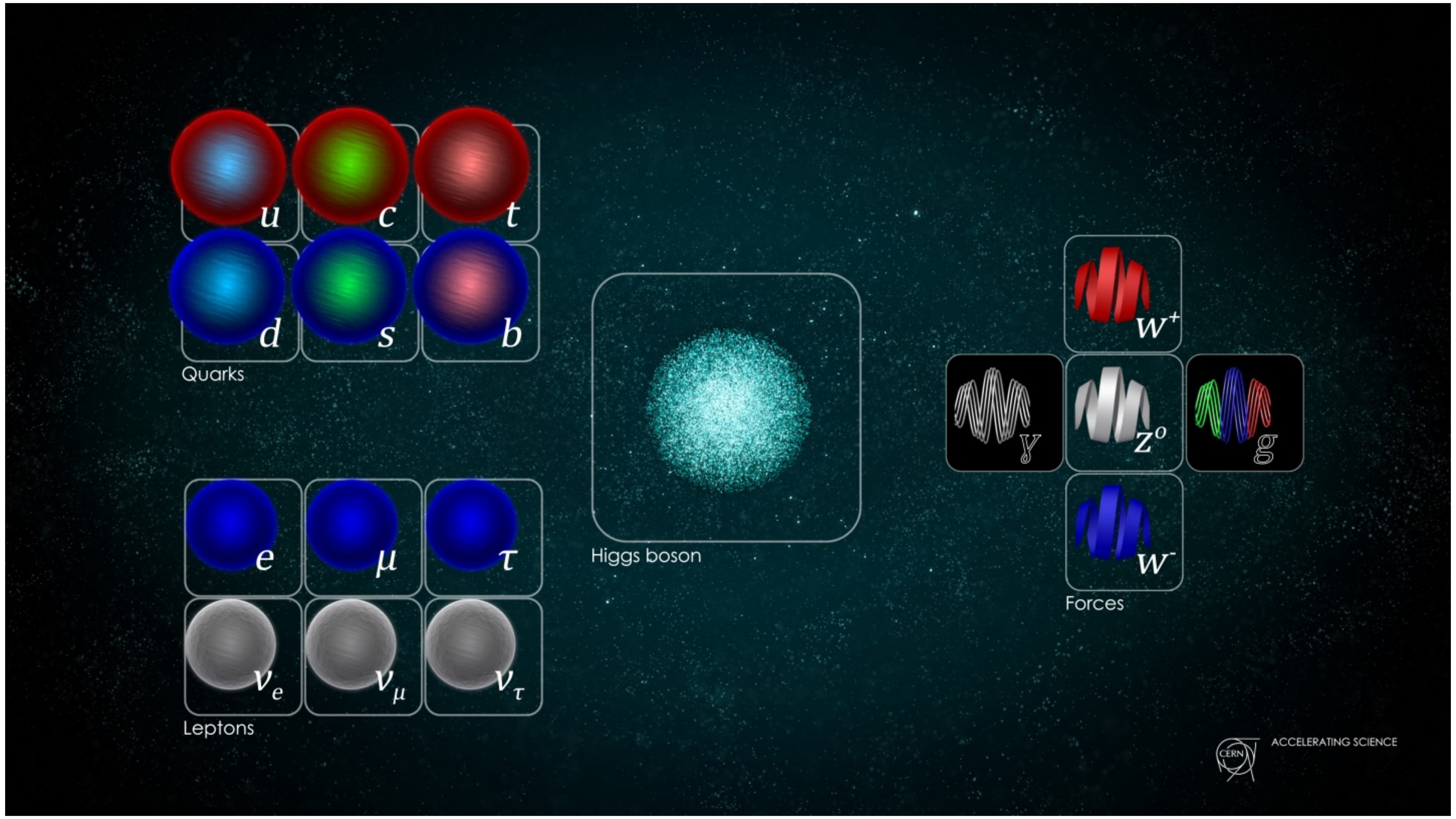
Erfolgreich
präzise
offen

Was es brillant erklärt – und warum es trotzdem nicht das letzte Wort sein kann.

Für Lehrkräfte an Gymnasien · Stand Juli 2026

Fachlicher Stand: CERN / Particle Data Group (PDG), siehe Quellenfolie.

Die Teilchenfamilie: klein, aber nicht einfach



Drei Generationen

- 6 Quarks
- 6 Leptonen
- Kraftteilchen + Higgs

Für den Unterricht: Die Tabelle ist eine Landkarte – nicht die ganze Theorie.

Bild: Daniel Dominguez/CERN, OPEN-PHO-CHART-2015-001-1. Inhalt: CERN, „The Standard Model".

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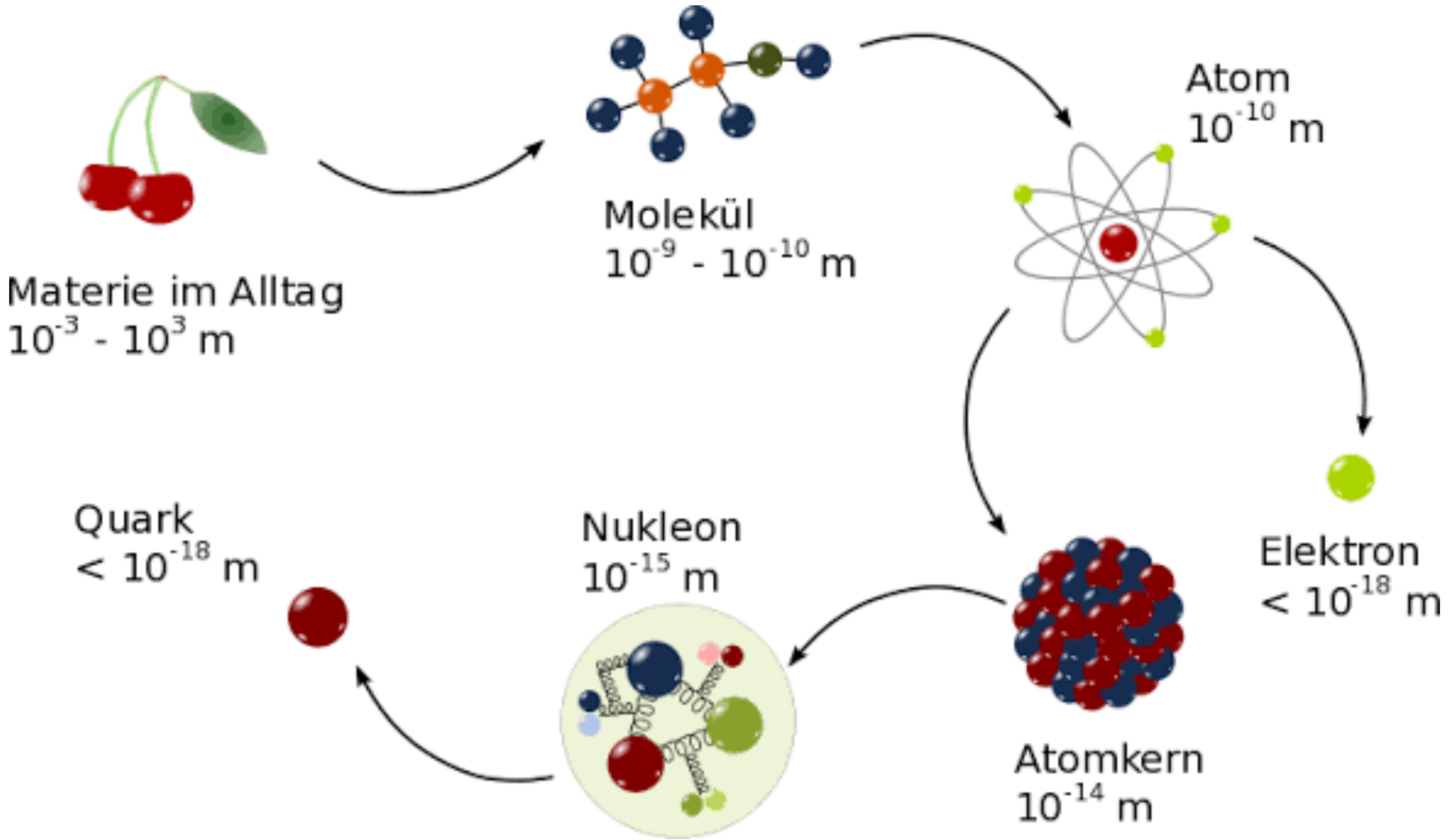
Materie im Alltag
10^{-3} - 10^{3} m
Molekül
10^{-9} - 10^{-10} m
Atom
10^{-10} m
Elektron
< 10^{-18} m
Atomkern
10^{-14} m
Nukleon
10^{-15} m
Quark
< 10^{-18} m

Atome

Atome

500 BC: Demokrit

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Atome

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ca. 1810: Dalton

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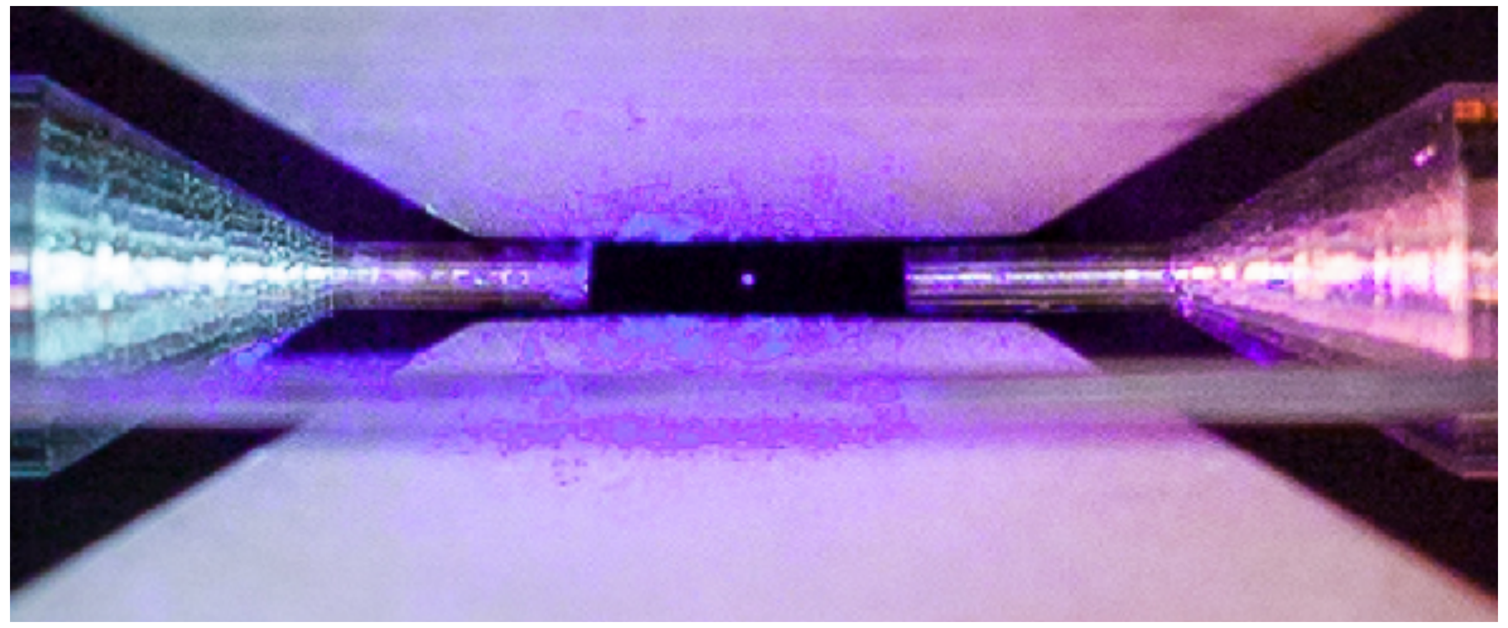

Nadlinger 2018

https://qz.com/1205279/photo-of-an-atom-a-scientist-captured-an-incredible-photograph/

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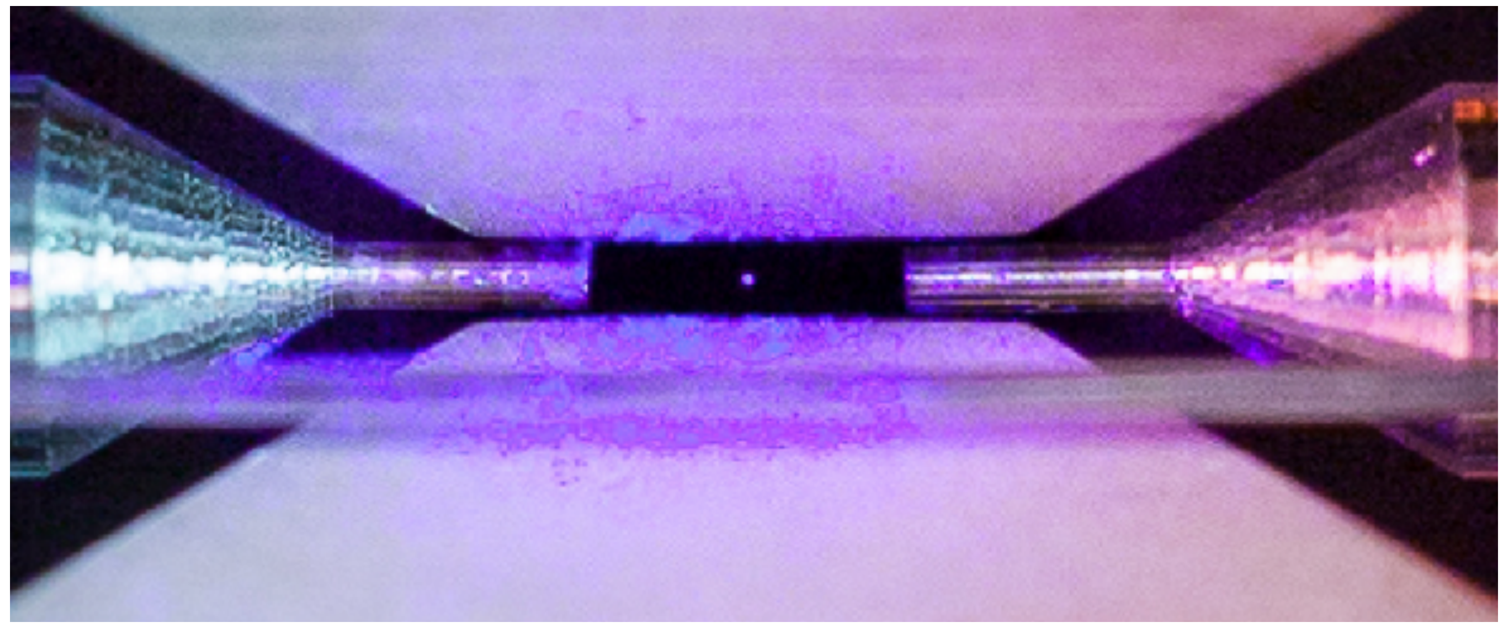

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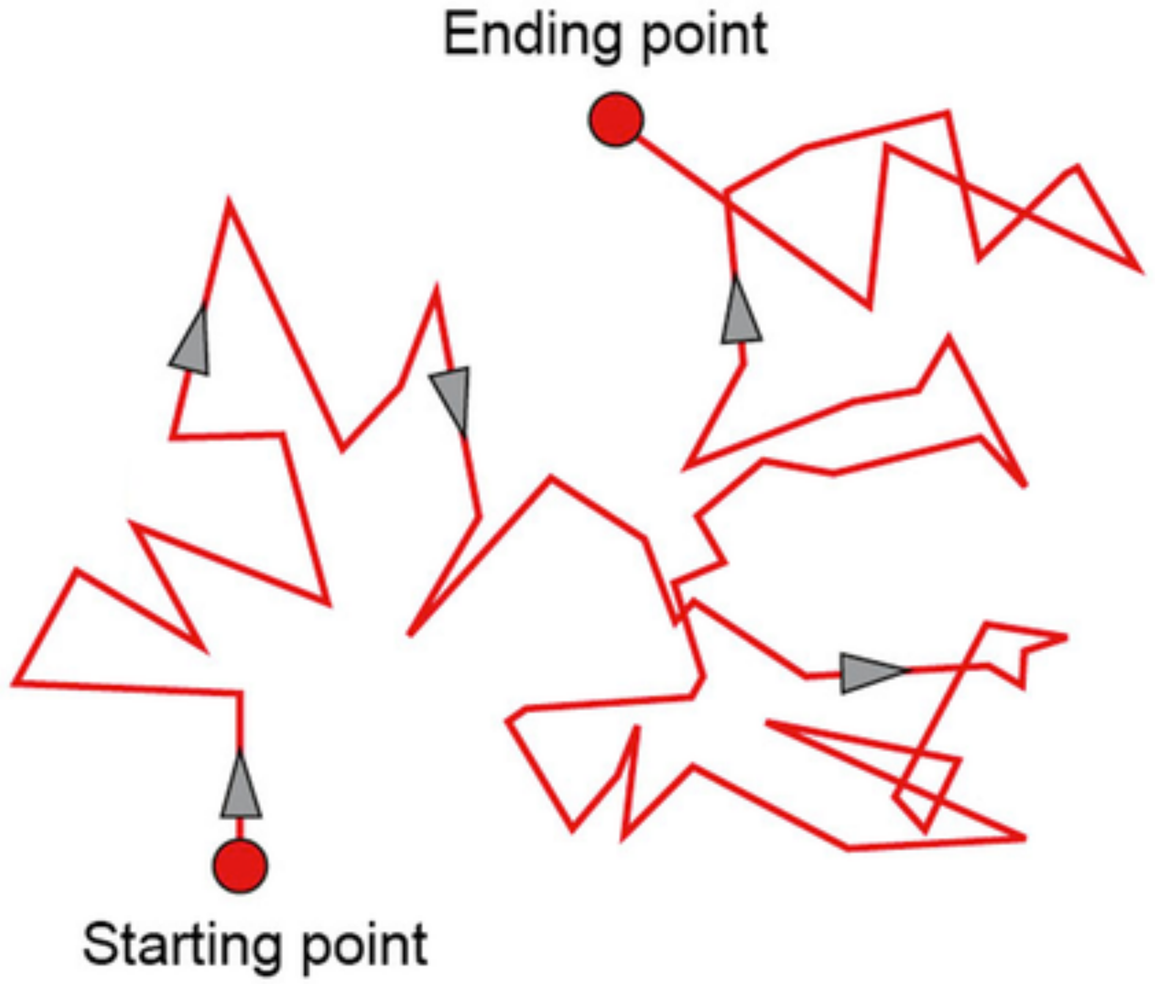

Brown 1827

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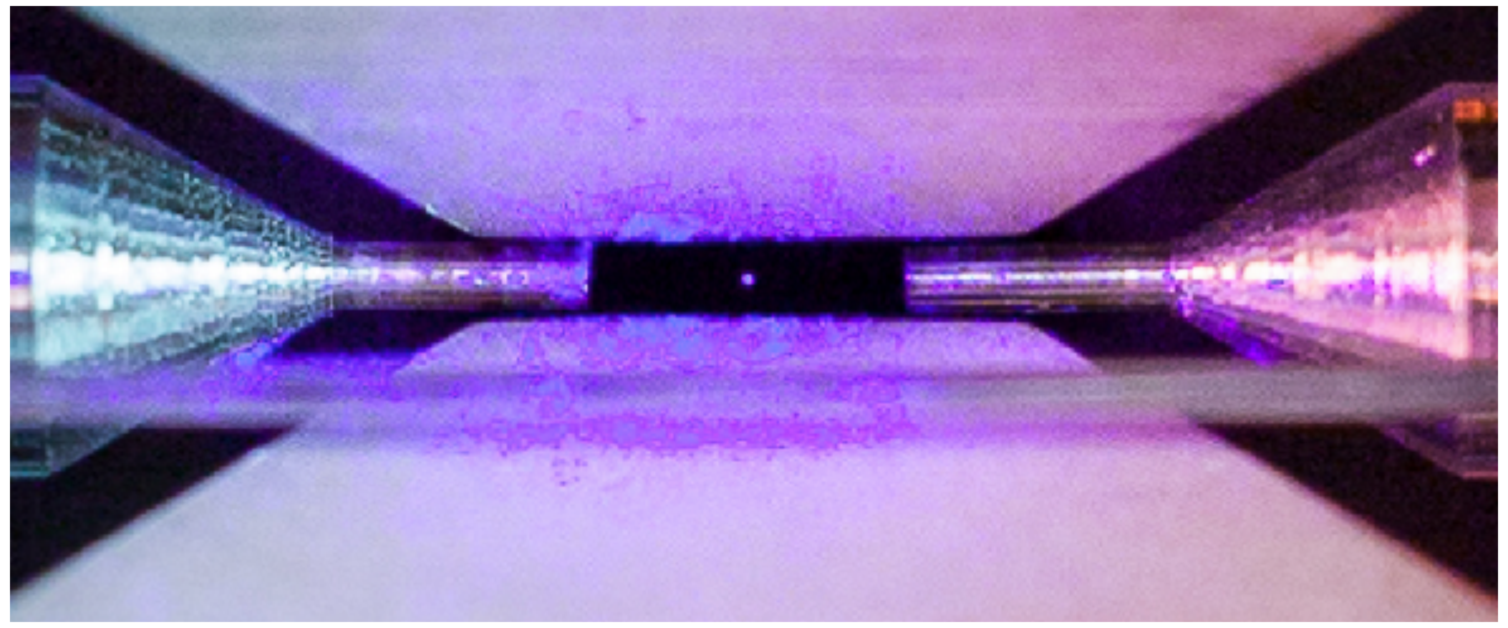

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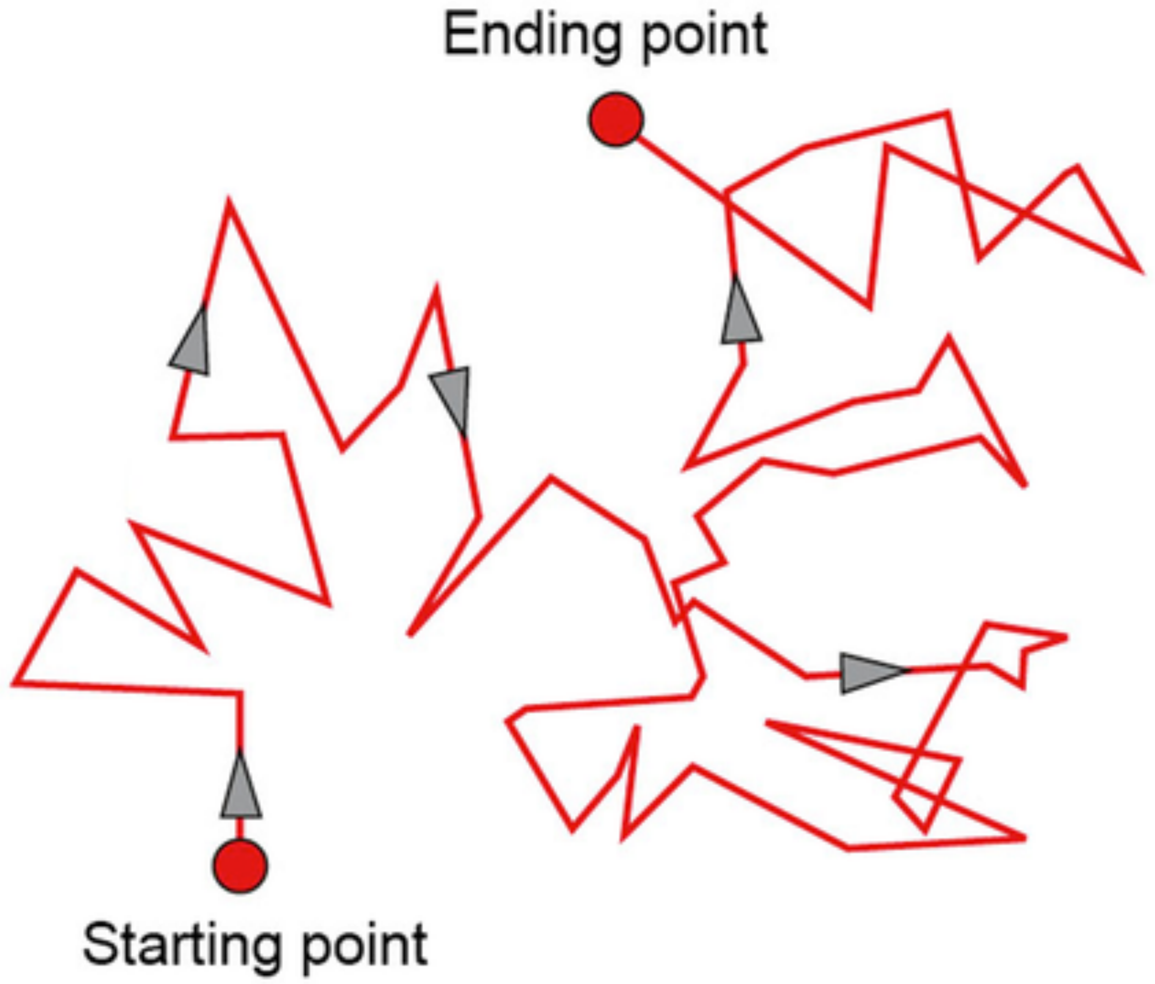

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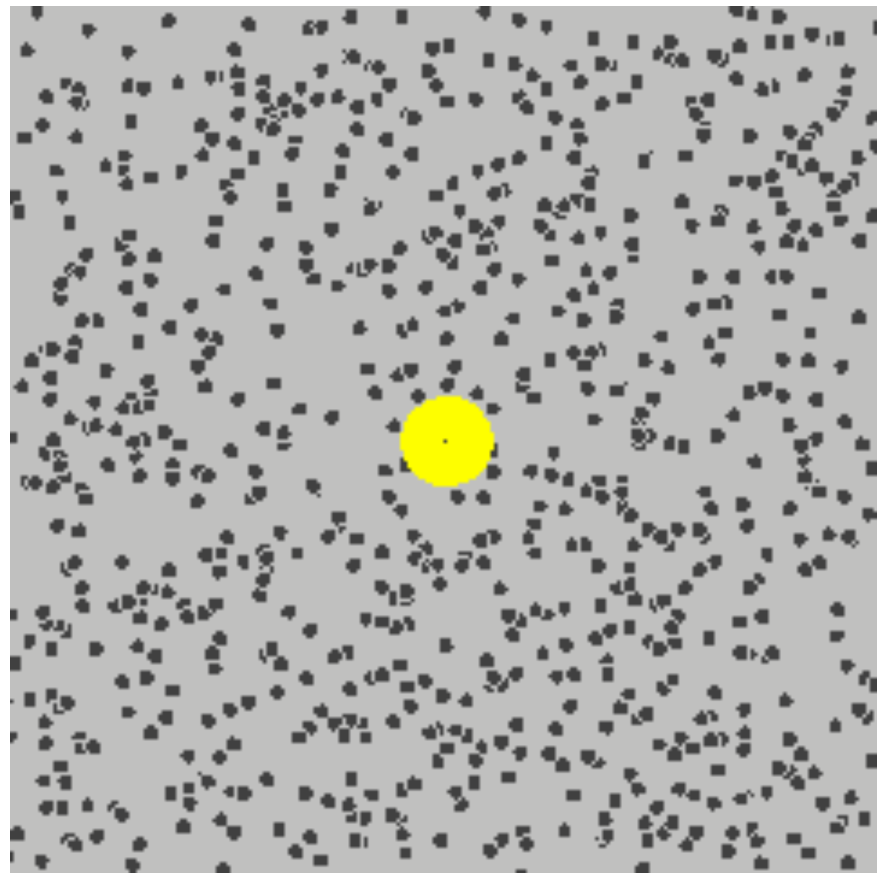

Einstein 1905

Atome

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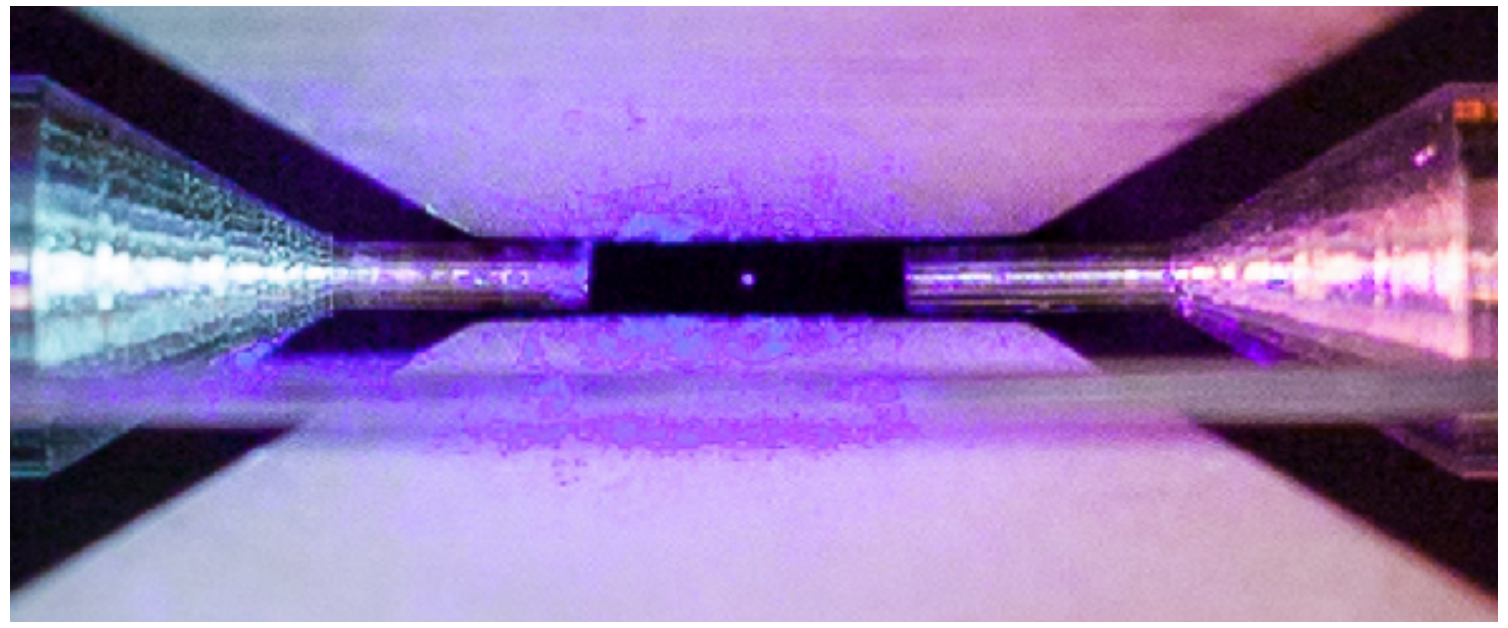

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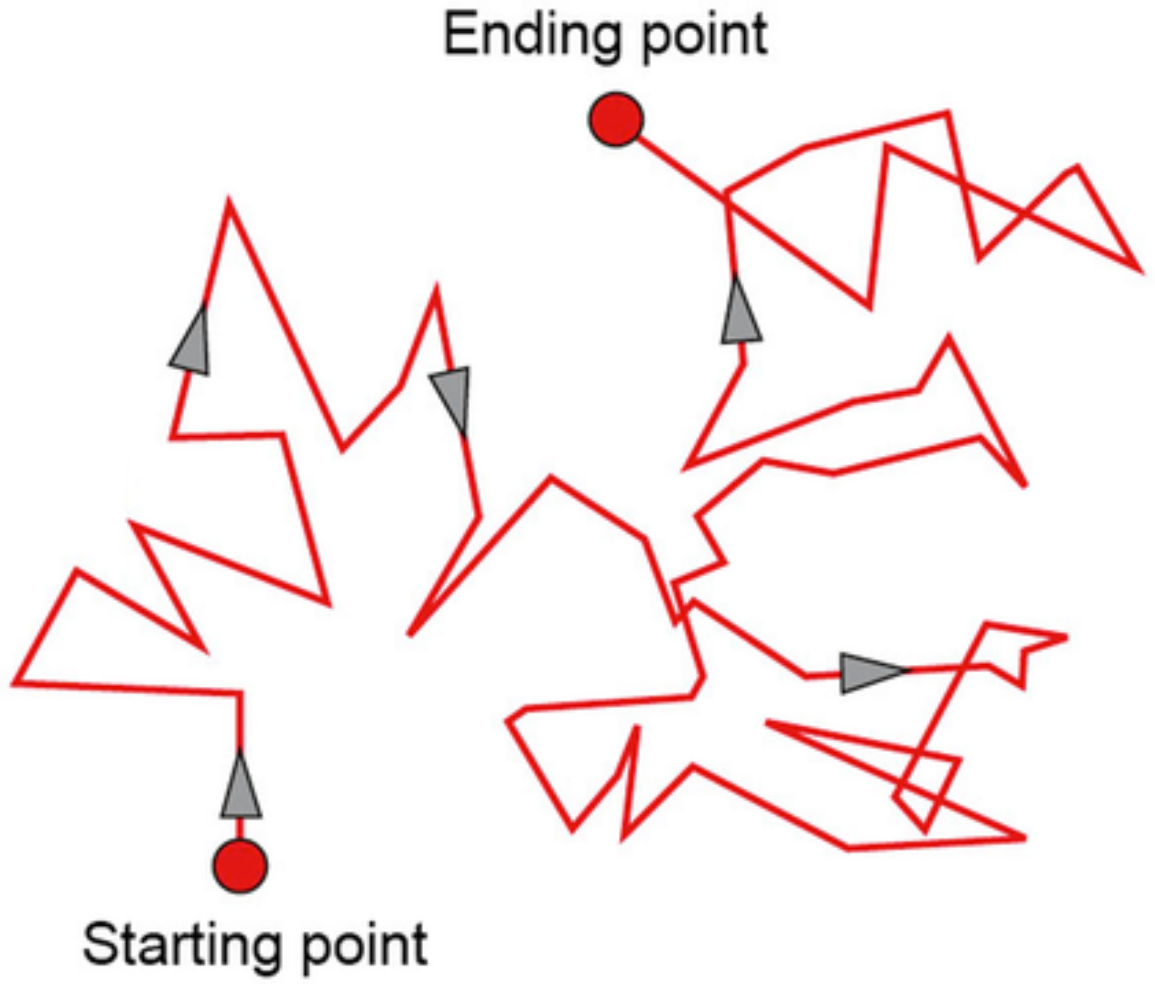
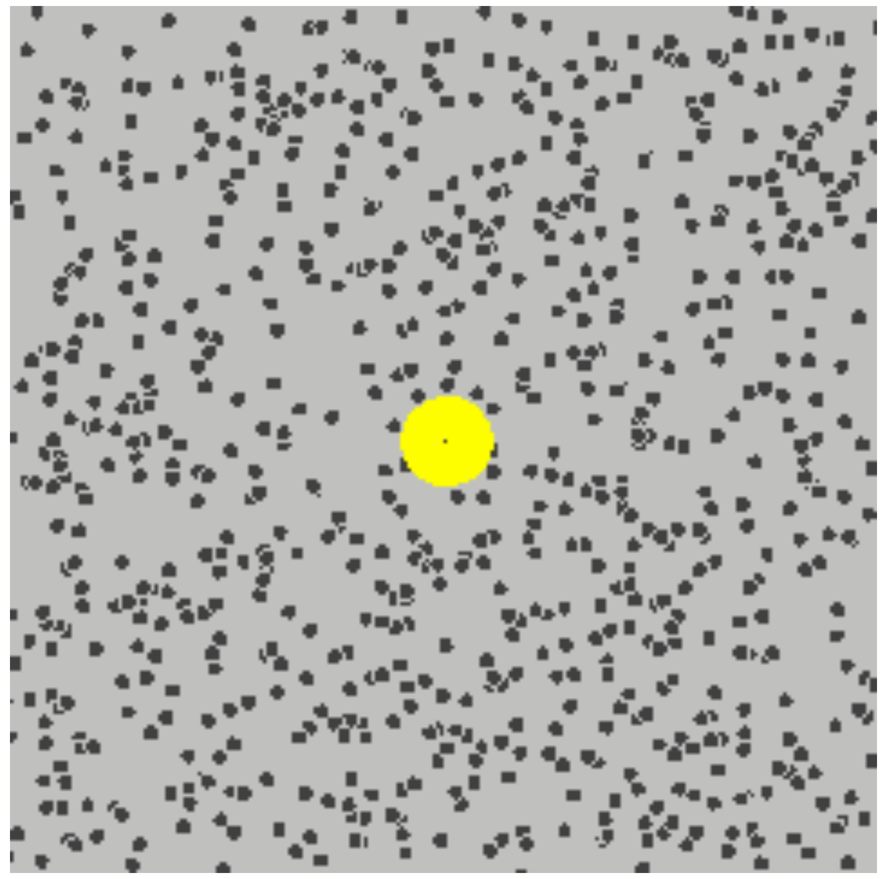


Brown 1



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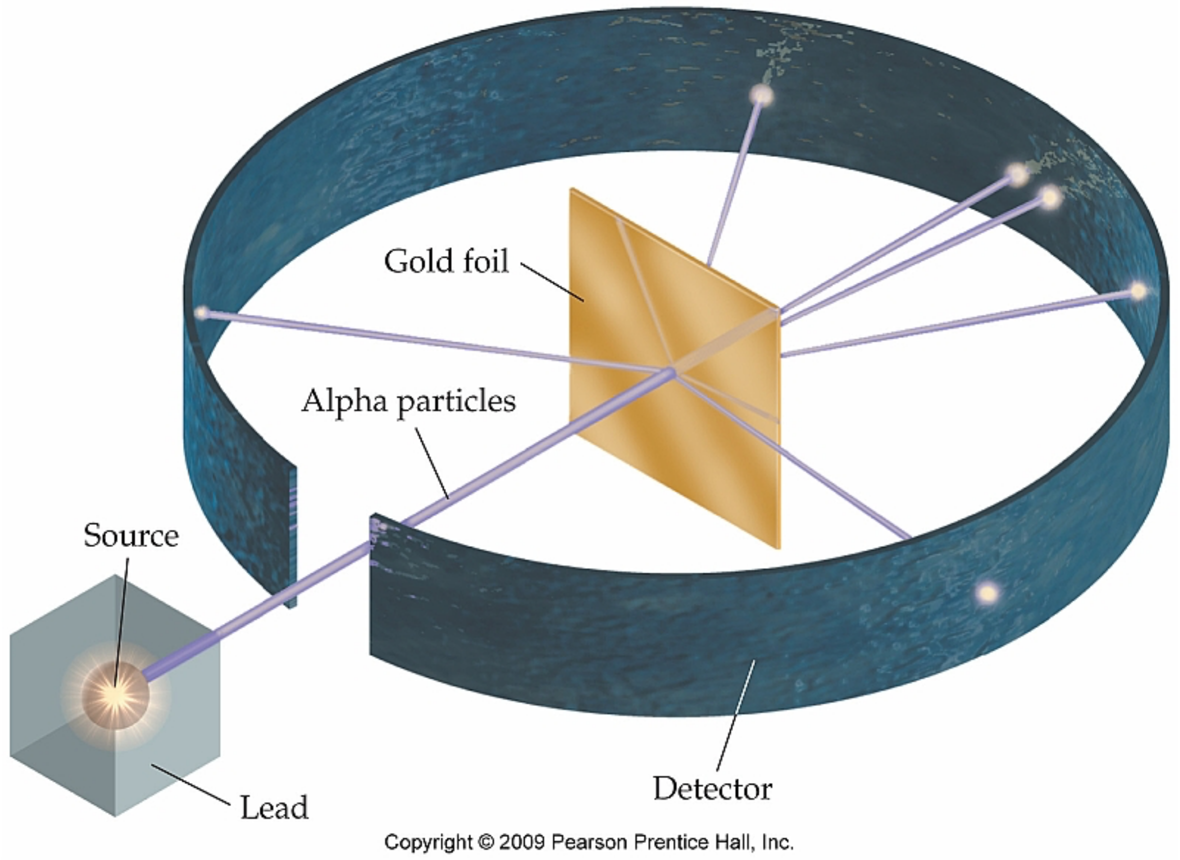
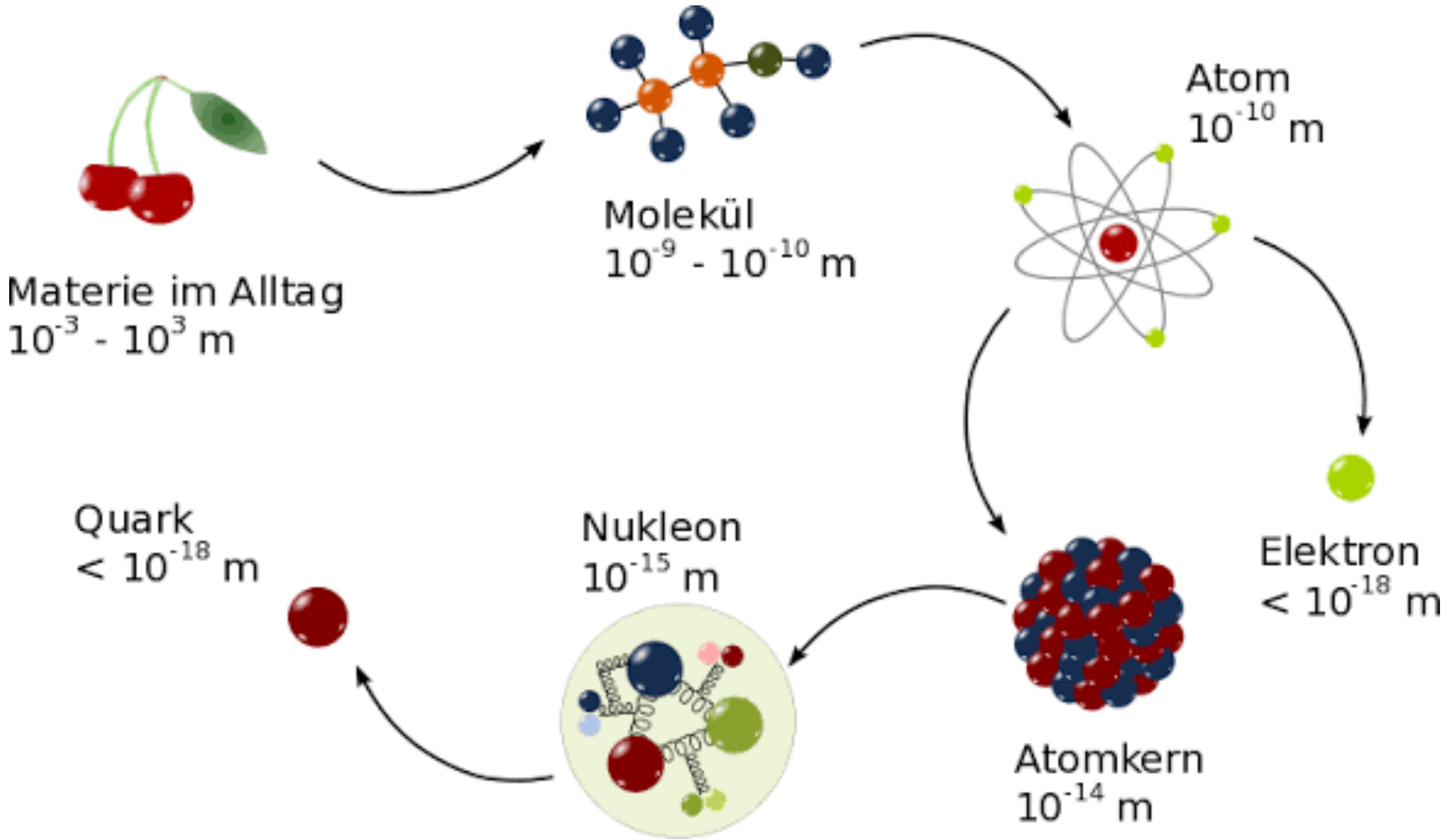


Rutherford 1909
Geiger, Marsden



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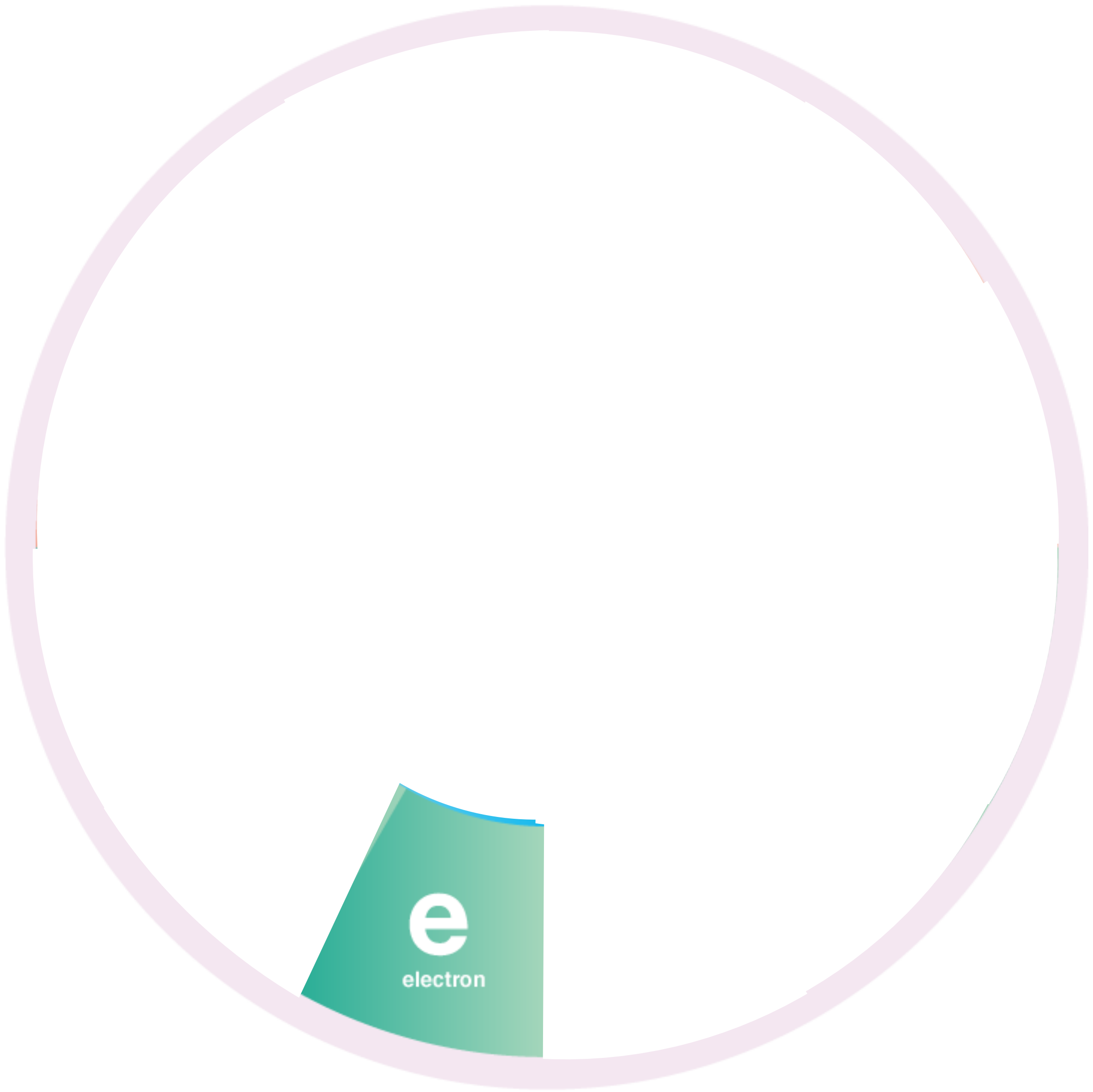
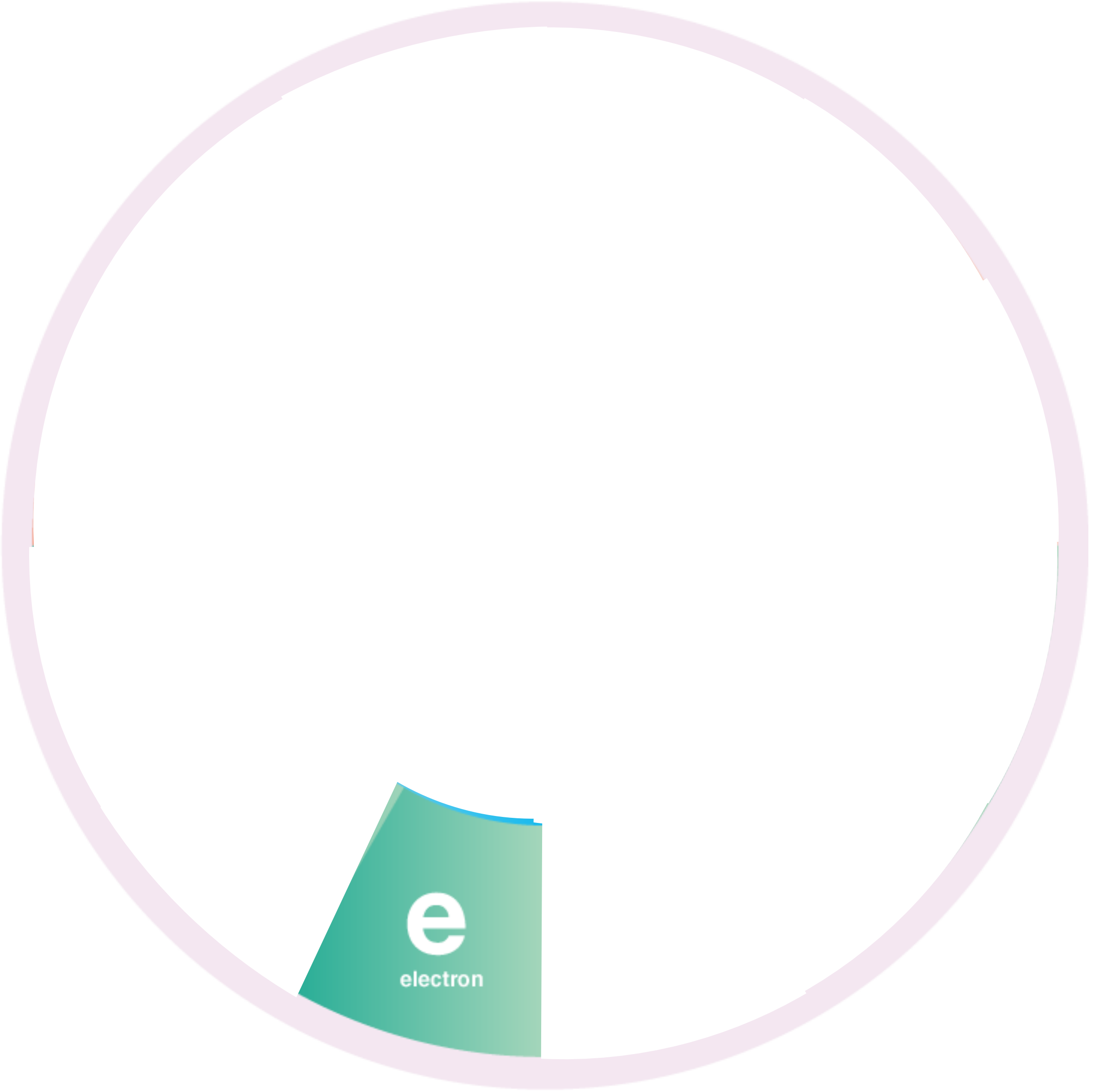
Elektron



1897 Thomson

Elektron



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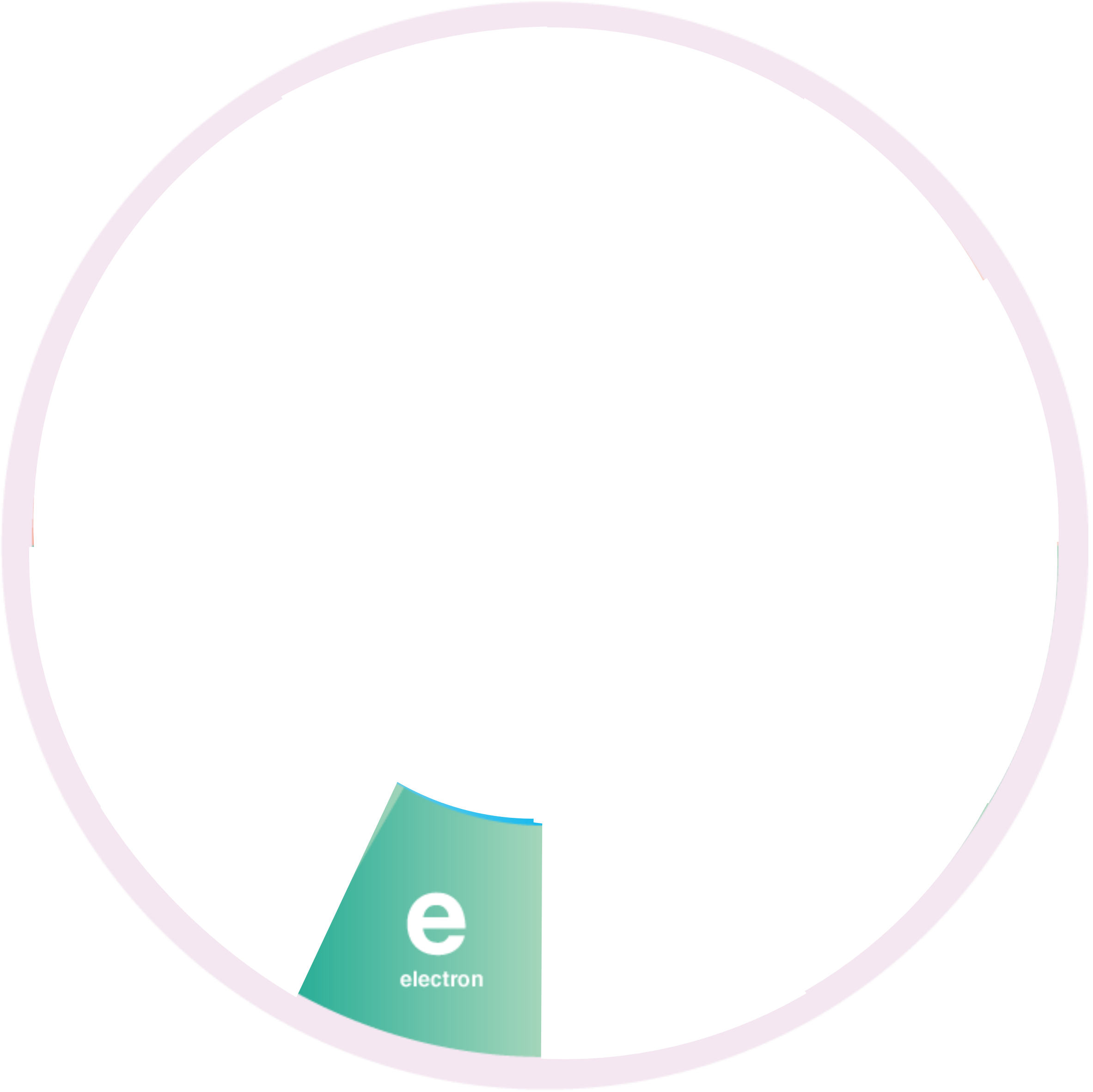

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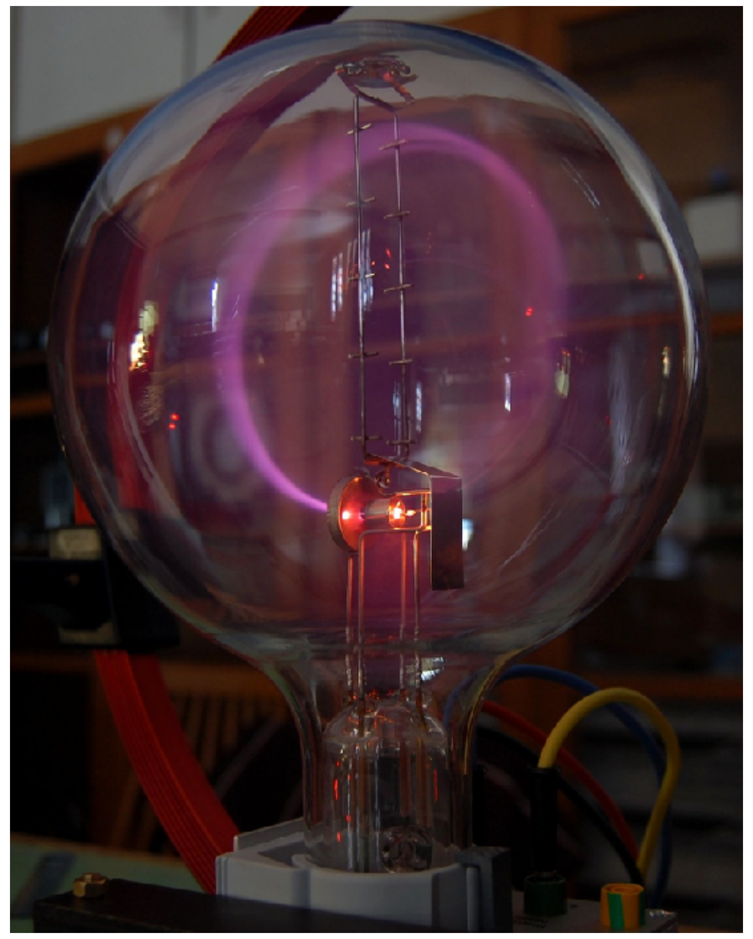

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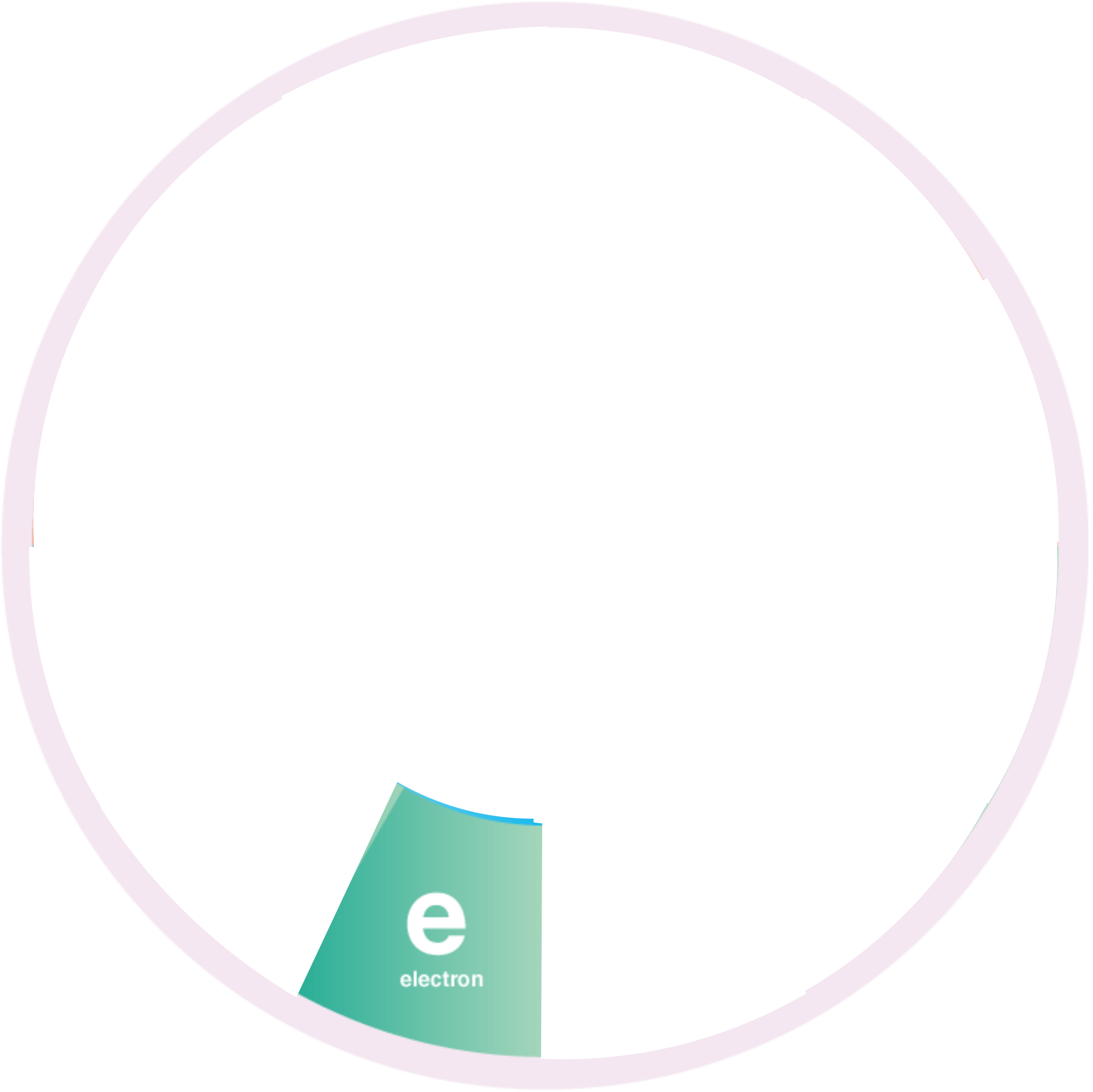

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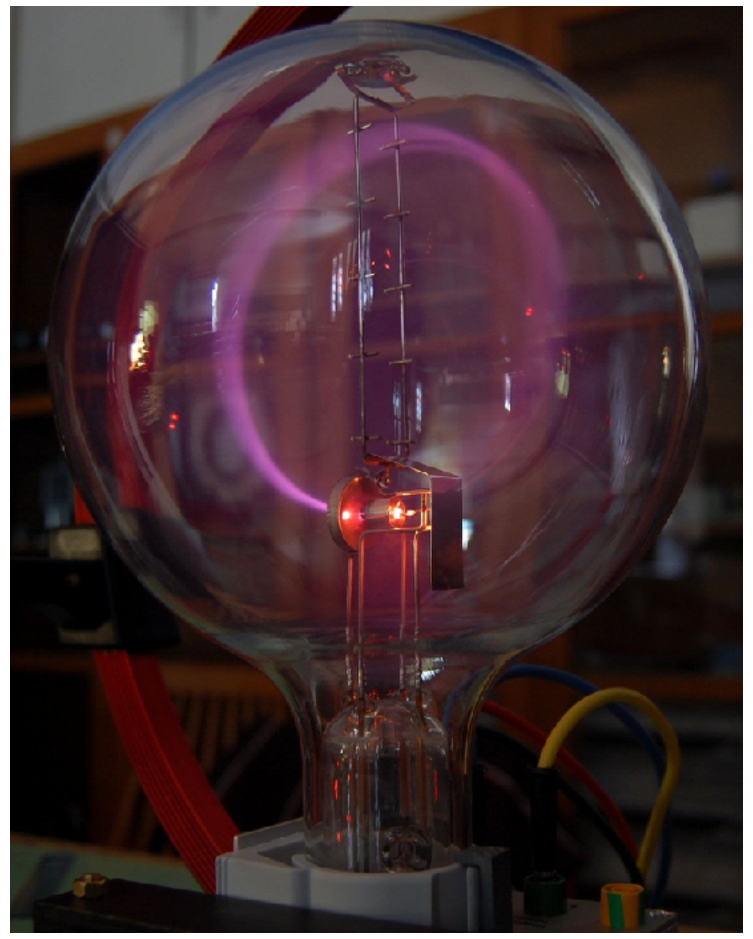
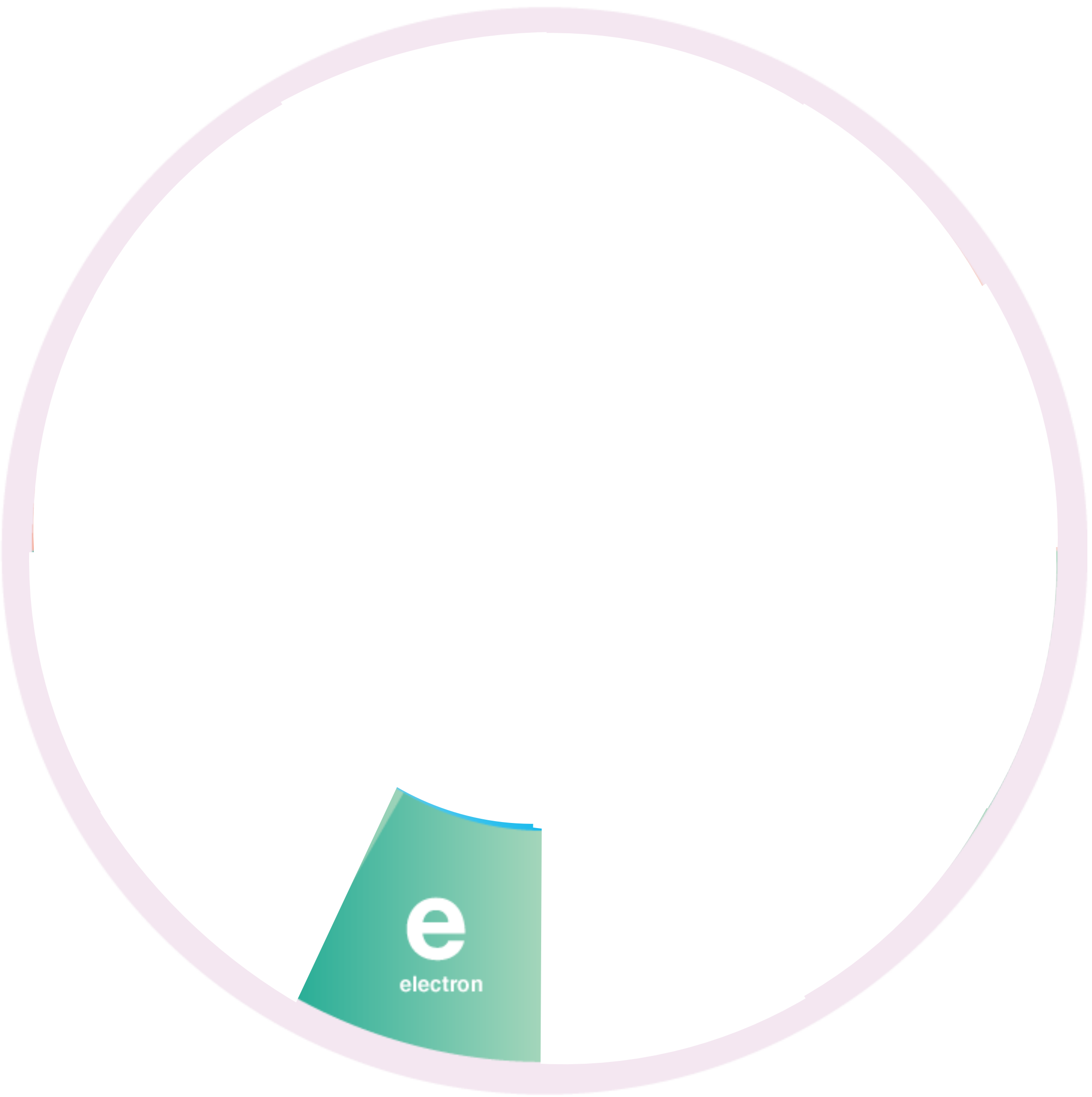


$$\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

Elektron



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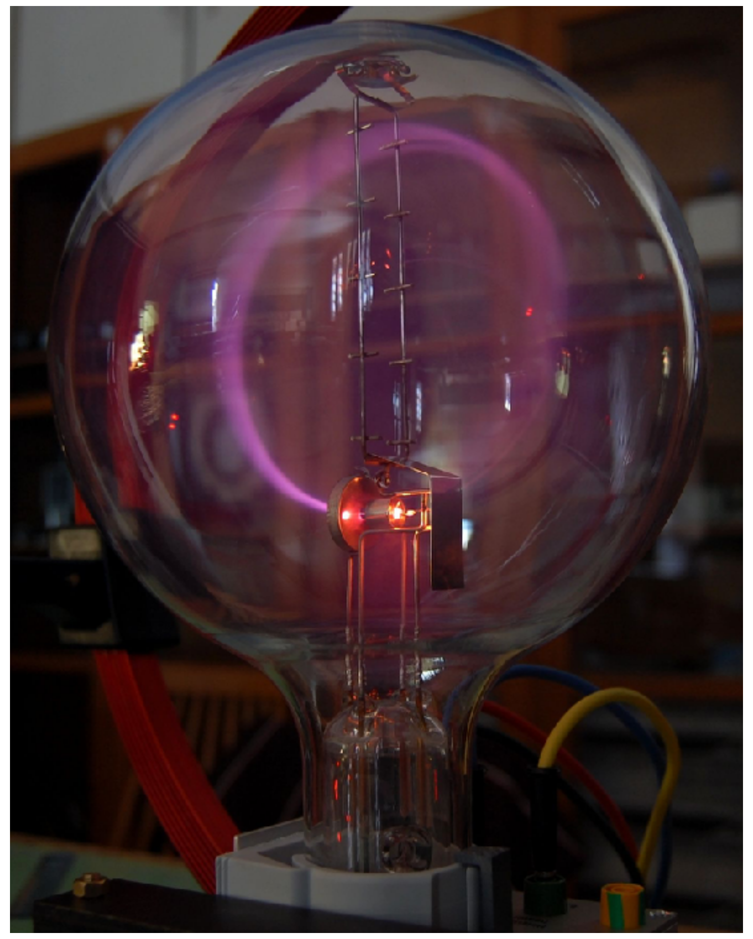


$$\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B})$$

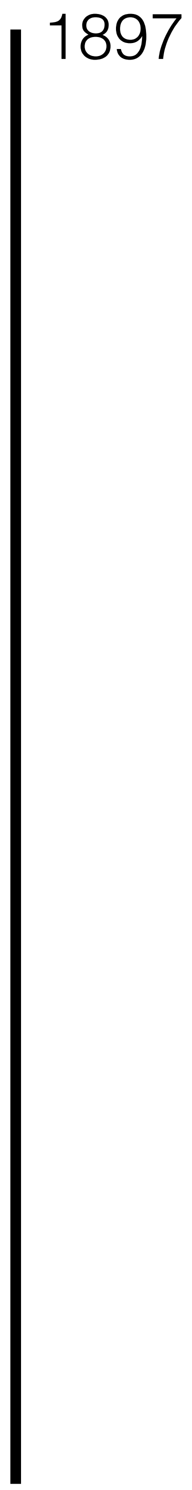
As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.

Thomson 1897

Photonen

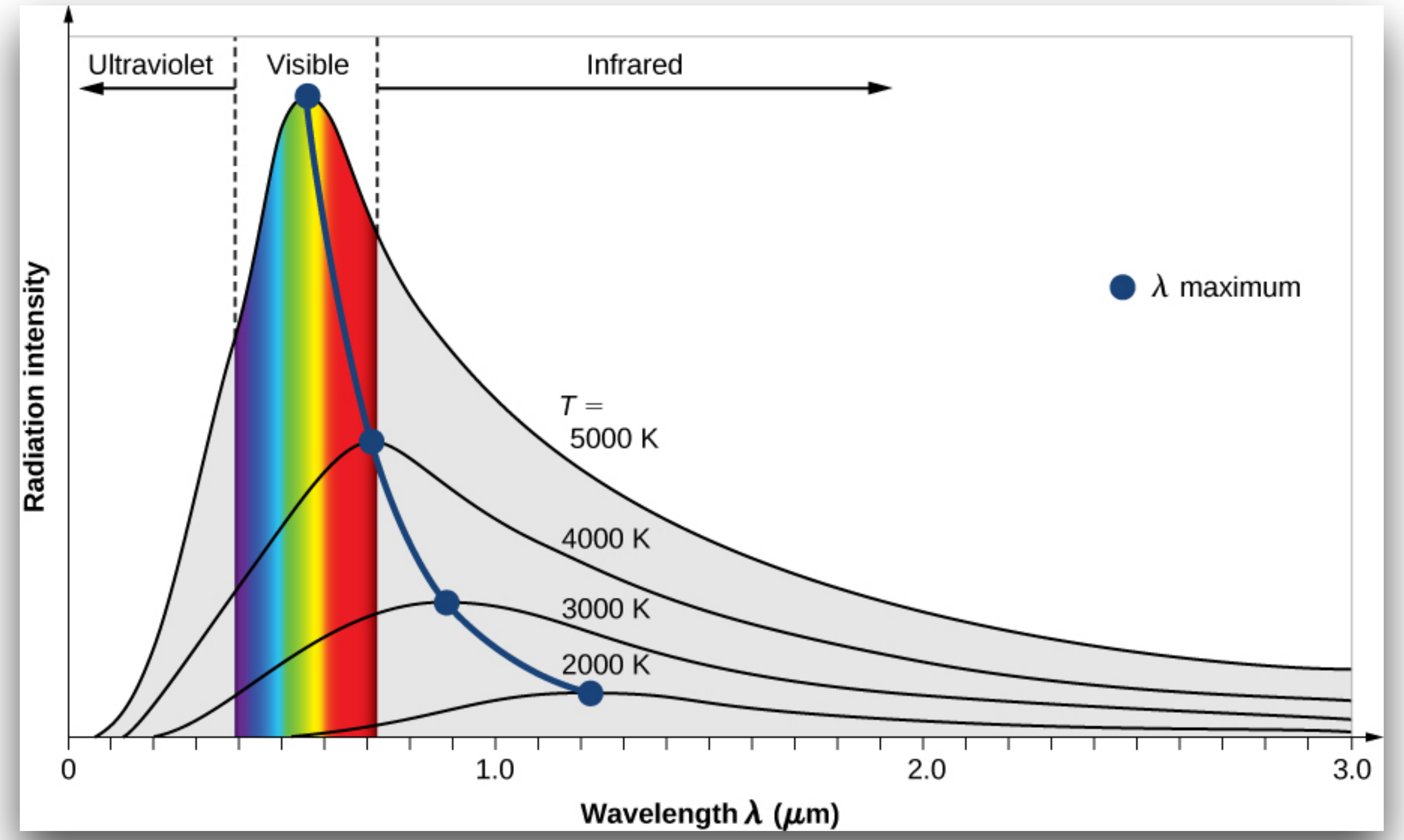
1897

Photonen



Photonen

1897
1900 Planck



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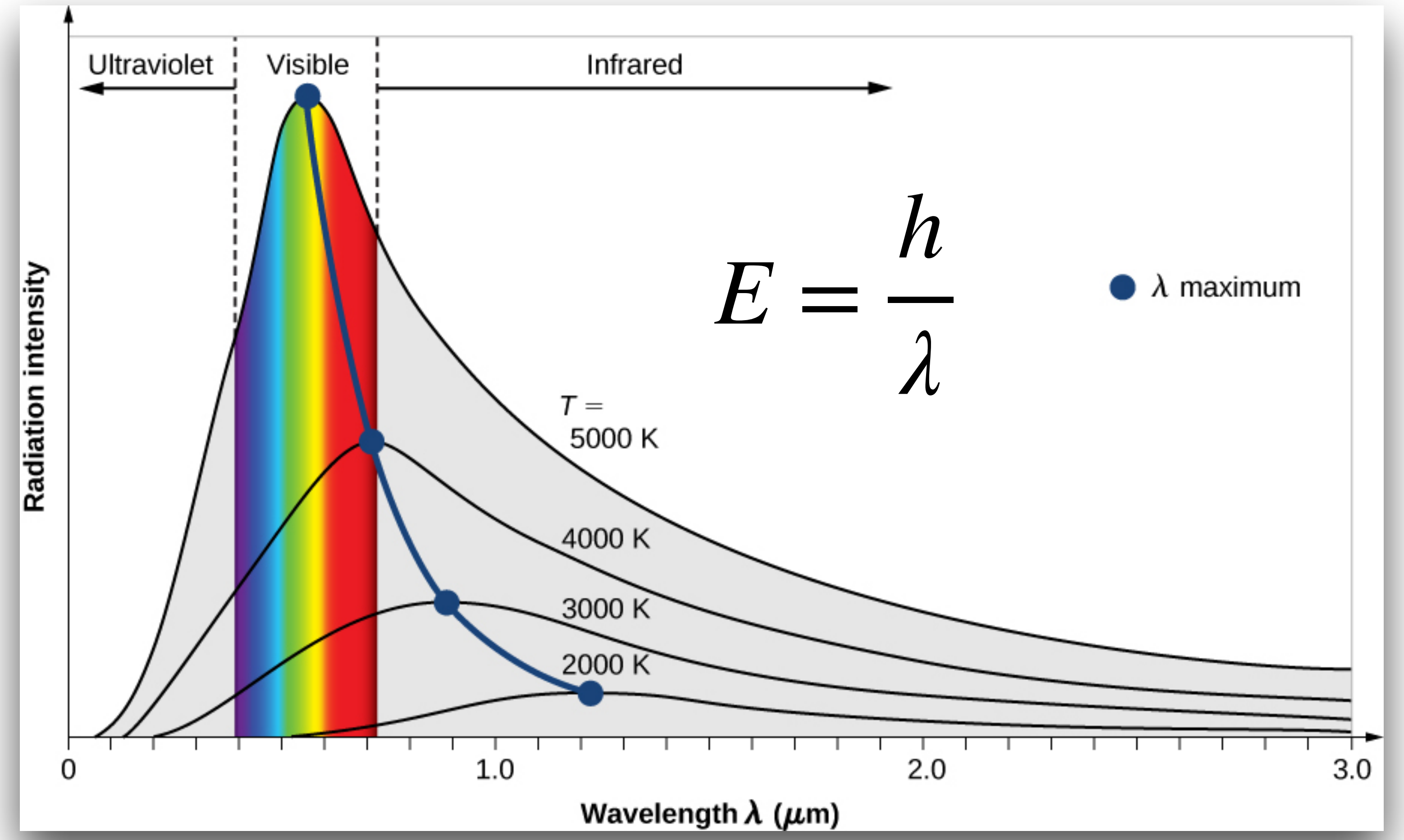
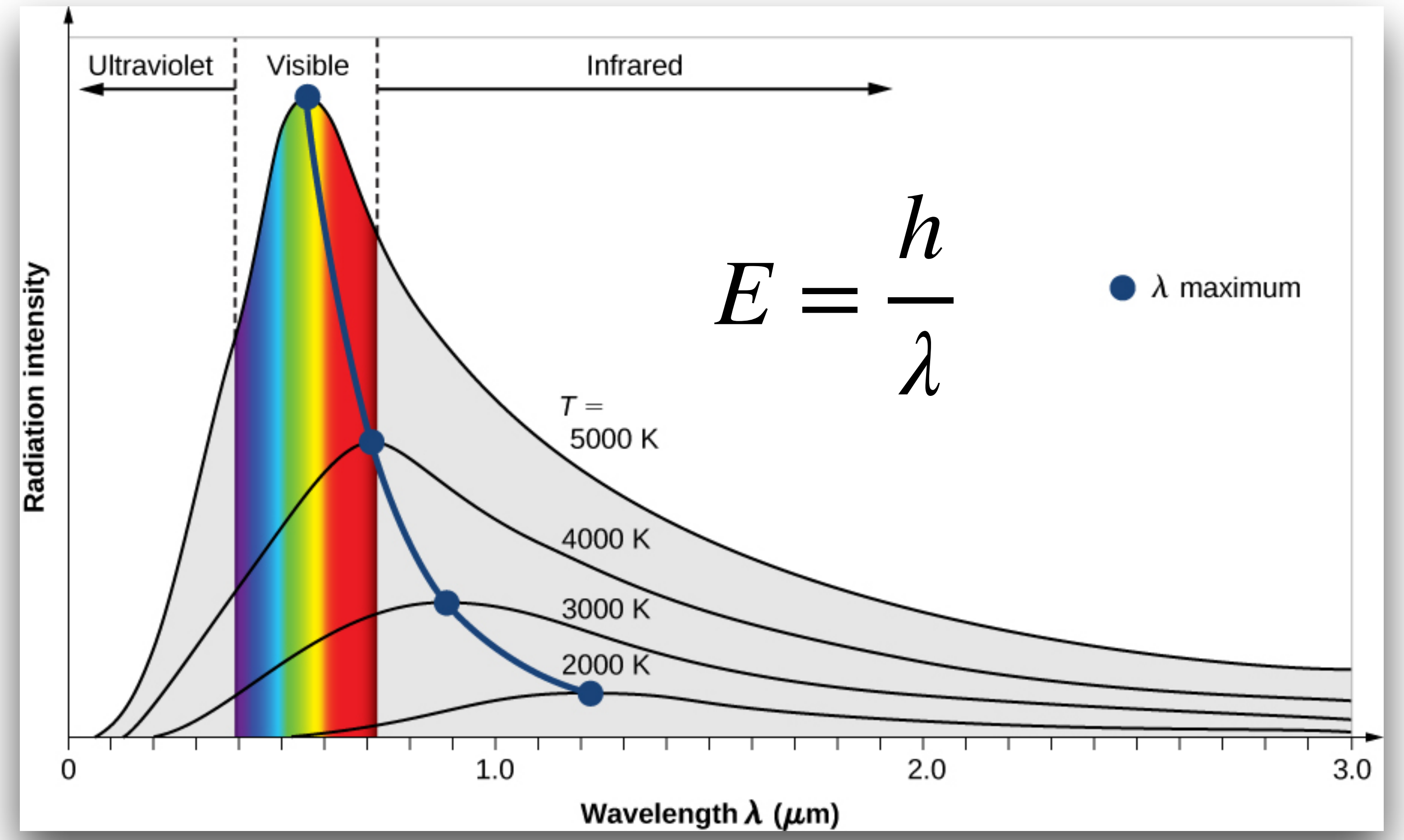
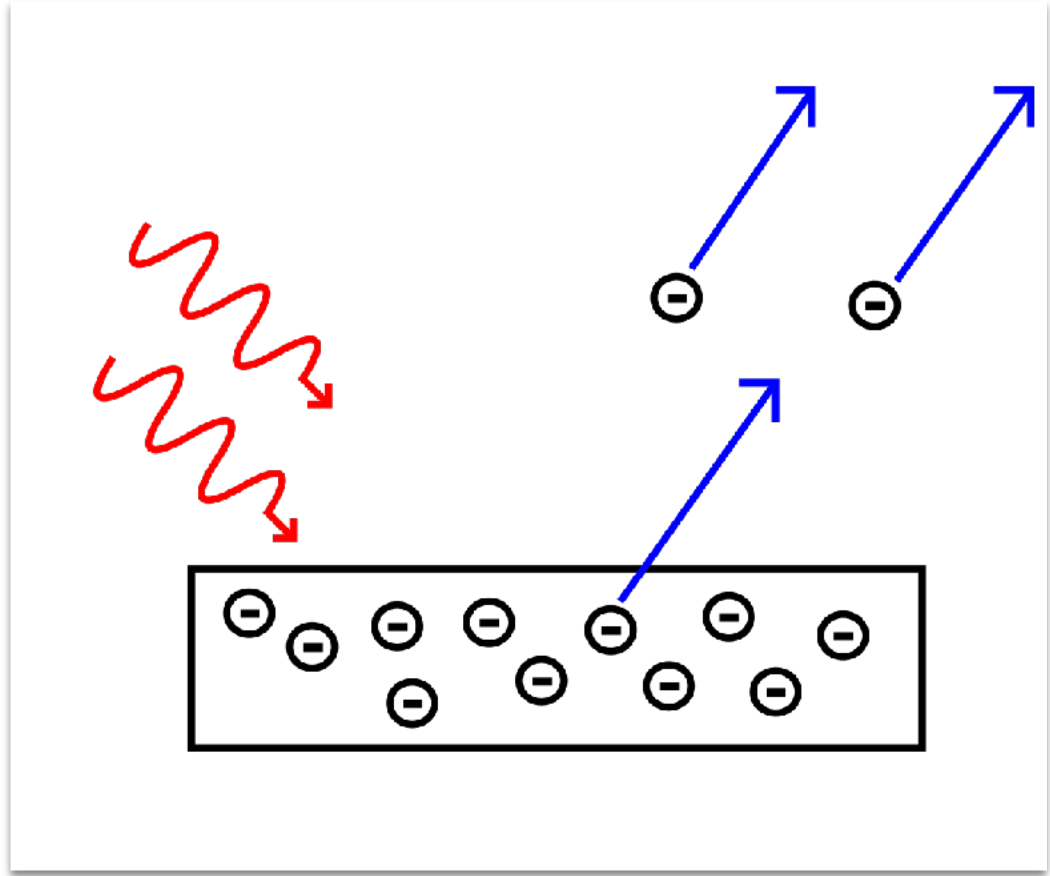


Photonen

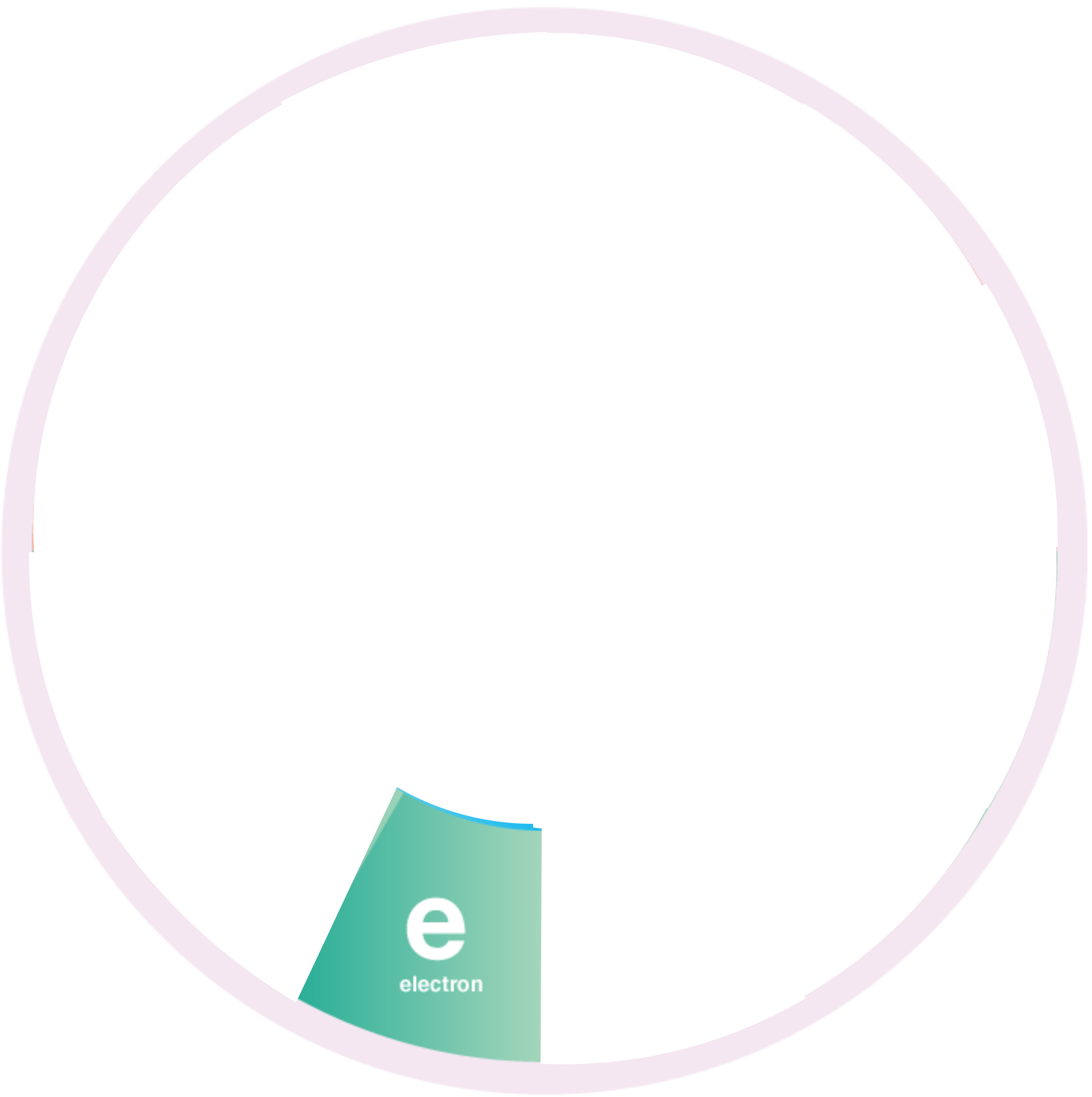

photon
electron


1897
1900 Planck
1905 Einstein


Ultraviolet
Visible
Infrared
$E = \frac{h}{\lambda}$
λ maximum
Radiation intensity
T =
5000 K
4000 K
3000 K
2000 K
0
1.0
2.0
3.0
Wavelength λ (μm)



Elektron



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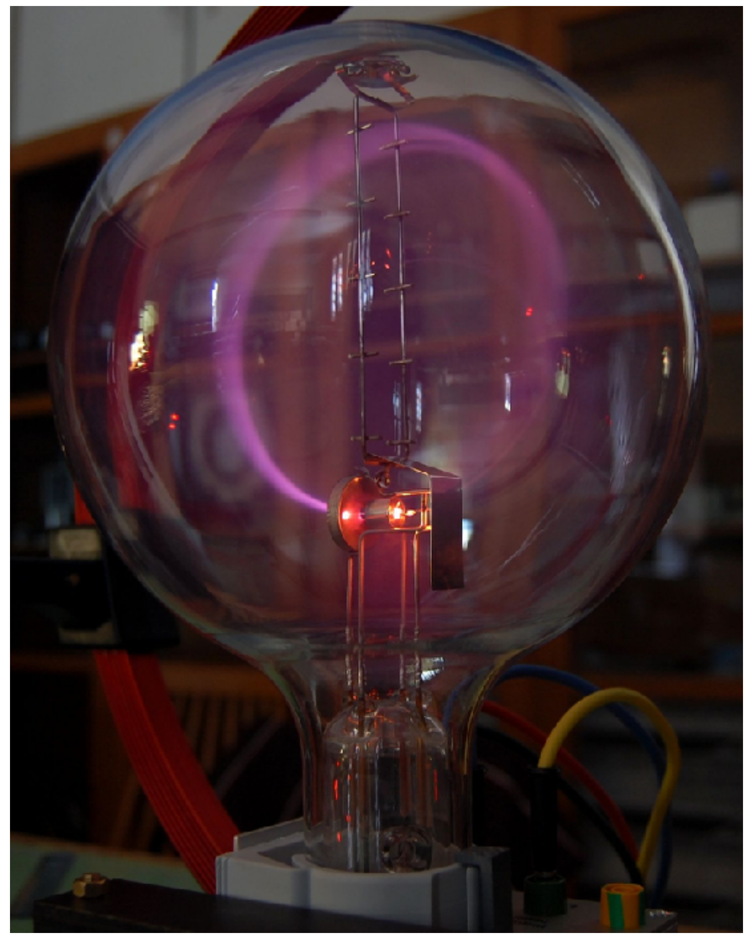

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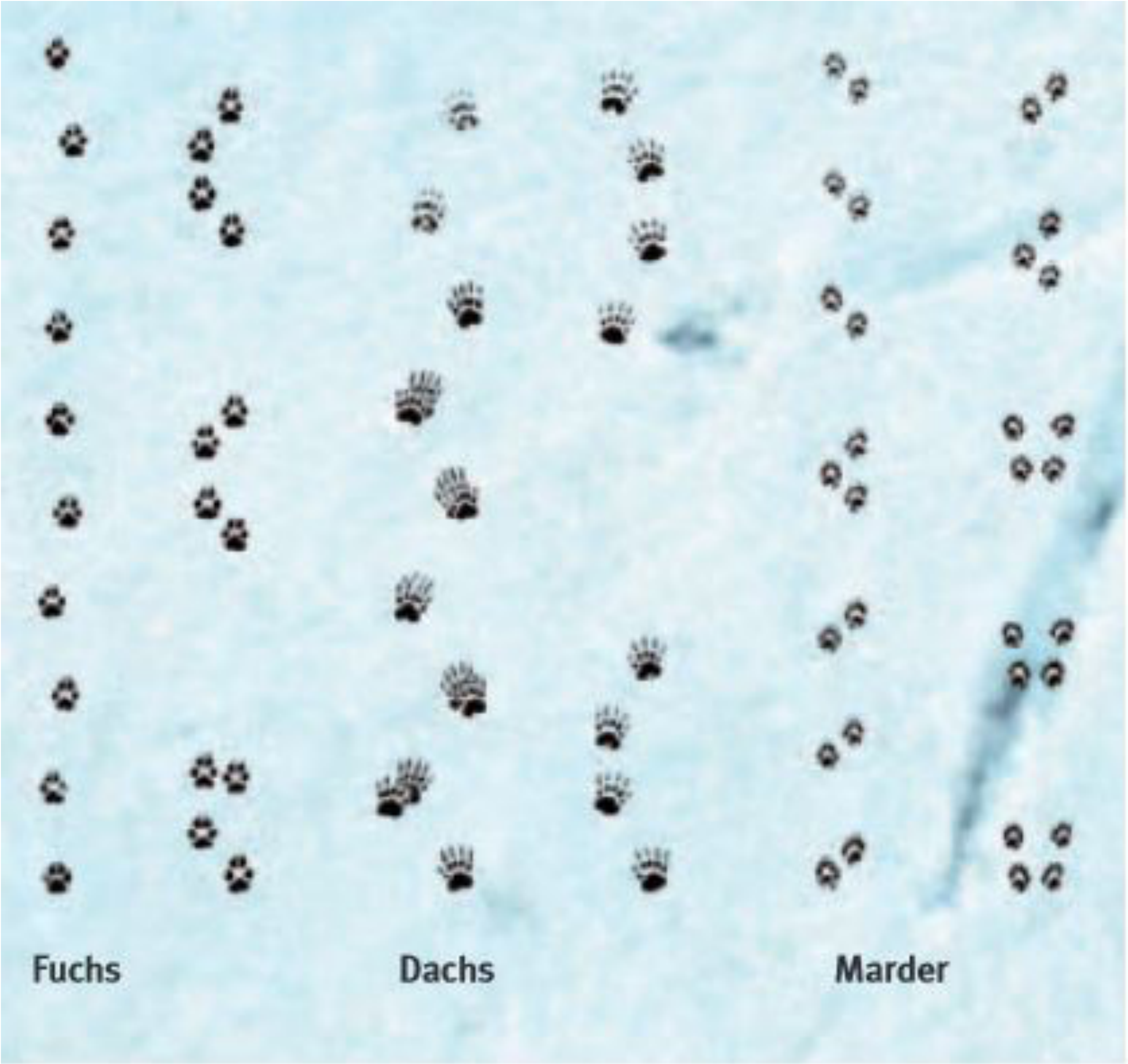

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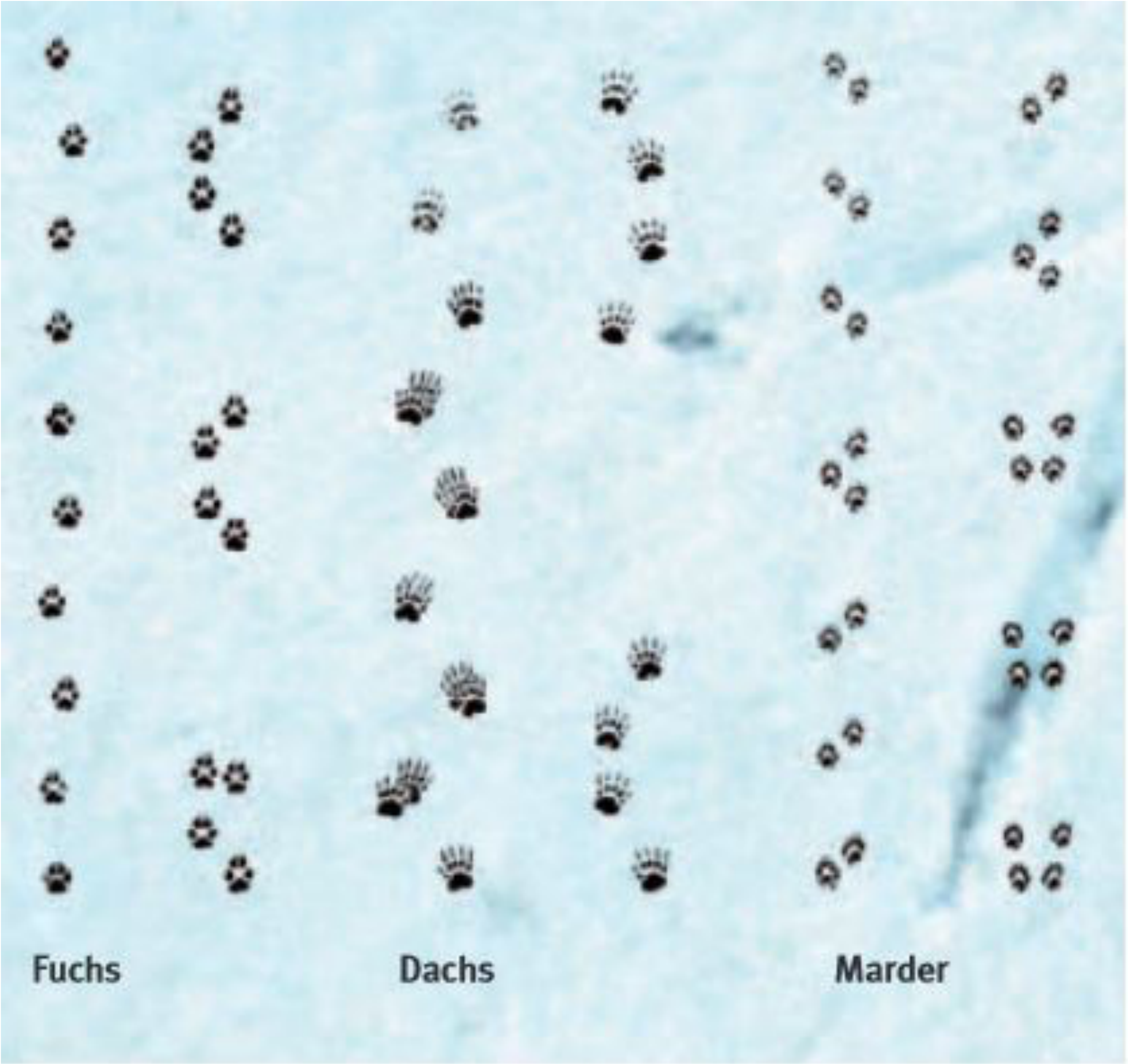
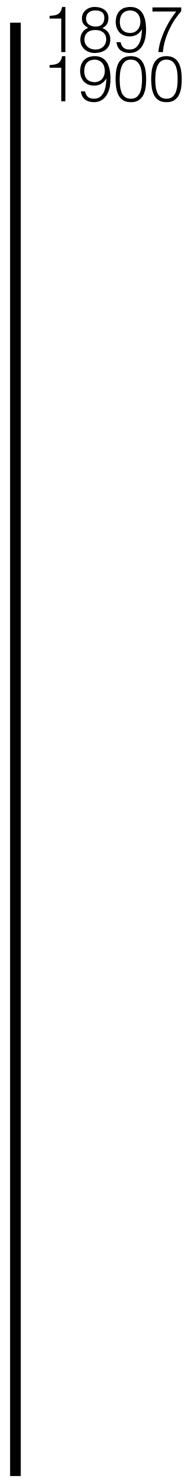
Spuren



Spuren

Ungewöhnliche Spuren



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Spuren

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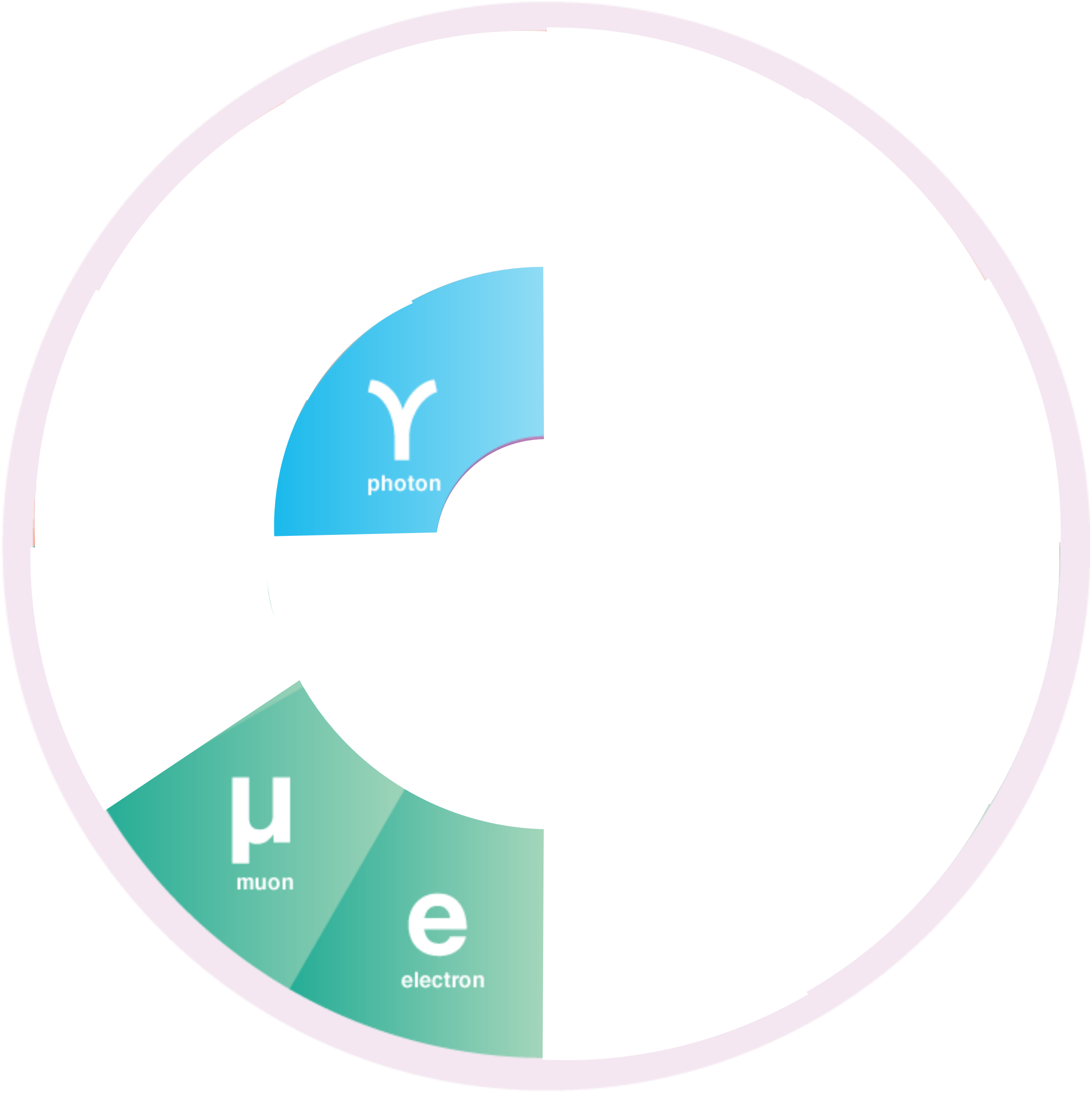
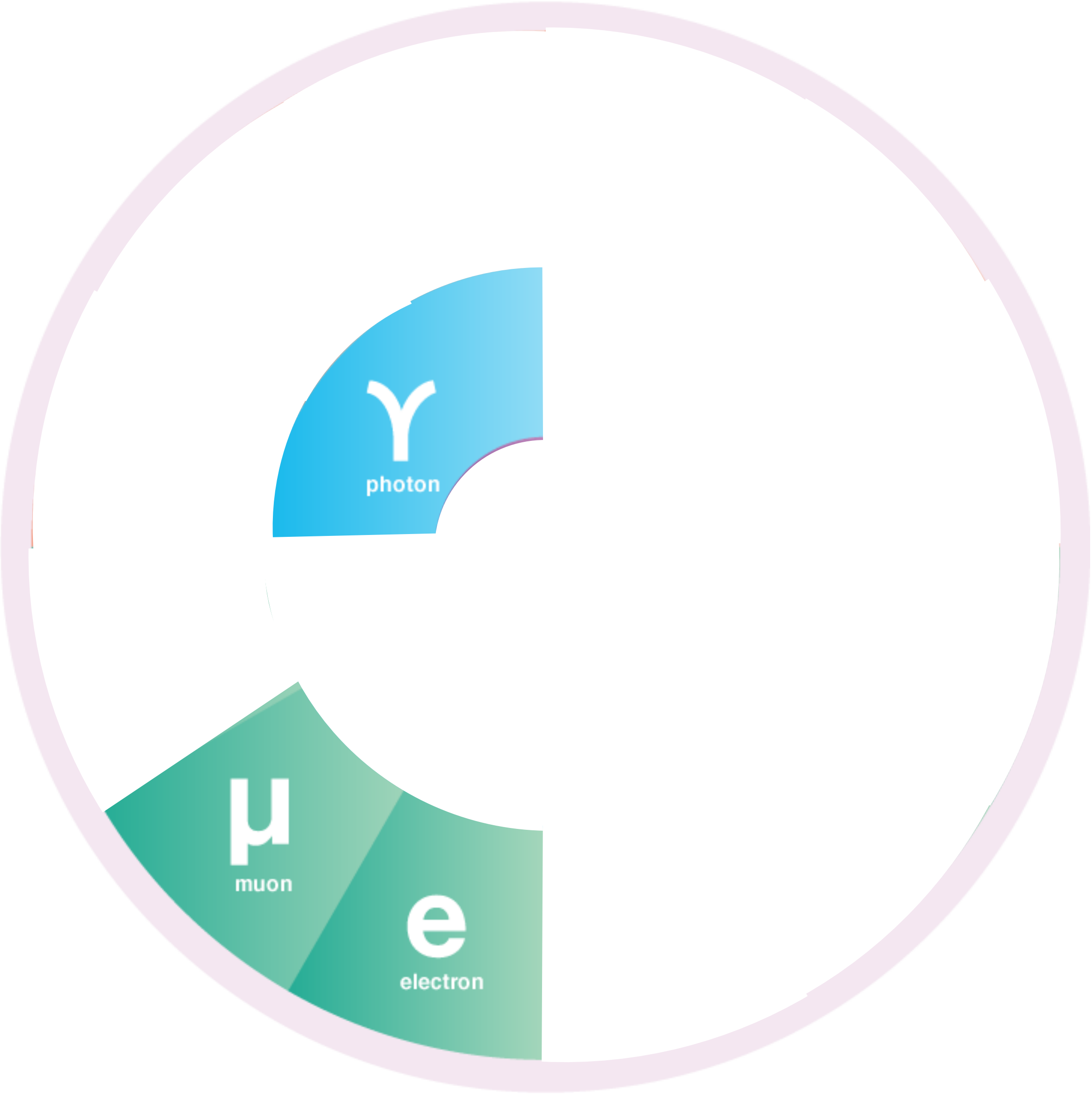


1897
1900

Spuren

Ungewöhnliche Spuren

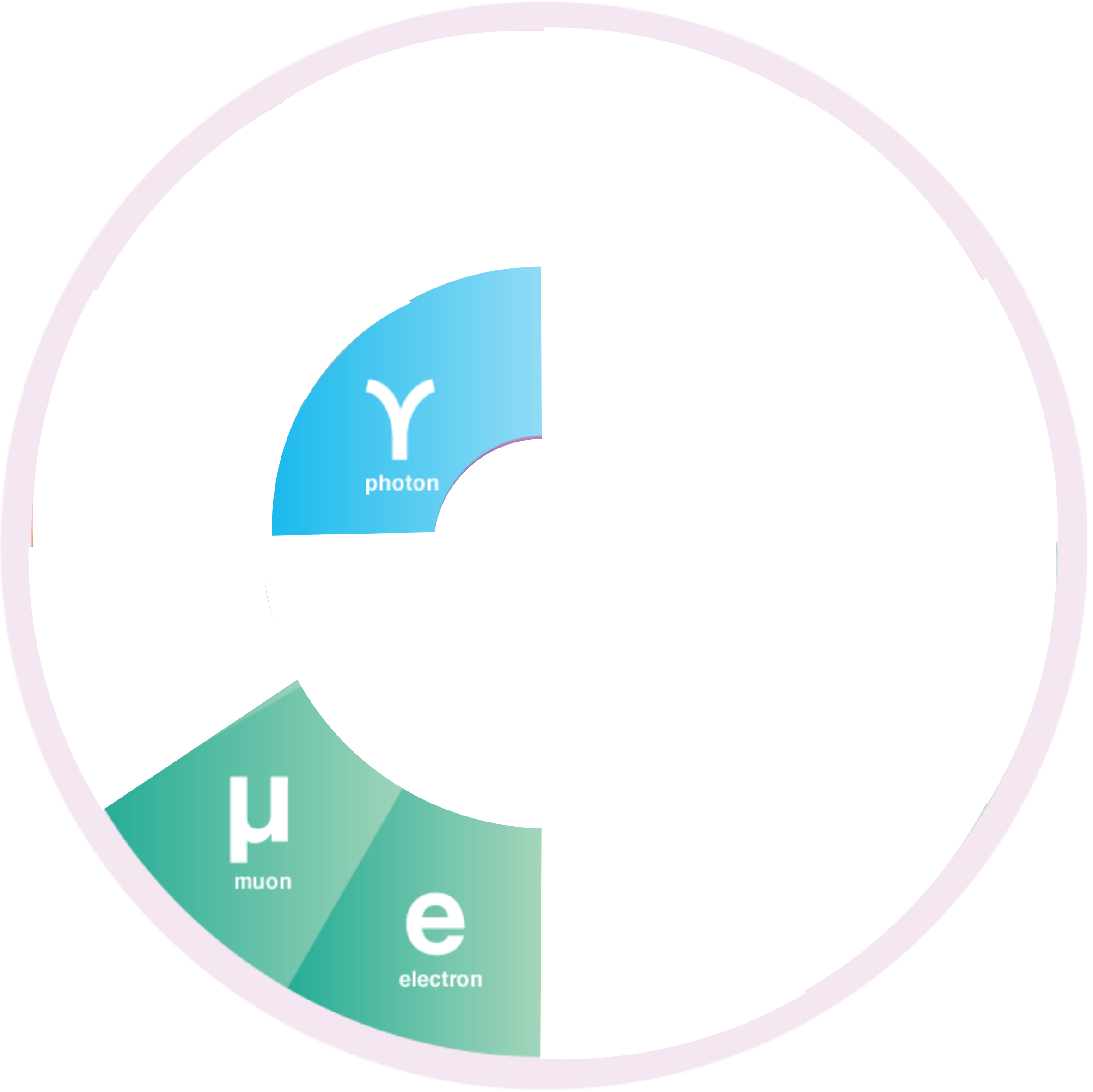


1897
1900

1937 Neddermeyer + Anderson

Spuren

Ungewöhnliche Spuren



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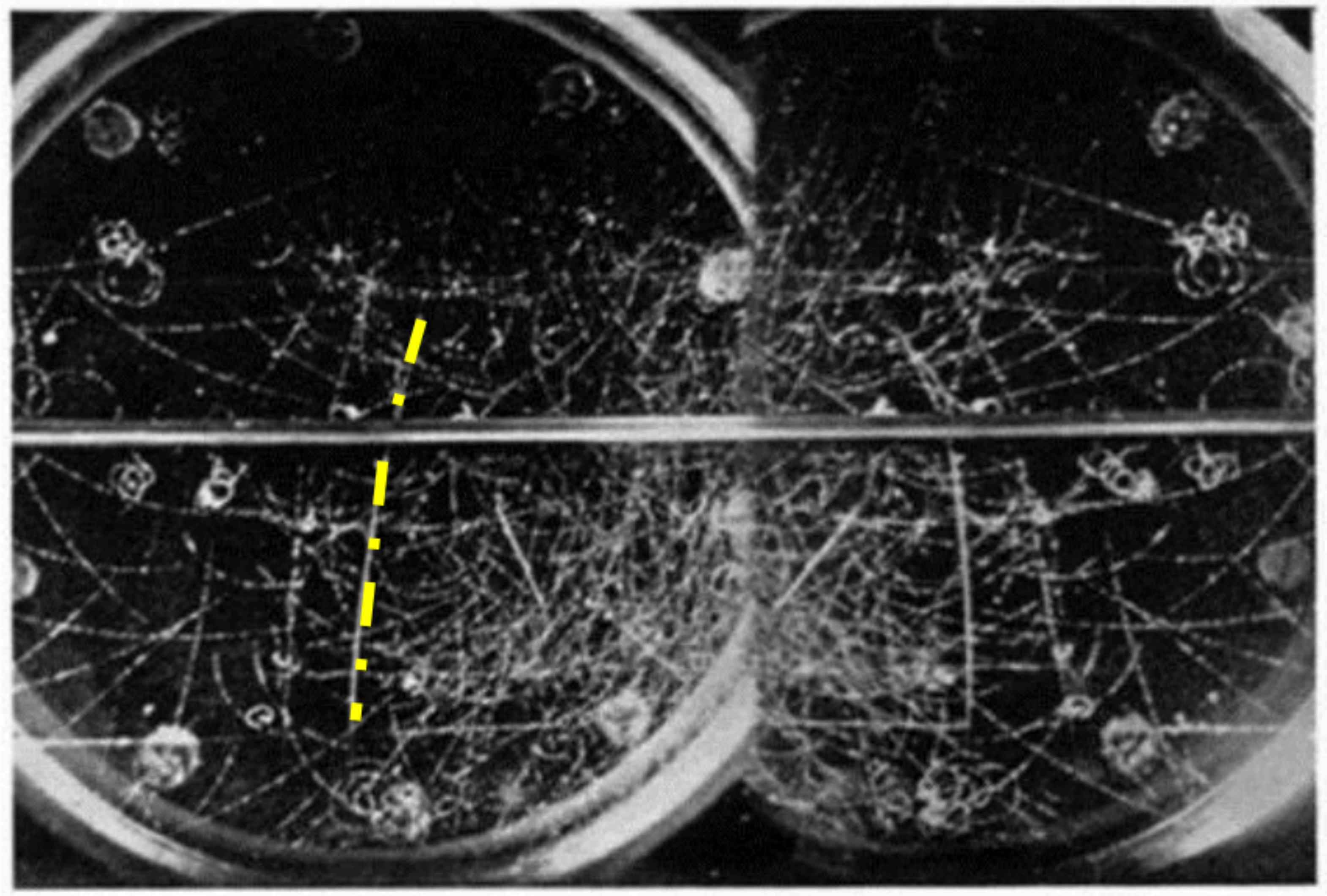
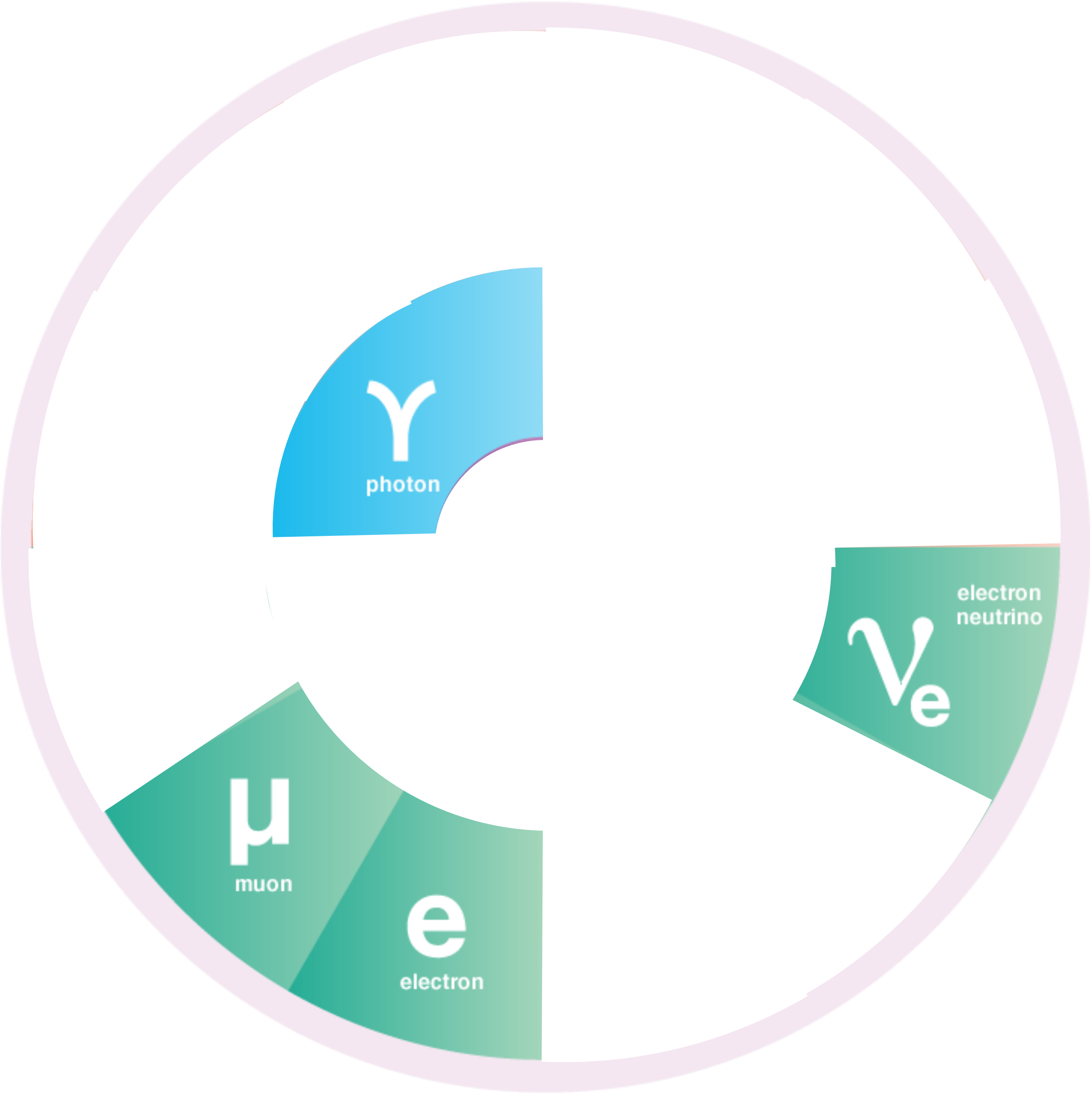
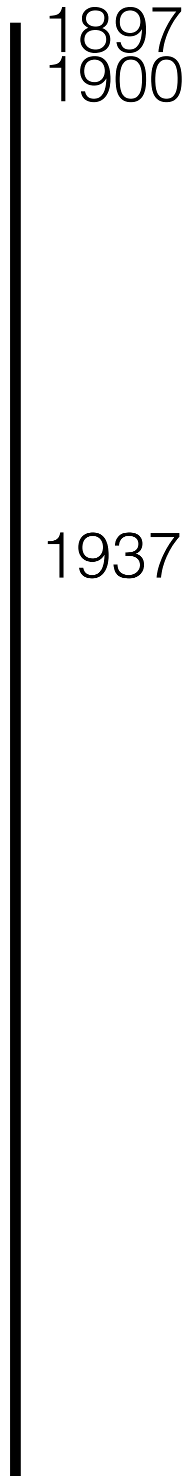


FIG. 13. Pasadena, 4500 gauss. A complex electron shower not clearly defined in direction, and three heavy particles with specific ionizations definitely greater than that of electrons. The sign of charge of two of these heavy particles represented by short tracks cannot be determined, but the assumption that they represent protons is consistent with the information supplied by the photograph. The third heavy track appears above the 0.35 cm lead plate where it has a specific ionization not noticeably different from that of an electron. It penetrates the lead plate and appears in the lower half of the chamber as a nearly vertical track near the middle. Below the plate it shows a greater ionization than an electron, and is deviated in the magnetic field to indicate a positively charged particle. Its $H\rho$ is apparently at most 1.4×10^5 gauss cm, which corresponds to a proton energy of 1 MEV and a range of only 2 cm in the chamber, whereas the observed range is greater than 5 cm. A difficulty of the same nature was discussed in the description of the previous photograph.

Neutrinos

keine Spuren

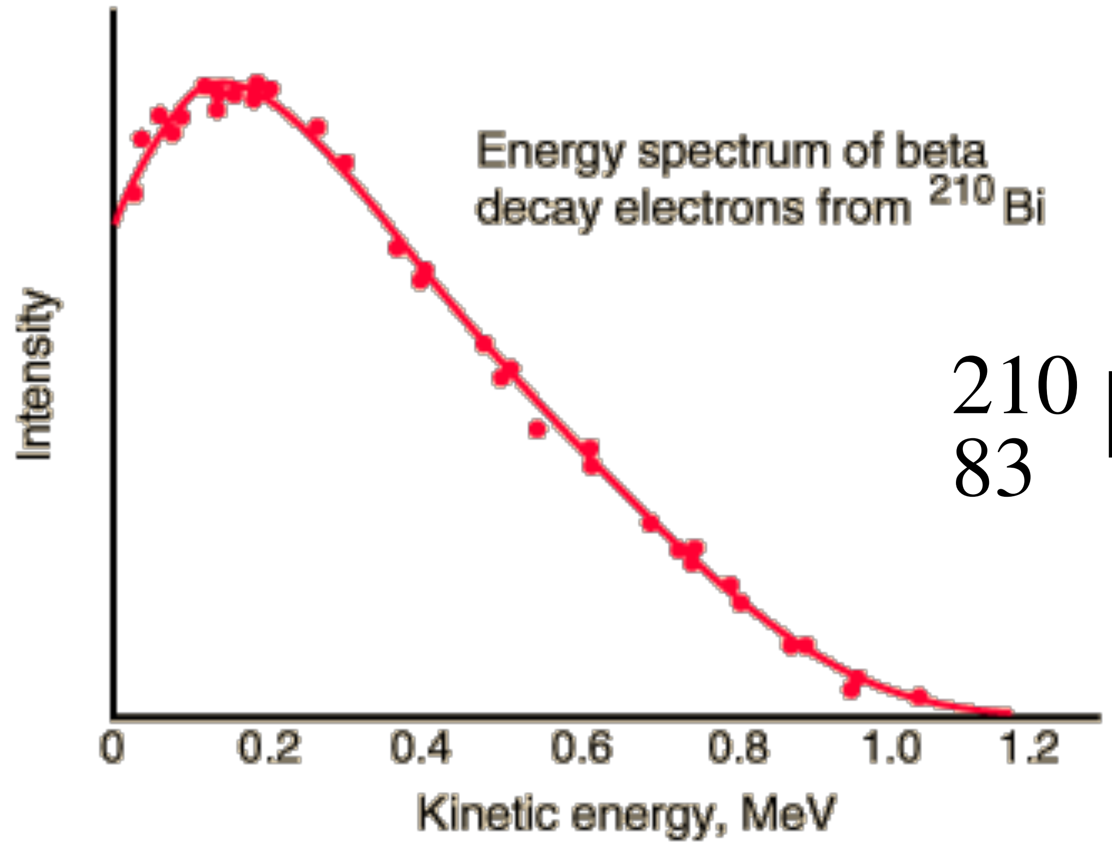




Neutrinos

keine Spuren

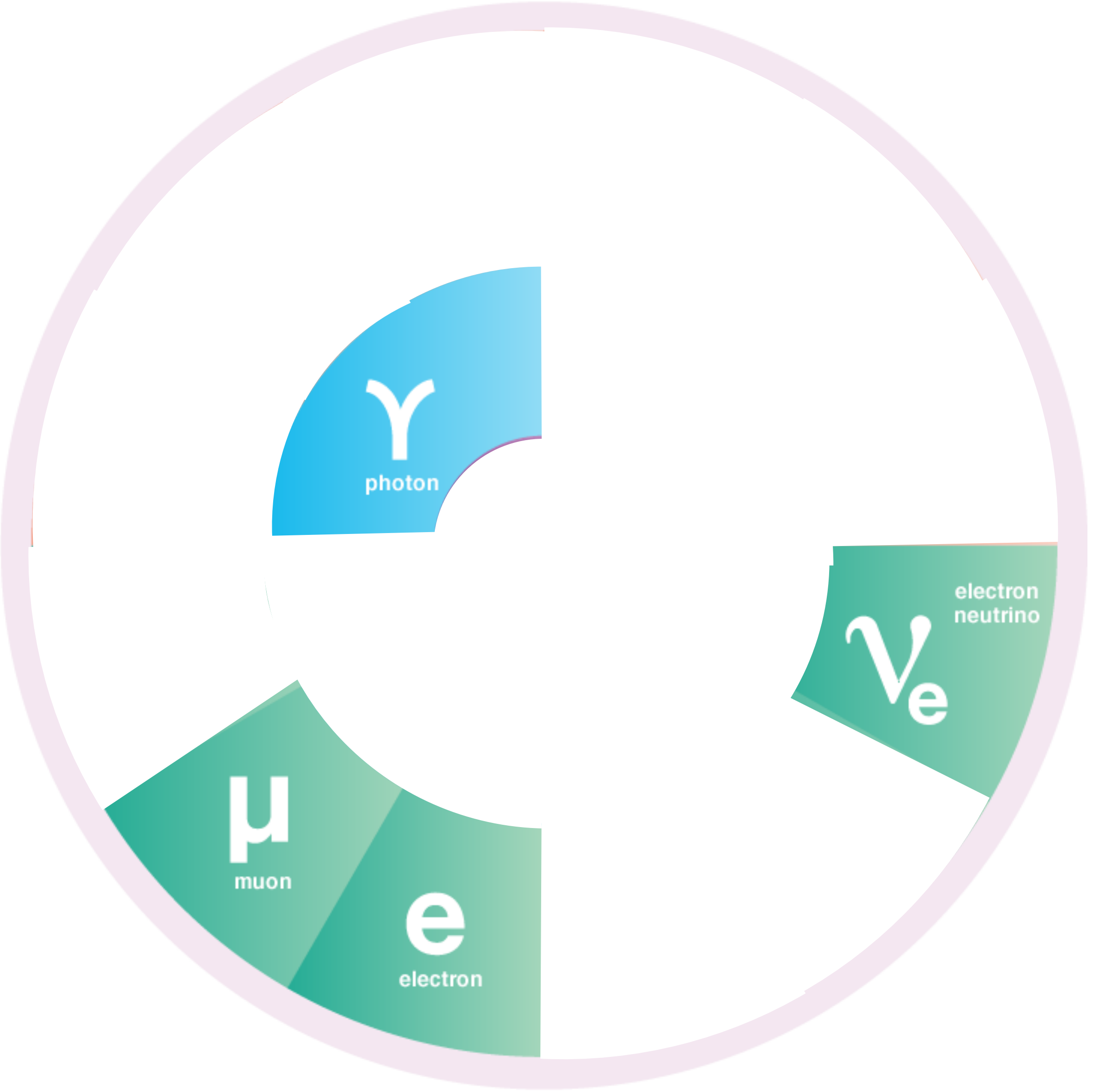
1897
1900
1937



$$^{210}_{83}\mathrm{Bi} \to {}^{210}_{82}\mathrm{Pb} + e^{+}$$

Neutrinos

keine Spuren



1897
1900

1930 Pauli
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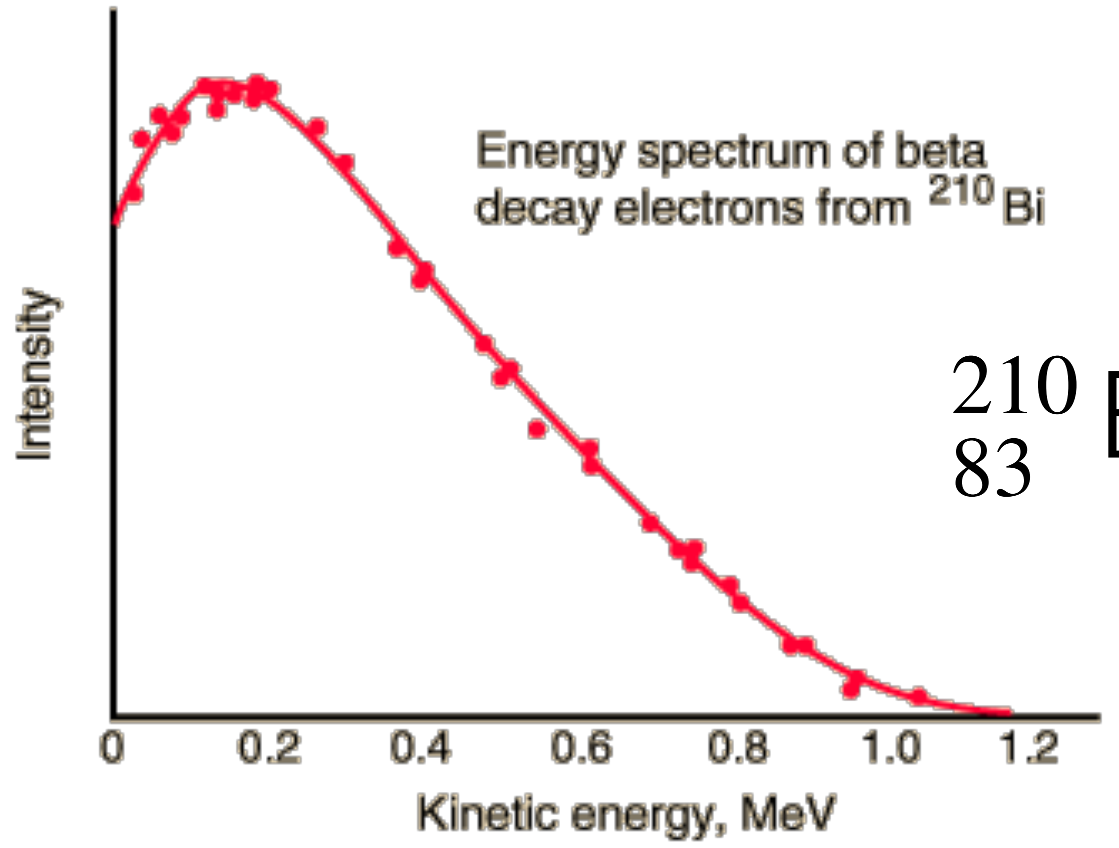

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Neutrinos

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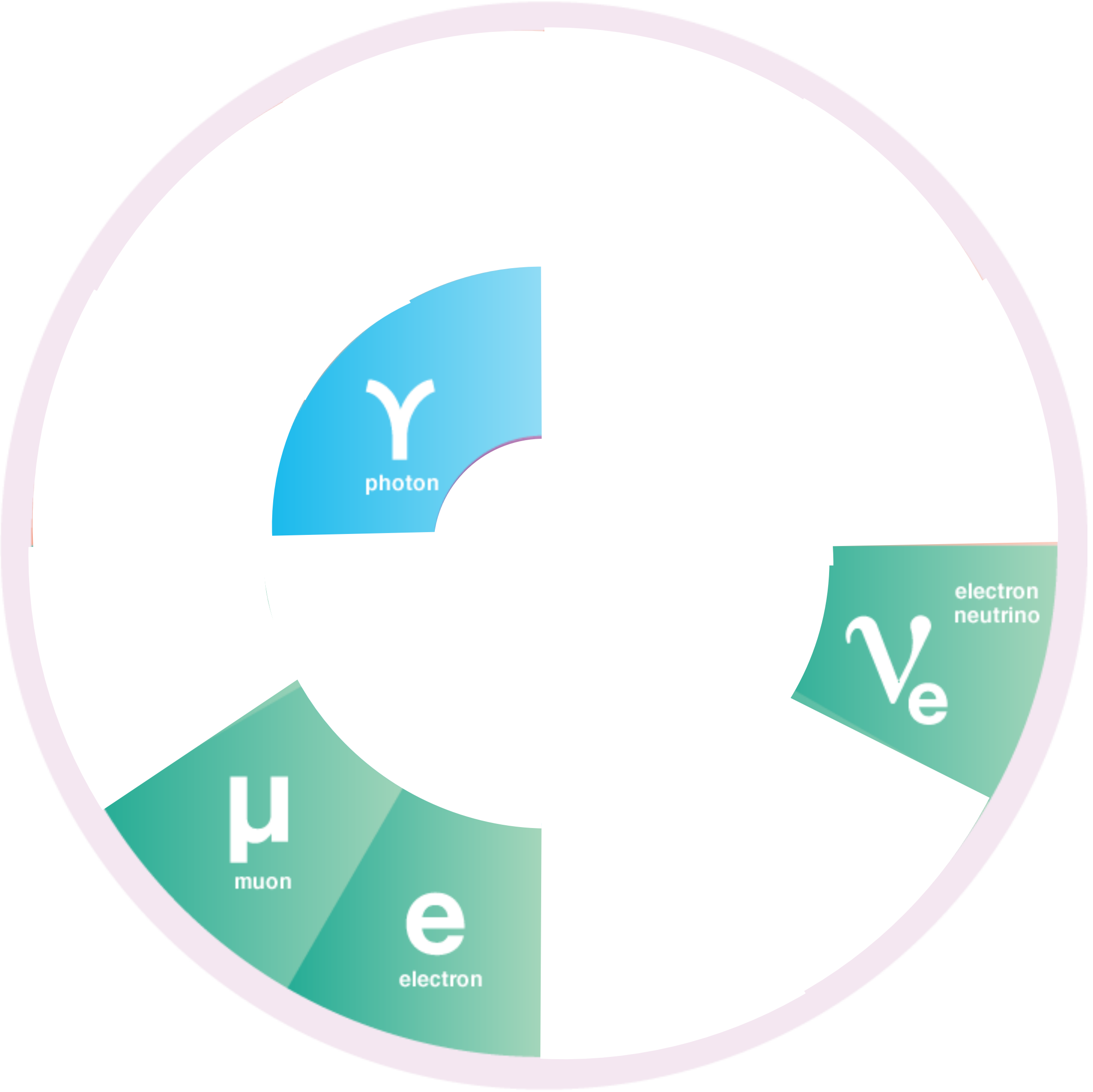
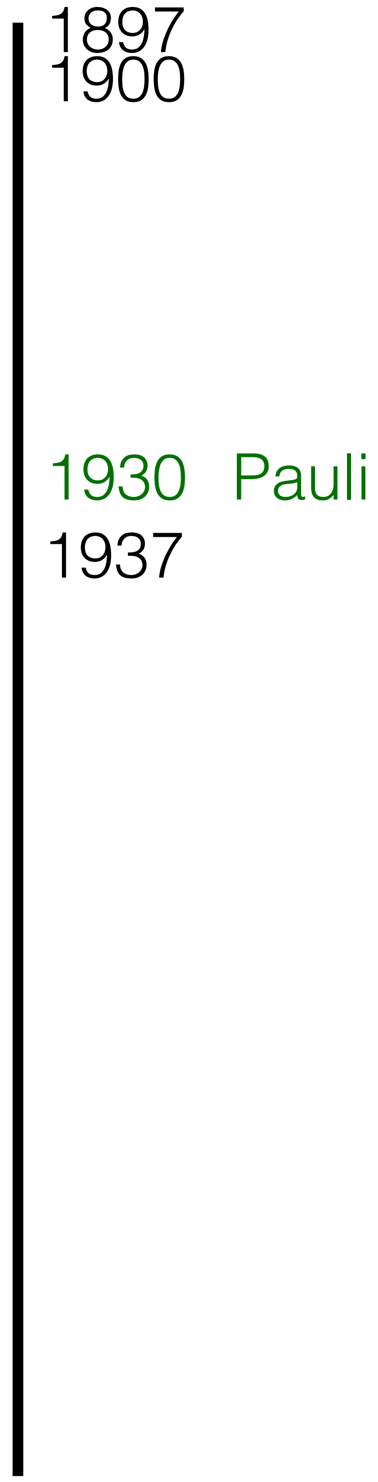
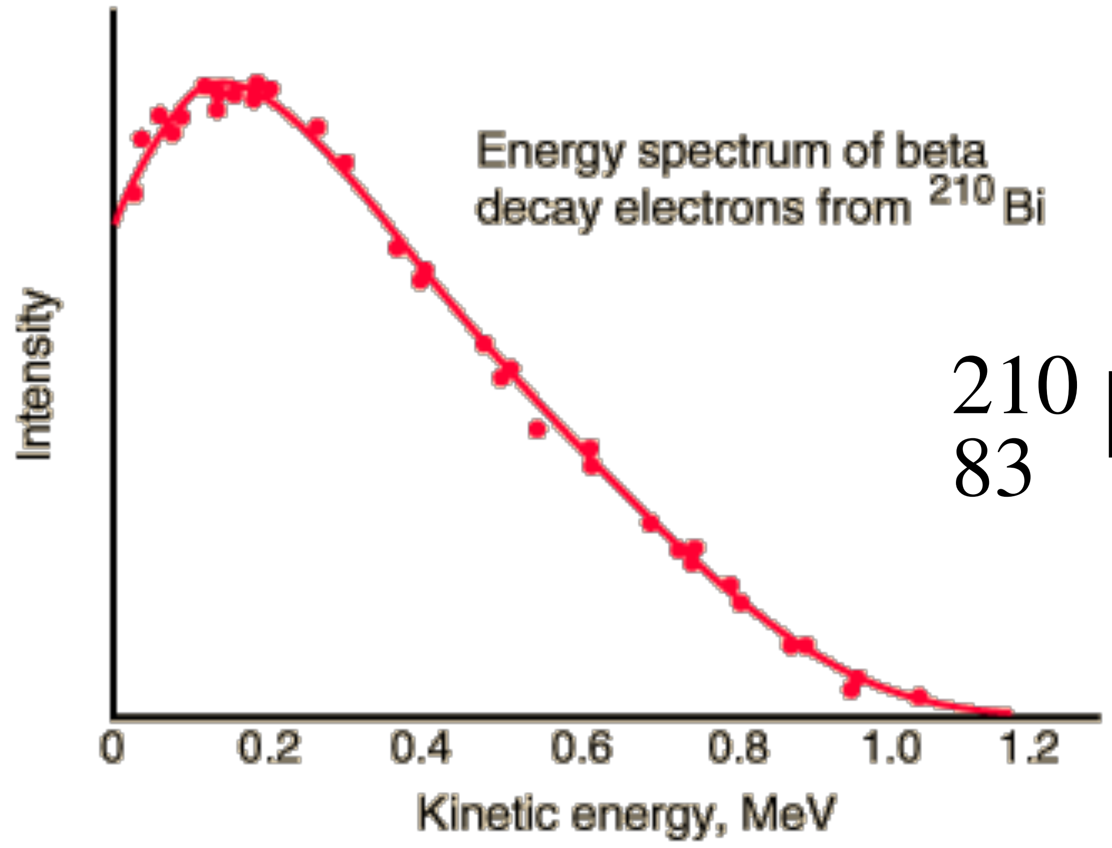


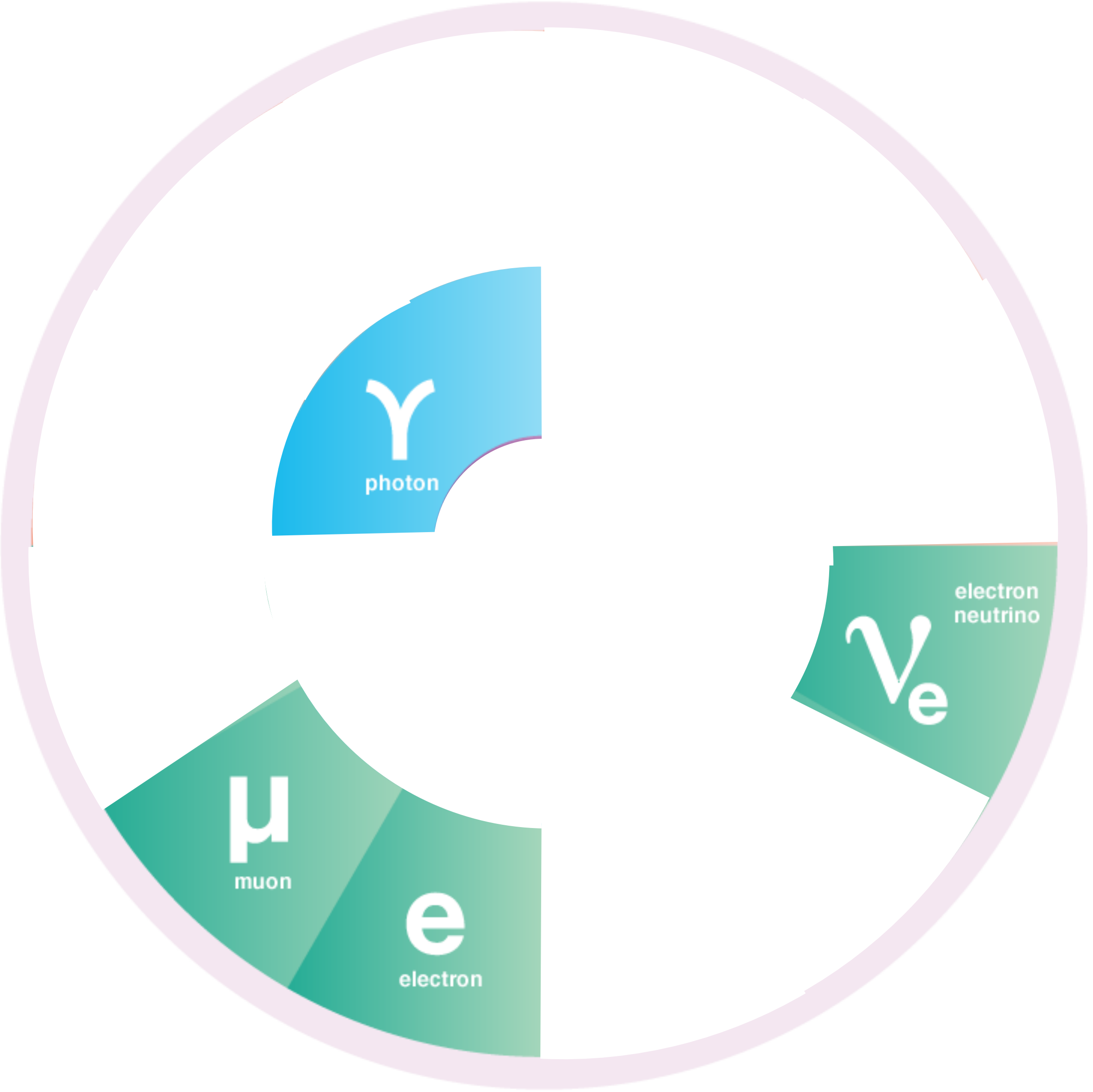




$$^{210}_{83}\mathrm{Bi} \to {}^{210}_{82}\mathrm{Pb} + e^{+} + \nu_e$$

Neutrinos

keine Spuren



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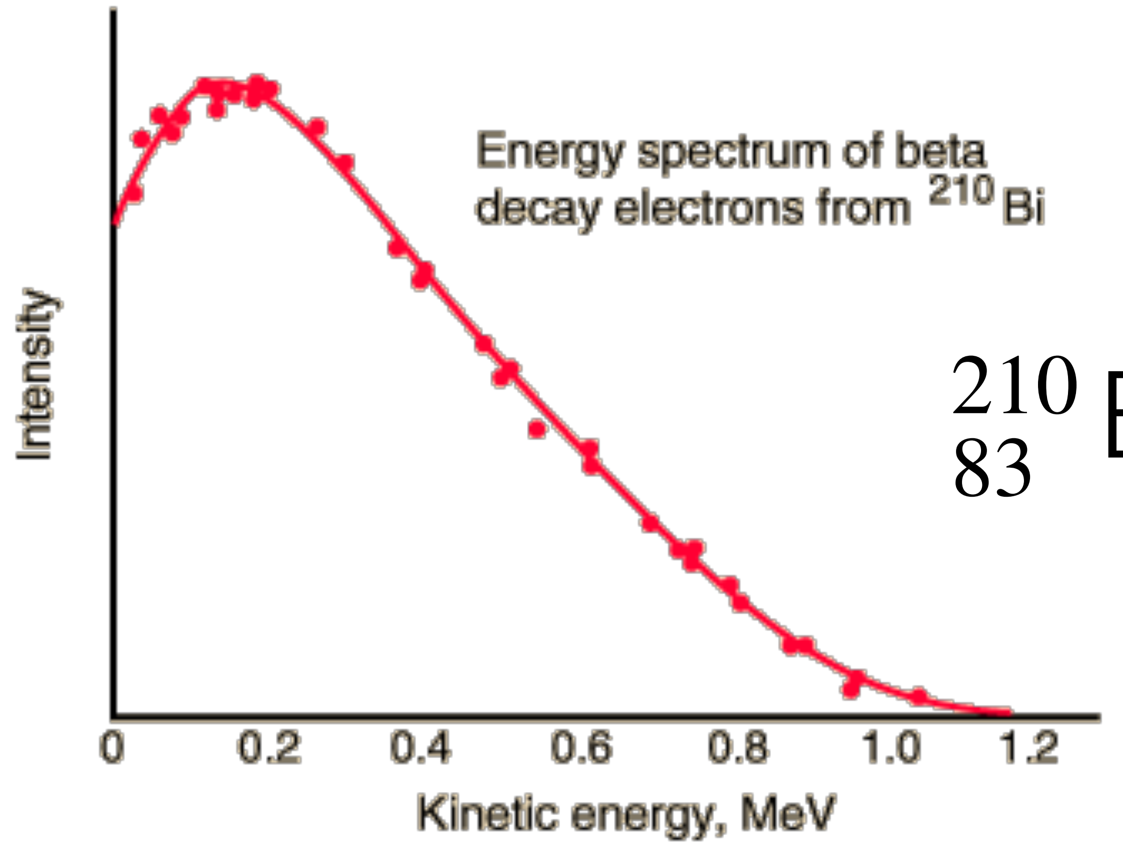

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Neutrinos

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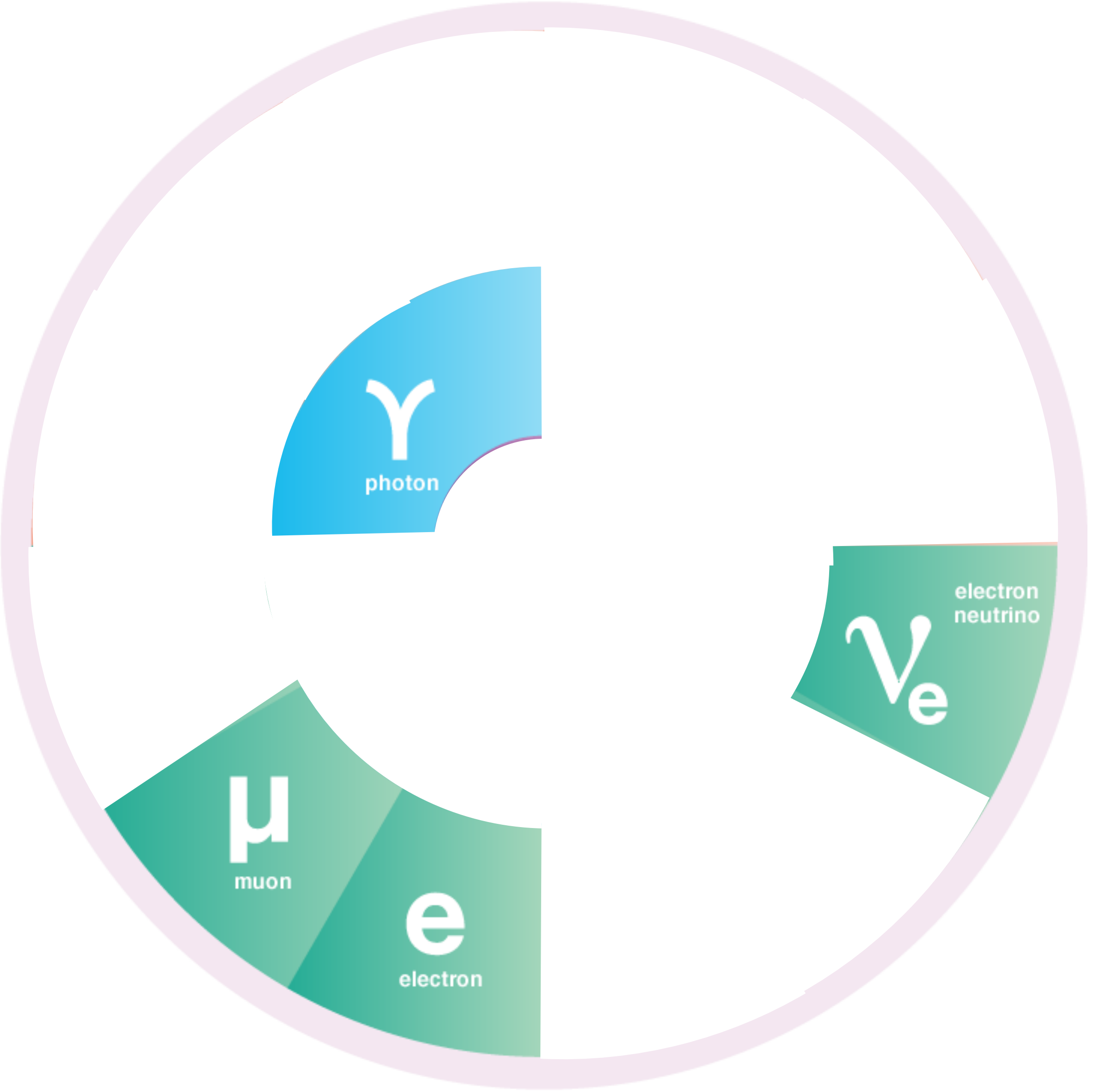

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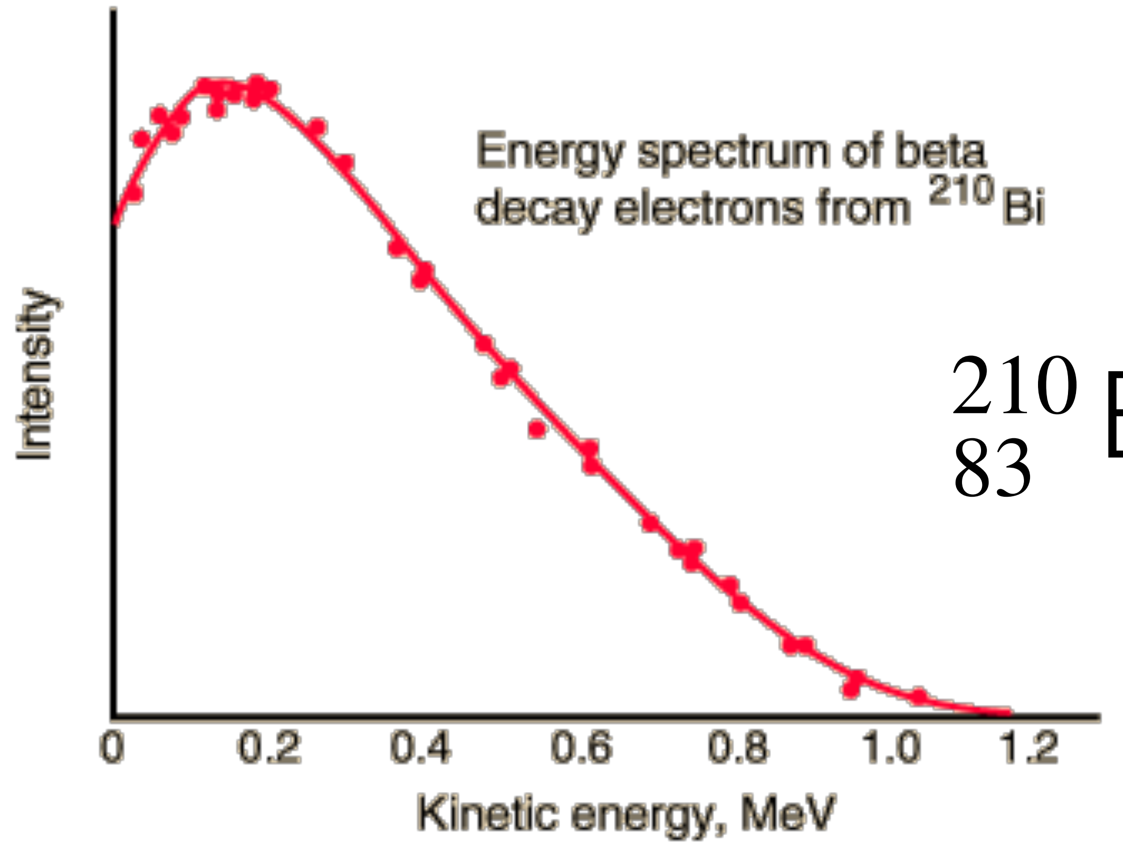

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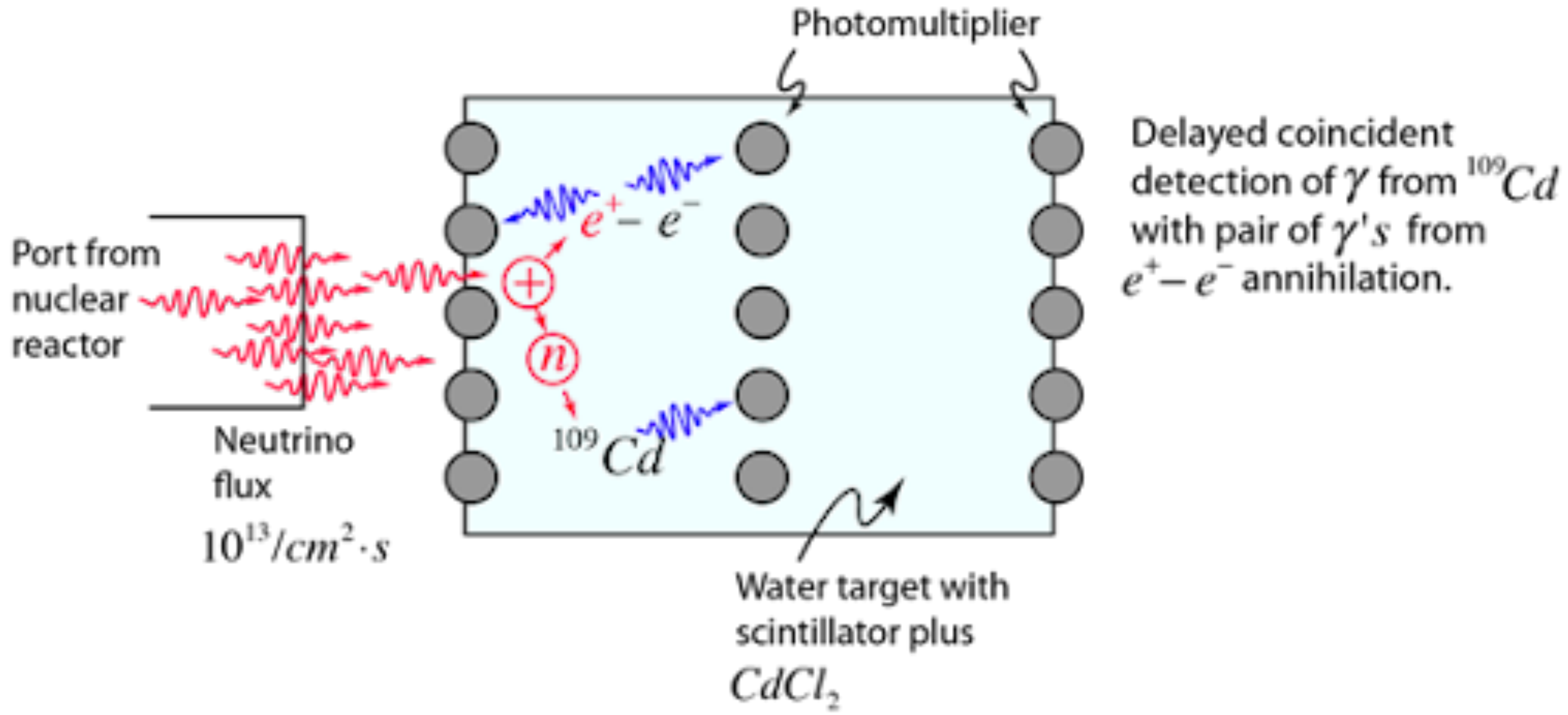

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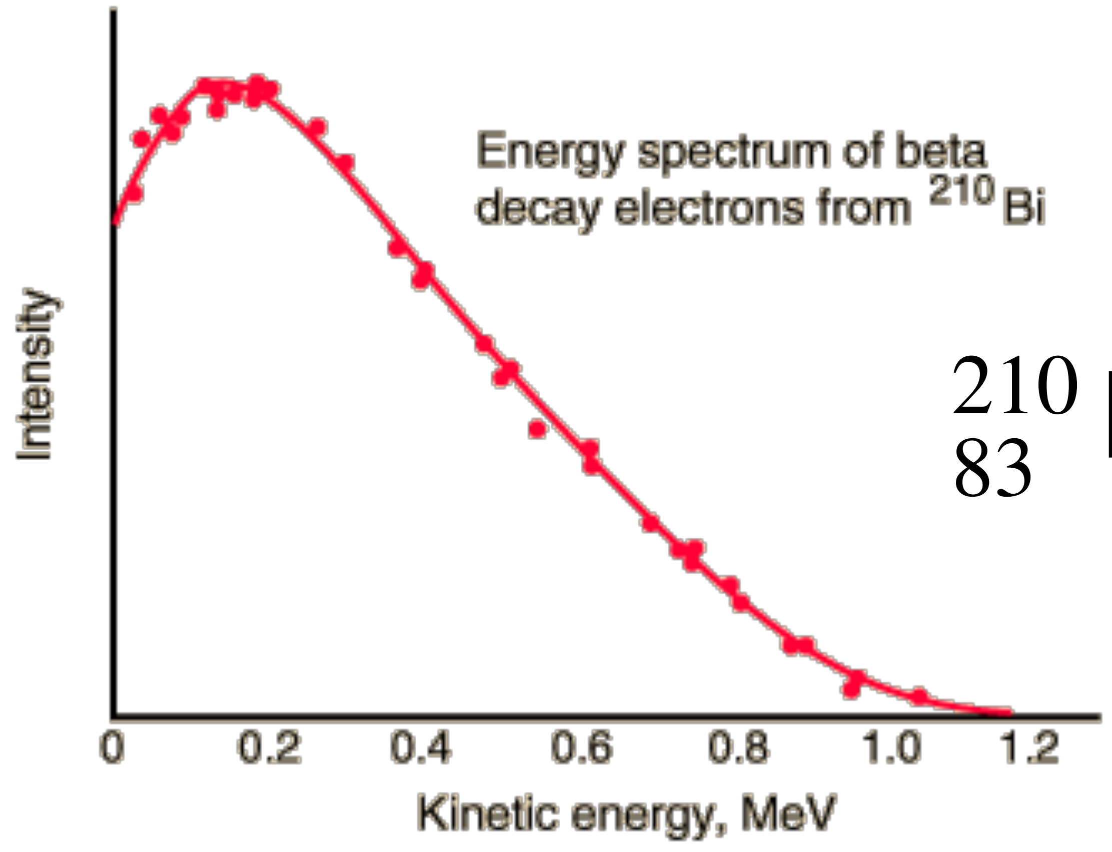

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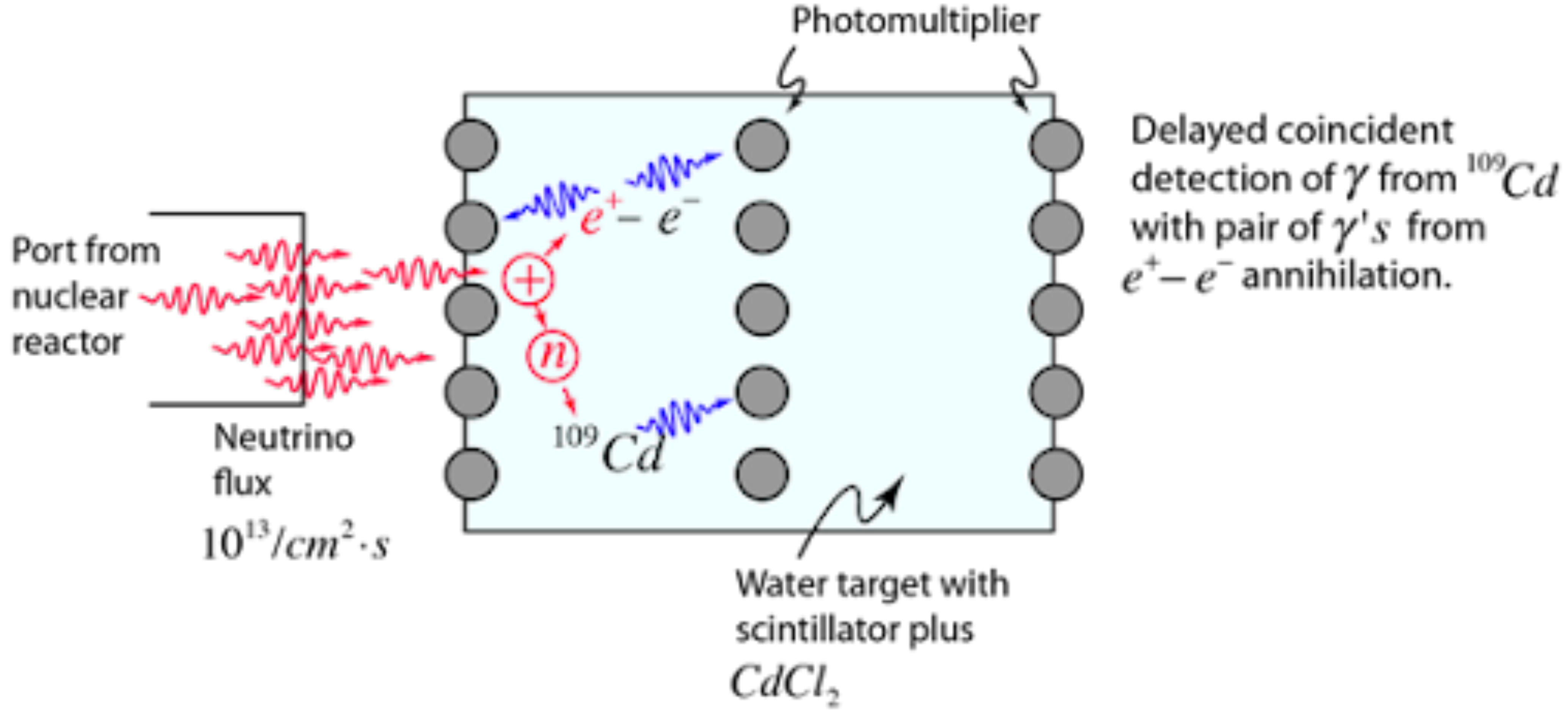
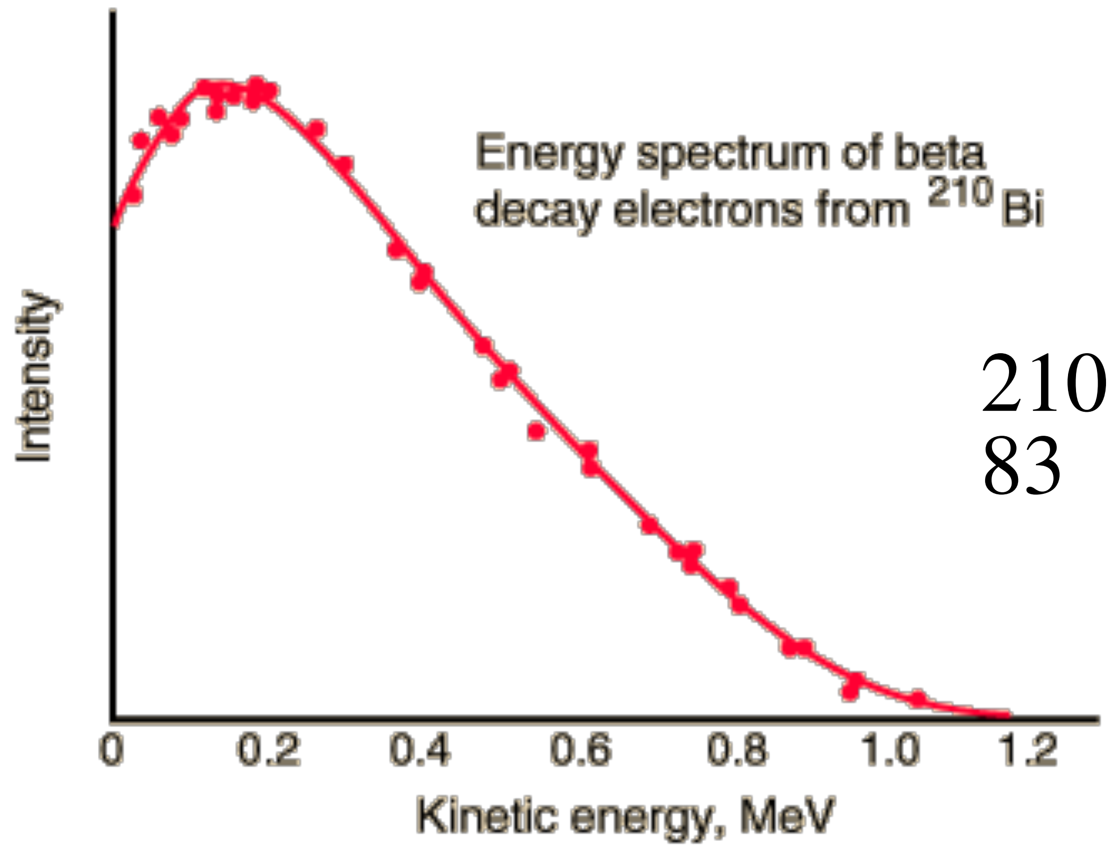


Was ist ein Teilchen?



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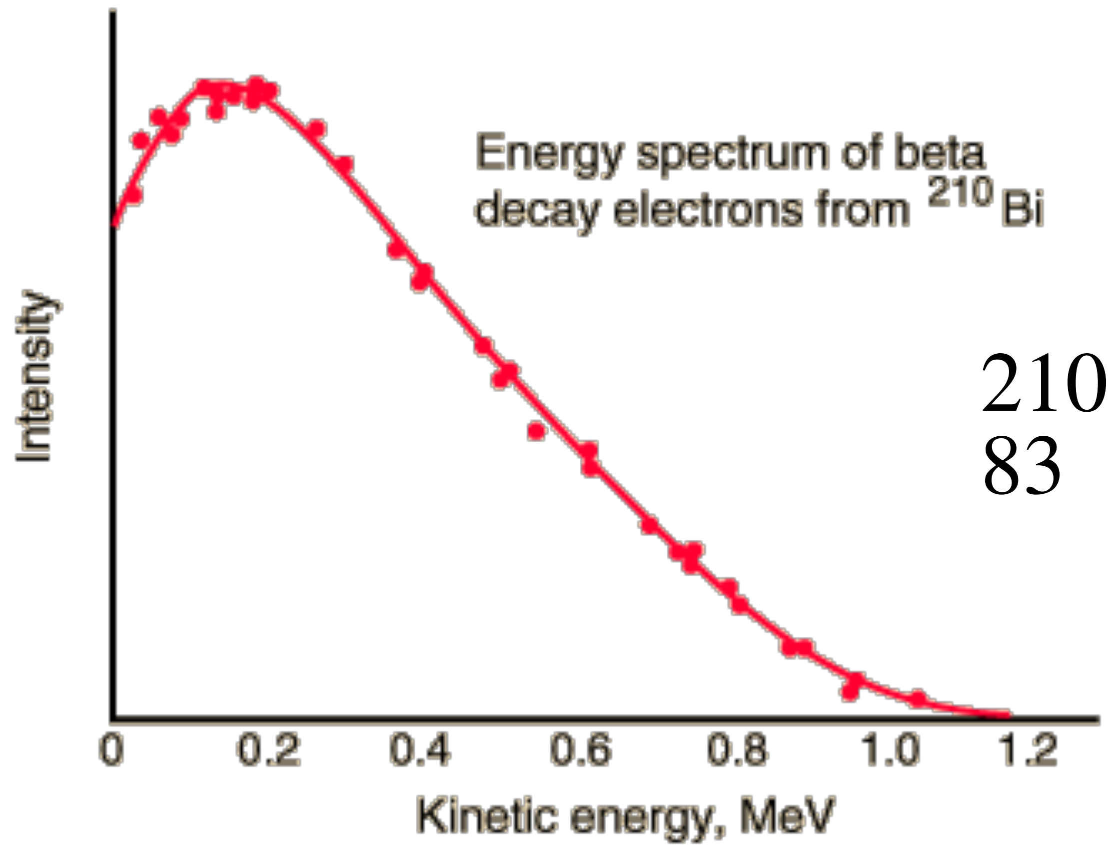

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$$p \to n + e^{+} + \nu_e$$

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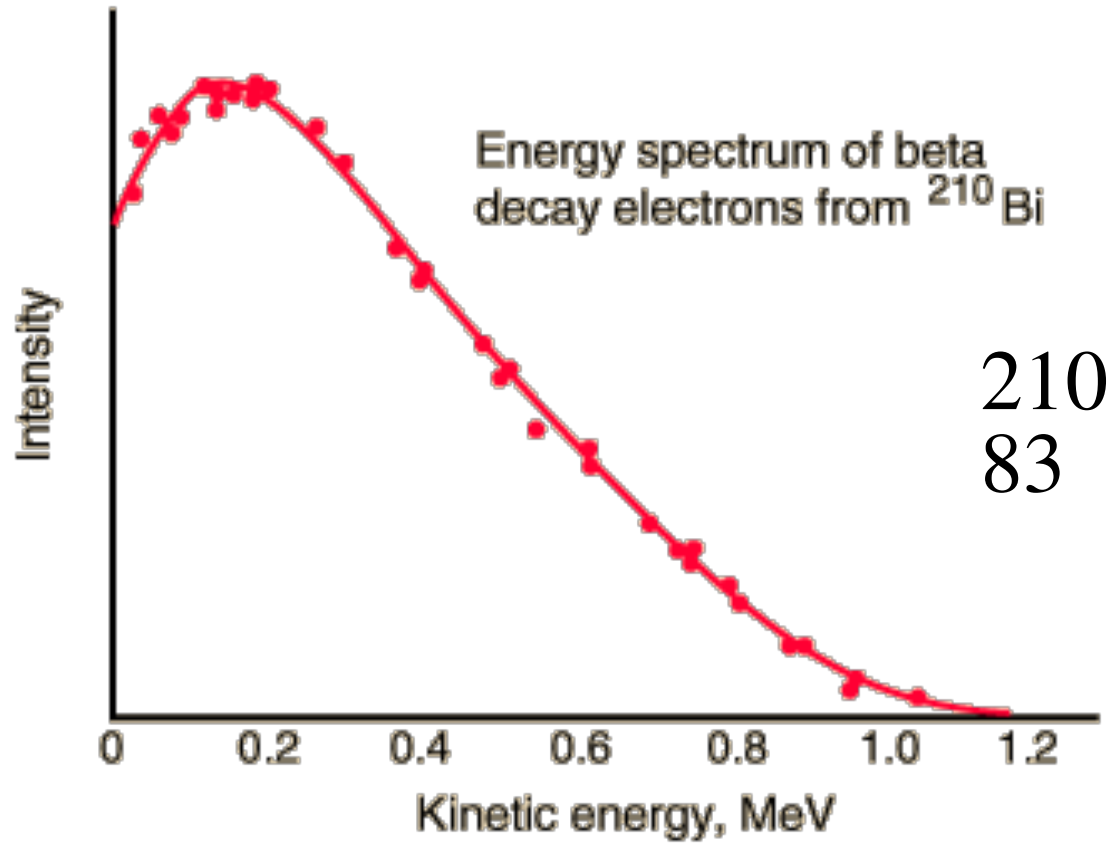
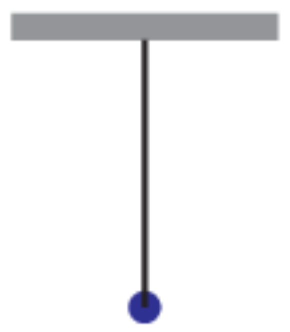


$$^{210}_{83}\mathrm{Bi} \to {}^{210}_{82}\mathrm{Pb} + e^{+} + \nu_e$$

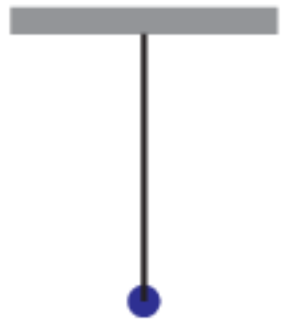
$$p \to n + e^{+} + \nu_e$$

$$\begin{pmatrix} u \\ u \\ d \end{pmatrix} \to \begin{pmatrix} u \\ d \\ d \end{pmatrix} + e^{+} + \nu_e$$

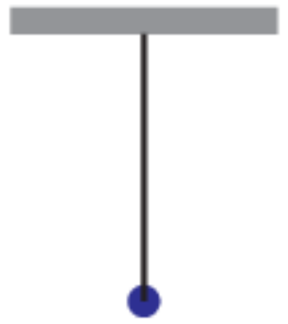
Newton:



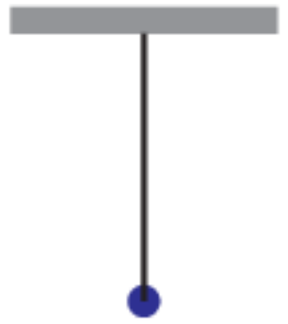
Newton:



Newton:

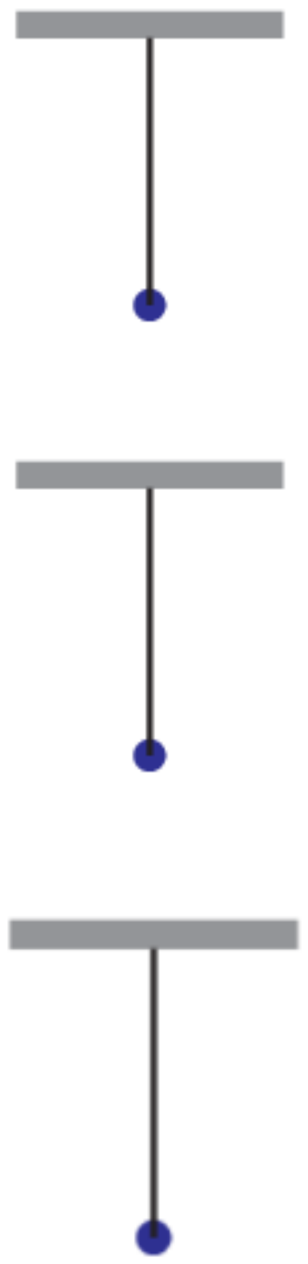


$E \sim \omega^2 \alpha^2$



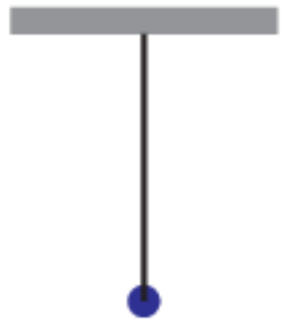
Newton:

$E \sim \omega^2 \alpha^2$

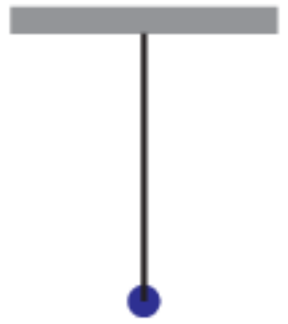


$E = 0$

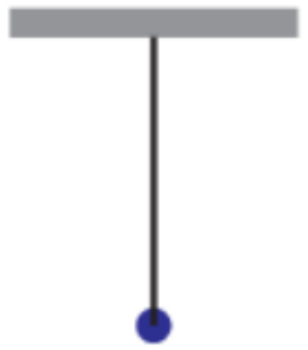
Newton: Quantenmechanik:



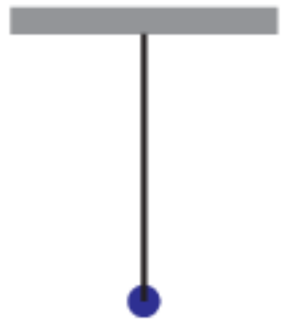
$E \sim \omega^2 \alpha^2$



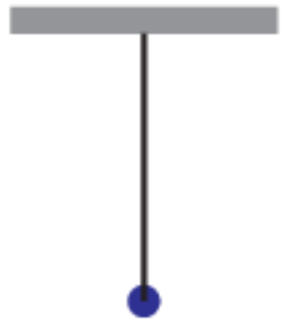
$E = 0$



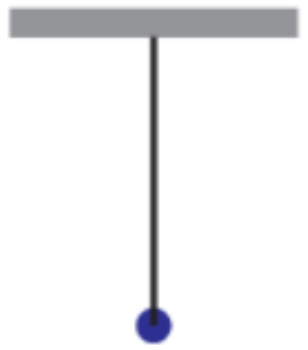
Newton:



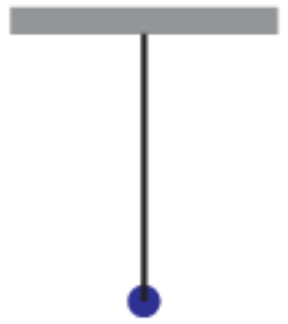
$E \sim \omega^2 \alpha^2$



$E = 0$



Quantenmechanik:

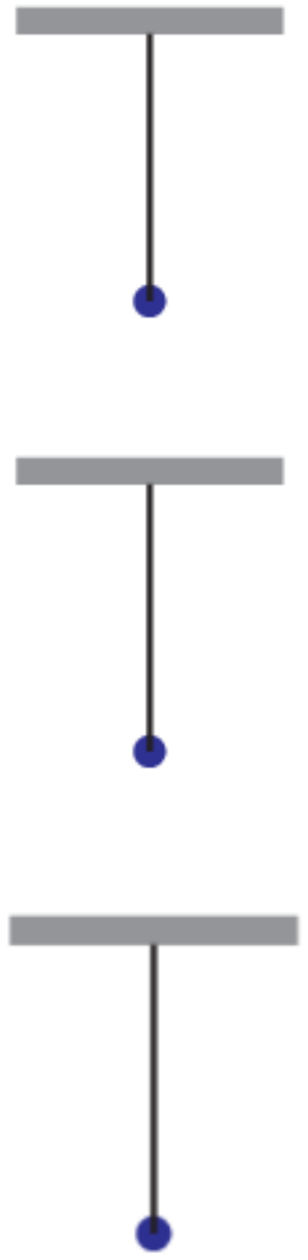


$E_1 = \hbar\omega$

Newton:

$E \sim \omega^2 \alpha^2$

$E = 0$

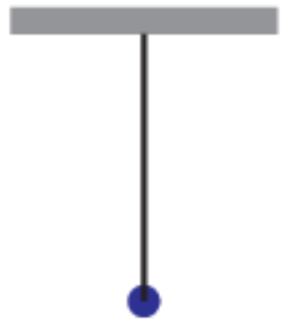


Quantenmechanik:

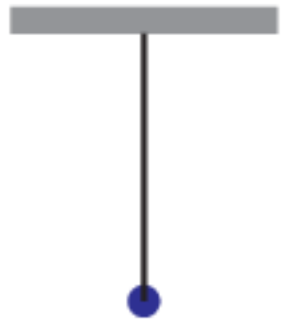
$E_1 = \hbar\omega$

$E_0 = 0$

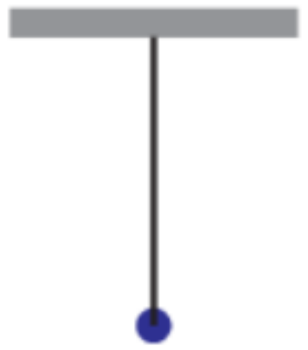
Newton:



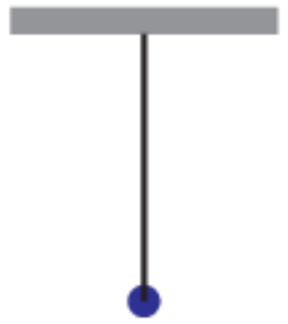
$E \sim \omega^2 \alpha^2$



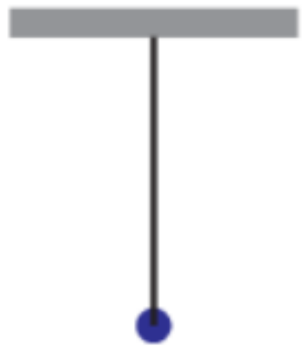
$E = 0$



Quantenmechanik:



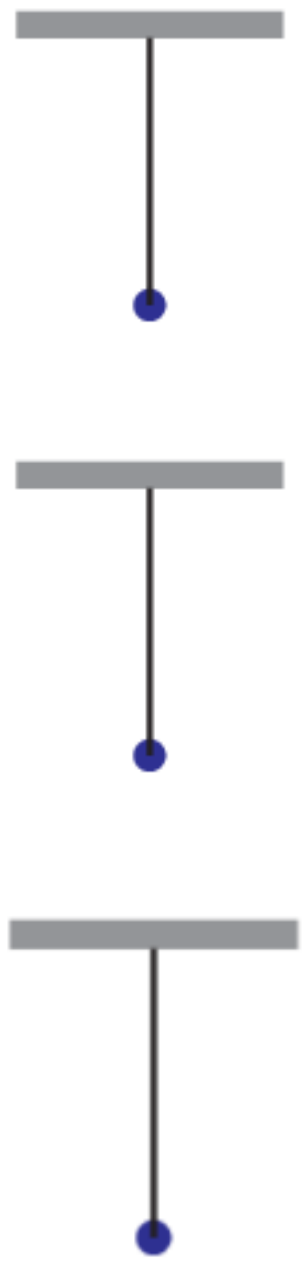
$$E_1 = \hbar\omega + \frac{\hbar\omega}{2}$$



$$E_0 = 0 + \frac{\hbar\omega}{2}$$

Newton:

$E \sim \omega^2 \alpha^2$



$E = 0$

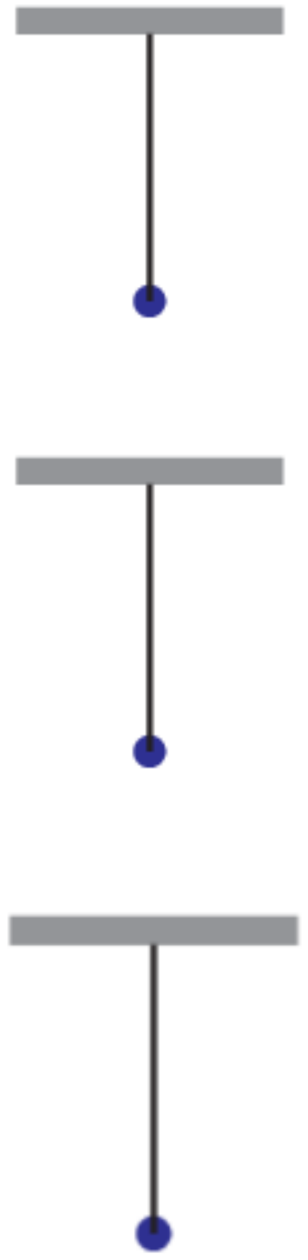
Quantenmechanik:

$E_1 = \hbar\omega + \frac{\hbar\omega}{2}$

$E_0 = 0 + \frac{\hbar\omega}{2}$

Newton:

$E \sim \omega^2 \alpha^2$

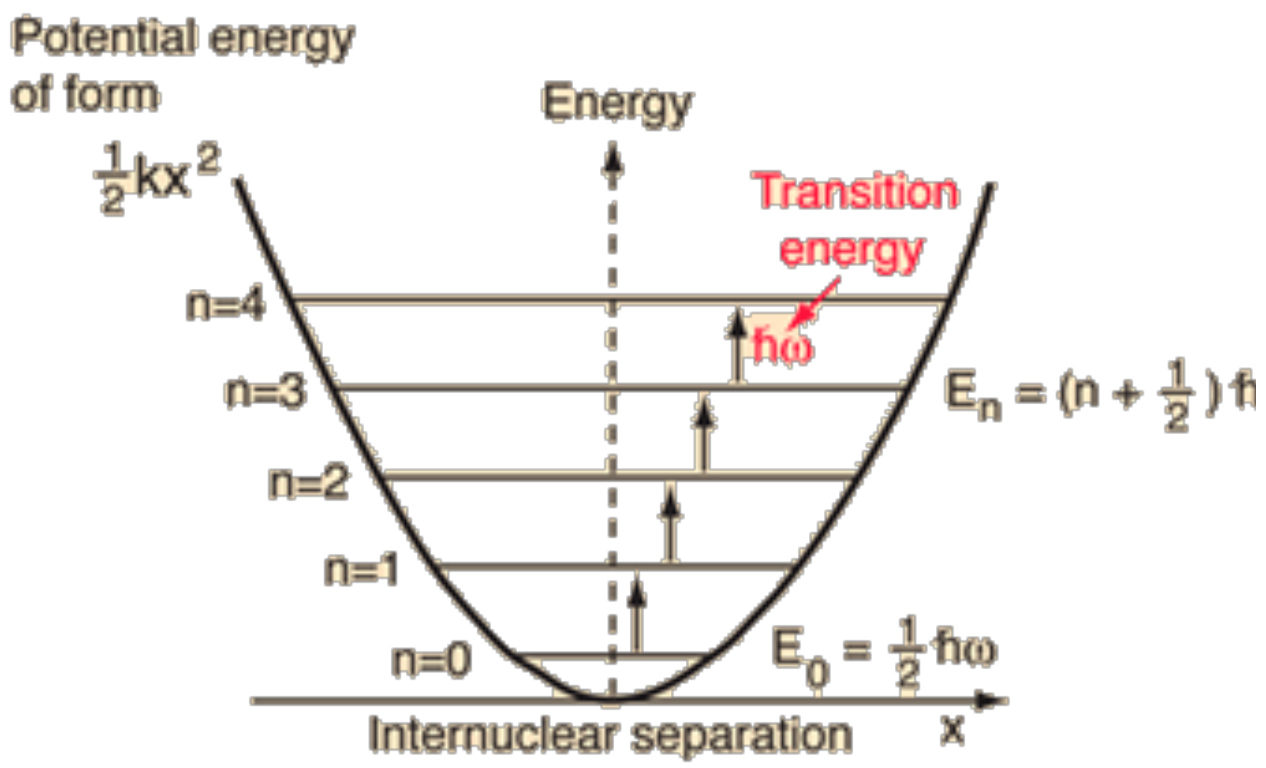


$E = 0$

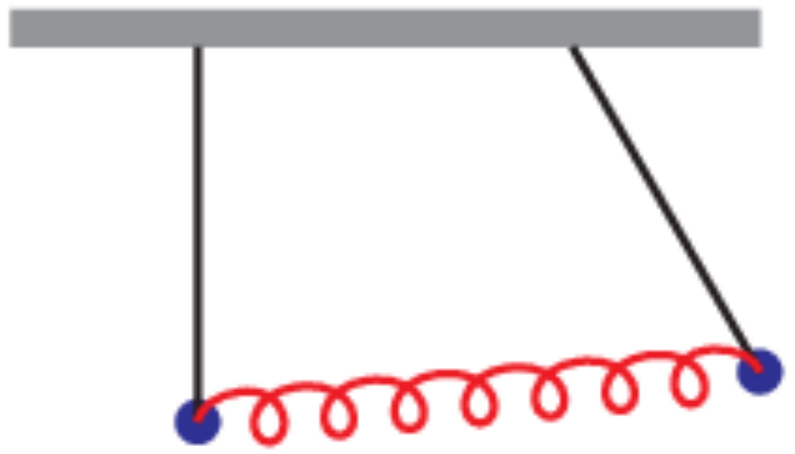
Quantenmechanik:

$E_1 = \hbar\omega + \frac{\hbar\omega}{2}$

$E_0 = 0 + \frac{\hbar\omega}{2}$



klassische Mechanik



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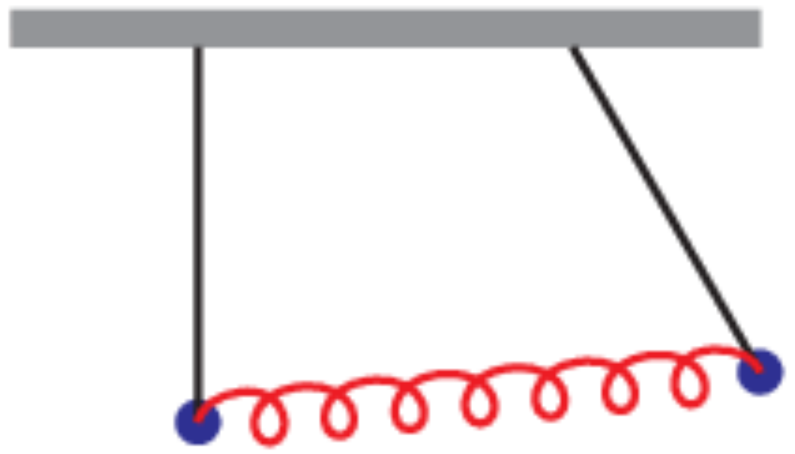

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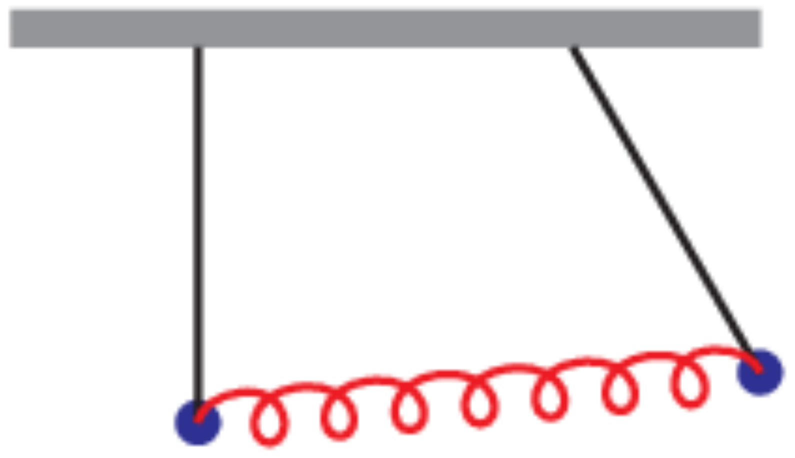

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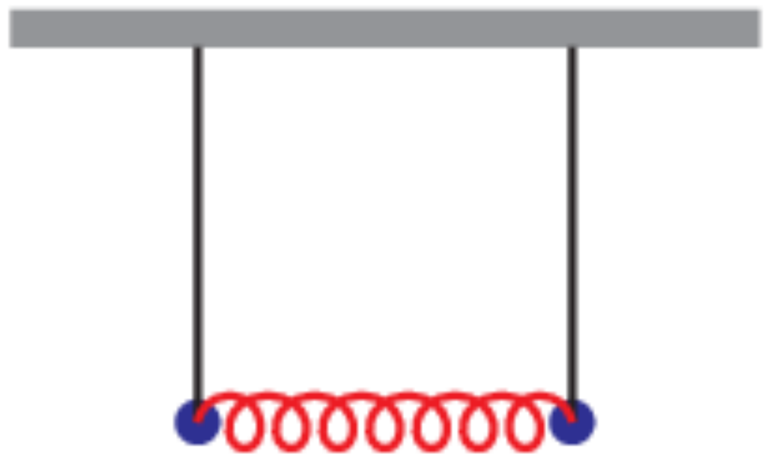

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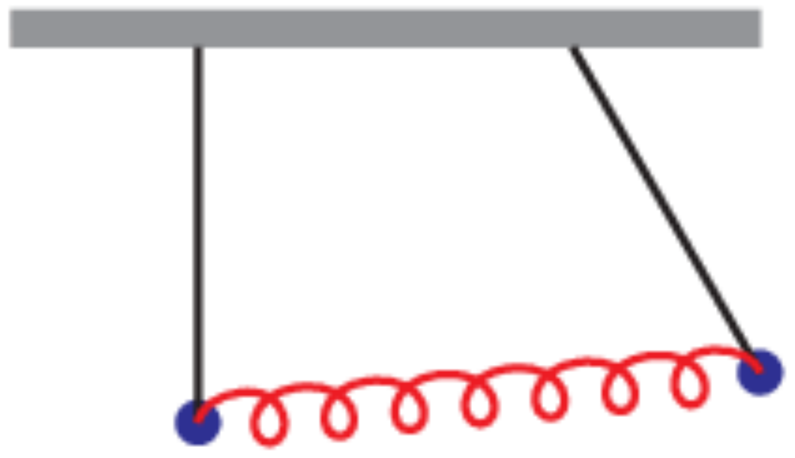

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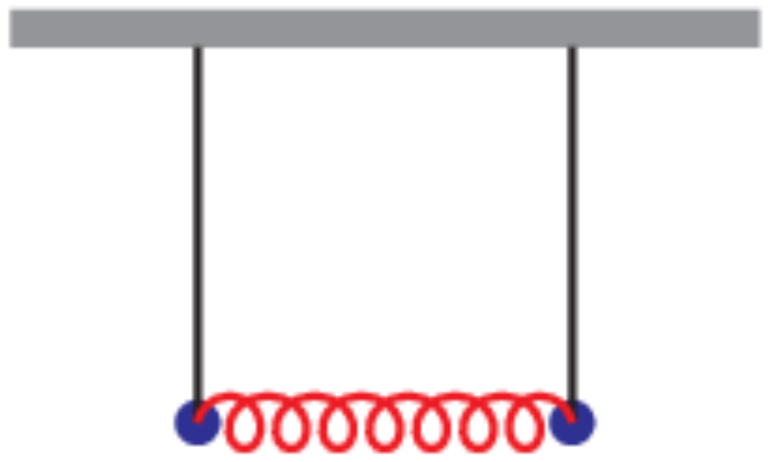
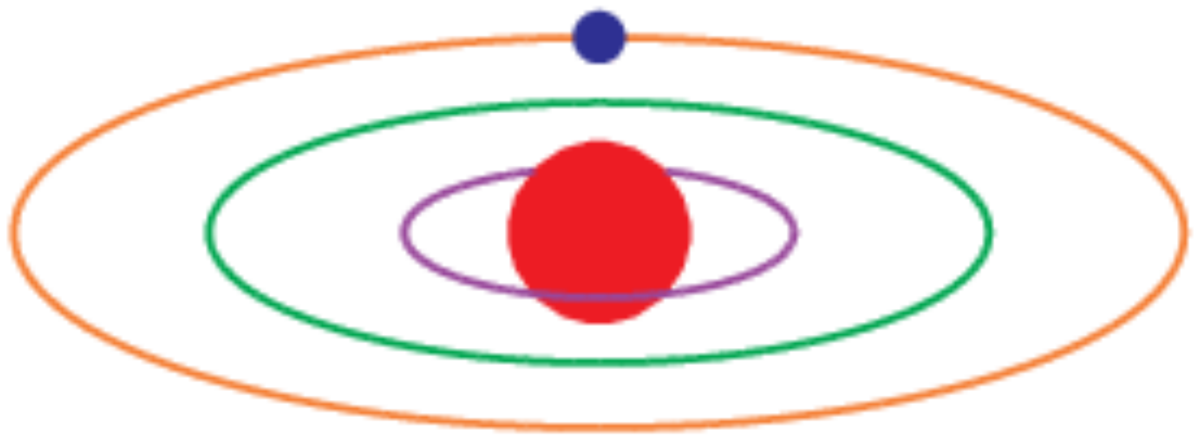
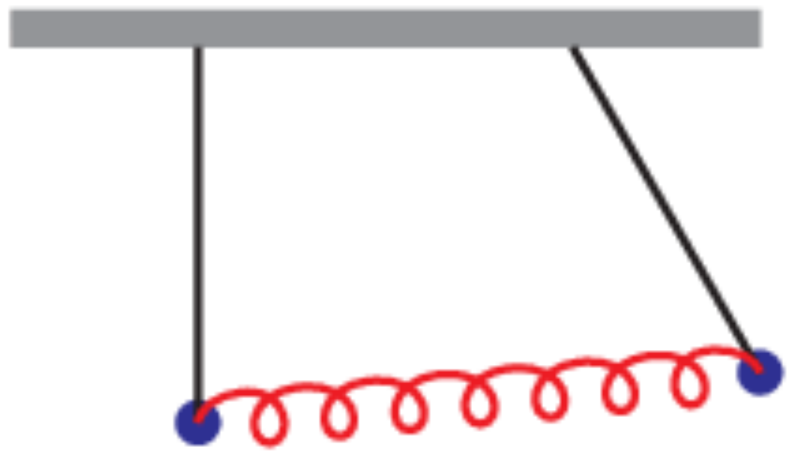
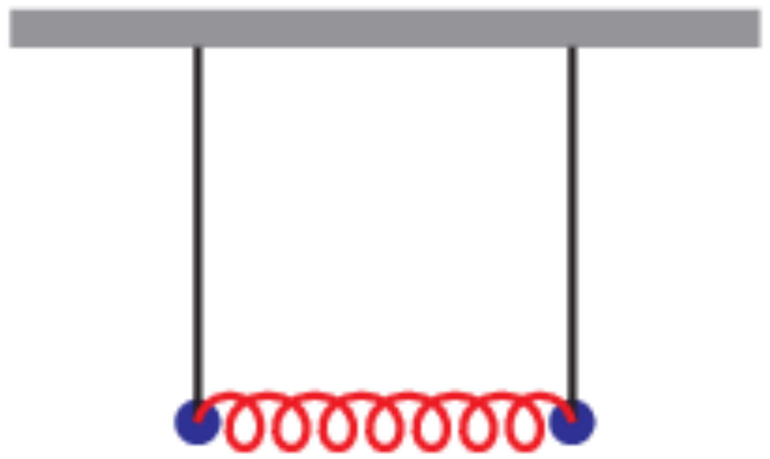


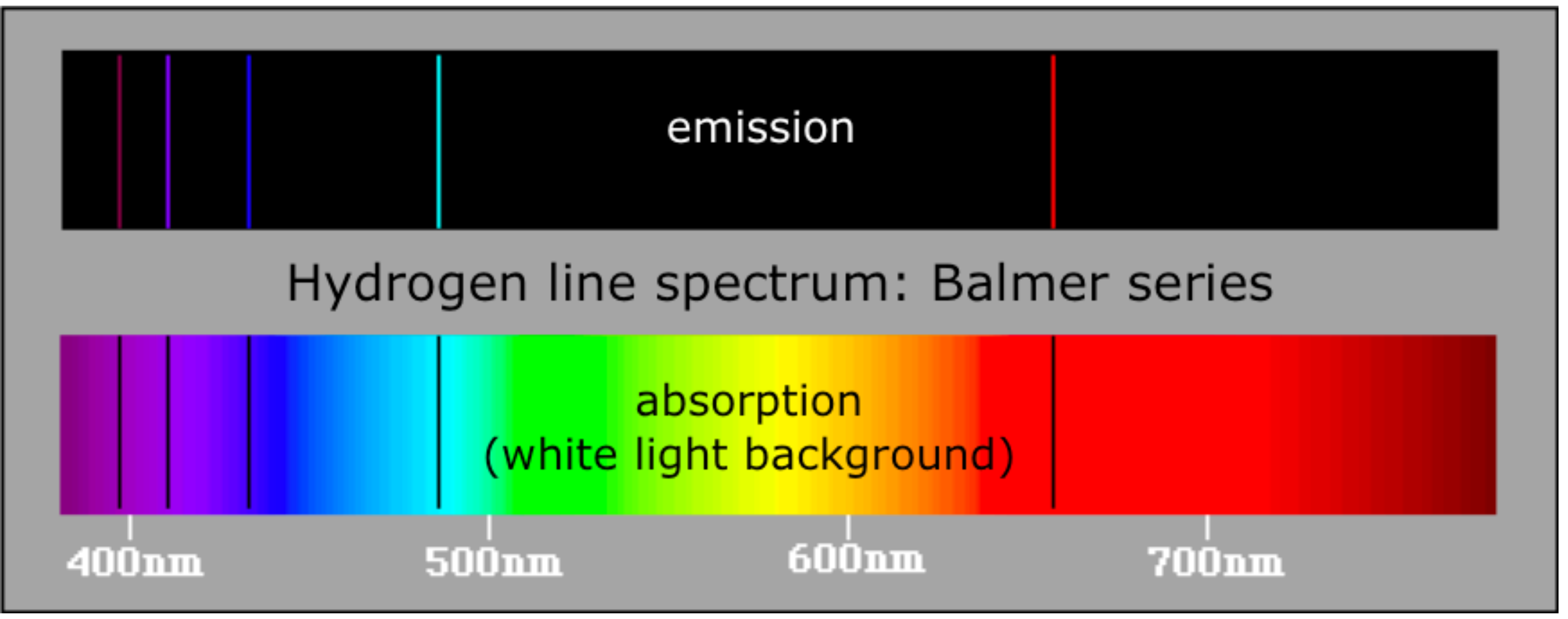


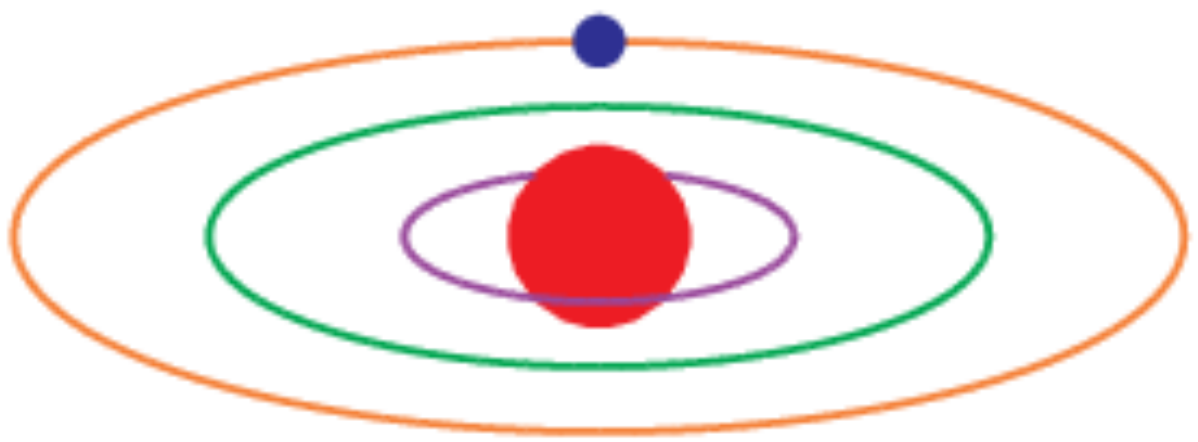
klassische Mechanik

Quantenmechanik









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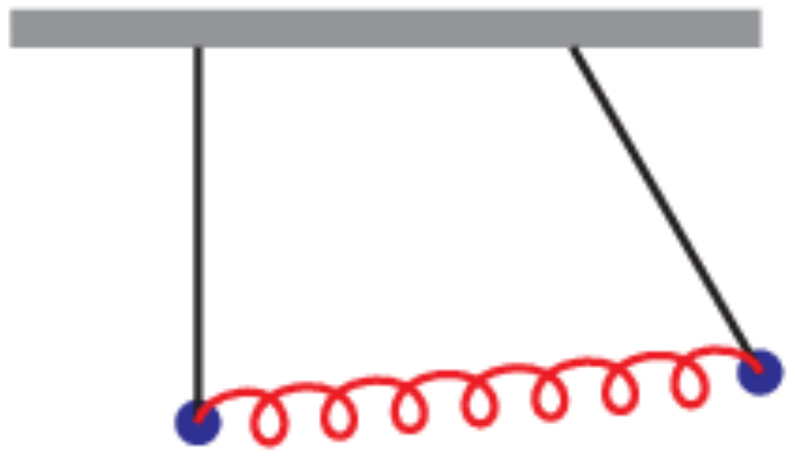

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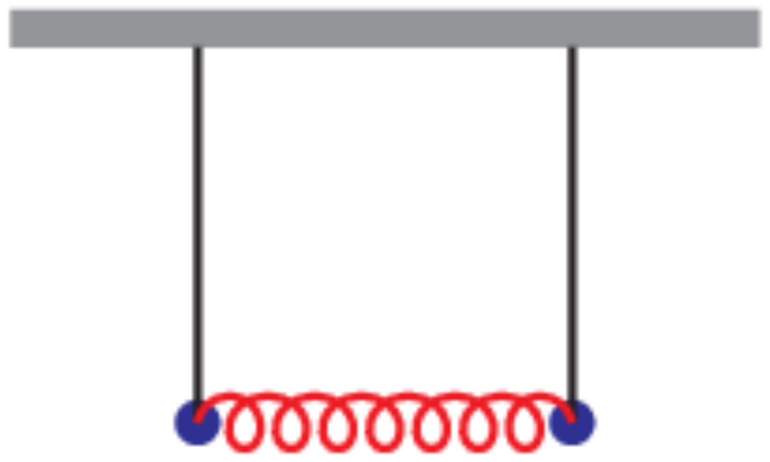

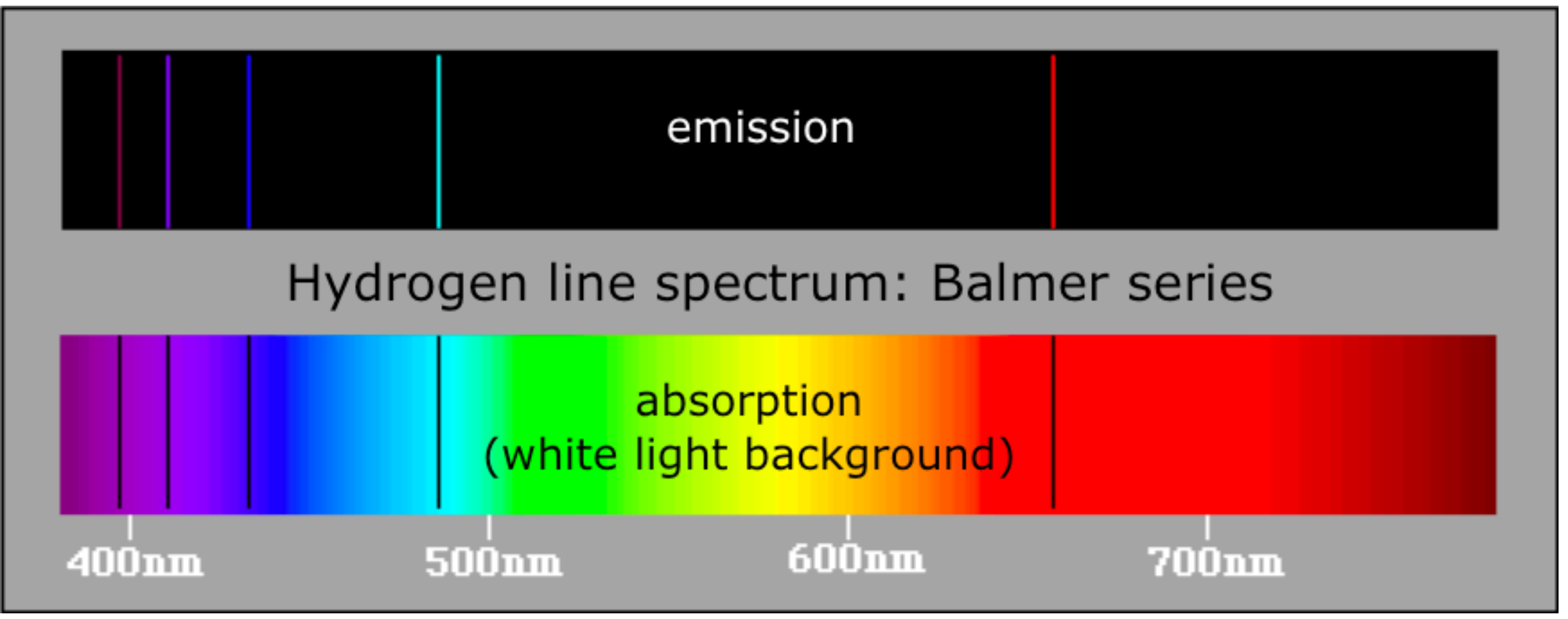

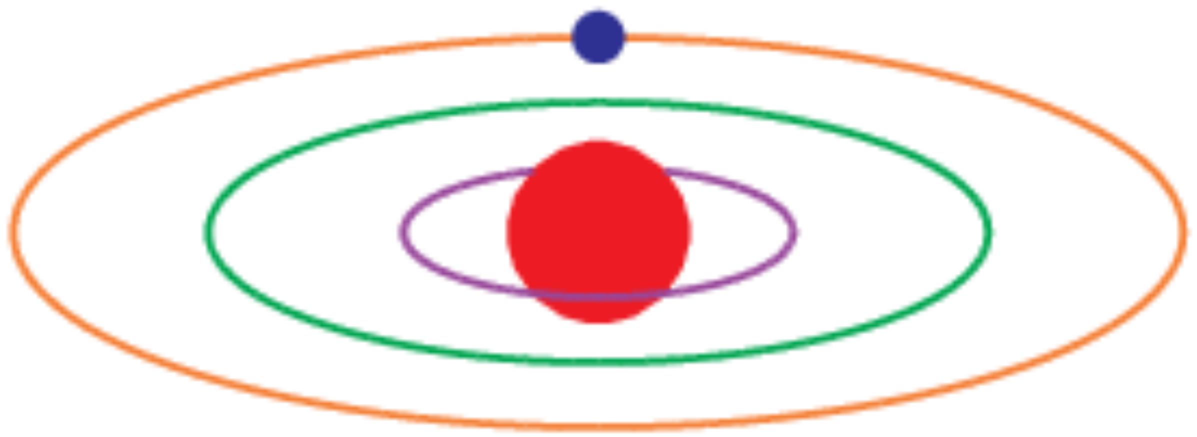

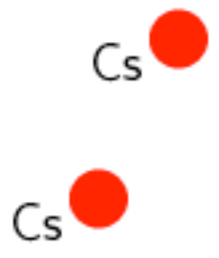

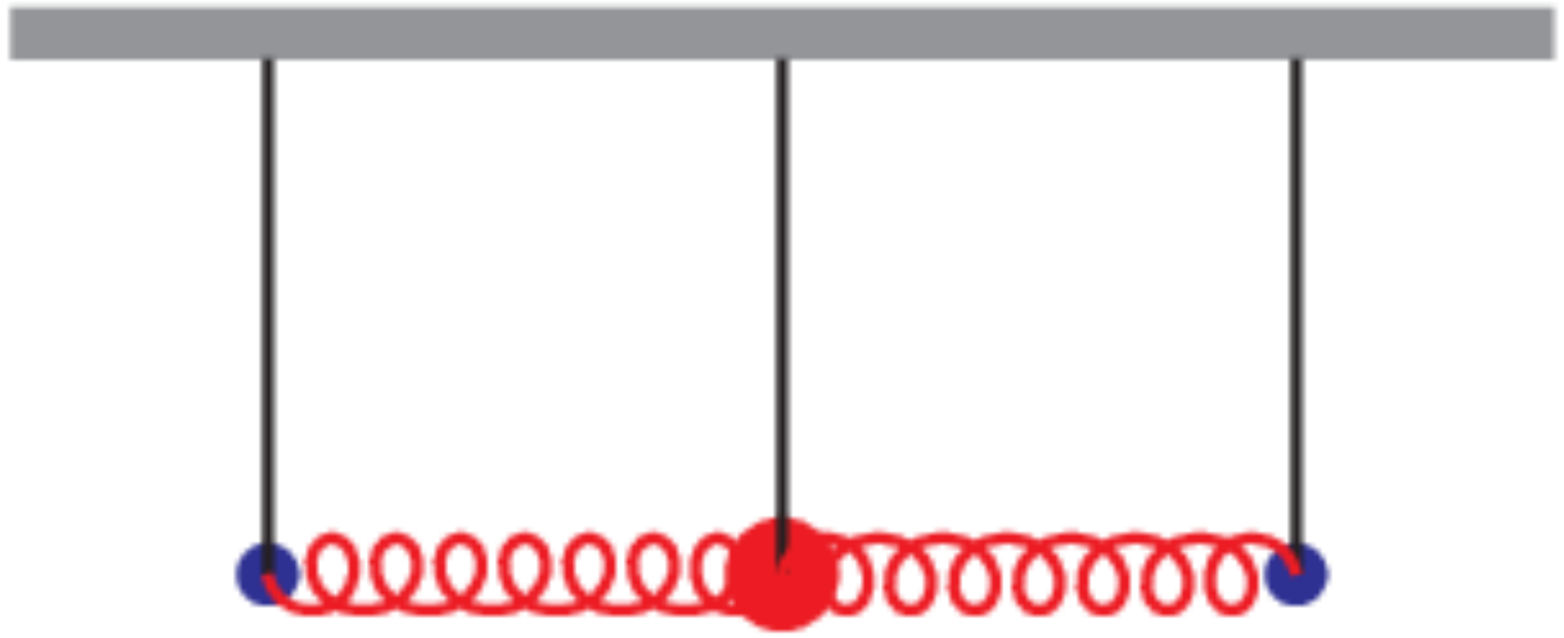

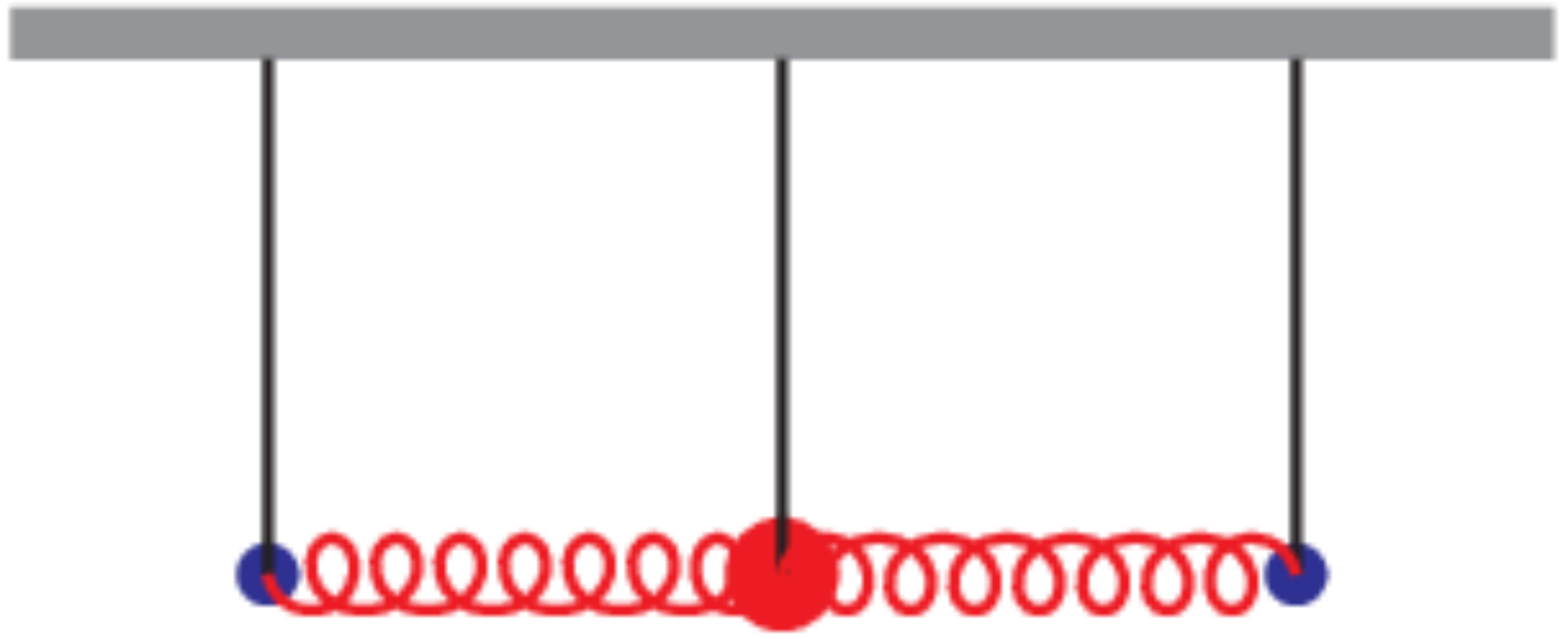

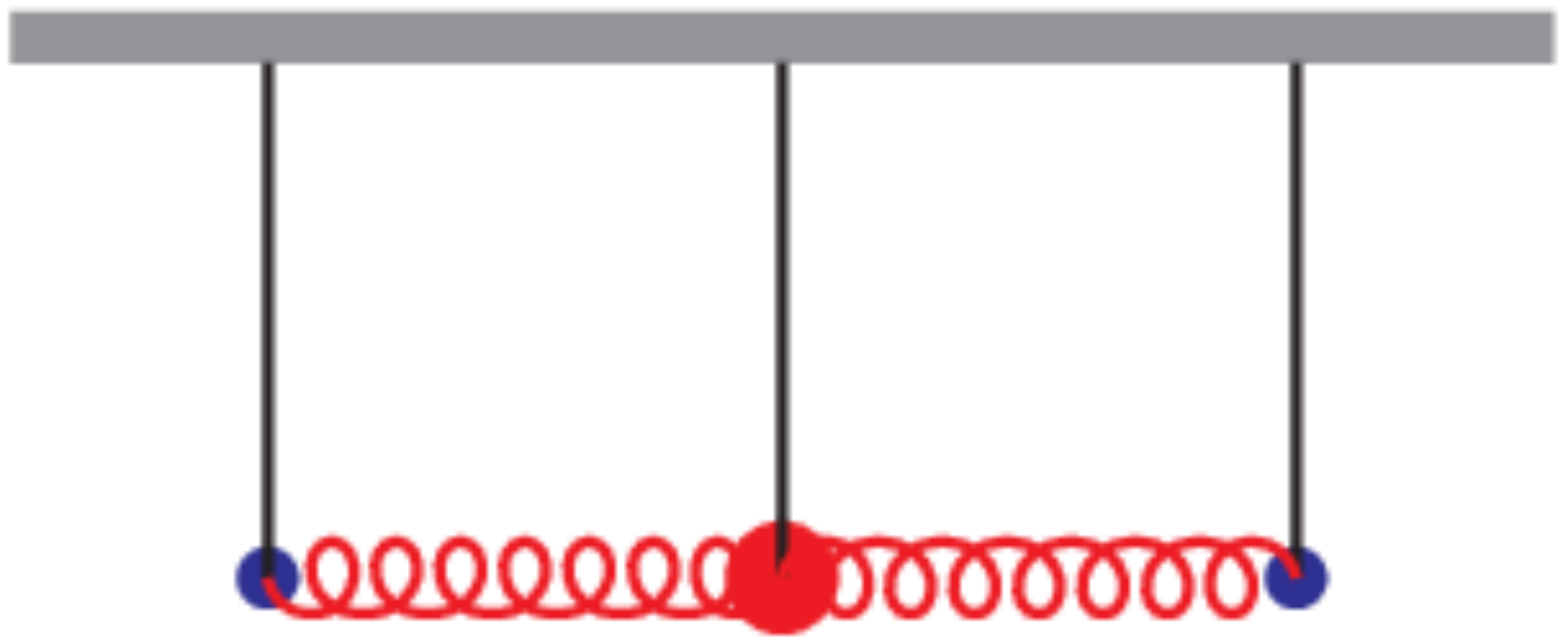

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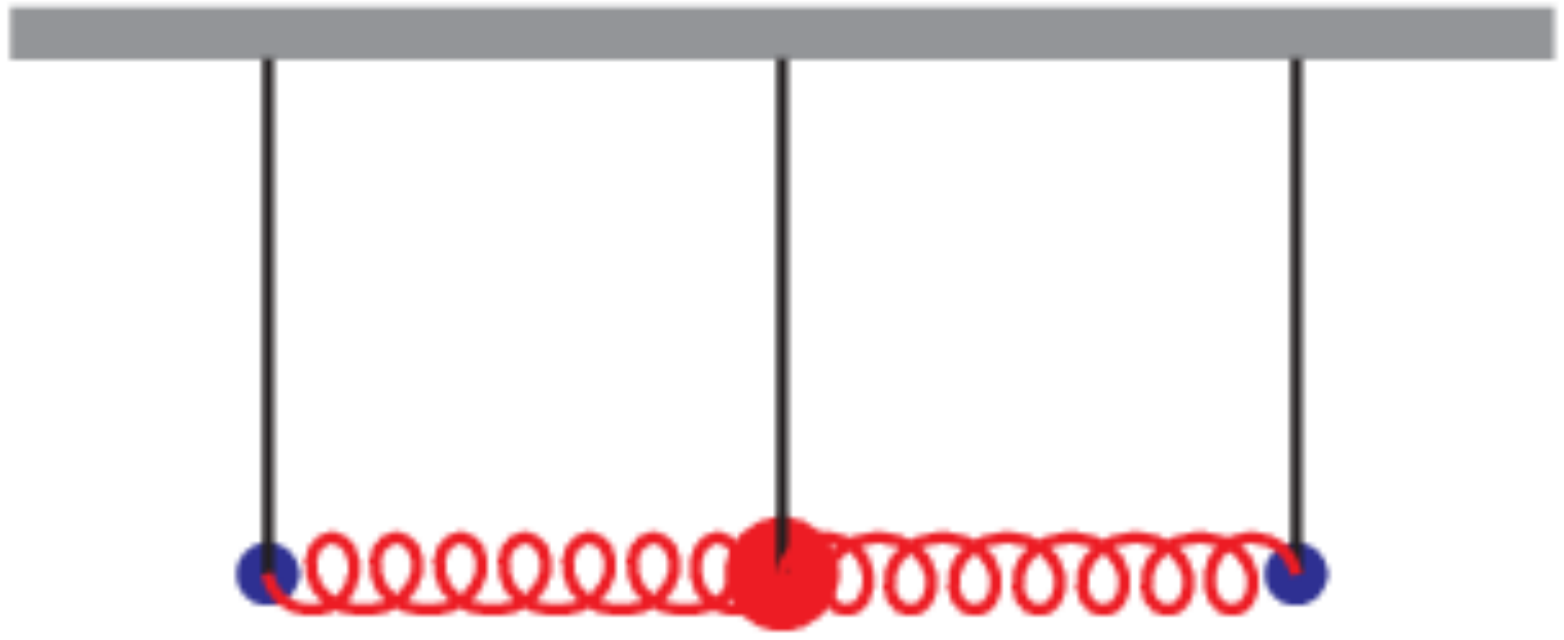

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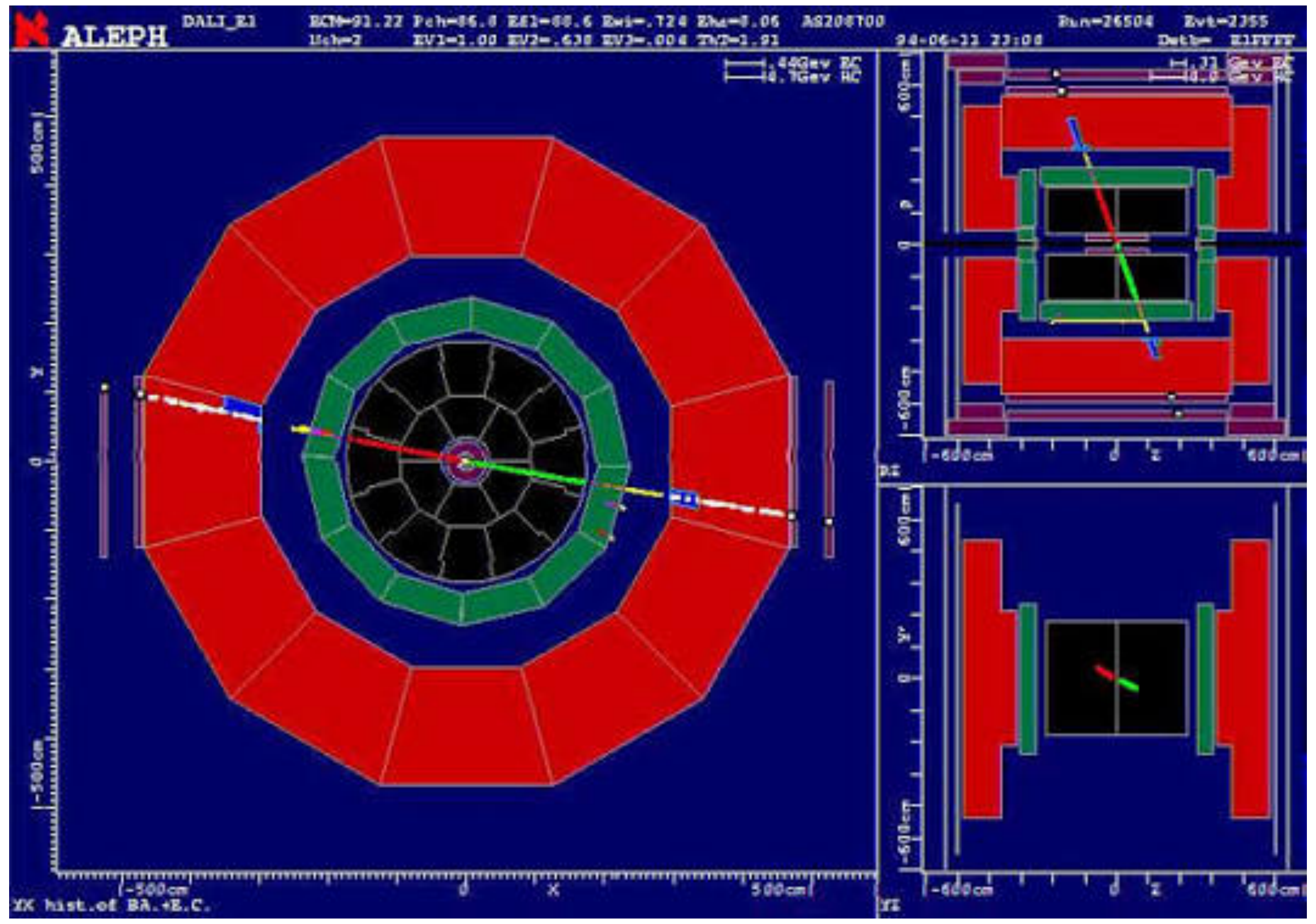
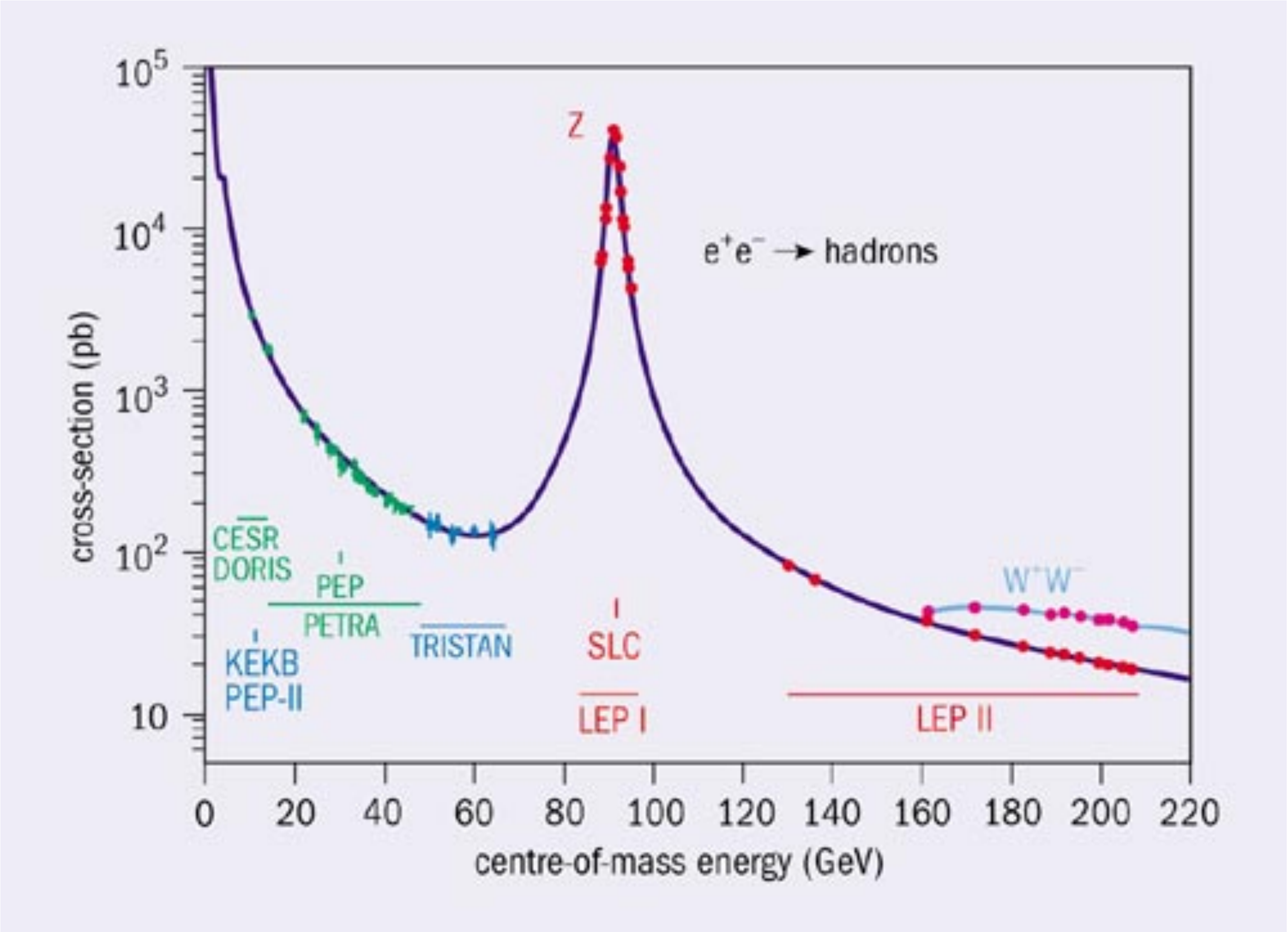
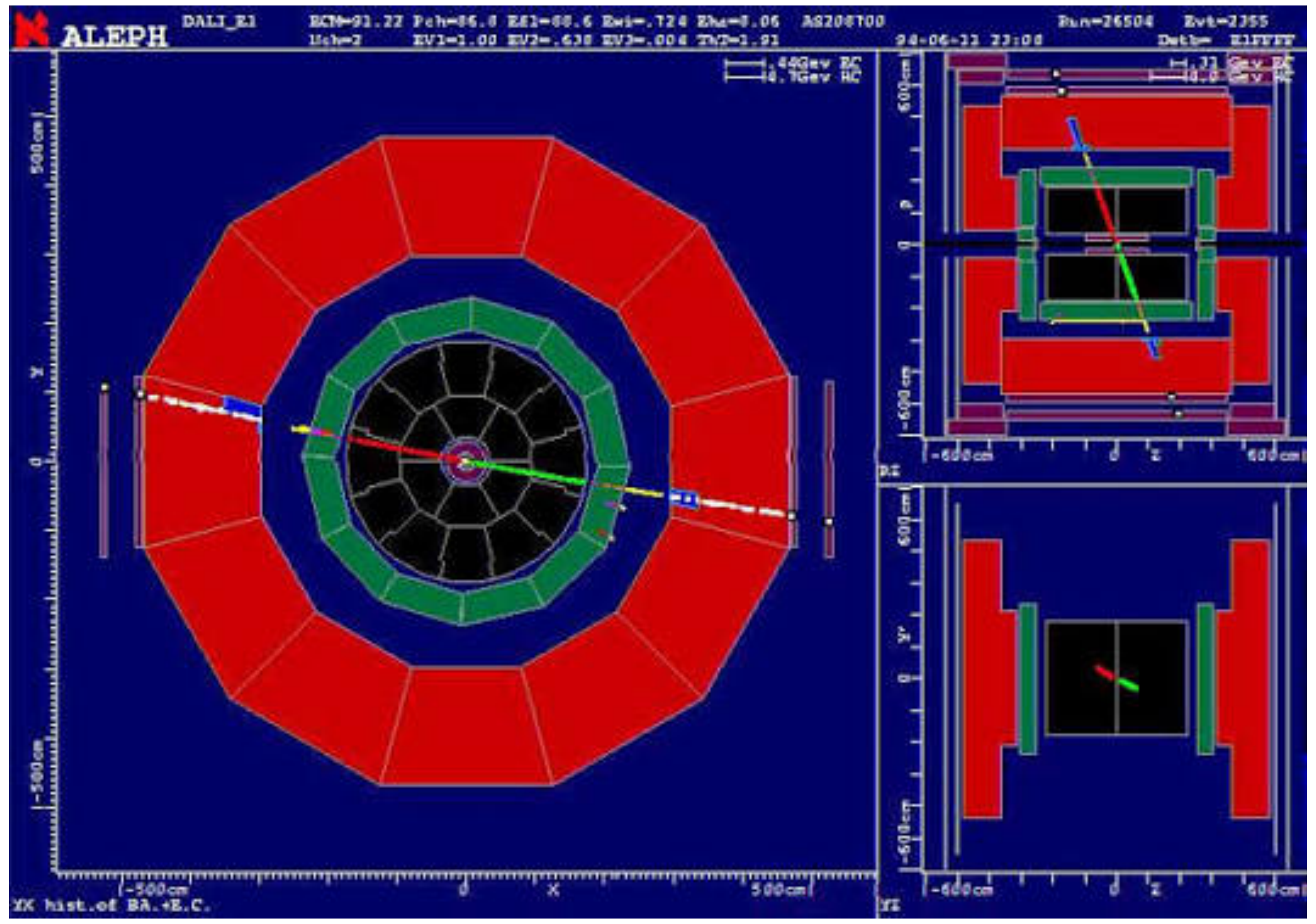




Z
e⁺e⁻ → hadrons
cross-section (pb)
centre-of-mass energy (GeV)
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W⁺W⁻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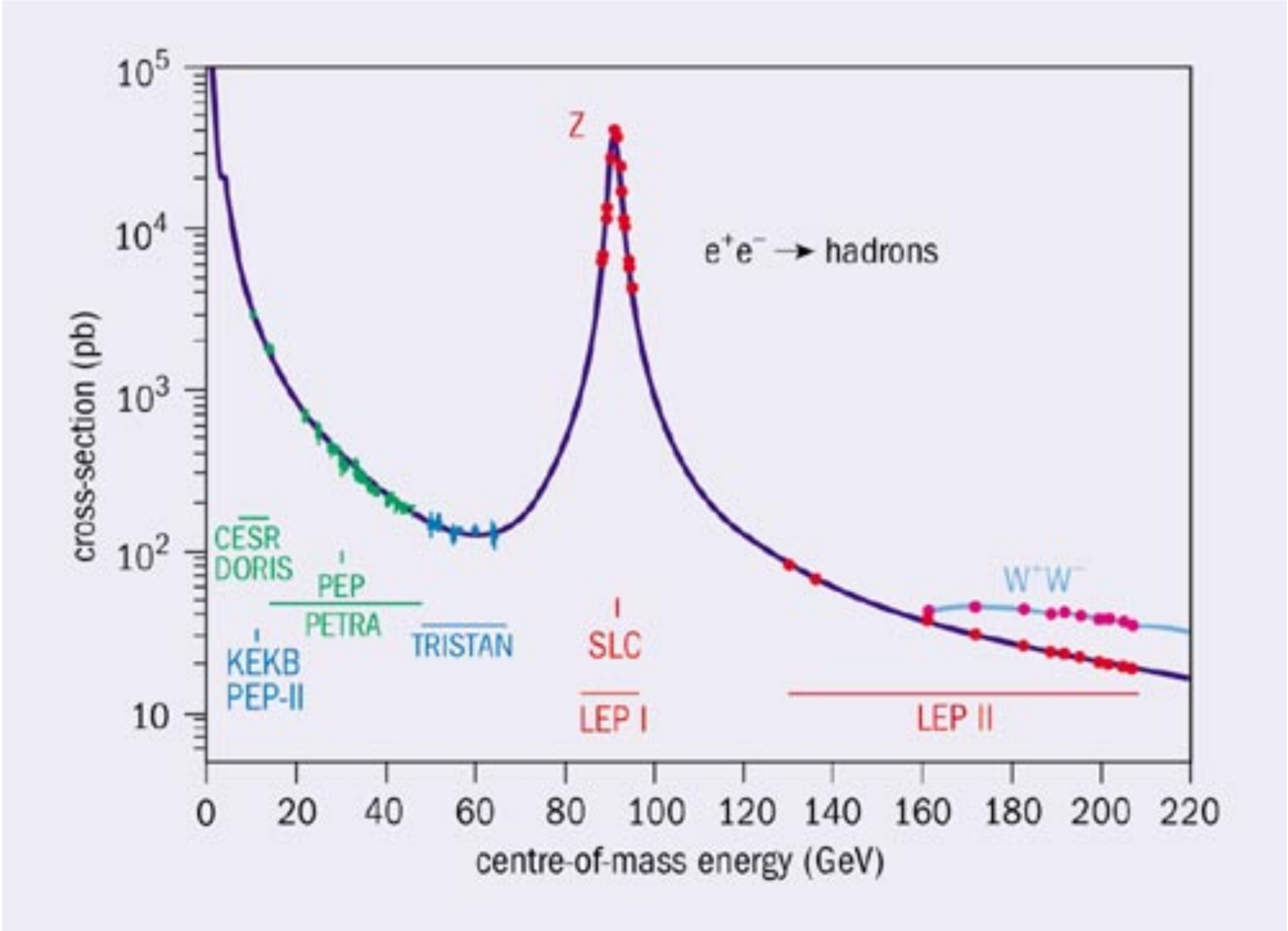
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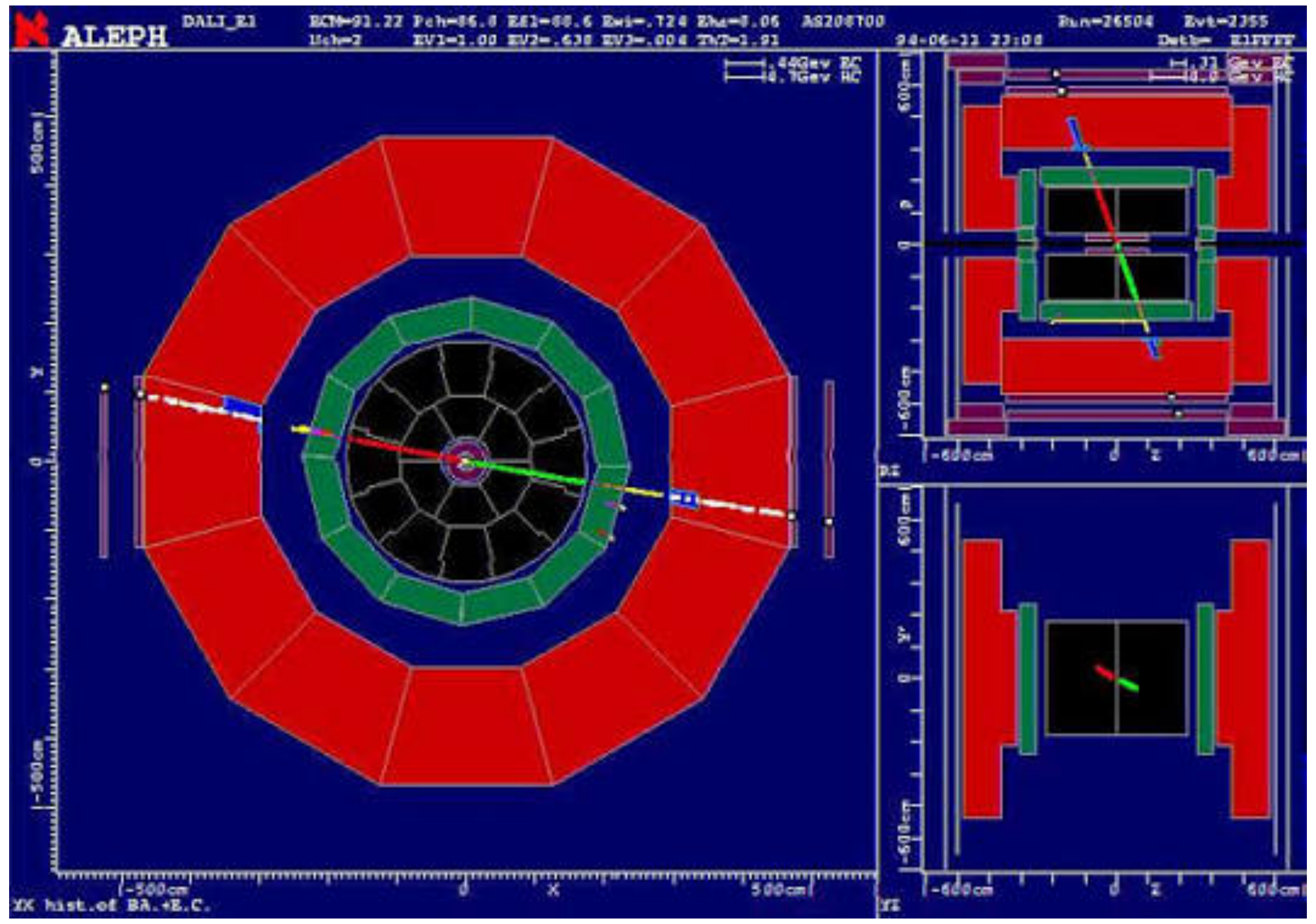
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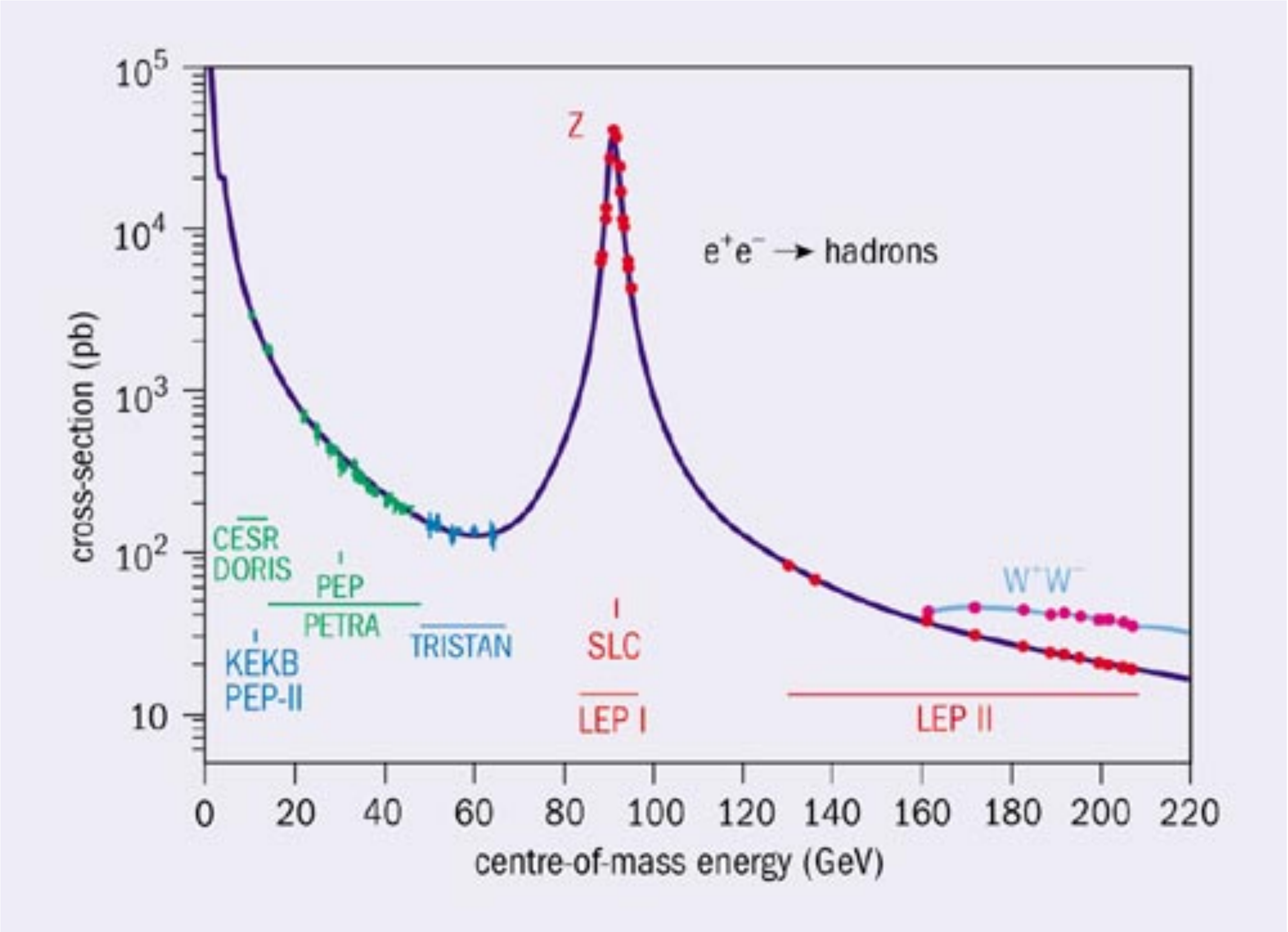
cross-section (pb)
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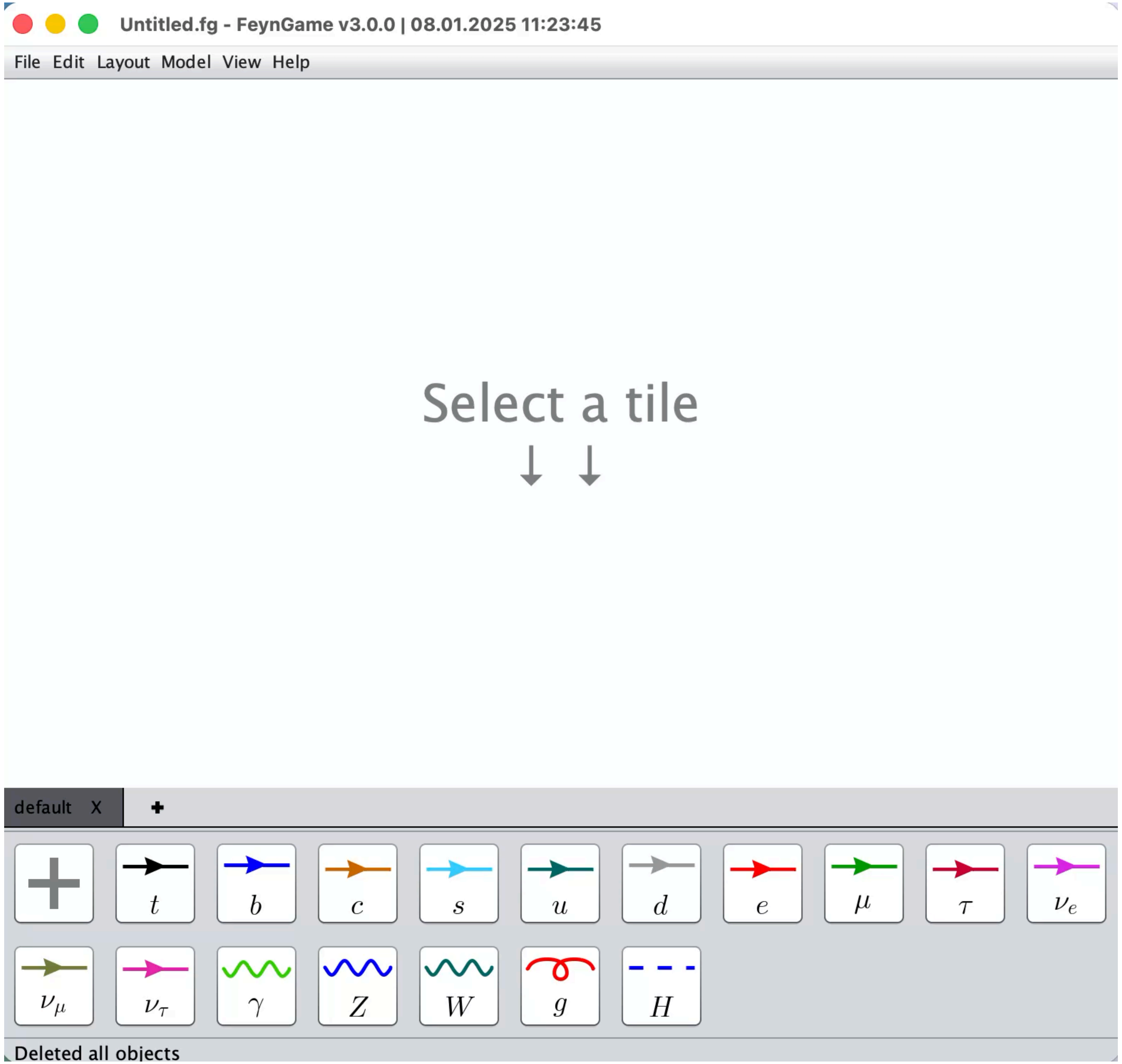
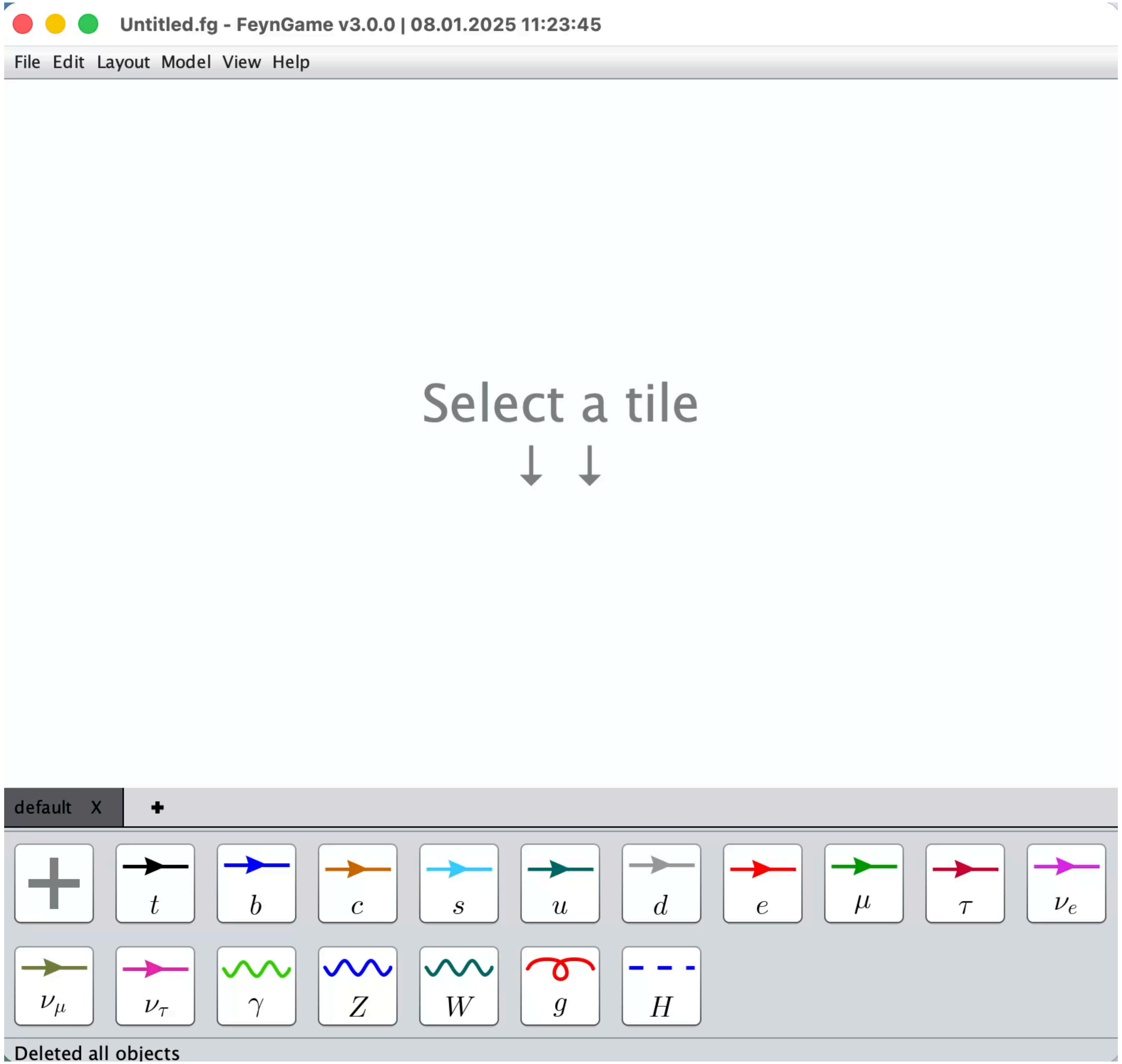
e⁺e⁻ → hadrons
Z
W⁺W⁻
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
10
10²
10³
10⁴
10⁵

FeynGame


Untitled.fg - FeynGame v3.0.0 | 08.01.2025 11:23:45
File Edit Layout Model View Help
Select a tile
default X
t b c s u d e μ τ ν_e
ν_μ ν_τ γ Z W g H
Deleted all objects

FeynGame



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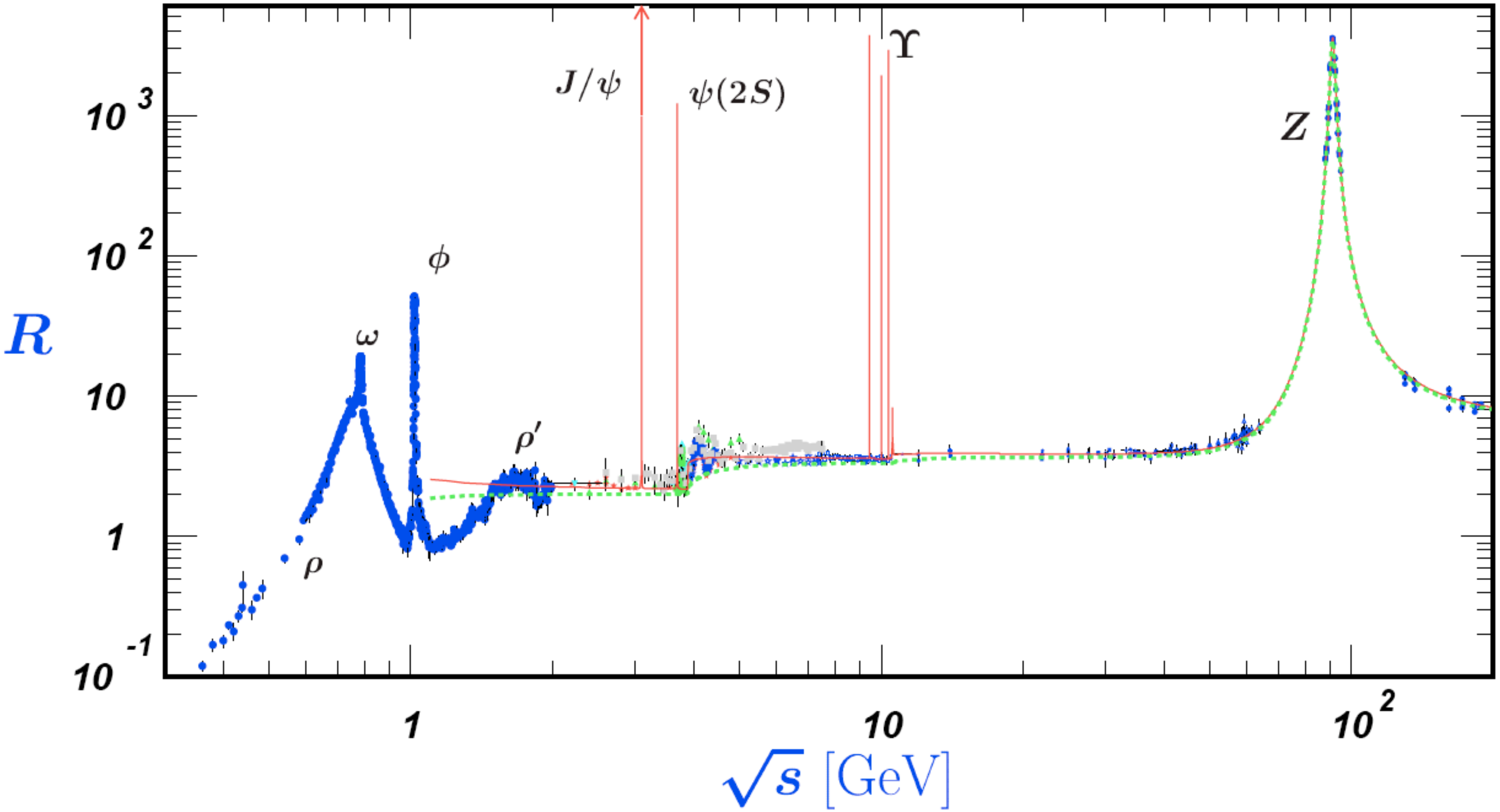
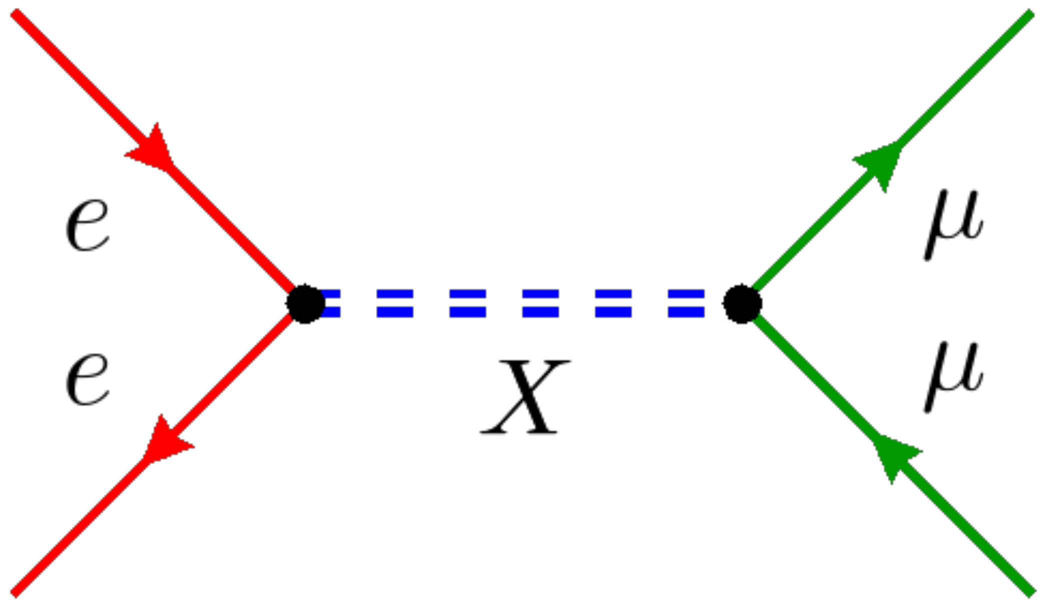
Select a tile
default X
t b c s u d e μ τ ν_e
ν_μ ν_τ γ Z W g H
Deleted all objects

Quarks





Resonanzen

Quarks

1897
1900

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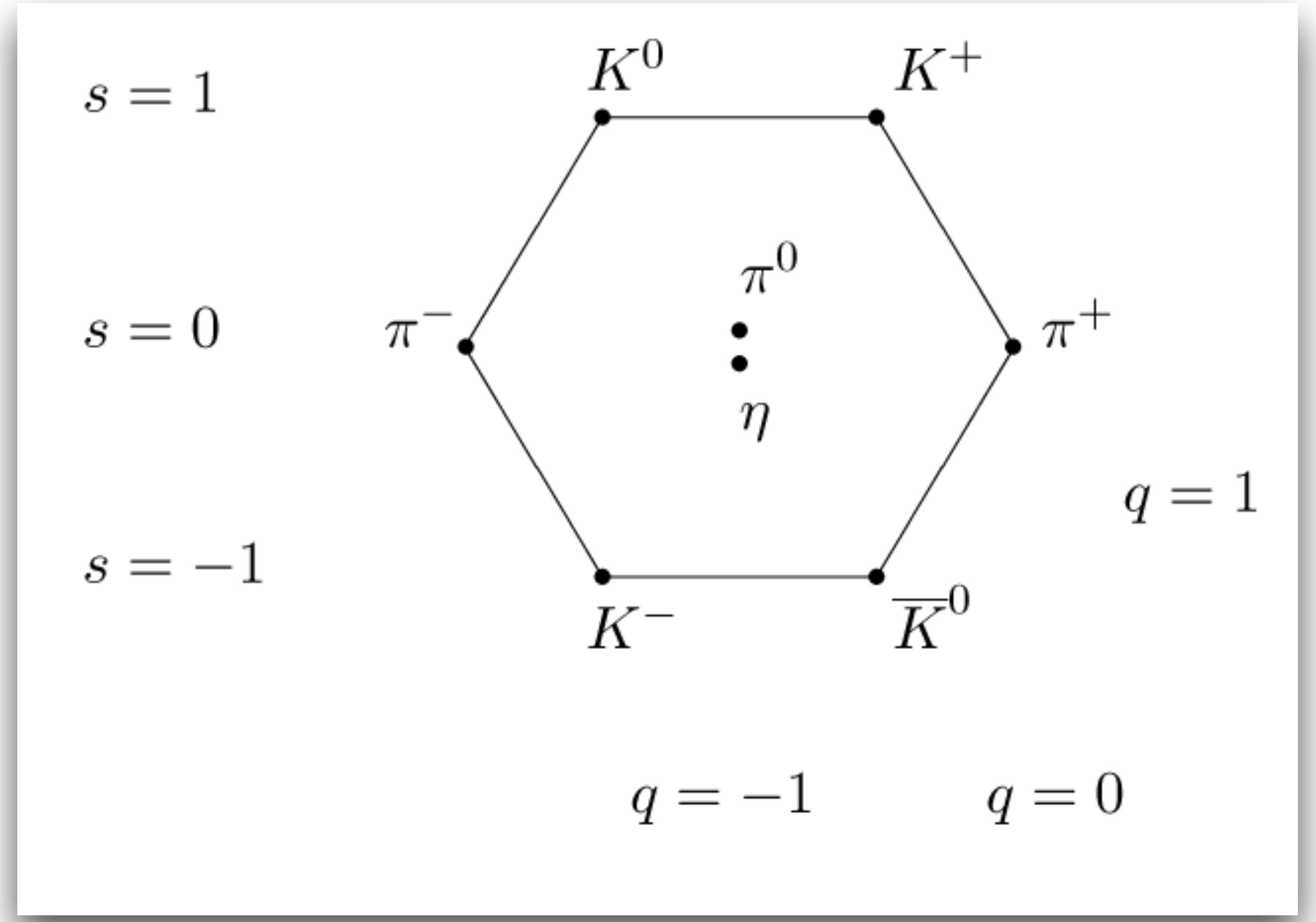
1956 Gell-Mann
1964 Zweig



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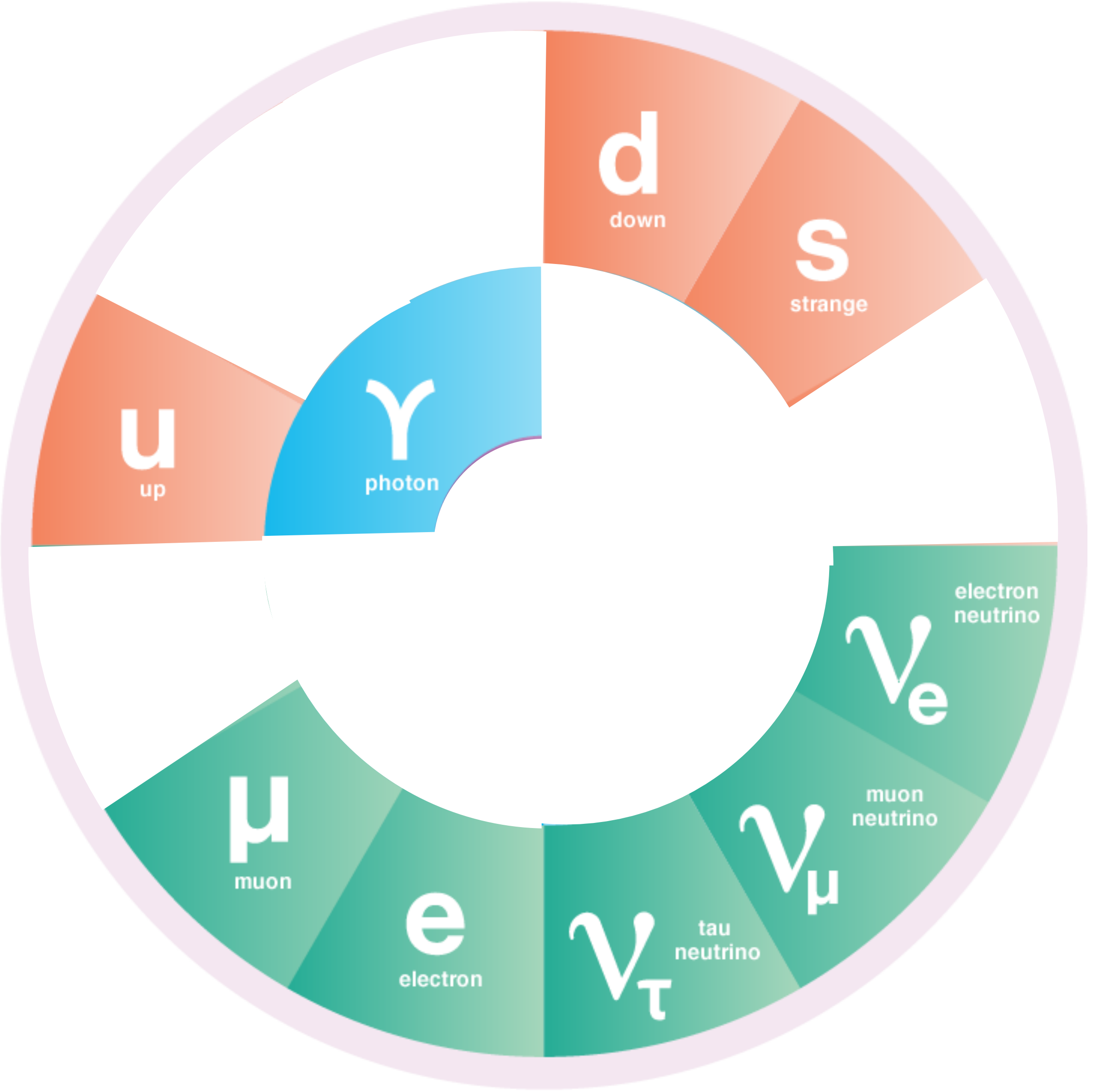

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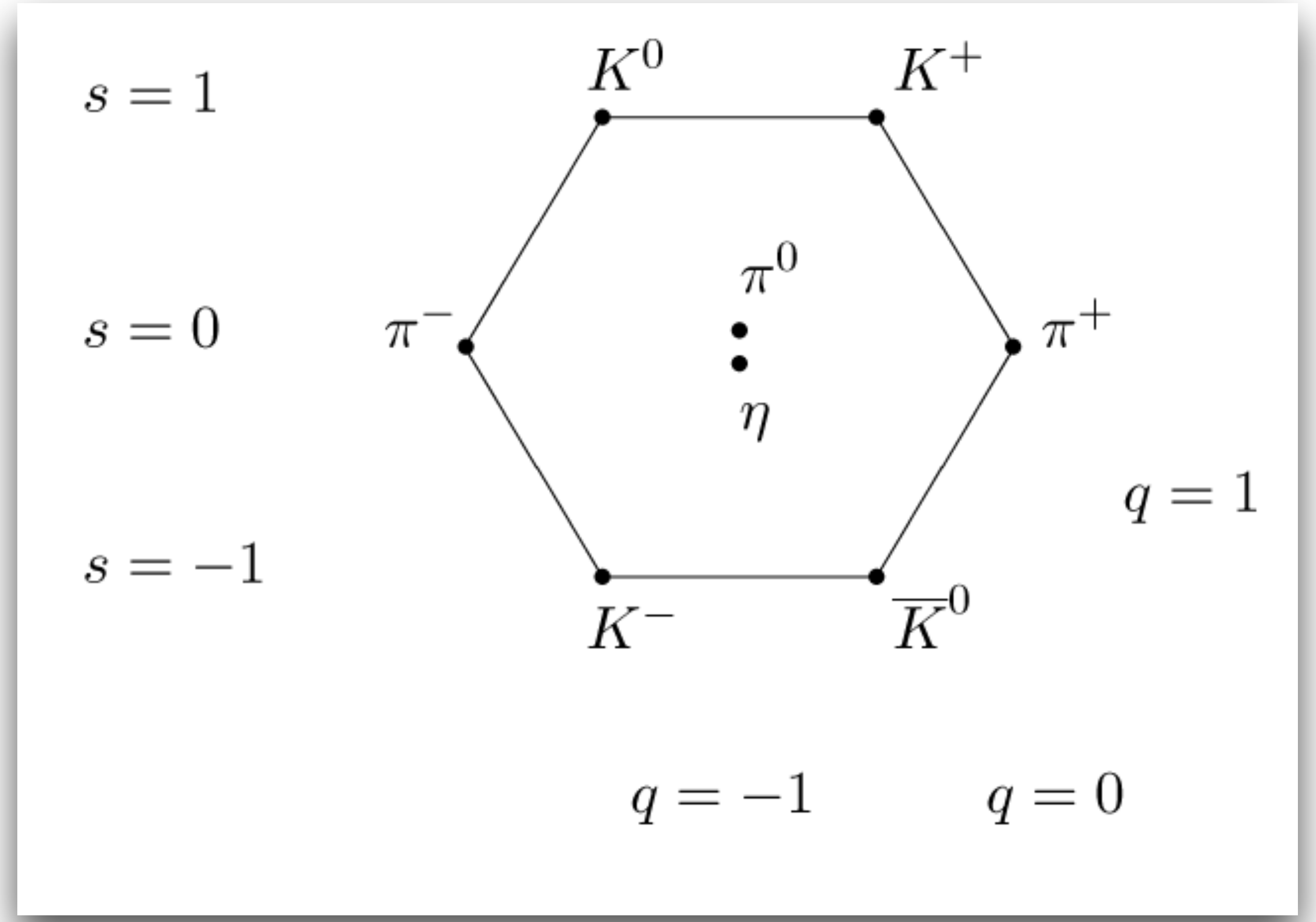

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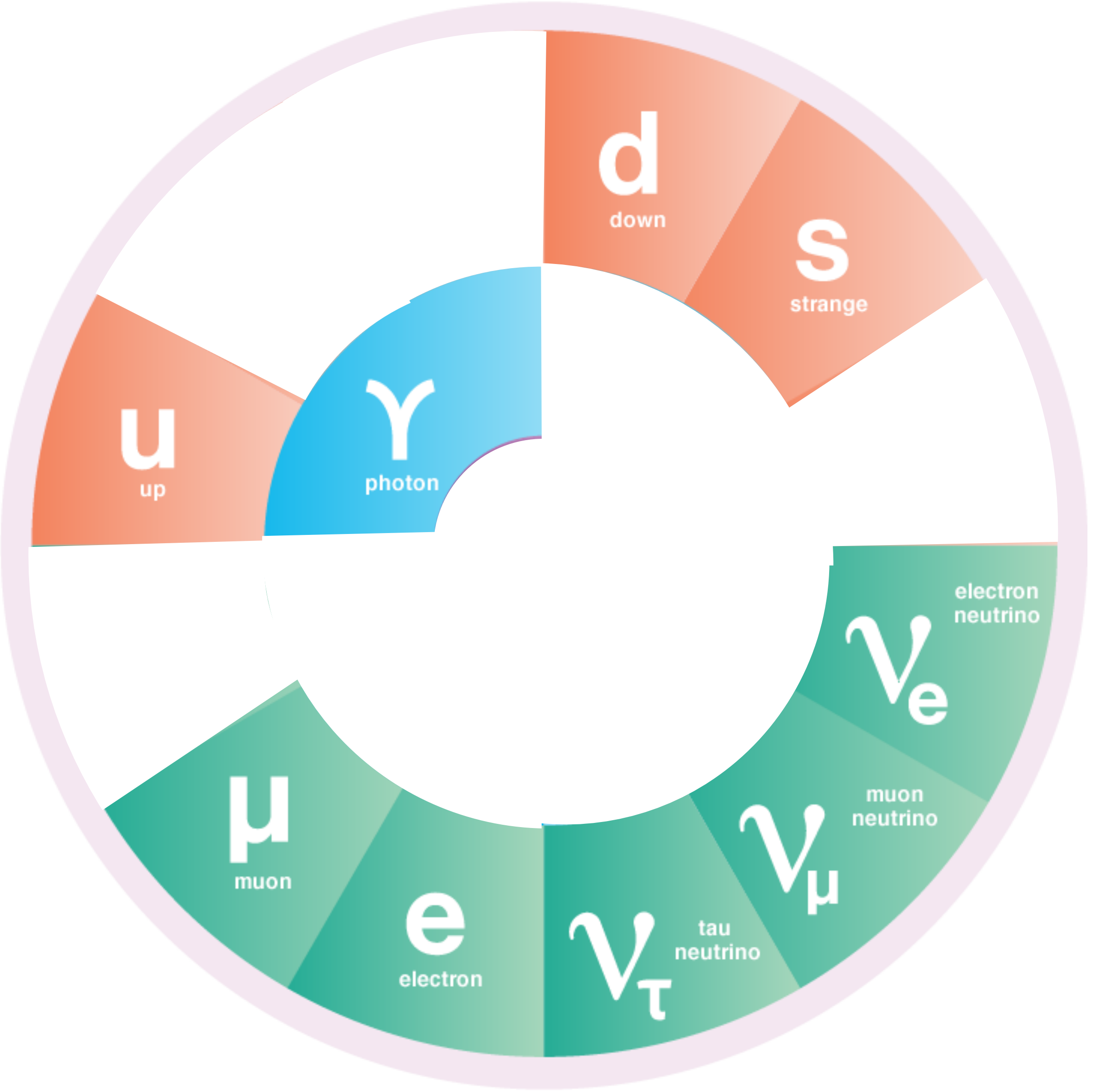

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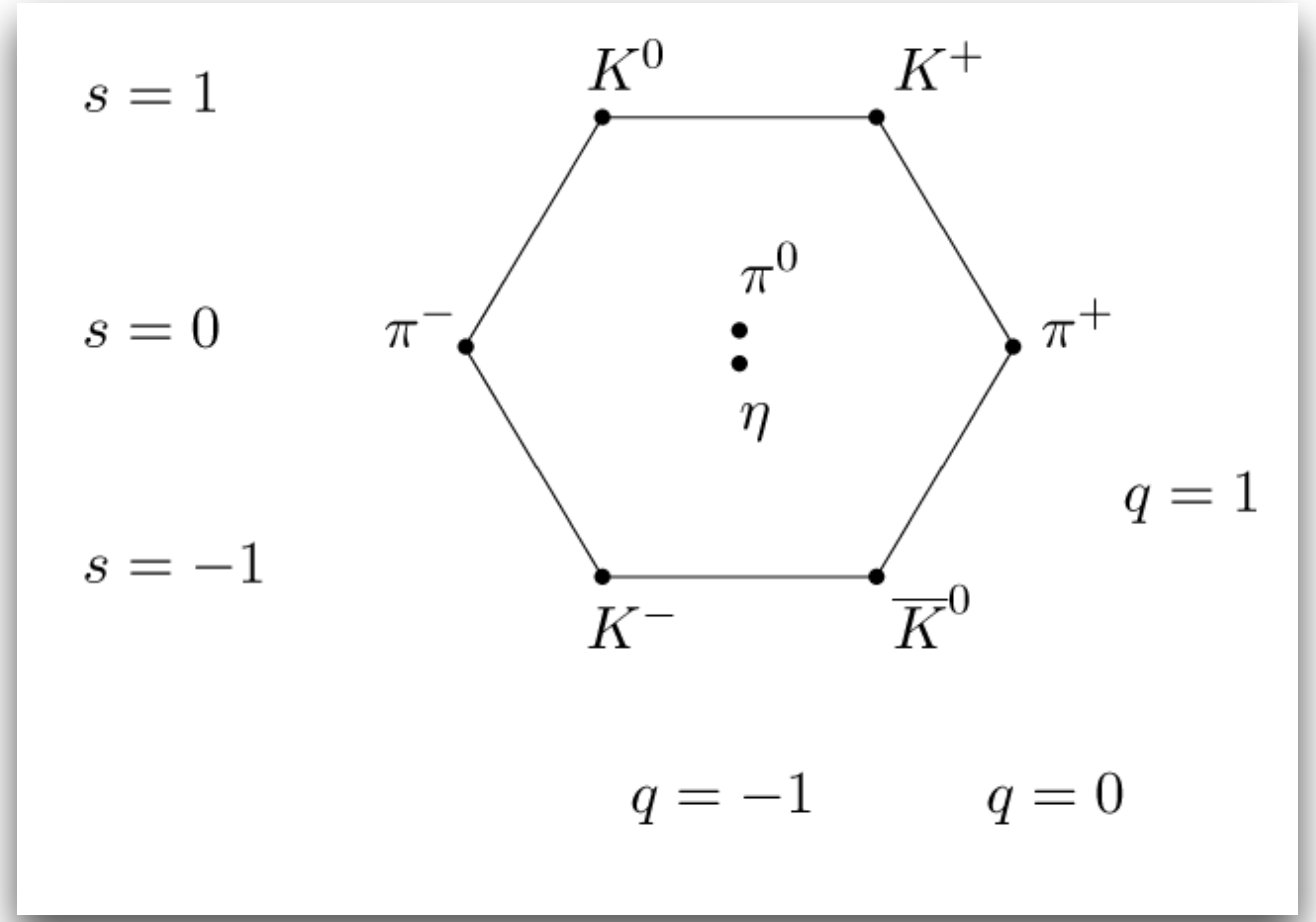
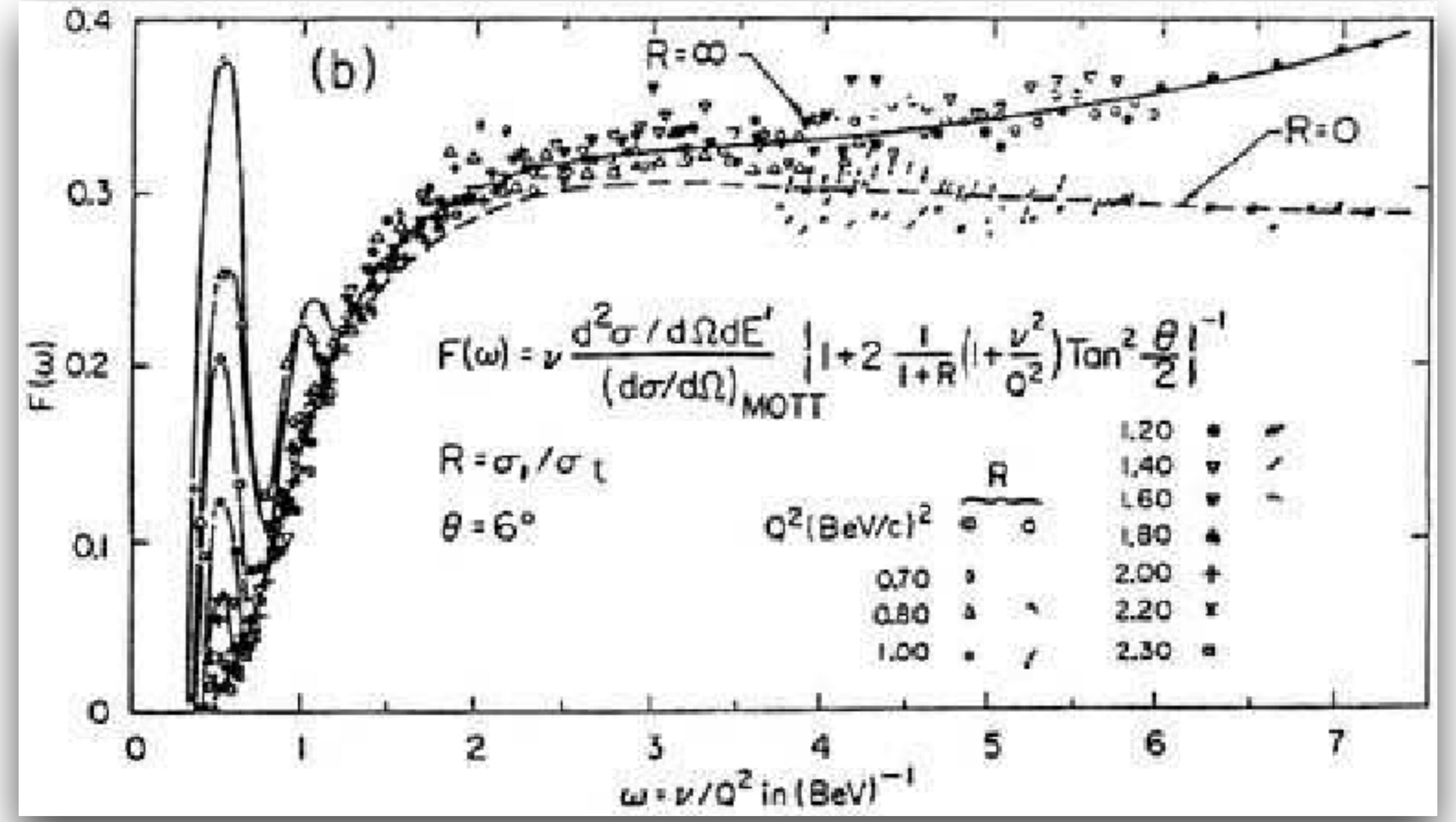
Feynman





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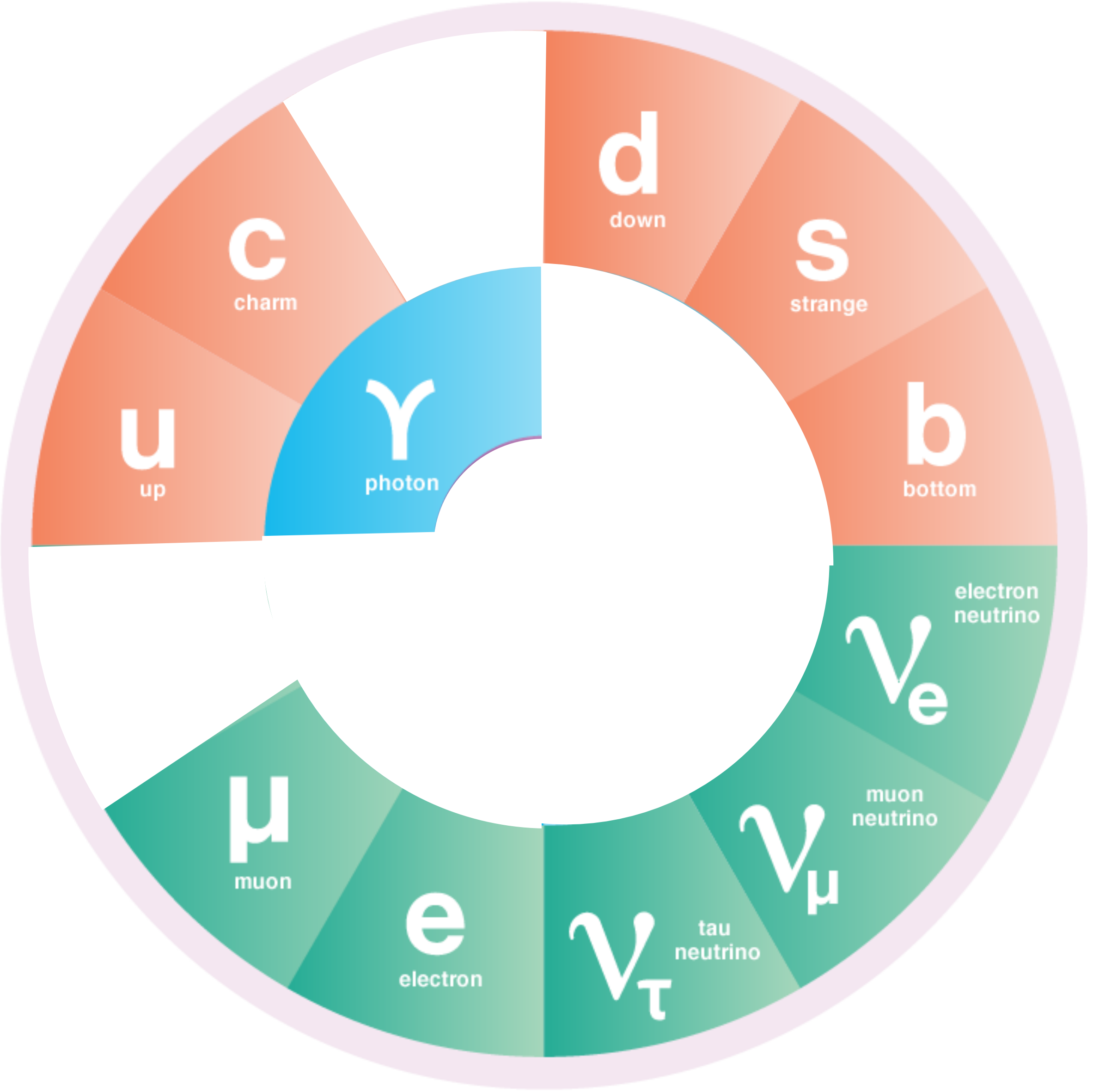

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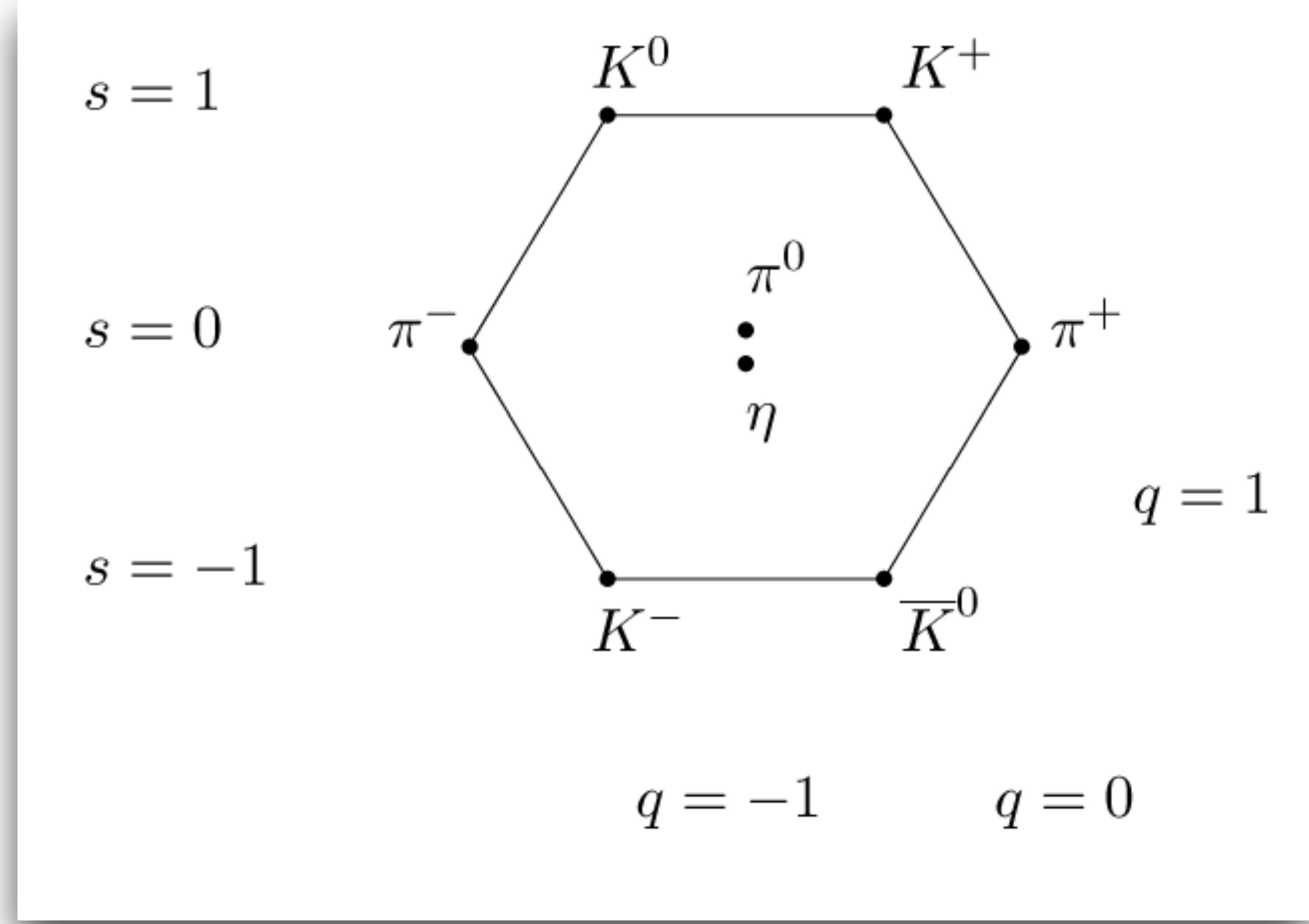
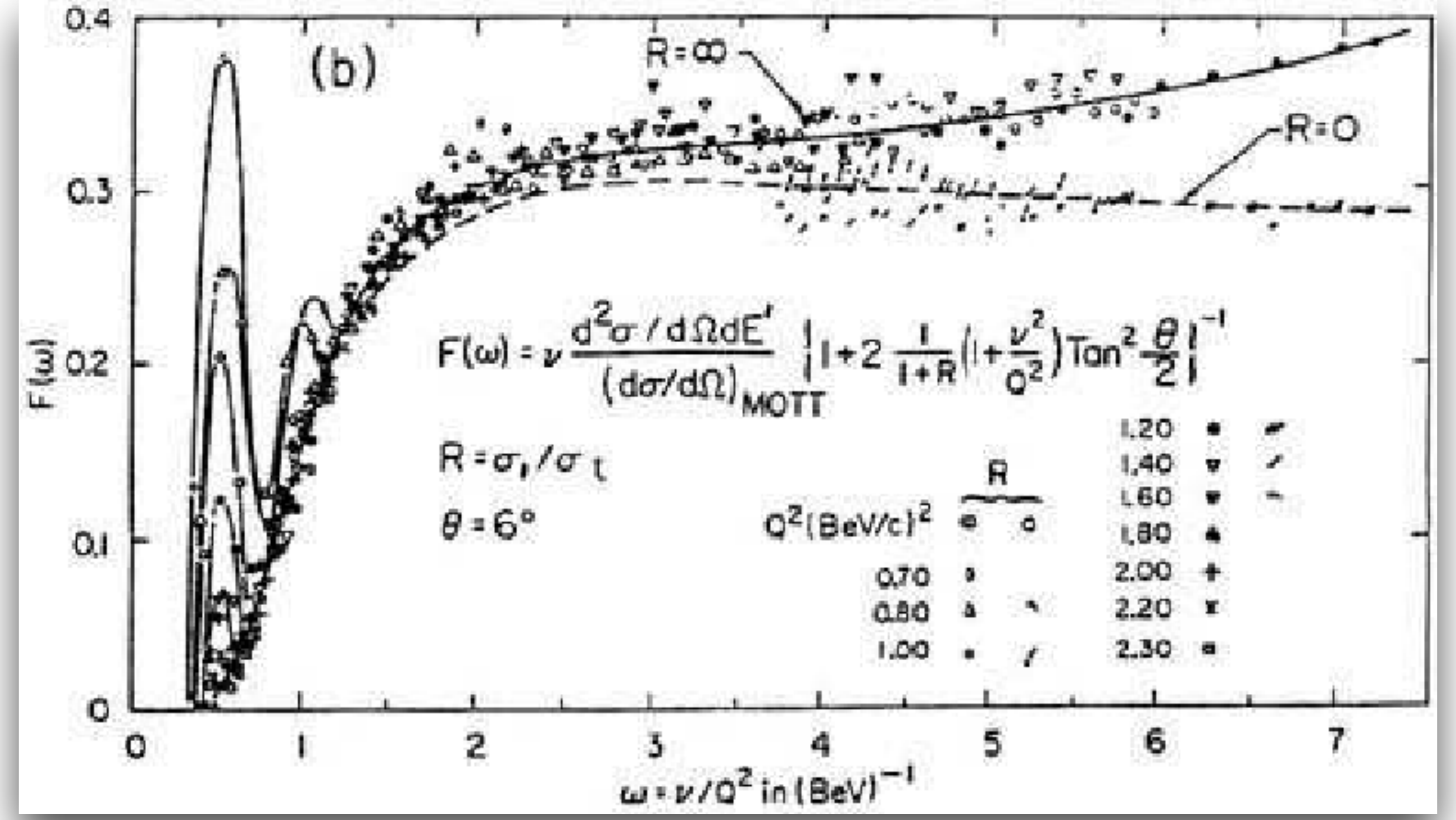
Feynman





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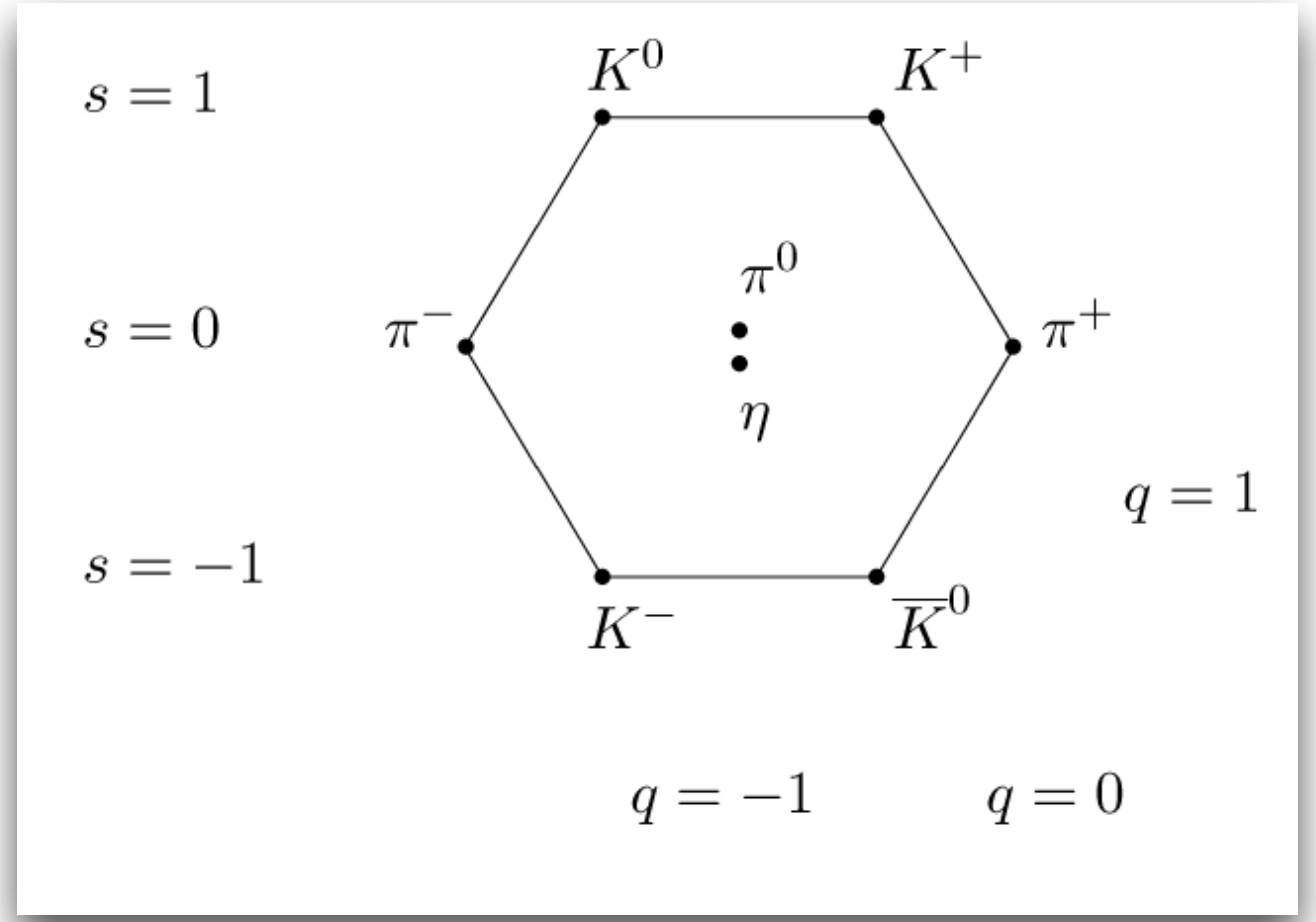
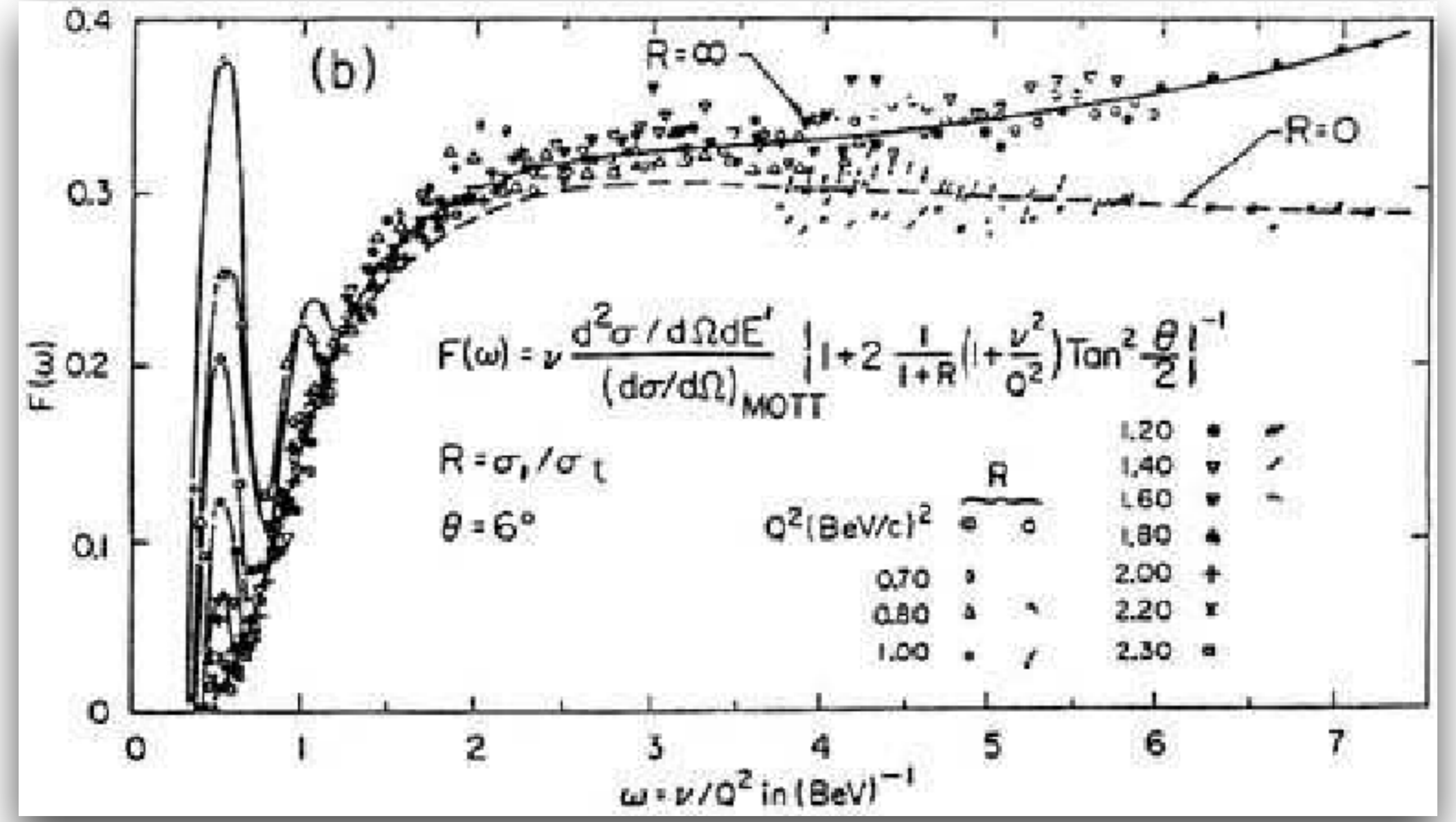
Feynman





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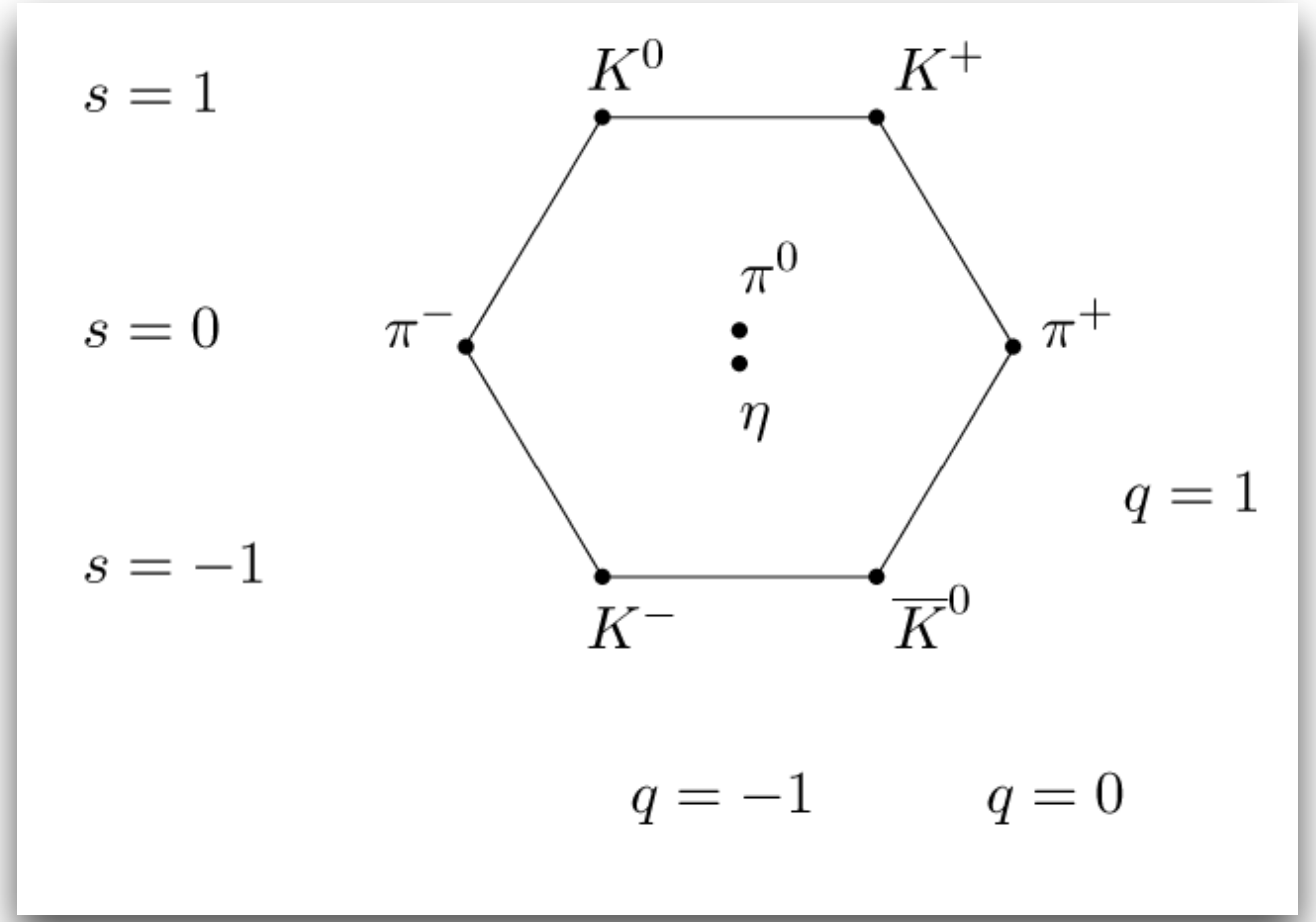

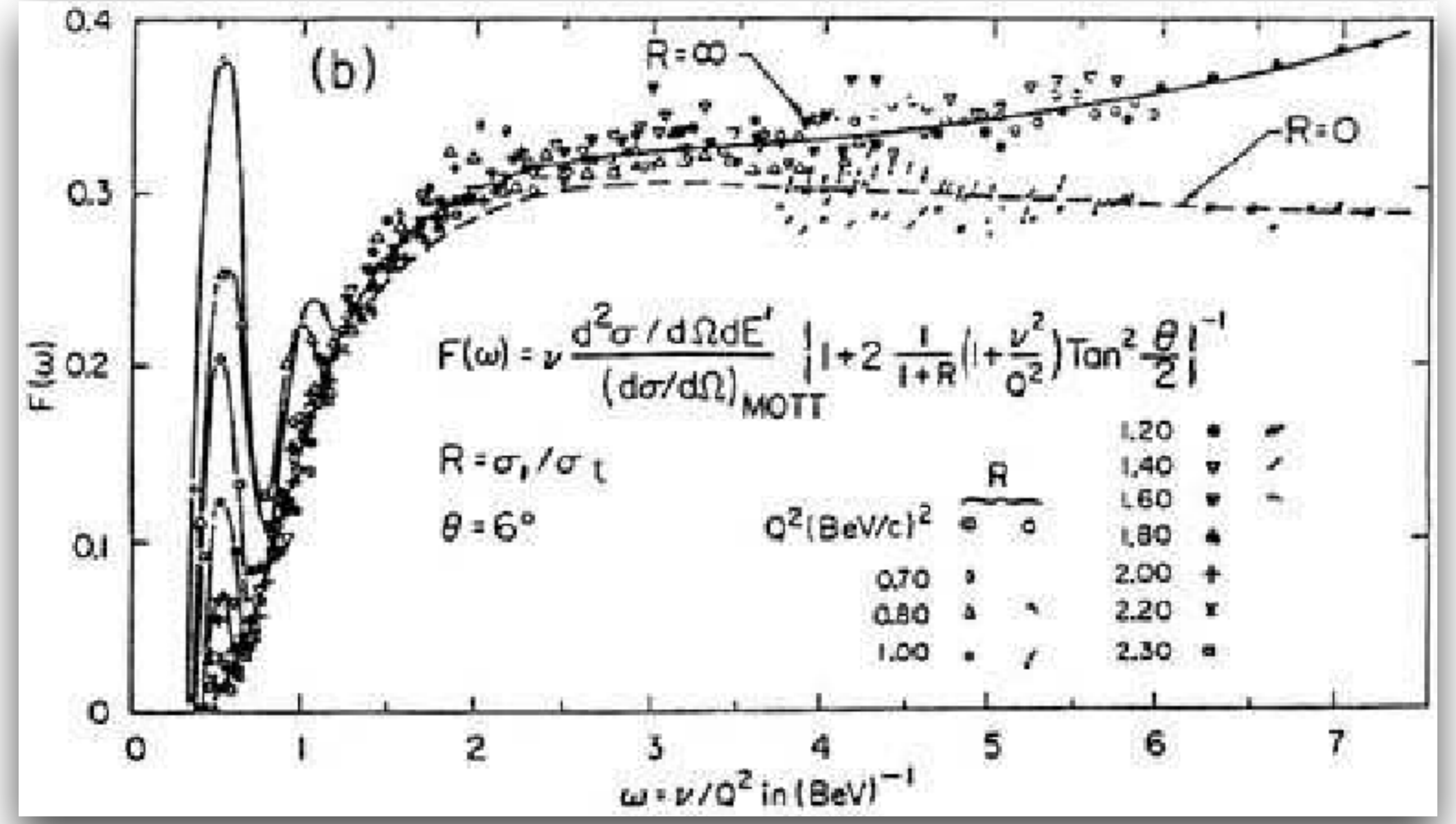

Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

Top quark

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top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
τ
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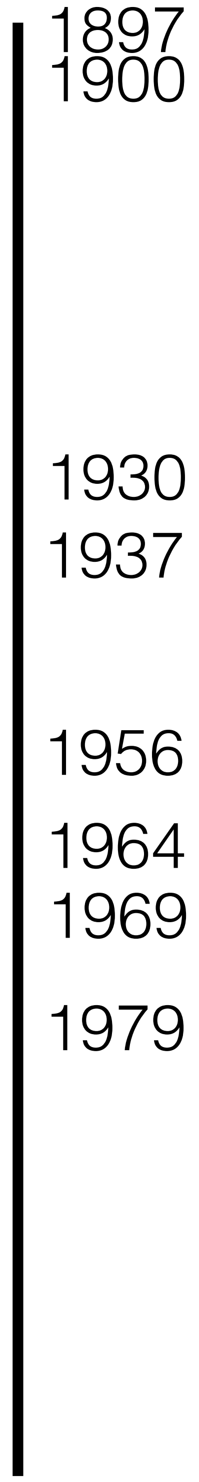
W
W boson
Z
Z boson
electron neutrino
μ
muon
e
electron
tau neutrino
muon neutrino



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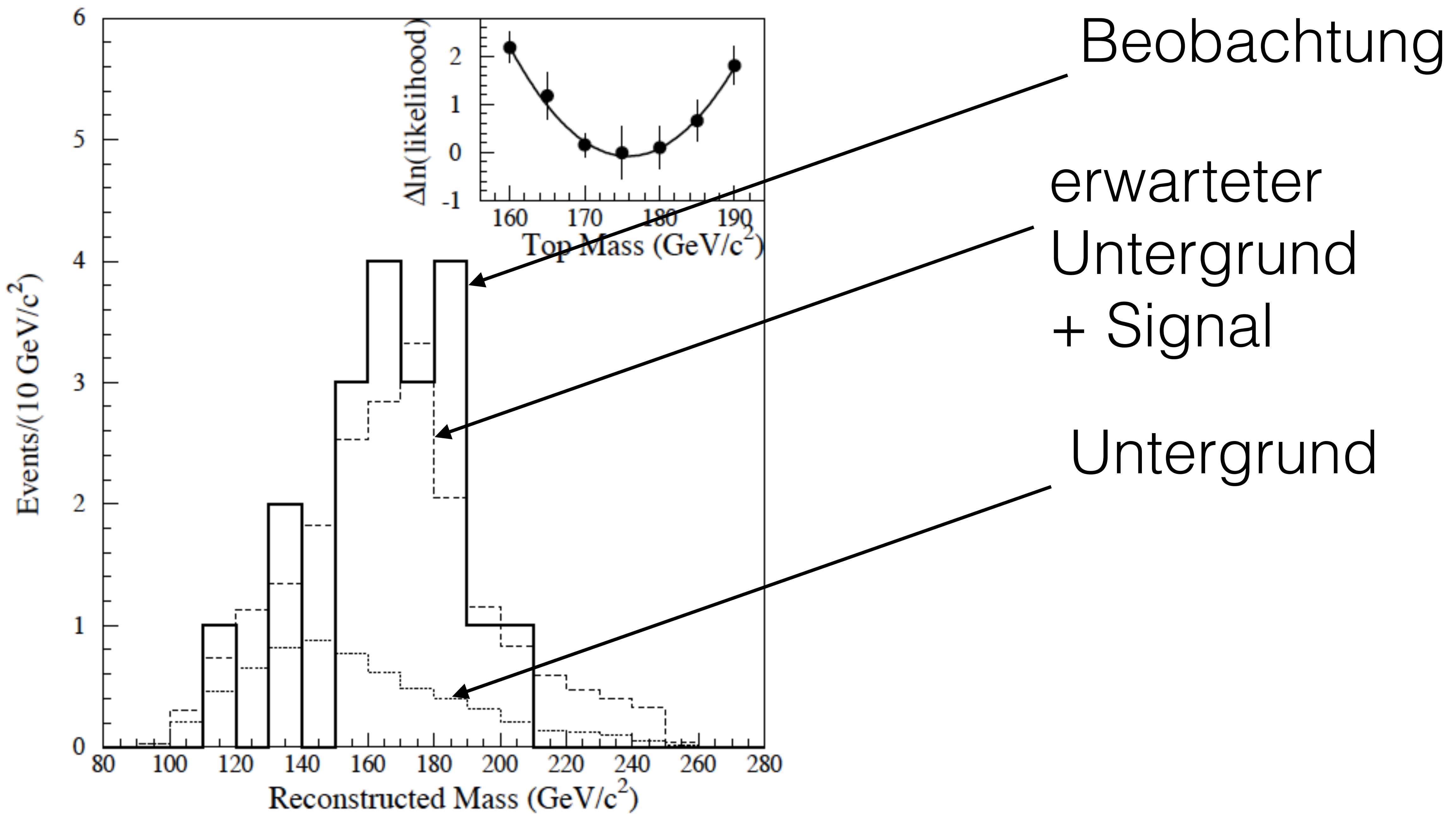
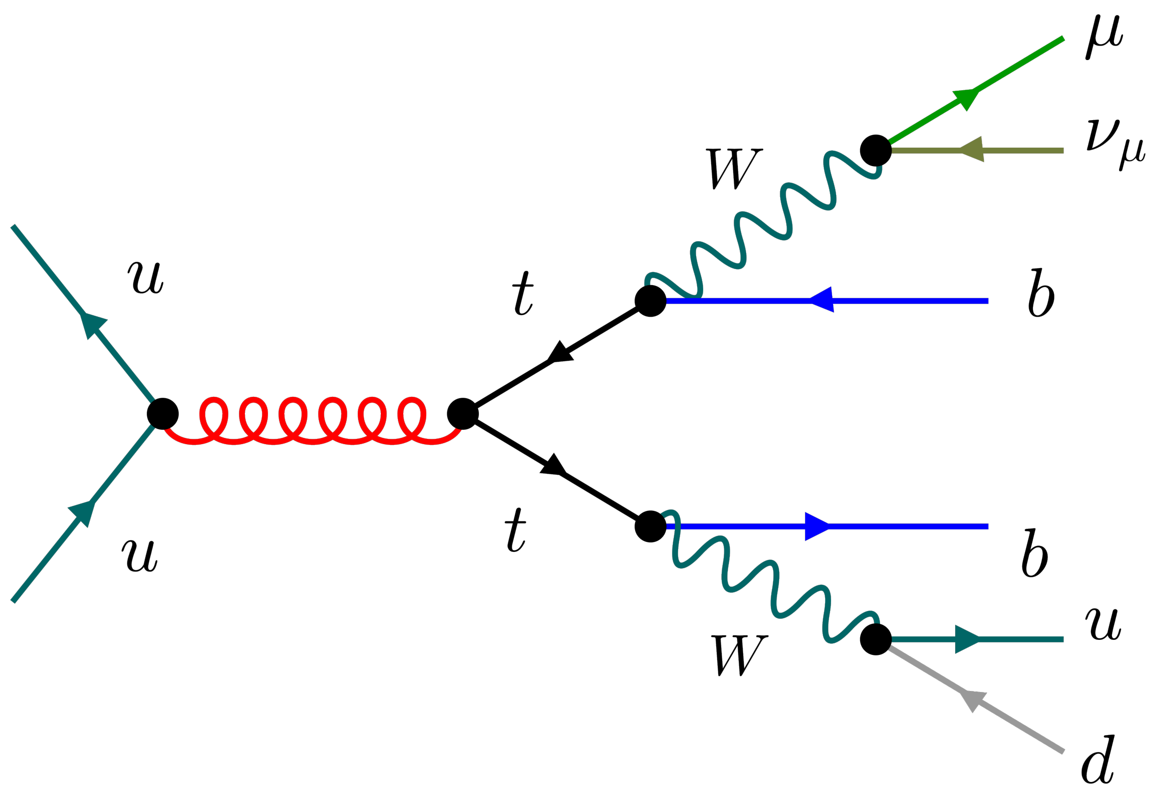


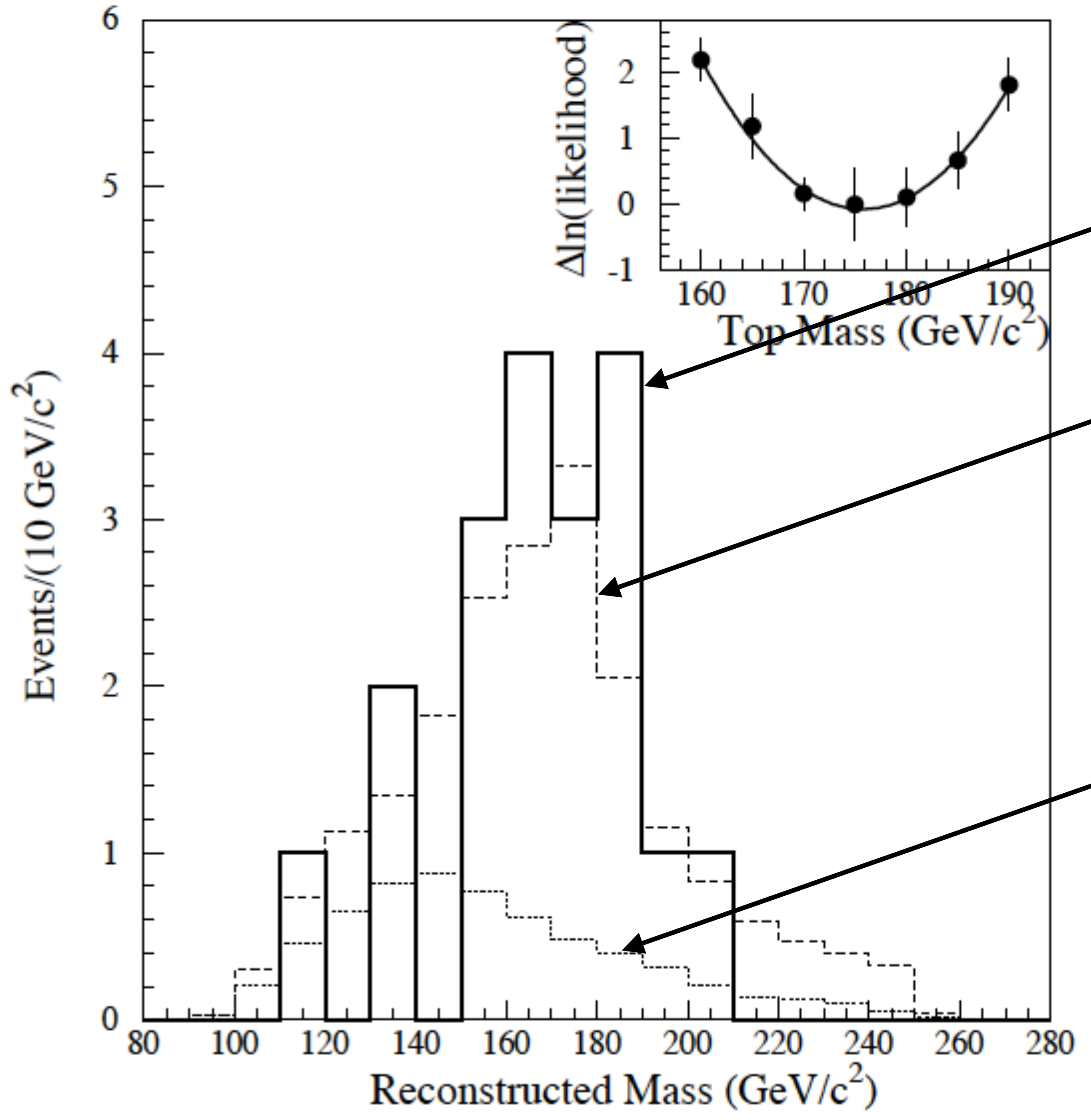
Events/(10 GeV/c²)
Reconstructed Mass (GeV/c²)
Δln(likelihood)
Top Mass (GeV/c²)
Beobachtung
erwarteter Untergrund + Signal
Untergrund



u
u
t
t
W
W
b
b
μ
ν_μ
u
d

Top quark

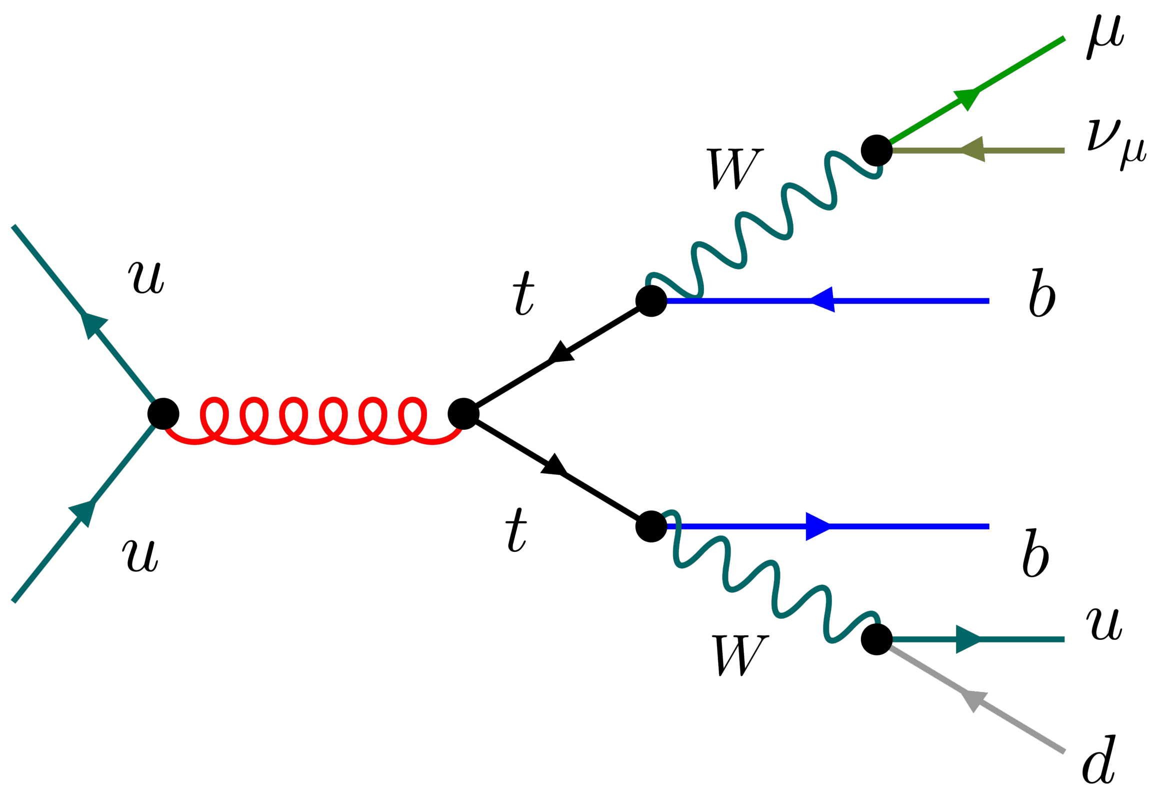
1897
1900
1930
1937
1956
1964
1969
1979
1995 CDF D0



Beobachtung

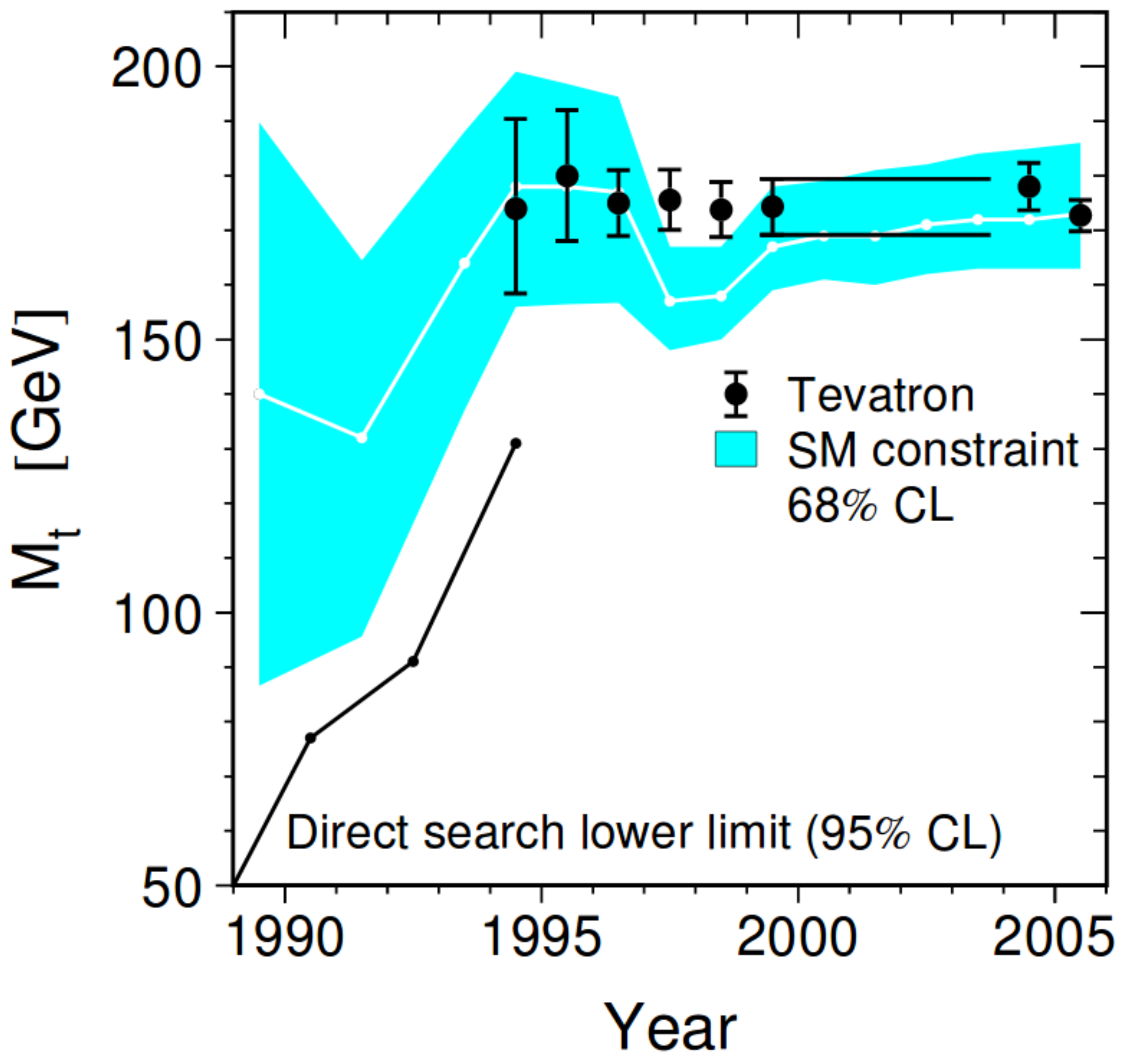
erwarteter Untergrund + Signal

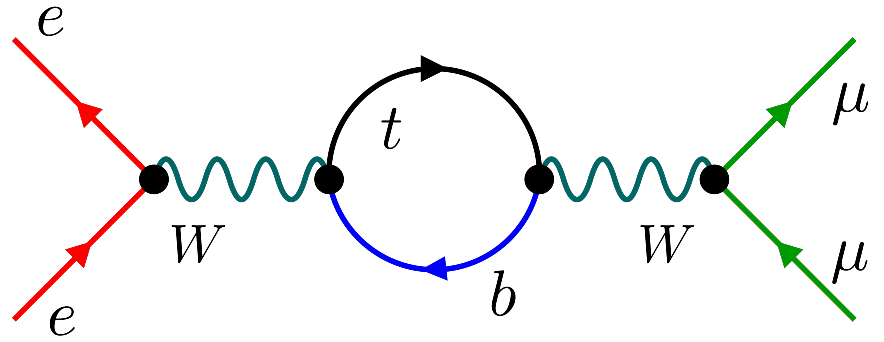
Untergrund



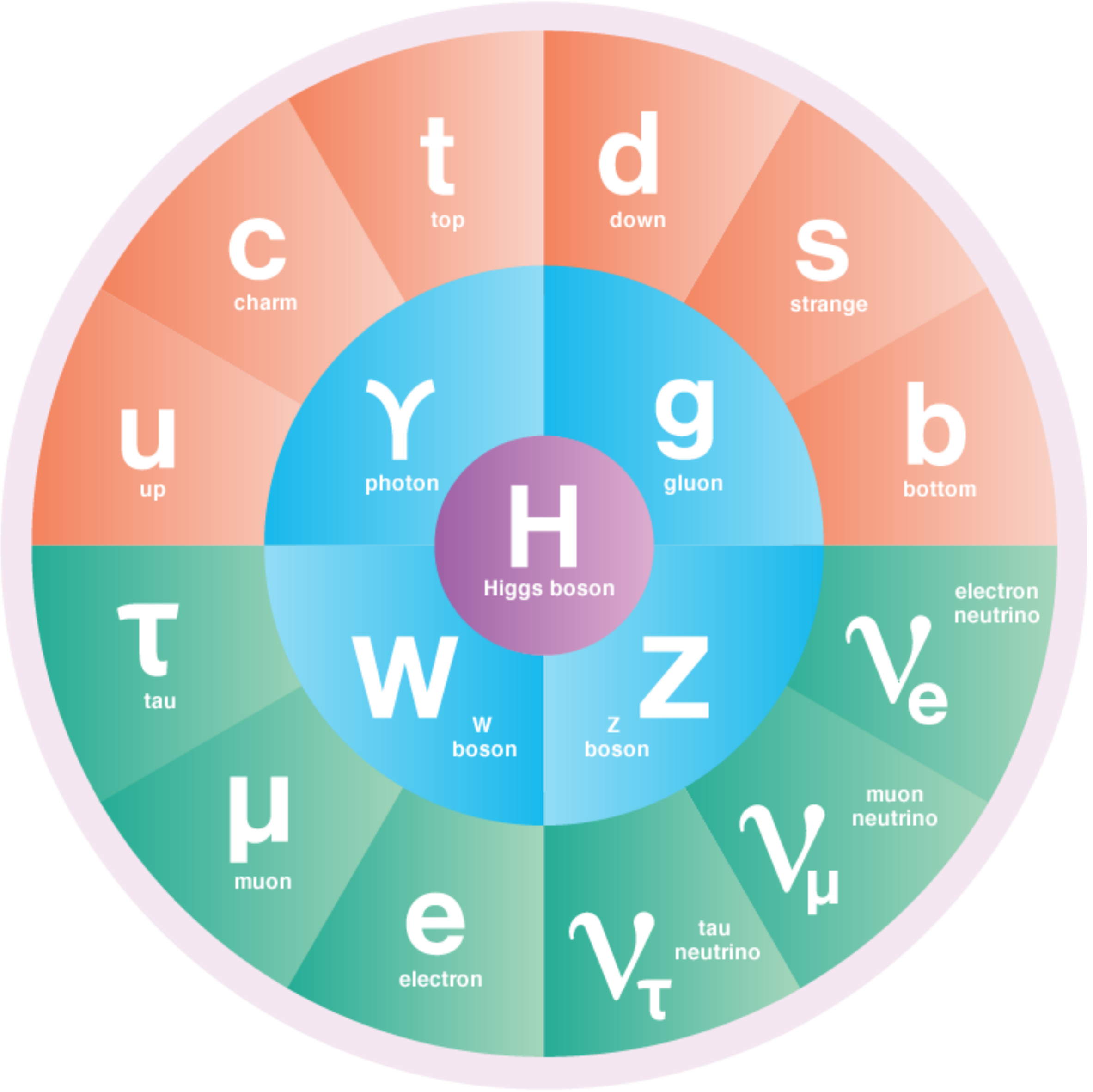
Top quark

1897
1900
1930
1937
1956
1964
1969
1979
1995

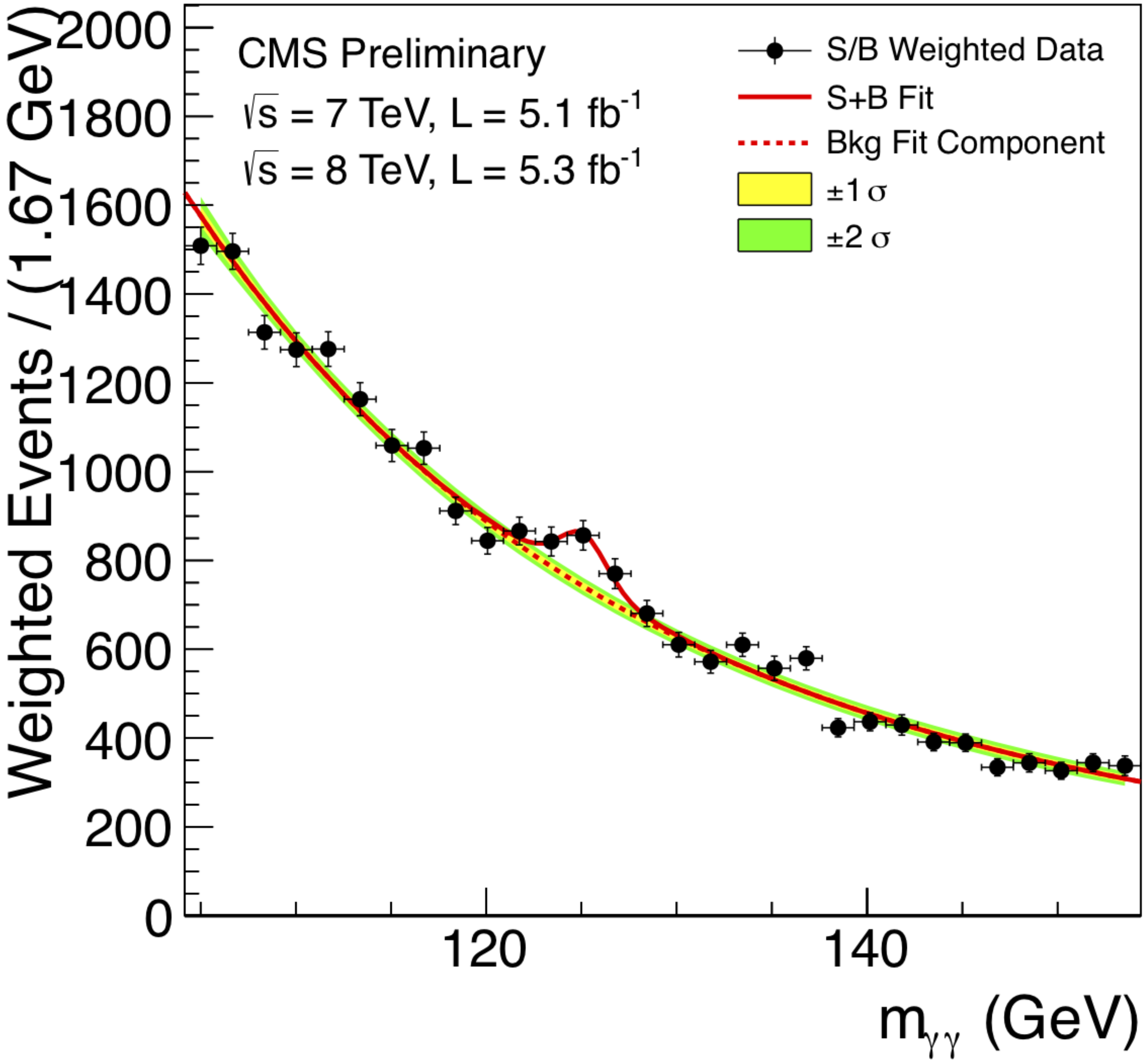


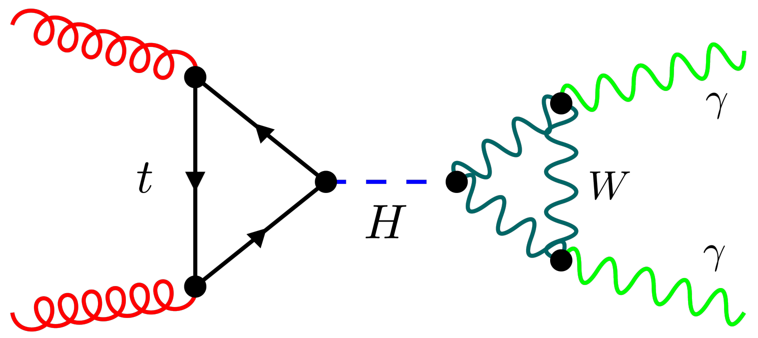


Higgs

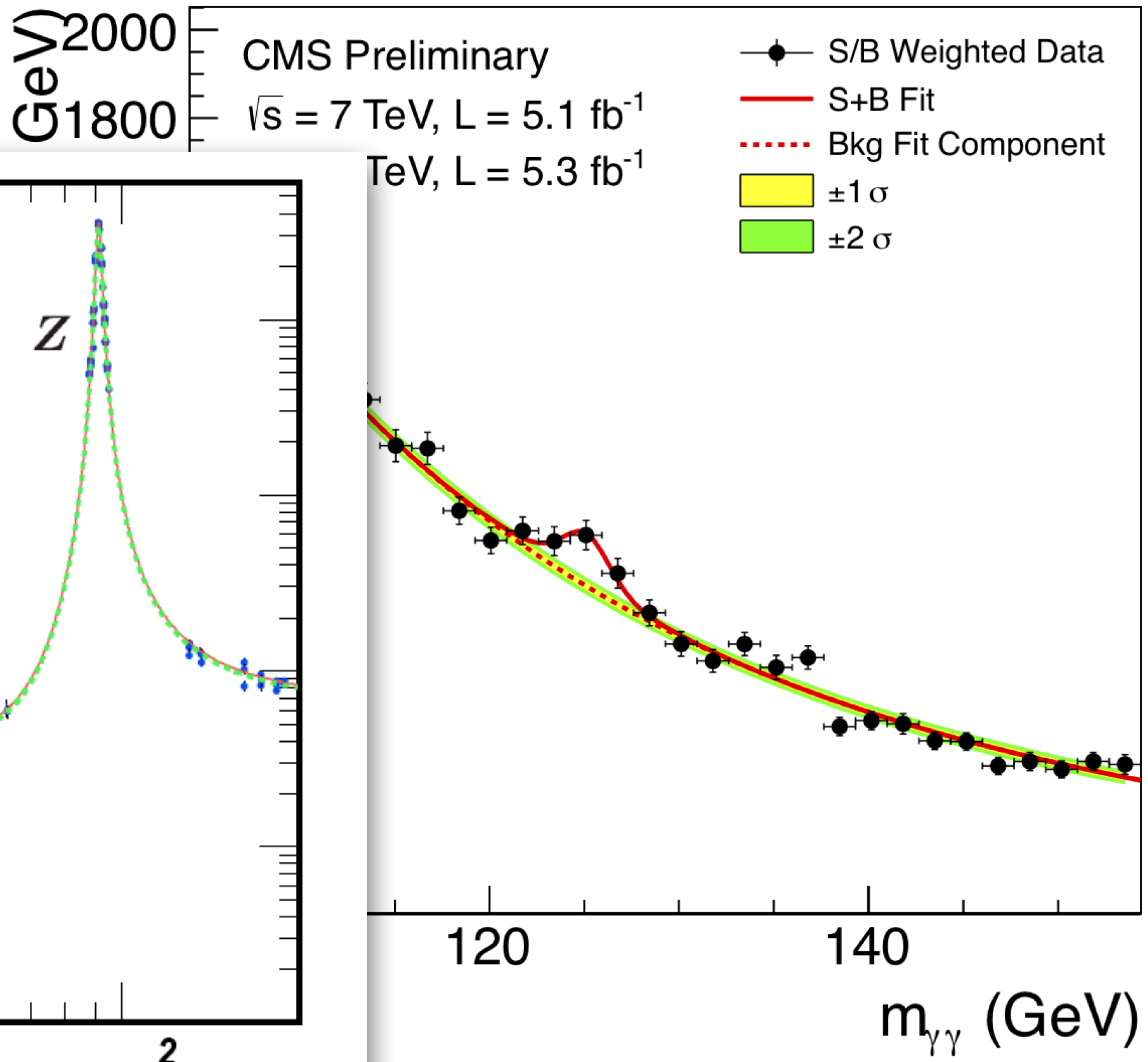


1897
1900
1930
1937
1956
1964
1969
1979
1995
2012

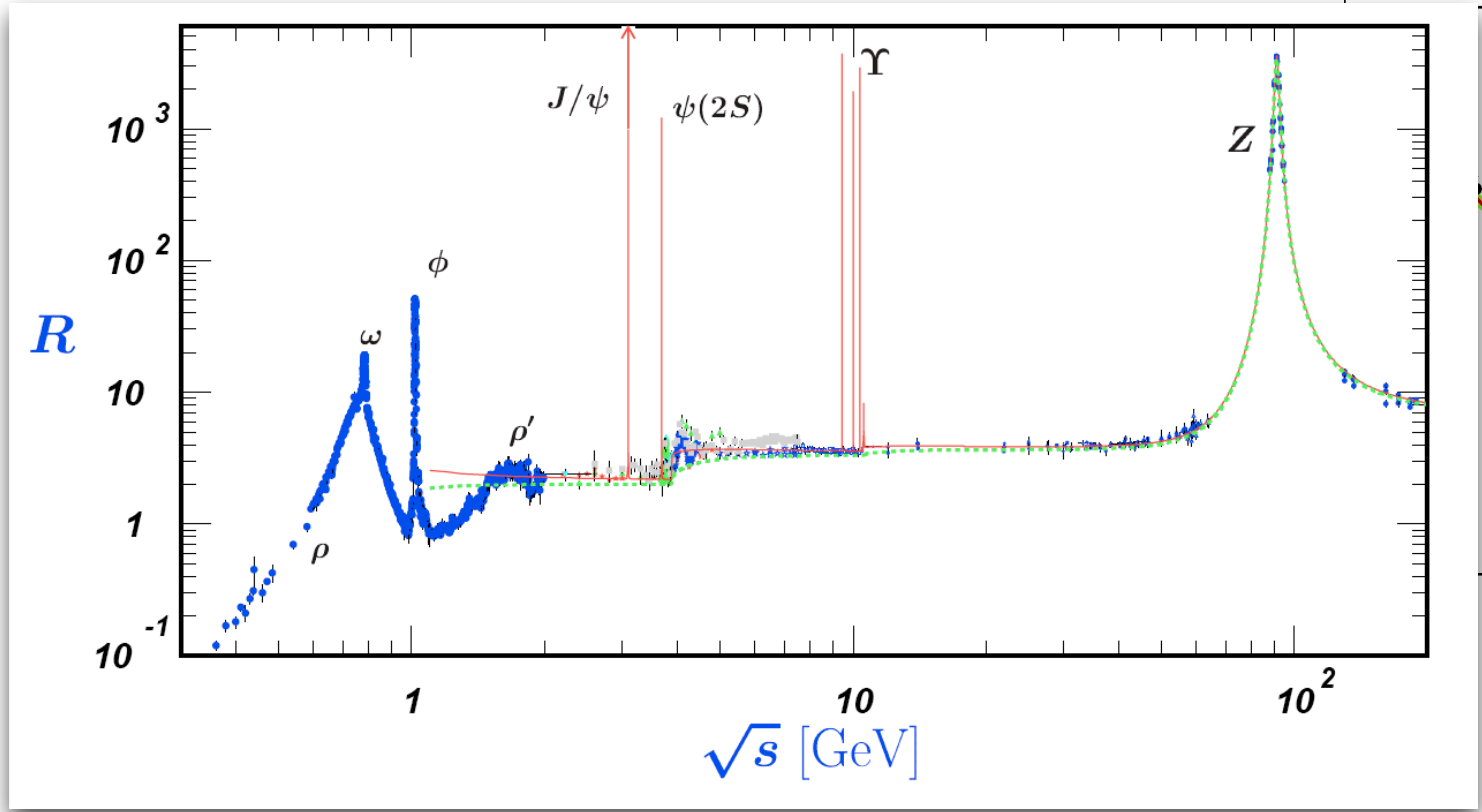




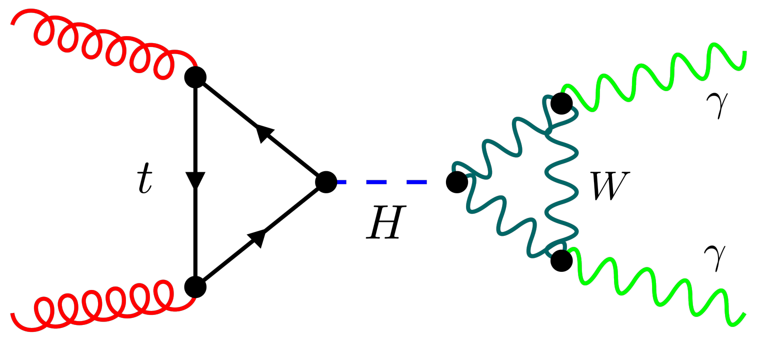
Higgs



CMS Preliminary
√s = 7 TeV, L = 5.1 fb^{-1}
TeV, L = 5.3 fb^{-1}
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
2000
1800
GeV)
120
140
$m_{\gamma\gamma}$ (GeV)

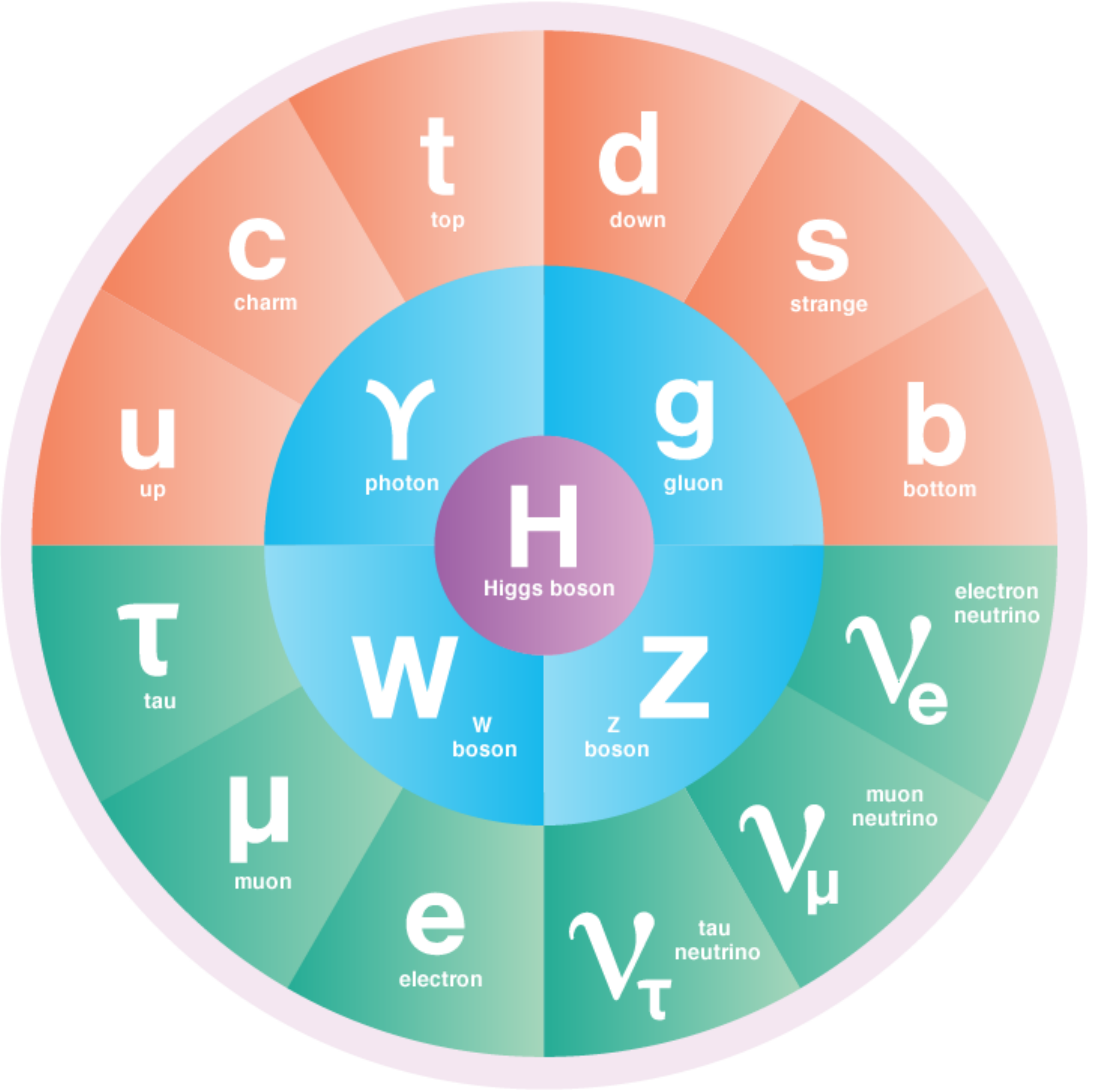


R
10^3
10^2
10
1
10^{-1}
1
10
10^2
$\sqrt{s}$ [GeV]
J/ψ
$\psi(2S)$
Υ
Z
ϕ
ω
ρ'
ρ



t
H
W
γ
γ

Higgs



1897
1900
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1937
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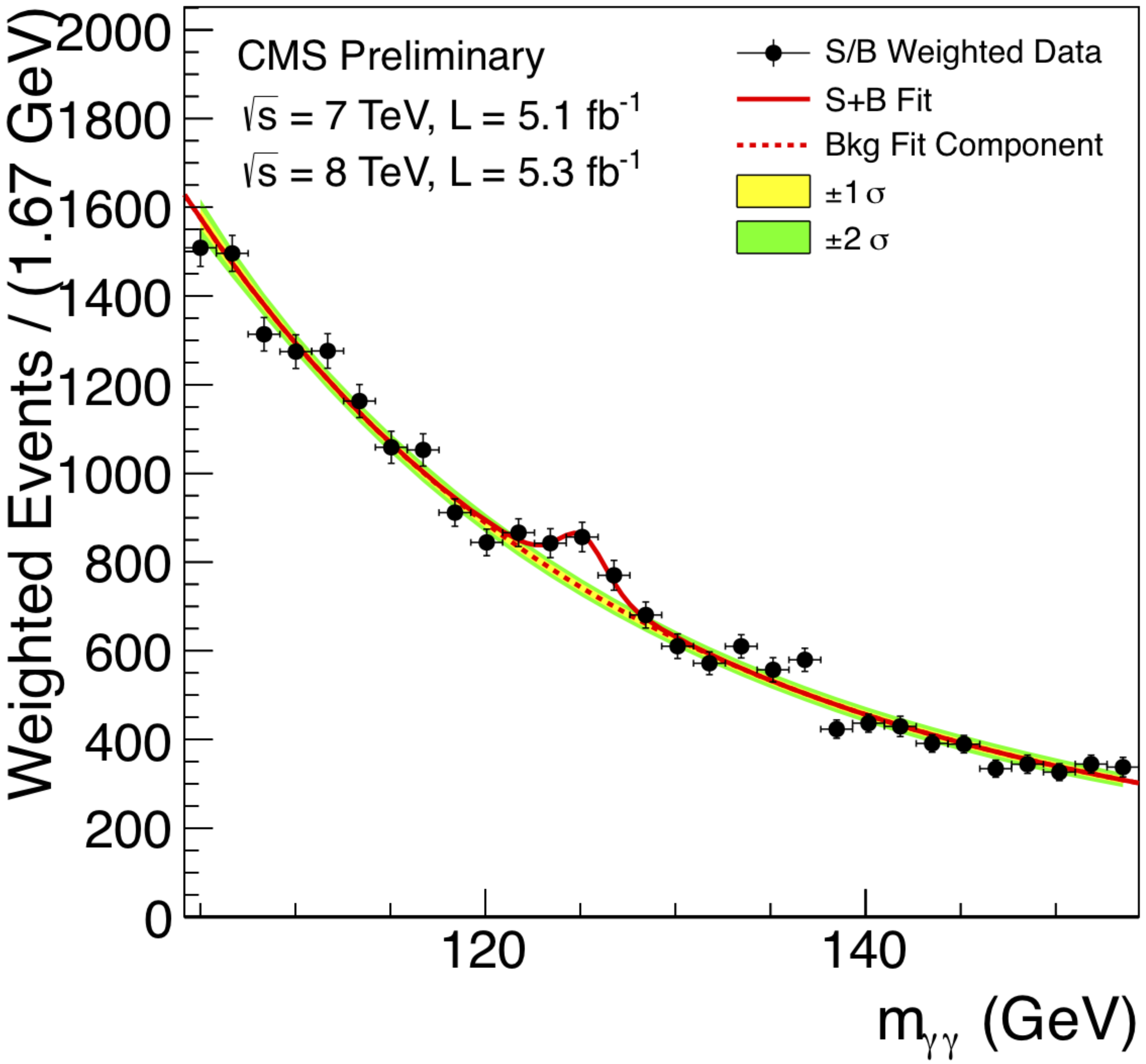
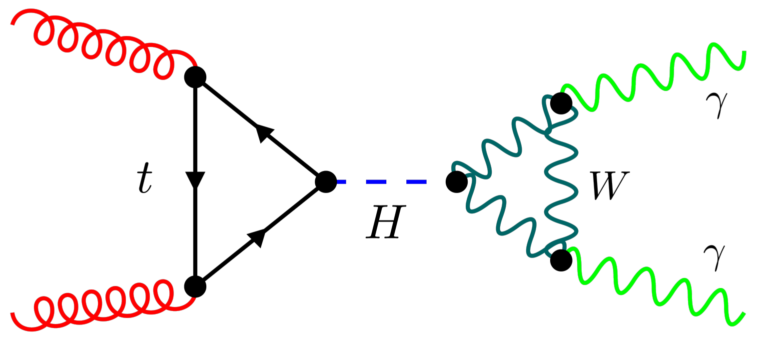
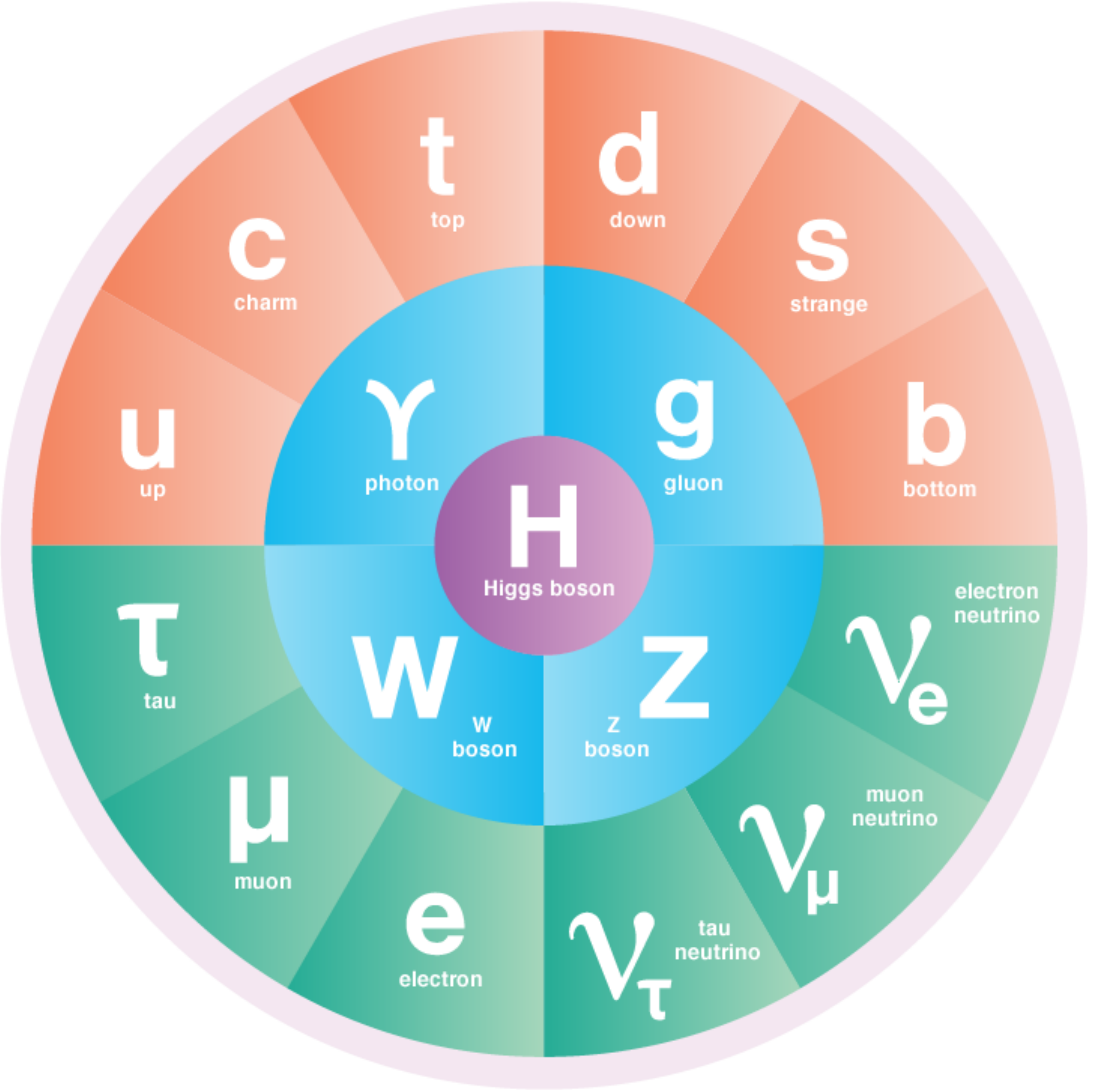
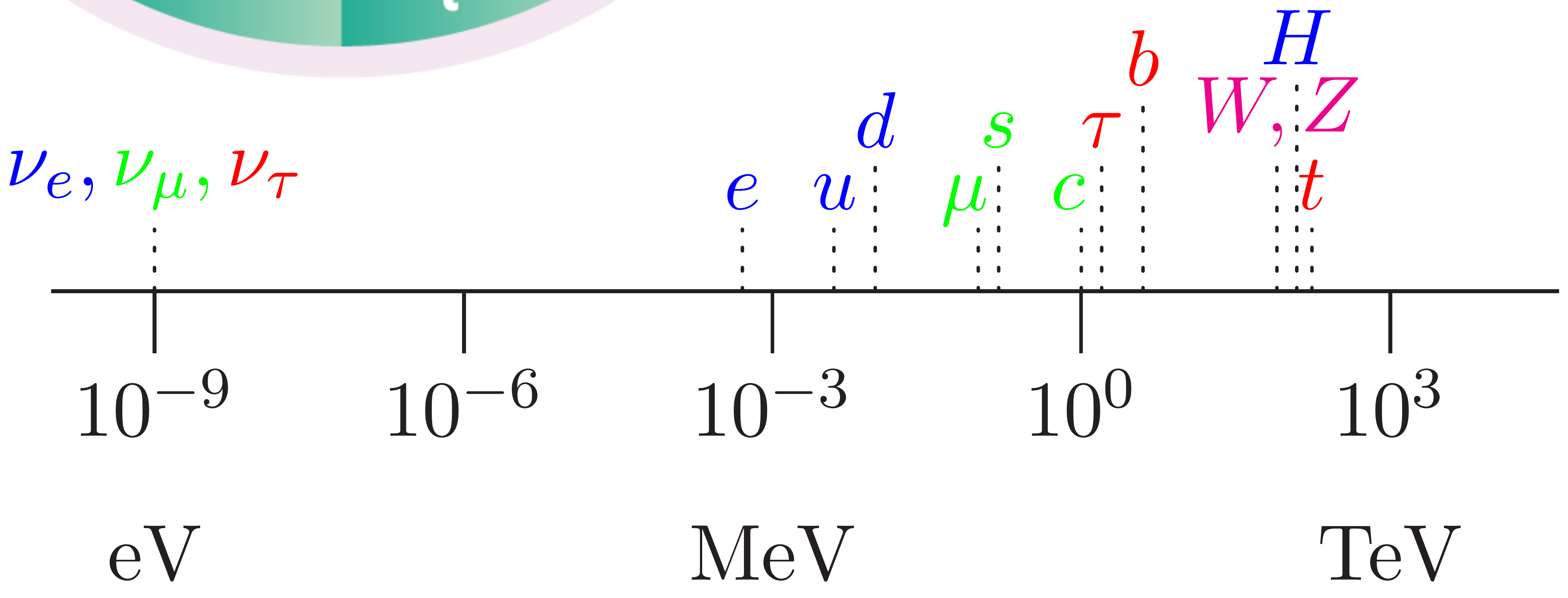
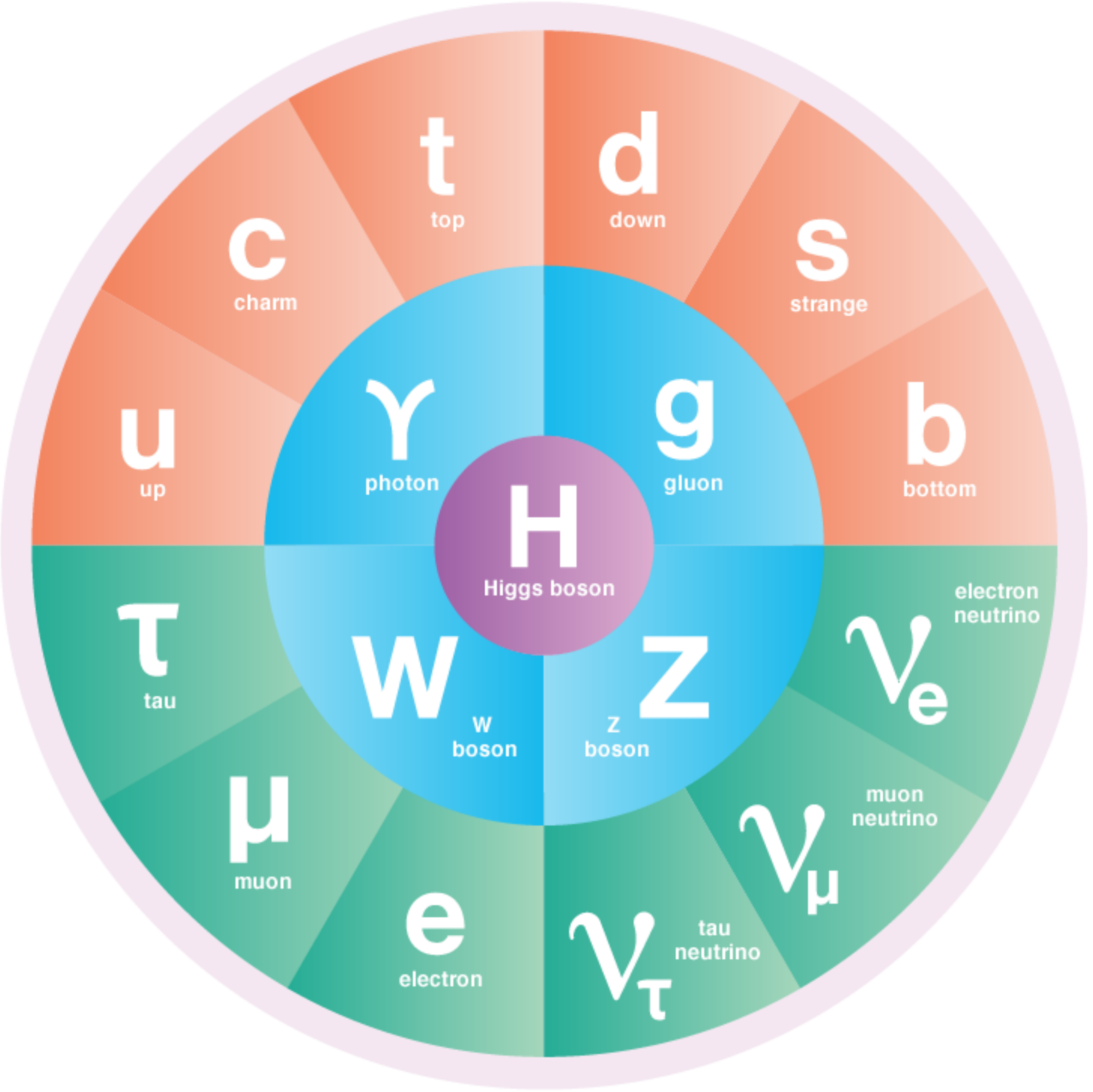
1995
2012



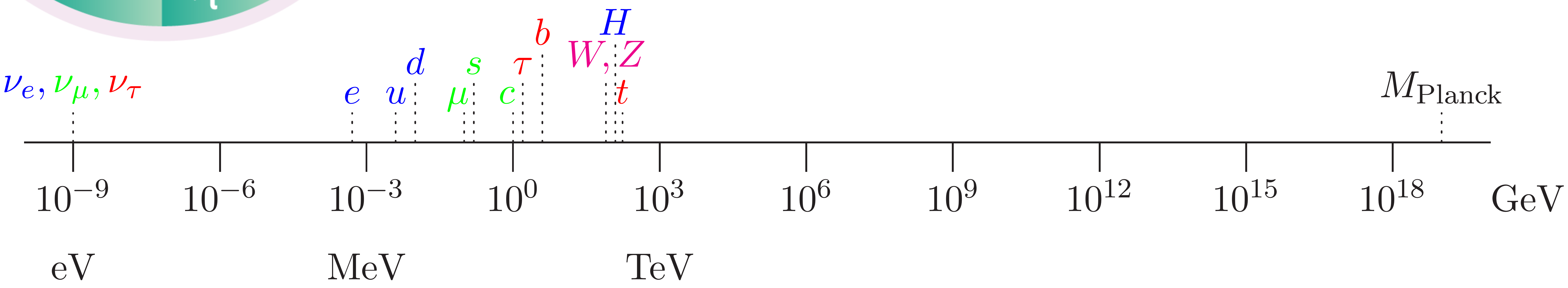



t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
electron neutrino
ν_e
μ
muon
muon neutrino
ν_μ
e
electron
ν_τ
tau neutrino

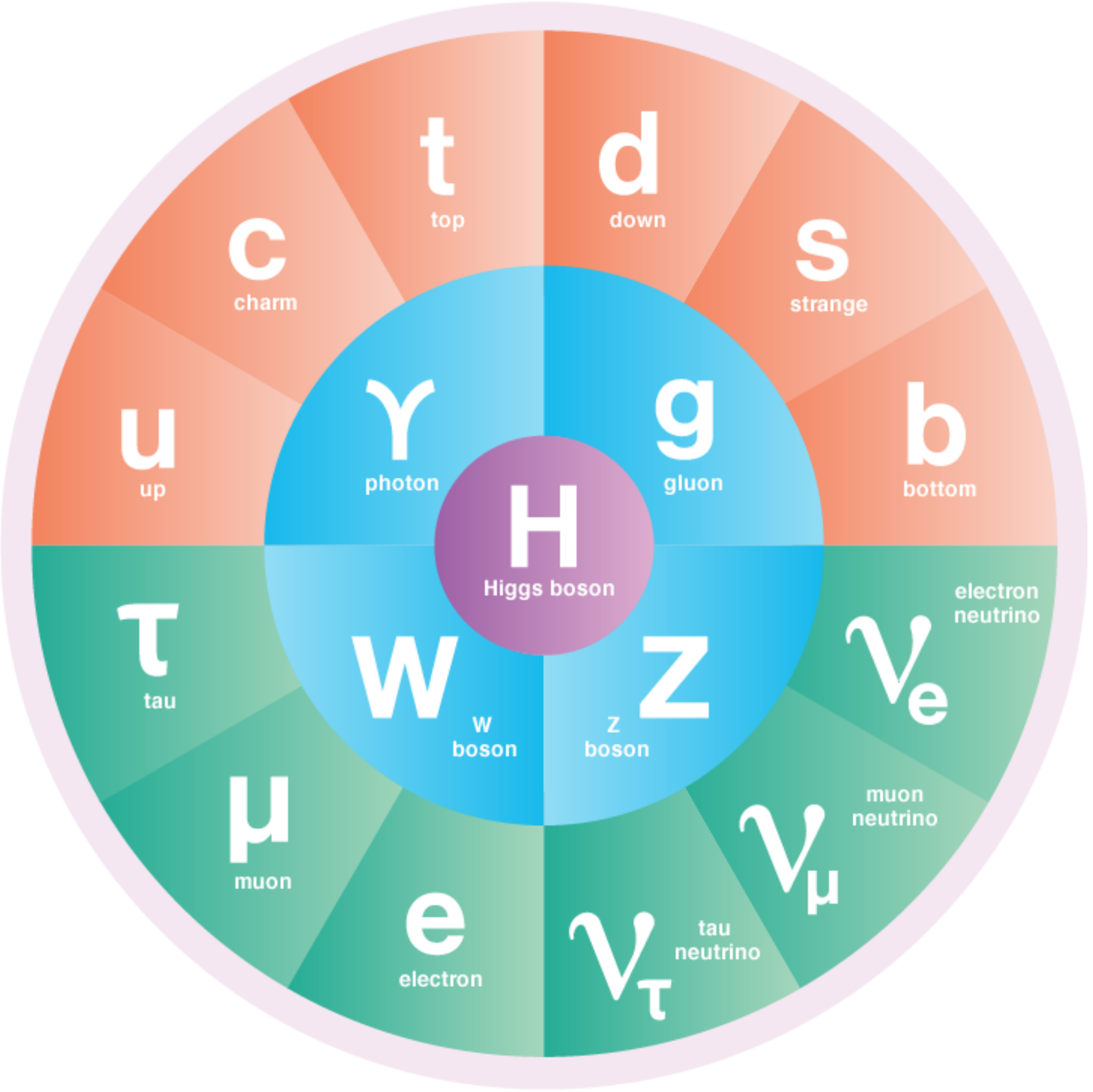

ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
W, Z
H
t
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
eV
MeV
TeV



t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W
boson
Z
Z
boson
ν_e
electron
neutrino
μ
muon
ν_μ
muon
neutrino
e
electron
ν_τ
tau
neutrino



ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
W, Z
H
t
M_{Planck}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV


t
top
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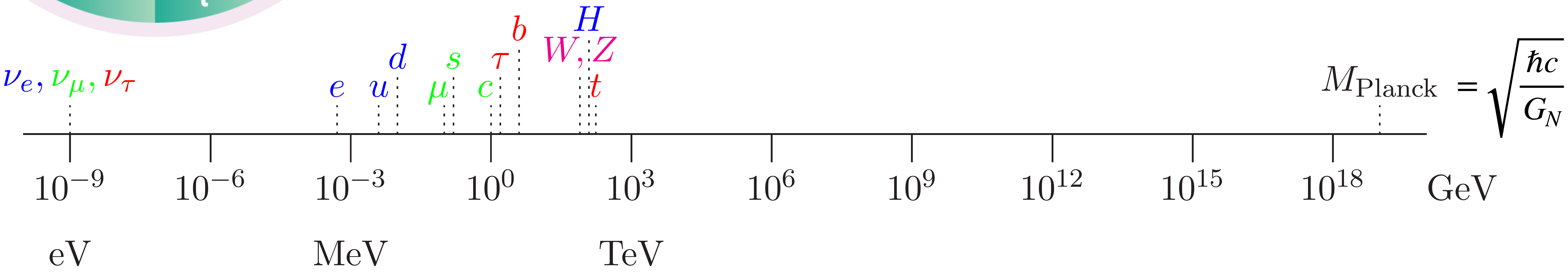
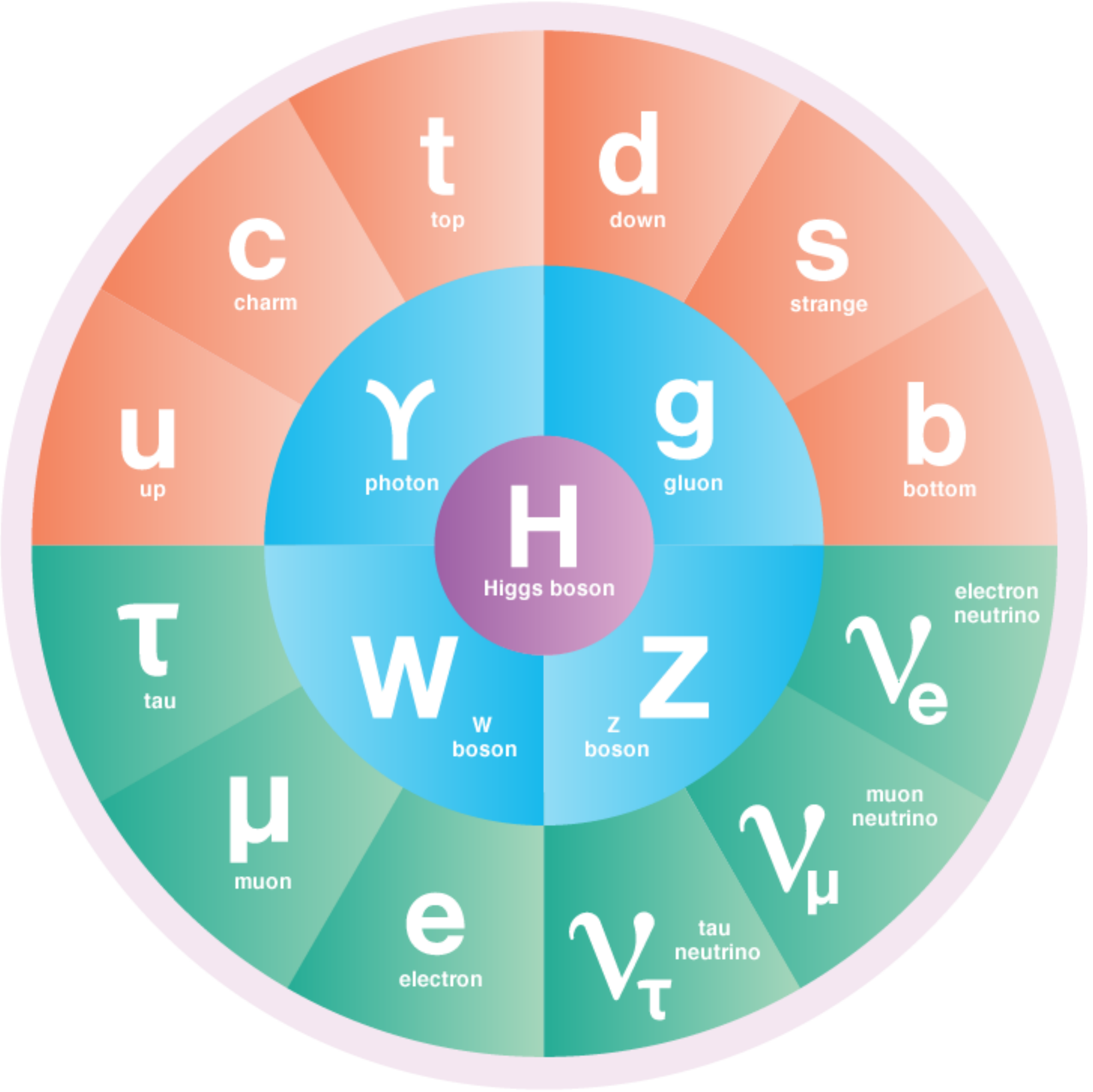
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino


ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
H
W, Z
t
$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}}$
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
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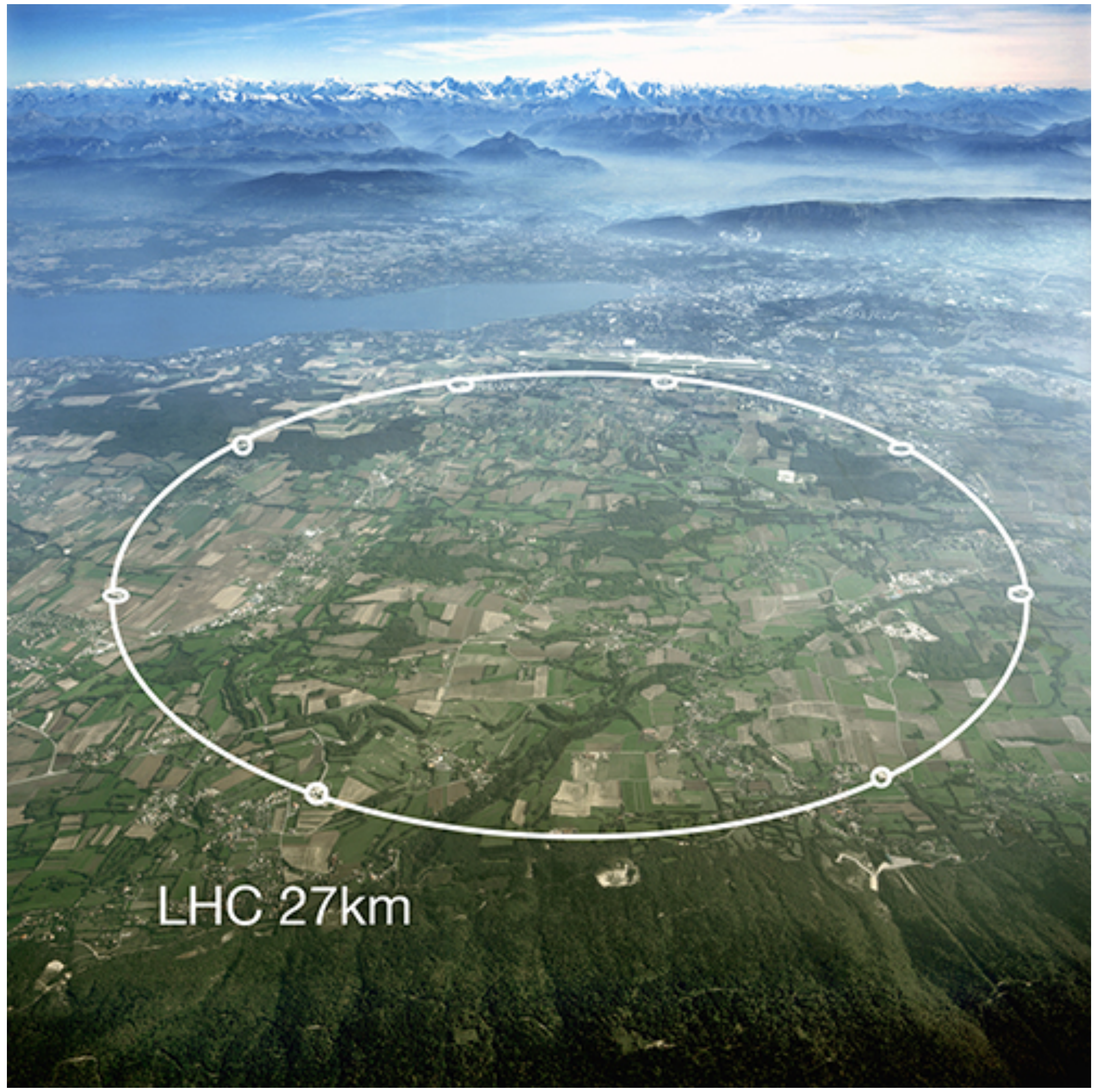
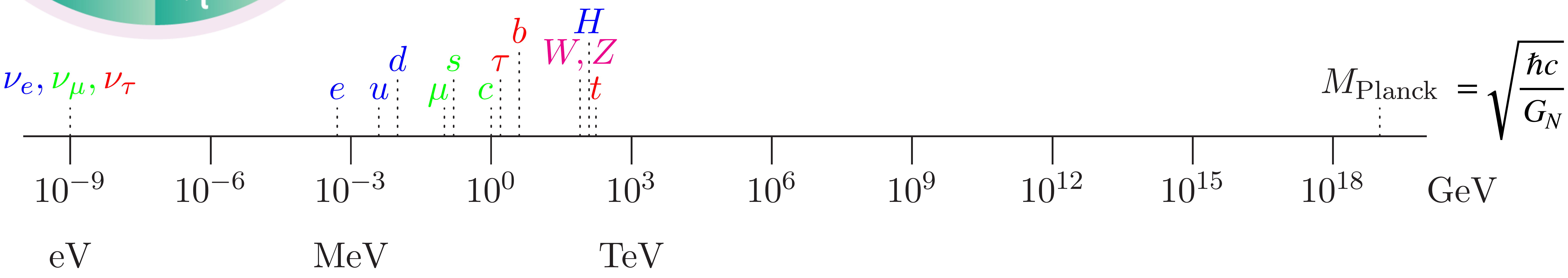
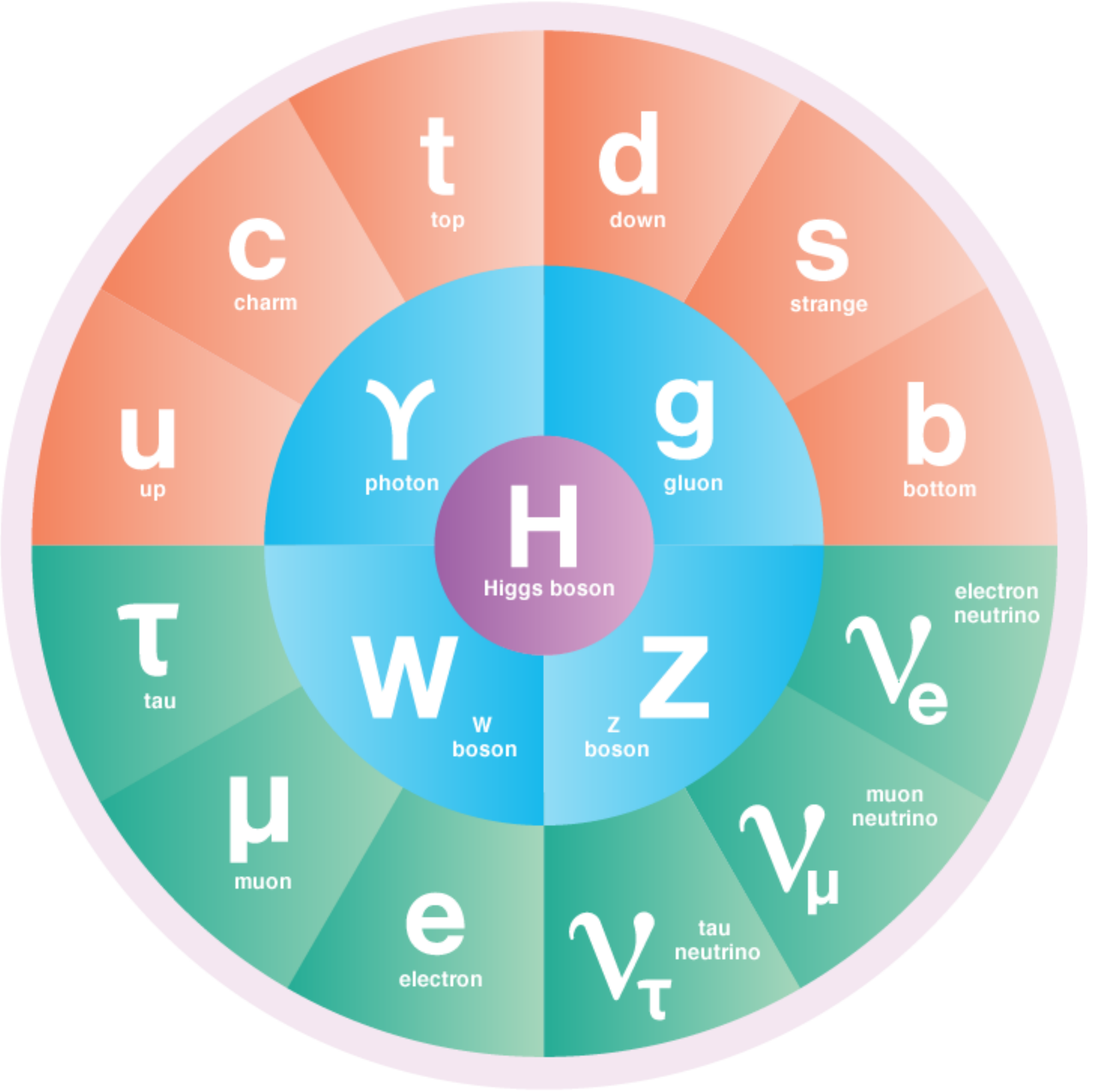
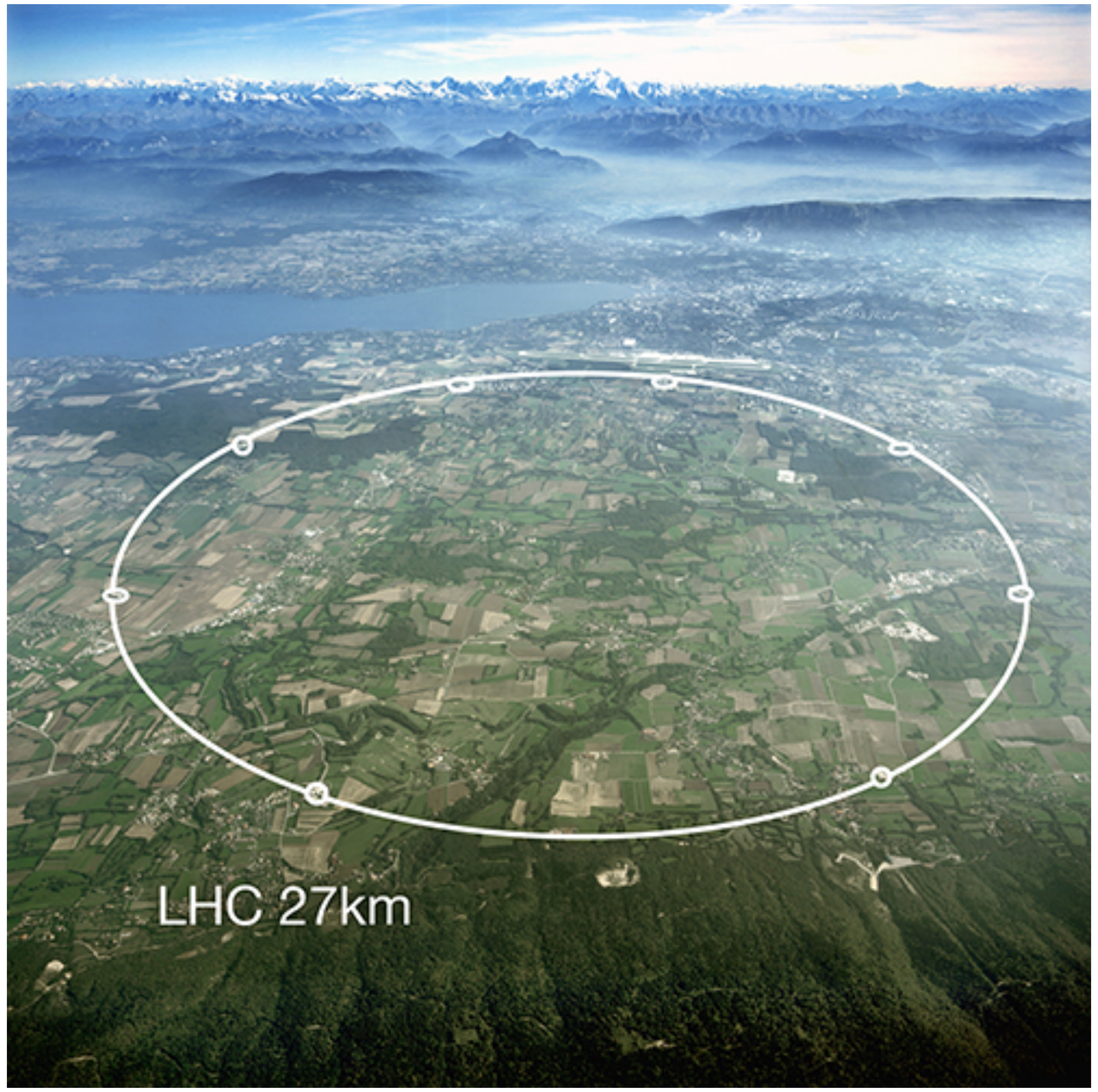
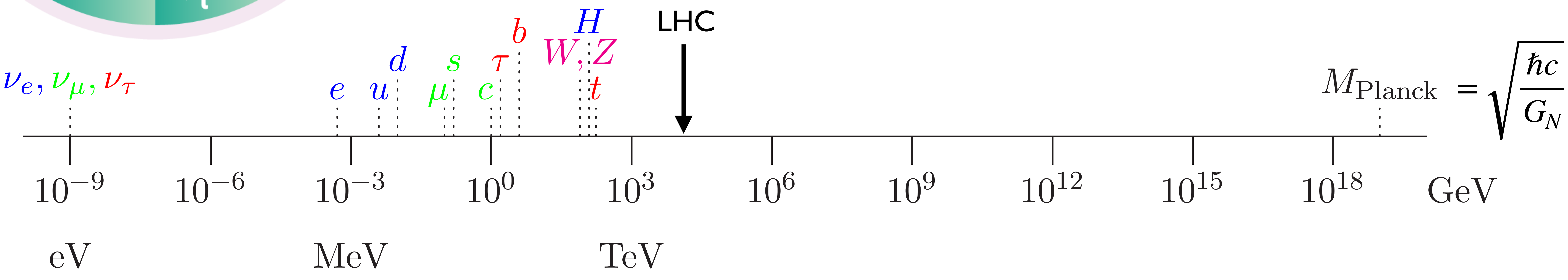
W
W boson
Z
Z boson
electron neutrino
νe
μ
muon
muon neutrino
νμ
e
electron
ντ
tau neutrino

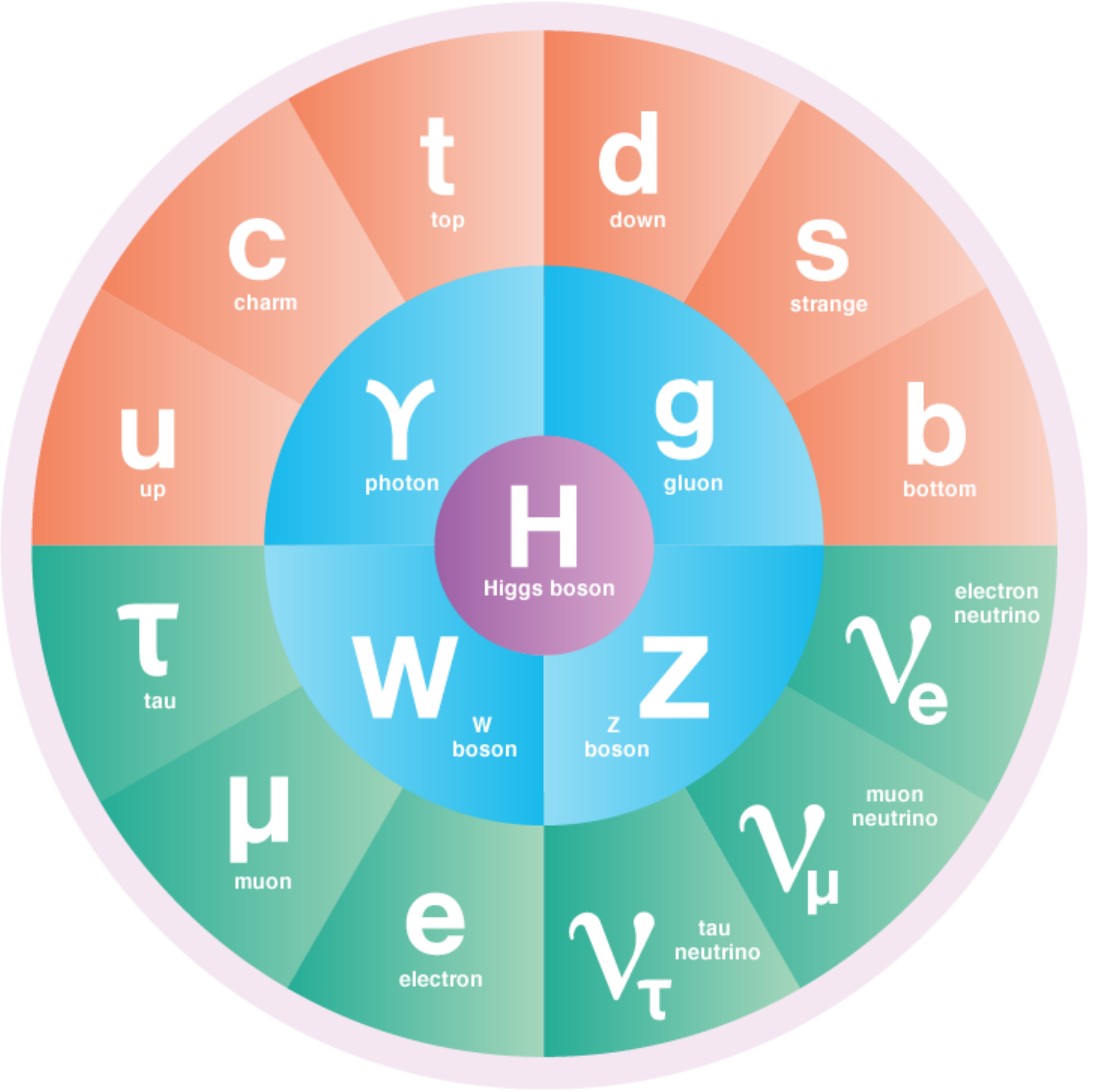

LHC 27km

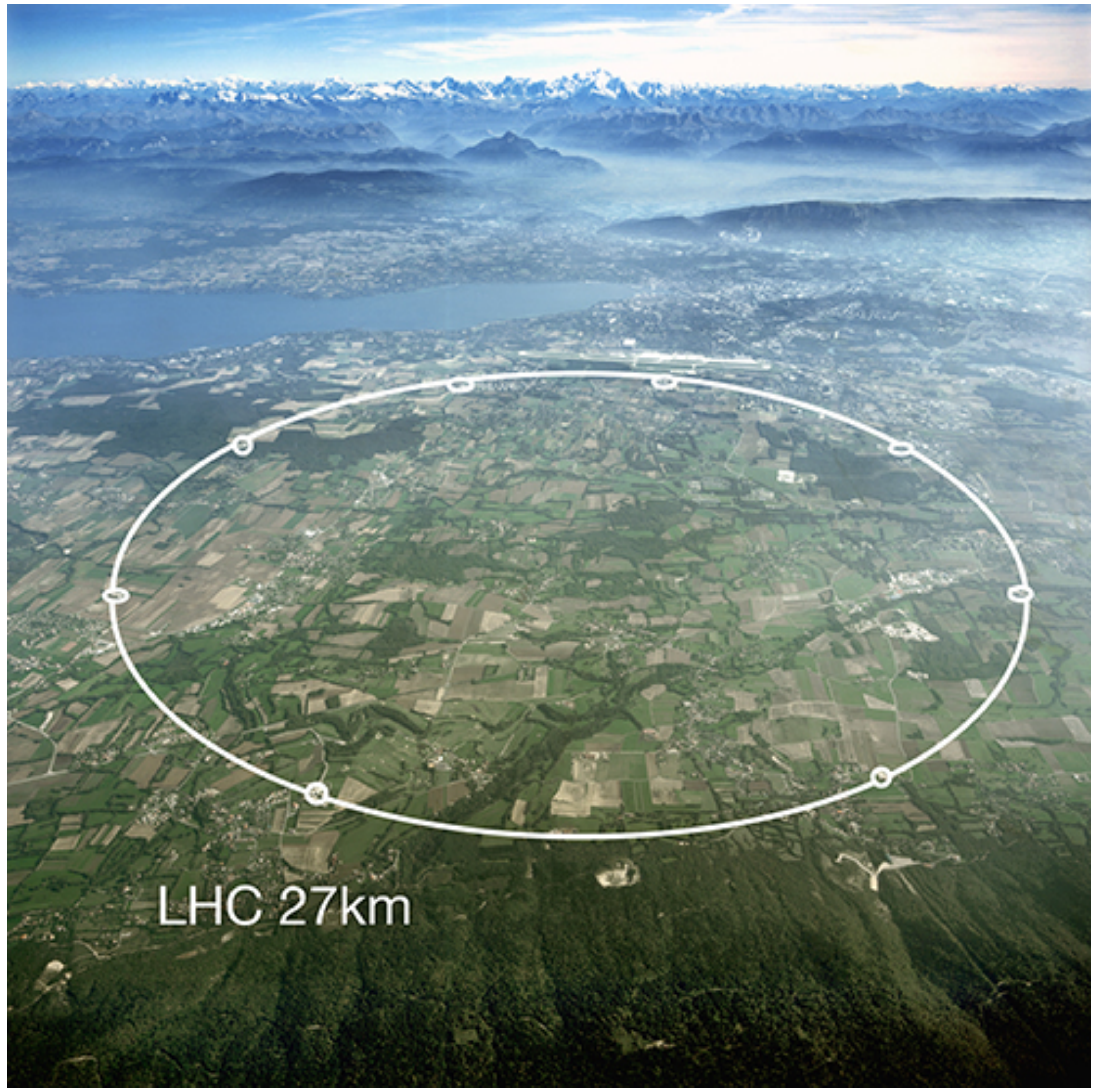

ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
W, Z
H
t
$M_{\rm Planck} = \sqrt{\frac{\hbar c}{G_N}}$
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV

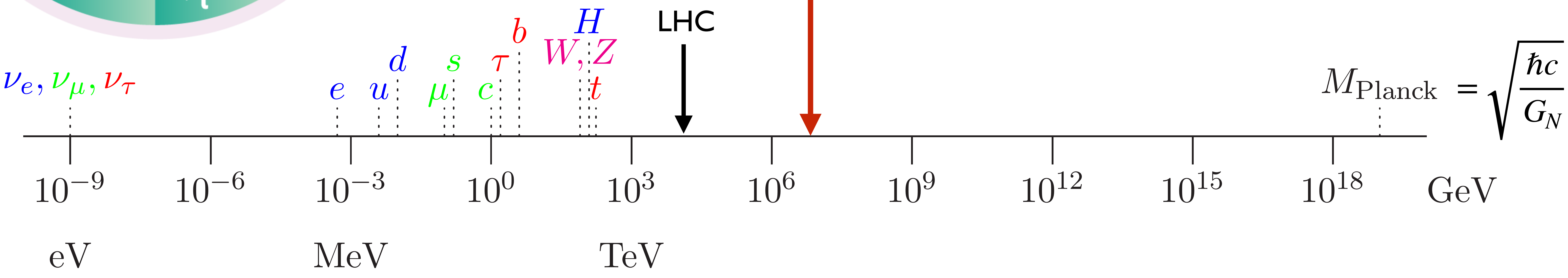

t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino


LHC 27km

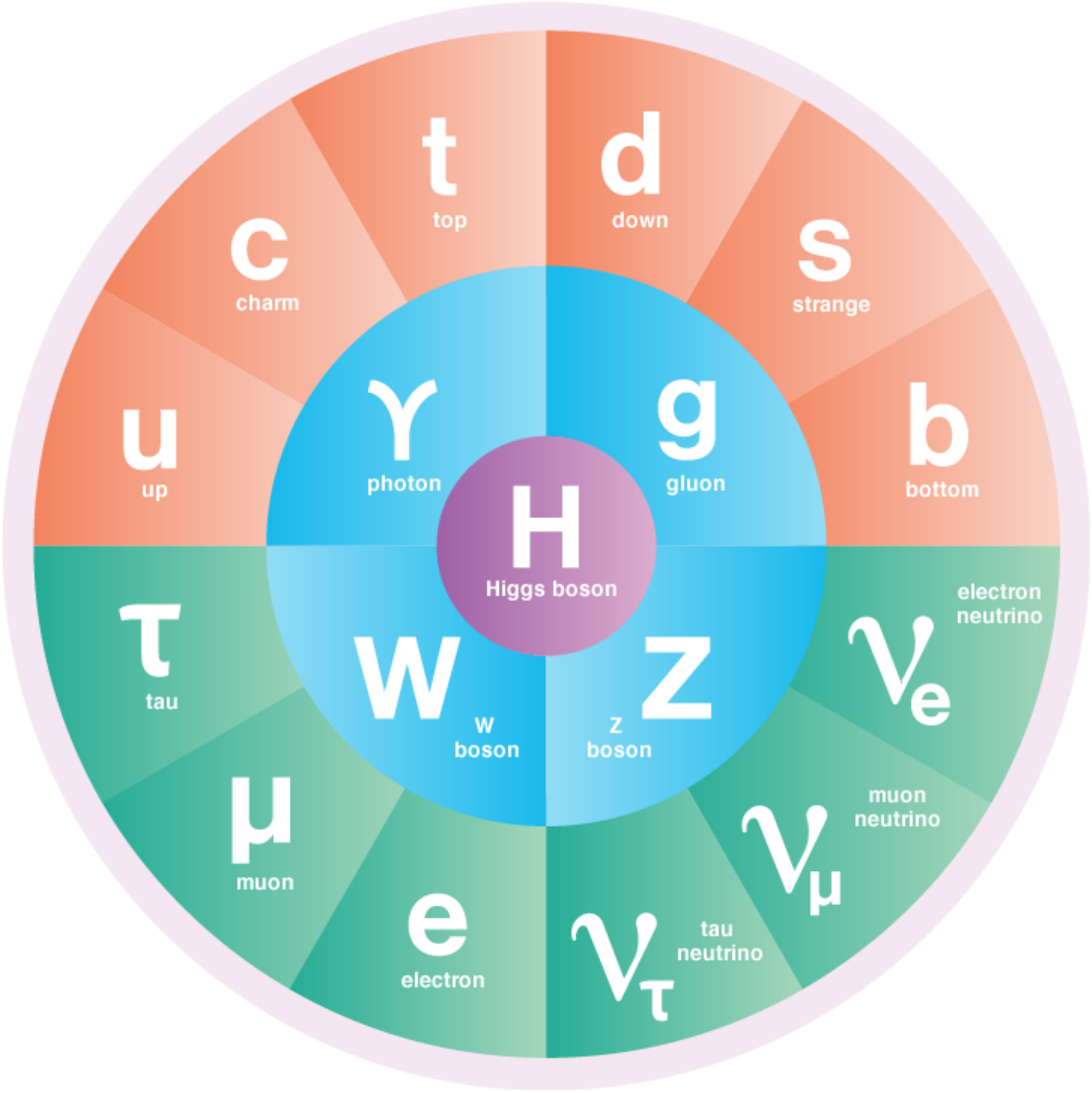

ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
W, Z
H
t
LHC
$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}}$
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV


t
top
d
down
c
charm
s
strange
u
up
b
bottom
γ
photon
g
gluon
H
Higgs boson
τ
tau
W
W boson
Z
Z boson
ν_e
electron neutrino
μ
muon
ν_μ
muon neutrino
e
electron
ν_τ
tau neutrino

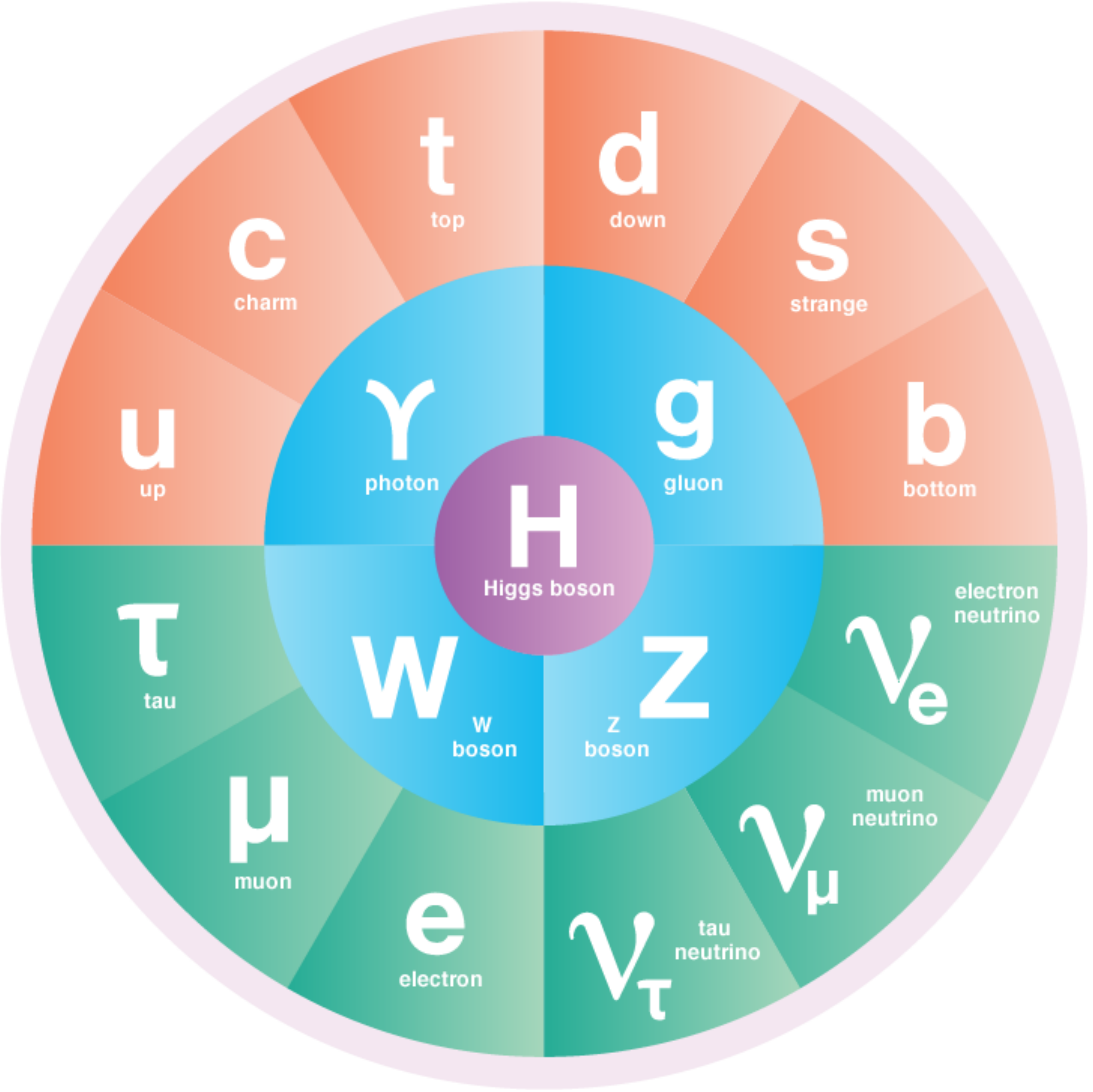

LHC 27km

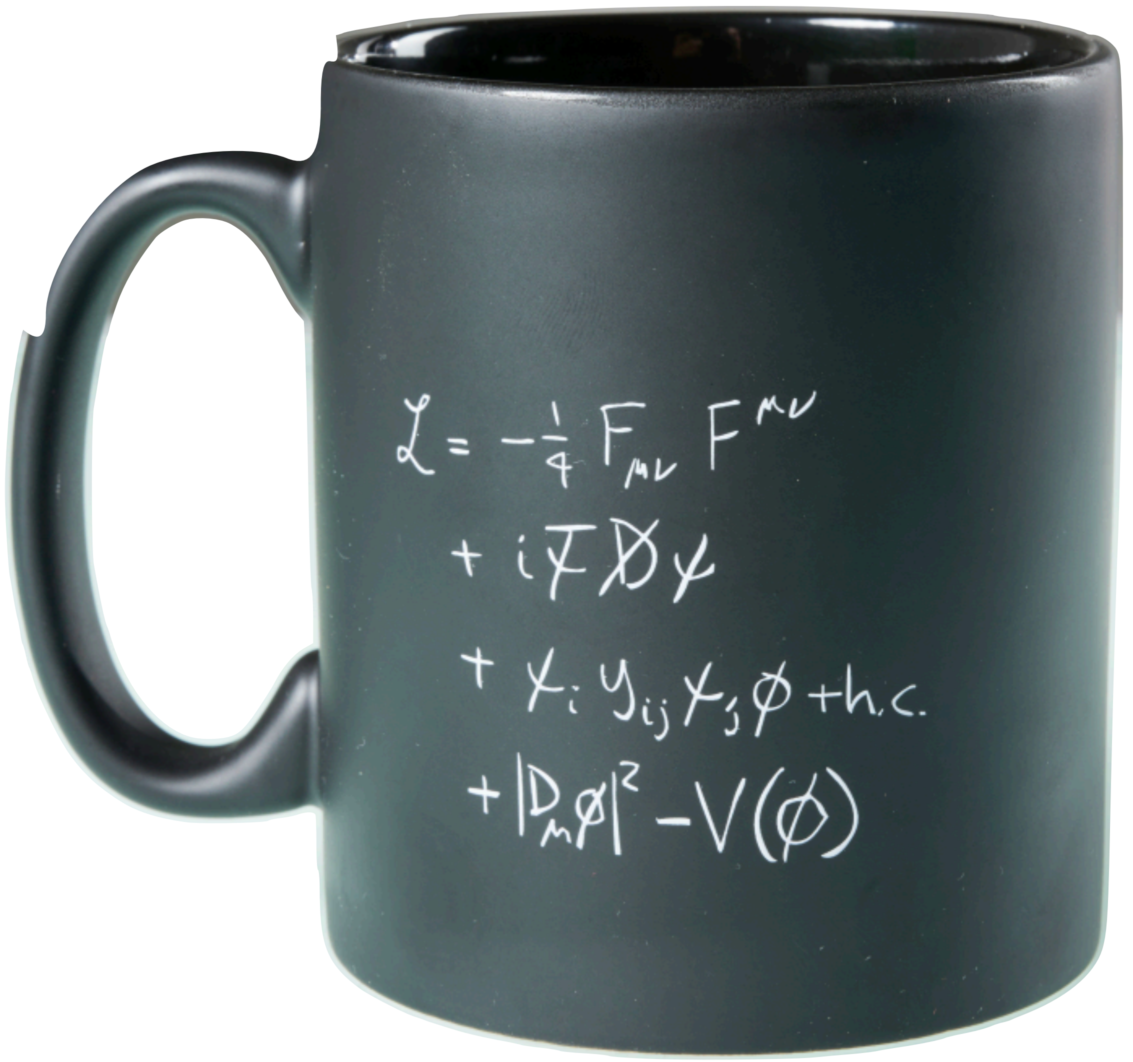

ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
H
W, Z
t
LHC
$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G_N}}$
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV

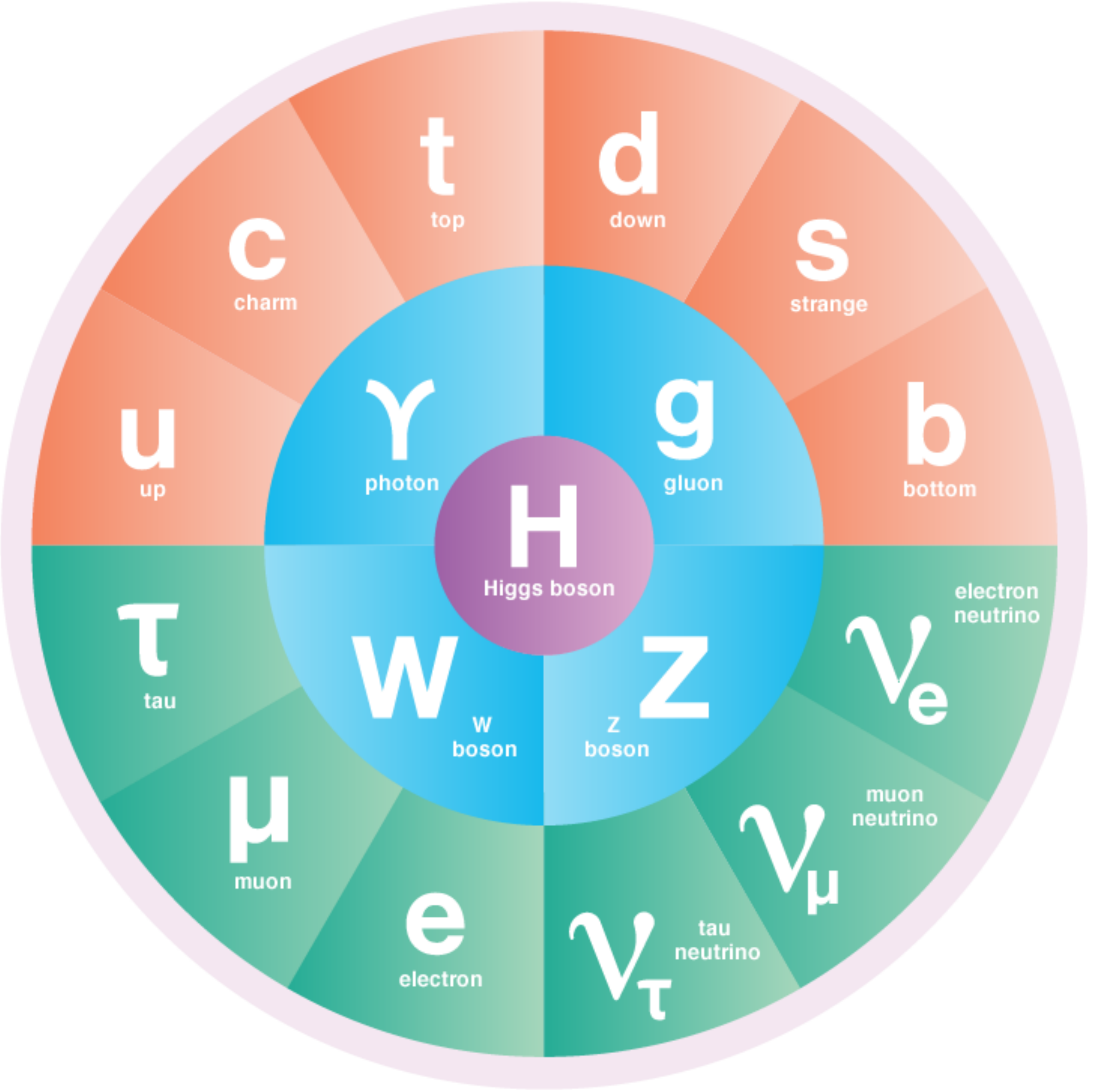
Standardmodell

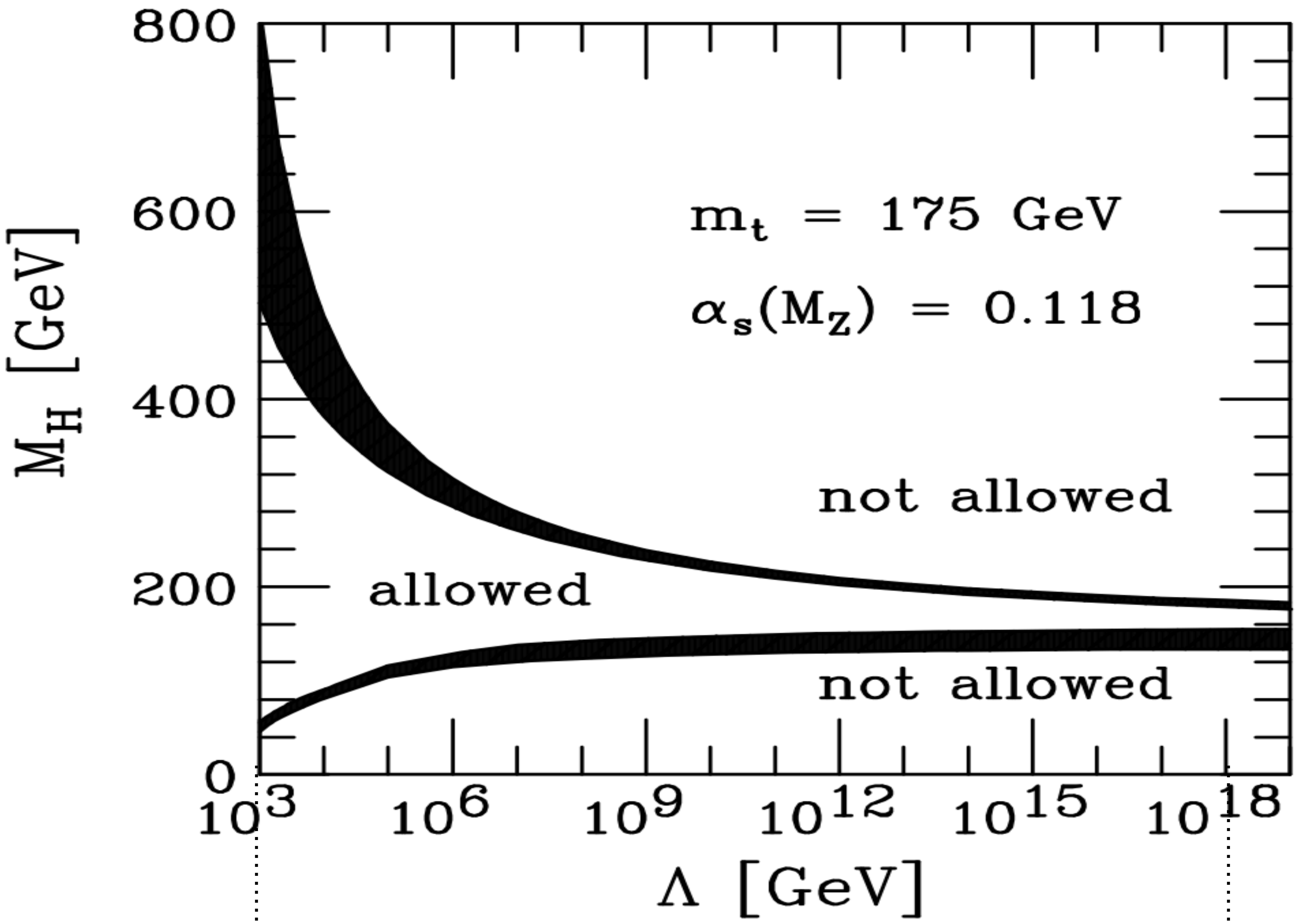


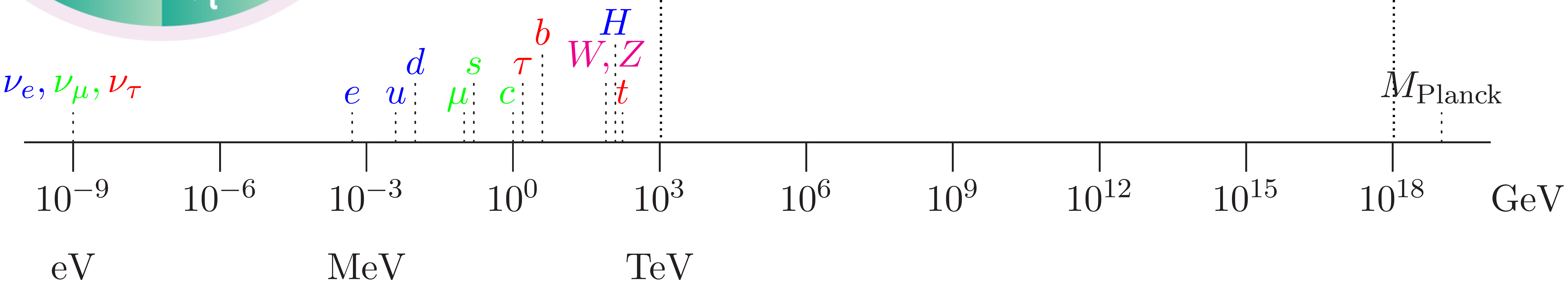
Standardmodell

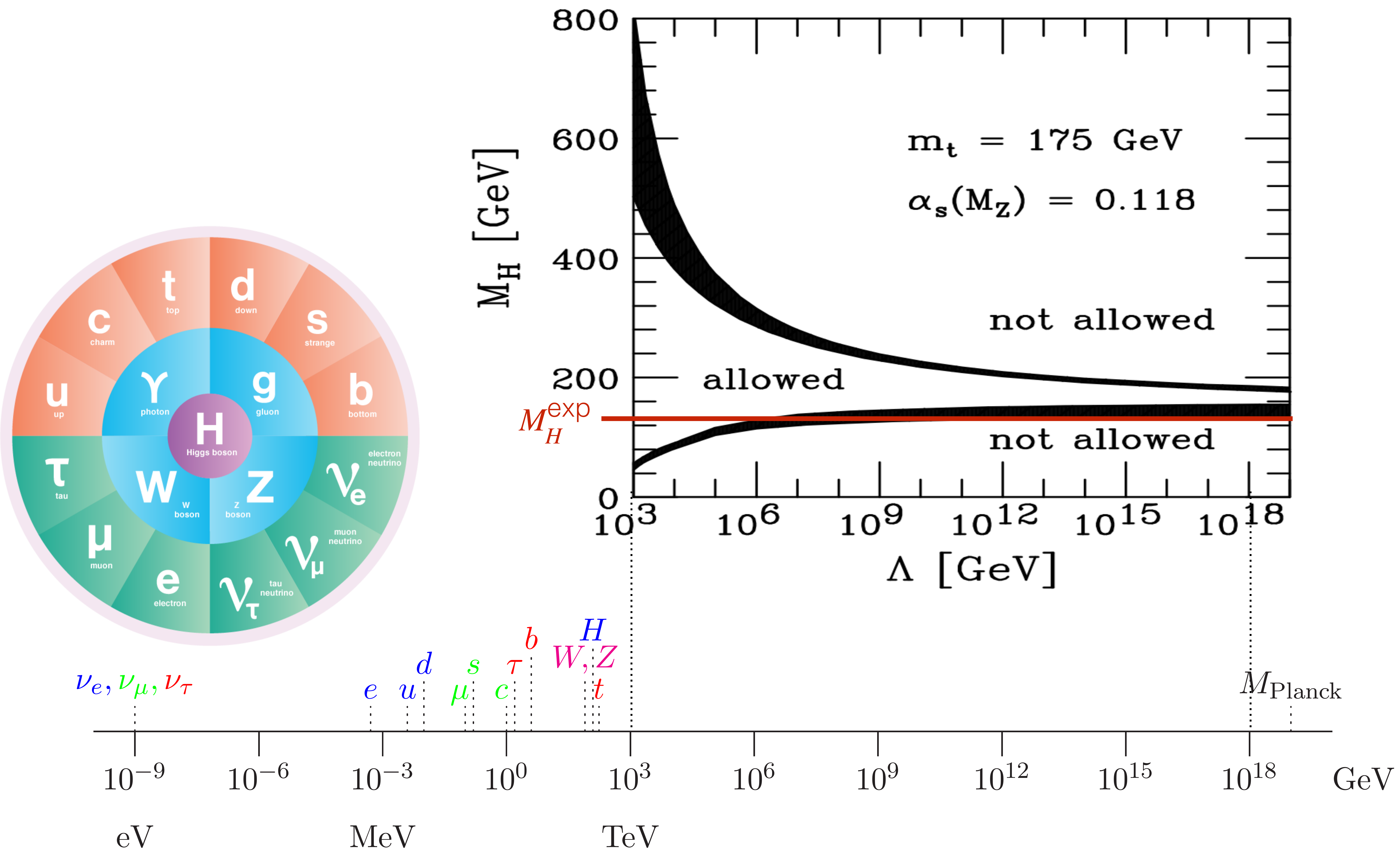





c
charm
t
top
d
down
s
strange
u
up
γ
photon
H
Higgs boson
g
gluon
b
bottom
τ
tau
W
W
boson
Z
Z
boson
ν_e
electron
neutrino
μ
muon
e
electron
ν_τ
tau
neutrino
ν_μ
muon
neutrino


800
600
400
200
0
M_H [GeV]
m_t = 175 GeV
$\alpha_s(M_Z)$ = 0.118
not allowed
allowed
not allowed
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
Λ [GeV]


ν_e, ν_μ, ν_τ
e
u
d
μ
s
c
τ
b
W, Z
H
t
M_{Planck}
10^{-9}
10^{-6}
10^{-3}
10^0
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
GeV
eV
MeV
TeV



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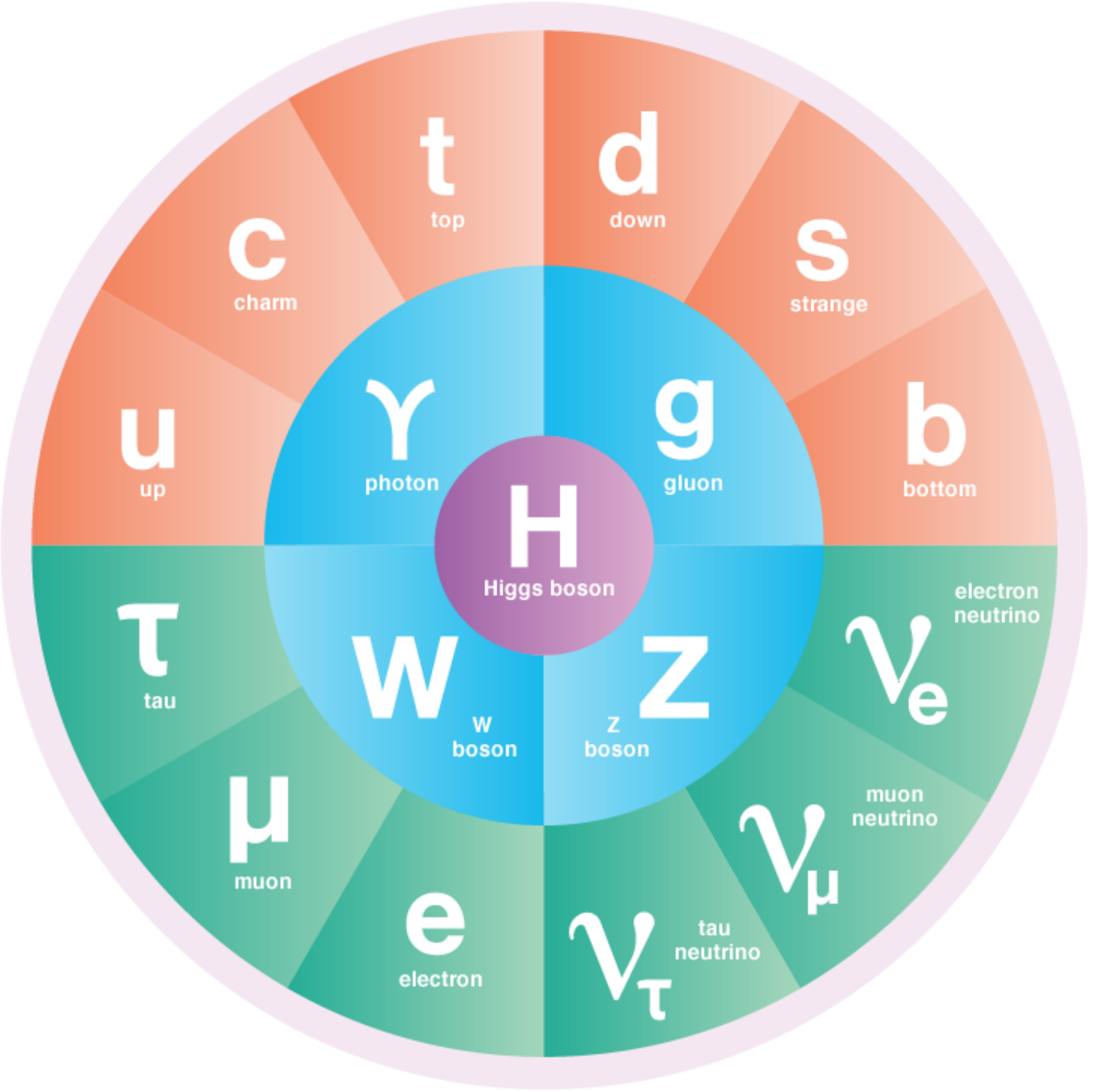
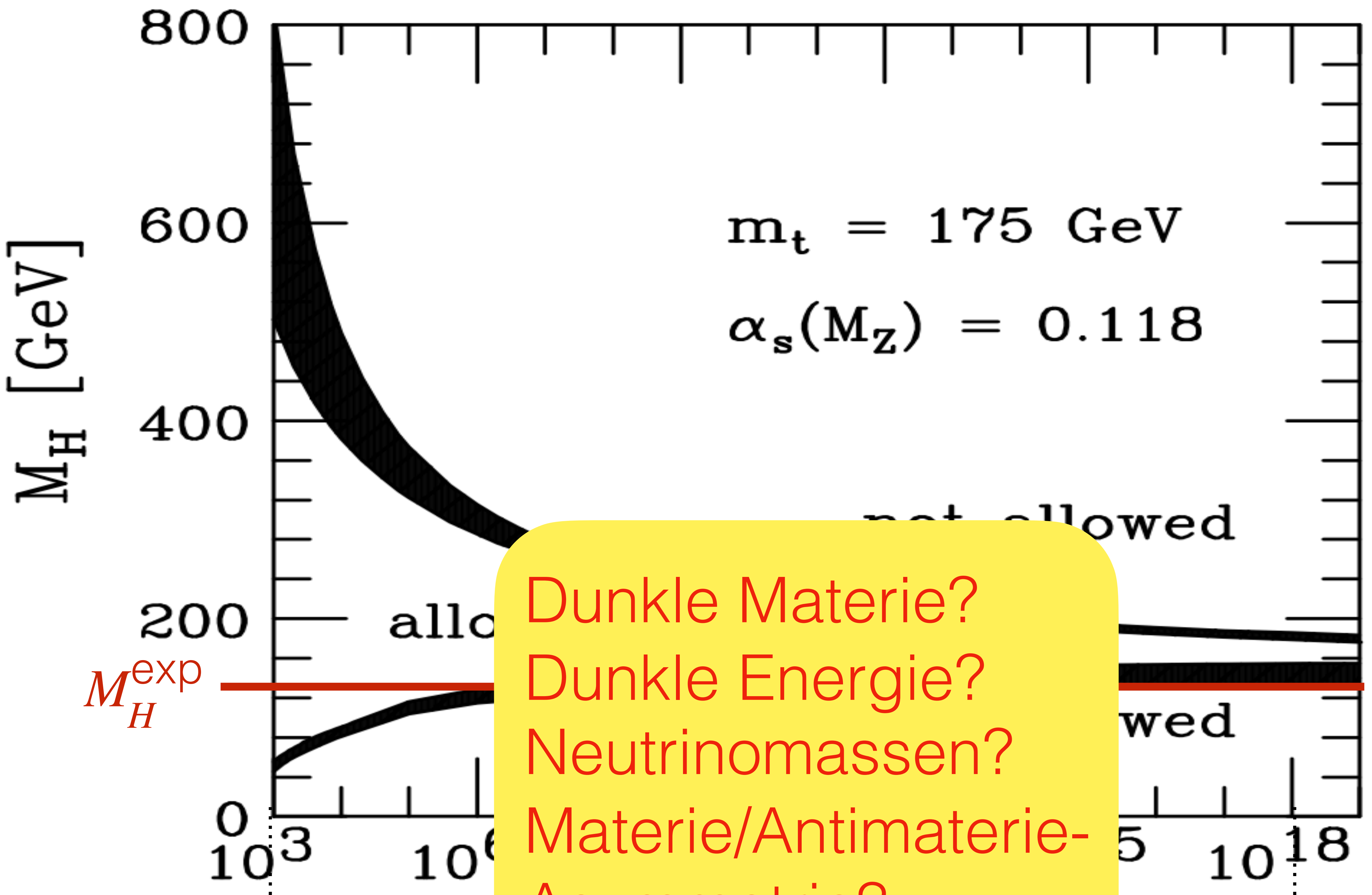
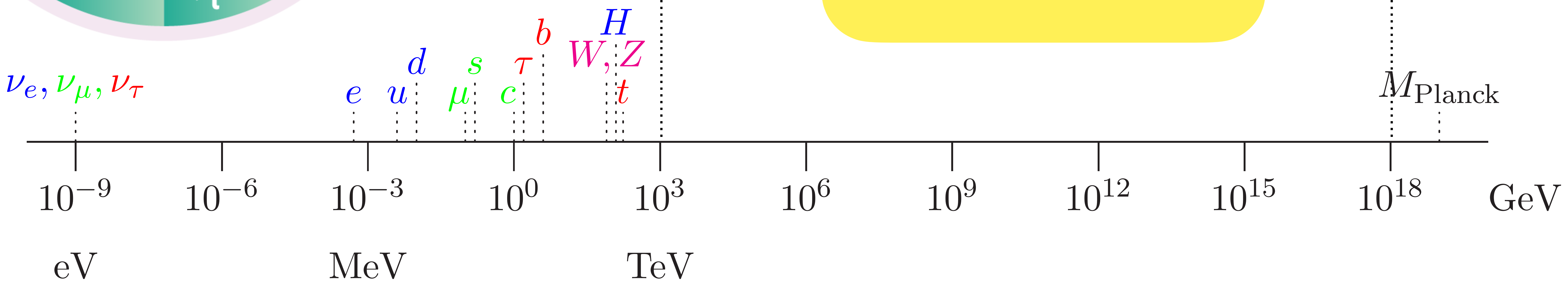
RWTH AACHEN UNIVERSITY





Dunkle Materie?
Dunkle Energie?
Neutrinomassen?
Materie/Antimaterie-Asymmetrie?
…



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https://doi.org/10.1140/epjh/s13129-023-00053-4

THE EUROPEAN PHYSICAL JOURNAL H

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Regular Article

The end of the particle era?

Robert Harlander[1], Jean-Philippe Martinez[1,a], and Gregor Schiemann[2]

[1] Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Aachen, Germany
[2] Faculty of Humanities and Cultural Studies, University of Wuppertal, Wuppertal, Germany

Received 24 November 2022 / Accepted 20 March 2023

Entdeckung

Spuren? Theorie? Peaks?

Sammle Hinweise, bis es “no escape” gibt.

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RWTH AACHEN UNIVERSITY

Entdeckung

Spuren? Theorie? Peaks?

Sammle Hinweise, bis es “no escape” gibt.

Entdeckung

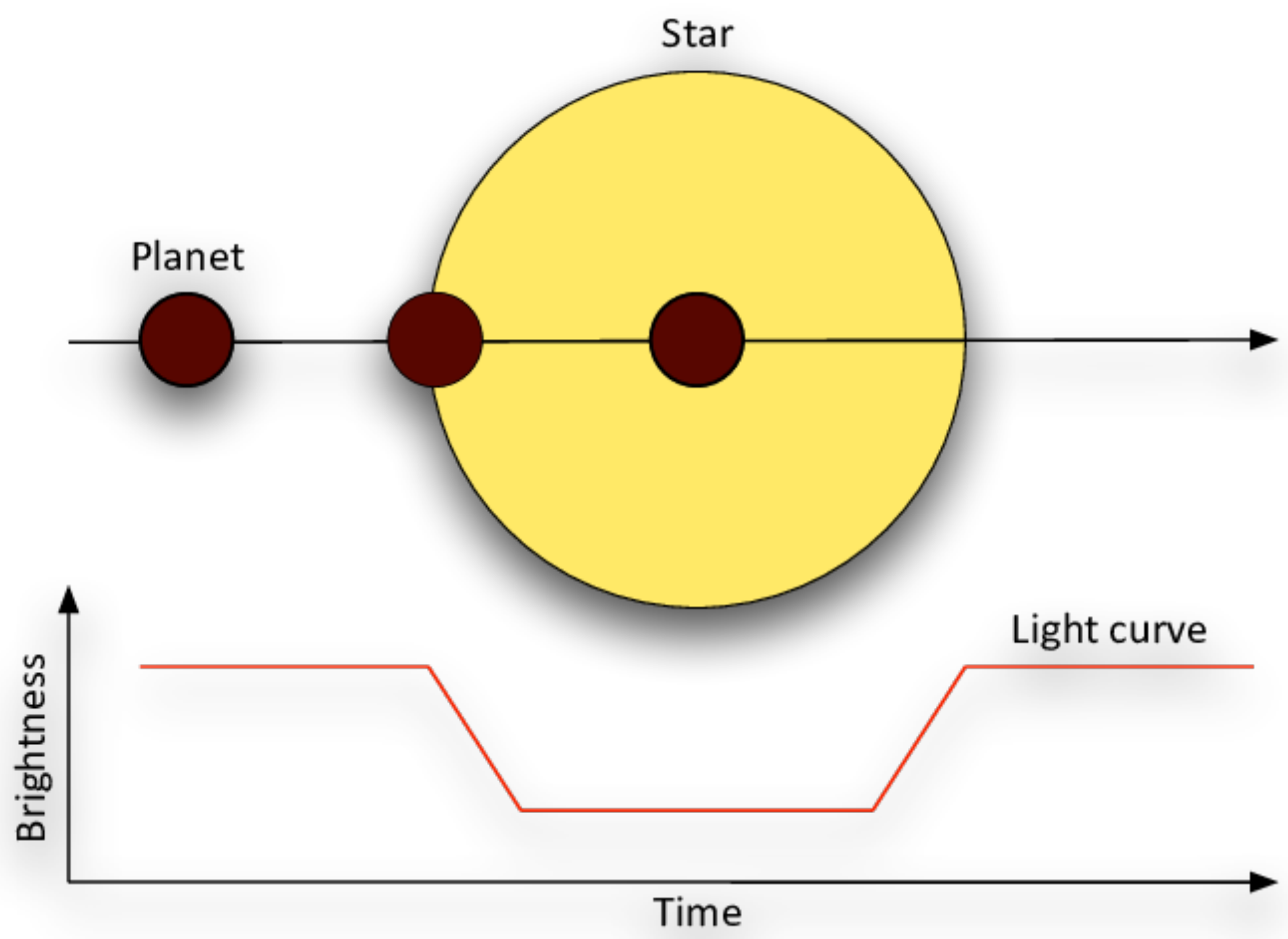
Spuren? Theorie? Peaks?

Sammle Hinweise, bis es “no escape” gibt.

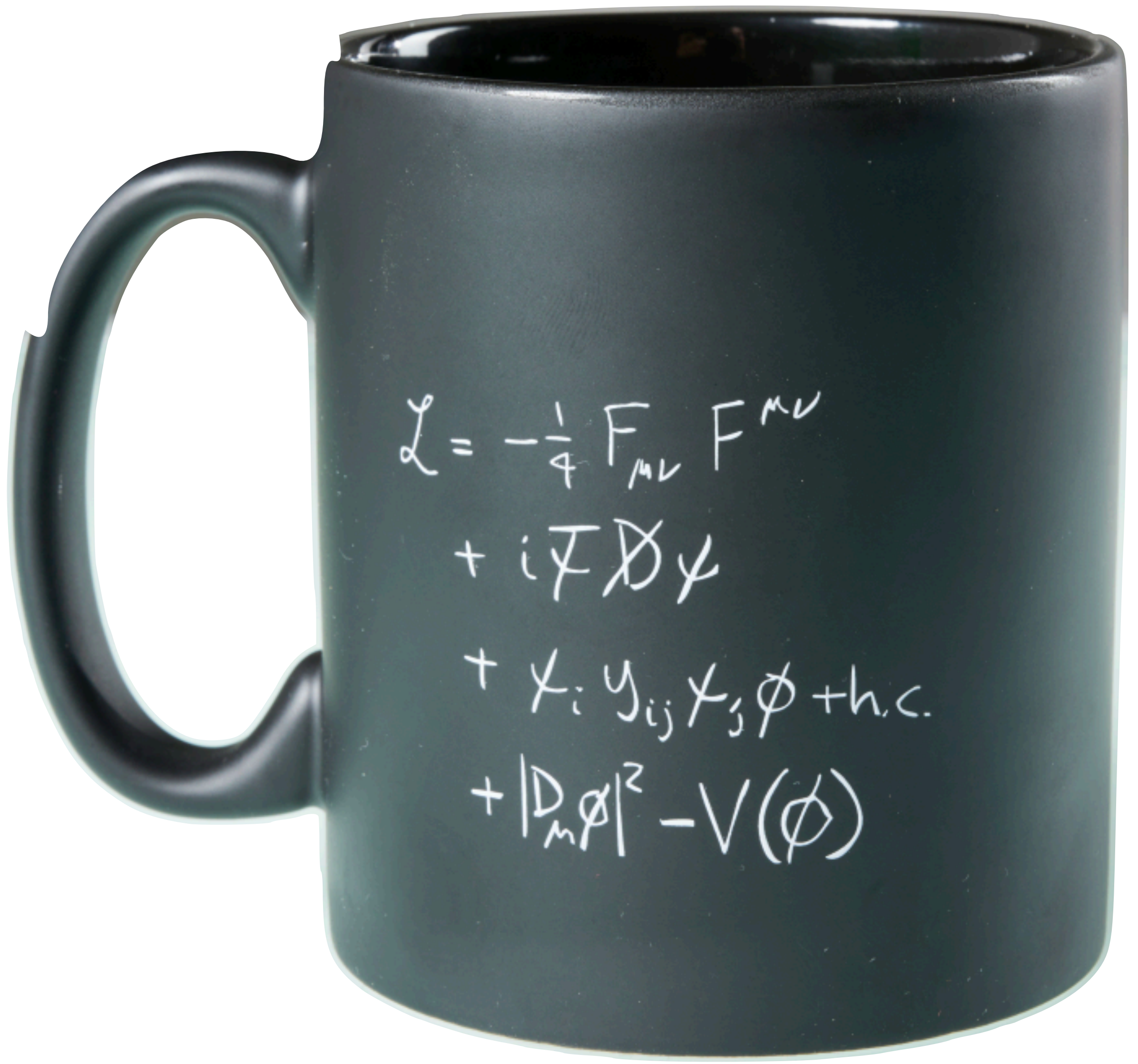
Entdeckung

Spuren? Theorie? Peaks?

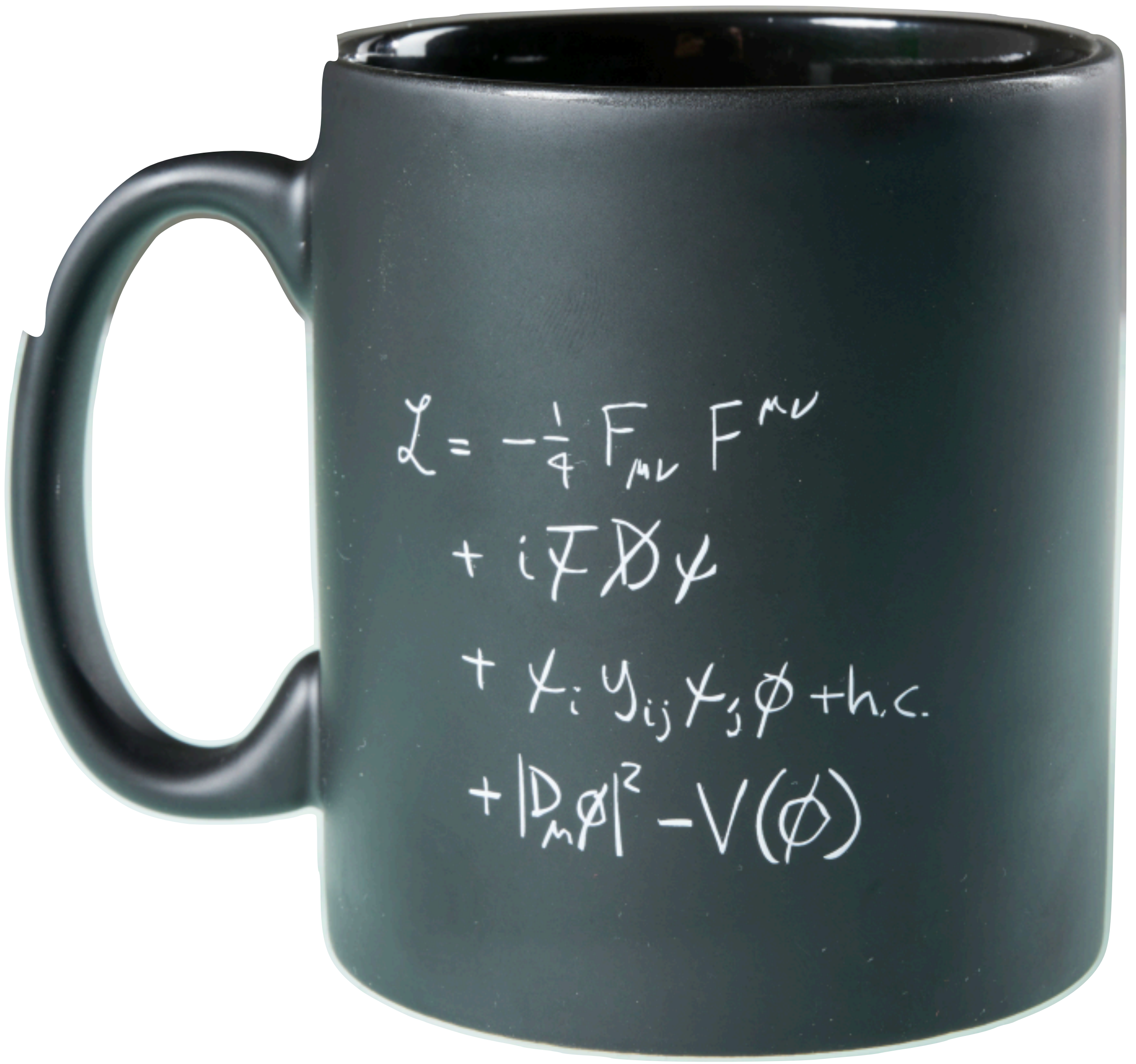
Sammle Hinweise, bis es “no escape” gibt.



Effektive Feldtheorien



Effektive Feldtheorien



+

Four-quark operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators (9)

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}\,W^I_{\mu\nu},$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi\,W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}\,B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi}\,G^A_{\mu\nu},$$

Two-quark-two-lepton operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_j\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

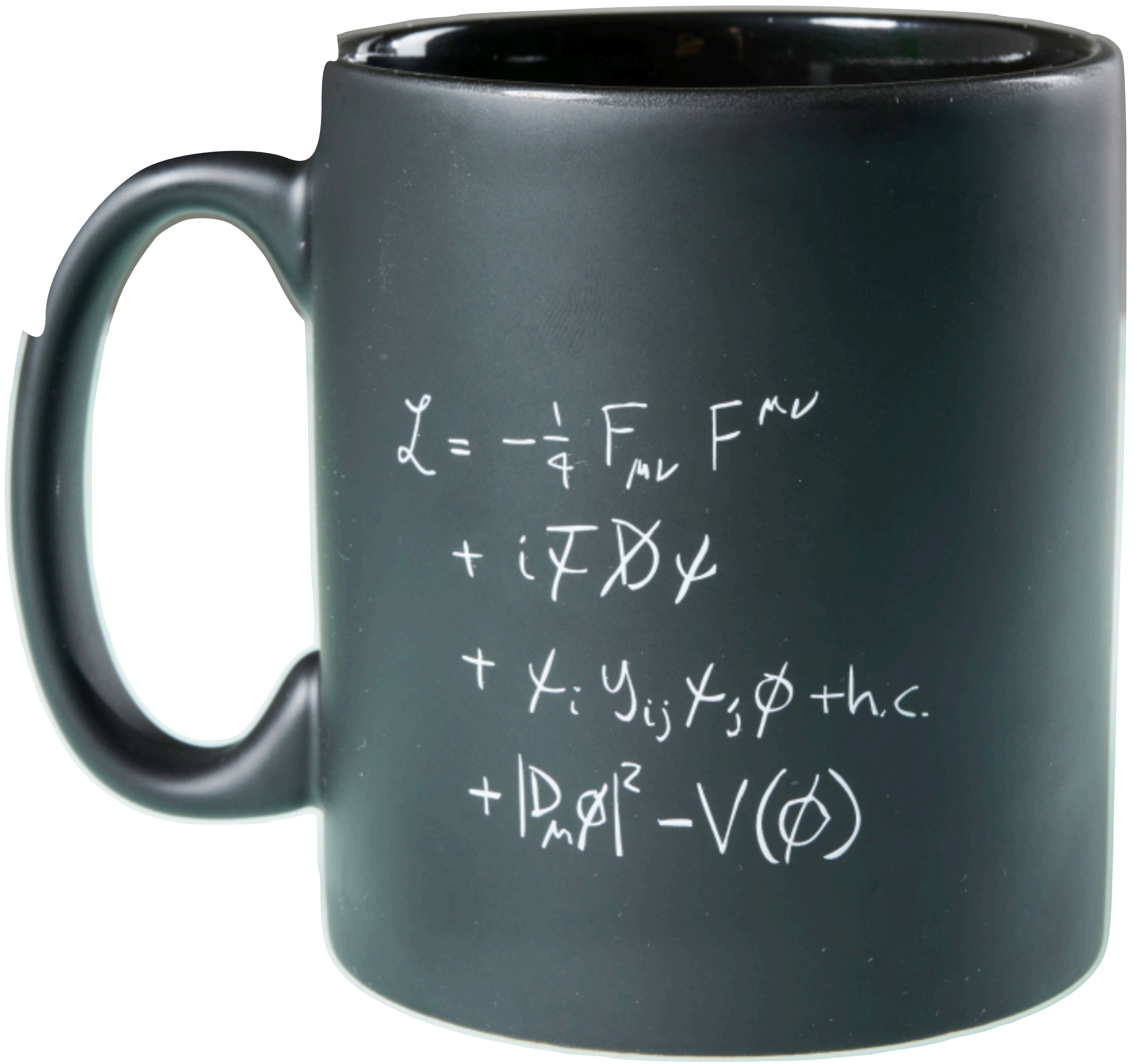
$\not{B}$ and $\not{L}$ operators (5)

$$O_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha}\tau^I\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\tau^I\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma}.$$

+ *ijkl* generation index assignments

q, l: left-handed doublets
u, d, e: right-h. singlets

Effektive Feldtheorien



$+$

Four-quark operators (11)

$O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l),$

$O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l),$

$O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l),$

$O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l),$

$O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l),$

$O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l),$

$O_{uu}^{(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l),$

$O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l),$

$O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l),$

$O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\, \varepsilon\, (\bar{q}_k d_l),$

$O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\, \varepsilon\, (\bar{q}_k T^A d_l),$

Two-quark operators (9)

$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\, (\varphi^\dagger \varphi),$

$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),$

$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),$

$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),$

$O_{\varphi ud}^{(ij)}$

$O_{uW}^{(ij)}$

$O_{dW}^{(ij)}$

$O_{uB}^{(ij)}$

$O_{uG}^{(ij)}$

Two-quark-two-lepton operators (8)

$O_{lq}^{1(ijkl)} = (\bar{l}_j \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),$

$O_{lq}^{3(ijkl)} = (\bar{l}_j \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),$

$O_{lu}^{(ijkl)} = (\bar{l}_j \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l),$

$O_{eq}^{(ijkl)} = (\bar{e}_j \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),$

$= (\bar{e}_j \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),$

$= (\bar{l}_i e_j)\, \varepsilon\, (\bar{q}_k u_l),$

$= (\bar{l}_i \sigma^{\mu\nu} e_j)\, \varepsilon\, (\bar{q}_k \sigma_{\mu\nu} u_l),$

$= (\bar{l}_i e_j)(\bar{d}_k q_l),$

$\not{L}$ operators (5)

$= (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma} \varepsilon l_l)\, \epsilon^{\alpha\beta\gamma},$

$O_{qqu} = (\overline{q^c}_{i\alpha} \varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\, \epsilon^{\alpha\beta\gamma},$

$O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha} \varepsilon q_{j\beta})(\overline{q^c}_{k\gamma} \varepsilon l_l)\, \epsilon^{\alpha\beta\gamma},$

$O_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha} \tau^I \varepsilon q_{j\beta})(\overline{q^c}_{k\gamma} \tau^I \varepsilon l_l)\, \epsilon^{\alpha\beta\gamma},$

$O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\, \epsilon^{\alpha\beta\gamma}.$

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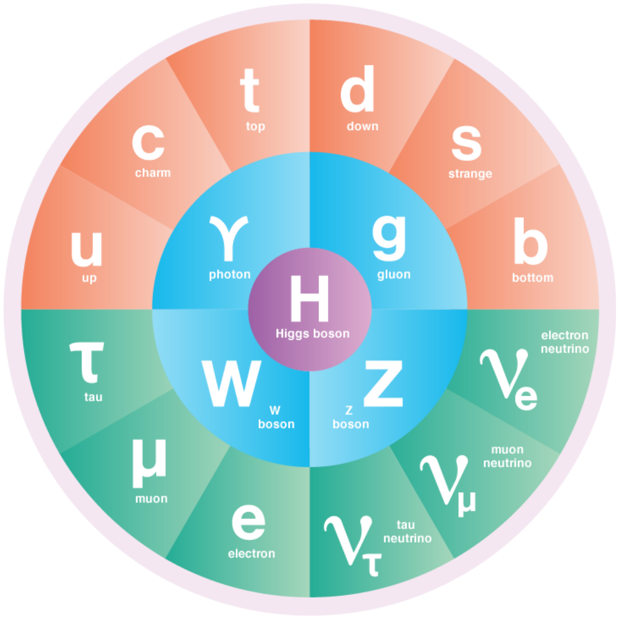
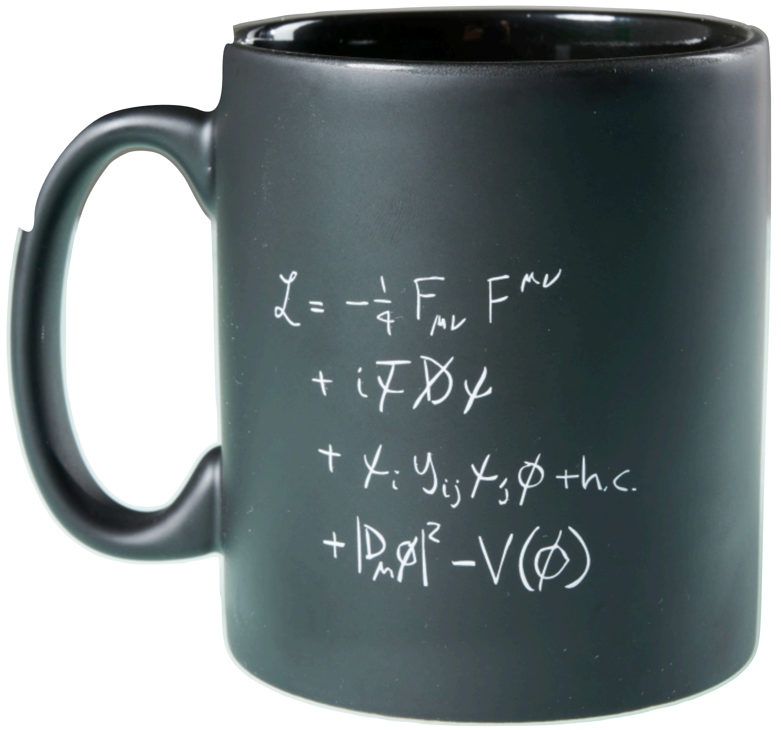
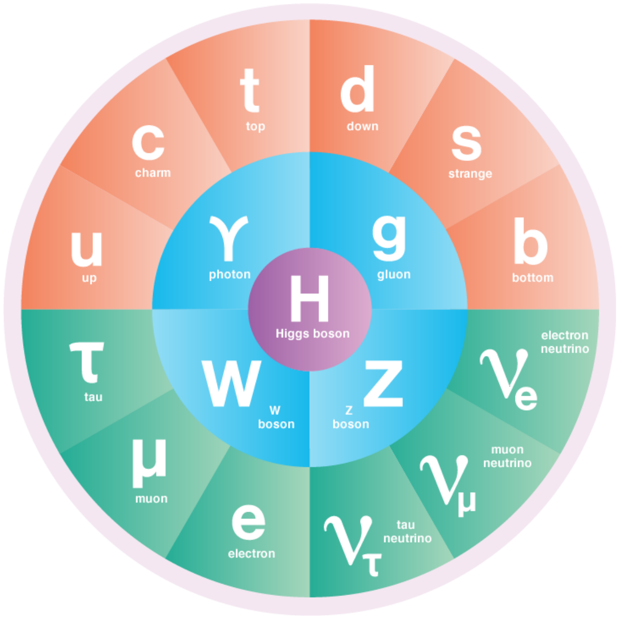
Fazit

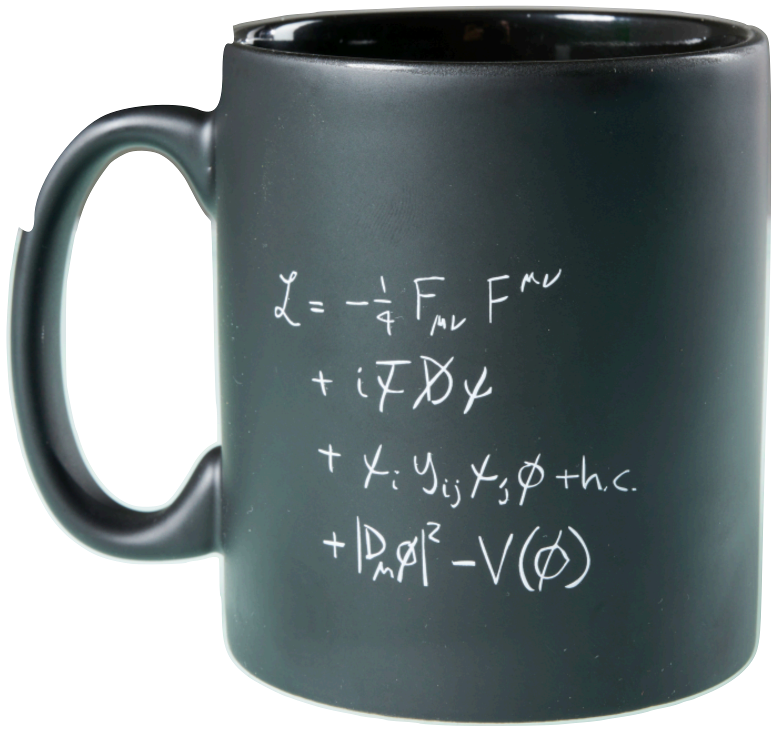




Standardmodell mit höchster Präzision überprüft;
18 Parameter, tausende Tests

Fazit





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Entdeckung/Beobachtung hat viele Facetten.

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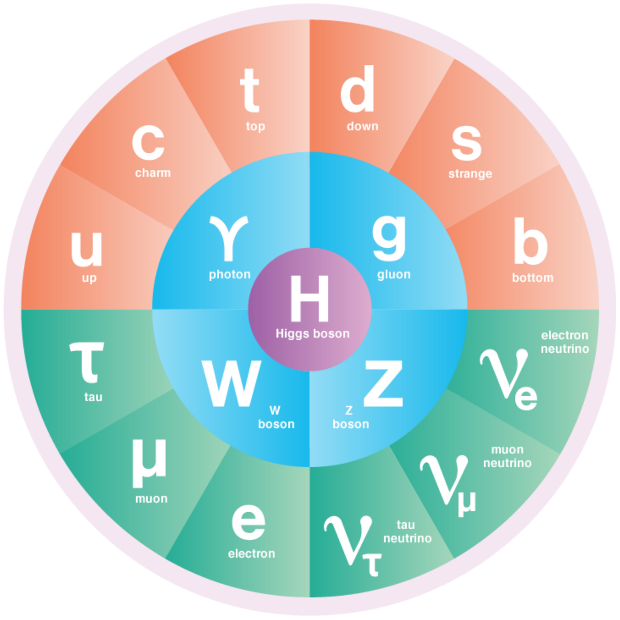

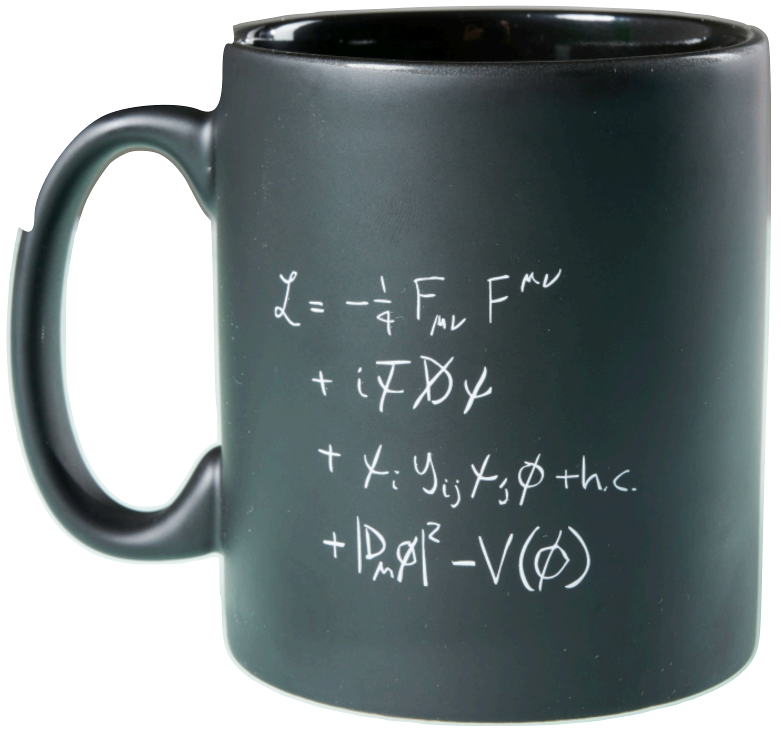

Standardmodell mit höchster Präzision überprüft;
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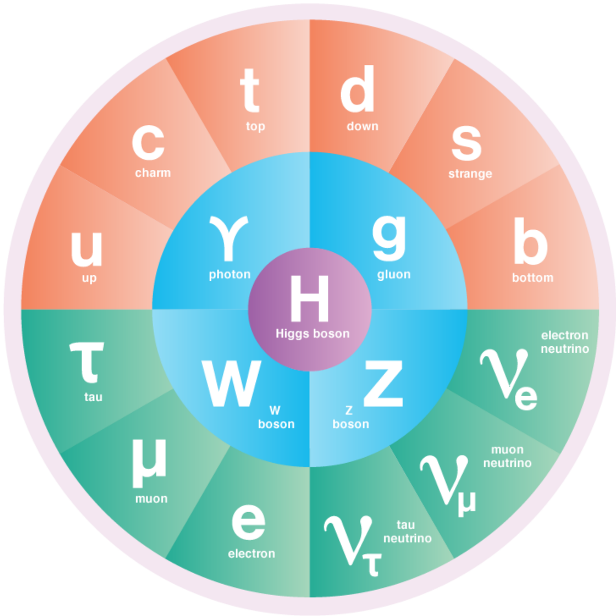
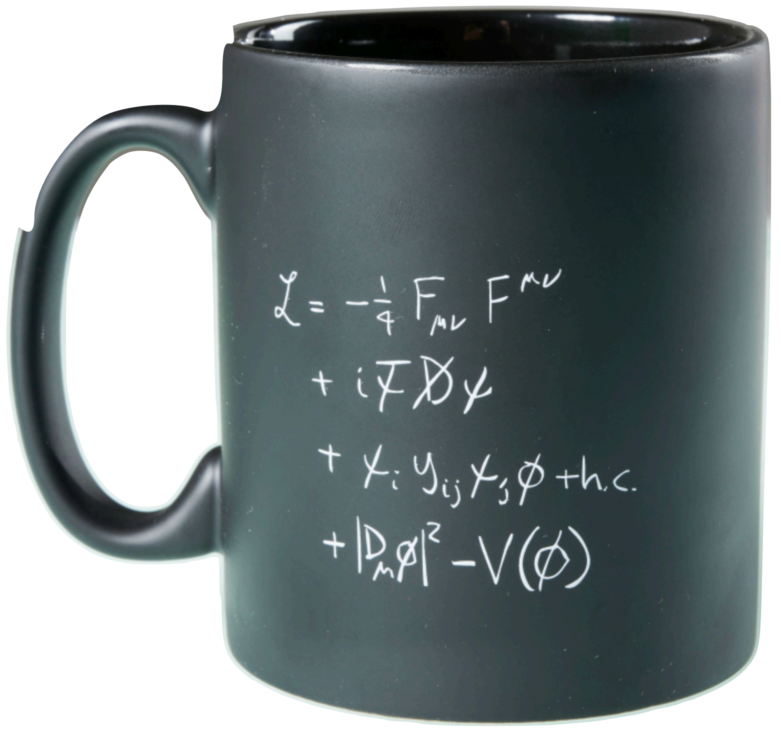
Entdeckung/Beobachtung hat viele Facetten.

Higgs könnte das letzte entdeckte “Teilchen” sein.

Fazit





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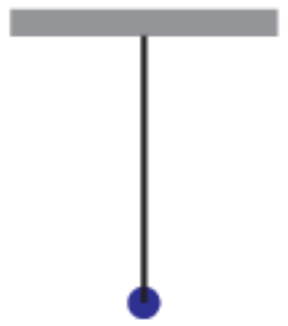
Aber: Es gibt eine Welt jenseits von Teilchen:



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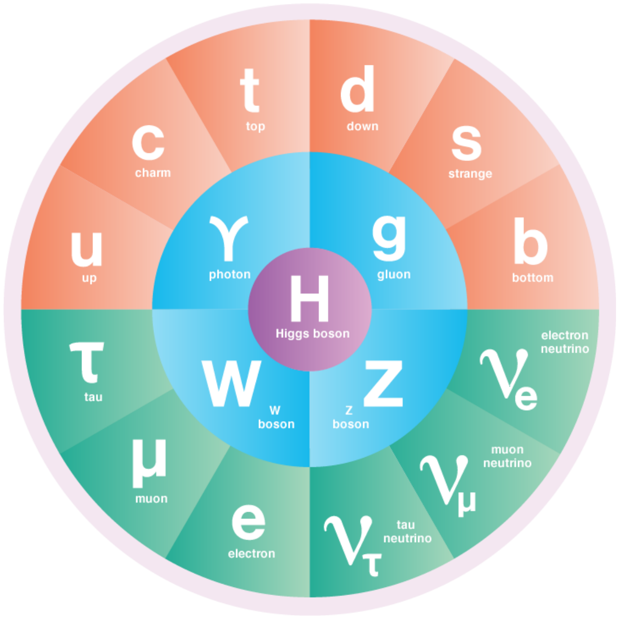

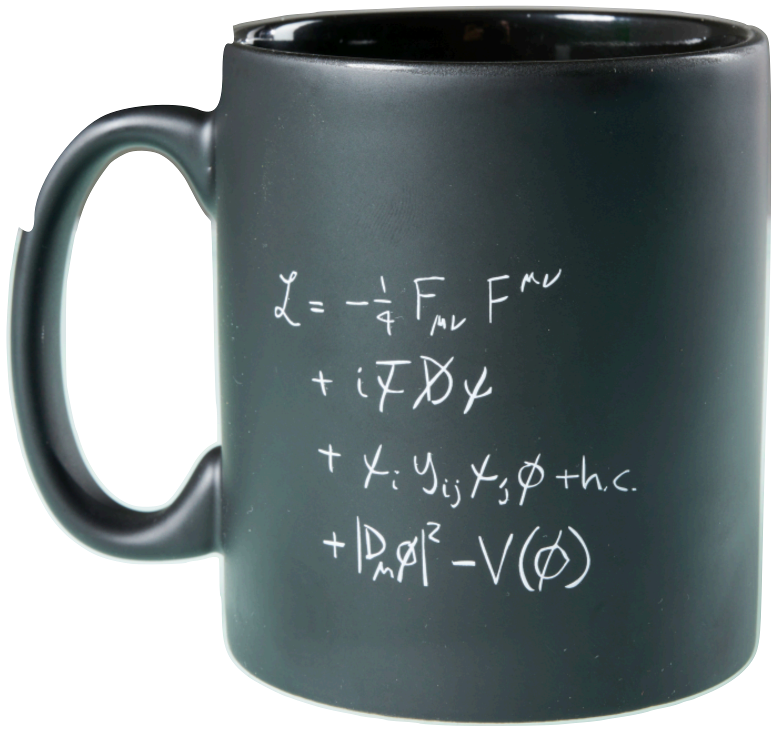

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