The future of particle discoveries

Robert Harlander
RWTH Aachen University

based on work with
Jean-Philippe Martinez and Gregor Schiemann

2nd International Conference of the Research Unit
"The Epistemology of the Large Hadron Collider"
8-10 December 2022

extended version: https://indico.desy.de/event/32950/contributions/130153/

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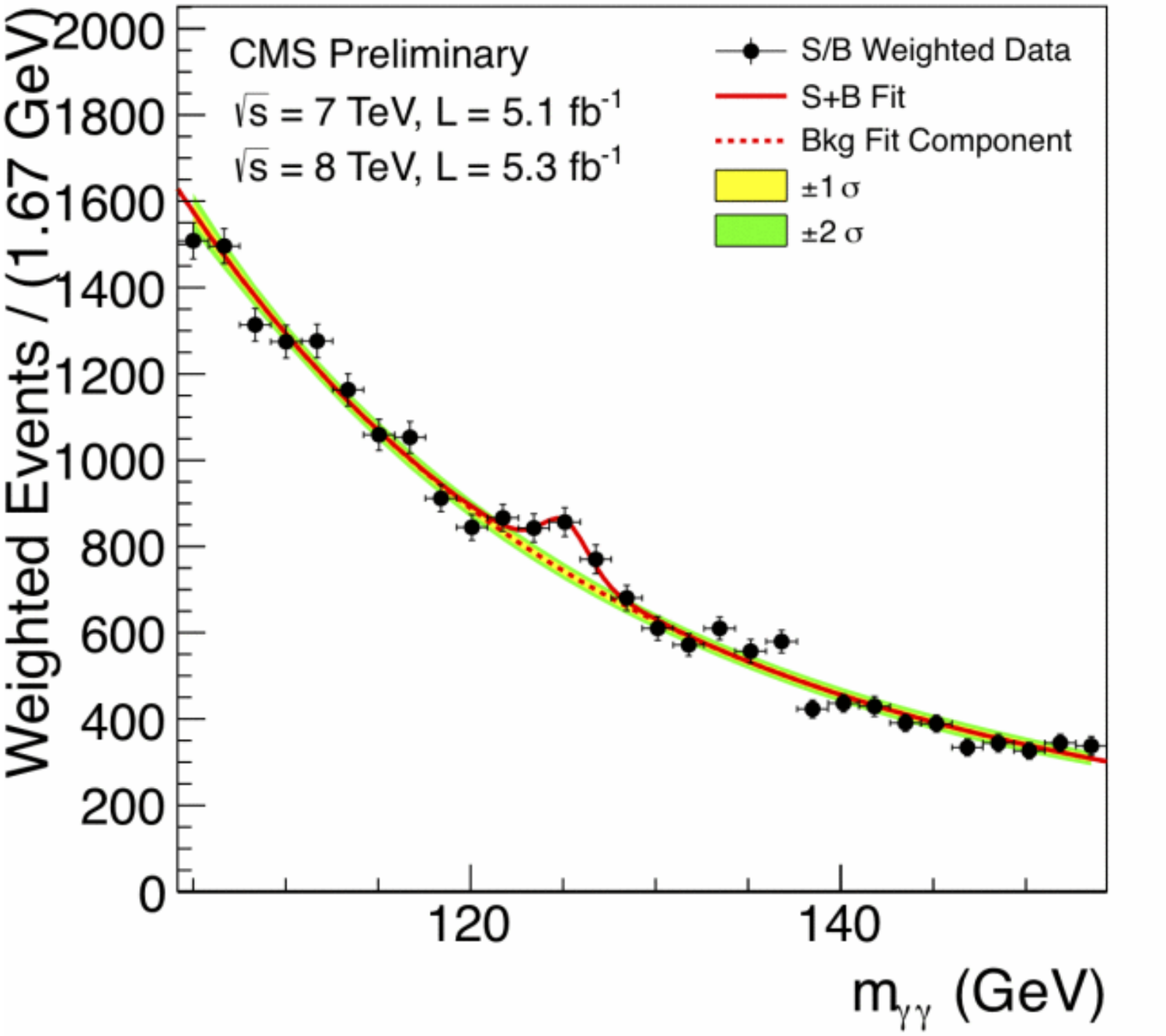
Discovering particles today



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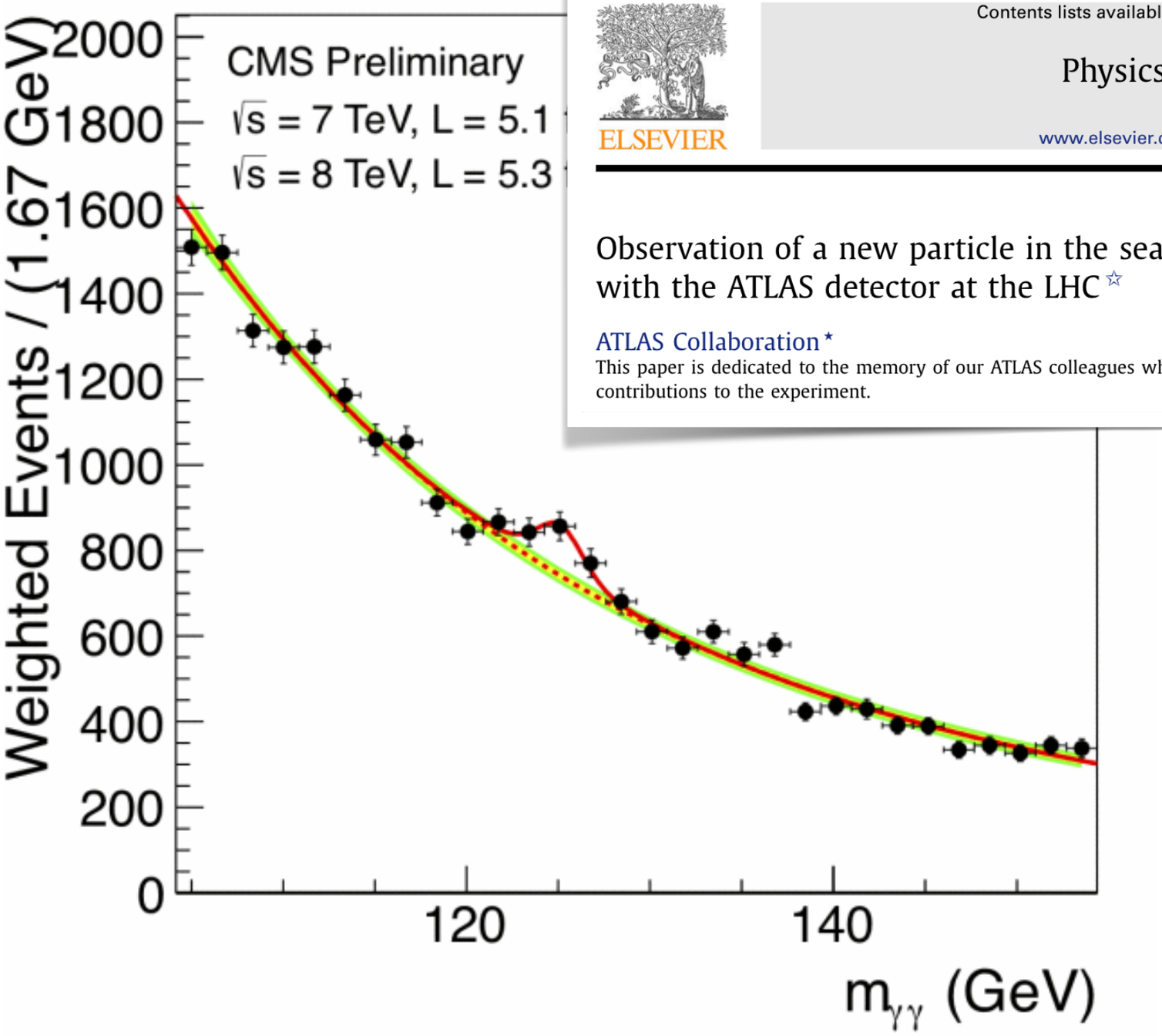

Physics Letters B 716 (2012) 1–29

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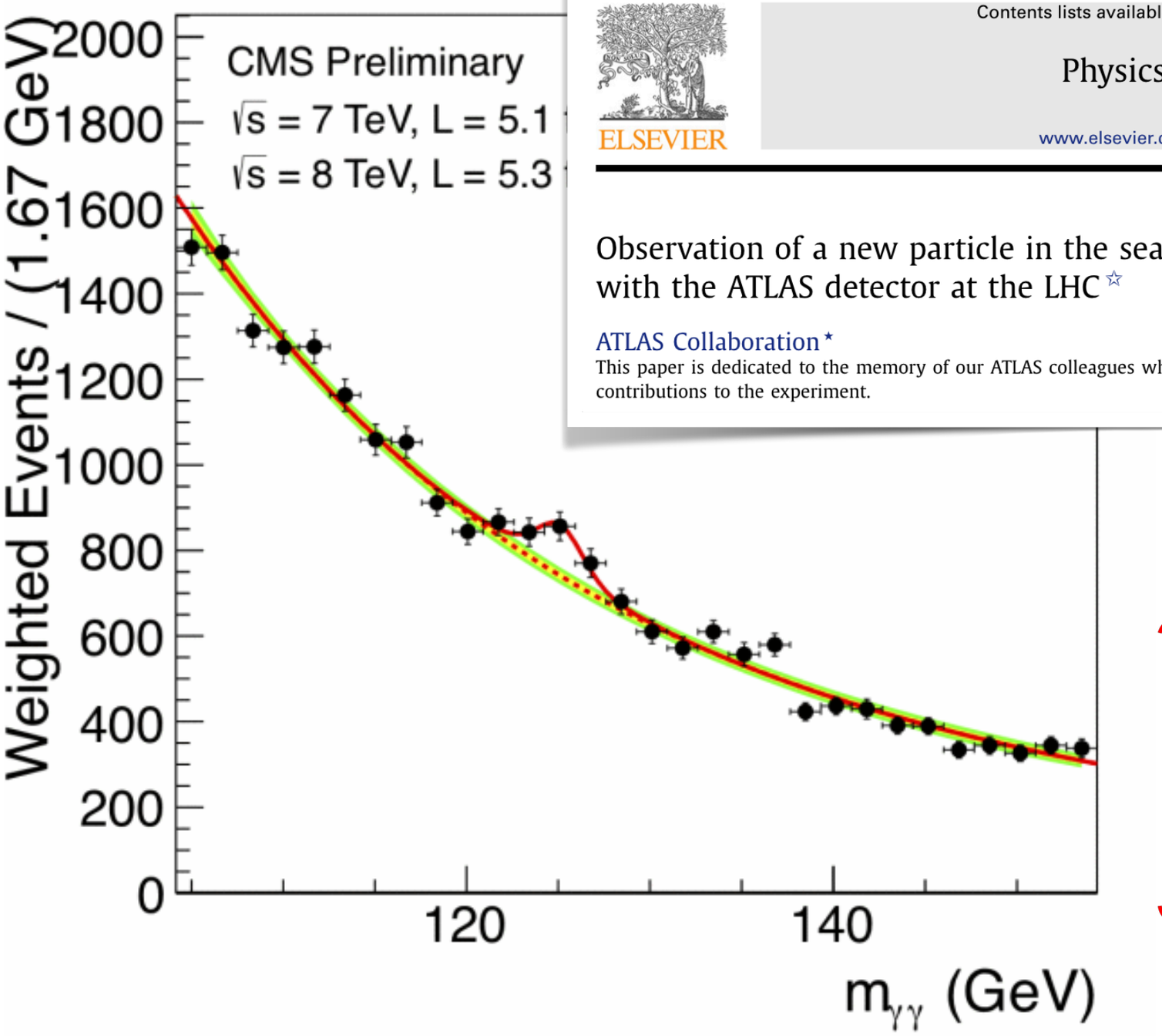
Discovering particles today



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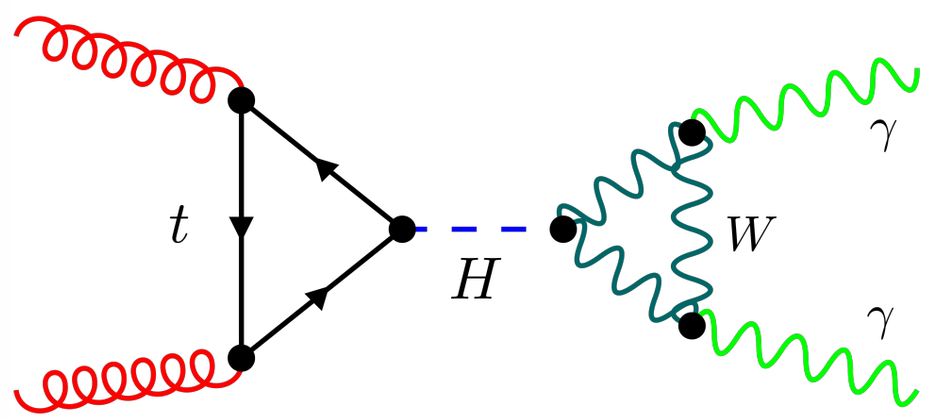
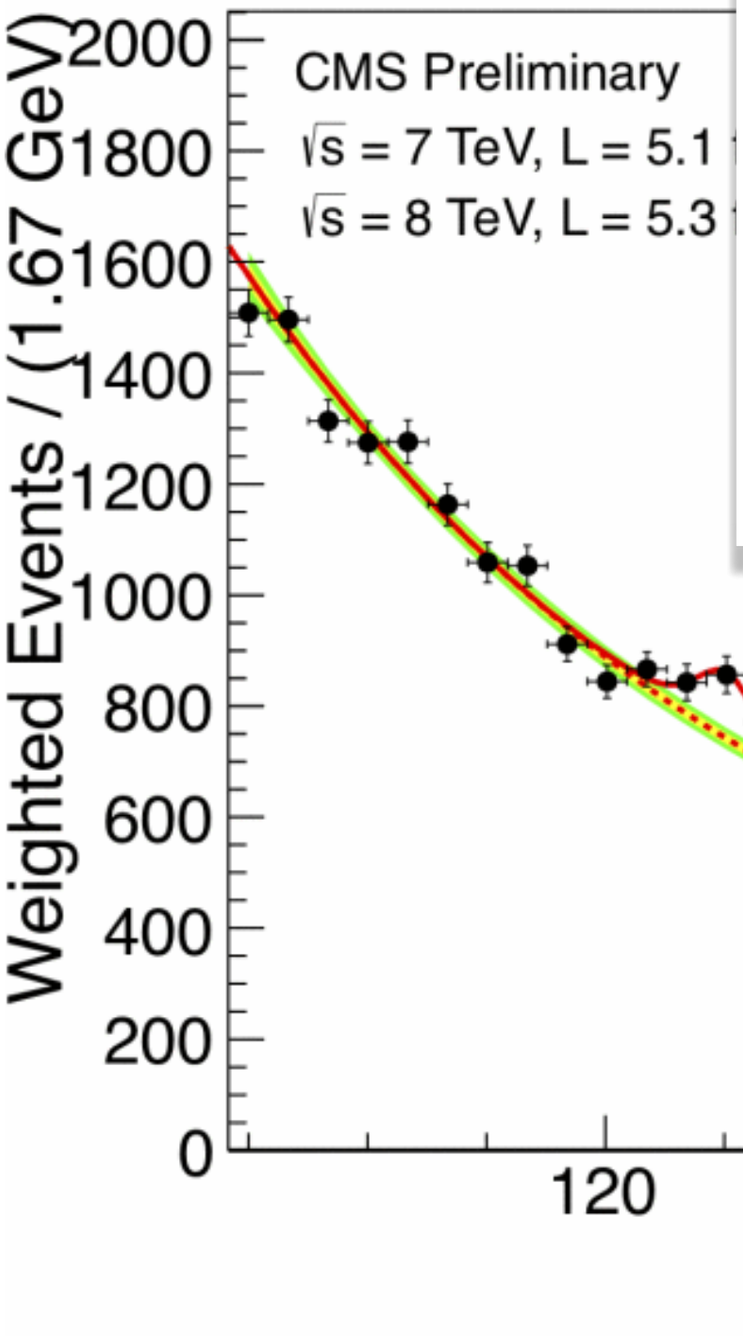


Discovering particles today



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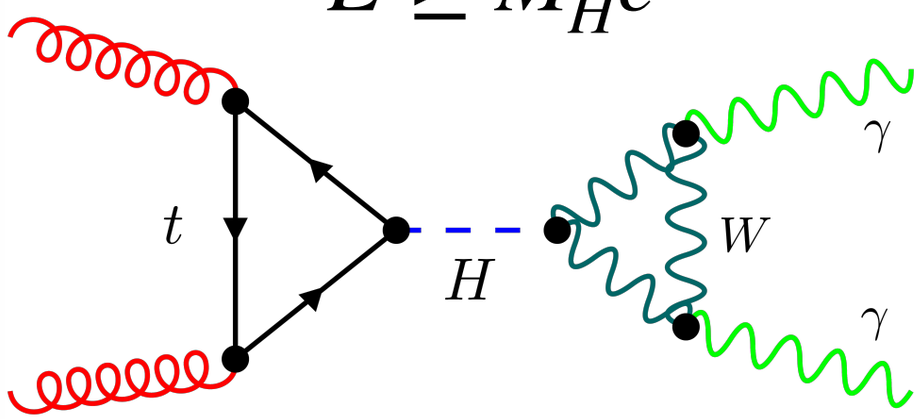
$$E \geq M_H c^2$$



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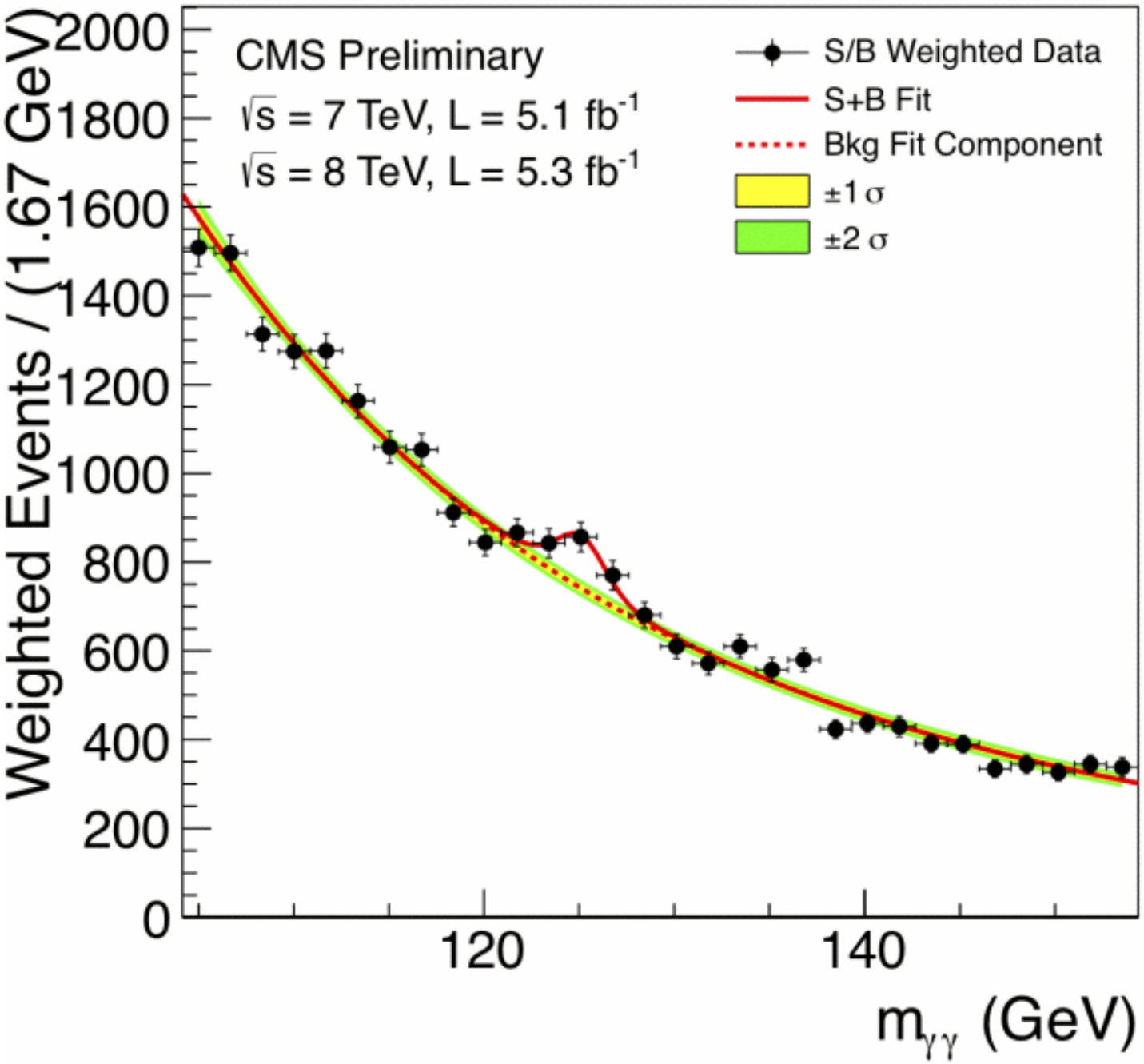
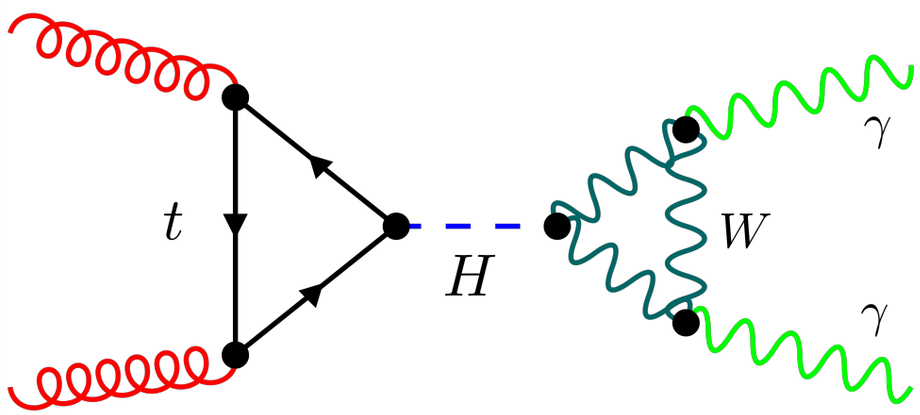
Observing particles today





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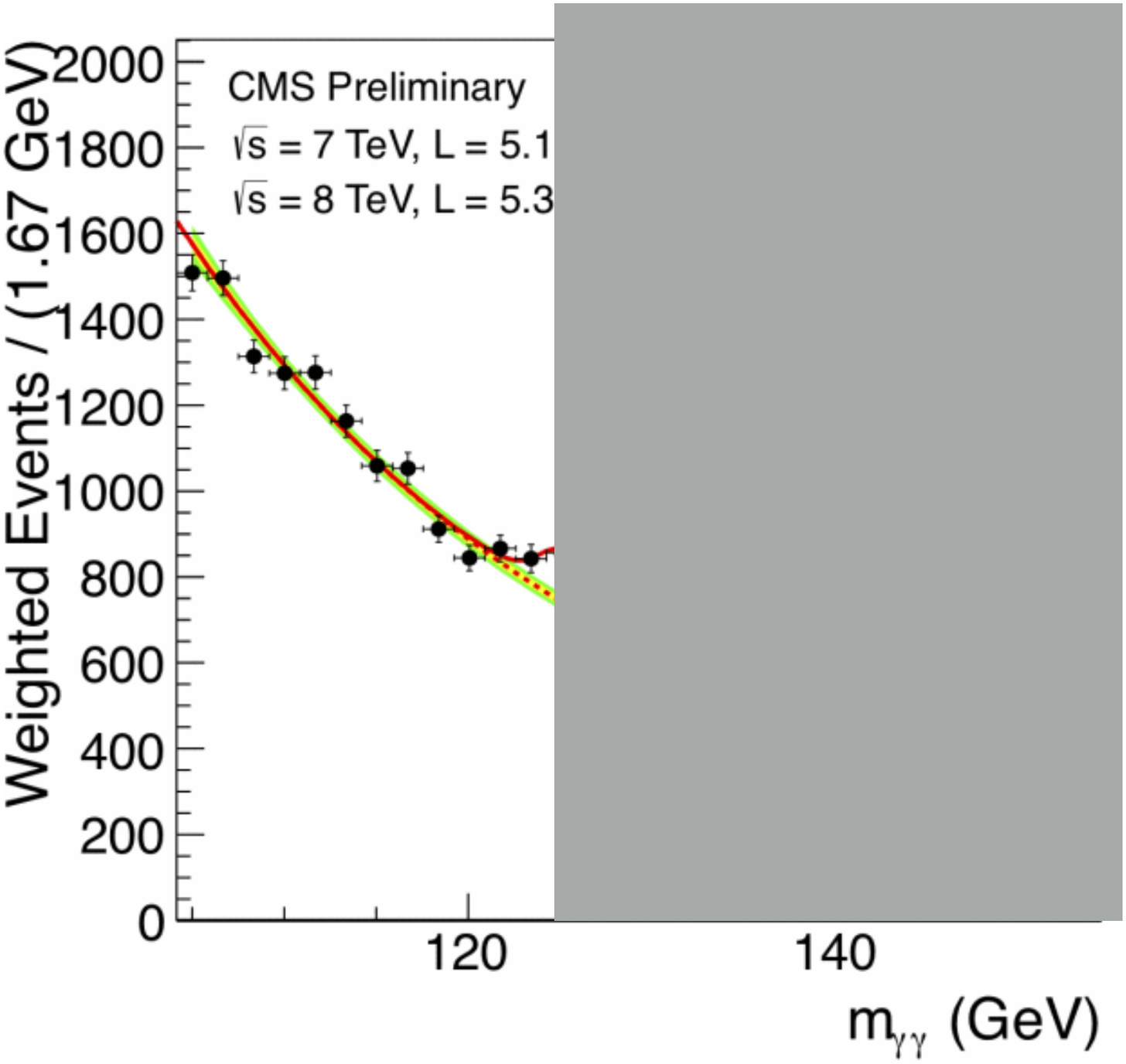
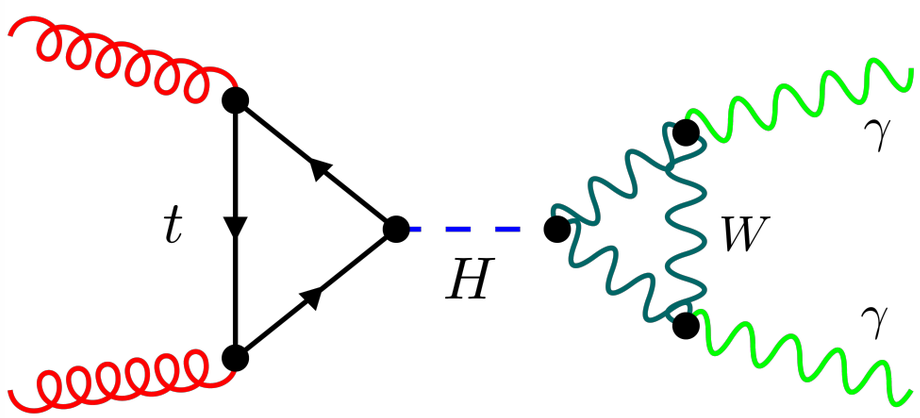
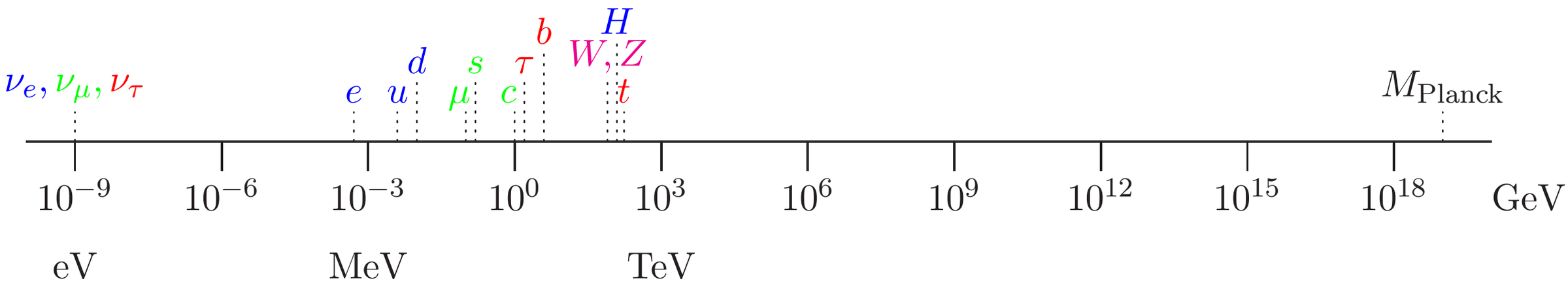




How far can we go?



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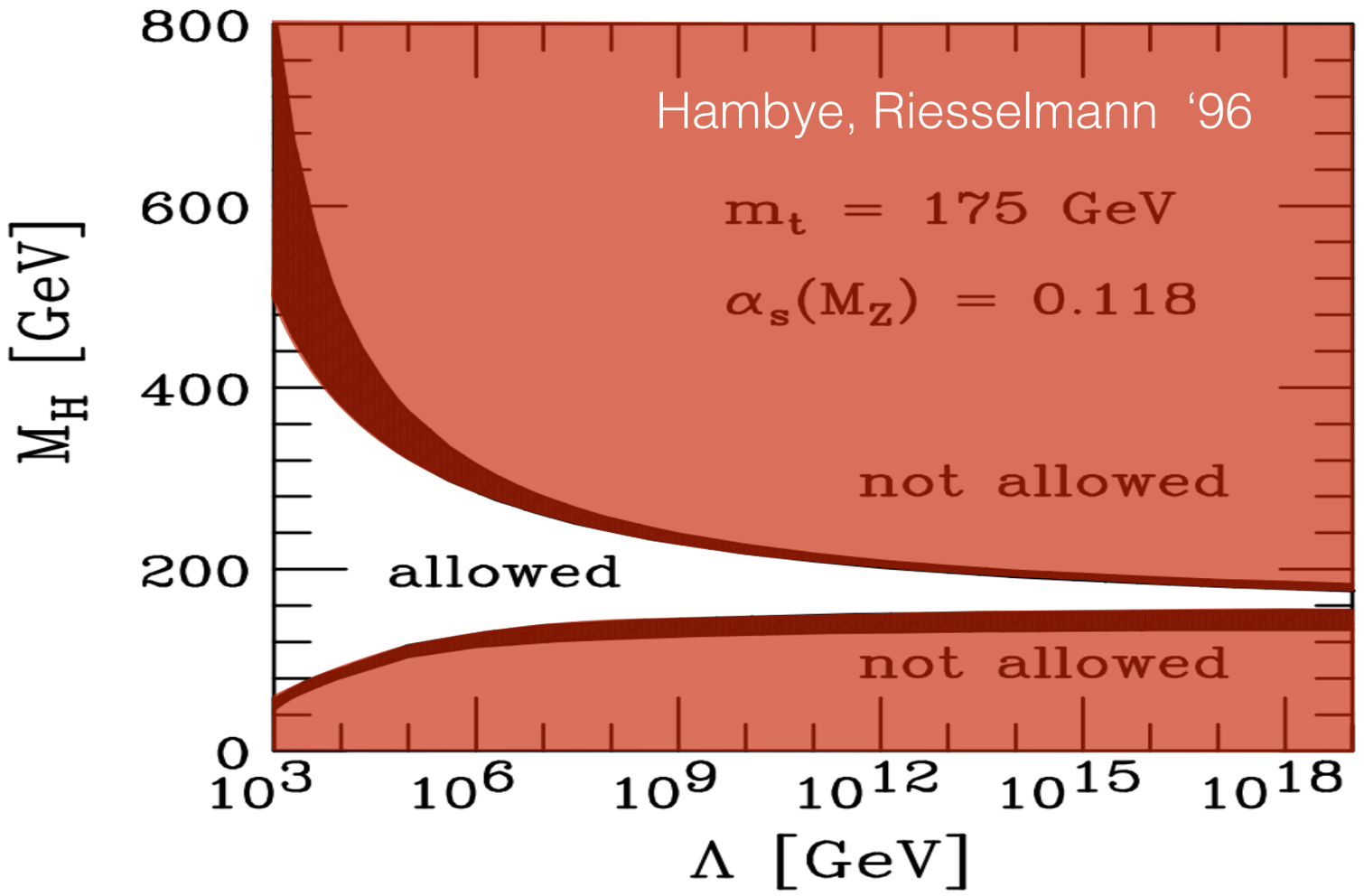
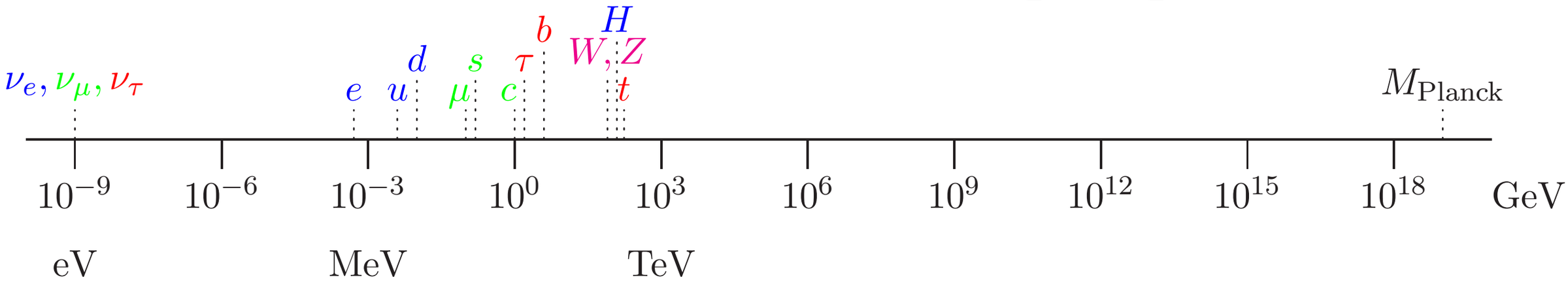
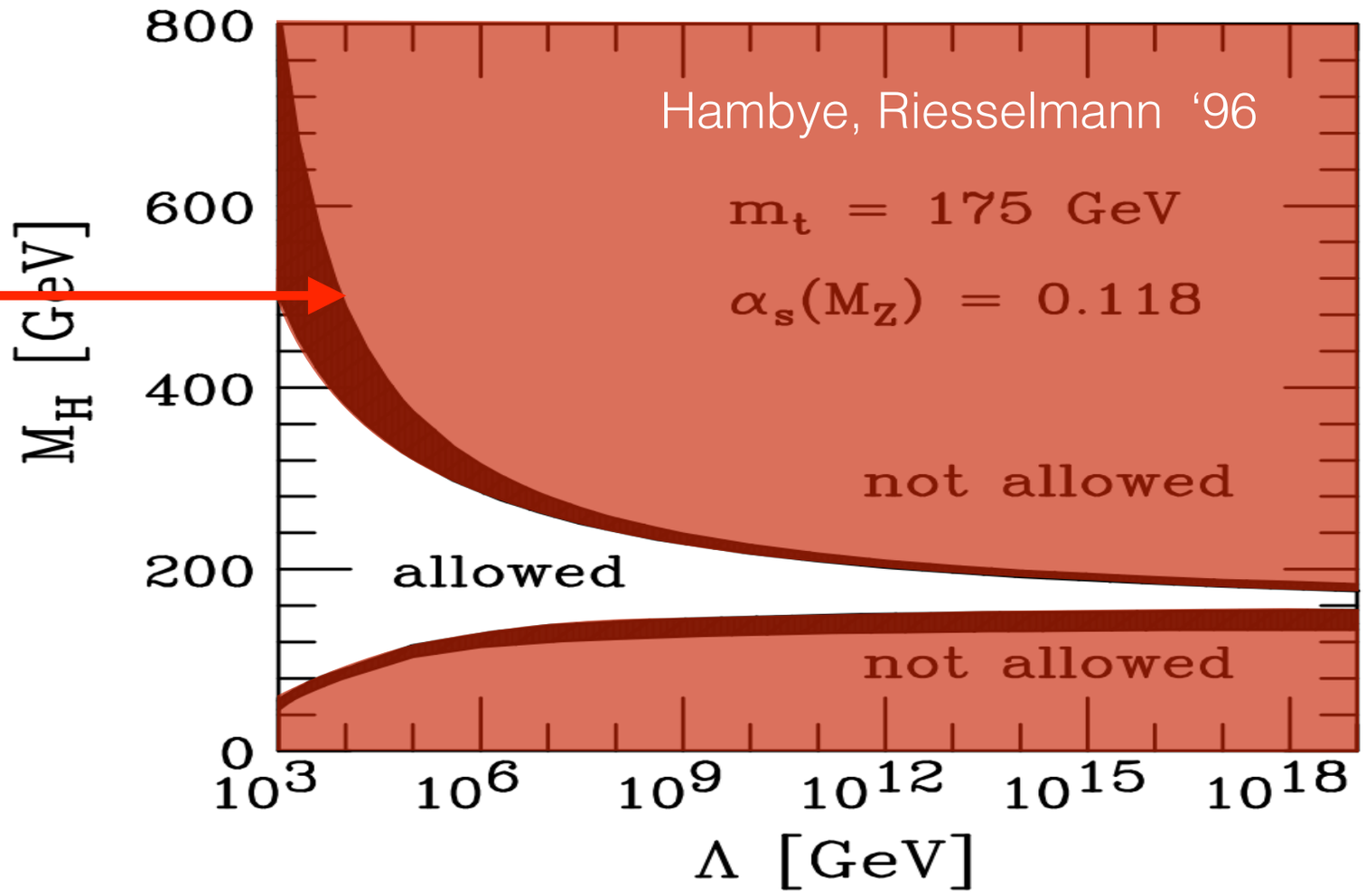
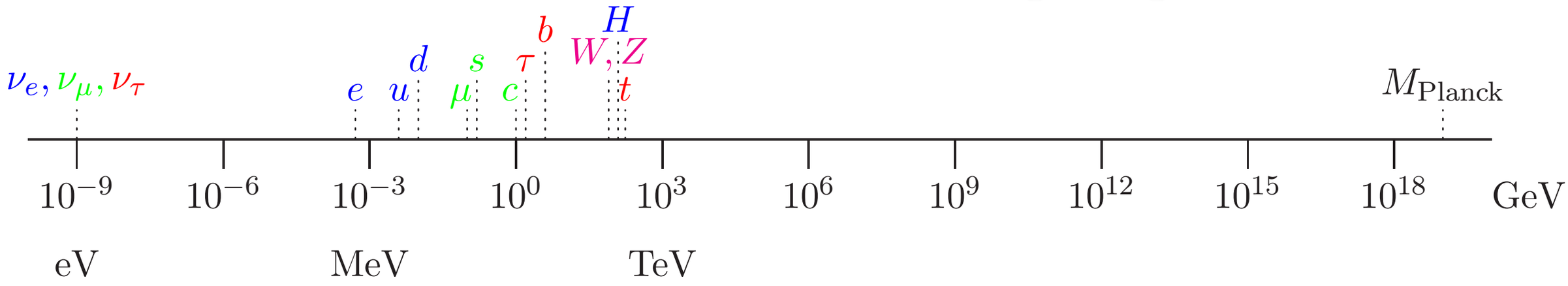




How far can we go?

$M_H = 500\,\text{GeV}$





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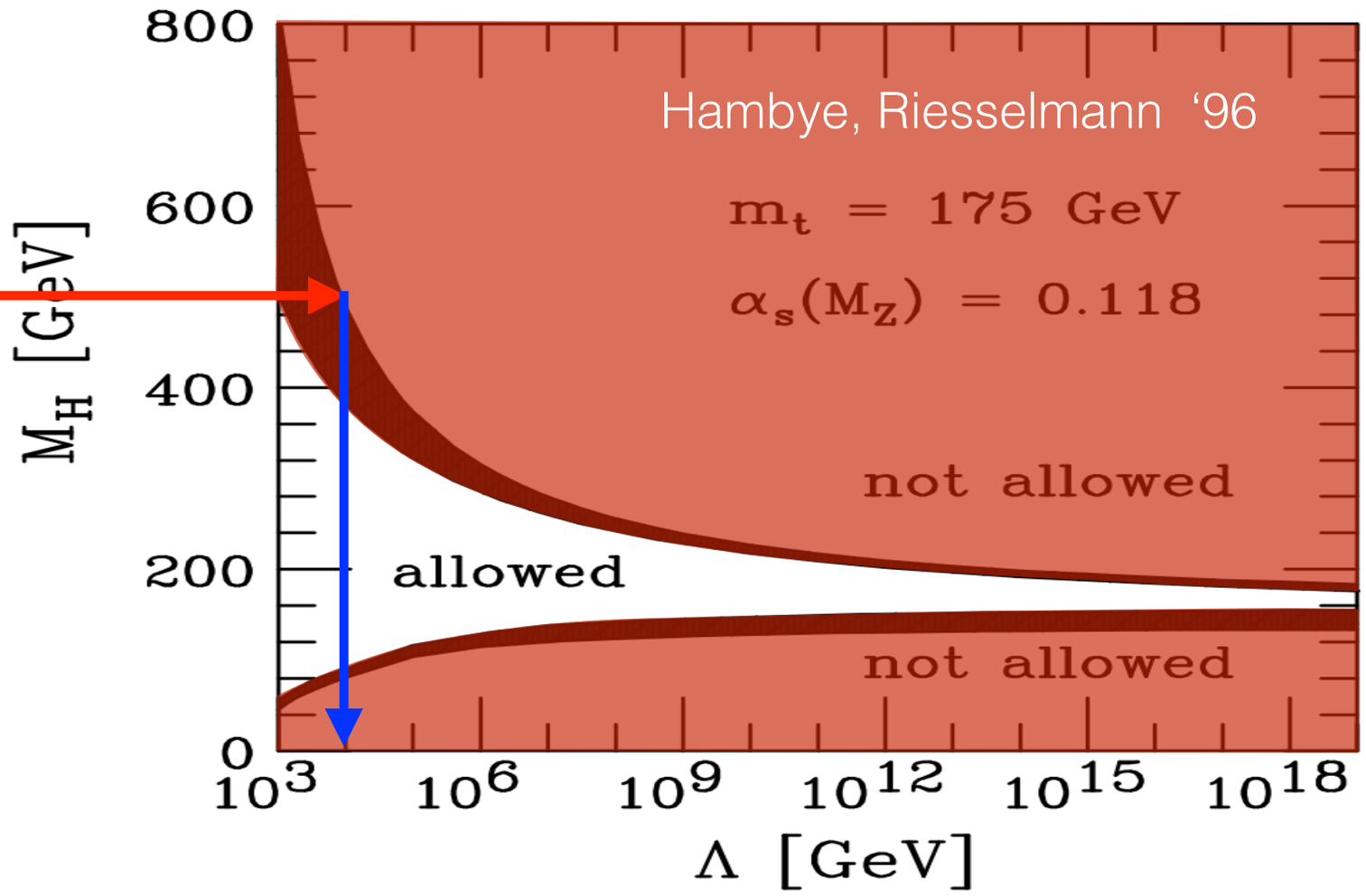

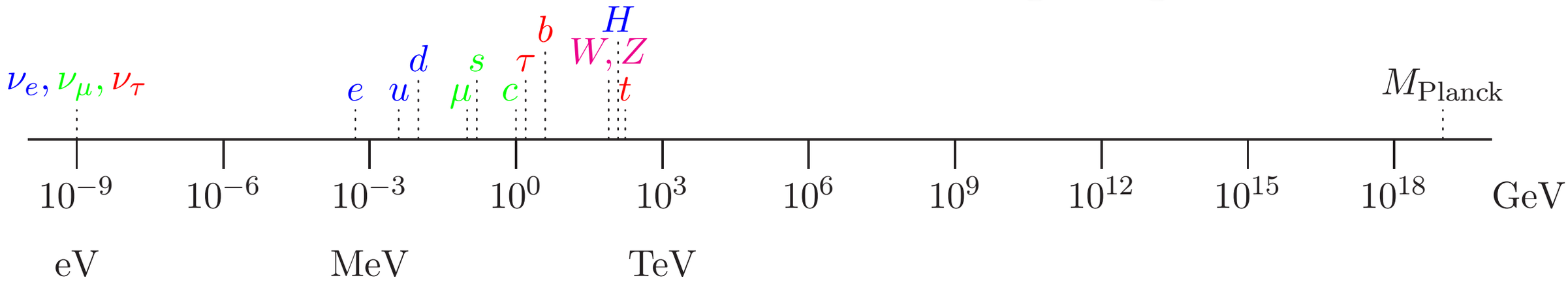

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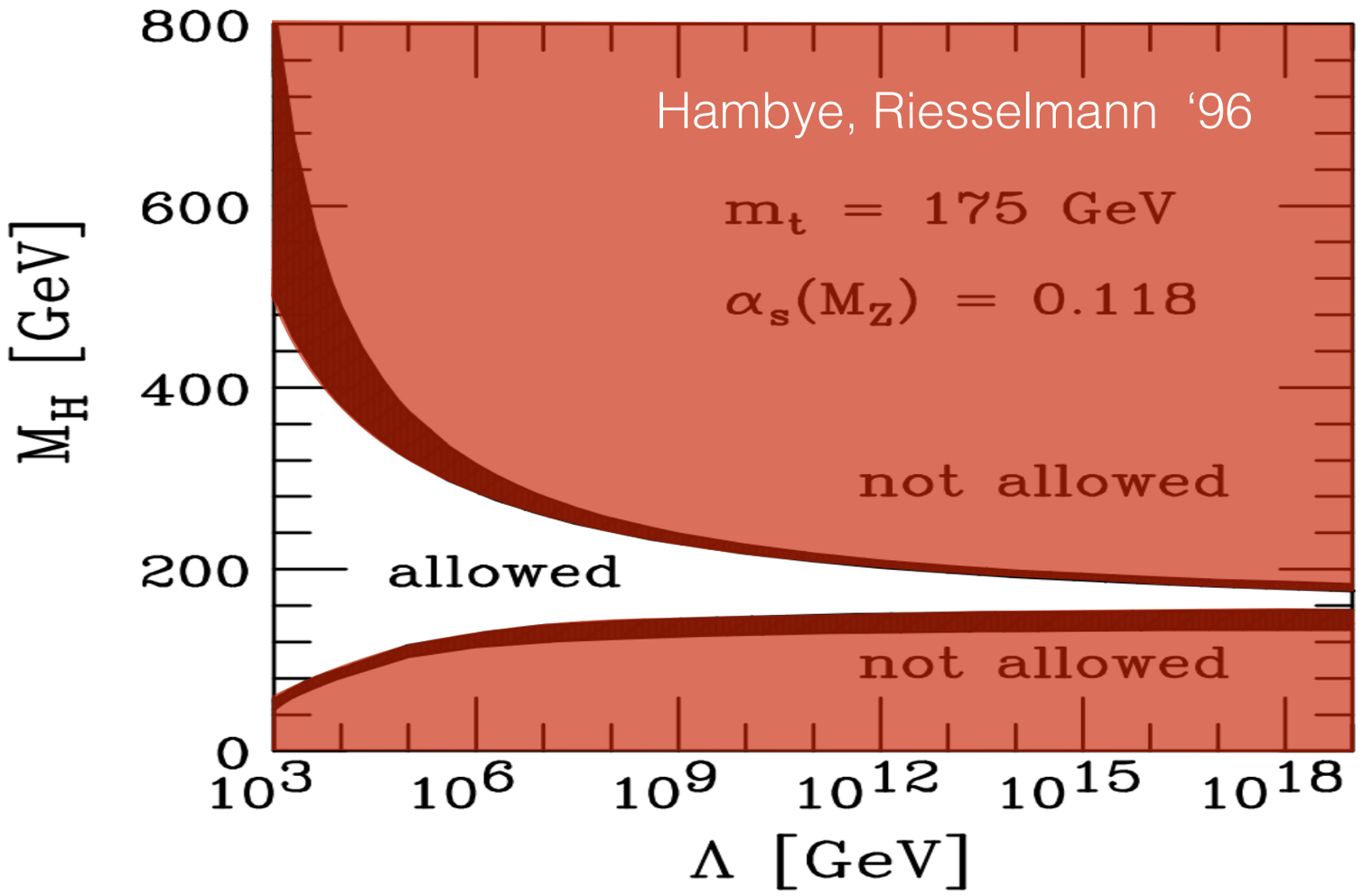

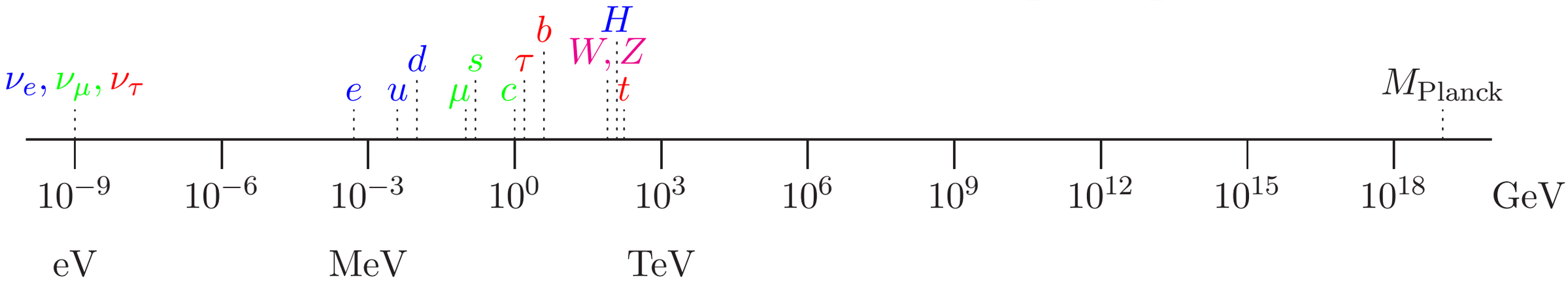

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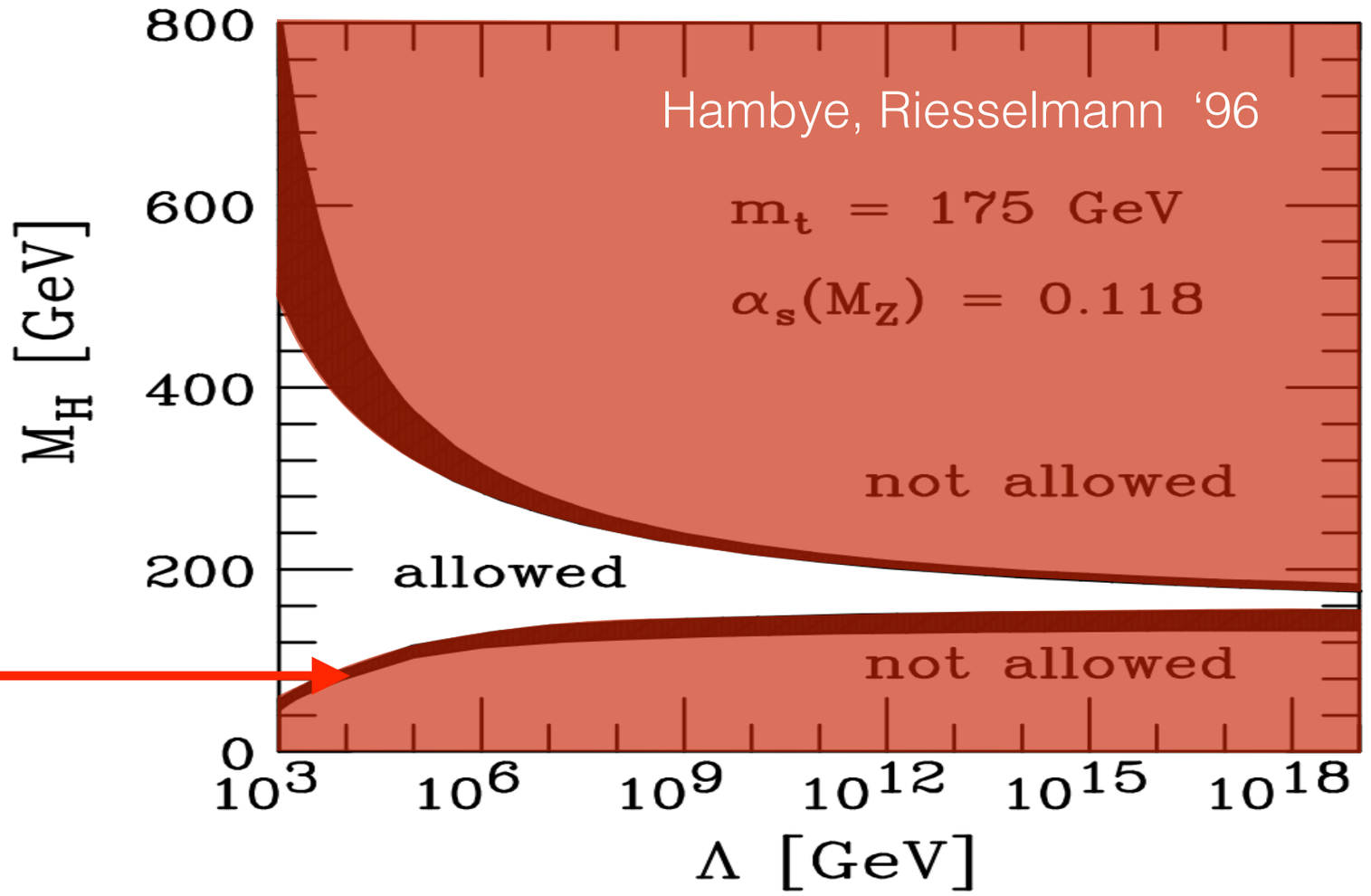
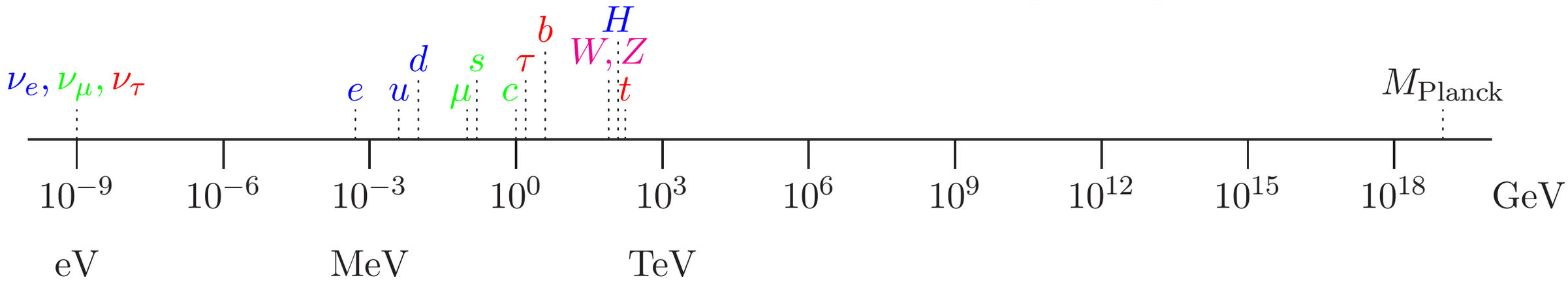


$M_H = 80\,\text{GeV}$



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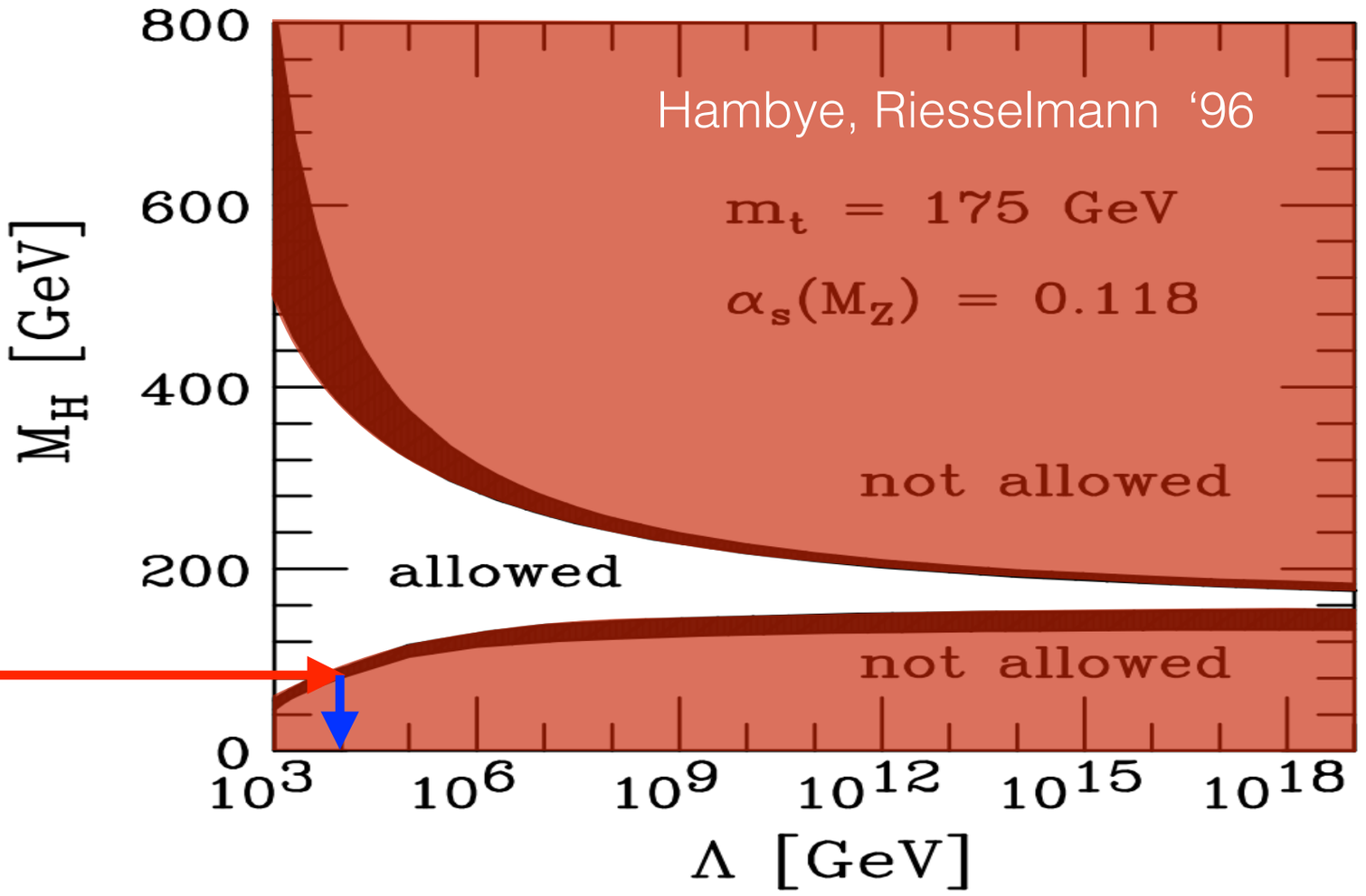

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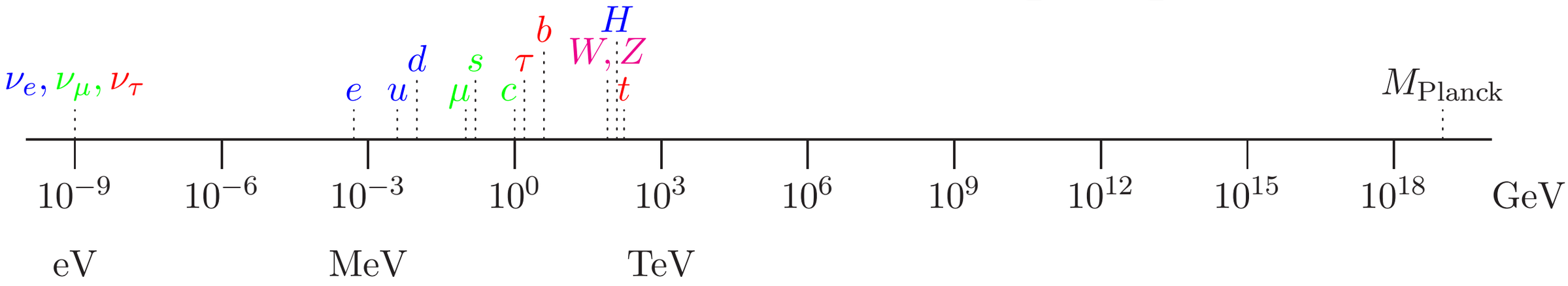

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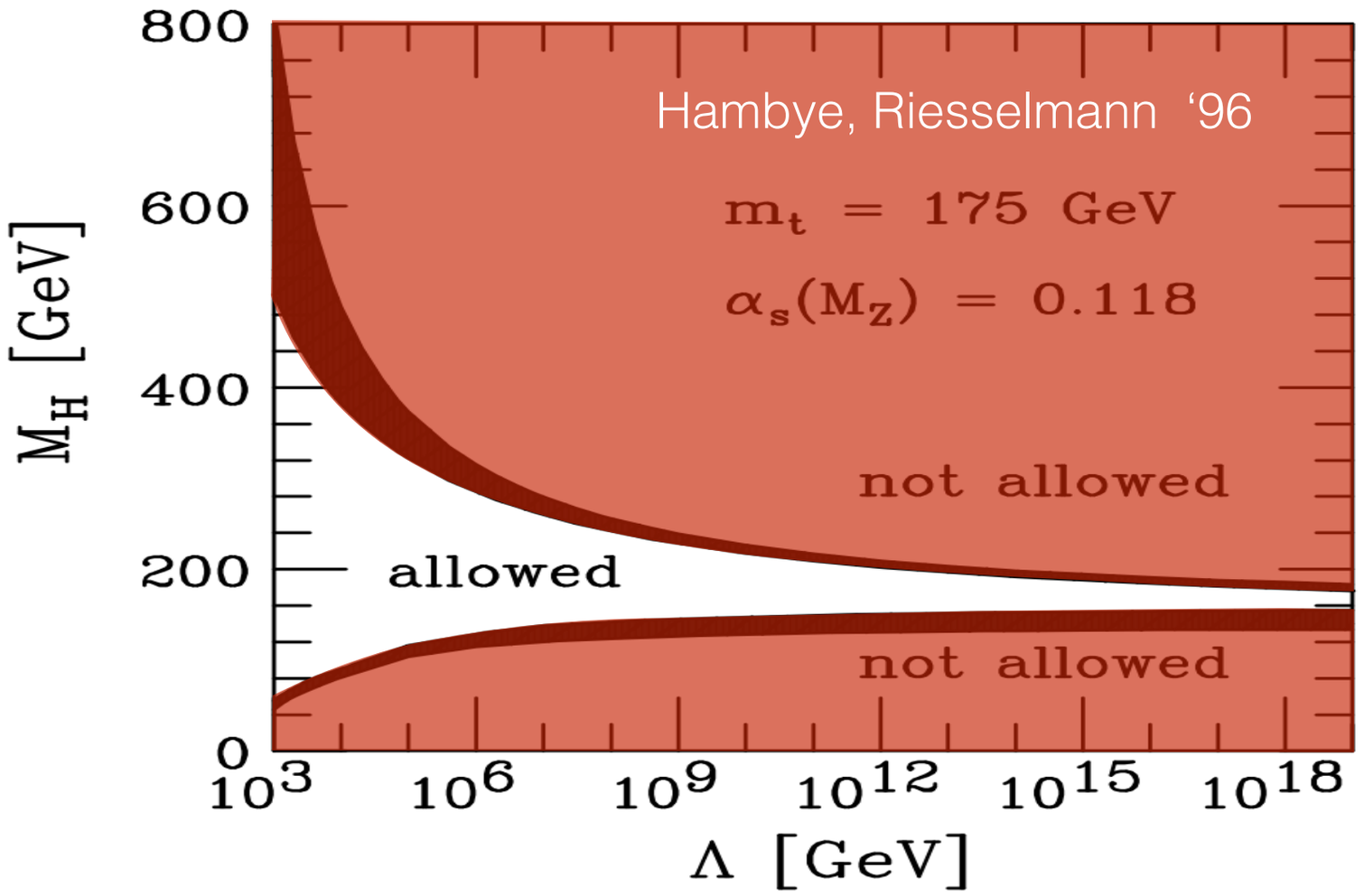

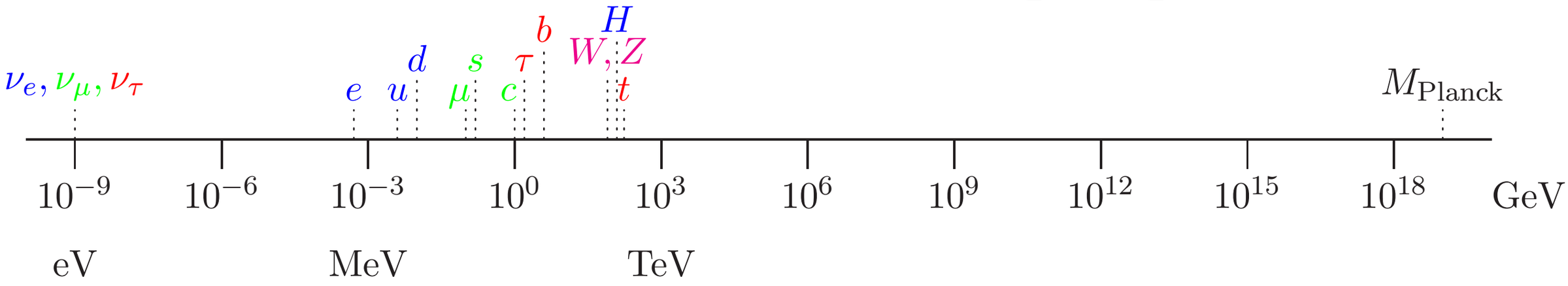

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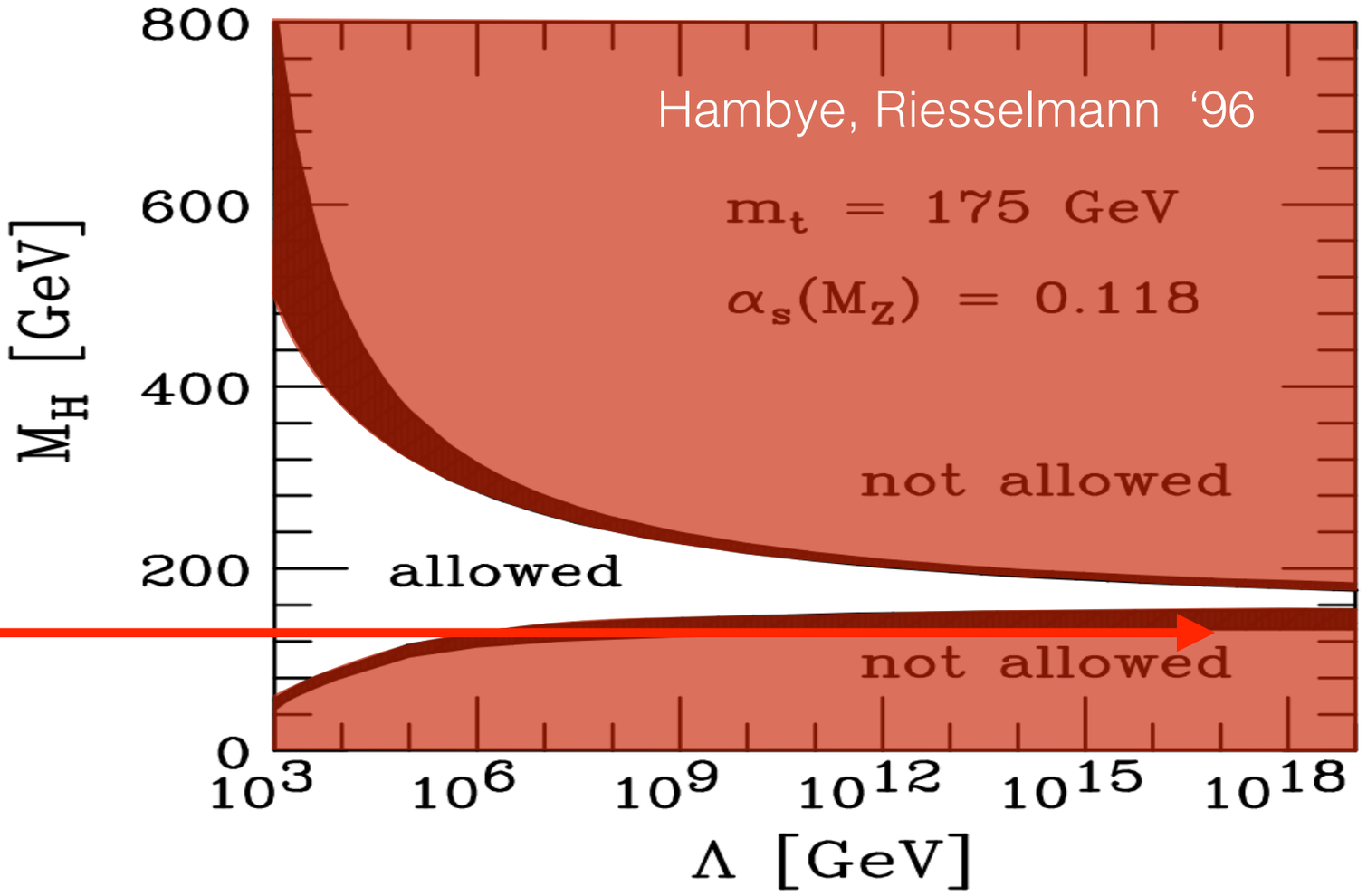
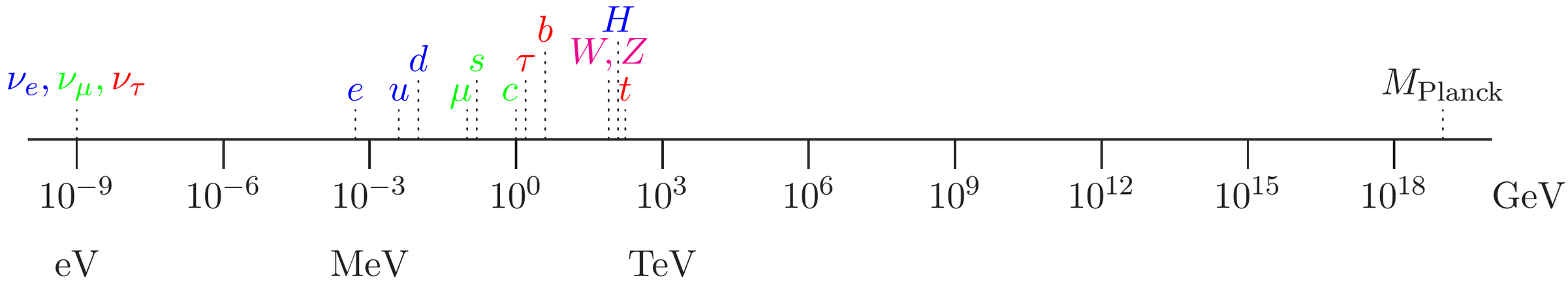


$M_H = 125\,\text{GeV}$



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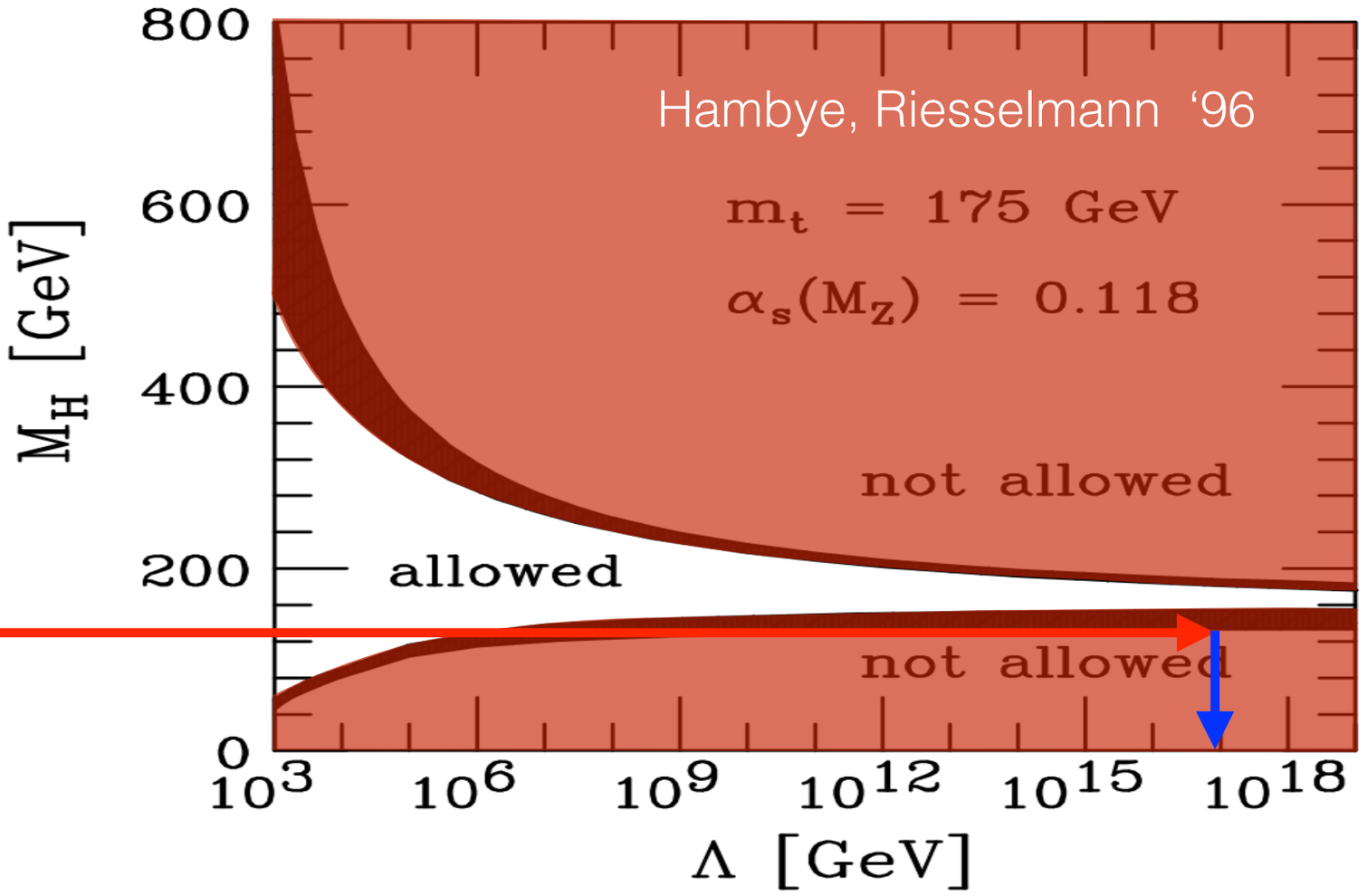

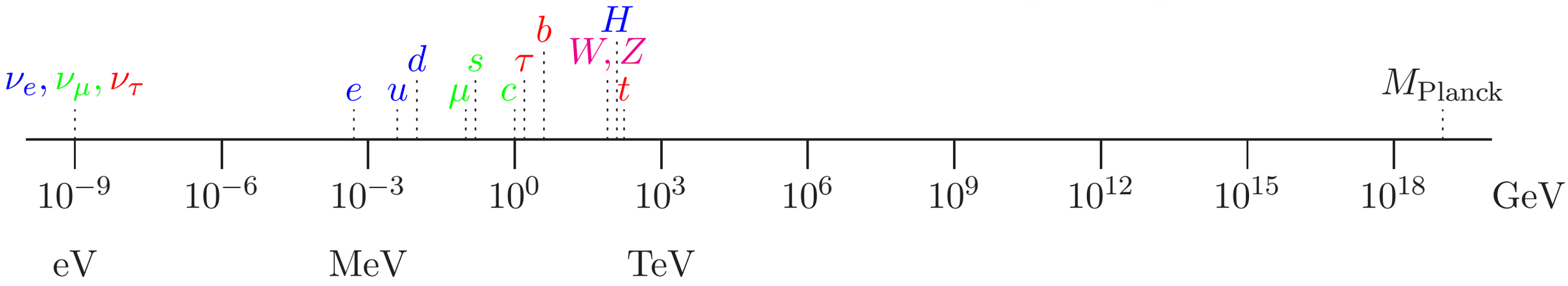

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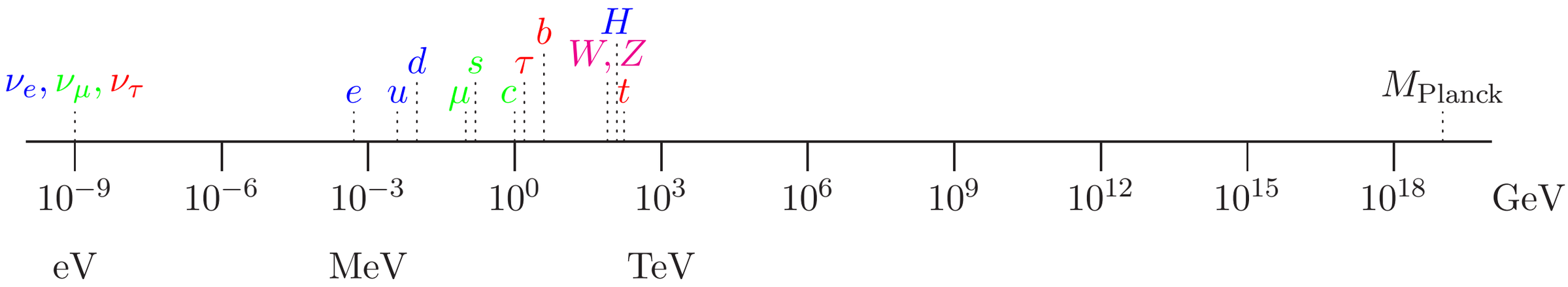

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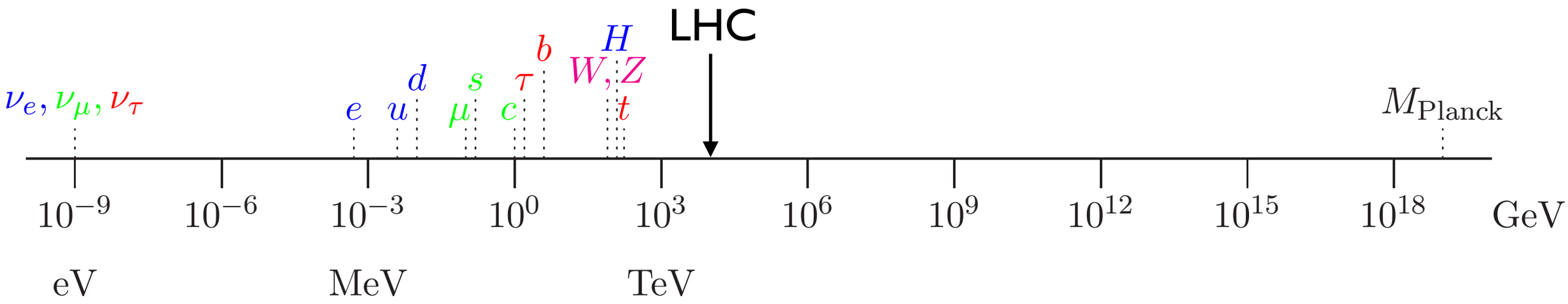

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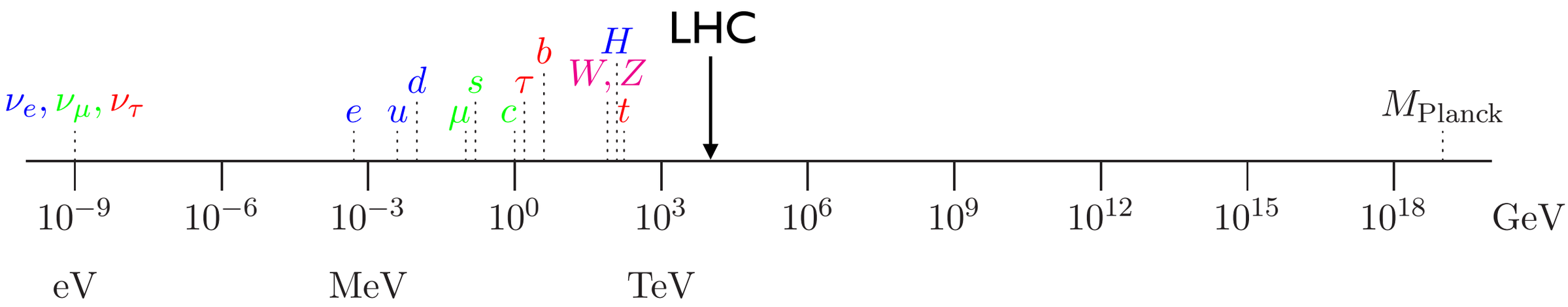

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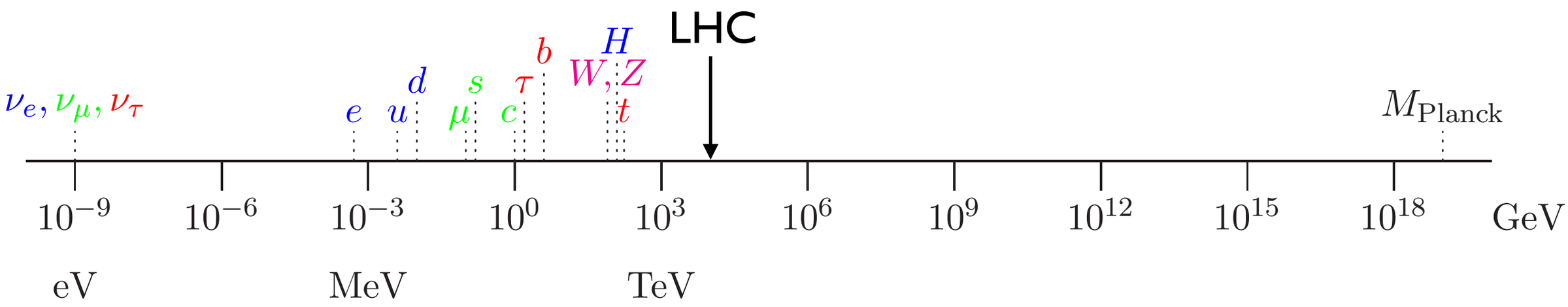

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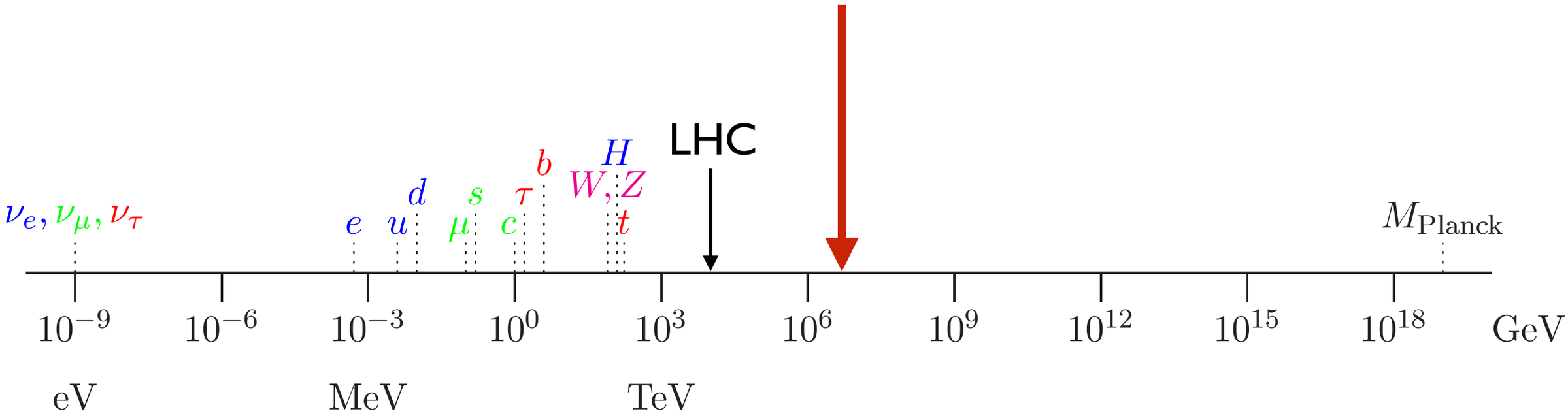

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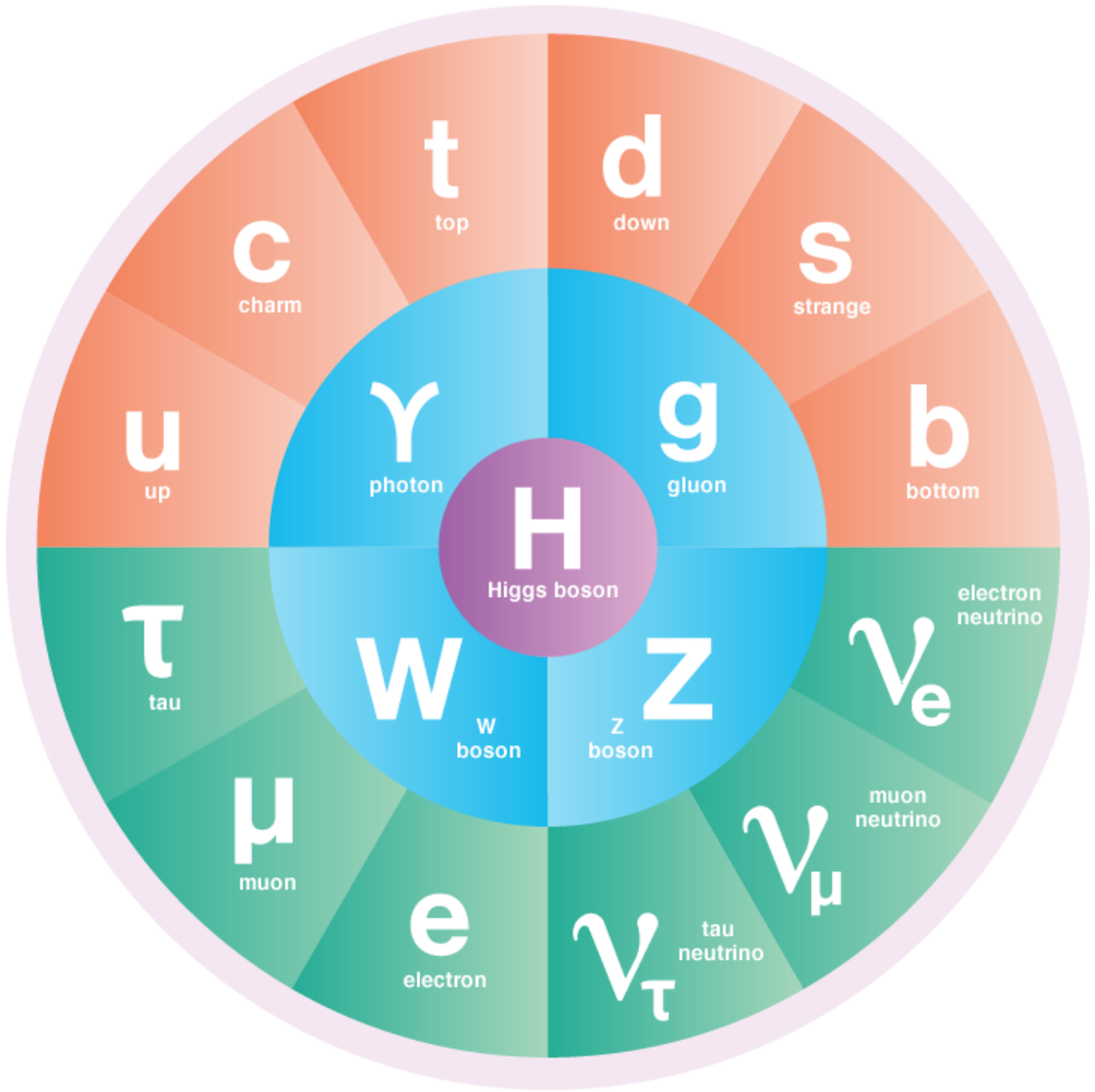
The future?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u
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γ
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g
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b
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H
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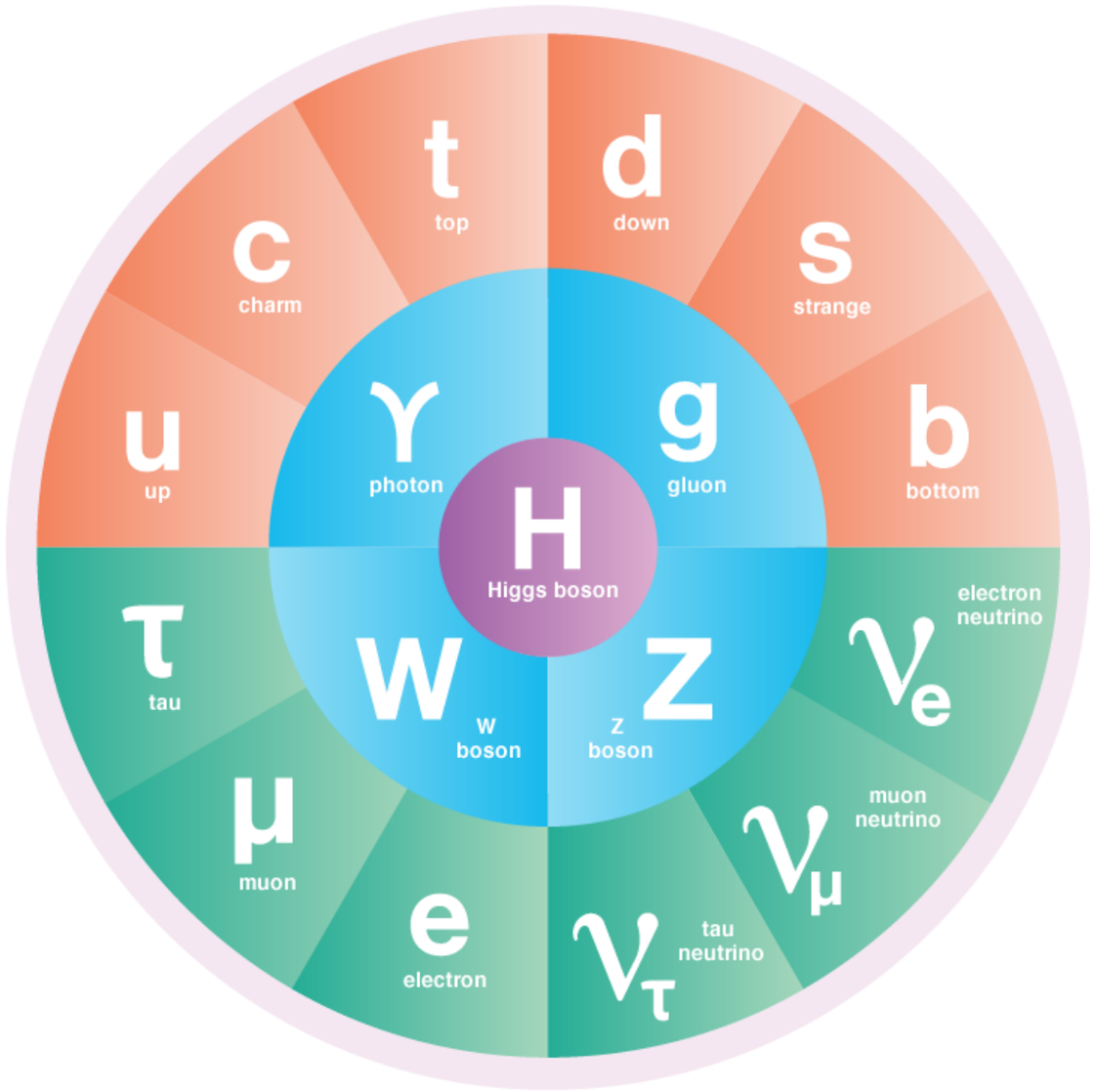
τ
tau
W
W boson
Z
Z boson
electron neutrino
muon neutrino
μ
muon
e
electron
tau neutrino

The future 2010



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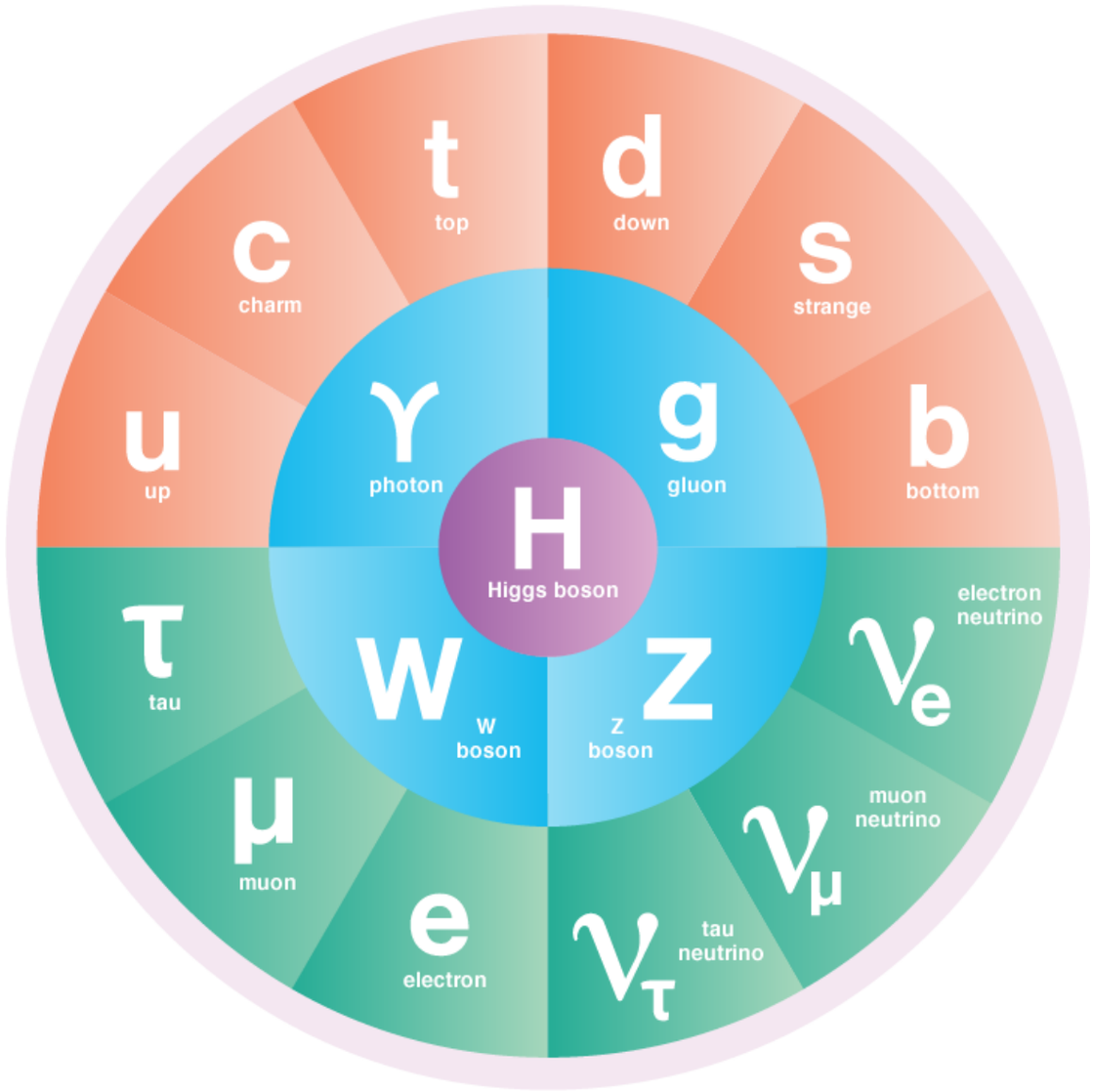
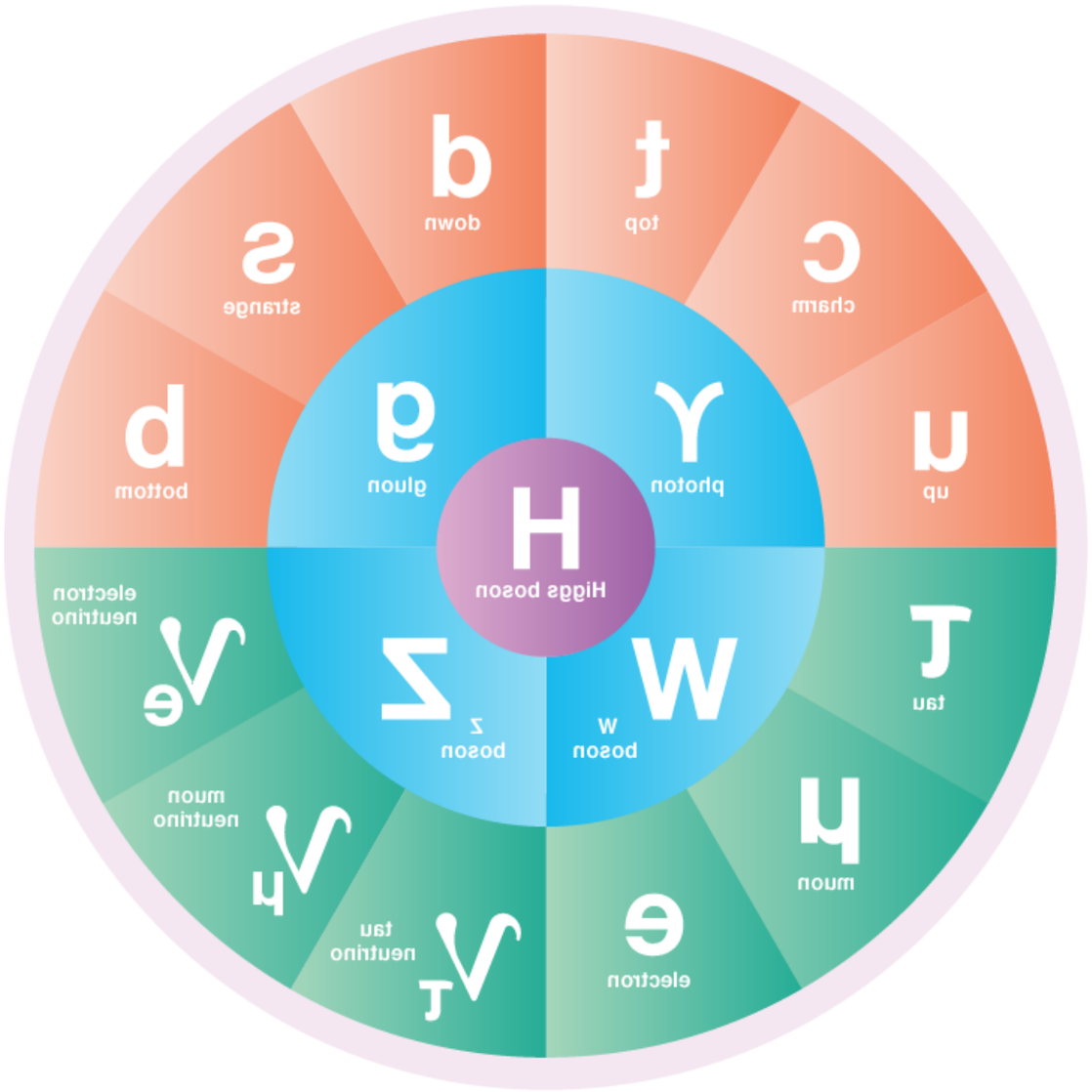
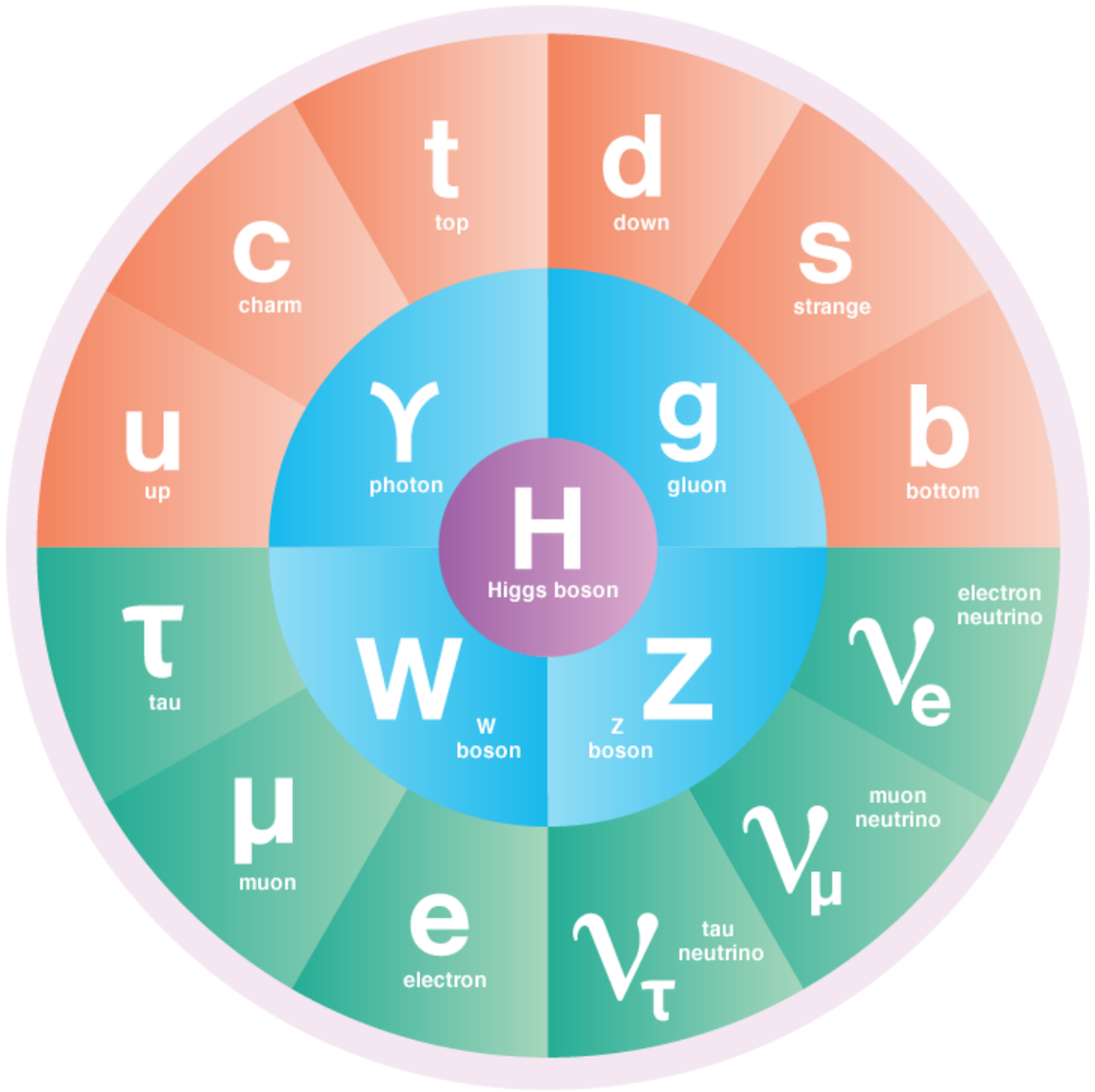




The future 2022



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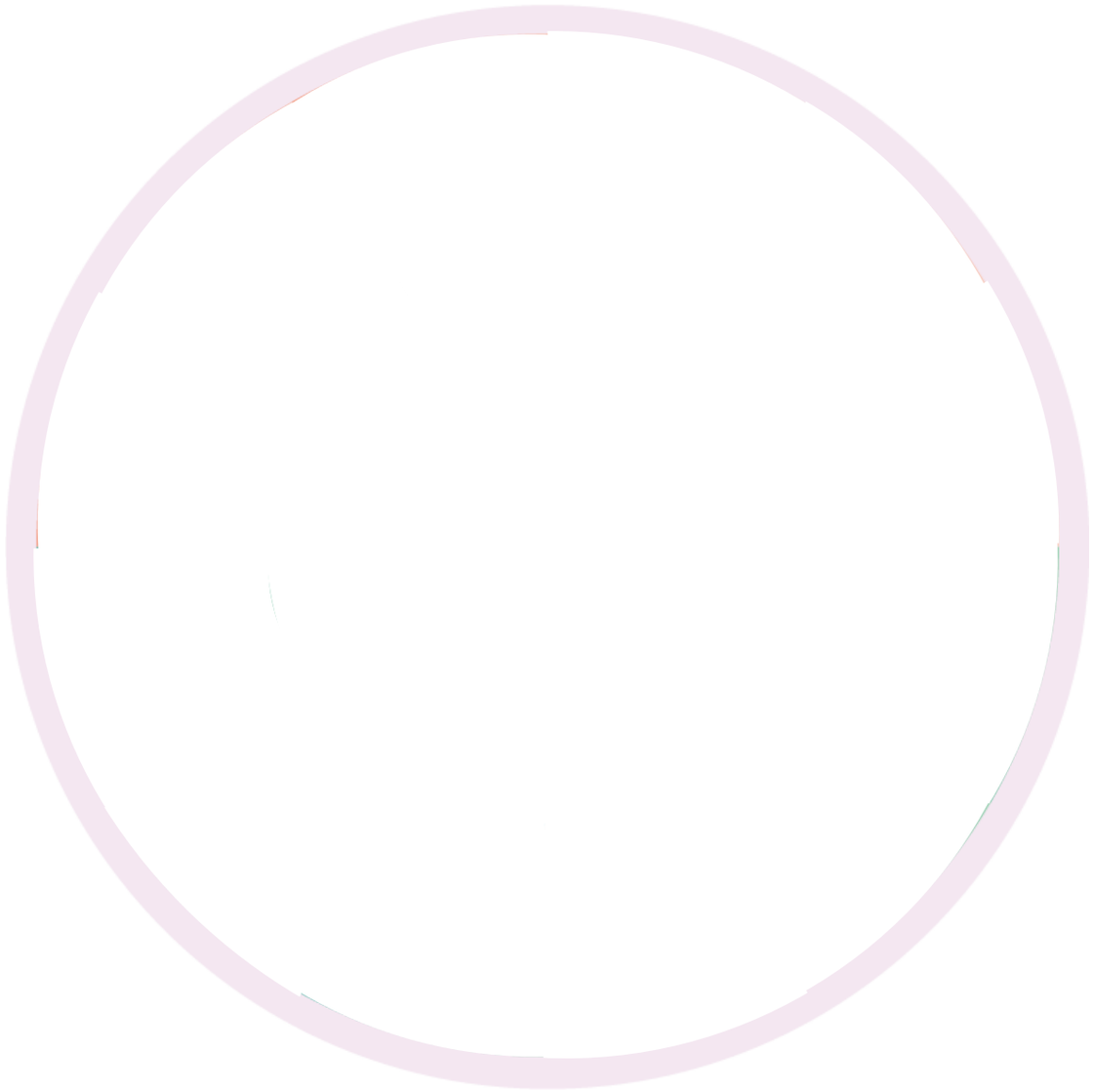
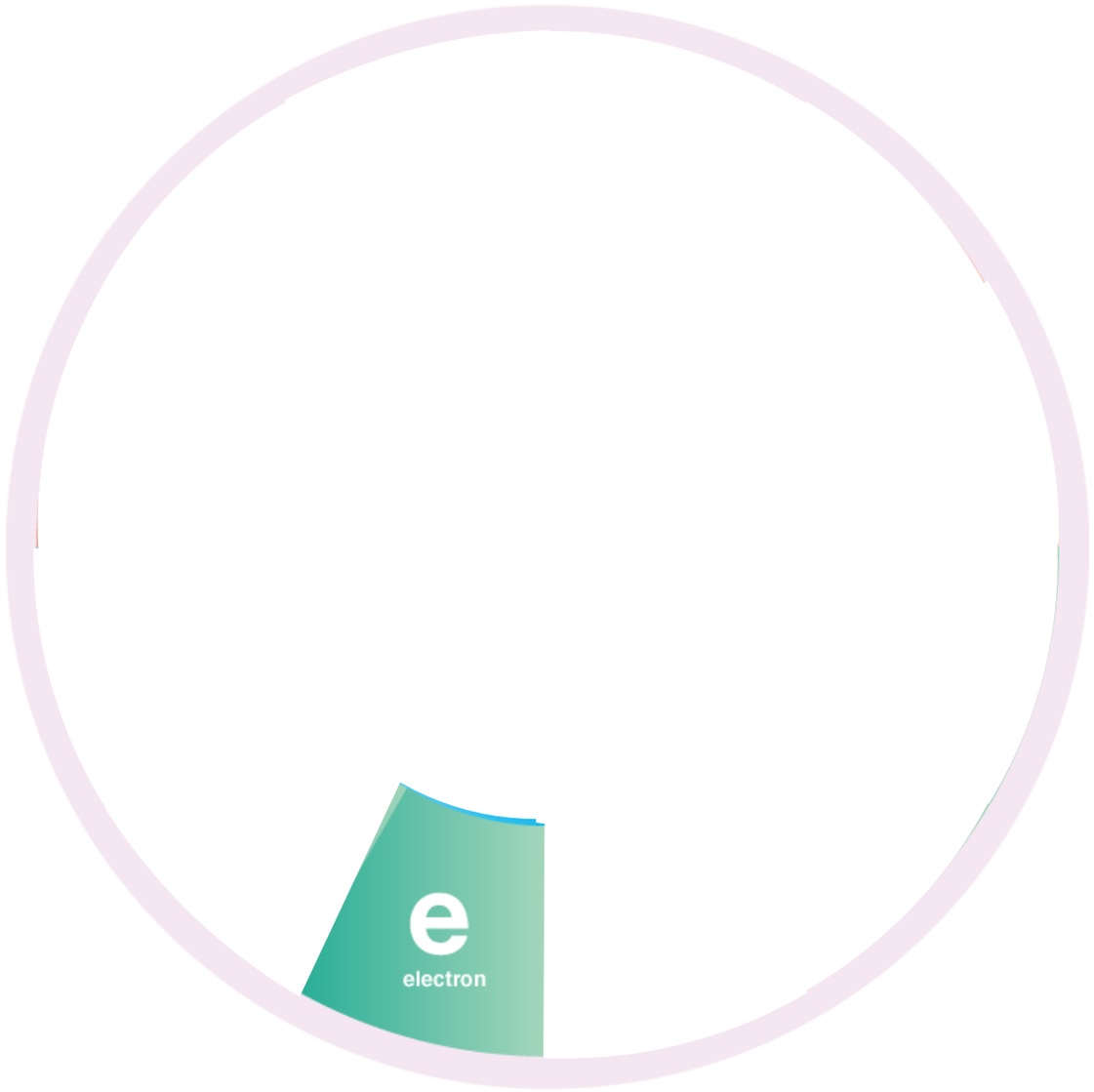
The past



Electron



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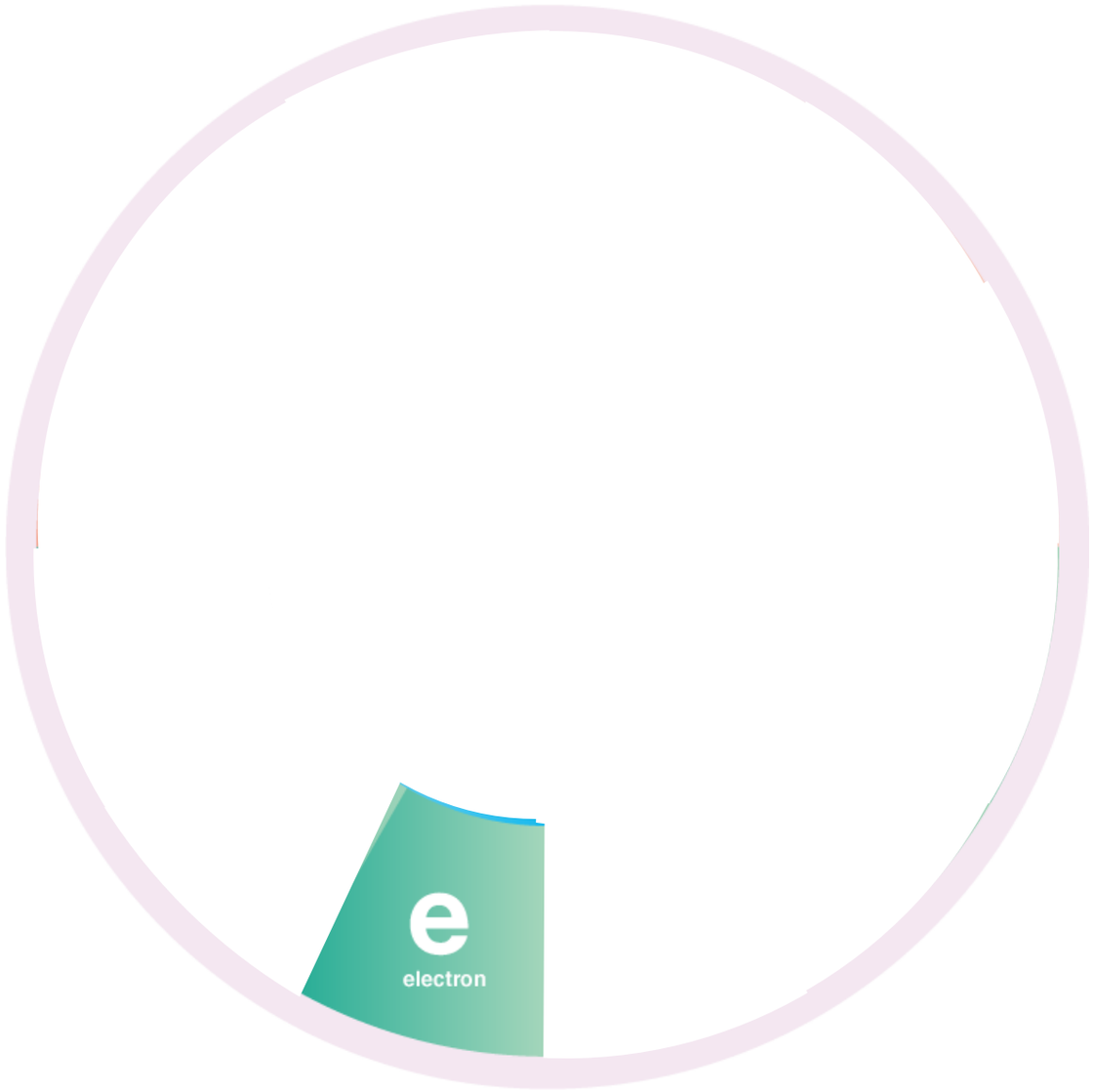

1897 Thomson

Electron

Thomson did not “see” electrons.

Electron

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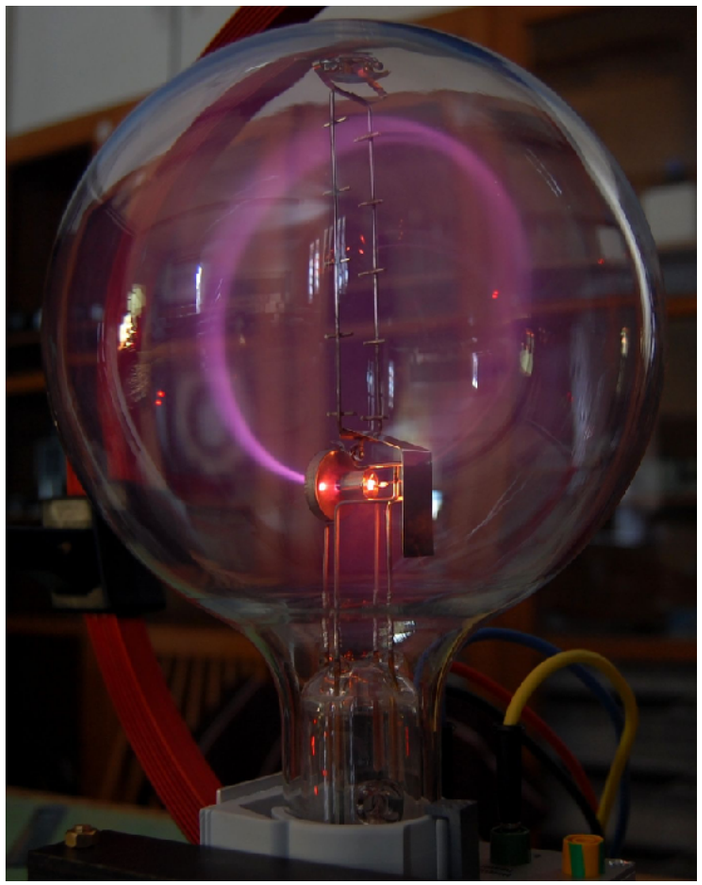
He understood what cathode rays are.



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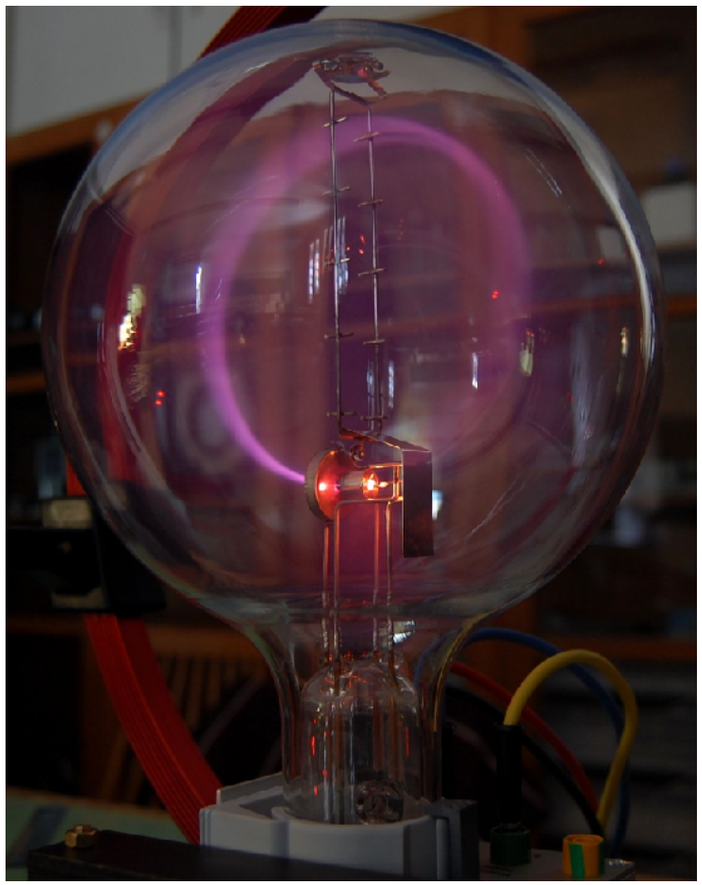

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Electron

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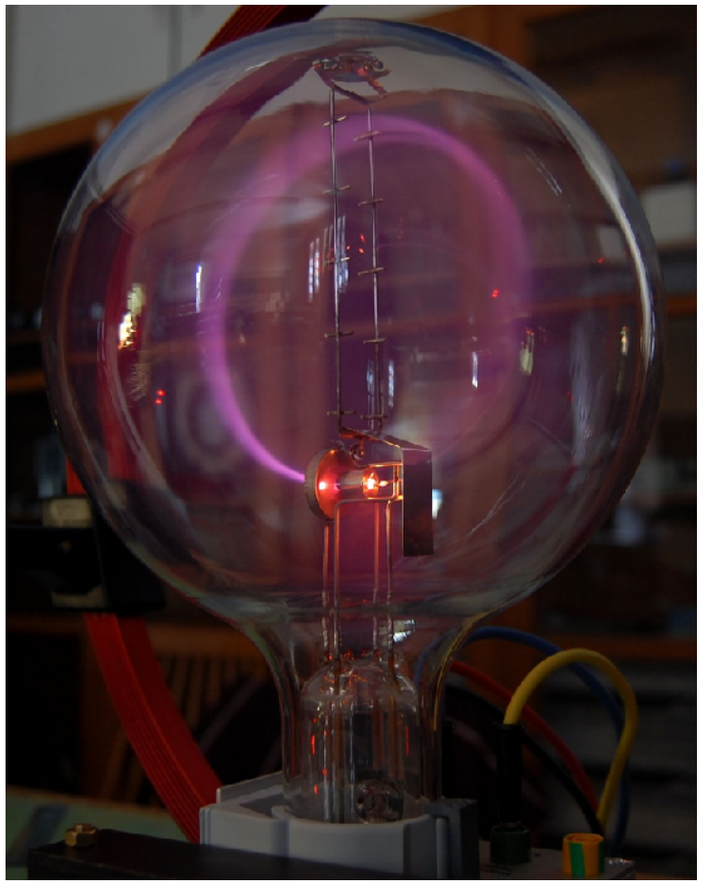

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

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

Atoms

500 BC: Democritus

ca. 1810: Dalton

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Atoms

500 BC: Democritus

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→ classical particle: discrete and localizable

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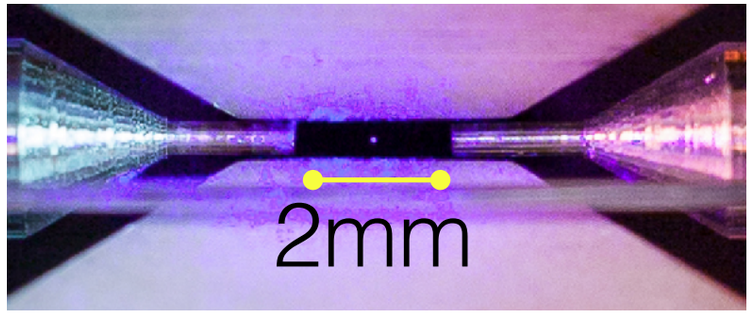
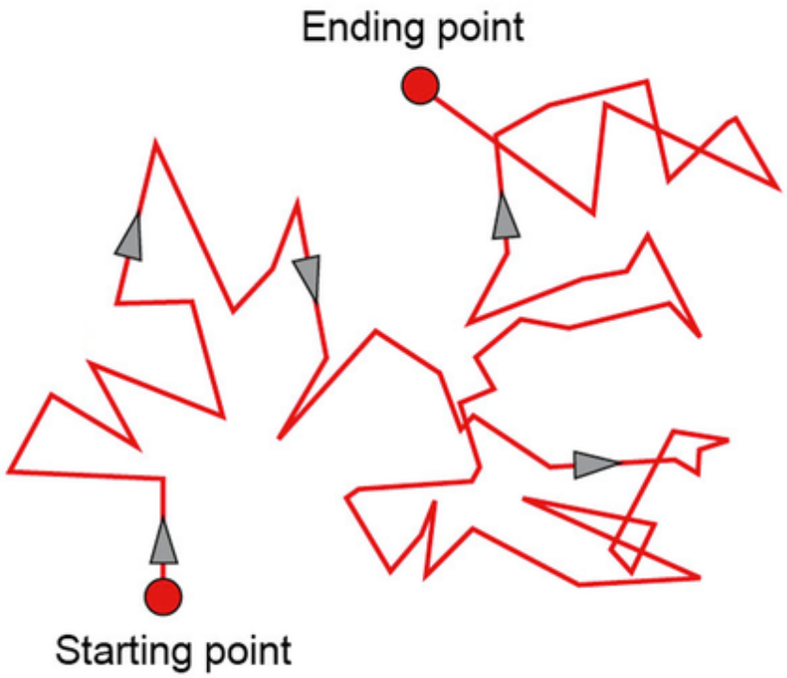


Nadlinger 2018

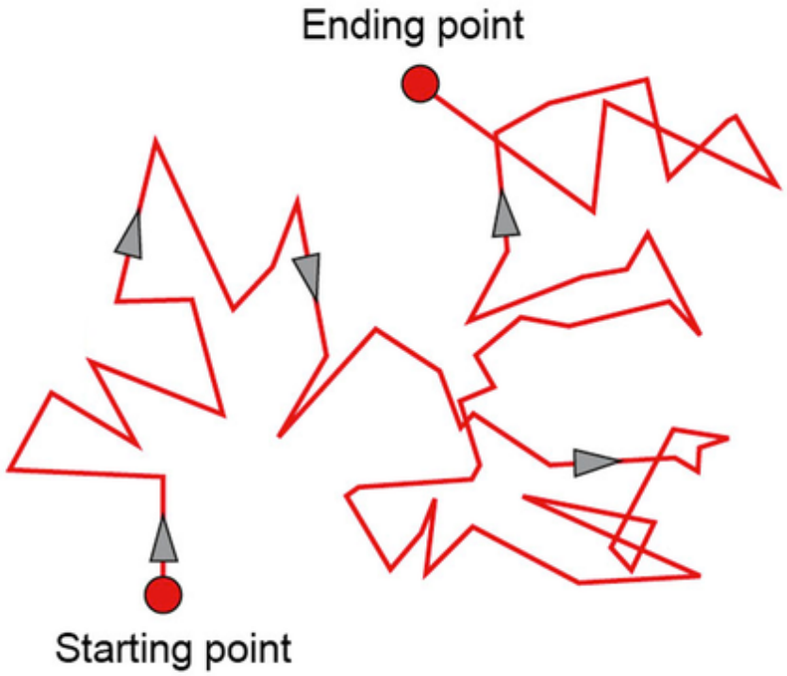
https://qz.com/1205279/photo-of-an-atom-a-scientist-captured-an-incredible-photograph/

Observing atoms

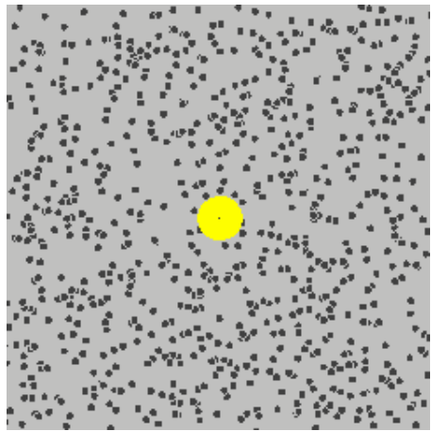


Brown 1827

Observing atoms

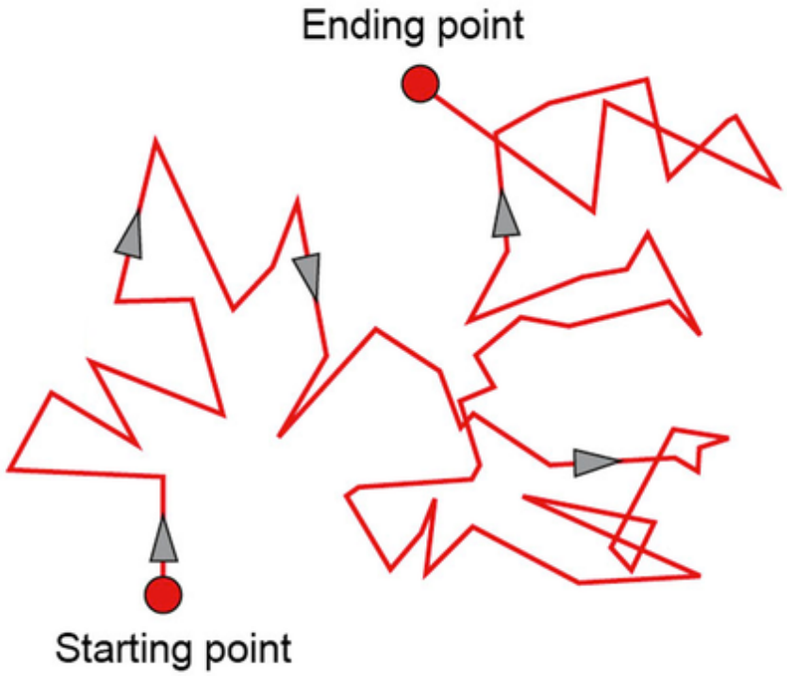


Brown 1827



Einstein 1905

Observing atoms



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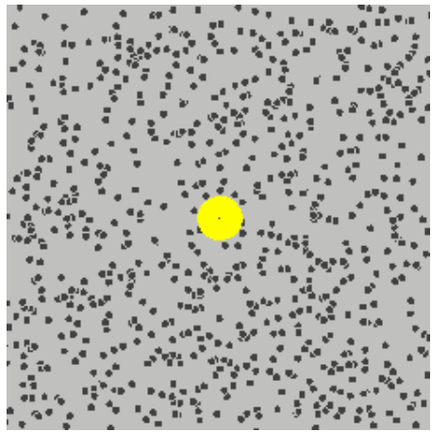
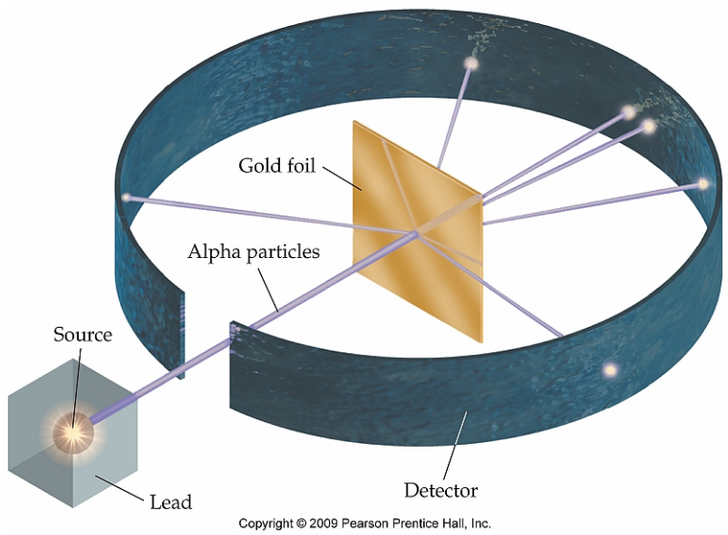
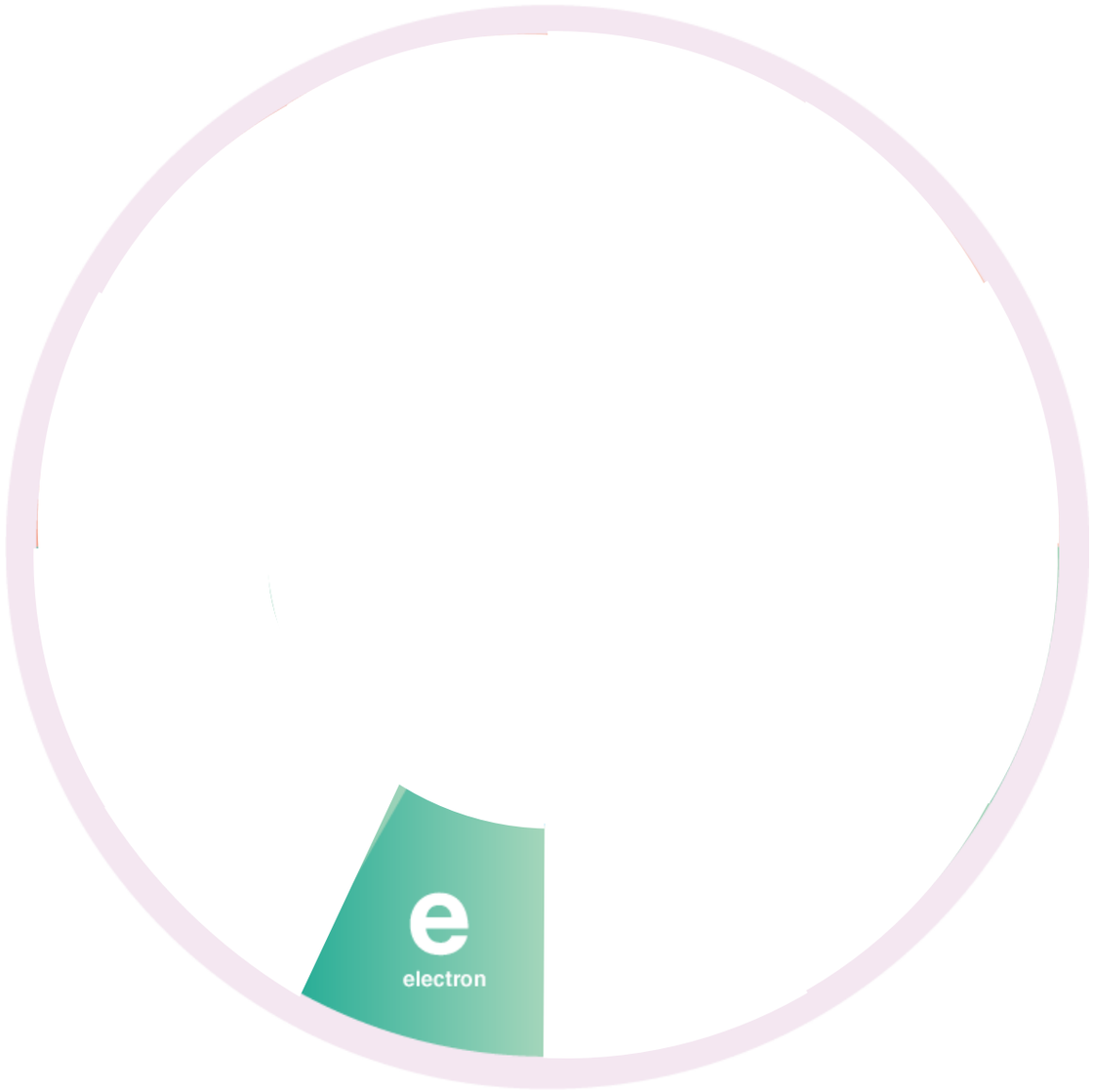


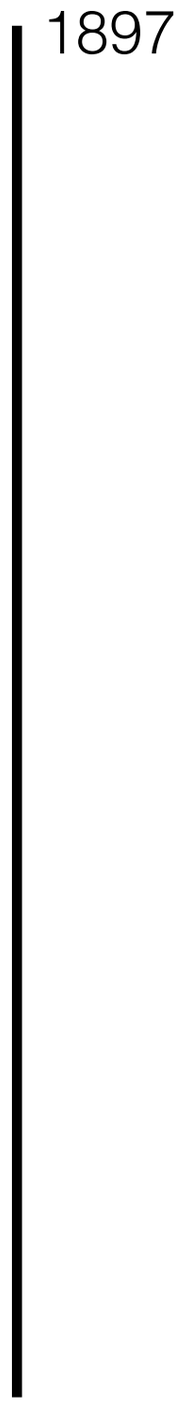
Einstein 1905



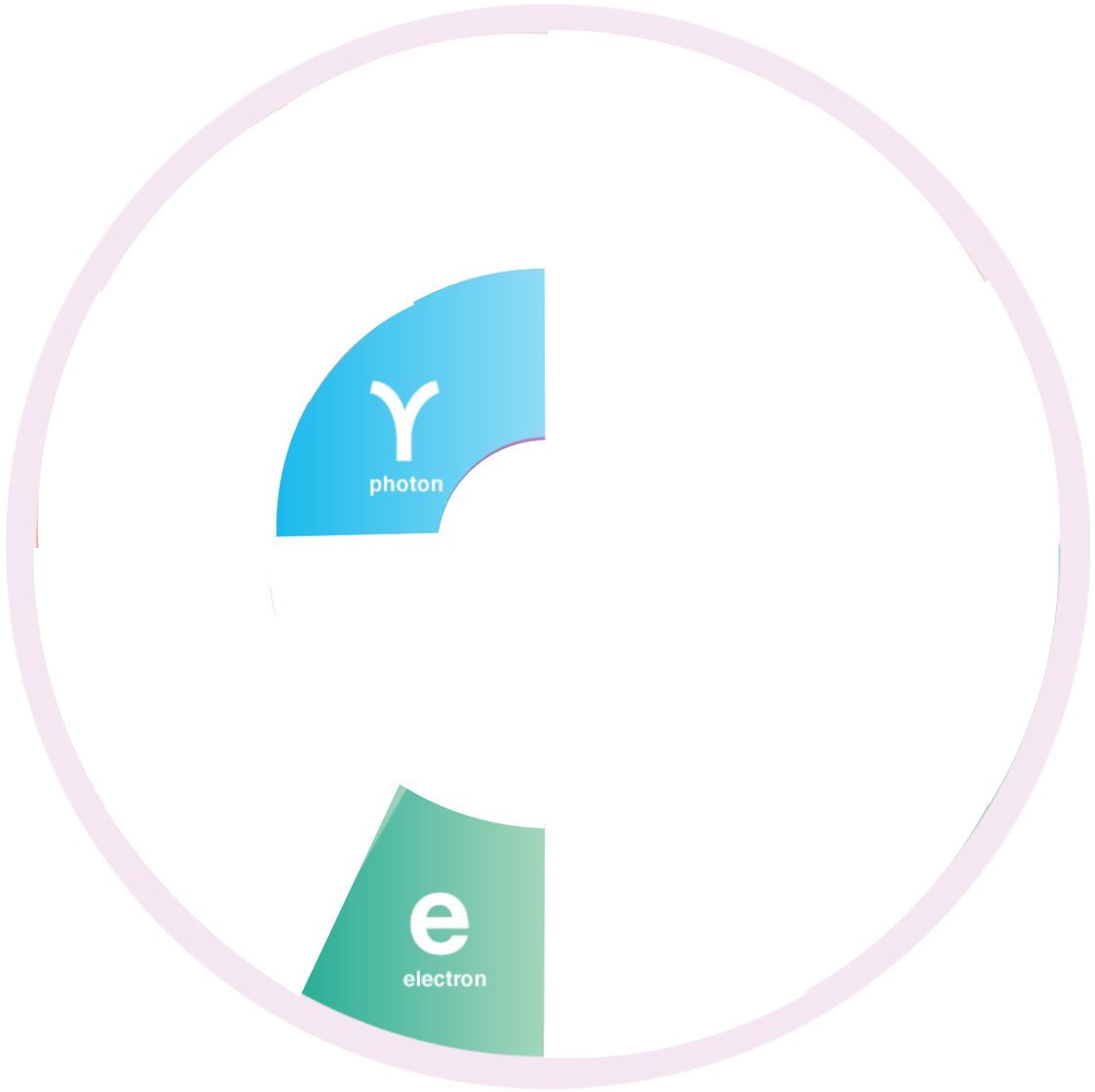
Rutherford 1909
Geiger, Marsden

Photon



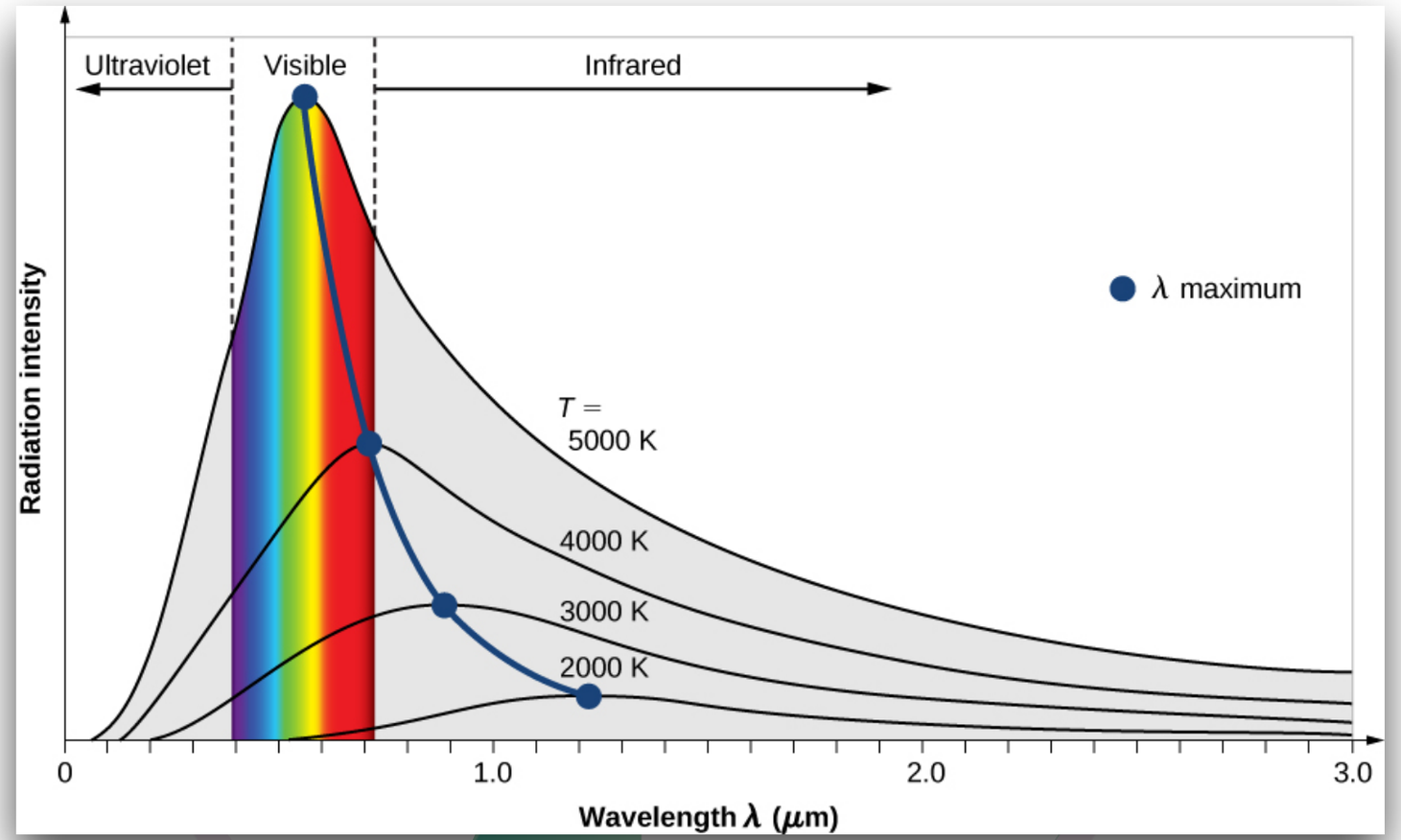


Photon



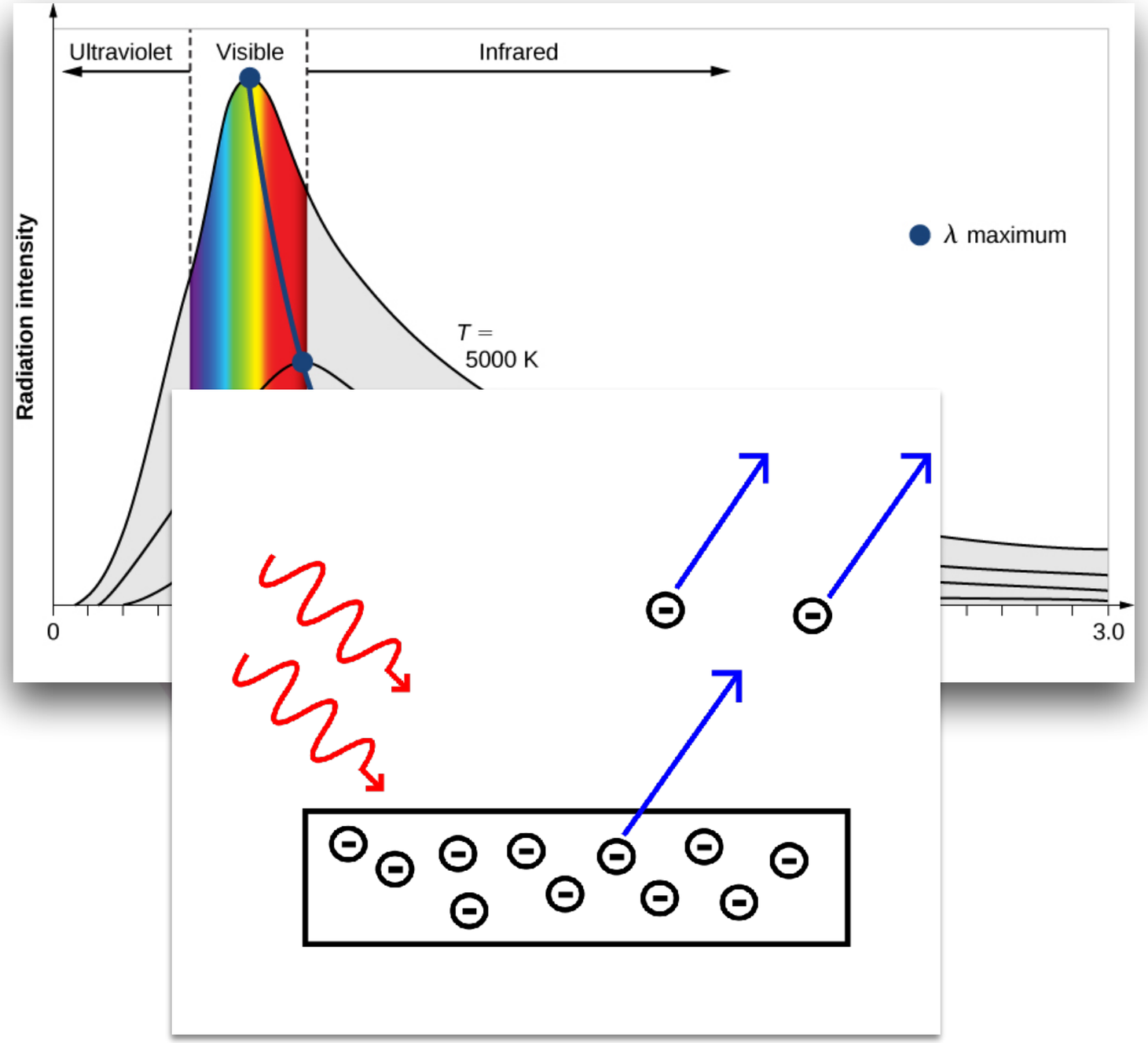
1897

Photon



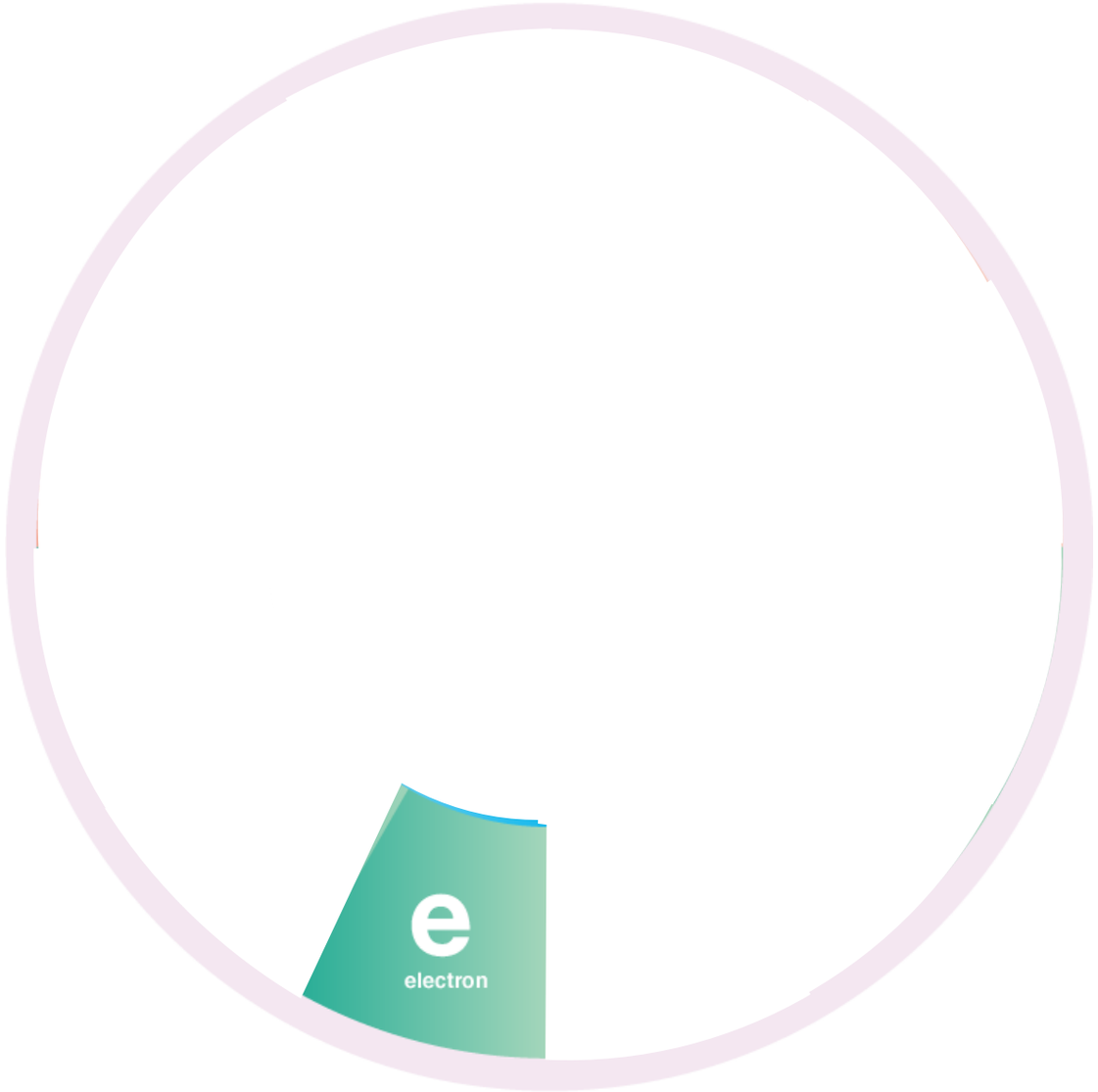
1897
1900 Planck

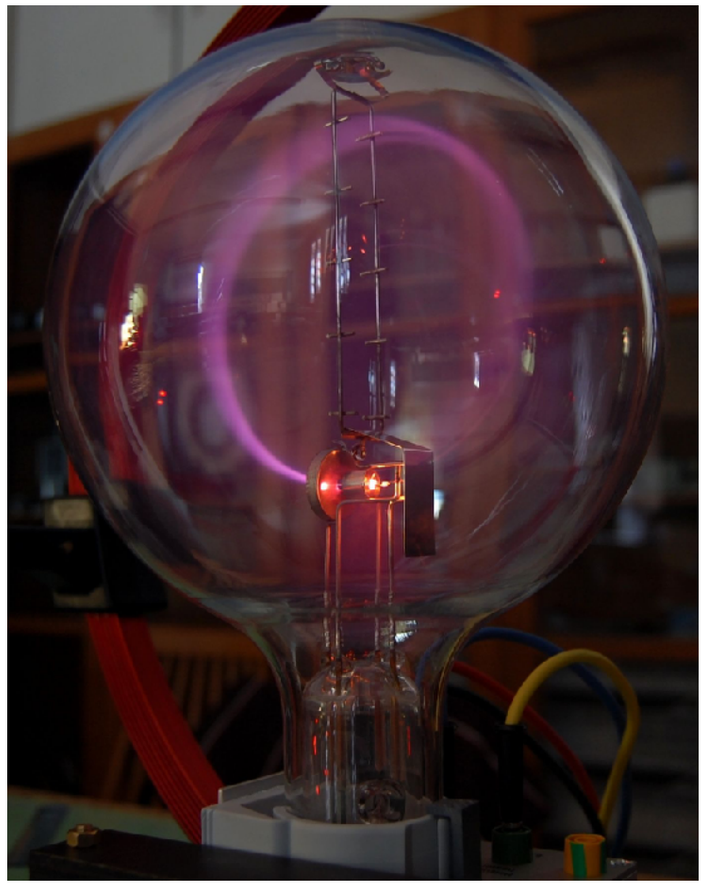
Photon



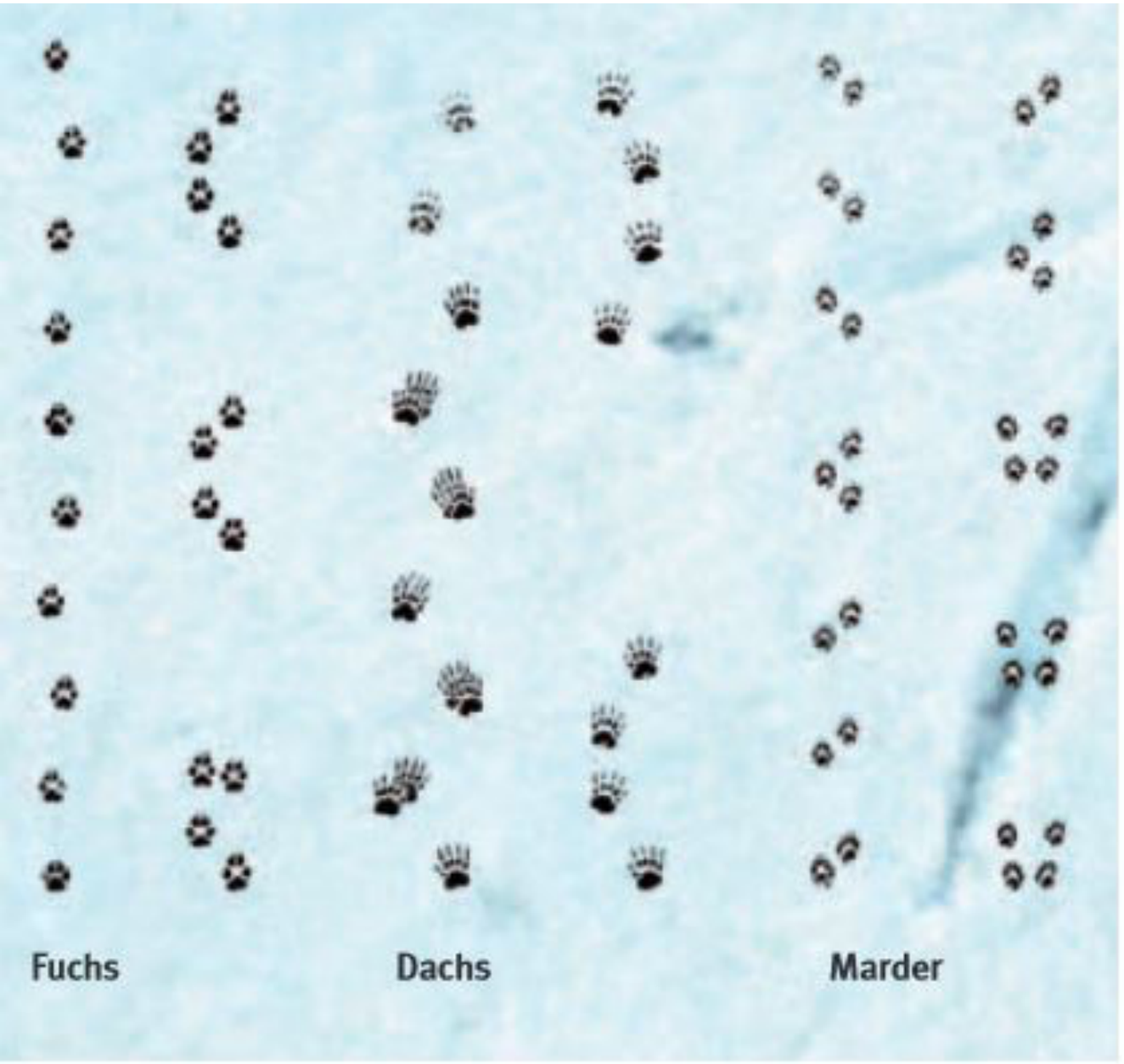
1897
1900 Planck
1905 Einstein

Electron

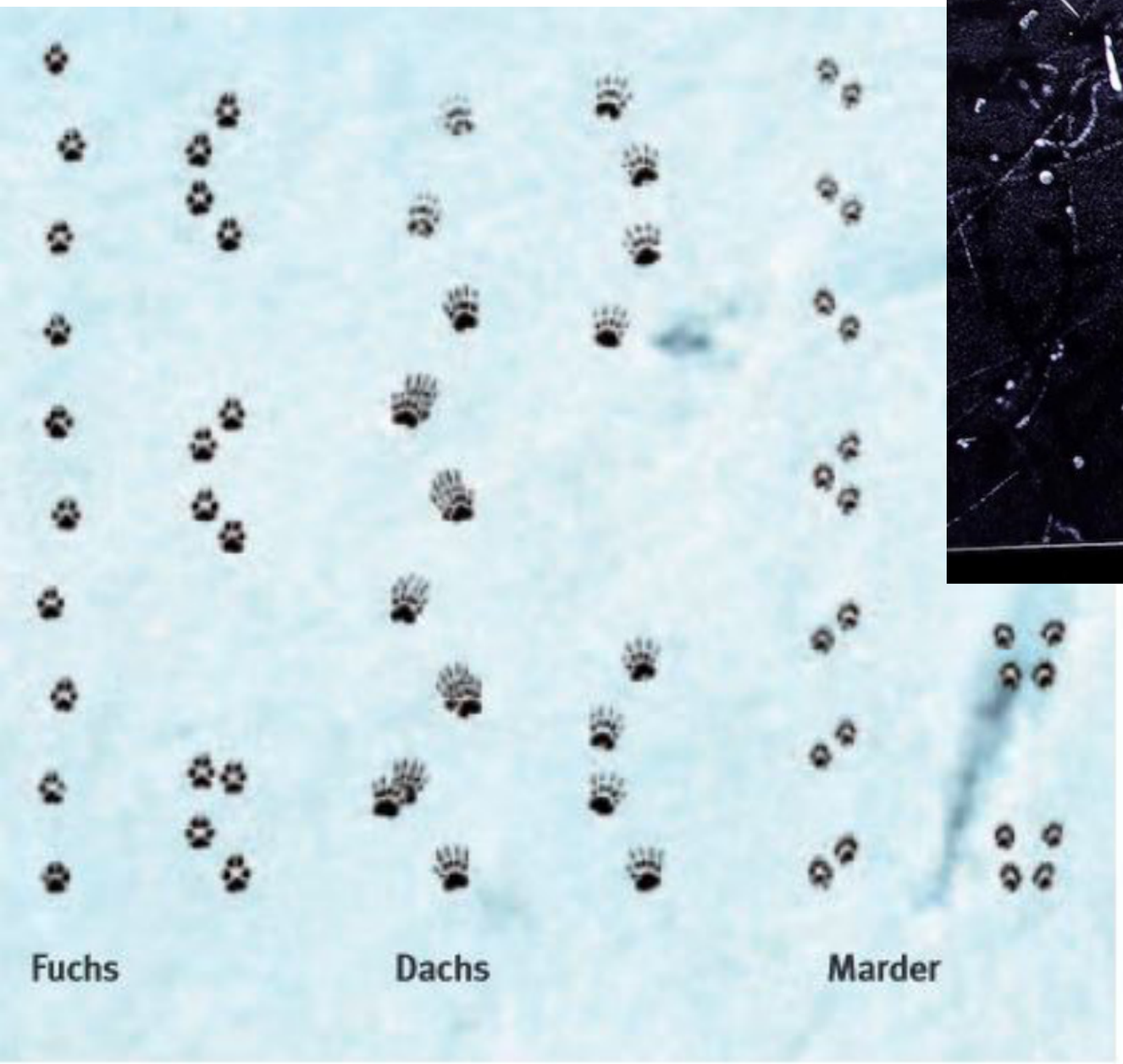




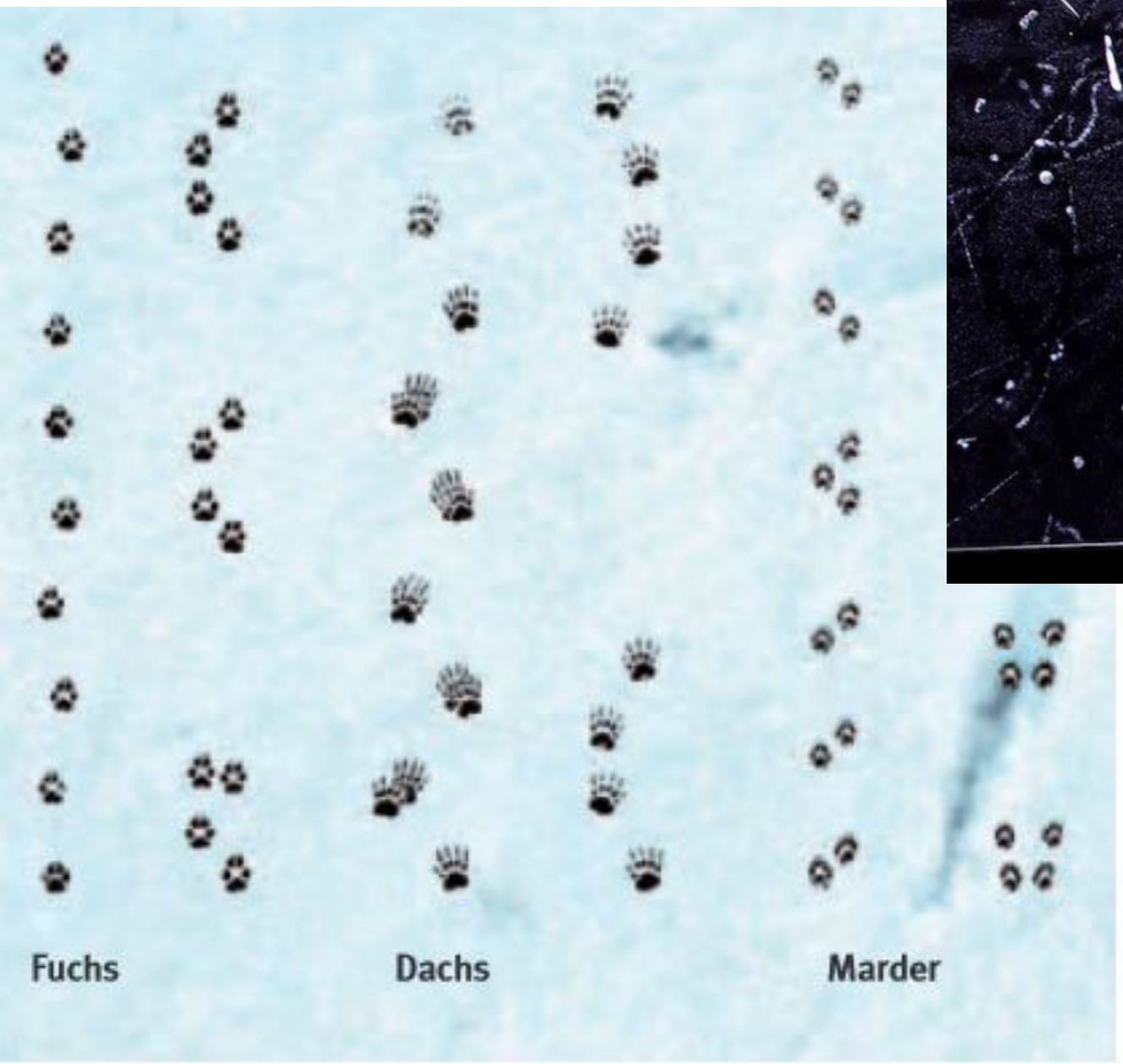
Tracks

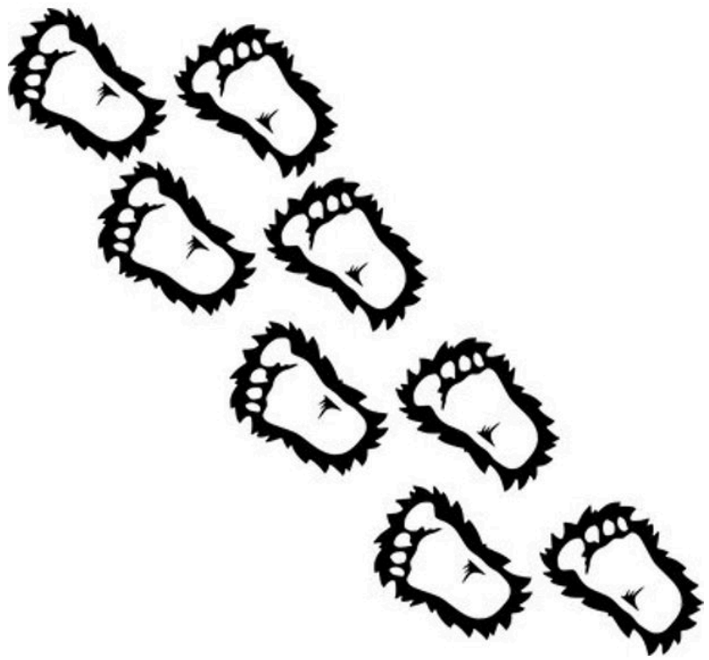


Tracks



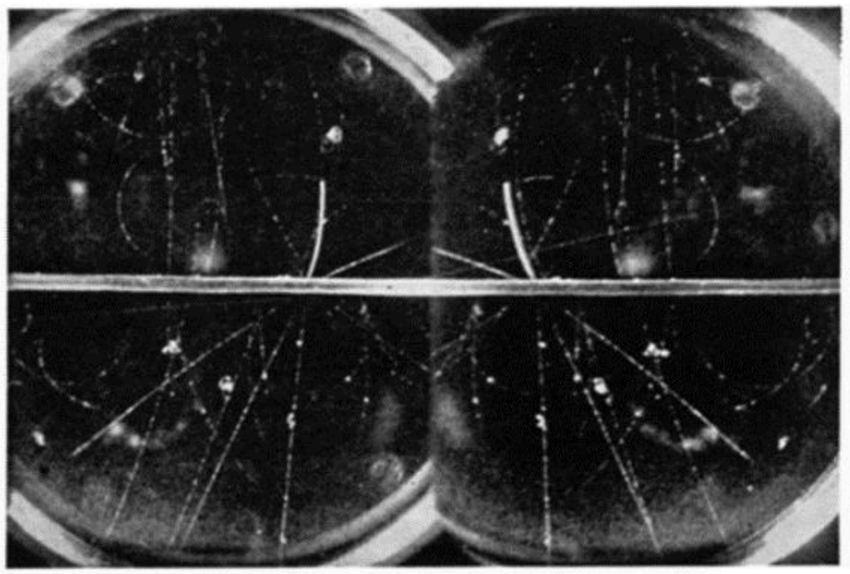
Tracks





Muon

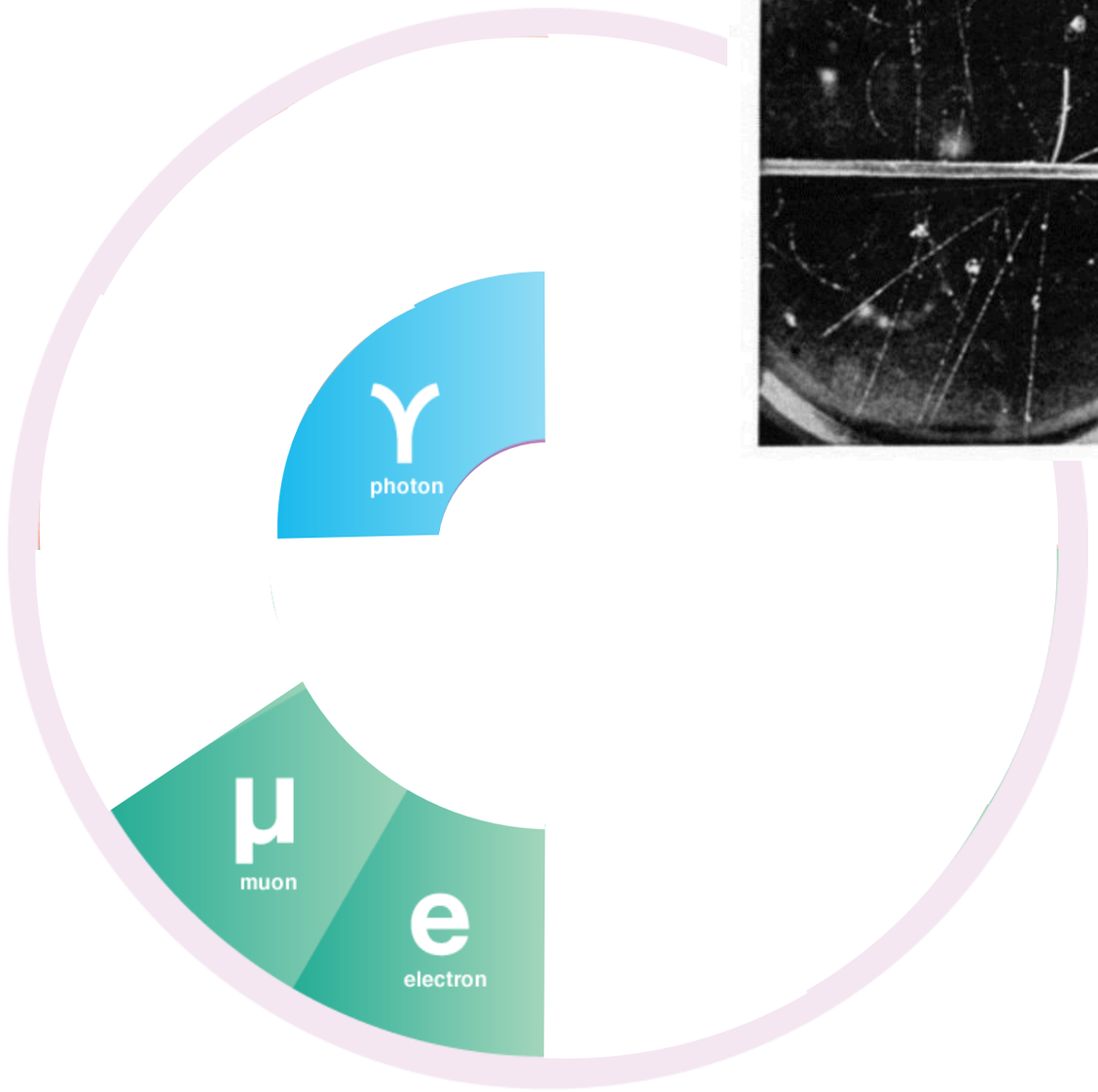
Unusual tracks

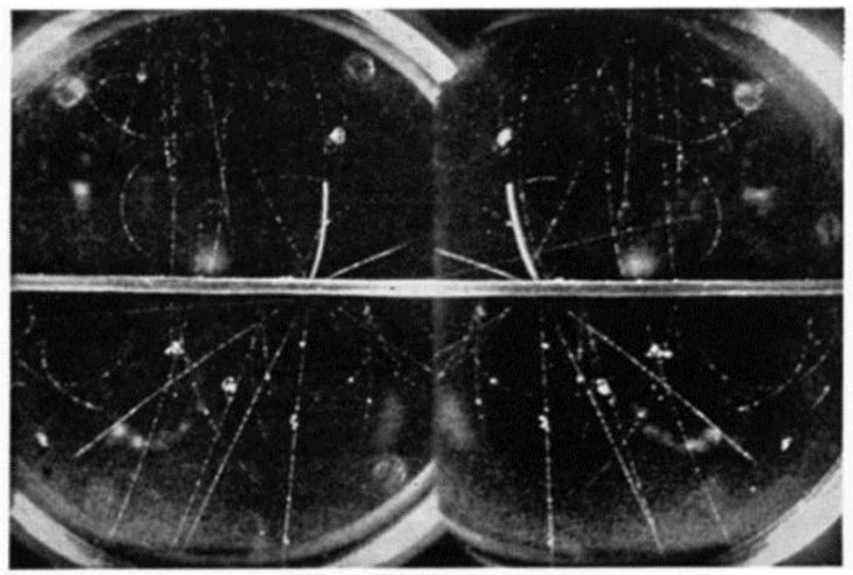


1897
1900

Muon

Unusual tracks

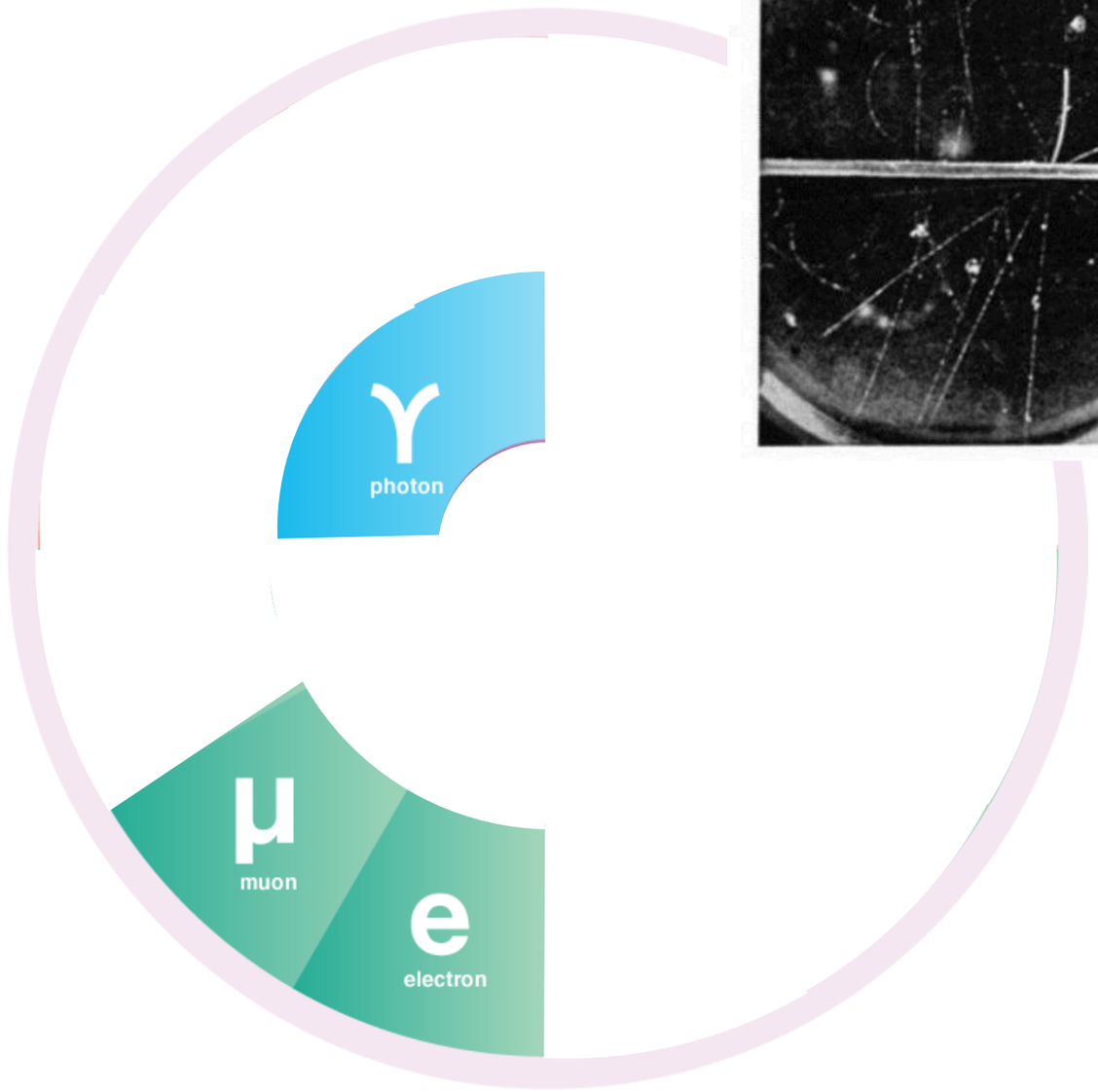


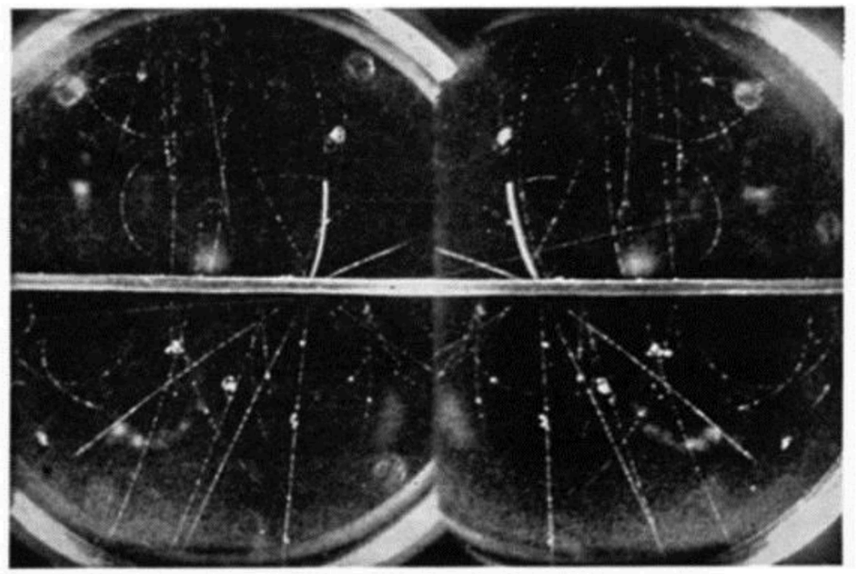


1897
1900

Muon

Unusual tracks

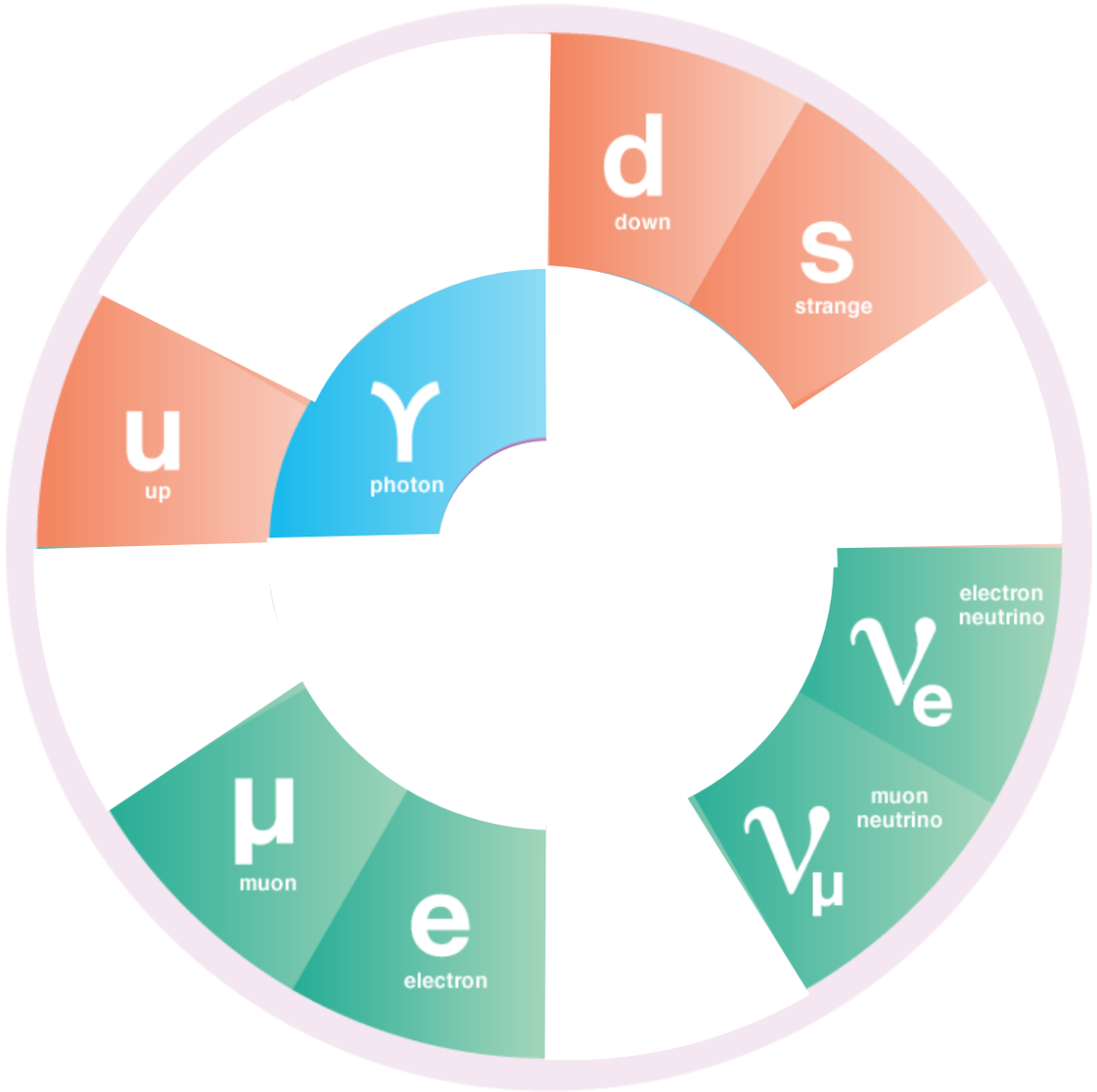




1897
1900

1937 Neddermeyer + Anderson

Quarks



1897
1900
1937
1956
1962

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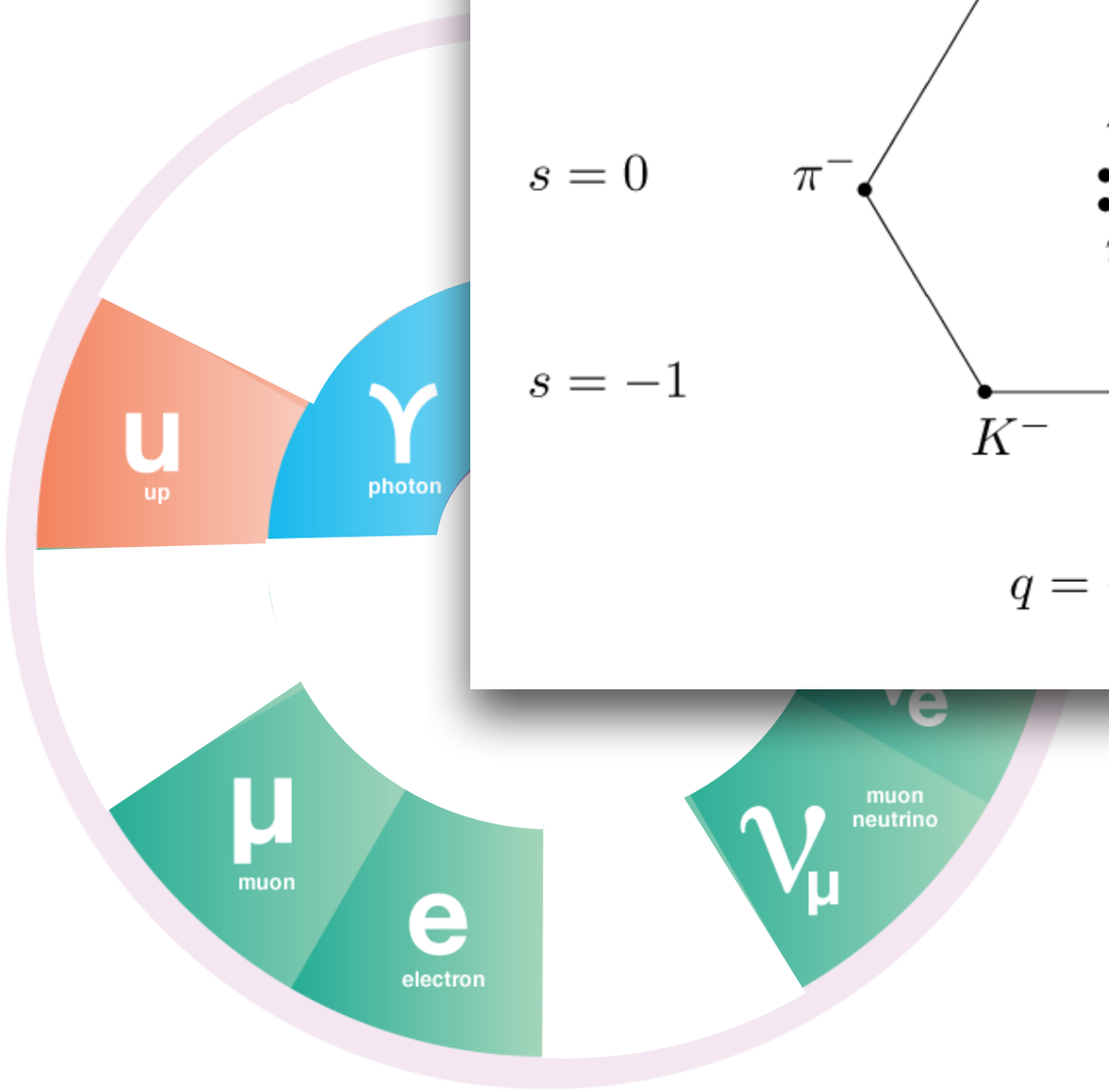
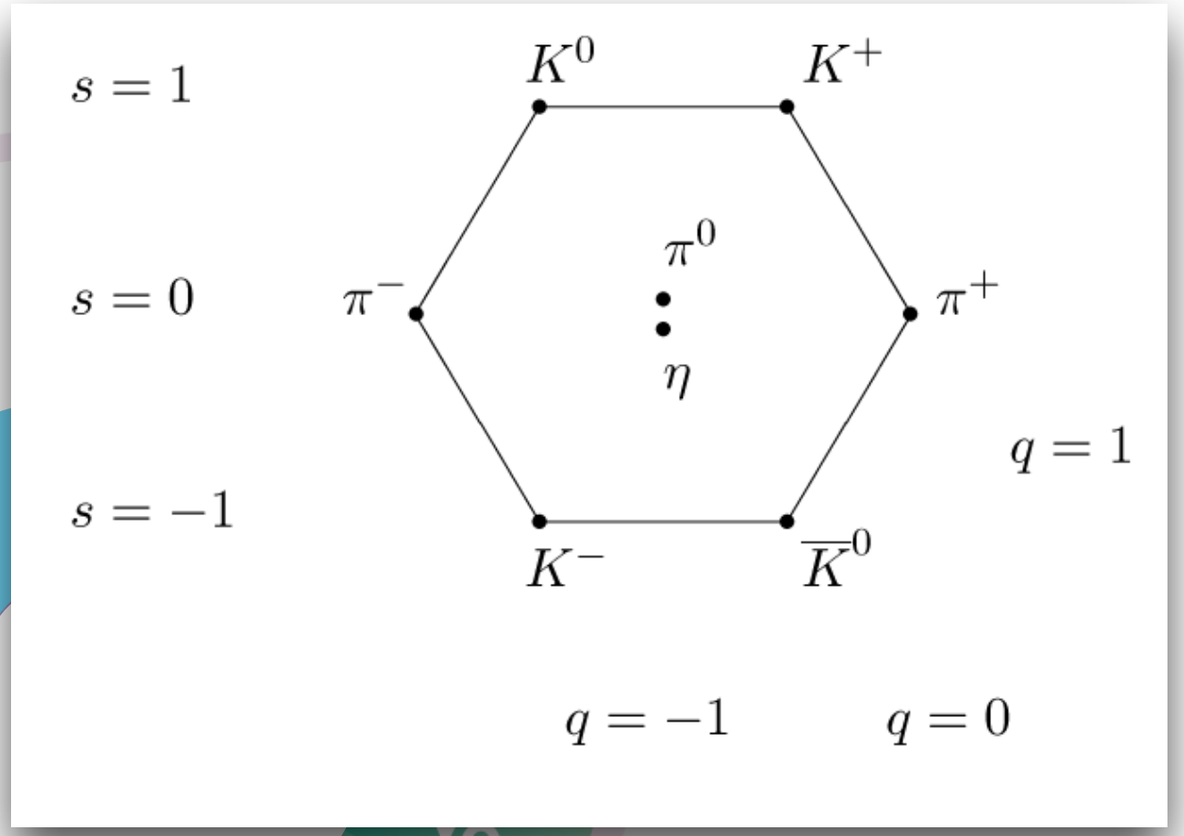
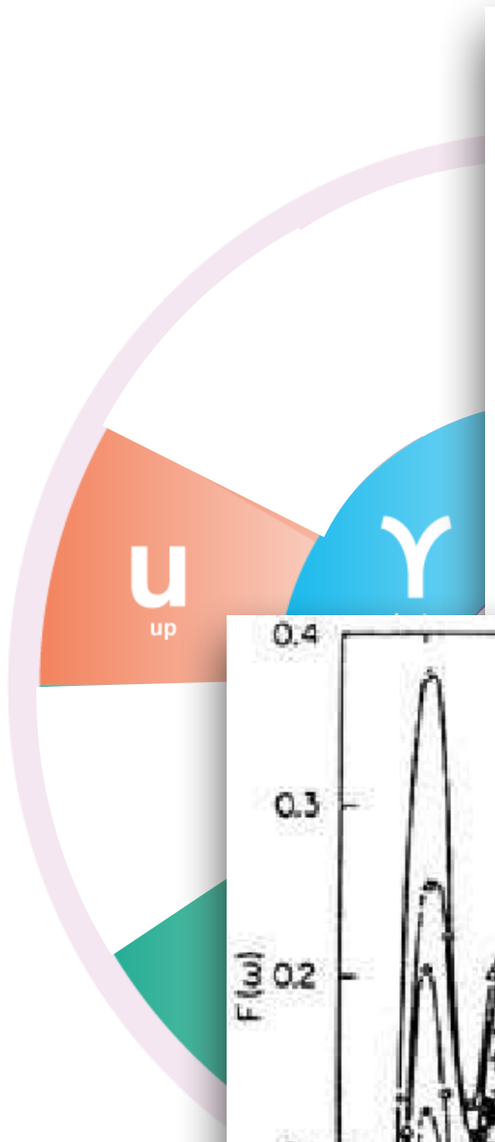
Quarks

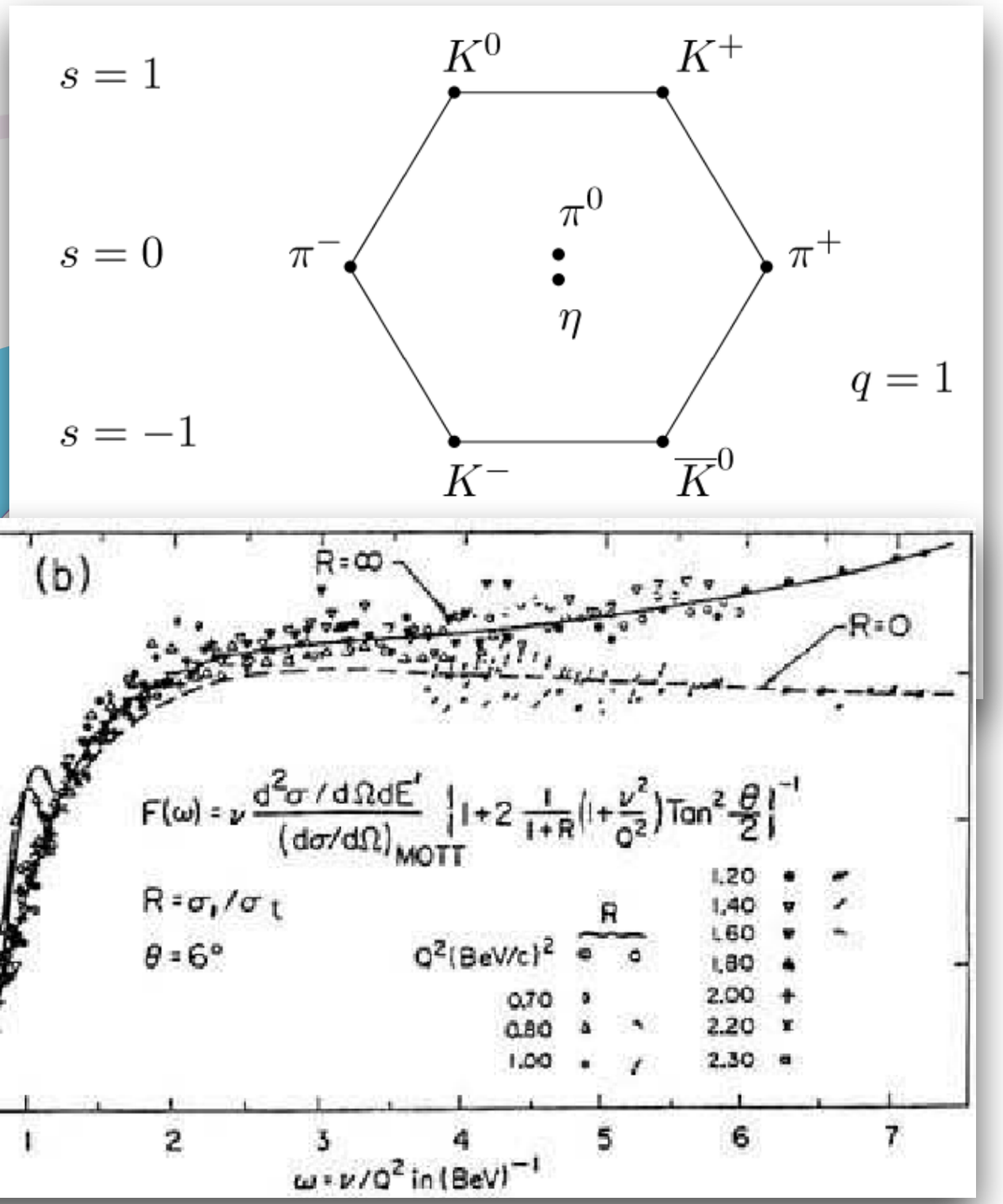




1897
1900
1937
1956
1962
1964 Gell-Mann Zweig

Quarks





1897
1900

1937

1956
1962
1964 Gell-Mann
Zweig
1969 Bjorken
Feynman

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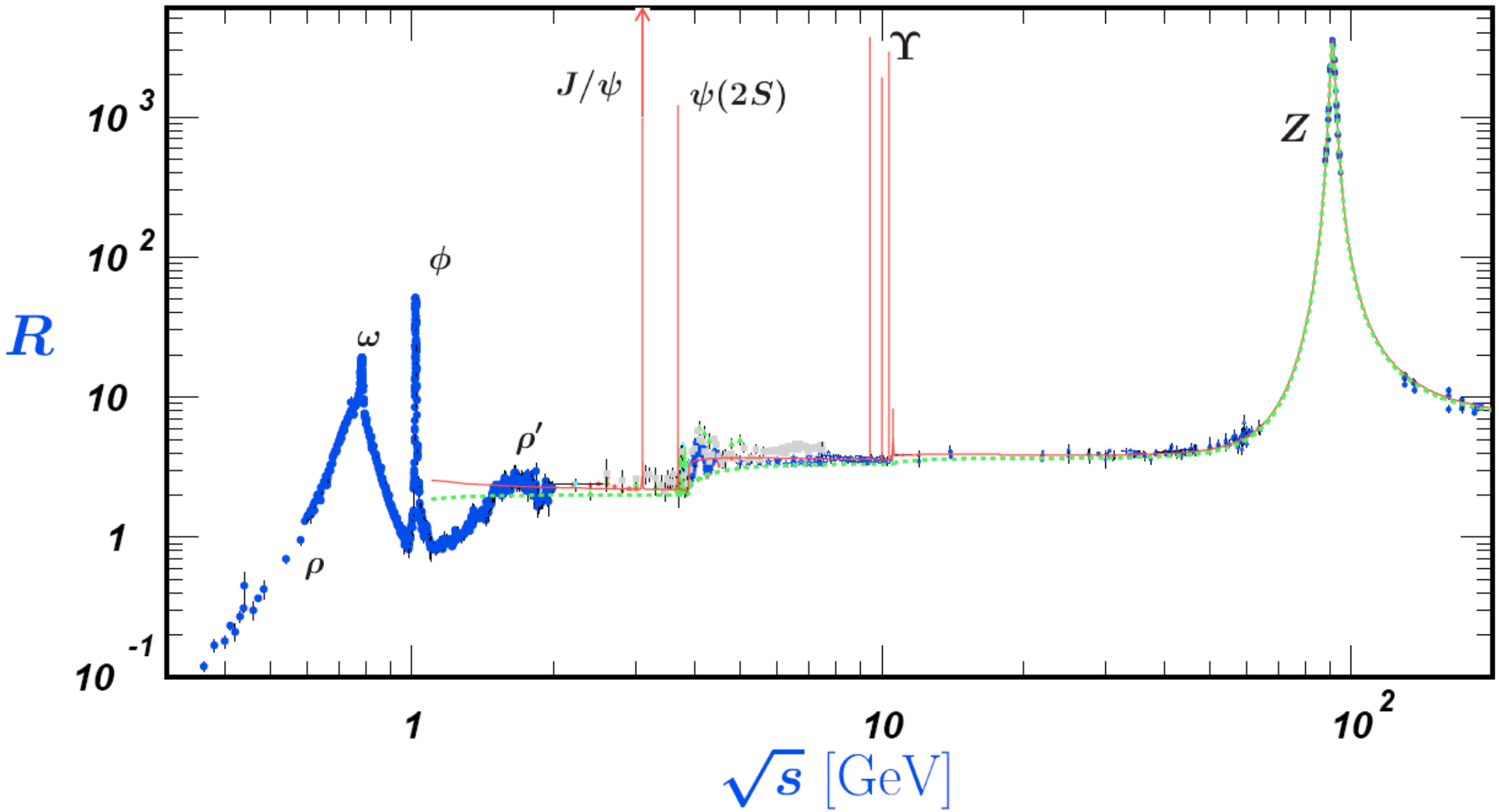
Resonances


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

Top quark

1900 1897

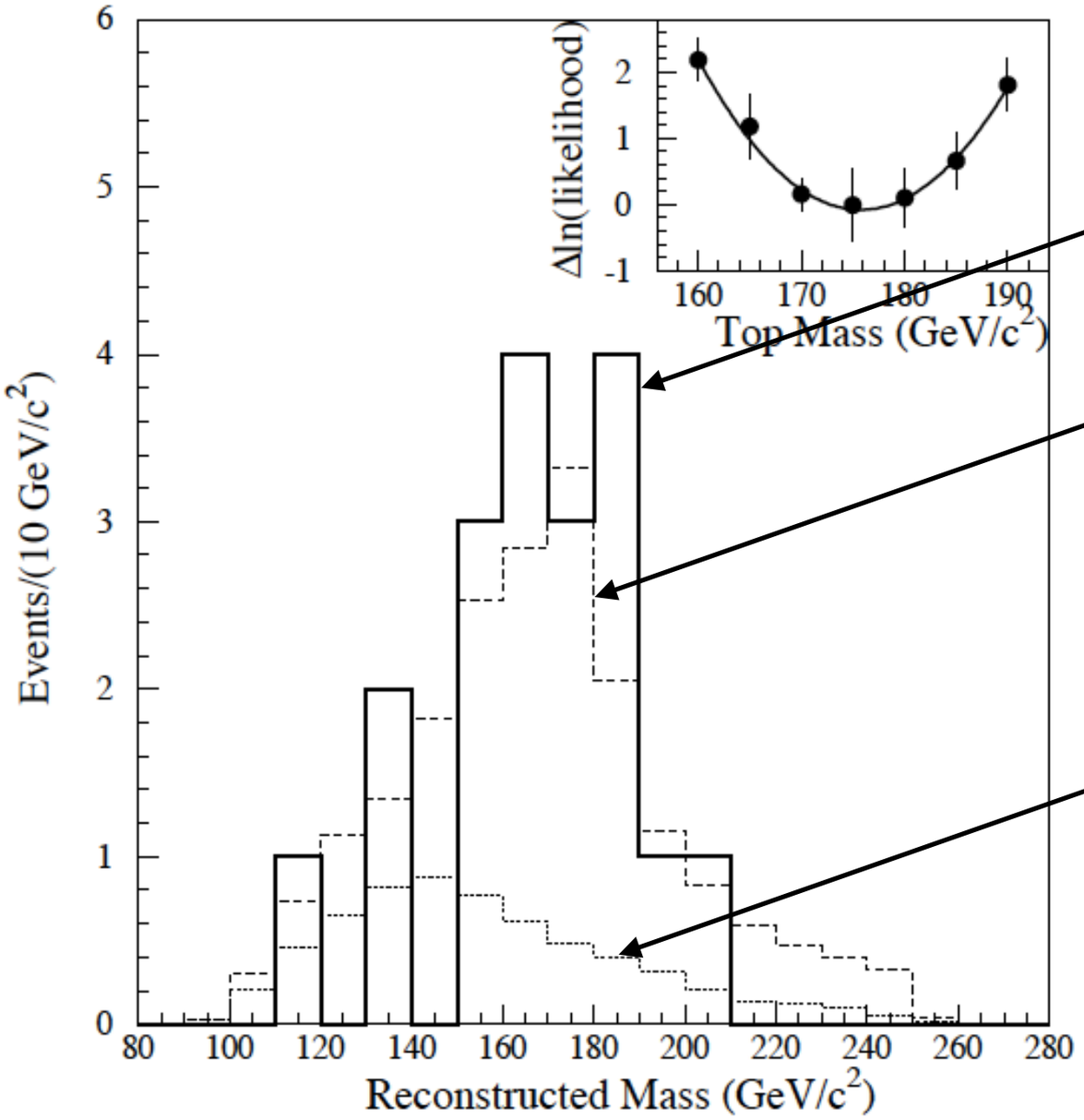
1937

1956
1962

1969
1975 1974
1979 1977
1983

1995 CDF
D0

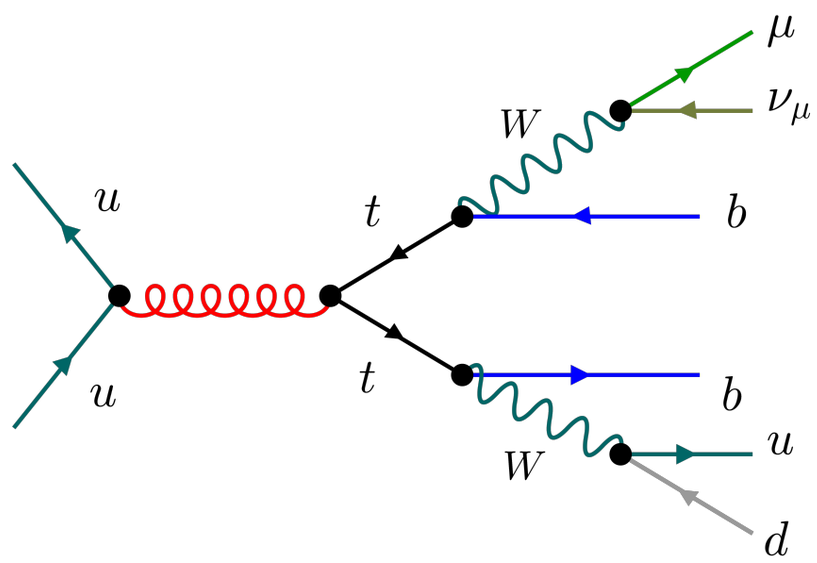
Top quark



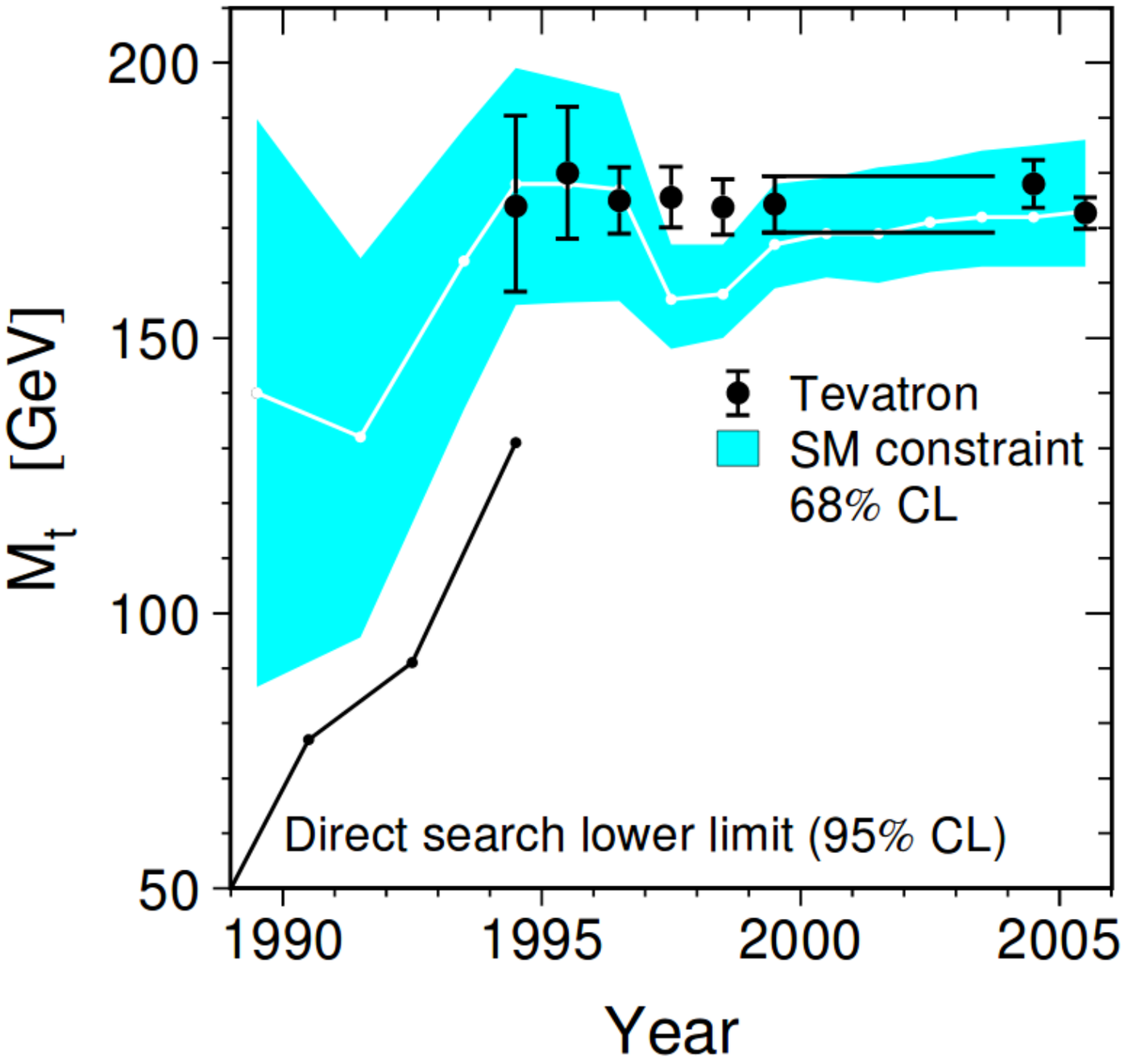
"observation"

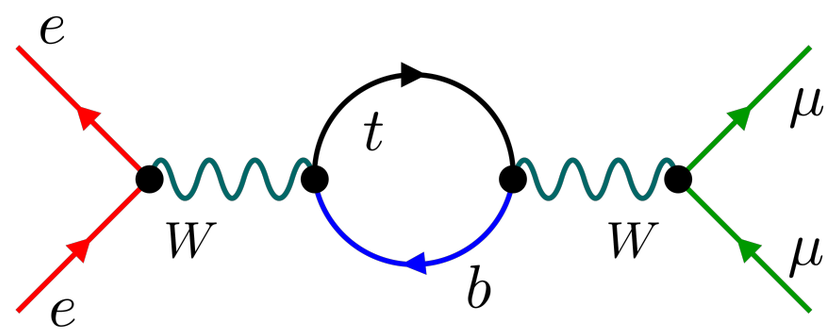
expected BG
+ signal

background

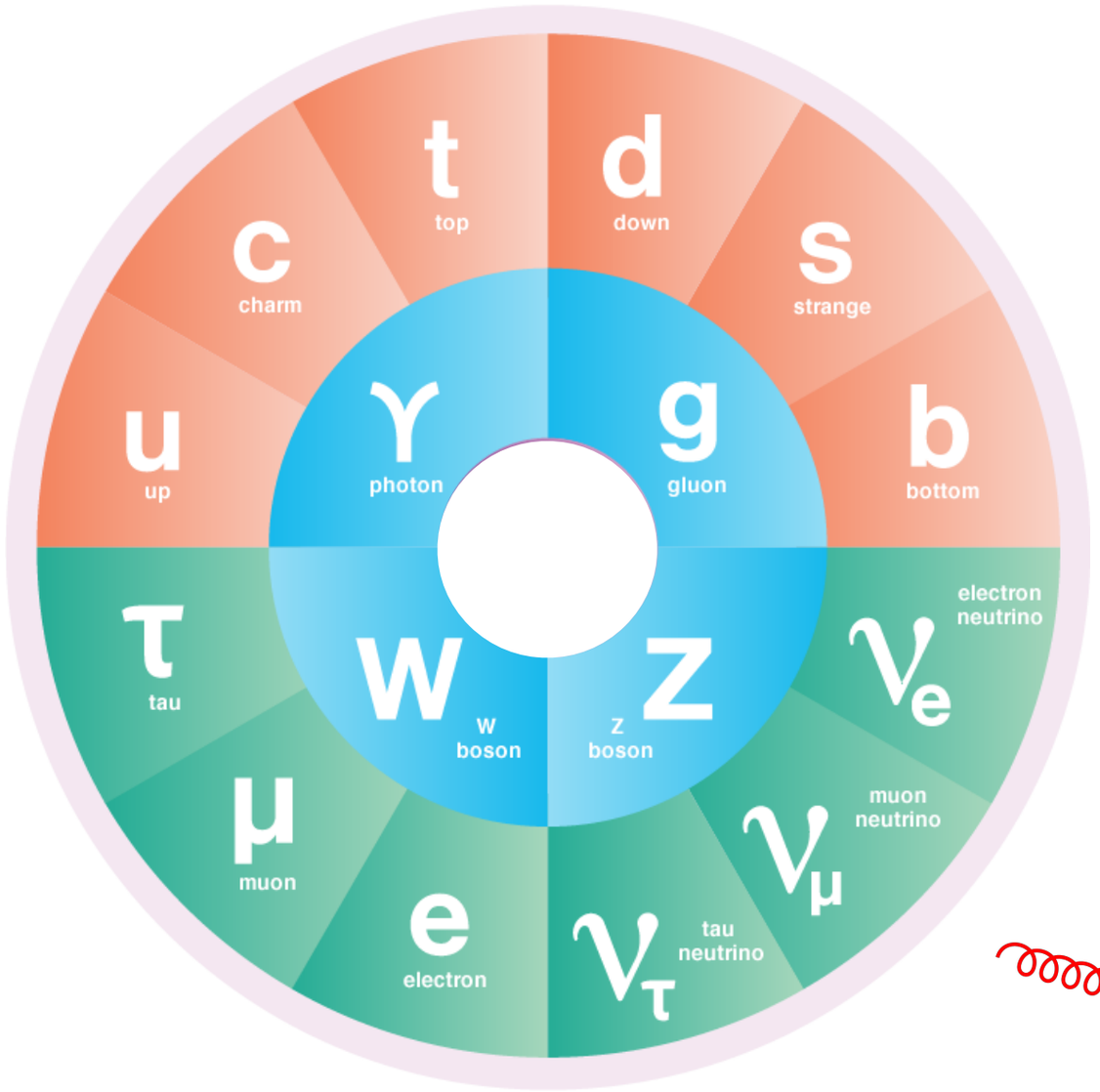


Top quark


200
150
100
50
M_t [GeV]
Tevatron
SM constraint
68% CL
Direct search lower limit (95% CL)
1990
1995
2000
2005
Year


e
e
W
t
b
W
μ
μ

Higgs



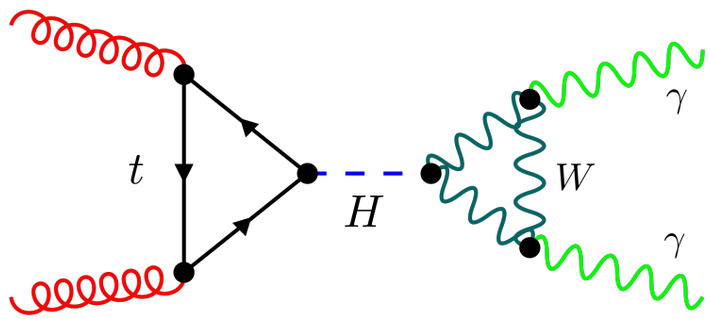
1900 1897

1937

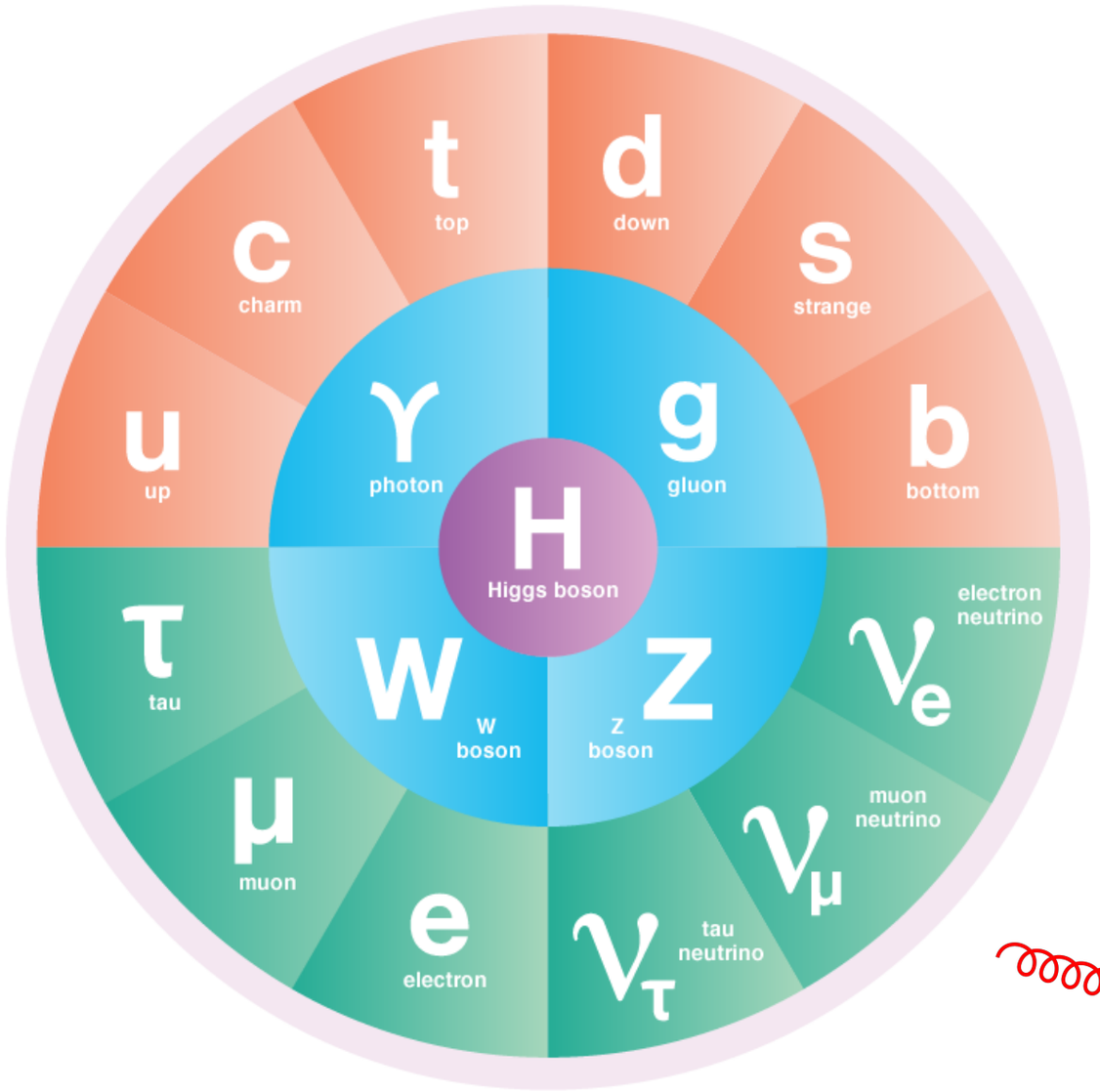
1956
1962

1969
1975 1974
1979 1977
1983

1995



Higgs



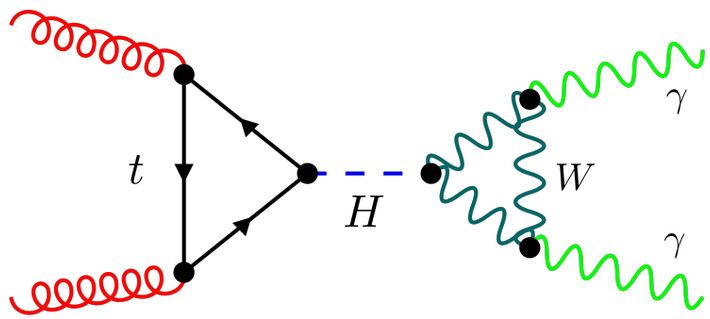
1900 1897

1937

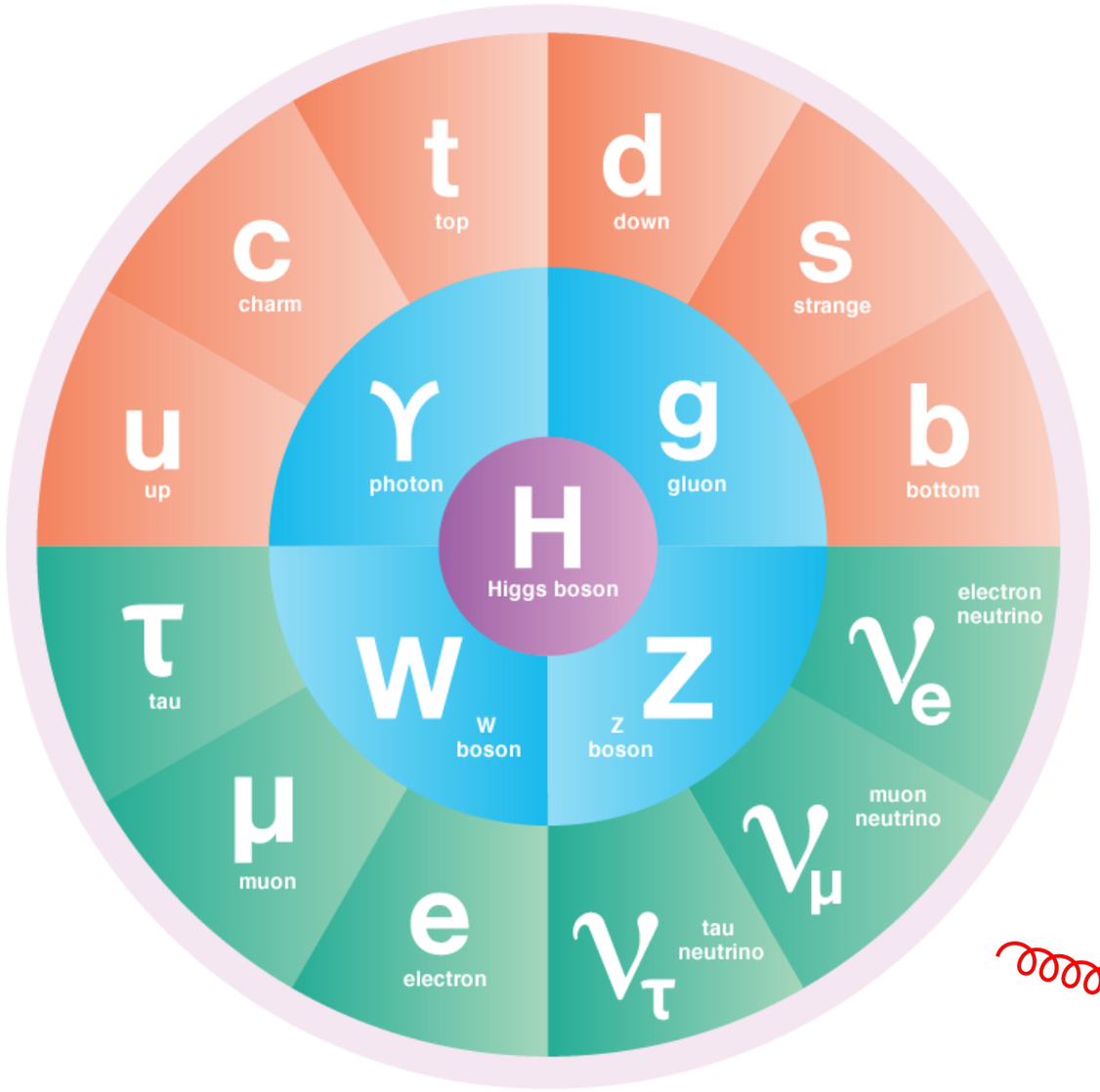
1956
1962

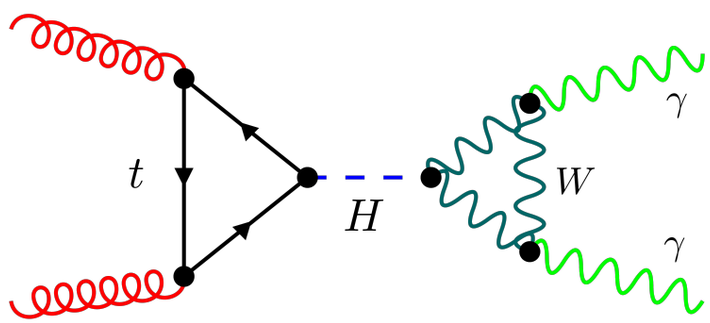
1969
1975 1974
1979 1977
1983

1995



Higgs





1900 1897

1937 Higgs
Brout+Englert

Gouralnik,
1956 +Hagen+Kibble

1962 1964

1969
1975 1974
1979 1977
1983

1995

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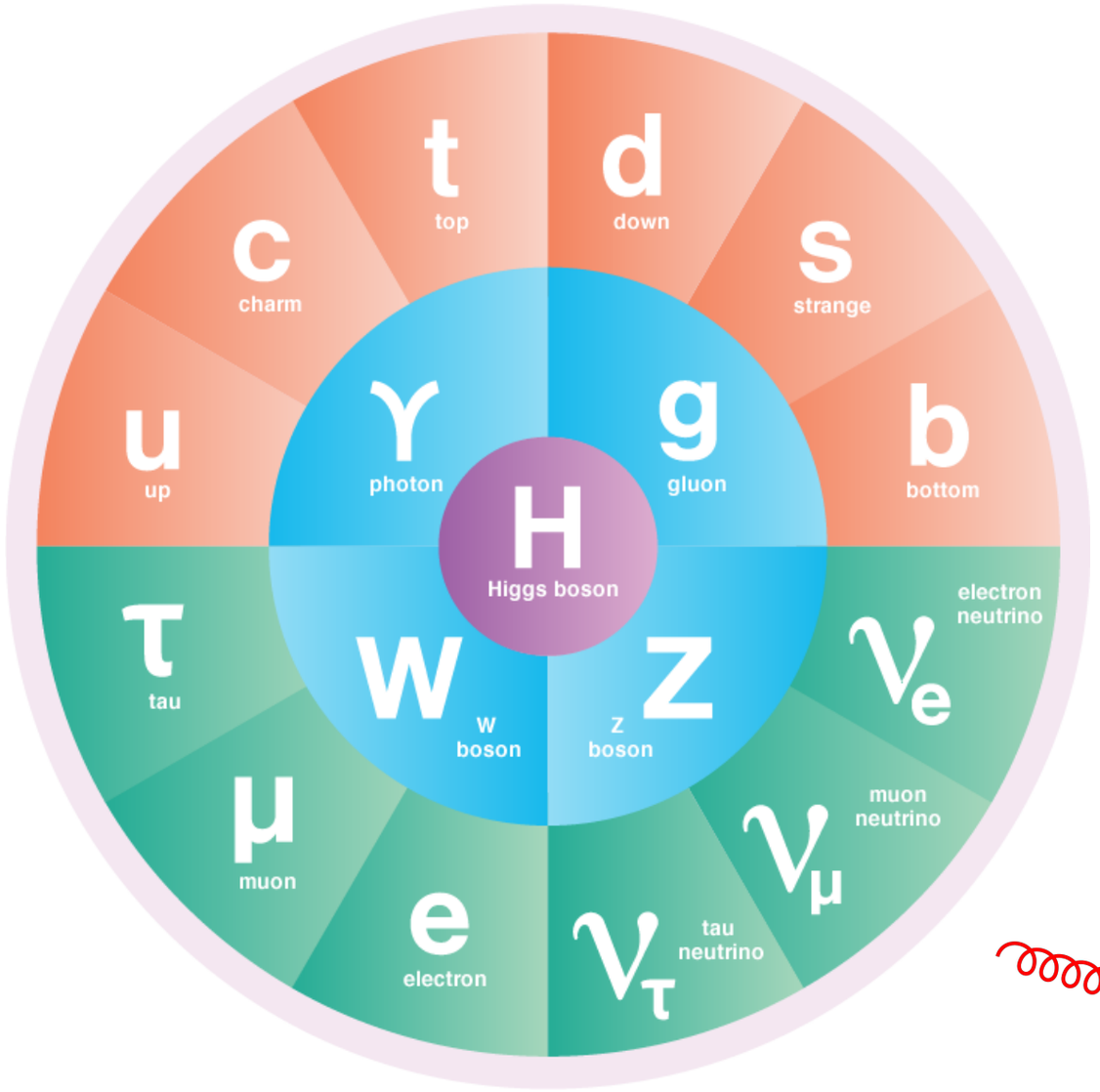
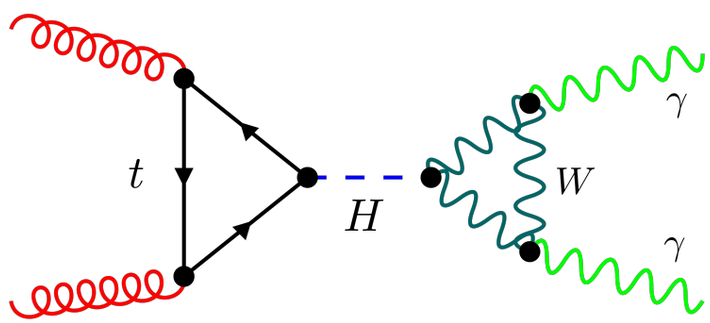
Higgs





1900 1897

1937 Higgs
Brout+Englert

Gouralnik,
1956 +Hagen+Kibble

1962 1964

1969
1975 1974
1979 1977
1983

1995

2012 ATLAS
+CMS

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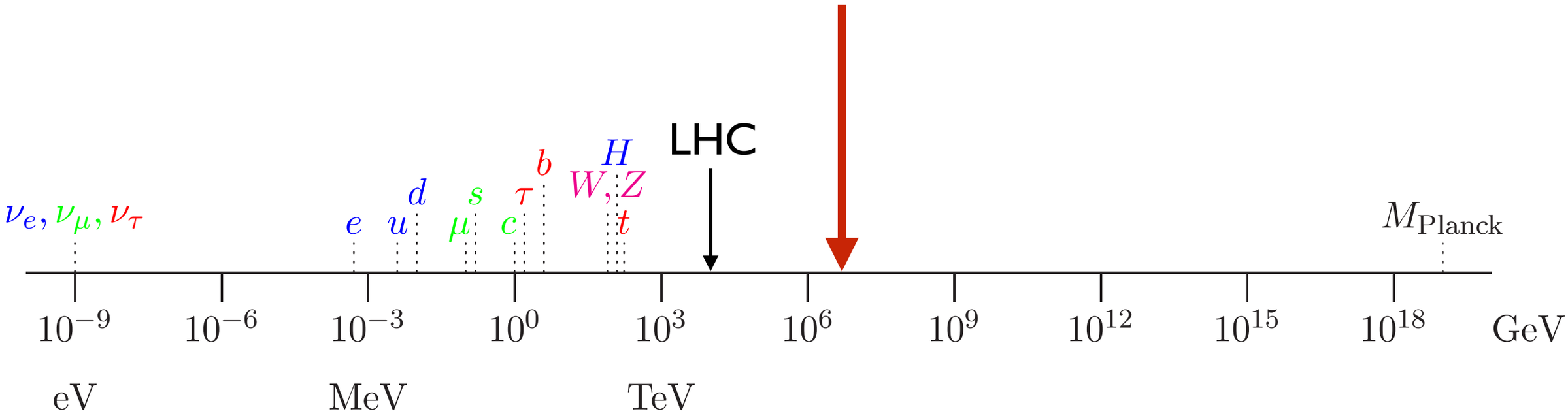
How far can we go?



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The past, the present, and the future

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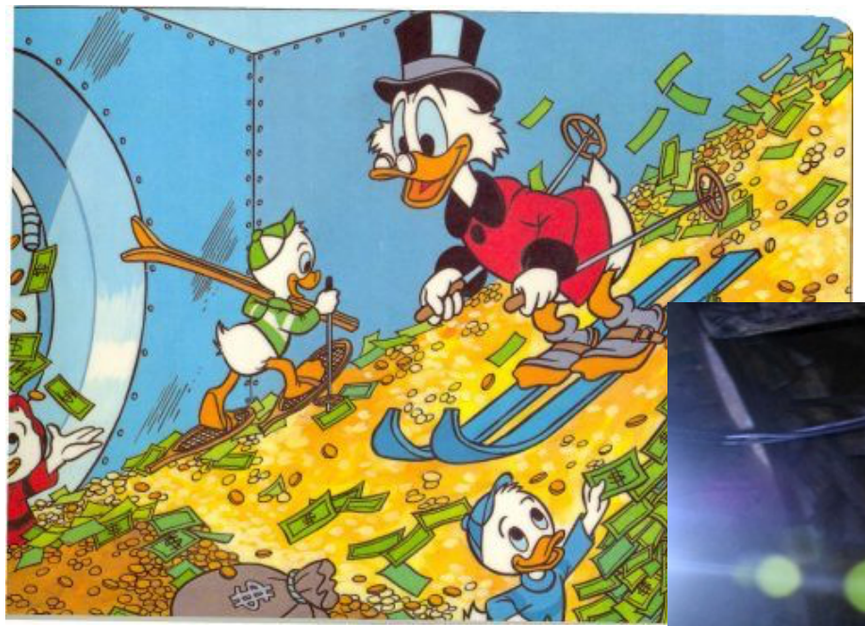
The past, the present, and the future

The past…

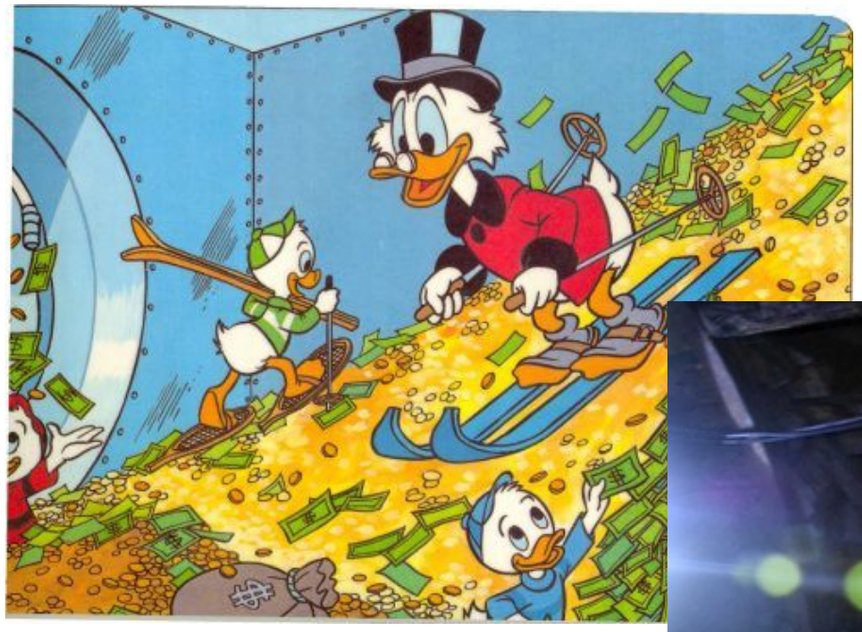
The past, the present, and the future



The past…

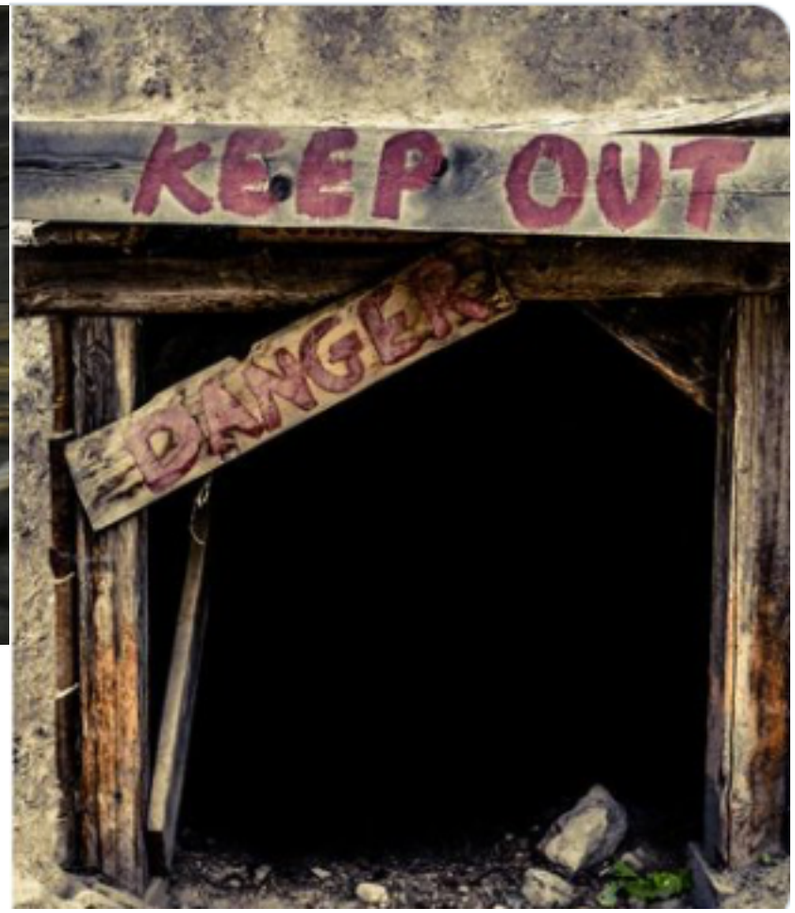
… the present …

The past, the present, and the future



The past…

… the present …



… the future?

The future

On-shell production of particles may belong to the past.

Not required for discovery.

“Observation” has evolved: we keep learning.

The future

On-shell production of particles may belong to the past.

Not required for discovery.

“Observation” has evolved: we keep learning.

The future

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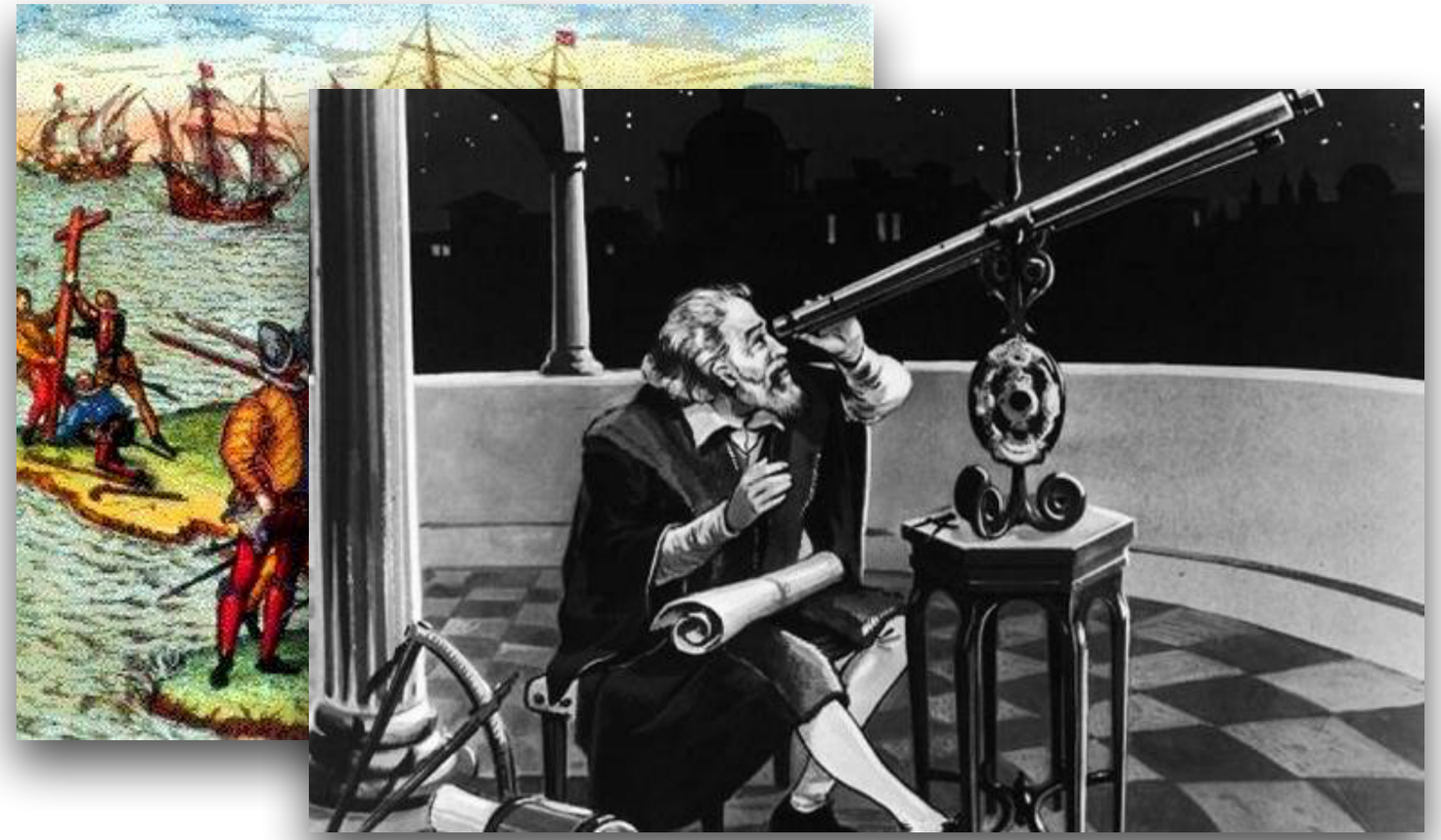

The future

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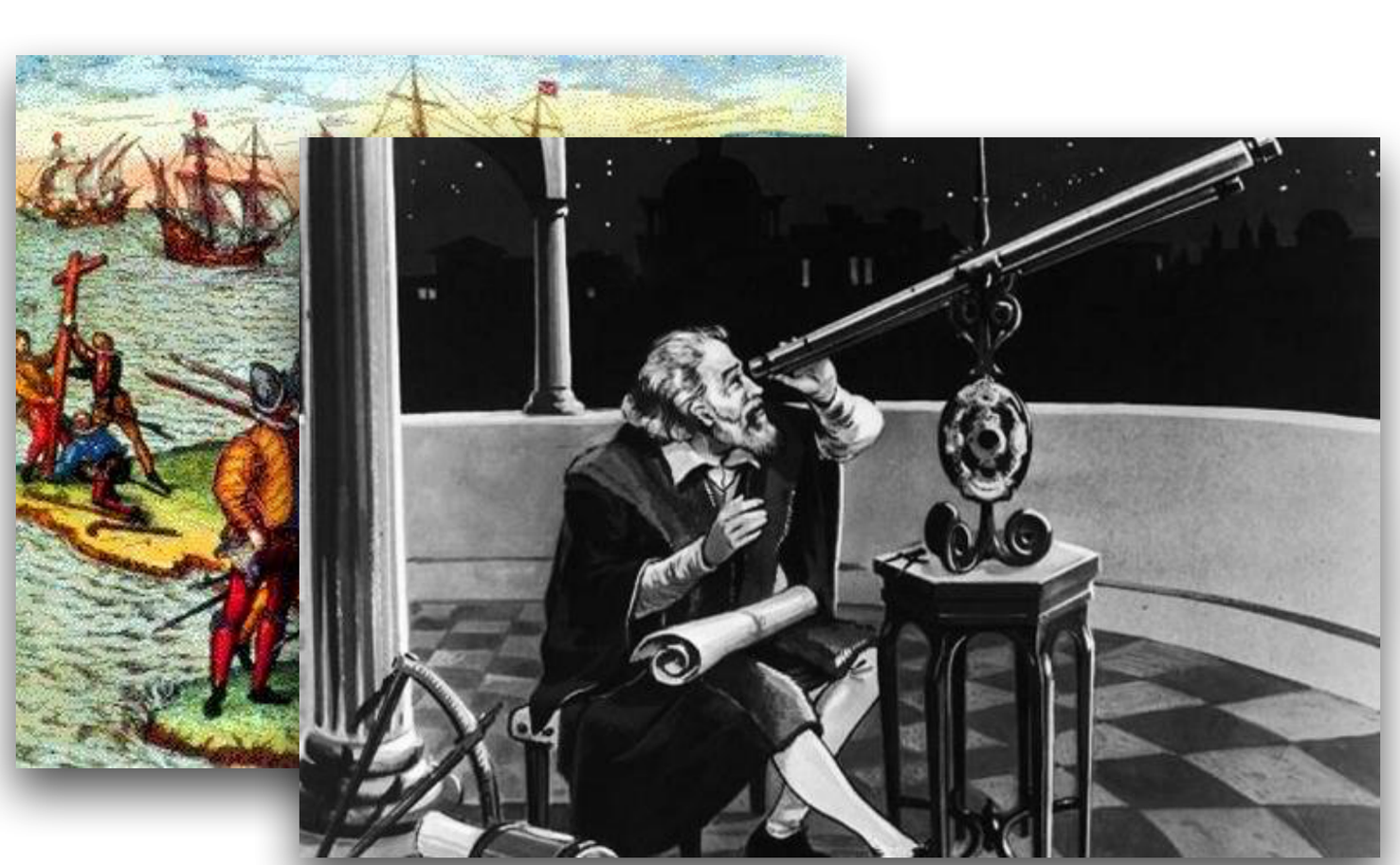

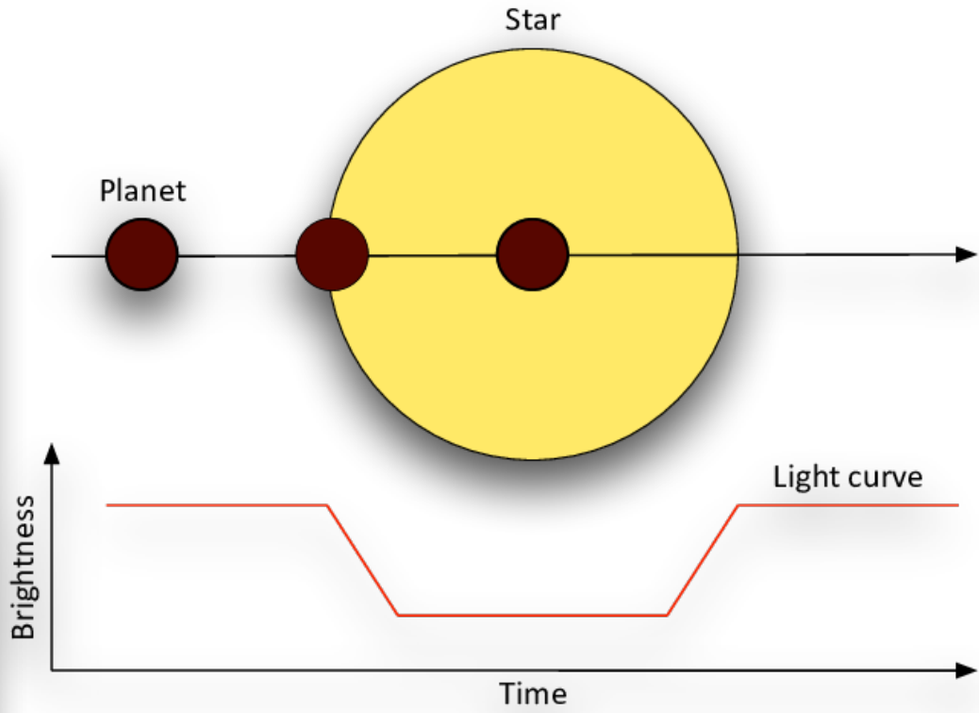

The evolution of the particle concept

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The evolution of the particle concept

Classical particle: discrete and localizable

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The evolution of the particle concept

Classical particle: discrete and localizable

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The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

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The evolution of the particle concept

Classical particle: discrete and localizable

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The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)

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The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)

The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)
- decay (neutral kaons)

The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)
- decay (neutral kaons)
- resonances (quarks)

The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)
- decay (neutral kaons)
- resonances (quarks)
- confinement (gluons)

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The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)
- decay (neutral kaons)
- resonances (quarks)
- confinement (gluons)
- Feynman diagrams (Z, W, Higgs, …)

The evolution of the particle concept

Classical particle: discrete and localizable

But: these properties are not essential for observation/discovery!

- kinematics (cathode rays)
- interaction with matter (tracks)
- decay (neutral kaons)
- resonances (quarks)
- confinement (gluons)
- Feynman diagrams (Z, W, Higgs, …)
- ???

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

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Four-quark operators (11)

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

+ *ijkl* generation index assignments

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

Two-quark operators (9)

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i\gamma^\mu \tau^I q_j),$$

Two-quark-two-lepton operators (8)

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

operators (5)

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

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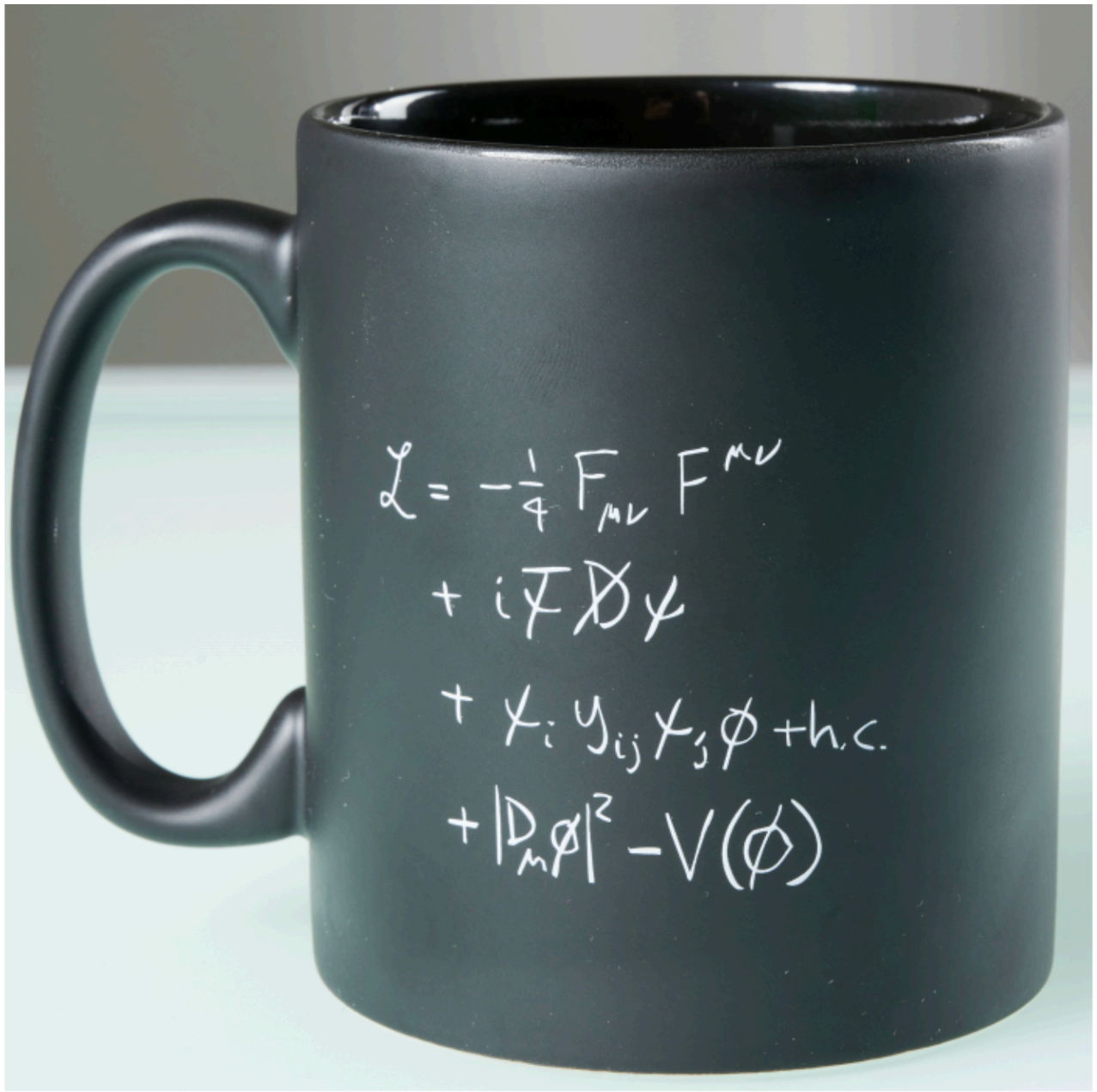

It's a quantum field theory.

Thank you!

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