Physics of the early universe and the intensity frontier of particle physics

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Particle physics and cosmology

- Particle physics investigates small distances: $l \lesssim \text{ Fermi} \sim 10^{-13} \text{ cm}$
- Cosmology considers large distances: $l \gtrsim \text{ parsec} \sim 10^{18} \text{ cm}$
- Both domains of physics overlap and strongly influence each other in the early Universe, when it was hot and dense, and the interactions between elementary particles were decisive.

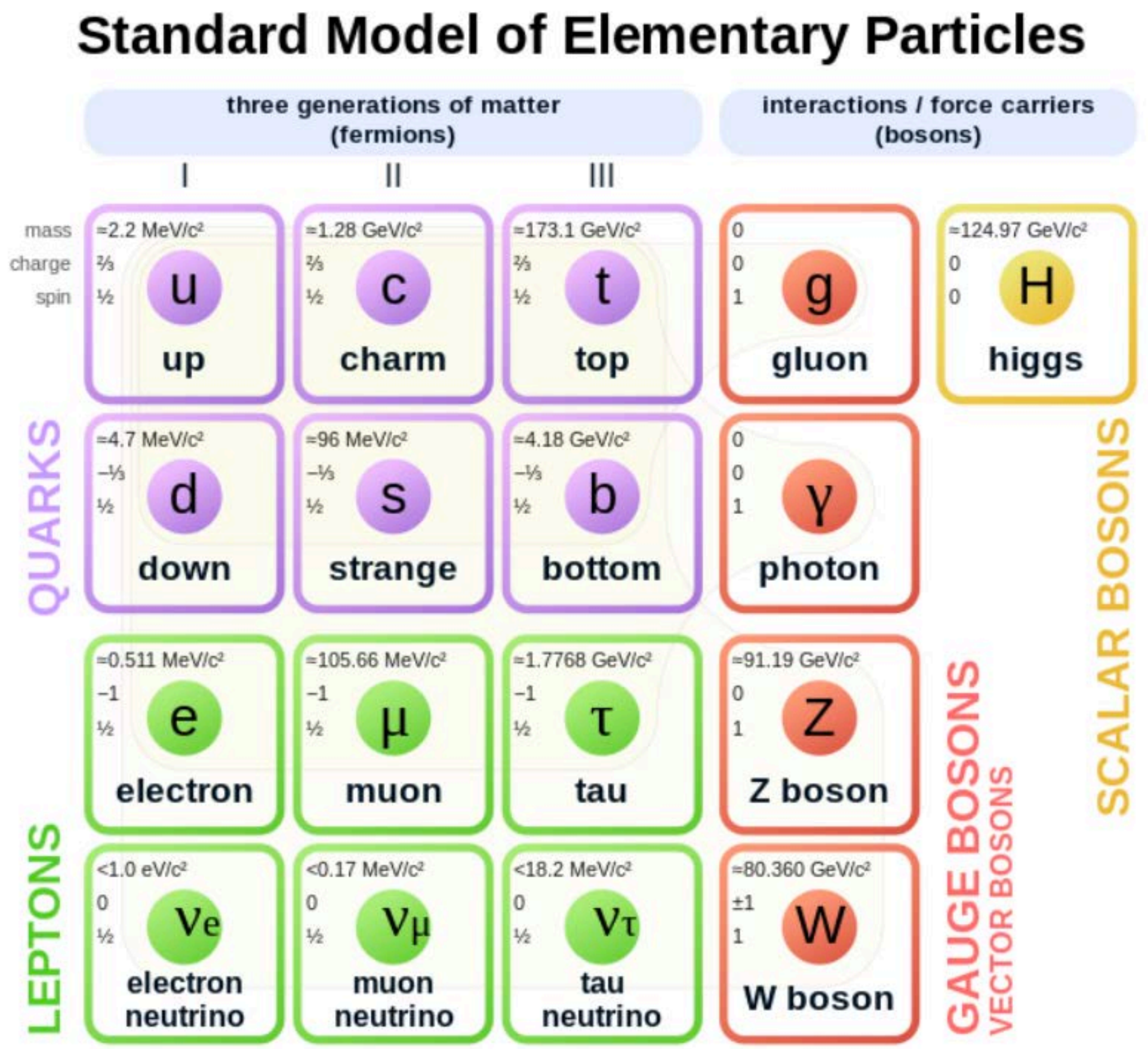
  Big Bang relation between the temperature T and the age t of the Universe:

$$\left(\frac{t}{\text{sec}}\right) \sim \left(\frac{\text{MeV}}{T}\right)^2$$

What kind of particle physics should be used to study the Early Universe?

The Standard Model (SM) of particle physics was invented in 1967 and completed with the discovery of the Higgs boson at the LHC 45 years later, in 2012.

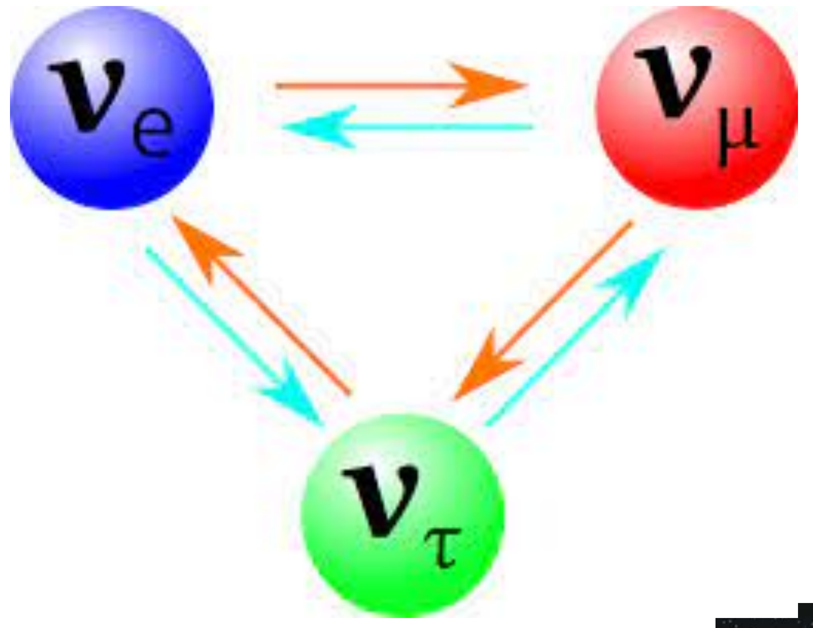
- SM describes strong, weak and electromagnetic interactions of all known elementary particles
- it is a self-consistent theory that allows to describe physics at very small and very large energies, possibly running all the way up to the Planck scale 10^{19} GeV (15 orders of magnitude larger than the LHC energy!).
- it is consistent with almost all experiments in particle physics



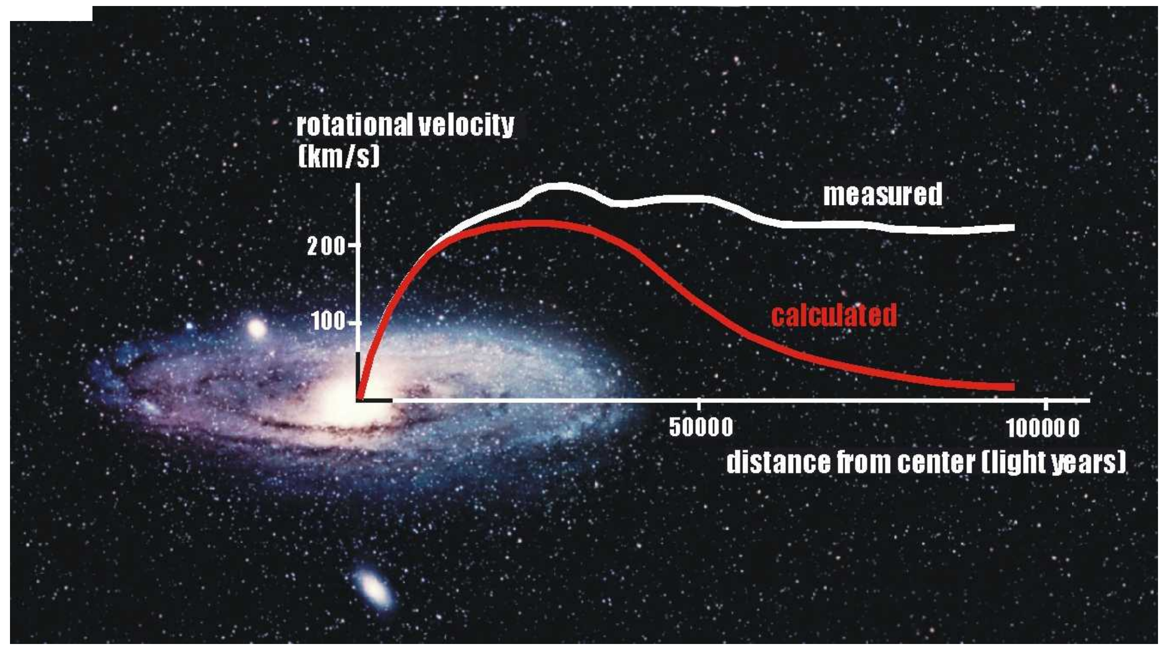
This is not a final story!

Where the Standard Model cracks

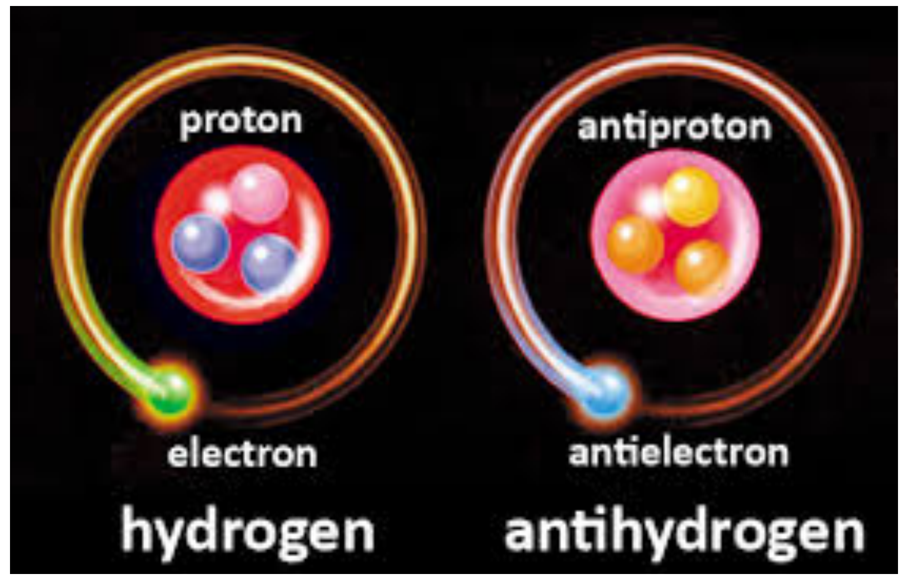
- Experimentally neutrinos have tiny, but non-zero masses. In the Standard Model neutrinos are exactly massless.



- Our Universe contains an unidentified substance: Dark Matter. None of the known particles can play the role of dark matter.



- Our Universe contains matter but no antimatter. The Standard Model fails to explain this.



Early Universe: 50% matter, 50% antimatter.
Now: everything annihilated.

→ New Physics beyond SM is required!

Energy scale of new physics

In the past we were sure that the LHC will discover something new: either the Higgs boson or new physics. Without the Higgs boson the theory was inconsistent.

The SM with 125 GeV Higgs is self-consistent up to the Planck scale $\sim 10^{19}$ GeV.

The solid theory guidance which has led to the discovery of the Higgs boson is now over.
Can we at least get the energy scale of new physics from experiments? Not really.

- Neutrino masses and oscillations: can be explained by introducing new particles with masses from 1 eV to 10^{15} GeV
- Dark matter, absent in the SM:
the masses of proposed DM particles can be as small as 10^{-22} eV or as large as 10^{20} GeV
- Baryon asymmetry of the Universe: the masses of new particles, responsible for baryogenesis can vary from 10 MeV to 10^{15} GeV
- Cosmological Inflation of the Universe: inflaton mass can be from few GeV to 10^{10} GeV.
Also, the Standard Model Higgs boson can drive inflation - no new particle is needed

How many new elementary particles still remain to be discovered to solve the problems of the Standard Model?

Possible clues for the answer:

- Theoretical questions - we do not understand why the Standard Model is constructed in a way it is:
    - why there are 3 generations of fermions?
    - why the top quark is much heavier than electron?
    - how to unify all interactions with gravity?
    - etc, etc…
- Experimental guidance: find a theory which works better than the Standard Model in explaining observations - neutrino masses, dark matter, baryon asymmetry.

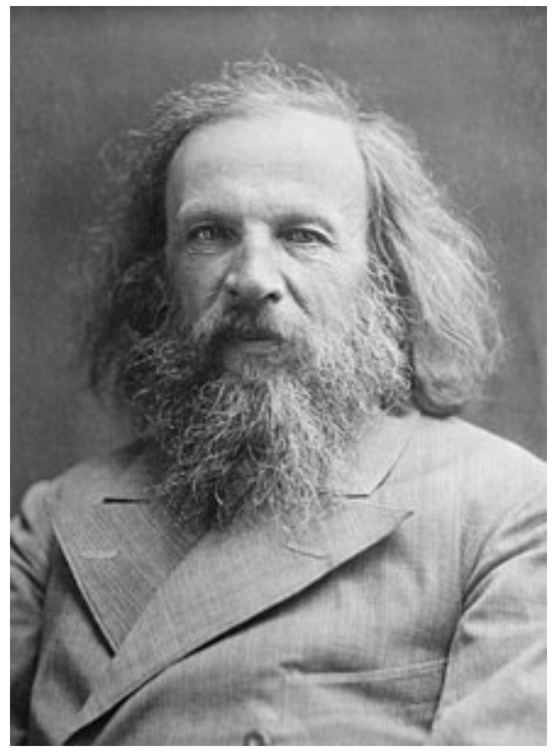
Some proposals for new particles

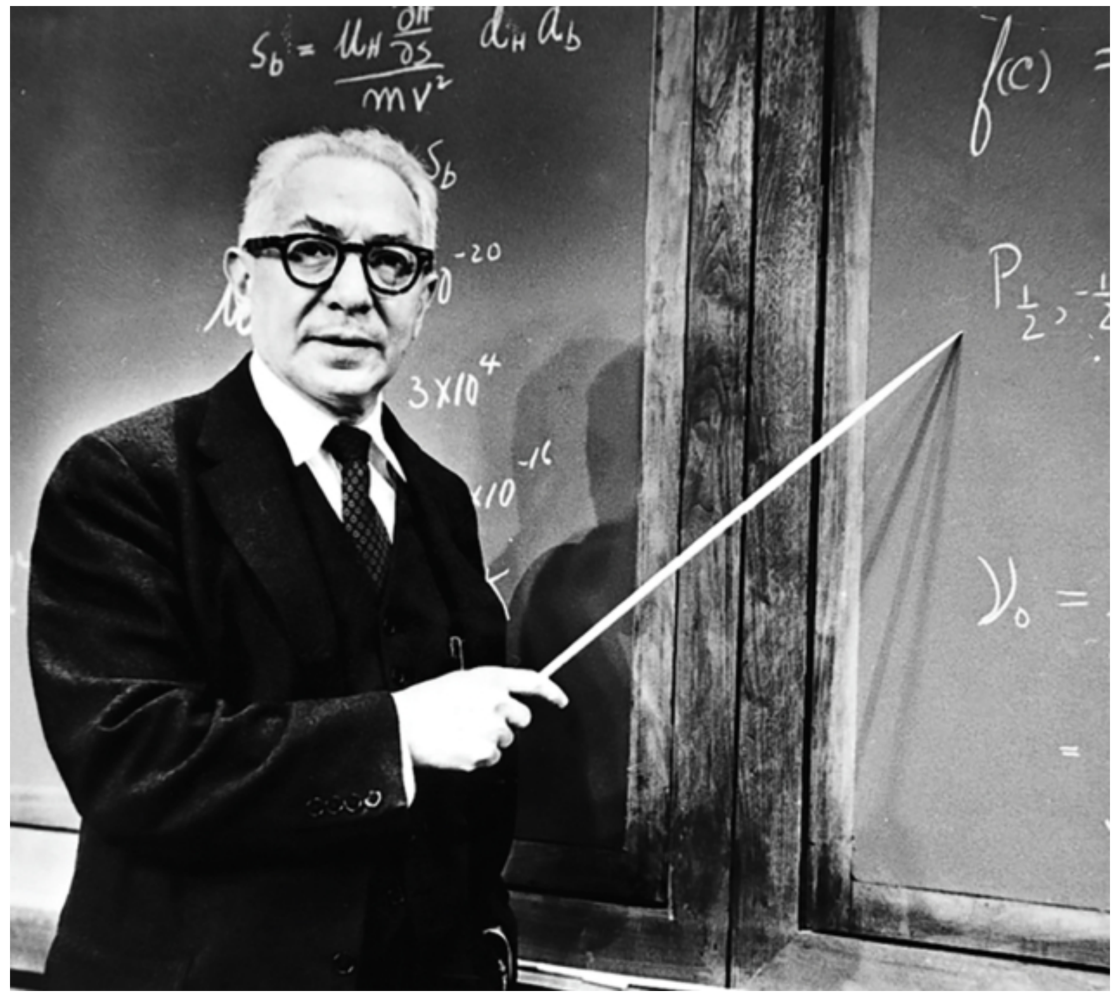
- No new particles to be discovered? We have found everything we could, all troubles of the Standard Model are resolved by its unification with gravity. The energy scale is so high, that we will never reach it experimentally.
- Add similar number as we already have in SM? Every known particle could have its supersymmetric partner.
- Large extra dimensions? The theory predicts Kaluza-Klein excitations right above the Fermi scale.
- Composite Higgs boson? The theory generically predicts new resonances right above the Fermi scale.

So far no new particles of these types were found, but many physicists were expected to see them at LEP and/or LHC.

Possible strategies, worked well in the past:

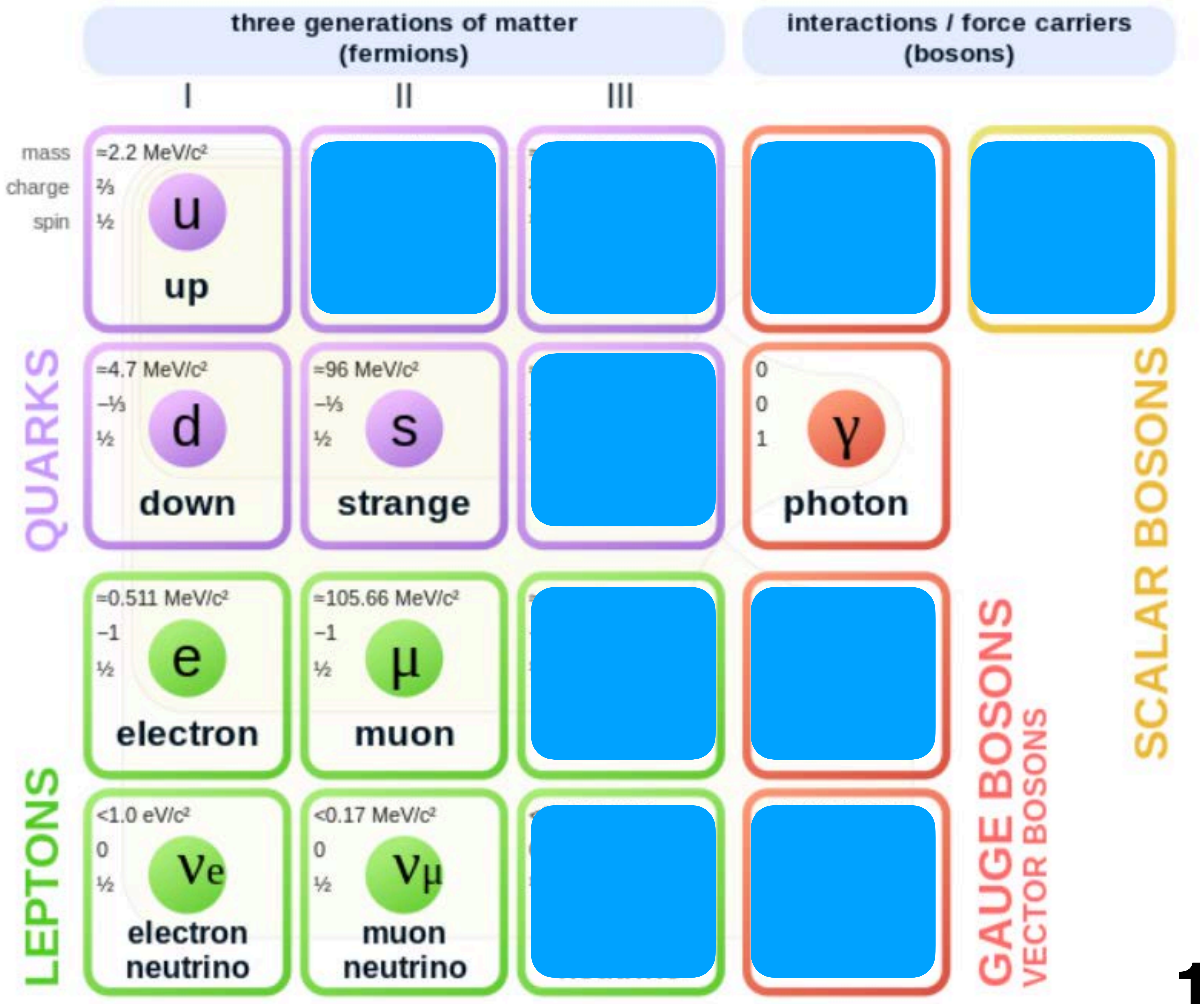
- Mendeleev in 1871 predicted several new elements by putting already known into a smart periodic table.
- Isaac Raby, when the muon was discovered in 1936, asked: “Who ordered that?” Perhaps, every new particle should have a “Raison d’être”…





In this way, many elementary particles of the SM were discovered in the past

Standard Model of Elementary Particles



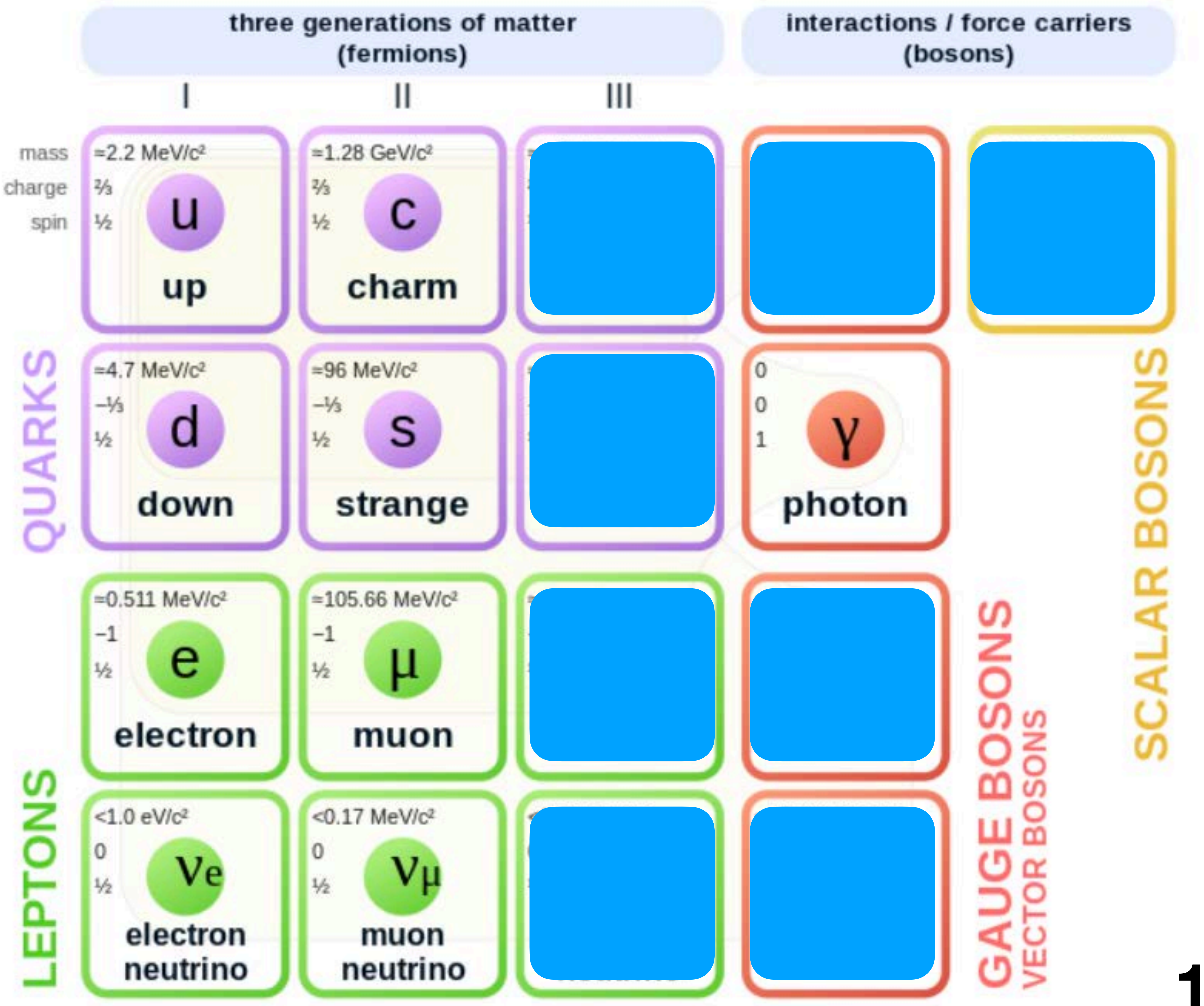
		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u **up**	[redacted]	[redacted]	[redacted]	[redacted]
		≈4.7 MeV/c^2 −⅓ ½ d **down**	≈96 MeV/c^2 −⅓ ½ s **strange**	[redacted]	0 0 1 γ **photon**	
LEPTONS		≈0.511 MeV/c^2 −1 ½ e **electron**	≈105.66 MeV/c^2 −1 ½ μ **muon**	[redacted]	[redacted]	
		<1.0 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	[redacted]	[redacted]	

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

1973

Standard Model of Elementary Particles



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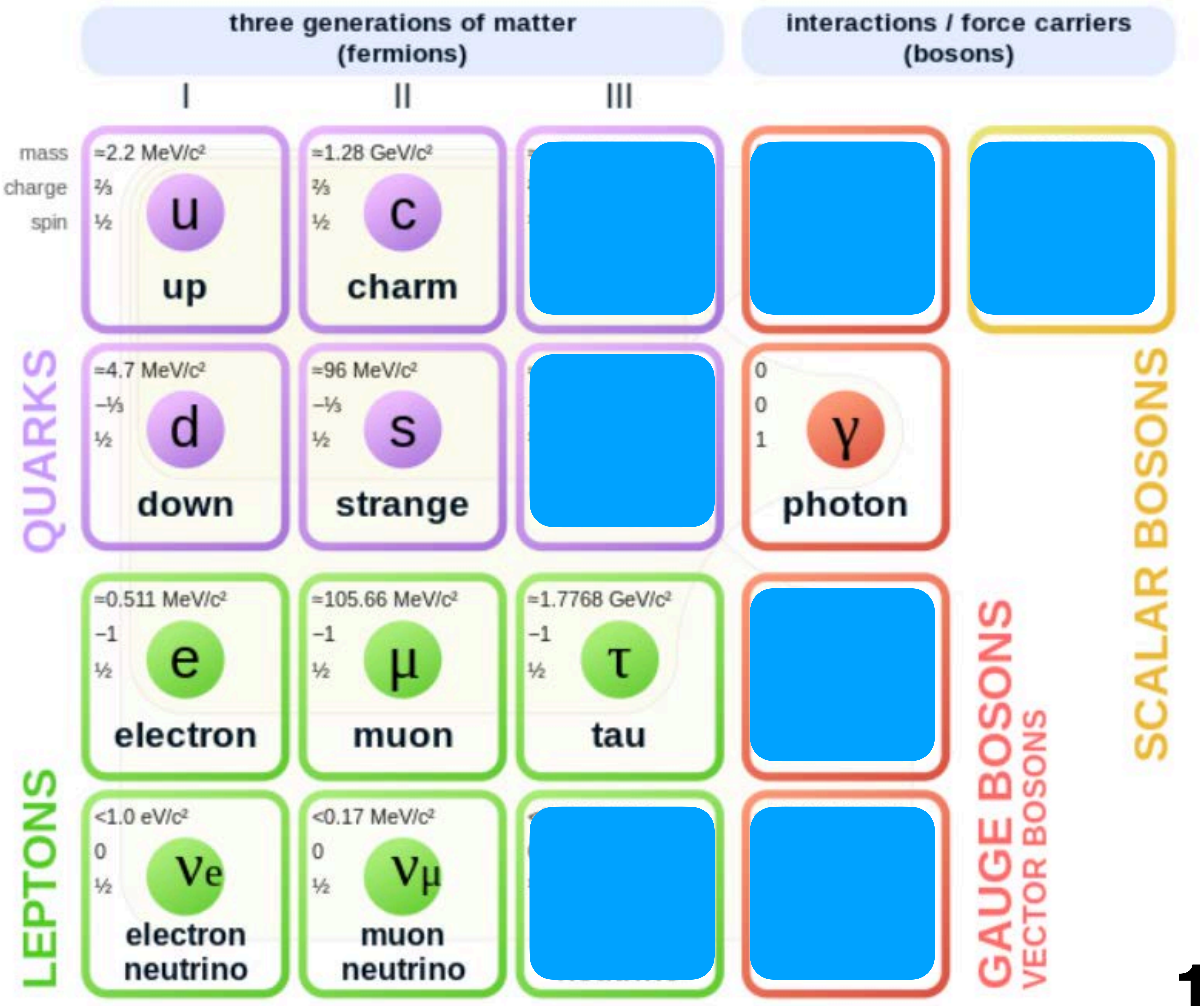
1974

Standard Model of Elementary Particles



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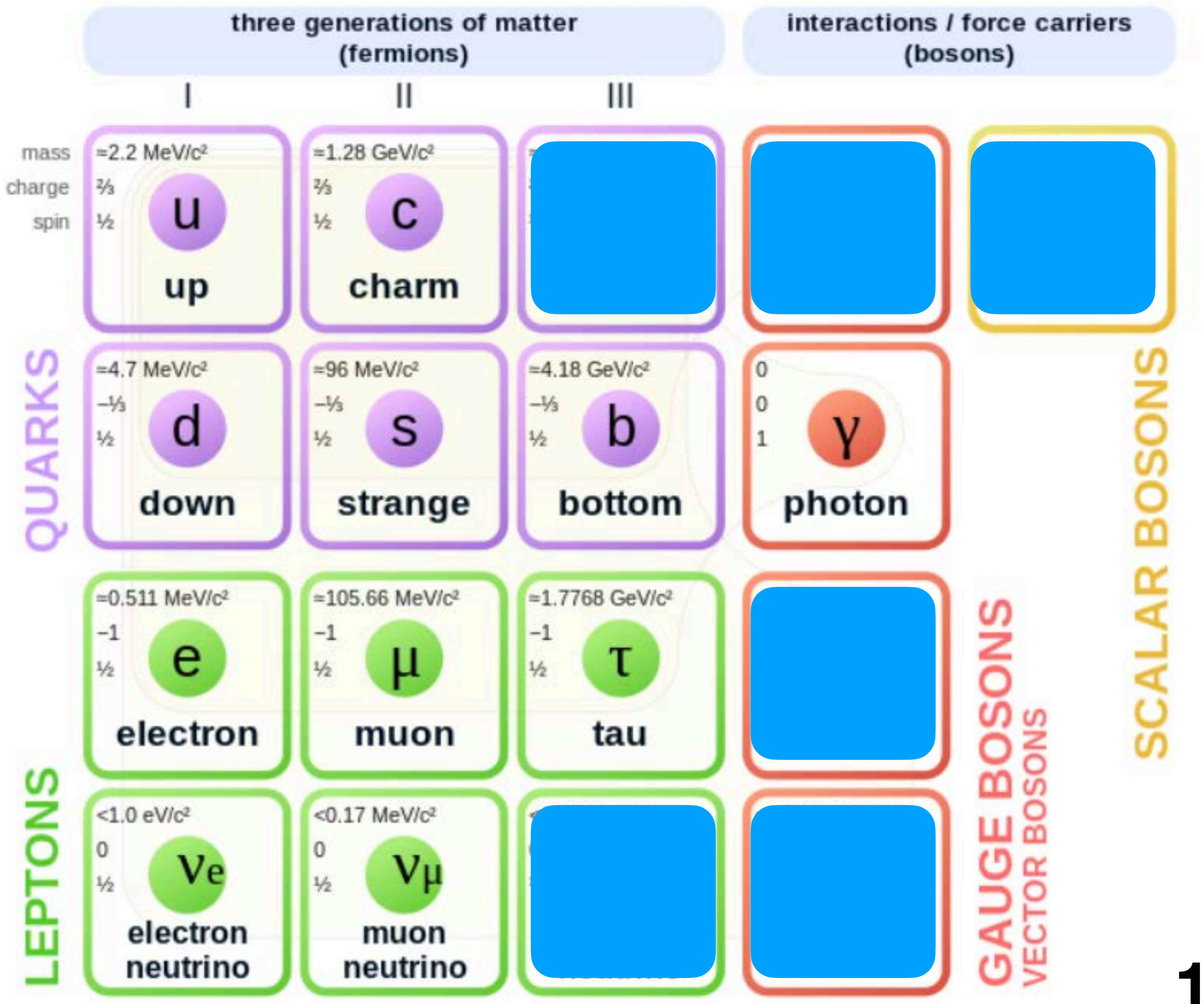
		≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	[redacted]	0 0 1 γ photon	SCALAR BOSONS
LEPTONS		≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	[redacted]	
		<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	[redacted]	[redacted]	GAUGE BOSONS VECTOR BOSONS

1975

Standard Model of Elementary Particles



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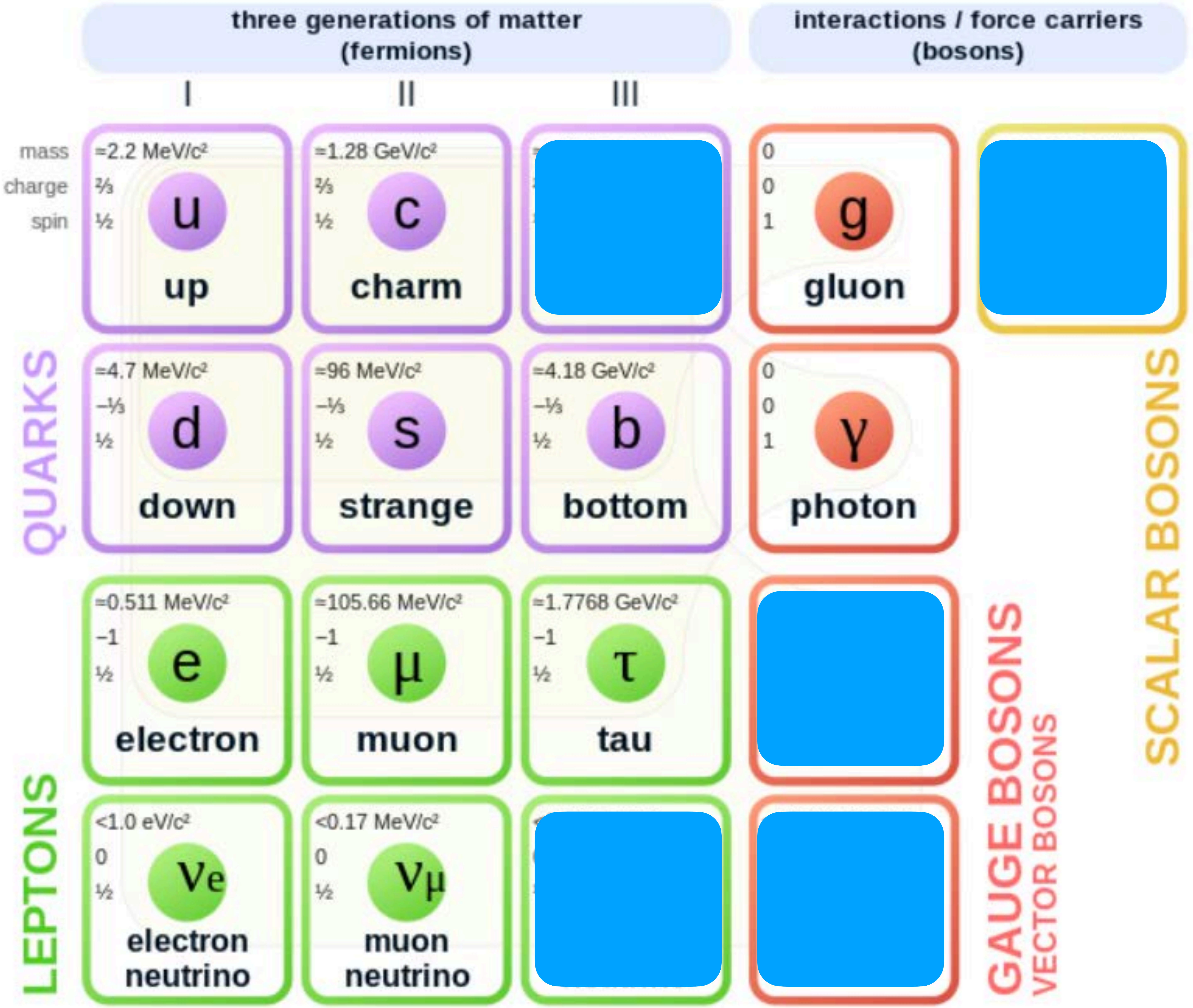
GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

1977

Standard Model of Elementary Particles



	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u **up**	≈1.28 GeV/c^2 ⅔ ½ c **charm**	[redacted]	0 0 1 g **gluon**	[redacted]
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d **down**	≈96 MeV/c^2 −⅓ ½ s **strange**	≈4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	SCALAR BOSONS
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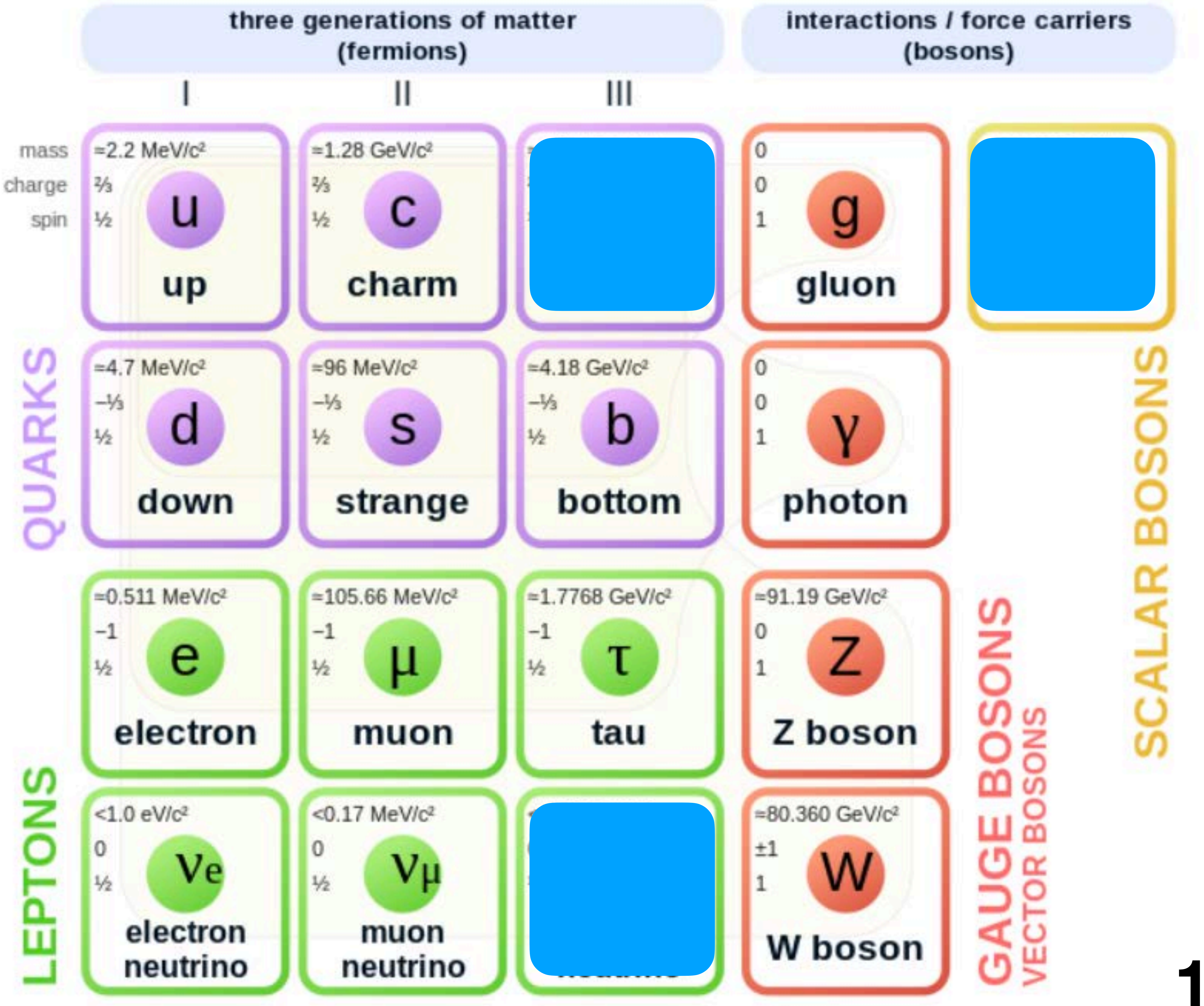
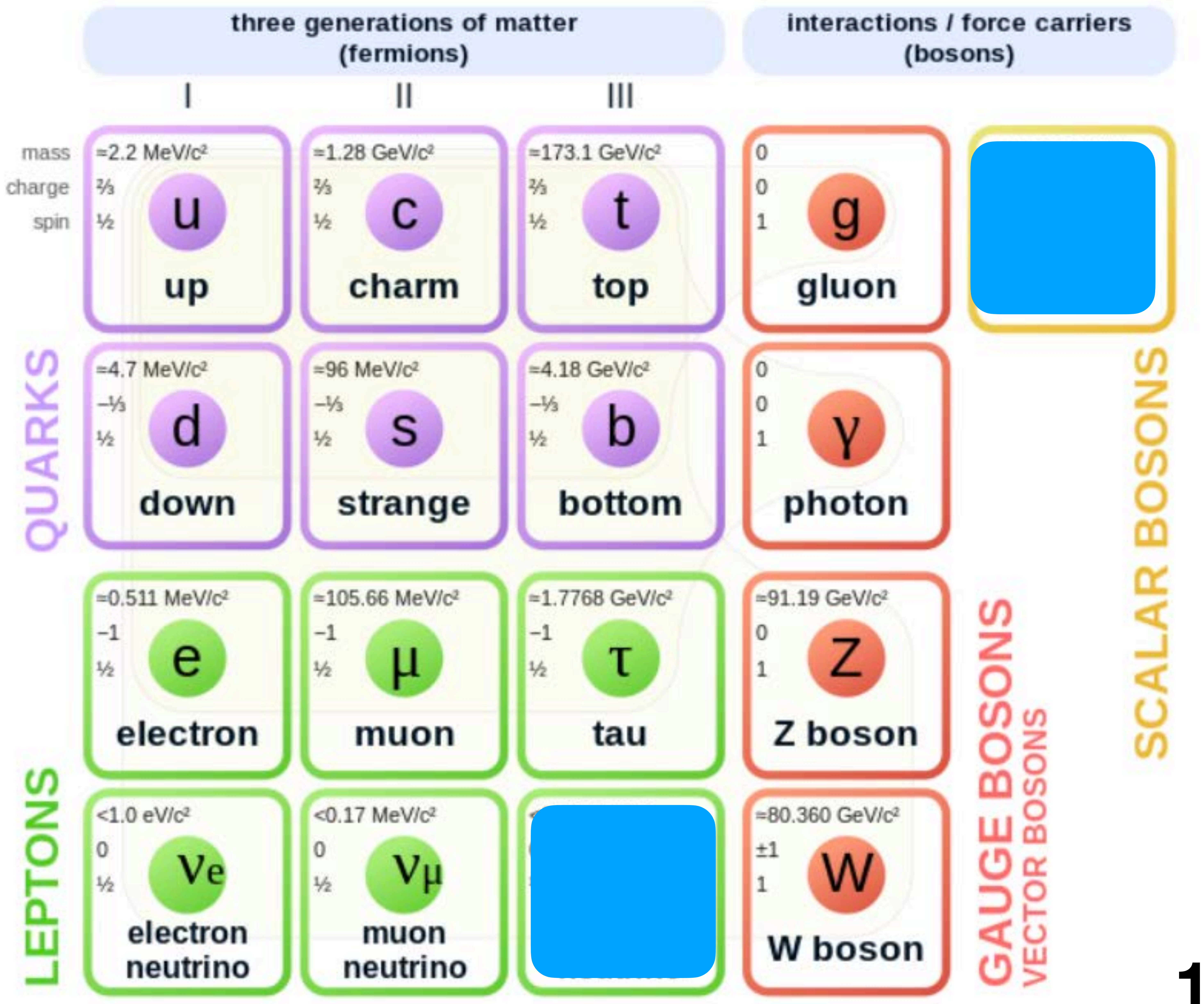
Standard Model of Elementary Particles



mass charge spin	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
QUARKS	$\approx 2.2\ \mathrm{MeV}/c^2$ ⅔ ½ u **up**	$\approx 1.28\ \mathrm{GeV}/c^2$ ⅔ ½ c **charm**	[redacted]	0 0 1 g **gluon**	[redacted]
QUARKS	$\approx 4.7\ \mathrm{MeV}/c^2$ −⅓ ½ d **down**	$\approx 96\ \mathrm{MeV}/c^2$ −⅓ ½ s **strange**	$\approx 4.18\ \mathrm{GeV}/c^2$ −⅓ ½ b **bottom**	0 0 1 γ **photon**	SCALAR BOSONS
LEPTONS	$\approx 0.511\ \mathrm{MeV}/c^2$ −1 ½ e **electron**	$\approx 105.66\ \mathrm{MeV}/c^2$ −1 ½ μ **muon**	$\approx 1.7768\ \mathrm{GeV}/c^2$ −1 ½ τ **tau**	$\approx 91.19\ \mathrm{GeV}/c^2$ 0 1 Z **Z boson**	
LEPTONS	$<1.0\ \mathrm{eV}/c^2$ 0 ½ ν_e **electron neutrino**	$<0.17\ \mathrm{MeV}/c^2$ 0 ½ ν_μ **muon neutrino**	[redacted]	$\approx 80.360\ \mathrm{GeV}/c^2$ ±1 1 W **W boson**	GAUGE BOSONS VECTOR BOSONS

1983

Standard Model of Elementary Particles



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		I	II	III		
QUARKS	mass charge spin	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	
		≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	
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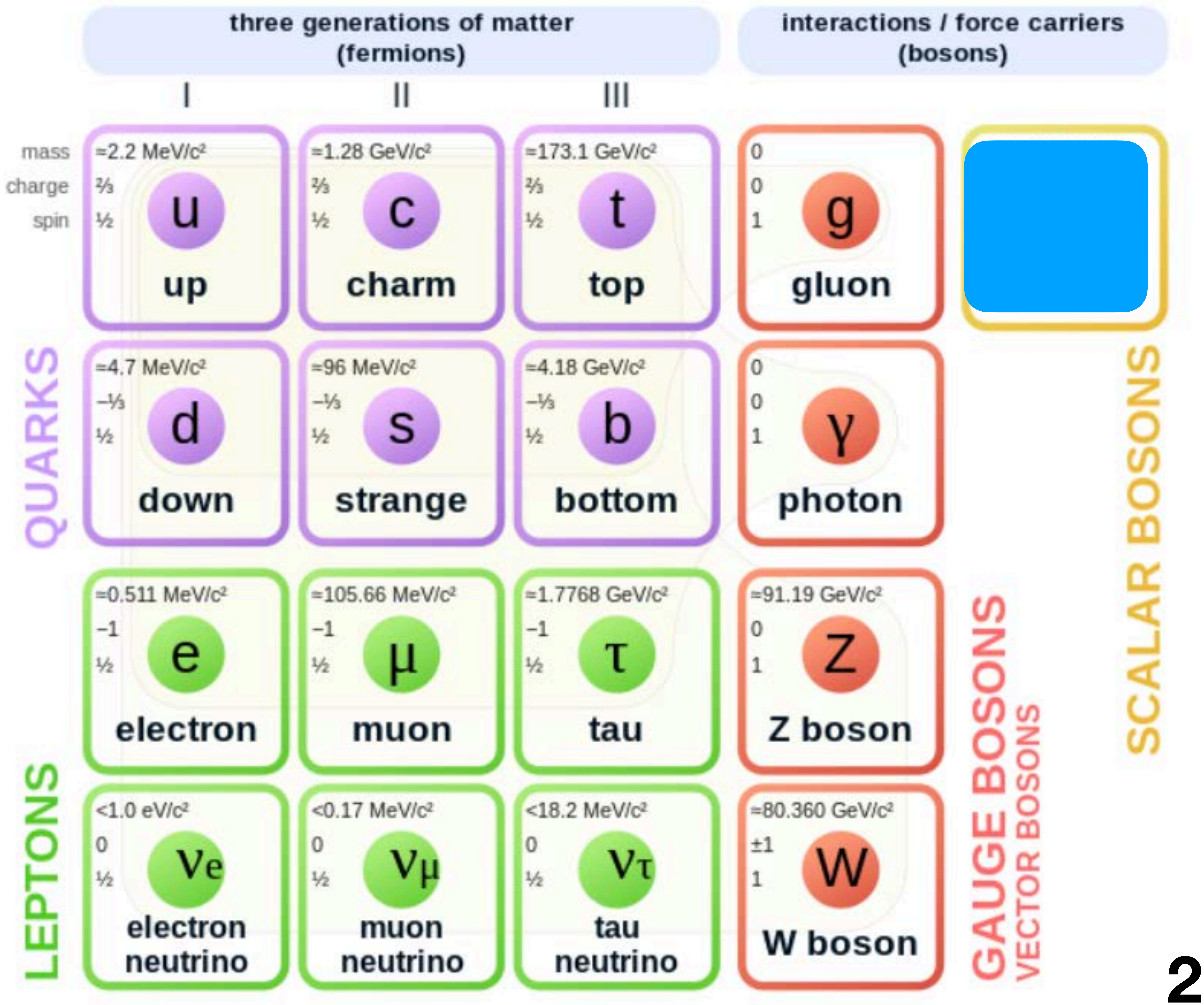
GAUGE BOSONS

VECTOR BOSONS

SCALAR BOSONS

1995

Standard Model of Elementary Particles



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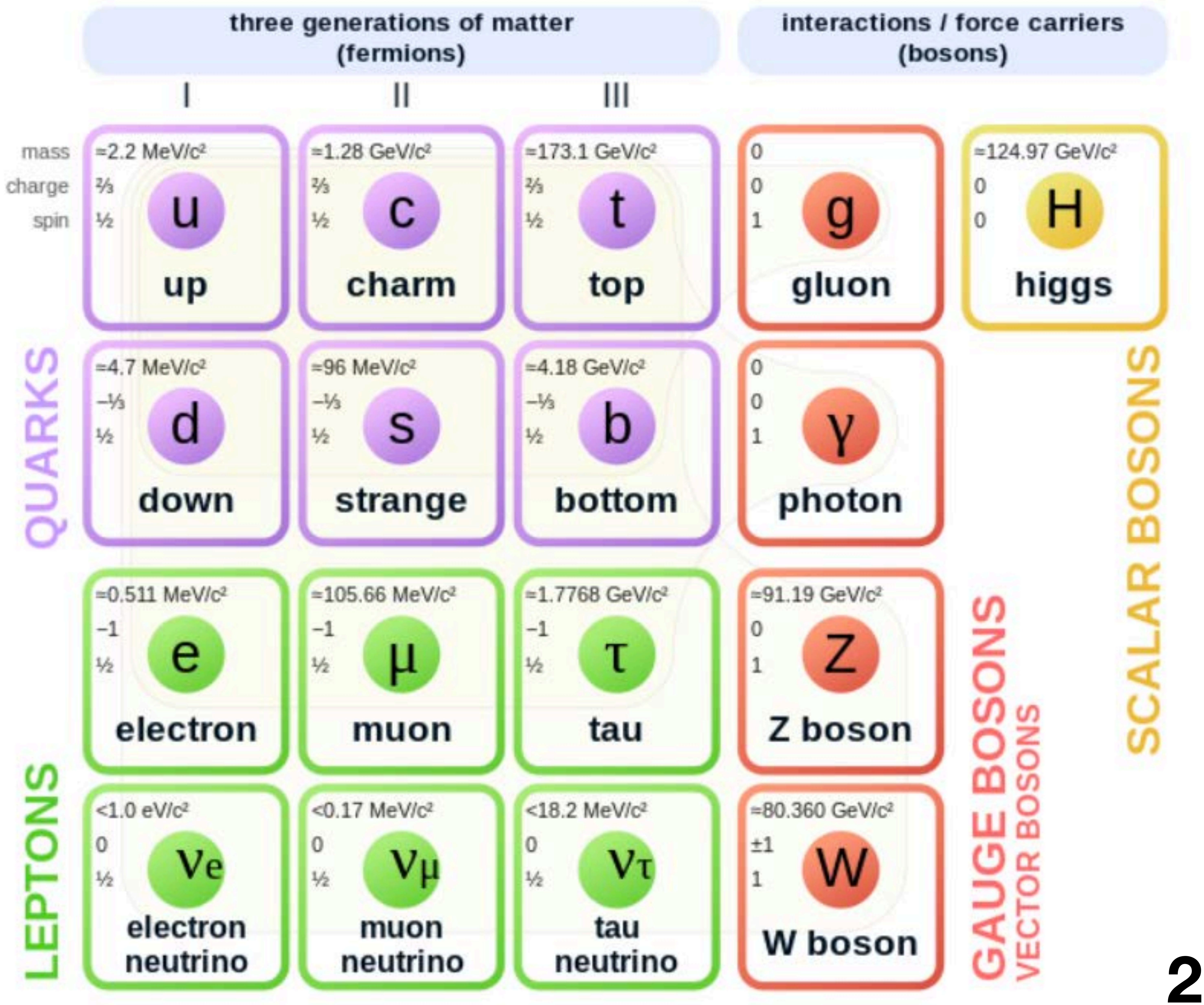
LEPTONS	<1.0 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino	≈80.360 GeV/c^2 ±1 1 W W boson	

2000

Standard Model of Elementary Particles



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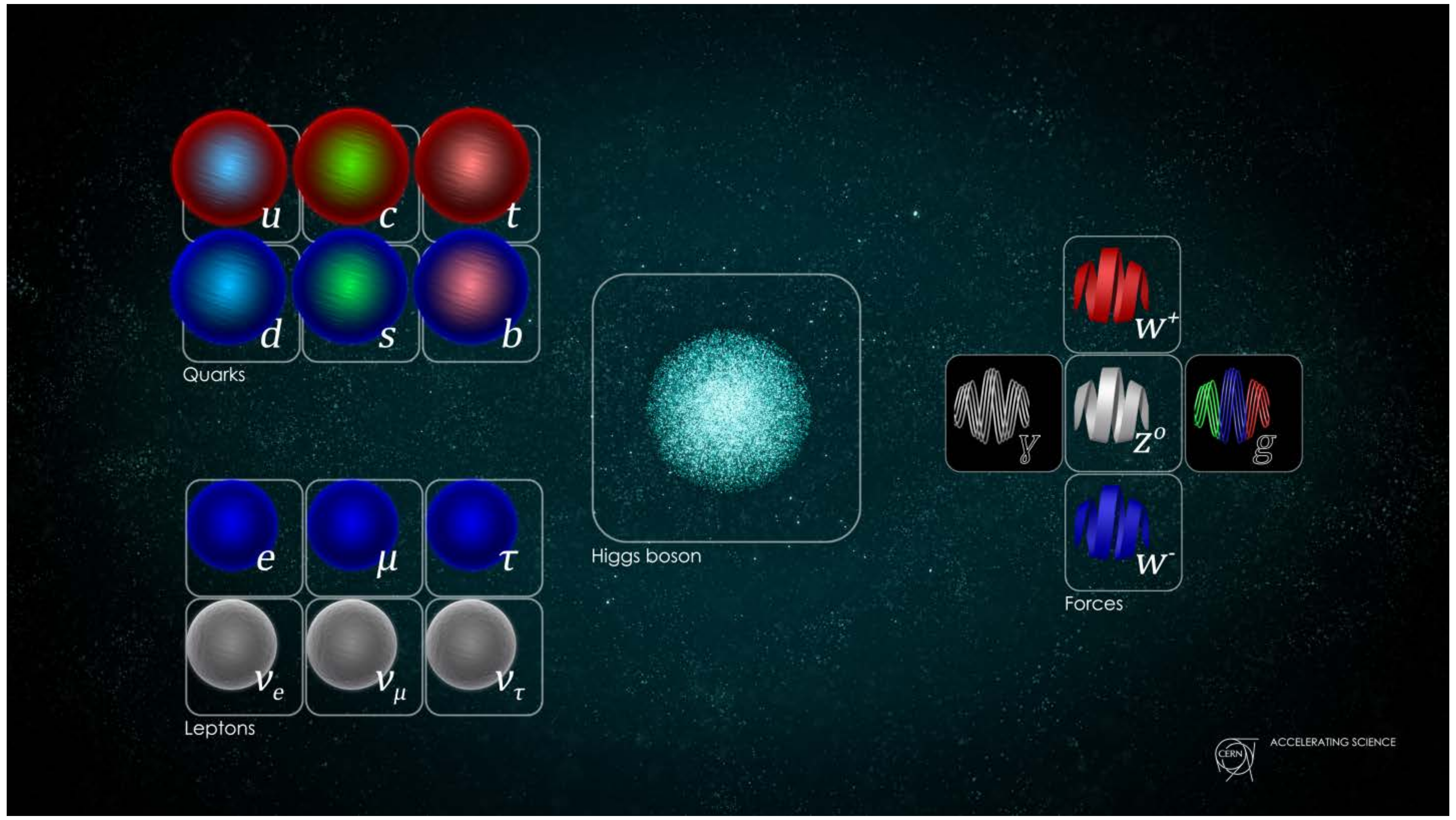
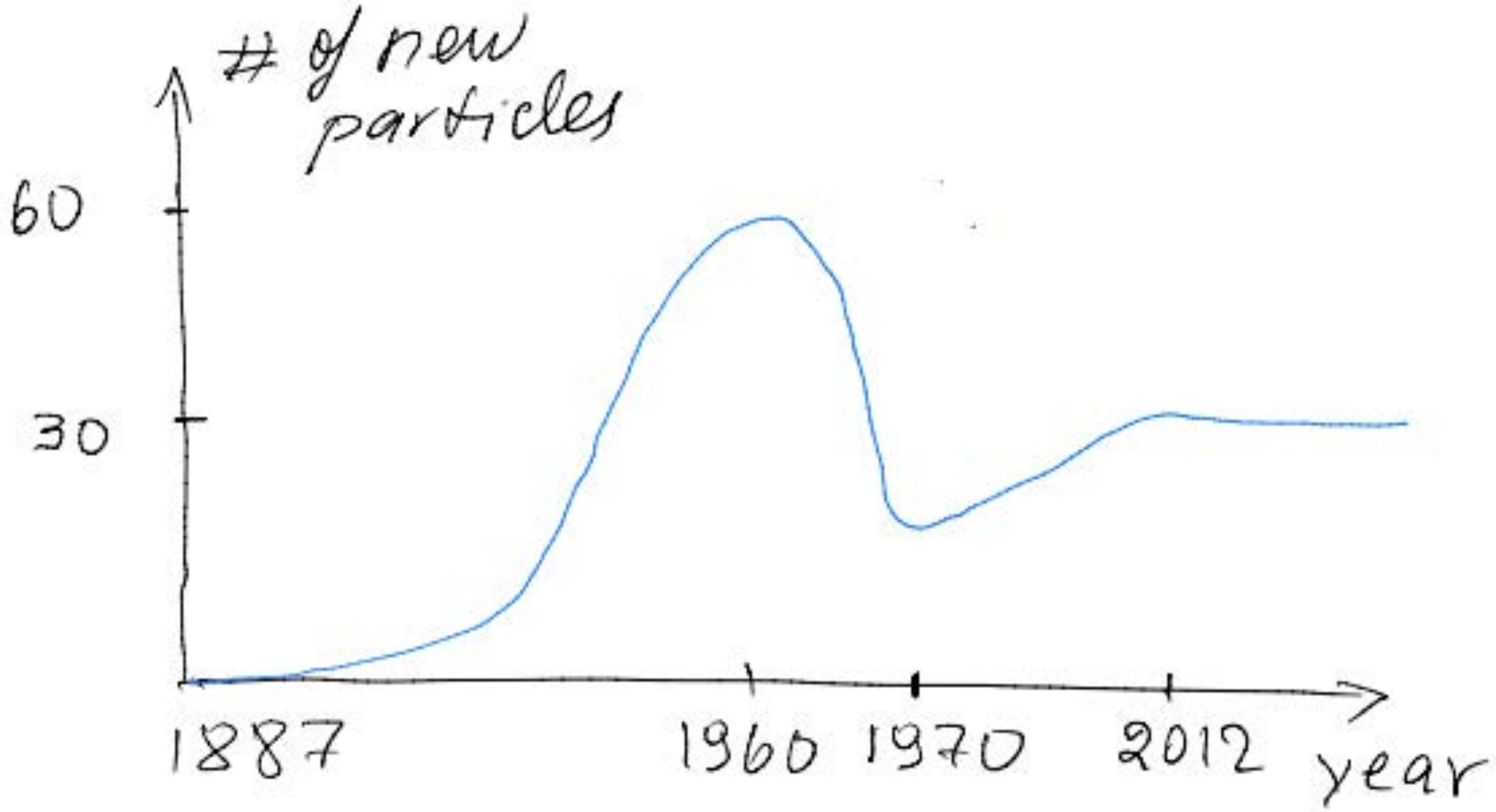
2012

New particle every 5 years (in average)!

New particles over years

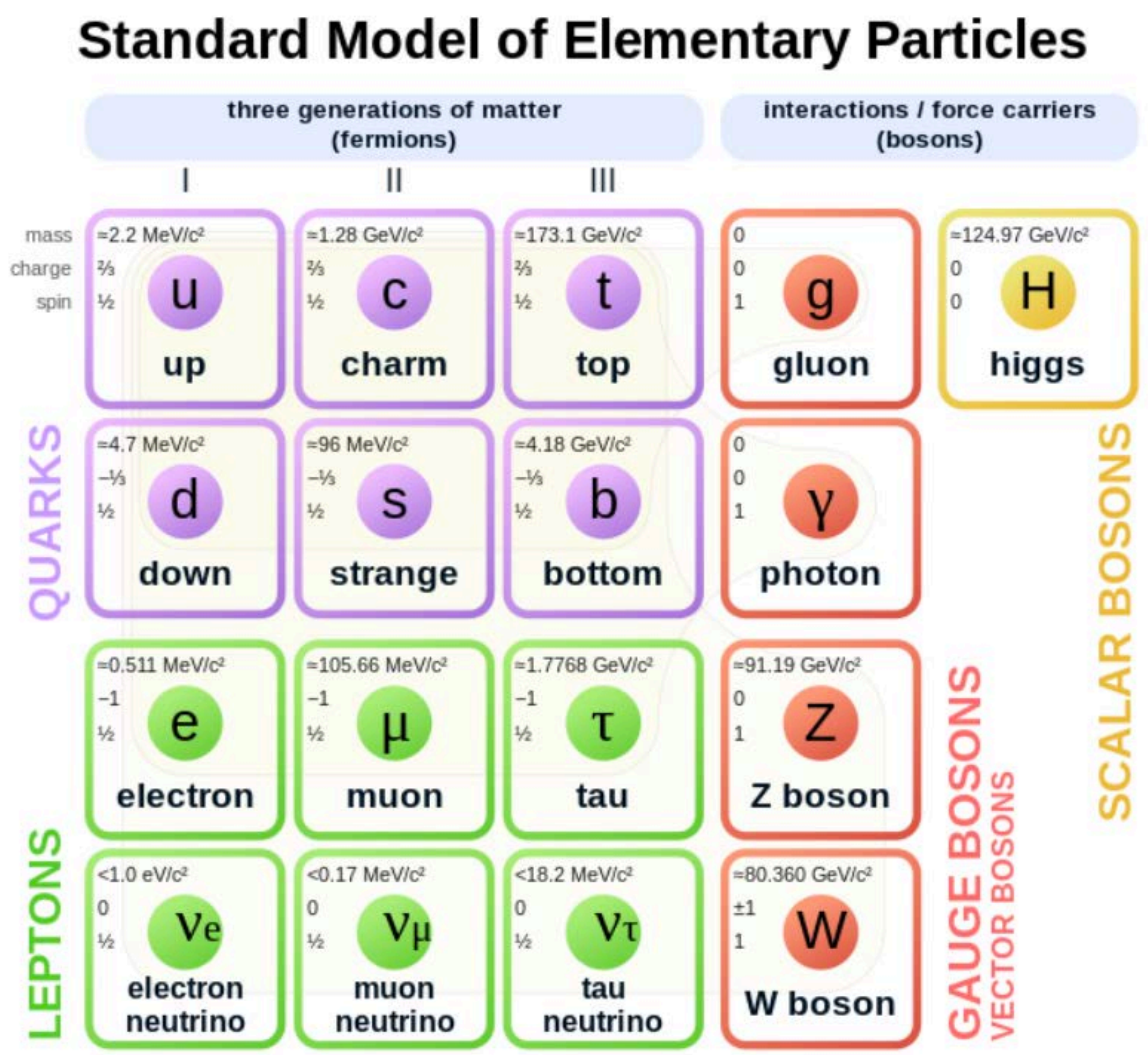




Plateau since the Higgs boson discovery in 2012

Standard Model in now complete with
3 families of quarks and leptons,
gluons, W and Z bosons, Higgs boson

From Mendeleev table to Standard Model



Standard Model of Elementary Particles

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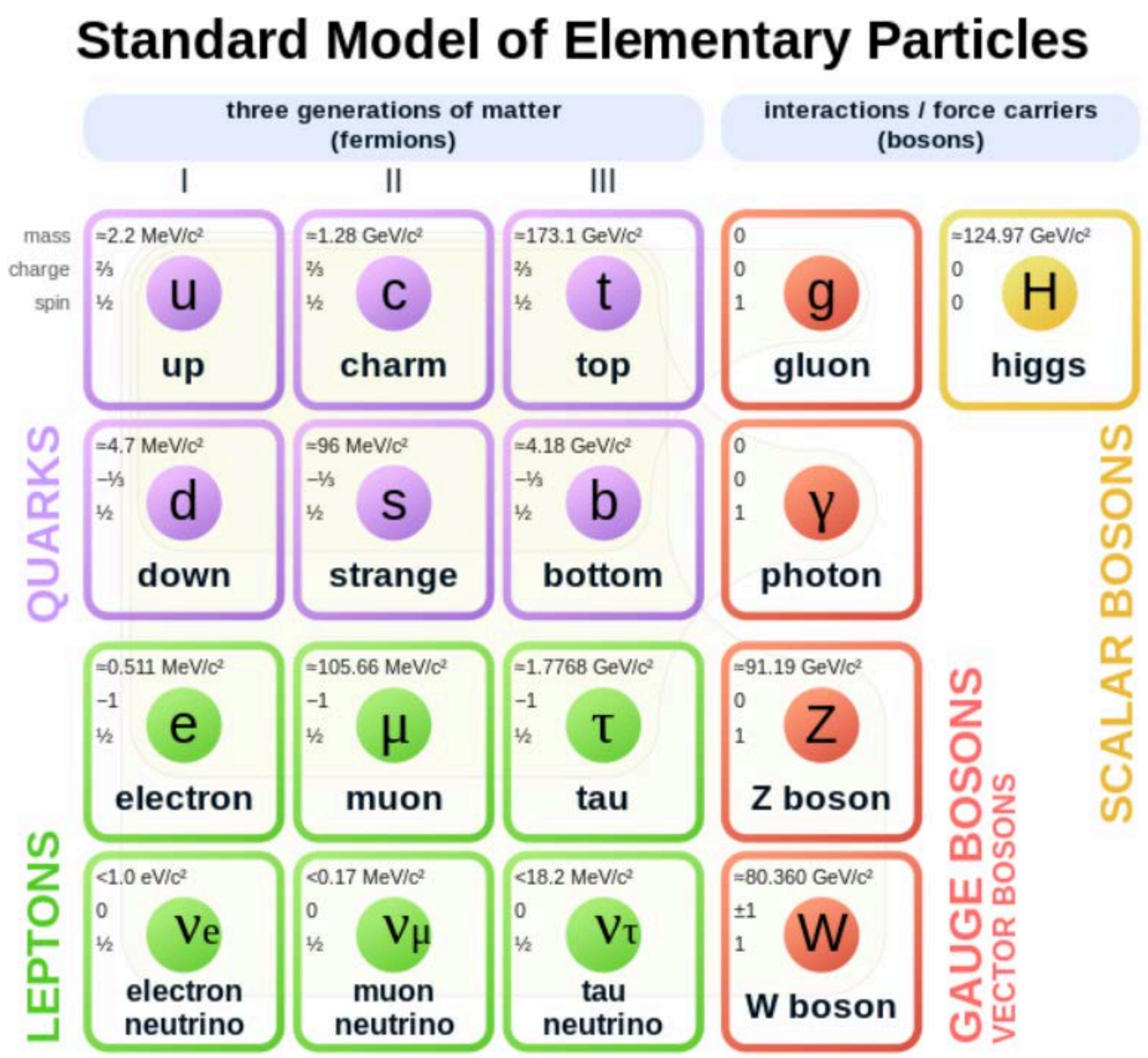
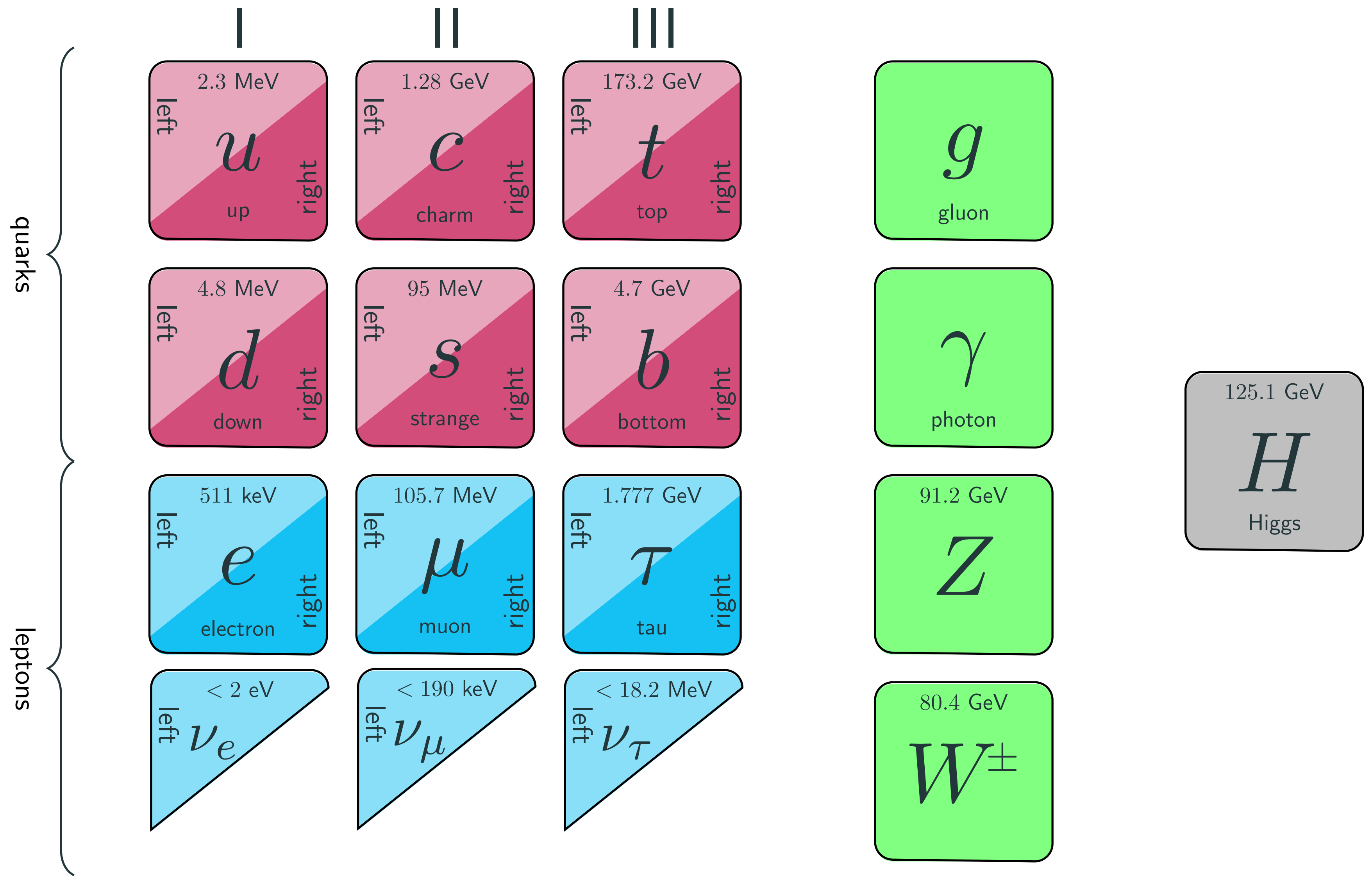
Wikipedia picture

From Mendeleev table
to Standard Model

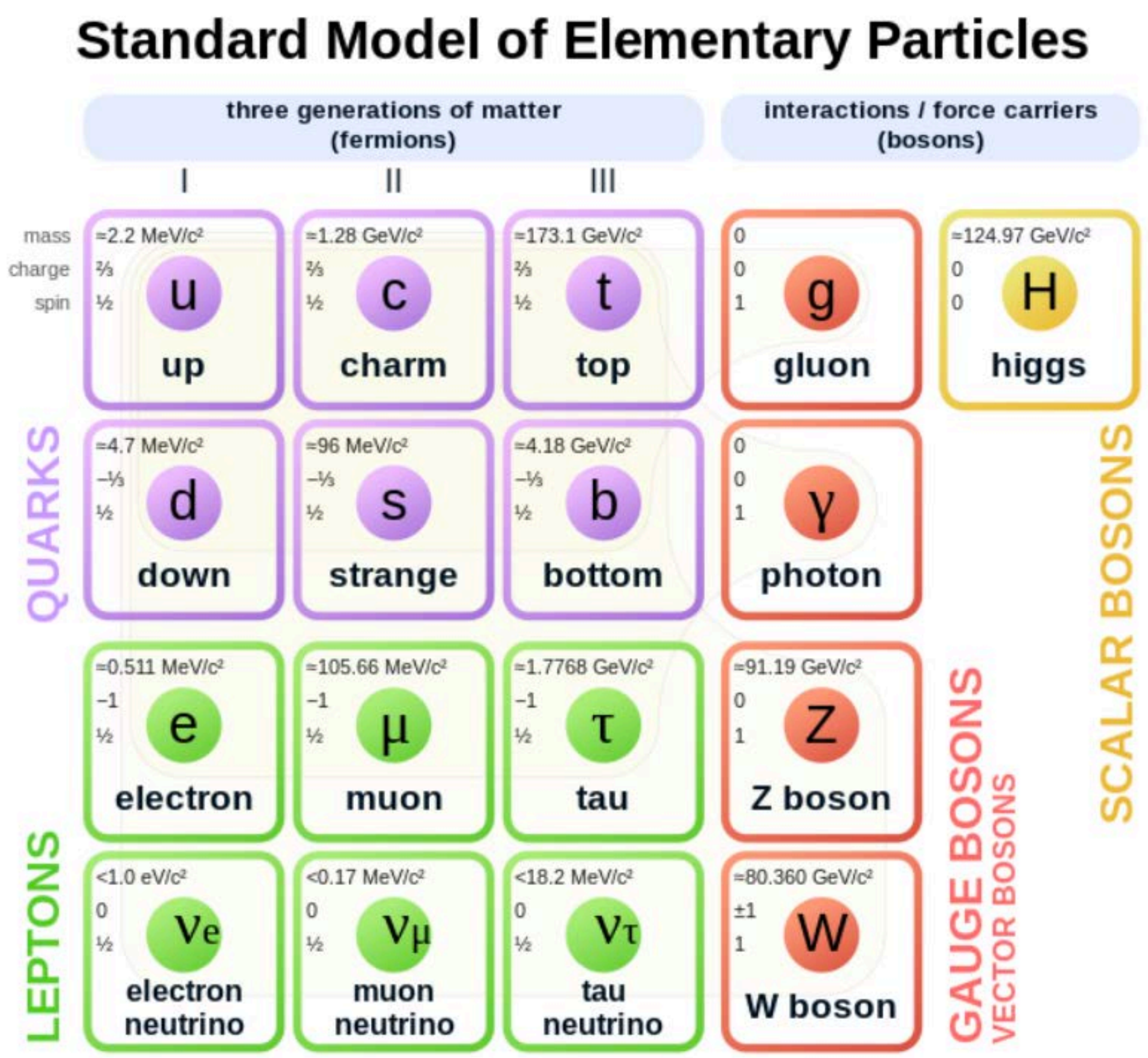


Wikipedia picture



Accurate picture

From Mendeleev table
to Standard Model



Standard Model of Elementary Particles

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QUARKS	≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
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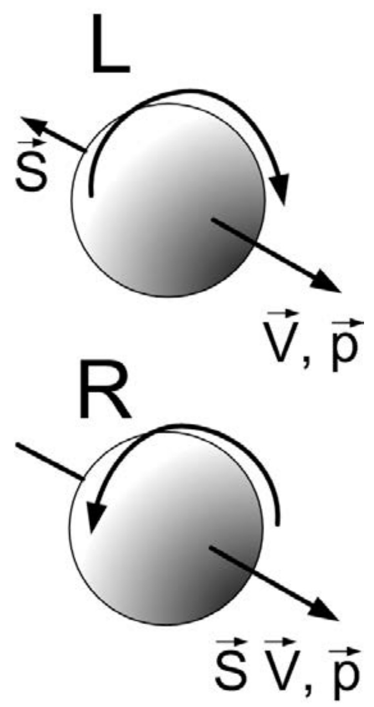
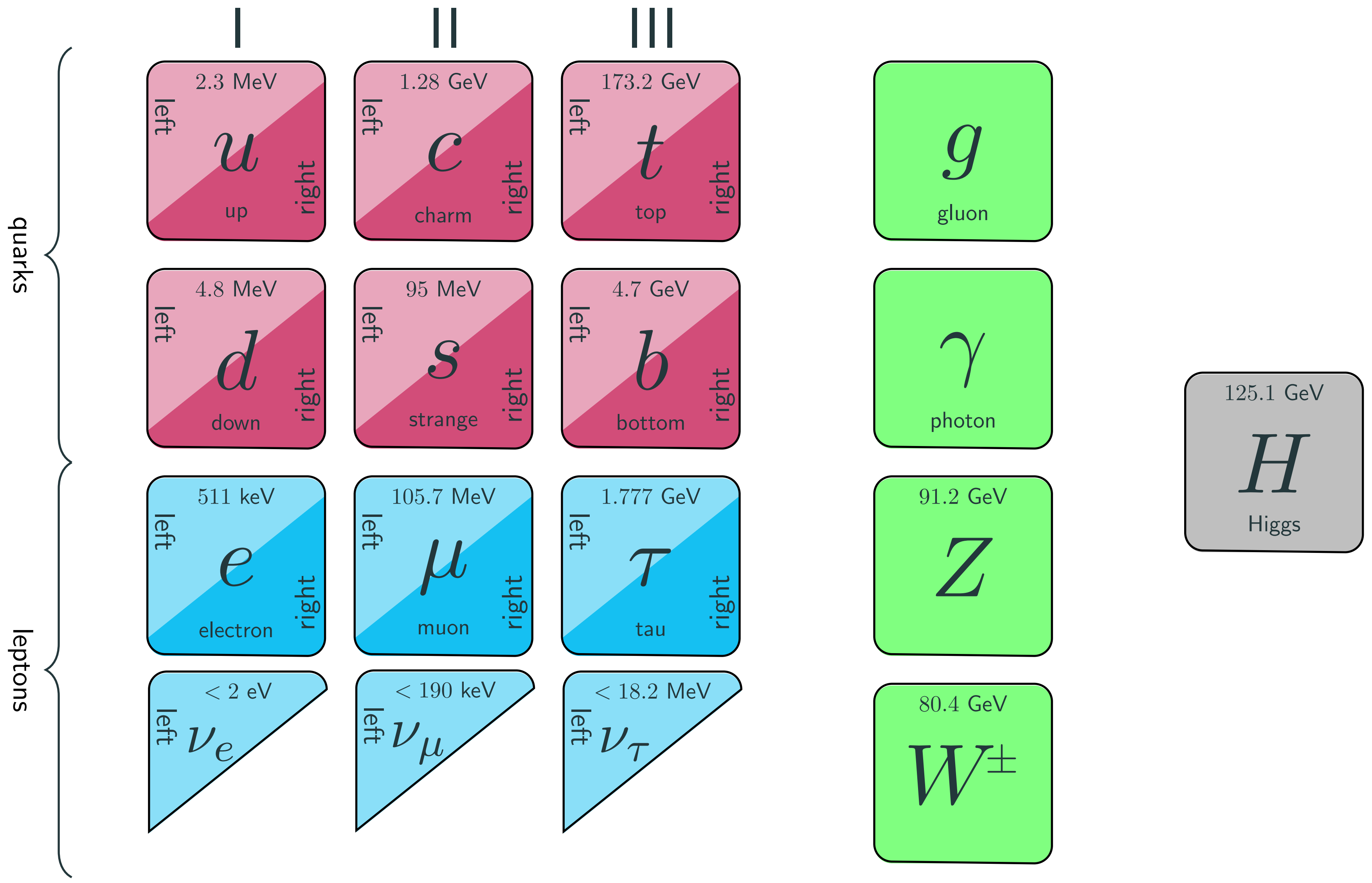
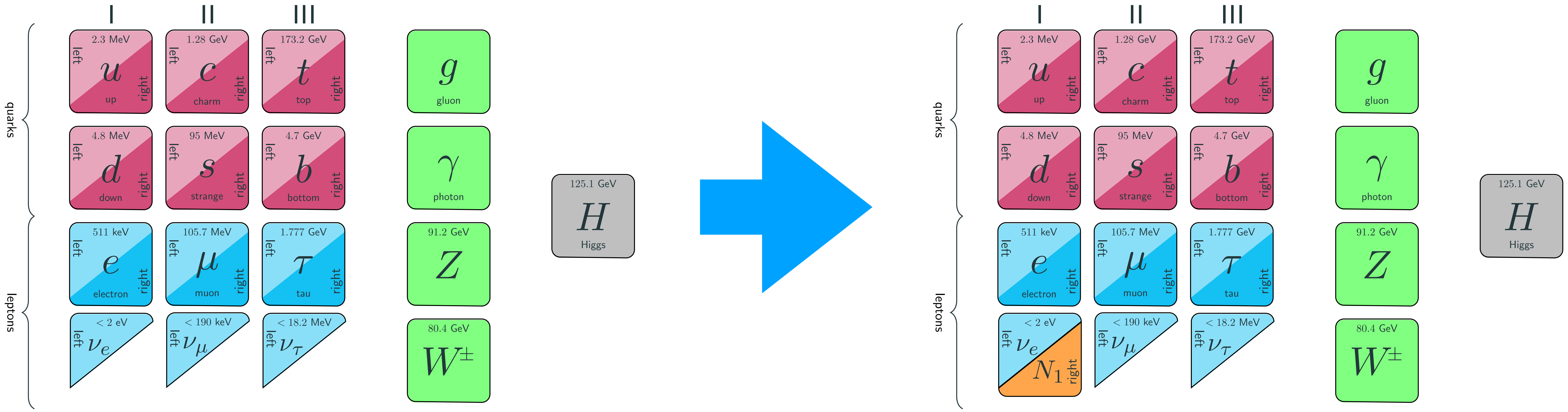




	I	II	III		
quarks	2.3 MeV left u right up	1.28 GeV left c right charm	173.2 GeV left t right top	g gluon	
	4.8 MeV left d right down	95 MeV left s right strange	4.7 GeV left b right bottom	γ photon	125.1 GeV H Higgs
leptons	511 keV left e right electron	105.7 MeV left μ right muon	1.777 GeV left τ right tau	91.2 GeV Z	
	< 2 eV left ν_e	< 190 keV left ν_μ	< 18.2 MeV left ν_τ	80.4 GeV $W^\pm$	

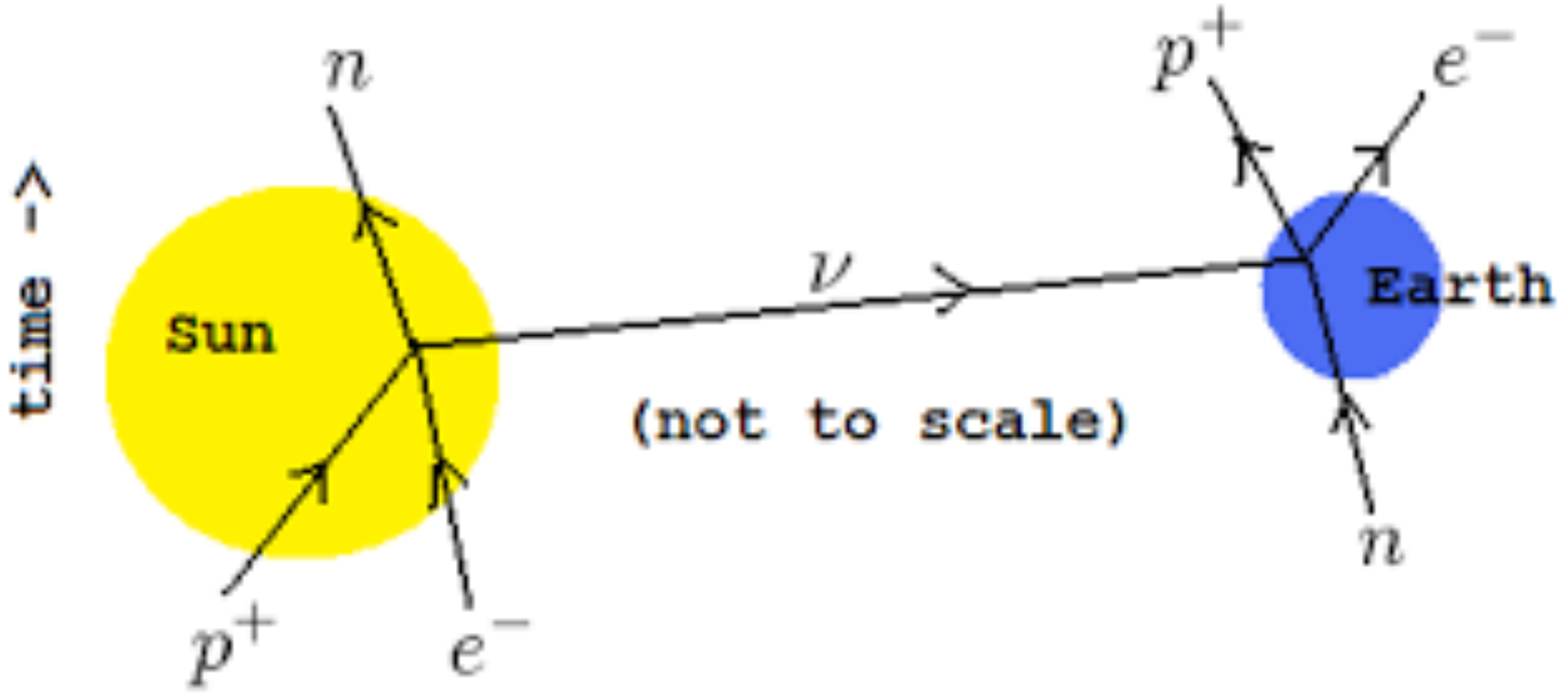
Wikipedia picture **Accurate picture**

Filling the empty boxes



Who ordered that?

⇒ Solar neutrino oscillations are explained



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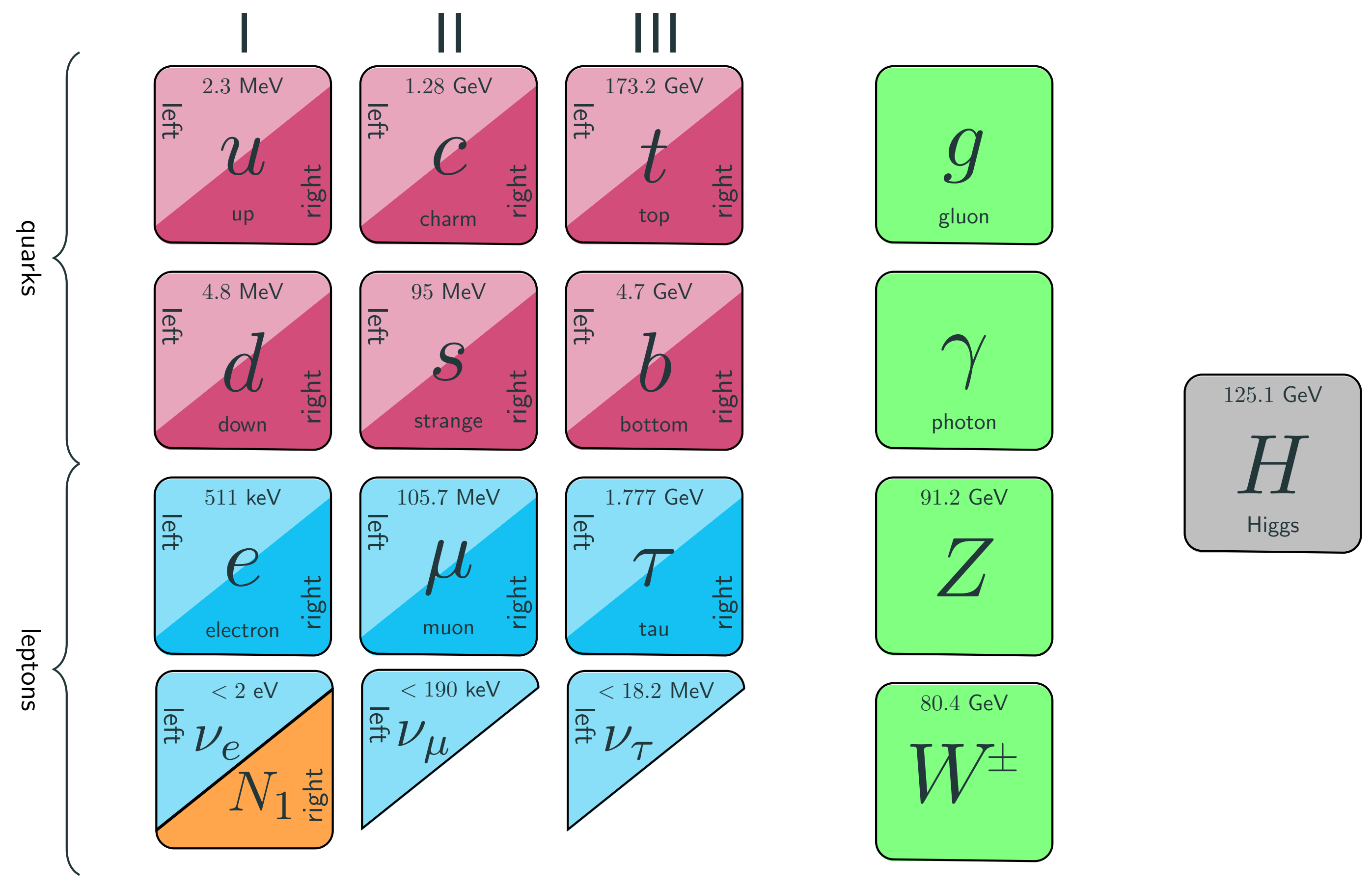

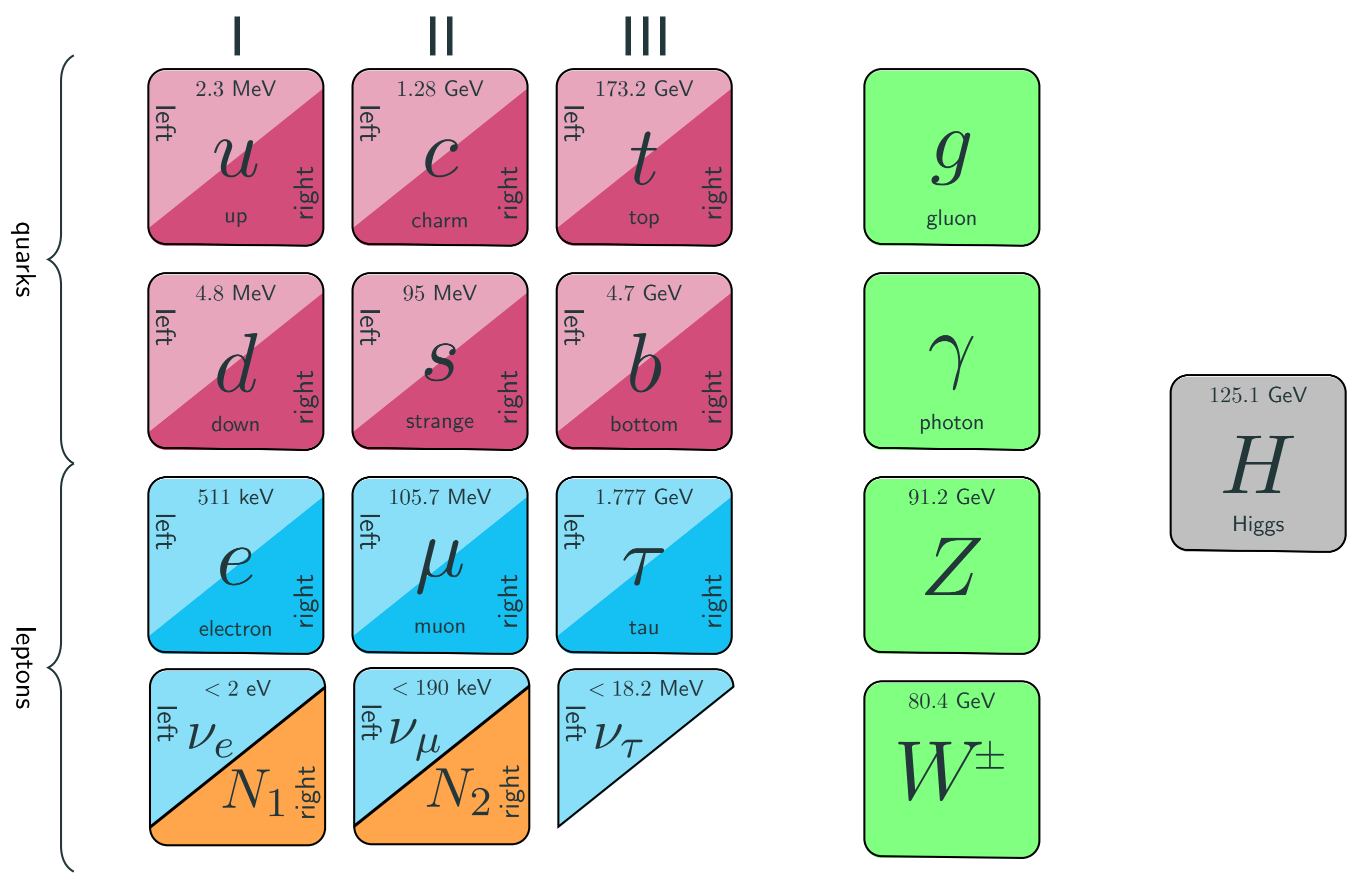

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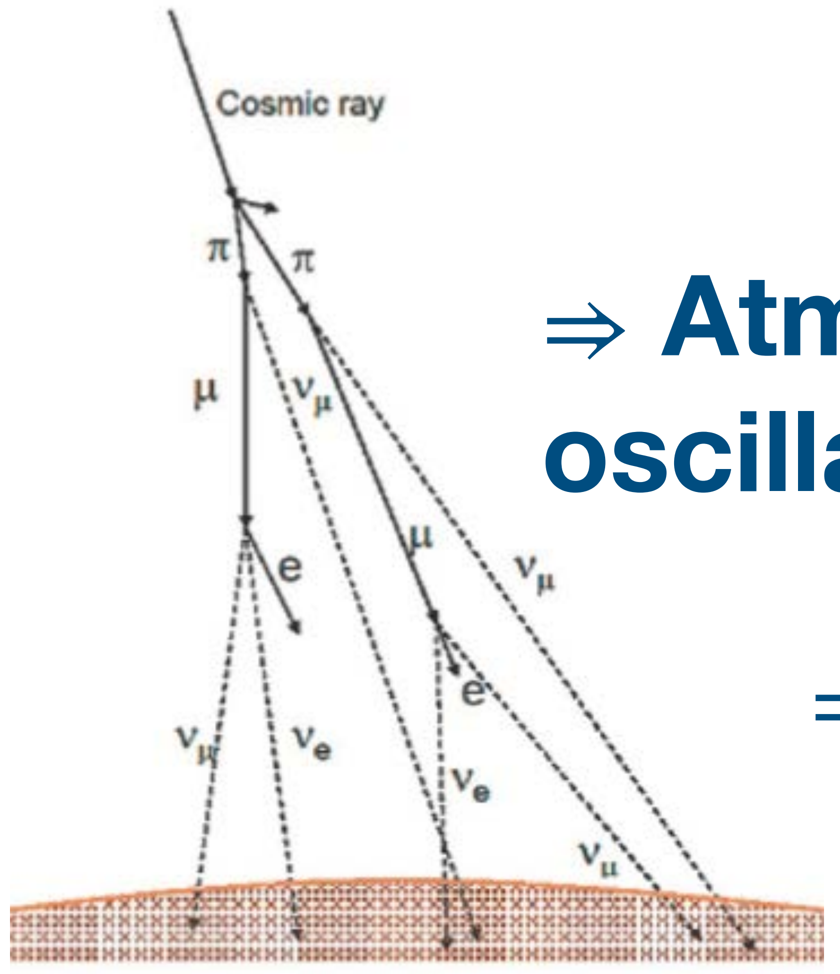
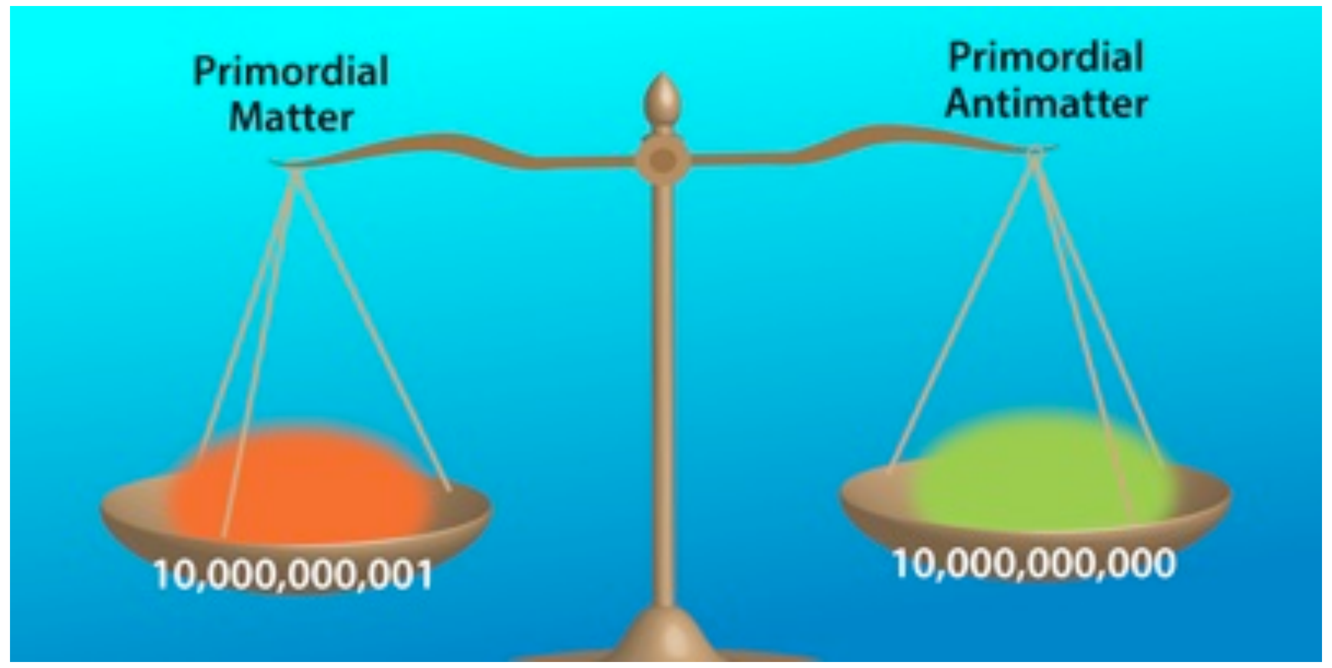


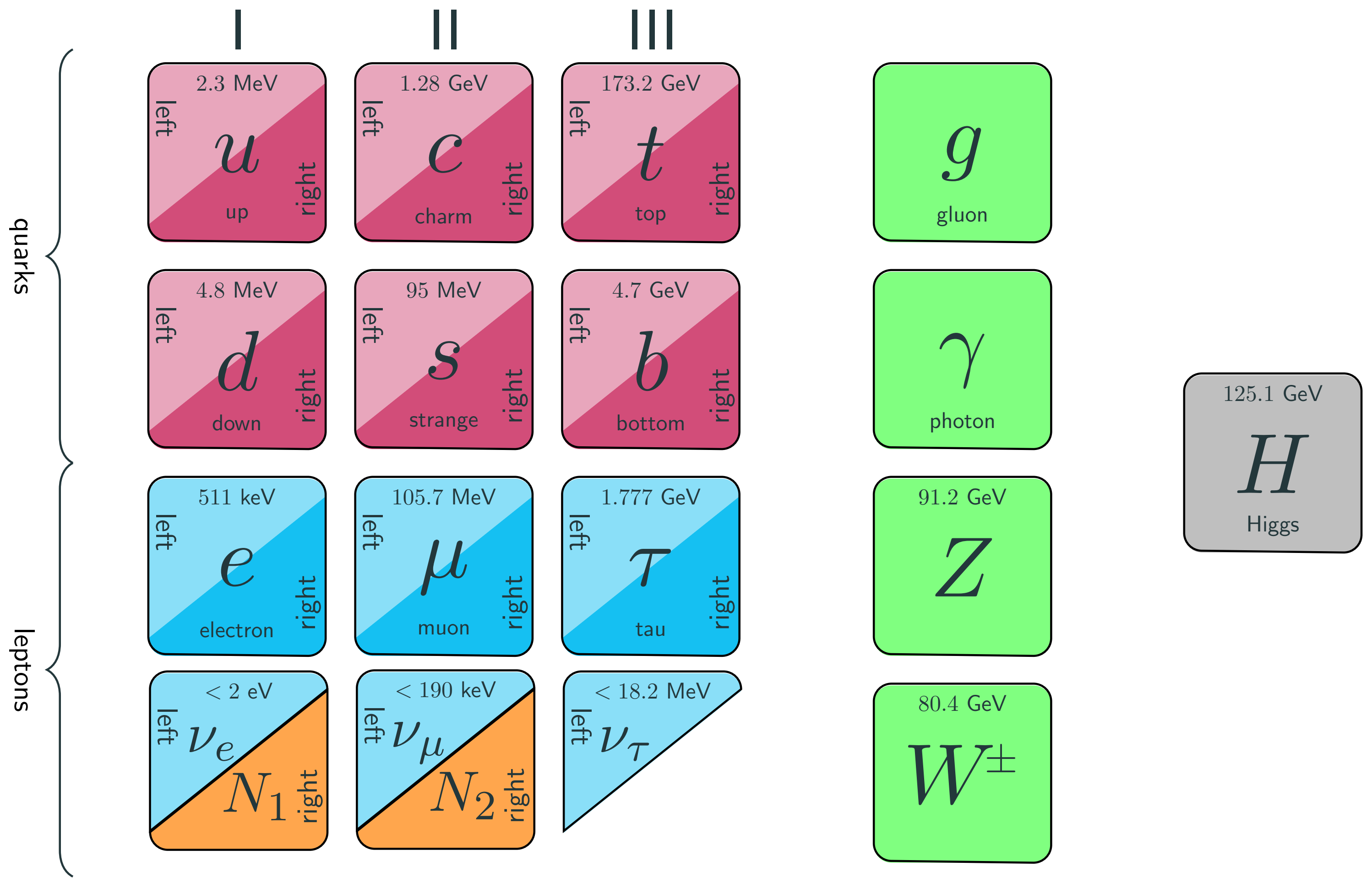
⇒ Atmospheric neutrino oscillations can be explained

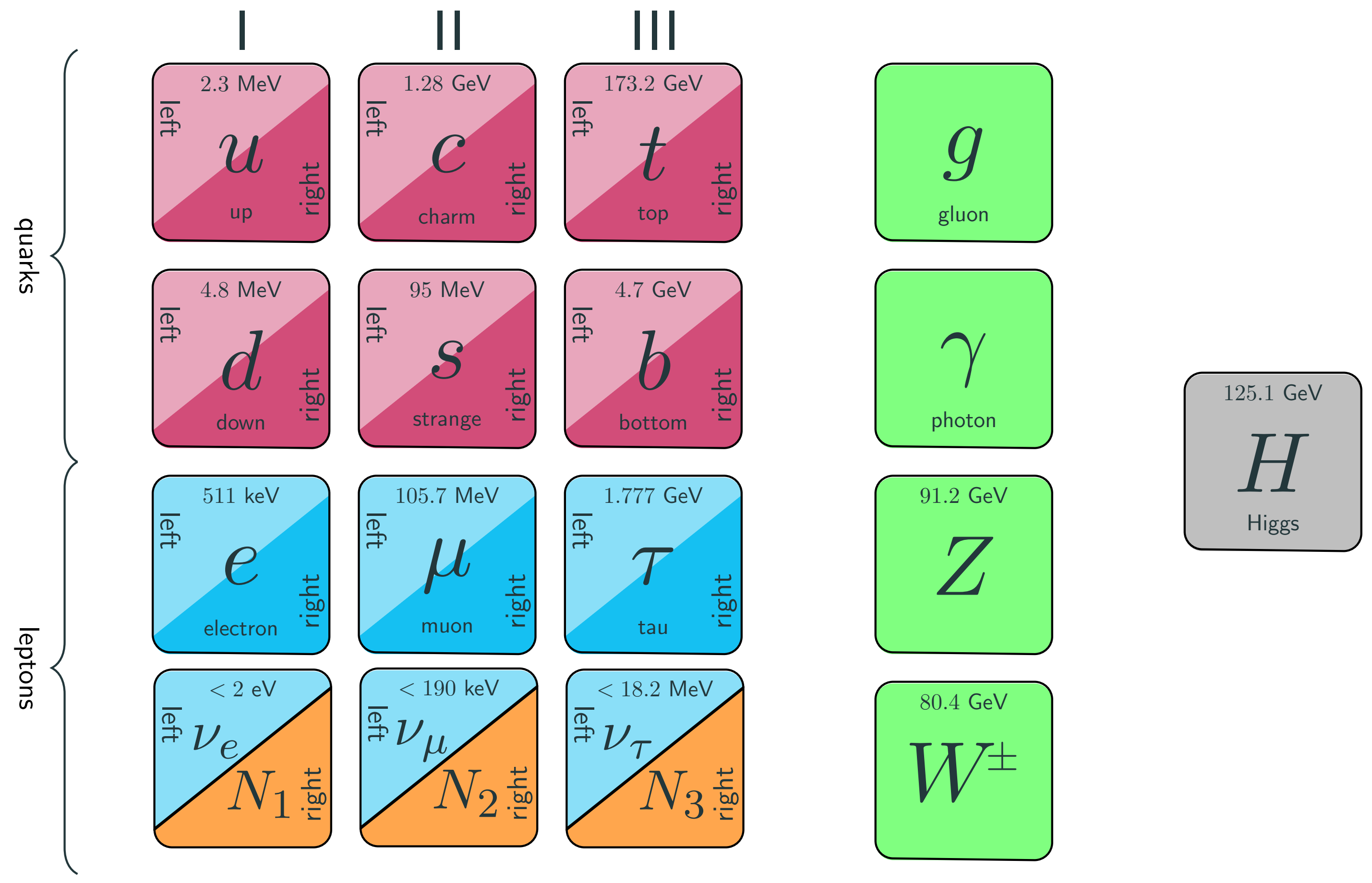
⇒ All neutrino physics can be understood

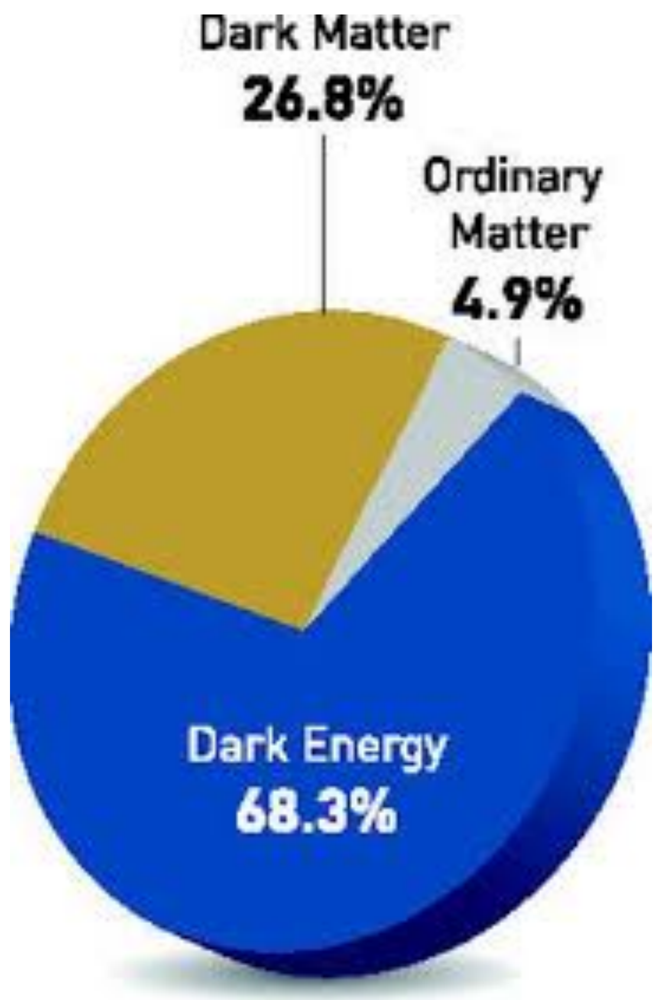


⇒ Baryon asymmetry of the Universe can be explained.

Filling the empty boxes







Who ordered that?

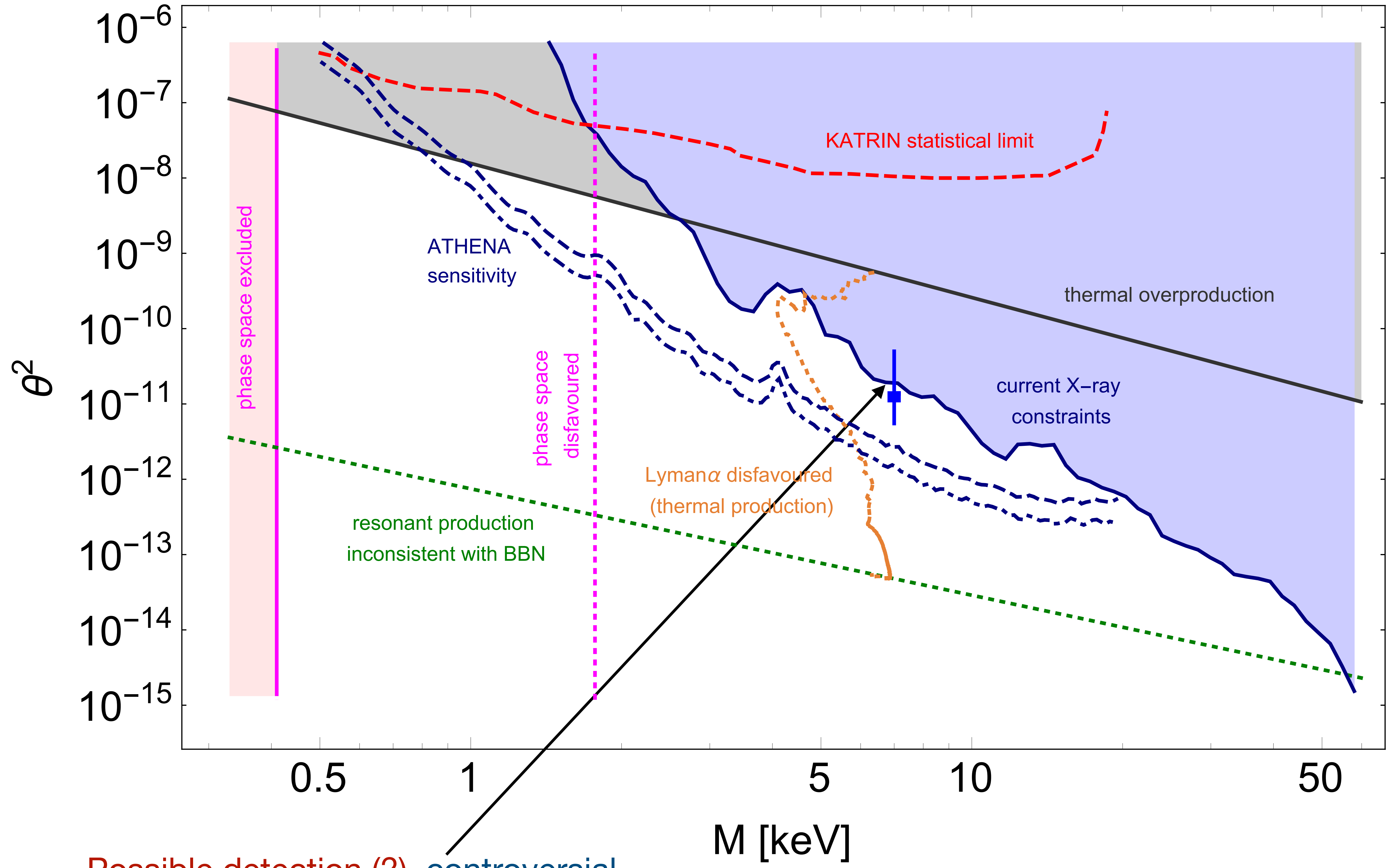
⇒ Dark matter in the Universe can be explained.

New particles are called “Heavy neutral leptons” NHL, sometimes sterile neutrinos.

Model: the νMSM (neutrino minimal Standard Model)

Dark Matter

Dark matter HNL: long-lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N \to \gamma\nu$, what allows for experimental detection by X-ray telescopes in space.

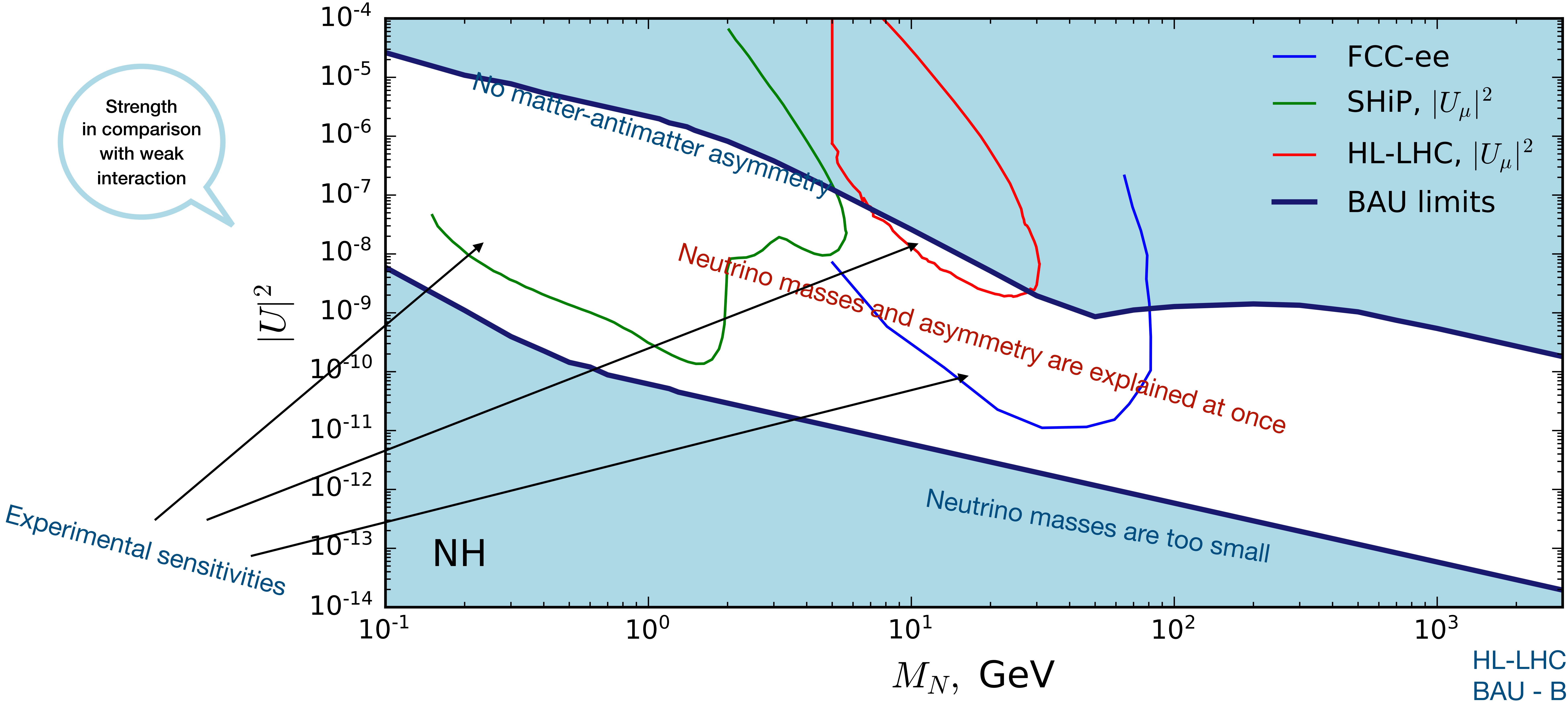

Available parameter space

Possible detection (?), controversial
Bulbul et al; Boyarsky et al

Future experimental searches:
- Xrism satellite (launched in 2023)
- Large ESA X-ray mission Athena + (2028?)

Theoretical challenges:
How DM sterile neutrinos are produced in the early Universe?
What is their spectrum?
Warm or cold Dark Matter?

Matter-antimatter asymmetry and neutrino masses



Strength
in comparison
with weak
interaction

HL-LHC - High Luminosity Large Hadron Collider
BAU - Baryon asymmetry of the Universe
NH - normal neutrino hierarchy

The mechanisms of neutrino mass and matter-antimatter asymmetry generation can be verified experimentally.

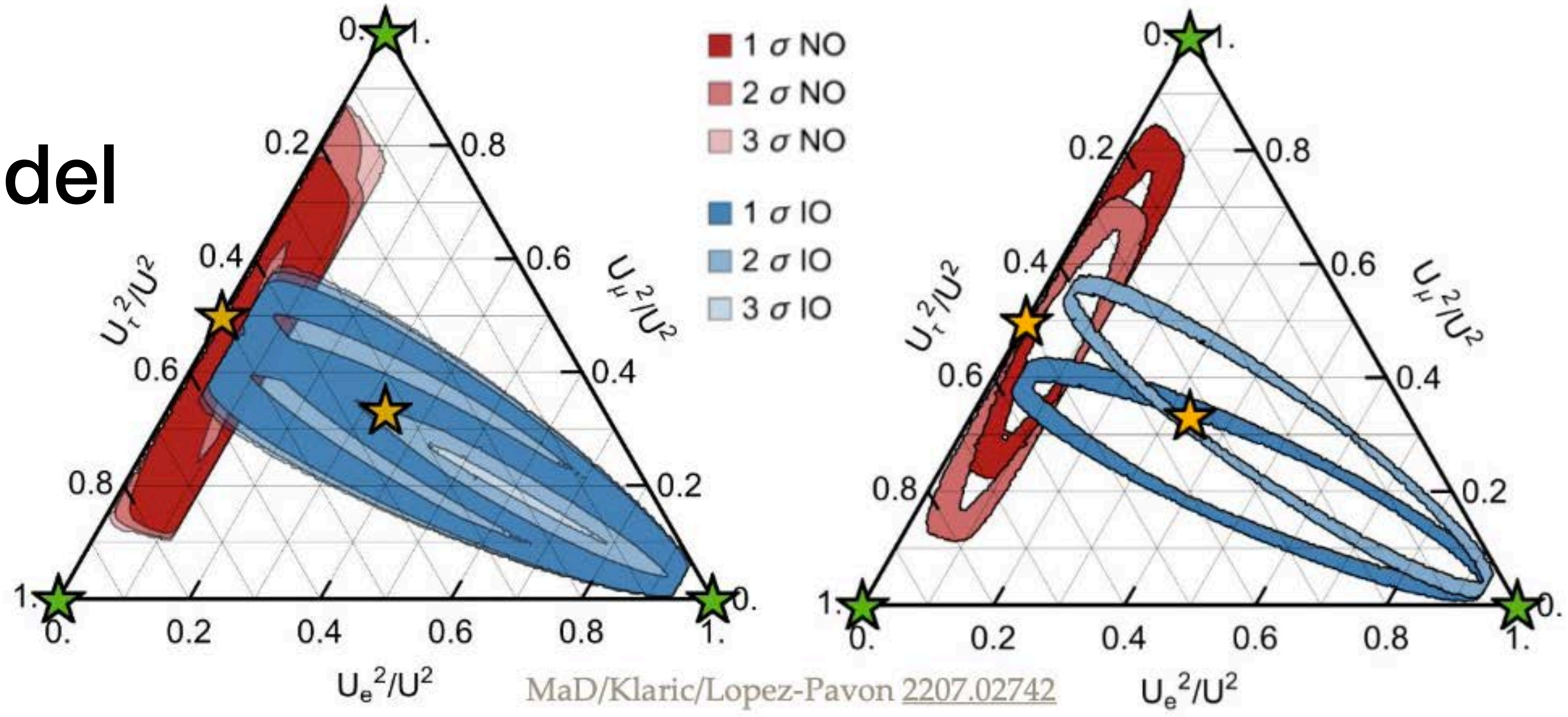
Exciting connection with neutrino physics

Total number of parameters of the Model: 11, with 5 already known from neutrino experiments, 6 unknowns. Number of future inputs (ν experiments, SHiP and FCC-ee) is at least 6:

- Dirac phase in PMNS matrix (1), neutrinoless double β-decay rate (1), HNL average mass $\bar{M} = (M_2 + M_3)/2$ (1), HNL mixings with e, μ and τ flavours (3)
- Very challenging measurements: HNL mass difference $\Delta M = M_2 - M_3$ is required to be small from

Testable model

U_e- coupling to electron
U_μ-coupling to muon
U_τ-coupling to tau



MaD/Klaric/Lopez-Pavon 2207.02742

Current constraints

DUNE projection

Hernández et al,
1606.06719

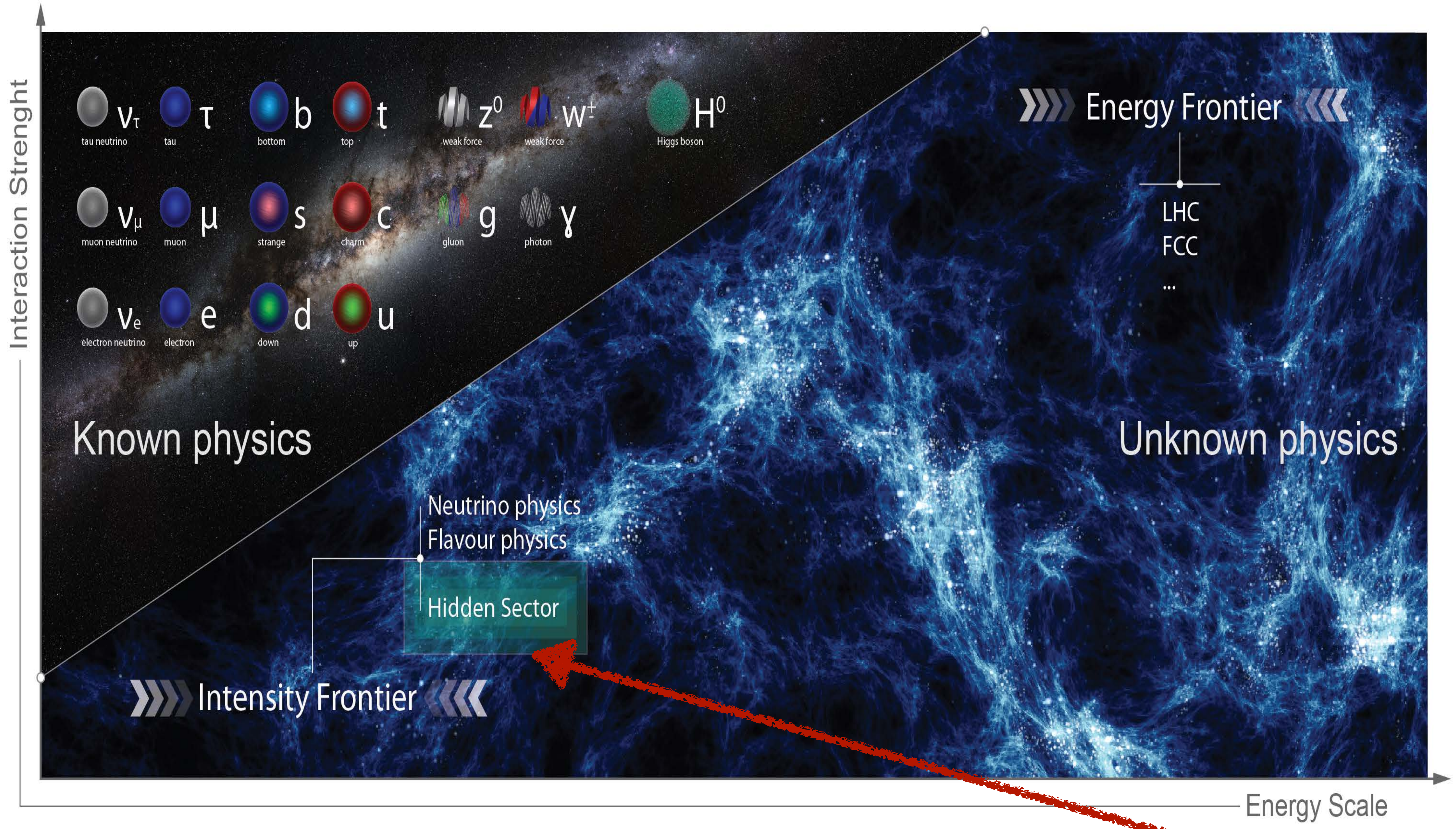
Important remark

Many other extensions of the SM explaining neutrino masses, baryon asymmetry of the Universe and Dark matter are possible and under intensive investigations. They contain more parameters and are less predictive.

How to search for this type of New physics?

Precision frontier. The **indirect** search for New Physics: measurements of possible deviations from the SM at any energy scale in high-precision experiments (e.g. LHCb, NA62, …)

Energy frontier. The **direct** search for New Physics: observation of new phenomena at high energies, such as the production of new types of massive particles (e.g. ATLAS, CMS, …).



Intensity frontier. The **direct** search for New Physics: looking for feebly interacting, relatively light particles using high intensity beams (e.g. SHiP, …)

New light long-lived particles

Feebly interacting hidden particles

"Feebly" = weaker than weak interactions

Other extensions of the SM offer extra feebly interacting particles: hidden photon, dark scalar, axion-like particles, etc…

Common features of feebly interacting hidden particles

- Can be produced in decays of different mesons (π, K, charm, beauty) , Z and W
- Can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Experimental search for hidden particles

Hidden particle production and decays are highly suppressed
=> Dedicated experiments are needed:

- **New generic purpose experiments** to search for all sorts of relatively light dark sector particles (heavy neutral leptons, dark photons, hidden scalars, etc).
- **The existing experiments** adapted for the quest of hidden sector particles.

Generic requirements for fixed target and collider experiments

- Have a high number of protons on target (pot), with the energy enough to produce charmed (or beauty) mesons or W and Z.
  Or, tune e^+e^- energy to Z-resonance.

- Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)

- Have the detector as large as possible to increase the probability of hidden particle decay inside the detector

- Have the detector as empty as possible to decrease neutrino and other backgrounds

Searches for dark sectors

NA62 P326

SHiP
Search for Hidden Particles

DARKLIGHT

Belle II

CMS Compact Muon Solenoid

T2K

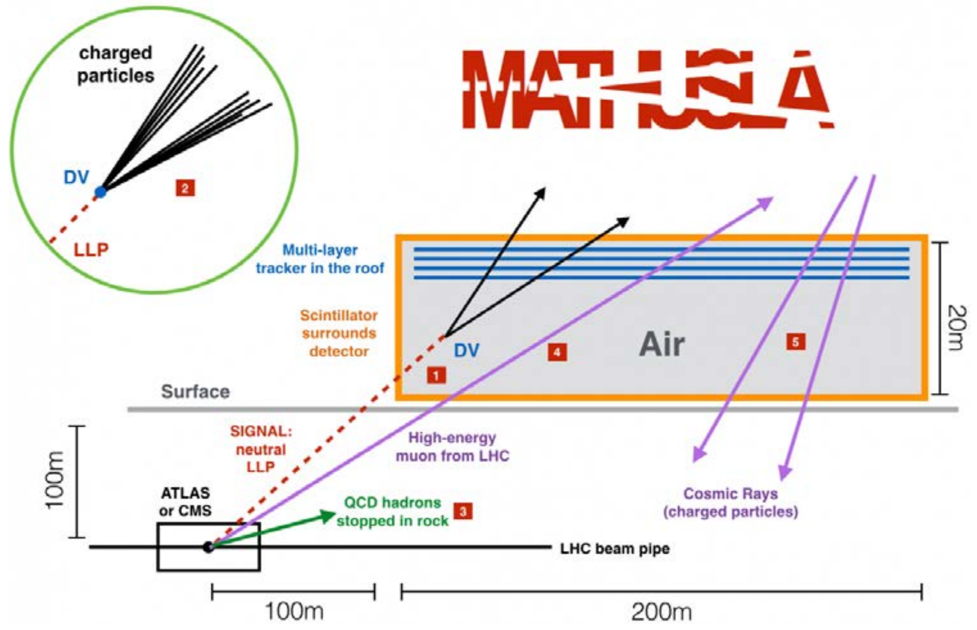
LHCb

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

ATLAS EXPERIMENT

NA64 Search for dark sectors in missing energy events

MATHUSLA

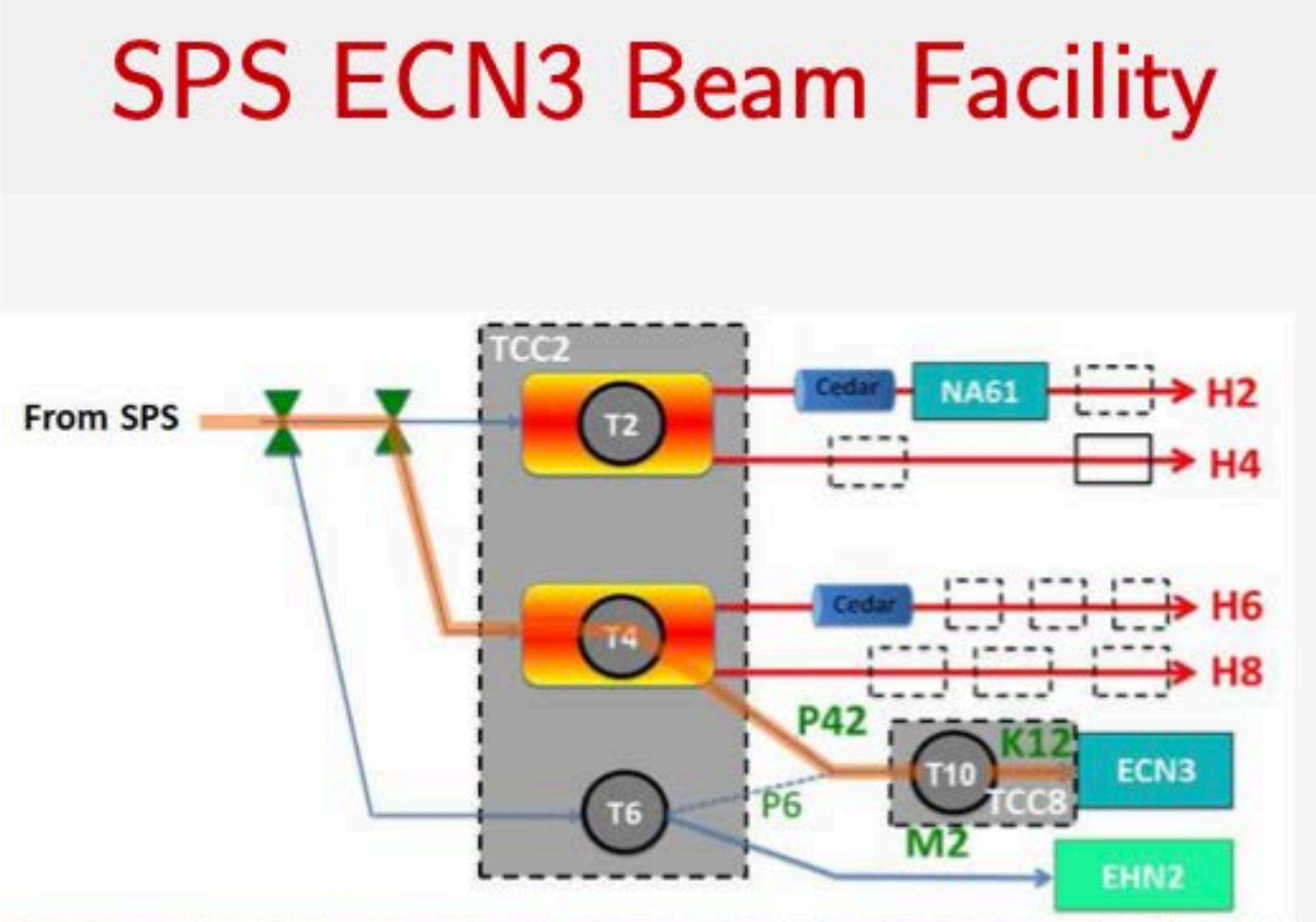


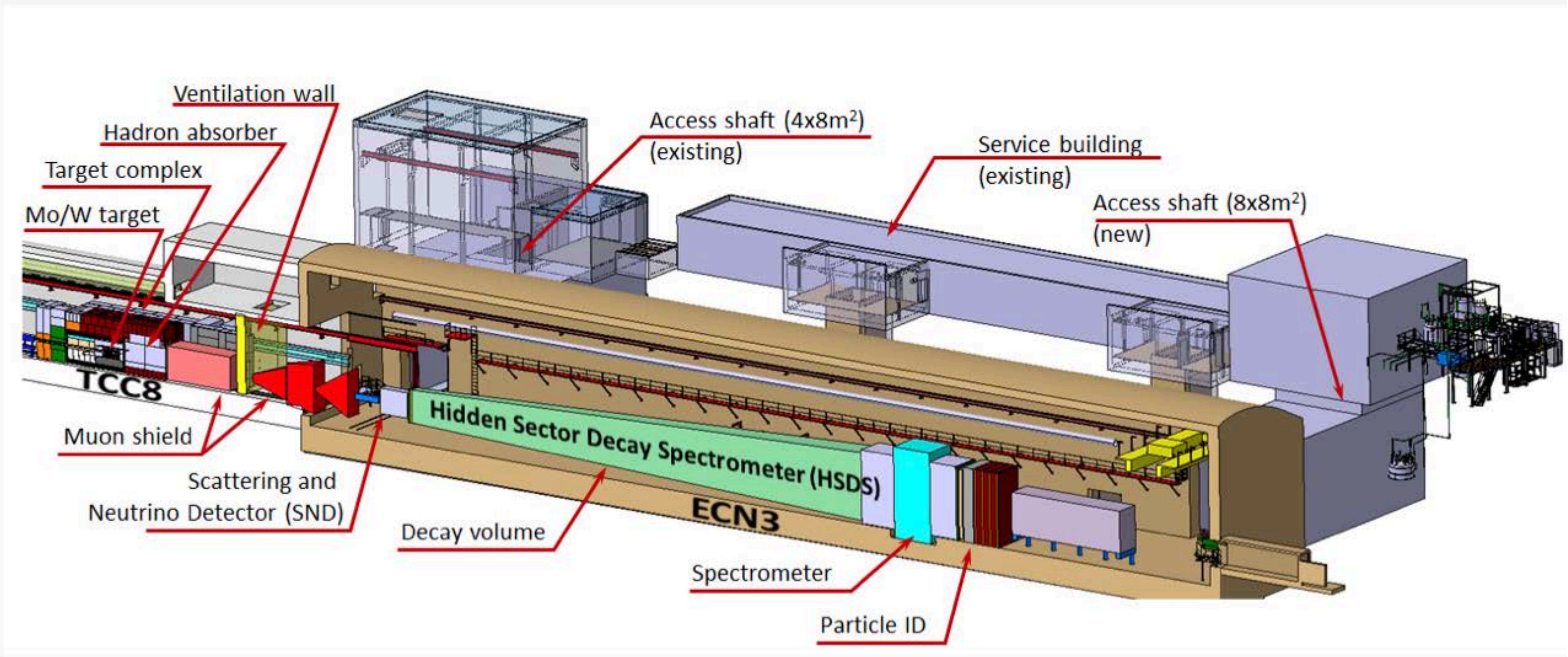
FCC hh ee he

FASER

SHiP
Search for Hidden Particles

High intensity proton beam at CERN SPS (400 GeV)

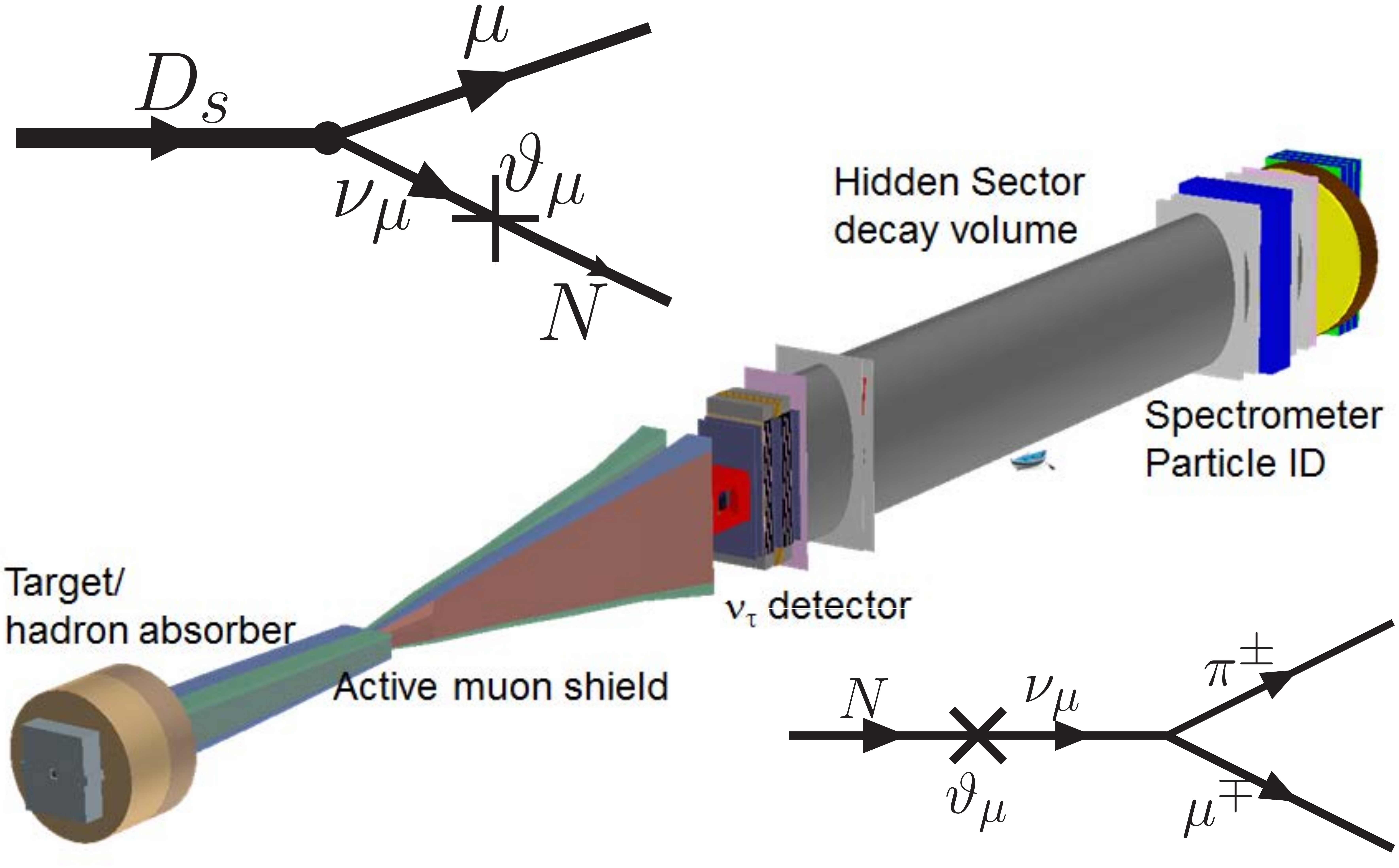

SPS ECN3 Beam Facility



Experiment selected at CERN in March 2024, data taking in 2031 (?) **https://ship.web.cern.ch/**

Sensitivity in number of events is ~ 10,000 times better than in previous experiments

SHiP experiment



Hidden Sector
decay volume

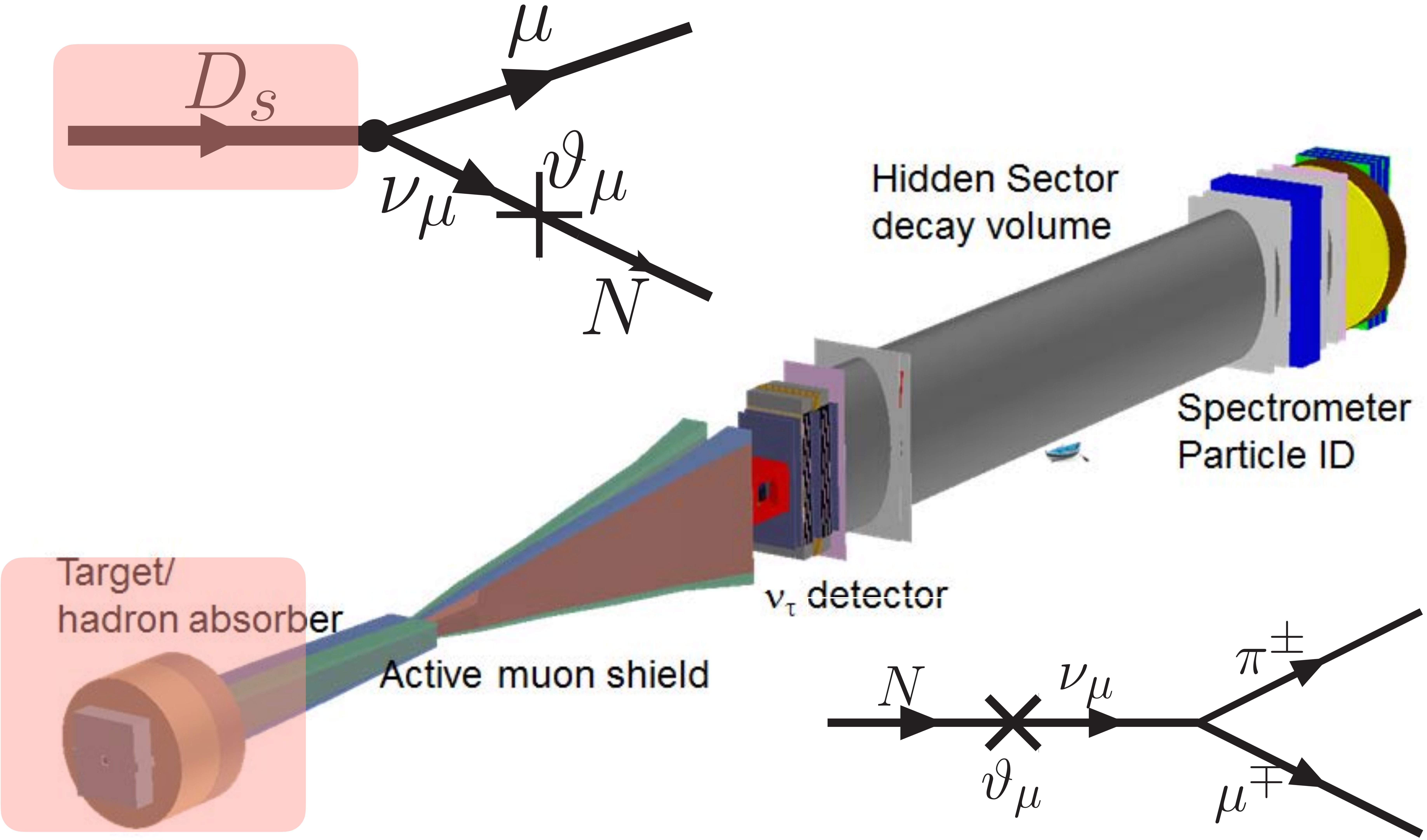
Spectrometer
Particle ID

ν_τ detector

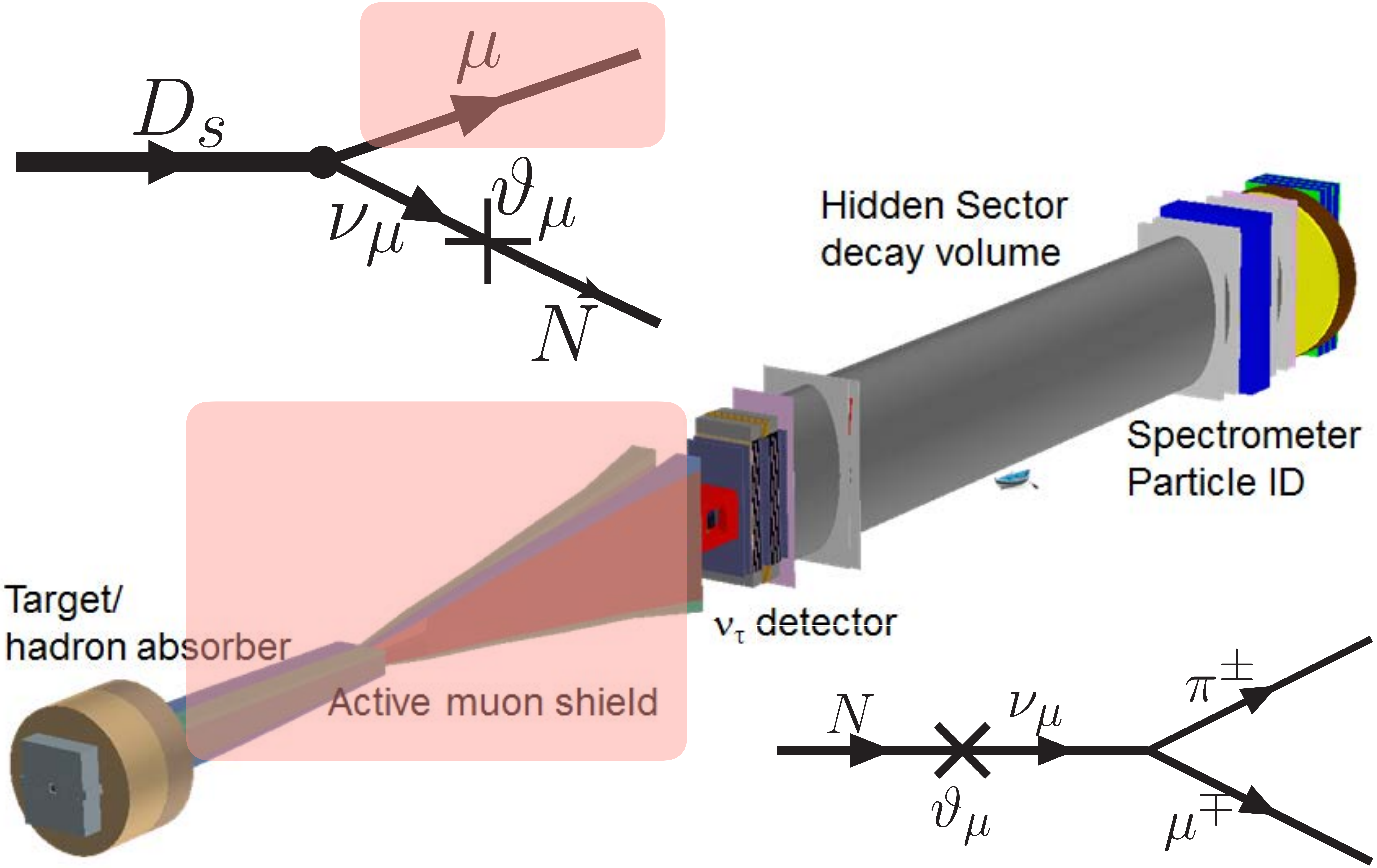
Target/
hadron absorber

Active muon shield

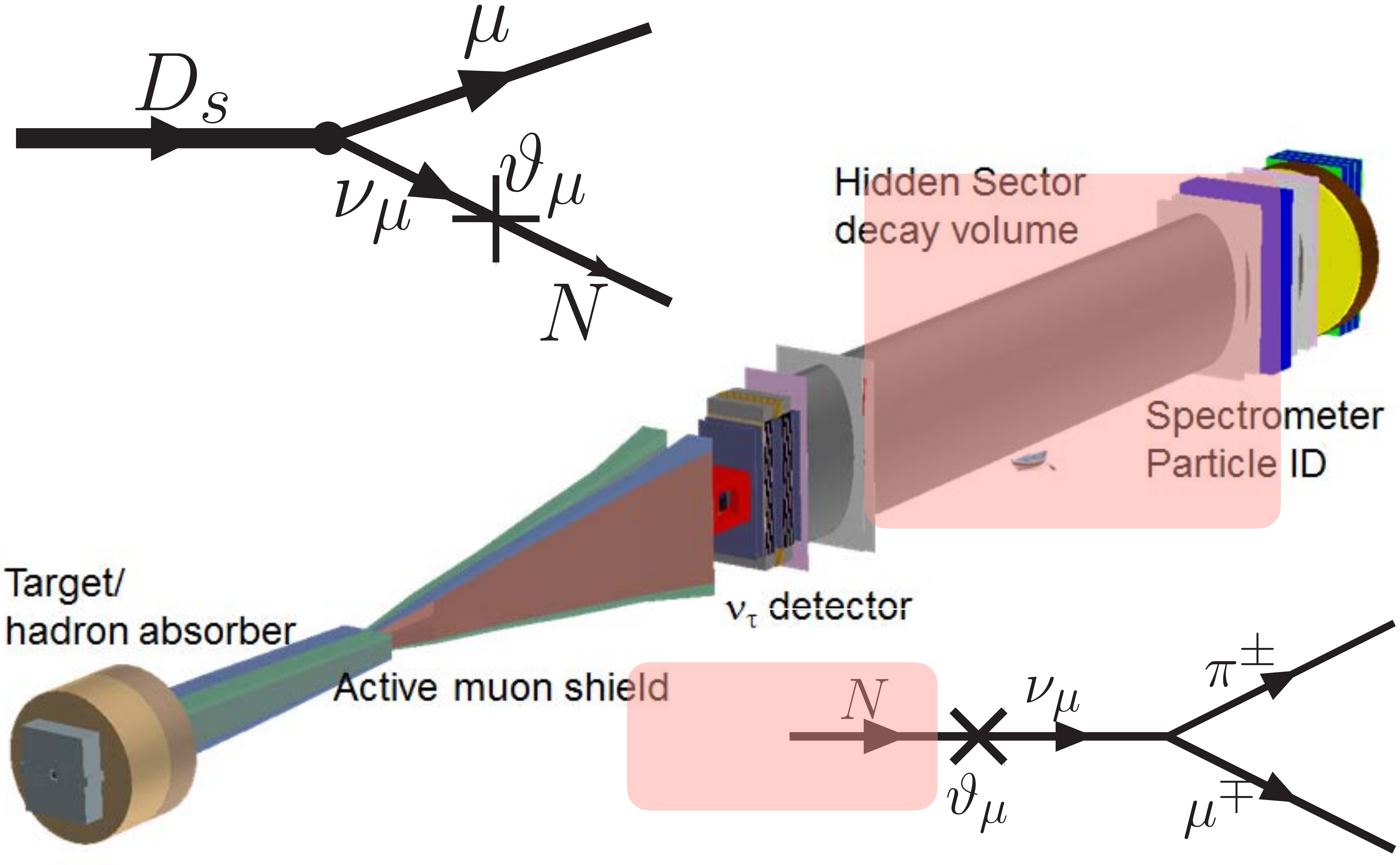
SHiP experiment



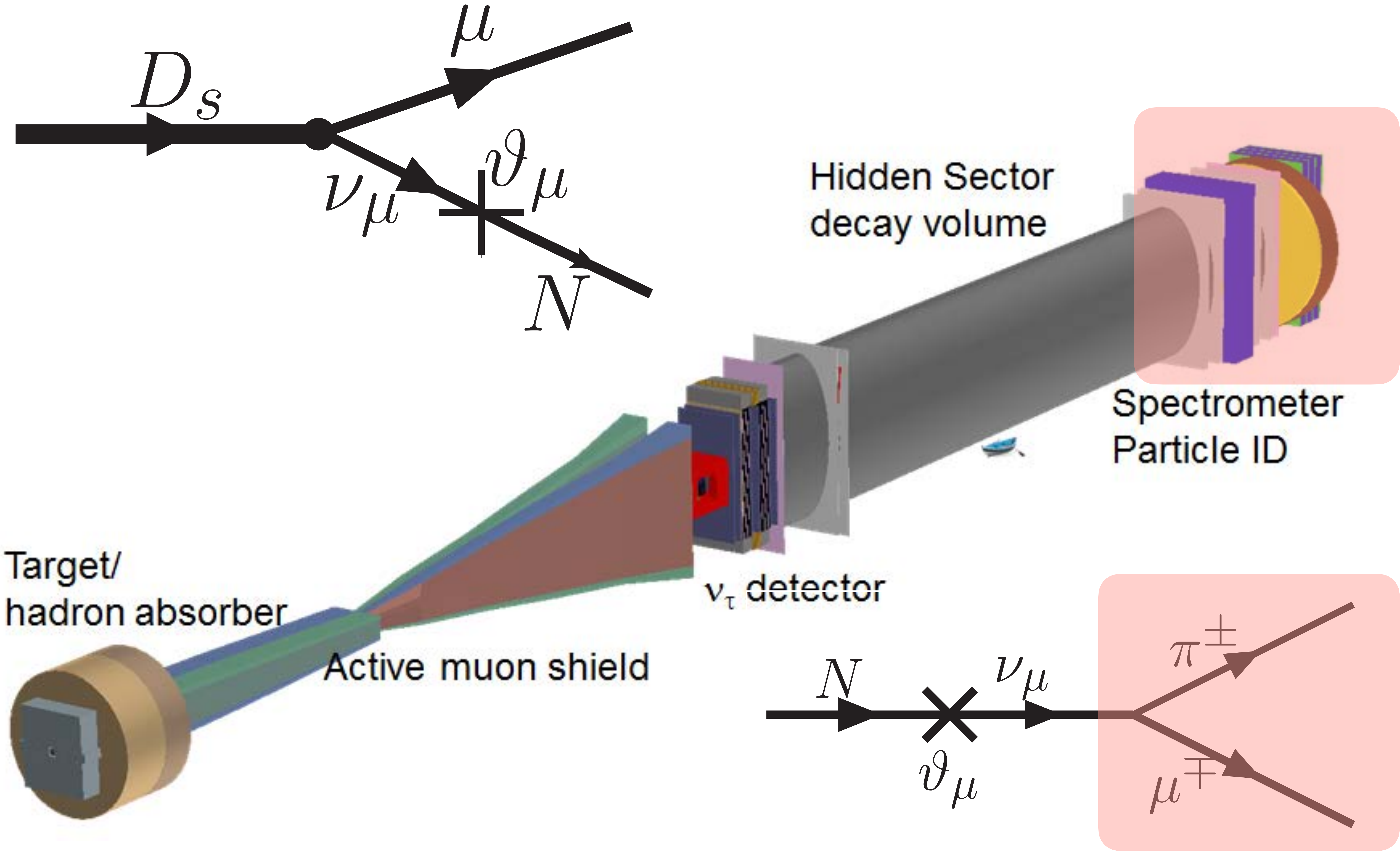
SHiP experiment



SHiP experiment



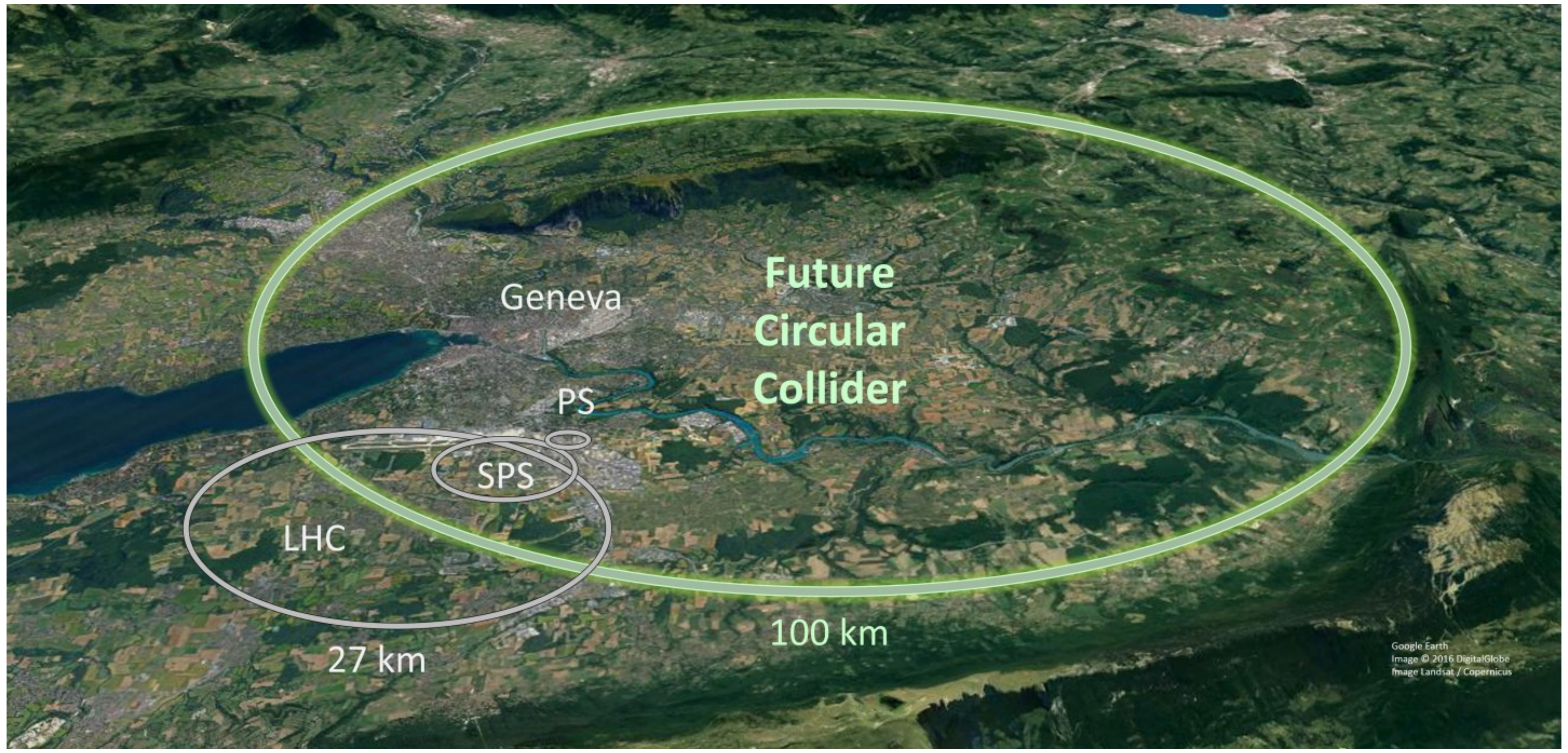
SHiP experiment



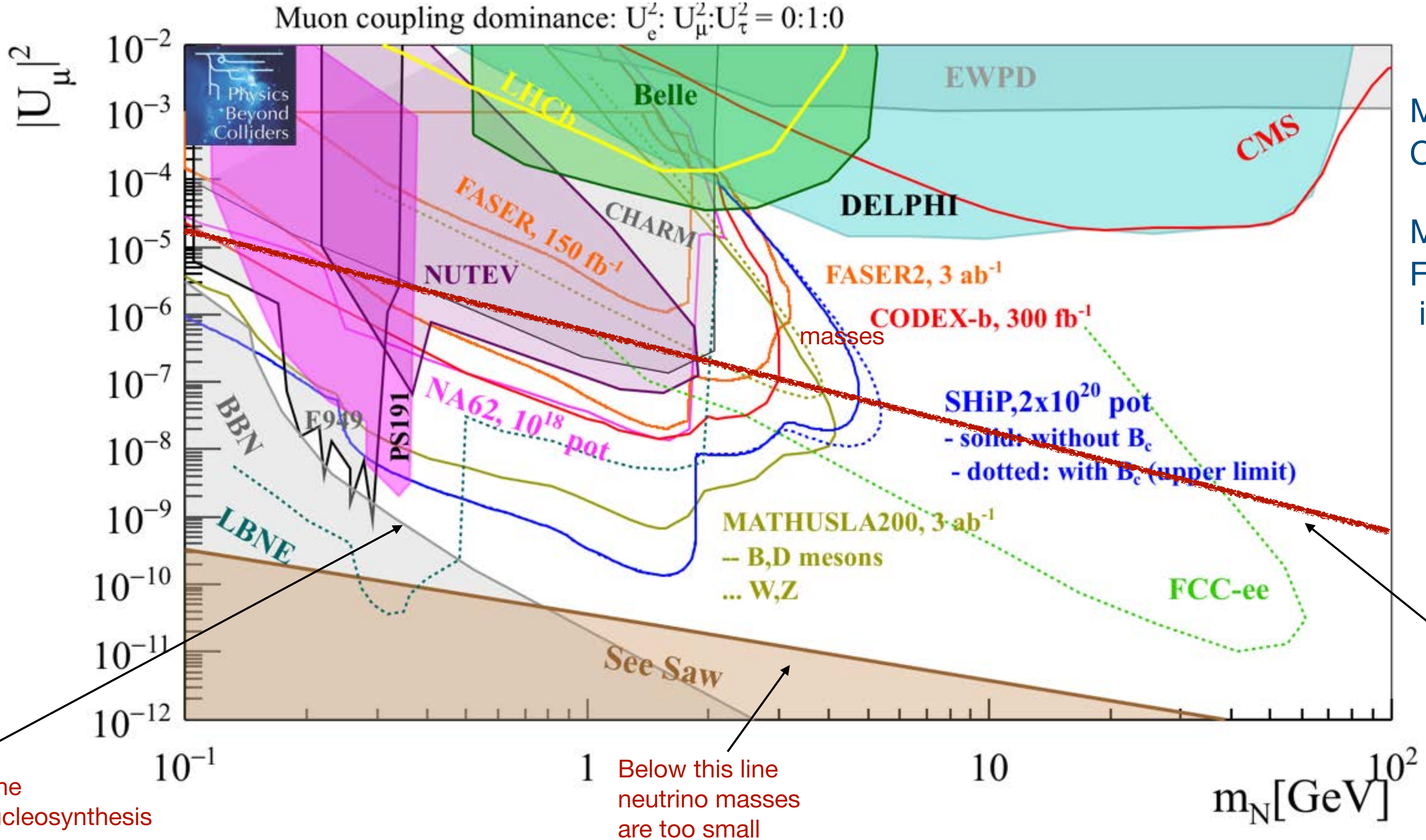
FCC-ee

Heavier $N_{2,3}$ can be searched at Future Circular Collider in e^+e^- mode (FCC-ee), with energy tuned to Z-boson resonance:

$$e^+e^- \to Z \to \nu N,\ N \to l\pi$$



Projection of bounds on HNLs



Mass below ~ 3 GeV -
CERN SPS: SHiP

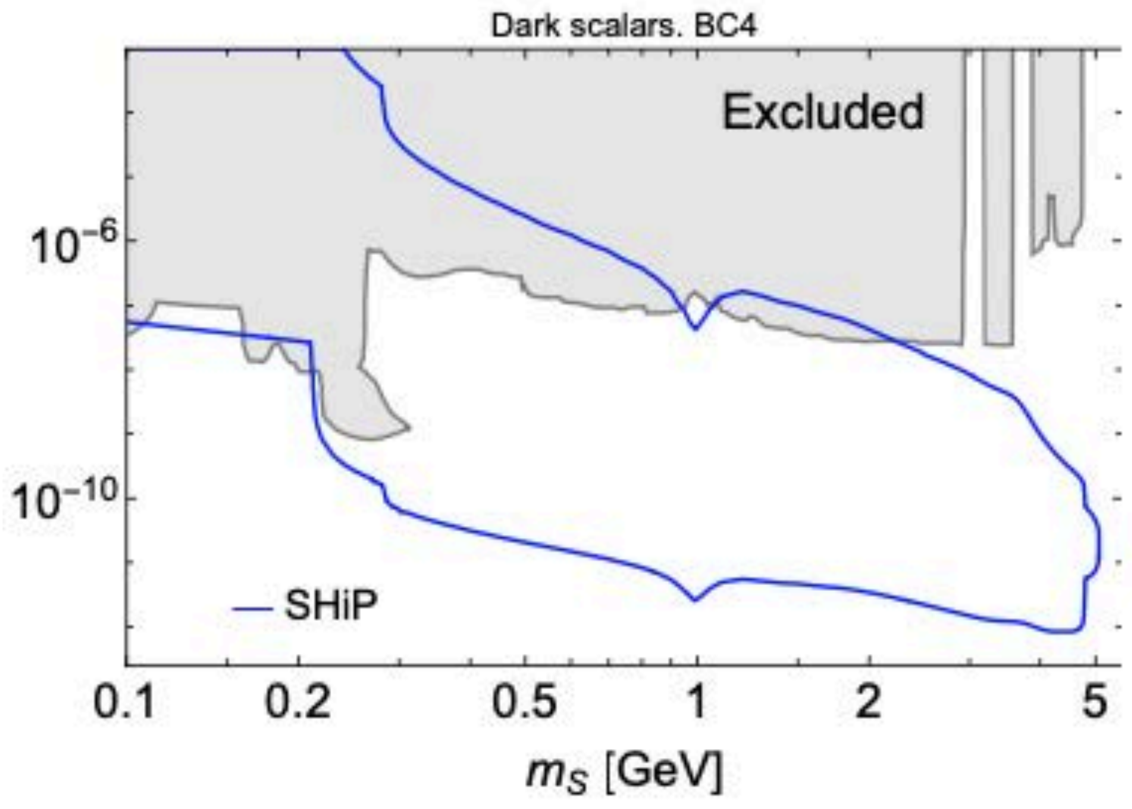
Mass above ~ 3 GeV -
FCC, CEPC in e+e− mode
in Z-peak, LHC

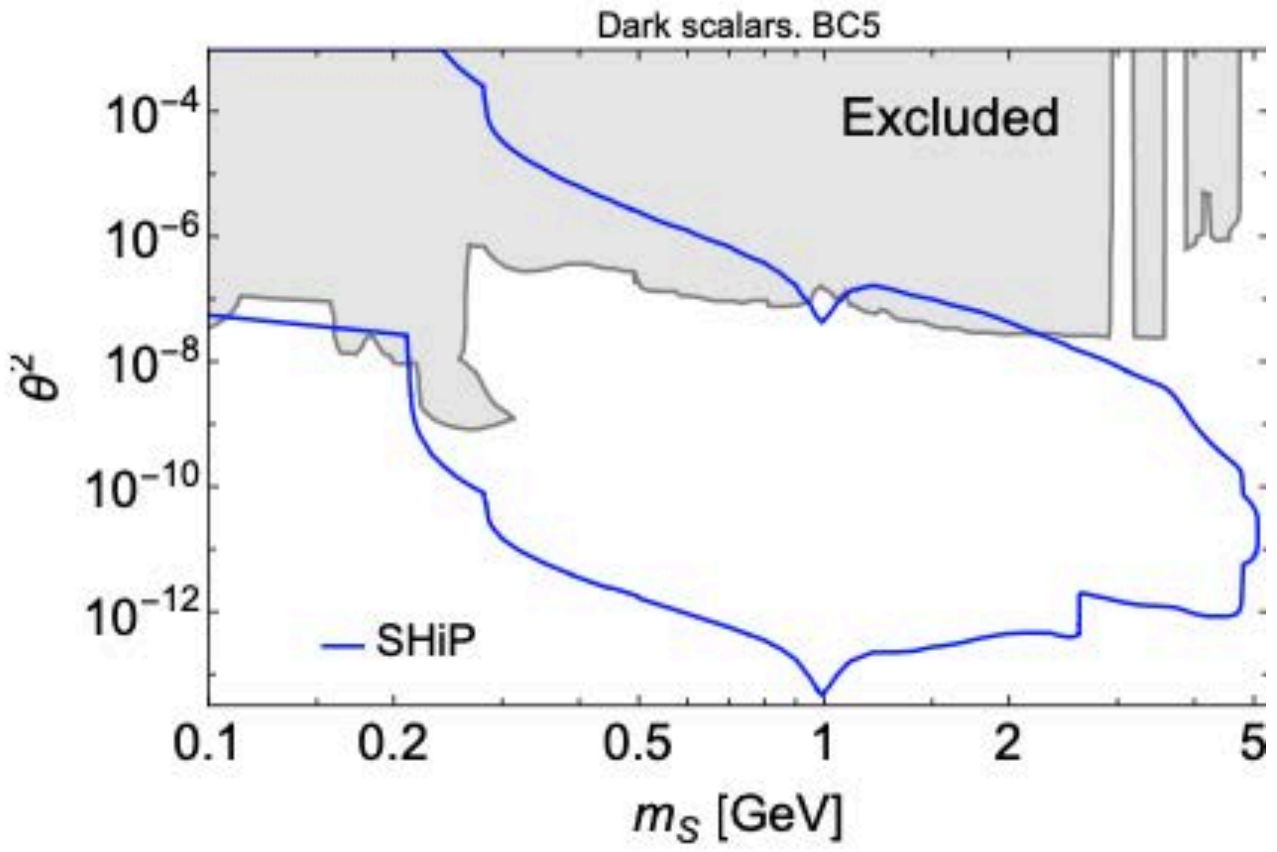
Below this line
neutrino masses
and baryon asymmetry
can be explained at once

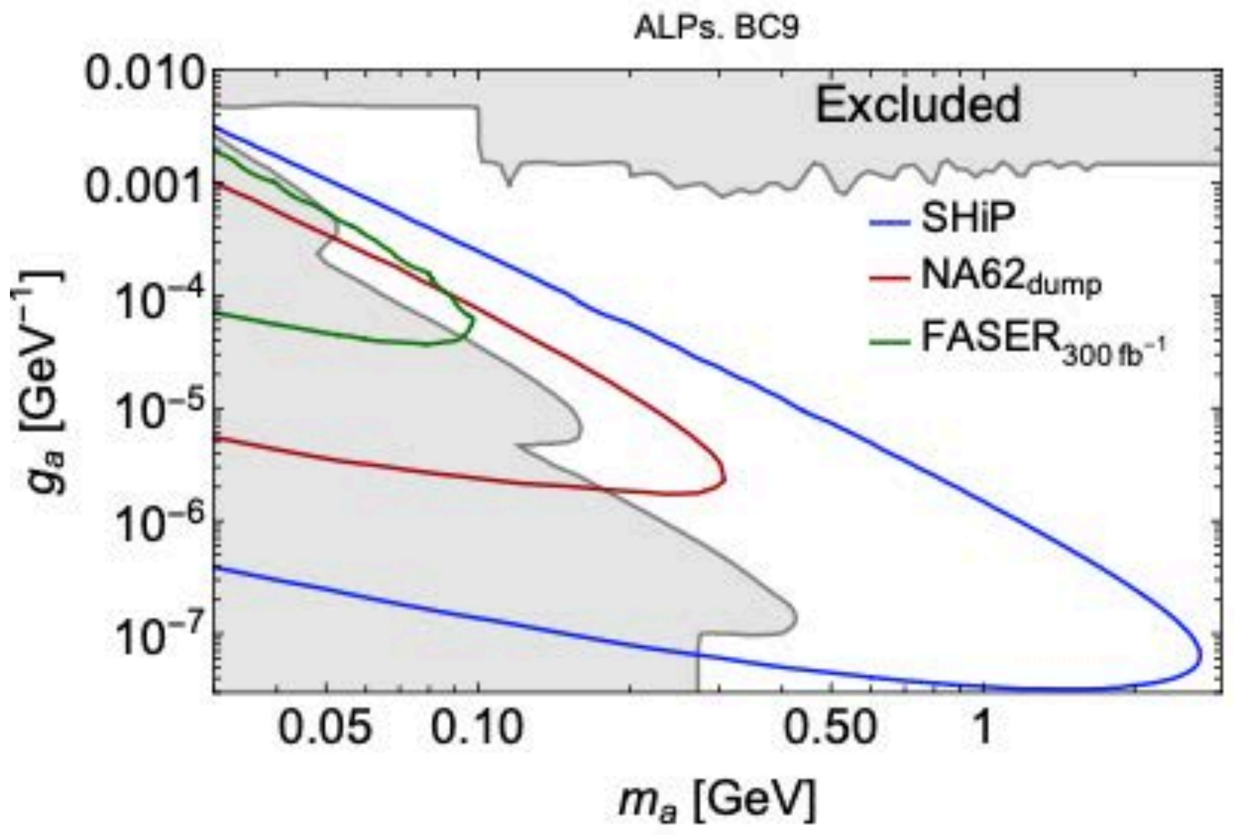
Below this line
Big Bang Nucleosynthesis
is spoiled

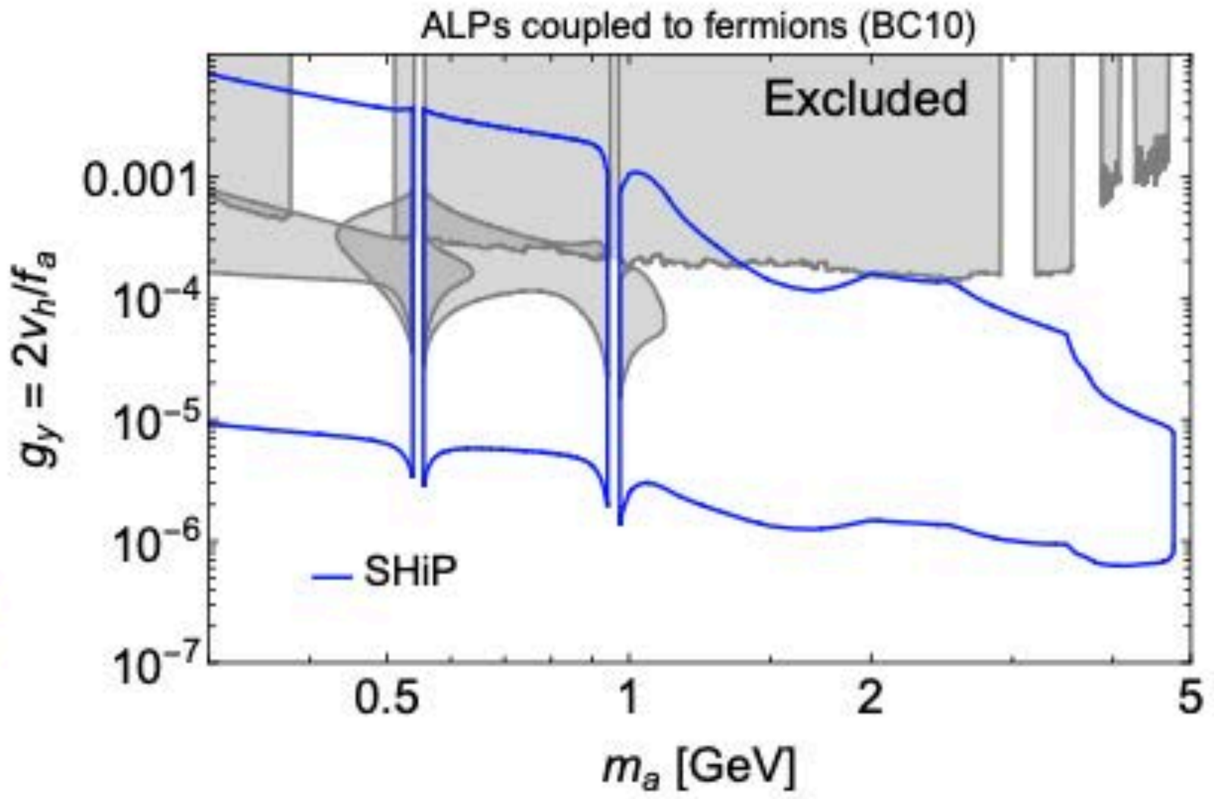
Below this line
neutrino masses
are too small

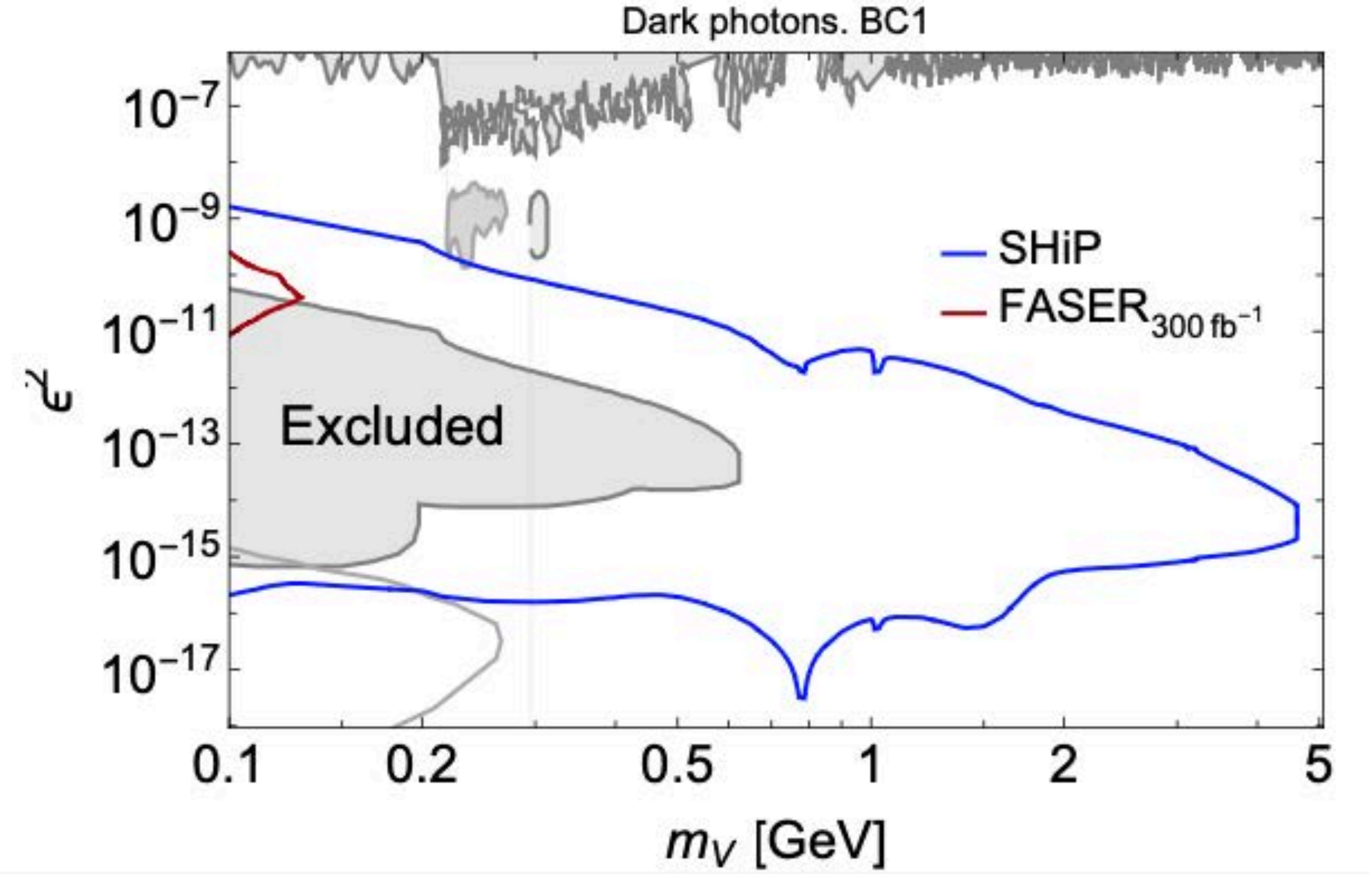
Other types of FIPs


Dark scalars. BC4


Dark scalars. BC5


ALPs. BC9


ALPs coupled to fermions (BC10)


Dark photons. BC1

SHiP sensitivities to FIPs are orders of magnitude better than existing limits

Conclusions

Light feebly interacting particles (heavy neutral leptons in particular) can be a key to the phenomena which the Standard Model of particle physics cannot explain: (neutrino masses and oscillations, baryon asymmetry of the Universe, dark matter).

Hopefully, we will be soon at an exciting point in history: the future experiments at the intensity frontier such as SHiP and FCC-ee in the Z-resonance mode have chances to uncover the origin of neutrino masses and baryon asymmetry of the Universe, while X-ray telescopes - the origin of DM in the Universe.