UNIVERSITÀ DEGLI STUDI DI TRIESTE

INFN TRIESTE

The Standard Model of particle physics

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Preliminary table of contents

1. Preliminaries: fermions, Lagrangians, symmetries…
2. Abelian symmetries
3. QED
4. Non-Abelian symmetries
5. QCD
6. Spontaneous symmetry breaking and Higgs mechanism
7. Weak interactions
8. Flavour physics
9. QCD at low energies
10. Precision tests
11. More on flavor
12. Neutrino physics

Suggested readings

Books on the SM

- Grossman & Nir - The Standard Model
  (also online https://www.classe.cornell.edu/~yuvalg/GNB/GNB-master-03302022.pdf)
- Fabbrichesi: The Standard Model
- Doneghue et al: Dynamics of the Standard Model
  https://www.cambridge.org/core/books/dynamics-of-the-standard-model/FF8A95F0F22A67FABA729DBB39BA2816

QFT books

- Schwartz - Quantum field theory
- Peskin & Schroeder - QFT

Why a course in English?

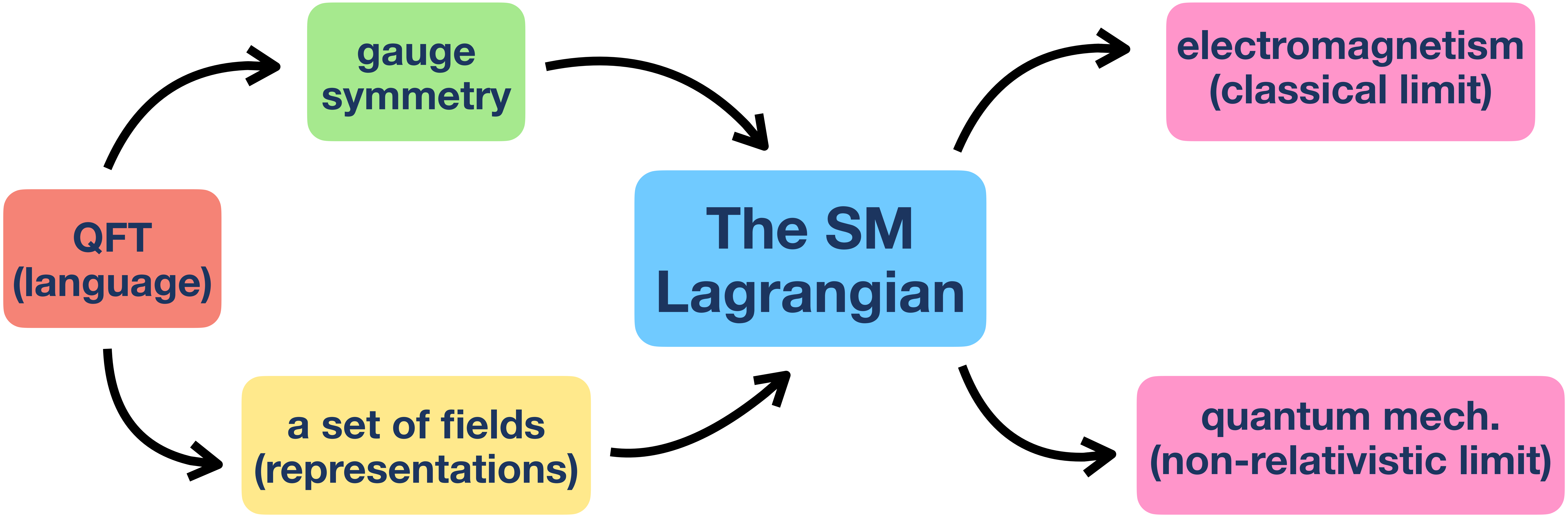
- Because you asked it (students' survey 2024)
- Why should the lectures be in a different language?
- Because physics is done in English. Period.
- You will need it. No-one cares about your oxford certificates: English is just taken as given. You will have to communicate with your boss, colleagues, clients, from day-1.
- This is no language class: I want you to learn physics. You can ask questions in any language (almost any) and ask me to repeat in Italian (or Friulano)
- Take it as an experiment

Exam

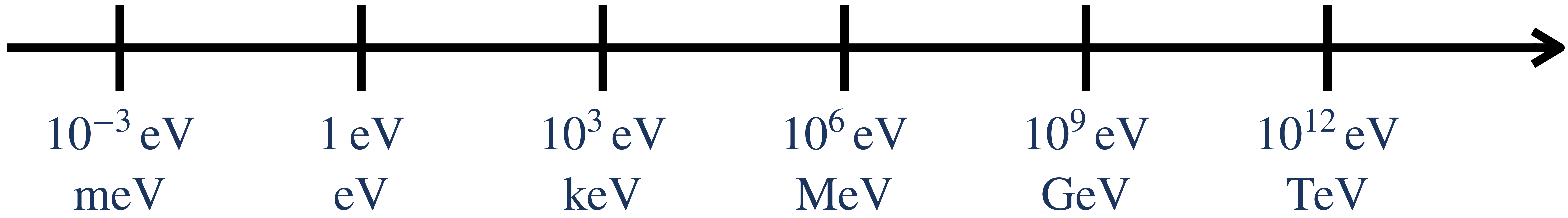
- Problem sets: 2-4 problems assigned weekly
- Solutions should be handed in one week before the exam
- Oral exam discussing your solution and its relation with the course content
- The exam can be held in Italian or in English, your choice
- We will agree on 2-3 dates in June-July.

The Standard Model

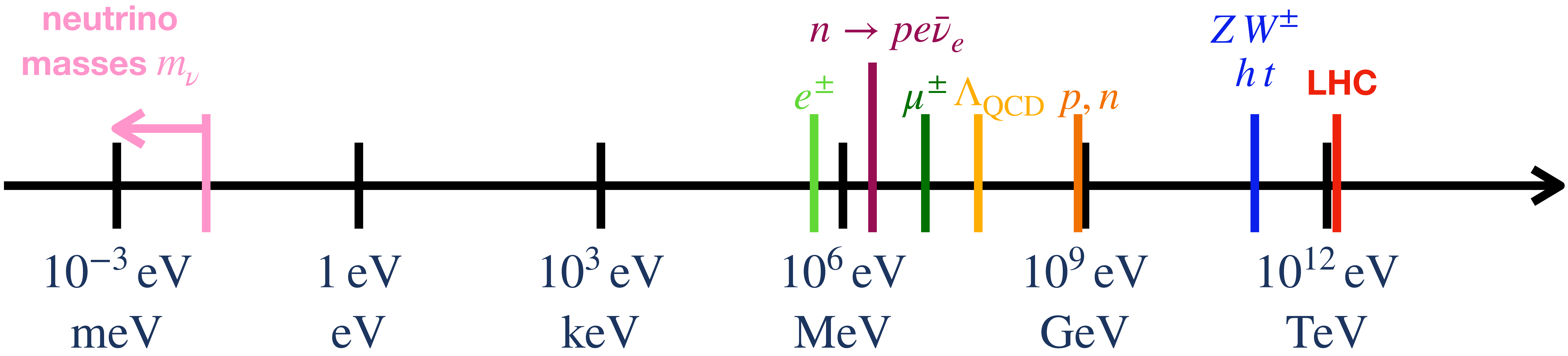
The Standard Model is the theory that describes the phenomenology of elementary particles and their interactions



Energy scales



Energy scales



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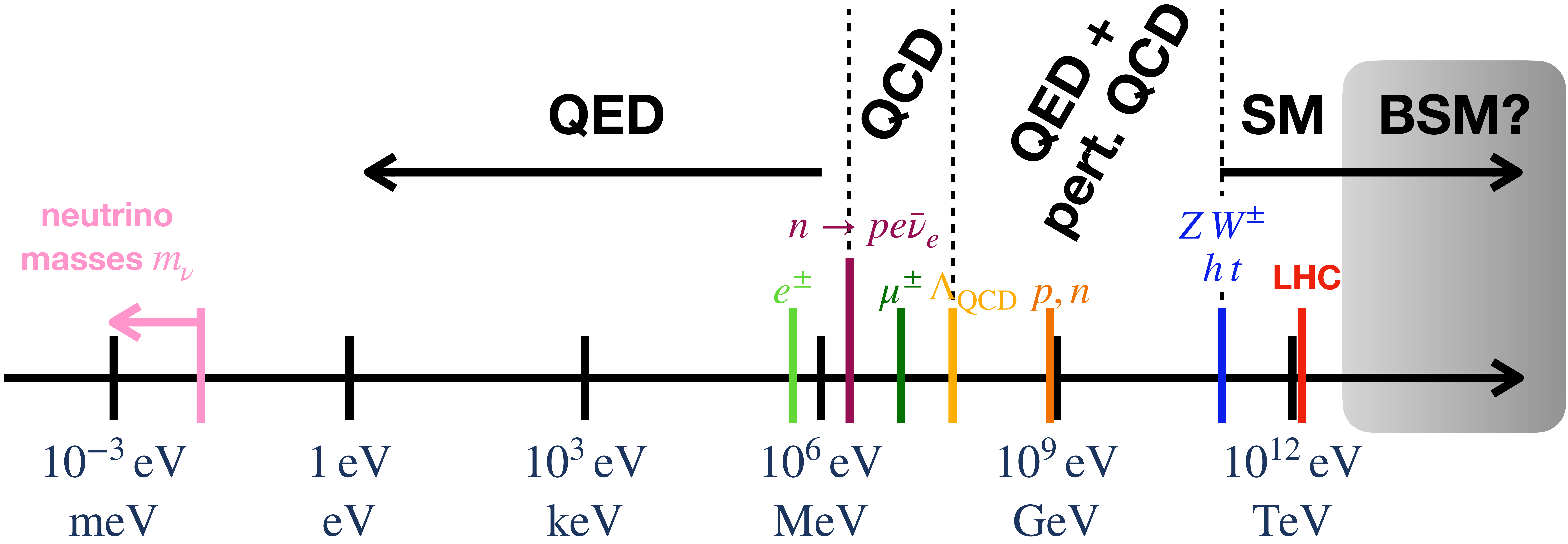

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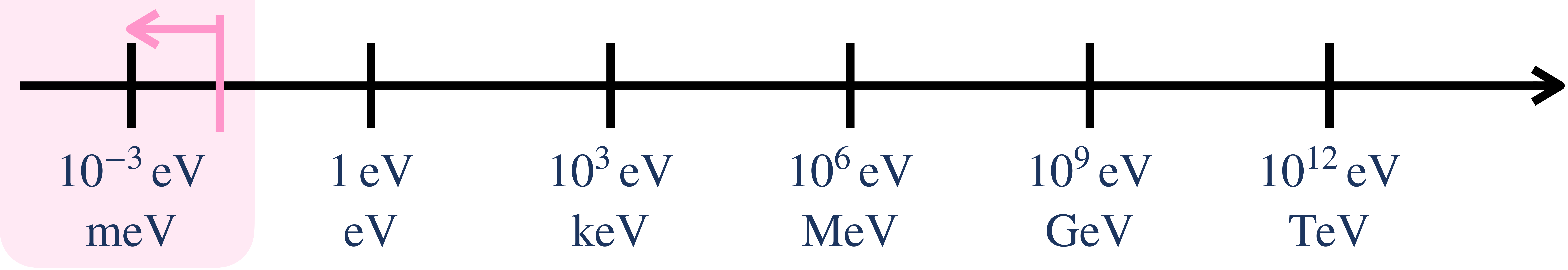
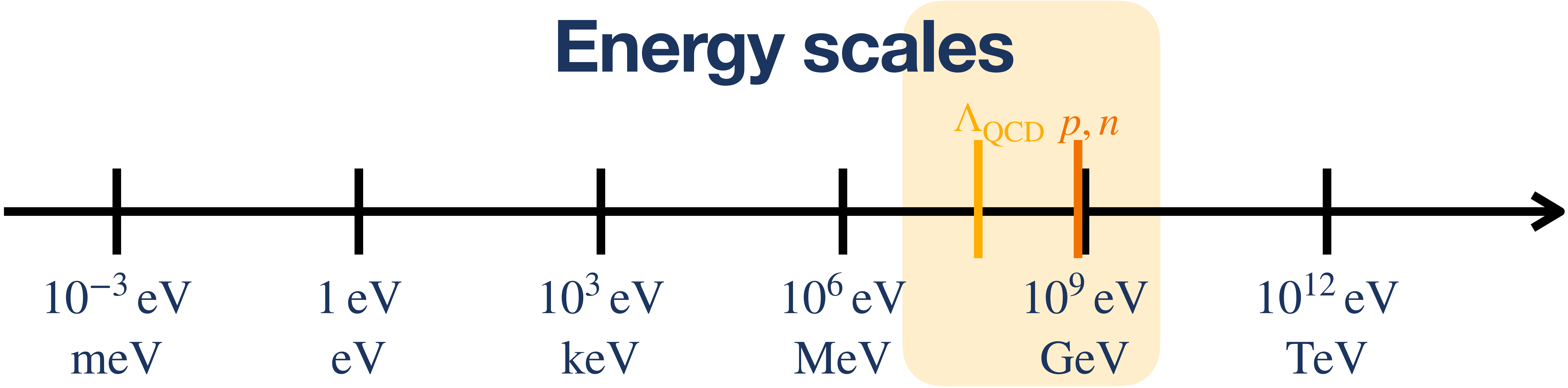


Oscillation experiments: neutrino oscillate from one species to another

- $\nu_e \to \nu_{\mu/\tau}$ [solar neutrino oscillations - SNO 2001-02]
- $\nu_\mu \to \nu_\tau$ [atmospheric oscillation - SuperKamiokande
- oscillations $\implies m_\nu \neq 0$ (with current data $m_\nu \sim \mathrm{meV} - 0.1\,\mathrm{eV}$)

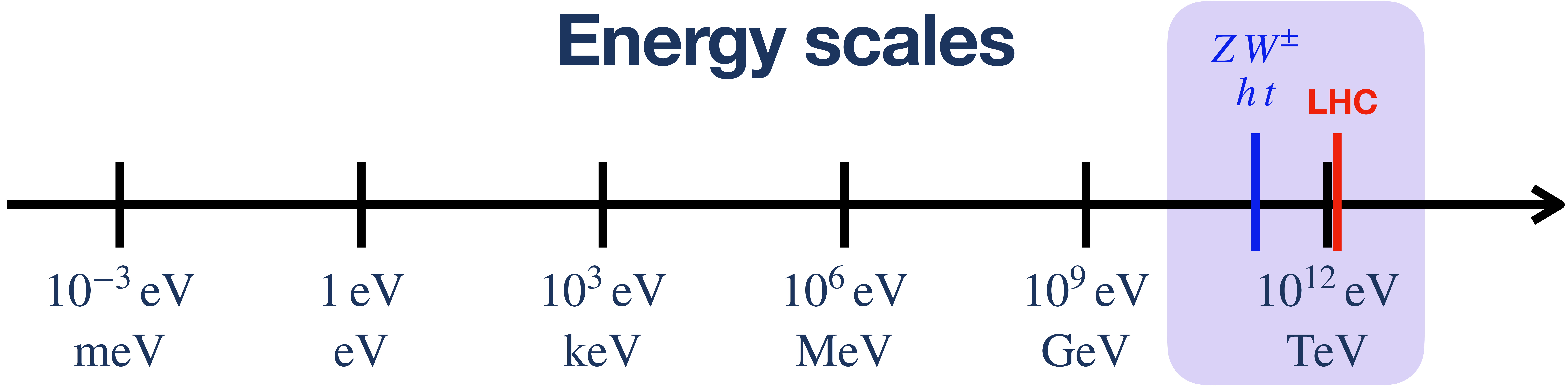
Energy scales



Quantum chromodynamics (QCD): controls strong interaction

- strong coupling below Λ_{QCD}
- perturbative at higher energy
- responsible for *confinement,* and the dynamics of nucleons (p,n) mesons (π's etc.) and baryons

Energy scales



Electroweak scale:

- $m_W \approx 80.4\,\mathrm{GeV},\ m_Z \approx 91.2\,\mathrm{GeV},\ m_h \approx 125\,\mathrm{GeV},\ m_t \approx 173\,\mathrm{GeV}$
- the Higgs mechanisms "breaks" the gauge symmetry and gives mass to SM particles
- tested up to an energy $\sim \mathrm{TeV}$ by many experiments (LHC and others)

Experimental tests

The SM describes *qualitative* and *quantitative* aspects of high energy physics, with only a few notable exceptions

- example of precision prediction: anomalous magnetic moment

$$H = \frac{\vec{p}^2}{2m} + V(r) + \frac{e}{2m}\vec{B}\cdot(\vec{L} + g\vec{S})$$

- in QED $g = 2 + \alpha/\pi$

$\sim 2.32 \times 10^{-3}$
First order (1-loop) correction
Schwinger, Feynman, Tomonaga 1948

- today known at the 10^{-13} level

Shortcomings

neutrino masses
do not appear in the SM
necessarily BSM

hierarchy problem
why $\Lambda_{\mathrm{EW}} \ll \Lambda_{\text{new phys}}$?

strong CP
do strong interactions
respect CP? Why?

dark matter
what is DM made of?

dark energy
what is DE made of?

baryon asymmetry
why are there more
particles than antiparticles?

flavor structure
why three flavors?
origin of mass hierarchy
charge assignment

Shortcomings

Theoretical prejudice

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why $\Lambda_{\rm EW} \ll \Lambda_{\text{new phys}}$?

strong CP
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Unexplained observations

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necessarily BSM

dark matter
what is DM made of?

dark energy
what is DE made of?

baryon asymmetry
why are there more particles than antiparticles?

Shortcomings

Particle physics

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do not appear in the SM
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Cosmology

What is the Standard Model?

A definition

The SM is a **Lorentz-invariant** **quantum field theory** describing elementary particles and their interactions.

It is constructed as a **chiral gauge theory** based on the group

$$\mathscr{G}_{\mathrm{SM}} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$

spontaneously broken to the $\mathrm{U}(1)_{\mathrm{e.m.}}$ subgroup by the Higgs field.

Given the field content, the SM is the most general Lagrangian which is **renormalizable** and invariant under $\mathscr{G}_{\mathrm{SM}}$. Many of its properties descend from the **mass and charge assignment**.