Particle Physics Landscape and the Motivation for future Experiments

Jochen Schieck

Institute of High Energy Physics
Austrian Academy of Sciences

Technische Universität Wien
Atominstitut

https://www.oeaw.ac.at/en/hephy/staff/jochen-schieck/

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

TU WIEN TECHNISCHE UNIVERSITÄT WIEN

The very big Question

- How to describe nature in one theory:
  - **General Relativity** - the theory describing the nature at large scales (incl. Cosmology)
  - **Quantum Field Theory** - relativistic description of quantum mechanics for small scales (incl. Standard Model of Particle Physics)

➡ Something must happen at the **Planck Scale** $\sim 10^{19}$ GeV

The very big Question

- Theoretical studies trying to approach this fundamental problem

  - String Theory, Loop Quantum Gravity,…

  ➡ **“Theory of Everything”**

- Beyond every experimental (currently) accessible energy Scale

- Search for new Physical phenomena “at the edge” of the existing theoretical description

Image Credit: Quanta Magazine

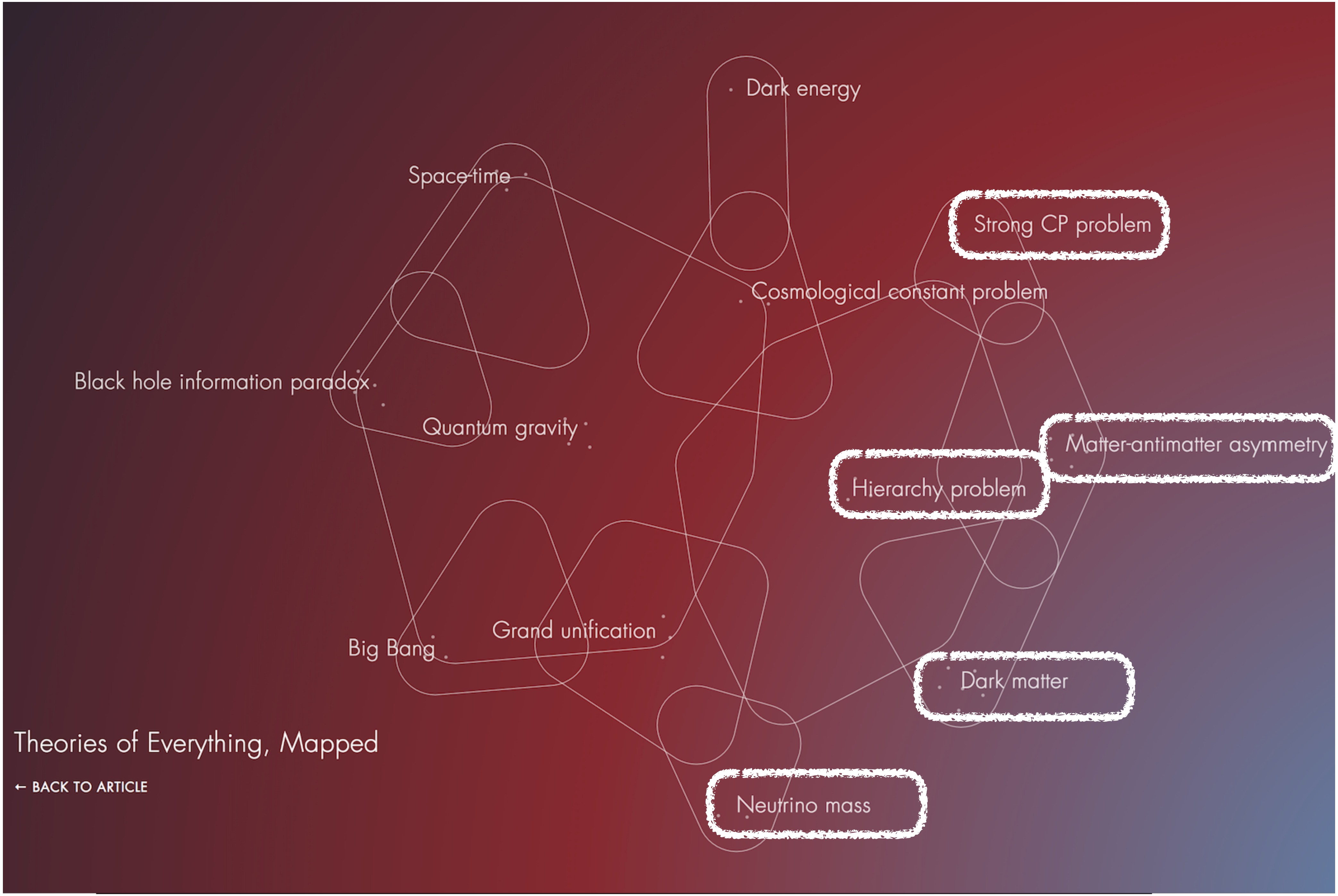
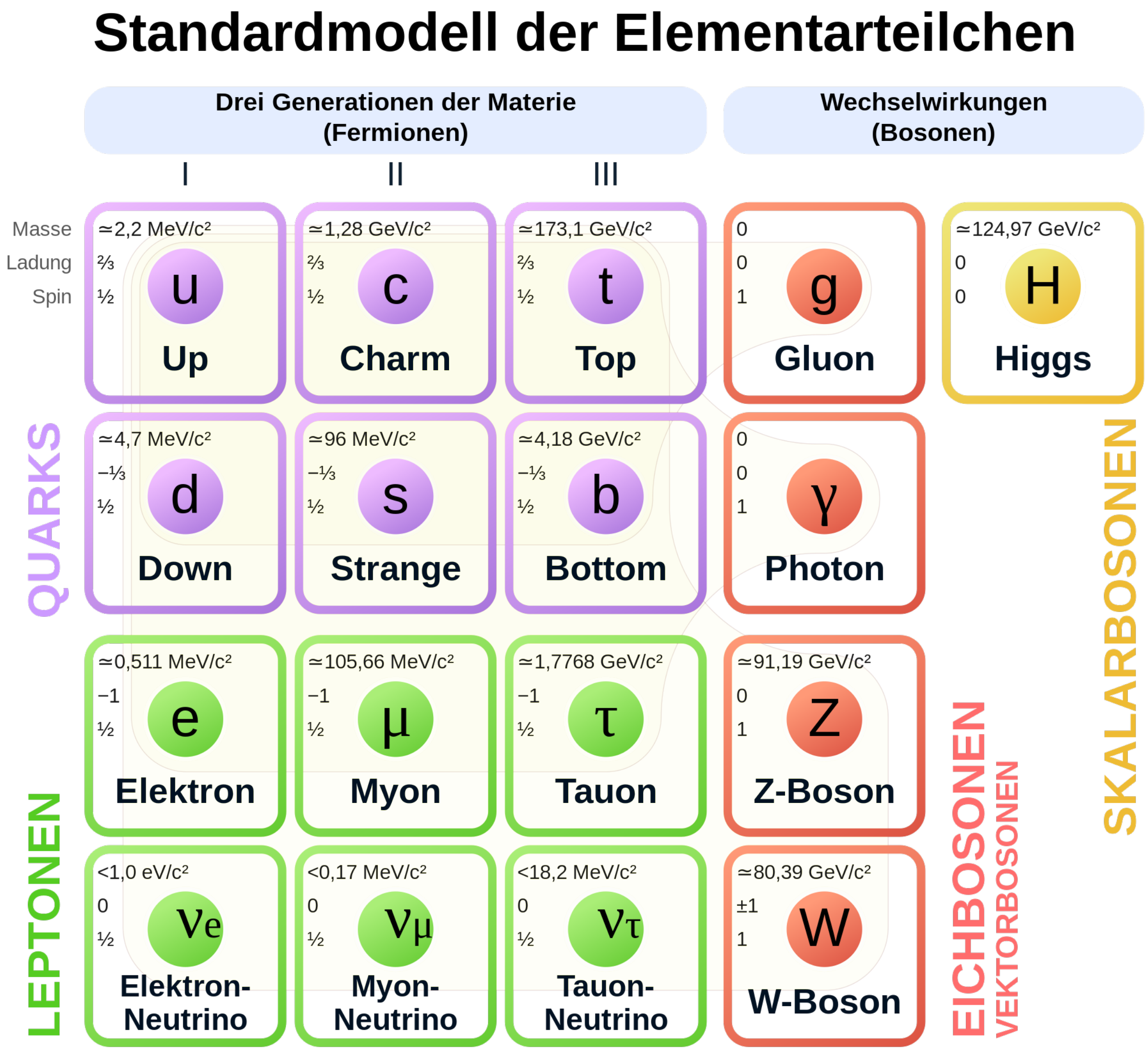


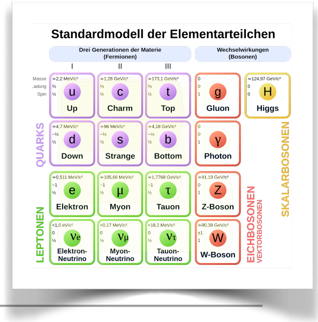
Image Credit: Quanta Magazine

The Standard Model of Particle Physics



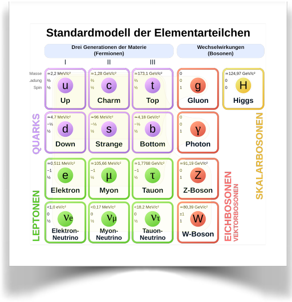
- The Standard Model of Particle Physics is a **success story**
- Development took decades of **hard experimental and theoretical work**
- Key features of the Standard Model were not immediately accepted as truth

The Standard Model of Particle Physics



- Free parameters in the Standard Model
  - The **“original”** Standard Model has 18 free parameters:
    - 3 lepton masses (e,μ,τ)
    - 6 quark masses (u,d,c,s,t,b)
    - 4 CKM-matrix (three mixing angles and one CP-violating phase)
    - 3 coupling constants (U(1), SU(2), SU(3))
    - 2 Higgs parameter (Higgs mass and vacuum expectation value)
  - **These parameters are reasonably well measured**

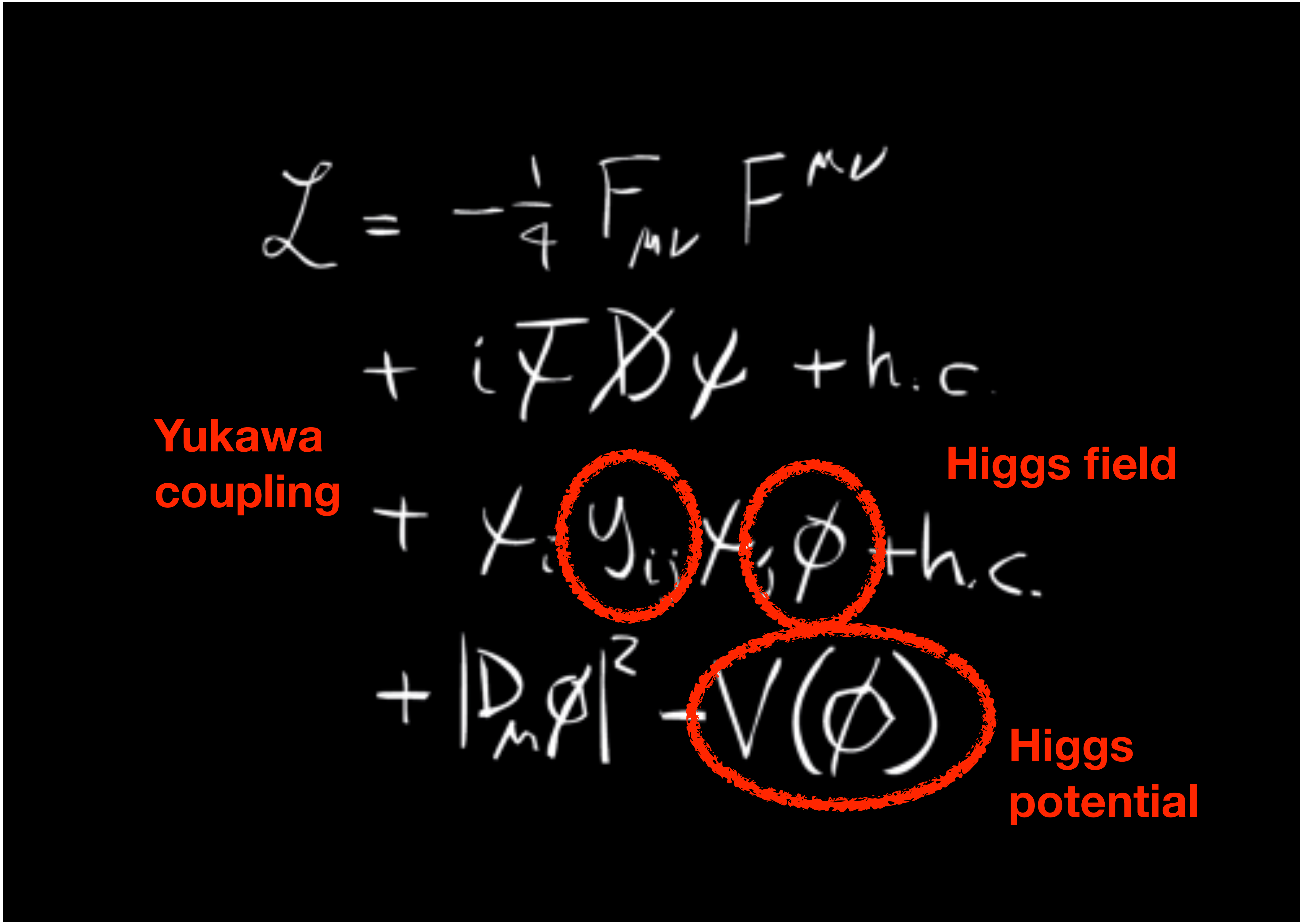
The Standard Model of Particle Physics



- Experimental observations towards physics beyond the standard model (Neutrino oscillations)
  - 3 mass terms for neutrino masses
  - 4 PNMS-matrix (three mixing angles and one CP-violating phase)
- more possible extensions of the Standard Model
  - 2 Majorana phases in the neutrino sector
  - 1 strong CP phase (plus axion field to set it to cancel it)
- **25 to 28 (maybe or more) free parameters**

Observations

- **15 out 18** parameters of the “original” Standard Model are **related to the Higgs mechanism**
    - 9 parameters for the fermion masses generated via coupling to the Higgs field


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
Yukawa coupling
Higgs field
Higgs potential

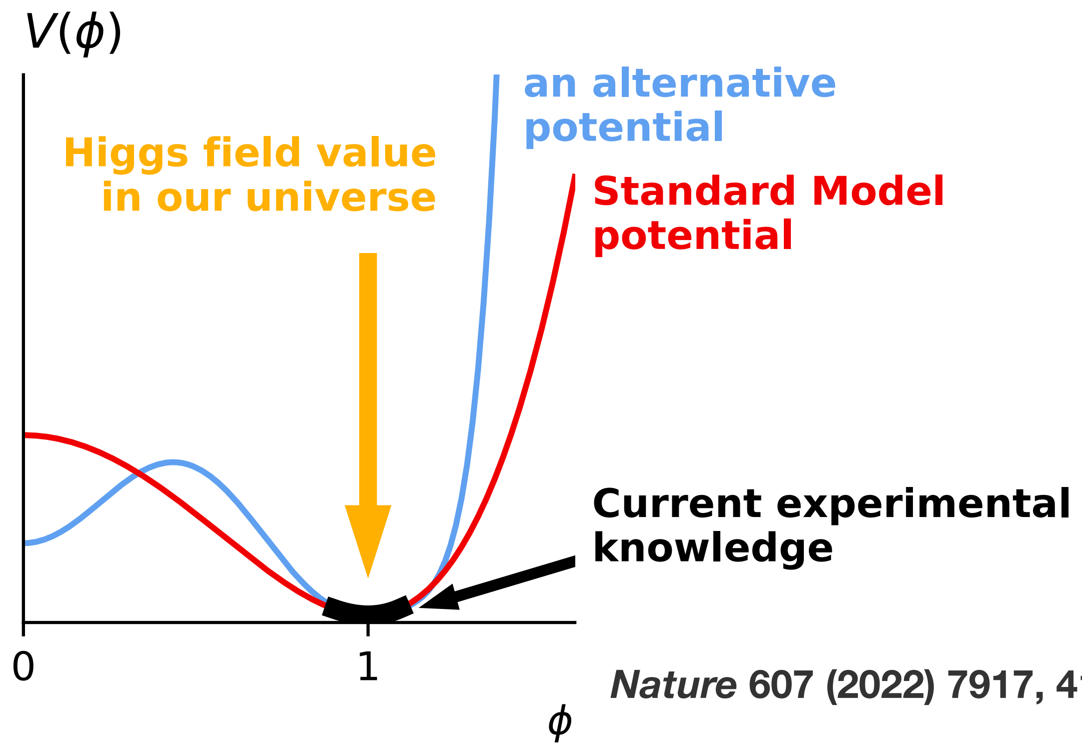
Observations

- **15 out 18** parameters of the “original” Standard Model are **related to the Higgs mechanism**
  - 9 parameters for the fermion masses generated via coupling to the Higgs field
  - 4 parameters for the CKM Matrix - three angles and one phase
  - 2 parameters related to the Higgs boson itself
- **Higgs boson** plays a significant role in the Standard Model
- Interactions are different to know gauge field interactions

The Higgs Boson

- Higgs boson was only **discovered recently**

- **A**ll measurements are **consistent with the expectations** from the Standard Model Higgs Boson



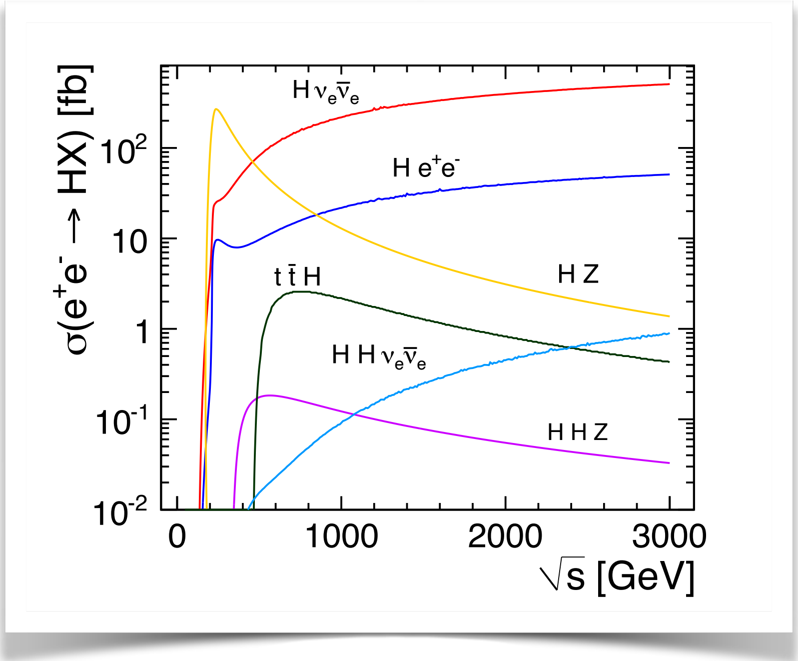
***Nature* 607 (2022) 7917, 41-47**

- The current knowledge of the Higgs potential is limited and leaves room for new physics

The Higgs Boson

- 2 out of the 15 parameters of the Higgs boson are directly related to the Higgs Potential:
  - $V(\Phi) = \frac{1}{2}\, \boldsymbol{\mu}\, \phi^\dagger\phi + \frac{1}{4}\, \boldsymbol{\lambda}\, (\phi^\dagger\phi)^2.$
    with $\pm v = \pm\sqrt{(-\mu^2/\lambda)}$ being being the vev and $m_h = \sqrt{-2\mu^2}$

$V(\Phi) = \frac{1}{2}\, m_h^2\, h + \lambda\, v\, h^3 + \frac{1}{4}\, \lambda\, h^4$



Higgs mass

Higgs self interaction terms

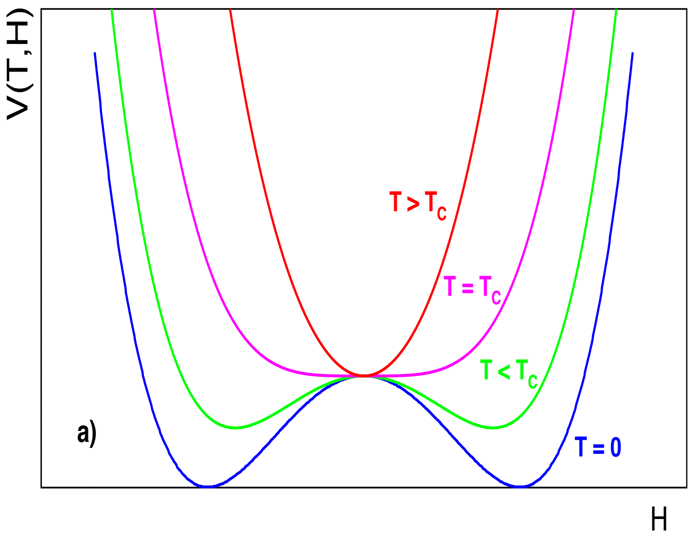
The Higgs Boson

Further fundamental questions related to the Higgs Boson

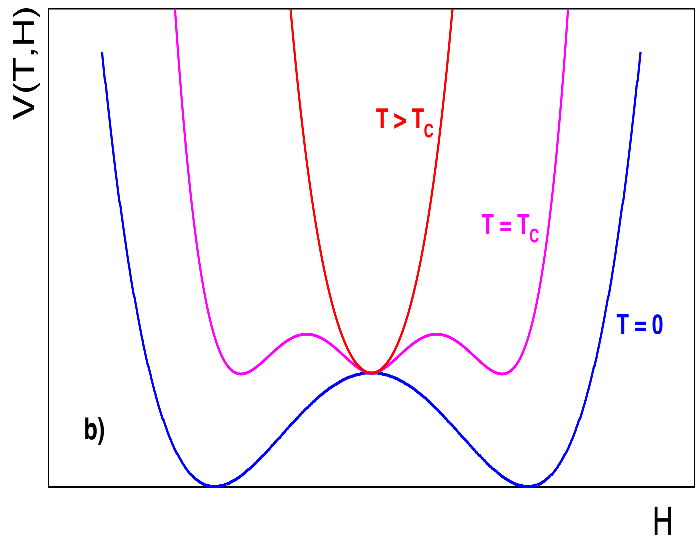
- Naturalness problem:

$$m_H^2 = m^2 + \frac{3\Lambda^2}{8\pi^2 v^2}[m_Z^2 + 2m_W^2 + m^2 - 4m_t^2] + O(\ln \frac{\Lambda}{m})$$

- Which order is the electroweak phase transition



second-order phase transition



first order phase transition

arXiv:1911.08893

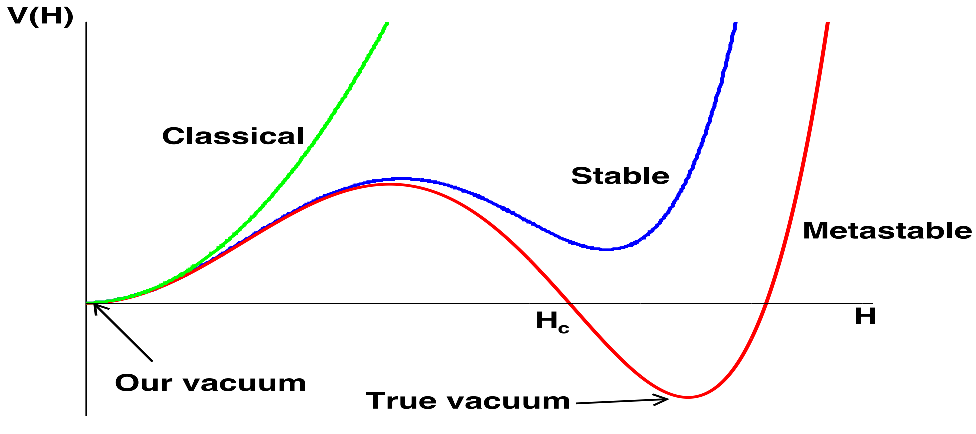
The Higgs Boson

Further fundamental questions related to the Higgs Boson

- The Higgs Potential and the relation to the Cosmological Constant: $V = V_{Higgs} + V_0$
  $V_{Higgs} \sim \frac{1}{4} \lambda v^4 \sim 1.2 \times 10^8\ GeV^4 \sim 10^{44}\ eV^4$
  $V_{CC} \sim (0.003)^4\ eV^4 \sim 10^{-10}\ eV^4$

- Is the vacuum stable?

- Is the Higgs boson related to the Inflaton?



arXiv:1911.08893

The Higgs Boson - take home messages

- The discovery of the Higgs boson is not the end of the story
- The Higgs boson is the only fundamental scalar particle
- Studying the Higgs boson in more detail - precision measurements - to understand its nature has the highest priority

➡ **Construction of a Higgs-factory**

➡ **Which parameters can be measured?**

➡ **Every deviation from expectation is a clear hint of new Physics**

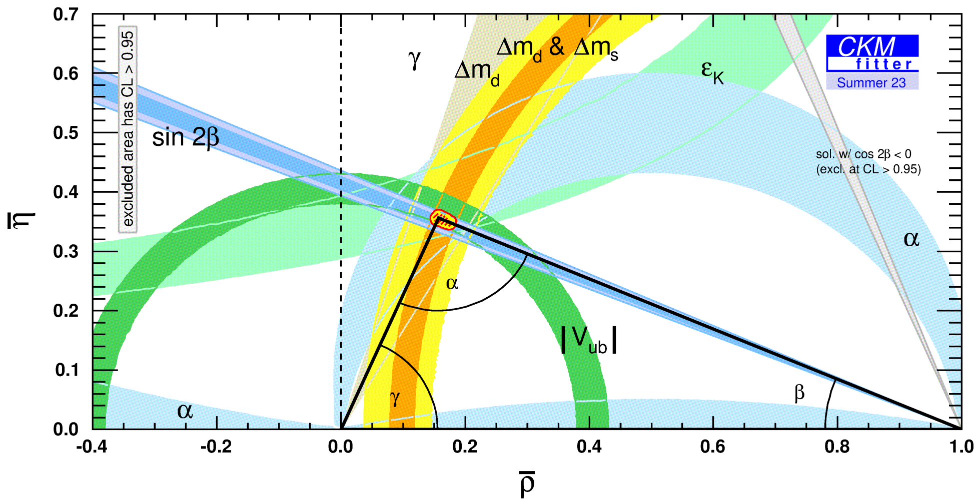
➡ **What can we learn from studying a fundamental scalar**

Neutrino Physics

- The neutrino sector of the Standard Model is the least well-measured part of the Standard Model
- 3 masses - 4 entries in the PNMS matrix - maybe 2 Majorana phases
  - We know the neutrino has a mass
    - No absolute value (only upper limit) and ambiguity of the ordering of masses
  - Measurement of mixing values ongoing, including CP-violating phase
  - The neutrino is the only fundamental particle that can be its antiparticle
    - A possible explanation for small mass scale (seesaw mechanism)
    - Heavy right-handed neutrinos as dark matter candidates?

The CKM Matrix and Flavour Physics

- Phase in CKM Matrix is currently the only source for CP violation in the Standard Model
  - CP violation is a crucial ingredient to reaching a matter-antimatter asymmetry
  - CP violation in CKM is not enough to reach the observed asymmetry
  - additional sources needed



- flavor precision measurements (B, K) offer a unique window for BSM physics
- sensitivity to several O(10^4) TeV via indirect measurements

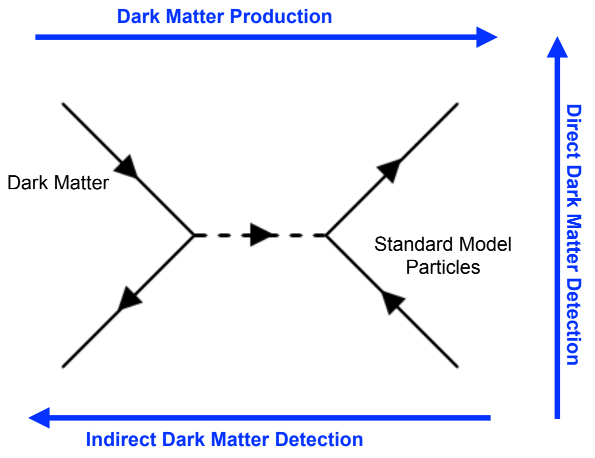
The strong CP problem - search for ALPs

- The strong sector of the Standard Model offers an option for CP-violation
  - Additional term in Lagrangian provides CP violating

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

  - CP in strong sector experimentally not observed
    - Why are Θ and Θ’ equal to zero, or are the terms in the Standard Model allowed but not realized?
    - Dynamical solution with an additional axion field provides an elegant solution
  - Axion and generic axion-like particles (ALPS) are also a valid dark matter candidate
  - Generic ALPS searches at accelerators possible

My favourite - search for dark matter

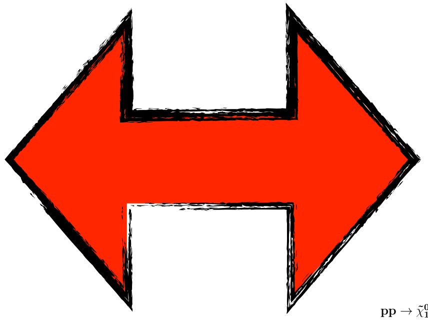


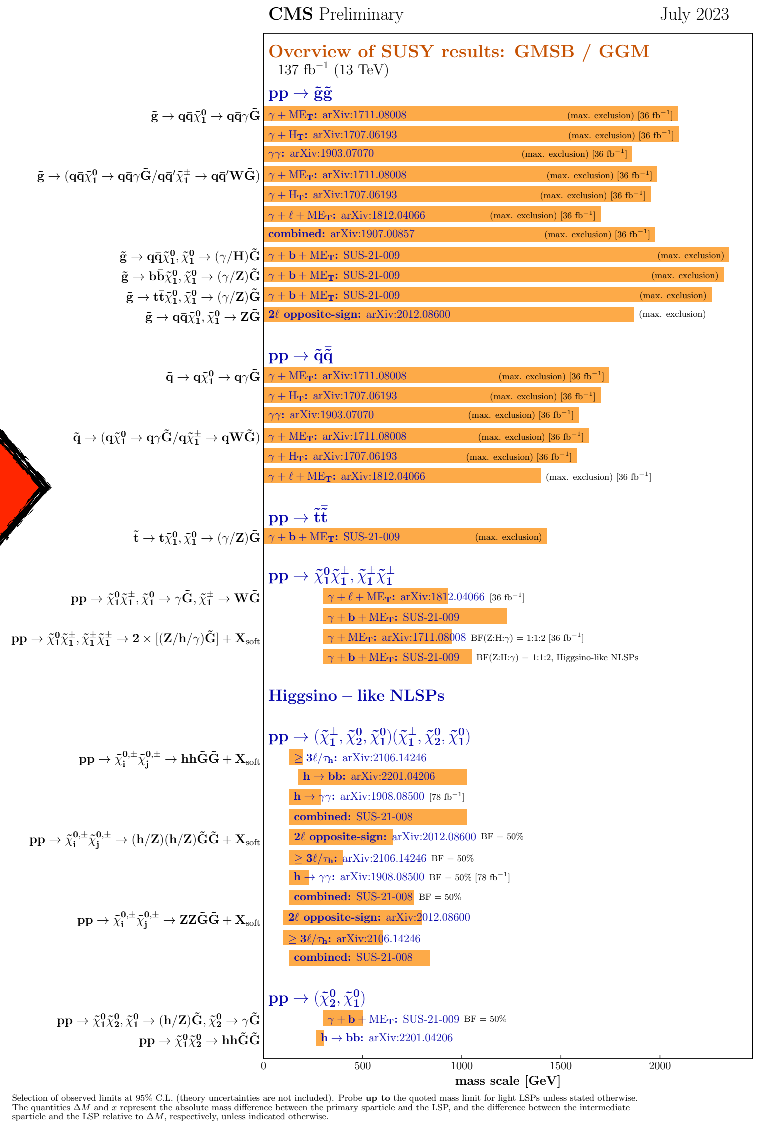
- Undisputed observation of Dark Matter at a large range of astrophysical scales
    - Observation based on gravitational interaction only
    - Hypothesis for unobserved dark matter particles is well-justified
    - Requires interaction stronger than gravitational interaction
- Searches with orthogonal approaches and different strengths
    - Convincing dark matter claim requires observation with orthogonal approaches

➡ Astrophysics

Physik beyond the Standard Model - SUSY

Schrödinger's Cat





- High energy is the key for Physics beyond the Standard Modell

My personal summary

- It’s good to have a science-based discussion
- The discovery of the Higgs completes the Standard Model
  - The Higgs sector offers a broad range of open questions (and possible solutions)
- The neutrino sector is the least well-measured part of the SM
- The interplay between direct and indirect searches is crucial to move the field forward
  - “I only believe it when it's on the mass shell”
- More ideas than resources → Priority setting