FACULTY OF PHYSICS UW

Problems of the Standard Model and their possible solutions

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Plan

- Standard Model (SM) of Fundamental Interactions
- SM problems:
  - no candidate for dark matter
  - CP violation and baryonic asymmetry
  - Other cosmological difficulties
  - Other problems
- Solutions to SM problems
- Summary

Standard Model of Fundamental Interactions

- Objective: to describe the interactions between the fundamental components of matter (quarks, leptons)
- SM language: quantum field theory (modeled on electrodynamics)
- Assumptions of SM:
  - Lorentz invariance: $x_\mu \rightarrow x'_\mu = \Lambda_\mu^\nu x_\nu$, $x_\mu x^\mu = x'_\mu x'^\mu$, $\mu = 0,1,2,3$
  - Gauge symmetry, e.g. in electrodynamics: $A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \lambda(x)$
  - Weak interactions "carried" by "massive charged photons $W^\pm$" (charged intermediate boson hypothesis)

We construct MS (electrodynamics is the pattern)

$$S = \int d^4x \mathcal{L}\,(A_\mu, \psi, \phi)$$

Quantization

particles and their interactions

We construct MS
(the example is electrodynamics)

$$S = \int d^4x\, \mathcal{L} = \int d^4x\, [-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi]$$

$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$

$D_\mu \equiv \partial_\mu + ieqA_\mu$

Lorentz symmetry:

$$x_\mu \to x'_\mu = \Lambda_\mu^\nu x_\nu$$

Gauge symmetry:

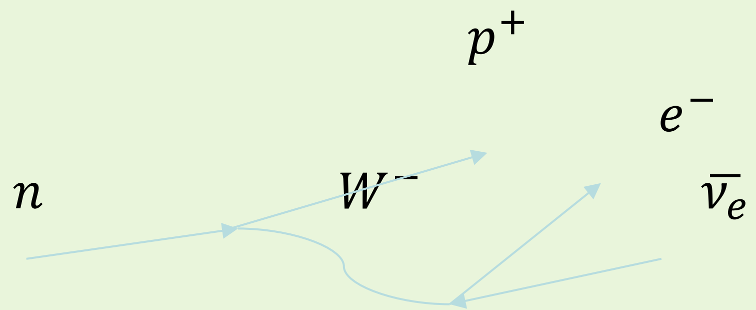
$$A_\mu(x) \to A_\mu(x) + \partial_\mu \lambda(x)$$

$$\psi(x) \to e^{-ieq\lambda(x)} \psi(x)$$

$$D_\mu \psi(x) \to e^{-ieq\lambda(x)} D_\mu \psi(x)$$

We construct SM

we need massive charged bosons $W^{\pm}$ that would "carry" weak interactions (beta decay): $n \to p^+ W^- \to p^+ e^- \overline{\nu_e}$



- The problem: photons have no mass ($\frac{1}{2} m_\gamma^2 A_\mu A^\mu$)

$$S = \int d^4x \, \mathcal{L} = \int d^4x \, [-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi]$$

- $\frac{1}{2} m_V^2 A_\mu A^\mu$ is prohibited by gauge symmetry:

$$A_\mu(x) \to A_\mu(x) + \partial_\mu \lambda(x)$$

We construct SM

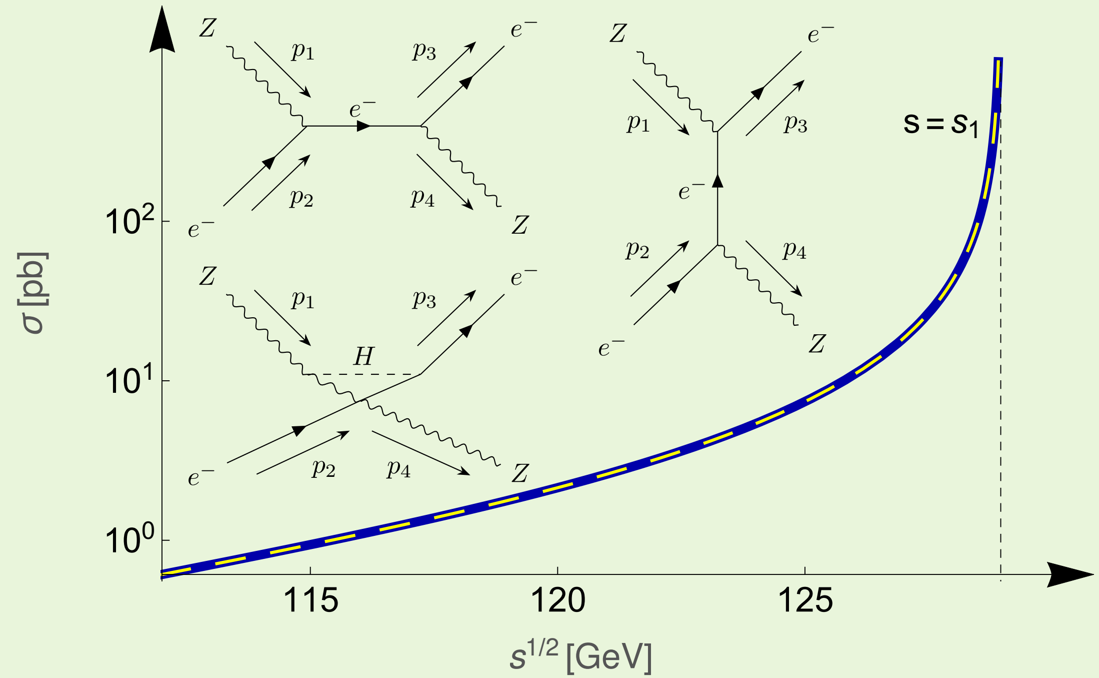
- We need massive charged (non-Abelian) bosons $W^{\pm}$ that would carry weak interactions (beta decay)

$$n \to p^{+} W^{-} \to p^{+} e^{-} \overline{\nu_e}\ .$$

- Electrodynamics is renormalizable, but massive vector theory is not.
- Renormalizability: the possibility of removing divergences by redefining the parameters of the theory.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m_V^2 A_\mu A^\mu$$

We construct SM – renormalizability
”tree" Feynman diagrams are usually finite

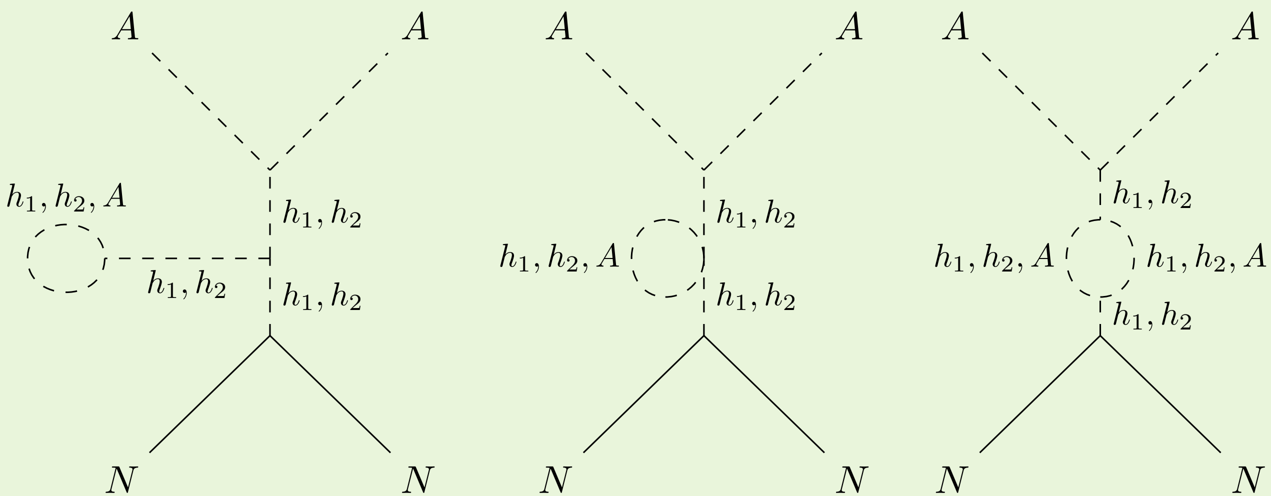


BG, M.Iglicki, S.Mrówczyński, „t-channel singularities in cosmology and particle physics”, *Nucl.Phys.B* 984 (2022)
M.Iglicki, „Thermal regularization of t-channel singularities in cosmology and particle physics: the general case”, *JHEP* 06 (2023) 006

We construct SM

”loop" Feynman diagrams are usually divergent

(∞)



- we want to maintain renormalizability -

D. Azevedo, M.Duch, BG, D. Huang, M. Iglicki, et al., „Testing scalar versus vector dark matter”, *Phys.Rev.D* 99 (2019) 1, 015017;
„One-loop contribution to dark-matter-nucleon scattering in the pseudo-scalar dark matter model”
JHEP 01 (2019) 138

We construct SM

1971 Veltman and t'Hooft argue that theories with spontaneously broken gauge symmetries are renormalizable
1999 Nobel prize

↓

Theories with massive vector intermediate particles can be renormalizable!

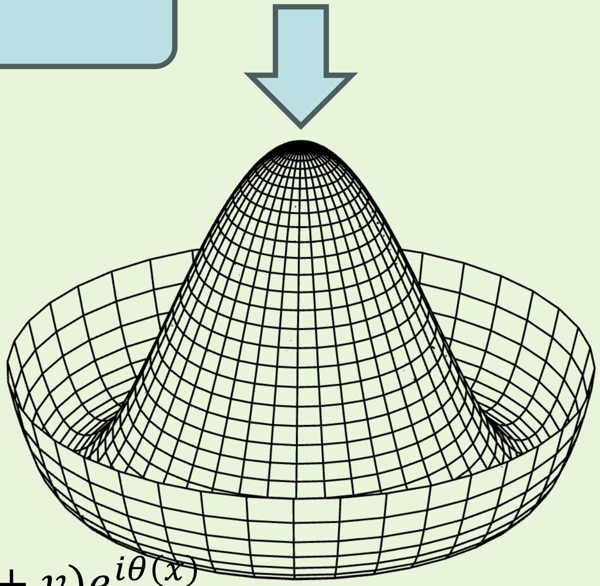
- "massive photons" -

Standard Model of Fundamental Interactions

We construct SM

$$S = \int d^4x[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \partial_\mu\phi^*\partial^\mu\phi - \lambda(|\phi|^2 - v^2)^2]$$

- Global symmetry



- Spontaneous violation of global continuous symmetry:

Lagrangian is invariant, its minimum is not

- Goldston's theorem:

$$\phi(x) = (h(x) + v)e^{i\theta(x)},$$

$\theta(x)$ - Massless Goldston boson,
$h(x)$ - Massive Higgs boson

Standard Model of Fundamental Interactions

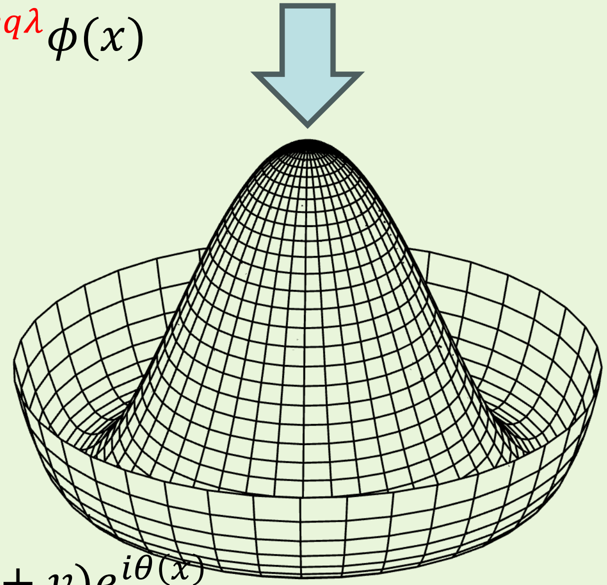
We construct SM

$$S = \int d^4x[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \partial_\mu\phi^*\partial^\mu\phi - \lambda(|\phi|^2 - v^2)^2]$$

- Global symmetry U(1):

$$\phi(x) \to e^{-ieq\lambda}\phi(x)$$

- Spontaneous violation of global continuous symmetry:



Lagrangian is invariant, its minimum is not

- Goldston's theorem:

$$\phi(x) = (h(x) + v)e^{i\theta(x)},$$

$\theta(x)$ - Massless Goldston boson,
$h(x)$ - Massive Higgs boson

Standard Model of Fundamental Interactions

$$S = \int d^4x[-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - \lambda(|\phi|^2 - v^2)^2]$$

- Local gauge symmetry U(1):

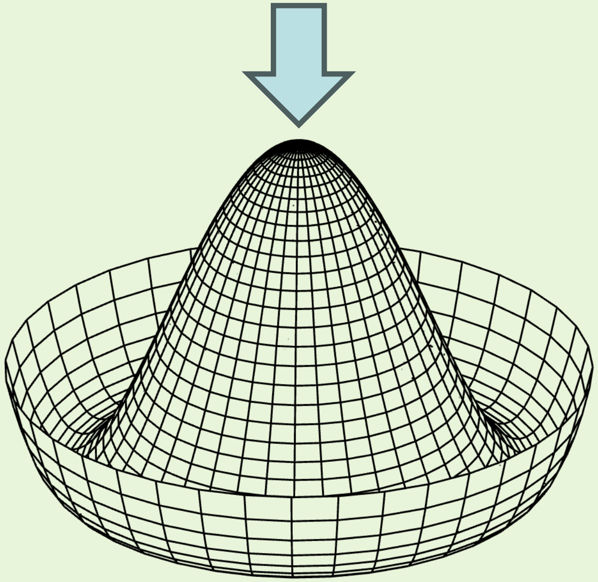
$$A_\mu(x) \to A_\mu(x) + \partial_\mu\lambda(x)$$

$$\phi(x) \to e^{-ieq\lambda(x)}\phi(x)$$

$$D_\mu\phi \equiv (\partial_\mu + ieqA_\mu)\phi \to e^{-ieq\lambda(x)}\, D_\mu\phi$$

- Spontaneous gauge symmetry violation:

The potential is invariant,
its minimum is not.



- Higgs mechanism:

$$\phi(x) = (h(x)+v)e^{i\theta(x)},$$

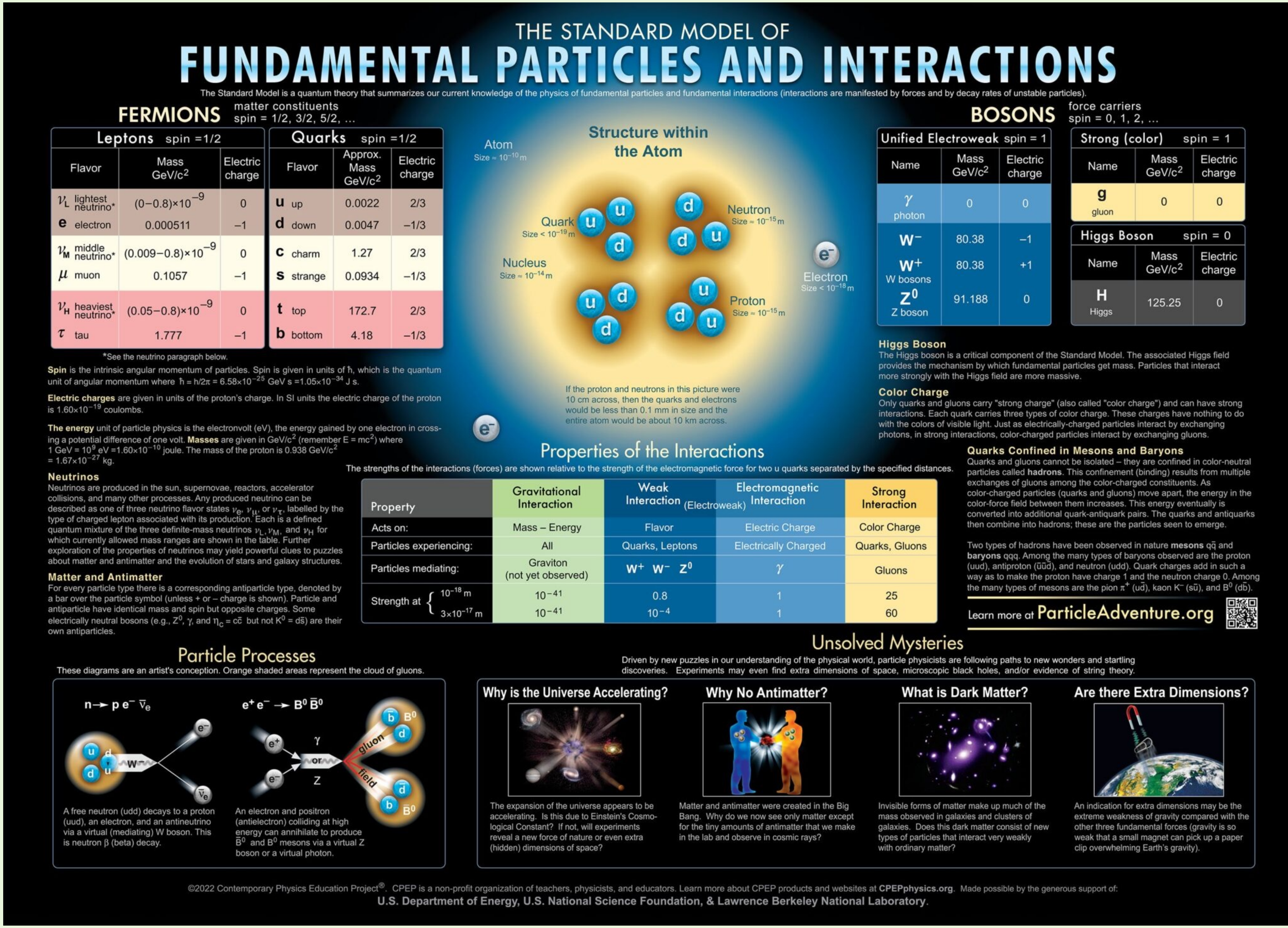
  - A mass term appears for the gauge field: $m_V^2 A_\mu A^\mu$, $m_V = ev$,
  - $\theta(x)$ - the massless Goldston boson disappears – it becomes the longitudinal component of the massive gauge boson,
  - $h(x)$ - massive Higgs boson

Standard Model of Fundamental Interactions

- Gauge theory with spontaneously broken symmetry
- It describes electromagnetic and weak (and strong) interactions
- Symmetry group: $SU(2)_L \times U(1)_Y$ (4 generators)
- Gauge bosons (vectors): $W^{\pm}, Z, \gamma$
- Other bosons (scalar): h
- Fermions: quarks, leptons
- Transformations upon the symmetry group (representations):
  - quarks: $q_L \propto \left(\frac{1}{2}, \frac{1}{3}\right)$, $u_R \propto (0, \frac{4}{3})$, $d_R \propto \left(0, -\frac{2}{3}\right)$
  - leptons: $l_L \propto \left(\frac{1}{2}, -1\right)$, $l_R \propto (0, -2)$, $\nu_R \propto (0,0)$
  - scalars (Higgs boson)): $\phi \propto (\frac{1}{2}, 1)$

One parameter with mass dimension: $v \cong 246\ GeV/c^2$

All masses $\propto v$


THE STANDARD MODEL OF
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin =1/2
Flavor | Mass GeV/c² | Electric charge
νL lightest neutrino* | (0–0.8)×10⁻⁹ | 0
e electron | 0.000511 | –1
νM middle neutrino* | (0.009–0.8)×10⁻⁹ | 0
μ muon | 0.1057 | –1
νH heaviest neutrino* | (0.05–0.8)×10⁻⁹ | 0
τ tau | 1.777 | –1
Quarks spin =1/2
Flavor | Approx. Mass GeV/c² | Electric charge
u up | 0.0022 | 2/3
d down | 0.0047 | –1/3
c charm | 1.27 | 2/3
s strange | 0.0934 | –1/3
t top | 172.7 | 2/3
b bottom | 4.18 | –1/3
*See the neutrino paragraph below.
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where ħ = h/2π = 6.58×10⁻²⁵ GeV s =1.05×10⁻³⁴ J s.
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ coulombs.
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember E = mc²) where 1 GeV = 10⁹ eV =1.60×10⁻¹⁰ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10⁻²⁷ kg.
Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states νe, νμ, or ντ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos νL, νM, and νH for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ, and ηc = cc̄ but not K⁰ = ds̄) are their own antiparticles.
Structure within the Atom
Atom Size ≈ 10⁻¹⁰ m
Quark Size < 10⁻¹⁹ m
Nucleus Size ≈ 10⁻¹⁴ m
Neutron Size ≈ 10⁻¹⁵ m
Proton Size ≈ 10⁻¹⁵ m
Electron Size < 10⁻¹⁸ m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name | Mass GeV/c² | Electric charge
γ photon | 0 | 0
W⁻ | 80.38 | –1
W⁺ W bosons | 80.38 | +1
Z⁰ Z boson | 91.188 | 0
Strong (color) spin = 1
Name | Mass GeV/c² | Electric charge
g gluon | 0 | 0
Higgs Boson spin = 0
Name | Mass GeV/c² | Electric charge
H Higgs | 125.25 | 0
Higgs Boson
The Higgs boson is a critical component of the Standard Model. The associated Higgs field provides the mechanism by which fundamental particles get mass. Particles that interact more strongly with the Higgs field are more massive.
Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.
Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.
Two types of hadrons have been observed in nature mesons qq̄ and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton (ūūd̄), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π⁺ (ud̄), kaon K⁻ (sū), and B⁰ (db̄).
Learn more at ParticleAdventure.org
Properties of the Interactions
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.
Property | Gravitational Interaction | Weak Interaction (Electroweak) | Electromagnetic Interaction | Strong Interaction
Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge
Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons
Particles mediating: | Graviton (not yet observed) | W⁺ W⁻ Z⁰ | γ | Gluons
Strength at 10⁻¹⁸ m | 10⁻⁴¹ | 0.8 | 1 | 25
Strength at 3×10⁻¹⁷ m | 10⁻⁴¹ | 10⁻⁴ | 1 | 60
Particle Processes
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.
n → p e⁻ ν̄e
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
e⁺ e⁻ → B⁰ B̄⁰
An electron and positron (antielectron) colliding at high energy can annihilate to produce B̄⁰ and B⁰ mesons via a virtual Z boson or a virtual photon.
Unsolved Mysteries
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.
Why is the Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?
Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?
What is Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?
Are there Extra Dimensions?
An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).
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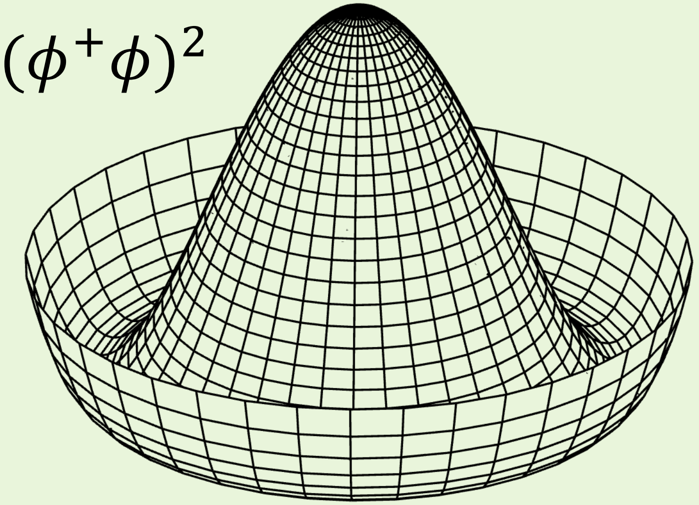
Standard Model of Fundamental Interactions

Sector pol skalarnych (Higgs boson) of the SM

$$SU(2)_L \times U(1)_Y : \phi \propto (\frac{1}{2}, 1)$$

$$\phi(x) = \begin{pmatrix} G^+(x) \\ \frac{h(x) + v + i\,G^0(x)}{\sqrt{2}} \end{pmatrix}$$

$$V(\phi) = \mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2$$



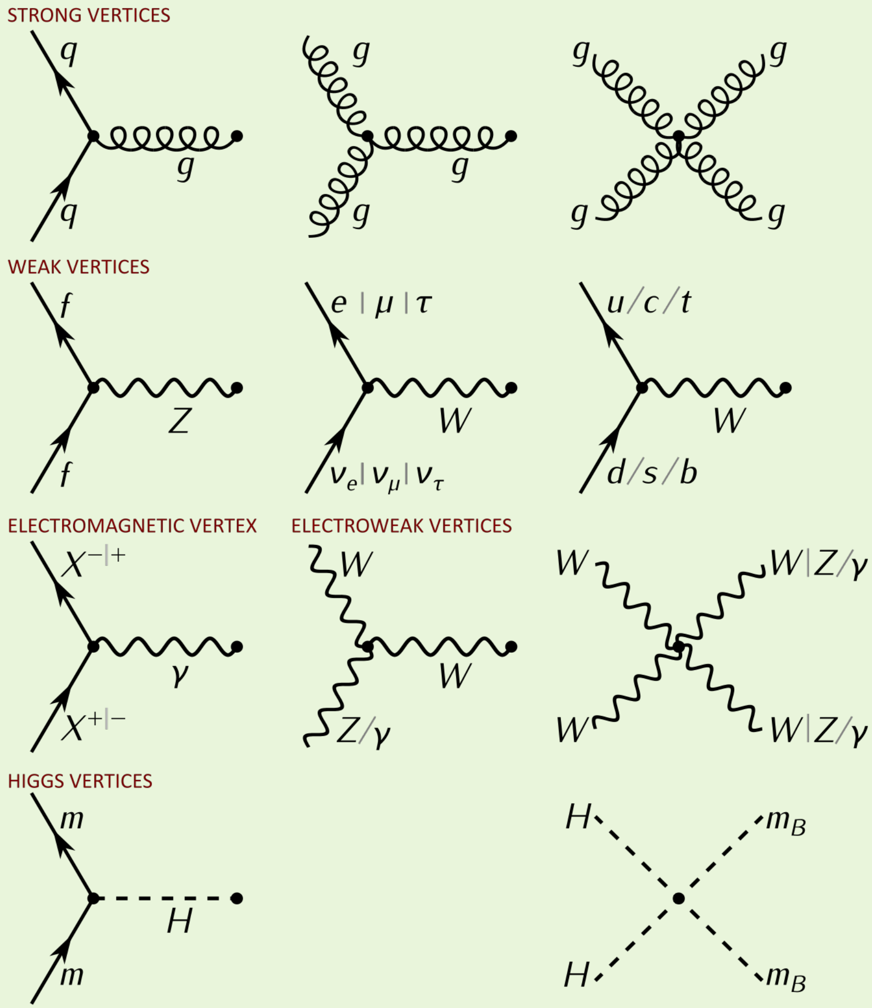
$G^{\pm,0}$ - Goldston bosons

h - Higgs boson

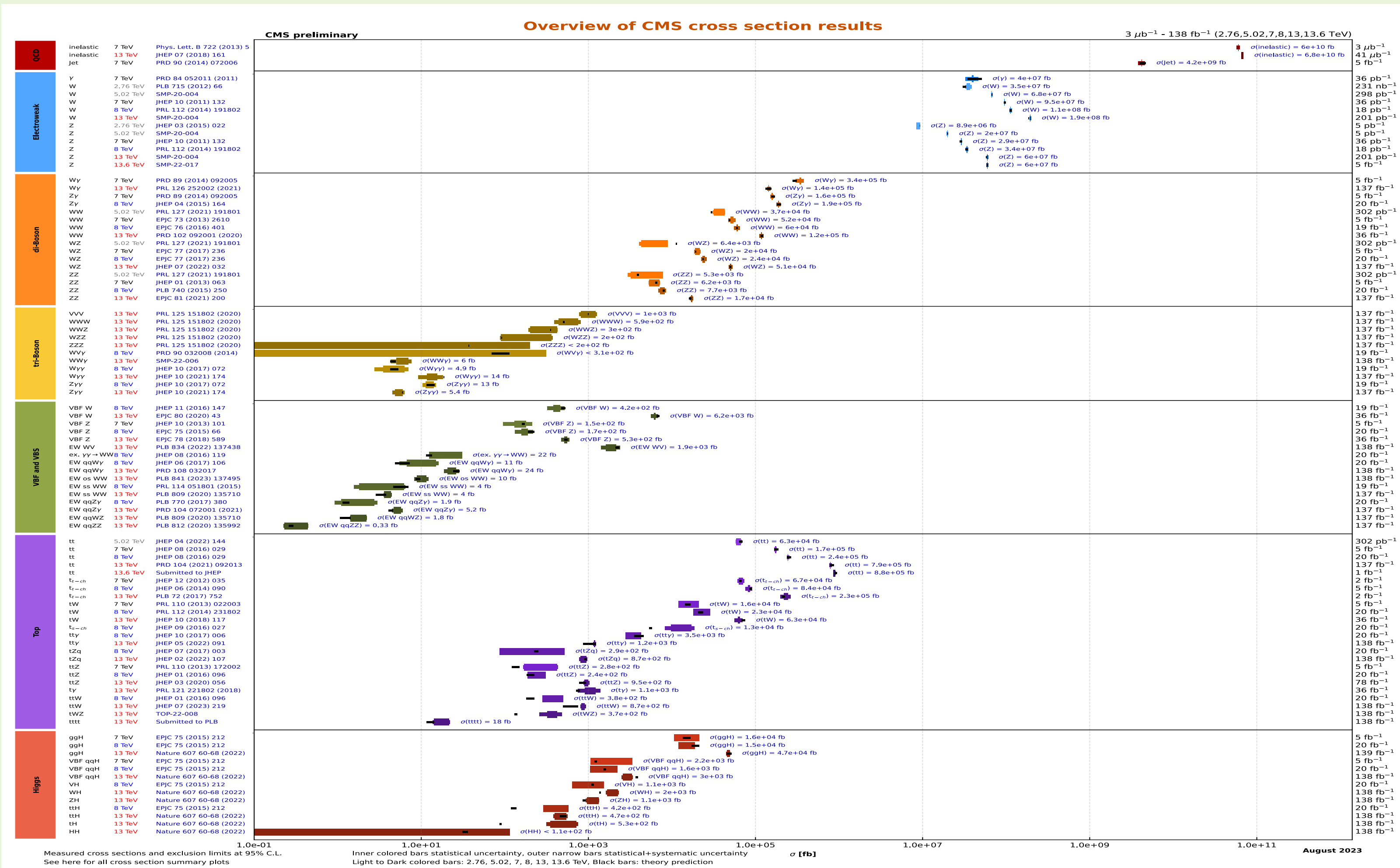
$v = 246\ GeV/c^2$ - vev

Standard Model of Fundamental Interactions

SM - interactions



Standard Model Tests



Standard Model Tests

On July 4, 2012, the discovery of a new elementary particle by the ATLAS and CMS collaborations was announced in experiments conducted at the Large Hadron Collider (LHC) at CERN. In April 2013, the CMS and ATLAS teams finally concluded that the particle is the Higgs boson predicted by the SM.

The inspiration was the desire to generalize electrodynamics neatly so that massive vector bosons appear in a renormalizable way !!

- SM predictions have been experimentally confirmed in several dozen (several hundred?) measurements
- The largest deviations from SM predictions observed in accelerator measurements:
  - masss of the $W^{\pm}$ (CDF, Fermilab) : $\sim 7\sigma$ (large theoretical uncertainties)
  - the muon's anomalous magnetic moment, a_{μ} (The Muon g-2 experiment, Fermilab) : $4.2\ \sigma$ (large theoretical uncertainties)

Standard Model of Fundamental Interactions

8 October 2013
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

and

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Standard Model Problems

1. Is there/Why is there only one Higgs boson?
2. Where do the masses of particles come from and why are they the way they are – what are they?
3. Where did antimatter go? We need additional sources of CP symmetry violation.
4. The strong CP problem.
5. Where and what is the invisible part of the Universe? ("dark matter" and "dark energy")
6. How did the early Universe form – "where/what" is the inflaton?

We believe that the Standard Model is not the ultimate theory of fundamental interactions

Standard Model Problems

We believe that the Standard Model is not the ultimate theory of fundamental interactions

Effective field theory (EFT) with $SU(2)_L \times U(1)_Y$ symmetry and operators of dim > 4:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c}{\Lambda} O_5 + \frac{1}{\Lambda^2} \sum_i c_i \, \mathrm{O}_i$$

"Warsaw basis": 59 operators O_i (dim 6) built from SM fields

BG, M. Iskrzynski, M. Misiak, J. Rosiek, „Dimension-Six Terms in the Standard Model Lagrangian", *JHEP* 10 (2010) 085

Specific models/theories generalizing SM (BSM):

- Additional gauge bosons, e.g.. $U(1)'$,
- Additional fermions, e.g. vector quarks,
- Additional Higgs bosons, e.g. 2HDM, 3HDM

SM as an effective field theory, EFT

Beyond the SM theories:
decoupling of heavy degrees of freedom
(higher mass fields/particles)
via the Appelquist-Carazzone theorem
(e.g. QED with light and heavy fermions)

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- $\mathcal{L}_{SM}^{(4)}$ is the SM dim 4 renormalizable Lagrangian
- Dim 5: $\mathcal{O}_{\nu\nu}=\left(\tilde{\phi}^\dagger l_p\right)^T C \left(\tilde{\phi}^\dagger l_r\right)$
- For dim 6, e.g. $\mathcal{O}_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^* \left(\phi^\dagger D_\mu \phi\right)$
- EoM relevant for redundancy
- The same symmetry and field content as in the SM

Standard Model Problems

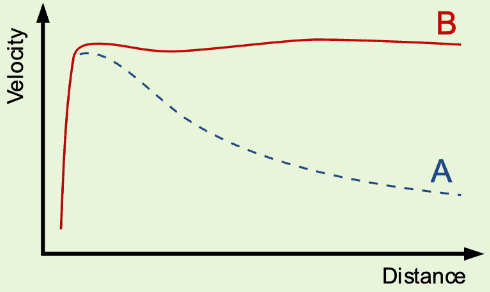
1. Since there are many fermions (quarks, leptons) and many vector bosons (photons, $W^{\pm}$, Z, gluons), wouldn't it be more natural to be many Higgs bosons, e.g. 3 doublets (families), similar to 3 families of quarks and leptons
2. SM does not contain fields responsible for cosmological inflation. Can the Higgs boson be an inflaton?
3. SM does not contain fields/particles that make up the dark matter. Can other Higgs boson-type particles be dark matter?

It is very likely that the solution to the problems of modern cosmology will allow us to find the "ultimate" theory of fundamental interactions "by the way"

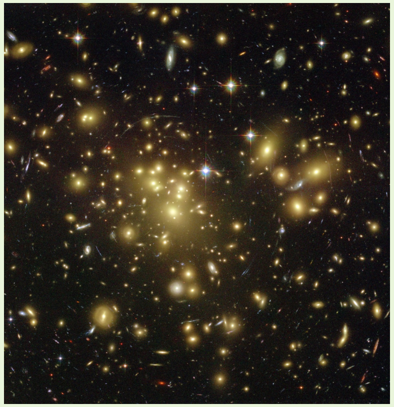
- theory of everything -

Standard Model Problems

Dark matter exists



- rotational curves, 1933 Fritz Zwicky,
- gravitational lensing,
- CMB, Planck Collaboration:
  $\Omega_c h^2 = 0.120 \pm 0.001$
- structure formation



Hubble Space Telescope in Abell 1689

MOND (modified Newtonian dynamics): $m\vec{a}\left(\frac{a}{a+a_0}\right) = \vec{F}$

where $a_0 \sim 10^{-10} m/s^2$

Baryonic asymmetry:
We don't observe antimatter in the Universe

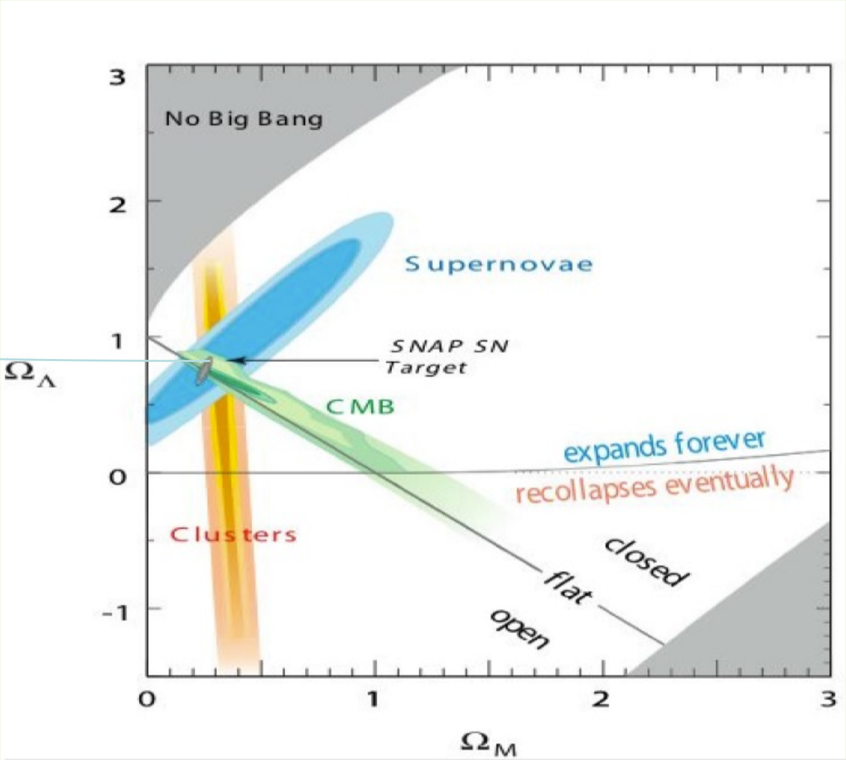
- CP breaking in SM is too weak to explain baryonic asymmetry
- A prerequisite for explaining the asymmetry: stronger CP symmetry breaking
- Complex parameters in Lagrangian ⟹ CP breaking

Standard Model Problems

The problem of dark energy (the problem of the cosmological constant)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = -8\pi \frac{G}{c^4} T_{\mu\nu}$$

$$\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c}$$



$\Omega_\Lambda \sim 0.7$

$\rho_\Lambda \sim 10^{-46}\ GeV^4$

Gravity $\rho_\Lambda \sim M_{Pl}^4 \sim 10^{76} GeV^4$

Solutions to MS problems

Extension of the Scalar Field (Higgs) sector:

- the existence of an electrically neutral and stable particle (dark matter),
- the existence of new sources of CP symmetry violation

Postulates:

- additional actual scalar field, S , or
- additional complex scalar field, S, or
- additional SU(2) doublet of scalar fields, $\phi_{2,}$ (2HDM), or
- additional two SU(2) doublets of scalar fields, $\phi_{2,}$ $\phi_{3,}$, (3HDM).

Solutions to SM problems

Additional real scalar sield S

$$V(\phi, S) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 - \mu_S^2 S^2 + \lambda_S S^4 + \kappa S^2 |\phi|^2$$

- ϕ - SM Higgs boson
- Z_2 - unbroken symmetry: $S \to -S$, ⇨ stability
- S – dark matter candidate
- real parameters ⇨ no additional CP breaking

Solutions to SM problems

Additional complex scalar field S

$$V(\phi, S) = \underbrace{-\mu_\phi^2|\phi|^2 + \lambda_\phi|\phi|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|\phi|^2}_{U(1)\text{ – invariant}} \; \underbrace{- \mu^2(S^2 + S^{*2})}_{\text{soft breaking } U(1)}$$

- ϕ - SM Higgs boson
- Z_2 - exact symmetry: $S \to -S$, ⇨ stability $Im\, S$
- $U(1)$ softly broken by $\mu^2(S^2 + S^{*2})$ ⇨ pGDM
- Natural suppression of scattering on nuclei in direct detection experiments
- real parameters ⇨ no additional CP breaking

Solutions to SM problems

Additional $SU(2)$ doublet scalar fields

$$V(\phi_1,\phi_2) = -\frac{1}{2}\left\{m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 + \left[m_{12}^2\,\phi_1^\dagger\phi_2 + H.c.\right]\right\} + \frac{1}{2}\lambda_1|\phi_1|^4 + \frac{1}{2}\lambda_2|\phi_2|^4 + \lambda_3|\phi_1|^2\,|\phi_2|^2 + \lambda_4\phi_1^\dagger\phi_2\phi_2^\dagger\phi_1 + \left\{\frac{1}{2}\lambda_5\left(\phi_1^\dagger\phi_2\right)^2 + \left[\lambda_6|\phi_1|^2 + \lambda_7|\phi_2|^2\right]\phi_1^\dagger\phi_2 + H.c.\right\}$$

- $m_{12}^2, \lambda_{5,6,7}$ - complex → additional breaking CP
- no candidate for dark matter

Solutions to SM problems

Minimal model containing a dark matter candidate and
an additional source of CP breaking

Solutions to SM problems

Minimal model containing a dark matter candidate and
an additional source of CP breaking

- $\phi_{1,2}$ ⇨ complex parameters ⇨ breaking CP
- singlet $SU(2)$, real or complex, symmetry Z_2 ⇨ A candidate for the dark matter

N. Darvishi, BG, „Pseudo-Goldstone dark matter model with CP violation", *JHEP* 06 (2022) 092

BG, O.M. Ogreid, P. Osland, et al., „Exploring the CP-Violating Inert-Doublet Model", *JHEP* 06 (2011) 003

Solutions to SM problems

Minimal model containing a dark matter candidate and an additional source of CP breaking

- $\phi_{1,2}$ ⇨ complex parameters ⇨ breaking CP
- singlet $SU(2)$, real or complex, symmetry Z_2 ⇨ A candidate for the dark matter

N. Darvishi, BG, „Pseudo-Goldstone dark matter model with CP violation”, *JHEP* 06 (2022) 092

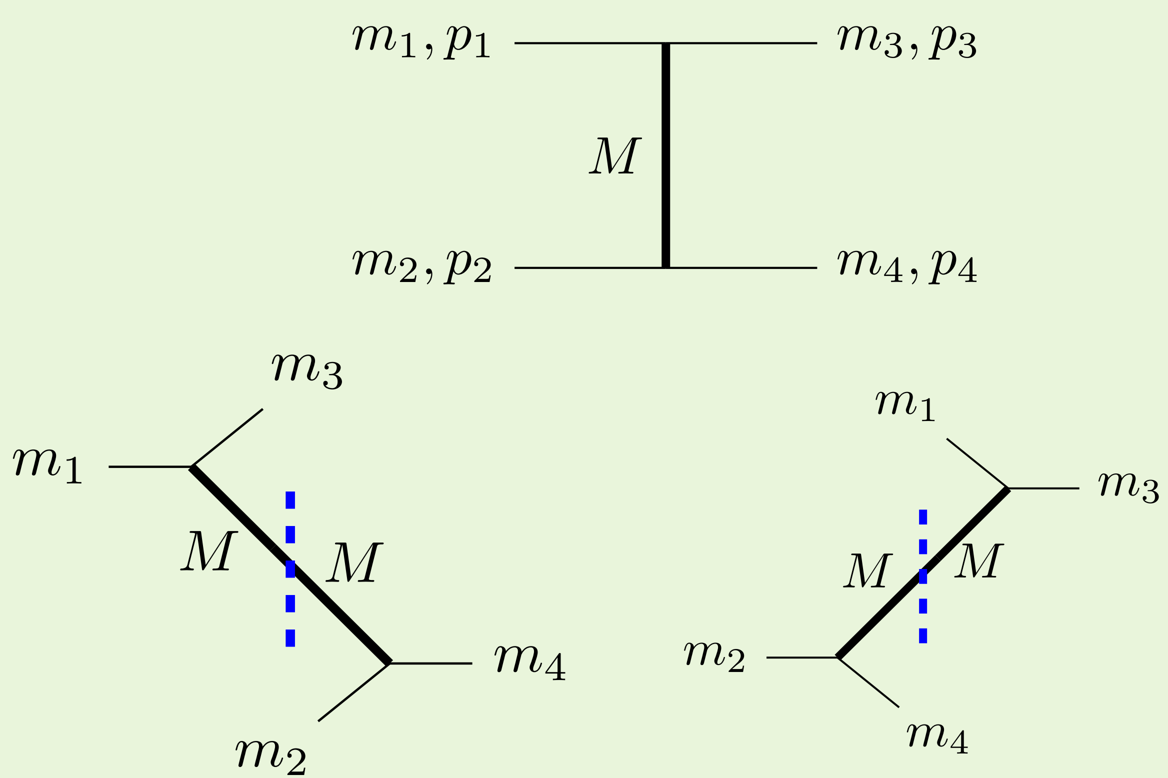
- $\phi_{1,2}$ ⇨ complex parameters ⇨ CP breaking
- ϕ_3 - dublet $SU(2)$, symmetry Z_2 ⇨ dark matter candidate

BG, O.M. Ogreid, P. Osland, et al., „Exploring the CP-Violating Inert-Doublet Model”, *JHEP* 06 (2011) 003

Summary

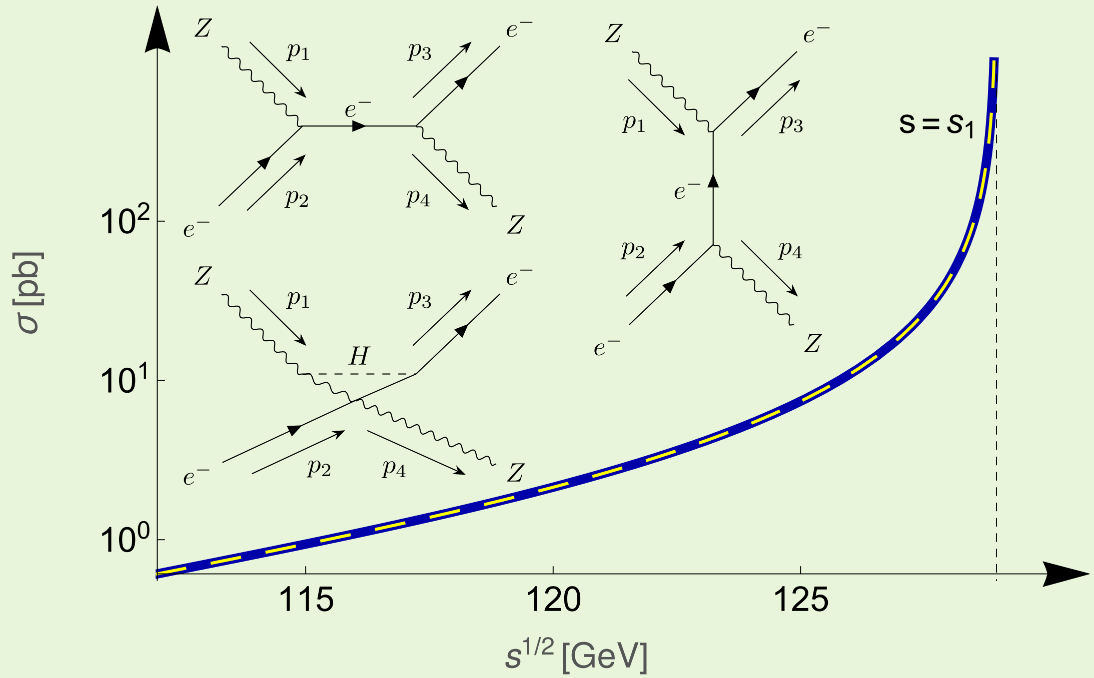
- SM is not perfect (dark matter, baryonic asymmetry, dark energy, strong CP breaking) and has to be fixed/expanded.
- Models containing additional doublets and singlets of scalar fields offer attractive MS generalizations.
- 3HDM provides a dark matter candidate and additional sources of CP violation.

Digression: "the t-channel singularity "



If mediator M is stable($\Gamma_M = 0$) there may be a singularity in $t = M^2$.

Dygresja: „osobliwość w kanale t”



Standard Model Problems

1. SM parameters:
   - fermion masses (Yukawa couplings): 6(quarks)+3(charged leptons)
   - couplings ($g, g', g_s, \lambda, U_{CKM}$): 4+4
   - parametr masowy (μ^2): 1

2. Is/Why there is only one Higgs boson?

3. Where do the masses of particles come from and why are they the way they are – what are they??

4. Where has antimatter gone? We need additional sources of CP violation.

5. The problem of strong CP breaking.

6. Where and what is the invisible part of the Universe? ("dark matter" and "dark energy")

7. How did the early Universe form – "where" is the inflaton?

We believe that the Standard Model is not the ultimate theory of fundamental interactions