THEORETICAL PERSPECTIVES ON PARTICLE PHYSICS

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- Standard model of particle physics.
- Beyond the standard model.
- Supersymmetry and implications.
- Supergravity and string models.
- Extra dimensions of spacetime.

STANDARD MODEL OF PARTICLE PHYSICS

Scales of fundamental forces

- The electromagnetic force has a long range and is sizable at all lengths. It has no characteristic energy scale.
- The weak force has a short range and is sizable only below the Fermi length. The characteristic energy scale at which it becomes relevant is the Fermi scale $\boldsymbol{M_{\mathbf{F}} \sim 10^2\ \mathbf{GeV}}$.
- The strong force has a more complex behavior. Its characteristic energy scale can be defined as the typical binding energy involved in hadrons: $\boldsymbol{M_{\mathbf{H}} \sim 1\ \mathbf{GeV}}$.
- The gravitational force has a long range, but its coupling depends on the energy. The characteristic energy scale where it becomes sizable is the Planck scale $\boldsymbol{M_{\mathbf{P}} \sim 10^{19}\ \mathbf{GeV}}$.

Structure of the standard model

The SM describes the electromagnetic, weak and strong interactions, with couplings $\alpha_{\mathbf{E}}$, $\alpha_{\mathbf{W}}$ and $\alpha_{\mathbf{S}}$. It ignores the gravitational interaction, whose effective coupling is $\alpha_{\mathbf{G}}(E) \sim (E/M_{\mathbf{P}})^2$.

It is a relativistic quantum field theory. It has a Lagrangian that involves a finite number of fields and parameters, and the structure of interactions is fixed by local gauge symmetries.

Particle content

Leptons: e^- μ^- τ^- Int. bos: γ $W^\pm$ Z^0 Higgs: H

ν_e ν_μ ν_τ

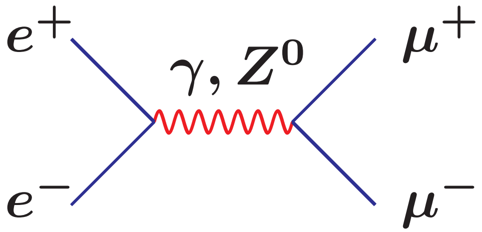
Quarks: u_α c_α t_α Gluons: g_a

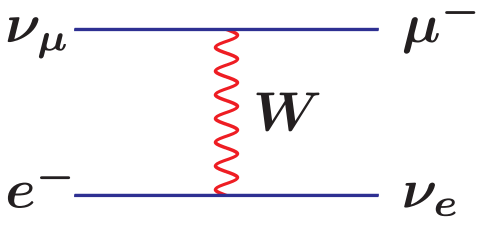
$$\underbrace{d_\alpha \quad s_\alpha \quad b_\alpha}_{\text{flavor}}$$

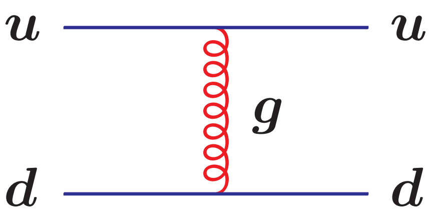
Processes and diagrams

The quadratic terms in the Lagrangian describe free particles, whereas the cubic and quartic terms define interactions, whose effects can be computed using perturbation theory. This results in Feynman diagrams.

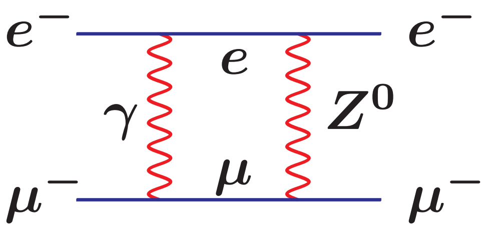
Diagrams without closed loops are similar to classical effects:

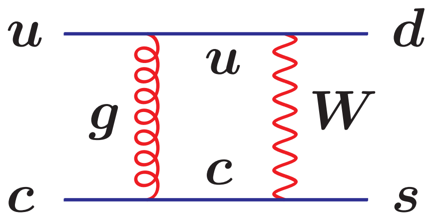


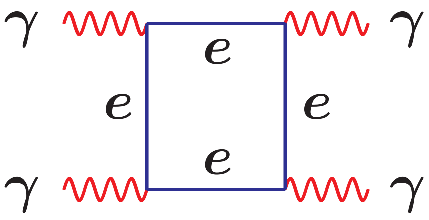




Diagrams with closed loops are genuine quantum effects:





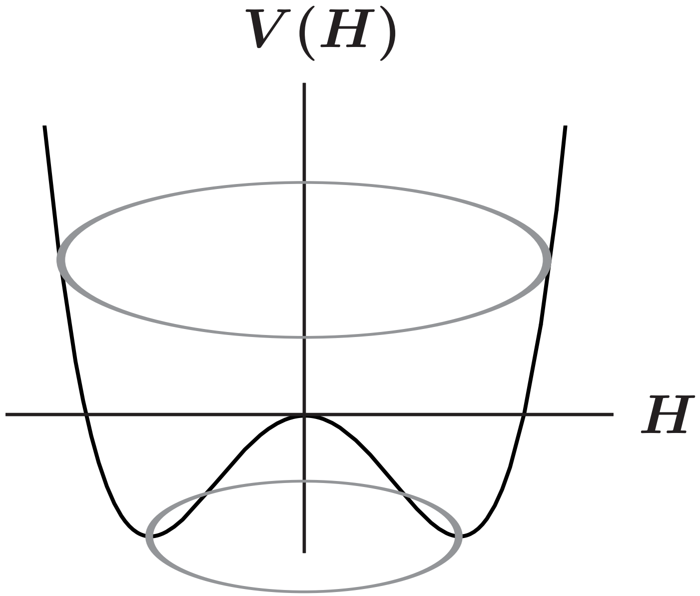


Electroweak sector

Weinberg 1967
Salam 1968

The electromagnetic and weak interactions rest on a $SU(2) \times U(1)$ local gauge symmetry. This allows 2 dimensionless couplings constants but forbids mass terms.

The mass terms are induced by partial spontaneous symmetry breaking: $SU(2) \times U(1) \rightarrow U(1)$. This is triggered at the classical level by a Higgs scalar, whose vacuum expectation value sets the scale M_{F}.

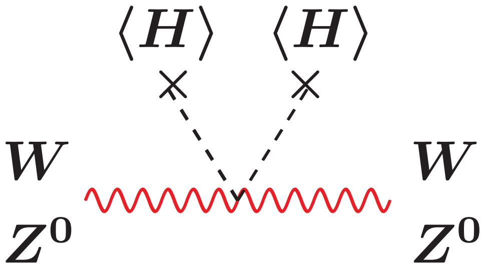


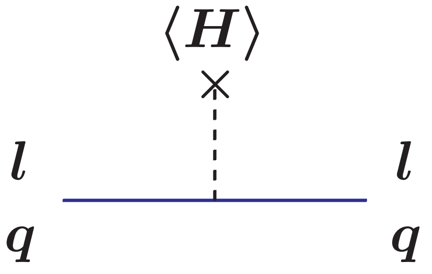
$$V(H) = -m^2 H^2 + \lambda H^4$$

$$\langle H \rangle = \frac{1}{\sqrt{2}} \frac{m}{\sqrt{\lambda}} = \frac{1}{\sqrt{2}} M_{\mathrm{F}}$$

$$m_H = \sqrt{2}\, m = \sqrt{2\lambda}\, M_{\mathrm{F}}$$

The weak vector bosons get masses from the gauge couplings of H, wheras the photon remains massless. The matter fermions get masses from extra Yukawa couplings with H.





Strong sector

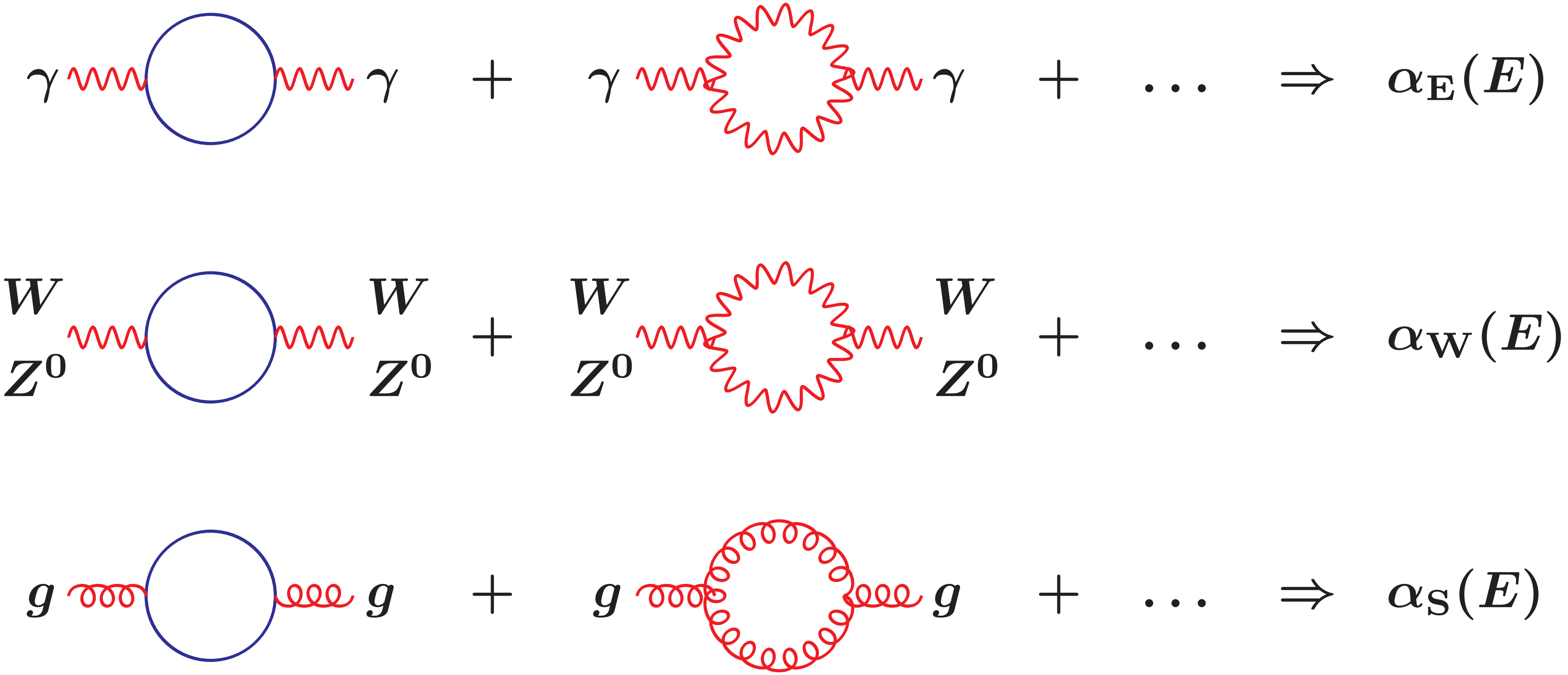
Gross, Wilczek 1973
Politzer 1974

The strong interactions are based on an $SU(3)$ local gauge symmetry. This allows 1 dimensionless couplings constants. This symmetry remains unbroken and the gluons are massless.

The scale M_{H} arises in a more subtle way, through quantum effects, as the scale where these interactions become effectively strong.

Running of couplings

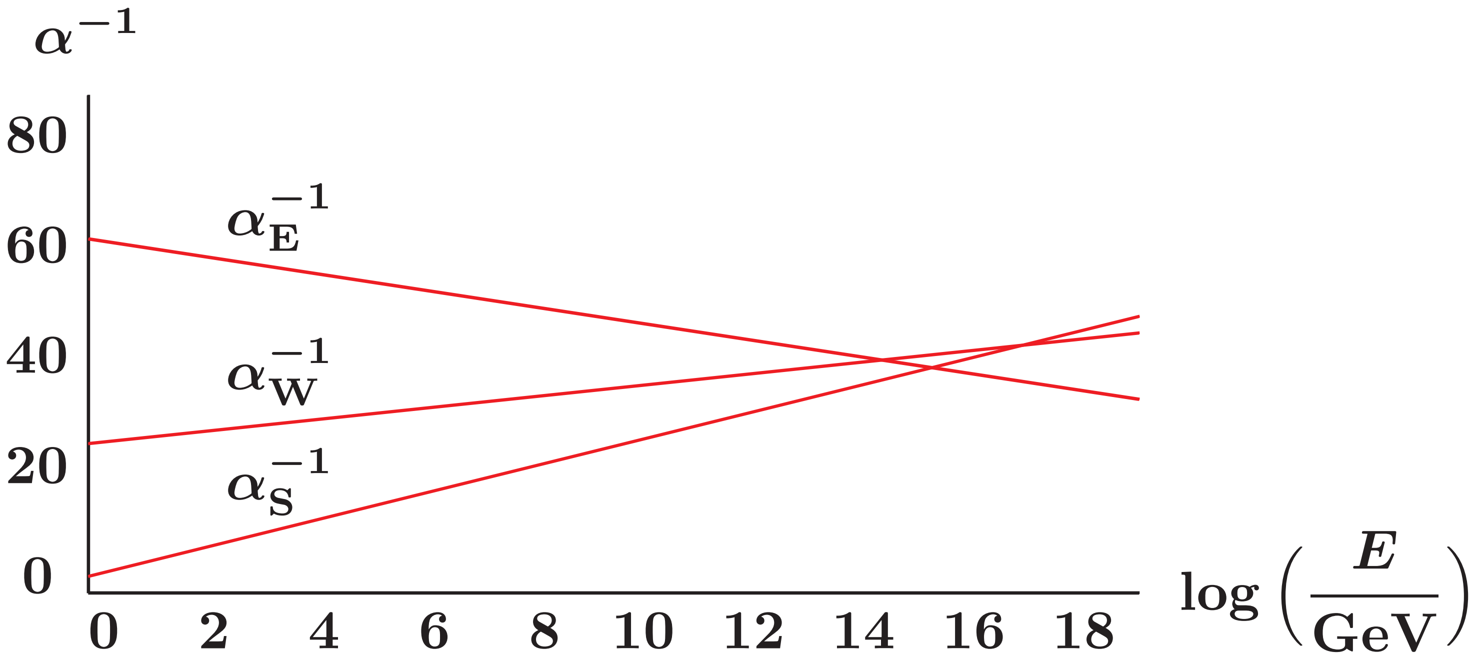
At the classical level, the three couplings are dimensionless constants. But quantum corrections induce a logarithmic energy dependence for these quantities.



The result is that:

$$\alpha^{-1}(E_2) - \alpha^{-1}(E_1) = \beta \ln \frac{E_2}{E_1}$$

Extrapolating the values measured around M_F one finds:



Experimental perspective

- The SM has been verified to very good accuracy up to $\mathbf{200\ GeV}$, somewhat below $M_{\mathbf{F}}$. The Higgs particle has however not been observed yet: $m_H > \mathbf{115\ GeV}$.
- New experiments will soon probe the model up to more than $\mathbf{10\ TeV}$, beyond $M_{\mathbf{F}}$. This should allow to verify the mechanism of electroweak symmetry breaking.

Theoretical perspective

- The SM is expected to be an effective theory valid at most up to $M_{\mathbf{P}}$, where gravitational interactions become important.
- The Higgs particle must be light enough for perturbation theory to be reliable: $m_H < \mathbf{1\ TeV}$.

Nice features:

- Simple general structure fixed by symmetry principles, in particular the $SU(3) \times SU(2) \times U(1)$ local gauge invariance.
- Special properties related to further accidental symmetries, like for instance B and L.

Limitations:

- Does not include gravitational interactions, which should become relevant at $M_{\mathbf{P}}$ $\Rightarrow$ Unification.
- Partial understanding for the value of $M_{\mathbf{H}}$ but not for that of $M_{\mathbf{F}}$, with respect to $M_{\mathbf{P}}$ $\Rightarrow$ Hierarchy.
- No intuition on the large hierarchies between masses of matter fermions of different families $\Rightarrow$ Flavor.

PHYSICS BEYOND THE STANDARD MODEL

Unification of gauge forces

Georgi, Glashow 1974

The three gauge forces are described in a very similar way in the SM. Moreover, their strengths become comparable at $M_{\mathbf{U}} \sim \mathbf{10^{15-17}\ GeV}$, slightly below $M_{\mathbf{P}}$.

This suggests that a more fundamental theory might underly the SM, where theses gauge forces are unified.

- There exist candidates that are still field theories, but with a larger spontaneously broken local gauge symmetry and $\mathbf{1}$ coupling.
- They predict new particles with a mass of the order of $M_{\mathbf{U}}$, and some constraints on the SM parameters.

Unification of gauge and gravitational forces

The proximity of $\boldsymbol{M_{\mathbf{U}}}$ and $\boldsymbol{M_{\mathbf{P}}}$ suggests that the gravitational force might also get unified with the gauge forces close to $\boldsymbol{M_{U}}$.

Ideally, the ultimate theory should have $\mathbf{1}$ scale $\boldsymbol{M_{\mathbf{U}}}$ and $\mathbf{1}$ coupling $\boldsymbol{\alpha_{\mathbf{U}}}$, and all the other scales and parameters should be derived.

- The existing candidates are not field theories but string theories, where point particles are replaced by extended objects with typical size $\boldsymbol{M_{\mathbf{U}}^{-1}}$.
- They predict infinitely many new particles, with mass of order $\boldsymbol{M_{\mathbf{U}}}$. Their structure is complicated but constrained by consistency.
- Gravity is modified at $\boldsymbol{M_{\mathbf{U}} < M_{\mathbf{P}}}$, where its effective strength is comparable to that of the gauge interactions: $\boldsymbol{(M_{\mathbf{U}}/M_{\mathbf{P}})^{2} \sim \alpha_{\mathbf{U}}}$. This implies that $\boldsymbol{M_{\mathbf{P}} \sim \alpha_{\mathbf{U}}^{-1/2} M_{\mathbf{U}}}$, which is roughly realized.

Hierarchy of scales

Assuming that there exists a fundamental scale close to M_{P}, it would be desirable to understand how the much lower scales M_{H} and M_{F} arise in the theory.

Quantum fluctuations tend to push any dimensionful coupling close to the fundamental scale at which they are cut off, and large hierarchies between scales are a priori unnatural.

- The hierarchy $M_{\mathrm{H}}/M_{\mathrm{P}}$ results from the slow running induced by quantum effects for the dimensionless coupling α_{S}.
  ⇒ Satisfactory.
- The hierarchy $M_{\mathrm{F}}/M_{\mathrm{P}}$ is achieved by a huge tuning of the mass coupling in the Higgs potential to cancel quantum corrections.
  ⇒ Unsatisfactory.

New physics at low scales

The electroweak symmetry breaking mechanism of the SM is considered unsatisfactory at the theoretical level. Moreover, it has not been directly probed at the experimental level.

Much effort has been devoted to finding a more compelling mechanism, by modifying the SM in this sector already close to M_F. There exist two main classes of models.

- Weakly coupled: $M_{\mathbf{F}}$ is set as in the SM, but some new weakly interacting sector is added to cut off quantum corrections.
  ⇒ Supersymmetry.
- Strongly coupled: $M_{\mathbf{F}}$ is set as the strong coupling scale of a new interaction sector that is added to the SM.
  ⇒ Technicolor.

Flavor structure

Froggatt, Nielsen 1979

The masses of matter fields display a broad range of values, most of which are much smaller than $M_{\mathbf{F}}$.

This is fine, since the relevant Yukawa couplings are dimensionless and receive only small quantum corrections.

Nevertheless, this fact has motivated the search for mechanisms that could explain flavor more naturally.

- There exist candidates based on a flavor symmetry broken slightly below $M_{\mathbf{U}}$. Yukawa couplings effectively arise from more complex couplings suppressed by powers of $M_{\mathbf{U}}^{-1}$.
- The hierarchies in Yukawa couplings can then be explained by selection rules, as powers of a small breaking parameter.

SUPERSYMMETRY

Supersymmetry

Volkov, Akulov 1973
Wess, Zumino 1974

Supersymmetry is a unique extension of Poincaré spacetime symmetries. The new supertransformations mix bosons and fermions, and interfere with translations, rotations and boosts.

- It can be realized only on multiplets with the same number of bosons and fermions with equal masses. Scalar masses are then protected because they are linked to fermion masses.
- It limits quantum corrections, thanks to cancellations between bosonic and fermionic virtual partners.
- It is believed to play an important role concerning the consistency of any fundamental theory.

Minimal supersymmetric standard model

Dimopoulos, Georgi 1981

The MSSM is obtained by adding to the SM first a second Higgs field and then a superpartner for each ordinary field.

Particles

Leptons: e^- μ^- τ^- Int. bos: γ $W^\pm$ Z^0 Higgs: H $\phi_{1\text{-}2}$ $\phi^\pm$

ν_e ν_μ ν_τ

Quarks: u_α c_α t_α Gluons: g_a

d_α s_α b_α

Sparticles

Sleptons: $\tilde{e}^-$ $\tilde{\mu}^-$ $\tilde{\tau}^-$ Chargini: $\chi^\pm_{1\text{-}2}$ Neutralini: $\chi^0_{1\text{-}4}$

$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$

Squarks: $\tilde{u}_\alpha$ $\tilde{c}_\alpha$ $\tilde{t}_\alpha$ Gluini: $\tilde{g}_a$

$\tilde{d}_\alpha$ $\tilde{s}_\alpha$ $\tilde{b}_\alpha$

Supersymmetry breaking

Sparticles have not been observed experimentally. Supersymmetry must therefore be broken in such a way to induce a mass splitting with respect to particles, given by some scale M_{B}.

The quantum corrections that tend to increase M_{F} are cut off at M_{B}. The scale M_{B} should be close to M_{F} to solve the hierarchy naturalness problem.

The general paradigm is to add to the standard supersymmetric sector a breaking sector where supersymmetry is spontaneously broken, as well as a mediating sector that transmits the effect.

The effect of supersymmetry breaking can be parametrized by finitely many soft breaking terms, whose coefficients depend on the details of the breaking and mediation mechanisms:

$$\mathcal{L} = \mathcal{L}_{\mathrm{S}} + \mathcal{L}_{\mathrm{B}}$$

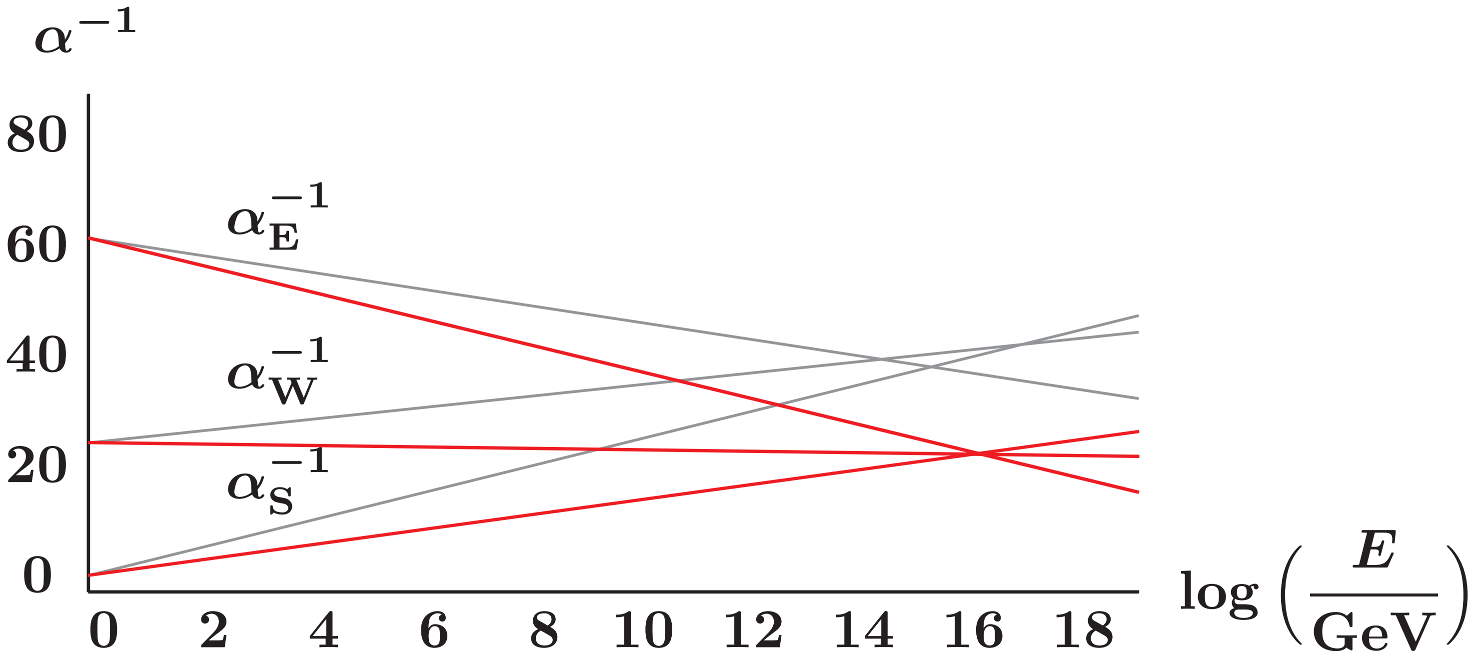
Phenomenological characteristics

The phenomenology of the MSSM can be studied as a function of the values of the soft terms. It works pretty well in general.

- The Higgs is predicted to be very light, with $m_H < 130\ \mathrm{GeV}$. This is barely compatible with the direct experimental bound $m_H > 115\ \mathrm{GeV}$.
- Sparticles imply potentially strong indirect effects also at energies below M_{F}, since M_{B} is close to it. These are harmless only if the soft terms posses some peculiar features.
- The lightest sparticle is stable, due to some discrete symmetry that is needed for proton stability, and represents a good candidate for the dark matter required by cosmology.

Running of couplings

The presence of sparticles, besides particles, changes the running of gauge couplings. Extrapolating again the values around $\boldsymbol{M_{\mathrm{F}}}$ one finds a more precise unification at $\boldsymbol{M_{\mathrm{U}} \sim 10^{16\text{–}17}\ \mathrm{GeV}}$:



Signatures

If supersymmetry is to explain the electroweak hierarchy, with $\boldsymbol{M}_{\mathbf{B}}$ close to $\boldsymbol{M}_{\mathbf{F}}$, it should be discovered at the forthcoming LHC experiment at CERN.

A comparison between theory and experiment rests however on the form of the soft terms, which carry the information about how supersymmetry is broken.

A important theoretical issue is then to identify a satisfactory mechanism of supersymmetry breaking. There are two main classes of proposals.

- Gauge mediation: the mediators are new particles having ordinary gauge interactions.
- Gravity mediation: the mediator is the graviton, the particle that is supposed to mediate gravitational interactions.

SUPERGRAVITY AND STRINGS

Local supersymmetry

Freedman, van Nieuwenhuizen, Ferrara 1976

The Poincaré group of global spacetime symmetries can be promoted to a local symmetry. This gives rise in a very elegant way to Einstein's theory of gravity.

The supersymmetric extension of the Poincaré group can be promoted in a similar way to a local symmetry. This gives rise to supergravity.

Graviton: h

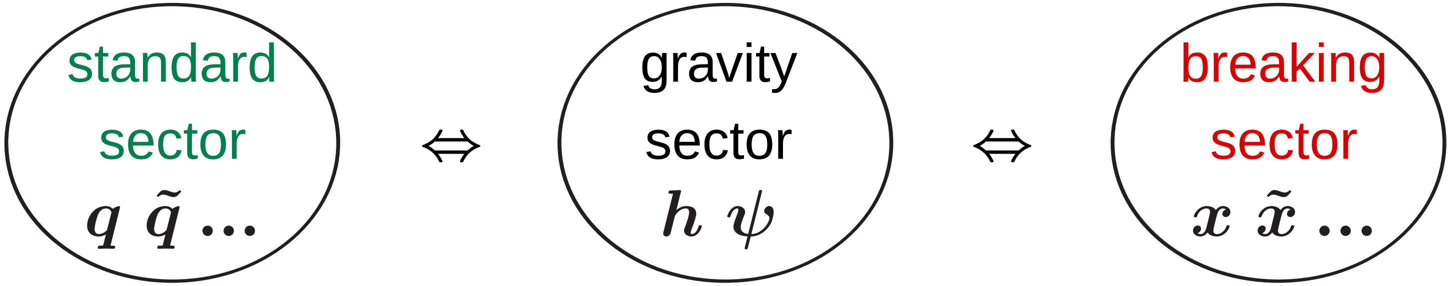
Gravitino: ψ

Supergravity represents the union of supersymmetry and gravity, and emerges also as an effective description of string theory below $M_{\mathbf{U}}$.

Gravity mediated supersymmetry breaking

Arnowitt, Chamseddine, Nath 1982
Barbieri, Ferrara, Savoy 1982

The standard sector and the breaking sector unavoidably interact among themselves through gravity. Supergravity represents therefore a natural mediation sector.



standard sector $q\ \tilde{q}\ \ldots$ ⇔ gravity sector $h\ \psi$ ⇔ breaking sector $x\ \tilde{x}\ \ldots$

There exist effective interactions suppressed by powers of M_{P}^{-1} that mix the standard and breaking sectors. If supersymmetry is spontaneously broken at some scale M_{S}, soft terms are induced.

$$M_{\mathrm{B}} = \frac{M_{\mathrm{S}}^2}{M_{\mathrm{P}}} \qquad\qquad M_{\mathrm{B}} \sim M_{\mathrm{F}} \ \text{ if } \ M_{\mathrm{S}} \sim \sqrt{M_{\mathrm{F}} M_{\mathrm{P}}}$$

Phenomenologically delicate points

Supergravity does well in providing all the needed soft terms. However, there are a few delicate points, among which the tiny observed value of the cosmological constant: $M_\Lambda \sim 10^{-12}\ \mathrm{GeV}$.

- The breaking sector potential sets both M_B and M_Λ through its overall scale and minimum value. Its is then unnatural to have M_Λ much smaller than M_B. ⇒ Cosmological flatness.
- The breaking scalars can mediate new exotic forces and affect primordial nucleosynthesis. They have to be stabilized with a large enough mass of order M_B. ⇒ Cosmological stability.
- The soft terms operators arise at M_P, where flavor is supposed to be explained. It is then difficult to understand why soft terms should be universal and Yukawa couplings not. ⇒ Flavor.

Cosmological constraints

The huge hierarchy between M_Λ and M_B is also considered to be a very severe problem. This is again because quantum corrections tend increase M_Λ towards M_B.

In this case no simple idea for a natural explanation exists. One needs to rely on a tuning of parameters to achieve a huge cancellation between the matter and the gravitational contributions to the potential.

It is possible to study the general conditions under which a supergravity model can admit flat and stable vacua. These have particularly strong implications for string models. [Gomez-Reino, Scrucca 2006]

Supersymmetric flavor problem

The flavor non-universality of squark and slepton mass matrices is strongly constrained by precision measurements. For $M_{\mathbf{B}} \sim M_{\mathbf{F}}$ one finds in both cases:

$$\frac{\delta m^2}{m^2} < 10^{-3}$$

This bound puts interesting indirect constraints on physics at high scales. The sensitivity will be further improved by the MEG experiment at PSI.

- If the supergravity validity is pushed up to $M_{\mathbf{P}}$, where $\alpha_G \sim 1$, a robust explanation for this small number would be desirable.
- If the supergravity validity is limited to $M_{\mathbf{U}}$, where $\alpha_G \sim \alpha_{\mathbf{U}}$, one could postulate that leading order effects are universal, and subleading non-universal effects would be just barely tolerable.

EXTRA SPACETIME DIMENSIONS

Effects of extra dimensions

Kaluza 1921
Klein 1929

Theoretically it is possible that the number of spacetime dimensions is actually greater than $\mathbf{4}$. This represents yet another type of extension of spacetime symmetries.

Extra dimensions can be tolerable if they are compact, with a sufficiently small size $M_{\mathbf{C}}^{-1}$. By Fourier decomposition, any light field gives rise to an infinite tower of extra modes with masses of order $M_{\mathbf{C}}$.

At energies below $M_{\mathbf{C}}$, these extra states influence only mildly the physics of the light modes.

Interesting features

- Localizing or delocalizing fields in an extra dimension restricts the effective theory even below $M_{\rm C}$, in a way that goes beyond the effect of internal symmetries.

  $\Rightarrow$ Sequestering.

- The decomposition properties of representations of the Lorentz group under dimensional reduction gives an interesting unification of different types of fields.

  $\Rightarrow$ Unification.

Unpleasant features

- Beyond $M_{\rm C}$, the effective theory is higher-d and has dimensionful couplings. This limits its range of validity to the scale $\alpha^{-1} M_{\rm C}$.

String models

Green, Schwarz 1985
Dixon, Harvey, Vafa, Witten 1985

String theory predict a $\mathbf{10}$-d spacetime. Viable models assume that this is the product of the ordinary $\mathbf{4}$-d spacetime and a $\mathbf{6}$-d compact manifold with characteristic size $M_{\mathbf{C}}$.

- The low-energy effective theory below $M_{\mathbf{C}}$ is a supergravity model with peculiar characteristics.
- The manifold characteristics and the coupling constant are fixed dynamically as vacuum expectation values of light scalar fields.
- This neutral sector of the theory is a natural and good candidate breaking sector, since a non-trivial potential is anyhow needed.

Gauge-Higgs unification

Manton 1979
Fairlie 1979

In the presence of a compact extra dimension, the Higgs field of the SM could be the internal component of some gauge field: $\boldsymbol{H = \oint dy A_y}$.

Higher-d gauge invariance puts severe constraints on $\boldsymbol{V(H)}$. This is now controlled by quantum corrections cut off at $\boldsymbol{M_{\mathbf{C}}}$, and one finds:

$$\boldsymbol{M_{\mathbf{F}} \sim \alpha^{-1/2} M_{\mathbf{C}}}$$

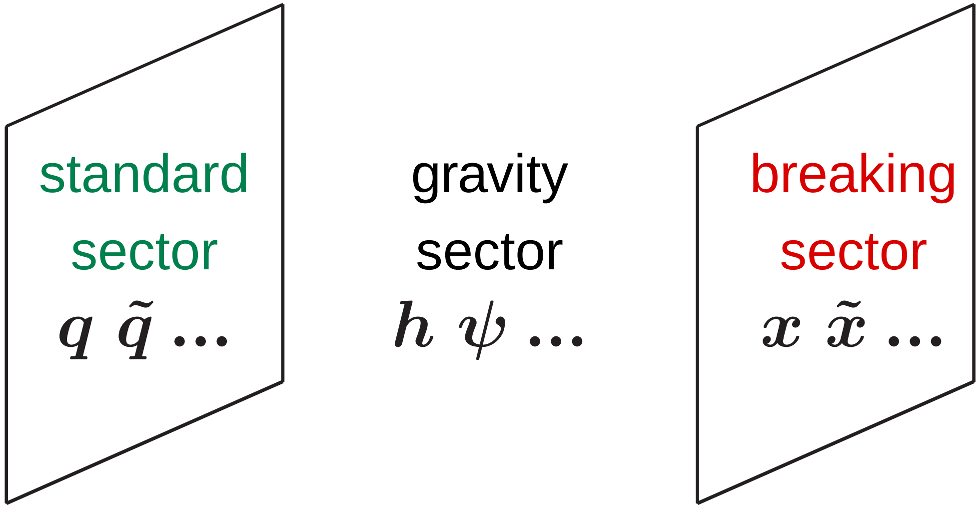
- The hierarchy problem is postponed to the cut-off scale $\boldsymbol{\alpha^{-1} M_{\mathbf{C}}}$, which is not far from $\boldsymbol{M_{\mathbf{F}}}$. The idea of unification is lost.
- One can build viable models, but there is some tension with the experimental bound $\boldsymbol{M_{\mathbf{C}} > 1\ \mathbf{TeV}}$. [Scrucca, Serone, Silvestrini 2003]
- Yukawa's arise as effective couplings, and flavor symmetries are naturally incorporated. [Martinelli, Salvatori, Scrucca, Silvestrini 2005]

Sequestered supersymmetry

Randall, Sundrum 1998

The presence of a compact extra dimension, with a new field associated to it, gives also new opportunities in supergravity model building.

The standard and the breaking sectors could be localized on branes that are separated along the extra dimension. Soft breaking terms are then controlled by quantum corrections cut off at M_{C}.



standard sector $q\ \tilde{q}\ \ldots$

gravity sector $h\ \psi\ \ldots$

breaking sector $x\ \tilde{x}\ \ldots$

$$M_{\mathrm{B}} \sim \left(\frac{M_{\mathrm{C}}}{M_{\mathrm{P}}}\right)^2 \frac{M_{\mathrm{S}}^2}{M_{\mathrm{P}}}$$

This setup leads to a number of interesting distinct features for model building, in particular as far as the flavor problem is concerned.

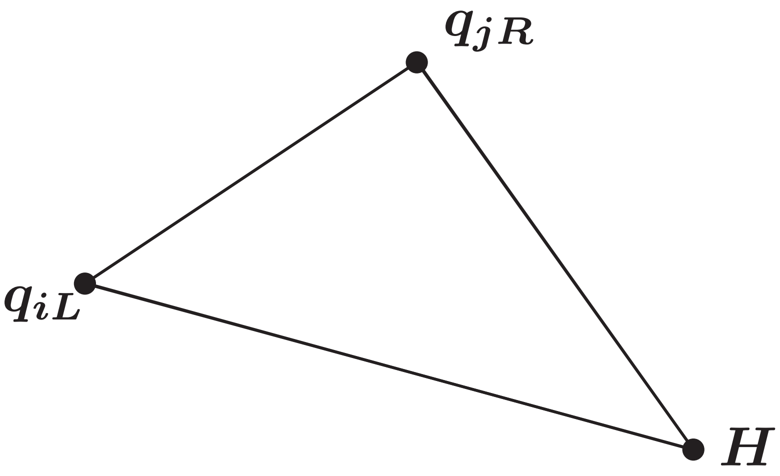
- Soft term are induced by quantum corrections at the scale $M_{\mathbf{C}}$, where gravity is flavor universal.
- One can construct viable models with $M_{\mathbf{C}} \sim \alpha_{\mathbf{U}} M_{\mathbf{P}}$, in which certain gauge and gravitational quantum corrections compete and yield realistic soft terms. [Rattazzi, Scrucca, Strumia 2003]
- Non-universal subleading effects are predicted to be again close to the experimental bound. [Gregoire, Rattazzi, Scrucca 2005]

Sequestered flavor

Cremades, Ibanez, Marchesano 2001

Extra dimensions give also interesting possibilities for theoretical model building concerning the flavor structure in string models.

Different flavors of matter fields and the Higgs field could be localized at distinct points in the extra dimensions. Yukawa couplings are then controlled by semi-classical effects.



$$y_{ij} \sim \exp\left\{-A_{ij} M_{\mathrm{U}}^{2}\right\}$$

This situation provides interesting peculiarities that can be exploited to give an explanation of flavor in string models.

- The SM cubic Yukawa's depend exponentially on the area that separates the fields. Large hierarchies of masses are then traced back to small differences in areas.
- The soft masses in the MSSM dominantly depend on properties of the model at the corresponding localization point, and can be approximately universal.
- Non-universal subleading effects remain to be studied. But they are likely to be again close to the experimental bound.

CONCLUSIONS

- General concepts like naturalness or unification suggest that a set of new ingredients should appear in a really fundamental theory of elementary particle physics.
- Forthcoming accelerator experiments should provide new crucial information to turn some of these speculations into true progress in our understanding of nature.
- The question of whether there really exists a fundamental theory describing all the interactions in a unified way might soon become more accessible.