Fundamental Concepts in Particle Physics

Lecture 4 :
Towards Beyond the Standard Model

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Charges of Standard Model Fields

Field	$SU(3)$	$SU(2)_L$	T^3	$\frac{Y}{2}$	$Q = T^3 + \frac{Y}{2}$
g_μ^a (gluons)	$\mathbf{8}$	$\mathbf{1}$	0	0	0
$(W_\mu^\pm, W_\mu^0)$	$\mathbf{1}$	$\mathbf{3}$	$(\pm 1, 0)$	0	$(\pm 1, 0)$
B_μ^0	$\mathbf{1}$	$\mathbf{1}$	0	0	0
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{6}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
u_R	$\mathbf{3}$	$\mathbf{1}$	0	$\frac{2}{3}$	$\frac{2}{3}$
d_R	$\mathbf{3}$	$\mathbf{1}$	0	$-\frac{1}{3}$	$-\frac{1}{3}$
$E_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	$\mathbf{1}$	$\mathbf{1}$	0	-1	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\frac{1}{2}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$
$\Phi^c = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$-\frac{1}{2}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$

Left-handed versus right-handed spinors

Nature is symmetric under the group of Lorentz transformations, rotations, and translations which all together form the Poincaré group.

Particles are classified by spin: scalars, fermionic spinors, vector bosons. They correspond to irreducible representations of the Poincaré group

Spinors are of two types: the fundamental (left-handed) and the anti-fundamental (right-handed). **The chirality of a spin 1/2 field refers to whether it is in the fundamental or the anti-fundamental and is therefore a label associated with a representation of the Lorentz group**

Weyl spinors

$$\Psi_L : (\frac{1}{2}, 0)$$

$$\Psi_R : (0, \frac{1}{2})$$

Dirac spinor

$$\Psi = \begin{bmatrix} \Psi_L \\ \Psi_R \end{bmatrix}$$

Chirality versus helicity

helicity is a physical quantity: it is the projection of the spin onto the direction of motion

for a massless particle: chirality= helicity

$SU(2)_L$

(thus we call the fundamental spinors the left-handed spinors and the anti-fundamental spinors the right-handed spinors)

The Standard model is a chiral theory: the left-handed and right-handed spinors not only transform differently under the Lorentz group but also under the EW gauge group **$SU(2)_L$*U(1)**

The left-handed fields are denoted **$Q=(u_L, d_L)$** and **$L=(nu_L, e_L)$** while the right-handed fields are denoted **u, d and e**.

Fermion masses

Lorentz invariant: $\bar{\psi}\psi \,\square\, \psi_L^* \psi_R \,\square\, \psi_R^* \psi_L$

-> Dirac mass $\mathfrak{L} = m \square e_L^* e_R \,\square\, e_R^* e_L \square$

-> violates EW gauge symmetry

How do a left-handed and right-handed particle of different quantum numbers become a single massive particle?

The key is the gauge invariant Yukawa interaction:

$$\Delta\mathcal{L}_Y = -\phi(Q_i \lambda_{ij}^U u_j^c + L_i \lambda_{ij}^N N_j) - \phi^+(Q_i \lambda_{ij}^D d_j^c + L_i \lambda_{ij}^E e_j^c) + h.c.$$

Once the Higgs condenses, these couplings become the mass of the SM fermions

The CKM matrix

Both up and down-type quarks acquire mass matrices

$$M_u = Y_u v, \qquad M_d = Y_d v.$$

Need to be diagonalized with four independent unitary rotations:

$$M_u^\dagger M_u = V_{u_R} D_u^2 V_{u_R}^\dagger, \qquad M_u M_u^\dagger = V_{u_L} D_u^2 V_{u_L}^\dagger,$$
$$M_d^\dagger M_d = V_{d_R} D_d^2 V_{d_R}^\dagger, \qquad M_d M_d^\dagger = V_{d_L} D_d^2 V_{d_L}^\dagger.$$

mass eigen values: $$D_u = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}, \qquad D_d = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

u_L and d_L live in a doublet. There is no basis in which both components are in a mass eigenstate.

$$Q_i = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} = \begin{pmatrix} (V_{u_L})_{ij} u_{Lj}^m \\ (V_{d_L})_{ij} d_{Lj}^m \end{pmatrix}$$

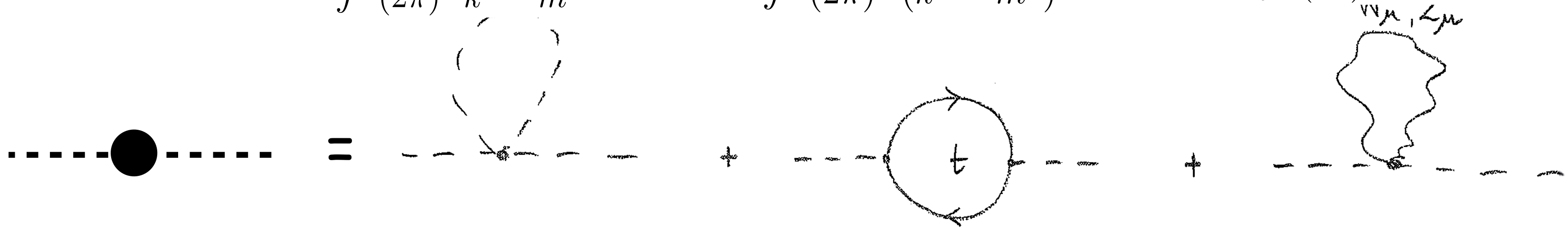
-> Cabbibo-Kobayashi-Maskawa mixing matrix of the Standard Model $V_{CKM} = V_{u_L}^\dagger V_{d_L}$

The hierarchy problem

As soon as we introduce a fundamental scalar field in the theory (the Higgs), this generates a puzzle: the so-called "hierarchy problem".

= the fact that the Higgs self-energy receives radiative contributions that are quadratically divergent.

$$\int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{k^2}{(k^2-m^2)^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2-m^2} \propto \Lambda^2$$

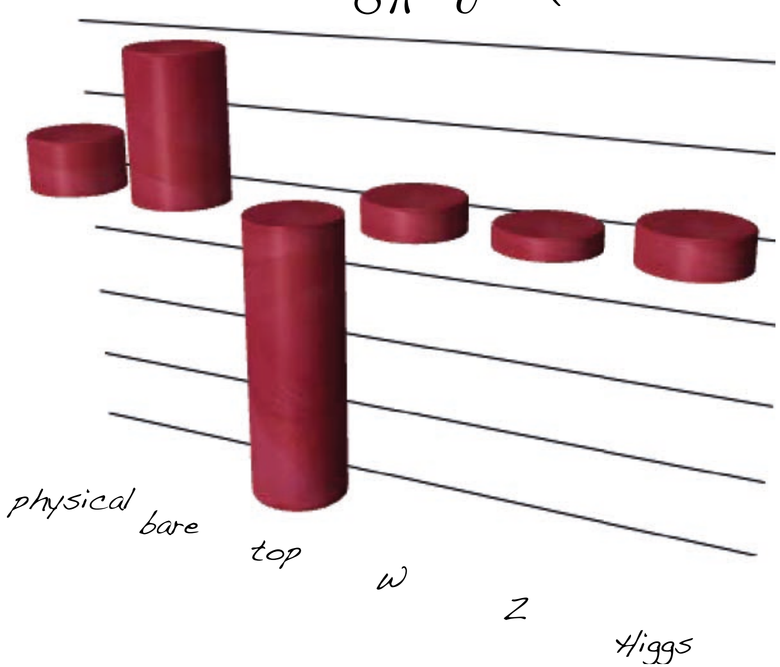


+ Higher loops
Smaller Yukawa

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \sim -(0.23\ \Lambda)^2$$

strong sensitivity on high energy unknown physics

Λ , the maximum mass scale that the theory describes



To stabilise the Higgs mass at the EW scale against the Planck scale, we need to adjust the parameter of the Higgs potential at a level of 10^{-32}.

History repeats itself?

There are examples in physics where unexpected and precise parameter cancellations were actually the signal of the existence of new particles.

For instance, the electron self energy has a power divergence that can be cured only by the introduction of the positron.

Similarly, the extreme sensitivity of the Higgs self energy with respect to physics at high momentum can be naturally reduced by introducing new symmetries and new degrees of freedom, such as supersymmetry, or extra spacial dimensions or additional global symmetries.

Classical/Quantum Electromagnetism & Antimatter

an electron makes an electric field which carries an energy

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

electric charge

classical size of the electron

and interacts back to the electron and contributes to its mass $\delta m c^2 = \Delta E_{\text{Coulomb}}$

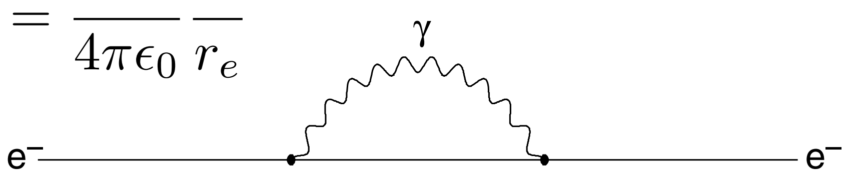
$$\delta m \sim m_e \quad \Rightarrow \quad r_e \sim \frac{e^2}{4\pi\epsilon_0 m_e c^2} \sim 10^{-13}\ \text{m}$$

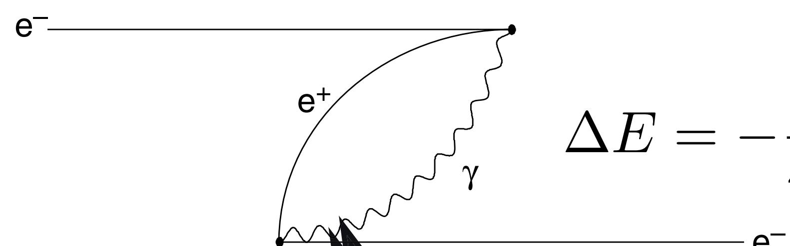
The electron repels itself due to its charge, how to keep electric charge in a small pack?

electron point like!

antimatter comes to rescue the 19th century "electron crisis"

$$\Delta E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$





$$\Delta E = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$\Delta E = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{r_e m_e c}$$

Weisskopf '39

new states ≈ softer UV behavior, small correction to the mass

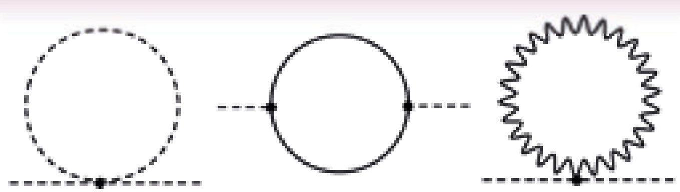
The hierarchy problem: What is keeping the Higgs boson light?

we need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale

a problem that arises for any elementary SCALAR particle

does not arise for fermions (protected by chiral symmetry) or
gauge bosons (protected by the gauge symmetry)

What is cancelling the divergent diagrams?



$$\Rightarrow \delta M_H^2 \propto \Lambda^2$$

A light Higgs calls for New Physics at the TeV scale

the "hierarchy problem": the main motivation for building the LHC

Addressing the hierarchy problem

$$\left(\delta m_h^2\big|_{1-loop} \sim -\frac{y_t^2}{8\pi^2}\Lambda_{UV}^2 \right)$$

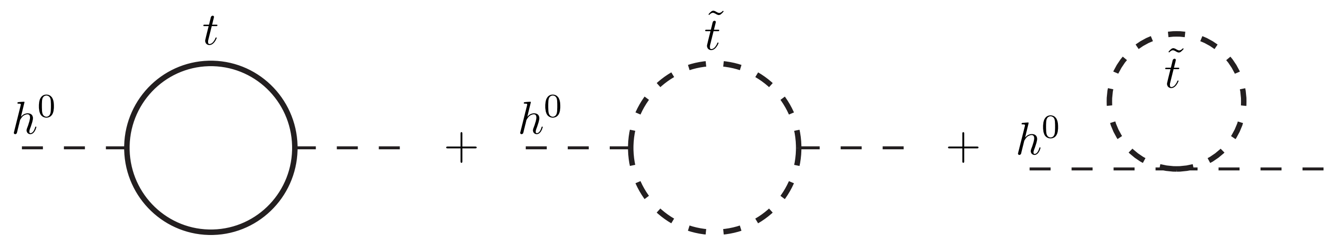
with a new symmetry

Supersymmetry	Extra dimensions	new global symmetry
fermion	vector	scalar
$\Psi \to e^{i\theta\gamma_5}\ \Psi$	$A_\mu \to A_\mu + \partial\theta$	$H \to H + \theta$
Ψ massless:	A_μ massless:	H massless:
protected by chiral symmetry	protected by gauge invariance	protected by a global symmetry
$\Psi \overset{\text{SUSY}}{\longleftrightarrow} H$	In 5 dimensions: $H=A_5$	

The Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry can solve the "big" hierarchy and naturalness is preserved up to very high scales if superparticle masses are at the weak scale

$\Delta(m^2_{h^0}) =$



$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

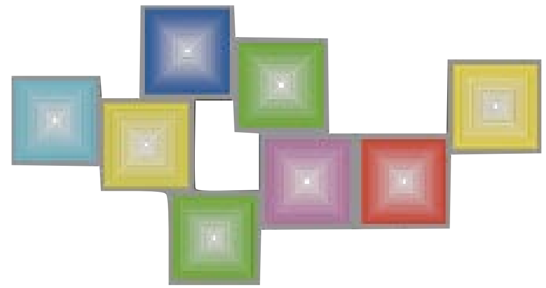
An elegant solution to the hierarchy pb: Supersymmetry

2 categories of particles:

Fermions

matter particles

fermions repel
each other

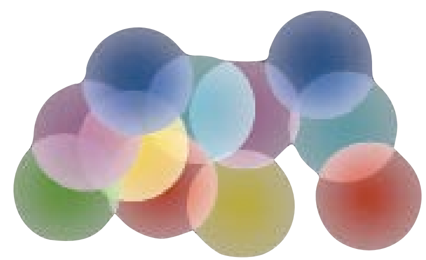


[Enrico Fermi 1901-1954]

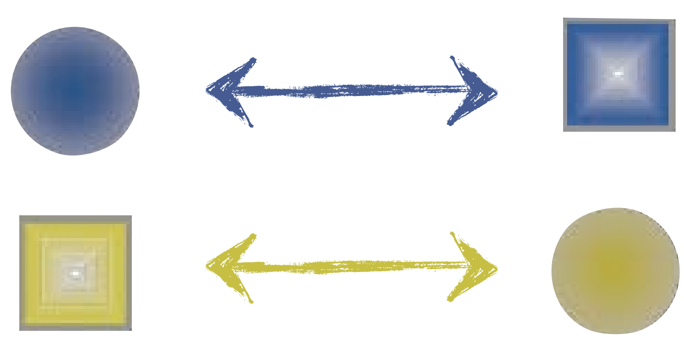
Bosons

force carriers

bosons can pile up



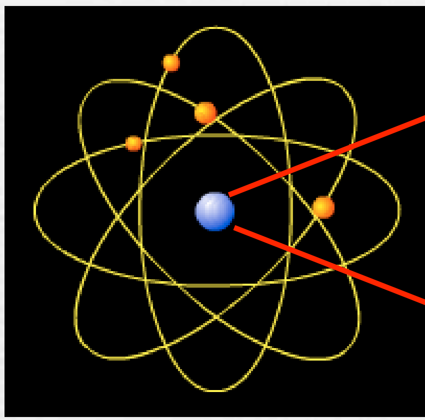
[Satyendra Bose 1894-1974]



String Theory

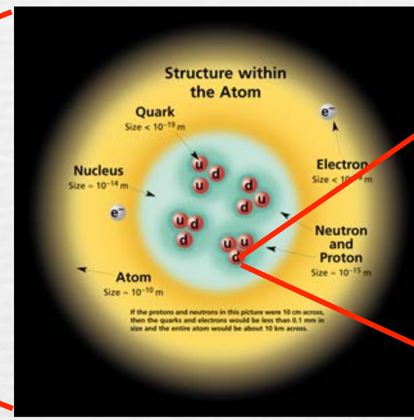
unification of the Standard Model forces with gravity

(observable universe)	(Earth)	(Hair)
10^{-10}m	10^{-17}m	10^{-35}m



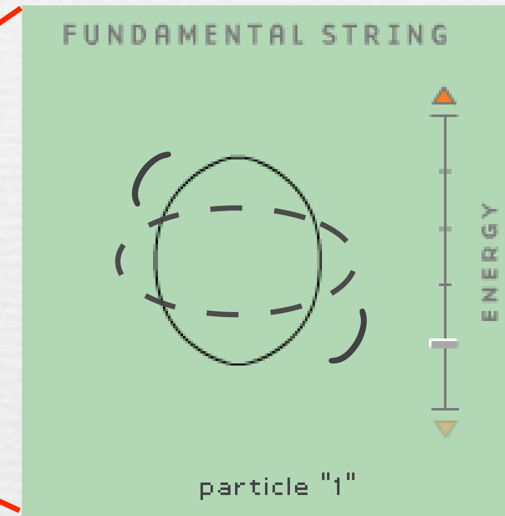
Atom

electrons + nucleus



Nucleus

quarks

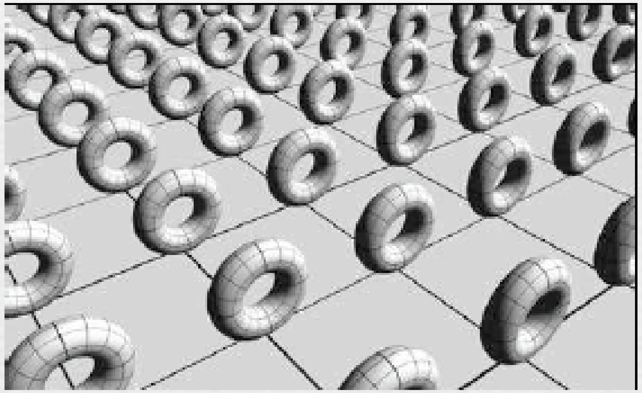


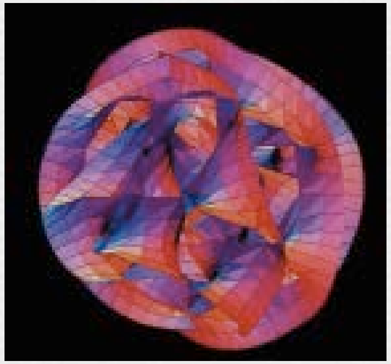
(Super)String

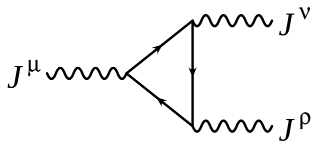
Extra Dimensions

String theories are (well) defined only in spacetime with 10 or 11 dimensions

These extra dimensions are assumed to be curled up







$\partial_\mu J^\mu = \partial_\nu J^\nu = \partial_\rho J^\rho = 0$

$\sum_R \mathrm{Tr}\, T_R^A \{T_R^B, T_R^C\} = 0$

Good reason for unification : Anomaly cancellation in the Standard Model

$Q_e = T_3 + Y$

1. SU(N)–G^2: $T_{\mathrm{G}} = 1$, so need $\sum_R \mathrm{Tr}\, T_R^A = 0$, trivial for $N > 1$
   - U(1)$_{\mathrm{Y}}$: $\sum_{\mathrm{fermions}} Y = (+1/6) \cdot 2 \cdot 3 + (-2/3) \cdot 3 + (+1/3) \cdot 3$ $+ (-1/2) \cdot 2 + 1 = 0$! Quarks and leptons cancel separately.
2. SU(3)^3 automatic: QCD is vectorlike (# of 3 = # of $\overline{3}$)
3. SU(2)^3 automatic: $\frac{1}{8} \sum_{\mathrm{doublets}} \mathrm{Tr}\, \sigma^A \{\sigma^B, \sigma^C\} = \frac{1}{4} \delta^{BC} \mathrm{Tr}\, \sigma^A = 0$
4. U(1)$^3_{\mathrm{Y}}$: $\sum_{\mathrm{fermions}} Y^3 =$ $(+1/6)^3 \cdot 2 \cdot 3 + (-2/3)^3 \cdot 3 + (+1/3)^3 \cdot 3 + (-1/2)^3 \cdot 2 + 1^3 = 0$
   - Cancellation between quarks and leptons in each generation!
5. SU(3)^2–U(1)$_{\mathrm{Y}}$: $\propto \sum_{\mathrm{quarks}} Y = 0$ (just like gravitational anomaly)
6. SU(2)^2–U(1)$_{\mathrm{Y}}$: $\propto \sum_{\mathrm{doublets}} Y \mathrm{Tr}\{\sigma^B, \sigma^C\} \propto \sum_{\mathrm{doublets}} Y = (+1/6) \cdot 3 + (-1/2) = 0$
   - Cancellation between quarks and leptons again!

Highly non-trivial cancellation and suggestive connection between quarks and leptons

The Standard Model as a remnant of a Grand Unified Theory ?

There are gauge groups for which the anomalies automatically cancel, e.g. SO(10)

Good reason for unification II : Charge quantization $Q_e = T_3 + Y$

How come is the electric charge quantized?

- Eigen values of the generators of the abelian U(1) are continuous
  e.g. in the symmetry of translational invariance of time,
  there is no restriction in the (energy) eigen values.

- Eigen values of the generators of a simple non-abelian group are discrete

  e.g. in SO(3) rotations, the eigen values of the third component of angular momentum can take only integers or 1/2 integers values. In SU(5), since the electric charge is one of the generators, its eigen values are discrete and hence quantized.

simple unification group -> charge quantization

$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$

SM matter content fits nicely into SU(5)

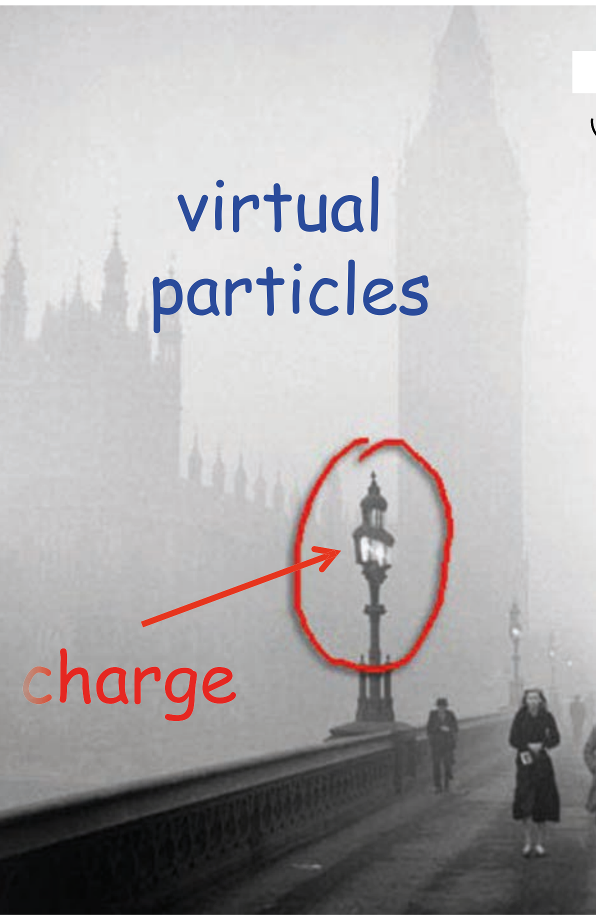
relation between color SU(3) and electric charge.

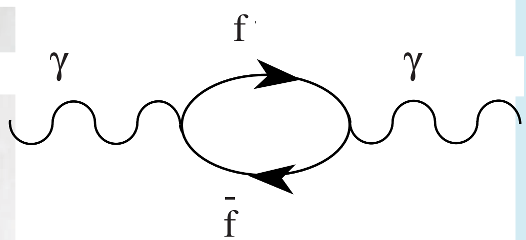
Quarks carry 1/3 of the lepton charge because they have 3 colors. The SU(5) theory provides a rationale basis for understanding particle charges and the weak hypercharge assignment in the SM

Evolution of coupling constants

Classical physics: the forces depend on distances

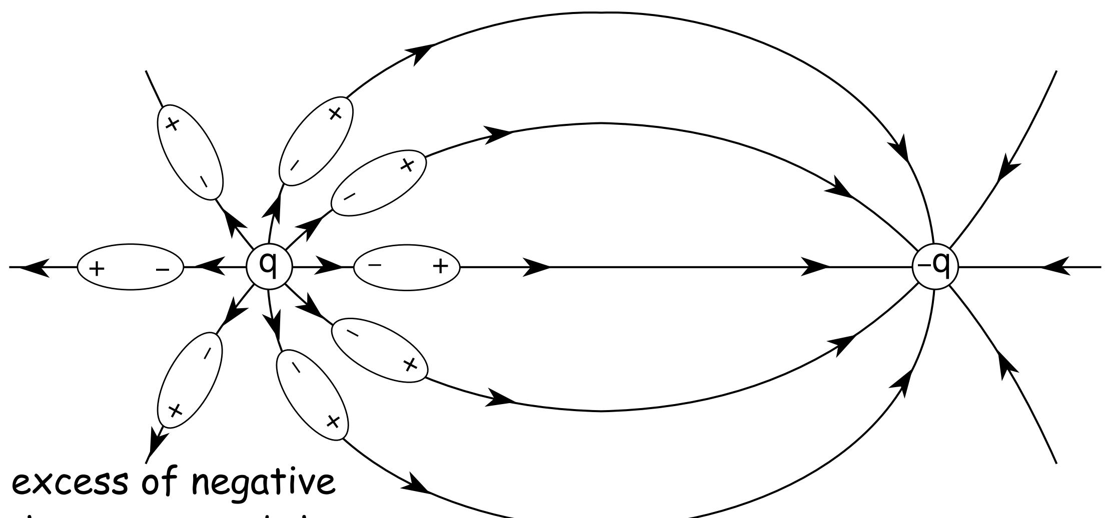
Quantum physics : the charges depend on distances





The electromagnetic coupling decreases at large distances.
Charge screening (vacuum polarization) due to virtual fermion-antifermion pairs

The vacuum behaves as a polarized dielectric medium



excess of negative charges around the positron: screening

An opposite effect for the strong coupling

because of the **non-abelian** nature of the underlying SU(3) gauge symmetry: the gauge boson self-interactions generate an **anti-screening** effect through gauge boson loops. This effect is larger than the one from fermion loops --> the strong coupling decreases at short distances

$$\frac{\partial \alpha_s}{\partial \log E} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi}\left(-\frac{11 N_c}{6} + \frac{N_f}{3}\right)$$

$\alpha_s \nearrow$ when $d \nearrow$

$$\alpha_s = g_s^2/4\pi$$

property of 'asymptotic freedom'

quarks behave as free particles when the energy becomes very large

Evolution of gauge couplings

The evolution of gauge couplings is controlled by the renormalization group equations

$$\frac{d\alpha(\mu)}{d\log\mu} \equiv \beta(\alpha(\mu))$$

At one loop:

$$\beta(\alpha) \equiv \frac{d\alpha(\mu)}{d\log\mu} = \frac{-b}{2\pi}\,\alpha^2 + \mathcal{O}(\alpha^3)$$

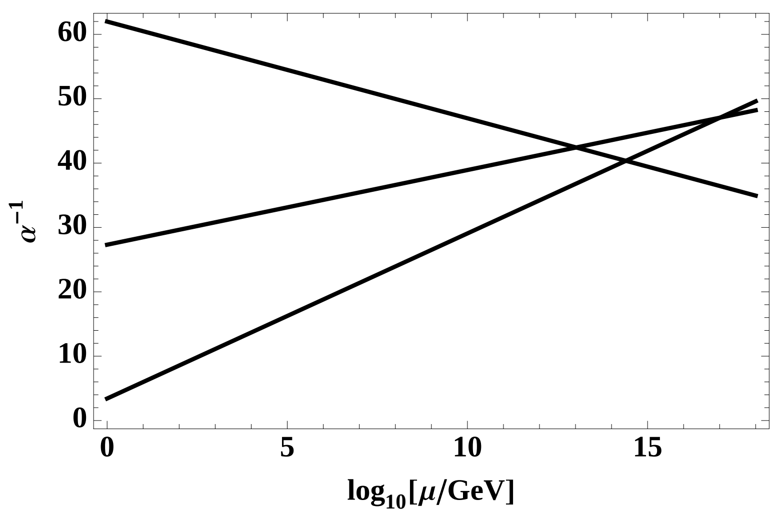
So couplings vary logarithmically as a function of the energy scale:

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(\mu_0)} + \frac{b_i}{2\pi}\log\frac{\mu}{\mu_0}$$

$$\alpha_i = g_i^2/4\pi \qquad i = SU(3), SU(2), U(1)$$

b_i : defined by the particle content

we observe different couplings but it looks like a low energy artefact



Good reason for unification

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- SU(3)$_c$xSU(2)$_L$xU(1)$_Y$ ⊂ SU(5)

SM matter content fits nicely into SU(5)

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad u^c_R = (\bar{3},1)_{-2/3}, \quad d^c_R = (\bar{3},1)_{1/3},$$

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad e^c_R = (1,1)_1$$

$$\bar{5} = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}}$$

$$\bar{5} = L + d^c_R$$

$$\chi^a = \left(d^{c1}\ d^{c2}\ d^{c3}\ e^-\ -\nu_e\right)^T_L,$$

$$10 = (5\times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}}$$

$$10 = u^c_R + Q_L + e^c_R$$

$$\psi_{ab} = \frac{1}{\sqrt{2}}\left(\begin{array}{ccc|cc} 0 & u^{c3} & -u^{c2} & -u_1 & -d_1 \\ -u^{c3} & 0 & u^{c1} & -u_2 & -d_2 \\ u^{c2} & -u^{c1} & 0 & -u_3 & -d_3 \\ \hline u_1 & u_2 & u_3 & 0 & -e^+ \\ d_1 & d_2 & d_3 & e^+ & 0 \end{array}\right)_L.$$

SU(5) adjoint rep.

$$\left(\begin{array}{c|c} SU(2) & \\ \hline & SU(3) \end{array}\right)$$

$$T^{12} = \sqrt{\frac{3}{5}}\left(\begin{array}{cc|ccc} 1/2 & & & & \\ & 1/2 & & & \\ \hline & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{array}\right) = \sqrt{\frac{3}{5}}Y$$

additional U(1) factor that commutes with SU(3)*SU(2)

$$\mathrm{Tr}(T^aT^b) = \frac{1}{2}\delta^{ab}$$

$$g_5 T^{12} = g'Y \qquad g_5\sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

$\sin^2\theta_W = \frac{3}{8}$ @ M$_{GUT}$

Standard Model beta functions

$$b = \frac{11}{3}T_2(\text{spin-1}) - \frac{2}{3}T_2(\text{chiral spin-1/2}) - \frac{1}{3}T_2(\text{complex spin-0})$$

$$Tr(T^a(R)T^b(R)) = T_2(R)\delta^{ab} \quad T_2(\text{fund}) = \frac{1}{2} \quad T_2(\text{adj}) = N$$

universal contribution coming from complete SU(5) representations ($4N_F/3$ in SM in $4N_F/3$ *3/2 in susy)

from gauge bosons

So in the SM:

$$b_3 = \frac{11}{3}\times N_c - \boxed{\frac{2}{3}\times N_f\left(\frac{1}{2}\times 2 + \frac{1}{2}\times 1 + \frac{1}{2}\times 1\right)} = 7$$

$$b_2 = \frac{11}{3}\times 2 - \boxed{\frac{2}{3}\times N_f\left(\frac{1}{2}\times 3 + \frac{1}{2}\times 1\right)} - \frac{1}{3}\times\frac{1}{2} = \frac{19}{6}$$

x 3/5

$$b_Y = -\boxed{\frac{2}{3}\times N_f\left((\frac{1}{6})^2\times 2\times N_c + (\frac{-2}{3})^2\times N_c + (\frac{1}{3})^2\times N_c + (\frac{-1}{2})^2\times 2 + (1)^2\right)}$$

$$-\frac{1}{3}(\frac{1}{2})^2\times 2 = -\frac{41}{6} \quad\longrightarrow\quad b_1 = b_Y\times\frac{3}{5} = -\frac{41}{10}$$

from Higgs

Only the Higgs and the SM gauge bosons can affect the relative running

In the MSSM, extra contributions from the higgsinos and gauginos

SM

$$b = \frac{11}{3} T_2(\text{spin-1}) - \frac{2}{3} T_2(\text{chiral spin-1/2}) - \frac{1}{3} T_2(\text{complex spin-0})$$

$$Tr(T^a(R)T^b(R)) = T_2(R)\delta^{ab} \qquad T_2(\text{fund}) = \frac{1}{2} \qquad T_2(\text{adj}) = N$$

chiral superfield

complex spin-0
Weyl spin-1/2
in same representation R of gauge group

vector superfield

Weyl spin-1/2
real spin-1
in same representation V of gauge group

MSSM

$$b = \frac{11}{3} T_2(\texttt{vector}) - \underbrace{\frac{2}{3} T_2(\texttt{vector})}_{\text{gauginos}} - \frac{2}{3} T_2(\texttt{chiral}) - \underbrace{\frac{1}{3} T_2(\texttt{chiral})}_{\text{scalars}} = 3\,T_2(\texttt{vector}) - T_2(\texttt{chiral})$$

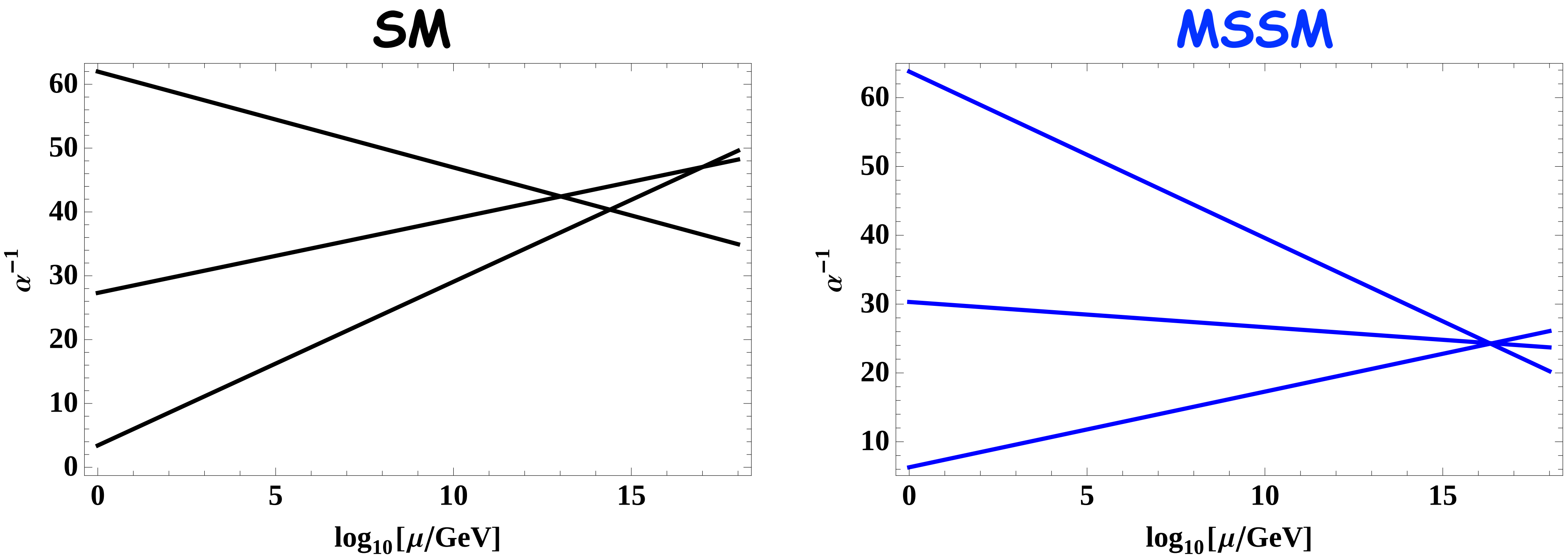
$$b_{SU(3)} = \overset{g}{3 \times 3} - \left(\overset{Q_L}{\frac{1}{2} \times 2 \times 3} + \overset{U}{\frac{1}{2} \times 1 \times 3} + \overset{D}{\frac{1}{2} \times 1 \times 3} \right) = 3$$

$$b_{SU(2)} = \overset{W^\pm, Z}{3 \times 2} - \left(\overset{Q_L}{\frac{1}{2} \times 3 \times 3} + \overset{L}{\frac{1}{2} \times 1 \times 3} \right) - \overset{H_u}{\frac{1}{2}} - \overset{H_d}{\frac{1}{2}} = -1$$

$$b_Y = -\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3 \times 2 \times 3} + \overset{U}{\left(-\frac{2}{3}\right)^2 3 \times 3} + \overset{D}{\left(\frac{1}{3}\right)^2 3 \times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2 \times 3} + \overset{E}{(1)^2 \times 3} \right) - \overset{H_u}{\left(\frac{1}{2}\right)^2 \times 2} - \overset{H_d}{\left(\frac{1}{2}\right)^2 \times 2} = -11 \longrightarrow b_{T^{12}} = -\frac{33}{5}$$

Comparison

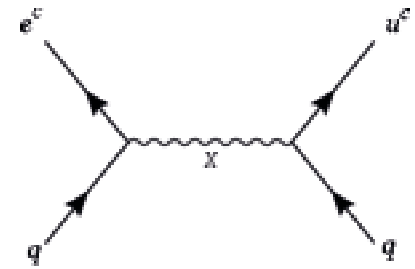
1-loop evolution of *gauge couplings*



Proton decay

Baryon number is violated via the exchange of GUT gauge bosons with GUT scale mass resulting in effective interactions suppressed by $1/M_{GUT}^2$

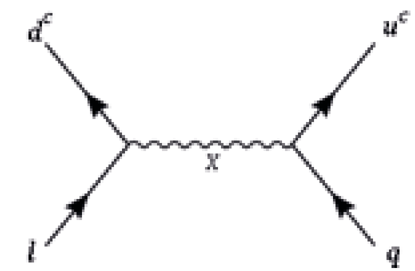
The dominant decay mode is $p \rightarrow e^+\pi_0$



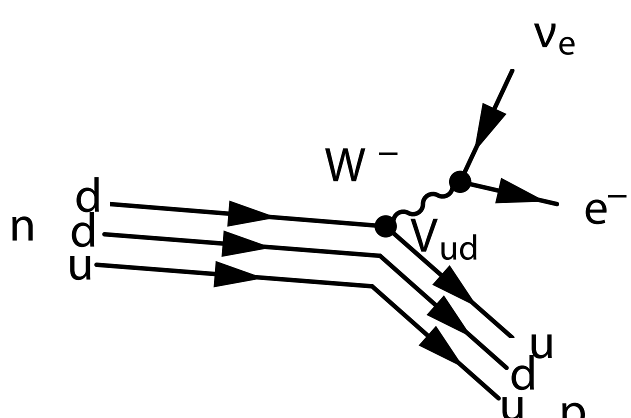
The proton lifetime is given by:

$$\tau(p \rightarrow \pi_0 e^+) \approx \left(\frac{M_{GUT}}{10^{16}}\right)^4 \left(\frac{1/35}{(\alpha_{GUT}}\right)^2 \times 4.4 \times 10^{34} \text{ yr}$$

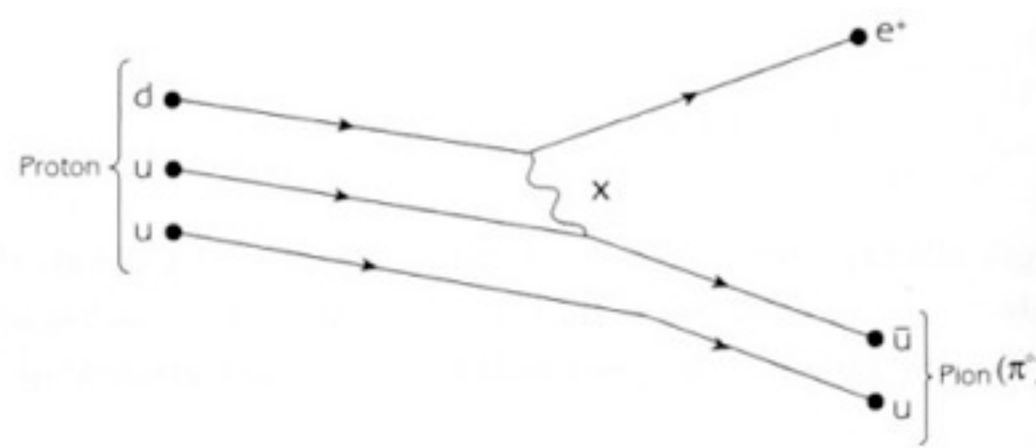
Experimental constraints lead to: $\tau_p > 5.3 \times 10^{33}$ yr



i.e $$M_{GUT} > \left(\frac{\alpha_{GUT}}{1/35}\right)^{1/2} \times 6 \times 10^{15} \text{ GeV}$$



beta decay



The Dark Matter of the universe

Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects

15% baryonic matter (1% in stars, 14% in gas)

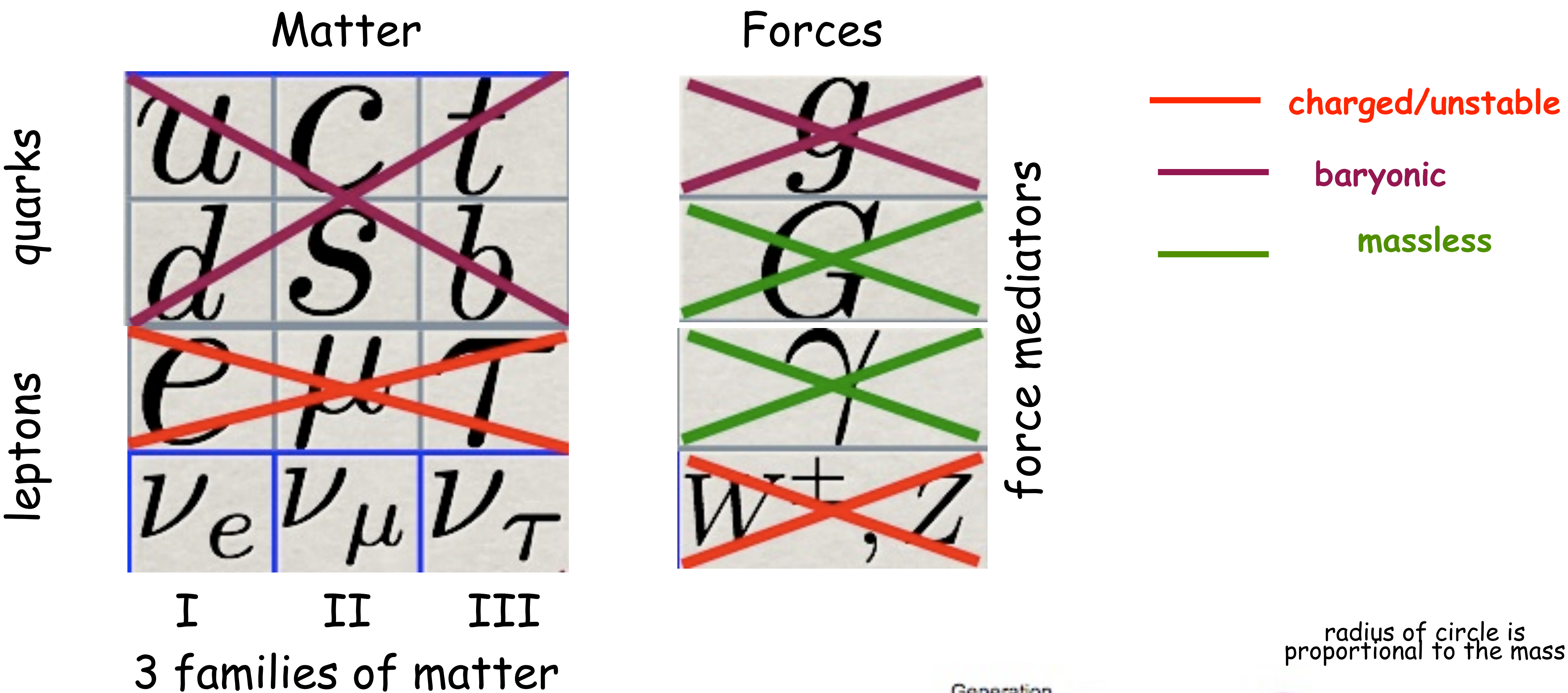
85% dark unknown matter

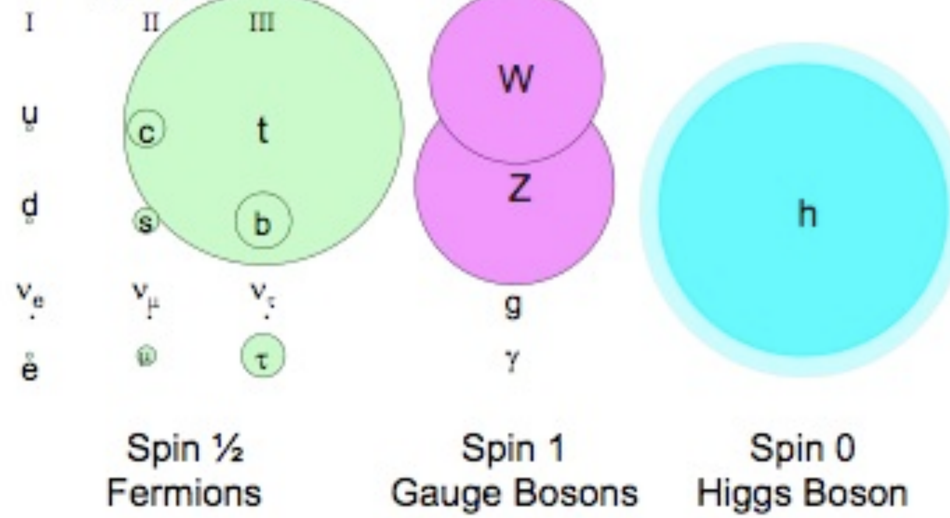
$$\Omega_{DM} = \frac{\text{energy density of the universe stored in dark matter}}{\text{total energy density of the universe}} \sim 25\ \%$$

$\Omega_{\text{dark energy}} \sim 70\ \%$

$\Omega_{SM} = \ \sim 5\ \%$

Dark matter can't be explained by the Standard Model



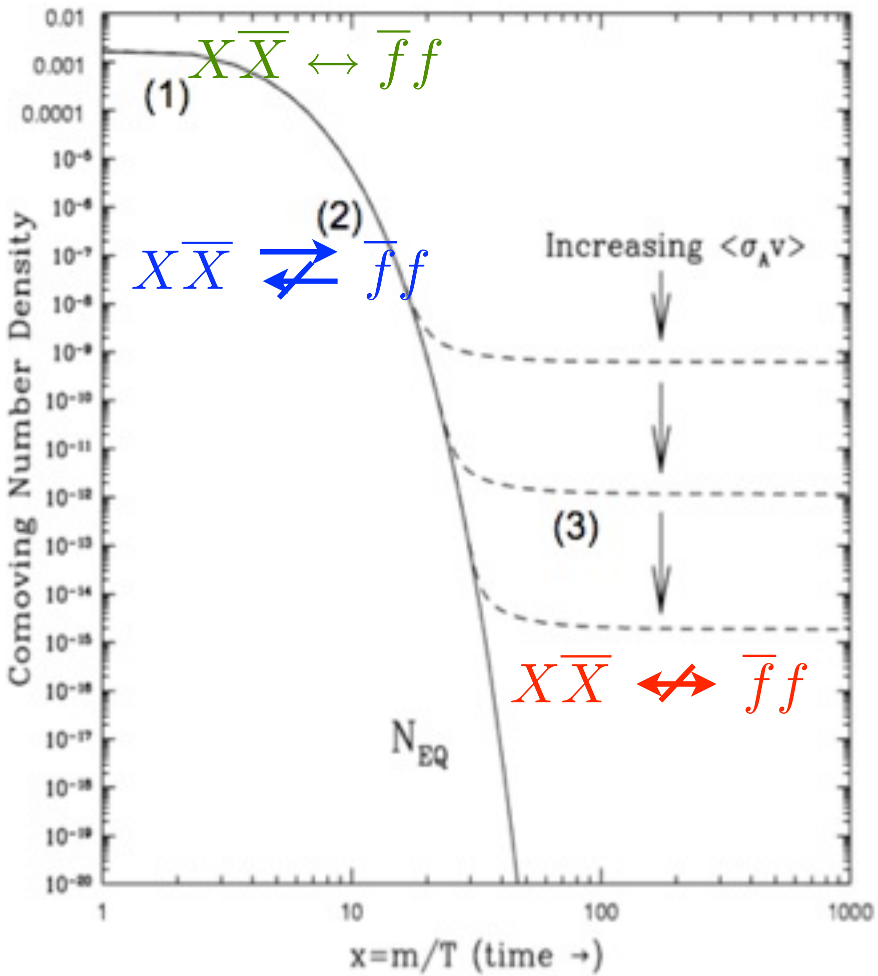


contribution to the energy budget of the universe

Particle	Ω	type
Baryons	4 - 5 %	cold
Neutrinos	< 2 %	hot
Dark matter	20 - 26 %	cold

The relic abundance of a stable particle follows from the generic thermal freeze-out mechanism in the expanding universe

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$



expansion rate of universe

freese-out :

annihilation rate of particle

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}} \sim \Gamma = n\sigma v$$

Thermal relic: $\Omega_{DM} \propto 1/\sigma_{anni}$

$\Rightarrow \sigma_{anni} \approx 1$ pb

$\sigma \sim \alpha^2/m^2$

$\Rightarrow$ m ~ 100 GeV

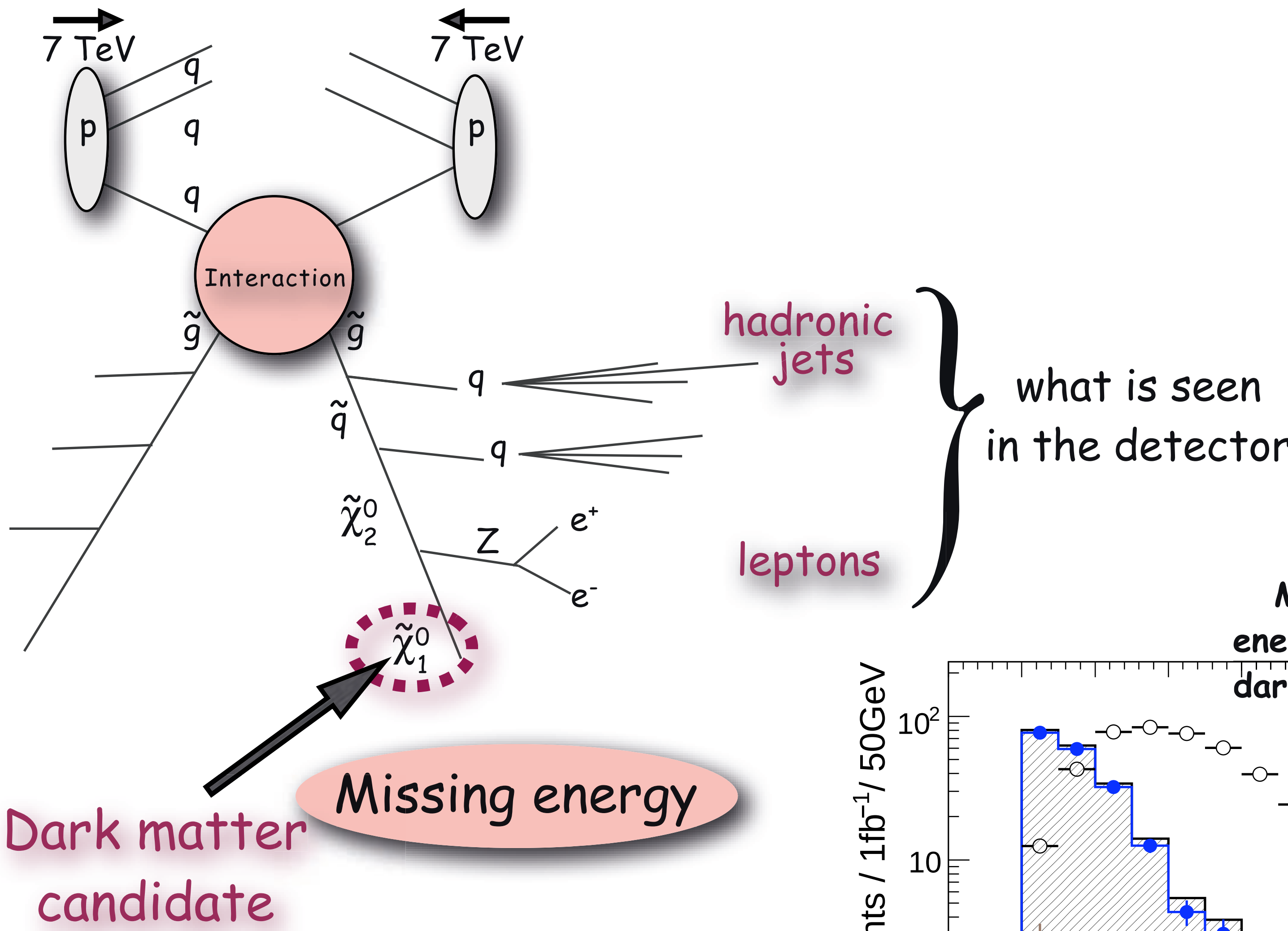
The "WIMP miracle"

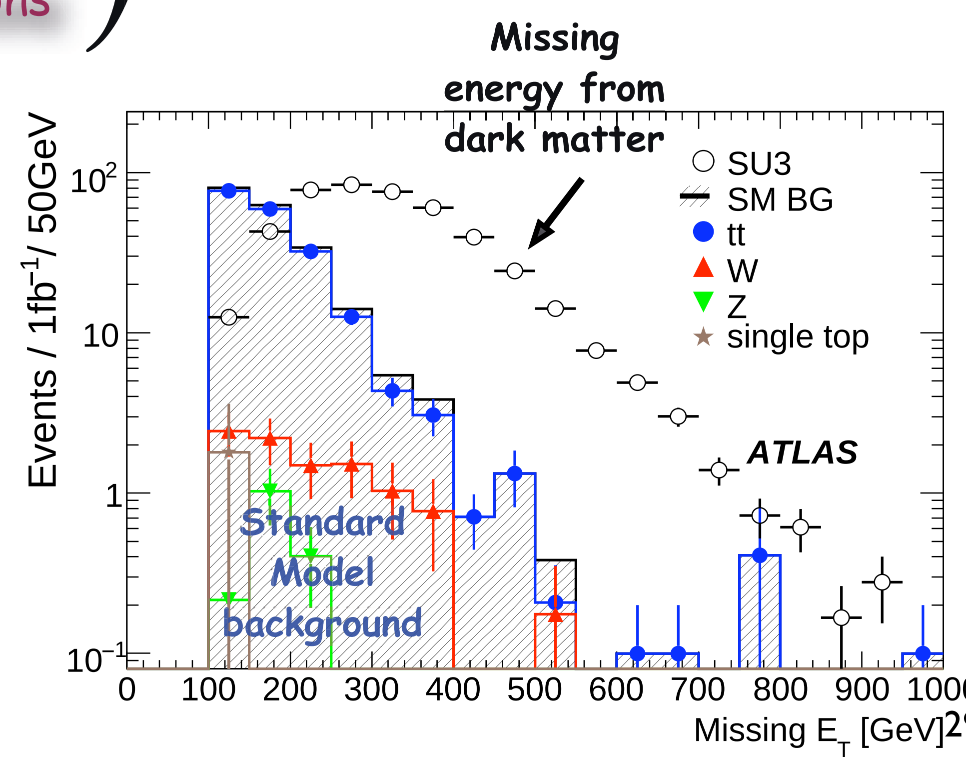
$$\boxed{\Omega_{DM} \approx \frac{O(1)\ \mathrm{pb}}{\sigma_{anni}}}$$

→ a particle with a typical EW-scale cross section

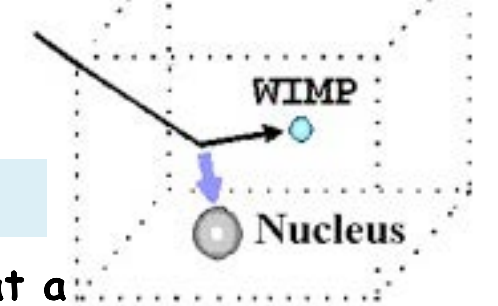
$\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

Producing Dark Matter at LHC = "Missing Energy" events



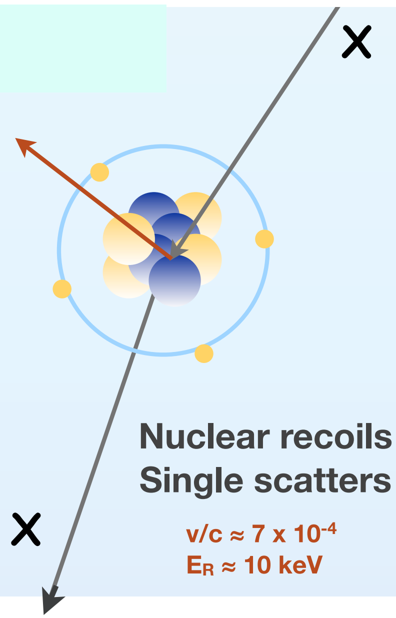


Direct Detection

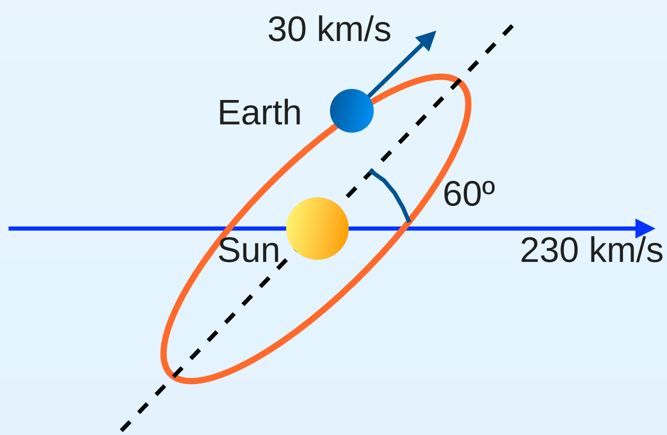


WIMP flux on Earth: ~ 10^5 cm^{-2}s^{-1} (for a 100 GeV WIMP)

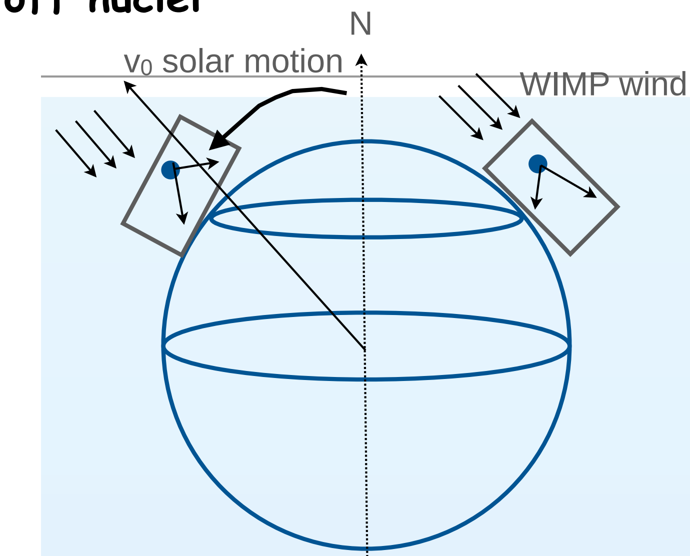
even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei



Nuclear recoils
Single scatters



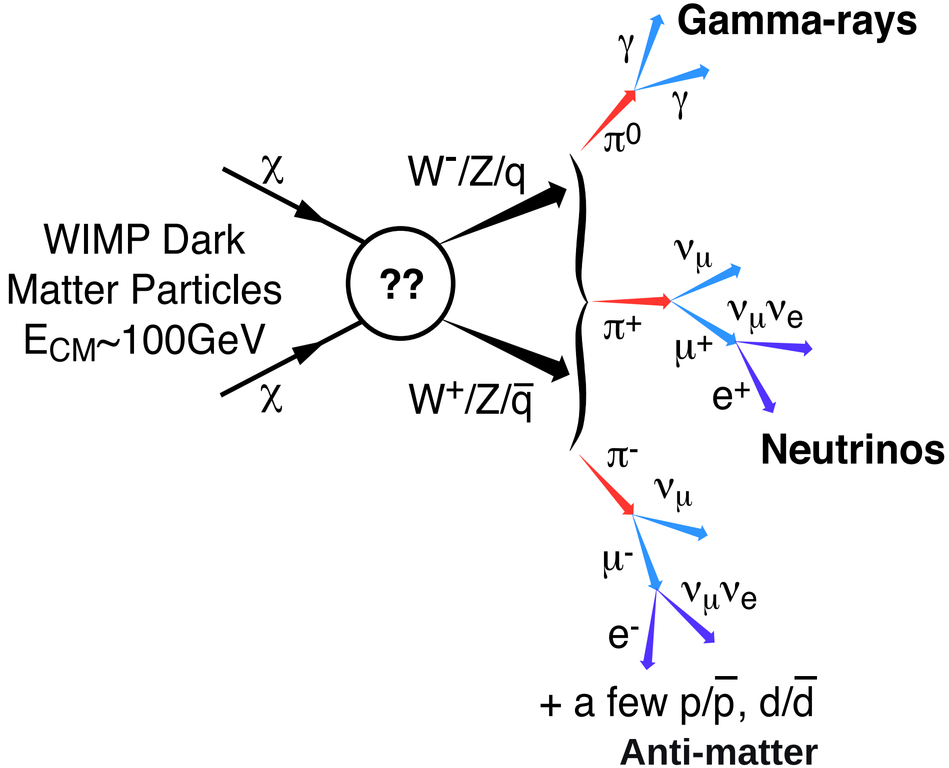
Annual rate variation
~ few % effect



Diurnal directional modulation:
~ 50% effect

for example, "EDELWEISS":

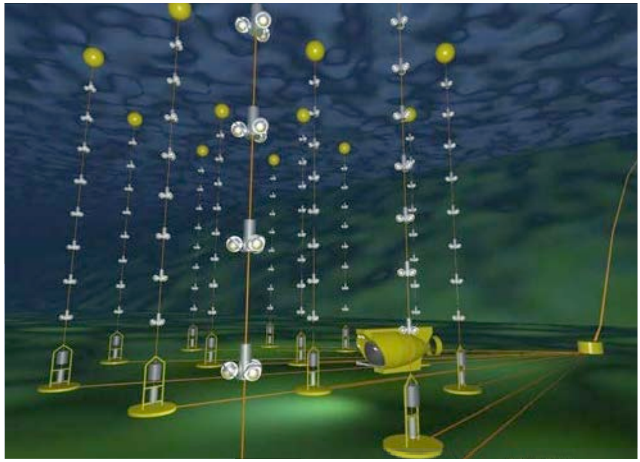
WIMP indirect detection



Indirect Detection

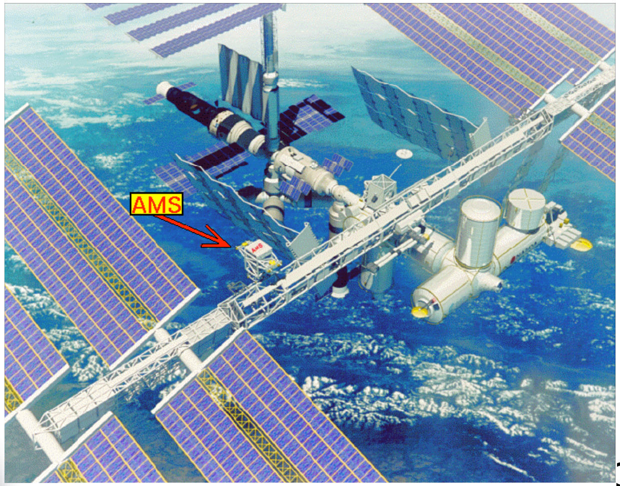
Search for neutrinos in the South Pole

In the Mediterranean



Antarès

Search for antiprotons in space



AMS

Indirect Detection

Search for dark matter photons on Earth

Hess

and in space

Fermi

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

$\sim 6.\ 10^{-10}$

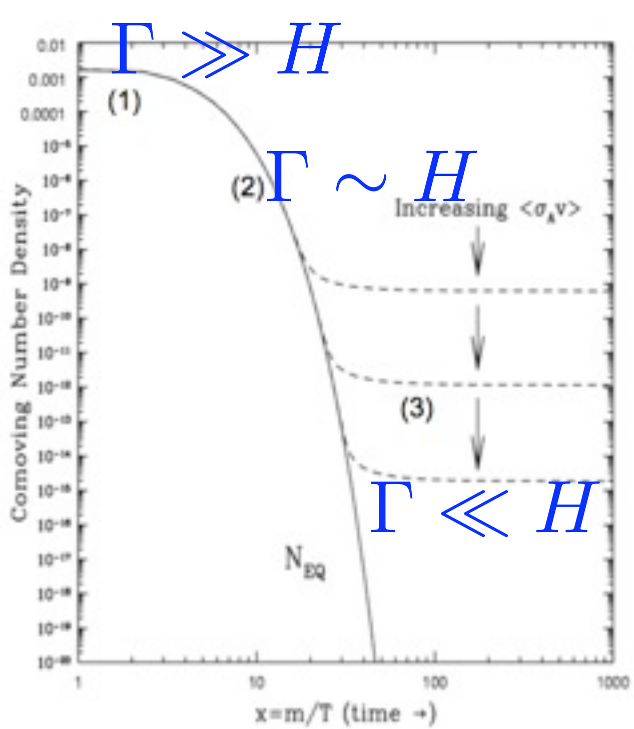
How much nucleons would there be in a symmetric universe?

The great annihilation between nucleons & anti-nucleons

nucleon and anti-nucleon densities are maintained by annihilation processes

$$n + \bar{n} \rightarrow \pi + \pi \rightarrow \gamma + \gamma + \ldots$$

which become ineffective when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$



corresponding to a freeze-out temperature $T_F \sim 20$ MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001 Matter	10 000 000 000 Anti-matter

1 (us)

The Standard Model is unable to explain this aymmetry.