

Mise à niveau Astroparticules M2 ASEP

Elements of Particle Physics

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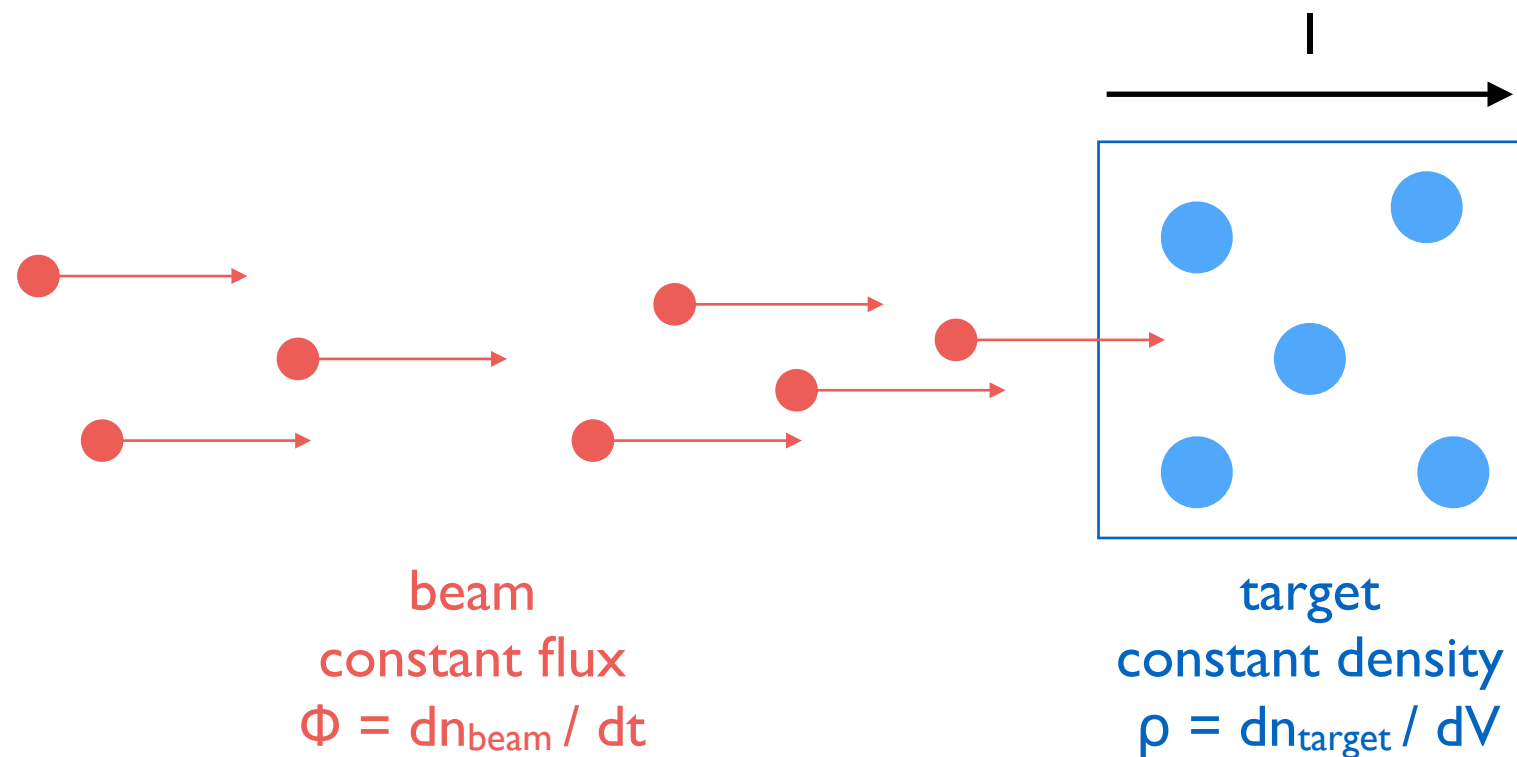
Bibliography

- A. De Angelis, M. Pimenta “Introduction to Particle and Astroparticle Physics” Springer 2019 (available at OMP library)
- D. Griffiths “Introduction to Elementary Particles”, Wiley 2008

Links Particle Physics - Astro/Cosmo

- high-energy astrophysical phenomena
- multimessenger astronomy (cosmic rays, neutrinos, gravitational waves)
- dark matter, dark energy, inflation, origin of matter-antimatter asymmetry

Cross section

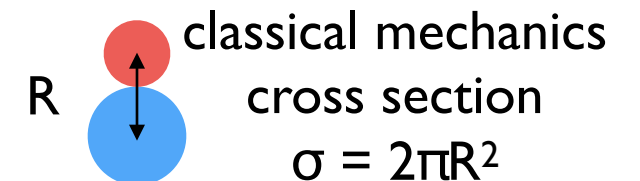


the number of interactions per time and length interval in the target is constant

$$dn_{\text{interact}} / dt dl = \Phi \rho \sigma$$

σ is the cross section

- for classical mechanics collision = physical contact surface
- for generic interaction we define a cross section such that it describes the interaction probability in the same way



Standard model of Particle Physics

from Symmetry magazine, T. D. Gutierrez

- describes elementary constituents of Nature and their interactions
- from 100 years of observations/ experiments, first with cosmic rays and then mainly with particle colliders

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\mu W_\mu^- - \\
 & W_\mu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^+ W_\nu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
 & d_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Standard Model of Elementary Particles

three generations of matter (fermions)				
	I	II	III	
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0
charge	$2/3$	$2/3$	$2/3$	0
spin	$1/2$	$1/2$	$1/2$	1
QUARKS	u up	c charm	t top	g gluon
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
	$-1/3$	$-1/3$	$-1/3$	0
	$1/2$	$1/2$	$1/2$	1
	d down	s strange	b bottom	γ photon
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$
	-1	-1	-1	0
	$1/2$	$1/2$	$1/2$	1
	e electron	μ muon	τ tau	Z Z boson
	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$
	0	0	0	± 1
	$1/2$	$1/2$	$1/2$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
				GAUGE BOSONS
				SCALAR BOSONS

+ antiparticles

Interactions and gauge symmetries

- fundamental interactions are mediated by vector boson field/particles
- gauge invariance/symmetry: special transformations of fields do not change any observable quantity
 - classical analogous, electrostatic potential $V \rightarrow V + C$, same electric field
- Noether's theorem:
gauge symmetry $\Leftrightarrow$ **conserved** quantity = **charge**
- charge is a discrete **additive** quantum number

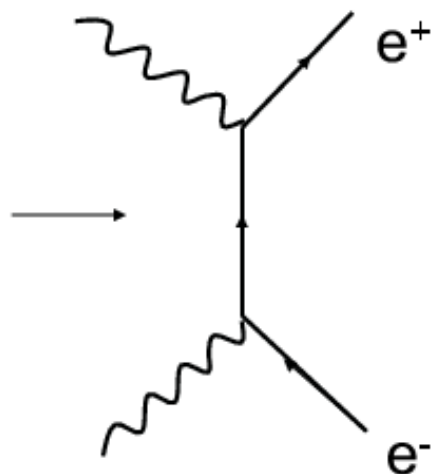
Transformations/Discrete multiplicative quantum numbers/Symmetries?

- **C**: charge conjugation
 - invert sign of all charges
- **P**: parity (mirror reflection)
 - inverts all vectors, e.g., positions, momenta
 - preserves pseudo-vectors, e.g., angular momentum/spin
- **T**: time reversal
 - inverts time flow

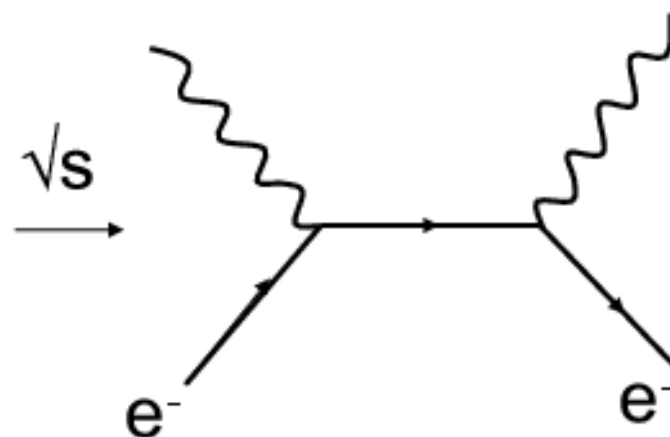
Electromagnetic interaction

- Quantum ElectroDynamics (QED): quantum version of electromagnetism
 - charge: electric charge
 - charged leptons: -1 (anti $+1$)
 - quarks type u $+2/3$, type d $-1/3$ (antiquarks ...)
 - mediator field: photon/electromagnetic field (massless)
- Feynman graphs

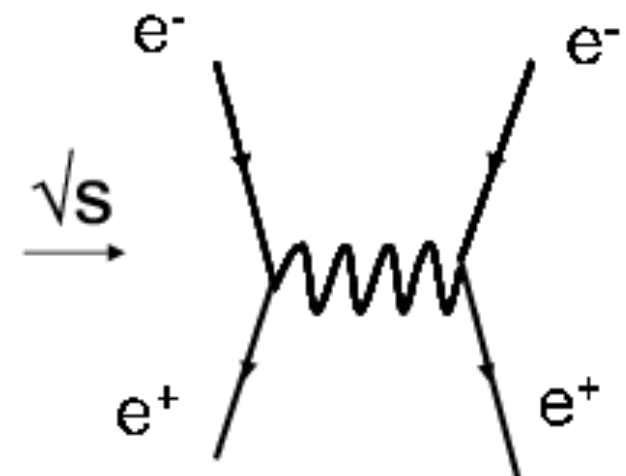
pair production



Compton ($e\gamma$) scattering



Bhabha (e^-e^+) scattering

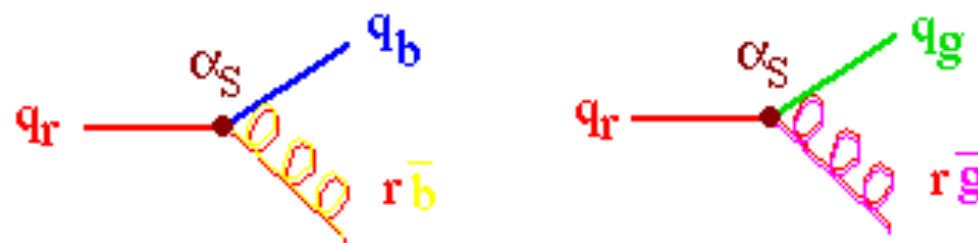


Hadrons

- hadrons are aggregates of quarks
 - baryons = 3 quarks (or antiquarks)
 - e.g., $p = uud$, $n = udd$, $\Lambda^0 = uds$
 - mesons = quark + antiquark
 - e.g., $\pi^- = \bar{u}d$, $\pi^0 = \bar{u}u$ (or $d\bar{d}$)
- most are unstable, decay with mean lifetimes 10^{-24} to 10^{-6} s
- mass of quarks is small, e.g., $u \sim 2.4 \text{ MeV}/c^2$, mass of hadrons is mostly energy of strong interaction field

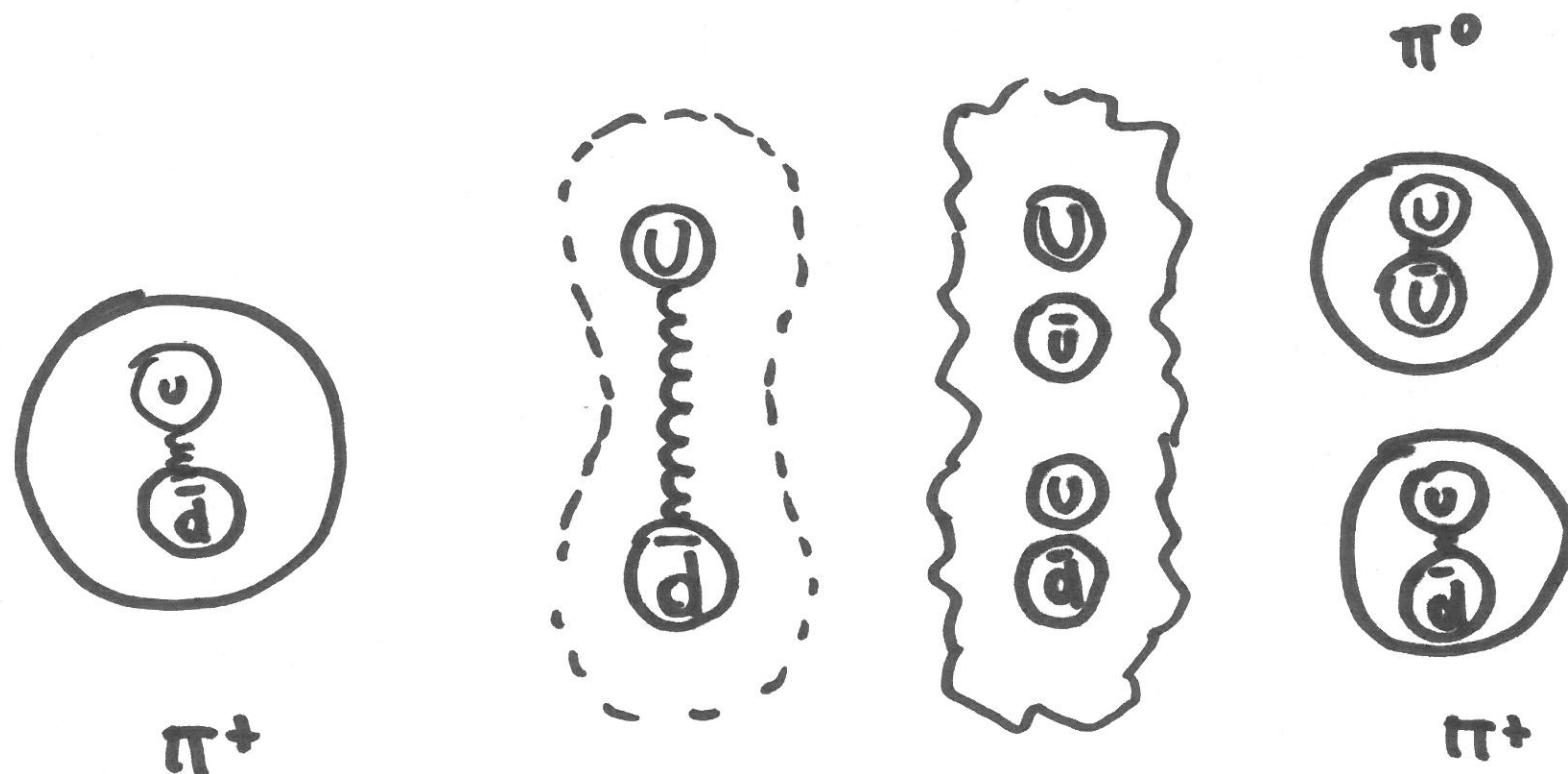
Strong interaction - I

- charge: color, in 3 “types” R, G, B (+ 3 anticolors)
- each quark carries a color (anticolor)
 - aggregates are “white” = neutral
 - baryons = R+G+B
 - mesons = color + anticolor
 - nuclear force = residual strong force between hadrons
- mediator field: gluon (massless)
 - carry color + anticolor, $2^3 = 8$ gluons
- Feynman vertices



Strong interaction - II

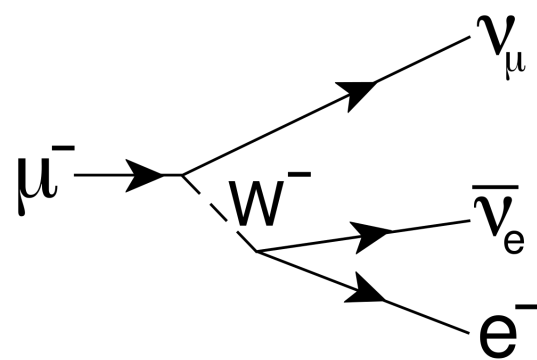
- implications of gluons carrying color + quarks producing virtual (i.e., fast lived) gluons
 - asymptotic freedom: near a quark net color $\sim$ white $\rightarrow$ strong interaction strength is very weak
 - antiscreening: the farther you go the stronger the color field gets
 - quark confinement/hadronization processes: quarks cannot be isolated



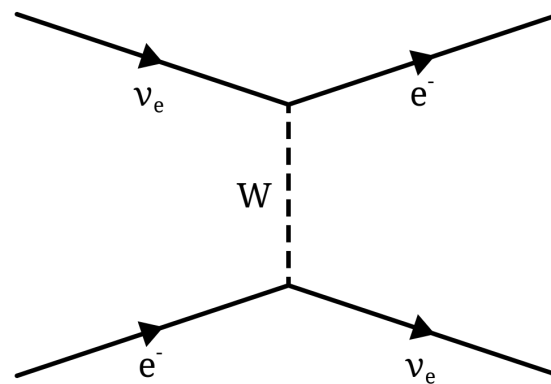
Weak interaction

- “charge”*: weak isospin
- lepton couples are part of weak isospin (+1/2, -1/2) doublet, e.g. (ν_e, e^-)
- mediator fields: (W^+, W^-) , Z^0 , mass 80, 90 GeV/c²
- *not proper gauge symmetry can be defined for massive mediators
- Feynman graphs

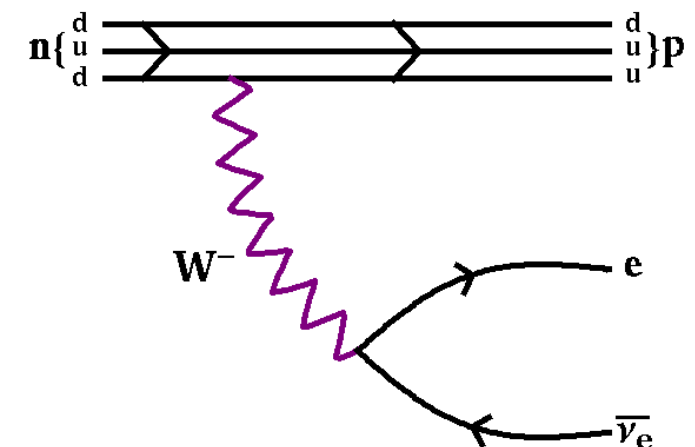
muon decay



e ν scattering



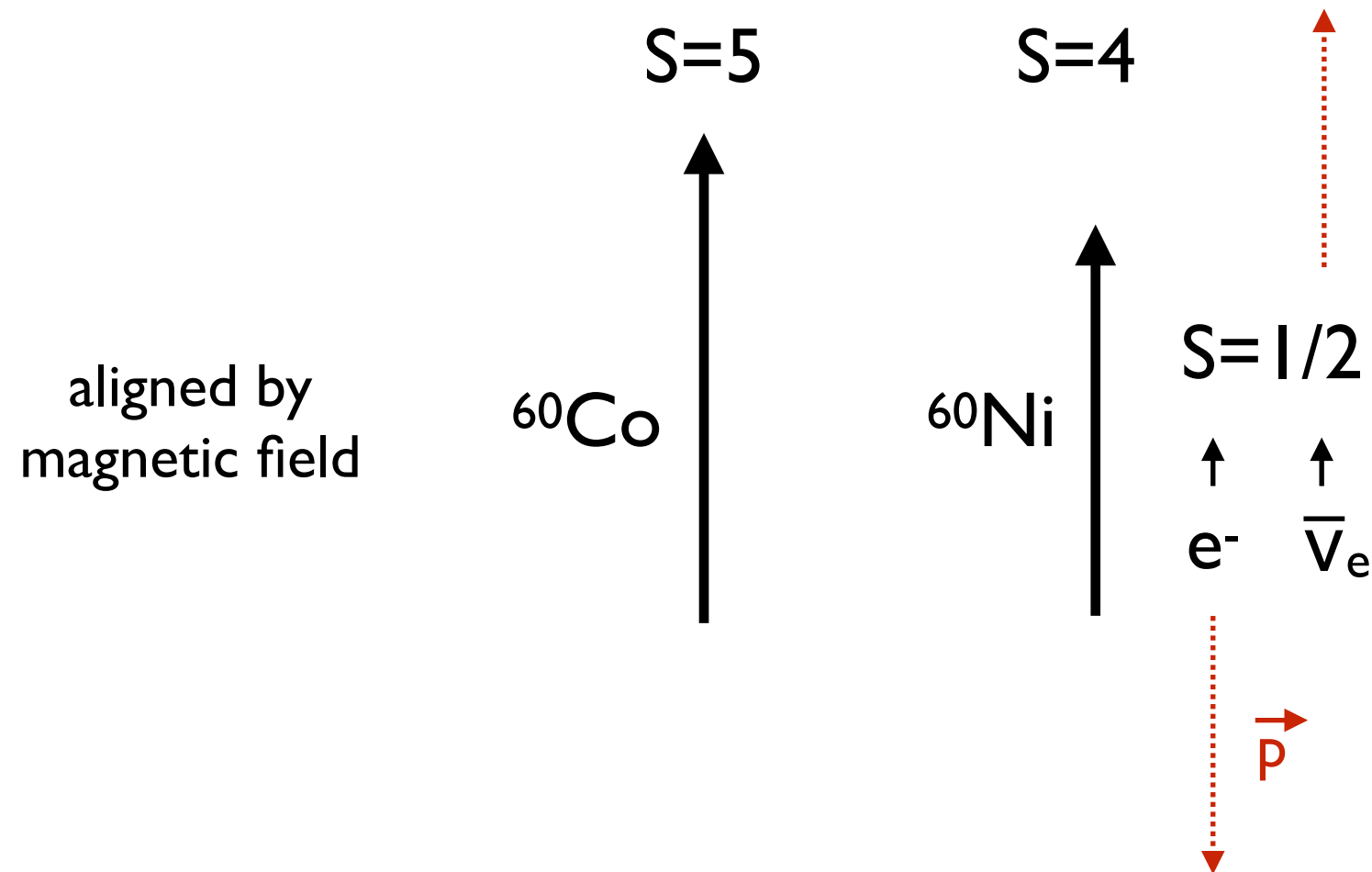
neutron decay



Chirality and weak interaction

- **helicity**: spin along flight direction (not a Lorentz invariant)
- a spin 1/2 particle/antiparticle couple (bispinor) can be decomposed in **chirality** (Lorentz invariant) eigenstates
 - for massless particle chirality L (R) $\rightarrow$ helicity -1 (+1)
 - for a massive particle chirality L (R) $\rightarrow$ helicity $-\beta$ ($+\beta$)
- experimentally verified: weak interaction couples only with left-handed fermions, right-handed antifermions
- each lepton generation has
 - two weak isospin doublets, e.g., (ν_{eL}, e^-_L) and $(e^+_R, \bar{\nu}_{eR}) = (+1/2, -1/2)$ subject to weak interactions
 - two singlets, e.g., e^-_R , $e^+_L = 0$ not subject to weak interaction
 - R ν and L anti- ν are not interacting (not existing?)
- weak interaction breaks the C and P symmetries (maximally)

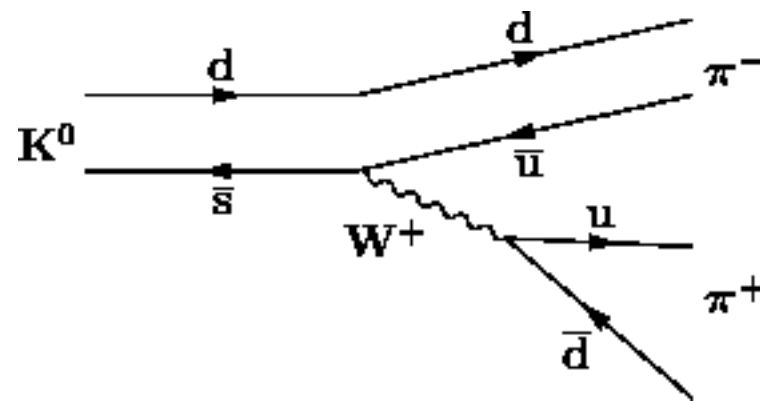
Wu's experiment (1957)



- electrons preferentially emitted opposite to magnetic field = spin direction
→ negative helicity
- in the mirror: $\vec{p} \rightarrow -\vec{p}, \vec{S} \rightarrow \vec{S}$, opposite result! but CP is a symmetry ...

Quark mixing and CP violation

- weak interactions vertex couples leptons in the same generation
- observed weak interactions between hadrons of different generations (hadronic flavor violation)



- weak interaction couples with a quantum superposition of the (u,d) , (c,s) , (t,b) quark doublets
- Cabibbo-Kobayashi-Maskawa mixing matrix
- measurements show that CP is violated for quarks at $O(10^{-3})$ through mixing (e.g., oscillation of kaons)

Fundamental Interactions: Summary

Interaction	Mediator	Charge	Mass	Range	Strength
Strong	8 gluons	color	0	∞ (quark confinement)	1
Electromagnetic	photon	charge	0	∞	1/137
Weak	$W^\pm, Z^0$	(weak isospin)	90 GeV/c ²	10 ⁻¹⁸ m	10 ⁻⁶
Gravitational	graviton?	energy-momentum	0	∞	10 ⁻⁴⁰

- weak interaction alone not described by gauge theory → no proper charge
- gravity is not part of the standard model, there is not a quantum field theory of gravity

Electroweak unification

- the W bosons are electrically charged: link between electromagnetic and weak force?
- can rearrange charge/weak isospin and fields

$$Y_W = 2(Q - I_{W_z}) \qquad W^\pm = \frac{1}{\sqrt{2}}(W_1 \pm iW_2)$$

$$\begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \frac{1}{\sqrt{g^2 + g'^2}} \begin{pmatrix} g & -g' \\ g' & g \end{pmatrix} \begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} \cos \theta_w & -\sin \theta_w \\ \sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} W_3 \\ B \end{pmatrix}$$

- implications

$g^2 \sin^2 \theta_w \rightarrow \text{strength of electromagnetic force}$

$\frac{g^2}{M_W^2} \rightarrow \text{strength of charged current weak force}$

$$\theta_w \simeq 29^\circ$$

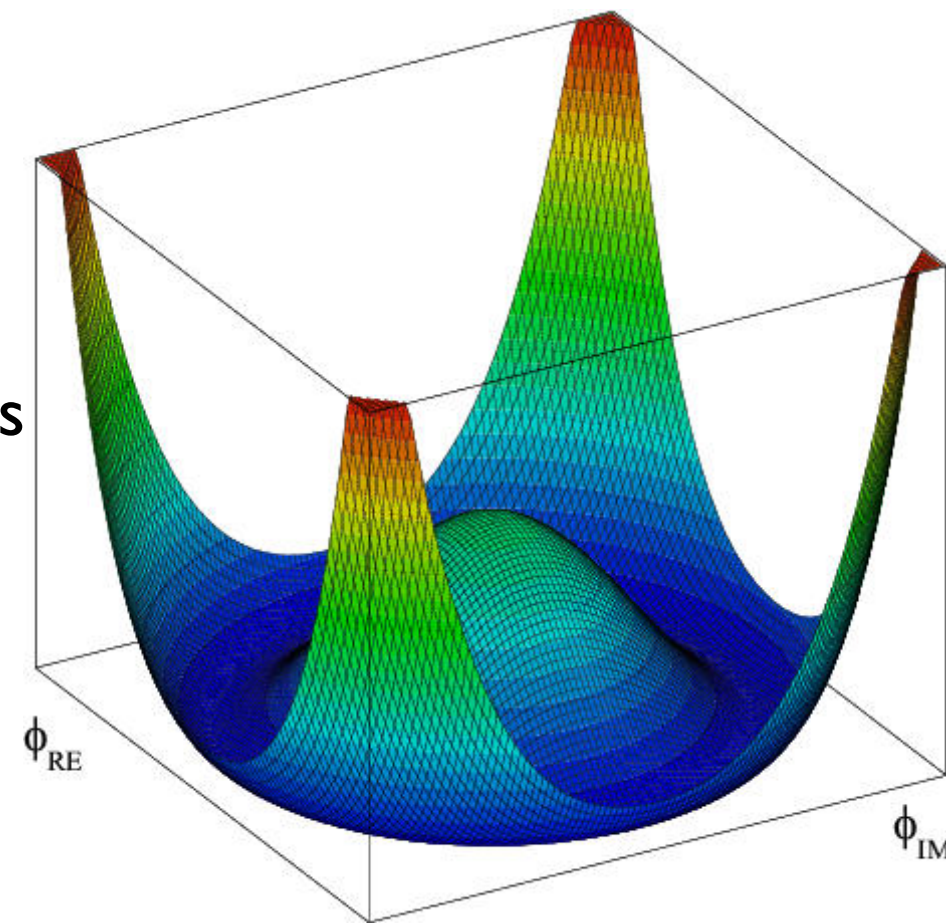
$$m_Z = \frac{M_W}{\cos \theta_w}$$

verified experimentally 10
years after the theory!

Higgs mechanism

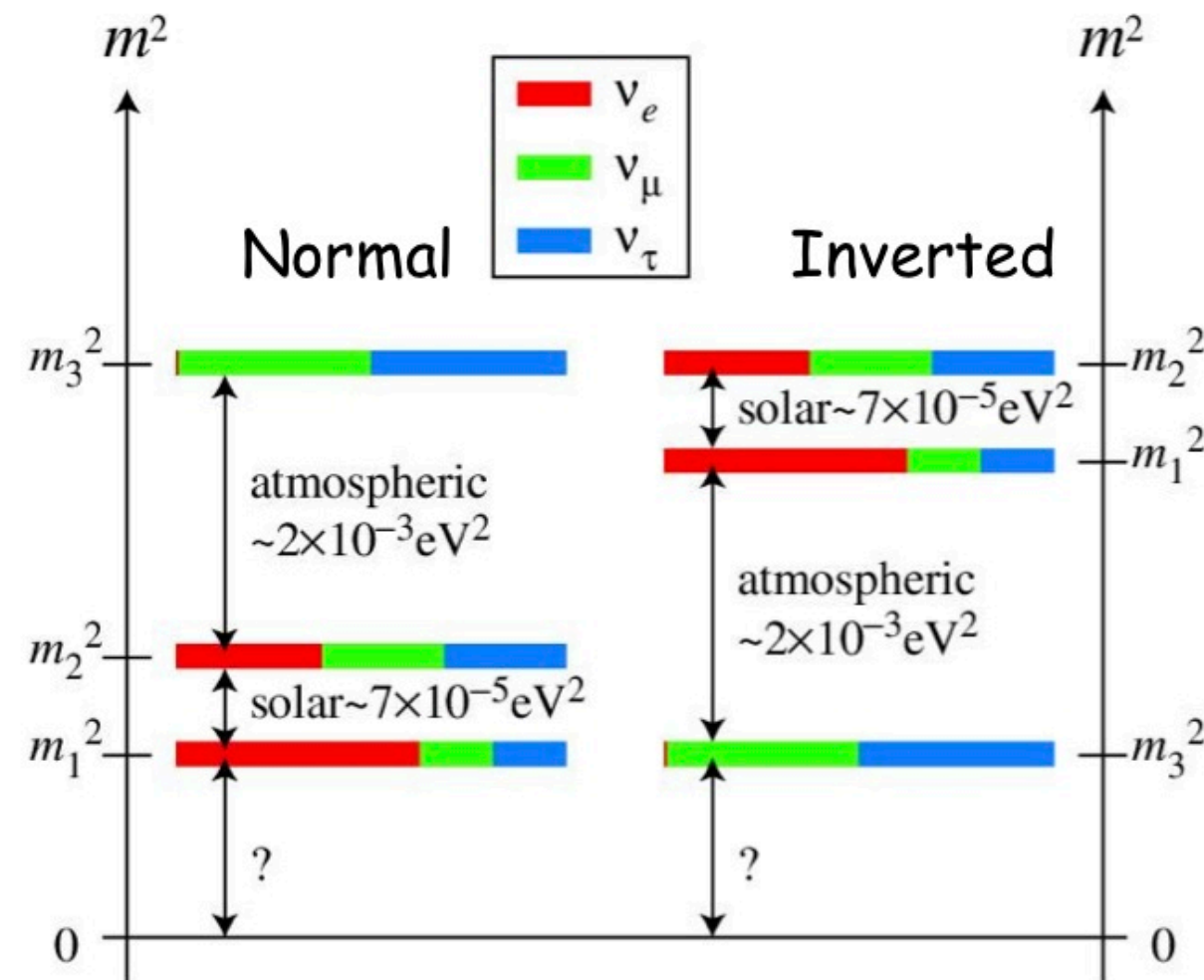
- vector boson masses →
 - why photon/weak boson asymmetry?
 - no gauge theory for massive mediators
- Higgs (ABEGHHK'tH) mechanism
 - start with electroweak interaction with massless mediators and gauge invariance
 - add scalar boson (weak isospin doublet) with potential
 - invariant w.r.t. gauge transformations of V-B fields
 - ground state (vacuum) not invariant w.r.t. gauge transformations
 - at ground state
 - gauge symmetry spontaneously broken
 - bosons/fermions (except ν) acquire mass

https://commons.wikimedia.org/wiki/File:Mecanismo_de_Higgs_PH.png
Credit: Gonis



Beyond the standard model: neutrino oscillations and masses

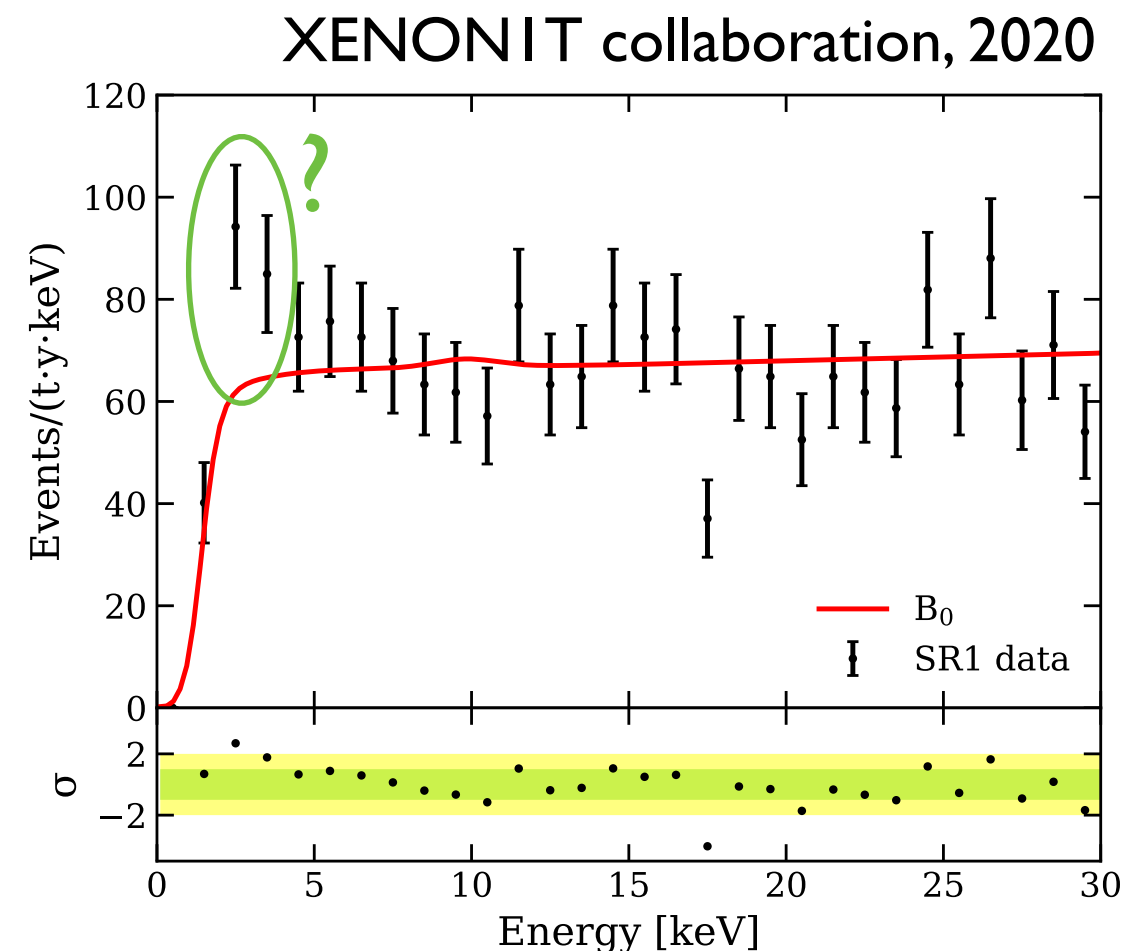
- actual neutrinos (ν_1, ν_2, ν_3) are quantum superposition of leptonic flavor (weak force) eigenstates (ν_e, ν_μ, ν_τ)
- leptonic flavor eigenstates morph into each other (e.g., deficit of ν_e from Sun)
- neutrinos have non-null masses (sum < 0.23 eV, from CMB)



from Steve King, <https://neutrell.wordpress.com/2011/03/16/neutrino-mass-models-by-steve-king/>

Beyond the standard model: dark matter and dark energy

- Astrophysical/cosmological observations show that the matter described by the standard model accounts only for $\sim 5\%$ of the total energy content of the Universe
- The rest: dark matter, dark energy
- Many physics theories attempt to provide particle/field candidates to account for them
- Examples for dark matter:
supersymmetric particles, axions ... $\rightarrow$
industry of experiments to look for them but no unambiguous result yet



Beyond the standard model: Matter-antimatter asymmetry

- Matter-antimatter behave almost symmetrically in SM (baryonic number conservation, CP only slightly broken)
 - Expected asymmetry $O(10^{-18})$
- Observations indicate that our Universe is strongly asymmetric with matter predominance at $O(10^{-9})$ (primordial nucleosynthesis, CMB)
- Baryogenesis: add new field that dynamically produces asymmetry
 - (larger) CP violation
 - non-conservation of baryonic number
 - out-of-equilibrium evolution