Particles and Universe

Lecture 6 Spin and weak interaction

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I. Spin. Fermions and bosons

II. Weak interaction and generations of particles

III. Z and W+,W- bosons

Spin – yet another quantum number

- Spin - „intrinsic” angular momentum (spin, kręt)

like spinning tennis ball

(pure quantum effect; description as for *orbital angular momentum L, but only* *formally*)

- These „rotations” are quantized. Each elementary particle has defined value of spin, quantum number s
- Unit ħ (h/2π, h – Planck constant) - spin of elementary particles - multiplication of ½ ħ (s = 0,½,1,3/2..).
- Spin - a vector quantity, only some projections on arbitrary axis are allowed -> number of different spin states (polarization states) for a massive particle is equal to 2s+1

Spin - THE quantum number

Examples:

electron, proton - spin ½ (2 spin states)

neutrino - spin ½ (1 spin states)

photon - spin 1 (2 spin states)

Z, W+/- - spin 1 (3 spin states) ★

Higgs - spin 0 (1 spin states)

The highest spins (2015): 15/2 and 6.

★ If mass = 0 only 2 !

SPIN- discovery

Bohr’s atom

Emission/absorption spectral lines

Doubling of lines

States in atoms

Description of states of atom –> quantum numbers (integer numbers)

main (energy E) = n

orbital (momentum L) = l (0≤ l ≤n-1; n- states)

magnetic (projection of L) = m (|m| ≤ l)

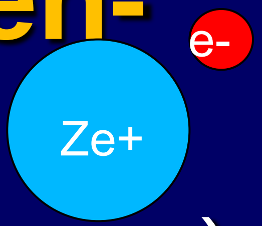
(-l,-l+1…,l-1,l; 2l+1 states)

State of atom – occupation of electrons of various shells

emission of photons if electron is loosing energy

absorption of photons if electron is gaing energy

Hydrogen atom and hydrogen-like atoms (Bohr, 1912)



- Hydrogen and hydrogen-like atoms (one e-)
- Potential energy – Coulumb interaction between nucleus [+Ze] and electron [-e]

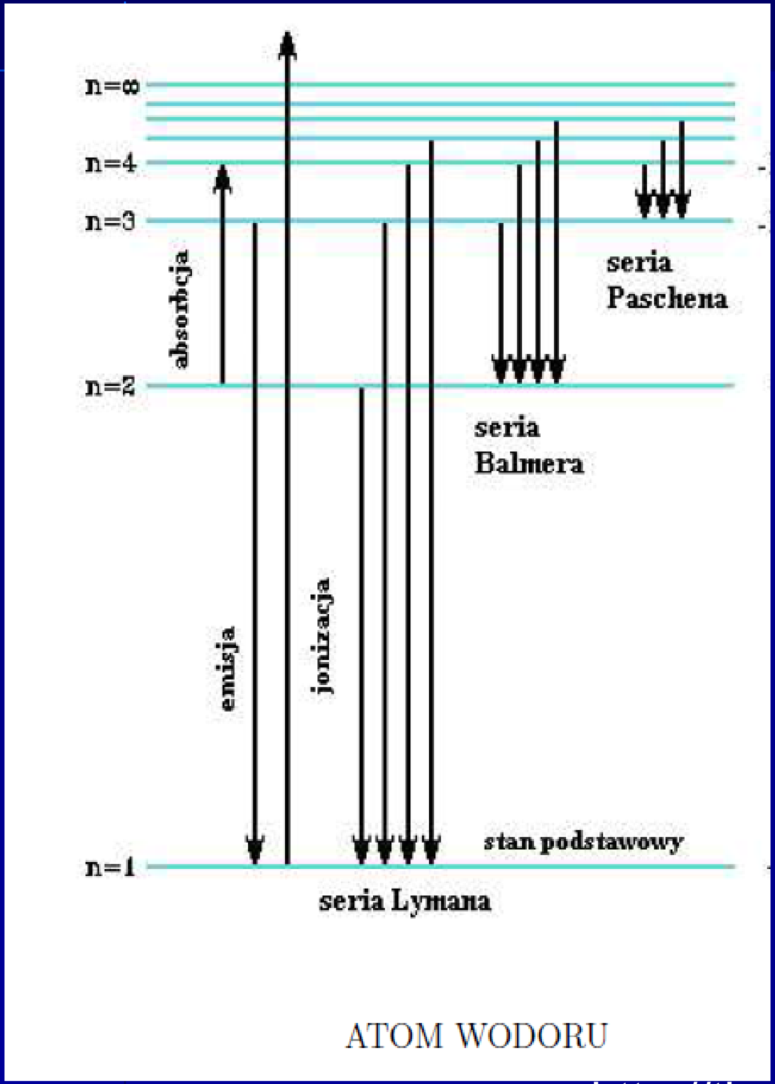
$$V(r) = -\frac{Ze^2}{r}$$

$$E_n = -\frac{\mu Z^2 e^4}{2\hbar^2 n^2}$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

- States are degenerated with respect to l,m → energy depends only on n (circular orbit):
- degeneracy with respect to m – since central
- degeneracy with respect to l -- since 1/r

Spectrum – hydrogen atom (Bohr)



For hydrogen atom Z=1
(in atomic units)

$$\Delta E_{n_1 n_2} = \frac{\mu}{2}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

$$\Delta E_{n_1 n_2} = h\nu = h\frac{c}{\lambda}$$

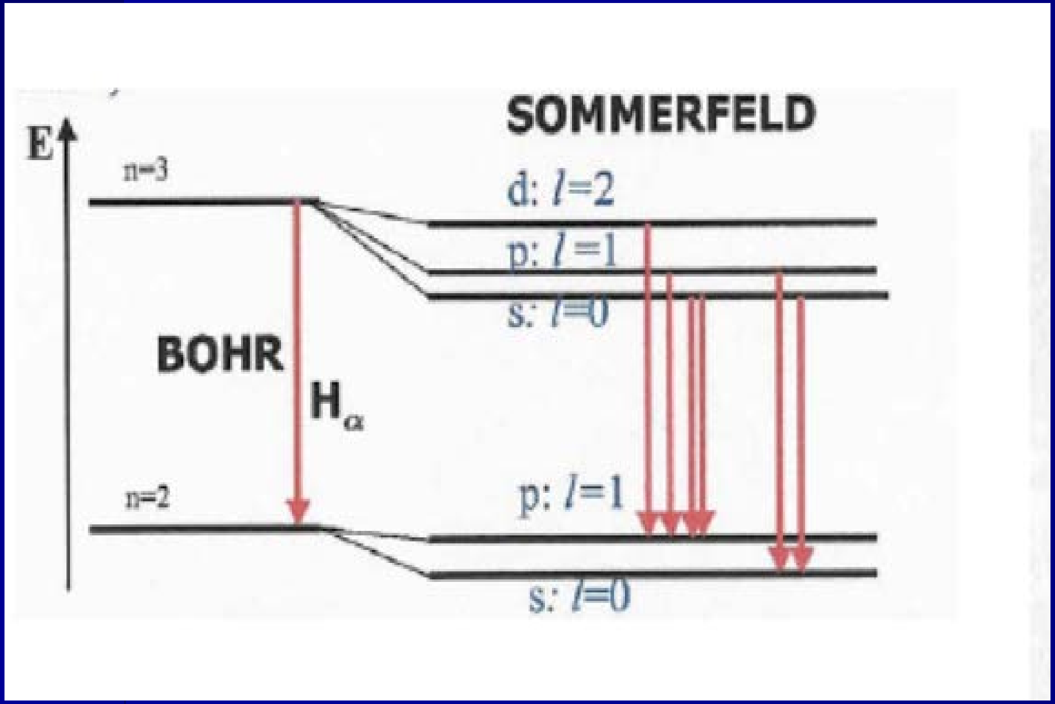
Balmer 1885 (95)

http://tiger.chem.uw.edu.pl/staff/mjezior/wstw3z13.pdf

Relativistic corrections→ splitting of emission lines

Sommerfeld 1916 (dependence on l)

→ energy of states E(n, l)



http://www.fuw.edu.pl/~marysia/wfaccs/wyklad5.pdf

The normal Zeeman effect

- External field (magn. or electric) may break spherical symmetry removing degeneracy with respect to l, m. This leads to a separation (splitting) of lines (subtle structure of lines).
- 1892 - P. Zeeman observed widening of lines for sodium (hydrogen-like), when sodium flame was between magnetic poles
- This widening was in fact a splitting of lines

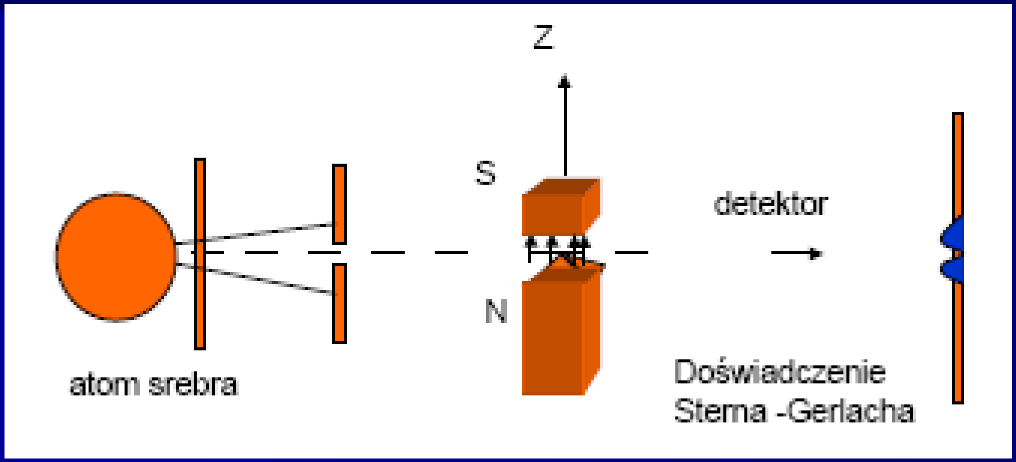
  (observed for many other atoms as well)

If spectrum in agreement with quantum numbers l and m in the magnetic field - the *normal Zeeman effect*

(the Stark effect – similar effect in the electric field)

Stern-Gerlach experiment (1921)

Stern and Gerlach (1921) for silver: **doubling** of lines in magnetic field.



Movement on the electron on orbit →
magnetic moment for atom in magnetic field. Here only the last electron is important (hydrogen-like structure).

Teoria kwantów, Białynicki-Birula, M. Cieplak, J. Kamiński

The anomalous Zeeman effect

The anomalous Zeeman effect –

doubling of lines- this was a problem!

Formaly it was possble to describe spectra by

introducing a new quantum number

$j = l \pm ½$

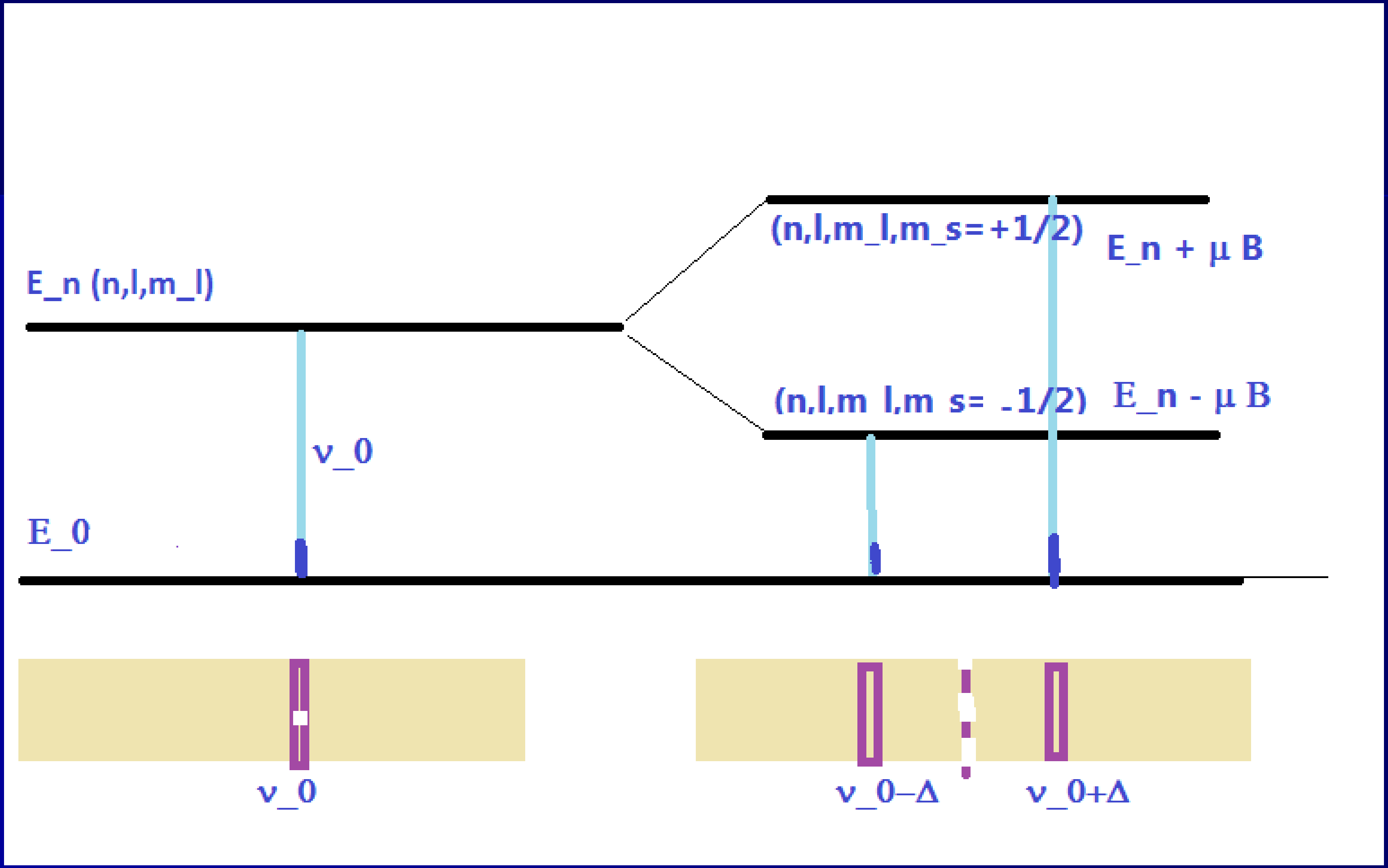
Pauli 1925: „two valuedness not describable classically"

a need of 4 (not 3) quantum numbers

and exclusion principle

Podstawy fizyki współczesnej, V. Acosta, C. L. Cowan, B. J. Graham, rozdz. 20-22

Doubling of lines



Doubling of lines in the magnetic field: besides magnetic moment related to the magnetic quantum number m – projection of orbital angular momentum l (here m_l) there is „intrinsic" magnetic moment (magn. quantum number, here m_s) related to the „intrinsic" angular momentum s - with only two values.

Discovery of electron's spin 1925 – story by S. Goudsmit 1971

→ *http://www.ilorentz.org/history/spin/goudsmit.html*

Z Phys. Rev. Letters (PRL) *http://prl.aps.org/edannounce/PhysRevLett.101.010002,*

(PRL was founded by Goudsmit in 1958):

'Goudsmit - while still a graduate student, he and his fellow student George E. Uhlenbeck hypothesized that the electron possessed angular momentum – that is, spin – in addition to mass and charge.

Their motivation was to explain the mystery of doublet and higher order spectral line splitting.

subtelna struktura linii widmowych

Their insight furnished a missing link leading to the final triumph of the then-struggling birth of quantum mechanics.'

Hypotheses of spin

- A. H. Compton: postulated 'quantized electron rotation' (1918-21)

(Bohr i Pauli – against)

- R. Kronig (PhD student) proposed 'spin' few monts before Goudsmit and Uhlenbeck, but Pauli was against his publication (*'it is indeed very clever but of course has nothing to do with reality'*)
- In 1925 Goudsmit and Uhlenbeck – hypothesis of spin *(Pauli against; their superviser Ehrenfest sent their work for publication; his comment wasthat they are so young that can have unreasonable paper)*
- W 1926 correct relativistic calculation by L.H.Thomasa (factor ½) and Pauli accepted spin *(and introduced Pauli matrices 2x2 to describe spin 1/2)*.

Today spinotronics (*→ quantum computer*)

http://www.mif.pg.gda.pl/homepages/maria/pdf/NM_3.pdf

Spin discovery

http://www.lorentz.leidenuniv.nl/history/spin/goudsmit.html

Leiden 1924. From left to right: Dieke, Goudsmit, Tinbergen, Ehrenfest, Kronig, Fermi. Note: Tinbergen later changed from physics to economy and became the first Nobel laureate in economy (1969).

Fermions and bosons

In Nature – only two types of elementary particles:

- Particles with half-integer spin = fermions

  - Fermi-Dirac statistics

  - Pauli exclusion (1925):

    two fermions can not be in the same quantum state

> This explains structure of atoms – if states at some energy shell are all occupated – next electron has to go to the higher shell … (shell = n)

- Particles with integer spin = bosons

  - Bose-Einstein statistics

  - more bosons better (lasers, condensats)

Spin of fundamental particles

in unit $\hbar$

- Quarks i leptons (fermions) – spin ½
- Carriers of interactions (bosons) :
  photon, gluons, bosons W i Z – spin 1
- Higgs particle (boson) – spin 0

Spin 1-vector (intermediate) bosons

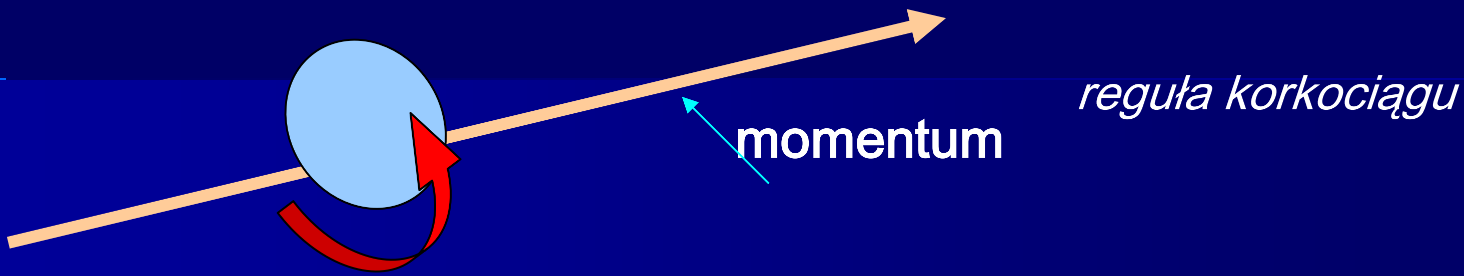
Name	symbol	el.charge	mass
Boson	W+	+ 1	80.4 GeV
Boson	W-	- 1	80.4 GeV
Boson	Z	0	91.2 GeV
Photon	γ	0	0
Gluons(8)	g	0	0

- W^+ antiparticle to W-
- γ , Z – (self antiparticles)
- gluon$_{a\,\bar{b}}$ antiparticle to gluon $_{\bar{a}\,b}$

  (a, b – colors)
- Hipotetical graviton – spin 2, el. charge 0, mass 0 (antiparticle)

Left and right particles - spin 1/2

- Left (left-handed) particle



Left ? This is relative, since if I will be faster than this particle its momentum vector will change into opposite one – and it becomes a right particle!. So, if there is a left than there is a right particle: <u>→ two states of massive particle with spin 1/2.</u>

For massless particle this argument does not hold.

- Massless neutrino – only left,
- massless antineutrino – only right

(in the Standard Model!)

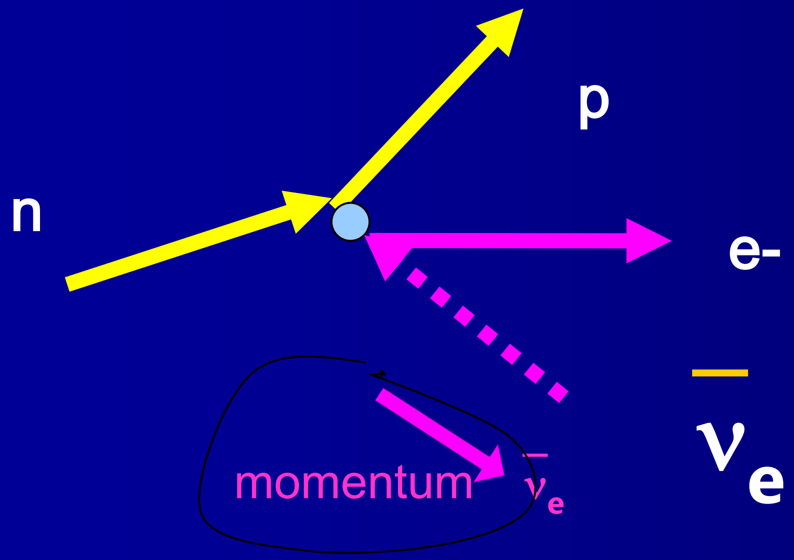
Generations and weak interaction

Weak interactions

- Particles (p, n) and (neutrino el., electron) - in some processes appear in pair (doublets)
- eg. in beta decay

Becquerel 1896

radioactivity β



Vectors (lines) - momentum of particles

Convention: arrows on lines along momenta for fermions while for antifermions opposite to the momenta

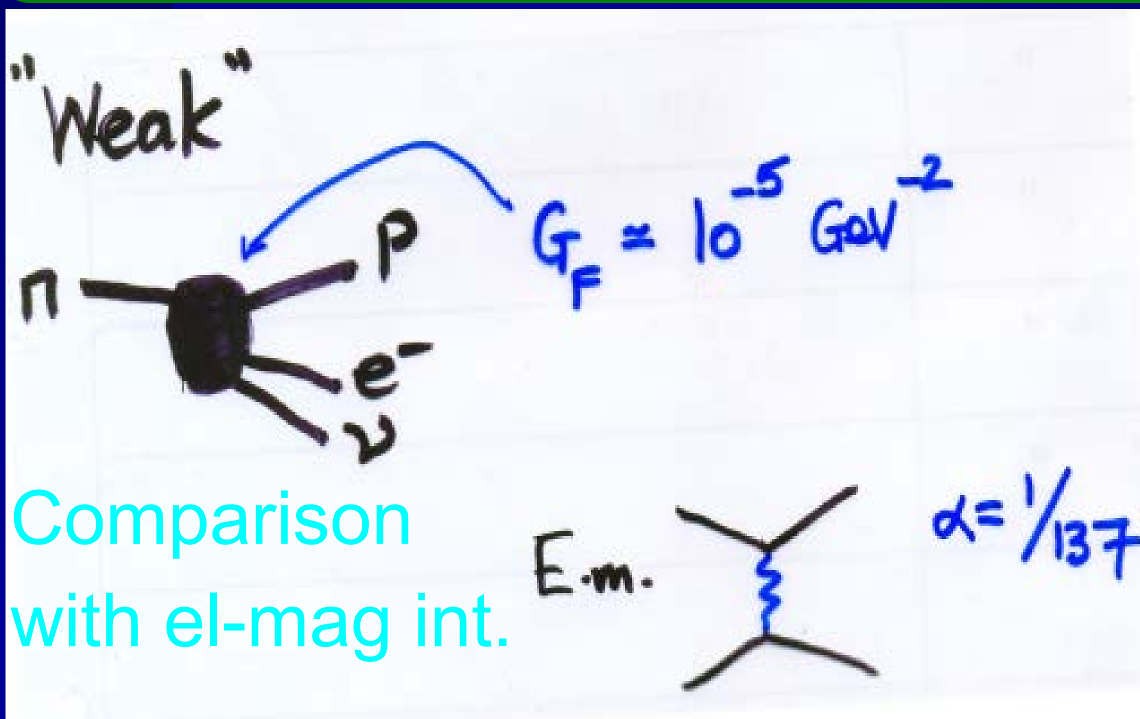
- E. Fermi 1934 → theory (*pointlike-, 4 fermion-, charge current- interaction*) – **weak interaction**

Weak Interaction
- Fermi

lectures by F. Close w CERN

Fermi model (1934) for beta decay of neutron

prąd hadronowy x prąd leptonowy



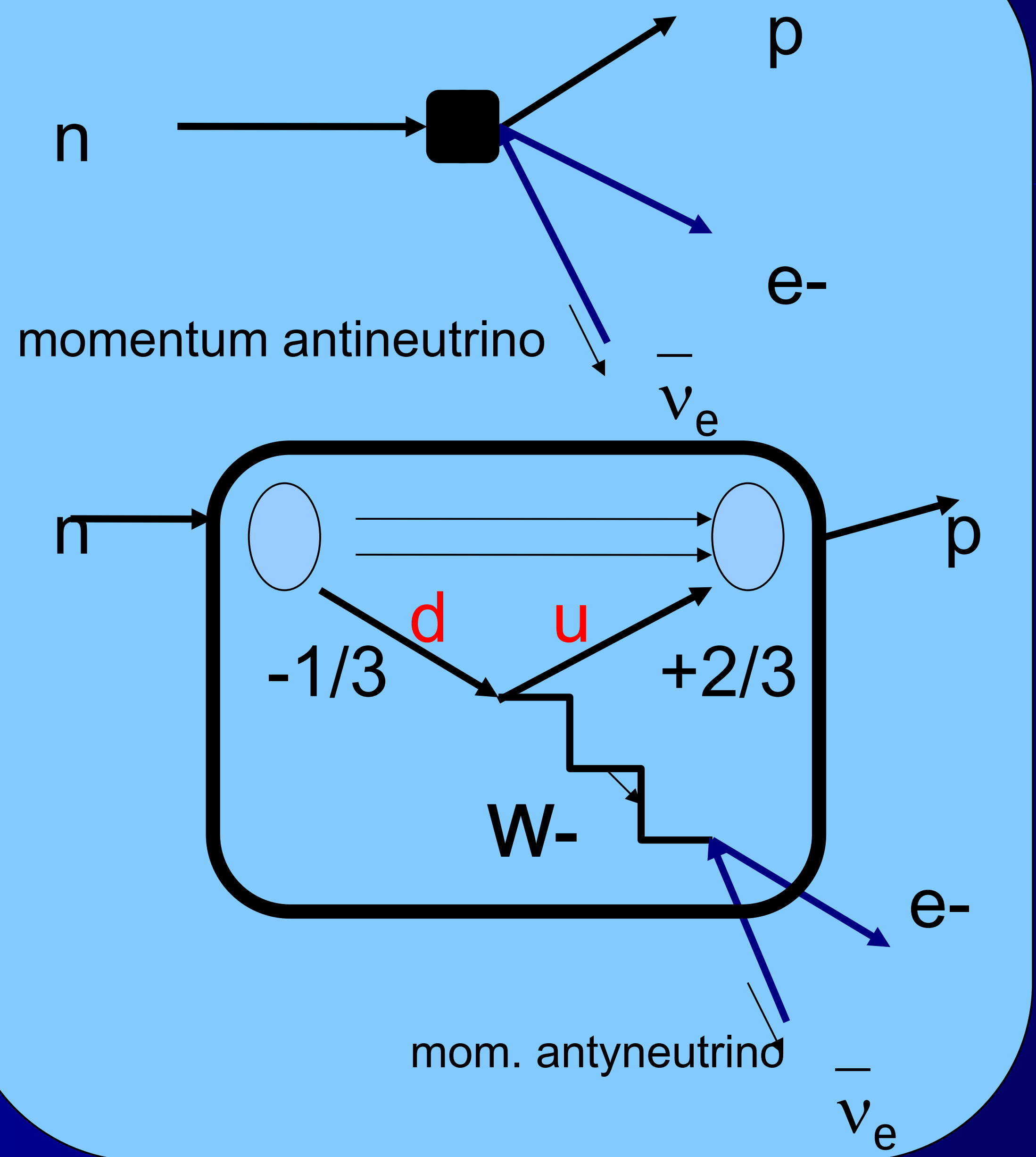
Comparison
with el-mag int.

Effective „strenght" of interaction "G_F " (Fermi constant) value from data (G_F=10^(-5) geV ^-2

Black box

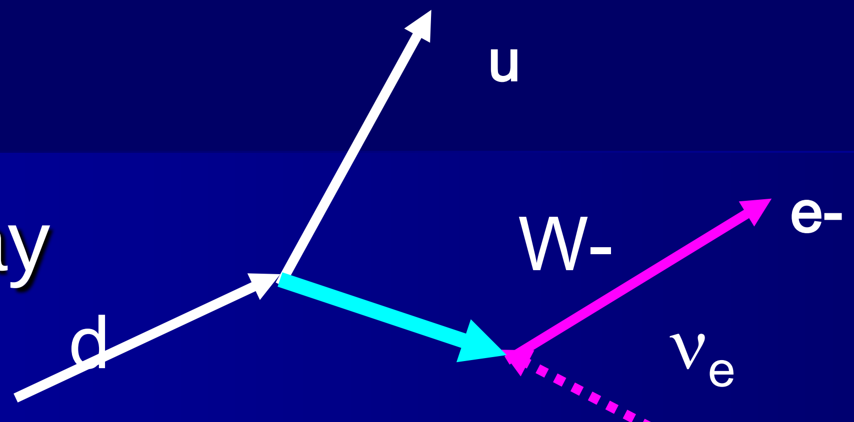
but with higher resolution we see exchange of W

el. change conservation.



Fundamental weak int.

- β decay



vertex d $\rightarrow$ u W- and W- $\bar{\nu}$ $\rightarrow$ e-

coupling constant g (g -„weak charge ”)

$\alpha_w = g^2/4\pi = 1/32$

larger than the corresponding coupling for electromagn. interaction (e- el. charge)

$\alpha_{em} = e^2/4\pi = 1/137$ (*subtle coupling constant*).

- Weak interaction weaker since exchange of massive particle W „costs,,..

Electroweak int.: bosons W+,W-, Z

- 1864 Maxwell combined electric and magnetic int. into electro-magnetic interaction –first unification of forces

- 1970 Glashow, Weinberg i Salam – combination of weak and electro-magnetic int. *(partial unification)* → electro-weak (EW).

  Prediction: besides W+, W- a neutral boson Z (Z^0) exists

  Nobel 1979

- 1983-4 Collision of protons with antiprotons (experiments UA1, UA2 at CERN) – in quark and antiquarks collision production of bosons W+, W- and Z (discovery).

  Rubbia (head of exp.) and van der Meer (antiprotons beams in accelerators)

  Nobel(1984) - discovery of W/Z

Generations (Families)

Weak interaction groups quarks and leptons in dublets

u	c	t	ν_e	ν_μ	ν_τ
d	s	b	e	μ	τ

exchange W+, W-

CC „charged current"

First generation = two light doublets of fermions (spin ½)

- quarks el. charge 2/3 u (3 colors)
- -1/3 d (3 colors)
- leptons 0 ν_e
- -1 e (electron e-)
-
- antifamily
- eg. antilepton doublet:
- el. change
- +1 $\bar{e}$ (positron e+)
- 0 $\bar{\nu}_e$

Note: In Standard Model neutrinos are massless.
Experiments (2001-2) – *neutrinos have very small masses*

Second generation = two doublets of fermions - spin 1/2

- Quarks el. charge. 2/3 c (3 colors)

  -1/3 s (3 colors)

- Leptons 0 ν_μ

  -1 μ (mion -)

- antileptons:

  :

  el. charge

  +1 $\bar{\mu}$ (mion+)

  0 $\bar{\nu}_\mu$

Third generation = two heavy doublets of fermions - spin 1/2

- quarks el.charge 2/3 t (3 colors)

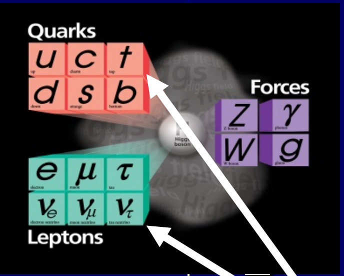
  -1/3 b (3 colors)
- leptons 0 ν_τ

  -1 τ (taon -)
- antileptons:

  el. charge

  +1 $\bar{\tau}$ (taon +)

  0 $\bar{\nu}_\tau$

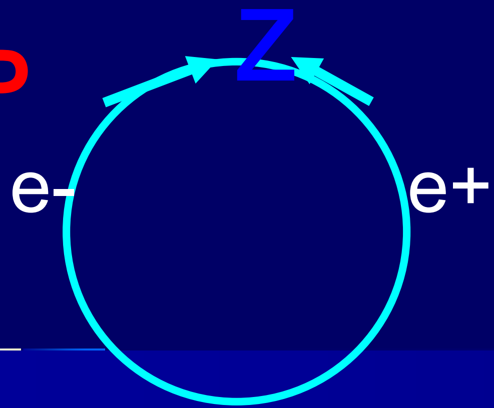


3 generations (families)

- This is a table of fundamental particles
  Families (doublets of spin ½ fermions) are
  ordered in masses:
  I generation – the lighest, III – the heaviest
  (like periodic Mendelejew's table of elements, but
  without regularalities)
- Origin of masses: Brout-Englert-Higgs mechanism
- Other generations ?
- Experiment: not, if neutrinos light.
- Theory?

BOSON Z

LEP



LEP (CERN, 1989 - 2002r)

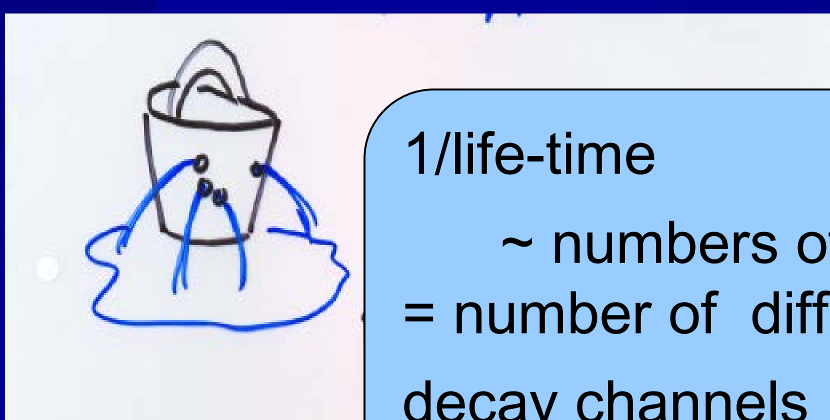
collision e- e+

In 1989-1995 energy of collision → resonant production of Z :

E+ + E- = M_Z = 91 GeV

Boson Z decays in a democratic way

pairs:quark-antiquark, lepton-antilepton
(np. e+e-, neutrino el - antineutrino el.)



1/life-time
~ numbers of holes
= number of different
decay channels

LEP: 4 experiments→
collected 20 mln of Z

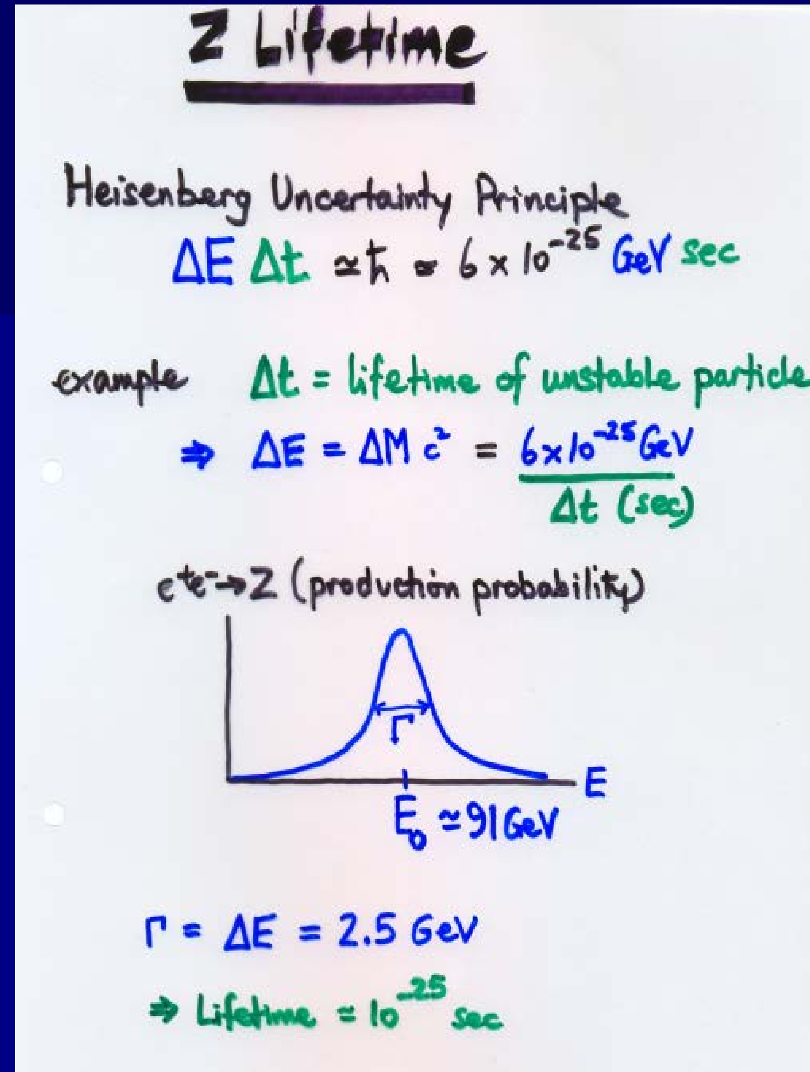
Lifetime of boson Z

<u>Uncertainty principle (Heisenberg)</u>

$\Delta E \, \Delta t = 6 \times 10^{-25}$ GeV sec.

If Δt = life time of decaying particle then rest energy (mass) spread

$\Delta E = 6 \times 10^{-25}$ GeV sec$/\Delta t$

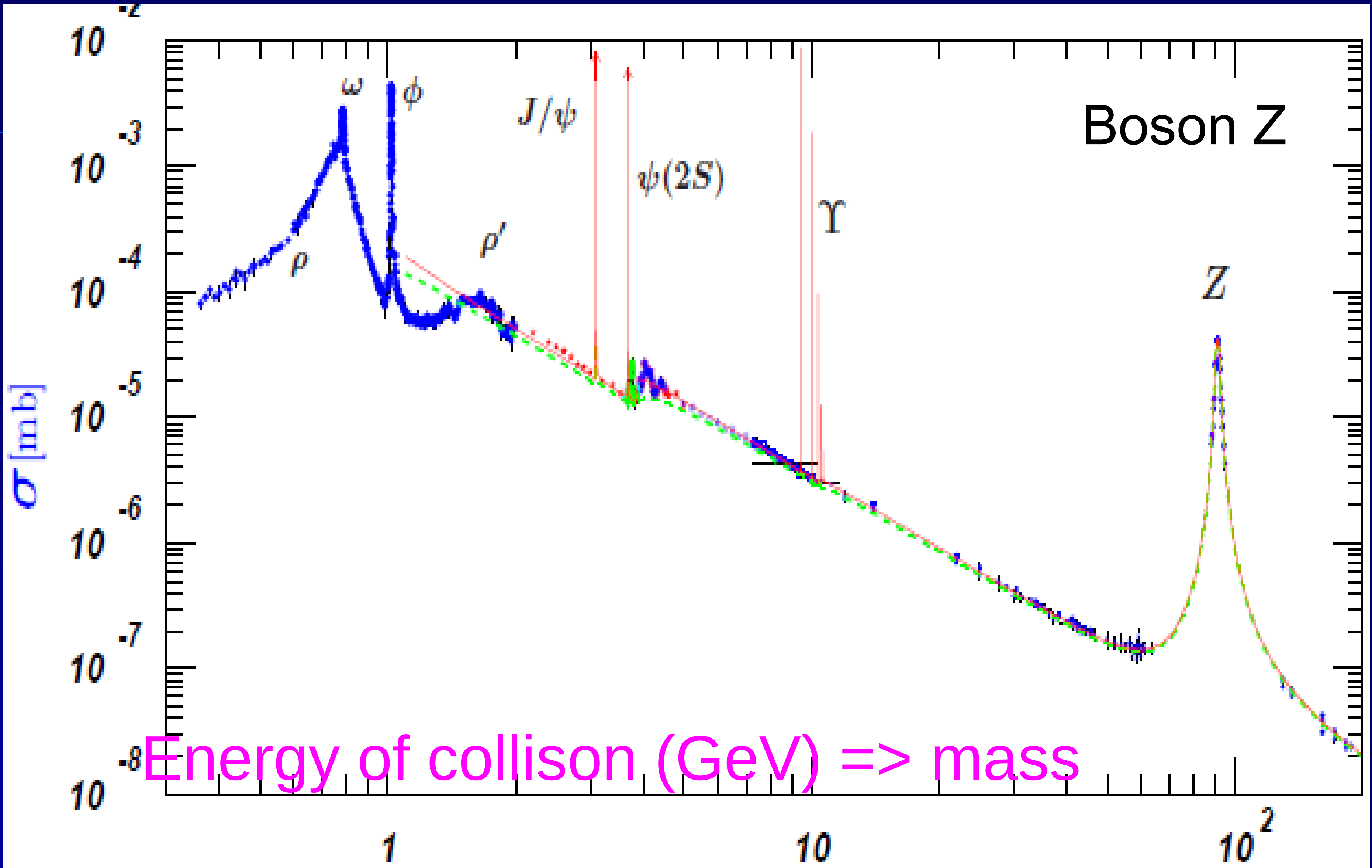


For Z (decay width – half width)

$\Gamma = \Delta E = 2.5$ GeV

$\Delta t \sim 2 \times 10^{-25}$ s

LEP: number of events in the e+e- collision



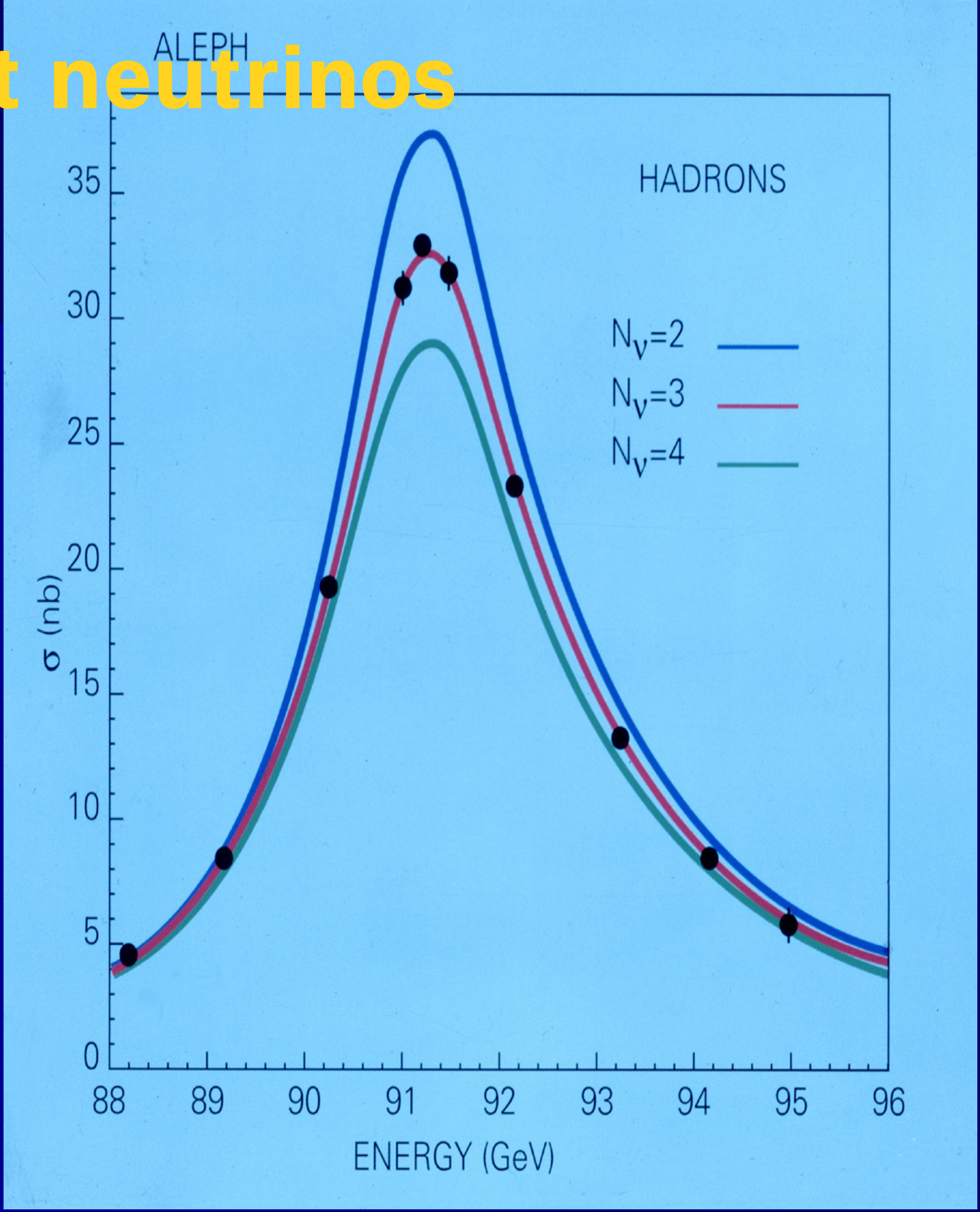
Number of light neutrinos

Probability of Z bosons decaying into hadrons for

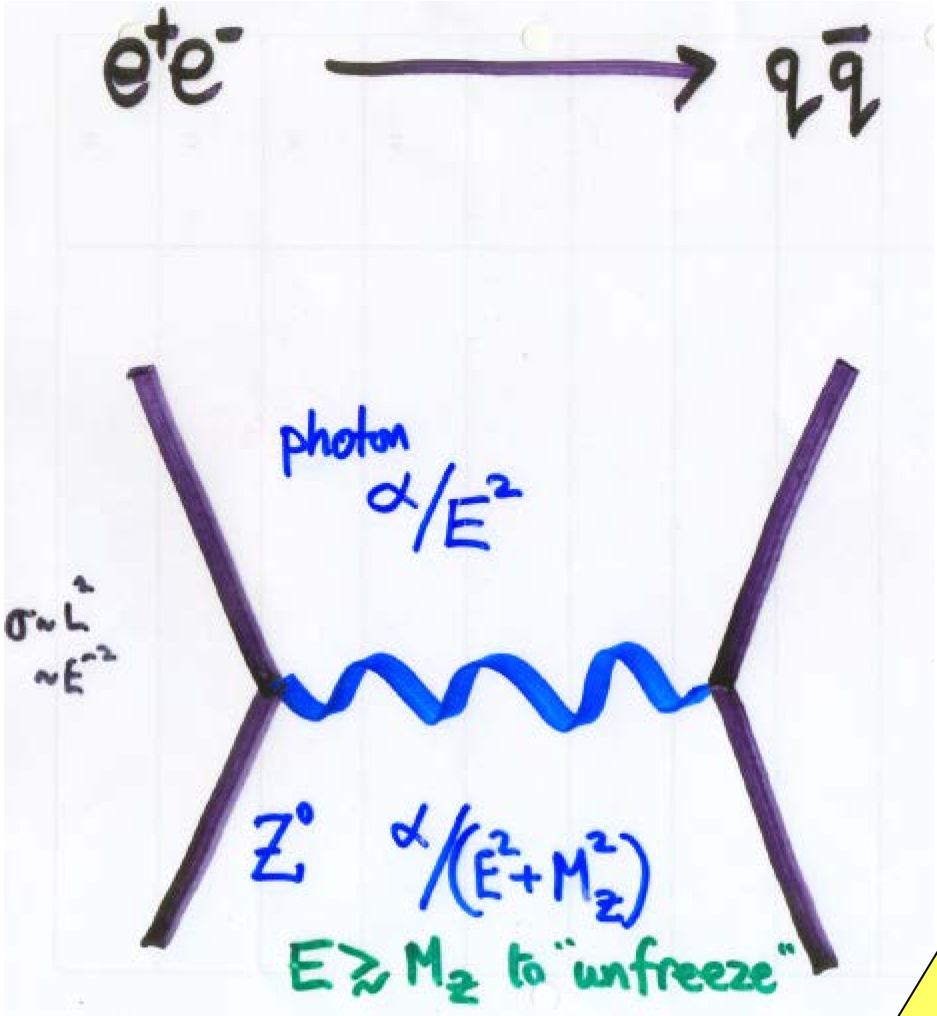
2, 3, 4 pairs of $\nu \bar{\nu}$

(light neutrinos - with masses below 45 GeV)

Agreement for $N_\nu = 3$!



Weakness of weak interaction

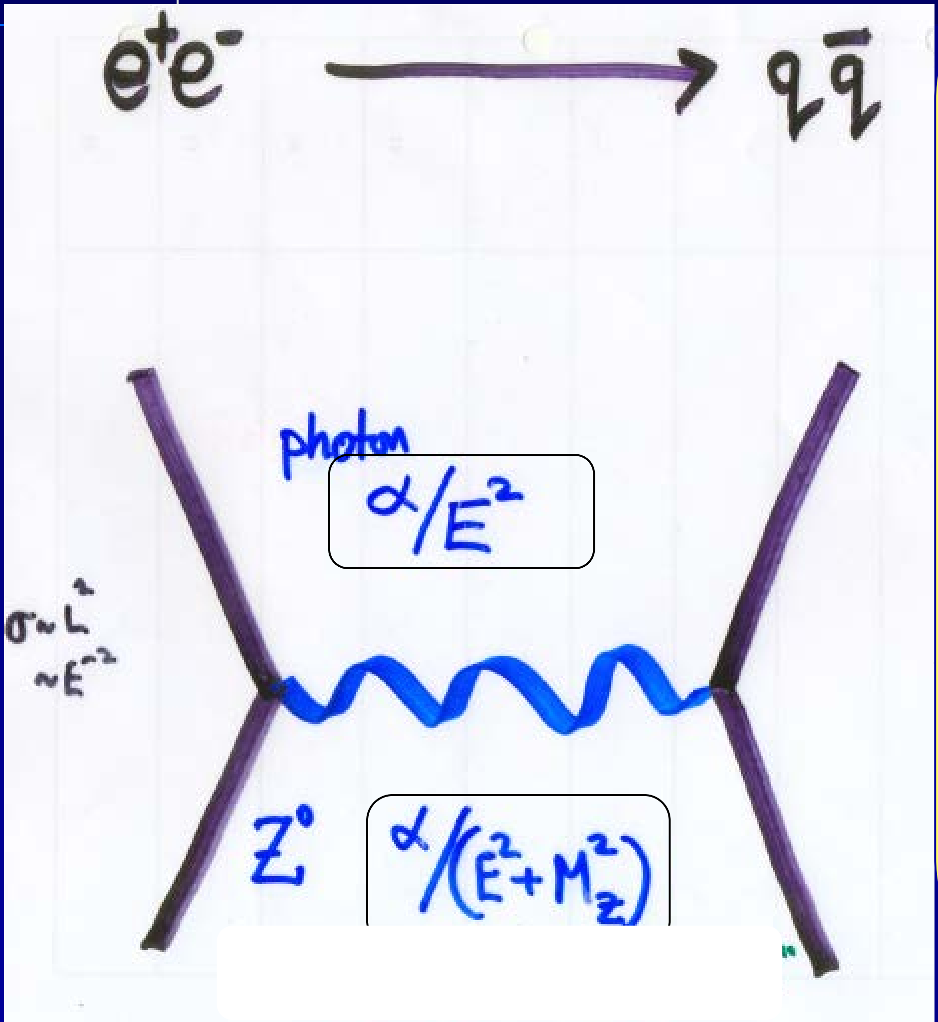


Feynman rules:

If energy E flows through the transmitted "virtual" particle (photon; Z) it costs 1/(E^2+M^2)

If E >> M the cost is 1/E^2….like the case of the photon

Comparison of boson Z and photon exchange in collision e+ e-



Feynman rules
(probability of process)

Energy E curried by a virtual particle

→ factor $1/(E^2+M^2)$

M- mass of virtual particle

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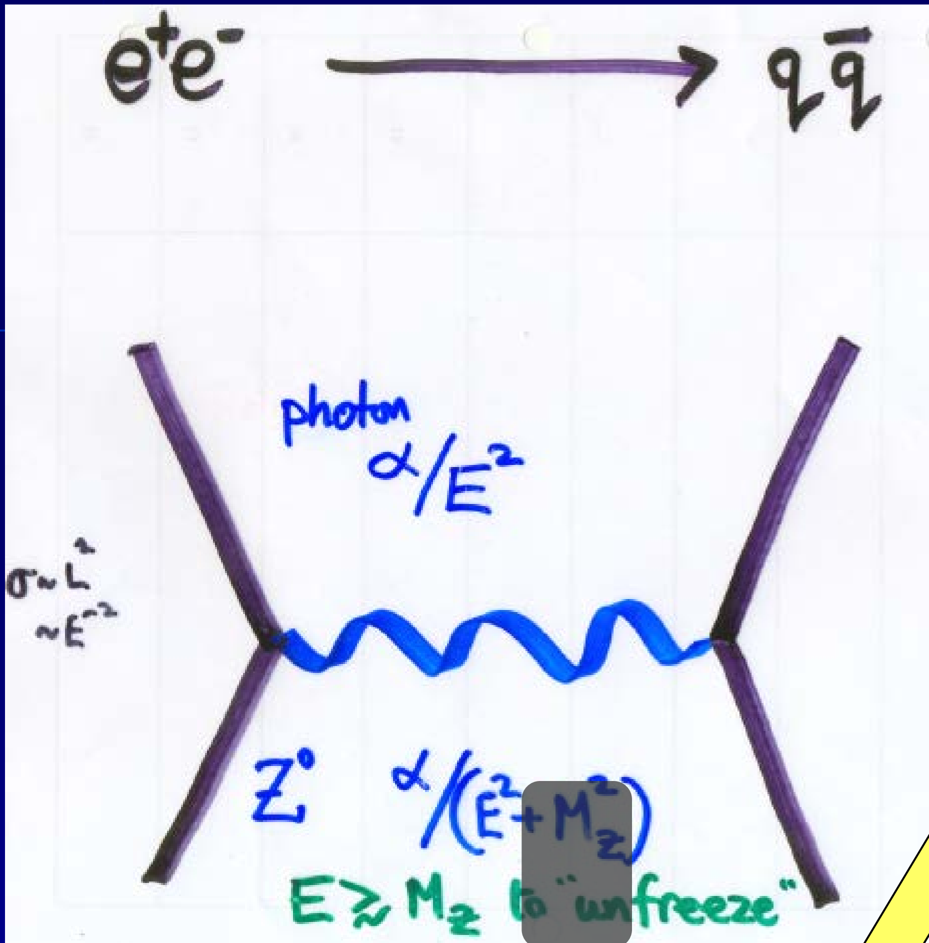
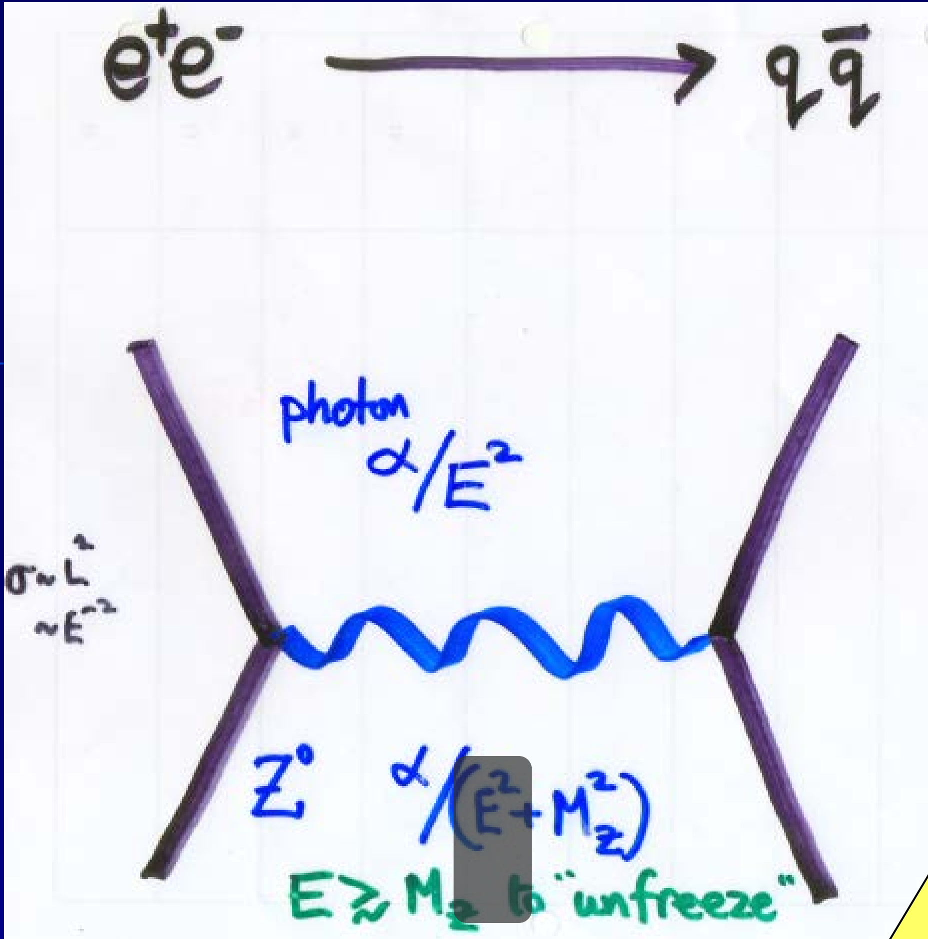


$$1/(E^2+M^2)$$

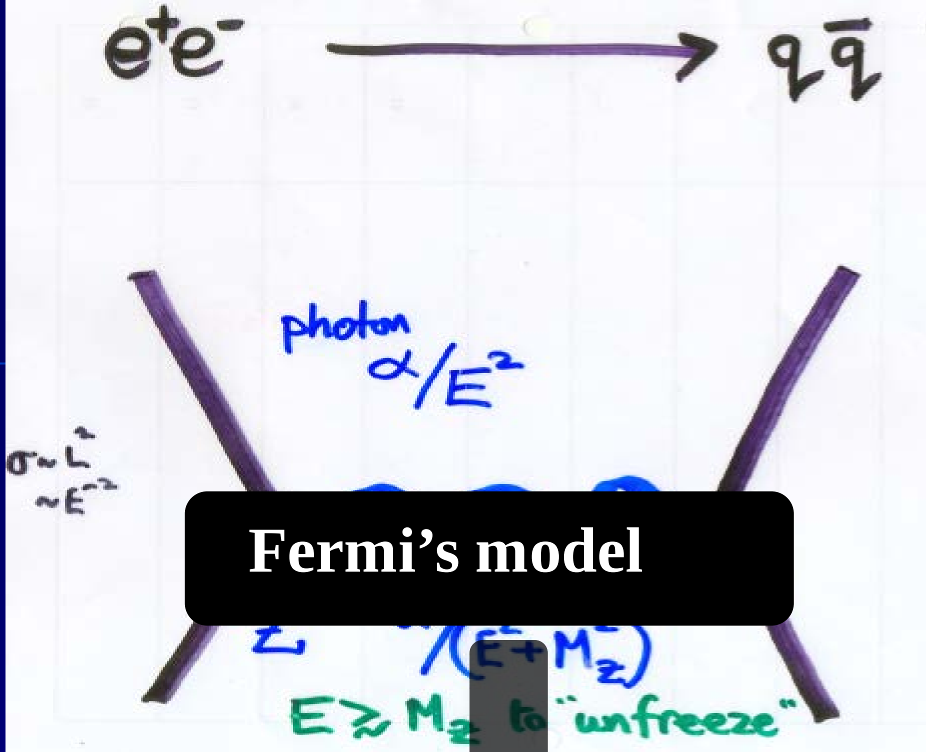
For E >> M , so approximately factor $1/E^2$…as for photon



$1/(E^2+M^2)$

For E >> M - approximately $1/E^2$…like for photon

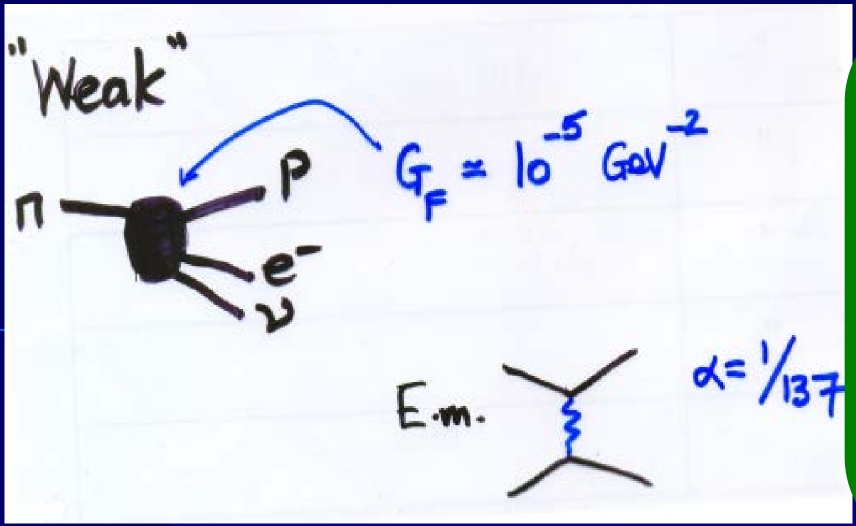
However for E << M, factor $1/M^2$



Dla E << M to tylko $1/M^2$

So for exchange of Z formula without energy. This is like a pointlike interaction - Fermi model !

Here exchange of Z boson, but model was formulated for CC ie. with exchange of W+/- .



"weak int" is weak – why?

coupling $\alpha_w = g^2/4\pi = 1/32$
(dla małych energii)
larger than for el-mag int. ~1/137
so it is weak since W mass large

Weak interaction is the weakest!

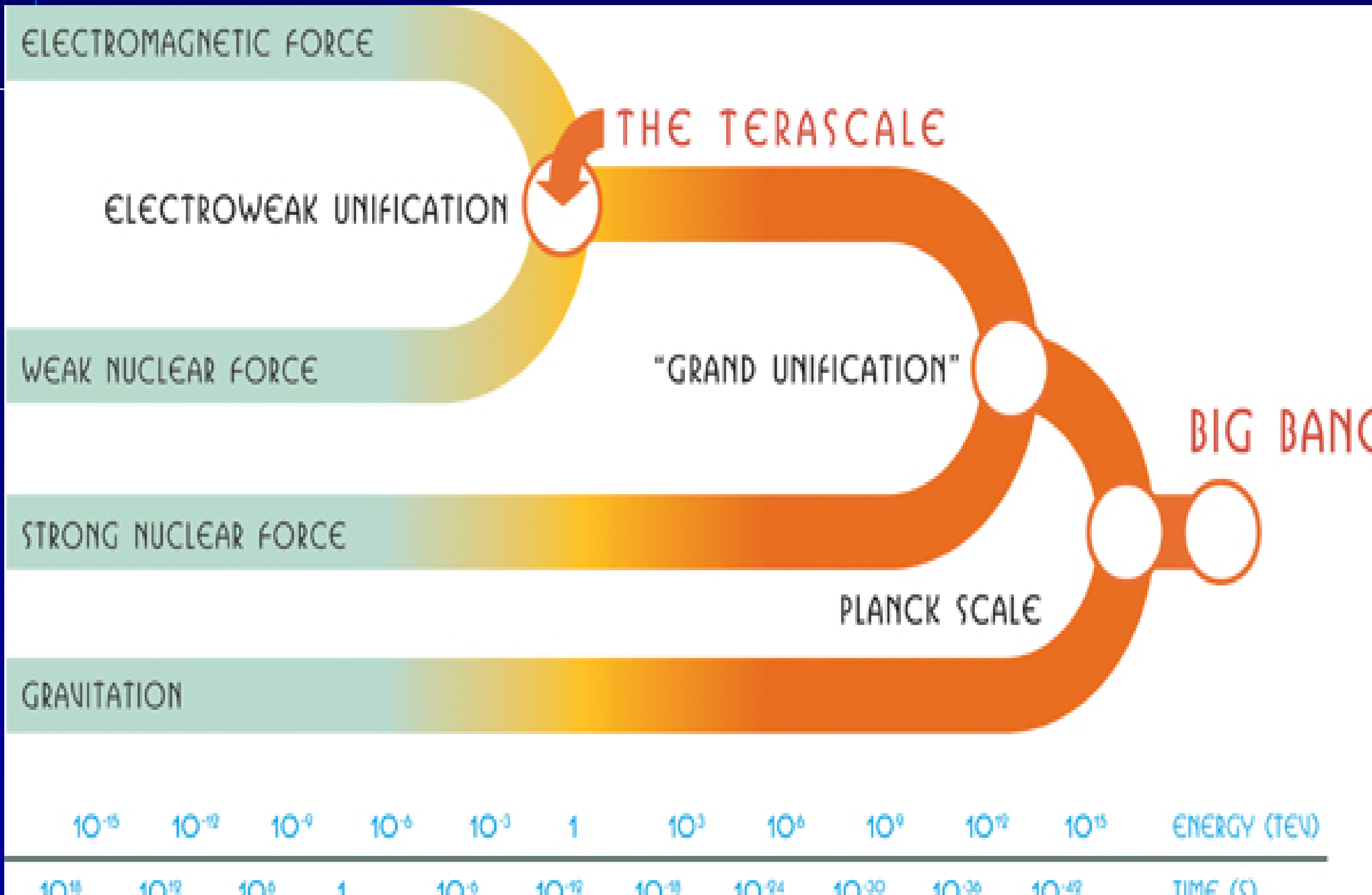
Mass W+/- = 80 GeV, Z = 91 GeV

the only massive agent of interaction

Couplings constants are running (due to quantum corrections)

electroweak (unification of el-mag. and weak) – *more later…*

UNIFICATION



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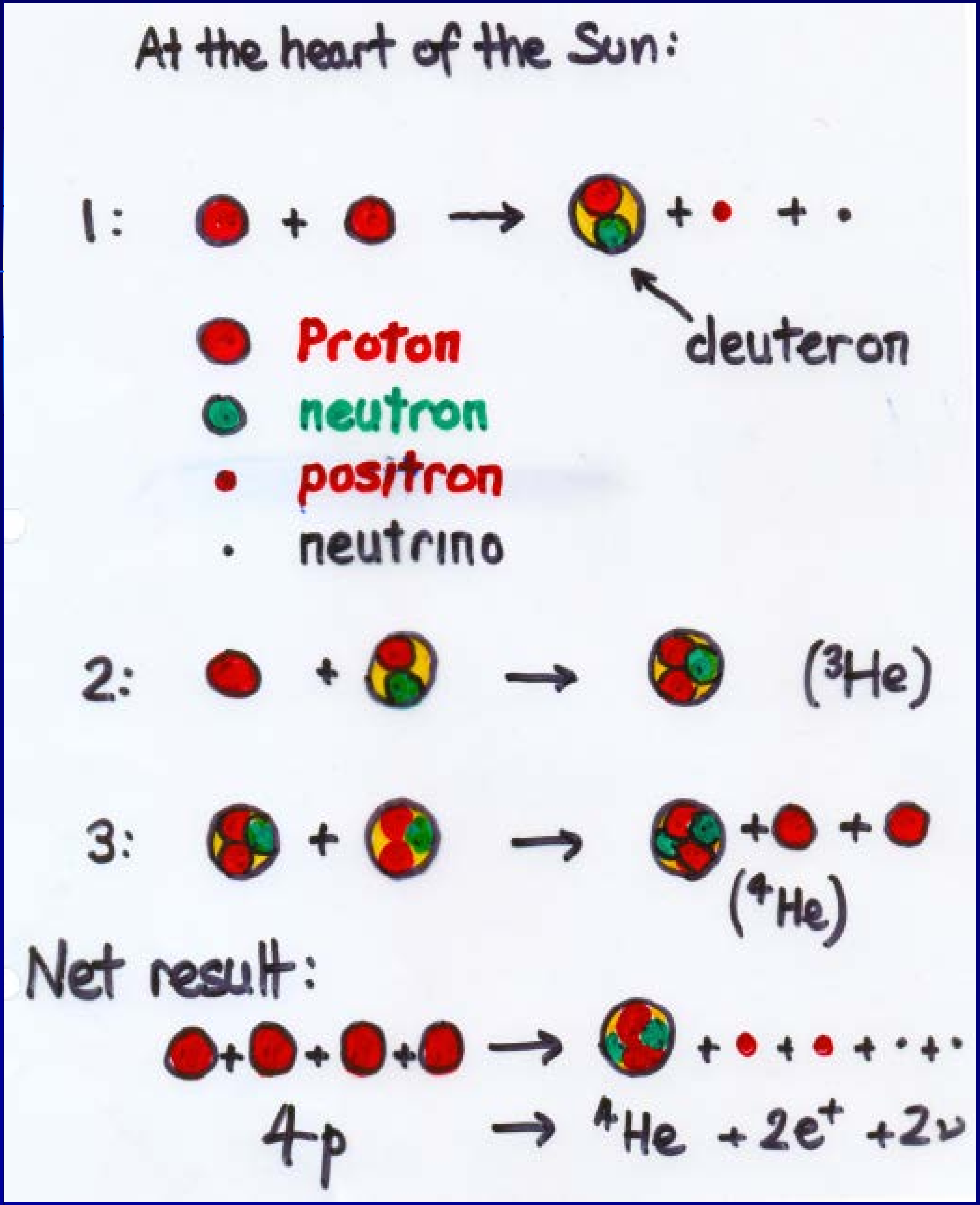
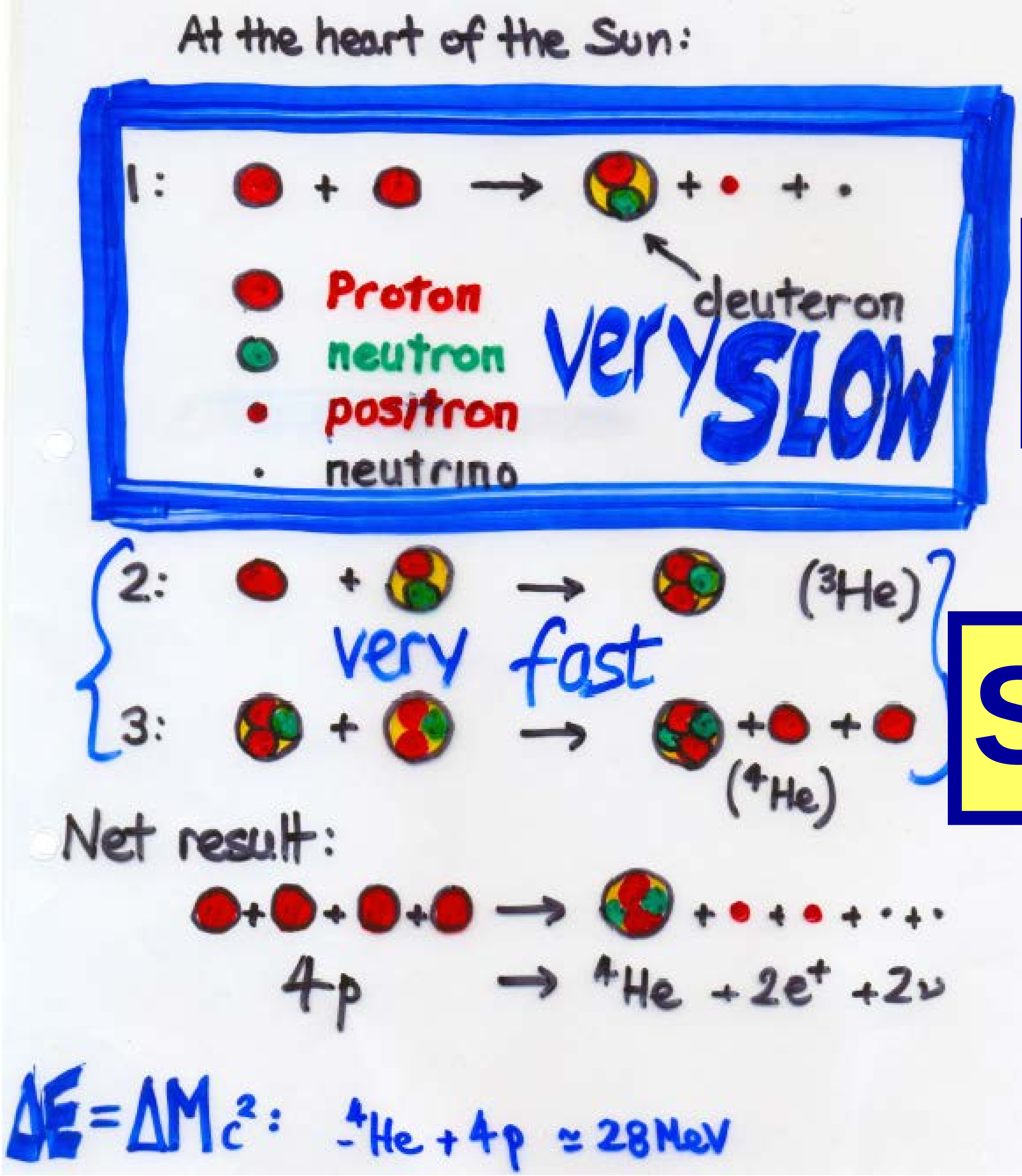
W+, W- BOSONS

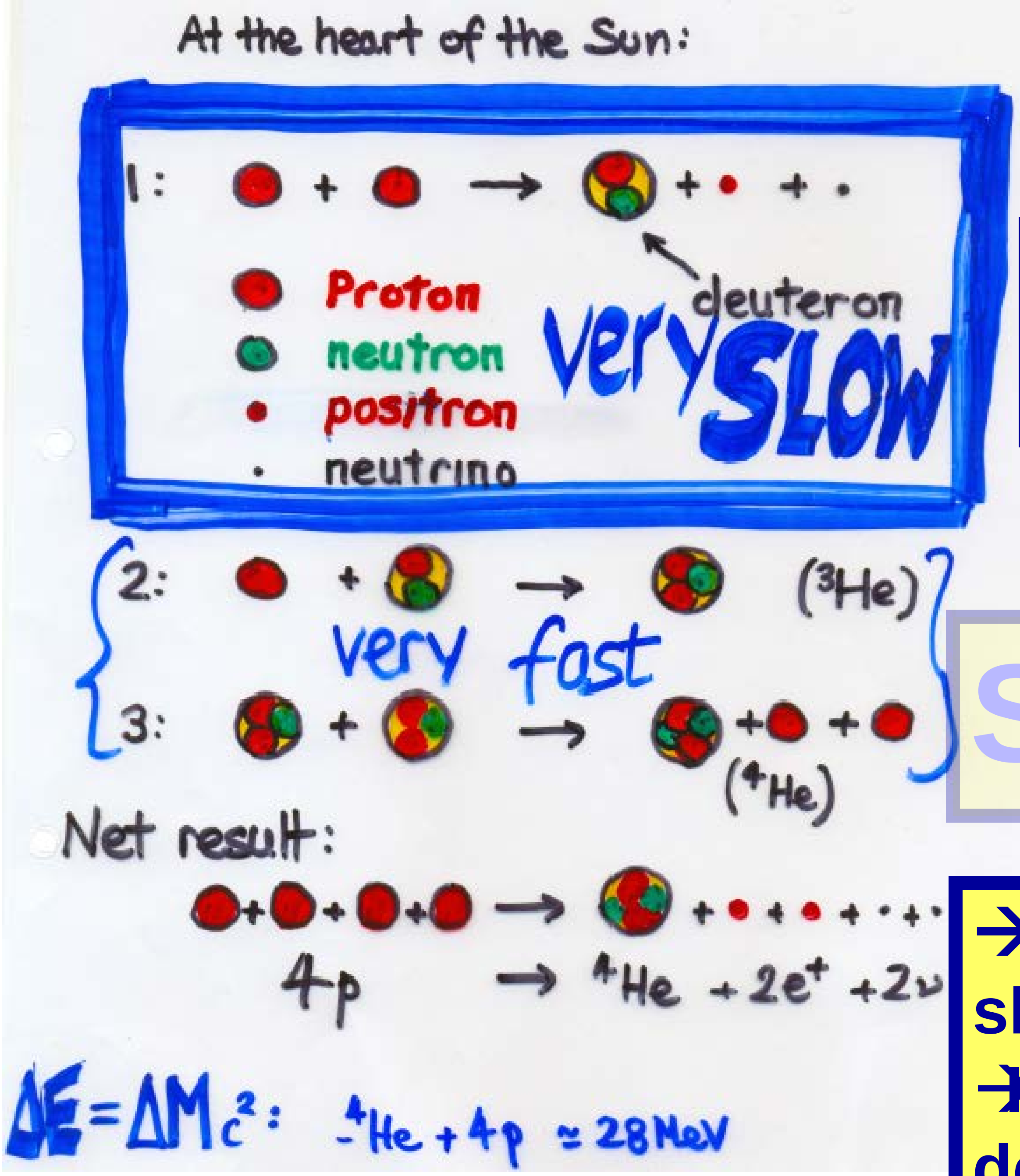

At the heart of the Sun:
1:
deuteron
Proton
neutron
positron
neutrino
2:
(^{3}He)
3:
(^{4}He)
Net result:
4p → ^{4}He + 2e$^+$ + 2ν

F.Close(CERN)


At the heart of the Sun:
1:
deuteron
Proton
neutron
positron
neutrino
very SLOW
2:
(³He)
very fast
3:
(⁴He)
Net result:
4p → ⁴He + 2e⁺ + 2ν
ΔE = ΔMc²: -⁴He + 4p ≃ 28MeV

WEAK

STRONG



WEAK

STRONG

→ why sun has shone for 5 Byr…
→intelligent life developed

The weak force is feeble in the Sun ..

..because 10,000,000K ~ 1 keV << 80 GeV

…this is why the sun has stayed active long enough for us to have evolved and be having this conversation.

→ We exist because m(W) is not zero

→ Mass matters

Questions for lecture 6

How many different spin states has massive particle with spin s?

Does exist an elementary particle with spin 7/2 ?

Does exist a right neutrino in the Standard Model ? How many fundamental particles with spin 3/2 do exist?

What is a difference between fermion and boson?

Spin of boson Z is equal to ..?

t quark is in doublet with what type of quark ?

Write antileptons of the 2nd family

Write beta decay a the fundamental level?

What is electric charge of the photon?

Write all intermediate gauge bosons (together with antibosons) of electromagnetic and weak interactions

Questions for lecture 6

- When the first unification theory has been formulated?
- In what kind of collisions boson Z has been discovered?
- How many Z bosons have been produced at LEP collider?
- What is mass and half width of Z ?
- What is the lifetime of Z boson?
- How do we know that there are only 3 generations of light neutrinos?
- Give the value of the weak coupling for low energies α_W
- The Fermi coupling is equal to ?
- Are weak interactions weak due to large mass of W ?
- Does the sun shine so long due to strong or weak interactions?
- How much energy is emitted in one proton cicle in the Sun?
- At what enery electromagnetic and weak interactions have similar strength?