Particles and Universe

Lecture 6 Spin and weak interaction

Maria Krawczyk, Aleksander F. Żarnecki

Faculty of Physics UW

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 <u>formally</u>)*
- 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 (2017): 15/2 and 6.

★ If mass = 0 only 2 !

SPIN- discovery

Bohr's atom

Emission/absorption spectral lines

Doubling of lines

States in atoms

Bohr, Schrodinger

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

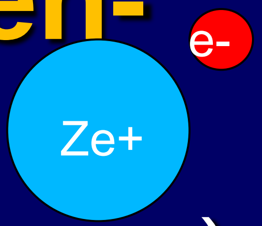
main (energy E) = n
orbital (momentum L) = l (0≤ l ≤n-1; n- states)
magnetic (projection of L) = m (|m| ≤ l)
(-l,-l+1…,l-1,l; 2l+1 states)
(moving el. charge →magnetic moment of the atom)

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]

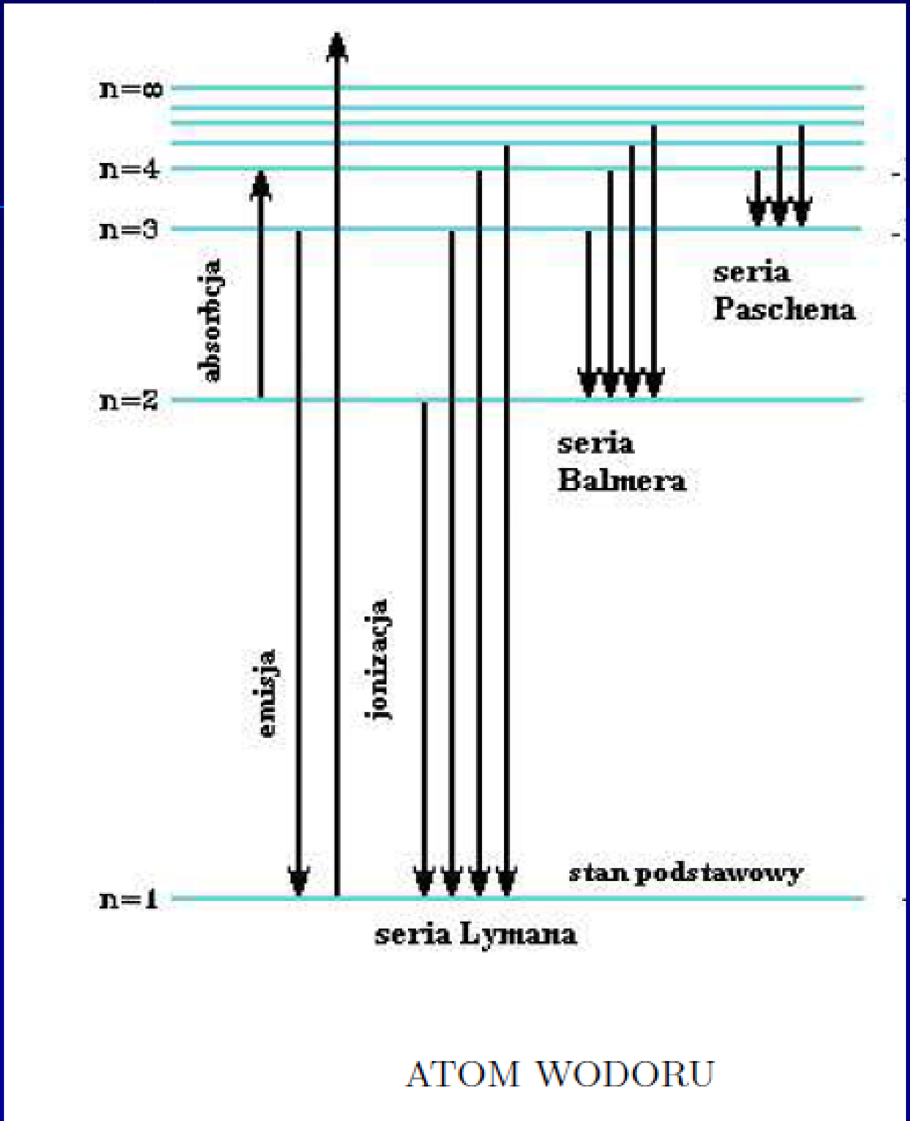
$$V(r) = -\frac{Ze^2}{r}$$

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

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

- 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)



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

For hydrogen atom Z=1
(in atomic units)

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

Balmer 1885 (95)

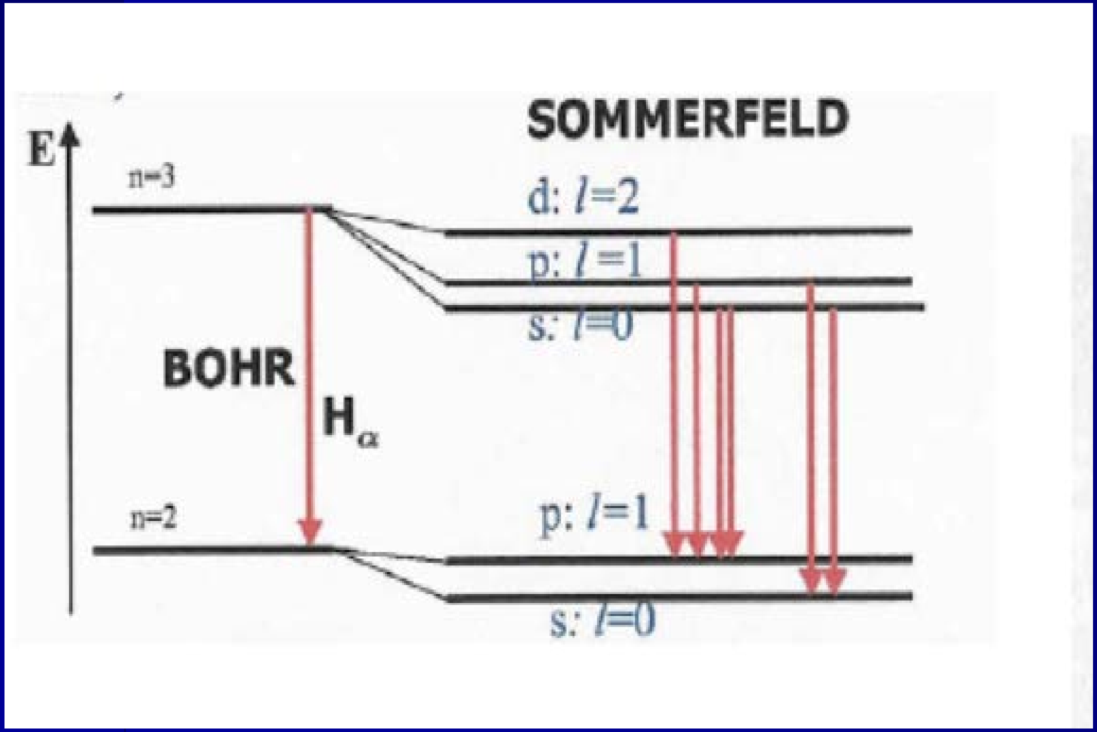
$$\Delta E_{n_1 n_2} = h\nu = h\frac{c}{\lambda}$$

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

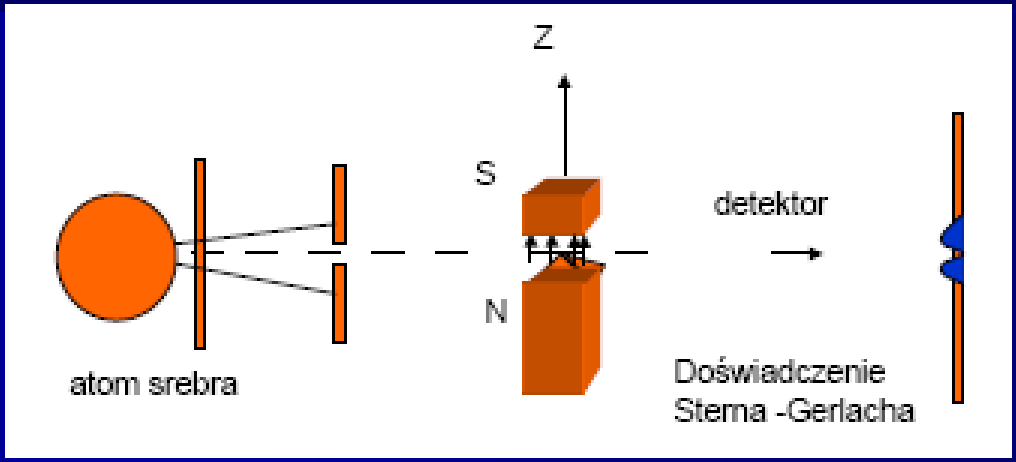
  (observed for many other atoms as well)

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 (el. charge) 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!

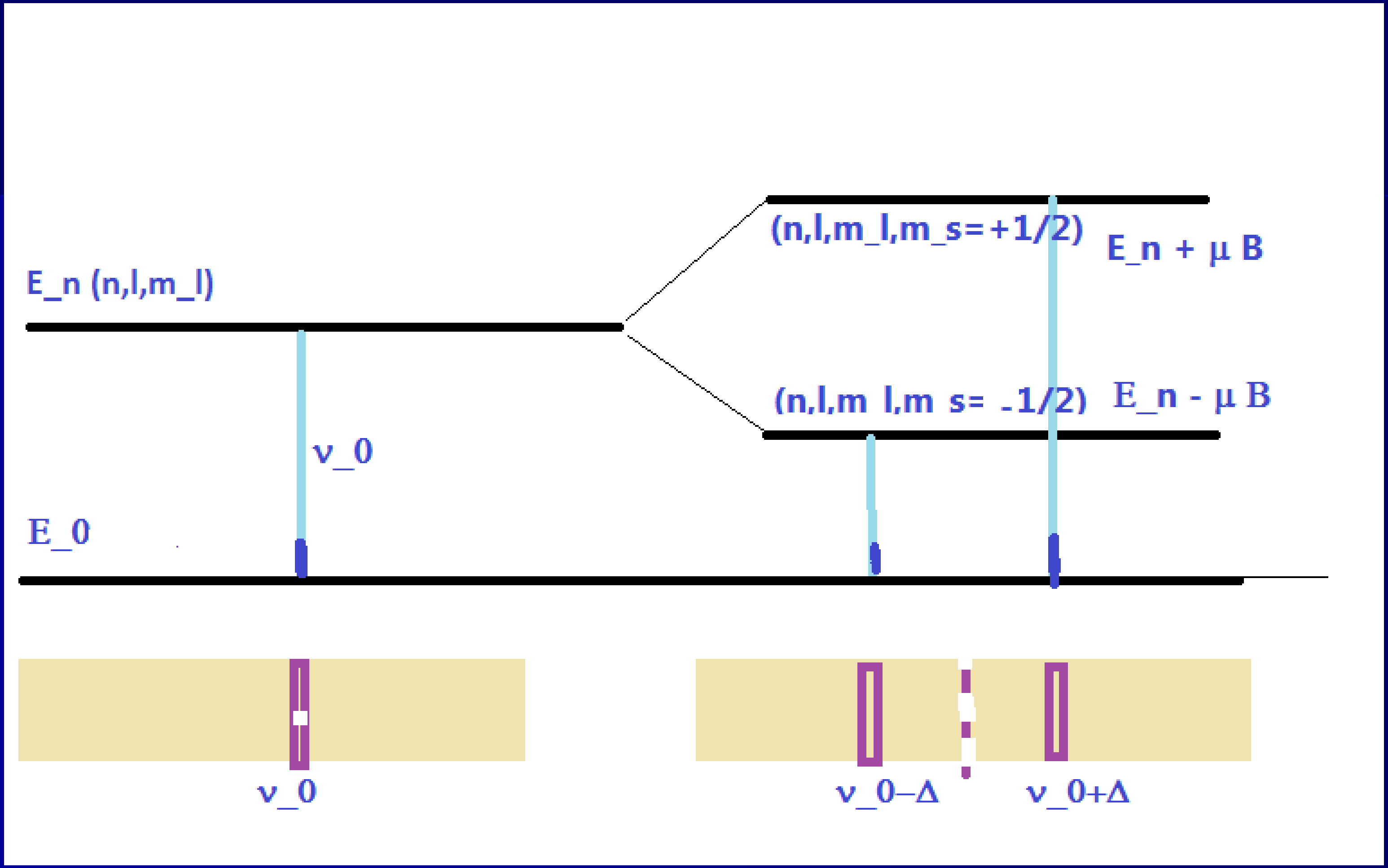
Formally it was possble to describe spectra by
introducing a new quantum number

$$j = l \pm ½$$

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 written 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 was that 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 has 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 ħ

- 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

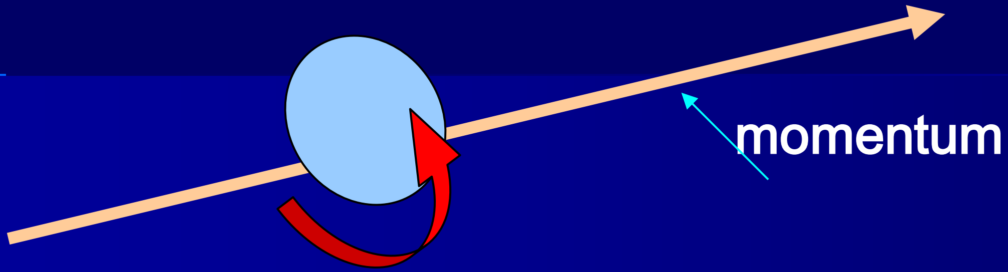
- W^+ antiparticle to W-
- γ , Z – (self antiparticles)
- gluon$_{a\,\bar{b}}$ antiparticle to gluon $_{\bar{a}\,b}$

(a, b – colors)

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

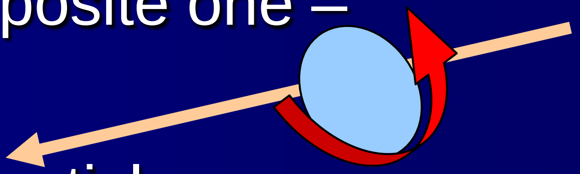
Left and right particles - spin 1/2

- Left (left-handed) particle



reguła korkociągu

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 SM

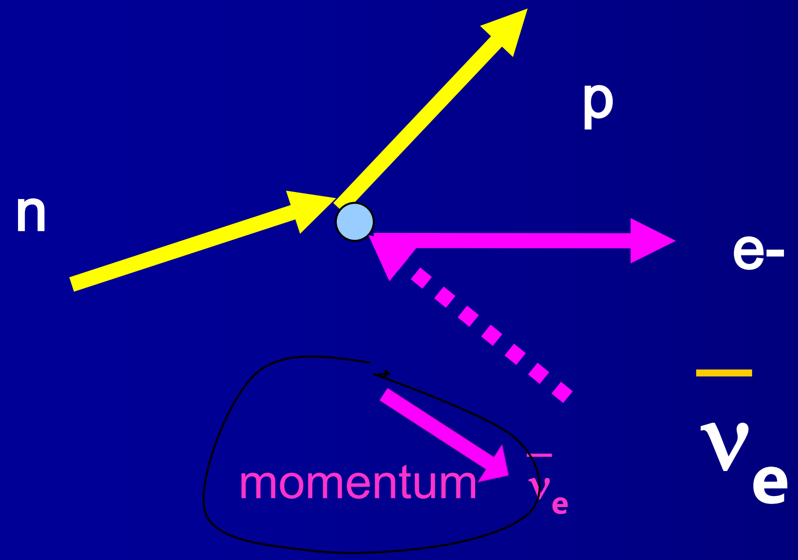
Generations and weak interaction

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

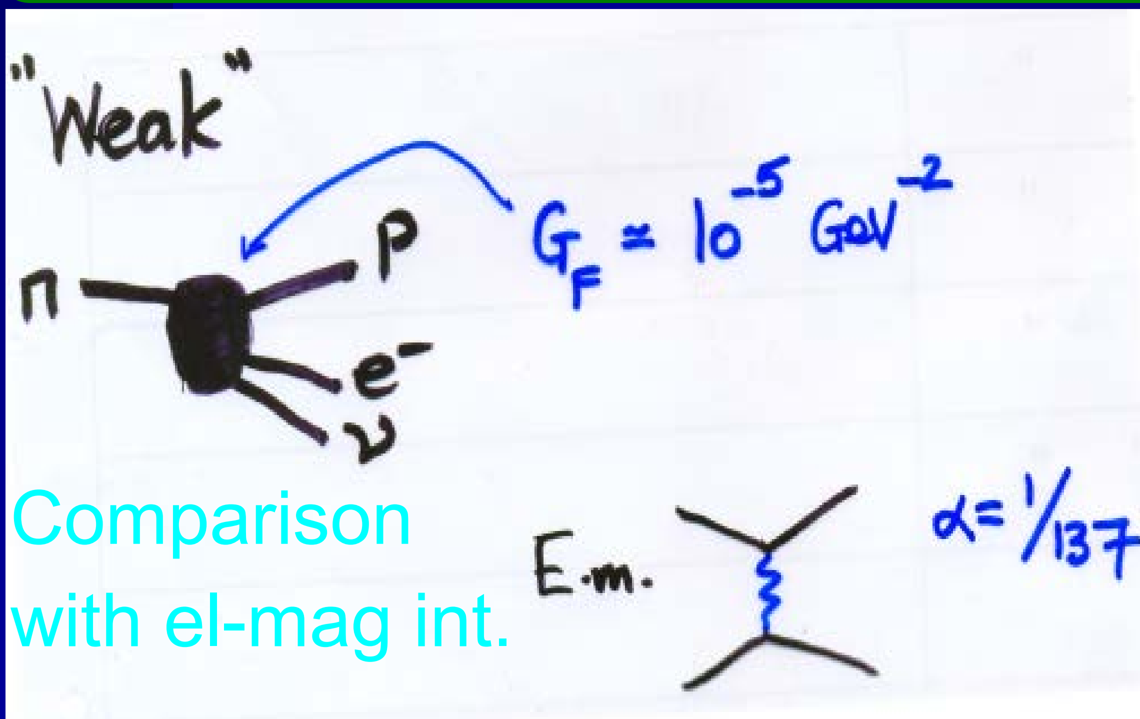
- E. Fermi 1934 → theory (*pointlike-, 4 fermion-, charge current- interaction*) – **weak interaction**

Weak Interaction - Fermi

lectures by F. Close w CERN

Fermi model (1934) for beta decay of neutron

prąd hadronowy x prąd leptonowy



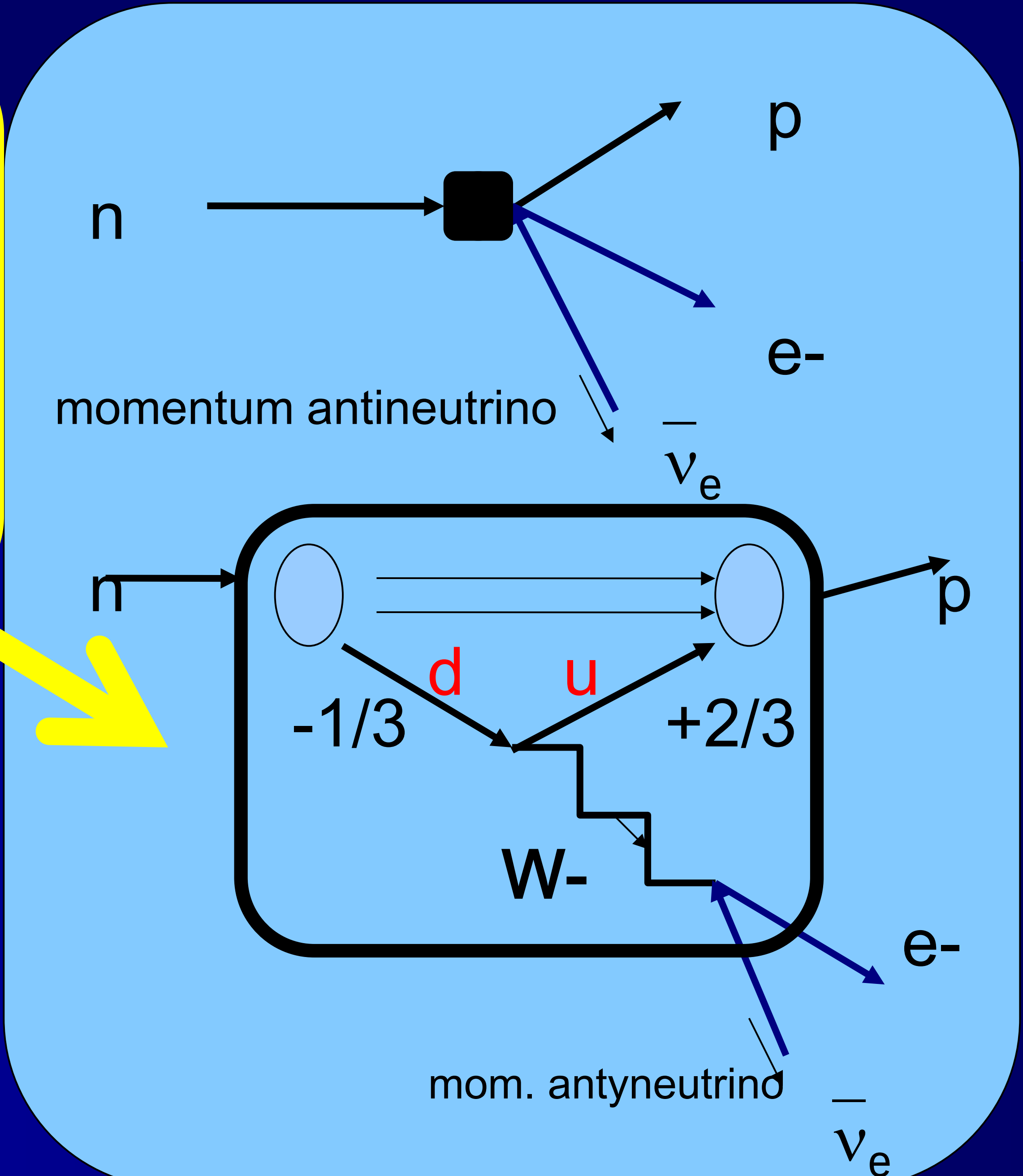
Comparison with el-mag int.

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 interaction

- β decay

vertex d → u W- and W- $\bar{\nu}$ → 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

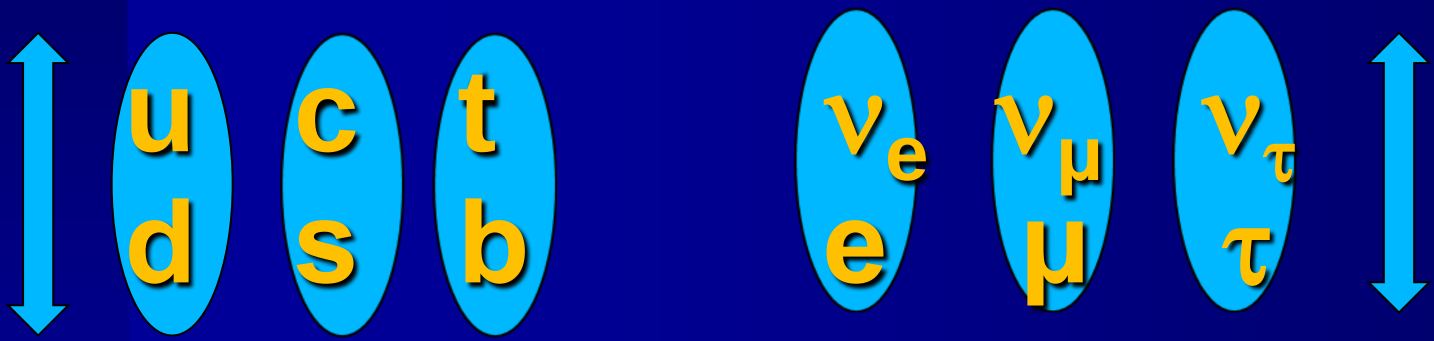
- 1983-4 Collision of protons with antiprotons (experiments UA1, UA2 at CERN) – in quark and antiquarks collision production of bosons W+, W- and Z (discovery).

  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



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

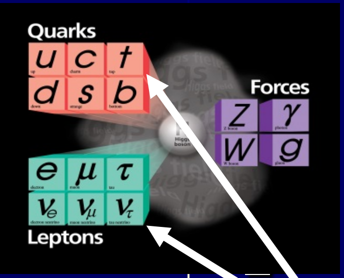
Third generation = two heavy doublets of fermions - spin 1/2

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

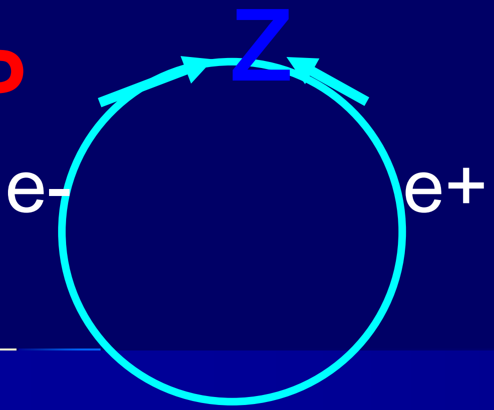


3 generations (families)

- 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+

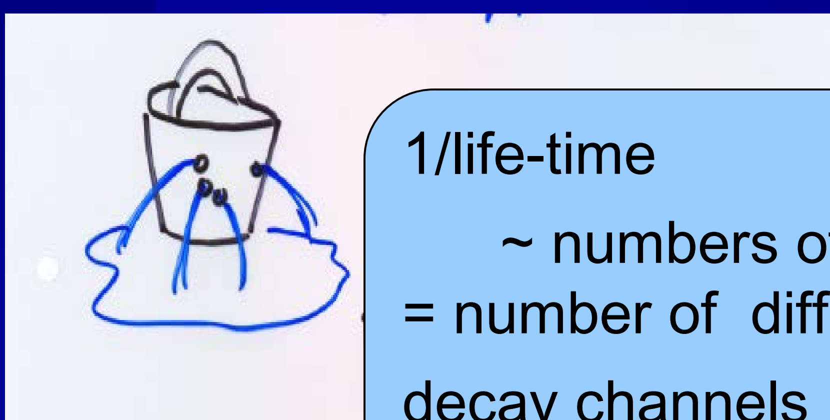
In 1989-1995 energy of collision →

resonant production of Z :

$$E+ + E- = M_Z = 91 \text{ GeV}$$

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

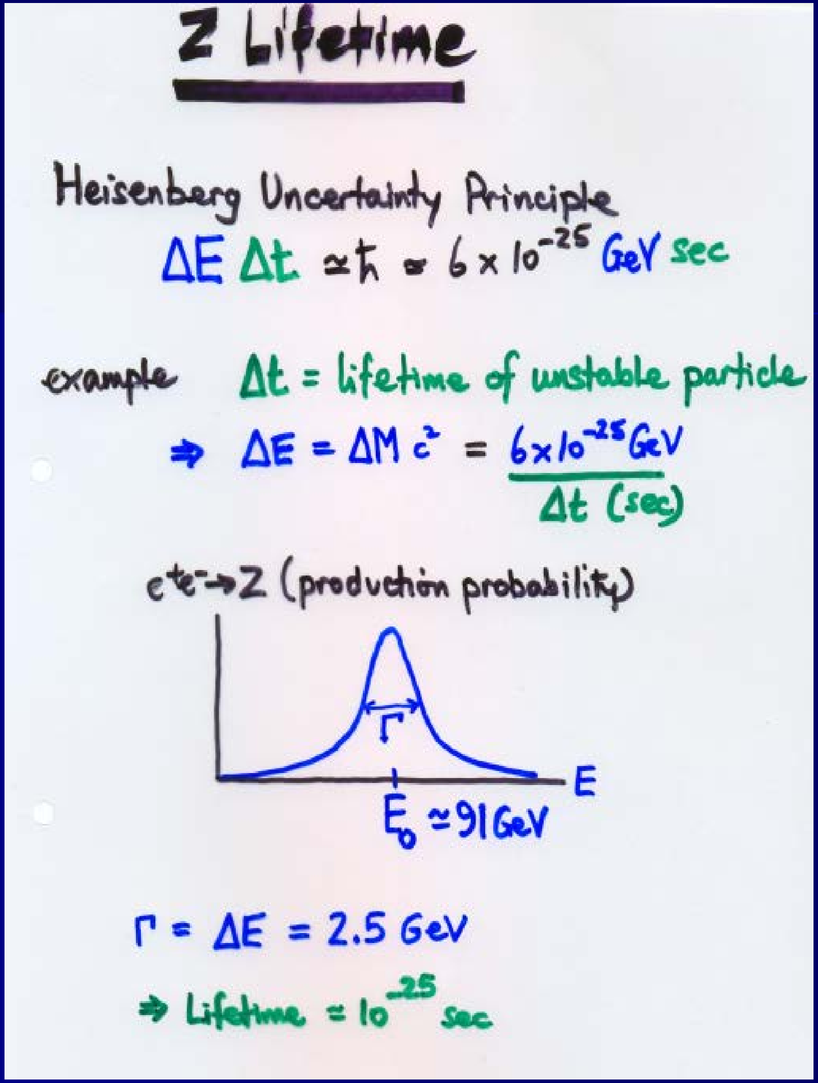
Lifetime of boson Z

Uncertainty principle (Heisenberg)

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

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

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

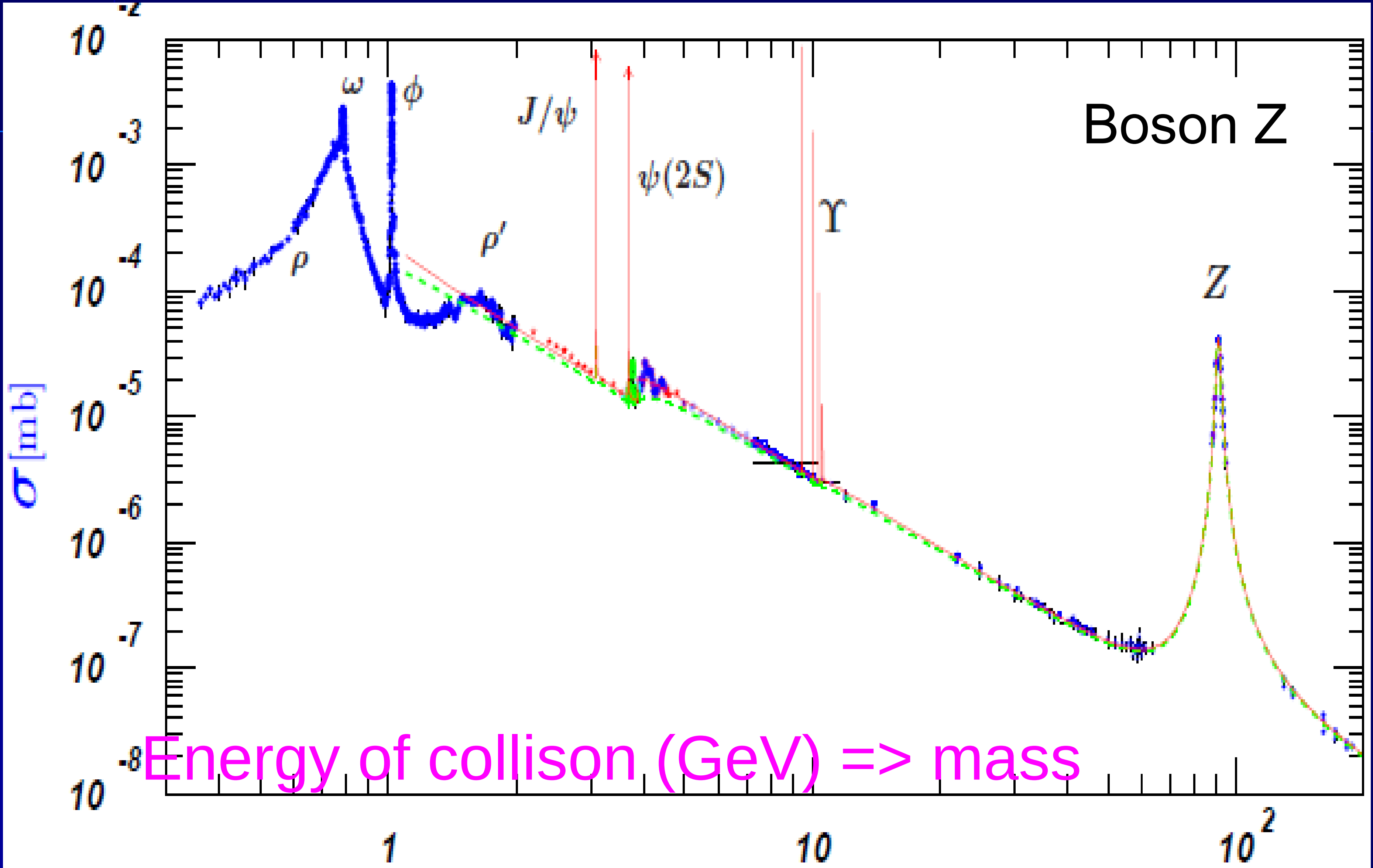


For Z (decay width – half width)

$\Gamma = \Delta E = 2.5$ GeV

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

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

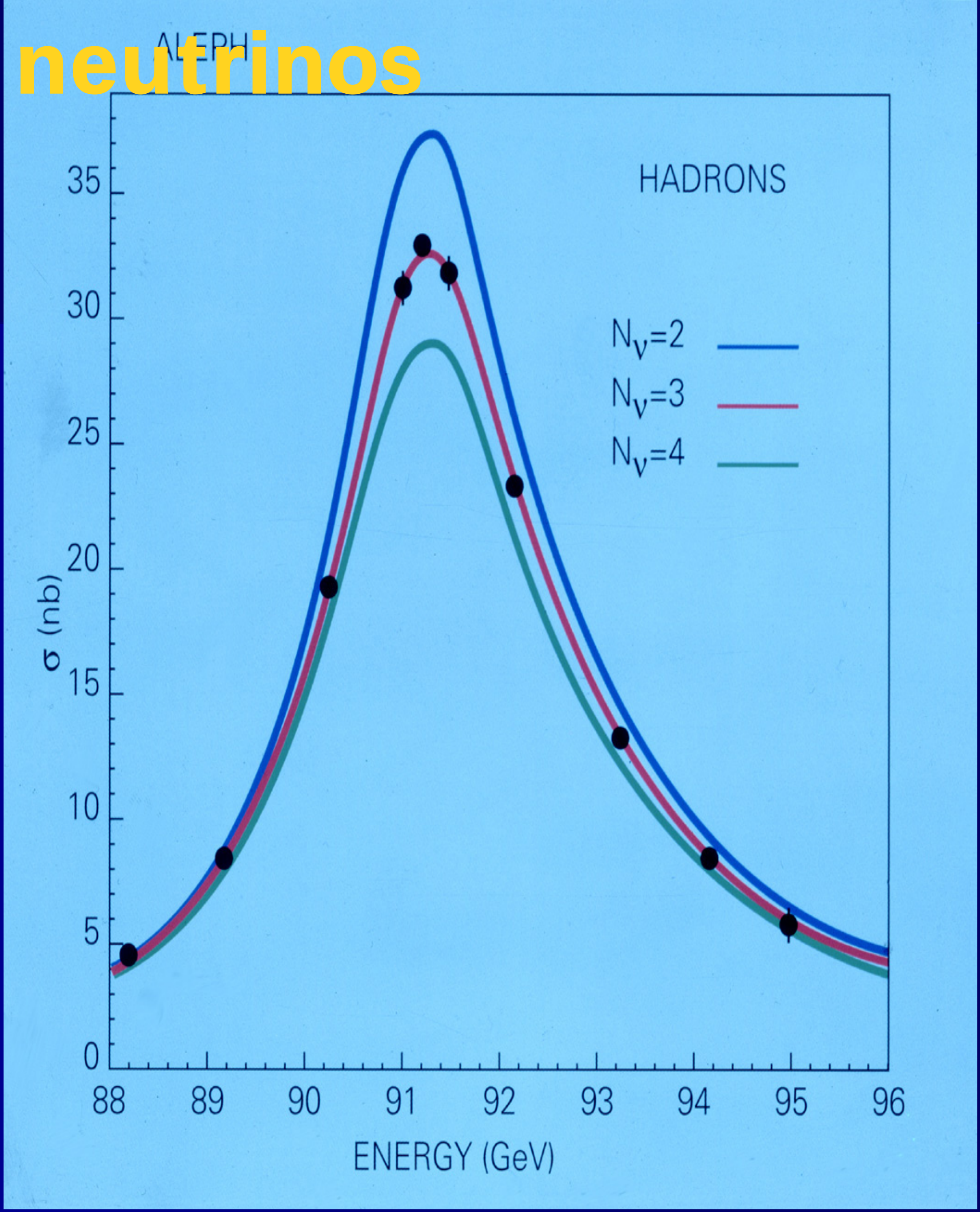


Number of light neutrinos

Probability of Z bosons decaying into hadrons for

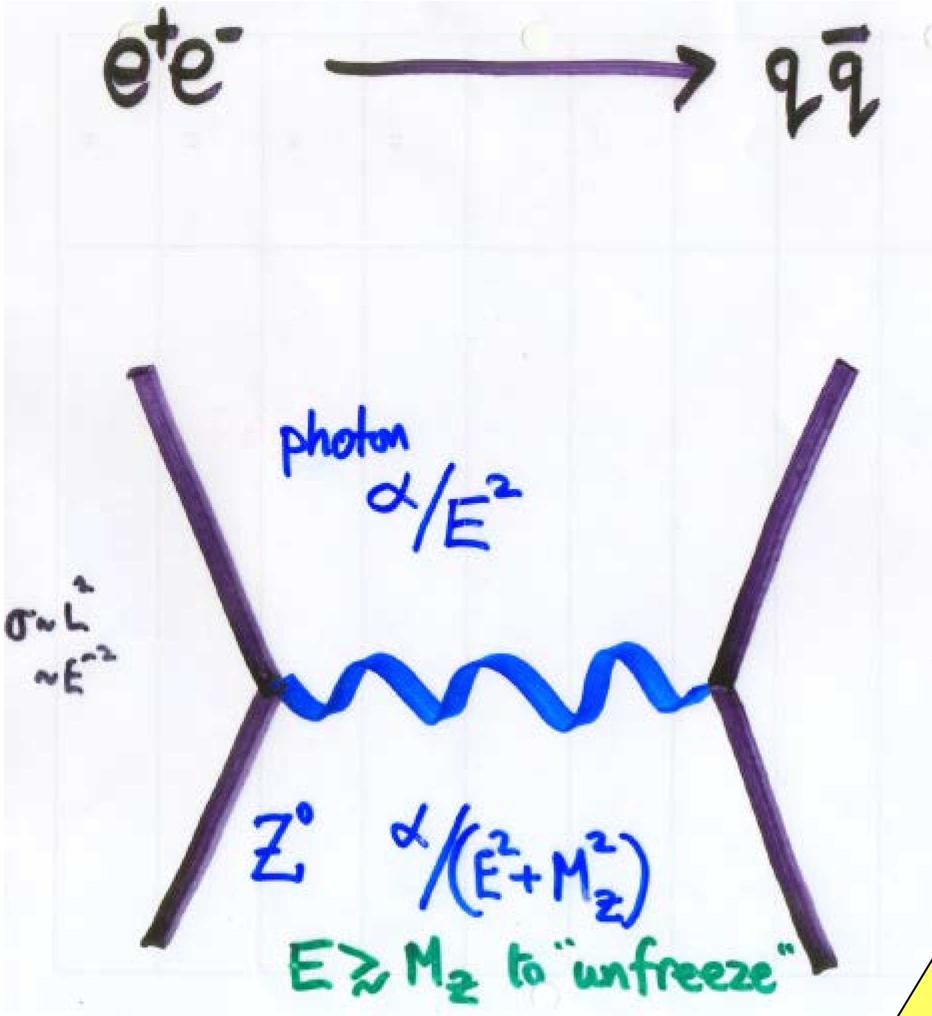
2, 3, 4 pairs of $\nu\ \bar{\nu}$

(light neutrinos - with masses below 45 GeV)



Agreement for $N_\nu = 3$!

Weakness of weak interaction

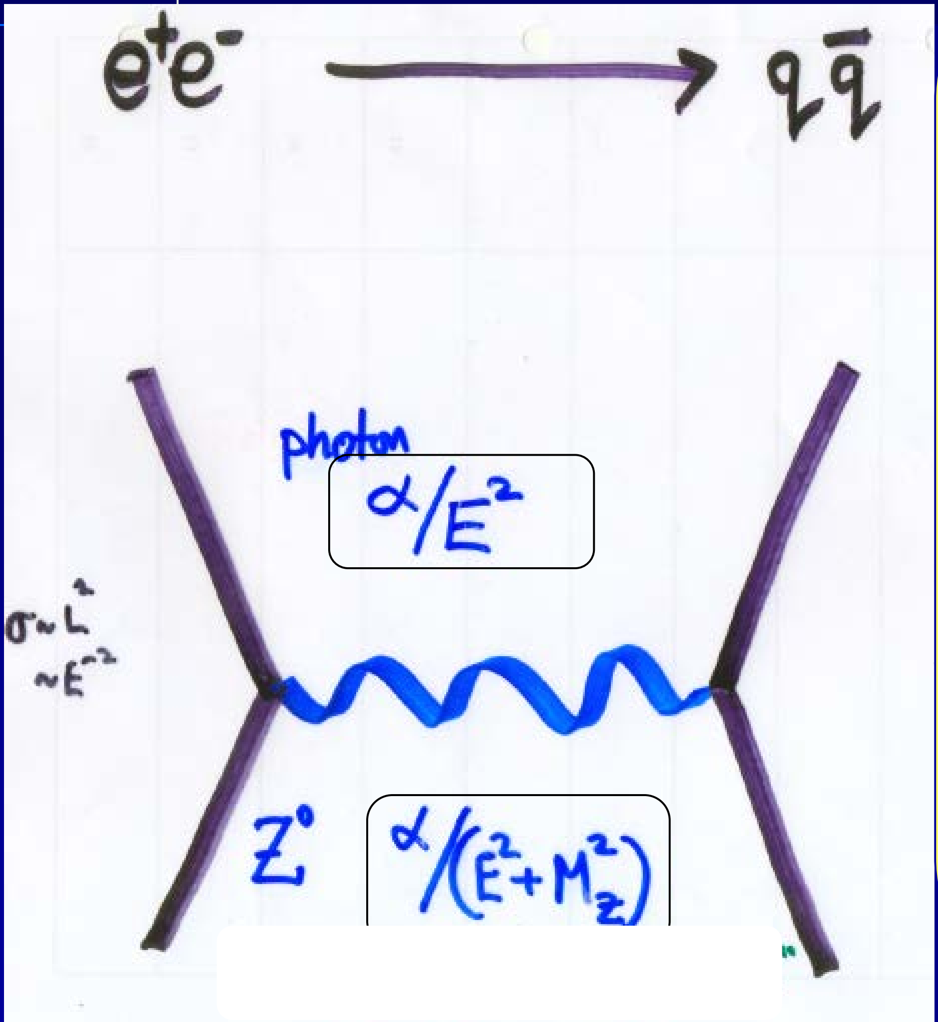


Feynman rules:

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-

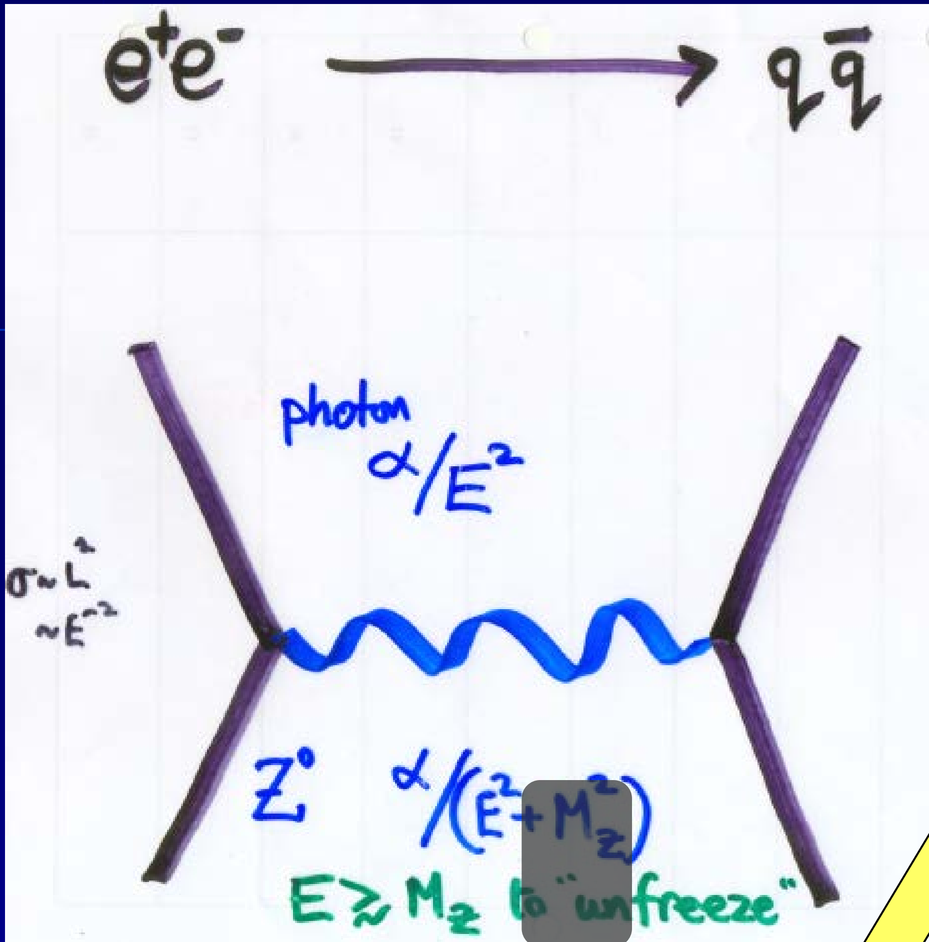


Feynman rules (probability of process)

Energy E curried by a virtual particle

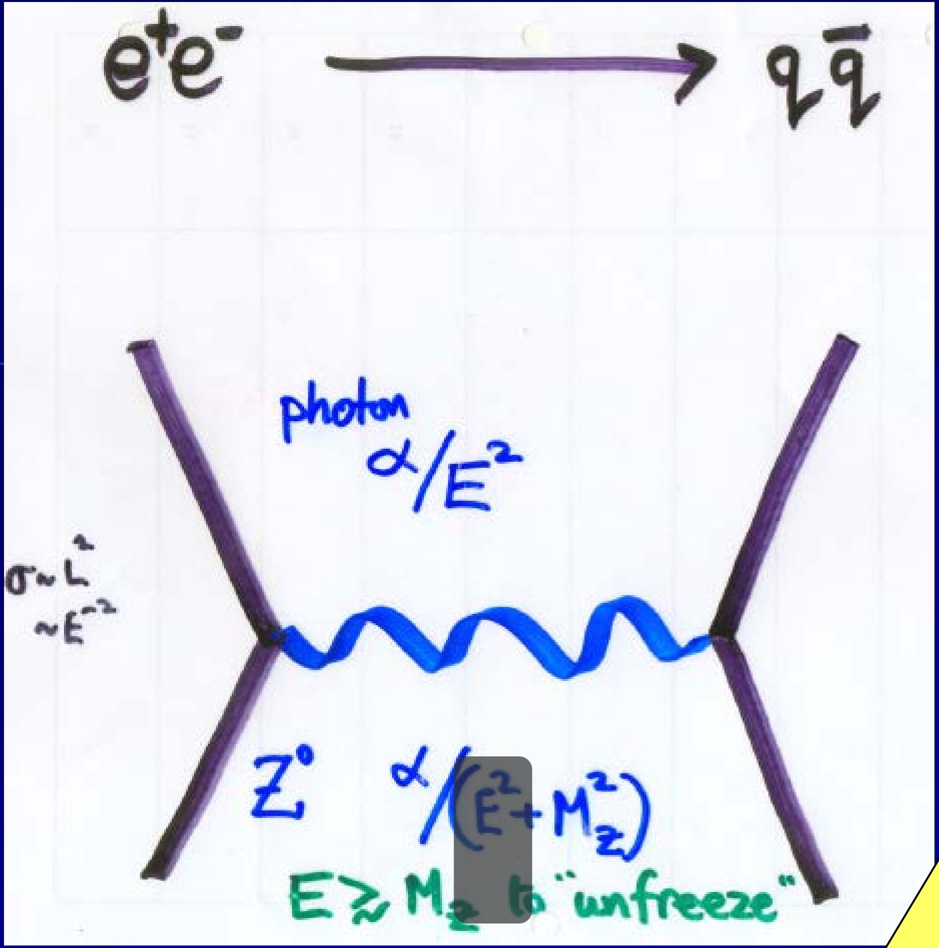
→ factor $1/(E^2+M^2)$

M- mass of virtual particle



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

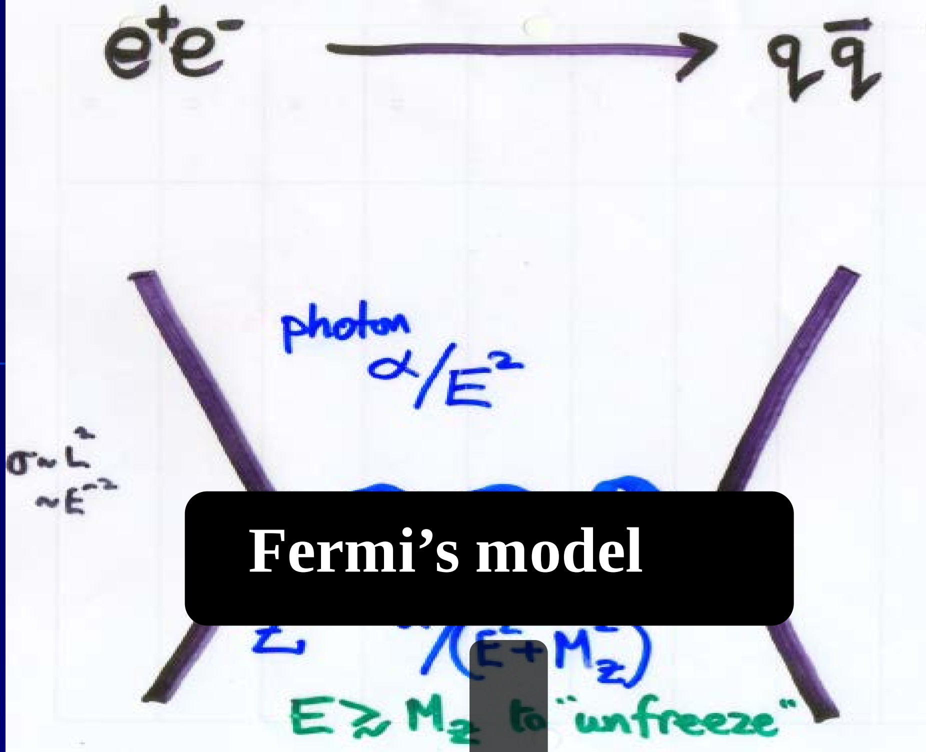
For E >> M , so approximately factor $1/E^2$…as for photon



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

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

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

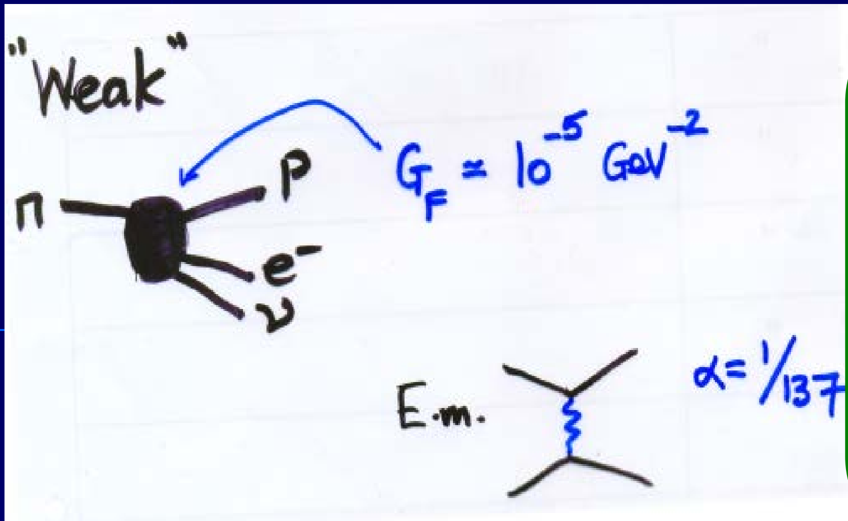


Fermi's model

Dla $E \ll M$ 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!

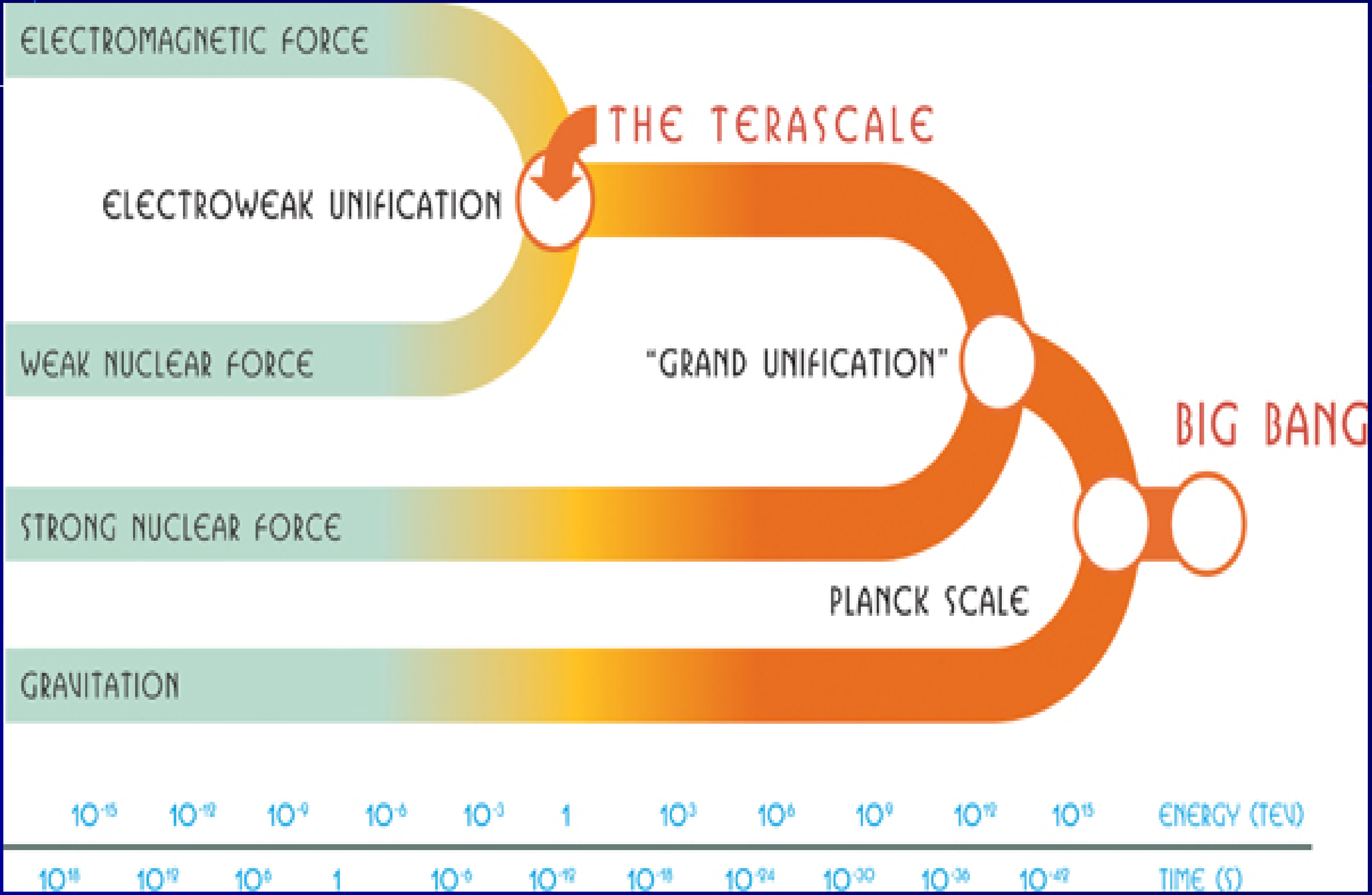
Mass W+/- = 80 GeV, Z = 91 GeV

the only massive agent of interaction

Couplings constants are running (due to quantum corrections)

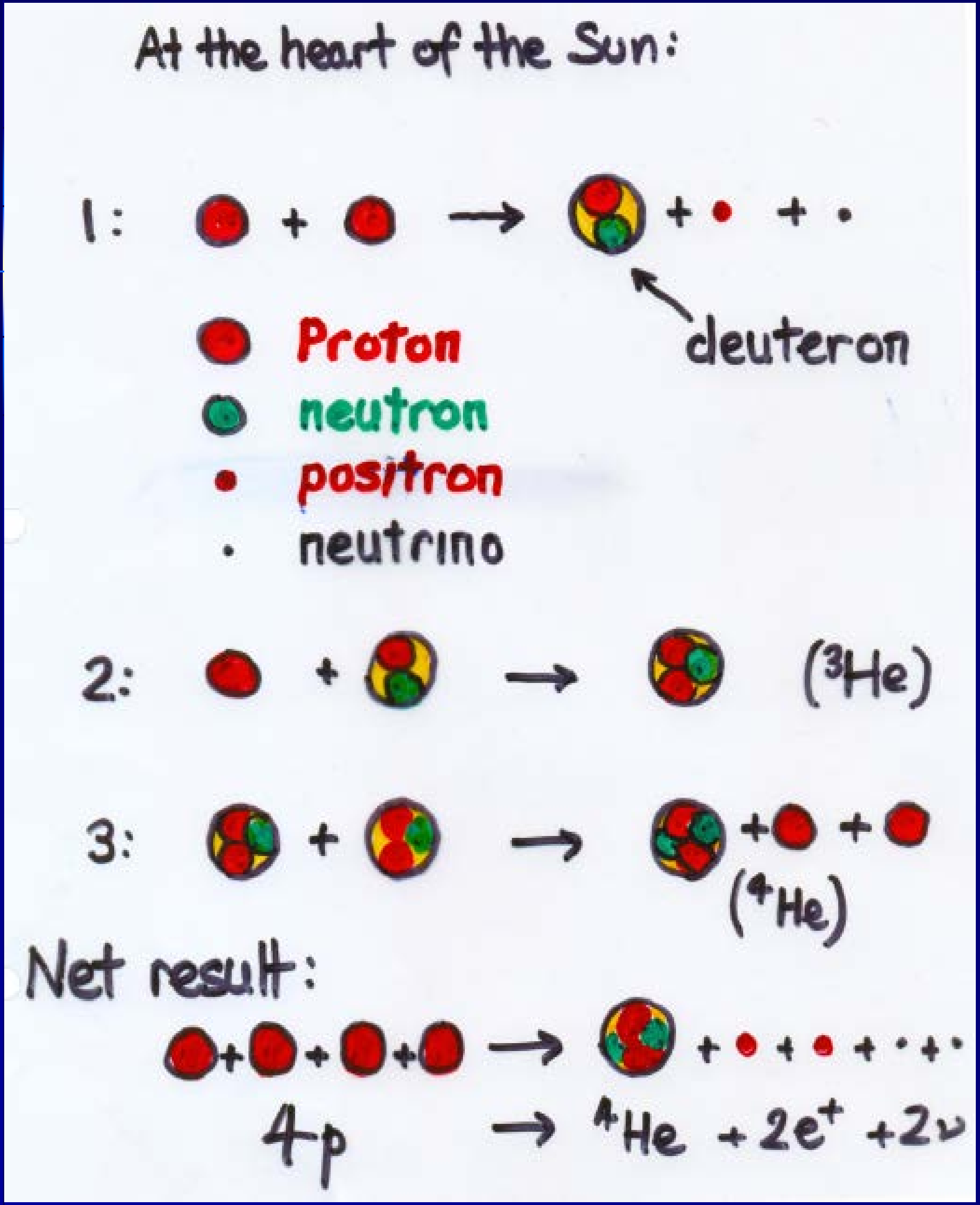
electroweak (unification of el-mag. and weak) – *more later…*

UNIFICATION



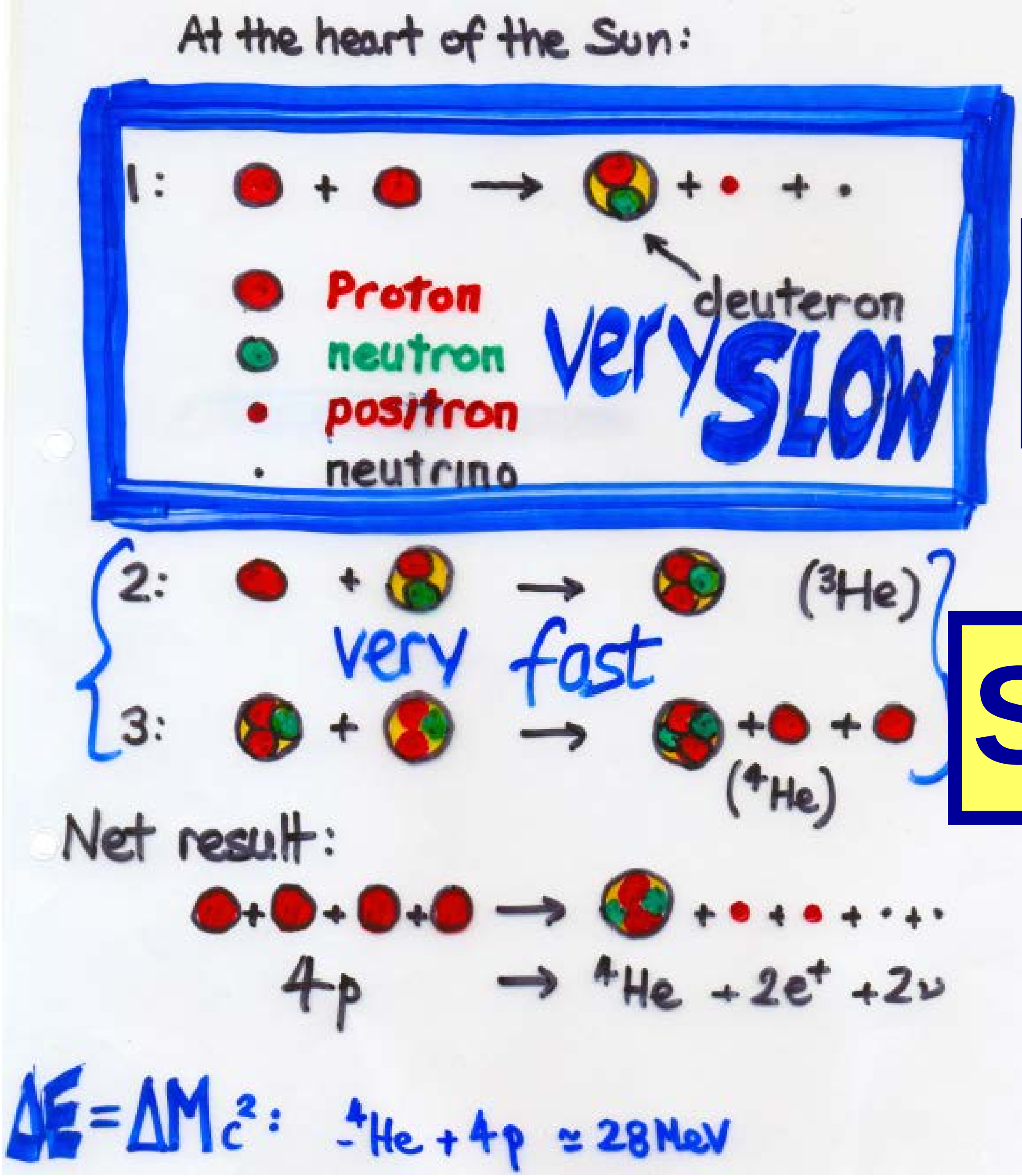
44

W+, W- BOSONS



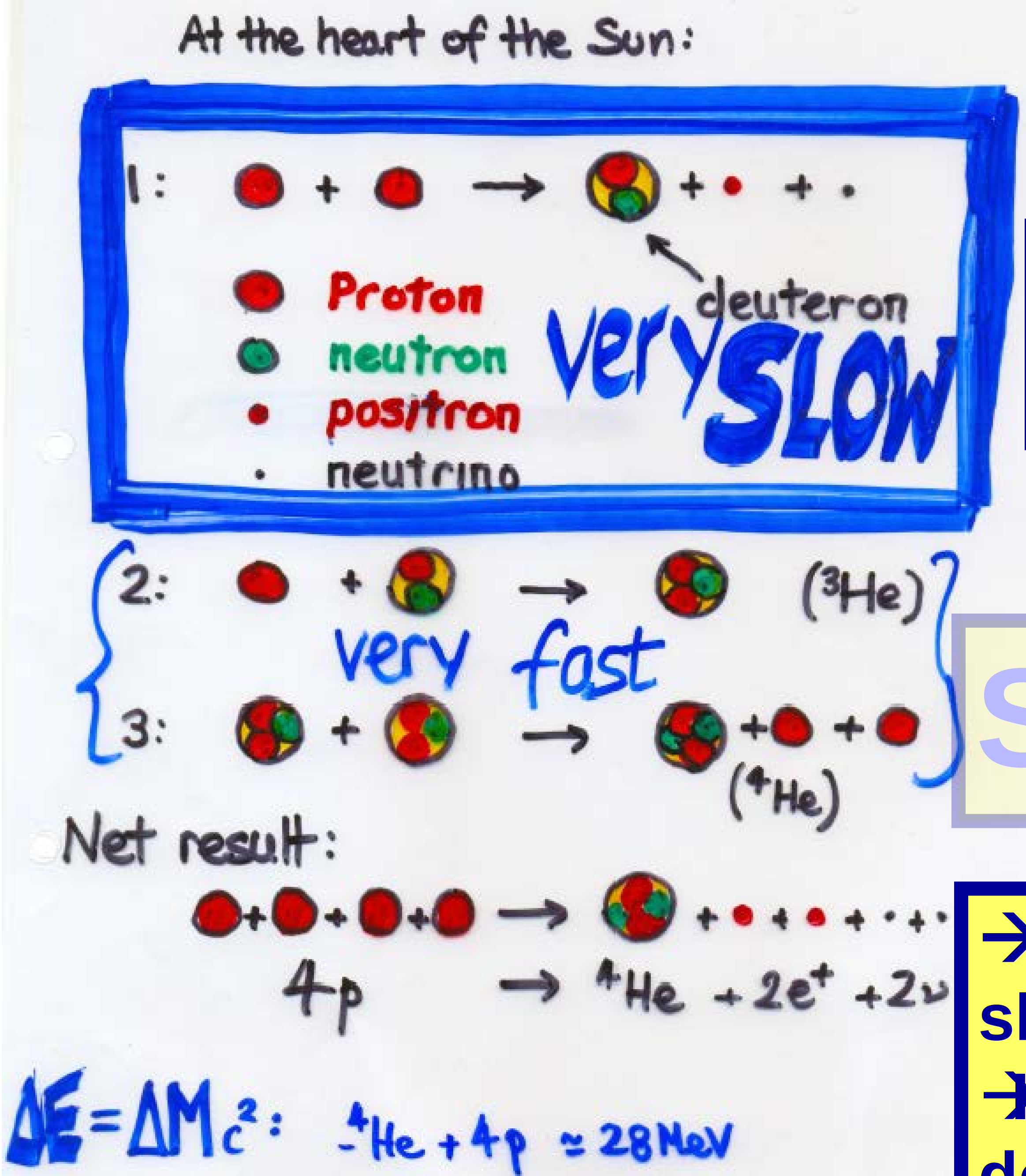
At the heart of the Sun:
1:
deuteron
Proton
neutron
positron
neutrino
2:
(³He)
3:
(⁴He)
Net result:
4p → ⁴He + 2e⁺ + 2ν

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:
$4p \rightarrow {}^4He + 2e^+ + 2\nu$
$\Delta E = \Delta M c^2$: $-{}^4He + 4p \simeq 28 MeV$

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 energy electromagnetic and weak interactions have similar strength?