Particles and Universe

Lecture 7 Coupling constants

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I. Comparison of coupling constants

II. Feynman diagrams

III. Running coupling constants, asymptotic freedom

Interactions

In macro- and micro scales:

- gravitation – act between all massive particles, only attraction, responsible for Sun system, large astronomical objects, etc.

- electromagnetism (e-m, el-mag) – electric charge of both signs, attraction and repulsion, atoms ...

In microworld in addition interactions:

- strong (nuclear) - bounding nucleons in nuclei (pions exchange) range 10^{-15} m

  strong fundamental (color) - between quarks (gluons exchange), range 10^{-15} m

-- weak (nuclear), eg. neutron decay, range smaller that for strong (pointlike interaction)

weak fundamental between quarks and leptons (exchange of gauge boson W/Z), range 10^{-18} m

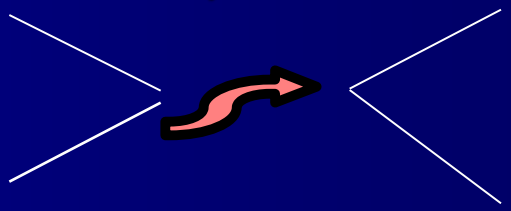
Range of interactions

$c = \hbar = 1$

- Interaction in microworld = emission and absorption of bosons (photon, W/Z, gluons..) → exchange of particles

- Range (Heisenberg, Yukawa) is related to the mass of exchanged particle (carrier of interactions)

$$x \sim 1/M$$



- gravitation and el-mag infinite range → graviton mass? photon mass = 0
- color (strong) int. : range ~ proton radius 10^{-15} m (although mass of gluons zero, confinement!)
- weak int. range 10^{-18} m, related to the mass of bosons W/Z ~80-90 GeV

Strenght of interactions

- gravitation and el-mag are very different - gravitation very weak (gravitation between two protons 10^{36} times weaker than el-mag interaction)
- Strenght's hierarchy at low* energies:

strong> electromagn.> weak > gravitation

** low energies: 1 GeV up to 100 GeV*

in the Standard Model – no gravitation!

- Parameter of strenght of elementary action

→ coupling constant

Coupling constants

Strenght of elementary act of interaction = coupling constant

el-m: $e^- \rightarrow e^- \gamma$, $e^- \gamma \rightarrow e^-$ — e (el. charge)

weak fund.: — g ('weak' charge)

$e^- \rightarrow \nu_e W^-$, $\nu_e \rightarrow e^- W^+$

$d \rightarrow u W^-$, $t \rightarrow b W^+$

$d \rightarrow d Z$, $Z \rightarrow \nu \bar{\nu}$

strong fund., color: — g_s ('strong' charge, color charge)

$u_R \rightarrow u_G + g_{R,\text{anty G}}$

Probability of elementary processes*,**

el-m — $\alpha = \alpha_{el} = e^2/4\pi \simeq 1/137$

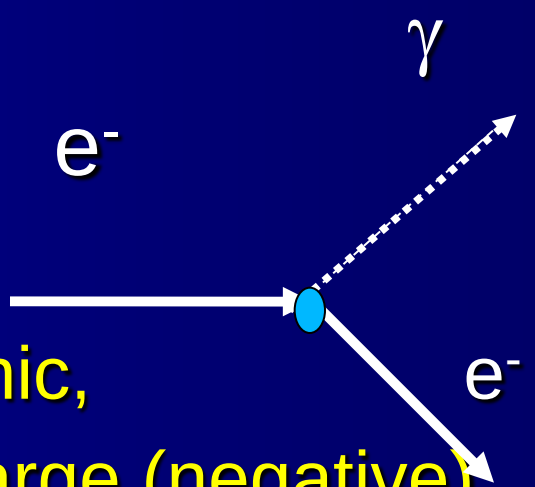
weak fund. — $\alpha_w = g^2/4\pi \simeq 1/32$

strong fund, color — $\alpha_s = g_s^2/4\pi \simeq 1$

** called coupling constant as well,** for energy ~1 GeV*

Feynman diagrams

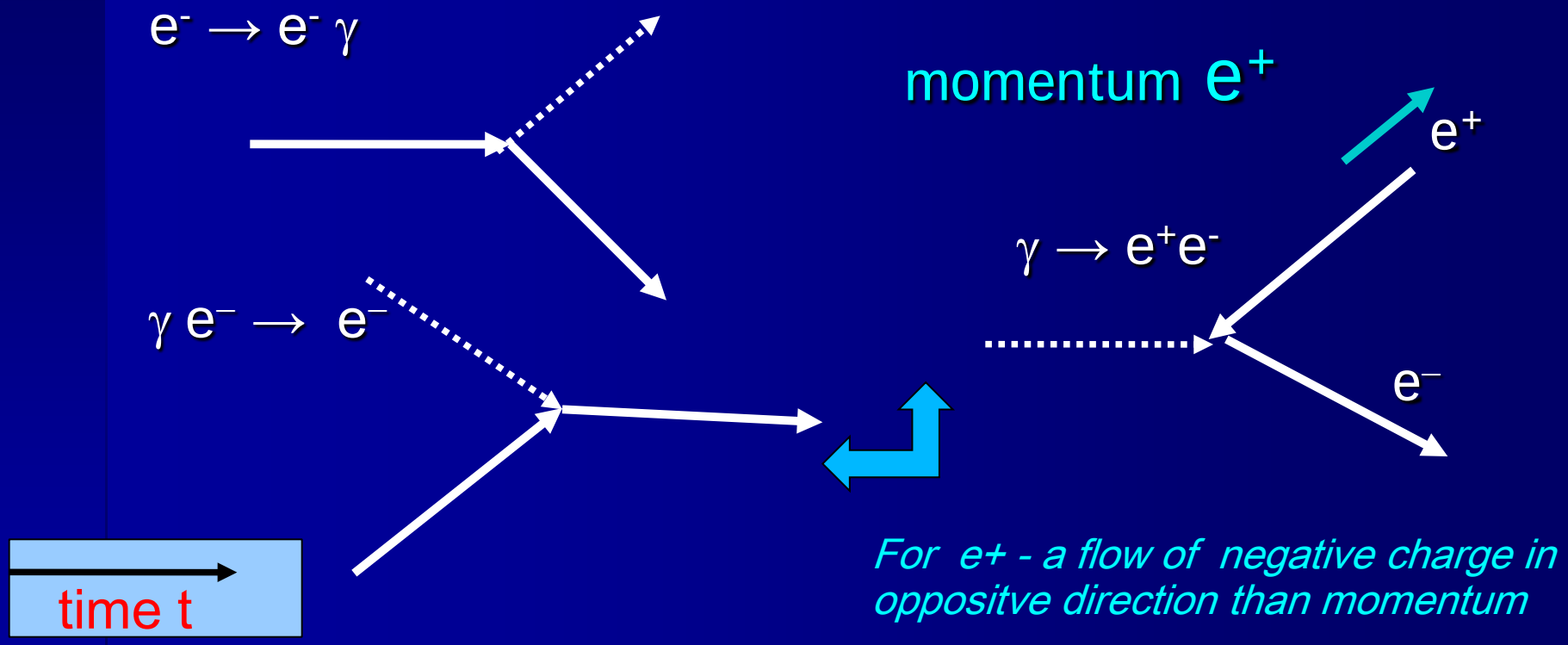
Feynman diagrams –
particles are represented by different lines,
act of elementary interaction - by a vertex
eg. emission of the photon by electron



Arrows on a continous line (fermionic, here for e^-) → flow of electric charge (negative) and momentum, while arrow on the photonic line (here dashed) → only momentum

Feynman diagrams for crossing processes

Crossing processes involving e e γ



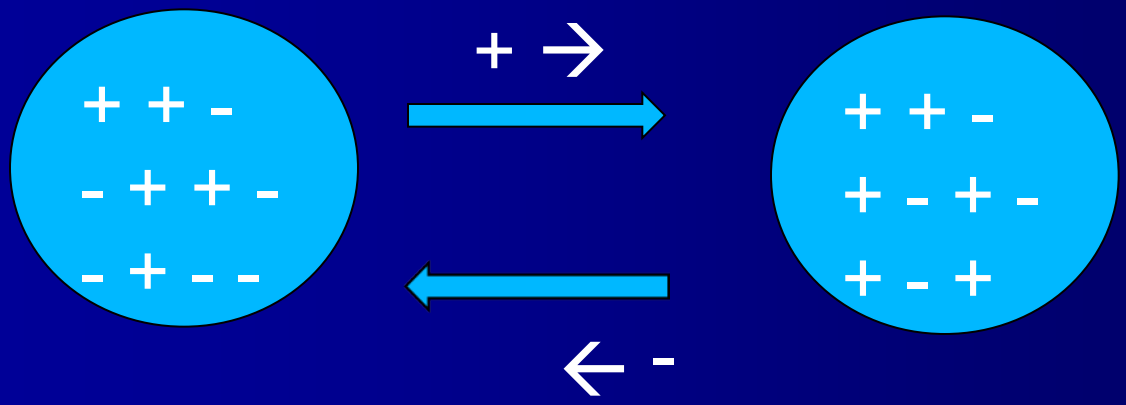
For e+ - a flow of negative charge in oppositve direction than momentum

Flow of charges

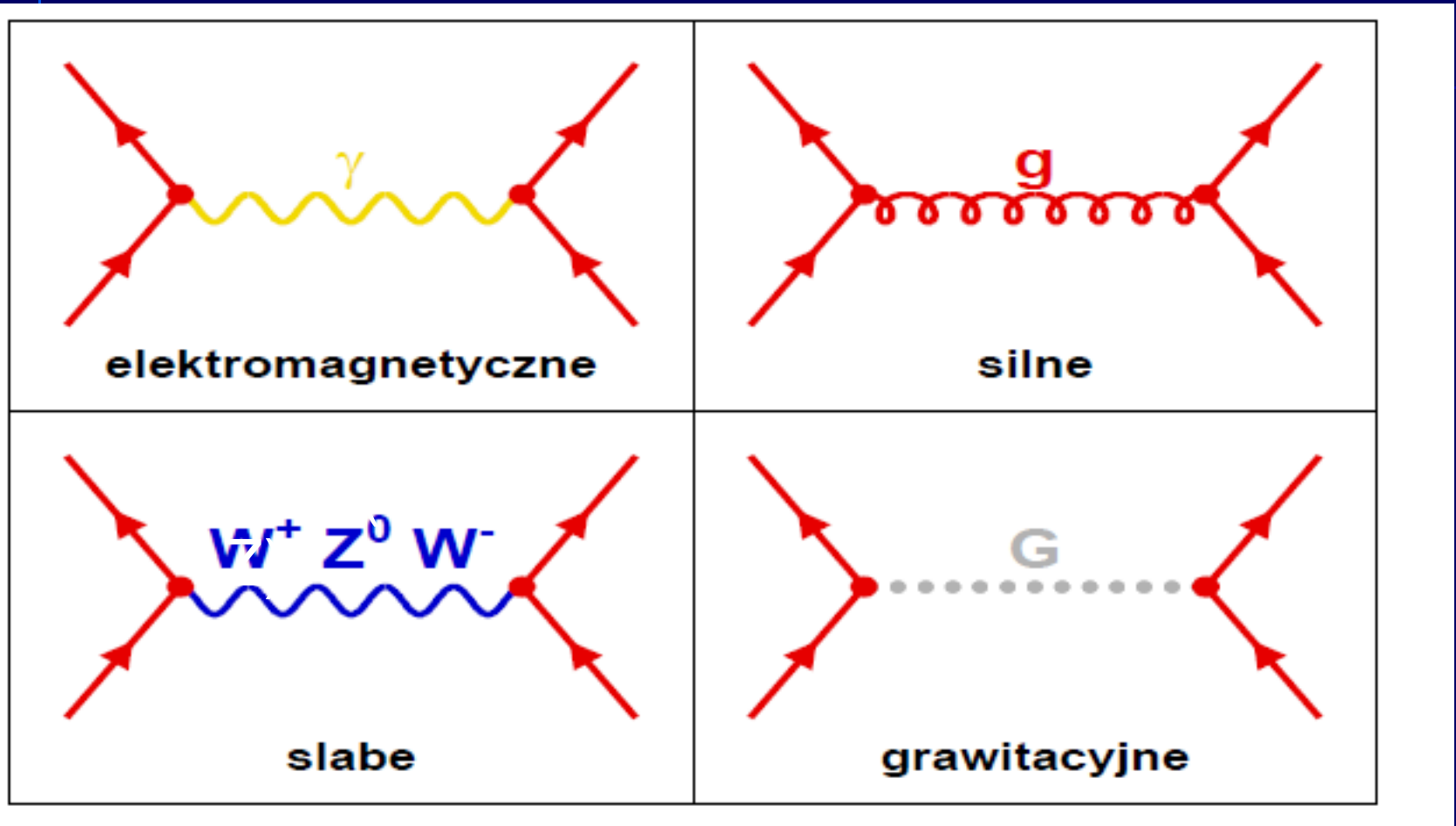
Charge of a system

$N_- = n_- - n_+$

$N_+ = n_+ - n_-$



Feynman diagrams



Electromagnetism and gravity

- Why gravity, so weak compared to electromagnetism was known first?
- Gravity only added while el-magn interaction canceled out for big

- The force for electron (with mass m) and proton (mass M) in the hydrogen atom H

$$F_{el} = e^2/r^2 \quad F_{gr} = GMm/r^2$$

- Ratio $GMm/e^2 = 10^{-40}$

Fundamental constants

Relation to physical phenomena

c – relativistic physics

velocity of light

ħ – quantum physics

Planck constant $\hbar = h/2\pi$

G – gravitation

gravitational constant (Newton)

Subtle coupling constant

Electric charge e

$\alpha \equiv e^2/4\pi\hbar c \sim 1/137$ – a subtle coupling constant, introduced to describe interaction of electrons with photons by Sommerfeld in 1916 (*in subtle emission spectrum of hydrogen and silver*)

→ important in relativistic (c), quantum (ħ) theory of electric charge (e)

quantum electrodynamics (funded in 20-30 XX),

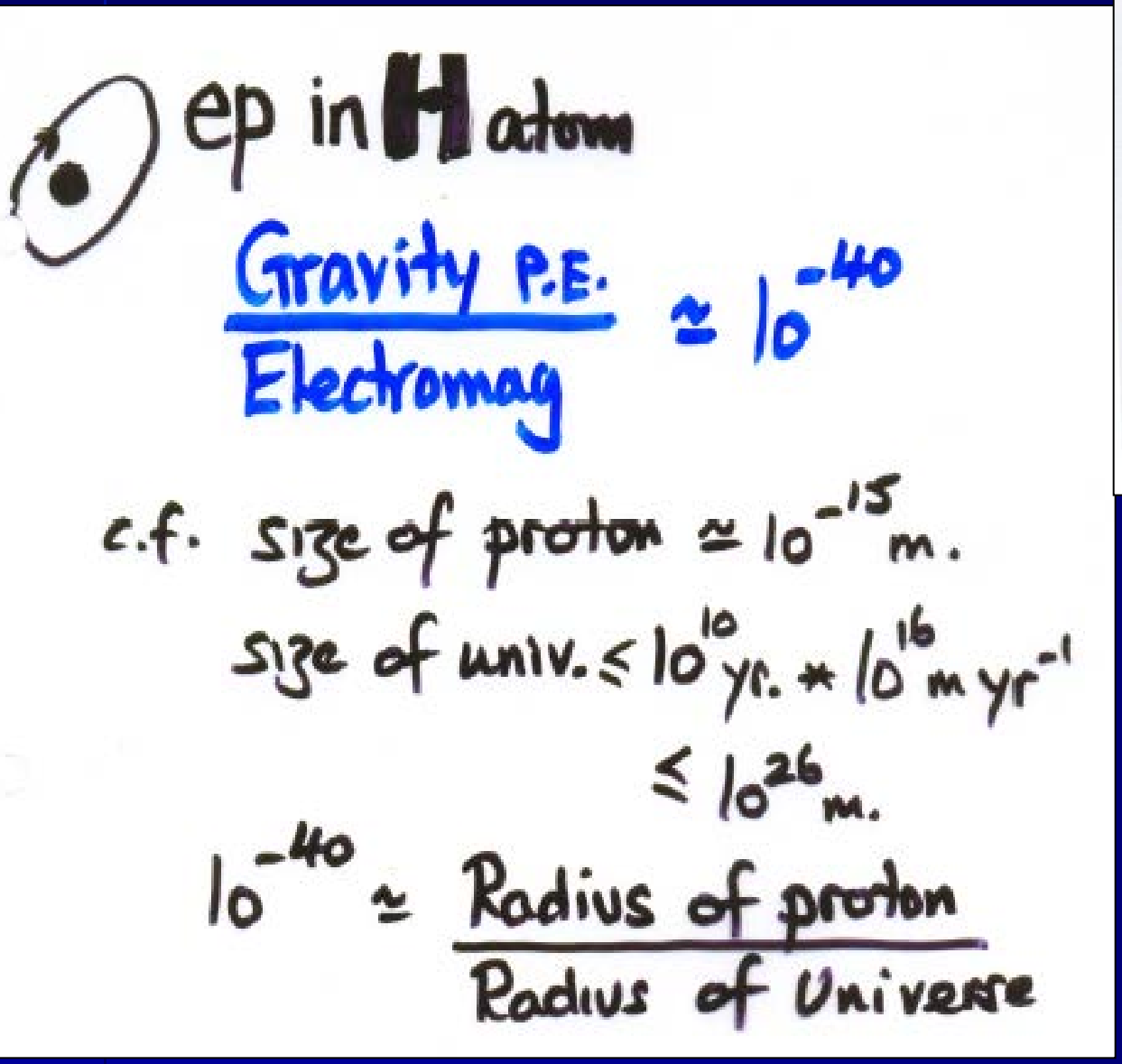
where α (or α_{em}, α_{el}) – measures „strenght" of el-mag interaction of elecrons and photons (→ coupling constant)

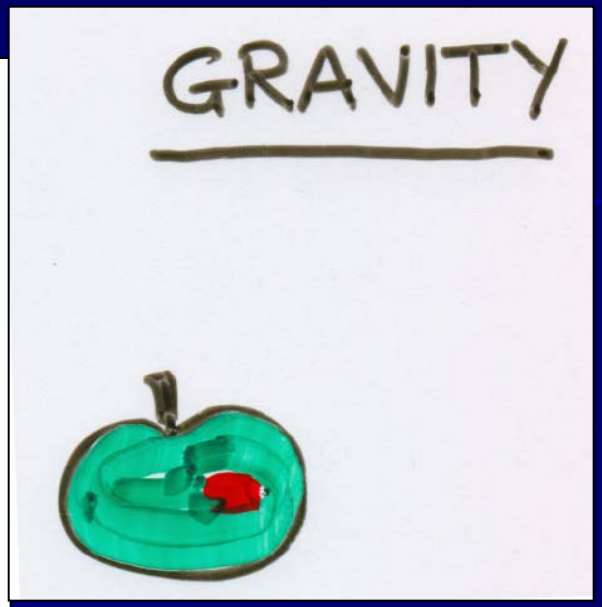
Note: formally we often take ħc =1 , eg.. on page 5 in definition of various coupling constants

Gravitation – PLANCK scales

- We neclect gravitation for individual particles at current energies
- When gravitation important in microworld?
  From G, h and c we can construct quantity
  $(\hbar c/G)^{1/2}$ - Planck mass
- Planck's scales :
  Planck's mass (energy) = 10^{19} GeV
  Planck's lenght = 10^{-35} m
- For these scales → relativistic quantum gravity. We are still looking for such theory...

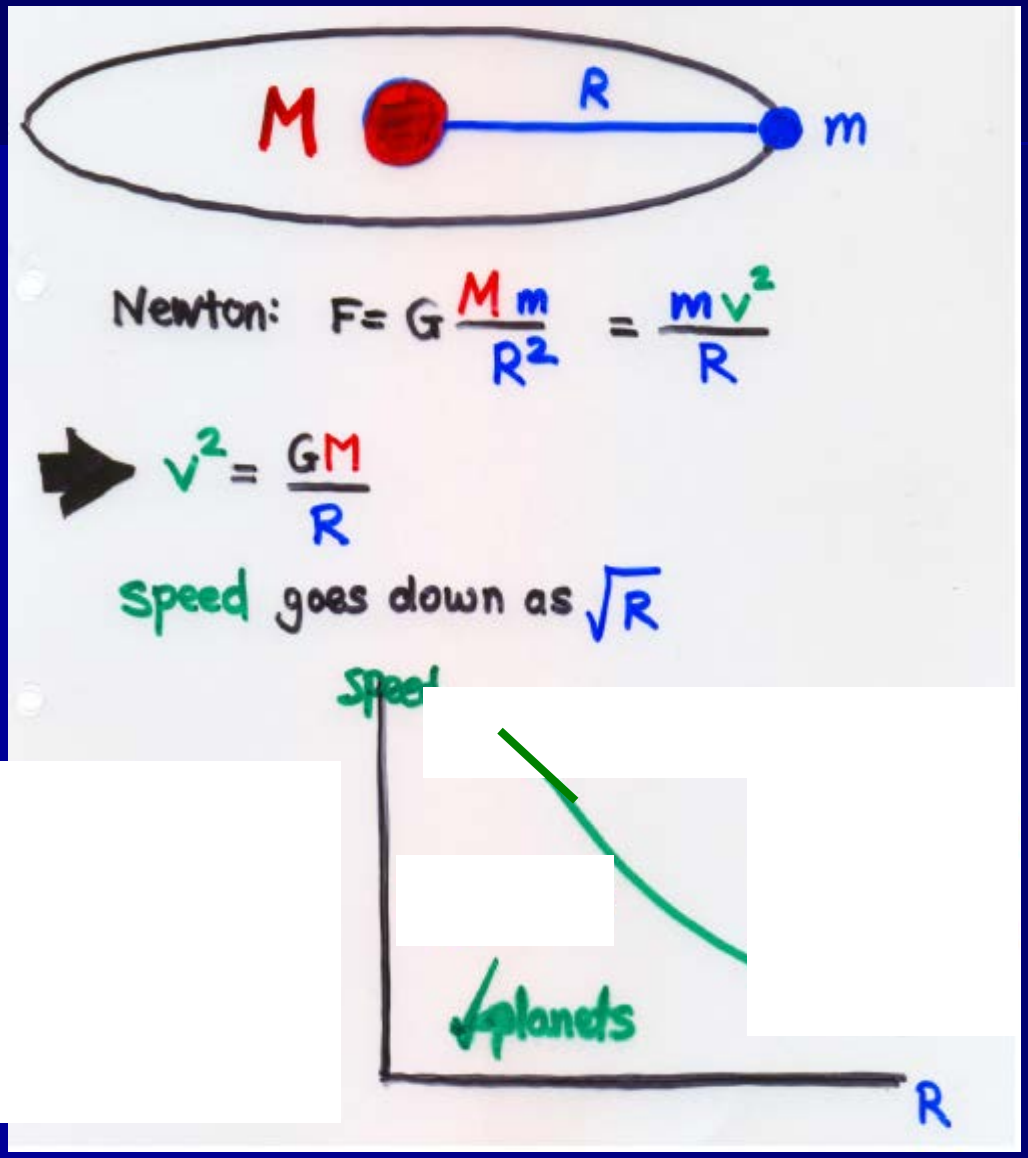
Gravity contra electromagnetism





Lecture by
F. Close

Velocity of object with mass m in the movement due to the gravitational attraction by mass M

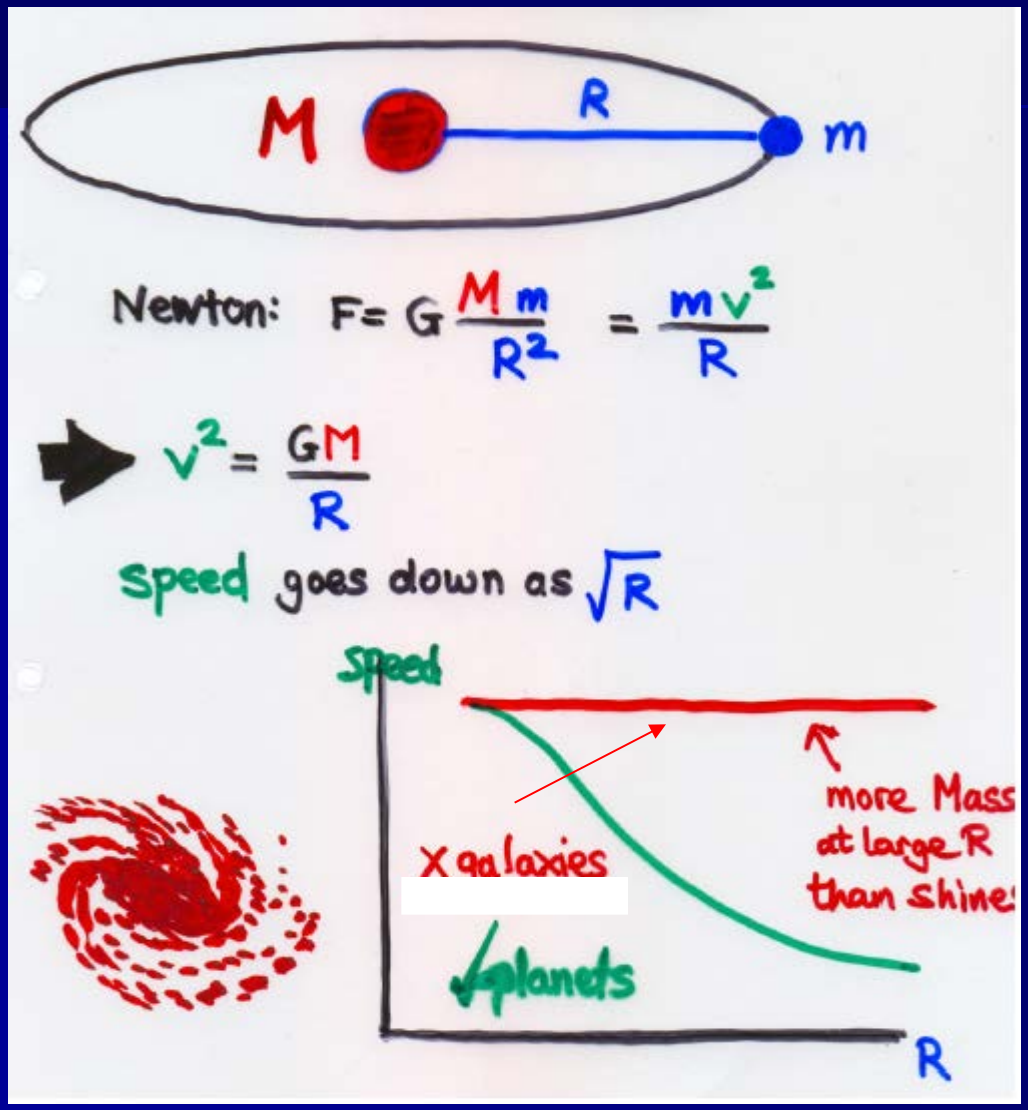


Velocity decreases for larger radius R

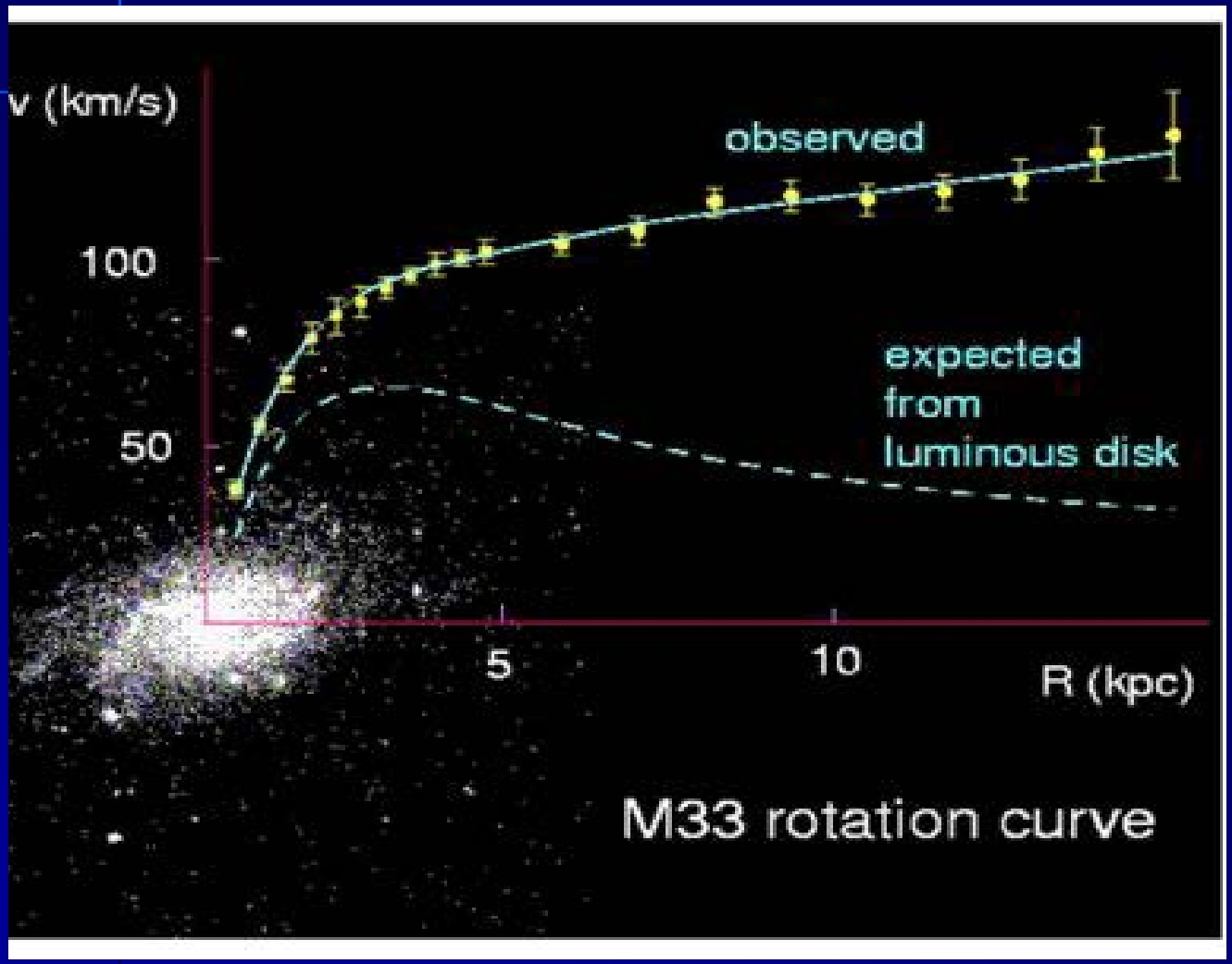
For planetes !

Velocity of particles in galaxies?

Dark Matter



Rotation curve



Dark matter?

- We do not know what it is, but it must be neutral and:
- cold dark matter – heavy dark matter (small kinetic energy)

  or
- hot dark matter – light dark matter (large kinetic energy)

more – next lectures

Electromagnetic interaction contra strong (color) interaction

Electrostatics

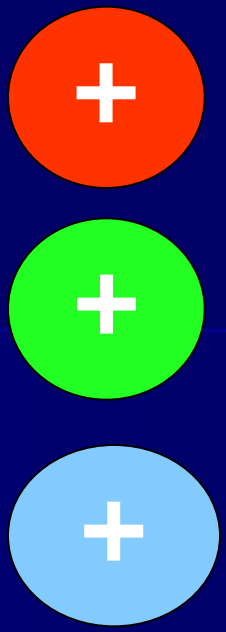
- Two types of electric charges positive (+) and negative (–)

CHROMOSTATICS

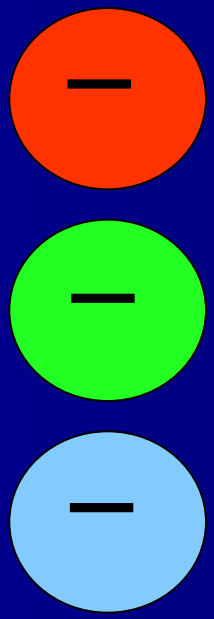
- Three types of color charges (colors), each „positive” (+) and „negative” (–) → means color and anticolor

3 colors

quarks



antiquarks

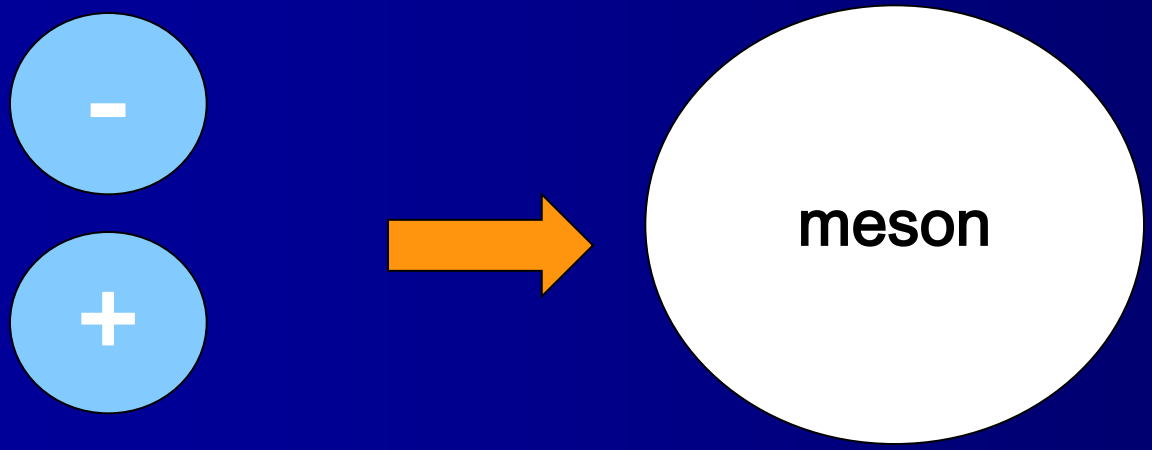


Known rule:

“The same colors repulsive, opposite colors- attractive”

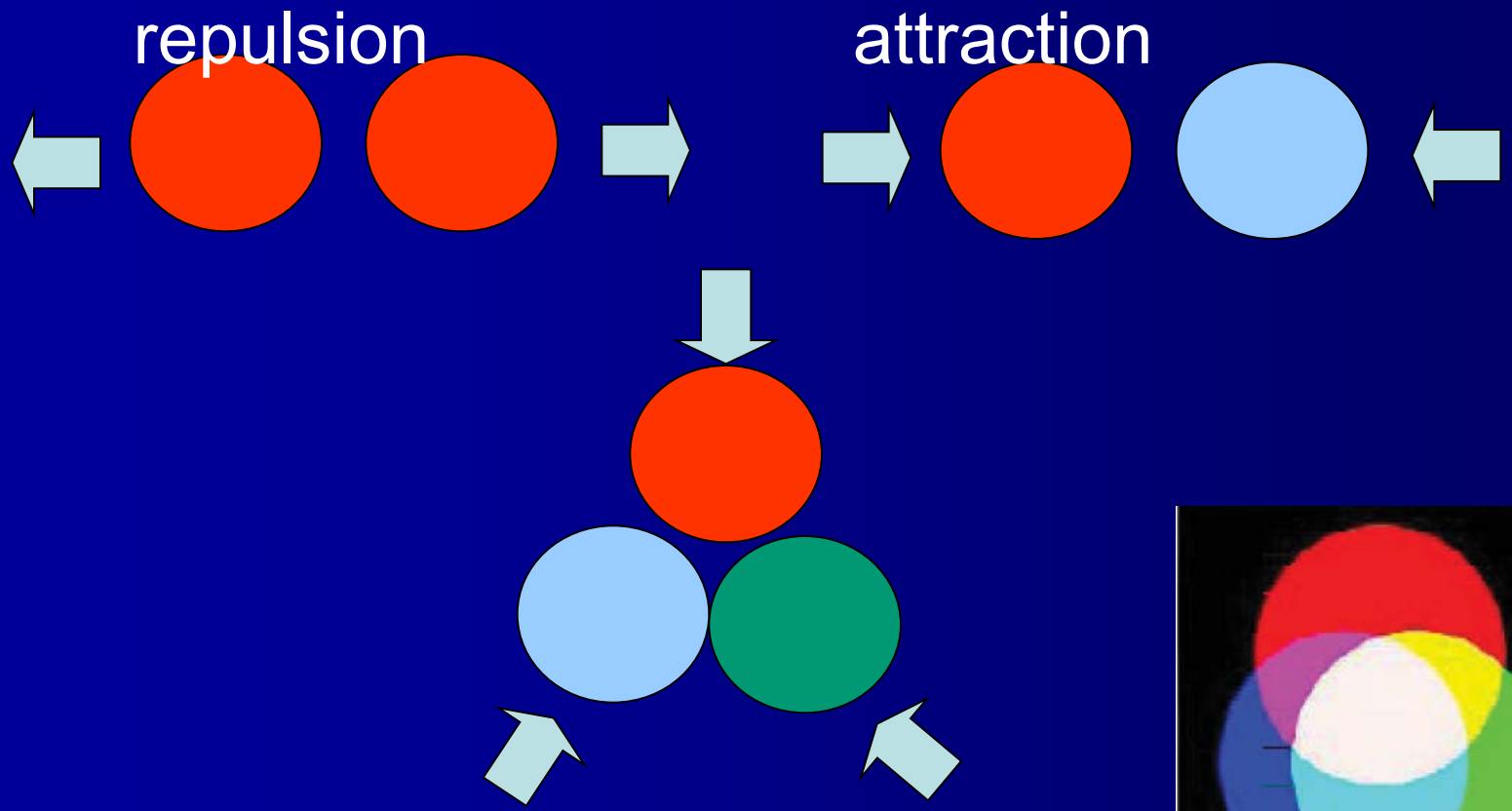
The simplest system: meson= quark+antiquark

Colors vanish, eg.



3 colors

Needed to get white baryons (3 quarks)
(eg. proton)



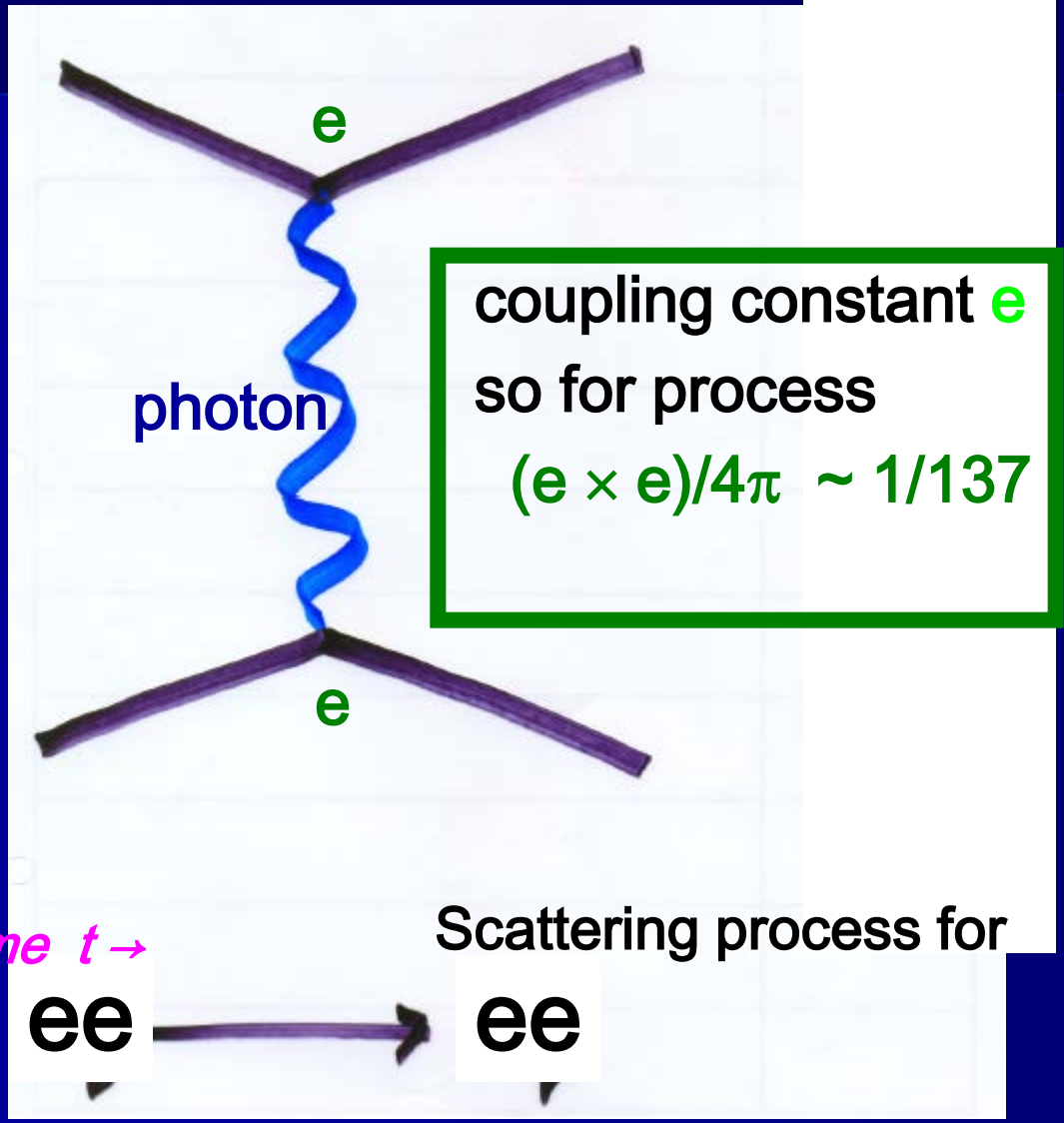
Quantum Electrodynamics: QED

Electric charge → Atom → Molecule

Quantum Chromodynamics: QCD

Color charge → Nucleon → Nucleus

Feynman's diagram for elecromagnetic interaction



coupling constant e

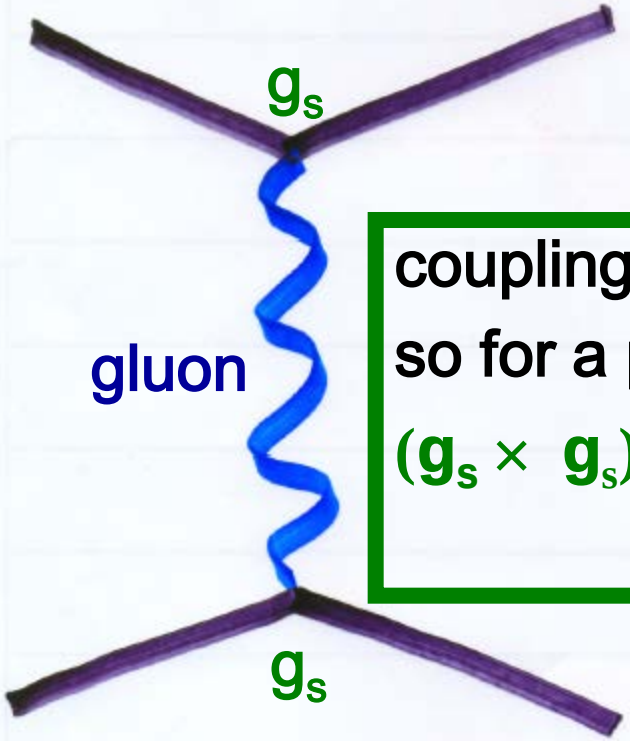
so for process

$(e \times e)/4\pi \sim 1/137$

α

Scattering process for two electrons

Feynman's diagram for color interaction



coupling constant g_s

so for a process

$(g_s \times g_s)/4\pi \sim 1$

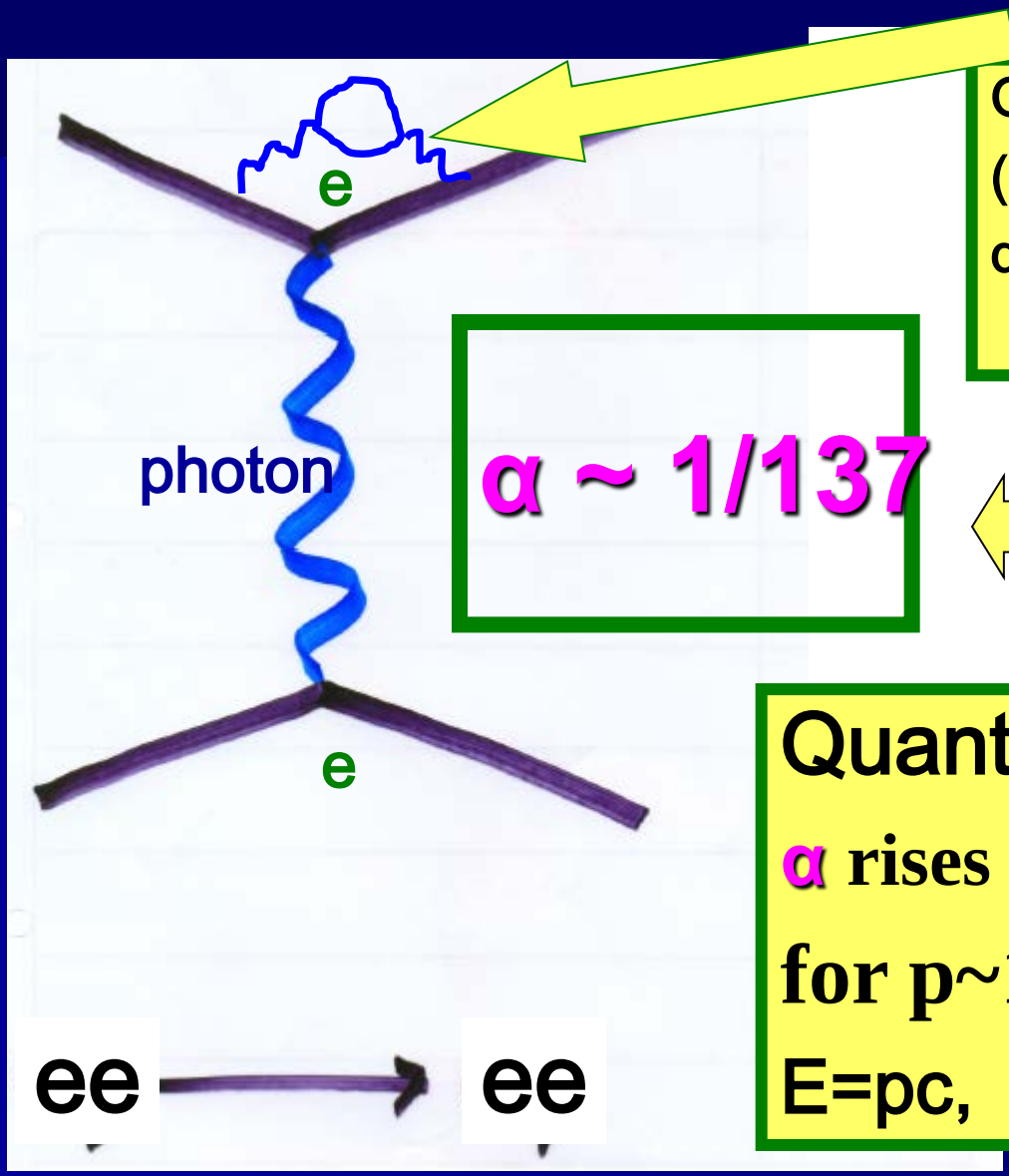
α_s

Scattering process for two quarks

Time t →

qq → qq

Elektromagnetic interaction



Quantum effect
(here e+e- loop)
depends on momentum p

$\alpha \sim 1/137$ ⟺ (for $p \to 0$)

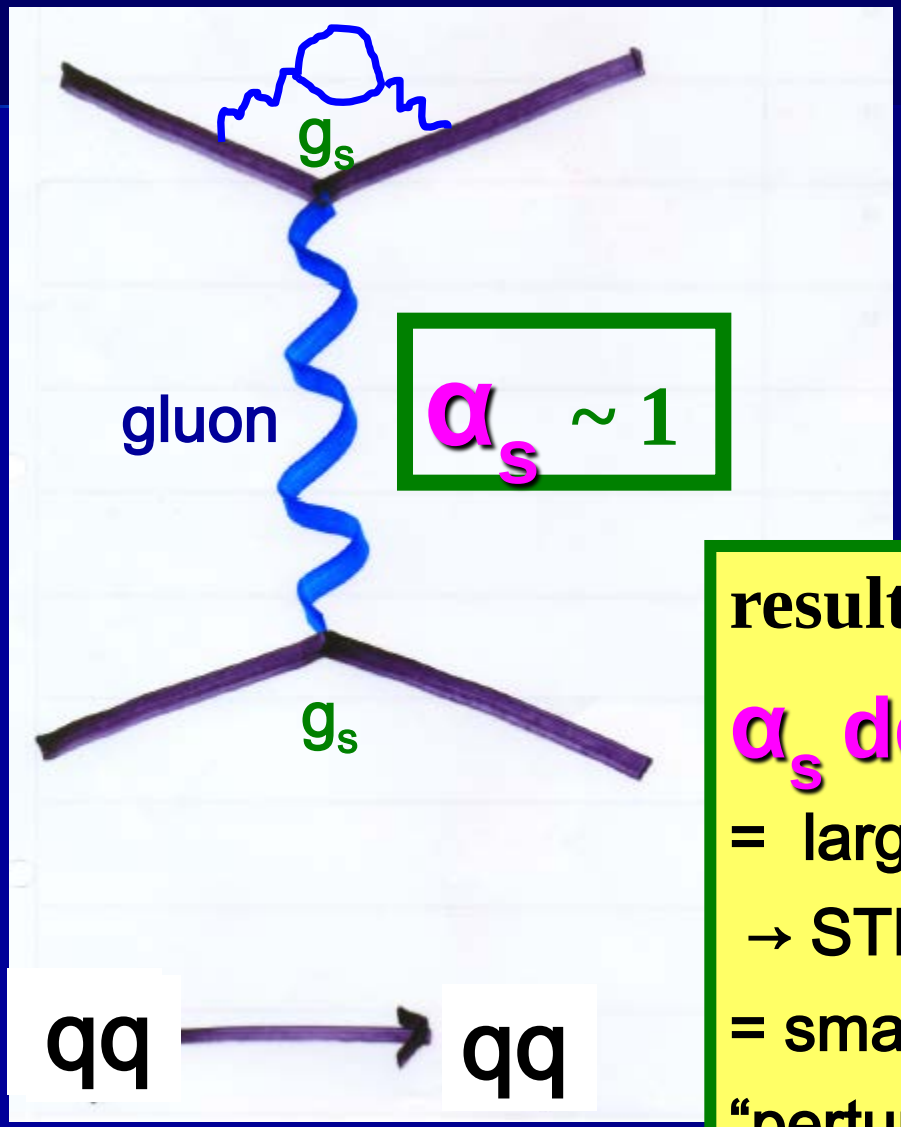
Quantum effect:

α rises with momentum:

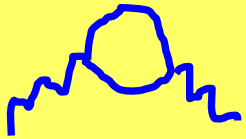
for p~100 GeV ~1/128

E=pc, [p]=GeV/c

Color interaction



Quantum effect in QCD as in QED:



quark loop

In QCD in addition gluon loop !

result:

α_s decreases with p !

= large for small p

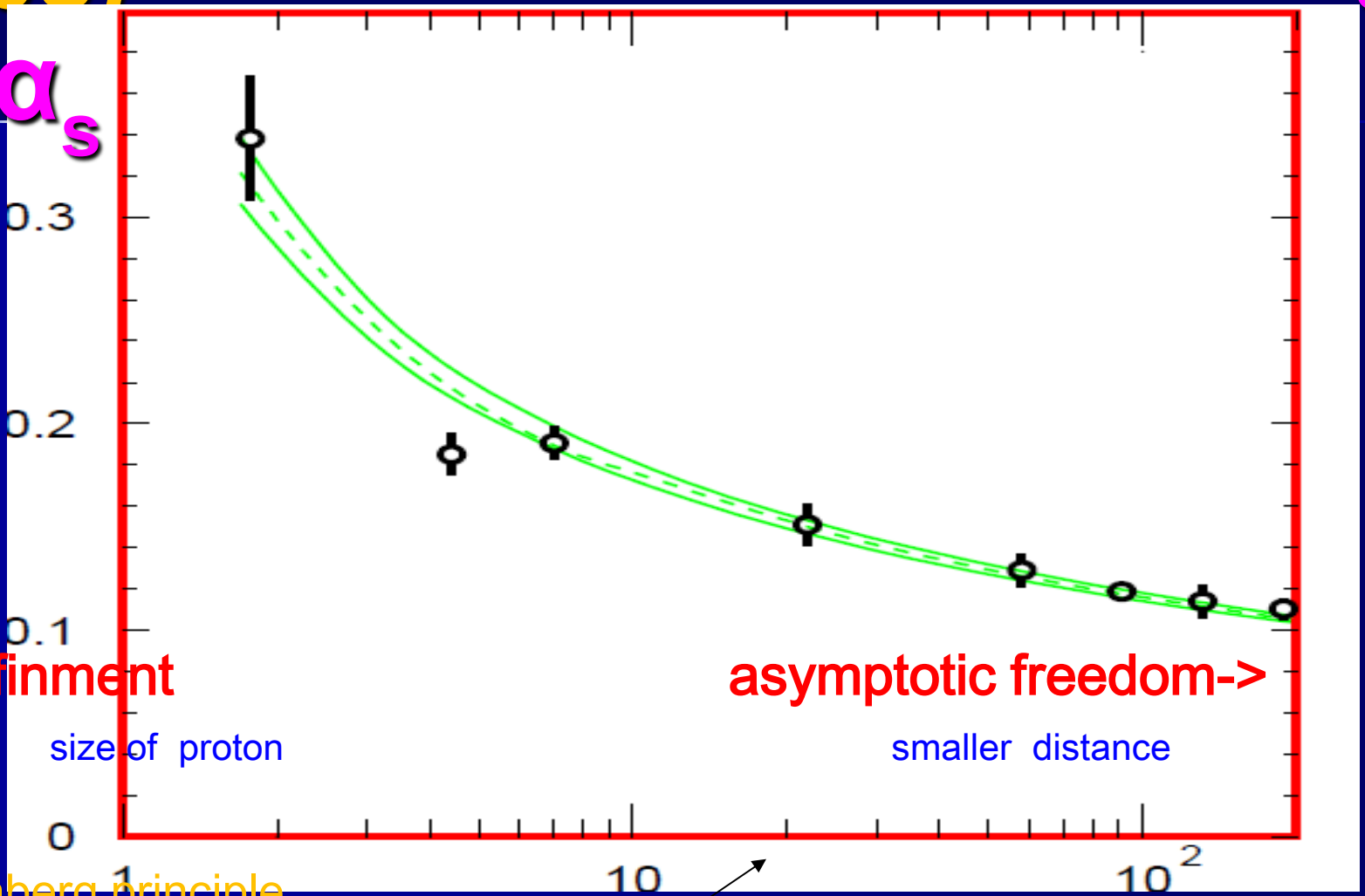
→ STRONG INTERACTION!

= small for large momentum

"perturbative QCD"

Running coupling constant (2008)

α_s



← confinment

size of proton

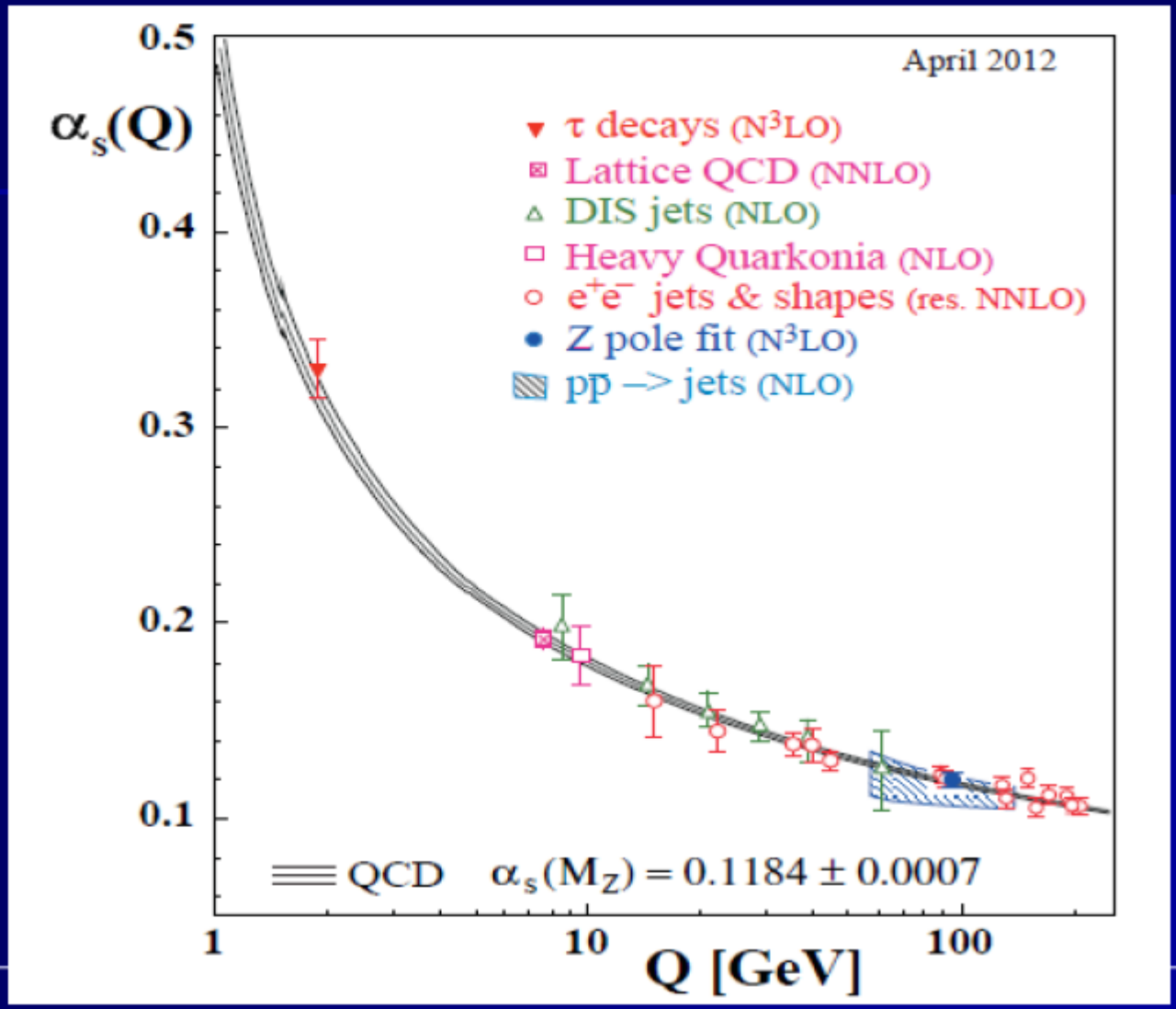
asymptotic freedom->

smaller distance

Heisenberg principle

$\Delta x \sim 1/\Delta p$ ($\hbar c=1$)

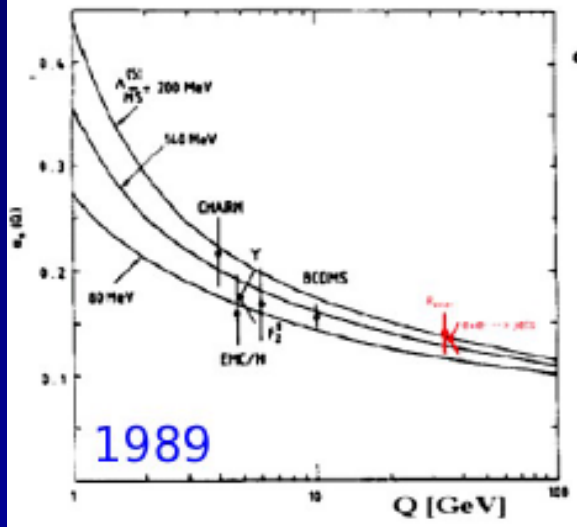
Running coupling constant
April 2012



Determination of the QCD coupling α_s

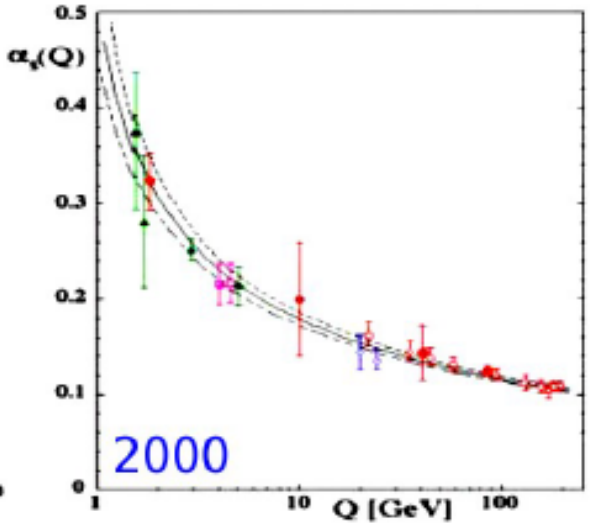
α_s = Single free parameter in QCD (in the $m_q \to 0$ limit). Determined at a given ref. scale (e.g. m_Z). Decreases as ~$\ln(Q^2/\Lambda^2)$, with Λ~0.25 GeV

- Least precisely known of all couplings: $\delta\alpha$ ~$3\cdot10^{-10}$, δG_F~$5\cdot10^{-8}$, δG~10^{-5}, $\delta\alpha_s$~$5\cdot10^{-3}$
- Impacts all LHC cross-sections.
- Key for SM precision fits (e.g. uncertainties b,c Yukawa).
- BSM physics (e.g. couplings at GUT).



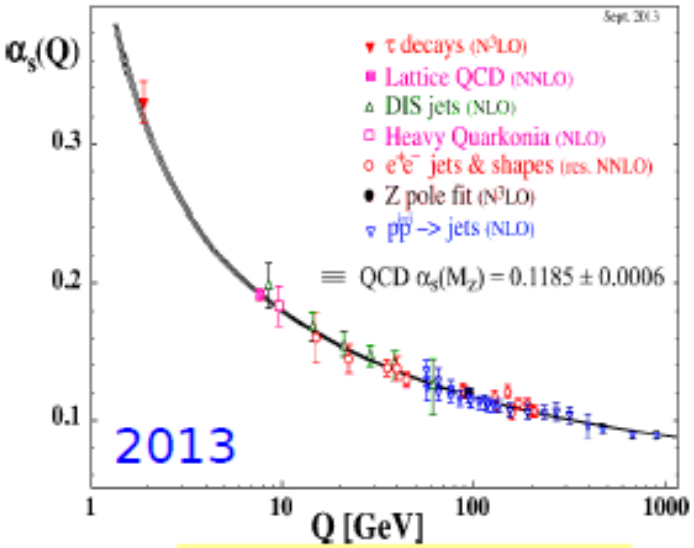
$\alpha_s(M_z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989



$\alpha_s(M_z) = 0.1184 \pm 0.0031$ (NNLO)

S. B., J. Phys. G 26, 2000

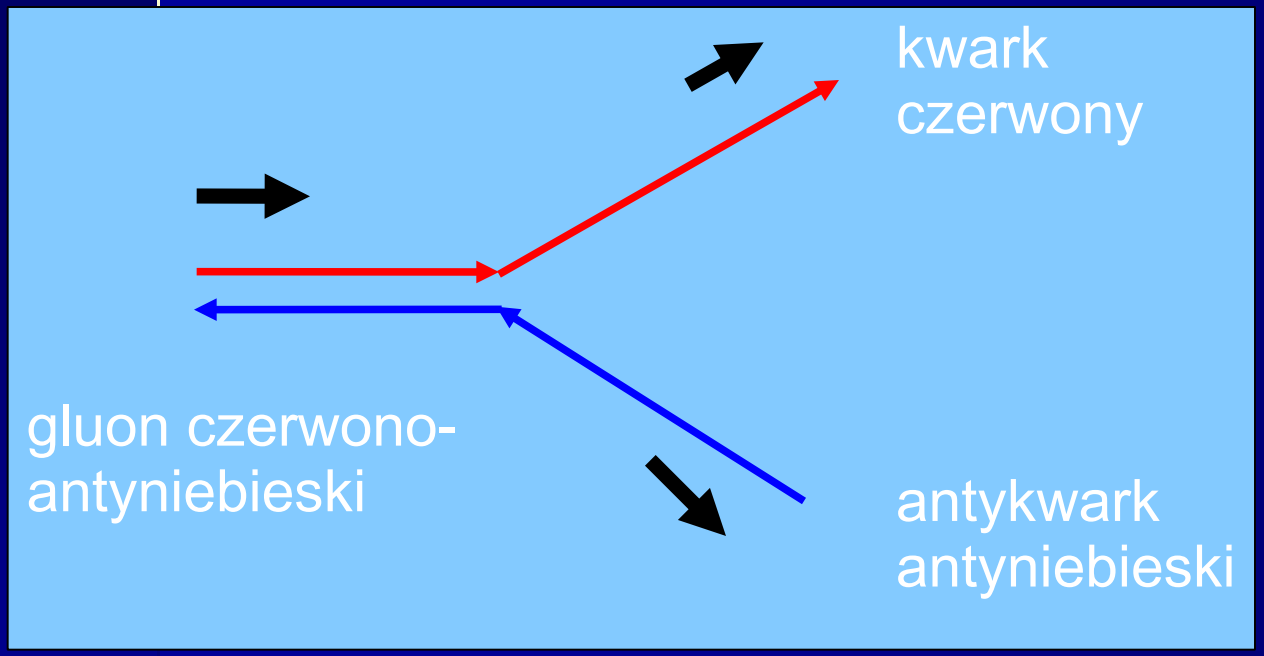


$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

Current uncertainty: ±0.5%
(lattQCD disputed by some: ±1%)

Color interaction

Example gluon-> quark + antiquark



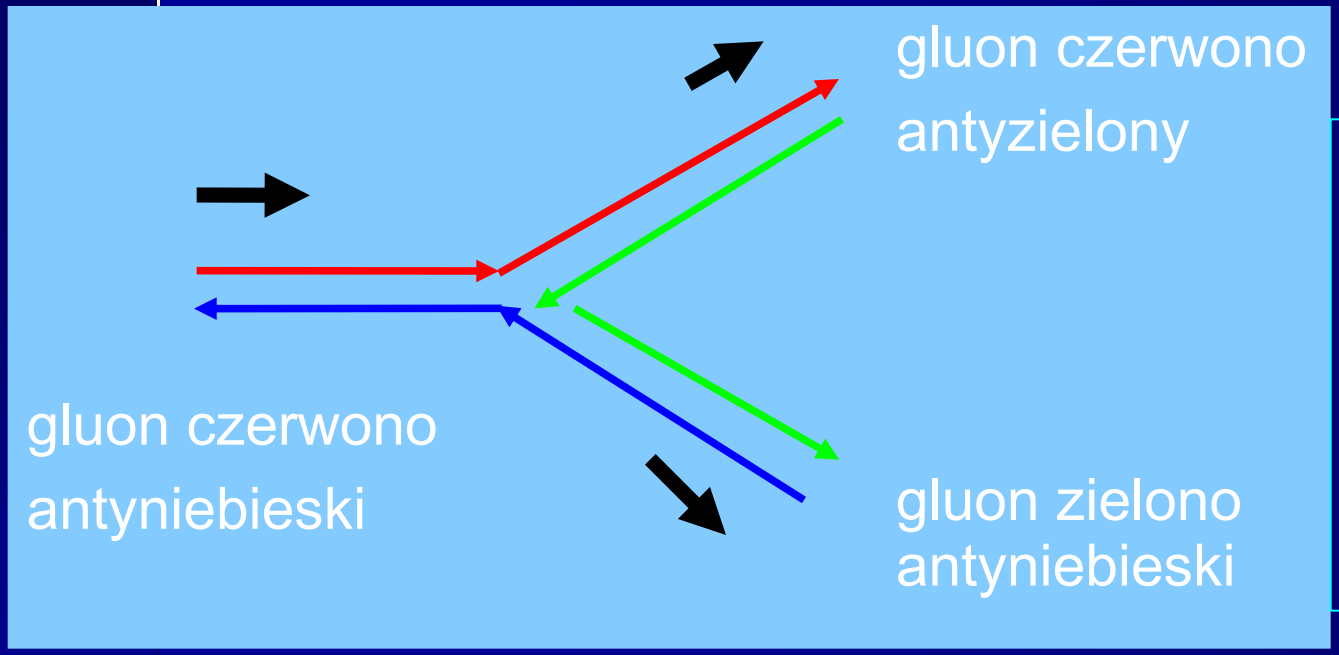
gluon line 

← here we follow a color

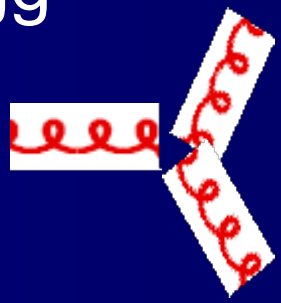
- color lines - flow of color (color conservation)
- black arrows – momenta of particles (momenta conservation)

Color interaction

Example gluon-> gluon+ gluon



ggg

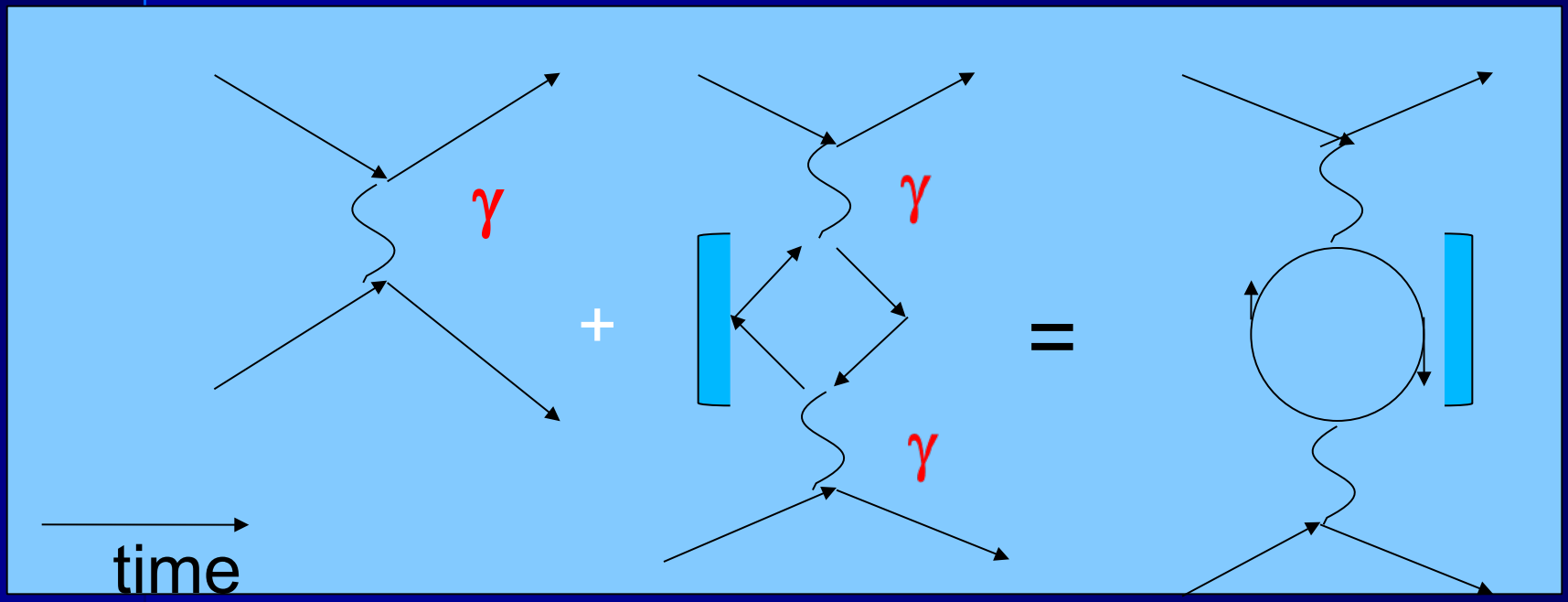


Also gggg

- color lines - flow of color (color conservation)
- black arrows – momenta of particles (momenta conservation)

Extraction of α

Measurement of α in $e^-e^- \rightarrow e^-e^-$

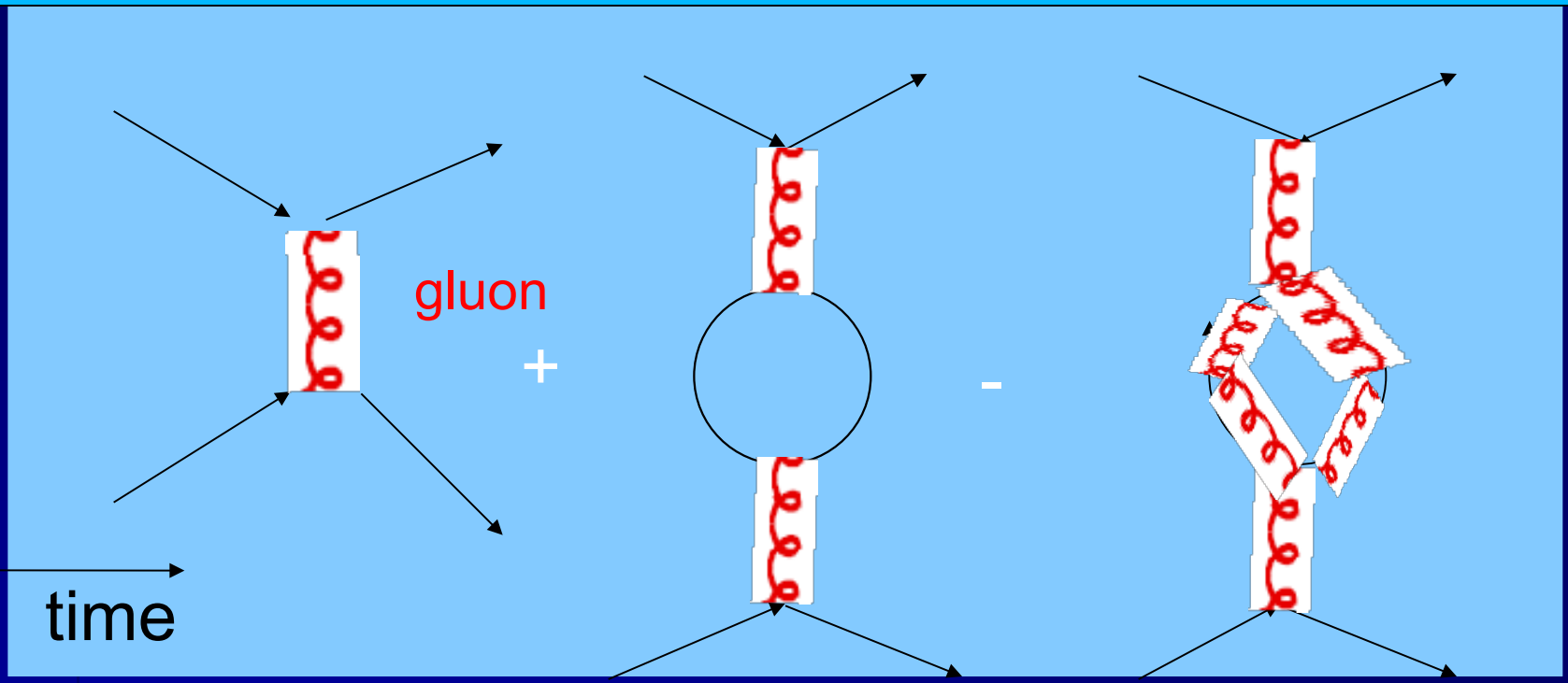


$$\alpha \times [1 + \text{corrections}(p)] = \alpha(p)$$

Electron loop $\rightarrow \alpha$ depends on momentum p (‚runs'); is rising with energy (momemtum)

Extraction of α_s

Scattering qq -> qq



Pętla kwarkowa - efekt podobny jak dla oddziaływań el-mag (powoduje wzrost stałej α_s). Tu dodatkowo pętla gluonowa, która ma przeciwny znak →

i w efekcie α_s maleje ze wzrostem pędu !!

Running coupling constants - unification?

- Couplings are running with energy (momentum) – this is an effect of quantum corrections
- Structure of interaction decides about rising or decreasing of coupling constants

  key point - are carries of interactions „charged" or not (means do they interact with themselves), eg. photon neutral, while gluons „charged"
- if some couplings are rising and other decreasing – at some energy they can have similar values

→ unified description?

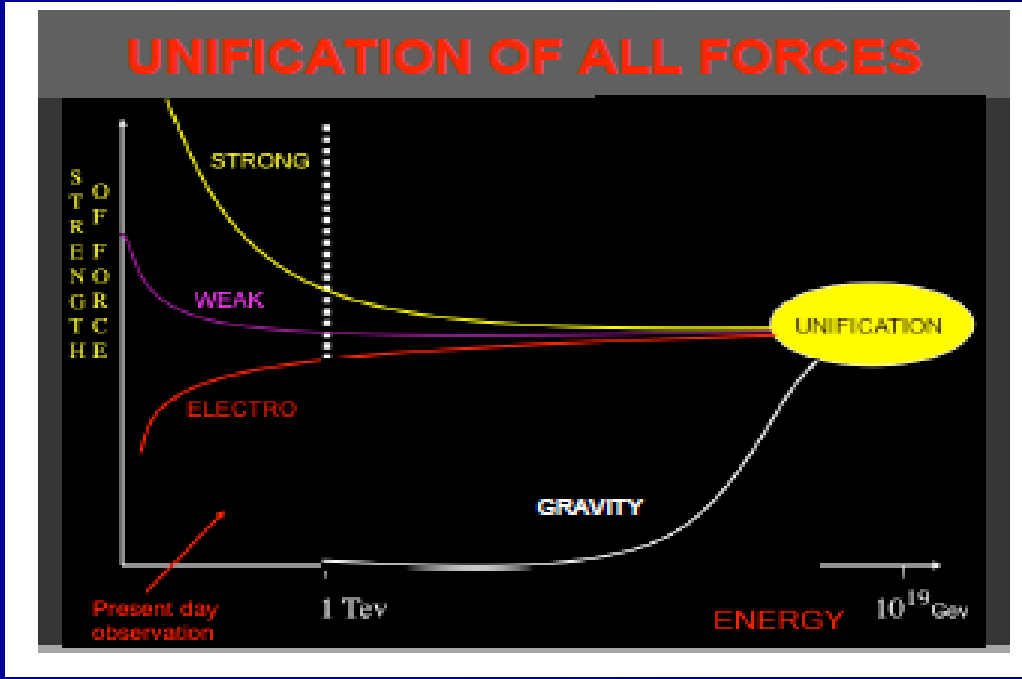
(‚Running couplings constants')!

For larger energy: strong interaction weaker
weak interaction - weaker
el-mag interaction stronger

α_s

α_w

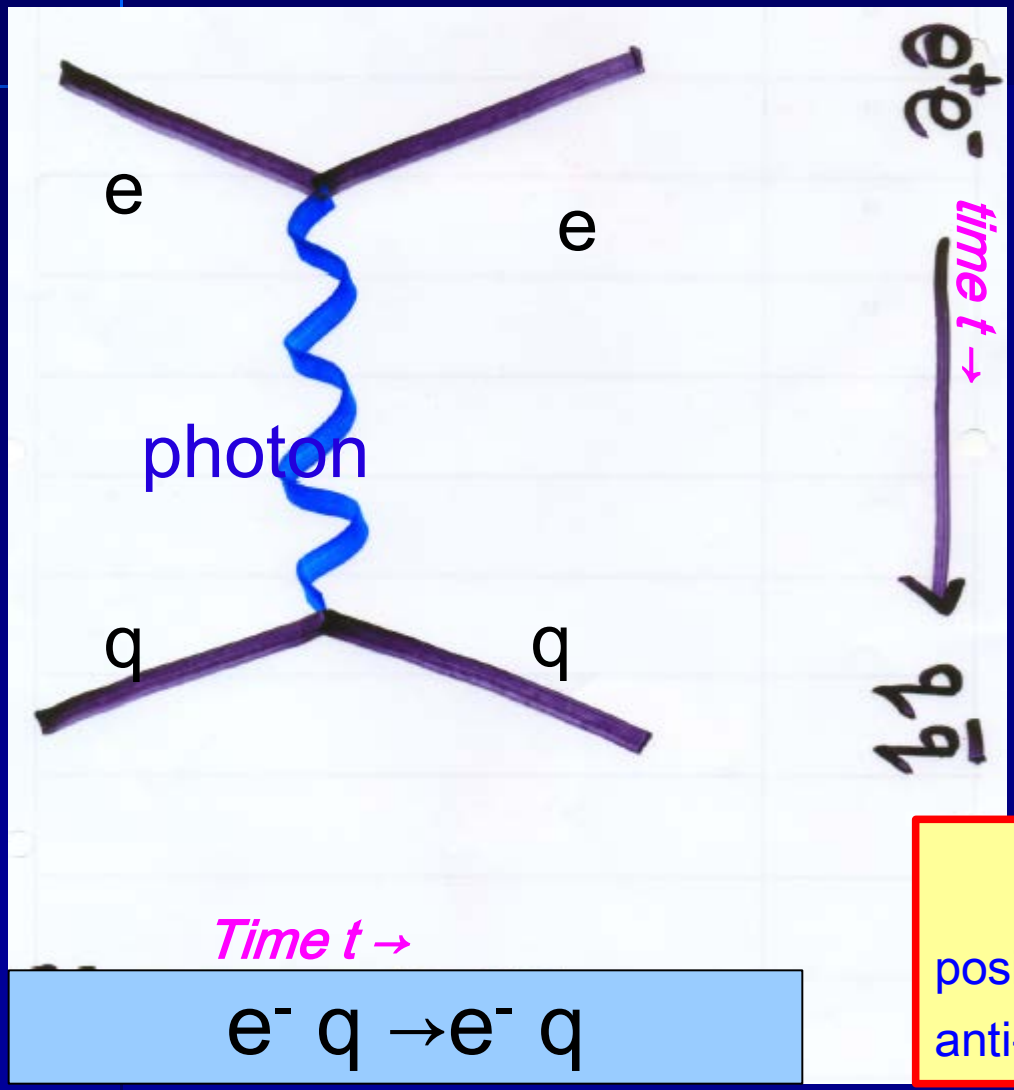
α_{el}



D. Gross, Photon 2005

Gravity ???

Crossing for fixed external particles



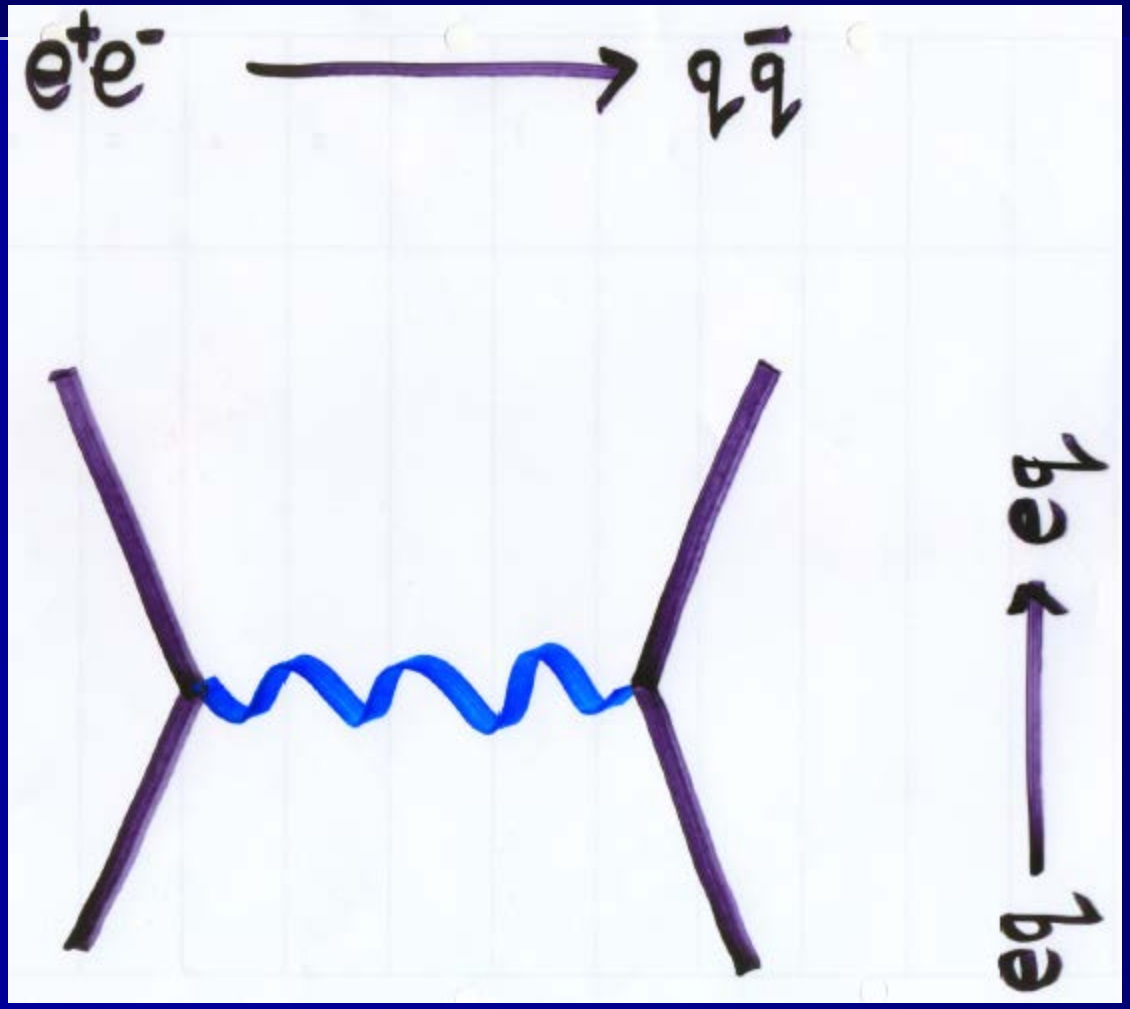
Here 2 e
(e- e- lub e+ e+, lub e-e+)
And 2 quarks q
(q q , q anty-q,
anty-q anty-q)

Crossing processes

positron in <-> electron out

anti-q out <-> q in

Feynman diagram



Crossing processes – example: e-e- → e-e-

***(time** – from left to right)*

- Other processes (crossing processes) we got exchage replacing initial particles with the final particles simultanous replacing particles with antiparticles

- Yellow particle -> to be transfered to the future (as antiparticle) and pink particle – to be transfered to the past (as an antipariticle):
- e-e- → e-e- ⟹ e- e+ → e- e+, and next
  - e- e+ → e- e+ ⟹ e+e+ → e+ e+