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

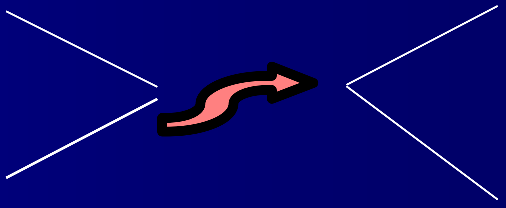
Range of interactions

$c = \hbar = 1$

- 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

Strength of interactions

- Long range forces gravitation and el-mag very different - gravitation very weak

  (gravitation between two protons 10^{36} times weaker than el-mag interaction)

- Strength'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 strength of elementary action

  → coupling constant

Coupling constants

Strength of elementary act of interaction = coupling constant

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

weak fund.: g ('weak' charge)

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

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

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

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*

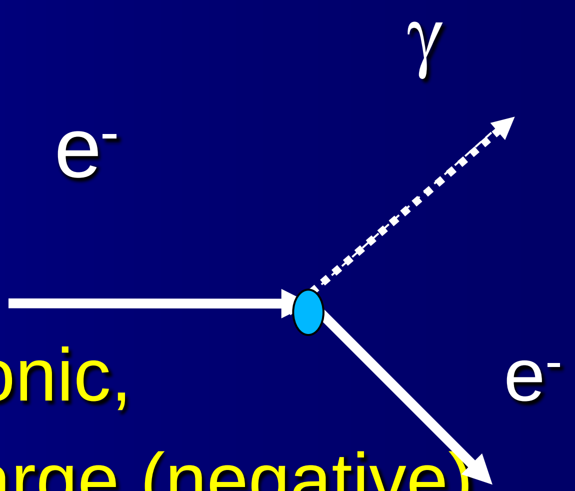
Feynman diagrams

Feynman diagrams –

particles are represented by different lines,

act of elementary interaction - by a vertex

eg. emission of the photon by electron

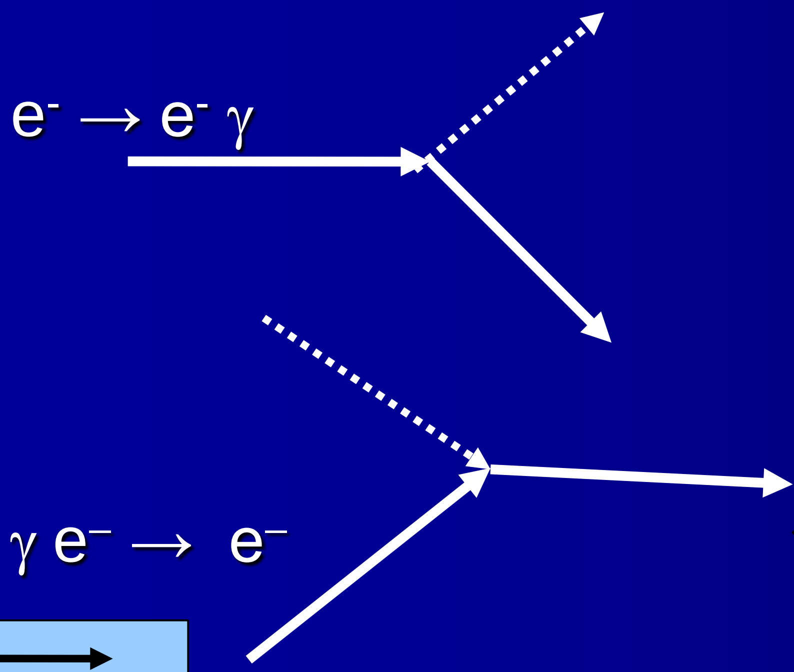


Arrows on a continuous line (fermionic, here for e^-) → flow of electric charge (negative) and momentum, while arrow on the photonic line (here dashed) → only momentum

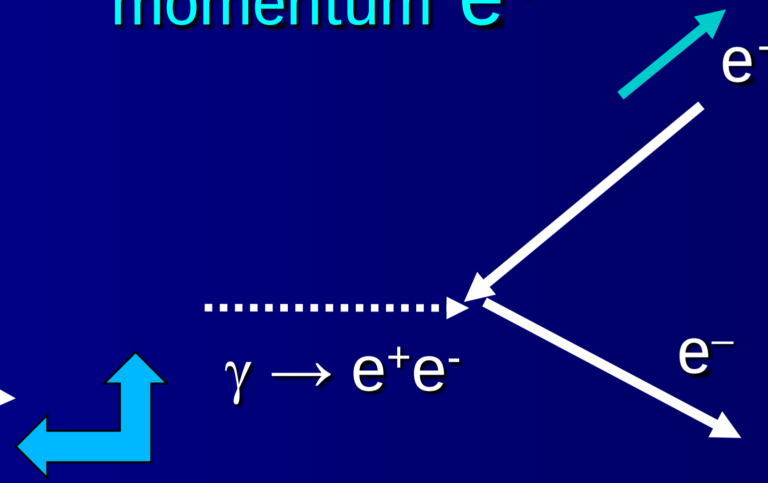
Feynman diagrams for crossing processes

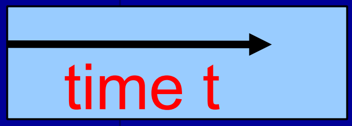
Crossing processes involving e e γ

(e represents e+ and e-)



momentum e^+

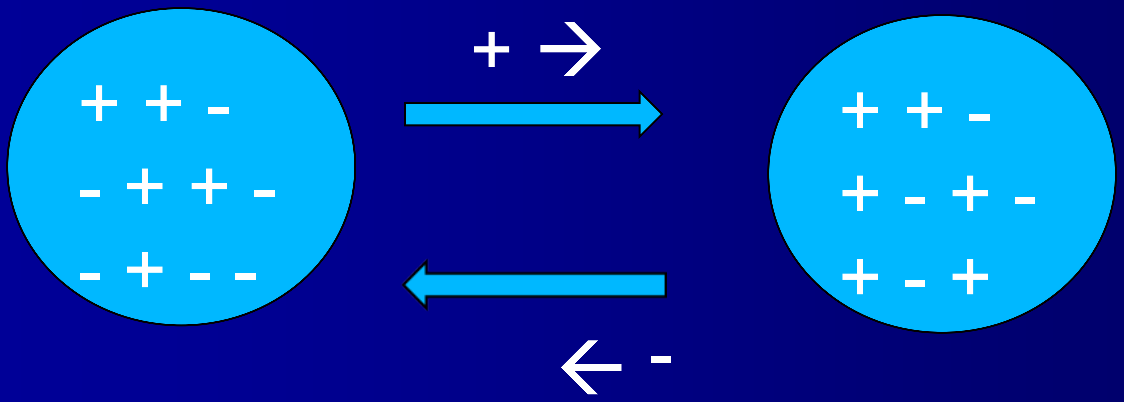




For e+ - a flow of negative charge in oppositve direction than momentum

Flow of charges

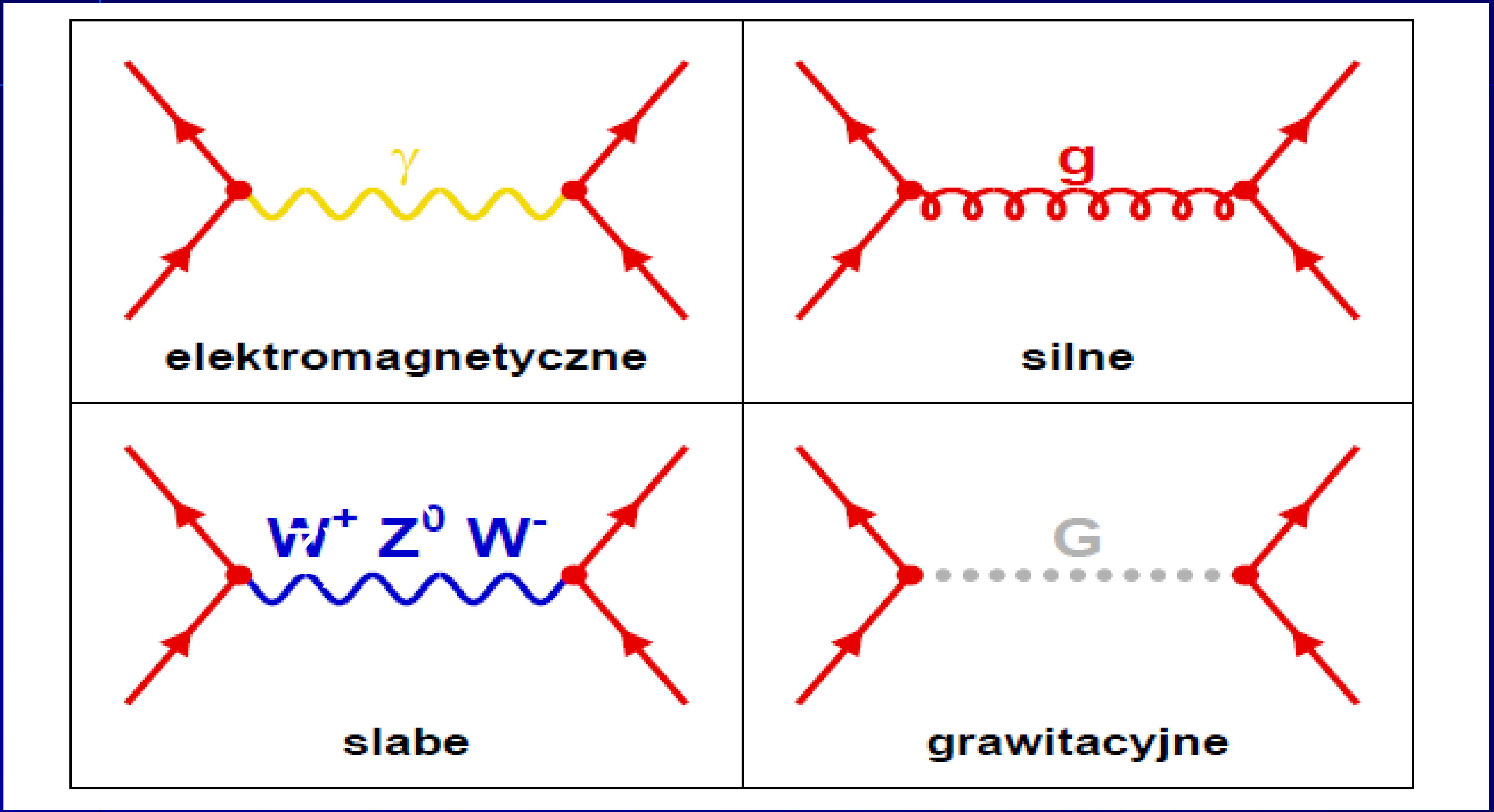
charge of
a system



$N_+ = n_+ - n_-$

$N_- = n_- - n_+$

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

$\hbar$ – 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 „strength" of el-mag interaction of electrons 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

ep in H atom

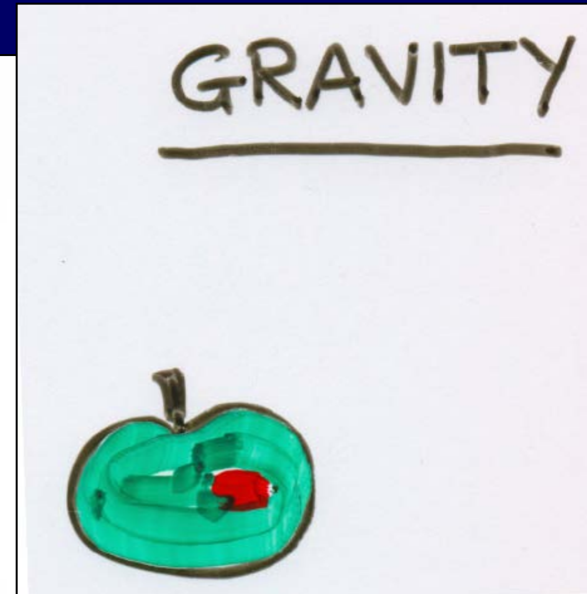
$$\frac{\text{Gravity P.E.}}{\text{Electromag}} \simeq 10^{-40}$$

c.f. size of proton $\simeq 10^{-15}$ m.

size of univ. $\lesssim 10^{10}$ yr. $\times$ 10^{16} m yr^{-1}

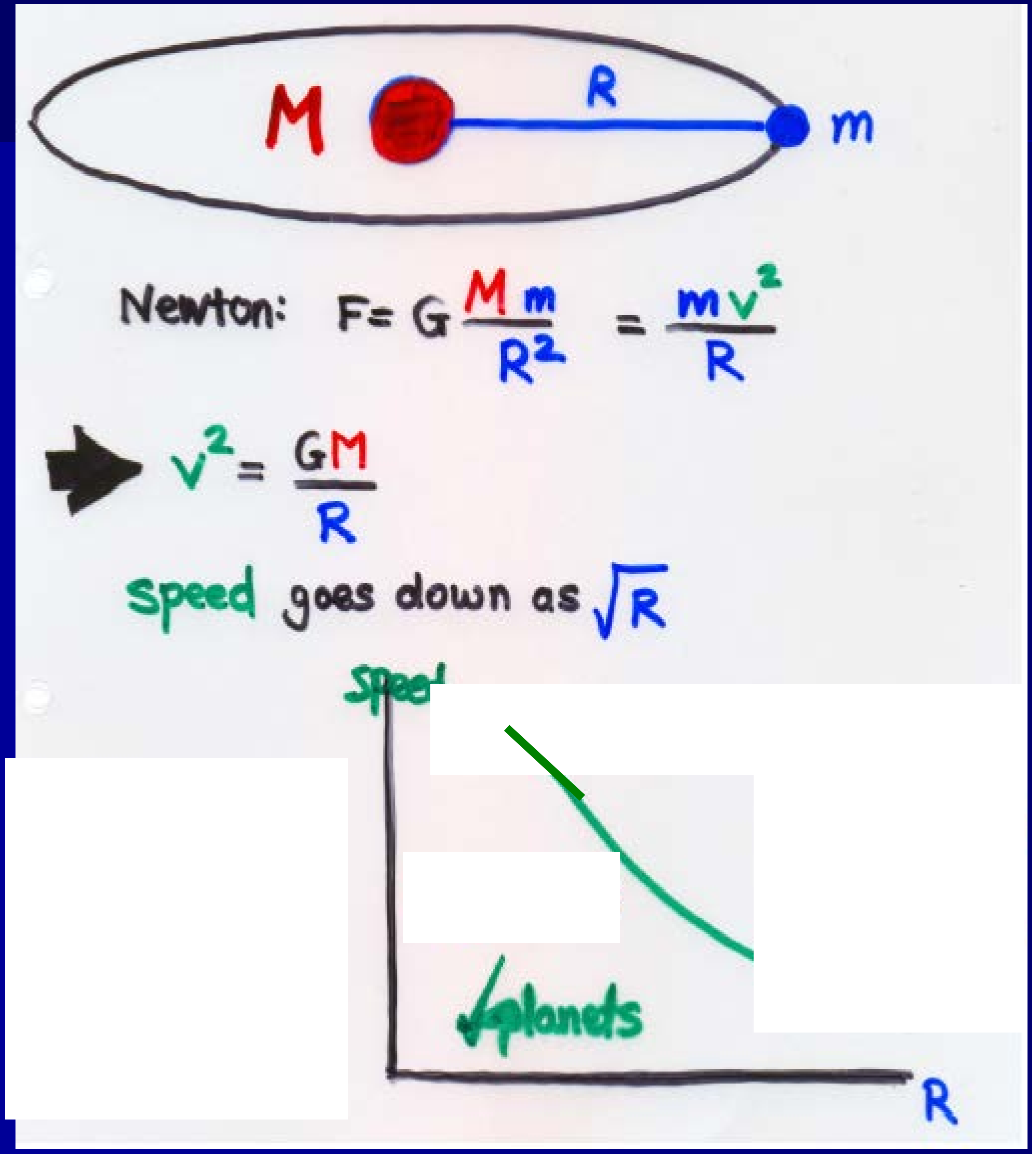
$\lesssim 10^{26}$ m.

$$10^{-40} \simeq \frac{\text{Radius of proton}}{\text{Radius of Universe}}$$



Lecture by F. Close

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

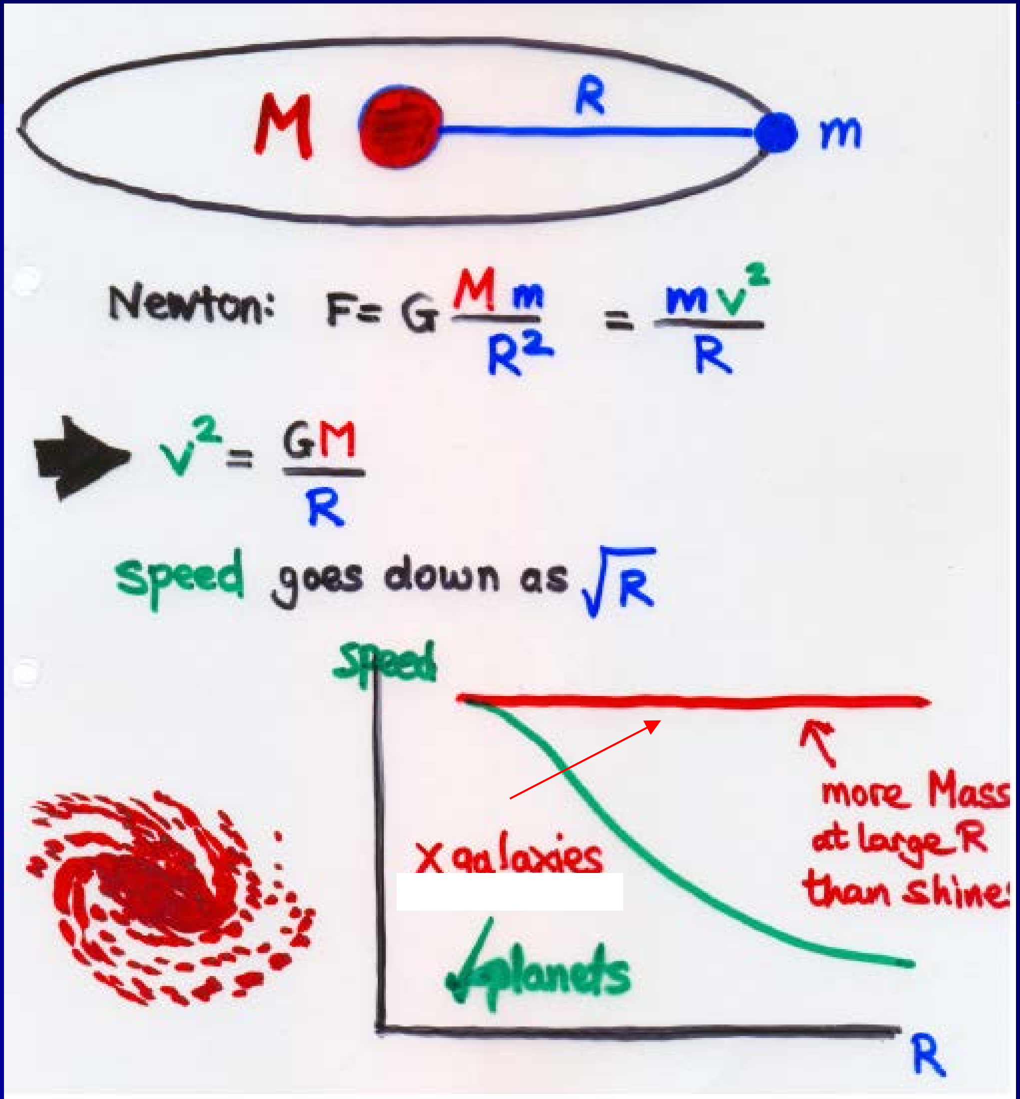


Velocity decreases for larger radius R

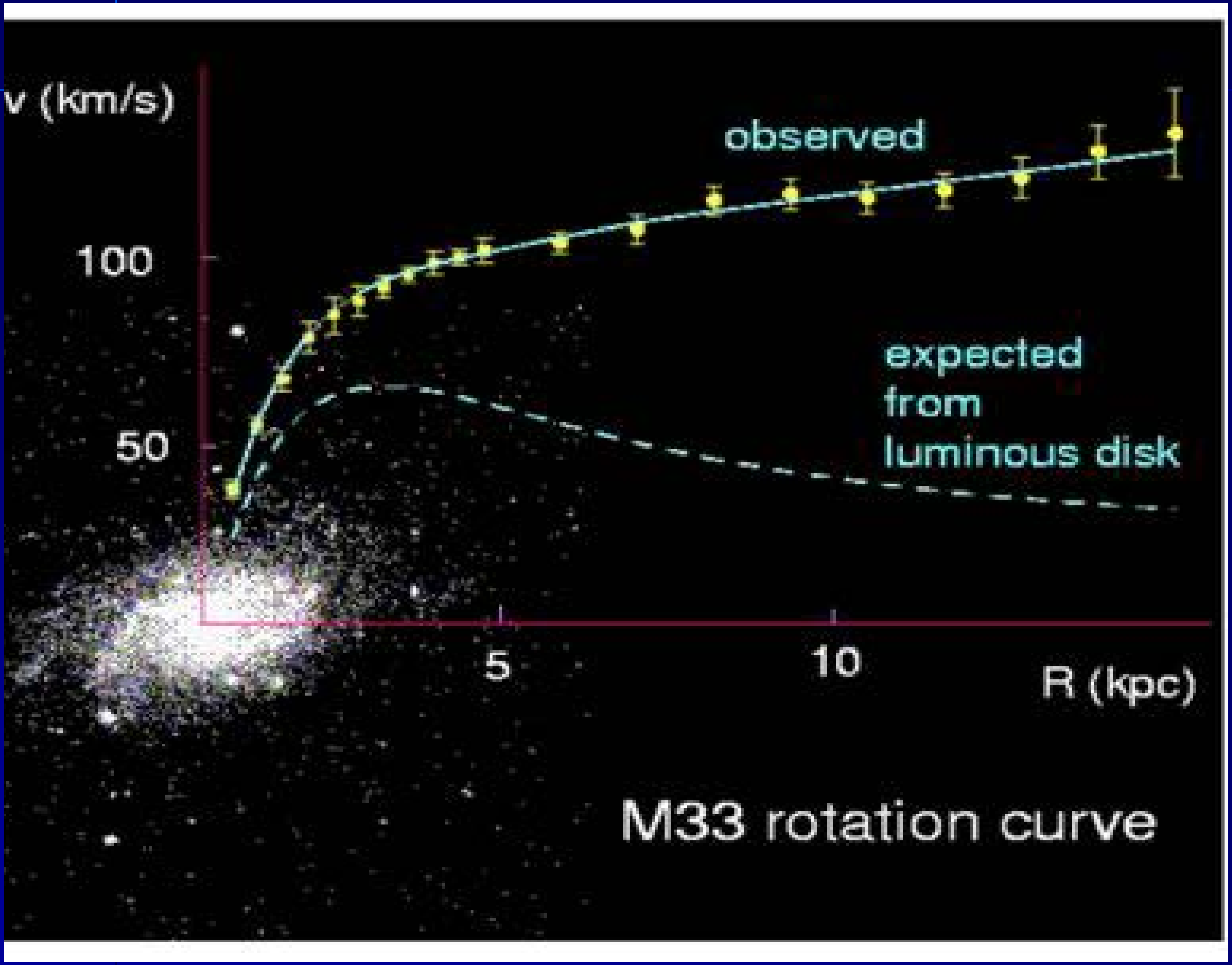
For planetes !

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

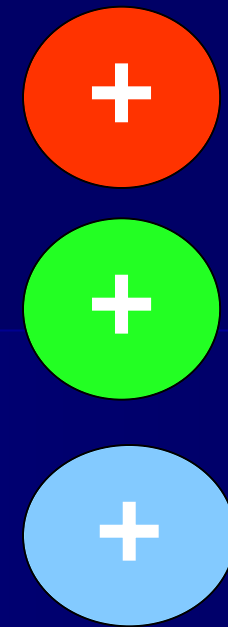
- Two types of electric charges
  positive (+) and negative (–)

CHROMOSTATICS

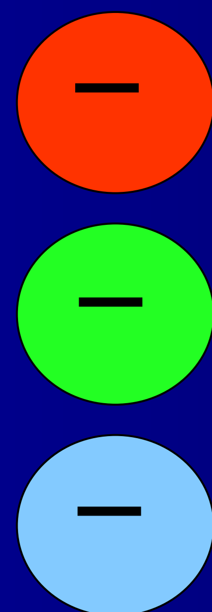
- Three types of color charges (colors),
  each „positive” (+) and „negative” (–) →
  means color and anticolor

3 colors

quarks



antiquarks

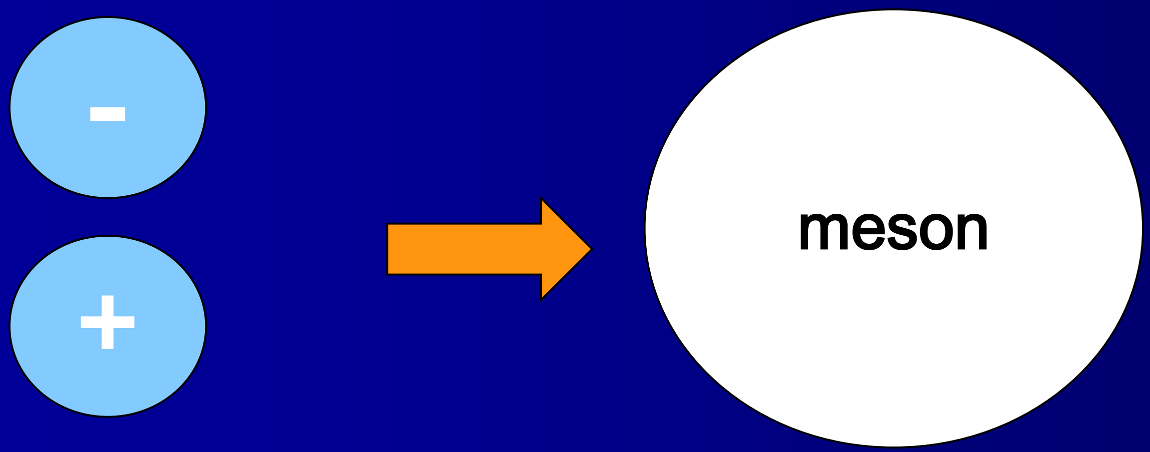


Known rule:

“The same colors repulsive, opposite colors- attractive”

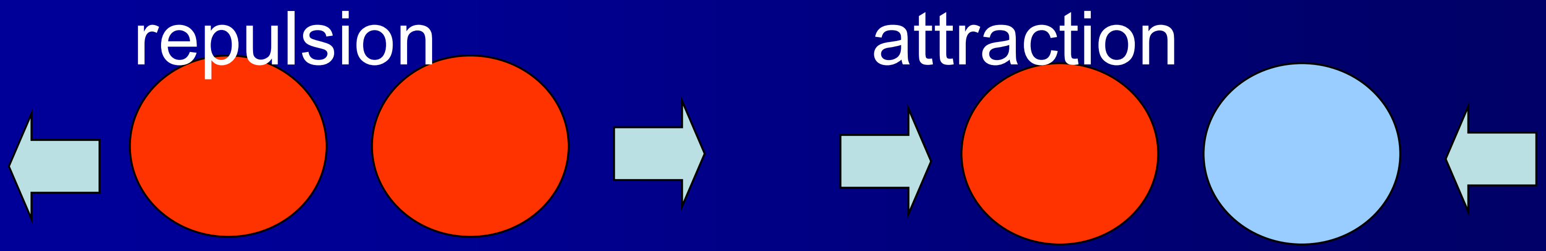
The simplest system: meson= quark+antiquark

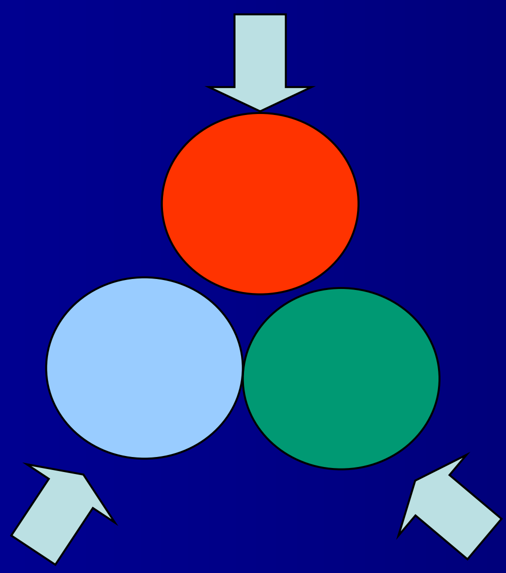
Colors vanish, eg.

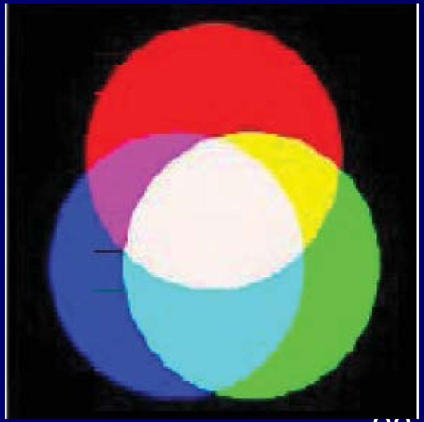


3 colors

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







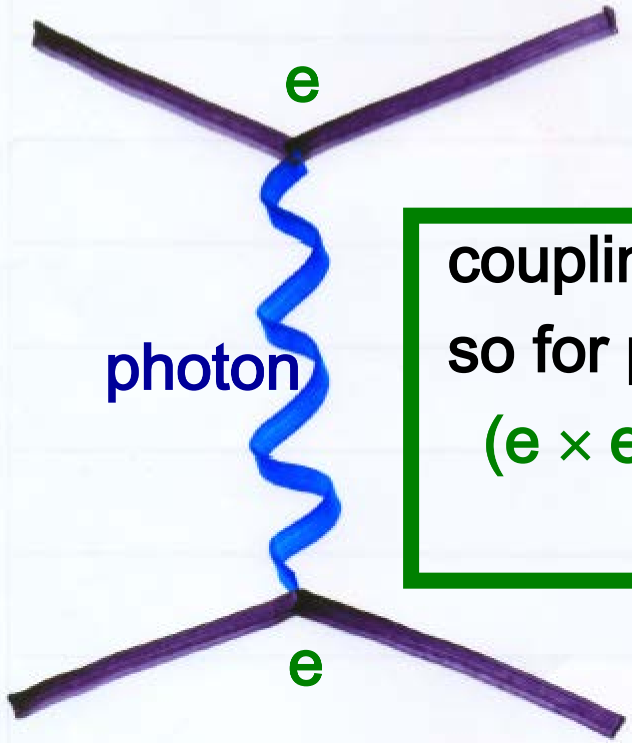
Quantum Electrodynamics: QED

Electric charge → Atom → Molecule

Quantum Chromodynamics: QCD

Color charge → Nucleon → Nucleus

Feynman's diagram for elecromagnetic interaction



coupling constant e
so for process
$(e \times e)/4\pi \sim 1/137$

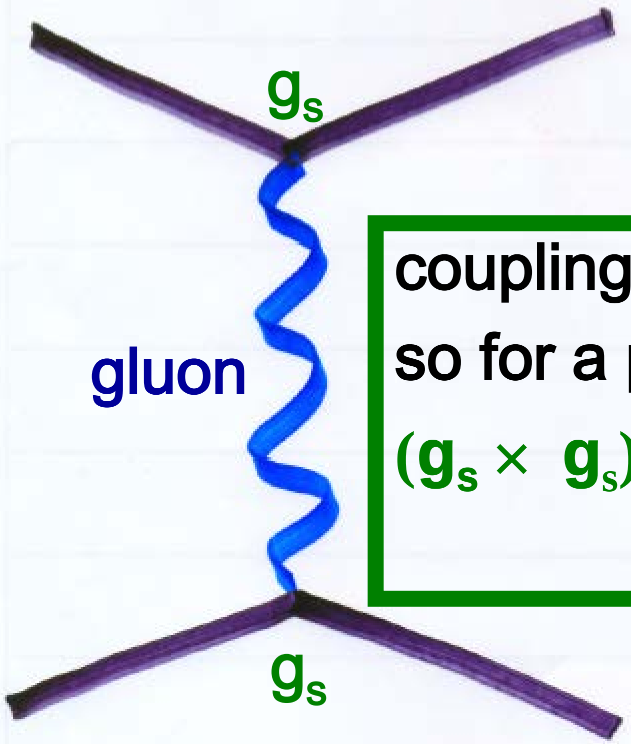
α

Time t →

Scattering process for two electrons

ee → ee

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

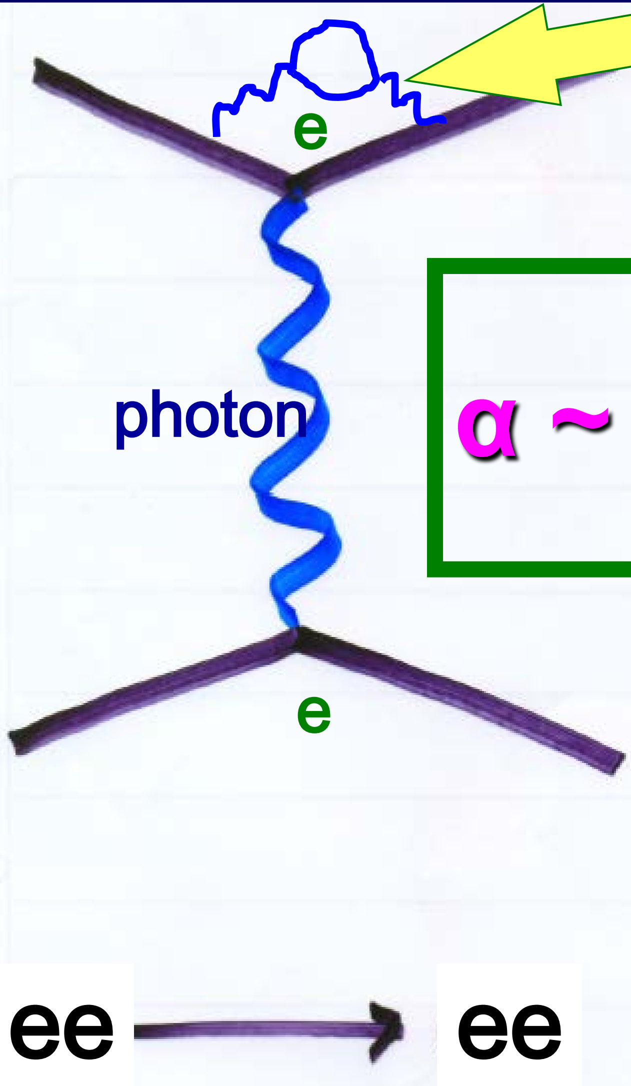
Scattering process for two quarks

Time t →

qq → qq

Elektromagnetic interaction

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



$\alpha \sim 1/137$ ⇔ (for p → 0)

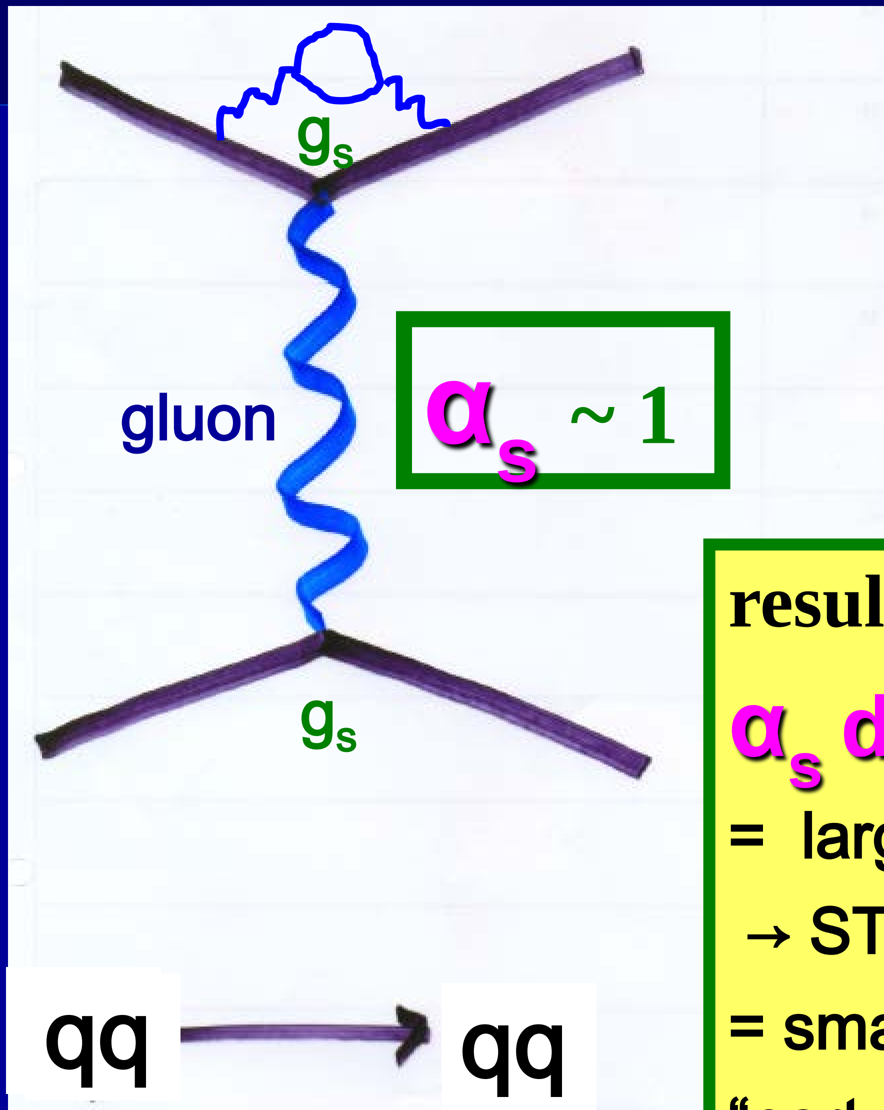
Quantum effect:

α rises with momentum:

for p~100 GeV ~1/128

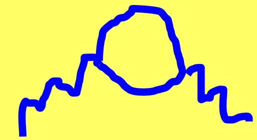
E=pc, [p]=GeV/c

Color interaction



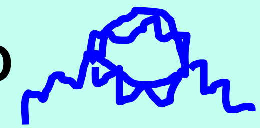
$\alpha_s \sim 1$

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

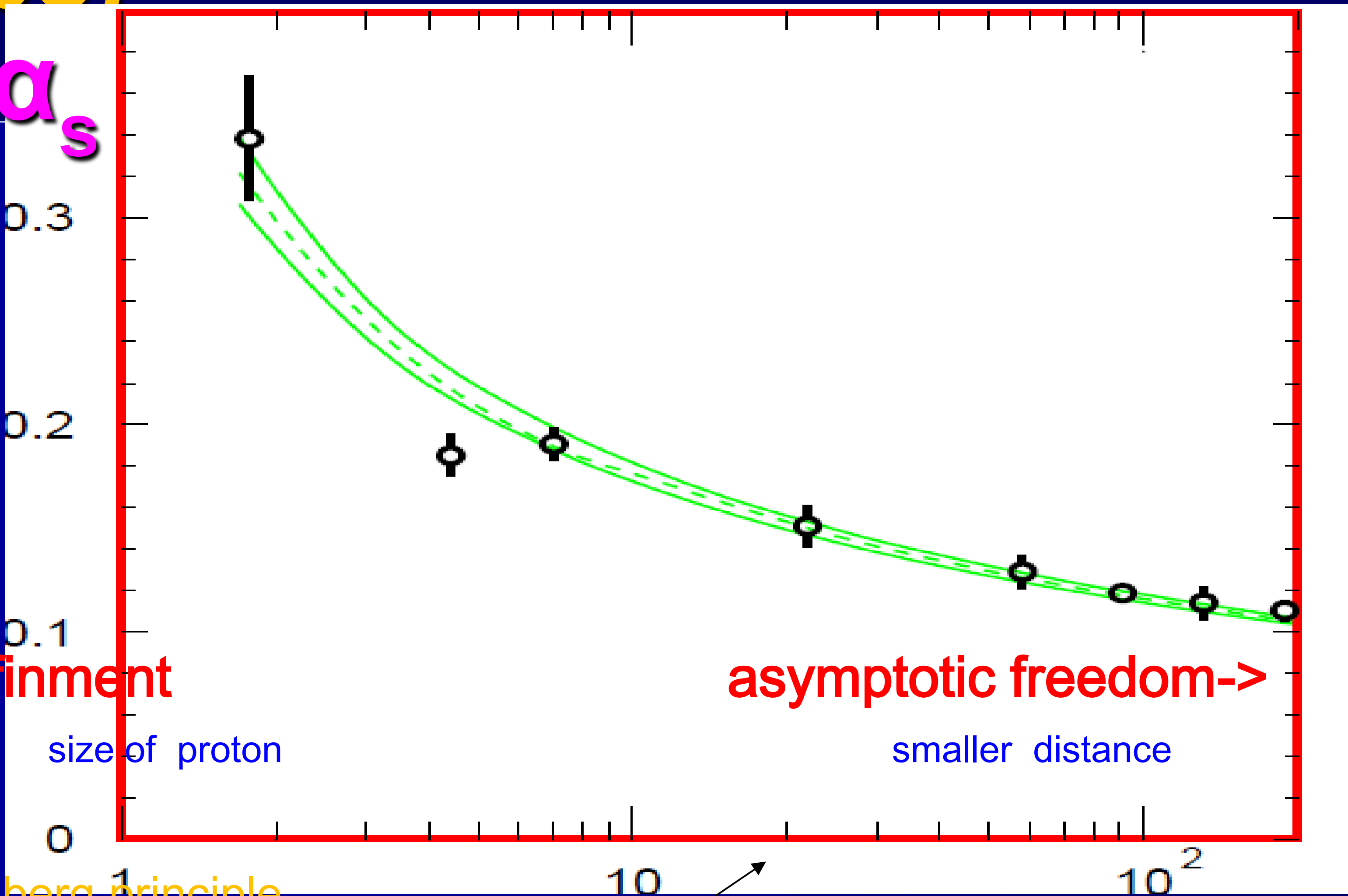
→ STRONG INTERACTION!

= small for large momentum

"perturbative QCD"

Running coupling constant (2008)

α_s



← confinment

size of proton

asymptotic freedom->

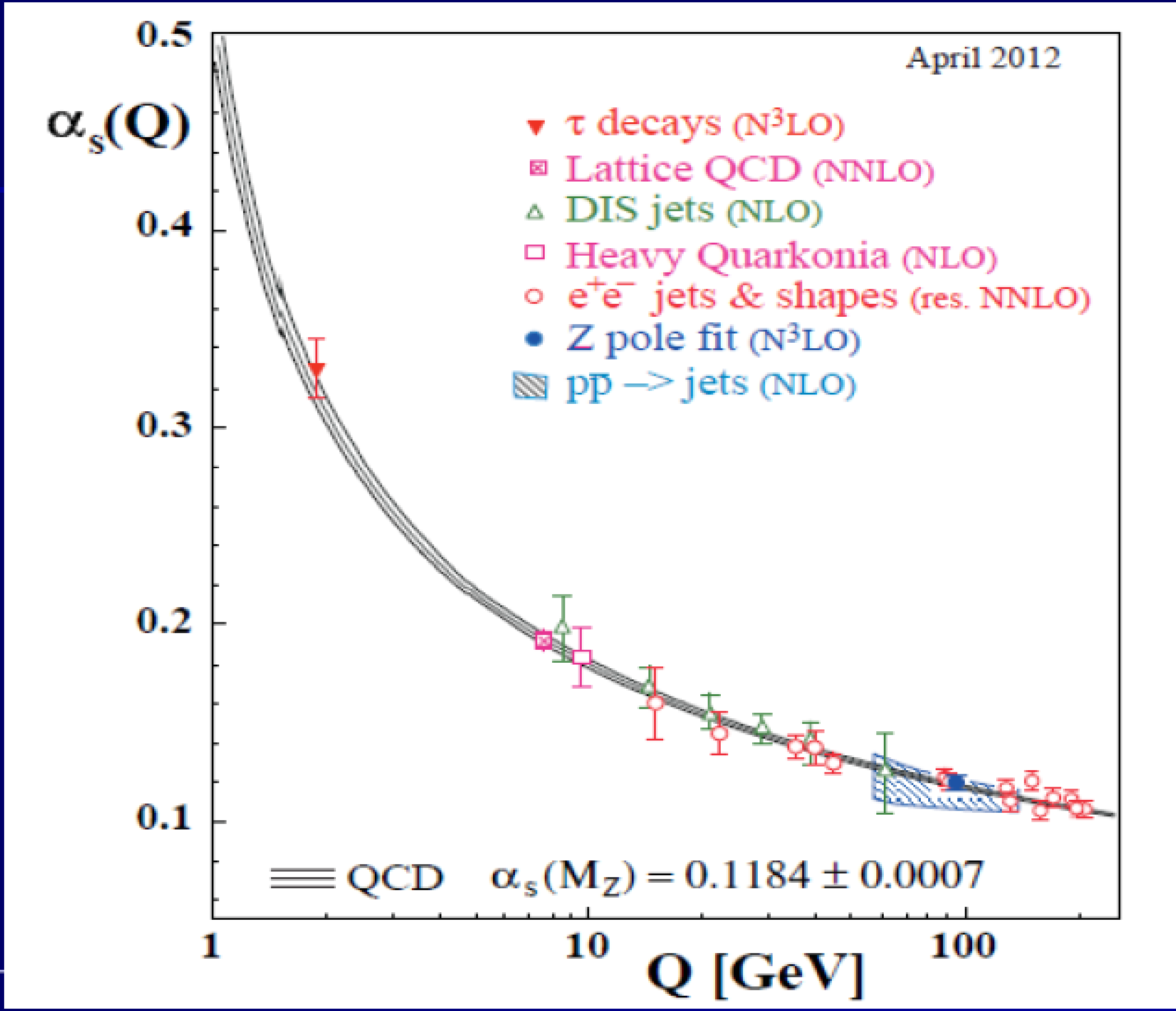
smaller distance

momentum (GeV)

Heisenberg principle

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

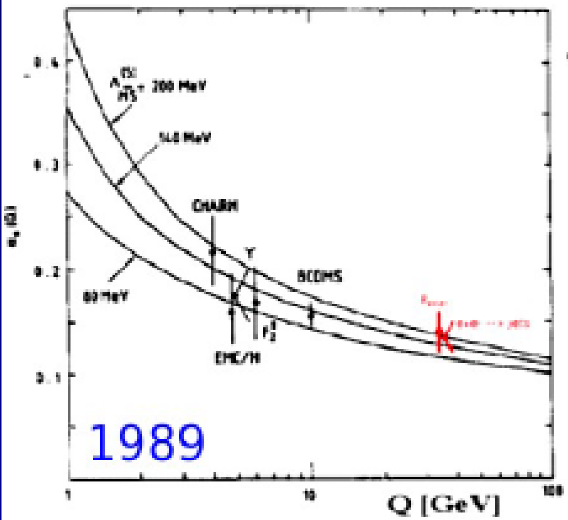
Running coupling constant April 2012



Determination of the QCD coupling α_s

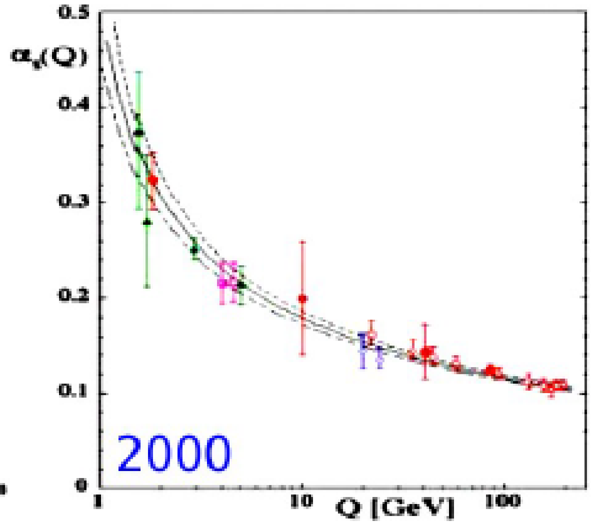
α_s = Single free parameter in QCD (in the $m_q \rightarrow 0$ limit). Determined at a given ref. scale (e.g. m_Z). Decreases as $\sim\ln(Q^2/\Lambda^2)$, with $\Lambda\sim0.25$ GeV

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



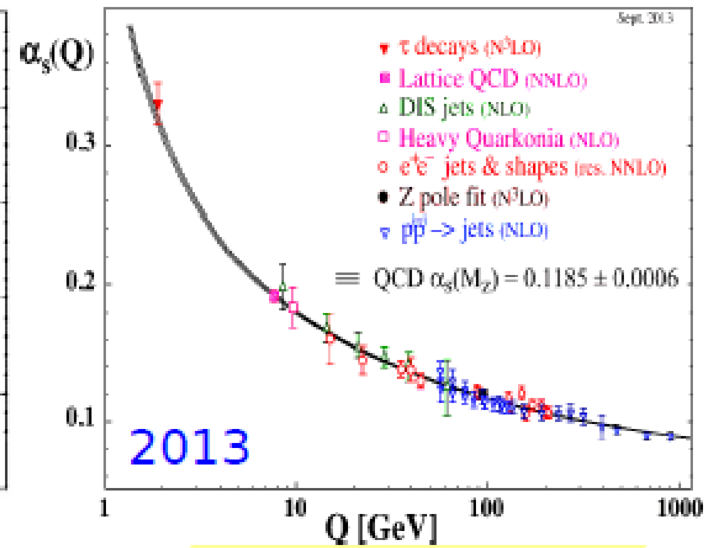
$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

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

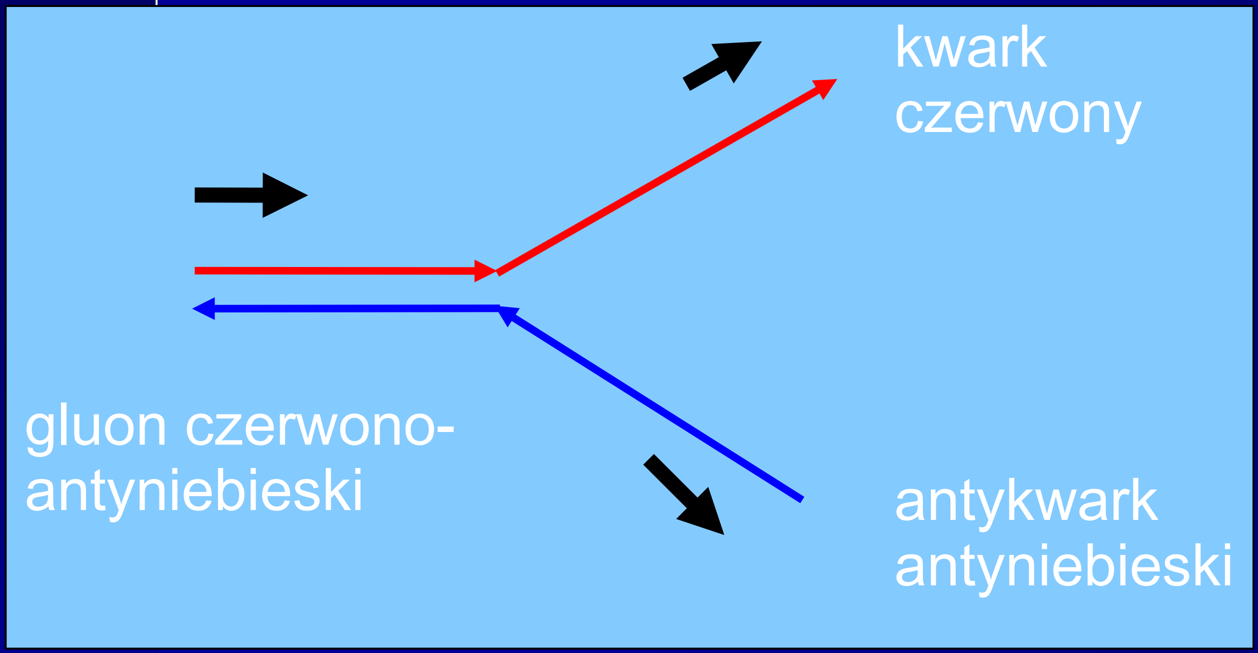


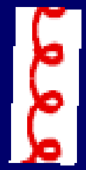
$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (NNLO)

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

Color interaction

Example gluon-> quark + antiquark



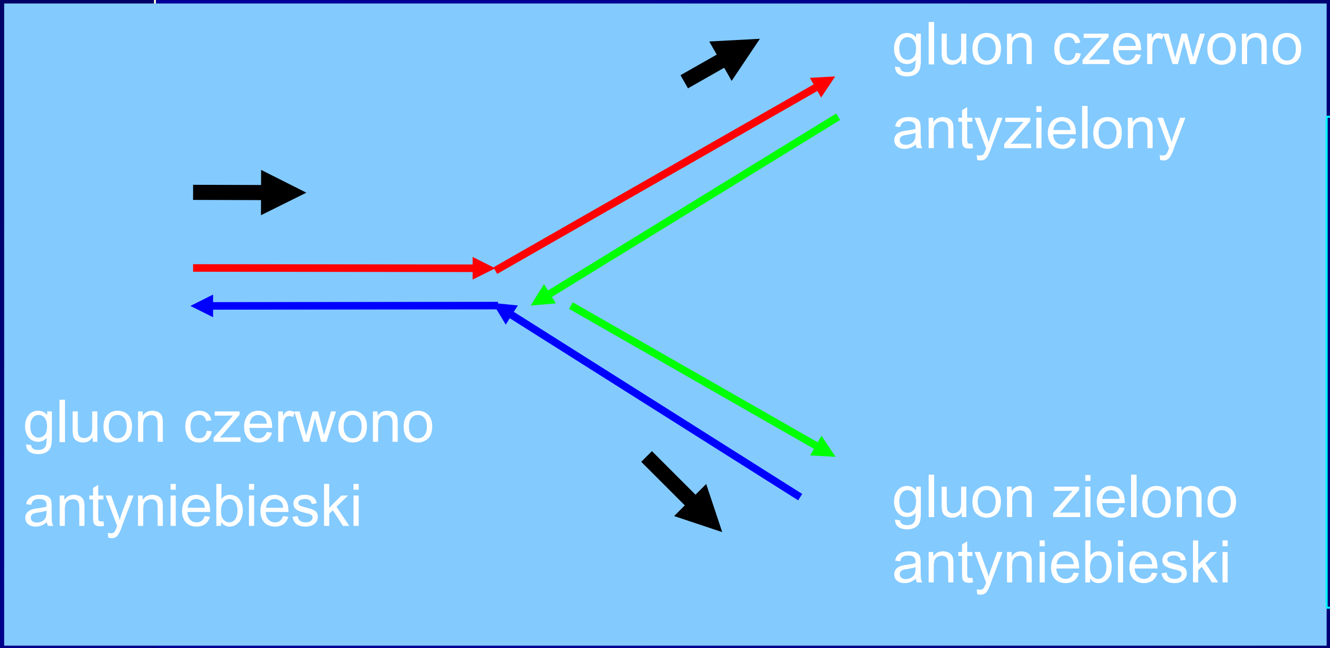
gluon line 

← here we follow a color

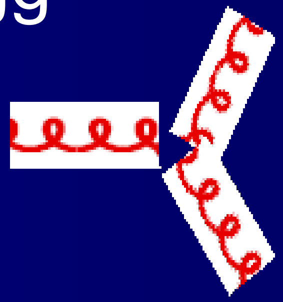
- color lines - flow of color (color conservation)
- black arrows – momenta of particles (momenta conservation)

Color interaction

Example gluon-> gluon+ gluon



ggg

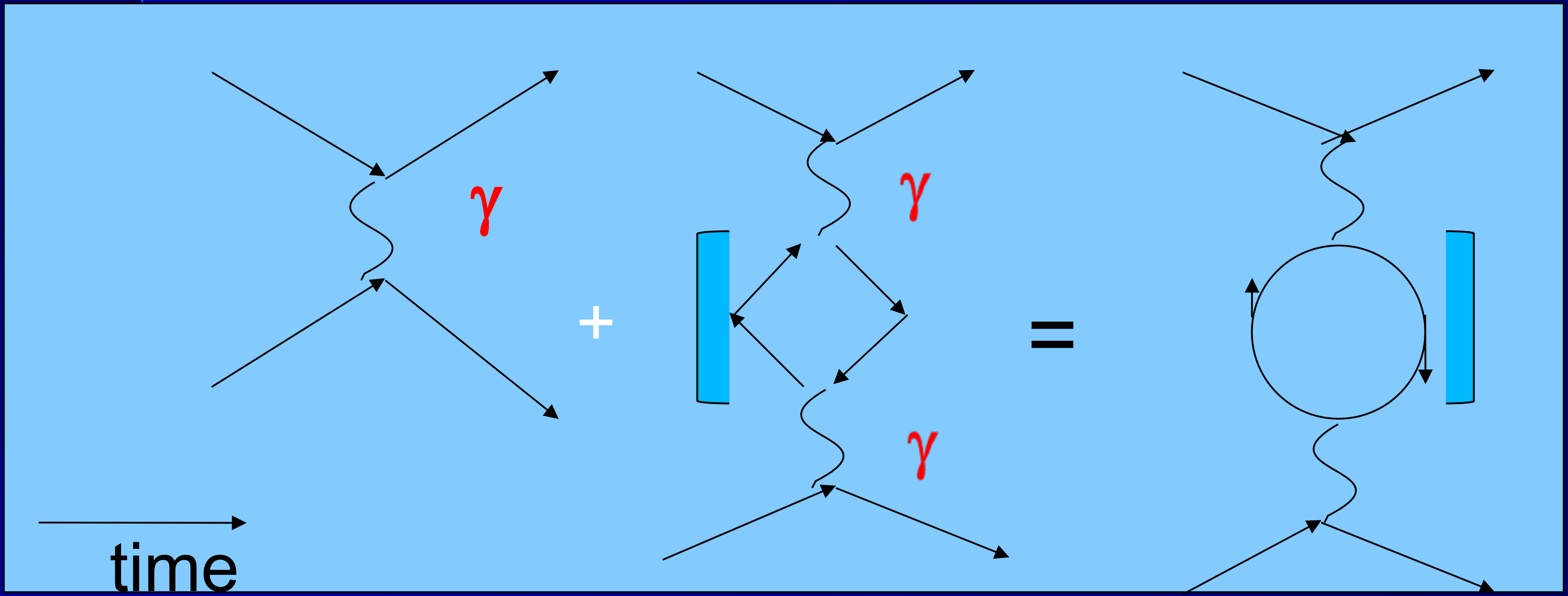


- color lines - flow of color (color conservation)
- black arrows – momenta of particles (momenta conservation)

Also gggg

Extraction of α

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

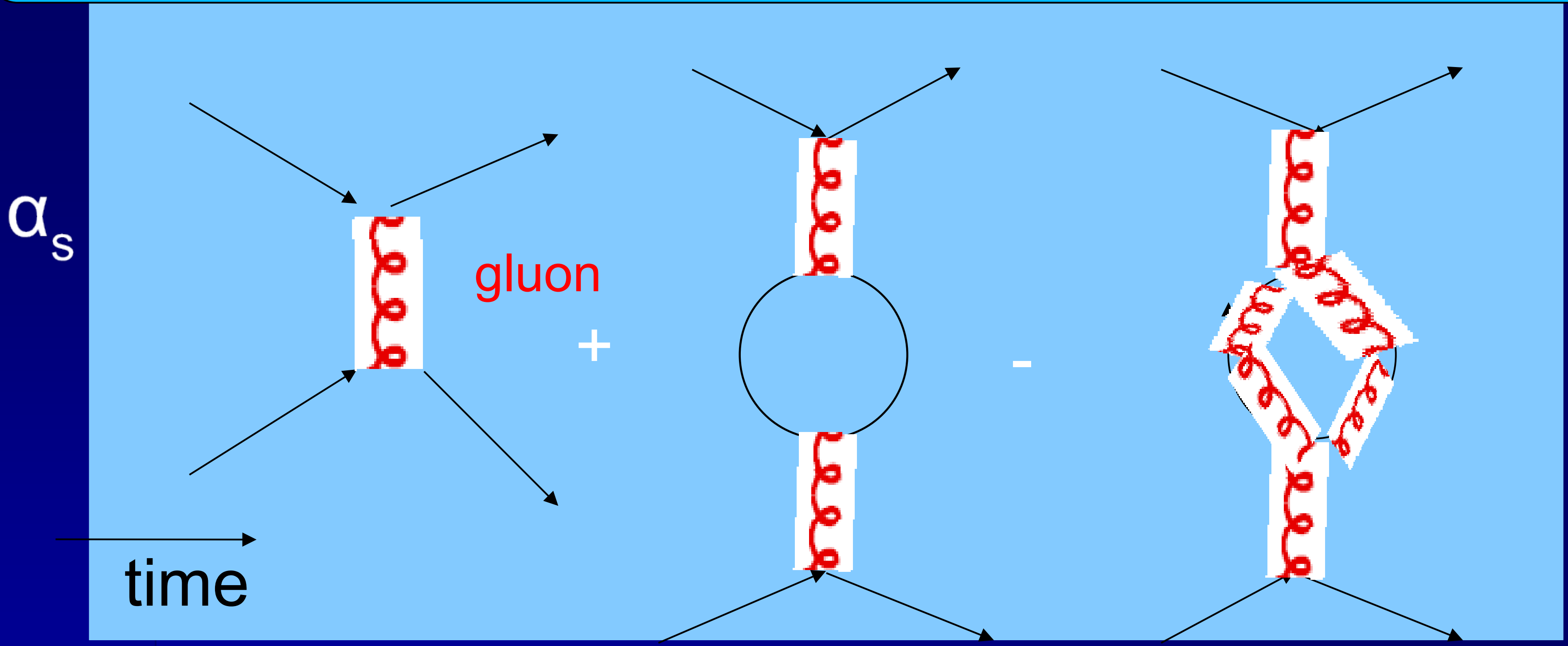


$$\alpha \times [1 + \text{corrections}(p)] = \alpha(p)$$

Electron loop $\to \alpha$ 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?

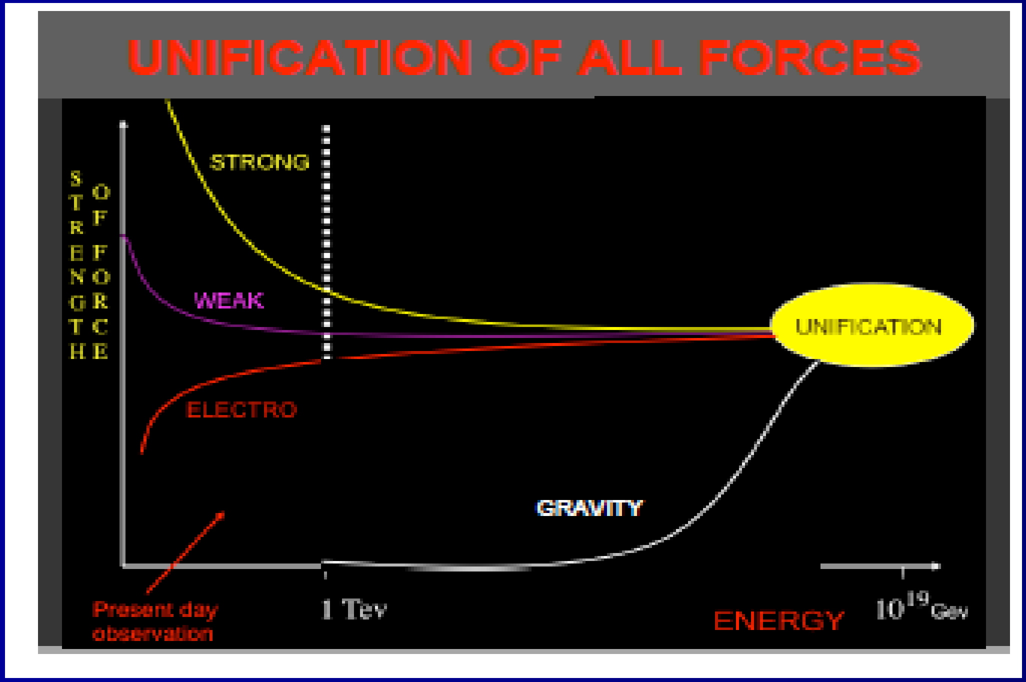
(‚Running couplings constants')!

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

α_s

α_w

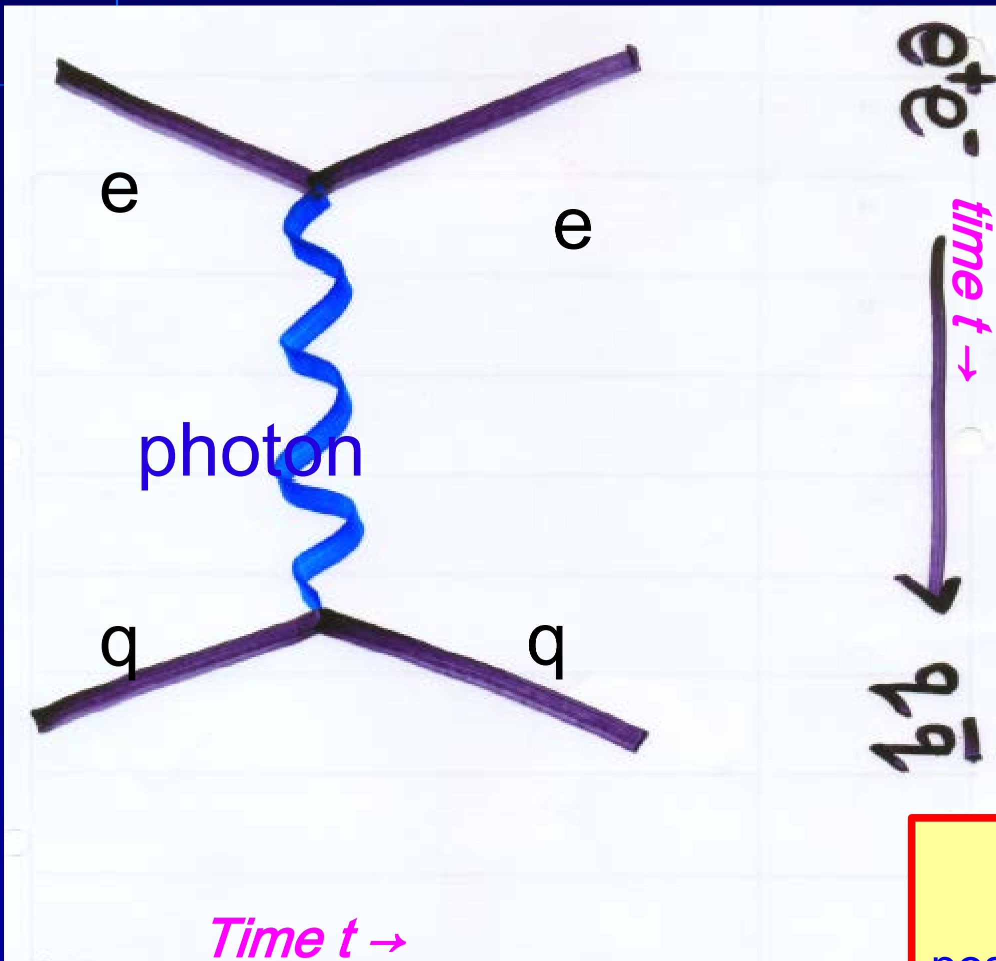
α_{el}



D. Gross, Photon 2005

Gravity ???

Crossing for fixed external particles



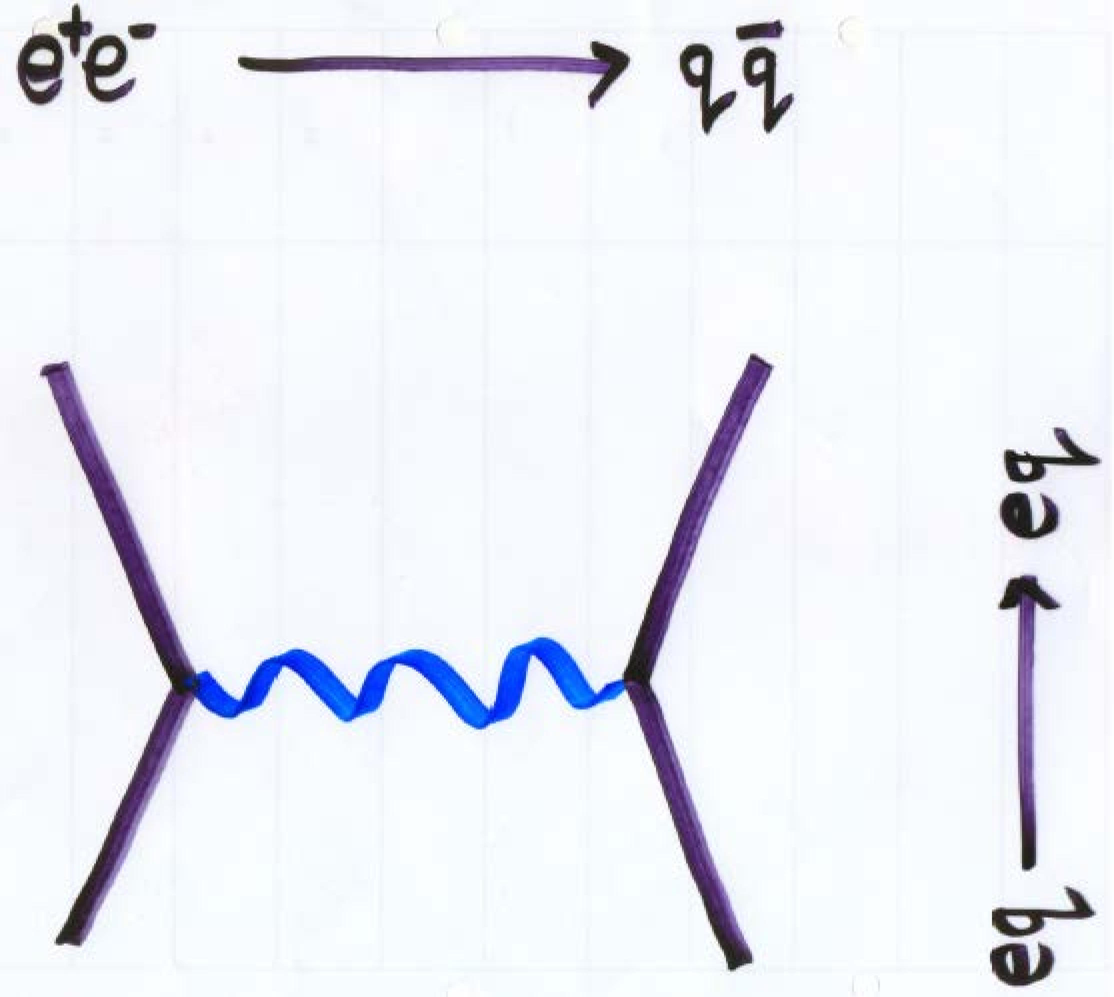
$e^- \, q \rightarrow e^- \, q$

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+

Question to lecture 7

- Is the range of weak forces larger or smaller then the range of strong interactions?
- Which particles interact using nuclear forces, which particles using the color forces .
- Is gravitation important in the microworld for low energies?
- What is the value of the Planck length? What is value of the Planck mass?
- Write 3 elementary acts of interactions between partcicles from the first family
- What is the value of subtle coupling constant for momentum $p \rightarrow 0$?, for momentum p= 100 GeV ?
- Do two electrons interact stronger or weaker for larger energies (momenta)?
- What is value of strong coupling constant for momentum (energy) about 1 GeV? For which momentum α_s is equal to 1/10?
- When quarks are more free: for small or large energies?
- Write 2 processes obtained by crossing of the scattering process $u\, d \rightarrow u\, d$
- To what quarks does the green-antired gluon decay ?
- What is the reason of a running of coupling constants? Why the subtle coupling constat is growing while the strong coupling constant decreases with a grow of energy?