Research in Perturbative QCD

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JLAB & ODU

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QCD Lagrangian

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \sum_{\text{flavors}} \bar{q}^k (i\gamma_\mu D^\mu + m_q)^{kl} q^l$$

Enjoy the beauty!

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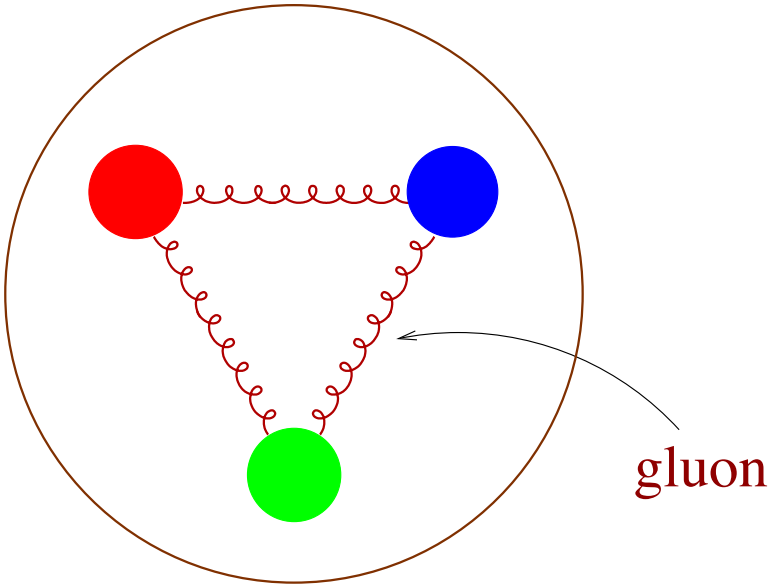
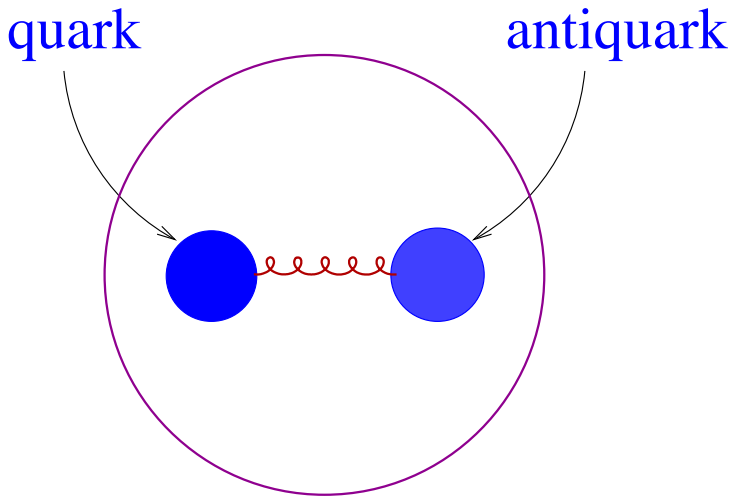
QCD describes:

- **Quarks and anti-quarks (spin $\frac{1}{2}$ fermions)**
  - 3 colors (red, blue, and green)
  - 6 flavors (u,d,s,c,b,t)
- **Gluons (spin 1 bosons)**
  - 8 colors - pairwise combinations of quark clolors (e.g. red and anti-blue)

Hadrons: colorless states of quarks bound by gluons



Baryons
(proton, neutron, ...)



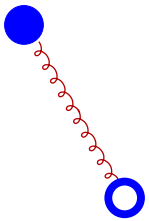
Mesons
(pion, kaon,ρ , ...)

Asymptotic Freedom and Quark Confinement

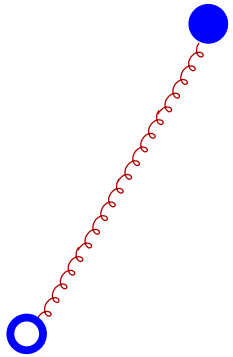
Short Distances/Large Momenta $\Rightarrow$ Small Coupling $\Rightarrow$ Asym. Freedom

Large Distances/Small Momenta $\Rightarrow$ Large Coupling $\Rightarrow$ Confinement

A toy model for a hadron - two quarks connected by a spring with a small k



at small distances force is weak – quarks are almost free



at large distances force increases – confinement

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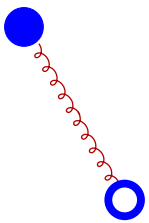

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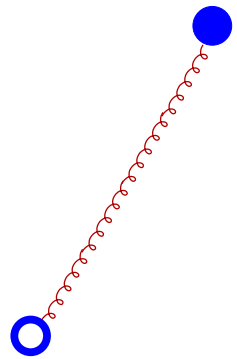

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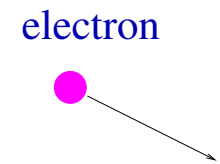
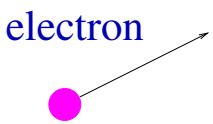
Perturbative QCD is a weak-coupling theory which resembles Quantum Electrodynamics (QED)

Scattering of electrons in QED





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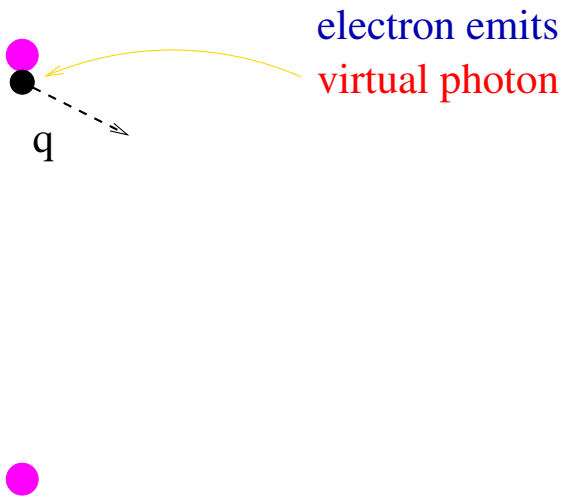

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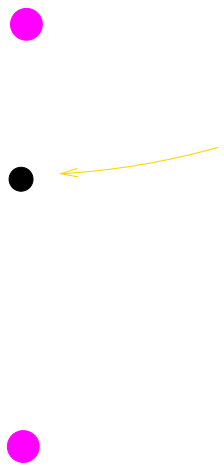

virtual photon with
virtuality $q_\mu q^\mu = q^2 = -Q^2$
lives for a short time $t \sim 1/Qc$

Scattering of electrons in QED

Scattering of electrons in QED

virtual photon is absorbred
by the second electron

Scattering of electrons in QED

Scattering of electrons in QED

Feynman diagram for electron scattering

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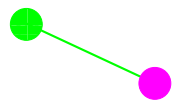

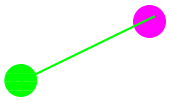

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Feynman diagram for electron scattering

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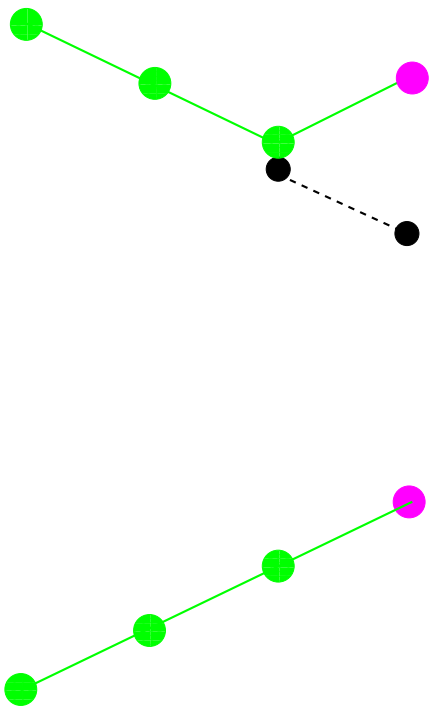

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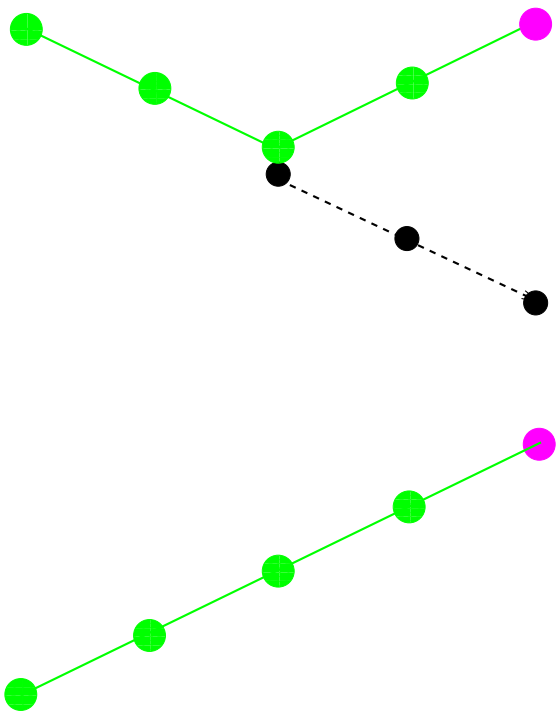

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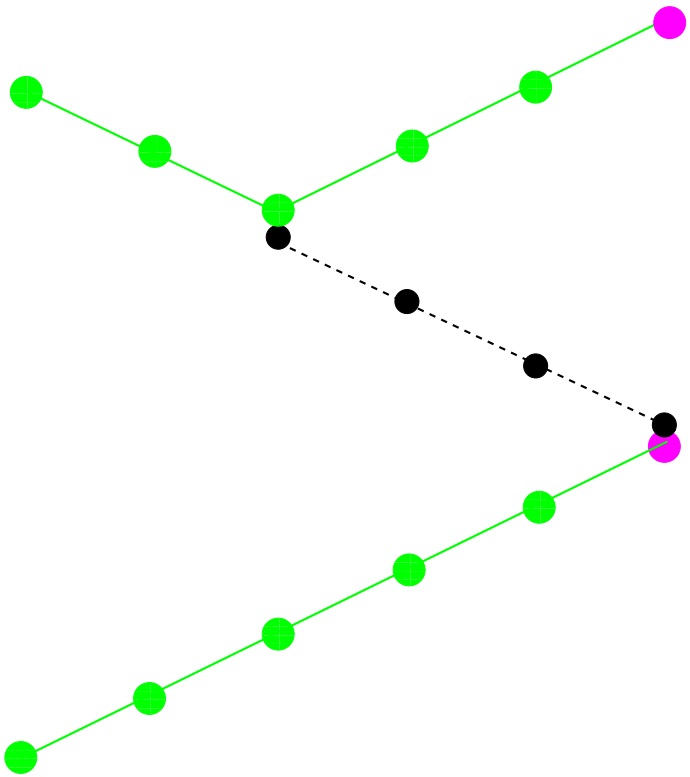

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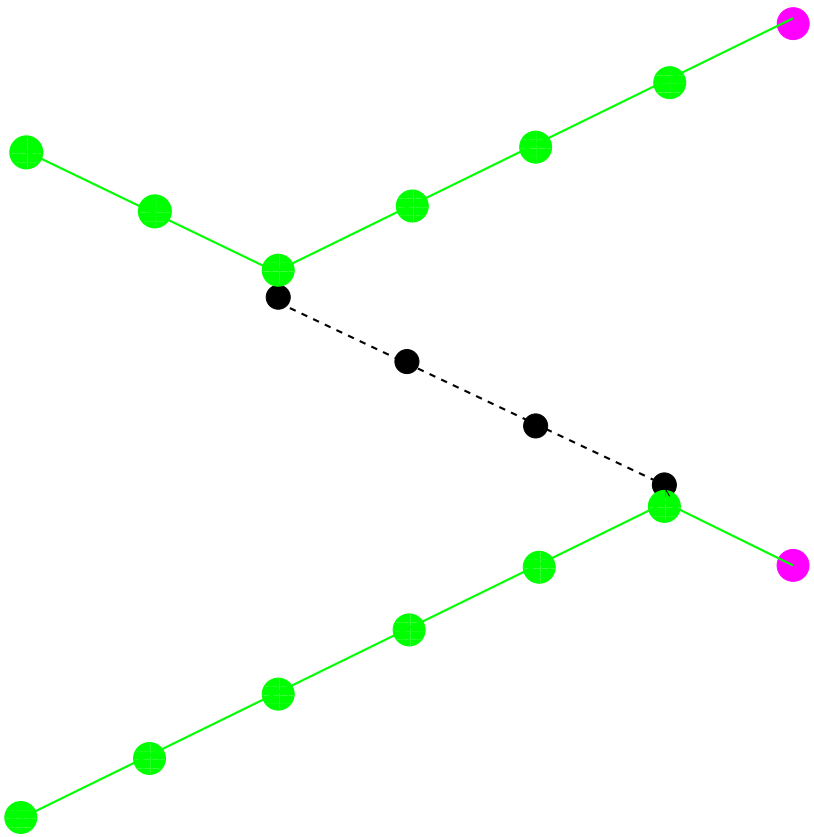

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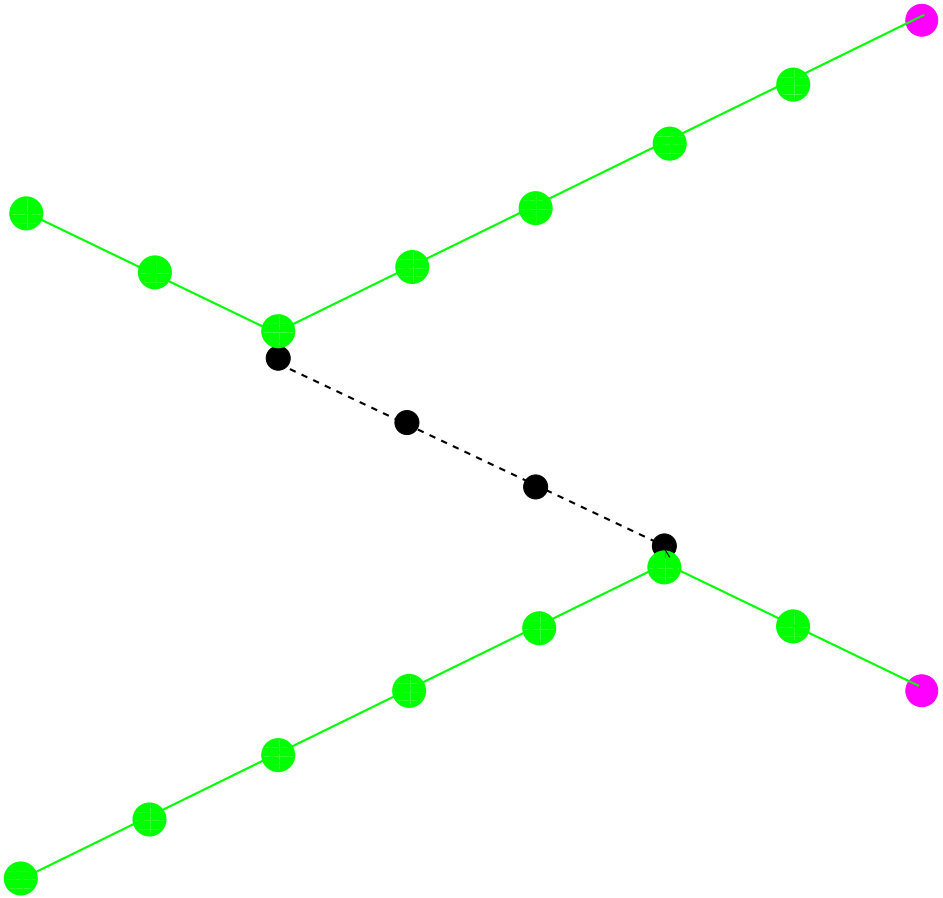

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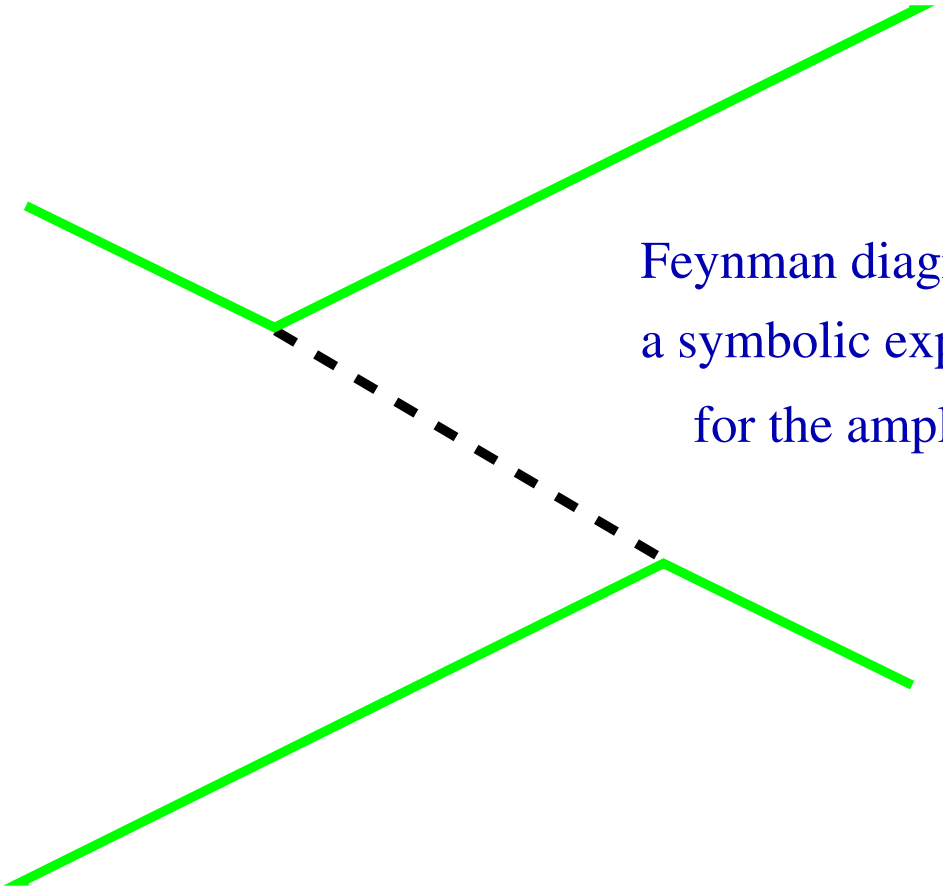
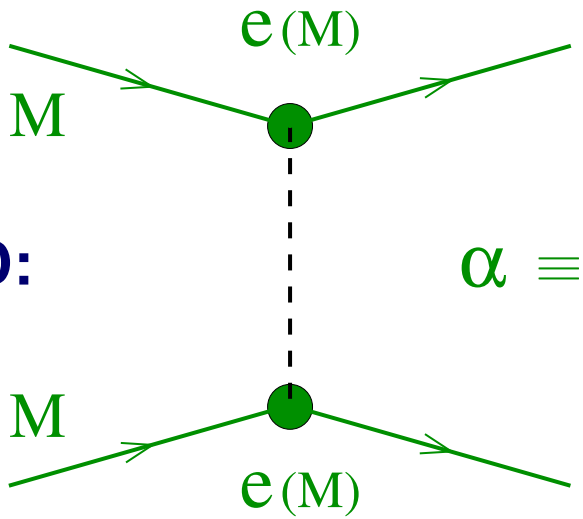


Feynman diagram:
a symbolic expression
for the amplitude

QCD *versus* QED



QED:

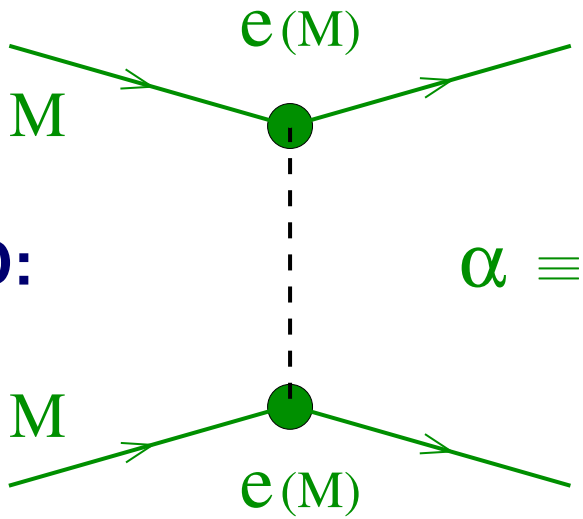
$$\alpha \equiv \frac{e^2}{4\pi\hbar c} \simeq \frac{1}{137}$$

The strength of the interaction depends on the mass scale

$$\alpha(M) = \frac{\alpha(m)}{1 - \frac{\alpha(m)}{3\pi} \ln \frac{M^2}{m^2}}$$

$\alpha(M)$ increases as $M \to \infty$

QCD *versus* QED



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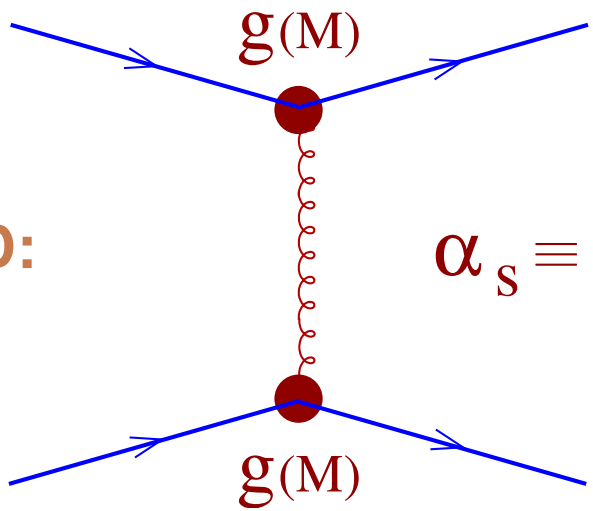


QCD:

$$\alpha_s \equiv \frac{g^2}{4\pi\hbar c}$$

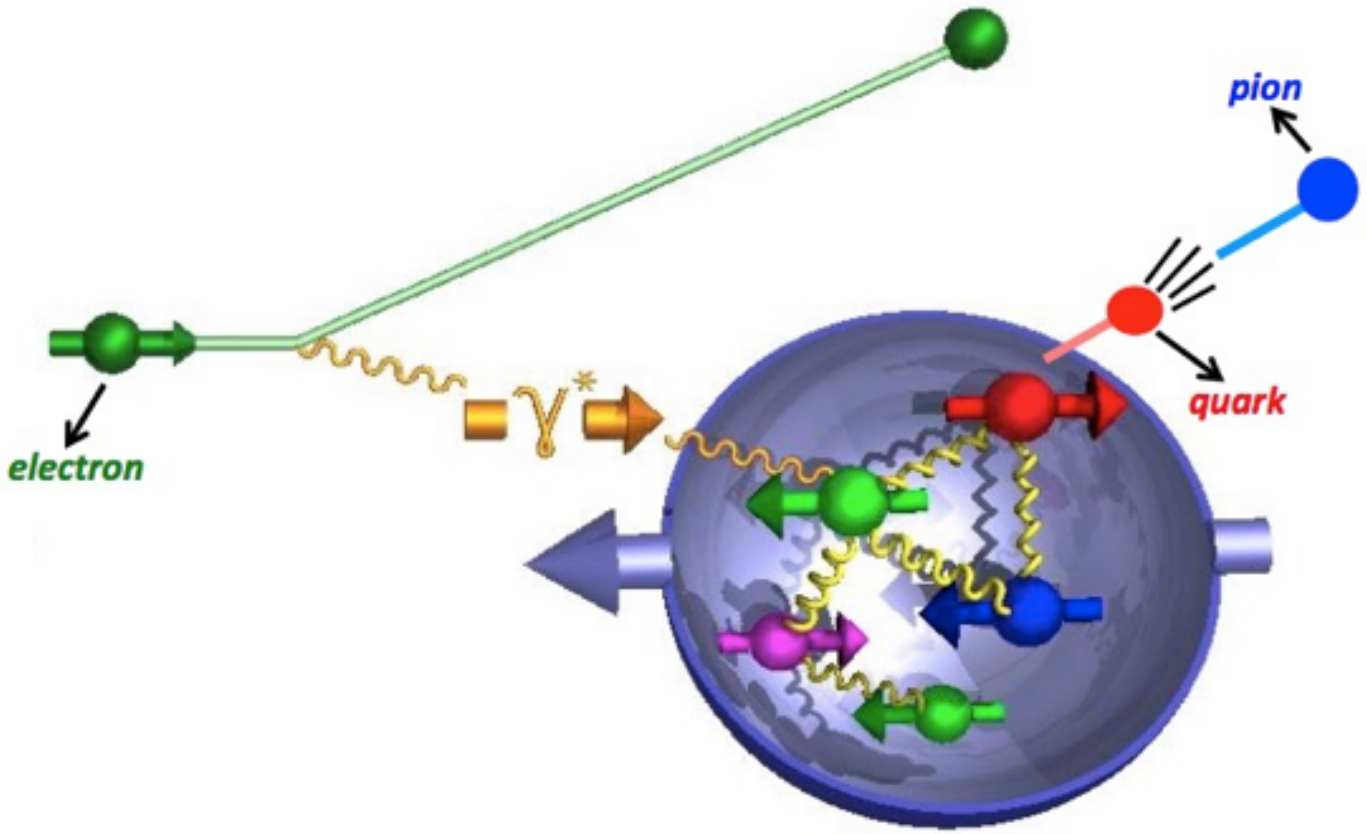
$$\alpha_s(M) = \frac{\alpha_s(m)}{1 + \frac{9\alpha_s(m)}{4\pi} \ln \frac{M^2}{m^2}}$$

$\Rightarrow \alpha(M) \to 0$ as $M \to \infty$

Asymptotic freedom

Gross, Politzer, Wilczek (1973)
Nobel Prize 2004

Deep inelastic scattering: modern Rutherford experiment



DIS - space-time picture and Feynman diagram

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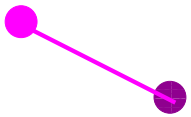

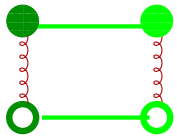

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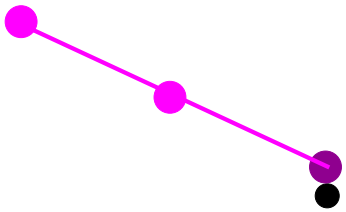

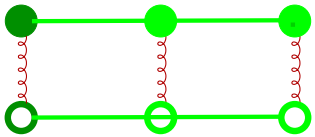

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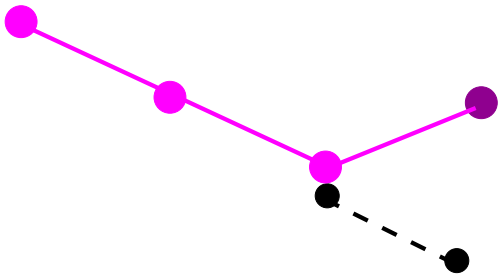

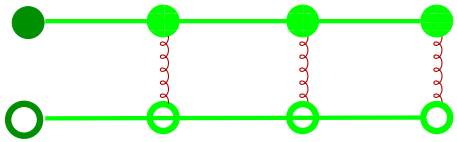

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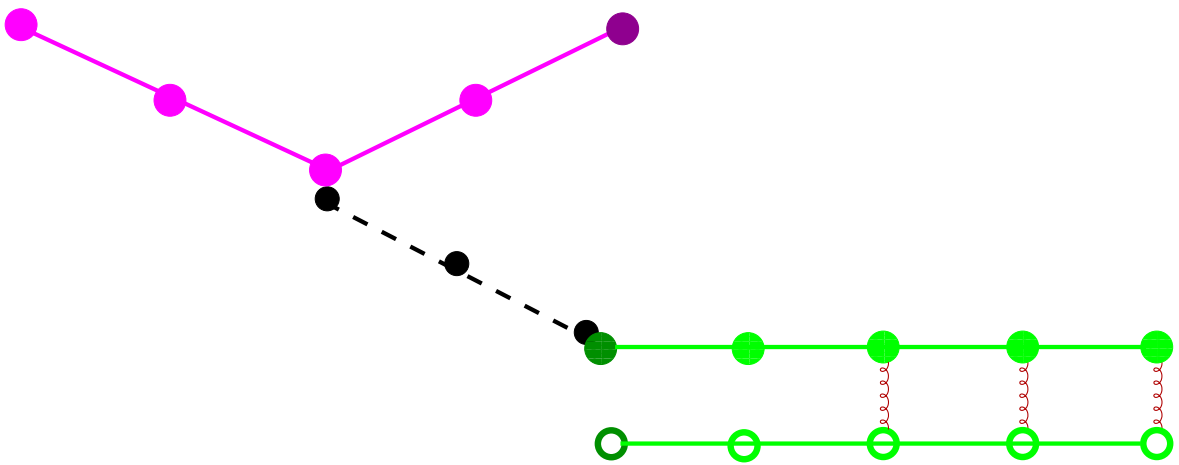

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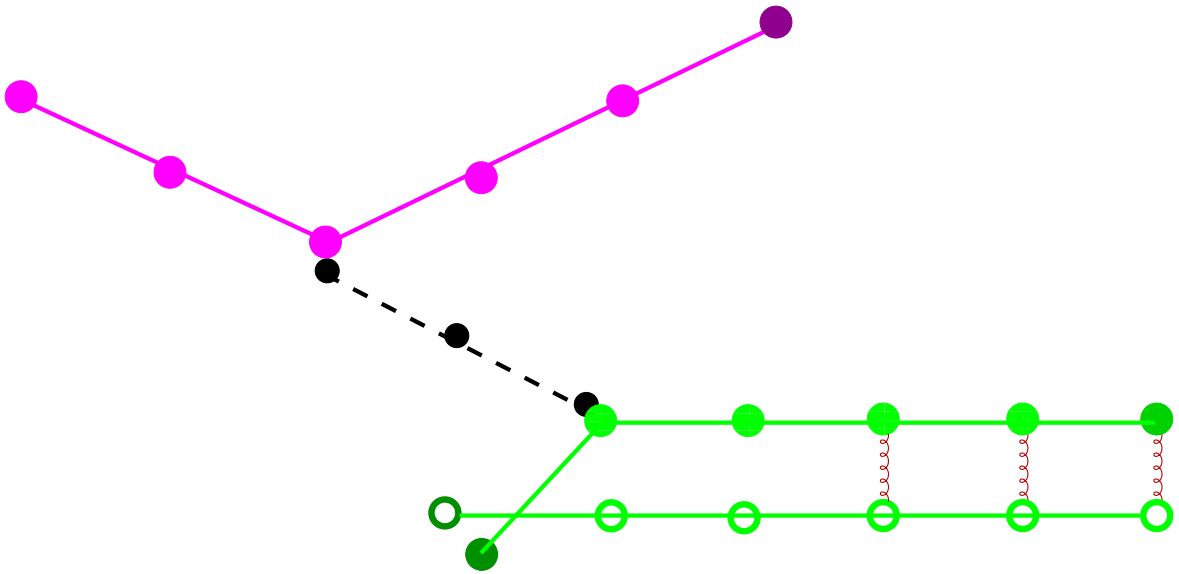

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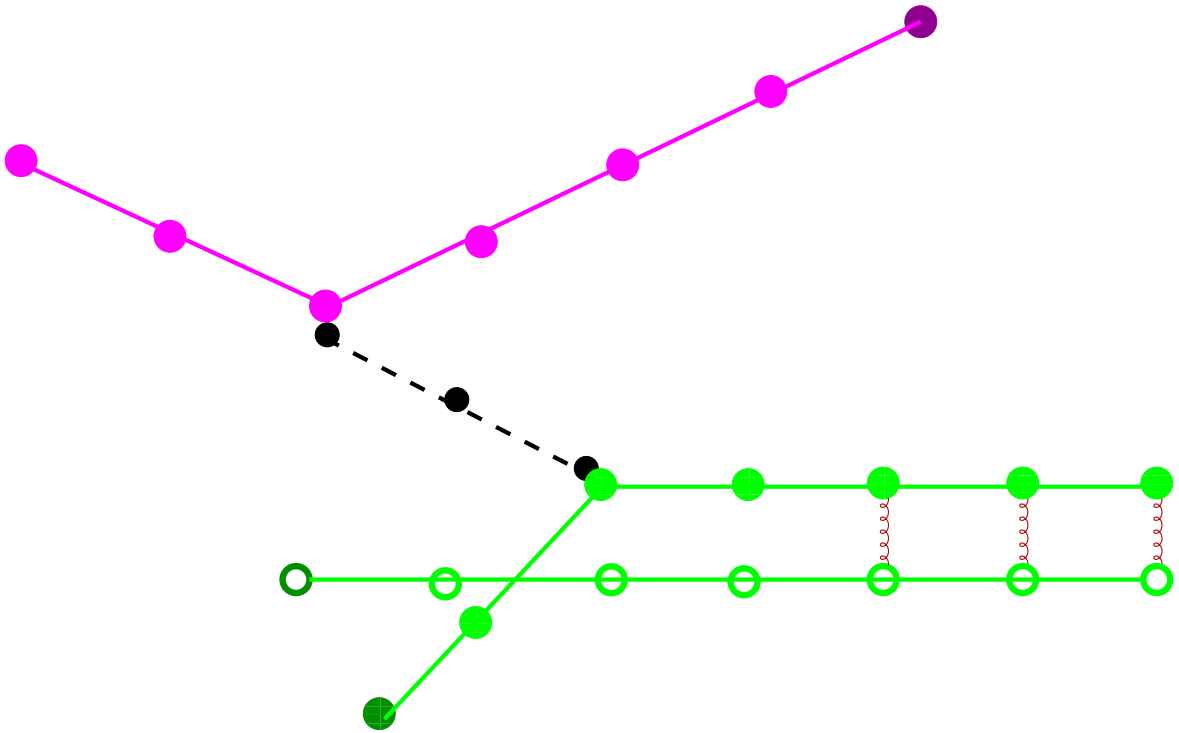

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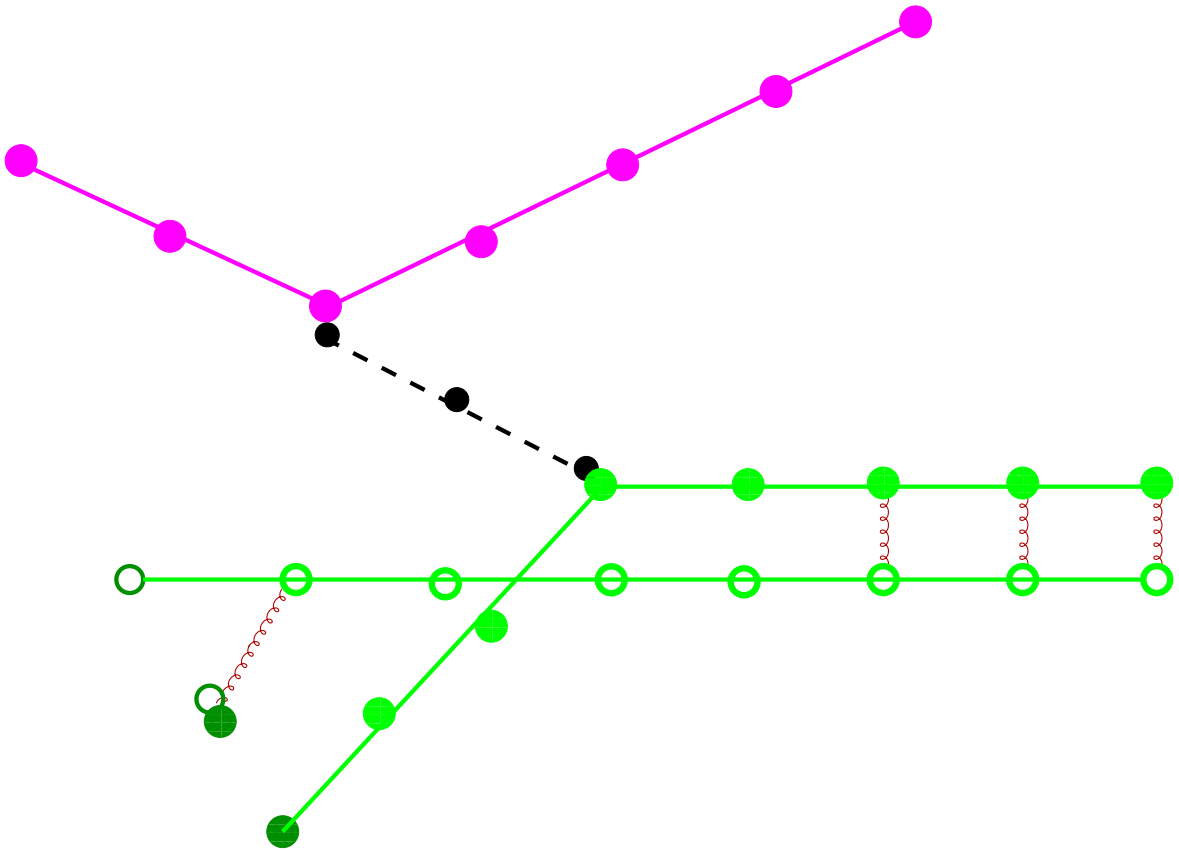

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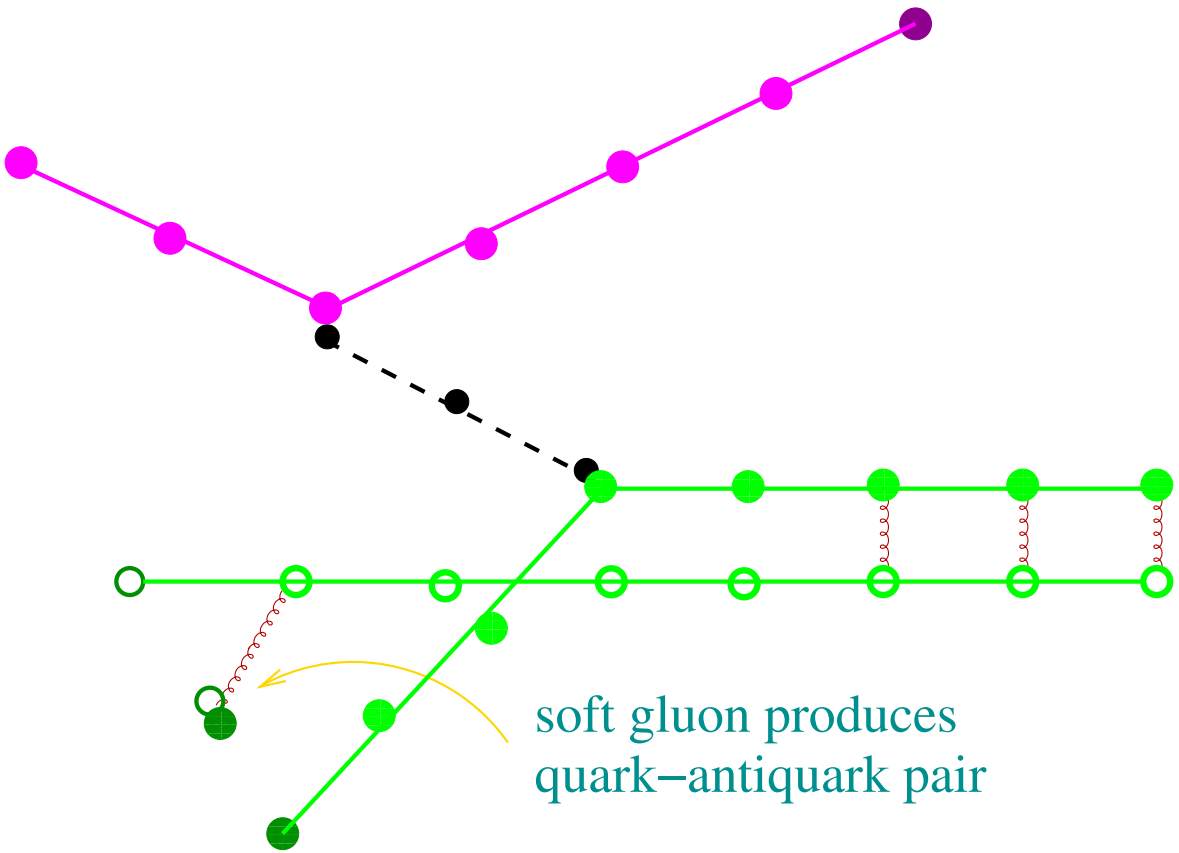

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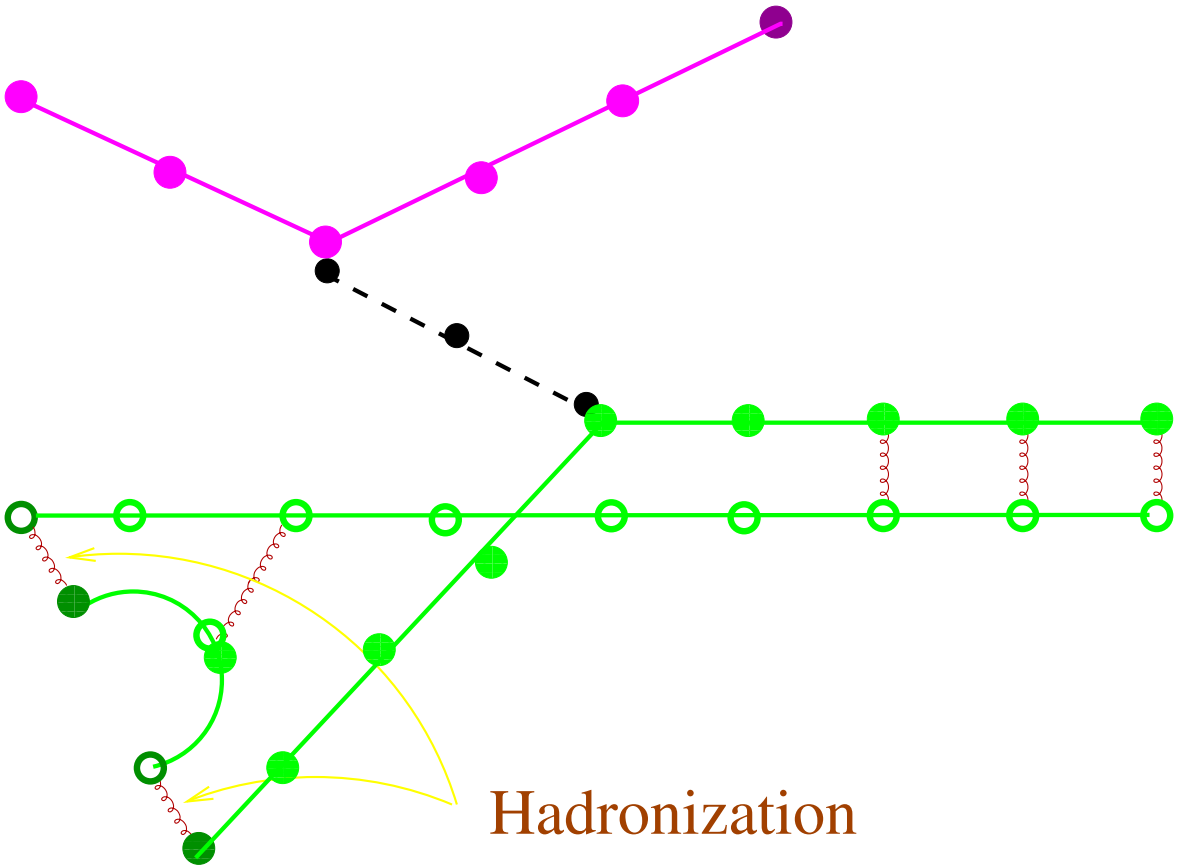

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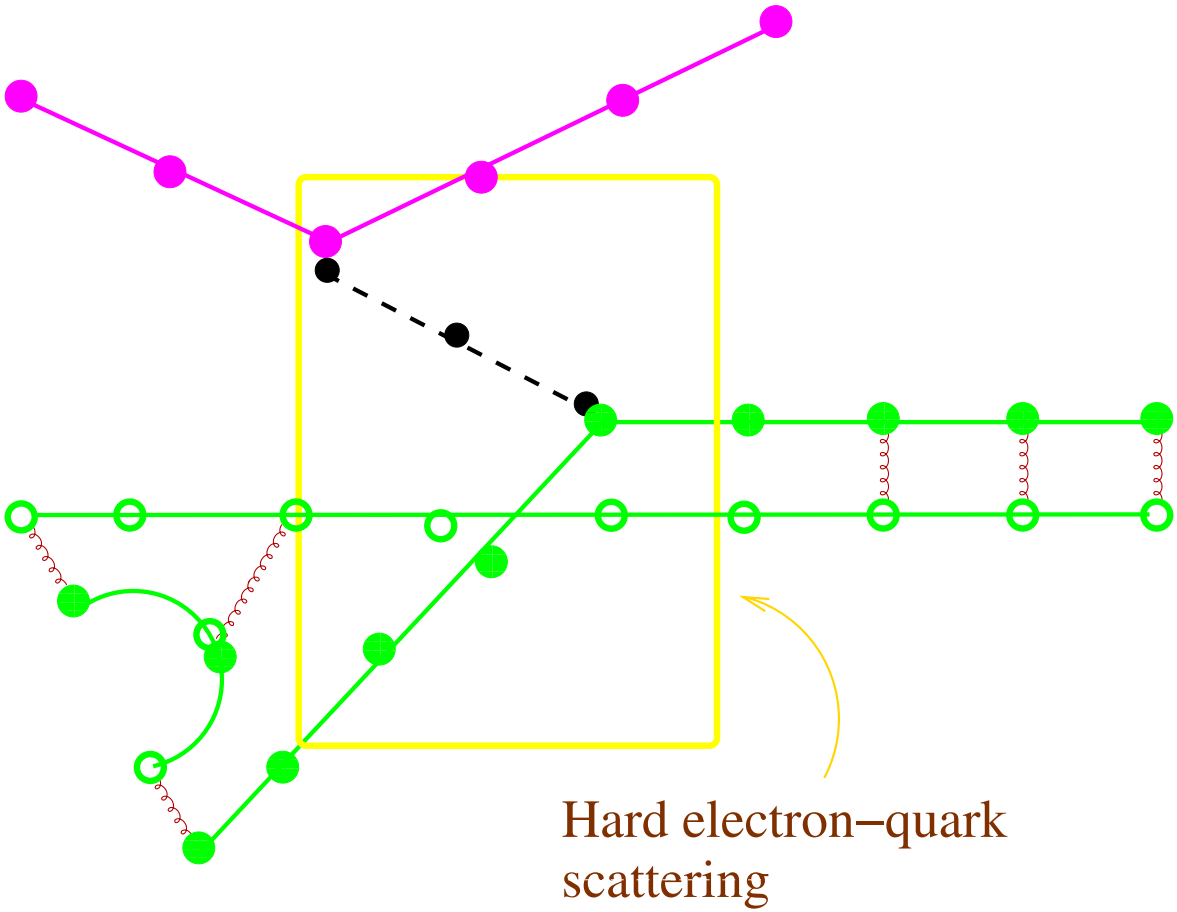

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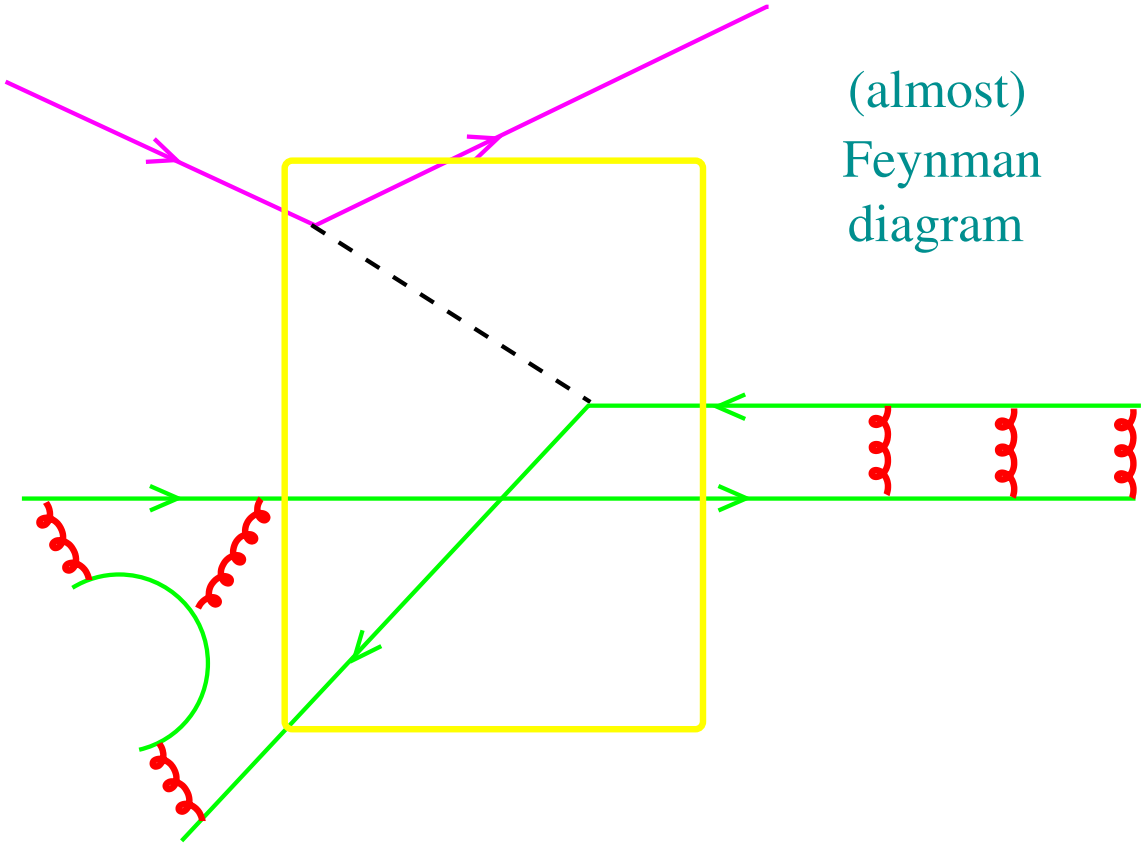
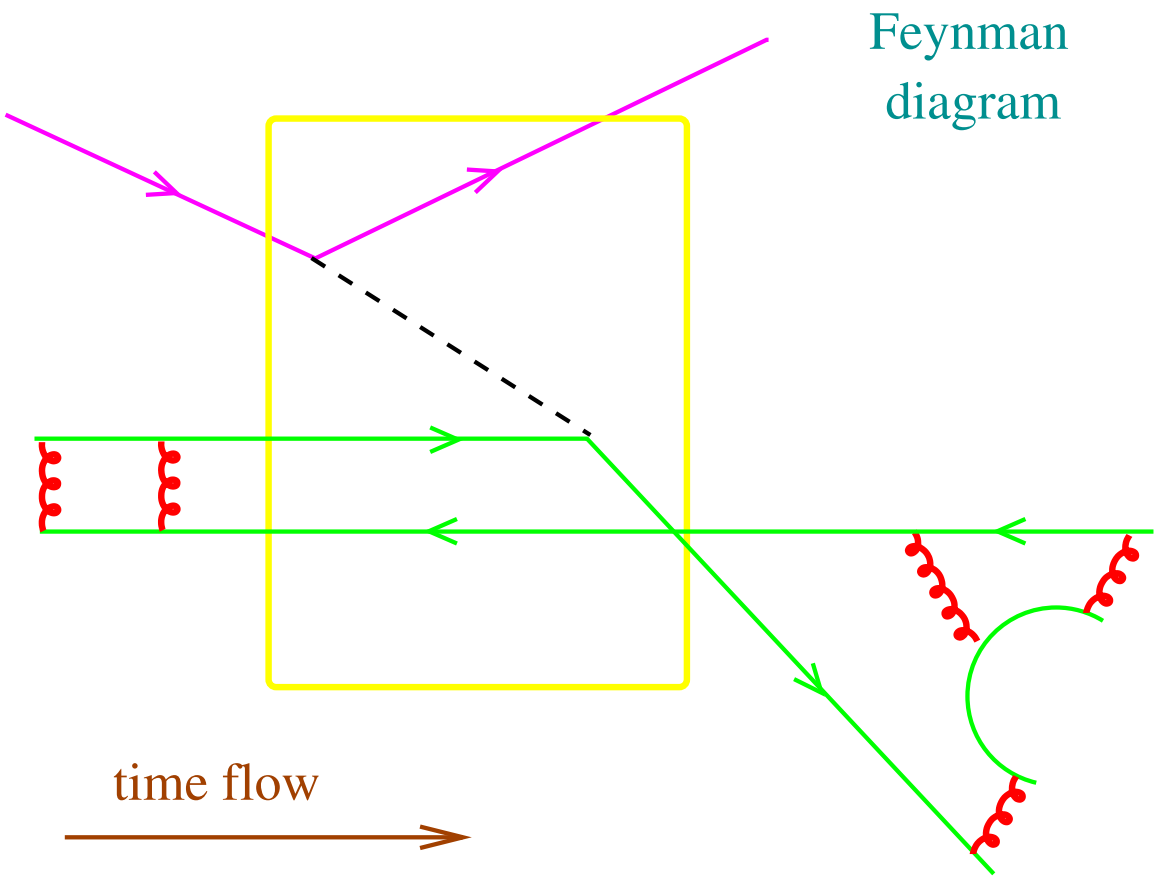
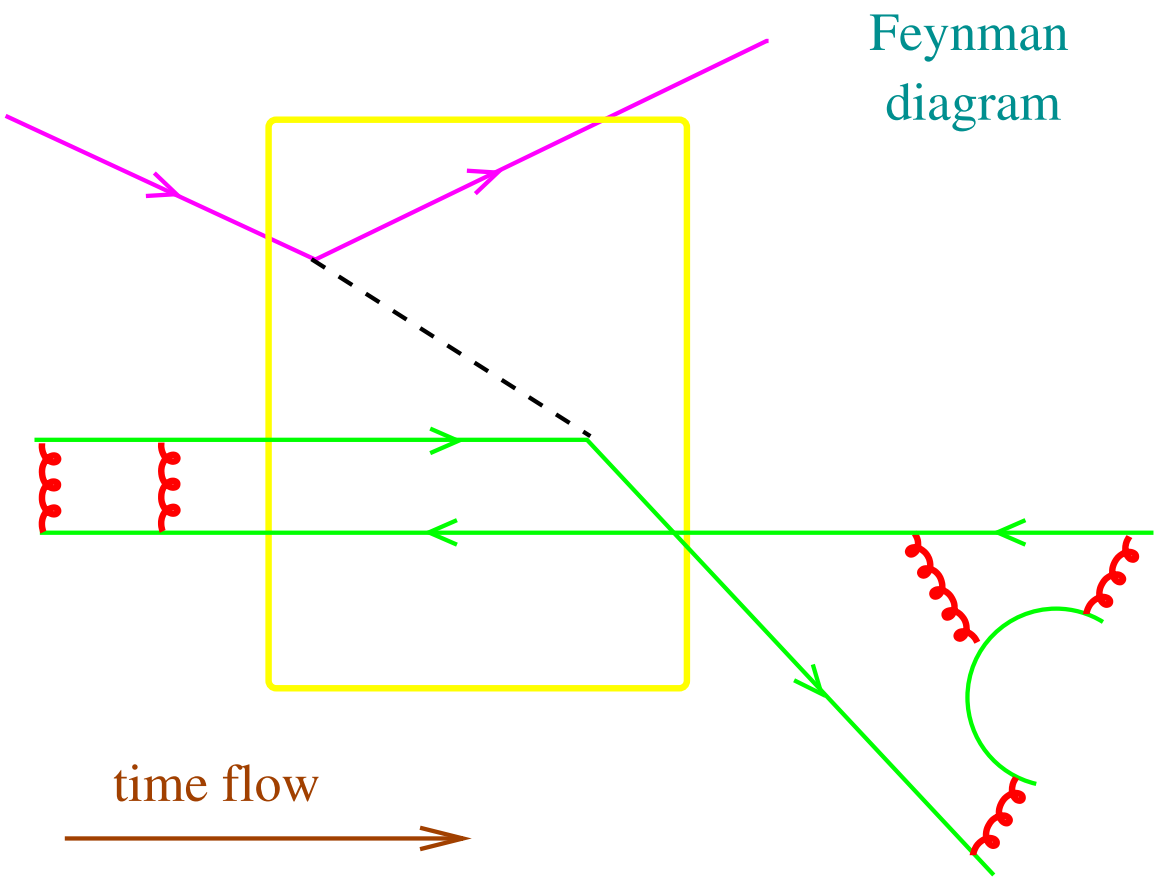


(almost)
Feynman
diagram

DIS - space-time picture and Feynman diagram



Factorization

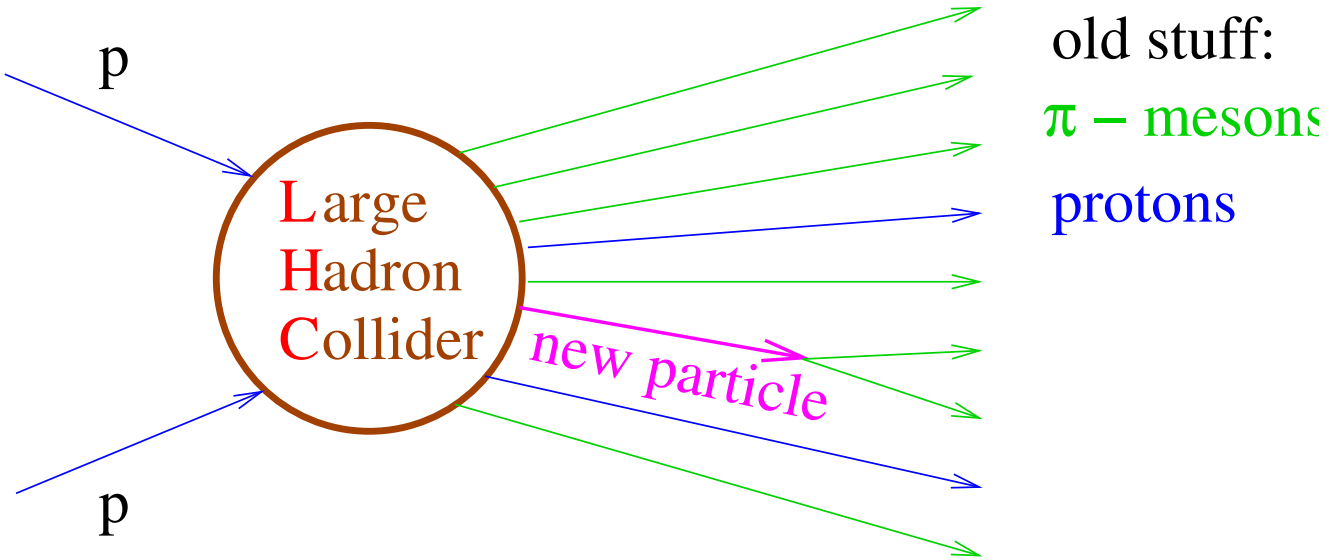


pQCD can calculate the amplitudes inside the yellow box. The rest is up to lattice QCD or models of hadron structure.

Uses of pQCD: (1) Search for new physics

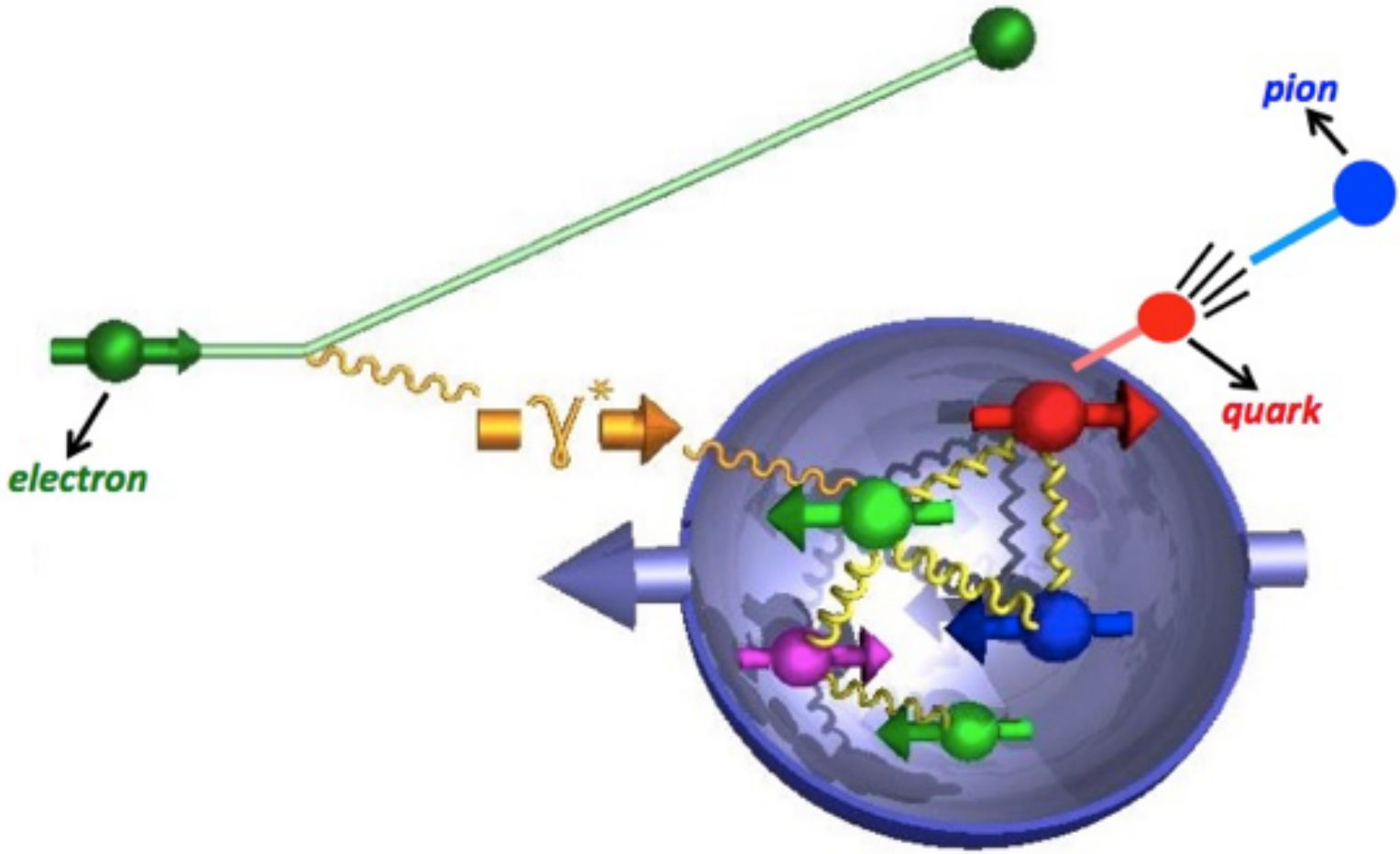
Heisenberg uncertainty principle: $\Delta x = \frac{\hbar}{p} = \frac{\hbar c}{E}$

LHC: E=14 TeV $\rightarrow$ distances $\sim 10^{-18}$cm $\Rightarrow$ pQCD is OK.



To separate a "new physics signal" from the "old" background one needs to understand the behavior of QCD cross sections at large energies

Uses of pQCD: (2) Probing the structure of hadrons



Electron- Ion Collider - 2025?

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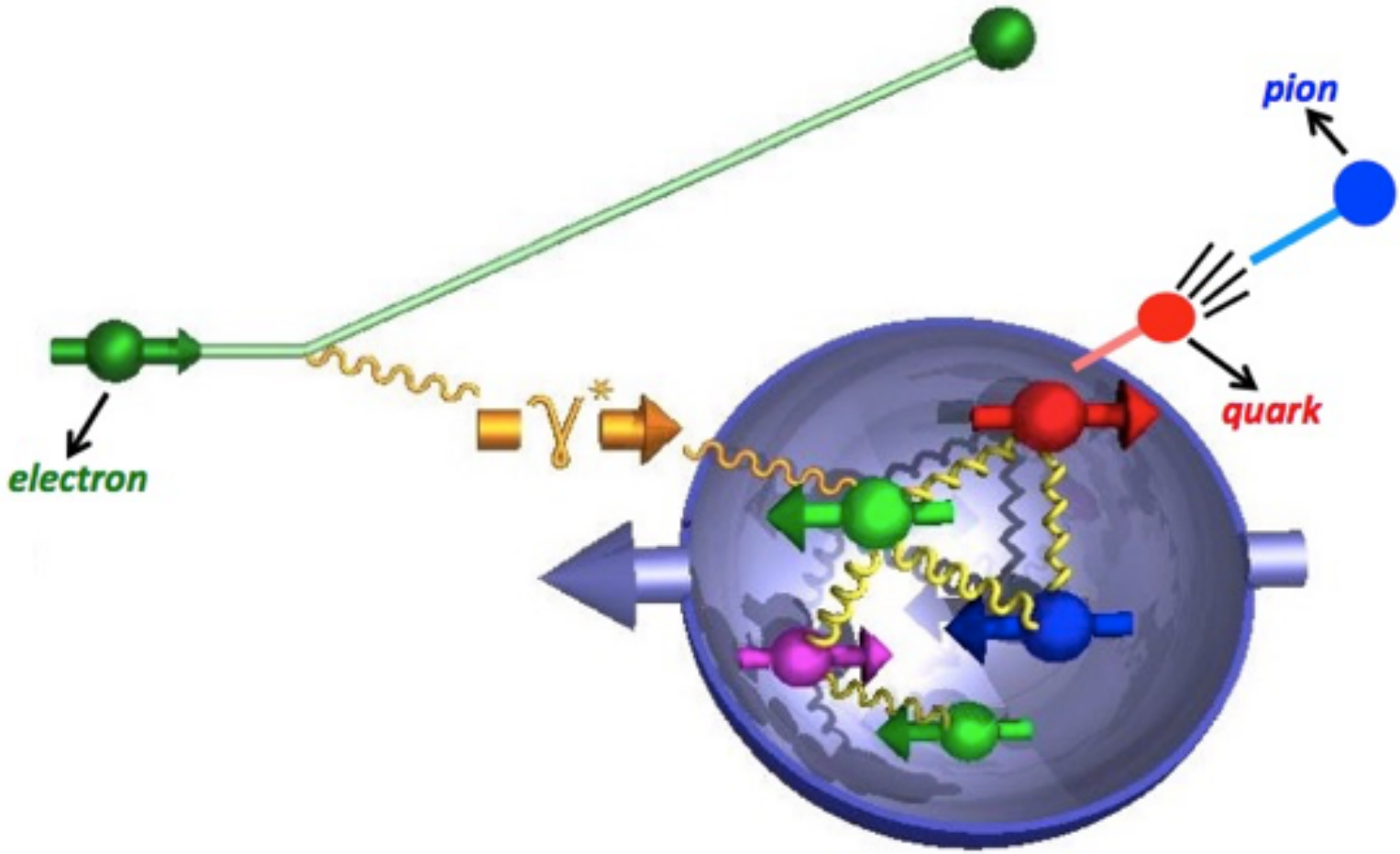

Electron- Ion Collider - 2025?

Thank you for attention!