Strong interactions: from the beginning to the NICA collider



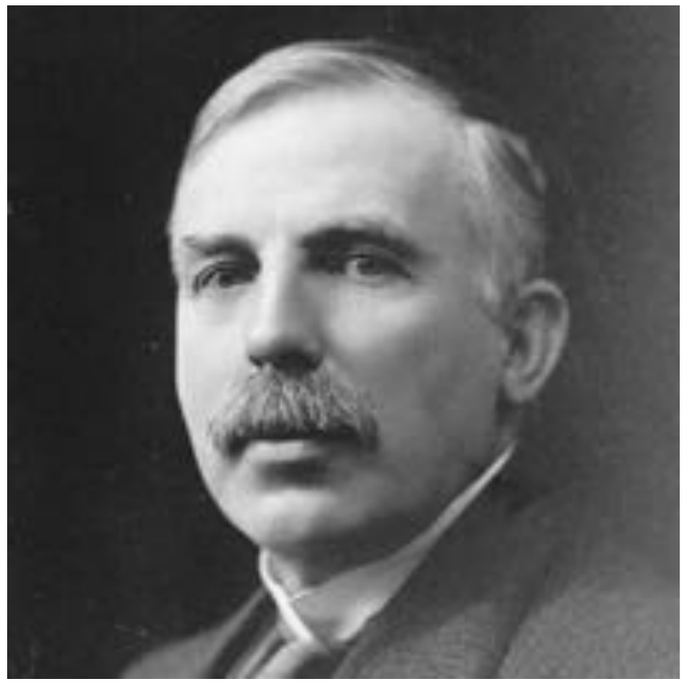
A. Guskov

avg@jinr.ru

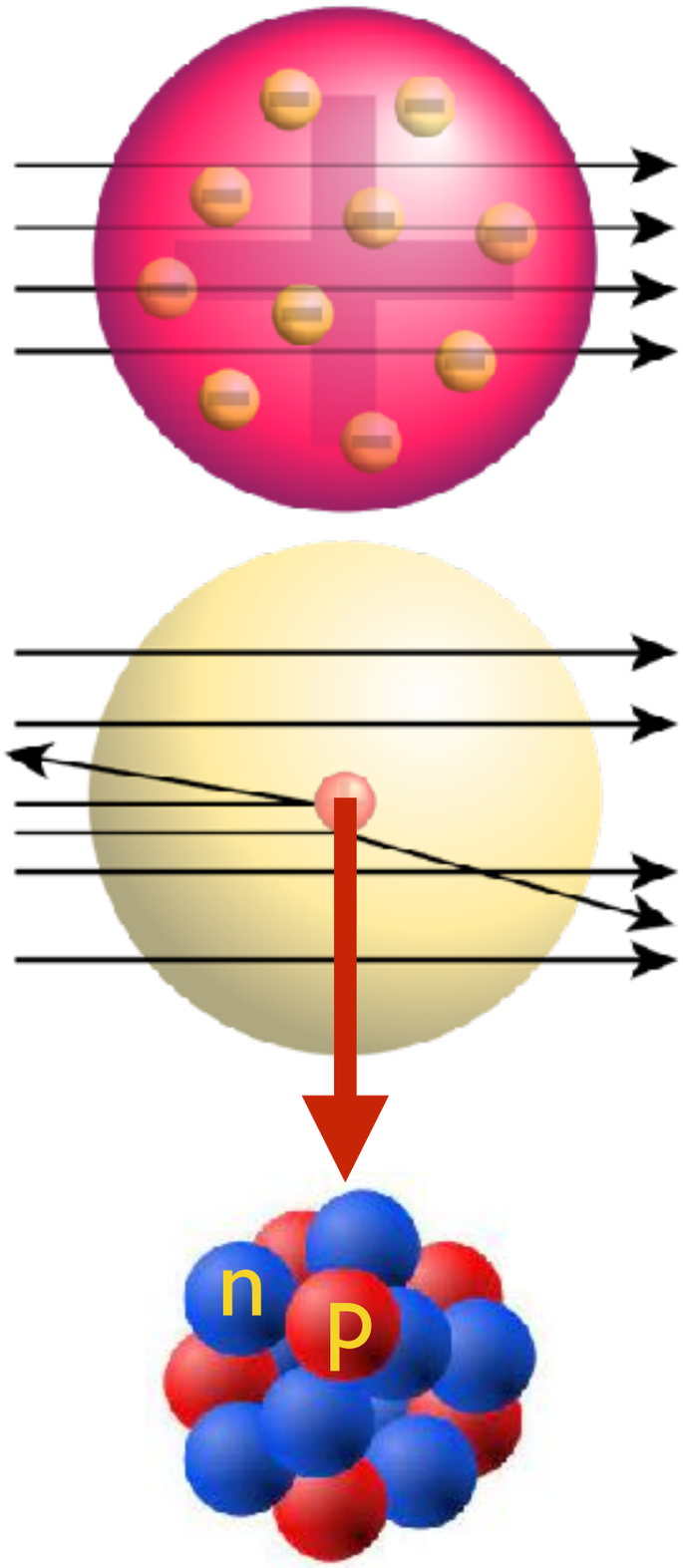
Outline

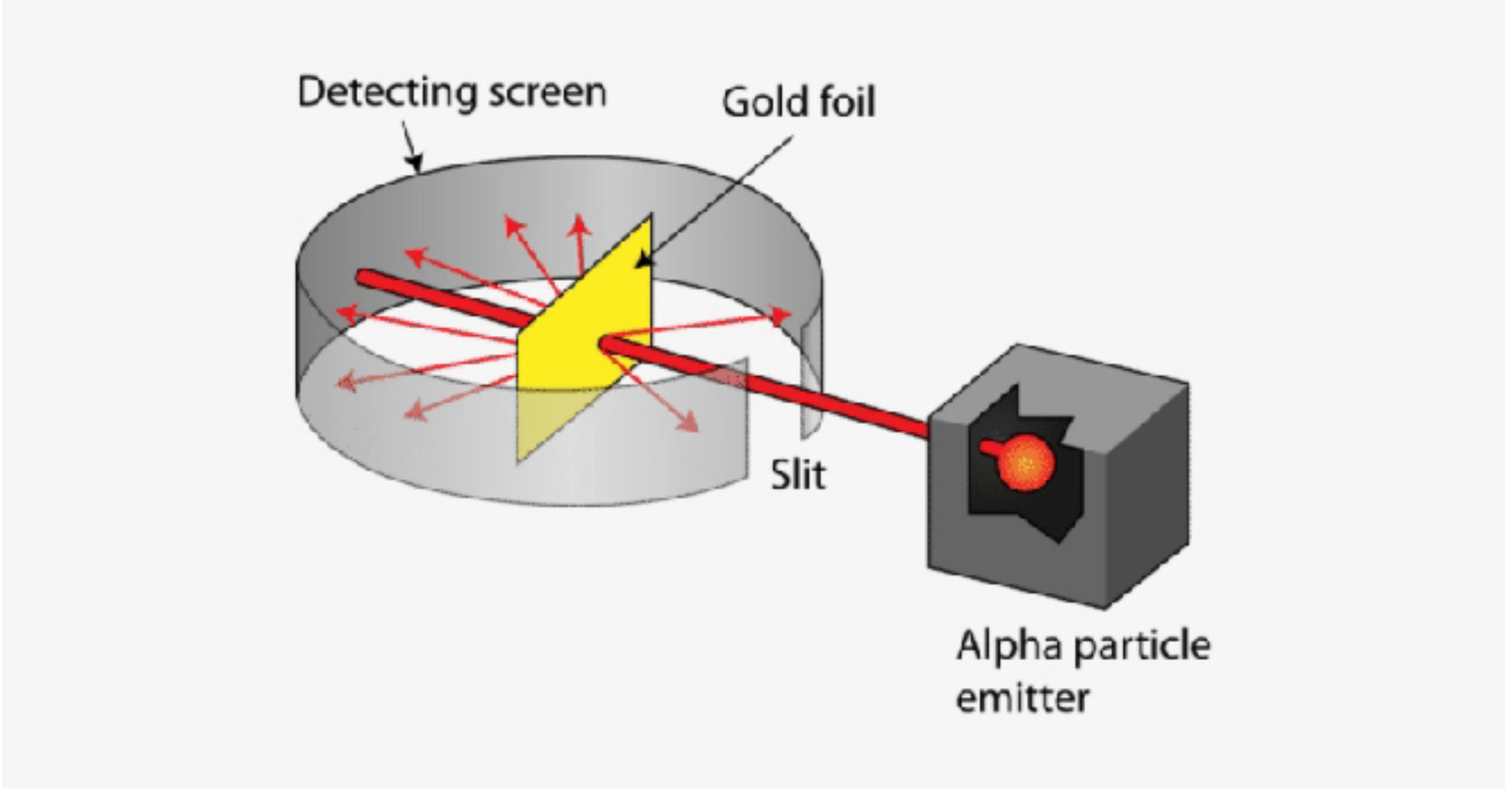
- Strong interaction: history
- QCD - true theory of strong interactions
- Actual problems of QCD
- QCD and beyond
- NICA as a factory for tests of QCD

Discovery of the nucleus



E. Rutherford
1909-1913

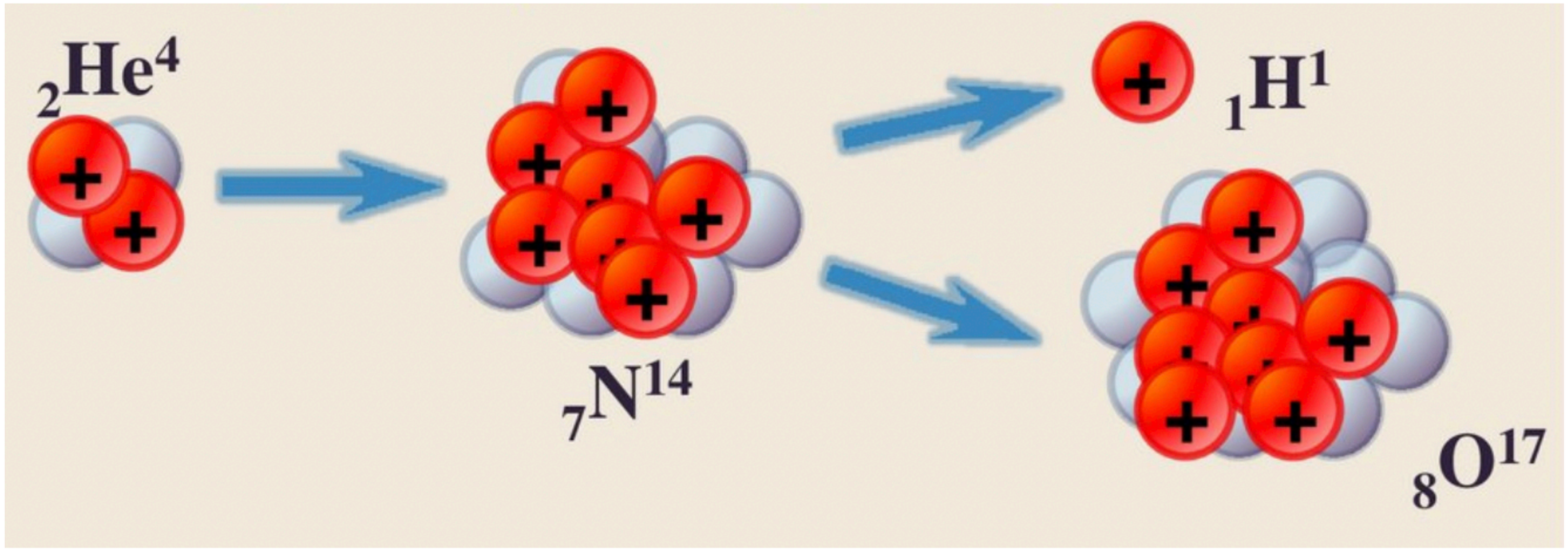




Discovery of the proton

E. Rutherford, 1919

$$ {}^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H $$



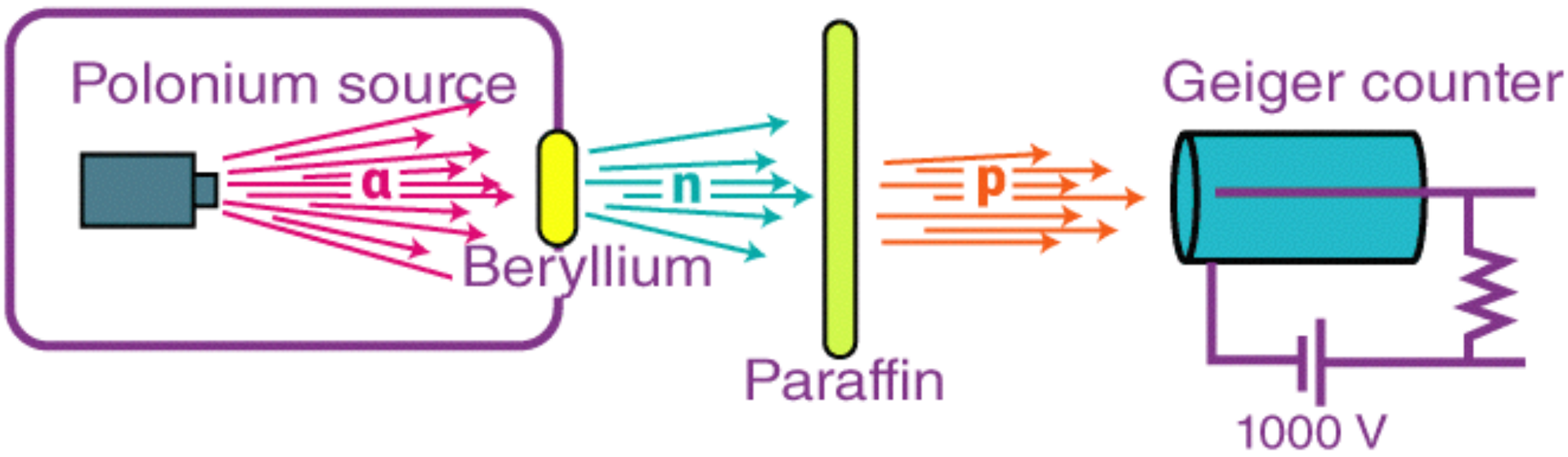
What is keeping the proton in the nucleus?!

Discovery of the neutron



J. Chadwick, 1932, the Nobel Prize in 1961

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + n$$



Yukawa potential

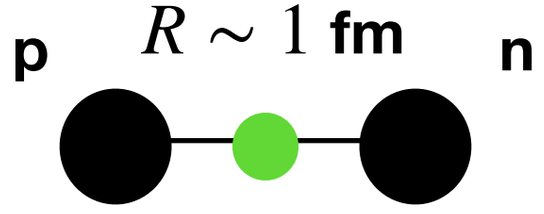


H. Yukawa, 1934

Exchange nature of nuclear forces

$$\Delta E \Delta t \geq \hbar$$

$$\Delta t = R/c$$



carrier particle

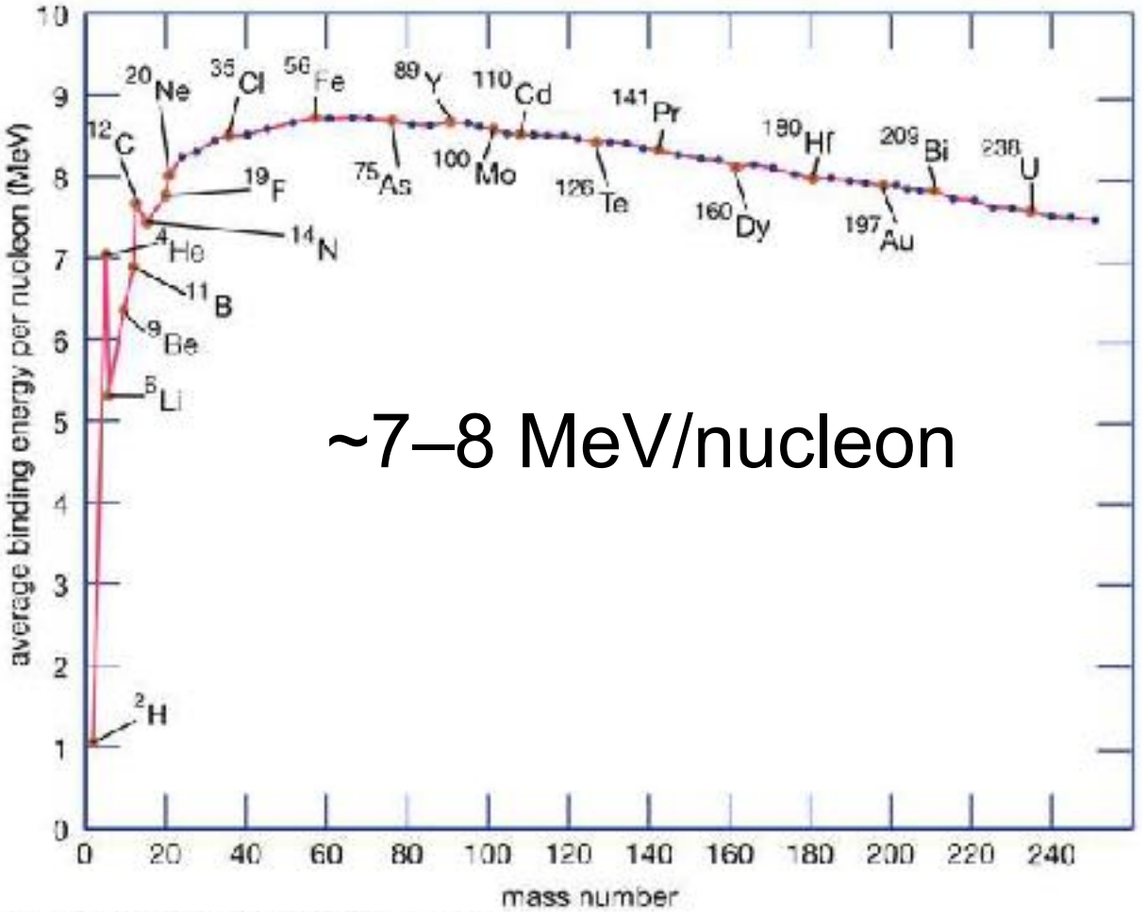
meson

$$m = \frac{\Delta E}{c^2} \sim \frac{\hbar}{Rc} = 200\,MeV$$

Potential of nucleon-nucleon interaction

$$V(r) = -\,g^2 \frac{e^{-mcr/\hbar}}{r}$$

Nuclear binding energy

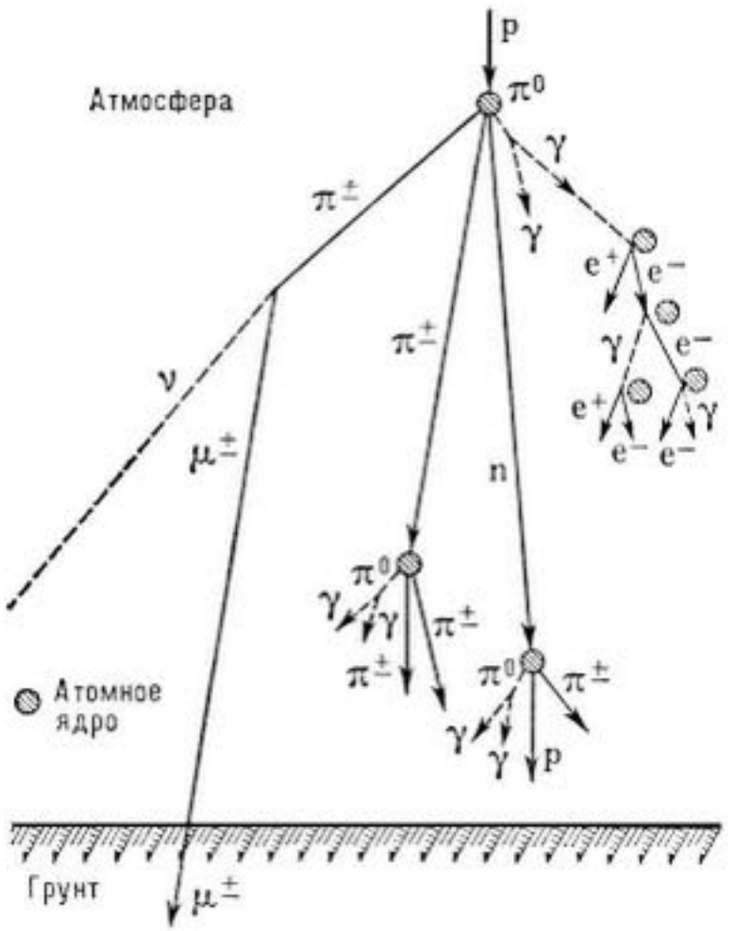


~7–8 MeV/nucleon





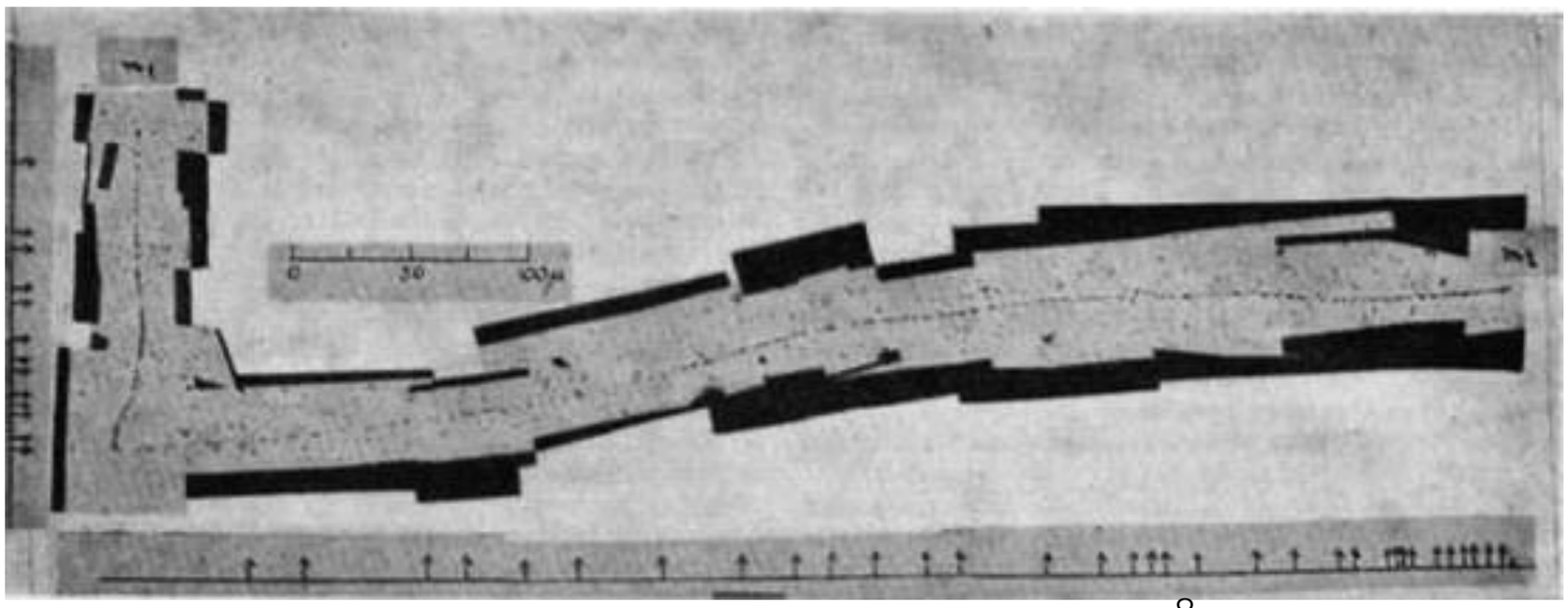
Discovery of $\pi^{\pm}$-mesons



1947

The nuclear emulsion was irradiated in the mountains by secondary cosmic rays. Short tracks of particles stopped in the emulsion were found, which then decayed.

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

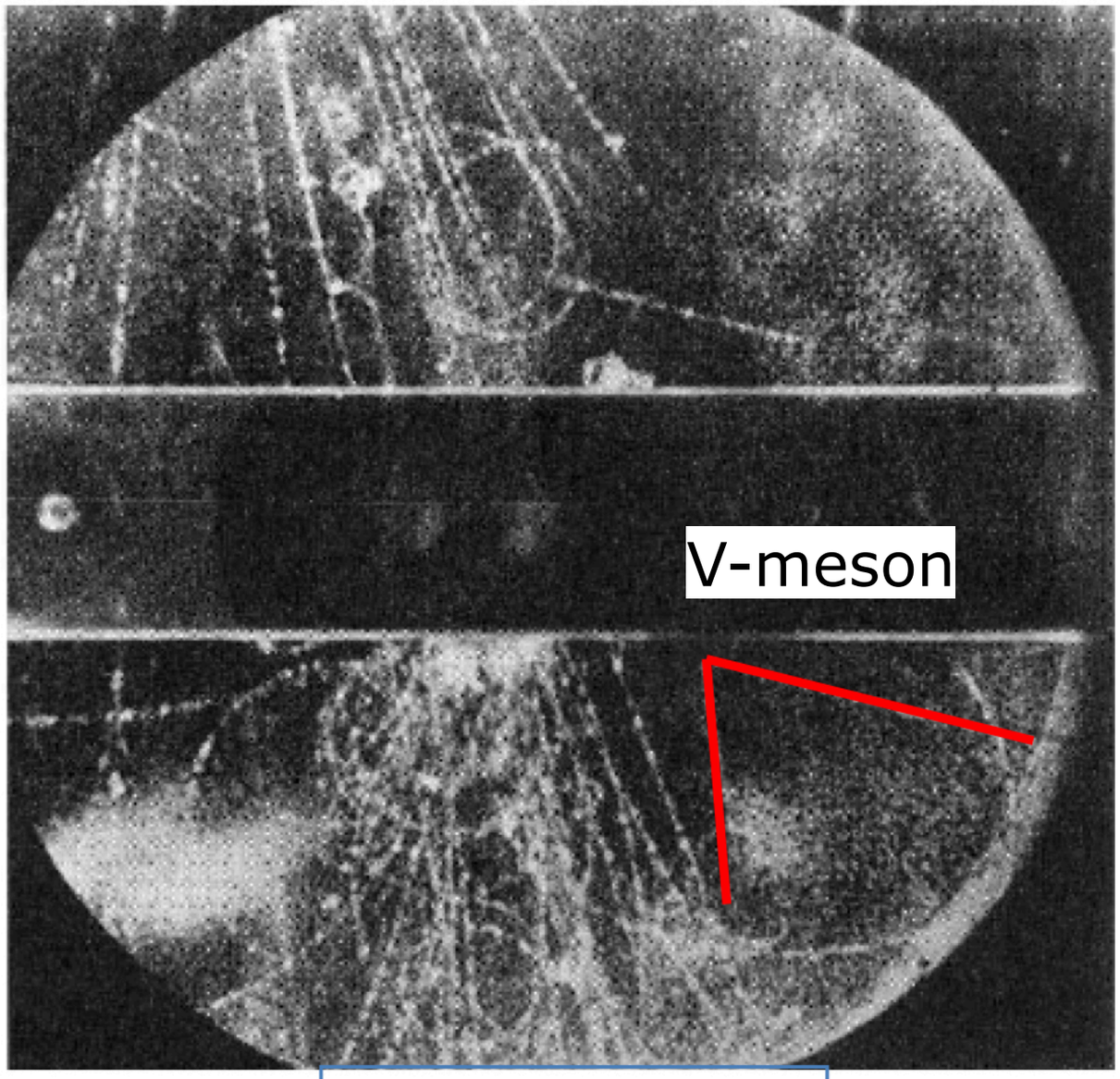


1950

Discovery of neutral π-meson

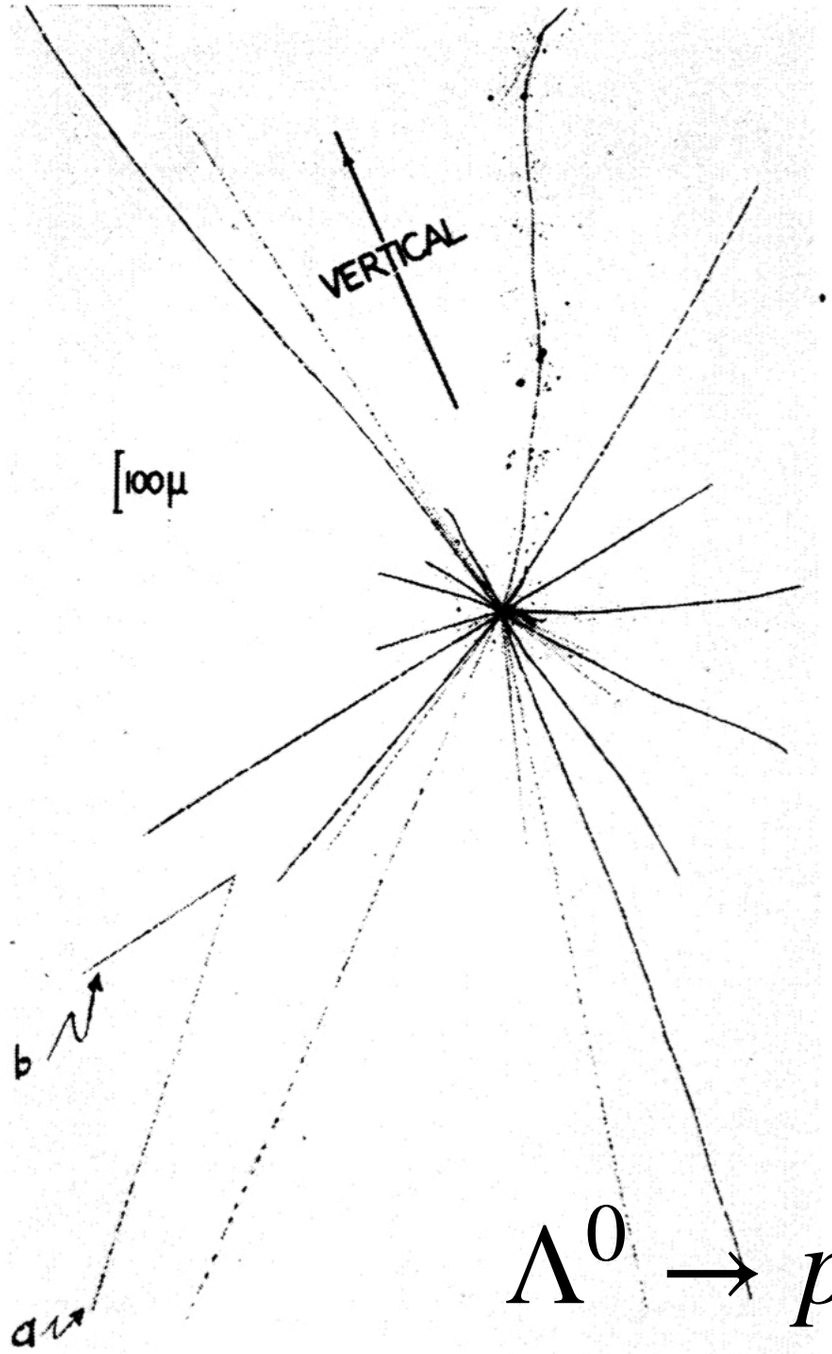
$$\pi^0 \rightarrow 2\gamma$$

Strange particles



$$K^0 \rightarrow \pi^- \pi^+$$

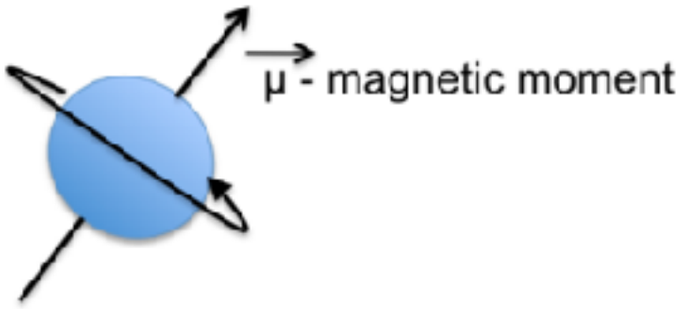
1947



$$\Lambda^0 \rightarrow p\pi^-$$

1950

Complexity of nucleons



$$\vec{\mu}_S = g_S \times \frac{e}{2m} \times \vec{S}$$

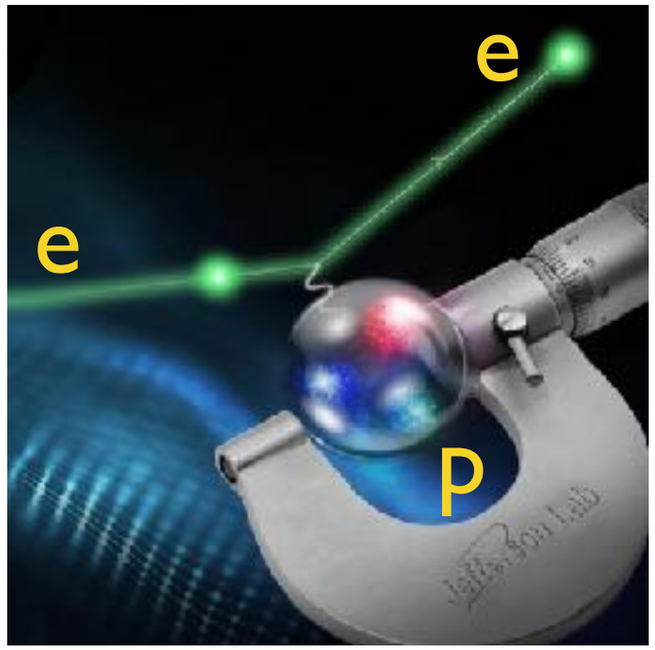
	g_S (expected)	g_S (measured)
e	-2	-2,0023
p	2	**5,58**
n	0	**-3,83**

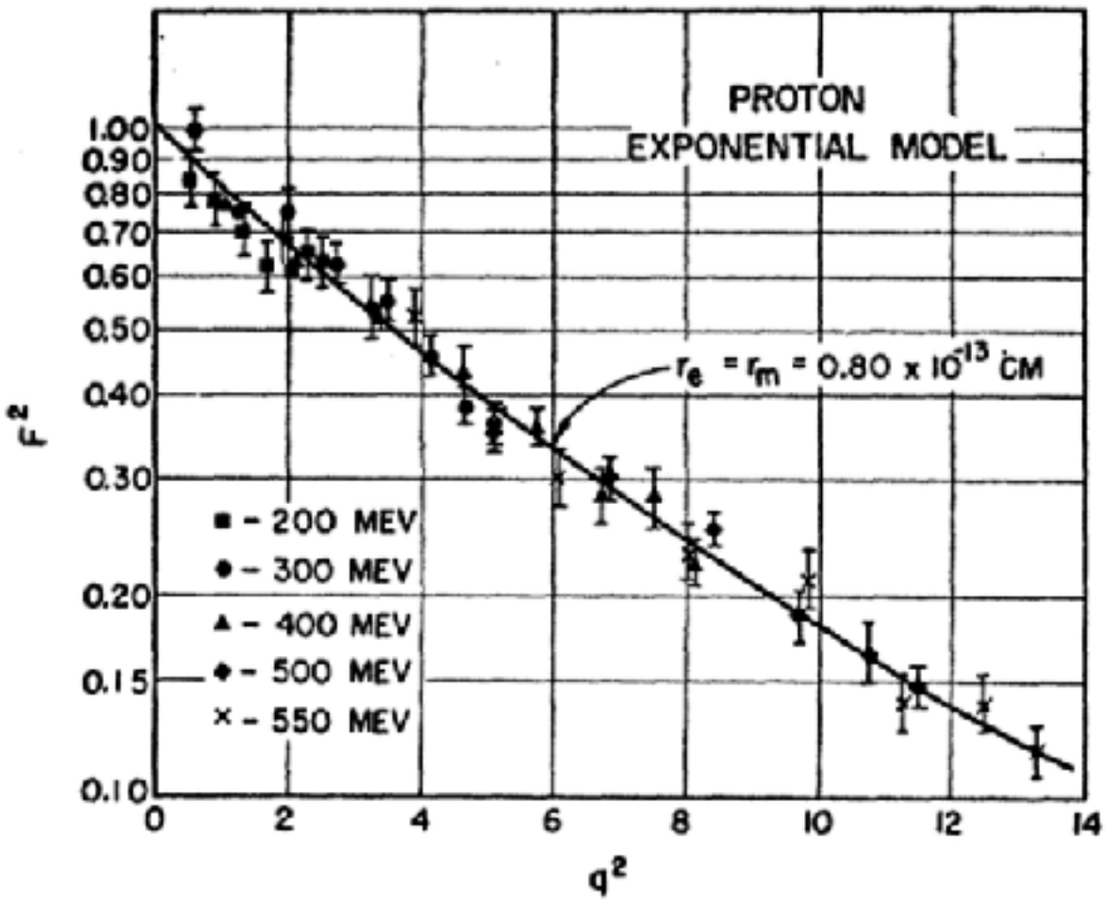
1930s

This was the first indication that nucleons could be composite objects.

Proton size







R. Hofstadter - the Nobel Prize in 1961

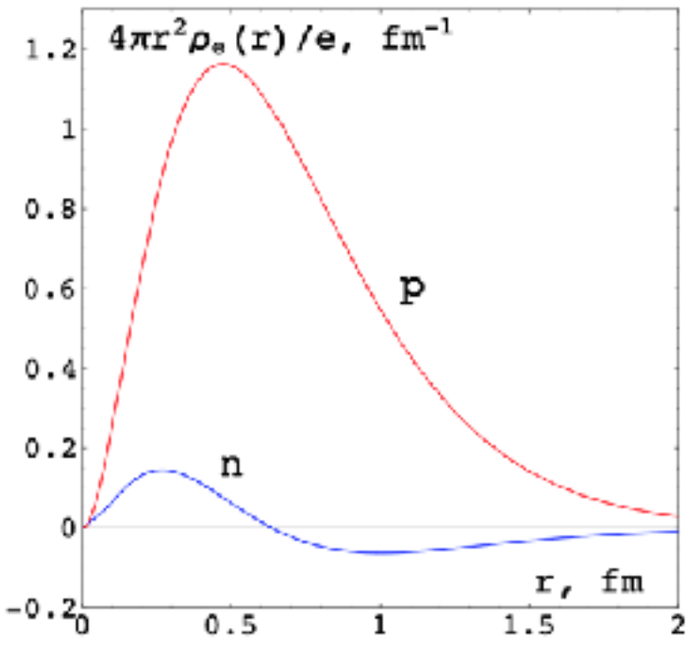
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point-like}} \times F^2(q^2)$$

Form-factor

transferred (four)-momentum

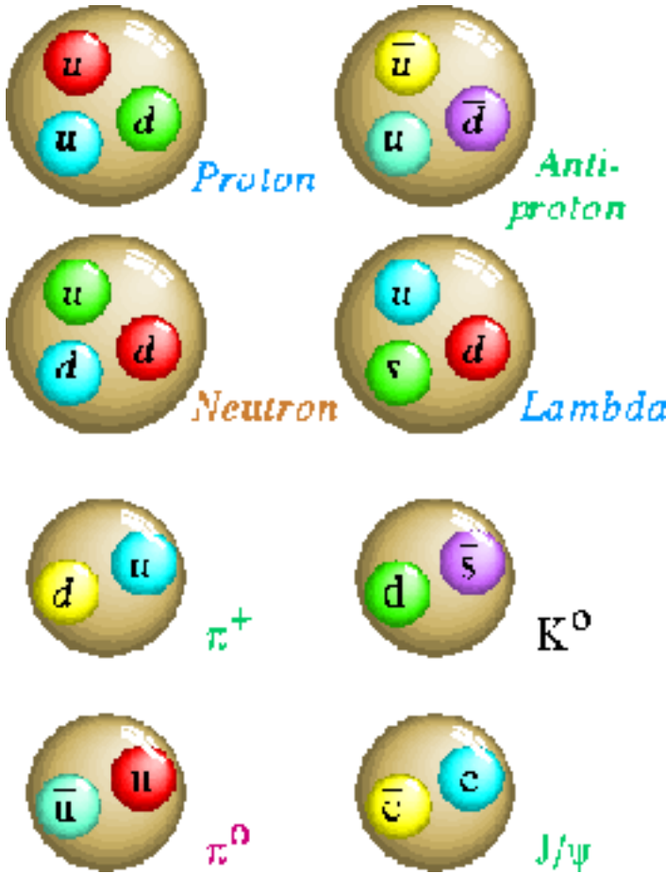
$$F(q^2) \approx 1 - \frac{q^2 < r^2 >}{6\hbar^2}$$

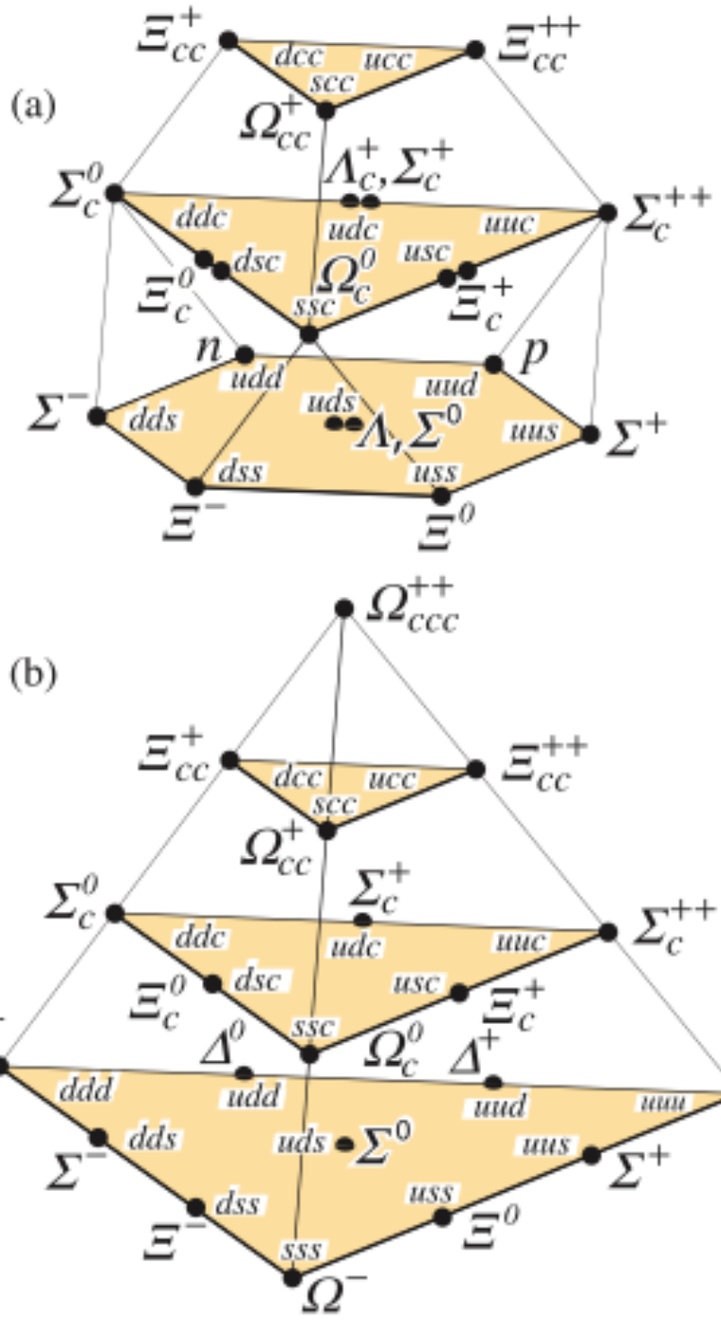
charge radius



Hypothesis of quarks

	I	II	III
mass→	2.4 MeV	1.27 GeV	171.2 GeV
charge→	⅔	⅔	⅔
spin→	½	½	½
name→	u up	c charm	t top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	-⅓	-⅓	-⅓
	½	½	½
	d down	s strange	b bottom





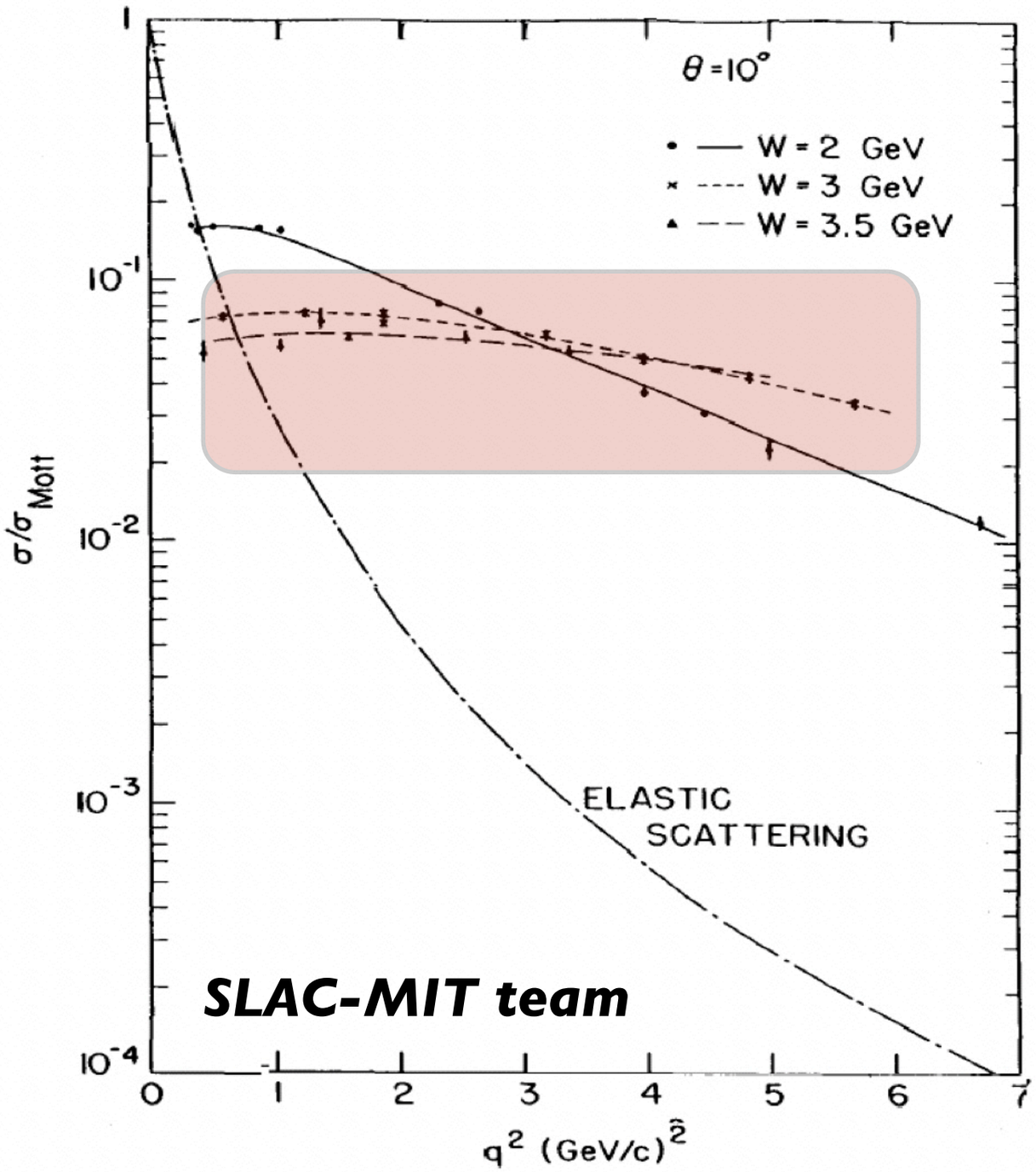




1964

M. Gell-Mann and G. Zweig - Nobel Prize in 1969

Partons



Partons - point-like objects inside the proton

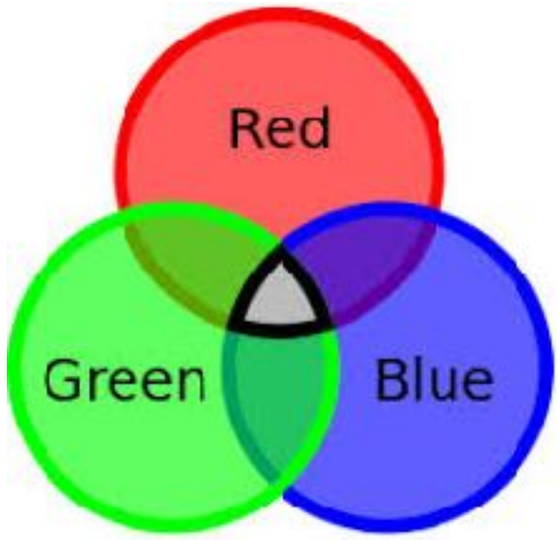
Partonic model -1969

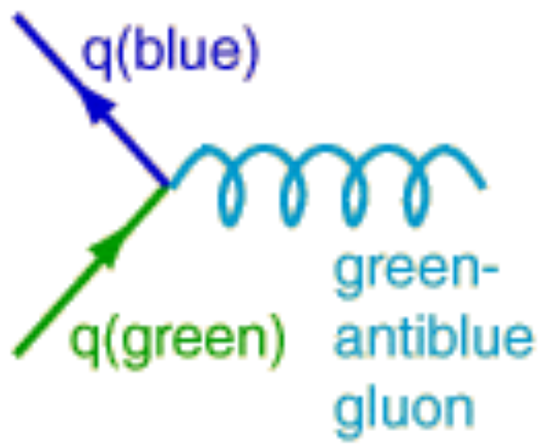


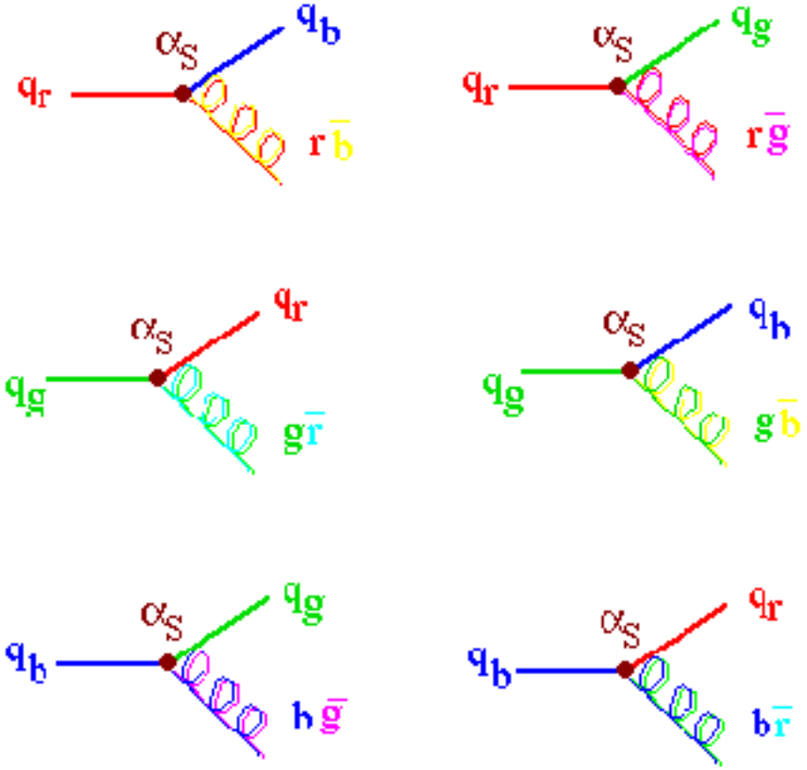
R. Feynman

In the beginning of 70th charged partons were associated with quarks

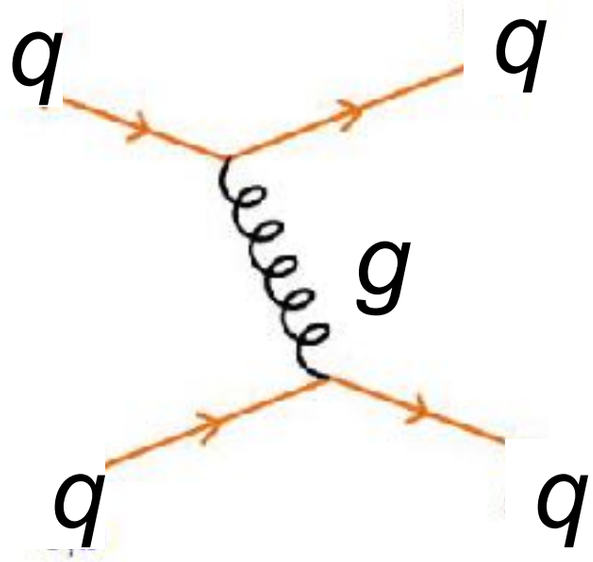
Quantum ChromoDynamics - QCD



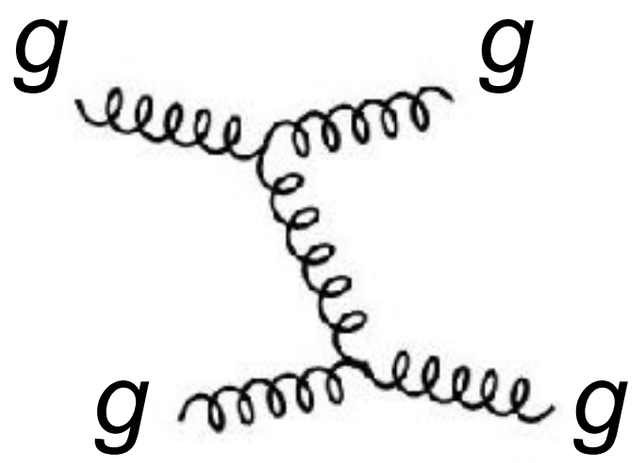




Color charge - source of strong force!

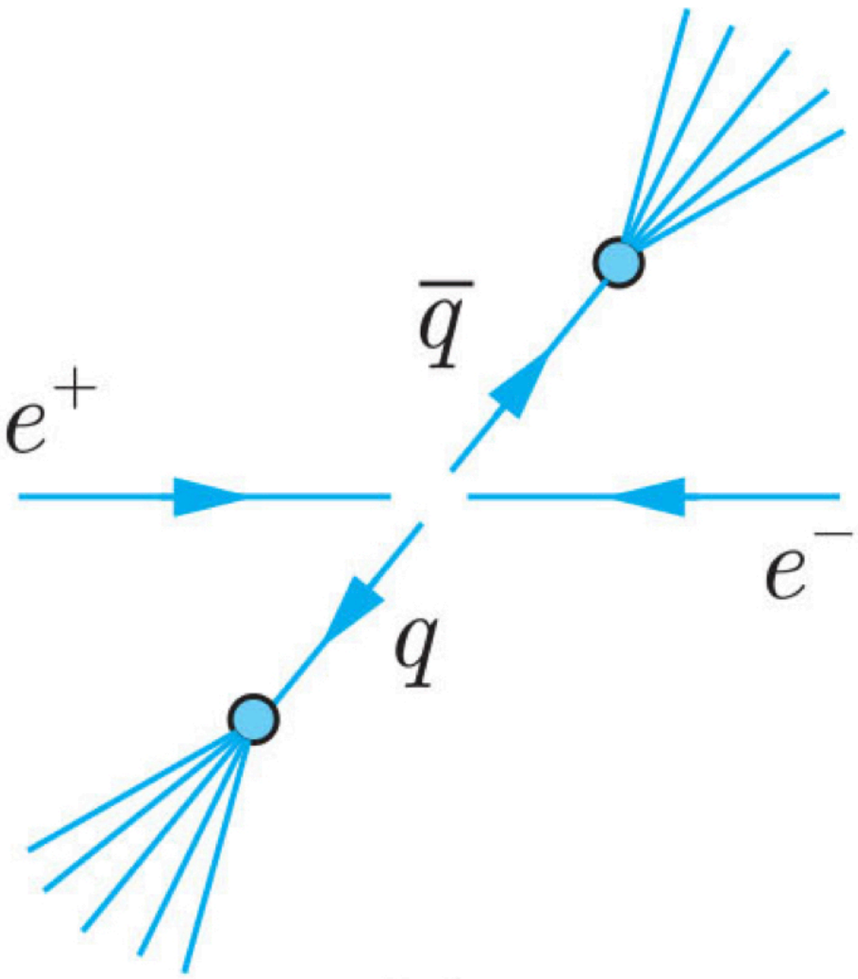


gluon exchange by 2 quarks



Analog in electrodynamics: **light emitting light !**

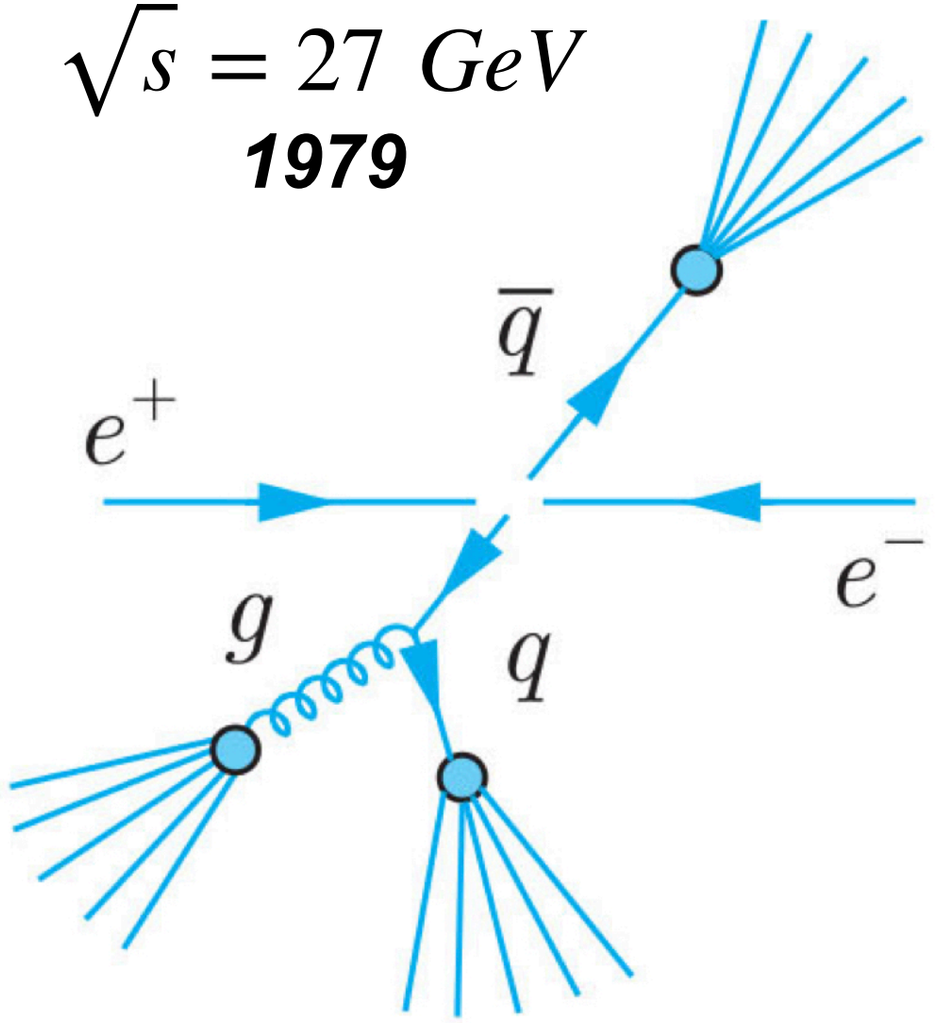
Gluons



PETRA

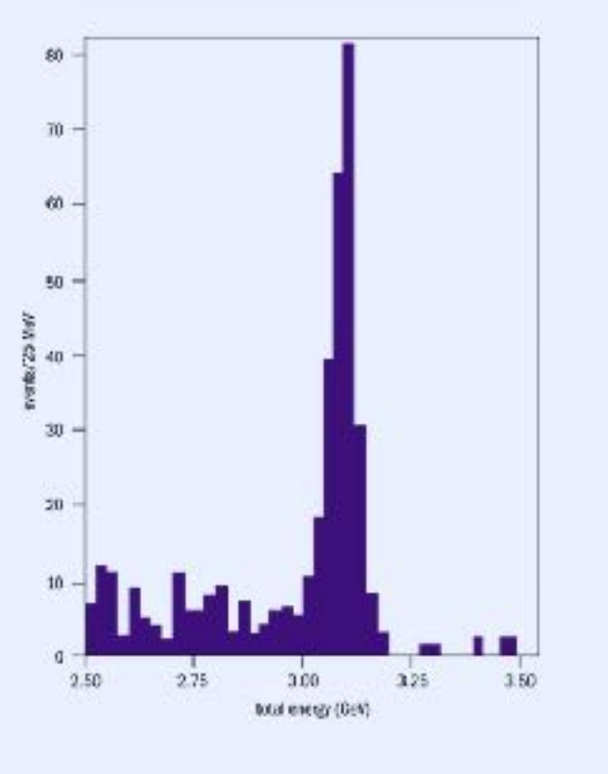
$\sqrt{s} = 27\ GeV$

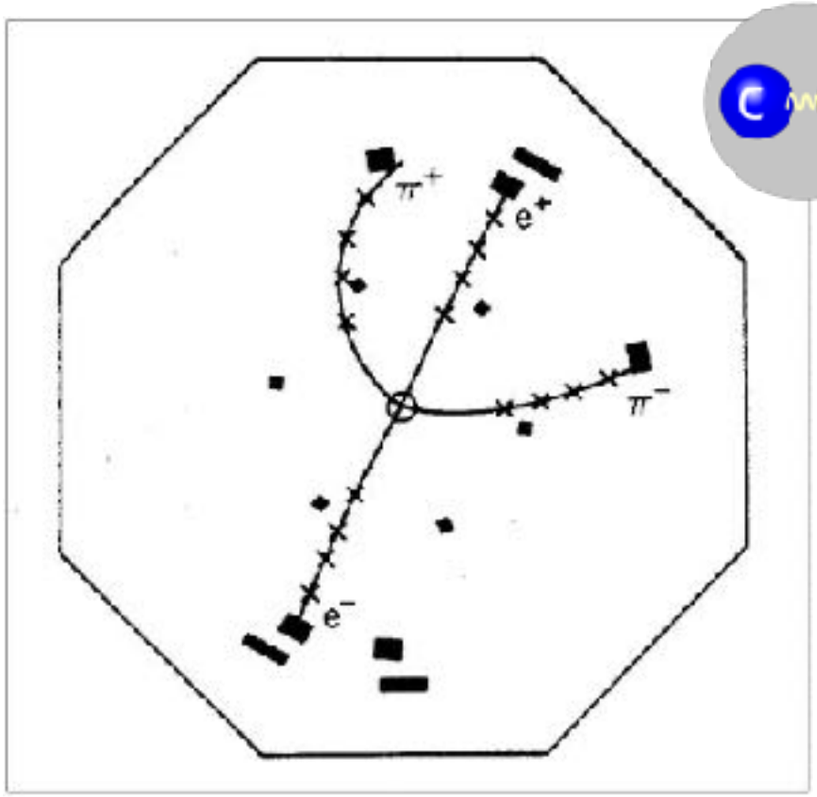
1979



November revolution

Discovery of the J/ψ meson - **4-th quark**





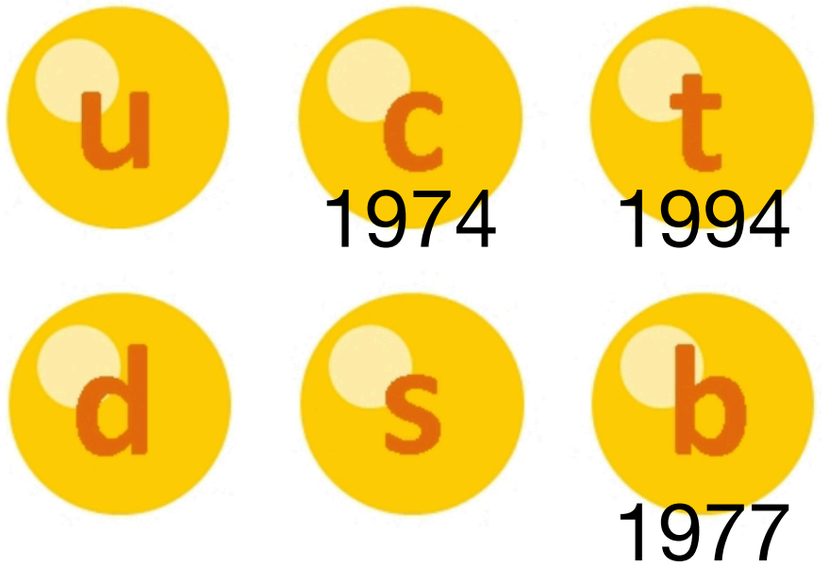
B. Richter & S.Ting



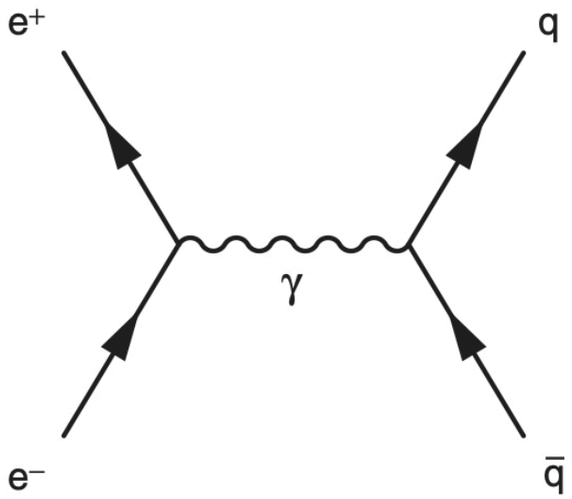
November, 11, 1974, the Nobel Prize in 1976

This discovery confirmed the existence of the c-quark, predicted by the electroweak theory, that strengthened the Standard Model.

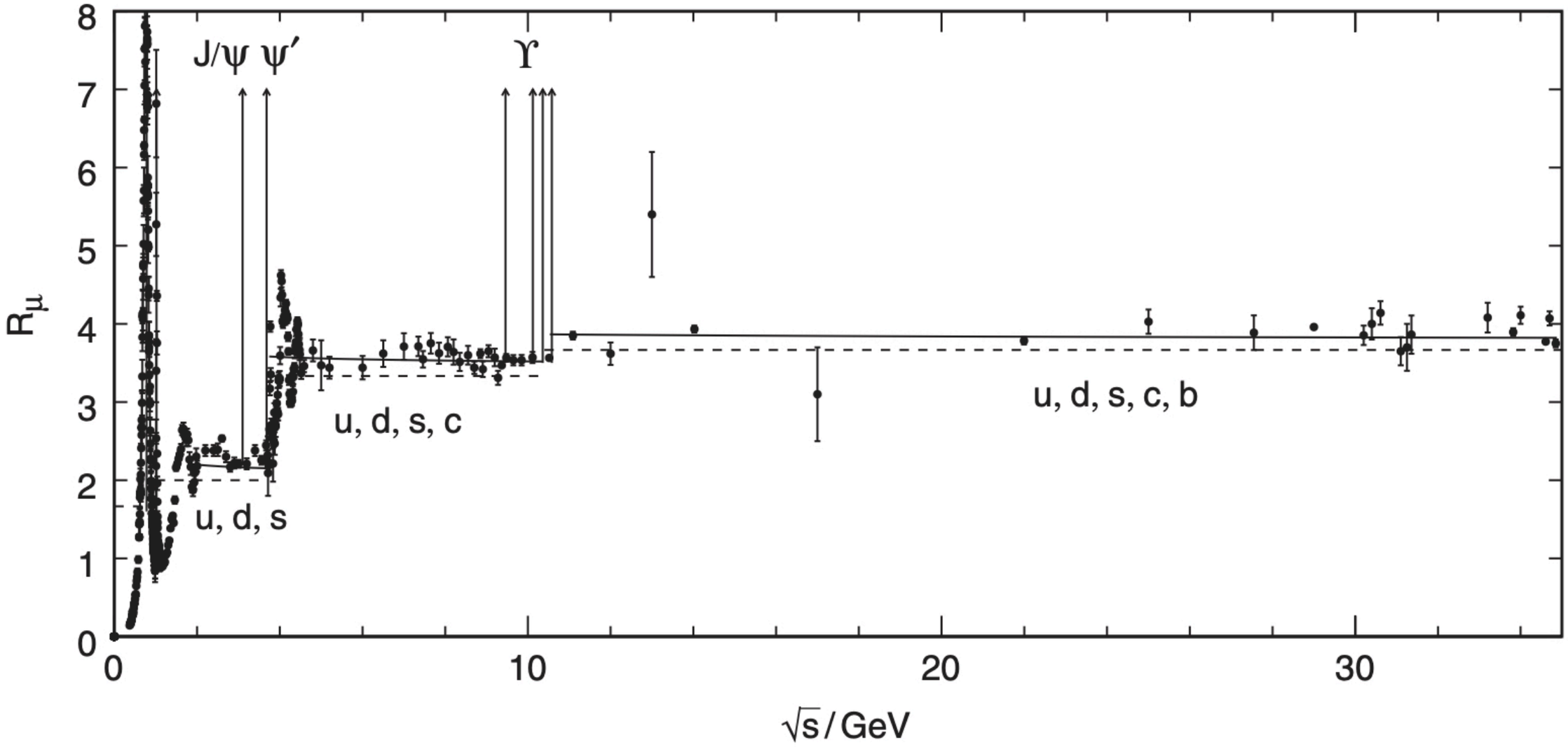
J/ψbecame a unique tool for studying the strong interaction.



R-ratio



$$R_\mu \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_{\text{flavours}} Q_q^2.$$



Quantum ChromoDynamics

QCD

$$L_{QCD} = -\frac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu}) + \bar{q}(i\gamma_\mu D^\mu - m)q$$

Lagrangian is very simple!

Non-Abelian nature（color degrees of freedom）

Flavor degrees of freedom

Self-interaction of Gluons → glueballs $f_0(1500)$?

Nobel Prize 2004

Heavy flavor physics

Asymptotic Freedom

Non-linear nature

Heavy quark symmetry

Strong coupling nature at low energy

Nontrivial Topology : Instanton (4 dimensioanl soliton)

Gluon Condensate
Scale Invariance violation
（Trace Anomaly）

Non-perturbative Vacuum

Millennium Prize problem

$U_A(1)$ Anomaly

Large mass of $\eta'(958)$

Color Confinement

Spontaneous
Chiral Symmetry Breaking

Quark Consensate

$\langle\bar{q}q\rangle = -(250\mathrm{MeV})^3$

Nobel Prize 2008

Compositeness of Hadrons

Nambu-Goldstone boson

Dynamical mass generation of Quarks

Flavor symmetry among u, d, s

String picture of Hadrons

Light pions : 140MeV

Pion exchange Nuclear Force

SU(6) spin-flavor symmetry

Regge trajectory of Hadrons
Hagedorn temperature
Flux-tube picture

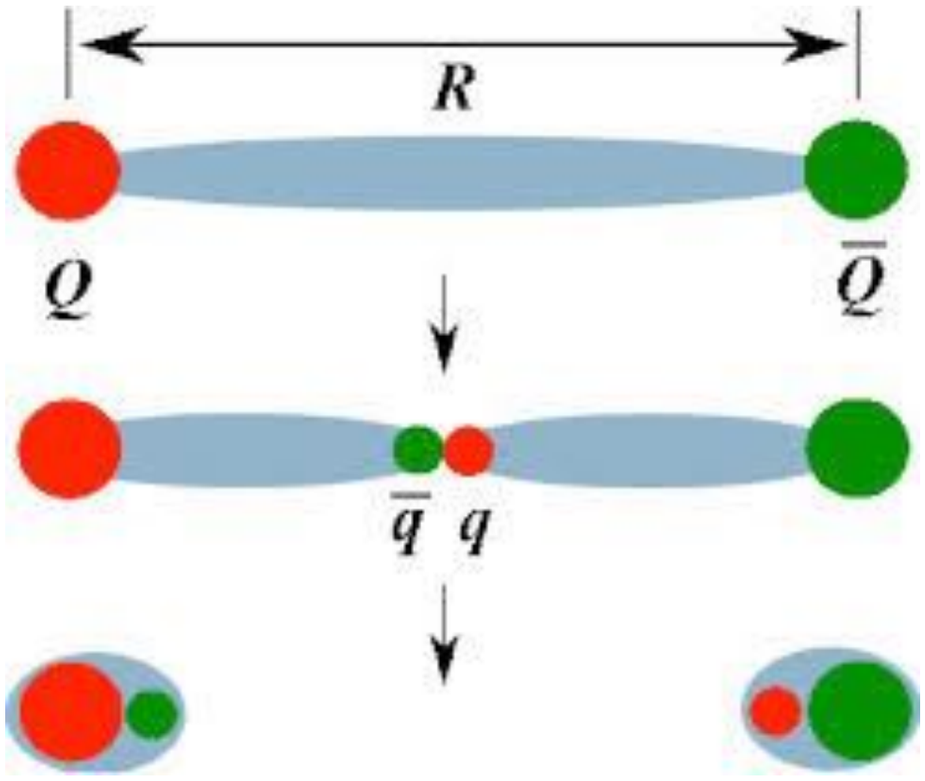
1fm range of Nuclear Force

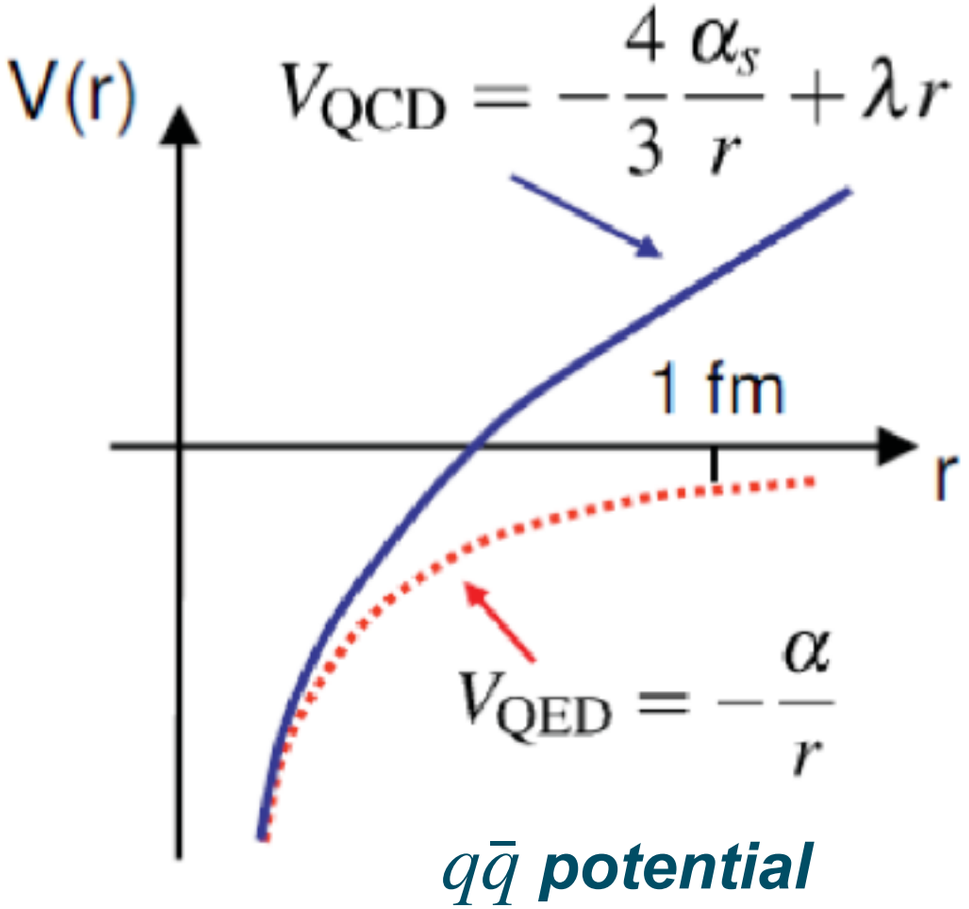
Formation of Nuclei

Physics of Hyperon and Hyper nuclei

Several fm size of Nuclei

Quantum ChromoDynamics - QCD





$q\bar{q}$ **potential**

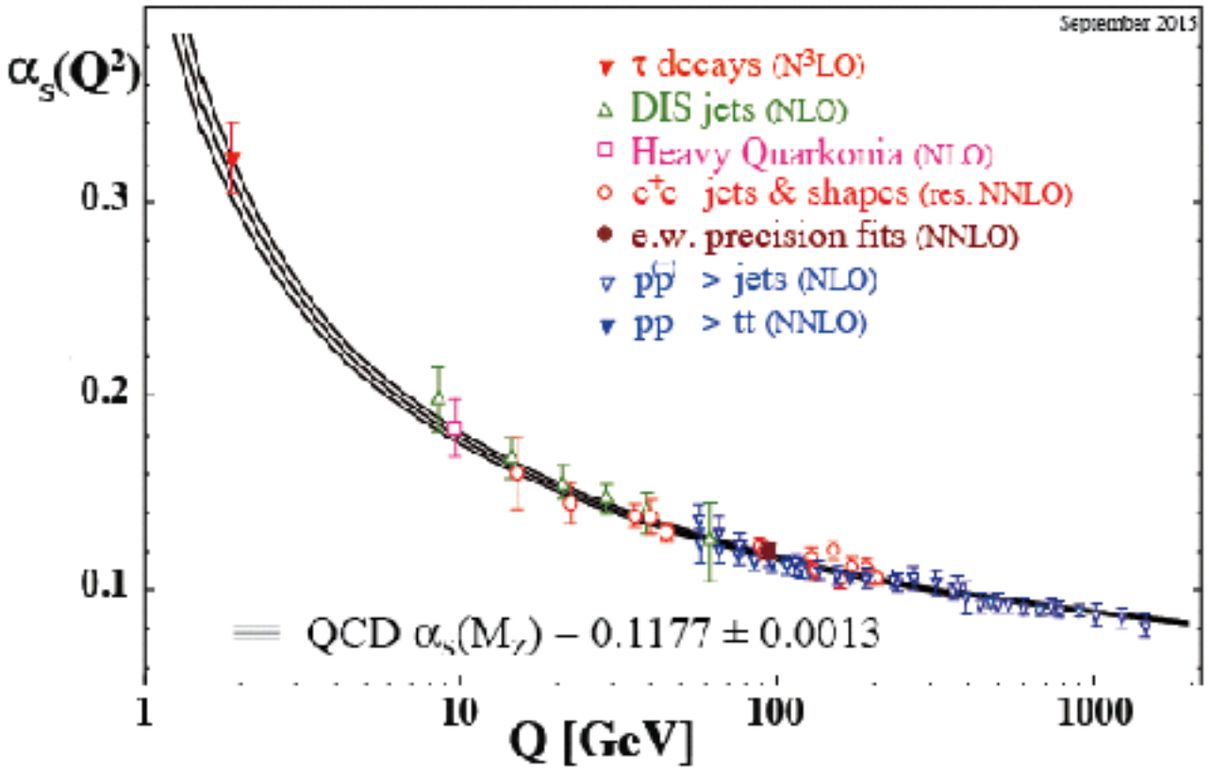
Quark confinement at large scale but asymptotic freedom at ~1 fm



D. Gross, D. Politzer,
F. Wilczek

Nobel Prize in 2004

Running constant α_s



$$\alpha_S(Q^2) = \frac{1}{B\ ln\dfrac{Q^2}{\Lambda^2_{QCD}}}$$

$$\Lambda_{QCD} = 200 - 300\ MeV$$

Confinement Λ_{QCD} **Asymptotic freedom**

Natural scale for light hadrons:

$$M \simeq \Lambda_{QCD}$$

$$R \simeq \frac{\hbar c}{\Lambda_{QCD}} \simeq 1\ fm$$

Λ_{QCD}

Nuclear physics

Hypernuclei

Quark-gluon plasma

Nuclear effects in hadronic interaction

Spectroscopy

Hadron structure

Hard processes

Hadronization

$Q \lesssim \Lambda_{QCD}$

Non-perturbative regime

Phenomenological models

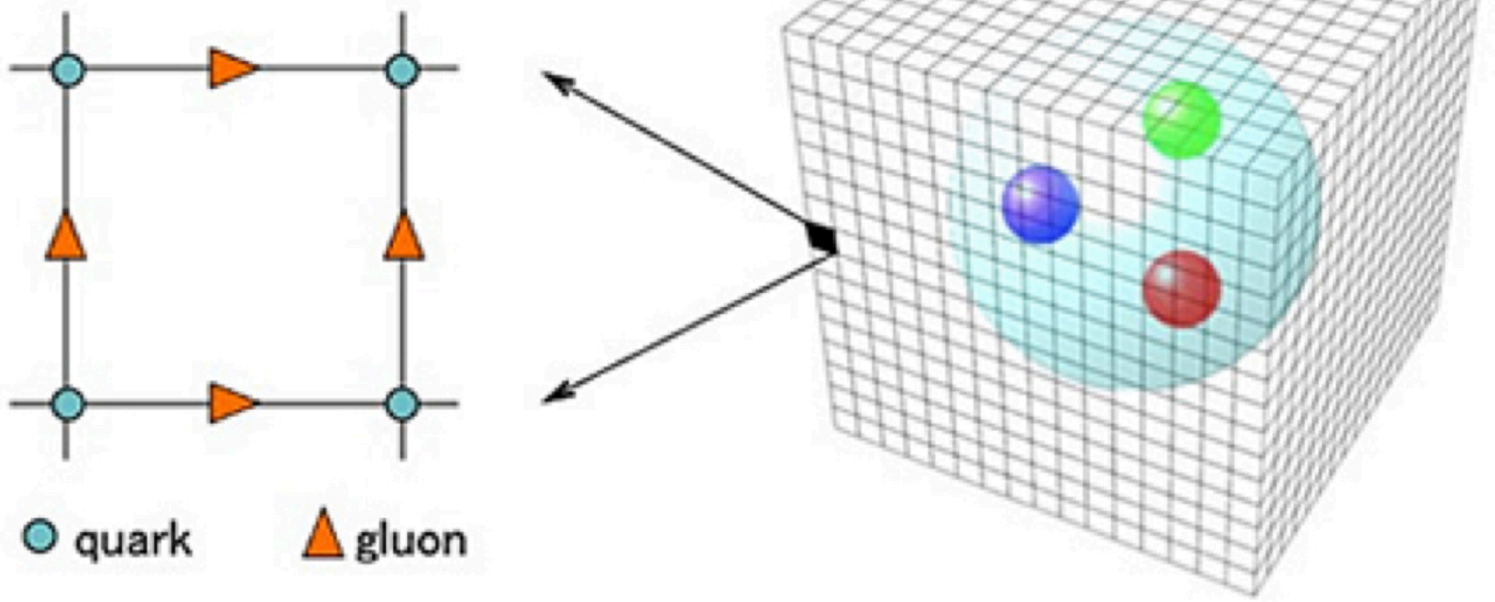
$Q \gg \Lambda_{QCD}$

Perturbative regime

“True” QCD

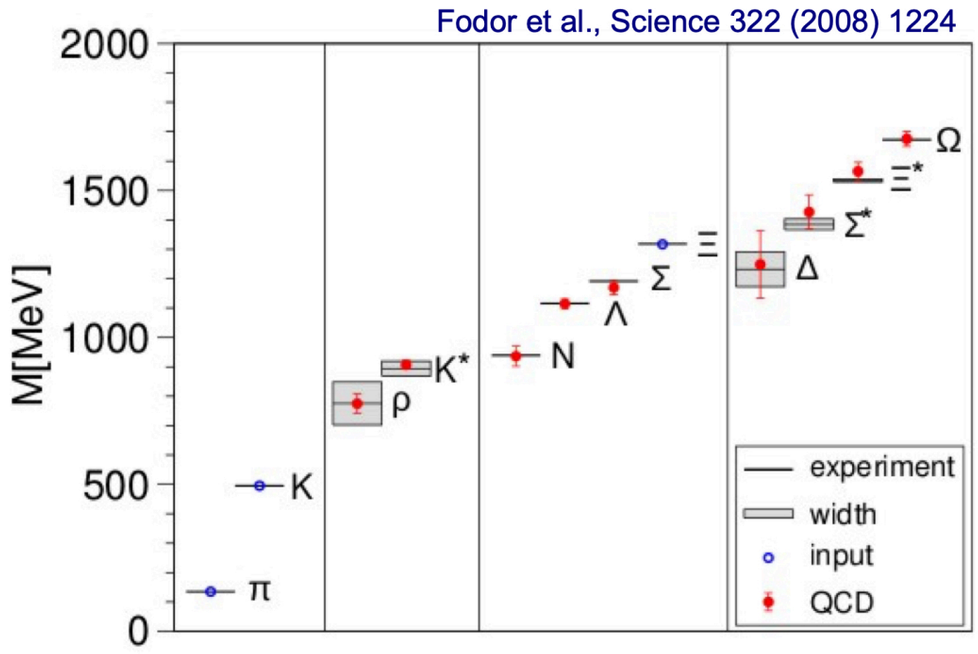
Lattice QCD

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA_{\mu}) - m_q\right]q$$

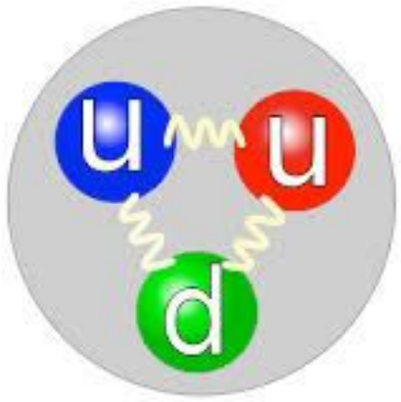


Main idea: discretize spacetime into a **4D grid (lattice)** and compute the QCD path integral numerically using Monte Carlo methods. This allows **for a first-principles**, non-perturbative calculation of hadron properties and strong interaction dynamics from the quark and gluon fields **directly**.

Fodor et al., Science 322 (2008) 1224



Hadrons in QCD

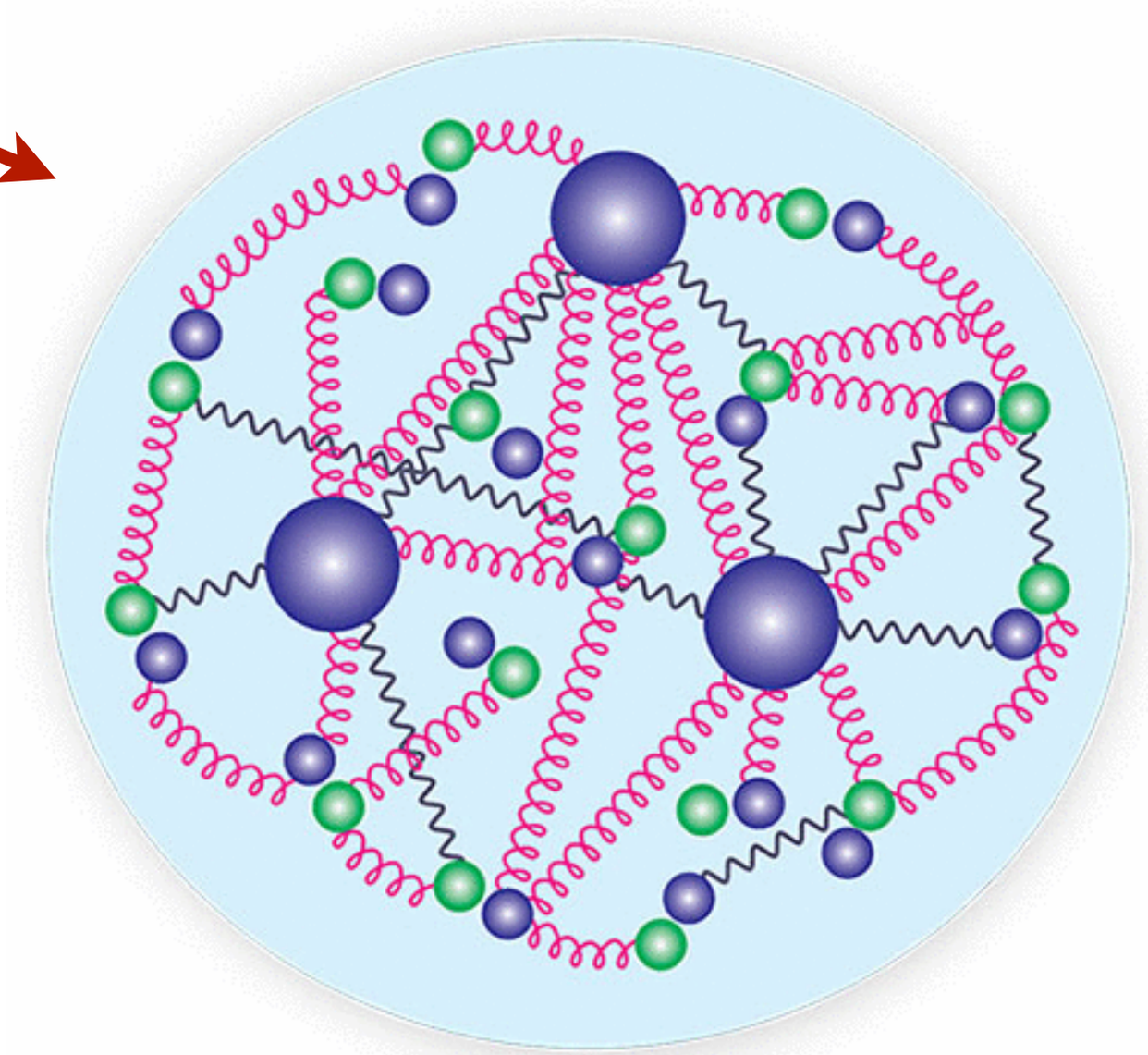


Valence quarks

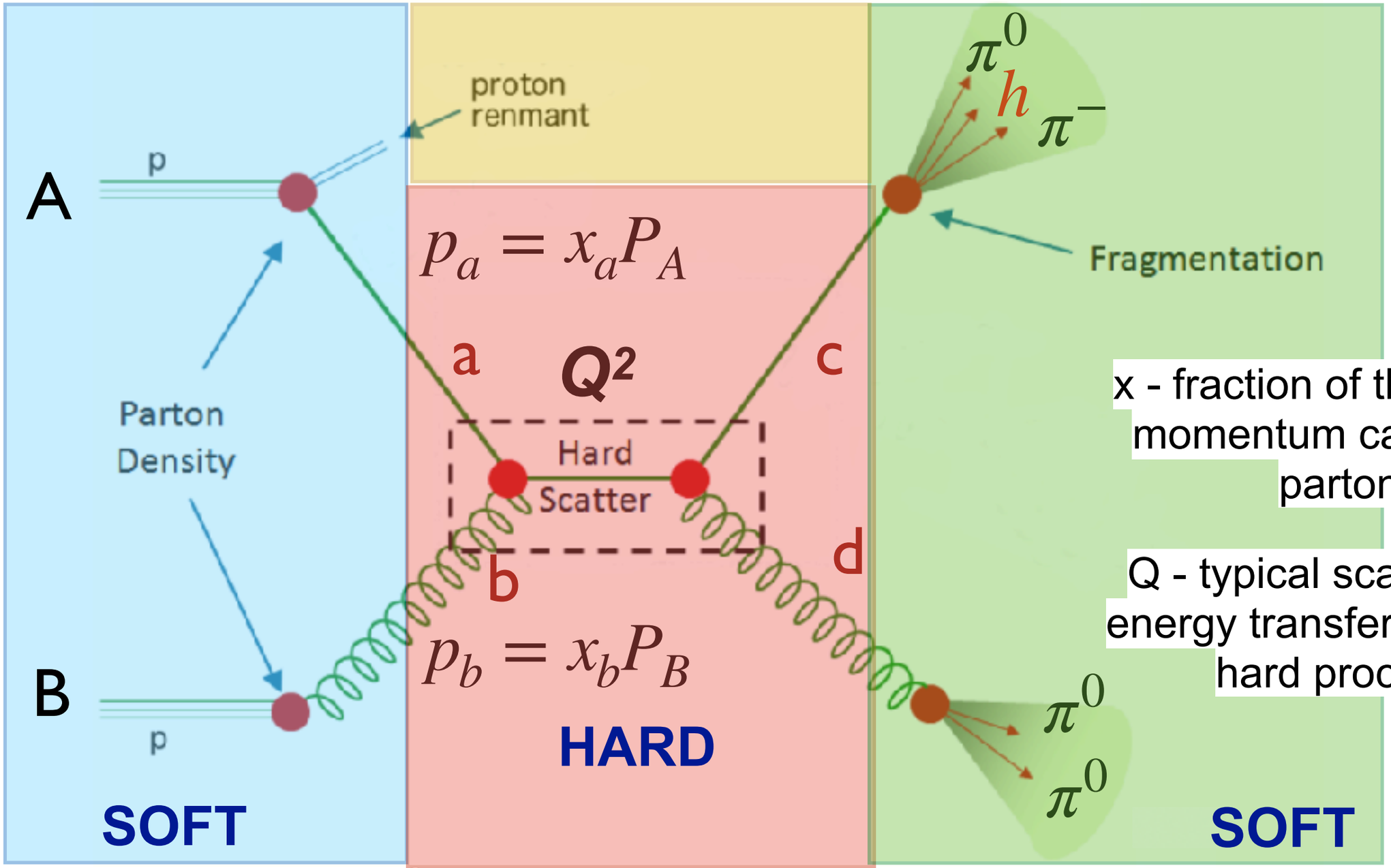
Gluons

Sea quarks and antiquarks

Proton



Factorization theorem



x - fraction of the proton momentum carried by parton

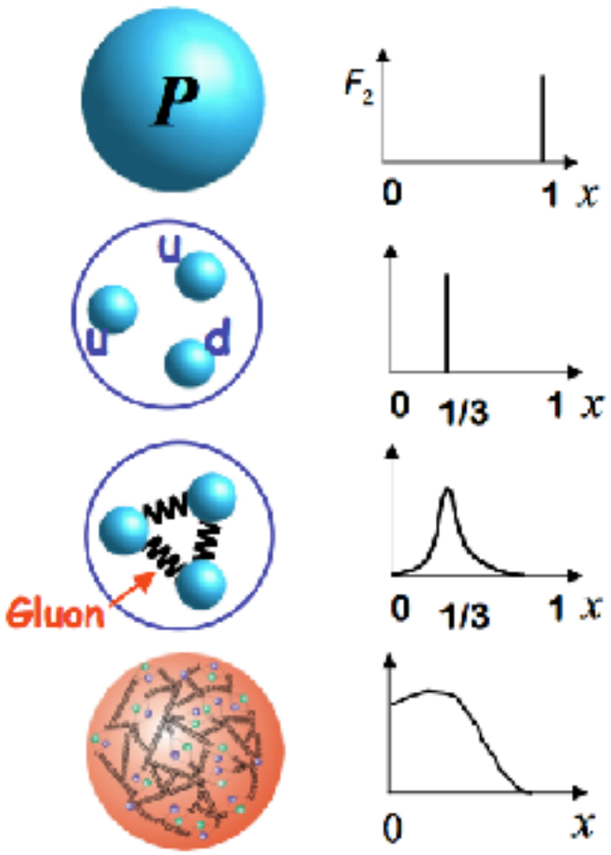
Q - typical scale of the energy transferred in the hard process

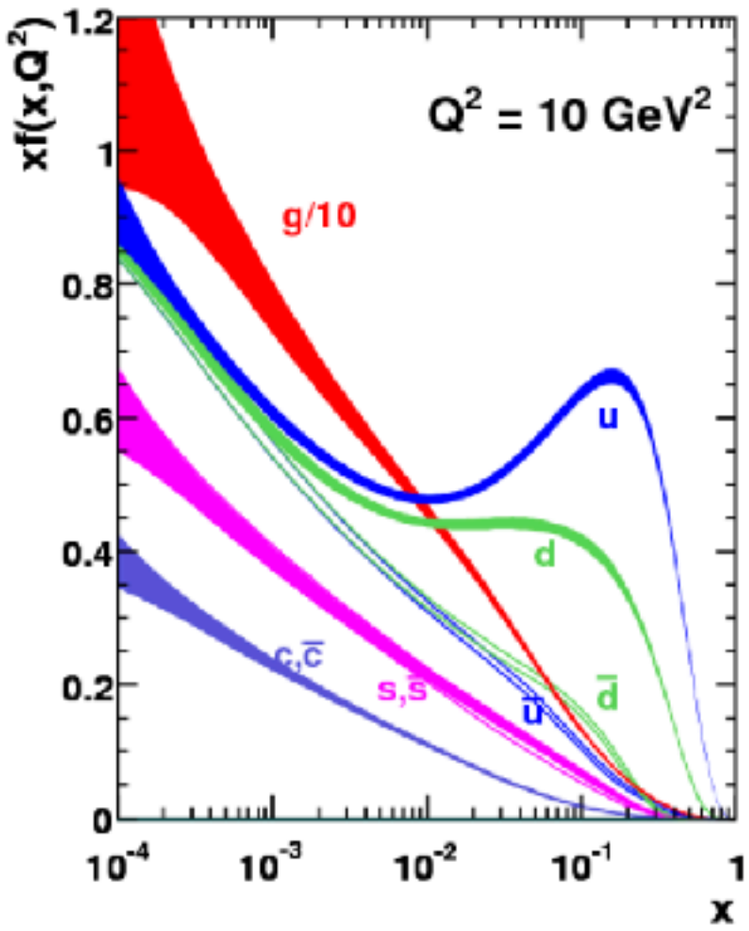
$$\sigma_{AB\to hX} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b \, f(x_a, Q^2) f(x_b, Q^2) \times \hat{\sigma}_{ab\to cd}(x_a, x_b, Q^2) \times D_{cd\to h}$$

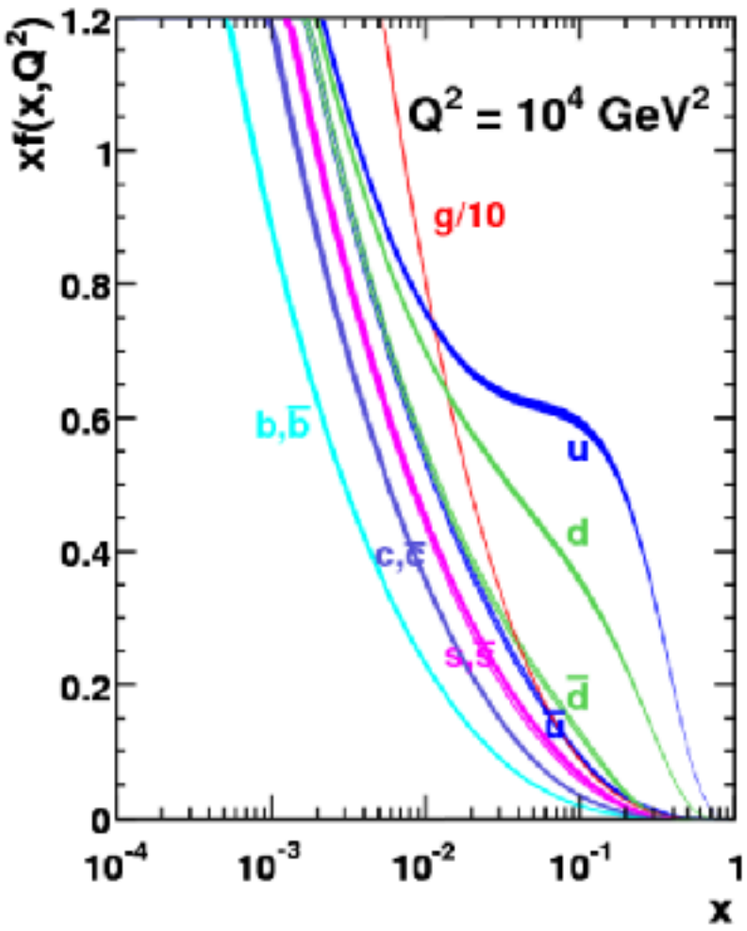
$Q^2 >> 1$ GeV^2/c^2

Parton structure of hadrons

Parton Distribution Functions PDFs $f(x,Q^2)$ describes probability for given Q^2 to find inside the proton a parton carrying momentum fraction x





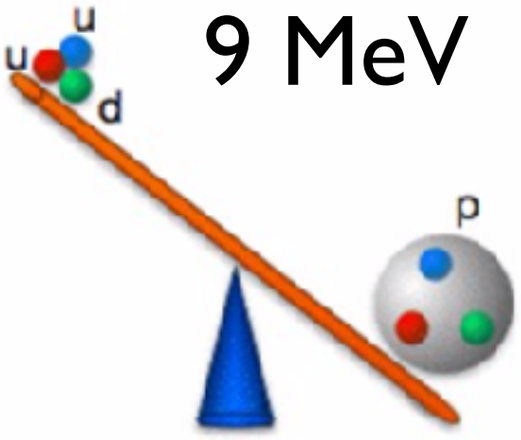


Sea partons becomes more important at high Q^2

QCD evolution equations: $f(x, Q_1^2) \rightarrow f(x, Q_2^2)$

PDFs are universal, they are independent on the hard process!

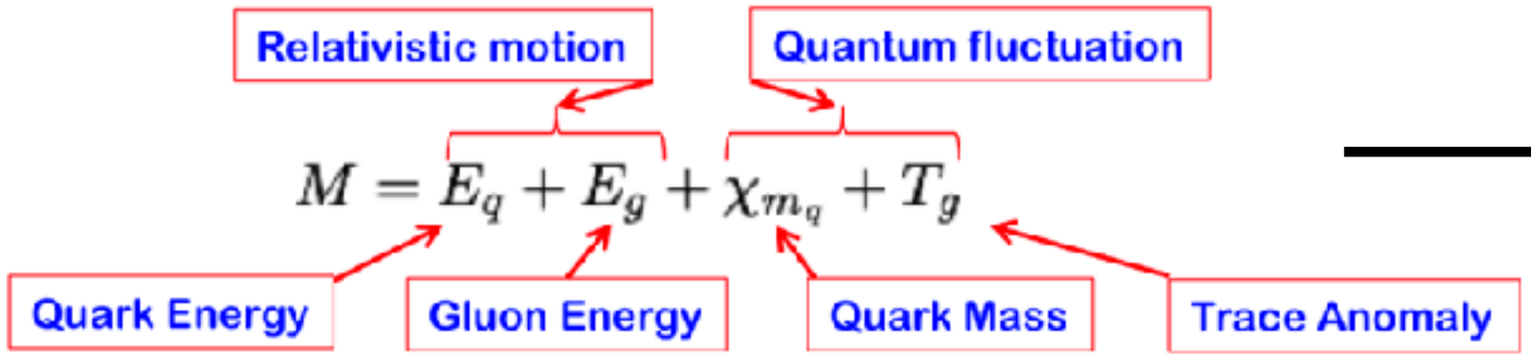
Mass of hadrons

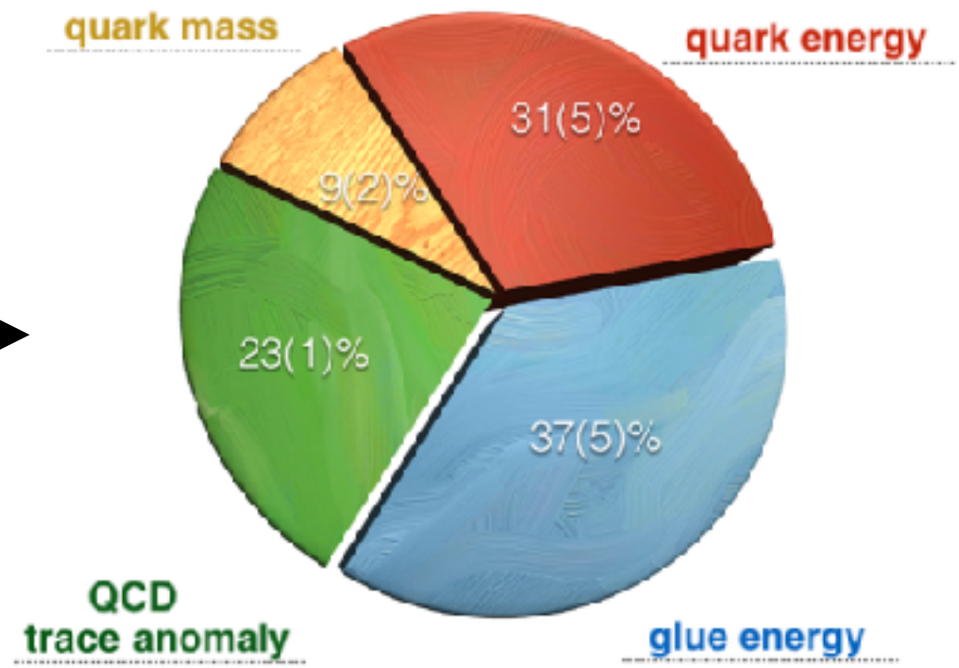


9 MeV

938 MeV

The Higgs mechanism has almost nothing to do with the formation of mass of light hadrons!



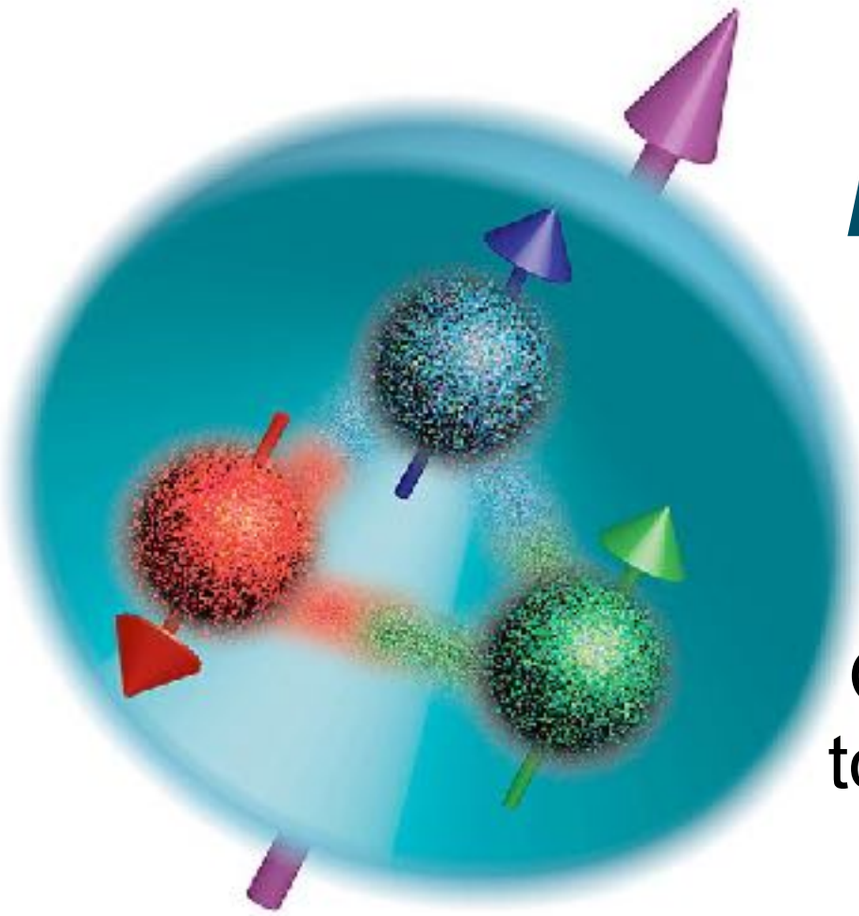


$$M_{Hadron} \approx \sum m_q + NPC$$

NPC ~Λ_{QCD} - non-perturbative contribution

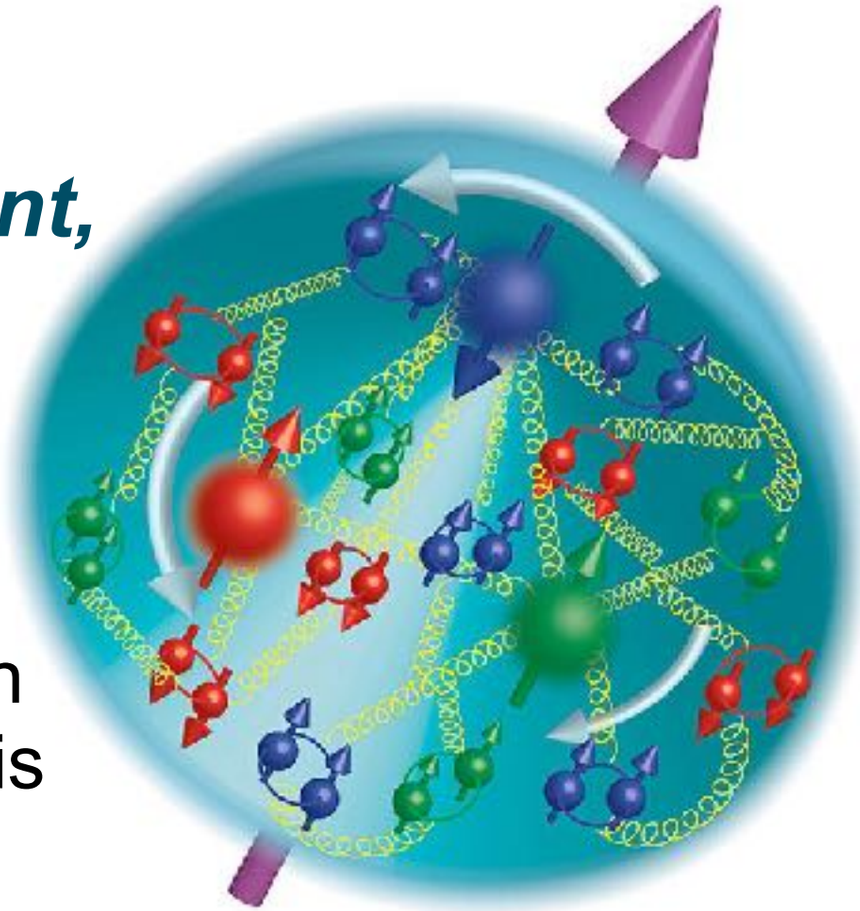
	Mass,	m_q	NPC
p	938	9	929
Pion	140	7	133
Kaon	494	96	398
Λ_c	2286	1280	1006
J/ψ	3097	2546	551
Υ	9460	8366	1094

Proton spin crisis



EMC experiment, CERN 1988

Quark contribution to the proton spin is below 30%!



Naive quark model

$$\frac{1}{2} = \sum_{q=u,u,d} (\frac{\vec{1}}{2})$$

Real situation

L - orbital moments of quarks and gluons

$$S_N = ½ = ½\,\Delta\Sigma + \Delta G + L$$

What carries the proton spin?!

“Exotic” content of hadrons

Proton wave function decomposition into the Fock states:

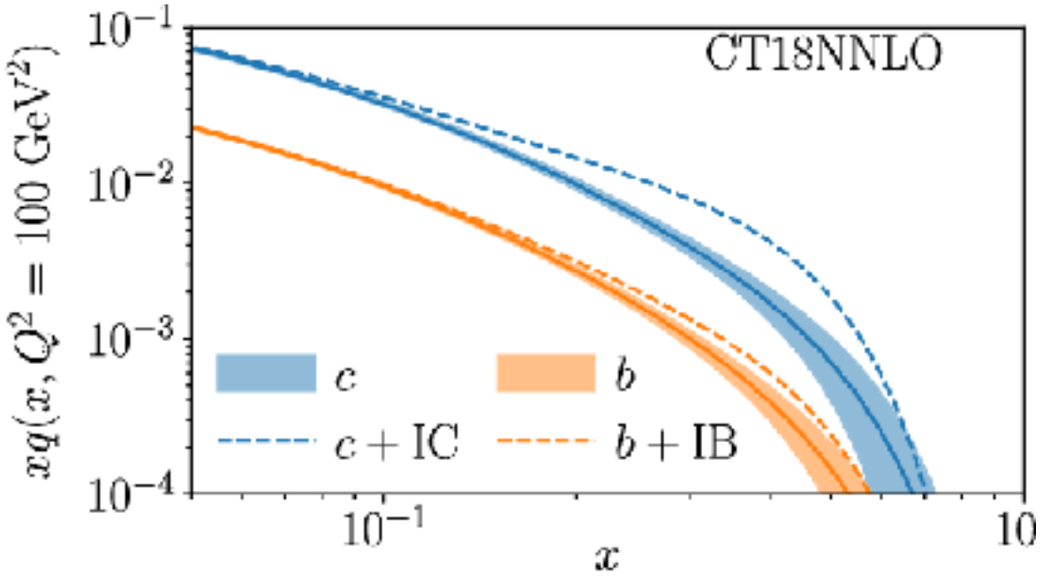
$$|p\rangle = a_0|uud\rangle + a_1|uud\bar{q}q\rangle + a_2|uud\bar{q}q\bar{q}q\rangle + \ldots$$

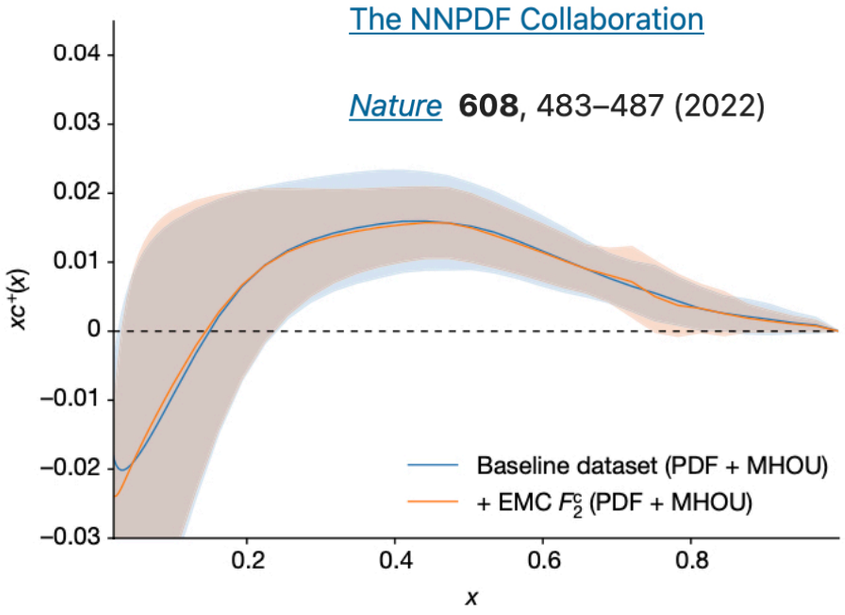
intrinsic:

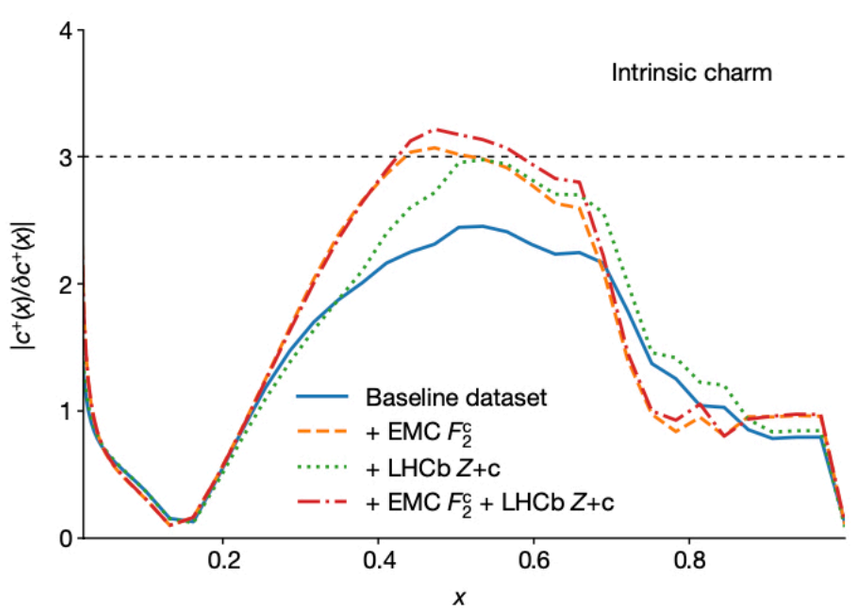
$|uud\bar{s}s\rangle$ strangeness

$|uud\bar{c}c\rangle$ charm

$|uud\bar{b}b\rangle$ beauty



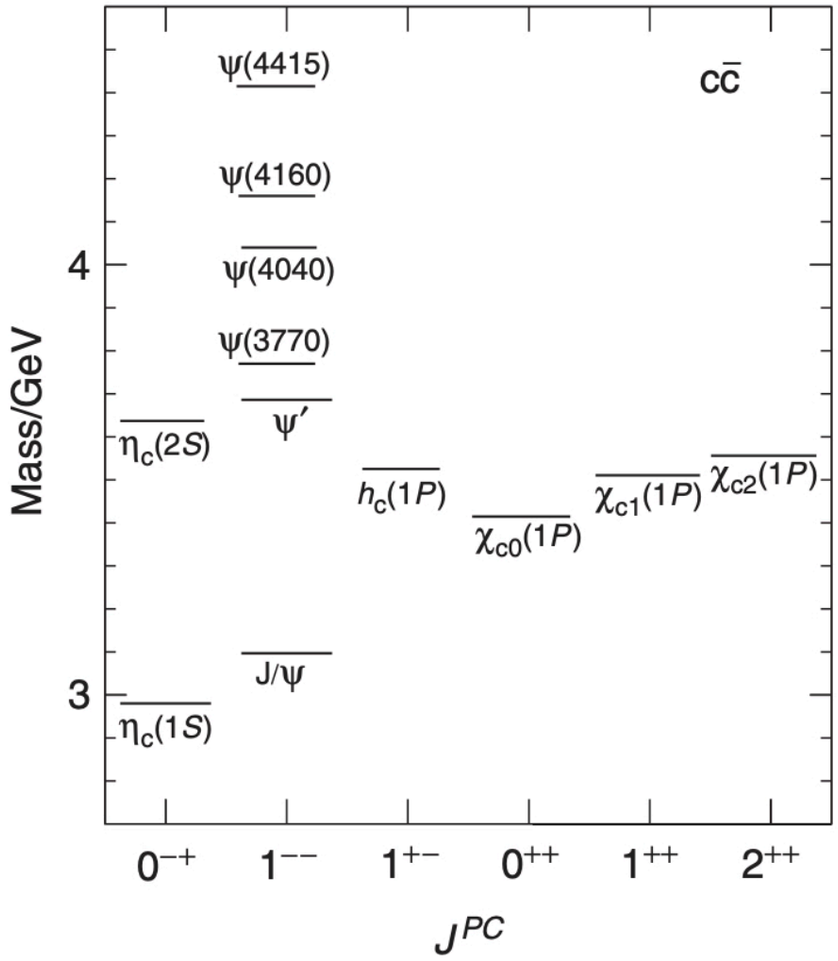


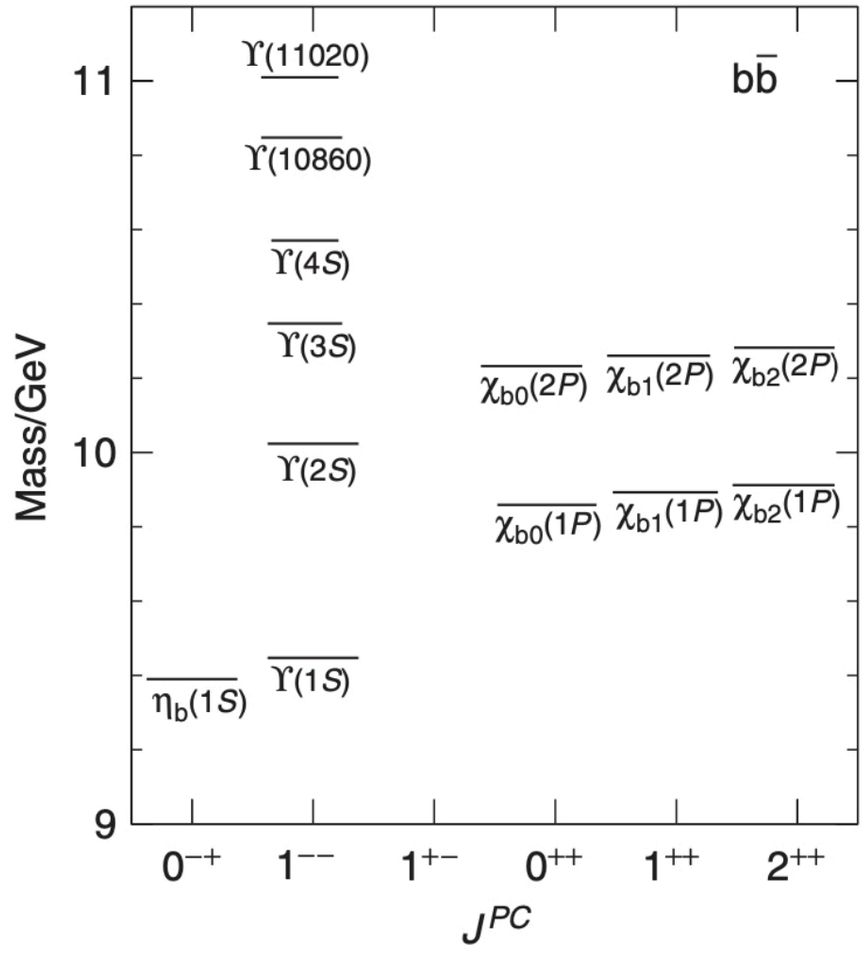


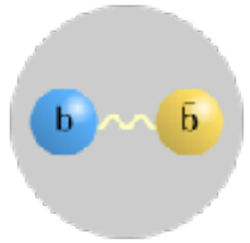
Glimpse of the intrinsic charm!

Quarkonia







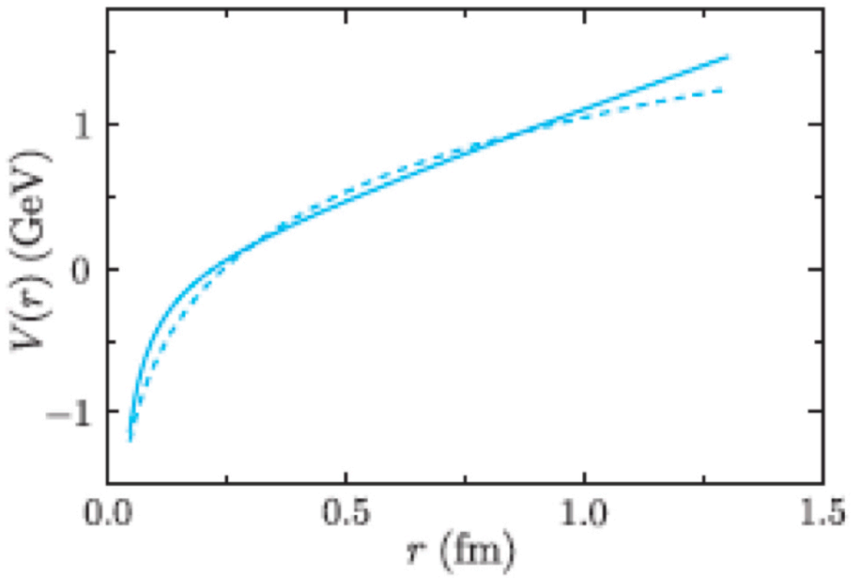


Quarkonia are nonrelativistic bound states:

$$c\bar{c} : (v/c)^2 \sim 0.3$$
$$b\bar{b} : (v/c)^2 \sim 0.1$$

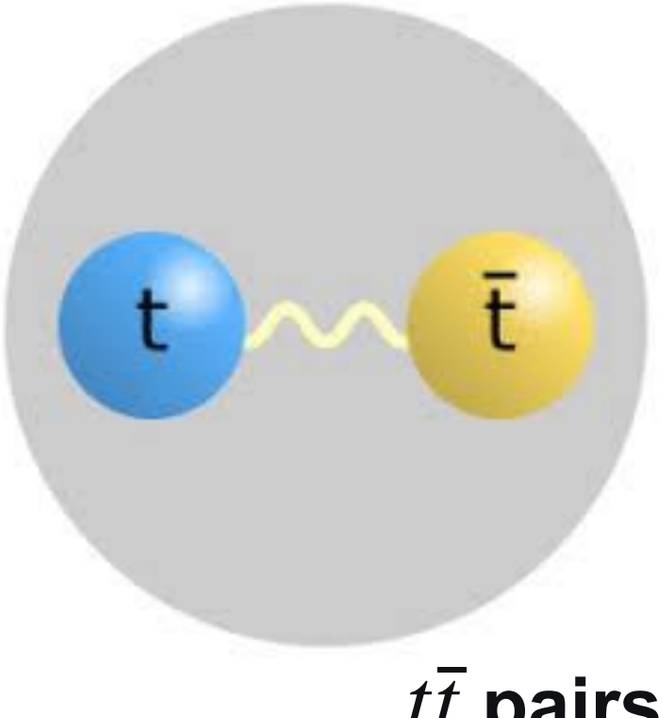
NRQCD: $\Lambda_{QCD} \ll Mv^2 \ll Mv \ll M$

"soft" "hard"



Energy levels + Schrödinger Eq. $\rightarrow q\bar{q}$ potential

Toponium ?



$$m_t = 173\ GeV$$

$$\alpha_s(m_t) \approx 0.1$$

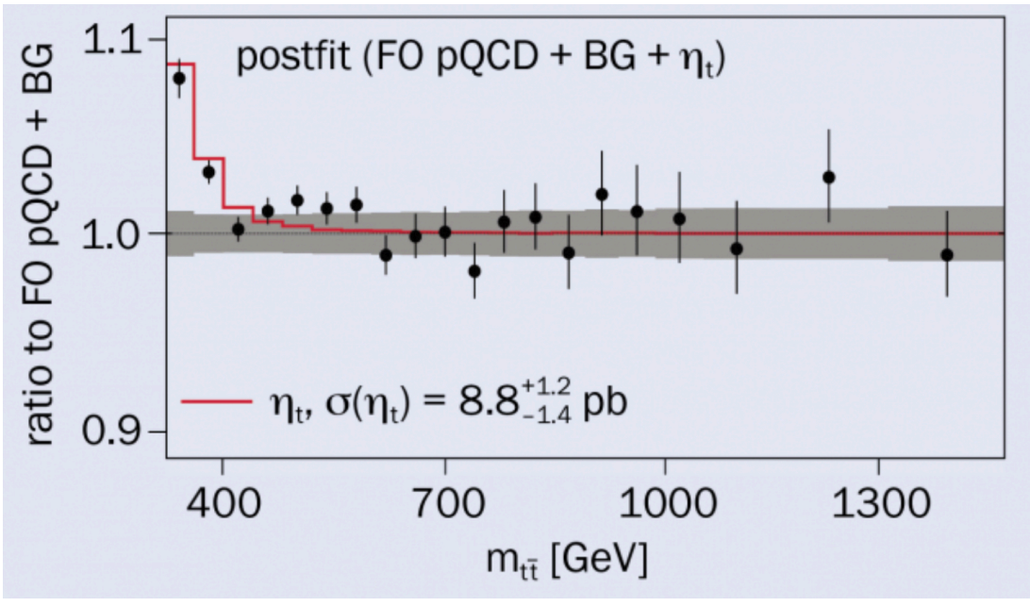
$$\tau_t = 5 \times 10^{-25}\ s$$

Minimal influence of non-perturbative effects

$t\bar{t}$ formation time $\sim 10^{-24}\ s$

tt pairs shouldn't have time to form bound states!

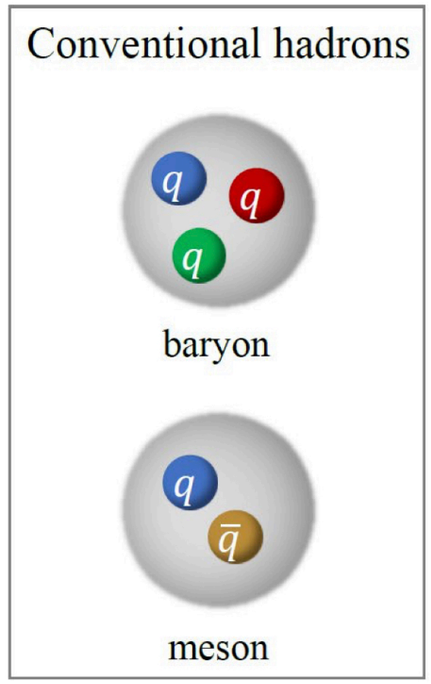
But:

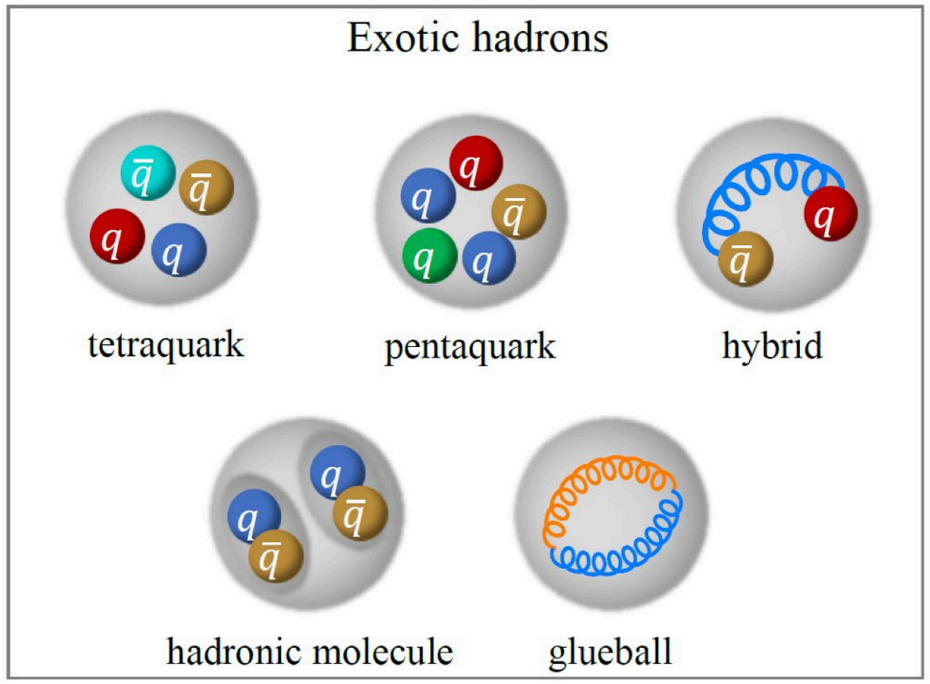


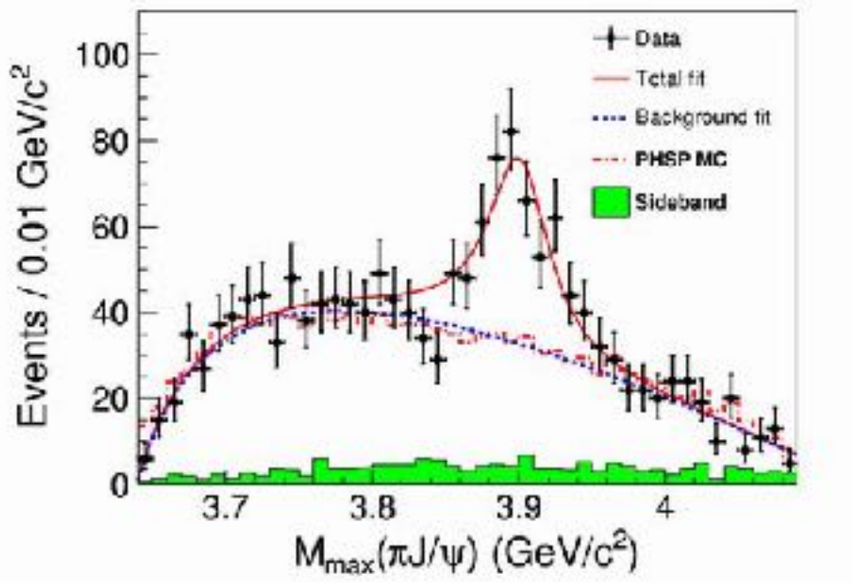
CMS 2025

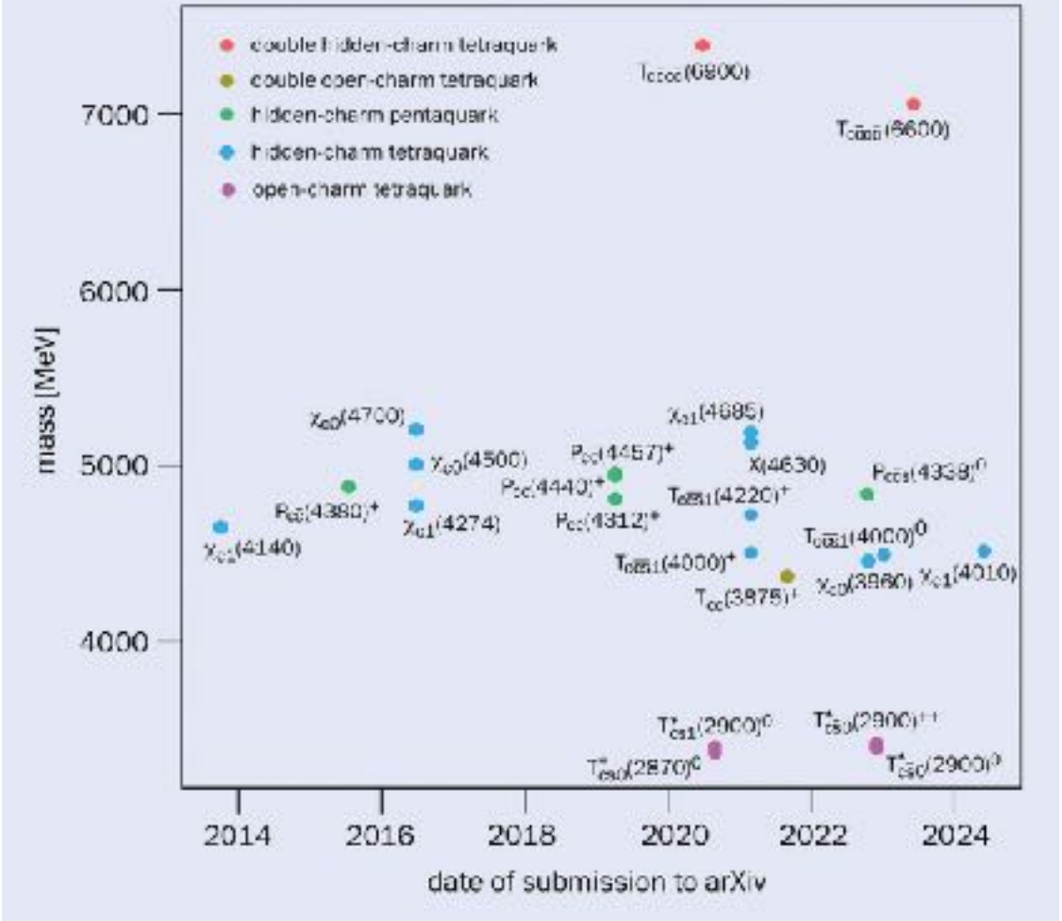
First glimpse of (quasi-)bound state?

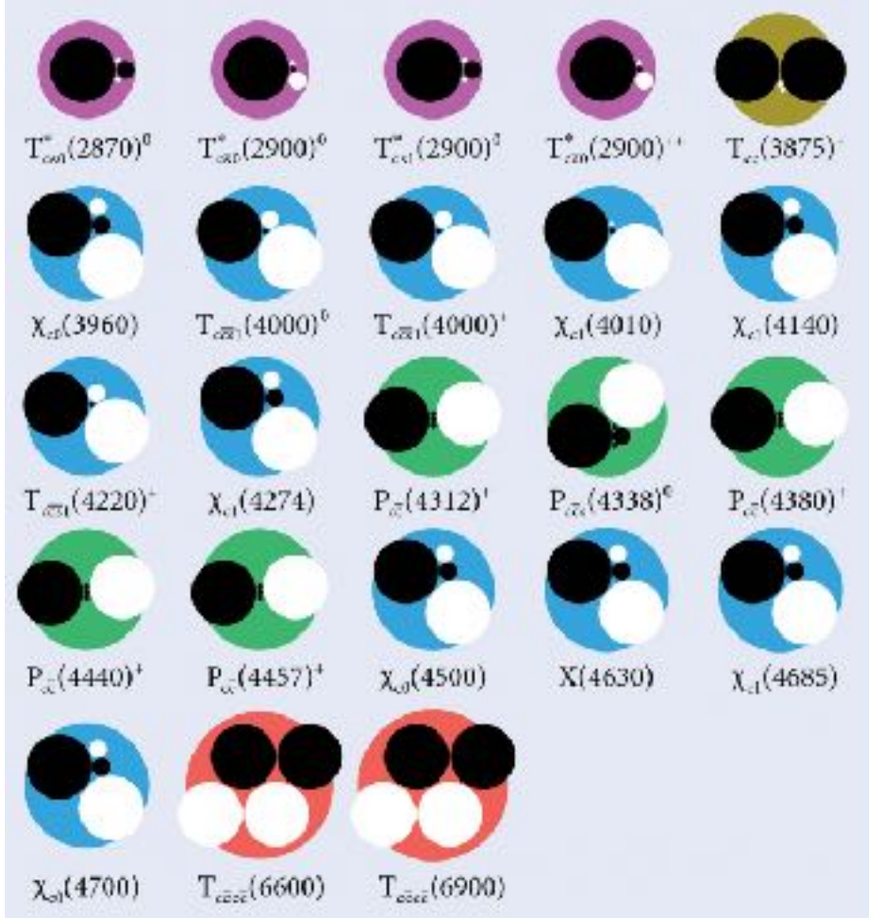
Exotic hadrons











23 exotic hadrons have been discovered at LHC

Nuclear effects

A-A and p-A interactions cannot be simply reduced to N-N interactions!

$$\sigma_{pA} \sim A^{0.68}$$

Higher multiplicity. In a p-A collision, the incoming proton can interact sequentially with multiple nucleons inside the nucleus

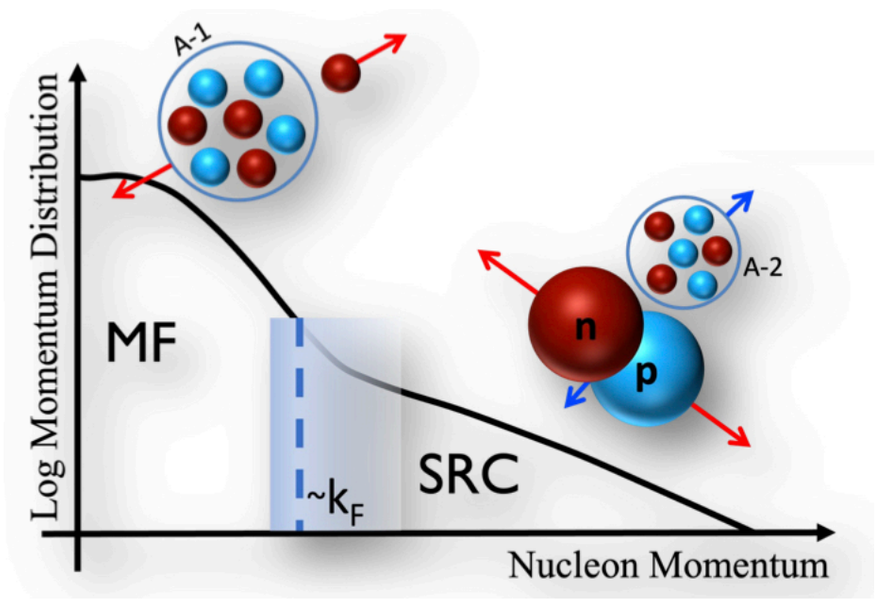
Short-range correlations. They represent closely interacting nucleon pairs (or triples)

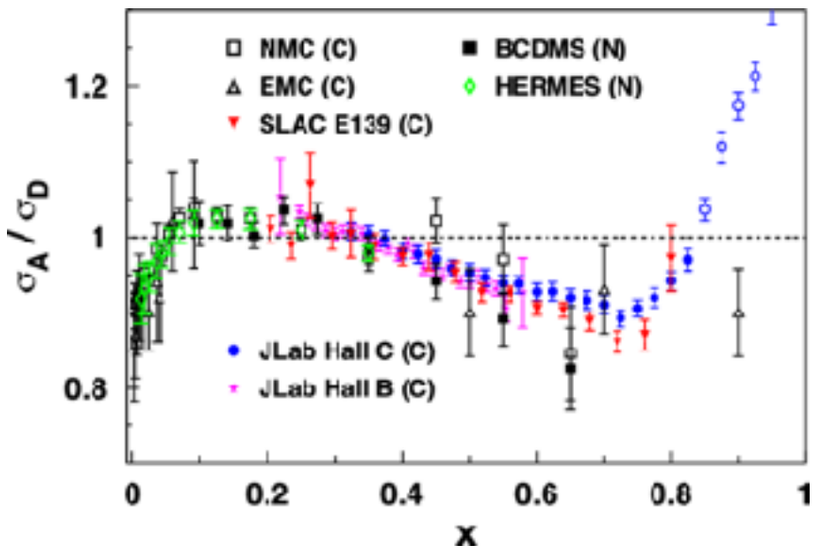
Nuclear effects in the initial state. The partons inside the nucleons of the nucleus have different momentum distributions than those in a free proton (EMC-effect).

Final-State Interactions. Particles produced in the initial collision must propagate through the dense nuclear medium. This leads to:

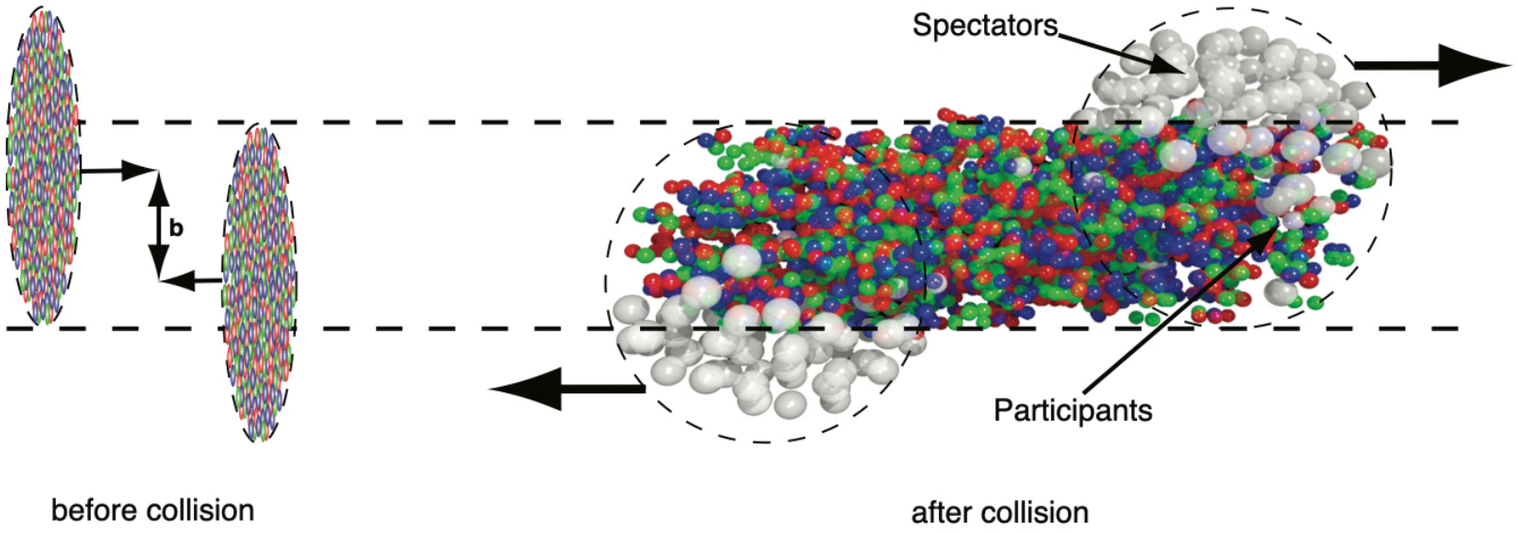
Absorption: Some secondary hadrons can be broken up or absorbed via interactions with other nucleons.

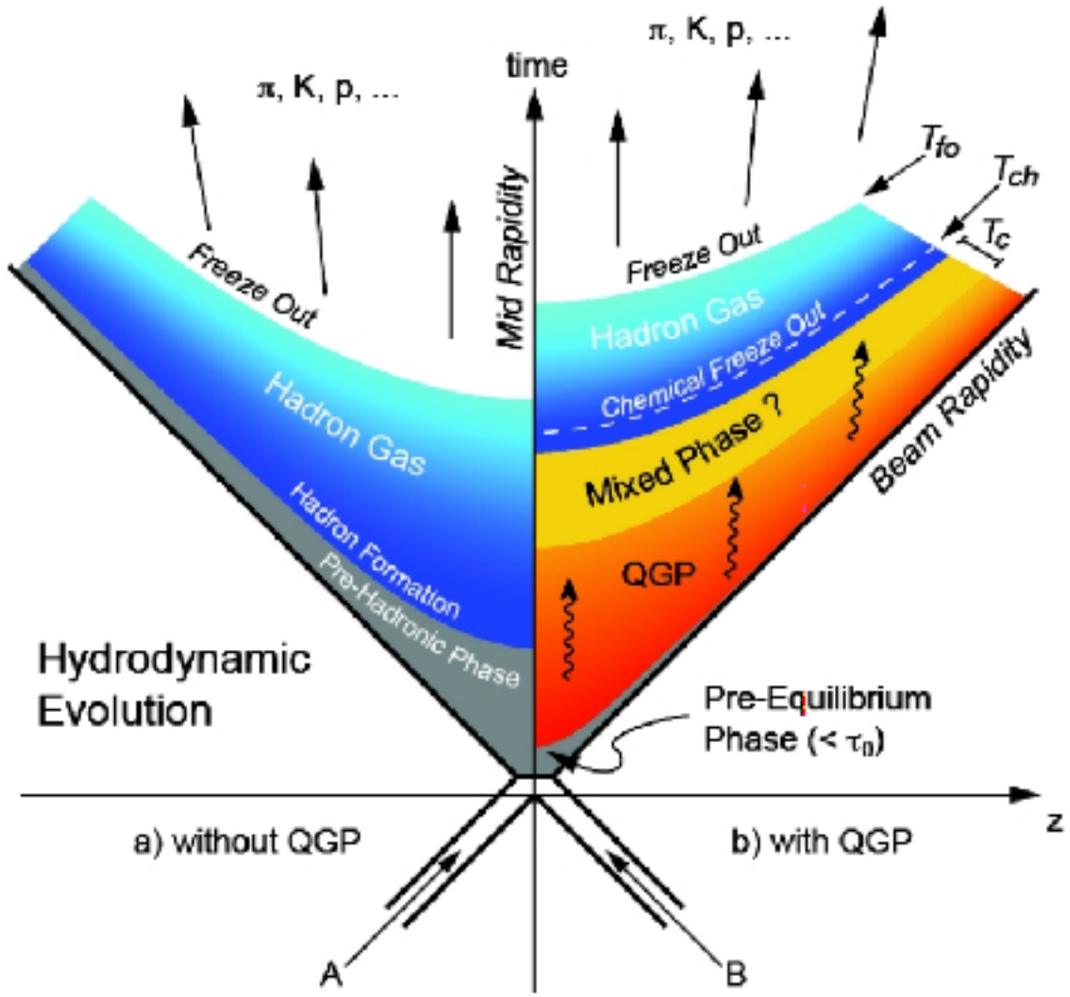
Rescattering: Particles can lose energy and change their momentum by scattering on their way out of the nucleus.





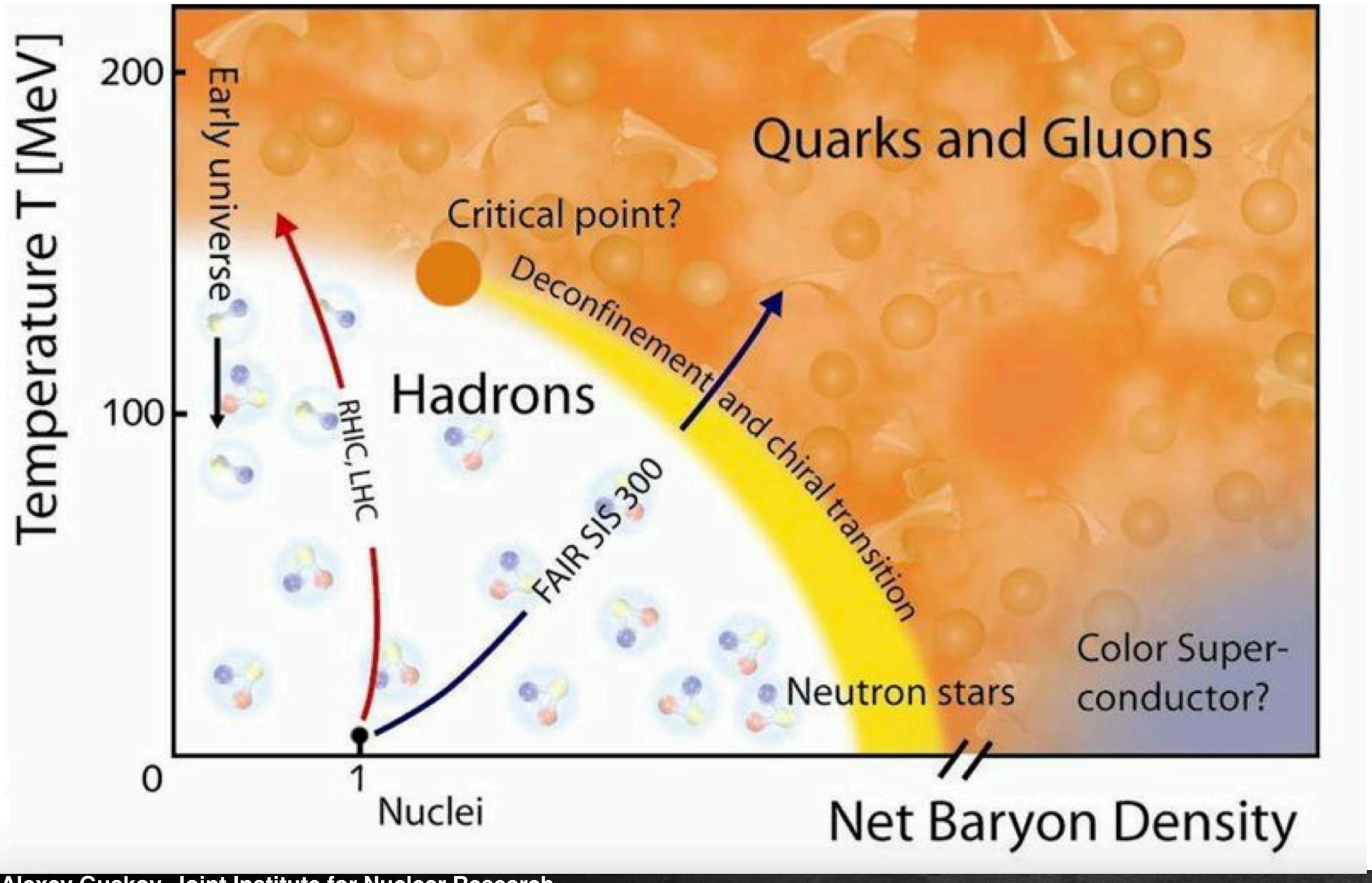
Quark-gluon plasma



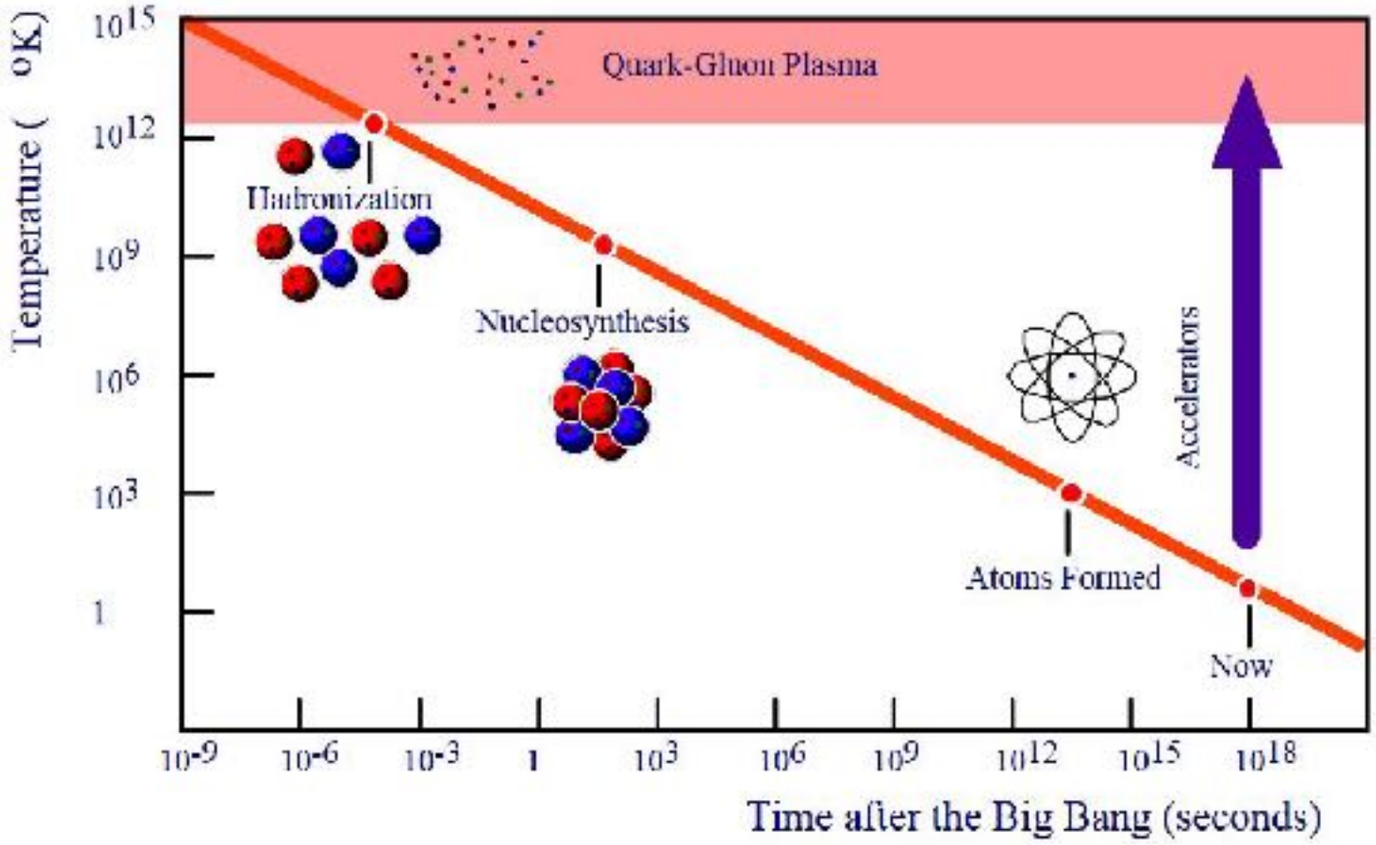


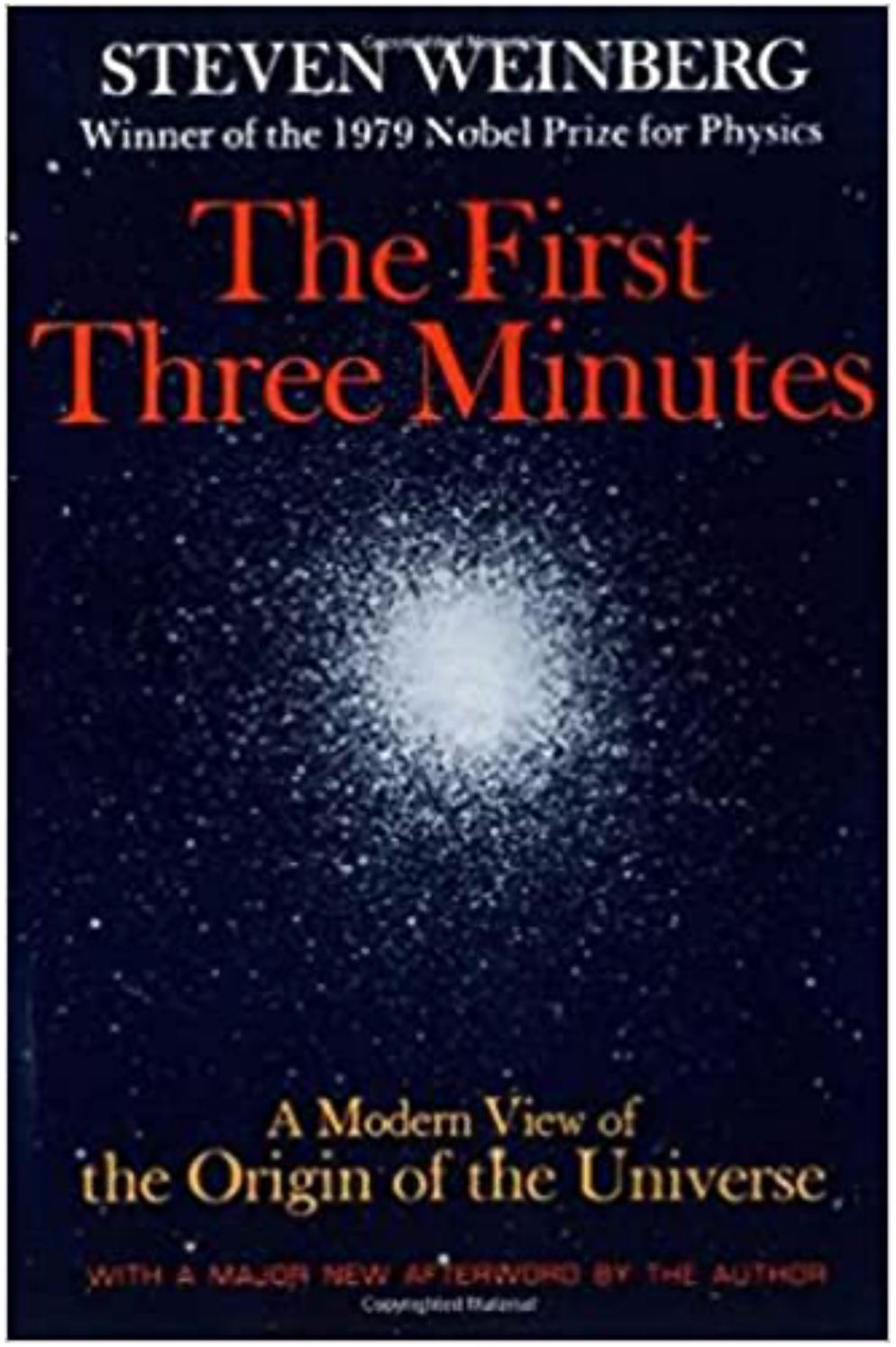
- Extreme temperature and density
- Perfect liquid behavior
- Deconfinement
- Collective interaction
- Extremely short-lived state in local thermal equilibrium
- Restoration of chiral symmetry
- Partial restoration of flavor SU(3) symmetry

QCD matter at extreme conditions

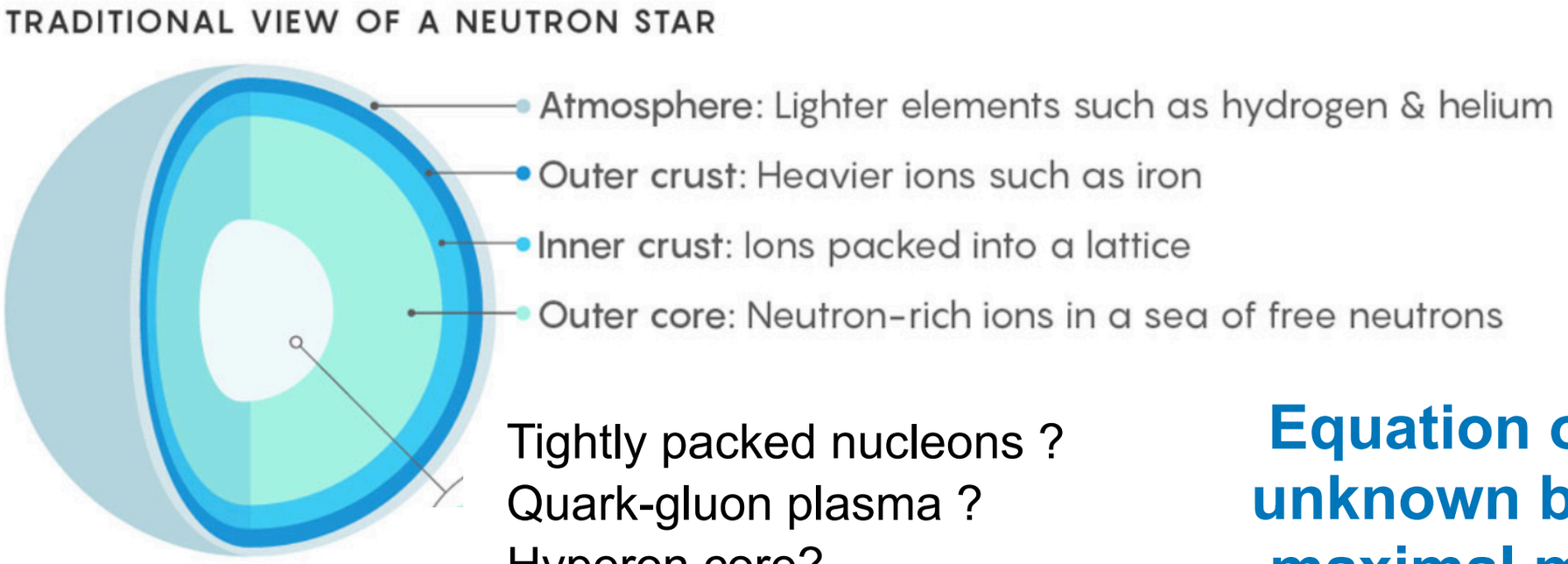


QGP and cosmology





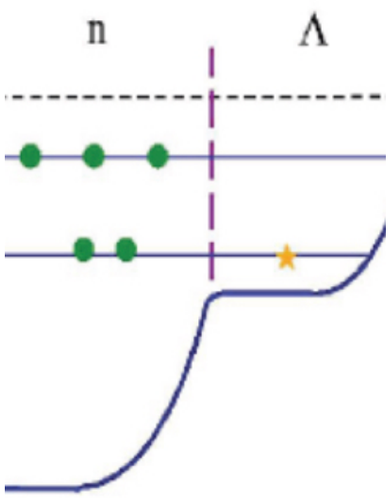
Neutron stars: hyperon puzzle



Tightly packed nucleons ?
Quark-gluon plasma ?
Hyperon core?
Kaon core?

Equation of state (EoS) is unknown but it defines the maximal mass of neutron stars!

Experimental evidence:
M_{max} ~2.0 M_0



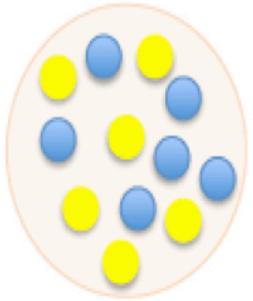
In terms of energy minimization, a fraction of the neutrons must convert into hyperons!

But in this case M_{max} << 2.0 M_0 !

- Better understanding of NY and YY potentials
- Three-body forces NNN, NNY, YYN, YYY
- …

Hypernuclei

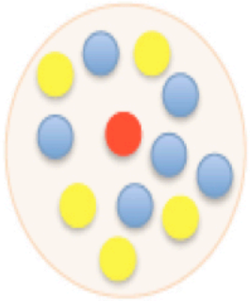
nucleons
(protons, neutrons)



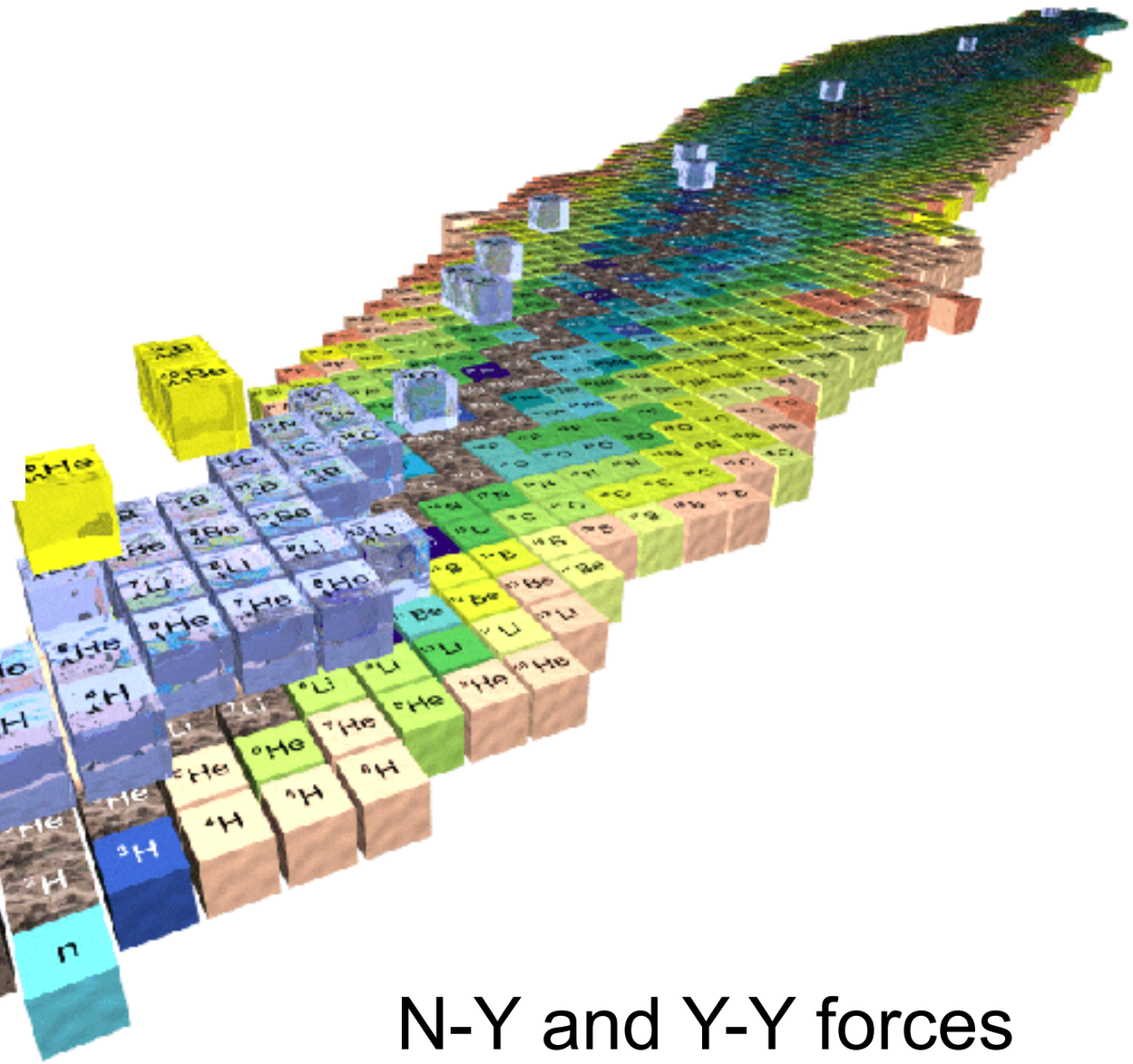
nucleus

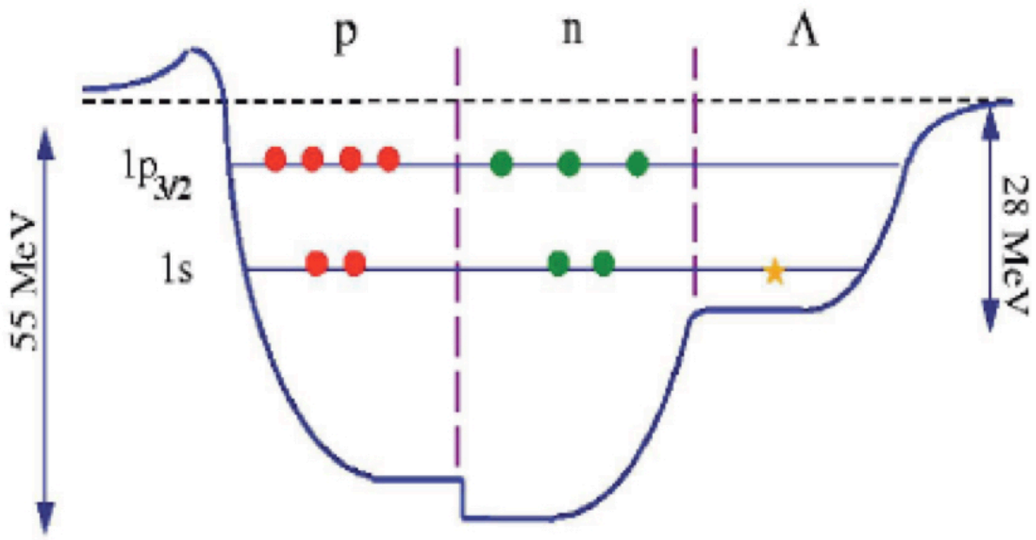


hiperon (Λ, Σ, Ξ ...)



hypernucleus



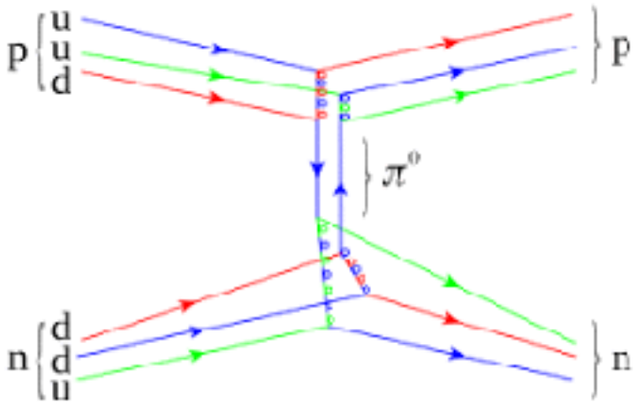


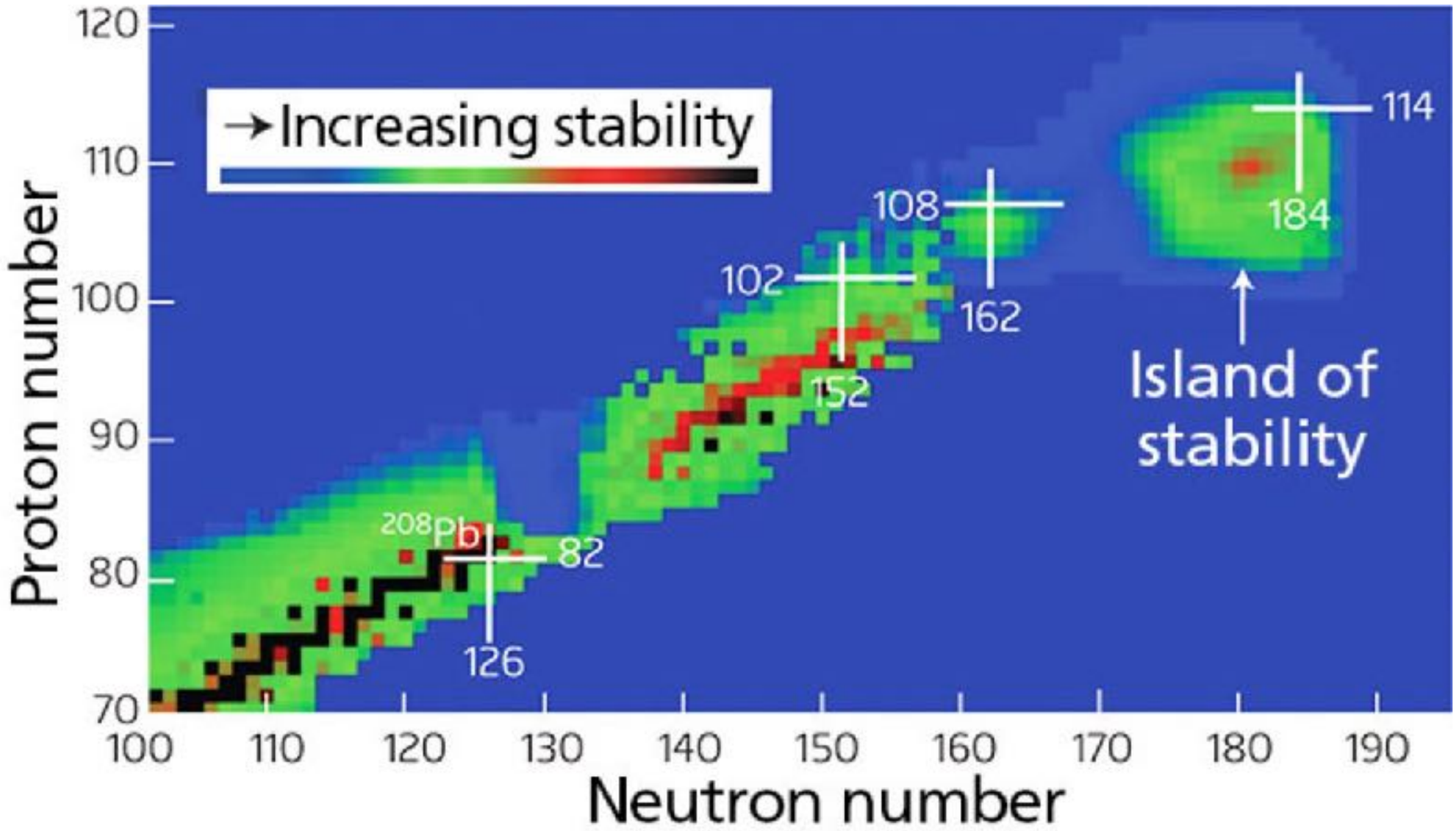
Simple s.p. model of ${}^{12}_{\Lambda}C$

N-Y and Y-Y forces

What about mesonic nuclei?

Super heavy elements



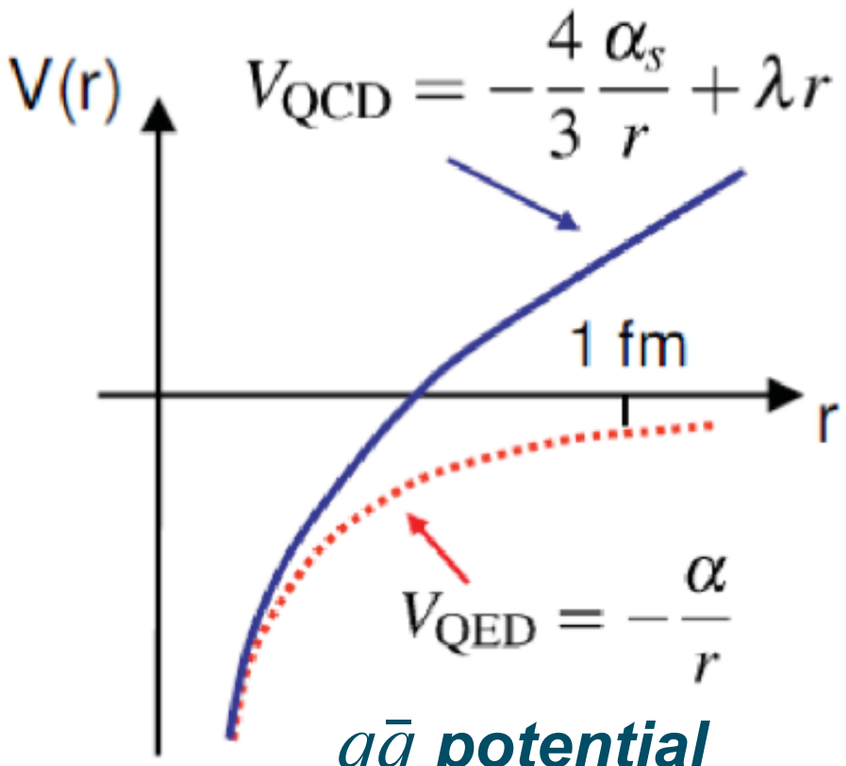


Confinement problem

- We cannot rigorously derive the confinement property from the first principles of Quantum Chromodynamics. **It is just an empirical fact**.

- Lattice QCD confirms confinement but do not provide a simple, intuitive physical picture.

One of a Millennium Prize Problem!



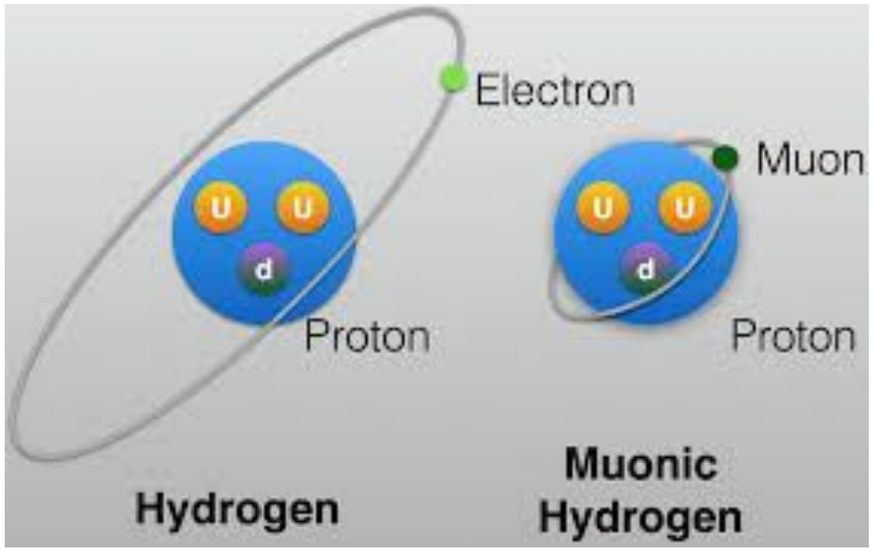
$q\bar{q}$ **potential**

$$\times e^{\frac{-m_g c r}{\hbar}}$$

Massive gluon = deconfinement!

$$m_g < 1.3\ MeV$$

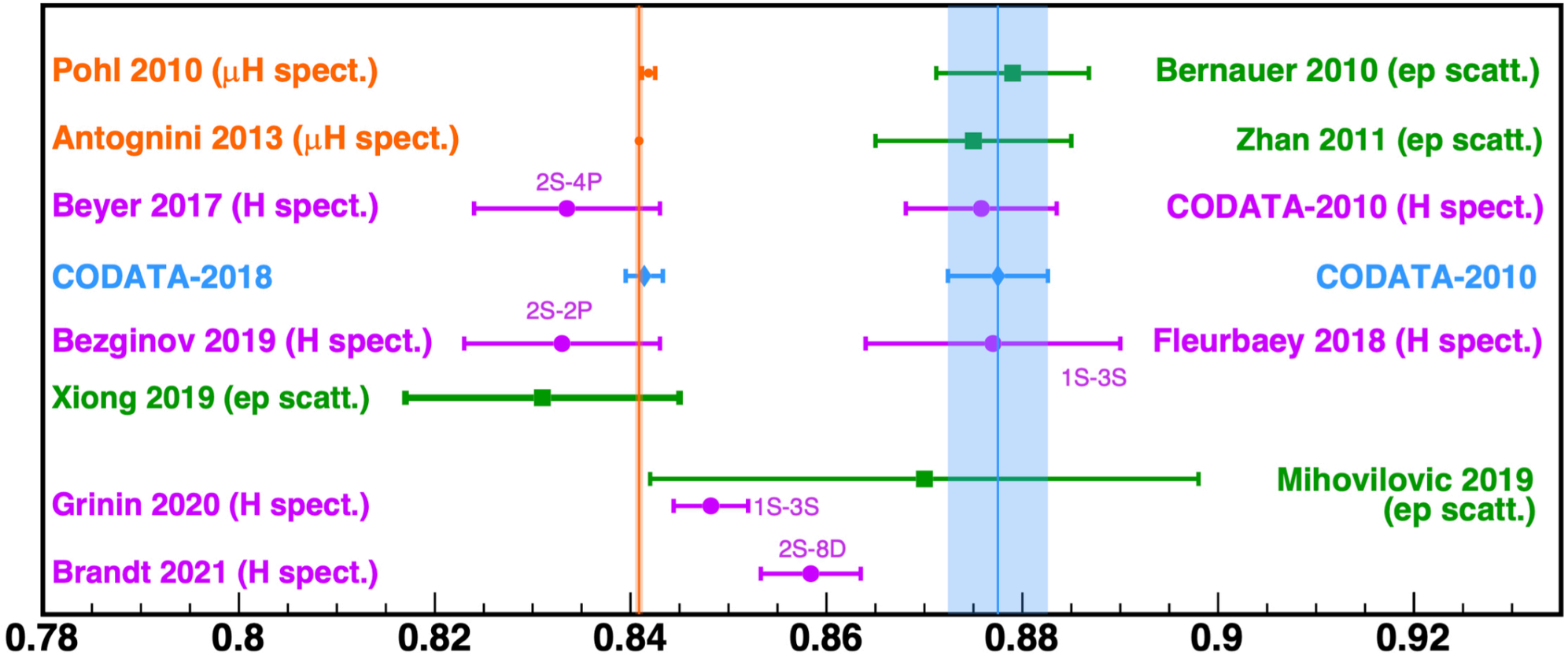
Proton radius puzzle



Different approaches give different results!

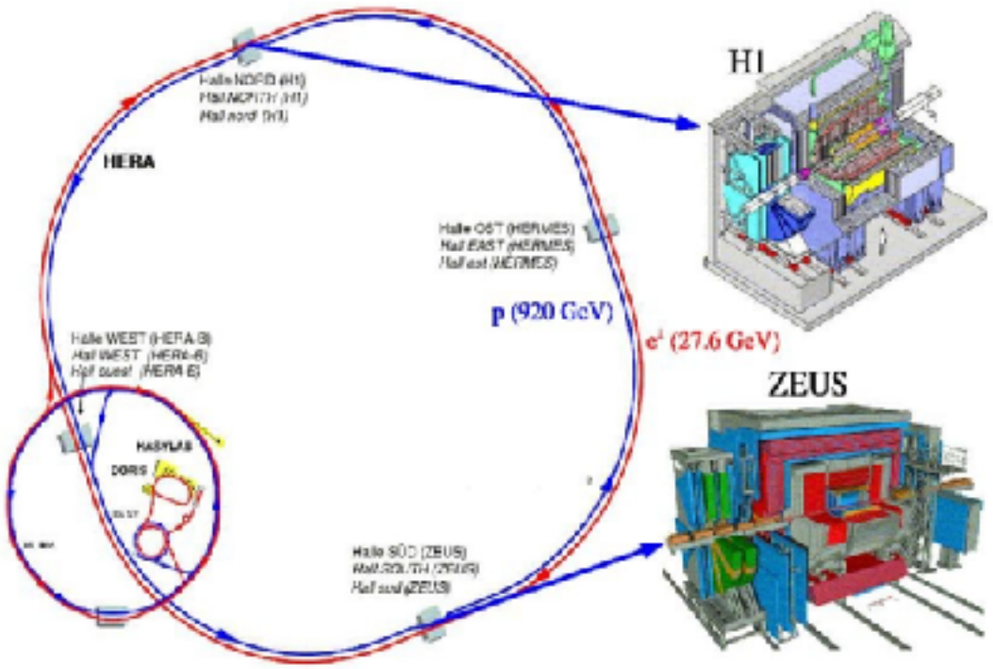
Possible explanations:

- experimental or methodological errors
- *new physics: lepton universality violation*



Solved or not?

Quark size

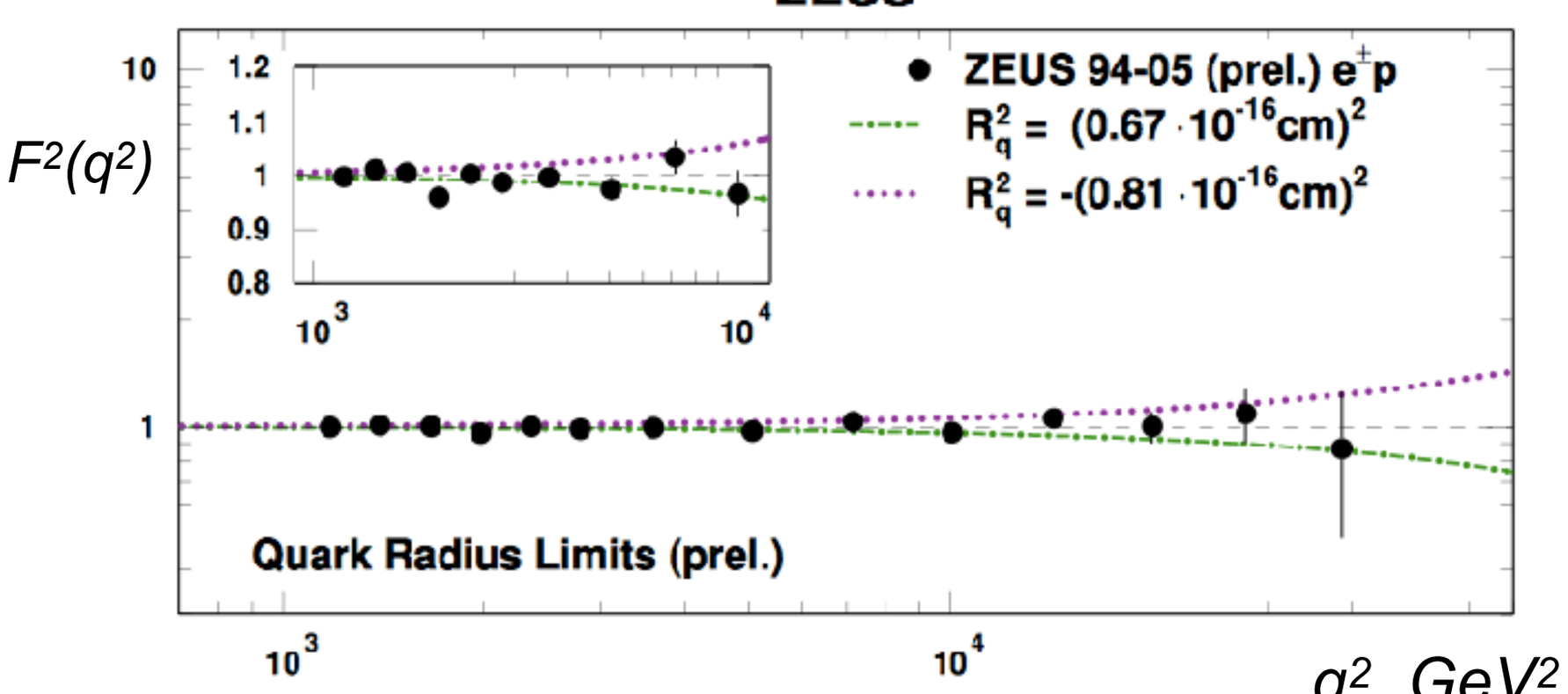


HERA - high-energy electron-proton collider at DESY (1992-2007)

At the moment there is no indication that quarks have an internal structure

$$F(q^2) \approx 1 - \frac{q^2 < r_q^2 >}{6\hbar^2}$$

$r_q < 0.7 \times 10^{-3}$ fm



QCD & beyond

Quark substructure:

In the SM quarks are point-like fundamental particles. We currently have no knowledge of a force that could bind constituents inside a quark

But there are models beyond SM where quarks are more complex objects

(No) CP violation in QCD sector:

Strong CP violation is useful for explaining the asymmetry between matter and antimatter in the Universe. But we do not see it. Why?

$$\mathcal{L}_{\not{CP}} = \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \qquad \theta \leq 10^{-10}$$

Peccei–Quinn mechanism → axion → light dark matter candidate

t-quark - instrument for stringent SM test an search for physics beyond:

Interaction strength with the Higgs field is proportional to mass of fundamental particles. t-quark is the most massive one.

New physics could manifests itself in t-quark behavior on the top of the QCD prediction

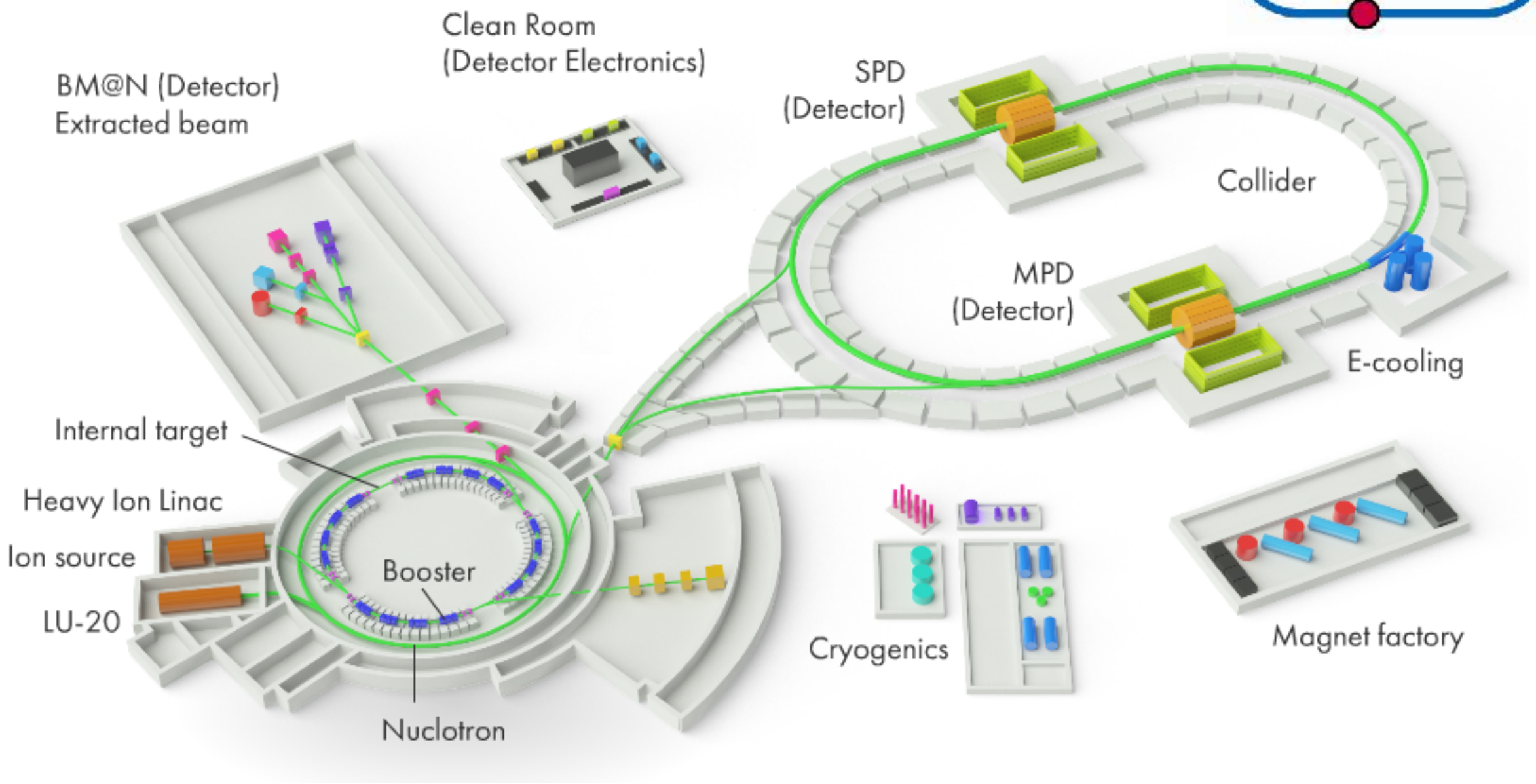
Study of rare and search for forbidden decays of hadrons

Electric dipole moment of hadrons

...

NICA collider

Nuclotron-based Ion Collider fAcility



NICA collider



NICA landscape

➤ 13.6.24 - NICA technological launch



➤ First beam in the collider - December 2025

NICA: experimental setups

BM@N

The study of the strange matter production in heavy-ion collisions in the fixed-target mode

NICA MPD

The search for novel phenomena in the baryon-rich region of the QCD phase diagram by means of colliding heavy nuclei

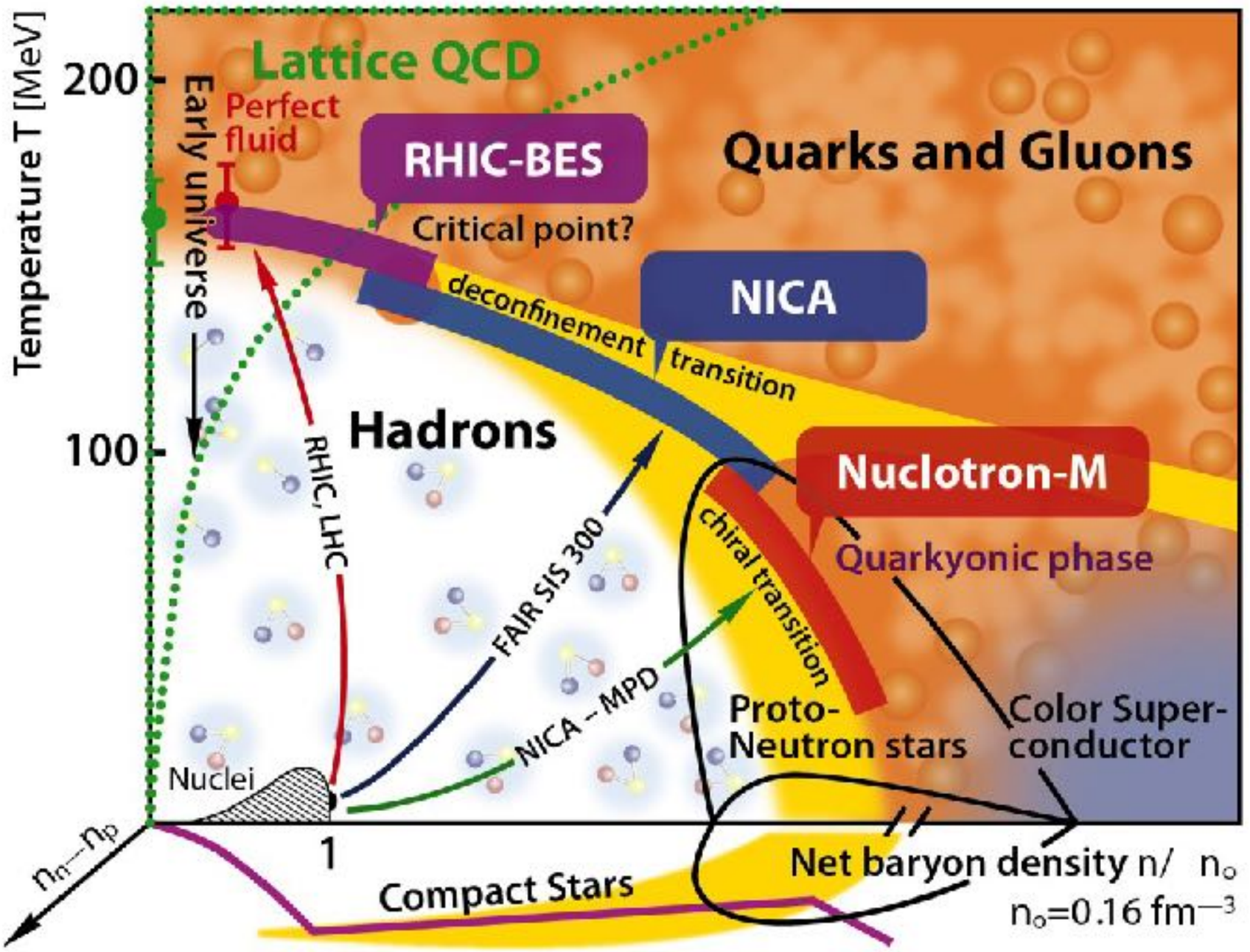
SPD NICA

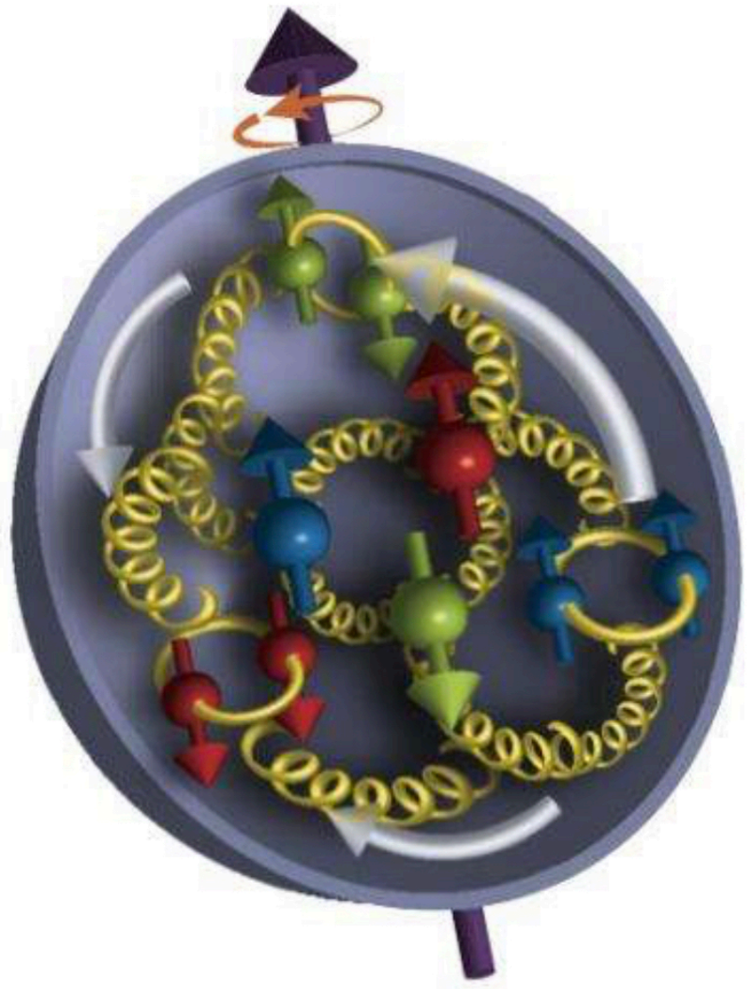
The study of the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams

ARIADNA beamlines

Applied research

QCD at NICA


Temperature T [MeV]
200
100
Lattice QCD
Perfect fluid
Early universe
RHIC-BES
Critical point?
Quarks and Gluons
NICA
deconfinement transition
Hadrons
RHIC, LHC
Nuclotron-M
chiral transition
FAIR SIS 300
Quarkyonic phase
NICA – MPD
Proto-Neutron stars
Color Super-conductor
Nuclei
$n_n - n_p$
1
Compact Stars
Net baryon density n/ n_o
n_o=0.16 fm^{-3}



QCD at NICA

Nuclear physics

Λ_{QCD}

Hypernuclei

Quark-gluon plasma

Nuclear effects in hadronic interaction

Spectroscopy

Hadron structure

Hard processes

Hadronization

$Q \lesssim \Lambda_{QCD}$

Non-perturbative regime

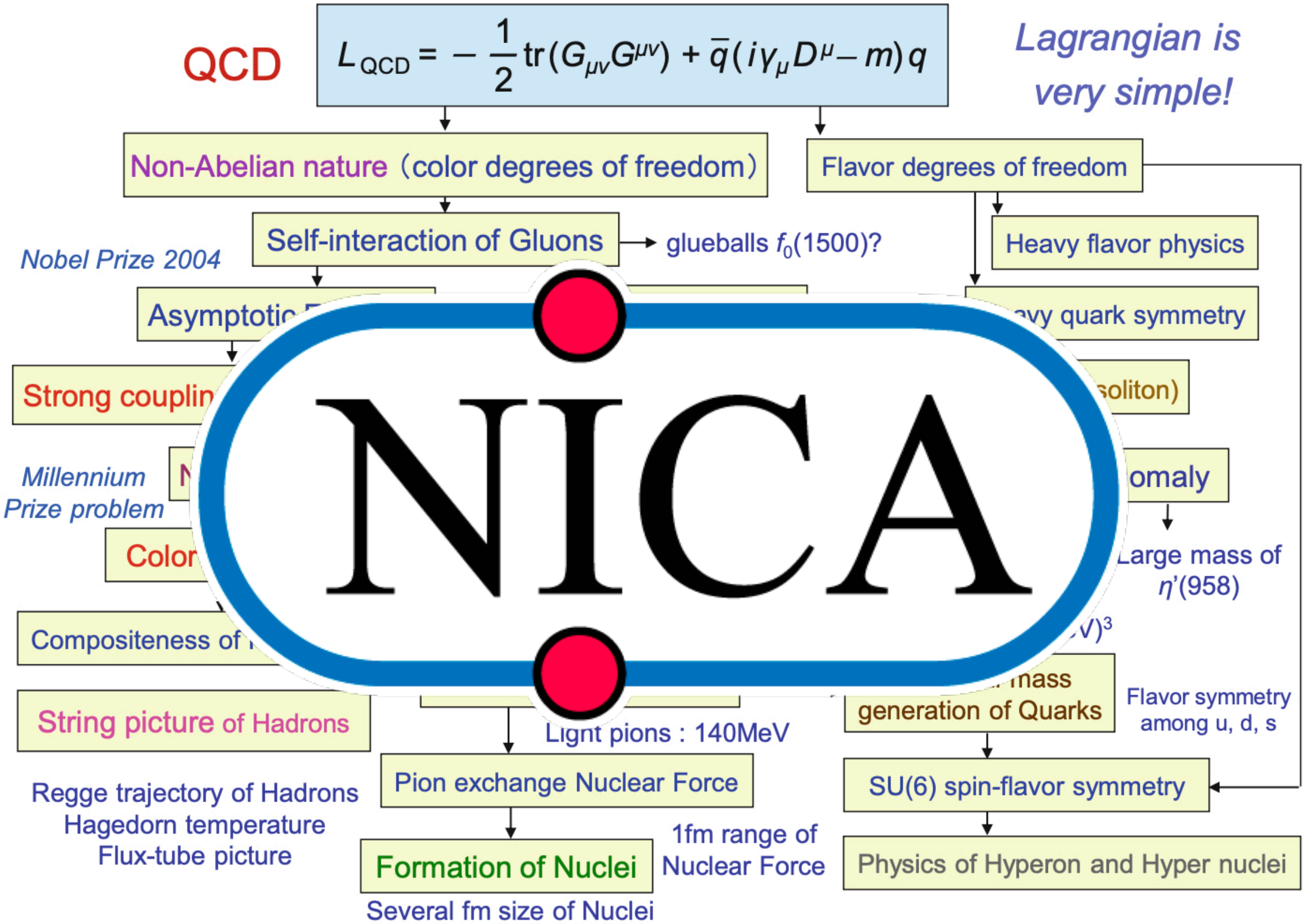
Phenomenological models

$Q \gg \Lambda_{QCD}$

Perturbative regime

“True” QCD

Summary


QCD
$L_{QCD} = -\frac{1}{2}\mathrm{tr}(G_{\mu\nu}G^{\mu\nu}) + \bar{q}(i\gamma_\mu D^\mu - m)q$
Lagrangian is very simple!
Non-Abelian nature（color degrees of freedom）
Flavor degrees of freedom
Self-interaction of Gluons
glueballs $f_0(1500)$?
Nobel Prize 2004
Heavy flavor physics
Asymptotic
avy quark symmetry
Strong couplin
soliton)
Millennium Prize problem
omaly
Color
Large mass of $\eta'(958)$
Compositeness of
$V)^3$
mass generation of Quarks
Flavor symmetry among u, d, s
String picture of Hadrons
Light pions : 140MeV
Regge trajectory of Hadrons
Hagedorn temperature
Flux-tube picture
Pion exchange Nuclear Force
SU(6) spin-flavor symmetry
1fm range of Nuclear Force
Formation of Nuclei
Physics of Hyperon and Hyper nuclei
Several fm size of Nuclei
NICA

Summary