THE FASCINATING PHYSICS OF QCD

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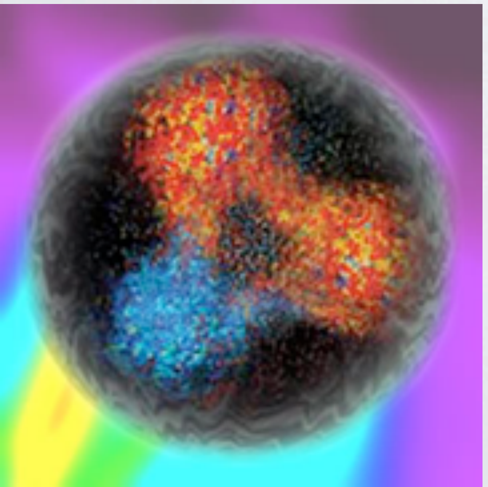
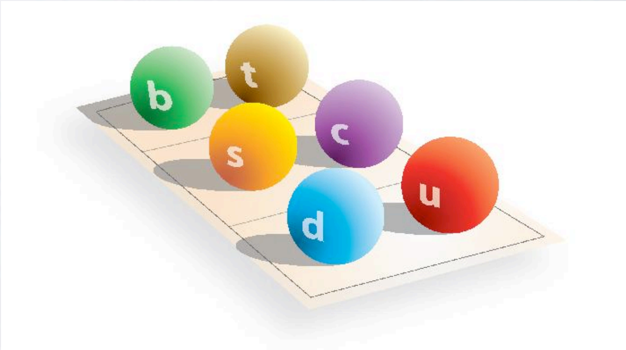
30/3/11

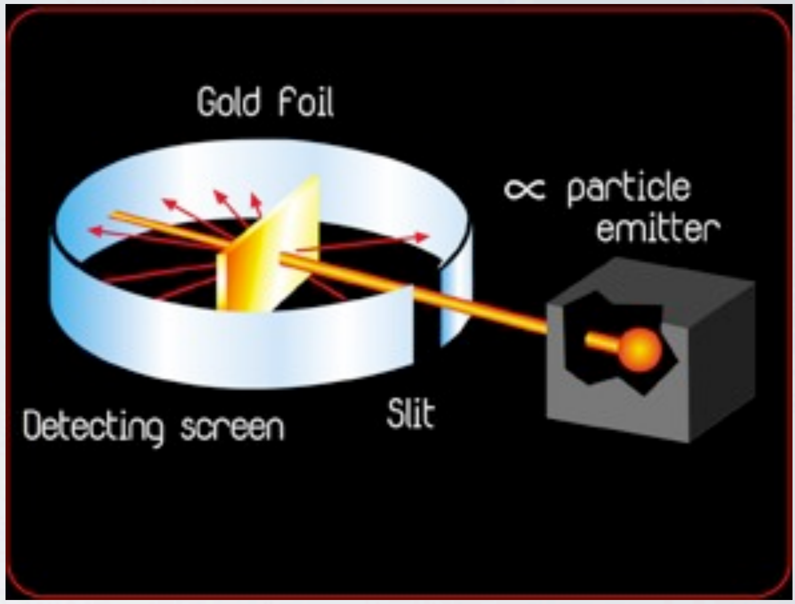




A brief history of discoveries leading to QCD

The experiment that started it all

Rutherford, Geiger & Marsden (1910-1911)



backward scattering of alpha particles signal an atomic nucleus size < 3×10^{-12} cm

sets in motion a revolution in physics

Bohr model of the atom paving the way for quantum mechanics and atomic physics

beginning of nuclear physics

beginning of particle physics

establishes scattering as key experimental method

Proton, neutron and the nuclear force

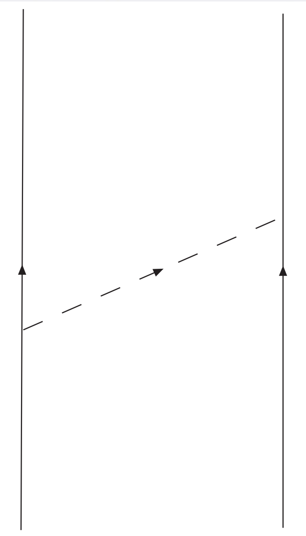
proton established by Rutherford (1919)
neutron established by Chadwick (1932)

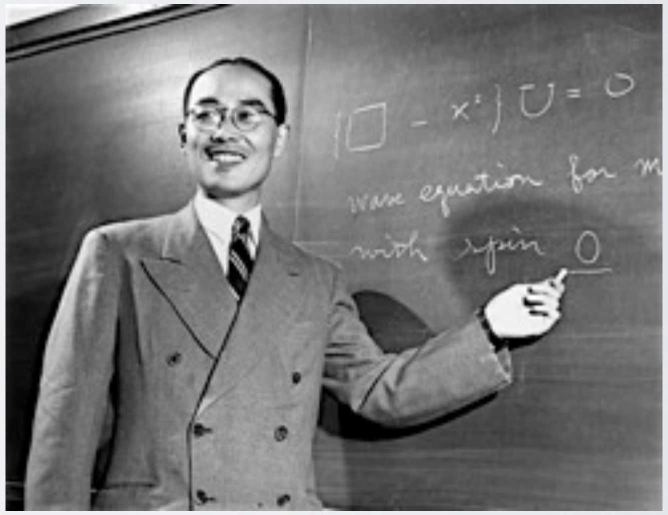
Model of atomic nuclei as bound system of protons and neutrons

Binding force must be of a new kind to overcome electrostatic repulsion between protons in nucleus

Yukawa hypothesis (1935):

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





meson particle proposed as mediator of strong interaction:

the pion, discovered in 1949

A new concept: Isospin

$$m_p = 938.27\ MeV/c^2 \qquad m_n = 939.56\ MeV/c^2$$

there is an internal symmetry associated with p, n and the nuclear forces (Heisenberg 1932!)

gives way to new fundamental aspect of particles: they can be arranged in multiplets associated with internal symmetries

this defines a new way physicists study particles and their interactions: symmetry principles take center stage

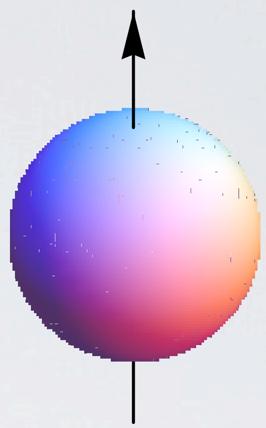
$$SU(2) \quad Isospin$$
$$SU(3) \quad Eightfold\ \ way$$

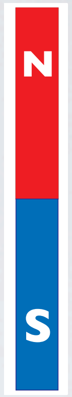
Flavor symmetries

The proton cannot be elementary!

Reason I: magnetic moment

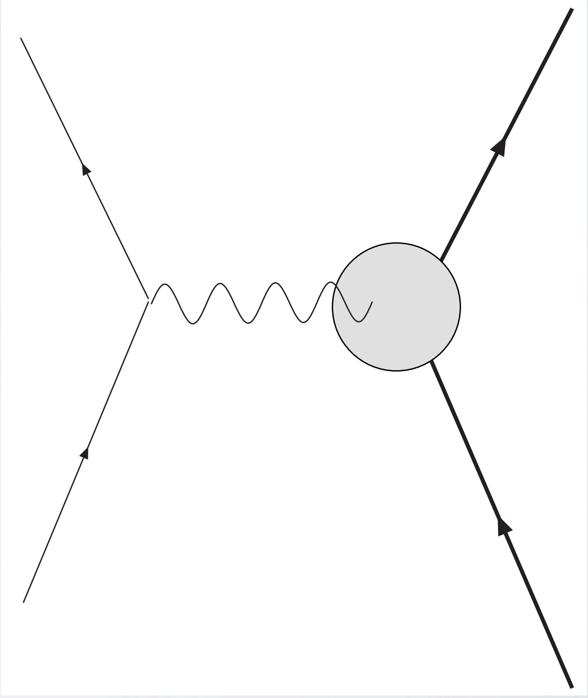
$$\mu_p = 2.8\,\mu_B$$





Reason II: extension measured
Hofstadter 1955

$$d\sigma = (d\sigma)_{Mott}\; F(q^2)$$



$r_0 = 9.5\times10^{-14}$cm   today: 8.4184×10^{-14}cm

establishes electron scattering as key tool to study hadrons and nuclei where JLab is the world leader

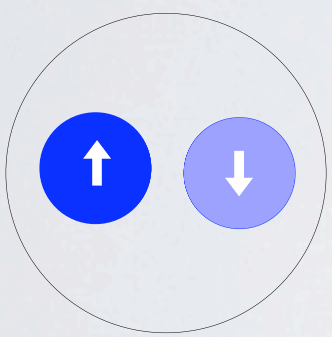
The quark model

1950's: large numbers of mesons and baryons discovered; strange hadrons

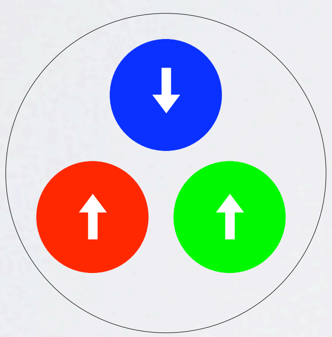
underlying structure is proposed

Gell-Mann; Zweig

quark model proposal 1964



Mesons

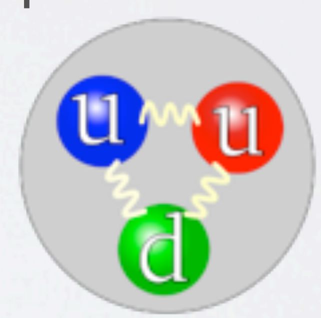


Baryons

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$$SU(3)$$

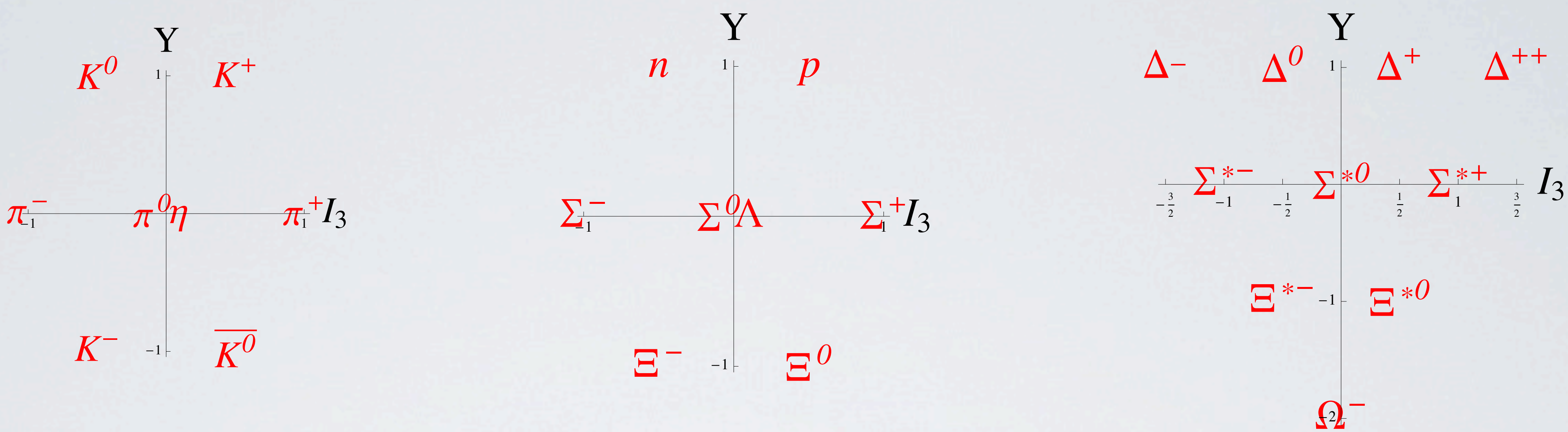
proton



neutron

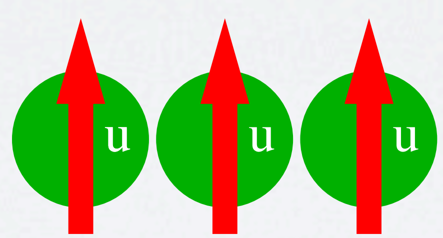
QM gave account of all known hadrons at the time and had accurate predictions from symmetry

The power of symmetry



SU(3) multiplets

… and a puzzle



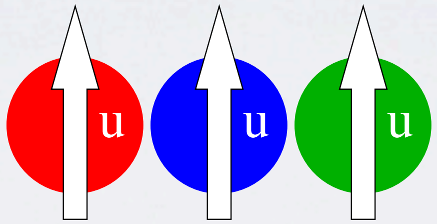
Δ^{++}

clash with Pauli exclusion principle

The need for color

a simple yet far reaching solution to the puzzle

Han & Nambu introduce new quantum degree of freedom



new SU(3) symmetry: color

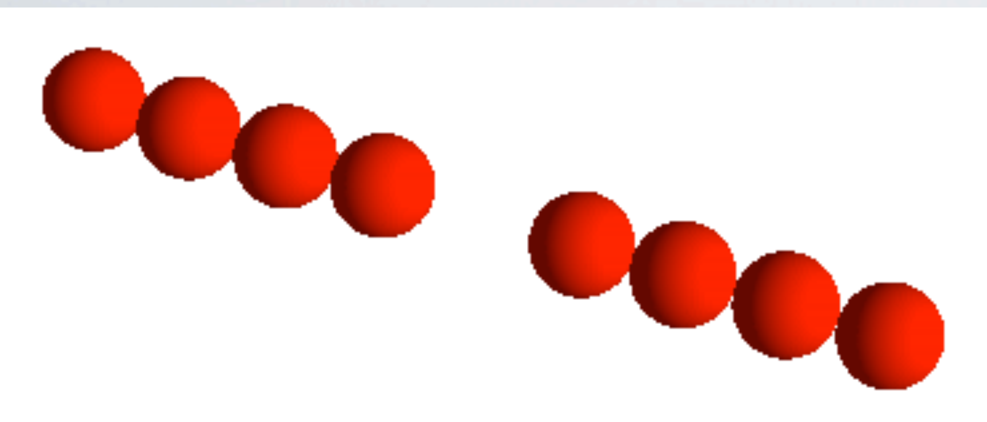
old puzzle: forces binding quarks together unknown

... and new puzzle: new degree of freedom is invisible!

A new fundamental force: QCD

gauge principle for the strong interactions is proposed

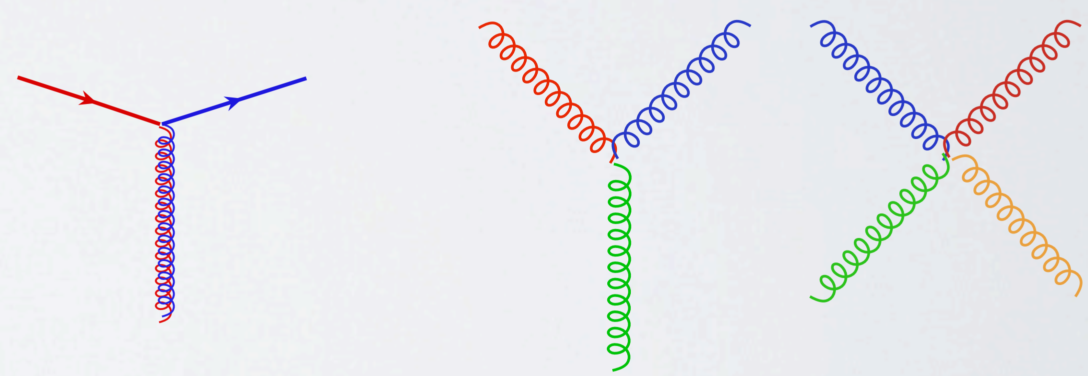
color SU(3) is a gauge symmetry



Yang-Mills type of theory

Fritzsch, Gell-Mann and Leutwyler
Politzer; Gross and Wilczek

spin 1/2 quarks in triplets of color
8 spin 1 massless particles, gluons



quarks

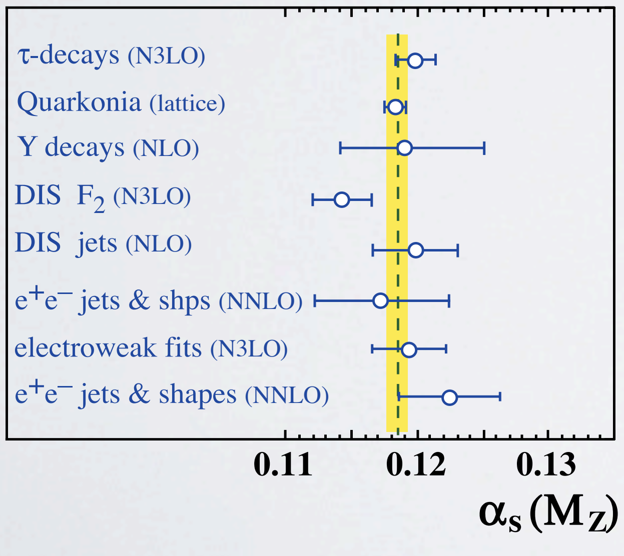
$$\mathcal{L}_{QCD} = \sum_f \bar{\psi}_f \,(i \not{D}(g\, G) - m_f)\, \psi_f - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

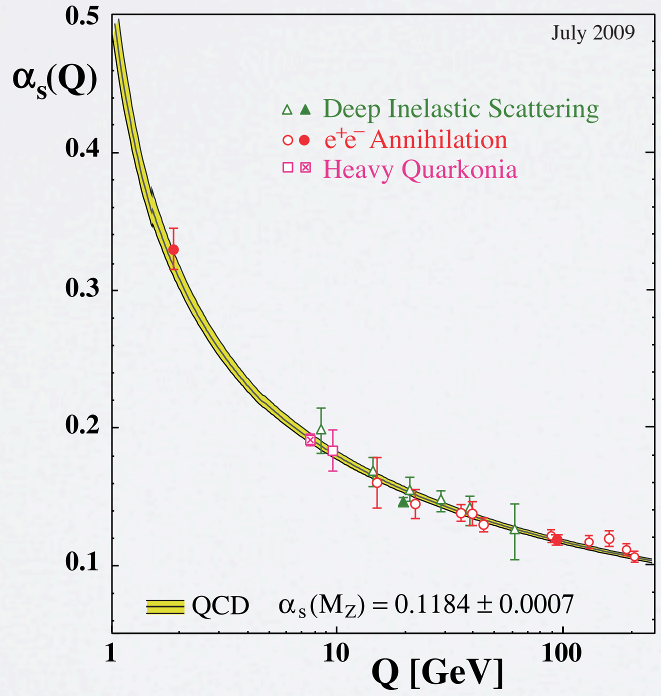
gluons

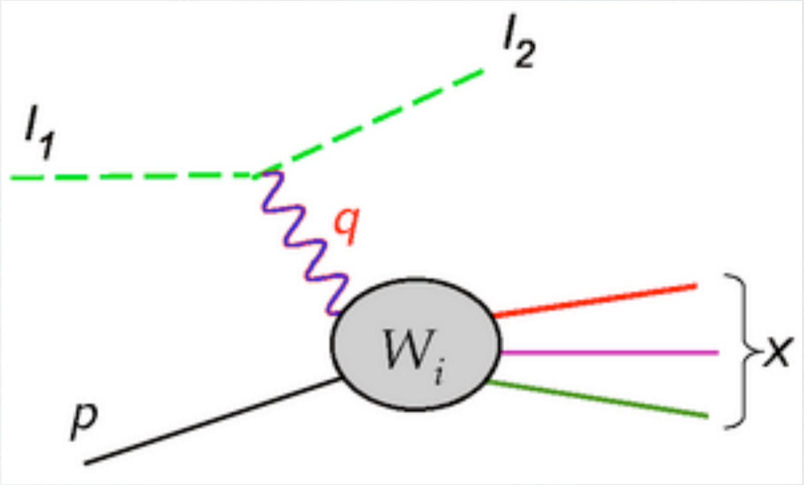
QCD's first hit: asymptotic freedom

$$\alpha_s(\mu) = \frac{4\pi}{(11 - \frac{2}{3}n_f)\, log \frac{\mu^2}{\Lambda^2_{QCD}}}$$

anti-screening phenomenon: purely quantum and unique to YM theories - explained scaling phenomenon in inelastic electron scattering







QCD's non-perturbative side

Color confinement

no unbound quarks have been observed

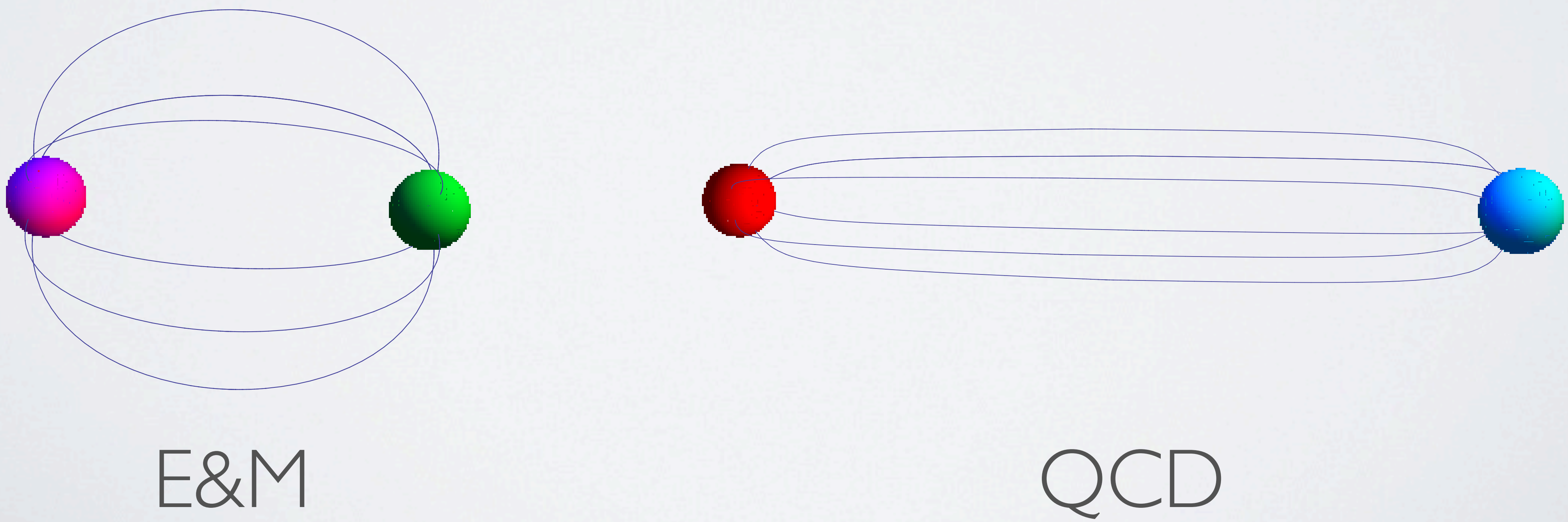
color is confined: only color singlet states, the hadrons are observed

least understood aspect of QCD, but we know:

must be quantum and non-perturbative

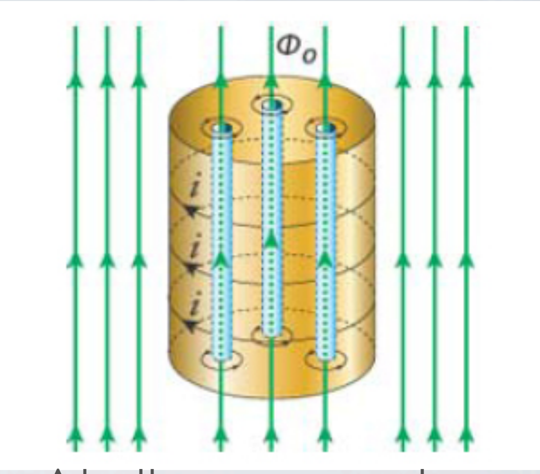
must be a property of the QCD vacuum

is reproduced in numerical simulations of QCD



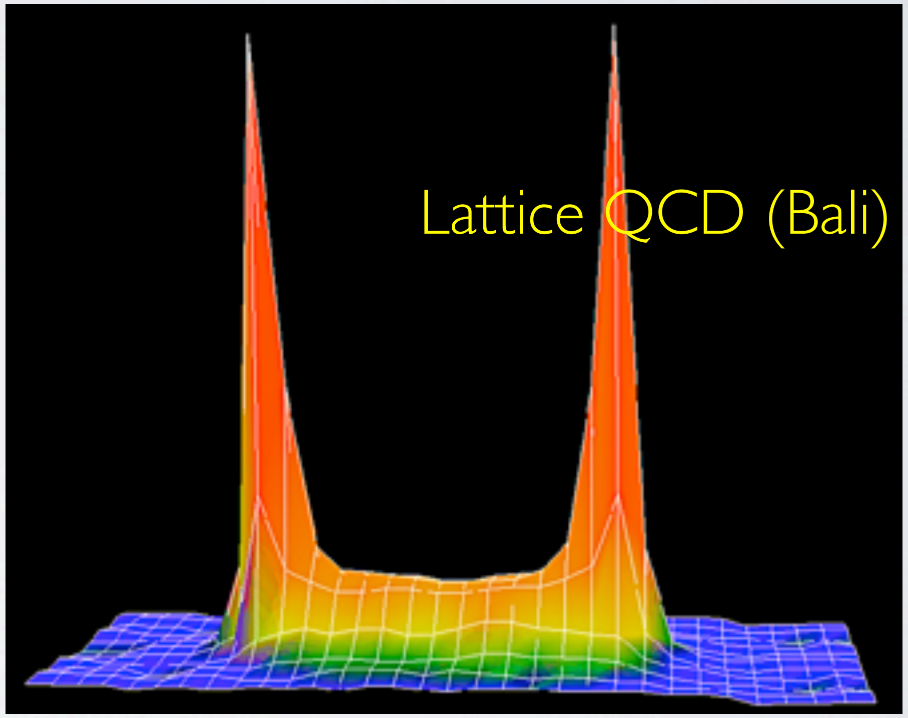
Models of confinement

Dual superconductor model
Stochastic vacuum model
Gribov horizons picture



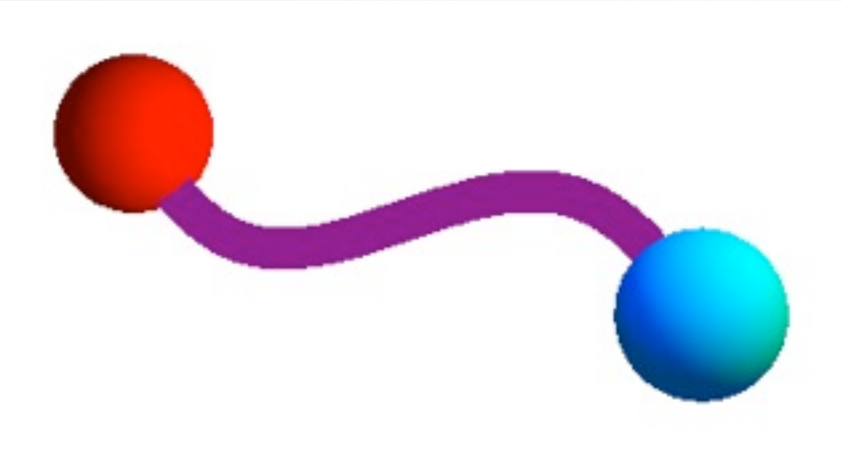
Abrikosov vortices

... but still biggest conceptual open problem in QCD and among "millenium problems"



real physical effects of flux tube

flux tube: 18 Tons!



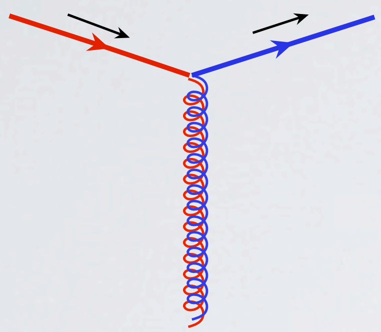
search for hybrid mesons

Hall D @ JLab

Mass from interactions

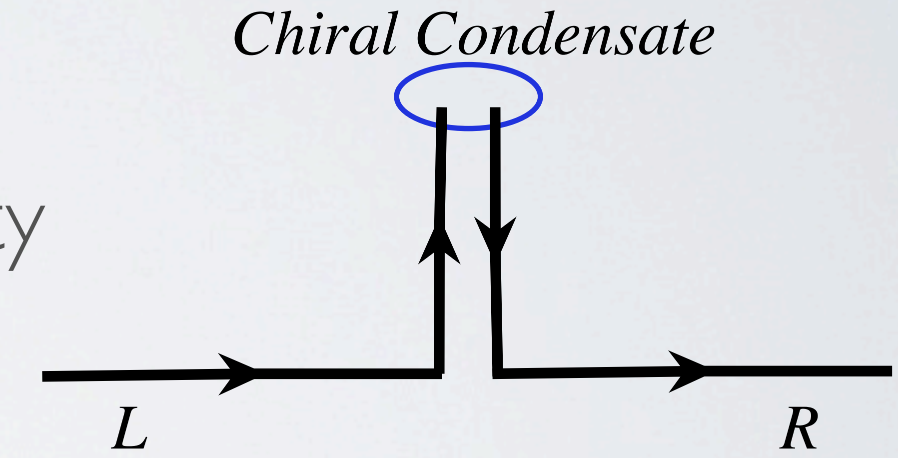
why is the π meson so much lighter than the proton ?

massless quarks → more symmetry: chiral symmetry



$$SU_L(3) \times SU_R(3)$$

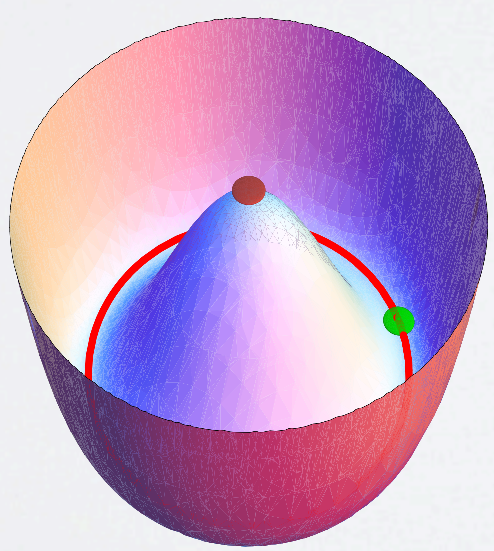
...but vacuum of QCD has less symmetry: $SU(3)$



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

phenomenon of (quark) pair condensation

analogous to Cooper pairs of superconductivity



spontaneous symmetry breaking phenomenon

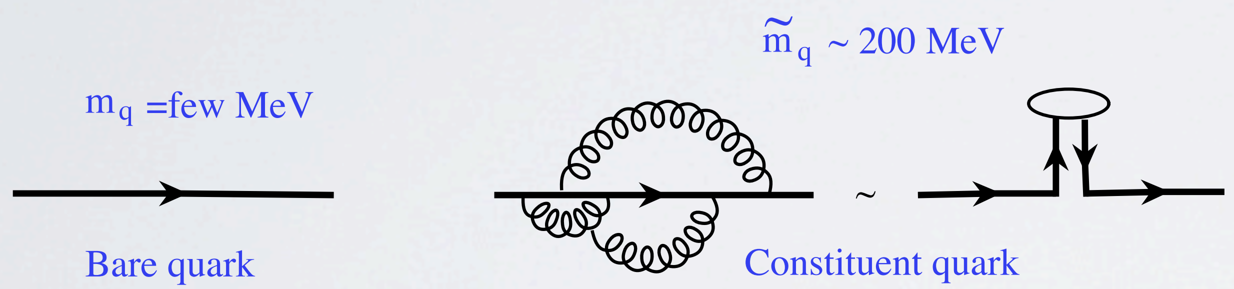
Lightest mesons are Nambu-Goldstone particles

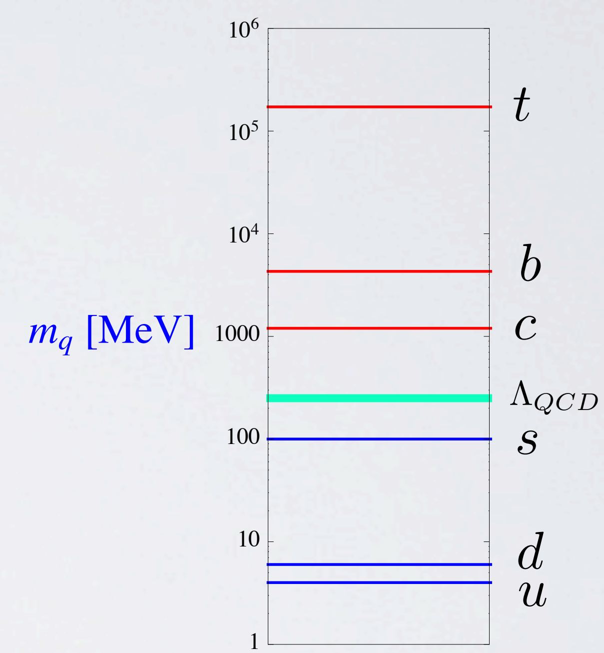
Nambu 1960

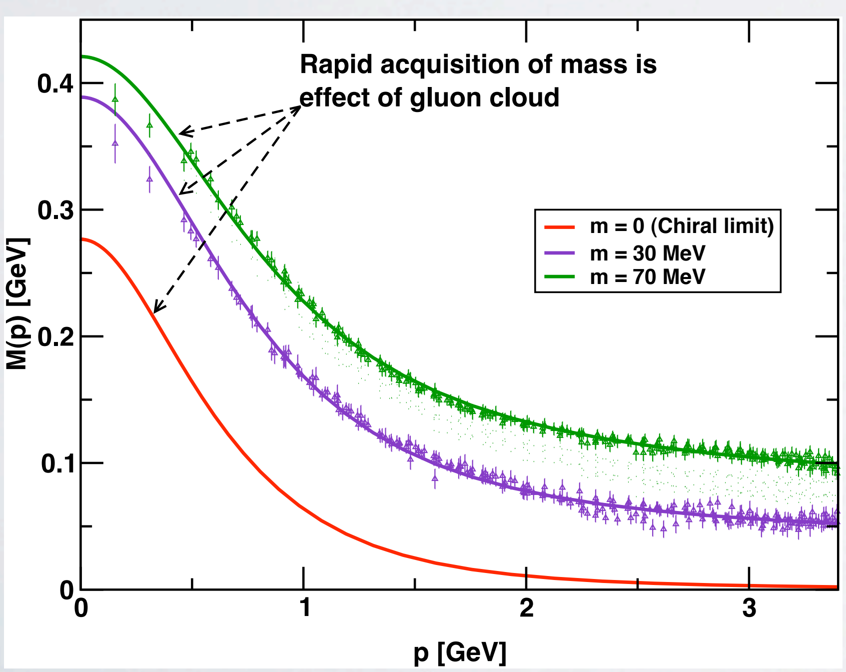
SSB → massless spin 0 particles

... but pion is not exactly massless $m_{quark} > 0$

$$M_\pi^2 = (m_u + m_d)\frac{\langle \bar{q}q \rangle}{F_\pi^2}$$





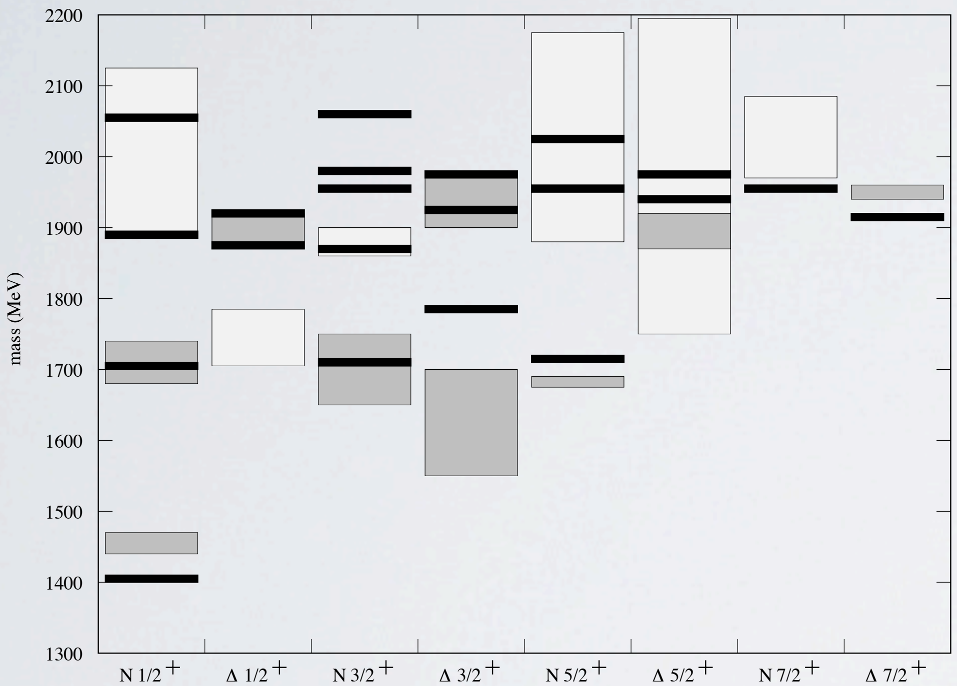


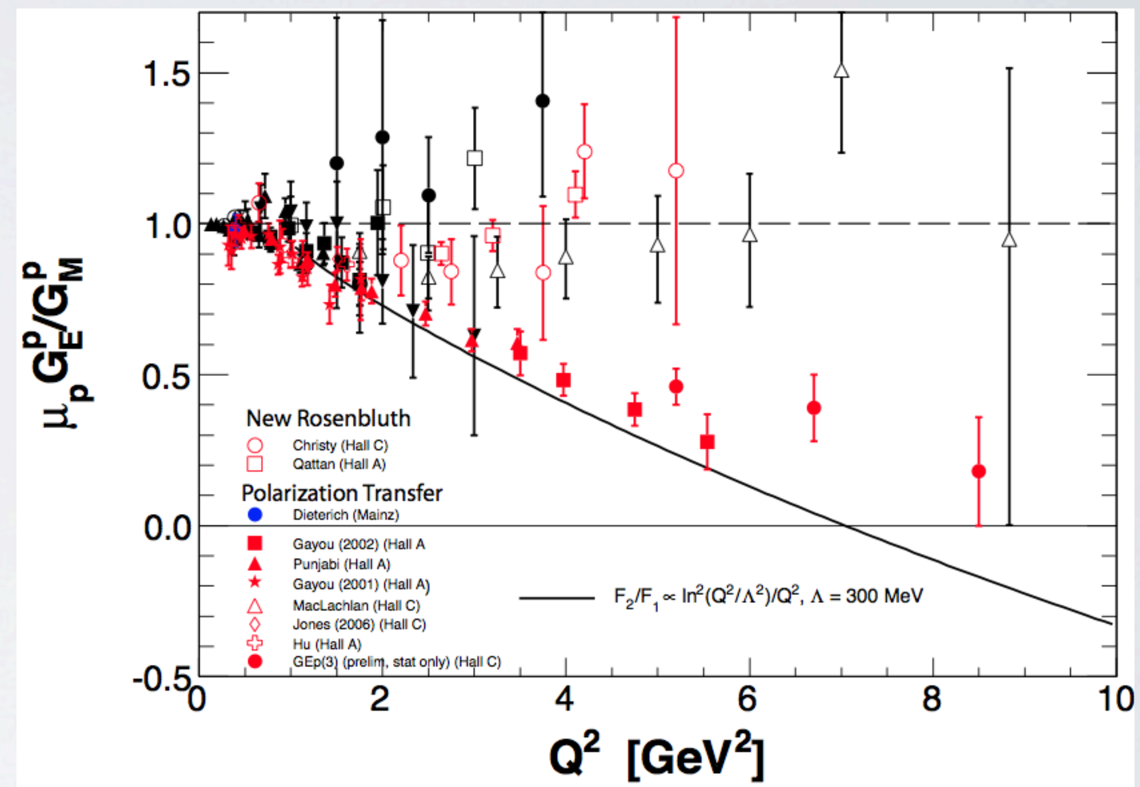
light hadrons get their masses via SSB

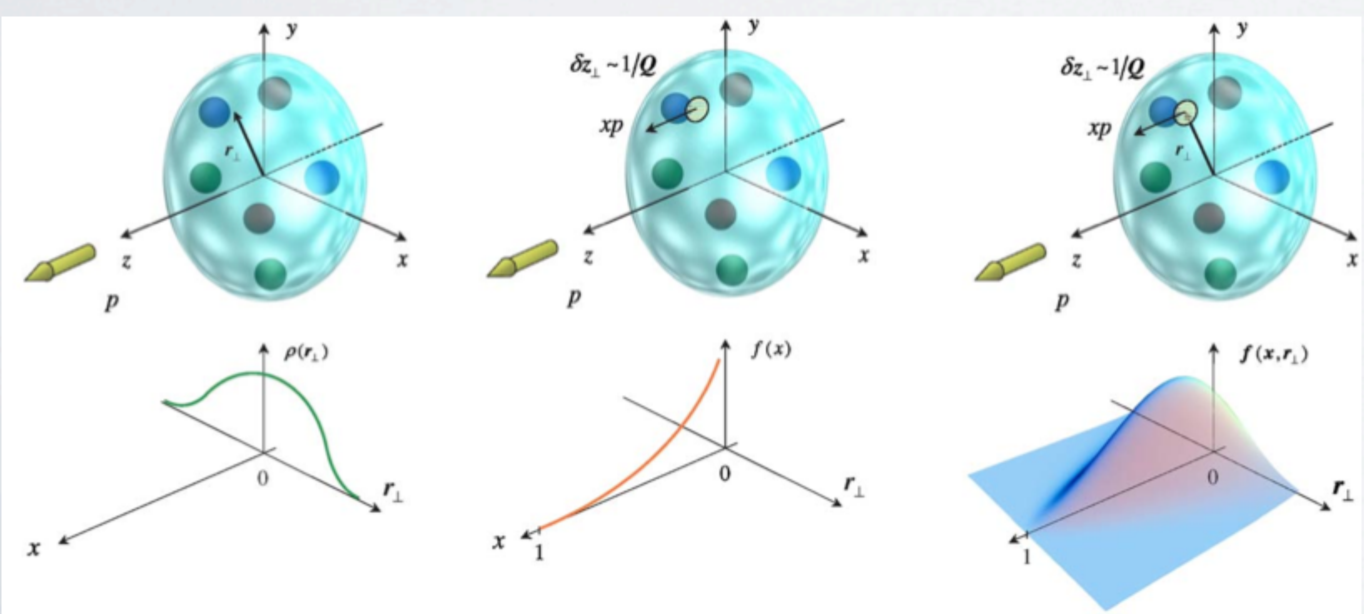
~98% of the mass of
visible matter in Universe
is due to this mechanism

Observables encoding strong QCD dynamics

- Meson and baryon spectra
- Meson and baryon form factors
- Momentum distributions of quarks in gluons







Experimental tools next door

Hadronic and nuclear structure in experimental programs at medium energy accelerators, especially JLab

12 GeV energy upgrade will add unique capabilities

- new experimental Hall D for meson spectroscopy
- upgrades to current Hall A, B and C
- many experimental programs: spectroscopy, exclusive, semi-inclusive and inclusive processes; spin physics; tests of the SM of EW interactions; nuclear effects; etc, etc

Theoretical tools

many and diverse

Low energy QCD: effective theories using hadronic degrees of freedom. Physics determined by symmetries and parameters aka low energy constants. Allow for the most accurate tests of QCD at hadronic level. Chiral perturbation theory; NNEFT

example: $\pi^0 \to \gamma\gamma$ fundamental test of chiral symmetry

theoretical prediction to 1% accuracy: $\Gamma^{Th}_{\pi^0} = 8.1 \pm 0.1\; eV$

JLab experiment PRIMEX: to appear in PhysRevLett

$$\Gamma^{Exp}_{\pi^0} = 7.82 \pm 0.14 \pm 0.17\; eV$$

HU physicists involved in theory and experiment

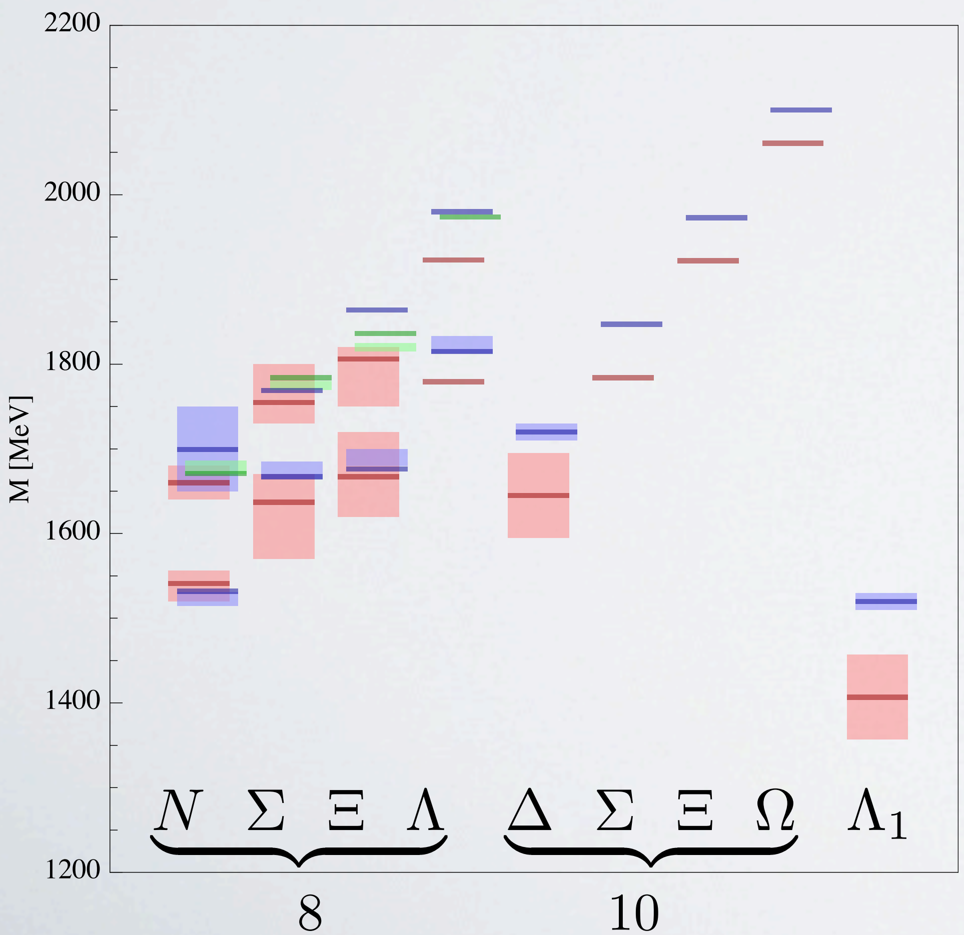
(MeV)

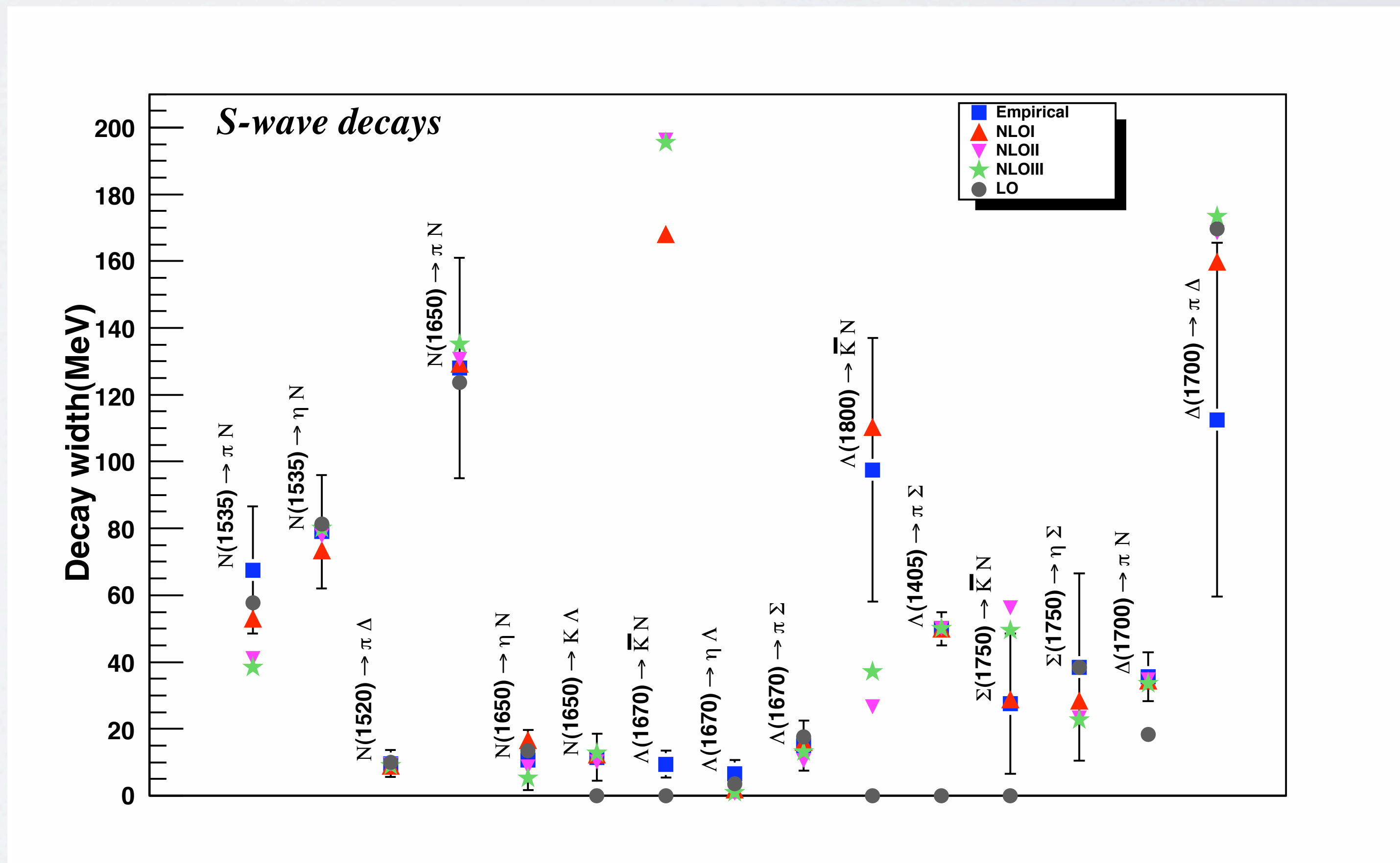
I/N expansion of QCD

SU(3) ⟶ SU(N) and expand in I/N ('tHooft 1974)

exploits extended symmetries QCD has in baryon sector for large N; corrections are ordered in powers of I/N

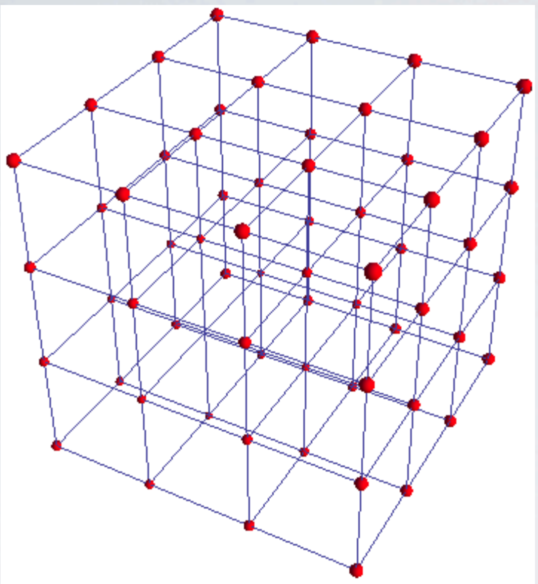
numerous applications in baryons





Lattice QCD: numerical simulations of QCD

discretize Euclidean space-time, quarks in nodes, gluons in links
evaluate Feynman path integral using Monte Carlo

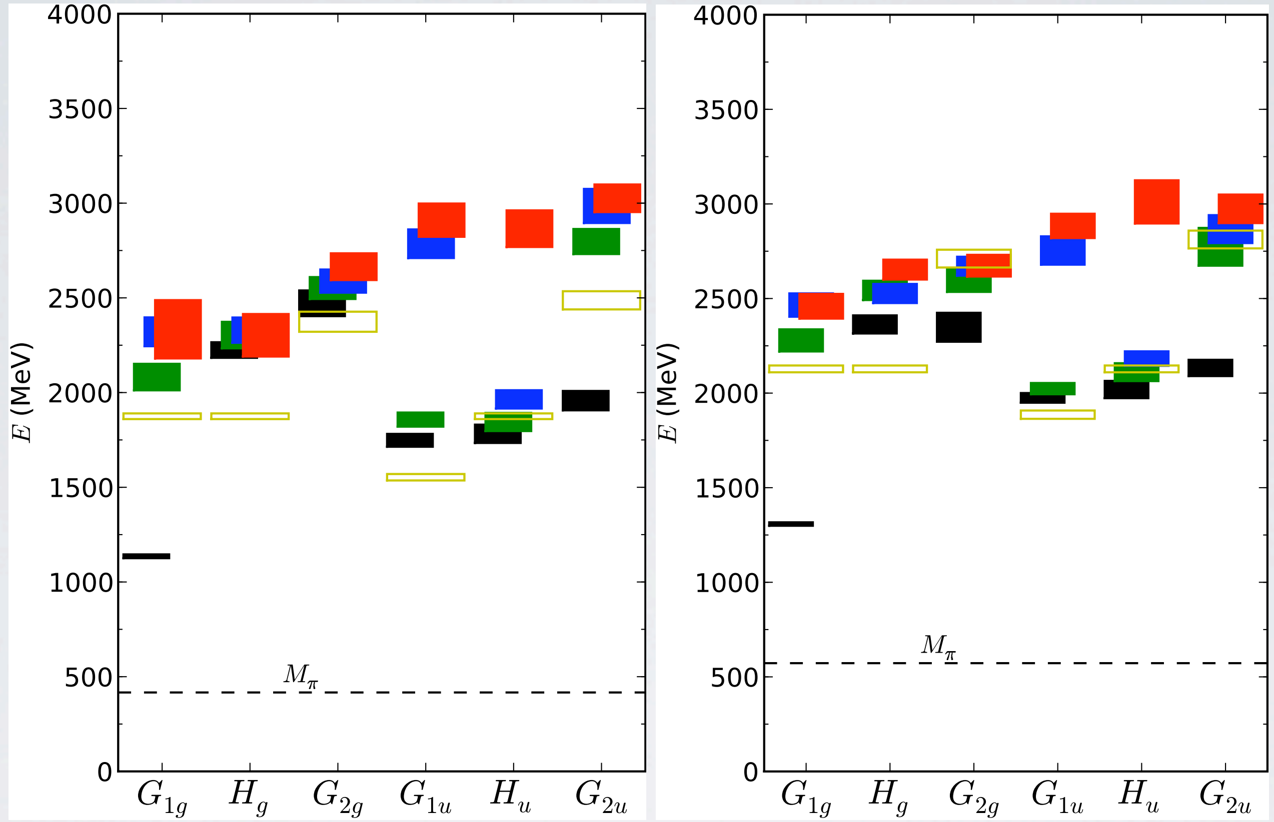


only known rigorous method to evaluate observables using fundamental QCD degrees of freedom

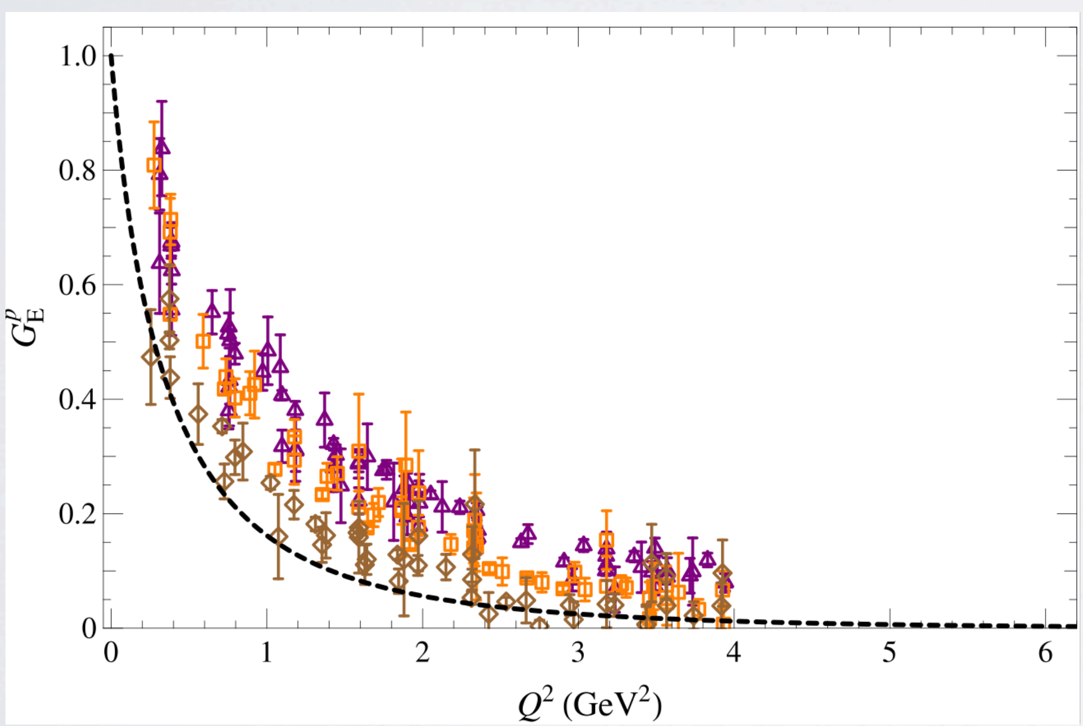
HPC @ JLab

Continuous progress in computer power and algorithms
JLab cluster: 100 Tflops

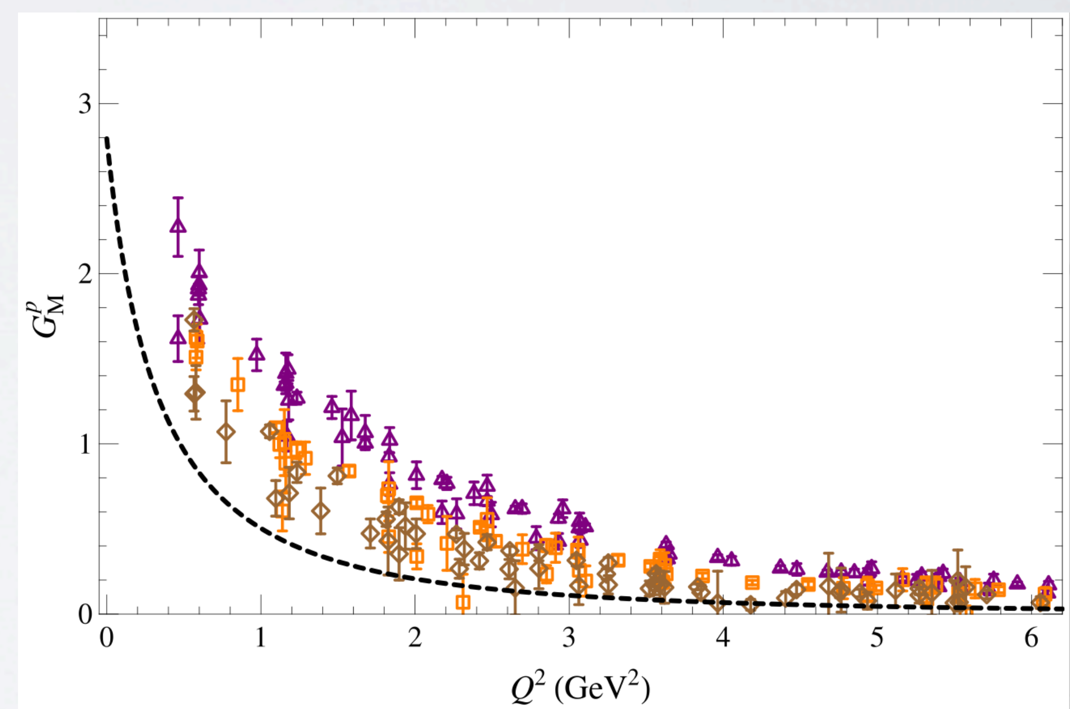
study wide variety of problems
hadron spectrum
confinement, SSB, phase transitions
form factors, DIS PDFs
hadron-hadron interactions
quark mass dependencies of observables
in some cases it can substitute experiments!



4000
3500
3000
2500
2000
1500
1000
500
0
E (MeV)
M_π
G_{1g} H_g G_{2g} G_{1u} H_u G_{2u}

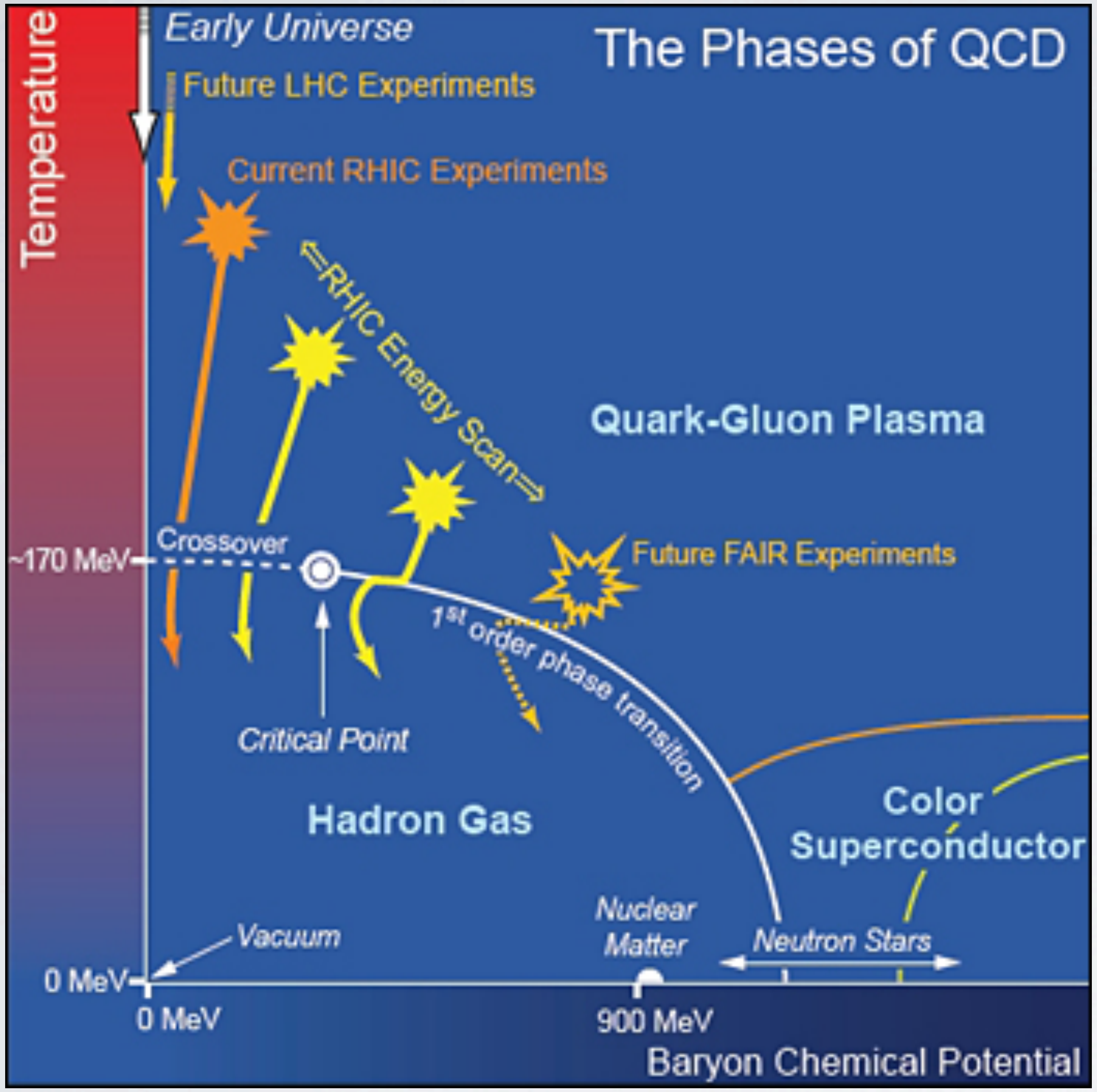


1.0
0.8
0.6
0.4
0.2
0
G_E^p
0 1 2 3 4 5 6
Q^2 (GeV^2)



3
2
1
0
G_M^p
0 1 2 3 4 5 6
Q^2 (GeV^2)

Extreme QCD



Hot QCD: relativistic heavy ion collisions (RHIC, LHC, FAIR)
quark-gluon plasma
studied also with Lattice QCD

Dense QCD: nuclei, neutron stars
great challenge for theorists; no available rigorous tools

Objective is to understand new forms of matter (phases) QCD gives rise under extreme conditions

Thoughts and outlook

- Progress in understanding strongly coupled QCD continues in theoretical and experimental fronts; never as active as today

- Novel access to quark and gluon dynamics in hadrons with new generation of experiments with electron scattering: JLab 12 GeV

- Advances with Lattice QCD: spectra, form factors, quark mass dependencies, etc; QCD at finite temperature

- Further development of theoretical tools: effective theories, 1/N expansion, AdS/QCD

- In QCD's bag of problems are some of the most interesting in physics

... an exciting journey continues!


Thank you