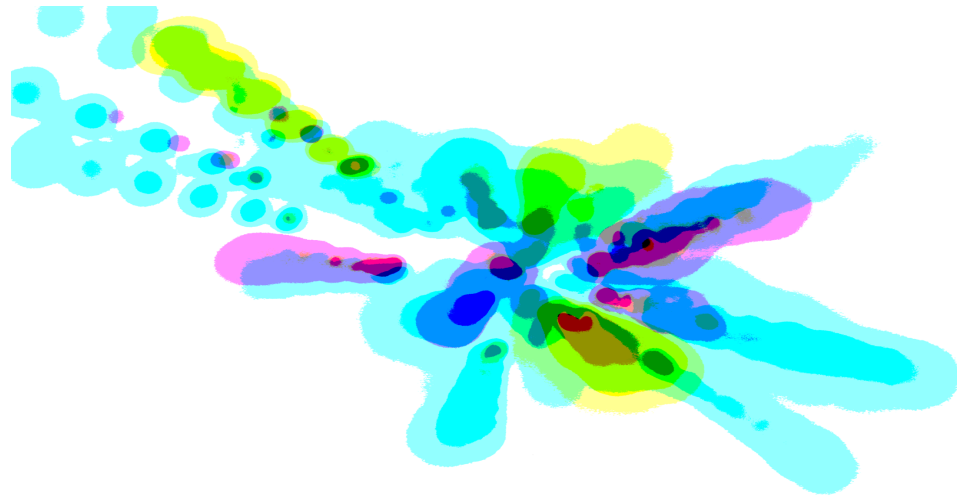
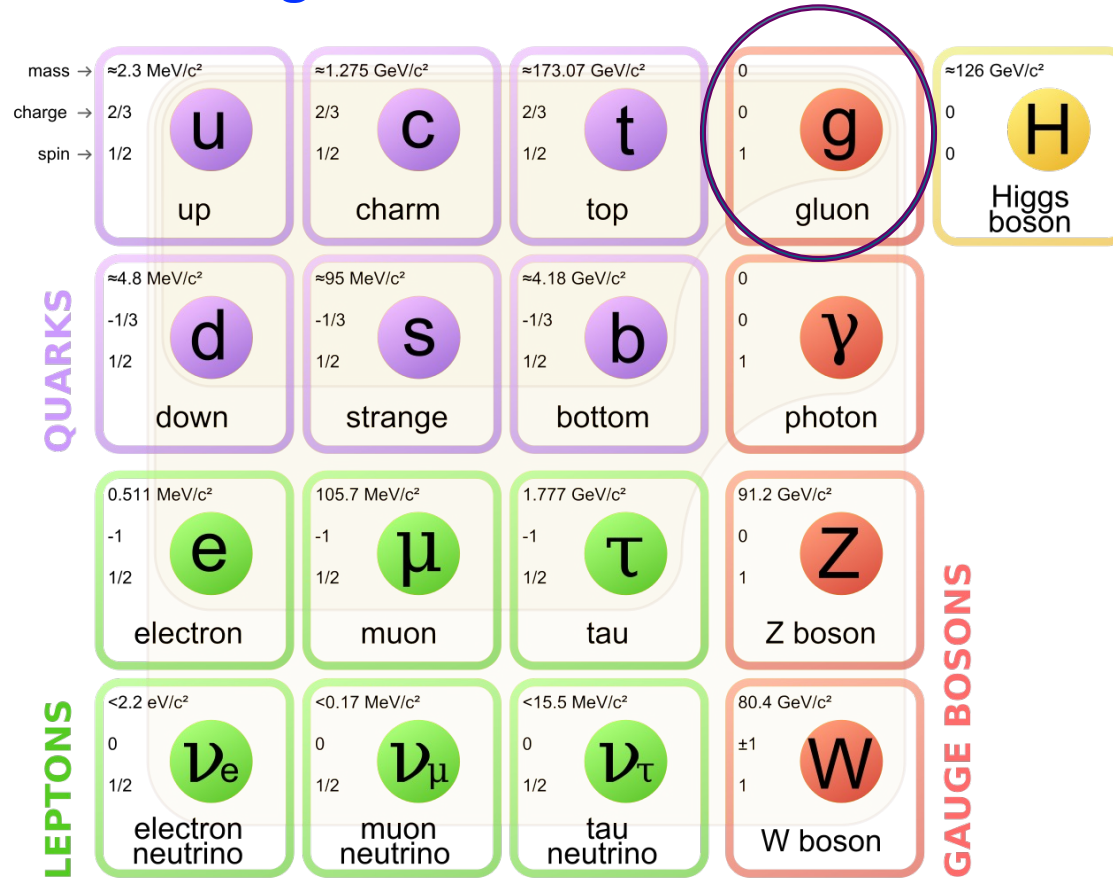


The essential mystery:
massless gluons and (nearly) massless quarks create the visible universe



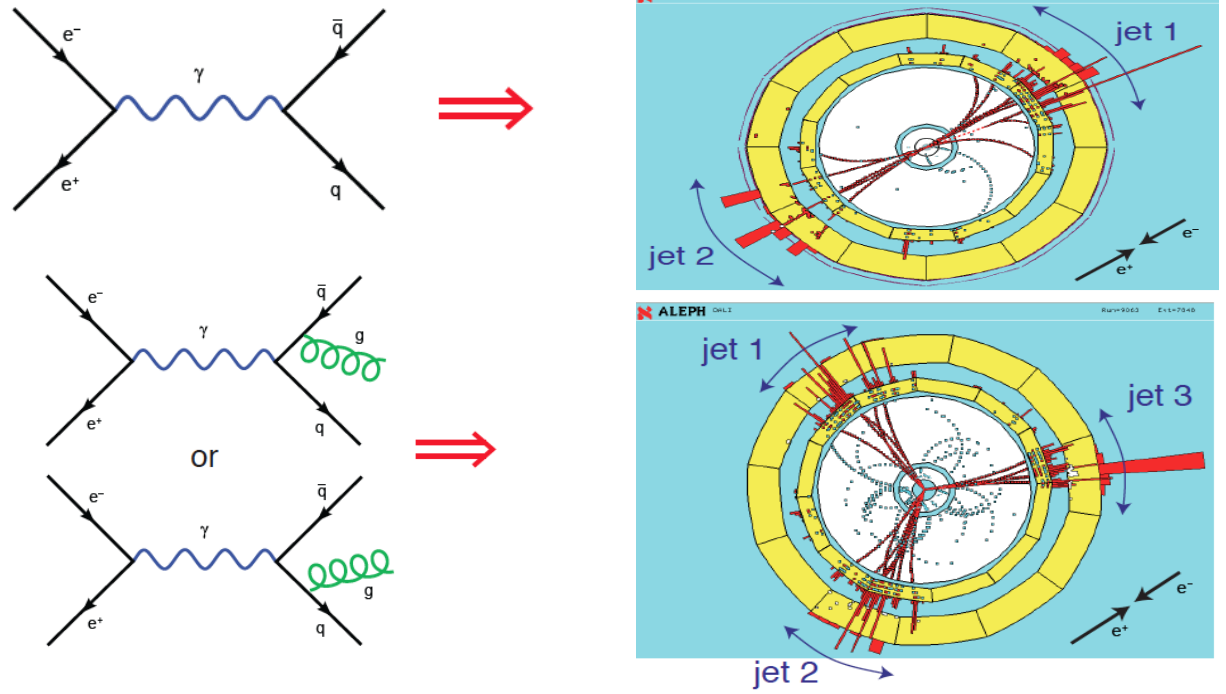
Raju Venugopalan, Higgs School, Colloquium I, May 25, 2026

The strong force in the standard model



Gluons, the force carriers of the strong force, are a fundamental building block of the standard model

Discovery of the gluon



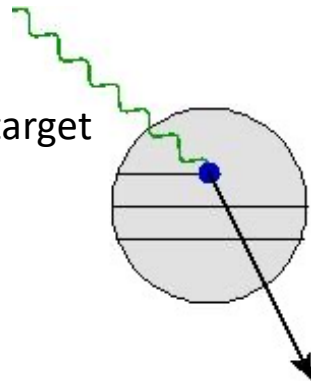
EVIDENCE FOR A SPIN-1 GLUON IN THREE-JET EVENTS

High-energy e^+e^- -annihilation events obtained in the TASSO detector at PETRA have been used to determine the spin of the gluon in the reaction $e^+e^- \rightarrow q\bar{q}g$. We analysed angular correlations between the three jet axes. While vector gluons are consistent with the data (55% confidence limit), scalar gluons are disfavoured by 3.8 standard deviations, corresponding to a confidence level of about 10^{-4} . Our conclusion is free of possible biases due to uncertainties in the fragmentation process or in determining the $q\bar{q}g$ kinematics from the observed hadrons.

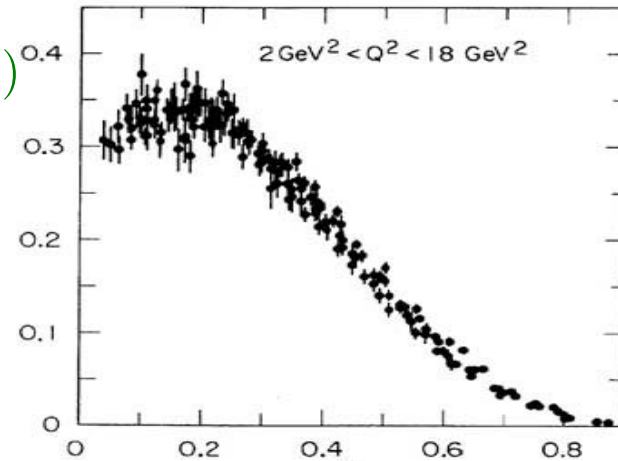
Physics Letters B, 15 December 1980

The deeply inelastic scattering (DIS) femtoscope

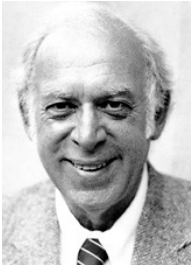
From SLAC fixed target
DIS... (late 1960s)



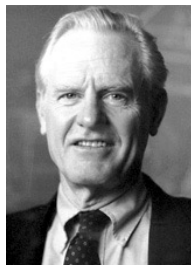
$F_2(x)$



Discovery of quasi-free point-like quarks!



Friedman



Kendall



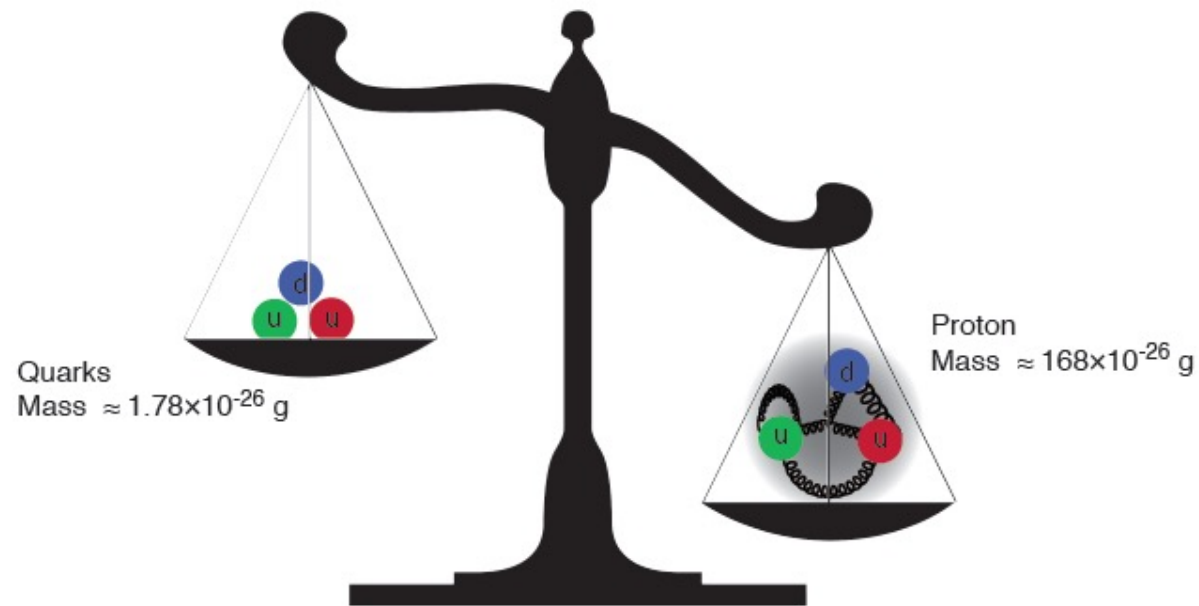
Taylor



(1990)

x

A cosmic koan



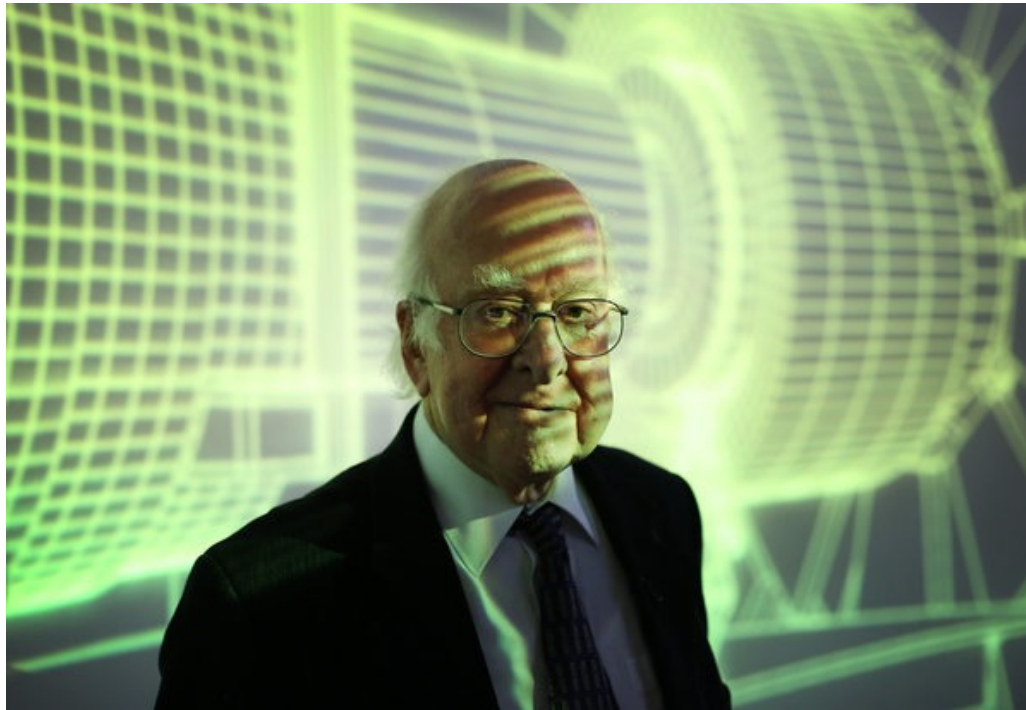
Glucos are massless, and (up and down) quarks, nearly so...
yet their dynamics is responsible for (nearly all) the mass of visible matter

The Higgs "God particle" is responsible for quark masses
 $\sim 1\text{-}2\%$ of the proton mass.



Samuel Jackson in the movie Pulp Fiction

Higgs and the strong force



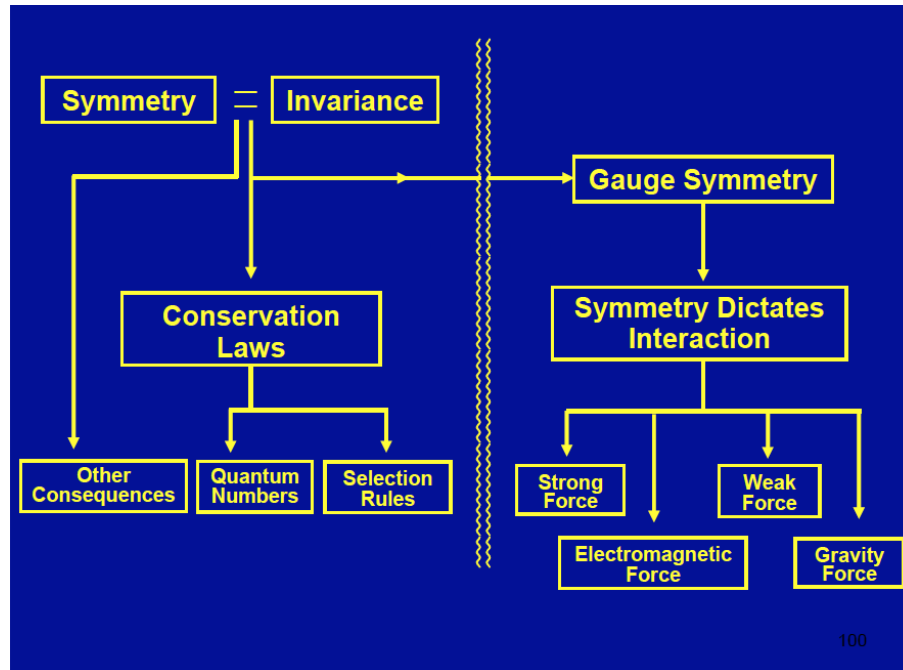
(2013)

When he invented his boson in 1964, he said, “I wasn’t sure it would be important.”

He explained, “At the time the thought was to solve the strong force.”

NY Times, Sept. 15, 2014

Symmetries dictate interactions



C. N. Yang

Non-Abelian gauge theories: Yang-Mills Theory



PHYSICAL REVIEW

VOLUME 96, NUMBER 1

OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS

Brookhaven National Laboratory, Upton, New York

(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistent with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a \mathbf{b} field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The \mathbf{b} field satisfies nonlinear differential equations. The quanta of the \mathbf{b} field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

Possibly the most important paper from BNL

From the Yang-Mills paper,

ISOTOPIC GAUGE TRANSFORMATION

Let ψ be a two-component wave function describing a field with isotopic spin $\frac{1}{2}$. Under an isotopic gauge transformation it transforms by

$$\psi = S\psi', \quad (1)$$

where S is a 2×2 unitary matrix with determinant unity. In accordance with the discussion in the previous section, we require, in analogy with the electromagnetic case, that all derivatives of ψ appear in the following combination:

$$(\partial_\mu - i\epsilon B_\mu)\psi.$$

B_μ are 2×2 matrices such that⁷ for $\mu = 1, 2,$ and $3, B_\mu$ is Hermitian and B_4 is anti-Hermitian. Invariance requires that

$$S(\partial_\mu - i\epsilon B_\mu')\psi' = (\partial_\mu - i\epsilon B_\mu)\psi. \quad (2)$$

Combining (1) and (2), we obtain the isotopic gauge transformation on B_μ :

$$B_\mu' = S^{-1}B_\mu S + S^{-1} \frac{i}{\epsilon} \frac{\partial S}{\partial x_\mu}. \quad (3)$$

The last term is similar to the gradient term in the gauge transformation of electromagnetic potentials. In analogy to the procedure of obtaining gauge invariant field strengths in the electromagnetic case, we

define now

$$F_{\mu\nu} = \frac{\partial B_\nu}{\partial x_\mu} - \frac{\partial B_\mu}{\partial x_\nu} + i\epsilon(B_\mu B_\nu - B_\nu B_\mu). \quad (4)$$

One easily shows from (3) that

$$F_{\mu\nu}' = S^{-1}F_{\mu\nu}S \quad (5)$$

we shall use the following total Lagrangian density:

$$\mathcal{L} = -\frac{1}{4} \mathbf{f}_{\mu\nu} \cdot \mathbf{f}_{\mu\nu} - \bar{\psi} \gamma_\mu (\partial_\mu - i\epsilon \boldsymbol{\tau} \cdot \mathbf{b}_\mu) \psi - m \bar{\psi} \psi. \quad (11)$$

All the elements, except...color

SU(3) gauge symmetry



Y. Nambu

M.-Y. Han

PHYSICAL REVIEW

VOLUME 139, NUMBER 4B

23 AUGUST 1965

Three-Triplet Model with Double $SU(3)$ Symmetry*

M. Y. HAN

Department of Physics, Syracuse University, Syracuse, New York

AND

Y. NAMBU

*The Enrico Fermi Institute for Nuclear Studies, and the Department of Physics,
The University of Chicago, Chicago, Illinois*

(Received 12 April 1965)

With a view to avoiding some of the kinematical and dynamical difficulties involved in the single-triplet quark model, a model for the low-lying baryons and mesons based on three triplets with integral charges is proposed, somewhat similar to the two-triplet model introduced earlier by one of us (Y. N.). It is shown that in a $U(3)$ scheme of triplets with integral charges, one is naturally led to three triplets located symmetrically about the origin of I_3 - Y diagram under the constraint that the Nishijima-Gell-Mann relation remains intact. A double $SU(3)$ symmetry scheme is proposed in which the large mass splittings between different representations are ascribed to one of the $SU(3)$, while the other $SU(3)$ is the usual one for the mass splittings within a representation of the first $SU(3)$.

Also, earlier work by O. Greenberg on the quark model

Glueon bremsstrahlung: “Herculean task...might even not be possible”

After magisterially disposing of the problem of IR divergences of soft photons and gravitons, Weinberg notes...

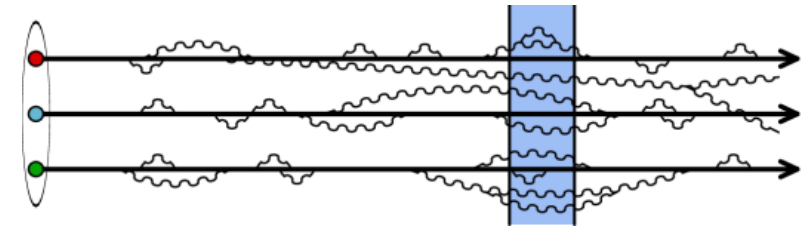


Weinberg

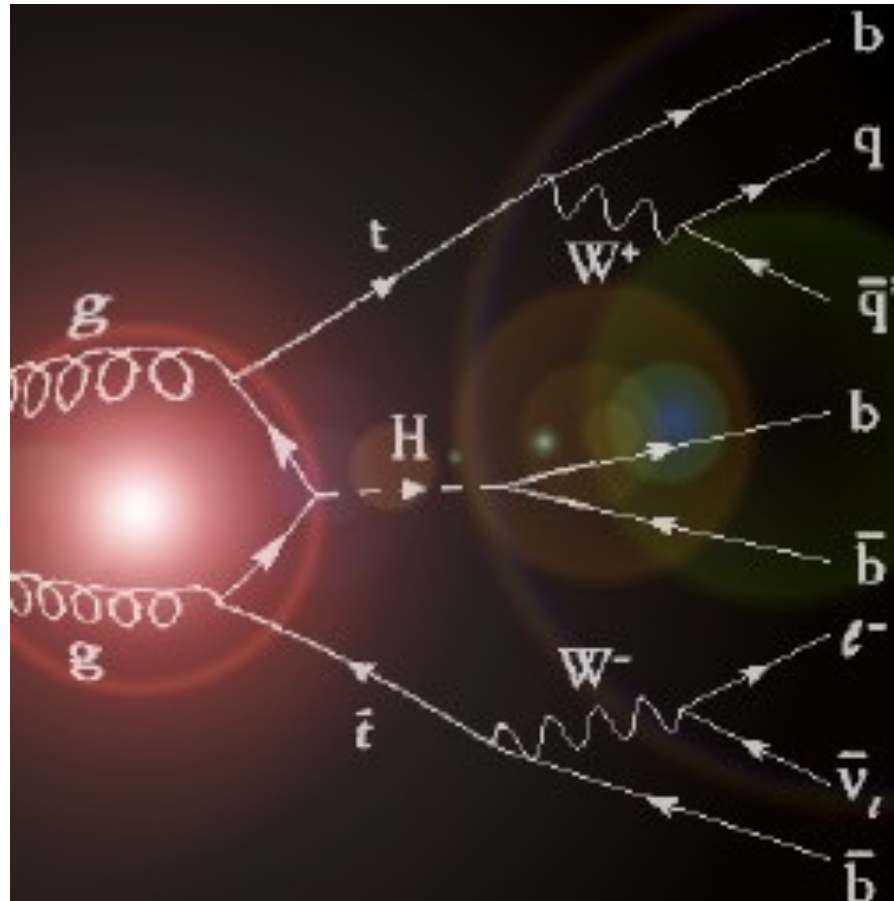
But these remarks do not apply to theories involving charged massless particles. In such theories (including the Yang-Mills theory) a soft photon emitted from an external line can itself emit a pair of soft charged massless particles, which themselves emit soft photons, and so on, building up a cascade of soft massless particles each of which contributes an infrared divergence. The elimination of such complicated interlocking infrared divergences would certainly be a Herculean task, and might even not be possible.

We may be thankful that the zero charge of soft photons and the zero gravitational mass of soft gravitons saves the real world from this mess. Perhaps it would not be too much to suggest that it is the infrared divergences that prohibit the existence of Yang-Mills quanta or other charged massless particles.

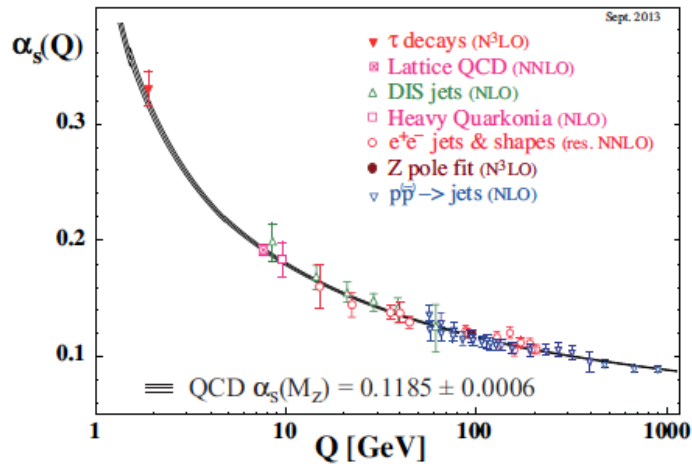
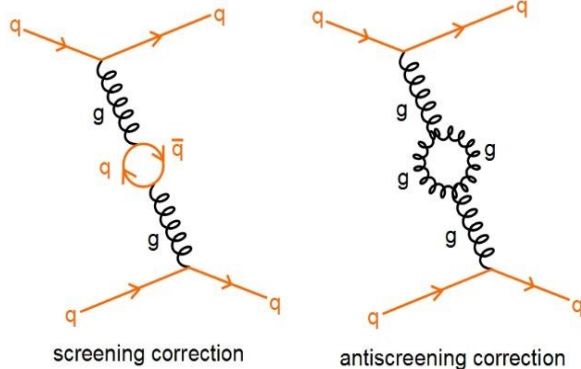
Weinberg, Phys. Rev. 140 (1965) B516



A splendid irony: Higgs from Gluon fusion



Asymptotic freedom: the role of glue



David Gross



David Politzer



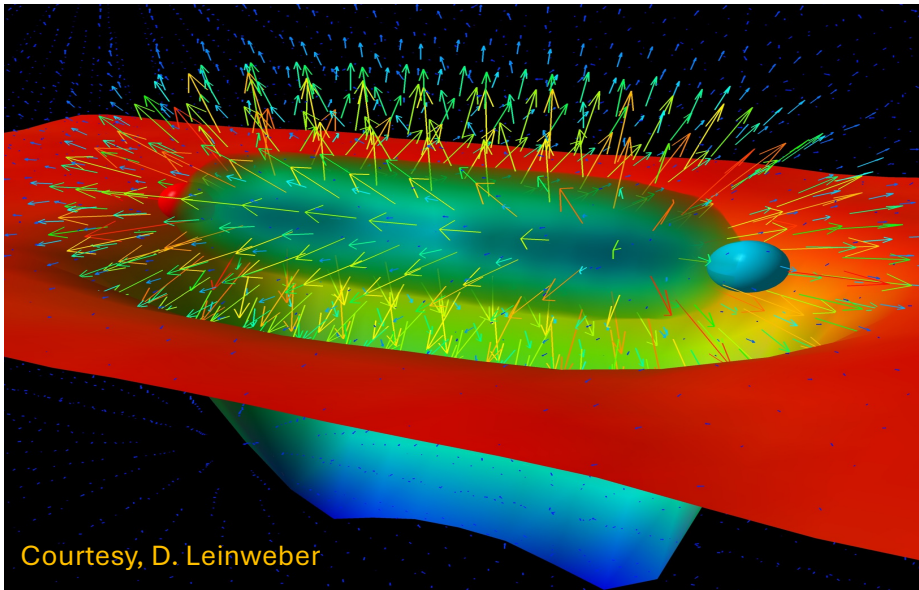
Frank Wilczek



2004

The self-interaction (of color charged) gluons is fundamentally responsible for the asymptotic freedom of quarks and gluons in Quantum Chromodynamics (QCD)

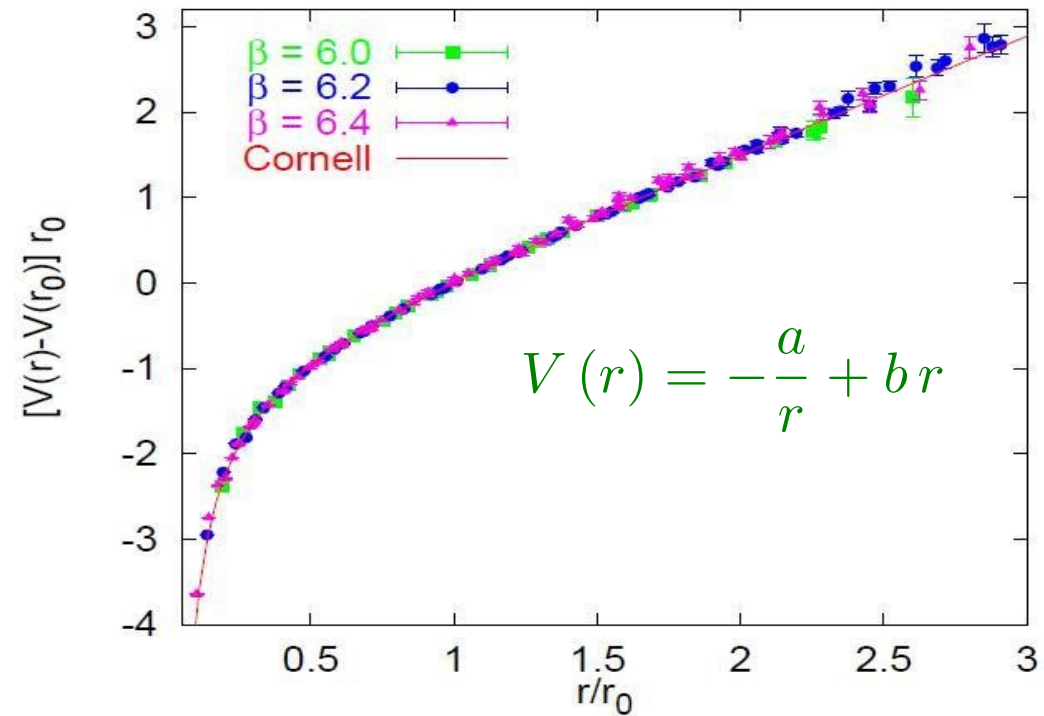
Quark (and Gluon) confinement: the role of glue



Courtesy, D. Leinweber

Quarks experience force of 16 tons at distances of ~ 1 Fermi (10^{-15} m)

“Gluon” potential between heavy quark-antiquark pair

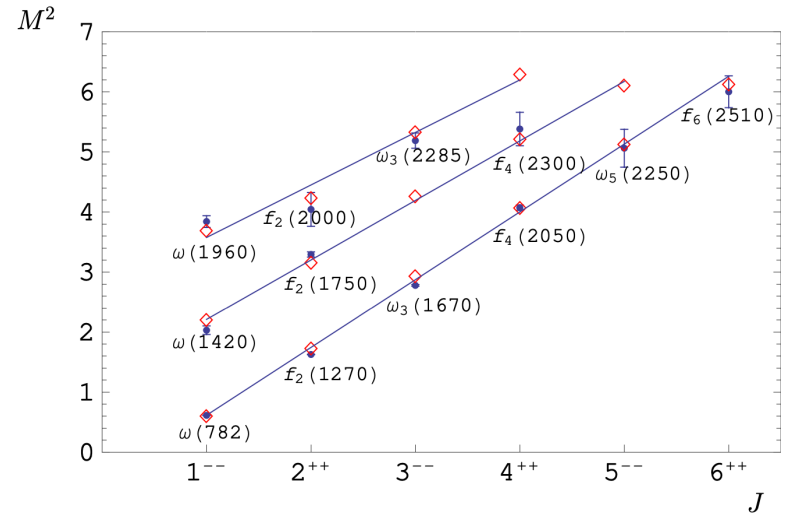
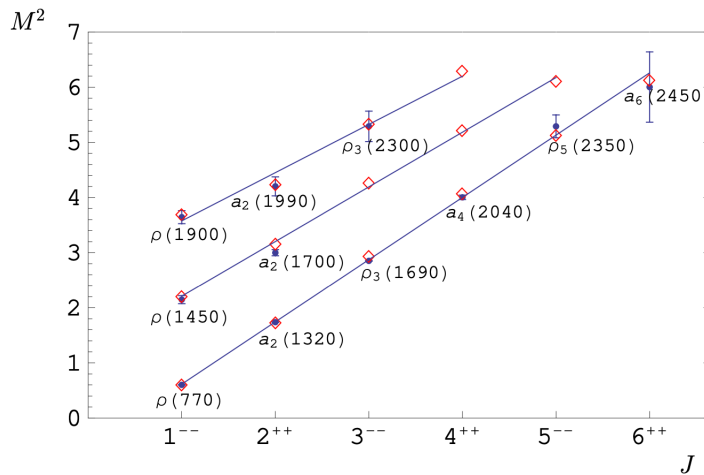


Bali, hep-ph/0001312

Quark (and Gluon) confinement: the role of glue

“Chew-Frautschi plots’
of Regge trajectories

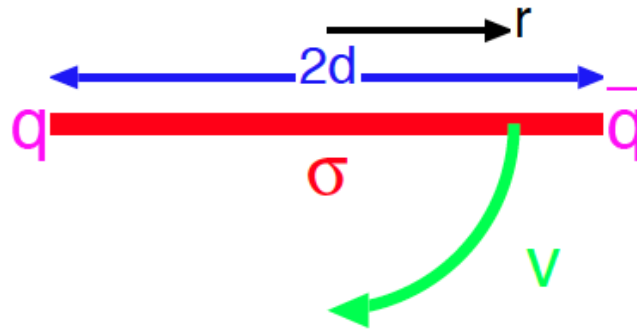
Ebert et al., arXiv:0903.5183



$$J(M^2) = \alpha(0) + \alpha' M^2$$

$$\text{Slope } \alpha' = \frac{1}{2\pi\sigma}$$

trajectory	$\sqrt{\sigma}/\text{MeV}$	ΔJ
π, b_1, \dots	469(6)	0.06
ρ, a_2, \dots	429(2)	0.03
ω, f_2, \dots	436(8)	0.12
ϕ, f'_2, \dots	437(5)	0.06
K, K_1, \dots	480(4)	0.04
K^*, K_2^*, \dots	424(5)	0.07

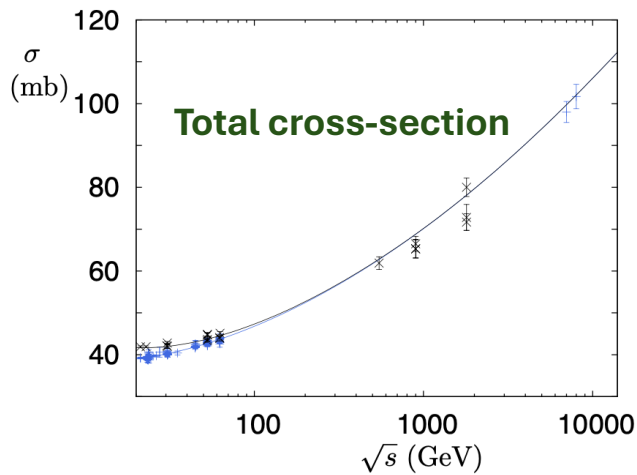


Relativistic quark model

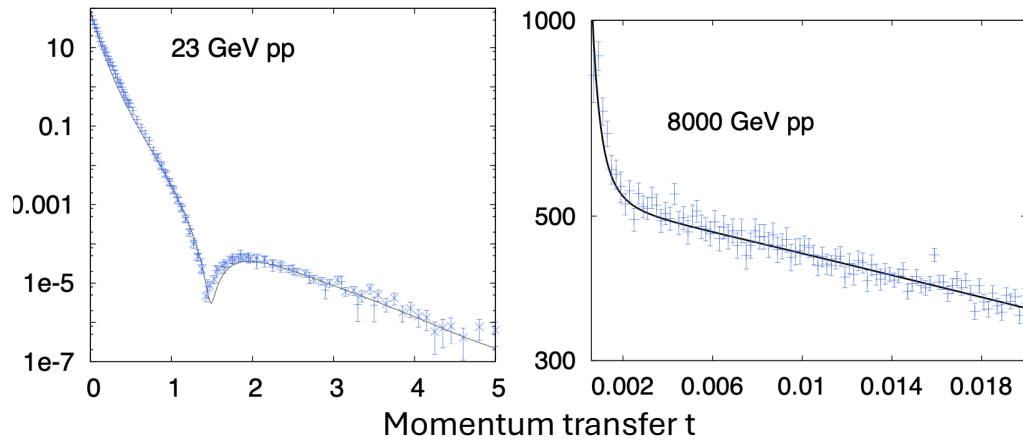
Intuitive picture of quark confinement- early motivation for string theory

Veneziano, Nuovo Cim. 57, 190 (1968)

What is the Pomeron in QCD?



Differential elastic cross-section



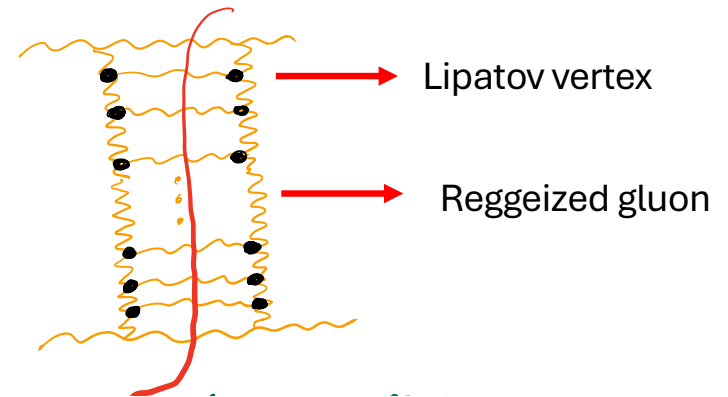
The behavior of total cross-sections over three orders of magnitude in energy (SPS \rightarrow LHC) is simply described in terms of effective Pomeron and Reggeon trajectories

Pomeron: t -channel exchange with vacuum quantum numbers dominates total hadron-hadron cross-sections:

Amplitude: $A(s, t) = s^{\alpha(t)}$ with $\alpha(t) = 1 + \varepsilon + \alpha' t$

Intercept $\varepsilon_P = 0.11$ String tension = 0.165 GeV^{-2}

Donnachie, Landshoff, Phys. Lett. B750 (2015) 669



BFKL Pomeron- compound color singlet state of "reggeized gluons" with vacuum quantum numbers

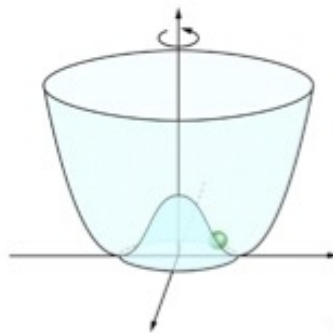
Chiral symmetry breaking

Chiral basis : $q_L = \frac{1}{2}(1 - \gamma_5)q, \quad q_R = \frac{1}{2}(1 + \gamma_5)q$

QCD Lagrangian : $\mathcal{L}_{cl} = \mathcal{L}_{cl}(q_L, A) + \mathcal{L}_{cl}(q_R, A)$

Quantum vacuum spontaneously breaks the symmetries of the Lagrangian:

Chiral condensate: spontaneously generate mass via the
Nambu-Goldstone mechanism

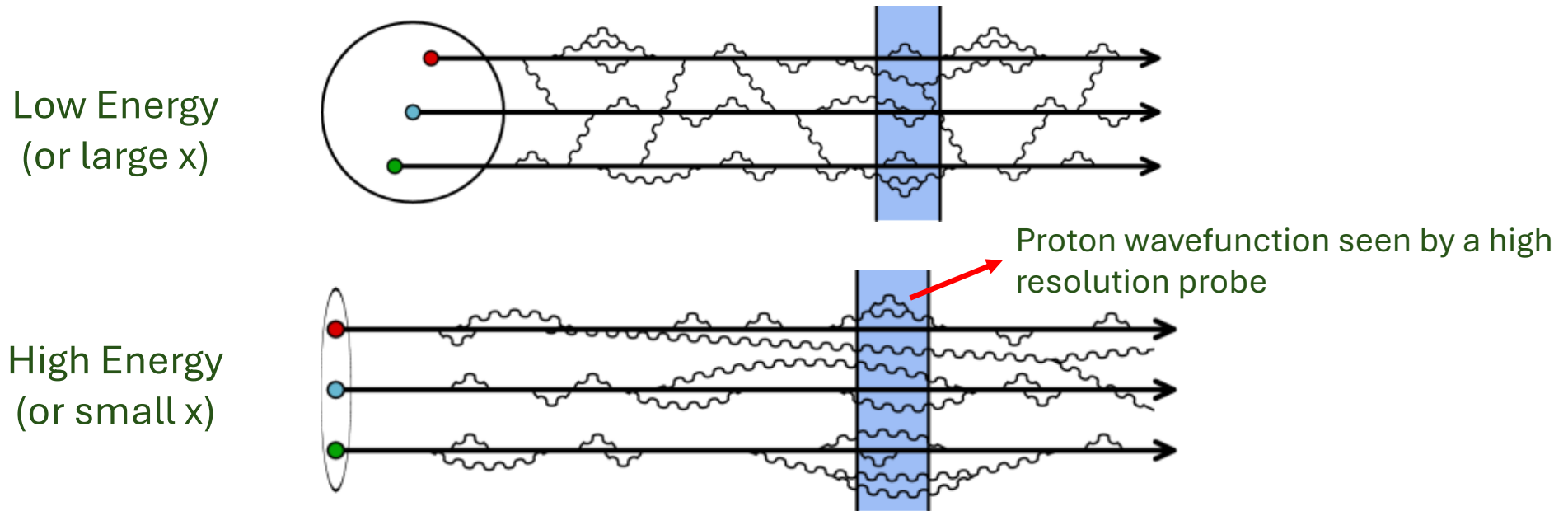


$\longrightarrow \langle \bar{q}_R q_L \rangle \neq 0$

How does this fit into the picture?

Anderson, Nambu, Jona-Lasinio (1957-1961)

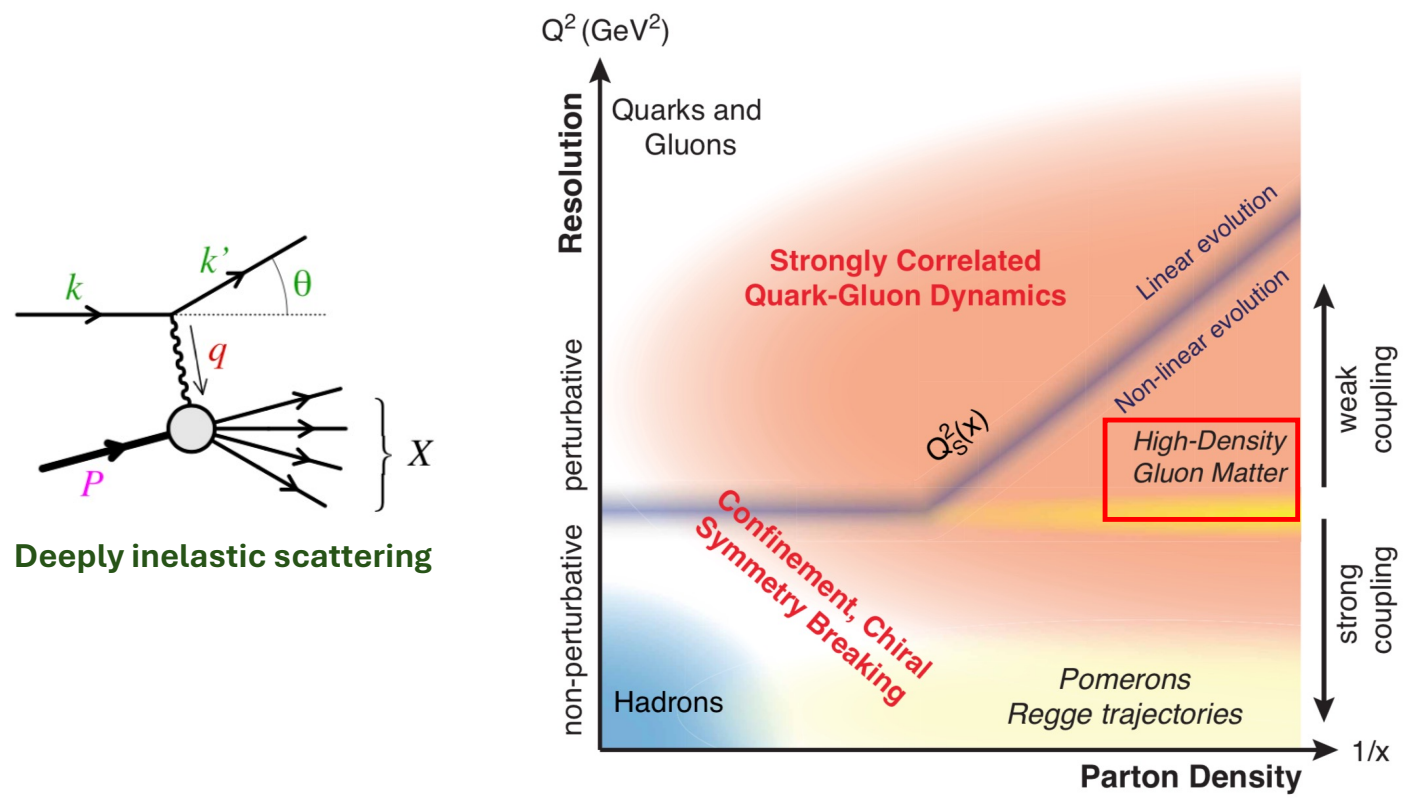
Lifting the veil: boosting the proton uncovers many-body structure



“Wee” parton fluctuations carrying a fraction $x \ll 1$ of proton’s moment are time dilated on strong interaction time scales.

Long lived (large x) gluons radiate shorter lived (small x) gluons...and so on, in a “Markovian”
Exponential growth of gluon multiplicity

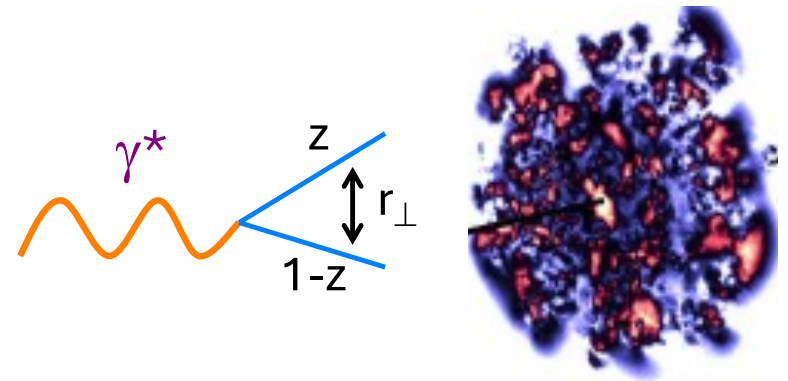
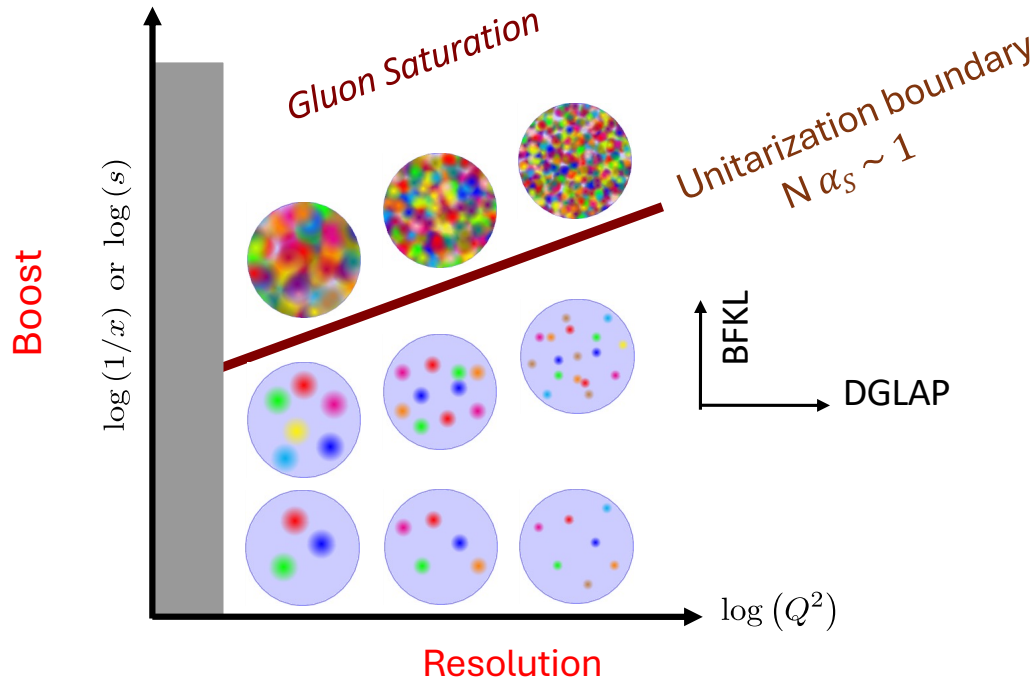
Landscape of QCD dynamics in resolution and energy



Aschenauer et al., arXiv:1708.01527
Rep.Prog. Phys. 82, 024301 (2019)

Many open questions: 3-D structure of quark-gluon structure of the proton, spin and orbital dynamics, many-body correlations, multi-particle production...

Maximal packing of gluons: Gluon saturation

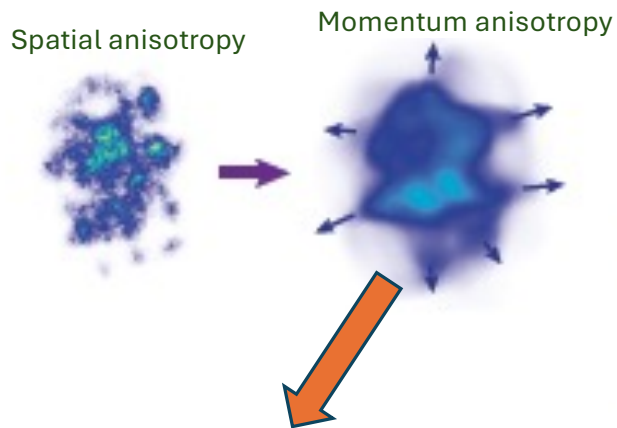


Wee partons color screened:
live on surface of sphere of radius
 $1/k^+ \sim 1/k_{\perp} \sim 1/Q_S(x, b)$

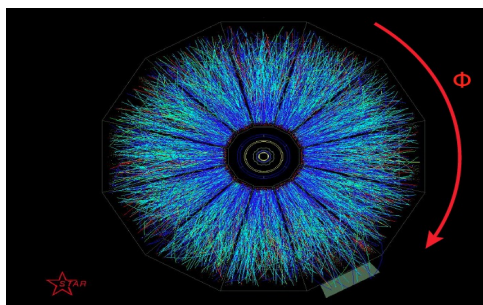
The emergence of a large saturation scale $Q_S(x, b)$ enables us – due to asymptotic freedom! - to compute dynamics in this strong field regime of QCD for hadrons and nuclei in one framework

Can we understand gluon saturation quantitatively and interface with experiment ?

Heavy-Ion collisions at ultra-relativistic energies



$\sim 10^3$ subatomic particles
produced in collisions
of Gold nuclei at 200 GeV/nucleon



STAR detector @ BNL's
Relativistic Heavy ion Collider (RHIC)

Experiments indicate... the violence of a nuclear collision settles to the calm of a nearly perfect fluid: the **Quark-Gluon Plasma**



Initial state:
Far from equilibrium

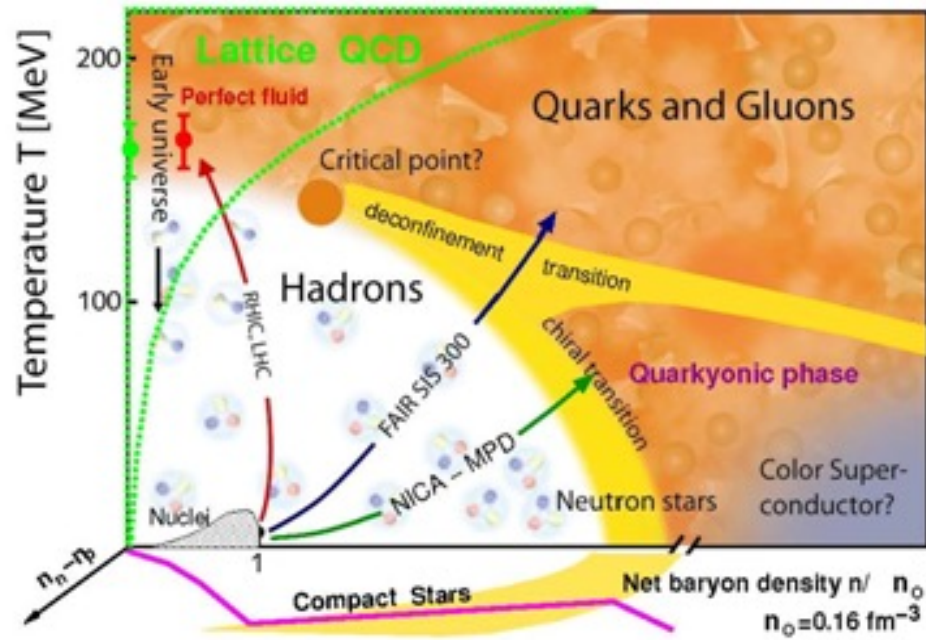
*Non-equilibrium
dynamics*

Final state:
Thermal equilibrium

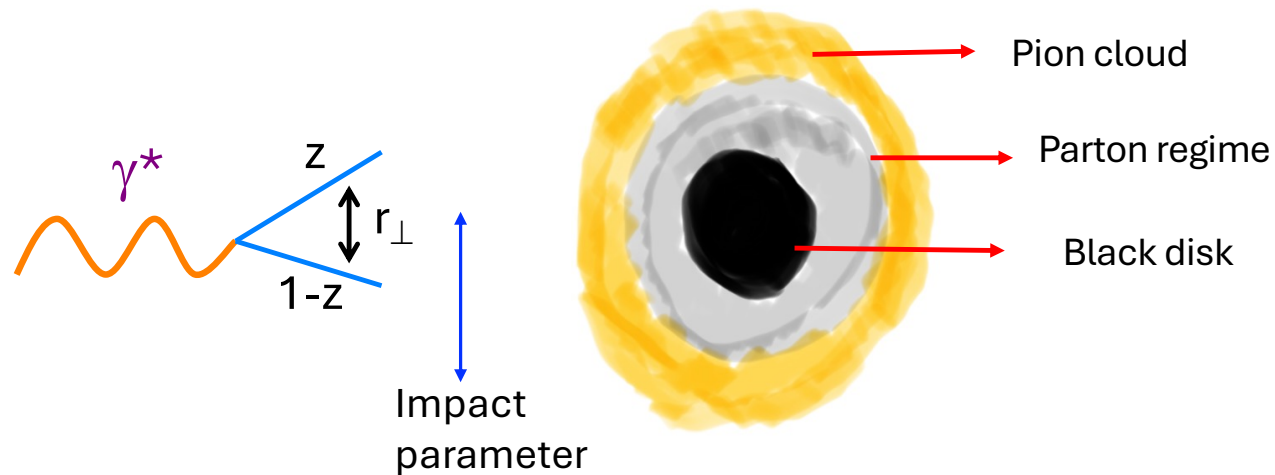


What is the thermalization process in heavy-ion collisions ?

The QCD phase diagram



The elephant in the room



Though our increased understanding of gluon saturation helps understand some features of the proton wavefunction, we still don't understand the mystery of how partons (quarks and gluons) \rightarrow hadrons (pions, kaons,...)

How to wake a sleeping elephant: insights into quark (and gluon) confinement from the buzz of wee partons



Clay Millennial Prize Problem:

Prove that for any compact simple gauge group G , a non-trivial quantum Yang–Mills theory exists on \mathbb{R}^4 and has a mass gap $\Delta > 0$. Existence include establishing axiomatic properties at least as strong as those cited in Streater & Wightman (1964),^[19] Osterwalder & Schrader (1973),^[20] and Osterwalder & Schrader (1975).^[21]

Arthur Jaffe and Ed Witten, courtesy Wikipedia

The essential mystery: quark and gluon confinement

(Nearly) all visible matter is made up of quarks and gluons

Yet quarks and gluons are not visible but are *confined* into colorless baryons and mesons

All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

Example: Mass from massless gluons and (nearly) massless quarks

There is an elegance and simplicity to nature's strongest force that we do not understand

Understanding the origins of visible matter demands we develop a *deep and varied knowledge* of this emergent dynamics