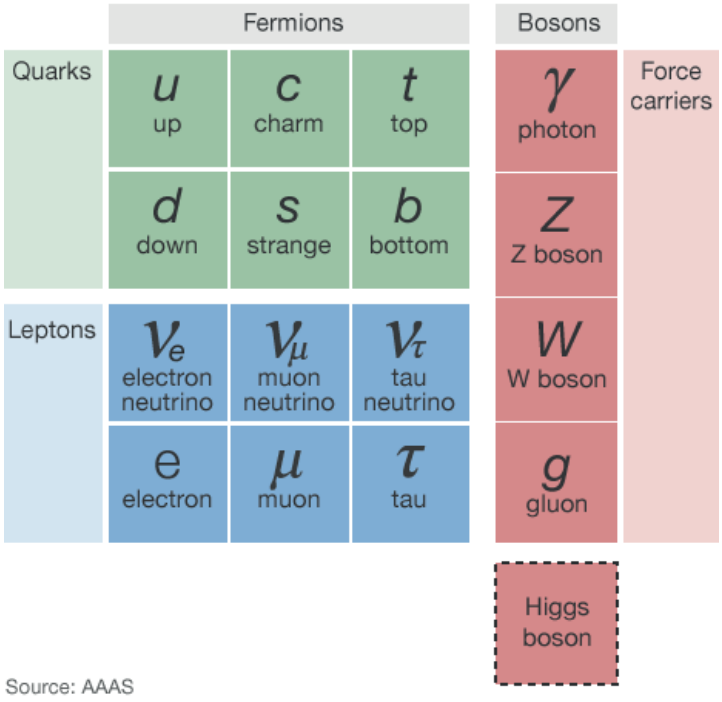
From nuclei to quarks and gluons

Gernot Eichmann

6th Lisbon Mini-School on Particle and Astroparticle Physics
July 15, 2021

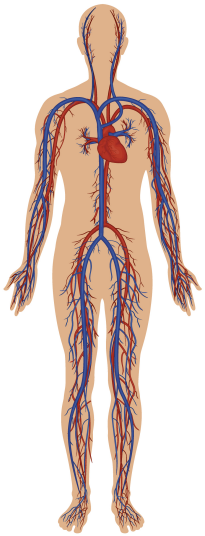
Standard model



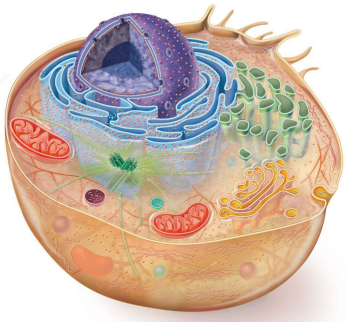
Quantum Chromodynamics (QCD):

Particles with **color charge**
interact by exchanging **gluons**

QCD binds us together



1 m

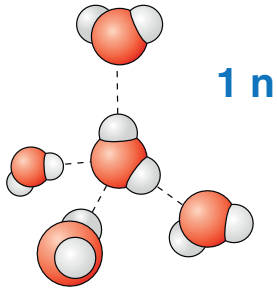


10 µm

Biology

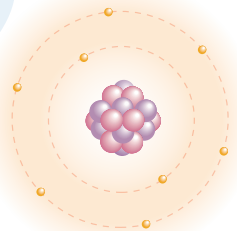
10 nm

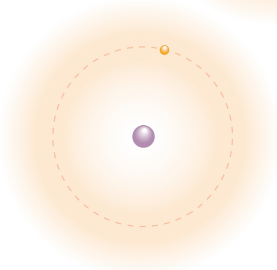
Chemistry



1 nm

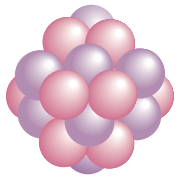
Atomic physics





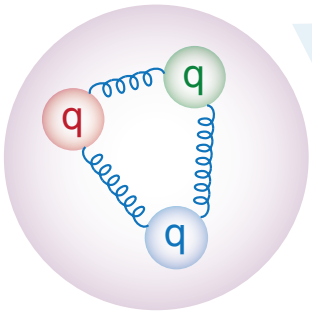
1 Å

Nuclear physics



10 fm

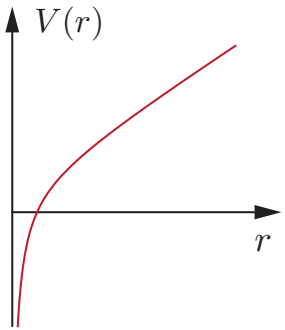
Quantum Chromo-Dynamics

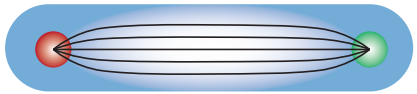


1 fm

Confinement

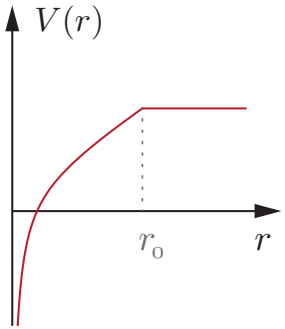
Quarks & gluons are confined in **colorless hadrons,**
so we can never observe them in isolation!

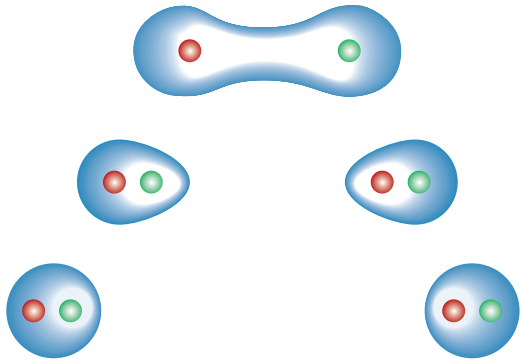




Potential between quarks grows **linearly** with distance

Microscopic origin still unclear – $1M prize

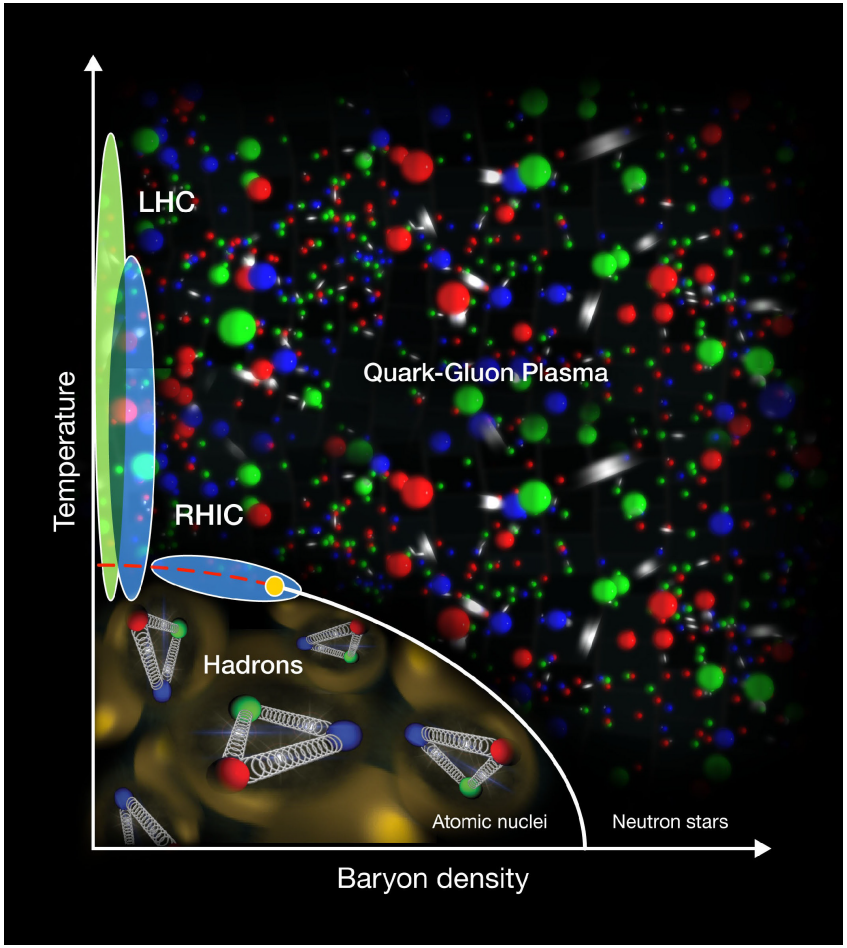




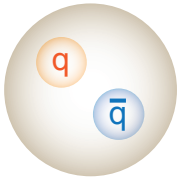
Eventually:
string breaking

→ Hands-on **Hadron Physics**

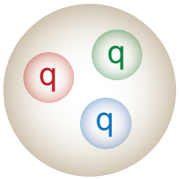
QCD forms hadrons



Mesons



Baryons



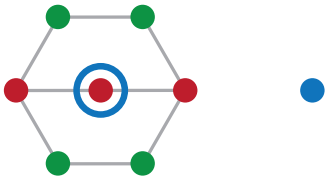
The hadron zoo

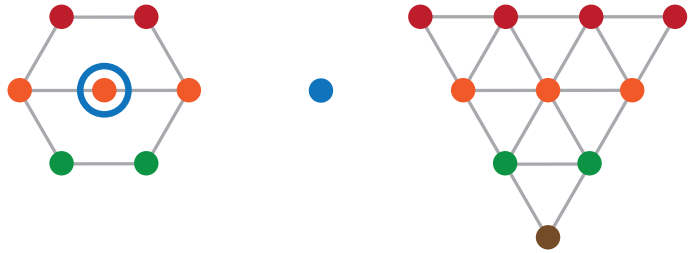
Mesons

0^{-+}	0^{++}	1^{-+}	1^{--}	1^{++}	1^{+-}	2^{-+}	2^{++}	3^{--}
$\pi(140)$	$a_0(980)$	$\pi_1(1400)$	$\rho(770)$	$a_1(1260)$	$b_1(1235)$	$\pi_2(1670)$	$a_2(1320)$	$\rho_3(1690)$
$\pi(1300)$	$a_0(1450)$	$\pi_1(1600)$	$\rho(1450)$	$a_1(1420)$		$\pi_2(1880)$	$a_2(1700)$	$\rho_3(1990)$
$\pi(1800)$	$a_0(1950)$		$\rho(1570)$	$a_1(1640)$				
			$\rho(1700)$					
			$\rho(1900)$					
$K(494)$	$K_0^*(800)$		$K^*(892)$	$K_1(1400)$	$K_1(1270)$	$K_2(1580)$	$K_2^*(1430)$	$K_3^*(1780)$
$K(1460)$	$K_0^*(1430)$		$K^*(1410)$	$K_1(1650)$		$K_2(1770)$	$K_2^*(1980)$	
$K(1830)$	$K_0^*(1950)$		$K^*(1680)$			$K_2(1820)$		
$\eta(548)$	$f_0(500)$		$\omega(782)$	$f_1(1285)$	$h_1(1170)$	$\eta_2(1645)$	$f_2(1270)$	$\omega_3(1670)$
$\eta'(958)$	$f_0(980)$		$\phi(1020)$	$f_1(1420)$	$h_1(1380)$	$\eta_2(1870)$	$f_2(1430)$	$\phi_3(1850)$
$\eta(1295)$	$f_0(1370)$		$\omega(1420)$	$f_1(1510)$	$h_1(1595)$		$f_2'(1525)$	
$\eta(1405)$	$f_0(1500)$		$\omega(1650)$				$f_2(1565)$	
$\eta(1475)$	$f_0(1710)$		$\phi(1680)$				$f_2(1640)$	
$\eta(1760)$							$f_2(1810)$	
							$f_2(1910)$	
							$f_2(1950)$	

Baryons

$\frac{1}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^+$	$\frac{3}{2}^-$	$\frac{5}{2}^+$	$\frac{5}{2}^-$	$\frac{7}{2}^+$
$N(939)$	$N(1535)$	$N(1720)$	$N(1520)$	$N(1680)$	$N(1675)$	$N(1990)$
$N(1440)$	$N(1650)$	$N(1900)$	$N(1700)$	$N(1860)$		
$N(1710)$	$N(1895)$		$N(1875)$	$N(2000)$		
$N(1880)$						
$\Delta(1910)$	$\Delta(1620)$	$\Delta(1232)$	$\Delta(1700)$	$\Delta(1905)$	$\Delta(1930)$	$\Delta(1950)$
	$\Delta(1900)$	$\Delta(1600)$	$\Delta(1940)$	$\Delta(2000)$		
		$\Delta(1920)$				
$\Lambda(1116)$	$\Lambda(1405)$	$\Lambda(1890)$	$\Lambda(1520)$	$\Lambda(1820)$	$\Lambda(1830)$	
$\Lambda(1600)$	$\Lambda(1670)$		$\Lambda(1690)$			
$\Lambda(1810)$	$\Lambda(1800)$					
$\Sigma(1189)$	$\Sigma(1750)$	$\Sigma(1385)$	$\Sigma(1670)$	$\Sigma(1915)$	$\Sigma(1775)$	
$\Sigma(1660)$			$\Sigma(1940)$			
$\Sigma(1880)$						
$\Xi(1315)$		$\Xi(1530)$	$\Xi(1820)$			
		$\Omega(1672)$				

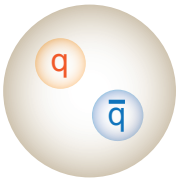




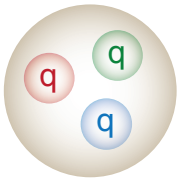
http://pdglive.lbl.gov

And it doesn't stop there ...

Familiar states

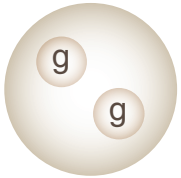


Mesons

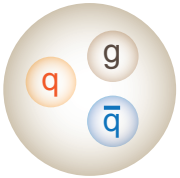


Baryons

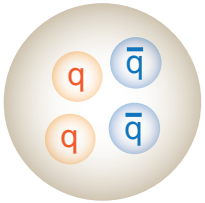
Exotic states



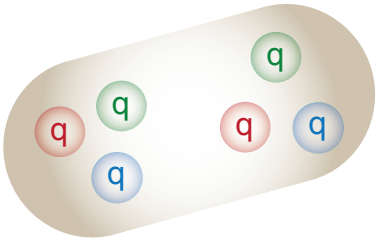
Glueballs?



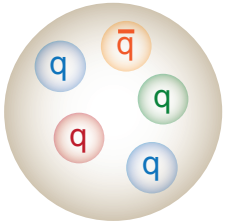
Hybrid mesons?



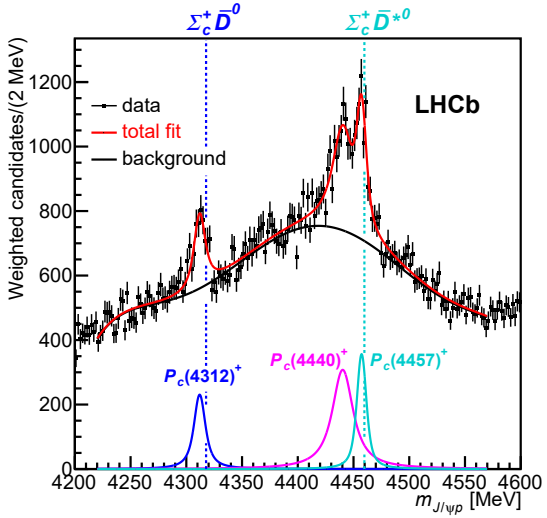
Tetraquarks?



Nuclei??



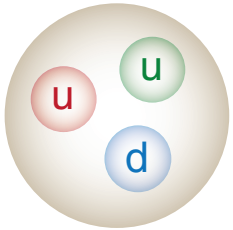
Pentaquarks?



Aaij et al., Phys. Rev. Lett. 112 (2019) 222001

To understand QCD, we must understand
spectrum and interactions of hadrons!

Mass generation



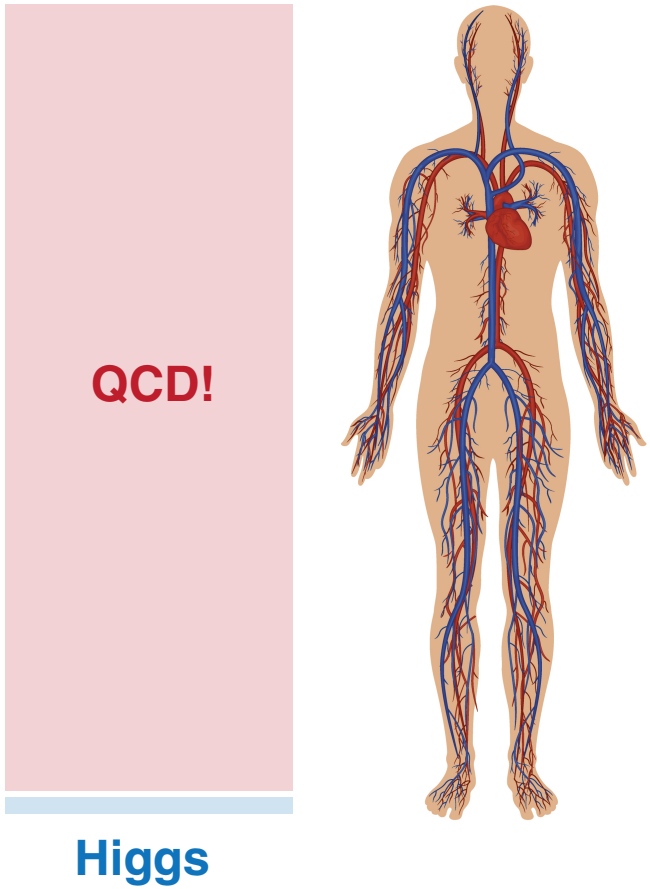
$2m_u + m_d$ ~ 10 MeV,
but **proton** ~ 1 GeV !?

Higgs → Current-quark masses

QCD → **Mass generation** due to spontaneous breaking of **chiral symmetry:** "constituent-quark masses"

u	d	s	c	b	t
3	5	100	1000	4000	175000
350	350	350	350	350	350

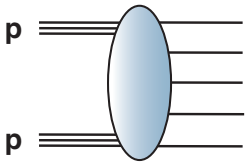
[MeV]



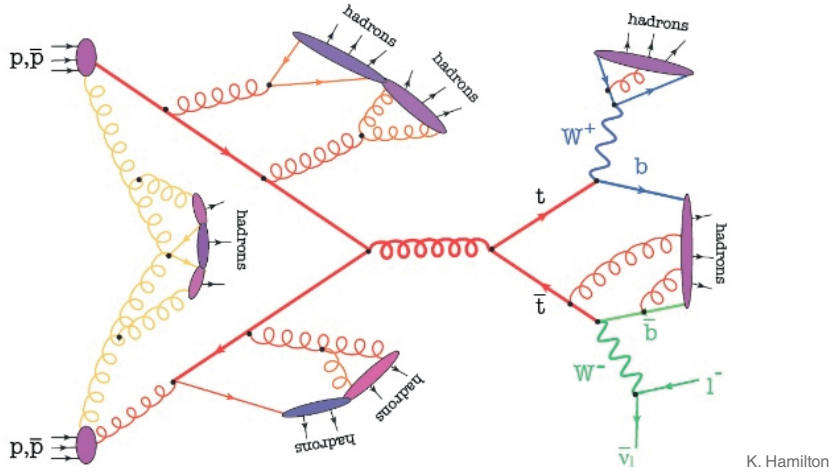
Experiments?

How can we **probe** quarks and gluons **experimentally** if we can never set them free?

- **pp, pA, AA → X, . . .**



LHC (CERN)
RHIC (BNL)
GSI/FAIR (Germany)
. . .



K. Hamilton

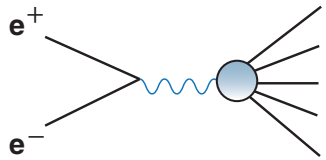
→ **Hadronization & Jets**
→ **QCD phase diagram**
→ **Quark-gluon plasma**

→ Hands-on **QCD Jets**

Experiments?

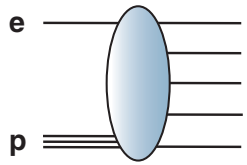
Use **electromagnetic probes:**

- $e^+e^- \to X$



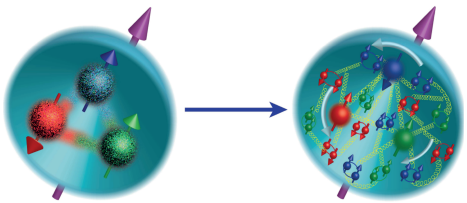
BES III,
Belle,
BaBar,
. . .

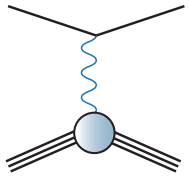
- $ep \to X$



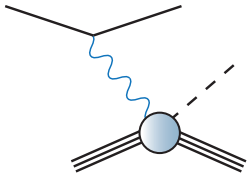
EIC (USA)
COMPASS (CERN)
Jefferson Lab (USA)
MAMI & ELSA (Germany)
. . .

- Extract properties of **individual hadrons**
- Quark-gluon substructure, **"Hadron tomography"**

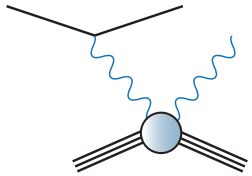




eN scattering



meson electro-production

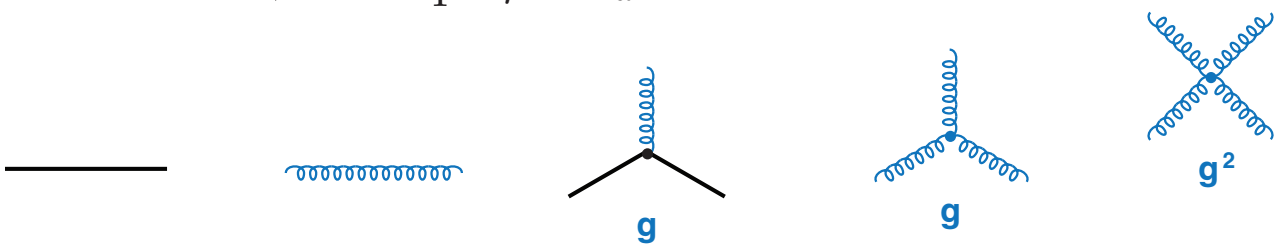


Compton scattering

- Extraction of **resonances**

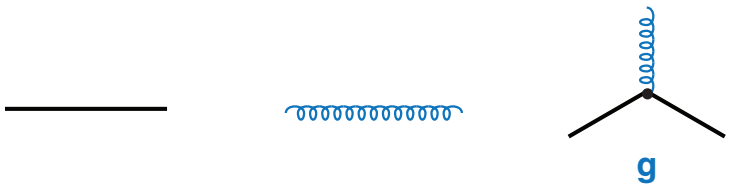
QCD Lagrangian

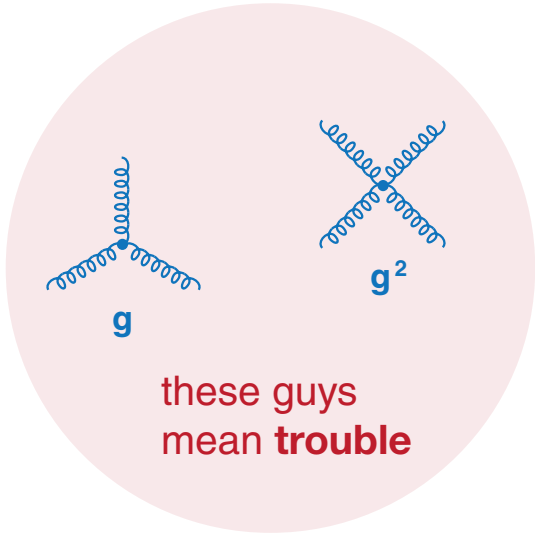
$$\mathcal{L} = \bar{\psi}\left(\not{\partial} + i\,g\not{A} + m\right)\psi + \frac{1}{4}\,F^{a}_{\mu\nu}\,F^{\mu\nu}_{a}$$



QCD Lagrangian

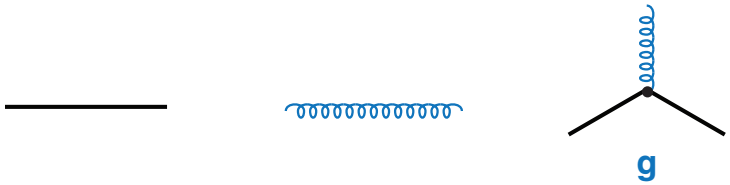
$$\mathcal{L} = \bar{\psi}\left(\not{\partial} + i\,g\not{A} + m\right)\psi + \frac{1}{4}\,F^{a}_{\mu\nu}\,F^{\mu\nu}_{a}$$

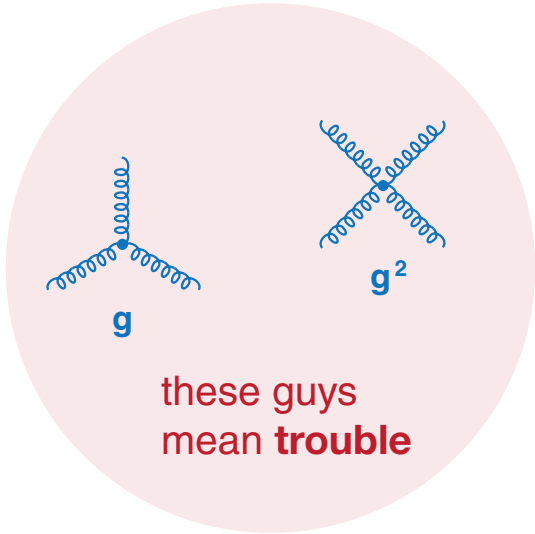




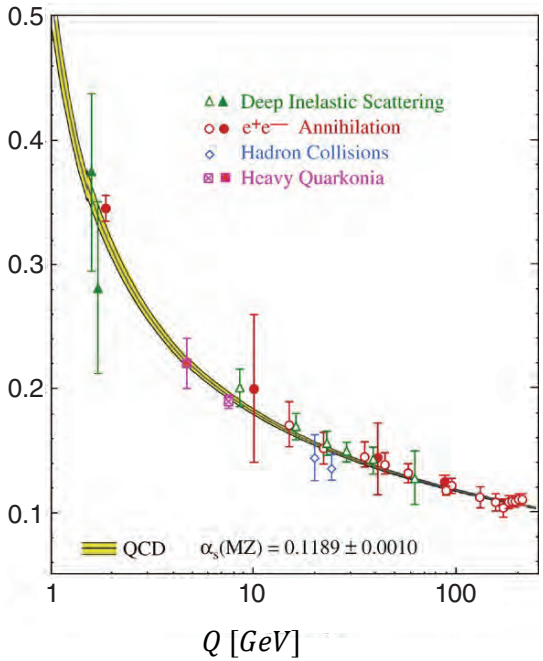
QCD Lagrangian

$$\mathcal{L} = \bar{\psi}\left(\not{\partial} + i\,g\not{A} + m\right)\psi + \frac{1}{4}\,F^{a}_{\mu\nu}\,F^{\mu\nu}_{a}$$





$$\alpha = \frac{g^2}{4\pi}$$



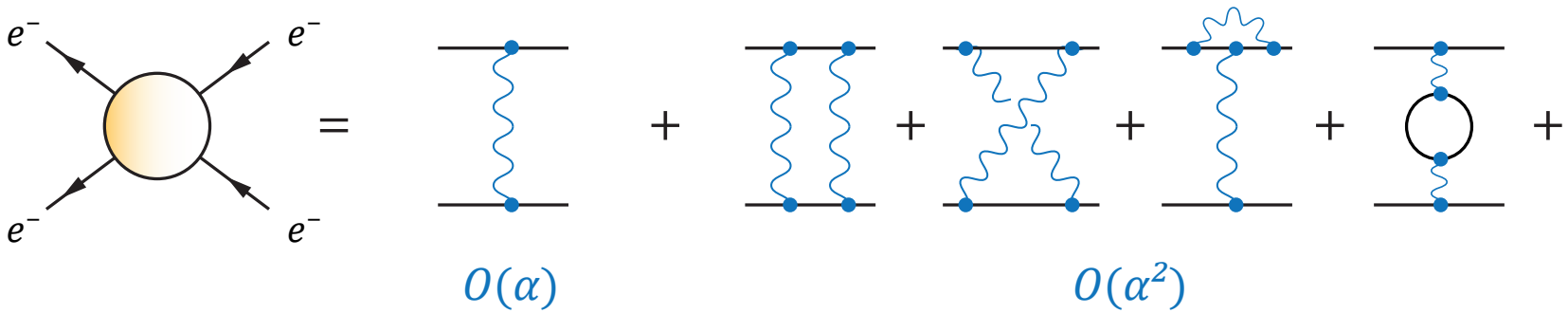
At small momenta, coupling becomes large → we need **nonperturbative methods!**

At large momenta, quarks & gluons behave as quasi-free particles: **asymptotic freedom**

Gross, Politzer, Wilczek 1973

Perturbative vs. nonperturbative

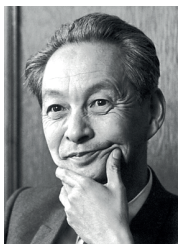
Interaction between **two electrons**:

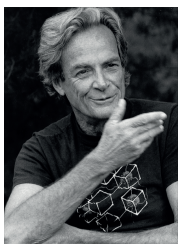


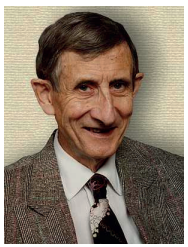
"Quantum mechanics"

Perturbative QFT:
Feynman diagrams & loops


J. S. Schwinger

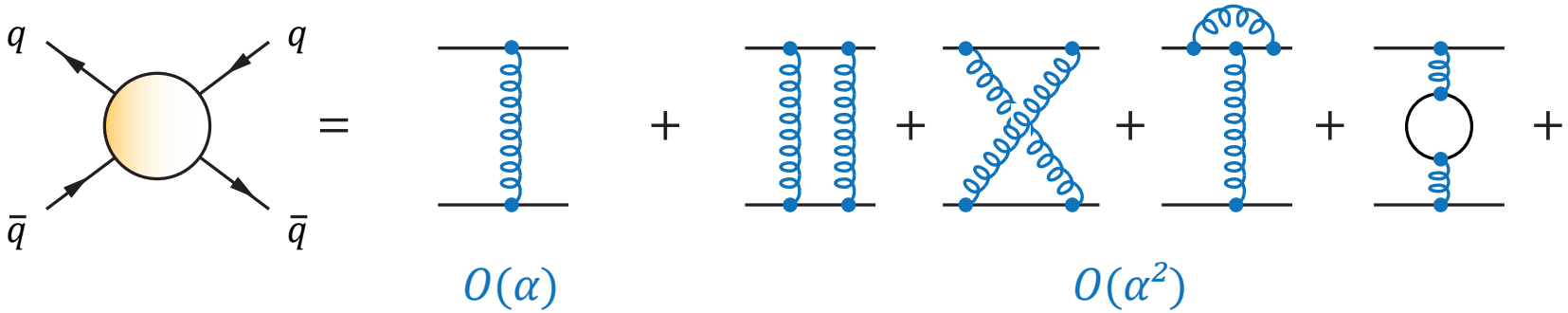

S. Tomonaga


R. P. Feynman

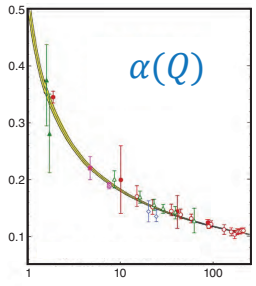

F. J. Dyson

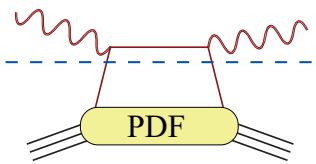
Perturbative vs. nonperturbative

Interaction between **quark and antiquark?**



Answer still correct at large momenta:
high-energy scattering experiments



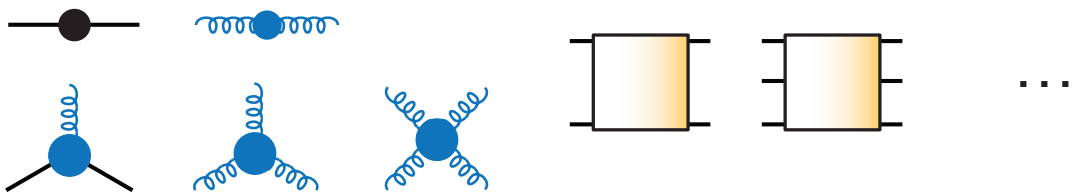


What about low momenta, confinement, mass generation, hadron physics?

→ need **nonperturbative methods!**

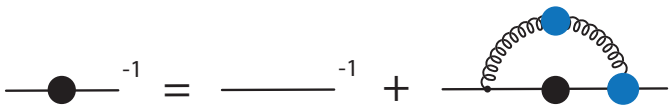
Mass generation

A QFT is completely determined by its **correlation functions:**

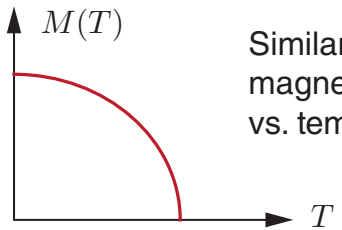


satisfy nonperturbative **Dyson-Schwinger** and **Bethe-Salpeter** equations

Quark mass function $M(p^2) \neq 0$, even for massless quarks: spontaneous breaking of chiral symmetry if $\alpha > \alpha_{\text{crit}}$



Cannot happen in perturbation theory!

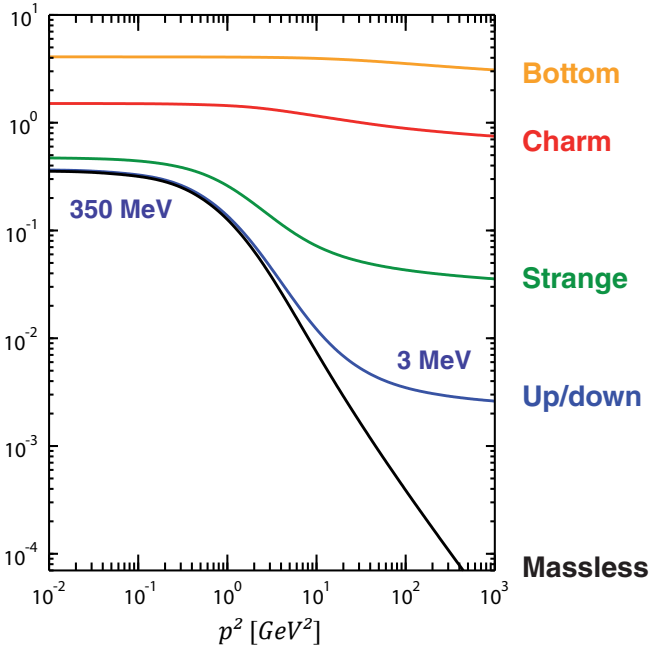


Similar: magnet, magnetization vs. temperature

$M(p^2)$

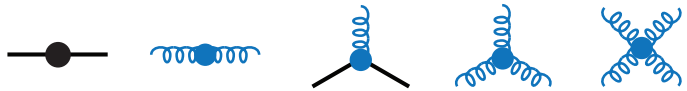
QCD!

Higgs

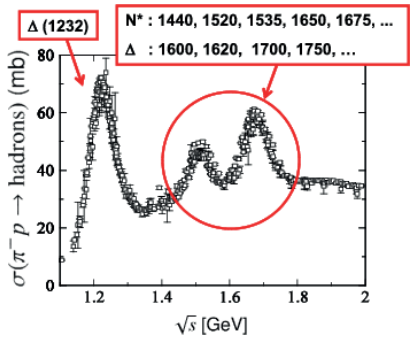


Theory tools

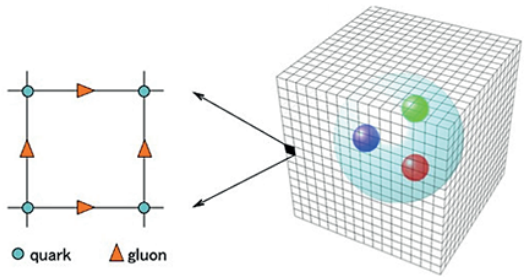
Functional methods
(DSEs & BSEs, FRG, ...)



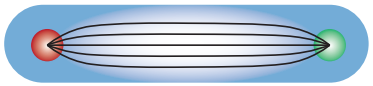
Amplitude analyses



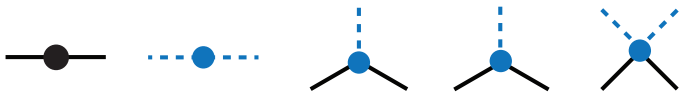
Lattice QCD



Phenomenological models

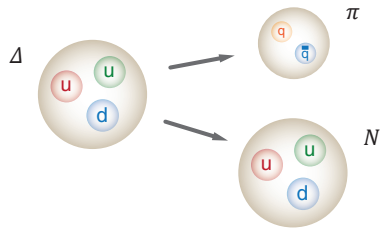


Effective theories
(ChPT, ...)

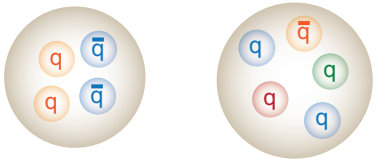


Some hot topics in QCD

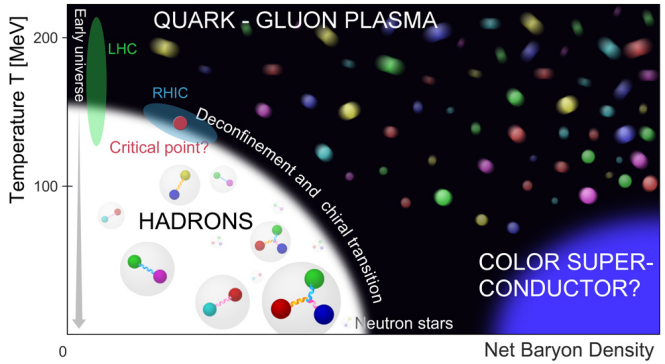
- **Confinement & mass generation**
- **Resonances:** most hadrons decay into other hadrons ↔ poles in complex plane



- **Hadron structure calculations:** form factors, PDFs, GPDs, ...
- **Exotic hadrons & multiquark states:** tetraquarks, pentaquarks, nuclei?



- **QCD contributions to BSM searches:** muon anomalous magnetic moment, flavor matrix elements, ...
- **QCD under extreme conditions:** early universe, exotic phases, hadrons at large T and μ



Toolbox

Physics:

- **Particle physics**
- **Quantum field theory**
- **QCD & Hadron physics**
- **Nuclear physics**
- **Group theory**

. . .

Math:

- **Linear algebra:**
  dealing with large matrices
- **Complex analysis:**
  accessing the complex plane
- **Integral equations:**
  nonperturbative calculations

Numerics:

- **Symbolic:**
  Mathematica, ...
- **Programming:**
  C++, Fortran, ...
- **Parallel computing:**
  MPI, OpenMP, CUDA, ...

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