QCD from its birth to its stubbornly unsolved problems
QCD’s early history

Known, too complex to review

Yang, C. N.; Mills, R. "Conservation of Isotopic Spin and Isotopic Gauge Invariance". Phys, Rev. 96, 191, 1954

H. Fritzsch and M. Gell-Mann “Current algebra, quarks and what else?” Proc. Int. Conf. on Duality and Symmetry, Tel Aviv 1971. QUARK COLOUR

Yang-Mills theory

e.g. QCD: gluons couple to gluons, the force-carrier is “CHARGED”

In this sense… much earlier precedent to YM
Nordtvedt test

\[ \delta g / g < 2 \times 10^{-13} \]

P.E. Super-OK

Precision of 3-G coupling

\[ \Delta M \propto - \frac{GM^2}{R} \]

\[ \frac{\Delta M \times}{M \times} \approx -4.6 \times 10^{-10} \]

\[ \frac{\Delta M_\mu}{M_\mu} \approx -2 \times 10^{-11} \]

Gravitons
WHO INVENTED QUARKS?

2 minutes.
Postponed to question period
How do Quarks “Function”? 
Confined !!
Unbelievable !
Observed ?

Peter Franken

A. Zichichi et al.
Before that, Feynman’s Pointlike(?) Partons
Bjorken’s Scaling
QCD’s Asymptotic Freedom

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green’s functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green’s functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.
God Went to Princeton
In his book In Search of the Ultimate Building Blocks (Cambridge University Press, 1997), Gerard 't Hooft relates: "In 1972 a small conference took place in Marseille. On arriving at Marseille airport, I discovered that (prominent field theorist) Kurt Symanzik and I had shared the same plane... He had been trying to understand Bjorken scaling [the behaviour seen in high-energy scattering when the incoming projectile particle transfers a lot of momentum to the target Ed.] in a quantum field theory, but had limited himself to what he considered to be the prototype of all field theories, a simple spin zero model. Unfortunately it had the wrong scaling behaviour.

"'If only I could turn this scaling behaviour round, ' Symanzik said, 'then you would get a theory where particles at close distance behave almost as free particles, but when they separate to larger distances they would feel much stronger forces.'"

"'Well, ' I ['t Hooft] cried,'that is exactly what you get in a Yang-Mills (spin one) gauge theory!'"

"Symanzik replied: 'You should publish this quickly, because this would be very important.' "

"Much to my later regret, I did not follow this sensible advice, "
Witness account: Frequent reference to work by ADR et al.

“I never travel without my diary. One should always have something sensational to read in the train.”

Golda Meir: Don't be humble... you're not that great. \[right x, t\]
First two papers on Asymptotic Freedom (Theory)
First four papers on Asymptotic Freedom (Phenomenology)
$J/\Psi$ as CHARMONIUM

Appelquist & Politzer

Annihilation

$d \sim 1/m_c$

$d \sim 1/\Lambda_{QCD}$

Why so narrow?

ADR & Glashow

$\varphi(s\bar{s}) \rightarrow 3\pi$

Hadronization !? Unitary !!
Bloom-Gilman Duality

\[ G_M(q^2) \leftrightarrow \nu W_2(\xi_p, q^2) \]

\[ \alpha_s \equiv \frac{g_s^2}{4\pi} = \]

\[ \frac{12}{25 \pi \ln[q^2/\Lambda^2]} \]

ADR PRL 26/3/74

Gross & Treiman
PRL 25/3/74

\( \alpha_s \leftrightarrow \Lambda(QCD) \)

B-G D-ity \arrow{red}{QCD} ADR, Georgi & Politzer
\[ \alpha_s(M_Z) = 0.1181 \pm 0.0013 \]

Leading Log, Leading Twist

\[ \alpha_s(Q^2) \]

October 2015

QCD

\[ \tau \text{ decays (N}^3\text{LO)} \]

\[ \text{DIS jets (NLO)} \]

\[ \text{Heavy Quarkonia (NLO)} \]

\[ e^+e^- \text{ jets & shapes (res. NNLO)} \]

\[ \text{e.w. precision fits (NNLO)} \]

\[ pp \rightarrow jets \text{ (NLO)} \]

\[ pp \rightarrow tt \text{ (NNLO)} \]

\[ QCD \alpha_s(M_Z) = 0.1181 \pm 0.0013 \]

[ΛQCD]

Only fundamental constant first measured by a theorist
If you would like your work to be ignored

BE A

PHENOMENOLOGIST
Progress; simplest example

Running:

\[ \mu^2 \frac{d\alpha_s}{d\mu^2} = \beta(\alpha_s) = -(b_0 \alpha_s^2 + b_1 \alpha_s^3 + b_2 \alpha_s^4 + \cdots) \]

\( b_0 \) to \( b_4 \) calculated

Measurement

\[ \frac{\sigma(e^+e^- \rightarrow \text{hadrons, } Q)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-, Q)} \equiv R(Q) = R_{\text{EW}}(Q)(1 + \delta_{\text{QCD}}(Q)) \]

\( \delta_{\text{QCD}}(Q) = \sum_{n=1}^{\infty} c_n \cdot \left( \frac{\alpha_s(Q^2)}{\pi} \right)^n + \mathcal{O} \left( \frac{\Lambda^4}{Q^4} \right) \)

\( c_1 \) to \( c_4 \) calculated

Scheme dependent

Slow convergence

Renormalons

\( n! \alpha_s^n \)
\( \alpha_s(Q^2 = M_Z^2) \)
Factorization [almost] OK for inclusive DIS

Semi-satisfactory for DY

Fairly un-satisfactory for hadron-hadron (e.g. LHC)
Dashed: At high transfer of momentum the proton behaves as if made of charged point-like "PARTONS".
An improved version of Bloom-Gilman duality is a consequence of QCD.

Proof relegated to question period.
QCD evolution was accepted as a precise prediction because the data were NOT precise.
Parton model

Factorization scale

\[
F_2(x, Q^2) = x \sum_q e_q^2 f_{q/p}(x), \quad F_L(x, Q^2) = 0
\]

Leading QCD evolution

\[
\mu_F^2 \frac{\partial f_{i/p}(x, \mu_F^2)}{\partial \mu_F^2} = \sum_j \frac{\alpha_s(\mu_F^2)}{2\pi} \int_1^1 \frac{dz}{z} P_{i\leftarrow j}^{(1)}(z) f_{j/p} \left( \frac{x}{z}, \mu_F^2 \right)
\]

\[
N\ldots LO:
\]

\[
C_{2,q}^{(0)} = e_q^2 \delta(1-z) \quad C_{2,g}^{(0)} = 0
\]

\[
F_2(x, Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z, Q^2, \mu_R^2, \mu_F^2) f_{i/p} \left( \frac{x}{z}, \mu_F^2 \right)
\]

\[
\mu_F, \mu_R : \text{Factorization, Renormalization Scales}
\]

Observable Turn bad news into good hopes

\[
\frac{\mu_F}{2} < \mu_F < 2 \mu_F, \quad \frac{\mu_R}{2} < \mu_R < 2 \mu_R
\]
Inclusive hadronic final states (cont.)

The shape of $R$ in $e^+e^- \rightarrow \text{hadrons}$

$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

$R_{\text{SLAC}}$

$D^*$

$1S$, $2S$, $3S$, $4S$

$W \rightarrow \infty$

$u, d, s, c + \text{heavy lepton?}$
ANALYTIC CONTINUATION TO $Q^2 < 0$, WHERE PERTURBATIVE QCD NO DOUBT WORKS

FINDING FANCY FLAVORS COUNTING COLOURED QUARKS

Counting quarks in $e^+e^-$ annihilation*

A. De Rújula and Howard Georgi†

*The Physics Laboratories, Harvard University, Cambridge, Massachusetts 02138

(Received 28 October 1975)

A comparison of asymptotically-free-quark-model predictions and $e^+e^-$ annihilation data can be made by using a dispersion relation to continue the data into the spacelike region. We make this comparison for several models, including when appropriate the effect of heavy-quark masses. We conclude that the "old" theory with no charm is excluded, the standard model with charm is acceptable if heavy leptons are produced, and six-quark models are viable if no heavy leptons are produced.
Quarks, families, $SU(3) \times SU(2) \times U(1)$ gauge theory...

1975: Not STANDARD

Considered by overwhelming majority:

A non-contagious tropical disease
Georgi & I discovered charm and the tau lepton

The technique to discover taus: $e^+ e^- \rightarrow \tau \bar{\tau}$; $\tau \rightarrow e\nu\bar{\nu}$; $\tau \rightarrow \mu\nu\bar{\nu}$

was invented and pioneered by Antonino Zichichi

BUT … … … …
If you would like to have your work fully recognized,

DO NOT ACT AS A PHENOMENOLOGIST.
Graviton, $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
Cut acceptance = 27.5%

- ATLAS data
- Background-only fit
- ATLAS best-fit
- Combined signal strength

Events/40GeV vs $m_{\gamma\gamma}$ [GeV]

I WANT TO BELIEVE
Non-inclusive final states
W production in hadron-hadron colls.

\[ \sigma(h_1 h_2 \rightarrow W + X) = \]
\[
\sum_{n=0}^{\infty} \alpha_s^n(\mu_R^2) \sum_{i,i} \int dx_1 dx_2 f_i/h_1(x_1, \mu_F^2) f_j/h_2(x_2, \mu_F^2) \]
\[
\times \hat{\sigma}_{ij \rightarrow W+X}^{(n)} \left( x_1 x_2 s, \mu_R^2, \mu_F^2 \right) + O \left( \frac{\Lambda^2}{M_W^4} \right) \]

Bad: Factorization not fully proved to serious people’s satisfaction, e.g.
Collins, Soper & Sterman hep-ph/0409313
Two gauge bosons $W$ and $Z$.
Back to e.g. Collins, Soper & Sterman

\[(\Phi^3)_6\]

In 6D renormalizable and asymptotically free

Factorization proofs completed even beyond leading twist. *Not so for QCD, even in DIS*

More: in QCD infrared divergencies do not cancel in pp scattering beyond leading “twist”

**BLT:** \(O[(\Lambda/Q)^n]\) corrections

Again: *relevant IN PRACTICE ???*

NNLO calcs. and LHC EXPERIMENTS reaching precision \(\exists O[(\Lambda/Q)^n]\) effects are NOT negligible
Observables calculated to $\mathcal{N}_N\ldots\mathcal{O}$

Understanding + looking for BSMStuff

Not sufficiently acknowledged
If you would like your work to be ignored

BE A Standard-Model PHENOMENOLOGIST
Non-inclusive hadronic final states, cont.

“Infrared-safe” observables of old

at hadron colliders:
jet rates, $p_T(jet)$, $p_T(Z,W)$

Event “shapes”, originally in $e^+ e^-$ ann.

“Thrust”

\[
\tau \equiv \text{Max} \sum_i p_i \subset \text{Hemisphere} \quad \frac{E_e}{1/2 \leq \tau \leq 1} \quad \text{back-to-back}
\]
Angular correlations four-jet events

Prior: \( \alpha_s \)

\[
C_F = 4/3
\]

\[
C_F = 1.30 \pm 0.01 \pm 0.09
\]

\[
C_A = 3
\]

\[
C_A = 2.89 \pm 0.03 \pm 0.21
\]

Recall triple-graviton coupling
Confronting Reality

- Hadronization
- QCD-evolved q, g shower
- Re-summed hard scatter.

Spectators

Underlying event
Confronting Reality (cont.)

QCD-evolved $q, g$ shower

Stop it at scale

$\sim 1 \text{ GeV}$

Back and forth tuning with observations

Hadronization

Stretching Strings

Colourless Clusters

Entirely classical (non-QM) MCs
DGG 1975: ADR, Georgi, Glashow

Constituent Quarks + QCD

“Hyperfine”

We explain (too well!) splittings between hadrons in same multiplet [e.g. \( \Xi^{-} \wedge [uds]_{J=\frac{1}{2}} \)] as “chronohyperfine”
Postdictions for ground-state mesons & baryons
OK
Of Course
\[ \nu_\mu p \rightarrow \mu^- \Sigma^{++}_c [uuc] \]

\[ \Sigma^{++}_c \rightarrow \pi^+ \Lambda^+_c [udc] \]

\[ \Lambda_c^+ \rightarrow \pi^+ \pi^+ \pi^- \Lambda^0 \]

\[ \Lambda[uds] \rightarrow \pi^- [d\bar{u}] p[uud] \]
total recoiling hadron mass \((\Lambda \pi^+ \pi^+ \pi^+ \pi^-)\) \(2426 \pm 12\) MeV.\(^{12}\)

This mass is in reasonable agreement with the values predicted by De Rujula, Georgi, and Glashow\(^{13}\) for the lowest-lying charmed-baryon states of charge +2, 2420 MeV \((J^P = \frac{3}{2}^+, I = 1, \Sigma_c^*)\)

Nick Samios et al., 1975

There are three \(\pi^+\)'s and thus three possible mass differences derivable from this event; these are observed to be 166 \(\pm\) 15 MeV, 338 \(\pm\) 12 MeV, and 327 \(\pm\) 12 MeV. The first of these differences is in remarkable agreement with the 160 MeV predicted for the decay of a spin-\(\frac{1}{2}\) charmed baryon \(\Sigma_c\) decaying into a charmed \(\Lambda_c\).
$\Lambda^+_c [udc]$
Lattice postdictions
Lattice predictions

\[
\begin{pmatrix}
V_{ud} & V_{cd} & V_{td} \\
V_{us} & V_{cs} & V_{ts} \\
V_{ub} & V_{cb} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

CKM matrix and Unitarity Triangle
Talk on LHCb results, Stefan Meiner

\[
\int_{q_\text{max}^2}^{15 \ GeV^2} \frac{d\Gamma(\Lambda_b \rightarrow p \mu^- \bar{\nu}_\mu)}{dq^2} \, dq^2 \, dq^2 \quad = \quad (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}
\]

\[
\int_{q_\text{max}^2}^{7 \ GeV^2} \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu)}{dq^2} \, dq^2 \quad = \quad (q = p - p').
\]

To extract \(|V_{ub}/V_{cb}|\) from this, need

\[
\langle p | \bar{u} \gamma^\mu b | \Lambda_b \rangle, \langle p | \bar{u} \gamma^\mu \gamma_5 b | \Lambda_b \rangle,
\]

\[
\langle \Lambda_c | \bar{c} \gamma^\mu b | \Lambda_b \rangle, \langle \Lambda_c | \bar{c} \gamma^\mu \gamma_5 b | \Lambda_b \rangle
\]

from lattice QCD.

“\(\Lambda_b \rightarrow p \ell^- \bar{\nu}_\ell\) and \(\Lambda_b \rightarrow \Lambda_c \ell^- \bar{\nu}_\ell\) form factors from lattice QCD with relativistic heavy quarks”

Easy way out: add

\[ \epsilon_R \, \bar{b} \, \gamma_\mu \, u_R \] to \[ \bar{b} \, \gamma_\mu \, u_L \]
Back to good-old V-A theory $\epsilon_R = 0$
Unmentioned

- Other lattice results, e.g. meson decays, $\tau$
- Glueballs, exotics, tetra/pentaquarks
- **QCD phase diagram**
- So-called early-universe plasma
- Chiral dynamics, symmetry breaking
- Heavy-quark methods
- Hadronic contributions to $(g - 2)_\mu$
- Etcœtera, etcœtera, etcœtera
Exp?: AXION

Th: CONFINEMENT

Nothing very decisive (for me) to say, but:
Good Old Lattice:

$$\lim_{{R \to \infty}} V_{QQ}(R) = \sigma \cdot R + \frac{\text{const}}{R}$$

Not a proof of confinement satisfying the Millennium Jury.

One Million Dollars prize.

The Seven Millennium Problems
The Clay Mathematics Institute of Cambridge, Ma.

http://claymath.org/millennium-problems/millennium-prize-problems
\[ p = [u \ u \ u \ d] \quad \pi^+ = [u \ d\bar{d}] \]

WHO INVENTED QUARKS?

BUT André Petermann in Nuclear Physics [63, 349, (1963)], in French!
received December 30th, 1963

Murray Gell-Mann’s paper received by Physics Letters on January 4th 1964

George Zweig’s unpublished work is a CERN preprint dated January 17th 1964
Gell–Mann: These ideas were developed ... in March 1963; the author would like to thank Professor Robert Serber for stimulating them.

INCLUDING LEADING EVOL. 

\[(\text{Ln}[Q^2/\Lambda^2])^d\]

DROP \(n\Lambda^2/Q^2\) EFFECTS "DGLAP"

\(\xi\) is Nachtman's variable, OPE
$P_n(\xi) = \sum_{m=0}^{n} C_m \xi^m$

$\xi_1 < \xi < \xi_2$

LTWist: no $n \frac{\Lambda^2}{Q^2}$ HTWist corrections

Higher $Q^2 \rightarrow$ bigger # moments with given precision

$\rightarrow$ Better and more local QCD duality, as observed
Why are power-corrections relevant \textit{in practice}???

NNLO calcs. and LHC EXPERIMENTS reaching precision \( \mathcal{O}[\left(\frac{\Lambda}{Q}\right)^n] \) effects are NOT negligible.

Want to understand... And to know "backgrounds" in looking for "new" physics.
A weak lower limit on the # of papers on the 750-GeV Di-photon