James Bjorken and the dawn of QCD

Davison E. Soper
University of Oregon

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This talk concerns Bjorken's contributions to the beginnings of quantum chromodynamics (QCD) in the period 1967-1971 when I was his student at SLAC.

In 1965, the idea that protons were somehow made of quarks was available, but there was only a nonrelativistic model of this.

QCD is a quantum field theory.

The first thing to note is that quantum field theory was accepted as the basis of the highly successful quantum electrodynamics.

But it was far from obvious that quantum field theory was the right language to describe the strong interactions.

An alternative was to study the S-matrix for the scattering of hadrons as an analytic function of the momenta involved, deriving, for example, “dispersion relations.”

A lot could be learned this way.

Perhaps this was the way forward.

Certainly a quantum field theory based on baryon and meson fields did not look promising.

A pair of books suggested that quantum field theory was worth serious study:

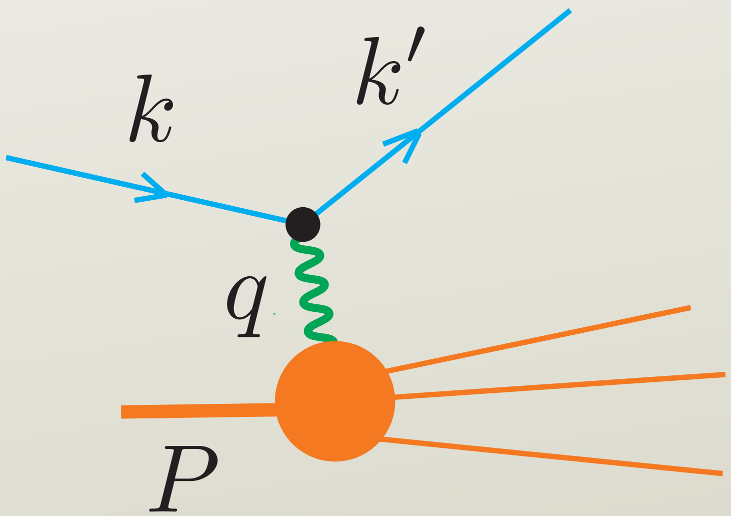
J.D. Bjorken and S.D. Drell
Relativistic Quantum Mechanics
Relativistic Quantum Fields
McGraw-Hill (1965)

Certainly everything that I knew about elementary particle theory at the time came from those books.

Deeply Inelastic Scattering

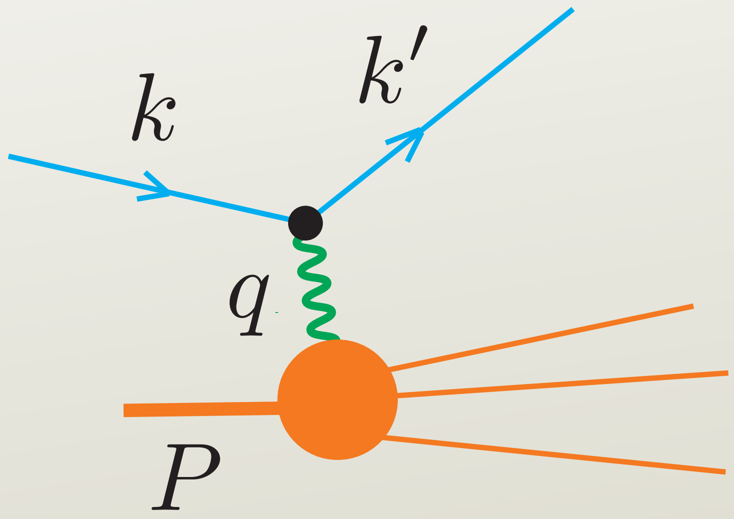
- The process is $l + h \to l' + X$.

$$Q^2 = -q^2$$
$$x_{bj} = \frac{Q^2}{2P \cdot q}$$



- "bj" = Bjorken.
- "Deeply inelastic" means $Q^2 \to \infty,\ x$ fixed.
- Only k' is measured.

$$d\sigma = \frac{4\alpha^2}{s}\,\frac{d^3\vec{k}'}{2|\vec{k}'|}\,\frac{1}{(q^2)^2}\, L^{\mu\nu}(k,q)\, W_{\mu\nu}(P,q).$$

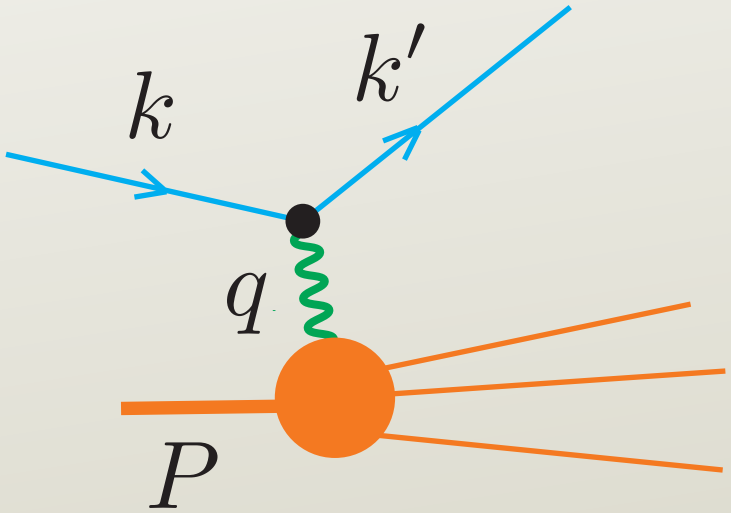


The structure of $W_{\mu\nu}$:

$$W_{\mu\nu} = -\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) F_1(x_{\mathrm{bj}}, Q^2)$$
$$+\left(P_\mu - q_\mu \frac{P\cdot q}{q^2}\right)\left(P_\nu - q_\nu \frac{P\cdot q}{q^2}\right)\frac{1}{P\cdot q}\, F_2(x_{\mathrm{bj}}, Q^2)$$

The functions F_1 and F_2 are the structure functions.

Simplest expectation



$F_1(x_{\rm bj}, Q^2)$ and $F_2(x_{\rm bj}, Q^2)$ fall quickly as Q^2 increases, like form factors, because the proton is full of soft stuff.

Bjorken scaling

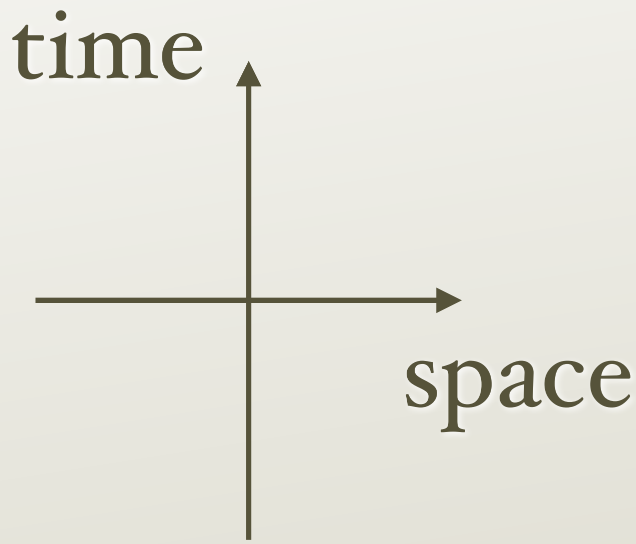
"$F_1(x_{\rm bj}, Q^2)$ and $F_2(x_{\rm bj}, Q^2)$ are independent of Q^2 at fixed $x_{\rm bj}$."

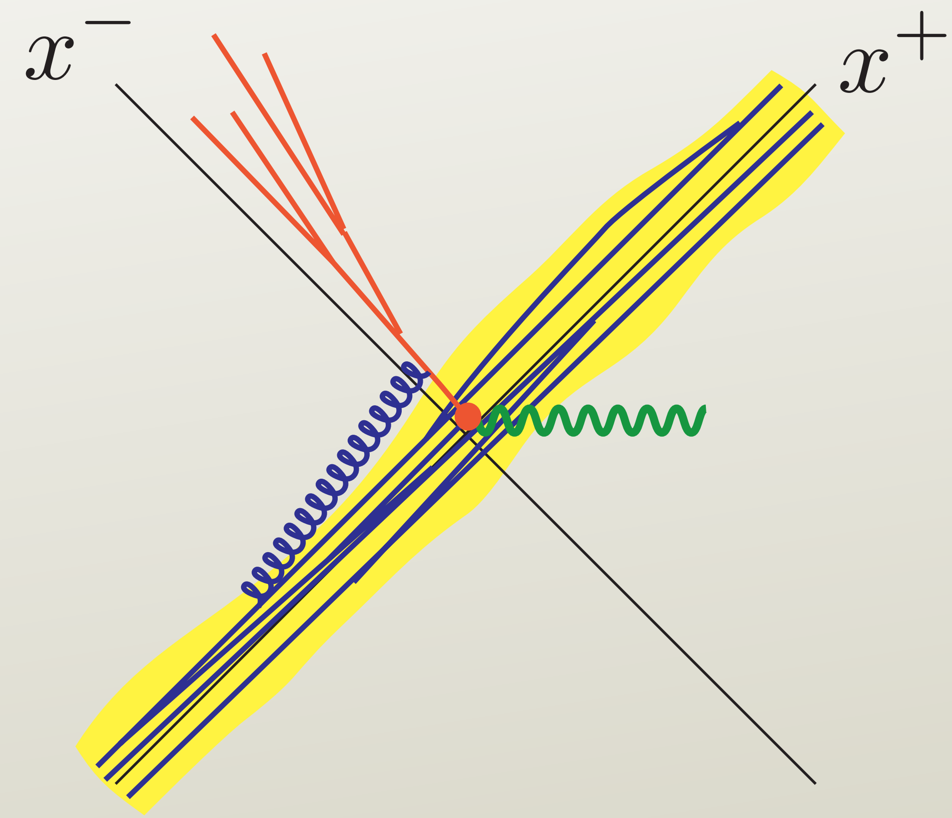
J. D. Bjorken,
"Asymptotic Sum Rules at Infinite Momentum,"
Phys. Rev. **179**, 1547 (1969)

Bjorken considered the commutator of the two currents in a reference frame in which the proton has a very large momentum.

Then he used current algebra and dispersion relations to argue that it was plausible that for very large Q^2 with fixed $x_{\rm bj}$, F_1 and F_2 would be independent of Q^2.

Parton model picture





Choose a reference frame in which the proton is moving with high velocity to the right.

Constituents ("partons") interact slowly as seen in this reference frame.

So the partons are effectively free.

This view was emphasized by Richard Feynman.

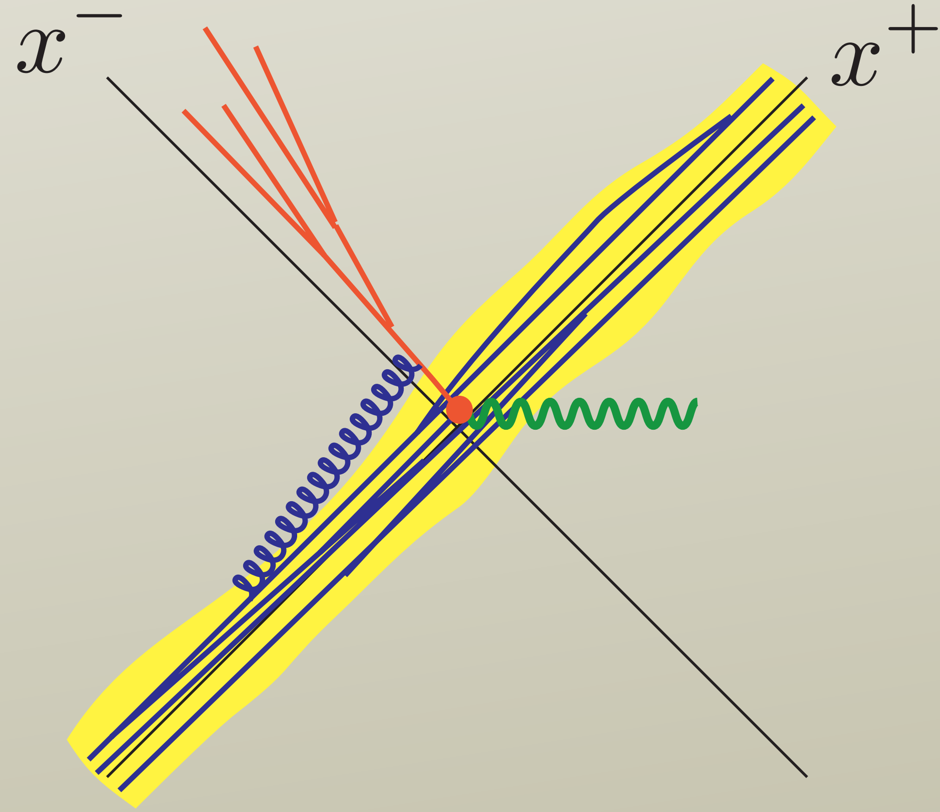
It leads to approximate Bjorken scaling.

The reasoning was nicely stated in

J.D. Bjorken and E.A. Paschos

"Inelastic electron-proton and γ-proton scattering and the structure of the nucleon,"

Phys. Rev. **185**, 1975 (1969)



Field theory model for parton scattering

J. D. Bjorken, J. B. Kogut and D. E. Soper,
"Quantum Electrodynamics at Infinite Momentum: Scattering from an External Field,"
Phys. Rev. D **3**, 1382 (1971)

Made use of previous paper “Quantum Electrodynamics in the Infinite Momentum Frame,” by Bjorken’s students Kogut and Soper. Briefly, define coordinates

$$x^{\pm} = \frac{1}{\sqrt{2}}\left(x^0 \pm x^3\right)$$

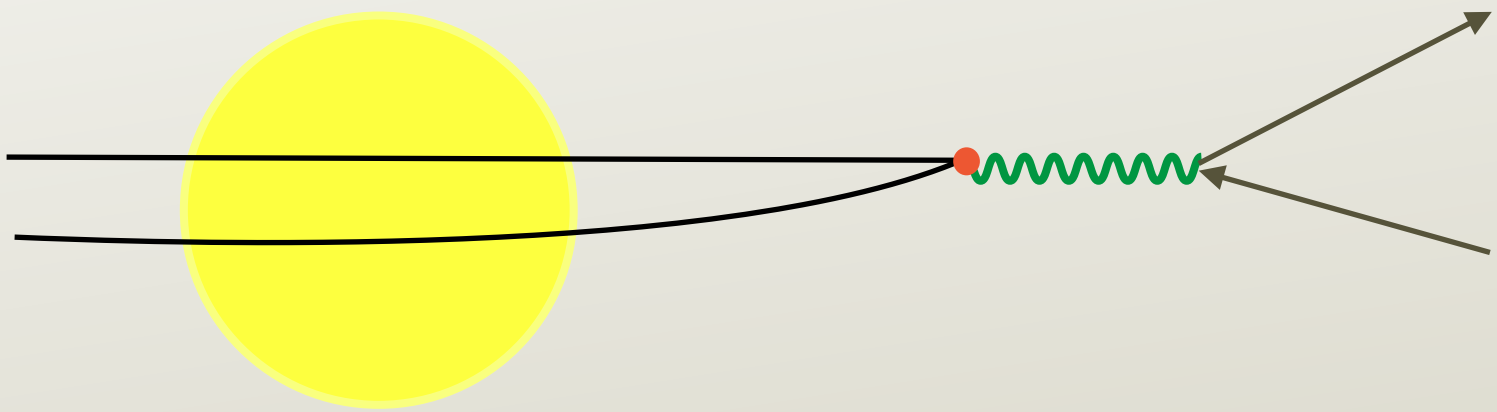
Develop quantum field theory according to Bjorken and Drell using x^+ as the time coordinate instead of x^0.

> “The motivation for developing a formal theory of quantum electrodynamics in the infinite-momentum frame was the hope that this exact theory would lead to an approximate ultrarelativistic theory which could provide a simple description of extremely high-energy phenomena, just as nonrelativistic field theories provide understanding of low-energy phenomena.”

Several examples involving scattering from an external field are worked out, illustrating the usefulness of this formulation of quantum electrodynamics.

One example is intended to model deeply inelastic scattering.

An high energy electron emits a virtual photon, which becomes a muon pair, which interacts with the external field. Only the final state electron is observed.



This field theory model exhibits approximate Bjorken scaling.

In fact, if the “muons” are quarks and the “external field” is the gluon field of the proton, this is the dipole picture of deeply inelastic scattering.

The result

These investigations showed that Bjorken scaling could work in a quantum field theory if the coupling were small enough to allow a perturbative picture.

In the parton model, Bjorken scaling followed as long as the partons' interactions were small enough to allow a perturbative picture.

But how could the partons appear to be almost free so that Bjorken scaling could hold in a quantum field theory?

The discovery in 1973 of "asymptotic freedom" of QCD, by Gross and Wilczek and by Politzer solved that mystery.

This led to the recognition of QCD as the theory of the strong interactions.

Bjorken tree at our house

sequoia sempervirens

A second generation clone from Bjorken's yard.

A good idea planted in fertile soil will grow.