From theorists dreams to reality
My (physics) adventures with AGW

Tony an Jan (on US hwy 10, 1992)
one, two, \ldots \infty \text{ gluons}

solitons and bags

confinement, dynamical $\chi$-sym. breaking

Dyson-Schwinger eqs.

poles, cuts and covariant amplitudes

pion form factor

$\rho$-$\omega$ mixing

strangeness in proton

$\phi$-production
one, two, \ldots \infty \text{ gluons}

poles, cuts and covariant amplitudes

pion form factor

$\rho$-$\omega$ mixing
Exclusive processes in perturbative quantum chromodynamics

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Stanley J. Brodsky
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 27 May 1980)

\[ F_\pi = \text{Hard Gluon Exchange} + \text{Higher Order } (\alpha_s)^n \]
\[ + \text{Higher Twist } \left( \frac{1}{Q^2} \right)^n \]
\[ + \text{Soft } \left( \text{no short distance subprocesses} \right) \]

Asymptotic $Q^2$ for Exclusive Processes in Quantum Chromodynamics

Nathan Isgur$^{(a)}$ and C. H. Llewellyn Smith
Department of Theoretical Physics, University of Oxford, Oxford OX1 3NP, England, United Kingdom
(Received 19 October 1983)
Model analysis of the nonleading twist contributions to the pion electromagnetic form factor

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\[
\phi(p, P) = \sum_{\beta=2}^{\infty} \int_{-1}^{1} dx \int_{0}^{\infty} dv^2 \frac{\tilde{g}_\beta(x, v, p, P)}{(p-x \cdot \frac{i}{2} P)^2 - [v^2 + m^2 - \frac{1}{4} (1-x^2) P^2] + i\epsilon} \]

\( Q^2(F(Q^2)[\text{GeV}^2]) \)

\( Q^2 [\text{GeV}^2] \)

Chernyak-Zhitnitsky w.f.s + LOpQCD

our calculation

assympt. w.f.s. + LOpQCD
asympotic \quad 6x(1 - x)

\phi_{\pi}(x)

Dyson-Schwinger

wee or valence quarks?

“longitudinal or transverse kick?“

\( P_{\gamma} = (0, 0, 0, -2P) \)

\( P = \frac{Q}{2} \)

\( P_{\pi} = (P, 0, 0, P) \)

low-x behavior of DA

\( 1 - x \sim 0 \quad x \sim 1 \)

\( 1 - x \sim \frac{1}{2} \quad x \sim \frac{1}{2} \)

"hardness" of the gluon

need to exchange hard gluons

"hardness" of the gluon
OGE or else?

$P_z \rightarrow \infty$

$\sum_i p_{i,z} = P_z \rightarrow \infty$

$p_{i,z}, \mu_{i,\perp} \sim O(1)$

$\Delta t$

perturbative tail of the wave function suppressed at the end-points $p_{zi} \sim 0$

$\Psi \sim \frac{1}{\Delta E} \sim \frac{p_{i,z}}{\mu_{i,\perp}^2}$

but for $p_{iz} \sim 0$

$\sqrt{\mu_{i,\perp}^2 + p_{i,z}^2} \rightarrow p_{i,z} + \frac{\mu_{i,\perp}^2}{2p_{i,z}}$

$\Delta E \sim \text{finite}$

wave function not suppressed and non-perturbative!

$L. Mankiewicz, APS$

P. Hoyer
\[ F(Q^2) = \int_0^1 dx \int \frac{d^2 k_1}{16\pi^3} \psi(x, k_1) \psi^*(x, k_1 + (1-x)q_1), \]

\[ \sim \int_{\lambda/Q}^1 dx |\psi(x, \lambda)|^2 \]

\[ \sim (\lambda/Q)^{1+2\delta}, \]

where \( \psi(x, \lambda) \sim (1-x)^\delta. \)

\[ F_\pi(Q^2) \sim \frac{\alpha(Q^2)}{Q^2} \]

vs

\[ F_\pi(Q^2) \sim \frac{(Q^2)^{0.5-\delta}}{Q^2} \]

e.g. \( \delta \sim 0.25 (\sim 0.29 \text{ in DS}) \) solves BaBar anomaly and is consistent with the Regge picture of a quark exchange.
E12-06-101 D.Gaskell, G.M.Huber,
“Measurement of the Charged Pion From Factors to High-Q^2”
BaBar anomaly \[ e^+ e^- \rightarrow \pi^0 e^+ e^- \]


\[ e^- \rightarrow \gamma^* (Q^2) F_{\gamma^* \gamma^0}(Q^2) \pi^0 \]

\[ e^+ \rightarrow \gamma \rightarrow \pi^+ \]

“pointlike”

“harder”

“hard”

“soft”

theory: G.P. Lepage, S. Brodsky
A. Radyushkin

\[
Q^2 F_{2\pi}(Q^2) \to 8\pi^2 f_\pi^2
\]

factor of 2-4

\[
Q^2 F_{2\pi}(Q^2) \to 8\pi^2 f_\pi^2 \left( \frac{\alpha_s(Q^2)}{0.5} \right)
\]
From the s-channel:

resonances (ρ, ω) at low energies

\[ Im F(s) = \sum_{X} t_{X}^{*}(s) \rho_{X}(s) F_{X}(s) \]

\[ Im F_{\pi \gamma} = t_{2\pi, \pi \gamma}^{*} \rho_{2\pi} F_{2\pi} + t_{3\pi, \pi \gamma}^{*} \rho_{3\pi} F_{3\pi} + \sum_{X} t_{X, \pi \gamma}^{*} \rho_{X} F_{X} \]

\((Q^2)^{\alpha}\) enhancement from multi-particle production
re ggized vs sin gle quark ex change

\[ \gamma^* (s) \]

soft

soft

\[ \gamma^* (s) \]

soft

soft

no central plateau

re ggized (ladder) quark

soft

soft
one, two, …\(\infty\) gluons

solitons and bags

confinement, dynamical \(\chi\)-syn breaking

Dyson-Schwinger eqs.

strangeness in proton

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\(\phi\)-production
one, two, \ldots \infty

\textit{gluons}

\textit{solitons and bags}

\textit{confinement, dynamical }\chi\text{-sym. breaking}

\textit{Dyson-Schwinger eqs.}
Early ideas about the origin of confinement

On the Implications of Confinement

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Dyson–Schwinger Equations and their Application to Hadronic Physics

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“One-gluon”

How does this relate to Regge trajectories?

~1/p^4 needed for linearly rising potential

G(0) = finite

L = 20 fm!

Gluon propagator

A. Cucchieri, et al.
Dual role of gluons

(all gluons are equal but some are more equal than others)

IR suppressed

IR enhanced

are confined

("constituent gluon" of large effective mass)

lead to confinement
Onset of confinement

\[
\begin{align*}
\text{QED} & \quad - \frac{1}{\nabla^2} \rightarrow - \frac{1}{\nabla D} \nabla^2 \frac{1}{\nabla^2} \quad \text{QCD}
\end{align*}
\]

\[
\frac{4\pi\alpha}{k^2}
\]

\[
\beta = 12 - 1 - \frac{2}{3}n_f
\]

\[
\alpha \rightarrow \alpha(k^2) = \frac{\alpha(\Lambda)}{1 - \frac{\alpha(\Lambda)\beta}{4\pi} \log \left(\frac{\Lambda}{k}\right)^2}
\]

If \( \omega(k) \neq k \) then

\[
\log \left(\frac{\Lambda}{k}\right)^2 \rightarrow \log \frac{\Lambda^2}{k^2 + m_g^2}
\]

\[
\alpha(\Lambda) \rightarrow \frac{4\pi}{\beta \log \frac{\Lambda^2}{m_g^2}} \quad \alpha(k) \sim \frac{4\pi}{\beta k^2}
\]

equal-time gluon propagator
\[ \omega_p \equiv \sqrt{p^2 + M^2(p)}. \]

\[ M^2(k) = \begin{cases} m^4/k^2 & \text{Gribov propagator} \\ m^2 & \text{massive propagator} \end{cases} \]

equal-time gluon propagator

\[ V(k) = -\frac{64}{3}e^{21/22} \frac{\Lambda_{\overline{MS}}}{|k|^3}. \]

\[ V(k) = -\frac{48\pi^2m^2}{k^4 \left( \frac{41}{20} \log \frac{m^2}{k^2} - \frac{\log 2}{4} + \frac{219}{25} \right)} \]

FIG. 2. Potential \( V(R) \) vs. \( R \), obtained from a Fourier transform to position space of the numerical solution for \( V(k) \). The result includes the self-energy, which is both ultraviolet and infrared divergent. The infrared divergence is cancelled, for a color singlet, by a corresponding term in the interaction, as explained in the text. To regulate the ultraviolet divergence we have made an arbitrary subtraction such that \( V(R) \) passes through zero at \( R = 1 \). \( V(R) \) is in units of \( m \), \( R \) in units of \( 1/m \).
string-less state \[ |Q\bar{Q}, R\rangle = Q(\bar{R}/2)\bar{Q}(\bar{R}/2)|\psi_0[A]\rangle \]
is not a QCD eigenstate

\begin{align*}
\sigma_0 R \\
\sigma_{Q\bar{Q}} R
\end{align*}

QCD: No-confinement without Coulomb confinement (Zwanziger)

Greensite, Olejnik (2009)
From stringless state to flux tubes

in 1-gluon (variational) approximation

Greensite, AS (2015)
new multiplets from lattice

large overlap with gluonic operators includes $1^{-+}$ exotic

quark model states

NEW states

lowest-mass hybrid multiplet

isovector meson spectrum with $m_{\pi} \sim 700$ MeV

same pattern in $\bar{s}s$, $\bar{c}c$

hybrid interpretation of the $Y(4260)$

Dudek, et al.
The image contains a diagram with the lowest-mass hybrid multiplet, where 0^+, 1^-, 2^+, 1^- are highlighted.

The physical gauge QCD (Hamiltonian) is shown with diagrams representing:
- $J^{P/\ell} = 1^{++}$
- $P_{q\bar{q}} = (-1)^{L+1}$
- $C_{q\bar{q}} = (-1)^{L+S}$
- $J^{P/C}_g = 1^{+-}$

The Hamiltonian includes:
- Two-body potential
- One-body (kinetic + self-energy)
- Three-body potential

Reference:
- Guo, Galata, Santopinto, AS (2008)
one, two, ... ∞ gluons
solitons and bags
confinement, dynamical χ-sym. breaking
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strangeness in proton

φ-production
Phi production as a measure of the strangeness content of the nucleon

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![Diagram of particle interactions](image)

![Graph of differential cross section](image)
LHCb Pentaquark(s)

\[ \Lambda_b \rightarrow K^- p J/\psi \]

Aaij, et al., LHCb (2015)

Nucleon bound meson atoms?

Possible signal at Jlab12?

\[ \gamma p \rightarrow \phi p \]


\[ \gamma p \rightarrow J/\psi p \]

A. Blin et al. JPAC (in preparation)
Long time ago hadrons were from valence quarks 

Z(4020)
...we need to know how to interpret “peaks”

\[ \Lambda_b \rightarrow K^- pJ/\psi \]

a resonance in \( pJ/\psi \) ?

... or a \( \bar{K} p \) reflection ?
If the width of particle $X$ is not very large we will stay close to the physical region. This almost singular behavior of $A(s)$ for certain physical $s$ causes the peaking effect to which we refer as an $(X, Y, Z)$ peak.

"Peierls mechanism"
COCKTAILS

Whisky sour
(whisky, zucchero, limone)

Manhattan
(whisky, martini rosso, angostura)

Old fashioned
(american whisky, angostura, soda)

Rusty nail
(whisky, drambuie)

Stinger
(cognac, crema di menta bianca)

Sidecar
(cognac, cointreau, limone)

Daiquiri
(rhum, limone, zucchero)

Banana daiquiri
(rhum Bacardi, banana frullata, limone)

Palm beach
(rhum, gin, ananas)

Shanghai
(rhum Bacardi, pompelmo, granatina)

Mojito
(rhum, zucchero, limone, menta fresca)

X.Y.Z.
(rhum, arancia, cointreau)

Margherita
(tequila, limone, cointreau)

Mexico 76

“dynamics”
S-matrix principles: Crossing, Analyticity, Unitarity

\[ A(s, t) = \sum_l A_l(s) P_l(z_s) \]

**Analyticity**

\[ A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon) \]

bumps/peaks on the real axis (experiment) come from singularities in physical sheets: cuts and unphysical sheets: poles

poles come from QCD
Origin of singularities (exchanges constrained by unitarity)

\[ A(s,t) \]

\[ \Lambda_b \rightarrow K^- p J/\psi \]

\[ Y(4260) \rightarrow \pi^+ \pi^- J/\psi \]

\[ s = s_p \text{ (pole)} \]

\[ \text{physical region} \]
Origin of singularities (exchanges constrained by unitarity)

$$A(s,t)$$

$$\Lambda_b \rightarrow K^- p J/\psi$$

$$Y(4260) \rightarrow \pi^+ \pi^- J/\psi$$

$$\beta$$

$$S_p - S$$

$$s = s_p$$ (pole)

$$s = s_b$$ (branch point)

Physical region
Origin of singularities (exchanges constrained by unitarity)

$$A(s,t)$$

$$\Lambda_b \rightarrow K^- \rho J/\psi$$

$$Y(4260) \rightarrow \pi^+ \pi^- J/\psi$$

(after s-channel projection + fsi)

$$s = s_p$$ (branch point)

$$s = s_b$$ (pole)

physical region
with resonance

\[ Y(4260) \rightarrow D\bar{D}^* \pi \]

without resonance

\[ Y(4260) \rightarrow \pi\pi J/\psi \]
The key to the XYZ phenomena are the many nearby channels.

Coleman-Norton requires

\[ M_{\Lambda_b^0} = 5.6195, \mu_{K^*} = 0.4937, \ m_1 = m_{\chi_{c1}} = 3.510, \ m_2 = m_p = 0.93827 \]
\[ \lambda = m_{\Lambda^*} = 1.89 \text{ (they take)} \]

\[ 1.89 < \lambda < 2.11 \text{ GeV} \]
\[ 4.45 < \sqrt{s_{\text{peak}}} < 4.65 \text{ GeV} \]
Joint Physics Analysis Center

Amplitude analysis: based on S-matrix principles

Events, X-sections, MC

QCD Predictions
JPAC : Example of Analysis Projects

Light meson decays and light quark resonance

\[ \omega/\phi \rightarrow 3\pi, \pi\gamma \text{ (dispersive)} \]
\[ \omega \rightarrow 3\pi \text{ (Veneziano, B4)} \]
\[ \eta \rightarrow 3\pi, \eta'/f1 \rightarrow \eta\pi\pi, \text{ (Khuri-Treiman, B4)} \]
\[ J/\Psi \rightarrow \gamma\pi 0\pi 0 \]

Photo-production: (production models, FESR and duality)

\[ \gamma p \rightarrow \pi 0 p \]
\[ \gamma p \rightarrow pK+K- \text{ (and Kp)} \]
\[ \gamma p \rightarrow \pi+\pi- p, \pi 0\eta p, \omega p \]

Exotica and XYZ’s:

\[ \pi^- p \rightarrow \pi^- \eta p \& \pi^- p \rightarrow \pi^- \eta' p \text{ (FESR)} \]
\[ B^0 \rightarrow \Psi' \pi^- K^+ u, \Psi(4260) \rightarrow J/\Psi \pi+\pi-, \Lambda_b \rightarrow K^- pJ/\Psi \]
\[ J/\Psi \rightarrow 3\pi, KK\pi \text{ (Veneziano, B4)} \]

Launched in the Fall of 2013

>20 analysis/papers published
\[ \gamma p \rightarrow \pi^0 p \]

We present the model published in [Mat15a].

The differential cross section for \( \gamma p \rightarrow \pi^0 p \) is computed with Regge amplitudes in the domain \( E_\gamma \geq 4 \text{ GeV} \) and \( 0.01 \leq |t| \leq 3 \text{ (in GeV)} \).

The formulas can be extrapolated outside these intervals.

We use the CGLN invariant amplitudes \( A_i \) defined in [Chew57a].

See the section Formalism for the definition of the variables.

The fitting procedure is detailed in [Mat15a]. We report here only the main feature of the model.

**Formalism**

The differential cross section is a function of 2 variables. The first is the beam energy in the laboratory frame \( E_\gamma \) (in GeV) or the total energy squared \( s \) (in GeV^2). The second is the cosine of the scattering angle in the rest frame \( \cos \theta \) or the momentum transferred squared \( t \) (in GeV^2).

The momenta of the particles are \( k \) (photon), \( q \) (pion), \( p_2 \) (target) and \( p_4 \) ( recoil). The pion mass is \( m_\pi \) and the proton mass is \( M \). The Mandelstam variables, \( s = (k + p_2)^2 \), \( t = (k - q)^2 \), \( u = (k - p_4)^2 \) are related through \( s + t + u = 2M^2 + m_\pi^2 \).

The differential cross section is expressed in terms of the parity conserving helicity invariant amplitudes in the \( t \) - channel \( F_t \):

\[ d \sigma \frac{dt}{dt} = \frac{38.94}{64\pi} \frac{k_t^2}{4M^2E_\gamma^2} \left[ 2 \sin^2 \theta_i \left( t|F|^2 + 4q_t|F|^2 \right) \right] (1 - \cos^2 \theta)

The differential cross section is expressed in \( \mu b/\text{GeV}^2 \). We used \( \langle hc \rangle \) to express the cross sections.

The \( t \) - channel is the rest frame of the process \( \gamma p^0 \rightarrow p\bar{p} \).

In the \( t \) - channel, the momenta of the nucleon \( p_2 \) and the pion \( p_4 \) and the photon \( k_t = \frac{1}{2}\sqrt{t - 4M^2} \) and the pion \( q_t = \frac{1}{2}\sqrt{u} \).

The invariant amplitudes \( F_t \) are related through the CGLN \( A_i \) amplitudes:

\[ F_t = -A_1 + 2M A_4, \quad F_2 = A_1 + tA_2, \quad F_3 = 2MA_1 - tA_4, \quad F_4 = A_3 \]

The \( F_t \) amplitudes have good quantum numbers of the \( t \) - channel. The naturality \( n = P(-1)^t \) and the product \( CP \).

Download the output file, plot with Ox-ct. the plot with Ox-\( t \)-cos.

In the file, the columns are: \( t \) (GeV^2), \( D/\text{Diag} \) (micro barn/GeV^2), \( D/\text{Diag} \) (micro barn)
Joint Physics Analysis Center (JPAC)

Develop theoretical, phenomenological/computational tools for hadron experiments

Experiment-theory collaboration

GLOBAL EFFORT
JPAC, IU, GW, ...
Italy, Germany, Spain...
Thank you

and happy birthday Tony!