High–\(Q^2\) resonance production in QCD
C. Weiss (JLab), EmNN*2012 Workshop, U. South Carolina, 13–Aug–12

- Transition form factors at high \(Q^2\)
  Wave function description
  Selection of configurations
  Small–size vs. end–point configurations
  Dynamical origin: pQCD, non–perturbative interactions

- Lessons from elastic form factors
  Pion FF: Model–independent analysis
  \(\text{LCWF} \leftrightarrow \text{large}–x \text{ PDFs. Miller, Strikman, CW 11}\)
  Nucleon FF: Light–cone sum rules \(\rightarrow\) Talk Braun

- Toward \(N^*\) transition FFs in QCD
  \(\pi N\) near threshold: Chiral LETs
  \(N^*\) DAs from large–\(N_c\) limit (\(\Delta\))
  Dynamical resonances from \(\chi\)EFT (\(S_{11}\))
  Lattice QCD (\(N^*1535\))

Correct high–\(Q^2\) asymptotics
QCD DOF, light–front formulation

Non–perturbative interactions
Chiral symmetry–breaking forces \(\rightarrow\) SDE

Clean interface quarks–hadrons
Wave functions, distribution amplitudes

Meson–baryon interactions parametrically controlled
Large–\(N_c\), \(\chi\)EFT
Wave function description

A) Infinite–momentum frame $P \to \infty$
- Gribov, Feynman; Bjorken, Kogut

B) Light–front quantization time $= x^+$
- WFs universal, frame–independent. Brodsky et al.

Momentum transfer transverse $t = -\Delta^2$
- Frame appropriate for $t \to \infty$, masses fixed

Hadron resolved in pointlike constituents with momentum fraction $x_i$, transv. position $r_i$

Quantum–mechanical superposition: Configs with different particle number, spatial size

Current operator sees transition density

$$F(t) = \int d^2b \ e^{i\Delta b} \ \rho(b) \quad \text{2D Fourier}$$

$$\rho(b) = \sum_{\text{configs}} \int dx \ \psi^*(x, r, ..) \psi(x, r, ..)$$

Selection of configurations

Large $|t| \leftrightarrow$ Small $b$  
- Singularity?

What kind of configurations contribute to density at small $b$?
Transition FF: Small–size configurations

- Two types of configurations contribute to small–$b$ density
  \[ x \sim \frac{1}{3} \quad \text{size} \ll R \quad \text{small–size} \]
  \[ x \rightarrow 1 \quad \text{size} \sim R \quad \text{end–point} \]

- Basic questions
  - What is their relative importance?
    Probability of end–point configurations constrained by quark PDF at $x \rightarrow 1$
  - How do they arise dynamically?
    Perturbative vs. non–perturbative interactions?
    Correlations in light–front wave function?

- Rest frame picture
  - Can be rigorously discussed in light–front quantization
    Intuition from non–relativistic systems:
    Angular momentum, orbital motion, etc.
Transition FF: Dynamical origin of small–size confs

- Perturbative interactions
  High–momentum component of wave function built up by pQCD interactions
  "Soft" wave function $k_T \sim R^{-1}$ as source
  $\Phi(x_i | \mu^2) = \int d^2 k_{Ti} \psi(x_i, k_{Ti})$ distribution amplitude
  Responsible for leading $|t| \to \infty$ asymptotics of pion FF Brodsky Lepage; Efremov, Radyushkin: pion

- Non–perturbative interactions
  Chiral symmetry breaking in QCD induced by short–range non–perturbative forces
  Range $\rho \sim 0.2 - 0.3$ fm $\ll R$
  Instanton vacuum model: Shuryak; Diakonov, Petrov
  Schwinger–Dyson equations $\rightarrow$ Talk Roberts
Pion form factor: Transition density

- Pion form factor $F_\pi(t)$
- Transition density $\rho(b)$

Calculated from dispersion integral over timelike FF from $e^+e^-$ data
Miller, Strikman, CW 11

Model–independent, controlled accuracy

High density at center $b \to 0$

Im$F_\pi(t)$ from analysis of $e^+e^-$ data. Bruch et al. 05
Pion form factor: Small–size configurations

- Is density in center due to small–size or end–point configurations?

- Model–independent assessment
  
  
  Miller, Strikman, CW 10

  End–point contribution constrained by quark density in pion at \( x \to 1 \)

  \( \pi A \) Drell–Yan data

  Density in center of pion mostly from small–size configurations!

- Dynamical explanation
  
  Small–size configurations in pion WF from chiral symmetry–breaking interactions
Nucleon FF: Configurations

- Transition densities known from FF data
- More complex system, more possibilities
  
  Uniform squeezing or diquark–like configurations?
  
  Contribution of end-point configurations $x \to 1$?
  Related to large--$x$ parton densities  JLab 12 GeV
  
  Mean–field picture generally successful:
  Quark model, chiral soliton $N_c \to \infty$
  Nature of dynamical correlations?

- Spin and orbital angular momentum
  
  $Q^2 F_2/F_1$ suggests important role
  of orbital angular momentum  Belitsky, Ji, Yuan 03

- Systematic approach: Light–cone sum rules
  
  Balitsky, Braun, Kolesnichenko 89; Braun et al. 02+
  
  pQCD–generated small–size configurations give leading asymptotic contribution
  
  End–point contributions reformulated as higher twist
  
  Can results be explained/reproduced in simple terms?
Nucleon FF: Key issues

• What is the relative importance of small–size and end–point configurations?
  Can be investigated in quasi–model independent manner!

• What is the role of non–perturbative short–distance interactions responsible for $\chi_{SB}$ in QCD
  Think of them as correlations between elementary QCD degrees of freedom
  Correlation length $\rho \sim 0.2 - 0.3 \text{ fm} \ll \text{hadronic size}$
  Express in language of light–front wave function
  Schweitzer, Strikman, CW 12: $q\bar{q}$ correlations
Toward $N^*$: Near-threshold $\pi N$

- Same picture applies to high-$Q^2$ production of $\pi N$ near threshold $W = M_N + M_\pi + \epsilon$

  $\Phi_{\pi N}(x_1 x_2 x_3; \zeta, W)$ distribution amplitude,

  $\zeta \leftrightarrow \cos \theta_{\text{CM}}$, partial wave expansion possible

- Soft-pion theorem for $\pi N$ DA

  $\langle \pi N | \psi \psi \psi | 0 \rangle \leftrightarrow \langle N | [Q_{\text{axial}}, \psi \psi \psi] | 0 \rangle$

  chiral rotation of QCD quark operator

- CLAS 6 GeV data $\rightarrow$ Talk K. Park

  LC sum rule calculations $\rightarrow$ Talk Braun
**Toward $N^*$: Resonances in QCD**

- **QCD description of high-$Q^2$ $N^*$ production**
  \[ \Phi_{N^*}(x_1 x_2 x_3) \text{ resonance distribution amplitude} \]
  How to define “resonance” in QCD?
  Need parametric control of hadronic FSI!
  Several possibilities

- **Large-$N_c$ limit of QCD**  
  Semiclassical limit. 'tHooft, Witten
  \[ N, \Delta \text{ degenerate, mass splitting } \sim 1/N_c \]
  \[ N, \Delta \text{ wave functions related: Rotational states} \]
  Meson–meson interactions suppressed, meson–baryon interactions strong:
  \[ g_{MM} \sim 1/\sqrt{N_c} \ll g_{MBB} \sim \sqrt{N_c} \]
  Guidance for phenomenology of $MB$ and $MM$ interactions
  Should be explored further!
Toward $N^*$: Dynamical generation of resonances

- Can one generate resonances dynamically through hadronic FSI? ... at least some?

- Chiral effective field theory
  Unitarized $\chi$EFT interactions, Bethe–Salpeter equation
  Constrained by chiral low–energy theorems
  Reasonable results for $S_{11}(1535,1650)$
  
  Could it be extended to $\pi N$ DAs with near–threshold DAs as input?
  $\chi$EFT guarantees universality, controlled accuracy

- Alt: Empirical phase shifts
  $\rho, \rho'$ DAs from $\pi\pi$ near threshold
  M. Polyakov, NPB555 (1999) 231; applied at HERA
Toward $N^*$: DAs from Lattice QCD

- $N^*$ distribution amplitudes from lattice
  → Talk Braun

$N^*(1535)$ parity–partner of $N$, by–product of nucleon calculation

First non–trivial moment determines distribution of bulk strength

- Transition FFs from light–cone sum rules

Power corrections estimated using asymptotic DAs

Promising “hybrid” approach

Higher moments and "shape" of DA from Lattice?
Higher–twist DAs for power corrections?

V. Braun et al., PRL 103 (2009) 072001.
**Toward $N^*$: Key issues**

- Explore regions where hadronic FSI is parametrically controlled
  
  Large–$N_c$ limit of QCD
  
  Chiral near–threshold region → dynamically generated resonances

- Assess ratio non–resonant/resonant production in QCD
  
  Information from quark–hadron duality