Exploring the soft-hard transition in forward and backward meson production

C. Weiss (JLab), Backward Angle u-Channel Physics Workshop, 21-Sep-2020

- High-energy meson production
  - Forward and backward regions
  - Exchange mechanisms
  - Soft-hard transition in $Q^2$

- Forward production
  - Soft: Pomeron/Reggeon exchange
  - Hard: Small-size $gg/q\bar{q}$ exchange, pQCD, GPDs
  - Vacuum and non-vacuum channels

- Backward production
  - Soft: Baryon Regge exchange, status, questions
  - Hard: Small-size $qqq$ exchange, pQCD, TDAs
  - Measurements needed
High-energy meson production

\[ \text{Projectile} + N \rightarrow M + N' \]

Above resonance region \( s \gg s_{\text{res}} \sim \text{few GeV}^2 \)

Projectile: Meson, \( \gamma, \gamma^*(Q^2) \)

Forward and backward regions

Forward: \( |t| \lesssim 1 \text{ GeV}^2, \mid u \mid \sim s \)

Backward: \( |u| \lesssim 1 \text{ GeV}^2, \mid t \mid \sim s \)

Exchange mechanisms

Formal: \( s \rightarrow \infty \) asymptotics governed by singularities in \( t, u \)

Dynamical: Hadrons, QCD DoF

Characteristics: Quantum numbers, \( Q^2 \) dependence in electroproduction
Forward production: Soft and hard regime

- **Soft**: Photo/electroproduction at $Q^2 \lesssim R_{\text{had}}^{-2} \approx M_\rho^2$
  
  Transverse range of interaction $\sim$ hadronic size $R_{\text{had}}$

  Exchange: Regge trajectories

  Vacuum quantum numbers: Pomeron, Reggeons
  Non-vacuum: Reggeons

  Features: $s \leftrightarrow t$ dependence, universality of trajectories

- **Hard**: Electroproduction at $Q^2 \gg R_{\text{had}}^{-2}$ or heavy meson
  
  Transverse range of interaction $\ll R_{\text{had}}$

  QCD factorization for $\gamma^*_{L}$, for $\gamma^*_T$ with modifications
  Collins, Frankfurt, Strikman 96

  Exchange: $gg, q\bar{q}$ with transverse size $\ll R_{\text{had}}$

  Coupling to nucleon: GPD

  Features: $Q^2$ scaling; $s$ and $t$ dep changing with $Q^2$ (evolution), universality of GPDs
Forward production: Soft-hard transition

• Study transition from soft to hard regime as function of $Q^2$

  Focus on model-independent features of each regime:
  $s$-dependence; interplay of $s$ and $t$ dependences; universality

• Interest

  QCD factorization is asymptotic approximation: Need to quantify region of applicability, magnitude of sub-asymptotic corrections. *Essential for processes in JLab12 kinematics.*

  Soft dynamics can guide modeling of GPDs: “Initial condition” of $Q^2$ evolution

  Soft dynamics as object of study: “Emergence” of Regge dynamics from QCD

  New possibility provided by electroproduction: Progress beyond study of photo- and hadroproduction, complementarity

• Strategy

  Review results in forward vacuum exchange processes  
  *HERA*

  Consider extension to forward non-vacuum exchange and backward processes  
  *JLab12, EIC*
Forward production: Vacuum exchange

- Vacuum exchange channels measured at HERA

\[ M = \rho^0, \phi, J/\psi, \Upsilon, \gamma \]
\[ W = 30–200 (300) \text{ GeV}, \quad Q^2 = 0–30 \text{ GeV}^2 \]

- Soft regime: Pomeron exchange

Well established, numerous tests

\[ \rho^0, \phi \text{ at } Q^2 = 0 \]

- Hard regime: GPD-based description

Gluon GPD, QCD evolution, effective scale, finite \( q\bar{q} \) size
Successful phenomenology, quantitative predictions

Frankfurt, Strikman, Koepf 96; Goloskokov, Kroll 08; Anikin, Ivanov, Pire, Szymanowski, Wallon 10. See also: Belitsky Müller 01; Ivanov, Szymanowski, Krasniov 04

\[ \rho^0, \phi \text{ for } Q^2 \gtrsim 10 \text{ GeV}^2; \quad J/\psi, \Upsilon \text{ any } Q^2 \]

- Soft-hard transition: Extensive studies
Forward production: $W$ dependence

- $W$ dependence of exclusive cross sections
  
  Fit $\sigma \propto W^\delta$, $\delta = \delta(Q^2)$

- Soft expectation
  
  $d\sigma/dt \propto (W^2)^{2\alpha_P(t) - 2}$

  $\alpha_P(t) = \alpha_P + t\alpha'_P$  
  Pomeran trajectory

  $\alpha_P = 1.08, \delta \approx 0.2$  
  finite average $t$

- Hard expectation
  
  QCD evolution: $x$-dependence of gluon GPD becomes steeper at higher $Q^2 \rightarrow \delta$ increases

- Observations
  
  $\delta(Q^2)$ rises from soft value

  Universality of vacuum exchange channels

Forward production: $W$ dependence

- $W$ dependence of exclusive photoproduction cross sections
  
  Light: $\rho^0, \phi$  
  expect soft

  Heavy: $J/\psi, \Upsilon$  
  expect hard

- Observations
  
  $\rho^0, \phi$: $W$ dependence agrees with soft expectation, same between $\rho^0$ and $\phi$

  $J/\psi, \Upsilon$: $W$ dependence steeper, $\Upsilon$ steeper than $J/\psi$, consistent with hard expectation

Figure: A. Levy, arXiv:0711.0737
Forward production: $t$ dependence

- $t$-dependence of exclusive meson production
  \[ \frac{d\sigma}{dt} \propto e^{Bt}, \quad B = B(Q^2) \]

- Observations
  
  $B$ decreases from $Q^2 = 0$ to $\sim 10$ GeV$^2$:
  Decrease of transverse range of interaction, soft $\rightarrow$ hard transition

  $B$ stable above $Q^2 \sim 10$ GeV$^2$:
  Hard regime, $t$-dependence from gluon GPD

  Universality of channels: Gluon GPD

- Further: Combined $W$ and $t$ dependence

  Effective Pomeron trajectory for fixed $Q^2$

  Effective $\alpha_P$ and $\alpha'_P$ depend on $Q^2$

- **Soft**: Regge phenomenology

  Basic features of amplitudes explained by well-known Regge pole exchanges ↔ meson spectrum
  Reviews Irving, Worden 77; Storrow 87

  Open questions: Absorption vs. NWSZ zeros, cuts

  Finite-energy sum rules: Resonances ↔ Regge exchanges
  Photoproduction: JPAC Nys et al 16+

- **Hard regime**: QCD factorization

  Nonsinglet quark GPDs: $q - \bar{q}$, $u - d$, helicity/transversity

  Pseudoscalars $\pi^0, \eta$: Chiral-odd GPDs/DAs, $\sigma_T$ dominant
  Goldstein Liuti et al 08, Goloskokov, Kroll 11

  Vectors $\rho, K^*$: Which structures work?

- **Soft-hard transition largely unexplored**

  $\alpha'_R \approx 0.8 \text{ GeV}^2$ – what happens at finite $Q^2$?
  Must be encoded in $x$-$t$ correlation in GPDs
  Form factors: Guidal, Polyakov, Radyushkin, Vanderhaeghen 05

  *Should be major focus of studies at JLab12 and EIC!*
Backward production: Soft and hard regimes

- **Soft:** Baryon Regge exchange

  Baryon spectrum well known $\rightarrow$ trajectories

  Symmetry constraints: Trajectories as parity doublets $\alpha_B^\pm(\sqrt{u})$

  Reggeization effects not well studied experimentally:
  $s$-dependence $\rightarrow \alpha_B$, combined $s-u$ dependence $\rightarrow \alpha'_B$

  Theoretical interest: LQCD spectroscopy, large-$N_c$ limit

- **Hard:** QCD mechanism with TDAs

  Similar as pQCD mechanism in baryon form factors – applicable?

  Large uncertainties from DAs/TDAs, QCD coupling

  $Q^2$ for $qqq$ pQCD mechanism expected much larger than for $q\bar{q}$

  Frankfurt, Polyakov, Pobyliitsa, Strikman 99; Pire, Semenov-Tian-Shansky, Szymanowski 10

  $\rightarrow$ Talk Semenov-Tian-Shansky

- **Soft-hard transition:** Unexplored
• Basic measurements of backward production in soft regime $Q^2 \sim \text{few GeV}^2$ would be very instructive:

A) $W$ dependence of $d\sigma/dt$ near $u = 0$ (or $u_{\text{min}}$), or of $u$-integrated $\sigma$:

→ Is it Regge-like dependence?
→ Is the exponent consistent with $\alpha_B(0)$?

B) Combined $W$ and $u$ dependence of $d\sigma/dt$ in backward peak:

→ Does $u$-dependence change with $W$?
→ Can we infer $\alpha'_B$?

C) Comparison of different channels: $\pi \leftrightarrow \sigma, \pi \leftrightarrow \rho, \rho \leftrightarrow \omega$

→ Reggeon couplings, universality, chiral symmetry

• How do these properties change with $Q^2$

→ Soft-hard transition?

• Formulation of detailed program requires further work (model predictions) and depends on outcome of measurements in soft regime
• Soft-hard transition as function of $Q^2$ is an attractive perspective for analyzing electroproduction processes

• Status and prospects in different channels

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<td>understood, quantitative</td>
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<td>$t$-channel</td>
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<td>$u$-channel</td>
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• “$u$-channel physics” should not be discussed in isolation, but as part of larger investigation involving also other channels, esp. $t$-channel nonvacuum

• Soft dynamics is an “emergent phenomenon” of QCD: Fundamental interest, high-level narrative