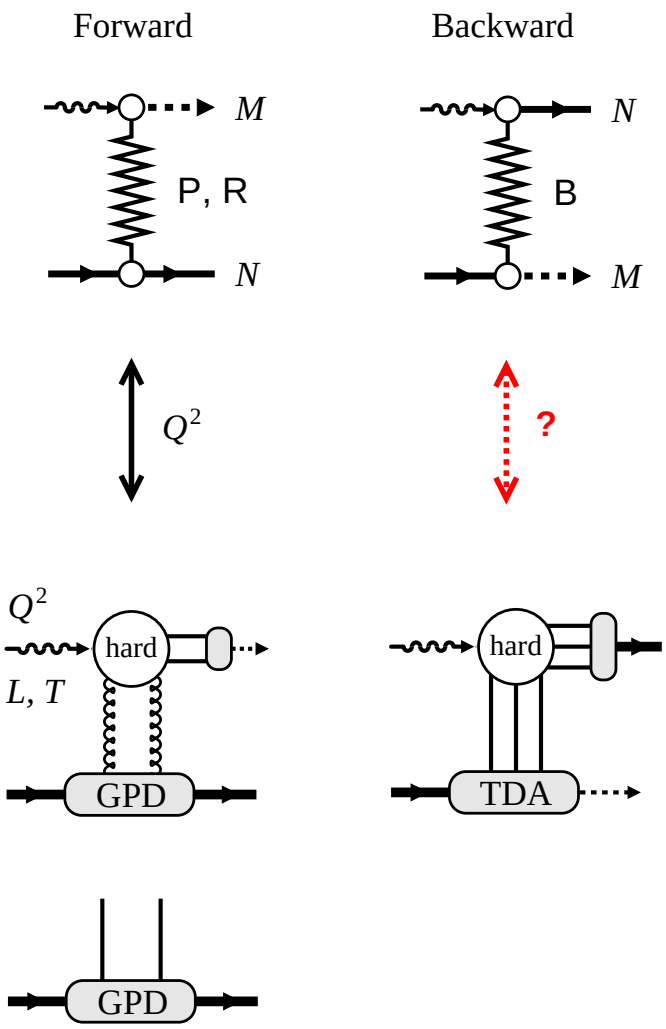
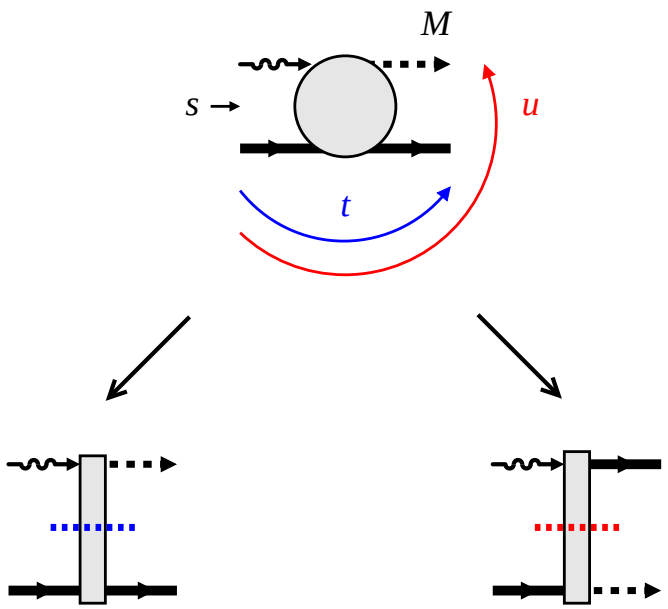
Exploring the soft-hard transition in forward and backward meson production

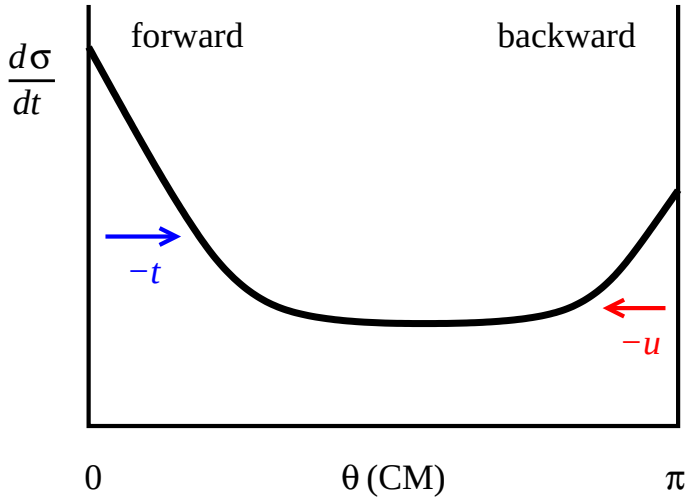
C. Weiss (JLab), Backward Angle u-Channel Physics Workshop, 21-Sep-2020



- 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

Meson production: Forward and backward regions 2





- High-energy meson production

  Projectile $+ N \to M + N'$

  Above resonance region $s \gg s_{\rm res} \sim$ few GeV^2

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

- Forward and backward regions

  Forward: $|t| \lesssim 1$ GeV^2, $\quad |u| \sim s$

  Backward: $|u| \lesssim 1$ GeV^2, $\quad |t| \sim s$

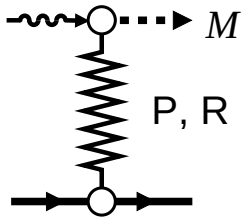
- Exchange mechanisms

  Formal: $s \to \infty$ 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



Pomeron
Reggeon

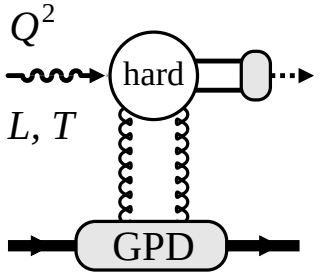
- Soft: Photo/electroproduction at $Q^2 \lesssim R_{\rm had}^{-2}$ $(\sim M_\rho^2)$

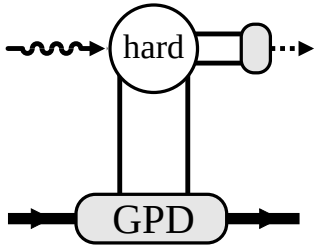
  Transverse range of interaction $\sim$ hadronic size $R_{\rm had}$

  Exchange: Regge trajectories

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

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





- Hard: Electroproduction at $Q^2 \gg R_{\rm had}^{-2}$ or heavy meson

  Transverse range of interaction $\ll R_{\rm had}$

  QCD factorization for γ_L^*; for γ_T^* with modifications
  Collins, Frankfurt, Strikman 96

  Exchange: $gg, q\bar{q}$ with tranverse size $\ll R_{\rm had}$

  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

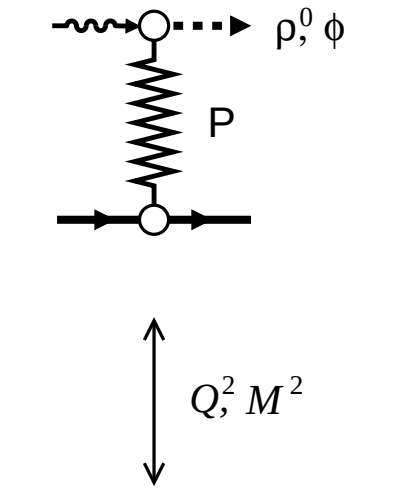
  New possibility provided by electroproduction: Progress beyond study of photo- and hadroproduction, complementarity

- 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) GeV, Q^2 = 0–30 GeV^2

- Soft regime: Pomeron exchange

  Well established, numerous tests

  ρ^0, ϕ at $Q^2 = 0$

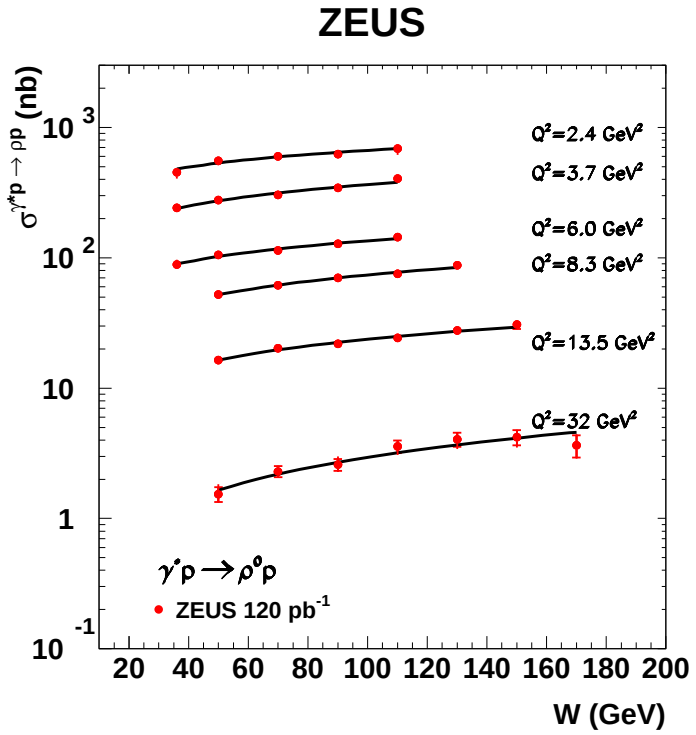
- Hard regime: GPD-based description

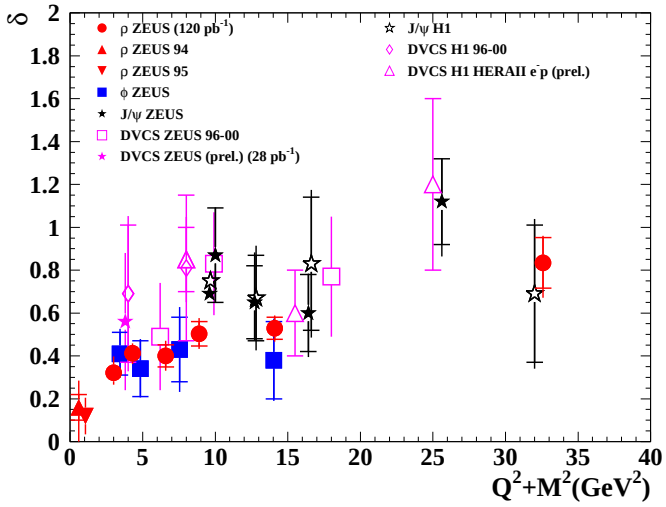
  Gluon GPD, QCD evolution, effective scale, finite $q\bar{q}$ size
  Successful phenomenology, quantitative predictions
  Frankfurt, Strikman, Koepf 96; Goloskokov, Kroll 08; Anikin, Ivanov, Pire, Szymanowski, Wallon 10. See also: Belitsky Müller 01; Ivanov, Szymanowski, Krasnkiov 04

  ρ^0, ϕ for $Q^2 \gtrsim$ 10 GeV^2; $J/\psi, \Upsilon$ any Q^2

- Soft-hard transition: Extensive studies

Forward production: W dependence





HERA data. Compilation by A. Levy, arXiv:0711.0737

- W dependence of exclusive cross sections

  Fit $\sigma \propto W^\delta,\ \delta = \delta(Q^2)$

- Soft expectation

  $d\sigma/dt \propto (W^2)^{2\alpha_{\rm P}(t)-2}$

  $\alpha_{\rm P}(t) = \alpha_{\rm P} + t\alpha'_{\rm P}$ Pomeron trajectory

  $\alpha_{\rm P} = 1.08,\ \delta \approx 0.2$ finite average t

- Hard expectation

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

- Observations

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

  Universality of vacuum exchange channels

Forward production: W dependence

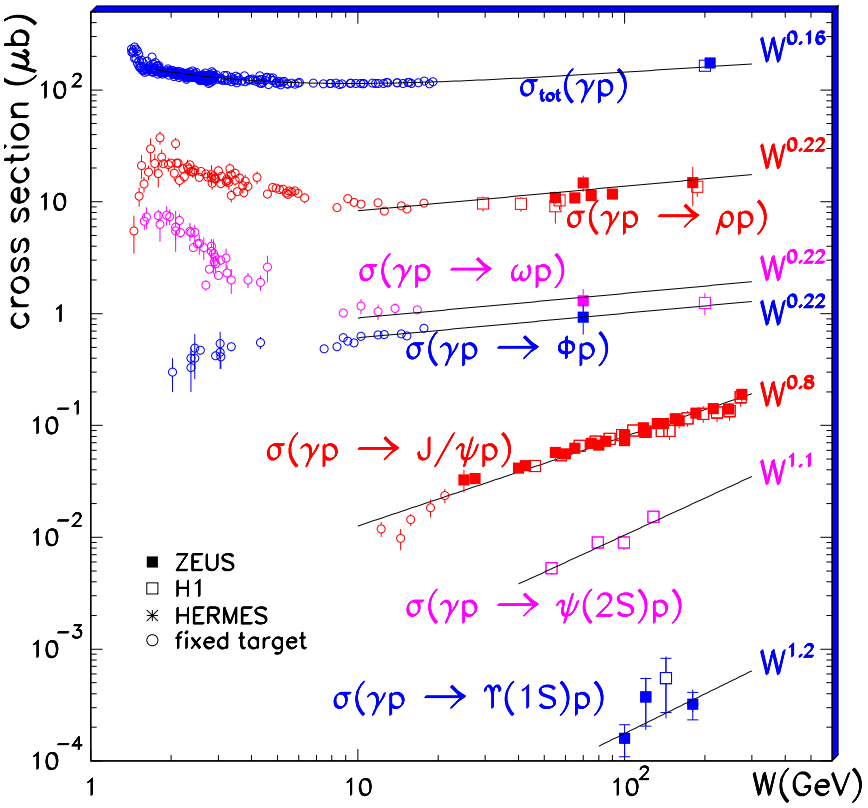


Figure: A. Levy, arXiv:0711.0737

- W dependence of exclusive photoproduction cross sections

  Light: ρ^0, ϕ expect soft

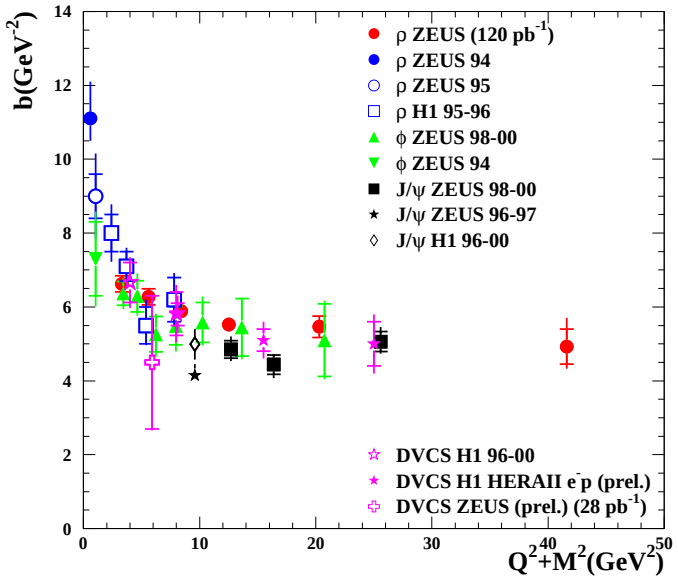
  Heavy: $J/\psi, \Upsilon$ expect hard

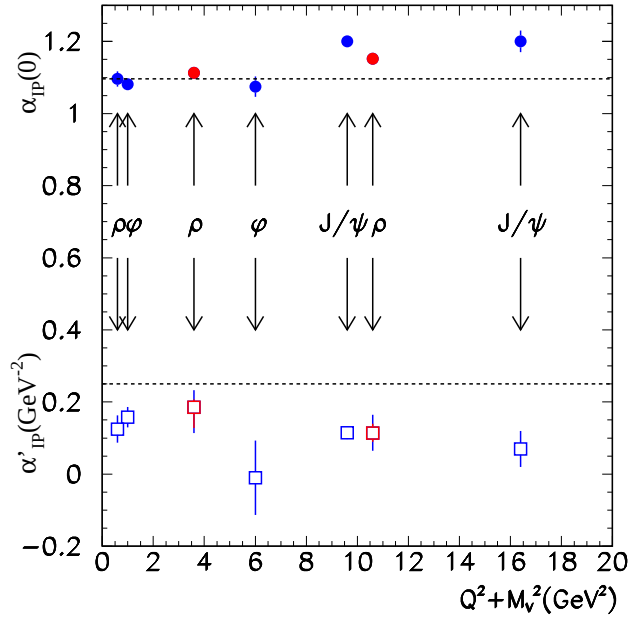
- Observations

  ρ^0, ϕ: W dependence agrees with soft expectation, same between ρ^0 and ϕ

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

Forward production: t dependence





Figures: A. Levy, arXiv:0711.0737

- t-dependence of exclusive meson production

  $d\sigma/dt \propto e^{Bt},\ B = B(Q^2)$

- Observations

  B decreases from $Q^2 = 0$ to ~ 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

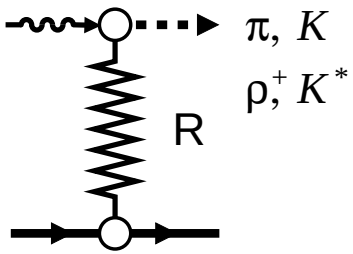
  Universality of channels: Gluon GPD

- Further: Combined W and t dependence

  Effective Pomeron trajectory for fixed Q^2

  Effective α_{P} and α'_{P} depend on Q^2

Forward production: Nonvacuum exchange

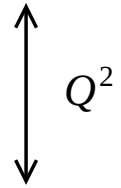


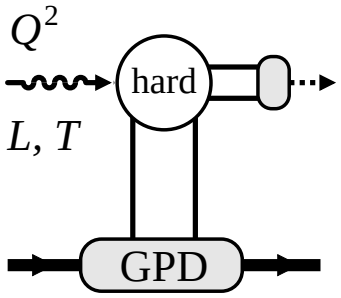
- Soft: Regge phenomenology

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

  Open questions: Absorption vs. NWSZ zeros, cuts

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





- Hard regime: QCD factorization

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

  Pseudoscalars π^0, η: Chiral-odd GPDs/DAs, σ_T dominant
  Goldstein Liuti et al 08, Goloskokov, Kroll 11

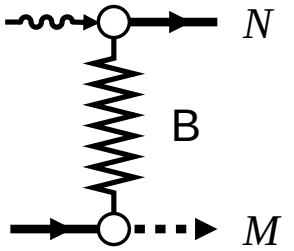
  Vectors ρ, K^*: Which structures work?

- Soft-hard transition largely unexplored

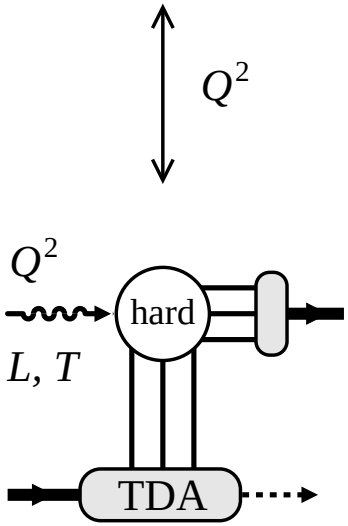
  $\alpha'_{\rm R} \approx 0.8$ GeV^2 – what happens at finite Q^2?
  Must be encoded in x-t correlation in GPDs
  Form factors: Guidal, Polyakov, Radyushkin, Vanderhaeghen 05

  Should be major focus of studies at JLab12 and EIC!

Backward production: Soft and hard regimes



Baryon exchange



- Soft: Baryon Regge exchange

  Baryon spectrum well known $\rightarrow$ trajectories

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

  Reggeization effects not well studied experimentally:
  s-dependence $\rightarrow \alpha_{\rm B}$, combined s–u dependence $\rightarrow \alpha'_{\rm B}$

  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, Pobylitsa, Strikman 99; Pire, Semenov-Tian-Shansky, Szymanowski 10
  $\rightarrow$ Talk Semenov-Tian-Shansky

- Soft-hard transition: Unexplored

Backward production: Measurements

- Basic measurements of backward production in soft regime $Q^2 \sim$ few GeV^2 would be very instructive:

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

  $\rightarrow$ Is it Regge-like dependence?

  $\rightarrow$ Is the exponent consistent with $\alpha_{\mathrm{B}}(0)$?

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

  $\rightarrow$ Does u-dependence change with W?

  $\rightarrow$ Can we infer α'_{B}?

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

  $\rightarrow$ Reggeon couplings, universality, chiral symmetry

- How do these properties change with Q^2

  $\rightarrow$ Soft-hard transition?

- Formulation of detailed program requires further work (model predictions) and depends on outcome of measurements in soft regime

Summary

- Soft-hard transition as function of Q^2 is an attractive perspective for analyzing electroproduction processes

- Status and prospects in different channels

t-channel vacuum exchange	soft: simple, well understood hard: understood, quantitative	transition studied HERA
t-channel nonvacuum exchange	soft: solid phenomenology hard: formalism, some successes, open questions	transition mostly unexplored JLab12, EIC
u-channel baryon exchange	soft: phenomenology, open questions hard: formalism, open questions	transition unexplored JLab12, EIC

- "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