Studying Color Transparency through Backward π^0 Electroproduction off a Nuclear Target

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Mandelstam variables (*s*,*t*,*u*–channels)

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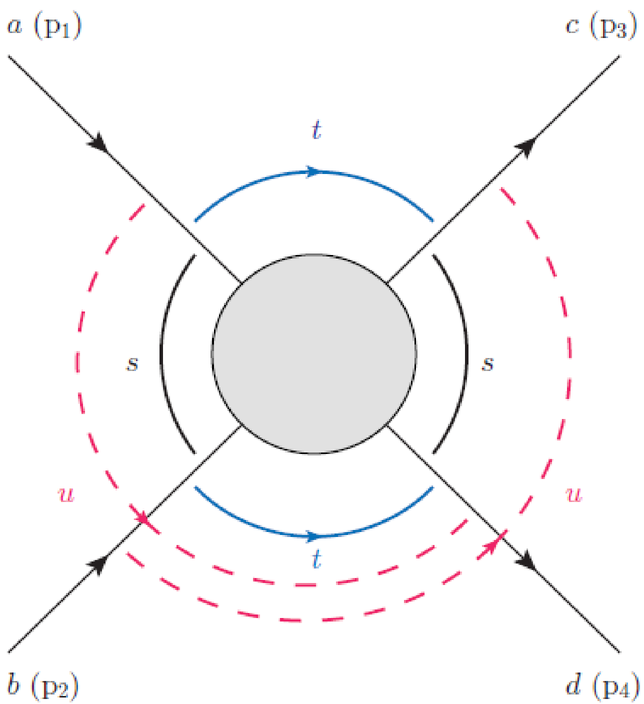


$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

s: invariant mass of the system

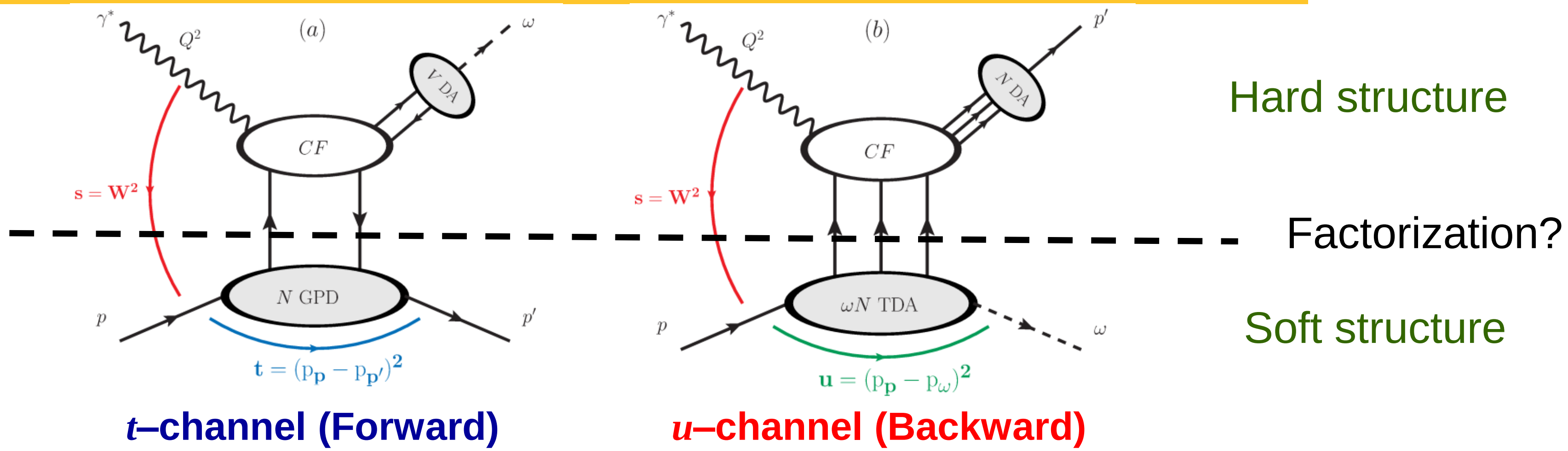
t: Four–momentum–transfer squared between **target before and after interaction**

u: Four–momentum–transfer squared between **virtual photon before interaction and target after interaction**

***t*-channel*: –t ~ 0*, after interaction**
- **Target: stationary**
- **Meson: forward**
- **Measure of how forward could the meson go.**

***u*-channel: *–u~0*, after interaction**
- **Target: forward**
- **Meson: stationary**
- **Measure of how backward could the meson go**

GPD–Like Model: TDA and Factorization



Baryon to Meson Transition Distribution Amplitude (TDA)

- Extension of collinear factorization to backward angle regime. Further generalization of the concept of GPDs.
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov *[arXiv:hep-ph/0211263]*
- TDAs describe the transition of nucleon to 3–quark state and final state meson *[gray oval of plot b]*
- A fundamental difference between GPDs and TDAs is that TDAs are defined as hadronic matrix elements of 3–quark operator, while GPDs involve quark–antiquark operator
- **Can be accessed experimentally in backward angle meson electroproduction reactions**

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Skewness in Backward Angle Regime

- **Forward angle kinematics,** $-t \sim -t_{min}$ and $-u \sim -u_{max}$, in the regime where handbag mechanism and GPD description may apply, Skewness is defined in usual manner:

$$\xi_t = \frac{p_1^+ - p_2^+}{p_1^+ + p_2^+} \quad \text{where } p_{1,2} \text{ refer to light cone + components}$$

$$\text{in } \gamma^*(q) + p(p_1) \rightarrow \omega(p_\pi) + p'(p_2)$$

- **Backward angle kinematics,** $-u \sim -u_{min}$ and $-t \sim -t_{max}$, Skewness is defined with respect to *u*–channel momentum transfer in TDA formalism

$$\xi_u = \frac{p_1^+ - p_\pi^+}{p_1^+ + p_\pi^+}$$

- GPDs depend on x, ξ_t and $t=(\Delta^t)^2=(p_2-p_1)^2$
  TDAs depend on x, ξ_u and $u=(\Delta^u)^2=(p_\pi-p_1)^2$

- Impact parameter space interpretation of TDAs is similar to GPDs, except one has to Fourier transform with respect to $\Delta^u{}_T \approx (p_\pi - p_1)_T$

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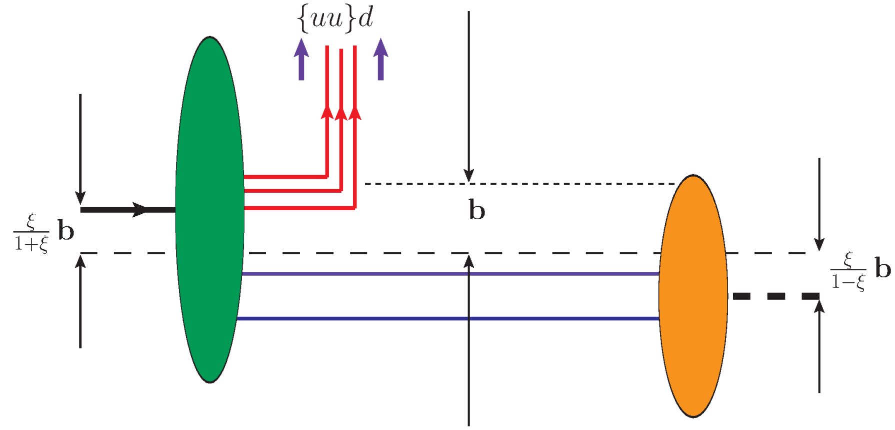
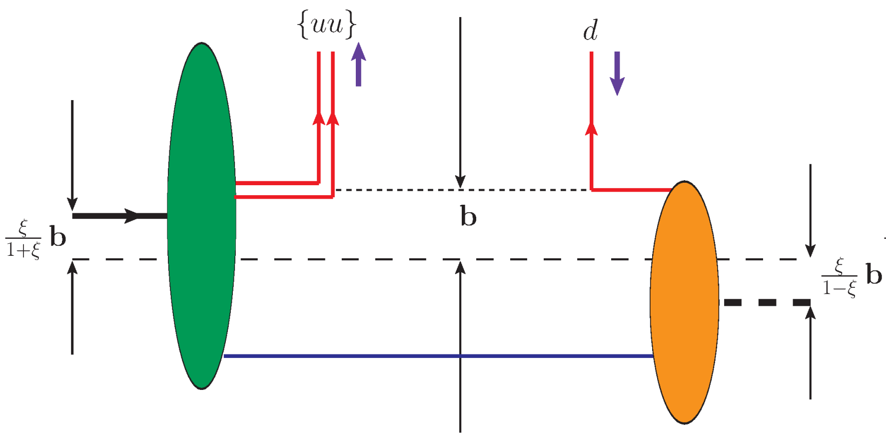
Impact parameter Interpretation of TDA

- After integrating over one momentum fraction x_i, the three exchanged quarks can be treated as an effective diquark+quark pair
- Impact picture then looks very much like that for GPDs



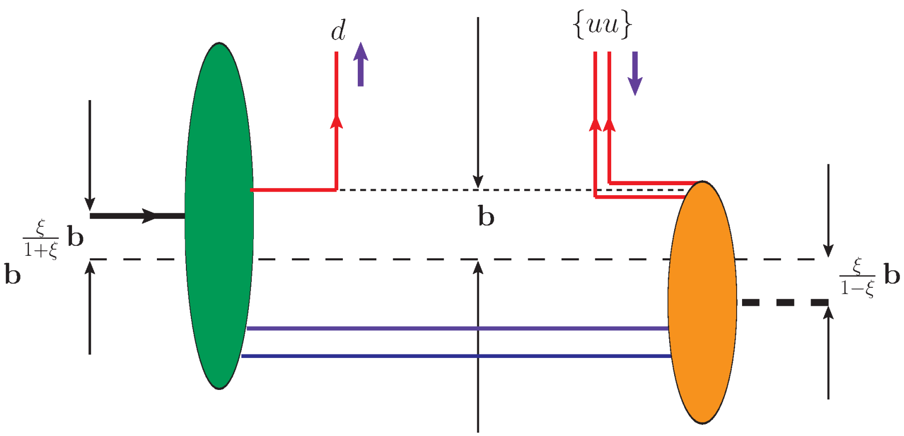
ERBL : $x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

$\longrightarrow$ All 3 quark momentum fractions x_i positive



DGLAP I : $x_3 = w_3 - \xi \leq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

$\longrightarrow$ One x_i negative



DGLAP II : $x_3 = w_3 - \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \leq 0;$

$\longrightarrow$ Two x_i negative

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Backward Angle Collinear Factorization

- **Kinematical regime for collinear factorization involving TDAs is similar to that involving GPDs:**
  - x_B fixed
  - $|u|$–momentum transfer small compared to Q^2 and s
  - Q^2 and s sufficiently large
- Early scaling for GPD physics occurs $2<Q^2<5$ GeV^2
  - Maybe something similar occurs for TDA physics…

Two Key Predictions in Factorization Regime:

- **Dominance of transverse polarization** of virtual photon, resulting in suppression of longitudinal cross section by at least $1/Q^2$: $\sigma_T \gg \sigma_L$
- Characteristic $1/Q^8$–scaling behavior of σ_T for fixed x_B

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p(e,e'p)ω Q^2–Dependence from Hall C

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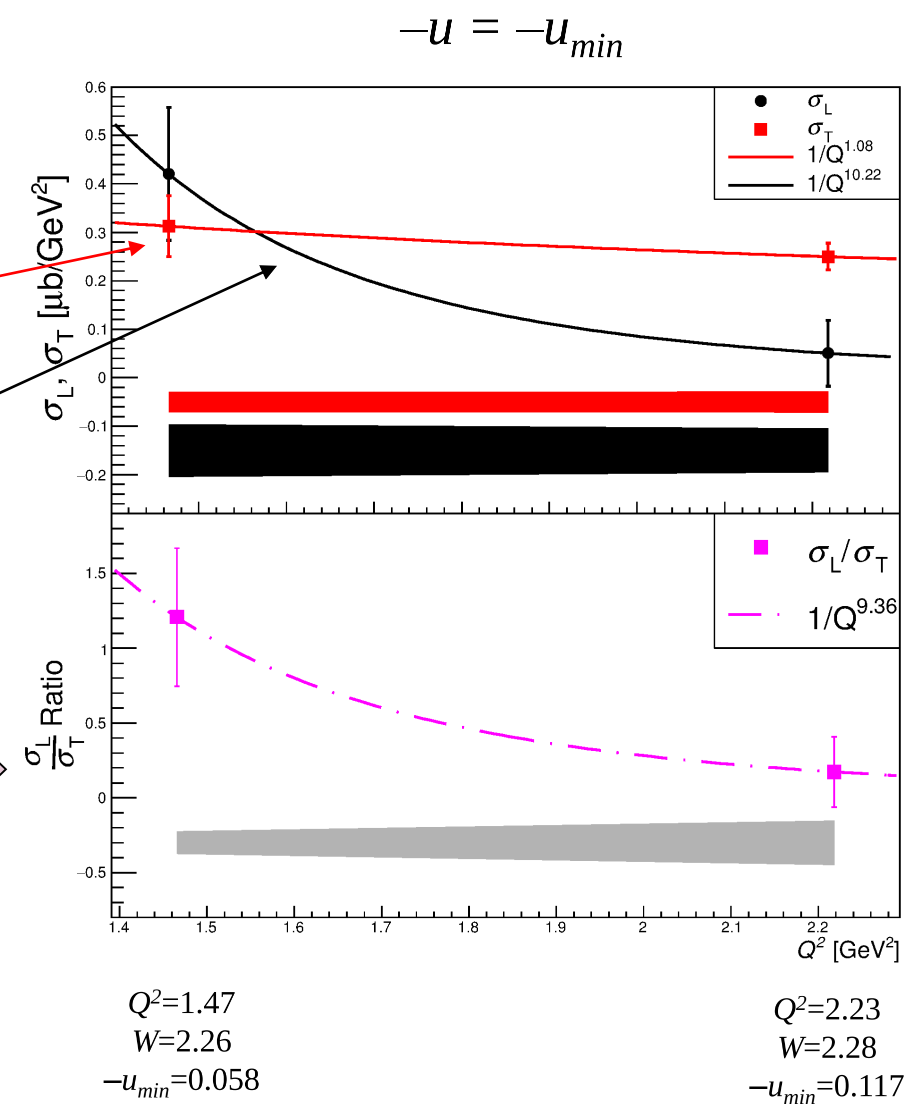
- To investigate Q^2–dependence, fit lowest $-u$ bin values of σ_T and σ_L to Q^{-n} function
  - σ_T appears to have a flat Q^2–dependence within measured range
  - σ_L shows much stronger decrease
- **Decreasing L/T ratio indicates the gradual dominance of σ_T as Q^2 increases.**
- Trend qualitatively consistent with prediction of TDA Collinear Factorization.



W. Li, et al. PRL **123** (2019) 182501

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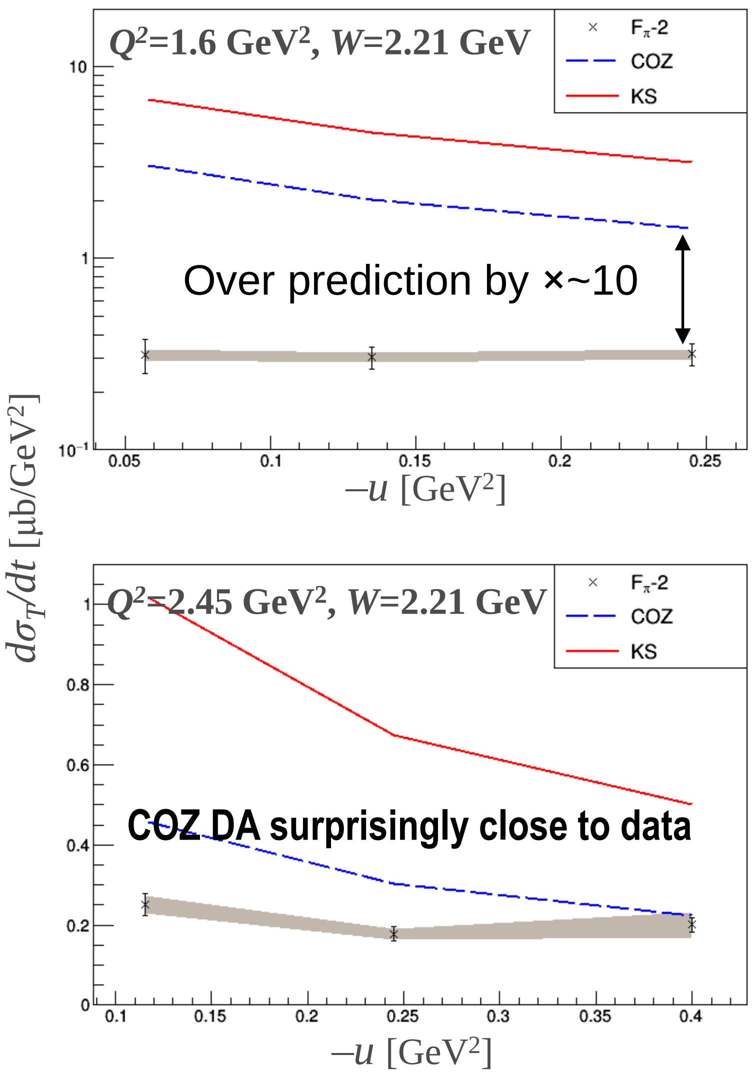
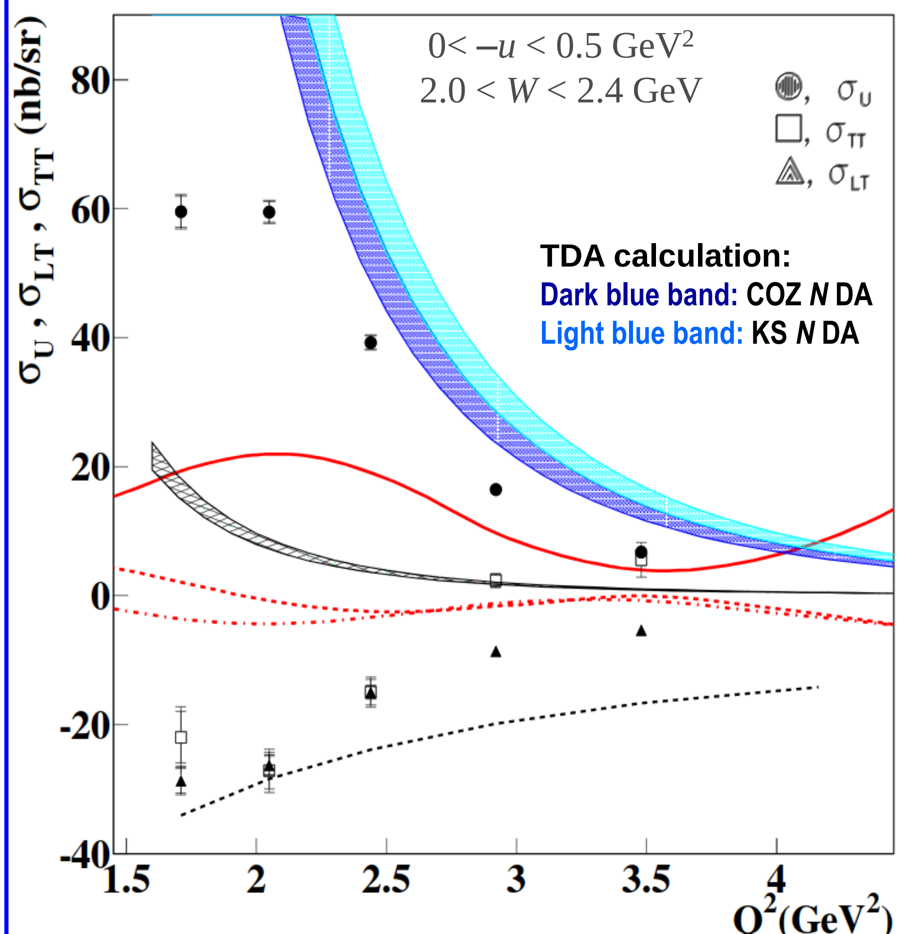
TDA model Comparison to Data



Hall C ω Electroproduction

W. Li, et al. PRL **123** (2019) 182501

Both data sets suggestive of early TDA scaling Q^2≈2.5 GeV^2 !?



Hall B π^+ Electroproduction

K. Park et al., PLB 7**80** (2017) 340

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Extension to Higher Q^2

- **The 6 GeV JLab Halls B,C data are qualitatively consistent with the predictions of the backward-angle factorization / TDA formalism, but they are at a too low Q^2 to be in quantitative agreement.**
  - CLAS–6 π^+ data, Hall C ω data
- **Studies of the applicability of TDA formalism are being extended in the 12 GeV era, by measuring general scaling trend of separated L/T cross sections for a variety of *u*–channel reactions**
  - 12 GeV data from Hall B
  - Hall C ρ, ω, φ data (E12-09-011)
  - Dedicated Hall C π^0 measurement (E12-20-007)

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Hall C 12 GeV data already acquired

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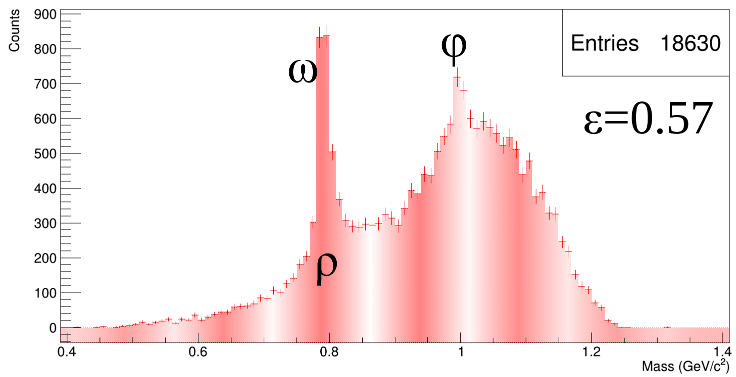
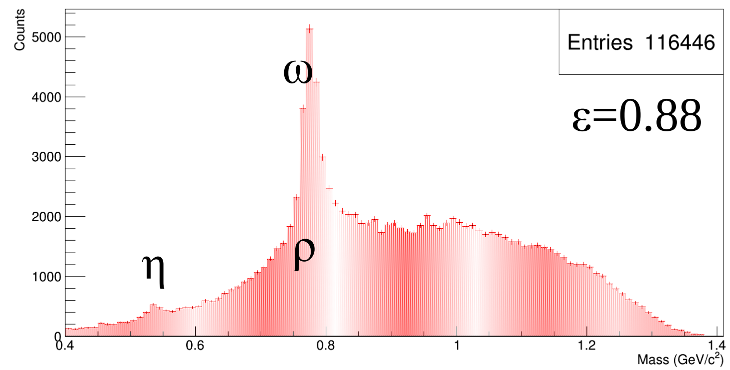
p(e,e'p)X Online Data Analysis

Q^2=3.00 W=2.32 θ_{pq}=+3.0° $-u$=0.15 ξ_u=0.15





Plots by Stephen Kay

K^+ L/T–experiment (E12–09–011)

Spokespersons: T. Horn, G.M. Huber, P. Markowitz

- Data acquired fall 2018–spring 2019
- Main purpose of experiment is to acquire *t*-channel L/T–separated *p(e,e'K⁺)Λ* data for reaction mechanism and *K*⁺ form factor studies
- Abundant *u*–channel *p(e,e'p)X* data acquired parasitically
  - Will allow backward angle studies for several meson states over a wide kinematic range

Setting	Low ε data	High ε data
Q^2=0.50 W=2.40	✓	✓
Q^2=2.1 W=2.95	✓	✓
Q^2=3.0 W=2.32	✓	✓
Q^2=3.0 W=3.14	✓	✓
Q^2=4.4 W=2.74	✓	✓
Q^2=5.5 W=3.02	✓	✓

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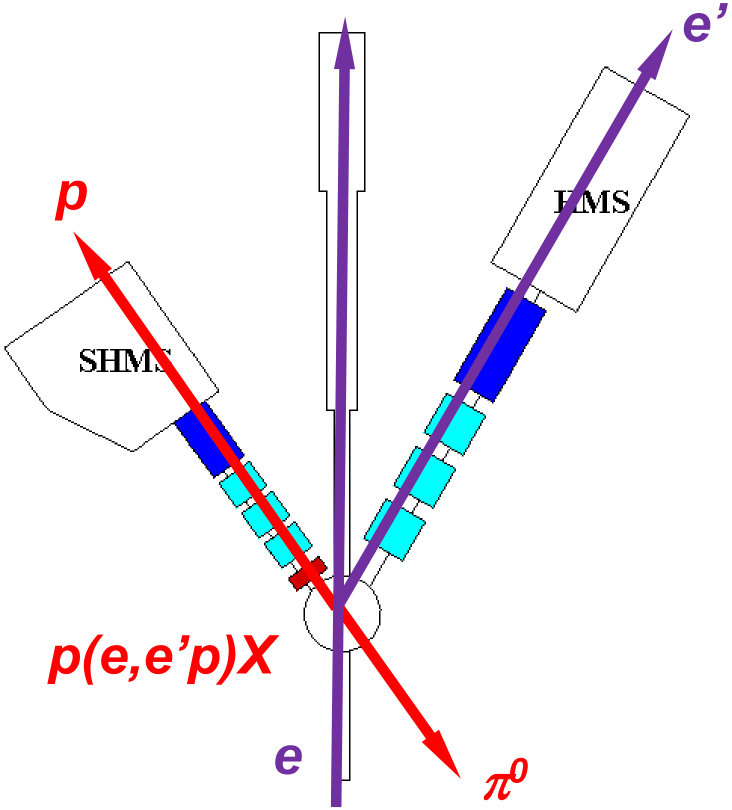
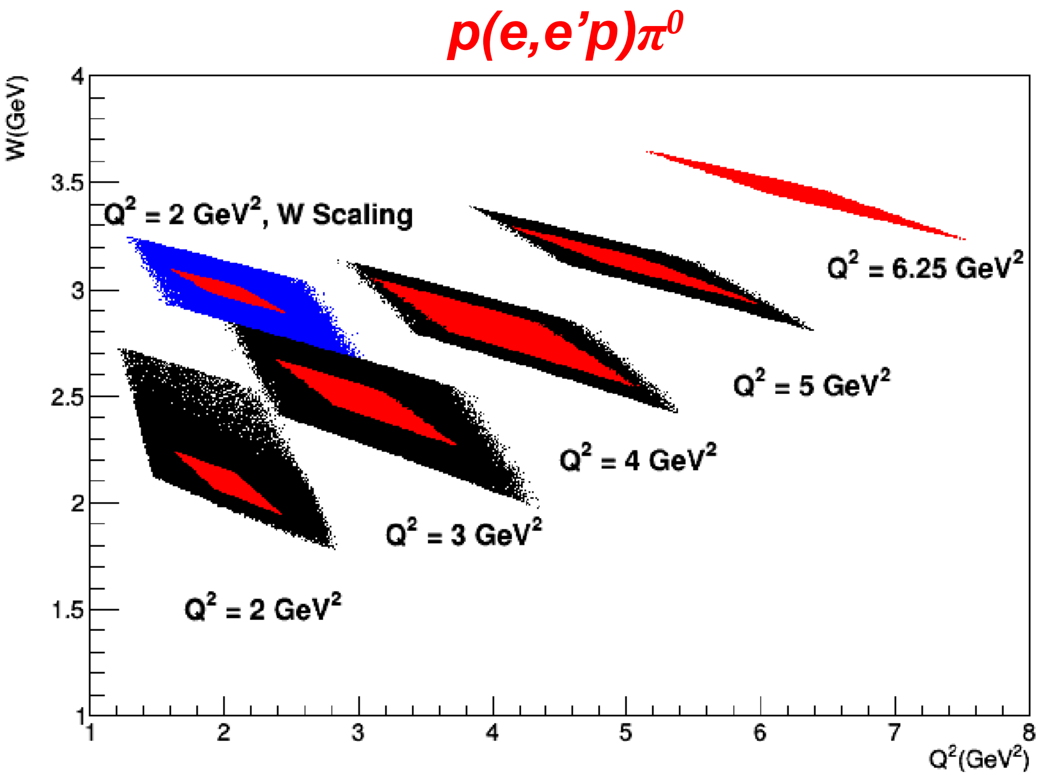
Backward Exclusive π^0 Production





E12–20–007: $u \approx 0$ π^0 production in Hall C

Spokespersons: W.B. Li, G.M. Huber, J. Stevens

Purpose: test applicability of TDA formalism for π^0 production

- Is σ_T dominant over σ_L?
- Does the σ_T cross section at constant x_B scale as $1/Q^8$?

- Kinematics overlap forward angle *p(e,e'π^0)p* experiment with NPS+HMS

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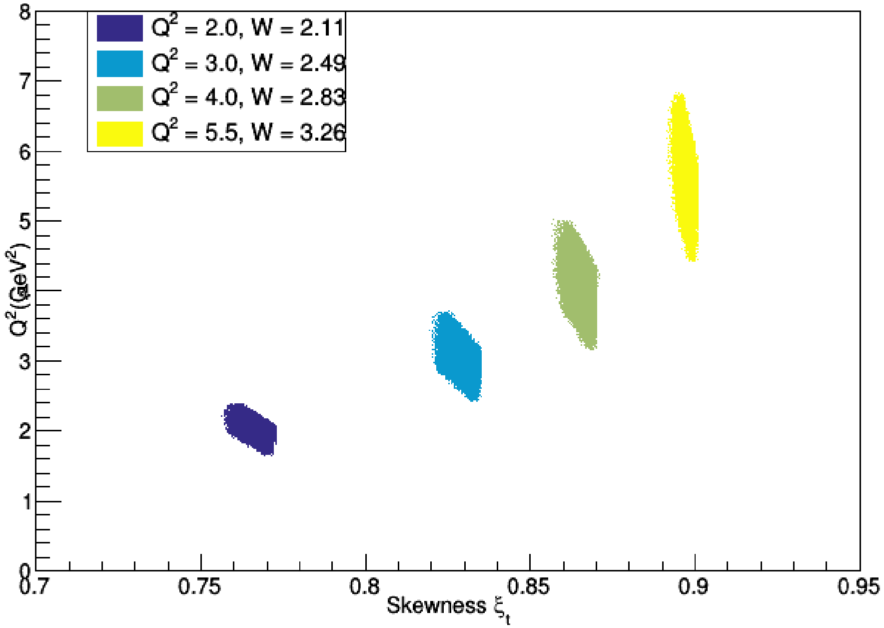
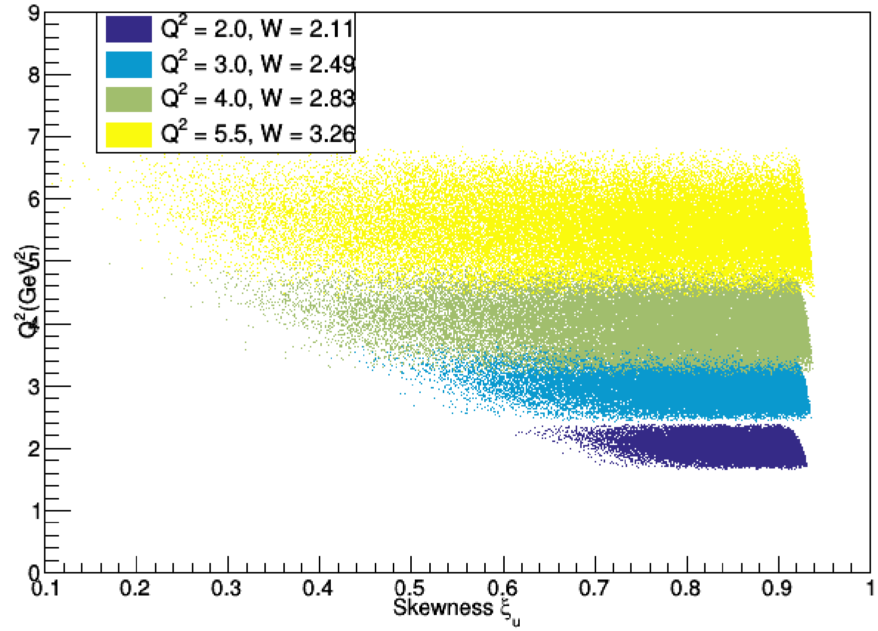
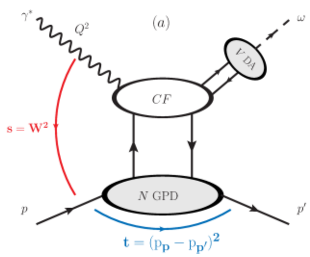
p(e,e'p)π^0 Skewness Range

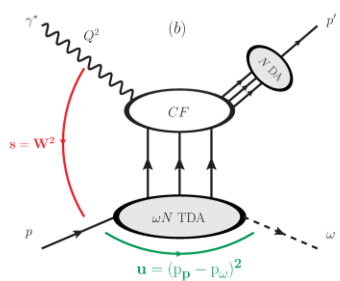






$$\xi_t = \frac{p_1^+ - p_2^+}{p_1^+ + p_2^+}$$ where $p_{1,2}$ refer to light cone + components

in $\gamma^*(q) + p(p_1) \to \omega(p_\omega) + p'(p_2)$



$$\xi_u = \frac{p_1^+ - p_\pi^+}{p_1^+ + p_\pi^+}$$

HMS and SHMS acceptance cuts, and diamond cuts applied

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CT and Backward-angle Factorization

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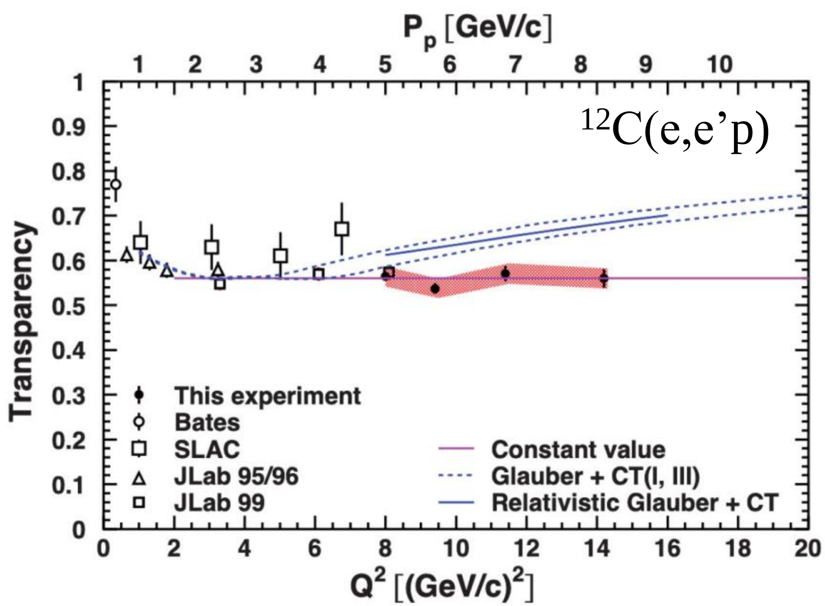
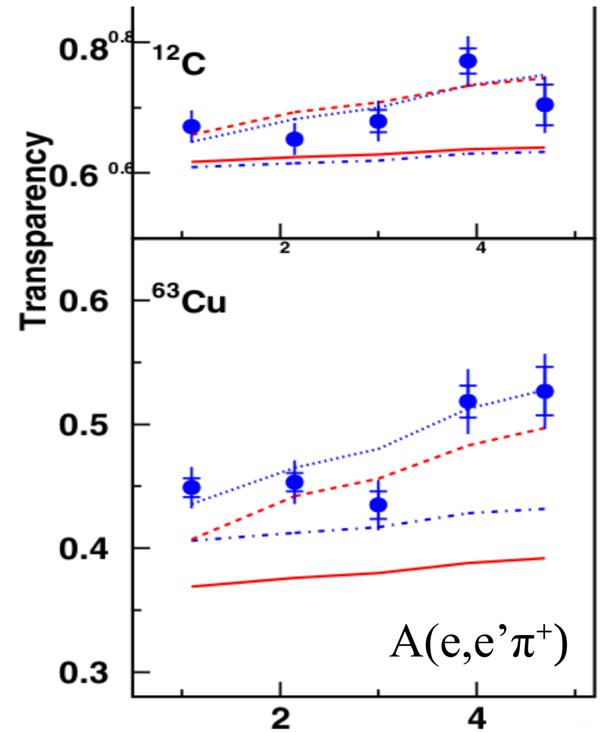
- CT has recently been shown to not apply in C(e,e'p) up to Q^2=14 GeV^2, in contrast to CT applying already in A(e,e'π^+) at Q^2≈5 GeV^2

Bhetuwal et al, PRL **126** (2021) 082301





Clasie et al, PRL **99** (2008) 242502

- **Color Transparency is a co-requisite of reaching the factorization regime, and is expected to be an equally valid requirement for both forward-angle and backward-angle factorizations**

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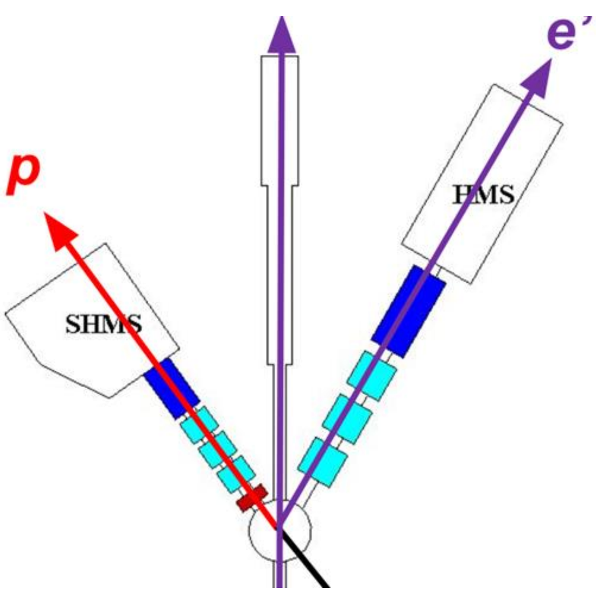
Backward-angle $A(e,e'p)\pi^0$

- Since JLab 6 GeV data are qualitatively consistent with early factorization in backward kinematics, backward-angle meson production events with a high momentum forward proton may provide an alternate means of probing Color Transparency
- Example is π^0 production, but technique extendable also to vector meson production. A short test could be attempted in E12-20-007



$A(e,e'p)\pi^0$ Kinematics E_{beam}=10.6 W=2 GeV					
Q^2 (GeV^2)	e' (GeV/c, deg)	p (GeV/c, deg)	π^0 (GeV/c, deg)	t (GeV^2)	u (GeV^2)
3	7.3 @ 11.3°	3.9-3.6 @ 23°-30°	0.2-0.5 @ 202°-95°	-5.7 to -5.2	+0.5 to -0.1
6	5.7 @ 18.1°	5.6-5.2 @ 19°-24°	0.1-0.5 @ 196°-79°	-8.8 to -8.2	+0.6 to 0.0
10	3.6 @ 29.7°	7.7-7.3 @ 13°-16°	0.0-0.5 @ 193°-61°	-12.8 to -12.1	+0.6 to -0.1
14	1.5 @ 56.7°	9.9-9.5 @ 7°-9°	0.1-0.5 @ 187°-50°	-16.8 to -16.2	+0.6 to -0.1

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Theoretical considerations

- Halls B,C 6 GeV data hint at applicability of backward-angle factorization mechanism as early as Q^2=2.5 GeV^2
- If this interpretation is correct, it can be confirmed by *u*-channel CT measurements such as A(e,e'p)π^0
- **Considerations:**
  - CT will not appear in the same way for backward π^0 as for the other experiments. This is because the π^0 does not originate from a point-like quark configuration, it is attached to the TDA which has no small transverse distance inside
  - Even if factorization applies, the π^0 will be subject to strong interactions in the nucleus, such as absorption, or formation of a 2π state
  - One should not insist on detecting the final meson. Rather, it would be sufficient to require $120<m_{missing}<500$ MeV. It is important to detect the high-momentum forward-going nucleon.
- More work would clearly be needed for model calculations of CT ratios for this new type of experiment. It gives rise to the intriguing idea of *"Half Color Transparency"* .[Bernard Pire]

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Summary

- **New experimental technique pioneered at JLab Hall C has opened up a unique kinematic regime for study:**
  - Extreme backward angle (u≈0) scattering
  - Detect forward–going proton in parallel kinematics
    - Leaves “recoil” meson nearly–at–rest in target
- Possible access to **Transition Distribution Amplitudes**
  - Universal perturbative objects in *u*–channel, analogous to GPDs
  - Access to 3–quark plus sea component $\psi_{(3q+q\bar{q})}$ of nucleon
- The approach of backward angle factorization regime can be studied via *u*-channel CT measurements, such as A(e,e’p)π^0, across a variety of nuclei

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