

Generalized Parton Distributions from charged current meson production

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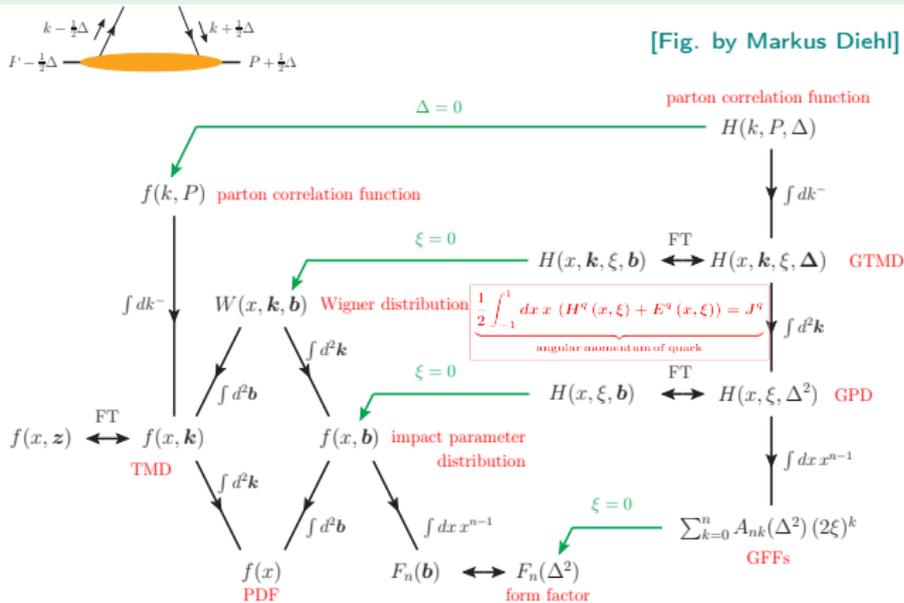
Based on:

Physical Review D99 (2019) no.11, 116005

Nucleon (hadron) structure

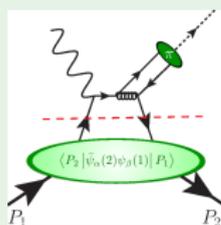
- Formidable theoretical problem (nonperturbative strongly interacting $\bar{q}qg$ ensemble)
- Parton distributions: convenient interface between theory and experiment

Relations between parton distributions



- Helicity of partons/target might be flipped
- Each distribution might depend on flavor

Factorization theorem



- Bjorken kinematics

$$Q^2 \rightarrow \infty, x_B = \text{const}$$

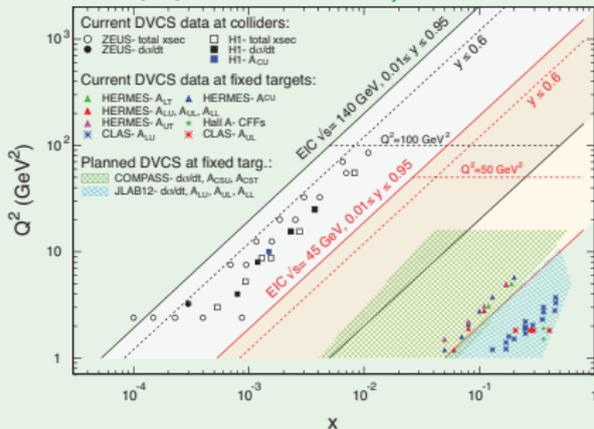
- $\mathcal{A} \sim \mathcal{C}_{\text{process}} \otimes H_{\text{target}}$

Challenge

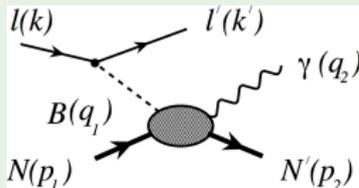
- No first principle parametrization
- Extracted objects are subject to nontrivial physical constraints

GPD extraction from DVCS

(EIC white paper, 1212.1701)



Kinematic coverage of DVCS experiments.



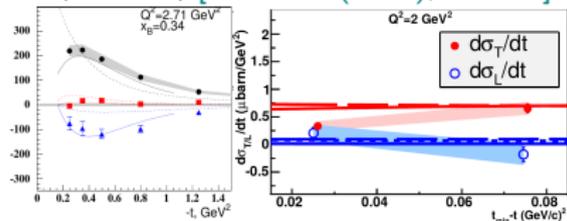
- Theoretically the cleanest, best understood is DVCS
- Interference with BH \Rightarrow phase of the amplitude
- Polarization asymmetries \Rightarrow separate $H, E, \tilde{H}, \tilde{E}$
- Sensitive only to

$$H_{DVCS} = \sum e_f^2 H^f + \mathcal{O}(\alpha_s) H^g$$

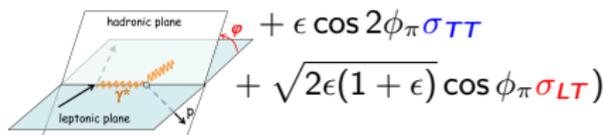
- DVMP may give access to GPD flavor structure, but theoretically is more complicated

Challenges in GPD extraction from meson production

CLAS, Hall A, [PRL 117 (2016), 262001] :



$$\frac{d^4 \sigma}{dQ^2 dx_B dt d\phi_\pi} = \frac{\Gamma(Q^2, x_B, E)}{2\pi} (\sigma_T + \epsilon \sigma_L)$$

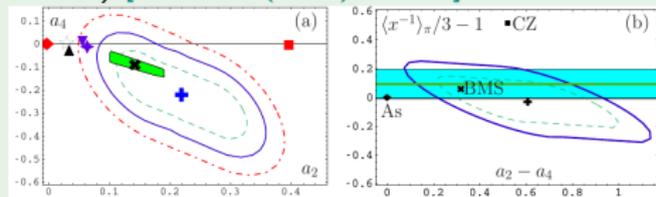


- Complicated interplay of tw-2 and tw-3 contributions
- σ_T probes H_T , E_T , σ_L probes \tilde{H} , \tilde{E}
- Tw-3/Tw-2 scales as $1/Q^n$ for $Q^2 \rightarrow \infty$
- ... but $\sigma_L \sim 1/Q^6$, can't go too far due to statistics!

Need more channels to study the GPDs

Pion distribution amps (DA)

- DA contributes as $\langle x^{-1} \rangle$ -moment in LO, more involved in NLO
- Shape characterized in terms of Gegenbauer moments a_{2n}
- Current 2σ -limits (CLEO, CELLO, Belle, BaBar) [PLB 578 (2004) 91–98]



- **20% uncertainty in $\langle x^{-1} \rangle \Rightarrow \gtrsim 40\%$ uncertainty in the cross-section**

ρ -meson DAs

- Theoretical models differ significantly
- Phenomenological constraints:

$$a_2^\rho = 0.18 \pm 0.1, a_4^\rho = ???$$

What we suggest ?

- Charged current $\pi/K/\rho$ -production

Advantages

- $V - A$ structure of interaction \Rightarrow probes unpolarized (“large”) GPDs H, E .
- $d\sigma_\rho$ vs. $d\sigma_\pi$: exactly the same set of GPDs, probes difference of π and ρ -meson DAs.
- Kaon production \Rightarrow access to strange quark GPDs

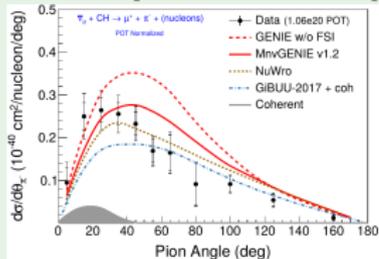
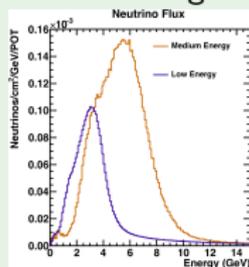
Where such processes could be studied ?

- + Need luminosity, rather than very large energies for such studies

Neutrino experiments?

(Minerva, DUNE, ...)

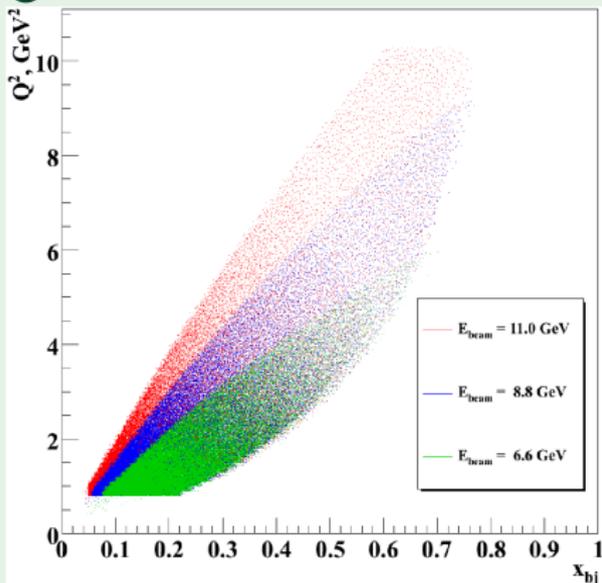
- + Large luminosity, possibility to measure with meaningful errorbars [arXiv:1906.08300]



- + Both ν_μ and $\bar{\nu}_\mu$ can be used
- Beam not monochromatic
- Detector=extended nuclear target

Jefferson Laboratory ?

- + Monochromatic beam, $E_e = 11 \text{ GeV}$
- + Large luminosity $\mathcal{L} \lesssim 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$
- + Beam/target can be polarized



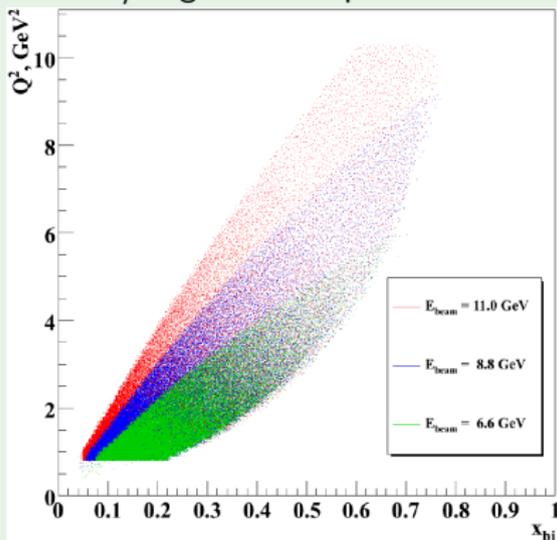
- Backgrounds from photoproduction

Charged current studies in ep experiments

- (HERA: luminosity insufficient for charged current exclusive processes)

Kinematic coverage of JLAB

- Monochromatic beam, $E_e = 11$ GeV
- Luminosity $\mathcal{L} = 10^{36} \text{cm}^{-2} \text{s}^{-1}$
- Beam/target can be polarized



E_p -energy of scattered proton, E_{π^-}

Suggested process: $ep \rightarrow \nu_e \pi^- p$

- Neutrino ν_e momentum reconstructed via momentum conservation

$$p_\nu = p' + p_\pi - p - p_e$$

-final hadrons are charged, could help with kinematics reconstruction.

Invariant vs. lab-frame variables

$$t = 2 m_p (m_p - E_p)$$

$$-Q^2 = 2m_p^2 + m_\pi^2 - 2m_p (E_\pi + E_p) + 2E_\pi E_p - 2\sqrt{E_p^2 - m_p^2} \sqrt{E_\pi^2 - m_\pi^2} \cos \theta_{\pi p}$$

$$x_B = \frac{Q^2}{Q^2 + m_\pi^2 + 2E_\pi E_p - 2\sqrt{E_p^2 - m_p^2} \sqrt{E_\pi^2 - m_\pi^2} \cos \theta_{\pi p}}$$

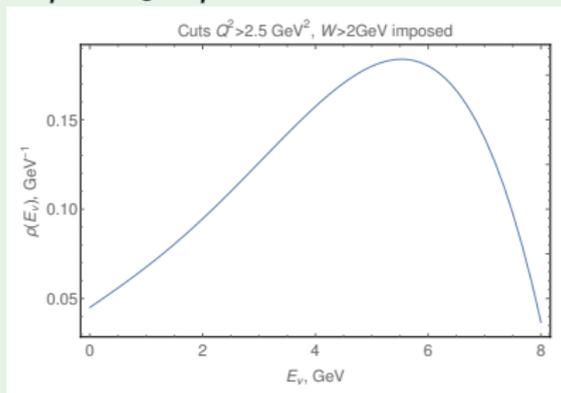
energy of π^- ; $\theta_{\pi p}$ -angle between π^- and p

What about backgrounds?

Pion misidentification as electron

Elastic scattering $e^- p \rightarrow e^- p$

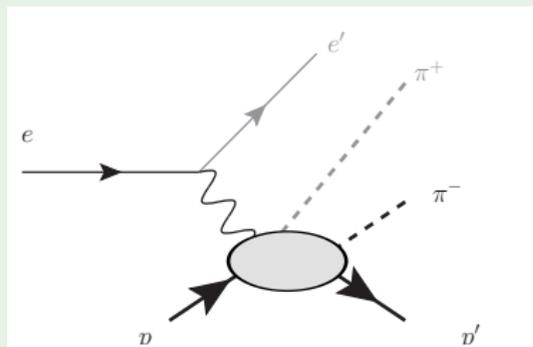
- Neutrino energy E_ν distribution after Bjorken regime cuts in $e^- p \rightarrow \nu_e \pi^- p$



- For elastic scattering " E_ν " $\equiv 0$

\Rightarrow Additional cut $E_\nu > 0.1$ GeV allows to get rid of elastic background

Multihadron photoproduction $e^- p \rightarrow X \pi^- p$



- Missing ("neutrino") momentum squared:

$$p_\nu^2 = \left(\sum_{i=\text{undetected}} p_i \right)^2 \geq \left(\sum_{i=\text{undetected}} m_i \right)^2$$

In case of true CCDVMP

$$p_\nu^2 = m_N^2 - Q^2 + 2E_e (E_p + E_\pi - m_N)$$

$$- 2\sqrt{E_e^2 - m_e^2} (p_{p,z} + p_{\pi,z}) \equiv m_\nu^2 \lesssim (\dots \text{eV})^2$$

\Rightarrow Cut $p_\nu^2 < m_\pi^2$ to eliminate this background

How do such events look like in lab frame?

Kinematic coverage of JLAB

- Monochromatic beam, $E_e = 11$ GeV
- Luminosity $\mathcal{L} = 10^{38} \text{ cm}^{-2} \text{ s}^{-1}$

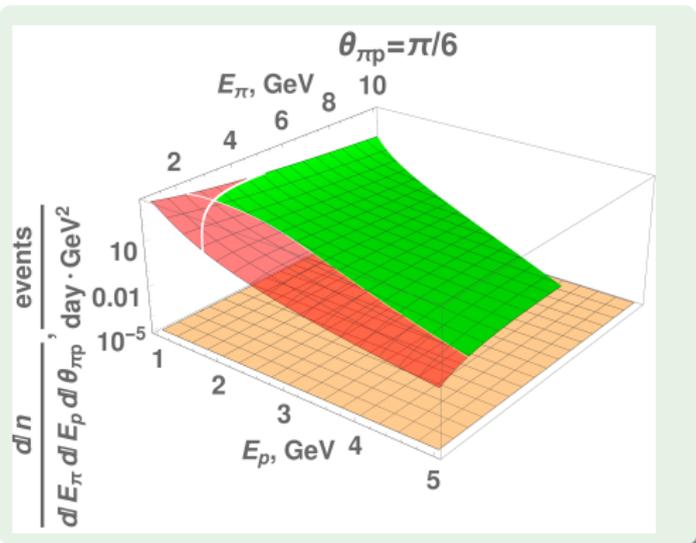
$$t = 2 m_p (m_p - E_p)$$

$$-Q^2 = 2m_p^2 + m_\pi^2 - 2m_p(E_\pi + E_p) + 2E_\pi E_p - 2|\vec{p}_\pi||\vec{p}_p|\cos\theta_{\pi p}$$

$$x_B = \frac{Q^2}{Q^2 + m_\pi^2 + 2E_\pi E_p - 2|\vec{p}_p||\vec{p}_\pi|\cos\theta_{\pi p}}$$

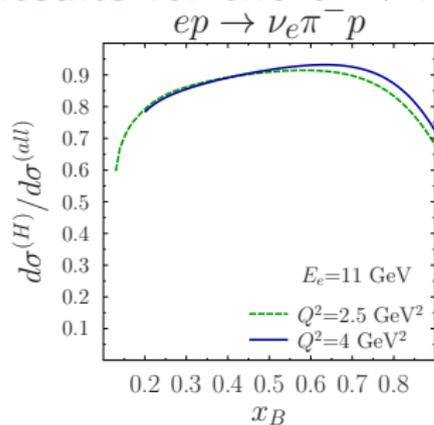
$$|\vec{p}_p| = \sqrt{E_p^2 - m_p^2}$$

$$|\vec{p}_\pi| = \sqrt{E_\pi^2 - m_\pi^2}$$

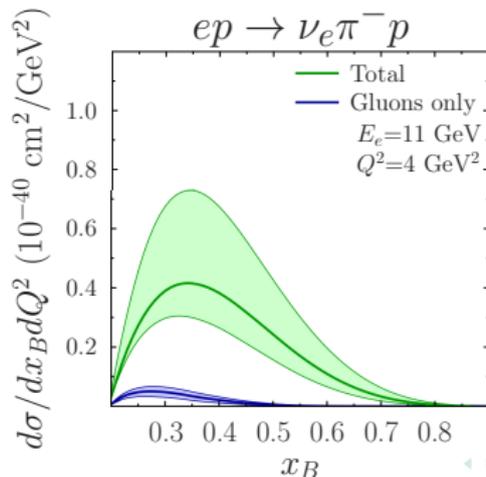
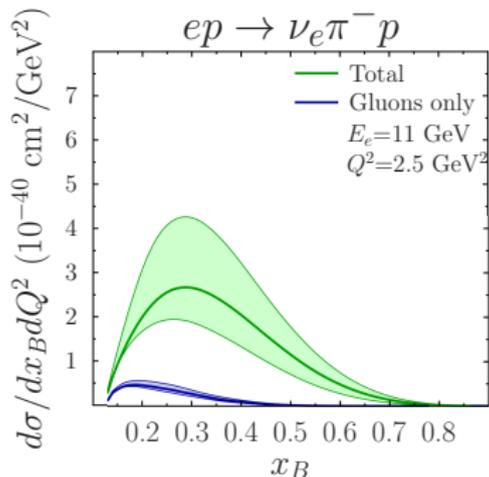


- Optimal angle: $\theta_{\pi p} \in (0.5, 0.8)$ rad
 - smaller angles lead to small $W_{\pi p} \lesssim 2$ GeV (resonance region)
 - larger angles lead to small $Q^2 \lesssim 2.5$ GeV

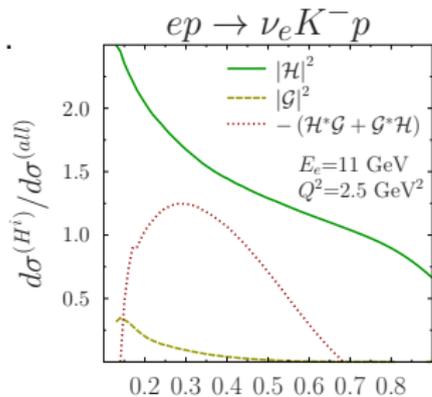
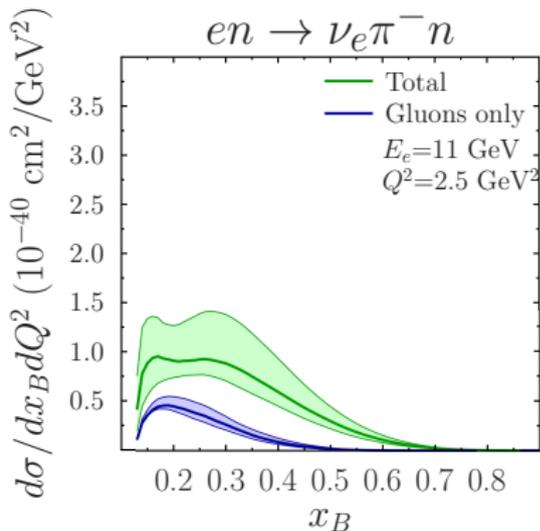
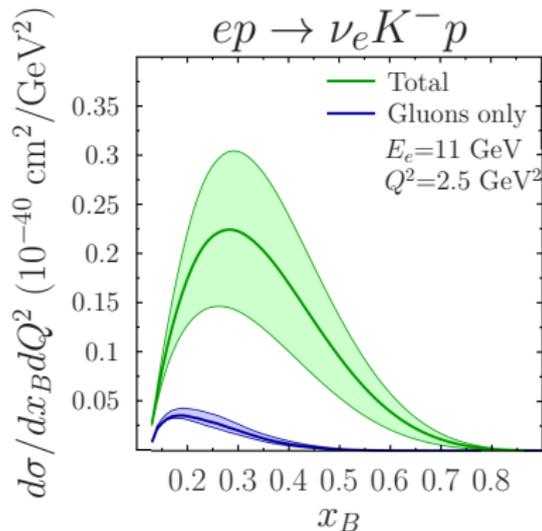
Results for the $e \rightarrow \nu_e M$ (NLO in α_s)



- Mostly sensitive to GPD H_u, H_d ($\gtrsim 80\%$ of result).
- Gluons give minor contribution and slightly decrease the cross-section (interference term $q - g$ is negative)
- For pions with beam luminosity $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ expect ~ 10 events/day (1 GeV bins in Q^2 assumed)



Results for the $e \rightarrow \nu_e M$ (NLO in α_s)



- For K -mesons, suppression by an order of magnitude (Cabibbo forbidden), smaller statistics
- Sizeable negative contribution from interference $\mathcal{H}^* \mathcal{G} + \mathcal{G}^* \mathcal{H}$
- For neutrons the cross-section is of the same order ($\sim 40\%$ less than in $ep \rightarrow \nu_e \pi^- p$), but kinematics reconstruction might be poorer

Contaminations by twist-3 & Bethe-Heitler mechanisms

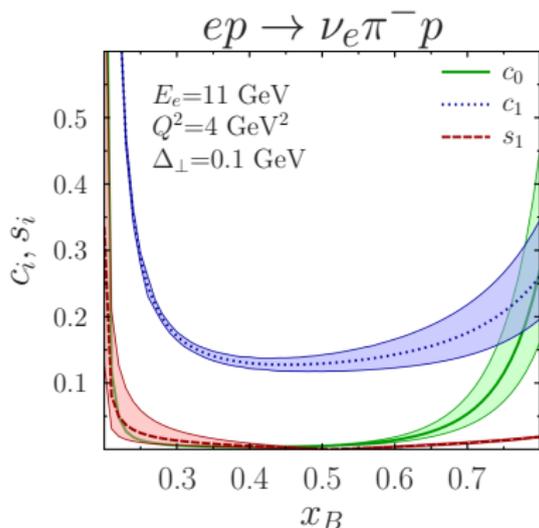
- Generate azimuthal asymmetry, quantify effect in terms of angular harmonics

$$\frac{d^4 \sigma^{(tot)}}{dt dQ^2 d \ln \nu d\phi} = \frac{1}{2\pi} \frac{d^3 \sigma^{(DVMP)}}{dt dQ^2 d \ln \nu} \times \sum (c_n \cos n\phi + s_n \sin n\phi)$$

Twist-3 effects

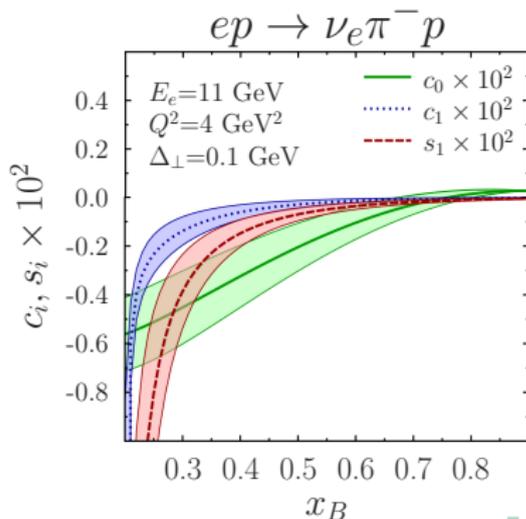
- Quark spin flip \Rightarrow probe (poorly known) transversity GPDs

$H_T, E_T, \tilde{H}_T, \tilde{E}_T$ (large at CLAS6)



Bethe-Heitler mechanism

- interaction with hadron via elastic t -channel photon exchange only
- suppressed by α_{em} , kinematically is enhanced by $Q^2 / (t \cdot \alpha_s^2(Q^2))$



CCDVMP as a probe of ρ -meson DAs

Extension to $ep \rightarrow \nu_e \rho_L^- p$

Leading twist: Quark structure differs from pion only by γ_5 :

$$\phi_{2;\pi}(u) \sim \int dz e^{i(2u-1)z} \langle 0 | \bar{\psi}(0) \gamma_+ \gamma_5 \psi(z) | \pi \rangle$$

$$\phi_{2;\rho}^{(L)}(u) \sim \int dz e^{i(2u-1)z} \langle 0 | \bar{\psi}(0) \gamma_+ \psi(z) | \rho_L \rangle$$

$e \rightarrow e M$ case

$\gamma_5 \Rightarrow$ sensitivity to different GPD sets,

$$\rho_L : (H, E) \quad \langle p' | \bar{\psi}(0) \gamma_+ \psi(z) | p \rangle$$

$$\pi : (\tilde{H}, \tilde{E}) \quad \langle p' | \bar{\psi}(0) \gamma_+ \gamma_5 \psi(z) | p \rangle$$

$e \rightarrow \nu_e M$ case

● sensitivity to exactly the same GPDs:

$$\gamma_5 \gamma_\mu (1 - \gamma_5) = \gamma_\mu (1 - \gamma_5)$$

Charged current, asymptotic DA

● For $\phi_{2;\pi}(x) = \phi_{2;\rho}^{(L)}(x) = 6x(1-x)$ in the leading twist

$$\mathcal{A}_{e \rightarrow \nu_e \rho_L^-}^{(tw-2,asy)} = \mathcal{A}_{e \rightarrow \nu_e \pi^-}^{(tw-2,asy)}$$

Charged Current, realistic DA

● Leading order (LO): DA enters as a multiplicative factor

$$\langle x^{-1} \rangle_M = \int dx \frac{\phi_{2;M}(x)}{x}$$

$$\Rightarrow R_{\rho/\pi} = \frac{d\sigma_{e \rightarrow \nu_e \rho_L^-}^{(tw-2)}}{d\sigma_{e \rightarrow \nu_e \pi^-}^{(tw-2)}} = \frac{f_\rho^2}{f_\pi^2} \left(\frac{\langle x^{-1} \rangle_{\rho;L}}{\langle x^{-1} \rangle_{\rho;\pi}} \right)^2$$

● NLO: mild logarithmic Q^2 -dependence
 $\sim \alpha(Q^2)$ in $R_{\rho/\pi}$

CCDVMP as a probe of ρ -meson DAs

Asymptotic DA

- For $\phi_{2;\pi}(x) = \phi_{2;\rho}^{(L)}(x) = 6x(1-u)$ in the leading twist

$$\mathcal{A}_{e \rightarrow \nu_e \rho^-}^{(tw-2, asy)} = \mathcal{A}_{e \rightarrow \nu_e \pi^-}^{(tw-2, asy)}$$

Realistic DA, leading order

- Leading order (LO):

$$\Rightarrow R_{\rho/\pi} = \frac{d\sigma_{e \rightarrow \nu_e \rho^-}^{(tw-2)}}{d\sigma_{e \rightarrow \nu_e \pi^-}^{(tw-2)}} \approx \text{const}$$

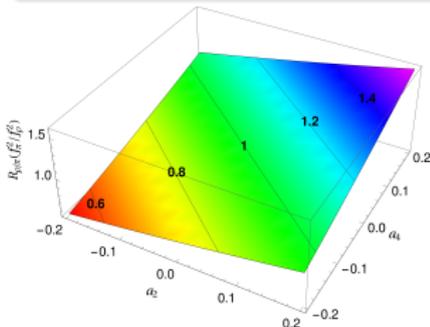
Realistic DA, next-to-leading order

- NLO: mild logarithmic Q^2 -dependence $\sim \alpha(Q^2)$ in $R_{\rho/\pi}$

$$R_{\rho/\pi} \approx \frac{f_\rho^2}{f_\pi^2} \left(1 + 2\alpha_s \sum_n \Delta a_{2n} r_{2n}(x, Q^2) \right)$$

$$\Delta a_{2n} = a_{2n}^\rho - a_{2n}^\pi$$

-difference of Gegenbauer moments of ρ and π .



$\Rightarrow R_{\rho/\pi}(x_B, Q^2) = \text{bounds on } \rho\text{-meson DA.}$

Summary

- Charged current Deeply Virtual Pion Production can be used as an additional source of information on proton structure (its GPDs)
 - ★ Can be studied in ep and νp experiments thanks to large luminosity of modern experiments.
 - ★ Has sensitivity to unpolarized GPDs H , E (large components); expect small contamination by higher twist and Bethe-Heitler corrections.
 - ★ Presents a challenge: huge backgrounds, need to impose cuts in missing energy and missing invariant mass squared to suppress them

THANK YOU FOR YOUR ATTENTION!