Studies of nonperturbative structure of hadrons from lepton production experiments

Marat Siddikov
In collaboration with Ivan Schmidt, B. Kopeliovich

UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

Based on:

PRD 96 (2017), 096006, PRD 95 (2017), 013004, PRD 91 (2015) 073002, PRD 89 (2014) 053001

PRD 87 (2013) 033008, PRD 86 (2012) 113018

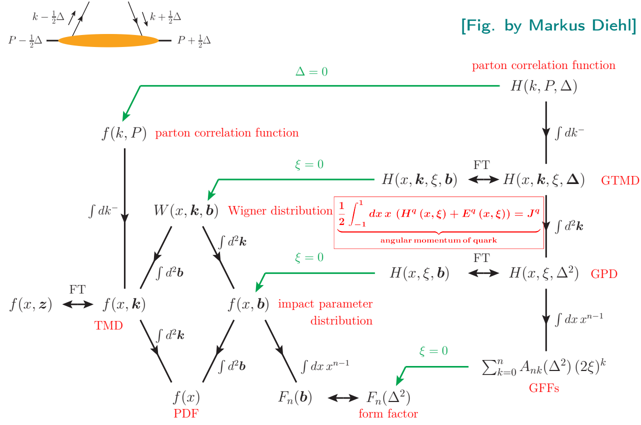
NON PERTURBATIVE ASPECT OF QFT AND LOEWE'S 65 FEST

¡Feliz Cumpleaños, Marcelo!

Nucleon (hadron) structure

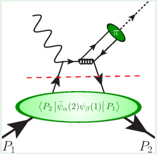
- Formidable theoretical problem (nonperturbative strongly interacting $\bar{q}qg$ ensemble)
- Parton distributions: convenient interface between theory and experiment

Relations between parton distributions



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

Factorization theorem



- Bjorken kinematics

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

- $\mathcal{A} \sim \mathcal{C}_{\text{process}} \otimes H_{\text{target}}$
- Multiparton distributions are suppressed in this kinematics

Curse of dimensionality

- Only formfactors and PDFs are reasonably measured.

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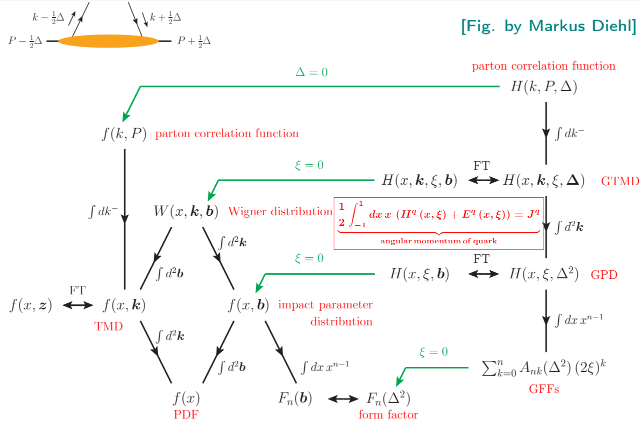

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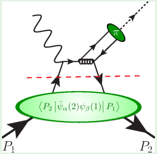


- Bjorken kinematics

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

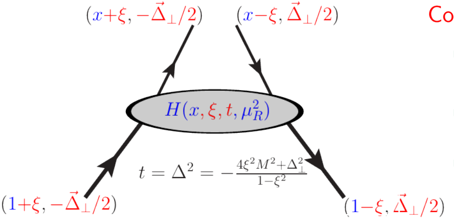
- $\mathcal{A}\sim\mathcal{C}_{\text{process}}\otimes H_{\text{target}}$

Challenge

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

GPD: formal definitions, models, constraints

$$\frac{\bar{P}^+}{2\pi}\int dz\, e^{ix\bar{P}^+z}\left\langle B(p_2)\middle|\bar{\psi}_{q'}\left(-\frac{z}{2}\right)\gamma_+\psi_q\left(\frac{z}{2}\right)\middle|A(p_1)\right\rangle = \Big(H_q(x,\xi,t)\,\bar{N}(p_2)\gamma_+N(p_1) + \frac{\Delta_k}{2m_N}E_q(x,\xi,t)\,\bar{N}(p_2)\,i\sigma_{+k}N(p_1)\Big)$$



Constraints on GPD parametrizations:

- $\lim\limits_{\Delta\to 0} H(x,\xi,t) = q(x)$, $\int_{-1}^{1} dx\, H(x,\xi,t) = F(t)$
- $\int_{-1}^{1} dx\, x^{n-1} H(x,\xi,t) = \sum\limits_{k=1}^{n} a_{kn}(t)\xi^k$
- Positivity (in impact space): For $\forall p_\sigma(x)$, $\int\limits_{|\xi|<x<1} \frac{dx\,d\xi}{(1-x)^5} p_\sigma^*\left(\frac{1-x}{1-\xi}\right) p_\lambda\left(\frac{1-x}{1+\xi}\right) F_{\sigma\lambda}\left(x,\xi,\frac{1-x}{1-\xi^2}b_\perp\right) \gtrsim 0$

GPDs from nonperturbative models of nucleon structure (χQSM, NJL, AdS/CFT, ...)

- If “wave functions” of quarks are known, evaluation is quite straightforward:

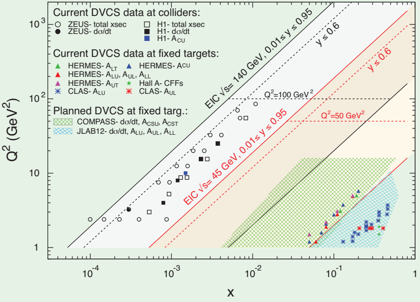
$$\Rightarrow H_i(x,\xi,t) \sim \sum_q \int d^2p_\perp \bar{\Phi}_q\left(x-\xi, \vec{p}+\frac{\vec{\Delta}_\perp}{2}\right)\Gamma_i\Phi_q\left(x+\xi, \vec{p}_\perp-\frac{\vec{\Delta}}{2}\right)$$

- Advantage: Automatically satisfy polynomiality & positivity constraints
- Yet agreement with experimental data is marginal.

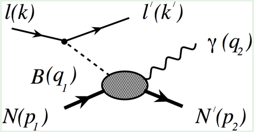
- ⇒Phenomenological approach predominant in the literature (EPJC 59, 809; EPJC 39, 1; PRD 72, 054013; NPB 841, 1, ...)

GPD extraction from DVCS

(EIC white paper, 1212.1701)



Kinematic coverage of DVCS experiments.

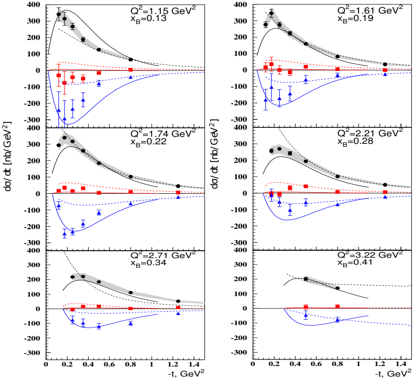


- Theoretically the cleanest, best understood is DVCS
- Interference with BH
  ⇒phase of the amplitude
- Polarization asymmetries
  ⇒ separate $H, E, \tilde{H}, \tilde{E}$
- Sensitive only to

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

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

Challenges in GPD extraction from pion production (CLAS)

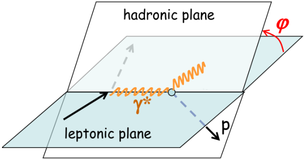


- Tw-2 contribution is small, probes

$$\sigma_L \sim \left|\{\tilde{H},\tilde{E}\}\otimes\phi_{2;\pi}\right|^2$$

⇐Dependence on azimuthal angle ϕ_π between ep and πp planes

- Should not exist in leading twist



- Signals that **tw-3 contributions are pronounced**

$$\sigma_{TT} \sim \left|\{H_T,E_T\}\otimes\phi_{3;\pi}\right|^2$$

$$\sigma_{LT} \sim \left|\{H_T,E_T\}\otimes\phi_{3;\pi}\right|^2$$

$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi_\pi} = \frac{\Gamma(Q^2,x_B,E)}{2\pi}\Big(\sigma_T+\epsilon\sigma_L + \epsilon\cos 2\phi_\pi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi\,\sigma_{LT}\Big)$$

⇒This channel requires significantly larger Q^2 to access GPDs

Challenge in GPD extraction from vector mesons

- Probe unpolarized GPDs H, E, smaller tw-3 contributions

Vector meson wave function unknown

- controlled by confinement (not SCSB), depends heavily on the model

Popular parametrizations:

AdS/CFT wave function

$$\varphi_q^{(i)}(x, \mathbf{k}_\perp) = N_q^{(i)} \frac{4\pi}{\kappa} \sqrt{\frac{\log(1/x)}{1-x}} \sqrt{f_q^{(i)}(x) \bar{f}_q(x)} \times \exp\left[-\frac{\mathbf{k}_\perp^2}{2\kappa^2} \frac{\log(1/x)}{(1-x)^2} \bar{f}_q(x)\right].$$

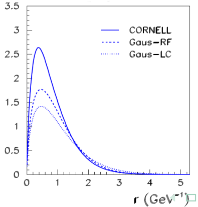
- $f_q(x)$, $f_{\bar{q}}(x)$-unknown functions, can be fixed from (hypothetical) DIS on ρ-mesons

Boosted Gaussian WF

$$\varphi_q^{\mathrm{BG}}(x, \mathbf{k}_\perp) = \mathcal{N}_\lambda 2[x(1-x)]^{b_\lambda/2} \sqrt{2\pi R_\lambda^2} \exp\left(\frac{m_f^2 R_\lambda^2}{2}\right) \times \exp\left(-\frac{\boldsymbol{k}_\perp^2 + m_f^2}{8[x(1-x)]^{b_\lambda}} R_\lambda^2\right)$$

everything except x and $\boldsymbol{k}_\perp$ are free parameters

Uncertainty in WF translates into significant uncertainty in extraction of GPDs from this channel



What we suggest ?

- Charged current π/K-production

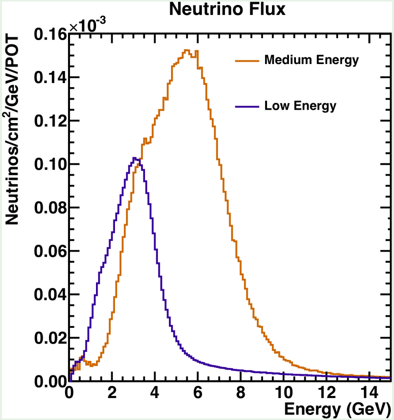
Advantages

- $V - A$ structure of interaction ⇒probes unpolarized (“large”) GPDs H, E; much smaller contamination by higher twist corrections
- Good knowledge of pion and kaon WF, closeness of wave functions due to SCSB⇒can extract full flavor structure of GPD

Where such processes can be studied ?

MINERvA@Fermilab

- Extremely large luminosity
- Both ν_μ and $\bar{\nu}_\mu$ can be used

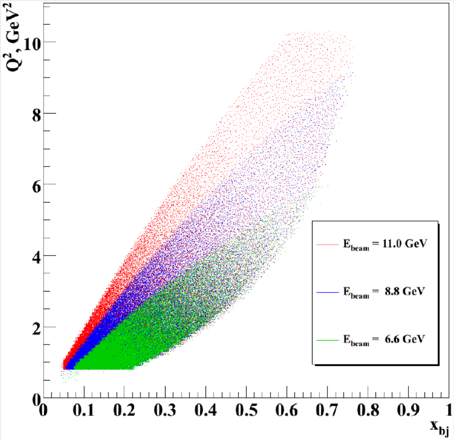


- Analysis of data in Bjorken kinematics has already started

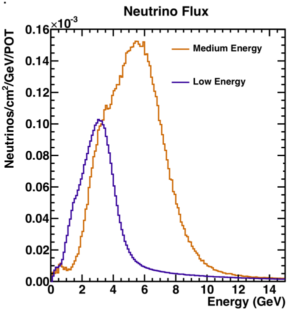
UTFSM MINERvA group: Jonathan Miller *et al.*

Jefferson Laboratory

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



MINERvA experiment (neutrinos)



Advantages

- Extremely large luminosity
- Both ν_μ and $\bar{\nu}_\mu$ can be used ($W^\pm$-induced production)

Challenges

- Beam not monochromatic, should consider spectrum averaged observables
- Detector=extended nuclear target, nuclear effects are important
- Accessible Q^2 is not very large, loop corrections might be pronounced (will DUNE improve the resolution?)

Flavor combinations of GPDs probed by various processes

(PRD 86 (2012) 113018)

- Experimentally easiest:$\nu p \to \mu^- \pi^+ p$, $\bar{\nu} p \to \mu^+ \pi^- p$ (ongoing analysis by MINERvA group @USM)

$$\mathcal{A}^{(\mathrm{LO})}_{\nu p \to \mu^- \pi^+ p} \sim \int_{-1}^{1} dx \left(\frac{H_d(x, \xi)}{x - \xi + i0} + \frac{H_u(x, \xi)}{x + \xi - i0} \right)$$

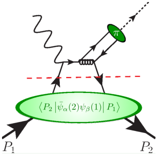
$$\mathcal{A}^{(\mathrm{LO})}_{\bar{\nu} p \to \mu^+ \pi^- p} \sim \int_{-1}^{1} dx \left(\frac{H_u(x, \xi)}{x - \xi + i0} + \frac{H_d(x, \xi)}{x + \xi - i0} \right)$$

- Can probe 29 CC processes in total if use $SU(3)$ flavour relations for transition GPDs $H_{p \to Y}$, e.g.

$$H_{p \to n} = H_u(x, \xi, t) - H_d(x, \xi, t)$$

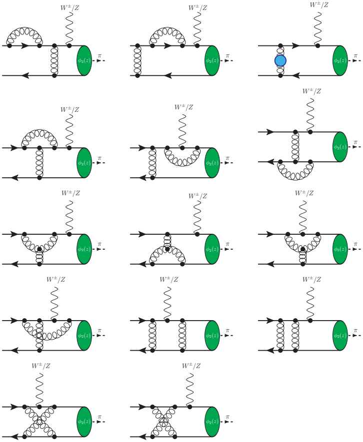
- In the NLO the coefficient functions $\frac{1}{x \pm \xi \mp i0}$ get much more complicated

Loop corrections

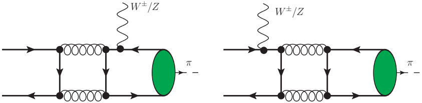


- *ep* experience: loop corrections are large in this kinematics (JETPL **80**, 226; EPJC **52**, 933)
- Challenge: separate corrections to coefficient function and GPD/DA$_\pi$ evolution kernel (scale μ_F)

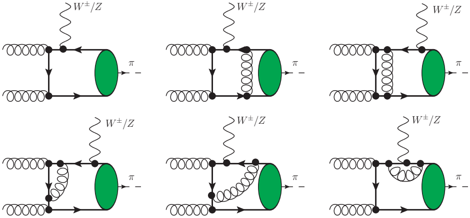
- **NLO coefficient functions**



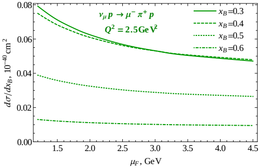
- Sea quarks contribution



- Gluons contribution (LO+NLO)

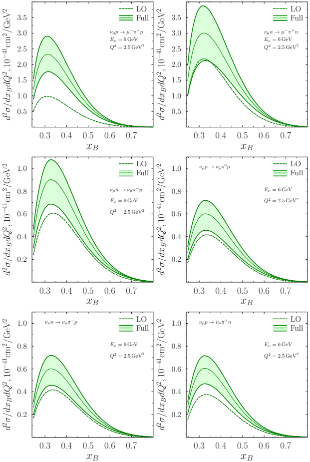


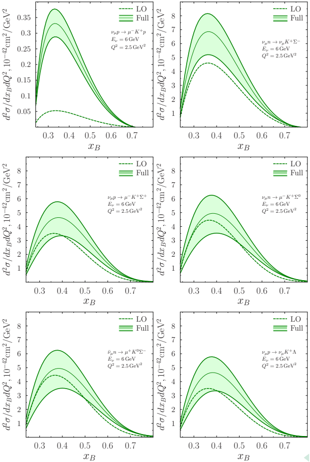
Loop corrections



- Weak dependence on factorization scale for $\mu_F \gtrsim 3$ GeV
- Scale choice: $\mu_R = \mu_F = Q$
- Estimates of NNLO corrections: $\mu_R = \mu_F \in (0.5, 2)Q$
- NLO corrections increase all the cross-sections $\gtrsim$50%

⇒NNLO corrections are needed !



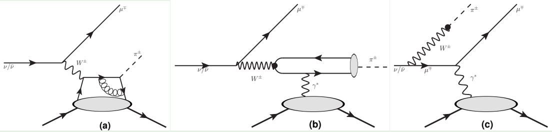


Contaminations by twist-3 & Bethe-Heitler mechanisms

Twist-3 contributions

- Quark spin flip ⇒ probe transversity GPDs H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$ (large at CLAS6)

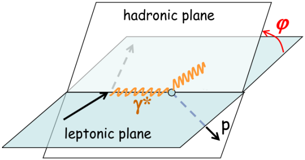
Bethe-Heitler mechanism (diagrams *b*, *c*)



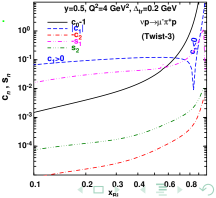
- formally is suppressed by α_{em}
- kinematically is enhanced by $Q^2/\left(t\cdot\alpha_s^2(Q^2)\right)$

- Both mechanisms generate azimuthal asymmetry

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



- Expect that harmonics c_n, s_n should be small

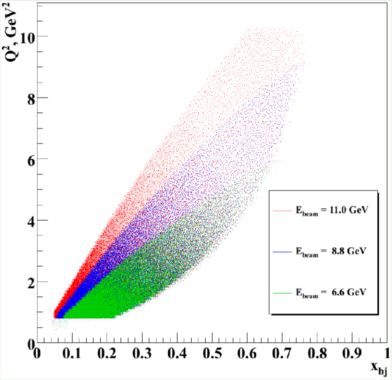


Charged current studies in *ep* experiments

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

Kinematic coverage of JLAB

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



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

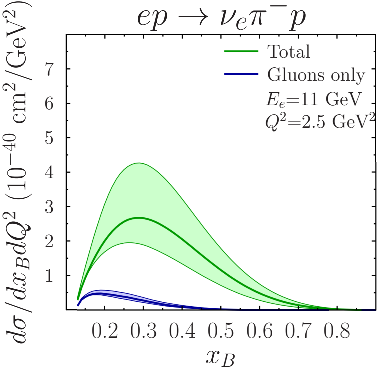
- Neutrino ν_e momentum reconstructed via momentum conservation

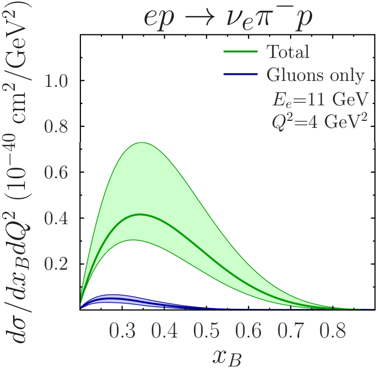
$$p_\nu = p' + p_\pi - p - p_e$$

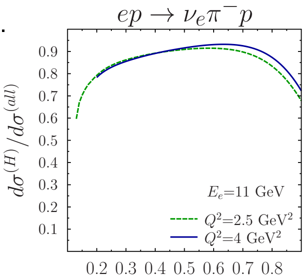
-final hadrons are charged, kinematics resolution should be good.

- Potentially can extend also to other members of mesonic and baryonic flavour multiplets, $SU(3)_f$-relations ⇒GPD flavour combinations

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







- For pions with beam luminosity $L \sim 10^{35}\mathrm{cm}^{-2}s^{-1}$ expect $\sim$ 40 events/day/bin (1 GeV bins in Q^2 assumed)
- Gluons give minor contribution and slightly *decrease* the cross-section (interference term $q-g$ is negative)
- **Mostly sensitive to GPD H_u, H_d** ($\gtrsim$ 80% of result).

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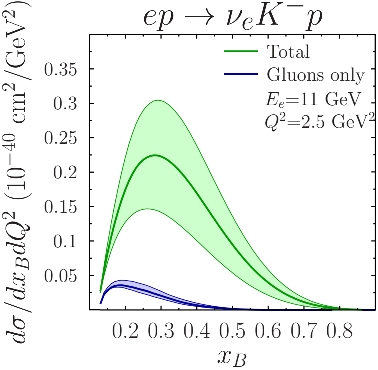
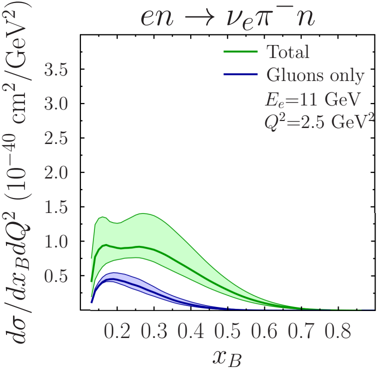
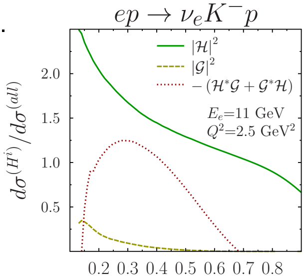






- For K-mesons, suppression by an order of magnitude (Cabibbo forbidden), smaller statistics
- Sizeable *negative* contribution from interference $\mathcal{H}^*\mathcal{G} + \mathcal{G}^*\mathcal{H}$

- For neutrons the cross-section is of the same order ($\sim$ 40% less than in $ep \to \nu_e \pi^- p$), but kinematics reconstruction might be poorer

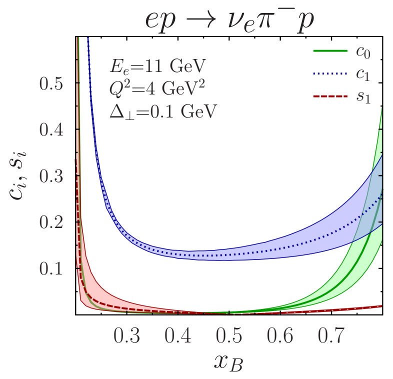
Contaminations by twist-3 & Bethe-Heitler mechanisms

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

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

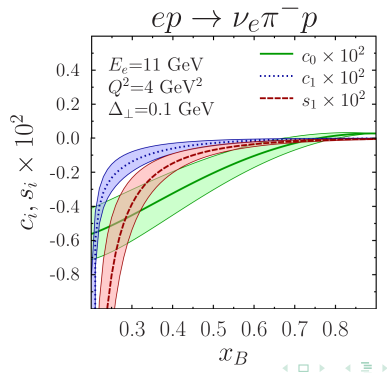
Twist-3 effects

- Quark spin flip ⇒ 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 $Q^2/\left(t \cdot \alpha_s^2(Q^2)\right)$



Summary

- Charged current Deeply Virtual Pion Production can be used as an additional source of information on proton structure (its GPDs)
  - ⋆ Can be studied at νp (ongoing analysis) and ep 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.
  - ⋆ NNLO analysis of coefficient functions is needed if Q^2 is not very large

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THANK YOU FOR YOUR ATTENTION!