Loop corrections to pion and kaon production
Use of charged currents for study of GPDs

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Based on:

PRD 95 (2017), 013004

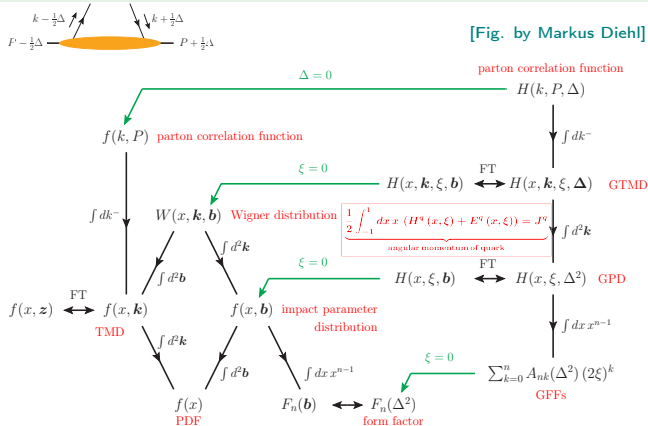PRD 91 (2015) 073002

PRD 89 (2014) 053001

PRD 87 (2013) 033008

PRD 86 (2012) 113018

Nucleon (hadron) structure

- Formidable theoretical problem (nonperturbative strongly interacting $\bar{q}qg$ ensemble)
- Can extract from experiment rather than evaluate

Relations between parton distributions

[Fig. by Markus Diehl]

$$\frac{1}{2}\int_{-1}^{1} dx\, x\, \langle H^q(x,\xi) + E^q(x,\xi)\rangle = J^q$$

angular momentum of quark

- Helicity of partons/target might be flipped
- Each distribution might depend on flavor
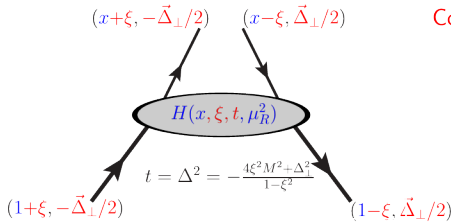
Factorization theorem
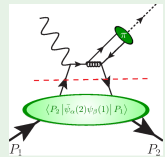
- Bjorken kinematics

$$Q^2 \to \infty, x_{\mathrm{B}} = \mathrm{const}$$

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

Experimental studies

- **HERA** (H1, ZEUS, HERMES)
- **JLAB** (Hall A, CLAS)
- **COMPASS**

GPD: formal definitions, models, constraints

$(x+\xi, -\vec{\Delta}_\perp/2)$ $(x-\xi, \vec{\Delta}_\perp/2)$

$H(x, \xi, t, \mu_R^2)$

$t = \Delta^2 = -\frac{4\xi^2 M^2 + \Delta_\perp^2}{1-\xi^2}$

$(1+\xi, -\vec{\Delta}_\perp/2)$ $(1-\xi, \vec{\Delta}_\perp/2)$

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 $\forall \rho_\sigma(x)$,
  $\int\limits_{|\xi|<x<1} \frac{dx\,d\xi}{(1-x)^5} \rho_\sigma^* \left(\frac{1-x}{1-\xi}\right) \rho_\lambda \left(\frac{1-x}{1+\xi}\right) F_{\sigma\lambda} \left(x, \xi, \frac{1-x}{1-\xi^2} b_\perp\right) \gtrsim 0$
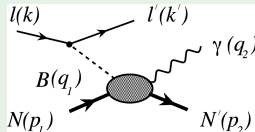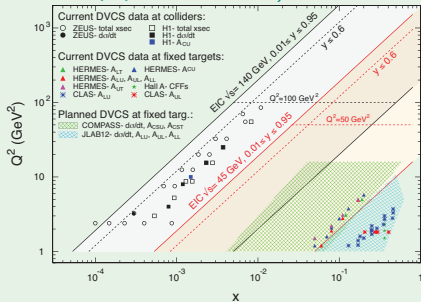
Formal definitions (quark sector)

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

$$\frac{\bar{P}^+}{2\pi} \int dz\, e^{ix\bar{P}^+ z} \left\langle B(p_2) \left| \bar{\psi}_{q'}\left(-\frac{z}{2}\right) \gamma_+ \gamma_5 \psi_q\left(\frac{z}{2}\right) \right| A(p_1) \right\rangle = \left(\tilde{H}_q(x, \xi, t)\, \bar{N}(p_2)\, \gamma_+ \gamma_5 N(p_1) \right.$$
$$\left. + \frac{\Delta_+}{2m_N} \tilde{E}_q(x, \xi, t)\, \bar{N}(p_2)\, N(p_1) \right),$$

- Several competing parametrizations of GPDs in the literature (EPJC 59, 809; EPJC 39, 1; PRD 72, 054013; NPB 841, 1, ...)

GPD extraction from DVCS

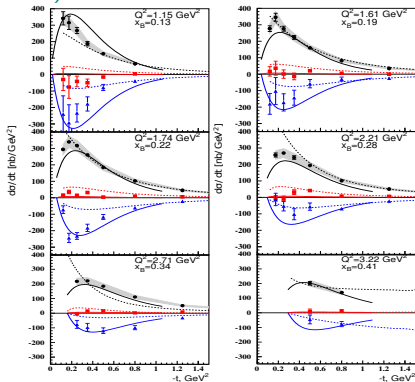Kinematic coverage of DVCS experiments.

- 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

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

$\Leftarrow$ Dependence on azimuthal angle ϕ_π between ep and πp planes
- Should not exist in leading twist
- Signals that **tw-3 contributions are pronounced**

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

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

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

$\Rightarrow$ This channel requires significantly larger Q^2 to access GPDs

Challenge in GPD extraction from vector mesons

Vector meson wave function unknown

- never measured directly in the experiment
- controlled by confinement (not SCSB), depends heavily on the model

$\Rightarrow$ Significant uncertainty in extraction of GPDs from this channel

How charged currents can help ?

Advantages

- $V - A$ structure of interaction $\Rightarrow$ 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$\Rightarrow$can extract full flavor structure of GPD

Where such processes can be studied ?

MINERvA@Fermilab

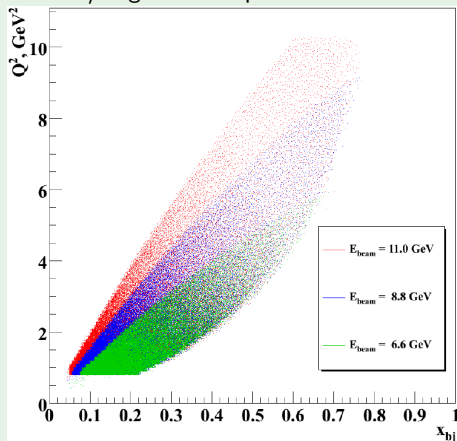- Extremely large luminosity
- Both ν_μ and $\bar{\nu}_\mu$ can be used
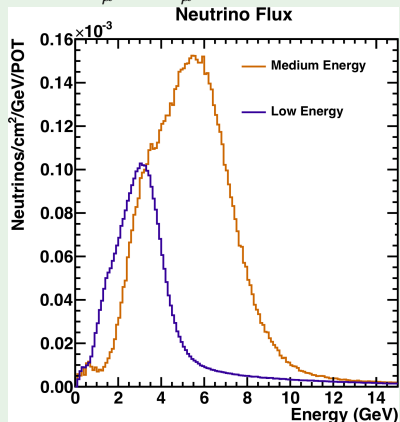
- Analysis of data in Bjorken kinematics has already started

UTFSM MINERvA group: Jonathan Miller *et al.*

Jefferson Laboratory

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

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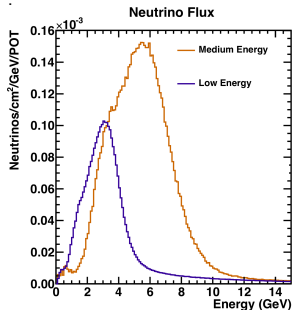
Advantages
- Extremely large luminosity
- Both ν_μ and $\bar{\nu}_\mu$ can be used ($W^\pm$-induced production)

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

Flavor combinations of GPDs probed by various processes

- Experimentally easiest:$\nu p \to \mu^- \pi^+ p$, $\bar{\nu} p \to \mu^+ \pi^- p$:

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

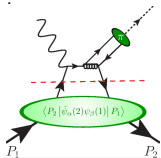$$\mathcal{A}^{(\mathrm{LO})}_{\bar{\nu} p \to \mu^+ \pi^- p} \sim \int_{-1}^{1} dx \left(\frac{H_u(x, \xi)}{x - \xi + i0} + \frac{H_d(x, \xi)}{x + \xi - i0} \right)$$

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

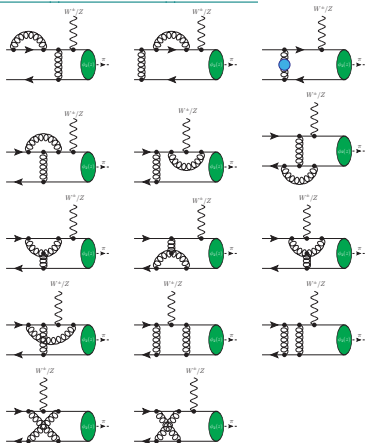$$H_{p \to n} = H_u(x, \xi, t) - H_d(x, \xi, t)$$

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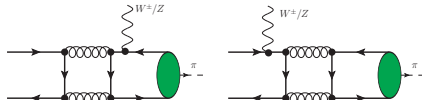
Loop corrections

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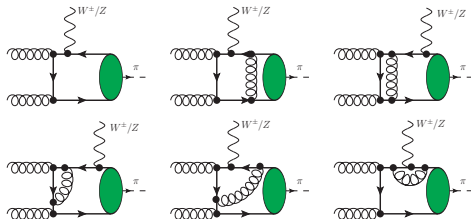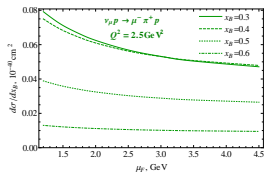- Challenge: separate corrections to coefficient function and GPD/DA$_\pi$ evolution kernel (scale μ_F)

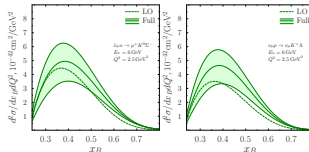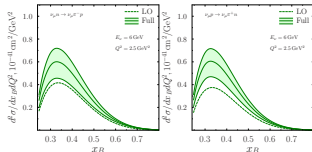- **NLO coefficient functions**

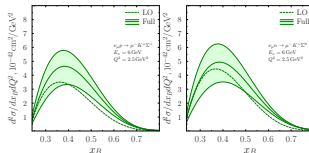

- Sea quarks contribution
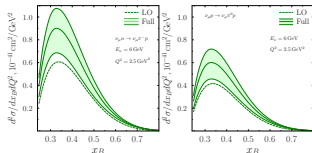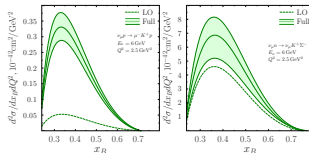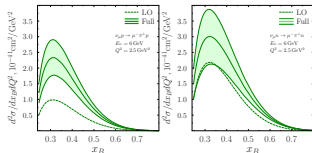

- Gluons contribution (LO+NLO)

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 $\gtrsim 50\%$
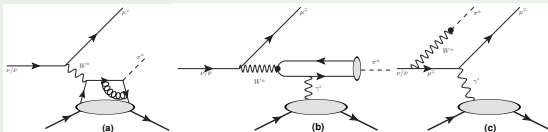$\Rightarrow$ NNLO corrections are needed !

Contaminations by twist-3 & Bethe-Heitler mechanism

Twist-3 effects
- Quark spin flip $\Rightarrow$ 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

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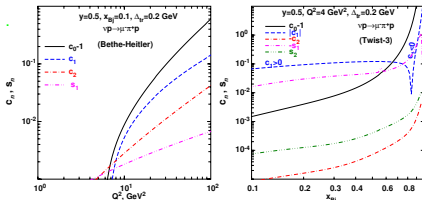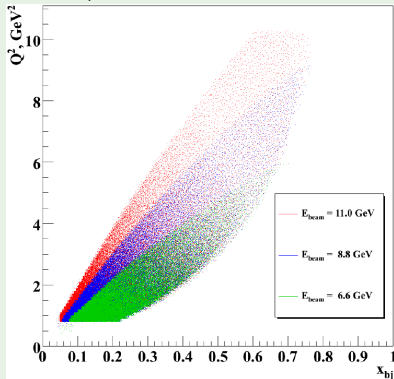

- Expect that harmonics c_n, s_n should be small

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 $\mathcal{L} = 10^{36} \text{cm}^{-2} s^{-1}$
- Beam/target can be polarized

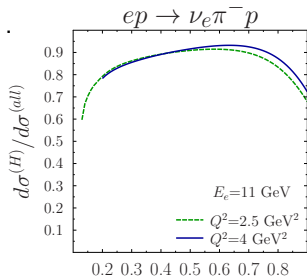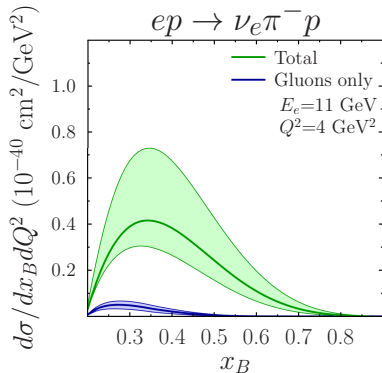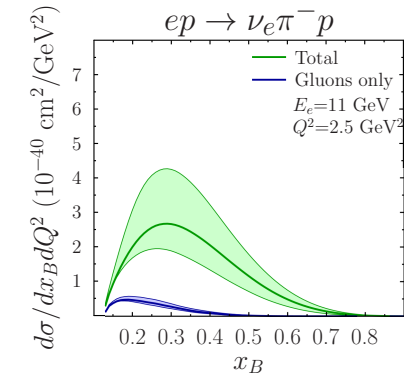

Suggested process: $ep \to \nu_e \pi^- p$

- Neutrino ν_e momentum reconstructed via momentum conservation

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

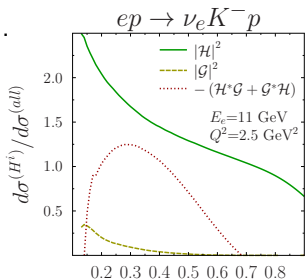-final hadrons are charged, kinematics resolution should be good.

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

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

$ep \to \nu_e \pi^- p$

$d\sigma / dx_B dQ^2$ $(10^{-40}$ cm^2/GeV$^2)$

Total
Gluons only
E_e=11 GeV
Q^2=2.5 GeV^2

x_B

$ep \to \nu_e \pi^- p$

$d\sigma / dx_B dQ^2$ $(10^{-40}$ cm^2/GeV$^2)$

Total
Gluons only
E_e=11 GeV
Q^2=4 GeV^2

x_B

$ep \to \nu_e \pi^- p$

$d\sigma^{(H)} / d\sigma^{(all)}$

E_e=11 GeV
Q^2=2.5 GeV^2
Q^2=4 GeV^2

- For pions with beam luminosity $L \sim 10^{35}$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).

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

$ep \to \nu_e K^- p$

- Total
- Gluons only

E_e=11 GeV
Q^2=2.5 GeV^2

$d\sigma/dx_B dQ^2$ (10^{-40} cm^2/GeV^2)

x_B

$en \to \nu_e \pi^- n$

- Total
- Gluons only

E_e=11 GeV
Q^2=2.5 GeV^2

$d\sigma/dx_B dQ^2$ (10^{-40} cm^2/GeV^2)

x_B

$ep \to \nu_e K^- p$

- $|\mathcal{H}|^2$
- $|\mathcal{G}|^2$
- $-(\mathcal{H}^*\mathcal{G} + \mathcal{G}^*\mathcal{H})$

E_e=11 GeV
Q^2=2.5 GeV^2

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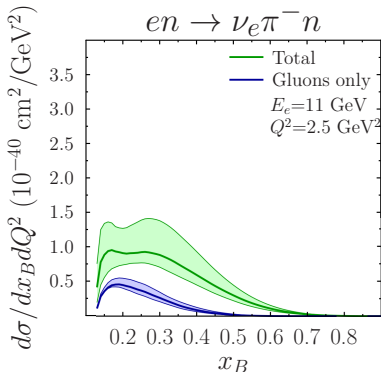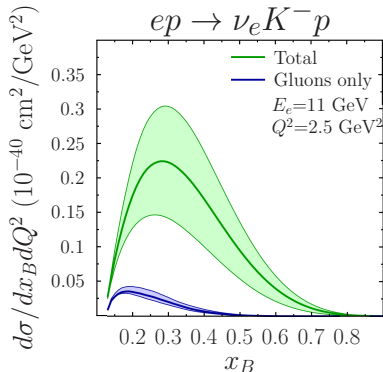
- For K-mesons, suppression by an order of magnitude (Cabibbo forbidden), smaller statistics
- Sizeable _negative_ contribution from interference $\mathcal{H}^*\mathcal{G} + \mathcal{G}^*\mathcal{H}$

- 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

Summary

- Charged current Deeply Virtual Pion/Kaon Production can be used as an additional source of information on proton structure (its GPDs)

  ★ Can be studied at νp and ep experiments thanks to large luminosity of modern experiments.

- The QCD NLO corrections are large for $Q^2 \sim 3 - 5$ GeV^2, NNLO corrections are needed (both for photo- and for charged current pion production)