Generalized parton distributions from neutrino experiments

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

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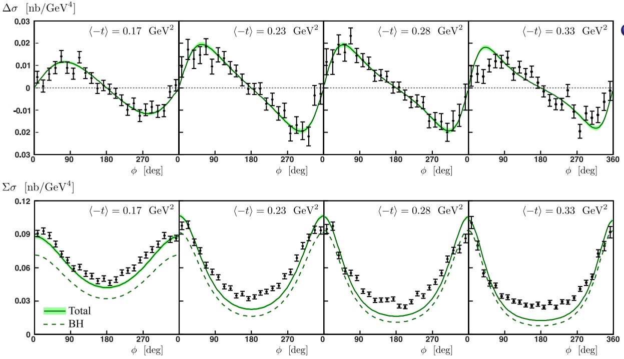
Generalized Parton Distributions

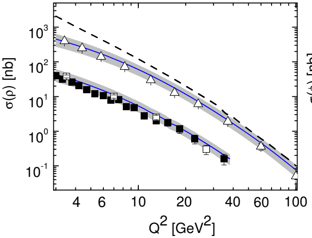
- Straightforward generalization of ordinary PDF to off-forward case
- Contain lots of information on the proton:
  - PDFs & Formfactors as limiting cases
  - Orbital angular momenta of partons
  - Distribution of partons in transverse plain ("tomography")
- In a collinear factorization approach, give amplitudes of a wide class of processes in Bjorken limit. Factorization theorems proved to all orders (X. Ji *et.al.* PRD 58 (1998) 094018, J. Collins *et.al.*, PRD 56(1997) 2982, PRD 59 (1999) 074009, S. Brodsy *et.al.* PRD 50(1994) 3134)
- Several competing parametrizations of GPDs on the market (Kroll *et.al.*, EPJC 59, 809; Diehl *et.al.* EPJC 39, 1; Guidal *et.al.* PRD 72, 054013; Kumericki *et.al.*, NPB 841, 1, ...)

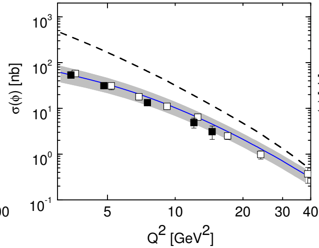
Generalized Parton distributons (contd.)

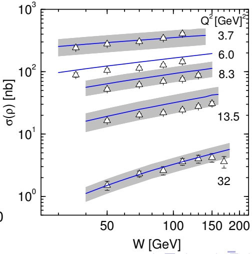
(Kroll-Moutarde-Sabatié model, EPJC 73 (2013), 2278, EPJC 53 (2008)367)



- Give reasonable description for various observables from JLAB up to HERA kinematics

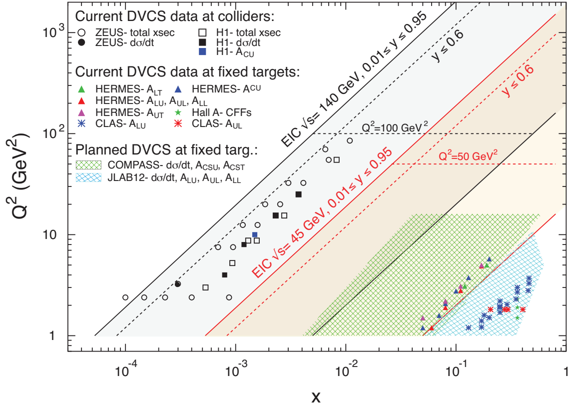






GPD extraction from DVCS

(EIC white paper, 2012, arXiv:1212.1701)

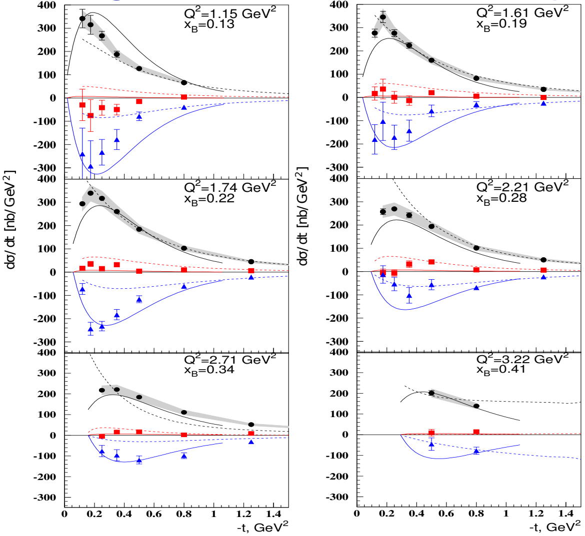


- Theoretically the cleanest and best understood is DVCS
- Interference with BH
  - $\Rightarrow$ phase of the amplitude
- Polarization asymmetries
  - $\Rightarrow$ separate $H, E, \tilde{H}, \tilde{E}$
- but is sensitive only to

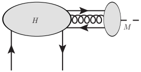
$$H = \sum_f e_f^2 H_f + \mathcal{O}(\alpha_s) H_g$$

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

Challenges in GPD extraction from pion production



- Tw-2 contribution is small $\sigma_L \sim \left|\{\tilde{H},\tilde{E}\}\otimes\phi_{2;\pi}\right|^2$
- Tw-3 are important
  $\sigma_{TT} \sim |\{H_T,E_T\}\otimes\phi_{3;\pi}|^2$
  $\sigma_{LT} \sim |\{H_T,E_T\}\otimes\phi_{3;\pi}|^2$
  (PRD 79 (2009) 054014; PRD 84 (2011) 034007; EPJA 47 (2011) 112)
- ϕ_π-angle between $\pi\, p$ and ep planes
- Data from (CLAS, PRL 109 (2012) 112001)
- In Tw-3 there are $\bar{q}qg$



(Anikin *et.al.*, PLB 682 (2010), 413)

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

Challenges in GPD extraction from vector meson DVMP

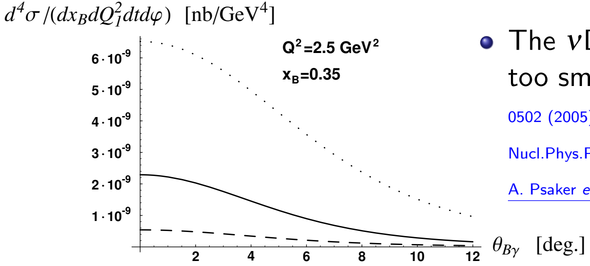
- At HERA (asymptotically small x_B) there are large BFKL-type logs $\sim \alpha_s \ln x$ (D. Y. Ivanov *et. al.*, EPJC 34 (2004) 297; JETP Lett. 80 (2004) 226; M. Diehl *et. al.*, EPJC 52 (2007) 933)
  - Need systematic resummation, take into account gluon recombination $(gg \to g)$
- At JLAB (larger x_B), usually virtuality Q^2 is not so large $\Rightarrow$ contributions of m_N/Q ?
- Vector meson wave function is needed
  - never measured directly in the experiment
  - controlled by confinement, depend on the model
  - should vanish at endpoints (assumed in collinear factorization)

$\Rightarrow$ Significant uncertainty in $\langle \phi^{-1} \rangle$

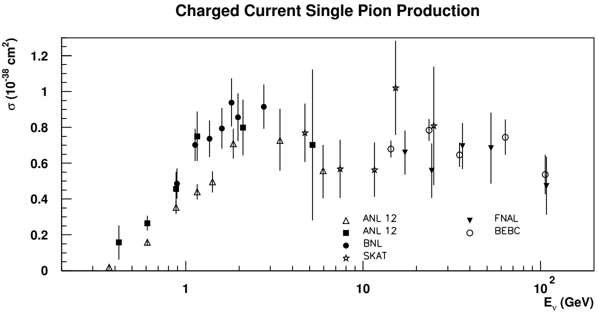
How neutrinos can help ?

- Collinear approach of the $\nu/\bar{\nu}$ processes is not immune to the above-mentioned problems
- But it allows us to check the **universality** of GPD parametrizations extracted from *ep*

Extraction of GPDs from $\nu/\bar{\nu}$ data



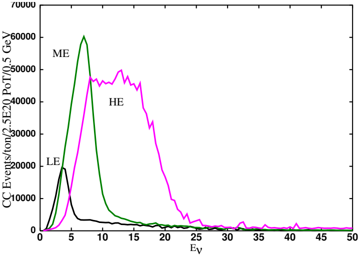
- The νDVCS cross-section too small (P. Amore *et.al.*, JHEP 0502 (2005) 038; C.Coriano *et.al.*, Nucl.Phys.Proc.Suppl. 168 (2007) 179; A. Psaker *et.al.*, Phys.Rev. D75 (2007) 054001)



- νDVMP has larger cross-section
- Only σ_t measured
- For coll. fact. need $d\sigma/dx_B dQ^2 dt$ in Bjorken kinematics

Extraction of GPDs from $\nu/\bar{\nu}$ data

Minerva@Fermilab will start in summer measurements with 6 GeV high-intensity $\nu/\bar{\nu}$-beam [potentially up to 20 GeV possible (Minerva proposal, hep-ex/0405002)]



- Challenge for analysis: $\nu/\bar{\nu}$ not monochromatic
  - Have to consider spectrum-averaged observables
- Test GPDs from *ep*, especially flavour structure, just from π & K production.
  - In contrast to *e*DVMP, for π- and K-meson νDVMP H, E dominate

    $\Rightarrow$ Expect smaller contamination by tw-3
  - $\phi_{2;\pi}$ compatible with ϕ_{as} ($F_{\pi\gamma\gamma}(Q^2)$@CLOE, CLEO, BABAR, BELLE).
  - For kaons chiral corrections are controlled by $\mathcal{O}(m_s/1\,\mathrm{GeV})$.

Flavour structure of various processes

(PRD 86 (2012) 113018)

Can probe NC and CC processes, $SU(3)$ for $H_{p\to Y}$ $\Rightarrow$ full flavour structure

Process	$\mathcal{H}_M$
$\nu\, p \to \mu^- \pi^+ p$	$V_{ud}\,(H_d c_- + H_u c_+)$
$\bar\nu\, p \to \mu^+ \pi^- p$	$V_{ud}\,(H_u c_- + H_d c_+)$
$\bar\nu\, p \to \mu^+ \pi^0 n$	$V_{ud}\,(H_u - H_d)(c_+ - c_-)/\sqrt{2}$
$\nu\, p \to \nu\, \pi^+ n$	$(H_u - H_d)(g_u c_- + g_d c_+)$
$\nu\, p \to \nu\, \pi^0 p$	$(g_u H_u - g_d H_d)(c_- + c_+)/\sqrt{2}$
$\bar\nu\, p \to \mu^+ \pi^- \Sigma_+$	$-V_{us}\,(H_d - H_s)\, c_+$
$\bar\nu\, p \to \mu^+ \pi^0 \Sigma_0$	$V_{us}\,(H_d - H_s)\, c_+/2$
$\bar\nu\, p \to \mu^+ \pi^0 \Lambda$	$V_{us}\,(2H_u - H_d - H_s)\, c_+/2\sqrt{3}$

$\nu\, p \to \mu^- K^+ p$	$V_{us}\,(c_+ H_u + c_- H_s)$
$\bar\nu\, p \to \mu^+ K^- p$	$V_{us}\,(H_u c_- + H_s c_+)$
$\bar\nu\, p \to \mu^+ K^0 \Sigma_0$	$-V_{ud}\,(H_d - H_s)\, c_-/\sqrt{2}$
$\bar\nu\, p \to \mu^+ K^0 \Lambda$	$-V_{ud}\,(2H_u - H_d - H_s)\, c_-/\sqrt{6}$
$\bar\nu\, p \to \mu^+ \bar{K}^0 n$	$-V_{us}\,(H_u - H_d)\, c_-$
$\nu\, p \to \mu^- K^+ \Sigma^+$	$-V_{ud}\,(H_d - H_s)\, c_-$
$\nu\, p \to \nu\, K^+ \Lambda$	$-(2H_u - H_d - H_s)(g_u c_- + g_d c_+)/\sqrt{6}$
$\nu\, p \to \nu\, K^+ \Sigma_0$	$(H_d - H_s)(g_u c_- + g_d c_+)/\sqrt{2}$
$\nu\, p \to \nu\, K^0 \Sigma^+$	$-g_d\,(H_d - H_s)(c_- + c_+)$

$\nu\, p \to \nu\, \eta\, p$	$(g_u H_u + g_d H_d - 2 g_d H_s)(c_- + c_+)/\sqrt{6}$
$\bar\nu\, p \to \mu^+ \eta\, n$	$V_{ud}\,(H_u - H_d)(c_- + c_+)/\sqrt{6}$
$\bar\nu\, p \to \mu^+ \eta\, \Sigma_0$	$V_{us}\,(H_u - H_d)(c_+ - 2c_-)/2\sqrt{3}$
$\bar\nu\, p \to \mu^+ \eta\, \Lambda$	$V_{us}\,(2H_u - H_d - H_s)(c_+ - 2c_-)/6$

Process	$\mathcal{H}_M$
$\nu\, n \to \mu^- \pi^+ n$	$V_{ud}\,(H_u c_- + H_d c_+)$
$\bar\nu\, n \to \mu^+ \pi^- n$	$V_{ud}\,(H_d c_- + H_u c_+)$
$\nu\, n \to \mu^- \pi^0 p$	$V_{ud}\,(H_u - H_d)(c_- - c_+)/\sqrt{2}$
$\nu\, n \to \nu\, \pi^- p$	$(H_u - H_d)(g_d c_- + g_u c_+)$
$\nu\, n \to \nu\, \pi^0 n$	$(g_u H_d - g_d H_u)(c_- + c_+)/\sqrt{2}$
$\bar\nu\, n \to \mu^+ \pi^- \Lambda$	$-V_{us}\,(2H_d - H_u - H_s)\, c_+/\sqrt{6}$
$\bar\nu\, n \to \mu^+ \pi^- \Sigma_0$	$-V_{us}\,(H_u - H_s)\, c_+/\sqrt{2}$
$\bar\nu\, n \to \mu^+ \pi^0 \Sigma^-$	$V_{us}\,(H_u - H_s)\, c_+/\sqrt{2}$

$\nu\, n \to \mu^- K^+ n$	$V_{us}\,(c_+ H_d + c_- H_s)$
$\bar\nu\, n \to \mu^+ K^- n$	$V_{us}\,(H_d c_- + H_s c_+)$
$\bar\nu\, n \to \mu^+ K^0 \Sigma^-$	$-V_{ud}\,(H_u - H_s)\, c_-$
$\nu\, n \to \nu K^0 \Lambda$	$-g_d\,(2H_d - H_u - H_s)(c_- + c_+)/\sqrt{6}$
$\nu\, n \to \nu K^0 \Sigma_0$	$-g_d\,(H_u - H_s)(c_- + c_+)/\sqrt{2}$
$\nu\, n \to \mu^- K^+ \Sigma^0$	$-V_{ud}\,(H_u - H_s)\, c_-/\sqrt{2}$
$\nu\, n \to \mu^- K^+ \Lambda$	$-V_{ud}\,(2H_d - H_u - H_s)\, c_-/\sqrt{6}$
$\nu\, n \to \mu^- K^0 p$	$-V_{us}\,(H_d - H_u)\, c_+$
$\nu\, n \to \nu\, K^+ \Sigma^-$	$-(H_u - H_s)(g_u c_- + g_d c_+)$

$\nu\, n \to \nu\, \eta\, n$	$(g_u H_d + g_d H_u - 2 g_d H_s)(c_- + c_+)/\sqrt{6}$
$\bar\nu\, n \to \mu^+ \eta\, \Sigma^-$	$V_{us}\,(H_u - H_s)(2c_- - c_+)/\sqrt{6}$
$\nu\, n \to \mu^- \eta\, p$	$V_{ud}\,(H_u - H_d)(c_- + c_+)/\sqrt{6}$

41 processes in total

Similar for contributions of $E, \tilde{H}, \tilde{E}$

$C_\pm$ known up to NLO (D. Ivanov *et. al.*, JETP Letters, 80 (2004), 226; M. Diehl *et. al.*, EPJC 52 (2007), 933)

Collinear approach (contd.)

- $SU(3)$ relations:

$$d\sigma_{\nu\,p\to\mu^-\pi^+p}=d\sigma_{\bar\nu\,n\to\mu^+\pi^-n},\quad d\sigma_{\bar\nu\,p\to\mu^+\pi^0 n}=d\sigma_{\nu\,n\to\mu^-\pi^0 p},\quad d\sigma_{\nu\,n\to\mu^-\pi^+ n}=d\sigma_{\bar\nu\,p\to\mu^+\pi^- p},$$

$$d\sigma_{\nu\,p\to\mu^-K^+\Sigma^+}=2\,d\sigma_{\bar\nu\,p\to\mu^+K^0\Sigma_0},\quad d\sigma_{\bar\nu\,n\to\mu^+K^0\Sigma^-}=2\,d\sigma_{\nu\,n\to\mu^-K^+\Sigma^0},\quad d\sigma_{\bar\nu\,p\to\mu^+\eta\,n}=d\sigma_{\nu\,n\to\mu^-\eta\,p},$$

$$d\sigma_{\bar\nu\,n\to\mu^+\pi^-\Sigma_0}=d\sigma_{\bar\nu\,n\to\mu^+\pi^0\Sigma^-}\quad d\sigma_{\bar\nu\,p\to\mu^+\pi^-\Sigma_+}=4\,d\sigma_{\bar\nu\,p\to\mu^+\pi^0\Sigma_0}\quad d\sigma_{\bar\nu\,n\to\mu^+\pi^-\Sigma_0}=d\sigma_{\bar\nu\,n\to\mu^+\pi^0\Sigma^-}$$

- There are other relations, e.g. taking linear combinations of amplitudes, like

$$|A+B|^2+|A-B|^2=2\left(|A|^2+|B|^2\right).$$

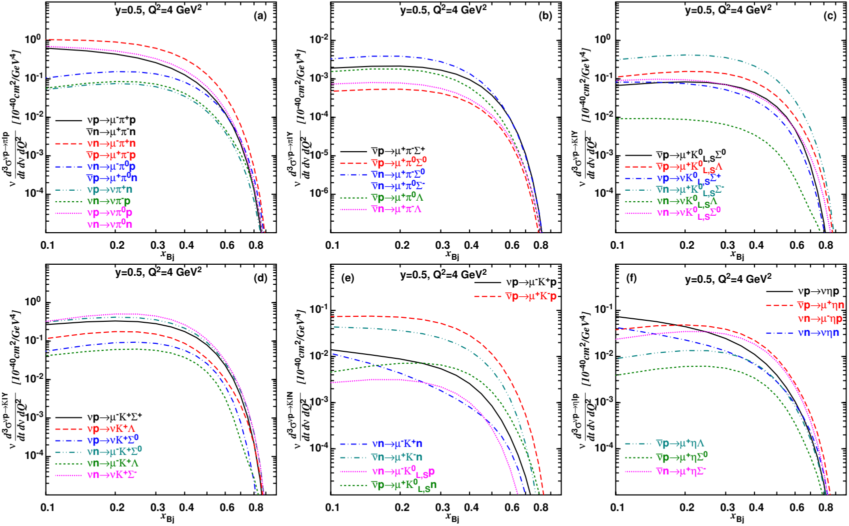
with

$$A=(H_u-H_d)\,c_-,\quad B=(H_u-H_d)\,c_+,$$

we get

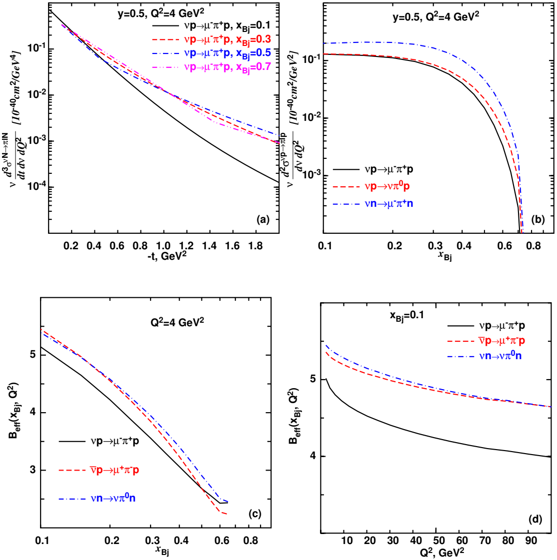
$$\underbrace{\left(d\sigma_{\bar\nu\,p\to\mu^+\bar K^0 n}+d\sigma_{\nu\,n\to\mu^-K^0 p}\right)}_{\text{Cabibbo suppressed},\,\Delta S=1}=\underbrace{\left|\frac{V_{us}}{V_{ud}}\right|^2\left(d\sigma_{\nu\,n\to\mu^-\pi^0 p}+3\,d\sigma_{\bar\nu\,p\to\mu^+\eta\,n}\right)}_{\text{Cabibbo allowed},\,\Delta S=0}.$$

DVMP cross-sections in GK model



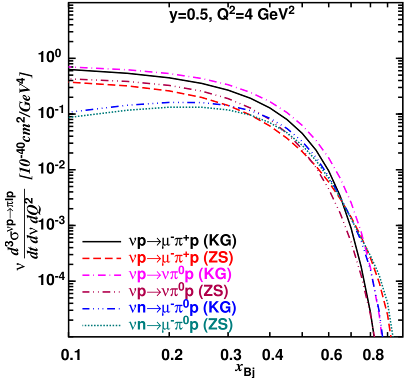
- $\Delta S = 0$ processes measurable with reasonable precision, $\Delta S = 1$ visible.
- Small-x: $N \to N$ senstitive to sea quarks, $N \to B'$ sensitive to valence quarks
- Large-x: suppression due to increase of $|t_{min}|$

DVMP cross-sections in GK model



- t-dependence is roughly given by $exp(B\,t)$
- x-dependence does not change a lot after integration over t
- The slope slightly depends on x, Q^2.

How much do results depend on GPD parametrization ?



Compare

- red with **black**
- magenta with purple

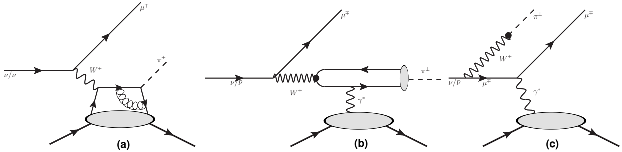
– differ up to a factor of two !

KG=Kroll-Goloskokov, ZS=Zero Skewness parametrization

$$H_i(x,\xi,t) = q_i(x)F_{i/N}(t)$$

Electromagnetic Bethe-Heitler corrections

- (PRD 87 (2013), 033008)
  - Interference with $\mathcal{O}(\alpha_{em})$ EM corrections



    - ★ (a) is suppressed at large-Q due to hard gluon in coef. function
    - ★ (b,c) are enhanced at small-$|t|$ due to γ^* in t-channel
    - ★ appears dependence on angle $\phi_{\nu p,\pi p}$
  - We'll discuss the size of effect in terms of angular harmonics c_n, s_n defined as

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

★ $c_0 = 1 + \mathcal{O}(\alpha_{em})$ $\quad c_1, s_1 = \mathcal{O}(\alpha_{em})$ $\quad c_2 = \mathcal{O}(\alpha_{em}^2)$

Electromagnetic Bethe-Heitler corrections (II)

- Coefficient s_1 can be directly extracted from cross-sections,

$$\frac{d^4\sigma_{asym}(\phi)}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}=\frac{d^4\sigma(\phi)}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}-\frac{d^4\sigma(-\phi)}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}=S_1^{int}\sin\phi,$$

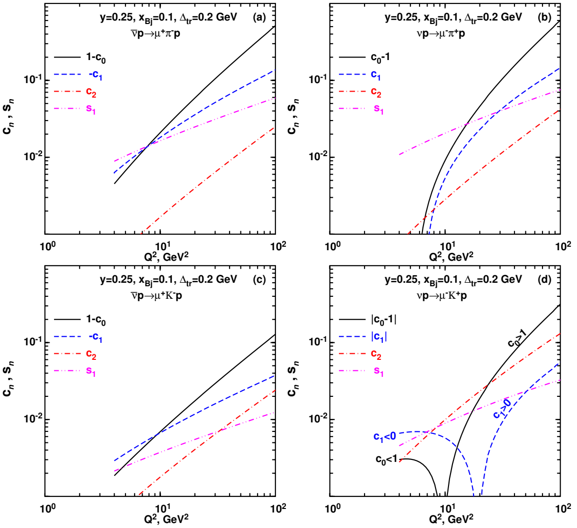
$$S_1=s_1\frac{d^3\sigma^{(DVMP)}}{dt\,dQ^2 d\ln\nu}\sim Im\mathscr{H}\left(F_1(t)+\mathscr{O}(x_B^2)F_2(t)\right)+\mathscr{O}(x_B^2)Im\mathscr{E}F_1(t)$$

- Can use isospin symmetry of DVMP:

$$\frac{d^4\sigma^{(int)}_{\bar\nu\,p\to\mu^+\pi^-p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}\approx\frac{d^4\sigma_{\bar\nu\,p\to\mu^+\pi^-p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}-\frac{d^4\sigma_{\nu\,n\to\mu^-\pi^+n}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}-\frac{d^4\sigma^{(BH)}_{\bar\nu\,p\to\mu^+\pi^-p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi},$$

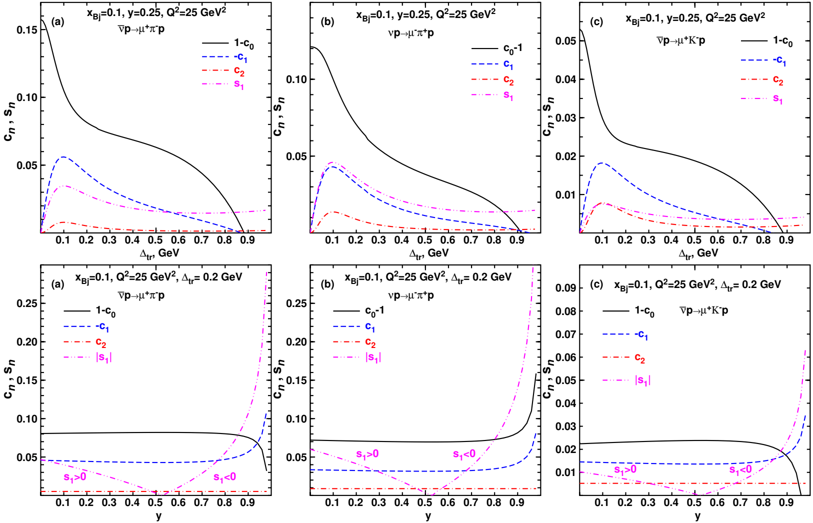
$$\frac{d^4\sigma^{(int)}_{\nu\,p\to\mu^-\pi^+p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}\approx\frac{d^4\sigma_{\nu\,p\to\mu^-\pi^+p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}-\frac{d^4\sigma_{\bar\nu\,n\to\mu^+\pi^-n}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}-\frac{d^4\sigma^{(BH)}_{\nu\,p\to\mu^-\pi^+p}}{dt\,d\ln x_{Bj}\,dQ^2 d\phi}.$$

Q^2-dependence of BH corrections



- Small in Minerva kinematics ($\sim \mathcal{O}(\alpha_{em})$), dominate in asymptotic Bjorken regime
- Real parts of π^-, K^- amplitudes have a node
  - not visible in total cross-section due to imaginary part (see s_1)

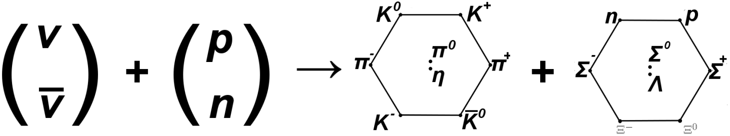
t- and y-dependence of BH corrections



- All harmonics decrease at large t due to photon propagator in t-channel; c_1, s_1 and c_2 have also $\Delta_\perp$ in prefactor $\Rightarrow$ maximal at $\Delta_\perp \sim 0.1$ GeV.
- y-dependence is flat, $s_1 \sim (1-2y) Im\mathscr{H} + \mathscr{O}(x_B)^2$

Summary

1. We argue that the neutrinoproduction of goldstones (π, K, η) can be an extra source of information for the phenomenological parametrizations of GPDs. MINERVA experiment will start measurement in a Bjorken kinematics and with sufficient sensitivity very soon.



2. We argue that due to interference with $\mathscr{O}(\alpha_{em})$ BH-type corrections the cross-sections depend on the angle between the lepton and hadron scattering planes and thus study of harmonics might be important.

We provide the code for evaluation of the cross-sections with arbitrary GPD parametrizations

(see e.g. http://prd.aps.org/supplemental/PRD/v87/i3/e033008)

Thank You for your attention !

Acknowledgements

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