Constraints on GPDs from neutrino experiments

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

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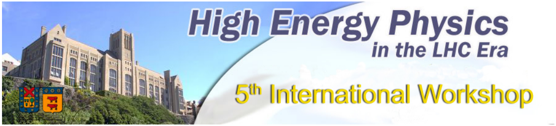
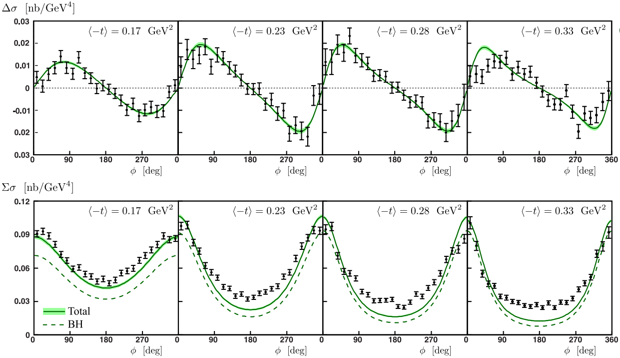


Generalized Parton Distributions

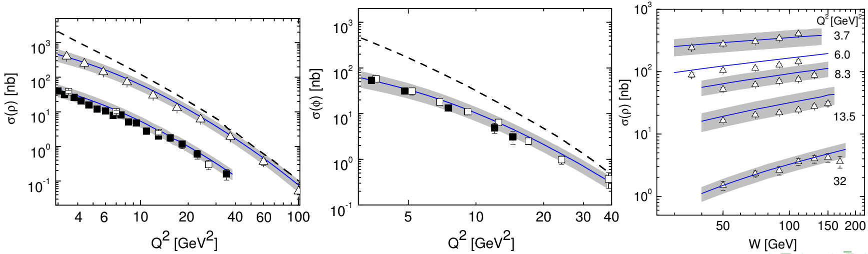
- Straightforward generalization of ordinary PDF to off-forward case
- Contain lots of information on the proton:
  - PDFs & Formfactors as limiting cases
  - Orbital angular momenta of partons
  - Distribution of partons in transverse plain ("tomography")
- In a collinear factorization approach, give 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)

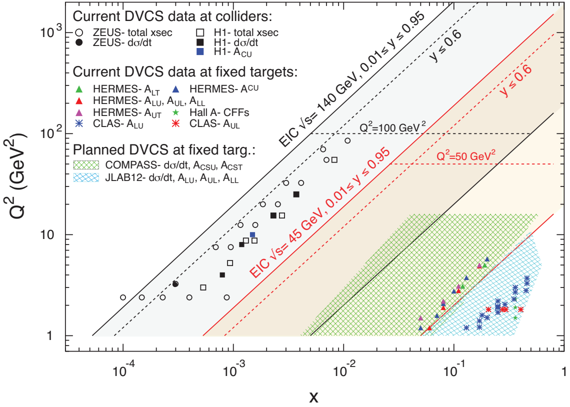


- Give reasonable description for various observables from JLAB up to HERA kinematics



GPD extraction from DVCS

(EIC white paper, 2012, arXiv:1212.1701)

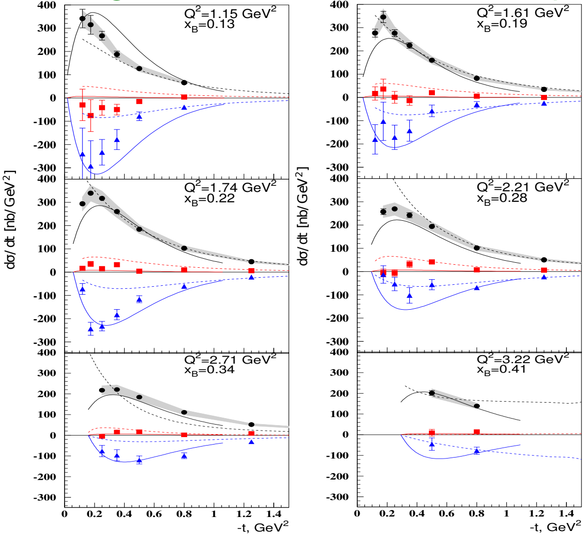


- Theoretically the cleanest and best understood is DVCS
- Interference with BH
  - $\Rightarrow$ phase of the amplitude
- Polarization asymmetries
  - $\Rightarrow$ separate $H, E, \tilde{H}, \tilde{E}$
- but is sensitive only to

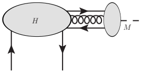
$$H = \sum_f e_f^2 H_f + \mathcal{O}(\alpha_s) H_g$$

- 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 πp 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)

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

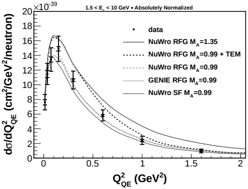
Challenges in GPD extraction from vector meson DVMP

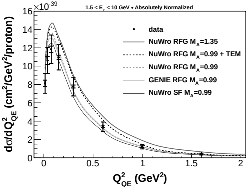
- At HERA (asymptotically small x_B) there are large BFKL-type logs $\sim \alpha_s \ln x$ (D. Y. Ivanov *et. al.*, EPJC 34 (2004) 297; JETP Lett. 80 (2004) 226; M. Diehl *et. al.*, EPJC 52 (2007) 933)
  - Need systematic resummation, take into account gluon recombination $(gg \to g)$
- At JLAB (larger 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*
- Luminosity is sufficient for measurements with reasonable accuracy:

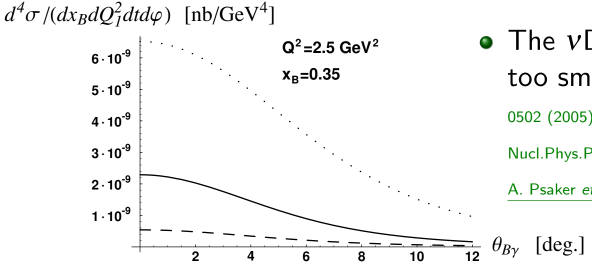
▶ 



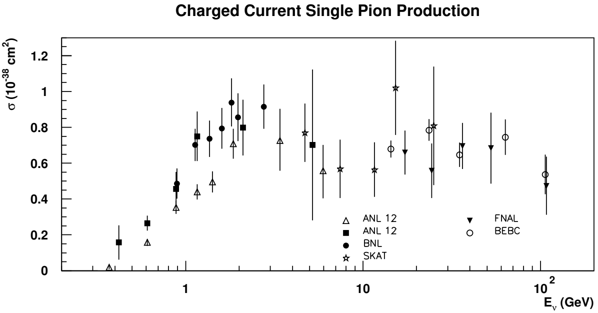
(Phys.Rev.Lett. 111 (2013) 022502) (Phys.Rev.Lett. 111 (2013) 022501)

First CCQE data from MINERvA for ν and $\bar{\nu}$ beams

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



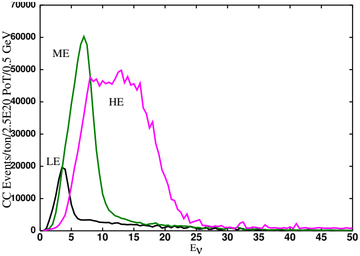
- The νDVCS cross-section too small (P. Amore *et.al.*, JHEP 0502 (2005) 038; C.Coriano *et.al.*, Nucl.Phys.Proc.Suppl. 168 (2007) 179; A. Psaker *et.al.*, Phys.Rev. D75 (2007) 054001)



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

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

Minerva@Fermilab recently started measurements with 6 GeV high-intensity $\nu/\bar{\nu}$-beam [potentially up to $20\,\mathrm{GeV}$ 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

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

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	$\mathscr{H}_M$	Process	$\mathscr{H}_M$
$\nu\, p \to \mu^-\pi^+ p$	$V_{ud}\,(H_d c_- + H_u c_+)$	$\nu\, n \to \mu^-\pi^+ n$	$V_{ud}\,(H_u c_- + H_d c_+)$
$\bar\nu\, p \to \mu^+\pi^- p$	$V_{ud}\,(H_u c_- + H_d c_+)$	$\bar\nu\, n \to \mu^+\pi^- n$	$V_{ud}\,(H_d c_- + H_u c_+)$
$\bar\nu\, p \to \mu^+\pi^0 n$	$V_{ud}\,(H_u - H_d)(c_+ - c_-)/\sqrt{2}$	$\nu\, n \to \mu^-\pi^0 p$	$V_{ud}\,(H_u - H_d)(c_- - c_+)/\sqrt{2}$
$\nu\, p \to \nu\,\pi^+ n$	$(H_u - H_d)(g_u c_- + g_d c_+)$	$\nu\, n \to \nu\,\pi^- p$	$(H_u - H_d)(g_d c_- + g_u c_+)$
$\nu\, p \to \nu\,\pi^0 p$	$(g_u H_u - g_d H_d)(c_- + c_+)/\sqrt{2}$	$\nu\, n \to \nu\,\pi^0 n$	$(g_u H_d - g_d H_u)(c_- + c_+)/\sqrt{2}$
$\bar\nu\, p \to \mu^+\pi^-\Sigma_+$	$-V_{us}\,(H_d - H_s)\,c_+$	$\bar\nu\, n \to \mu^+\pi^-\Lambda$	$-V_{us}\,(2H_d - H_u - H_s)\,c_+/\sqrt{6}$
$\bar\nu\, p \to \mu^+\pi^0\Sigma_0$	$V_{us}\,(H_d - H_s)\,c_+/2$	$\bar\nu\, n \to \mu^+\pi^-\Sigma_0$	$-V_{us}\,(H_u - H_s)\,c_+/\sqrt{2}$
$\bar\nu\, p \to \mu^+\pi^0\Lambda$	$V_{us}\,(2H_u - H_d - H_s)\,c_+/2\sqrt{3}$	$\bar\nu\, n \to \mu^+\pi^0\Sigma^-$	$V_{us}\,(H_u - H_s)\,c_+/\sqrt{2}$

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

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

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 between ν and $\bar{\nu}$ cross-sections:

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

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

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

- Other relations may be recovered with parallelogram identity:

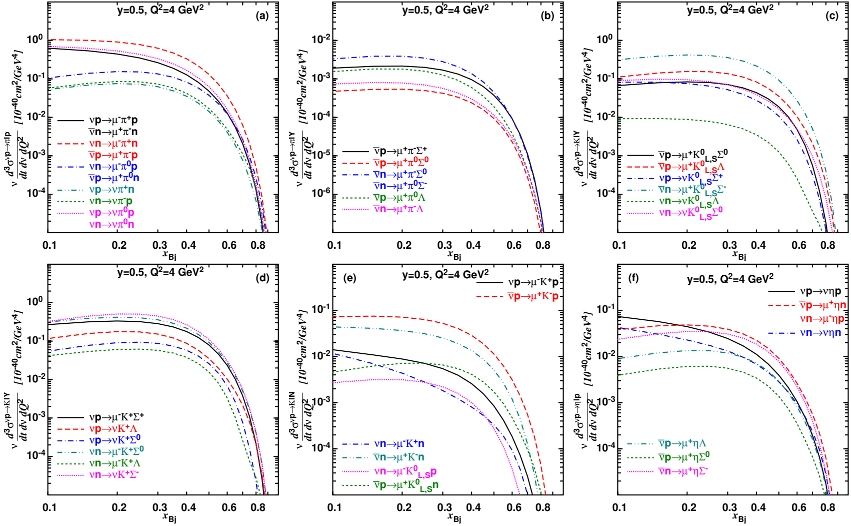
$$|A+B|^2 + |A-B|^2 = 2\left(|A|^2 + |B|^2\right).$$

e.g. with: $A = (H_u - H_d)\, c_-, \quad B = (H_u - H_d)\, c_+$ get

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

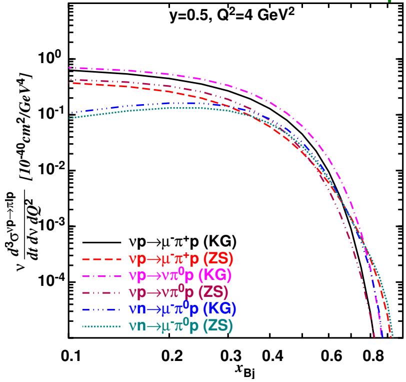
etc.

DVMP cross-sections in KG model



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

How much do results depend on GPD parametrization ?

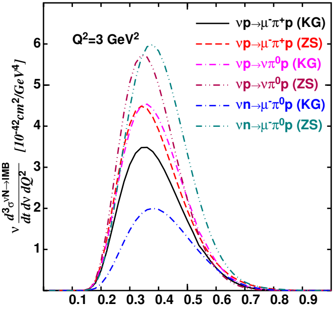


- Compare
  - red with **black**
  - magenta with purple

  differ up to a factor of 2!
- Averaging over $\nu/\bar{\nu}$-spectrum (ME):
  - Differences are smaller but sizeable

KG=Kroll-Goloskokov, ZS=Zero Skewness parametrization

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



Contamination by higher twist effects

- $$\mathscr{A} = \frac{1}{Q}\mathscr{A}_{tw-2} + \frac{1}{Q^2}\mathscr{A}_{tw-3} + \dots$$
- Consider only two-parton contributions,

$$\mathscr{A}_{tw-3} \propto \int dx\, dz\, C_3(x,\xi,z)\mathscr{H}(x,\xi,t)\Phi_3(z)$$

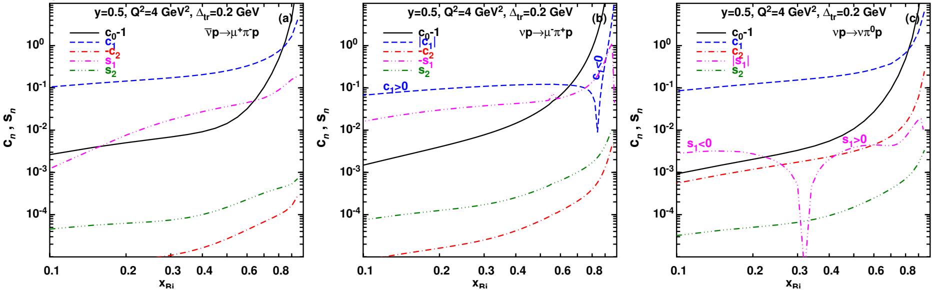
$$\mathscr{H} = \text{lin. comb.}\{H_T, E_T, \tilde{H}_T, \tilde{E}_T\},\ \Phi_3 = \text{lin. comb.}\{\phi_{3;\pi}^{(p)}, \phi_{3;\pi}^{(\sigma)}\}$$

- Collinear factorization holds only for tw-2, C_3 has collinear singularities like $C_3 \propto \frac{1}{(x\pm\xi\mp i0)^2} \Rightarrow$ sensitivity to transverse momenta
- Interference with LT $\Rightarrow$ dependence on angle $\phi = \phi_{\nu p,\pi p}$
- We'll discuss the size of effect in terms of angular harmonics c_n, s_n defined as

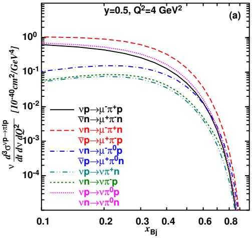
$$\frac{d^4\sigma^{(tot)}}{dt\, dQ^2 d\ln\nu\, d\phi} = \frac{1}{2\pi}\frac{d^3\sigma^{(DVMP)}}{dt\, dQ^2 d\ln\nu} \times \sum_n \left(c_n \cos n\phi + s_n \sin n\phi\right)$$

Contamination by higher twist effects

KG parametrization for $H_T, \bar{E}_T = E_T + 2\tilde{H}_T$ (Eur.Phys.J. A47 (2011) 112)

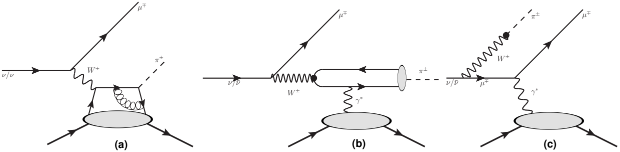


- Corrections are small, $c_0 - 1$ not more than $\sim 10\%$
  - Region $x_{Bj} \to 1$ corresponds to $t \to -\infty, d\sigma \to 0 \Rightarrow$
- Why different from eDVMP ?
  - 80-90% of LT from H, E (absent in eDVMP)
  - 10-20% of LT from $\tilde{H}, \tilde{E}$
  - Twist-3 correction is 10-20% of LT
- SU(3) relations broken – diff. weak isospin of ν, $\bar{\nu}$
- Decrease with Q^2 as $1/Q$



Electromagnetic corrections

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



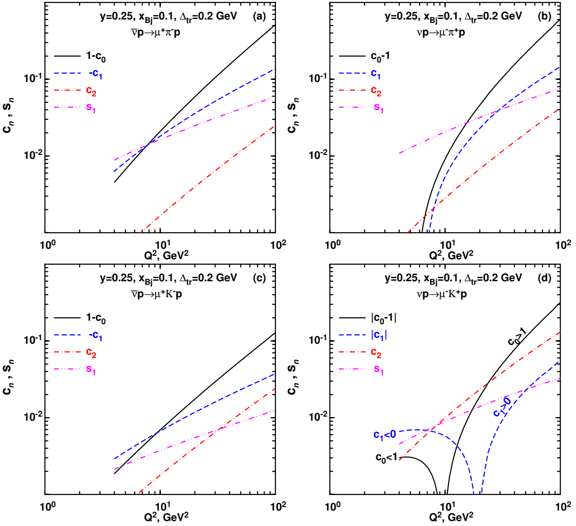
★ (a) is suppressed at large-Q due to hard gluon in coef. function
★ (b,c) are enhanced at small-$|t|$ due to γ^* in t-channel
★ appears dependence on angle $\phi_{\nu p,\pi p}$

  - We'll discuss the size of effect in terms of angular harmonics c_n, s_n defined as

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

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

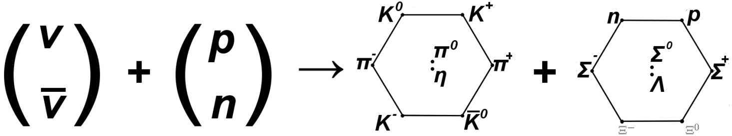
Q^2-dependence of EM corrections



- 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)

Summary

1. Neutrinoproduction of goldstones (π, K, η) can be an extra source of information for the phenomenological parametrizations of GPDs. MINERvA experiment recently started measurements in a Bjorken kinematics.



2. We estimate that contamination by higher twist corrections in case of νDVMP should be smaller than in eDVMP ($|c_0 - 1| < 10\%$).
3. In the asymptotic Bjorken regime $\mathcal{O}(\alpha_{em})$ EM corrections might be important.

We provide the code for evaluation of the cross-sections with arbitrary GPD parametrizations (LT + Tw-3 + EM) [available on demand, soon will be published]

Thank You for your attention !

Acknowledgements

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