

Generalized parton distributions with neutrinos

M. Siddikov

(PRD 86 (2012) 113018, PRD 87 (2013) 033008, PRD 89 (2014) 053001)



UNIVERSIDAD TÉCNICA
FEDERICO SANTA MARÍA

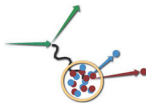
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Outline

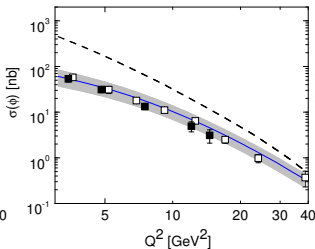
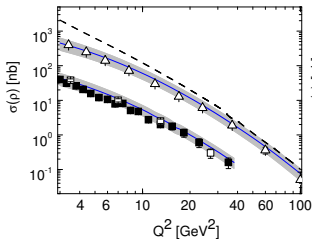
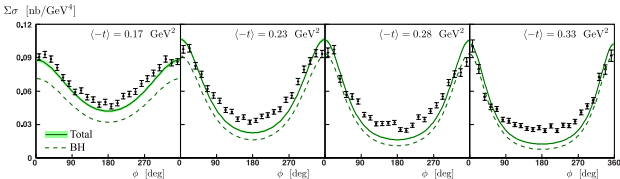
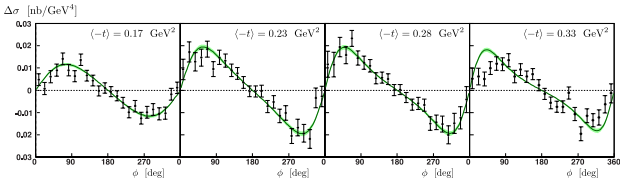
- Introduction
- Leading twist results
(PRD 86 (2012) 113018)
- Bethe-Heitler type corrections
(PRD 86 (2012) 113018, PRD 87 (2013) 033008)
- Higher twist effects
(PRD 89 (2014) 053001)
- Nuclear effects
(Under development)

Generalized Parton Distributions

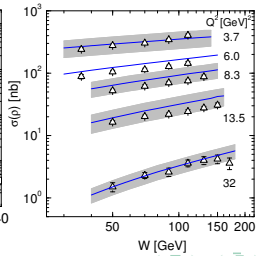
- Straightforward generalization of ordinary PDF to off-forward case
- Contain lots of information on the proton:
 - ▶ PDFs & Formfactors as limiting cases
 - ▶ Orbital angular momenta of partons
 - ▶ Distribution of partons in transverse plane (“tomography”)
- In a collinear factorization approach, 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. Brodsky *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)

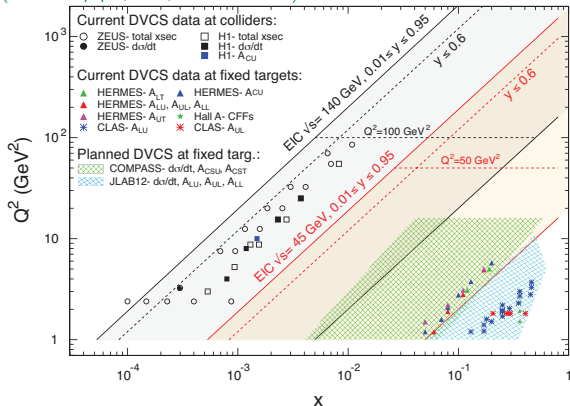


- Give reasonable description for various observables from JLAB up to HERA kinematics



GPD extraction from DVCS

(EIC white paper, 2012, arXiv:1212.1701)

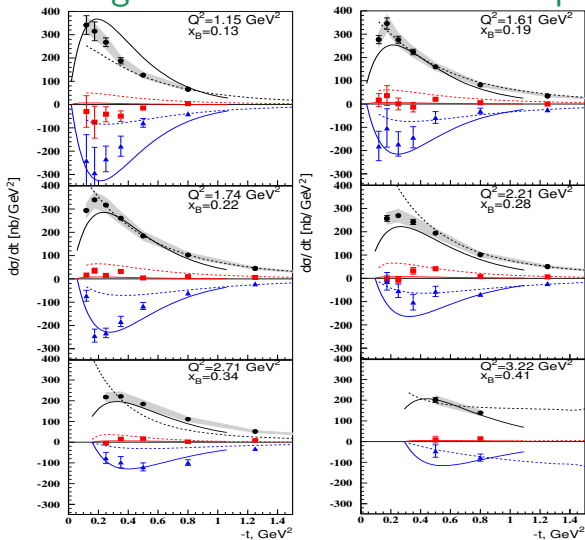


- Theoretically the cleanest and best understood is DVCS
- Interference with BH
 - ⇒ phase of the amplitude
- Polarization asymmetries
 - ⇒ separate $H, E, \tilde{H}, \tilde{E}$
- but is sensitive only to

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

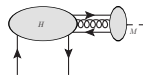
- DVMP may give access to GPD flavor structure, but theoretically is more complicated

Challenges in GPD extraction from pion production



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

- Tw-2 contribution is small $\sigma_L \sim |\{\tilde{H}, \tilde{E}\} \otimes \phi_{2;\pi}|^2$
- Tw-3 are important $\sigma_{TT} \sim |\{H_T, E_T\} \otimes \phi_{3;\pi}|^2$
 $\sigma_{LT} \sim |\{H_T, E_T\} \otimes \phi_{3;\pi}|^2$
- ϕ_π -angle between πp and ep planes
- Data from (CLAS, PRL 109 (2012) 112001)
- In Tw-3 there are $\bar{q}qg$



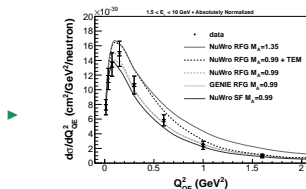
(Anikin *et.al.*, PLB 682 (2010), 413)

Challenges in GPD extraction from vector meson DVMP

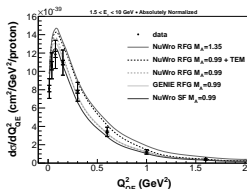
- At HERA (asymptotically small x_B) there are large BFKL-type logs $\sim \alpha_s \ln x$ (D. Y. Ivanov *et. al.*, EPJC 34 (2004) 297; JETP Lett. 80 (2004) 226; M. Diehl *et. al.*, EPJC 52 (2007) 933)
 - ▶ Need systematic resummation, take into account gluon recombination ($gg \rightarrow g$)
 - At JLAB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

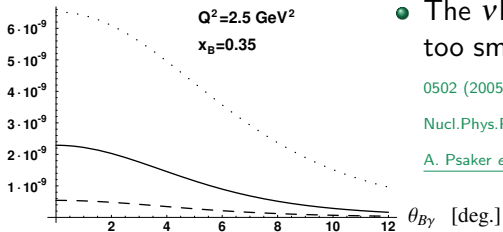


(Phys.Rev.Lett. 111 (2013) 022501)

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

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

$$d^4\sigma/(dx_B dQ^2 dt d\varphi) \text{ [nb/GeV}^4\text{]}$$



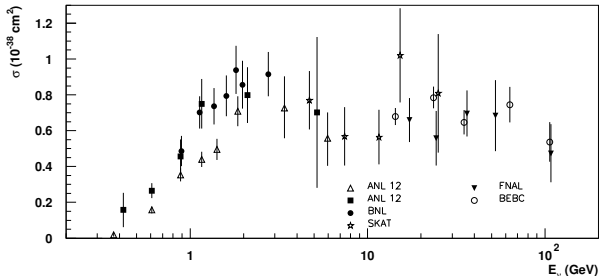
- The ν DVCS cross-section too small (P. Amore *et al.*, JHEP

0502 (2005) 038; C. Coriano *et al.*,

Nucl.Phys.Proc.Suppl. 168 (2007) 179;

[A. Psaker *et al.*, Phys.Rev. D75 \(2007\) 054001](#)

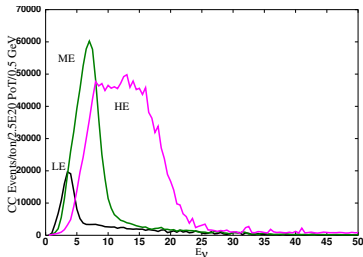
Charged Current Single Pion Production



- ν DVMP has larger cross-section
- Only σ_t measured
- For coll. fact. need $d\sigma/dQ^2 \dots$ 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 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 eDVMP, for π^- and K^- -meson ν DVMP H, E dominate
 - ⇒ 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 $\mathcal{O}(m_s/1\text{GeV})$.

Flavour structure of various processes

(PRD 86 (2012) 113018)

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

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

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

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

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

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

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

41 processes in total

C_{\pm} known up to NLO

(D. Ivanov et. al., JETP Letters, 80 (2004), 226; M. Diehl et. al., EPJC 52 (2007), 933)

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

Collinear approach (contd.)

- $SU(3)$ relations between ν and $\bar{\nu}$ cross-sections:

$$\begin{aligned}
 d\sigma_{\nu p \rightarrow \mu^- \pi^+ p} &= d\sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^- n}, & d\sigma_{\bar{\nu} p \rightarrow \mu^+ \pi^0 n} &= d\sigma_{\nu n \rightarrow \mu^- \pi^0 p}, & d\sigma_{\nu n \rightarrow \mu^- \pi^+ n} &= d\sigma_{\bar{\nu} p \rightarrow \mu^+ \pi^- p}, \\
 d\sigma_{\nu p \rightarrow \mu^- K^+ \Sigma^+} &= 2 d\sigma_{\bar{\nu} p \rightarrow \mu^+ K^0 \Sigma_0}, & d\sigma_{\bar{\nu} n \rightarrow \mu^+ K^0 \Sigma^-} &= 2 d\sigma_{\nu n \rightarrow \mu^- K^+ \Sigma_0}, & d\sigma_{\bar{\nu} p \rightarrow \mu^+ \eta n} &= d\sigma_{\nu n \rightarrow \mu^- \eta p}, \\
 d\sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^- \Sigma_0} &= d\sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^0 \Sigma^-} & d\sigma_{\bar{\nu} p \rightarrow \mu^+ \pi^- \Sigma_+} &= 4 d\sigma_{\bar{\nu} p \rightarrow \mu^+ \pi^0 \Sigma_0} & d\sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^- \Sigma_0} &= d\sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^0 \Sigma^-}
 \end{aligned}$$

- Other relations may be recovered with parallelogram identity:

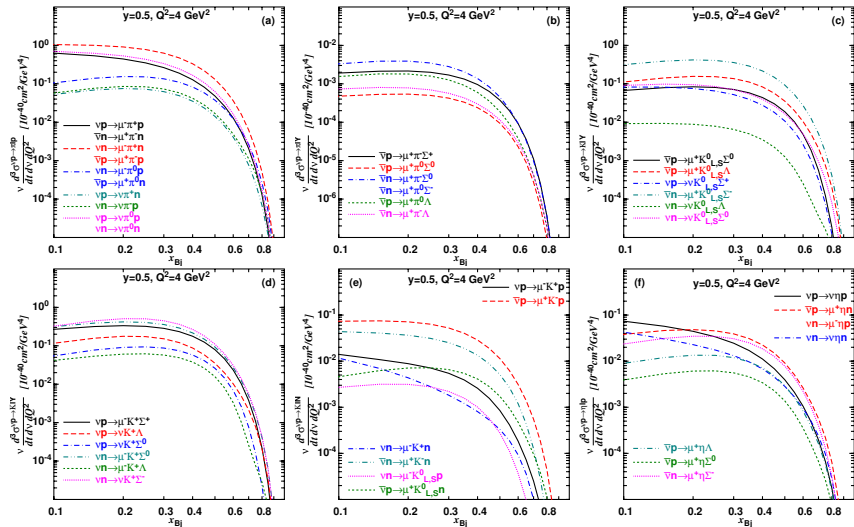
$$|A + B|^2 + |A - B|^2 = 2(|A|^2 + |B|^2).$$

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

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

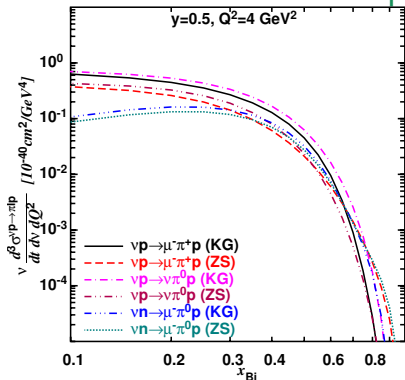
etc.

DVMP cross-sections in KG model



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

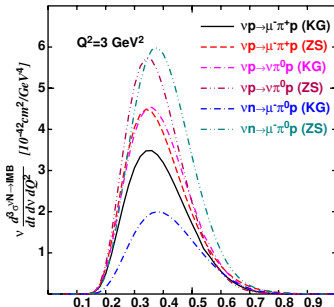
How much do results depend on GPD parametrization ?



KG=Kroll-Goloskokov, ZS=Zero Skewness parametrization

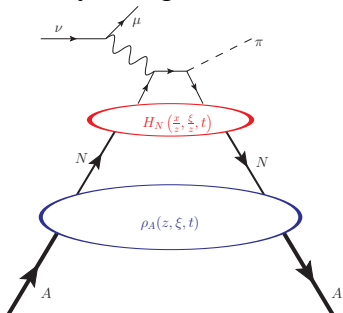
$$H_i(x, \xi, t) = q_i(x) F_{i/N}(t)$$

- Compare
 - ▶ red with black
 - ▶ magenta with purple
 differ up to a factor of 2!
- Averaging over v/\bar{v} -spectrum (ME):
 - ▶ Differences are smaller but sizeable

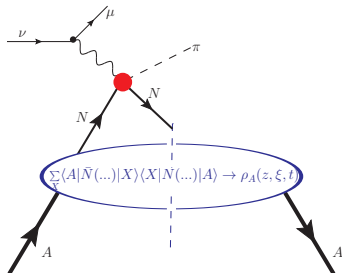


How important are nuclear effects ?

- Frequently experiments are done with nuclear targets (MINERvA: Fe, C, CH, Pb)
- Final baryon might be not detected, $\nu A \rightarrow \mu^\pm \pi^\mp X$



Coherent

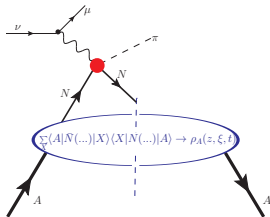
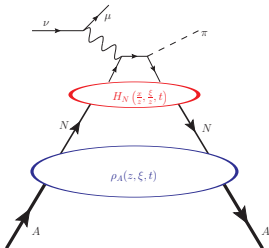


Incoherent

$$\mathcal{A}_A = \int \frac{dz}{z} \mathcal{A}_N \left(\frac{\xi}{z}, t \right) \rho_A(z, \xi, t) \quad \sigma_A = \int \frac{dz}{z} \sigma_N \left(\frac{\xi}{z}, t \right) \rho_A(z, 0, 0)$$

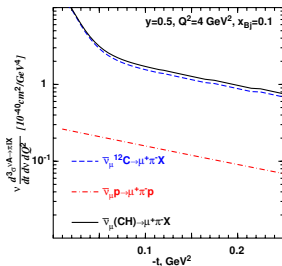
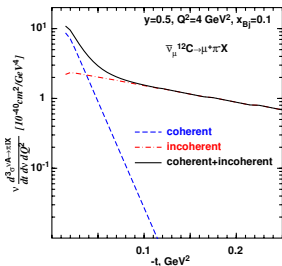
$\rho_A(z, \xi, t)$ —distribution of nucleons inside a nucleus

How important are nuclear effects ?



Coherent: $d\sigma/dt \sim F_A^2(t)$ Incoherent: $d\sigma/dt \sim F_N^2(t)$

- ▶ In case of molecules (e.g. CH), independent contribution of separate atoms



Contamination by higher twist effects

- $$\mathcal{A} = \frac{1}{Q} \mathcal{A}_{tw-2} + \frac{1}{Q^2} \mathcal{A}_{tw-3} + \dots$$

- Consider only two-parton contributions,

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

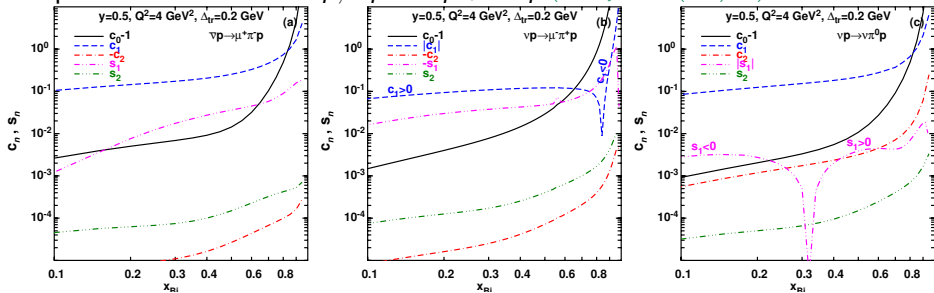
$$\mathcal{H} = \text{lin. comb.} \{H_T, E_T, \tilde{H}_T, \tilde{E}_T\}, \quad \Phi_3 = \text{lin. comb.} \{\phi_{3;\pi}^{(p)}, \phi_{3;\pi}^{(\sigma)}\}$$

- 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

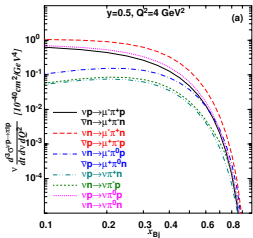
$$\frac{d^4 \sigma^{(tot)}}{dt dQ^2 d \ln v d\phi} = \frac{1}{2\pi} \frac{d^3 \sigma^{(DVMP)}}{dt dQ^2 d \ln v} \times \sum_n (c_n \cos n\phi + s_n \sin n\phi)$$

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)



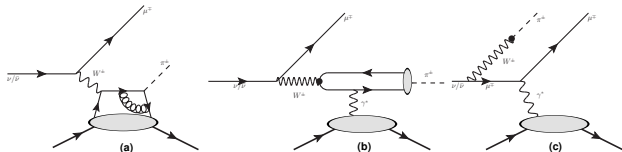
- Corrections are small, $c_0 - 1$ not more than $\sim 10\%$
 - ▶ Region $x_{Bj} \rightarrow 1$ corresponds to $t \rightarrow -\infty, d\sigma \rightarrow 0 \Rightarrow$
- Why different from eDVMP ?
 - ▶ 80-90% of LT from H, E (absent in eDVMP)
 - ▶ 10-20% of LT from \tilde{H}, \tilde{E}
 - ▶ Twist-3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

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

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

Electromagnetic corrections (II)

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

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

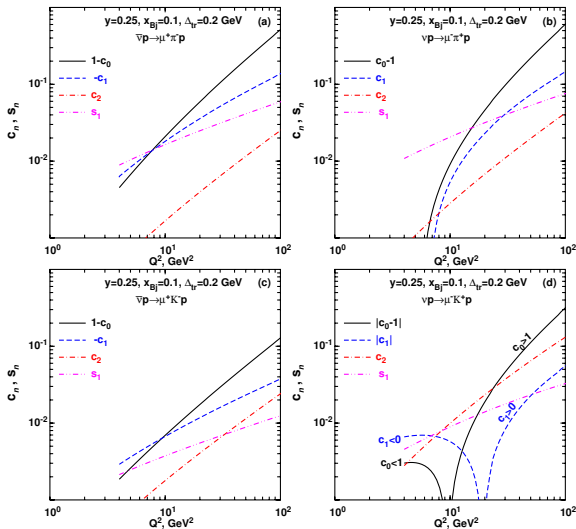
$$S_1 = s_1 \frac{d^3 \sigma^{(\text{DVMP})}}{dt dQ^2 d \ln v} \sim \text{Im} \mathcal{H}(F_1(t) + \mathcal{O}(x_B^2) F_2(t)) + \mathcal{O}(x_B^2) \text{Im} \mathcal{E} F_1(t)$$

- Can use isospin symmetry of DVMP:

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

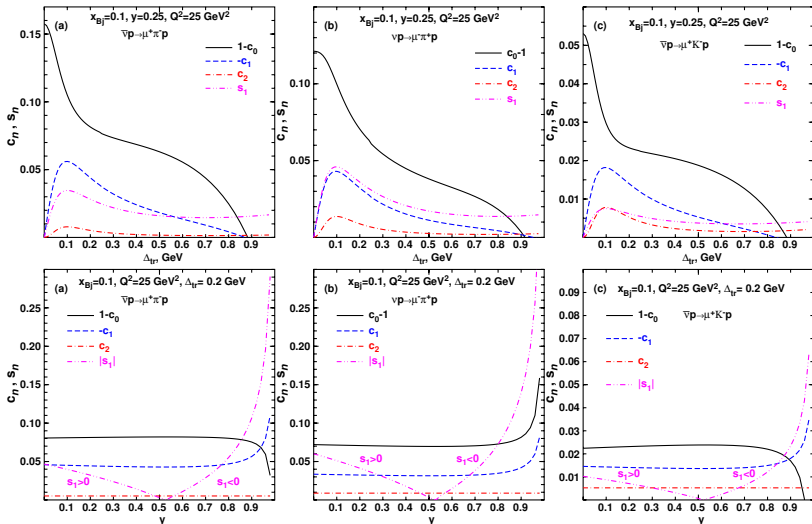
$$\frac{d^4 \sigma_{\nu p \rightarrow \mu^- \pi^+ p}^{(\text{int})}}{dt d \ln x_{Bj} dQ^2 d\phi} \approx \frac{d^4 \sigma_{\nu p \rightarrow \mu^- \pi^+ p}}{dt d \ln x_{Bj} dQ^2 d\phi} - \frac{d^4 \sigma_{\bar{\nu} n \rightarrow \mu^+ \pi^- n}}{dt d \ln x_{Bj} dQ^2 d\phi} - \frac{d^4 \sigma_{\nu p \rightarrow \mu^- \pi^+ p}^{(\text{EM})}}{dt d \ln x_{Bj} dQ^2 d\phi}.$$

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)

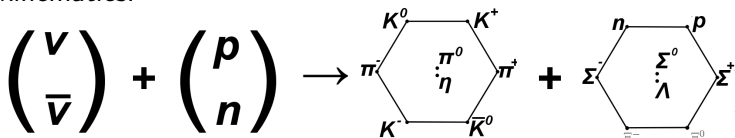
t - and y -dependence of EM corrections



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

Summary

- 1 Neutrino production 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 For nuclei, we can probe GPDs both with coherent and incoherent processes
- 3 We estimate that contamination by higher twist corrections in case of ν DVMP should be smaller than in eDVMP ($|c_0 - 1| < 10\%$).
- 4 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 + Nuclear effects) [available on demand, soon will

Thank You for your attention !