Polarization effects in ν-nucleon interactions

Beata Kowal, Krzysztof Graczyk
University of Wroclaw

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Outline

1. **Motivation**
2. **Quasielastic scattering**
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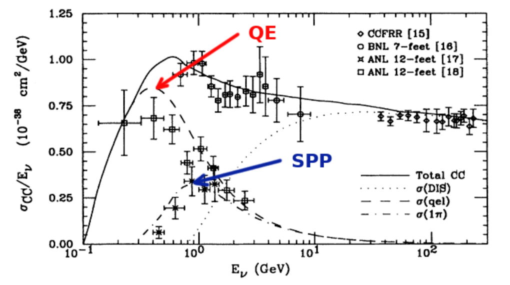
   - **Polarization observables**
3. **Single Pion Production**
   - **Formalizm of SPP**
   - **Polarization observables**
4. **Conclusion**

Motivation

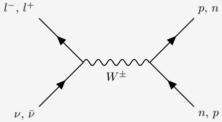
Neutrino interaction

Neutrino energy $E_\nu \sim 1$ GeV (accelerator neutrino experiments)

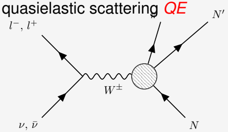
$$\sigma^{\nu N} = \sigma(QE) + \sigma(1\pi) + \sigma(DIS) + \ldots$$



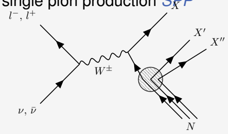
(P. Lipari et al, Phys.Rev. Lett.74(1995) 4384)



quasielastic scattering *QE*



single pion production *SPP*



deep inelastic scattering *DIS*

Neutrino Reactions at Accelerator Energies, Llewellyn Smith Phys.Rept. 3 (1972)

Motivation

CCQE

- **more precise measurements of F_A of the nucleon are needed**
- **an opportunity for searching for physics beyond the Standard Model**

SPP

- **procedures of testing SPP models to reduce model dependency**
- **studying of resonance and nonresonat background amplitudes, in particular relative phase between them**

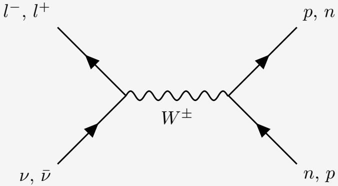
Quasielastic scattering formalism

Quasielastic scattering

CCQE channels

$$\nu_l + n \to l^- + p$$

$$\bar{\nu}_l + p \to l^+ + n$$



Vector-axial structure of nucleon vertex

$$\Gamma^\mu_+(q) \quad = \quad \gamma_\mu F_1^V + q_\mu \frac{F_3^V}{2M} + i\sigma^{\mu\nu} q_\nu \frac{F_2^V}{2M} - \left(\gamma_\mu F_A + q_\mu \frac{F_P}{2M} + i\sigma^{\mu\nu} q_\nu \frac{F_3^A}{M} \right) \gamma_5$$

1st class current, 2nd class current (SCC) - nonstandard interaction

SCC were considered theoretically and experimentally. No significant effect was found.

- Time reversal symmetry $\Longrightarrow$ real form factors
- Conserved vector current CVC $\Longrightarrow$ $F_3^V = 0$
  (weak F_1^V, F_2^V are related to the EM ones)
- Partial conservation of axial current PCAC $\Longrightarrow$ $F_P \sim F_A$

Our goal

- Proposing observables sensitive to the axial form factor
- Proposing observables sensitive to the beyond standard model contribution

- We propose polarization observables

Polarization properties of QE

Not discussed yet:

- Polarized target asymmetry
- Double-spin asymmetries
- Triple spin asymmetry

authors	papers	investigated particle polarisation
S. L. Adler	Il Nuovo Cimento (1955-1965) 30, 1020 (1963)	charged lepton and recoil nucleon
C. H. Llewellyn Smith	Phys. Rept. 3, 261 (1972)	charged lepton and recoil nucleon
K. Hagiwara et al.	Nucl. Phys. B668, 364 (2003)	τ-lepton
K. S. Kuzmin et al.	Nucl. Phys. Proc. Suppl. 139, 154(2005), Mod. Phys. Lett. A19, 2919 (2004)	τ-lepton
K. M. Graczyk	Nucl. Phys. A748, 313 (2005)	τ-lepton
M. Valverde et al.	Phys. Lett. B642, 218 (2006)	charged lepton
J. E. Sobczyk et al.	Phys. Rev. C100, 035501 (2019)	charged lepton
N. Jachowicz et al.	Phys. Rev. Lett. 93, 082501 (2004)	recoil nucleon
A. Fatima et al.	Phys. Rev. D98, 033005 (2018)	charged lepton and recoil nucleon (T-violation and *SCC*)
S. M. Bilenky et al.	Phys. Part. Nucl. Lett. 10, 651 (2013), J. Phys. G40, 075004 (2013)	recoil nucleon (the axial contribution to the polarization)
M. M. Block	Symmetries in Elementary Particle Physics (1965) p. 341	charged lepton and recoil nucleon (proposal of the measurement)

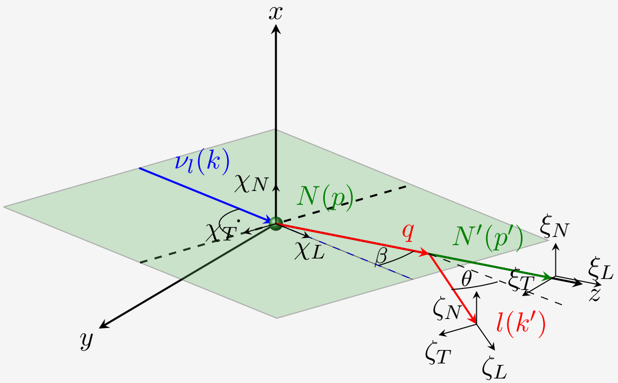
CCQE

Channels:

$$\nu_\mu + n \rightarrow \mu^- + p \quad , \quad \bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Angular distribution of the particles, in the laboratory frame

ζ, ξ, χ - spin components of the lepton, the nucleon and target



Three directions: L (longitiudinal), T (transverse), N (normal)

CCQE

The differential cross-section

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_0}{dQ^2}\Big(1 + \mathcal{P}^{\mu}_{l} s^{l}_{\mu} + \mathcal{T}^{\mu}_{N} s^{N}_{\mu} + \mathcal{P}^{\mu}_{N'} s^{N'}_{\mu} + s^{l}_{\mu} s^{N'}_{\nu} \mathcal{A}^{\mu\nu}_{lN'}$$
$$+ s^{l}_{\mu} s^{N}_{\nu} \mathcal{B}^{\mu\nu}_{lN} + s^{N}_{\mu} s^{N'}_{\nu} \mathcal{C}^{\mu\nu}_{NN'} + s^{l}_{\mu} s^{N}_{\nu} s^{N'}_{\alpha} \mathcal{D}^{\mu\nu\alpha}_{lNN'}\Big)$$

Seven spin observables:

1. recoil polarization asymmetry $\mathcal{P}^{\mu}_{N'}$
2. lepton polarization asymmetry $\mathcal{P}^{\mu}_{l}$
3. polarized target asymmetry $\mathcal{T}^{\mu}_{N}$
4. lepton-recoil asymmetry $A^{\mu\nu}_{lN'}$
5. target-lepton asymmetry $B^{\mu\nu}_{lN}$
6. target-recoil asymmetry $\mathcal{C}^{\mu\nu}_{NN'}$
7. target-lepton-recoil asymmetry $\mathcal{D}^{\mu\nu\alpha}_{lNN'}$

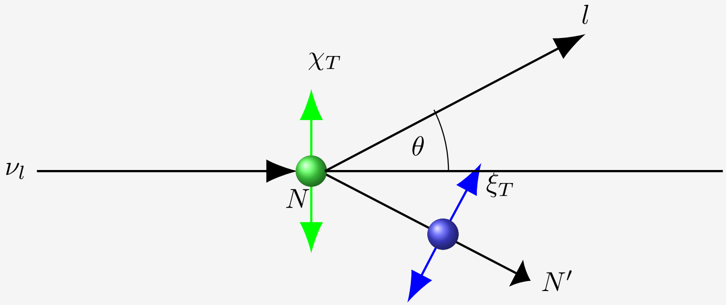
$$\mathcal{P}^{X}_{l} = \mathcal{P}^{\mu}_{l}\zeta^{X}_{\mu}, \quad \mathcal{A}^{XY}_{lN'} = \mathcal{A}^{\mu\nu}_{lN'}\zeta^{X}_{\mu}\xi^{Y}_{\nu}$$
$$\mathcal{D}^{XYZ}_{lNN'} = \mathcal{D}^{\mu\nu\alpha}_{lNN'}\zeta^{X}_{\mu}\xi^{Y}_{\nu}\chi^{Z}_{\alpha}$$

$$\mathcal{P}^{X}_{l} = \frac{\mathrm{d}\sigma(\zeta_X) - \mathrm{d}\sigma(-\zeta_X)}{\mathrm{d}\sigma(\zeta_X) + \mathrm{d}\sigma(-\zeta_X)}$$

$$\mathcal{A}^{XY}_{lN'} = \frac{\sum_{a,b=\pm 1} a \cdot b \cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}{\sum_{a,b=\pm 1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}$$

$$\mathcal{D}^{XYZ}_{lNN'} = \frac{\sum_{a,b,c=\pm 1} a \cdot b \cdot c \cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}{\sum_{a,b,c=\pm 1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}$$

CCQE



(scattering plane)

$$\mathcal{C}_{NN'}^{TT} = \mathcal{C}_{NN'}^{\mu\nu}\chi_\mu^T\xi_\nu^T$$

$$\mathcal{C}_{NN'}^{TT} = \frac{\sigma(\chi_T,\xi_T)+\sigma(-\chi_T,-\xi_T)-\sigma(-\chi_T,\xi_T)-\sigma(\chi_T,-\xi_T)}{\sigma(\chi_T,\xi_T)+\sigma(-\chi_T,-\xi_T)+\sigma(-\chi_T,\xi_T)+\sigma(\chi_T,-\xi_T)}$$

Form factors

Axial form factor (dipole parametrization)

$$F_A(q^2) = \frac{g_A}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

* we've checked also non-dipole parametrisation

$g_A = 1.2723 \pm 0.0023$
$M_A = 1.014 \pm 0.014 GeV$

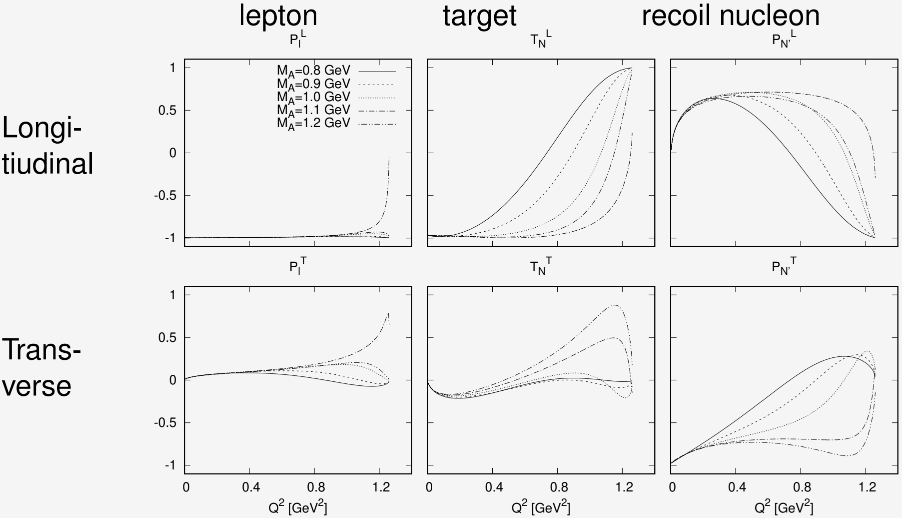
Cross-section is dominated by axial term.

New measurements of F_A parameters are still needed

$F_A(0) = g_A$
M_A obtained from

- ν-deuterium scattering
- CCQE, nuclear targets

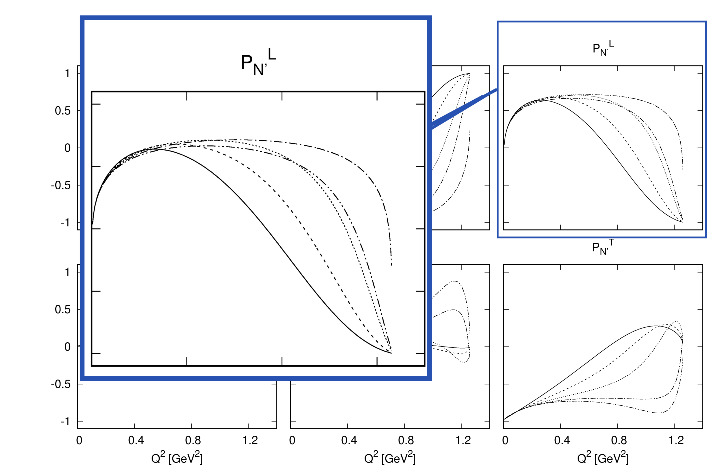
M_A - single spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$



$M_A = 0.8,\ 0.9,\ 1.0,\ 1.1,\ 1.2$ GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.
Normal asymmetry is 0

M_A - single spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$

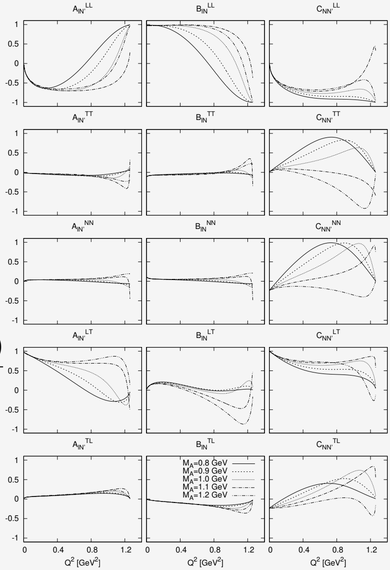
Sign and magnitude of the components depend strongly on M_A



$M_A = 0.8,\ 0.9,\ 1.0,\ 1.1,\ 1.2$ GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.
Normal asymmetry is 0

M_A - double spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$

$$\mathcal{A}_{IN'}^{XY} = \frac{\sum_{a,b=\pm1} a \cdot b \cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}{\sum_{a,b=\pm1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}$$



M_A = 0.8, 0.9, 1.0, 1.1, 1.2 GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.

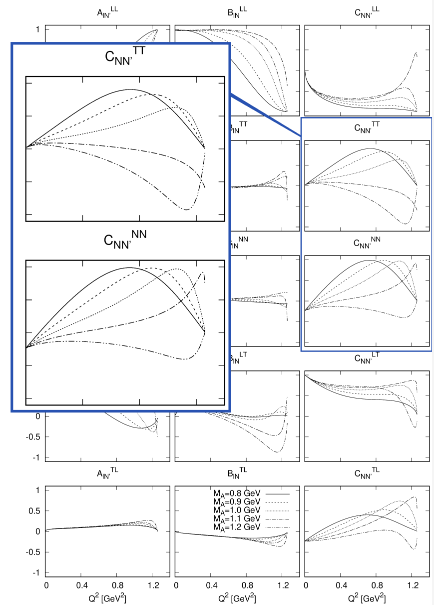
Normal asymmetry is 0

M_A - double spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$

$C^{TT}_{NN'}$ - transverse-transverse target-recoil asymmetry
$C^{LL}_{NN'}$ - normal-normal target-recoil asymmetry

Sign and magnitude of the components depend strongly on M_A

$M_A = 0.8, 0.9, 1.0, 1.1, 1.2$ GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.
Normal asymmetry is 0



Axial mass M_A establishing

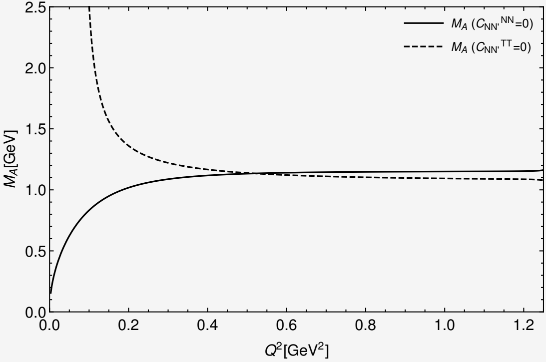
Axial mass dependence of the roots of the equations:

$$C^{NN}_{NN'}(E = 1GeV, M_A, Q^2) = 0$$

(solid line) and

$$C^{TT}_{NN'}(E = 1GeV, M_A, Q^2) = 0$$

(dashed line) obtained for the CCQE $\bar{\nu}_\mu p$ scattering.

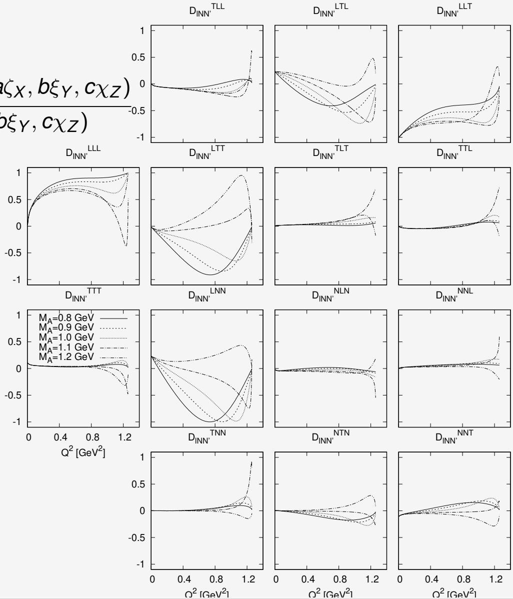


M_A - triple spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$

$$\mathcal{D}^{XYZ}_{INN'} = \frac{\sum_{a,b,c=\pm1} a\cdot b\cdot c\cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}{\sum_{a,b,c=\pm1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}$$

M_A = 0.8, 0.9, 1.0, 1.1, 1.2 GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.

Normal asymmetry is 0

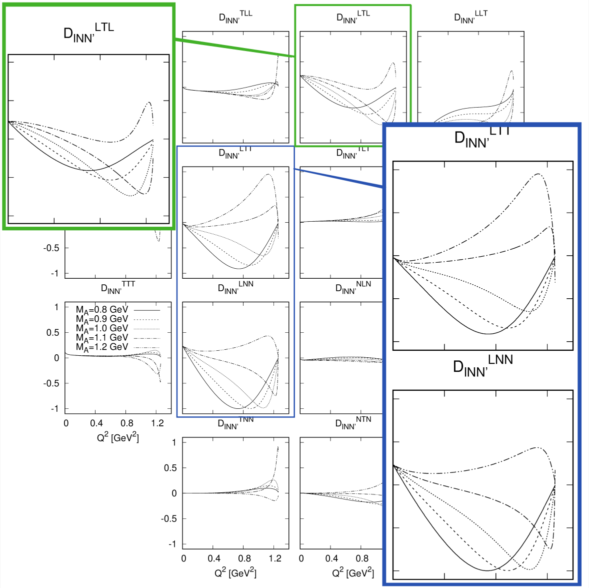


M_A - triple spin asymmetry $\bar{\nu}_\mu p \to \mu^+ n$

Sign and magnitude of the components depend strongly on M_A

$M_A = 0.8, 0.9, 1.0, 1.1, 1.2$ GeV, $F_3^A = 0$, neutrino energy $E = 1$ GeV.

Normal asymmetry is 0



Second class current

Vertex

$$\Gamma_{+}^{\mu}(q) = \gamma_\mu F_1^V(Q^2) + i\sigma^{\mu\nu} q_\nu \frac{F_2^V(Q^2)}{2M} - \left(\gamma_\mu F_A(Q^2) + q_\mu \frac{F_P(Q^2)}{2M} + i\sigma^{\mu\nu} q_\nu \frac{F_3^A(Q^2)}{M}\right)\gamma_5$$

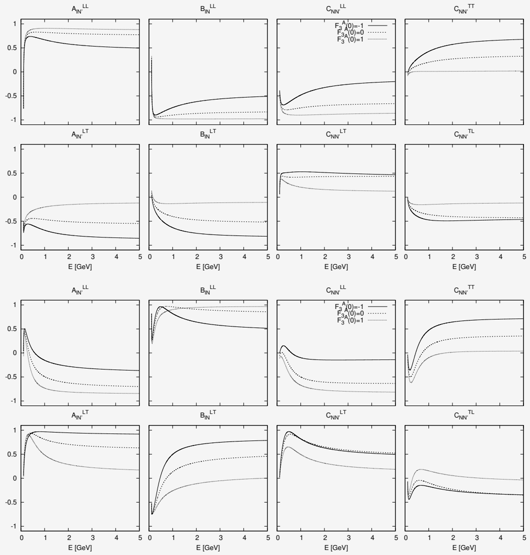
Conserved vector current CVC $\Longrightarrow$ $F_3^V = 0$

Dipole parametrization of F_3^A:

$$F_A^3(Q^2) = \frac{F_A^3(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

A. Fatima, M. Sajjad Athar, S. K. Singh, Phys. Rev. D98, 033005 (2018).

SCC - double spin asymmetry $\nu_\mu n$ and $\bar{\nu}_\mu p$



Sign and magnitude of the components depend strongly on F_A^3

$$\mathcal{A}_{IN'}^{XY} = \frac{\sum_{a,b=\pm 1} a \cdot b \cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}{\sum_{a,b=\pm 1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y)}$$

$F_3^A(0) = -1, 0, 1$, $M_A =$ 1.0 GeV, neutrino energy $E = 1$ GeV.

Normal asymmetry is 0

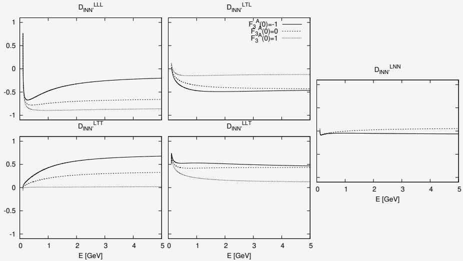
SCC - triple spin asymmetry $\nu_\mu n$ and $\bar{\nu}_\mu p$

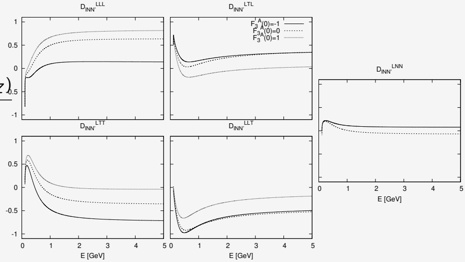
Sign and magnitude of the components depend strongly on F_A^3

$$\mathcal{D}_{INN'}^{XYZ} = \frac{\sum_{a,b,c=\pm 1} a \cdot b \cdot c \cdot \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}{\sum_{a,b,c=\pm 1} \mathrm{d}\sigma(a\zeta_X, b\xi_Y, c\chi_Z)}$$

$F_3^A(0) = -1, 0, 1$, $M_A =$ 1.0 GeV, neutrino energy $E = 1$ GeV.

Normal asymmetry is 0



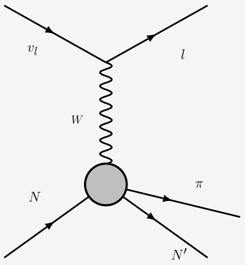


Single pion production formalism

SPP formalism

CC SPP channels

$$\nu_l + p \to l^- + p + \pi^+, \quad \bar{\nu}_l + n \to l^+ + n + \pi^-$$
$$\nu_l + n \to l^- + n + \pi^+, \quad \bar{\nu}_l + p \to l^+ + p + \pi^-$$
$$\nu_l + n \to l^- + p + \pi^0, \quad \bar{\nu}_l + p \to l^+ + n + \pi^0$$



Two mechanisms in the pion production:

- resonant (RES) - the nucleon is excited to the resonance state

$$N \to N^*$$

  which decays

$$N^* \to \pi N$$

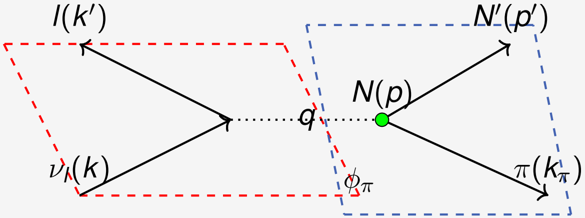
- nonresonant - no $N \to N^*$ transition

ν_l - neutrino, l - charged lepton
N - initial nucleon, N' -final nucleon
π - pion

SPP formalism

Models of SPP HNV: Hernandez, Nieves, Valverde, (Phys. Rev. D 76, (2007) 033005)
(Non-linear σ model)

FN: Fogli, Nardulli, (Nucl.Phys. B 160 (1979))
(Linear σ model)



the first resonance region ($\Delta(1232)$)

$q^\mu = k^\mu - k'^\mu$ 4-momentum transfer
SPP in charged current $N\nu$

Δ(1232) resonance

described by Rarita-Schwinger field

$$j^{\mu}_{\Delta P} = i\mathcal{C}^{\Delta P}\cos(\theta_C)\frac{f^*\sqrt{3}}{m_\pi}k^\alpha\bar{u}(p')\frac{\Lambda^{3/2}_{\alpha\beta}(p_\Delta)\Gamma^{\beta\mu}(p,q)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta(p_\Delta)}u(p),$$

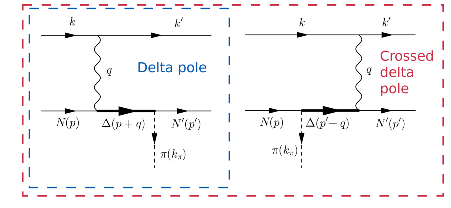
$$p_\Delta = p + q$$

$$j^{\mu}_{+C\Delta P} = i\mathcal{C}^{C\Delta P}\cos(\theta_C)\frac{\sqrt{3}f^*}{m_\pi}\bar{u}(p')\frac{\gamma^0\Gamma^{\dagger\,\alpha\mu}(p',-q)\gamma^0\Lambda^{3/2}_{\alpha\nu}(p_\Delta)}{p_\Delta^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta(p_\Delta)}k^\nu_\pi u(p),$$

$$p_\Delta = p' - q$$

FN **HNV**

$$\Gamma^{\alpha\mu}(p,q) = \left[\frac{C_3^A}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M^2}(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p^\mu_\Delta) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2}q^\alpha q^\mu\right] + \left[\frac{C_3^V}{M}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M^2}(g^{\alpha\mu}q\cdot p_\Delta - q^\alpha p^\mu_\Delta) + \frac{C_5^V}{M^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu) + C_6^V g^{\alpha\mu}\right]\gamma_5$$

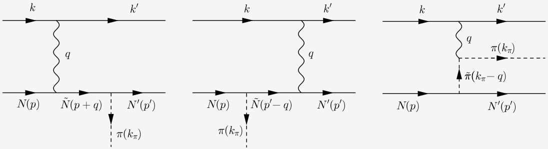


FN oversimplified

$C_3^A = 0,\ C_4^A = 0,\ C_6^A = 0,\ C_5^V = 0,\ C_6^V = 0$

FN: Nonresonant background

Linear sigma model (Nucl.Phys. B 160 (1979))



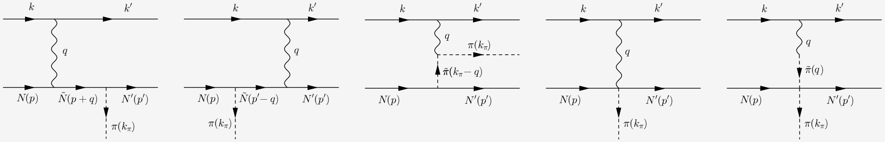
$$j^{\mu}{}_{NP} = i\sqrt{2} g_{NN\pi} C_{NP} \cos(\theta_C) \bar{u}(\mathbf{p}') \gamma_5 \frac{\not{p} + \not{q} + M}{(p+q)^2 - M^2 + i\epsilon} \left[V_N^{\mu}(q^2) - A_N^{\mu}(q^2) \right] u(\mathbf{p})$$

$$j^{\mu}{}_{CNP} = i\sqrt{2} g_{NN\pi} C_{CNP} \cos(\theta_C) \bar{u}(\mathbf{p}') \left[V_N^{\mu}(q^2) - A_N^{\mu}(q^2) \right] \frac{\not{p}' - \not{q} + M}{(p+q)^2 - M^2 + i\epsilon} \gamma_5 u(\mathbf{p})$$

$$j^{\mu}{}_{PF} = -i\sqrt{2} g_{NN\pi} C_{PF} \cos(\theta_C) F_{PF}(q^2) \frac{(2k_\pi - q)^{\mu}}{(k_\pi - q)^2 - m_\pi^2} \bar{u}(\mathbf{p}') \gamma_5 u(\mathbf{p})$$

HNV: Nonresonant background

Non-linear sigma model (Phys. Rev. D 76, (2007) 033005)



$$j^{\mu}{}_{NP} = -iC_{NP}\cos(\theta_C)\frac{g_A}{\sqrt{2}f_\pi}\bar{u}(\mathbf{p}')\not{k}_\pi\gamma_5\frac{\not{p}+\not{q}+M}{(p+q)^2-M^2+i\epsilon}\left[V_N^\mu(q^2)-A_N^\mu(q^2)\right]u(\mathbf{p})$$

$$j^{\mu}{}_{CNP} = -iC_{CNP}\cos(\theta_C)\frac{g_A}{\sqrt{2}f_\pi}\bar{u}(\mathbf{p}')\left[V_N^\mu(q^2)-A_N^\mu(q^2)\right]\frac{\not{p}'-\not{q}+M}{(p+q)^2-M^2+i\epsilon}\not{k}_\pi\gamma_5 u(\mathbf{p})$$

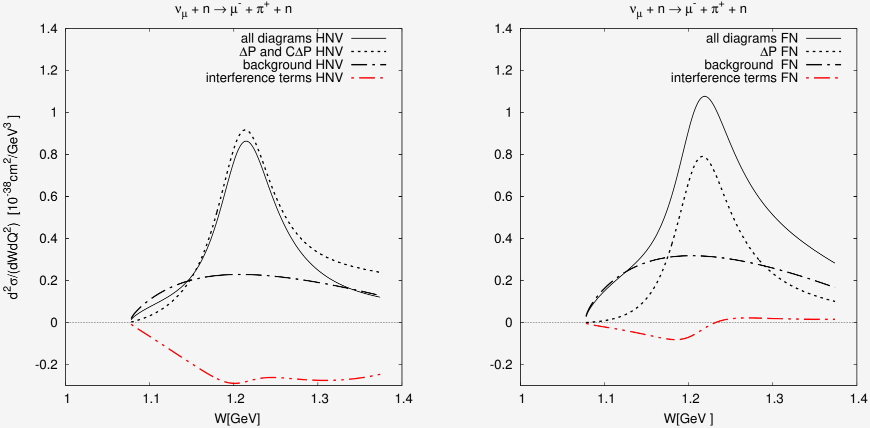
$$j^{\mu}{}_{PF} = -iC_{PF}\cos(\theta_C)F_{PF}(q^2)\frac{g_A}{\sqrt{2}f_\pi}\frac{(2k_\pi-q)^\mu}{(k_\pi-q)^2-m_\pi^2}\bar{u}(\mathbf{p}')\gamma_5 u(\mathbf{p})$$

$$j^{\mu}{}_{PP} = -iC_{PP}\cos(\theta_C)F_{PP}((k_\pi-q)^2)\frac{1}{\sqrt{2}f_\pi}\frac{q^\mu}{q^2-m_\pi^2}\bar{u}(\mathbf{p}')\not{q}u(\mathbf{p})$$

$$j^{\mu}{}_{CT} = -iC_{CT}\cos(\theta_C)\frac{1}{\sqrt{2}f_\pi}\bar{u}(\mathbf{p}')\gamma_\mu(g_A F_{CT}(q^2)\gamma_5 - F_{PP}((q-k_\pi)^2))u(\mathbf{p})$$

Different vertices and form factors

Similar shape - different components



SPP Cross-section in two different models. Solid line - cross-section in two models of SPP. Red line - interference between RES and NB, dotted - RES, dashed-dotted - NB. $E = 0.7$ GeV, $Q^2 = 0.1 GeV^2$

Summary

- There are various models of SPP. Different descriptions of RES and non-RES background.
- Structure of amplitude is a sum of RES and non-RES amplitudes with a phase between them

$$|A_{RES} + e^{i\psi} A_{NB}|^2$$

- We assume $e^{i\psi} = 1$
- We need to know relative phase between amplitudes. Experiments have been measured averaged over spin cross-section data. It makes difficult to distinguish RES and NB

Summary

- Developing of procedures of testing models is needed, to reduce model dependency
- Some new observables are needed to study RES and NB, relative phase between amplitudes
- We propose polarization observables

Polarization properties of SPP - the other's results

authors	papers	subject of investigation
K. Hagiwara et al.	Nucl. Phys. B668, 364 (2003)	polarization properties of the τ-lepton, only RES
K. S. Kuzmin et al.	Mod. Phys. Lett. A19, 2815 (2004)	polarization properties of the τ-lepton, only RES

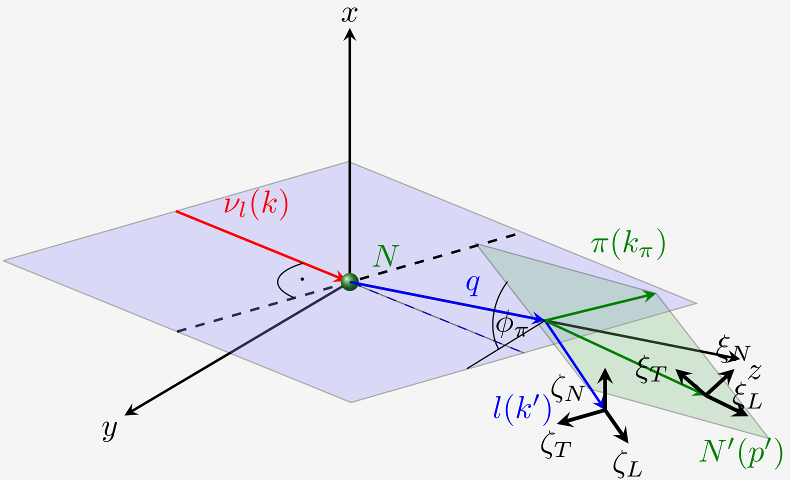
Not discussed yet:

- Polarization properties of nonresonant background of SPP process.
- Polarization properties of the target nucleon in the SPP process.
- Polarization properties of the final nucleon produced in the SPP process

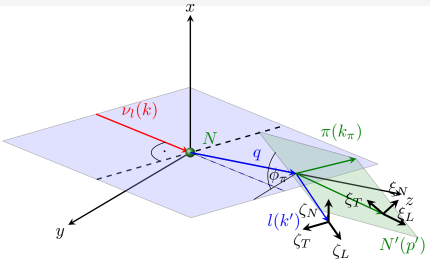
Polarization of the final particles in SPP

Polarization of the final particles

Angular distribution of the particles, in the laboratory frame
ζ and ξ - spin components of the lepton and the nucleon respectively.



Polarization of the final particles



ζ and ξ - spin components of the lepton and the nucleon respectively.

$\mathcal{P}^\mu$ - polarization

s^μ - spin of a particle

$$d\sigma \sim \frac{1}{2}|\mathcal{M}_{fi}|^2\left(1+\mathcal{P}^\mu s_\mu\right)$$

Three components of $\mathcal{P}^\mu$:

$\mathcal{P}_L$ (longitudinal),

$\mathcal{P}_T$ (transverse),

$\mathcal{P}_N$ (normal)

Polarization of lepton

$$\mathcal{P}^\mu = \mathcal{P}_L\zeta_L^\mu + \mathcal{P}_T\zeta_T^\mu + \mathcal{P}_N\zeta_N^\mu$$

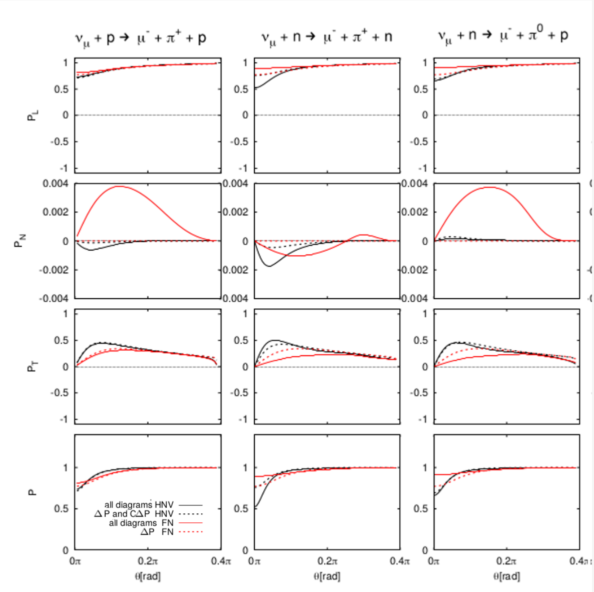
Polarization of nucleon

$$\mathcal{P}^\mu = \mathcal{P}_L\xi_L^\mu + \mathcal{P}_T\xi_T^\mu + \mathcal{P}_N\xi_N^\mu$$

Degree of polarization

$$\mathcal{P} = \sqrt{\mathcal{P}_L^2 + \mathcal{P}_N^2 + \mathcal{P}_T^2}$$

Polarization of final lepton



ν channels

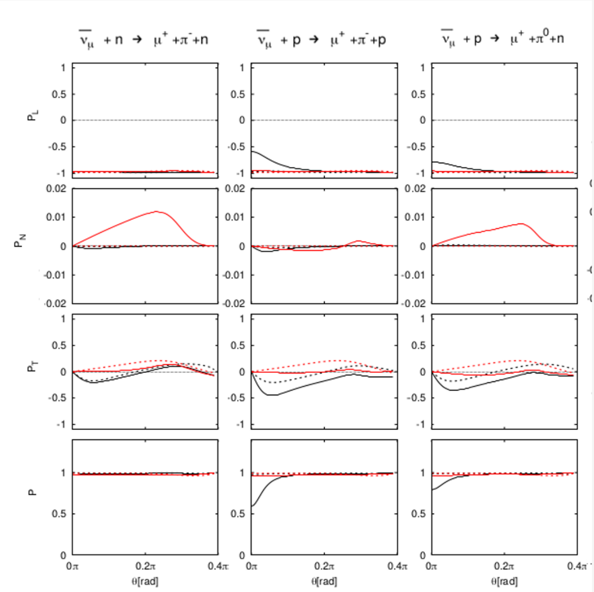
Red line - FN model
Black line - HNV model
Dotted line - only RES

Degree of polarization

$$\mathcal{P} = \sqrt{\mathcal{P}_L^2 + \mathcal{P}_N^2 + \mathcal{P}_T^2}$$

Dependence of the polarization $\mathcal{P}(\mathrm{d}^2\sigma/(\mathrm{d}\theta\mathrm{dE}'))$ on the scattering angle θ, $\omega = 0.2 GeV$, $E = 1 GeV$

Polarization of final lepton



$\bar{\nu}$ channels

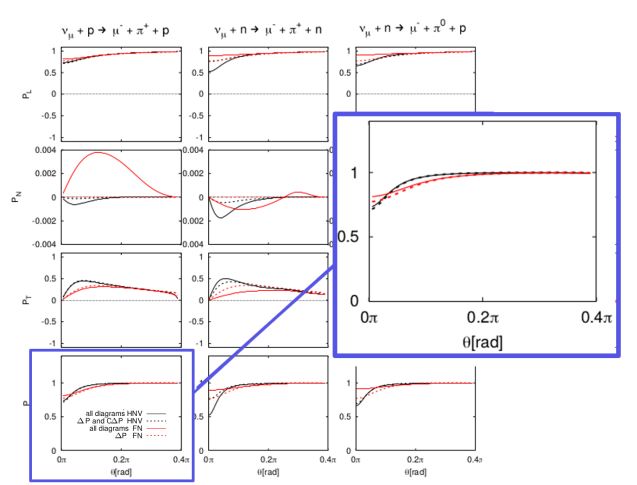
Red line - FN model

Black line - HNV model

Dotted line - only RES

Dependence of the polarization $\mathcal{P}(\mathrm{d}^2\sigma/(\mathrm{d}\theta\mathrm{dE}'))$ on the scattering angle θ, $\omega = 0.2 GeV$, $E = 1 GeV$

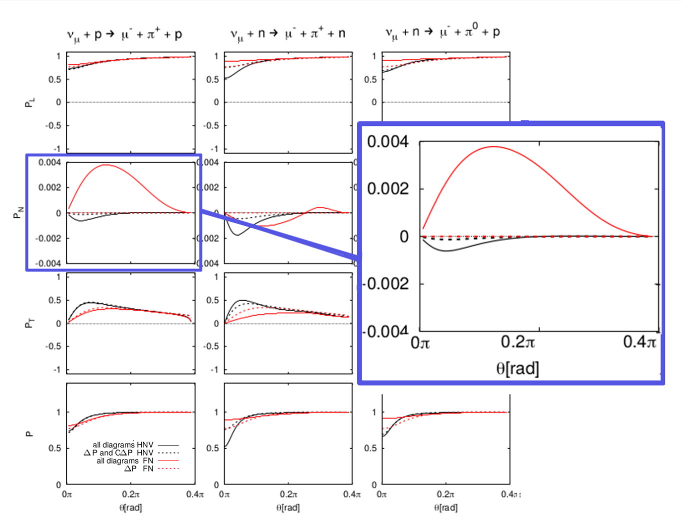
Polarization of final lepton



μ - a light particle - almost polarized. Partially polarized at low scattering angle.

Dependence of the polarization $\mathcal{P}(\mathrm{d}^2\sigma/(\mathrm{d}\theta\mathrm{d}\mathrm{E}'))$ on the scattering angle θ, $\omega = 0.2 GeV$, $E = 1 GeV$

Polarization of final lepton

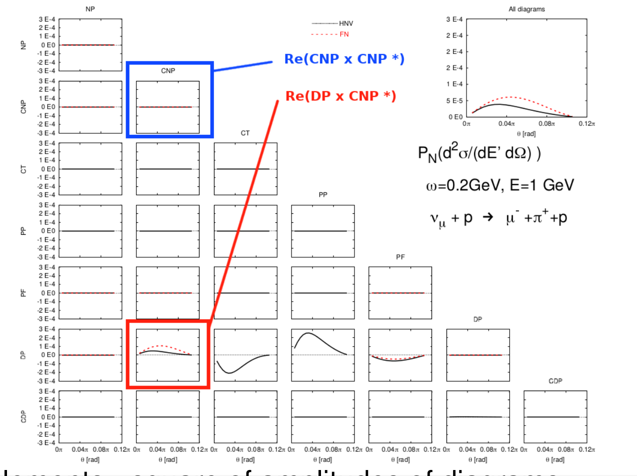


P_N is given by the RES-NB interference

Dependence of the polarization $\mathcal{P}(\mathrm{d}^2\sigma/(\mathrm{d}\theta\mathrm{d}\mathrm{E}'))$ on the scattering angle θ, $\omega = 0.2GeV$, $E = 1GeV$

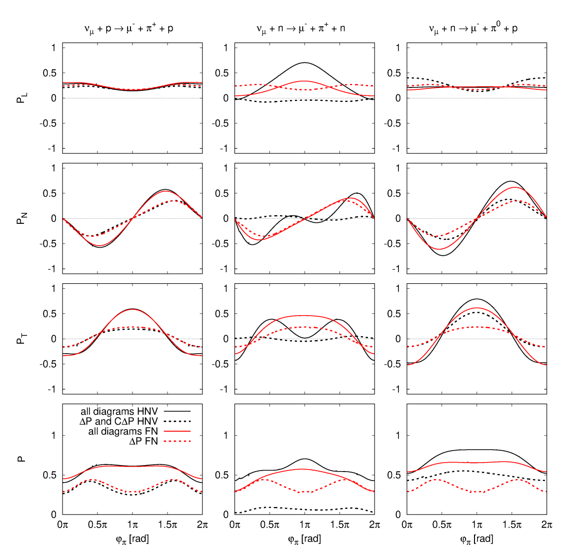
Polarization of final lepton

P_N is given by the RES-NB interference



Diagonal elements - square of amplitudes of diagrams
Non-diagonal elements - interference of diagrams

Polarization of final nucleon - T2K flux



ν channels

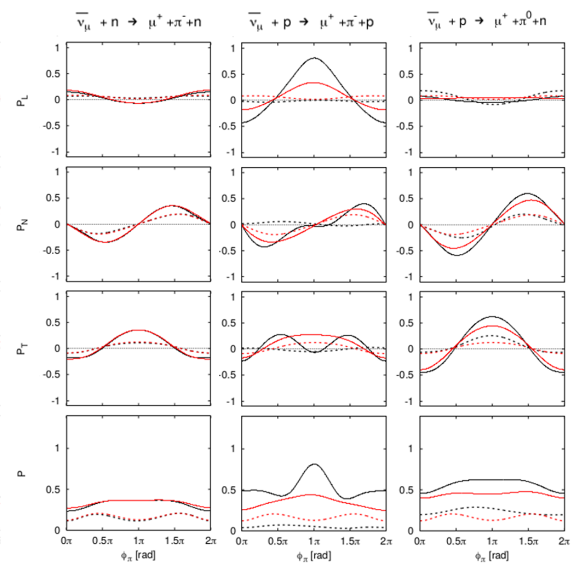
Red line - FN model

Black line - HNV model

Dotted line - only RES

Dependence of the polarization $\mathcal{P}(\mathrm{d}^3\sigma/(\mathrm{d}\Omega\mathrm{d}\phi_\pi\mathrm{dE}'))$ on the angle ϕ_π; $\omega = 0.2GeV$, $\theta = 5^\circ$, T2K flux

Polarization of final nucleon



$\bar{\nu}$ channels

Red line - FN model

Black line - HNV model

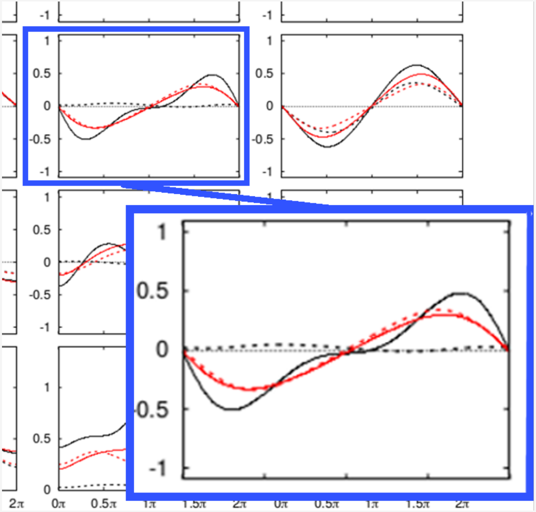
Dotted line - only RES

Dependence of the polarization $\mathcal{P}(\mathrm{d}^3\sigma/(\mathrm{d}\Omega \mathrm{d}\phi_\pi \mathrm{dE}'))$ on the angle ϕ_π; $\omega = 0.2 GeV$, $E = 1 GeV$, $\theta = 5^\circ$

Polarization of final nucleon

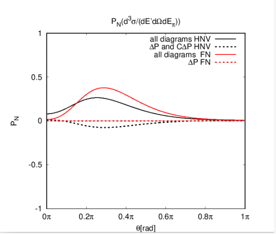
Interference RES-NB in the P_N - distortion of sinusoidal character:

$\mathcal{P}_N = a_1 \sin(\phi_\pi)$ (main part) $+ a_2 \sin(2\phi_\pi) + a_3 \sin^2(\phi_\pi)$



a_3 - is given by RES-NB interference.

Non-zero after integration over ϕ_π

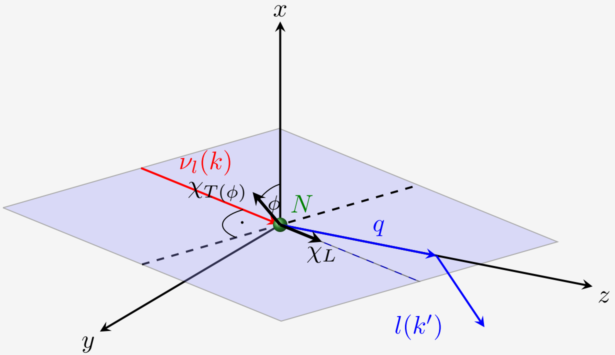


Dependence of the polarization $\mathcal{P}(\mathrm{d}^3\sigma/(\mathrm{d}\Omega\mathrm{d}\phi_\pi\mathrm{dE}'))$ on the angle ϕ_π; $\omega = 0.2GeV$, $\theta = 5^\circ$, $E = 1GeV$

Polarized target asymmetry in SPP

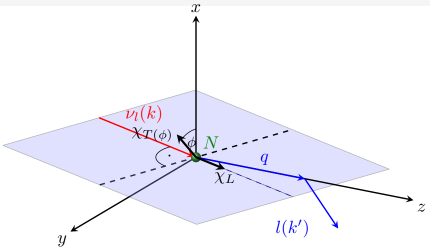
Polarized target asymmetry

Angular distribution of the particles, in the laboratory frame
χ_L, $\chi_T(\phi)$ - spin components of the nucleon.



χ_L - spin along the ν flux
$\chi_T(\phi)$ - spin perpendicularly to the ν flux,
ϕ - angle between spin and normal to scattering plane

Polarized target asymmetry



χ_L, $\chi_T(\phi)$ - spin components of the nucleon.
$\mathcal{A}^\mu$ - asymmetry

$$\mathcal{A}^\mu = \mathcal{A}_T(\phi)\chi_T^\mu(\phi) + \mathcal{A}_L\chi_L^\mu$$

s^μ - spin of a particle

$$\mathrm{d}\sigma \sim \frac{1}{2}|\mathcal{M}_{fi}|^2 \left(1 + \mathcal{A}^\mu \mathrm{s}_\mu\right)$$

Directions of target polarization

Target polarized longitudinally to the beam

$$\mathcal{A}_L = \frac{\mathrm{d}\sigma(\chi_L) - \mathrm{d}\sigma(-\chi_L)}{\mathrm{d}\sigma(\chi_L) + \mathrm{d}\sigma(-\chi_L)}$$

Target polarized perpendicularly to the beam

$$\mathcal{A}_T = \frac{\mathrm{d}\sigma(\chi_T) - \mathrm{d}\sigma(-\chi_T)}{\mathrm{d}\sigma(\chi_T) + \mathrm{d}\sigma(-\chi_T)}$$

Longitudinally polarized target

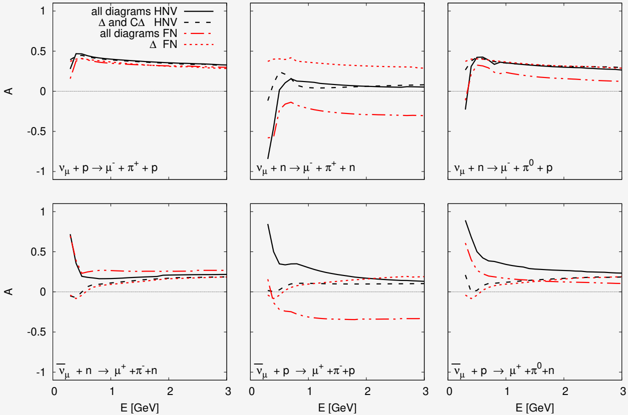


Figure: Dependence of $\mathcal{A}_L(\sigma)$ on the energy of neutrino

Longitudinally polarized target

For some channels $\mathcal{A}_L$ is quite model dependent and *NB* contribution modifies significantly.

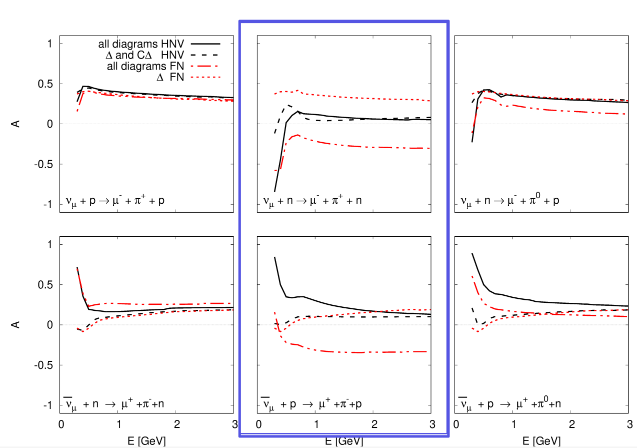
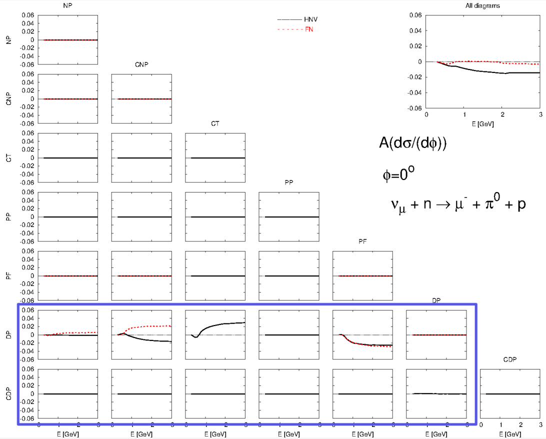


Figure: Dependence of $\mathcal{A}_L(\sigma)$ on the energy of neutrino

Perpendicularly polarized target

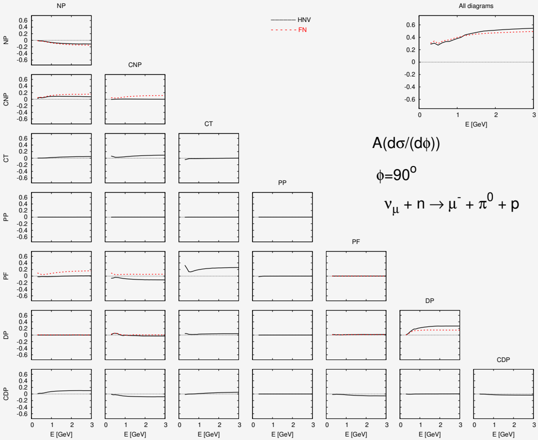
Contributions from different diagrams to $\mathcal{A}_T(\mathrm{d}\sigma/\mathrm{d}\phi)$, $\phi = 0°$, only RES-NB interference contributes



Diagonal elements - square of amplitudes of diagrams
Non-diagonal elements - interference of diagrams

Perpendicularly polarized target

Contributions from different diagrams to $\mathcal{A}_T(\mathrm{d}\sigma/\mathrm{d}\phi)$, $\phi = 90°$, contribution from all diagrams



Diagonal elements - square of amplitudes of diagrams
Non-diagonal elements - interference of diagrams

Perpendicularly polarized target

- $\mathcal{A}_T$ has a form

$$\mathcal{A}_T(\phi) = a_1 cos(\phi) + a_2 \sin(\phi)$$

- $\mathcal{A}_T(\phi)$ is dominated by the sinusoidal part a_2
- for $\phi = 0$ only a_1 contributes - RES interference with NB

Conclusions

QE

- Sign and magnitude of the polarization observables depend strongly on M_A
- They are promising observables for investigation of SCC in the neutrino scattering

SPP

- Polarization observables are sensitive to details of the SPP models
- The normal polarization is dominated by NB-RES interference, relative phase information

* calculated in the Wroclaw Centre for Networking and Supercomputing, Grant No. 268
** using symbolic programming language FORM

Thank You
for Your attention