Polarization effects in neutrino-nucleon interactions

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Outline

1. Motivation
2. Single Pion Production formalism
3. Polarization of final particles
4. Polarized target asymmetry
5. Summary

Results come from:

- **Polarization transfer in weak pion production off the nucleon**
  Krzysztof M. Graczyk and Beata E. Kowal
  Phys. Rev. D 97, 013001

- **Spin asymmetry in single pion production induced by weak interactions of neutrinos with polarized nucleons**
  Krzysztof M. Graczyk and Beata E. Kowal
  Phys. Rev. D 99, 053002

Neutrino oscillation

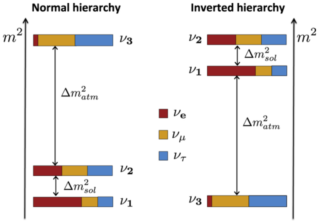
Measurement of oscillation parameters:

- squared mass differences Δm^2_{ij} (periodicity)
- neutrino mixing angles θ_{12}, θ_{23}, θ_{13} of PMNS matrix
- leptonic CP violation δ_{CP} (asymmetry matter/anti-matter)

$$a_{CP} = P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

Neutrino flavor state - a mixture of mass eigenstates.

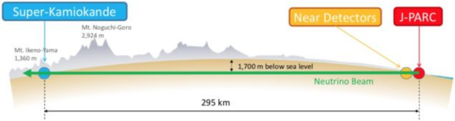
$$P(\alpha \to \beta) = \left| \sum_k U^*_{\alpha k} U_{\beta k} e^{i \frac{m_k^2 L}{2E}} \right|^2$$



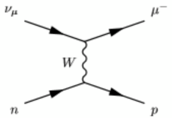
Mass hierarchy (Letter of intent for KM3NeT 2.0, Journal of Physics G) 43(8)

Neutrino interaction

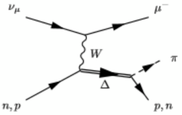
Accelerator experiments, $E \sim 1\text{GeV}$



Quasi-elastic scattering

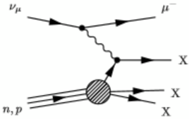


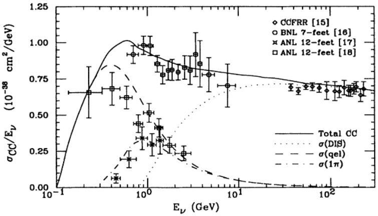
Resonant pion production



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

Deep inelastic scattering





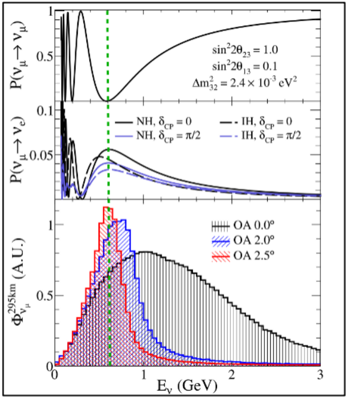
P. Lipari et al, Phys.Rev. Lett.74(1995) 4384

Oscillation analysis base on the detection of the QE scattering

Neutrino oscillation

$$P(\alpha \to \beta) = \left| \sum_k U^*_{\alpha k} U_{\beta k} e^{i\frac{m_k^2 L}{2E}} \right|^2$$

L-fixed distance



T2K neutrino oscillation results using 2017 data, C. Bronner

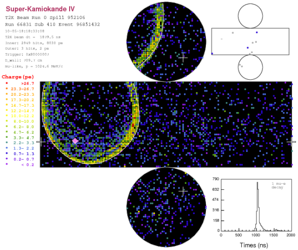
Lepton flavor appearance

$$\nu_\mu \to \nu_\mu$$

or disappearance

$$\nu_\mu \to \nu_e$$

Energy distribution, non-monoenergetic neutrino beam



Event displays from T2K beam interactions in Super-Kamiokande.

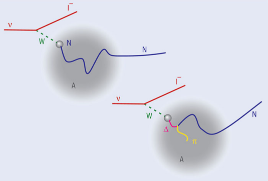
Energy reconstruction

Experiments base on the detection of the QE scattering

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

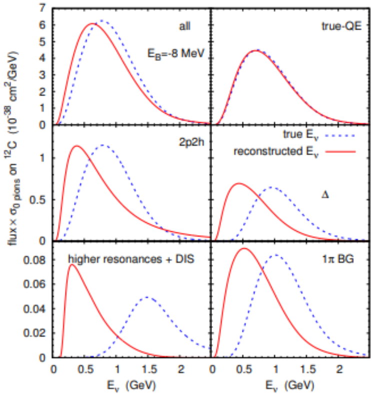
Energy from l^- parameters.

Fake QE-like events 0π:
SPP, 2p2h, DIS



True QE event and background in ν-nucleus scattering

(*Neutrinos on nuclei*, U.Mosel, Cern Courier, 09.2017)



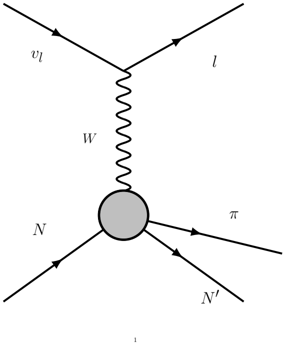
Dashed - distributions of zero pion events vs true energy, solid - distribution vs reconstructed energies. Phys. Rev. C 86, 054606

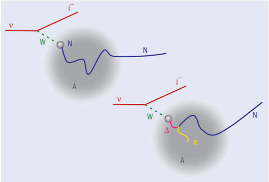
Single Pion Production

Charged current process

$$\nu_l(k) + N(p) \to l(k') + N'(p') + \pi(k_\pi)$$

- the SPP - background of the QE events
- we need to test and develop models of SPP





(*Neutrinos on nuclei*, U.Mosel,

Cern Courier, 09.2017)

ν_l - neutrino, l - charged lepton

N - initial nucleon, N' -final nucleon

π - pion

Single Pion Production

Two mechanisms in the pion production:

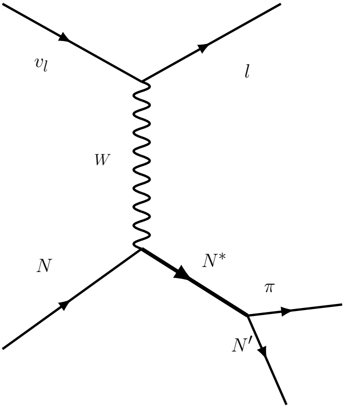
- resonant (RES) - the nucleon is excited to the resonance state

  $$N \to N^*$$

  which decays

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

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



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Polarization observables

- Different models of SPP
- to test models we should distinguish RES and NB (nonresonant background)

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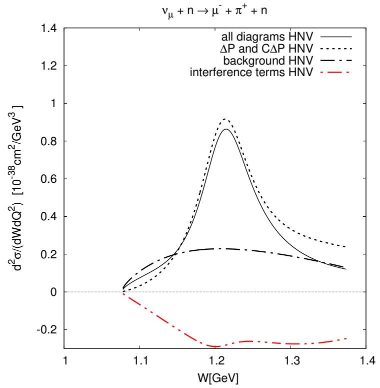
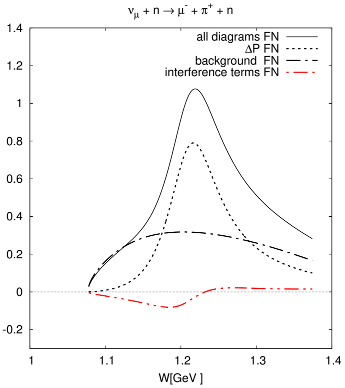
Similar shape - different components





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

Polarization observables

- Some new observables are needed to study RES and NB, relative phase between amplitudes

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

- It's difficult to distinguish RES and NB - the spin averaged cross-section has been measured
- We propose polarization observables

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Polarization observables

- Polarization observables in QE:
  - analyzing T-violation and second class currents
  (e.g. A. Fatima et al. Eur. Phys. J. A (2018))

  - strange particles production in $\bar{\nu}_\mu$-nucleon
  (C.H. Llewellyn Smith, Phys.Rept. 3 (1972))

  - τ polarization in $\bar{\nu}_\tau$-nucleus
  (K. Graczyk, Nucl.Phys. A748 (2005))

- Polarization observables in SPP:
  (oversimplified model, RES contribution, polarization of final lepton)
  K. Hagiwara et al., Nucl.Phys. B668 (2003),
  V. A. Naumov et al., Phys. of Particles and Nuclei 35(7) (2004)

- We present new results in SPP

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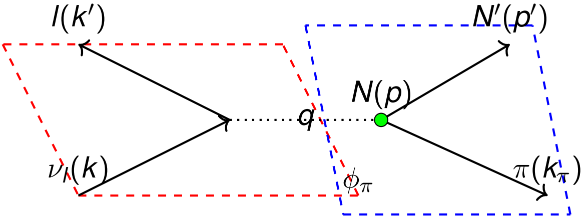
SPP formalism - leptonic and hadronic plane



$q^\mu = k^\mu - k'^\mu$ 4-momentum transfer

SPP in charged current $N\nu$

$\nu_\mu + p \to \mu^- + p + \pi^+$

$\nu_\mu + n \to \mu^- + p + \pi^0$

$\nu_\mu + n \to \mu^- + n + \pi^+$

$\bar{\nu}_\mu + p \to \mu^+ + p + \pi^-$

$\bar{\nu}_\mu + p \to \mu^+ + n + \pi^0$

$\bar{\nu}_\mu + n \to \mu^+ + n + \pi^-$

Nonresonant background

Two models considered:

HNV: Hernandez, Nieves, Valverde, PRD76 033005 (2007)
FN: Fogli, Nardulli, Nucl.Phys. B 160 (1979)

different formulas of currents, form-factors
and couplings

(Amplitudes calculated using FORM language, compared with Fayncalc)

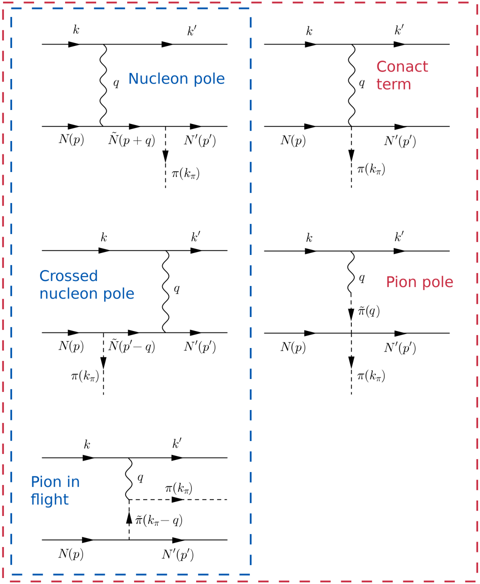


Figure: Background diagrams

SPP formalism

Δ(1232) **resonance**

HNV: Hernandez, Nieves, Valverde, PRD76 033005 (2007)
FN: Fogli, Nardulli, Nucl.Phys. B 160 (1979)

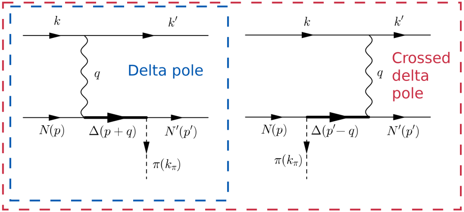


Figure: Resonance contributing to the SPP

Δ-propagator $P_{\alpha\beta}(p_\Delta)$:

$$P_{\alpha\beta}(p) = -\frac{(\not{p} + M_\Delta)}{p^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta(p)}\left(g_{\alpha\beta} - \frac{\gamma_\alpha\gamma_\beta}{3} - \frac{2p_\alpha p_\beta}{3M_\Delta^2} + \frac{p_\alpha\gamma_\beta - \gamma_\alpha p_\beta}{3M_\Delta}\right)$$

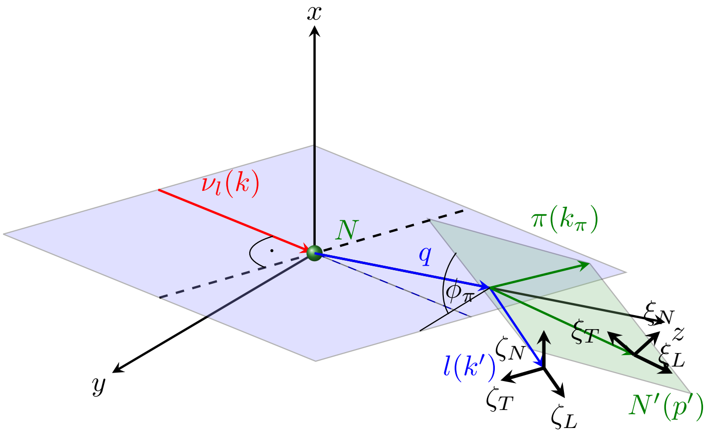
different resonance width Γ_Δ
and 6 form-factors of Δ

(Amplitudes calculated using FORM language, compared with FaynCalc)

Polarization of the final particles in SPP

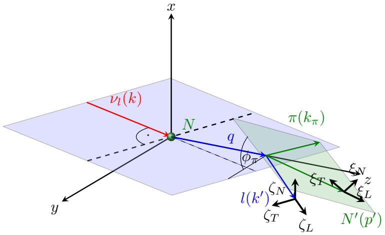
Polarization of the final particles

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



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

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

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

Three components of $\mathcal{P}^\mu$:
$\mathcal{P}_L$ (longitudinal),
$\mathcal{P}_T$ (transverse),
$\mathcal{P}_N$ (normal)

Polarization of lepton

$$\mathcal{P}^\mu = \mathcal{P}_L\zeta_L^\mu + \mathcal{P}_T\zeta_T^\mu + \mathcal{P}_N\zeta_N^\mu \quad (2)$$

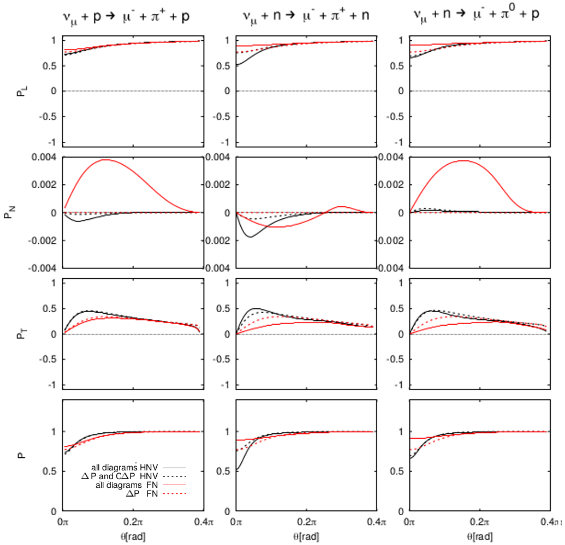
Polarization of nucleon

$$\mathcal{P}^\mu = \mathcal{P}_L\xi_L^\mu + \mathcal{P}_T\xi_T^\mu + \mathcal{P}_N\xi_N^\mu \quad (3)$$

Degree of polarization

$$\mathcal{P} = \sqrt{\mathcal{P}_L^2 + \mathcal{P}_N^2 + \mathcal{P}_T^2} \quad (4)$$

Polarization of final lepton

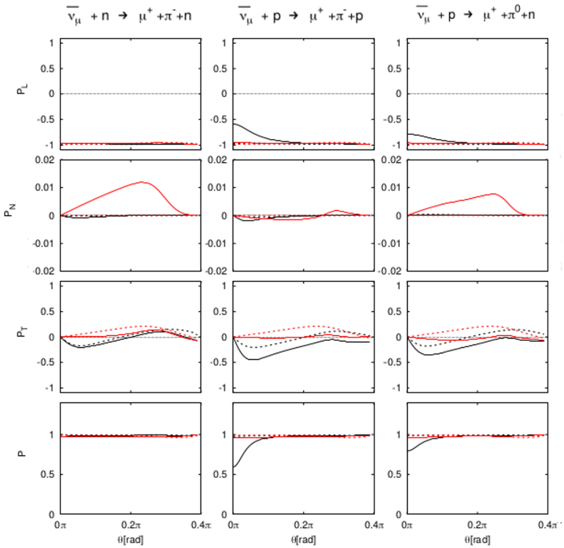


ν channels

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

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

Polarization of final lepton



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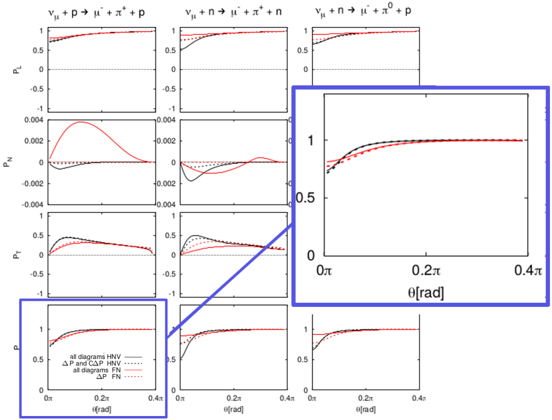
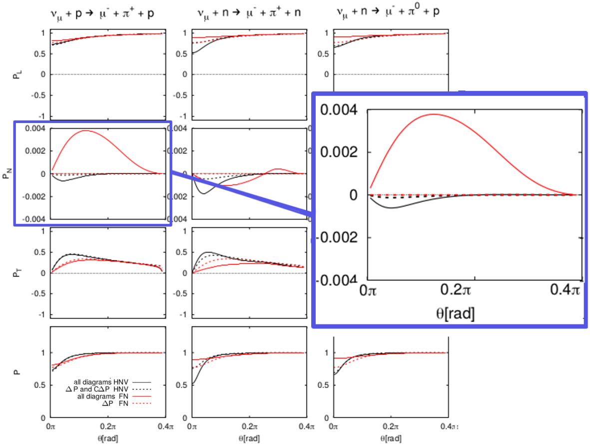
Polarization of final lepton



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, $\omega = 0.2GeV$, $E = 1GeV$

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

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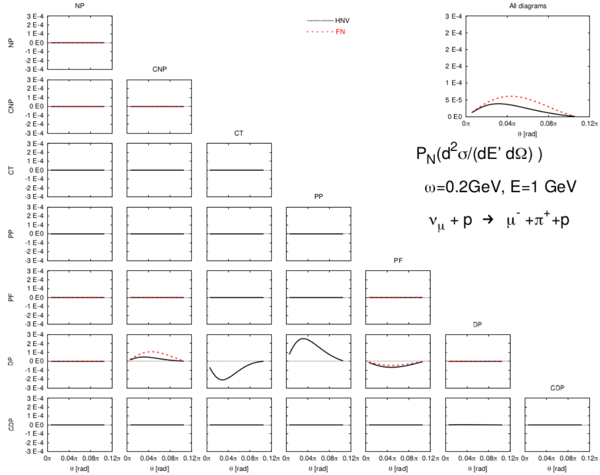
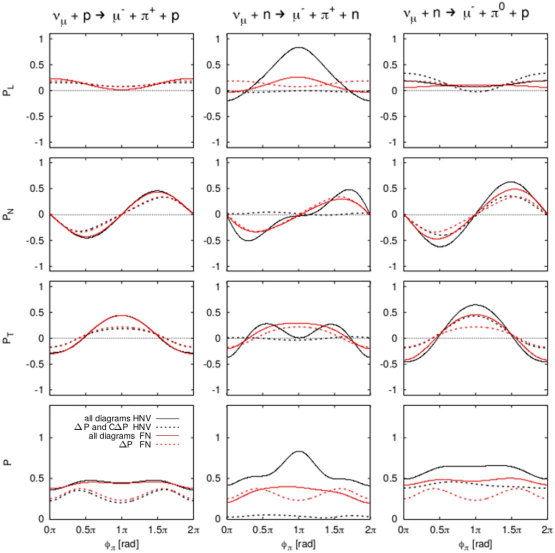


Diagonal elements - square of amplitudes of diagrams
Non-diagonal elements - interference of diagrams

Contribution from different diagrams for polarization $\mathcal{P}_N(\mathrm{d}^2\sigma/(\mathrm{d}\Omega\mathrm{d}E'))$, $\omega = 0.2GeV$, $E = 1GeV$

Polarization of final nucleon



ν channels

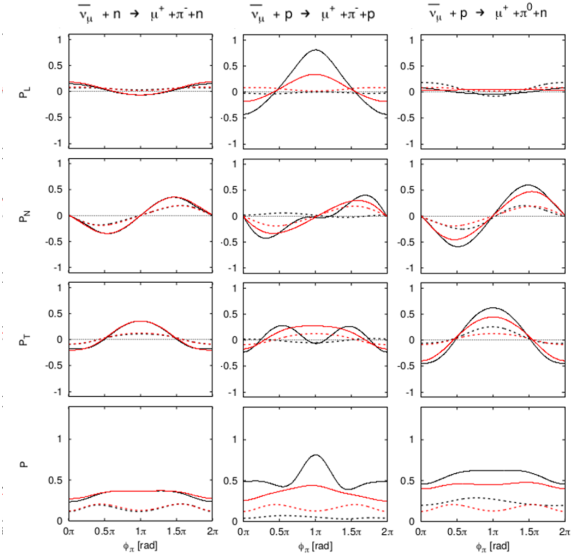
Red line - FN model

Black line - HNV model

Dotted line - only RES

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

Polarization of final nucleon



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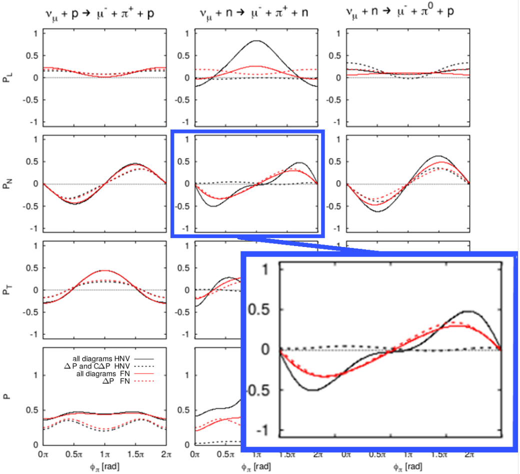
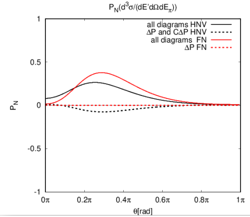
Polarization of final nucleon

Interference RES-NB in the P_N - distortion of sinusoidal character:
$\mathcal{P}_N \sim a_1 \sin(\phi_\pi)$ (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:



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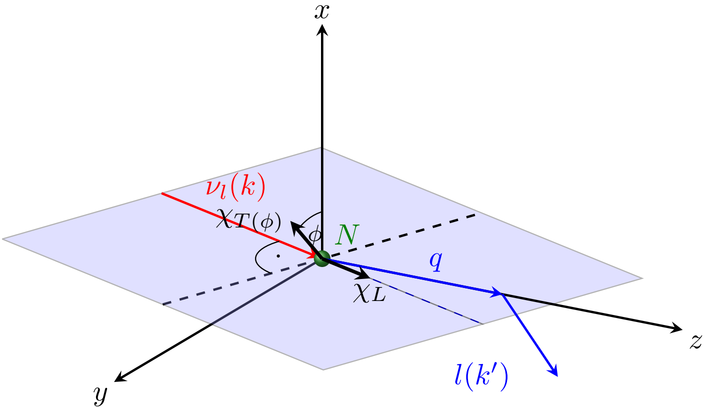
Polarized target asymmetry in SPP

Polarized target asymmetry

Angular distribution of the particles, in the laboratory frame

χ_L, $\chi_T(\phi)$ - spin components of the nucleon.

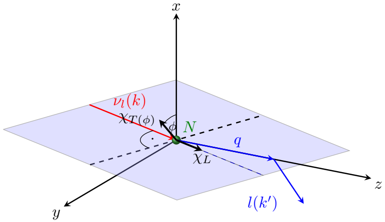


χ_L - spin along the ν flux

$\chi_T(\phi)$ - 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

$$\mathcal{A}^\mu = \mathcal{A}_T(\phi)\chi_T^\mu(\phi) + \mathcal{A}_L\chi_L^\mu \quad (5)$$

s^μ - spin of a particle

$$\mathrm{d}\sigma \sim \frac{1}{2}|\mathcal{M}_{fi}|^2 (1 + \mathcal{A}^\mu \mathrm{s}_\mu) \quad (6)$$

Two direction of target polarization:

Target polarized longitudinally to the beam

$$\mathcal{A}_L = \frac{\mathrm{d}\sigma(\chi_L^\mu) - \mathrm{d}\sigma(-\chi_L^\mu)}{\mathrm{d}\sigma(\chi_L^\mu) + \mathrm{d}\sigma(-\chi_L^\mu)} \quad (7)$$

Target polarized perpendicularly to the beam

$$\mathcal{A}_T = \frac{\mathrm{d}\sigma(\chi_T^\mu) - \mathrm{d}\sigma(-\chi_T^\mu)}{\mathrm{d}\sigma(\chi_T^\mu) + \mathrm{d}\sigma(-\chi_T^\mu)} \quad (8)$$

Longitudinally polarized target

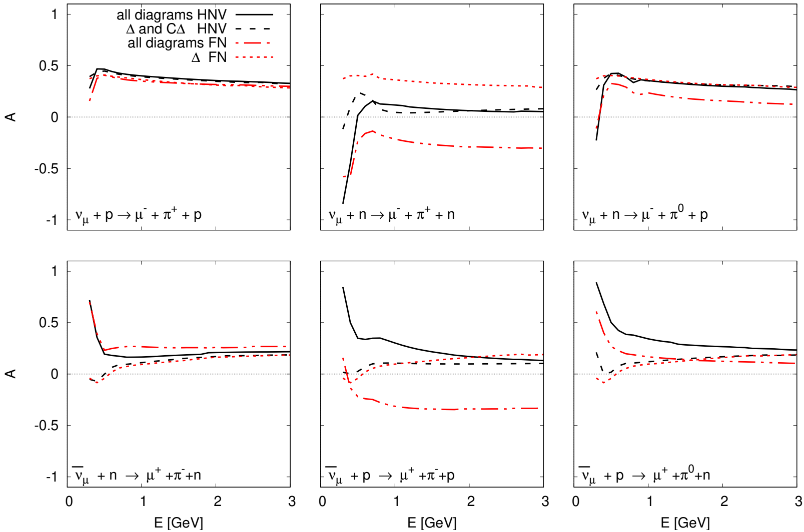


Figure: Dependence of $\mathcal{A}_L(\sigma)$ on the energy of neutrino

Longitudinally polarized target

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

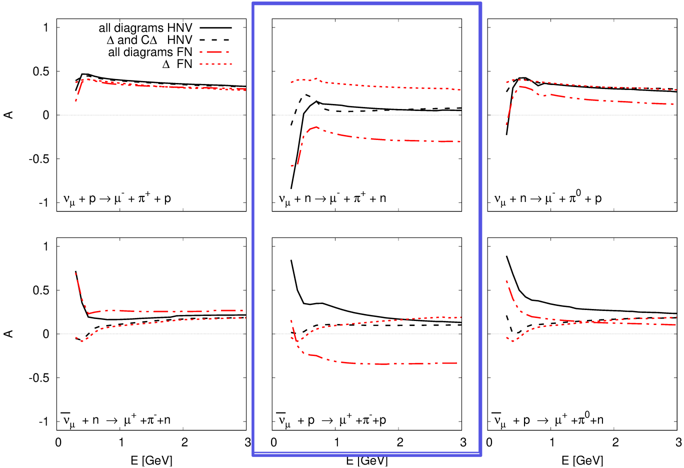
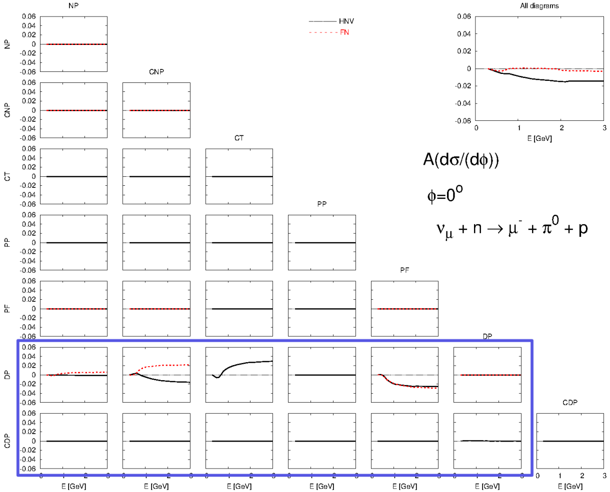


Figure: Dependence of $\mathcal{A}_L(\sigma)$ on the energy of neutrino

Perpendicularly polarized target

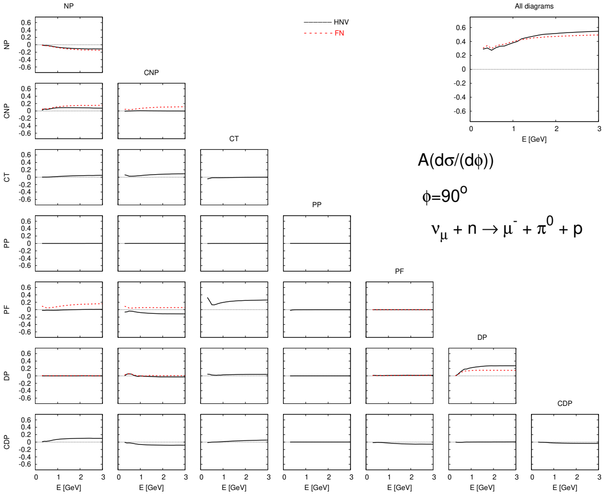
Contributions from different diagrams to $\mathcal{A}_T(\mathrm{d}\sigma/\mathrm{d}\phi)$, $\phi = 0$, only RES-NB interference contributes



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

Perpendicularly polarized target

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

Summary

- We presented new polarization observables for SPP
- Polarization observables are sensitive to details of the models
- The normal polarization is given by NB-RES contribution, has information about phase between them
- The asymmetry is sensitive to details of the models
- The perpendicular asymmetry is given by NB-RES contribution for $\phi = 0$
- The observables we propose can help us to construct theoretical model of SPP

The calculations have been carried out in Wroclaw Centre for Networking and Supercomputing (http://www.wcss.wroc.pl), grant No. 268.

$\nu_\tau + p \rightarrow \tau + p + \pi_+$