Coherent pion production

at low neutrino energies

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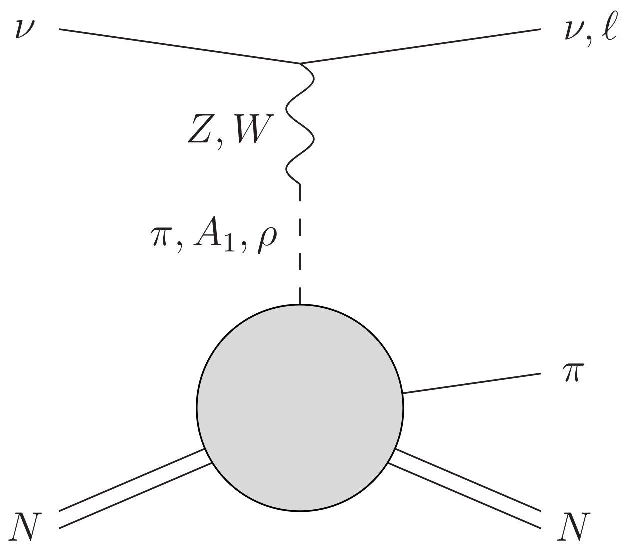
Motivation

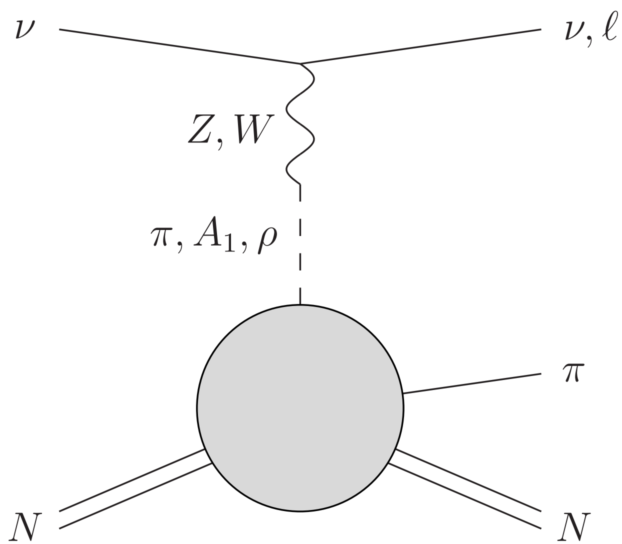


- Calculation of neutrino–nucleus scattering cross section

- *Aachen–Padova*: Alluminium target, neutral current
  $\langle E \rangle = 2$ GeV $\quad \sigma^{\nu} = (29 \pm 10) \cdot 10^{-40}$ cm^2/nucleus
  $\sigma^{\bar{\nu}} = (25 \pm \ \ 7) \cdot 10^{-40}$ cm^2/nucleus

- *Gargamelle*: Freon target, neutral current
  $\langle E \rangle = 3.5$ GeV $\quad \sigma^{\nu} = (31 \pm 20) \cdot 10^{-40}$ cm^2/nucleus
  $\sigma^{\bar{\nu}} = (45 \pm 24) \cdot 10^{-40}$ cm^2/nucleus

Motivation

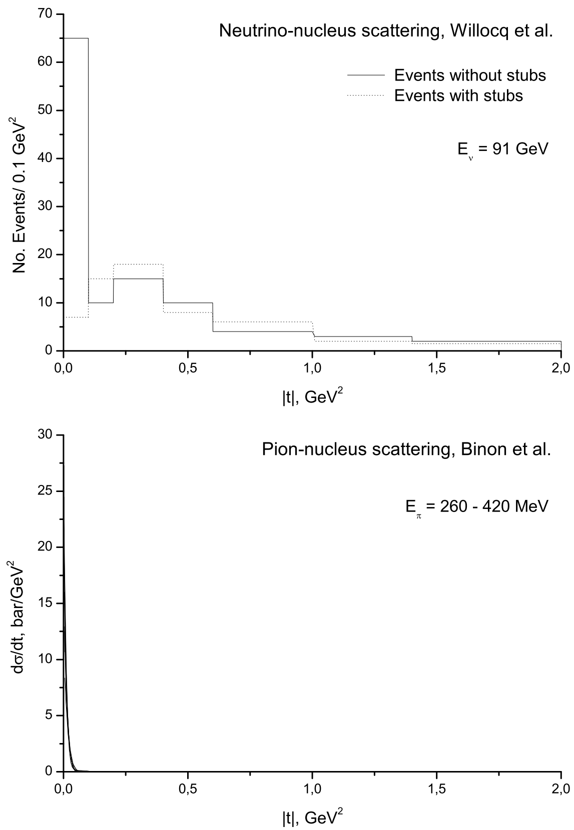


- Calculation of neutrino–nucleus scattering cross section
- Application in the precise neutrino oscillation experiments

- *K2K*: Carbon target, charged current, $E_\mu \geqslant 450$ MeV cut
  $\langle E \rangle = 1.3$ GeV $\sigma^{cc} \leqslant 7.7 \cdot 10^{-40}$ cm^2/nucleus

- *MiniBoone*: Carbon target, neutral and charged current
  $\langle E \rangle = 1.1$ GeV $\sigma^{nc} = (7.7 \pm 1.6 \pm 3.6) \cdot 10^{-40}$ cm^2/CH^2

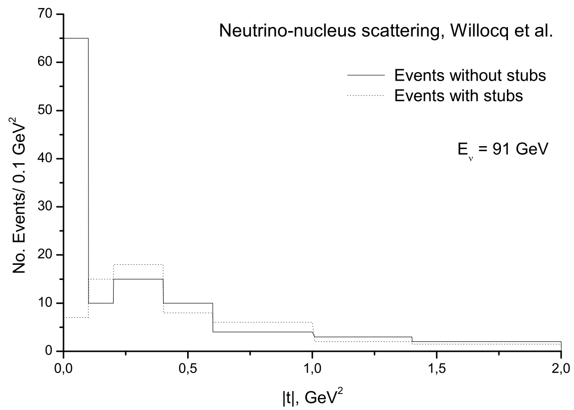
Experimental features

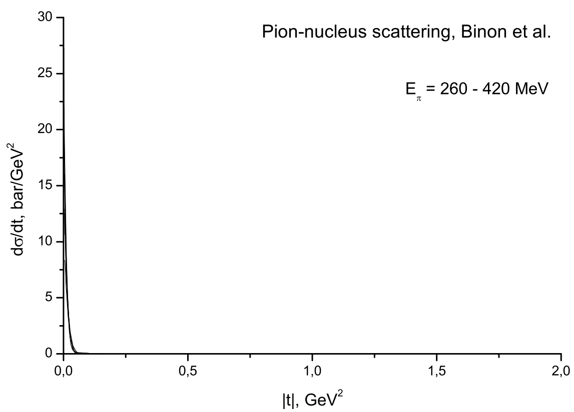


- Necleus remains intact

- In particular the nucleus does not break up

Experimental features

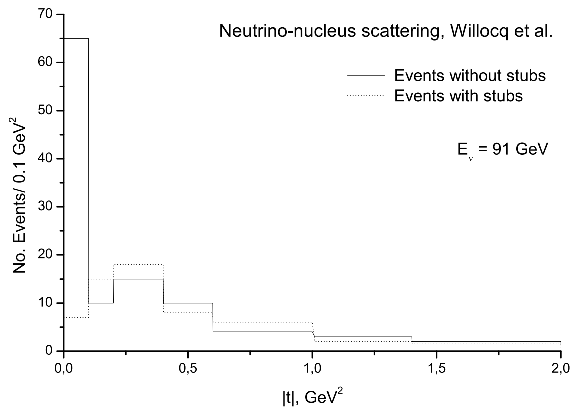


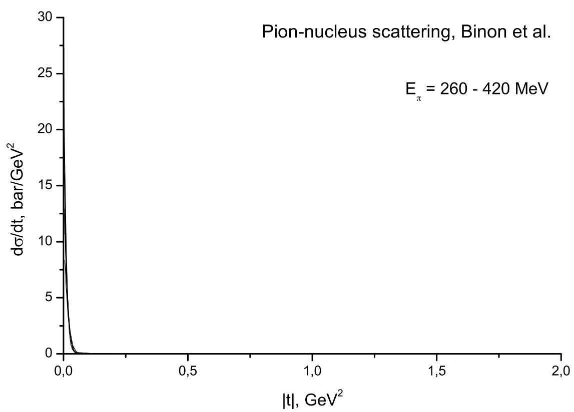


- Necleus remains intact
- Coherent cross section exhibits a peak at small $|t|$

- Pion–nucleus cross section exhibits similar peak, which is an argument in favor of the adopted physical picture.

Experimental features

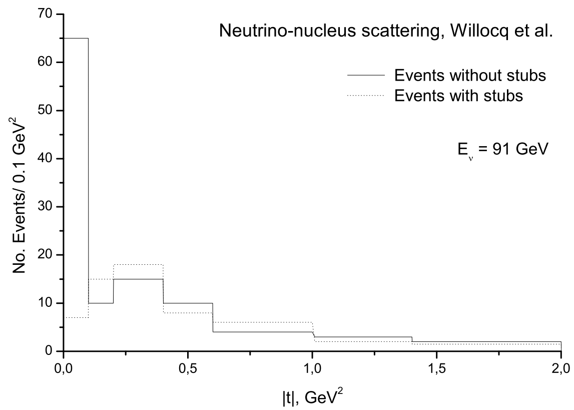


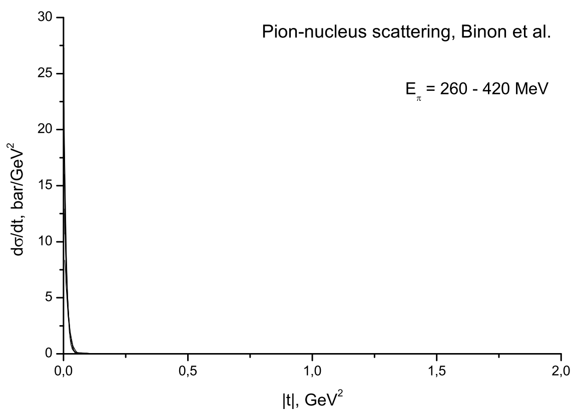


- Necleus remains intact
- Coherent cross section exhibits a peak at small $|t|$
- Coherent cross section exhibits also a peak at small Q^2

- This suggests that the PCAC can be used to calculate the cross section

Experimental features

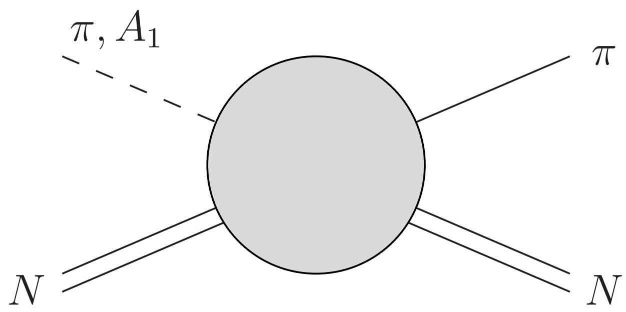


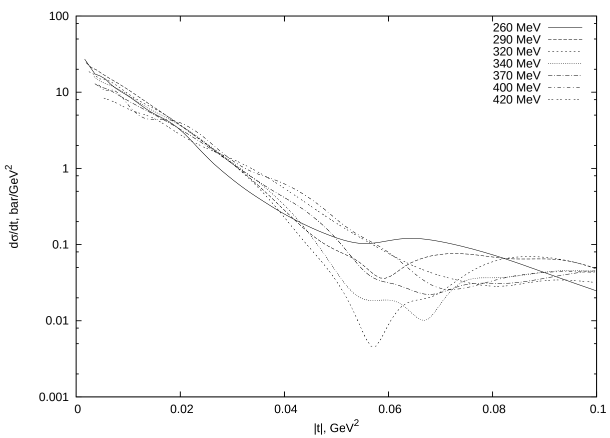


- Necleus remains intact
- Coherent cross section exhibits a peak at small $|t|$
- Coherent cross section exhibits also a peak at small Q^2
- Coherent ν and $\bar{\nu}$ cross sections are close at low energies

- The difference is due to the vector current; therefore its contribution is small at low neutrino energies

Hadron current



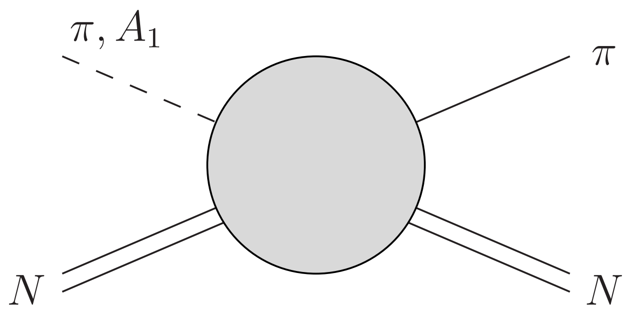


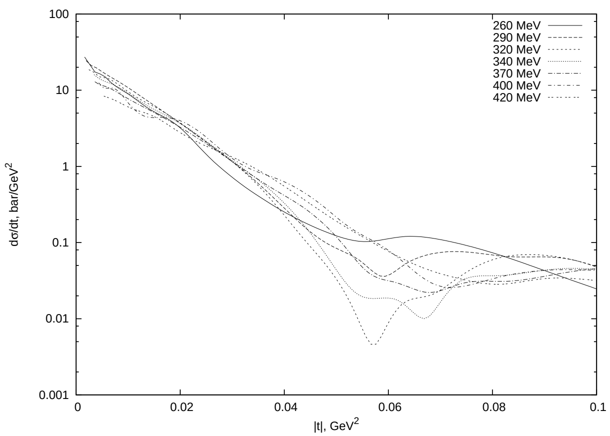
- Hadron axial current

$$\langle|A_\mu|\rangle = -\frac{f_\pi q^\mu}{Q^2+m_\pi^2}\langle|j_\pi|\rangle + R_\mu$$

- Here R_μ denotes contribution of axial mesons like $A_1, \ldots$

Hadron current





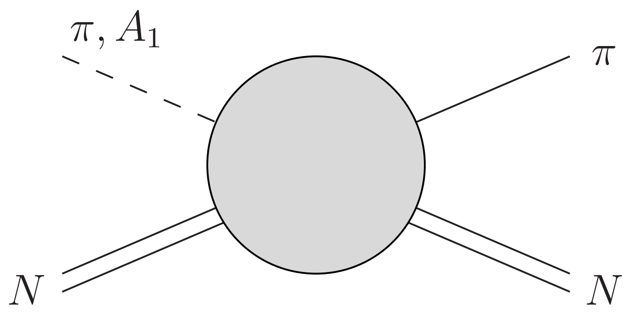
- Hadron axial current

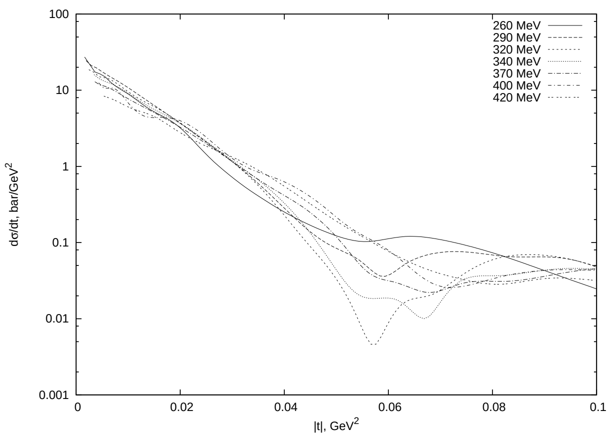
$$\langle|A_\mu|\rangle = -\frac{f_\pi q^\mu}{Q^2+m_\pi^2}\langle|j_\pi|\rangle + R_\mu$$

- The PCAC relates divergence of axial current to the pion field.

- Applicability of the PCAC is limited to small $Q^2 \lesssim m_\pi^2$

Hadron current





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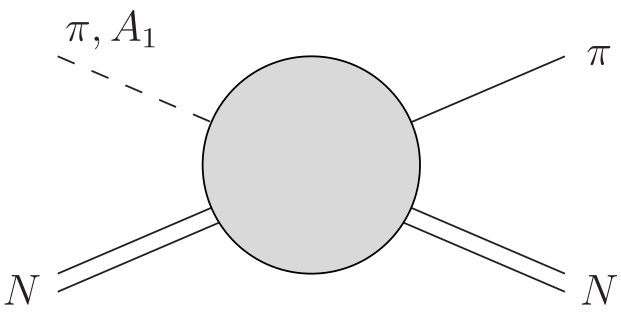
$$\langle|A_\mu|\rangle = -\frac{f_\pi q^\mu}{Q^2+m_\pi^2}\langle|j_\pi|\rangle + R_\mu$$

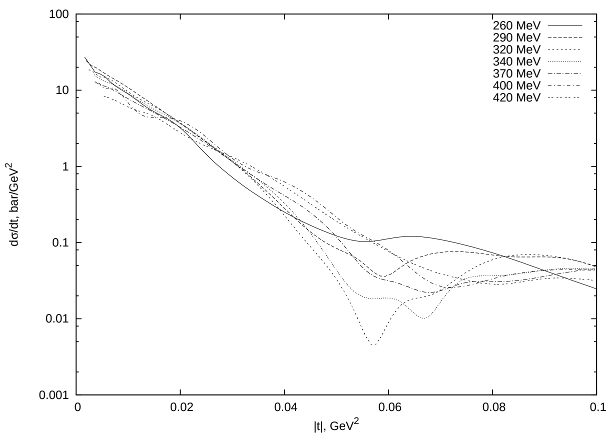
- The PCAC relates divergence of axial current to the pion field.
- From the PCAC it follows that

$$q^\mu R_\mu = -f_\pi\langle|j_\pi|\rangle$$

- Amplitude (modulo squared) of pion–nucleus scattering can be obtained from experimental data

Hadron current





- Hadron axial current

$$\langle|A_\mu|\rangle = -\frac{f_\pi q^\mu}{Q^2+m_\pi^2}\langle|j_\pi|\rangle + R_\mu$$

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- From the PCAC it follows that

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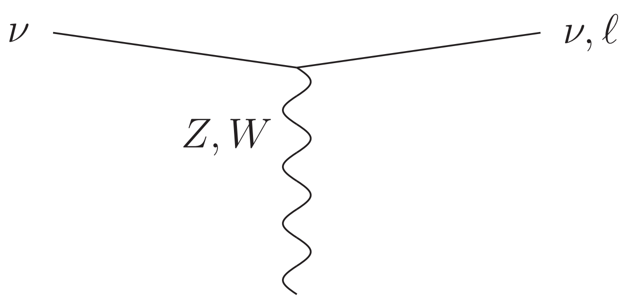
- We use pion–carbon data for the pion energies 260 – 420 MeV

- The data already includes nuclear shadowing, so that the calculation is free of the associated uncertainties.

Lepton current

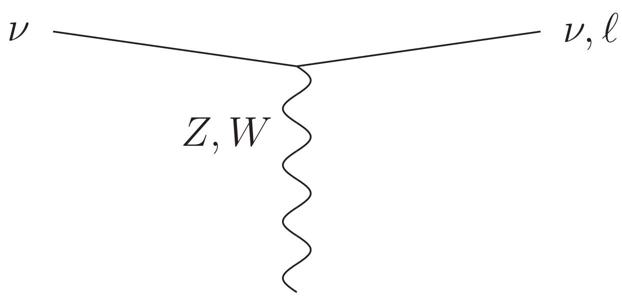


- Lepton current decomposition

$$j^{\mu}_{(\lambda)} = u(k', \lambda)\gamma^{\mu}(\bar{1} - \gamma^5)u(k) =$$
$$A_{(\lambda)}\epsilon^{\mu}_{S} + B_{(\lambda)}\epsilon^{\mu}_{R} + C_{(\lambda)}\epsilon^{\mu}_{L} + D_{(\lambda)}q^{\mu}$$

- The coefficients are functions of polarization and initial and final momenta

Lepton current



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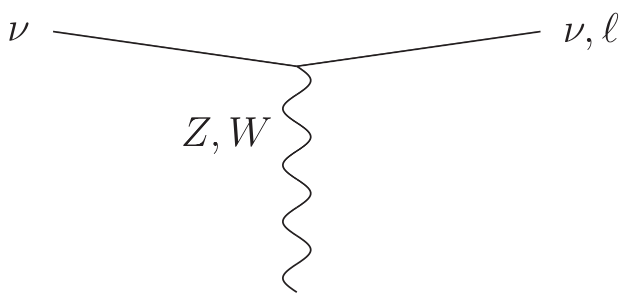
- The leading contribution is due to the “scalar” polarization

- In the massless limit $D_{(\pm)} = A_{(+)} = 0$, $A^2_{(-)} = \frac{4(4EE^{'} - Q^2)}{1 + \nu^2/Q^2}$

Lepton current



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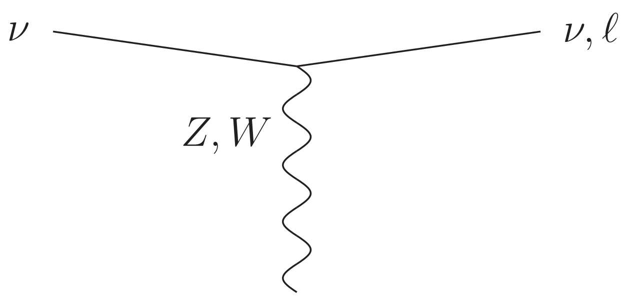
- The leading contribution is due to the “scalar” polarization
- In the forward direction “left” and “right” contributions vanish

- In the massless limit $B_{(-)}, C_{(-)} = \frac{\sqrt{2}(E+E^{'})}{(1+\nu^2/Q^2)^{\frac{1}{2}}} \pm \sqrt{2Q^2}$

Lepton current



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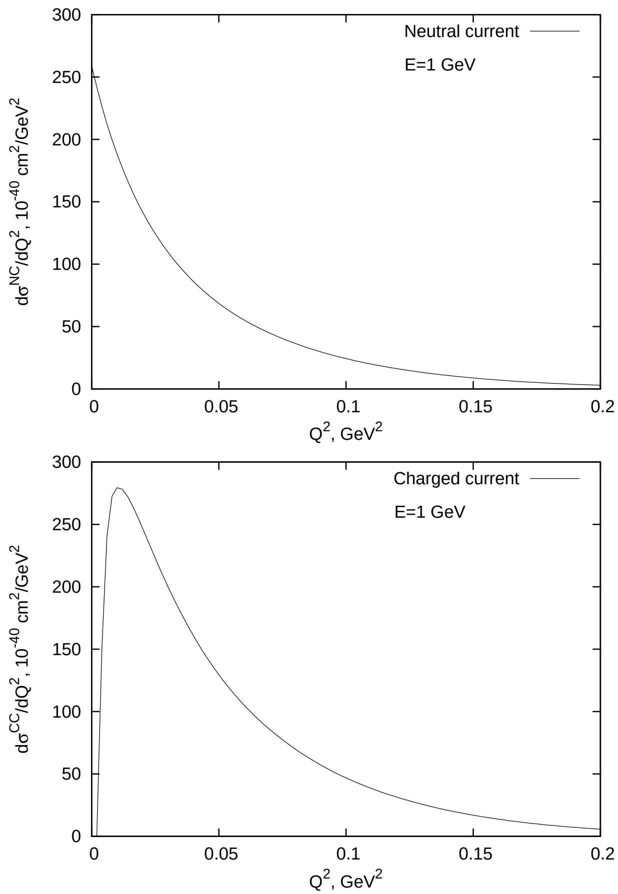
- The leading contribution is due to the “scalar” polarization
- In the forward direction “left” and “right” contributions vanish
- Contribution of q^μ is proportional to the lepton mass

- Polarization vectors ϵ are orthogonal to q^μ, so that only $D^2_{(\lambda)} \propto m^2_\ell$ contributes

Differential cross section

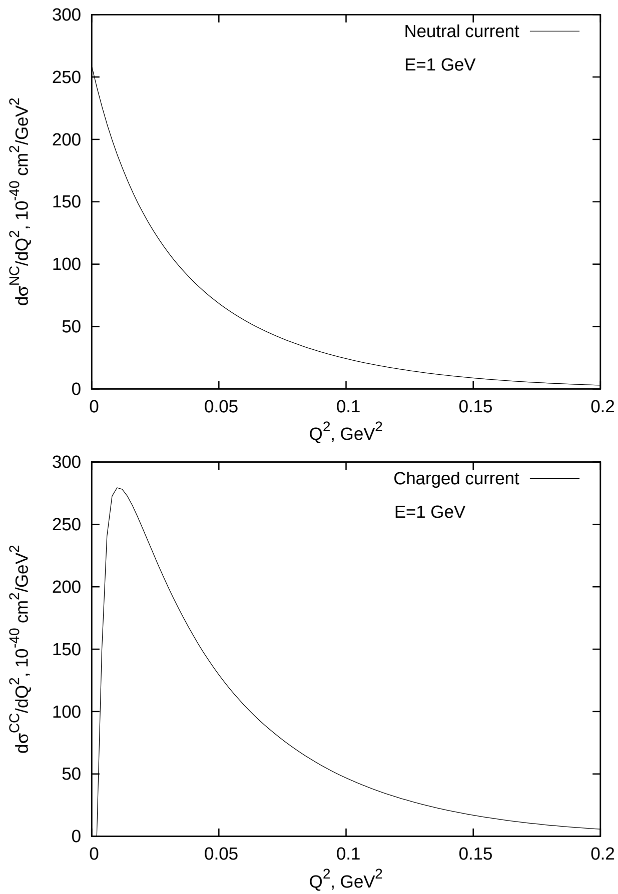


- Neutral current cross section

$$\frac{d\sigma^{nc}}{dQ^2 d\nu dt} = \frac{G^2 f_\pi^2}{16\pi^2} \frac{\nu}{E^2} \frac{4EE' - Q^2}{Q^2 + \nu^2} \frac{d\sigma_{\pi N}}{dt}$$

- In the $Q^2 = 0$ limit it coincides with the expression used by Rein and Sehgal

Differential cross section



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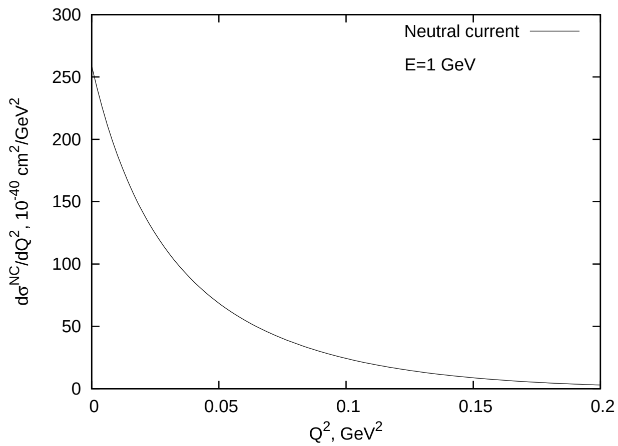
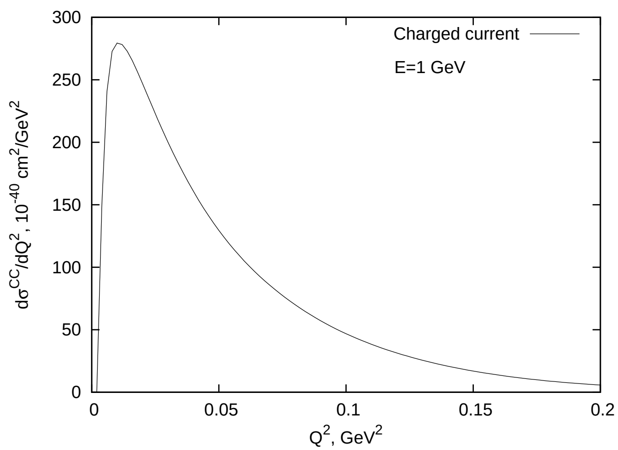
- Charged current cross section

$$\frac{d\sigma^{cc}}{dQ^2 d\nu dt} = 2 \frac{d\sigma^{nc}}{dQ^2 d\nu dt} + \mathcal{O}(m_\ell^2)$$

- The cross section fall-off at small Q^2 is due to the phase space suppression

Differential cross section





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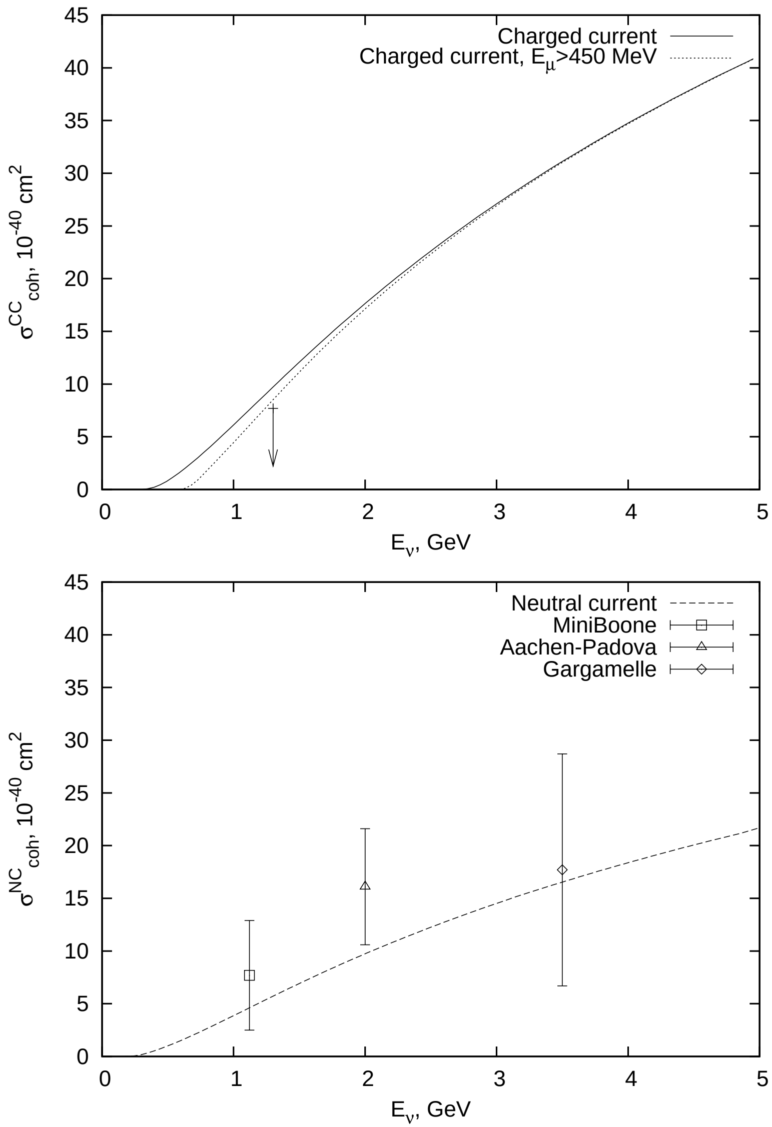
- Charged current cross section

$$\frac{d\sigma^{cc}}{dQ^2 d\nu dt} = 2\frac{d\sigma^{nc}}{dQ^2 d\nu dt} + \mathcal{O}(m_\ell^2)$$

- The cross sections rapidly fall off with increase of Q^2

- Therefore, the PCAC is applicable in the relevant range of Q^2

Total cross section

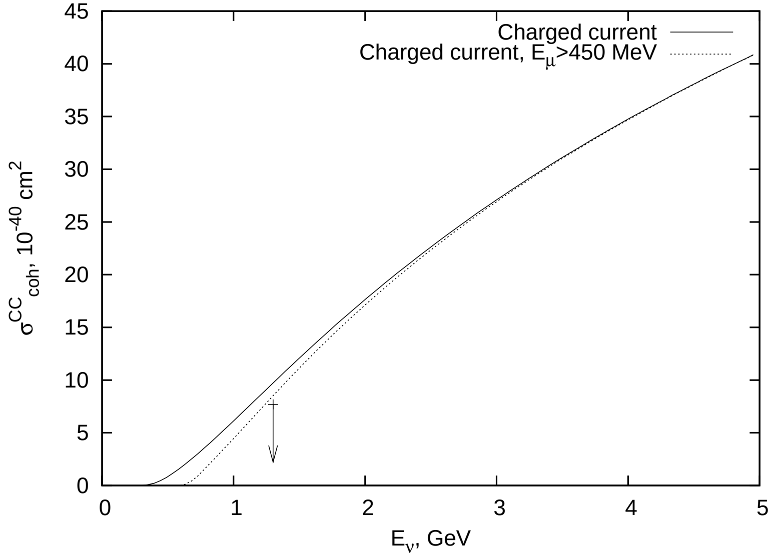


- The coherent cross section at $E = 1.3$ GeV

$$\sigma^{cc}_{coh} = 8.5 \cdot 10^{-40} \text{ cm}^2/\text{C}$$

- Consistent with the result of of *K2K*

Total cross section



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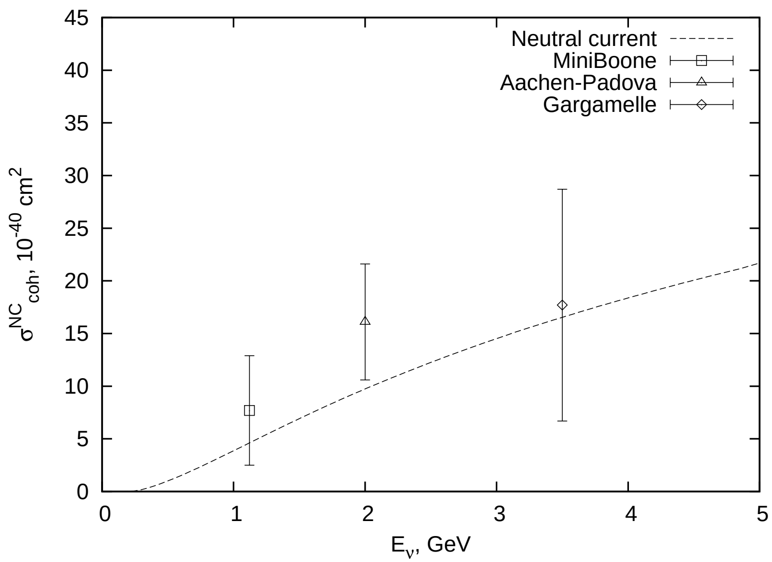

- The coherent cross section at $E = 1.1$ GeV
$$\sigma^{nc}_{coh} = 4.8 \cdot 10^{-40} \text{ cm}^2/\text{C}$$
- Consistent with the result of *MiniBoone*

Conclusions

- Coherent pion production by low energy neutrinos can be adequately described with the aid of the PCAC
- Improved Q^2 dependence and effects of nonzero lepton mass give relatively small corrections
- To avoid errors associated with nuclear corrections it is important to use experimental pion–nucleus data
- Obtained results can be used in the current and future precise neutrino oscillation experiments

hep-ph/0512139

Thank you for your attention

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