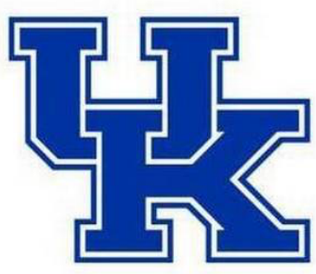
Phenomenology 2021
University of Pittsburg, USA

26 May, 2021

Axial and pseudoscalar form factors from charged-current quasielastic neutrino-nucleon scattering



University of Kentucky

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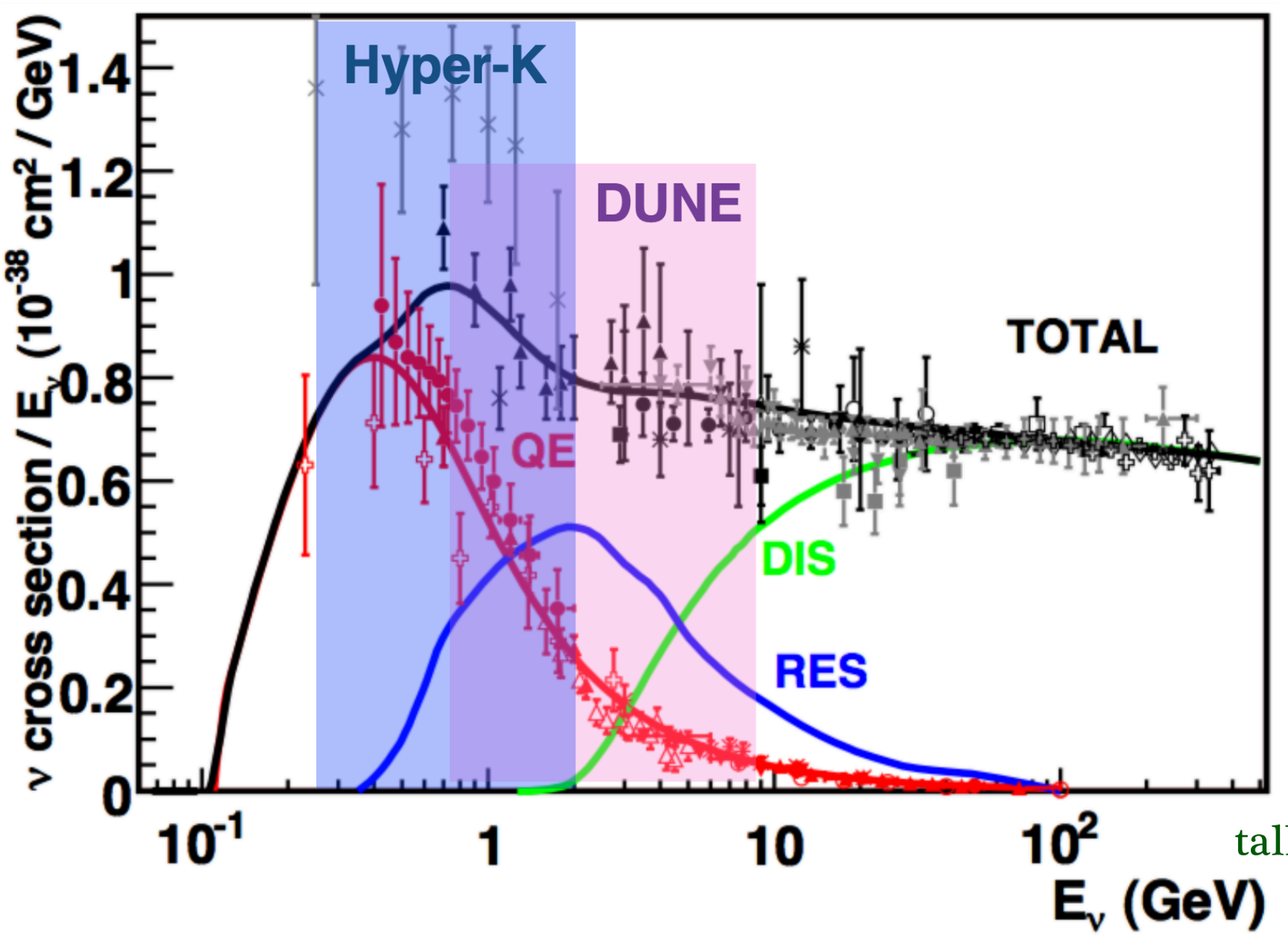
O.T., PRD (2021)

CCQE. Why should we care?

- neutrino-nucleus cross sections and future accelerator-based fluxes

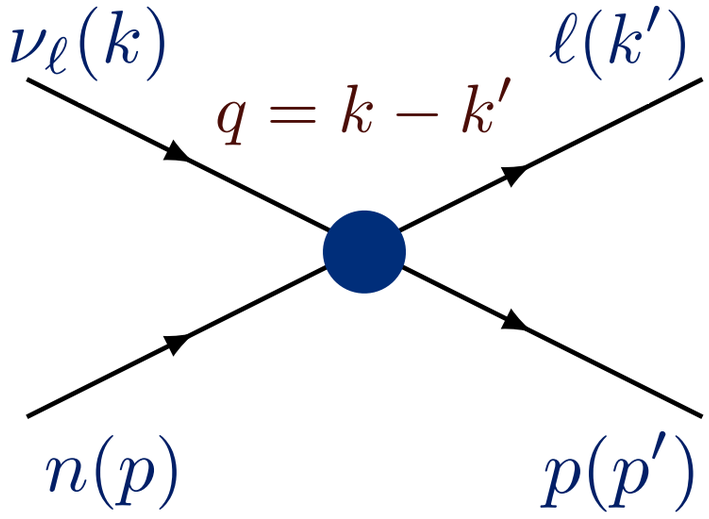


Formaggio and Zeller (2013)

Noemi Rocco talk at Neutrino 2020

- basic process: bulk of events at Hyper-K and DUNE
- best channel for reconstruction of neutrino energy

CCQE scattering on free nucleon



neutrino energy E_ν

momentum transfer $Q^2 = -q^2$

contact interaction at GeV energies

- nucleon current

$$\Gamma^\mu \left(Q^2\right) =< p|\bar{u}\left(\gamma^\mu - \gamma^\mu\gamma_5\right) d|n >$$

$$\Gamma^\mu(Q^2) = \gamma^\mu F_D^V(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M} F_P^V(Q^2) + \gamma^\mu\gamma_5 F_A(Q^2) + \frac{q^\mu}{M}\gamma_5 F_P(Q^2)$$

form factors: isovector Dirac and Pauli axial and pseudoscalar

$$F_{D,P}^V = F_{D,P}^p - F_{D,P}^n$$

tree-level amplitude

$$\mathrm{T} = \frac{\mathrm{G_F} V_{ud}}{\sqrt{2}} (\bar{\ell}(k')\gamma_\mu \left(1 - \gamma_5\right) \nu_\ell(k)) (\bar{p}(p')\Gamma^\mu(Q^2) n(p))$$

CCQE scattering on free nucleon

- only 3 experiments performed with deuterium bubble chamber

direct access to form-factor shape

ANL 1982: 1737 events

BNL 1981: 1138 events

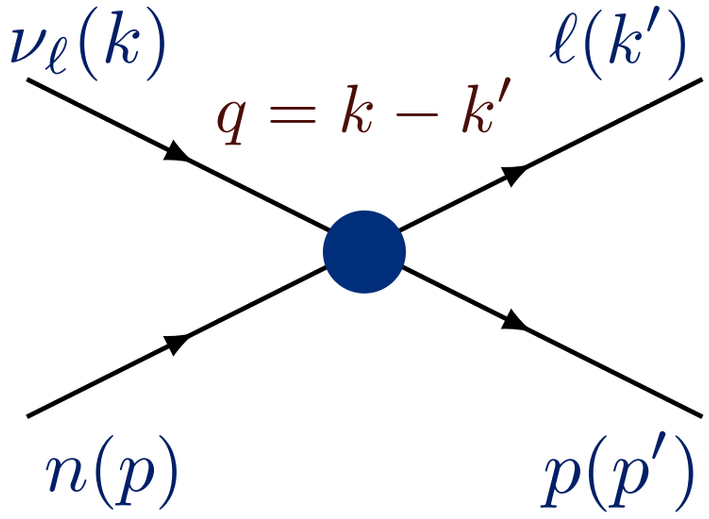
FNAL 1983: 362 events

world data: ~3200 events

Fermilab bubble chamber, Richard Drew

- axial form factor errors can be reduced with new measurements

CCQE scattering on free nucleon



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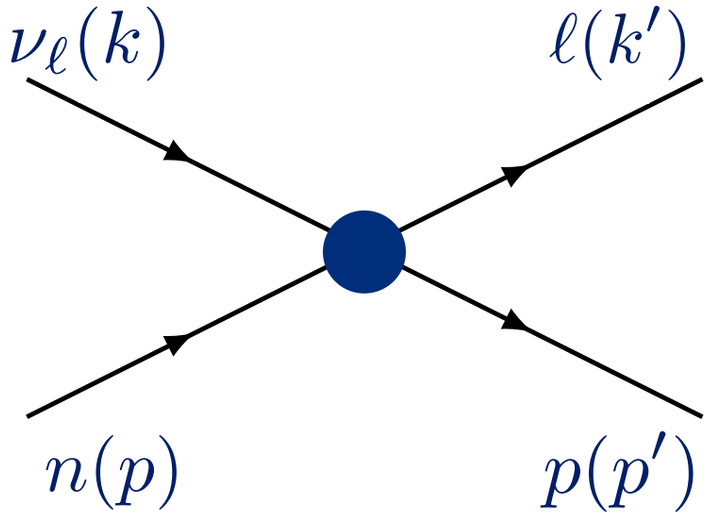
CCQE scattering on free nucleon



$$\nu = E_\nu/M - \tau - r^2$$

$$r = \frac{m_\ell}{2M} \qquad \tau = \frac{Q^2}{4M^2}$$

unpolarized cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \sim \frac{M^2}{E_\nu^2}\left(\left(\tau + r^2\right)A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau}C(Q^2)\right)$$

Llewellyn Smith (1972)

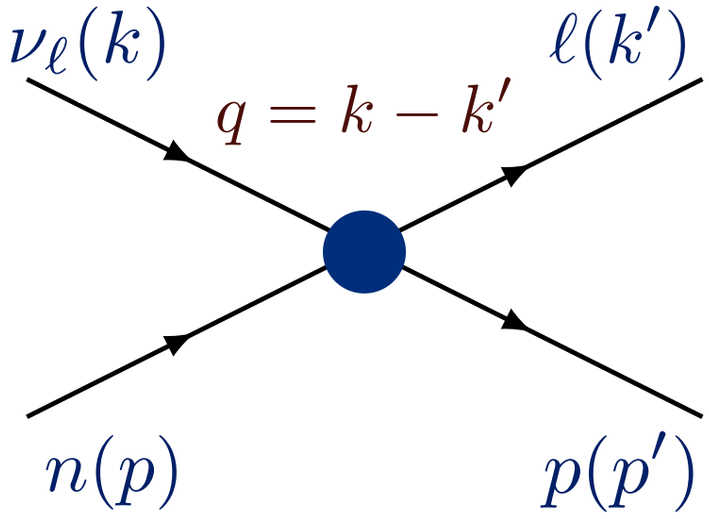
- structure-dependent functions

$$A = \tau\left(G_M^V\right)^2 - \left(G_E^V\right)^2 + (1+\tau)F_A^2 - r^2\left(\left(G_M^V\right)^2 + F_A^2 - 4\tau F_P^2 + 4F_A F_P\right)$$

$$B = \pm 4\tau F_A G_M^V \qquad C = \tau\left(G_M^V\right)^2 + \left(G_E^V\right)^2 + (1+\tau)F_A^2$$

- pseudoscalar form factor contribution is suppressed by lepton mass
- cross section is sensitive to both vector and axial contributions

CCQE scattering on free nucleon



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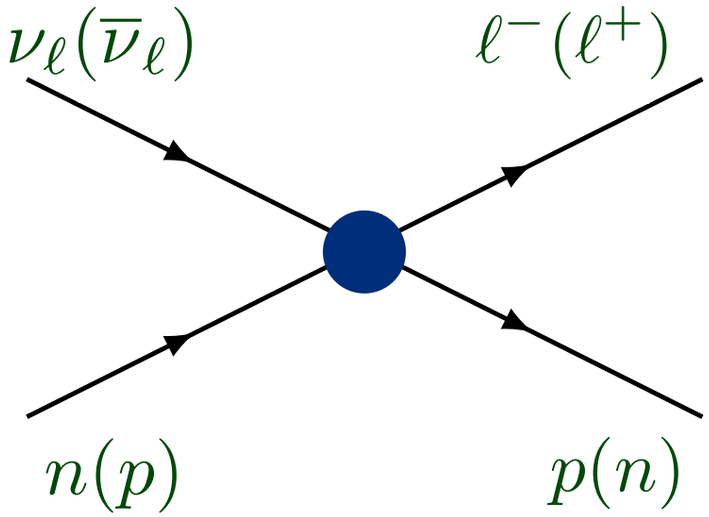
Form factors and polarization observables



polarized target and/or recoil

$$A = \frac{\mathrm{d}\sigma\left(S\right) - \mathrm{d}\sigma\left(-S\right)}{\mathrm{d}\sigma\left(S\right) + \mathrm{d}\sigma\left(-S\right)}$$

S. M. Bilenky et al. (2013), A. Fatima et al (2018),
J. Sobczyk et al (2019), B. Kowal et al (2019)

- spin asymmetries are not suppressed by m_ℓ or coupling constant:
  comparable to unpolarized cross section rates

$$\mathrm{T,R,L} = \frac{\left(\tau + r^2\right) A^{\mathrm{T,R,L}}(Q^2) - \nu B^{\mathrm{T,R,L}}(Q^2) + \frac{\nu^2}{1+\tau} C^{\mathrm{T,R,L}}(Q^2)}{\left(\tau + r^2\right) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau} C(Q^2)}$$

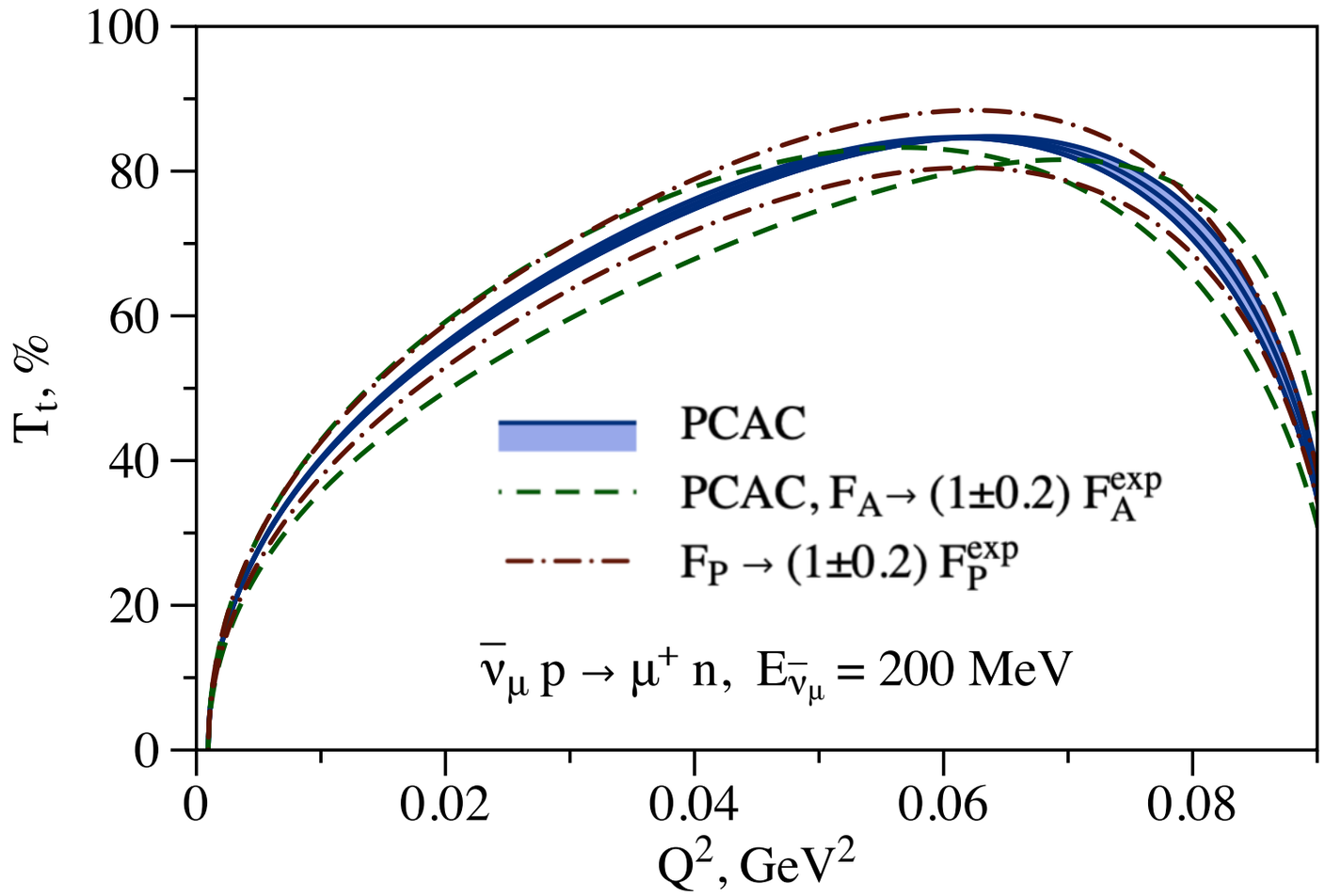
- target, recoil and lepton asymmetries with spin in scattering plane

- alternative way to access axial structure at GeV energies

Muon neutrinos

target transverse asymmetry

PCAC: $\mathrm{F_P} = \dfrac{2M^2}{m_\pi^2 + Q^2}\mathrm{F_A}$



R. Gupta et al. (2017-2020),
Ch. Chen et al. (2021),
C. Alexandrou et al. (2021)

modern nucleon form factors

A.S. Meyer, M. Betancourt, R. Gran and R.J. Hill (2016)

K. Borah, G. Lee, R. J. Hill and O. T. (2020)

- pseudoscalar form factor can be accessed with muon flavor
- very precise measurements can give constraints

Axial form factor at GeV energies

longitudinal flux-averaged asymmetries

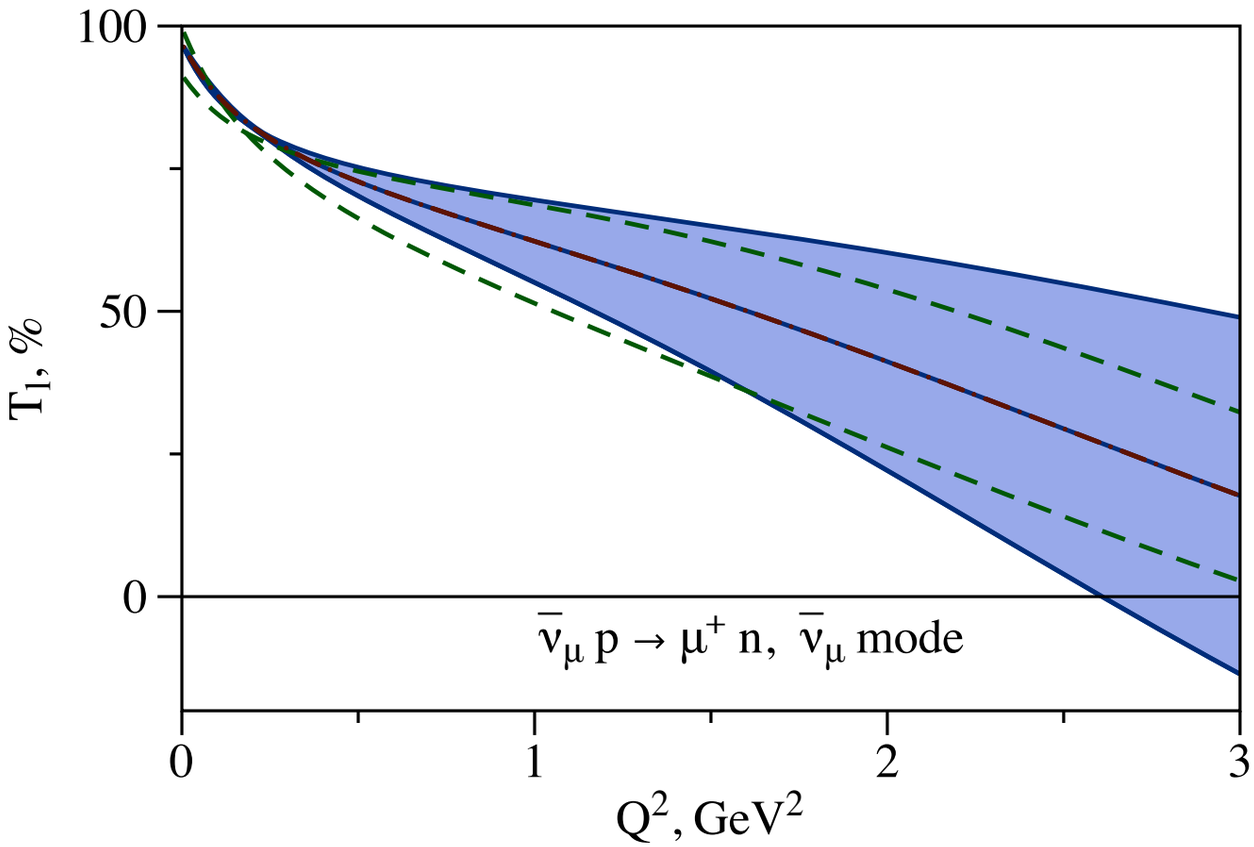
target

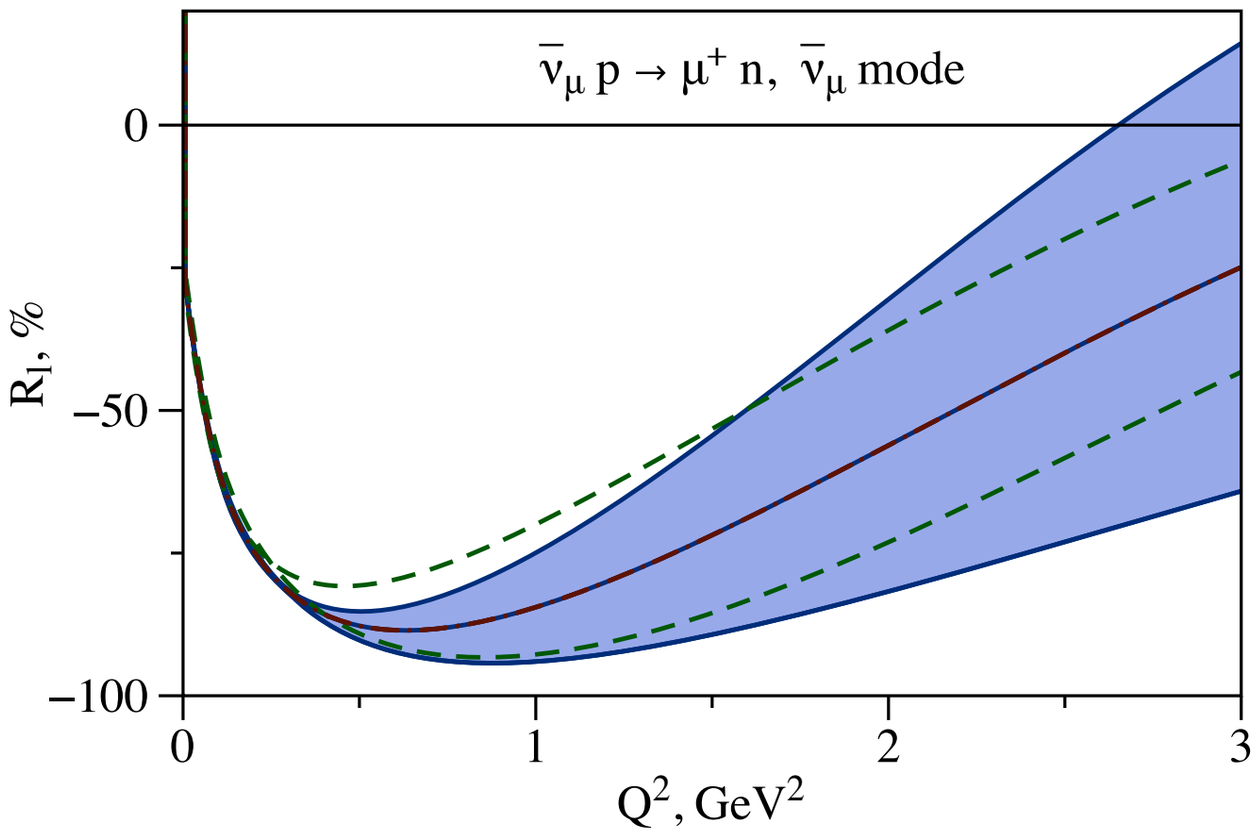
PCAC

PCAC, $F_A \to (1\pm0.2)\, F_A^{exp}$

$F_P \to (1\pm0.2)\, F_P^{exp}$

recoil

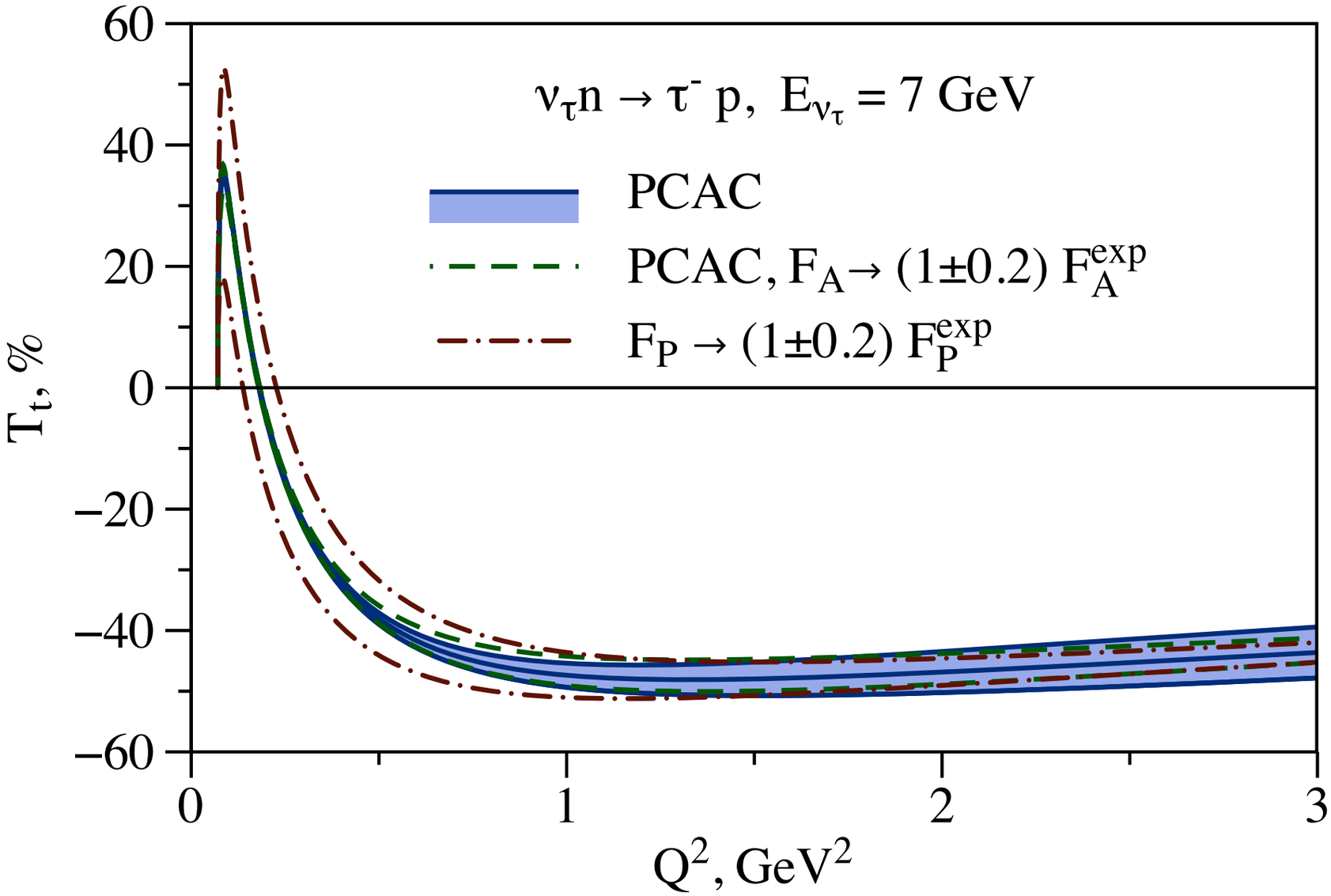




- antineutrino mode and polarized nucleons are promising
- sizable contribution of axial form factor at GeV energies

Tau neutrinos

target transverse asymmetry



- lepton asymmetries can provide only axial form factor
- transverse target and recoil asymmetries are sensitive to Fp

Conclusions and Outlook

$$A = \frac{\mathrm{d}\sigma\left(S\right) - \mathrm{d}\sigma\left(-S\right)}{\mathrm{d}\sigma\left(S\right) + \mathrm{d}\sigma\left(-S\right)}$$

alternative probe
of nucleon structure

- compact expressions for all tree-level single-spin asymmetries
- axial form factor:
  target longitudinal asymmetry with antineutrino beam
- pseudoscalar form factor:
  muon flavor at hundreds MeV but very precise measurements
  tau flavor above production threshold
- sensitivity to other physics in scattering on polarized nucleon?

Thanks for your attention !!!

Fermilab

This presentation is based upon work
that is supported by the Visiting Scholars Award Program
of the Universities Research Association