Tau neutrinos from GeV to EeV

NuTau 2021

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Axial and pseudoscalar form factors with tau neutrinos

Los Alamos NATIONAL LABORATORY

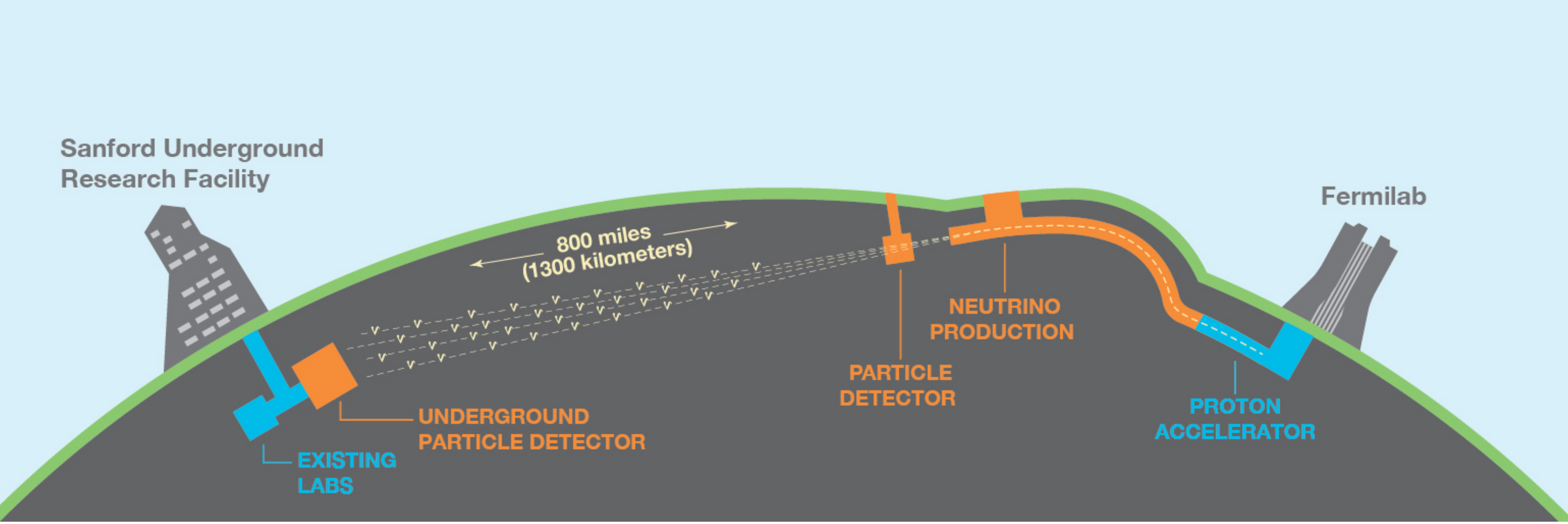
Oleksandr Tomalak

LA-UR-21-28872

O.T., PRD (2021)

Neutrino experiments

- DUNE and Hyper-K: leading-edge ν science experiments



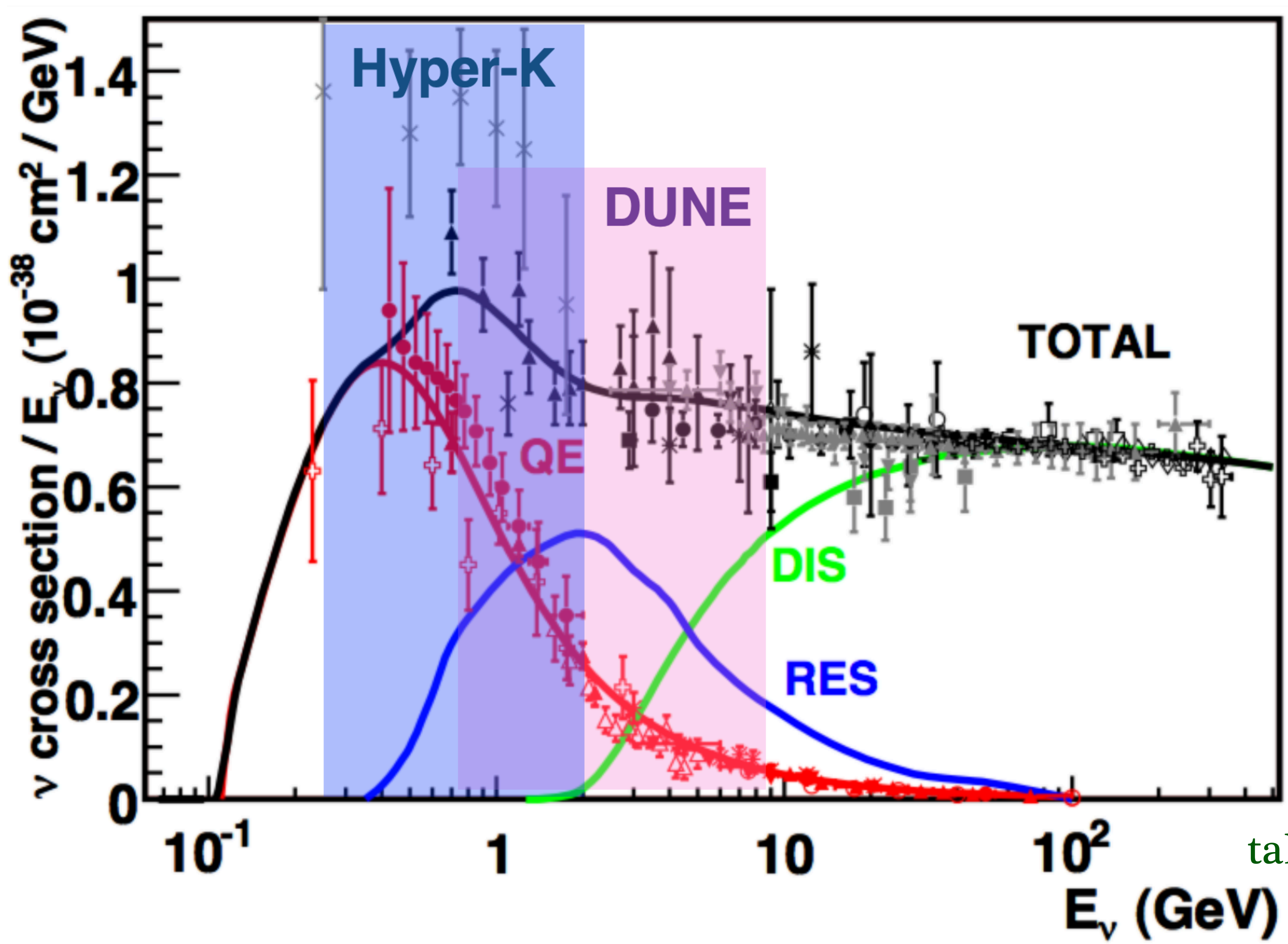
- measurement of $\nu_\mu(\overline{\nu}_\mu)$ disappearance and $\nu_e(\overline{\nu}_e)$ appearance

$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu \left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

- cross sections for precise measurements and discovery of lepton $\cancel{CP}$

CCQE. Why should we care?

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

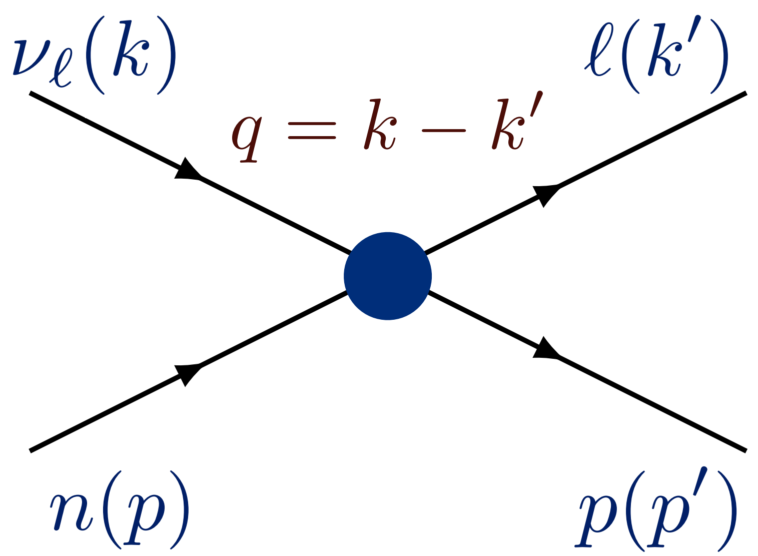


Formaggio and Zeller (2013)

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

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

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

form factors: isovector Dirac and Pauli axial and pseudoscalar

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

tree-level amplitude

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

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

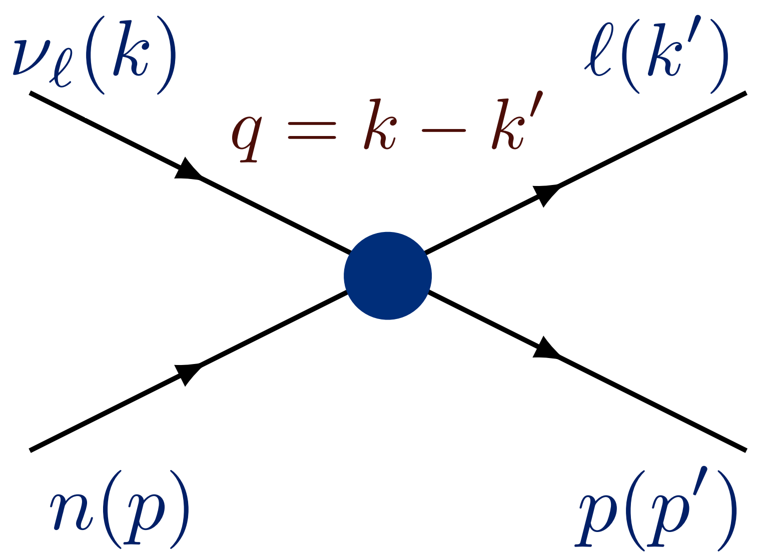
FNAL 1983: 362 events

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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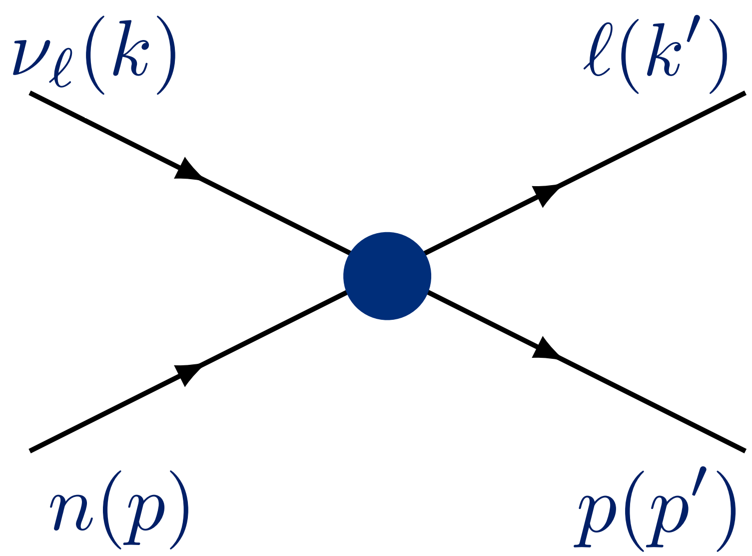


$$\nu = E_\nu/M - \tau - r^2$$

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

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

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

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

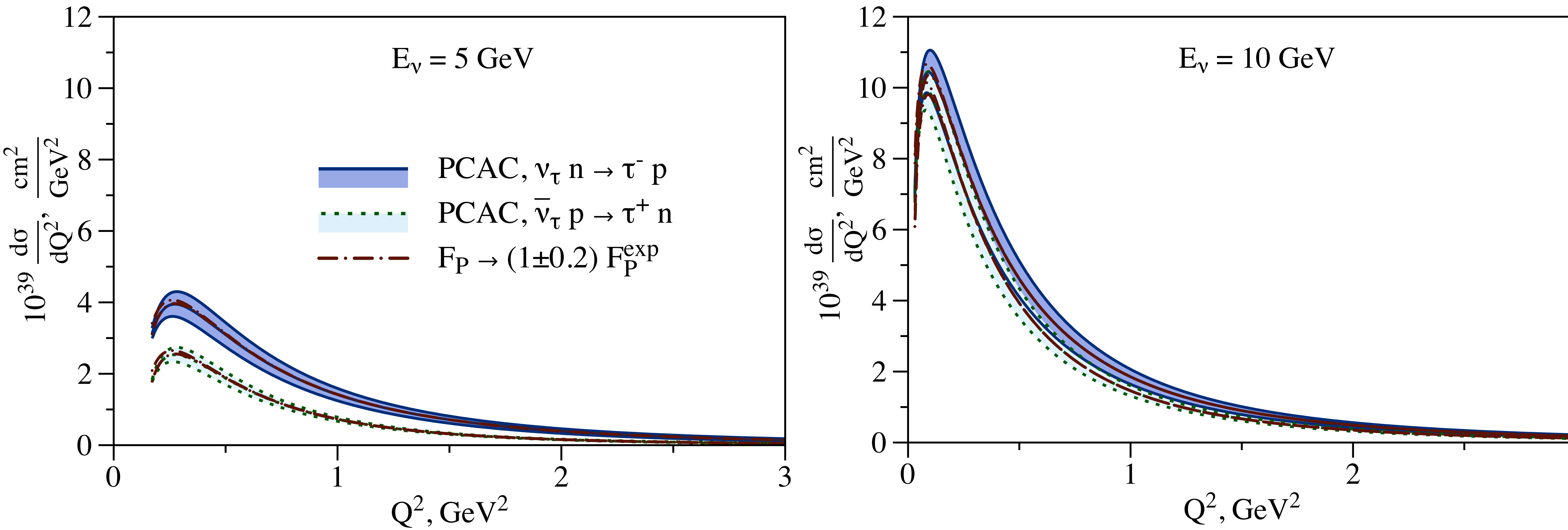
- pseudoscalar form factor contribution is suppressed by lepton mass
- cross section is sensitive to both vector and axial contributions

CCQE cross sections with τ

assumpt. for pseudoscalar form factor, label as PCAC: $F_P = \frac{2M^2}{m_\pi^2 + Q^2} F_A$

growths from production threshold ~ 3.5 GeV

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



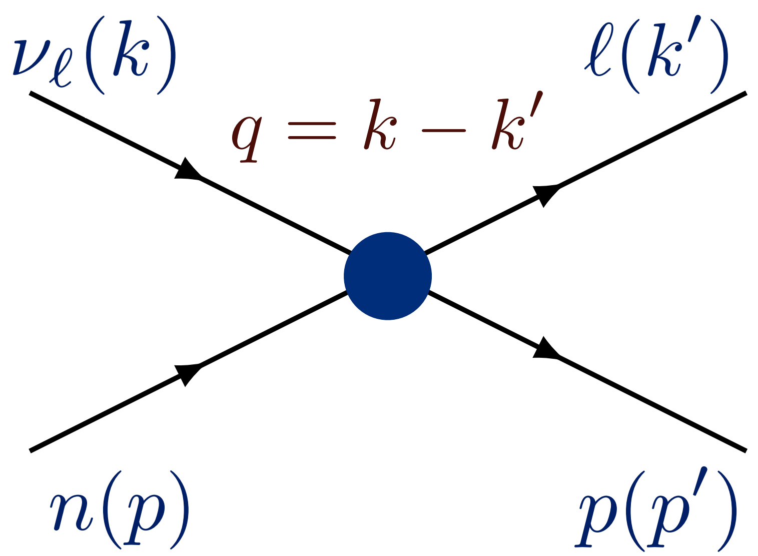
modern nucleon form factors

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

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

- distinct neutrino and antineutrino cross sections at "low" energy
- sensitivity to axial but not to pseudoscalar form factor

CCQE scattering on free nucleon



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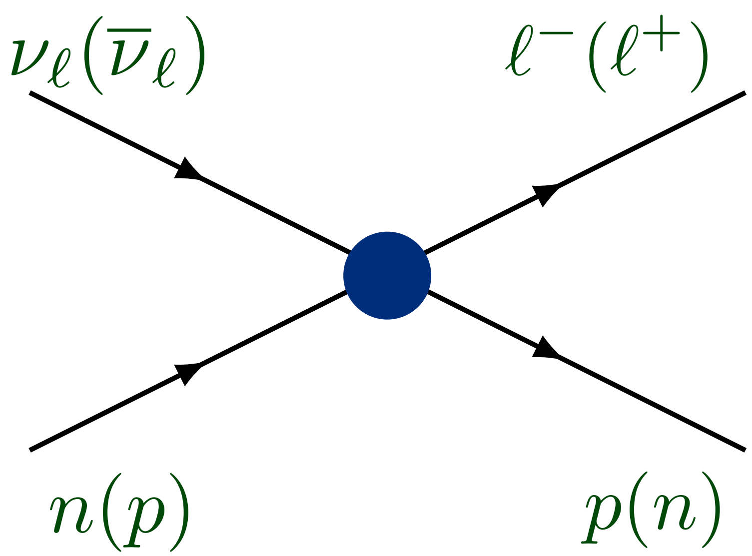
Form factors and polarization observables



polarized target and/or recoil

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

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

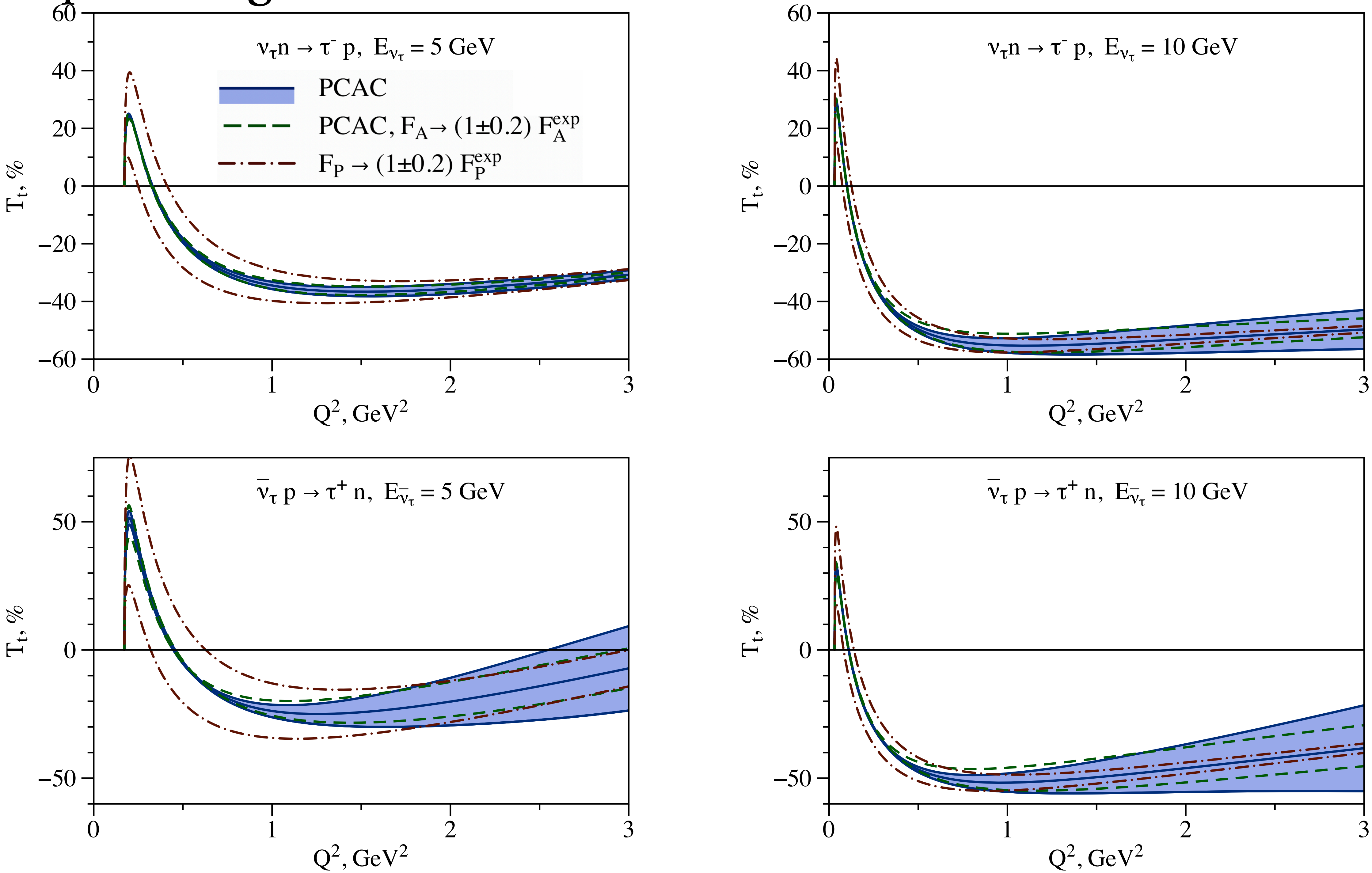
$$\mathrm{T, R, L} = \frac{\left(\tau + r^2\right) A^{\mathrm{T,R,L}}(Q^2) - \nu B^{\mathrm{T,R,L}}(Q^2) + \frac{\nu^2}{1+\tau} C^{\mathrm{T,R,L}}(Q^2)}{\left(\tau + r^2\right) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau} C(Q^2)}$$

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

- alternative way to access axial structure at GeV energies

Target transverse asymmetry

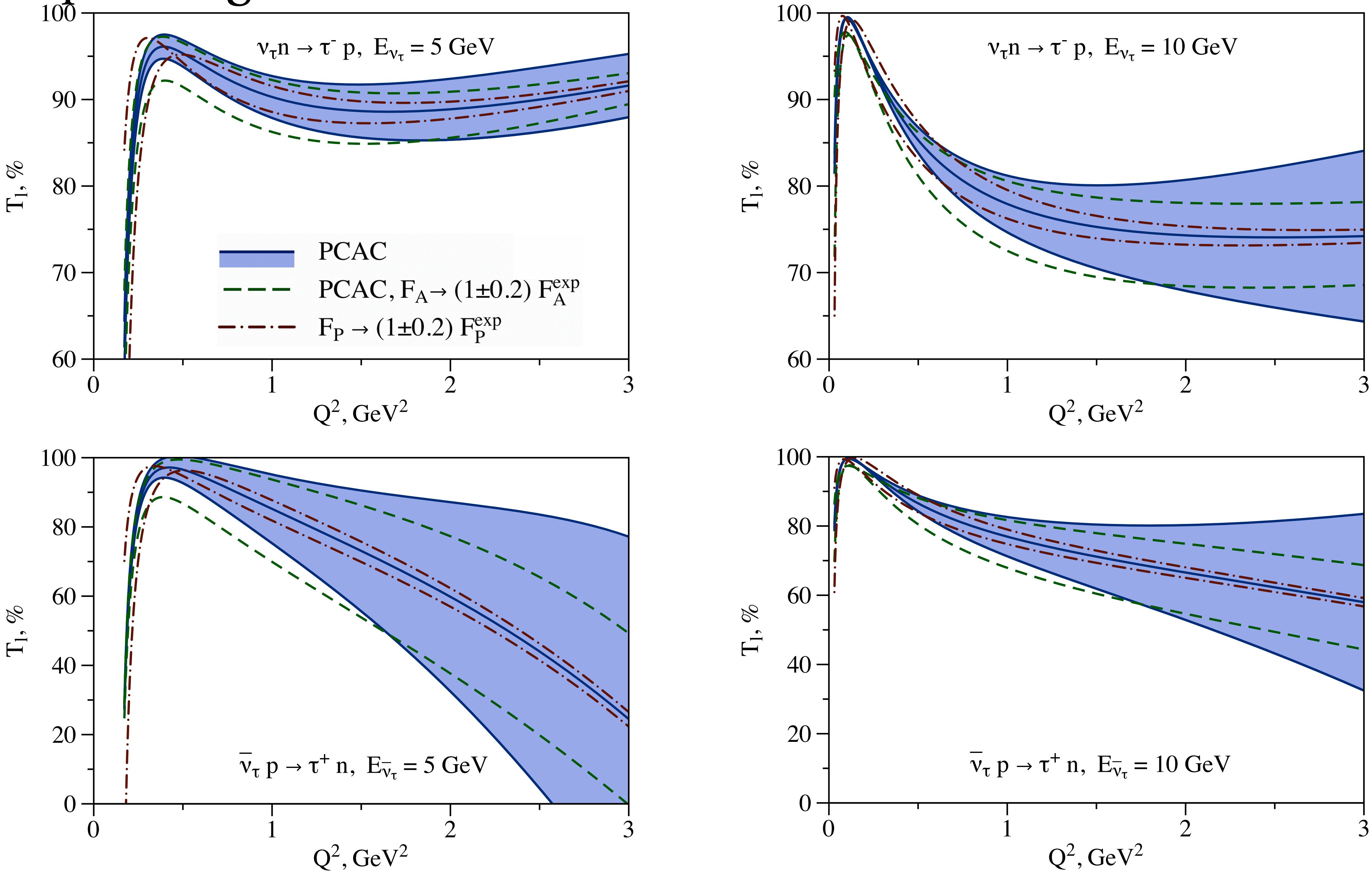
spin orthogonal to the beam direction



- sensitive to pseudoscalar form factor

Target longitudinal asymmetry

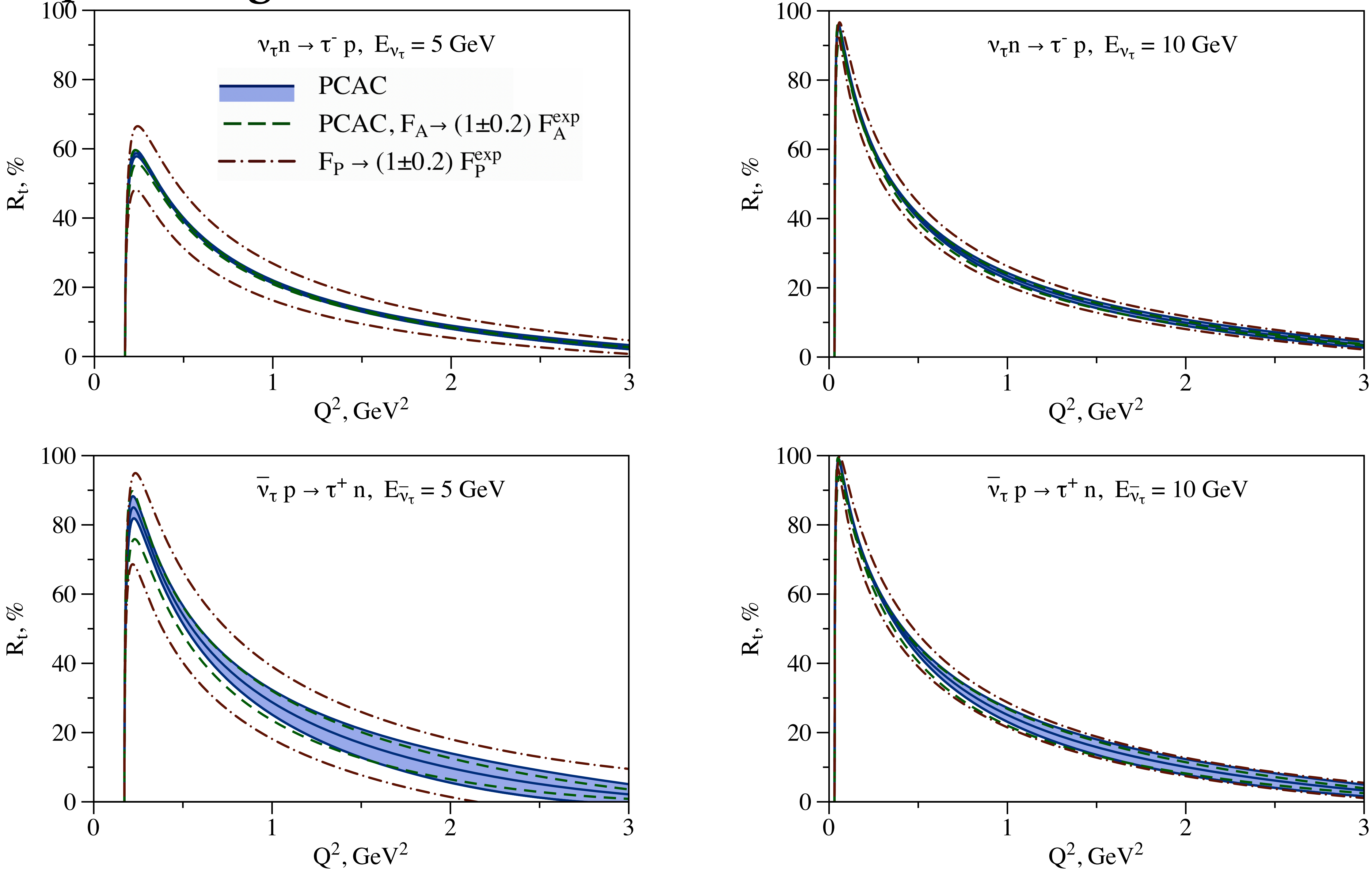
spin along the beam direction



- sensitive to both axial and pseudoscalar form factors

Recoil transverse asymmetry

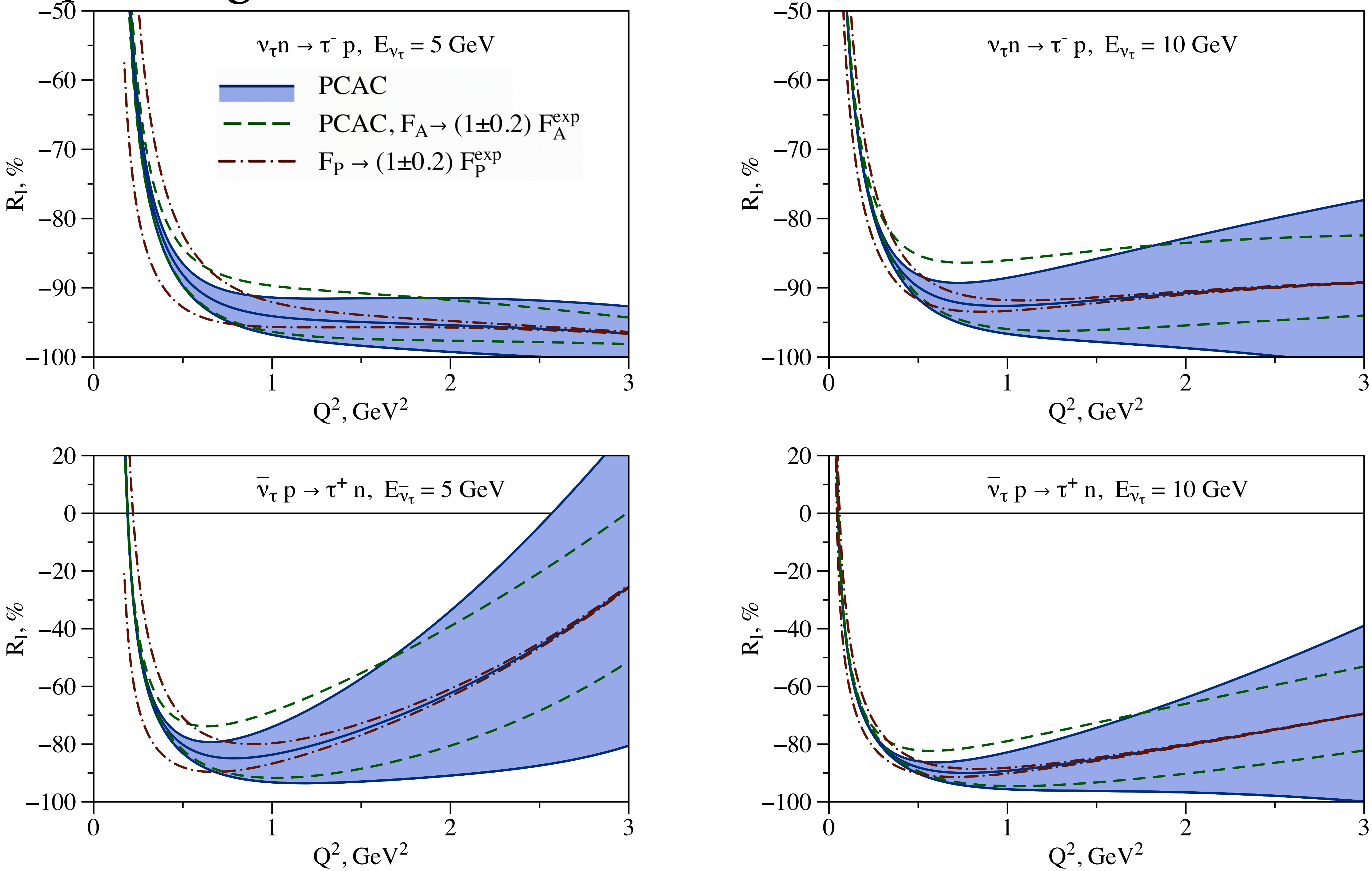
spin orthogonal to the recoil nucleon



- sensitive to pseudoscalar form factor

Recoil longitudinal asymmetry

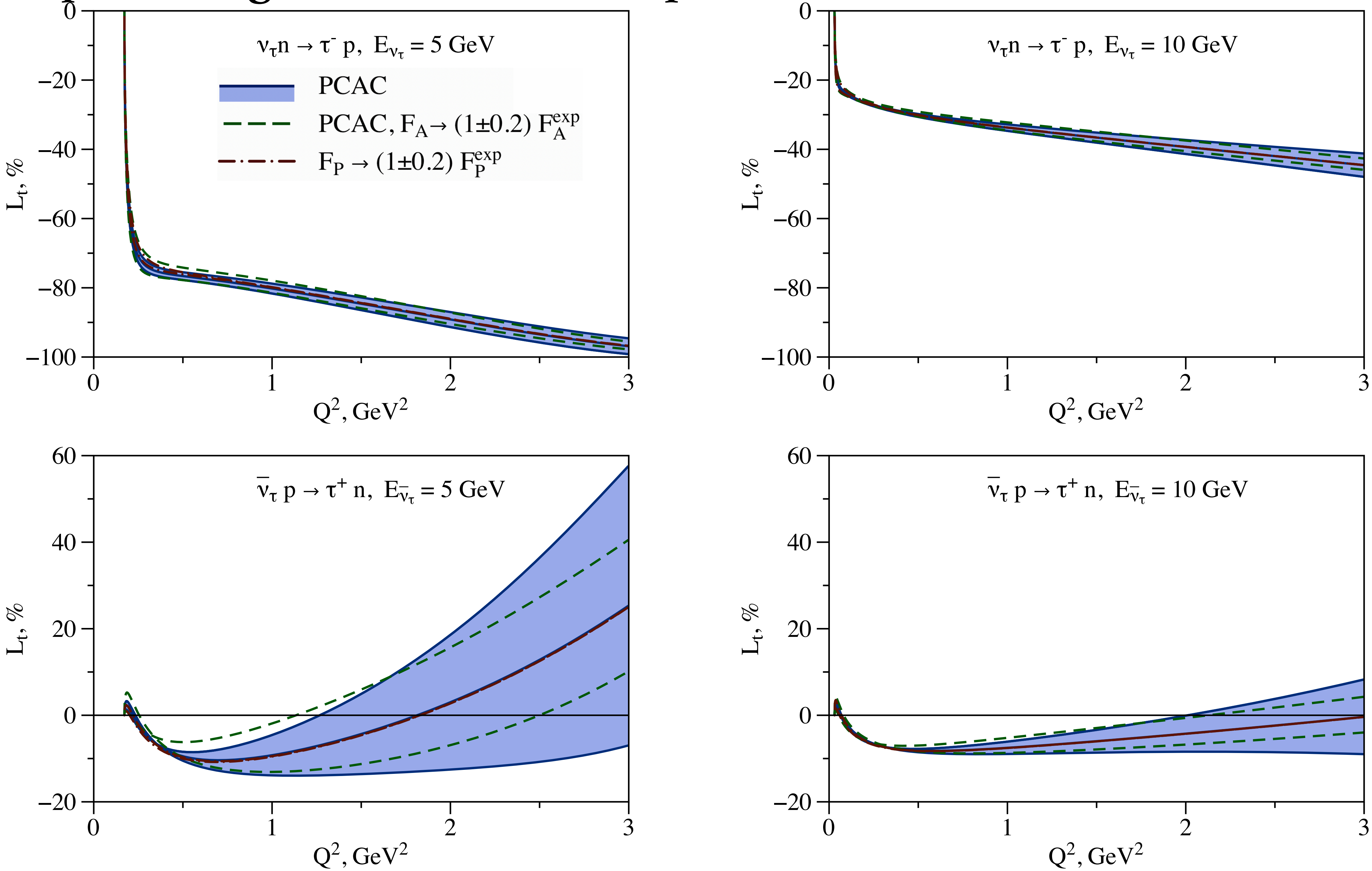
spin along the recoil nucleon momentum



- sensitive to both axial and pseudoscalar form factors

Lepton transverse asymmetry

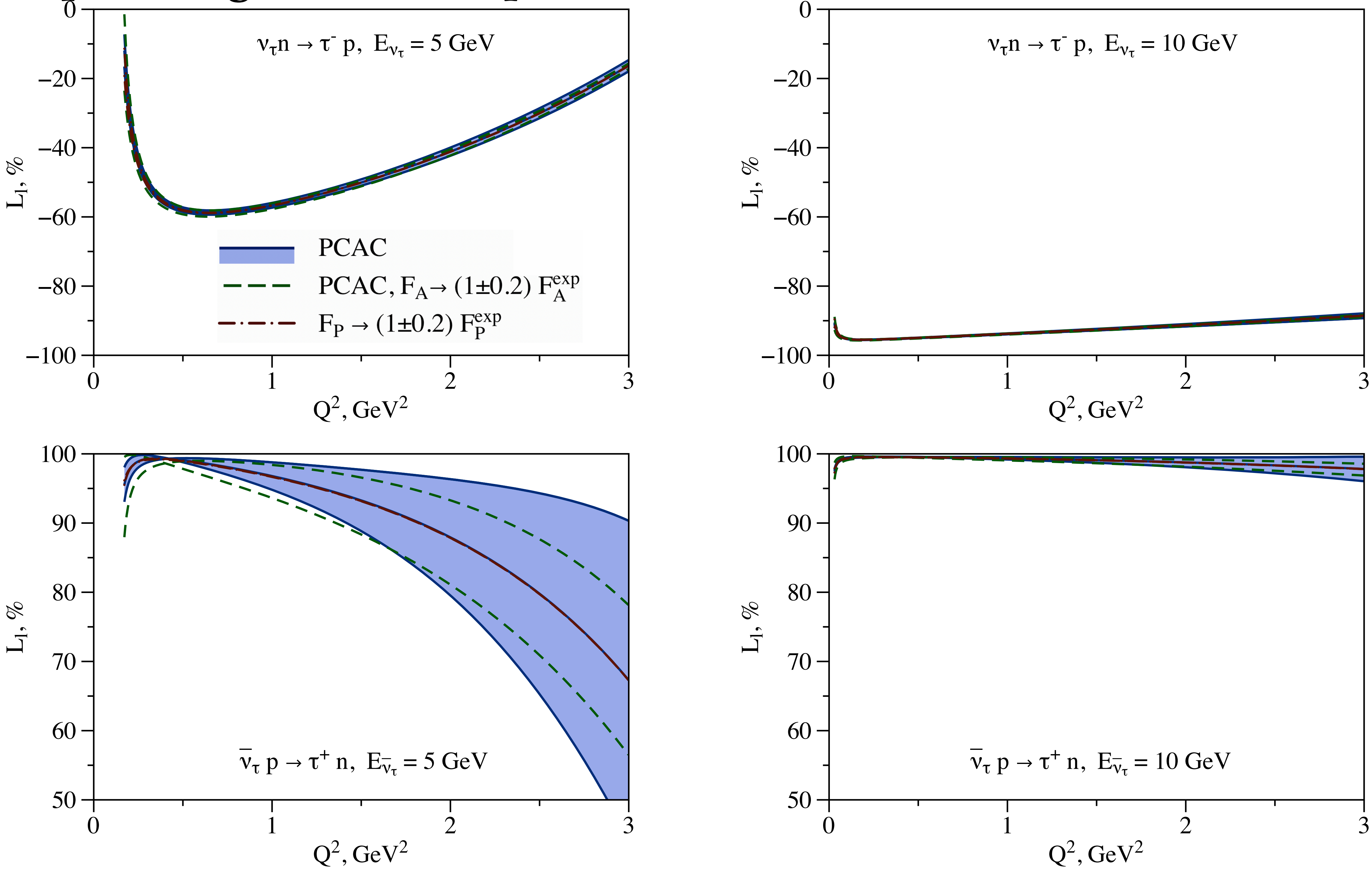
spin orthogonal to the recoil lepton



- sensitive to axial form factor

Lepton longitudinal asymmetry

spin along the recoil lepton momentum



- sensitive to axial form factor; helicity conservation at large E_ν

Conclusions and Outlook

$$A = \frac{\mathrm{d}\sigma\,(S) - \mathrm{d}\sigma\,(-S)}{\mathrm{d}\sigma\,(S) + \mathrm{d}\sigma\,(-S)} \longrightarrow$$

alternative probe of nucleon structure

- compact expressions for all tree-level single-spin asymmetries

- axial form factor:

  lepton asymmetries are accessible and "cheap"

  complementary measurements from asymmetries

- pseudoscalar form factor:

  tau flavor above the production threshold

  target and recoil transverse asymmetries

Thanks for your attention !!!

University of Kentucky

Fermilab

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