

ICHEP 2022

08 July, 2022

QED nuclear medium effects in lepton-nucleus scattering

O. T. and Ivan Vitev (arXiv: 2206.10637)

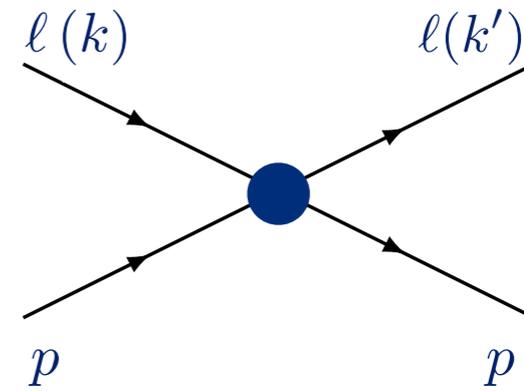
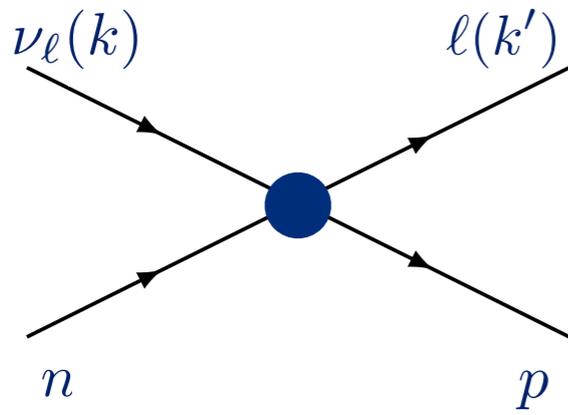


Oleksandr (Sasha) Tomalak

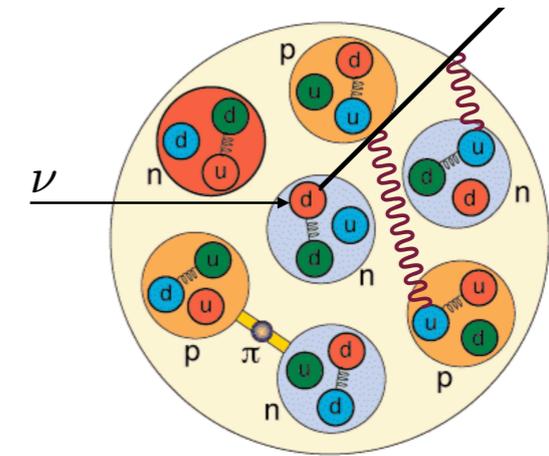
LA-UR-22-25980

Outline

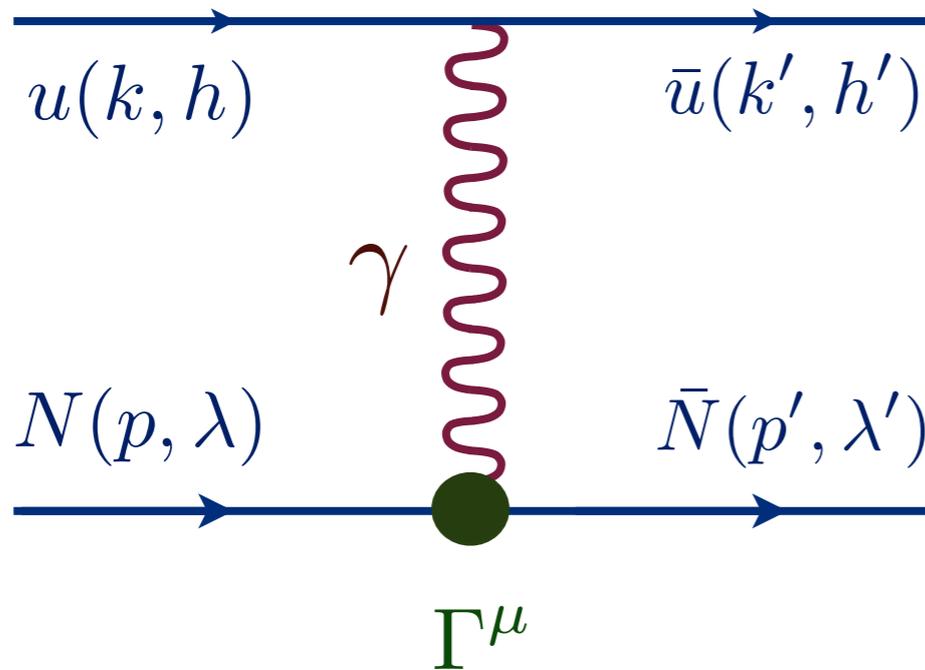
1) elastic scattering of leptons on nucleons



2) QED nuclear medium effects in (anti)neutrino-nucleus and electron-nucleus scattering



Electron-proton scattering



photon-proton vertex

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

Dirac and Pauli form factors

electron energy

$$E_e$$

momentum transfer

$$Q^2 = -(k - k')^2$$

1 γ amplitude

$$T = \frac{e^2}{Q^2} (\bar{u}(k', h') \gamma_\mu u(k, h)) \cdot (\bar{N}(p', \lambda') \Gamma^\mu(Q^2) N(p, \lambda))$$

Form factors measurement

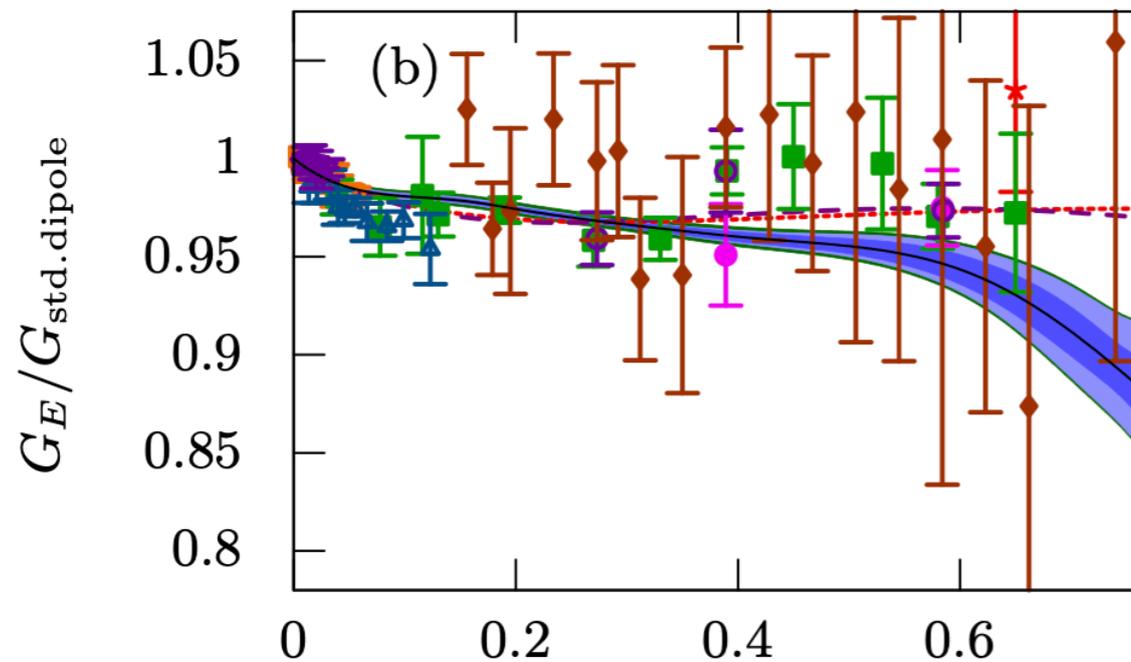
Sachs electric and magnetic form factors

$$\tau = \frac{Q^2}{4M^2}$$

$$G_E = F_D - \tau F_P \quad G_M = F_D + F_P$$

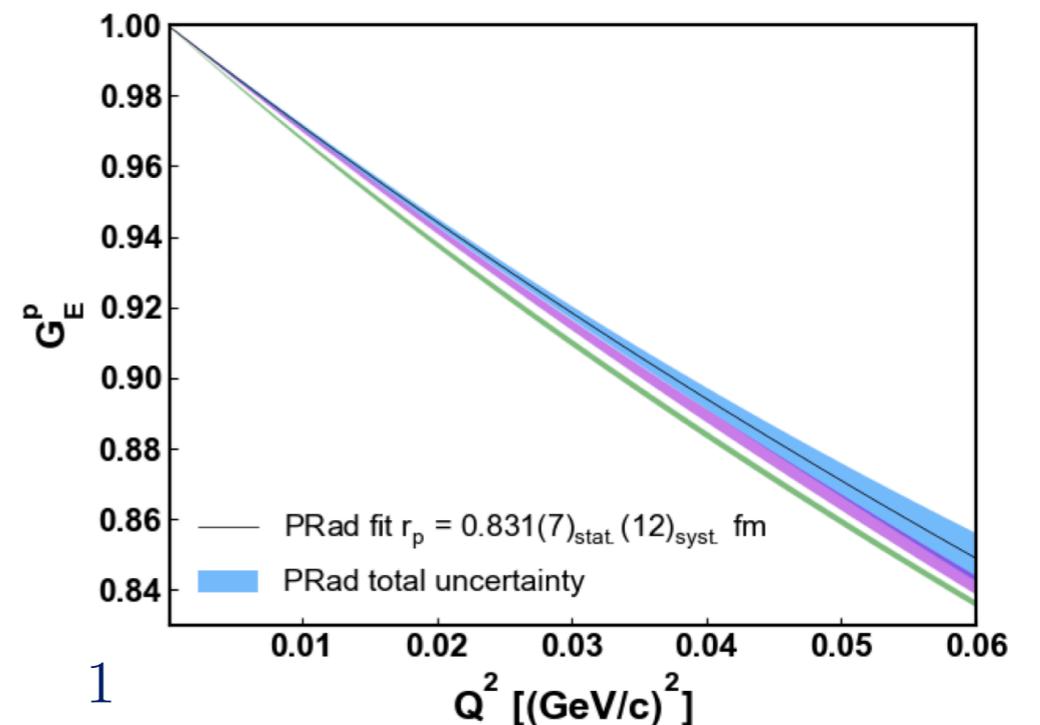
$$\varepsilon \leftrightarrow \theta_{\text{lab}}$$

$$\frac{d\sigma^{\text{unpol}}}{d\Omega} \sim G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$



$$0.003 \text{ GeV}^2 < Q^2 < 1 \text{ GeV}^2 \quad G_{\text{std.dipole}} = \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

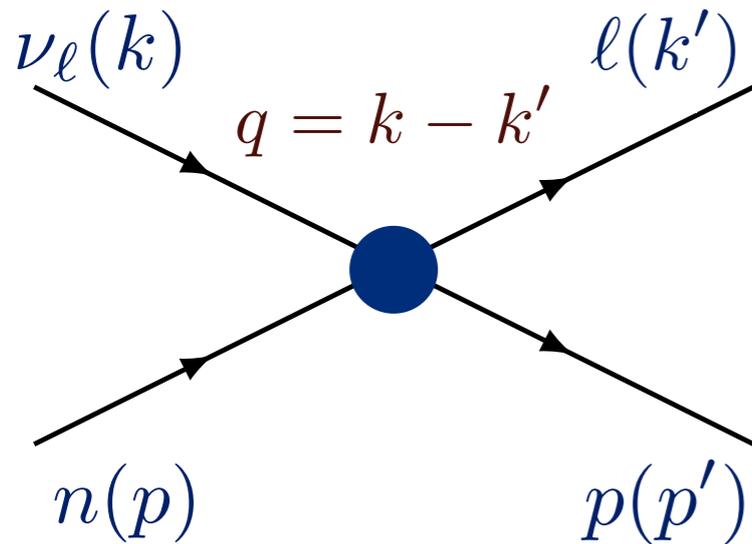
A1@MAMI: J. C. Bernauer et al. (2014)



PRAD@JLAB: W. Xiong et al. (2019)

- electromagnetic FFs known at % level and better, axial FF - 10-20 %

CCQE scattering on free nucleon



neutrino energy

$$E_\nu$$

momentum transfer

$$Q^2 = -q^2$$

contact interaction at GeV energies

- assuming isospin symmetry, nucleon current:

$$\Gamma^\mu(Q^2) = \langle p | \bar{u} (\gamma^\mu - \gamma^\mu \gamma_5) d | n \rangle$$

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

form factors: isovector Dirac and Pauli axial and pseudoscalar

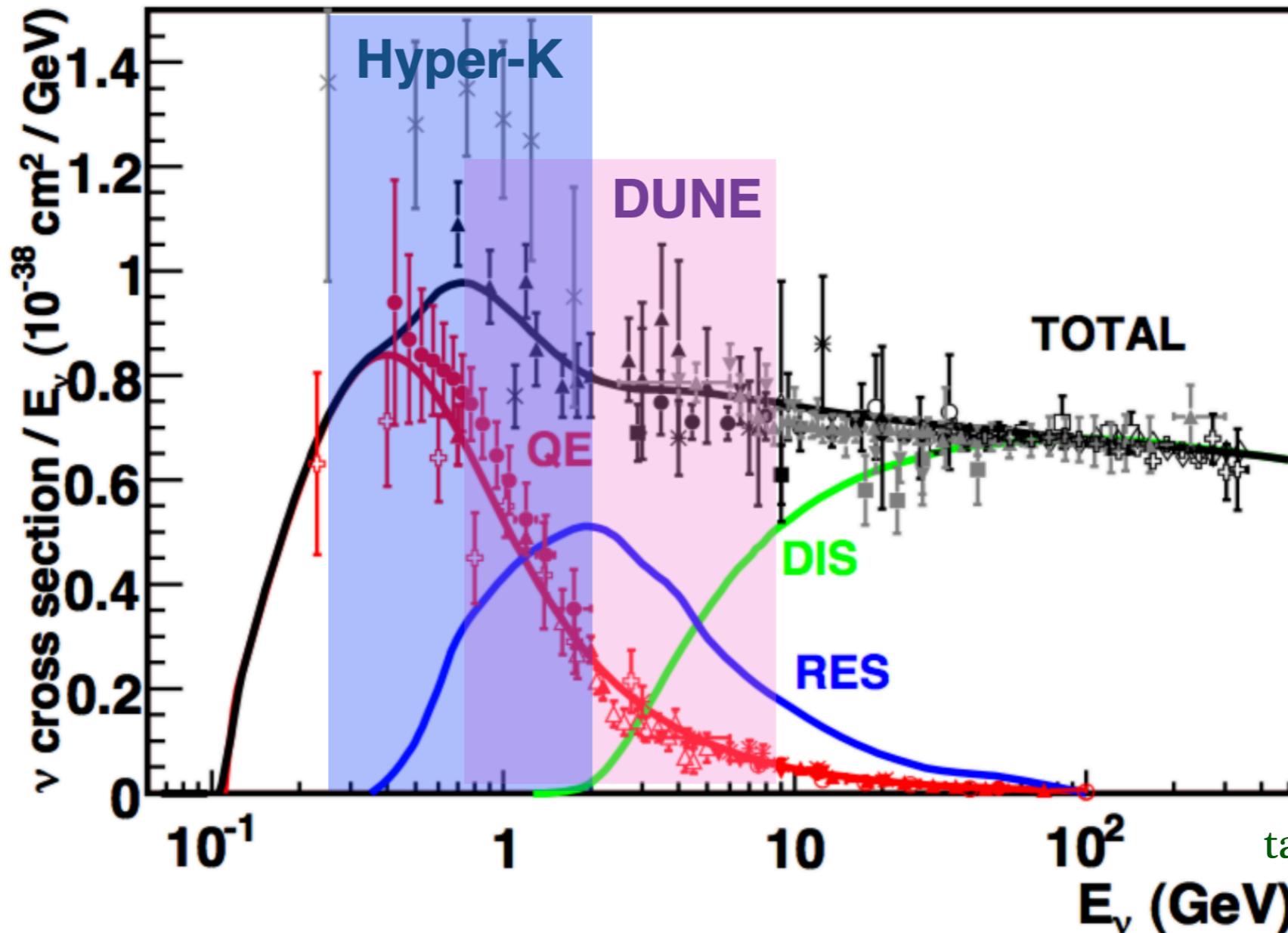
$$F_{D,P}^V = F_{D,P}^p - F_{D,P}^n$$

tree-level amplitude

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

CCQE. Why should we care?

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



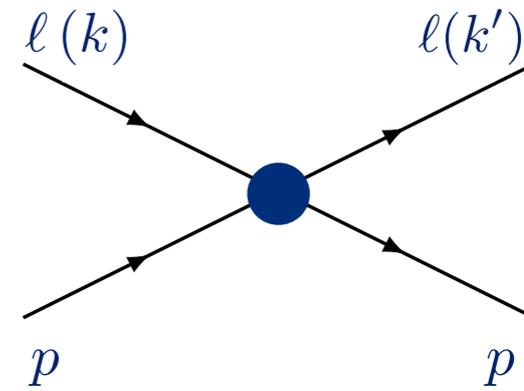
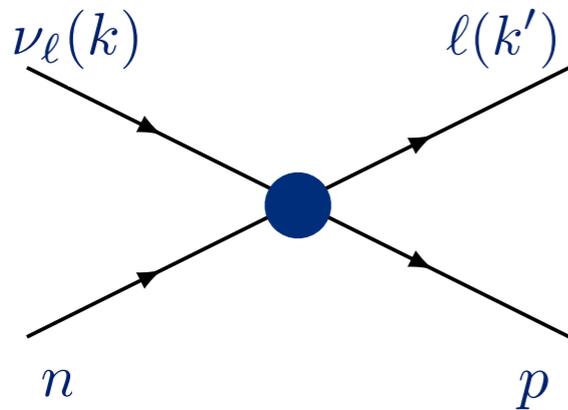
Formaggio
and Zeller
(2013)

Noemi Rocco
talk at Neutrino 2020

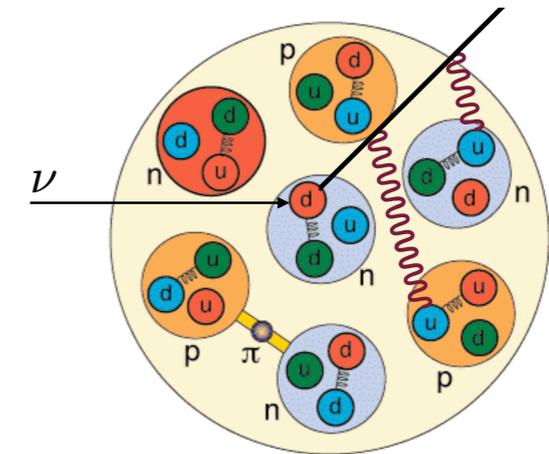
- basic process: bulk of events at Hyper-K and DUNE
- channel for reconstruction of neutrino energy

Outline

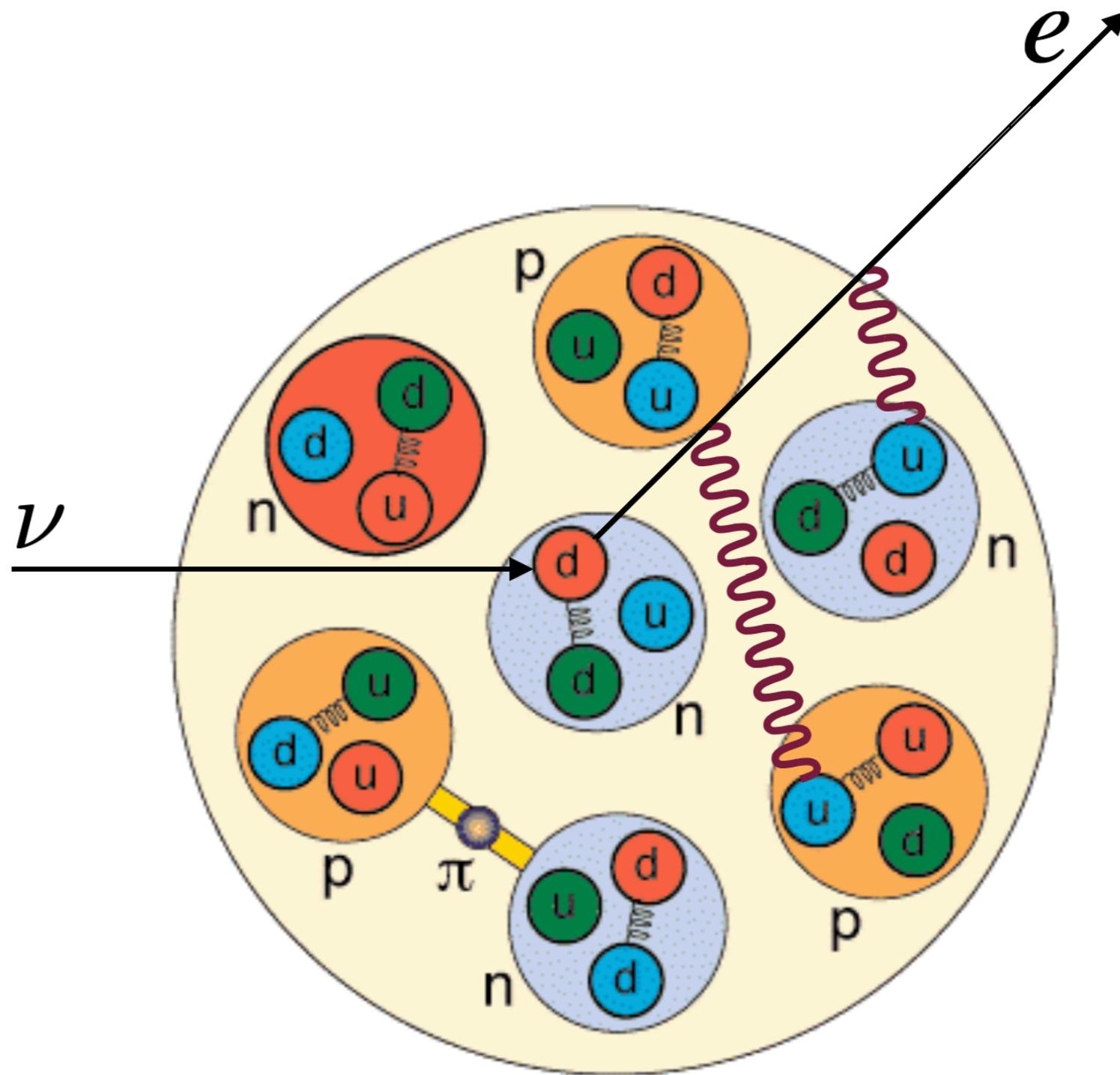
1) elastic scattering of leptons on nucleons



2) QED nuclear medium effects in (anti)neutrino-nucleus and electron-nucleus scattering



QED medium effects

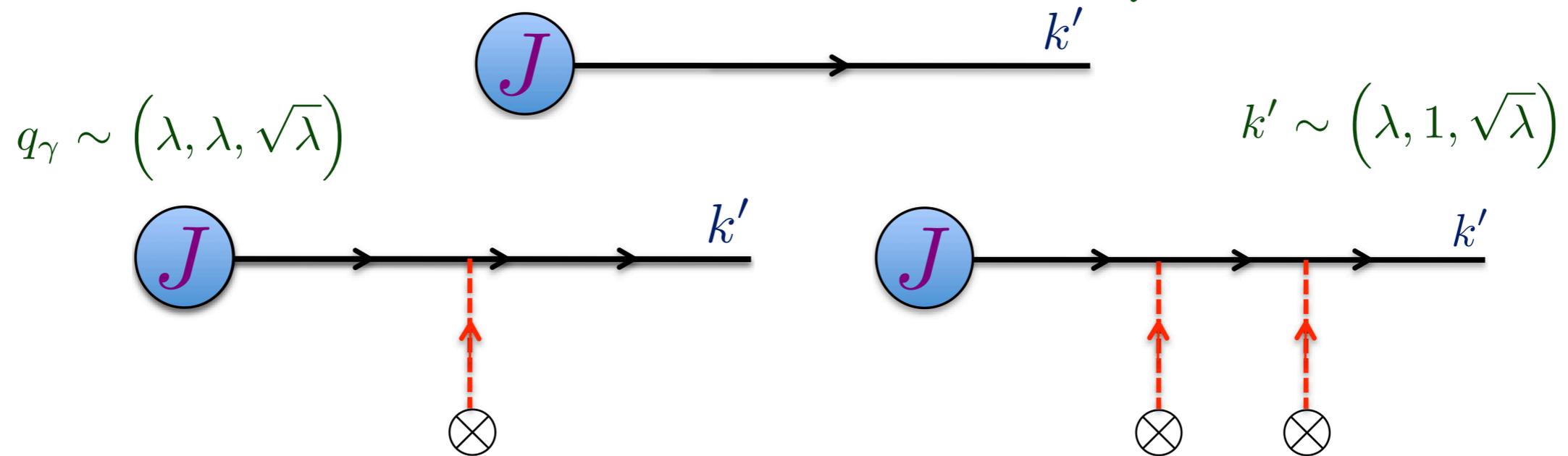


- charged lepton exchanges photons with nuclear medium

SCET_G formulation

- forward scattering is dominant process
- Glauber photons exchanged with a nuclear charge distribution

QCD: G. Ovanesyan and I. Vitev, JHEP (2011)



- change: integral along final lepton direction over charge and potential

$$\delta\sigma_f \sim \int_{\text{lepton line}}^{\text{final}} \rho(z) dz \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} |v(\vec{q}_\perp)|^2 \left(\sigma_0(\vec{k}, \vec{k}' - \vec{q}_\perp) - \sigma_0(\vec{k}, \vec{k}') \right)$$

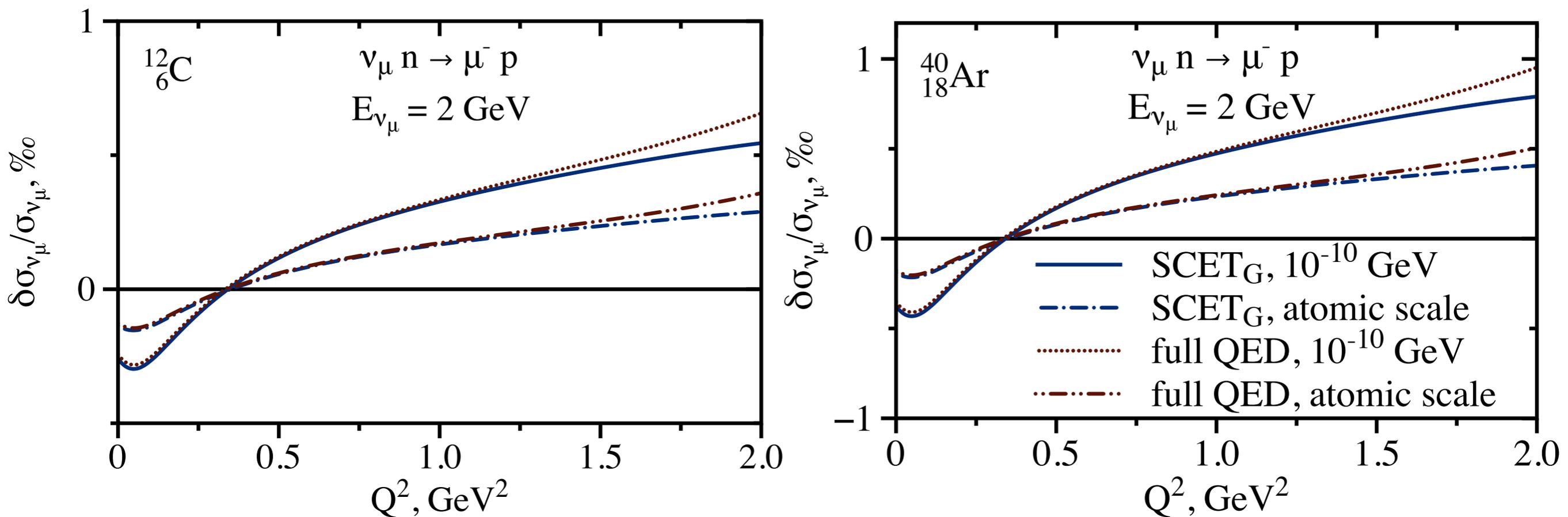
- leading-order cross sections are distorted
- EFT and full QED calculations are performed

Neutrino scattering

IR regularization

- relative correction per nucleon

$$v(q_{\perp}^2) = \frac{e^2}{q_{\perp}^2 + \lambda^2}$$



flavor-independent at GeV energies

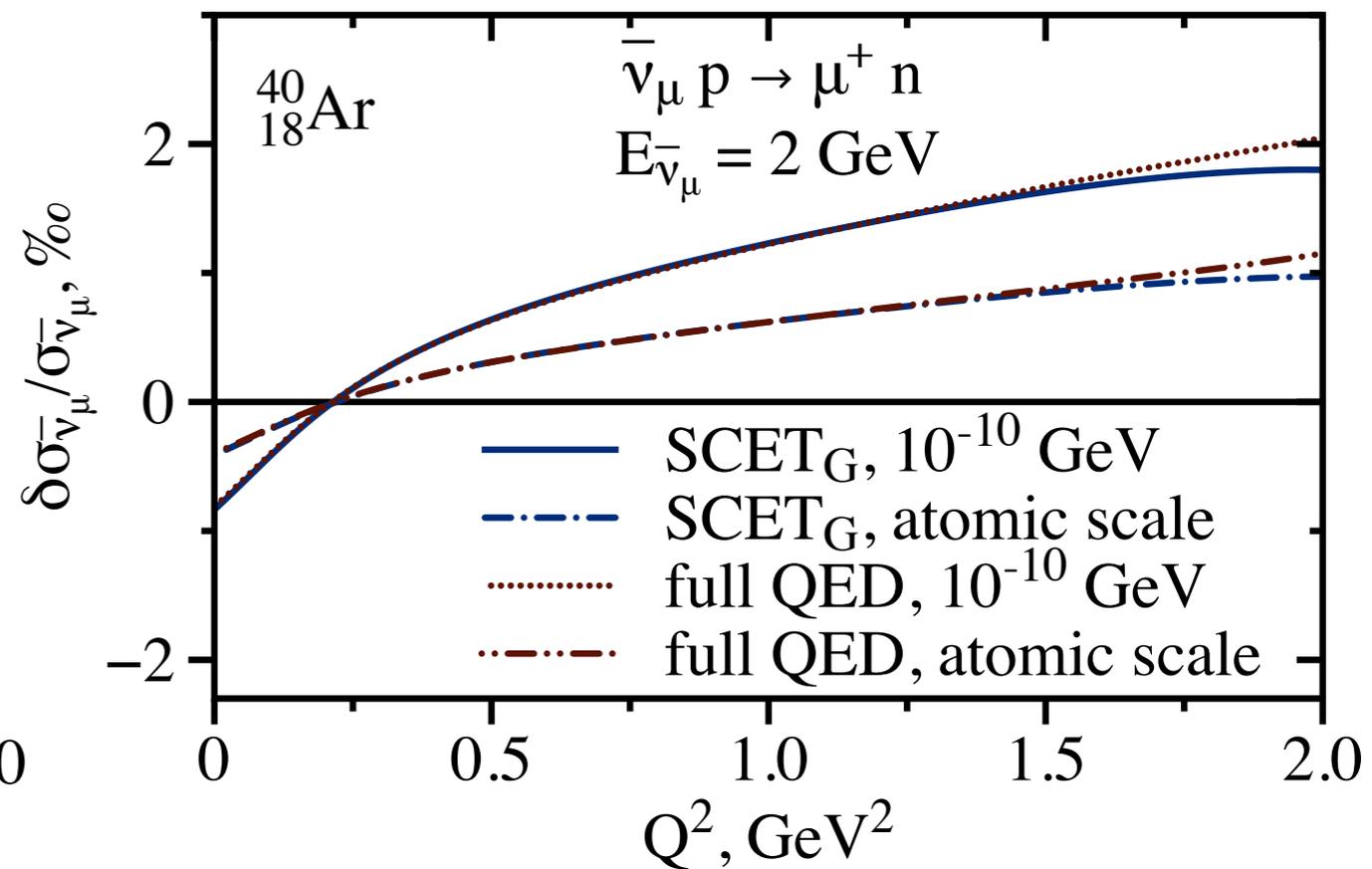
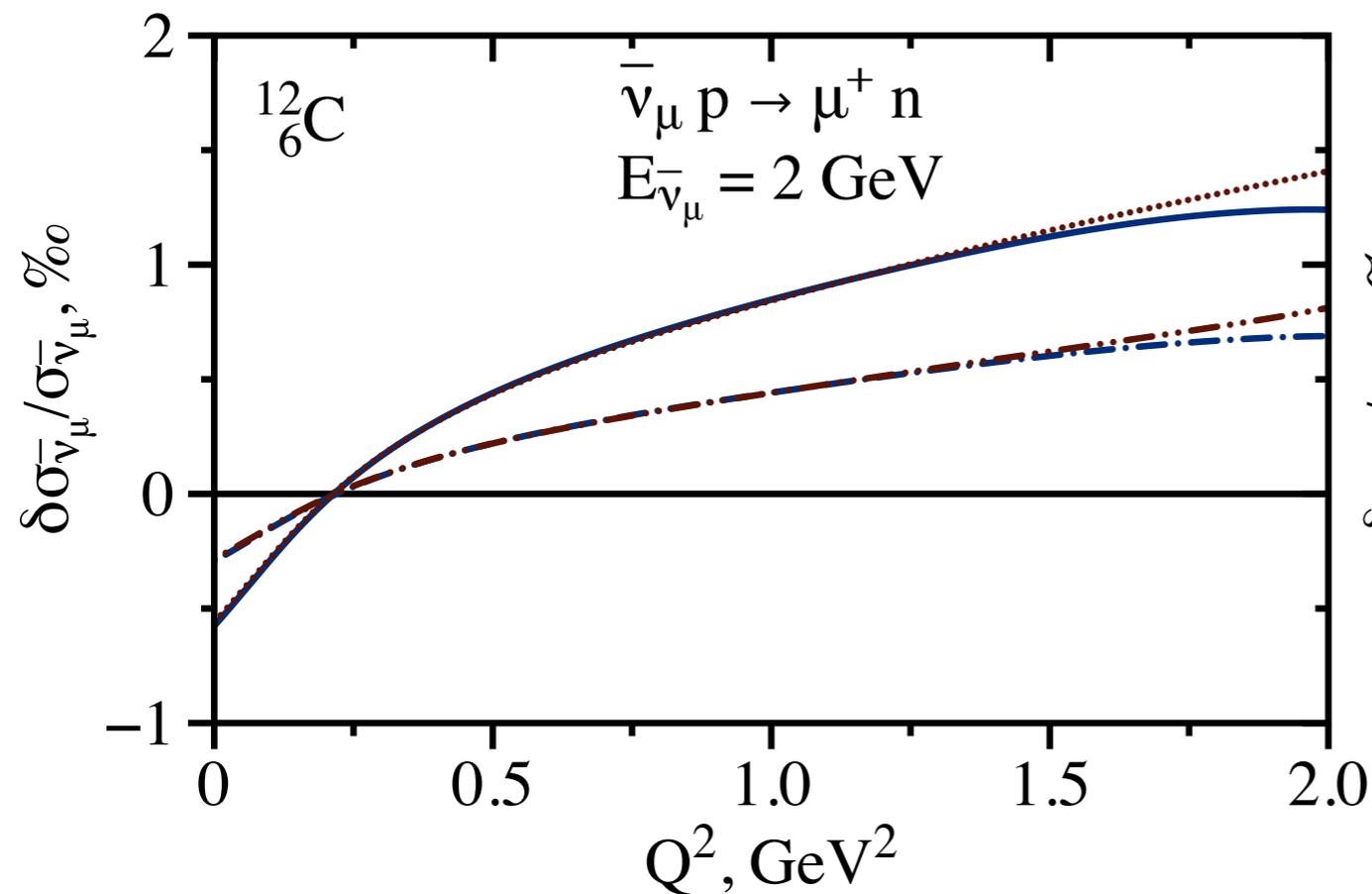
- permille-level distortion of cross sections: $\mathcal{O}(\alpha^2)$ correction
- smaller correction to inclusive cross section

Antineutrino scattering

- relative correction per nucleon

IR regularization

$$v(q_{\perp}^2) = \frac{e^2}{q_{\perp}^2 + \lambda^2}$$



flavor-independent at GeV energies

- permille-level distortion of cross sections: $\mathcal{O}(\alpha^2)$ correction
- larger correction than for neutrino scattering

SCET_G formulation

- forward scattering is dominant process
- Glauber photons exchanged with a nuclear charge distribution
- add initial-state exchanges, no interference with final-state exchanges
- change: integral along initial lepton direction over charge and potential

$$\delta\sigma_i \sim \int_{\text{lepton line}}^{\text{initial}} \rho(z) dz \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} |v(\vec{q}_\perp)|^2 \left(\sigma_0(\vec{k} + \vec{q}_\perp, \vec{k}') - \sigma_0(\vec{k}, \vec{k}') \right)$$

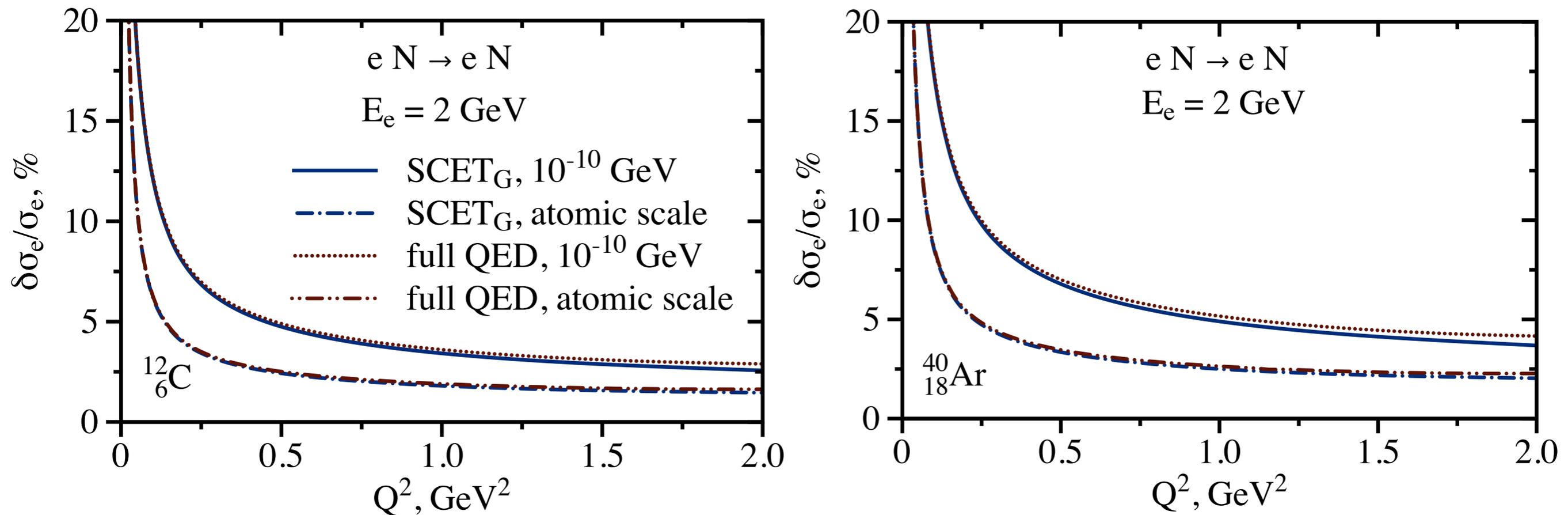
- change: integral along final lepton direction over charge and potential

$$\delta\sigma_f \sim \int_{\text{lepton line}}^{\text{final}} \rho(z) dz \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} |v(\vec{q}_\perp)|^2 \left(\sigma_0(\vec{k}, \vec{k}' - \vec{q}_\perp) - \sigma_0(\vec{k}, \vec{k}') \right)$$

- leading-order cross sections are modified
- EFT and full QED agree above the lepton mass scale

Electron scattering

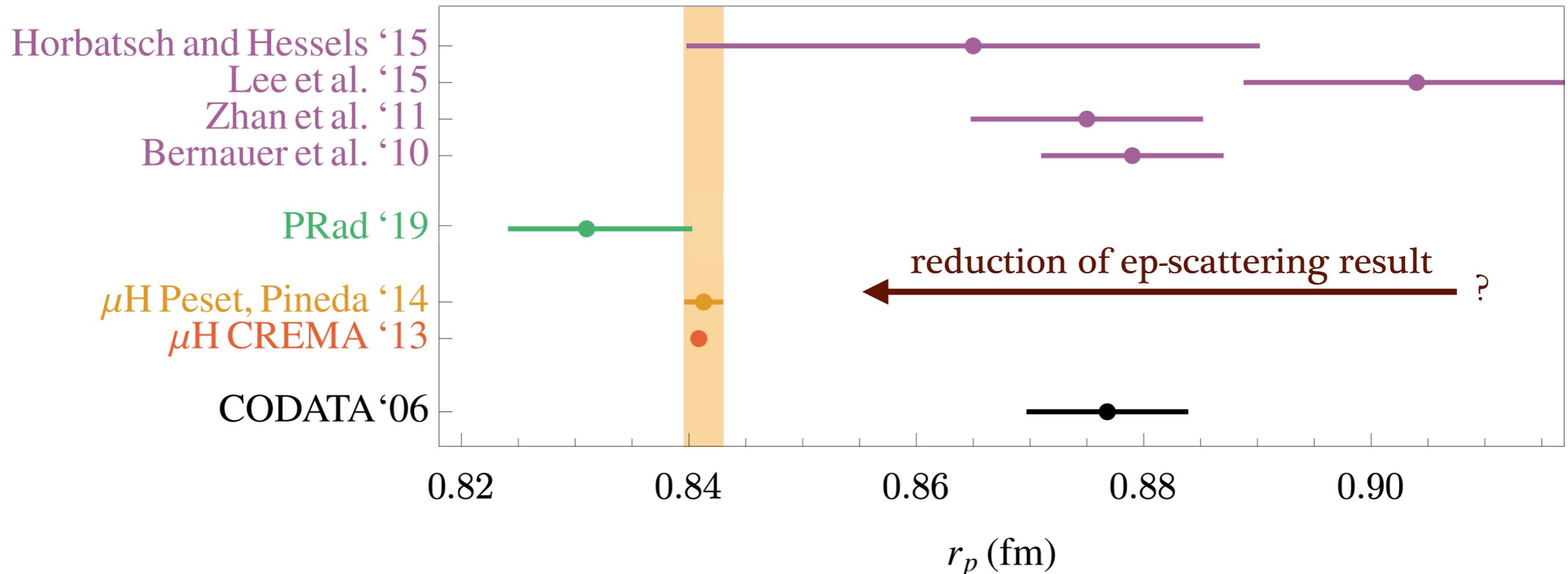
- relative correction per nucleus after incoherent sum over nucleons



- **percent-level** at low momentum transfers: $O(\alpha^2)$ correction
- **critical new effect** for electron scattering experiments

Proton charge radius extraction

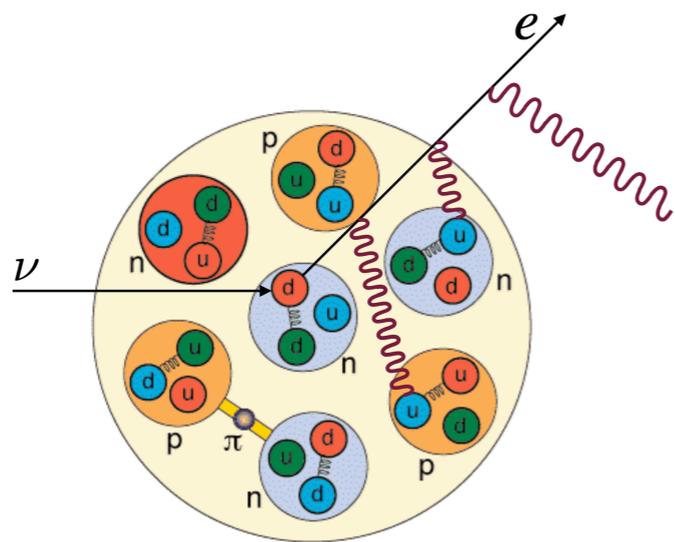
- determinations from elastic **electron-proton scattering data**
- determinations from **the Lamb shift in muonic hydrogen**
- combination of spectroscopic transitions in ordinary hydrogen



Clara Peset, Antonio Pineda and O. T., Prog. Part. Nucl. Phys. (2021)

- **QED medium effects** reduce tensions to **A1@MAMI** data
- calls for a more elaborate analysis of form factors

Conclusions



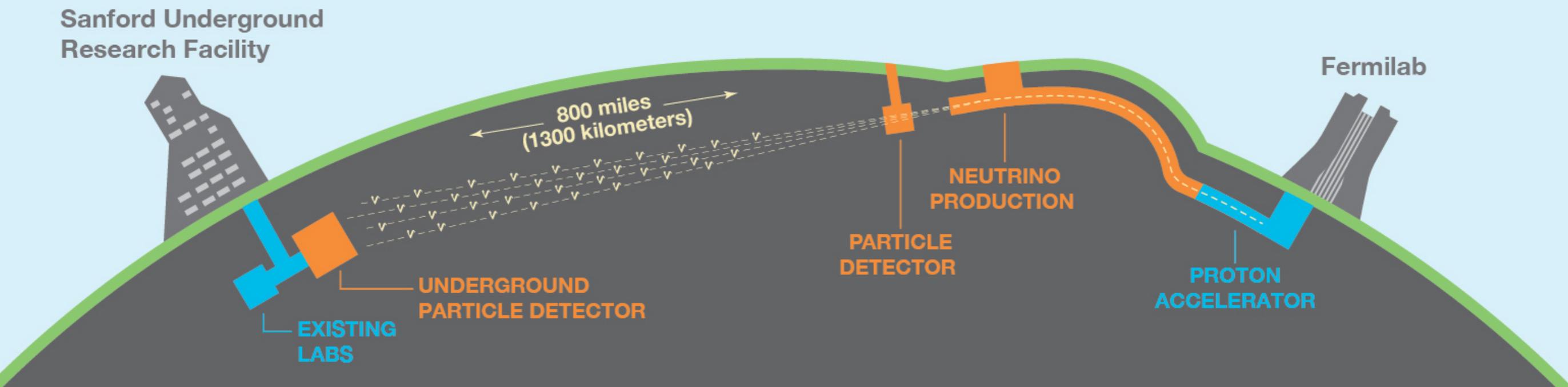
QED nuclear medium effects
SCET_G and full QED

- permille-level QED nuclear medium distortion of neutrino-nucleus cross sections: negligible at current state-of-the-art
- permille- to percent-level corrections in electron-nucleus scattering: calls for reanalysis of nucleon and nuclear form factors
- SCET_G works perfectly at GeV energies

Thanks for your attention !!!

Neutrino experiments

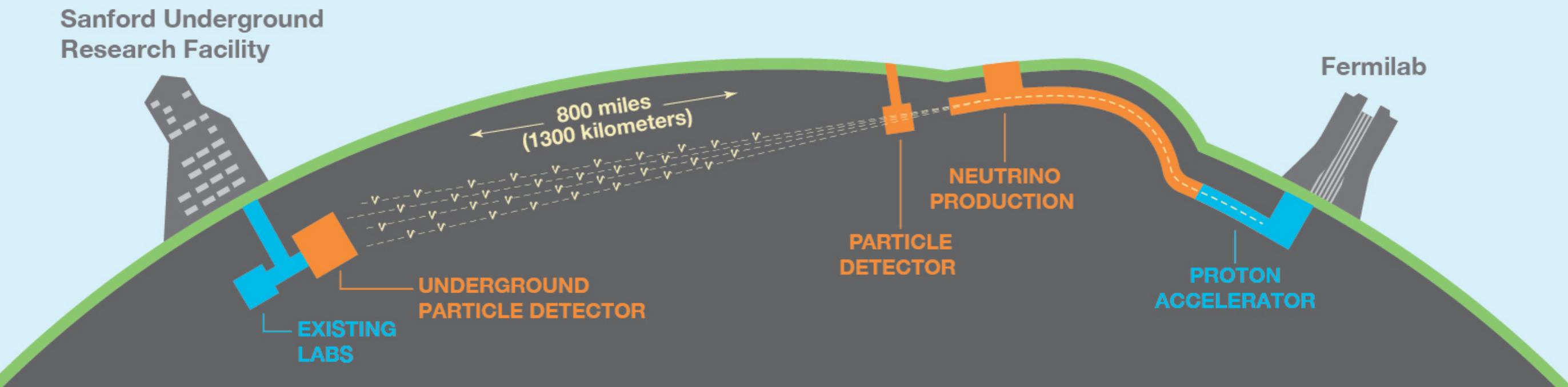
- **DUNE** and Hyper-K: leading-edge ν science experiments



- origin of matter-antimatter asymmetry δ_{CP}
- mass hierarchy and oscillation parameters PMNS matrix, Δm_{31}^2
- Grand Unified Theories proton decay
- dynamics of supernova explosion wait for one;)

Neutrino experiments

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



- measurement of ν_μ disappearance and ν_e appearance

$$N_\nu \sim \int dE_\nu \Phi_\nu(E_\nu) \times \sigma(E_\nu) \times R(E_\nu, E_\nu^{\text{rec}})$$

- near detector: determine flux and cross sections