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QED nuclear medium effects in neutrino-nucleus and electron-nucleus scattering

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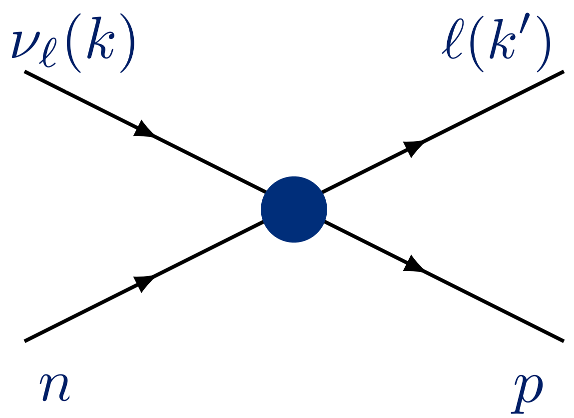
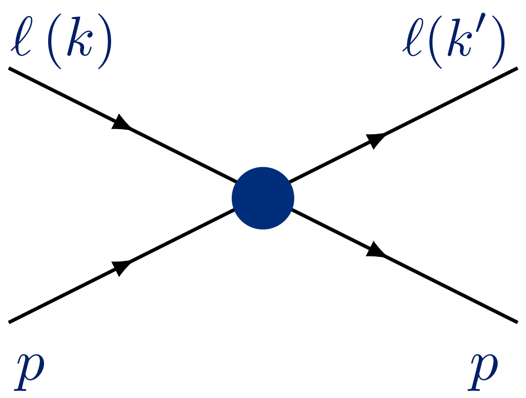
LA-UR-22-25998

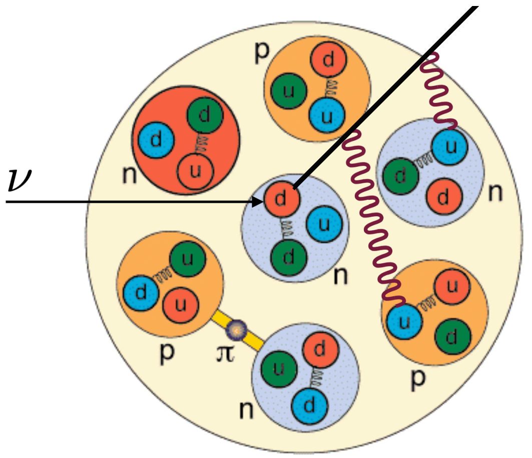
Outline

1) elastic scattering of leptons on nucleons

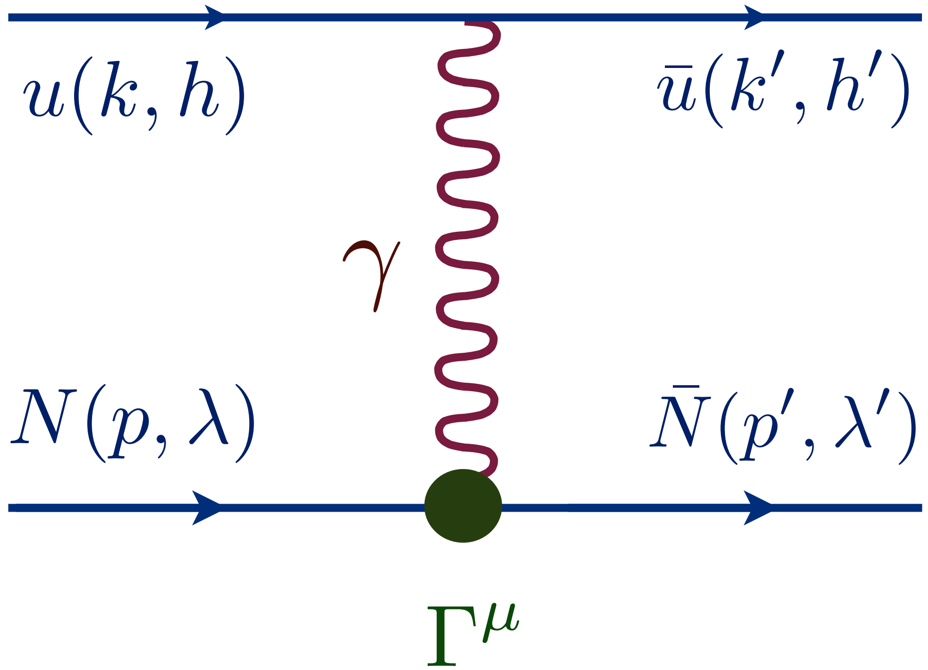




2) QED nuclear medium effects in (anti)neutrino-nucleus and electron-nucleus scattering



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

1ɣ amplitude

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

Form factors measurement

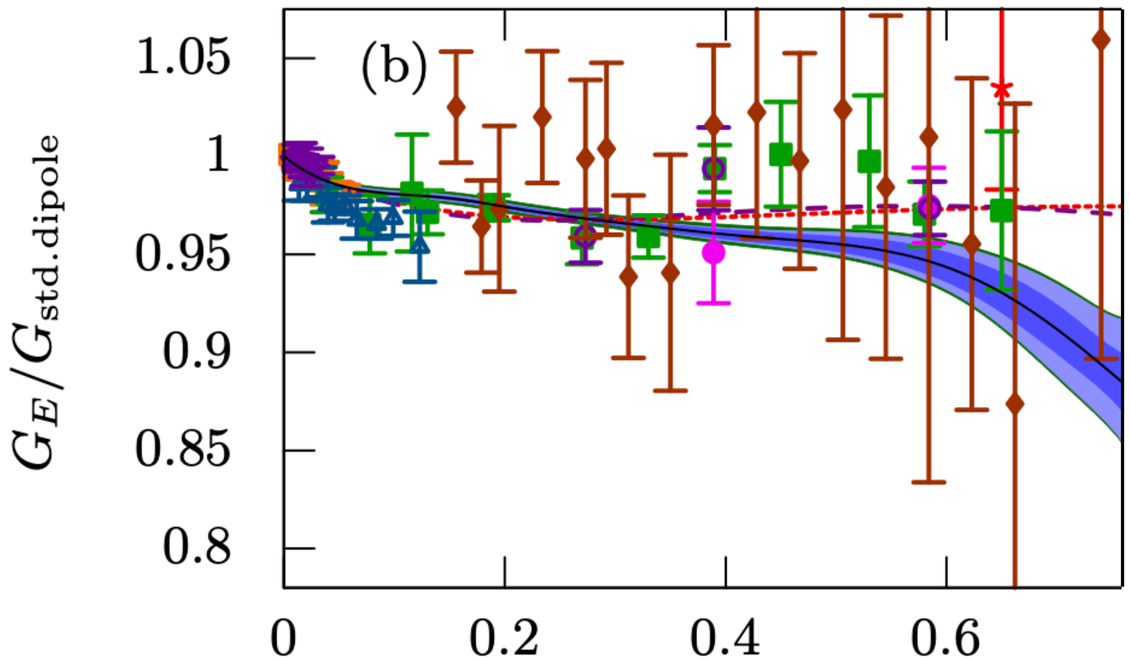
Sachs electric and magnetic form factors

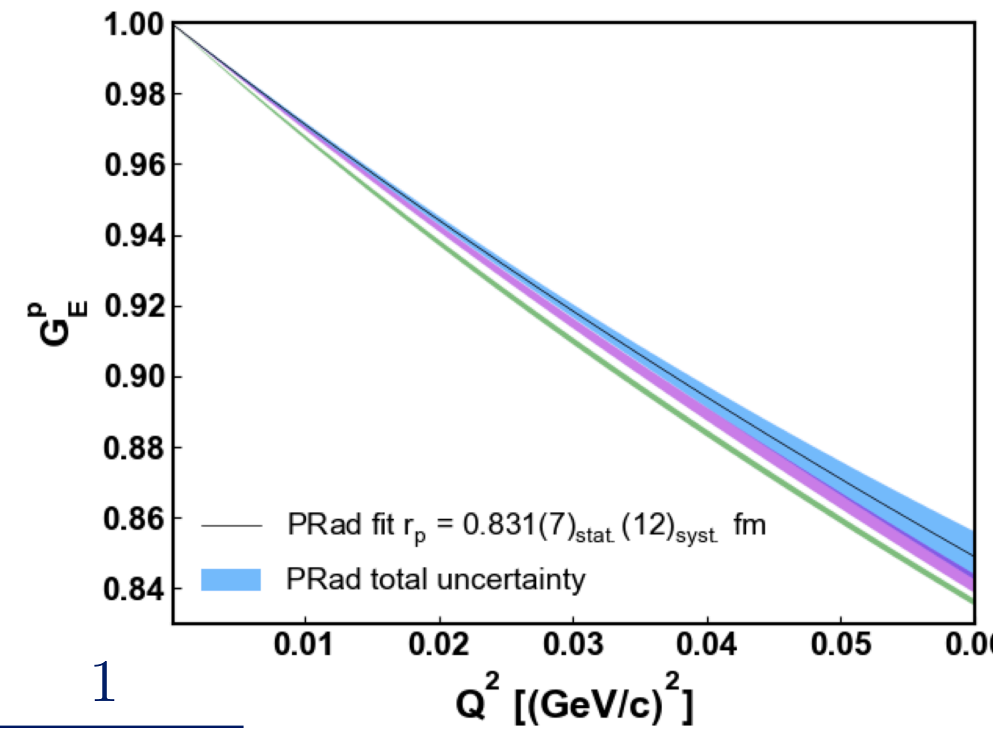
$\tau = \frac{Q^2}{4M^2}$

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

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

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





$0.003 \text{ GeV}^2 < Q^2 < 1 \text{ GeV}^2$

$$G_{\rm std.dipole} = \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

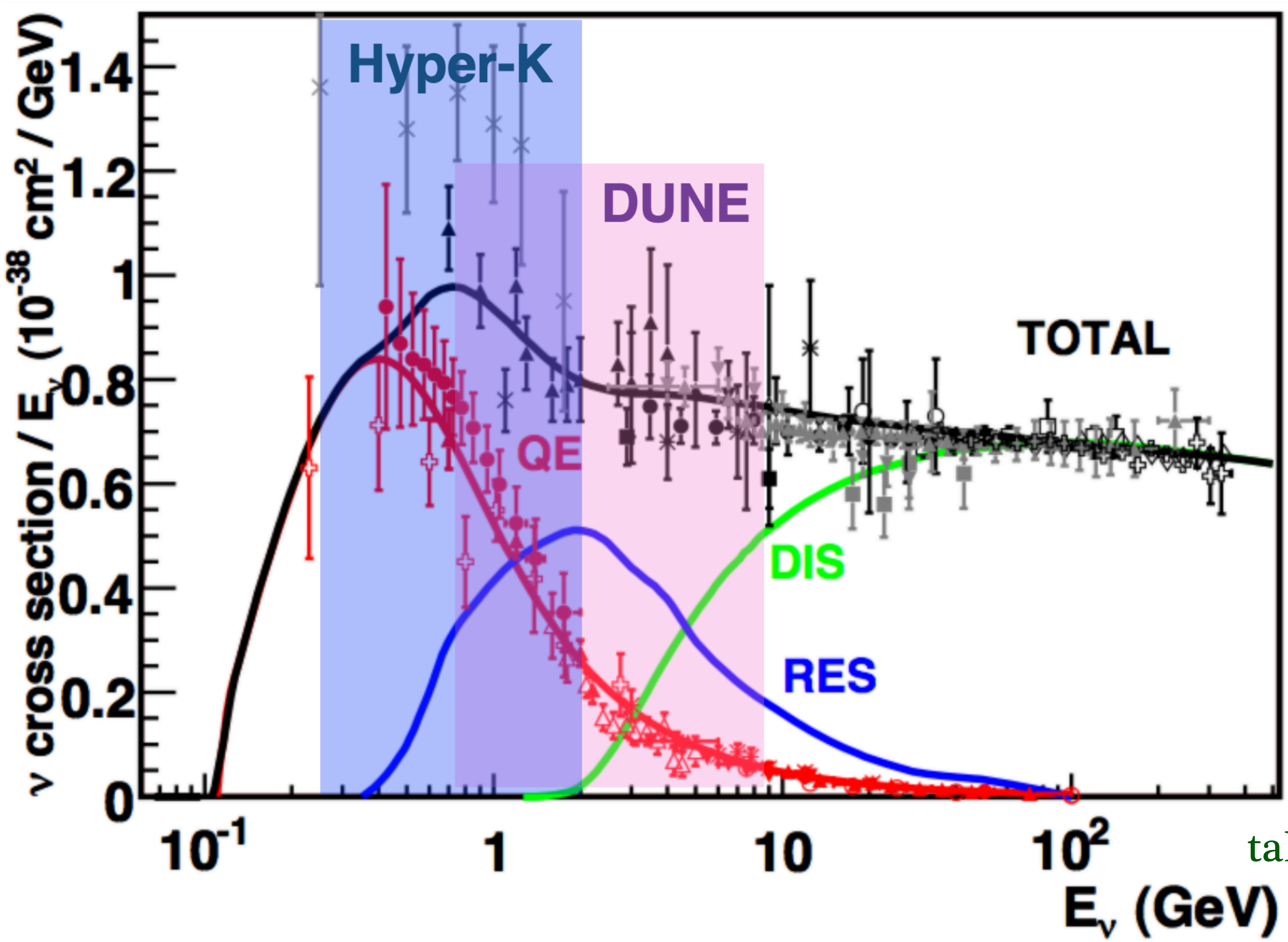
A1@MAMI: J. C. Bernauer et al. (2014)

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

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

CCQE. Why should we care?

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

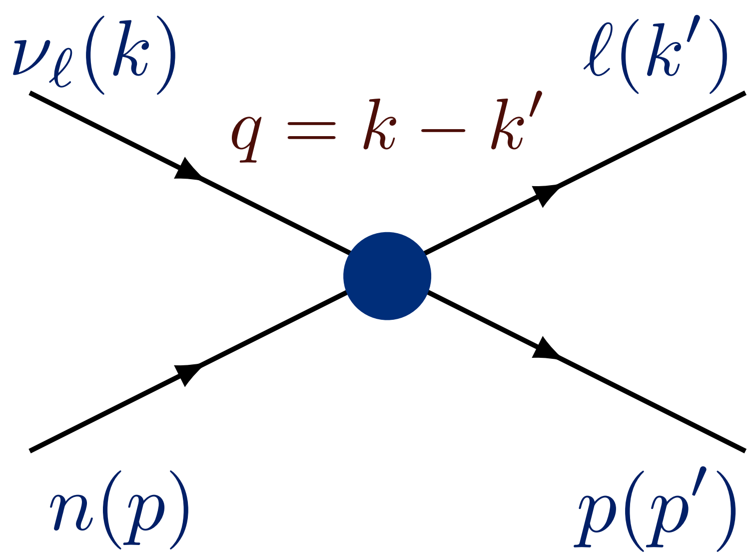


Formaggio and Zeller (2013)

Noemi Rocco talk at Neutrino 2020

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

CCQE scattering on free nucleon



neutrino energy E_ν

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

contact interaction at GeV energies

- assuming isospin symmetry, nucleon current:

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

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

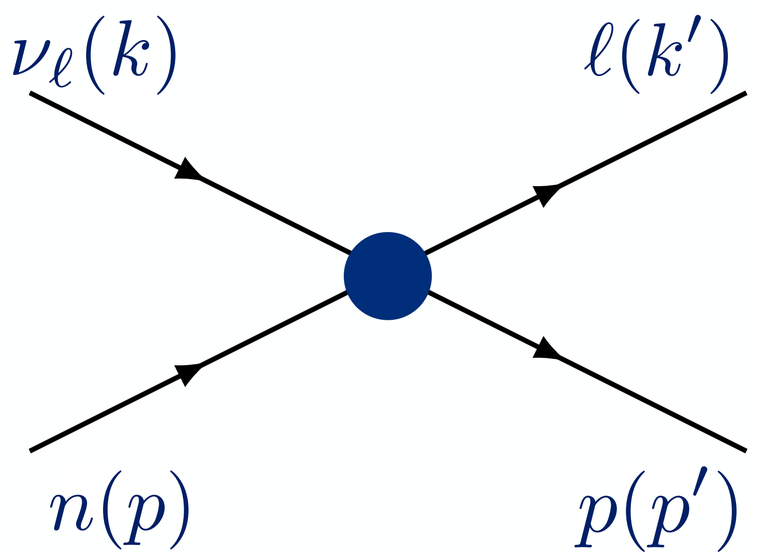
form factors: isovector Dirac and Pauli axial and pseudoscalar

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

tree-level amplitude

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

CCQE scattering on free nucleon



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

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

unpolarized cross section

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

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

Elastic 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

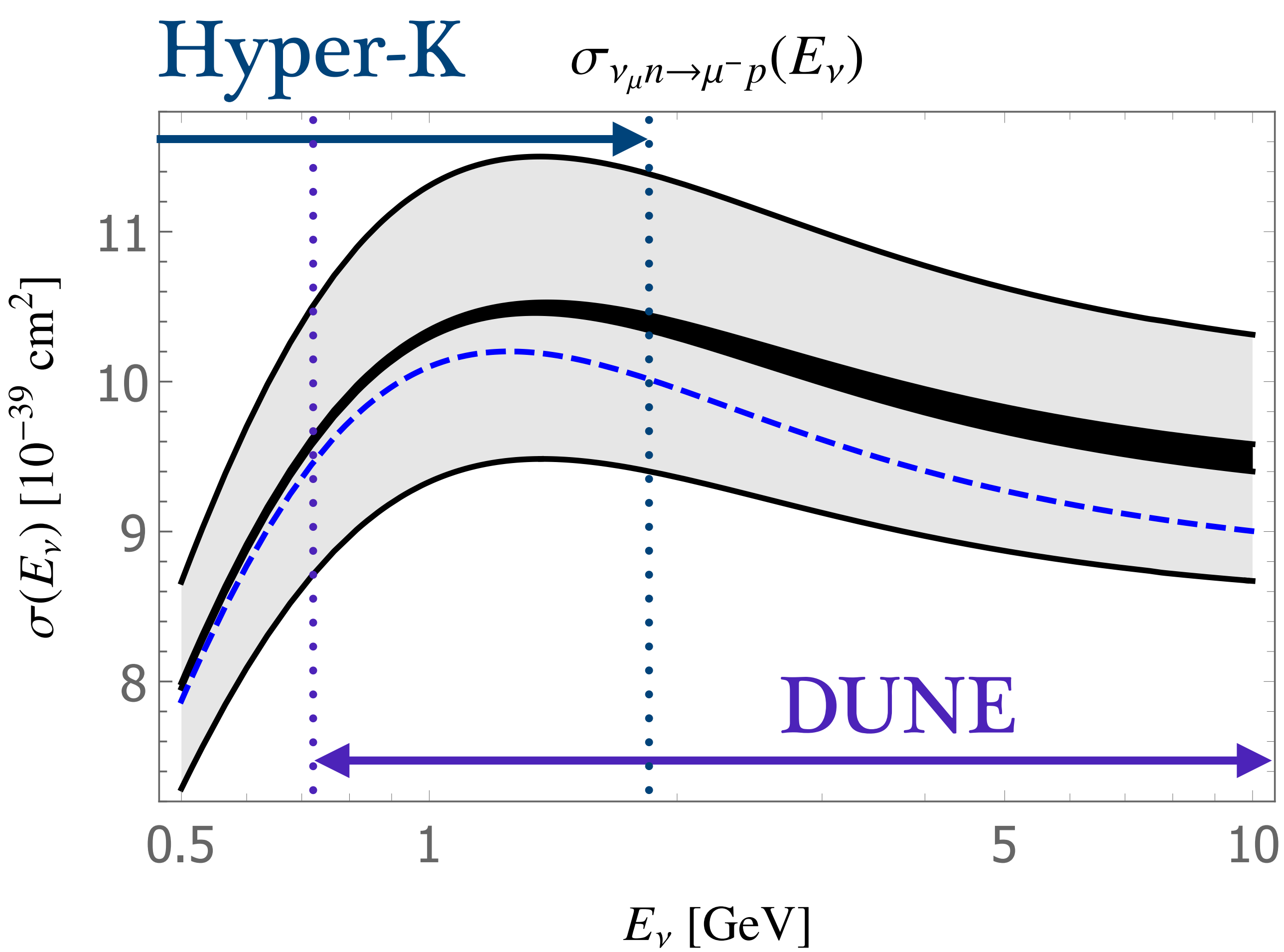
Fermilab bubble chamber, Richard Drew

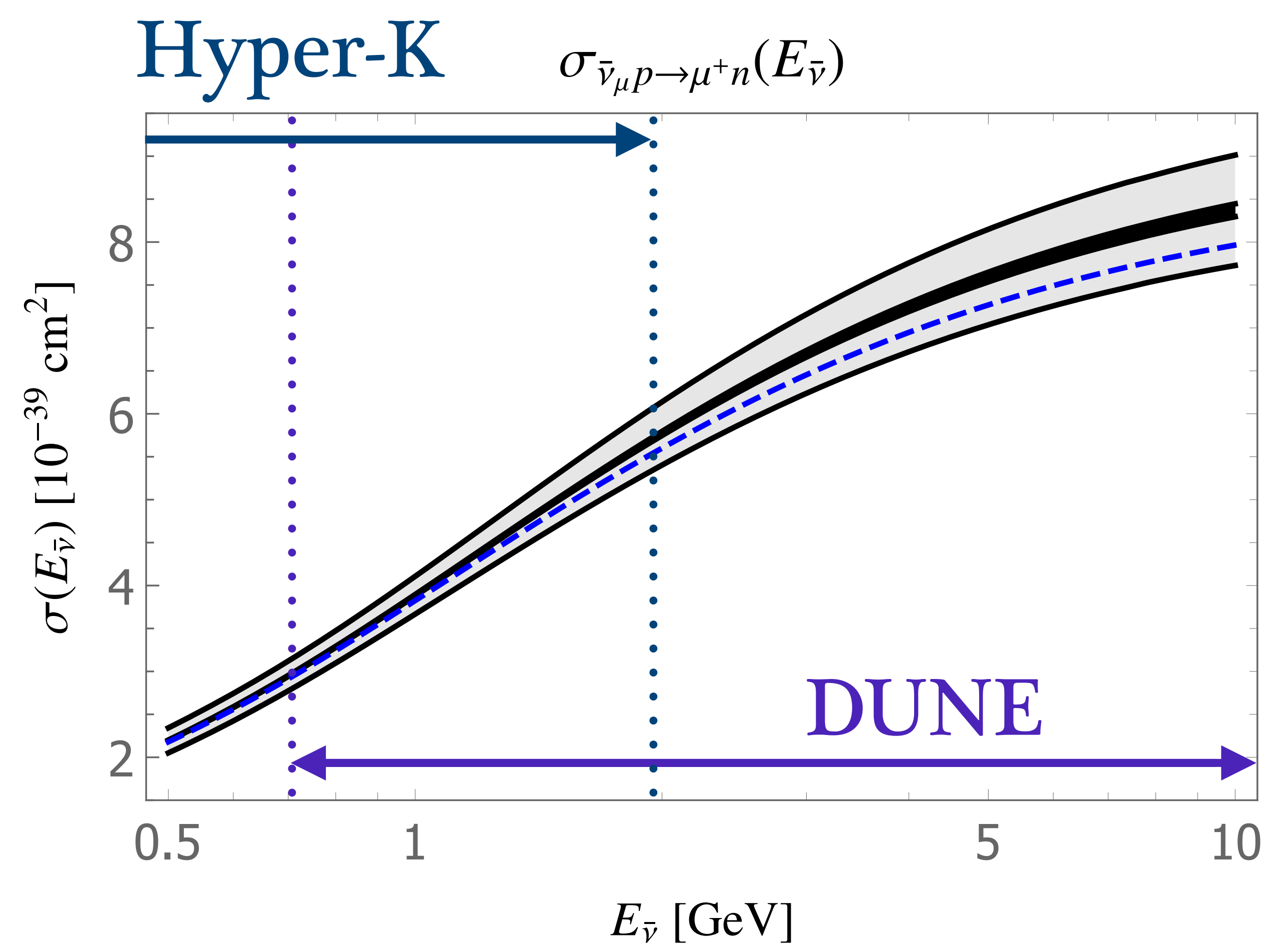
- axial form factor extracted based on electromagnetic structure

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

CCQE scattering cross section

- dark band: uncertainty of iso 1 fit
- light band: uncertainty of axial form factor
- blue line: BBBA2005 fit of electromagnetic form factors

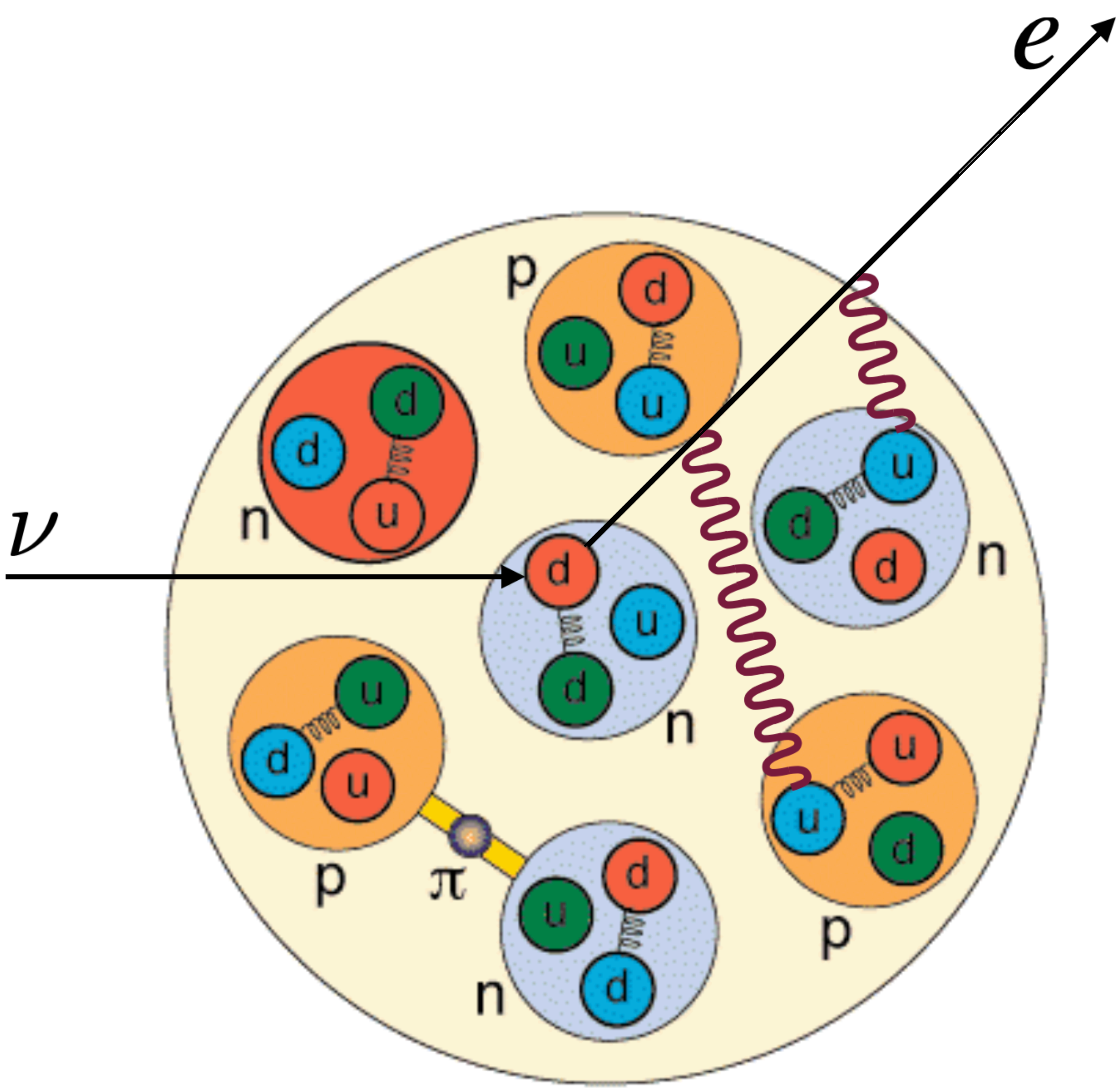




Kaushik Borah, Gabriel Lee, Richard J Hill and O. T., PRD (2020)

- 10-20 % level of uncertainties, vector form factors are important

QED medium effects



- charged lepton exchanges photons with nuclear medium

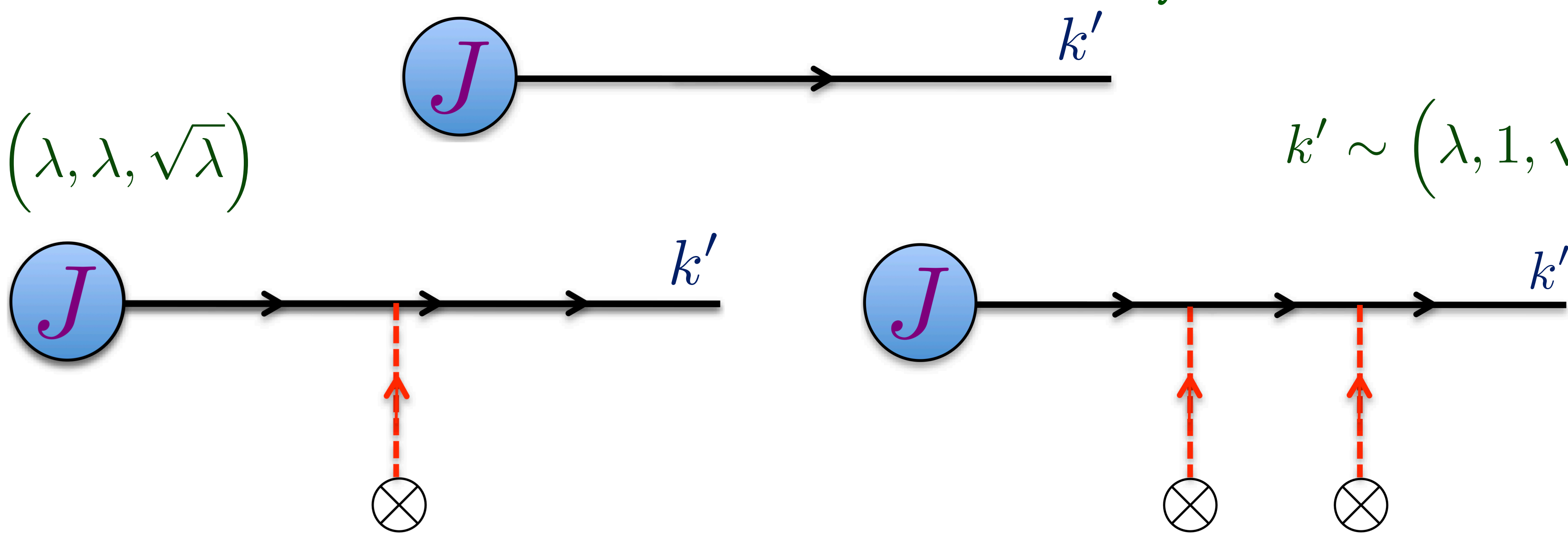
SCET$_G$ formulation

- forward scattering is dominant process

- Glauber photons exchanged with a nuclear charge distribution

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

$$q_\gamma \sim \left(\lambda, \lambda, \sqrt{\lambda}\right) \qquad k' \sim \left(\lambda, 1, \sqrt{\lambda}\right)$$



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

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

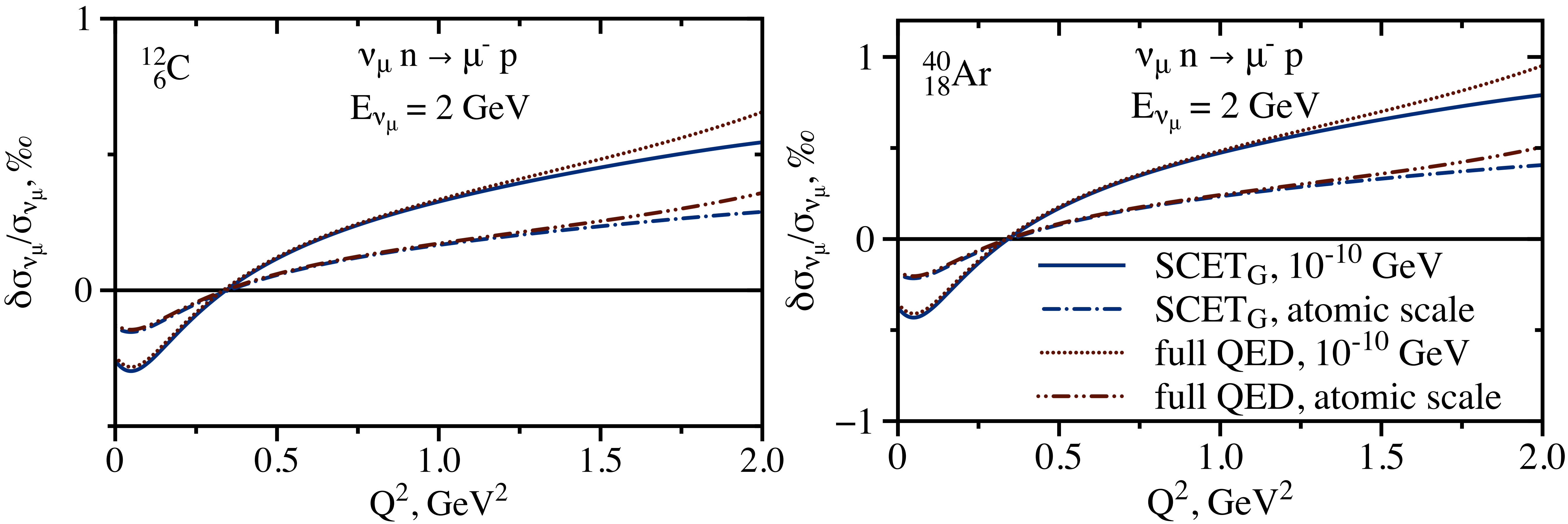
- leading-order cross sections are distorted
- EFT and full QED calculations are performed

Neutrino scattering

- relative correction per nucleon

IR regularization

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



flavor-independent at GeV energies

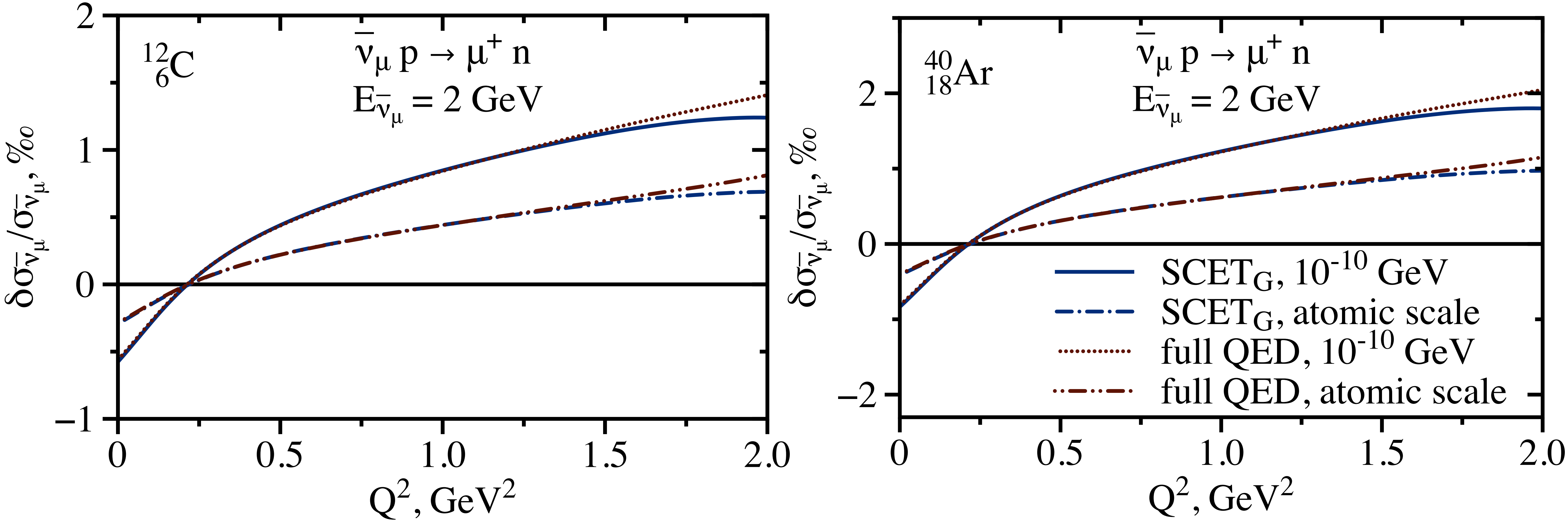
- permille-level distortion of cross sections: $O(\alpha^2)$ correction
- smaller correction to inclusive cross section

Antineutrino scattering

IR regularization

- relative correction per nucleon

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



flavor-independent at GeV energies

- permille-level distortion of cross sections: $O(\alpha^2)$ 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

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

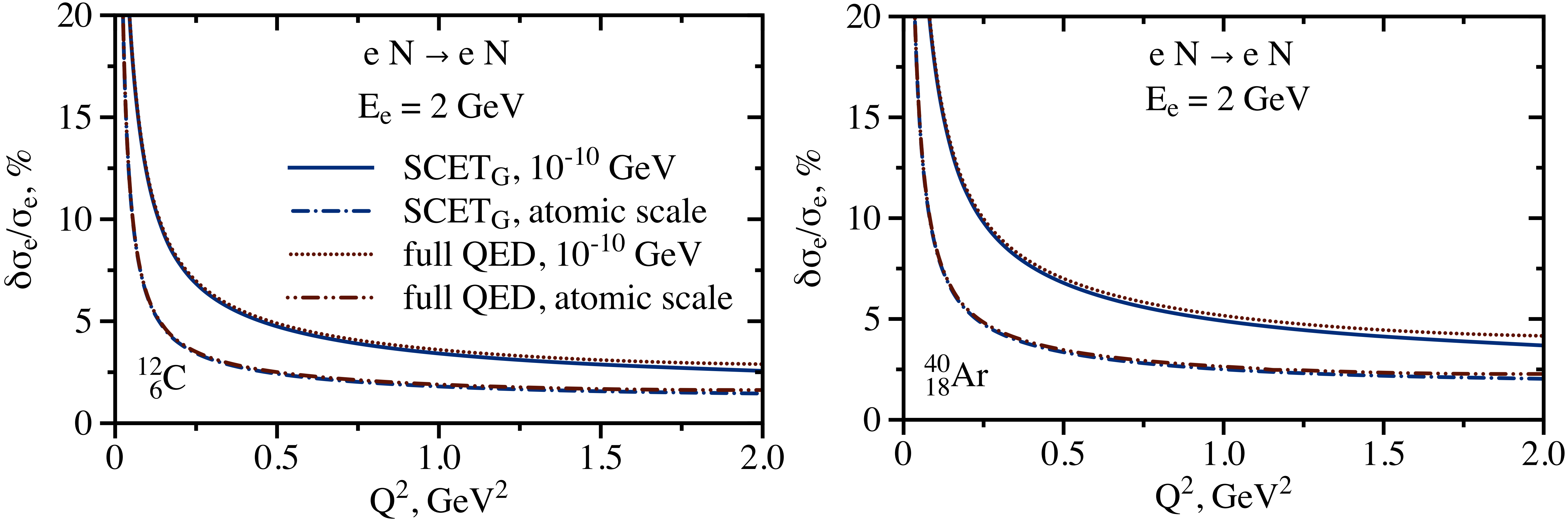
- change: integral along final lepton direction over charge and potential

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

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

Electron scattering

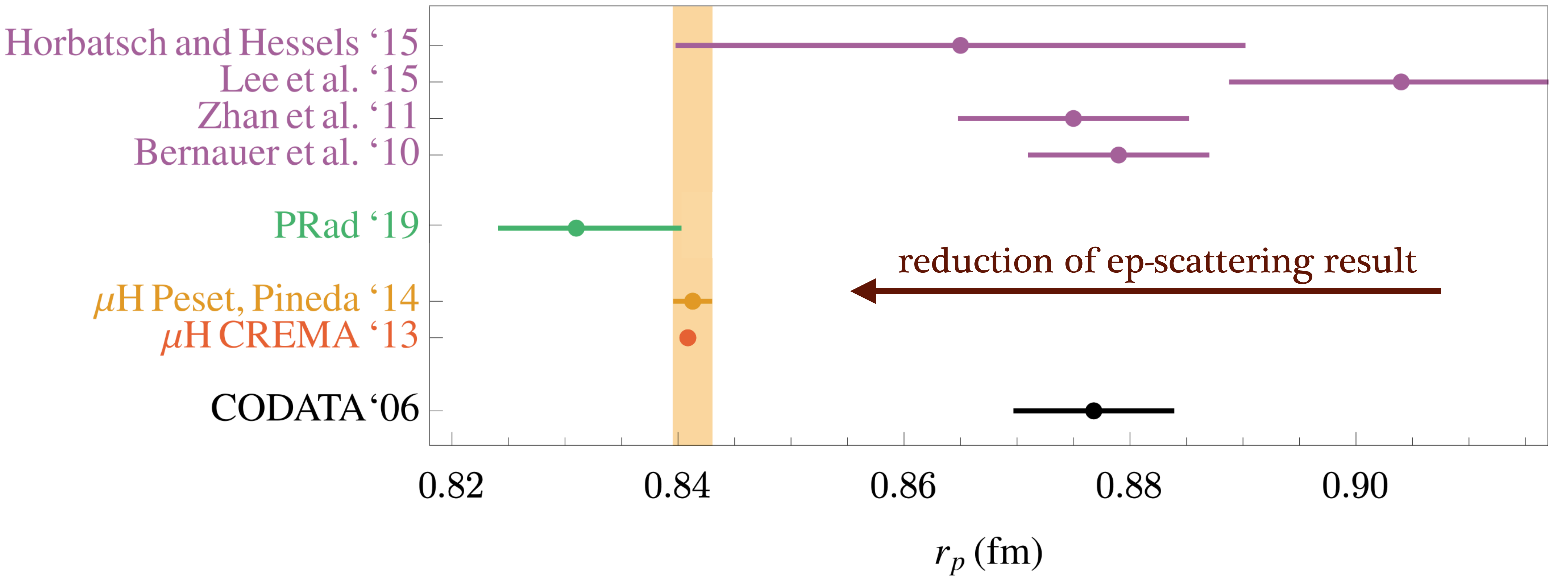
- relative correction per nucleus after incoherent sum over nucleons



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

Proton charge radius extraction

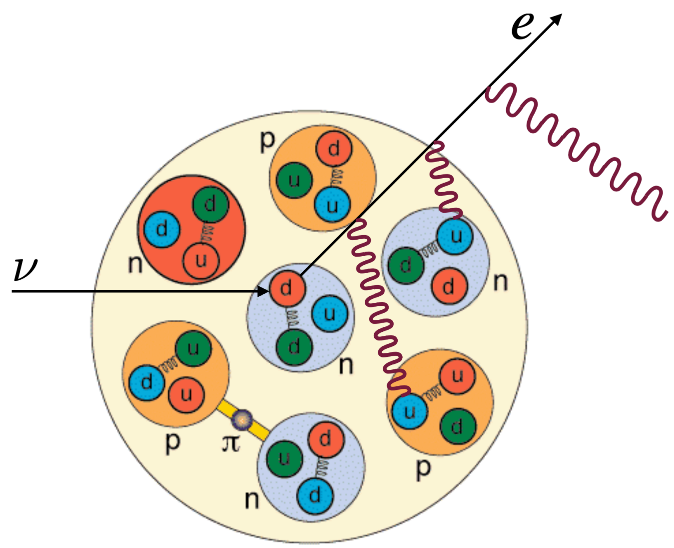
- determinations from elastic electron-proton scattering data
- determinations from the Lamb shift in muonic hydrogen
- combination of spectroscopic transitions in ordinary hydrogen



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

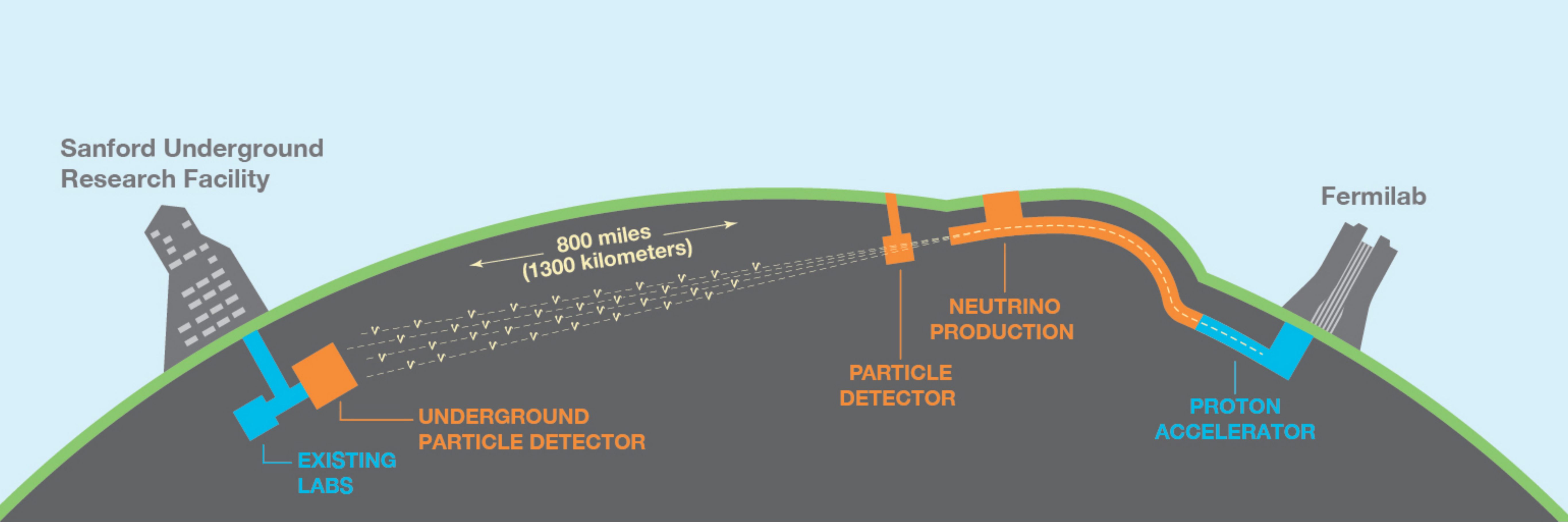
- permille- to percent-level corrections in electron-nucleus scattering: calls for reanalysis of nucleon and nuclear form factors

- $SCET_G$ works perfectly at GeV energies

Thanks for your attention !!!

Neutrino experiments

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

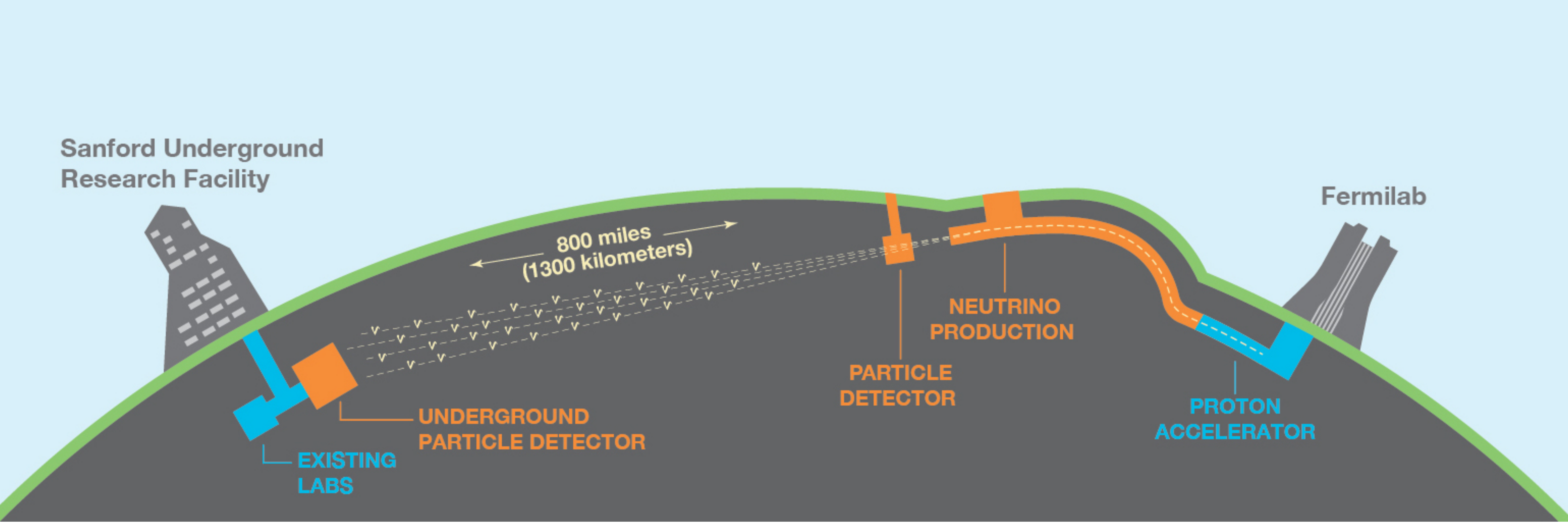


- origin of matter-antimatter asymmetry — δ_{CP}
- mass hierarchy and oscillation parameters — PMNS matrix, Δm_{31}^2
- Grand Unified Theories — proton decay
- dynamics of supernova explosion — wait for one;)

DUNE, CDR (2016), TDR (2020)

Neutrino experiments

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



- measurement of ν_μ disappearance and ν_e appearance

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

- near detector: determine flux and cross sections