EINN2023

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Nucleon axial-vector form factor, neutrino cross sections and QED nuclear medium effects

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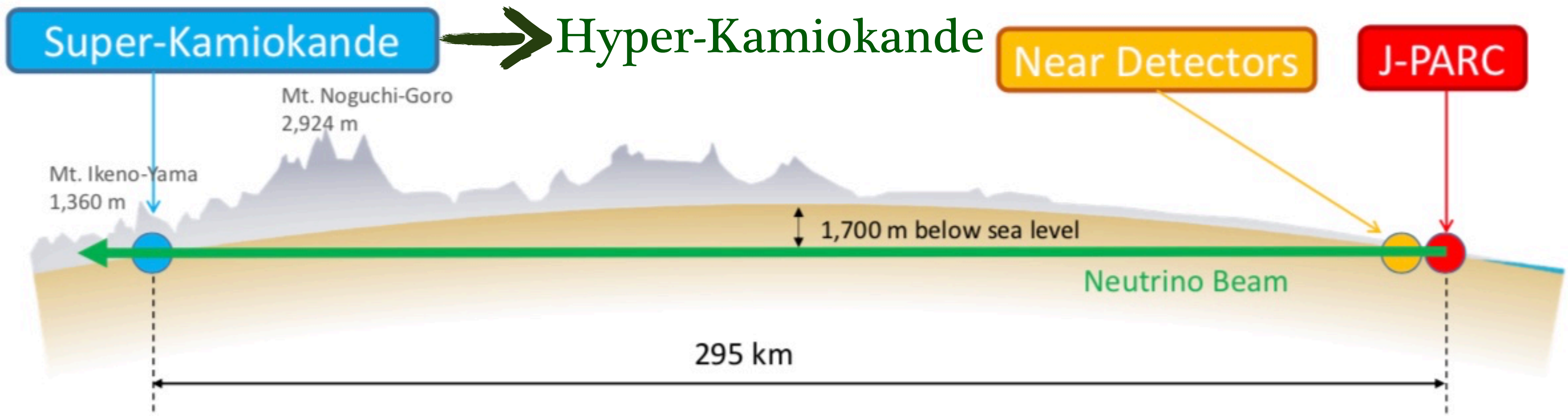
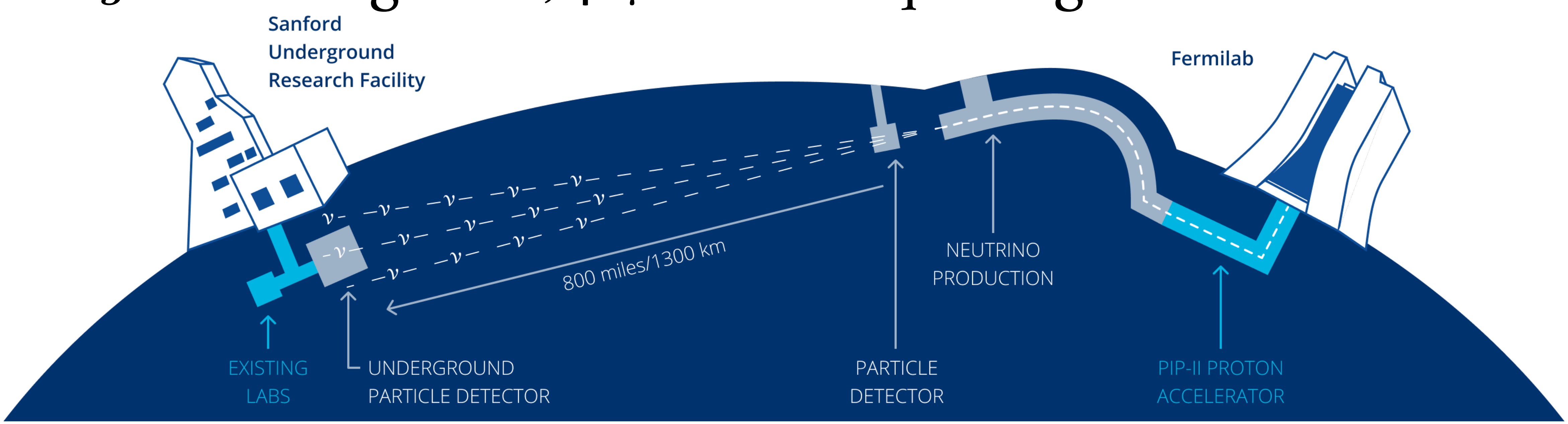
LA-UR-23-31769

CP violation and mass hierarchy@laboratory

650 m under rocks in mountain, 260000t of pure water

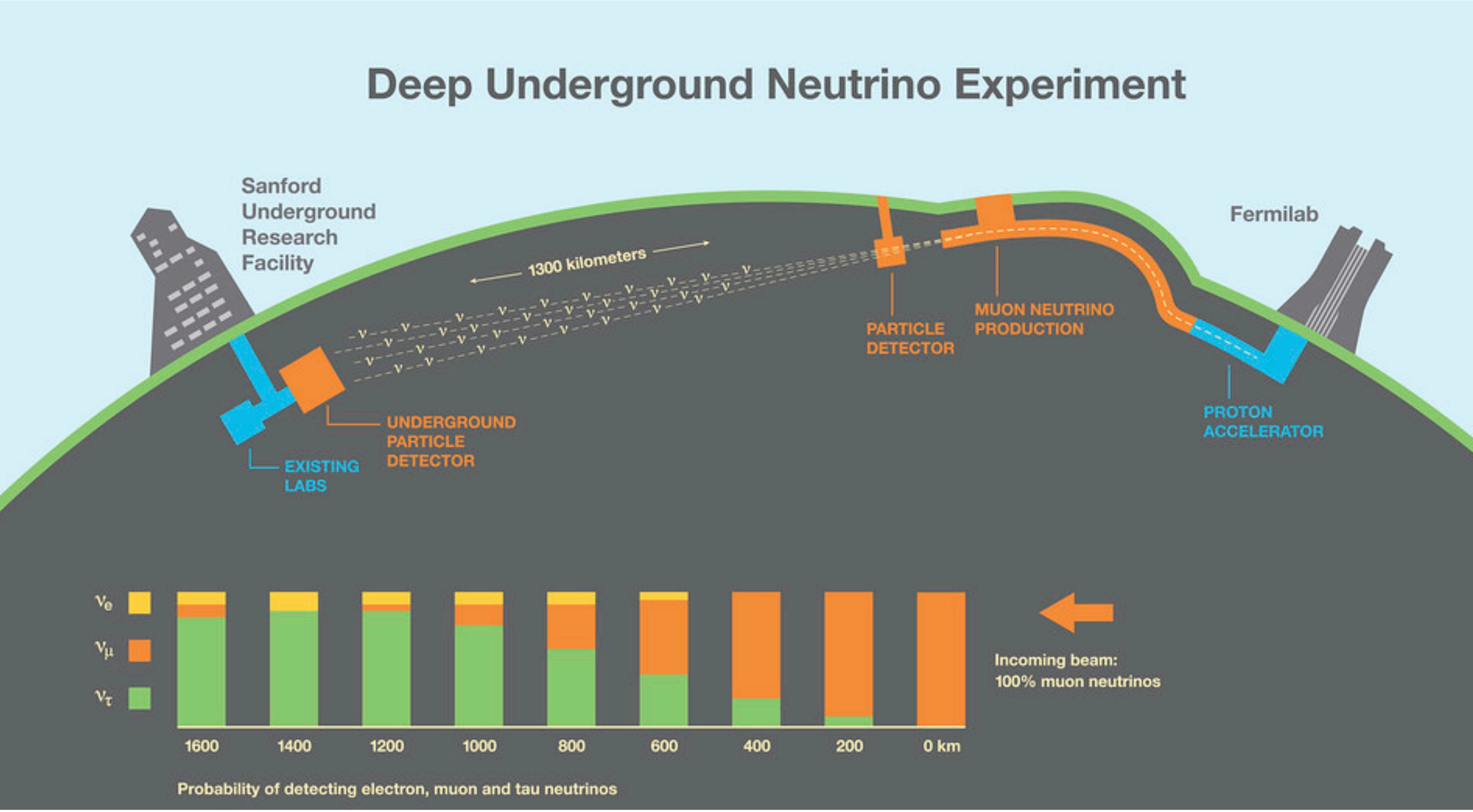


1.5 km underground, 4x70000t of liquid argon



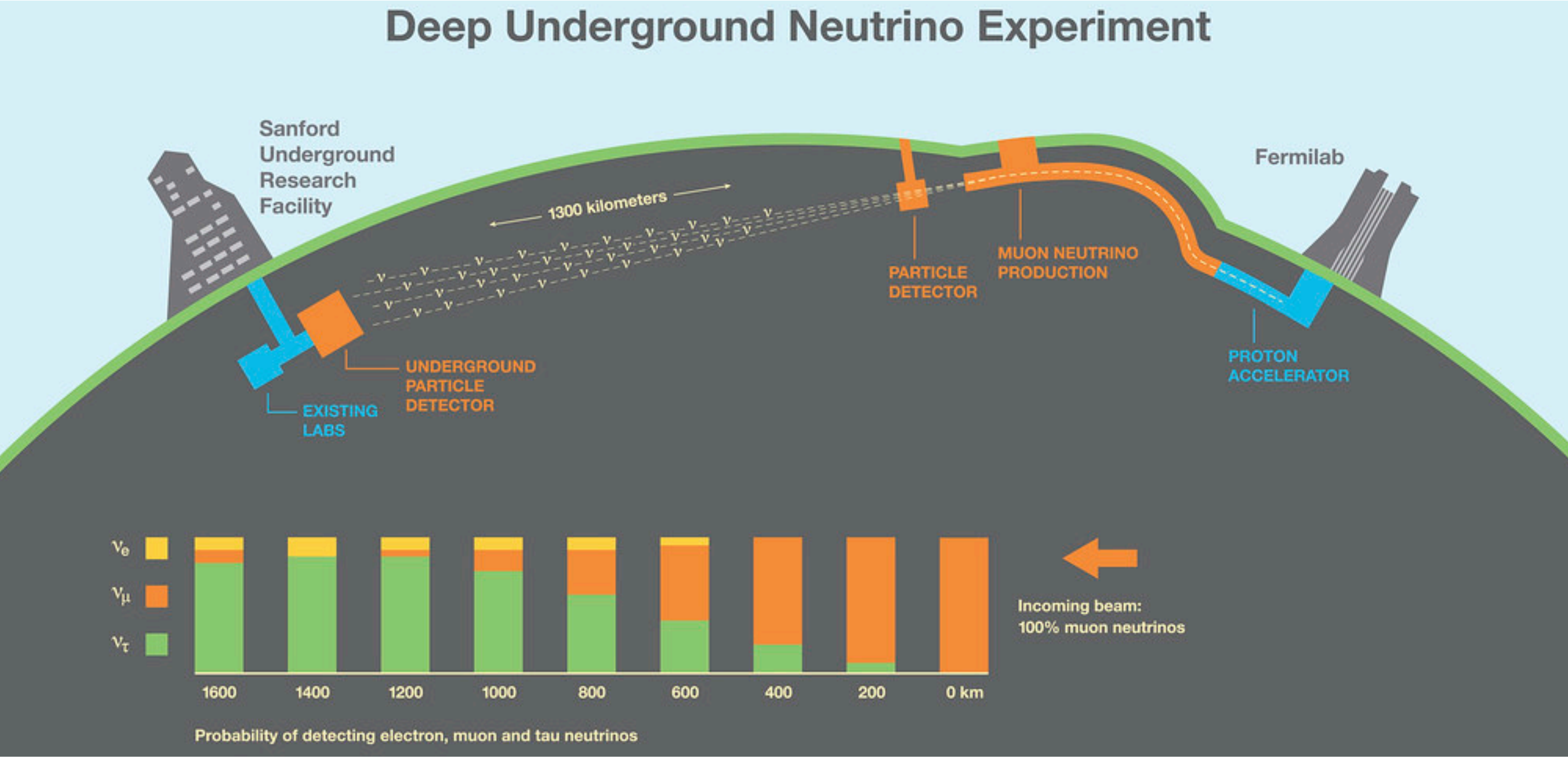
- CP violation in PMNS and mass hierarchy in next 10-20 years !!!

DUNE



- muon neutrinos oscillate to tau and electron flavors

Neutrino experiments

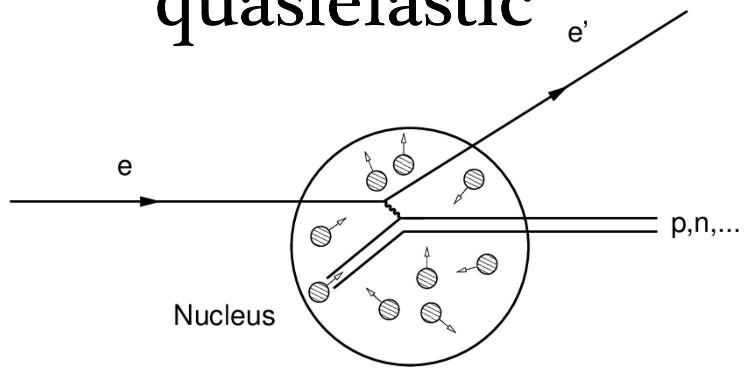


$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu\left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

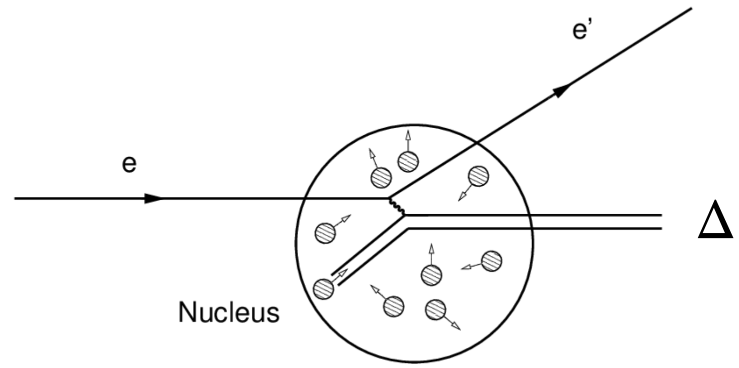
- precise neutrino physics: need in cross sections

Interaction mechanisms

quasielastic



resonance



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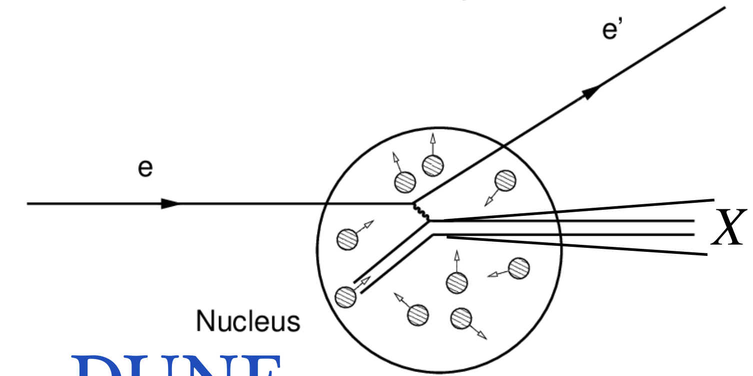
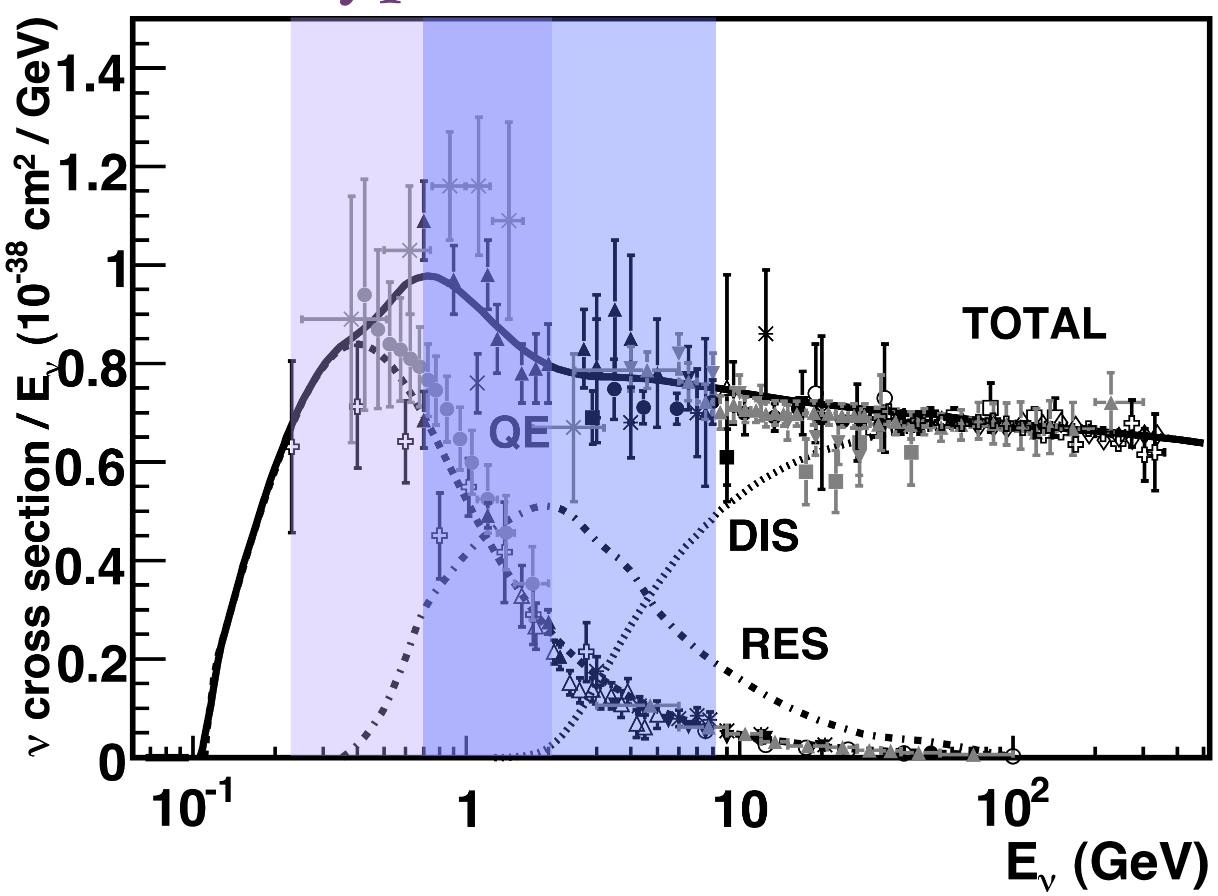
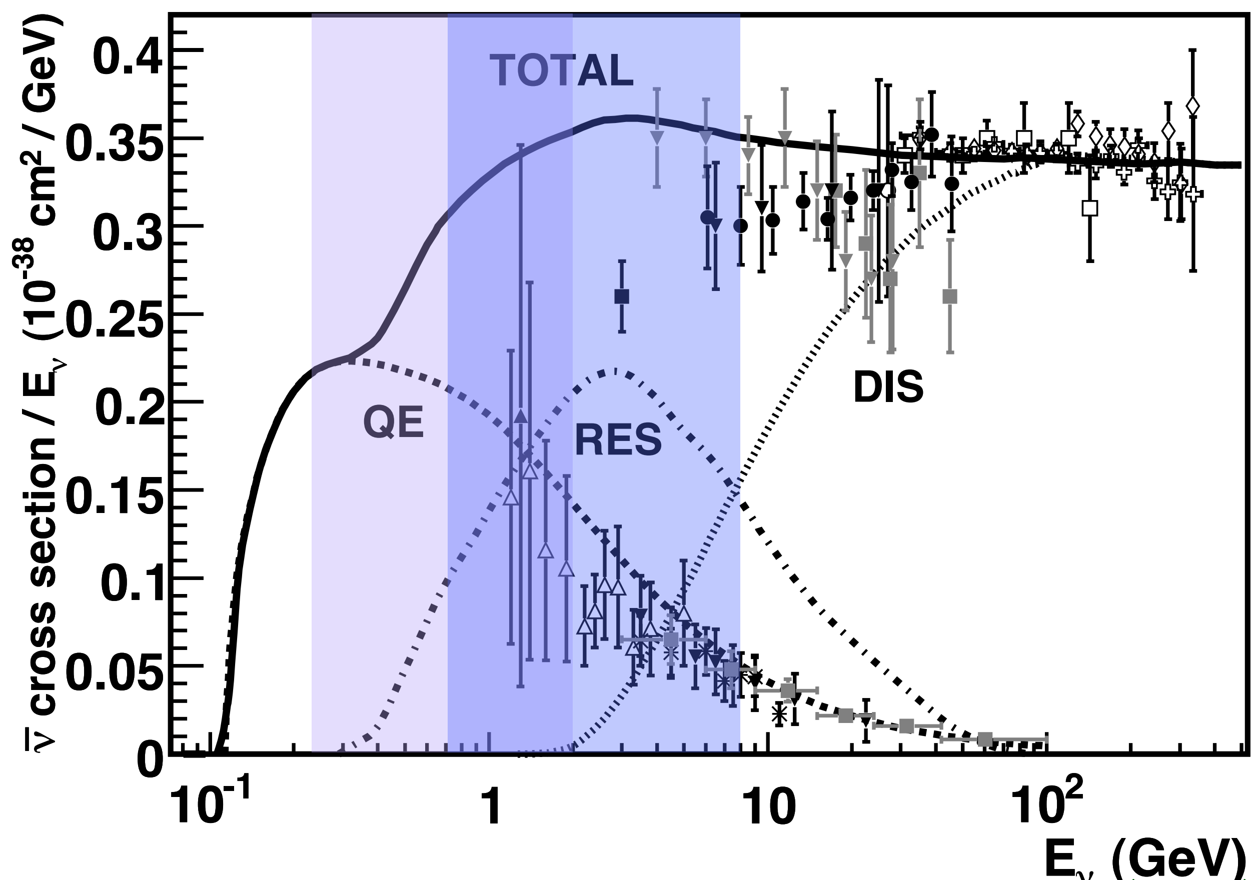


Hyper-K



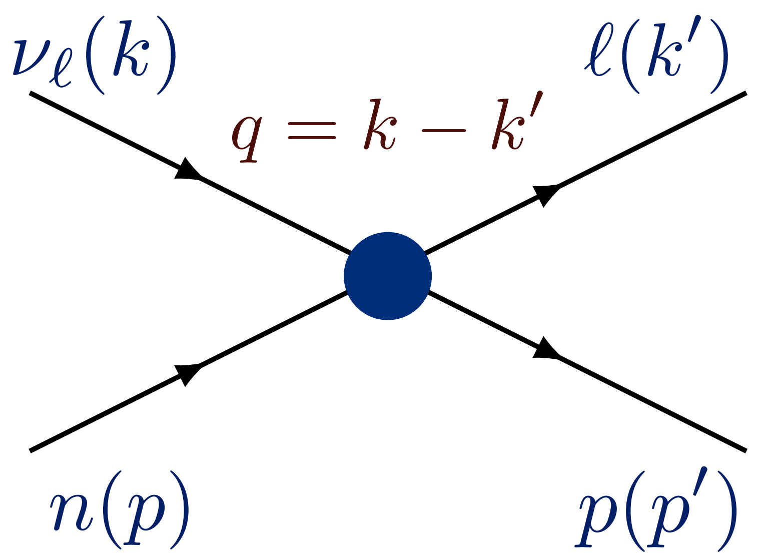
DUNE



Formaggio and Zeller (2013)

- significant overlap with prior and modern JLab energy range
- DUNE experimental program requires 3-5 % precise cross sections

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:

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

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

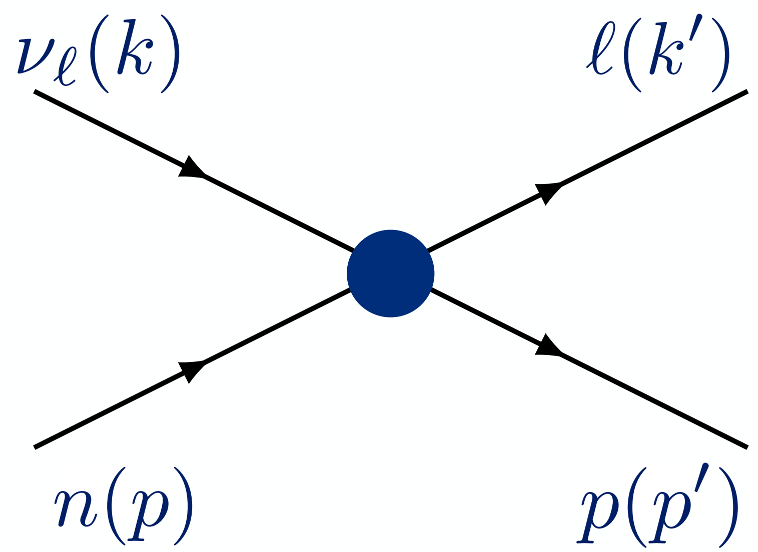
form factors: isovector Dirac and Pauli axial and pseudoscalar

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

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

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

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

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

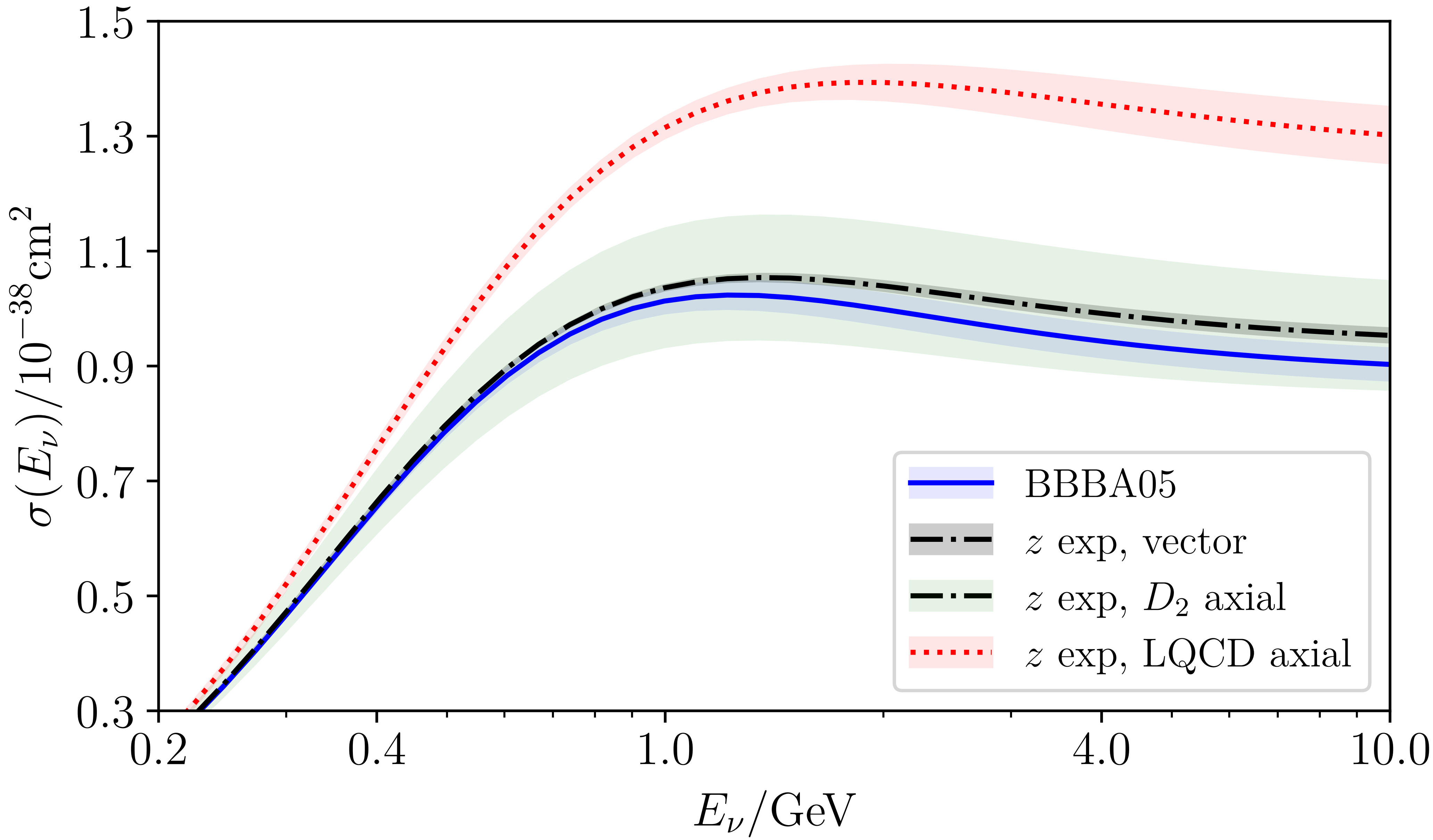
world data: ~3200 events

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)

Neutrino-nucleon scattering (CC)



A.S. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. of 72, 010622-120608 (2022)
A.S. Meyer, M. Betancourt, R. Gran, and R.J. Hill, PRD (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill, and O. T. , PRD (2021)

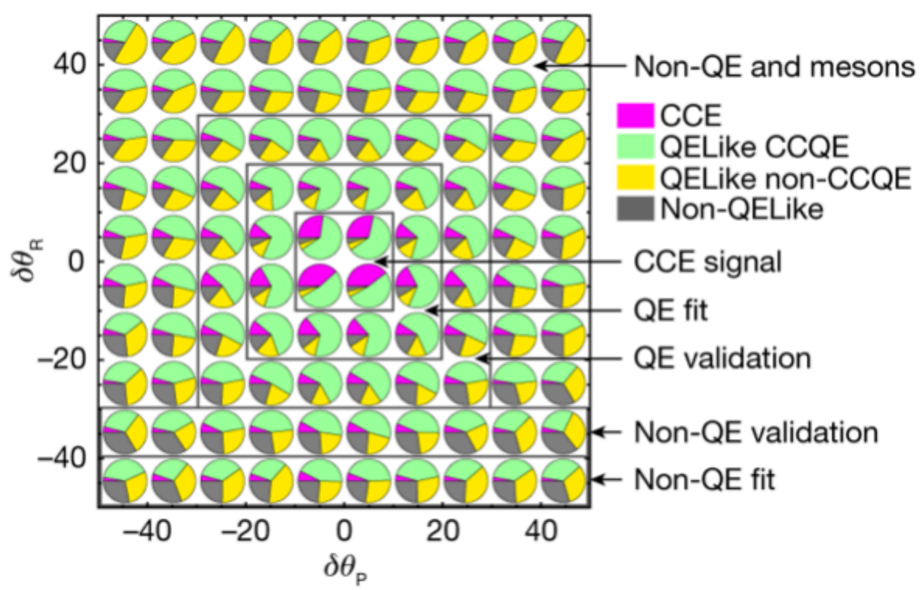
- knowledge of vector structure stops a progress in studies of axial
- acknowledged discrepancy: lattice QCD <-> experimental data

MINERvA result with free protons

- idea of scattering on molecular hydrogen realized !!!

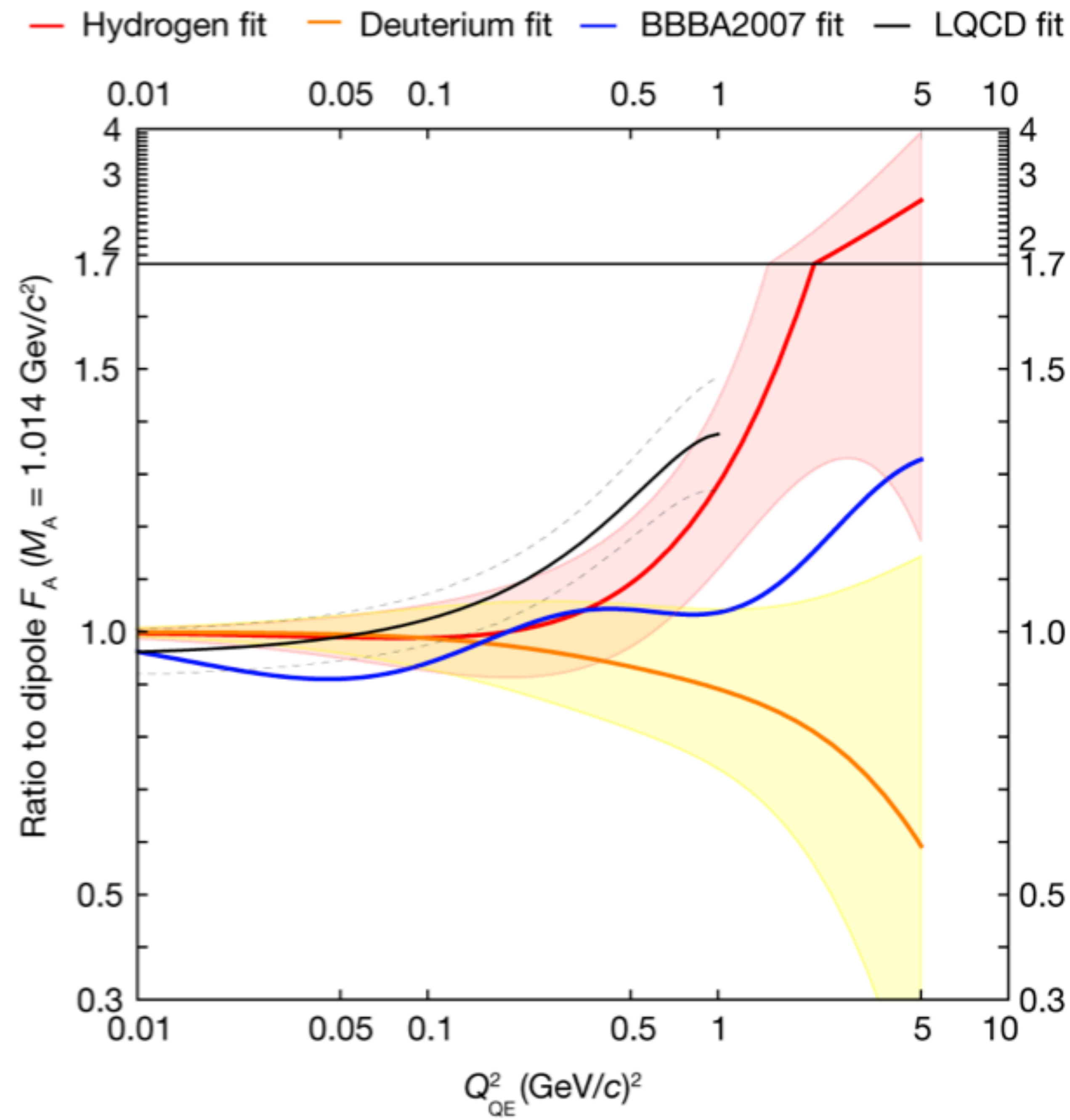
$\overline{\nu}_\mu p \to \mu^+ n$

kinematic selection



5580 events over
12500 background

background nuclear events
constrained by scattering of ν

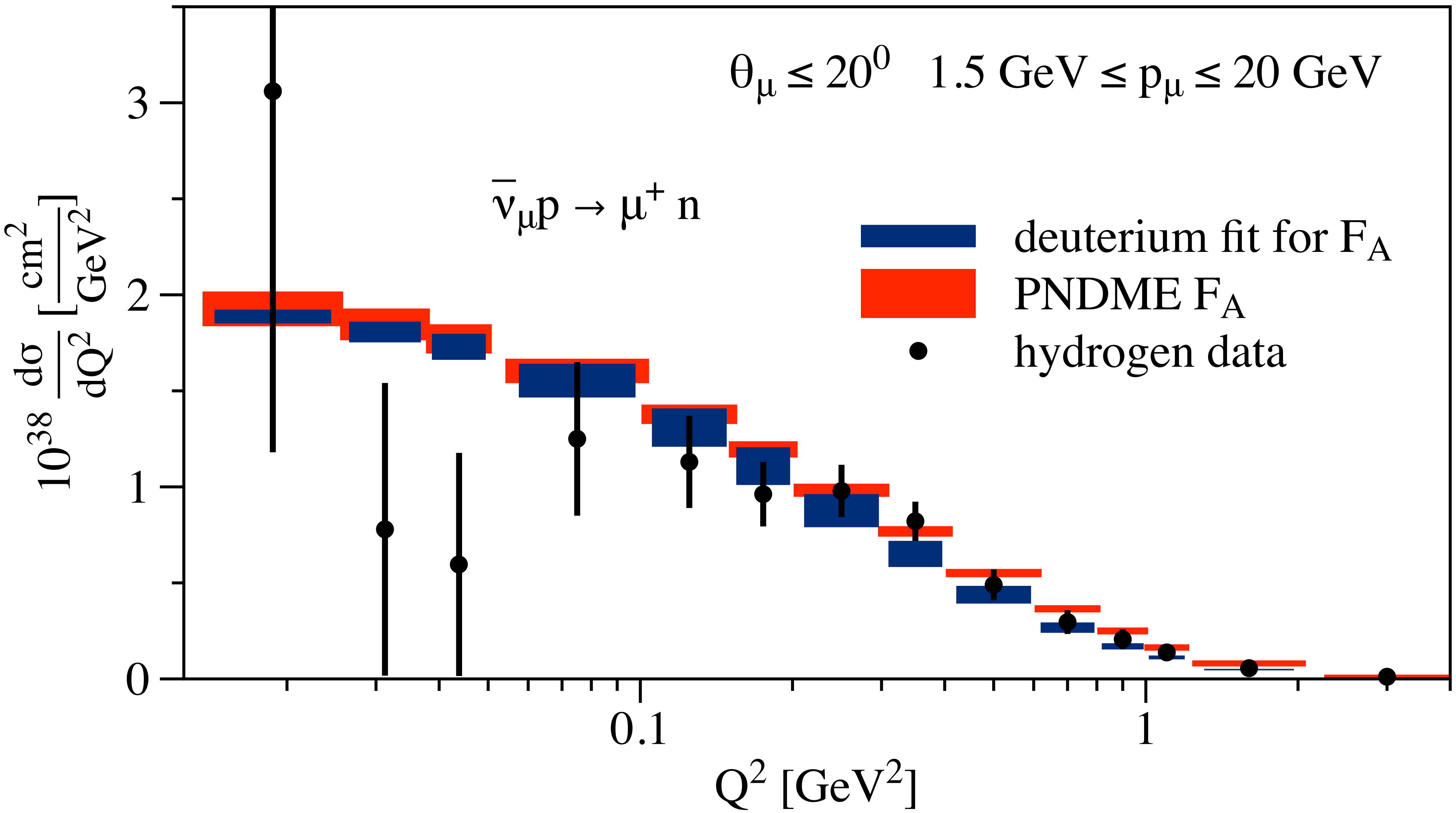


- 1st measurement of axial form factor on "free" protons $\overline{\nu}_\mu p \to \mu^+ n$

T. Cai et al., MINERvA Collaboration, Nature (2023), 614, 48-53

Lattice QCD vs MINERvA

- PNDME 2023 axial-vector form factor as representative of lattice QCD



- $\lesssim 1\sigma$ agreement for each bin besides two at small Q^2

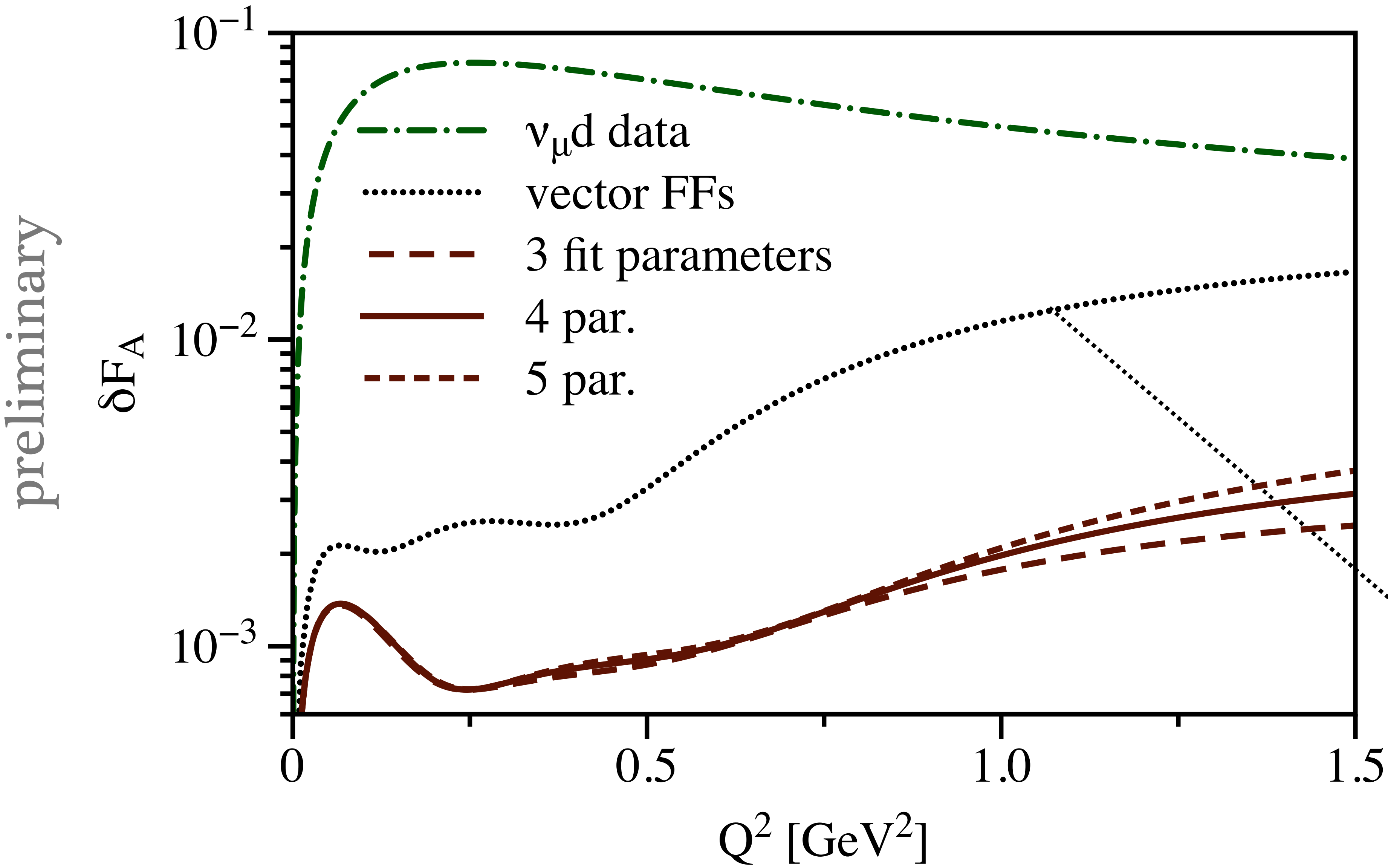
- 2-3σ tension between lattice QCD and deuterium data
- MINERvA hydrogen data consistent with LQCD and deuterium

O. T., Rajan Gupta, and Tanmoy Bhattacharya, Phys.Rev.D 108 (2023) 7, 074514

DUNE projections

- estimates for 700 kg of H in Straw Tube Tracker at near detector

H. Duyang, B. Guo, S. R. Mishra, and R. Petti (2016)



δr_A :

0.16 fm

0.02 fm

- order of magnitude improvement in axial form factor and radius
- DUNE will probe vector form factors and isospin symmetry

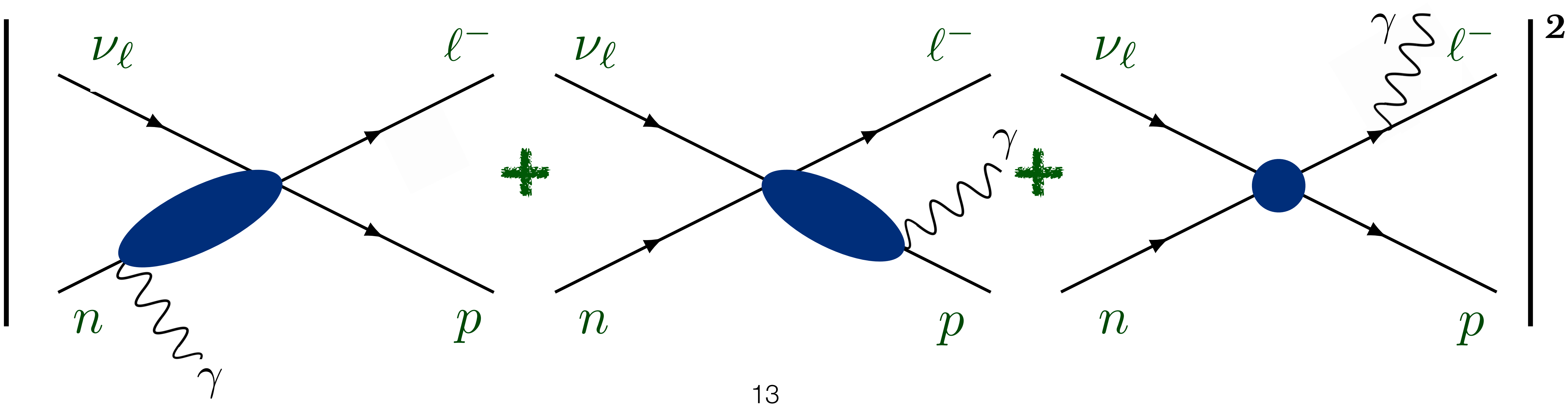
Roberto Petti, O. T., and Richard J. Hill, arXiv: 2309.02509 factorization for radiative corrections with model for hard function

Charged-current elastic scattering on nucleons

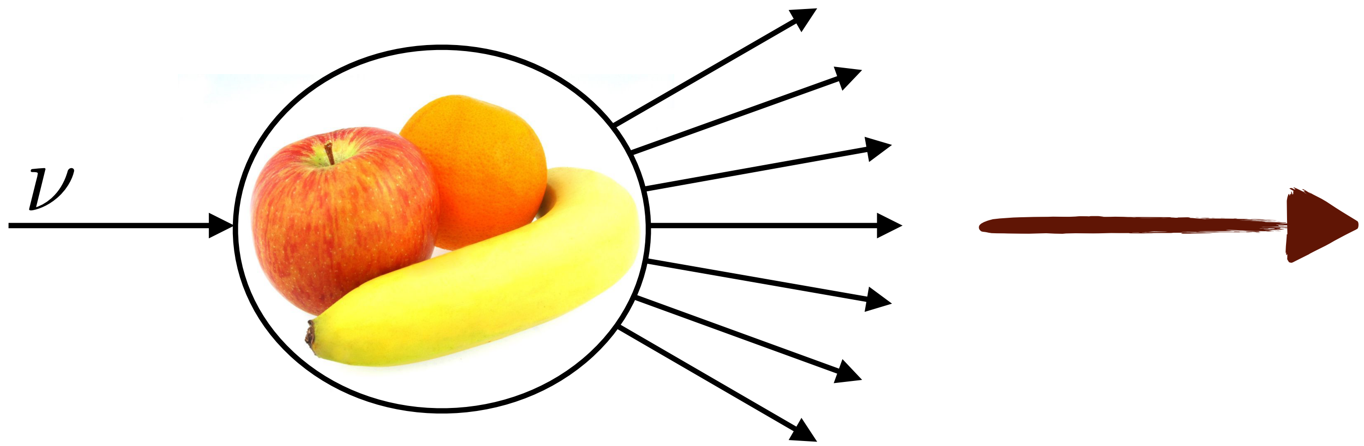
O. T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. 13 (2022), 1, 5286

O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
editors suggestion in Phys. Rev. D (2022)

precise predictions for flavor ratios and radiative corrections



Conclusions



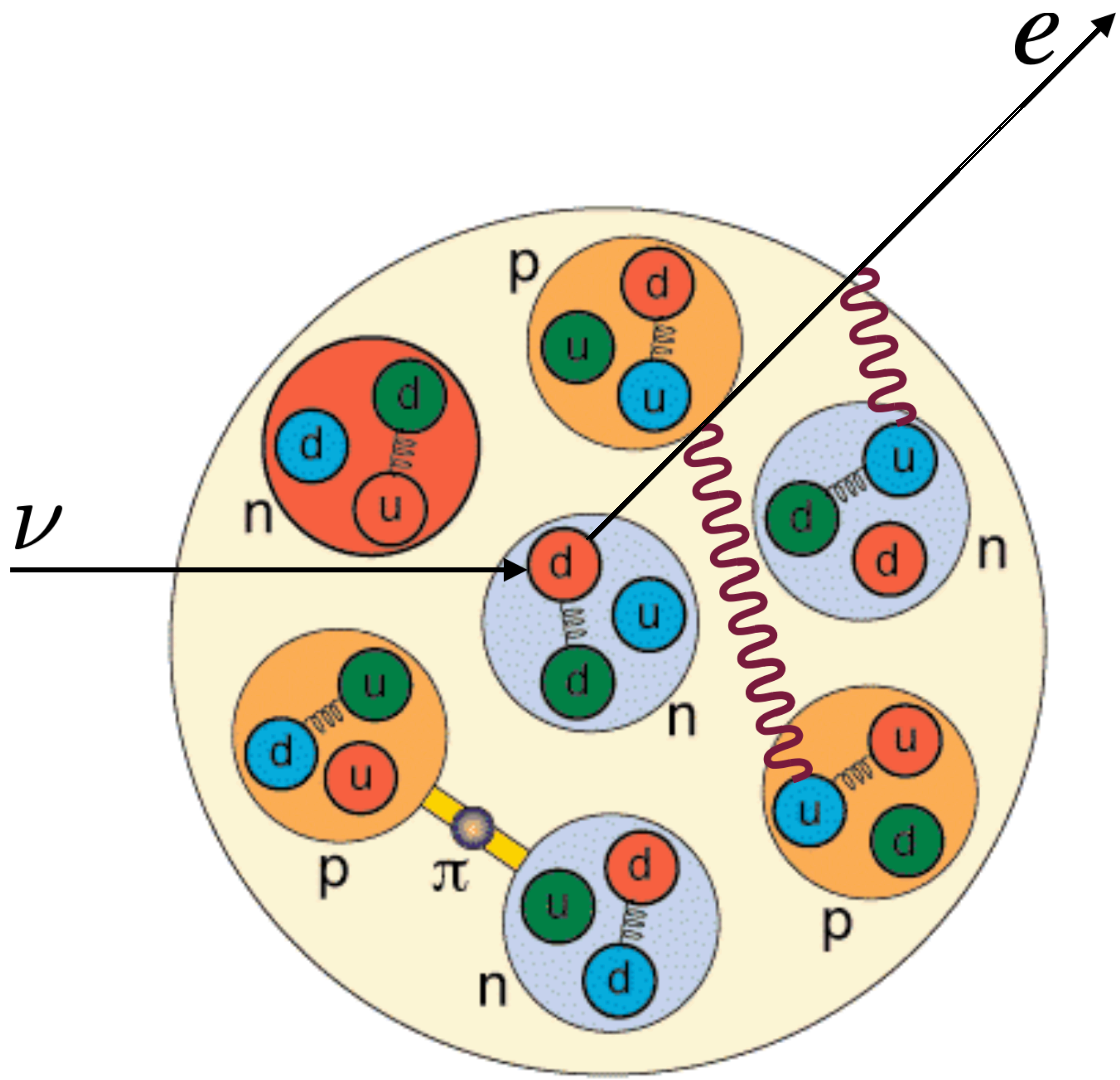
neutrino interactions

for precise measurements

- MINERvA data vs deuterium data and lattice QCD: within 1σ

- axial-vector form factor and radius at DUNE: subpermille precision

- radiative corrections to neutrino-nucleon cross sections formulated and evaluated in factorization framework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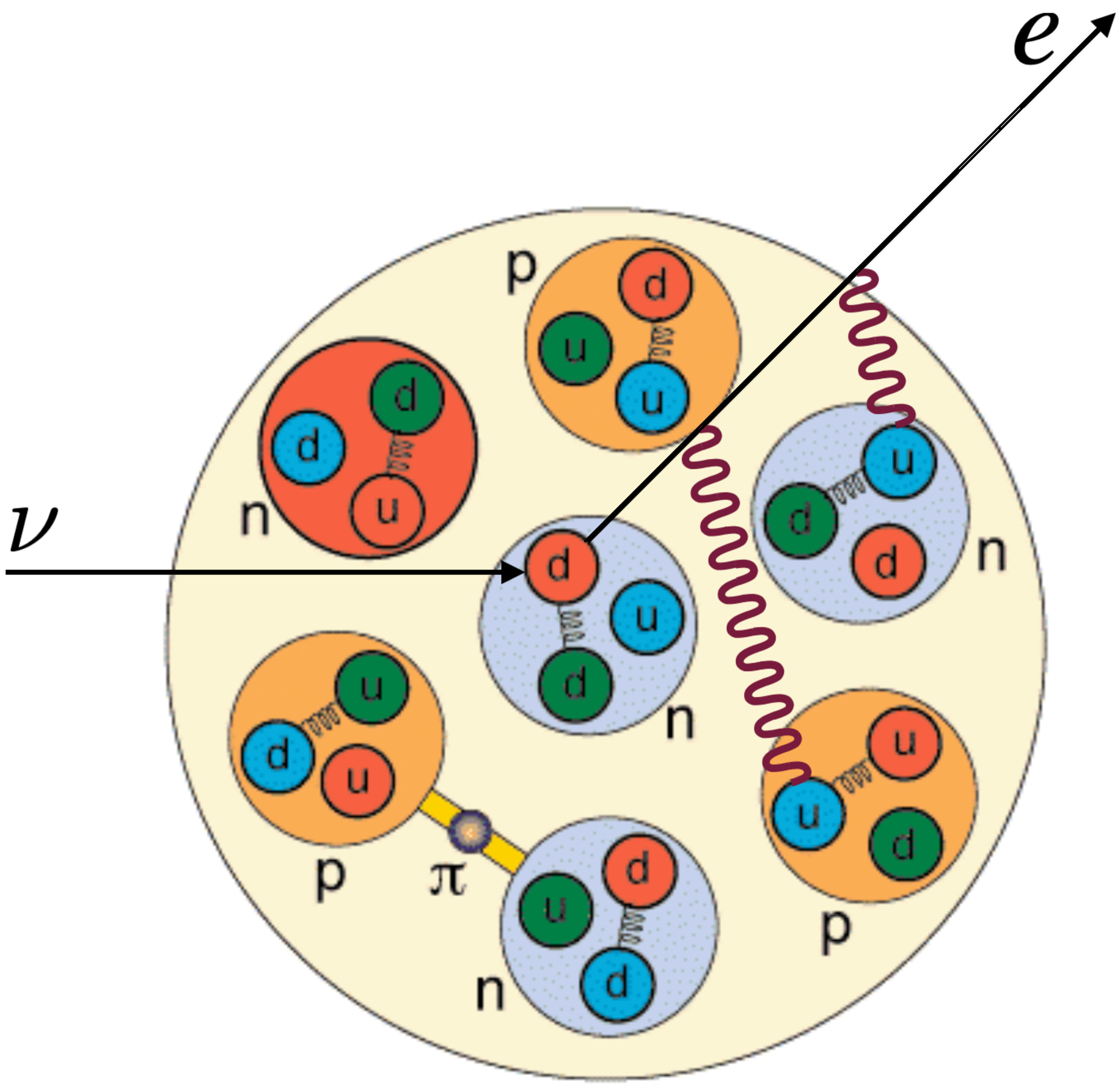
QED Nuclear Medium Effects

QED medium effects



- charged lepton exchanges photons with nuclear medium

SCET$_G$ formulation

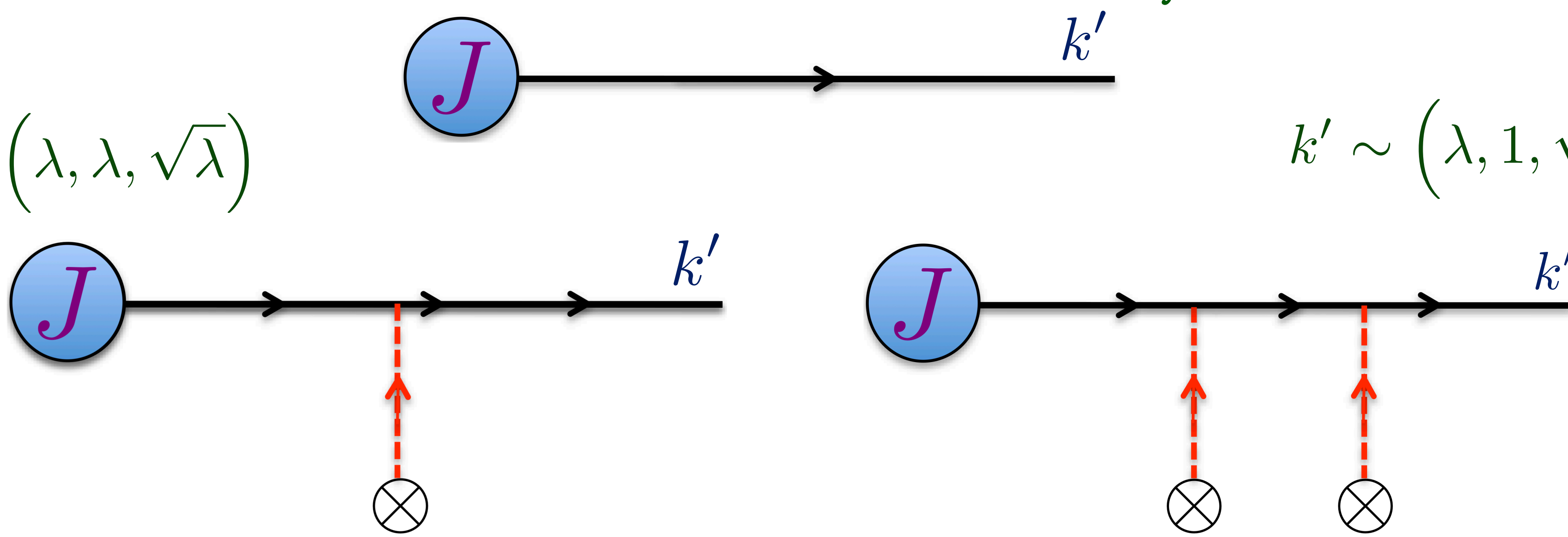
- forward scattering is dominant process

- Glauber photons exchanged with a nuclear charge distribution

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

$q_\gamma \sim \left(\lambda, \lambda, \sqrt{\lambda}\right)$

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



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

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

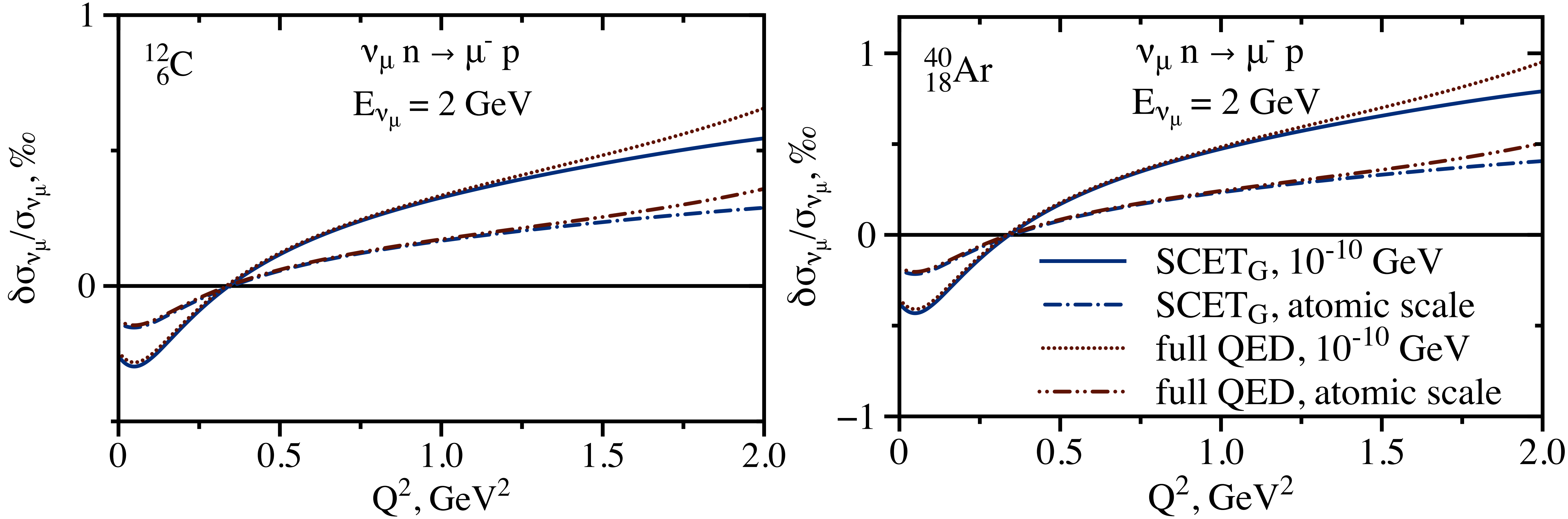
- leading-order cross sections are distorted
- EFT and full QED calculations are performed

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

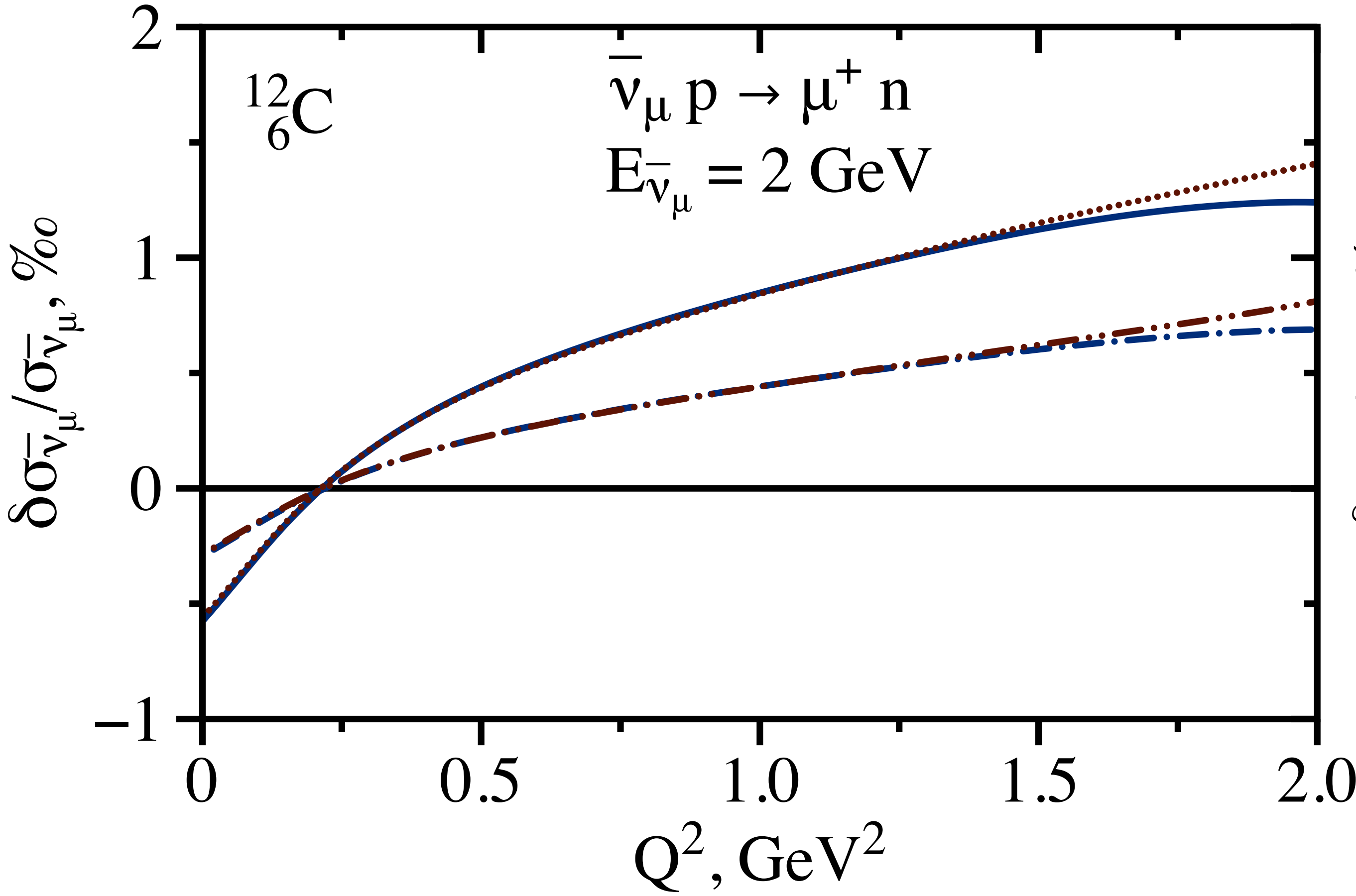
- permille-level distortion of cross sections: $O(\alpha^2)$ correction
- smaller correction to inclusive cross section

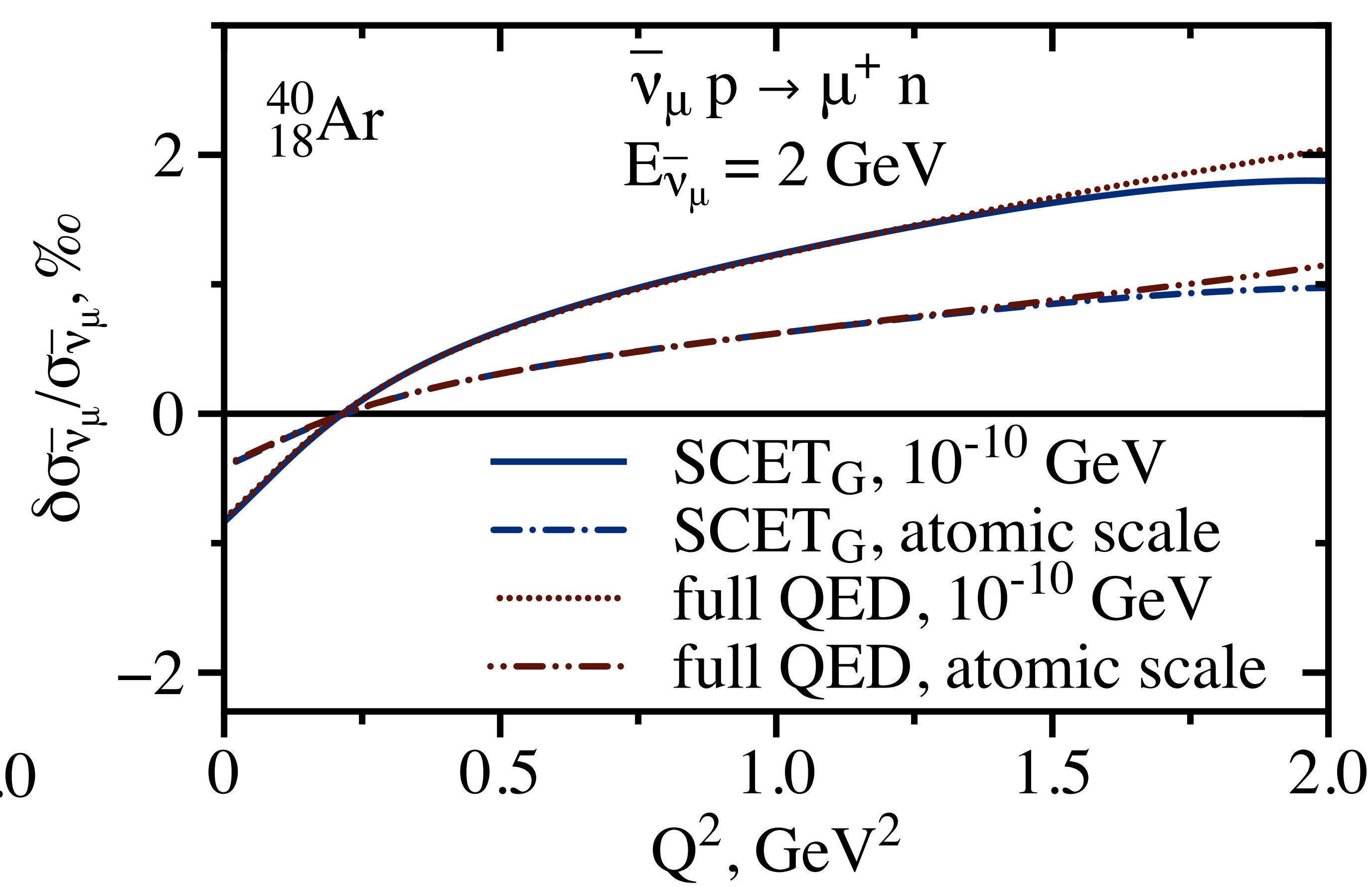
Antineutrino scattering

- 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
- 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

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

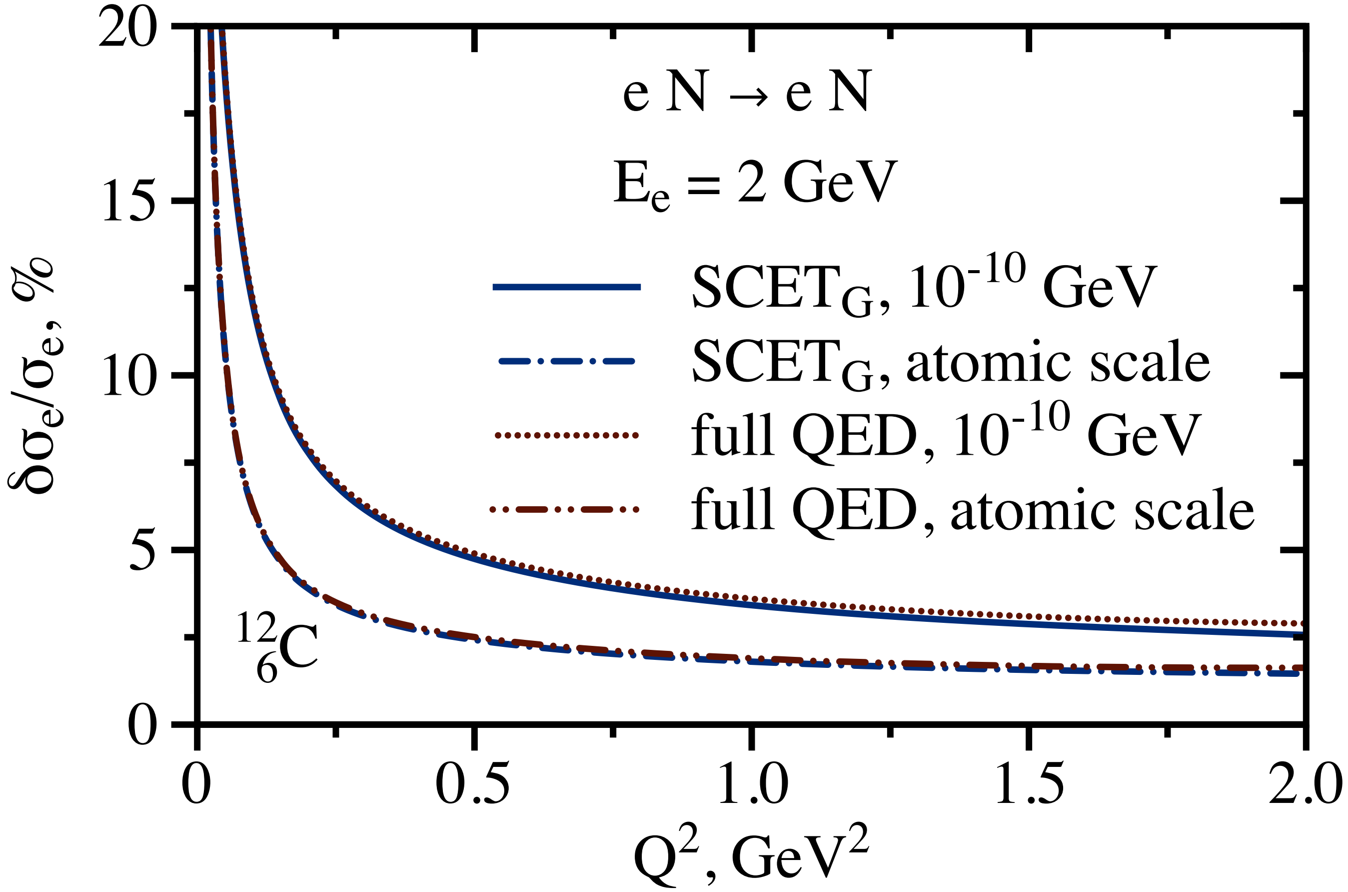
- change: integral along final lepton direction over charge and potential

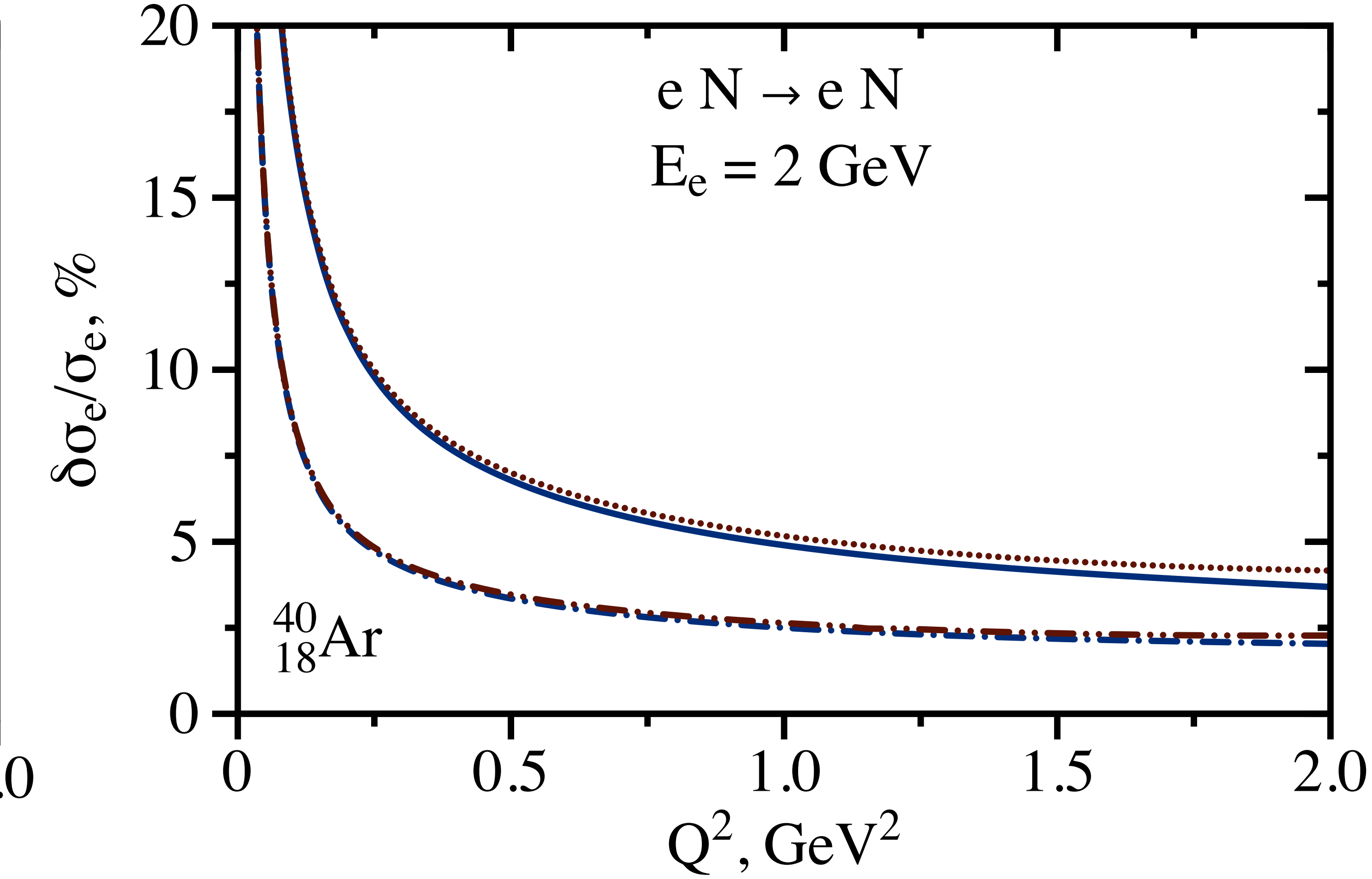
$$\delta\sigma_f \sim \int_{\text{lepton line}}^{\text{final}} \rho\left(z\right) \mathrm{d}z \int \frac{\mathrm{d}^2\vec{q}_\perp}{\left(2\pi\right)^2} |v\left(\vec{q}_\perp\right)|^2 \left(\sigma_0\left(\vec{k},\vec{k}'-\vec{q}_\perp\right) - \sigma_0\left(\vec{k},\vec{k}'\right)\right)$$

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

Electron scattering

- relative correction per nucleus after incoherent sum over nucleons



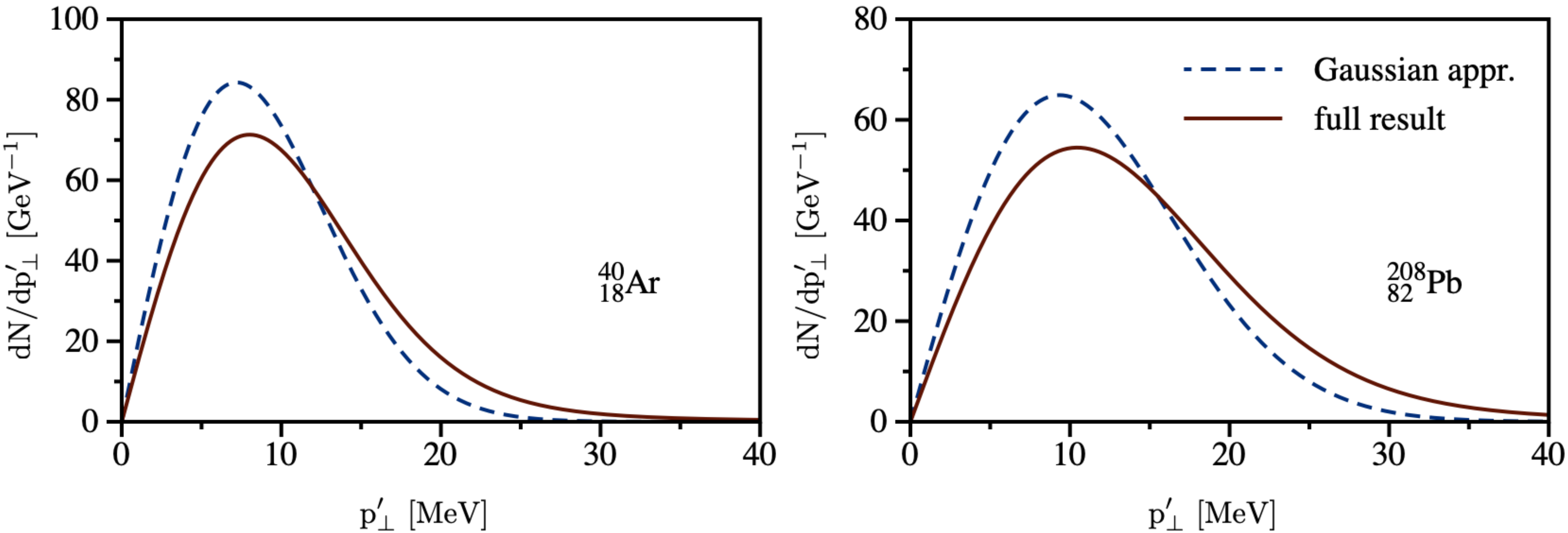


O. T. and Ivan Vitev, Phys. Lett. B 805, 135466 (2022)

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

Broadening of electron tracks

- multiple re-scattering generates transverse momentum



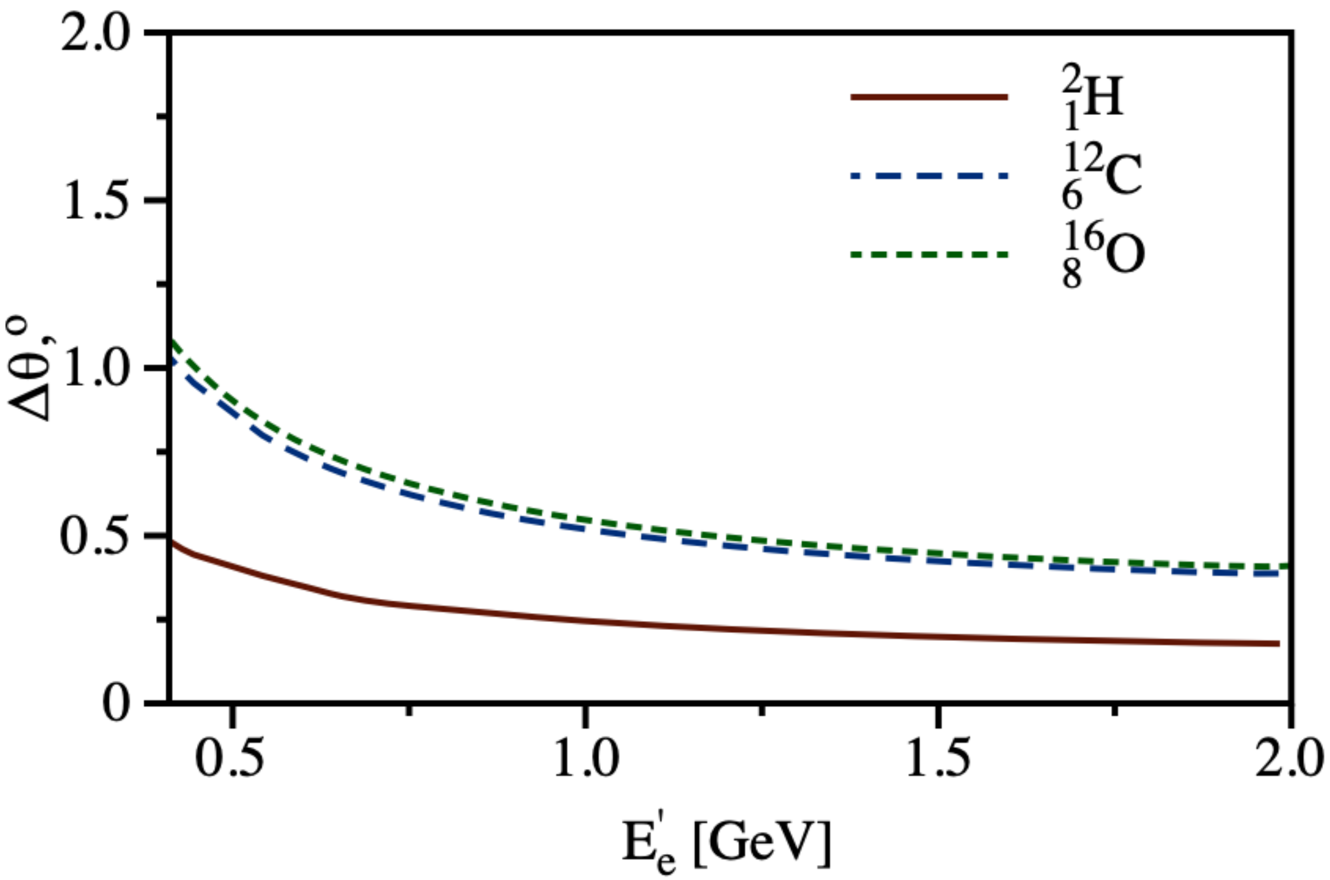
O. T. and Ivan Vitev, accepted in Phys. Rev. D (2023)

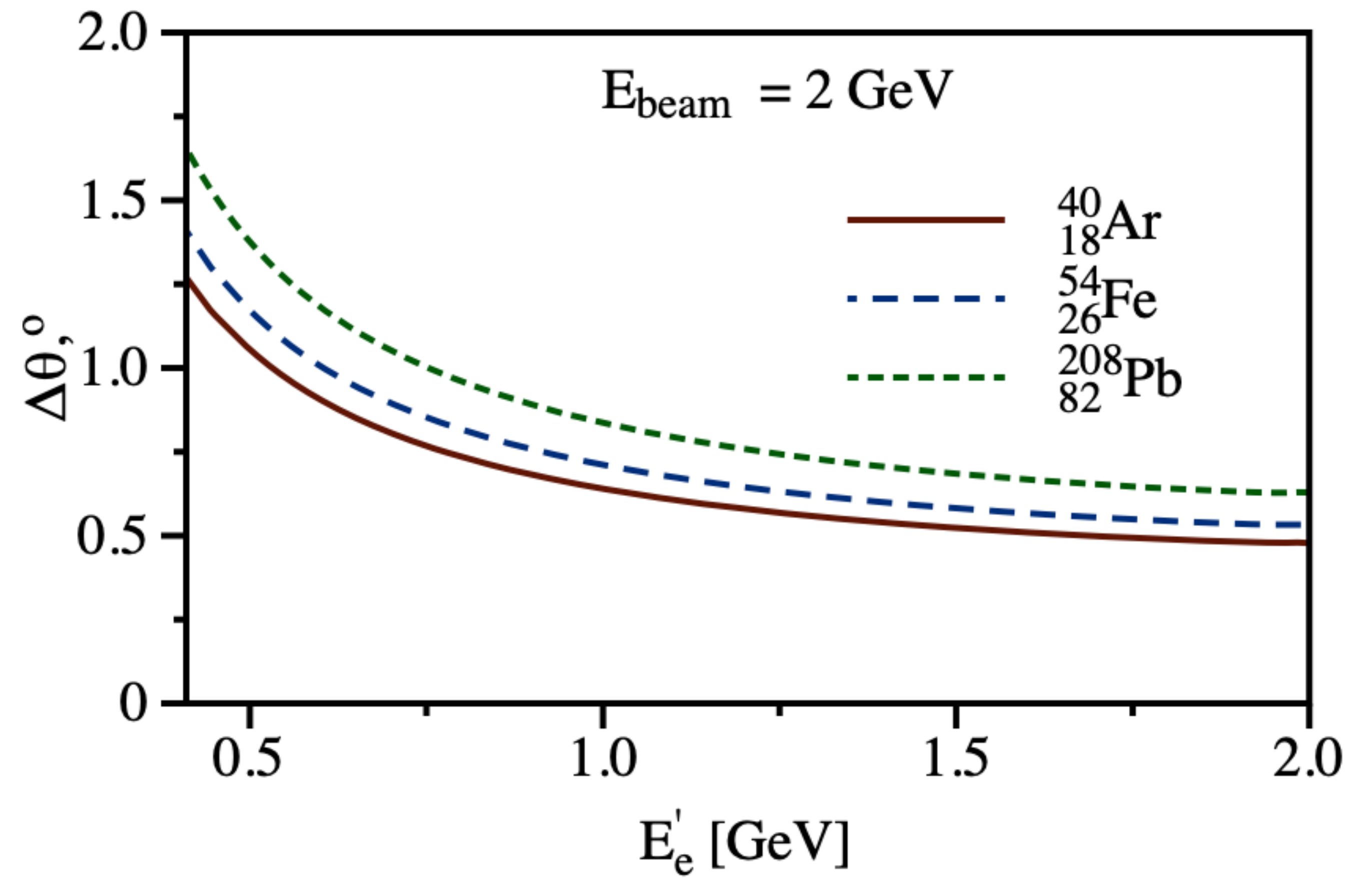
- exact resummation vs Gaussian approximation: nuclear size scale

- Glauber exchange induces 10-30 MeV transverse momentum

Broadening of electron tracks

- r. m. s. deflection angle after multiple rescattering





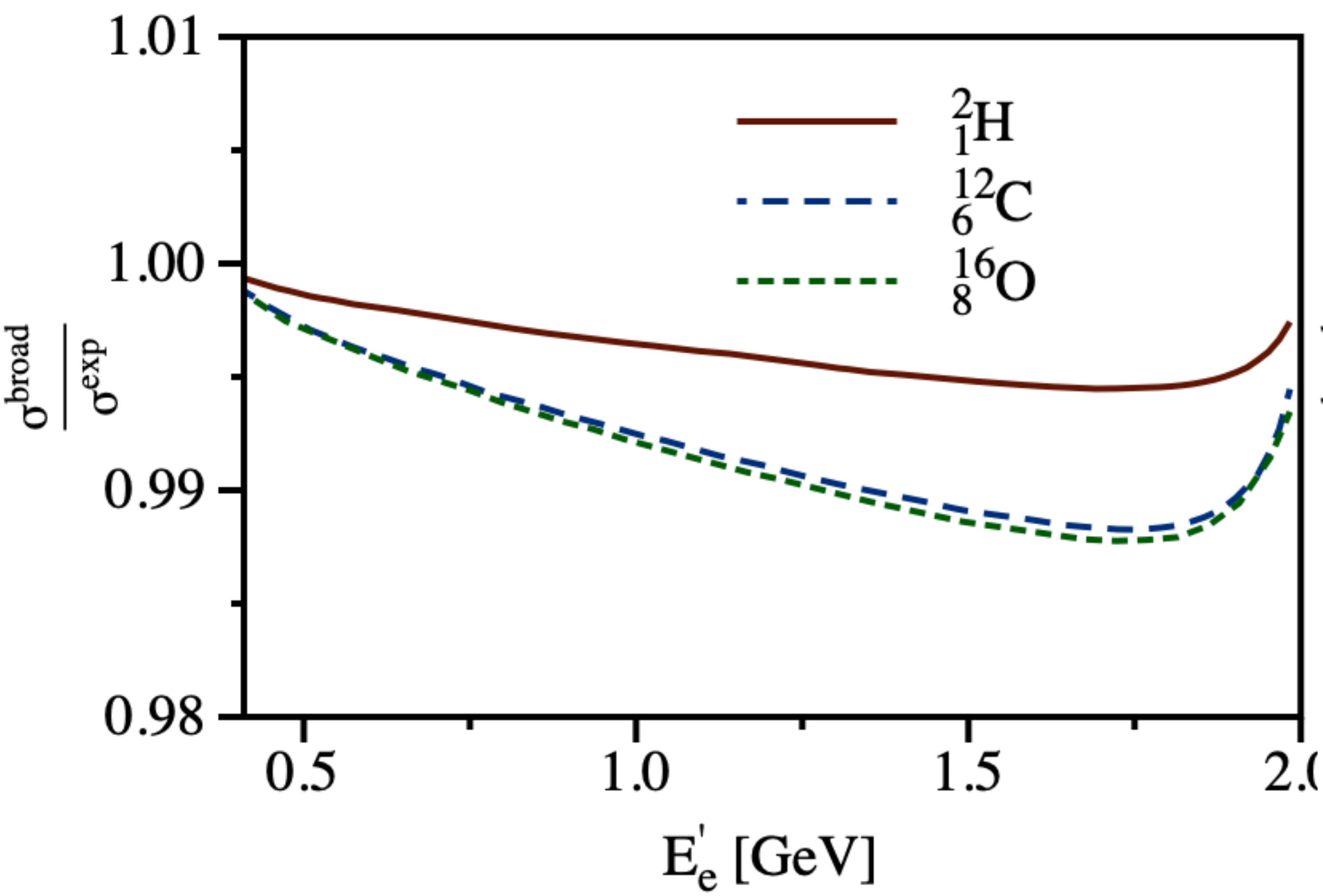
- nucleus approximated as sphere of constant density

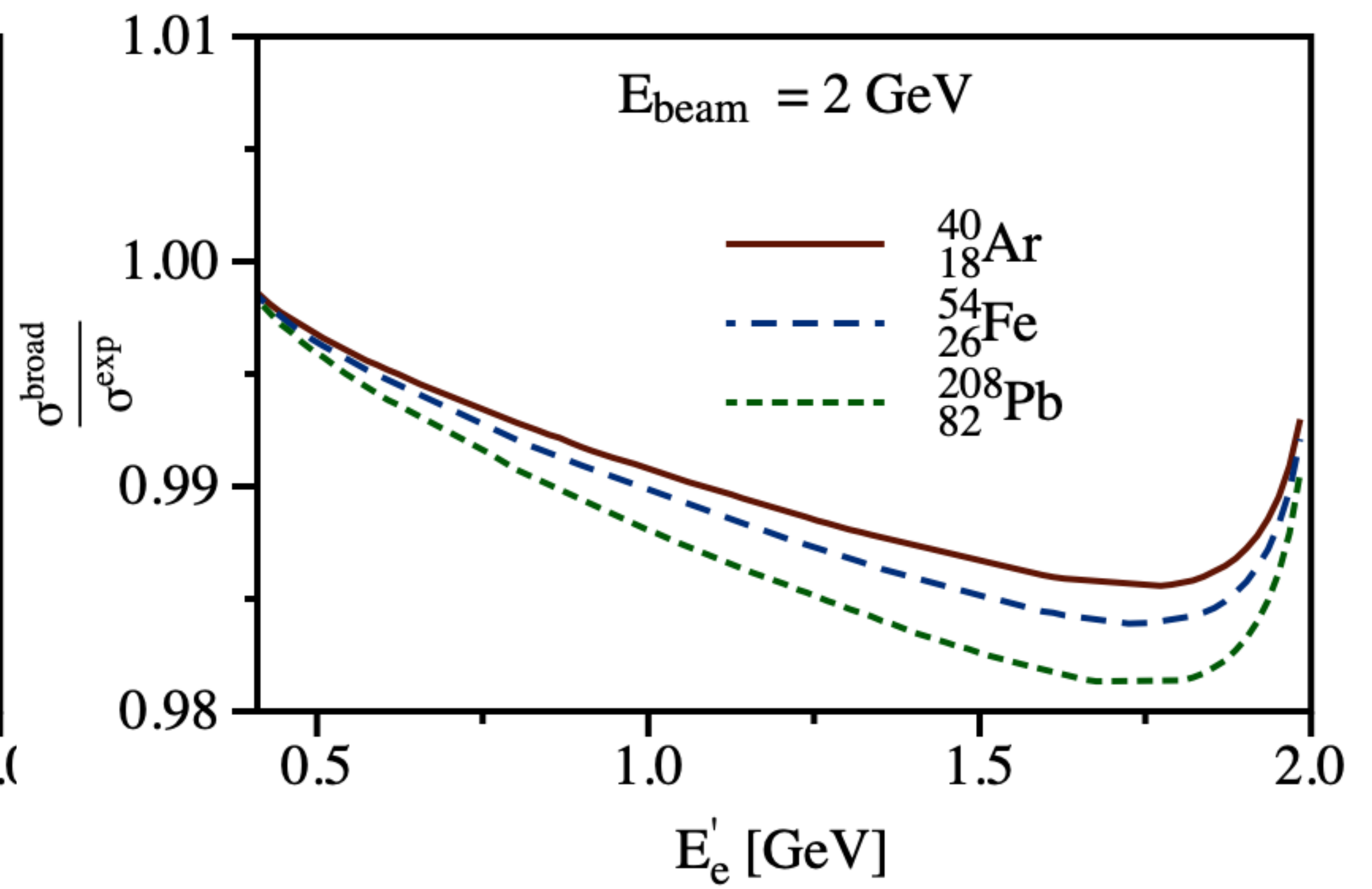
- sizable deflection of electron tracks $\sqrt{<(\Delta\theta)^2>} \sim 1/E$

Effect on unpolarized cross section

- initial and final re-scattering is taken into account

- momentum transfer from electron kinematics





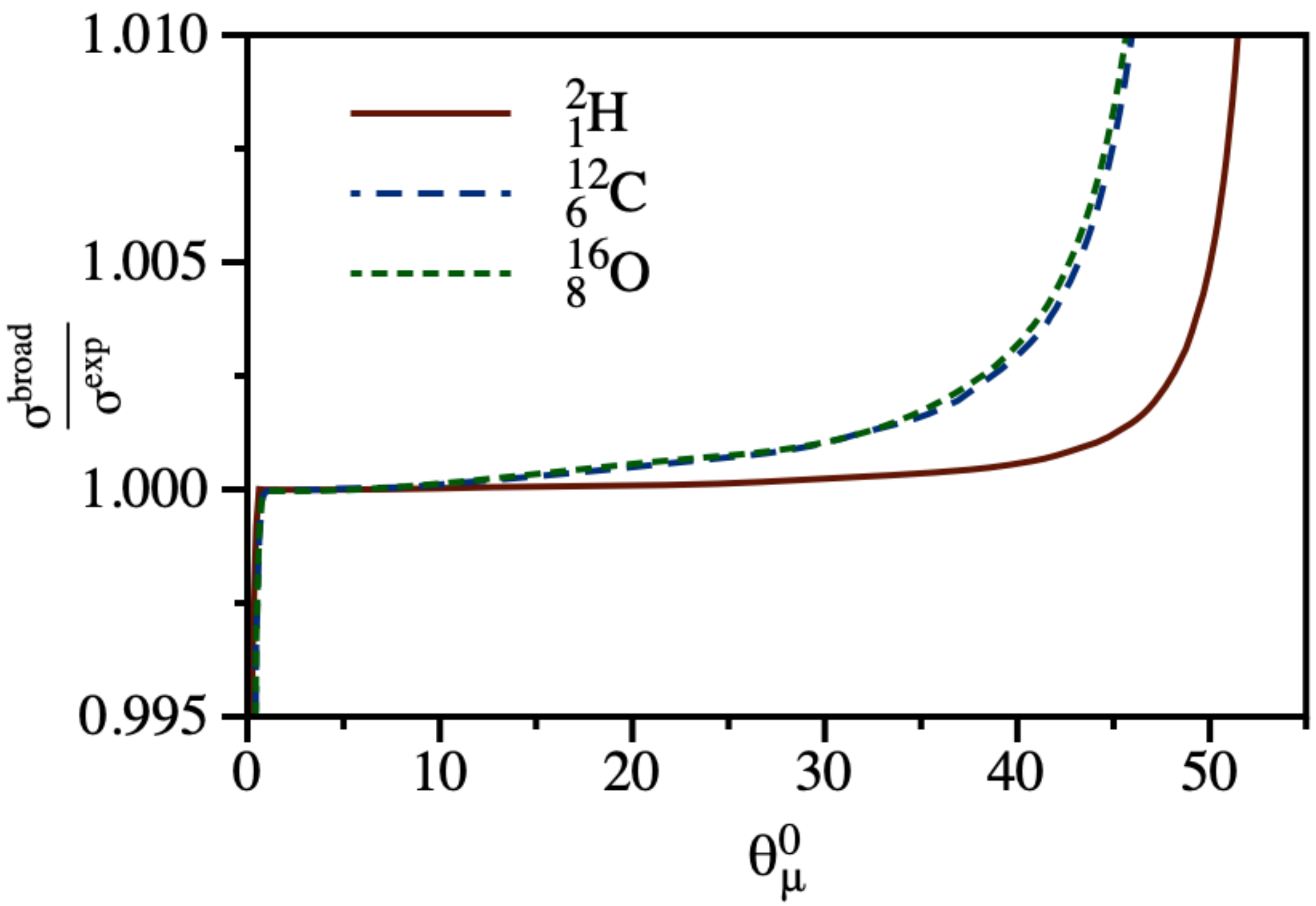
- nucleus approximated as sphere of constant density

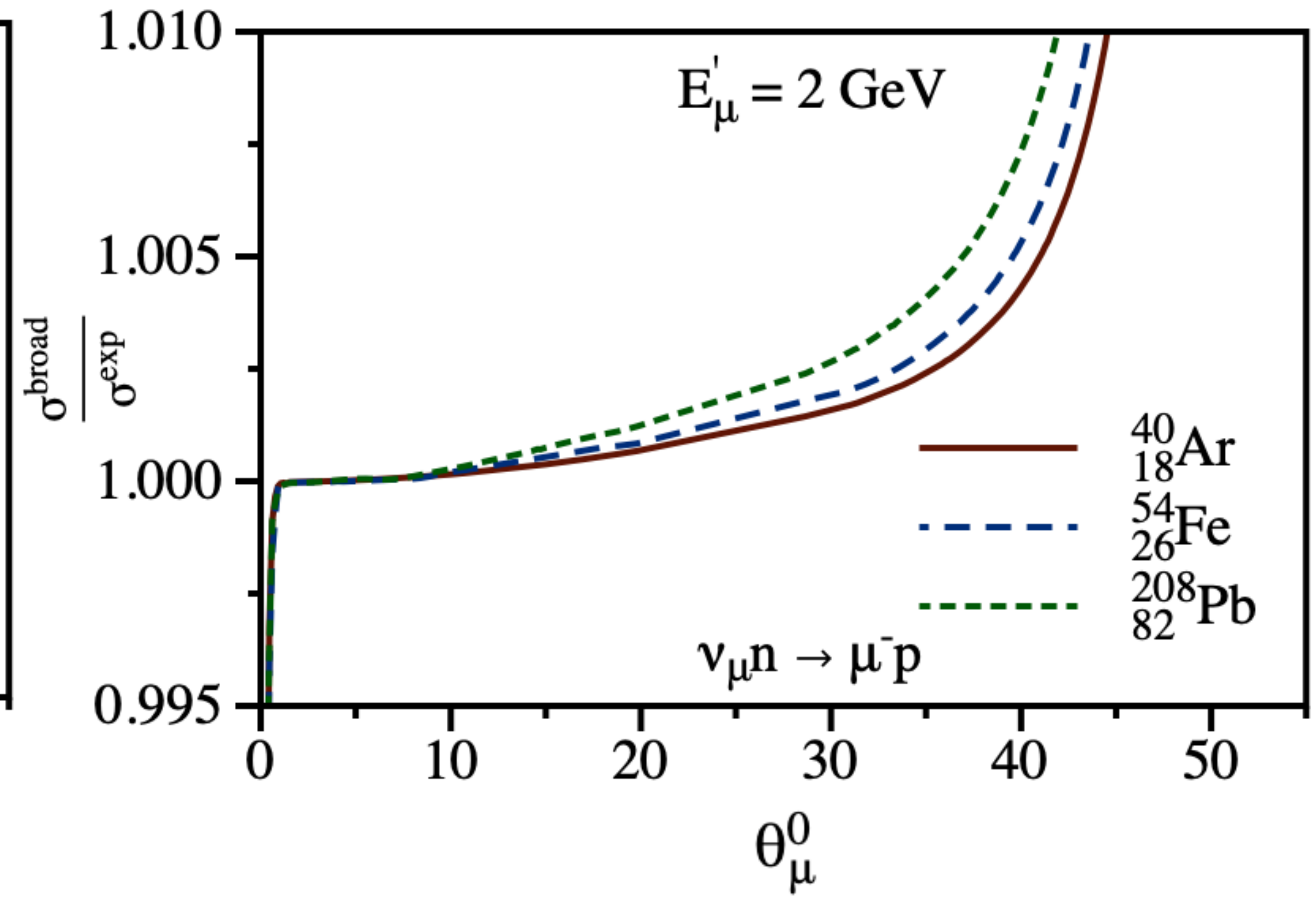
- percent-level electron-nucleus cross-section suppression

Effect on unpolarized cross section

- only final re-scattering present

$$E_\nu^r \approx \frac{E'_\mu - \frac{1}{2}\frac{E_B^2 - 2M_i E_B + m_\mu^2 + M_i^2 - M_f^2}{M_i - E_B}}{1 - \frac{E'_\mu}{M_i - E_B}\left(1 - \beta_\mu \cos\theta_\mu\right)}$$



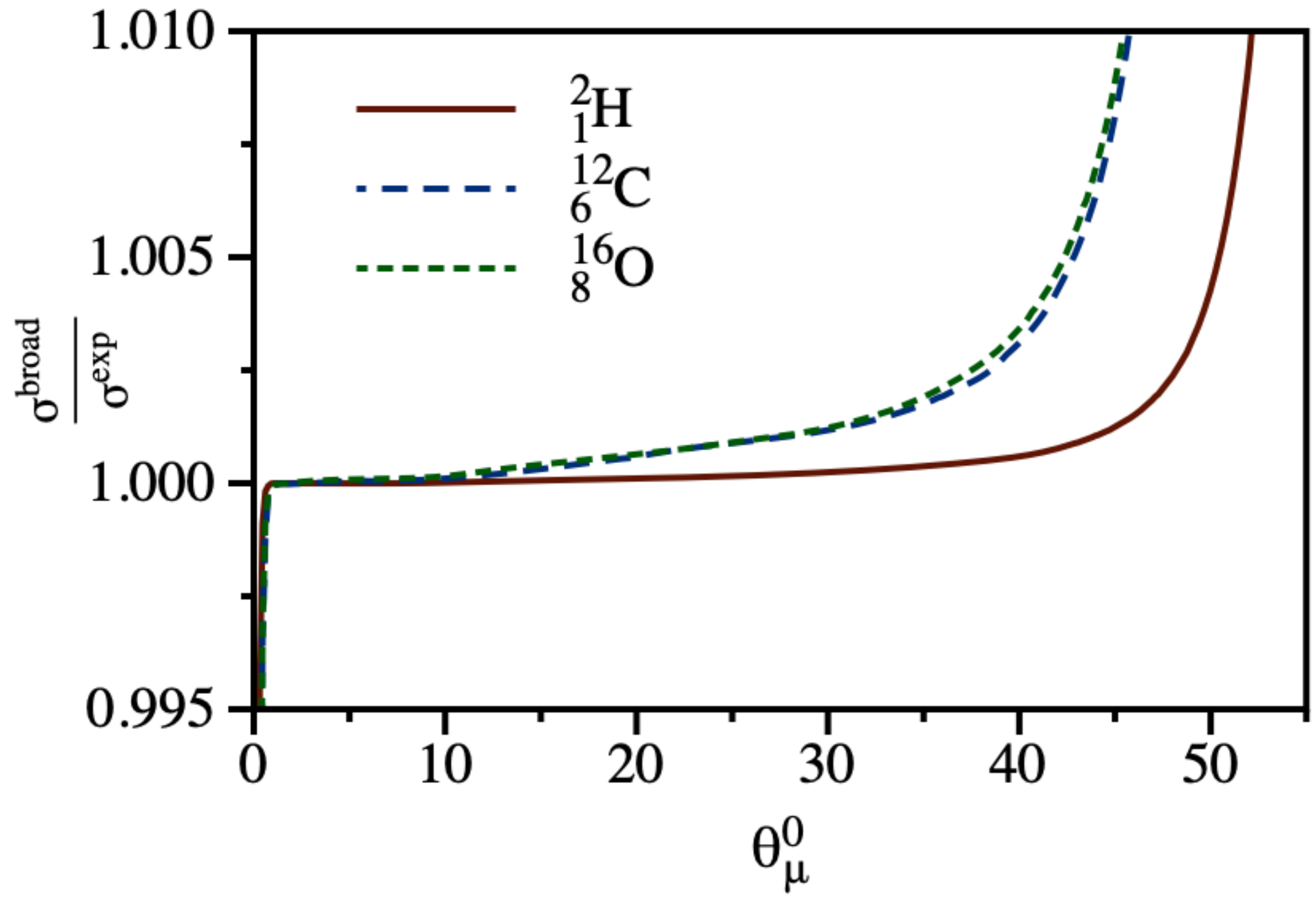


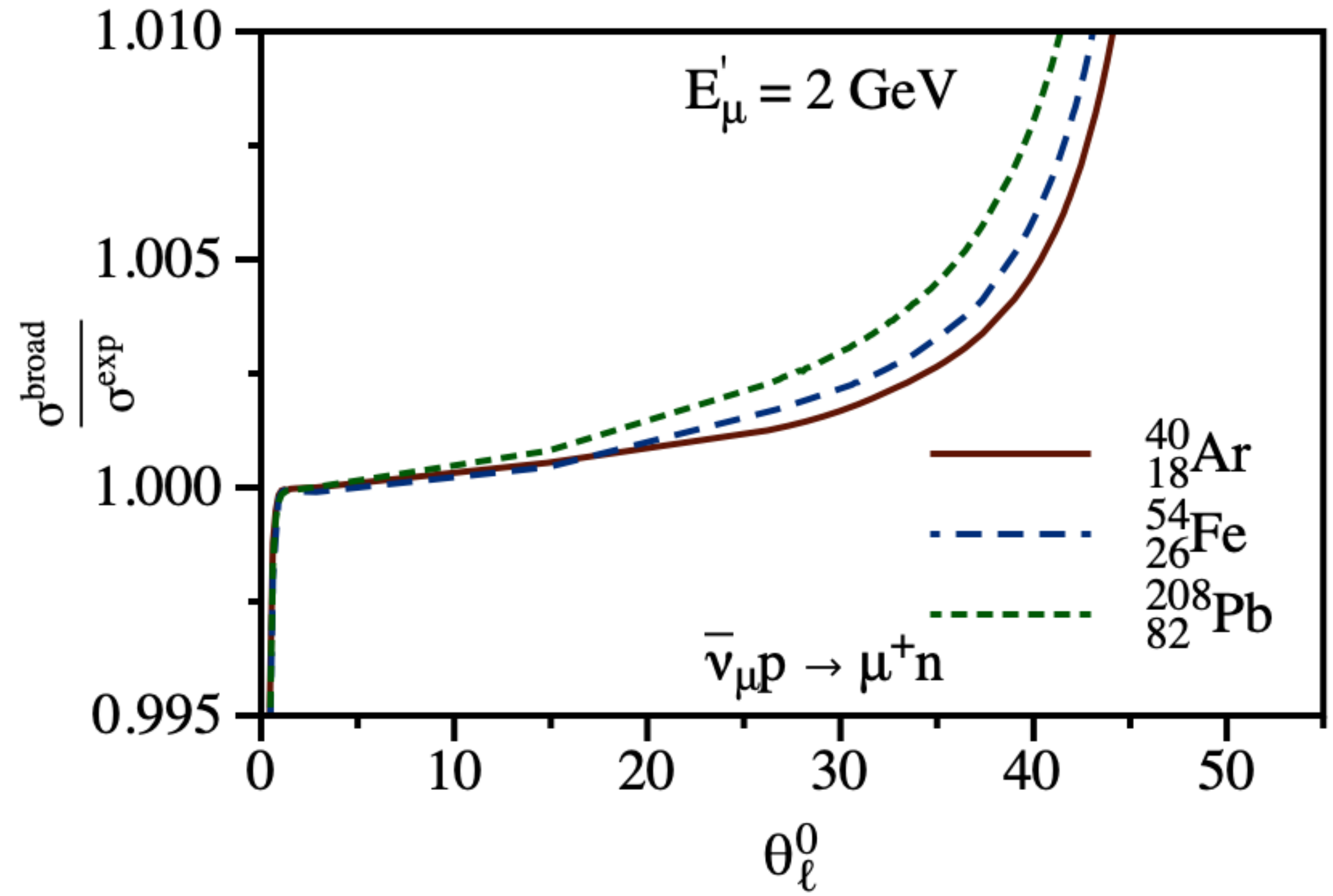
- nucleus approximated as sphere of constant density

- neutrino-nucleus: percent-level at kinematic endpoints

Effect on unpolarized cross section

- only final re-scattering present

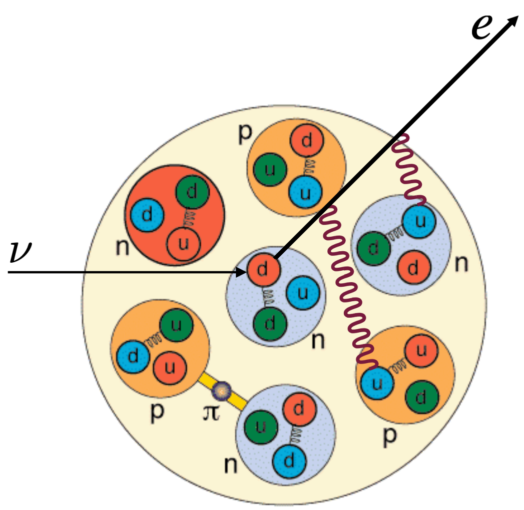




- nucleus approximated as sphere of constant density

- antineutrino-nucleus: percent-level at kinematic endpoints

Conclusions



QED nuclear medium effects

- permille-level distortion in neutrino-nucleus and percent-level corrections in electron-nucleus scattering

- $SCET_G$ works perfectly at GeV energies

- sizable deflection of charged lepton tracks

- multiple rescattering: percent-level corrections at GeV energies

Thanks for your attention !!!