

# NUSTEC Workshop on Electron Scattering

28 March, 2022

## Radiative corrections



Oleksandr Tomalak

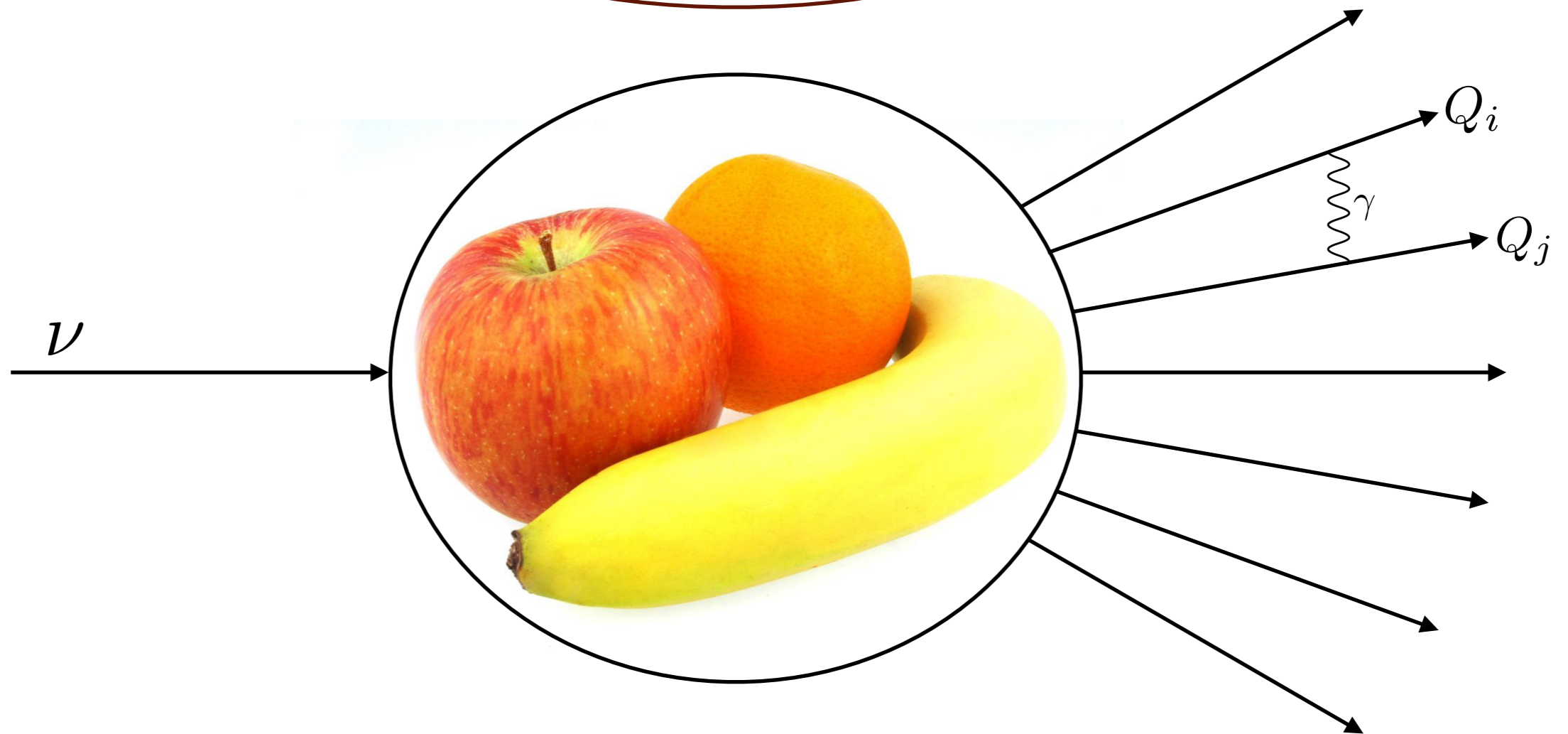
LA-UR-22-22434

# Outline

- 1) microscopic EFT for neutrino physics
- 2) coherent elastic **neutrino-nucleus** scattering (CE $\nu$ NS)
- 3) neutrinos from decays of muons and light mesons
- 4) charged-current scattering on **nucleons**
- 5) QED nuclear medium effects

# QED corrections

$$m_e \ll m_\mu \ll E_\nu$$

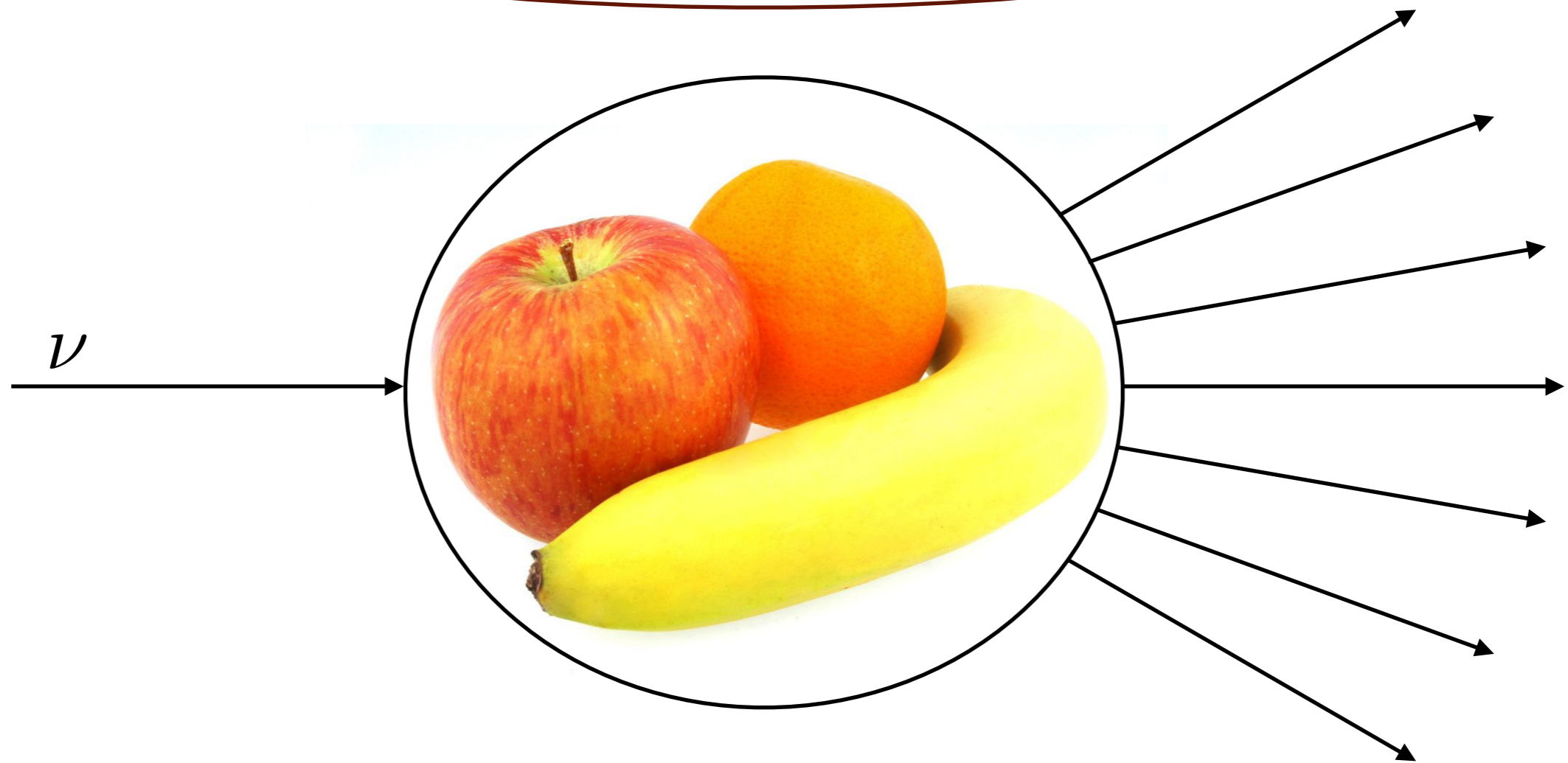


$$\frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by } \ln \frac{E_\nu}{m_e} \sim 6 - 10 \text{ or } \ln^2 \frac{E_\nu}{m_e} \sim 36 - 100$$

- scale separation introduces large flavor-dependent QED logarithms

# Electroweak corrections

$$m_e, m_\mu, M, E_\nu \ll M_W, M_Z, m_t, m_H$$



$$\frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by } \frac{1}{\sin^2 \theta_W}, \ln \frac{M_Z}{M}, \ln \frac{M_t}{M}, \dots$$

- electroweak corrections can be included in low-energy interactions



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couplings of **effective Lagrangian** are precisely determined

$$\mathcal{L}_{\text{eff}}^{\text{NC}} = -\bar{\nu}_l \gamma_\mu P_L \nu_l \cdot \bar{f} \gamma^\mu (c_L^{\nu_l f} P_L + c_R^{\nu_l f} P_R) f$$

$$\mathcal{L}_{\text{eff}}^{\text{CC}} = -2\sqrt{2}G_F \sum_{l \neq l'} \bar{\nu}_{l'} \gamma^\mu P_L \nu_l \bar{l} \gamma_\mu P_L l' - c^{qq'} \sum_{q \neq q'} \bar{l} \gamma^\mu P_L \nu_l \bar{q} \gamma_\mu P_L q'$$

# Neutrino-lepton, neutrino-quark scattering

O.T. and Richard J Hill, Phys. Lett. B 805, 3, 135466 (2020)

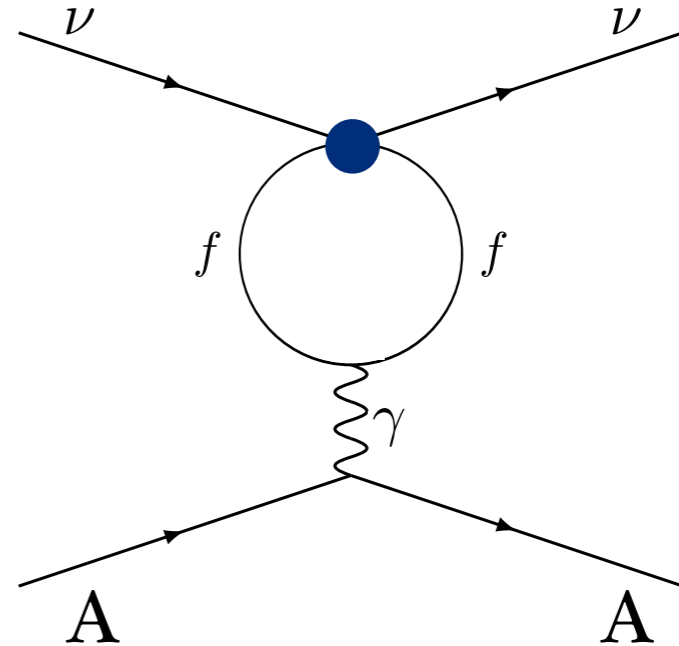
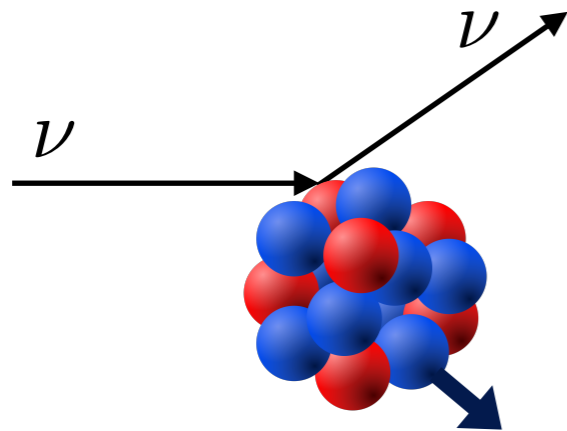
known at permille level



leading in  $G_F$  terms with loop expansion in  $\alpha, \alpha_s$  within Standard Model

poster at Neutrino 2020:

<https://youtu.be/mrW4aYjP57w>



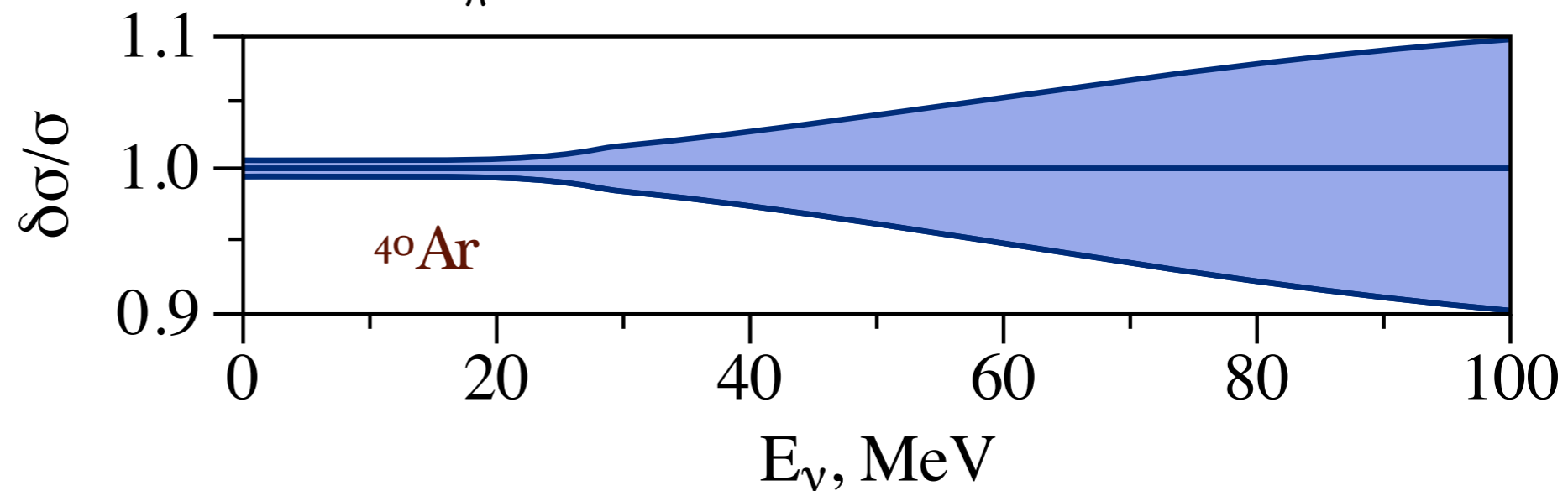
# Coherent elastic neutrino-nucleus scattering

O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

$$F_W(Q^2) \rightarrow F_W(Q^2) + \frac{\alpha}{\pi} [\delta^{\nu e} + \delta^{\text{QCD}}] F_{\text{ch}}(Q^2)$$

flavor-dependent  
at percent level

for Coherent and CCM

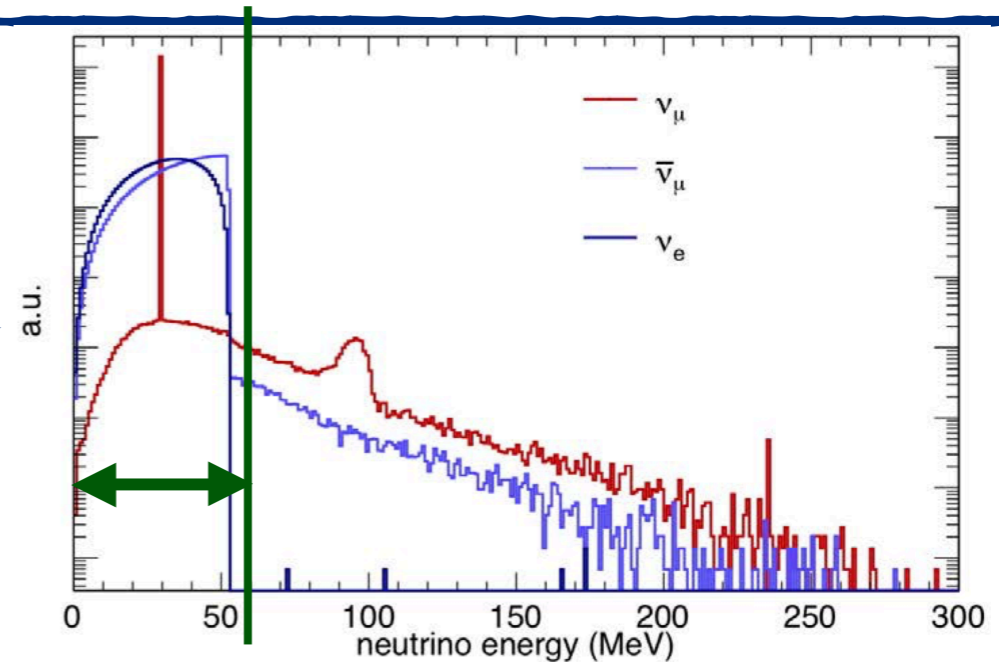


flavor-dependence at tree-level

energy spectra from  $\pi$ DAR  $\rightarrow$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



Akimov et al., Science 357 6356, 1123-1126 (2017)

# Neutrinos from muon, pion and kaon decays

O. T., arXiv: 2112.12395

$$\pi^+ \rightarrow \mu^+ \nu_\mu \gamma$$

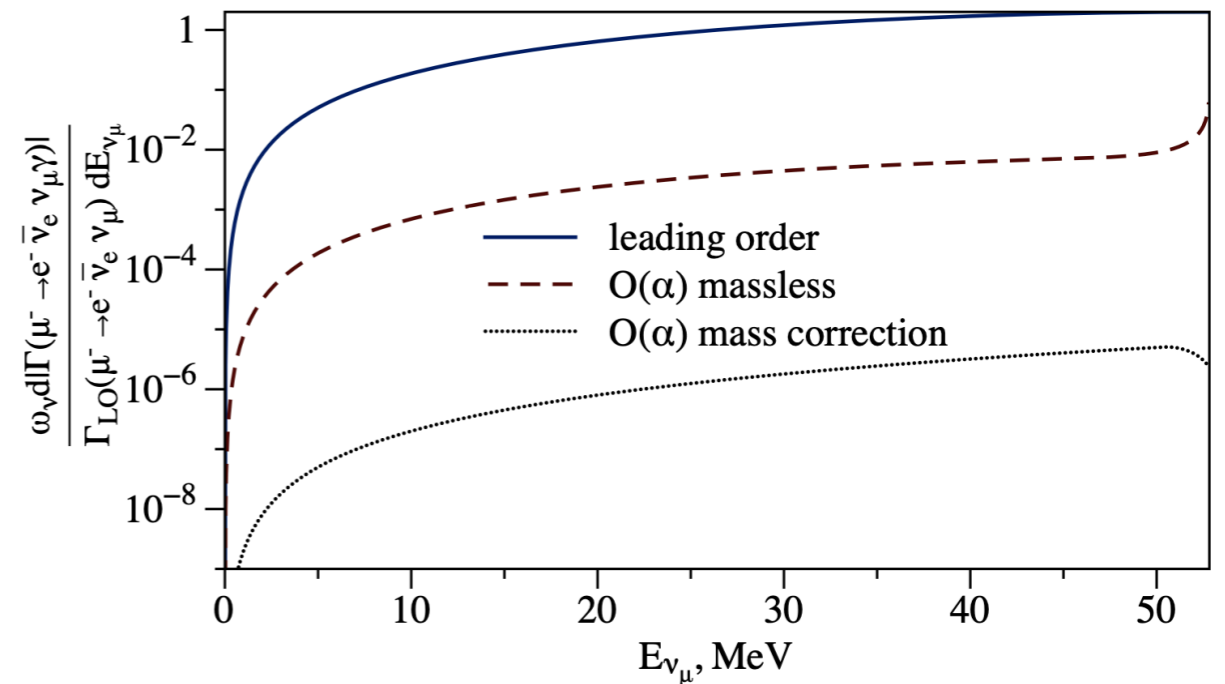
< 0.1 ‰

$$K^+ \rightarrow \mu^+ \nu_\mu \gamma$$

flavor-dependence is clarified to permille level analytically



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \gamma \quad 3-4 \text{ ‰}$$



first QED/EW form factors with different mass

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$$m_e \ll m_\mu \ll E_\nu$$

# Radiative corrections in CCQE on free nucleons

O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland (arXiv: 2105.07939)

O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland, Clarence Wret (arXiv: to appear)

# Factorization approach

- cross section is given by factorization formula

$$d\sigma \sim S \left( \frac{\Delta E}{\mu} \right) J \left( \frac{m_\ell}{\mu} \right) H \left( \frac{M}{\mu} \right)$$

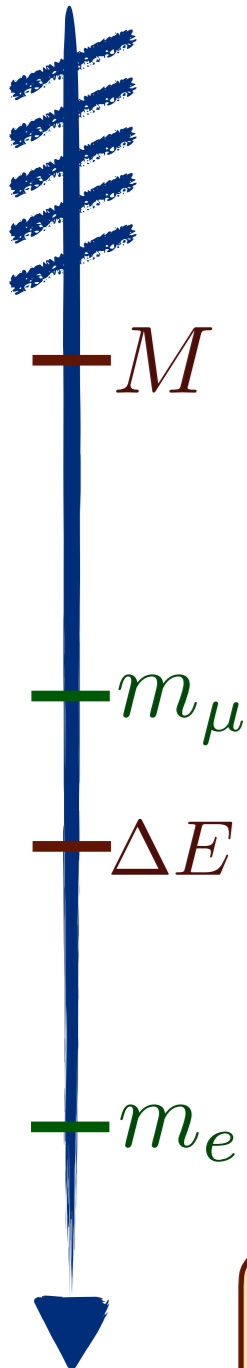
- determine hard function at hard scale by matching experiment or model to the theory with heavy nucleon

- RGE evolution of the hard function to scales  $\Delta E, m_\ell$

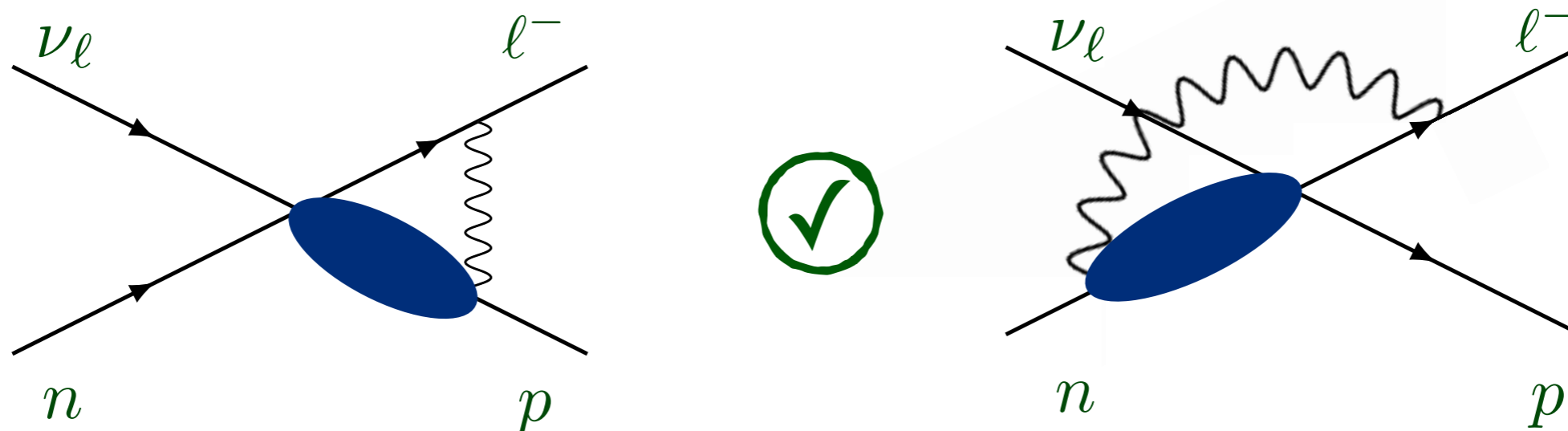
- soft and collinear functions are evaluated perturbatively

- calculate cross section at low energies accounting for **all large logs**  
ep scattering with soft radiation only: Hill (2016)

- soft and collinear functions obtained **analytically**
- **hard** function describes physics at GeV energies



factorization for radiative corrections with model for hard function

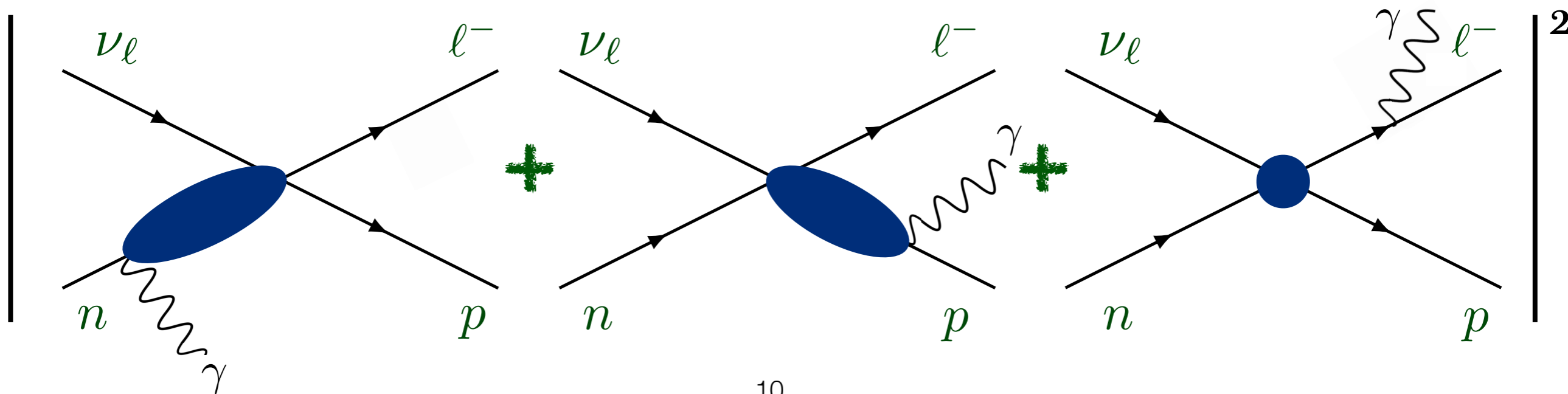


# Charged-current elastic scattering on nucleons

O. T., Qing Chen, Richard J. Hill and Kevin S. McFarland, arXiv: 2105.07939

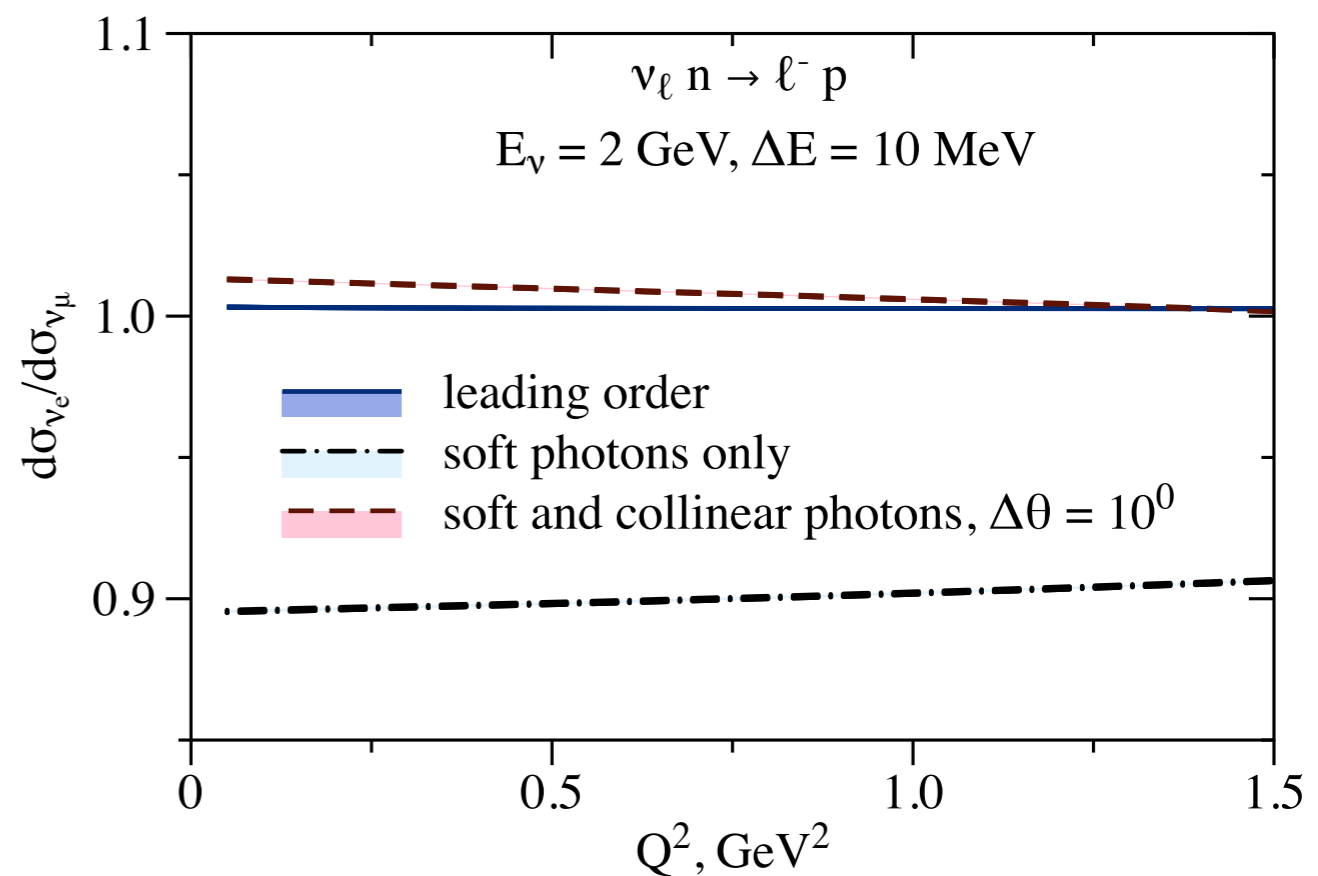
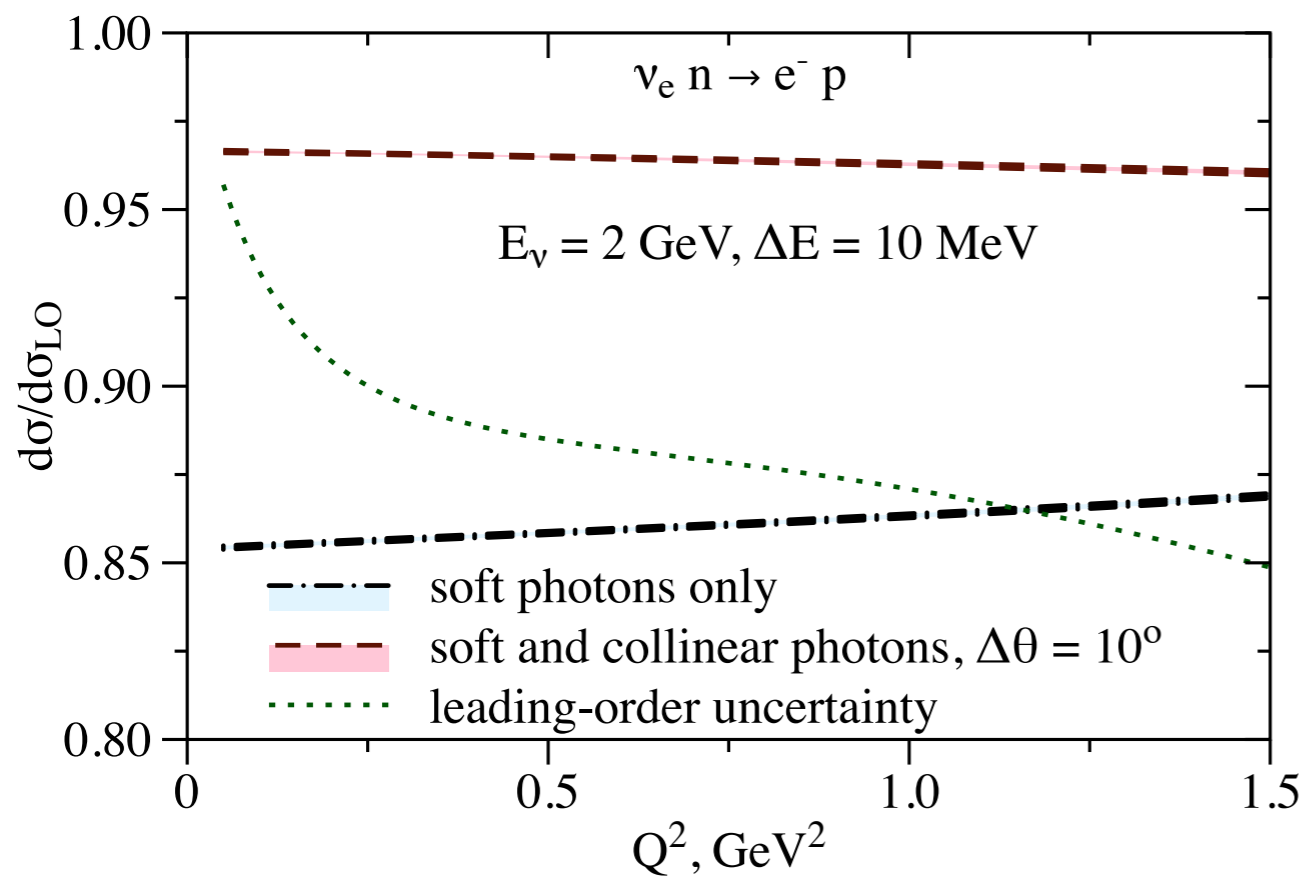
precise predictions for flavor ratios and radiative corrections

in exclusive and inclusive observables with GeV neutrino beams



# Exclusive observables

- cancellation of uncertainties from hard function for  $e/\mu$  and ratio to LO



- predict  $\sigma_{\nu_e}$  from  $\sigma_{\nu_\mu}$  measurements with neutrino beam



factorization for radiative corrections with model for hard function

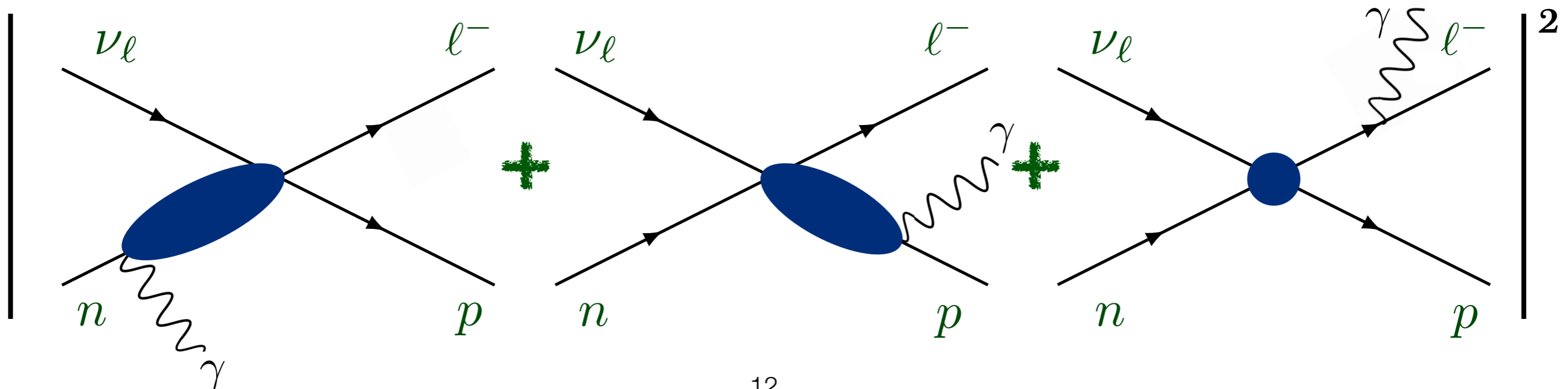


# Charged-current elastic scattering on nucleons

O. T., Qing Chen, Richard J. Hill and Kevin S. McFarland, arXiv: 2105.07939

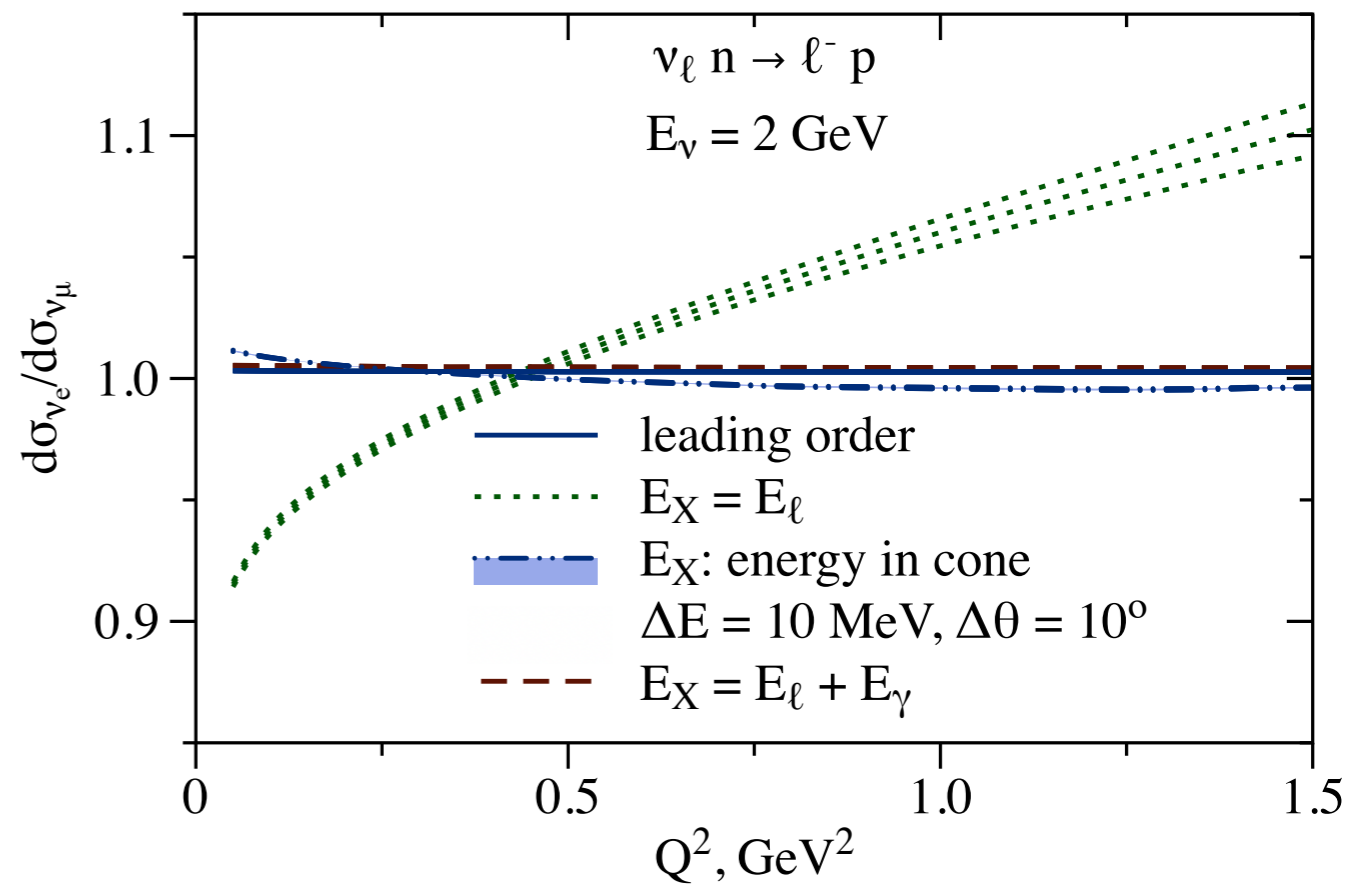
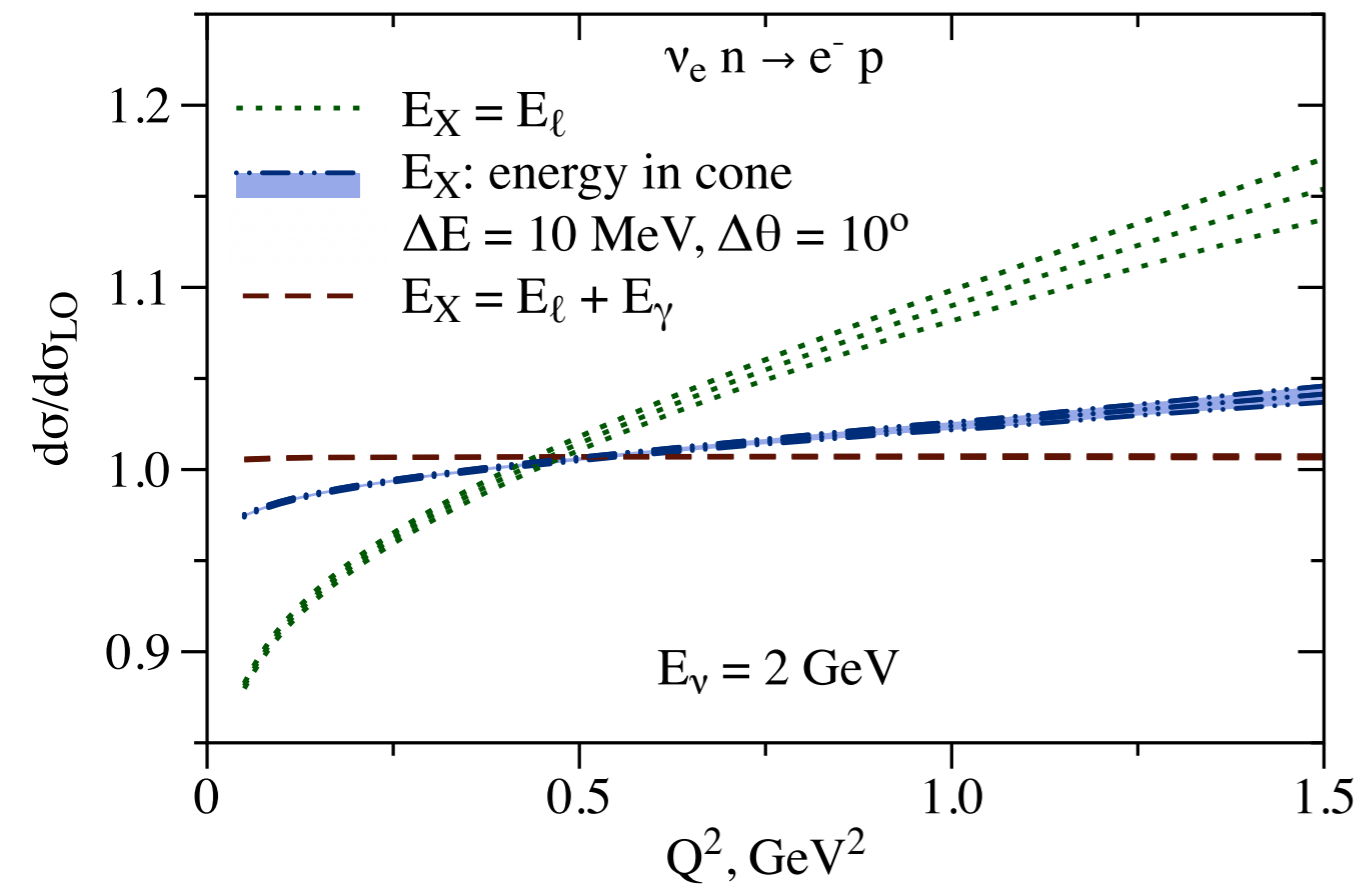
precise predictions for flavor ratios and radiative corrections

in exclusive and inclusive observables with GeV neutrino beams



# Inclusive observables

- kinematics  $Q^2 = 2M(E_\nu - E_X)$  is reconstructed with 3 different  $E_X$



- dependence on reconstruction of kinematics and cuts
- predict  $\sigma_{\nu_e}$  from  $\sigma_{\nu_\mu}$  measurements with neutrino beam

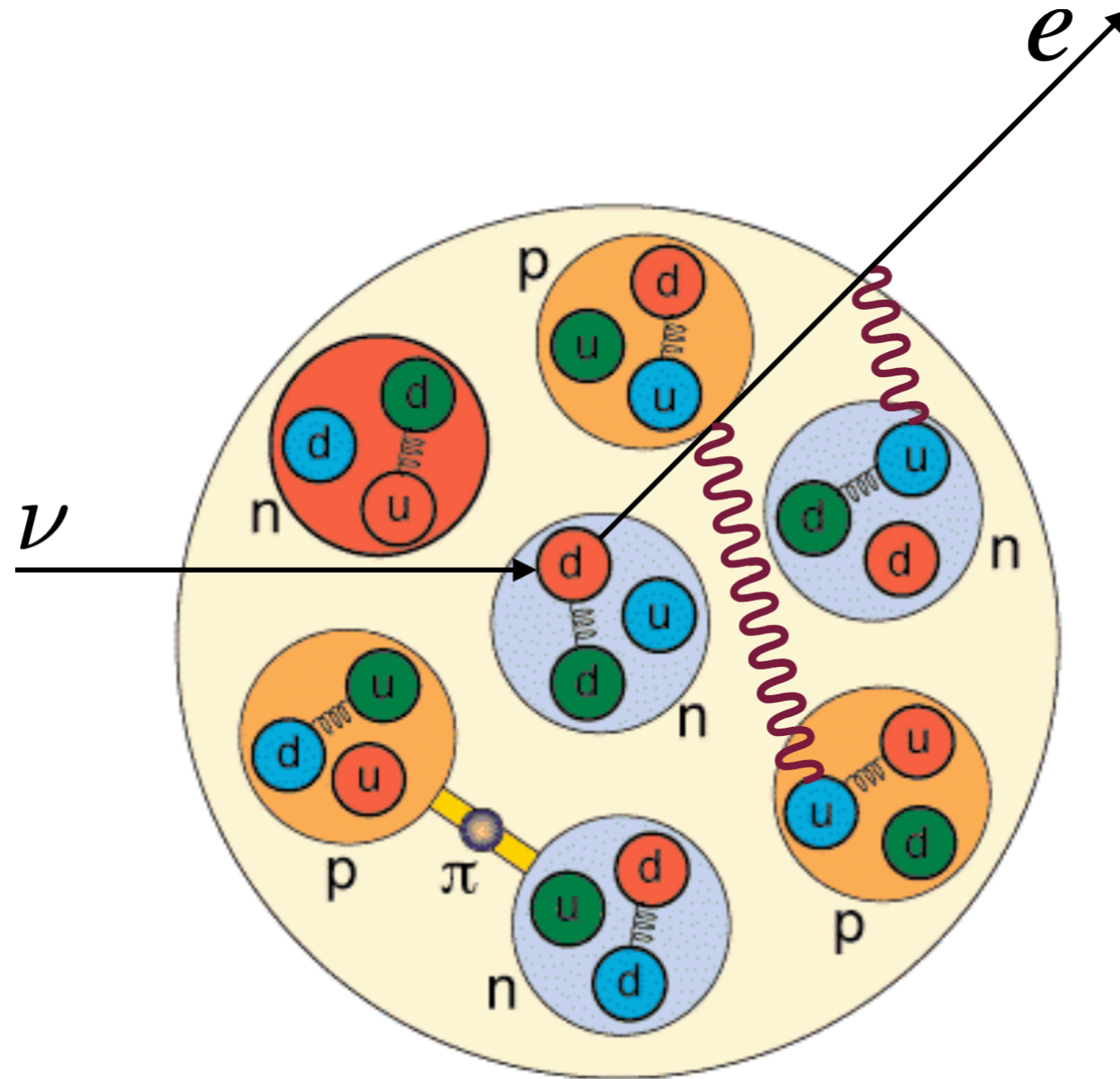


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# QED nuclear medium effects in neutrino-nucleus and electron-nucleus scattering

O.T., Ivan Vitev (arXiv: to appear)

# Medium effects

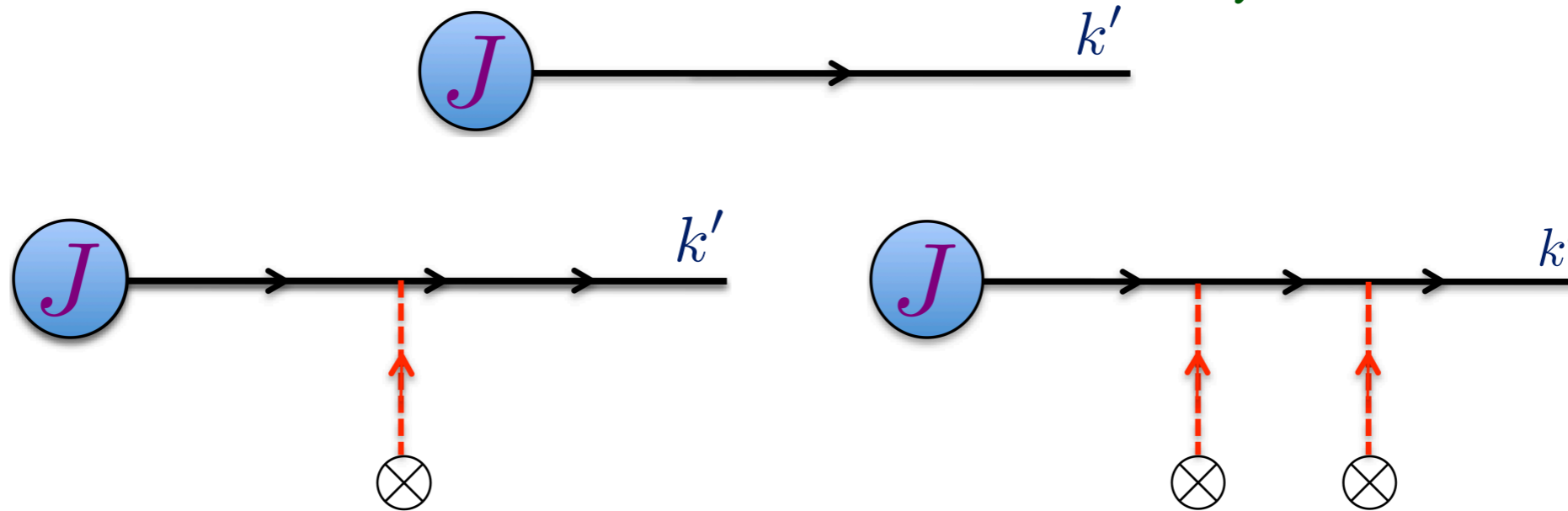


- charged lepton exchanges photons with nuclear medium

# SCET<sub>G</sub> formulation

- forward scattering is dominant process
- Glauber photons are exchanged with a nucleus

QCD: G. Ovanesyanyan, I. Vitev, JHEP (2011)



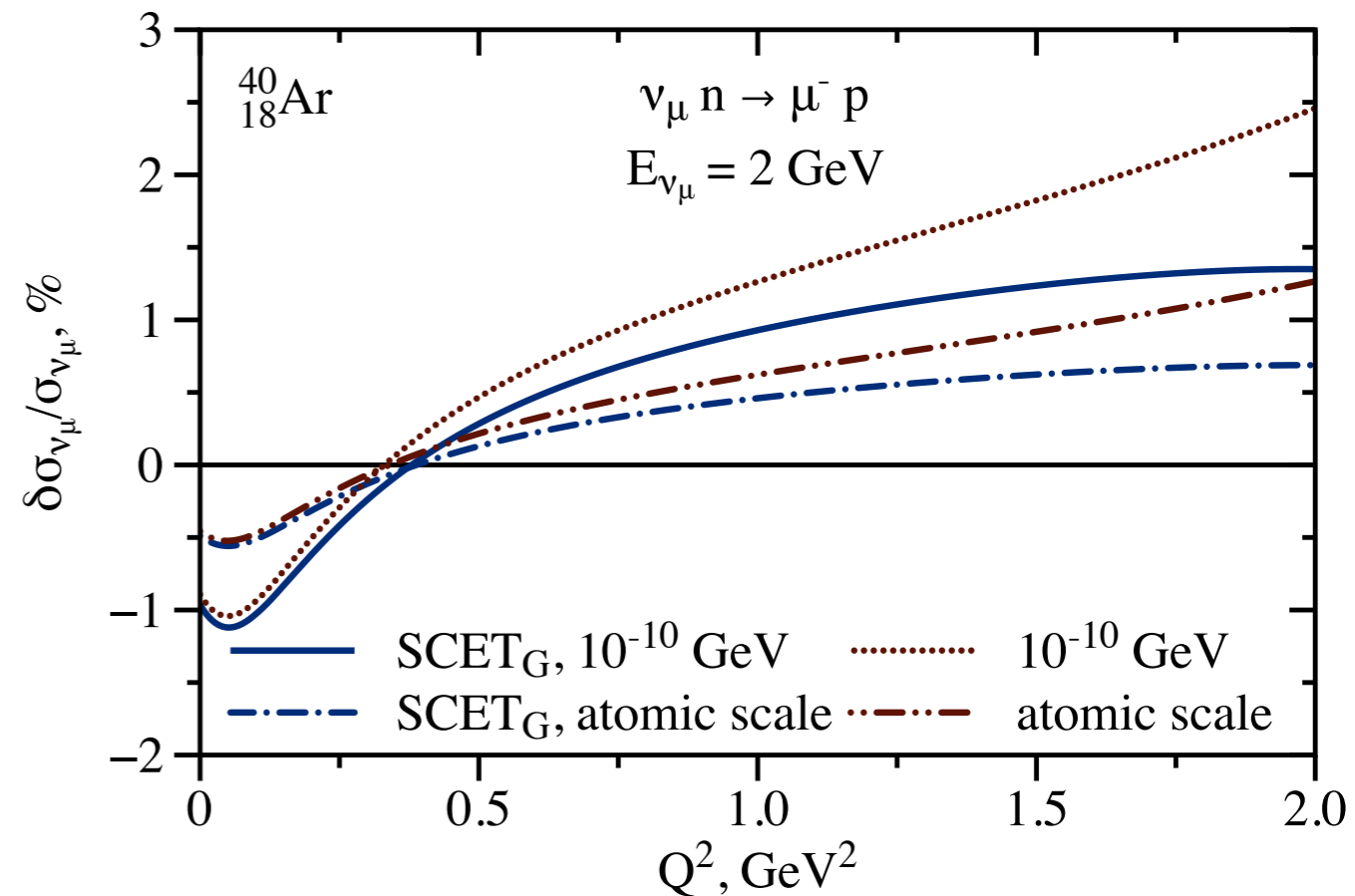
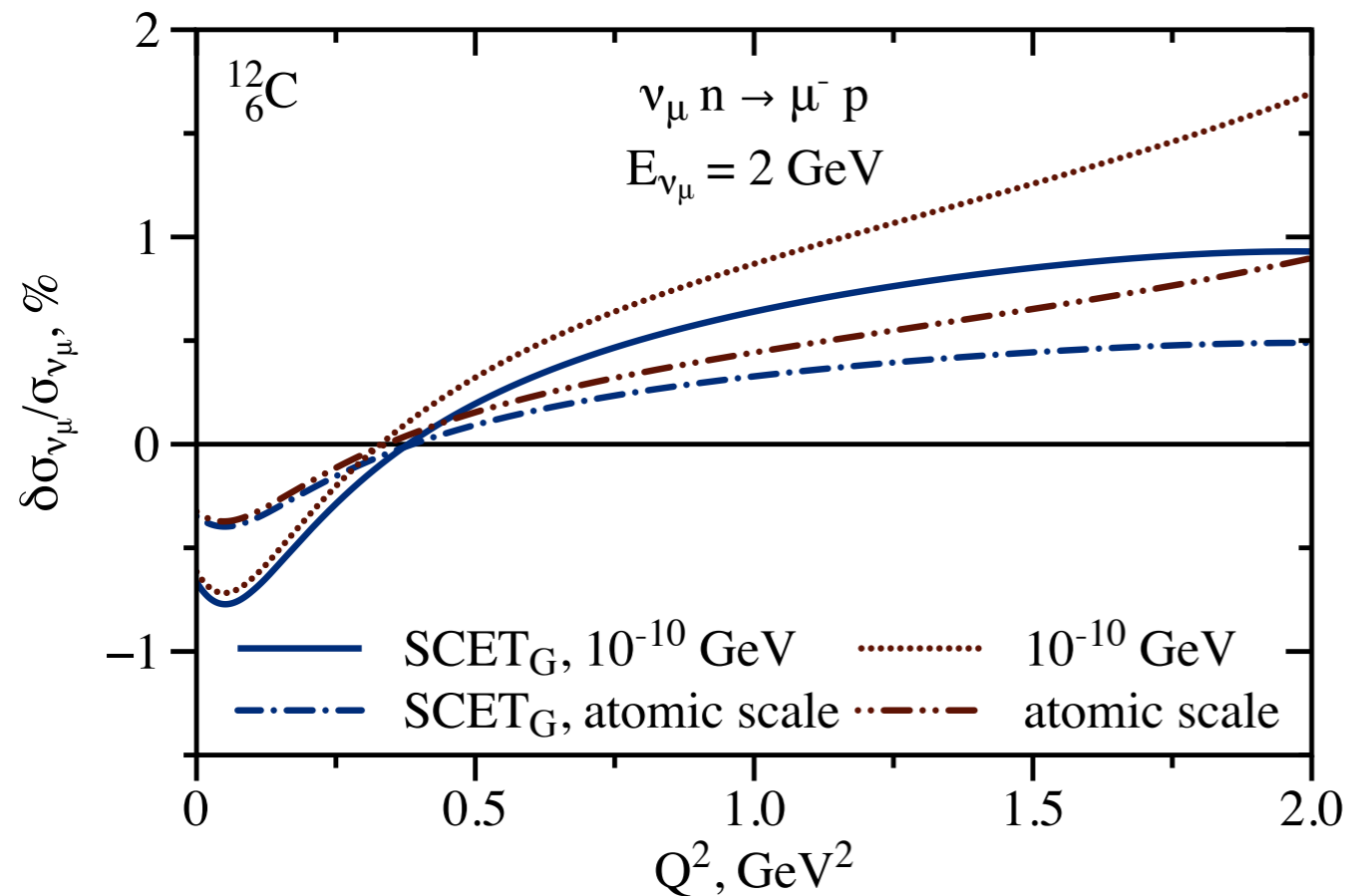
- approximation of **collinear charged lepton**

$$q_\gamma \sim (\lambda, \lambda, \sqrt{\lambda}) \quad k' \sim (\lambda, 1, \sqrt{\lambda})$$

- leading-order cross sections are modified
- EFT treatment developed, questioning with full QED

# Neutrino scattering

- relative correction per nucleon

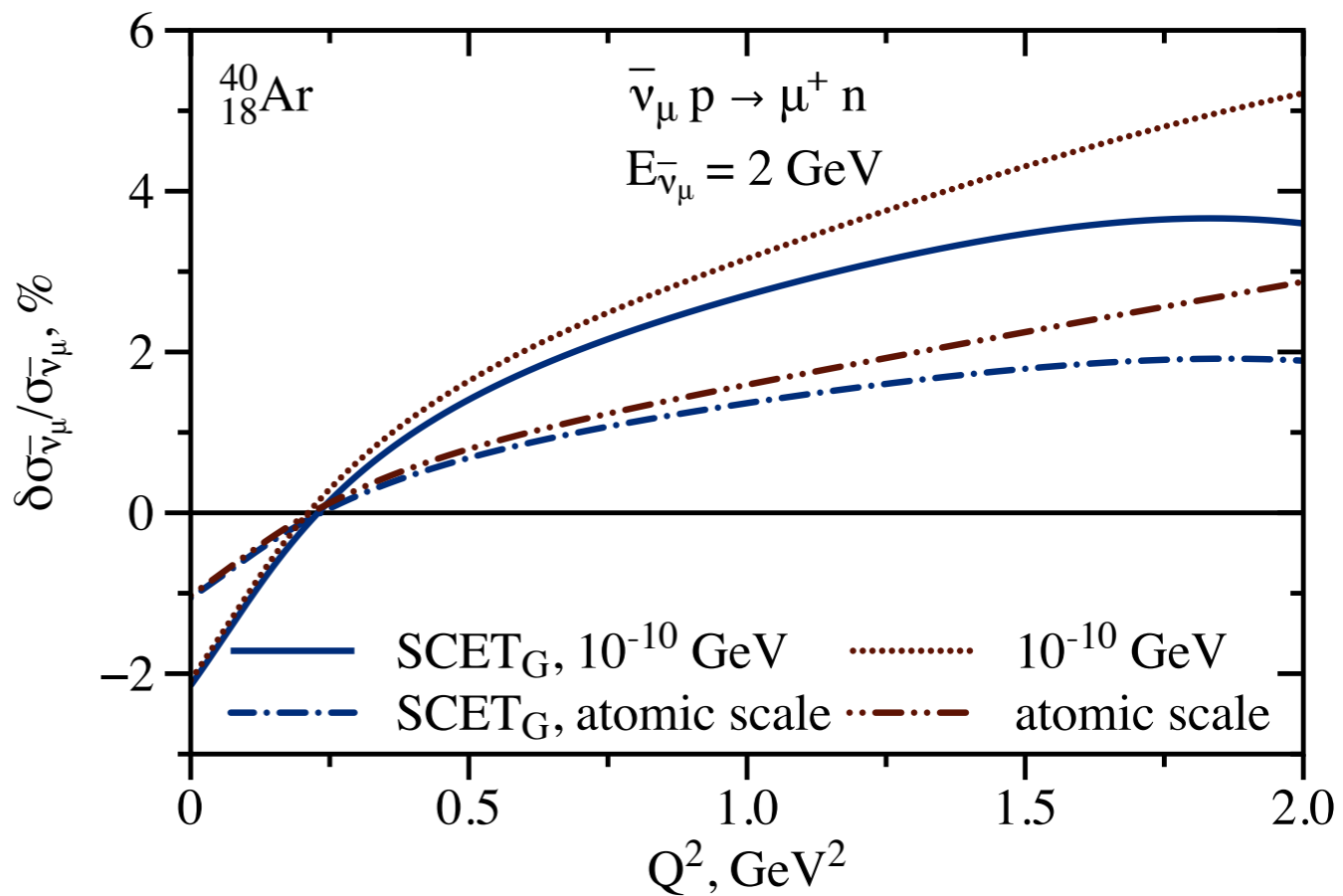
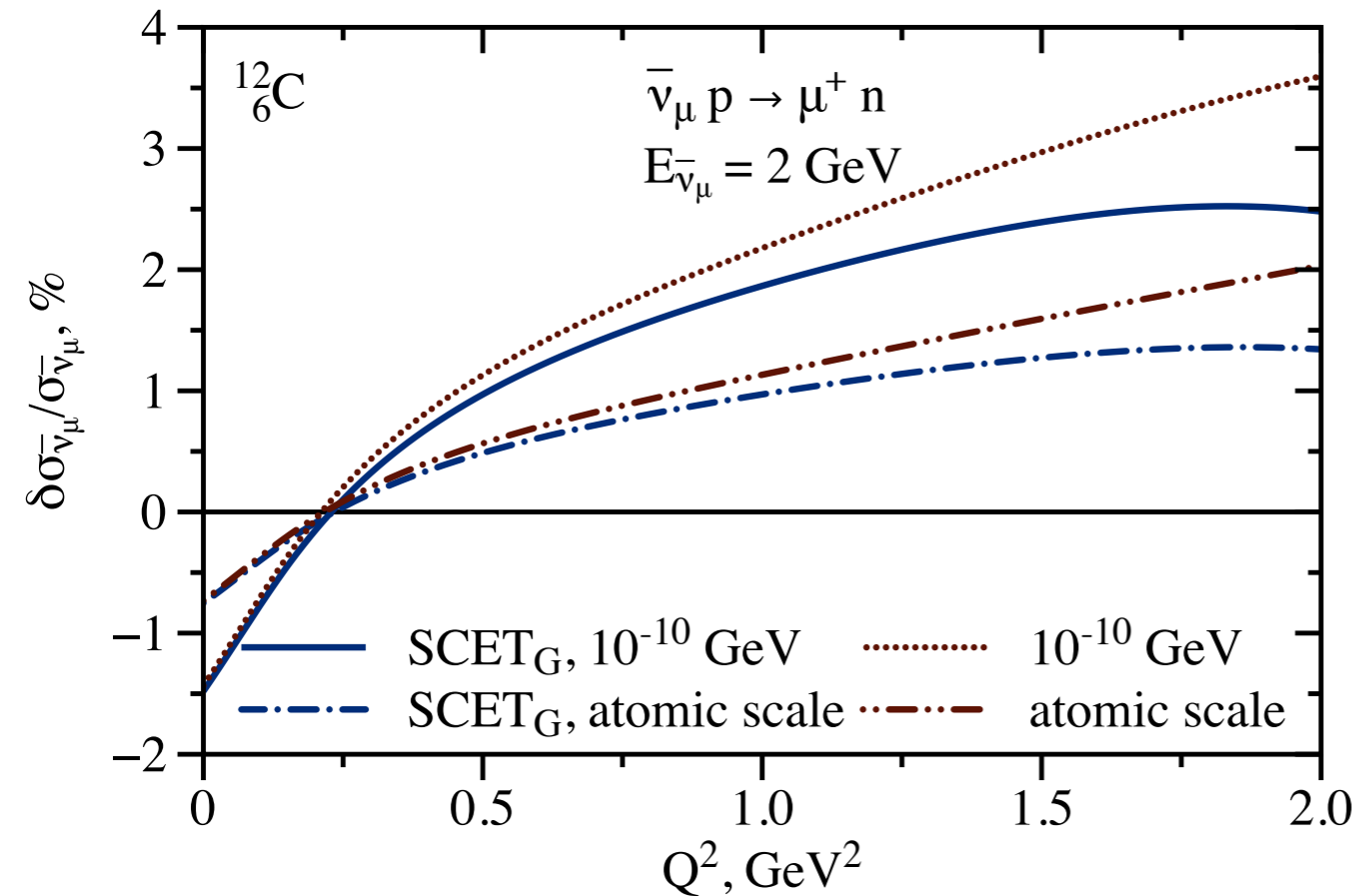


preliminary

- percent-level distortion of cross sections
- smaller correction to inclusive cross section

# Antineutrino scattering

- relative correction per nucleon



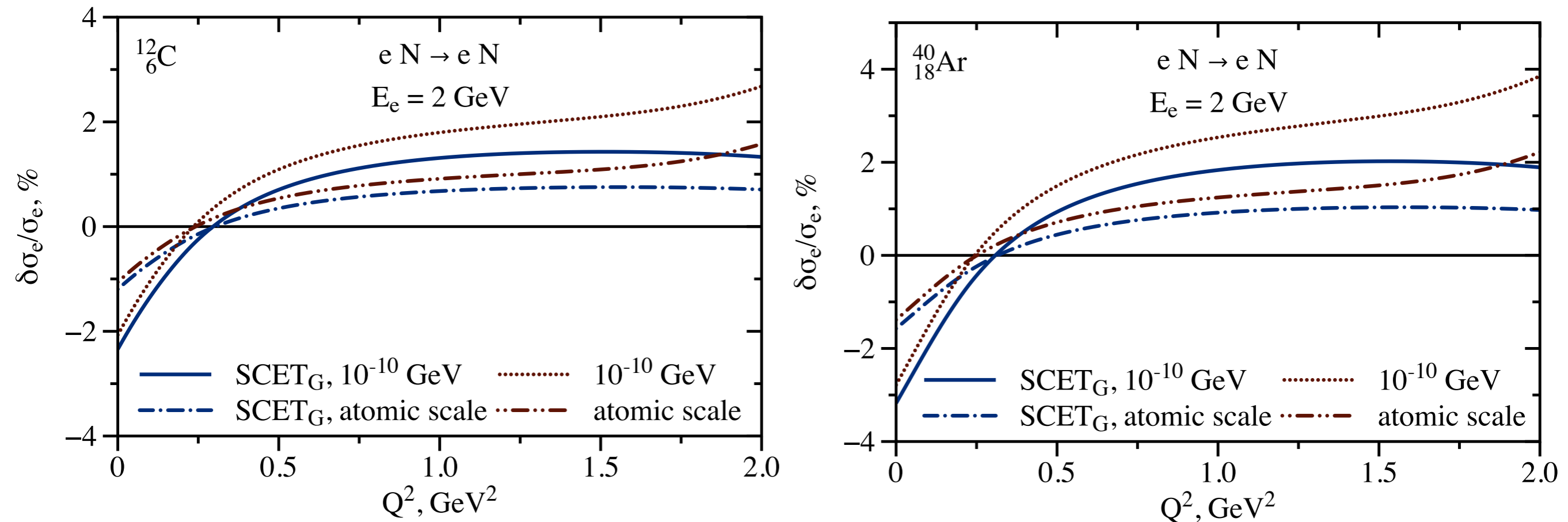
preliminary

- percent-level distortion of cross sections
- larger correction than for neutrino scattering



# Electron scattering

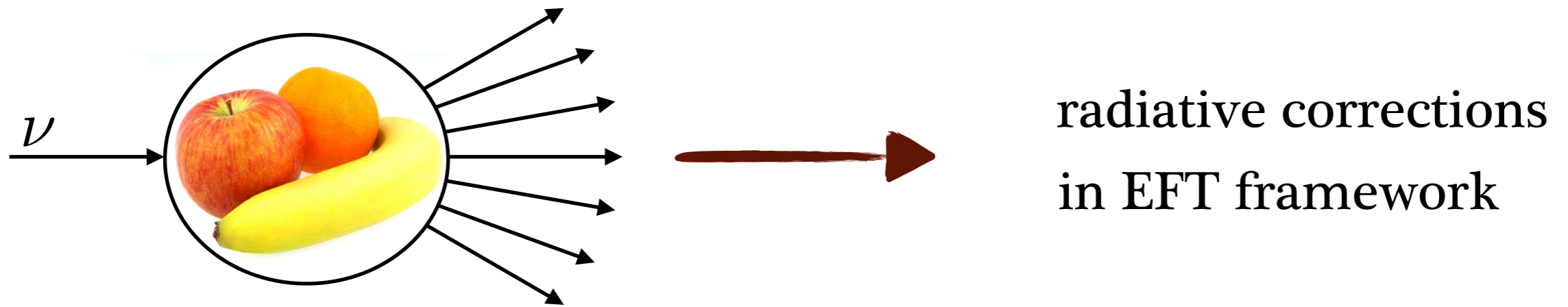
- relative correction per nucleus after incoherent sum over nucleons



preliminary

- percent-level distortion of cross sections
- critical new effect for electron scattering experiments

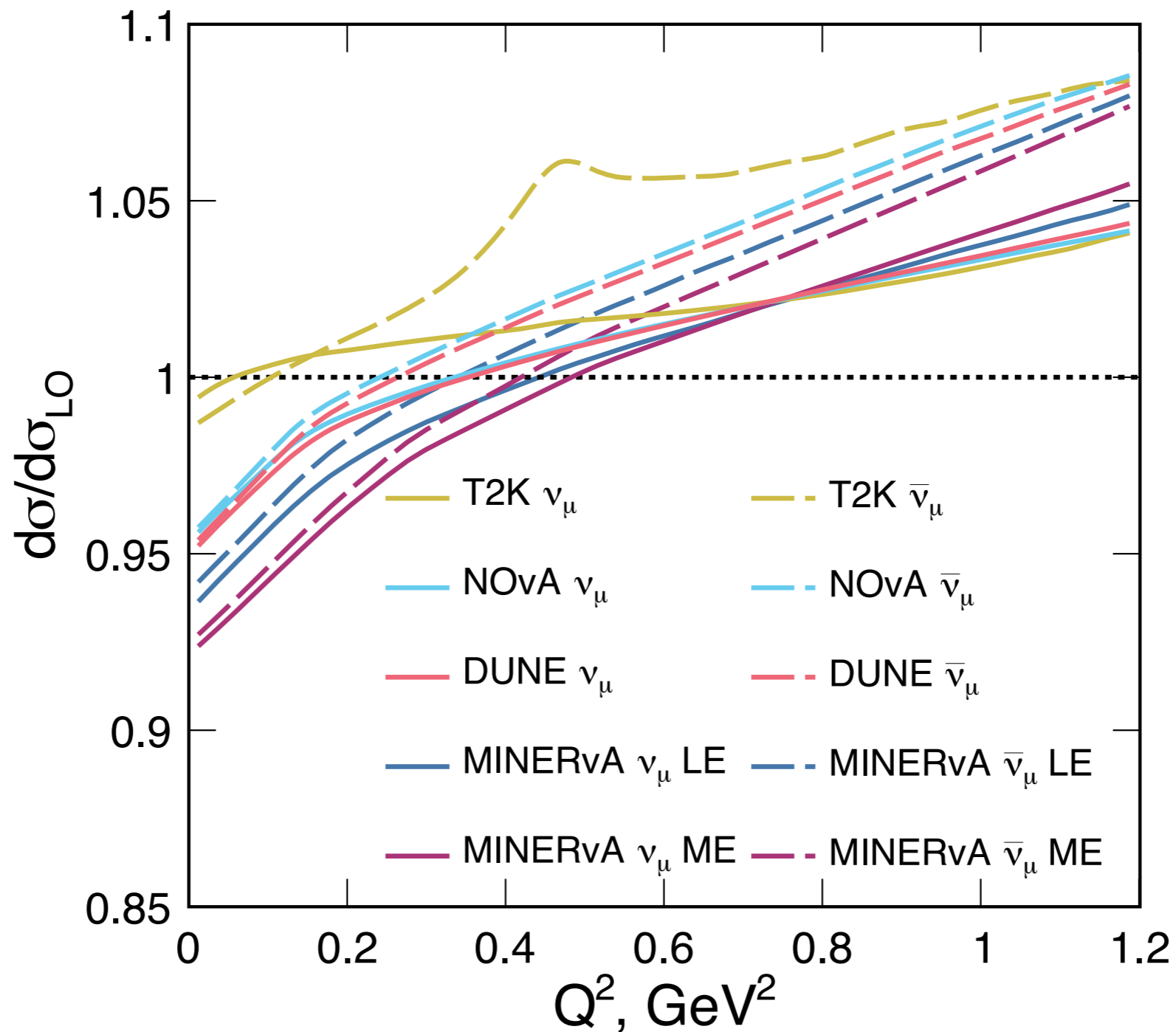
# Conclusions



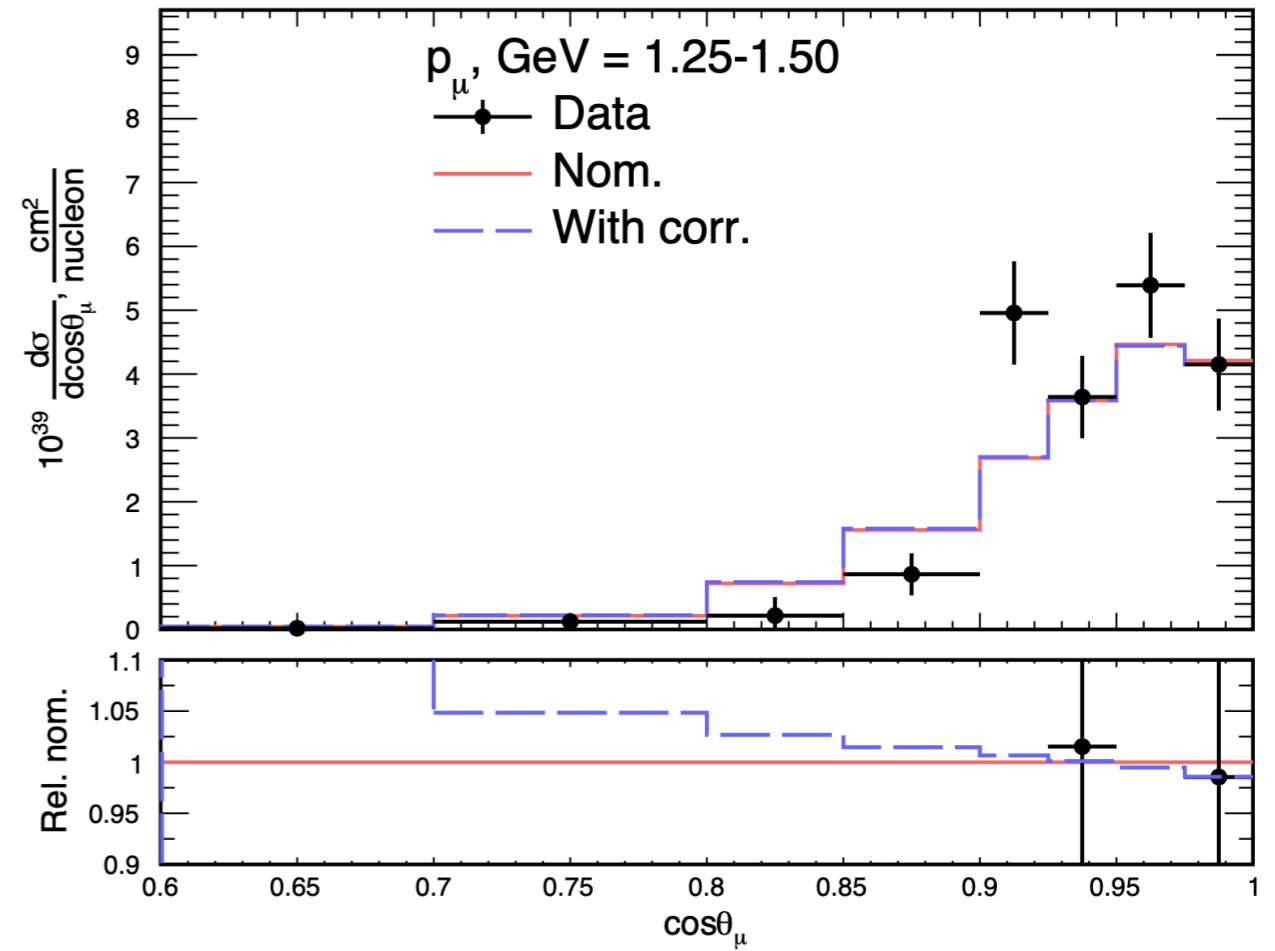
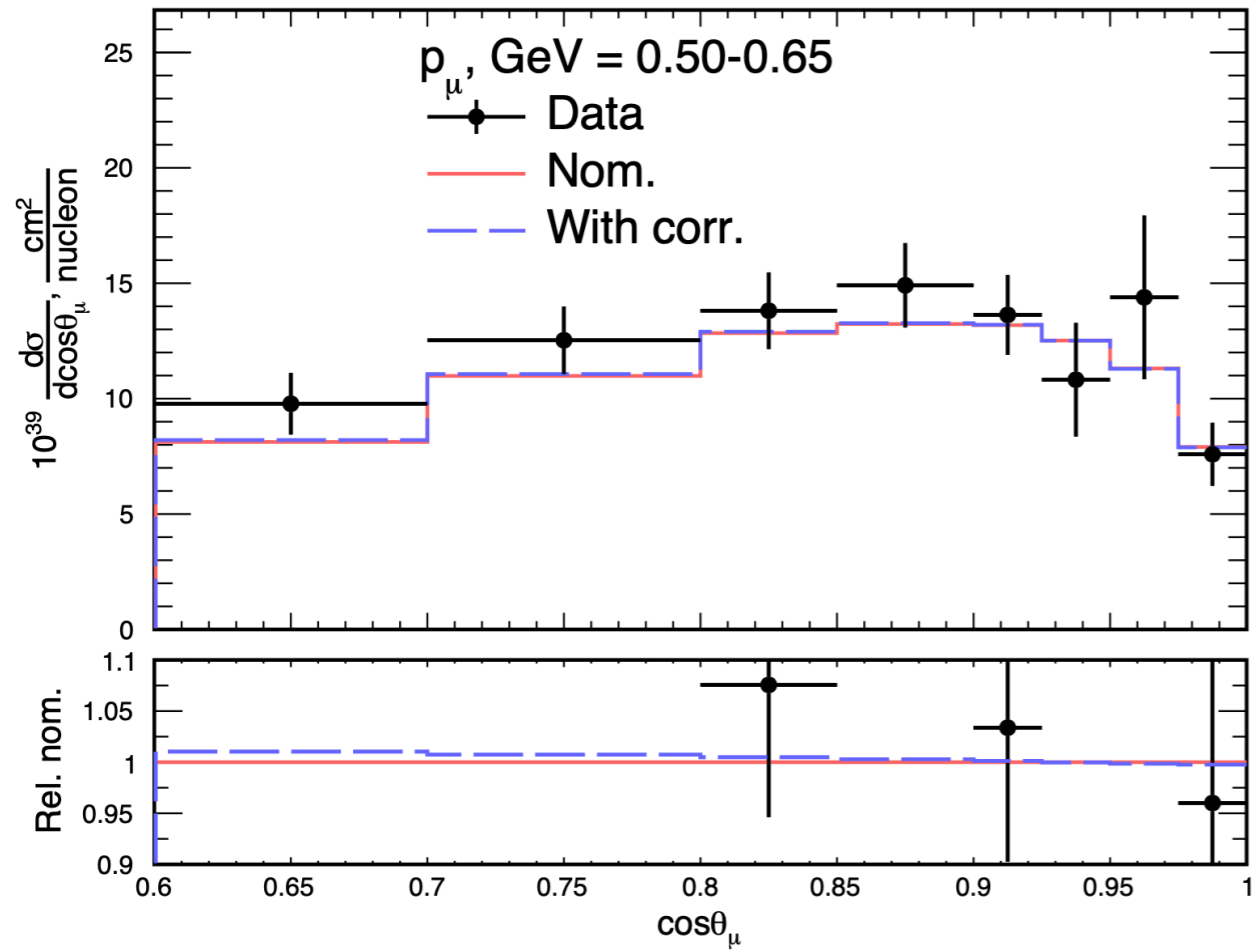
- radiative corrections for precise flux determinations
- charged-current elastic muon vs electron cross-section ratios evaluated from theory with sub percent uncertainty
- percent-level QED nuclear medium effects with EFT treatment

Thanks for your attention !!!

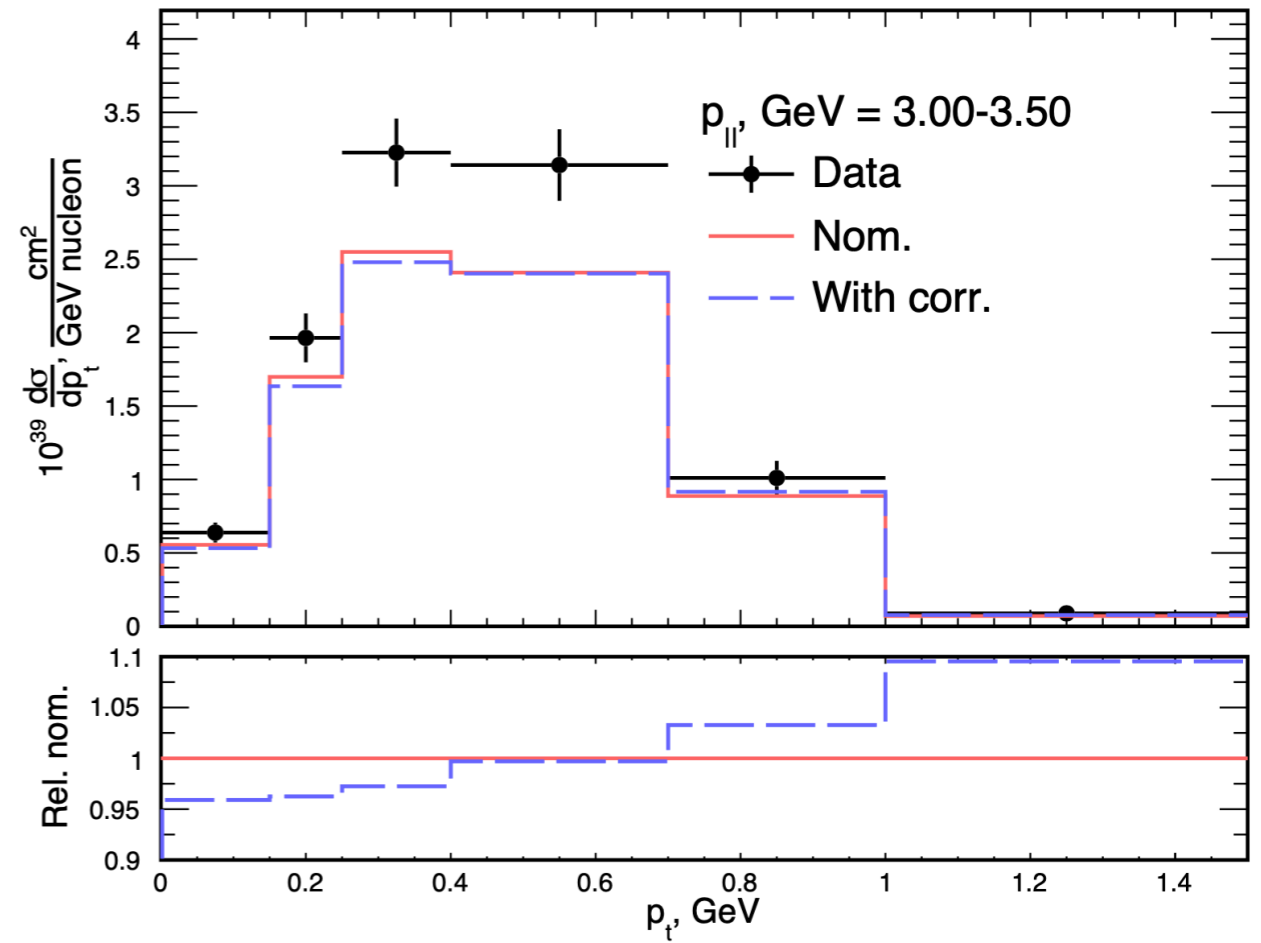
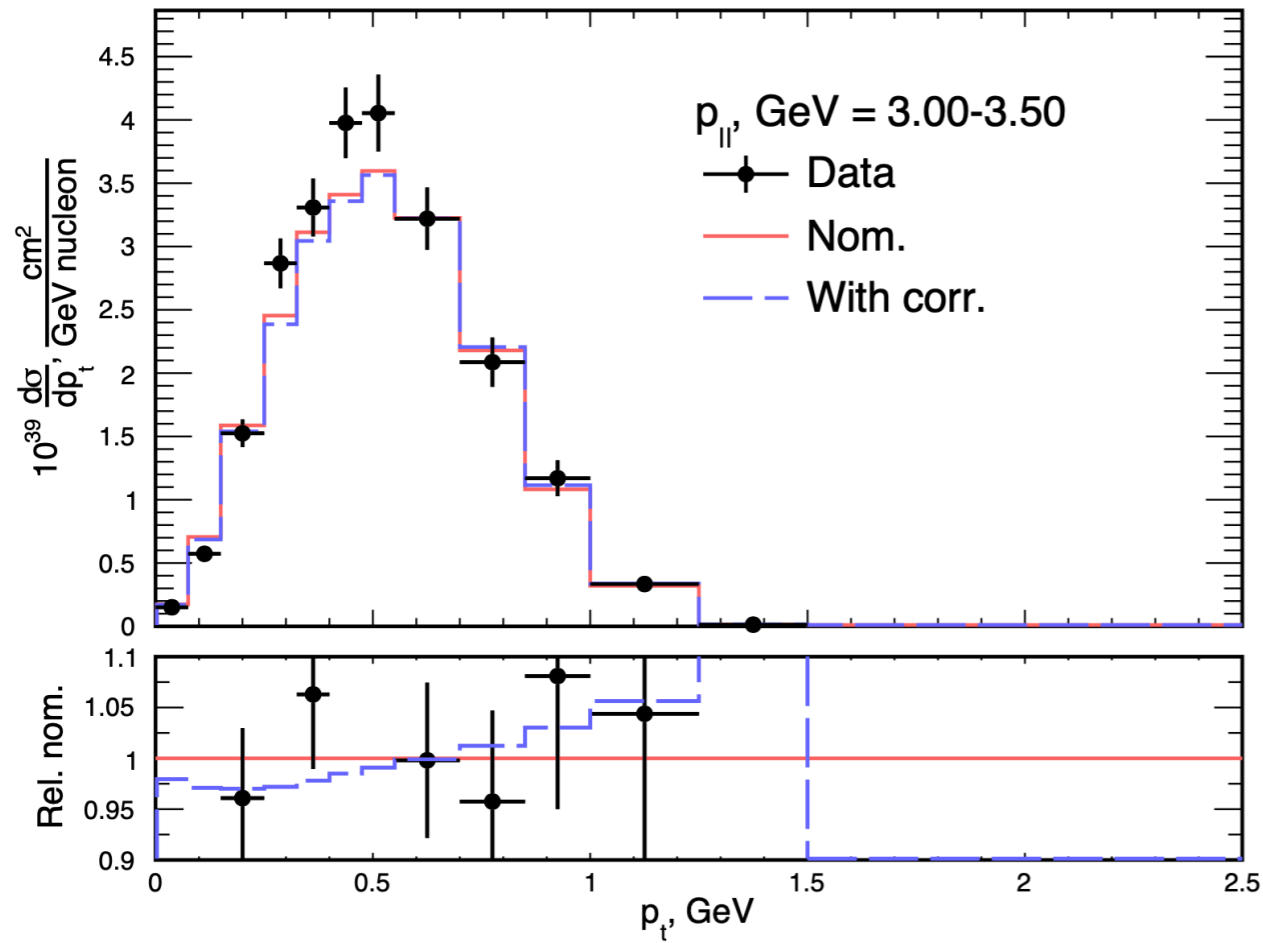
# Integrated over flux lepton energy spectra



# T2K ND280 data



# MINERvA LE data



# MINERvA ME data

