SCET Workshop

2022

22 April, 2022

Radiative corrections to charged-current neutrino scattering at GeV energies

Los Alamos NATIONAL LABORATORY

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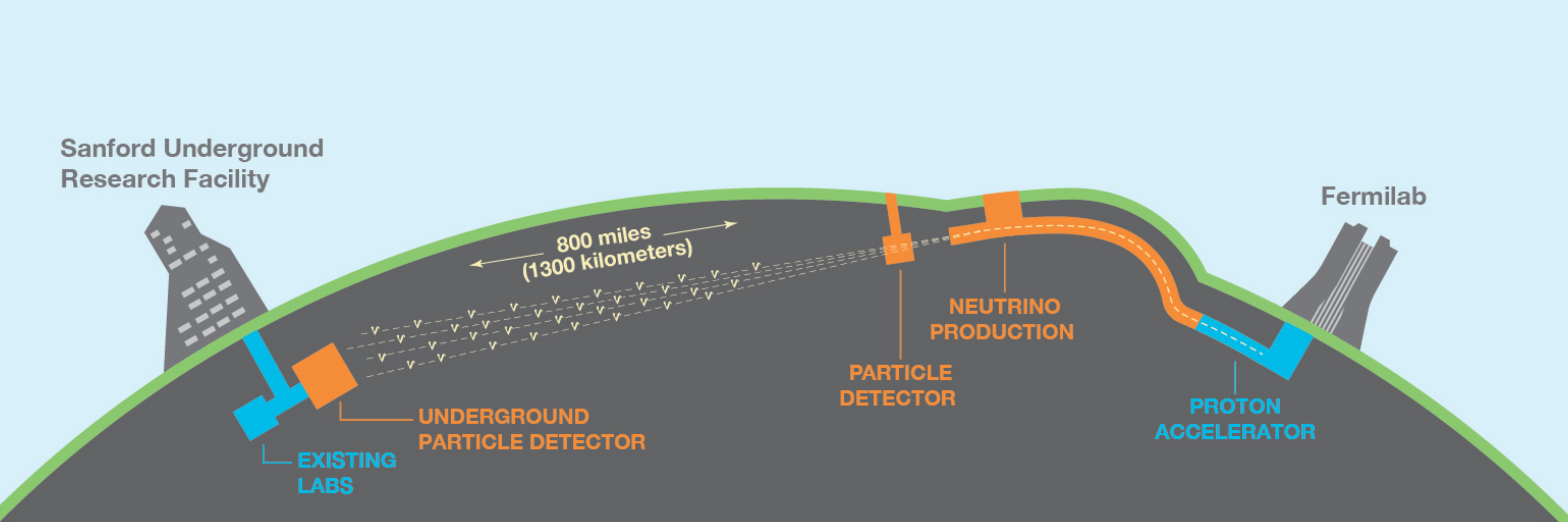
LA-UR-22-23396

Neutrino experiments

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

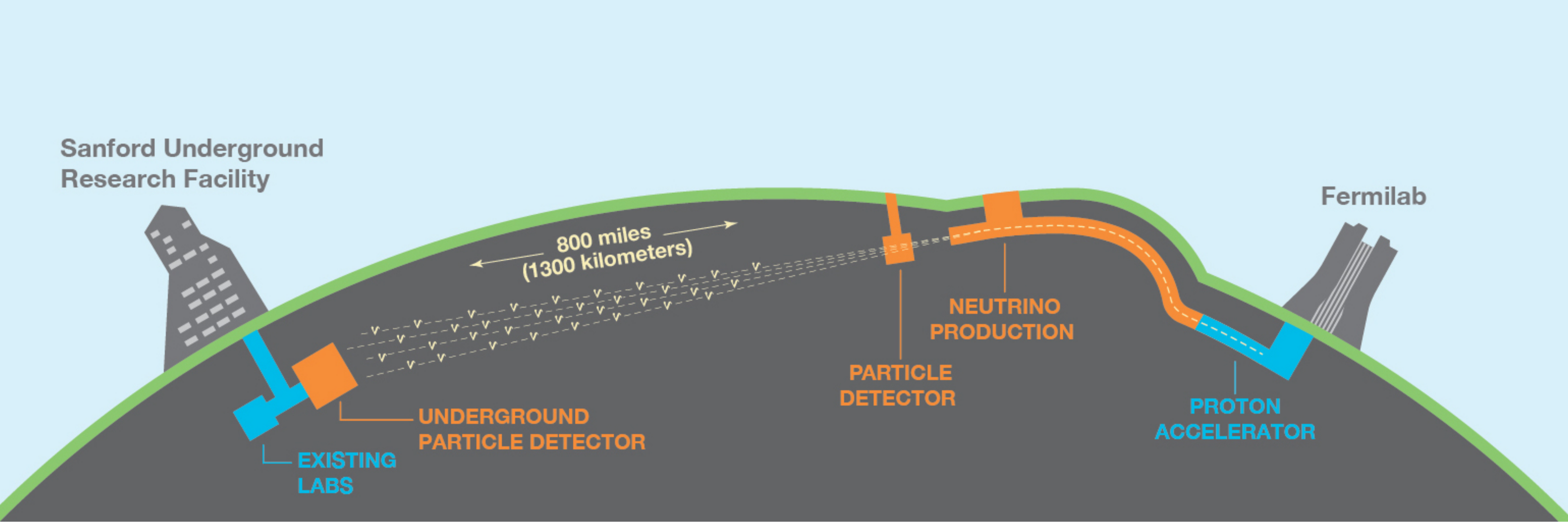


- origin of matter-antimatter asymmetry — δ_{CP}
- mass hierarchy and oscillation parameters — PMNS matrix, Δm_{31}^2
- Grand Unified Theories — proton decay
- dynamics of supernova explosion — wait for one;)

 DUNE, CDR (2016), TDR (2020)

Neutrino experiments

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



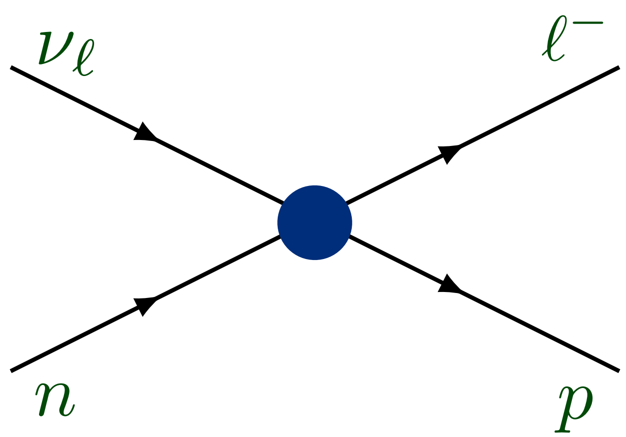
- measurement of ν_μ disappearance and ν_e appearance

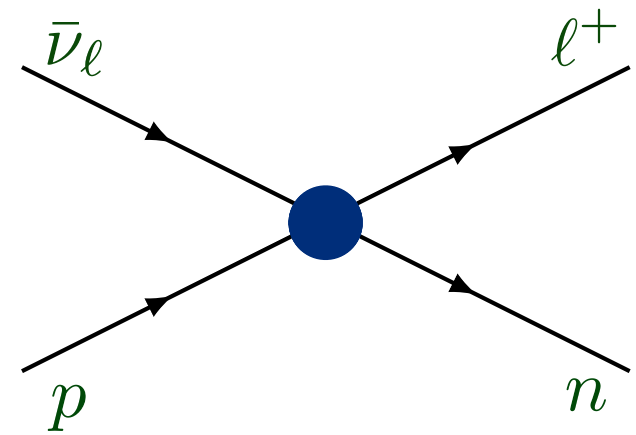
$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu (E_\nu) \times \sigma (E_\nu) \times R(E_\nu, E_\nu^{\text{rec}})$$

- near detector: determine flux and cross sections

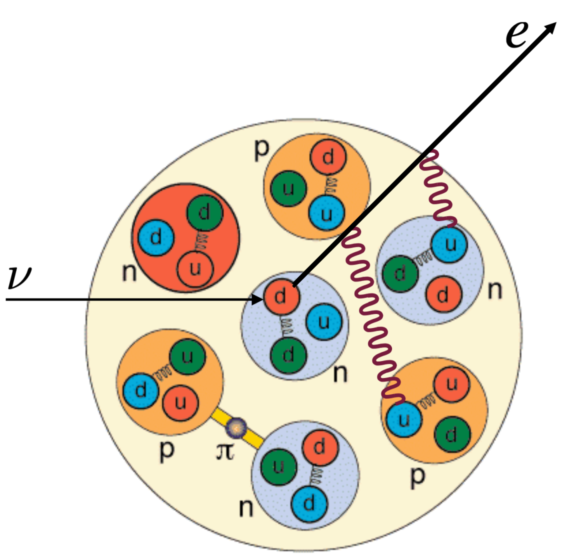
Outline

1) charged-current elastic scattering on nucleons

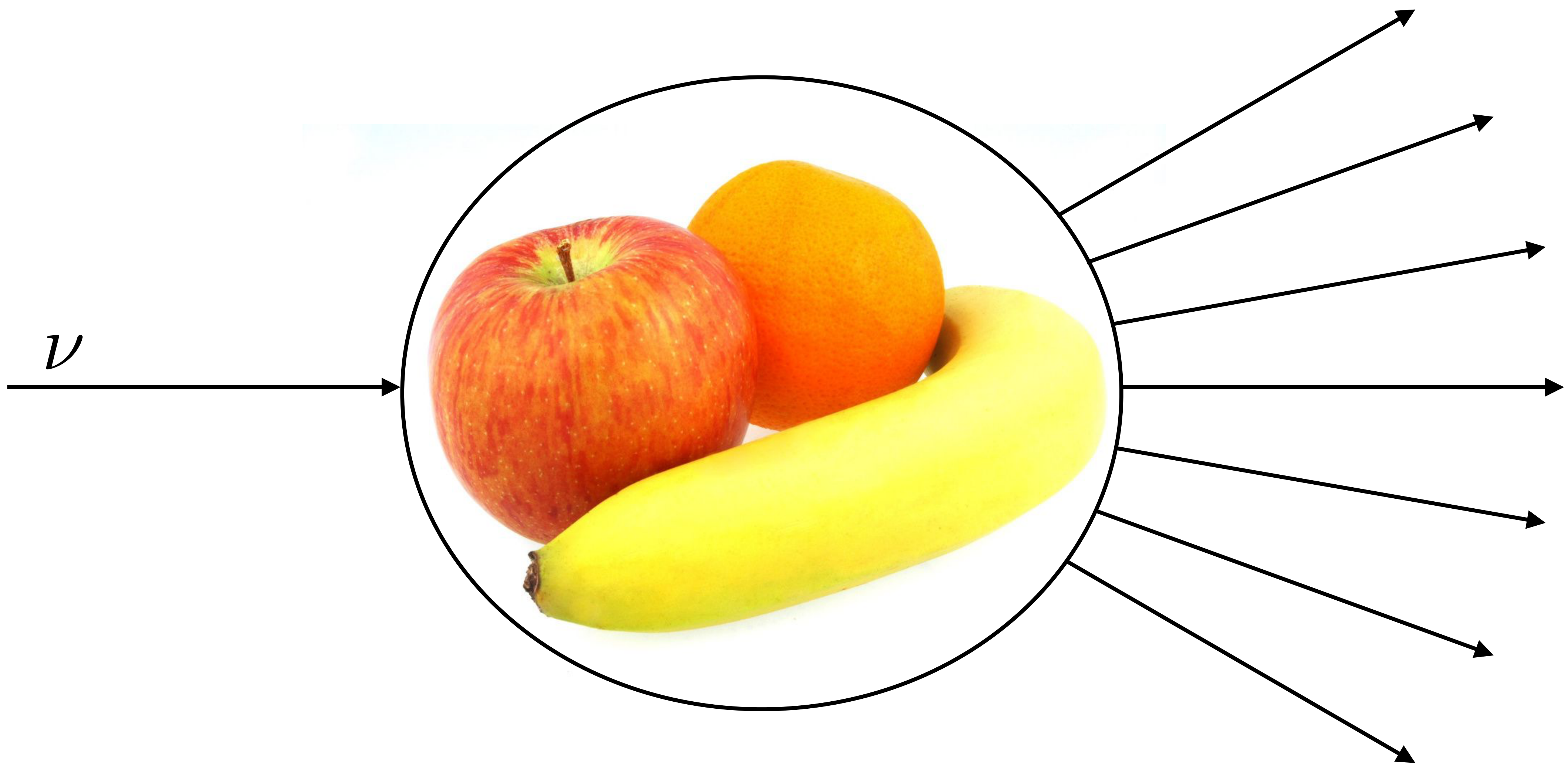




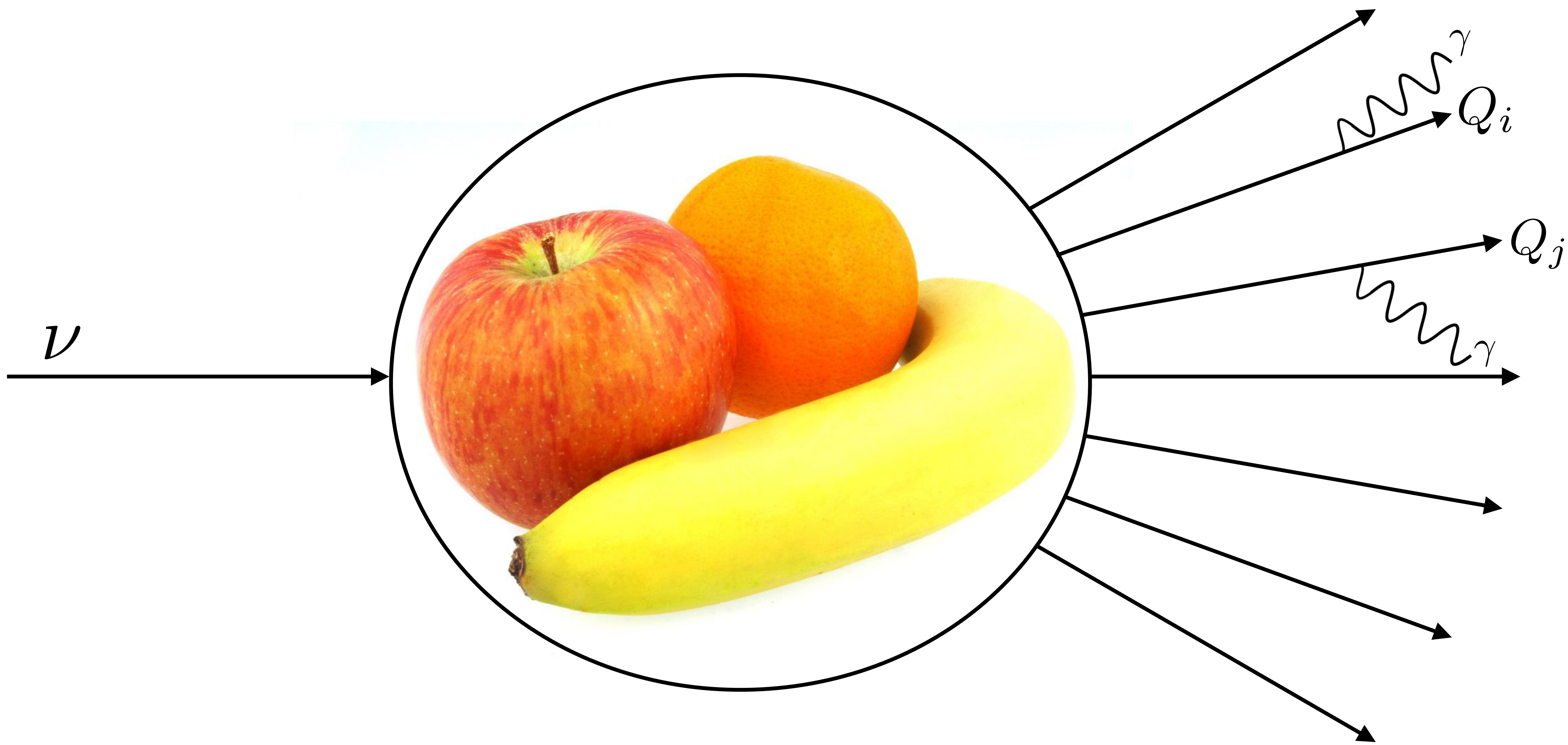
2) QED nuclear medium effects in (anti)neutrino-nucleus and electron-nucleus scattering



Neutrino interactions

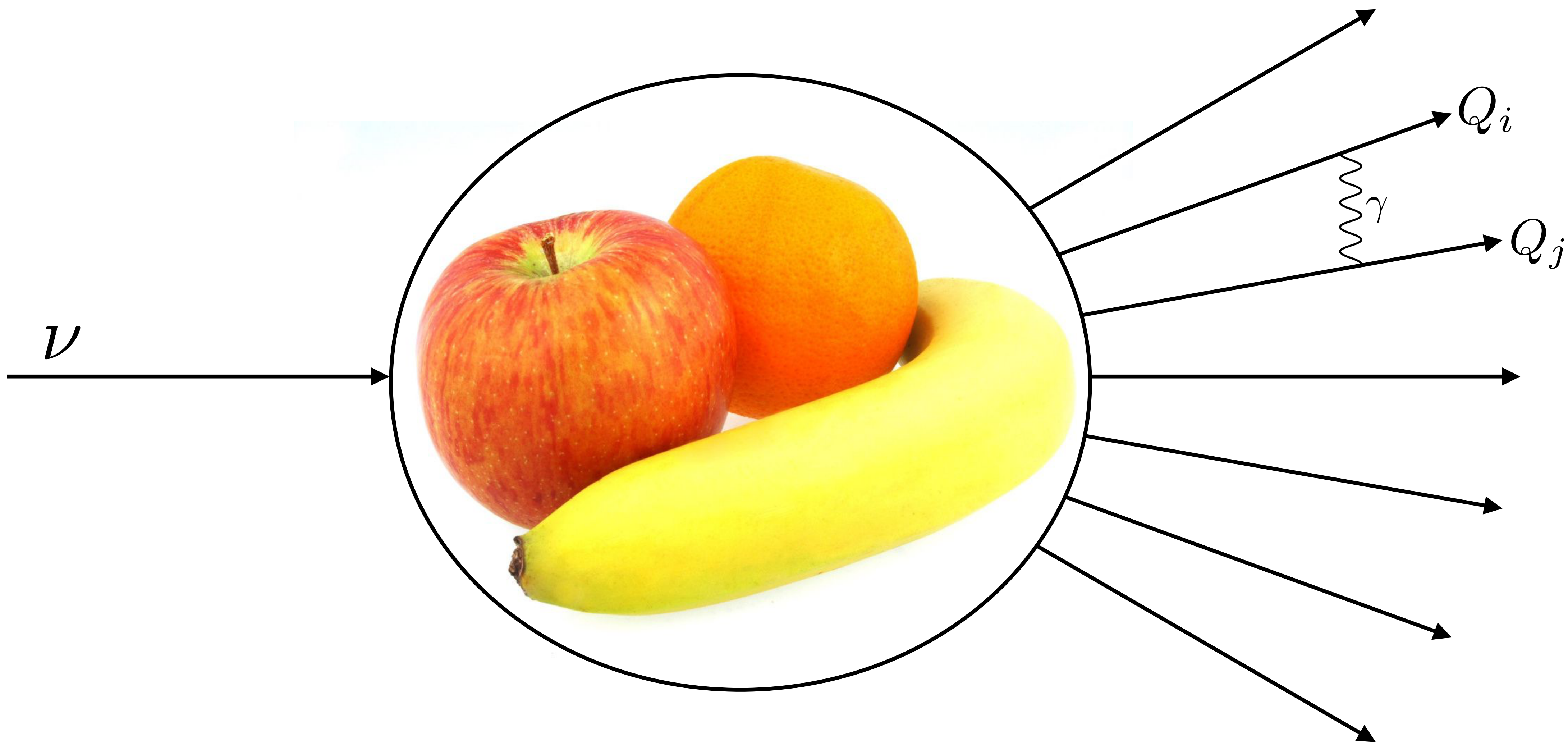


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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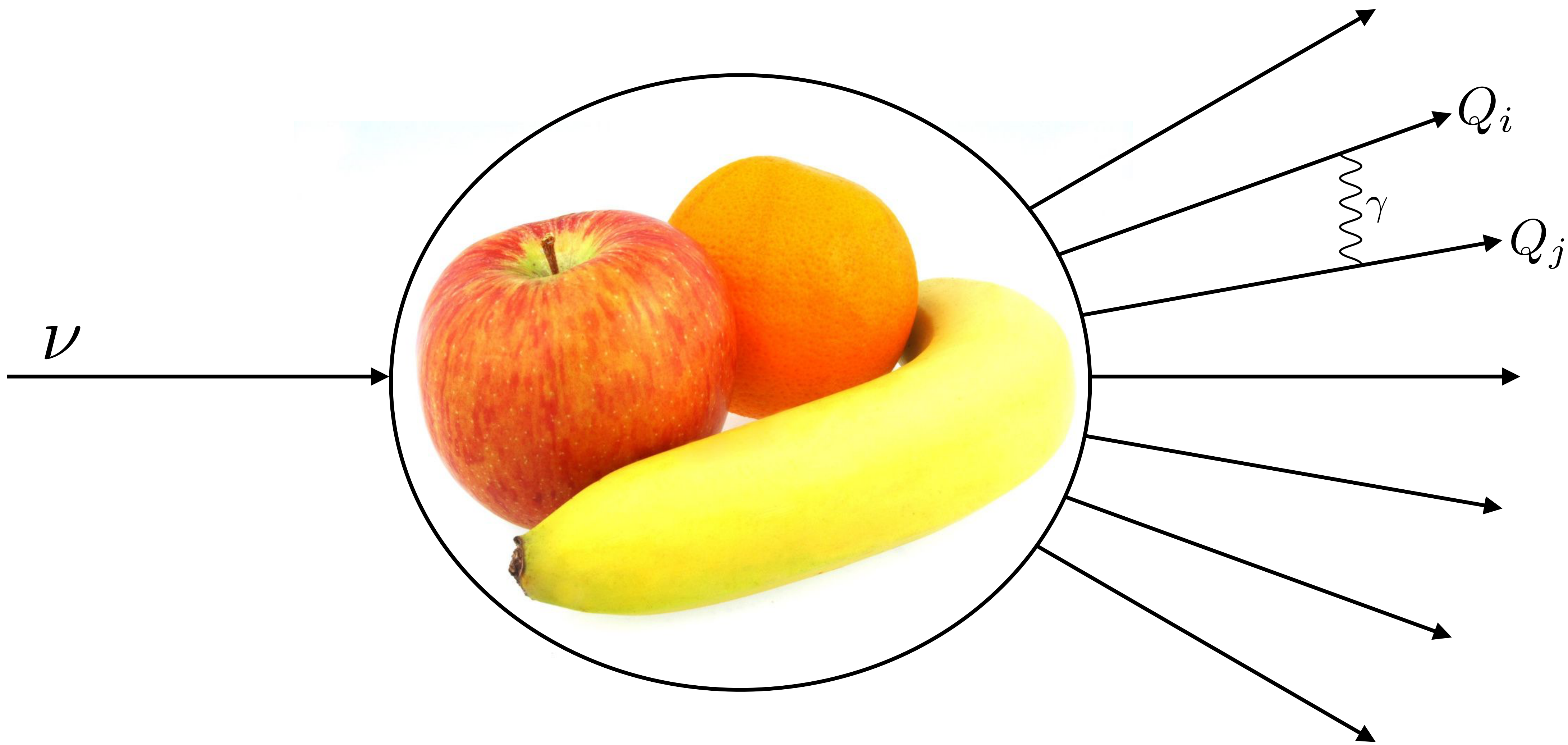
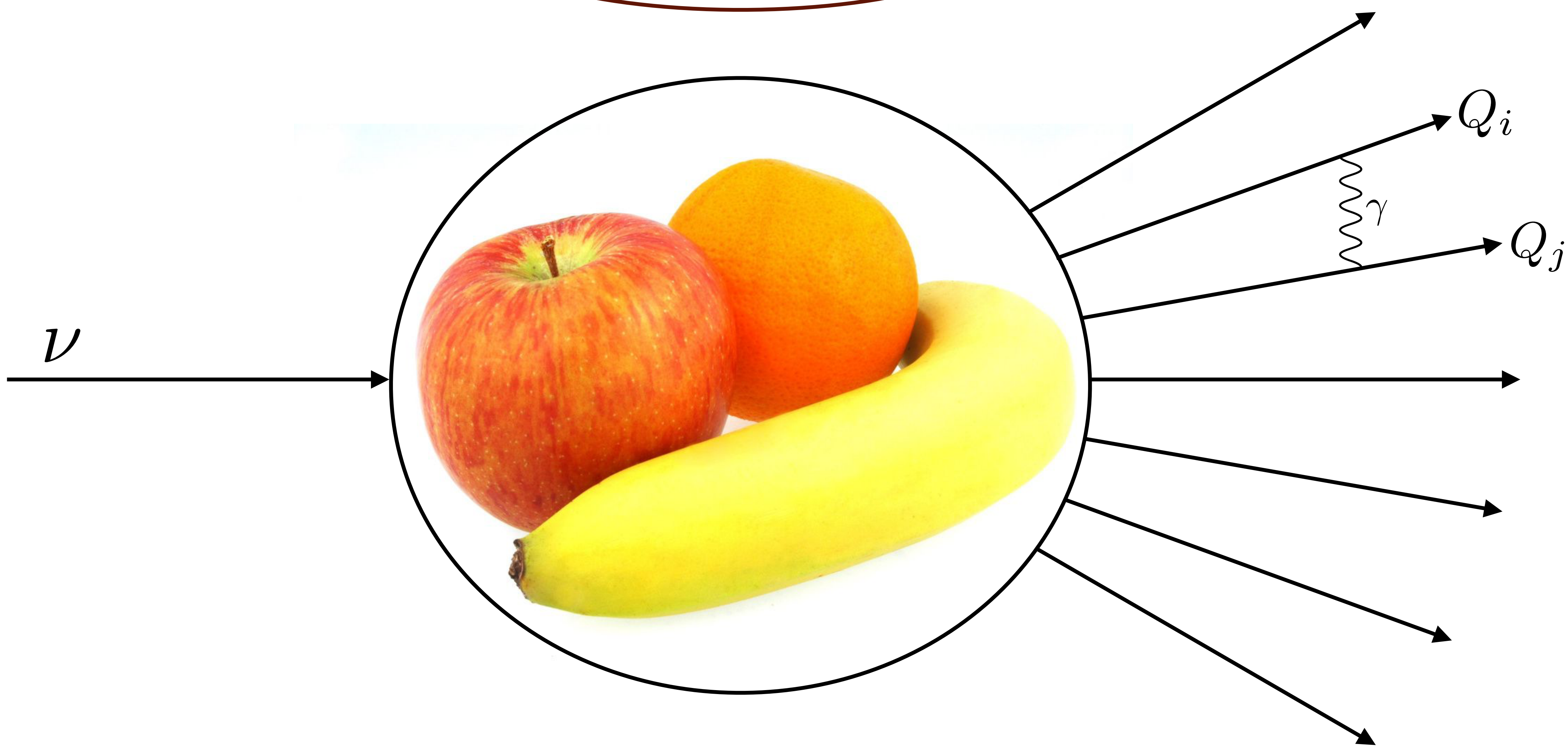
QED corrections



- $\frac{\alpha}{\pi} \sim 0.2~\%$ suppression by electromagnetic coupling constant

QED corrections

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



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

- scale separation introduces large flavor-dependent QED logarithms

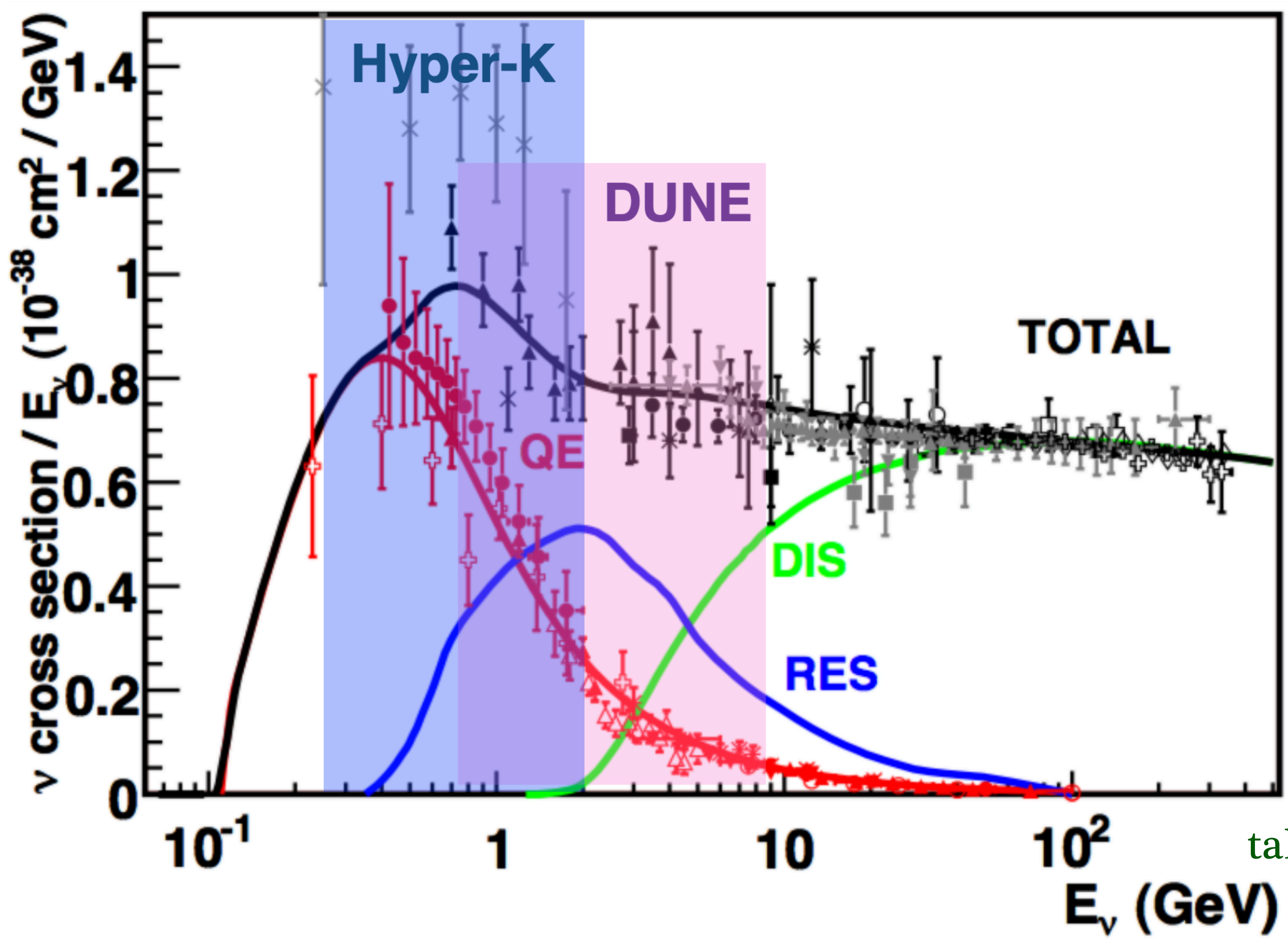
Radiative corrections in charged-current elastic scattering on free nucleons

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

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

CCQE. Why should we care?

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

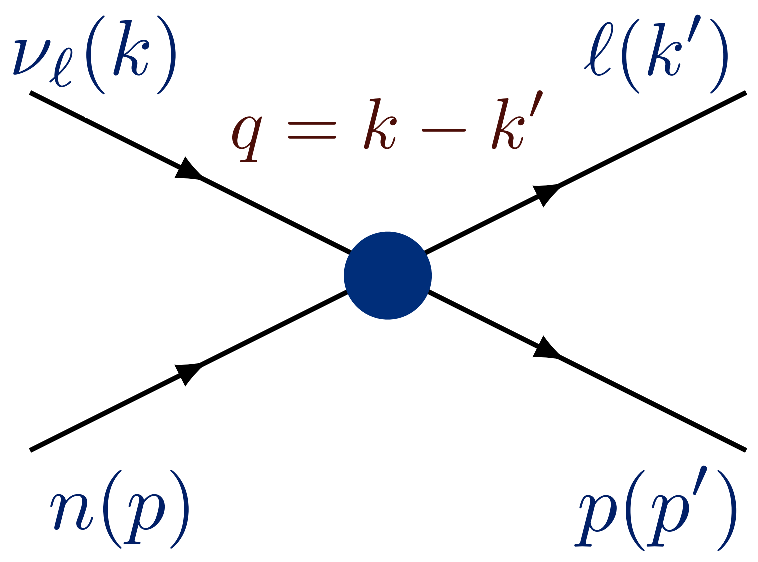


Formaggio and Zeller (2013)

Noemi Rocco talk at Neutrino 2020

- basic process: bulk of events at Hyper-K and DUNE
- 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

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

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

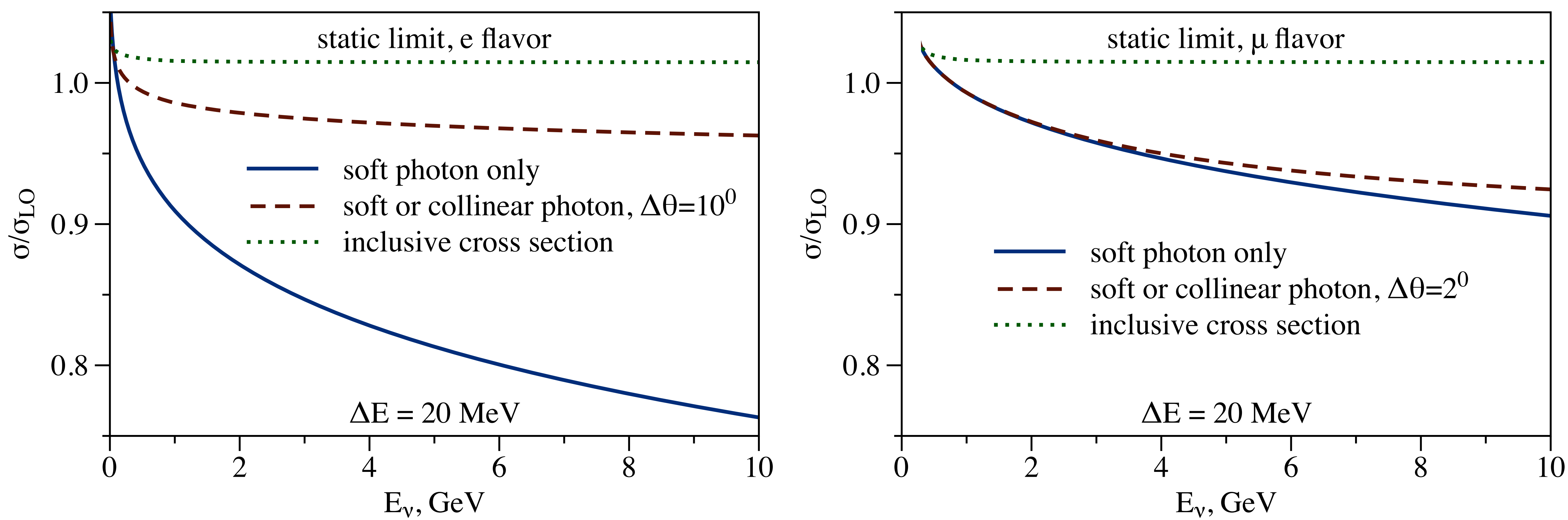
Fermilab bubble chamber, Richard Drew

- axial form factor extracted based on electromagnetic structure

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

Static nucleon limit

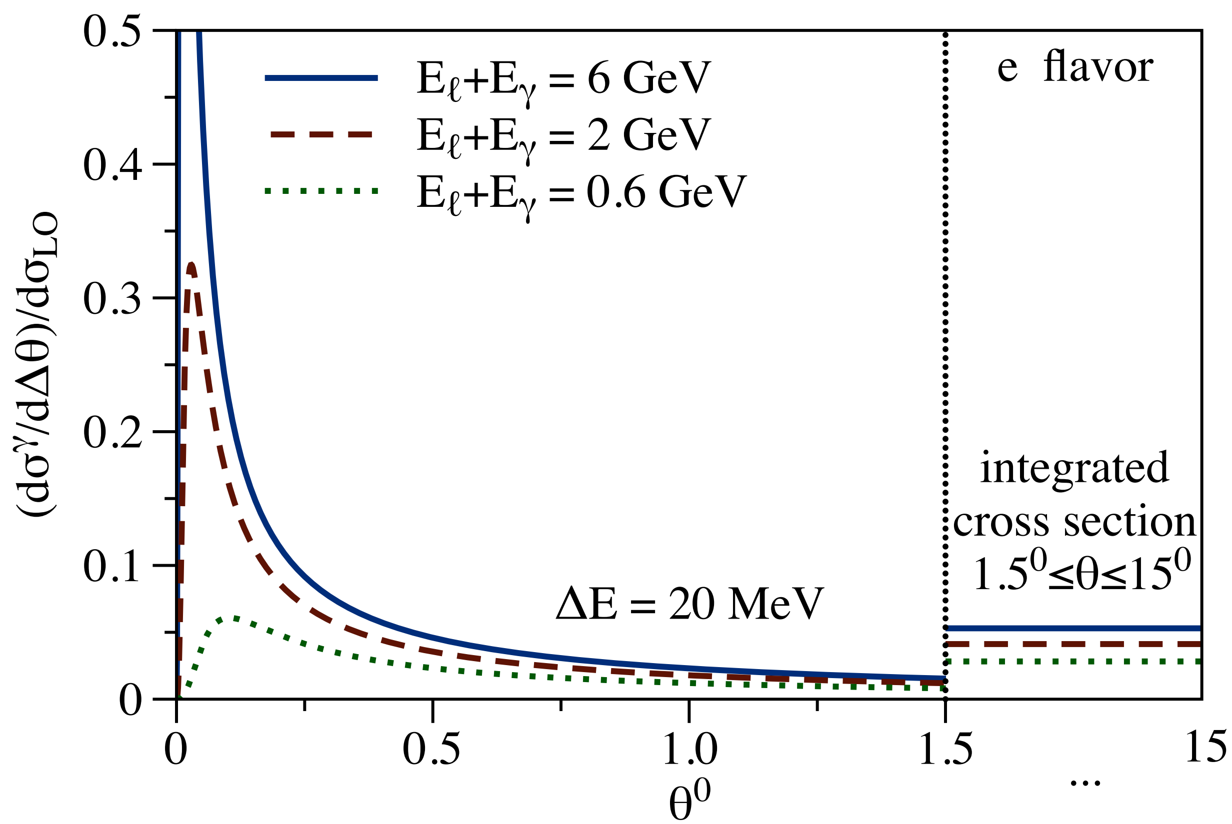
- formal limit of infinitely heavy nucleus $m_\ell \ll E_\ell \ll M$
- provides correct soft and collinear logarithms
- soft-photon energy < 20 MeV, jet size: 10° for electron and 2° for muon

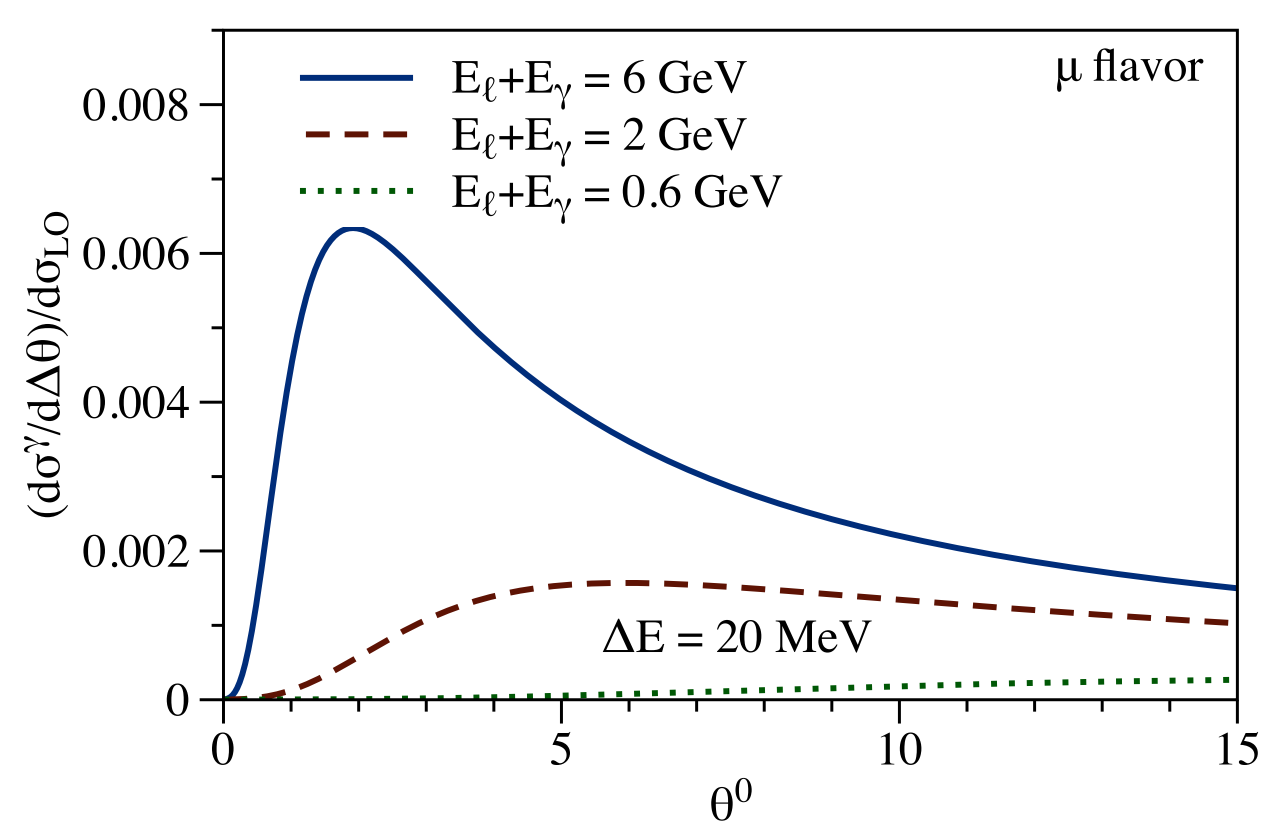


- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables ($+\gamma$): few % level, flavor independent

Electron vs muon jets

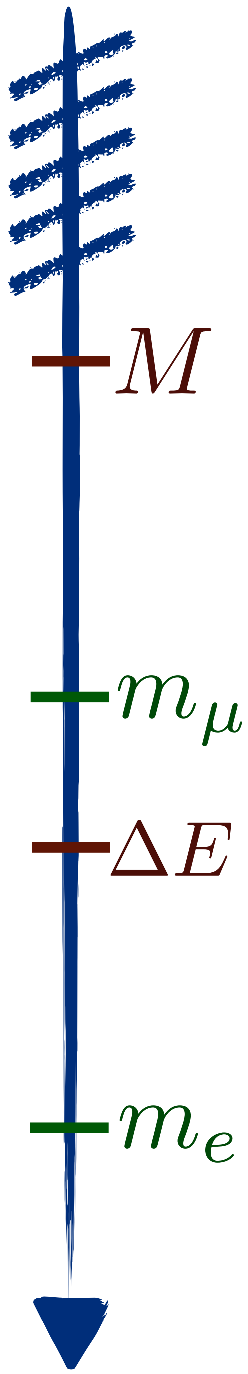
- factorization for radiation of collinear photons
- cone angle is defined to lepton direction
- photons of energy > 20 MeV, fixed energy in the cone





- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- forward-peaked radiation for electron flavor
- negligible radiation for muons with shifted peak position

Factorization approach



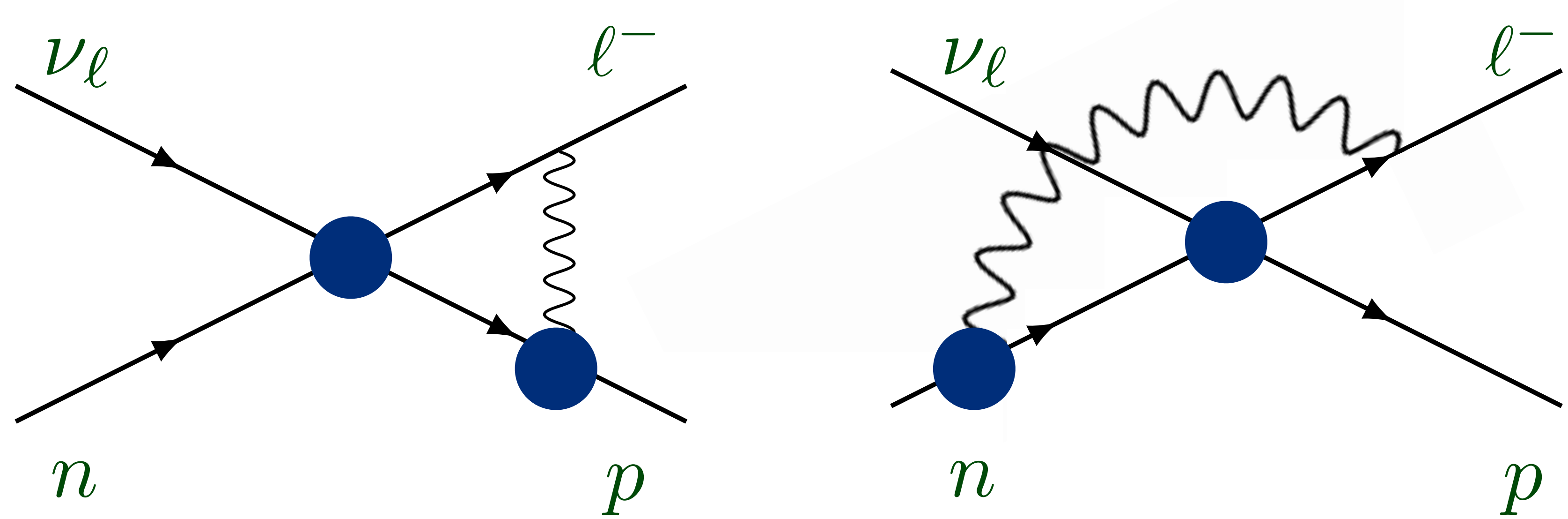
- cross section is given by factorization formula

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

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

- soft and collinear functions are evaluated perturbatively

Hadronic model at GeV scale



- exchange of photon between the charged lepton and nucleons

- assume onshell form for each interaction with dipole form factors

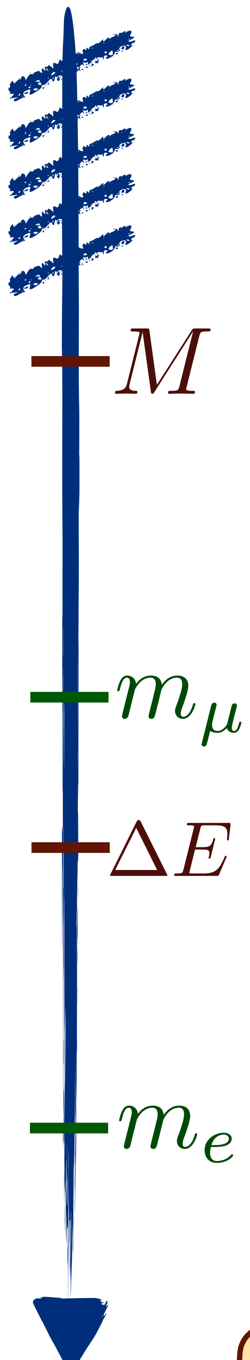
discussed for neutrino-nucleon scattering: Graczyk (2013)

- add self energy for charged particles

- reproduce soft and collinear regions of SCET

- best determination of hard function

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 hadronic 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

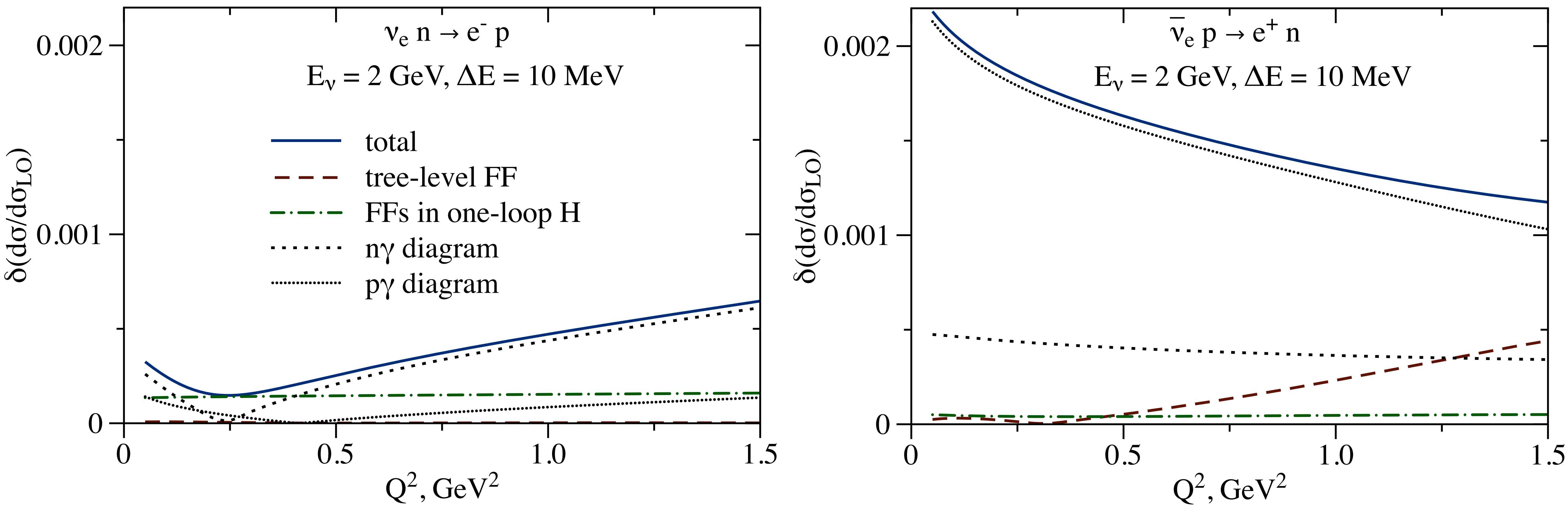
- calculate cross section at low energies accounting for all large logs

ep scattering with soft radiation only: Richard J. Hill (2016)

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

Error budget

- uncertainties from hard function



- nucleon form factors

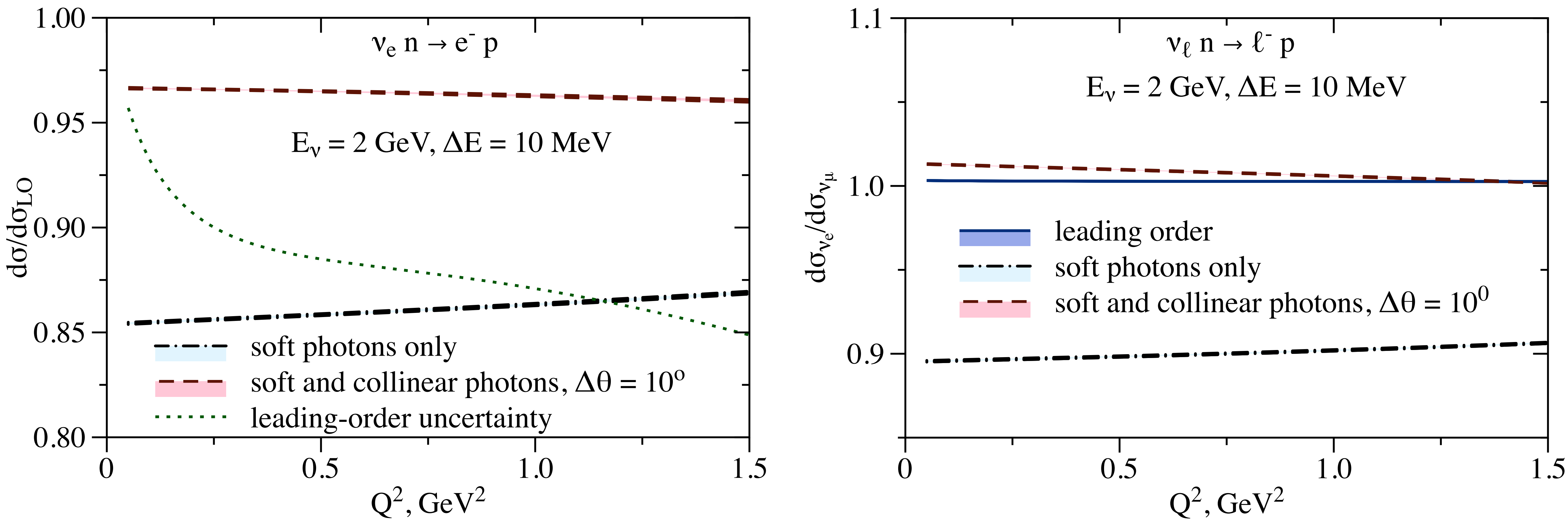
Meyer, Betancourt, Gran and Hill (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T. (2020)

- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result

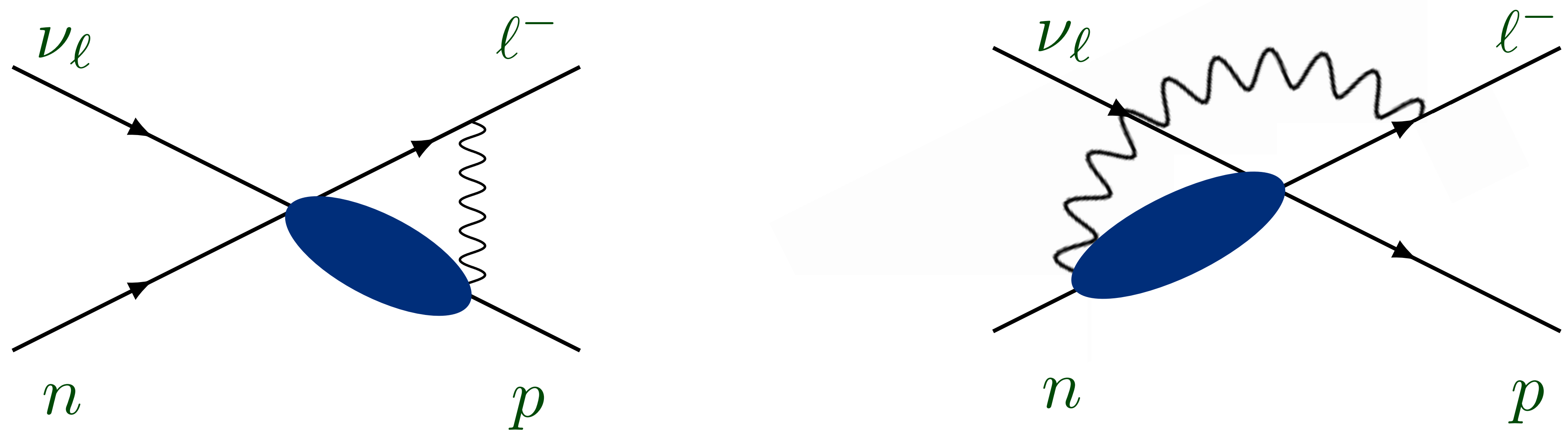
Exclusive observables

- cancellation of uncertainties from hard function for e/μ and ratio to LO



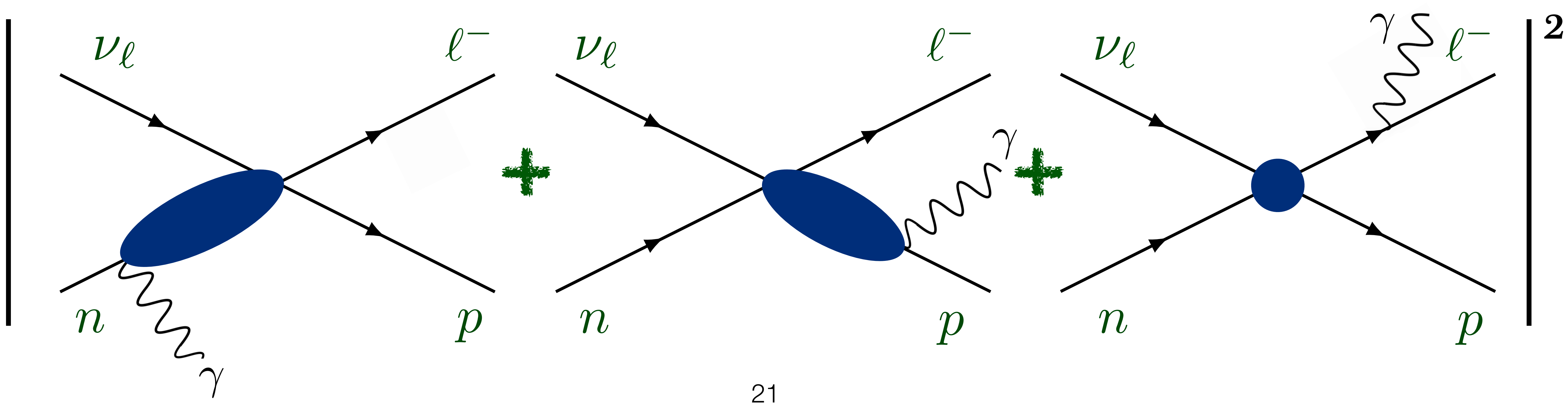
- ratios: cancellation of uncertainty from hard function

Inclusive observables



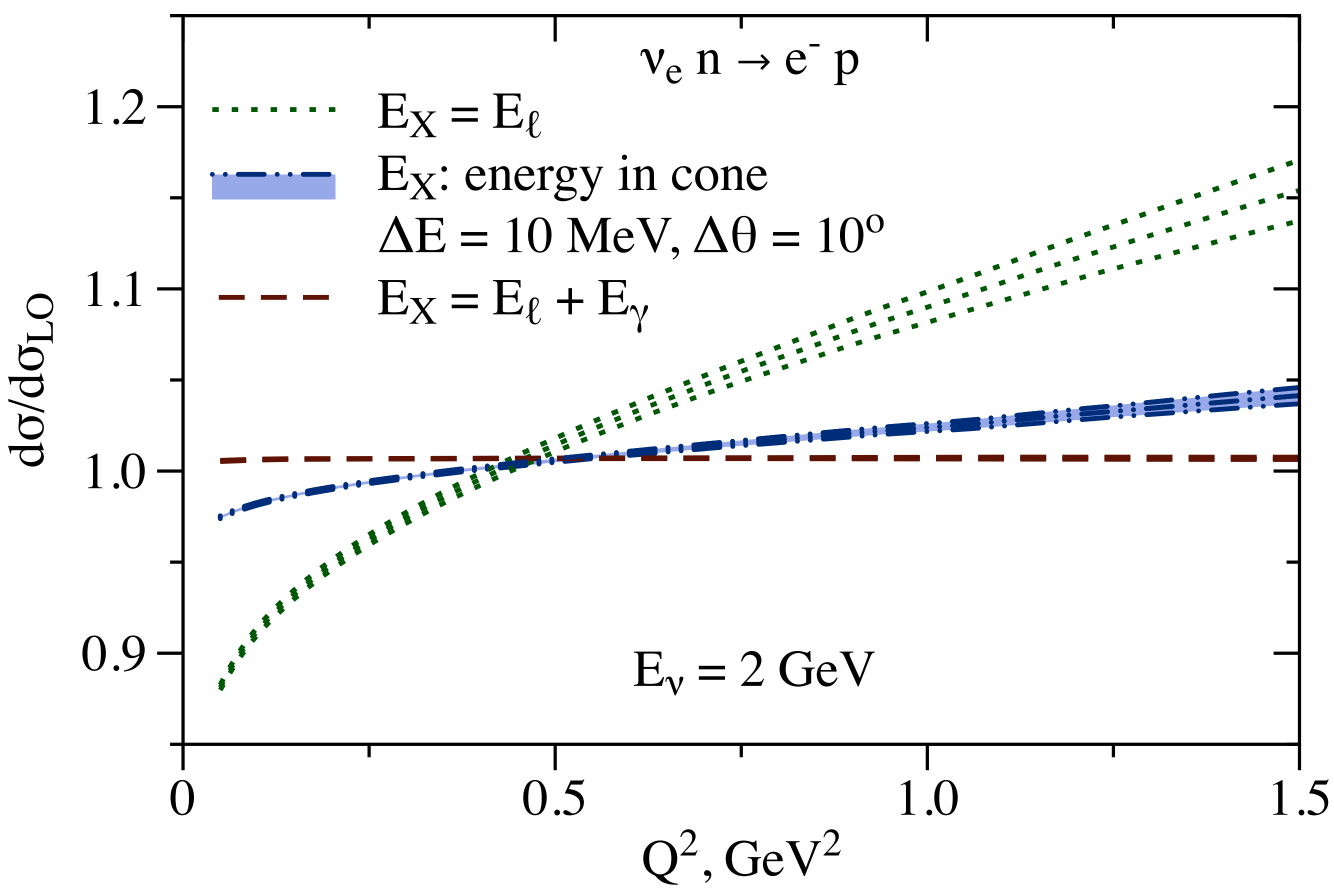
- the same gauge-invariant model for the real radiation

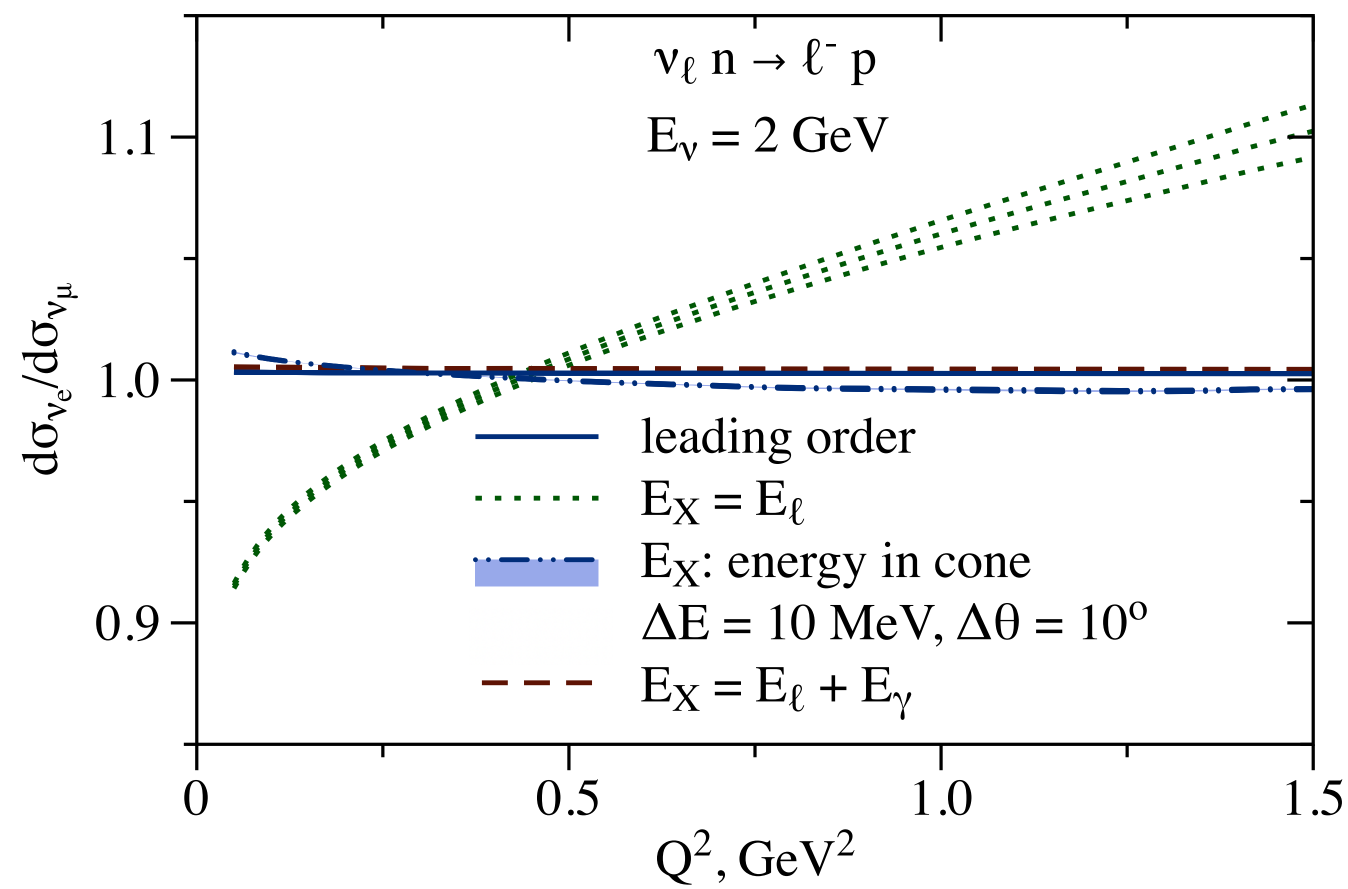
- arbitrary hard photons are part of the observable



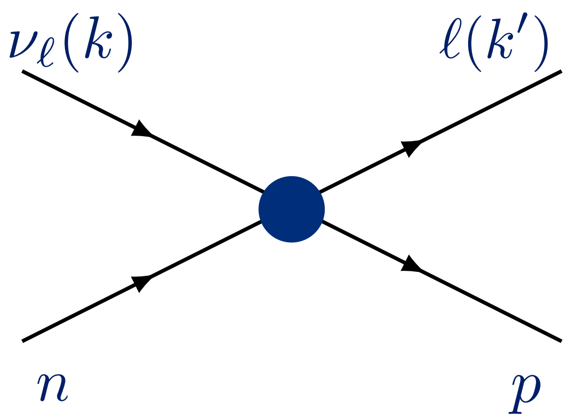
Inclusive observables

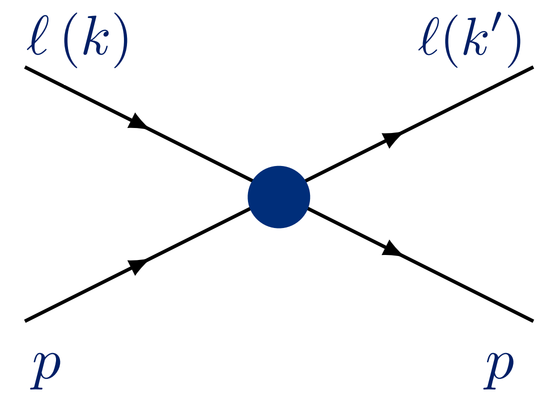
- kinematics $Q^2 = 2M\,(E_\nu - E_X)$ is reconstructed with 3 different E_X





- dependence on reconstruction of kinematics and cuts
- predict σ_{ν_e} from σ_{ν_μ} measurements with neutrino beam ✓

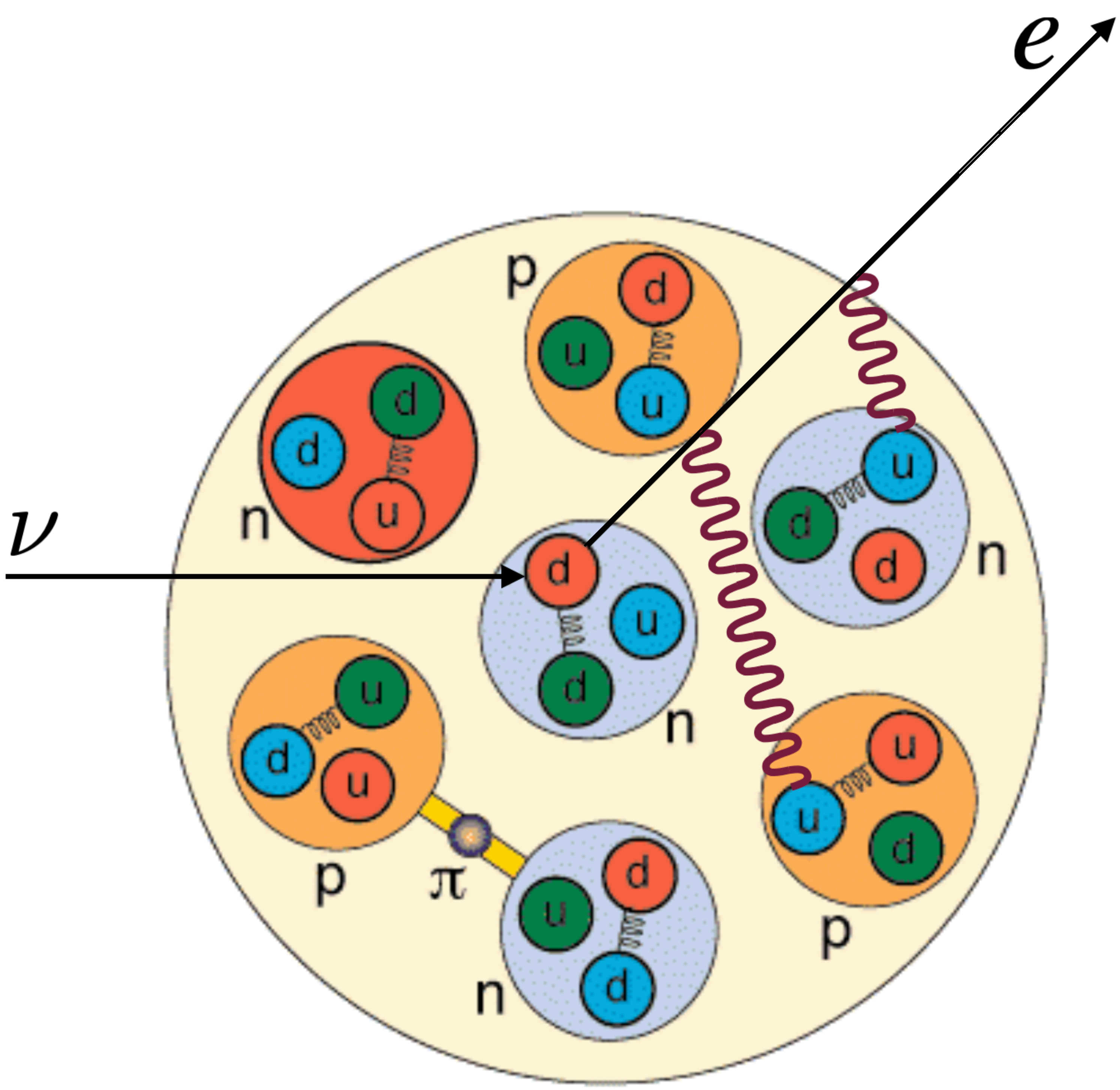




QED nuclear medium effects in neutrino-nucleus and electron-nucleus scattering

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

QED medium effects



- charged lepton exchanges photons with nuclear medium

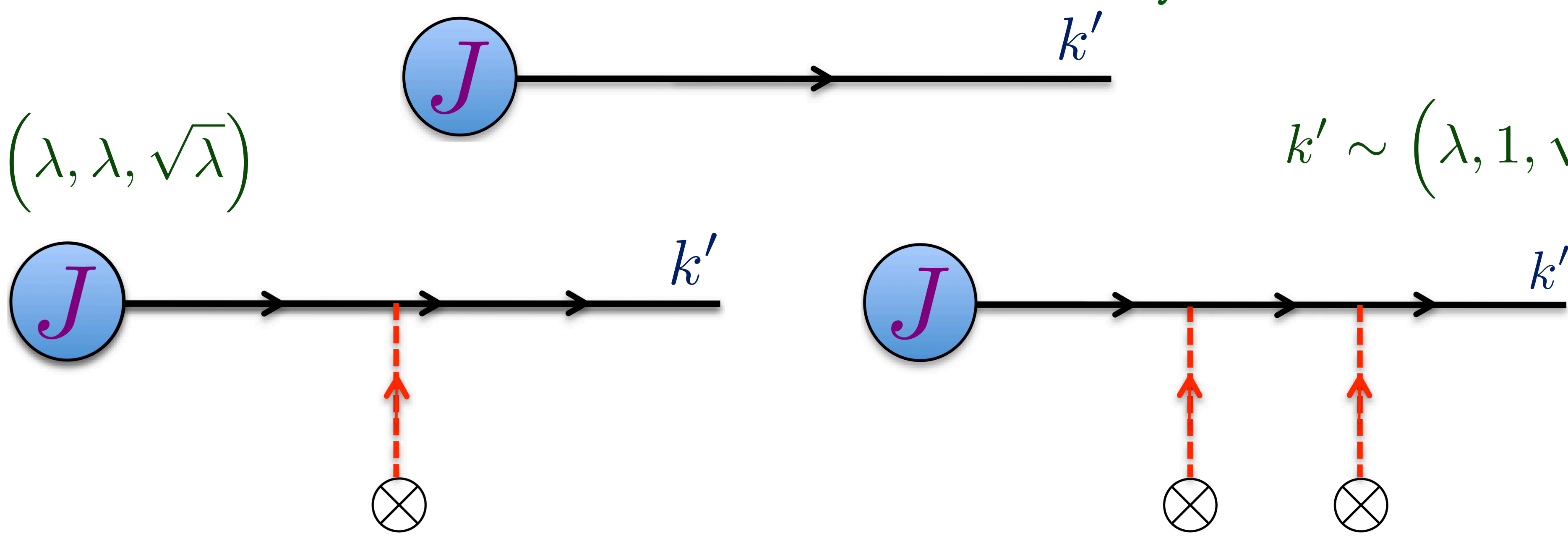
SCET$_G$ formulation

- 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

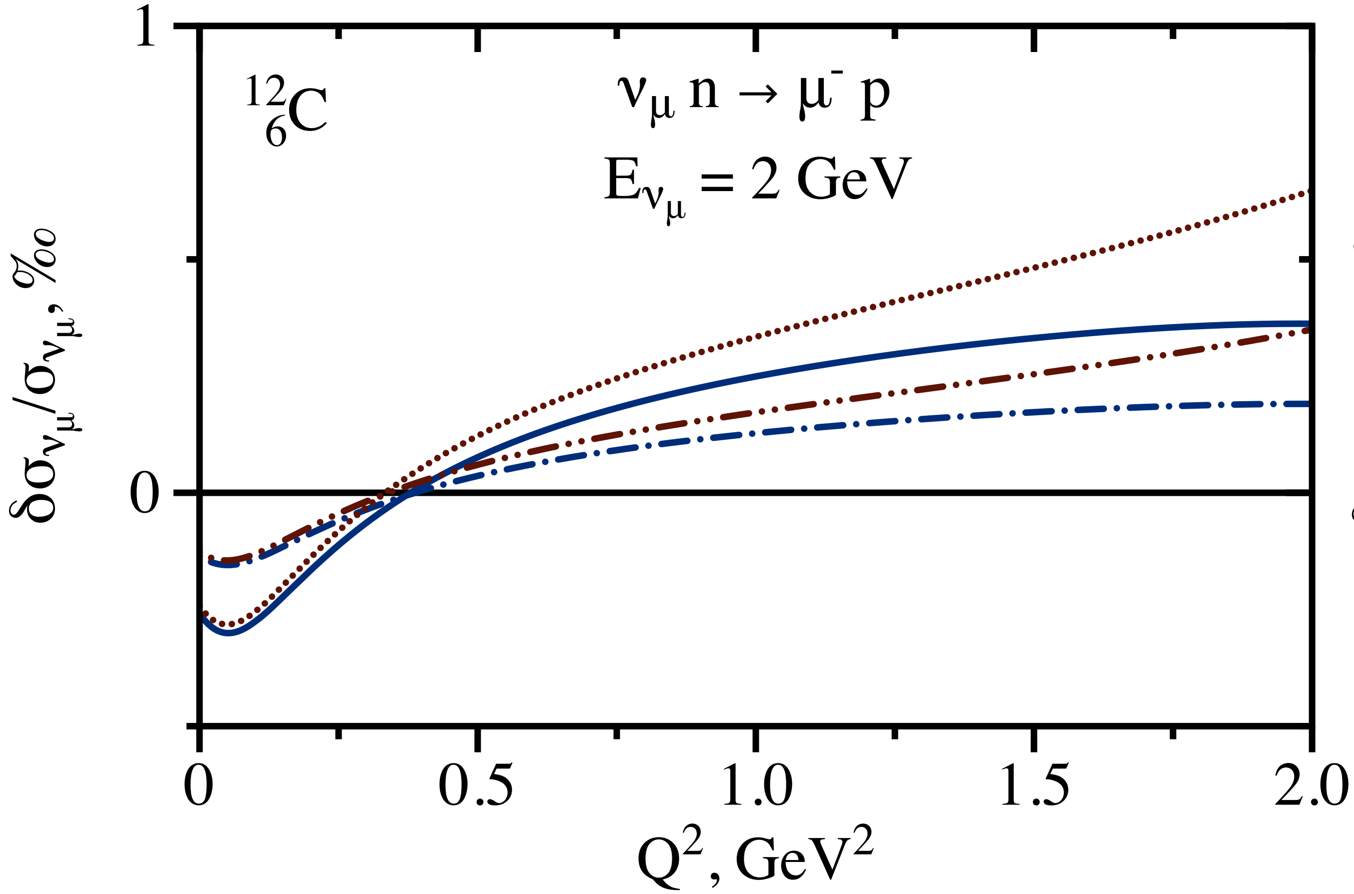
$$\delta\sigma_f \sim \int_{\text{lepton line}}^{\text{final}} \rho(z)\,\mathrm{d}z \int \frac{\mathrm{d}^2\vec{q}_\perp}{(2\pi)^2} |v(\vec{q}_\perp)|^2 \left(\sigma_0\left(\vec{k}, \vec{k}' - \vec{q}_\perp\right) - \sigma_0\left(\vec{k}, \vec{k}'\right)\right)$$

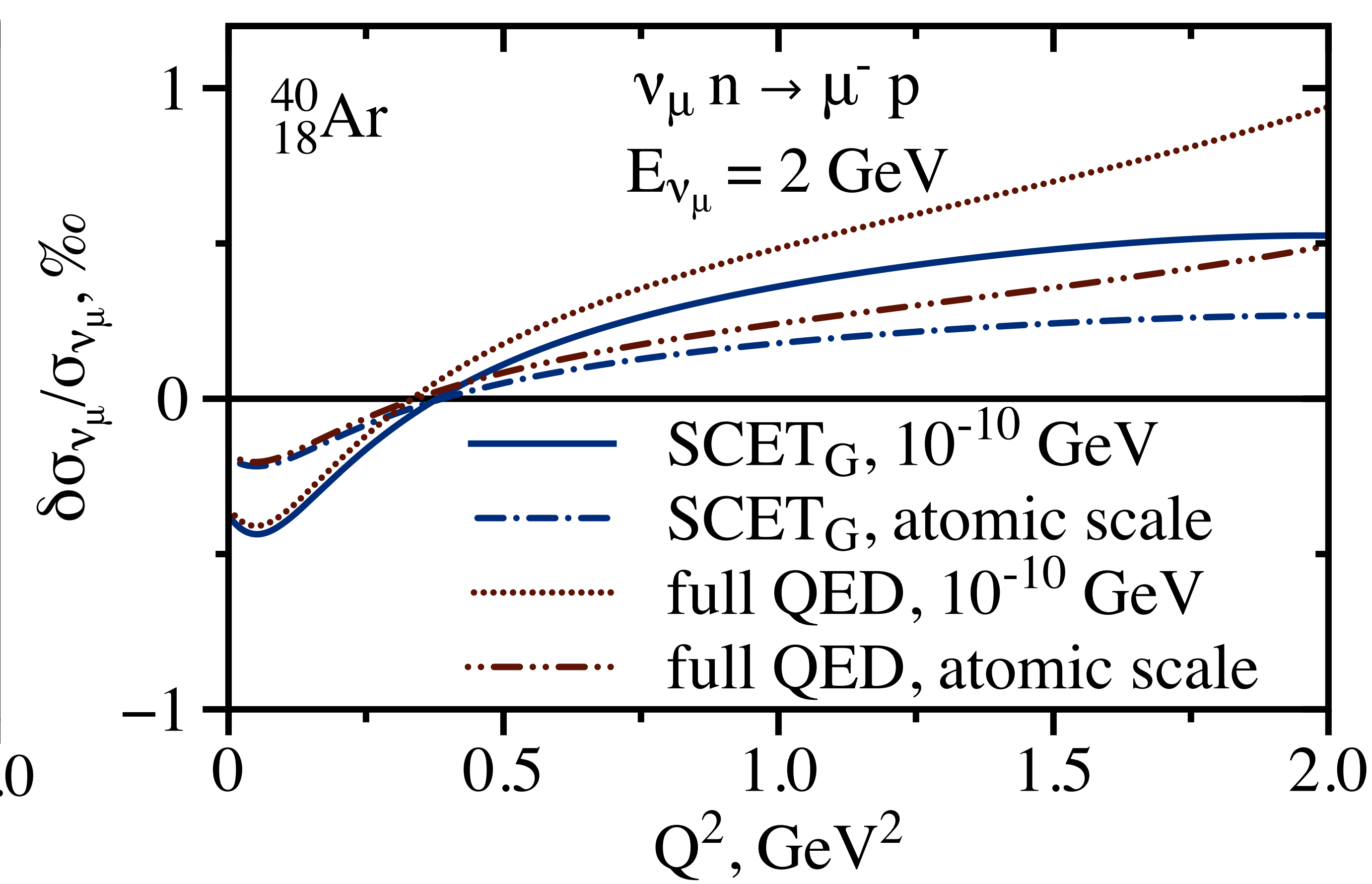
- leading-order cross sections are distorted
- EFT and full QED calculations are performed

Neutrino scattering

- relative correction per nucleon

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





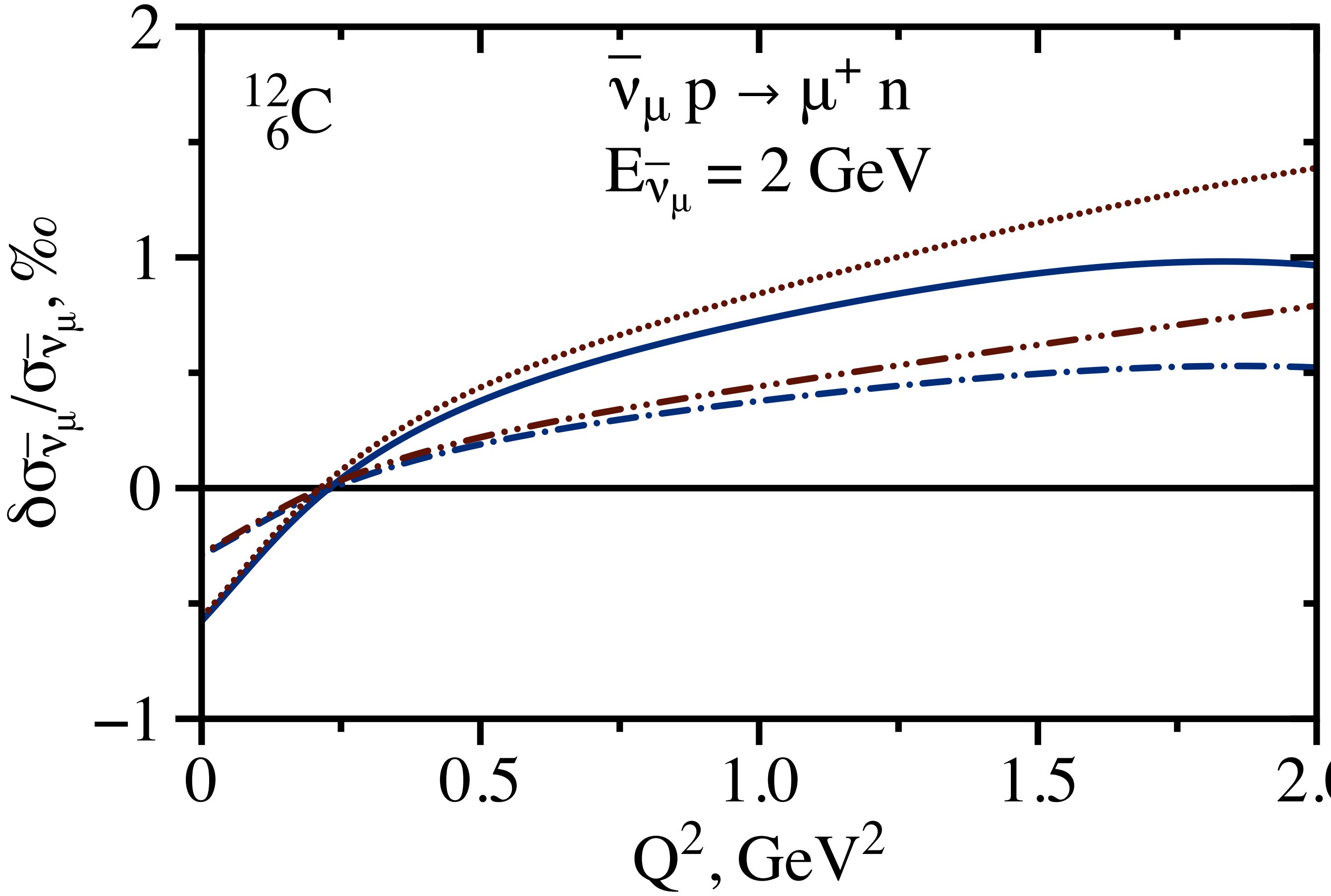
preliminary

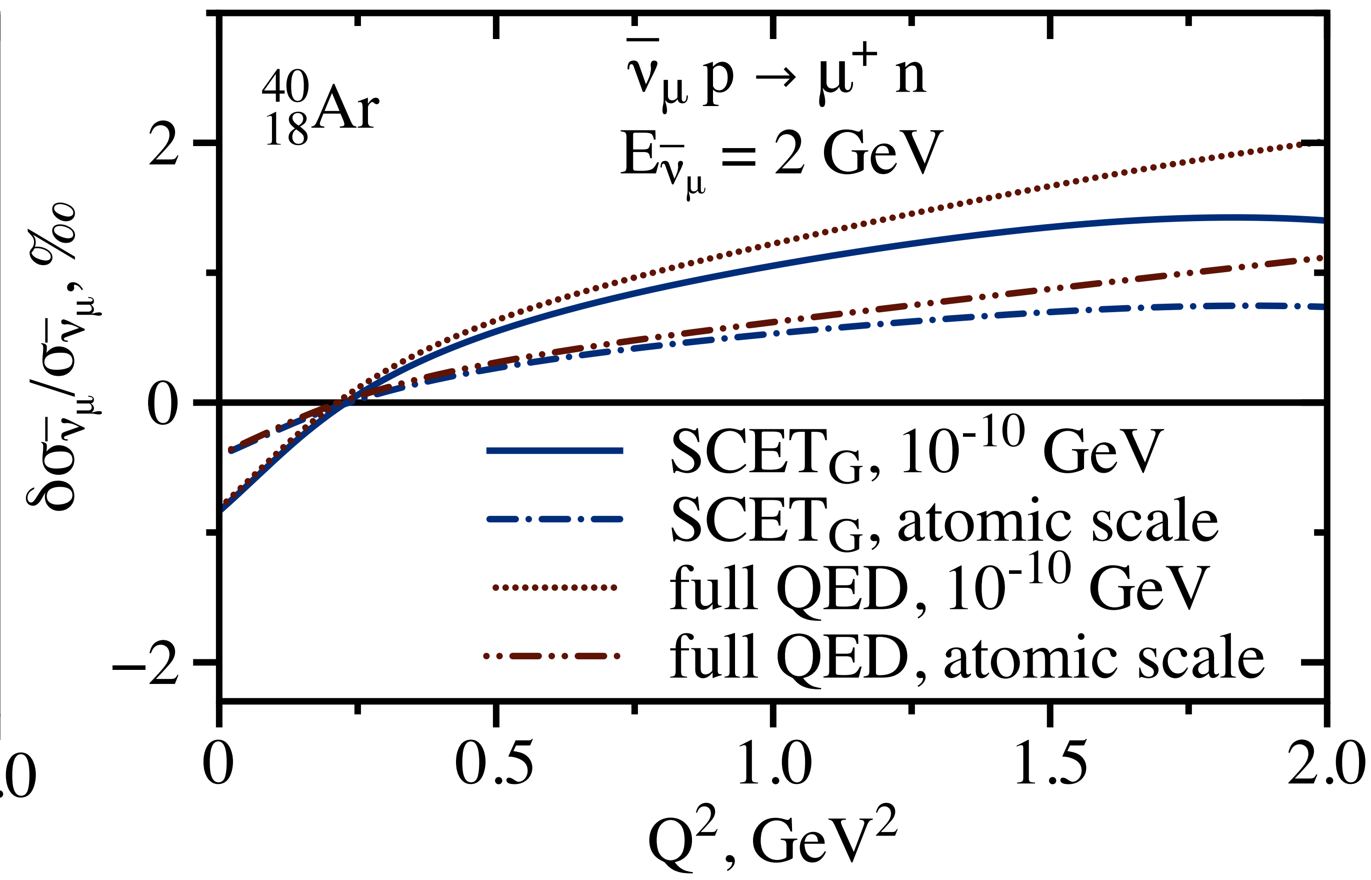
- permille-level distortion of cross sections: $O(\alpha^2)$ correction
- smaller correction to inclusive cross section

Antineutrino scattering

- relative correction per nucleon

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





preliminary

- 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

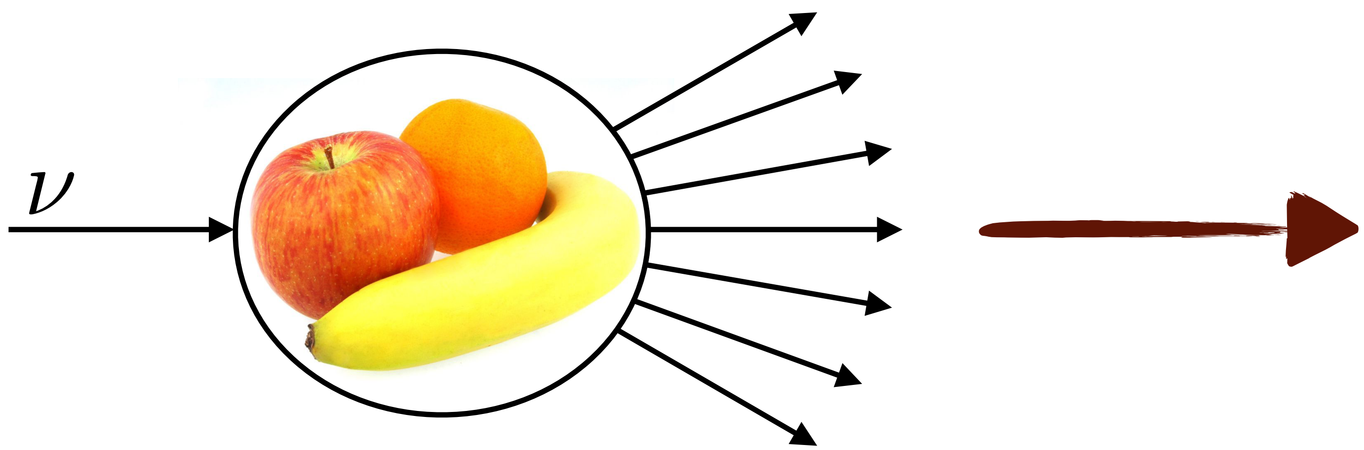
$$\delta\sigma_i \sim \int_{\text{lepton line}}^{\text{initial}} \rho(z)\,\mathrm{d}z \int \frac{\mathrm{d}^2\vec{q}_\perp}{(2\pi)^2} |v(\vec{q}_\perp)|^2 \left(\sigma_0\left(\vec{k}+\vec{q}_\perp, \vec{k}'\right) - \sigma_0\left(\vec{k}, \vec{k}'\right)\right)$$

- 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 calculations are ongoing

Conclusions



radiative corrections
in EFT framework

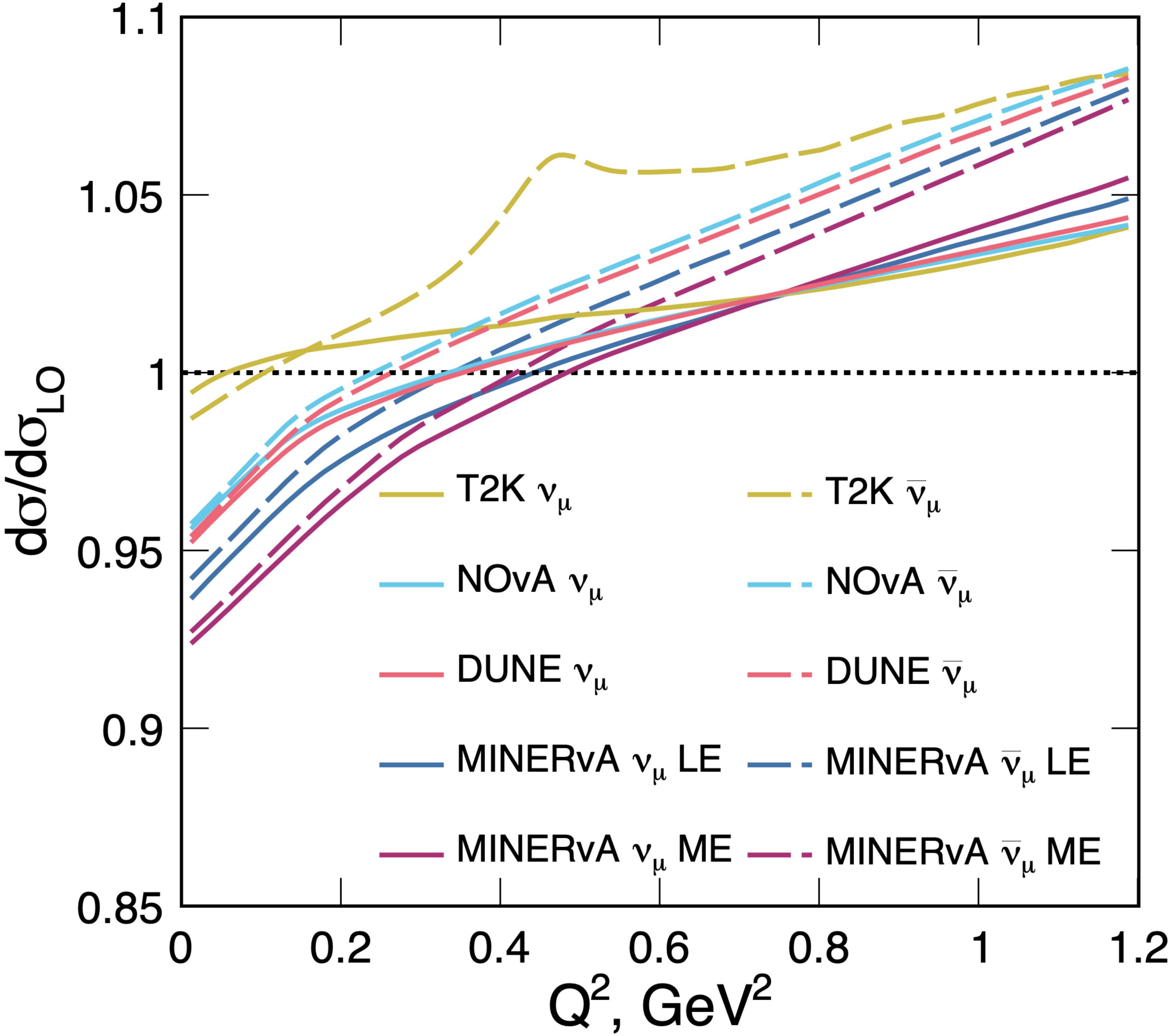
- radiative corrections to neutrino-nucleon cross sections formulated in factorization framework

- charged-current elastic electron vs muon cross-section ratios evaluated from theory with sub-percent uncertainty

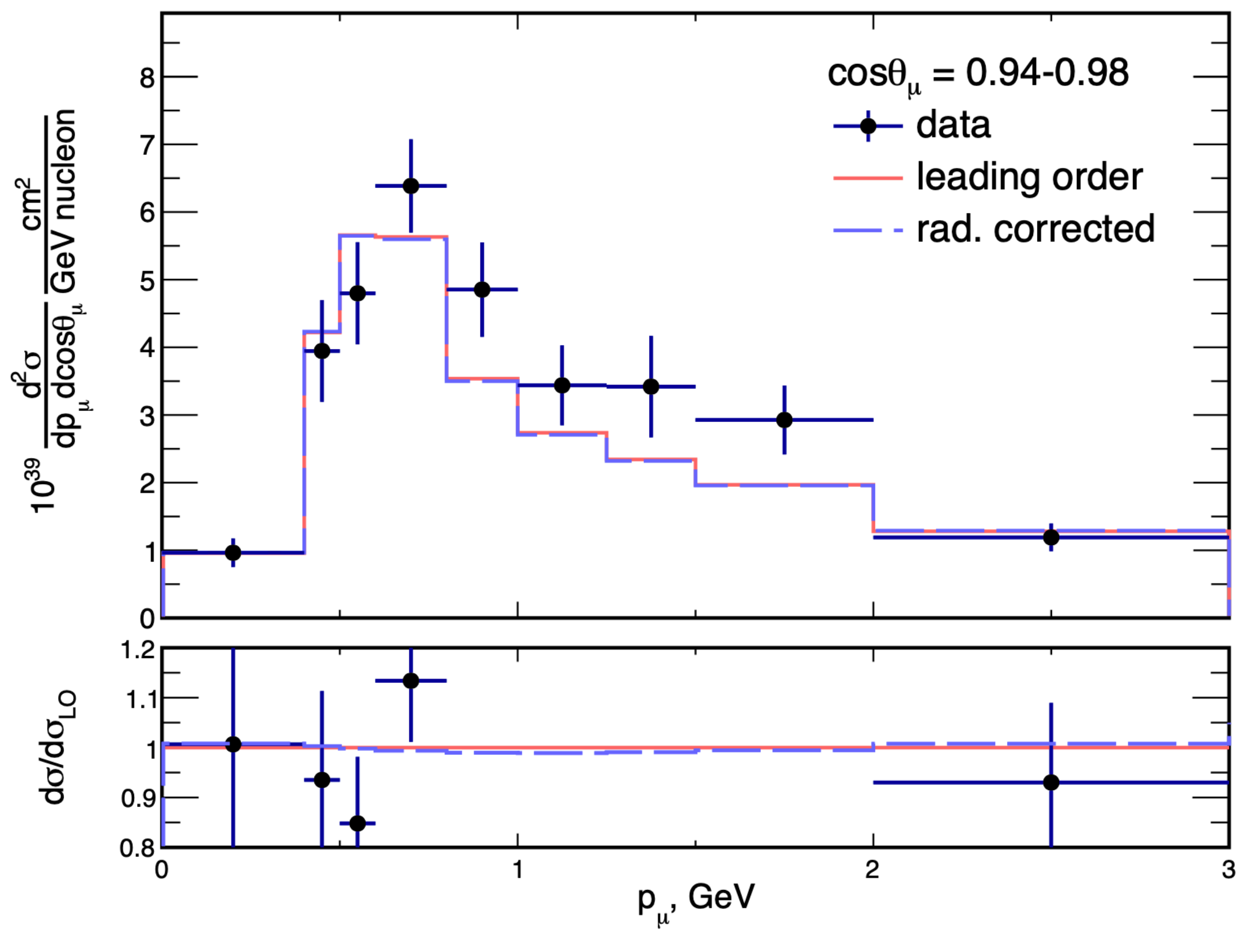
- permille-level QED nuclear medium effects in lepton-nucleus scattering with $SCET_G$ and full QED treatments

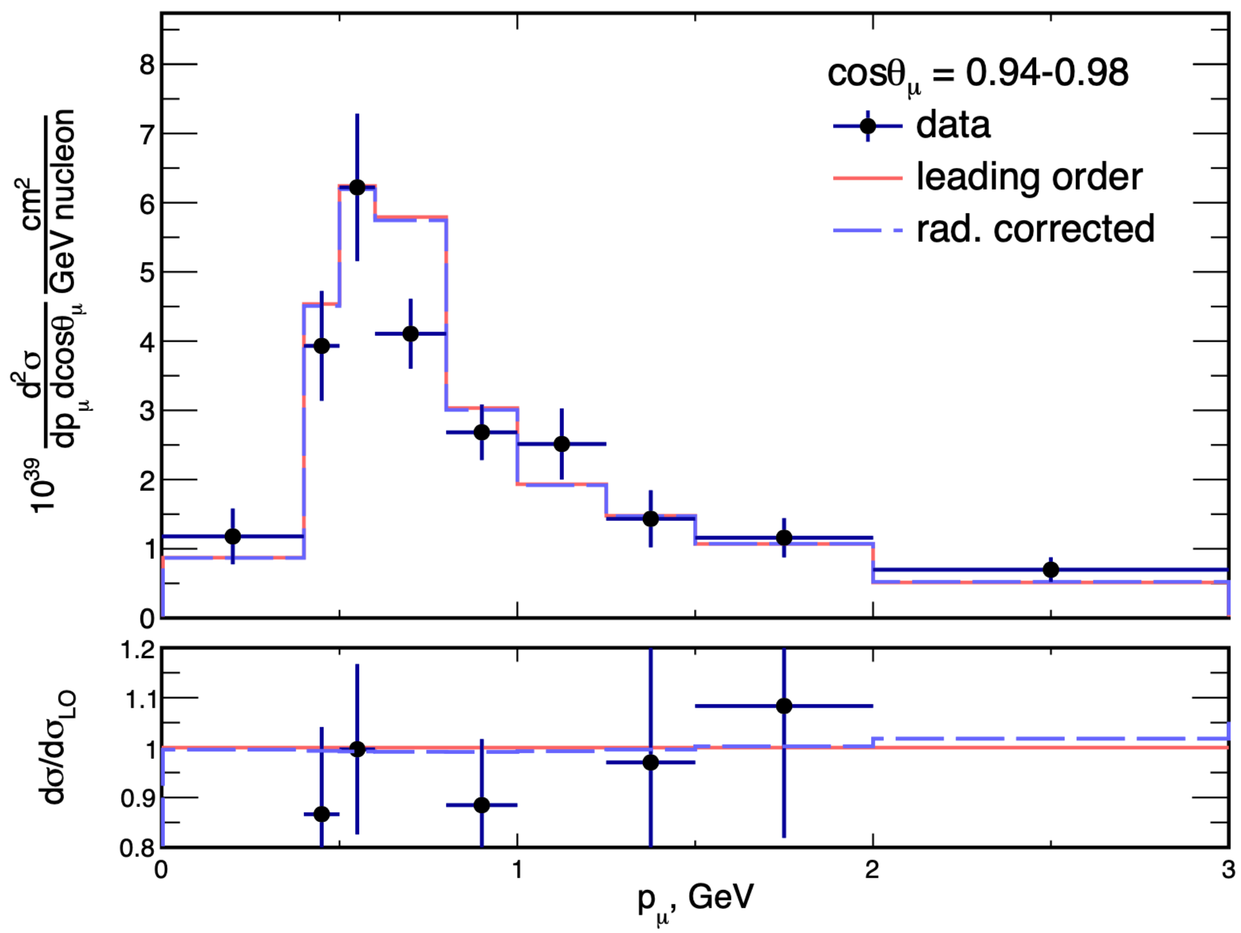
Thanks for your attention !!!

Integrated over flux lepton energy spectra

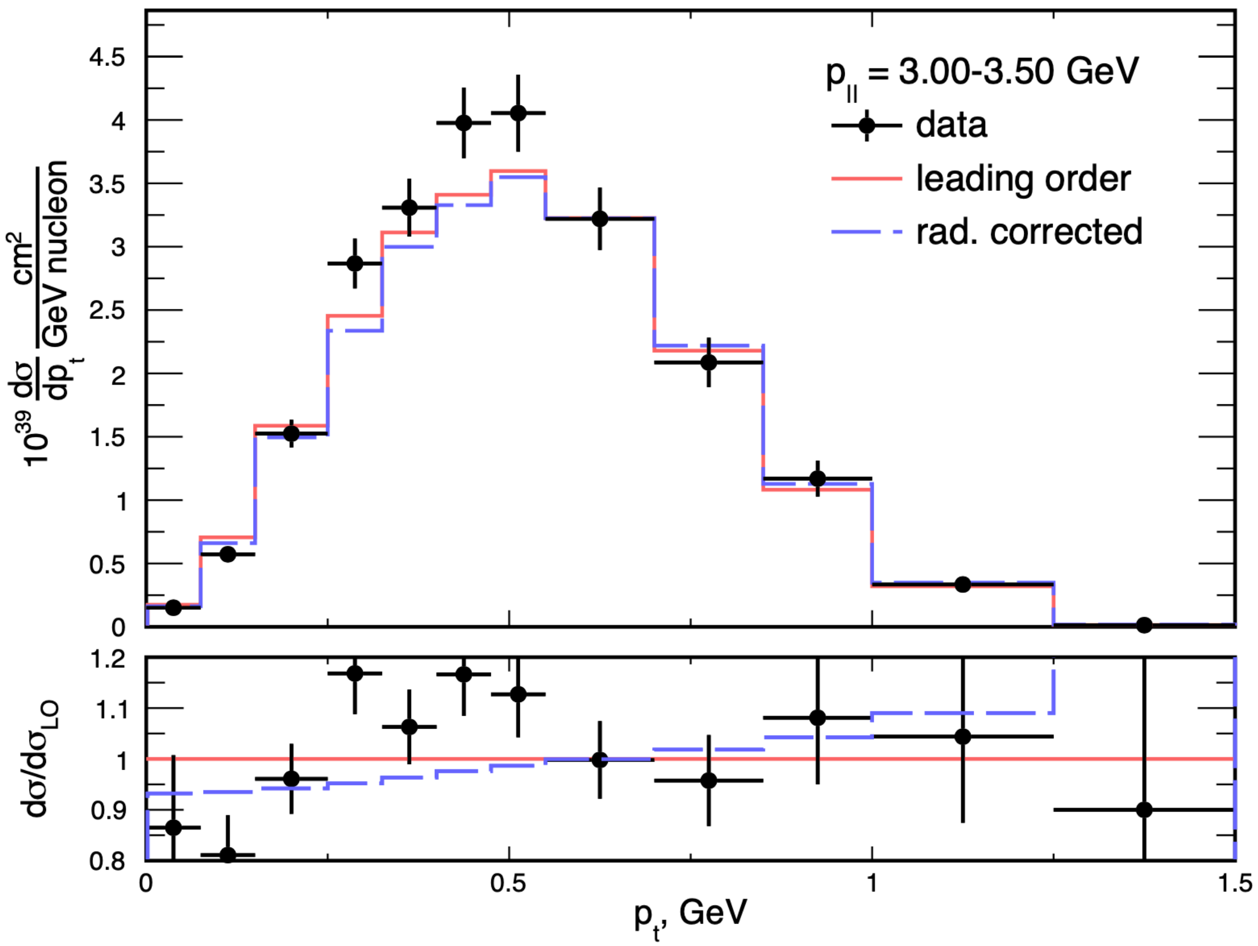


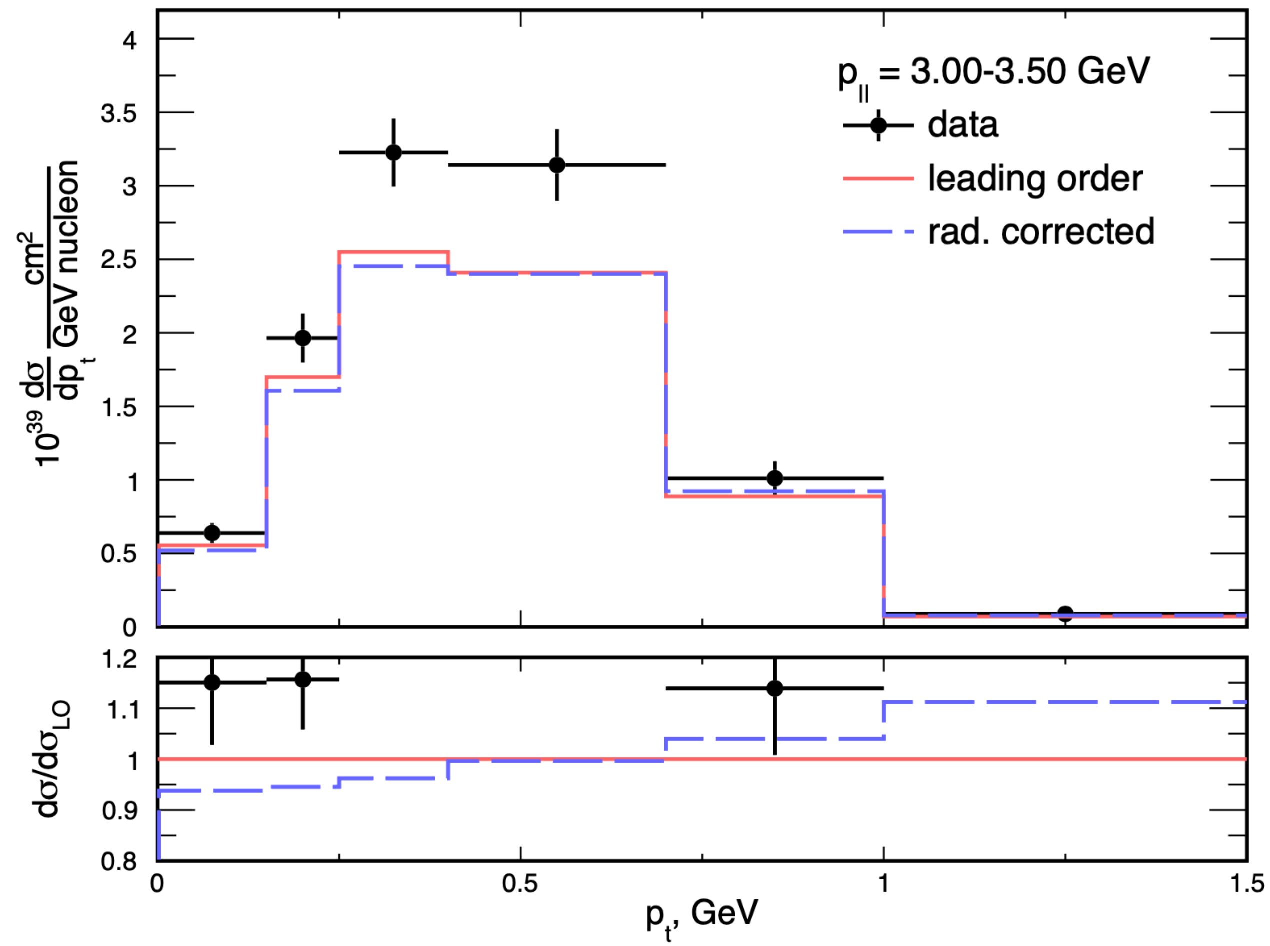
T2K ND280 data



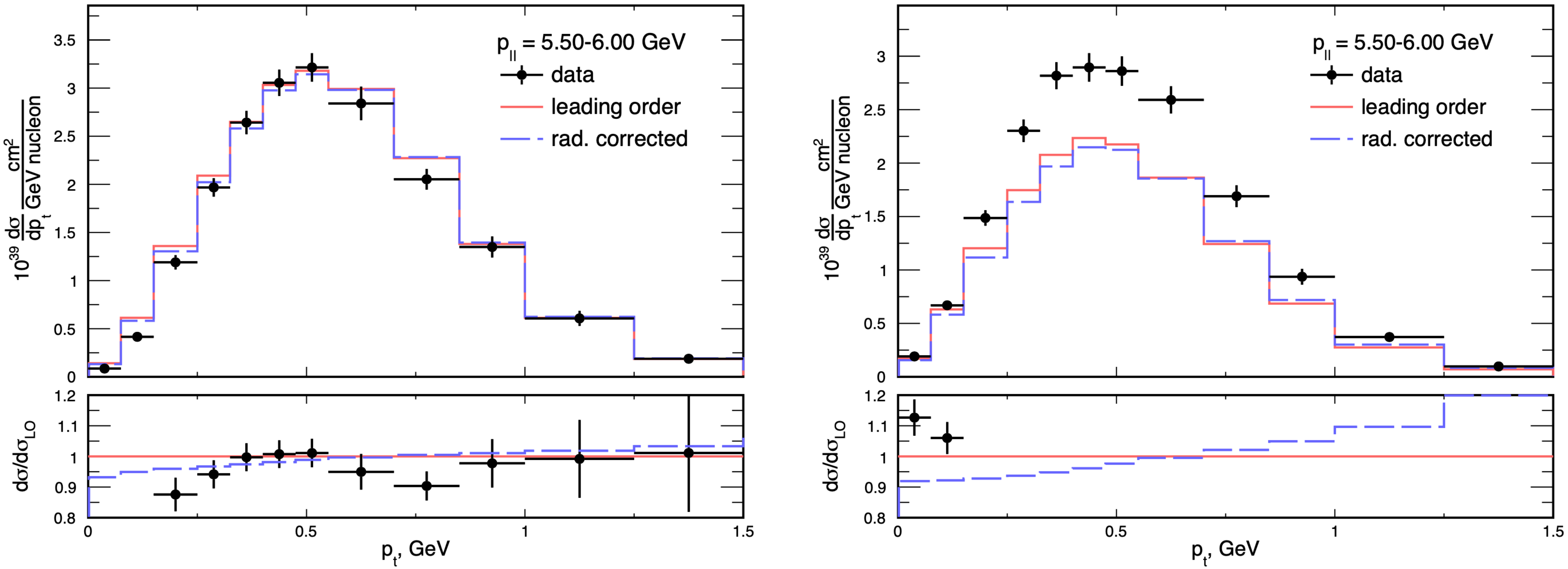


MINERvA LE data



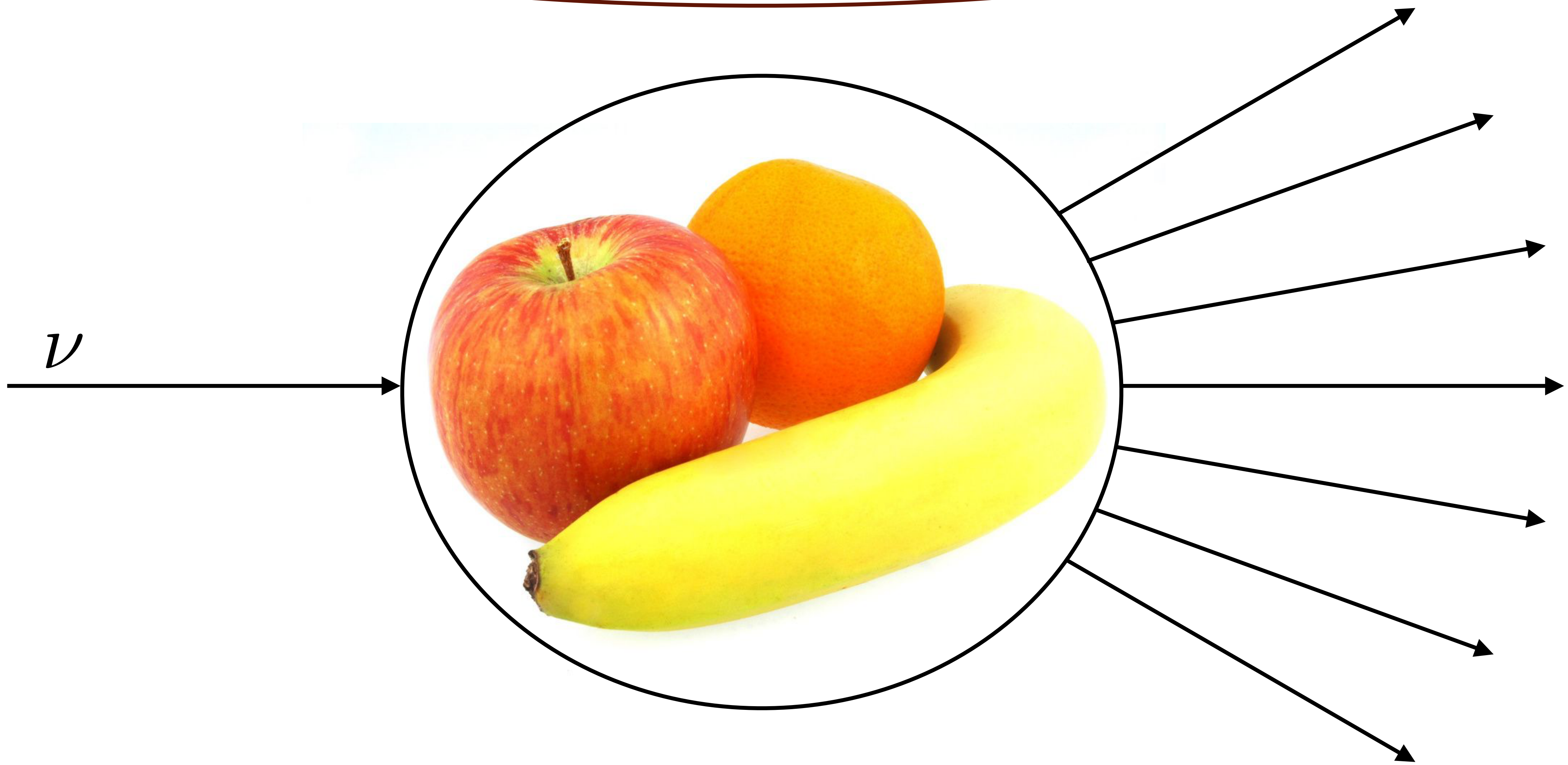


MINERvA ME data



Electroweak corrections

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



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

- electroweak corrections can be included in low-energy interactions couplings of effective Lagrangian are precisely determined

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

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

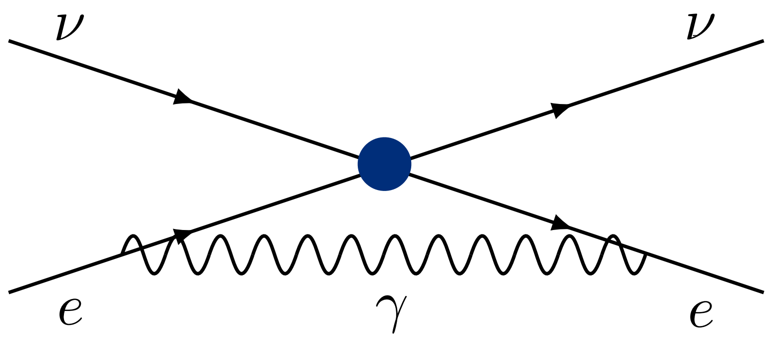
Neutrino-lepton, neutrino-quark scattering

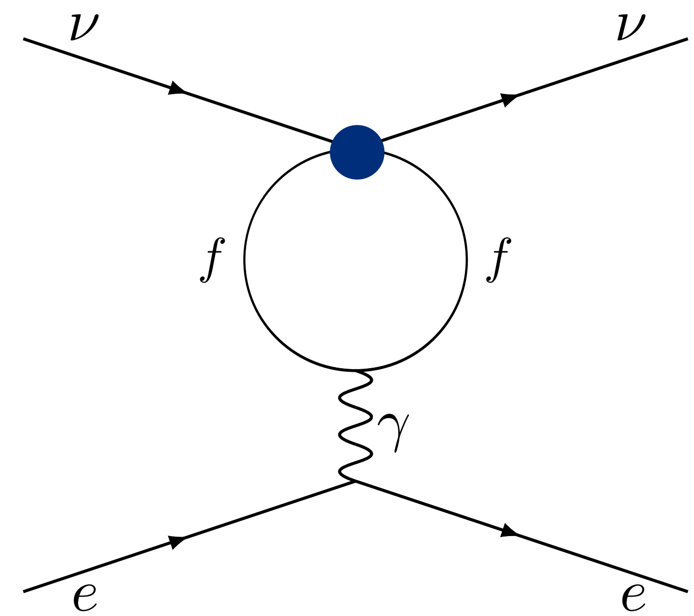
O.T. and Richard J Hill, Phys. Lett. B 805, 3, 135466 (2020)

known at permille level ✓

leading in $\mathrm{G_F}$ terms with loop expansion in α, α_s within Standard Model

poster at Neutrino 2020: https://youtu.be/mrW4aYjP57w



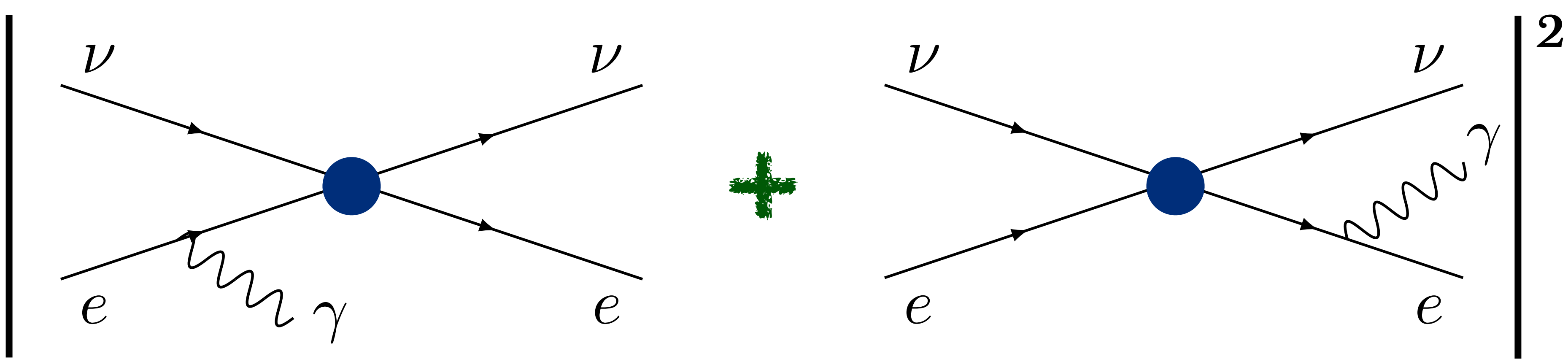


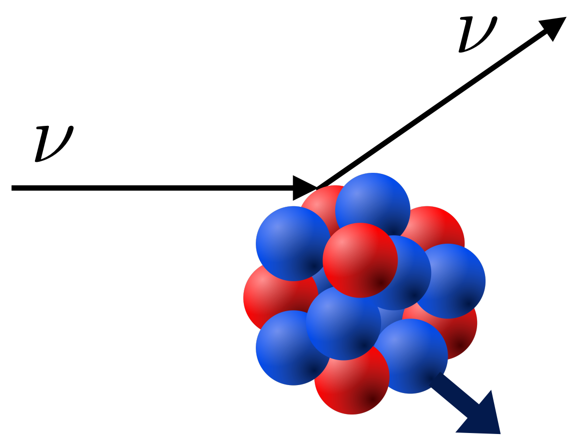
Neutrino-electron scattering

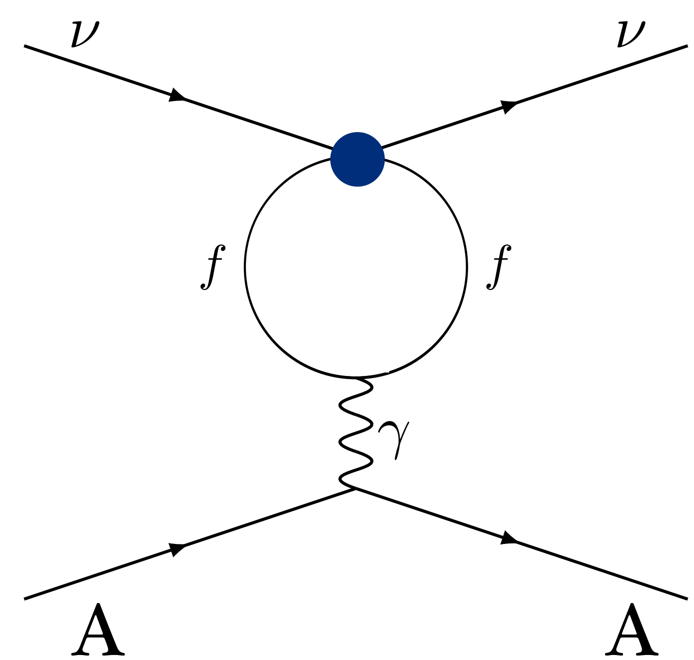
O.T. and Richard J Hill, Phys. Rev. D 101 3, 033006 (2020)

percent-level predictions for MINERvA

known analytically at permille level for NOvA and DUNE







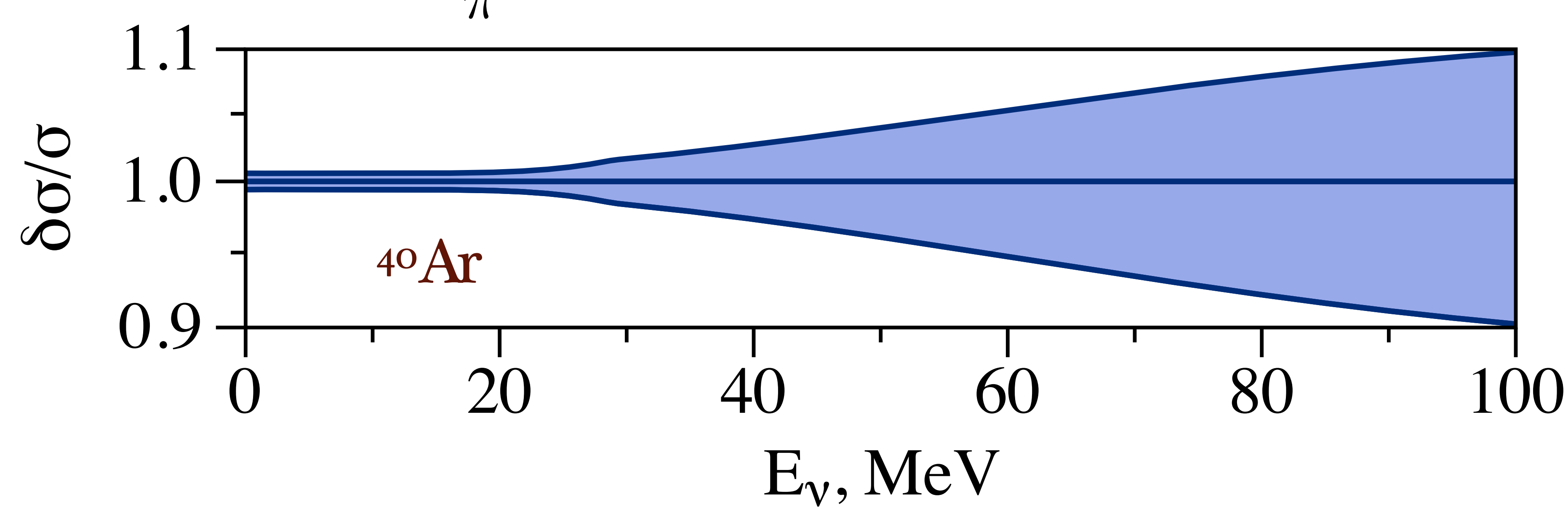
Coherent elastic neutrino-nucleus scattering

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

$$\mathrm{F_W}\left(Q^2\right) \to \mathrm{F_W}\left(Q^2\right) + \frac{\alpha}{\pi}[\delta^{\nu_\ell} + \delta^{\mathrm{QCD}}]\mathrm{F_{ch}}(Q^2)$$

flavor-dependent
at percent level

for Coherent and CCM

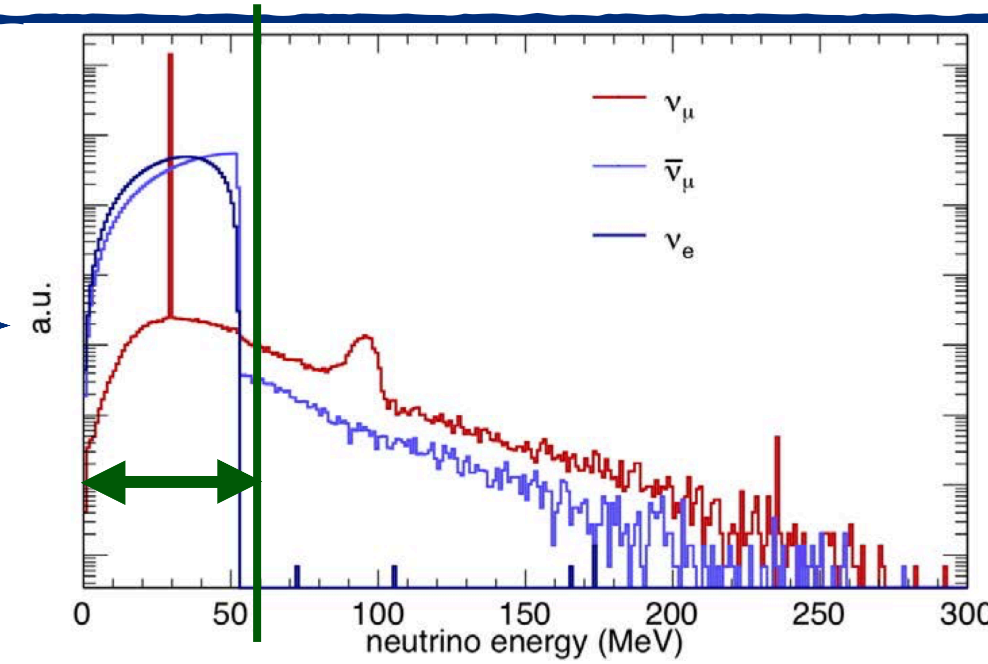


flavor-dependence at tree-level

energy spectra from πDAR

$$\pi^+ \to \mu^+ \nu_\mu$$

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



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

Neutrinos from muon, pion and kaon decays

O. T., arXiv: 2112.12395

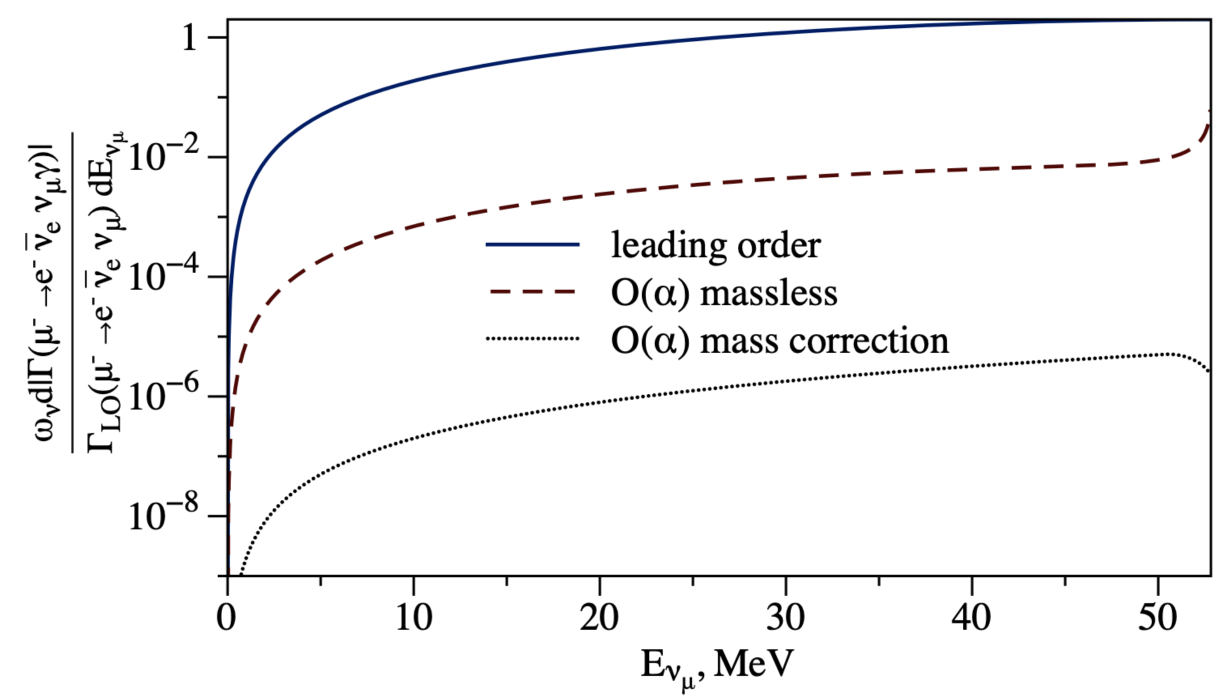
$$\pi^+ \to \mu^+ \nu_\mu \gamma$$

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

< 0.1 ‰

flavor-dependence is clarified to permille level analytically ✓

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



first QED/EW form factors with different mass