RADCOR-LoopFest 2021

Florida State University, USA

Virtual Conference

20 May, 2021

Radiative corrections in neutrino physics

University of Kentucky

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Outline

1) coherent elastic neutrino-nucleus scattering (CEvNS)

neutrino energy < 100 MeV

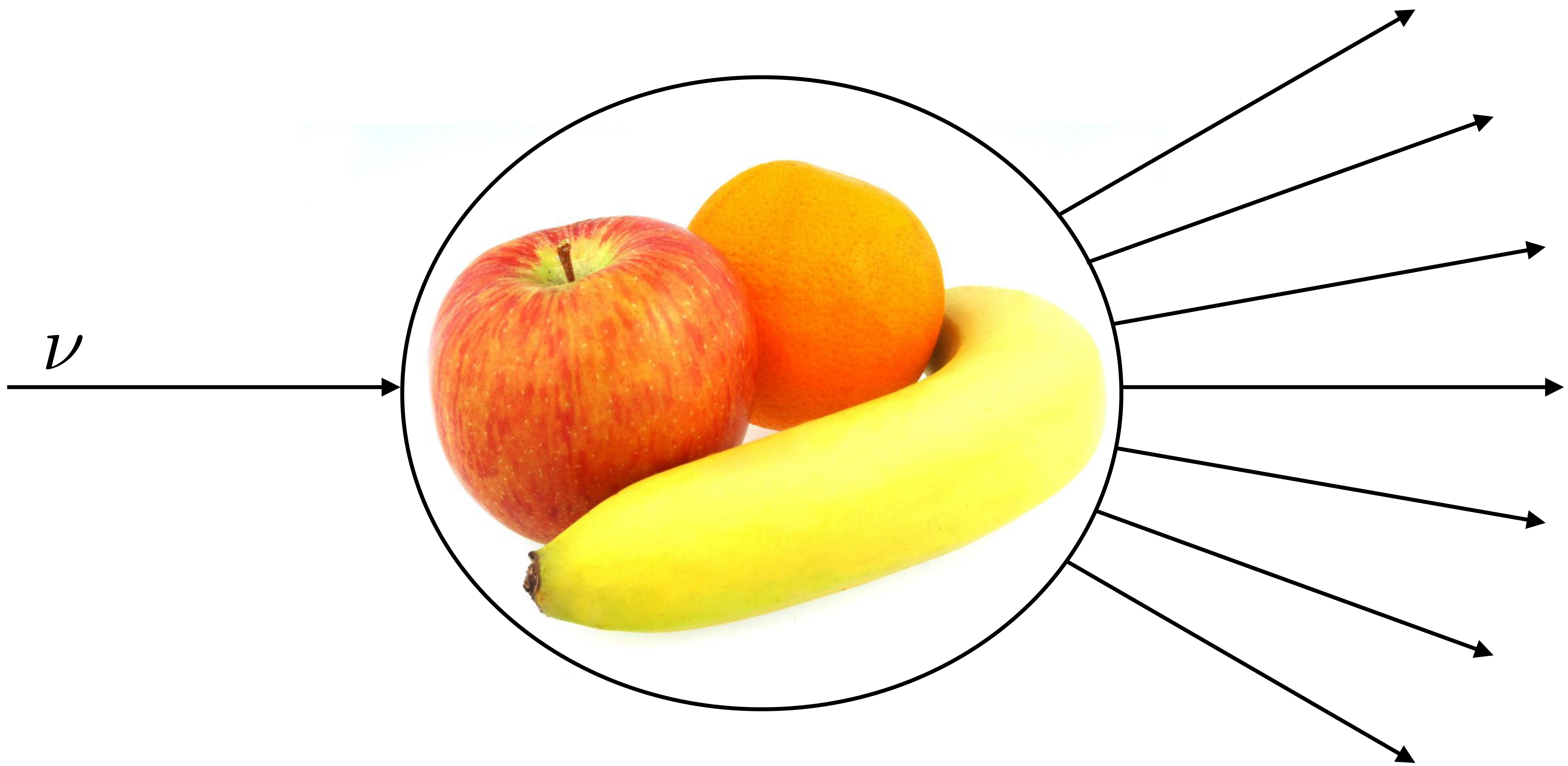
O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

2) charged-current elastic scattering on nucleons

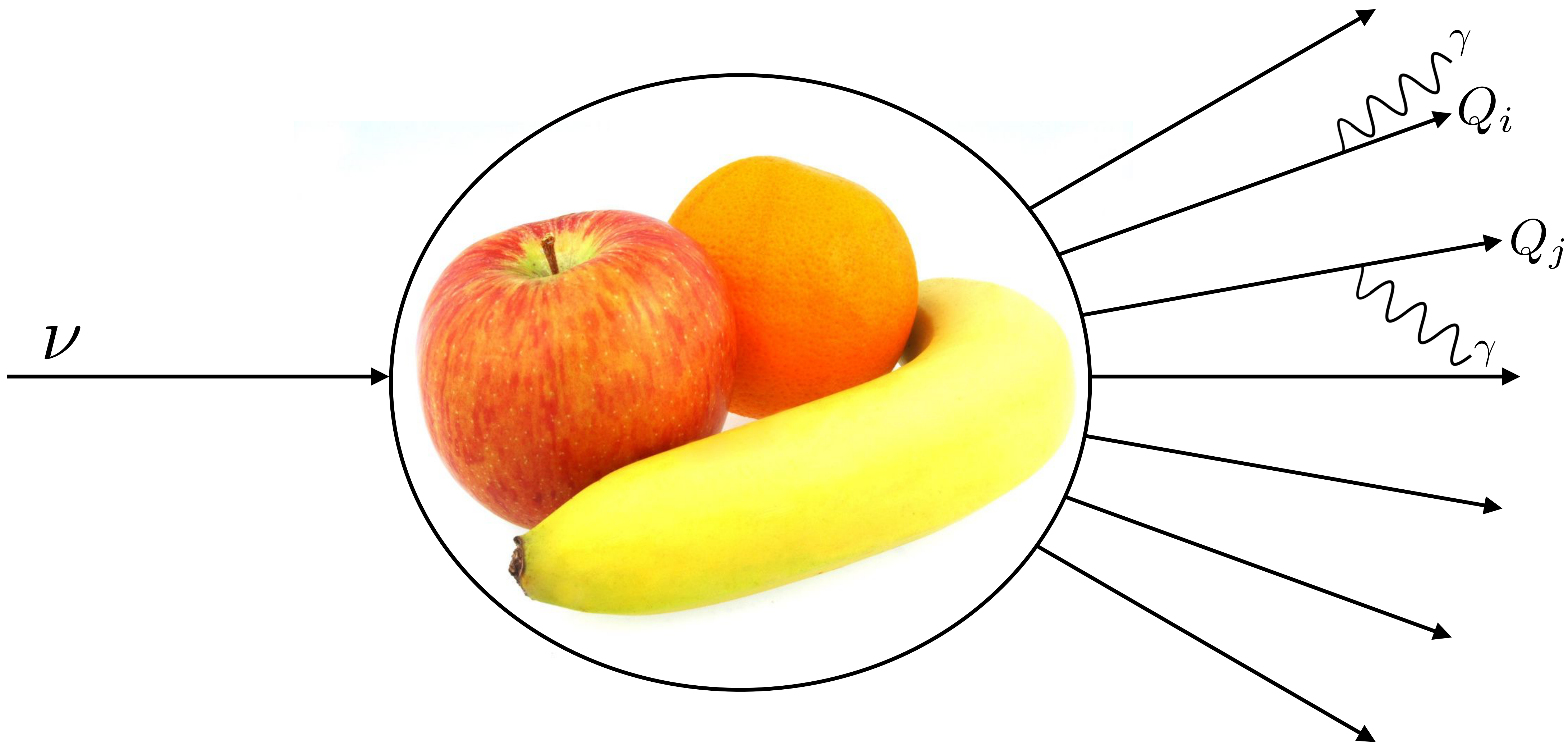
neutrino energy ~ 1 GeV

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

Neutrino interactions

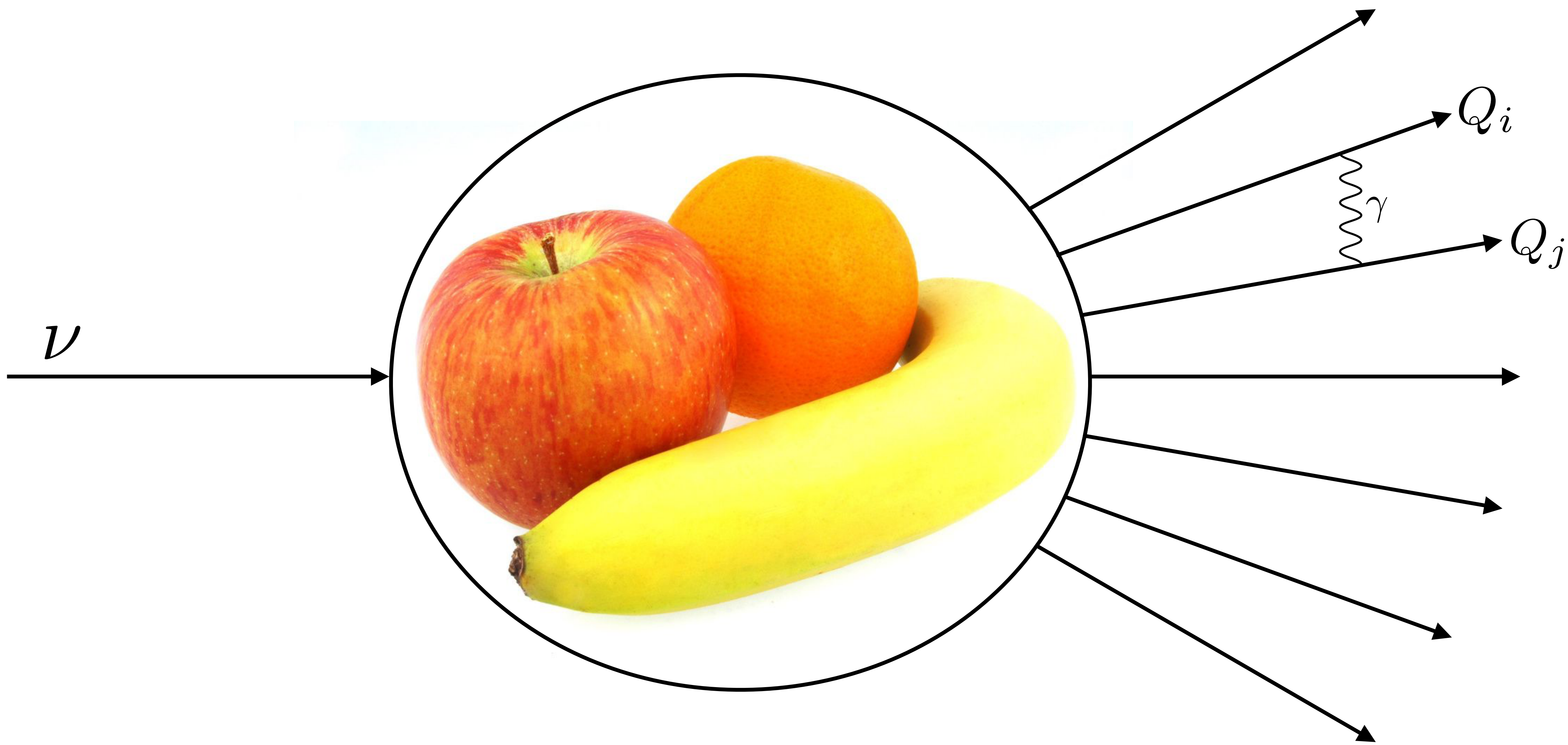


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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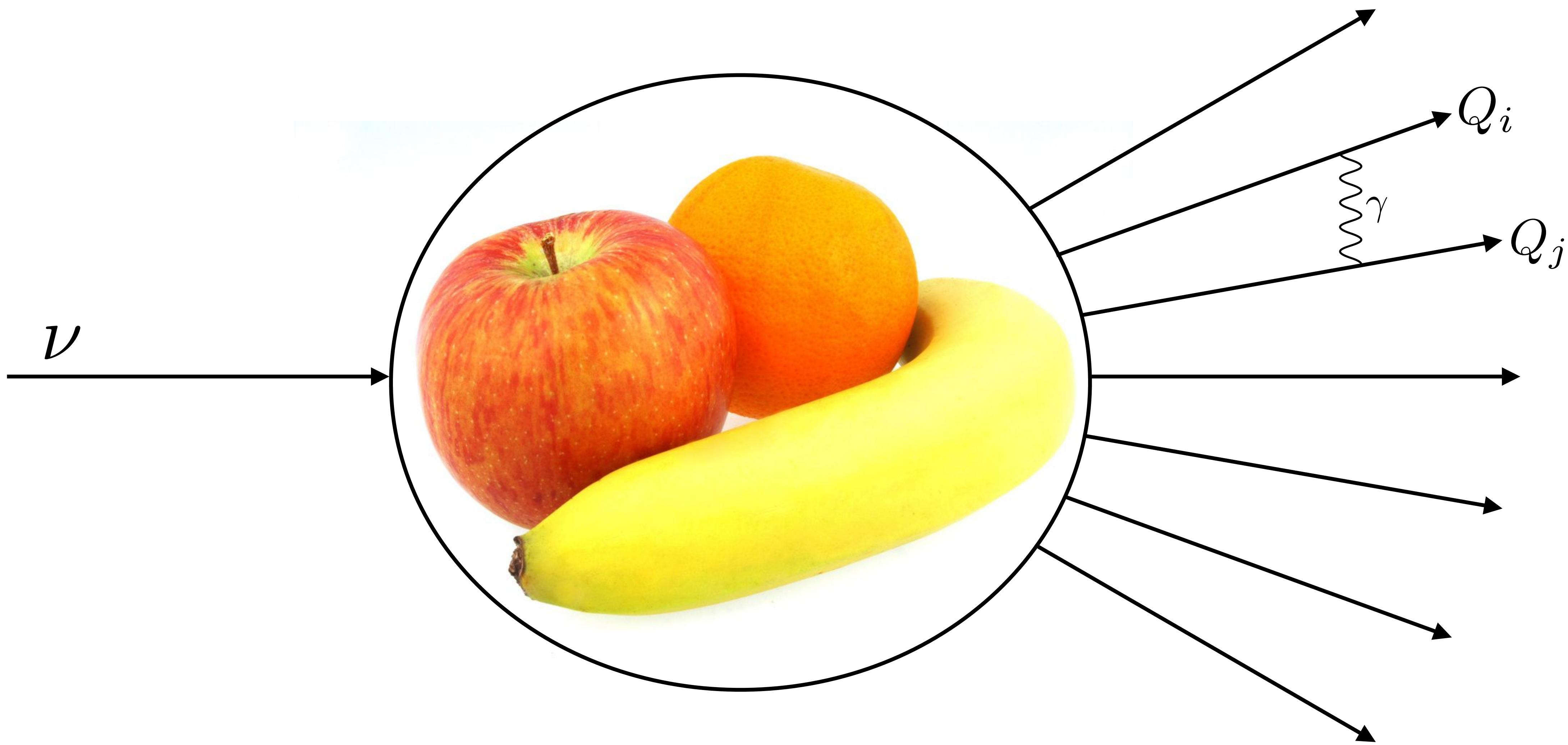
QED corrections



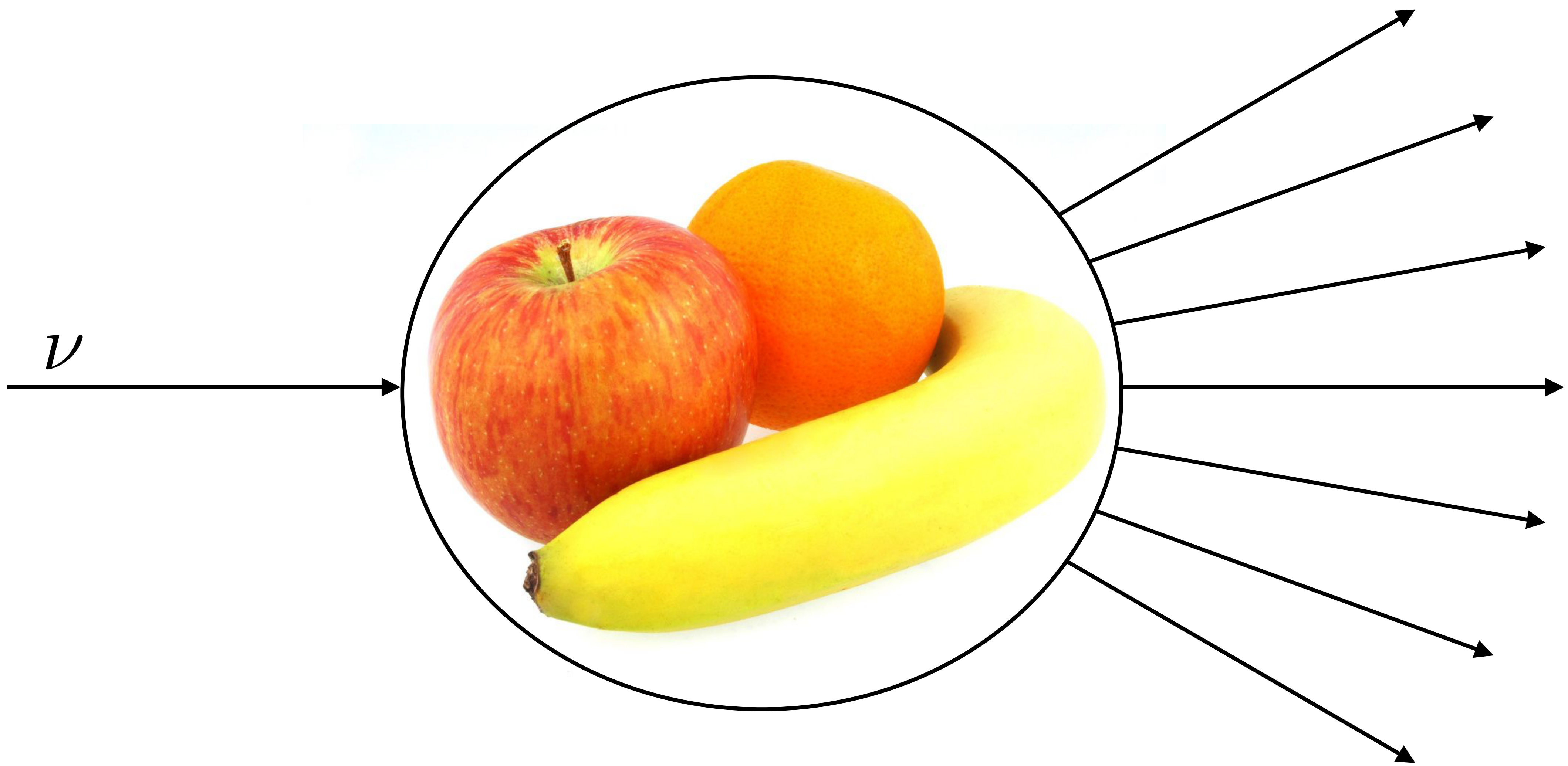
- $\frac{\alpha}{\pi} \sim 0.2\ \%$ suppression by electromagnetic coupling constant

QED corrections

CEvNS

neutral-current interactions

JHEP 2102, 097 (2021)



$X \frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by kinematic-dependent factors

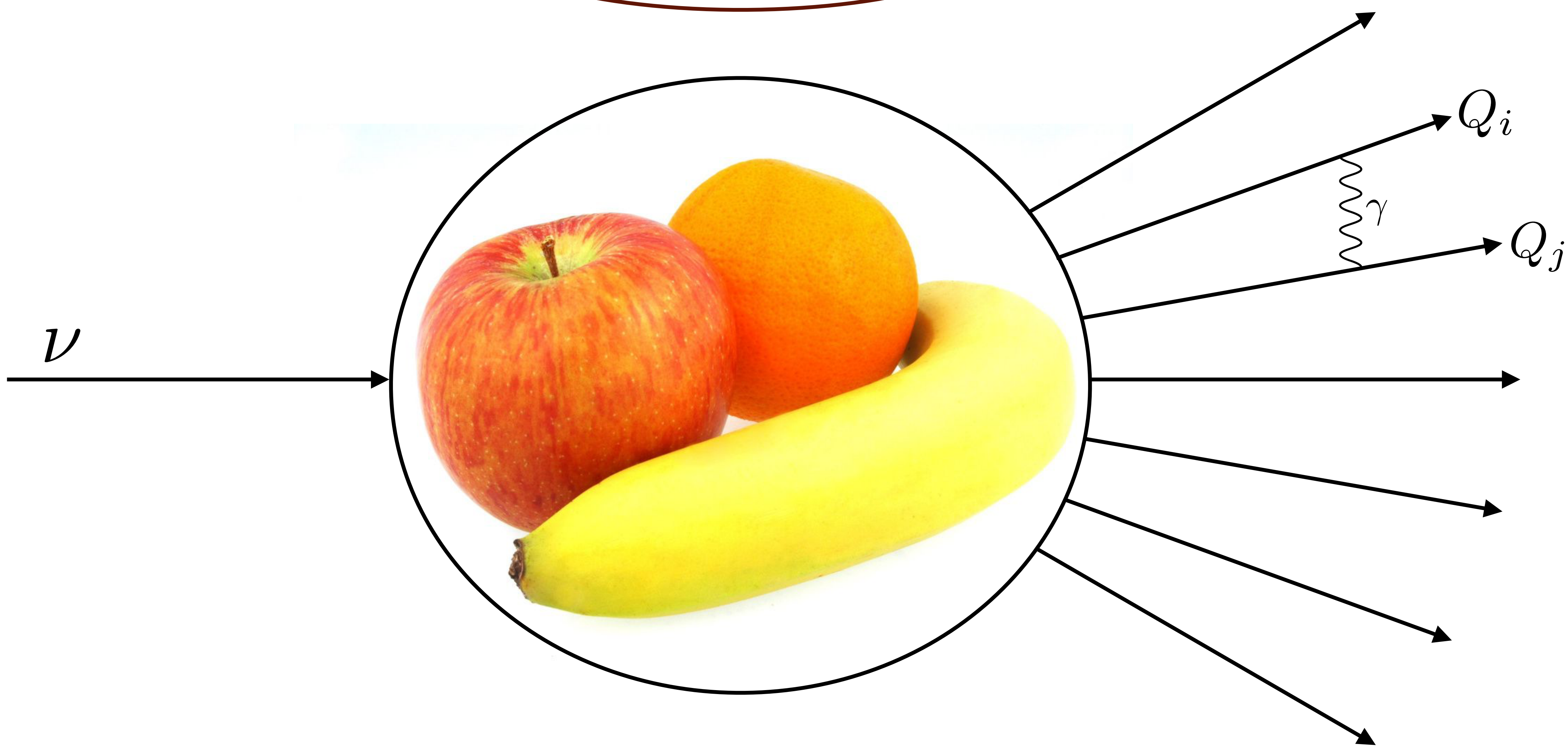
- kinematic dependence and factor X can enhance QED corrections

QED corrections

CCQE

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

arXiv: 2105.07939

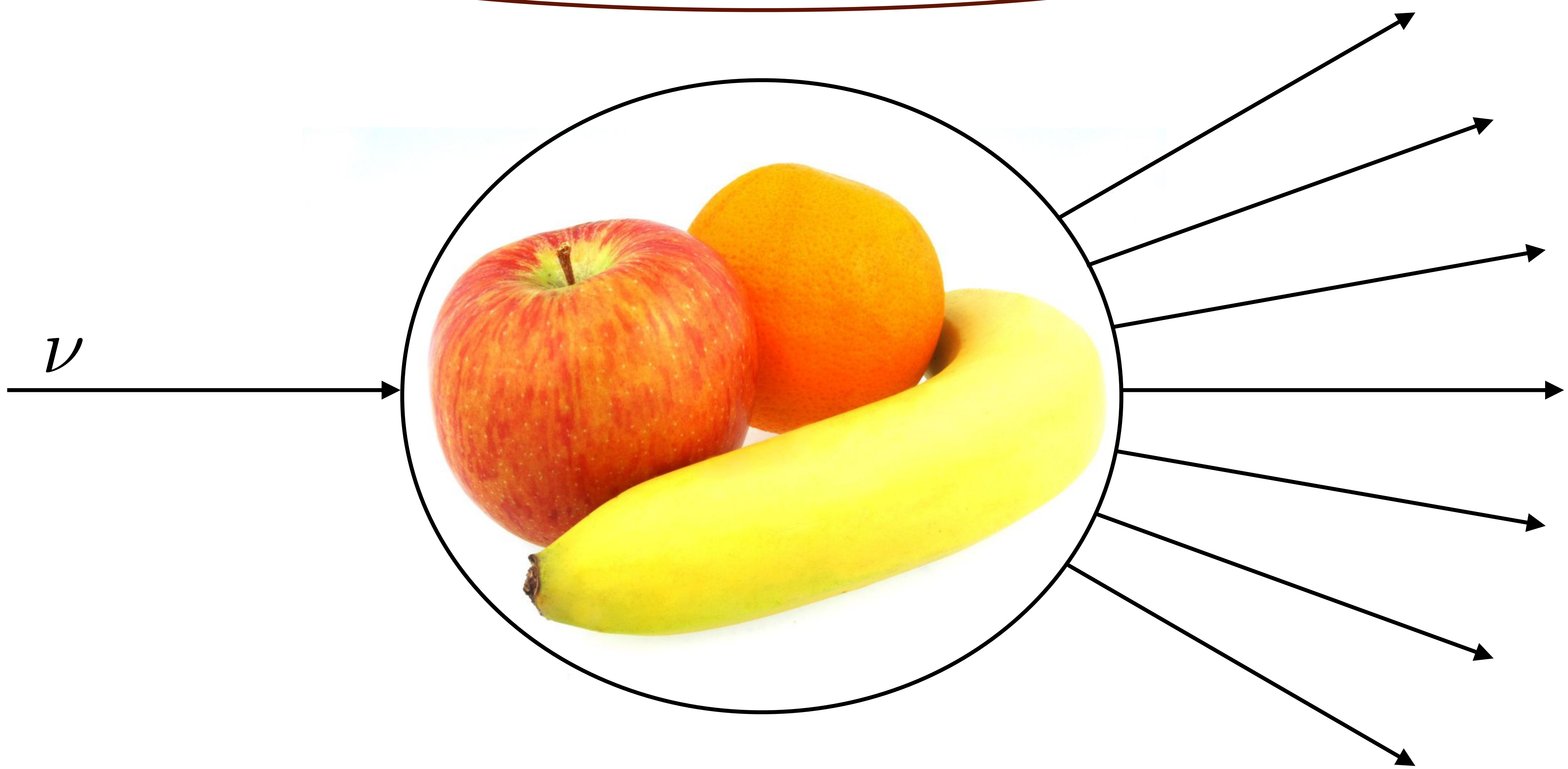


$$\frac{\alpha}{\pi} \sim 0.2\ \% \text{ multiplied by } \ln \frac{E_\nu}{m_e} \sim 6 - 10 \text{ or } \ln^2 \frac{E_\nu}{m_e} \sim 36 - 100$$

- scale separation: large flavor-dependent logarithms for GeV energy

Electroweak corrections

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



$\frac{\alpha}{\pi} \sim 0.2\ \%$ **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

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

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

Neutrino-lepton, neutrino-quark scattering

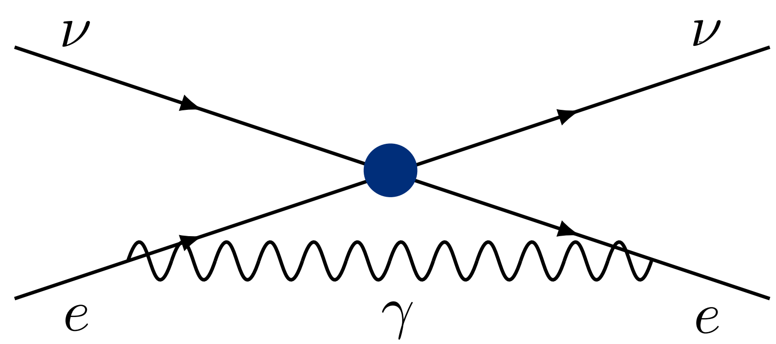
O.T. and Richard J Hill, Phys. Lett. B 805 (2020) 3, 135466

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

known at permille level ✓

leading in G_F terms with loop expansion in α, α_s within Standard Model

gauge-invariant matching and running, $\overline{\rm MS}$ renormalization scheme



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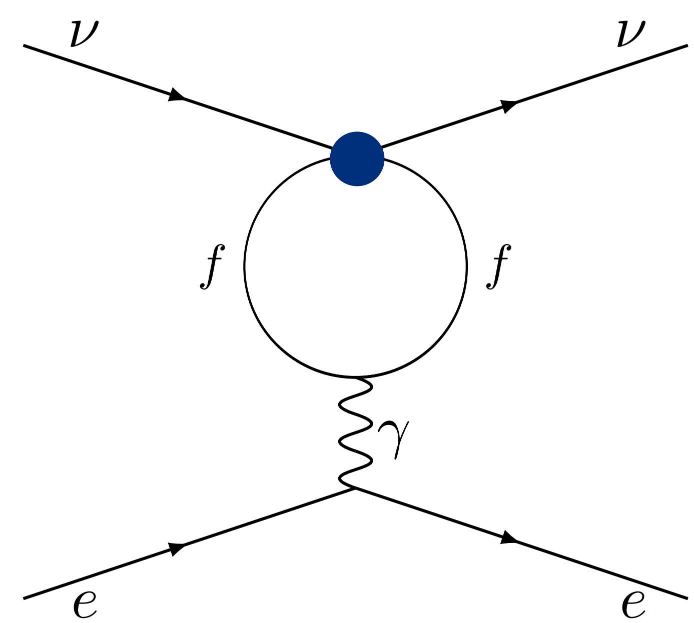
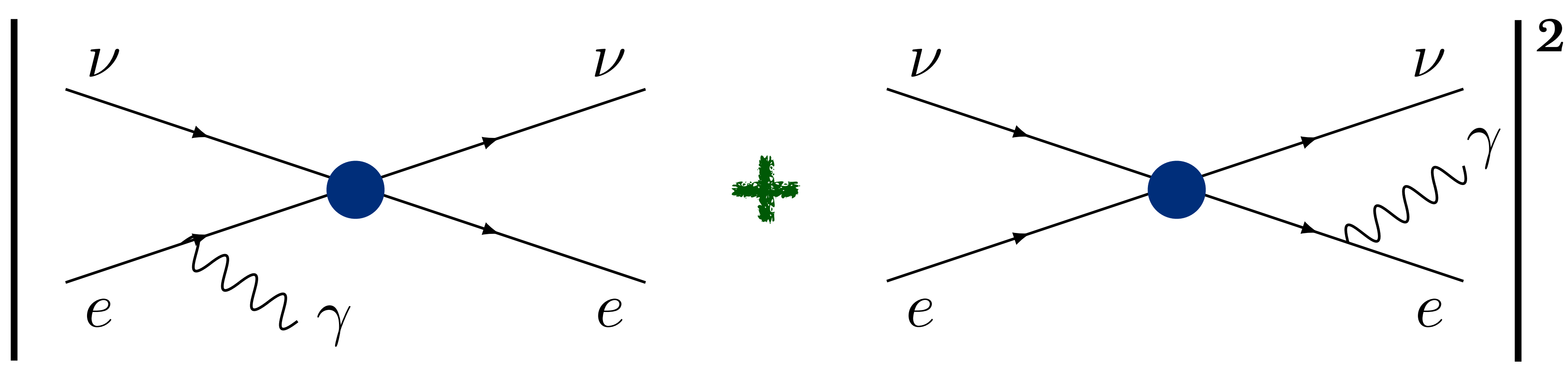


Neutrino-electron scattering

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

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

known at permille level



Coherent elastic neutrino-nucleus scattering

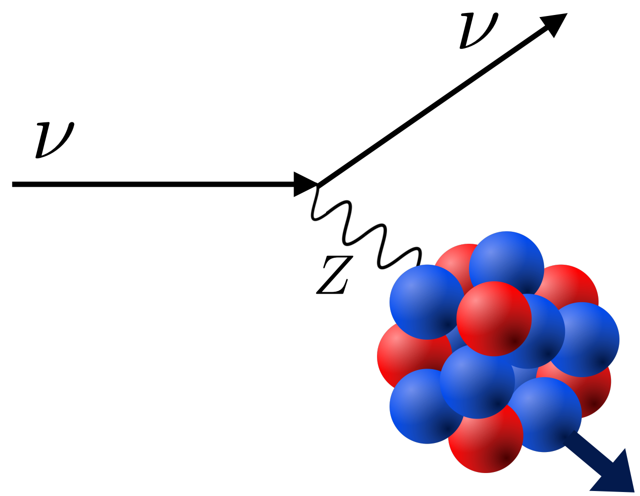
O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

Coherent elastic neutrino-nucleus scattering

- at low neutrino energies (<50 MeV) nuclear state is unchanged

  nucleus recoils as a whole

Stodolsky (1966), Freedman (1974), Kopeliovich and Frankfurt (1974)



recoil nucleus energy T

- large cross section scales as squared number of neutrons N^2

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{M_A T}{2E_\nu^2}\right)\left(N - \left(1 - 4\sin^2\theta_W\right) Z\right)^2$$

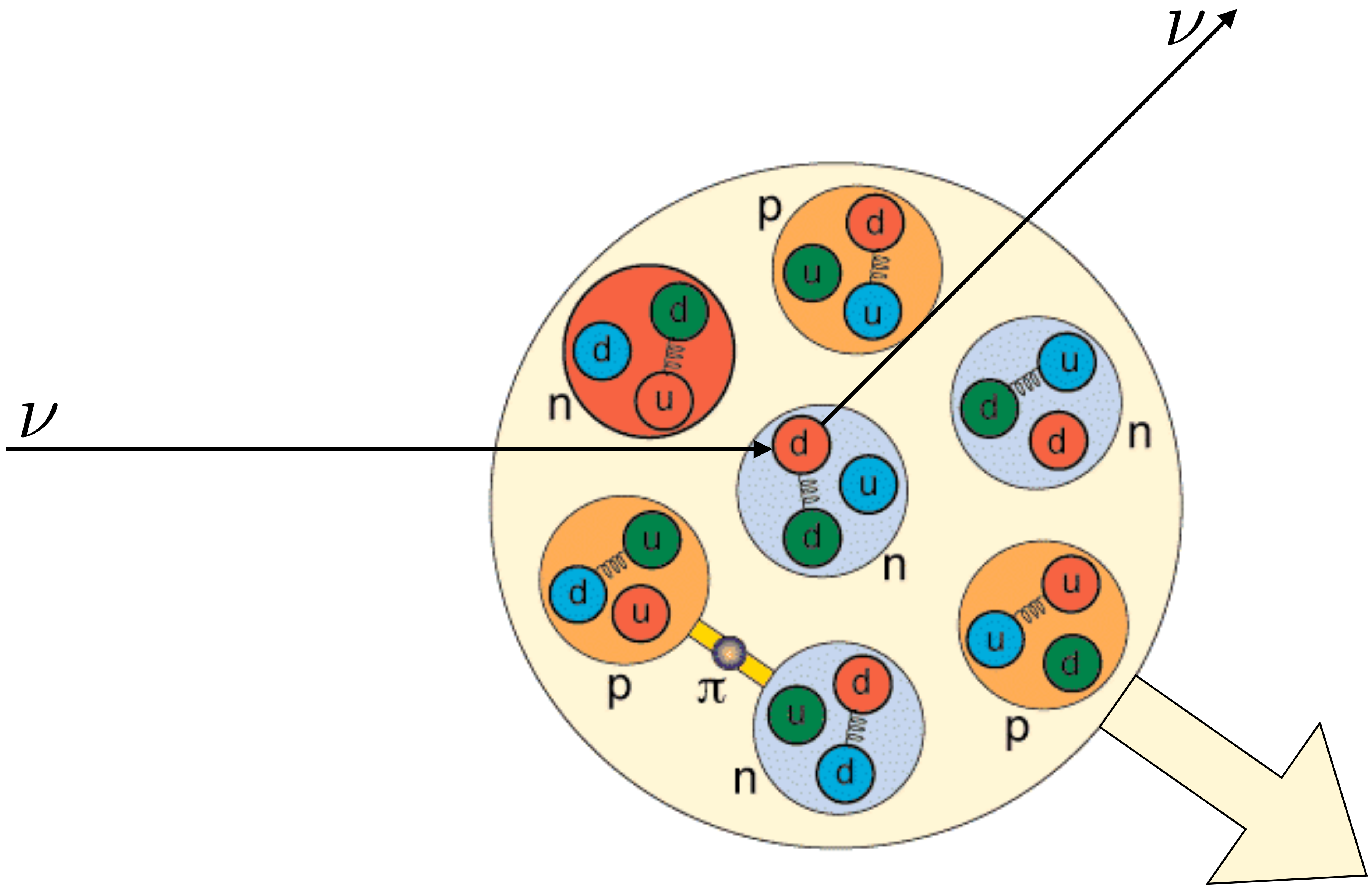
- first detection in 2017 at SNS (Oak Ridge), measured on CsI and Ar

COHERENT, Science 357 (2017) 6356, 1123-1126

- rapidly developing field nowadays

- CEvNS enters precision era with πDAR sources

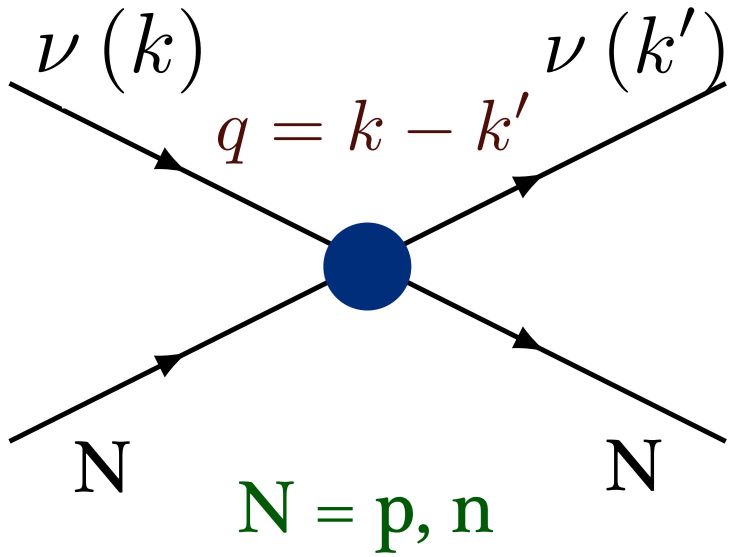
From quarks to nuclei



fafnir.phyast.pitt.edu

- scattering on quarks in nucleons in nucleus

From quarks to nucleons



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

contact interaction at GeV energies

- neutral-current nucleon matrix elements

$$\mathrm{P_{L,R}} = \frac{1 \mp \gamma_5}{2}$$

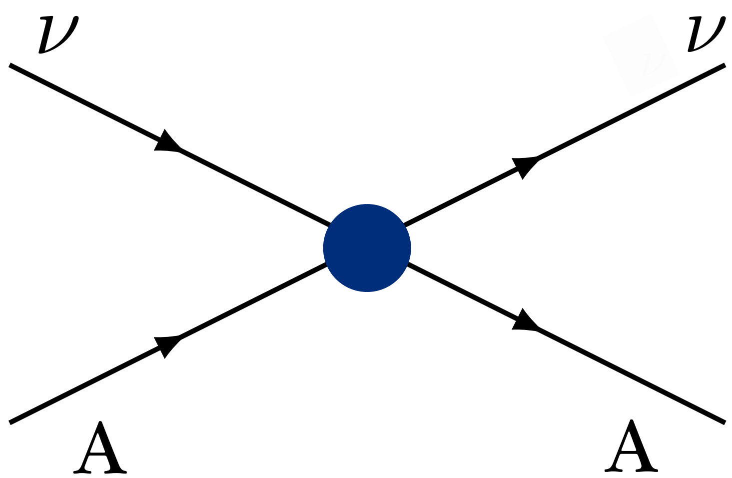
$$\mathcal{M} \sim \bar{\nu}_\ell \gamma_\mu \mathrm{P_L} \nu_\ell \cdot \langle N | \sum_q \bar{q} \gamma^\mu (c_{\mathrm{L}}^{\nu_\ell q} \mathrm{P_L} + c_{\mathrm{R}}^{\nu_\ell q} \mathrm{P_R}) q | N \rangle$$

$$\mathcal{M} \quad \sim \quad \mathrm{G_E}\left(Q^2\right), \mathrm{G_M}\left(Q^2\right), \quad \mathrm{F_A}\left(Q^2\right), \mathrm{F_P}\left(Q^2\right)$$

form factors: electric and magnetic axial and pseudoscalar

- form factors describe matrix elements of quark currents
- πDAR sources: only normalizations and charge radii

From nucleons to nuclei



- tree-level cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2E_\nu^2}\right) F_W^2\left(Q^2\right)$$

spin-0 nuclei

- sum over nucleons with point-nucleon form factors f_p, f_n

$$F_W = \left(\frac{c_L^{\nu_\ell u} + c_R^{\nu_\ell u}}{\sqrt{2}G_F} G_E^{n,u} + \frac{c_L^{\nu_\ell d} + c_R^{\nu_\ell d}}{\sqrt{2}G_F} G_E^{n,d}\right) f_n + (n \leftrightarrow p)$$

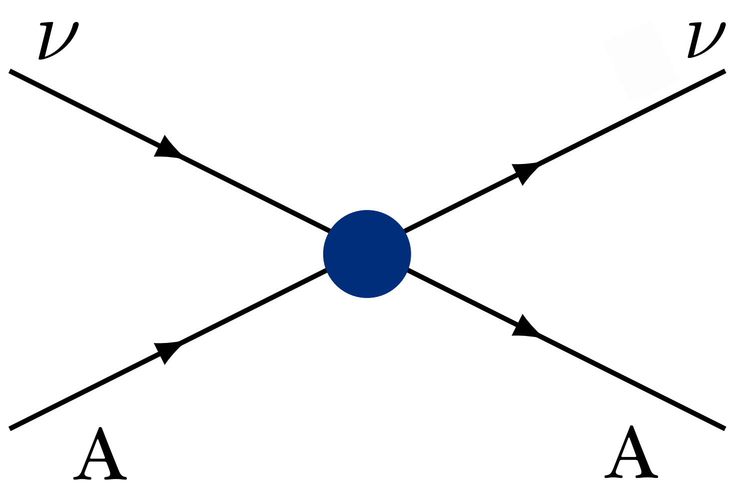
- flavor-independent form factor above GeV scale

- Q^2/M^2 corrections and spin-dependent terms are known

Hoferichter et al. (2020)

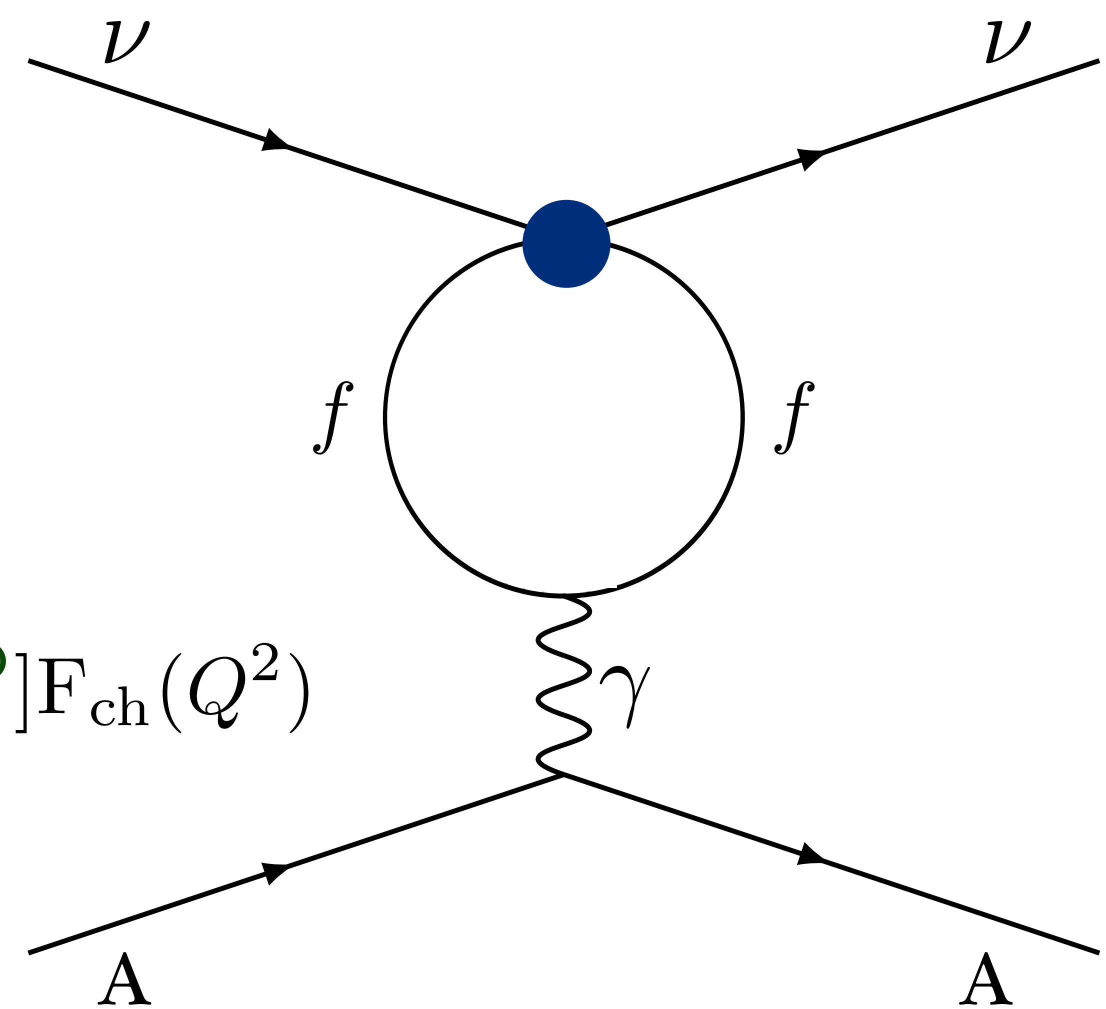
- point-nucleon form factors: distribution of nucleons in nuclei
- πDAR sources: factorization starting from quark level

CEvNS cross section on spin-0 nuclei



- tree-level cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{\mathrm{G}_{\mathrm{F}}^{2} M_{\mathrm{A}}}{4\pi}\left(1 - \frac{T}{E_{\nu}} - \frac{M_{\mathrm{A}} T}{2E_{\nu}^{2}}\right) \mathrm{F}_{\mathrm{W}}^{2}\left(Q^{2}\right)$$



- effect of radiative corrections

$$\mathrm{F}_{\mathrm{W}}\left(Q^{2}\right) \rightarrow \mathrm{F}_{\mathrm{W}}\left(Q^{2}\right) + \frac{\alpha}{\pi}[\delta^{\nu_{\ell}} + \delta^{\mathrm{QCD}}]\mathrm{F}_{\mathrm{ch}}(Q^{2})$$

- radiative corrections enter with the nucleus charge form factor

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT

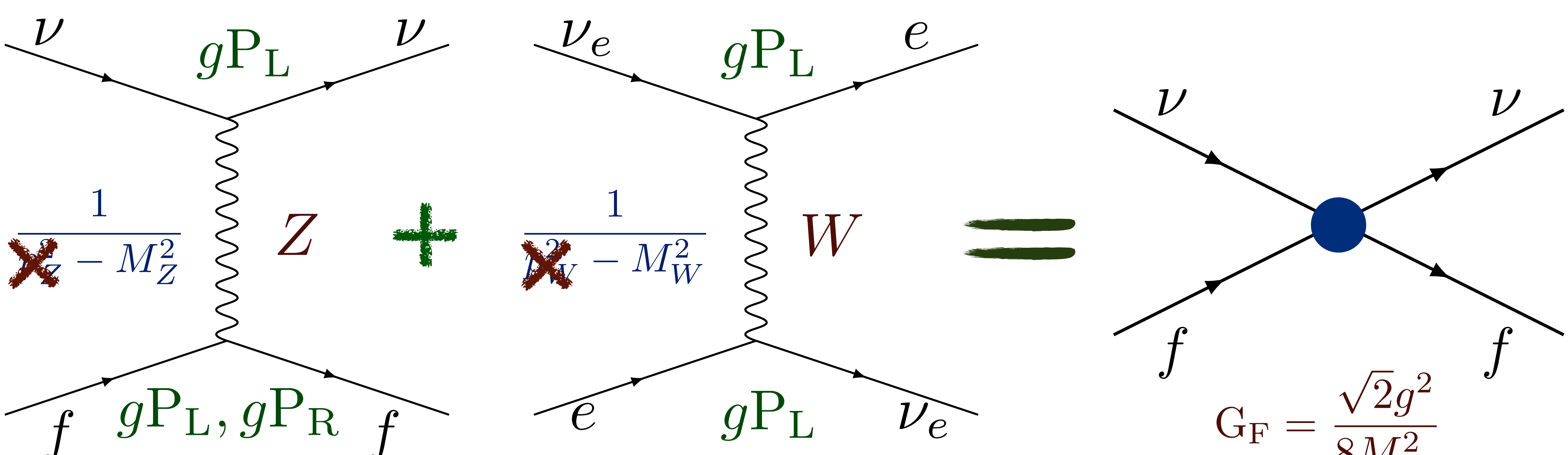
$$\mathcal{L}_{\text{eff}} = -\bar{\nu}_\ell \gamma_\mu \mathrm{P_L} \nu_\ell \cdot \bar{f} \gamma^\mu \left(c_{\mathrm{L}}^{\nu_\ell f} \mathrm{P_L} + c_{\mathrm{R}}^{\nu_\ell f} \mathrm{P_R} \right) f$$

couplings to electron

$$c_{\mathrm{R}} = 2\sqrt{2} \mathrm{G_F} \sin^2\theta_W \quad c_{\mathrm{L}} = 2\sqrt{2}\mathrm{G_F} \left(\sin^2\theta_W - 0.5 + \delta_{\nu,\nu_e} \right)$$

Weinberg (1967), 't Hooft (1971)

neutral current charged current



$$\mathrm{G_F} = \frac{\sqrt{2} g^2}{8 M_W^2}$$

- charged current contributes to couplings with the same flavor

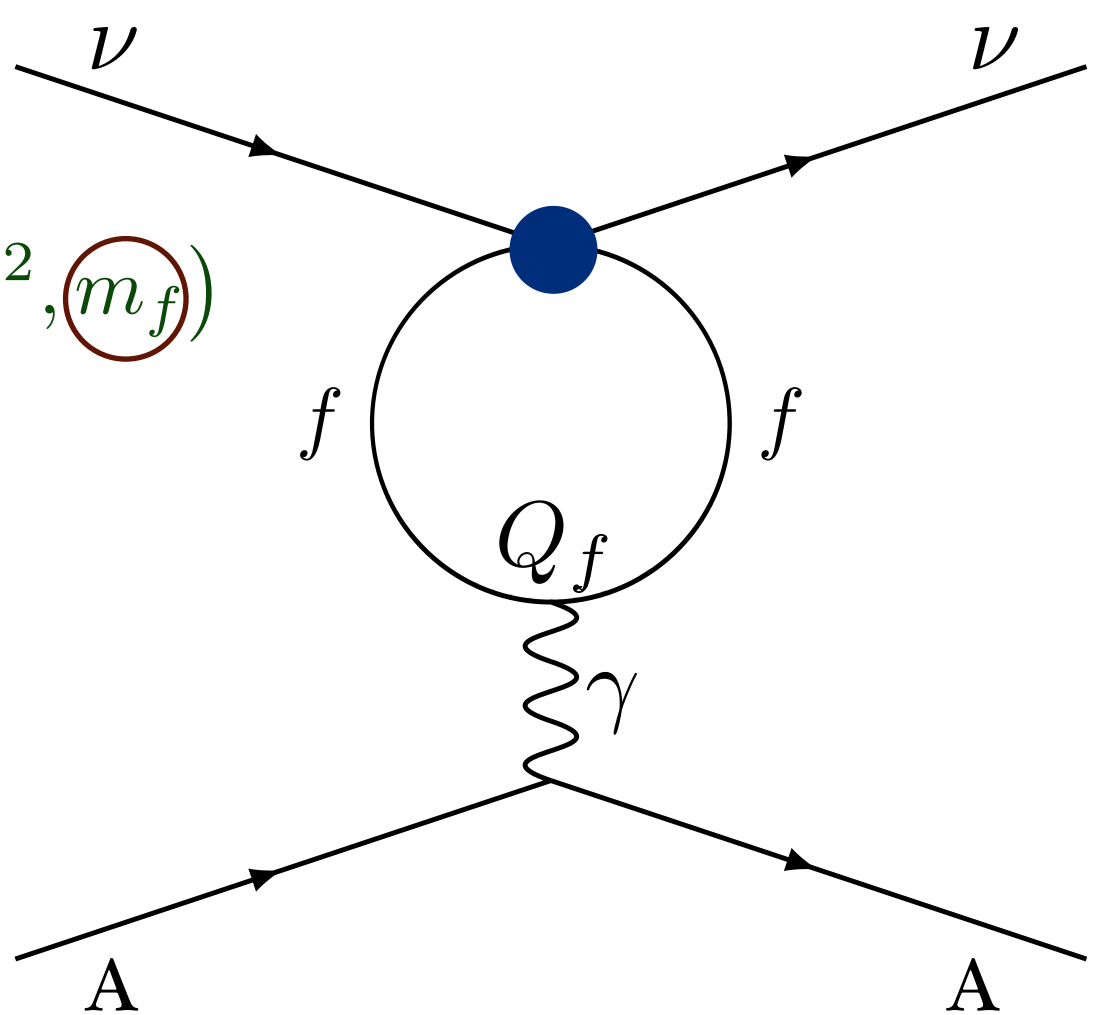
Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop

$$\mathcal{L}_{\text{eff}} = -\bar{\nu}_\ell \gamma_\mu \mathrm{P_L} \nu_\ell \cdot \bar{f} \gamma^\mu \left(c_{\mathrm{L}}^{\nu_\ell f} \mathrm{P_L} + c_{\mathrm{R}}^{\nu_\ell f} \mathrm{P_R} \right) f$$

- lepton loops

$$\delta^{\nu_\ell} = -\sum_f \frac{c_{\mathrm{L}}^{\nu_\ell f} + c_{\mathrm{R}}^{\nu_\ell f}}{\sqrt{2} \mathrm{G_F}} Q_f \Pi \left(Q^2, m_f \right)$$



- origin of flavor dependence

$$c_{\mathrm{L}}^{\nu_e \mu} = c_{\mathrm{L}}^{\nu_\mu e} \neq c_{\mathrm{L}}^{\nu_\mu \mu} = c_{\mathrm{L}}^{\nu_e e}$$

- lepton mass breaks "flavor universality"

Light-quark contribution

- description in terms of quarks is invalid at CEvNS kinematics

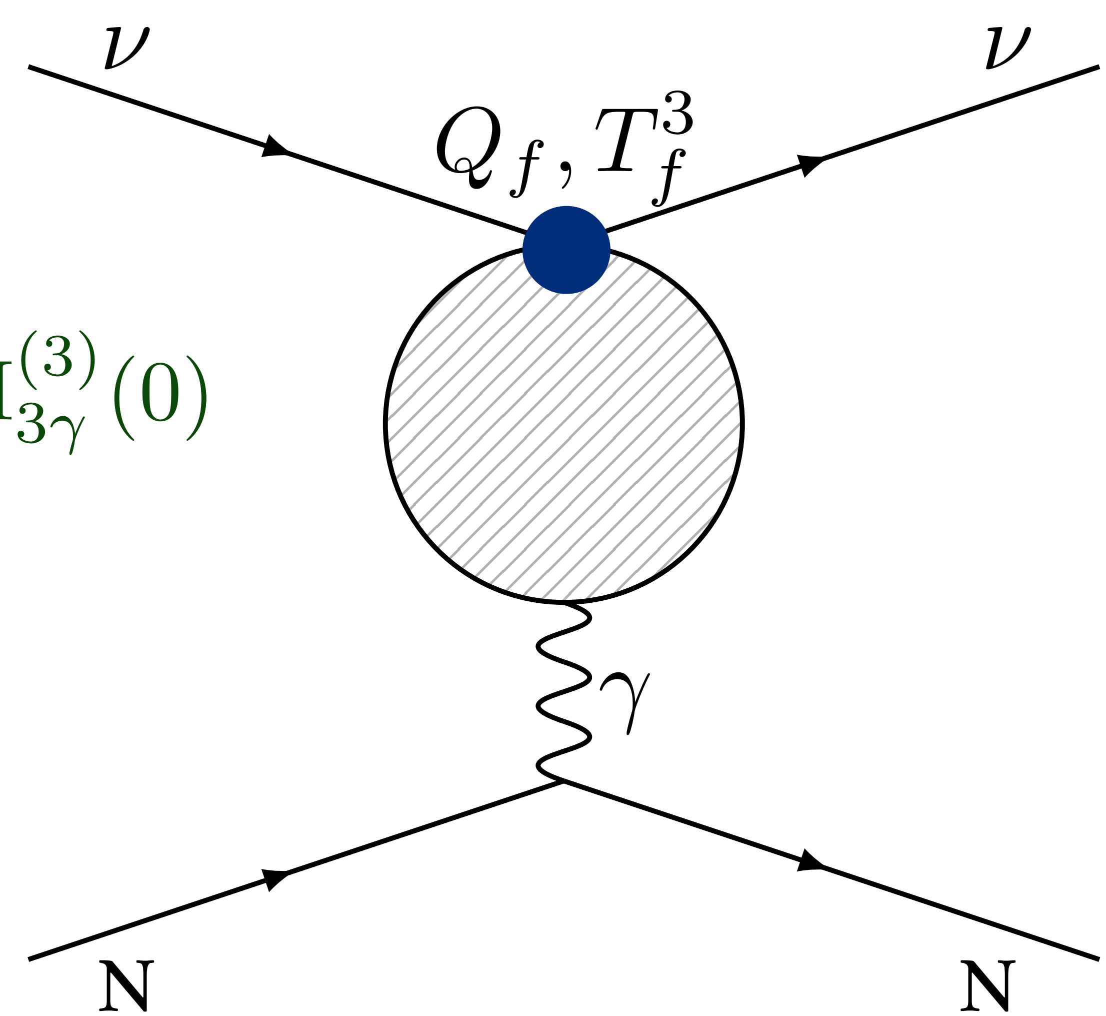
$$Q^2 \ll \Lambda^2_{\rm QCD}$$

- light quarks

$$\delta^{\rm QCD} = 4\Pi^{(3)}_{\gamma\gamma}(0)\sin^2\theta_{\rm W} - 2\Pi^{(3)}_{3\gamma}(0)$$

- chiral symmetry approximation

- flavor independent

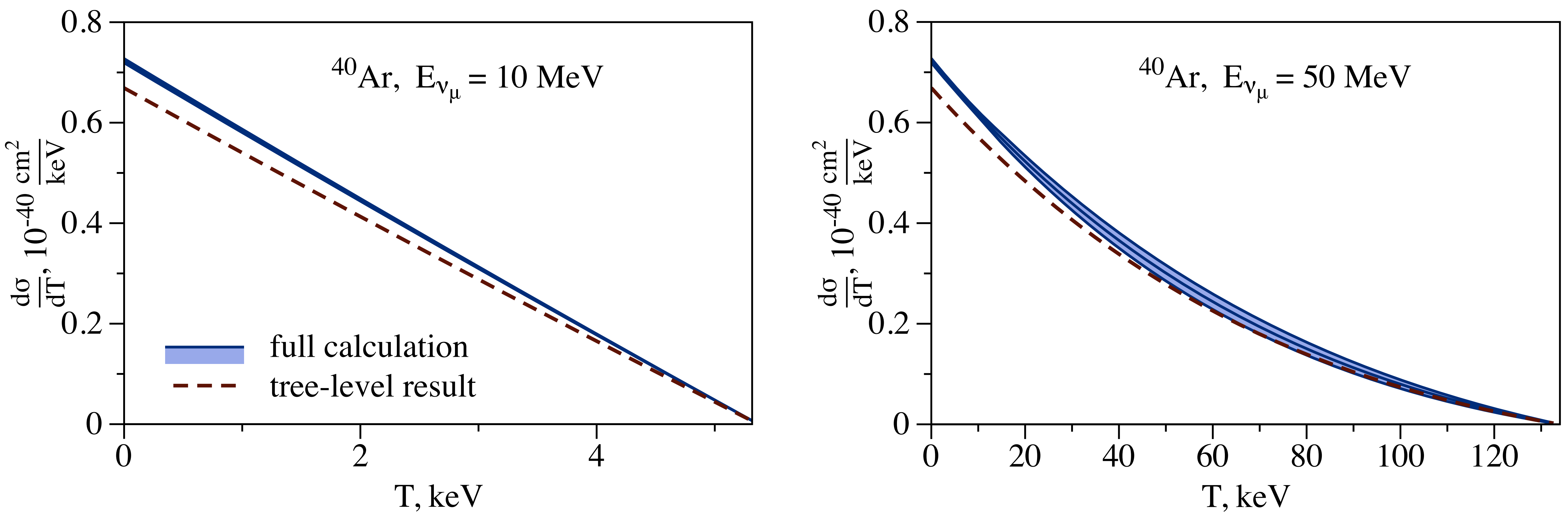


- non-perturbative light-quark contribution: error at low energy

Total and differential cross section

- recoil nucleus energy spectrum: one-loop vs tree level

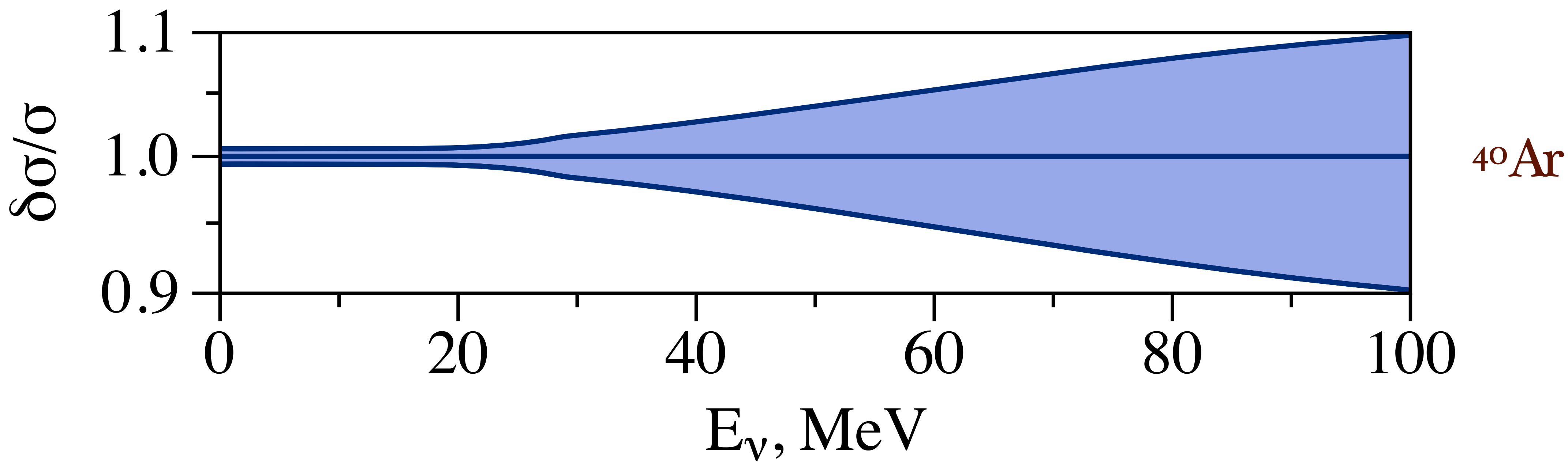
nuclear models for point-nucleon form factors:
Yang et al. (2019), Payne et al. (2019), Hoferichter et al. (2020), Van Dessel et al. (2020)



- % effect of radiative corrections on cross sections

Total cross section errors

- relative cross section error



- sources of uncertainty (%)

E_ν, MeV	Nuclear	Nucleon	Hadronic	Quark	Perturbative	Total
50	4	0.06	0.56	0.13	0.08	4.05
30	1.5	0.014	0.56	0.13	0.03	1.65
10	0.04	0.001	0.56	0.13	0.004	0.58

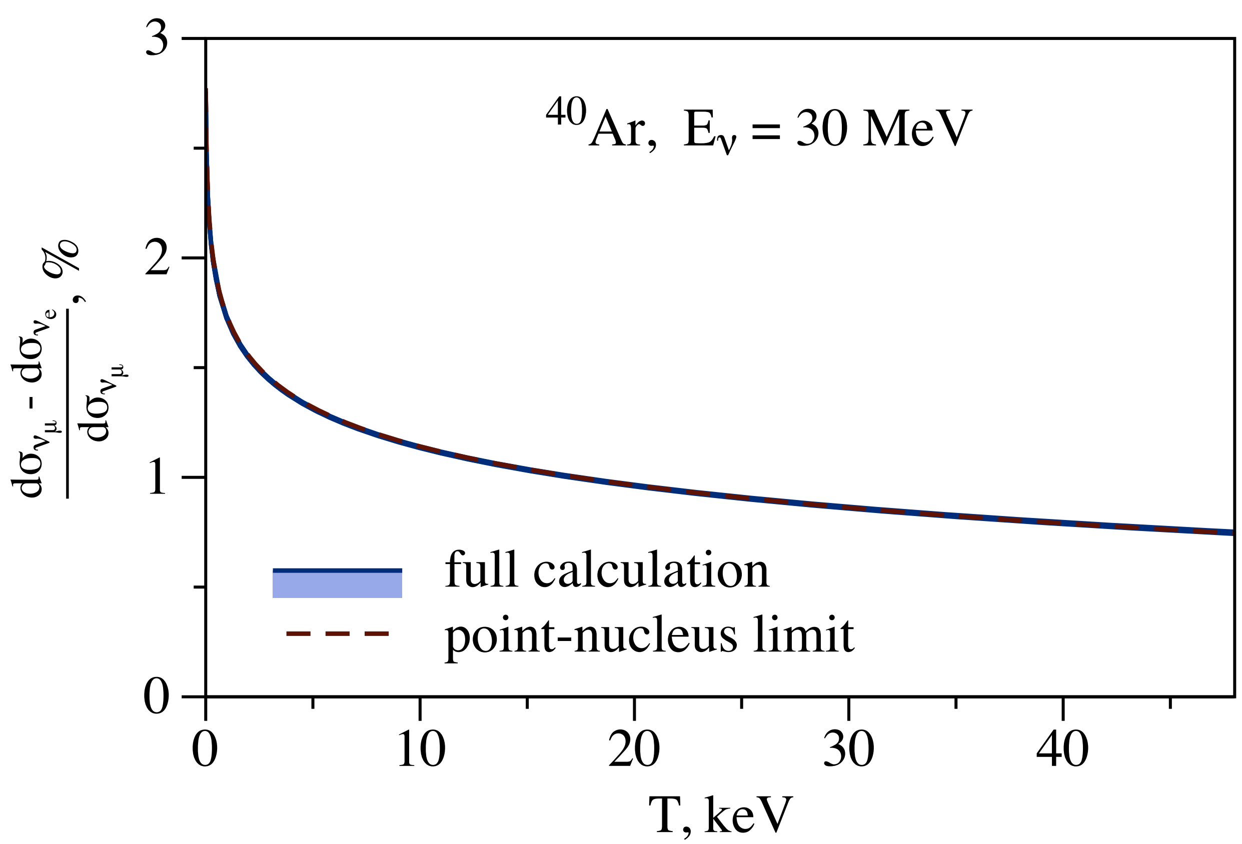
- hadronic error 0.6% at low energy, nuclear error at higher energy

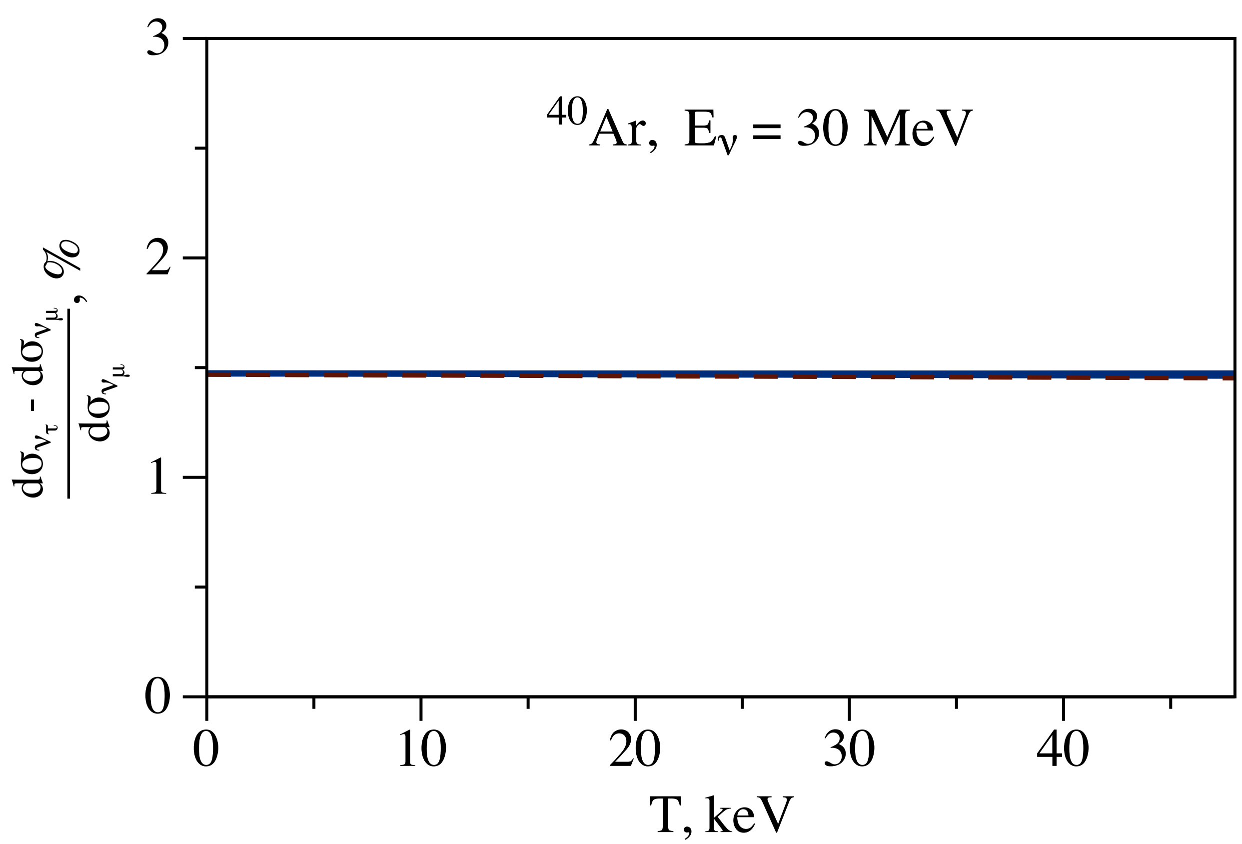
Flavor difference

- well described by point-nucleus limit

$$\lim_{R_p, R_n \to 0} \frac{\mathrm{d}\sigma_{\nu_\ell} - \mathrm{d}\sigma_{\nu_{\ell'}}}{\mathrm{d}\sigma_{\nu_\ell}} = 4\frac{\alpha_0}{\pi}\frac{Z}{Q_{\mathrm{W}}}\left[\Pi\left(Q^2, m_\ell\right) - \Pi\left(Q^2, m_{\ell'}\right)\right]$$

- kinematic dependence: full result vs point-nucleus limit





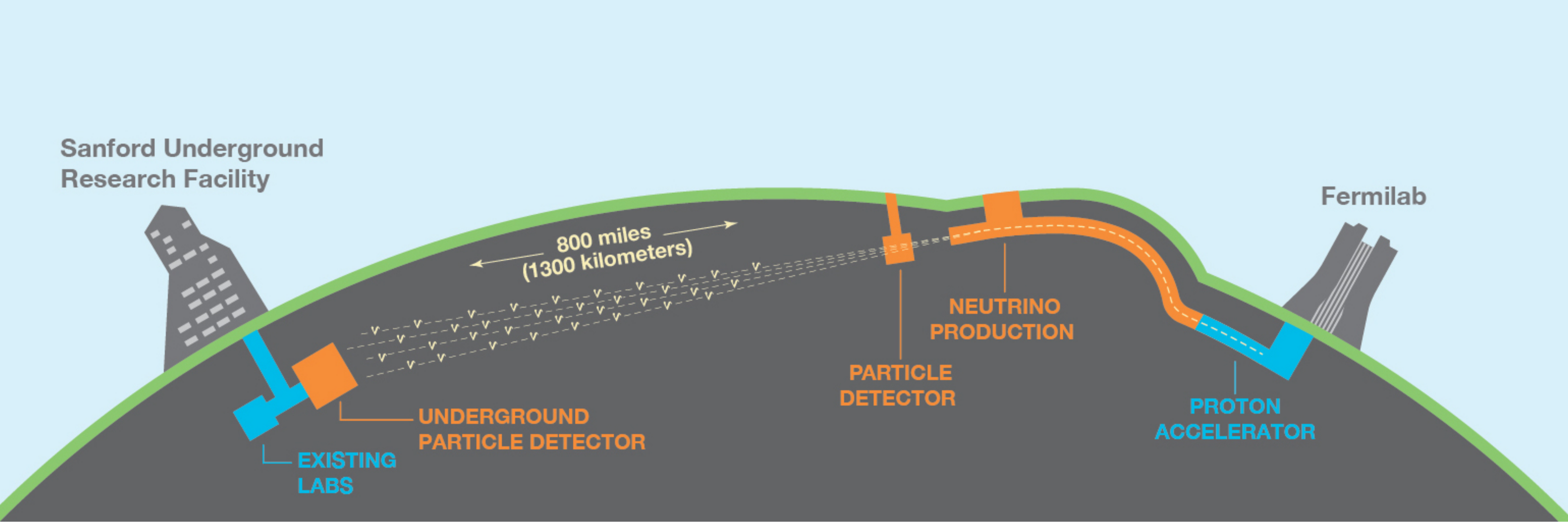
- factor 3-6 change in precisely predicted electron-muon asymmetry

Radiative corrections in CCQE on free nucleons

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

Neutrino experiments

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

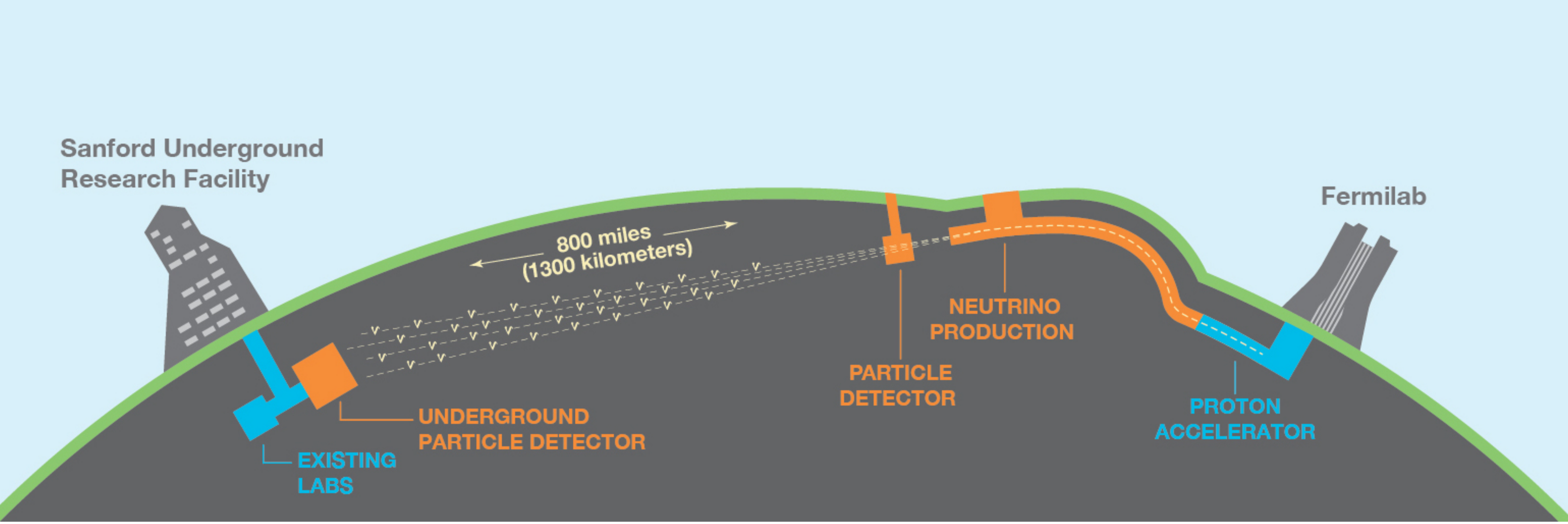


- origin of matter-antimatter asymmetry — δ_{CP}
- mass hierarchy and oscillation parameters — PMNS matrix, Δm_{31}^2
- Grand Unified Theories — proton decay
- dynamics of supernova explosion — wait for one;)

DUNE, CDR (2016), TDR (2020)

Neutrino experiments

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



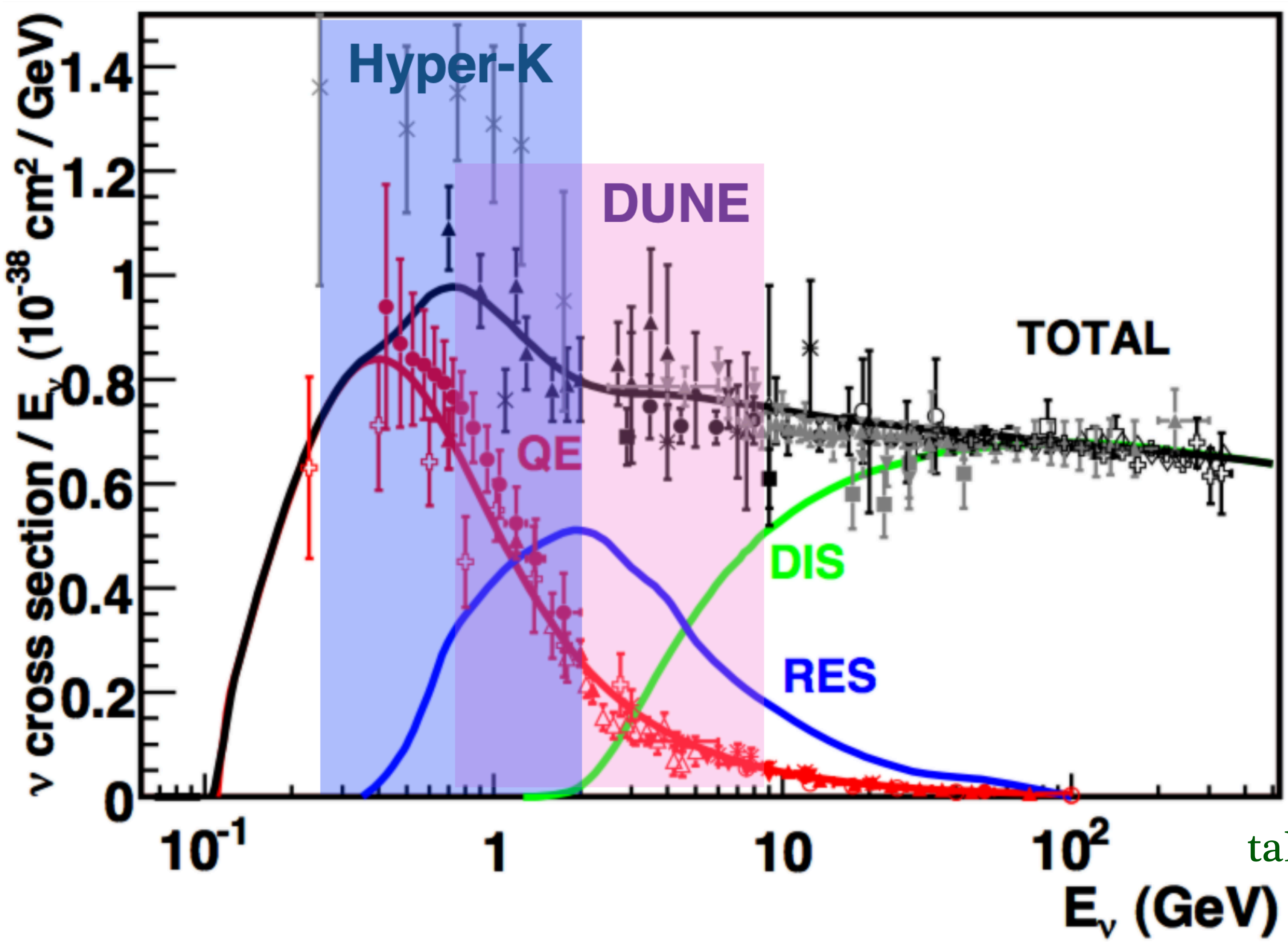
- measurement of ν_μ disappearance and ν_e appearance

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

- near detector: determine flux and cross sections

CCQE. Why should we care?

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

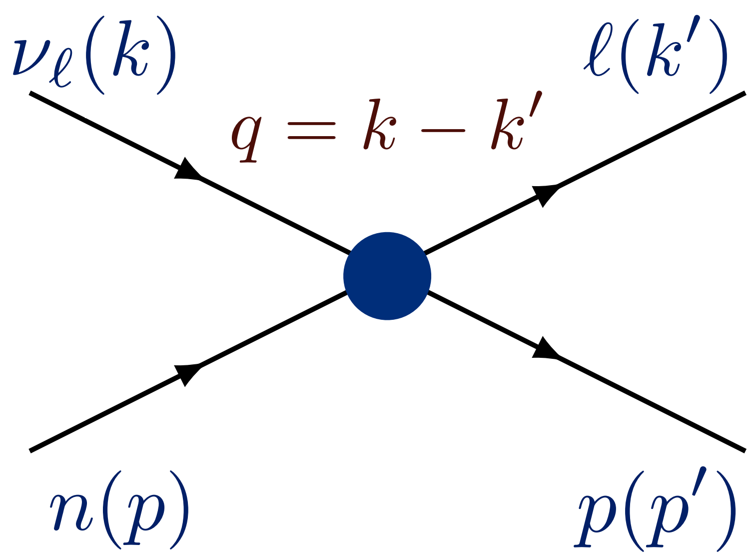


Formaggio and Zeller (2013)

Noemi Rocco talk at Neutrino 2020

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

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

Radiative corrections in CCQE

- large kinematic logarithms enhance radiative corrections

$$\frac{\alpha}{\pi} \sim 0.2\ \% \qquad \text{multiplied by} \qquad \ln \frac{E_\nu}{m_e} \sim 6 - 10$$

- CCQE with electron flavor is subject to large corrections

- phase-space restrictions enhance radiative corrections

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

$$E_\gamma < \Delta E \qquad \text{soft photons} \qquad 2 \ln \frac{E_\nu}{m_e} \ln \frac{\Delta E}{m_e} \sim 35 - 60$$

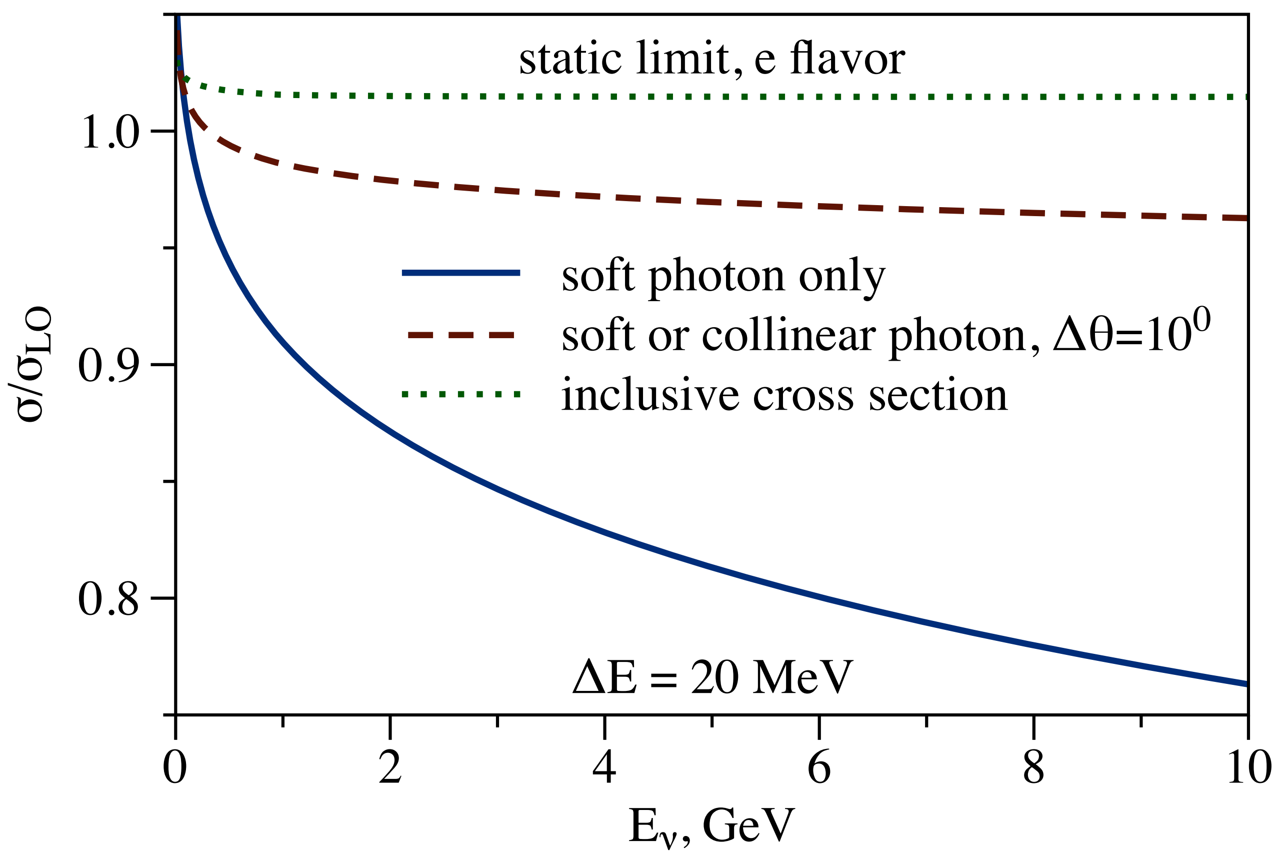
smaller collinear logarithms

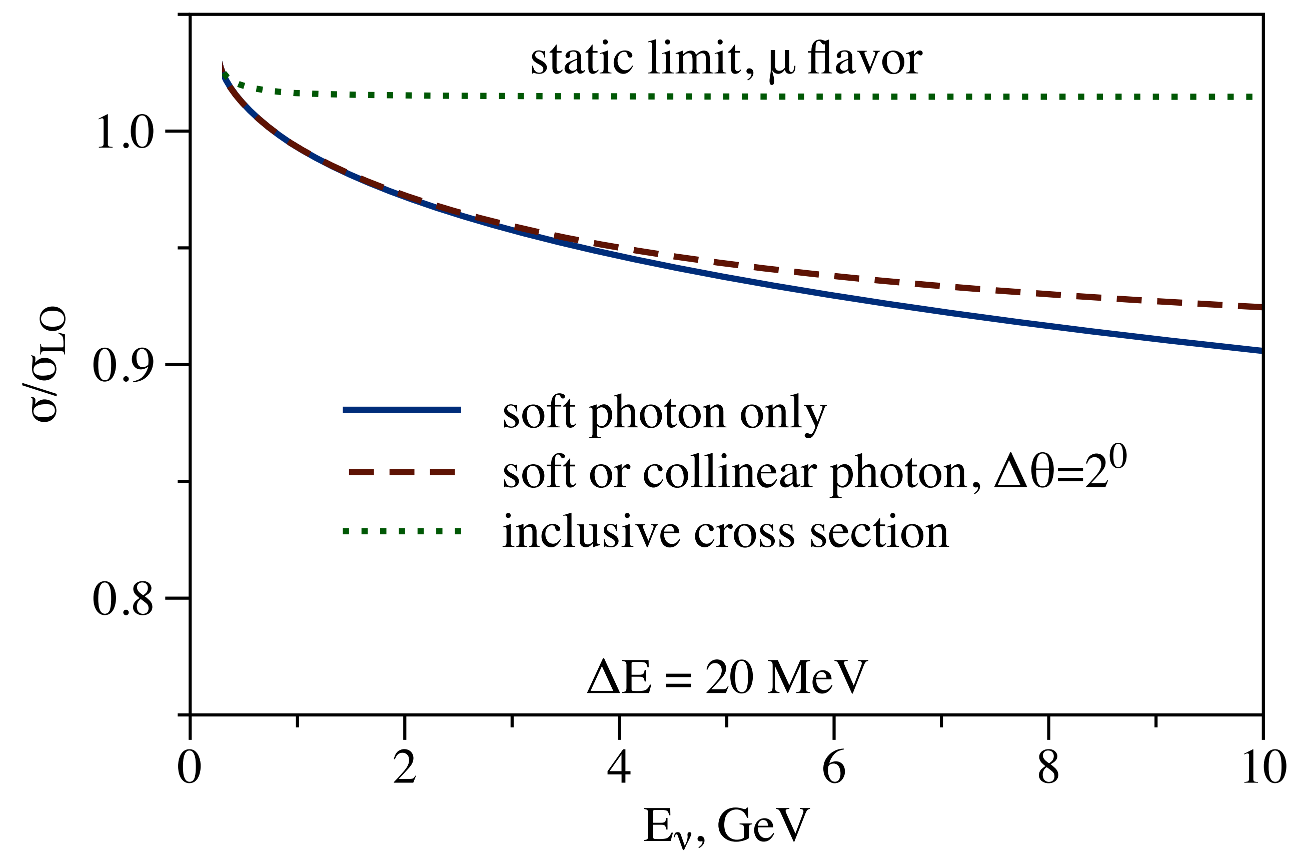
- crucial dependence on detector details

- radiative corrections crucial for %-level oscillation program

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

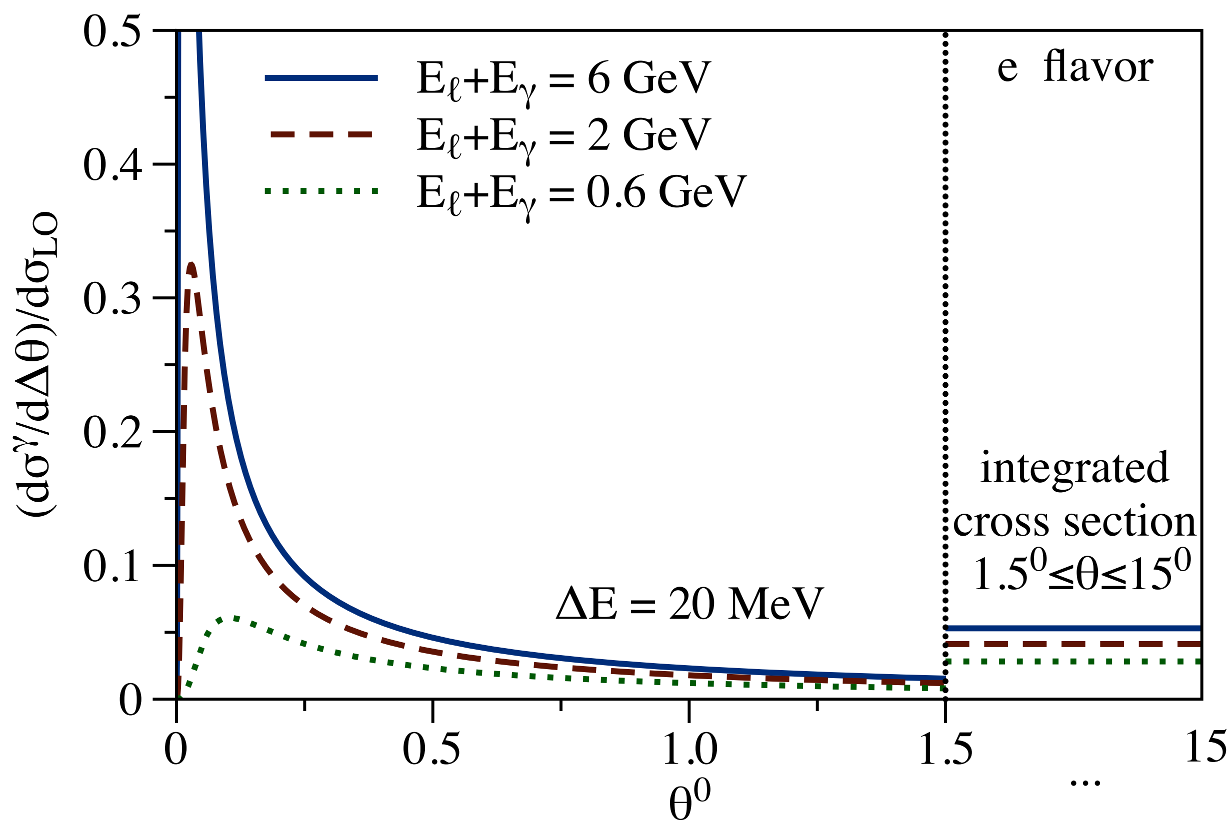


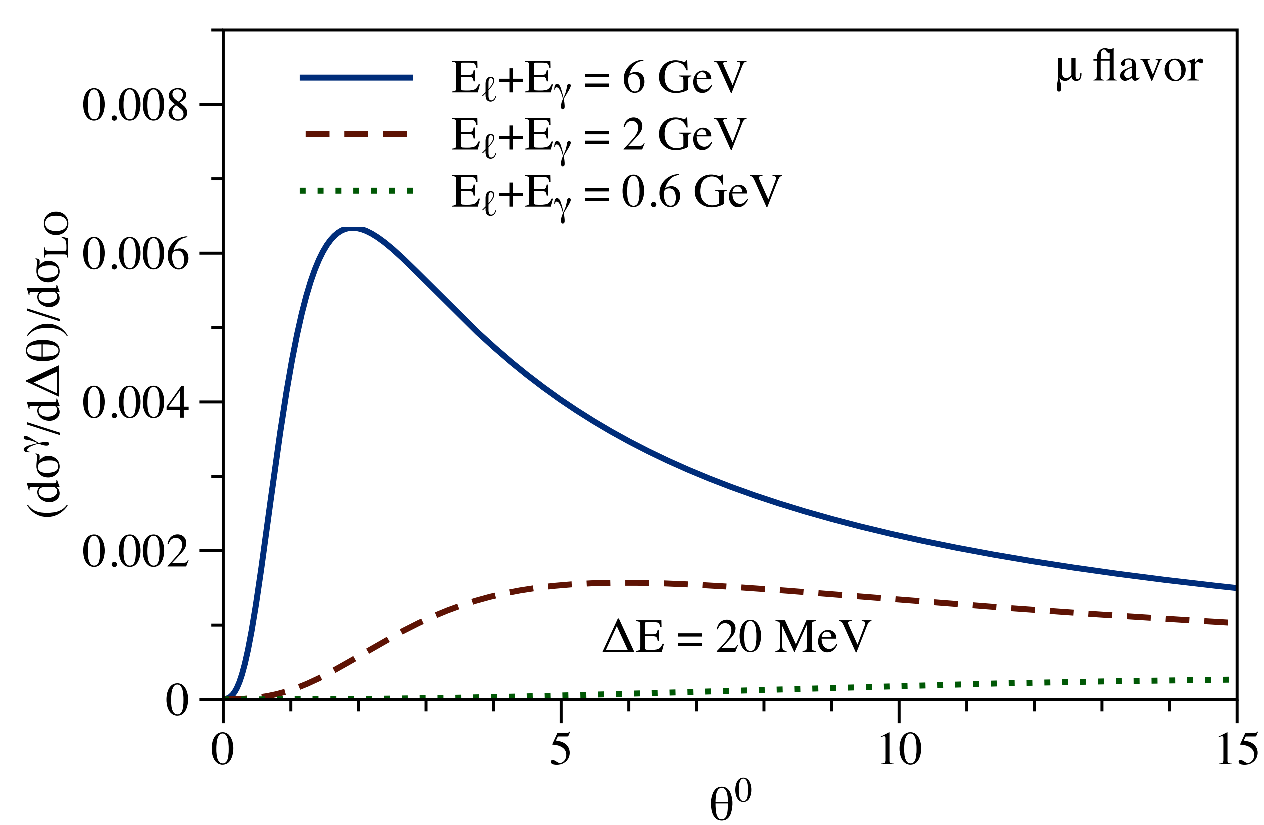


- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables ($+\gamma$): few % level, flavor independent

Electron vs muon jets

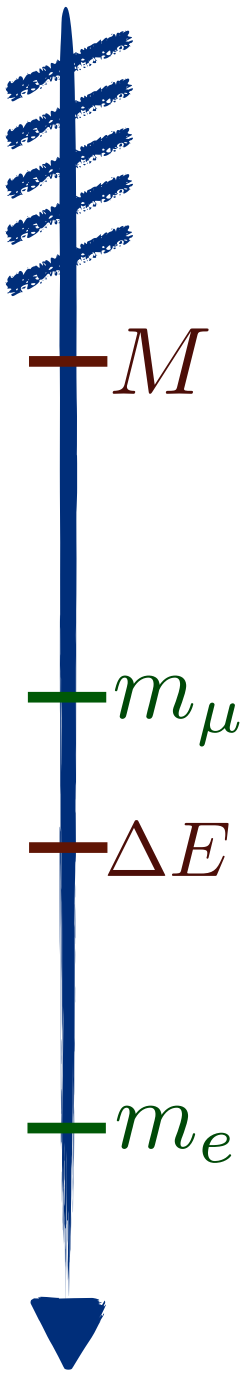
- factorization for radiation of collinear photons
- cone angle is defined to lepton direction
- photons of energy > 20 MeV, fixed energy in the cone





- 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



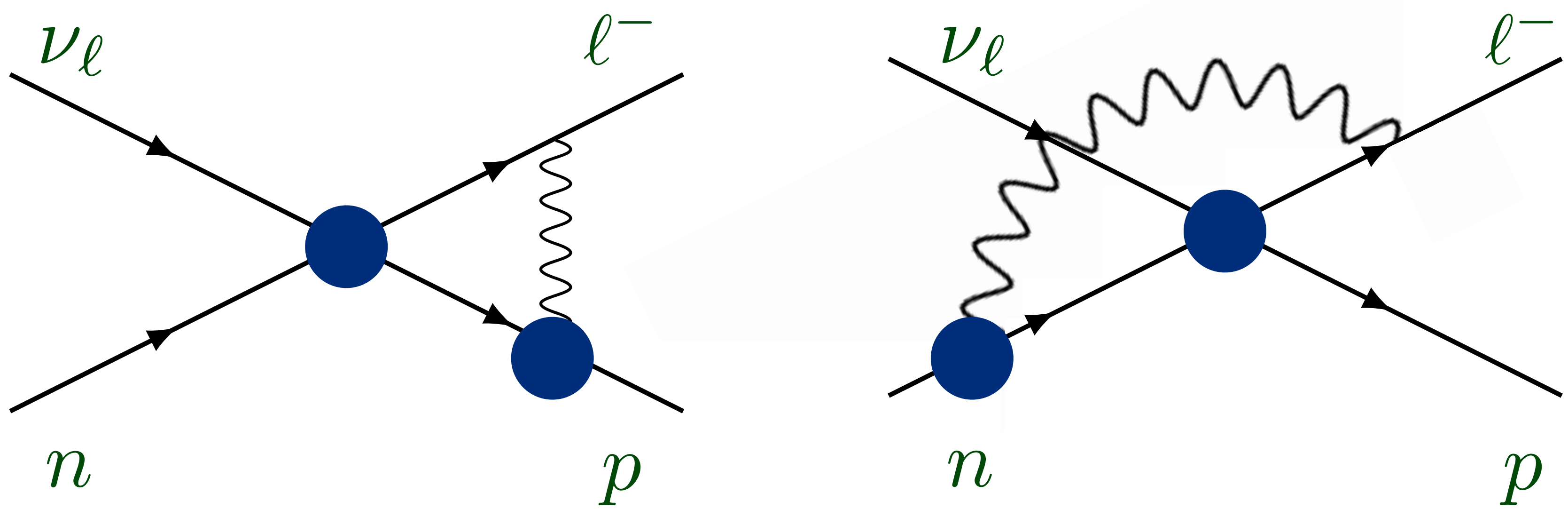
- cross section is given by factorization formula

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

- 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

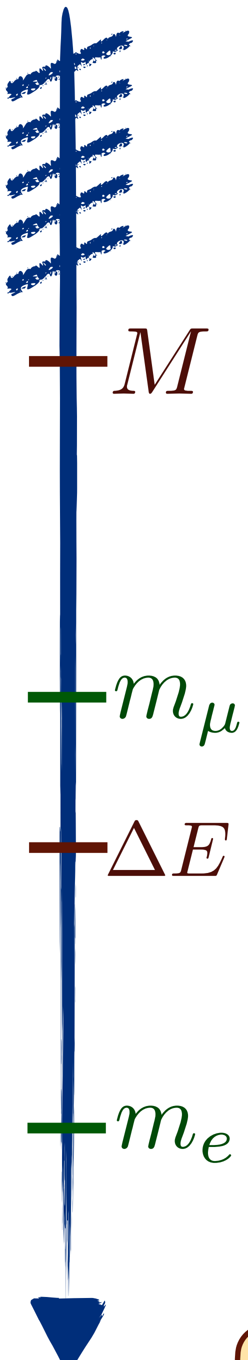
discussed for CCQE: Graczyk (2013)

- add self energy for charged particles

- reproduce soft and collinear regions of SCET

- best determination of hard function

Factorization approach



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

- 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

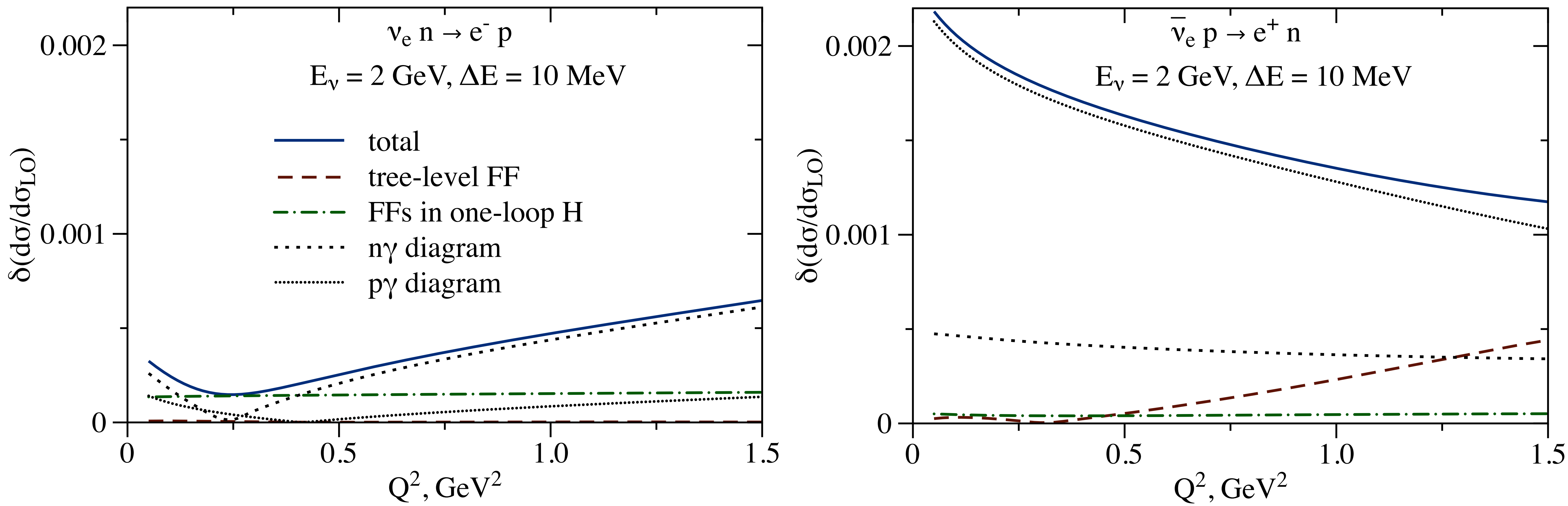
- calculate cross section at low energies accounting for all large logs

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

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

Assignment of errors

- uncertainties from hard function



- nucleon form factors

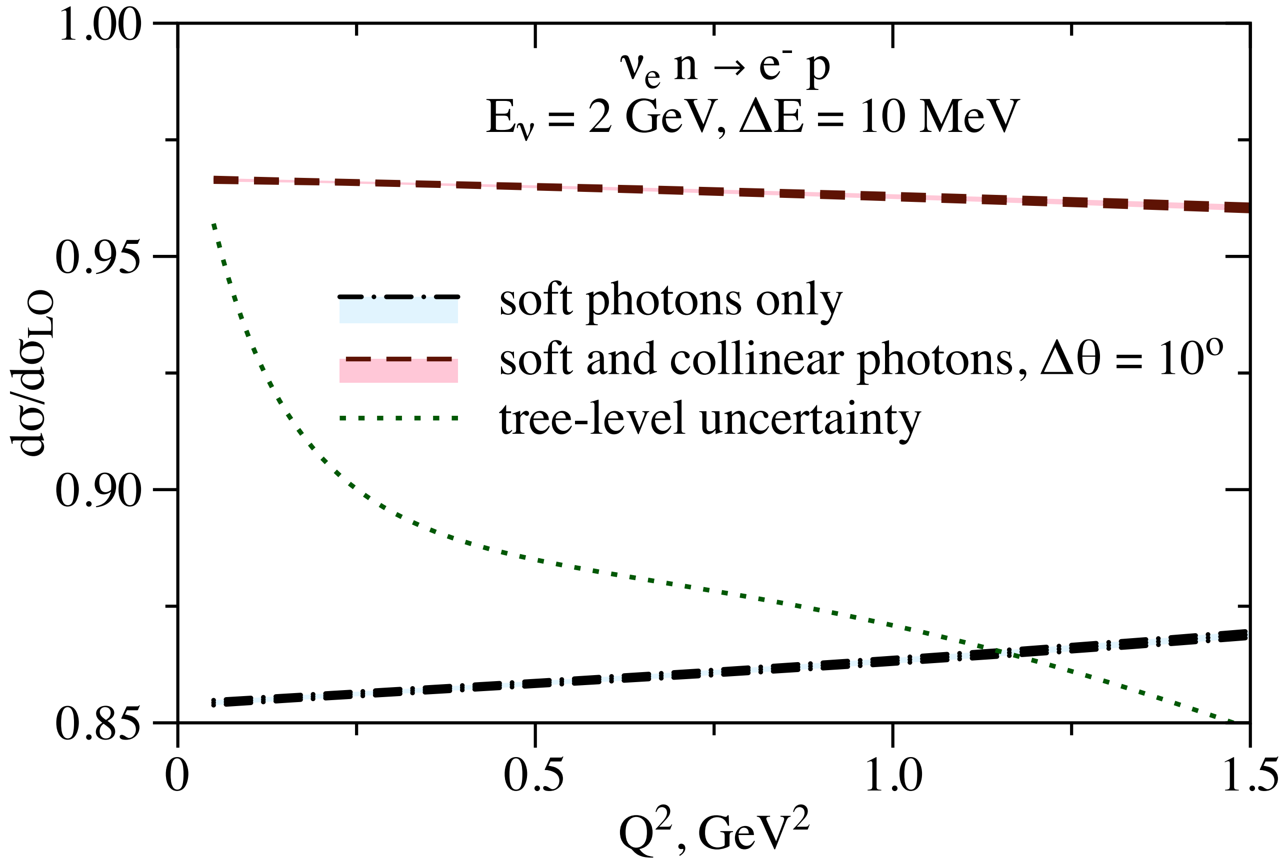
Meyer, Betancourt, Gran and Hill (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T. (2020)

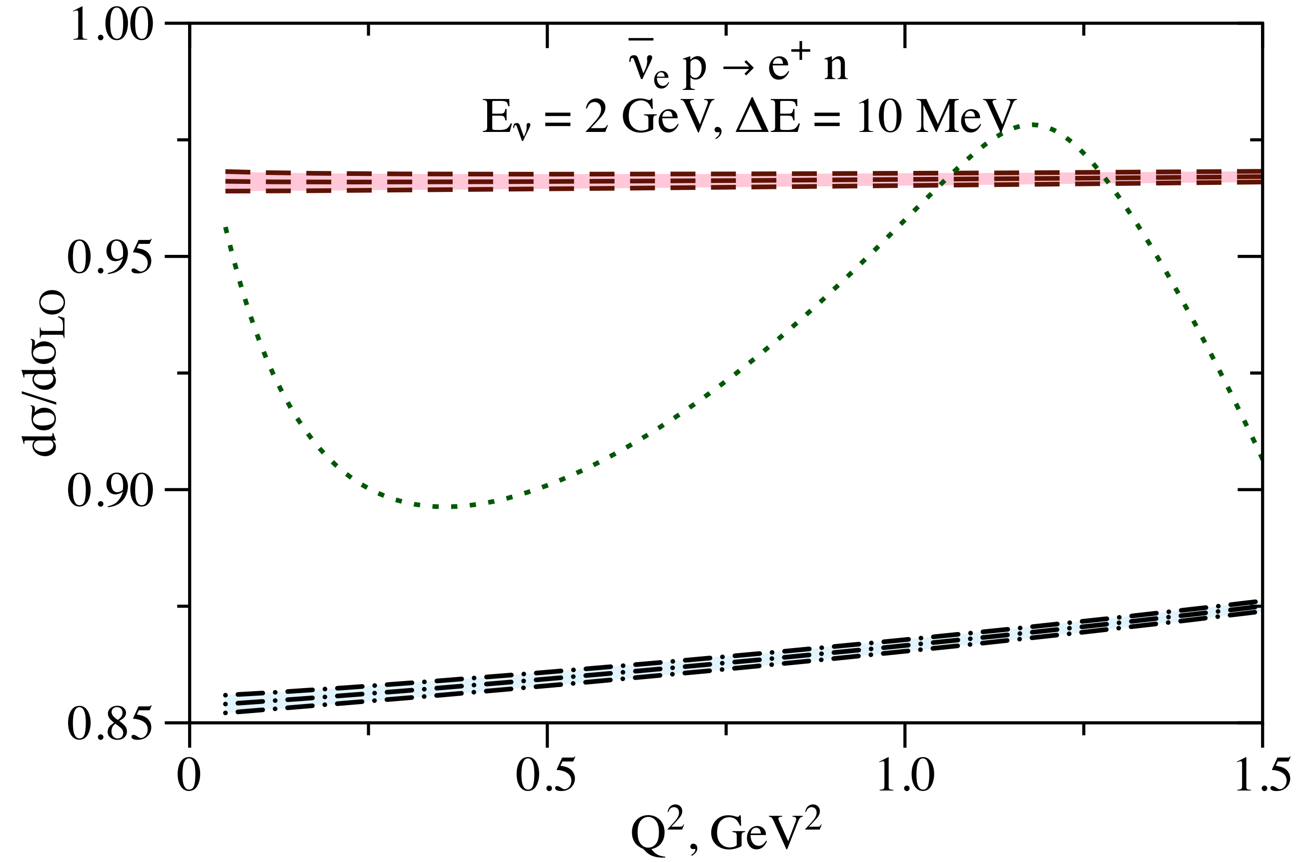
- add perturbative errors by variation of scale

- uncertainty of per mille level for the ratio to LO result

Cross section. Electron flavor

- exclusive observables

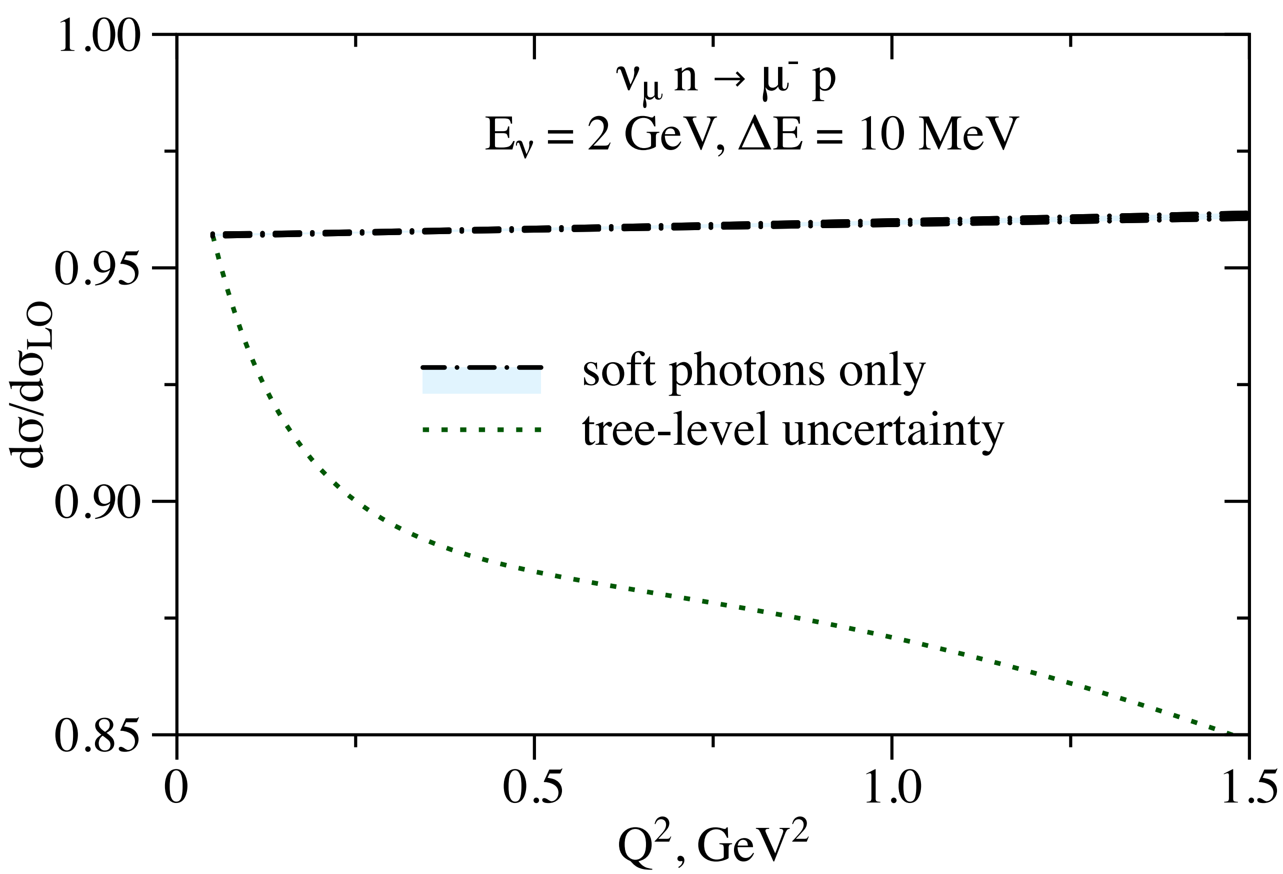


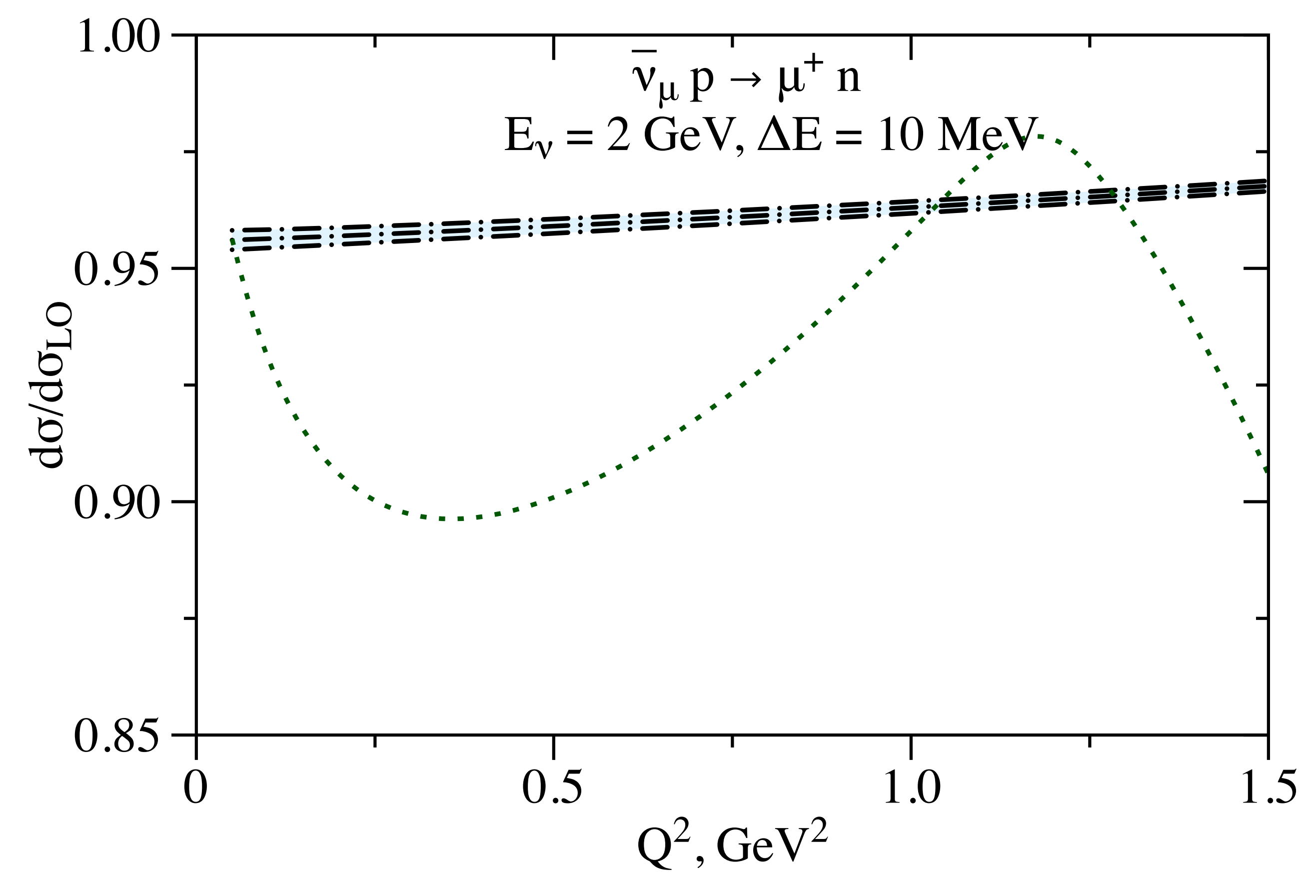


- cancellation of error from hard function for ratio to LO

Cross section. Muon flavor

- exclusive observables

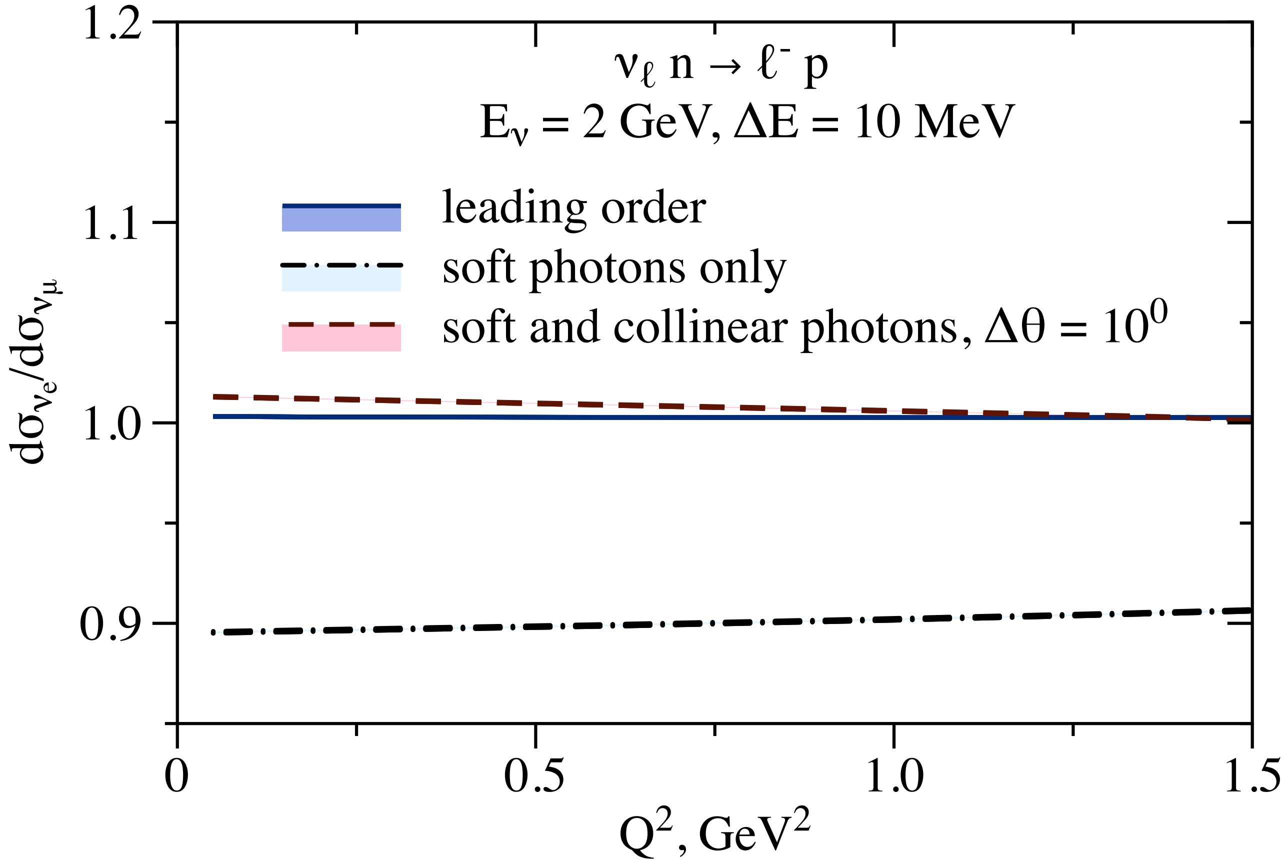


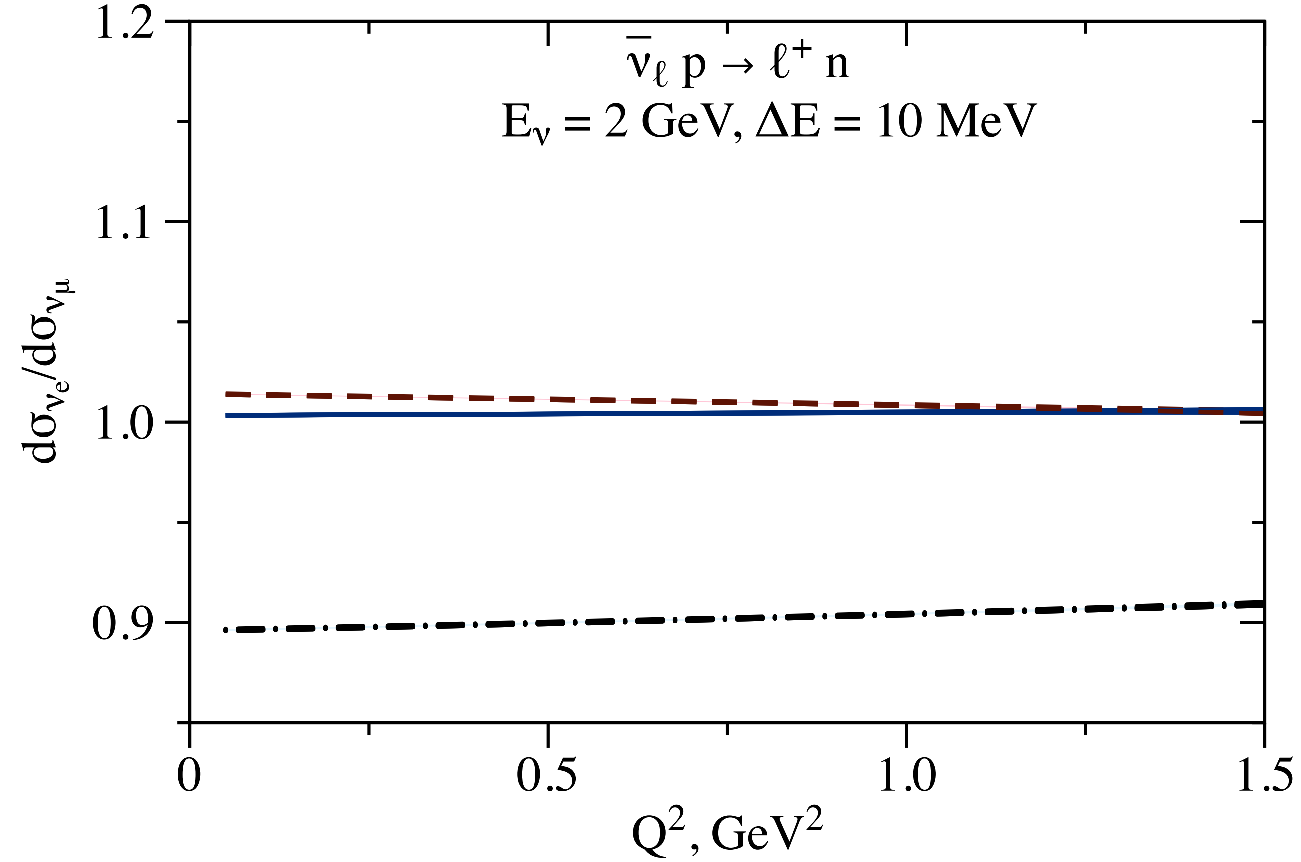


- cancellation of error from hard function for ratio to LO

Electron/muon ratio

- exclusive observables



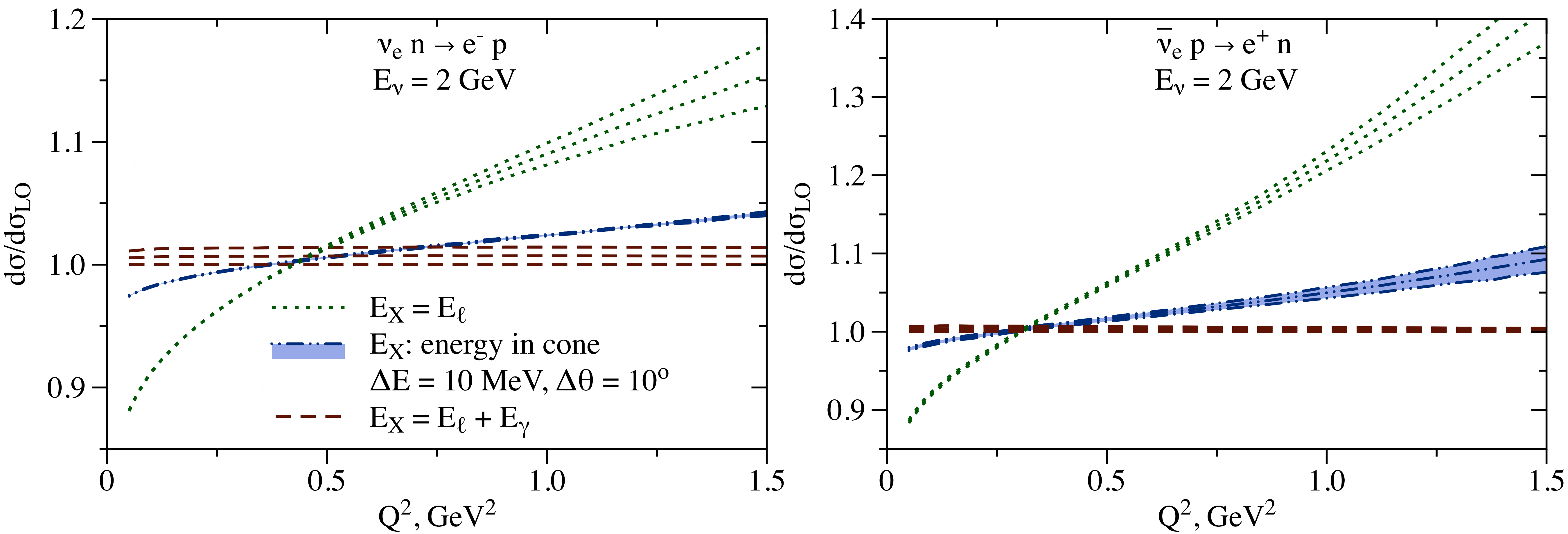


- small error: hard function does not depend on mass

Cross section. Electron flavor

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

- inclusive observables

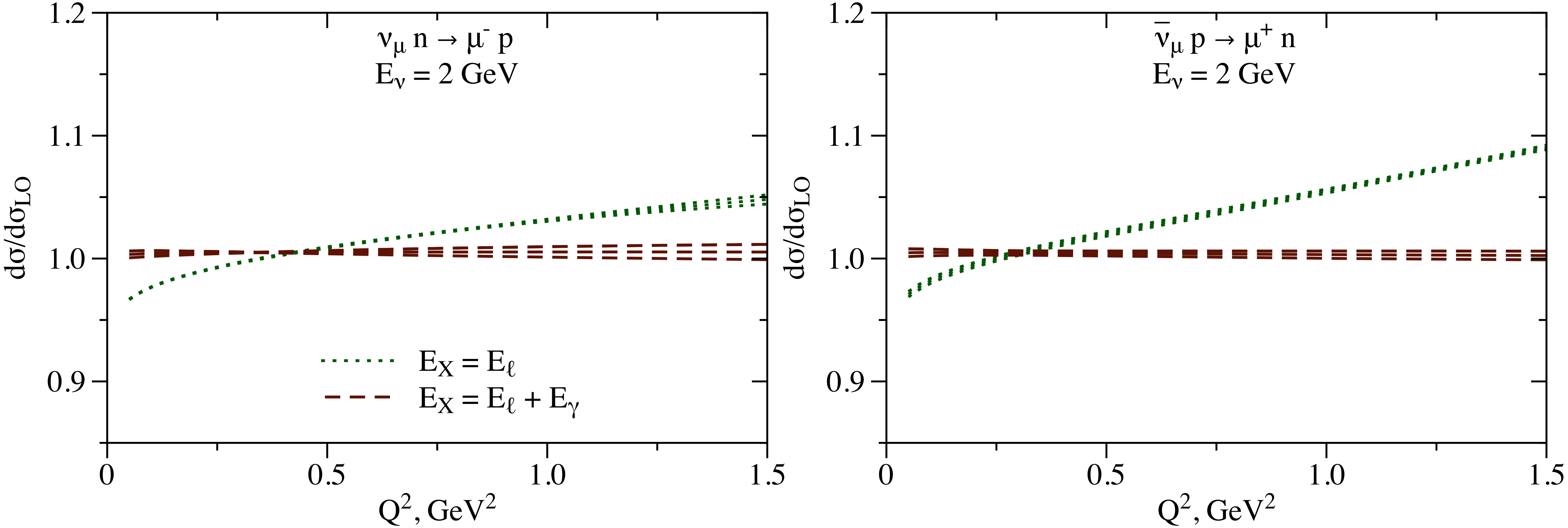


- dependence on reconstruction of kinematics and cuts

Cross section. Muon flavor

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

- inclusive observables

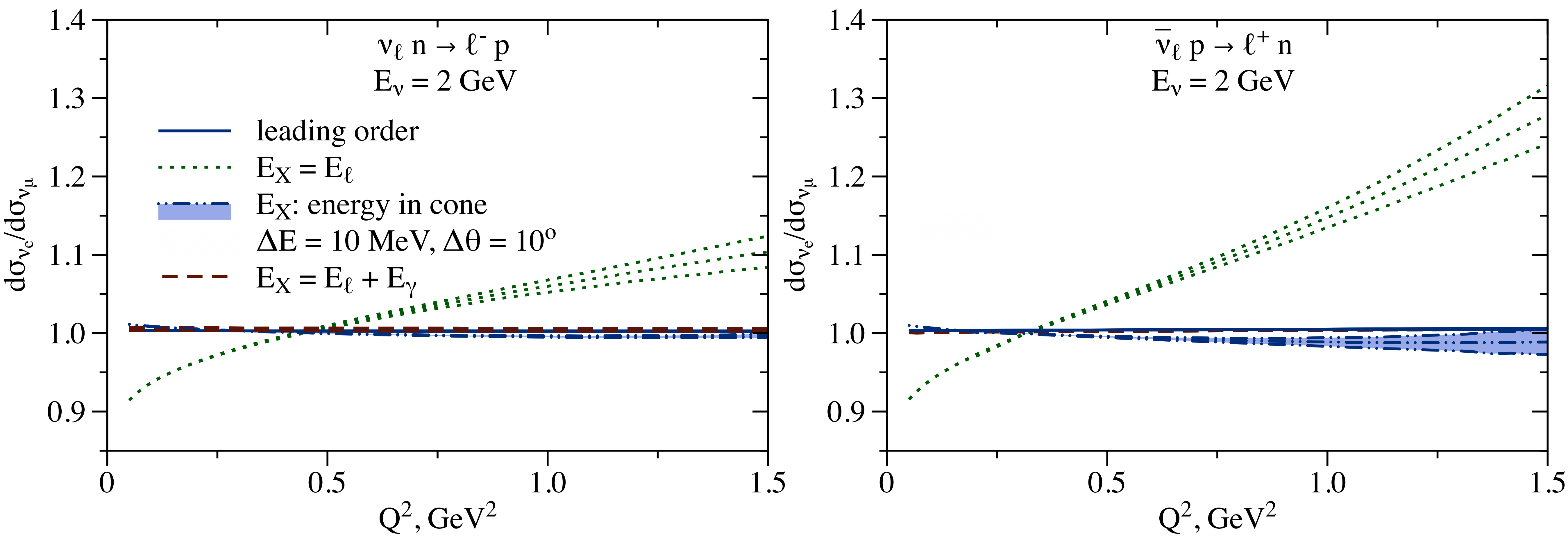


- dependence on reconstruction of kinematics and cuts

Electron/muon ratio

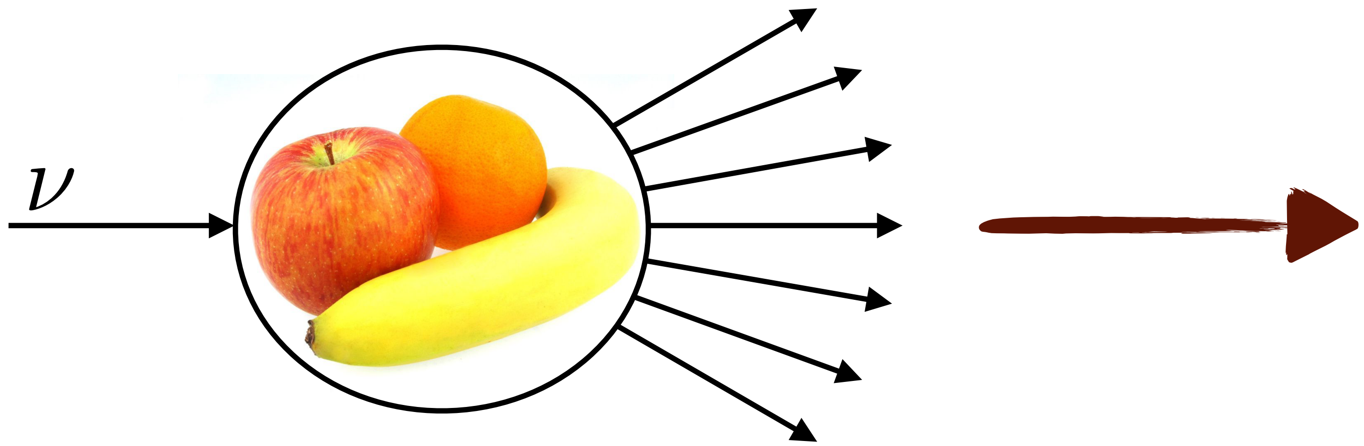
- kinematics $Q^2 = 2M\,(E_\nu - E_X)$ is reconstructed with 3 different E_X

- inclusive observables



- predict σ_{ν_e} from σ_{ν_μ} measurements with neutrino beam ✓

Conclusions



radiative corrections in EFT framework

- radiative corrections to CEvNS starting from four-fermion EFT

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

- σ_{ν_e} can be predicted from σ_{ν_μ} measurements with neutrino beam

Thanks for your attention !!!

Fermilab

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