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QED radiative corrections to charged-current neutrino-nucleon elastic scattering for accelerator neutrino experiments

University of Kentucky

Oleksandr Tomalak

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

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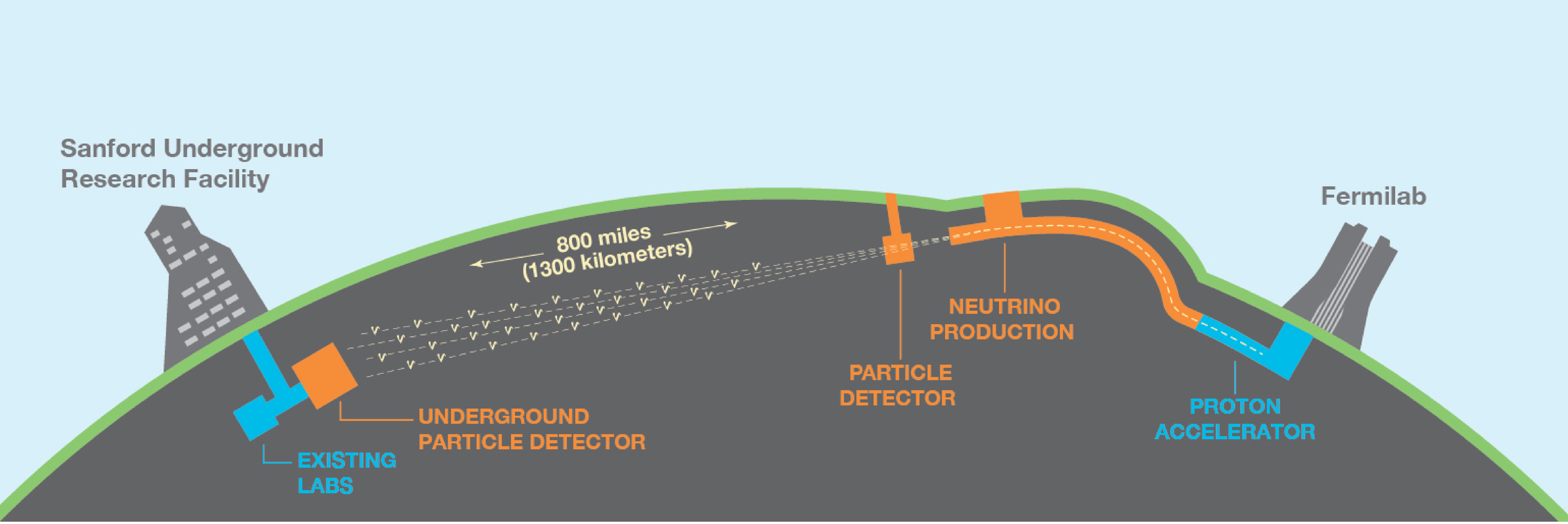
Neutrino experiments

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

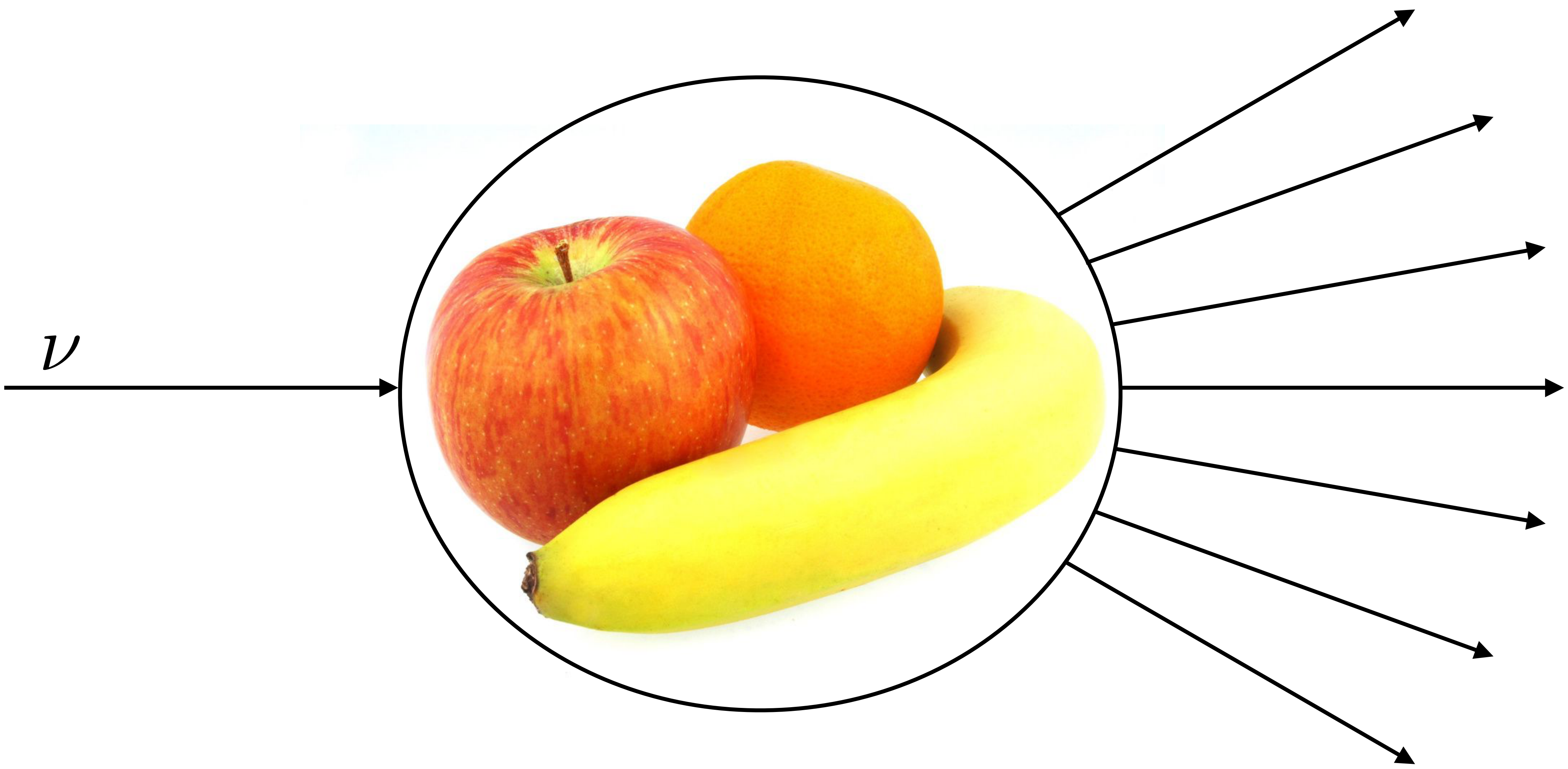


- measurement of ν_μ disappearance and ν_e appearance

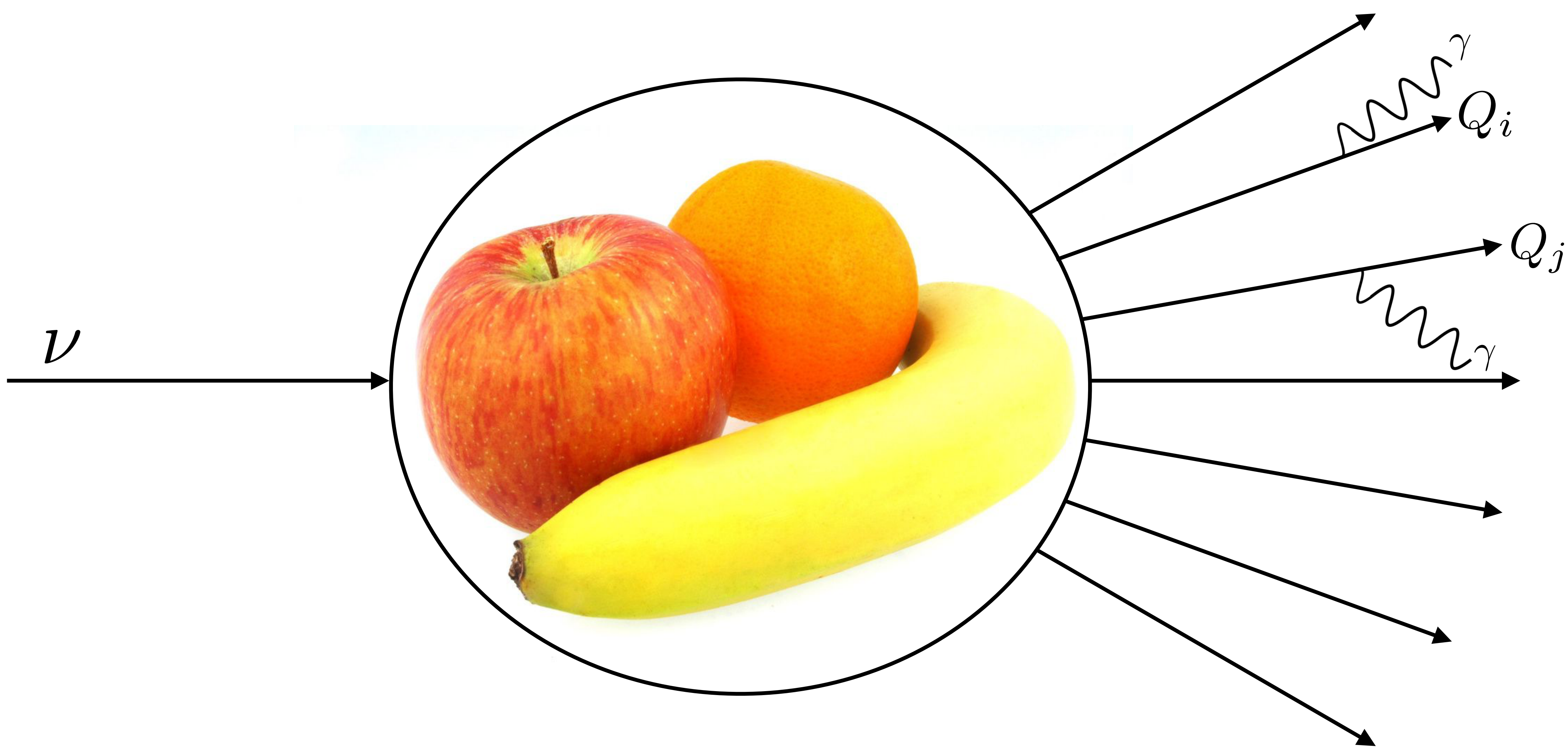
$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu \left(E_\nu\right) \times \sigma \left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

- near detector: determine flux and cross sections

Neutrino interactions

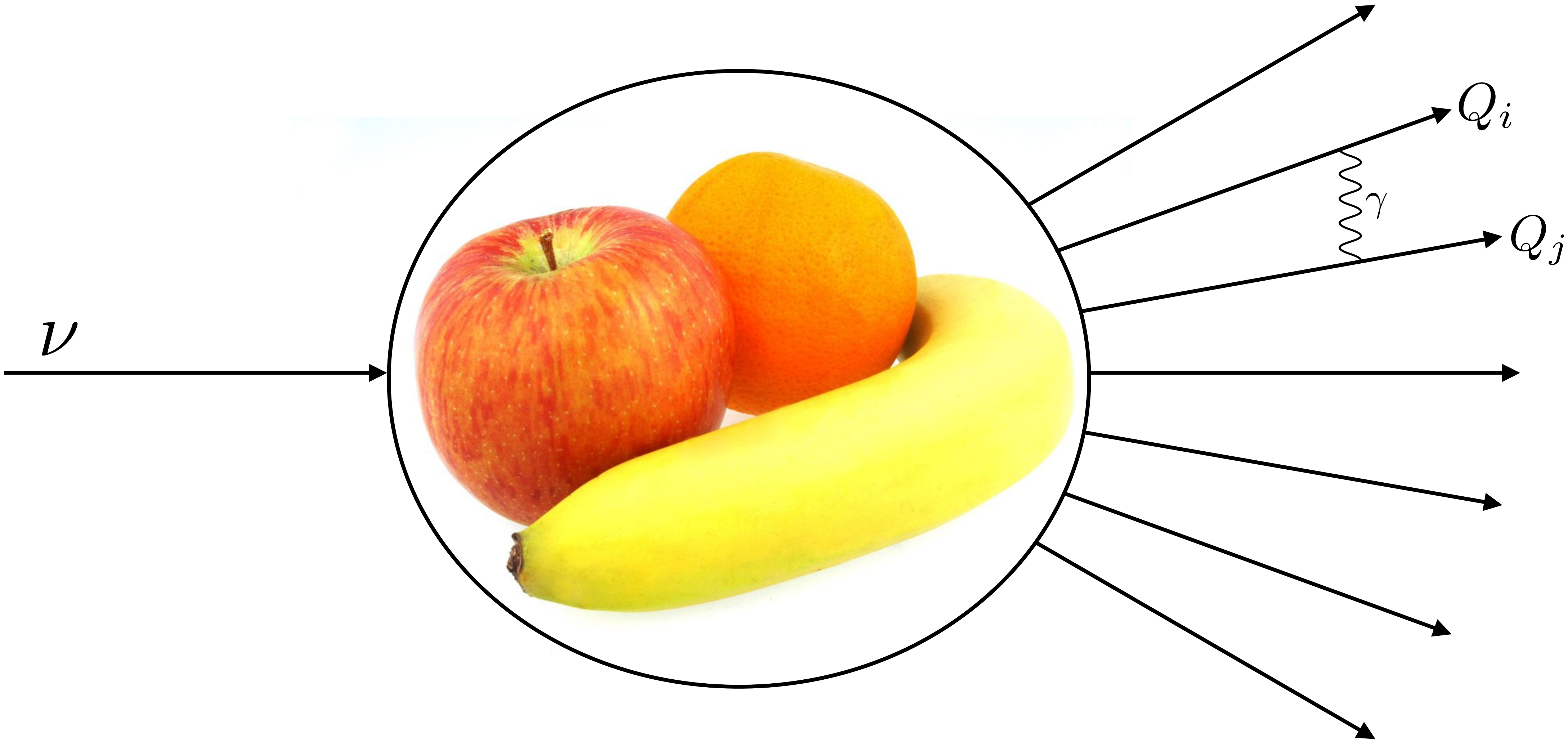


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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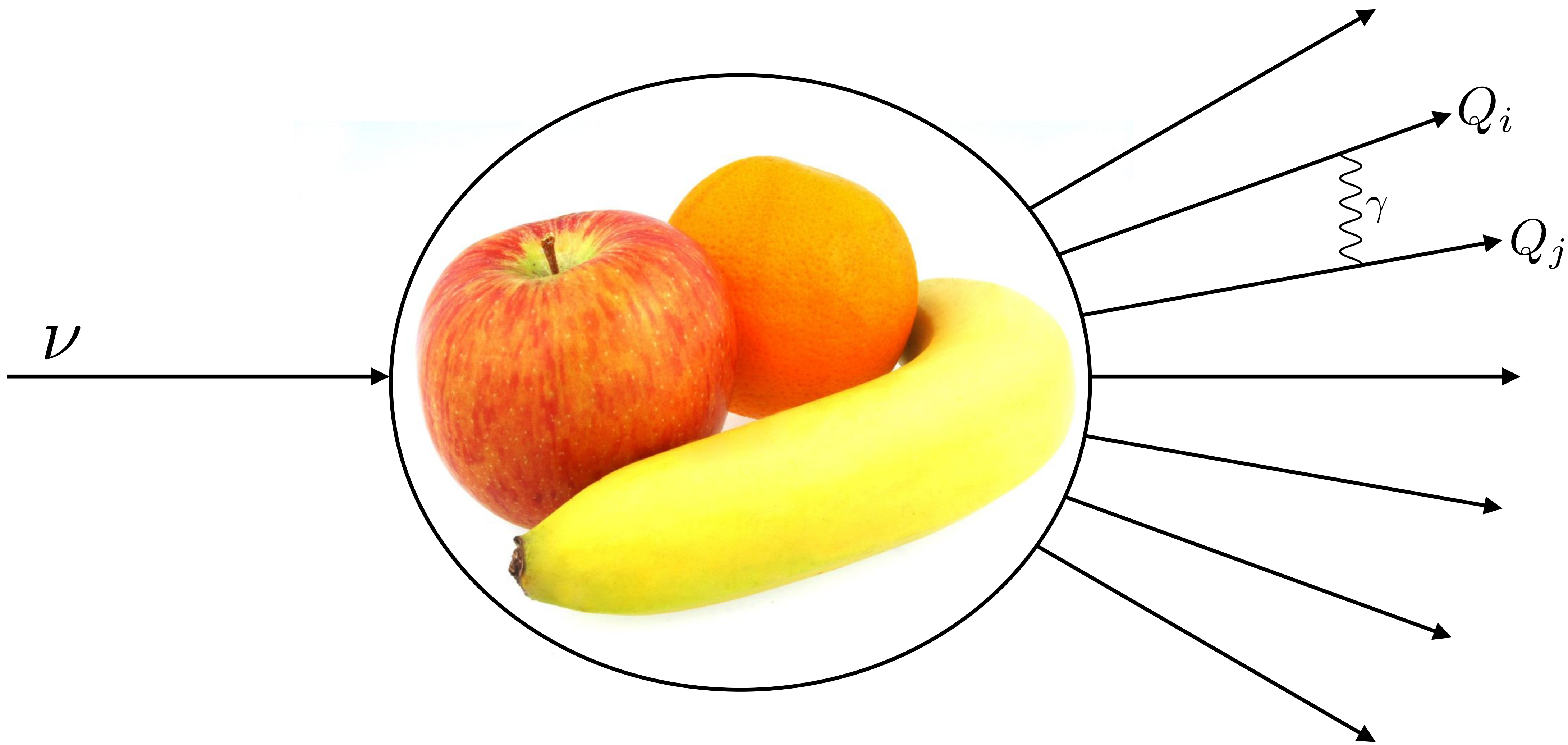
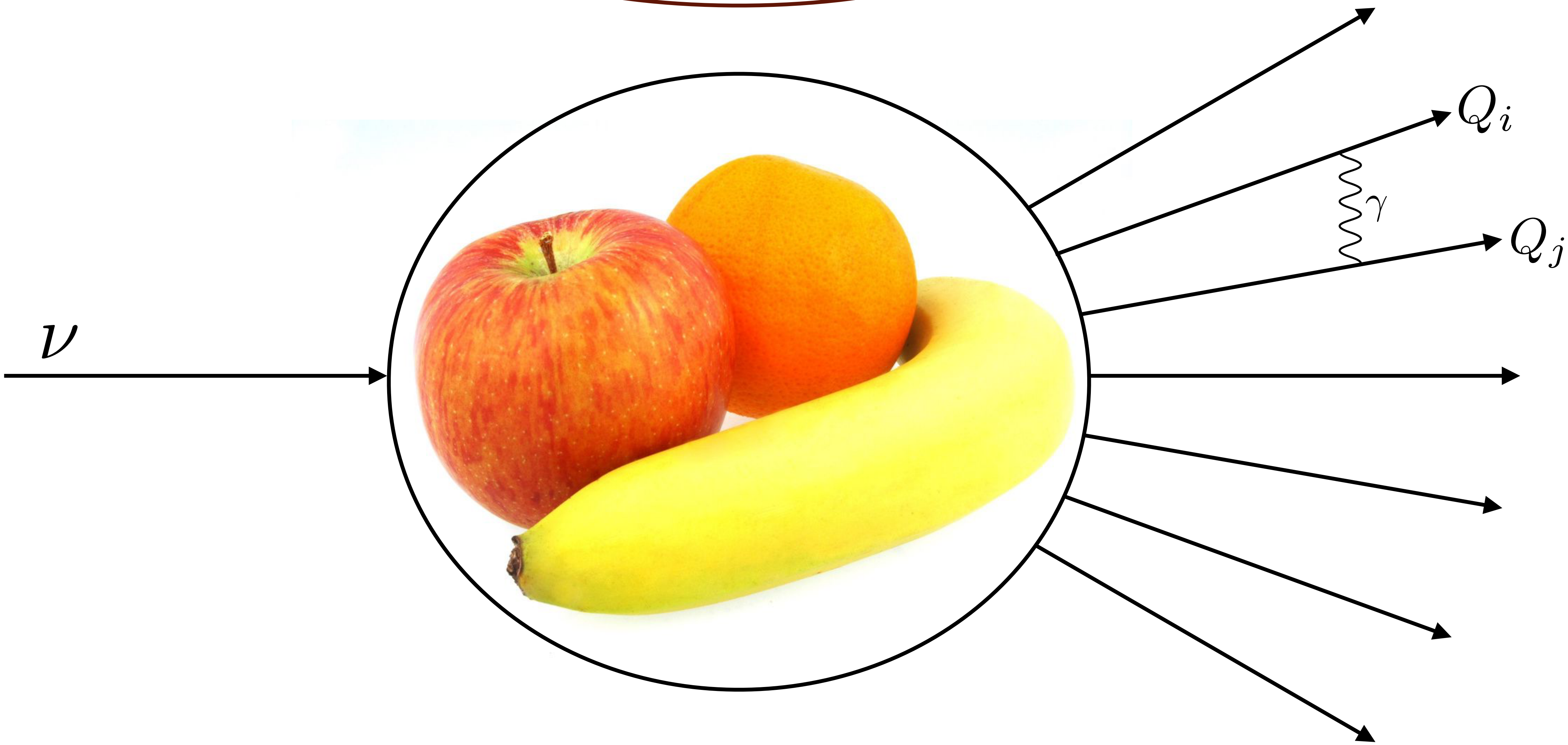
QED corrections



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

QED corrections

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

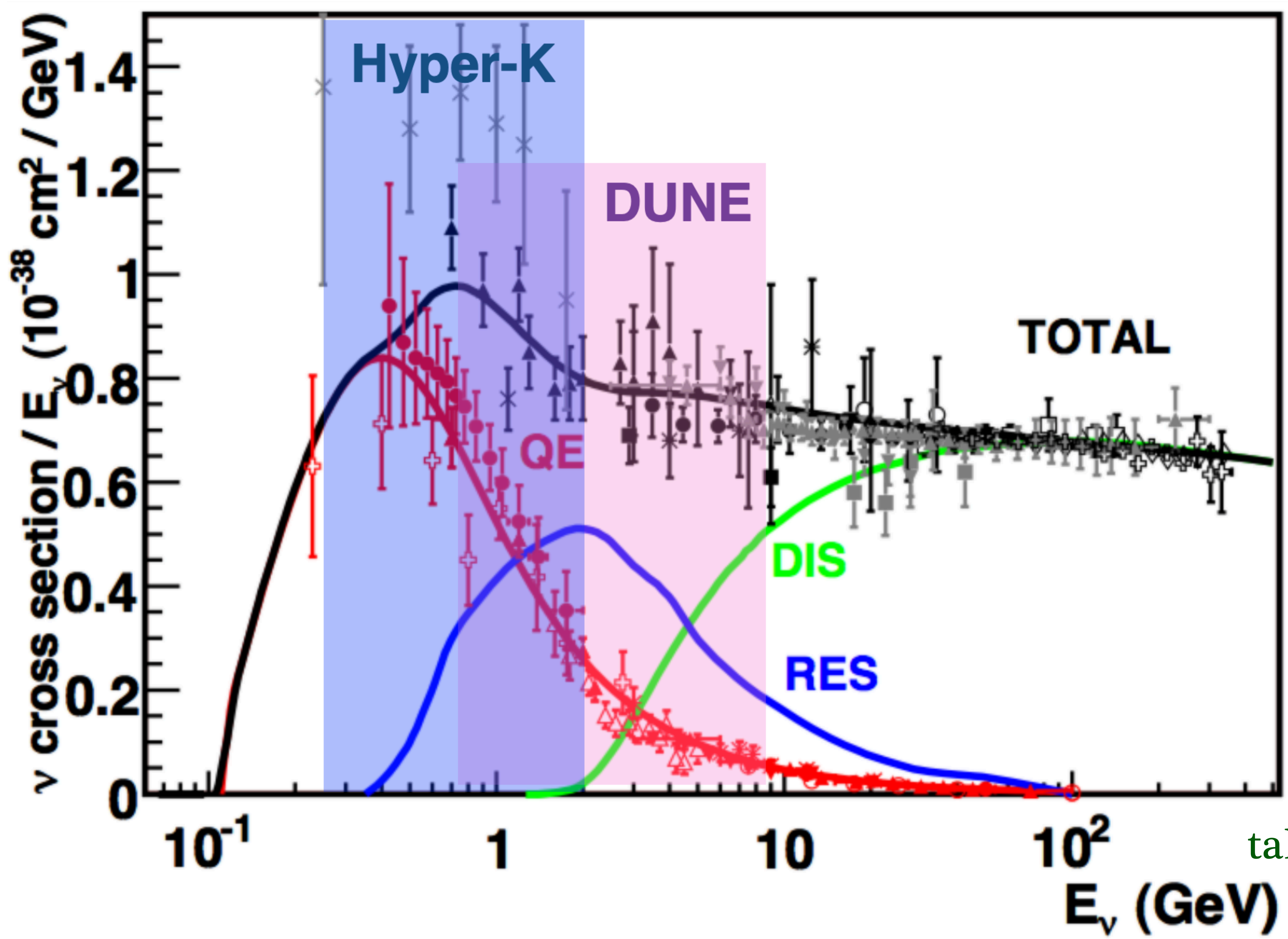


$\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by $\ln \frac{E_\nu}{m_e} \sim 6 - 10$ or $\ln^2 \frac{E_\nu}{m_e} \sim 36 - 100$

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

CCQE. Why should we care?

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

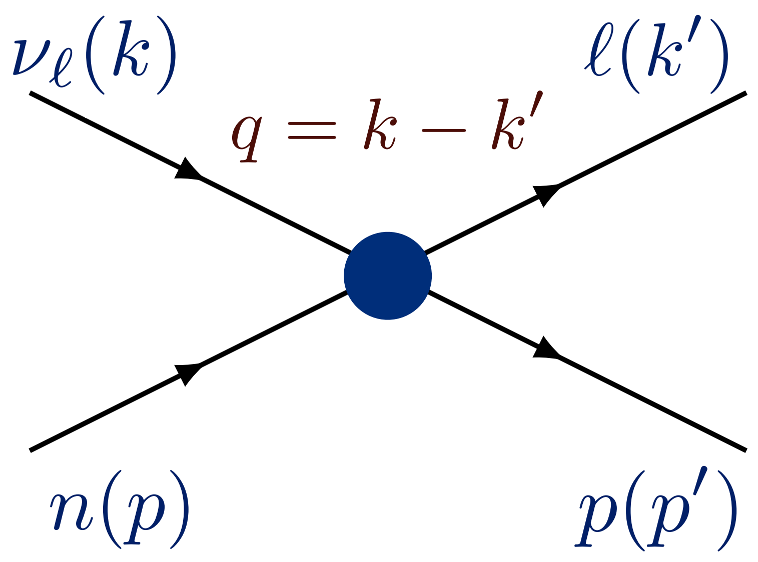


Formaggio and Zeller (2013)

Noemi Rocco talk at Neutrino 2020

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

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

- large kinematic logarithms enhance radiative corrections

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

- cross sections with electron flavor are subject to large corrections

- phase-space restrictions enhance radiative corrections

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

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

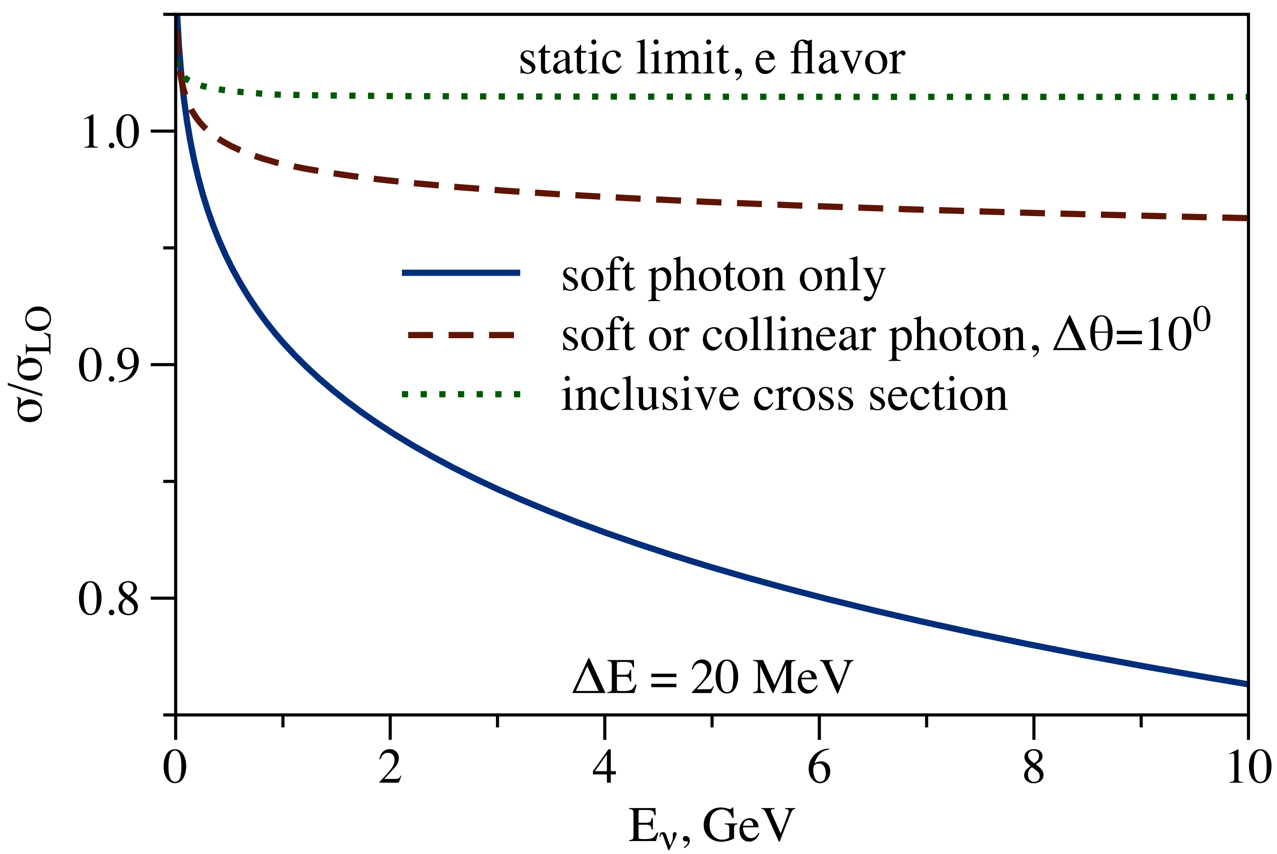
smaller collinear logarithms

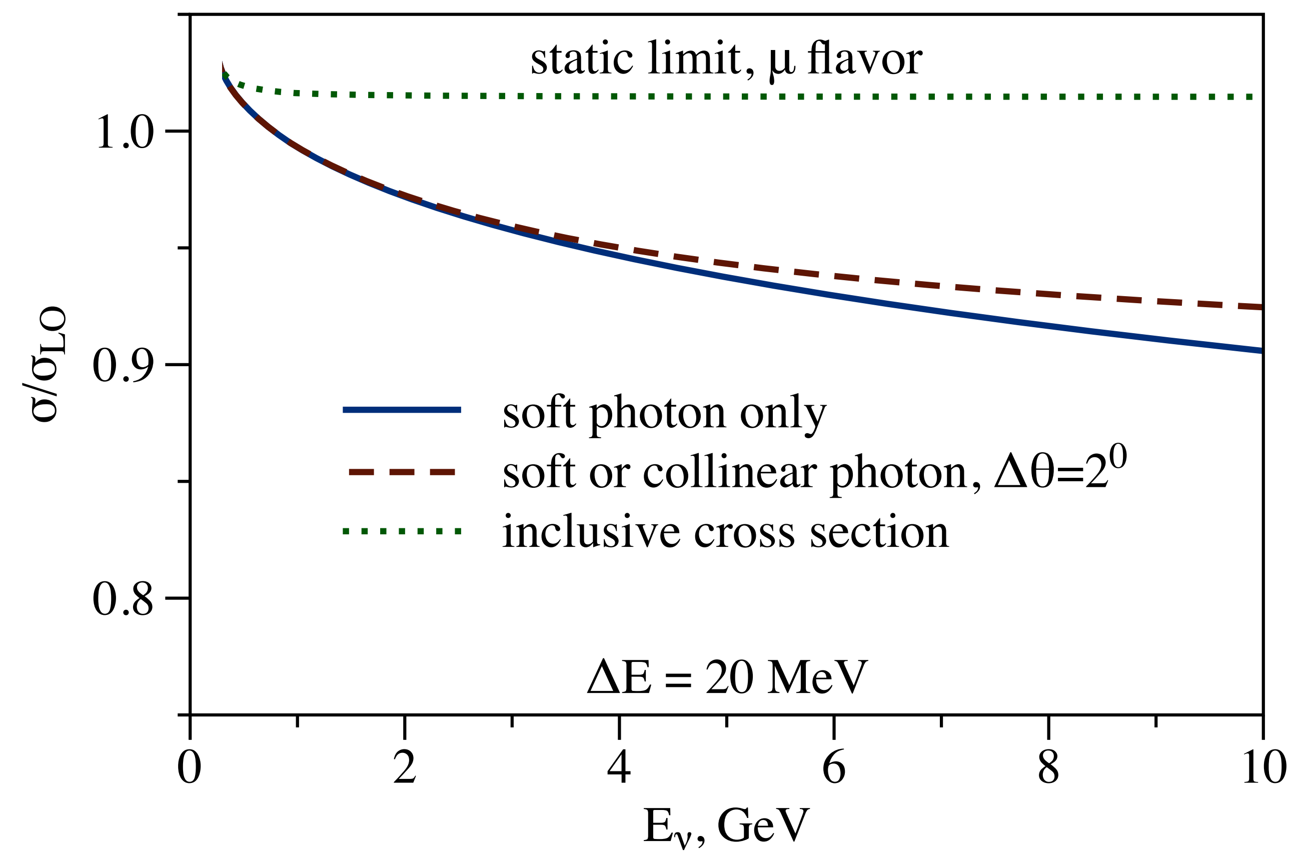
- crucial dependence on detector details

- 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

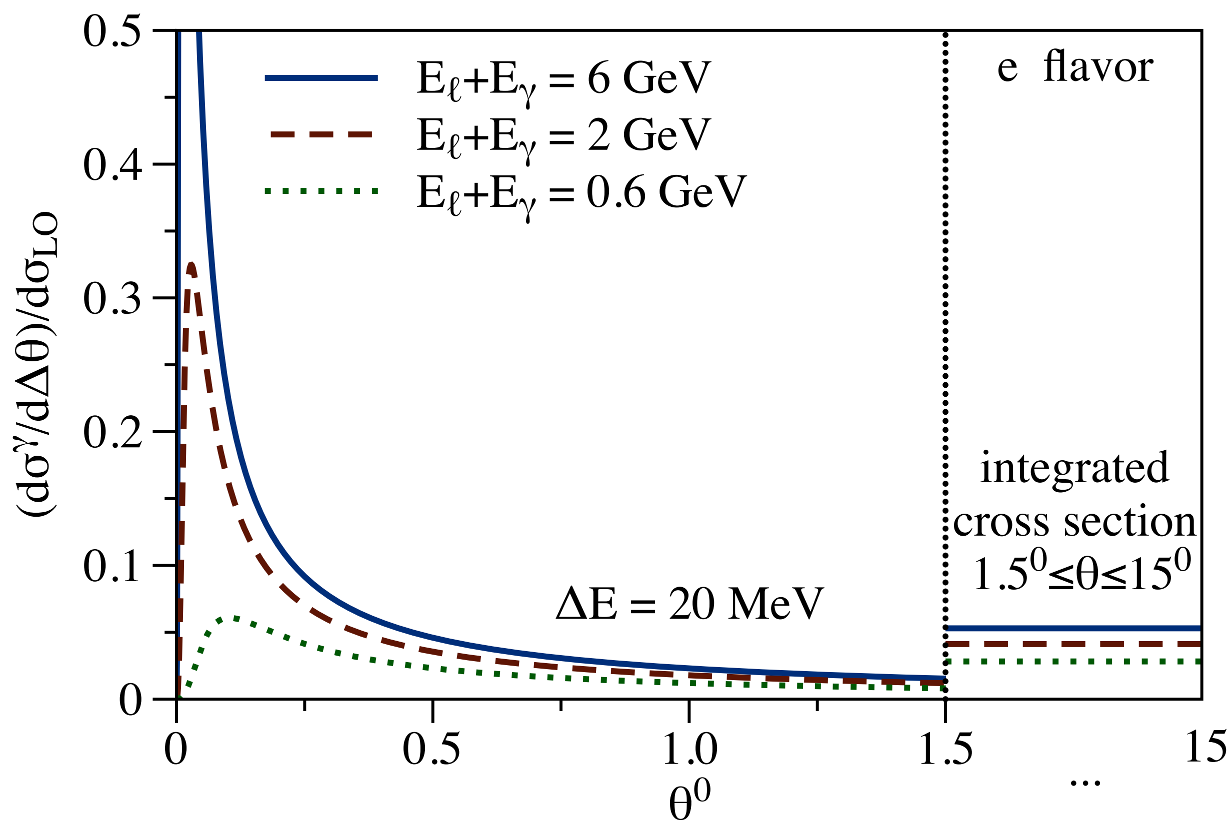


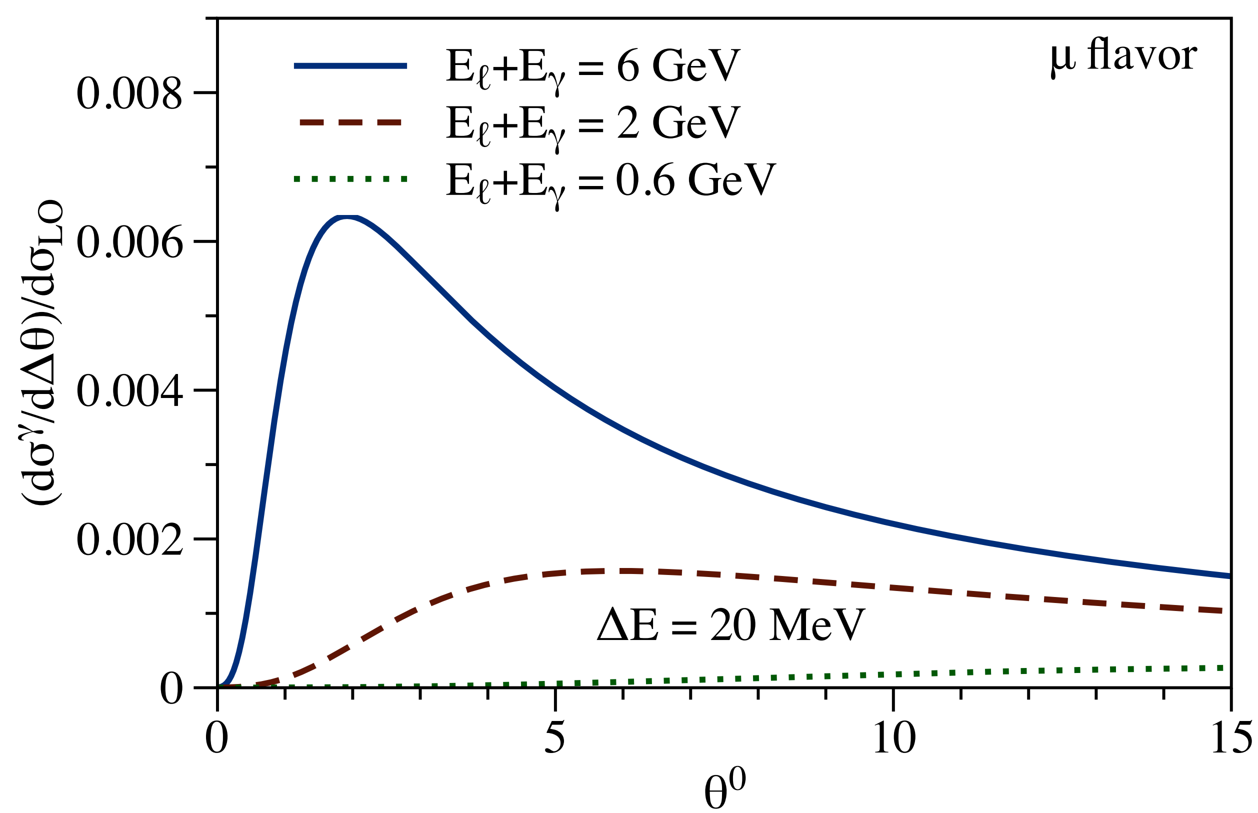


- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables ($+\gamma$): few % level, flavor independent

Electron vs muon jets

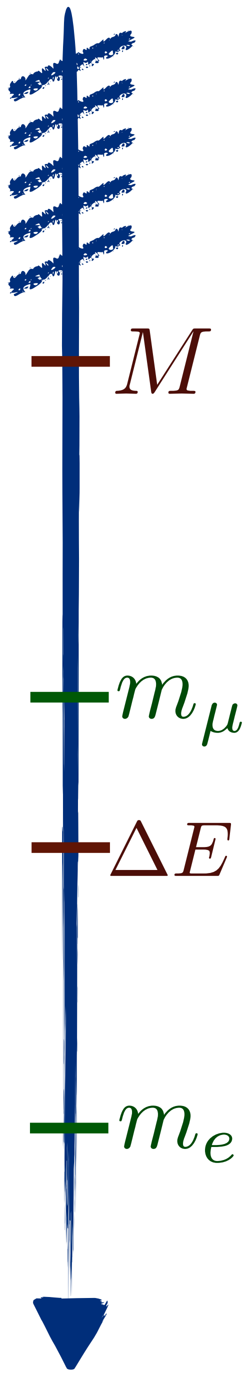
- factorization for radiation of collinear photons
- cone angle is defined to lepton direction
- photons of energy > 20 MeV, fixed energy in the cone





- 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



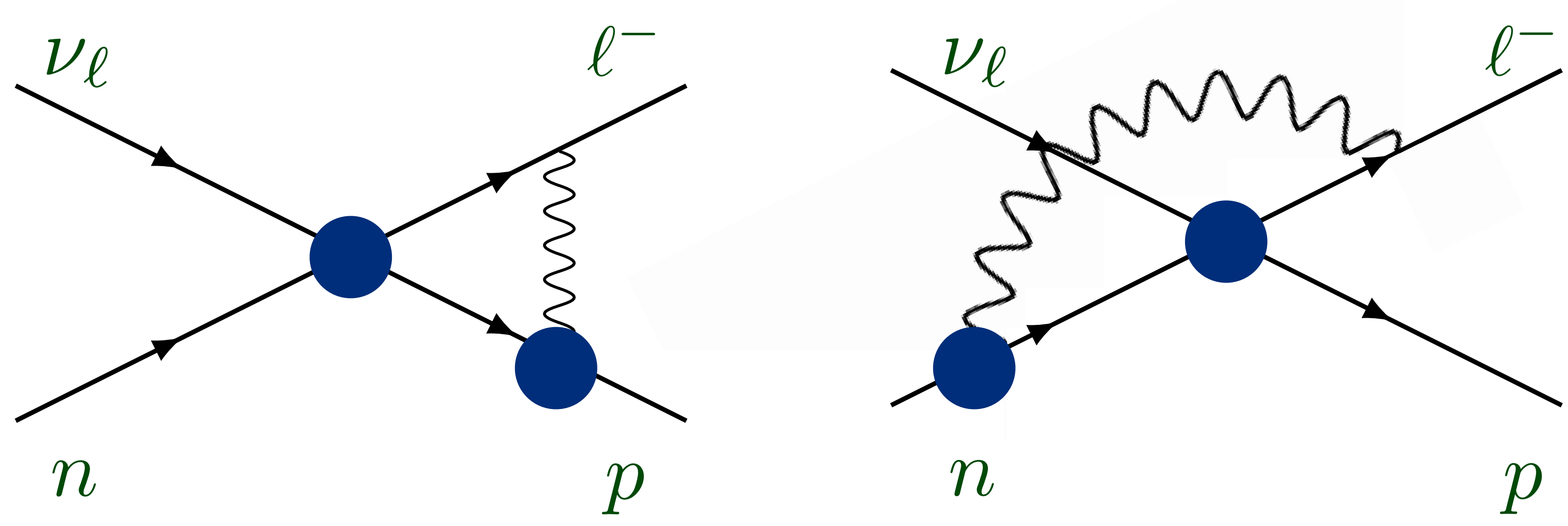
- cross section is given by factorization formula

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

- 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

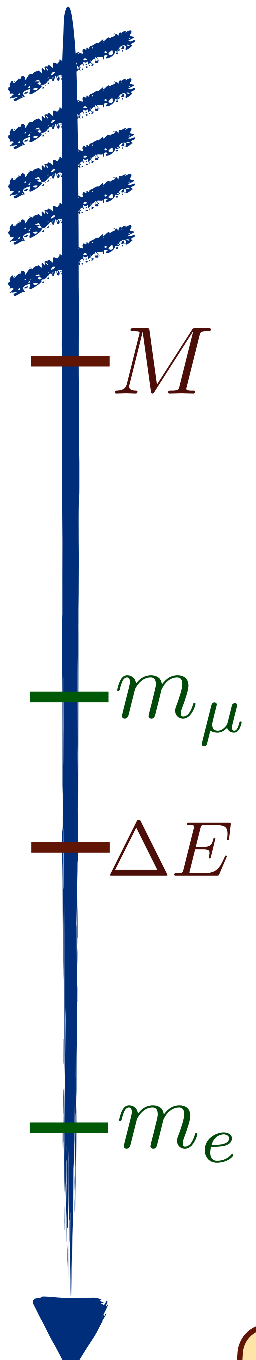
discussed for neutrino-nucleon scattering: Graczyk (2013)

- add self energy for charged particles

- reproduce soft and collinear regions of SCET

- best determination of hard function

Factorization approach



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- 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

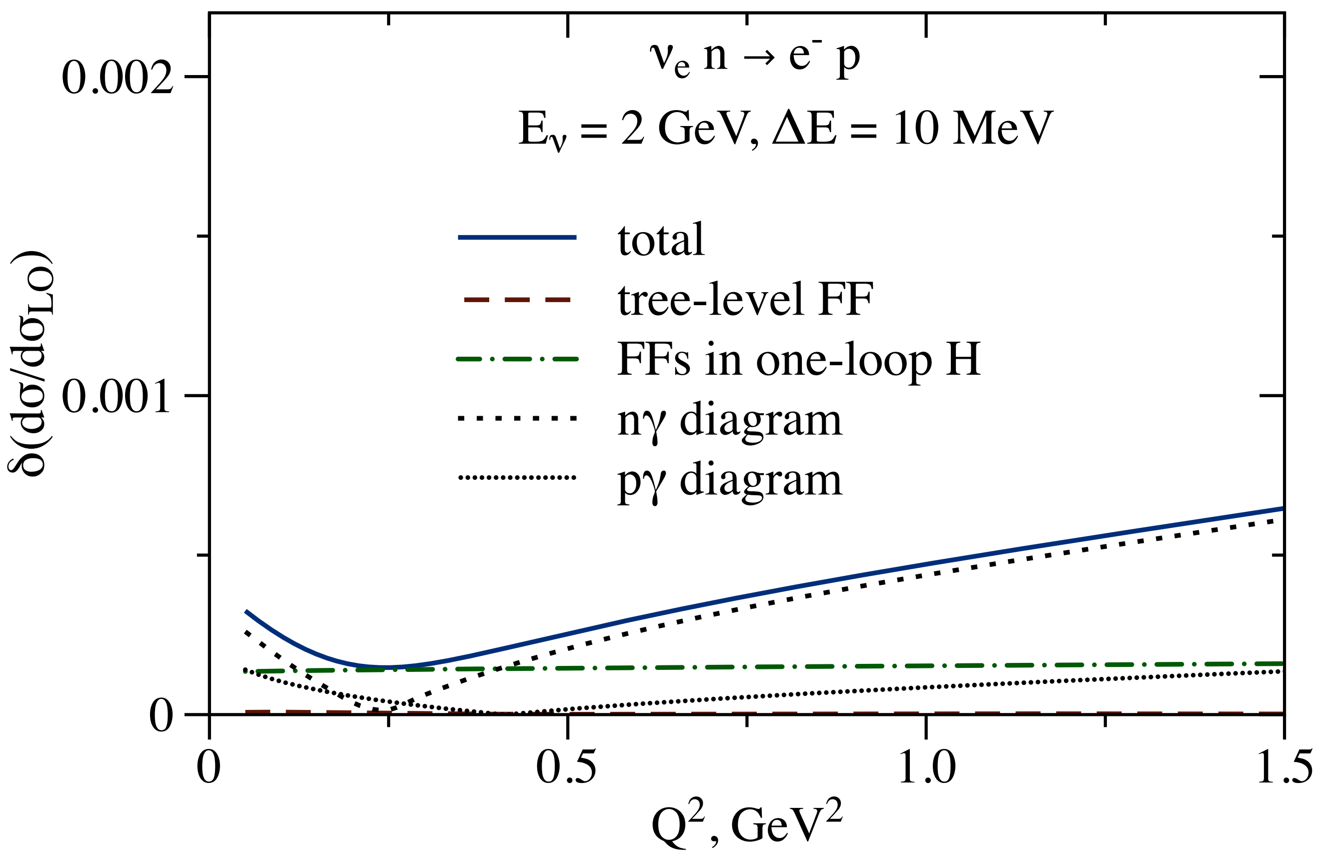
- calculate cross section at low energies accounting for all large logs

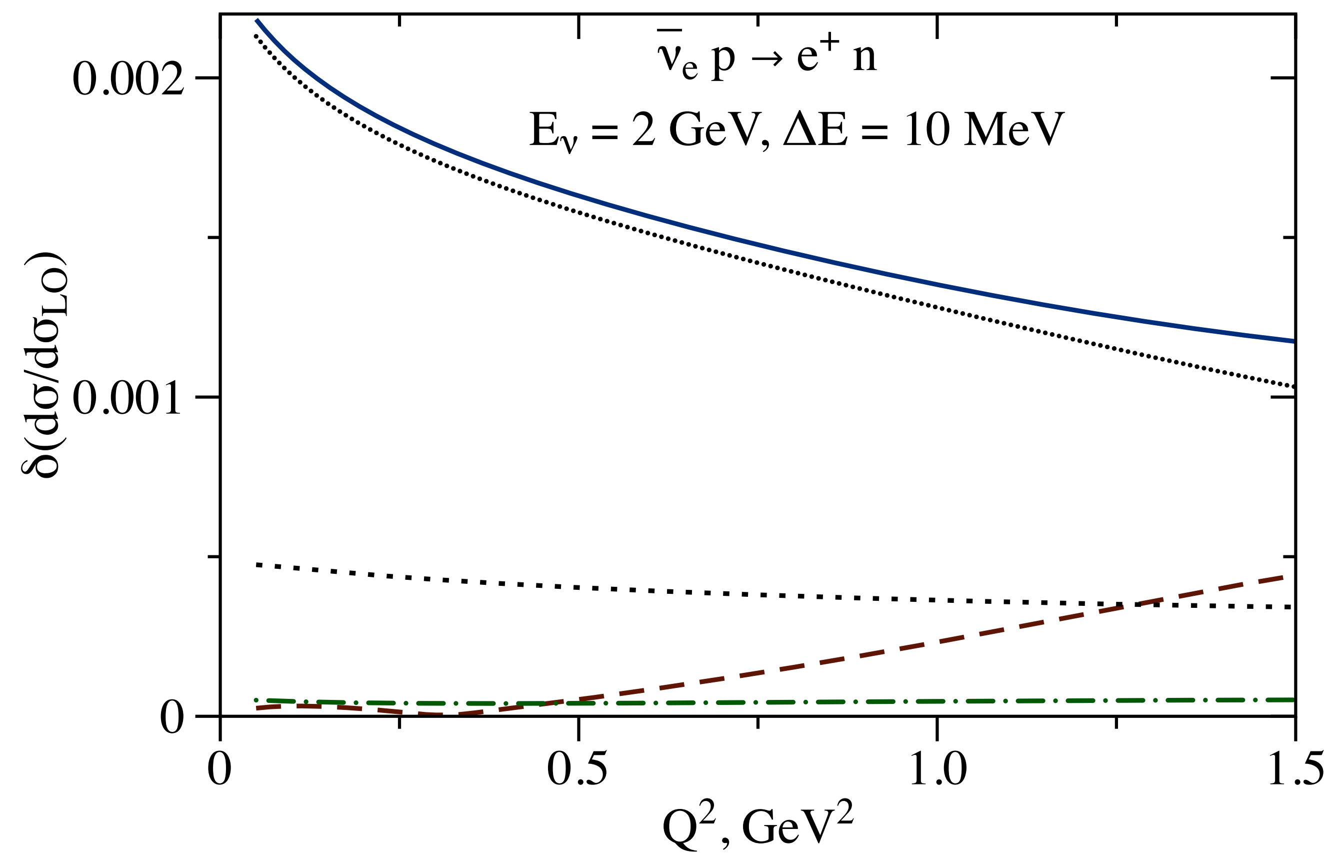
ep scattering with soft radiation only: Richard J. Hill (2016)

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

Error budget

- uncertainties from hard function





- nucleon form factors

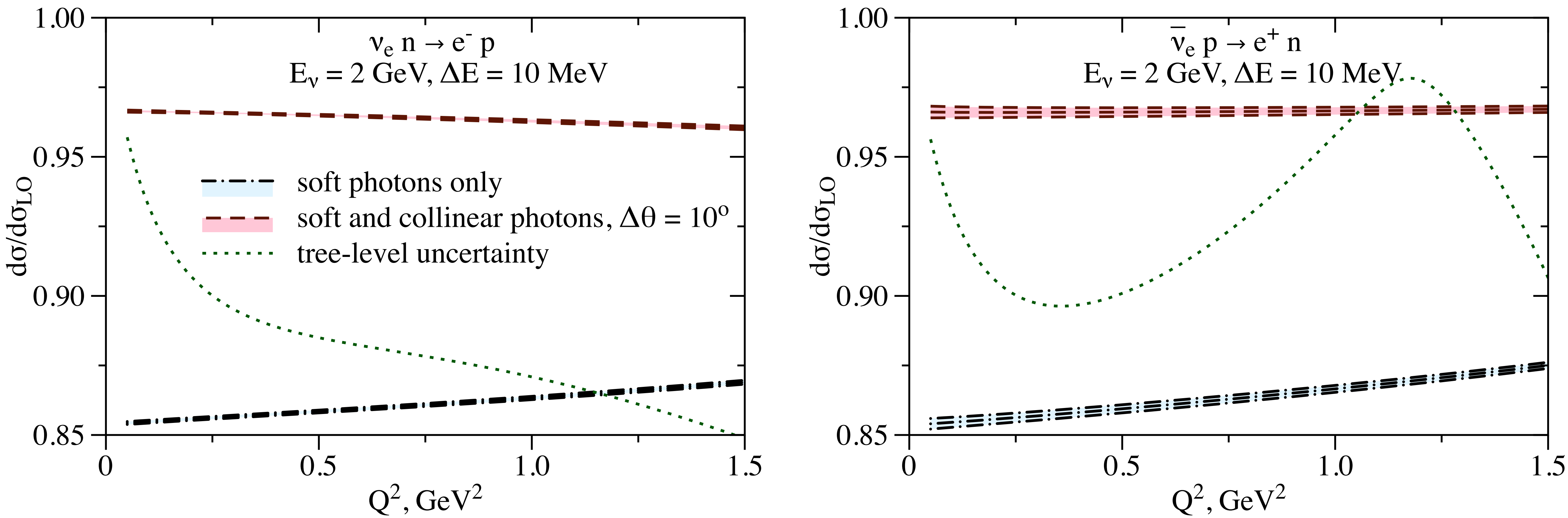
Meyer, Betancourt, Gran and Hill (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T. (2020)

- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result

Cross section. Electron flavor

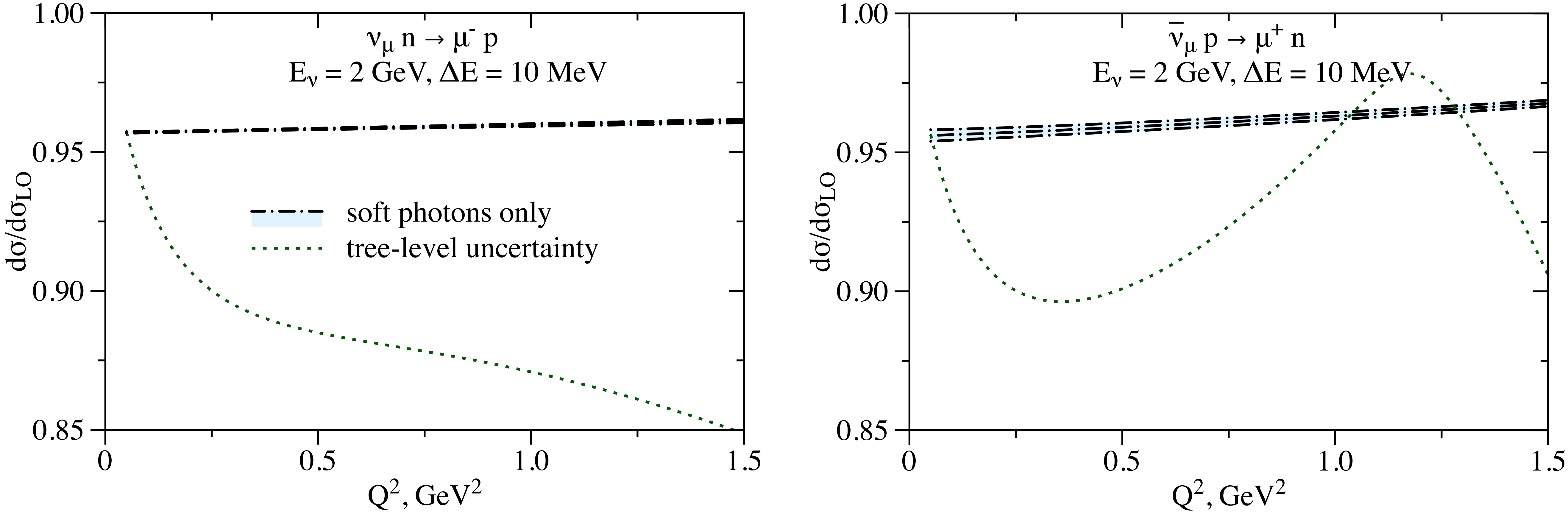
- exclusive observables



- ratio to LO: cancellation of uncertainty from hard function

Cross section. Muon flavor

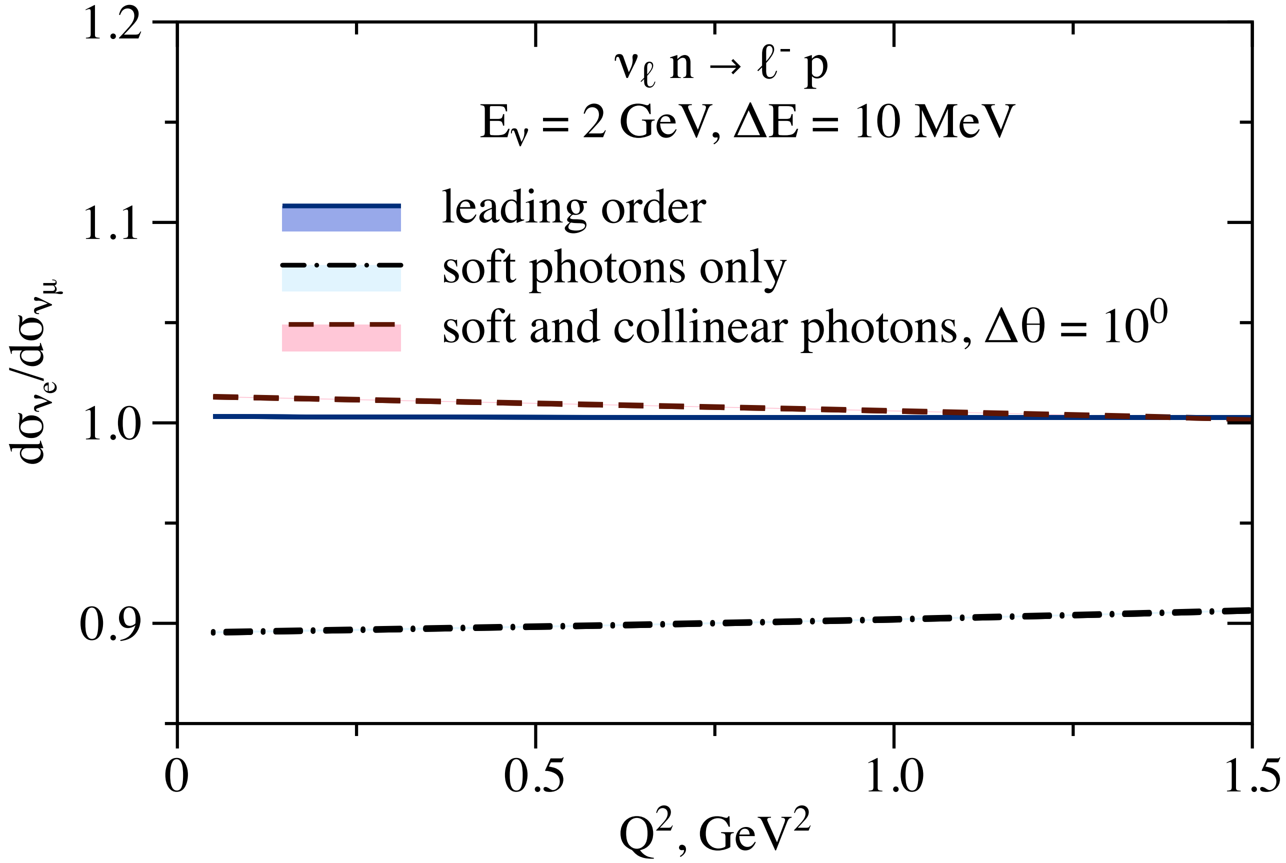
- exclusive observables

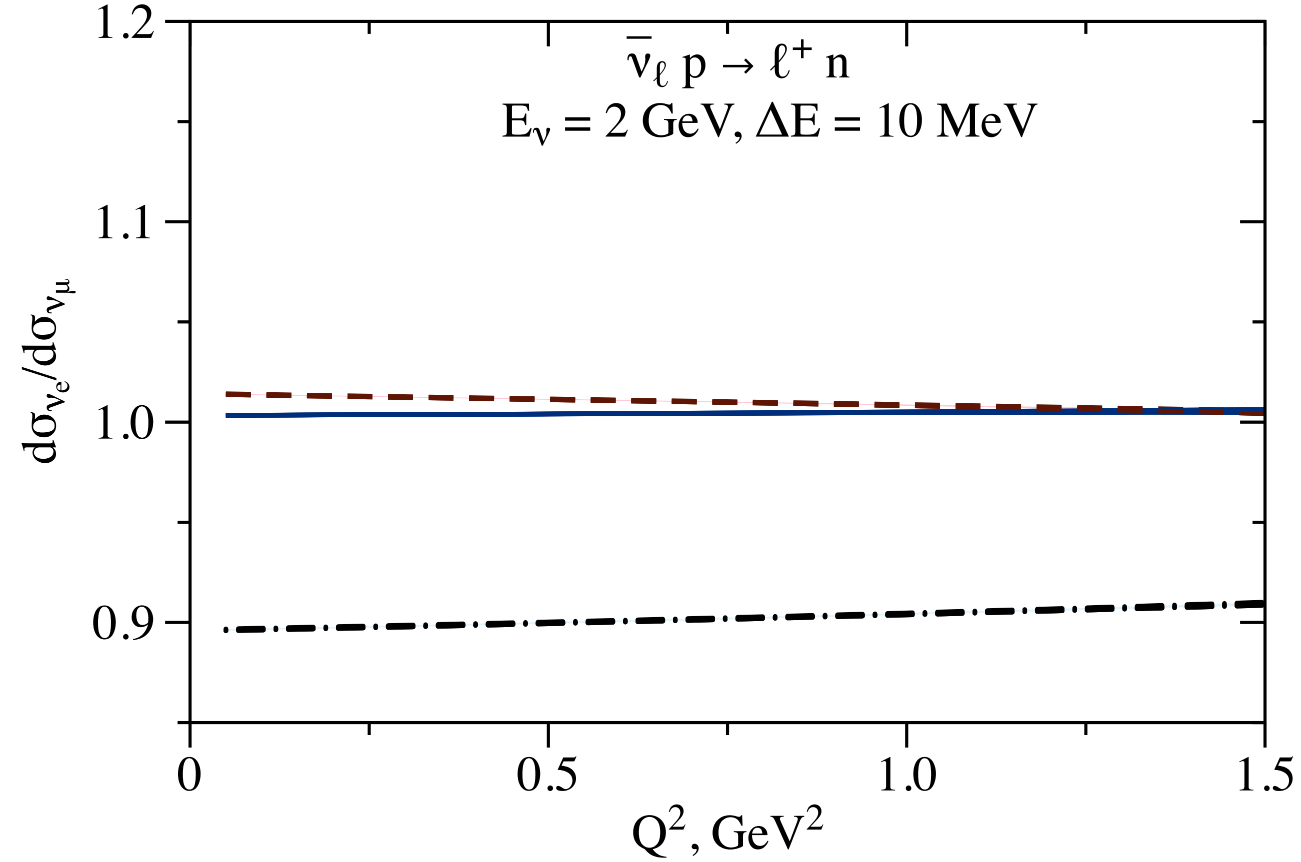


- ratio to LO: cancellation of uncertainty from hard function

Electron/muon ratio

- exclusive observables



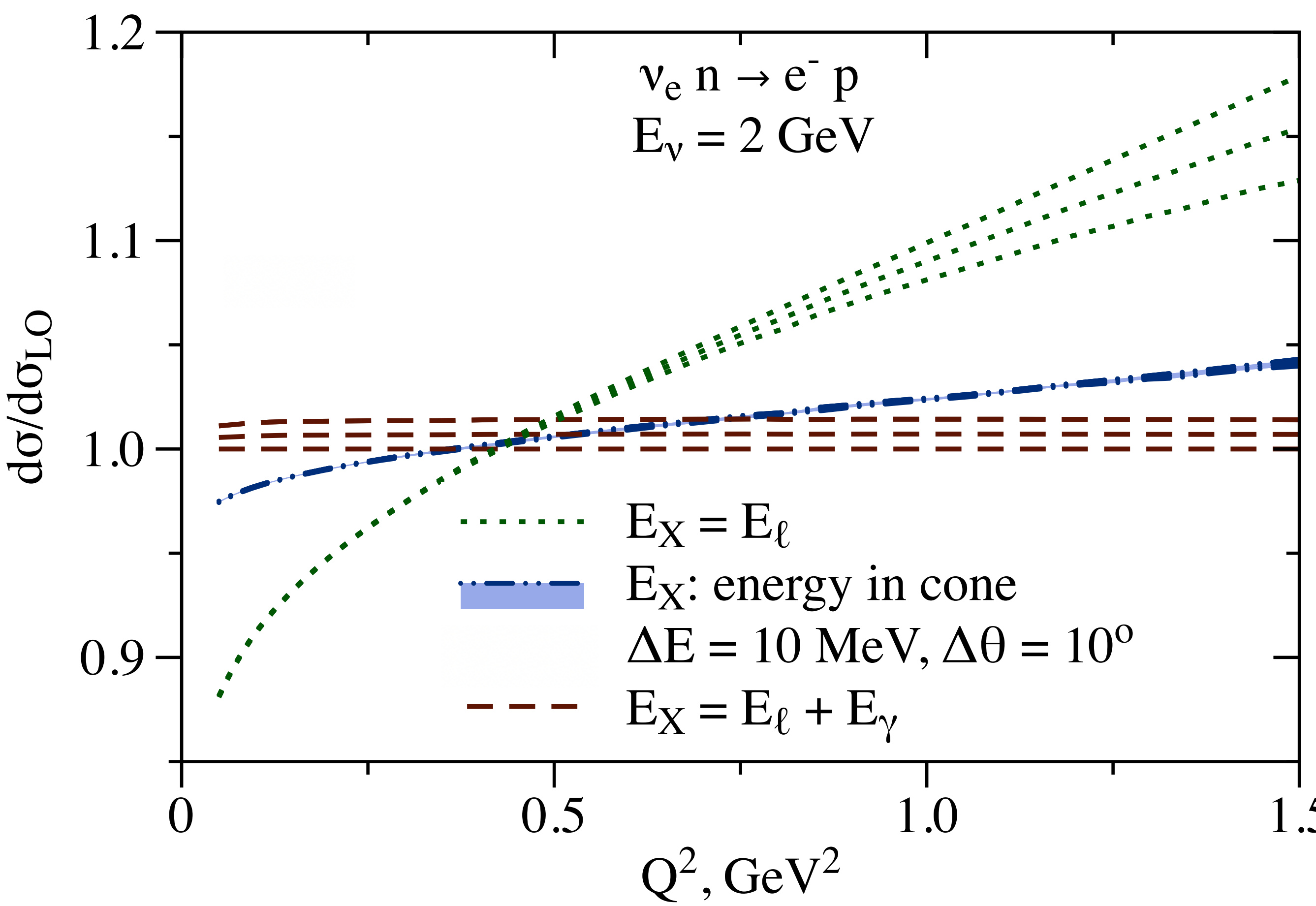


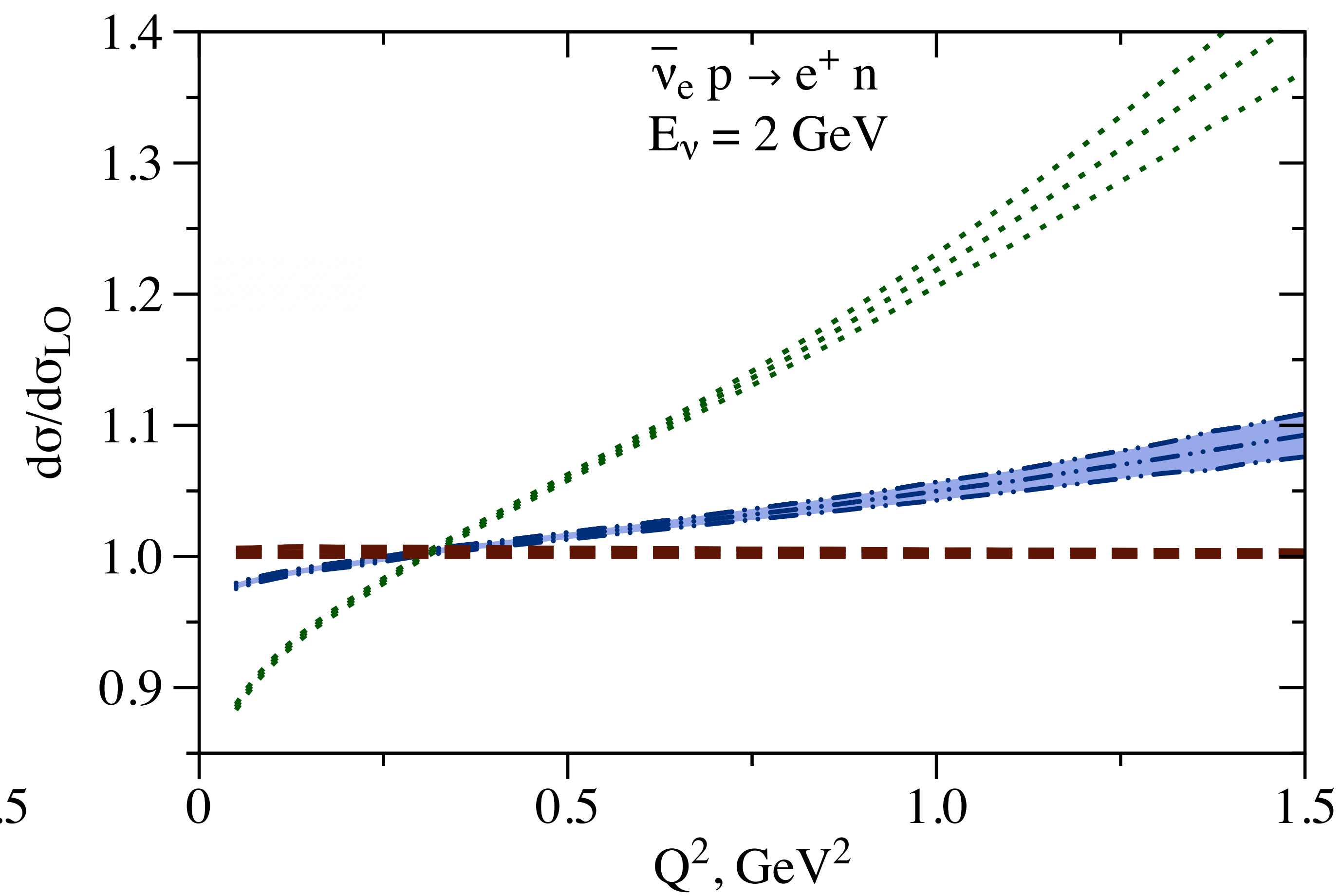
- small uncertainty: hard function does not depend on mass

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

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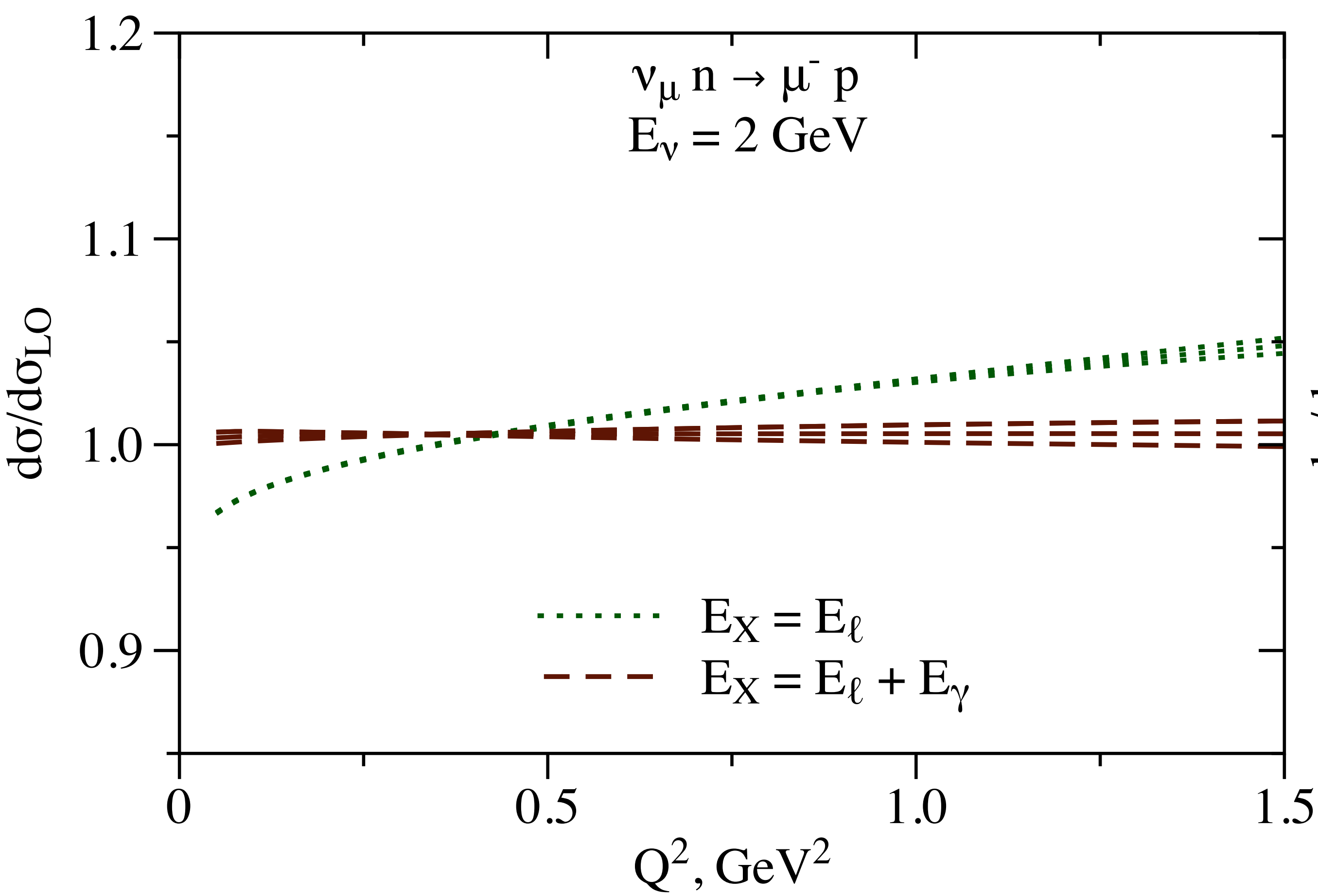
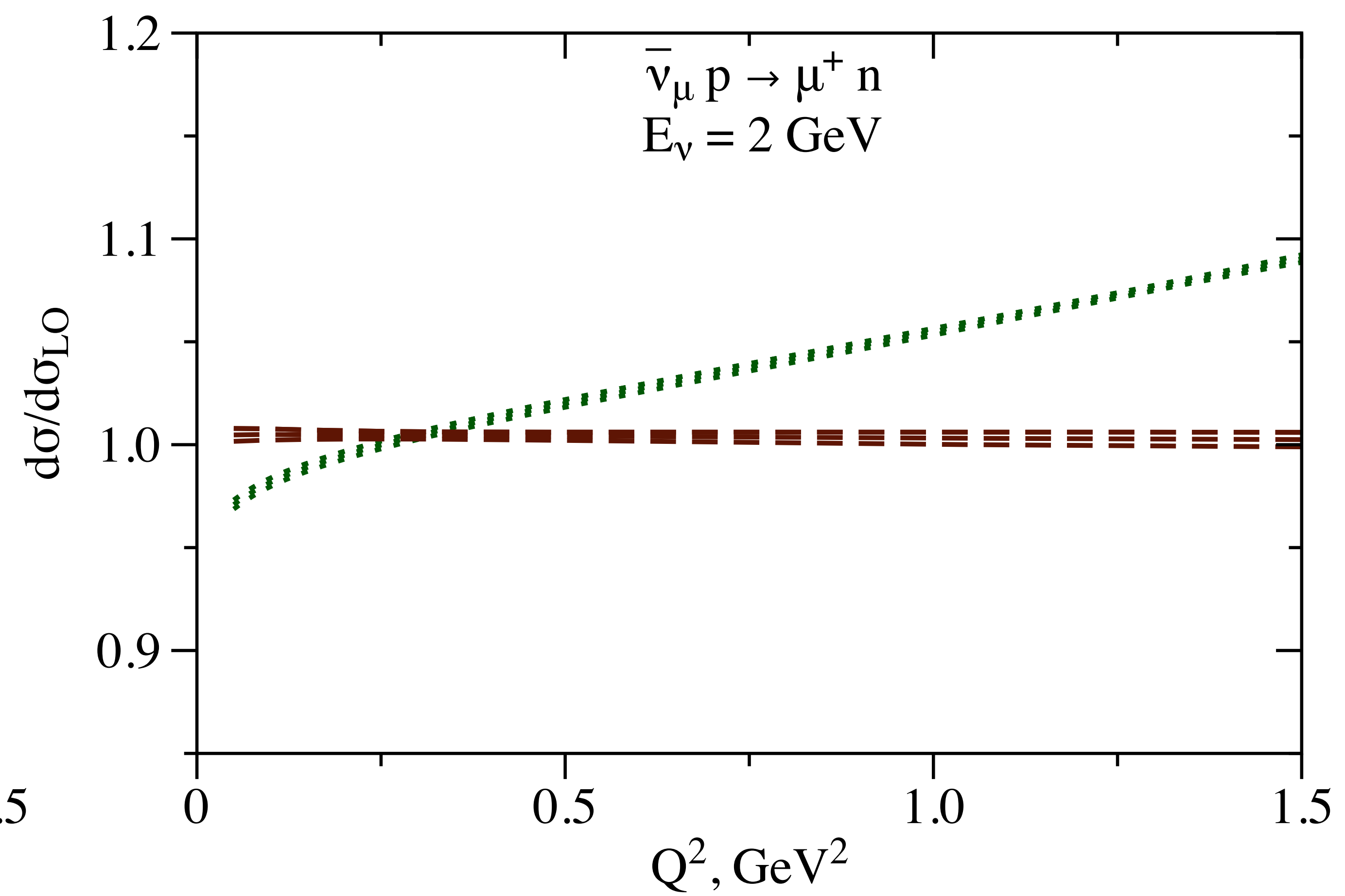
- inclusive observables





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Electron/muon ratio

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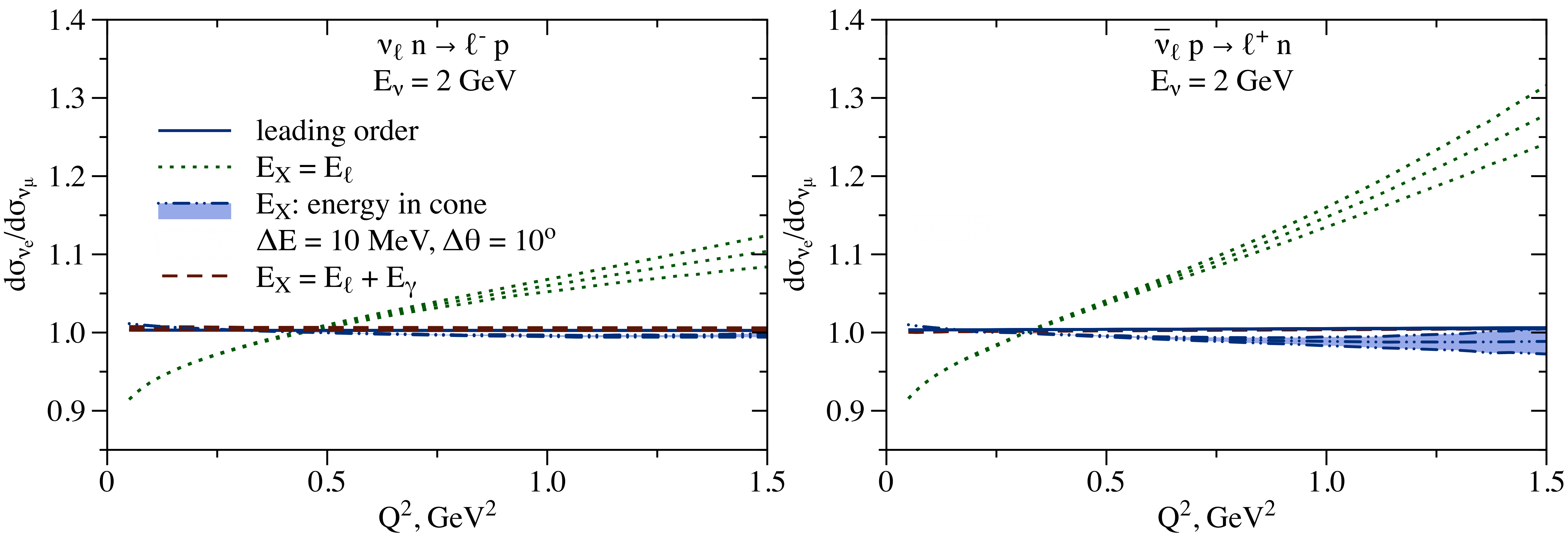
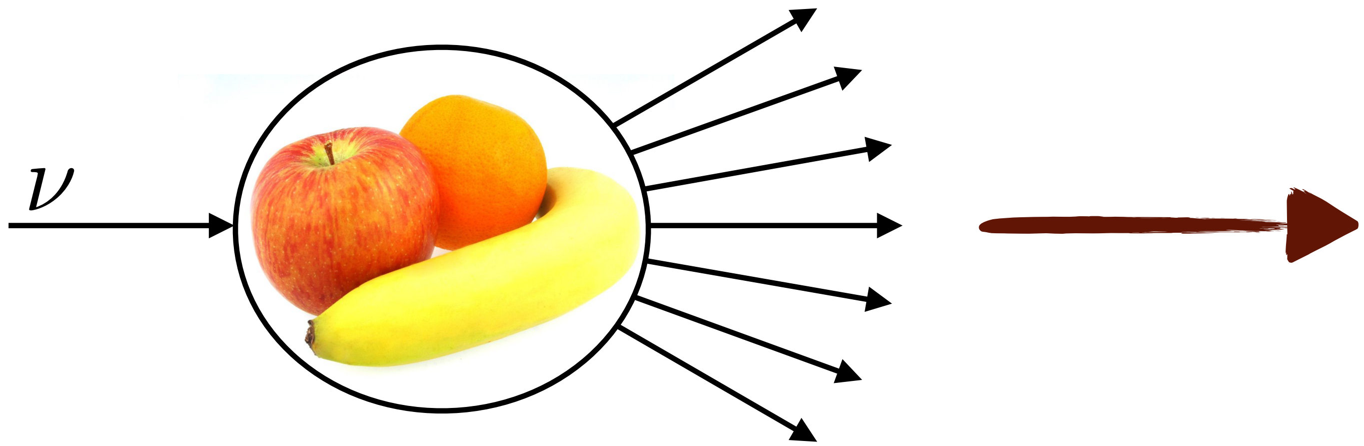


- predict σ_{ν_e} from σ_{ν_μ} measurements with neutrino beam ✓

Conclusions



radiative corrections in EFT framework

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

- model for the hard function

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

Thanks for your attention !!!

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