New directions in Neutrino-Nucleus Scattering

NUSTEC Workshop

16 March, 2021

Radiative corrections

University of Kentucky

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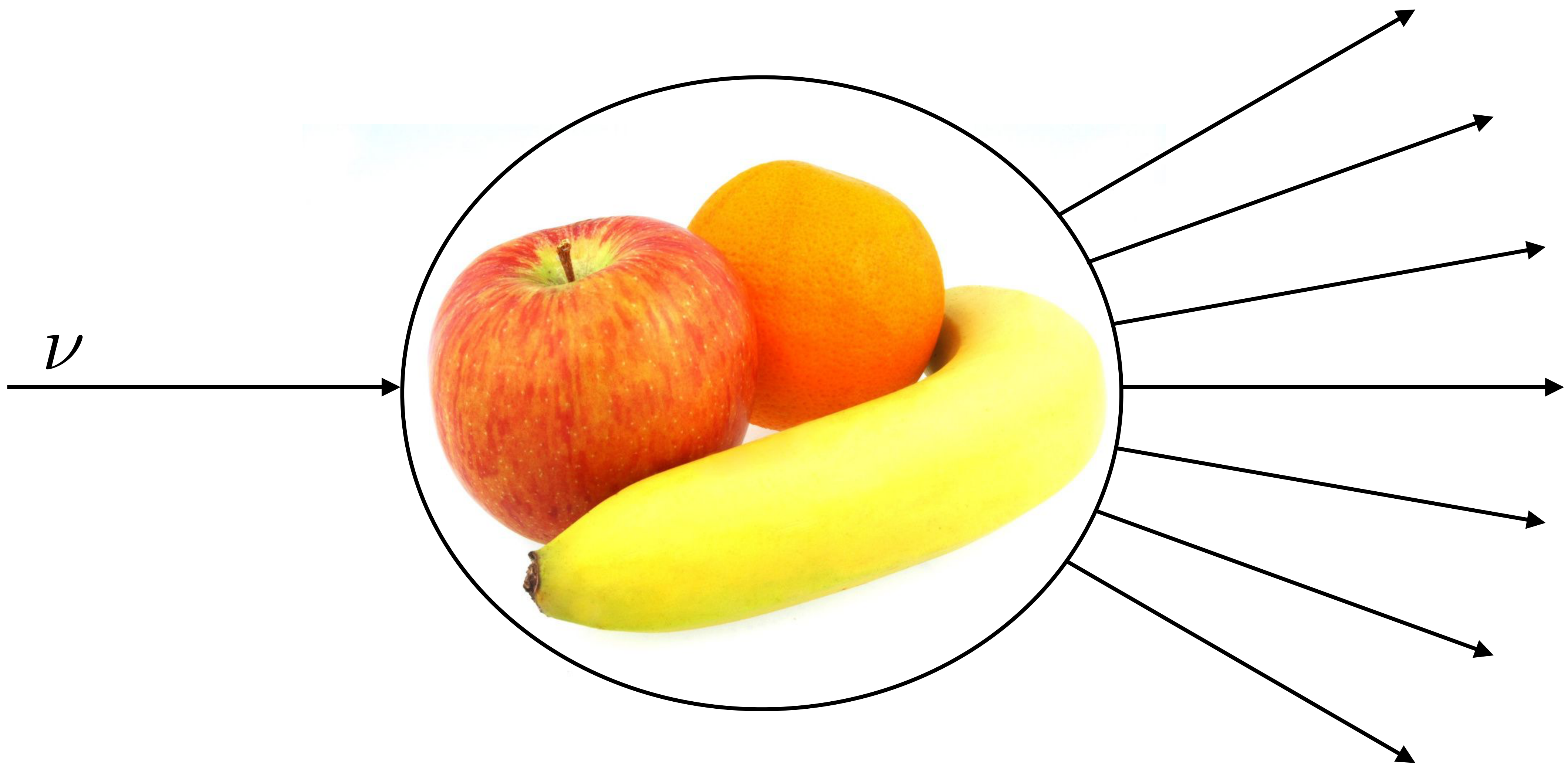
Outline

1) microscopic EFT for neutrino physics

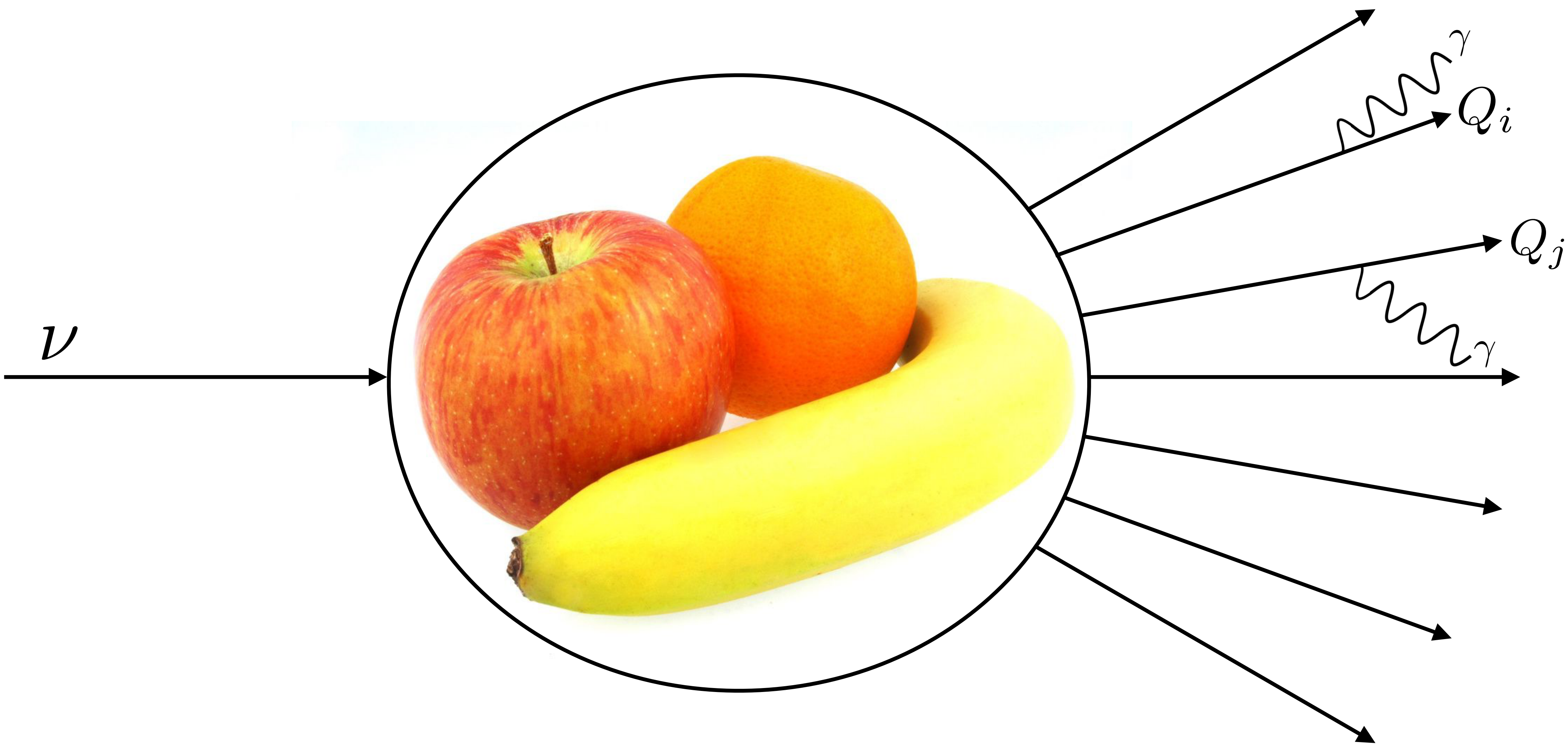
2) coherent elastic neutrino-nucleus scattering (CEvNS)

3) charged-current scattering on nucleons

Neutrino interactions

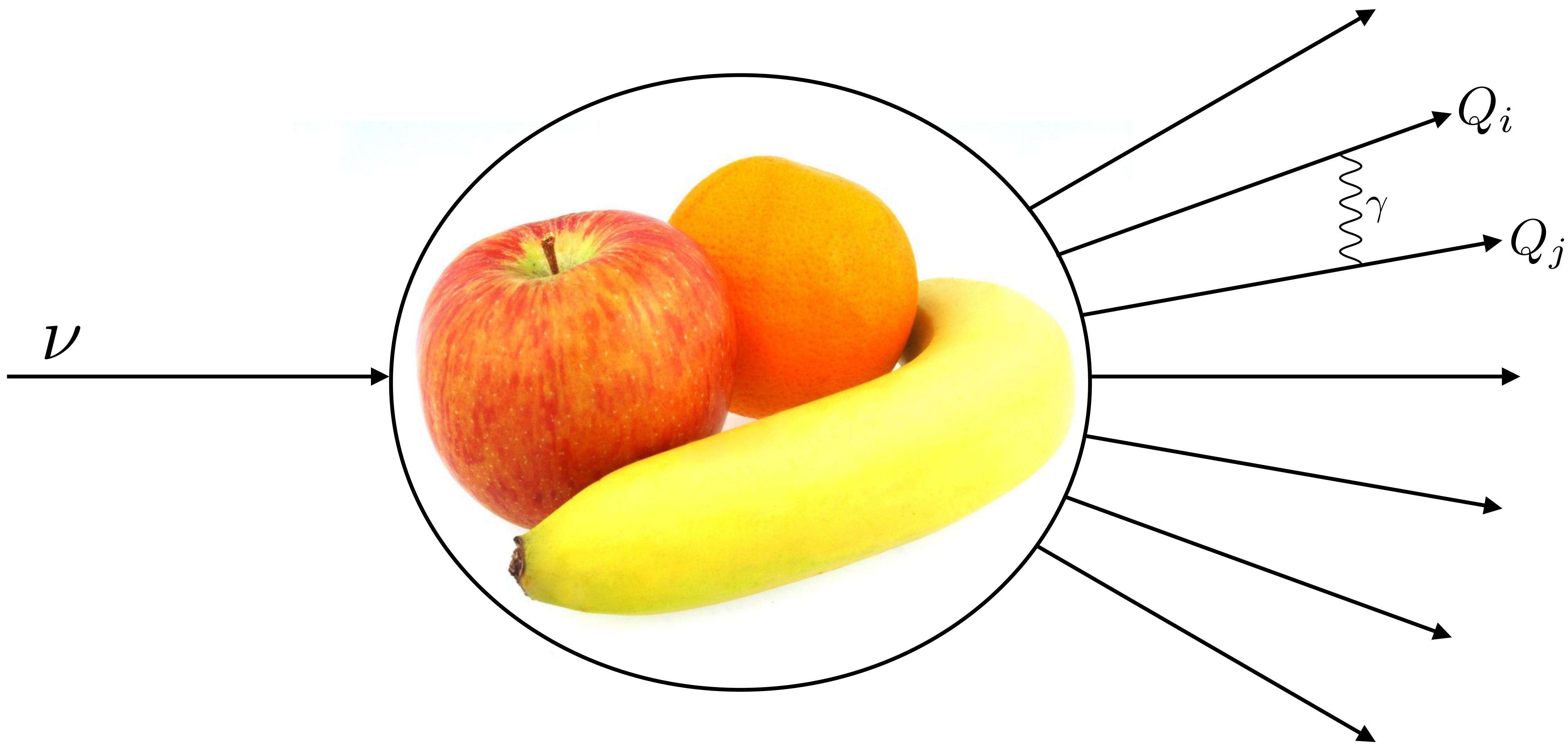


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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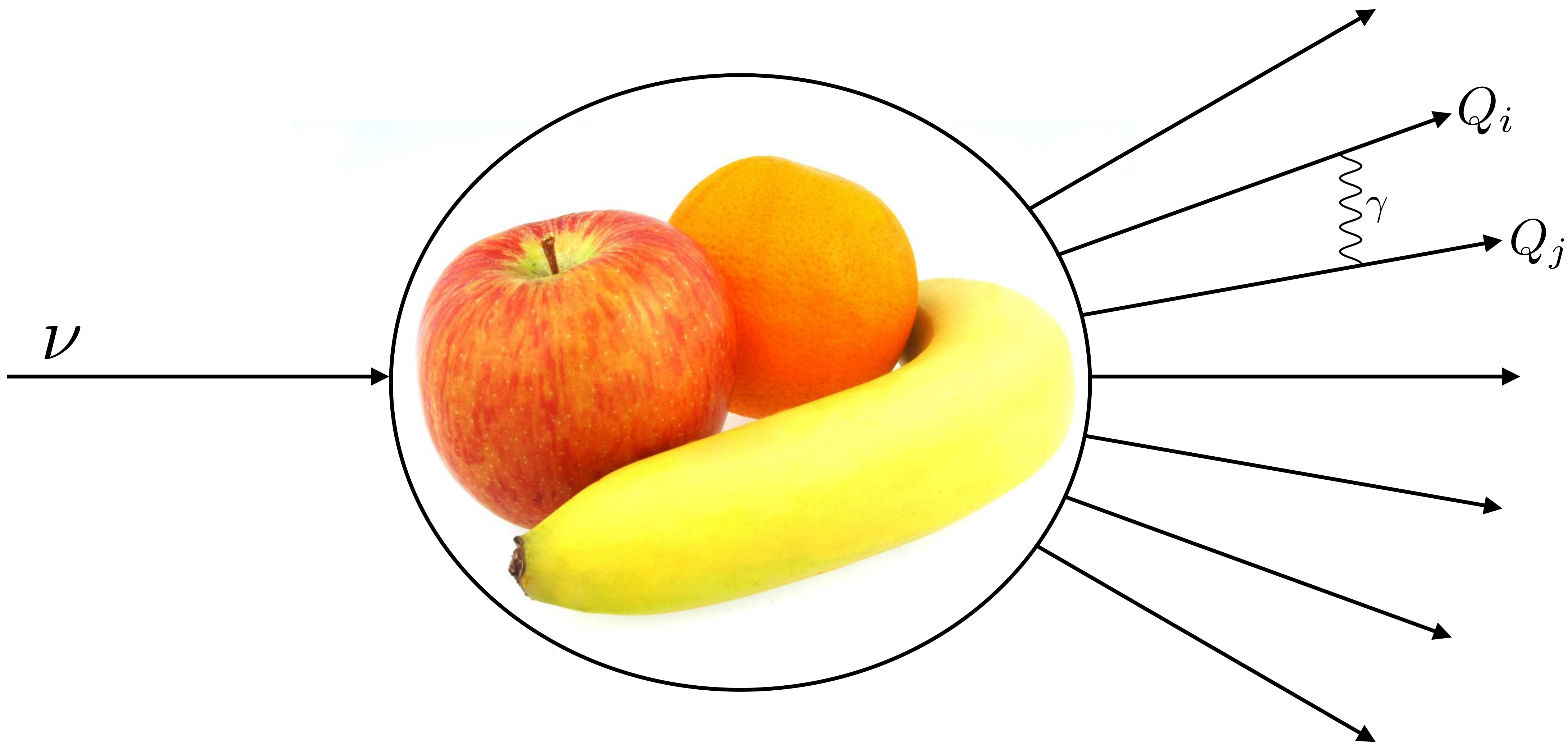
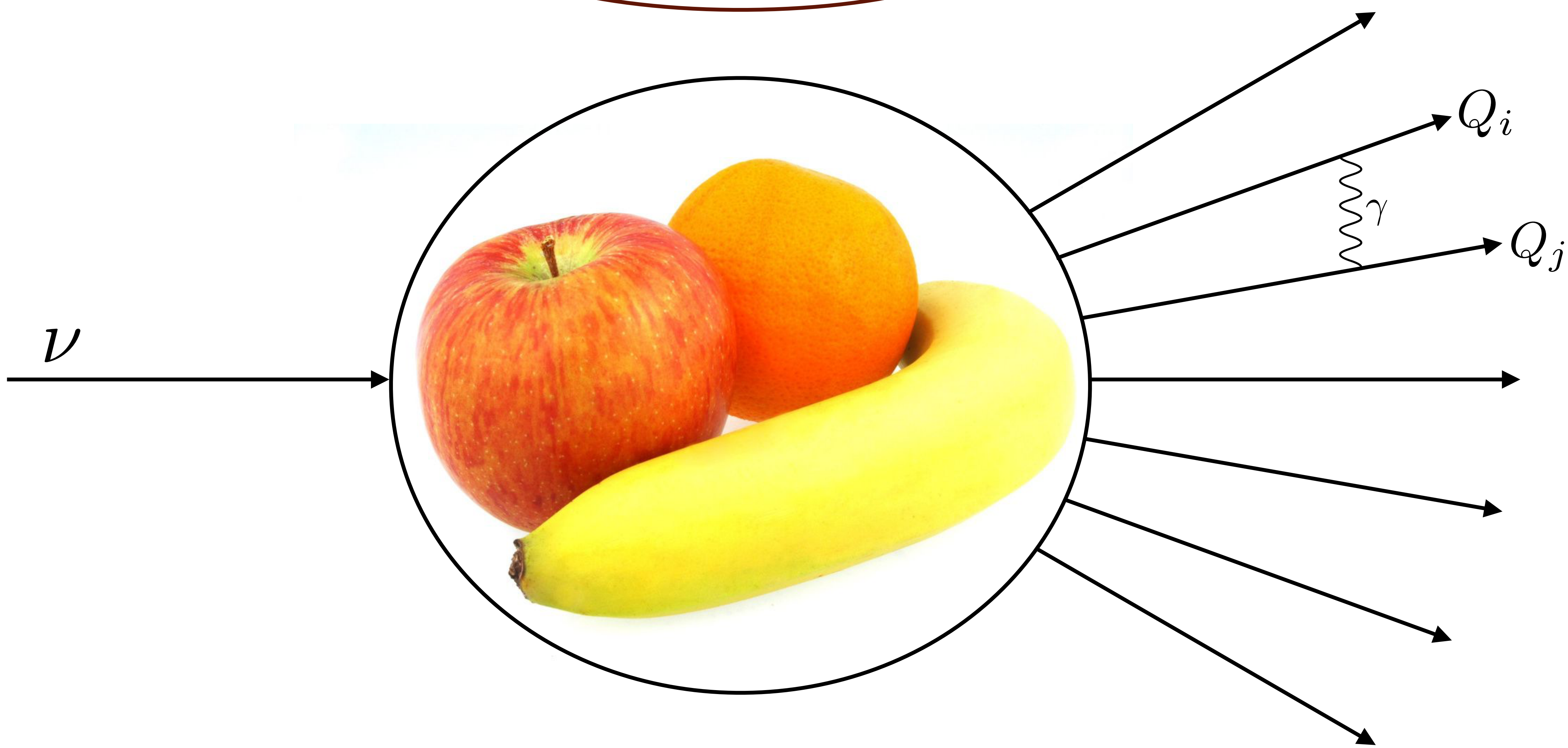
QED corrections



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

QED corrections

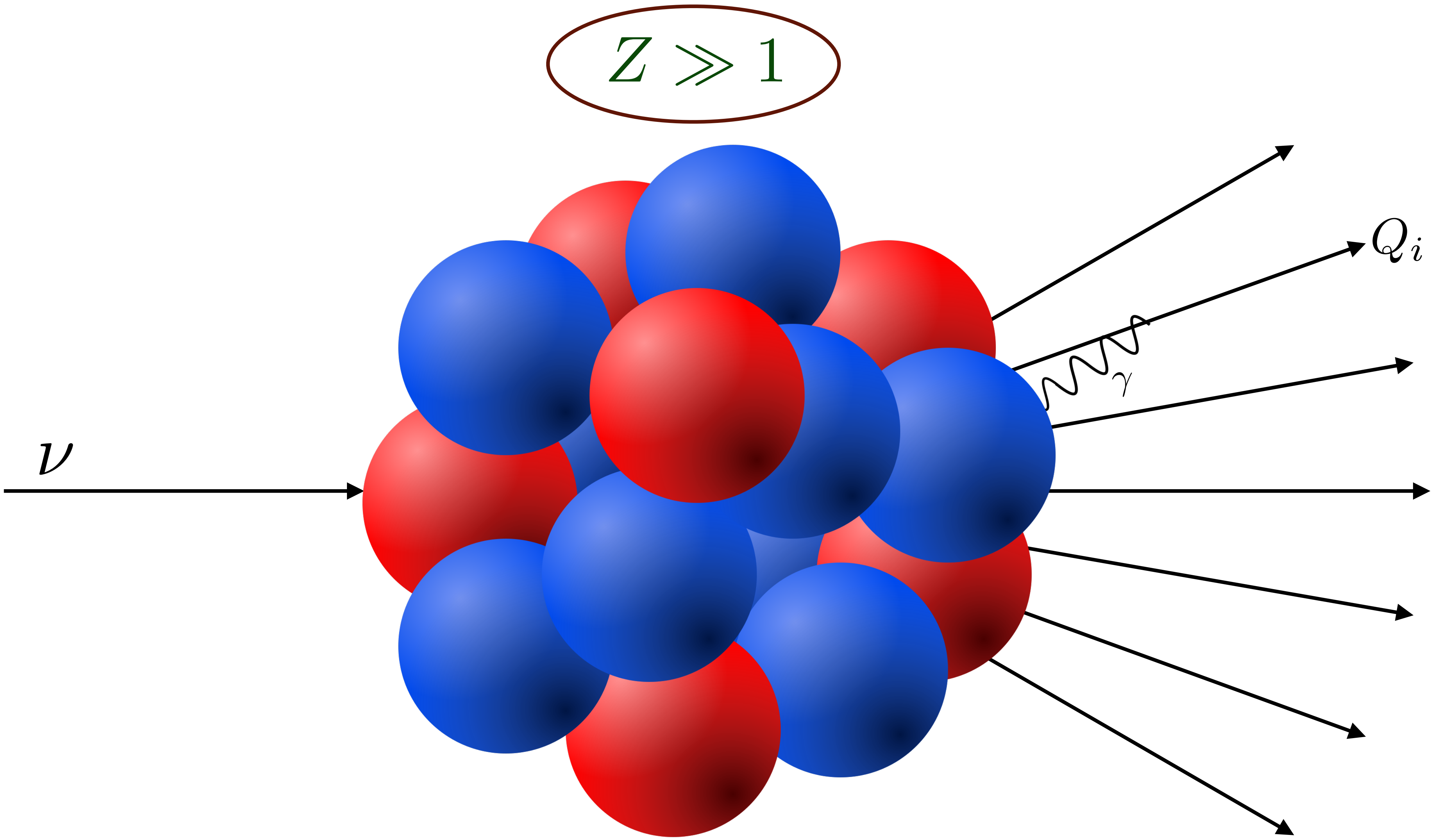
$$m_e \ll m_\mu \ll E_\nu$$



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

QED corrections



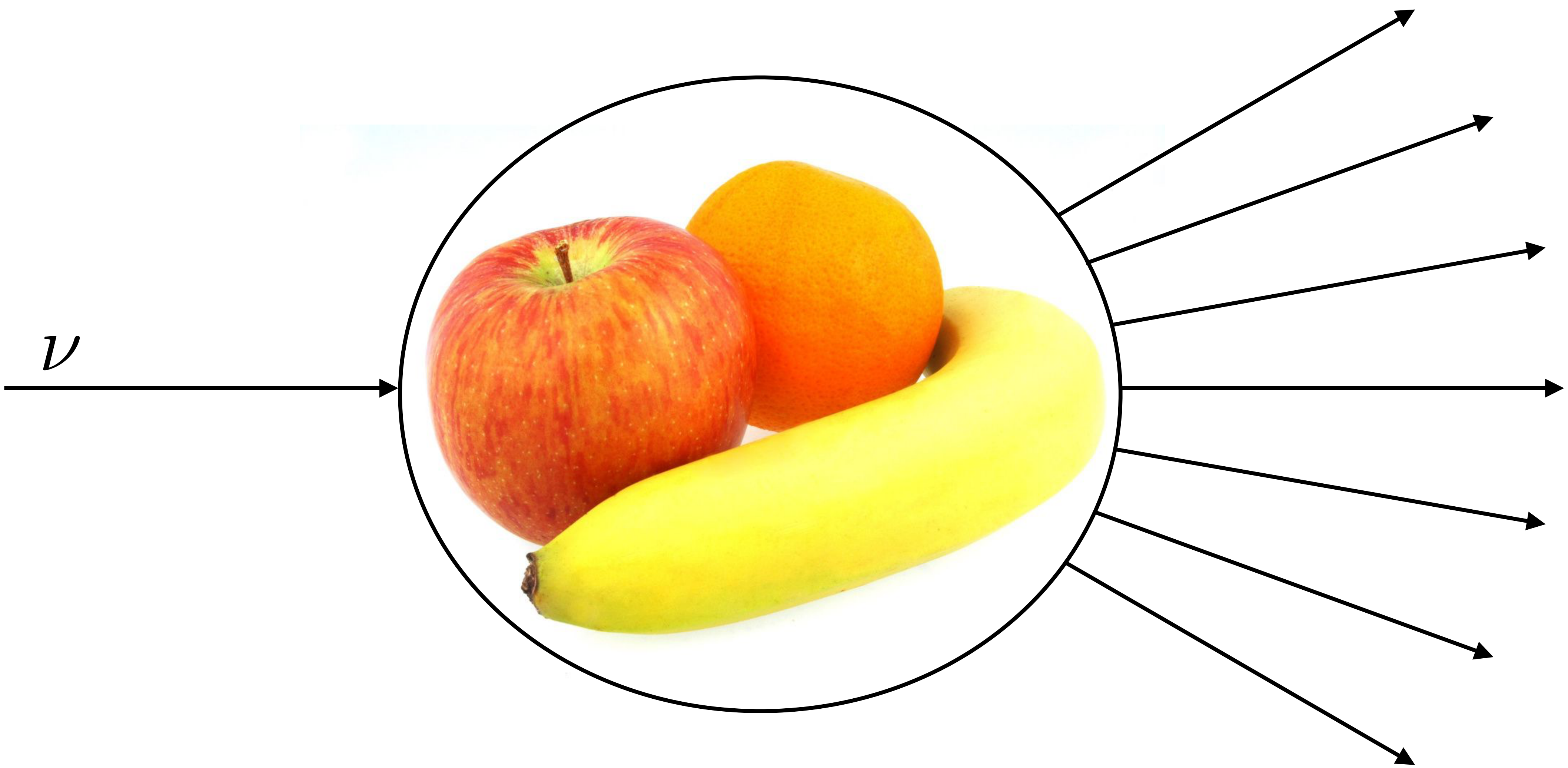
$\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by target nucleus charge $Z \lesssim 10 - 20$

talk by Ryan Plestid

- Coulomb corrections are enhanced by nucleus charge factor

QED corrections

neutral-current interactions

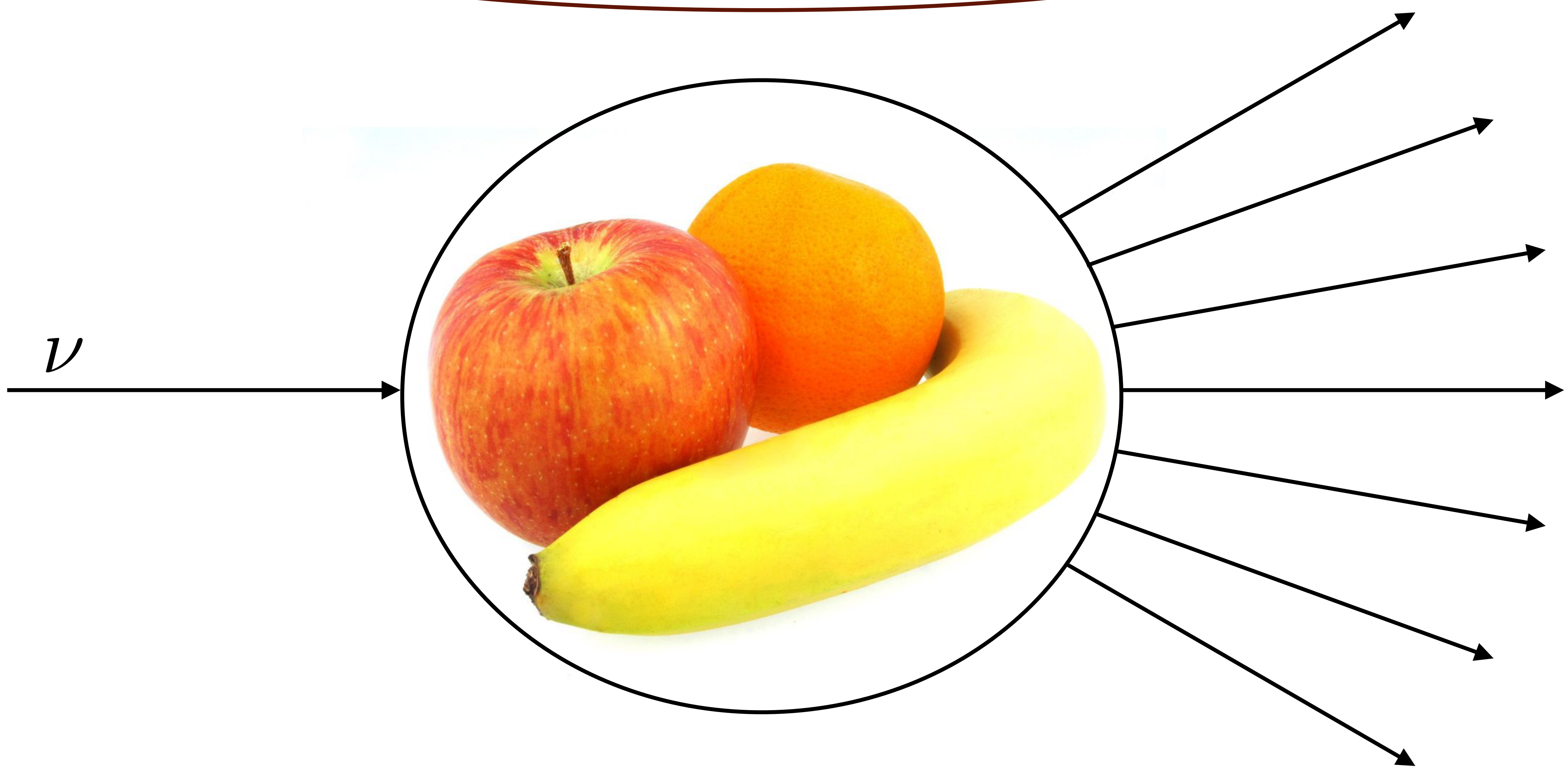


$\text{X}\,\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by kinematic-dependent factors

- kinematic dependence and factor X can enhance QED corrections

Electroweak corrections

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



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

- electroweak corrections can be included in low-energy interactions

Microscopic EFT for neutrino physics

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

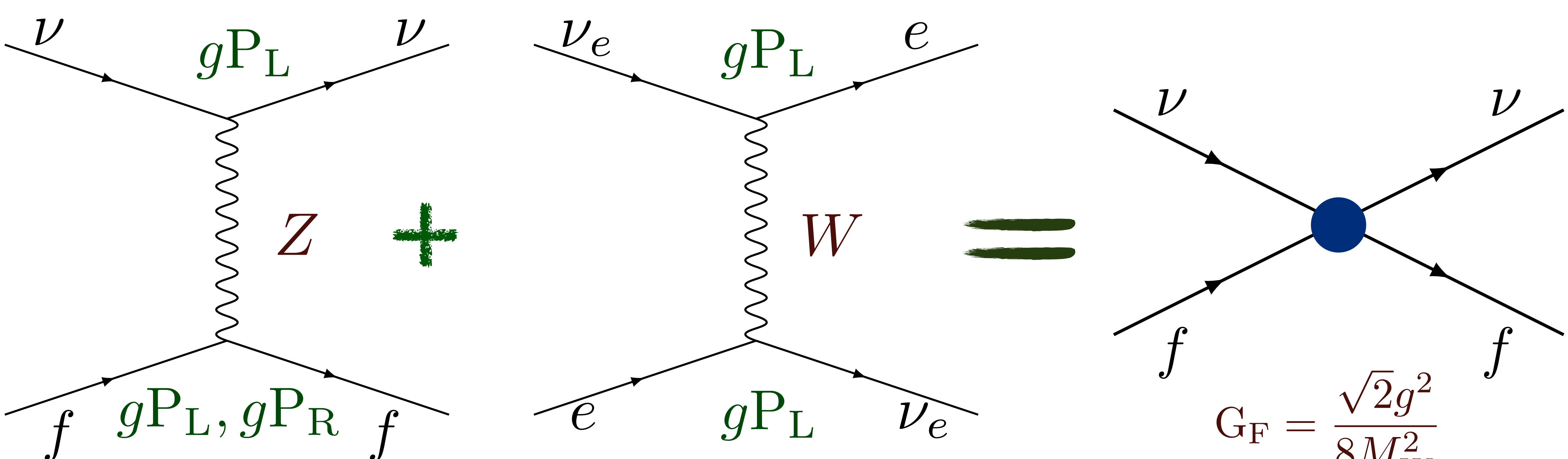
Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT

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

neutral current

charged current



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

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT

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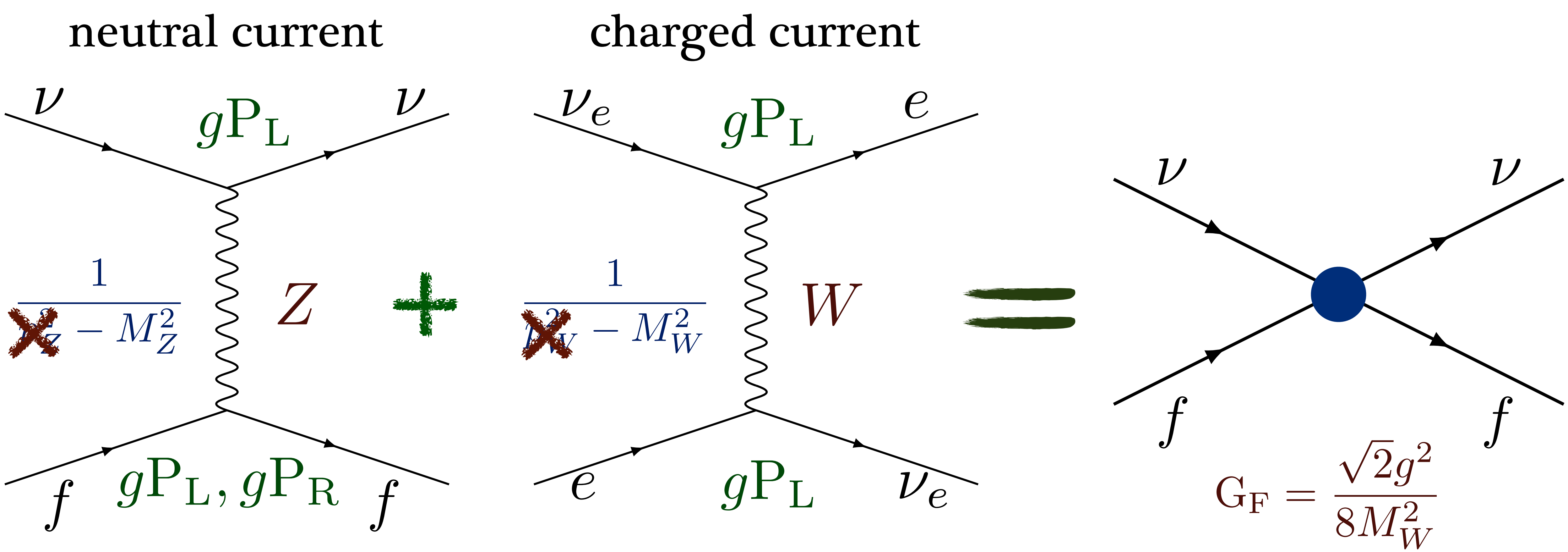

- masses of W and Z are large: integrate out W and Z at tree level

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT

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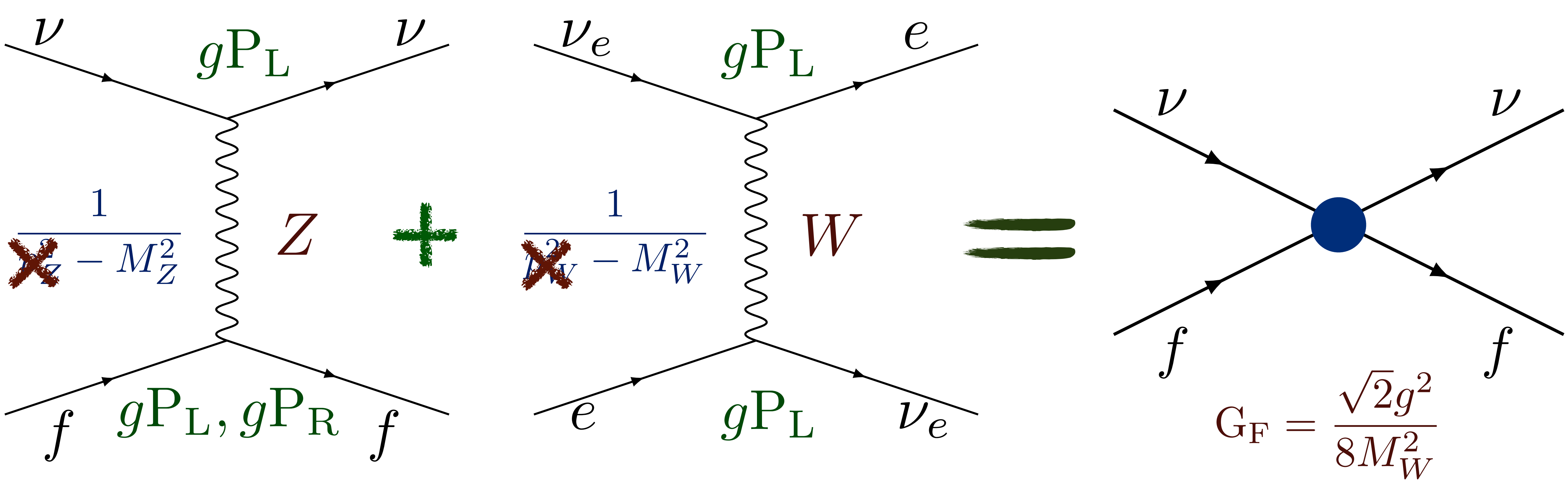
couplings to electron

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

Weinberg (1967), 't Hooft (1971)

neutral current charged current



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- matching to low-energy EFT

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- consider only leading in G_F terms: loop corrections in α, α_s

- gauge-invariant matching of amplitudes, renormalized in $\overline{\rm MS}$ scheme

$$\mathcal{M}^{\rm SM} = \mathcal{M}^{\rm EFT}$$

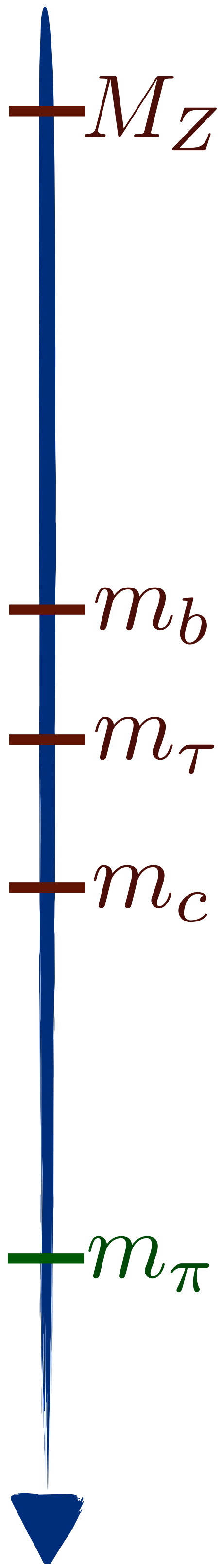
- G_F: combination of parameters is precisely measured

$$\mathrm{G_F} = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

MULAN (2012)

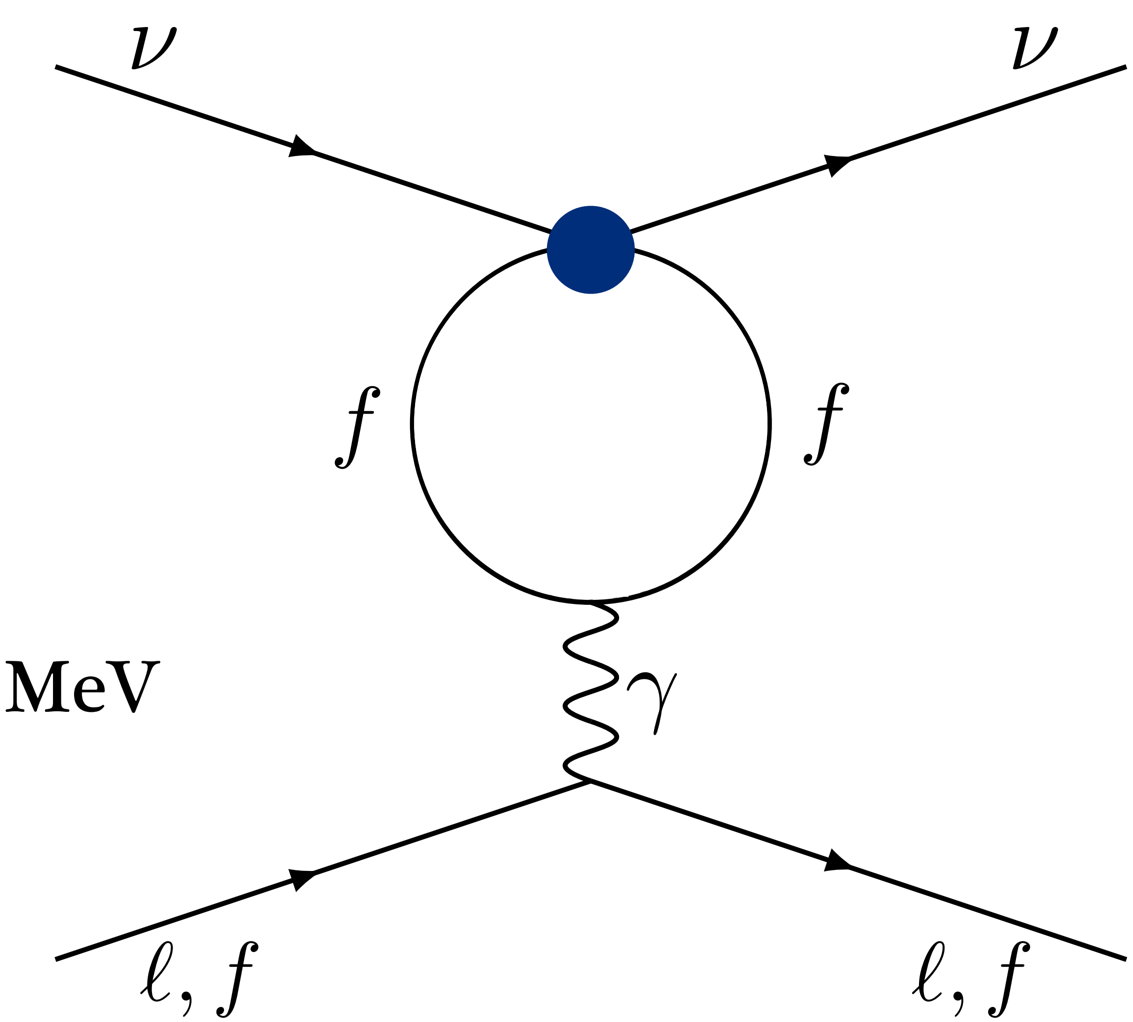
- matching at order $\alpha\alpha_s$: left- and right-handed couplings
- muon lifetime measurement improves precision

Running to low scales

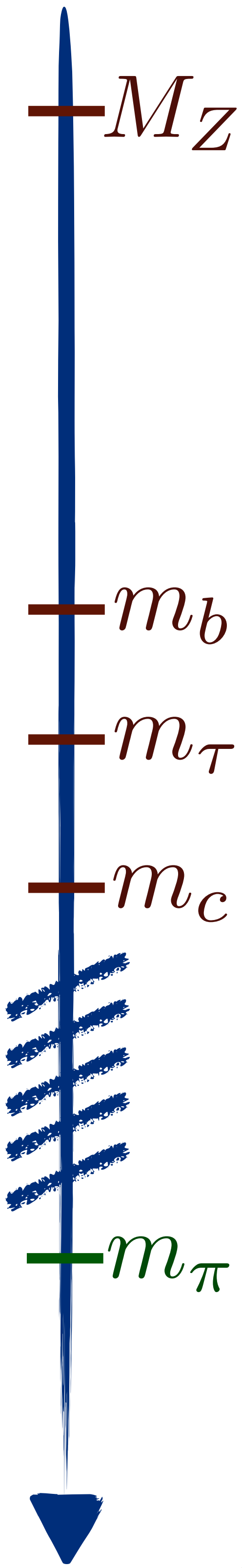


- integrate out top, Z, W, h
- integrate out GeV particles
- α_s becomes too strong
- hadronic physics down to 140 MeV
- theory with leptons

% running effects



Running to low scales



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

- integrate out GeV particles
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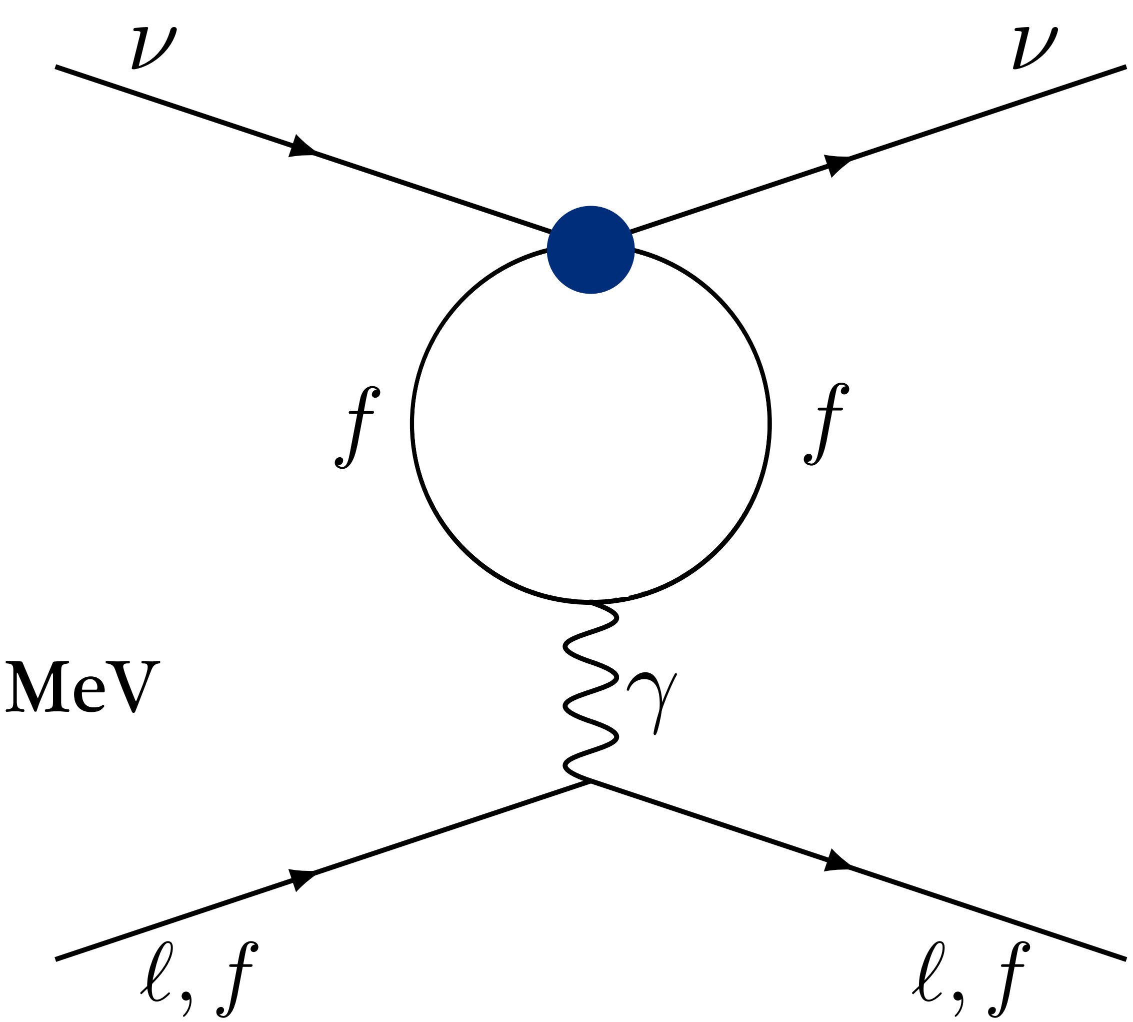
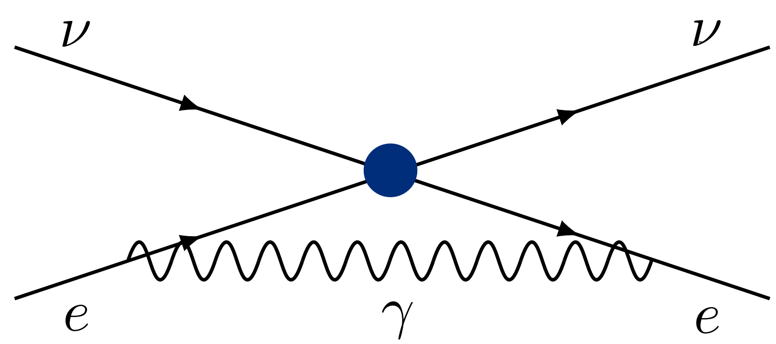
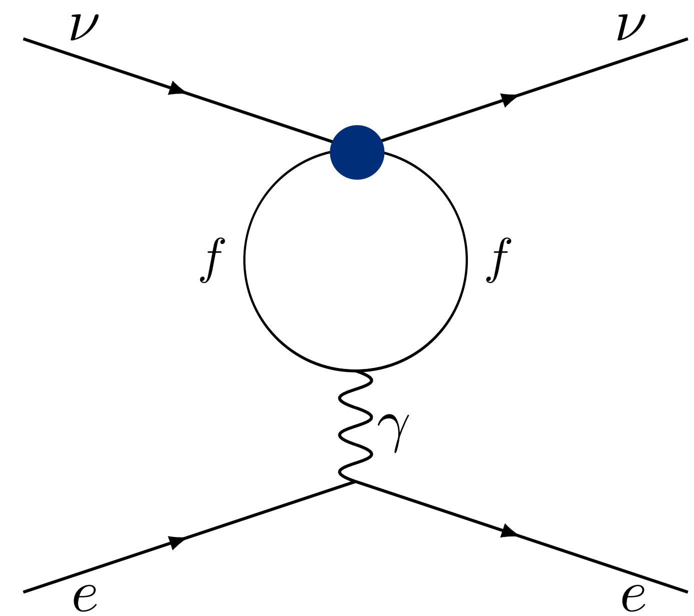


- precise mapping from electroweak to hadronic scales



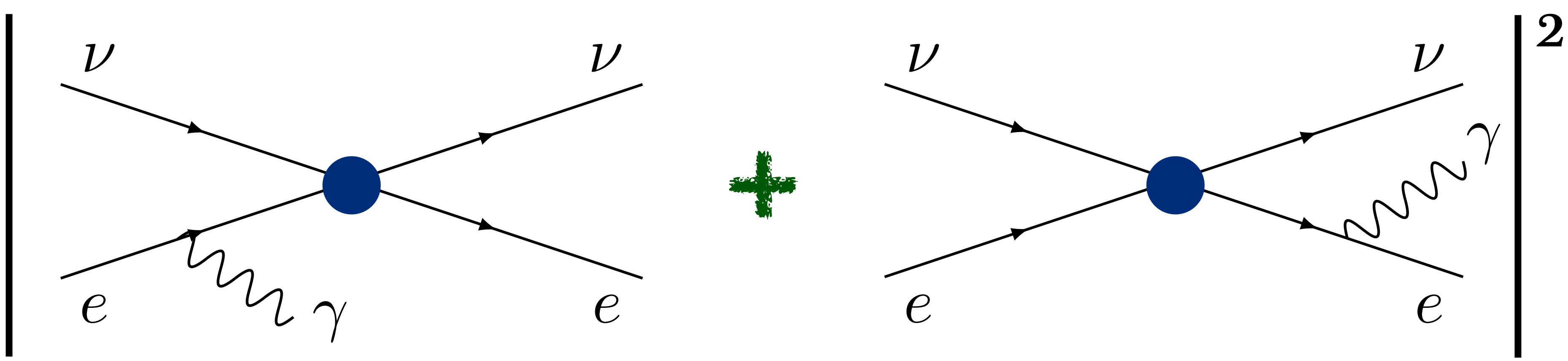


Neutrino-electron scattering

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



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Coherent elastic neutrino-nucleus scattering

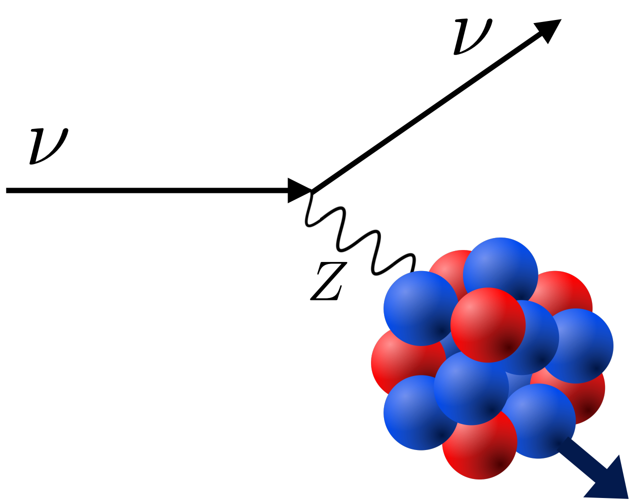
O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

talks by Yiyu Zhang, Erin Conley, Diego Aristizabal,
Dr. Matthew Heath, Dr. Sonia Bacca

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

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

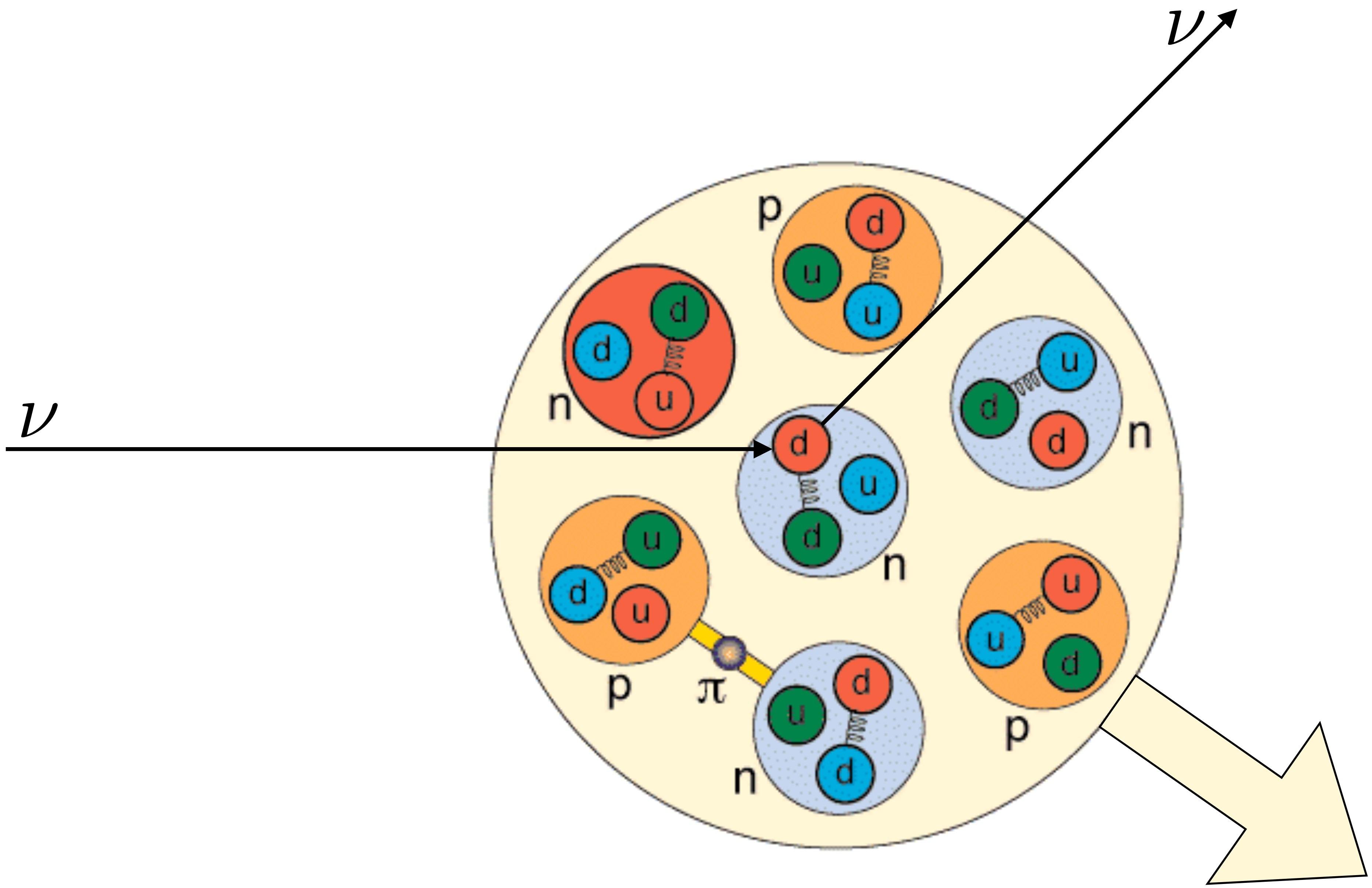
- first detection in 2017 at SNS, measured on CsI and Ar

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

- rapidly developing field nowadays

- CEvNS enters precision era with πDAR sources

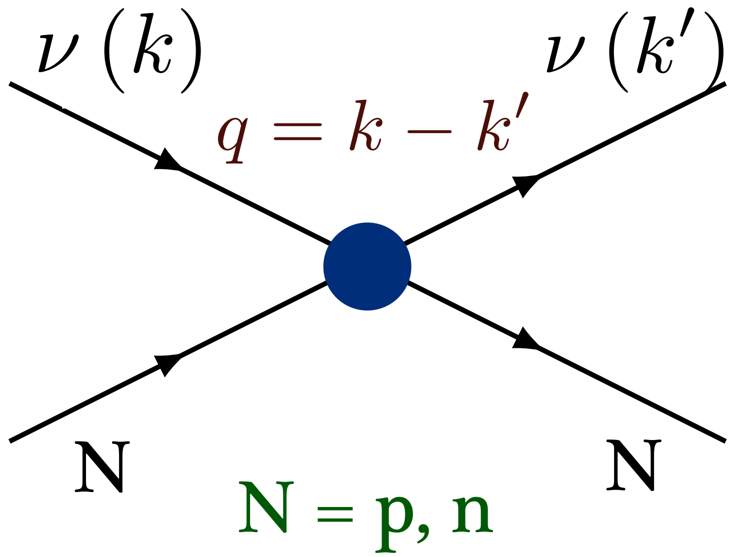
From quarks to nuclei



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

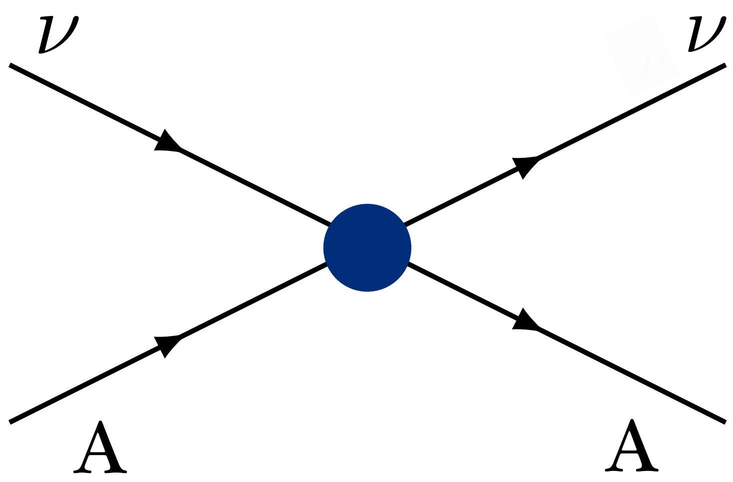
$$\mathcal{M} \sim \bar{\nu}_\ell \gamma_\mu \mathrm{P}_\mathrm{L} \nu_\ell \cdot \langle N | \sum_q \bar{q} \gamma^\mu (c_\mathrm{L}^{\nu_\ell q} \mathrm{P}_\mathrm{L} + c_\mathrm{R}^{\nu_\ell q} \mathrm{P}_\mathrm{R}) q | N \rangle$$

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

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

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

spin-0 nuclei

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

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

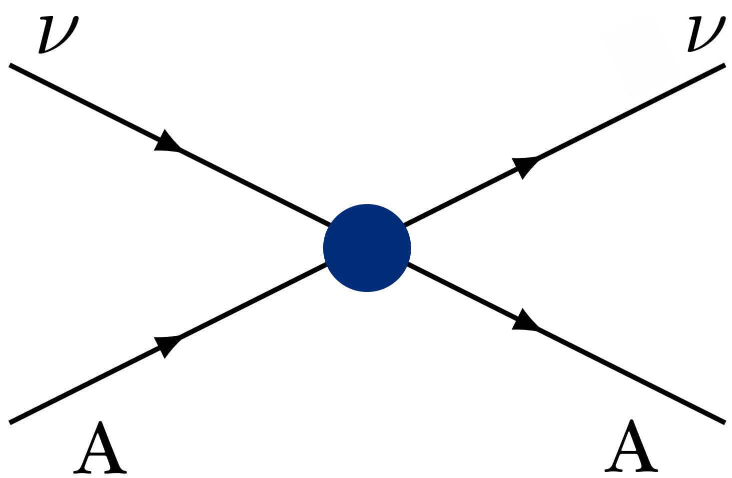
- flavor-independent form factor above GeV scale

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

Hoferichter et al. (2020)

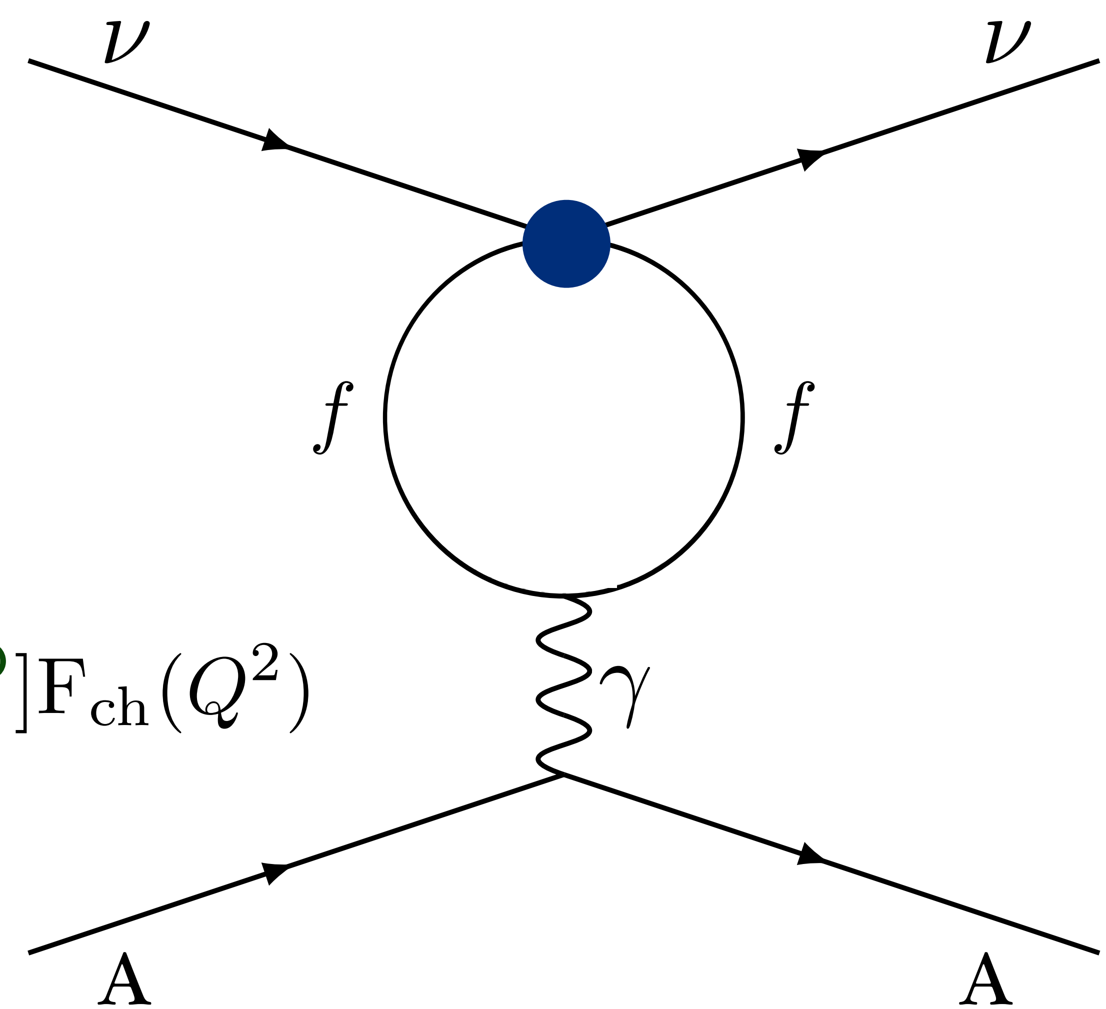
- point-nucleon form factors: distribution of nucleons in nuclei
- πDAR sources: factorization starting from quark level

CEvNS cross section on spin-0 nuclei



- tree-level cross section

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



- effect of radiative corrections

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

- radiative corrections enter with the nucleus charge form factor

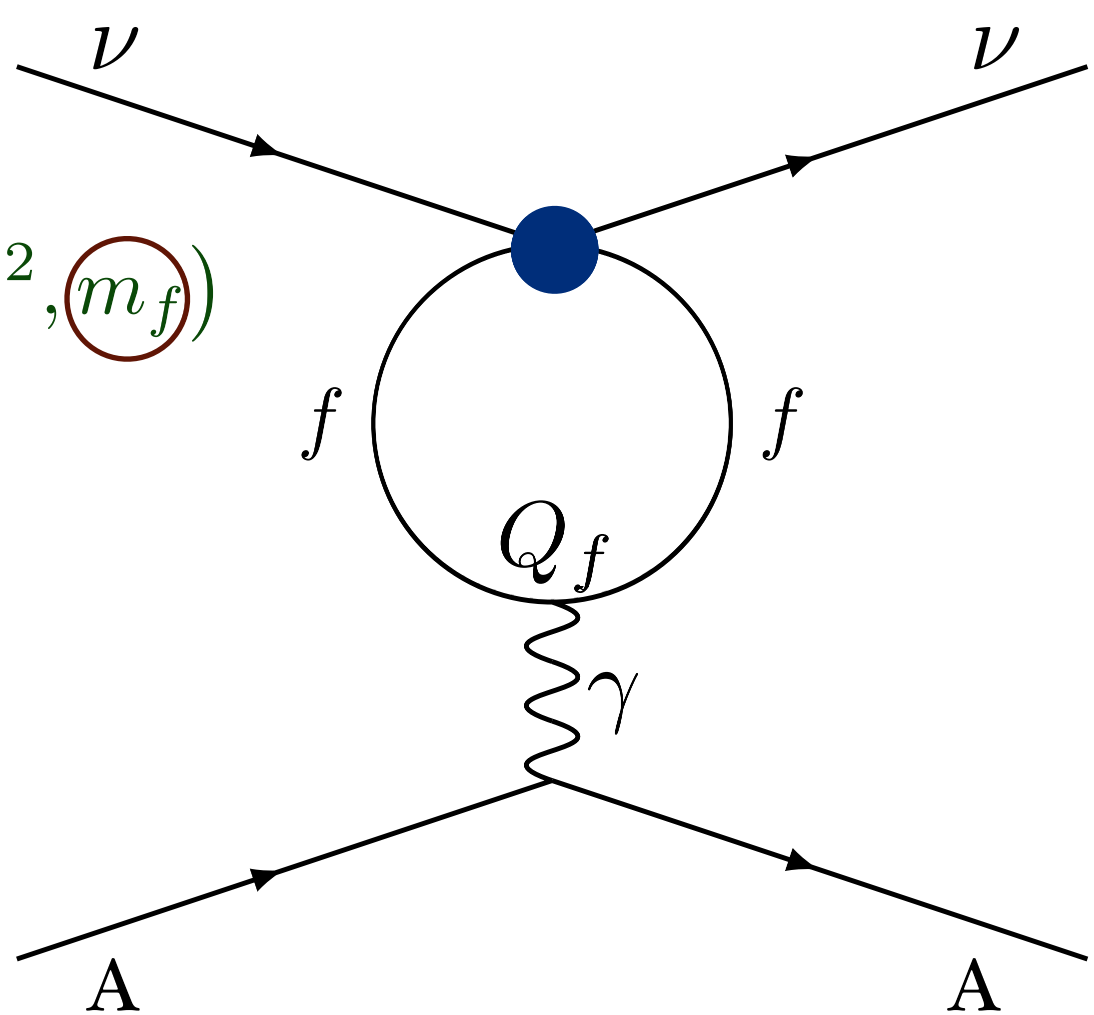
Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop

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

- lepton loops

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



- origin of flavor dependence

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

- lepton mass breaks "flavor universality"

Light-quark contribution

- description in terms of quarks is invalid at CEvNS kinematics

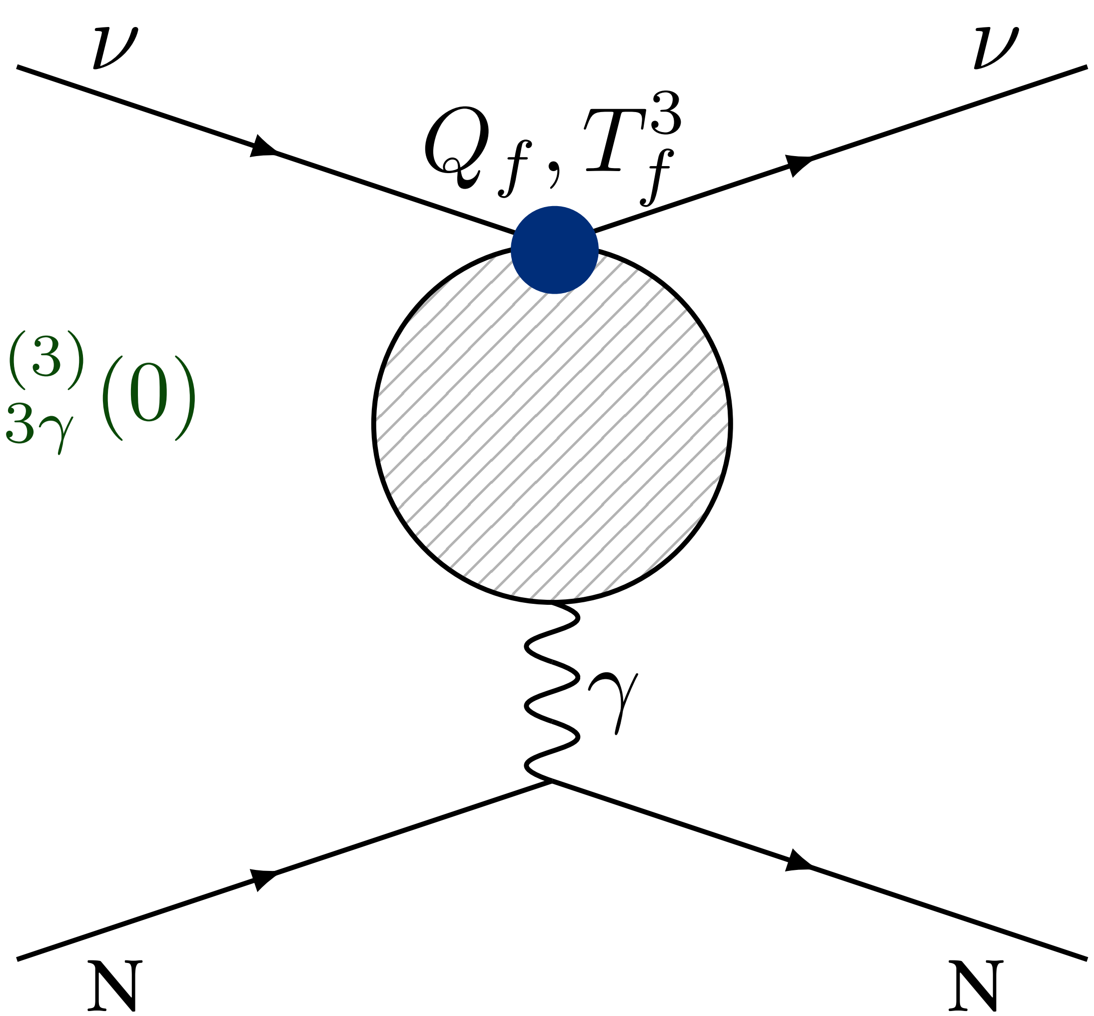
$$Q^2 \ll \Lambda^2_{\mathrm{QCD}}$$

- light quarks

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

- chiral symmetry approximation

- flavor independent

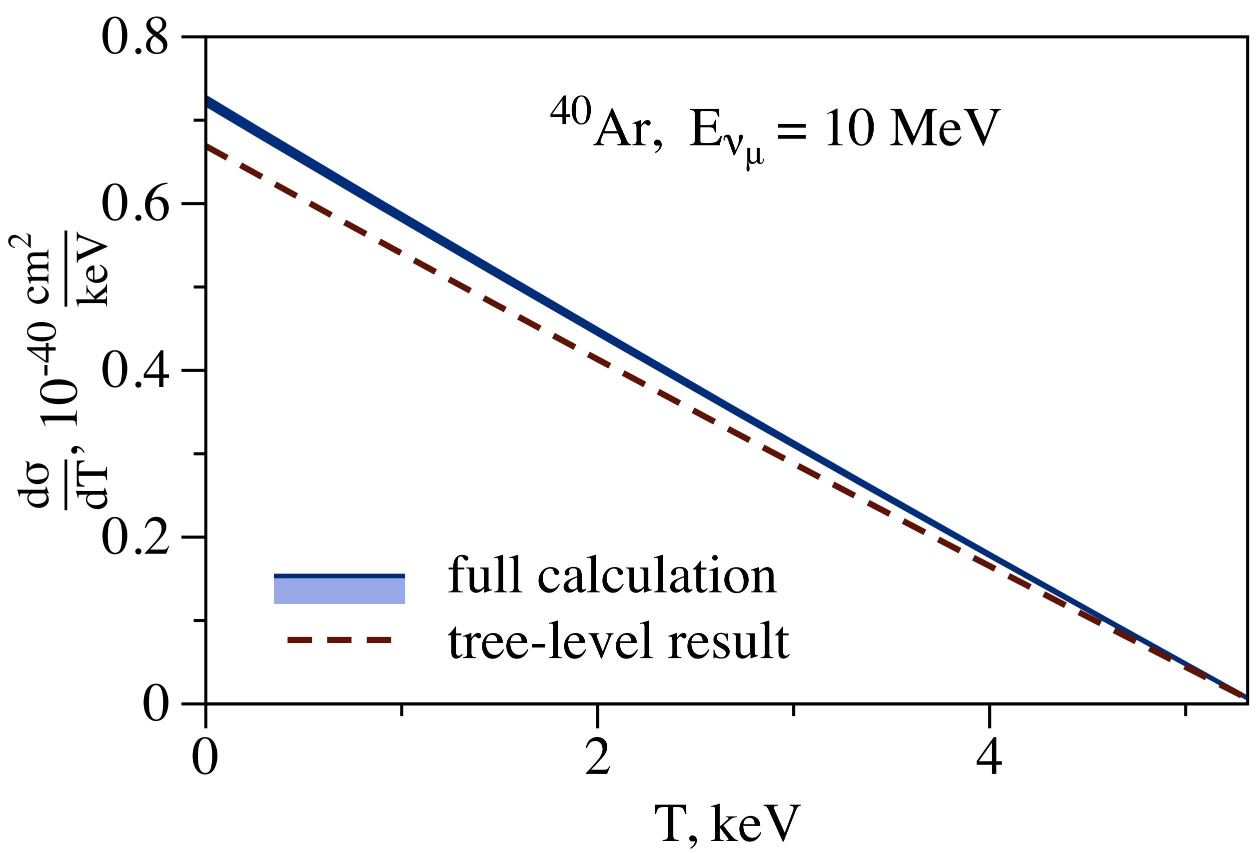


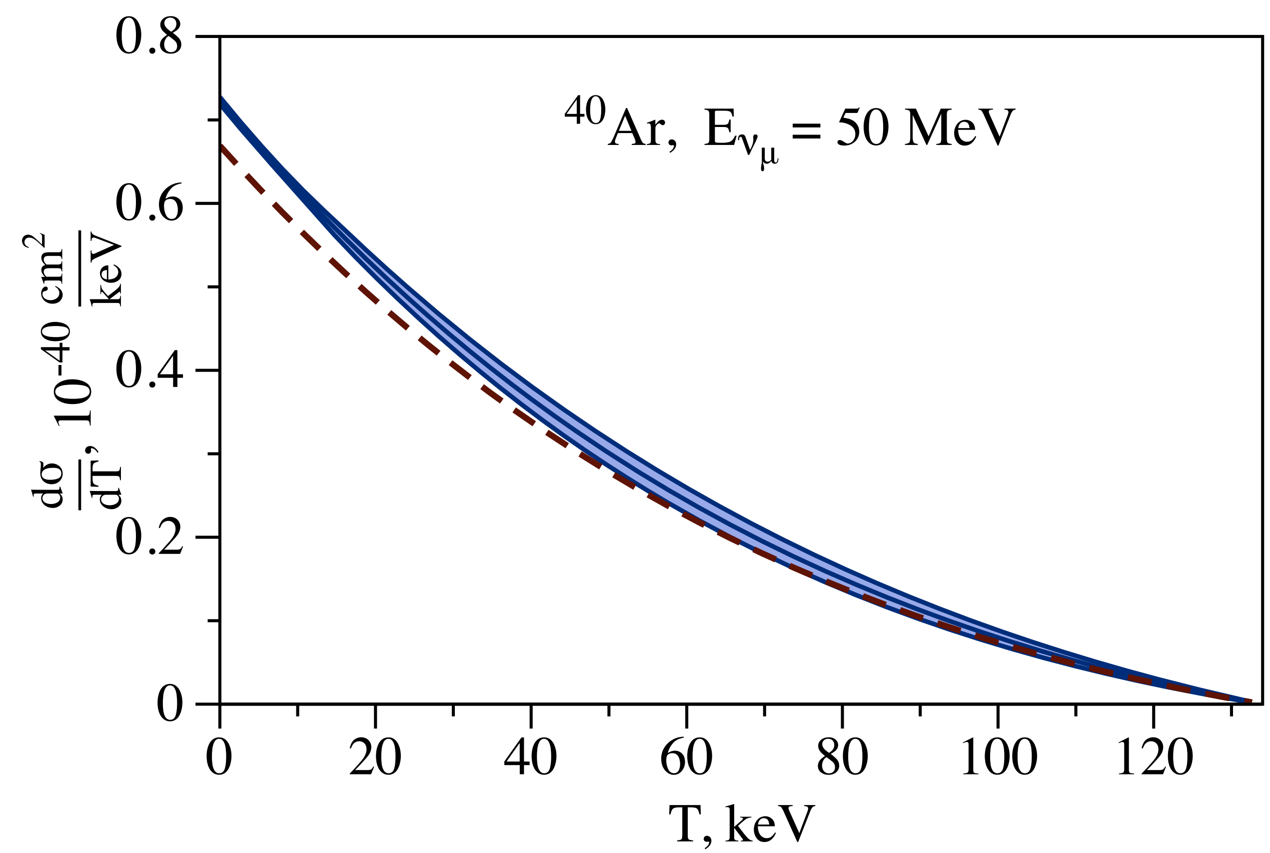
- non-perturbative light-quark contribution: error at low energy

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)

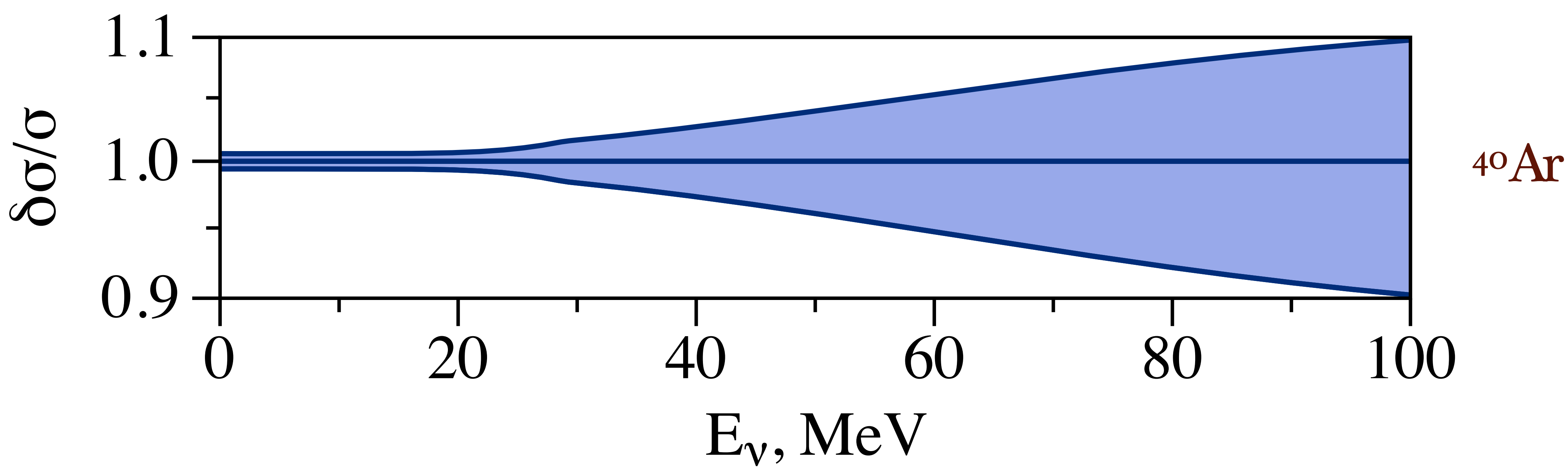




- % effect of radiative corrections on cross sections

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

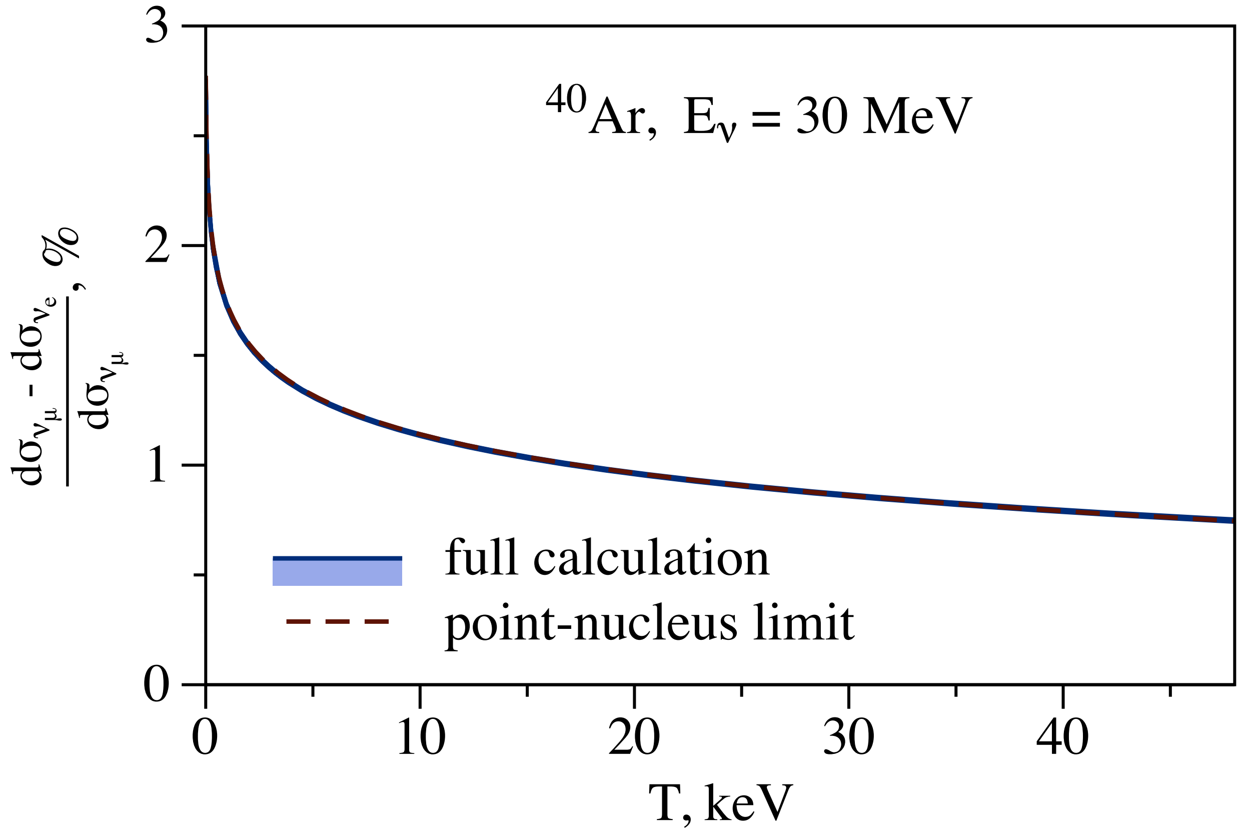
- hadronic error 0.6% at low energy, nuclear error at higher energy

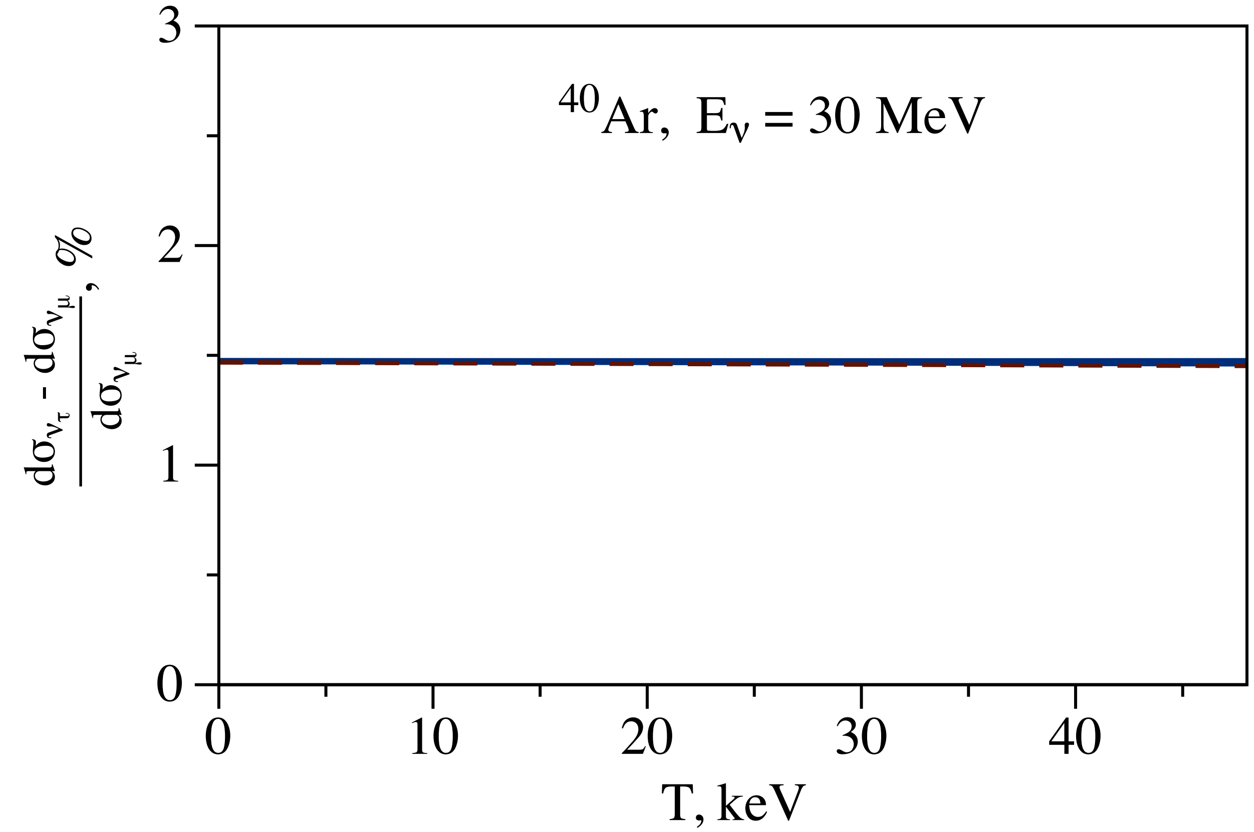
Flavor difference

- 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

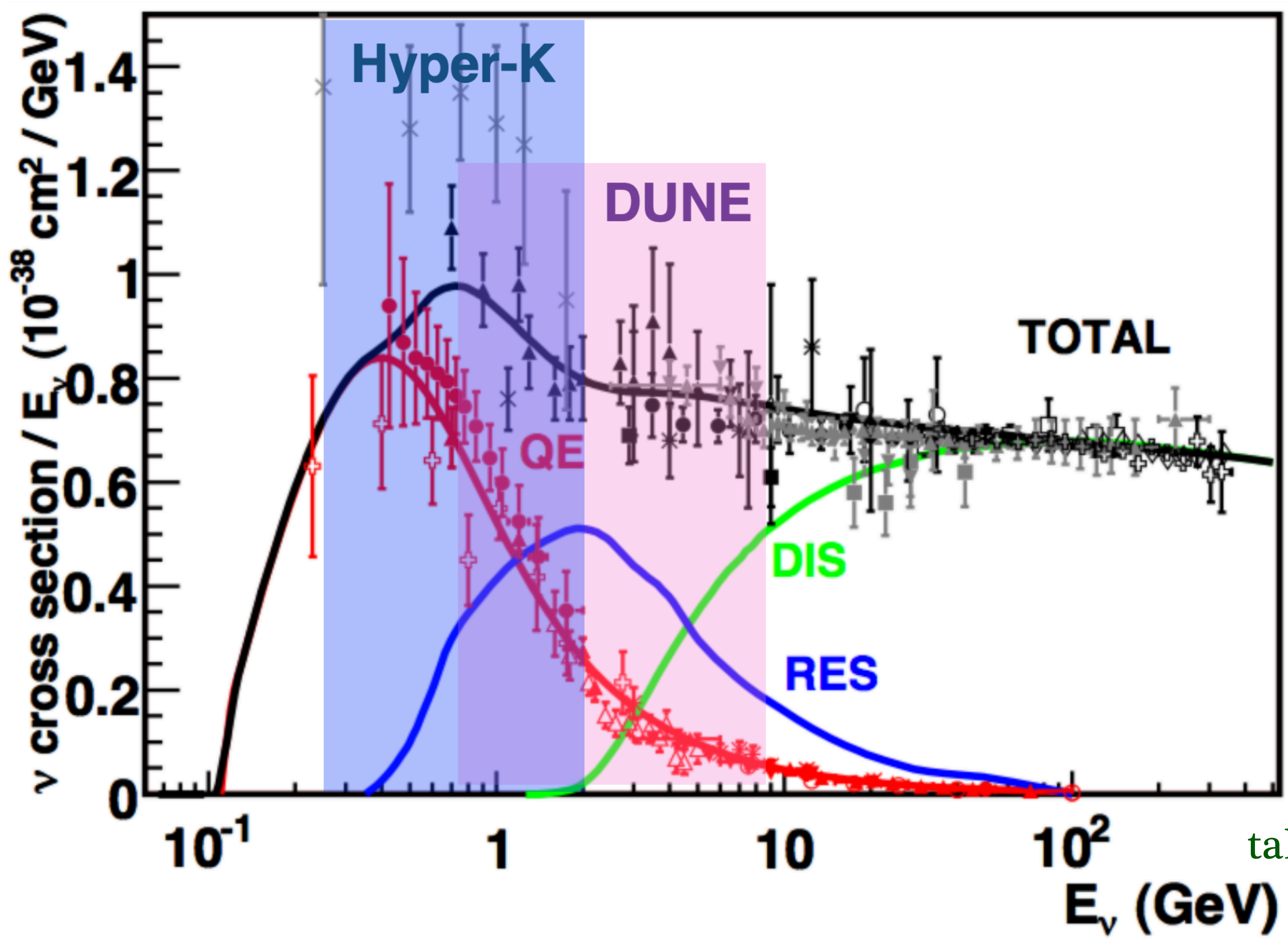
Radiative corrections in CCQE on free nucleons

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

CCQE. Why should we care?

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

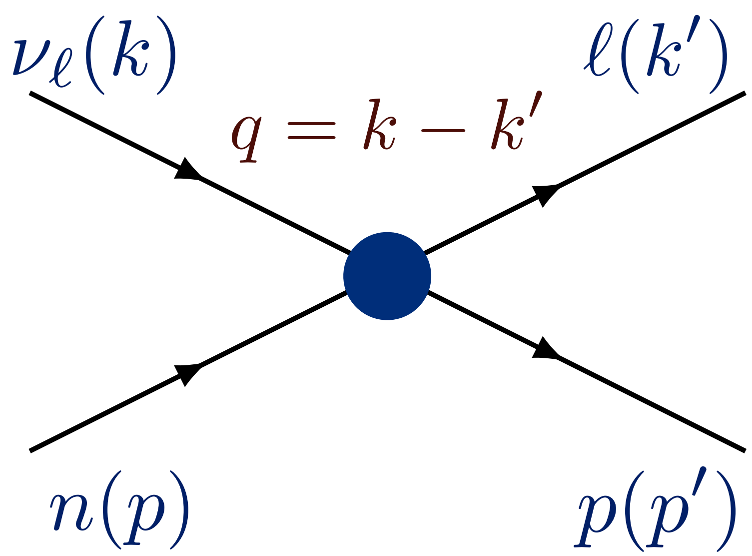
Formaggio and Zeller (2013)



Noemi Rocco talk at Neutrino 2020

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

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

talks by Aaron Meyer, Fernando Alvardo, Beata Kowal, Dr. Rafi Alam

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

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

- CCQE with electron flavor is subject to large corrections

- phase-space restrictions enhance radiative corrections

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

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

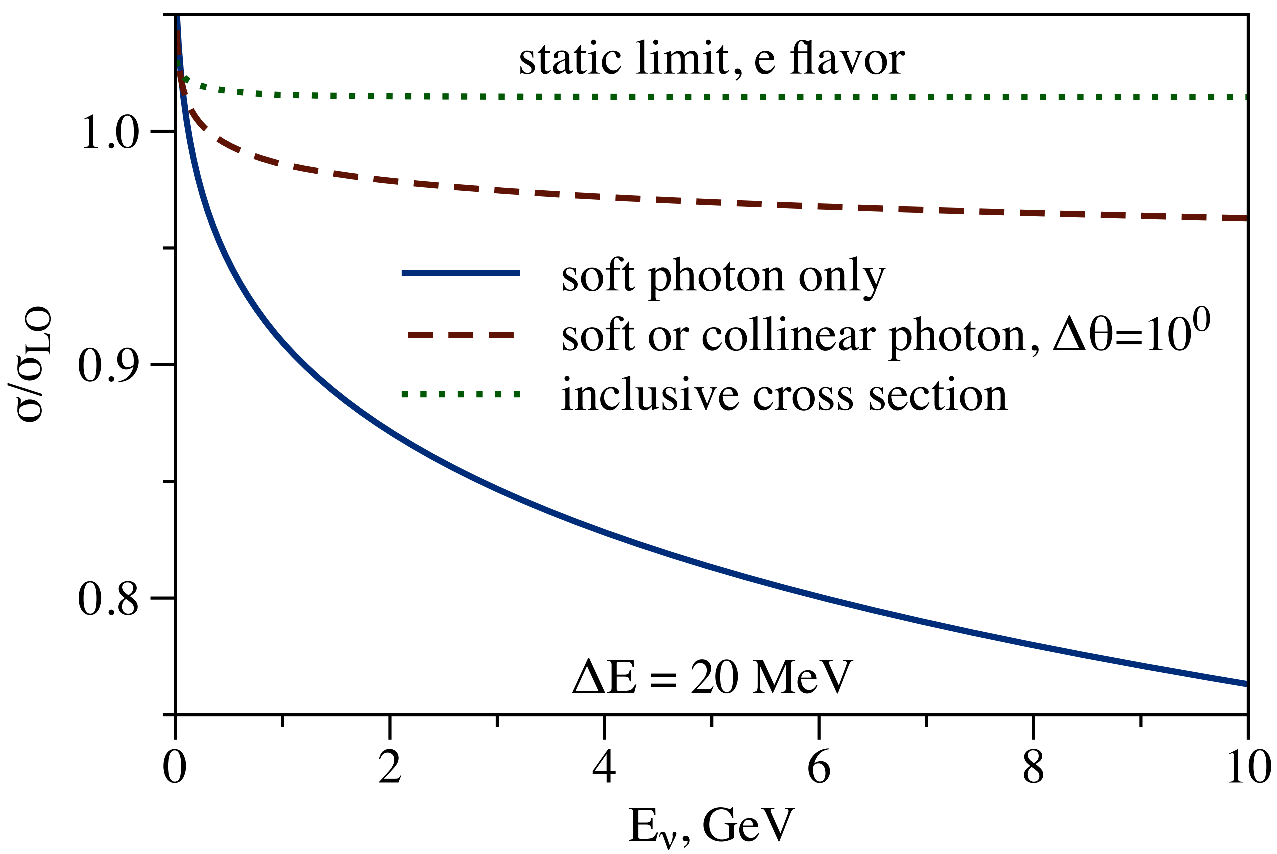
smaller collinear logarithms

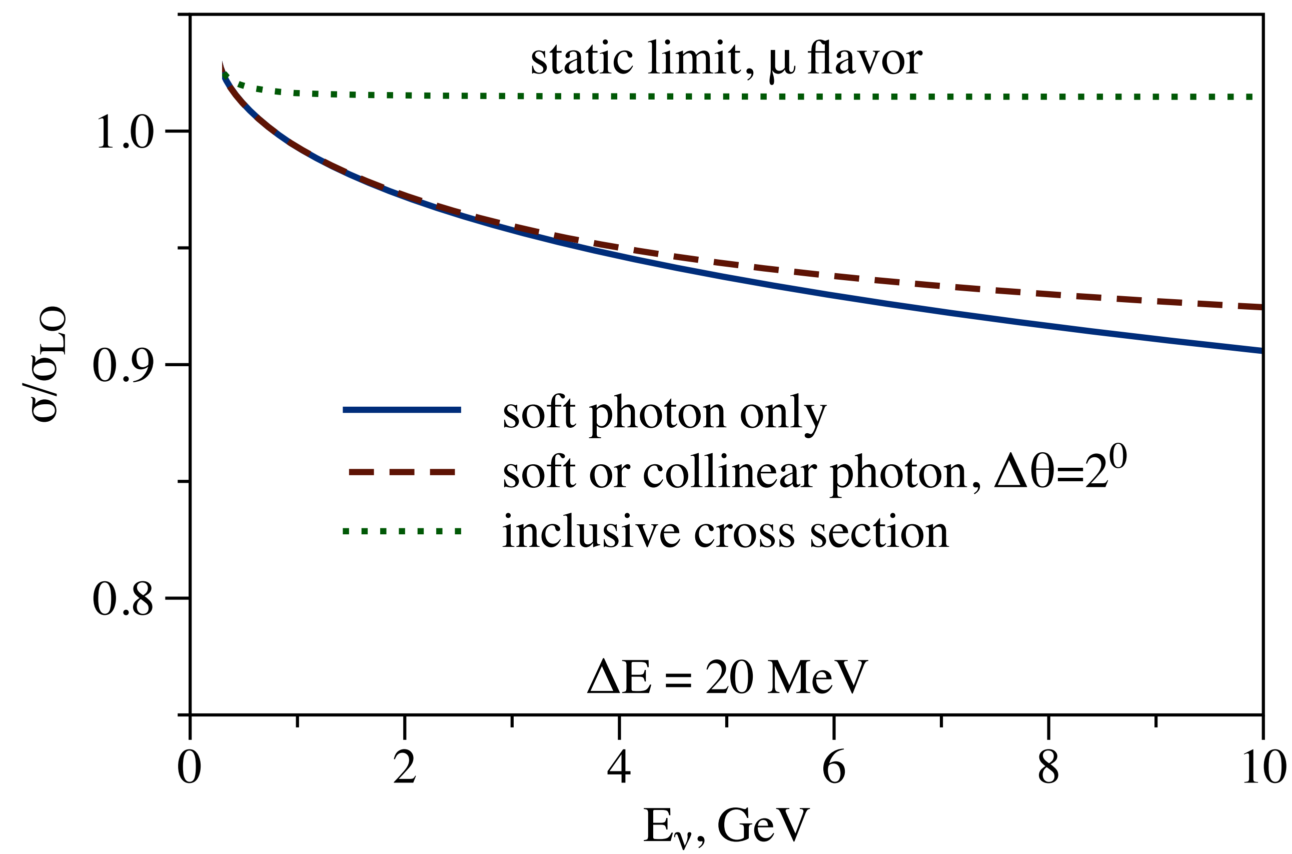
- crucial dependence on detector details

- 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: 10º for electron and 2º for muon

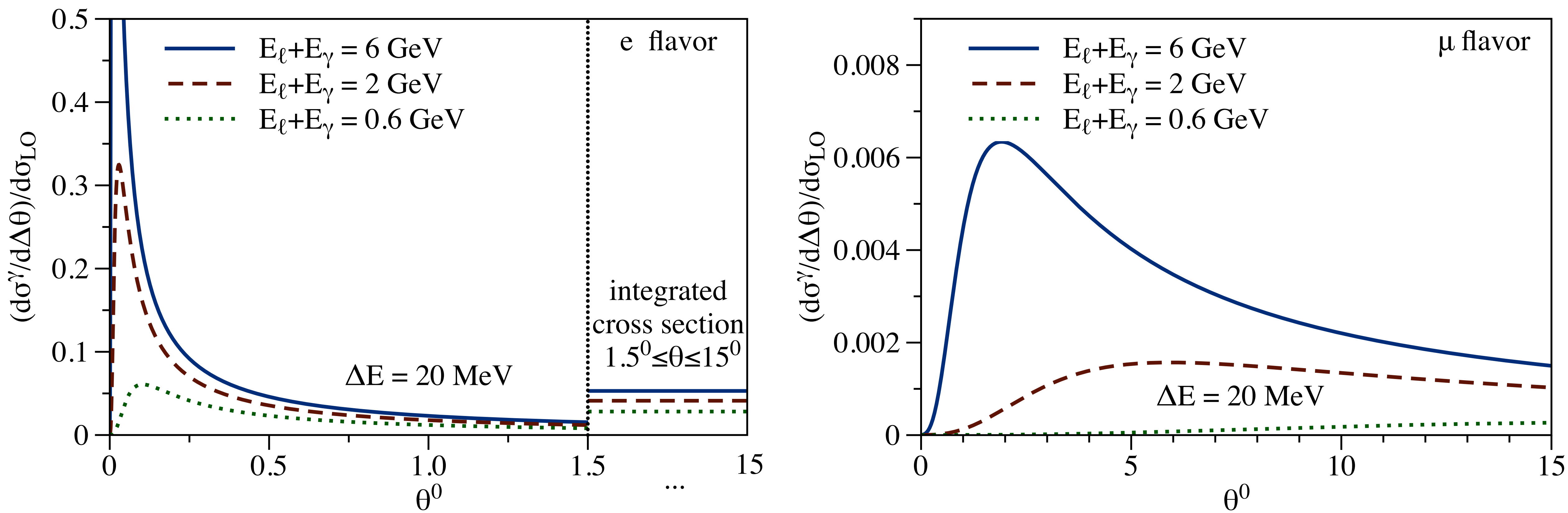




- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables (+γ): few % level, flavor independent

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

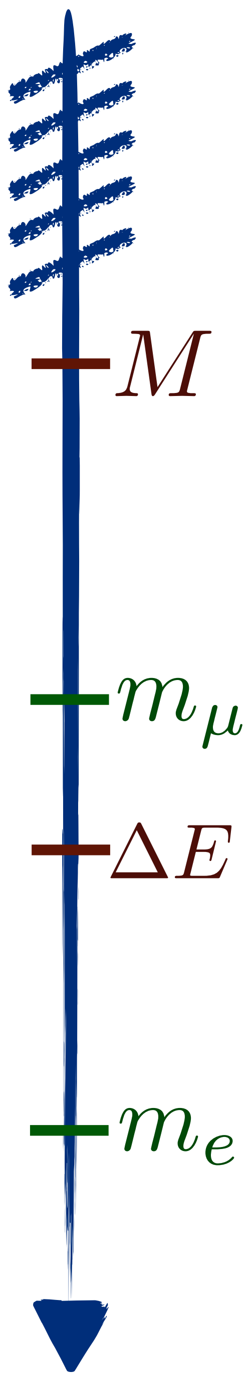


- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- forward-peaked radiation for electron flavor
- negligible radiation for muons with shifted peak position

Factorization approach

- cross section is given by factorization formula

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

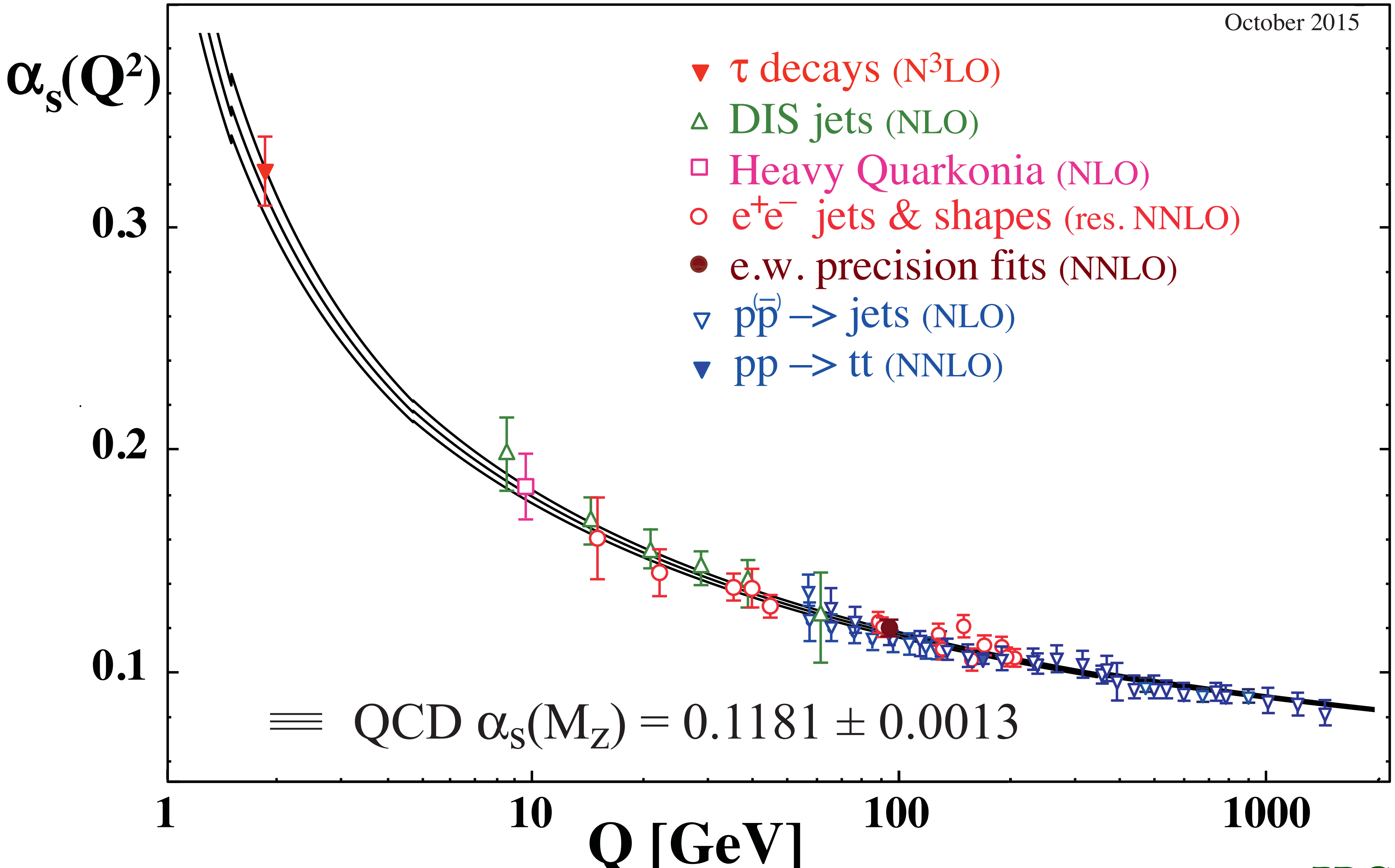


- determine hard function at hard scale by matching experiment or model to the theory with heavy nucleon

- soft and collinear functions are evaluated perturbatively

Interaction with nucleons

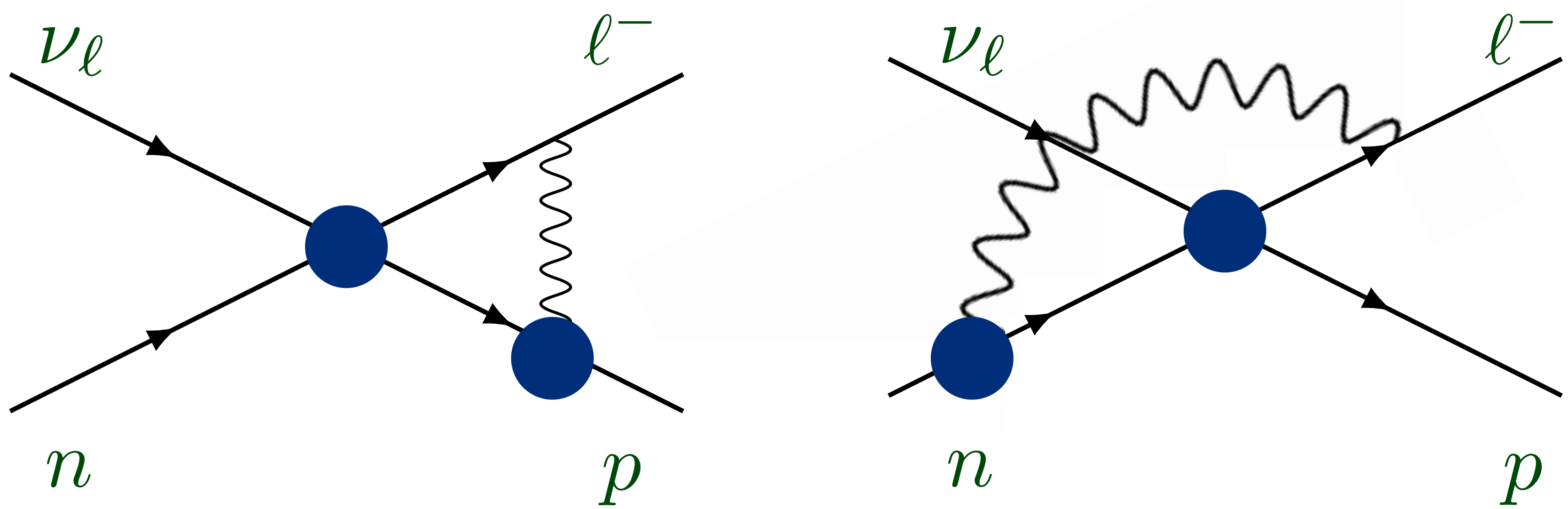
- QCD running coupling



PDG 2015

- hadrons are correct degrees of freedom at GeV energy

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

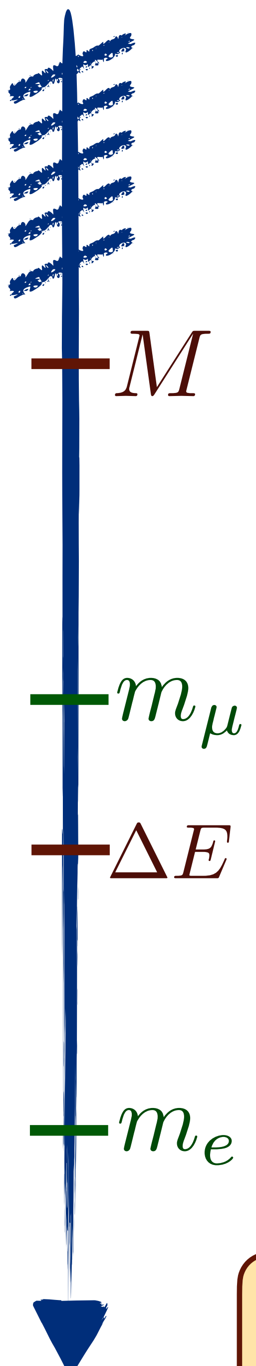
- best determination of hard function by matching to low-energy EFT

- gauge-dependent vertex and gauge-dependent form factors

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 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

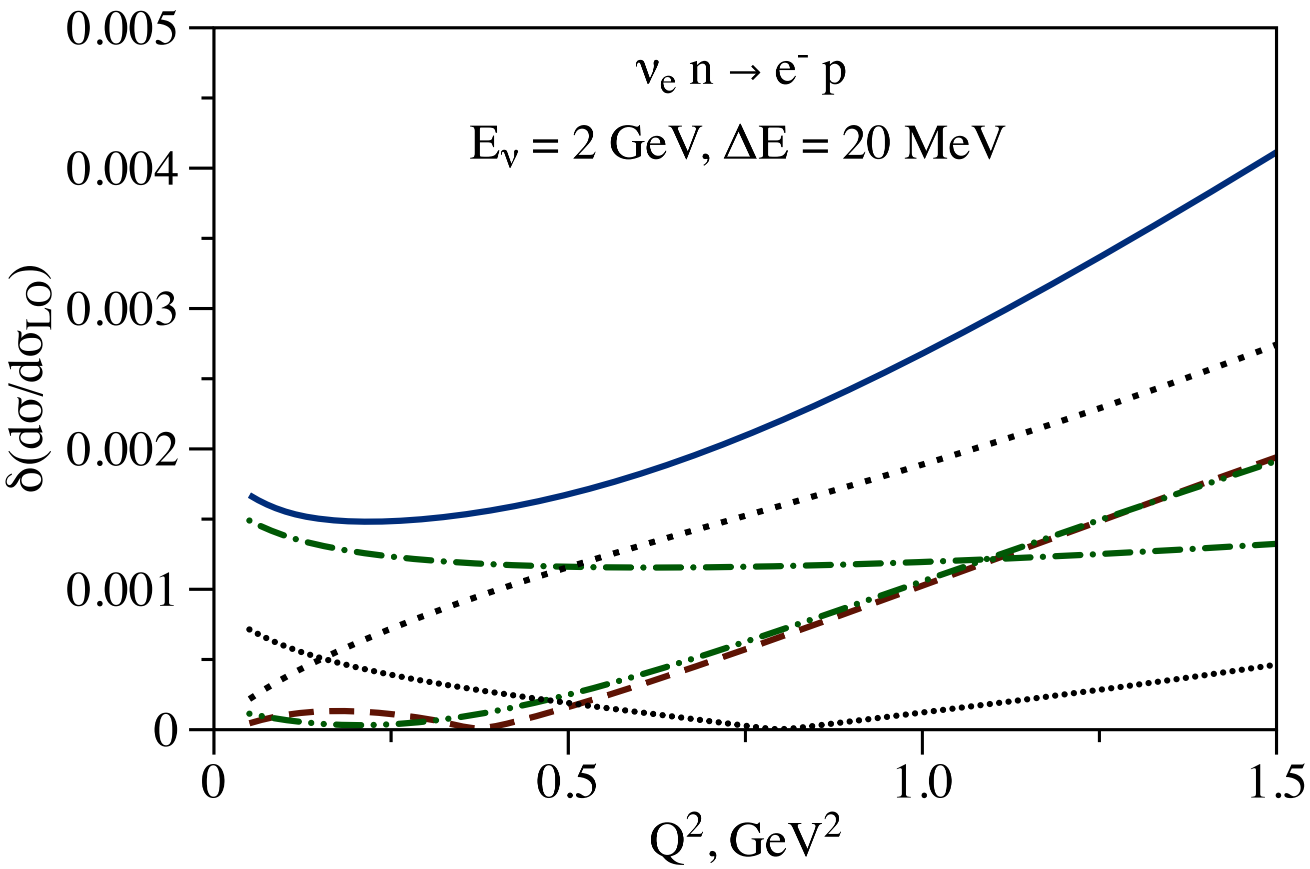
- calculate cross section at low energies accounting for all large logs

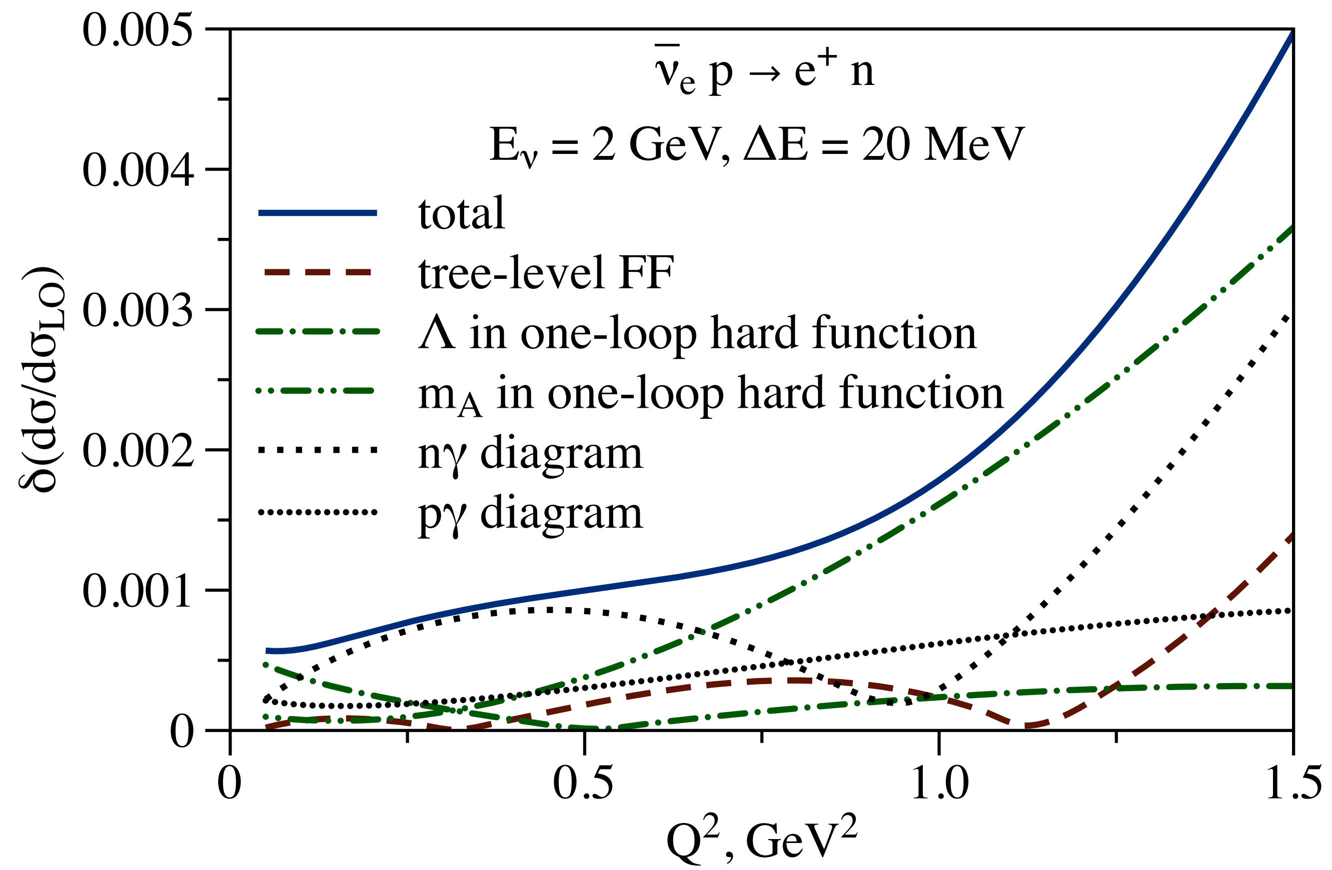
ep scattering with soft radiation only: Hill (2016)

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

Exclusive case: assignment of errors

- uncertainties from hard function





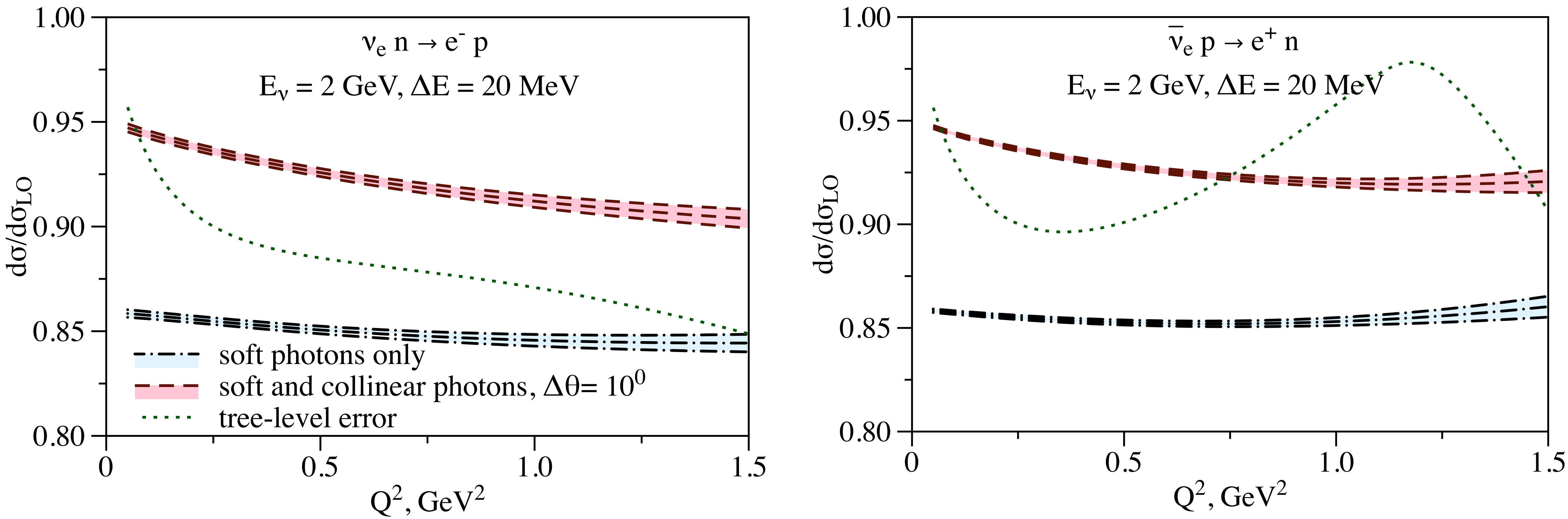
- nucleon form factors

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

- add perturbative errors by variation of scale

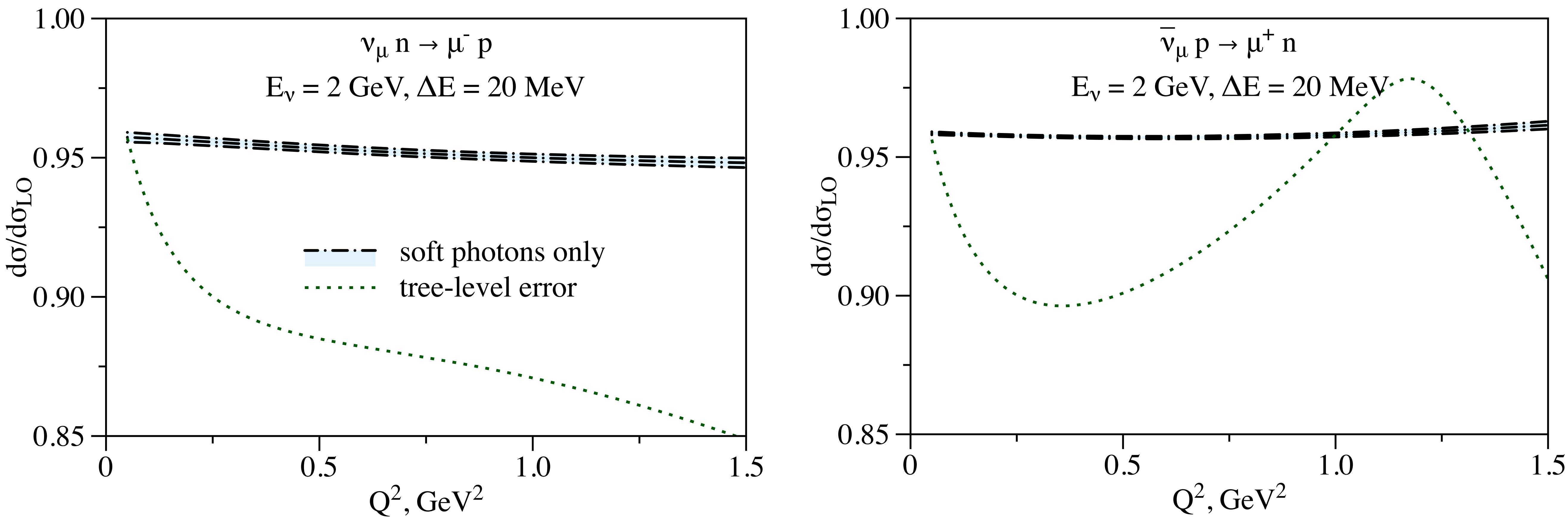
- uncertainty of per mille level for the ratio to LO result

Cross section. Electron flavor



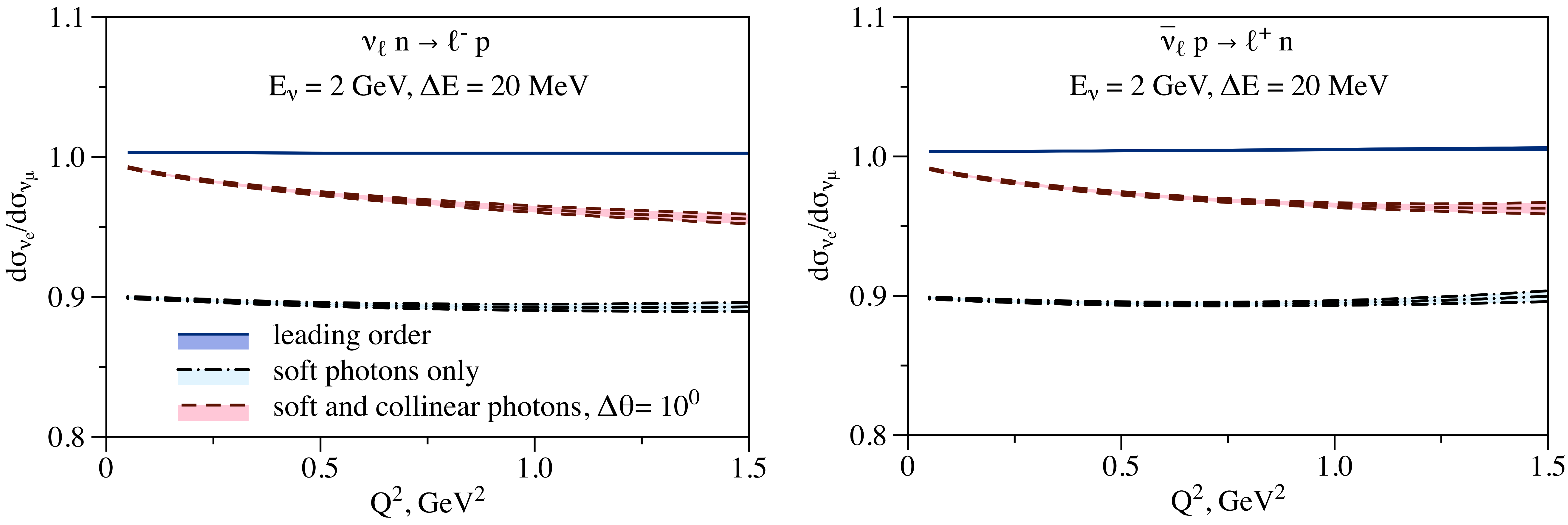
- cancellation of error from hard function for ratio to LO

Cross section. Muon flavor



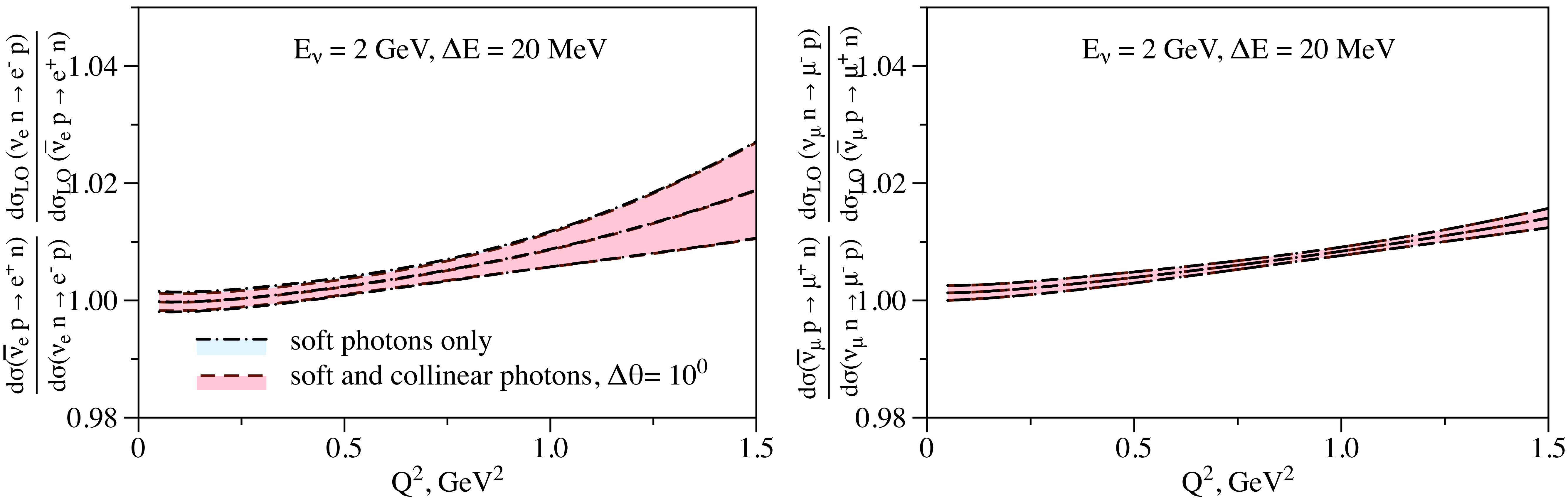
- cancellation of error from hard function for ratio to LO

Electron/muon ratio



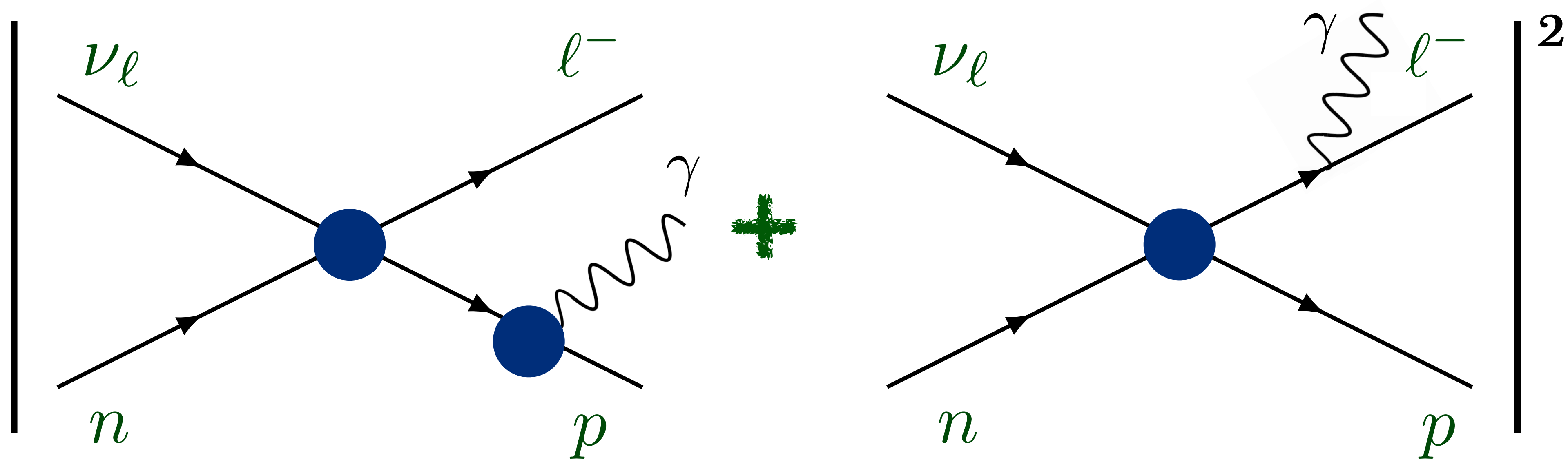
- small error: hard function does not depend on mass

Neutrino/antineutrino double ratio



- jet function is the same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$

Radiation of hard noncollinear photons



model I

- tree-level EW vertex with nucleon-leg kinematics for both diagrams
- reproduces SCET for collinear radiation
- gauge-invariant bremsstrahlung

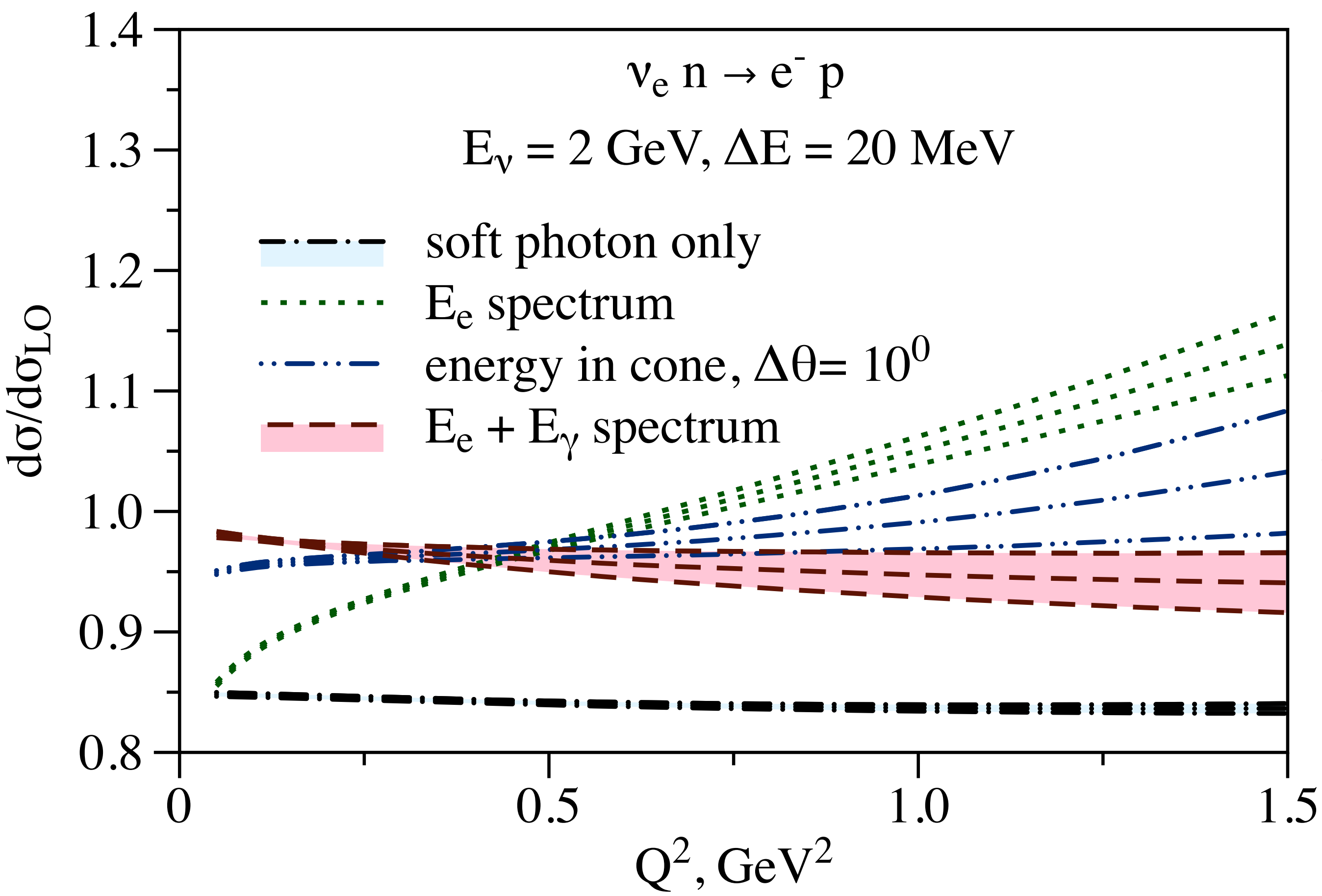
model II

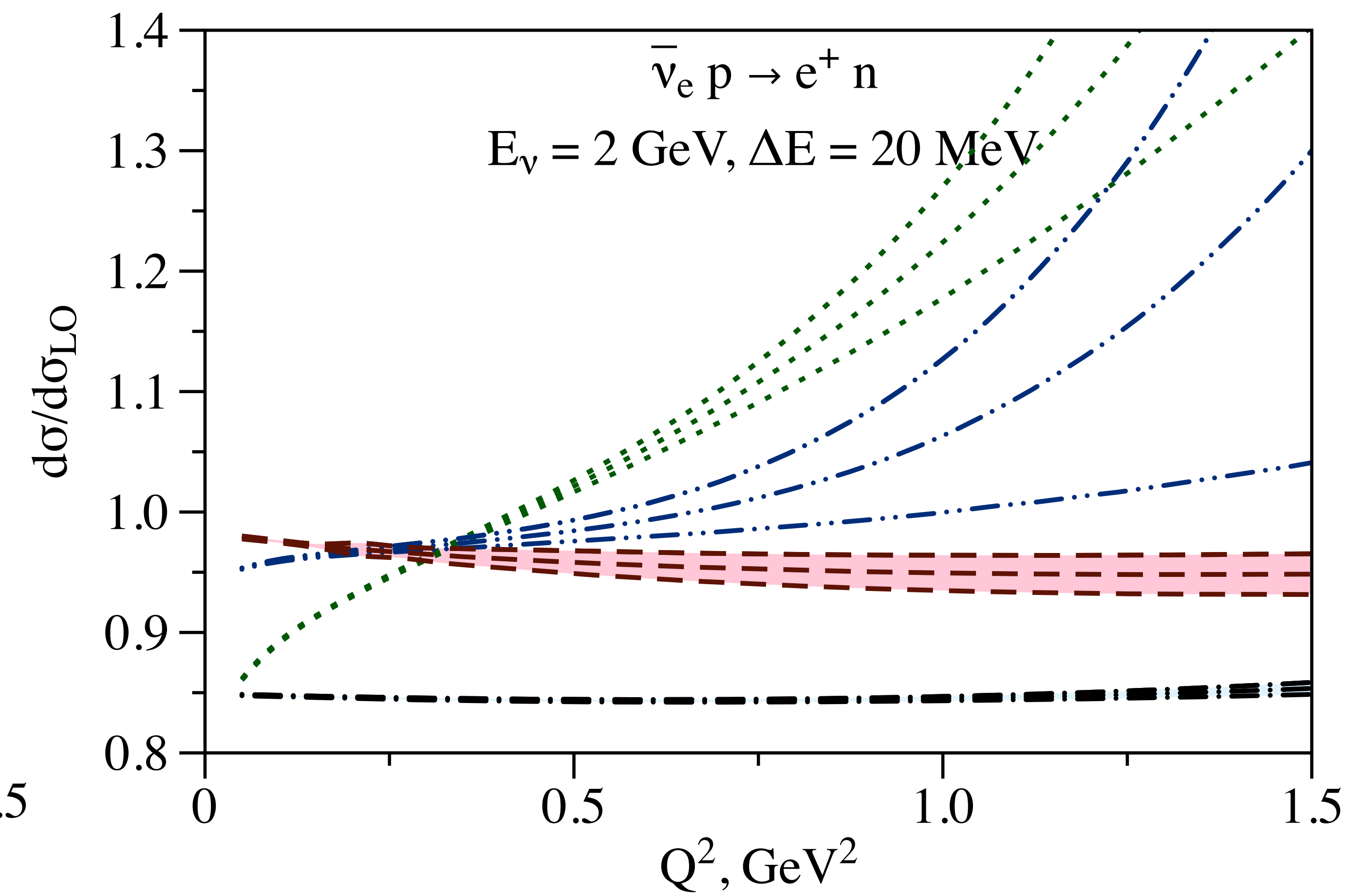
- all EW vertex arguments as for local field theory

- uncertainty is given as a difference between two models

Cross section. Electron flavor

- momentum transfer is defined as $Q^2 = 2M\left(E_\nu - E_\ell - E_\gamma\right)$
  $Q^2 = 2M\left(E_\nu - E_\ell\right)$ or from the energy in the cone

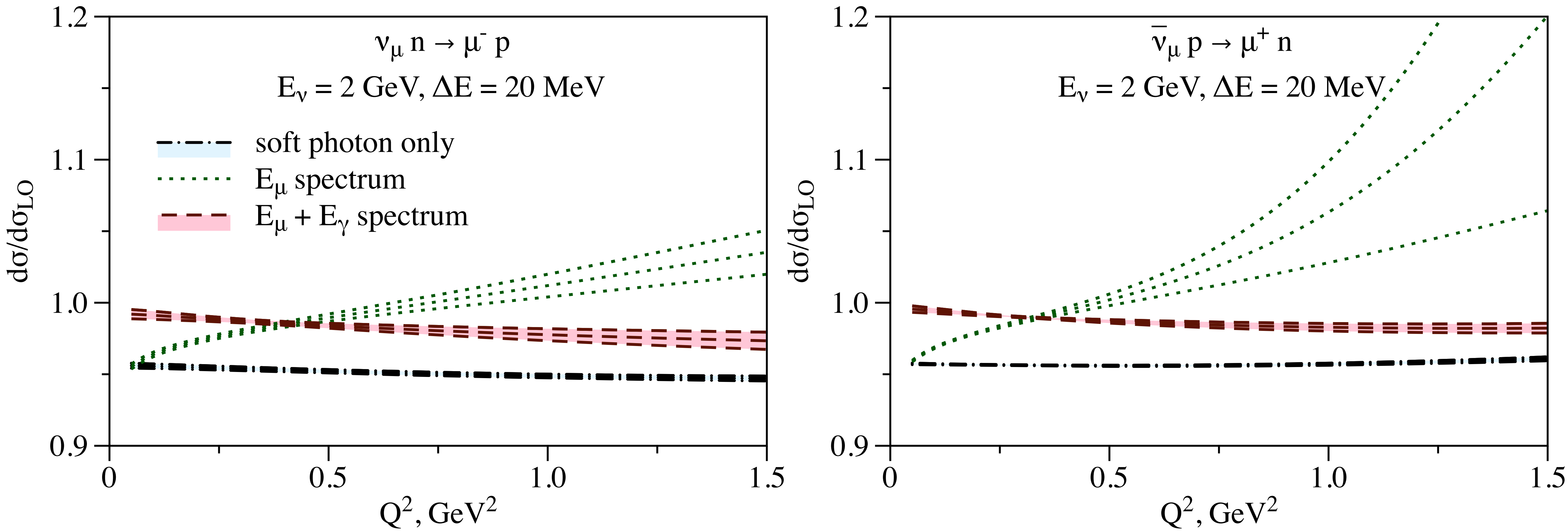




- preliminary uncertainty on plots with inclusive observables

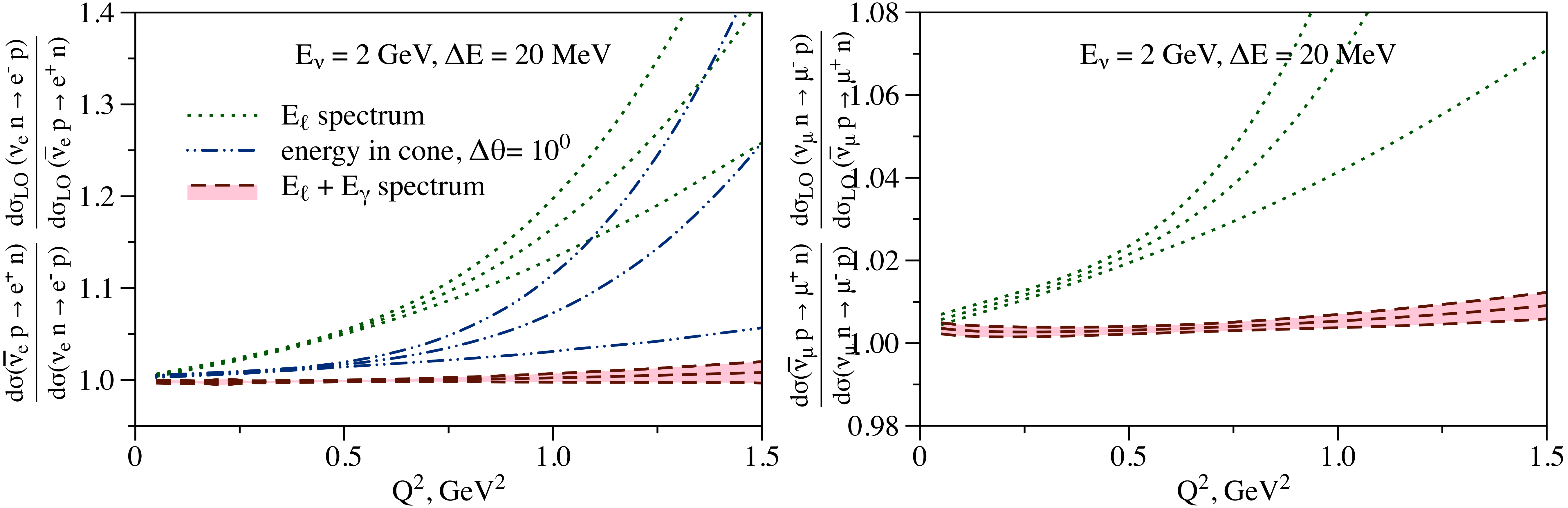
- dependence on reconstruction of kinematics

Cross section. Muon flavor



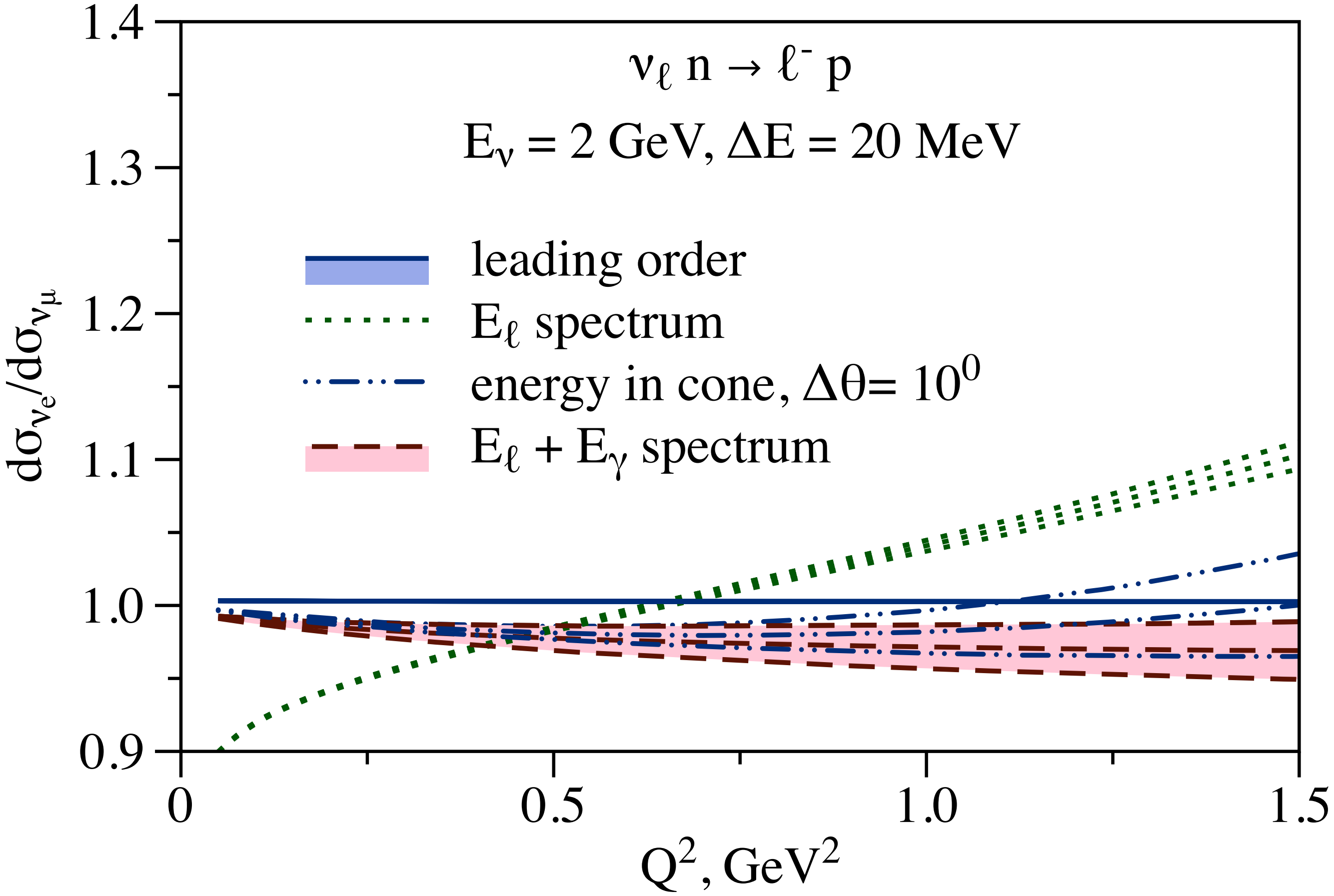
- dependence on reconstruction of kinematics

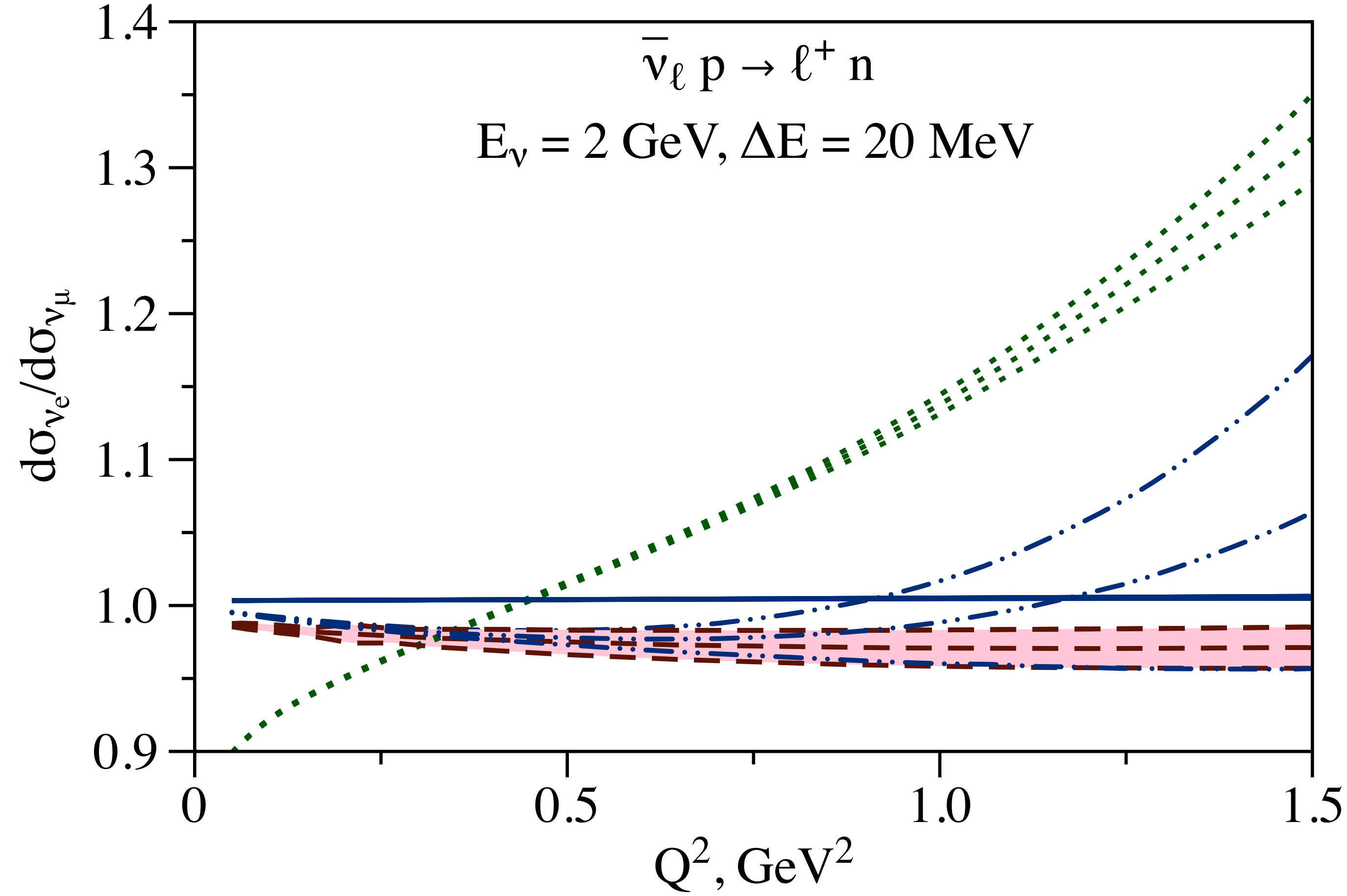
Neutrino/antineutrino double ratio



- deviations from 1 for E_ℓ spectrum

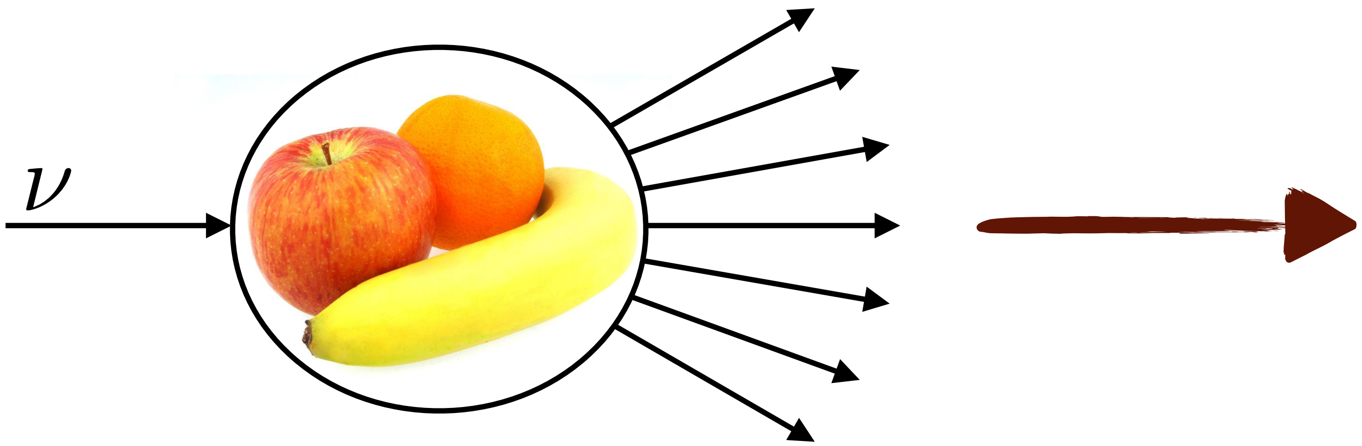
Electron/muon ratio





- energy in cone observable is close to $E_\ell + E_\gamma$ spectrum

Conclusions



radiative corrections
in EFT framework

- precision four-Fermi effective theory: basis for computations with sub-percent accuracy in neutrino interactions

- total and differential νe, CEvNS and CCQE cross sections evaluated from theory with first rigorous error analysis

- corrections to CCQE significantly depend on experimental details

Thanks for your attention !!!

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