CETUP* 2023

Lead/Deadwood Middle School

06 July, 2023

Radiative corrections in neutrino physics

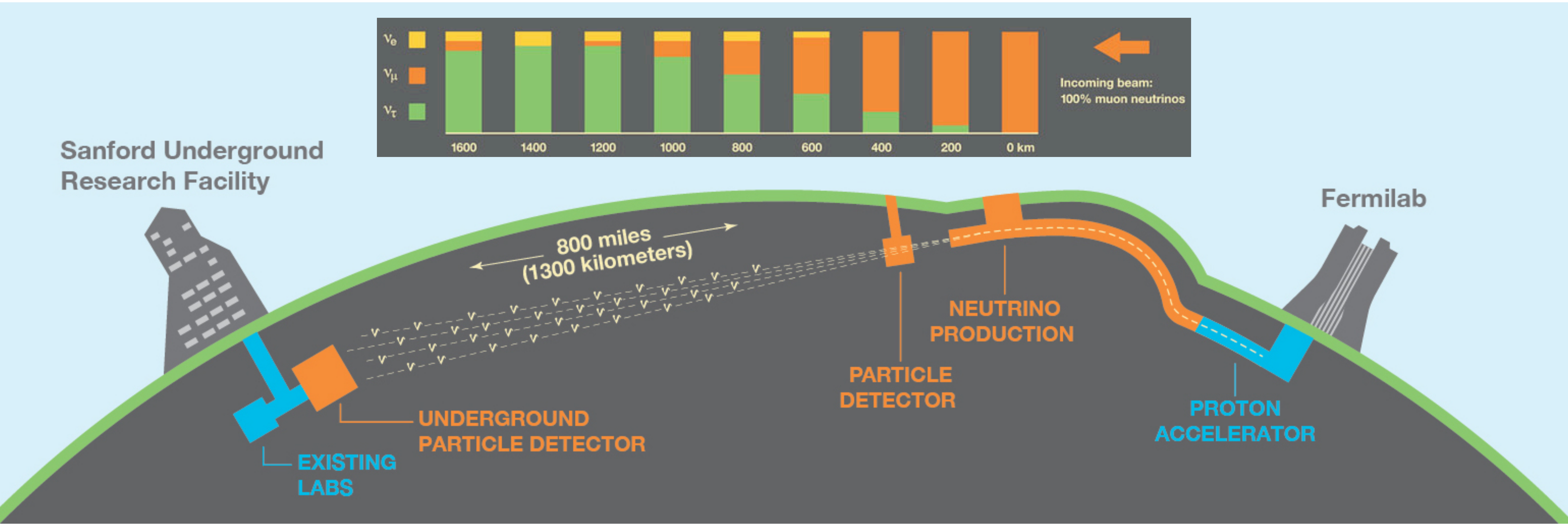
Los Alamos NATIONAL LABORATORY

Oleksandr (Sasha) Tomalak

LA-UR-23-27032

Neutrino experiments

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



- measurement of $\nu_\mu(\overline{\nu}_\mu)$ disappearance and $\nu_e(\overline{\nu}_e)$ 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

Outline

1) artificial neutrino sources

2) cross sections on electrons, nucleons, and nuclei

3) radiative corrections in neutrino physics

4) charged-current scattering on nucleons

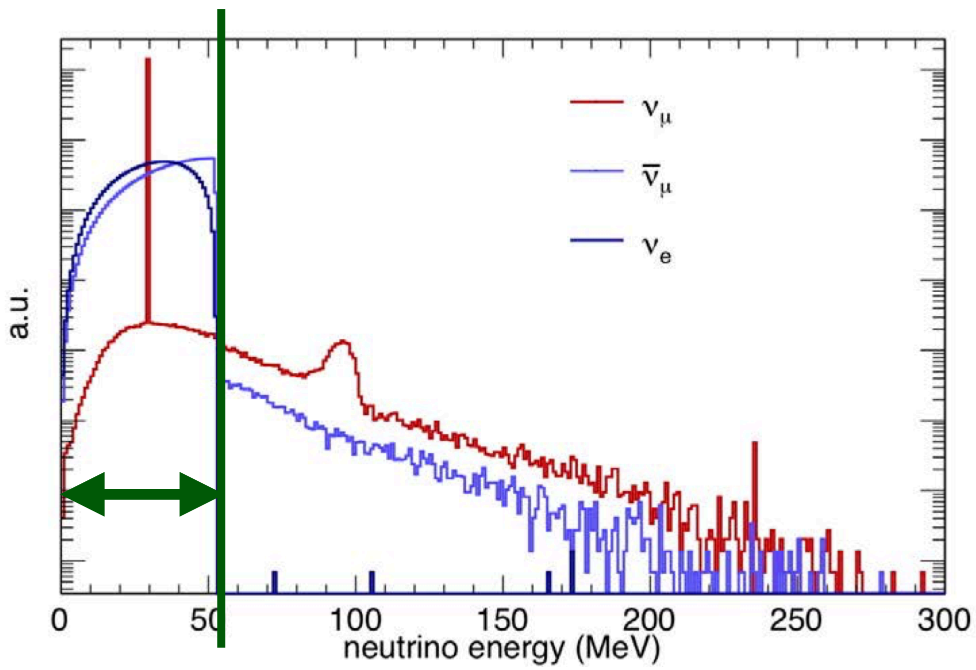
Artificial neutrinos: accelerator

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

decay at rest

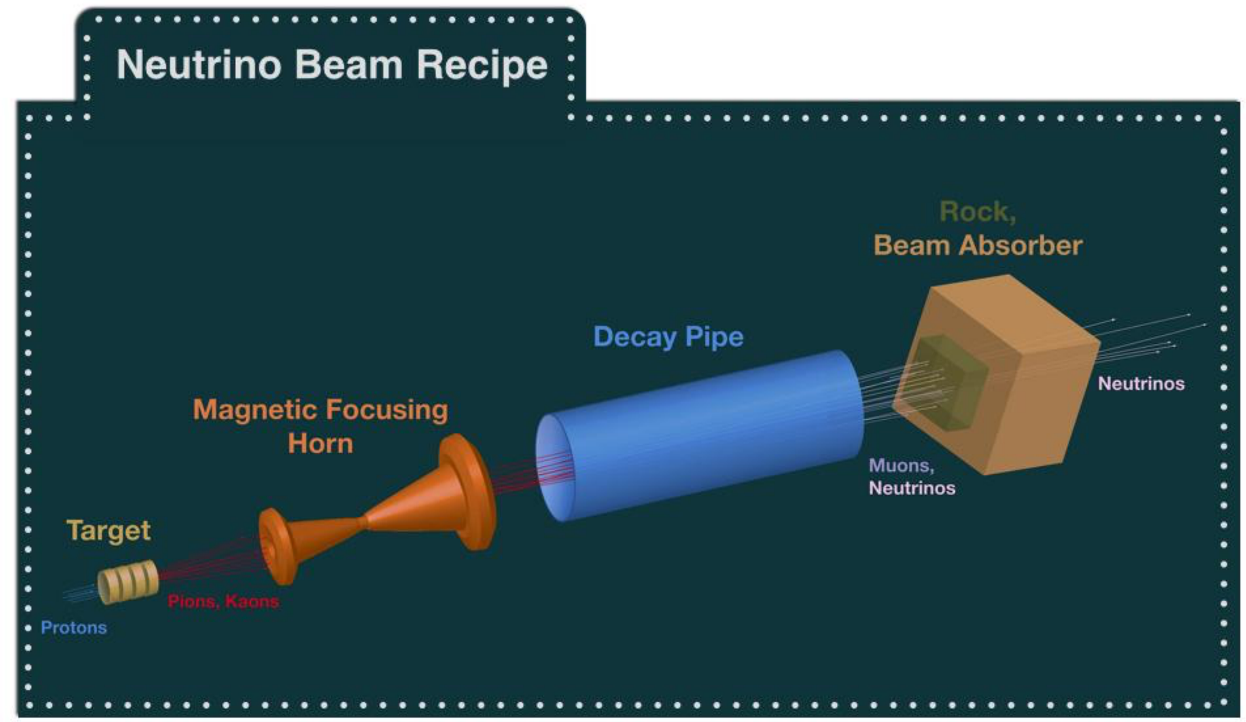
$$K^+ \to \pi^0 e^+ \nu_e \qquad K_L^0 \to \pi^\pm e^\mp \nu_e$$
$$K^+ \to \pi^0 \mu^+ \nu_\mu \qquad K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$$

decay in flight



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

Coherent and CCM

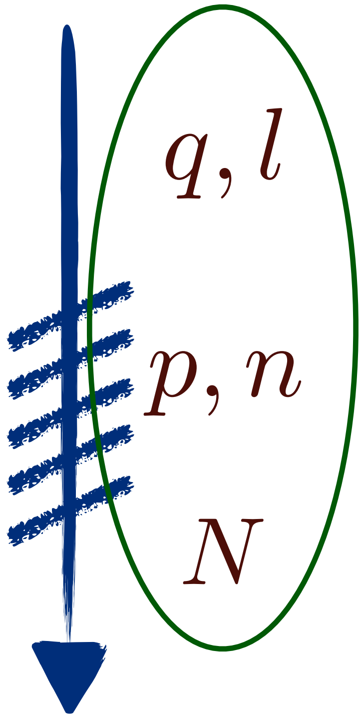


www.fnal.gov

T2K, NOvA, MiniBooNE, MicroBooNE
MINERvA, MINOS, NuTeV
SBN, DUNE, HyperK, ESSnuSB

meson decay: monochromatic line

- precise measurements of neutrino properties, EW, and BSM search
- physics program relies on neutrino cross sections in MeV-TeV range



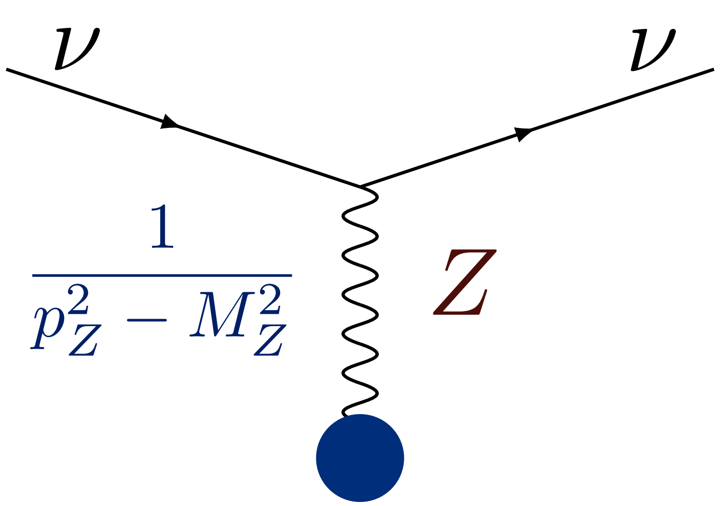
Cross sections on electrons, nucleons, and nuclei

Neutral- and charged-current processes

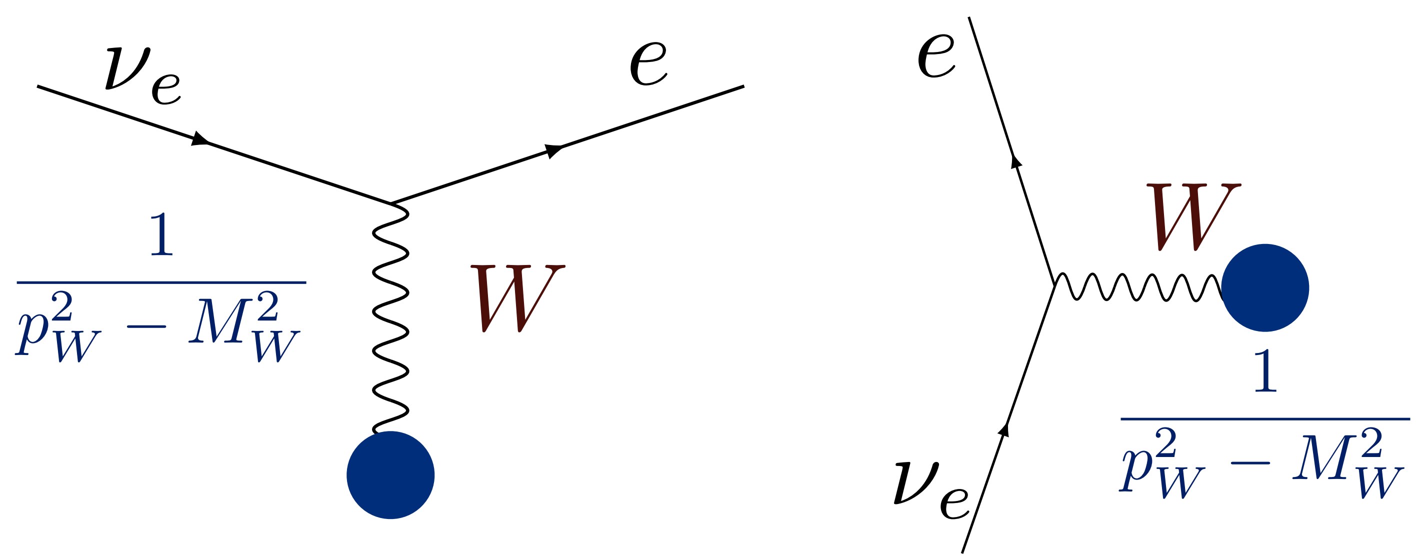
- cross sections determine neutrino-induced events

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

neutral current



charged current



- contact interactions at GeV energy scale and below

> - charged current (only): threshold to produce lepton and recoil
> - neutral current: no thresholds

Neutral- and charged-current processes

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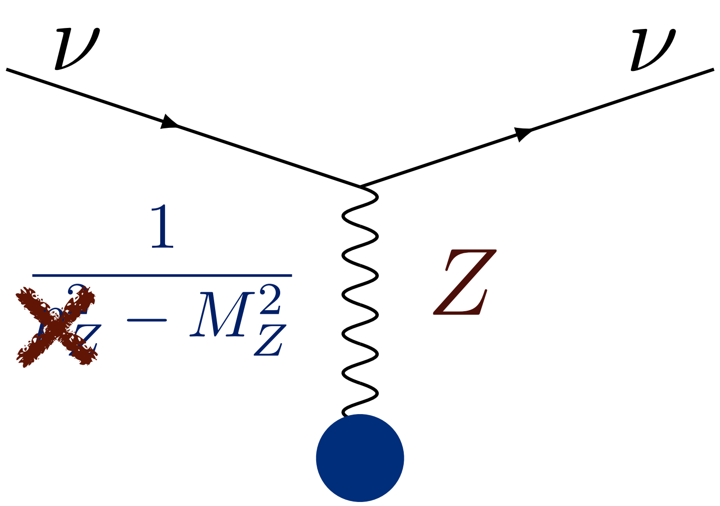
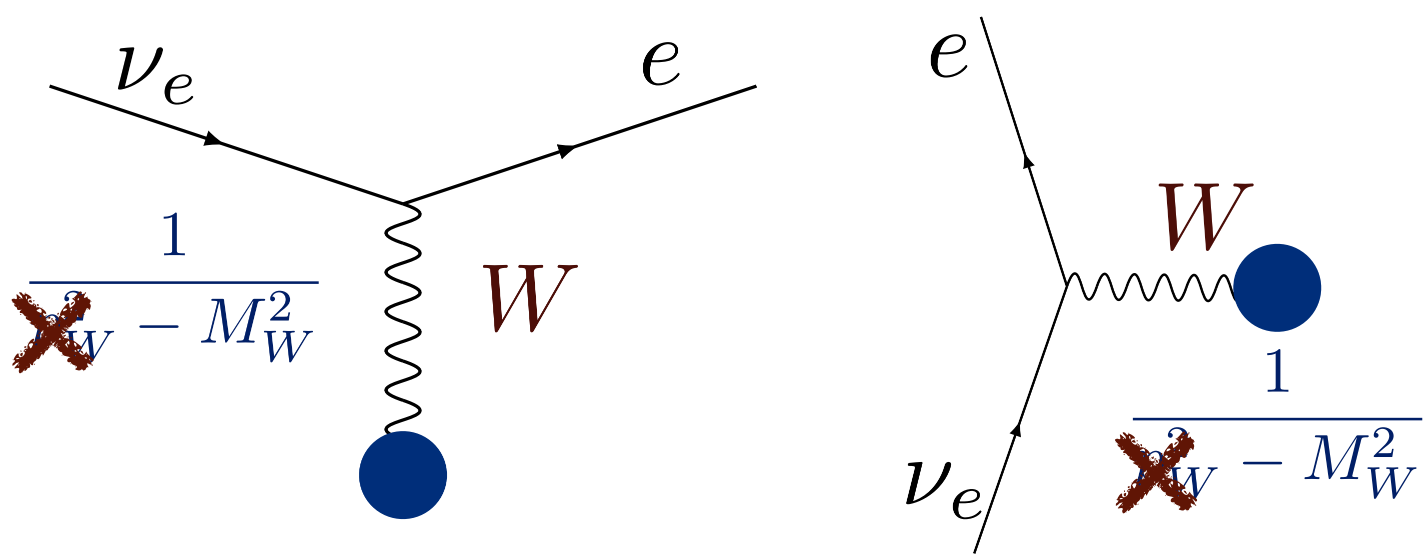
$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu\left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

neutral current



charged current



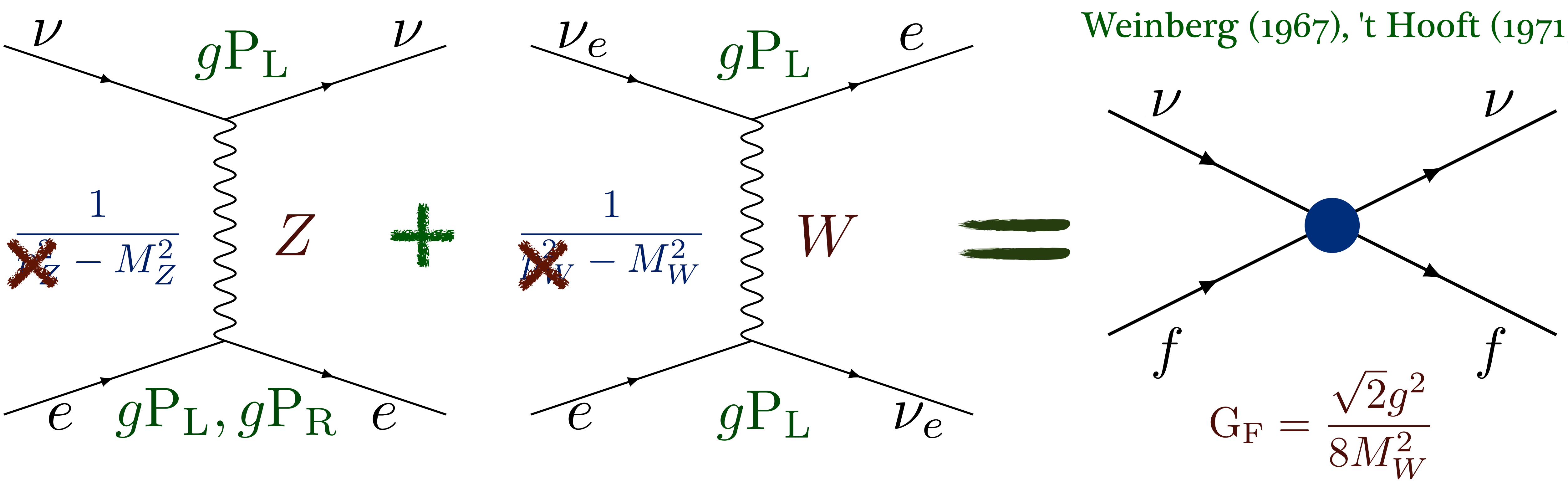
- contact interactions at GeV energy scale and below

- charged current (only): threshold to produce lepton and recoil
- neutral current: no thresholds

Neutrino-electron scattering

- Fermi theory at GeV energies and below, $\sigma \sim m$

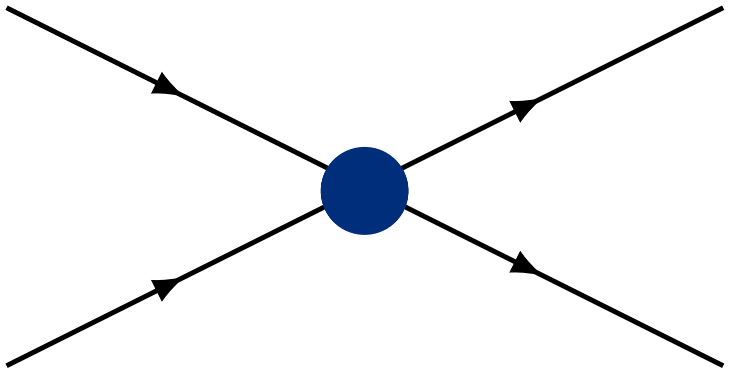
neutral current charged current



- s-channel resonant enhancement at vector-boson pole (PeV scale)

- historically: precise EW physics and BSM searches
- channel for in-situ flux constraints at accelerator experiments
- solar neutrinos@Super-K, SNO, Borexino
- recent observation of Glashow resonance by IceCube

Neutrino-nucleon scattering (CC)

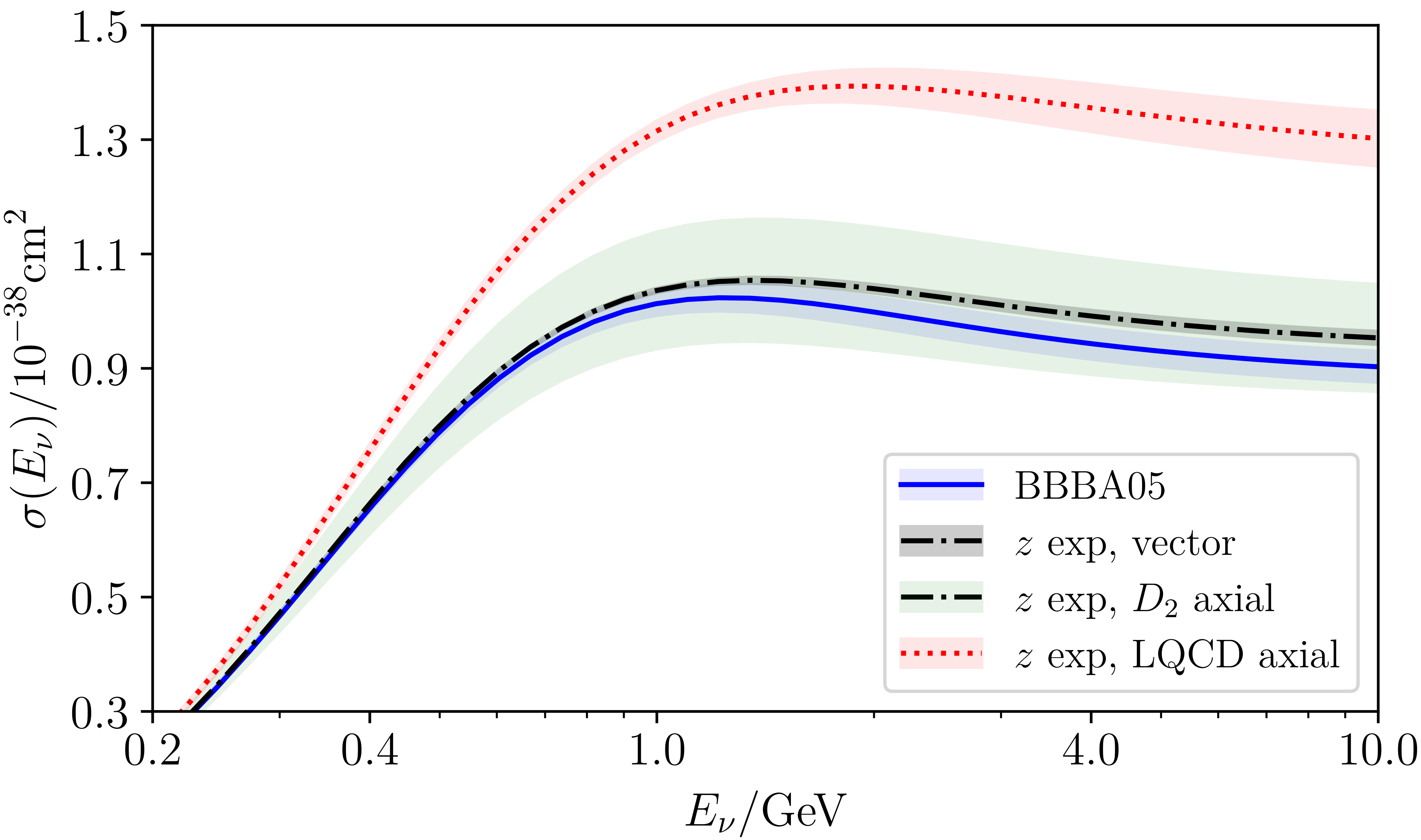


- 4-Fermi theory + ChPT @ and < pion-mass scale
- thresholds: muon ~ 110 MeV, tau ~ 3.5 GeV
- only electron flavor for supernova, solar and reactor neutrinos
- deuterium bubble chamber data in 1980th
- provide nucleon axial form factor
- target for many lattice QCD groups

Fermilab bubble chamber, Richard Drew

- elastic scattering -> pion production -> deep inelastic scattering

Neutrino-nucleon scattering (CC)



A.S. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. of 72, 010622-120608 (2022)
A.S. Meyer, M. Betancourt, R. Gran, and R.J. Hill, PRD (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill, and O. T. , PRD (2021)

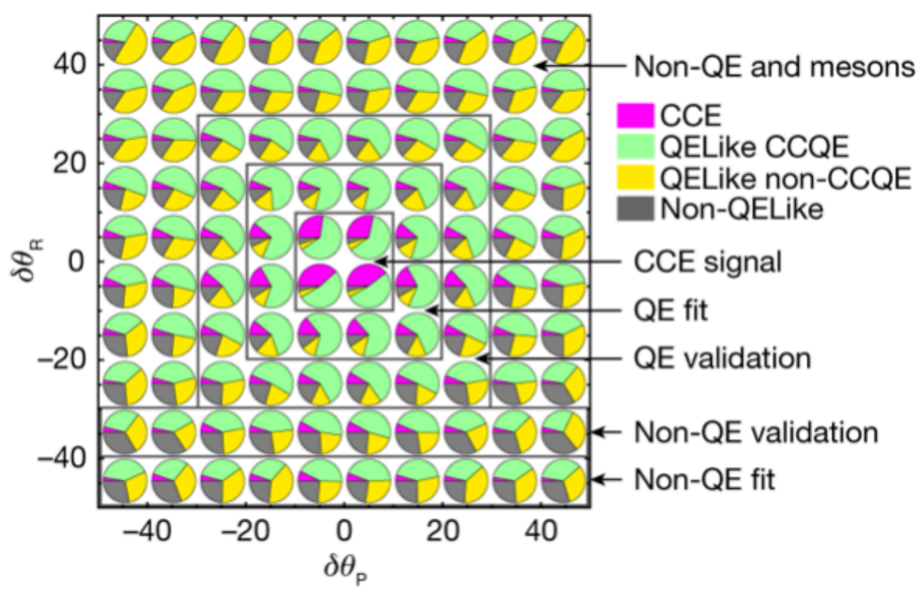
- knowledge of vector structure stops a progress in studies of axial
- acknowledged discrepancy: lattice QCD <-> experimental data

MINERvA result with free protons

- idea of scattering on molecular hydrogen realized !!!

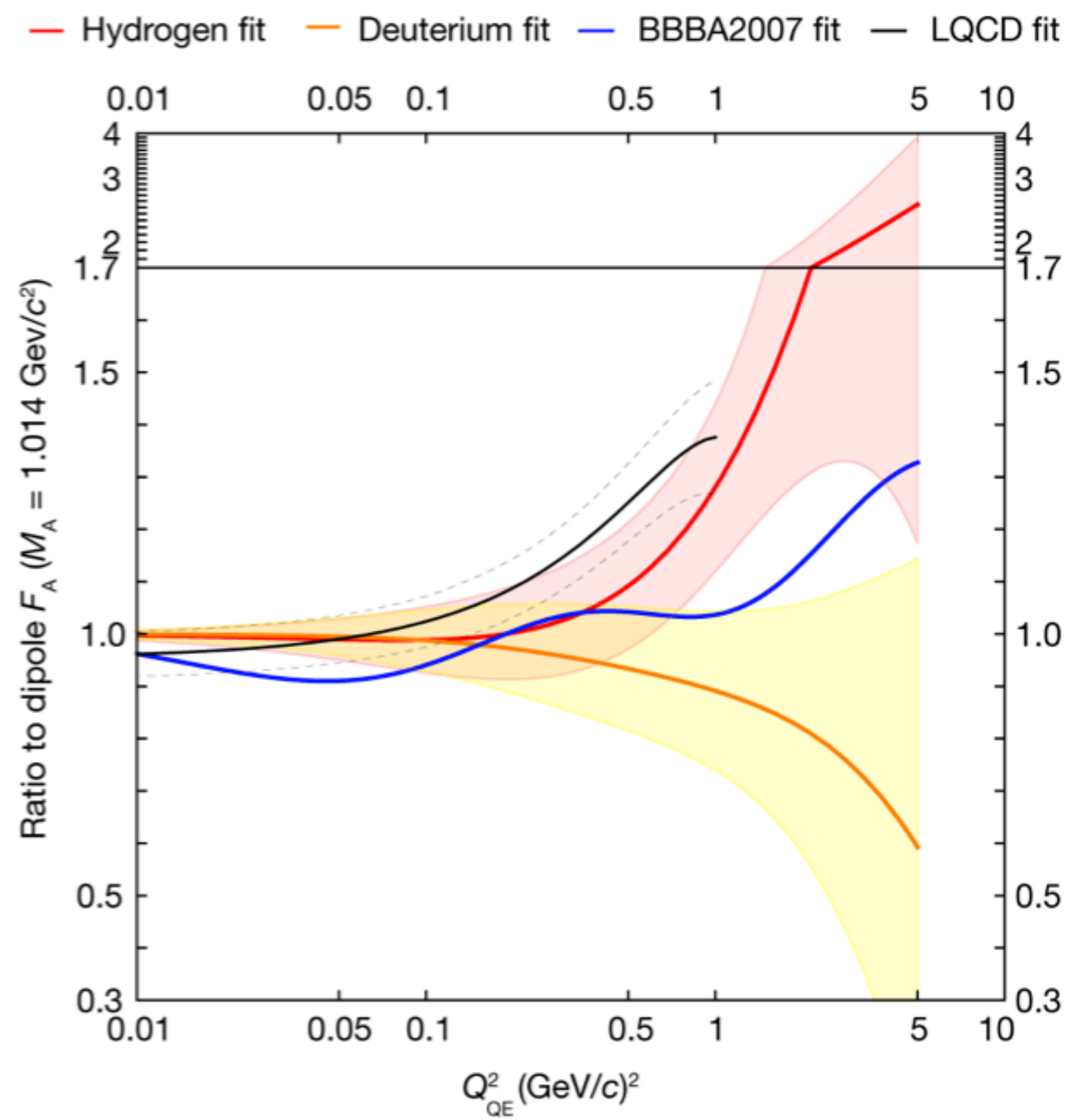
$\overline{\nu}_\mu p \to \mu^+ n$

kinematic selection



5580 events over
12500 background

background nuclear events
constrained by scattering of ν

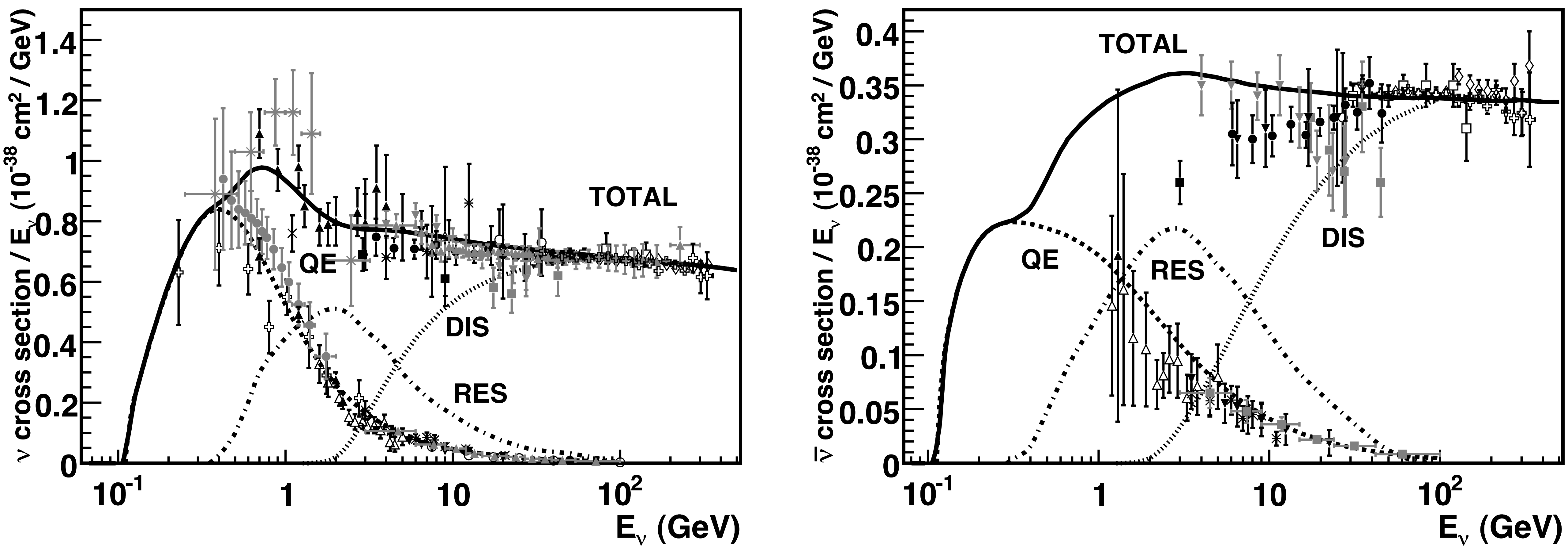


- 1st measurement of axial form factor on "free" protons $\overline{\nu}_\mu p \to \mu^+ n$

T. Cai et al., MINERvA Collaboration, Nature (2023), 614, 48-53

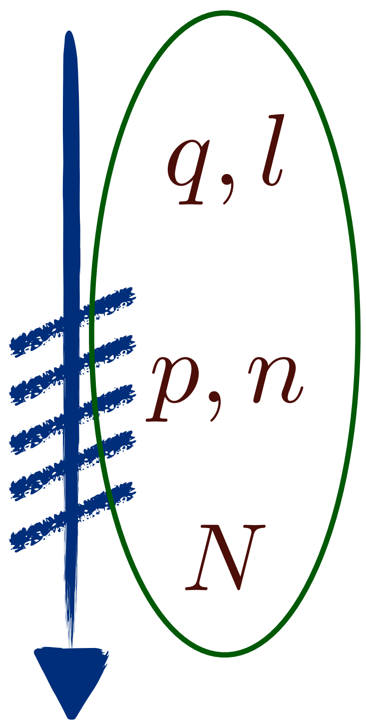
Neutrino-nucleus scattering

- NC scattering across all energies -> neutrino floor
- CC with electron flavor for supernova, solar, and reactor neutrinos
- same open channels as at nucleon level



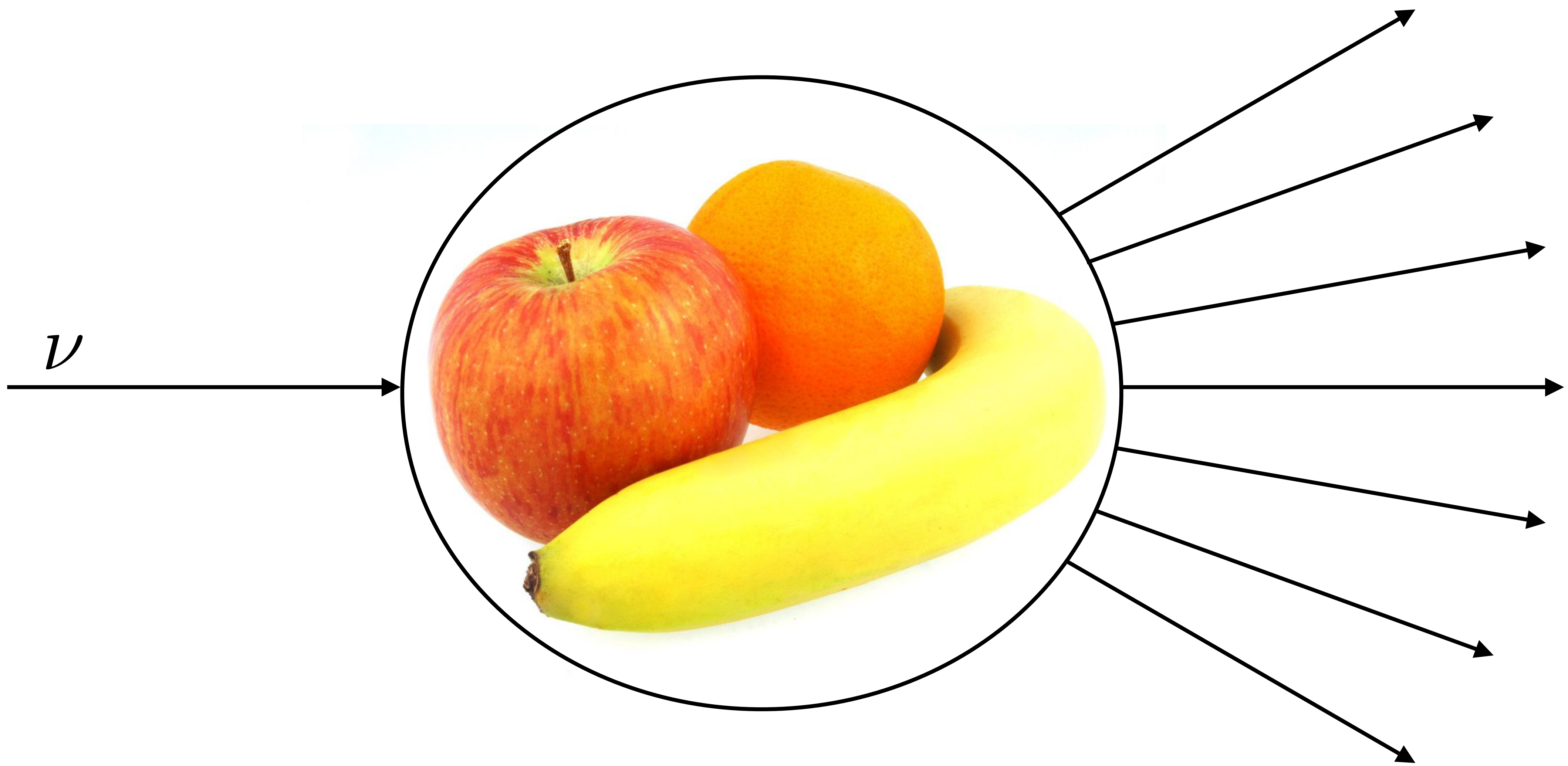
Formaggio and Zeller (2013)

- binding effects, Fermi motion, Pauli blocking
- meson exchange, 2p-2h, final-state interaction

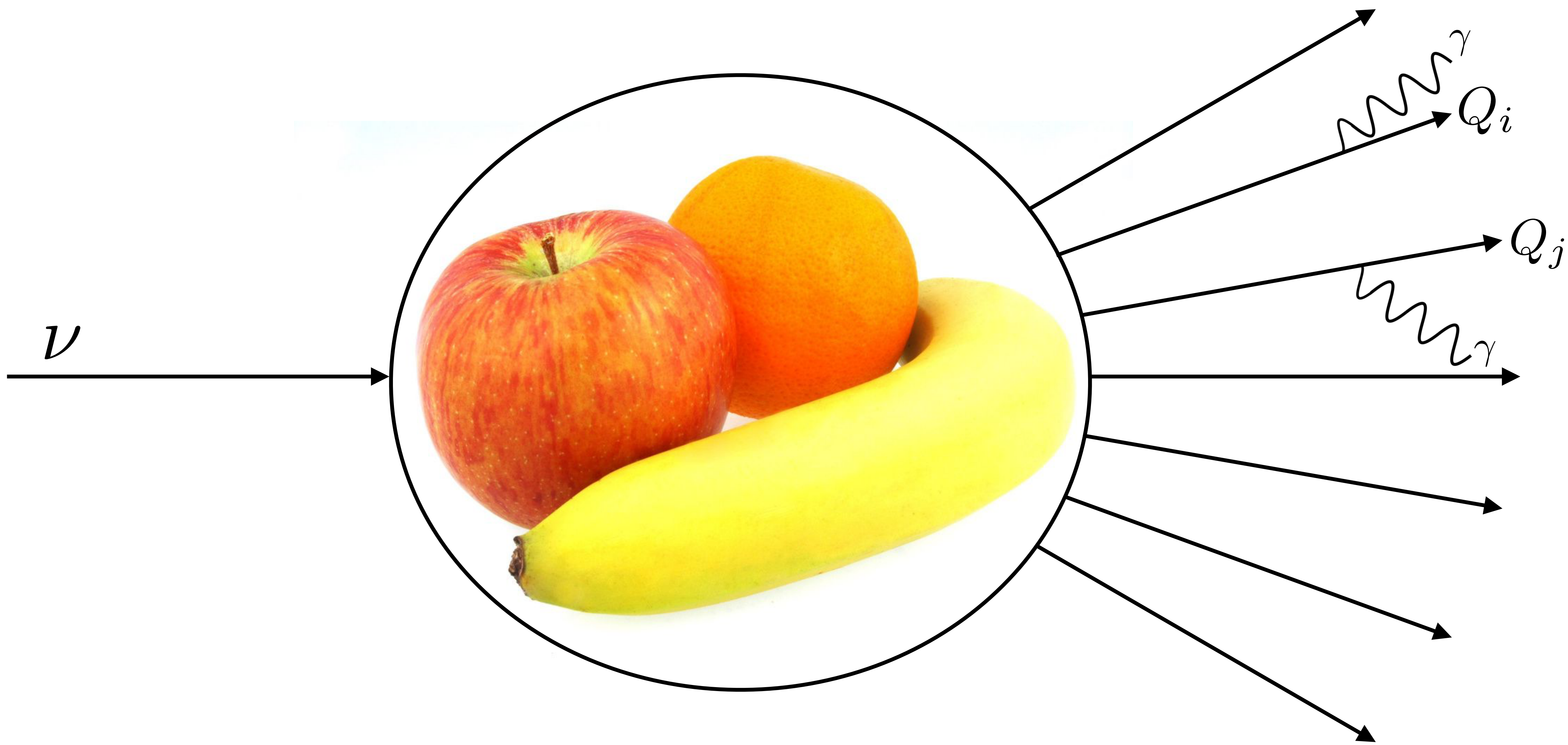


Radiative corrections in neutrino physics (at MeV-GeV energies)

Neutrino interactions

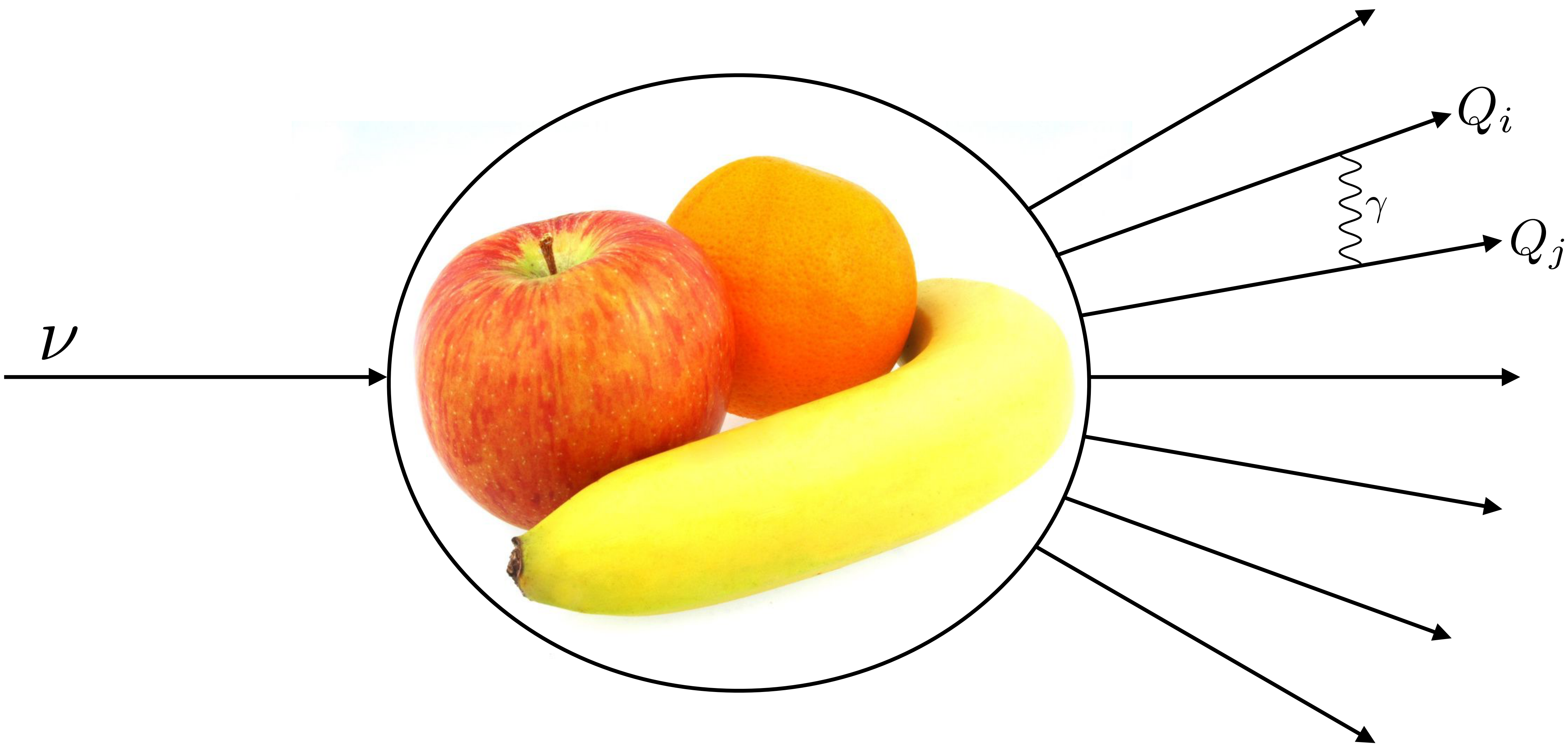


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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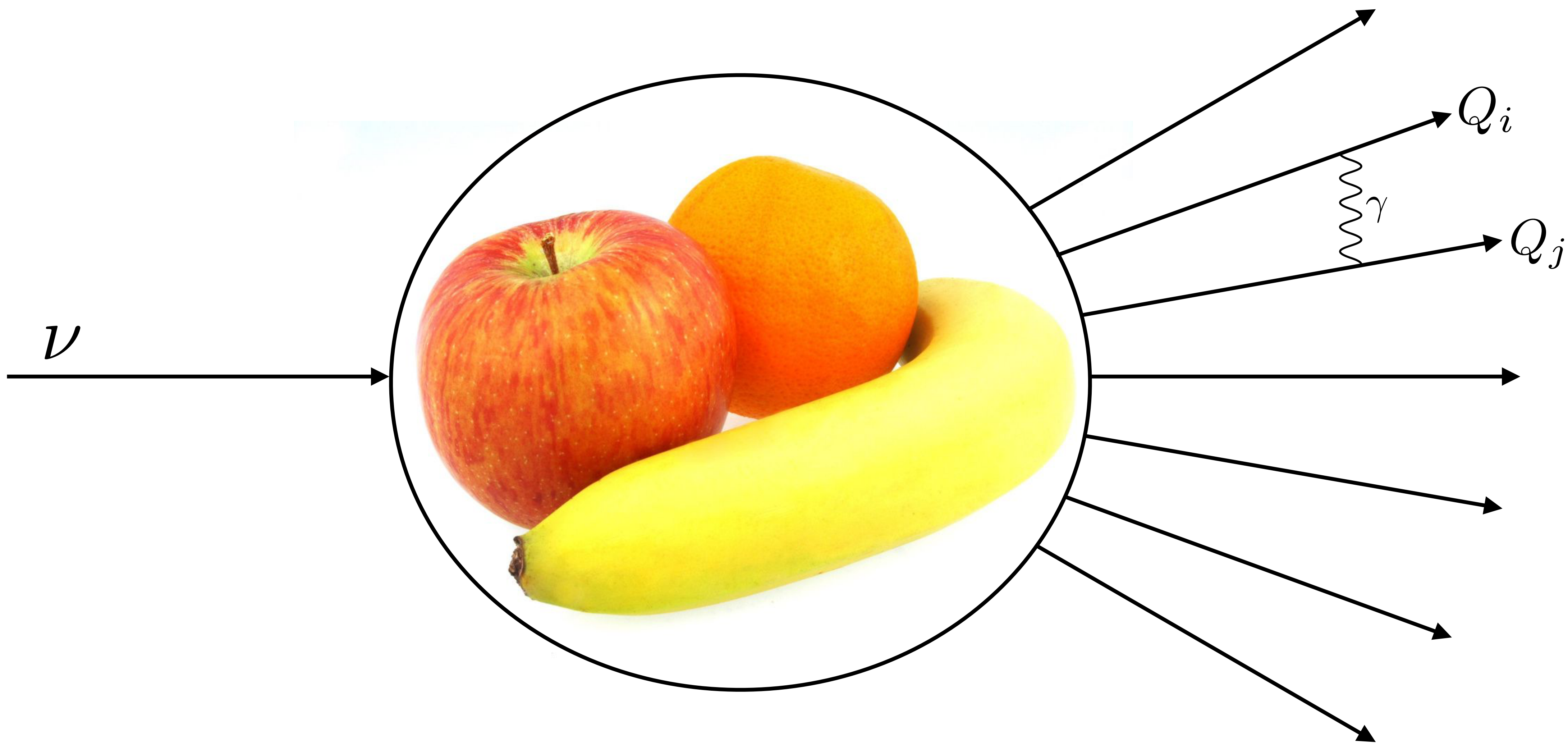
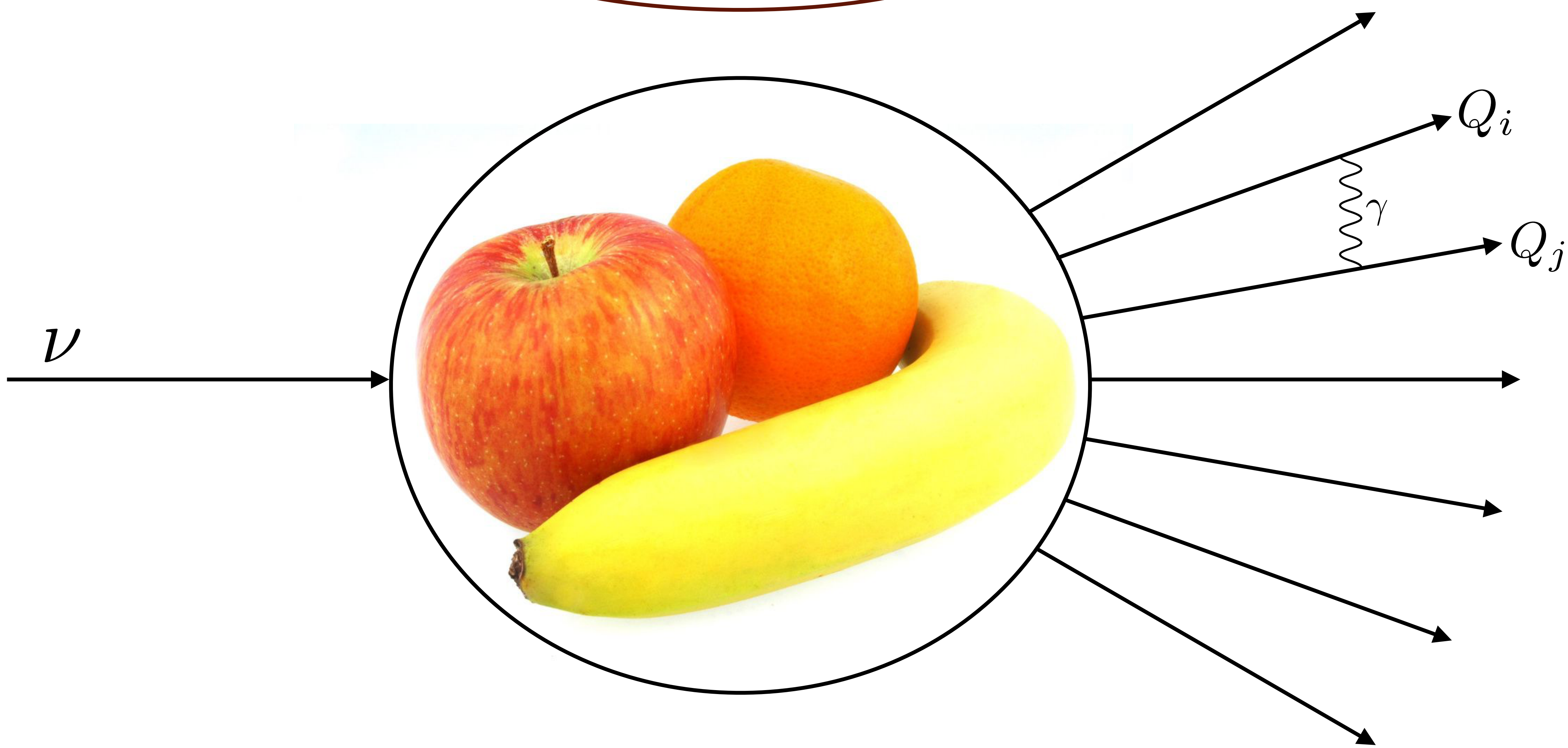
QED corrections



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

QED corrections

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

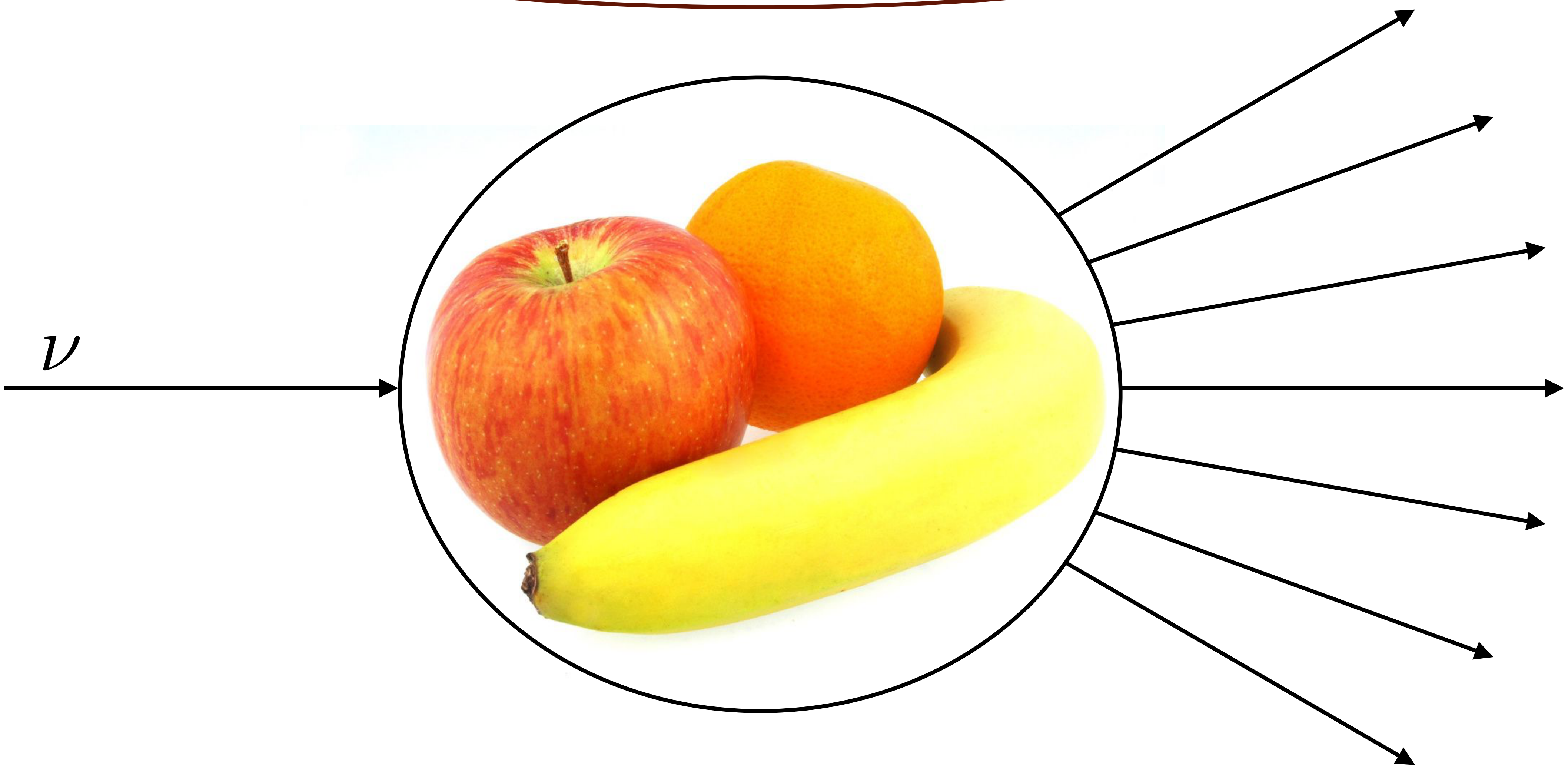


$\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by $\ln \frac{E_\nu}{m_e} \sim 6 - 10$ or $\ln^2 \frac{E_\nu}{m_e} \sim 36 - 100$

- scale separation introduces large flavor-dependent QED logarithms

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

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

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

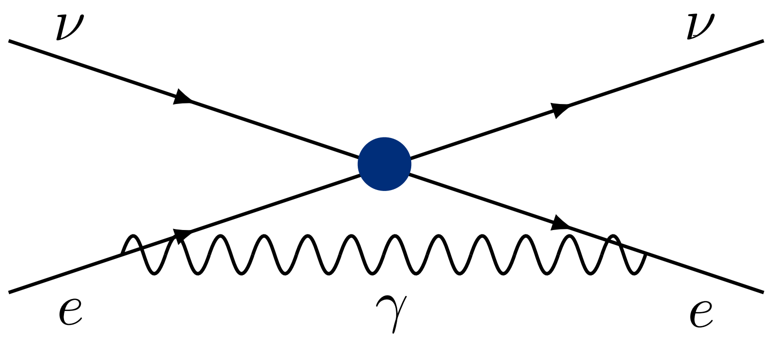
Neutrino-lepton, neutrino-quark scattering

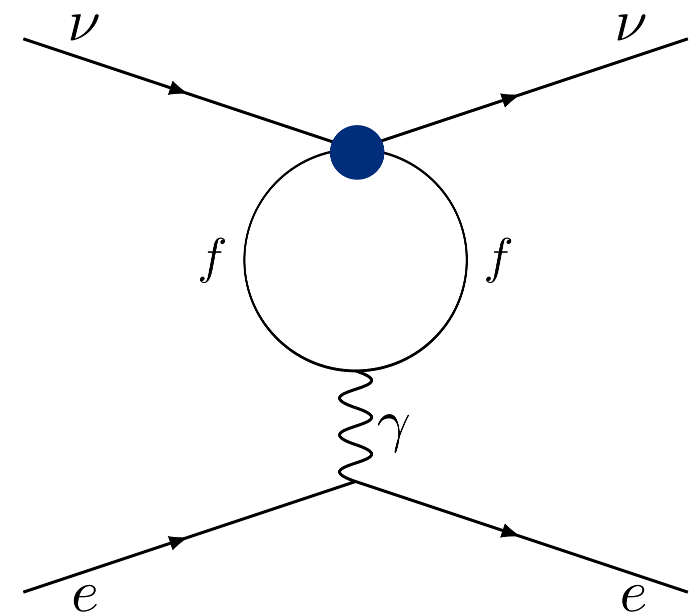
O.T. and Richard J Hill, Phys. Lett. B 805, 3, 135466 (2020)

known at permille level ✓

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

Leptonic probes: "Standard Candles" for flux constraints



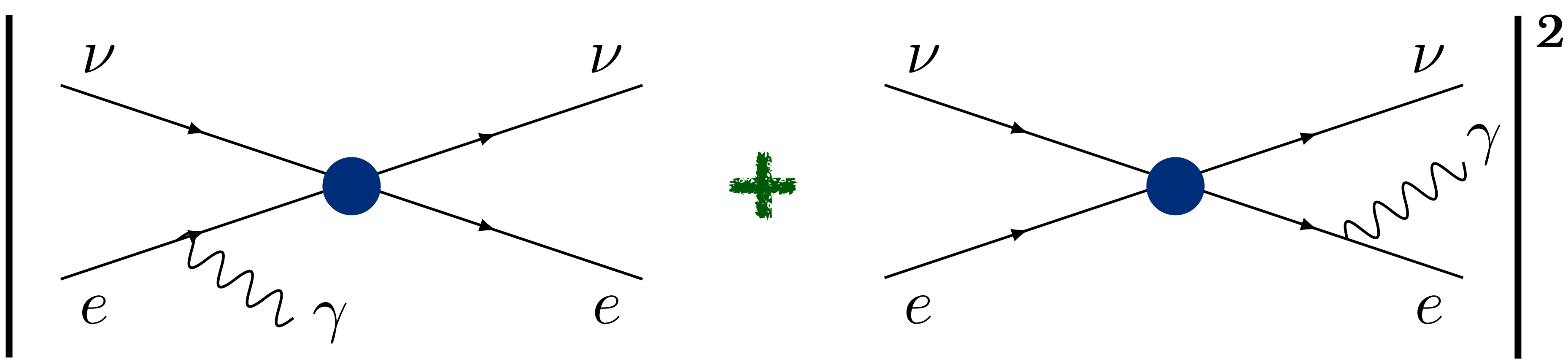


Neutrino-electron scattering

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, solar ν

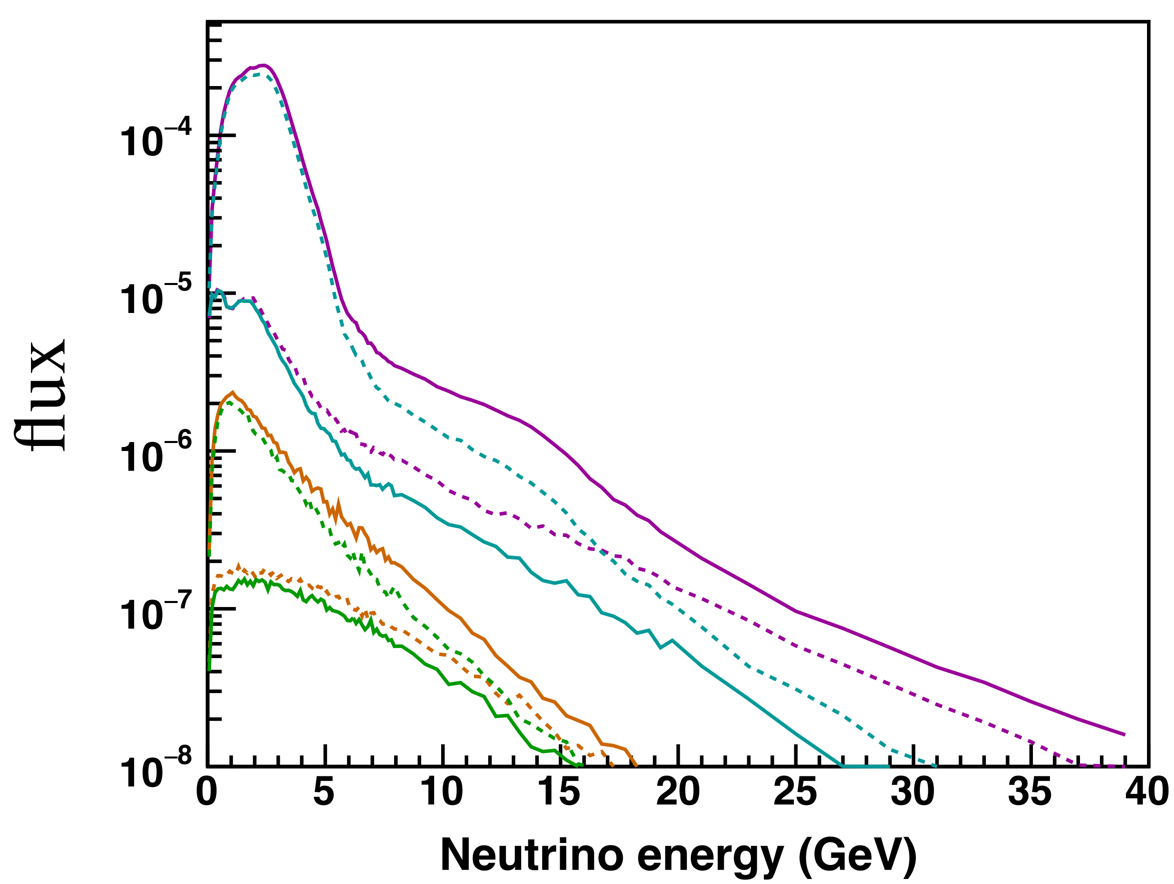


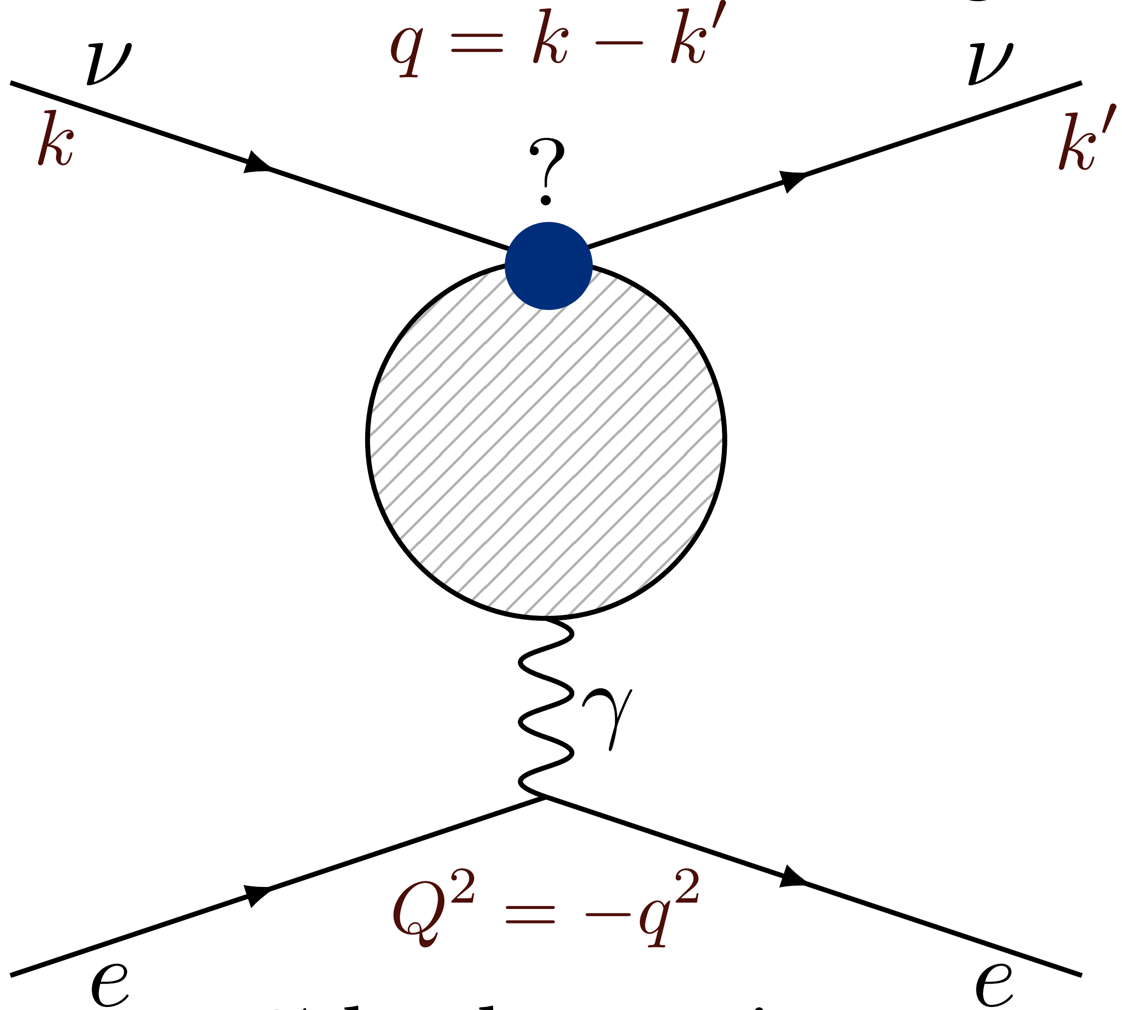
Main theoretical uncertainty

- kinematics is suppressed by electron mass:

$$s, Q^2 \lesssim 2mE_\nu \ll \Lambda^2_{\text{QCD}}$$

- description in terms of quarks is invalid for GeV neutrino energies





% level correction

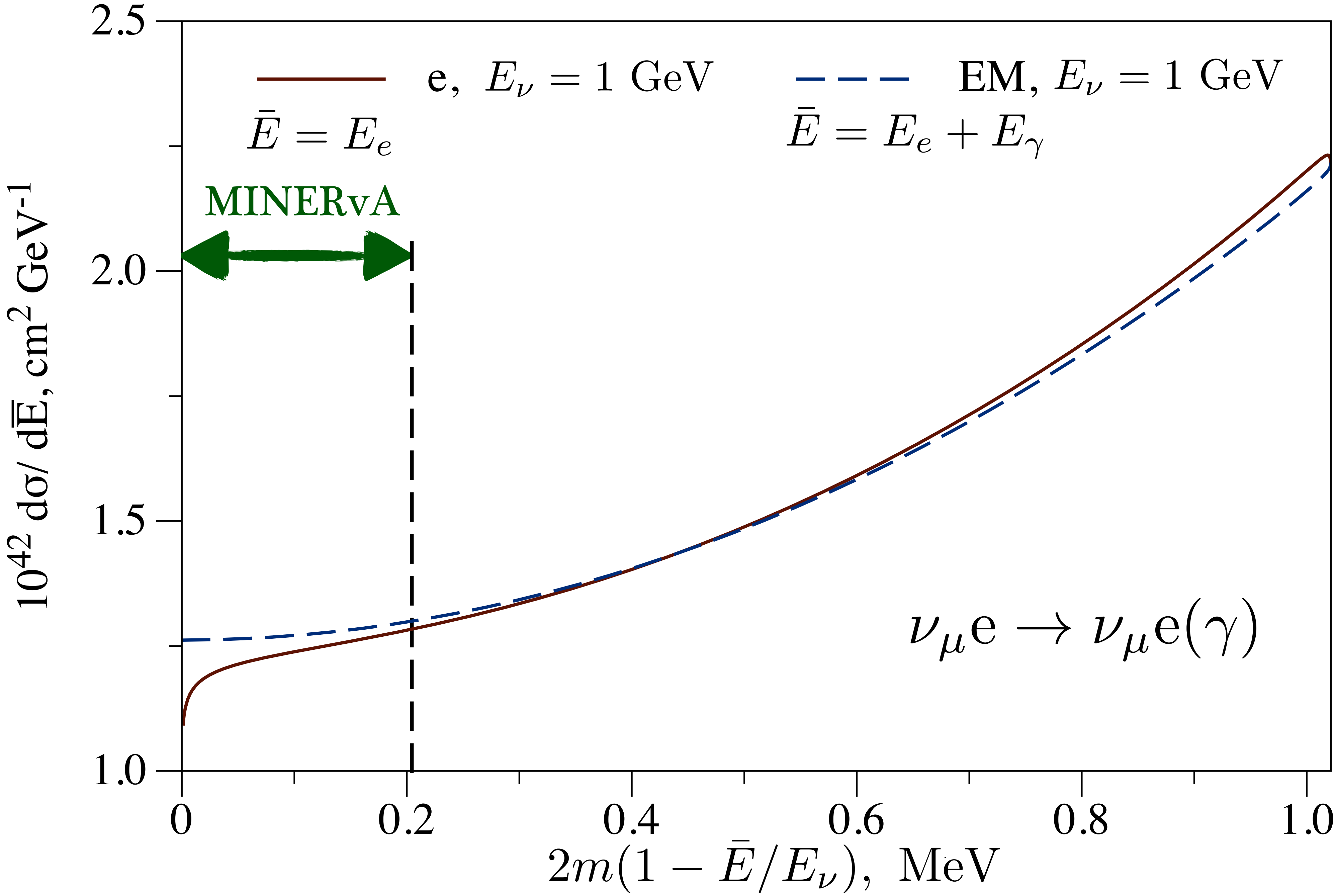
Ch. Marshall et al, Phys.Rev.D 101 3, 032002 (2020)

- hadronic correction is the main error in theory

Electron vs electromagnetic (EM) spectra

- resulting spectrum:

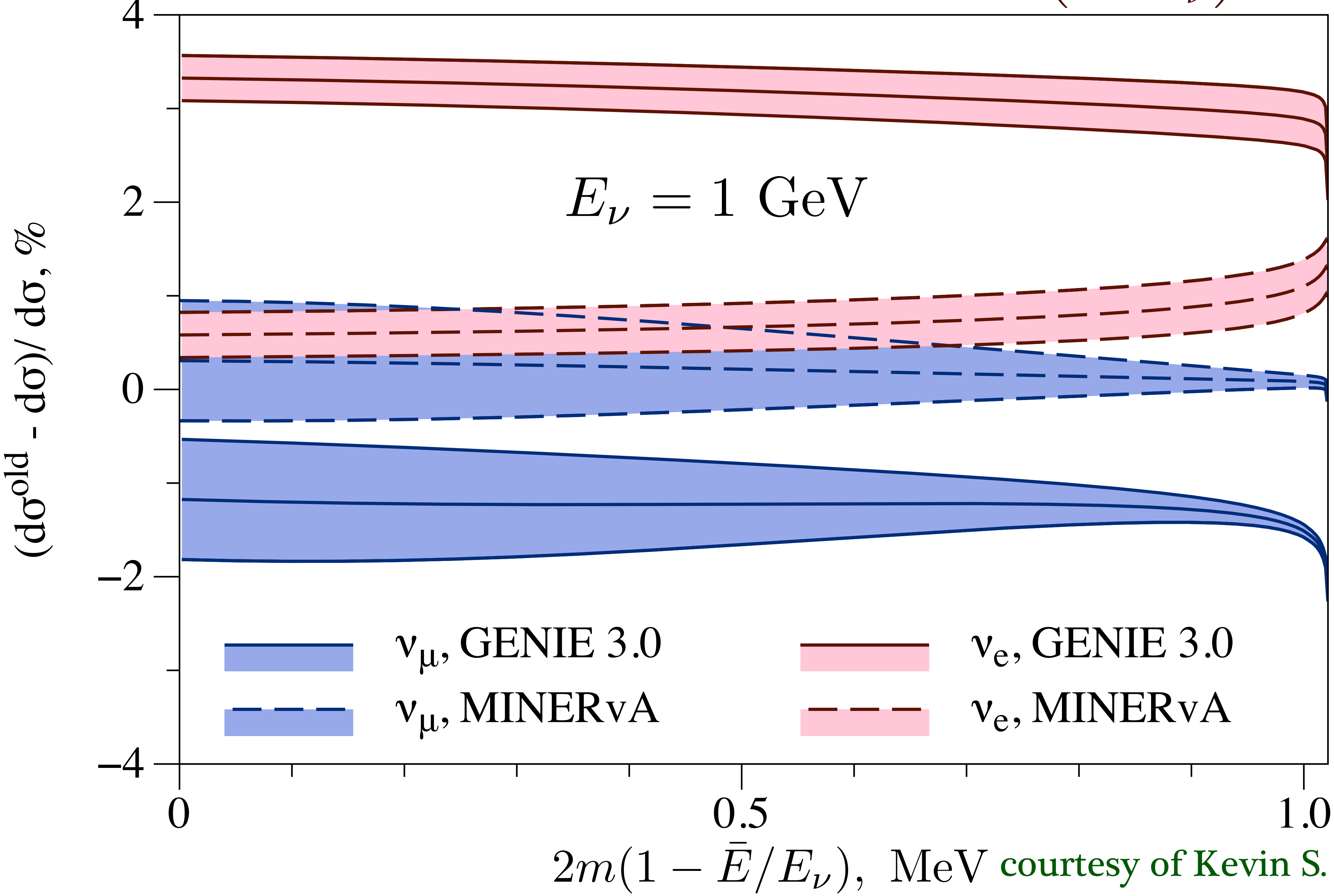
$$2m\left(1-\frac{\bar{E}}{E_\nu}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$$



- cut dependence after radiative corrections

Comparison to GENIE

- electromagnetic energy spectrum: $2m\left(1-\frac{\bar{E}}{E_\nu}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$



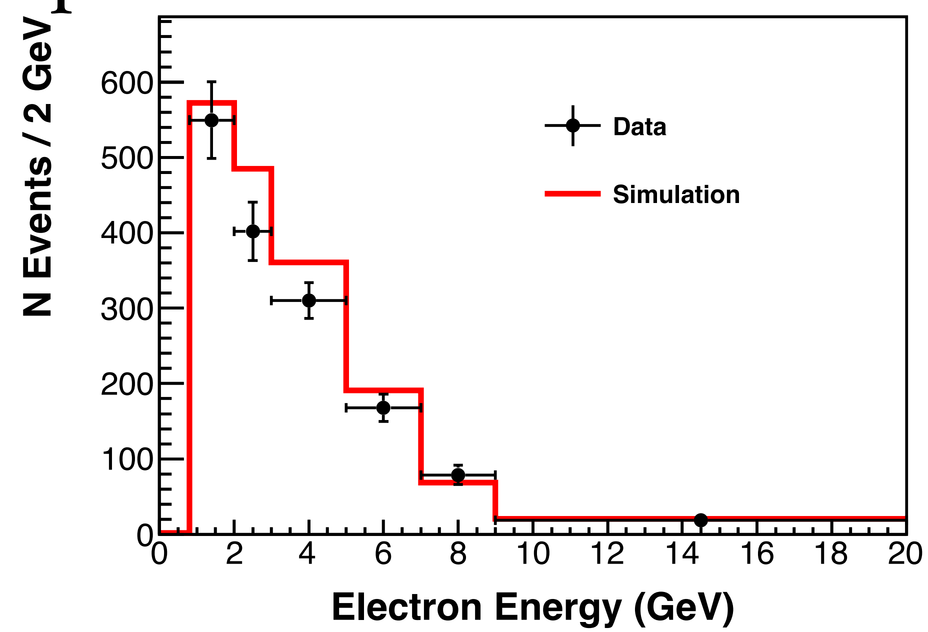
courtesy of Kevin S. McFarland

- correct description and definite improvement at GeV energies

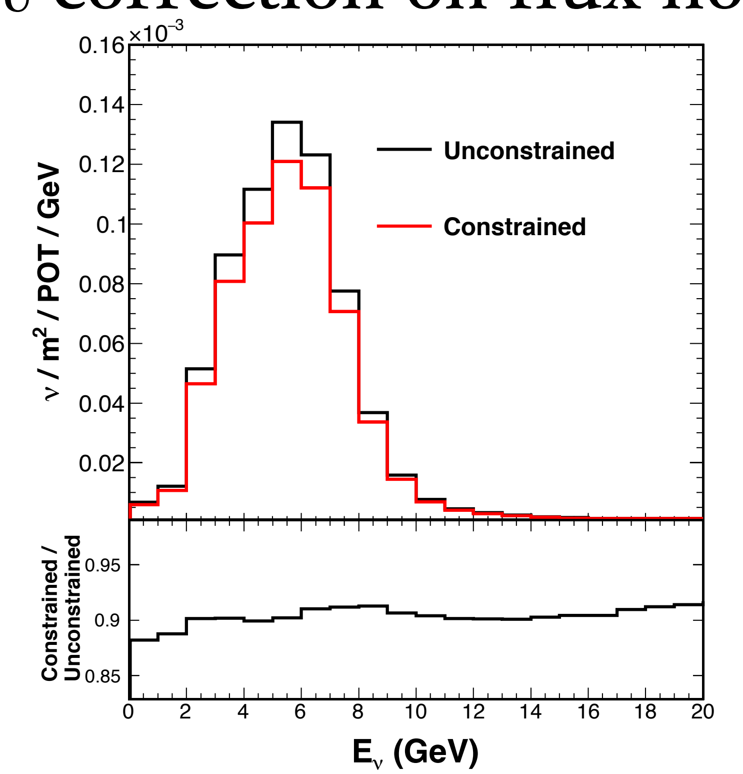
MINERvA constraint

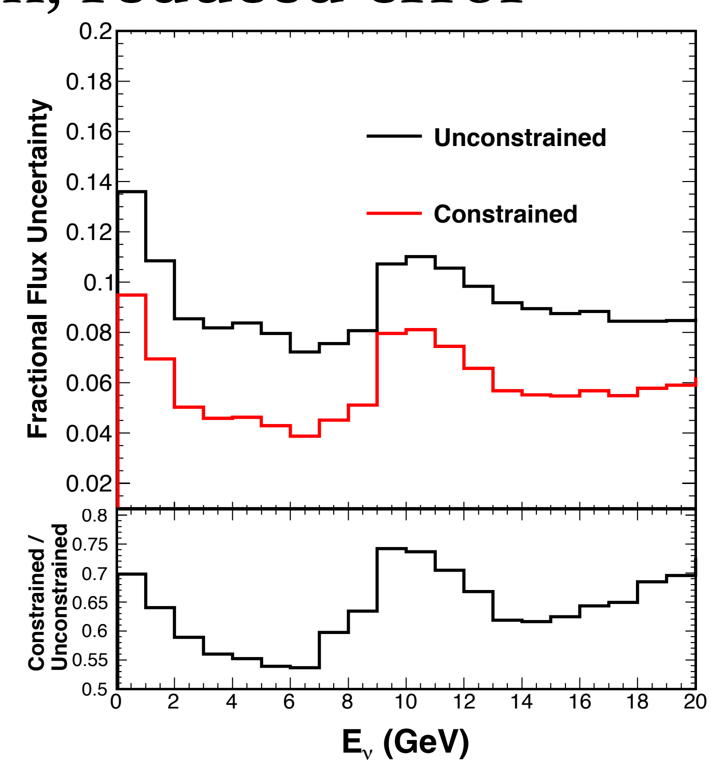
- electron energy spectrum:

MINERvA, Phys.Rev.D 100 9, 092001 (2019)



- 10% correction on flux normalization, reduced error





- successful implementation by MINERvA collaboration

Neutrino-electron scattering at Fermilab

- MINERvA experiment: measure neutrino-nucleus cross sections

- flux constraints via scattering on atomic electrons: 7.5% to 4%

MINERvA, Phys. Rev. D 93, 112007 (2016), Phys.Rev.D 100 9, 092001 (2019)

- cross section scales as target mass m

  10^{-4}-10^{-3} of cross section on nucleons and nuclei

- unique process free from structure effects

- huge statistics of DUNE near detector vs MINERvA: 8% to 2%

  5000-7000 events in a year vs 1100-1200 events in total

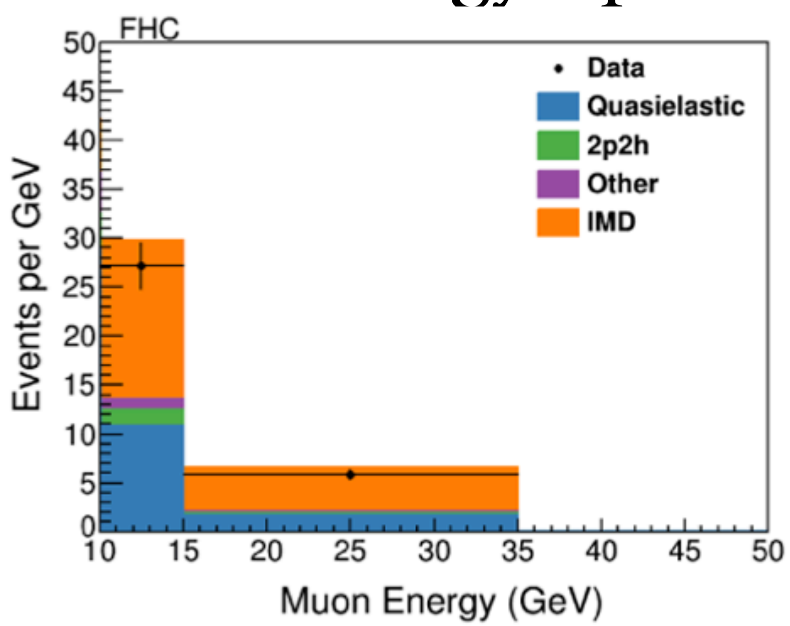
Ch. Marshall et al, Phys.Rev.D 101 3, 032002 (2020)

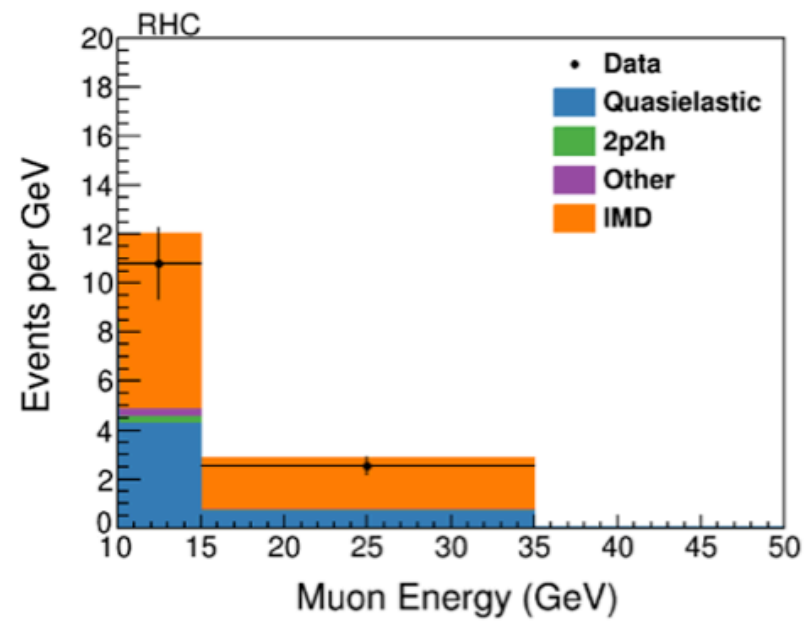
- νe scattering: standard candle to constrain neutrino flux

MINERvA constraint by inverse muon decay

- muon energy spectrum:

MINERvA, Phys.Rev.D 104, 092010 (2021)

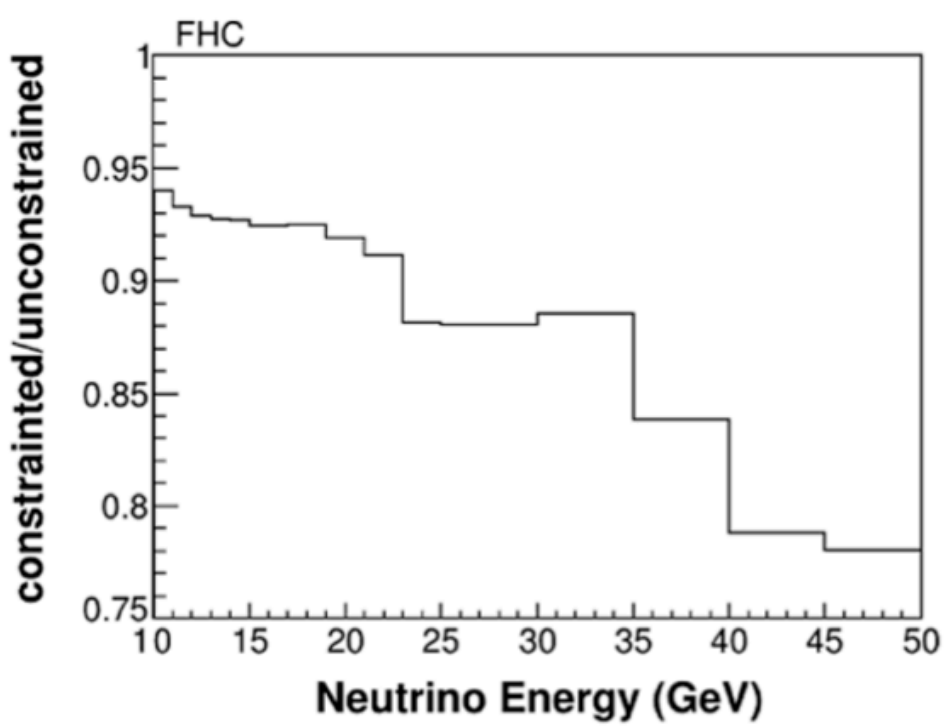


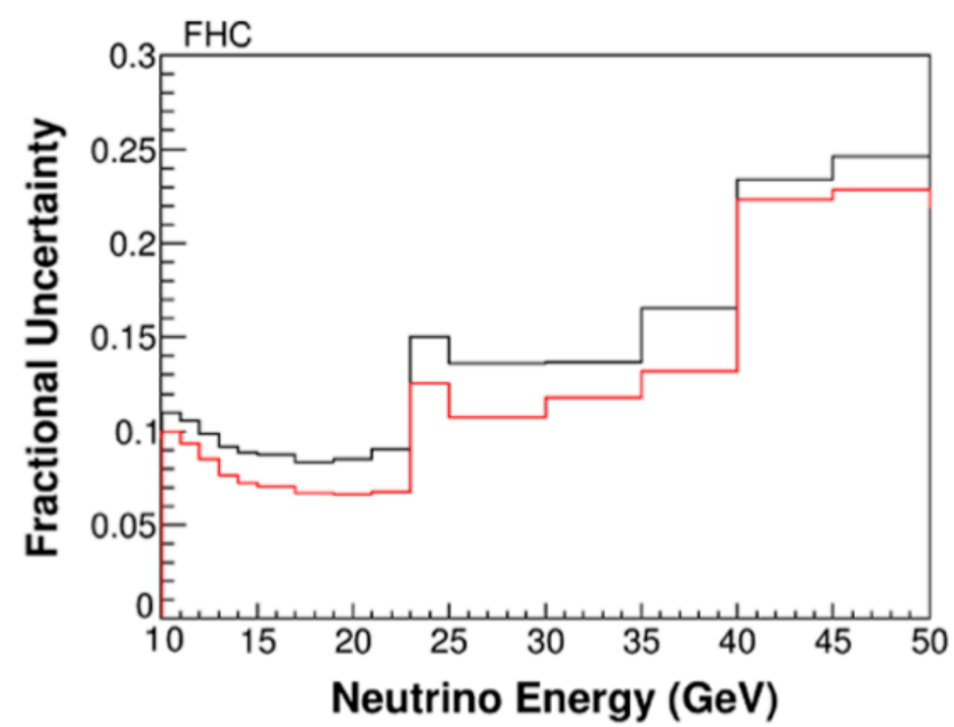


$$\nu_\mu e^- \to \nu_e \mu^-$$

$$E_\nu^{thr} \gtrsim 10.9 \text{ GeV}$$

- 10-20% correction on flux normalization, reduced error





- successful implementation by MINERvA collaboration

Inverse muon decay theory

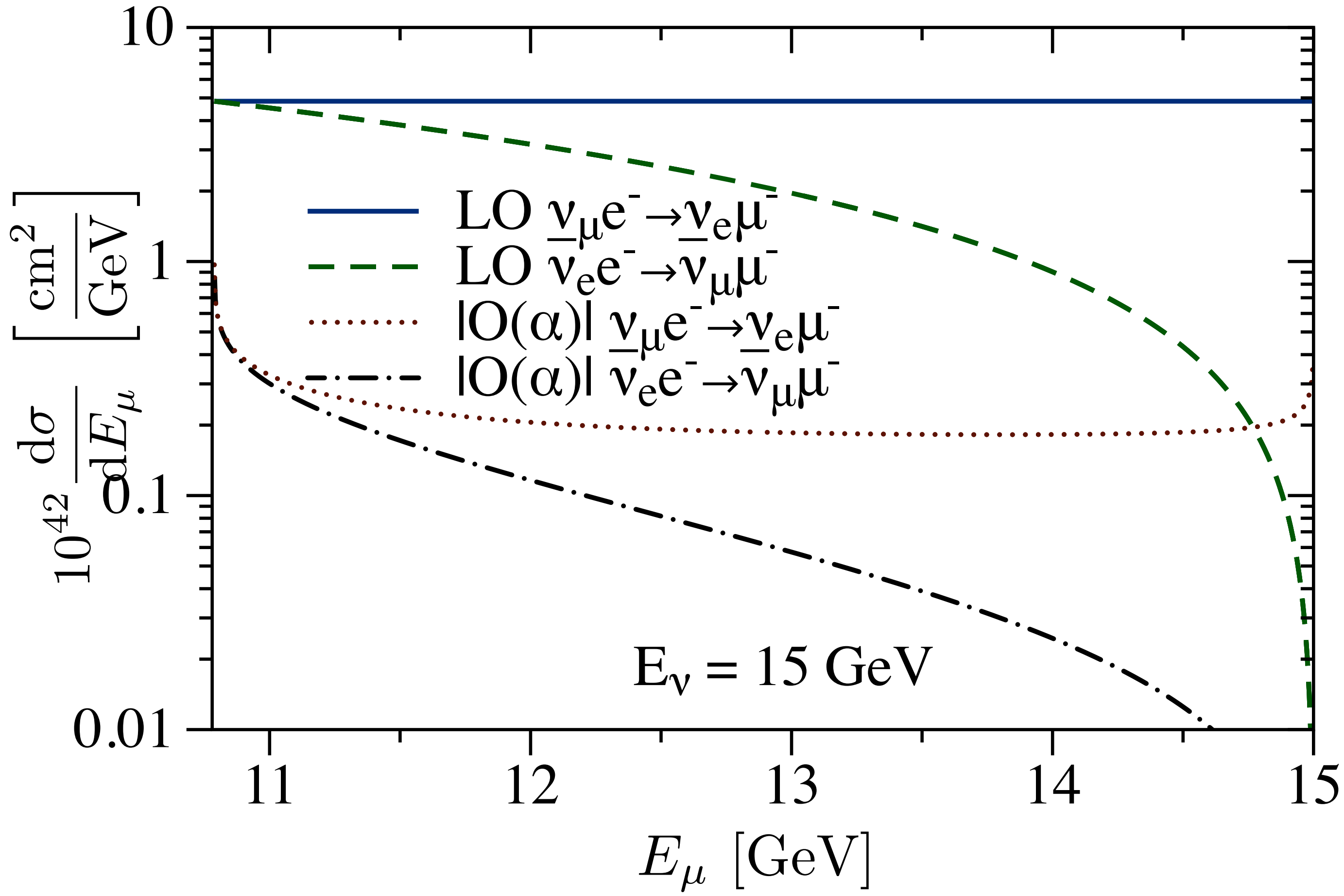
- precise Lagrangian with G_F from muon decay

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2}\mathrm{G_F}\bar{\nu}_e\gamma^\lambda \mathrm{P_L}\nu_\mu\,\bar{\mu}\gamma_\lambda \mathrm{P_L} e + \text{h.c.}.$$

- 2.5 from 3 cross sections reproduced by alternative method

Bardin and Dokuchaeva (1987)

- new total cross sections, energy spectra, and 2D cross sections



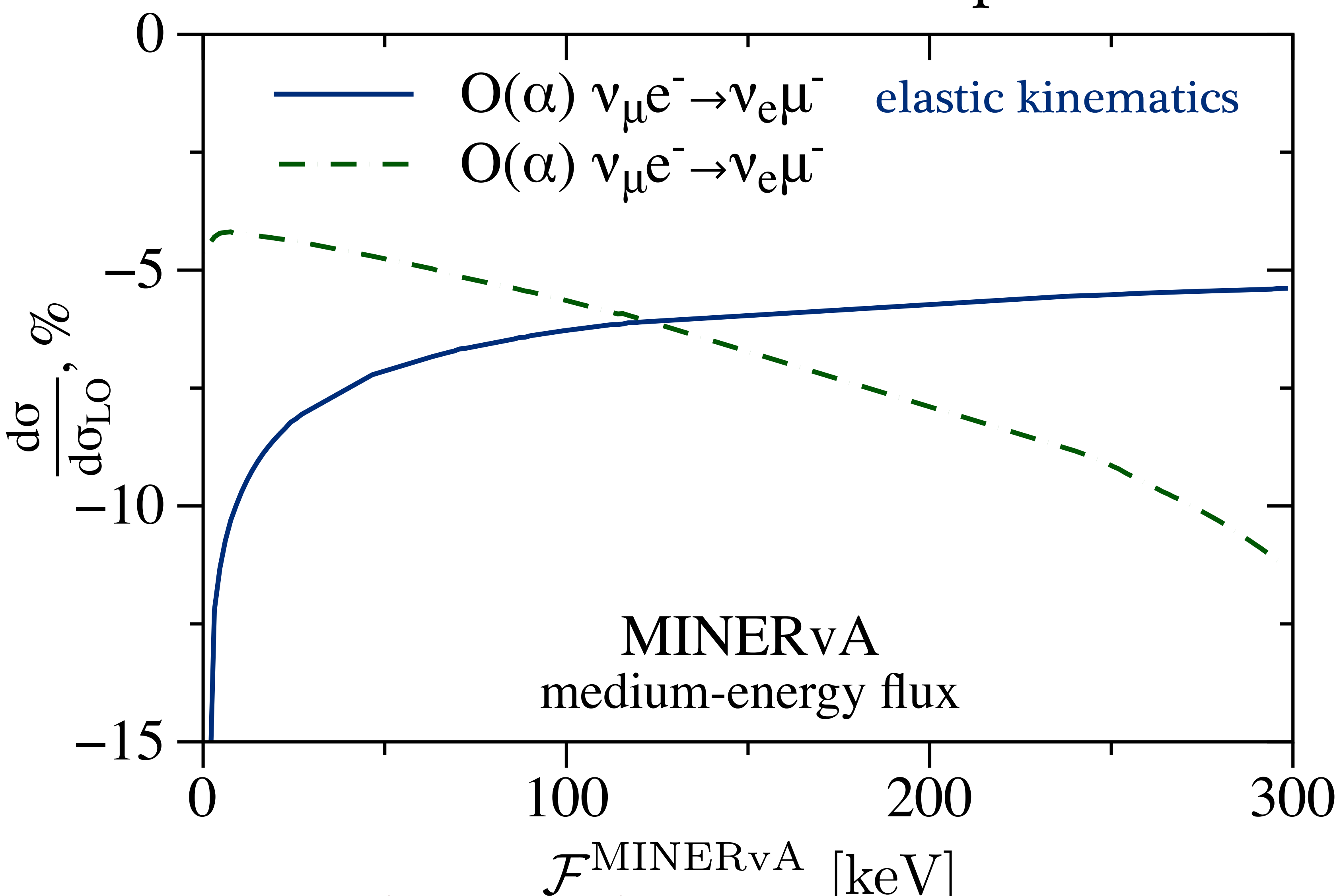
dominant neutrino component has larger cross section

energy spectrum in both channels

- muon energy spectrum verified $\nu_\mu e^- \to \nu_e \mu^-$, derived $\bar{\nu}_e e^- \to \bar{\nu}_\mu \mu^-$

Inverse muon decay theory

- radiative corrections to distribution of experimental discriminant



$$\mathcal{F} = E_\mu \theta_\mu^2 \approx \left(1 - \frac{E_\mu}{E_\nu}\right)\left(2m_e - \frac{m_\mu^2}{E_\mu}\right) \qquad \mathcal{F}^{\mathrm{MINERvA}} = \frac{E_\mu \theta_\mu^2}{1 - \frac{E_\mu}{35\ \mathrm{GeV}}}$$

O.T., Kaushik Borah, Richard J. Hill, Kevin S. McFarland, Daniel Ruterbories
Phys. Rev. D 107 9, 093005 (2023)

- double-differential distributions and corrections to $\mathcal{F}$ distribution

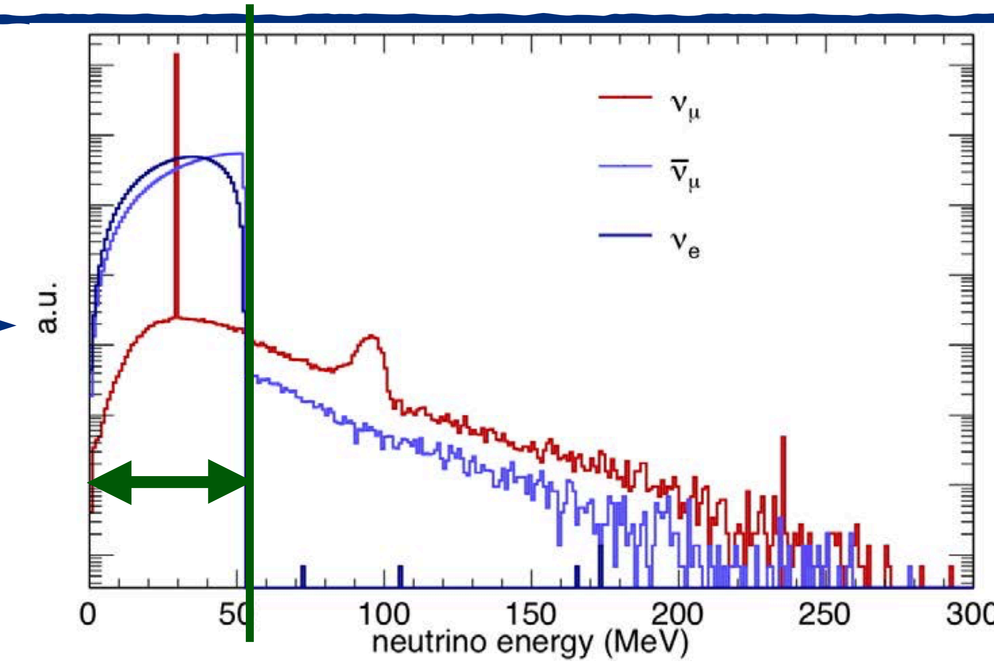
Neutrinos from muon, pion and kaon decays

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)

O. T., Phys. Lett. B 829, 137108 (2022)

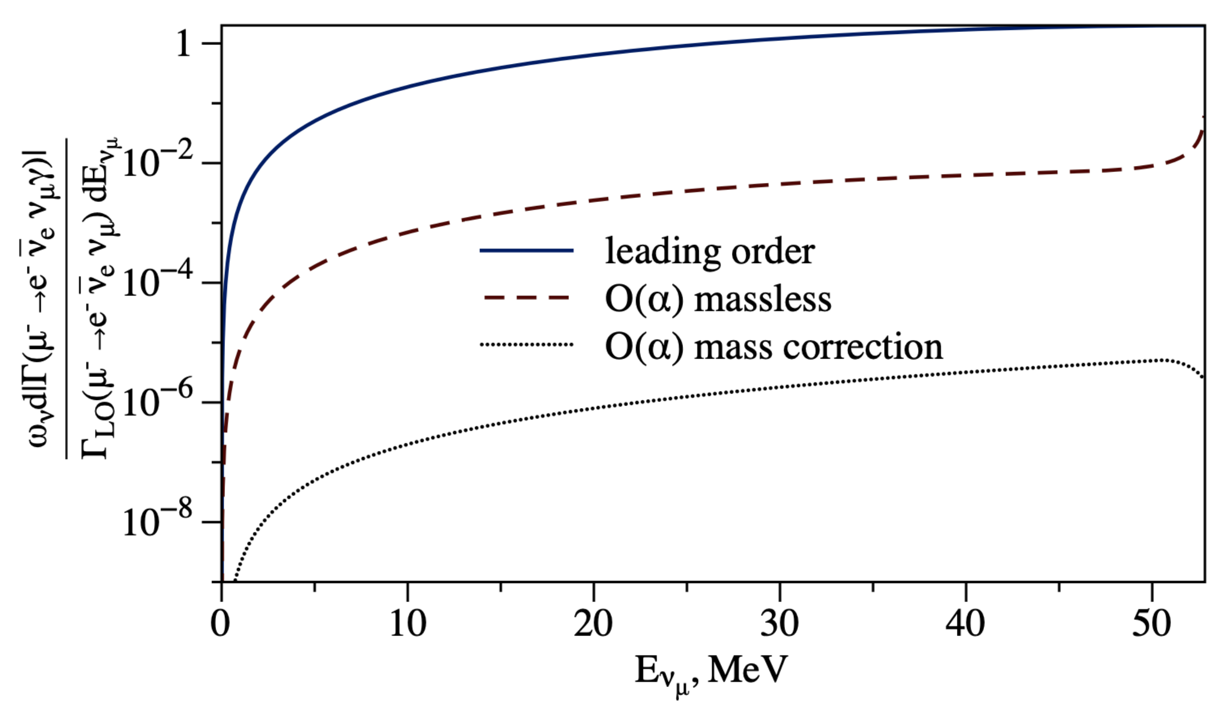
$$\pi^+ \to \mu^+ \nu_\mu \gamma$$

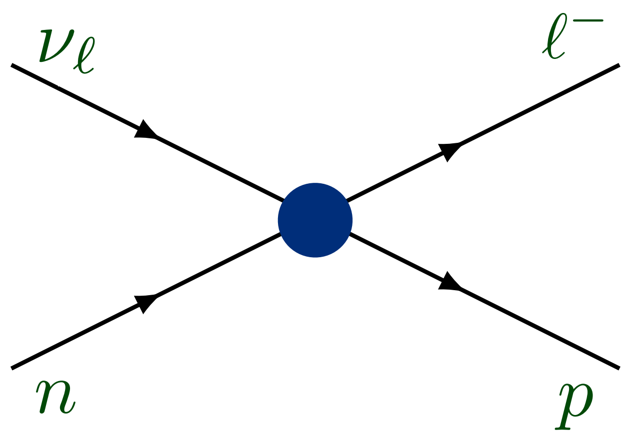
$$K^+ \to \mu^+ \nu_\mu \gamma$$

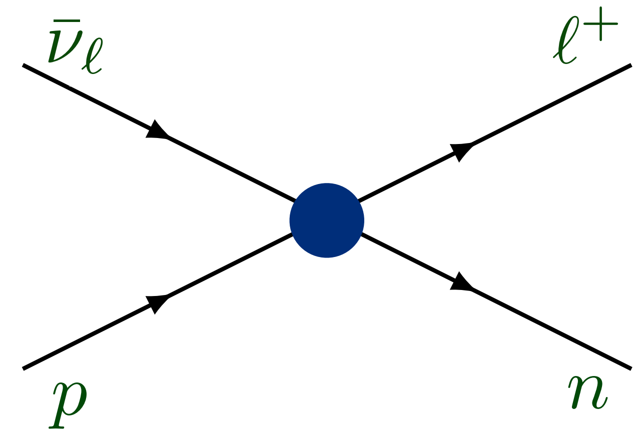
< 0.1 ‰

flavor-dependence is clarified to permille level analytically ✓

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



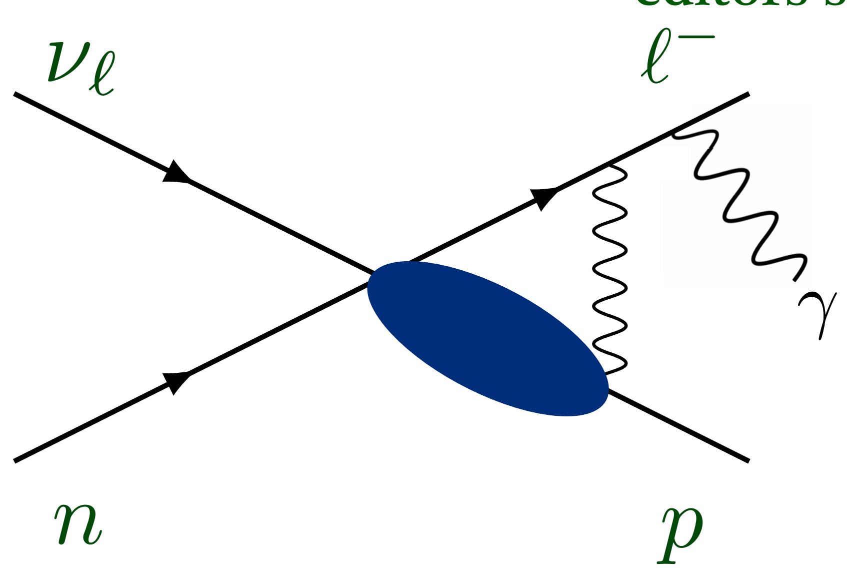




O. T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. 13 (2022), 1, 5286

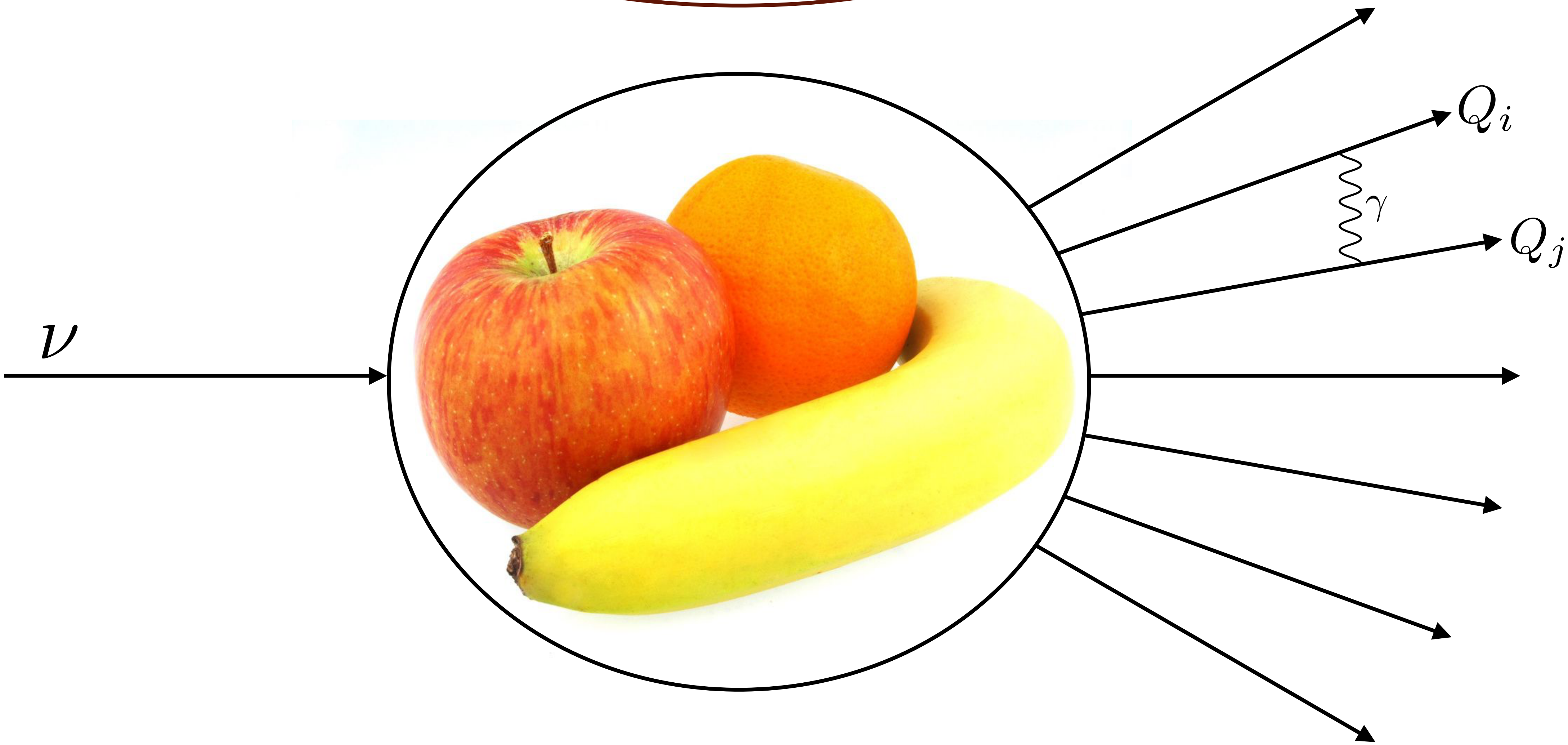
Radiative corrections in charged-current elastic scattering on free nucleons

O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
editors suggestion in Phys. Rev. D (2022)



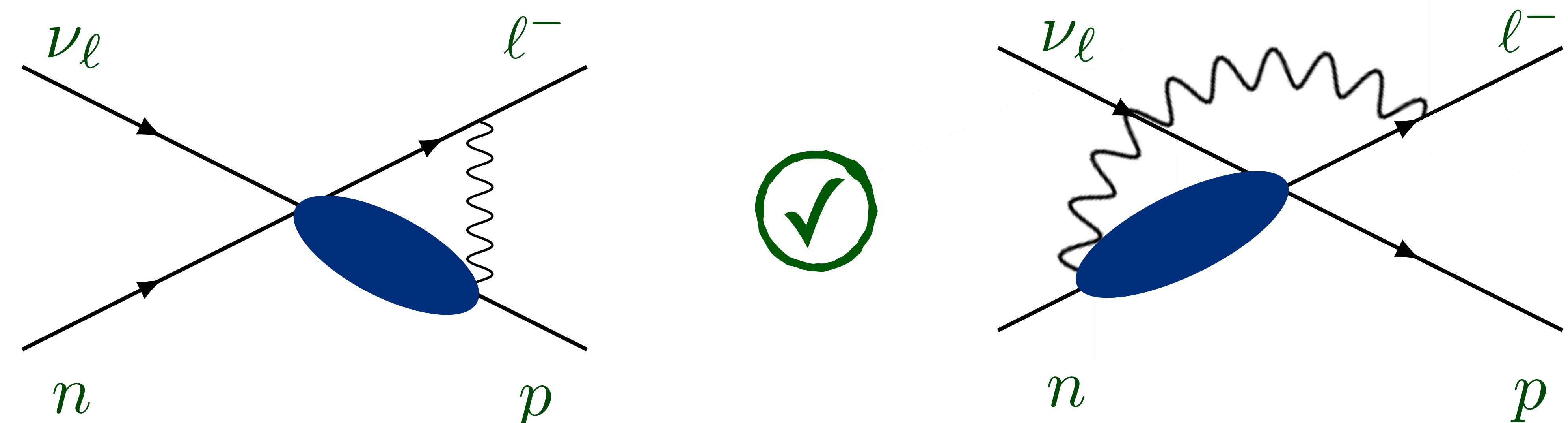
QED corrections

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



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

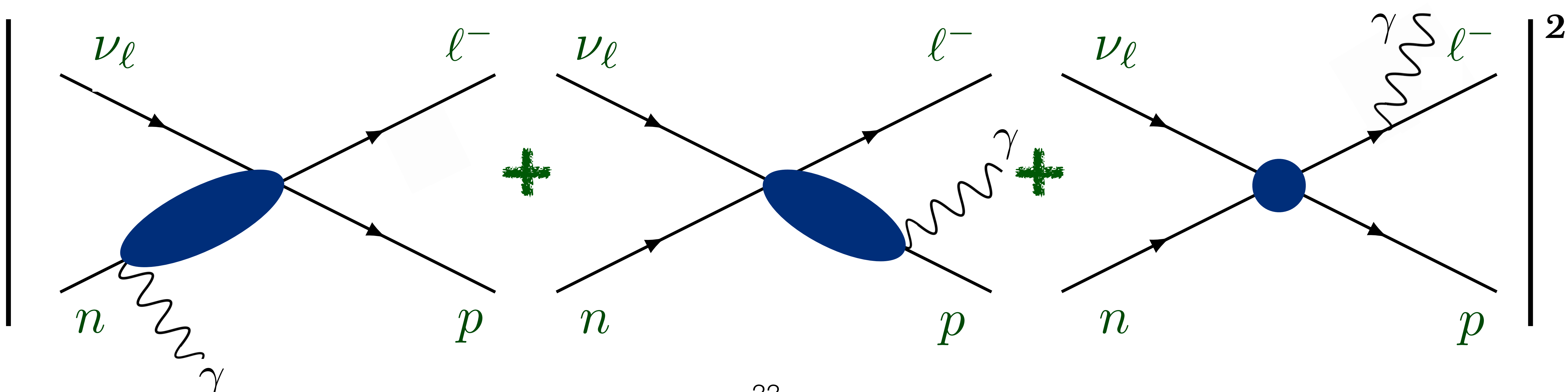
- scale separation introduces large flavor-dependent QED logarithms factorization for radiative corrections with model for hard function



Charged-current elastic scattering on nucleons

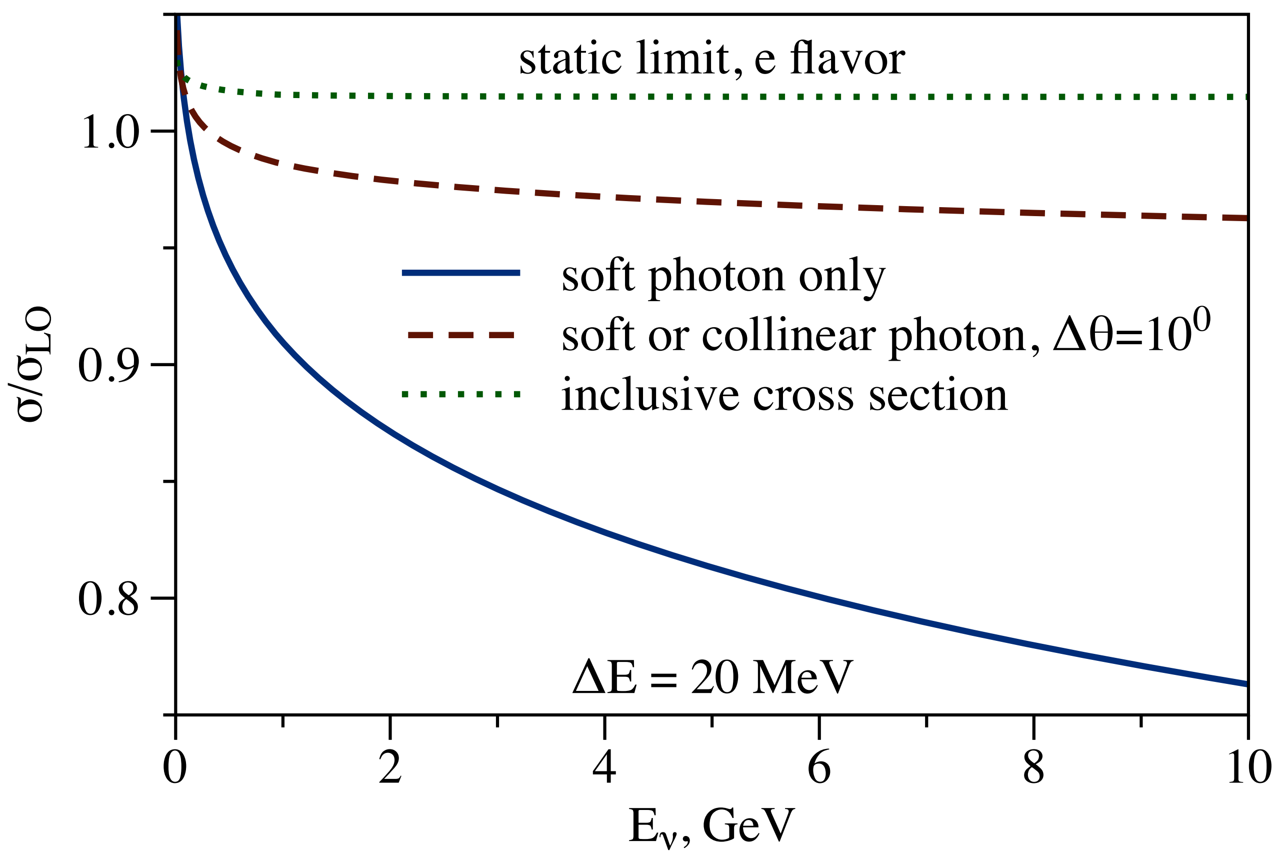
precise predictions for flavor ratios and radiative corrections

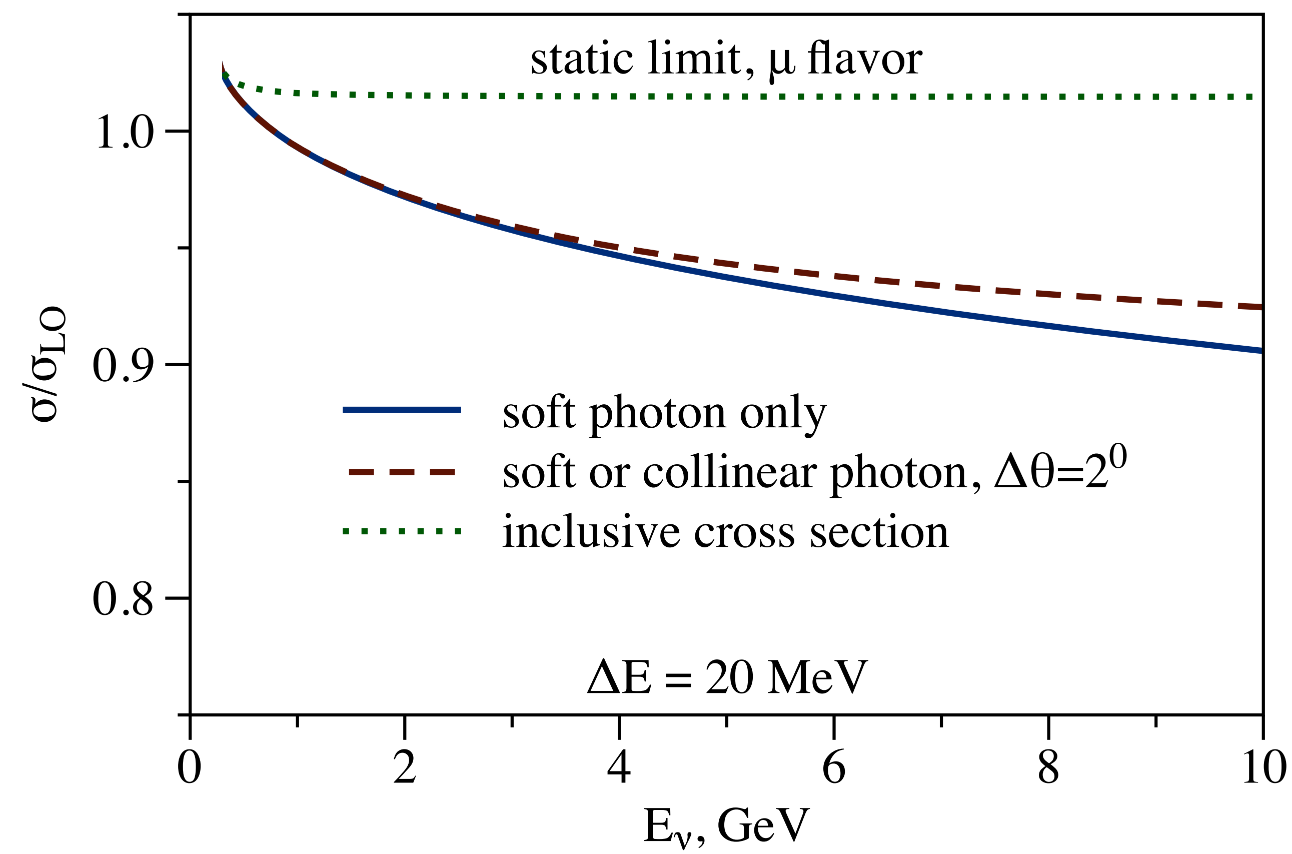
in exclusive and inclusive observables with GeV neutrino beams



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

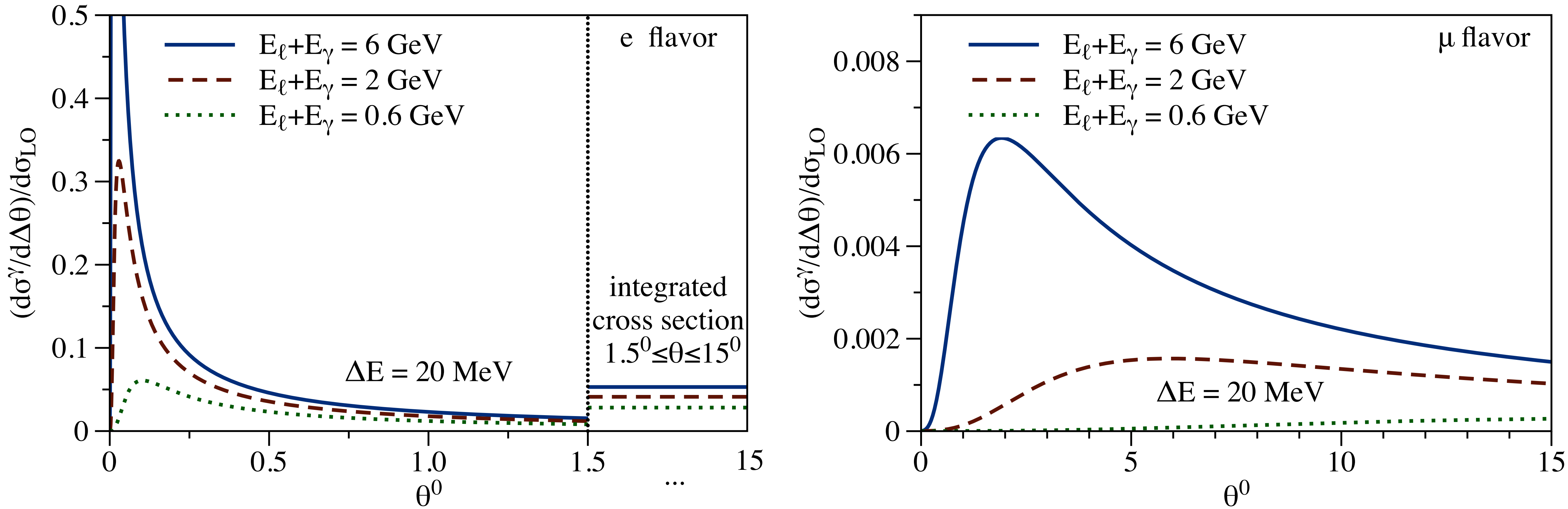




- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables (+γ): few % level, flavor independent

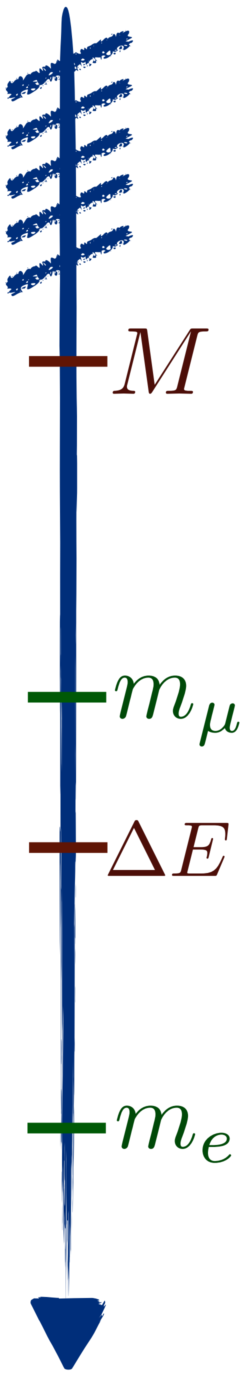
Electron vs muon jets

- 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 hadronic model to the theory with heavy nucleon

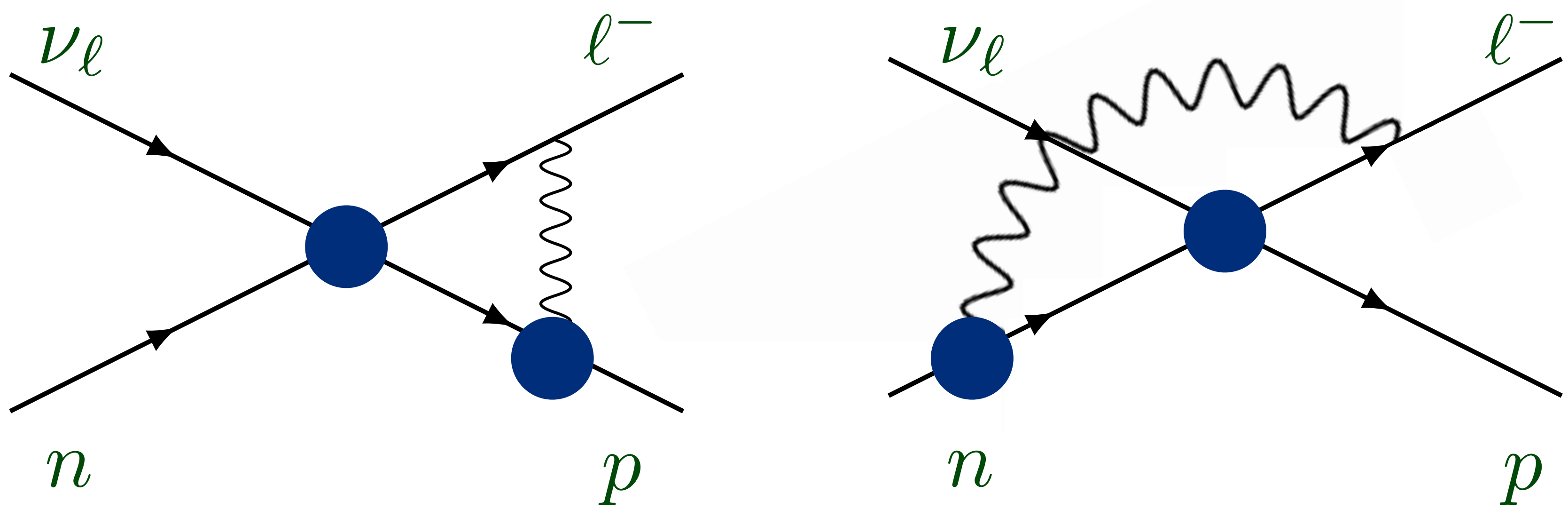
- soft and collinear functions are evaluated perturbatively

SCET power expansion parameter

$$\lambda \sim \frac{m_\mu^2}{E_\nu^2} \sim (\Delta\theta)^2 \sim \frac{\Delta E}{E_\nu}$$

$\ln\lambda$ enhancements

Hadronic model at GeV scale



- exchange of photon between the charged lepton and nucleons

- assume onshell form for each interaction with dipole form factors

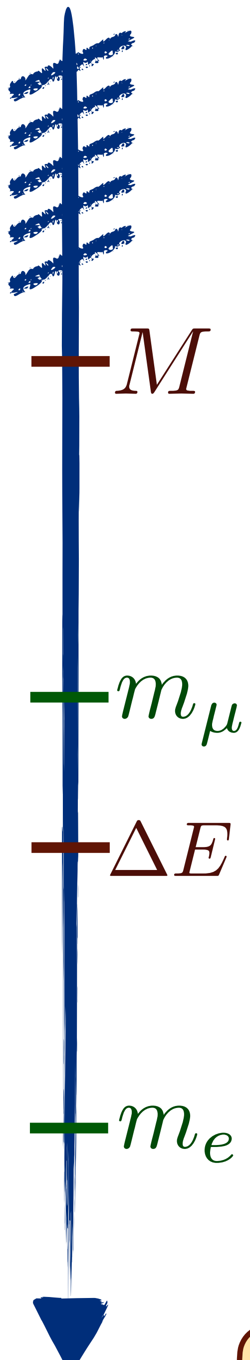
  discussed for neutrino-nucleon scattering: Graczyk, Phys. Lett. B 732, 315-319 (2013)

- 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

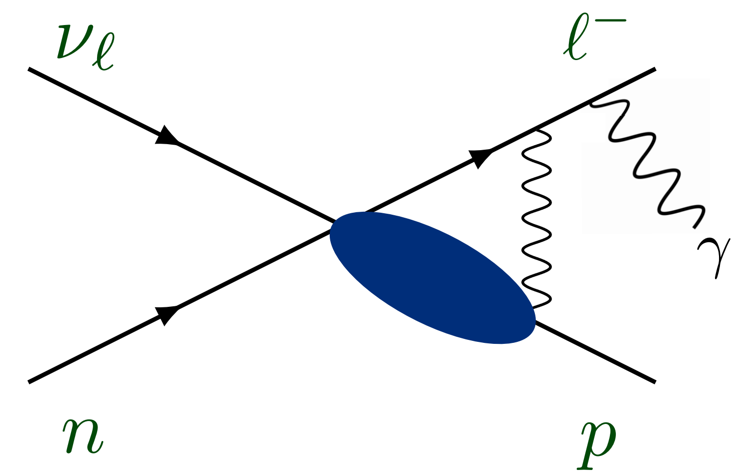
ep scattering with soft radiation only: Richard J. Hill, Phys. Rev. D 95 1, 013001 (2016)

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

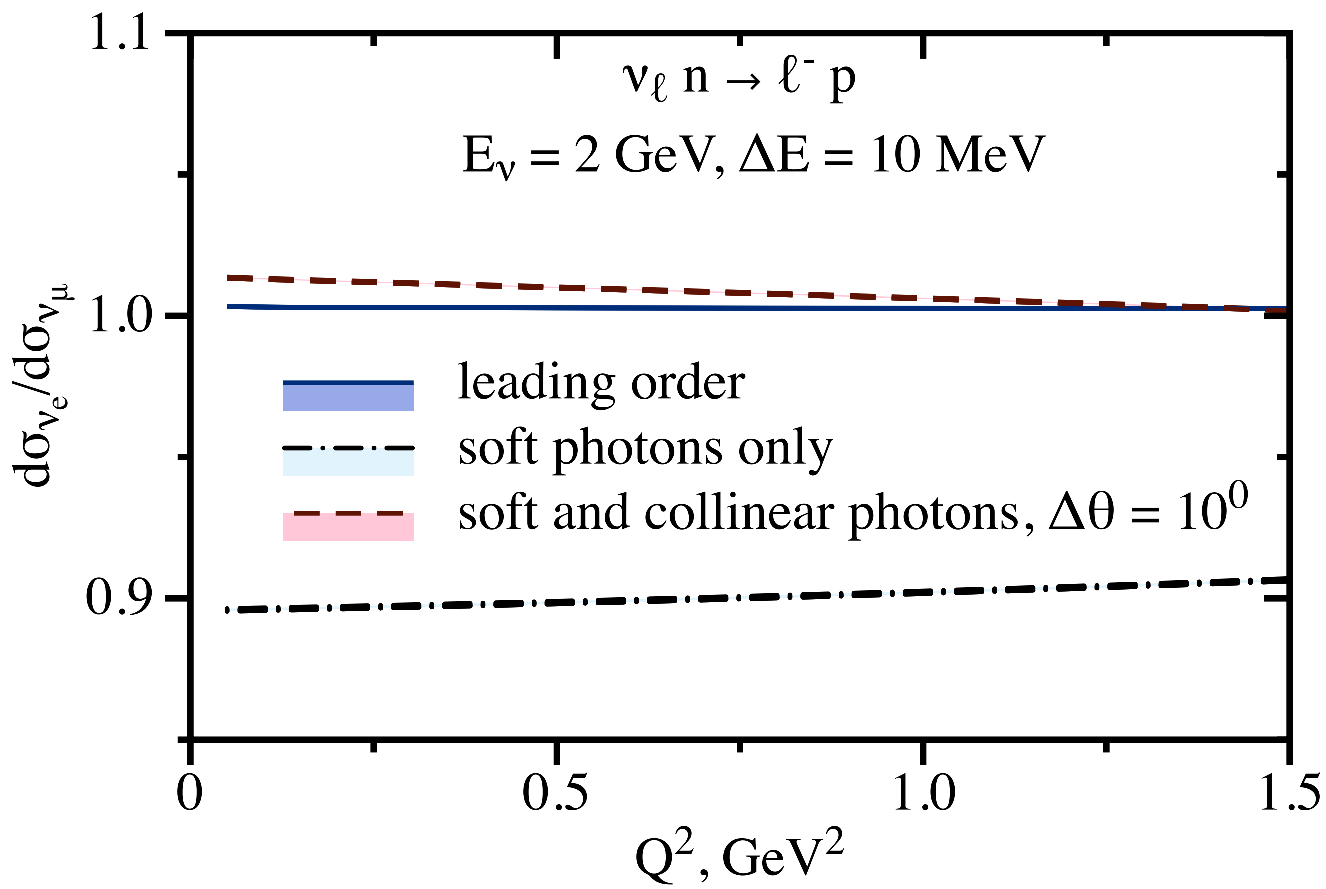
Charged-current scattering on nucleons

- theory and 1st-ever complete calculation
  10-20% hadronic uncertainties
  cancel for e/μ ratio

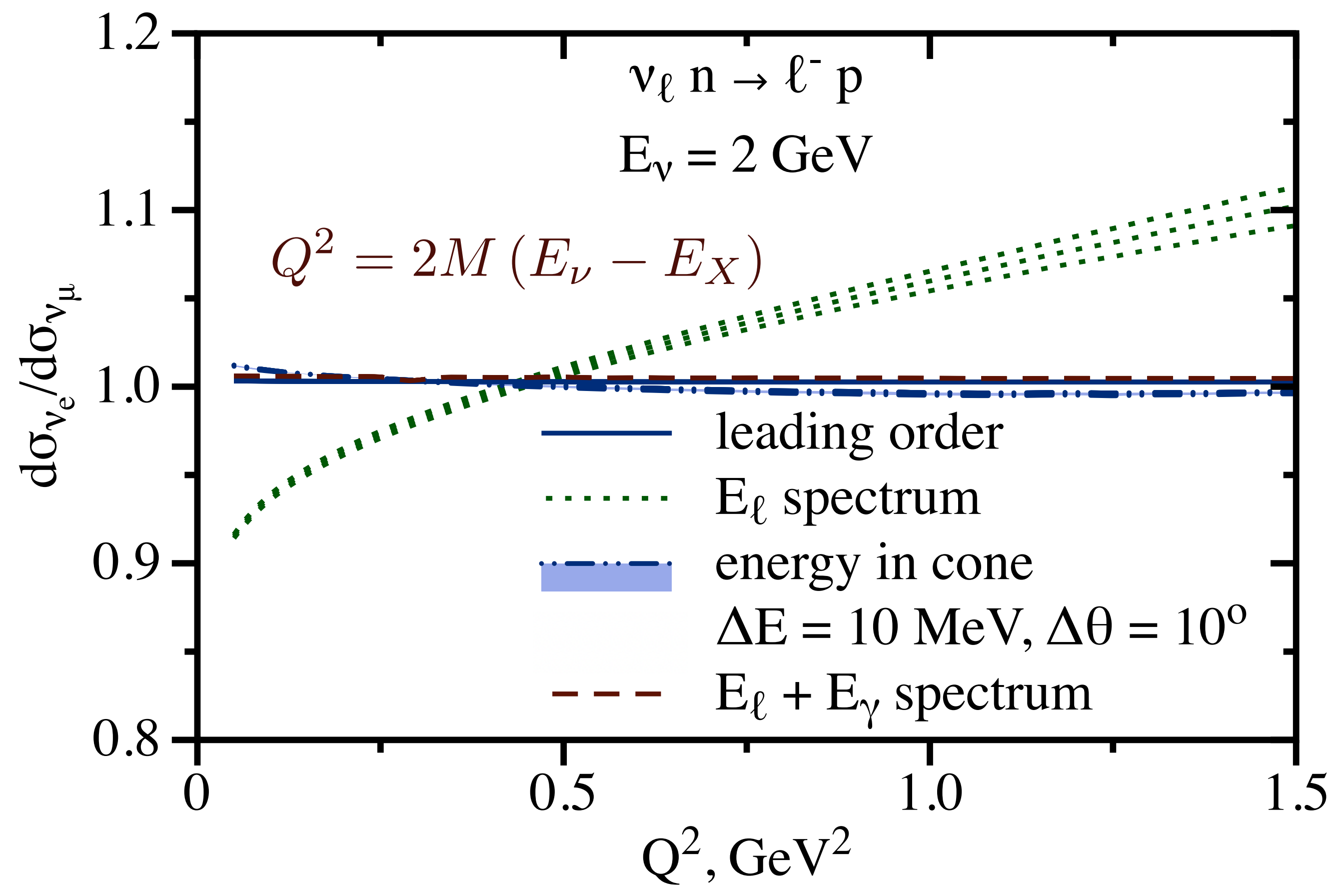
O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland, and Clarence Wret (2021, 2022)



exclusive



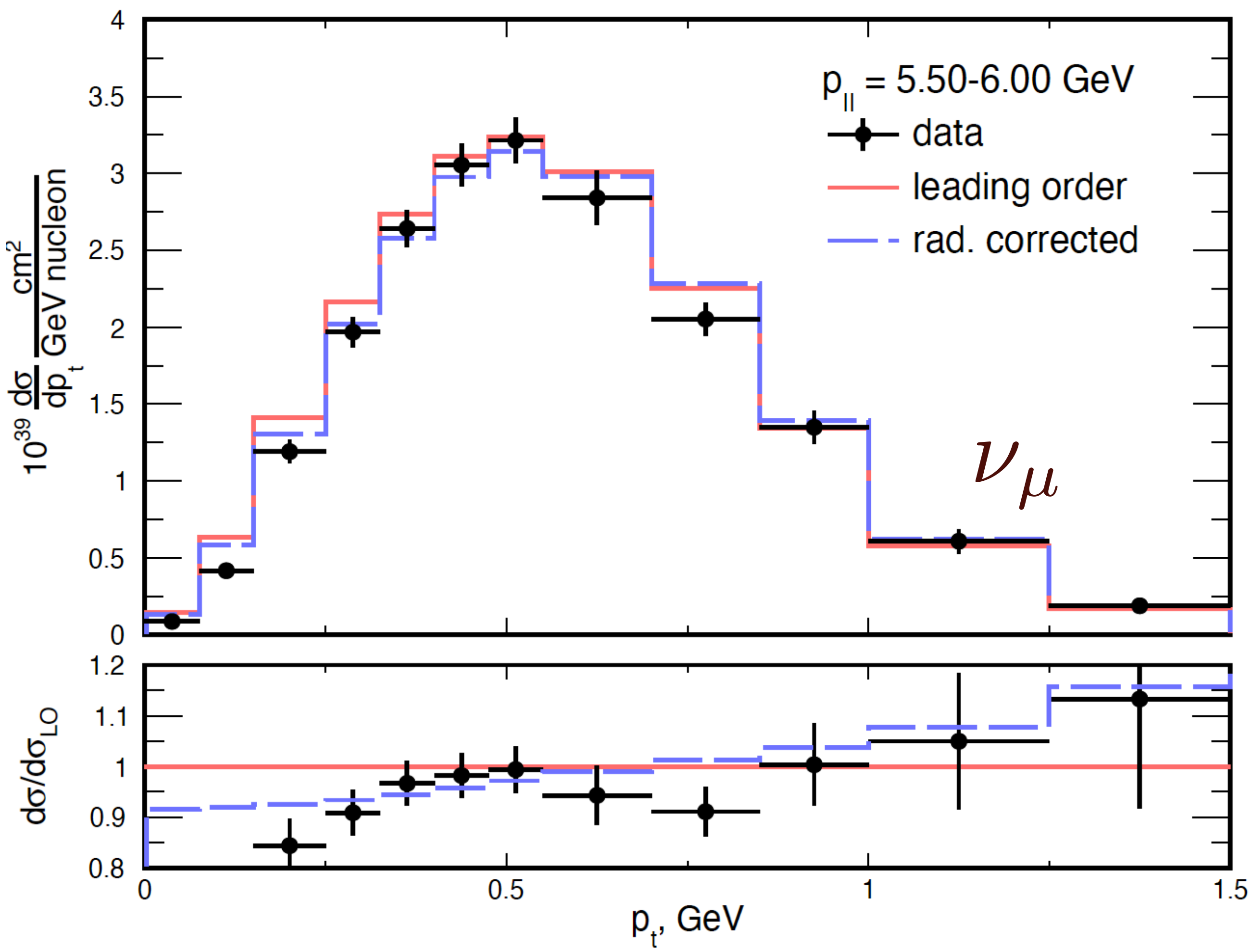
inclusive

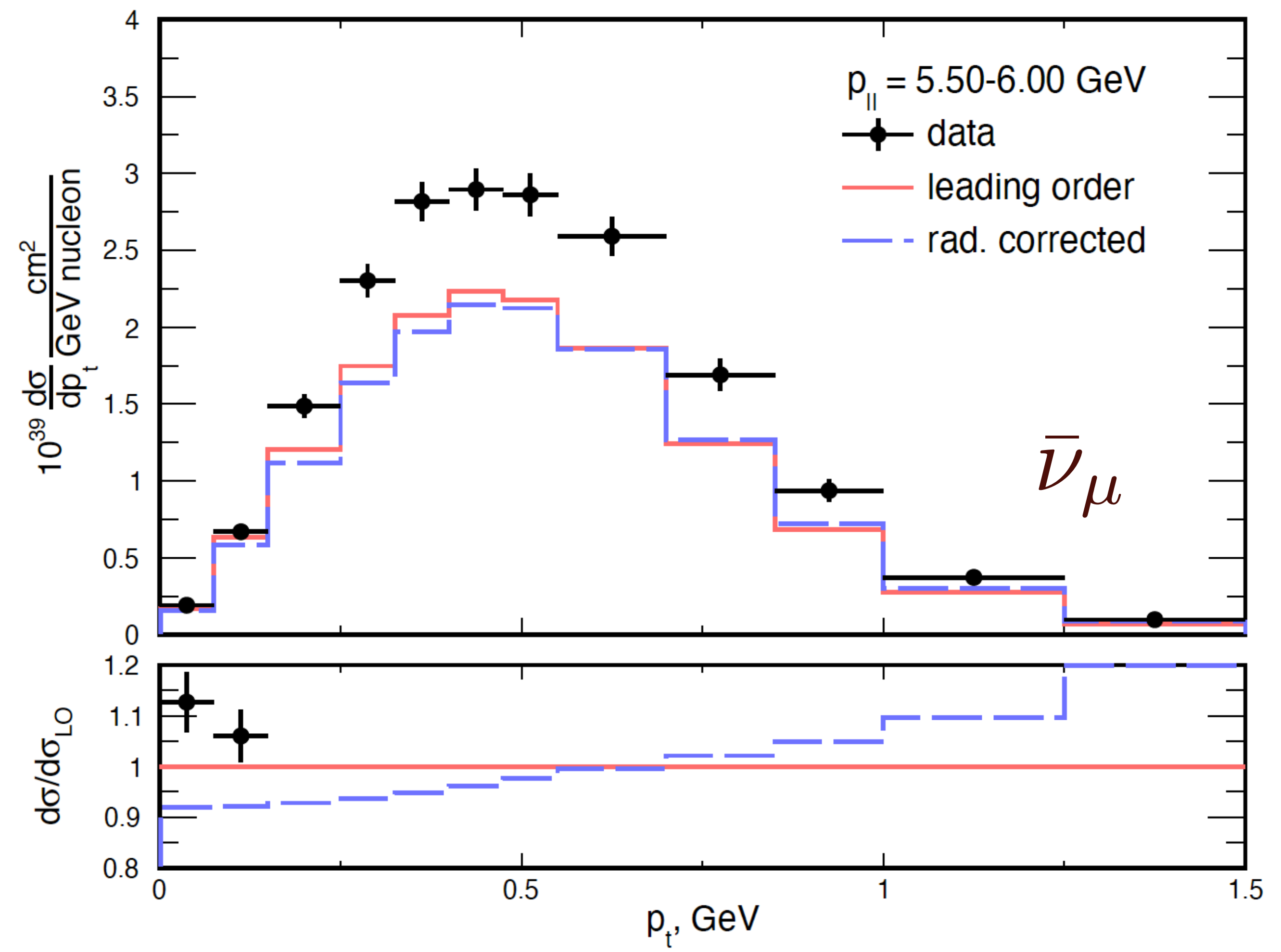


- critical dependence on details of experimental analysis
- predict σ_{ν_e} from σ_{ν_μ} measurements with neutrino beam ✓

Comparison to data

- medium-energy flux data from MINERvA@FERMILAB

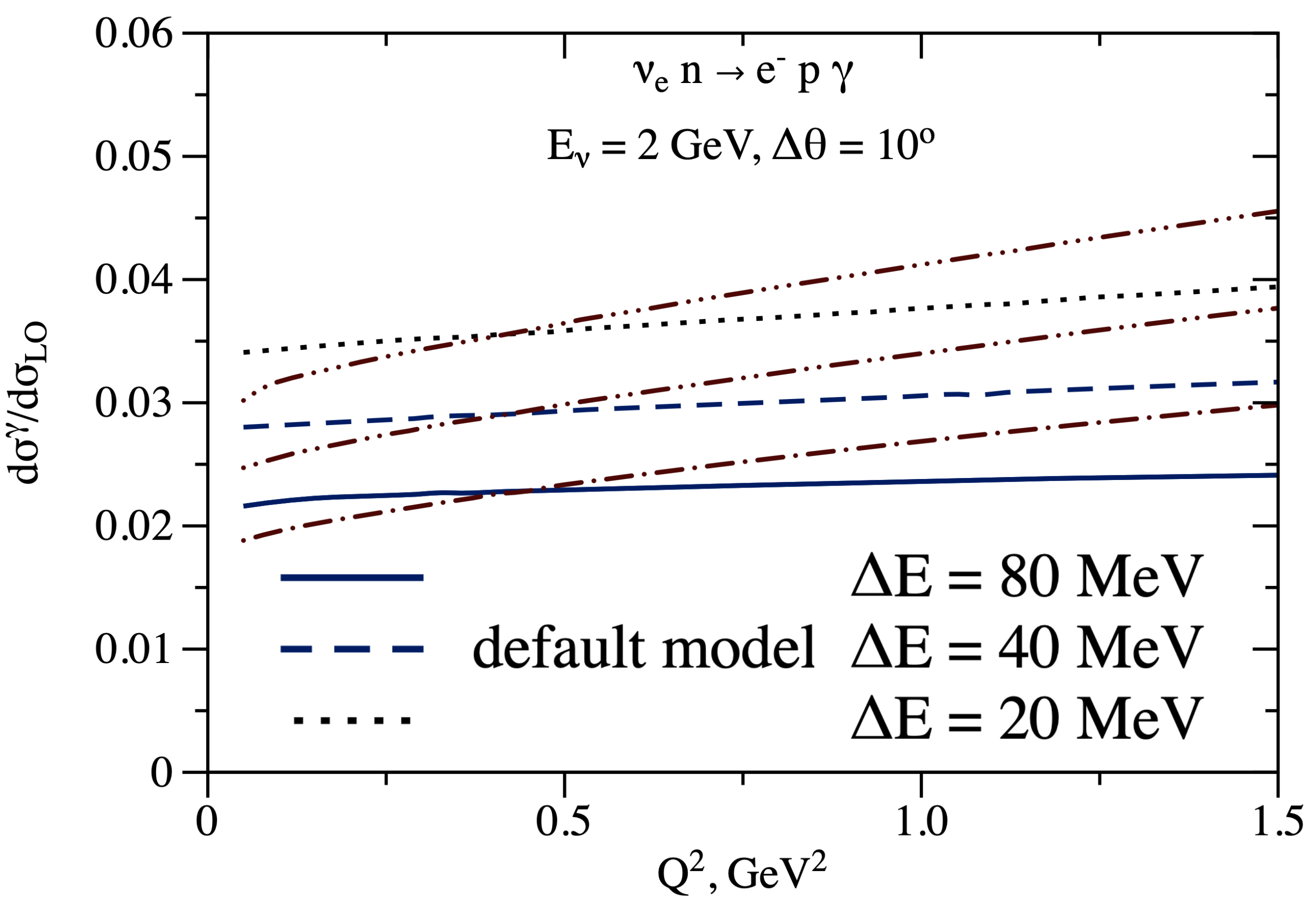


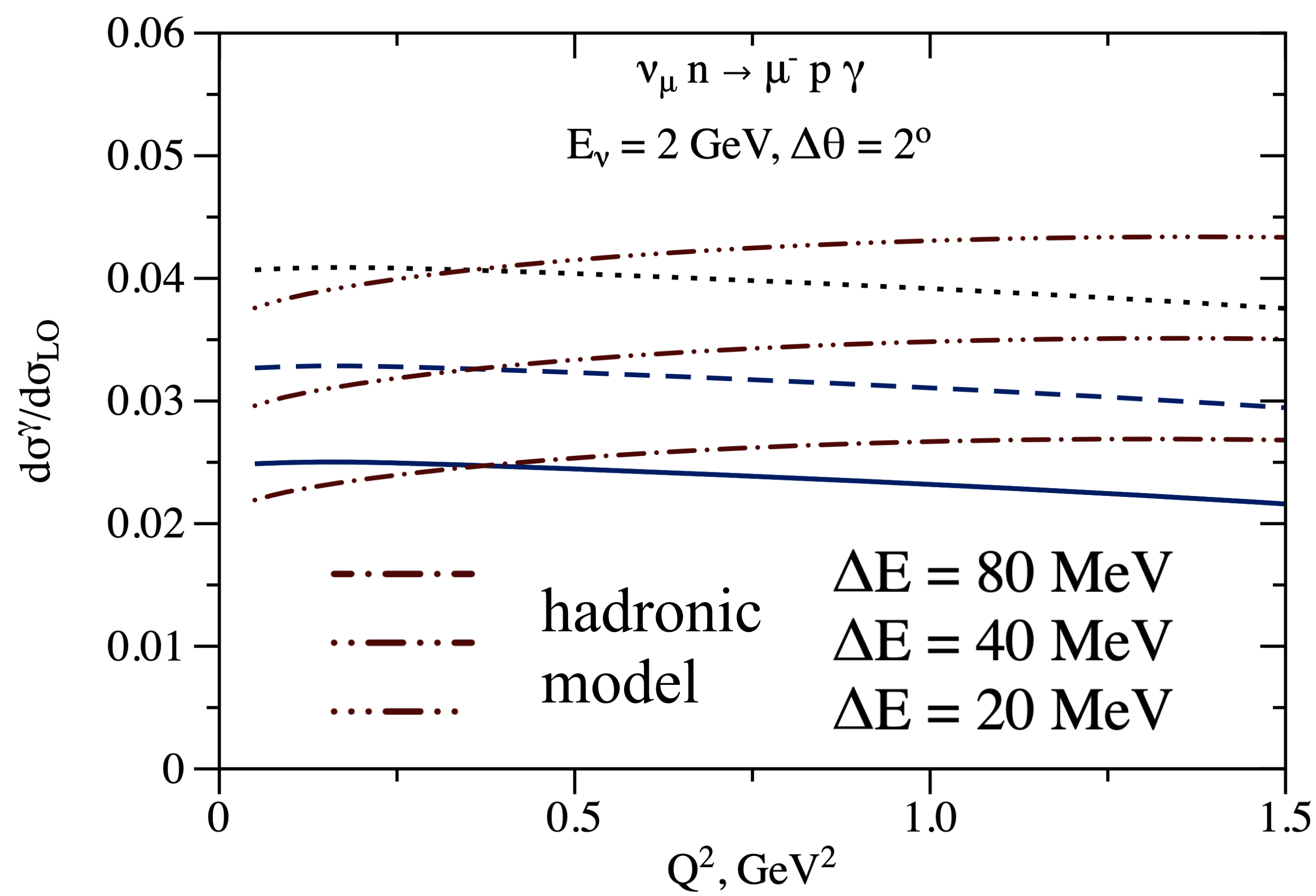


- electron flavor: measurements are uncertain
- muon flavor: comparable to experimental precision

Radiation of hard photons

- model-dependent description for radiation of hard photons





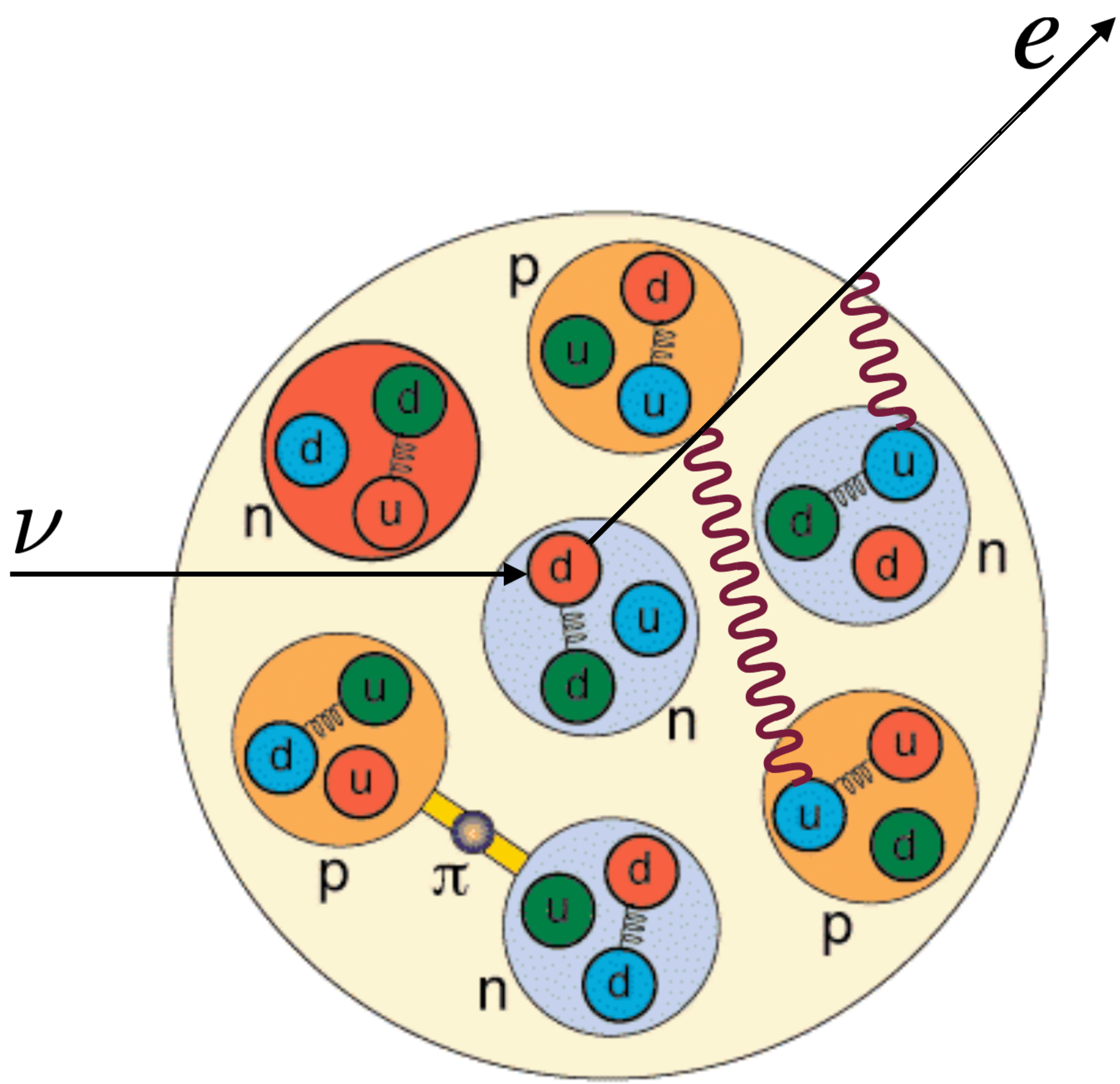
"Blunden calculation"

- photon energies are above 20, 40, and 80 MeV: default vs "SIFF"

"hadronic model"

- %-level radiation of non-collinear hard photons
- 10^{-4} flavor misidentification rate for NOvA&T2K kinematics

QED medium effects



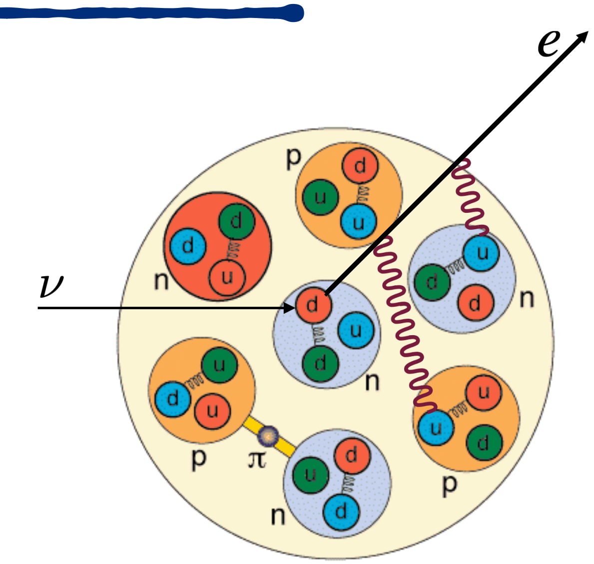
- charged lepton exchanges photons with nuclear medium

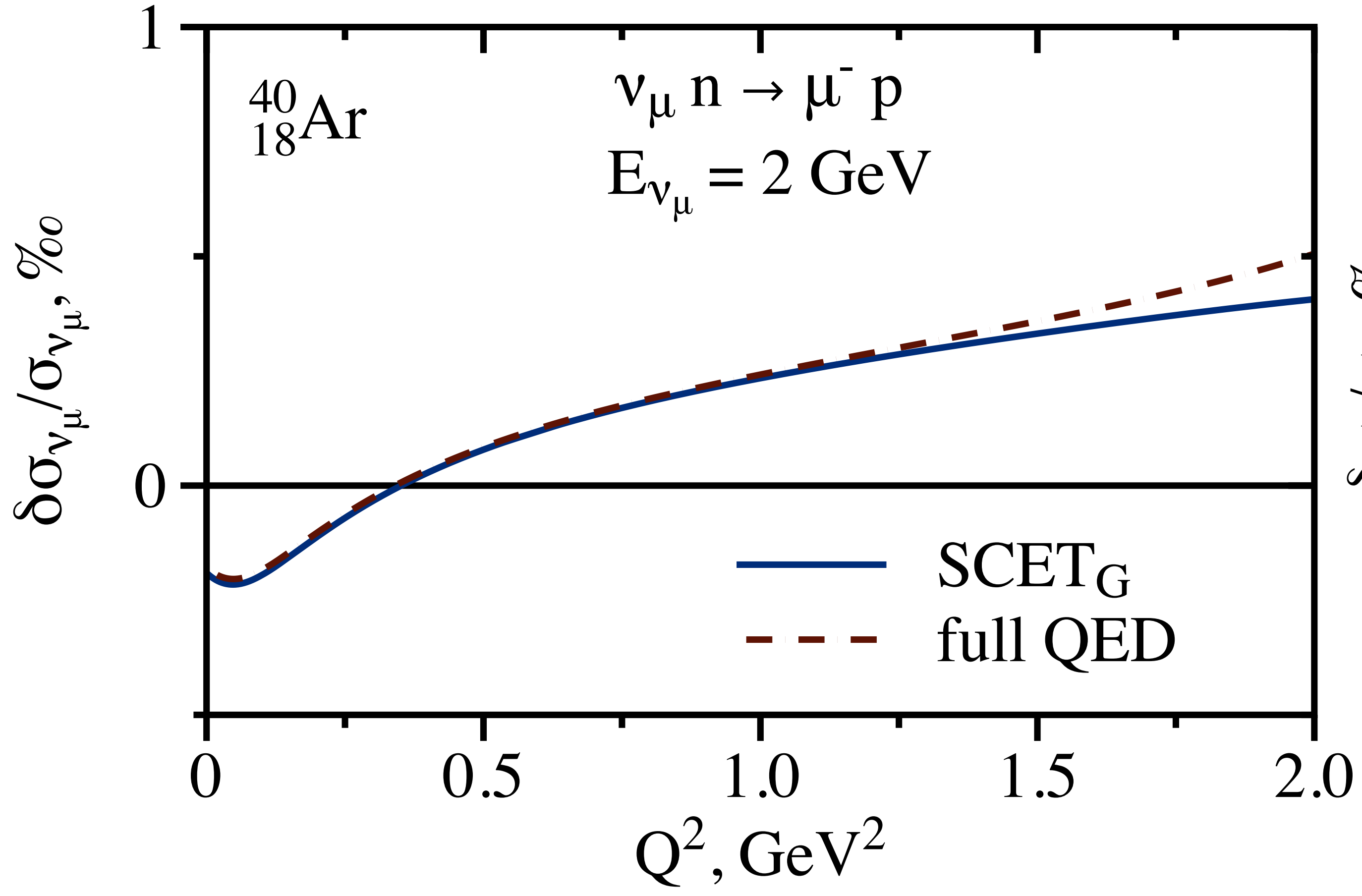
QED nuclear medium effects

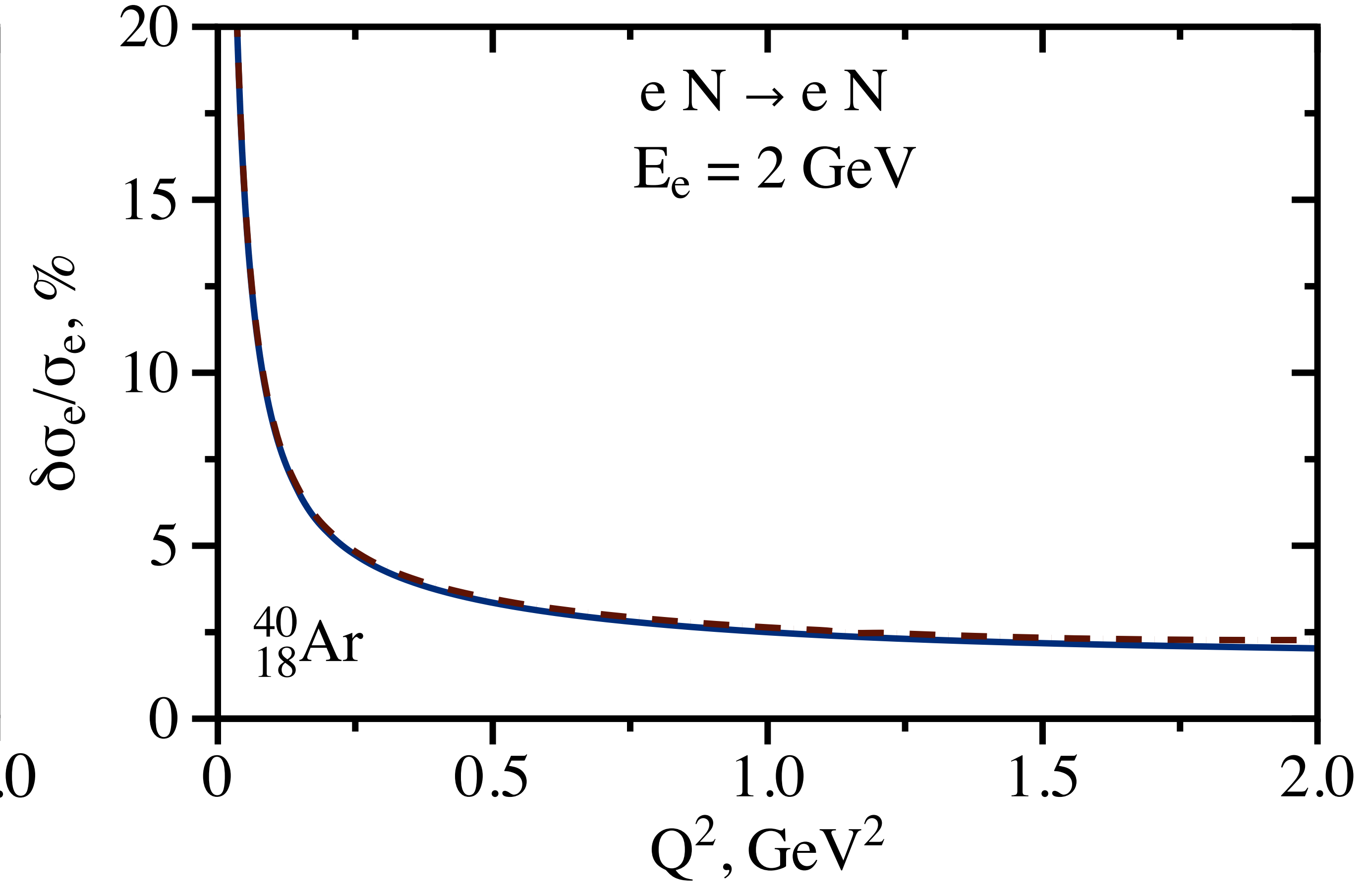
- theory and 1st-ever estimate by two methods:

SCET$_G$: Soft-collinear effective theory (Glauber)
QED: quantum electrodynamics

O. T. and Ivan Vitev, Phys. Lett. B 805, 135466 (2022)







- permille-level for ν_e A -> eA', percent-level for eA -> eA
- critical new effect for electron scattering experiments

Conclusions

- neutrino cross sections is the main tool to access neutrinos
- various production and interaction mechanisms at all energy scales
- radiative corrections (1-20%) for consistent uncertainty estimates
- radiative corrections for precise flux determinations
- QED nuclear effects in neutrino and electron scattering
- total and differential νe, $\nu_\ell n \to \ell^- p$ and $\bar{\nu}_\ell p \to \ell^+ n$
  flavor ratios evaluated from theory with rigorous error analysis

Thanks for your attention !!!