University of Washington
Institute for Nuclear Theory

19 January, 2023

Radiative corrections in neutrino physics

Los Alamos NATIONAL LABORATORY

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LA-UR-23-20009

Questions in neutrino physics

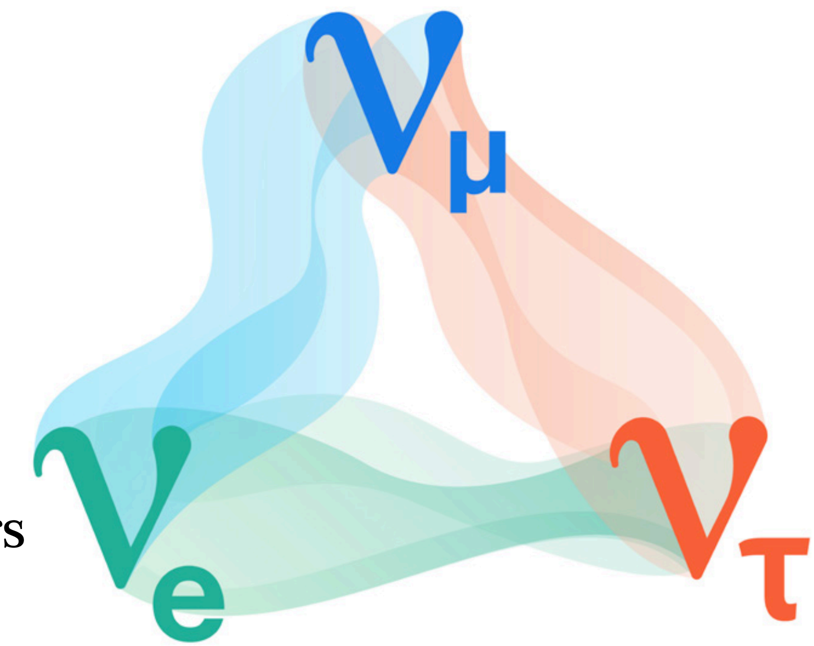
number of species

are there sterile neutrinos?

PMNS matrix

CP violation in lepton sector

precise values of oscillation parameters



neutrino masses

Dirac vs Majorana

hierarchy of masses

absolute values

Astrophysics and Cosmology

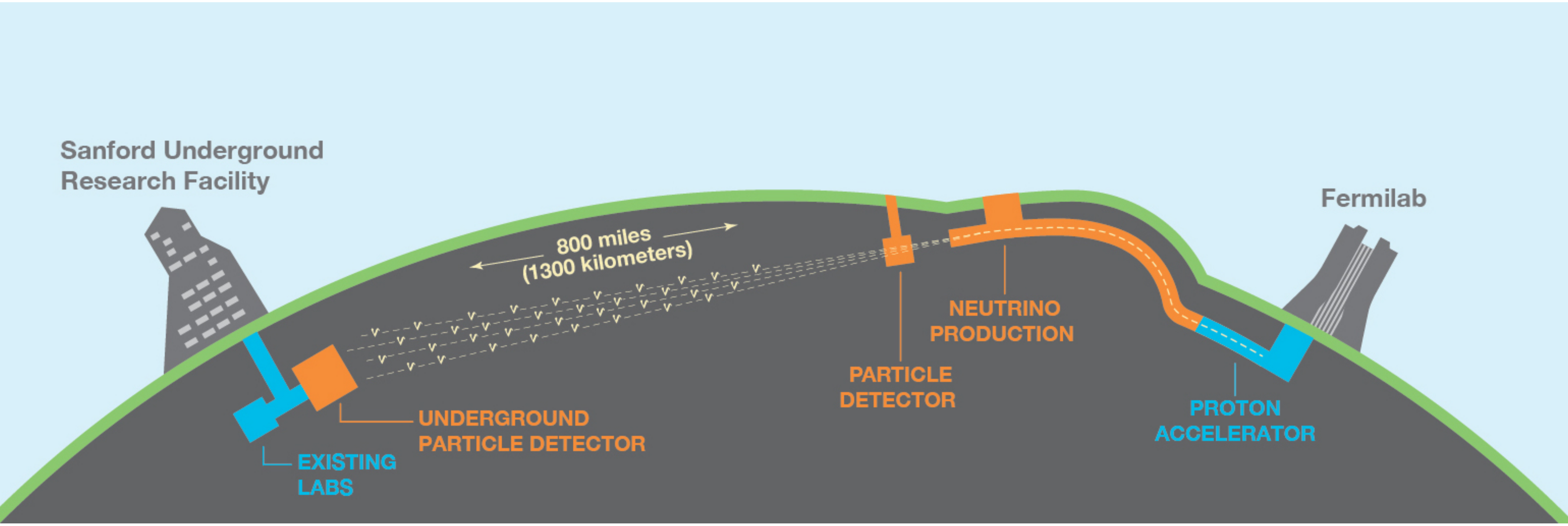
cosmic neutrinos

neutrinos as part of dark matter

detection of Big Bang relic neutrinos

Neutrino experiments

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

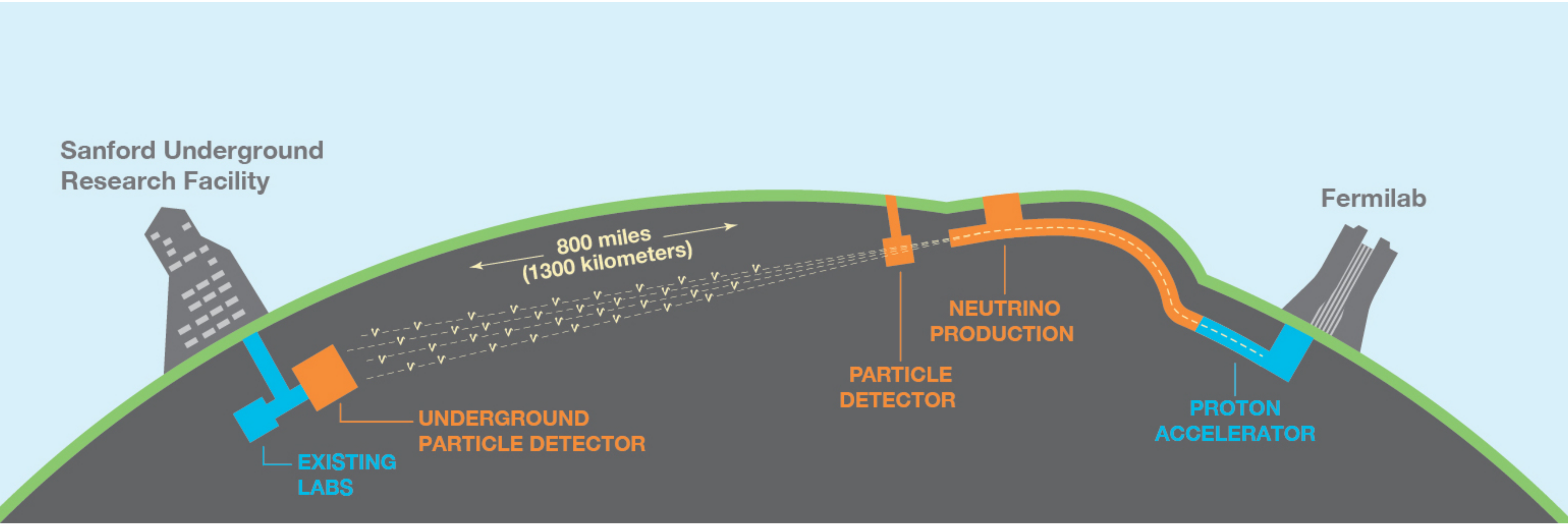


- origin of matter-antimatter asymmetry δ_{CP}
- mass hierarchy and oscillation parameters PMNS matrix, Δm_{31}^2
- Grand Unified Theories proton decay
- dynamics of supernova explosion wait for one;)

 DUNE, CDR (2016), TDR (2020)

Neutrino experiments

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



- measurement of $\nu_\mu(\overline{\nu}_\mu)$ 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) neutrino sources across energy scales

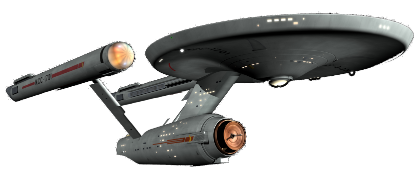
2) cross sections on electrons, nucleons, and nuclei

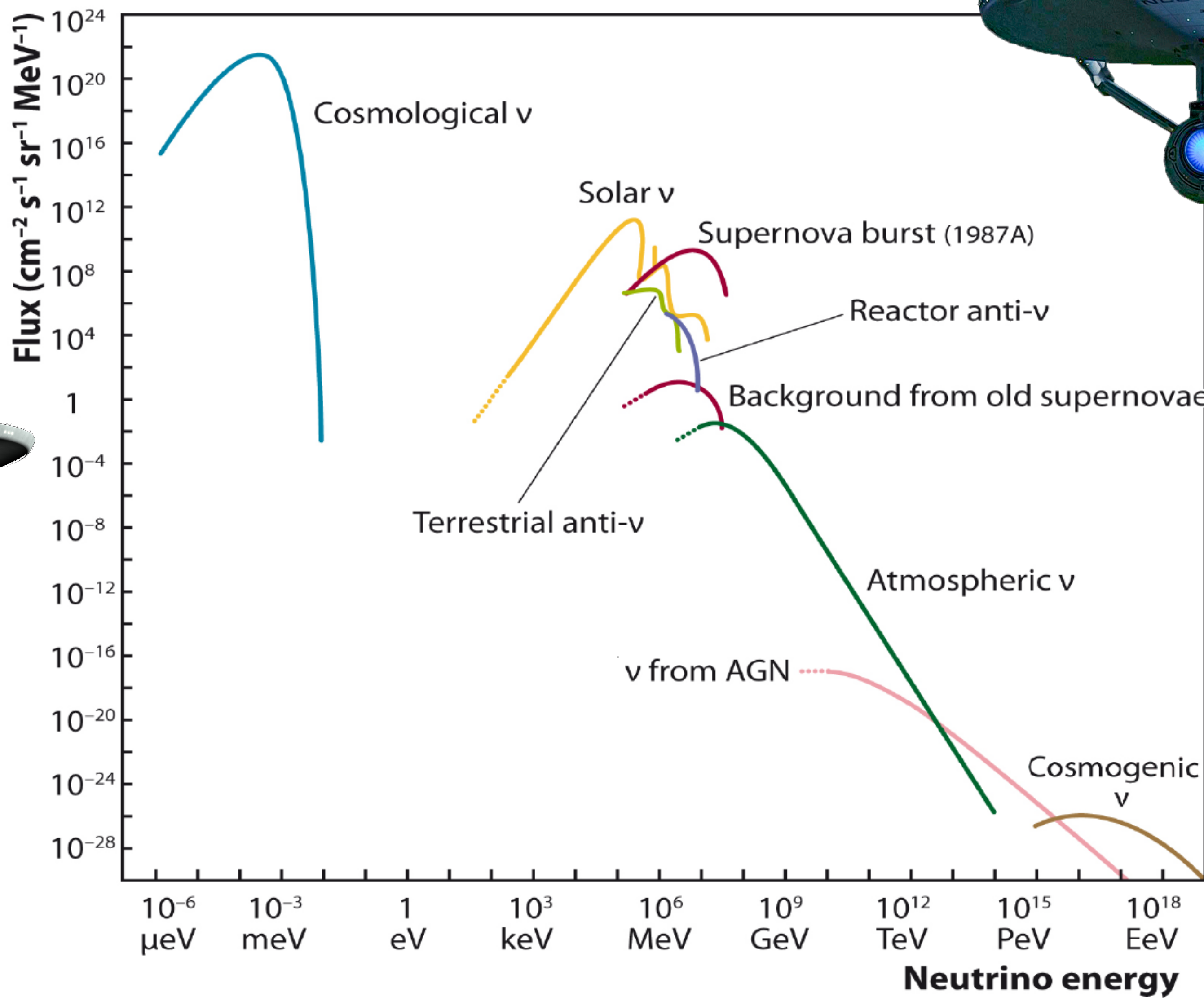
3) radiative corrections in neutrino physics

4) charged-current scattering on nucleons

Neutrino interactions across energy scales

Nature sources

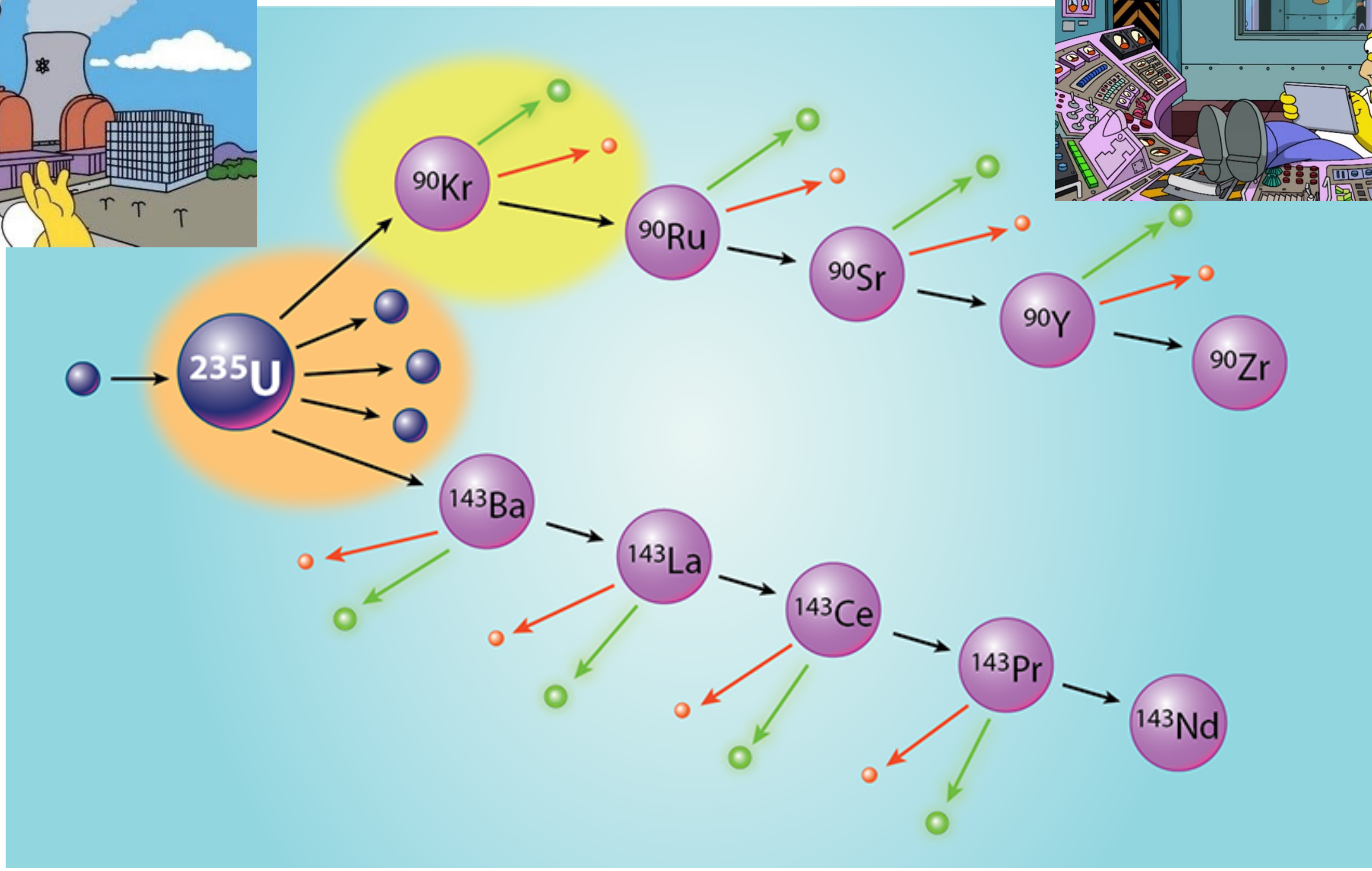


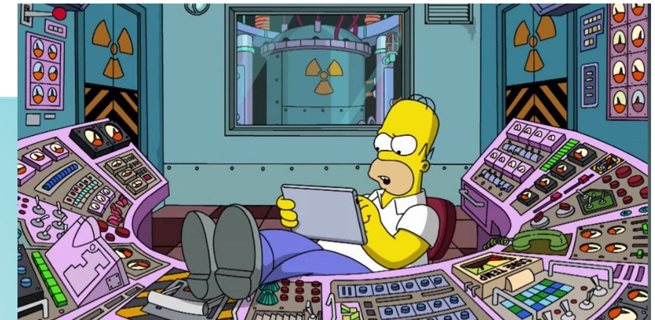


U.F. Katz, Ch. Spiering, Prog. Part. Nucl. Phys. 67, 651-704 (2012)

- cosmological, cosmogenic, supernova background: to be detected

Reactor (anti)neutrinos





A. Bernstein, N. Bowden, B.L. Goldblum, P. Huber,
I. Jovanovic, J. Mattingly, Rev. Mod. Phys. 92, 011003 (2020)

- first detected neutrinos; antineutrinos from nuclear beta decays

Artificial neutrinos: accelerator

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

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

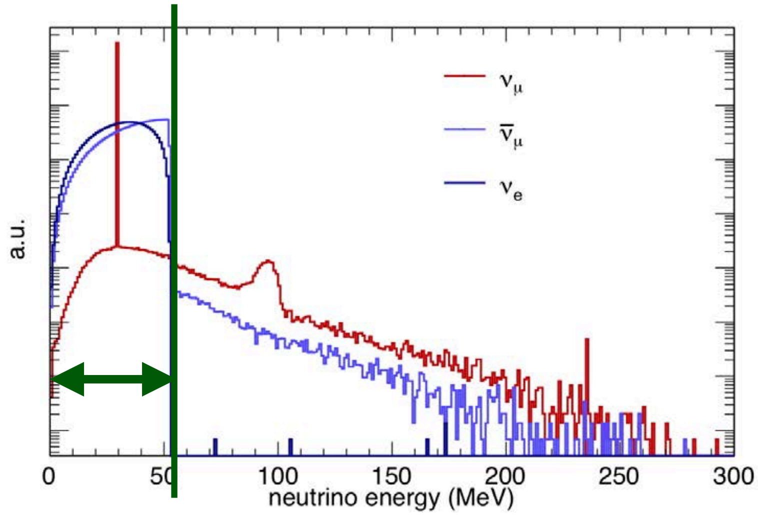
$K^+ \to \mu^+ \nu_\mu$

decay at rest

$K^+ \to \pi^0 e^+ \nu_e$ $\quad K_L^0 \to \pi^\pm e^\mp \nu_e$

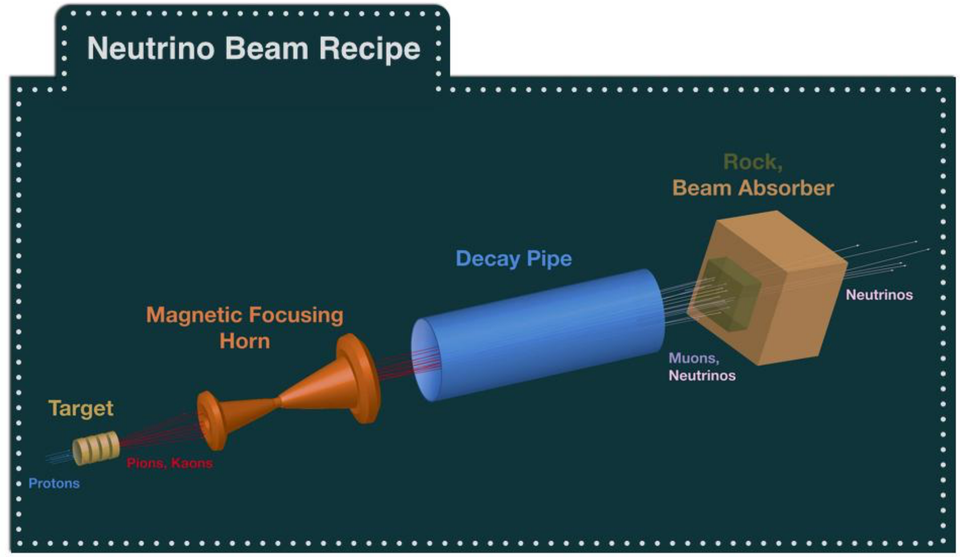
$K^+ \to \pi^0 \mu^+ \nu_\mu$ $\quad K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$

decay in flight



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

Coherent and CCM

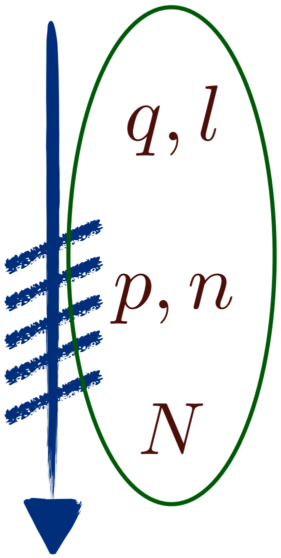


www.fnal.gov

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

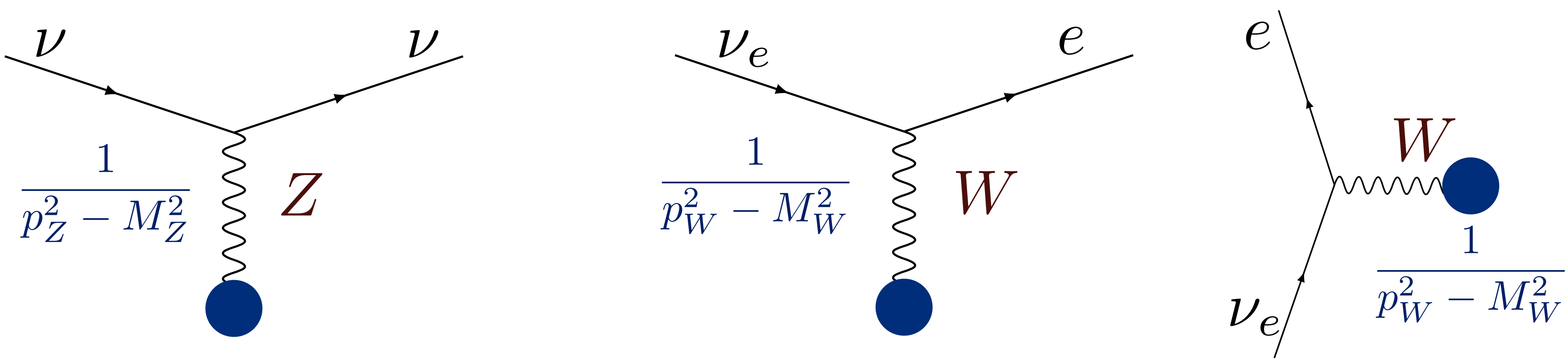
Neutral- and charged-current processes

- 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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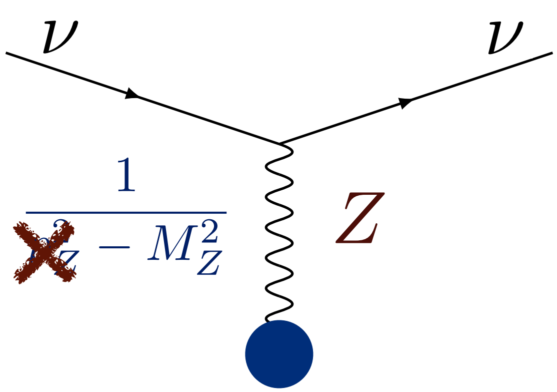
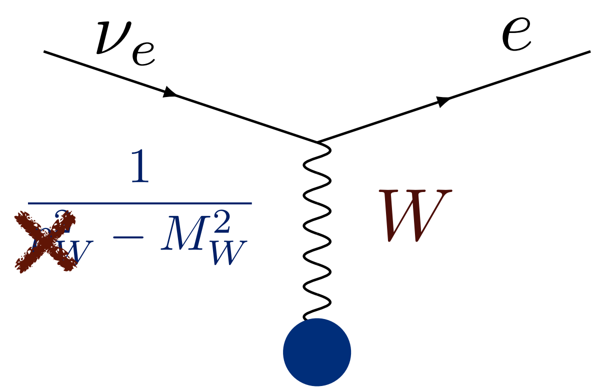
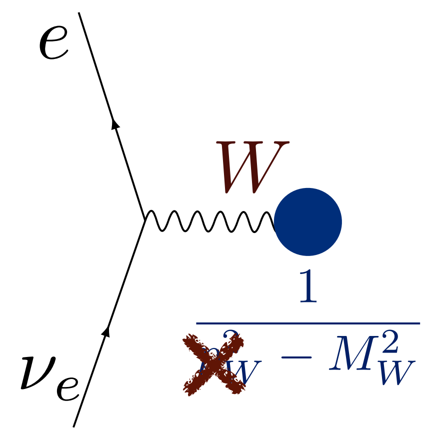
neutral current



charged current





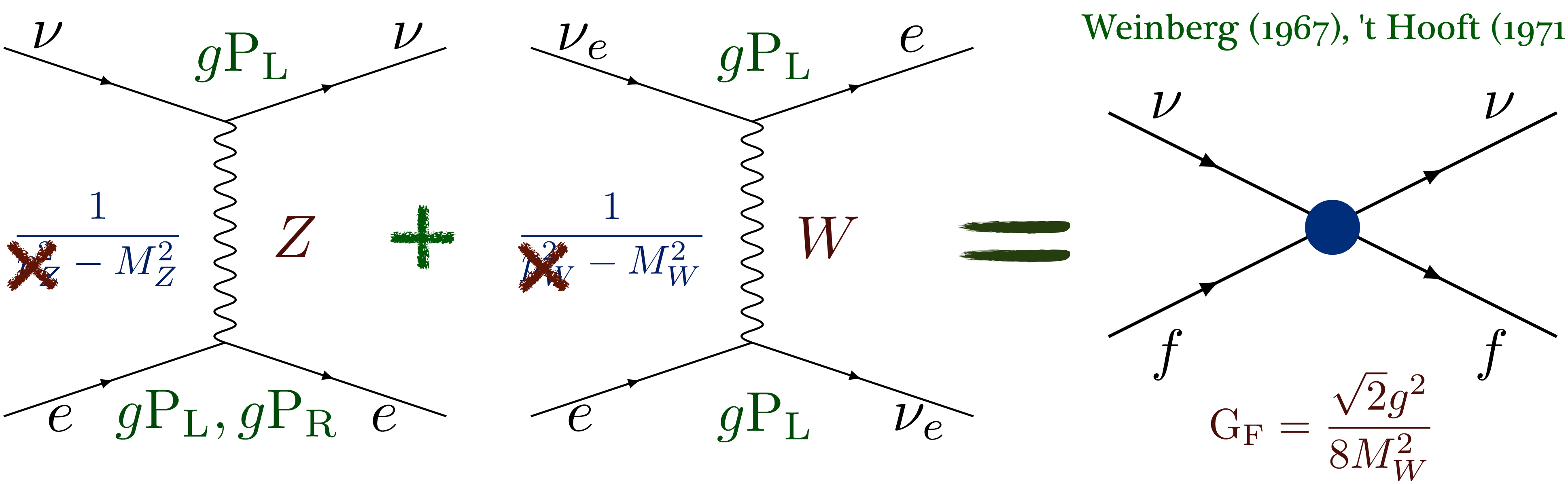
- contact interactions at GeV energy scale and below

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

Neutrino-electron scattering

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

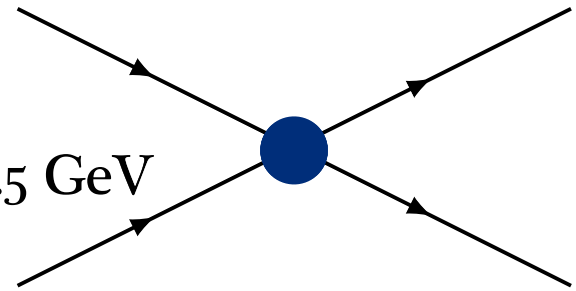
neutral current | charged current



- 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)

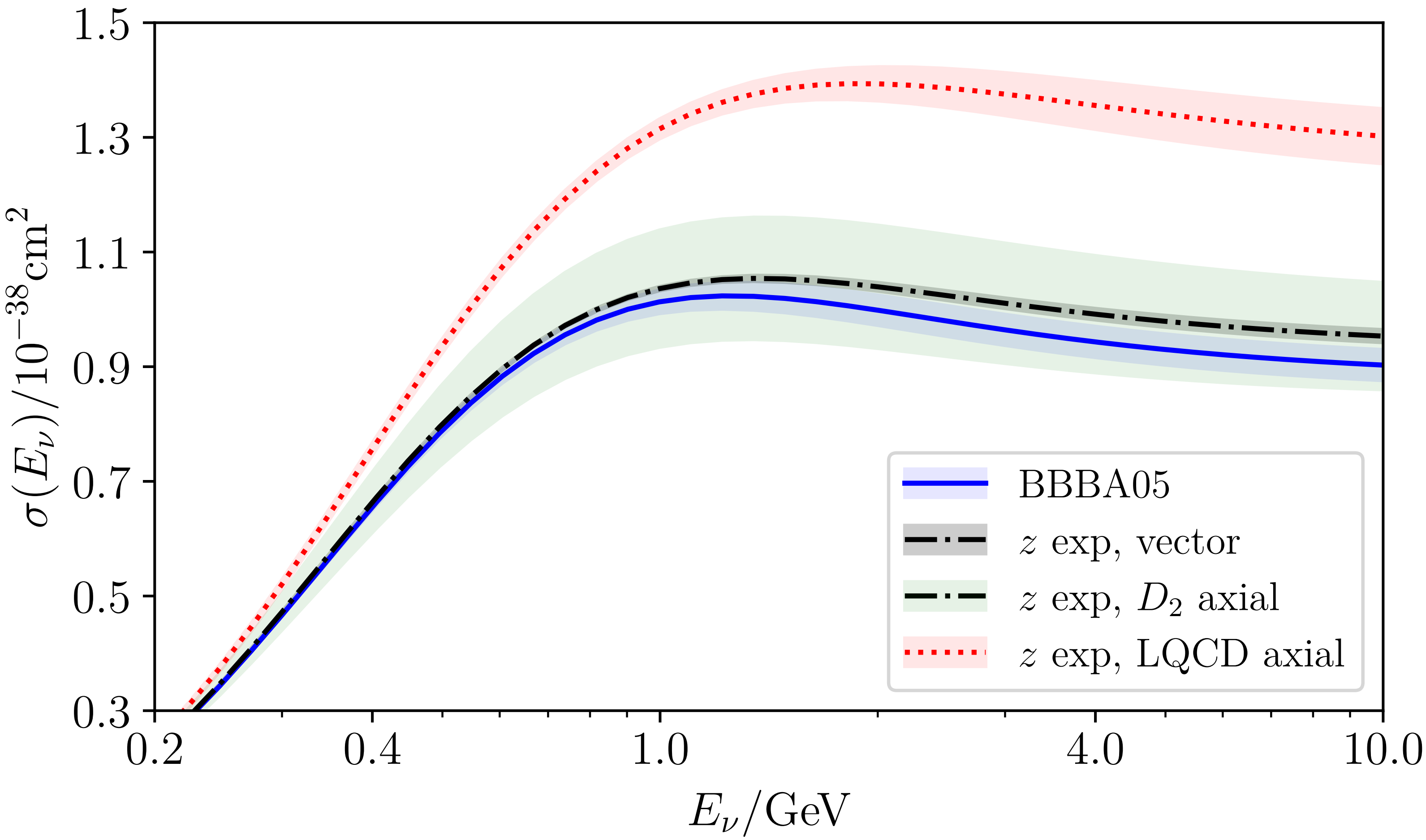


- 4-Fermi theory + ChPT @ and < pion-mass scale
- production thresholds: muon ~ 110 MeV, tau ~ 3.5 GeV
- only electron flavor for supernova, solar, and reactor neutrinos
- data from deuterium bubble chambers in 1980th
- CH2-C subtraction results are anticipated
- provide nucleon axial form factor
- target for many lattice QCD groups

Fermilab bubble chamber, Richard Drew

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

Neutrino-nucleon scattering (CC)

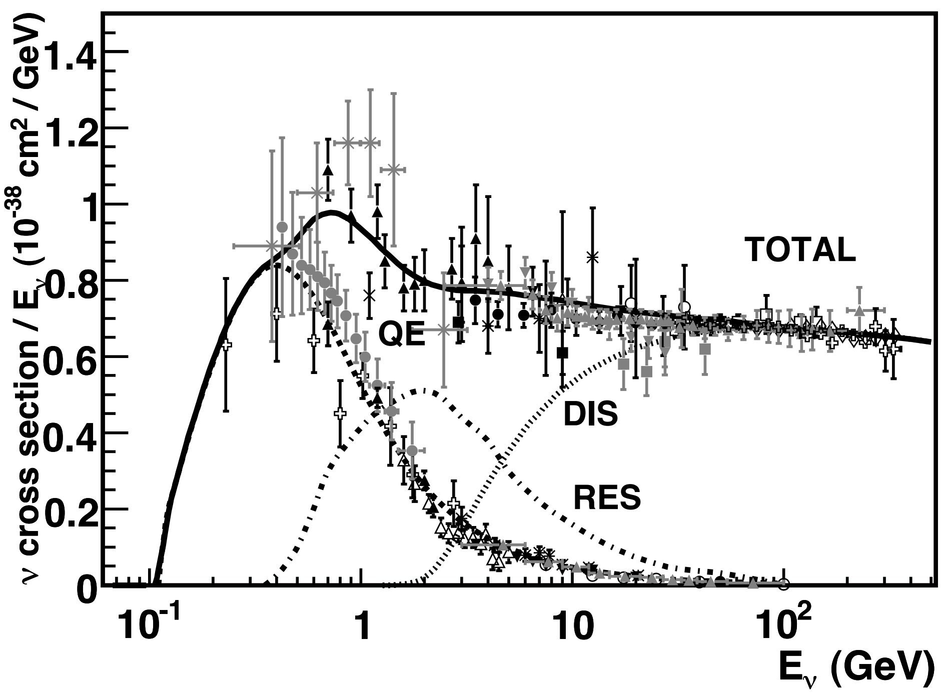


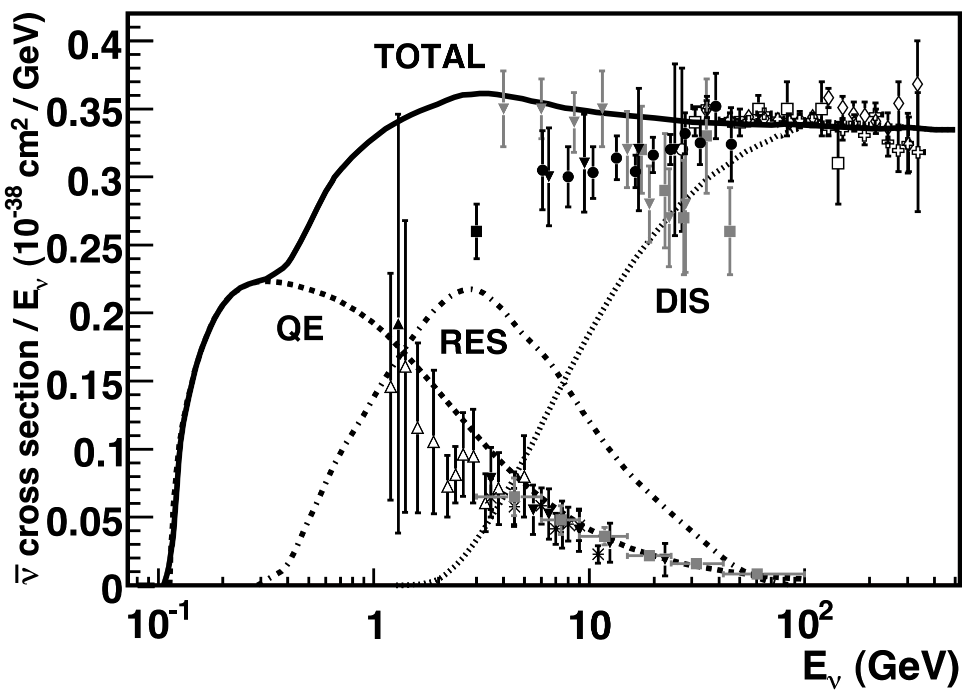
A.S. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. of 72, 010622-120608 (2022)
A.S. Meyer, M. Betancourt, R. Gran, and R.J. Hill, PRD (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill, and O. T. , PRD (2021)

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

Neutrino-nucleus scattering

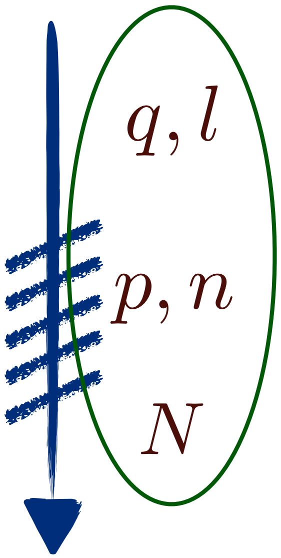
- NC scattering across all energies -> neutrino floor
- CC with electron flavor for supernova, solar, and reactor neutrinos
- same open channels as at nucleon level





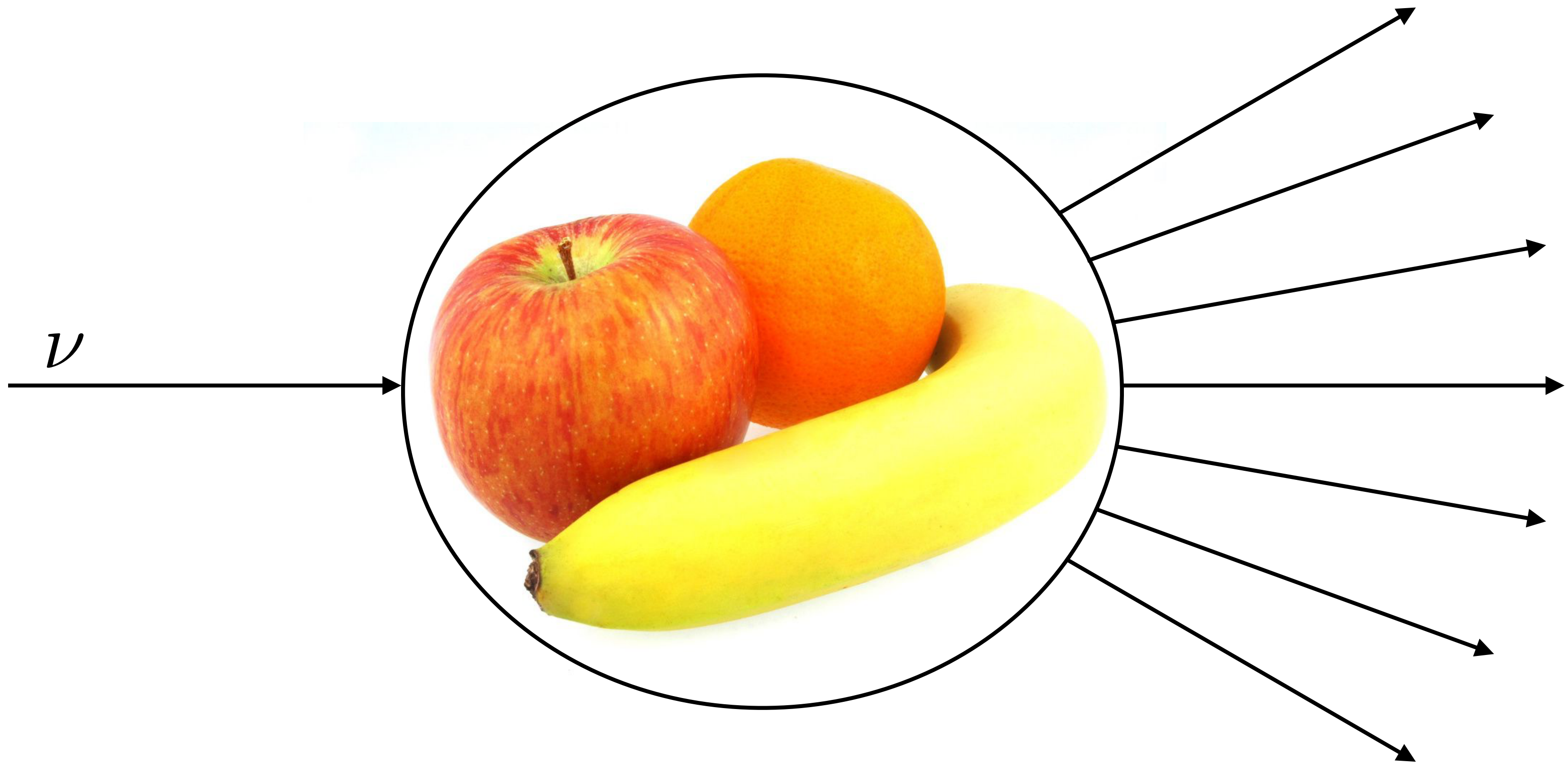
Formaggio and Zeller (2013)

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

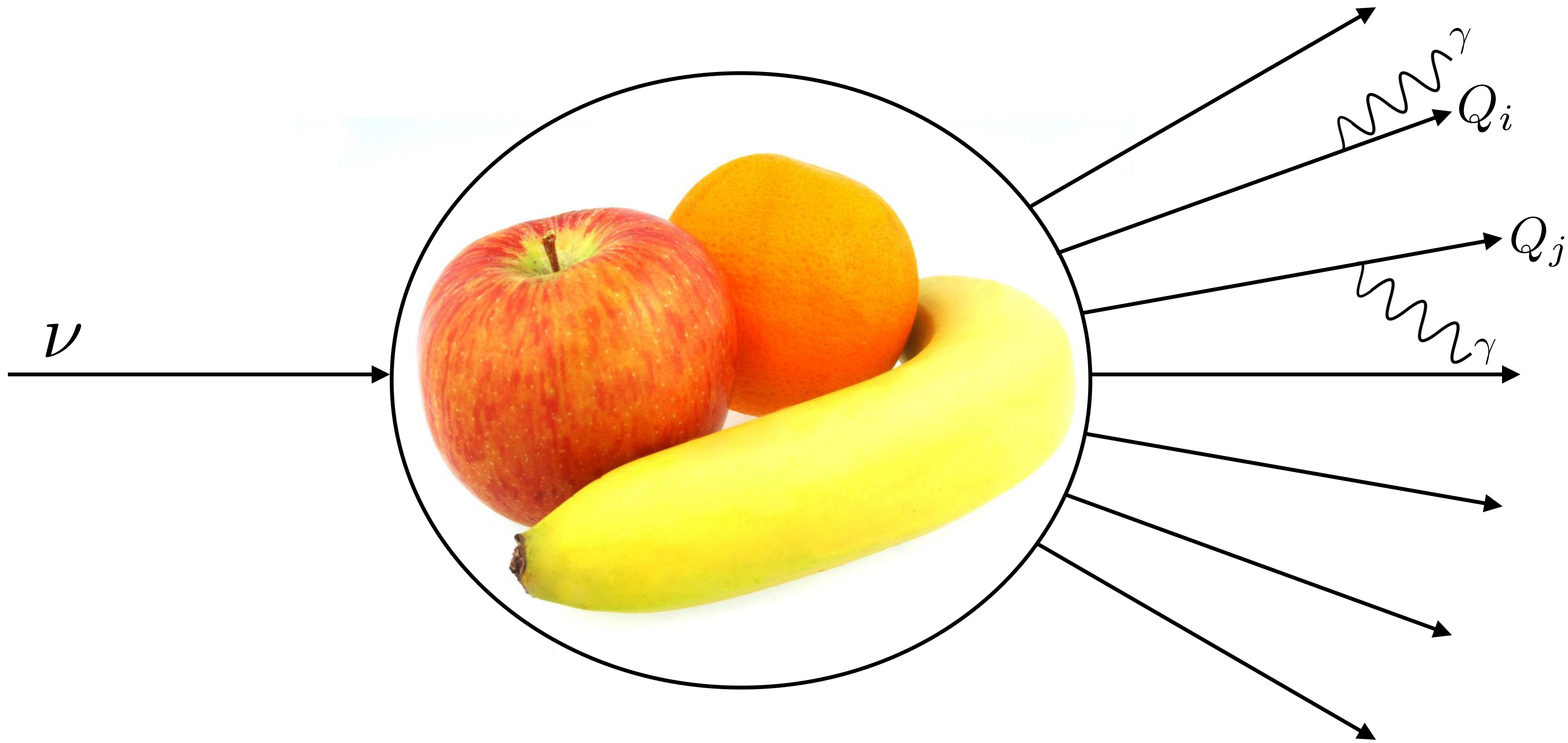


Radiative corrections in neutrino physics (at MeV-GeV energies)

Neutrino interactions

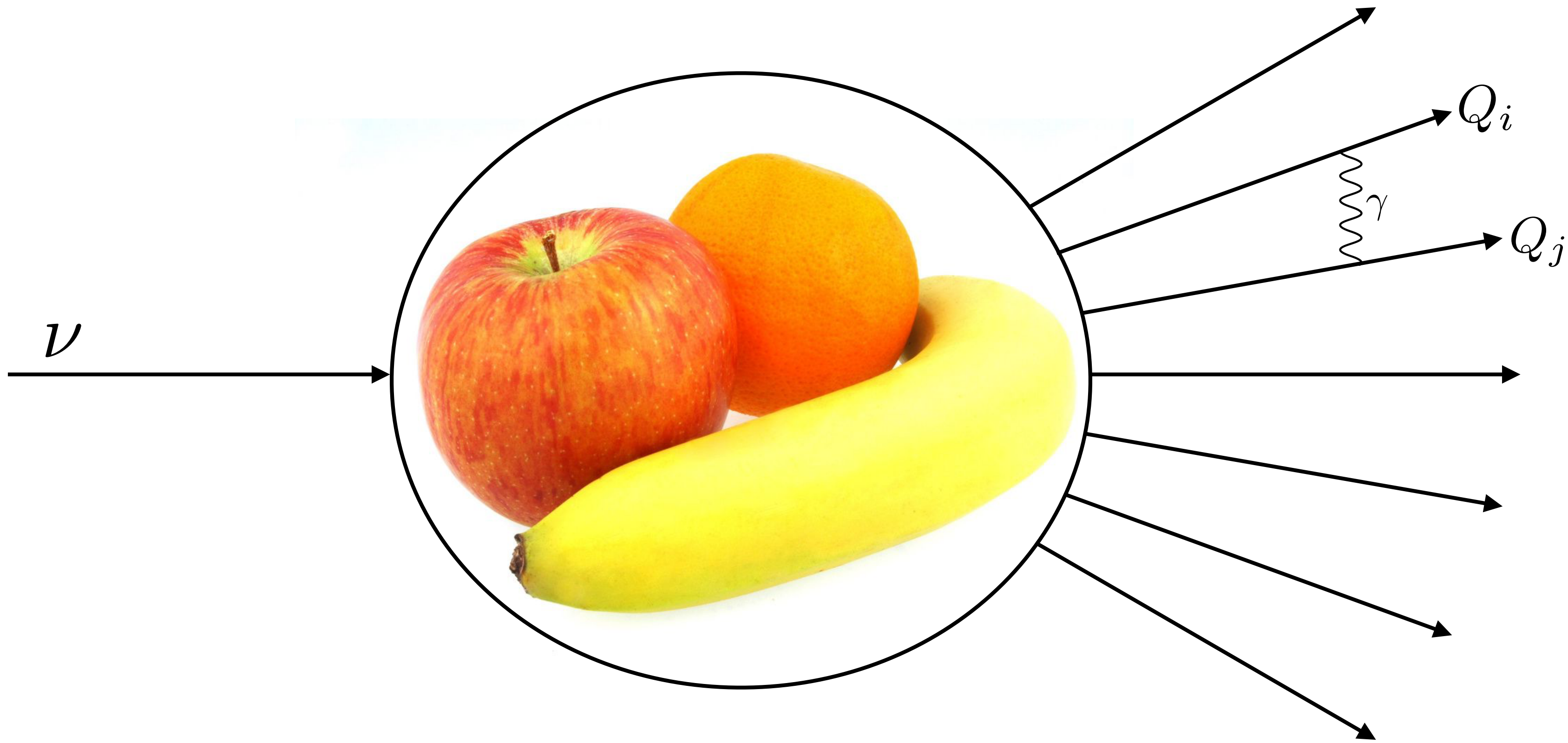


QED corrections



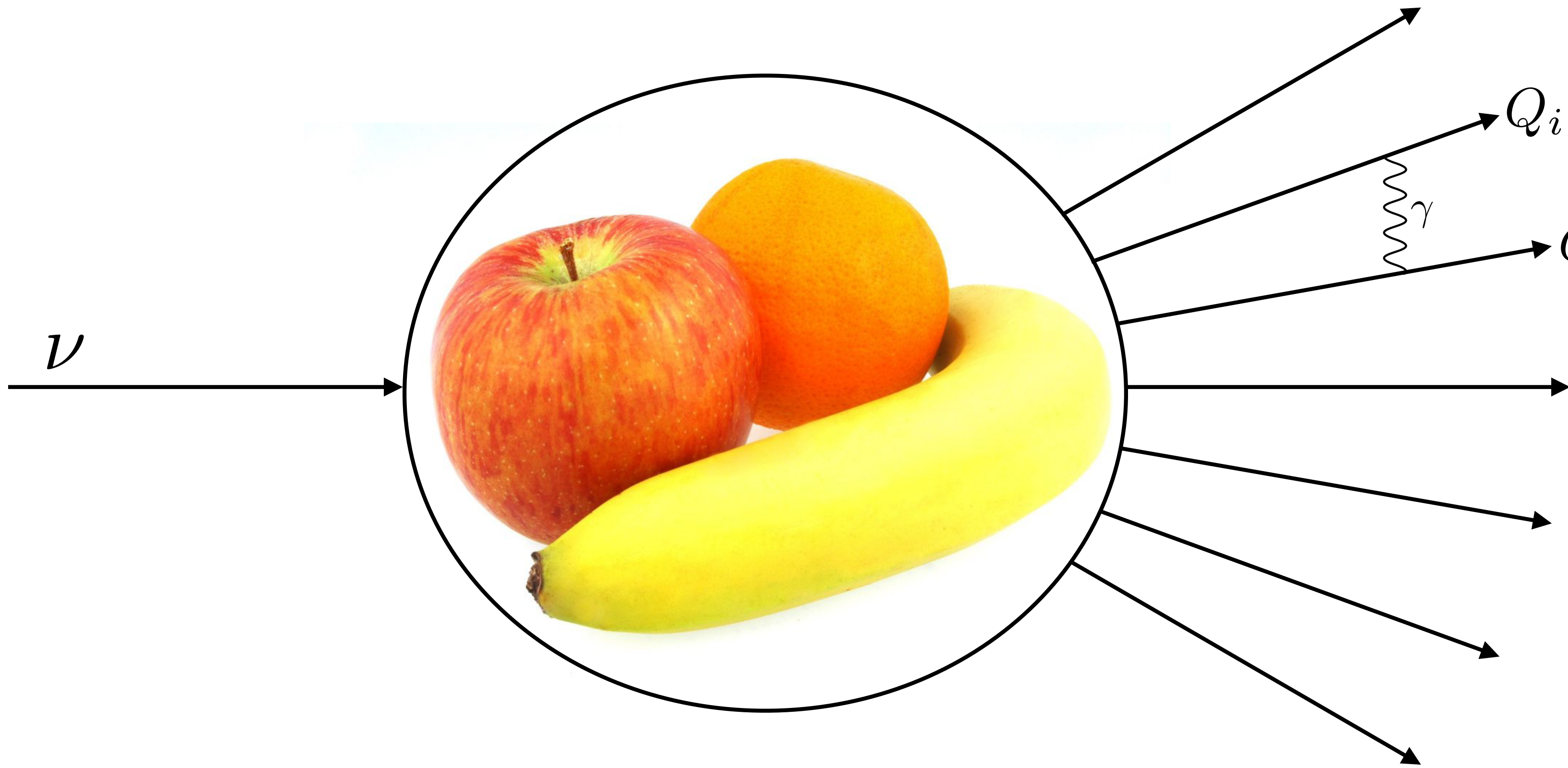
- all charged particles couple to real and virtual photons

QED corrections



- all charged particles couple to real and virtual photons

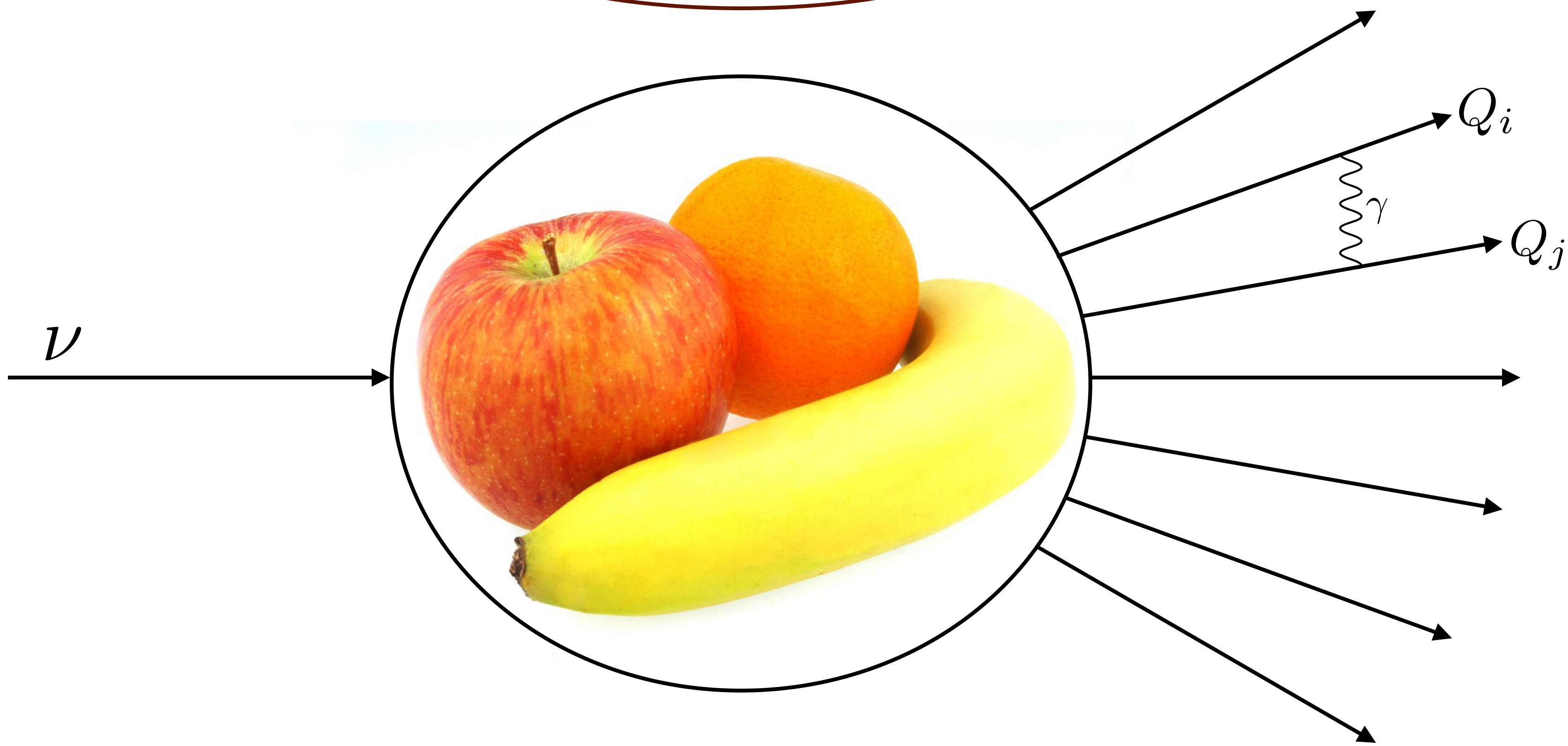
QED corrections



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

QED corrections

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

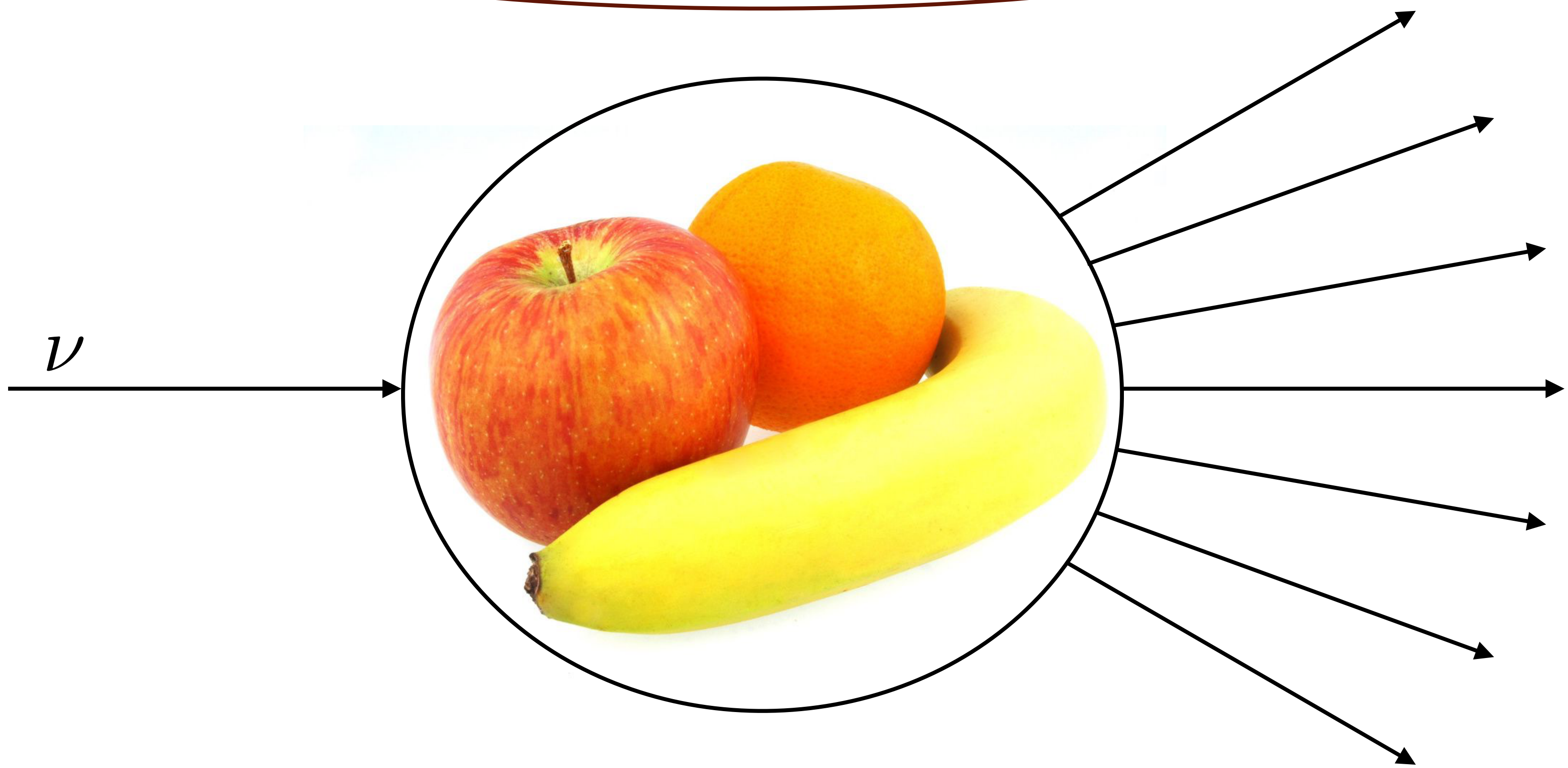


$\frac{\alpha}{\pi} \sim 0.2\ \%$ **multiplied by** $\ln \frac{E_\nu}{m_e} \sim 6 - 10$ **or** $\ln^2 \frac{E_\nu}{m_e} \sim 36 - 100$

- 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

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

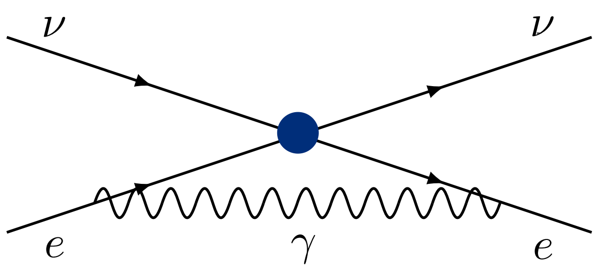
$$\mathcal{L}_{\rm eff}^{\rm CC} = -2\sqrt{2} \mathrm{G_F} \sum_{\ell \neq \ell'} \bar{\nu}_{\ell'} \gamma^\mu \mathrm{P_L} \nu_\ell \, \bar{\ell} \gamma_\mu \mathrm{P_L} \ell' - c^{qq'} \sum_{q \neq q'} \bar{\ell} \gamma^\mu \mathrm{P_L} \nu_\ell \, \bar{q} \gamma_\mu \mathrm{P_L} q'$$

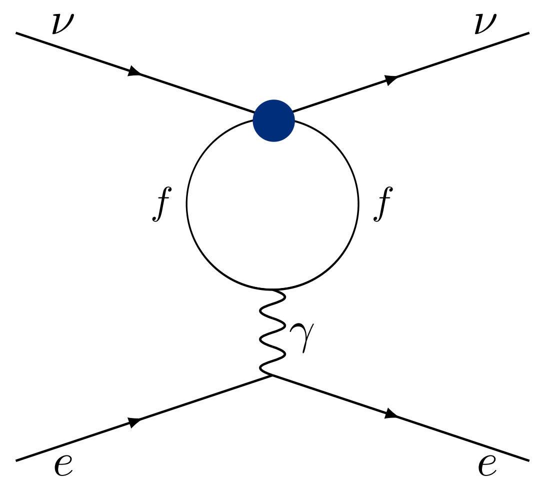
Neutrino-lepton, neutrino-quark scattering

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



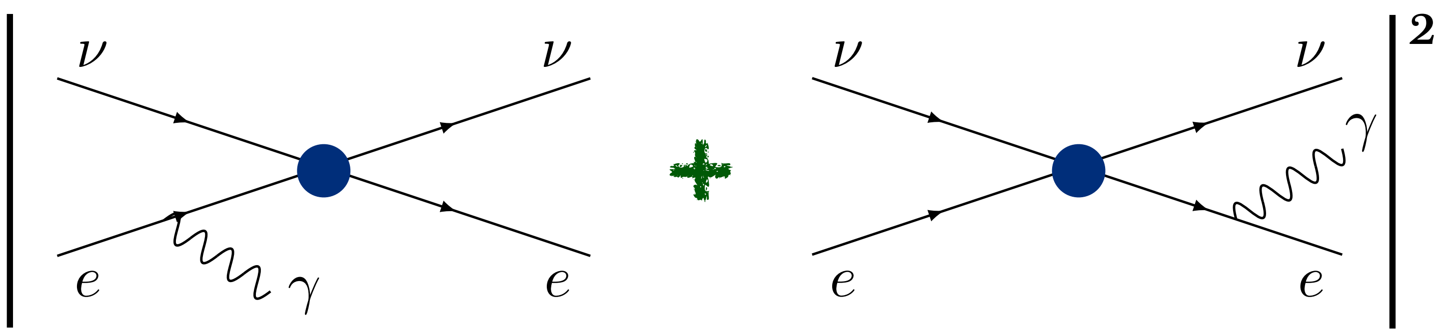


Neutrino-electron scattering

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

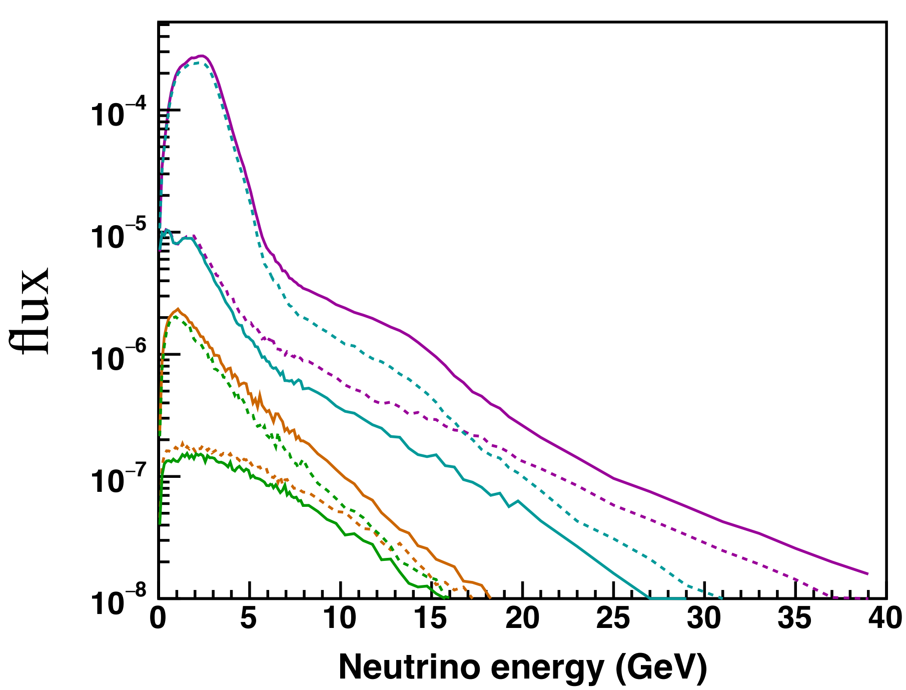


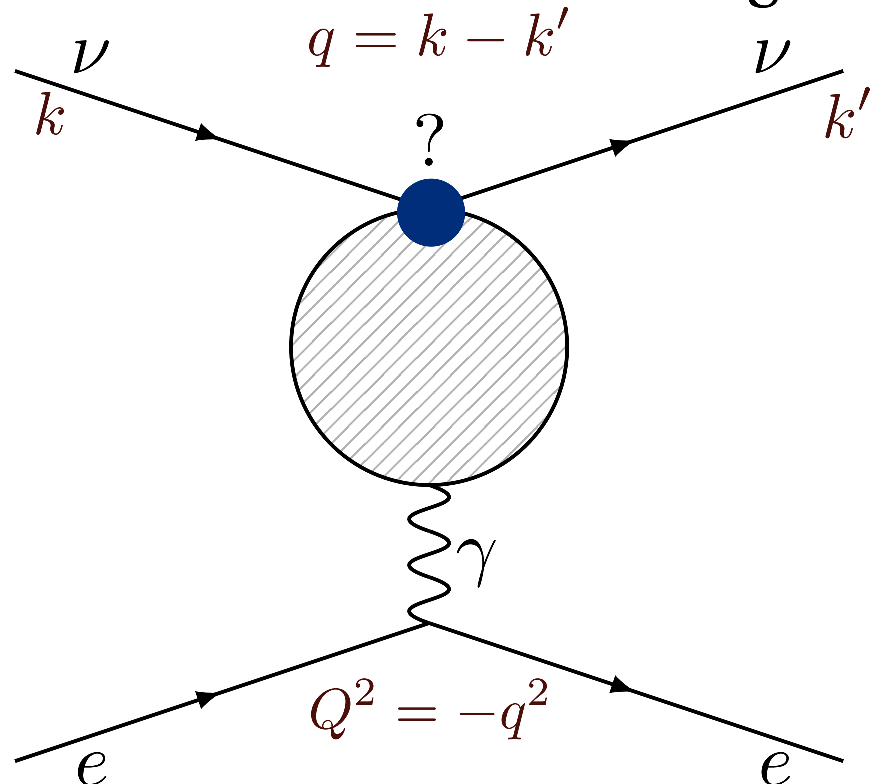
Main theoretical uncertainty

- kinematics is suppressed by electron mass:

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

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





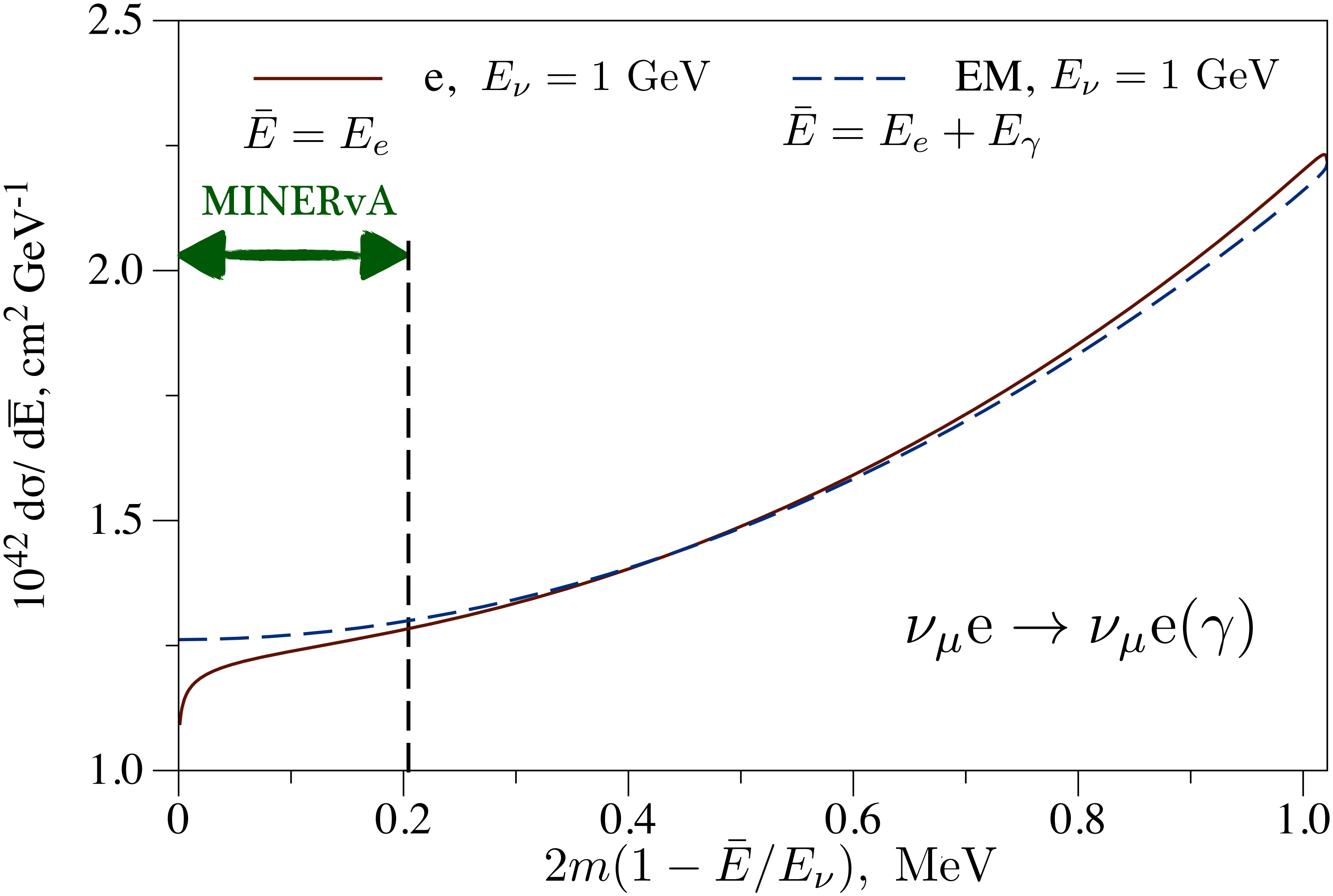
% level correction

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

- hadronic correction is the main error in theory

Electron vs electromagnetic (EM) spectra

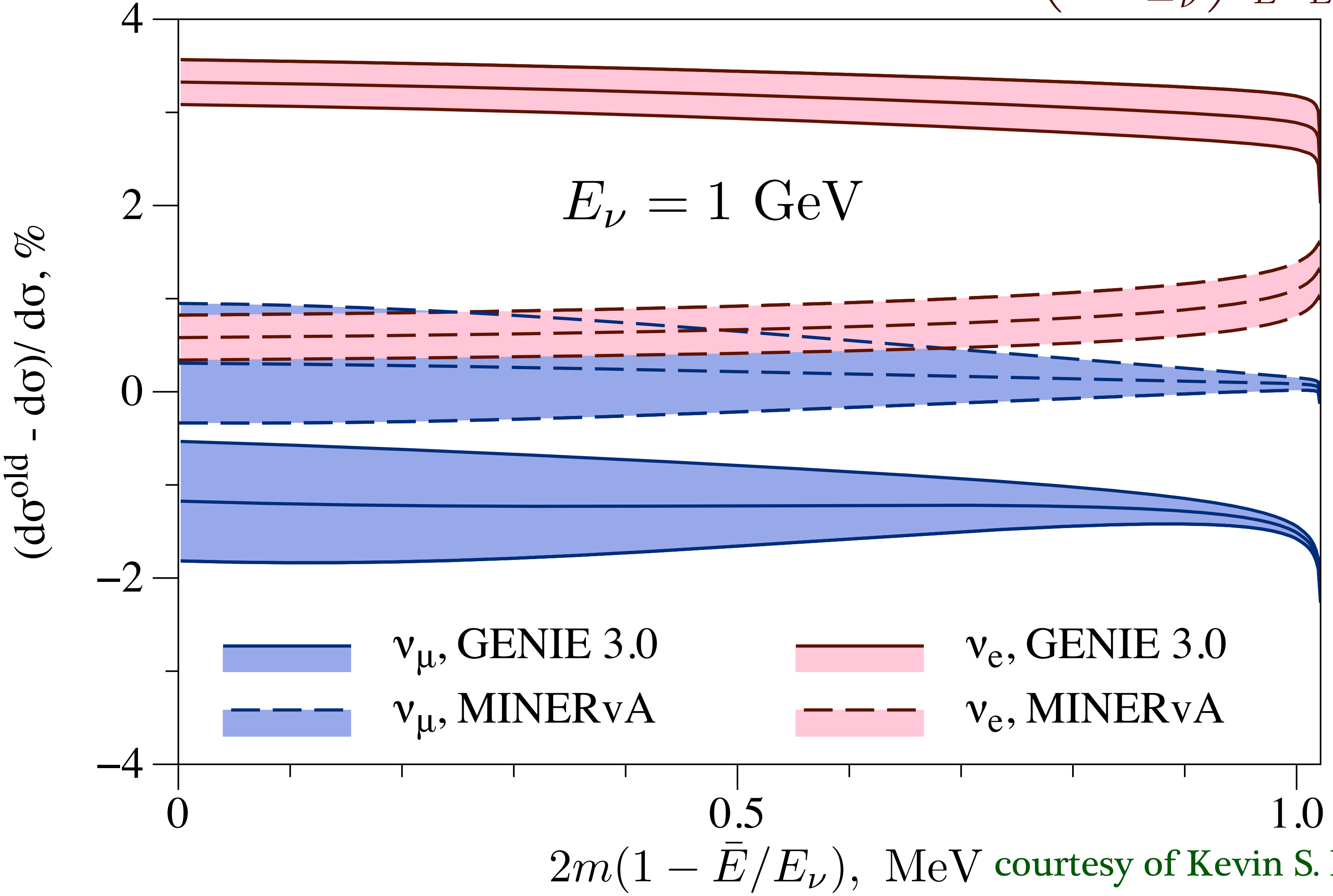
- resulting spectrum: $$2m\left(1-\frac{\bar{E}}{E_\nu}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$$



- cut dependence after radiative corrections

Comparison to GENIE

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



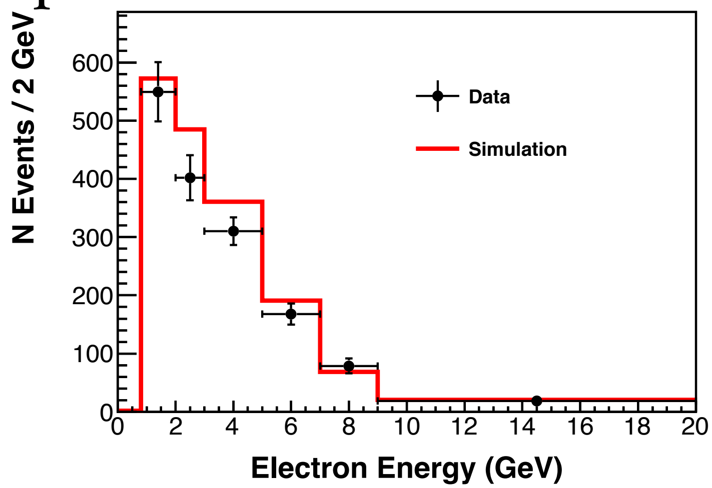
courtesy of Kevin S. McFarland

- correct description and definite improvement at GeV energies

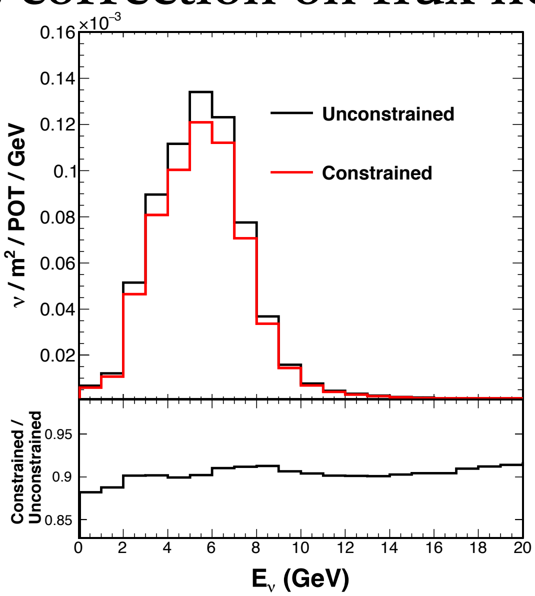
MINERvA constraint

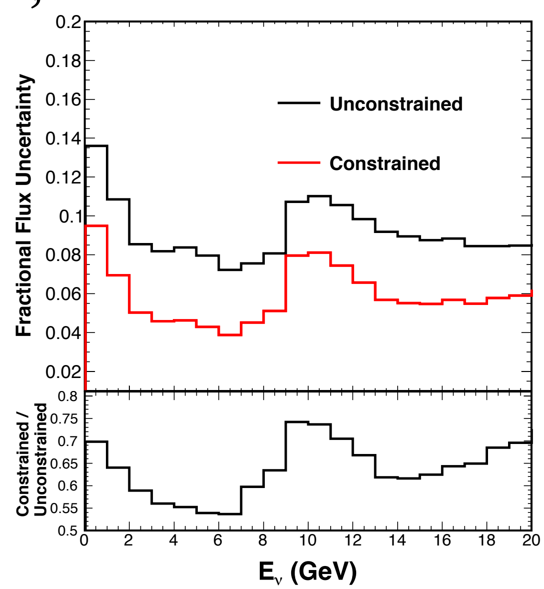
- electron energy spectrum:

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

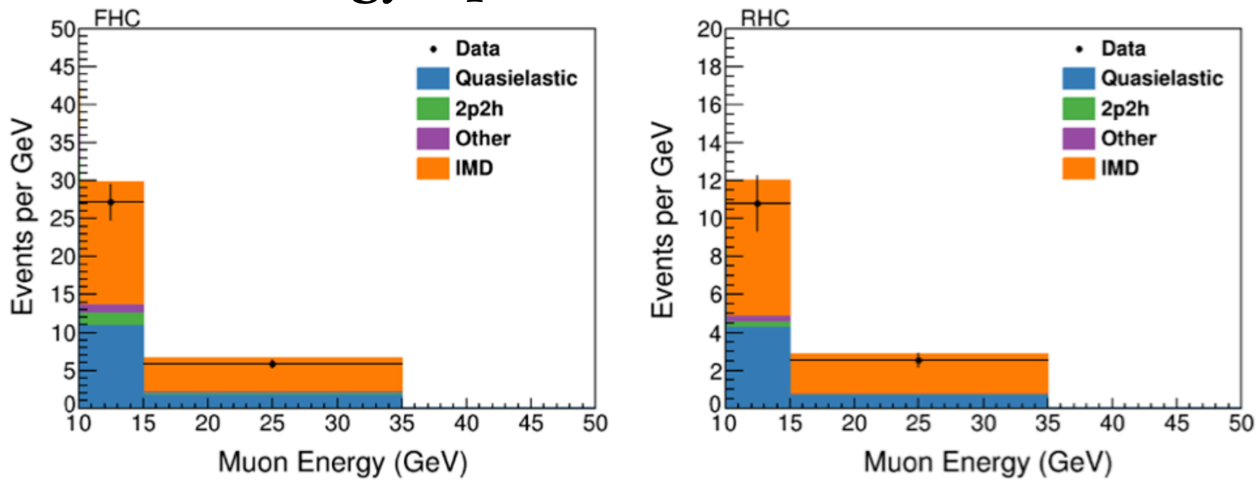
  Ch. Marshall et al, Phys.Rev.D 101 3, 032002 (2020)

- νe scattering: standard candle to constrain neutrino flux

MINERvA constraint by inverse muon decay

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

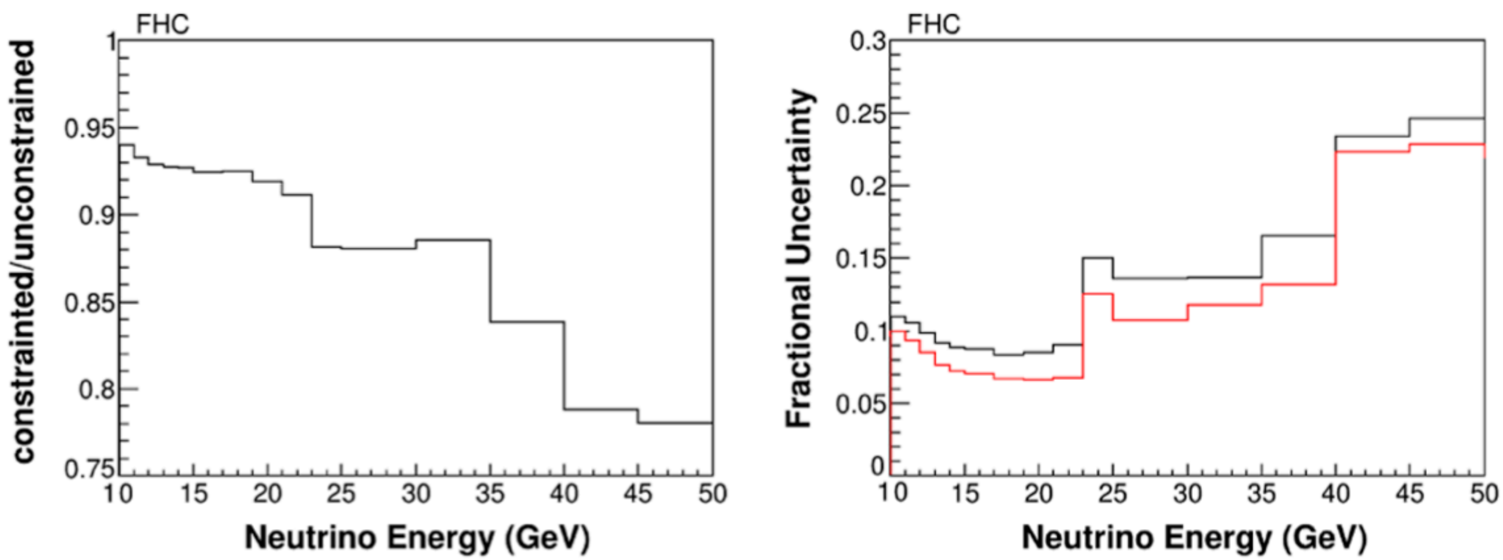
- muon energy spectrum:



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

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

- 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

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

- 2 from 3 distributions are reproduced by alternative method

Bardin and Dokuchaeva (1987)

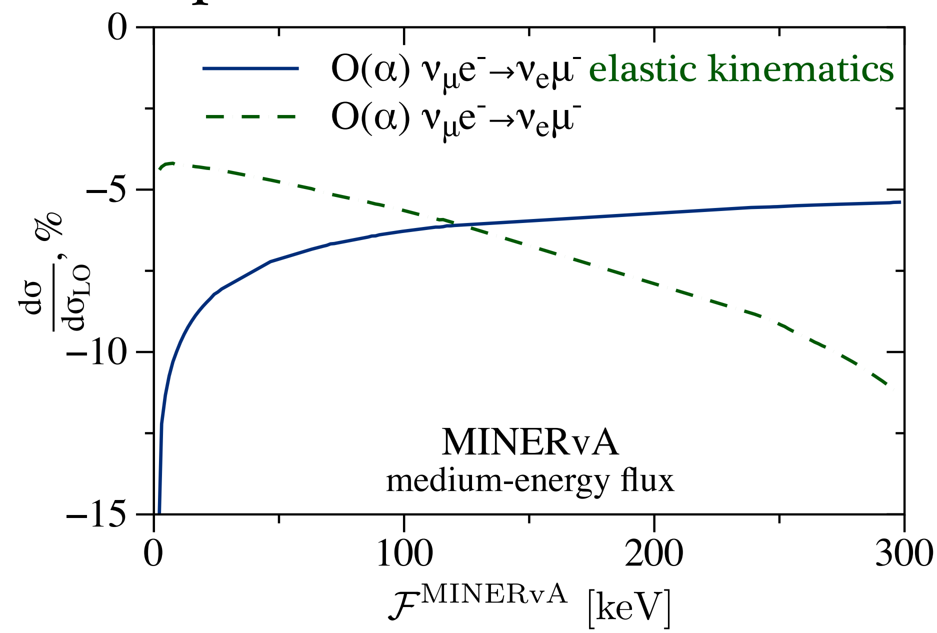
- first QED/EW form factors with different mass

- radiative corrections to distribution of experimental discriminant

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

$$\mathcal{F}^{\rm MINERvA} = \frac{E_\mu \theta_\mu^2}{1 - \frac{E_\mu}{35\ \mathrm{GeV}}}$$

O.T., Kaushik Borah, Richard J. Hill,
Kevin S. McFarland, Daniel Ruterbories (2023)



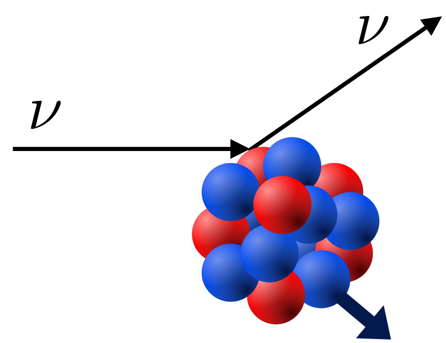
- double-differential distributions and corrections to $\mathcal{F}$ distribution

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

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

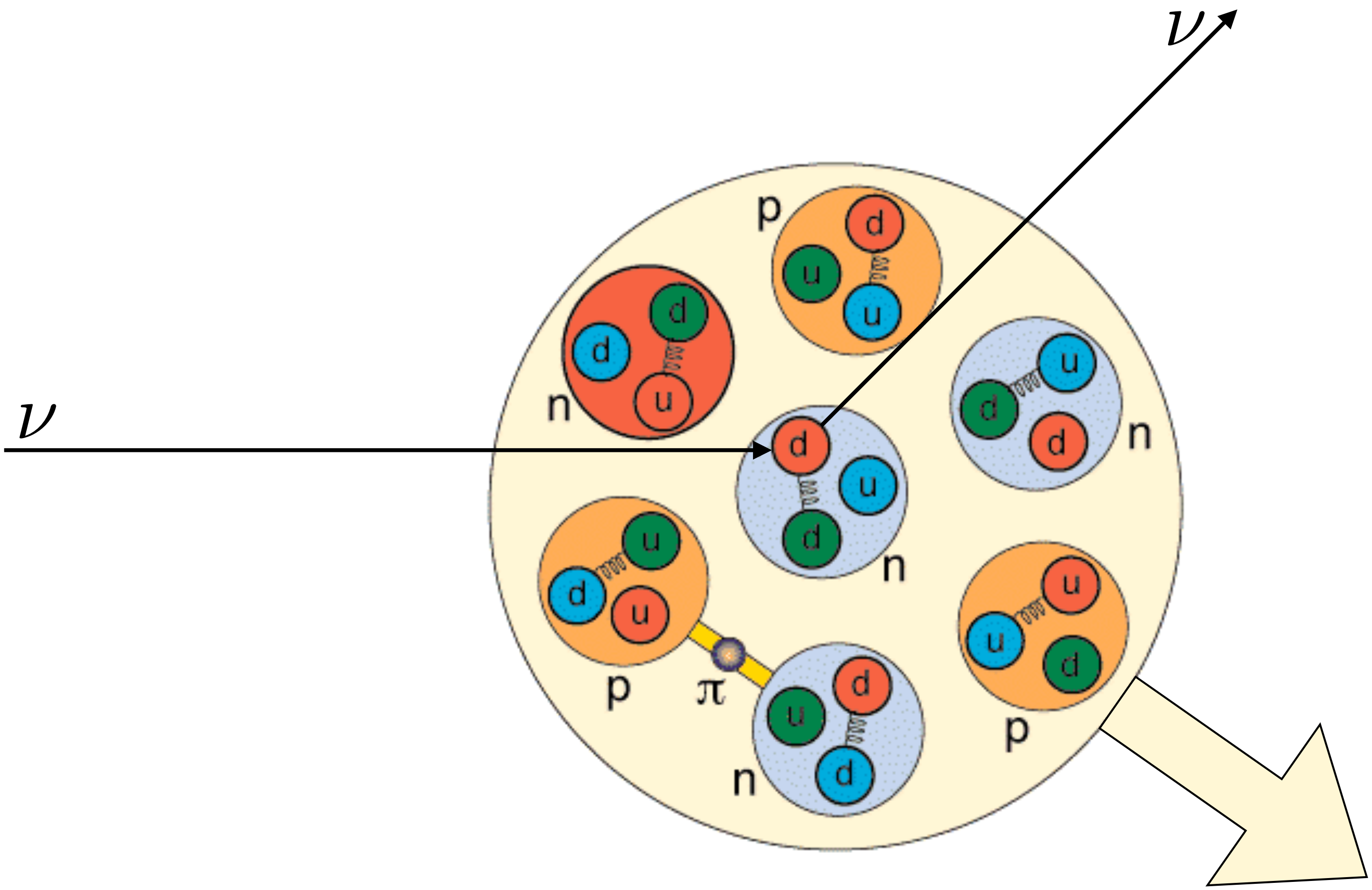
- first detection in 2017 at SNS, measured on CsI and Ar

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

- rapidly developing field nowadays

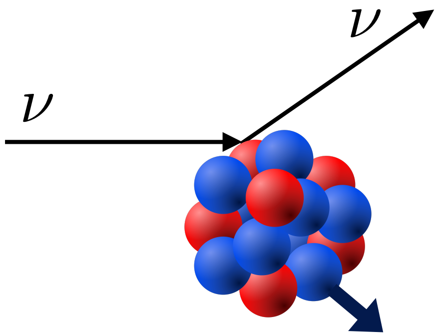
- CEvNS enters precision era with πDAR sources

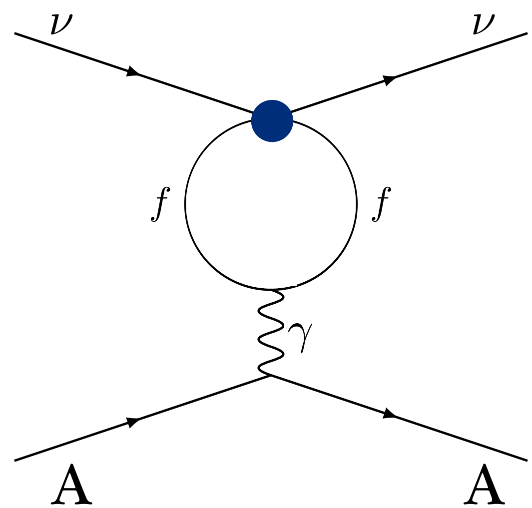
From quarks to nuclei



fafnir.phyast.pitt.edu

- scattering on quarks in nucleons in nucleus





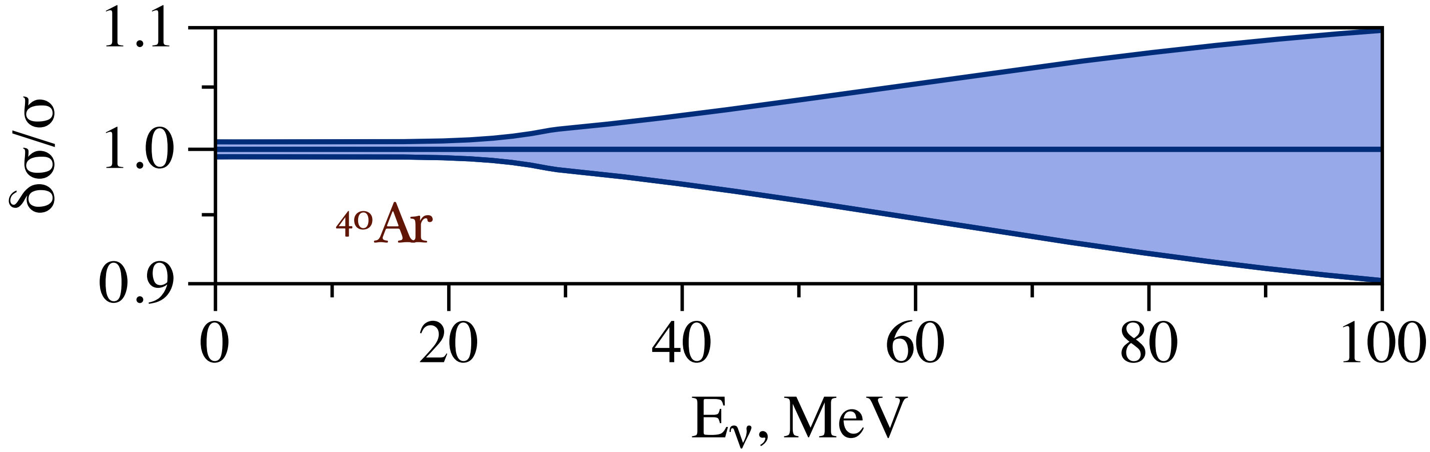
Coherent elastic neutrino-nucleus scattering

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

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

flavor-dependent
at percent level

for Coherent and CCM

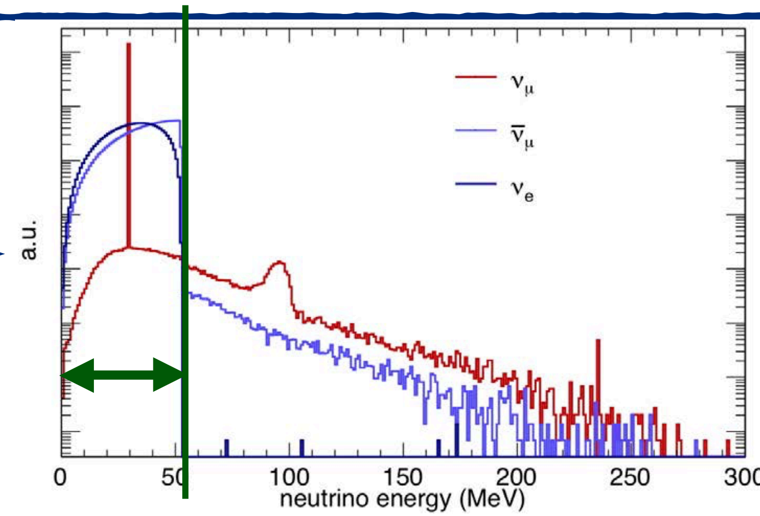


flavor-dependence at tree-level

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

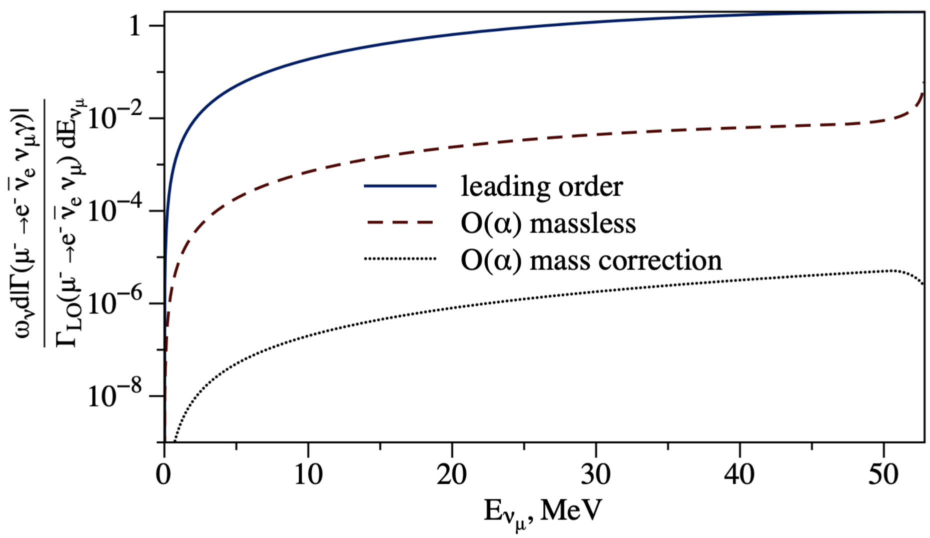
$$\pi^+ \to \mu^+ \nu_\mu \gamma$$

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

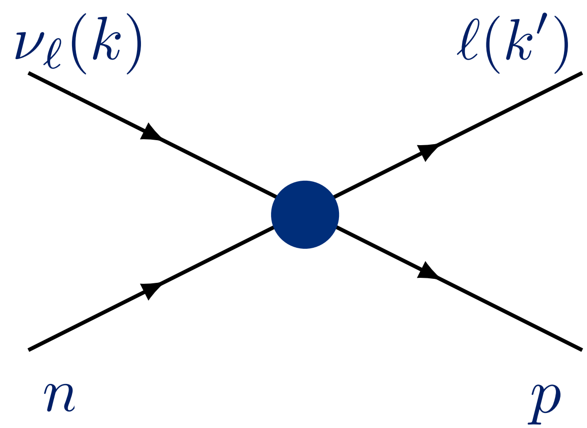
< 0.1 ‰

flavor-dependence is clarified to permille level analytically

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



first QED/EW form factors with different mass

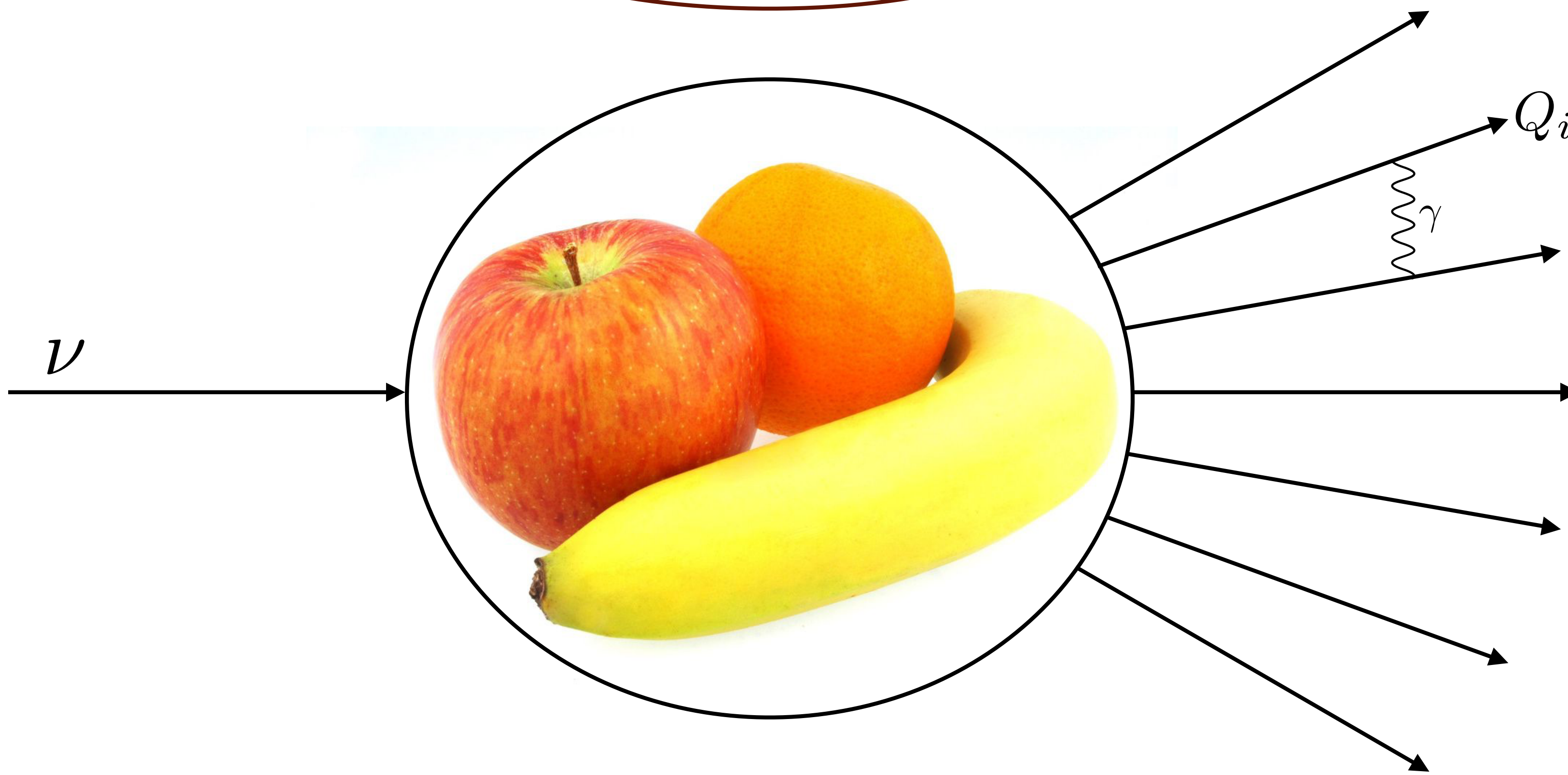


Radiative corrections to charged-current elastic scattering on free nucleons

neutrino energy ~ GeV

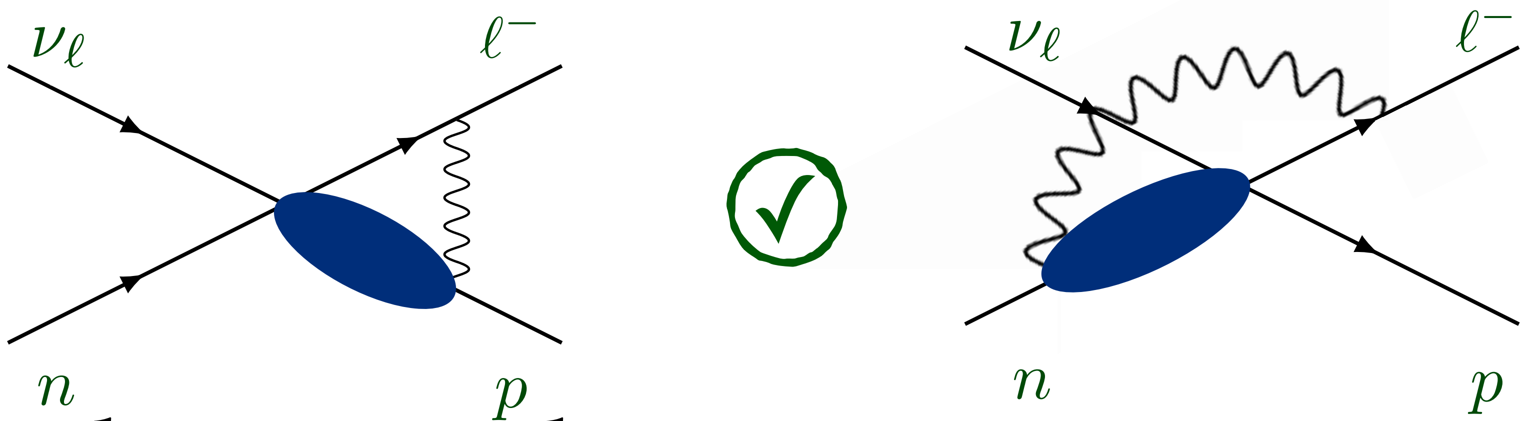
QED corrections

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



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

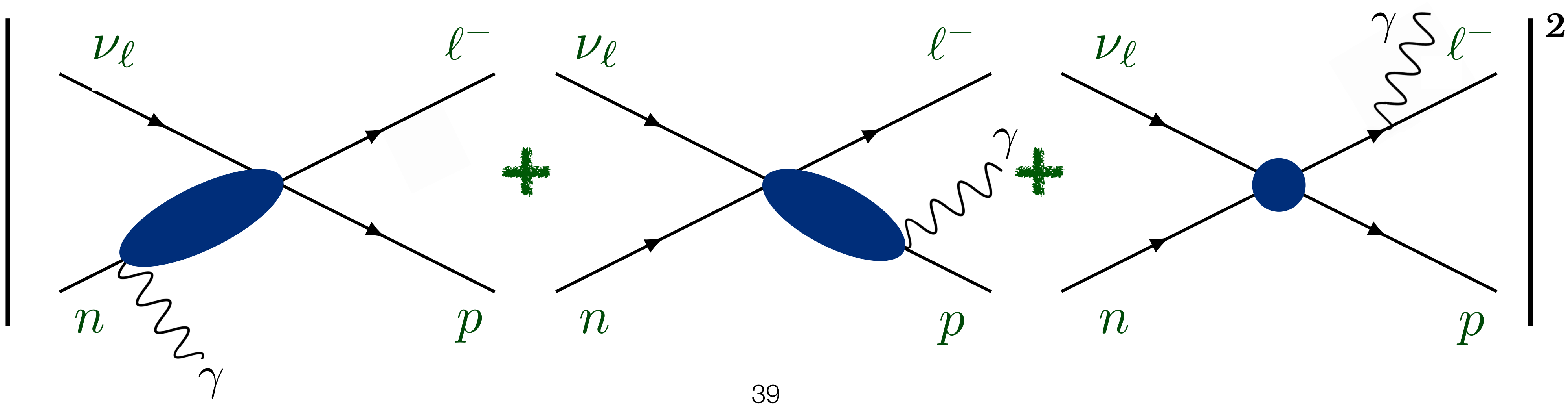
- scale separation introduces large flavor-dependent QED logarithms factorization for radiative corrections with model for hard function



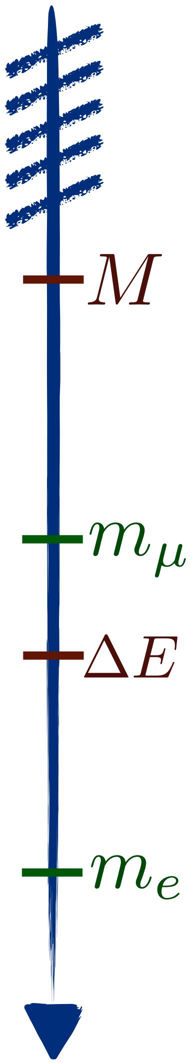
Charged-current elastic scattering on nucleons

precise predictions for flavor ratios and radiative corrections

in exclusive and inclusive observables with GeV neutrino beams



Factorization approach



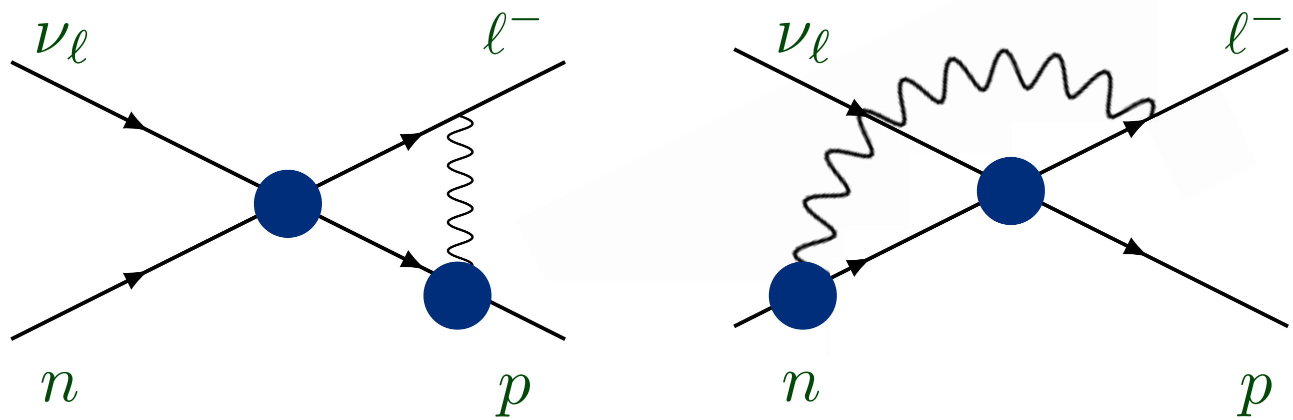
- cross section is given by factorization formula

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

- 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, Phys. Lett. B 732, 315-319 (2013)
- add self energy for charged particles

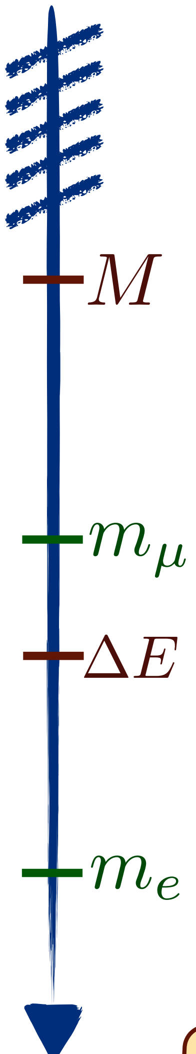
- reproduce soft and collinear regions of SCET

- best determination of hard function

Factorization approach

- cross section is given by factorization formula

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



- determine hard function at hard scale by matching experiment or <u>hadronic model</u> 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

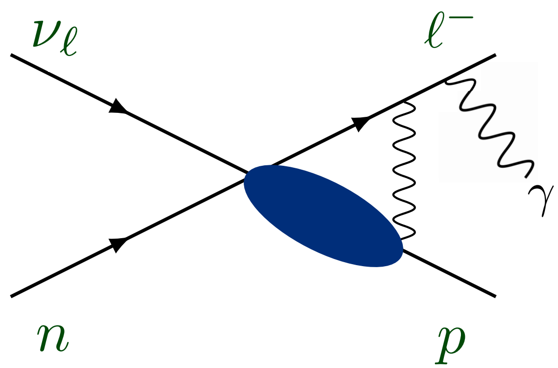
ep scattering with soft radiation only: Richard J. Hill, Phys. Rev. D 95 1, 013001 (2016)

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

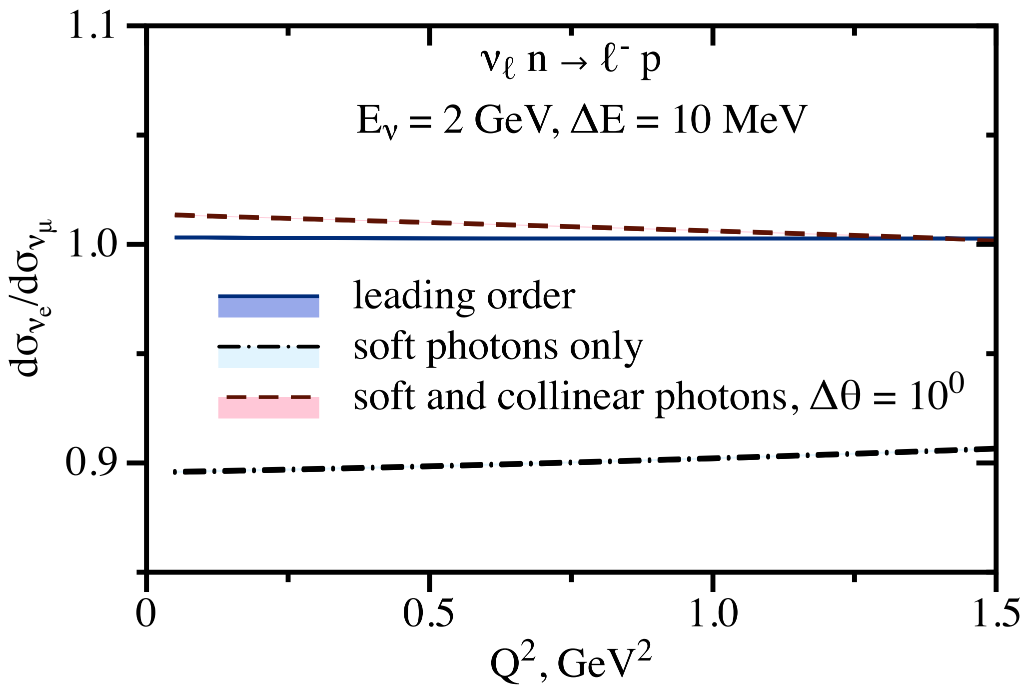
Charged-current scattering on nucleons

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

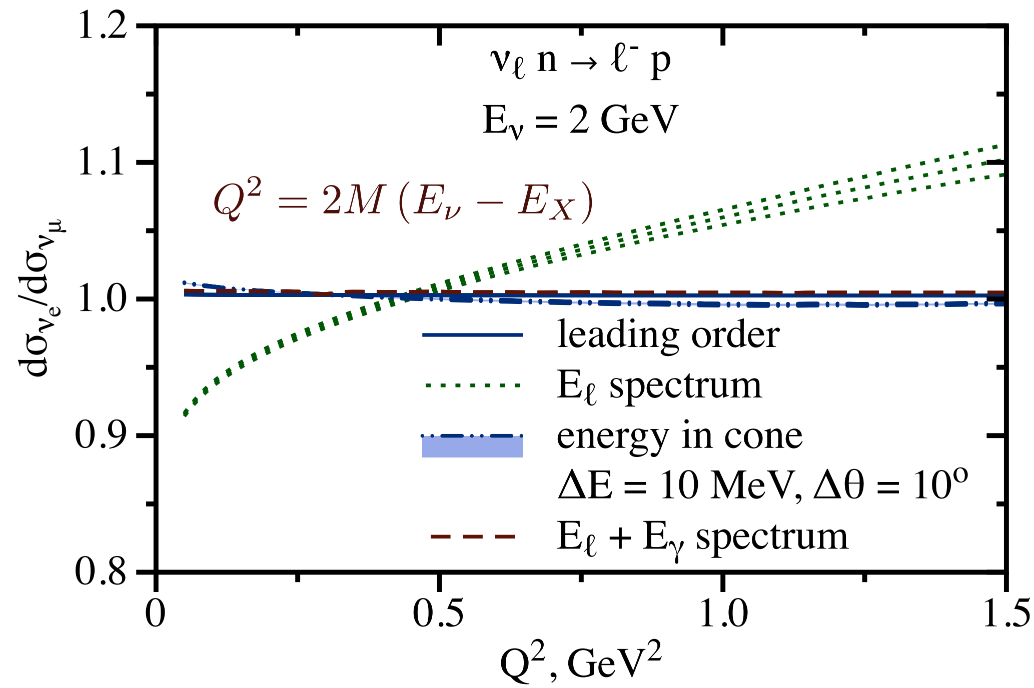
O. T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. 13 (2022), 1, 5286



exclusive



inclusive



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

Electron/muon ratio

	E_ν, GeV		$\left(\frac{\sigma_e}{\sigma_\mu}-1\right)_{\mathrm{LO}}$, %	$\frac{\sigma_e}{\sigma_\mu}-1$, %
T2K/HyperK	0.6	ν	2.47 ± 0.06	$2.84 \pm 0.06 \pm 0.37$
		$\bar{\nu}$	2.04 ± 0.08	$1.84 \pm 0.08 \pm 0.20$
NOvA/DUNE	2.0	ν	0.322 ± 0.006	$0.54 \pm 0.01 \pm 0.22$
		$\bar{\nu}$	0.394 ± 0.003	$0.20 \pm 0.01 \pm 0.19$

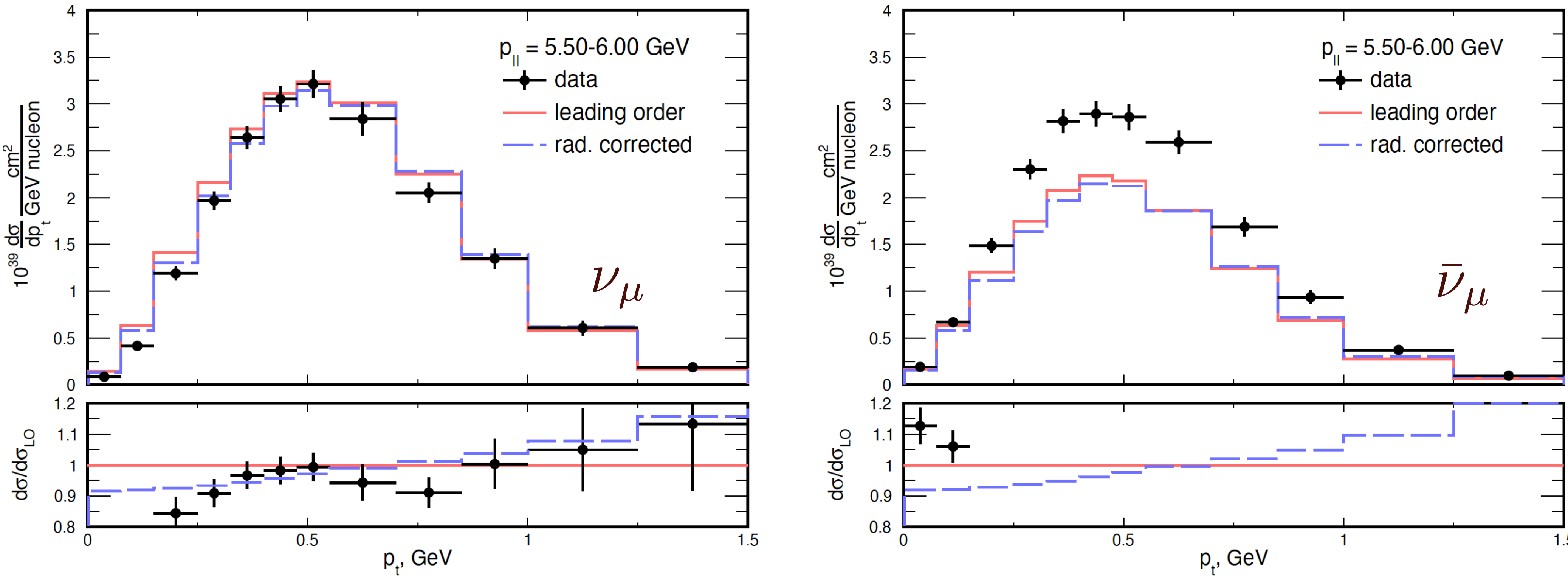
TABLE II: Inclusive electron-to-muon cross-section ratios for neutrinos and antineutrinos without kinematic cuts. Uncertainties at leading order are from vector and axial nucleon form factors. For the final result, we include an additional hadronic uncertainty from the one-loop correction to the first uncertainty, and provide a second uncertainty as the magnitude of the radiative correction.

$$\frac{\sigma\left(m_\ell \to 0\right)}{\sigma\left(m_\ell = 0\right)} \approx 1 + A m_\ell^2 + \alpha B m_\ell^2 \ln m_\ell$$

- inclusive cross sections and flavor ratios determined by KLN
- nuclear effects: suppressed by expansion parameters squared

Comparison to data

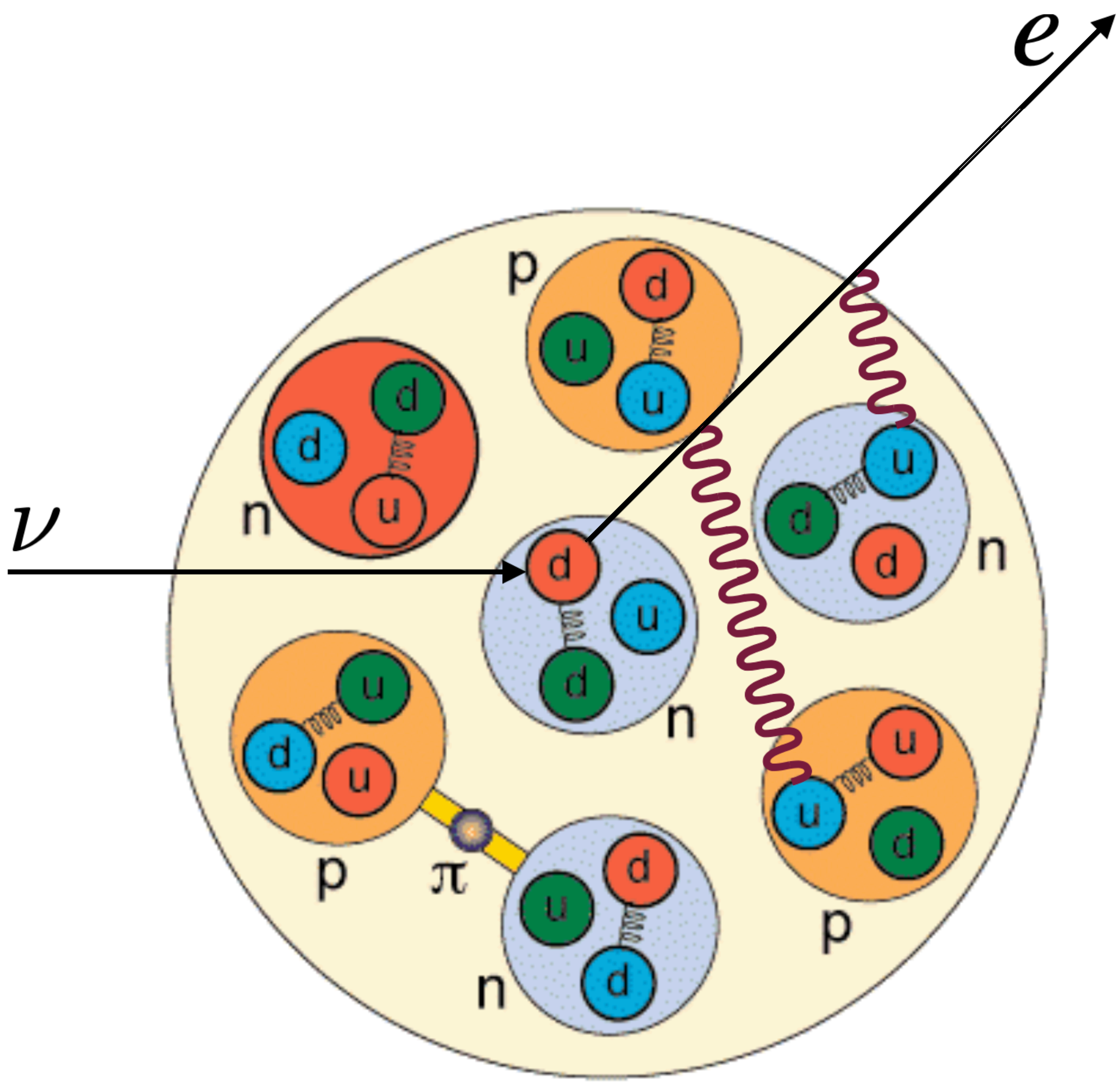
- medium-energy flux data from MINERvA@FERMILAB



O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
editors suggestion, Phys. Rev. D 106, 093006 (2022)

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

QED medium effects



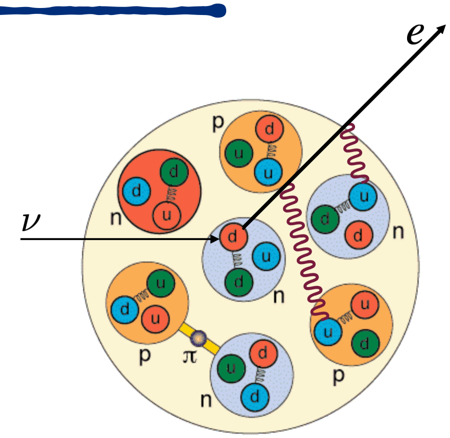
- charged lepton exchanges photons with nuclear medium

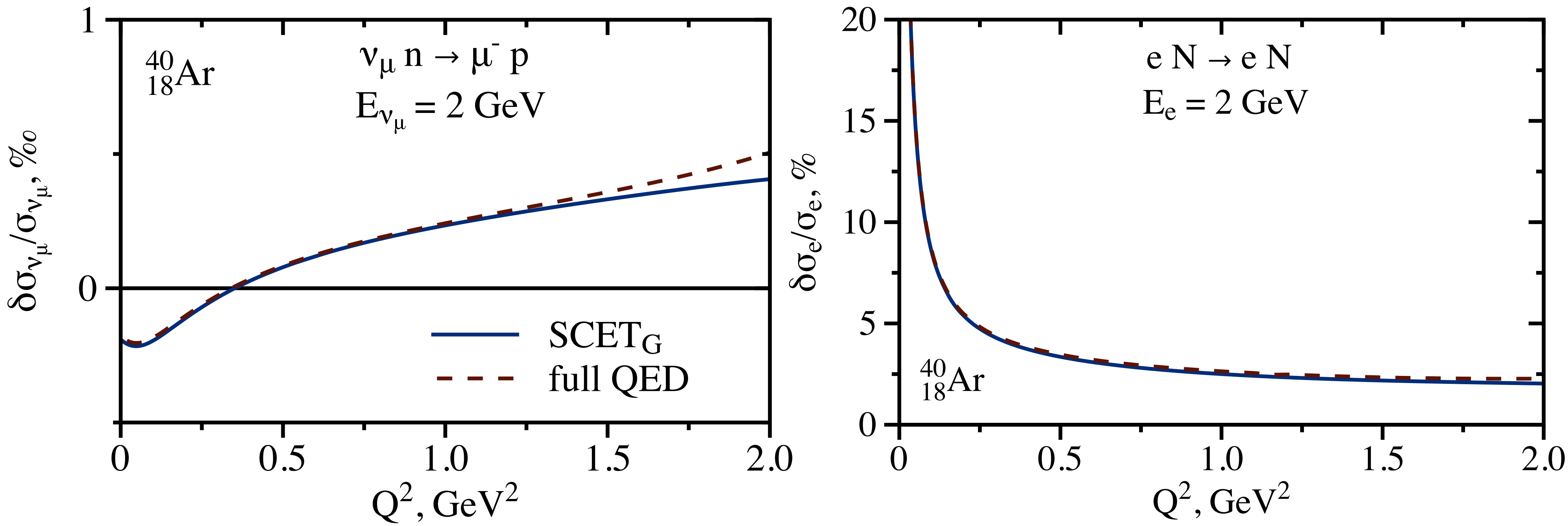
QED nuclear medium effects

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

Thanks for your attention !!!