Interplay of Nuclear, Neutrino and BSM Physics at Low-Energies
INT-23-85W, Seattle, USA

19 April, 2023

Radiative corrections to low-energy neutral-current neutrino scattering and DAR sources

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LA-UR-23-23047

Outline

1) microscopic EFT for neutrino physics

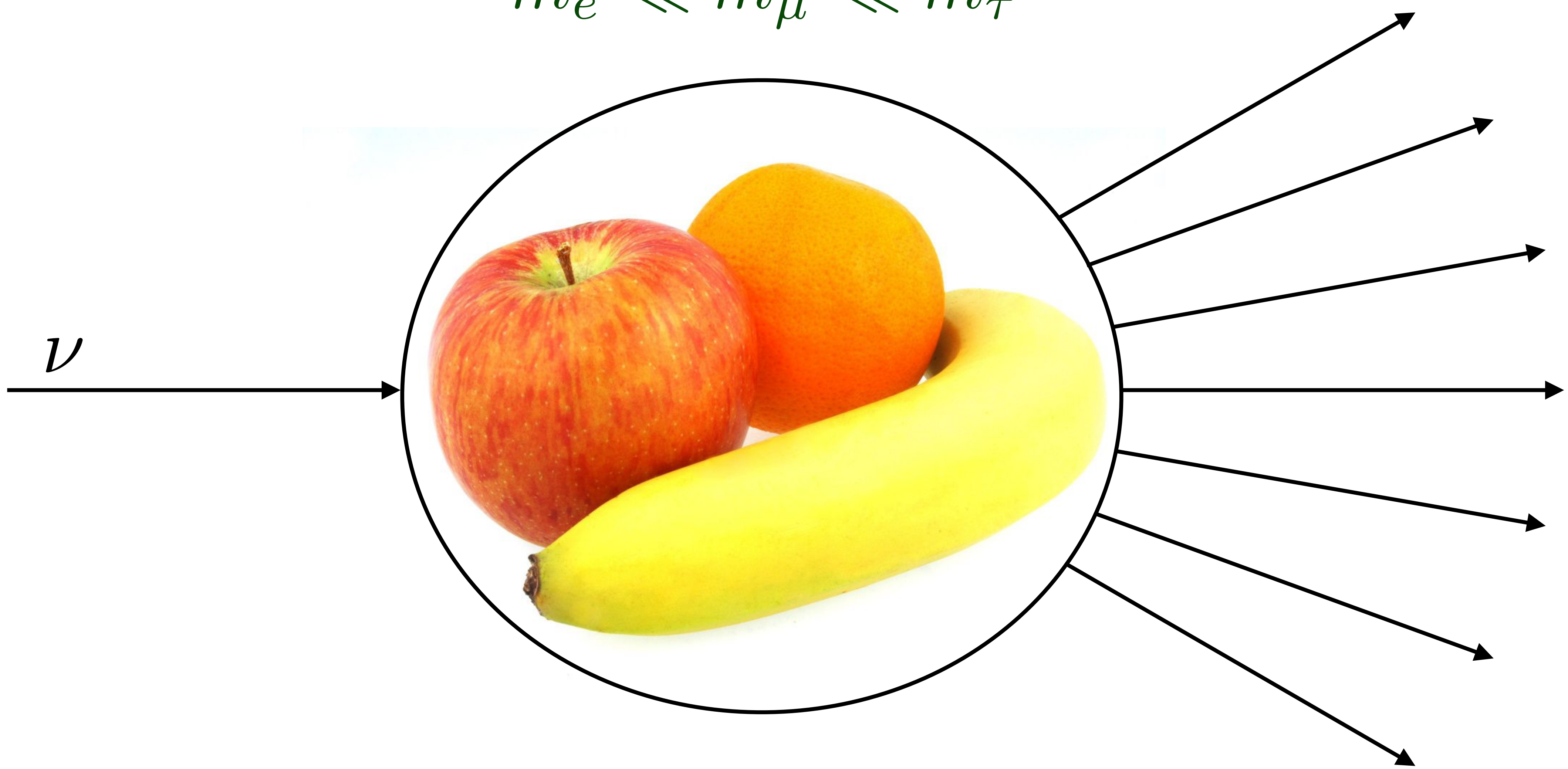
2) coherent elastic neutrino-nucleus scattering (CEvNS)

3) radiative correction to neutrino spectra

QED corrections

neutral-current interactions

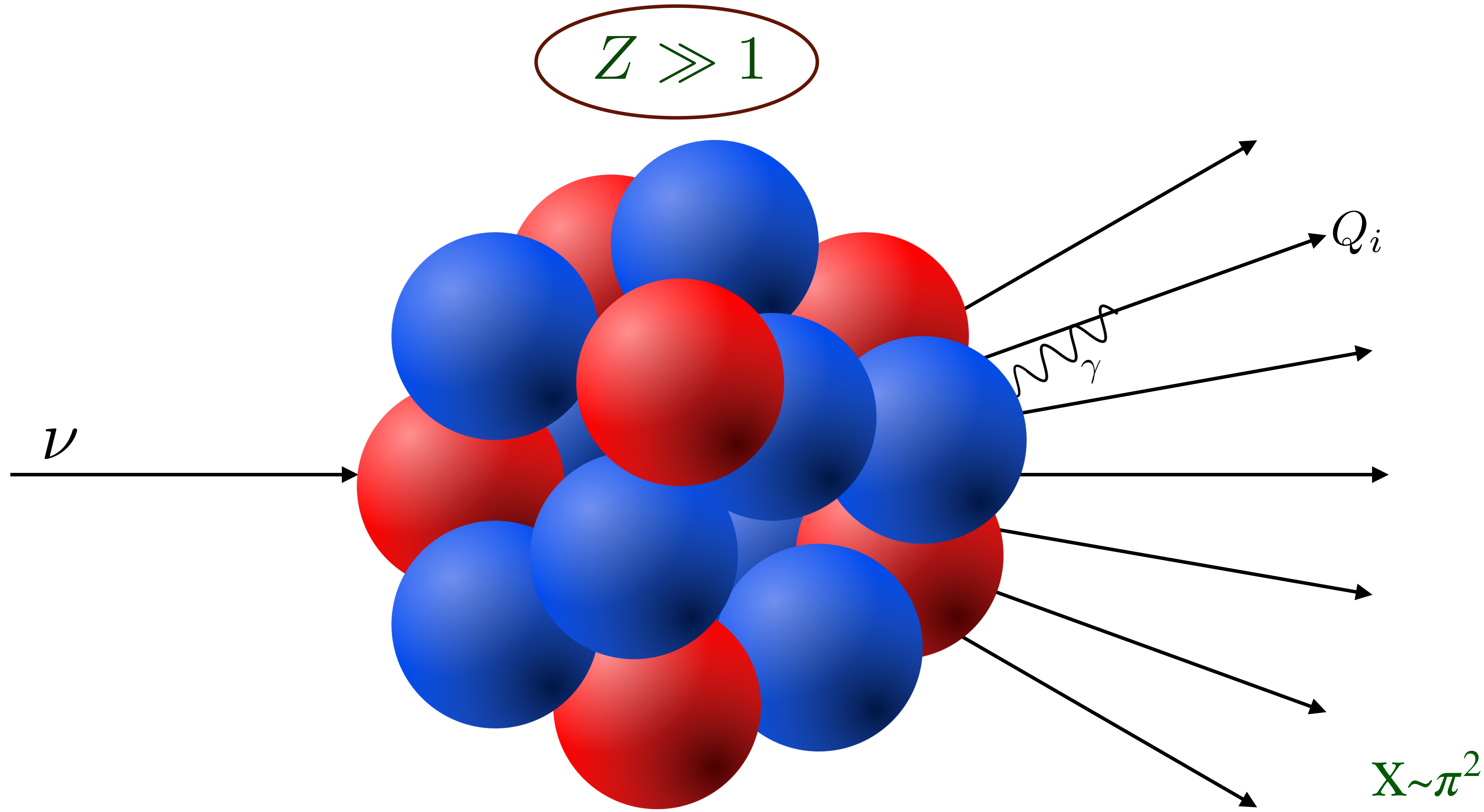
$$m_e \ll m_\mu \ll m_\tau$$



$X \frac{\alpha}{\pi} \sim 0.2~\%$ multiplied by kinematic-dependent factors $X \sim \ln \frac{m_e}{m_\mu}$

- kinematic dependence and factor X can enhance QED corrections

QED corrections



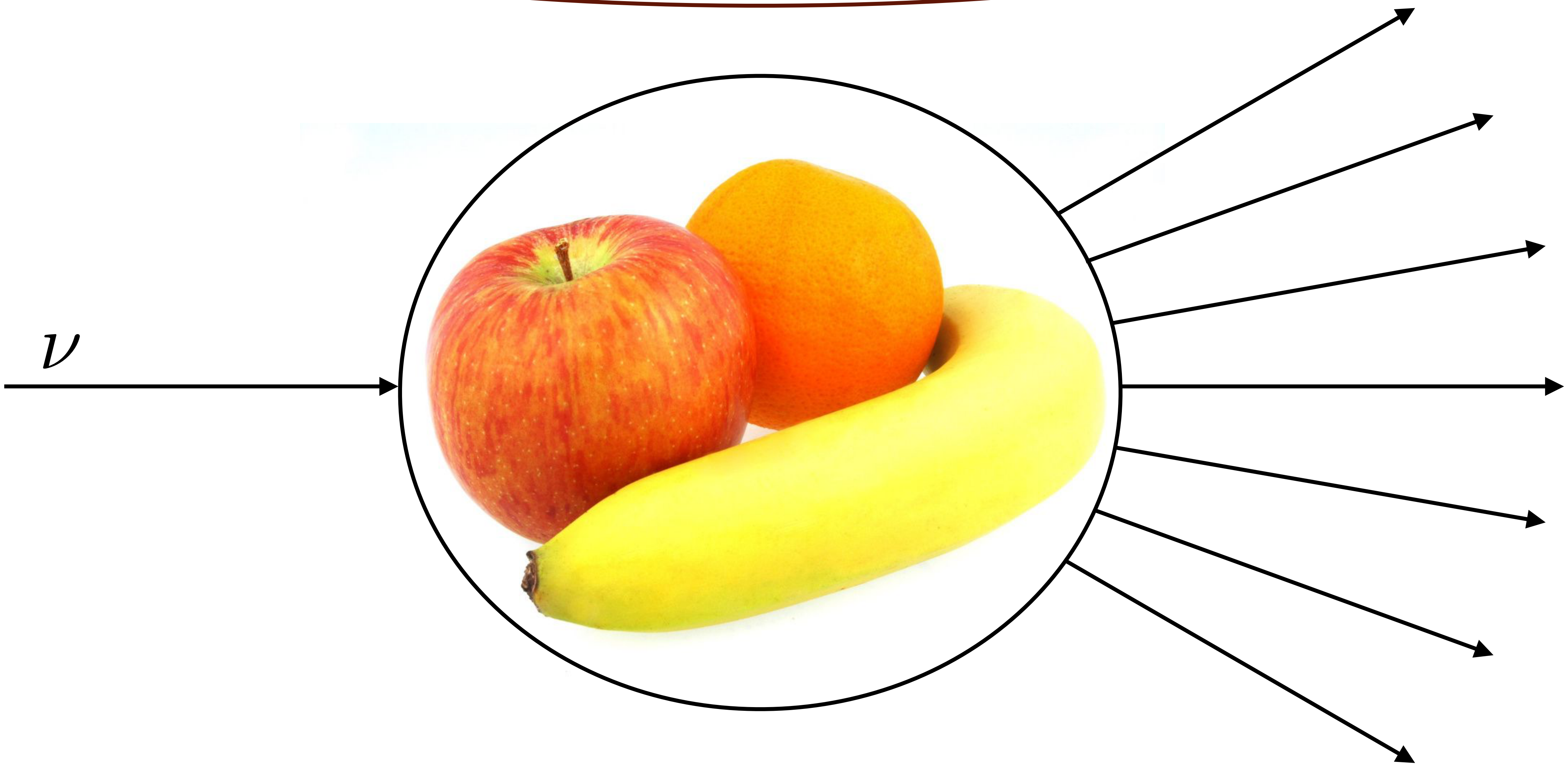
X $\frac{\alpha}{\pi} \sim 0.2\ \%$ multiplied by target nucleus charge $Z \lesssim 10-20$

@Ryan Plestid

- Coulomb corrections are enhanced by nucleus charge factor

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

Microscopic EFT for neutrino physics

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

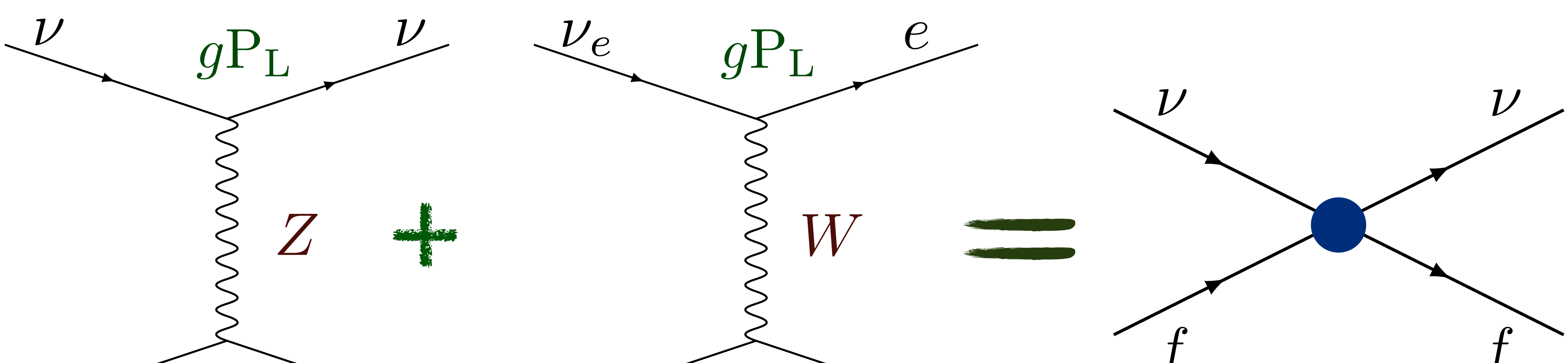
Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT

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

neutral current

charged current



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

Neutrino scattering in EFT. Matching

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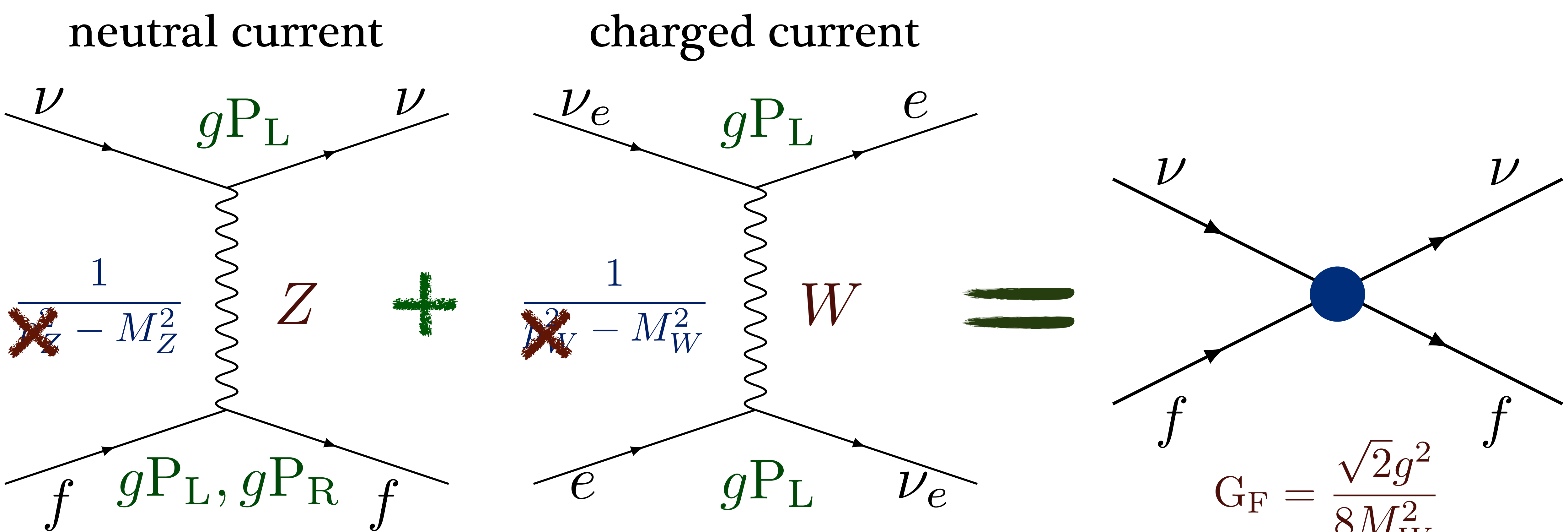

$$\mathrm{G_F} = \frac{\sqrt{2} g^2}{8 M_W^2}$$

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

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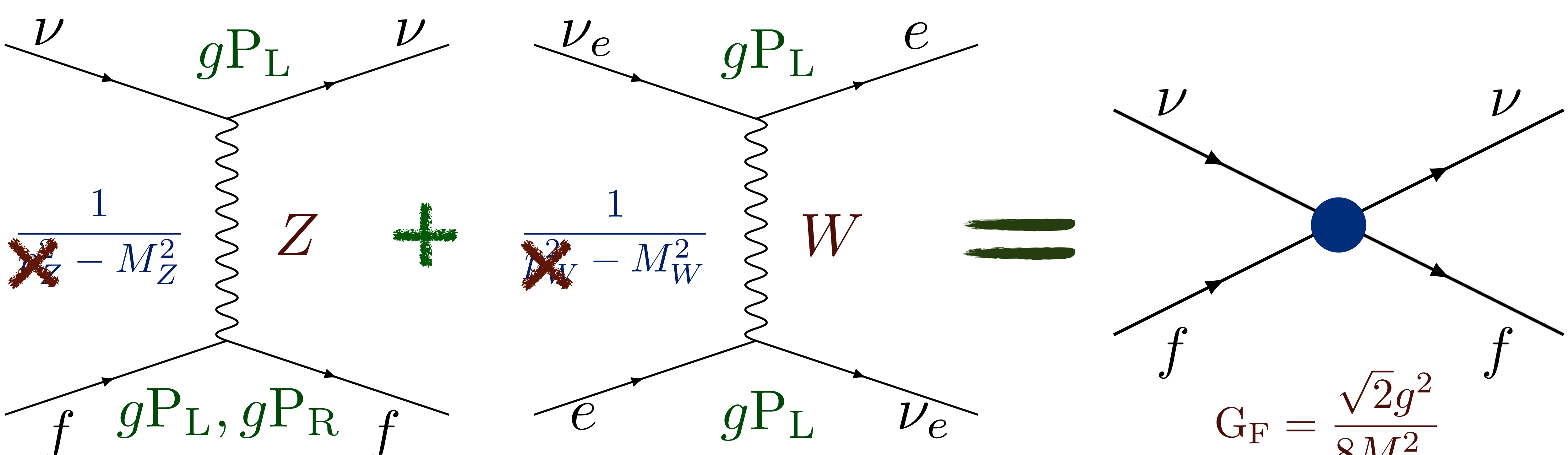
couplings to electron

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

Weinberg (1967), 't Hooft (1971)

neutral current charged current



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

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

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

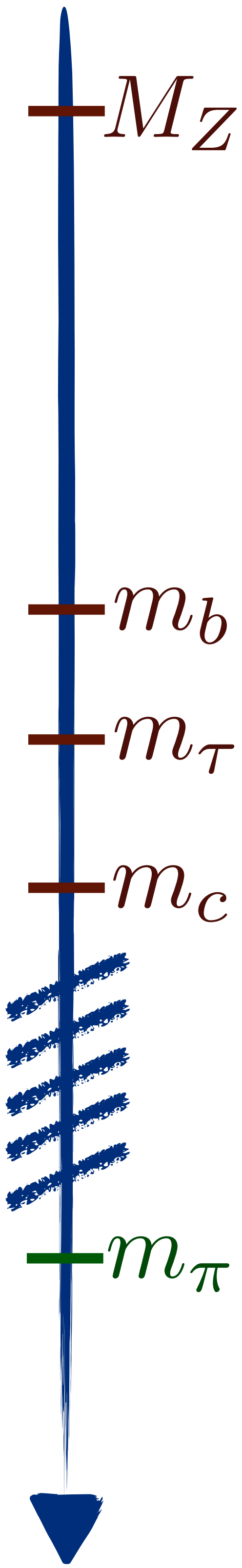
- G_F: combination of parameters is precisely measured

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

MULAN (2012)

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

Running to low scales

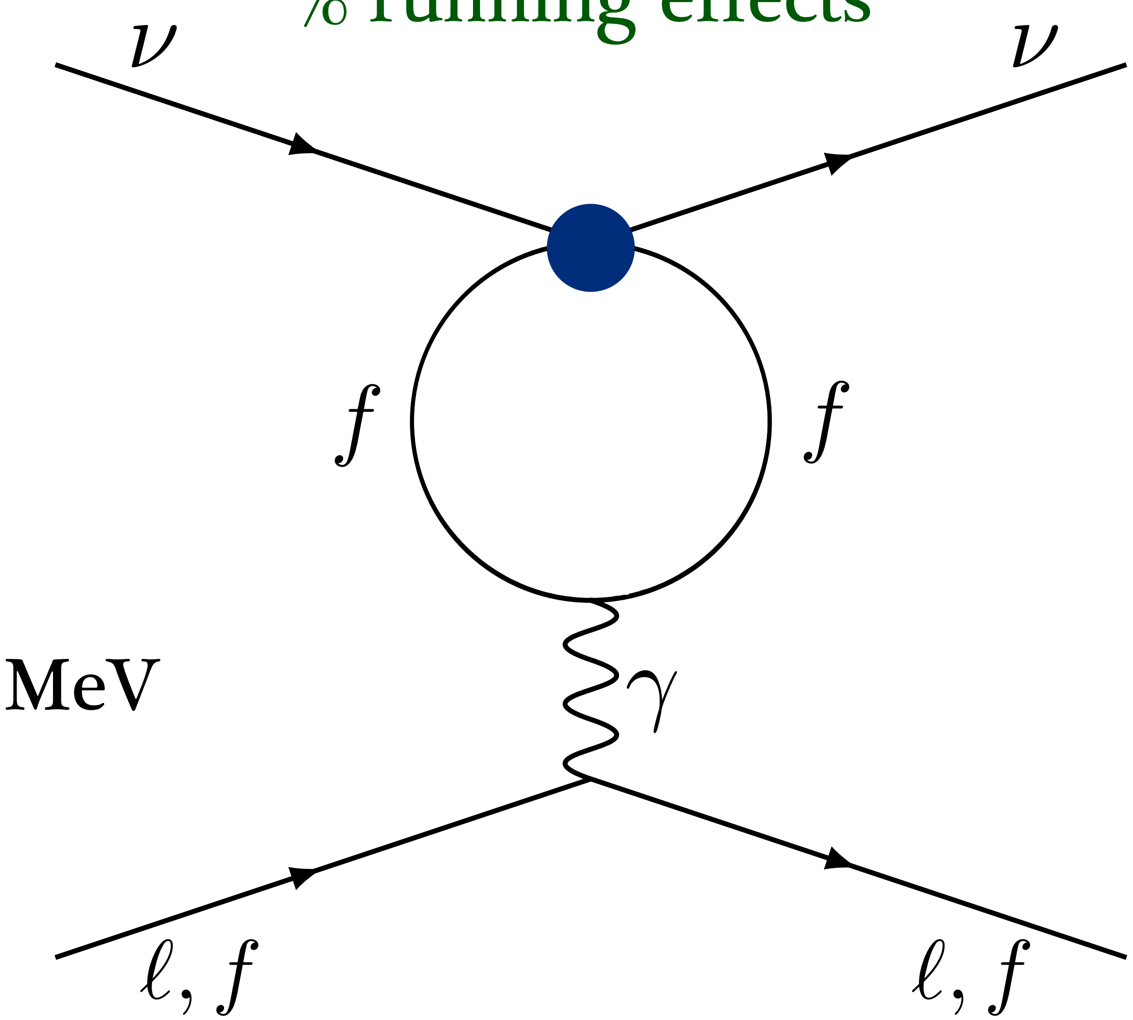


- integrate out top, Z, W, h

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

- integrate out GeV particles
- α_s becomes too strong
- hadronic physics down to 140 MeV
- theory with leptons

% running effects



- precise mapping from electroweak to hadronic scales

✓

Coherent elastic neutrino-nucleus scattering

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

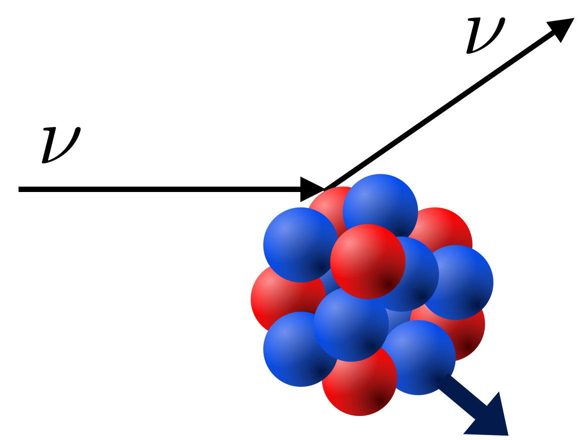
neutrino energy < 100 MeV

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]

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

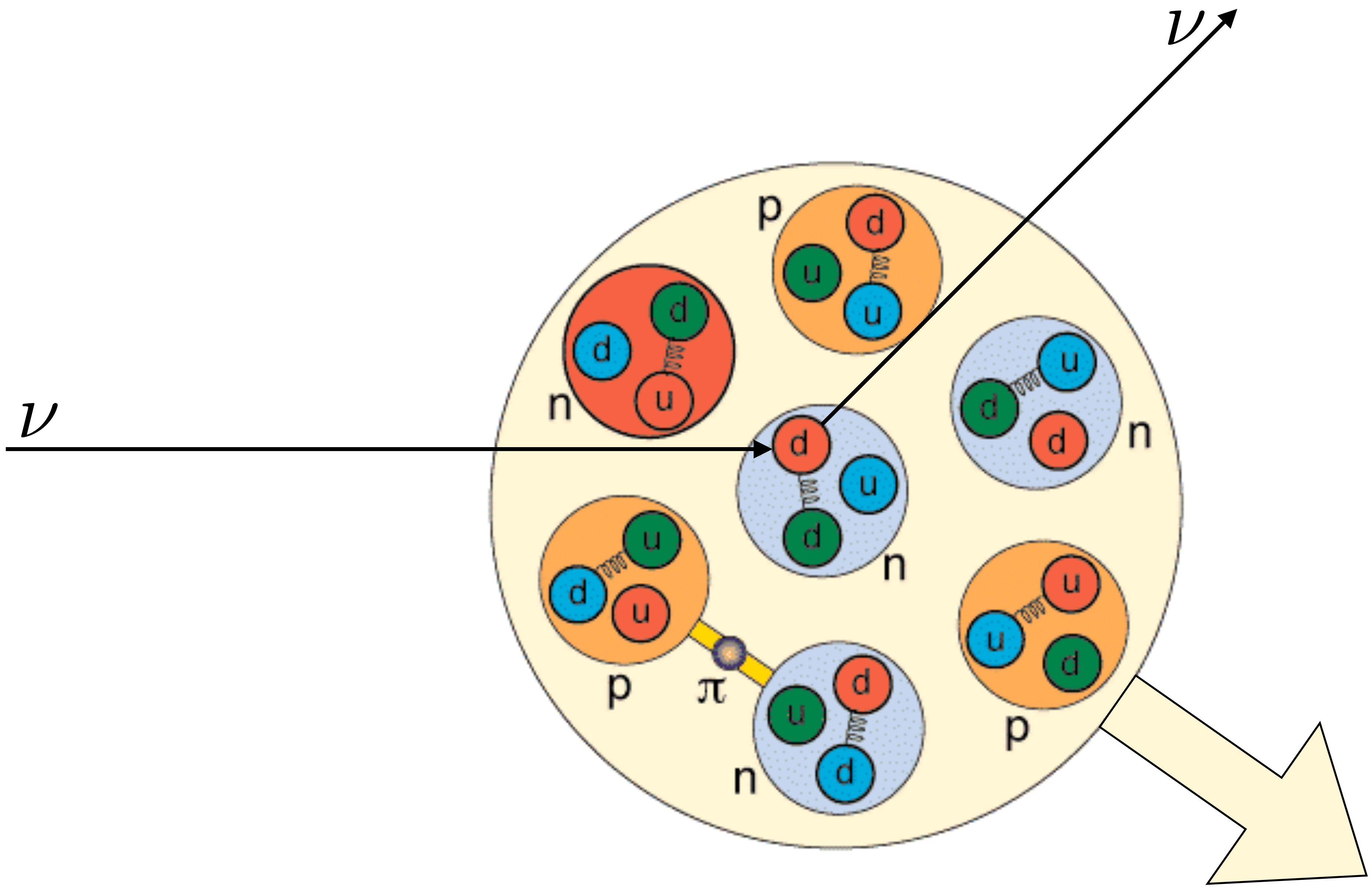
- first detection in 2017 at SNS, measured on CsI and Ar

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

- rapidly developing field nowadays

- CEvNS enters precision era with πDAR sources

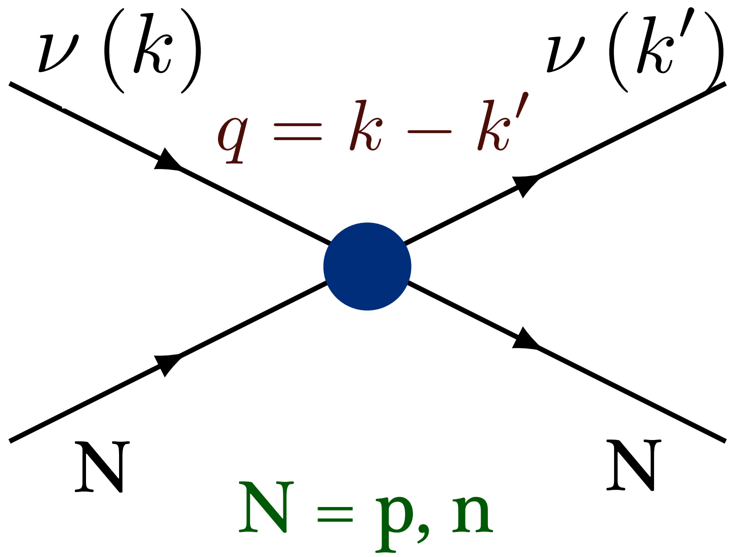
From quarks to nuclei



fafnir.phyast.pitt.edu

- scattering on quarks in nucleons in nucleus

From quarks to nucleons



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

contact interaction at GeV energies

- neutral-current nucleon matrix elements

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

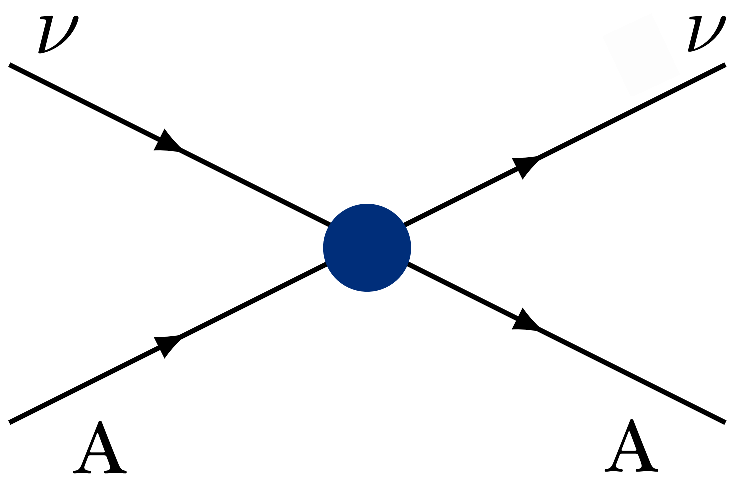
$$\mathcal{M} \sim \bar{\nu}_\ell \gamma_\mu \mathrm{P}_\mathrm{L} \nu_\ell \cdot \langle N | \sum_q \bar{q} \gamma^\mu (c_\mathrm{L}^{\nu_\ell q} \mathrm{P}_\mathrm{L} + c_\mathrm{R}^{\nu_\ell q} \mathrm{P}_\mathrm{R}) q | N \rangle$$

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

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

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

spin-0 nuclei

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

$$\mathrm{F}_\mathrm{W} = \left(\frac{c_\mathrm{L}^{\nu_\ell u} + c_\mathrm{R}^{\nu_\ell u}}{\sqrt{2}\mathrm{G}_\mathrm{F}}\mathrm{G}_\mathrm{E}^{n,u} + \frac{c_\mathrm{L}^{\nu_\ell d} + c_\mathrm{R}^{\nu_\ell d}}{\sqrt{2}\mathrm{G}_\mathrm{F}}\mathrm{G}_\mathrm{E}^{n,d}\right) f_n + (n \leftrightarrow p)$$

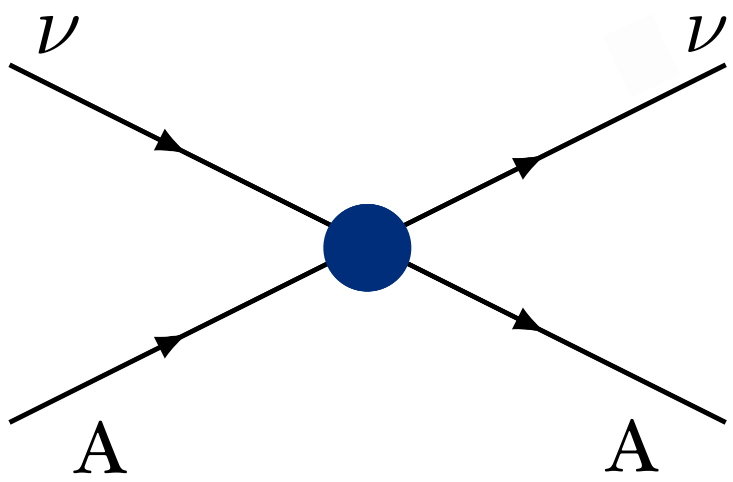
- flavor-independent form factor above GeV scale

- 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

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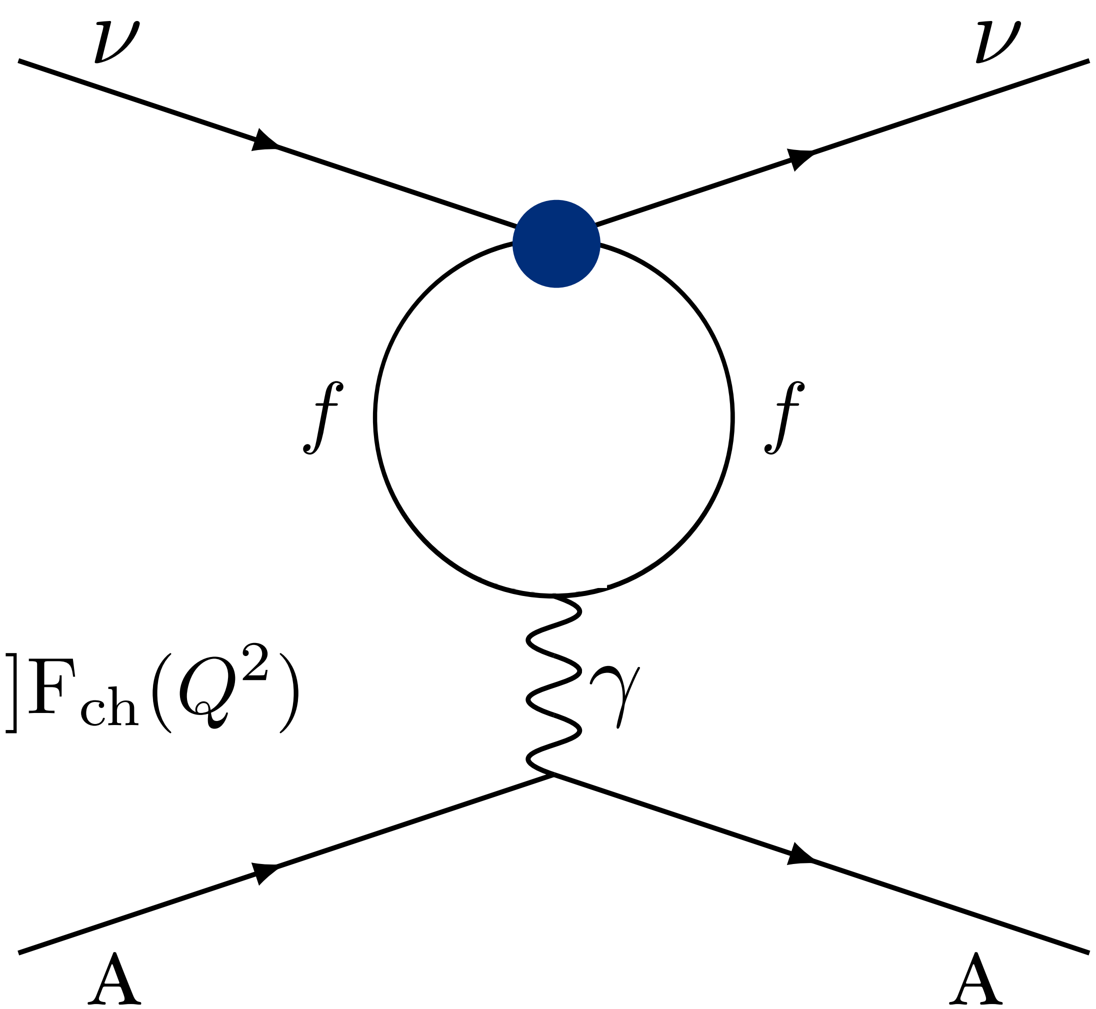


- effect of radiative corrections

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

- radiative corrections enter with the nucleus charge form factor

Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop

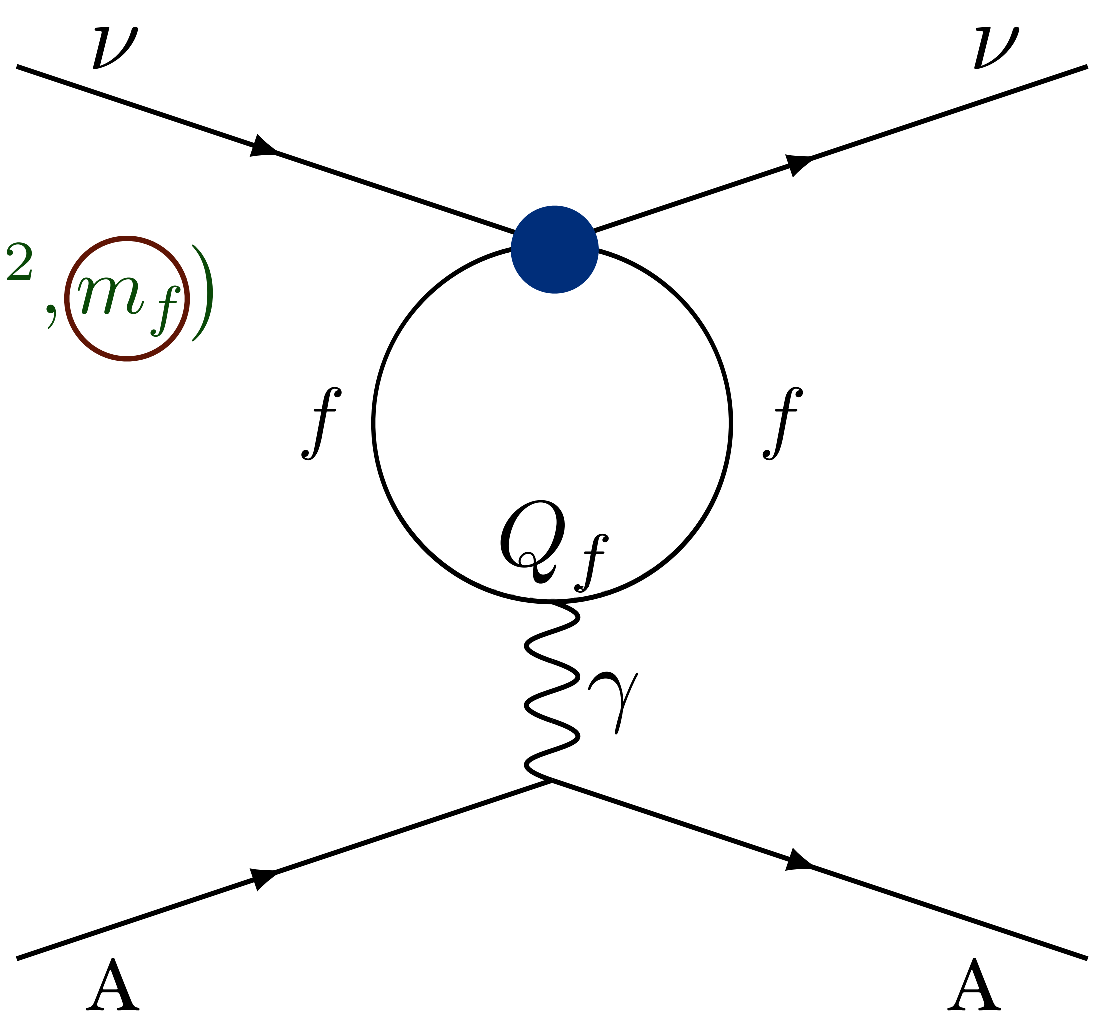
$$\mathcal{L}_{\text{eff}} = -\bar{\nu}_\ell \gamma_\mu \mathrm{P_L} \nu_\ell \cdot \bar{f} \gamma^\mu \left(c_{\mathrm{L}}^{\nu_\ell f} \mathrm{P_L} + c_{\mathrm{R}}^{\nu_\ell f} \mathrm{P_R} \right) f$$

- lepton loops

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

- origin of flavor dependence

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



- lepton mass breaks "flavor universality"

Neutrino scattering in EFT

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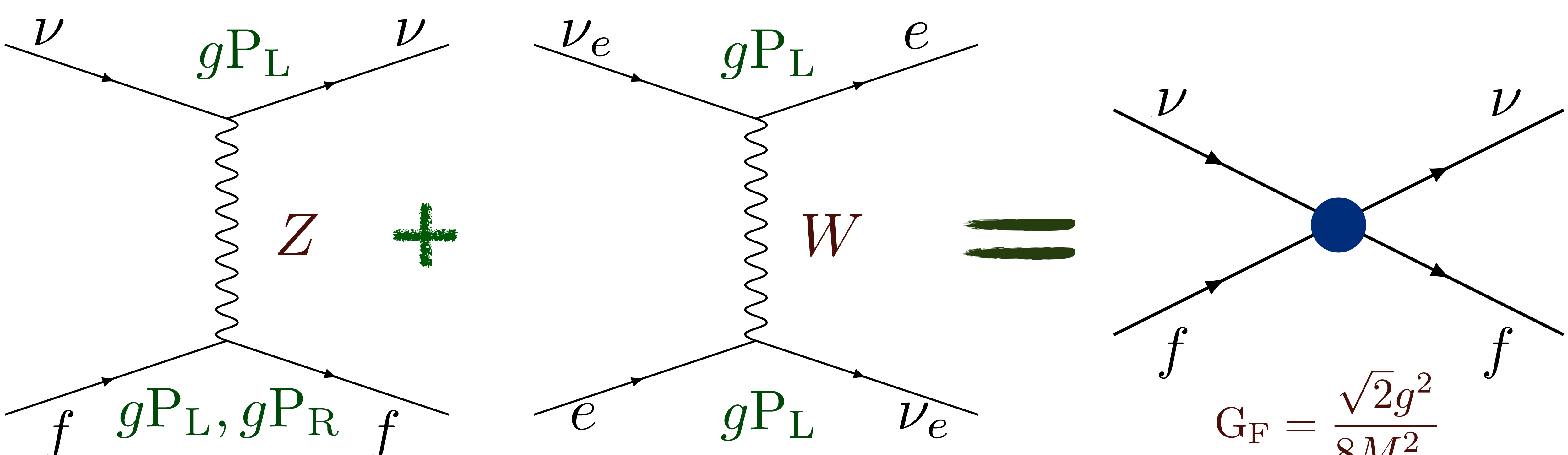
couplings to electron

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

Weinberg (1967), 't Hooft (1971)

neutral current charged current



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

- same-flavor left-handed coupling is enhanced by exchange of W

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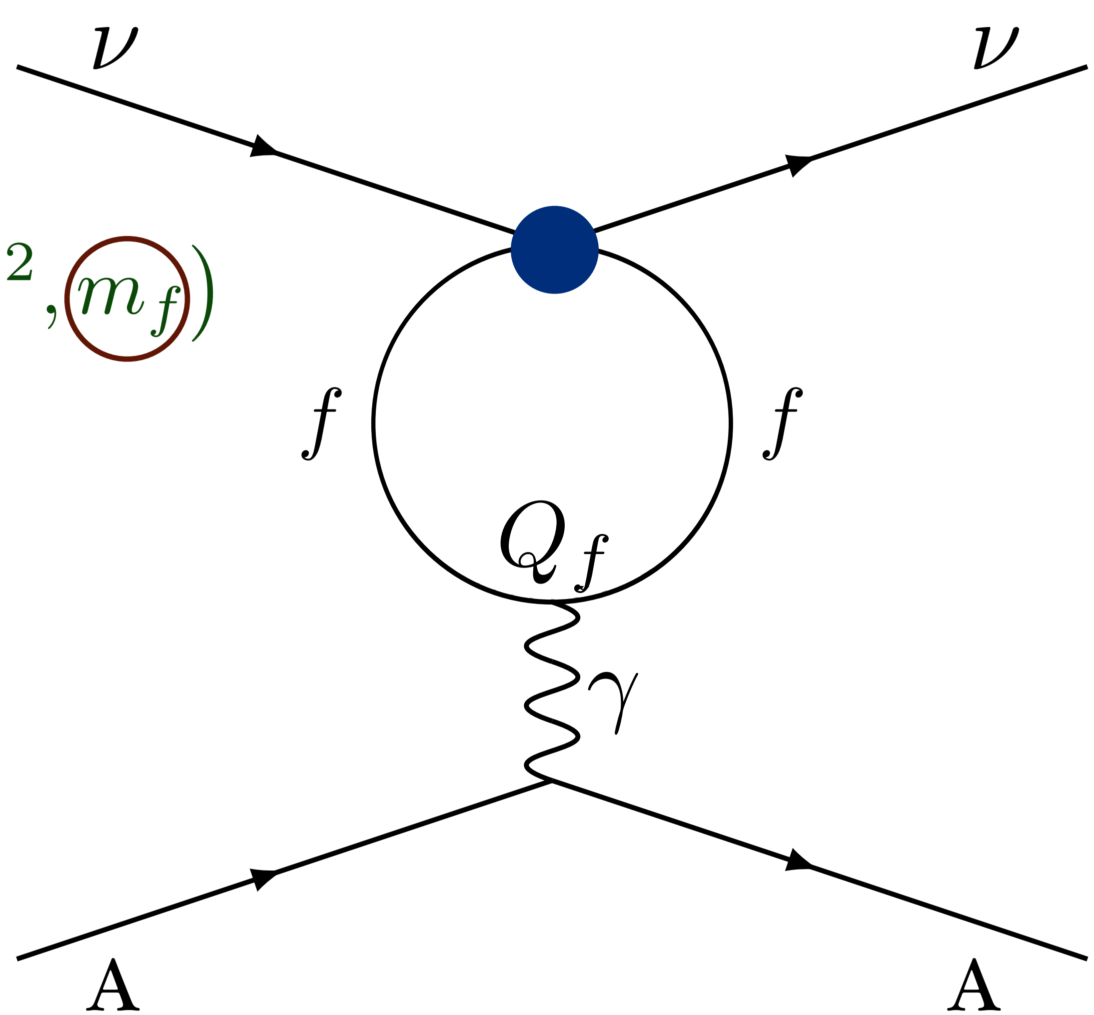

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- lepton mass breaks ``flavor universality”

Light-quark contribution

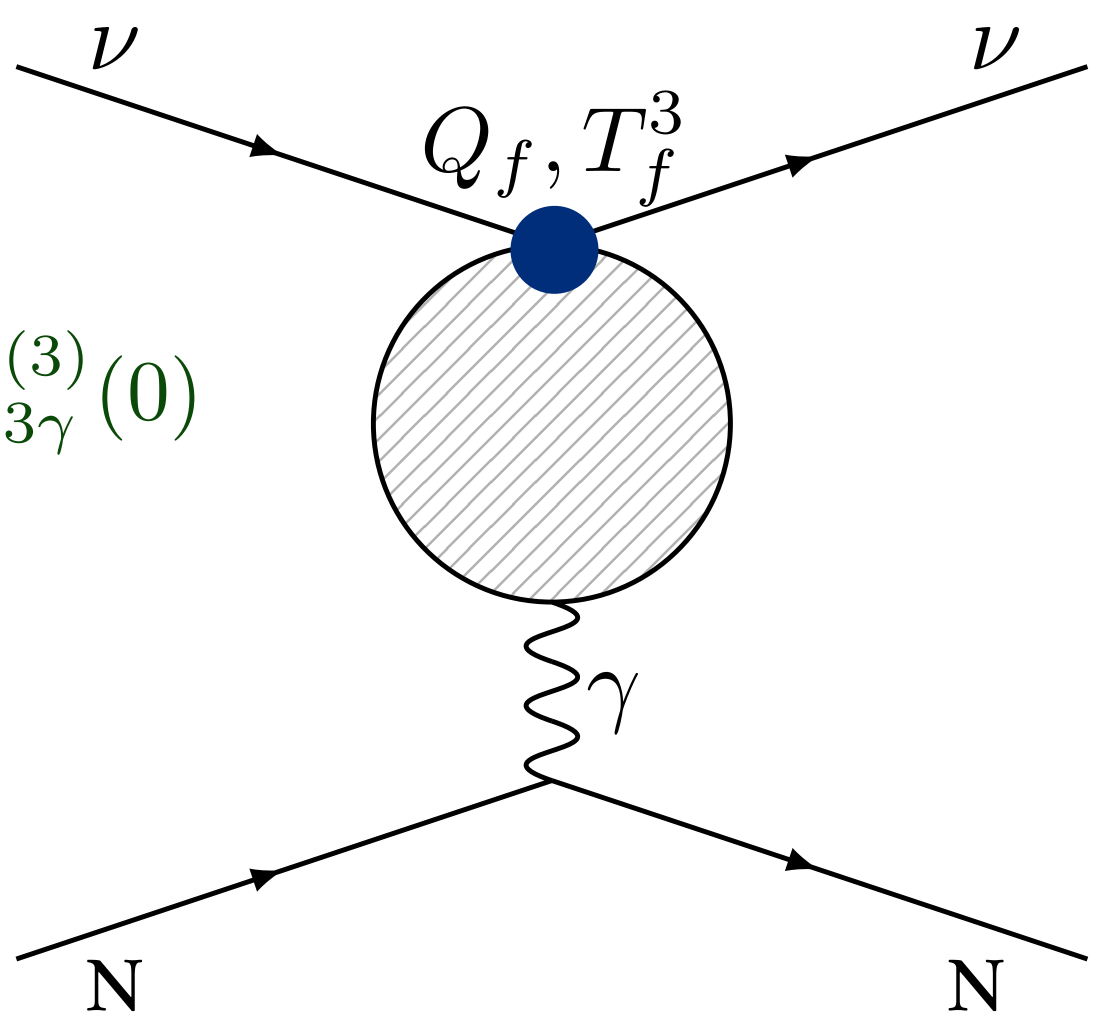
- description in terms of quarks is invalid at CEvNS kinematics

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

- 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

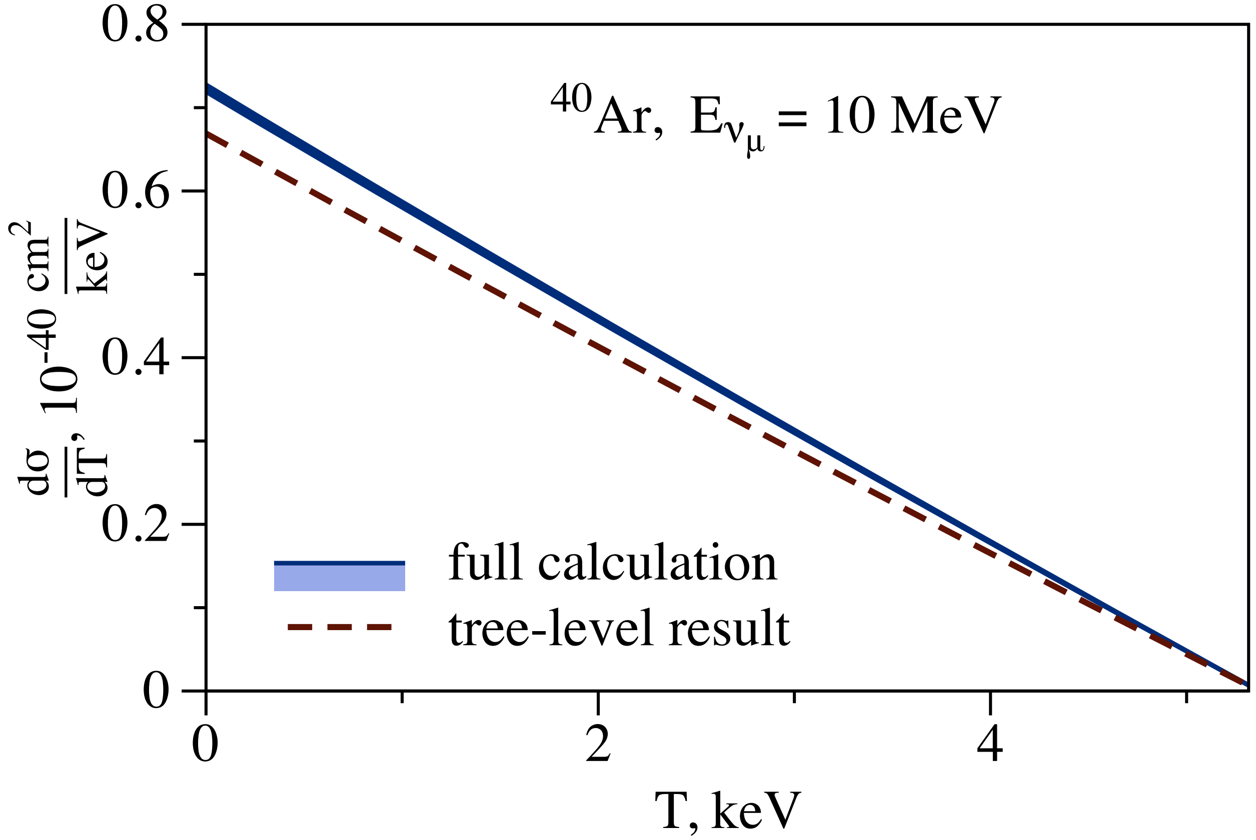


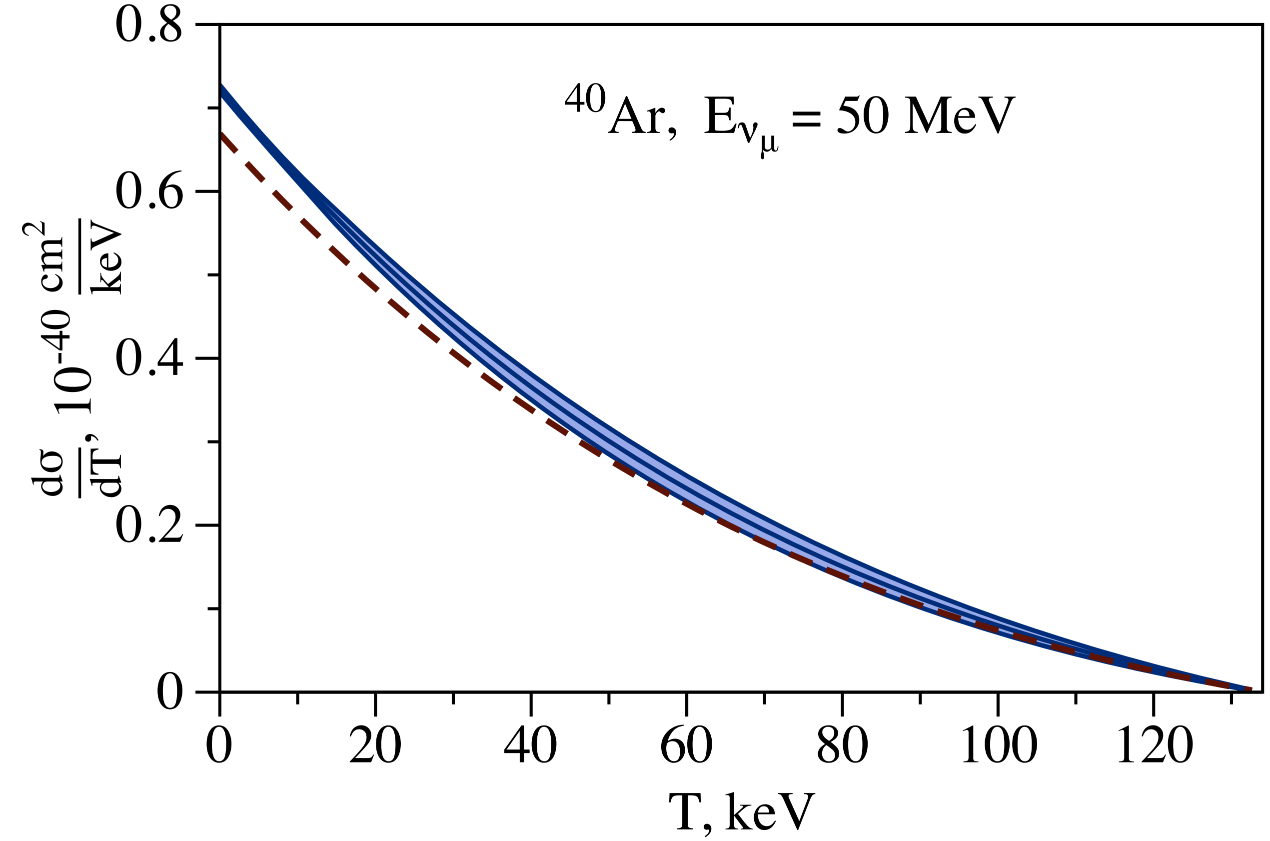
- non-perturbative light-quark contribution: error at low energy

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)

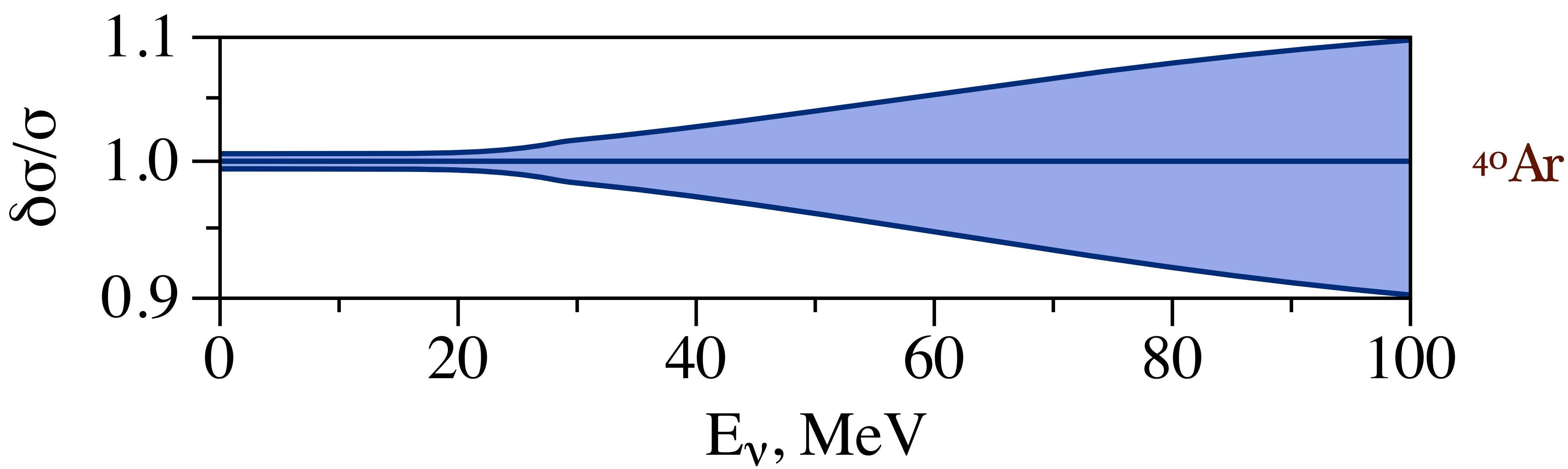




- % effect of radiative corrections on cross sections

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

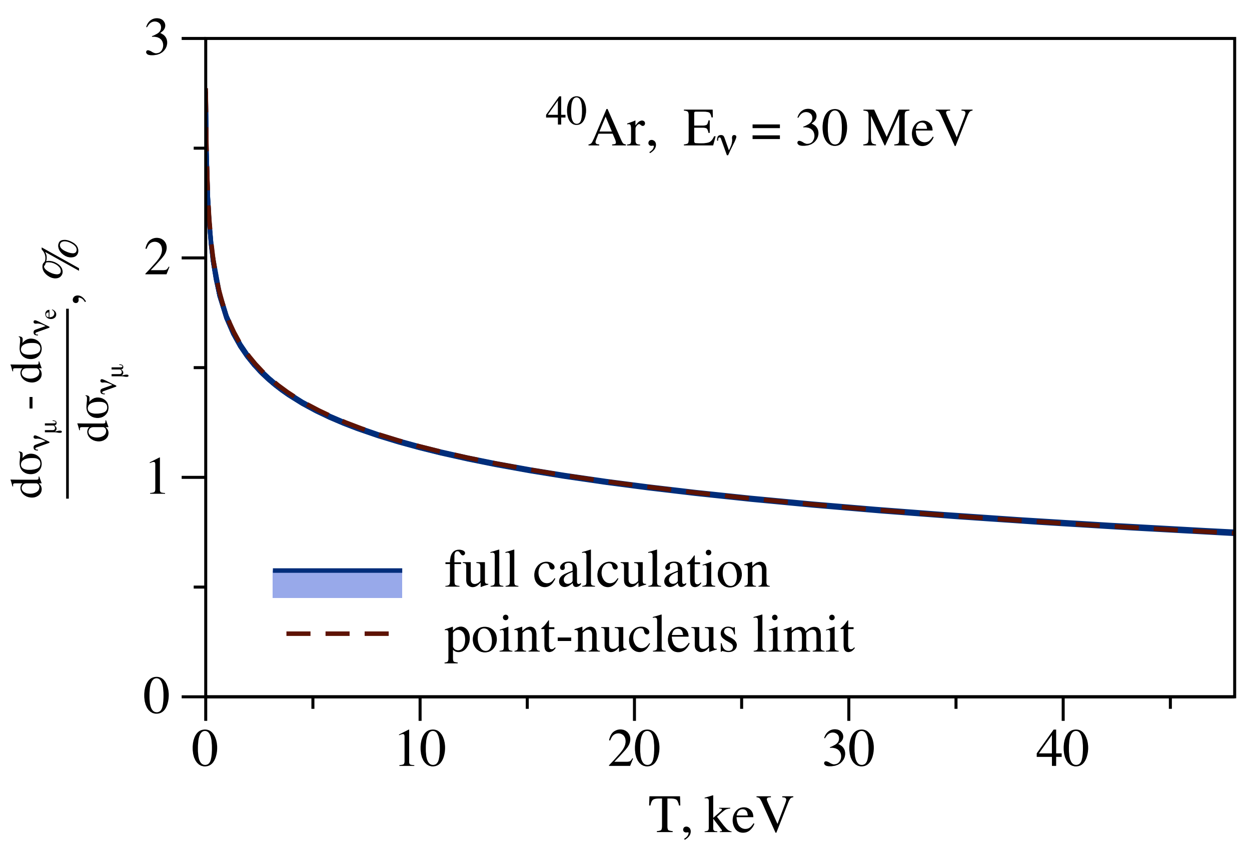
- hadronic error 0.6% at low energy, nuclear error at higher energy

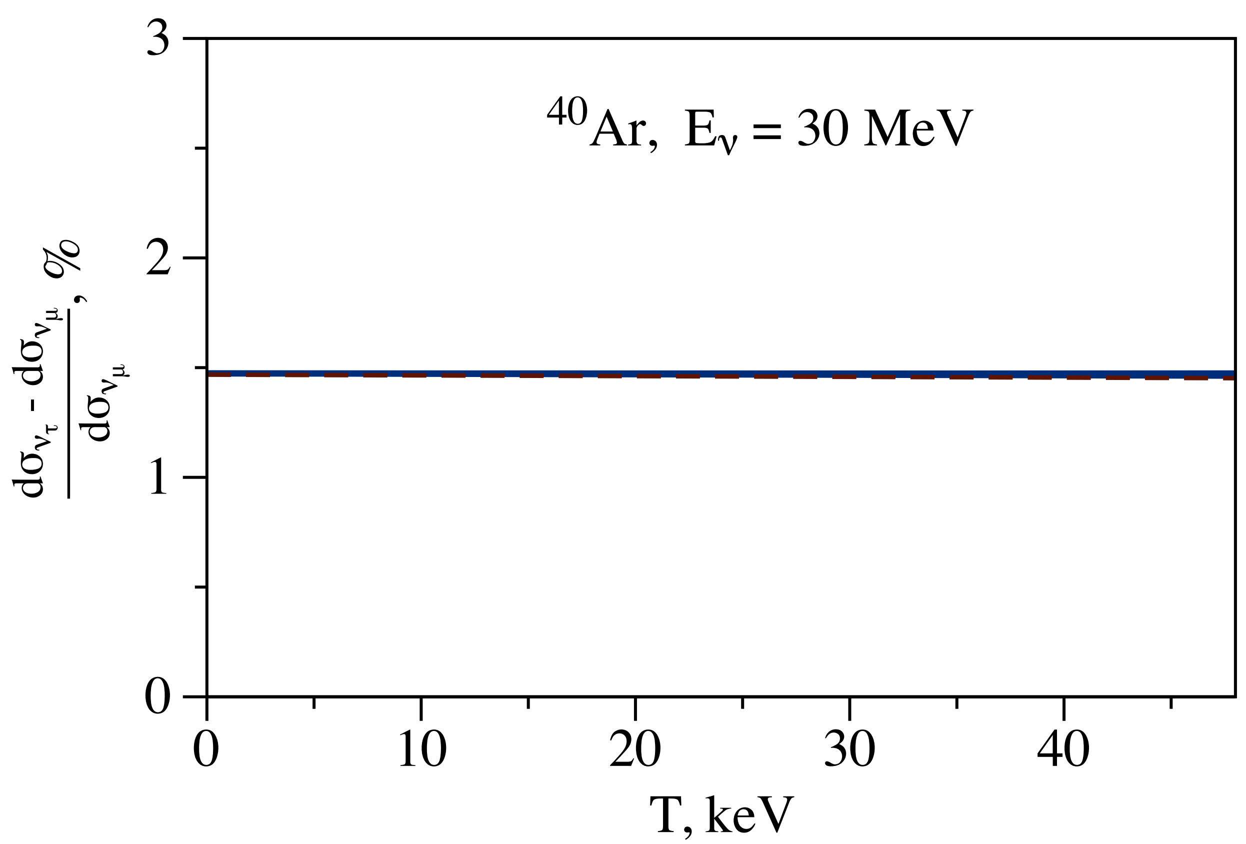
Flavor difference

- 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

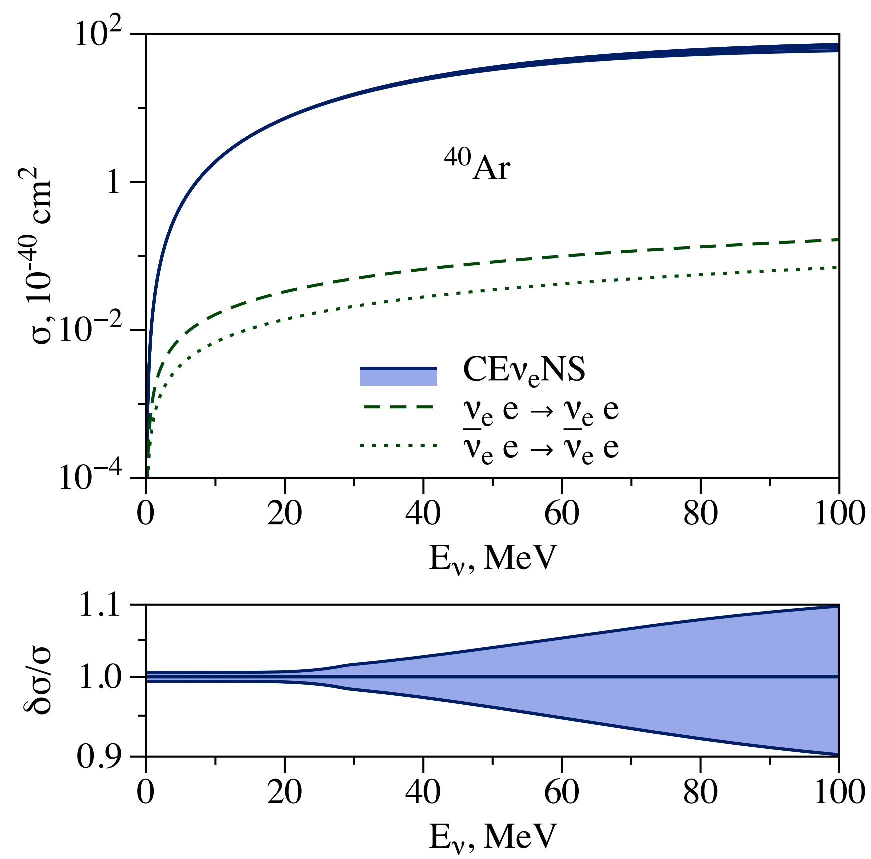
How to use precise CEvNS?

precision EW physics

Weinberg angle   charge radii   NSI

IsoDAR sources

CEvNS is precisely known



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Oscillation physics

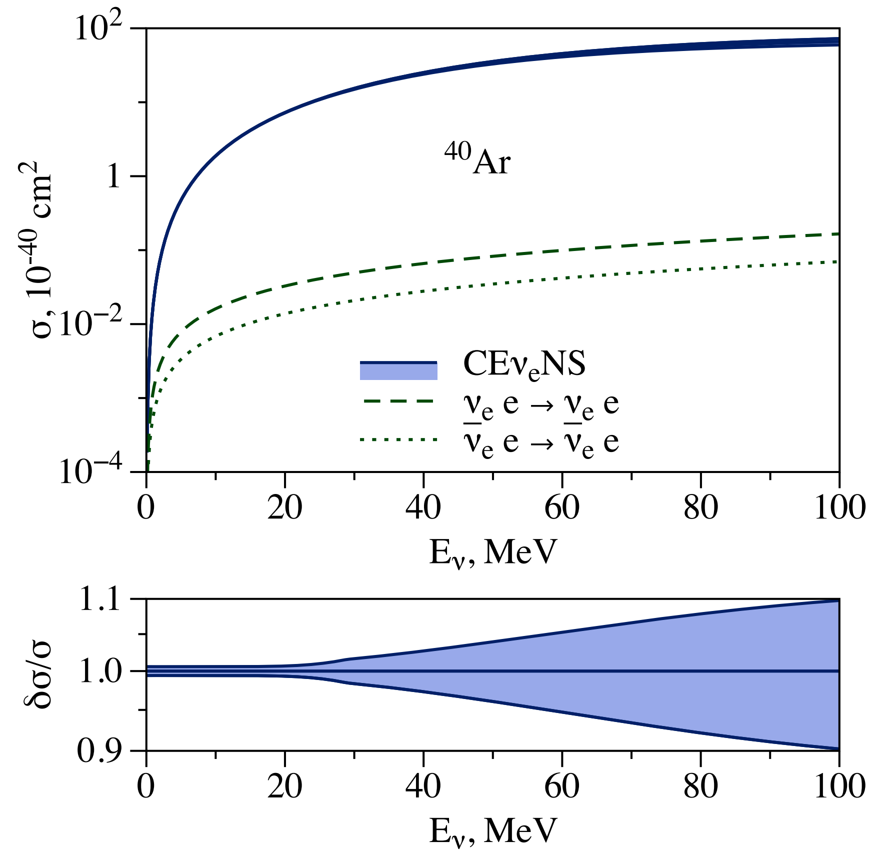
tau neutrino at low energy

$\nu_\mu \to \nu_\tau$

15 km from πDAR sources

0.6-1.3% change

in event rates



Sterile neutrino searches

SM result with errors

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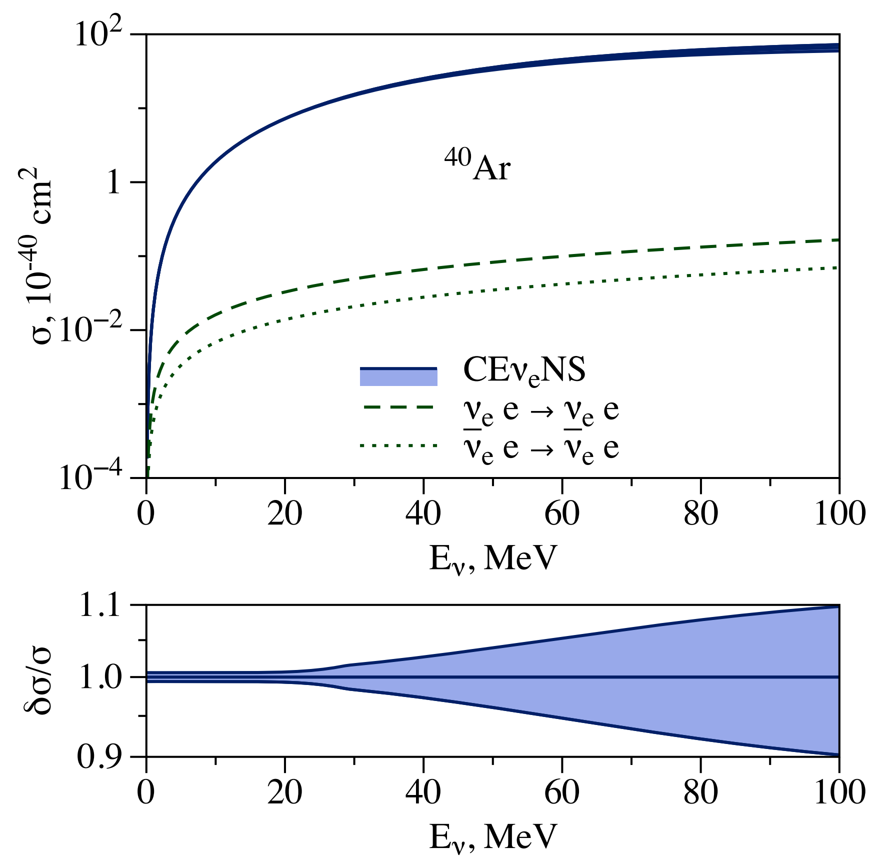


Sterile neutrino searches

SM result with errors

Nuclear reactors monitoring

measure neutrino flux with IBD

Dark matter searches

penetrate neutrino floor

How to use precise CEvNS?

precision EW physics

IsoDAR sources

neutrino magnetic moment

CEvNS is precisely known

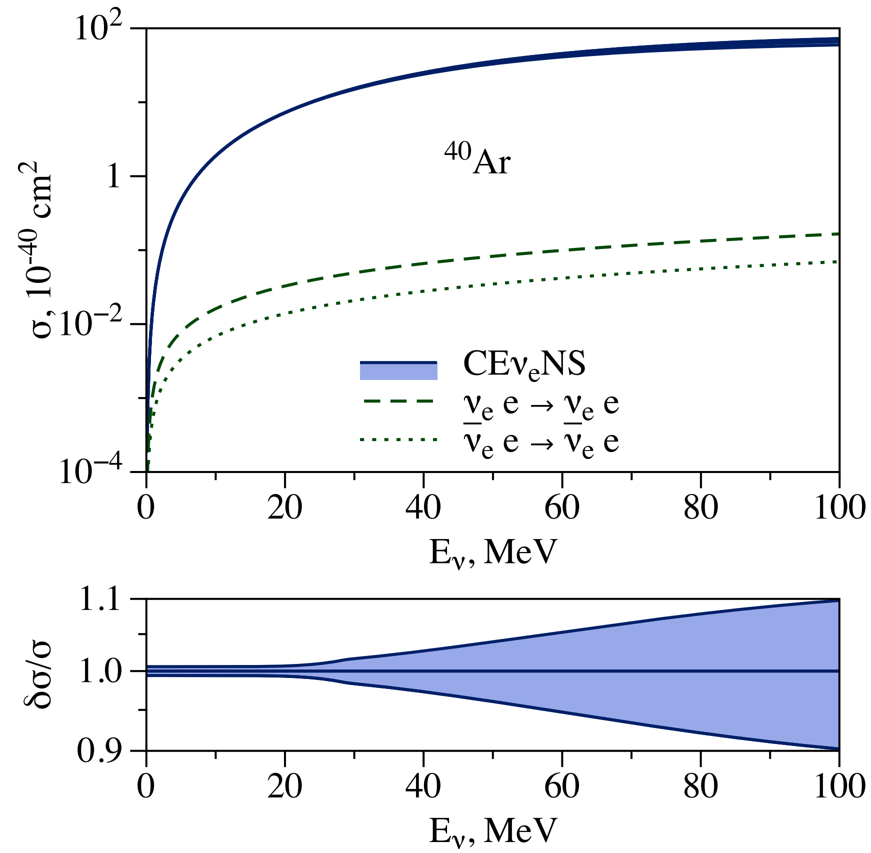
Solar neutrino physics

promising way to detect

flavor dependence

by day-night asymmetry

@Louis Strigari



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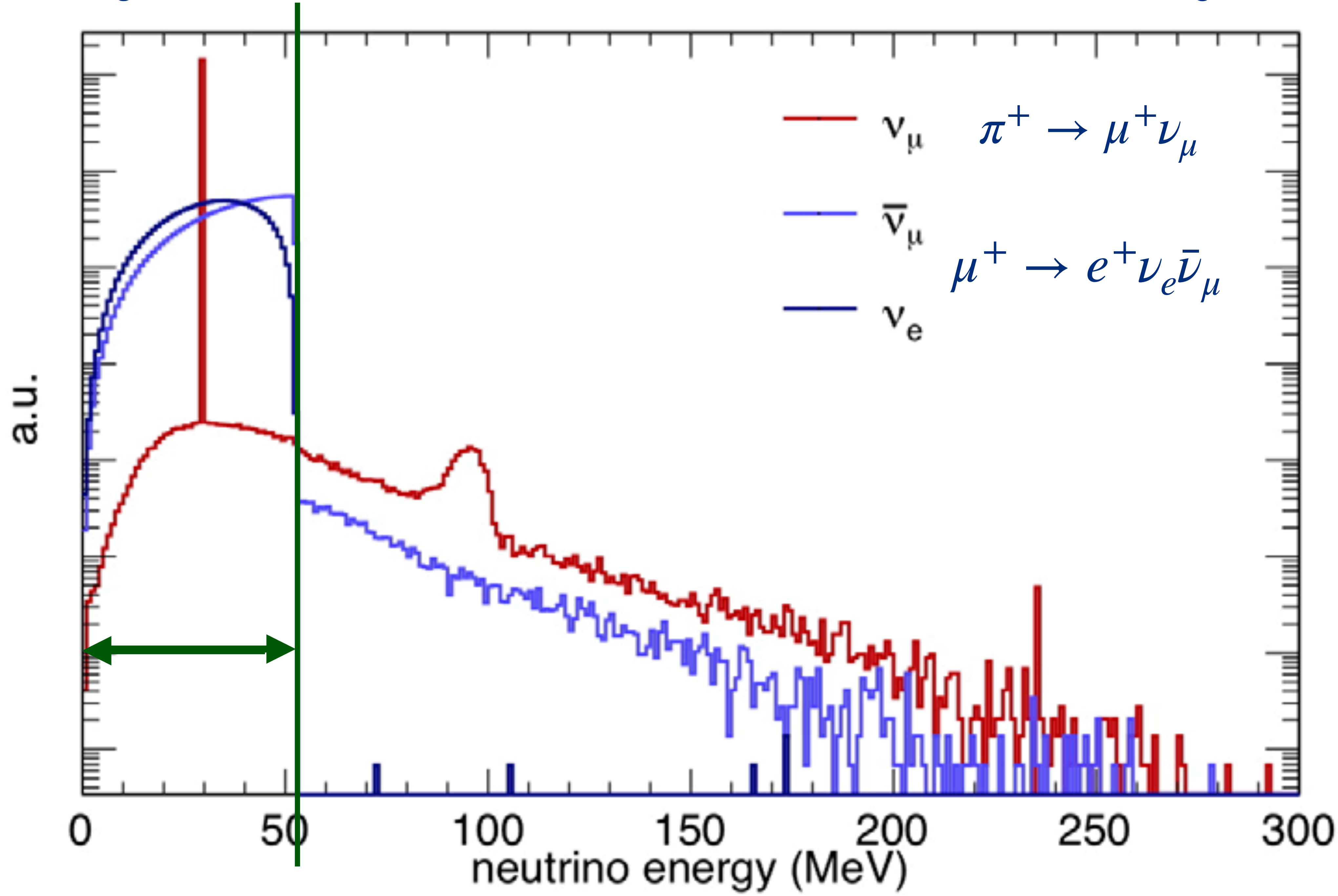
(Anti)neutrino energy spectra from muon, pion, and kaon decays

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

πDAR spectrum at tree level



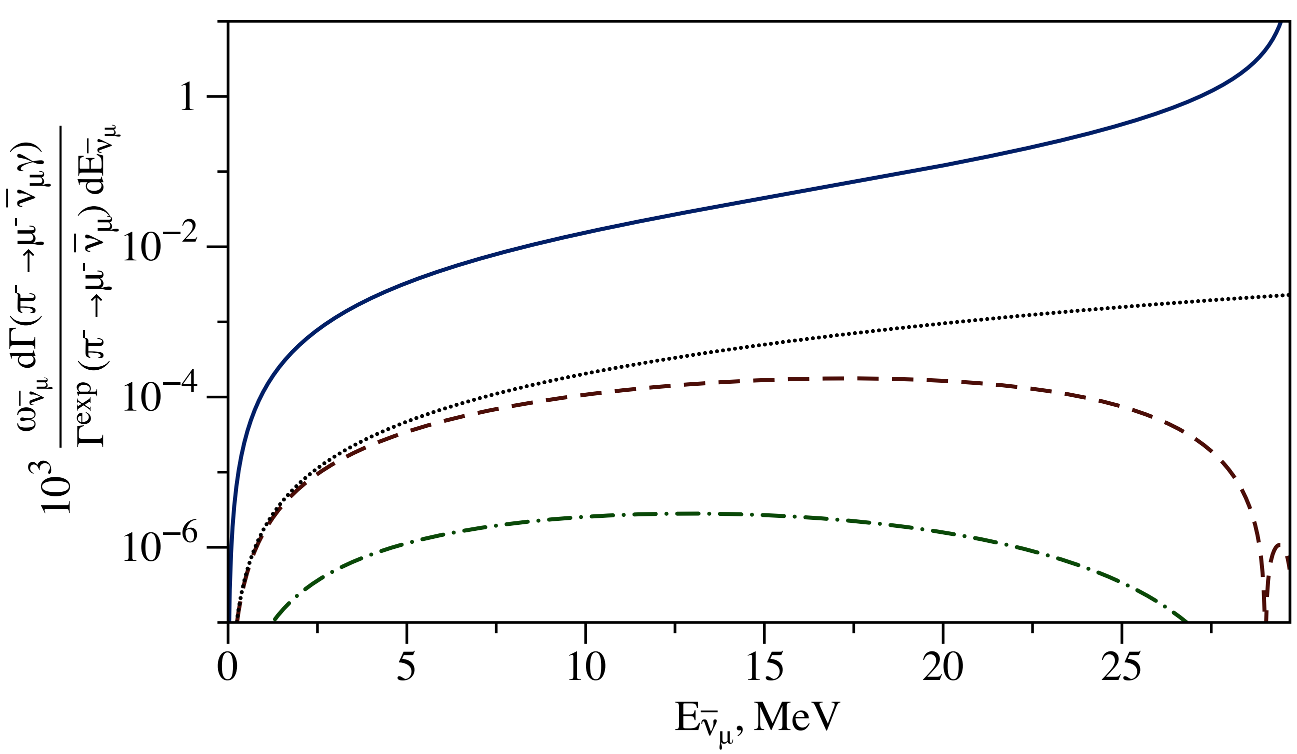
Akimov et al., Science 357 6356, 1123-1126 (2017)

- flavor-dependent spectrum at tree level with prompt ν_μ line

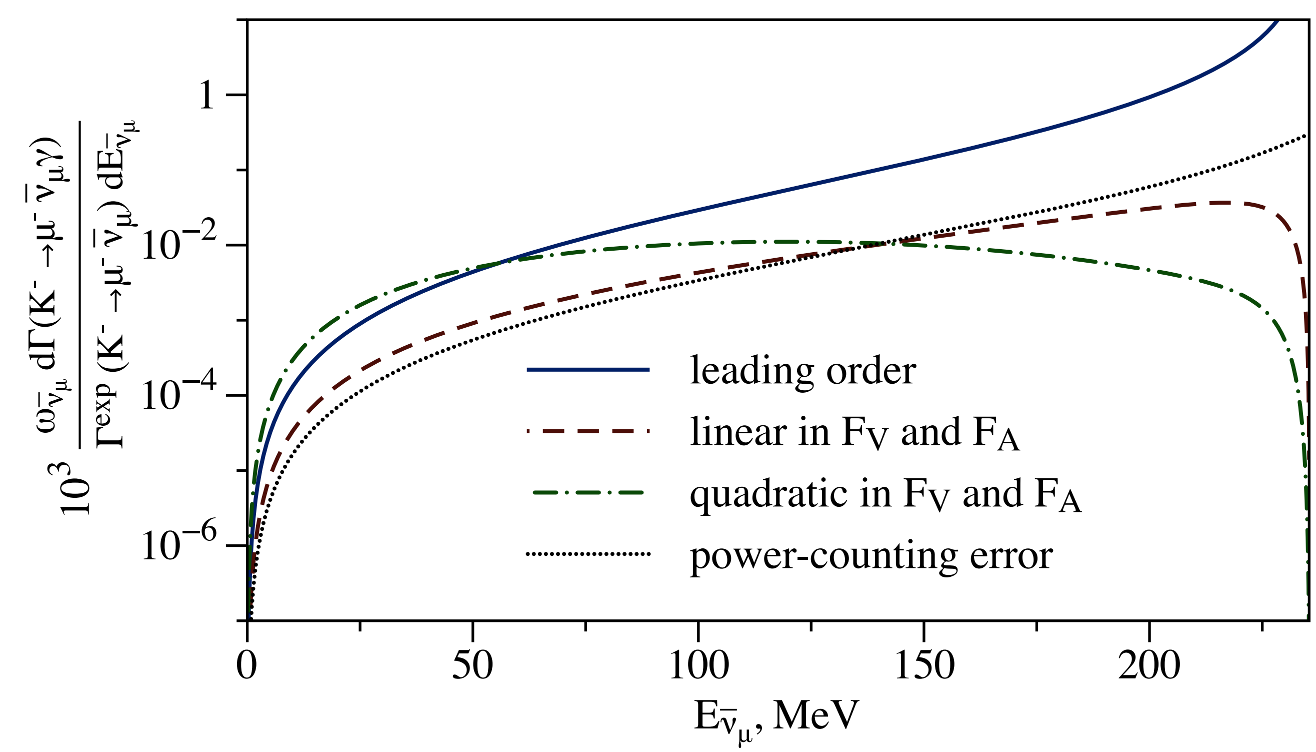
Radiative corrections to decay of mesons

- broadening of monochromatic line with elastic peak

$\pi^- \to \mu^- \bar{\nu}_\mu \gamma$



$K^- \to \mu^- \bar{\nu}_\mu \gamma$



- analytic spectra presented
- negligible change in flux-averaged cross sections due to distortion

$$\sigma_{\bar{\nu}_\mu}^{^{40}\mathrm{Ar}} = (15.1867 \pm 0.25) \times 10^{-40}\ \mathrm{cm}^2$$

$$\sigma_{\bar{\nu}_\mu,\mathrm{LO}}^{^{40}\mathrm{Ar}} = (15.1875 \pm 0.25) \times 10^{-40}\ \mathrm{cm}^2$$

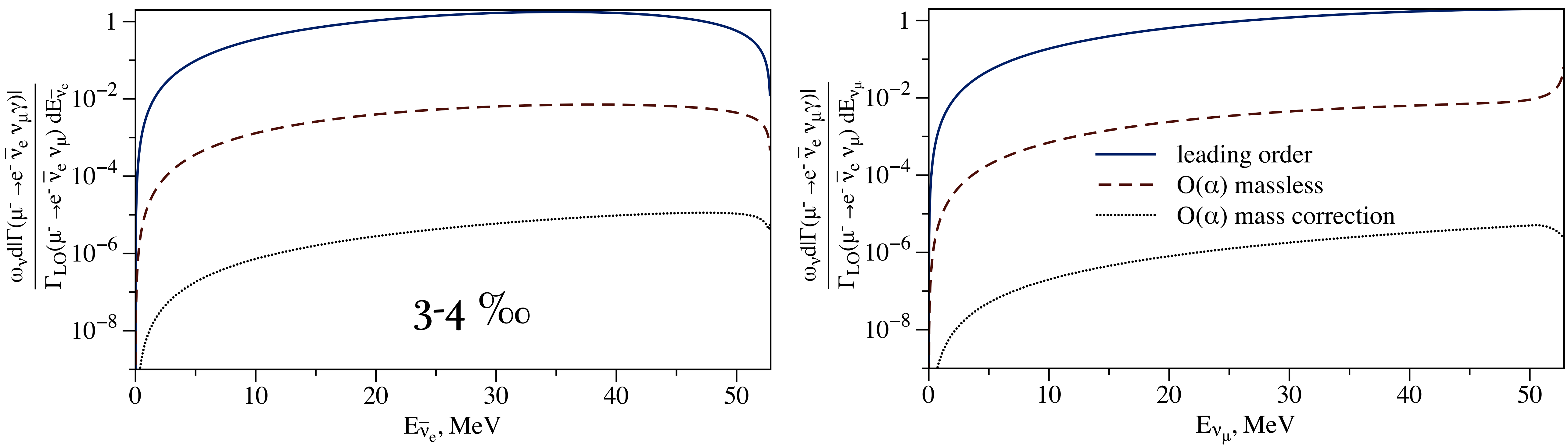
- $\lesssim 10^{-4}$ change in GeV (anti)neutrino fluxes

- negligible change when normalized to experimental lifetime

Radiative corrections to muon decay

- flavor-dependent distortions at permille level

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma$$



- analytic spectra presented in agreement with b decays within QCD
  M. Jezabek, J.H. Kuhn, Nucl. Phys. B 320, 20 (1989)
- permille change in flux-averaged cross sections due to distortion

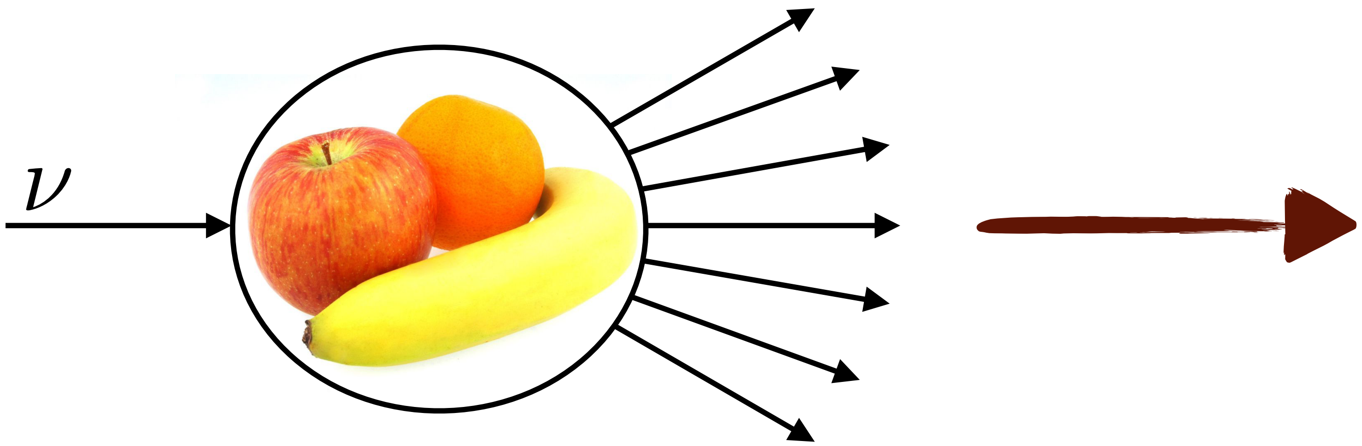
$$\sigma_{\bar{\nu}_e}^{^{40}\mathrm{Ar}} = (17.484 \pm 0.43) \times 10^{-40}\ \mathrm{cm}^2 \qquad \sigma_{\nu_\mu}^{^{40}\mathrm{Ar}} = (22.448 \pm 0.66) \times 10^{-40}\ \mathrm{cm}^2$$

$$\sigma_{\bar{\nu}_e,\mathrm{LO}}^{^{40}\mathrm{Ar}} = (17.490 \pm 0.43) \times 10^{-40}\ \mathrm{cm}^2 \qquad \sigma_{\nu_\mu,\mathrm{LO}}^{^{40}\mathrm{Ar}} = (22.454 \pm 0.66) \times 10^{-40}\ \mathrm{cm}^2$$

- modern QED/EW form factors with different mass of leptons

- permille-level change in agreement with KLN theorem

Conclusions



radiative corrections
in EFT framework

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

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

- precise neutrino spectra from muon, pion, and kaon decays

Thanks for your attention !!!