

Magnificent CEvNS 2023

Workshop

23 March, 2023

Munich, Germany

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



Los Alamos
NATIONAL LABORATORY

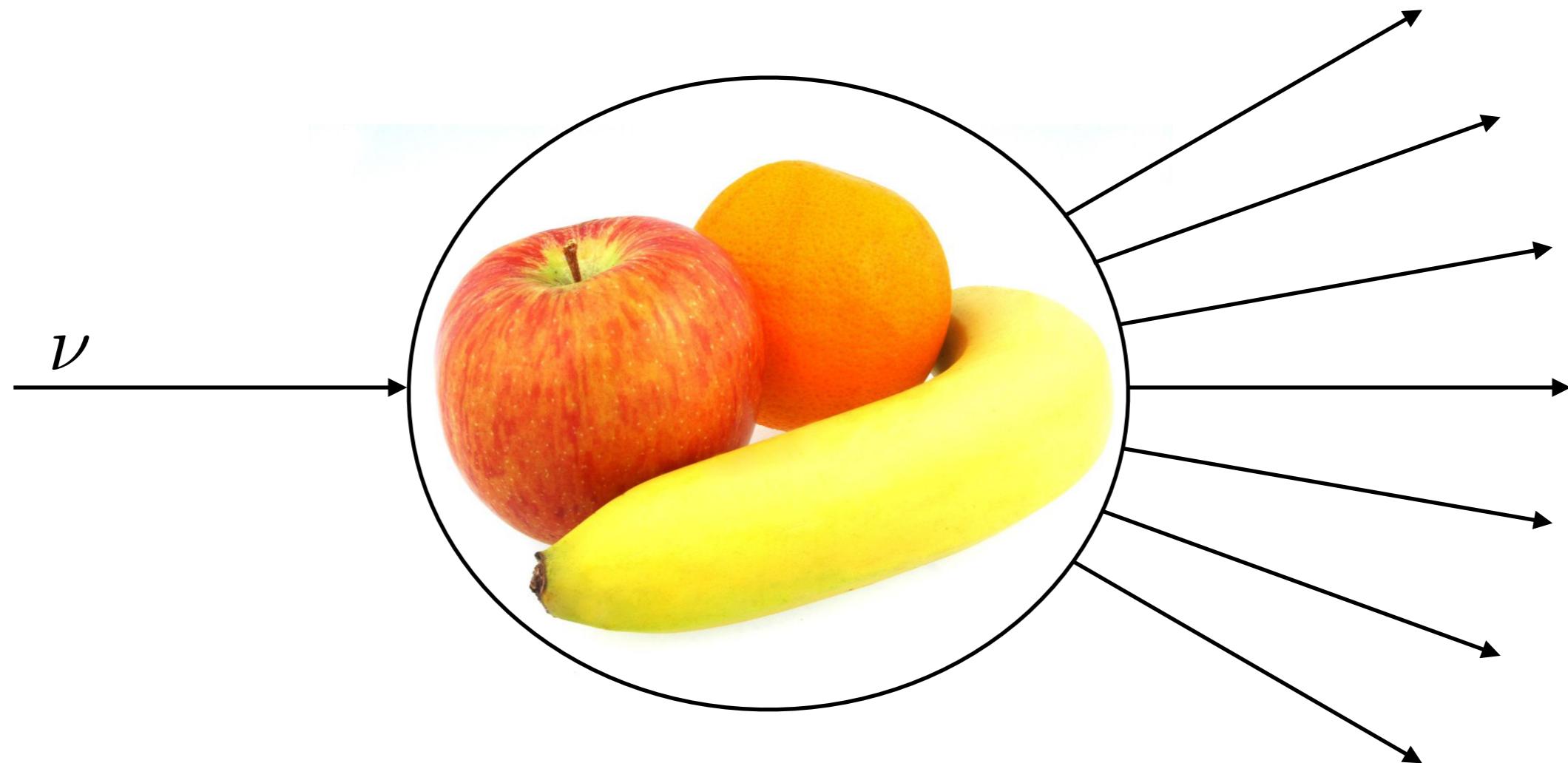
Oleksandr (Sasha) Tomalak
LA-UR-23-22297

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

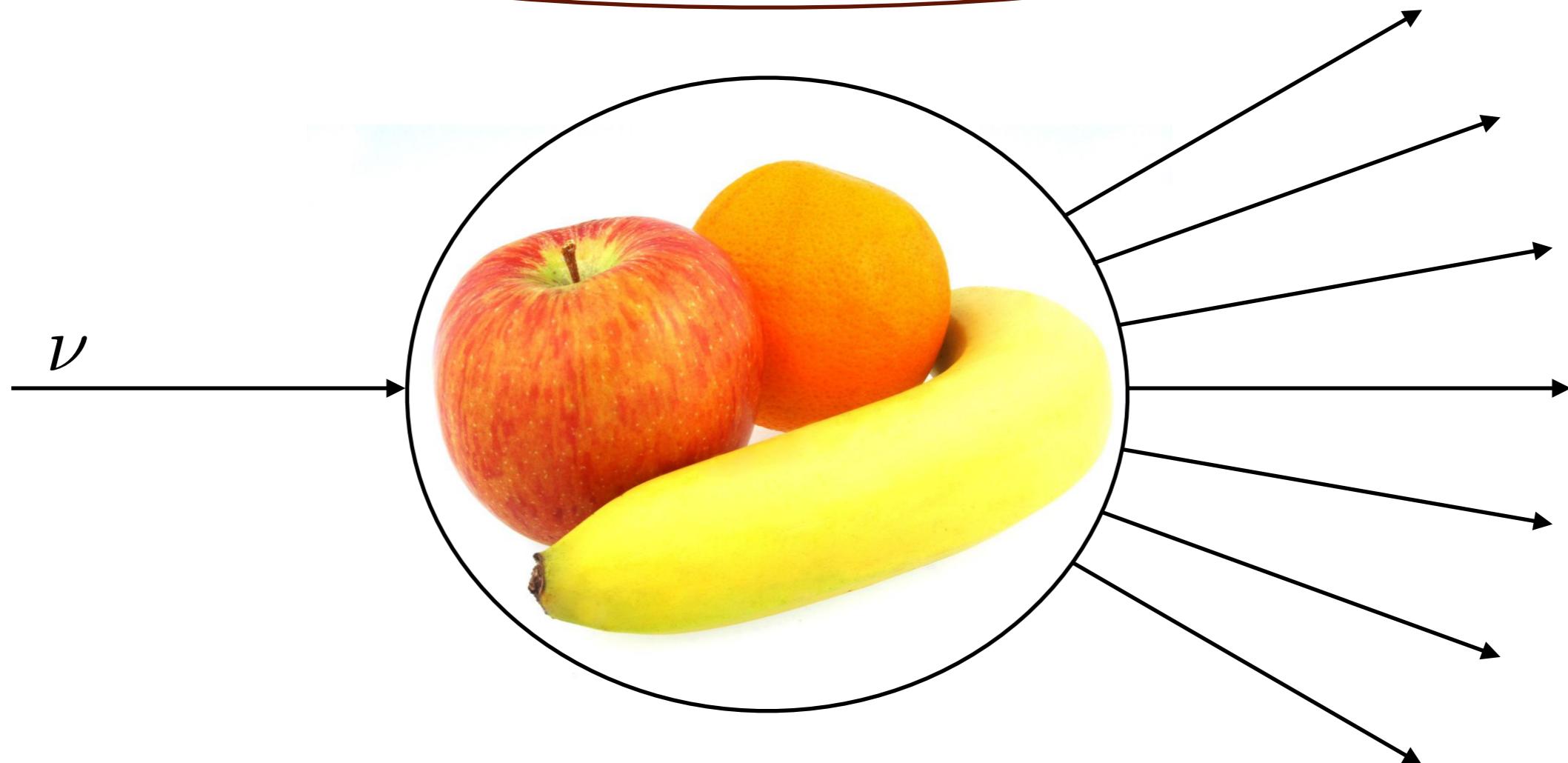


$$X \frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by kinematic-dependent factors}$$

- kinematic dependence and factor X can enhance QED corrections

Electroweak corrections

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



$$\frac{\alpha}{\pi} \sim 0.2 \% \text{ multiplied by } \frac{1}{\sin^2 \theta_W}, \ln \frac{M_Z}{M}, \ln \frac{M_t}{M}, \dots$$

- 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

- matching to low-energy EFT

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

- consider only leading in G_F terms: loop corrections in a, a_s
- gauge-invariant matching of amplitudes, renormalized in $\overline{\text{MS}}$ scheme

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

- G_F : combination of parameters is precisely measured

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

MULAN (2012)

- matching at order $a a_s$: left- and right-handed couplings
- muon lifetime measurement improves precision

Running to low scales

M_Z - integrate out top, Z, W, h

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

m_b

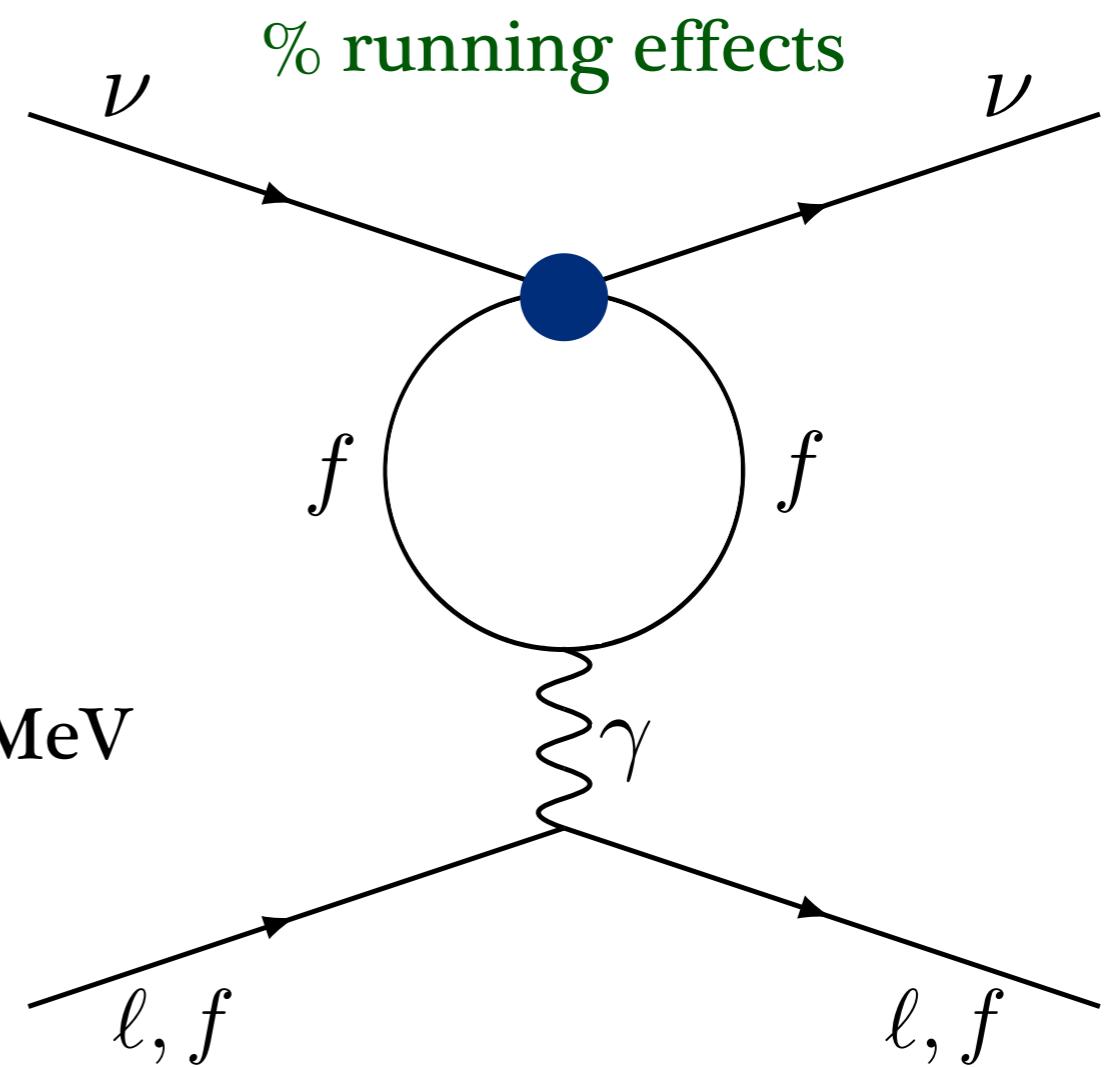
m_τ - integrate out GeV particles

m_c

- a_s becomes too strong
- hadronic physics down to 140 MeV

m_π

- theory with leptons



- precise mapping from electroweak to hadronic scales



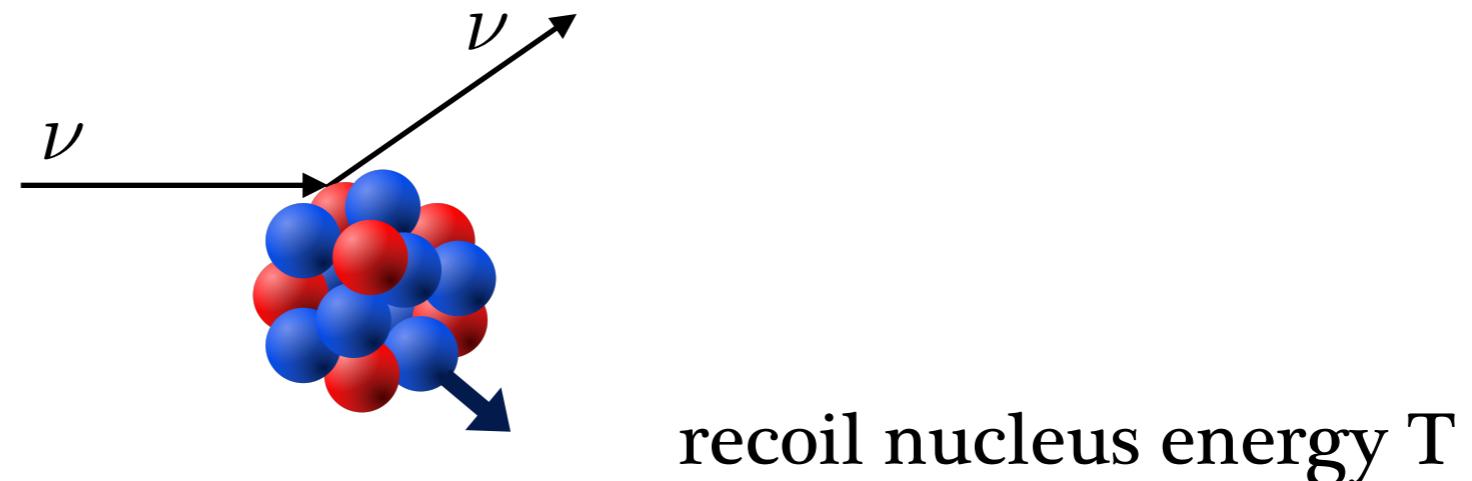
Coherent elastic neutrino-nucleus scattering

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

neutrino energy < 100 MeV

Coherent elastic neutrino-nucleus scattering

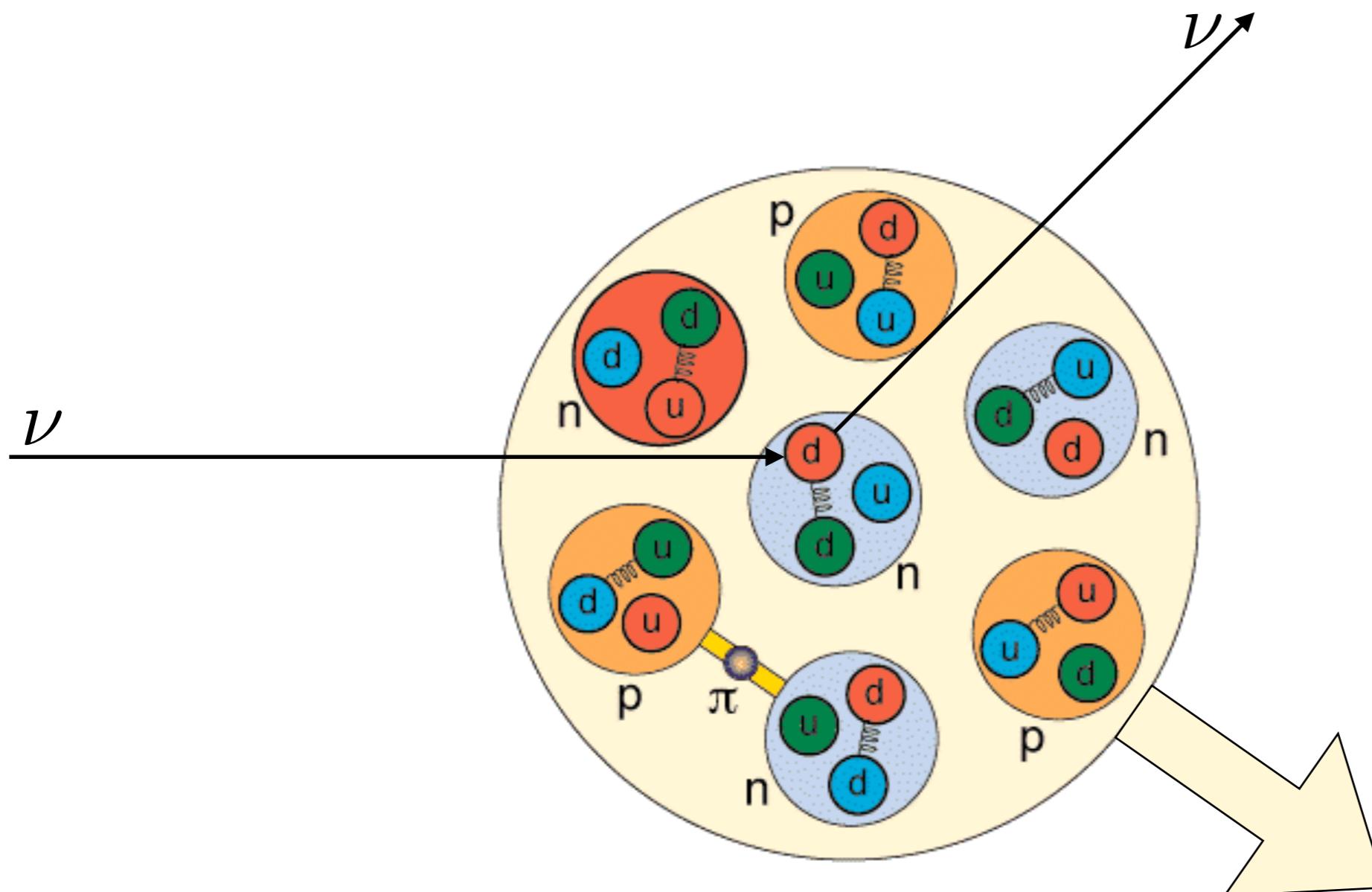
- at low neutrino energies (<50 MeV) nuclear state is unchanged
nucleus recoils as a whole
Stodolsky (1966), Freedman (1974), Kopeliovich and Frankfurt (1974)



- large cross section scales as squared number of neutrons N^2
- $$\frac{d\sigma}{dT} \approx \frac{G_F^2 M_A}{4\pi} \left(1 - \frac{M_A T}{2E_\nu^2}\right) \left(N - (1 - 4\sin^2\theta_W) Z\right)^2$$
- 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 π DAR sources

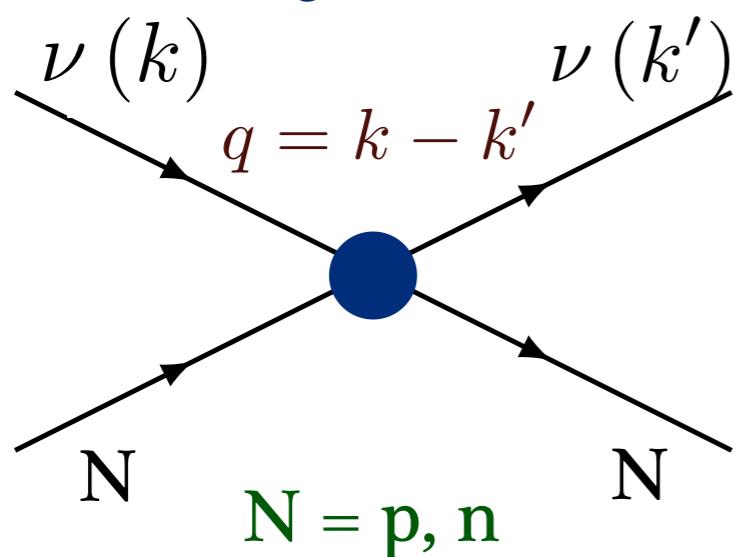
From quarks to nuclei



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

$$P_{L,R} = \frac{1 \mp \gamma_5}{2}$$

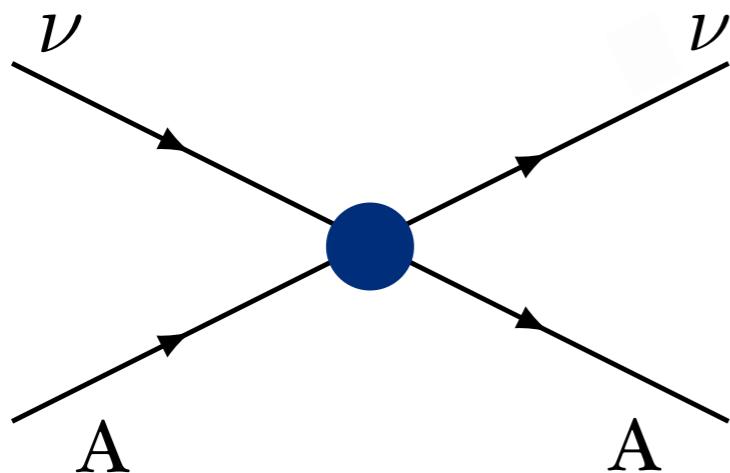
$$\mathcal{M} \sim \bar{\nu}_\ell \gamma_\mu P_L \nu_\ell \cdot \langle N | \sum_q \bar{q} \gamma^\mu (c_L^{\nu_\ell q} P_L + c_R^{\nu_\ell q} P_R) q | N \rangle$$

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

form factors: electric and magnetic axial and pseudoscalar

- form factors describe matrix elements of quark currents
- π DAR sources: only normalizations and charge radii

From nucleons to nuclei



- tree-level cross section

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

spin-0 nuclei

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

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

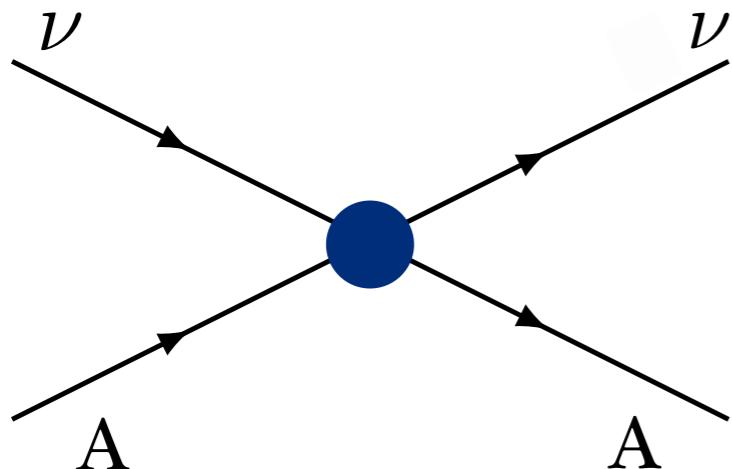
- flavor-independent form factor above GeV scale

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

Hoferichter et al. (2020)

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

CEvNS cross section on spin-0 nuclei

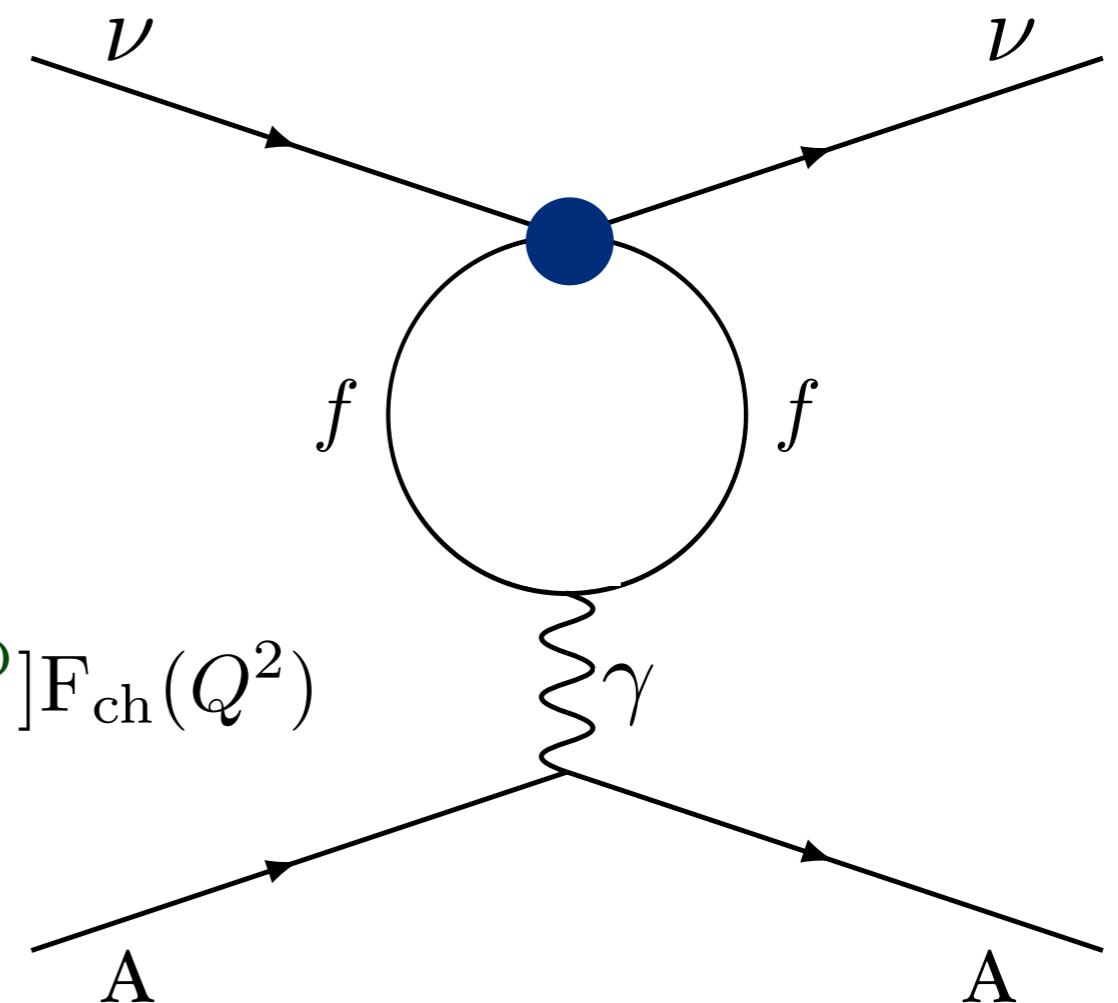


- tree-level cross section

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

- effect of radiative corrections

$$F_W(Q^2) \rightarrow F_W(Q^2) + \frac{\alpha}{\pi} [\delta^{\nu\ell} + \delta^{\text{QCD}}] F_{\text{ch}}(Q^2)$$



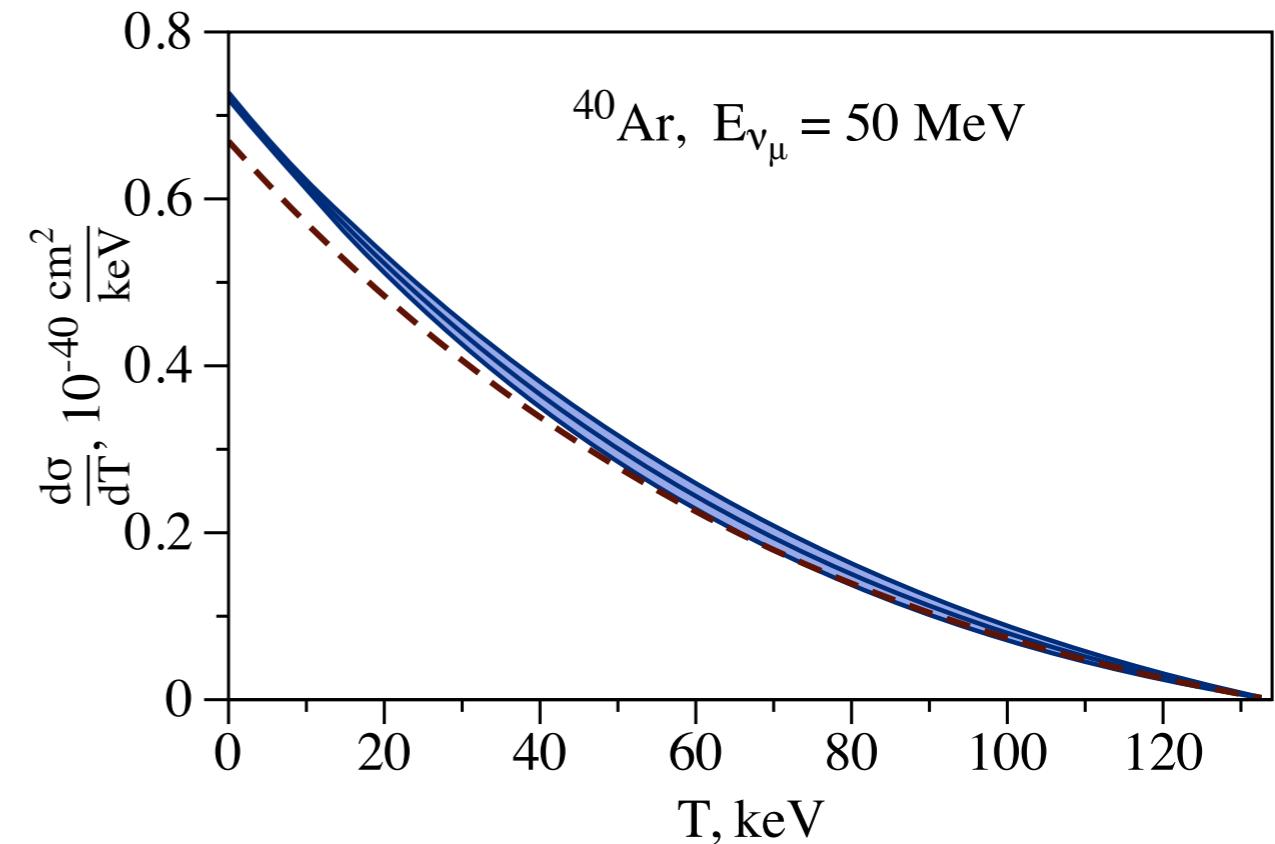
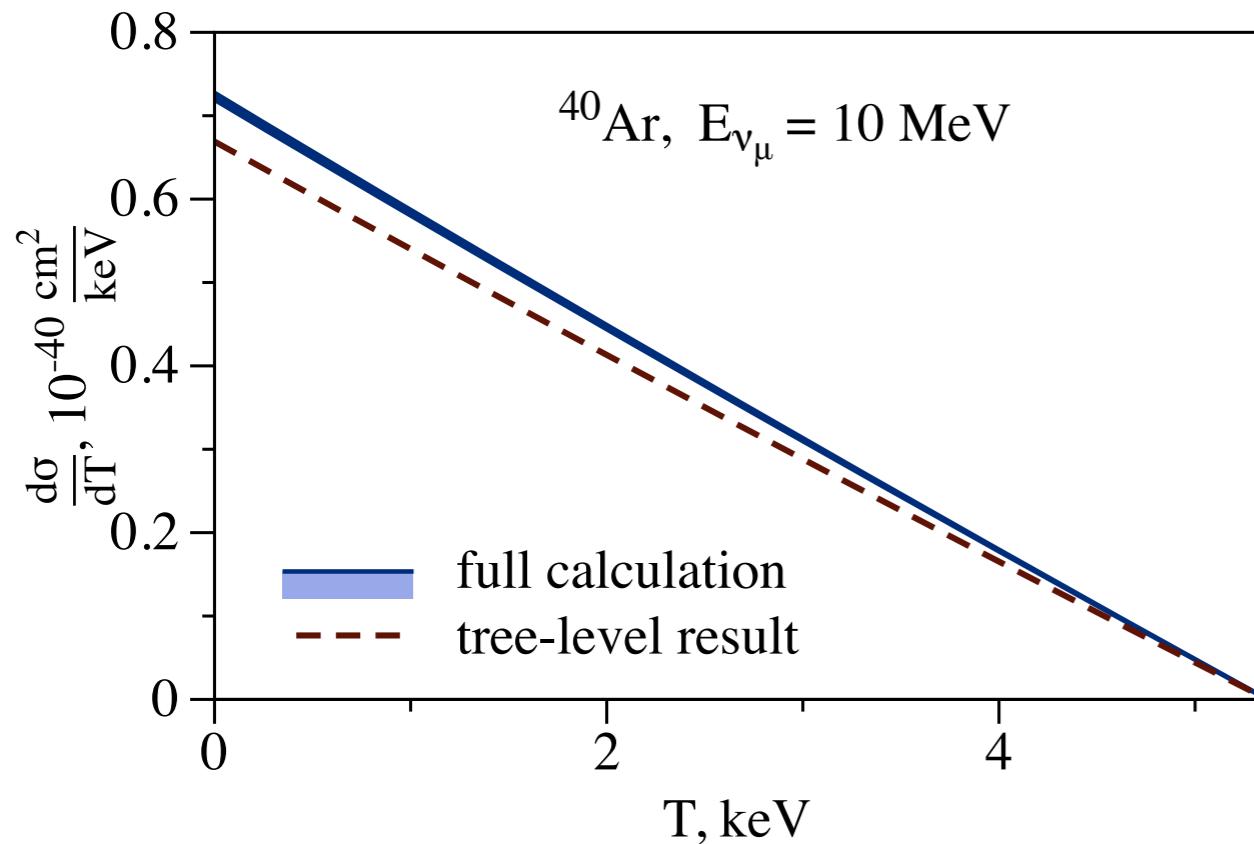
- radiative corrections enter with the nucleus charge form factor
- lepton mass breaks “flavor universality”

Total and differential cross section

- recoil nucleus energy spectrum: one-loop vs tree level

nuclear models for point-nucleon form factors:

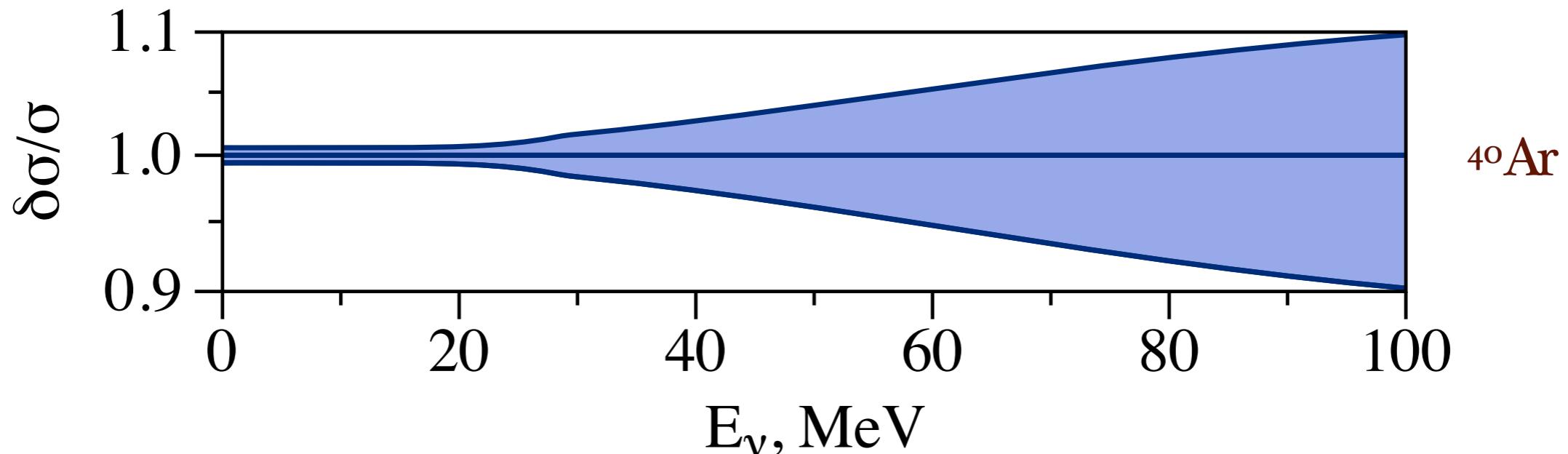
Yang et al. (2019), Payne et al. (2019), Hoferichter et al. (2020), Van Dessel et al. (2020)



- % 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

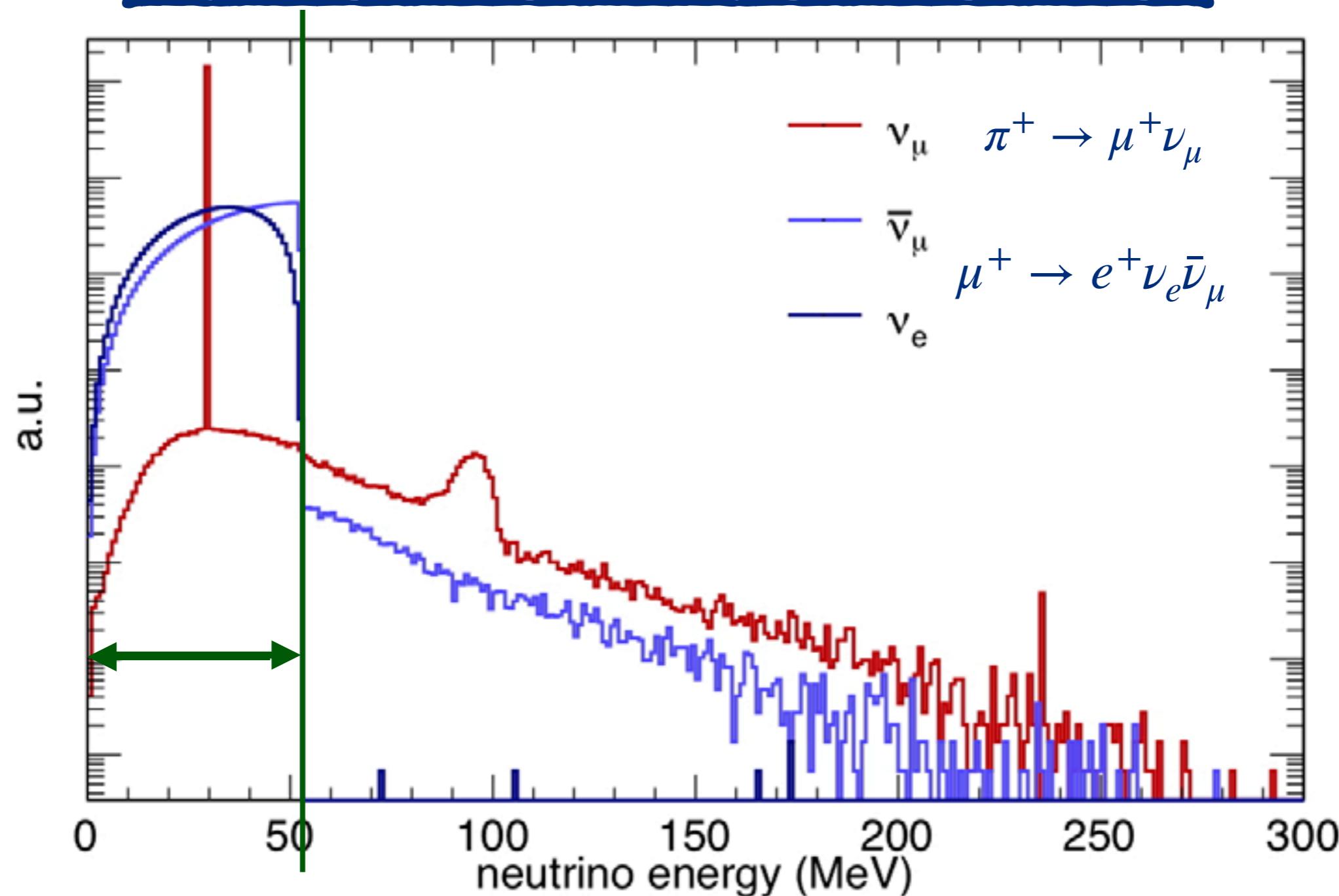


(Anti)neutrino energy spectra from muon, pion, and kaon decays

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



π DAR spectrum at tree level

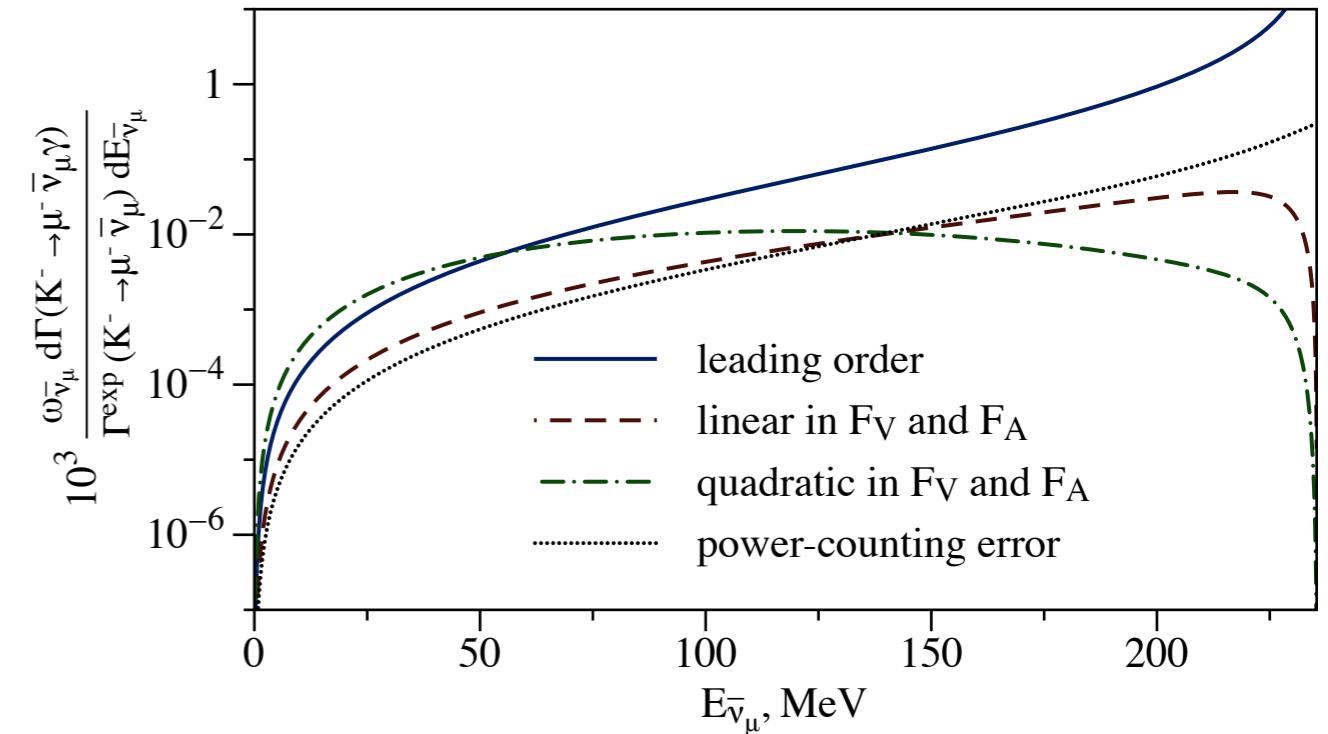
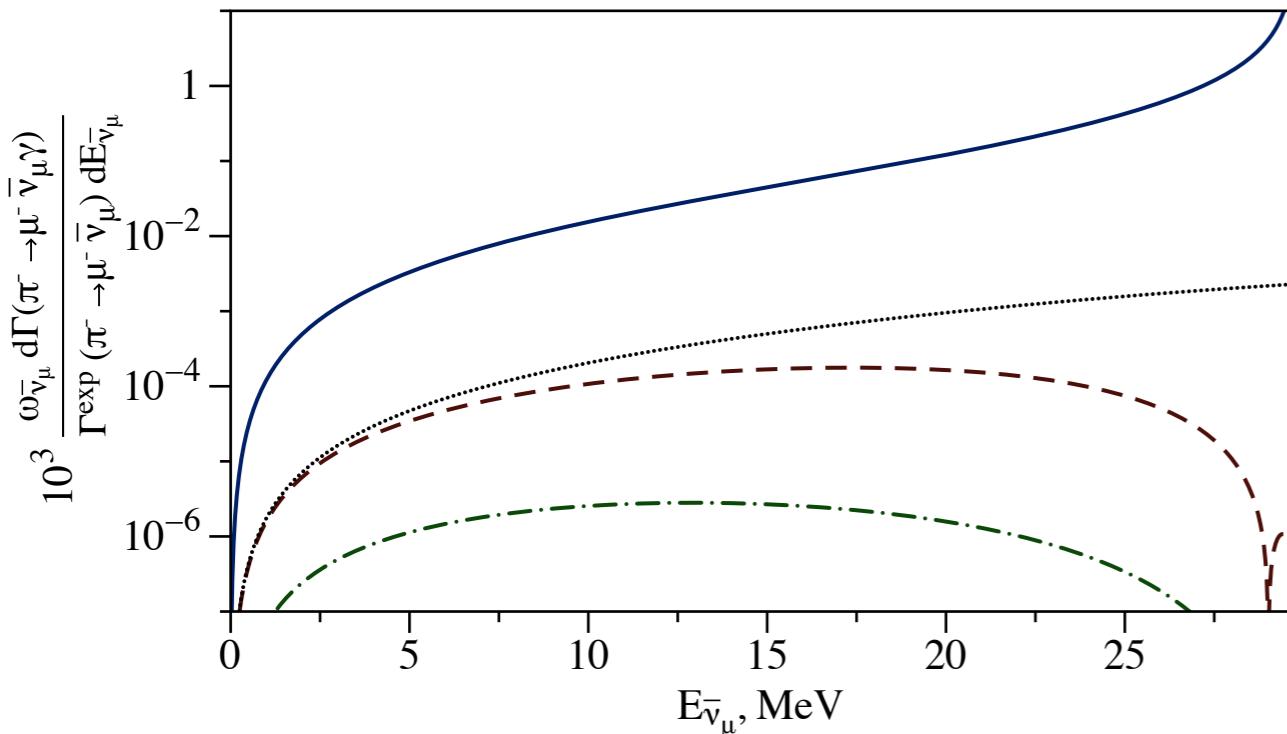


Akimov et al., Science 357 6356, 1123-1126 (2017)

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

Radiative corrections to decay of mesons

- broadening of monochromatic line with elastic peak



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

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

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

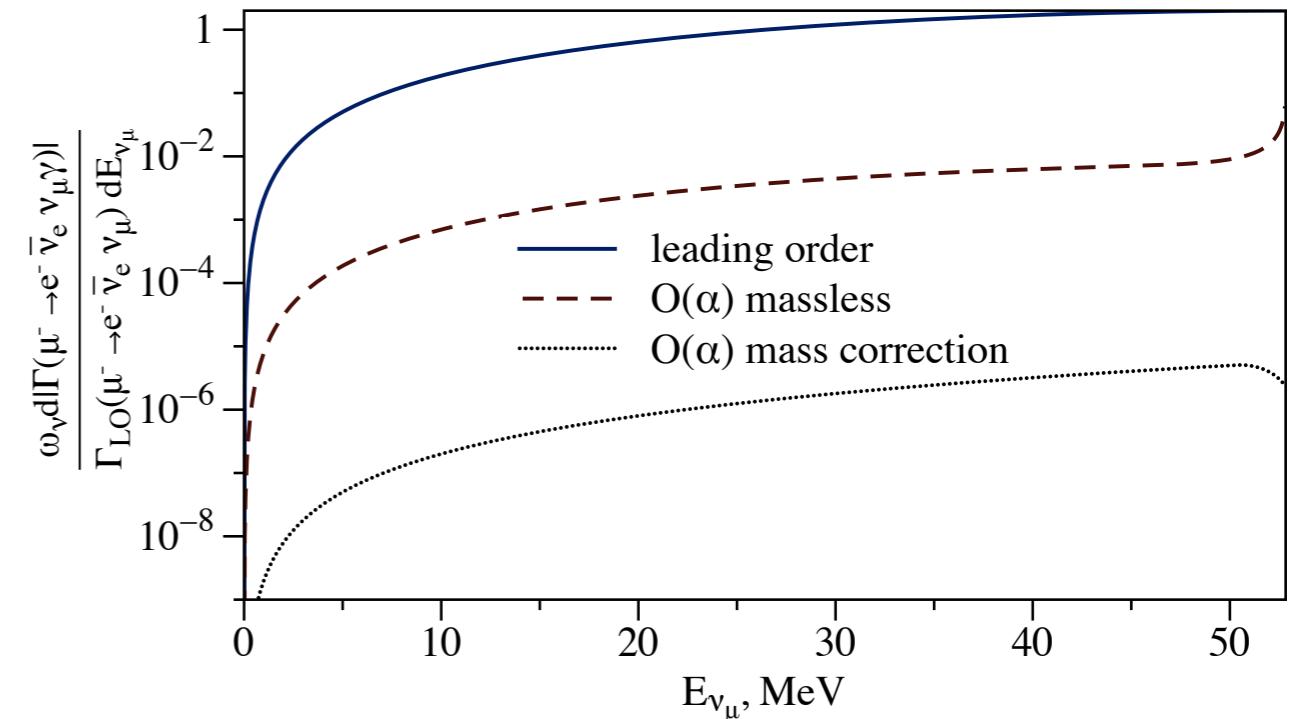
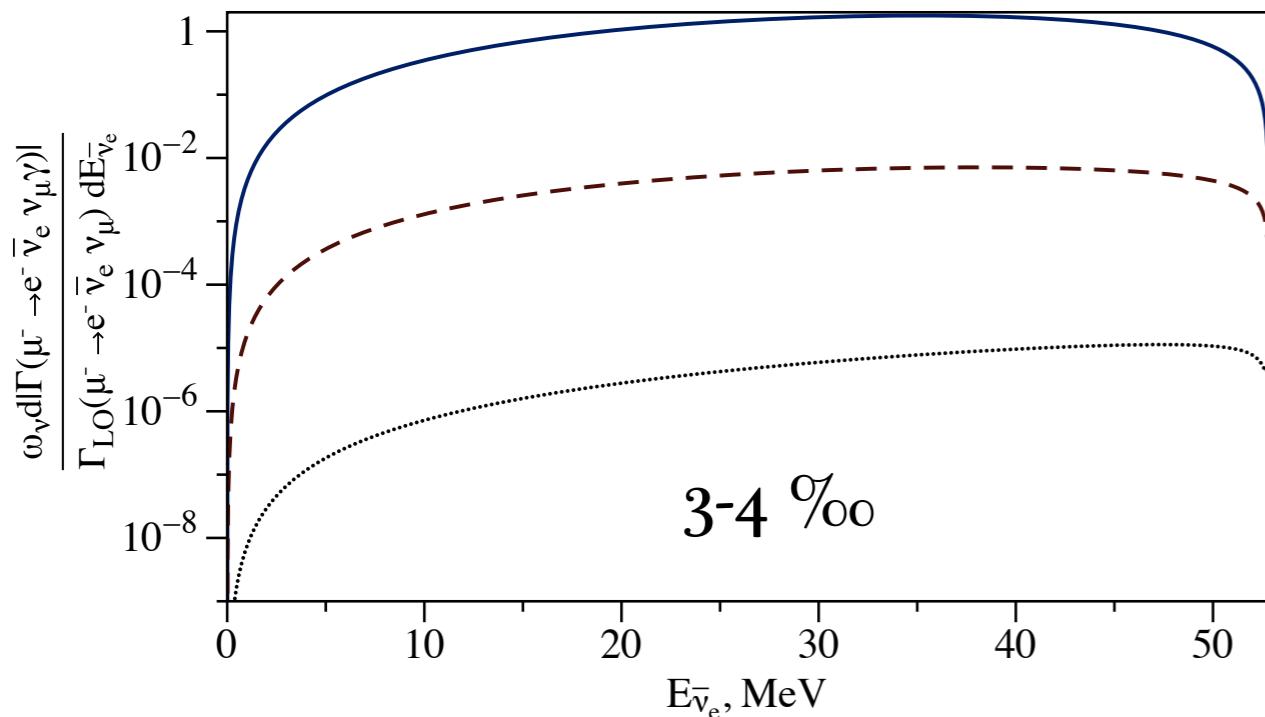
- $\lesssim 10^{-4}$ change in GeV (anti)neutrino fluxes

- negligible change when normalized to experimental lifetime

Radiative corrections to muon decay

- flavor-dependent distortions at permille level

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



- 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

$$\sigma_{\bar{\nu}_e}^{^{40}\text{Ar}} = (17.484 \pm 0.43) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\bar{\nu}_e, \text{LO}}^{^{40}\text{Ar}} = (17.490 \pm 0.43) \times 10^{-40} \text{ cm}^2$$

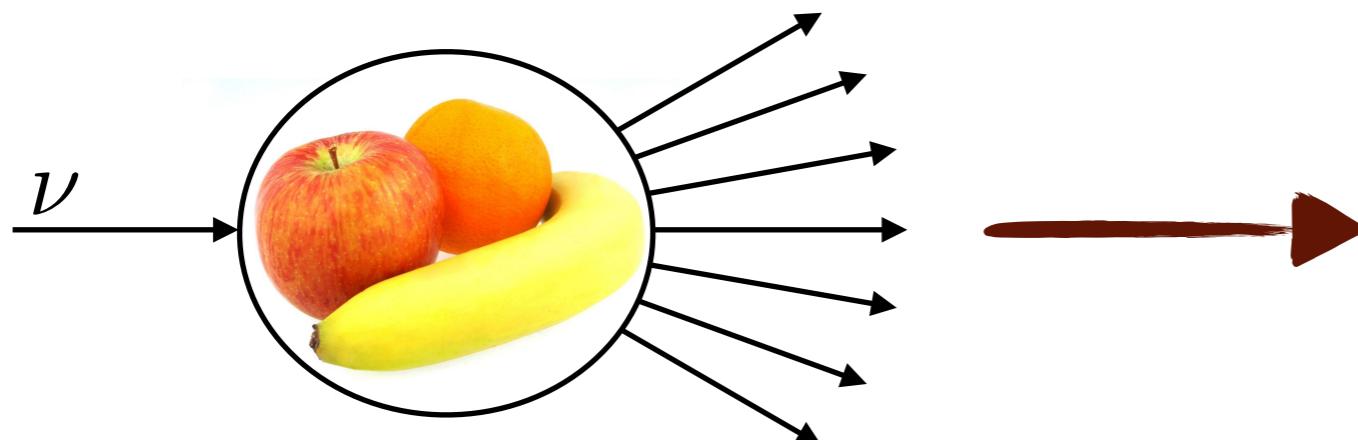
$$\sigma_{\nu_\mu}^{^{40}\text{Ar}} = (22.448 \pm 0.66) \times 10^{-40} \text{ cm}^2$$

$$\sigma_{\nu_\mu, \text{LO}}^{^{40}\text{Ar}} = (22.454 \pm 0.66) \times 10^{-40} \text{ cm}^2$$

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

- permille-level change in agreement with KLN theorem

Conclusions



radiative corrections
in EFT framework

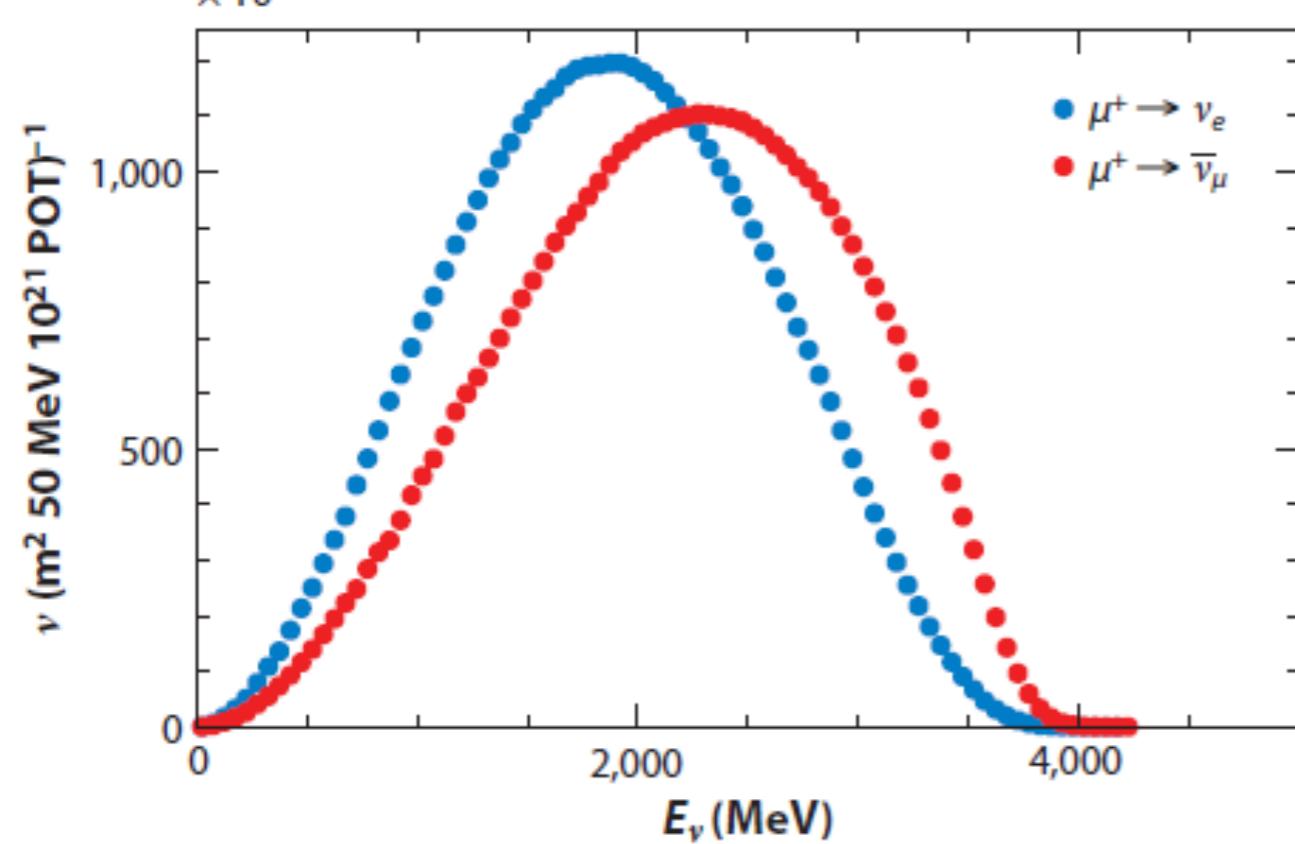
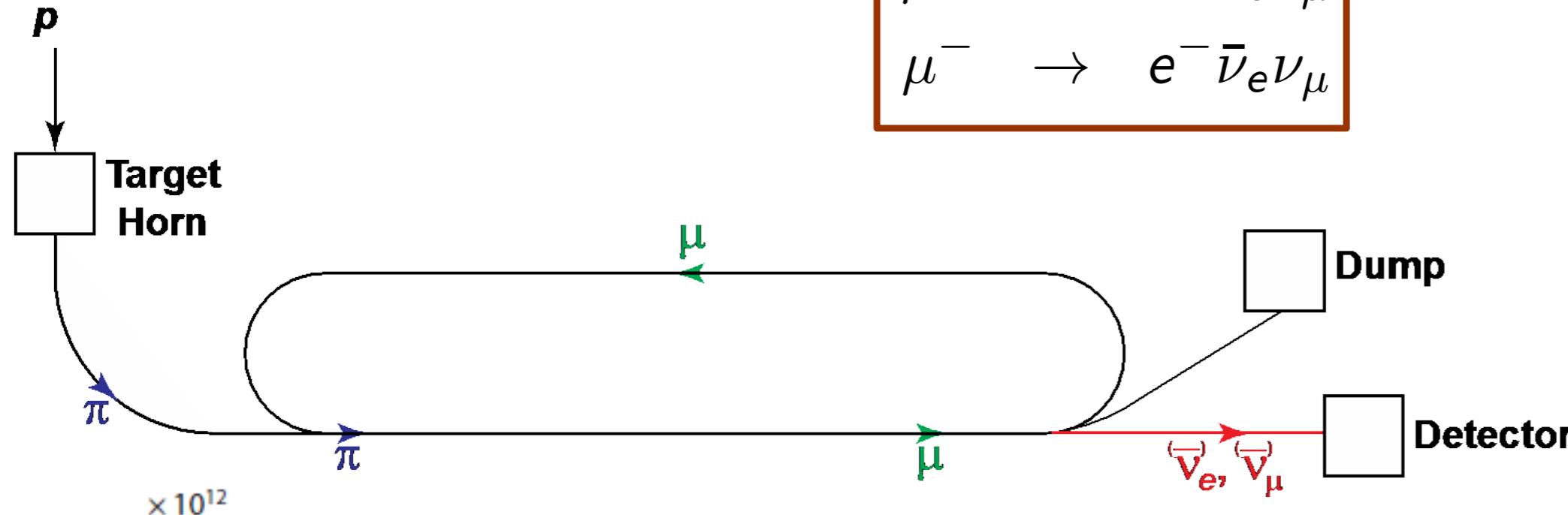
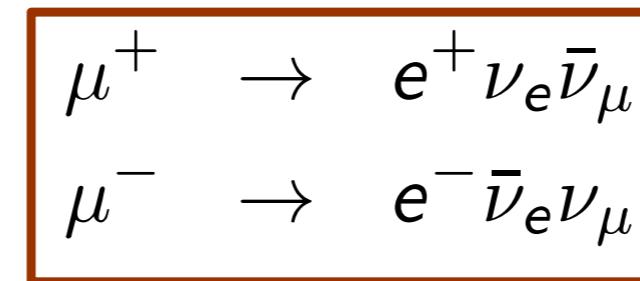
- precision four-Fermi effective theory: basis for computations with sub-percent accuracy in neutrino interactions
- total and differential CEvNS cross sections evaluated from theory with first rigorous error analysis
- precise neutrino spectra from muon, pion, and kaon decays

Thanks for your attention !!!

Precise fluxes for cross-section program

ν STORM

■ Neutrinos from Stored Muons



Adey et al., Annu. Rev. Nucl. Part. Sci. 2015.65

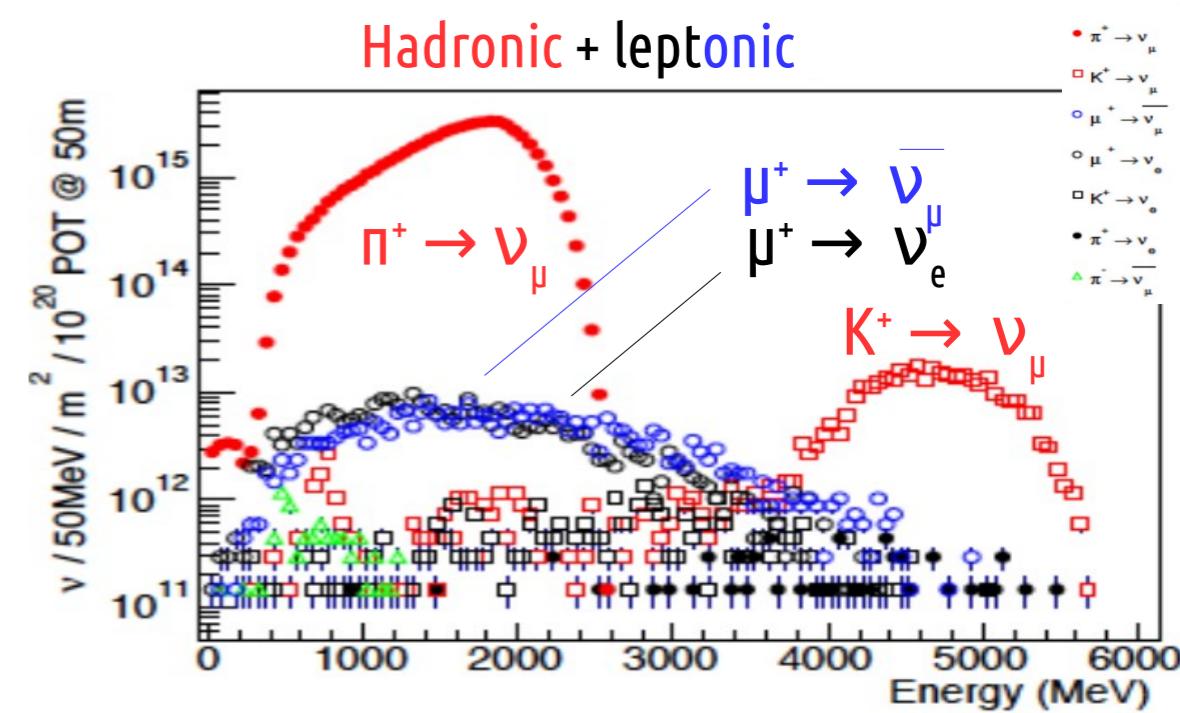
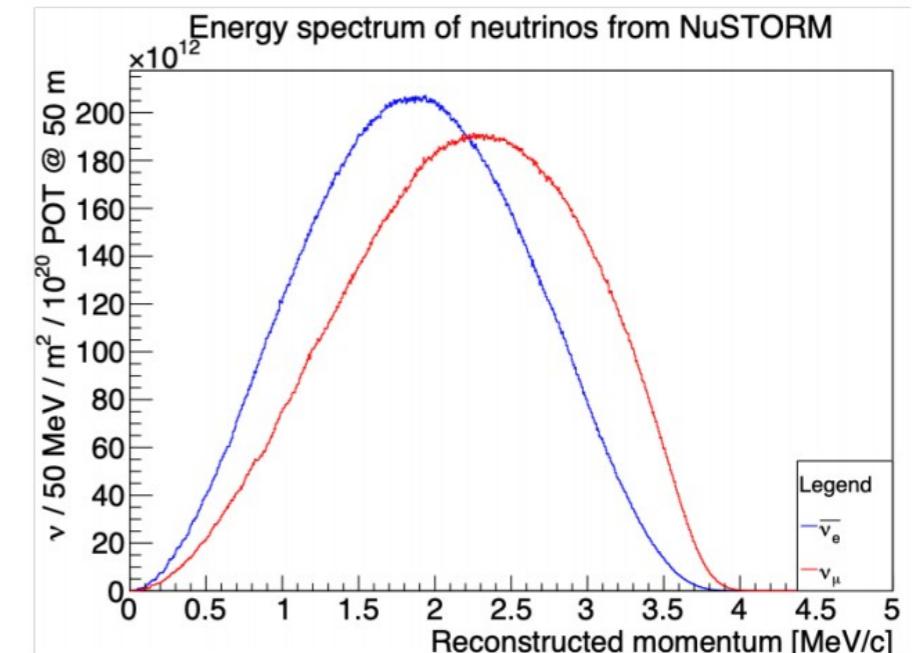
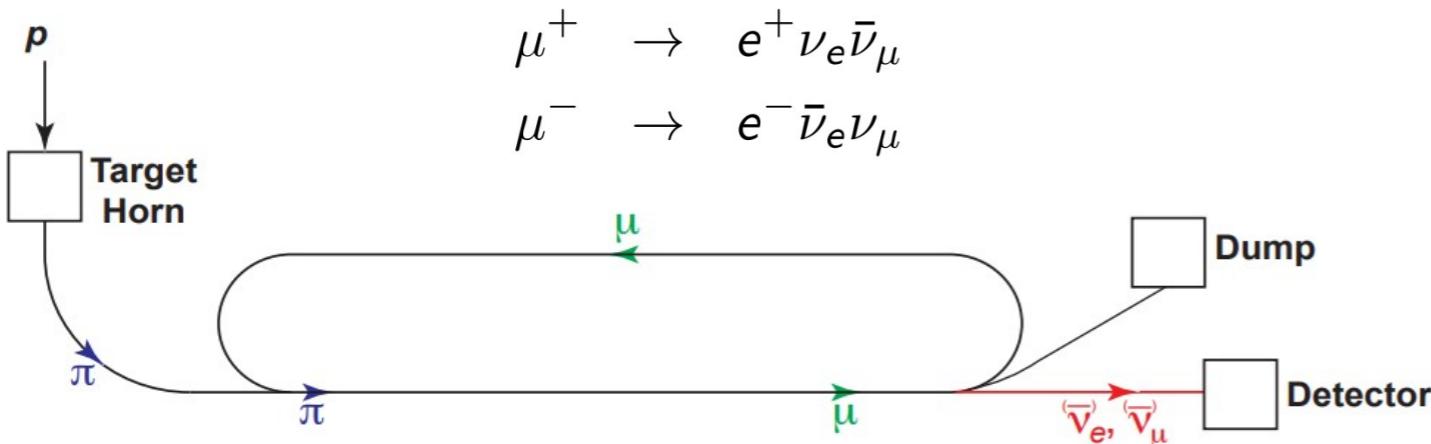
Precisely known flux:

- Normalization (< 1%)
- Flavor composition
- Energy spectrum

■ Feasibility at CERN: Ahdida et al., CERN-PBC-REPORT-2019-003

nuSTORM implementation at the SPS

ν_e and ν_μ beams from decay of circulating low-E muons



Novel beams (meson based)

ENUBET

Talk by G. Brunetti

2) Conventional “meson based” beams brought to a new standard → use a narrow band beam and shift the monitoring at the level of decays by instrumenting the decay tunnel (tag high-angle leptons) → remove the main limit to cross section measurements by reducing the flux normalization uncertainty from O(5-10%) to ~O(1%).



Hadro-production (p-target) uncertainties → by-passed by lepton “counting”

An **ancillary facility** providing **physics input** to the long-baseline program: reduction of systematics thanks to unprecedented measurements of the ν_e (and ν_μ) cross sections

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A.

681647, PI A. Longhin, Padova University, INFN

- **CERN Neutrino Platform: NP06**
- **Physics Beyond Colliders CERN study**



Aims at demonstrating the **feasibility** and **physics performance** of a neutrino beam where **lepton production is monitored at single particle level**

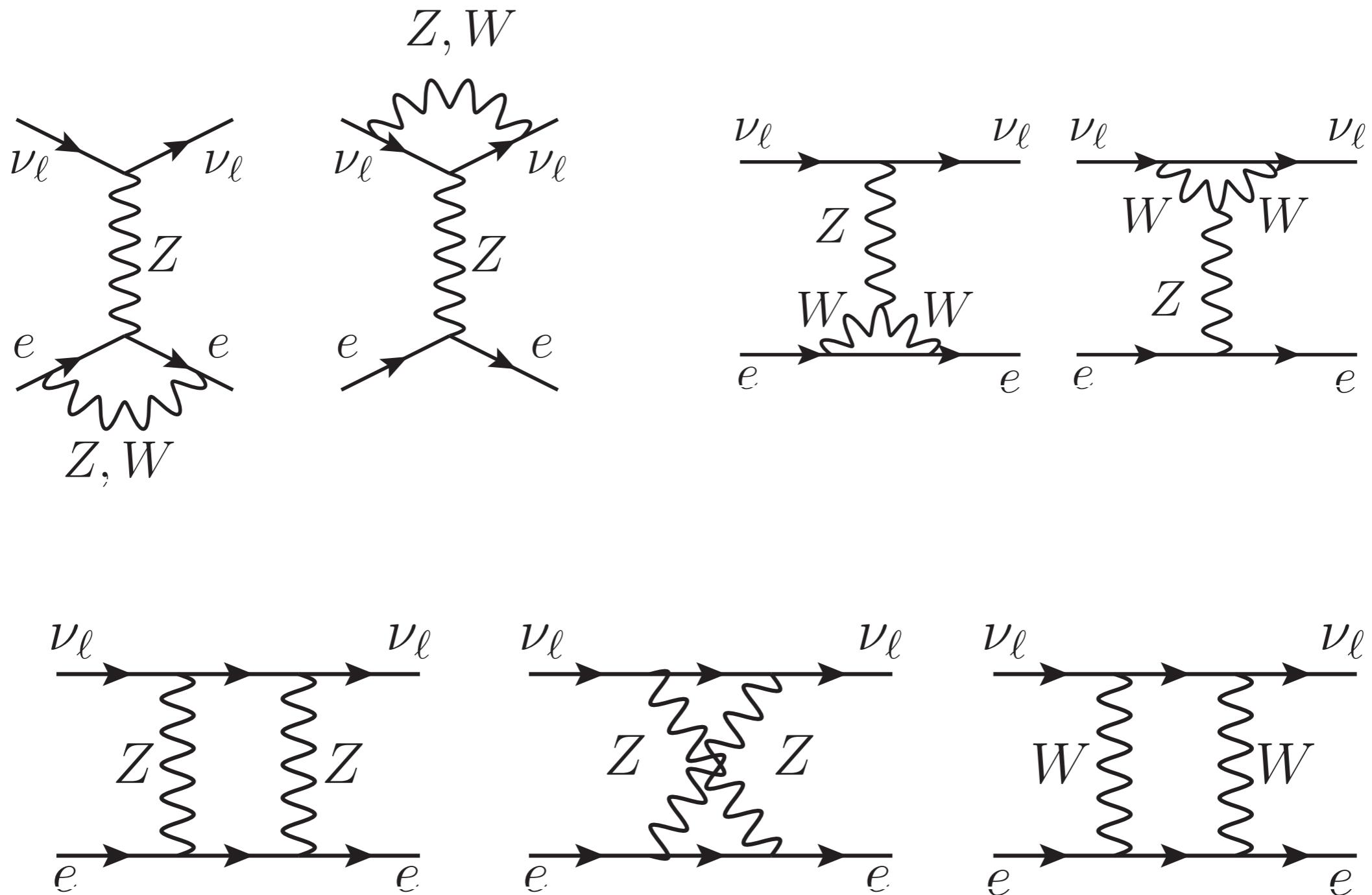
- **Instrumented decay region**
 - $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow (\text{large angle}) e^+$
 - $K^+ \rightarrow \mu^+ \nu_\mu \pi^0 \text{ or } \rightarrow \mu^+ \nu_\mu \rightarrow (\text{large angle}) \mu^+$
- **ν_e and ν_μ flux prediction from e^+/μ^+ rates**

Requires a **collimated p-selected hadron beam**
 → **only decay products hit the tagger** → **manageable rates**
 Requires a “short”, 40 m, tunnel (~all ν_e from K , ~1% ν_e from μ)
 → **Bonus:** an “*a priori*” constraint on the ν energy by exploiting correlations between E_ν and the position of interactions in the detector (narrow band beams)

Uncertainty reduction for the tagged flux component

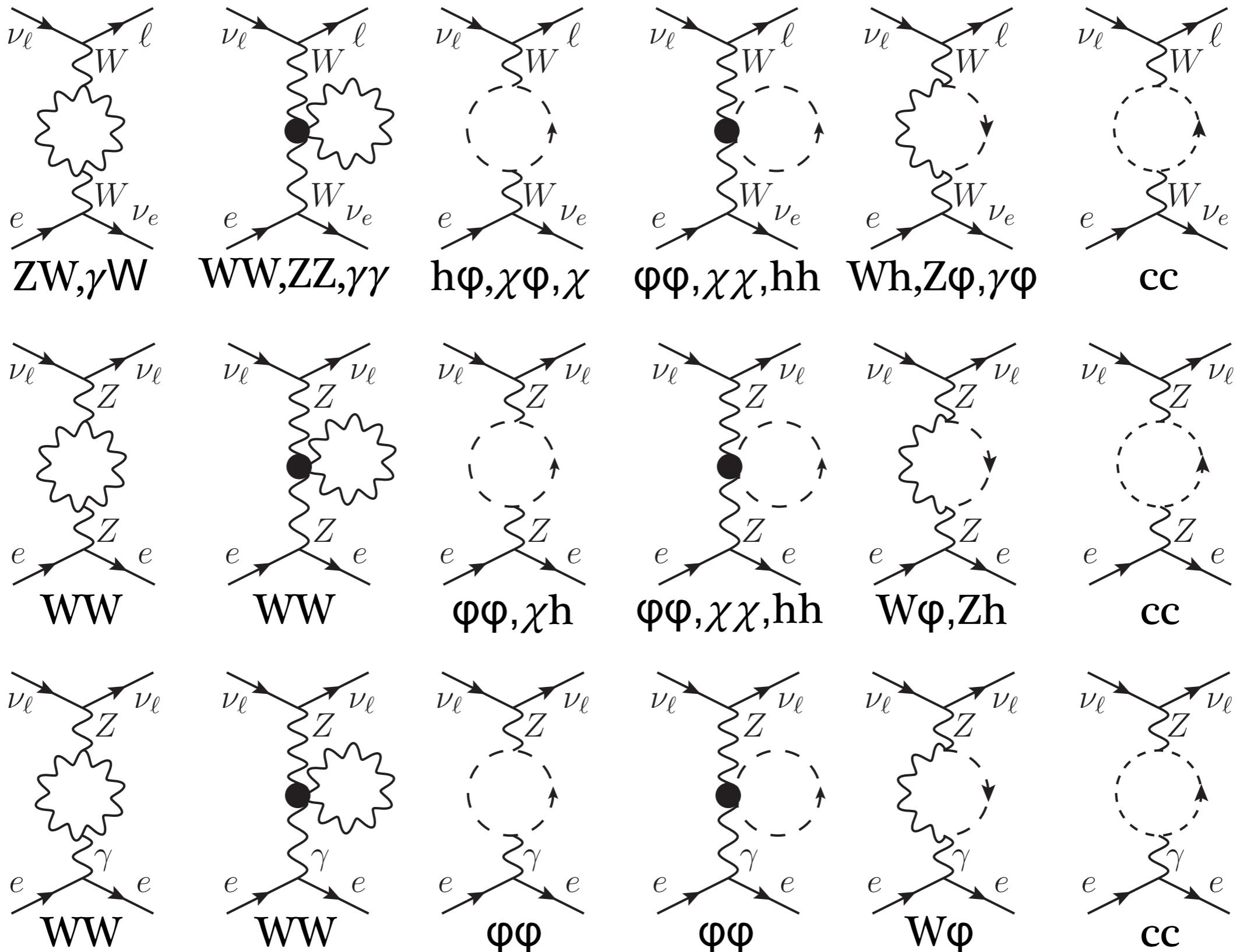
Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

Neutral current in SM

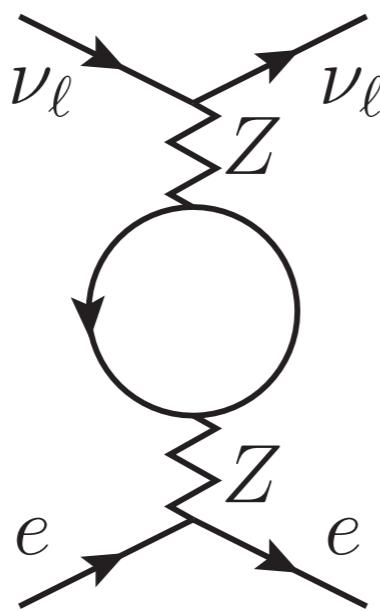
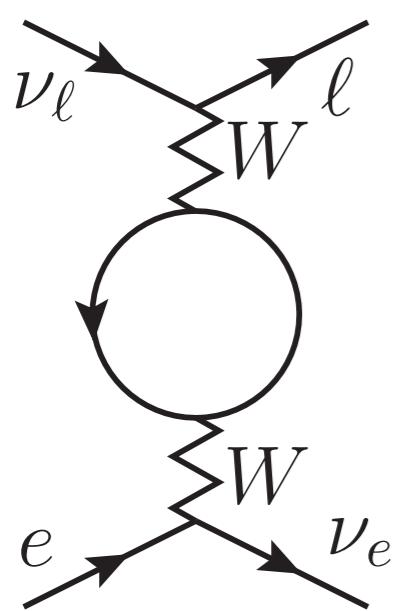


- contribution to effective couplings

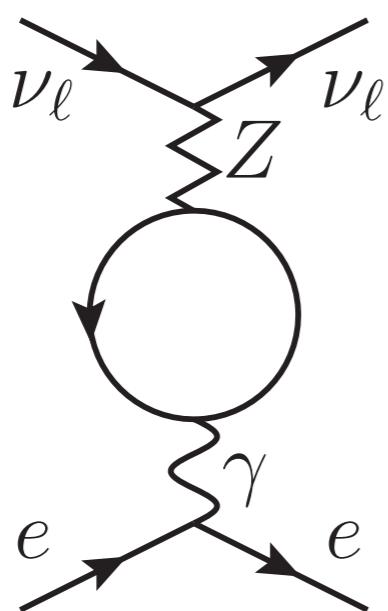
Self energy and γZ mixing. Boson loops



Self energy and γZ mixing. Fermion loops

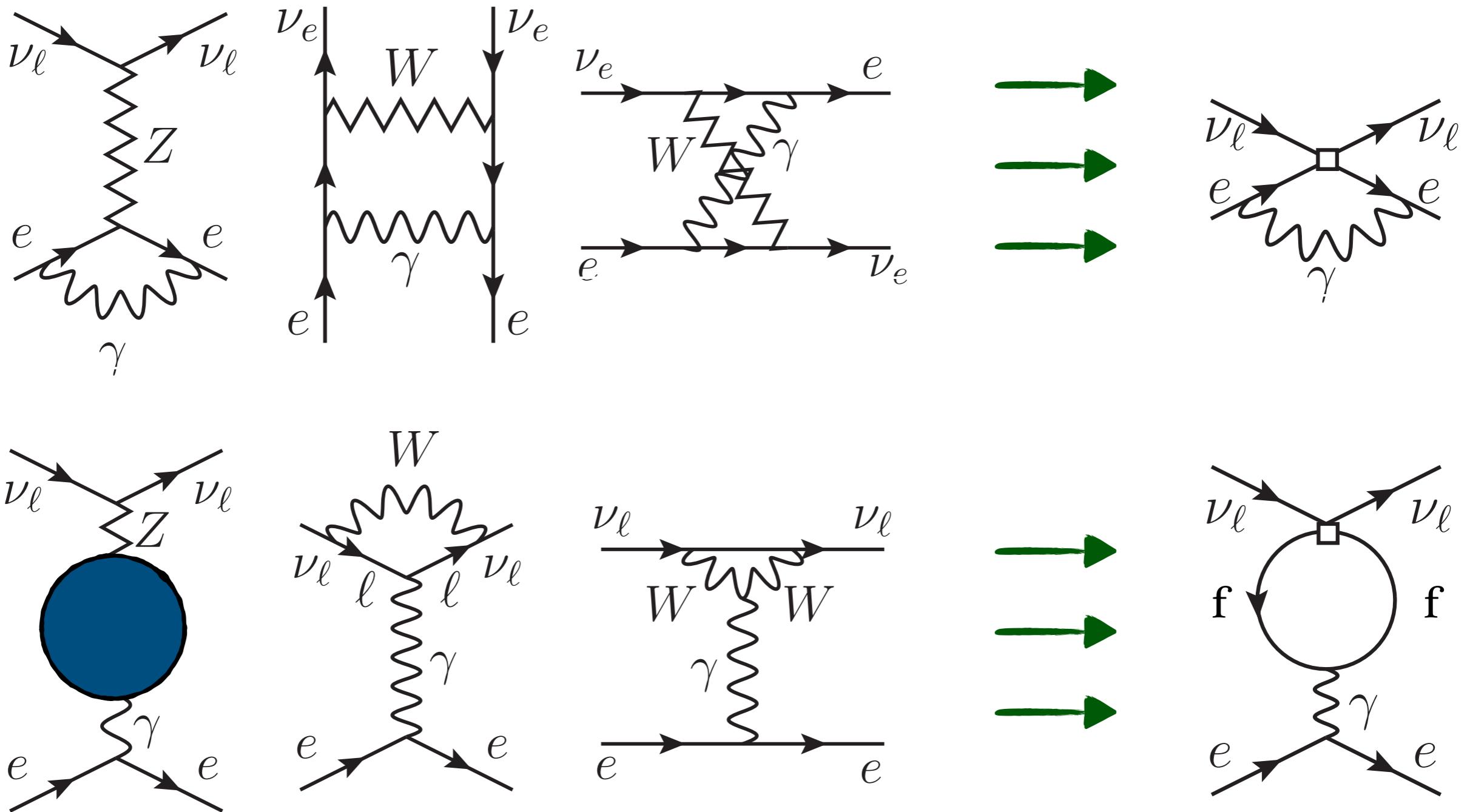


- vanishing contribution to matching besides loops with t quark
- finite contribution to self energy pole vs $\overline{\text{MS}}$ masses
- do not consider Higgs tadpoles (hVV): matching vs self energy cancellation



- gauge-independent contribution

Matching at one loop \rightarrow EFT side



- cancellation of infrared and collinear singularities

Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop

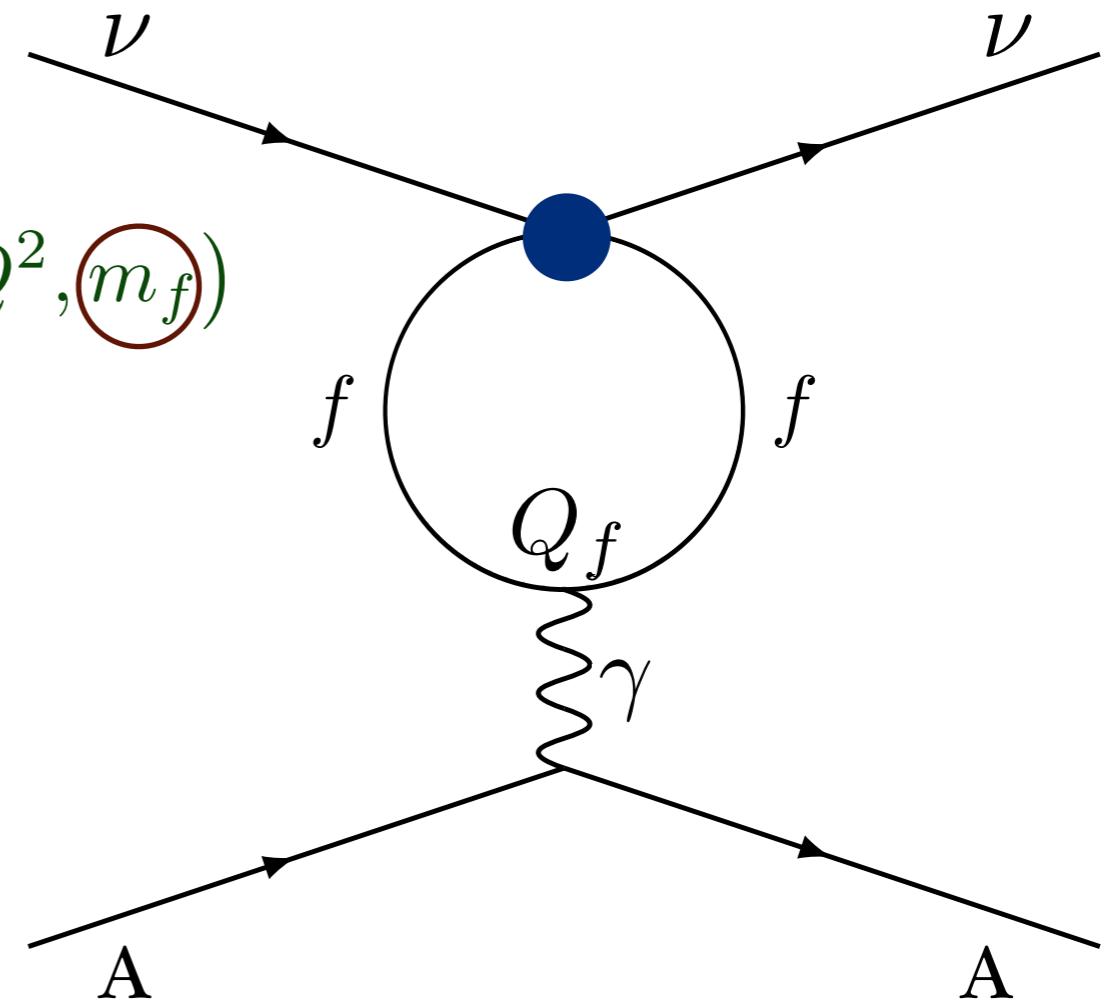
$$\mathcal{L}_{\text{eff}} = -\bar{\nu}_\ell \gamma_\mu P_L \nu_\ell \cdot \bar{f} \gamma^\mu \left(c_L^{\nu_\ell f} P_L + c_R^{\nu_\ell f} P_R \right) f$$

- lepton loops

$$\delta^{\nu_\ell} = - \sum_f \frac{c_L^{\nu_\ell f} + c_R^{\nu_\ell f}}{\sqrt{2} G_F} Q_f \Pi(Q^2, m_f)$$

- origin of flavor dependence

$$c_L^{\nu_e \mu} = c_L^{\nu_\mu e} \neq c_L^{\nu_\mu \mu} = c_L^{\nu_e e}$$



- lepton mass breaks “flavor universality”

Light-quark contribution

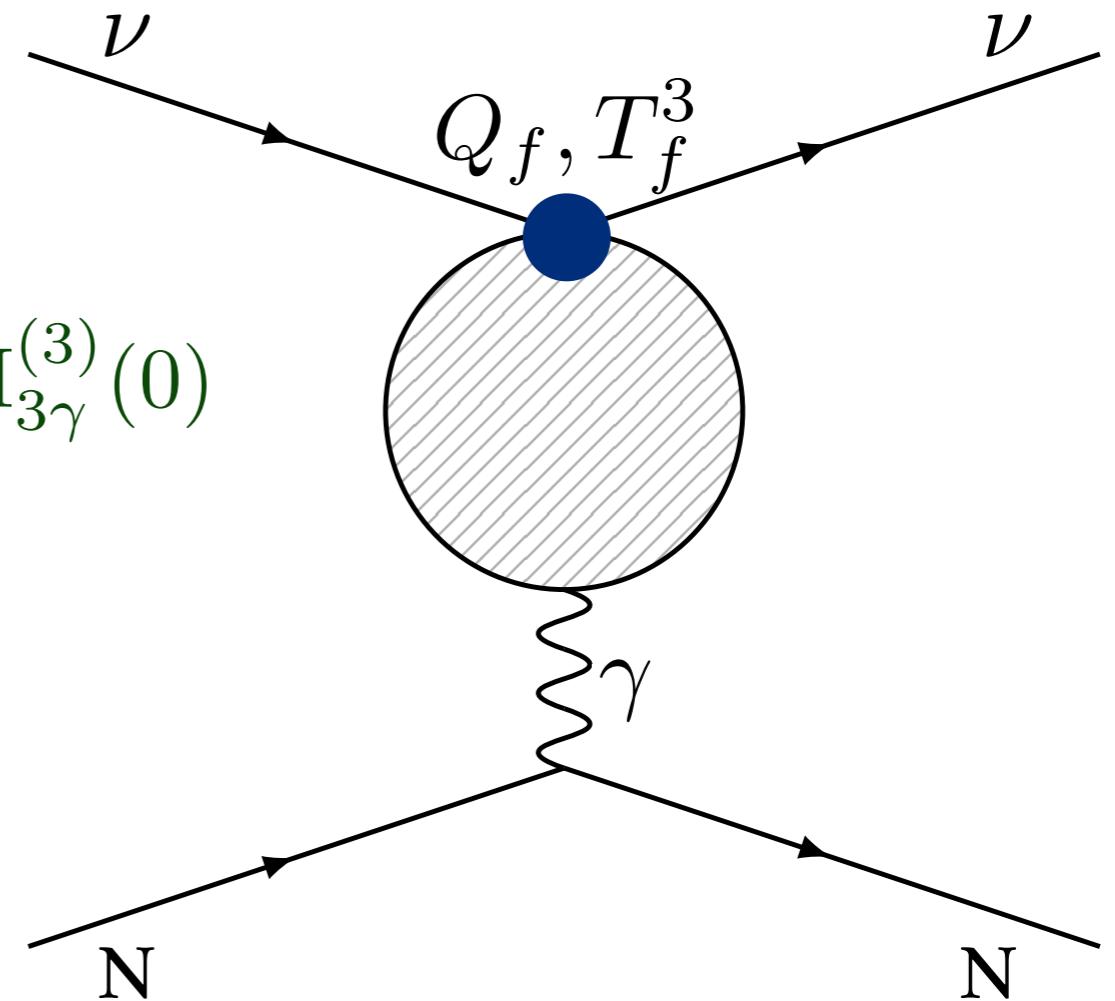
- description in terms of quarks is invalid at CEvNS kinematics

$$Q^2 \ll \Lambda_{\text{QCD}}^2$$

- light quarks

$$\delta^{\text{QCD}} = 4\Pi_{\gamma\gamma}^{(3)}(0) \sin^2 \theta_W - 2\Pi_{3\gamma}^{(3)}(0)$$

- chiral symmetry approximation
- flavor independent



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