Magnificent CEvNS 2020

Cyberspace

17 November, 2020

Flavor-dependent radiative corrections in coherent elastic neutrino-nucleus scattering

University of Kentucky

Oleksandr Tomalak

O.T. and R. J. Hill, PRD2020, PLB2020, (arXiv:1907.03379, arXiv:1911.01493)

O.T., P. Machado, V. Pandey and R. Plestid (arXiv: 2011.13640)

Outline

1) microscopic EFT for neutrino physics

2) radiative corrections to CEvNS

3) CEvNS cross sections on ^{40}Ar with complete errors

4) flavor asymmetries

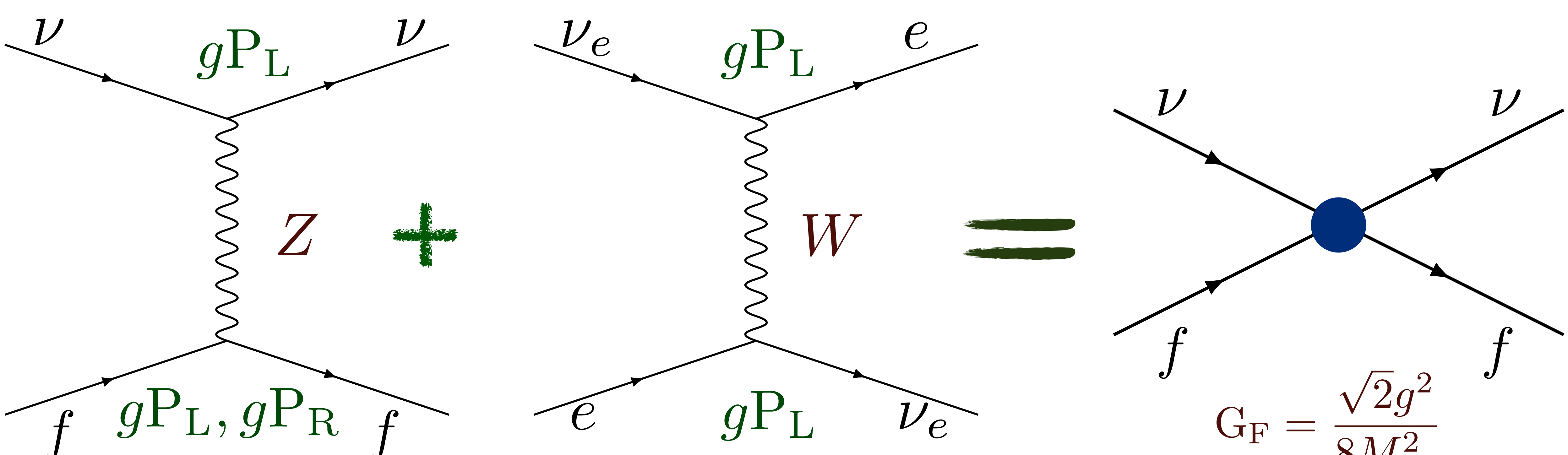
Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

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

neutral current

charged current



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

- integrate out W and Z at tree level

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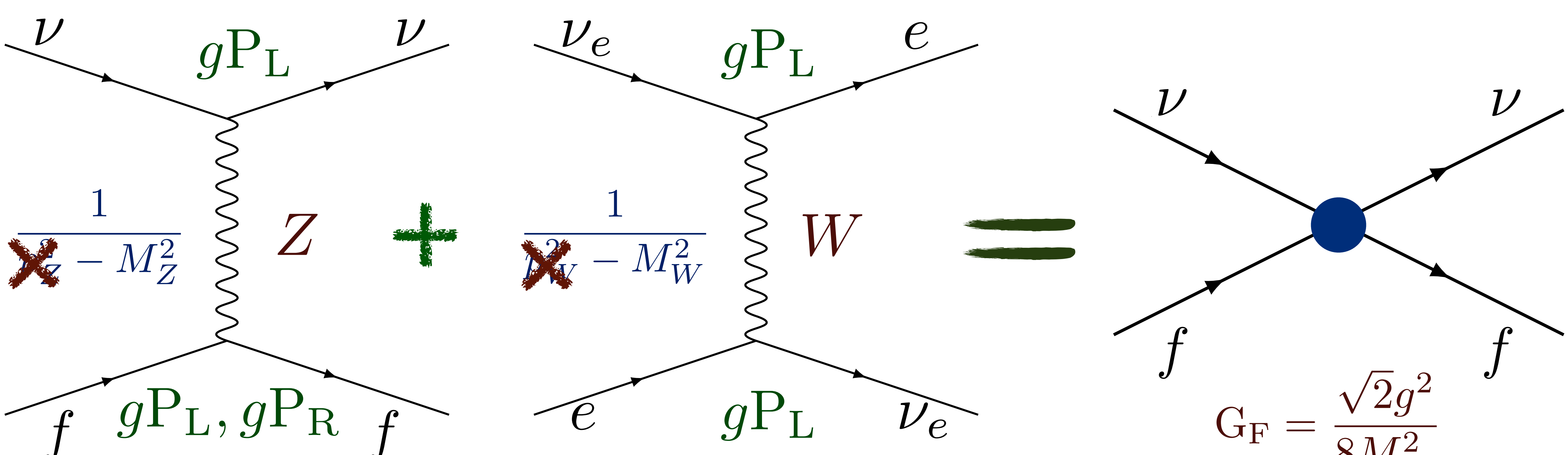
neutral current charged current



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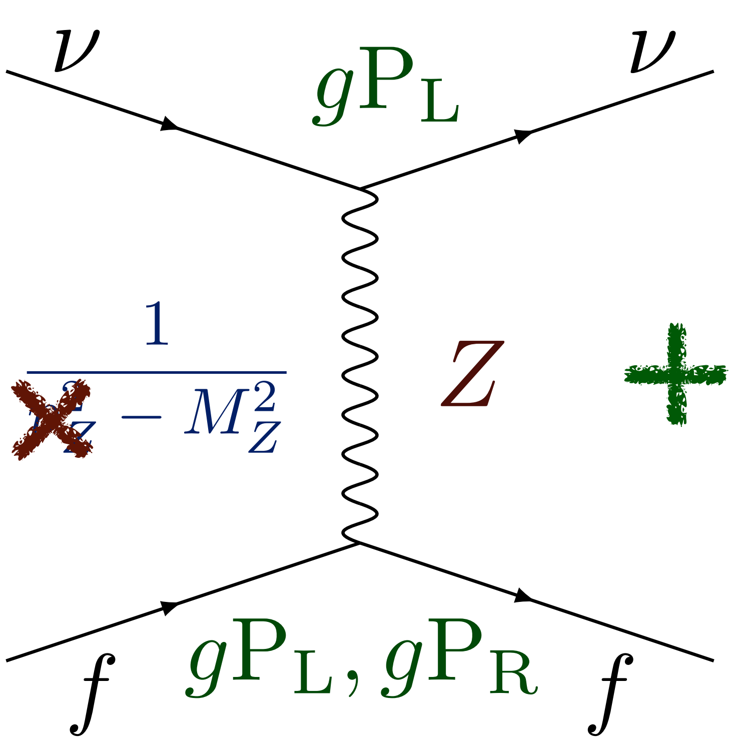
couplings to electron:

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

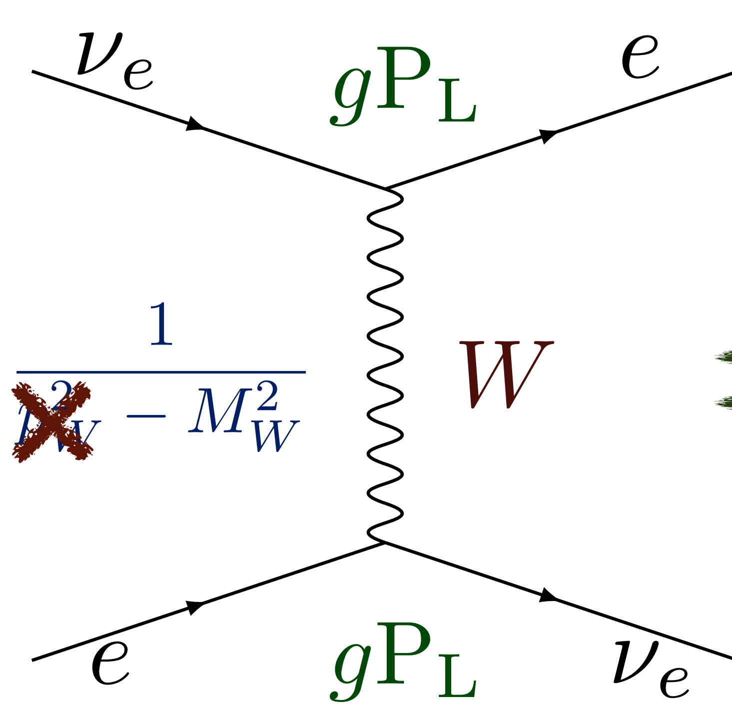
Weinberg (1967), 't Hooft (1971)

neutral current



+

charged current



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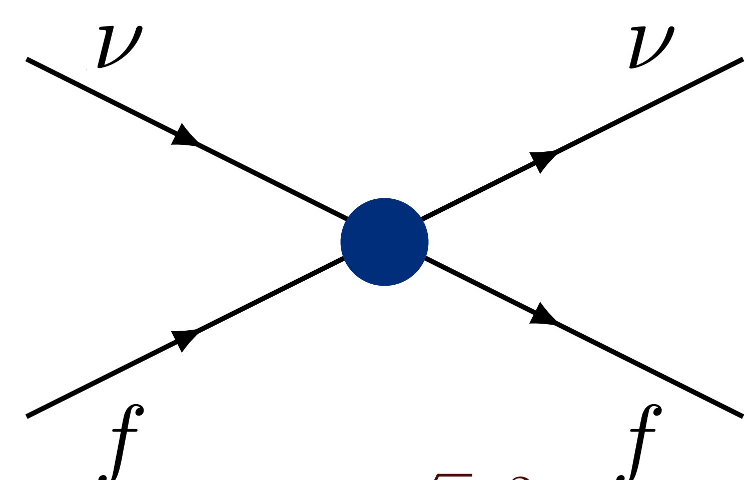

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Neutrino scattering in EFT. Matching

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

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

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

- neglect fermion masses besides top quark

  $\alpha \dfrac{m^2}{M_W^2}$ suppression

Neutrino scattering in EFT. Matching

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

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

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

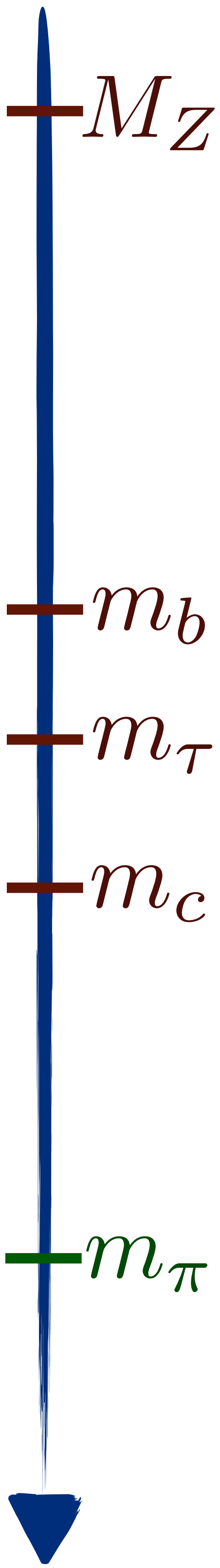
- G_F: combination of parameters is precisely measured

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

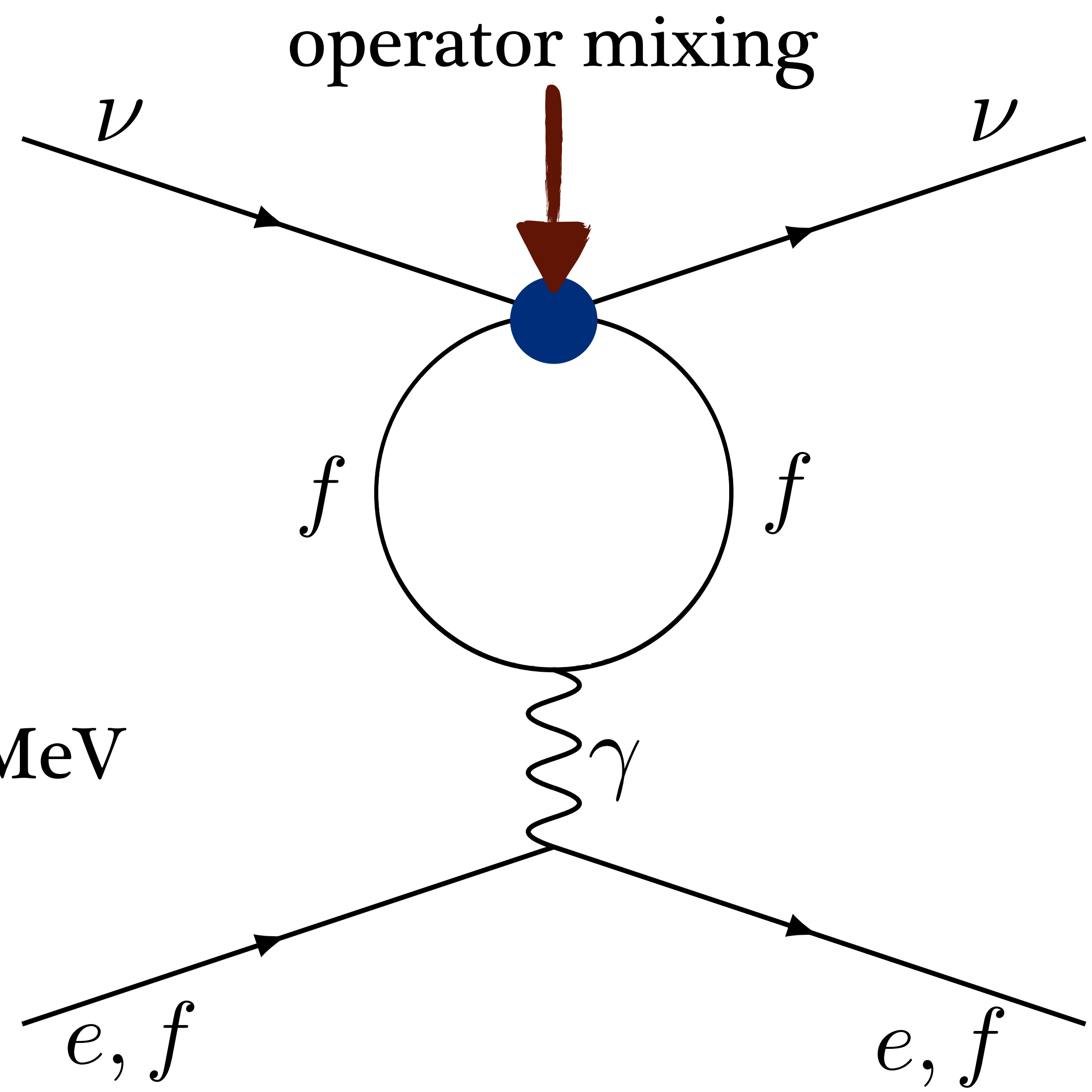
MULAN (2012)

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

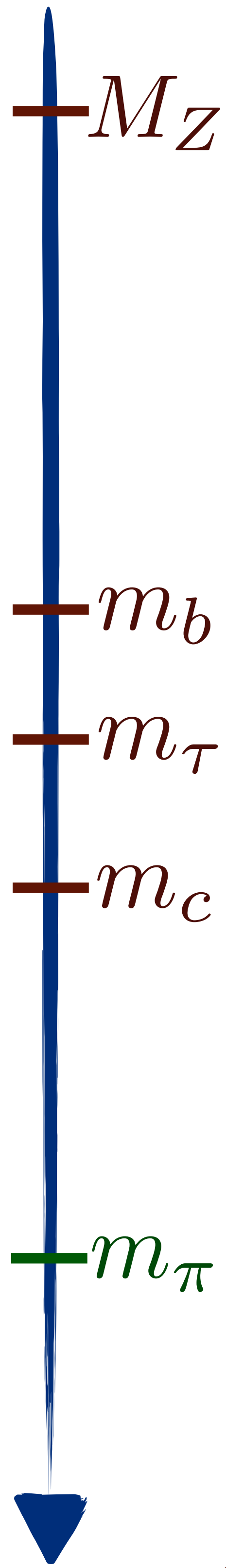
Running to low scales



- integrate out top, Z , W, h
- only one EFT coupling changes with scale
- integrate out GeV particles
- α_s becomes too strong
- hadronic physics down to 140 MeV
- theory with leptons



Scale-independent combinations



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

- chirally-symmetric universal running + flavor symmetry: 8 constraints on running in the theory:

$$c_{\mathrm{R}}^{b}(\mu) - c_{\mathrm{R}}^{d}(\mu) = 0,$$

$$c_{\mathrm{L}}^{\nu_e e}(\mu) - c_{\mathrm{L}}^{\nu_\mu e}(\mu) = 2\sqrt{2}\mathrm{G_F},$$

$$c_{\mathrm{L}}^{\nu_\mu e}(\mu) - c_{\mathrm{R}}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_e,$$

$$c_{\mathrm{L}}^{u}(\mu) - c_{\mathrm{R}}^{u}(\mu) = \sqrt{2}\tilde{\mathrm{G}}_u,$$

$$c_{\mathrm{L}}^{d}(\mu) - c_{\mathrm{R}}^{d}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_d,$$

$$c_{\mathrm{L}}^{b}(\mu) - c_{\mathrm{R}}^{b}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_b,$$

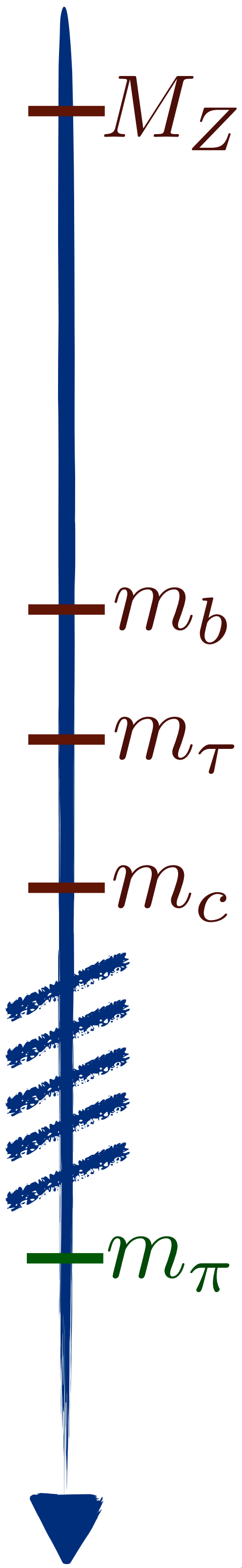
$$3c_{\mathrm{L}}^{u}(\mu) + 2c_{\mathrm{L}}^{\nu_\mu e}(\mu) = \sqrt{2}\mathrm{G}_u,$$

$$-3c_{\mathrm{L}}^{d}(\mu) + c_{\mathrm{L}}^{\nu_\mu e}(\mu) = 2\sqrt{2}\mathrm{G}_d.$$

- one Fermi coupling and one c_{R} at leading order

- only 1 effective coupling changes with scale

Fermi coupling constant



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

- Fermi coupling is scale independent
- comparison of scale-independent combinations

inputs	$\mathrm{G_F}$	$\tilde{\mathrm{G}}_e$	$\tilde{\mathrm{G}}_u$
$\mathrm{M_W}$, $\mathrm{M_Z}$, α	$1.16713(83)_{\rm i}(12)_{\rm p}$	$1.18161(85)_{\rm i}(33)_{\rm p}$	$1.16917(83)_{\rm i}(32)_{\rm p}$
$\mathrm{G_F}$, $\mathrm{M_Z}$, α	$1.1663787(6)_{\rm i}$	$1.18083(4)_{\rm i}(21)_{\rm p}$	$1.16841(4)_{\rm i}(20)_{\rm p}$

inputs	$\tilde{\mathrm{G}}_d$	G_u	G_d
$\mathrm{M_W}$, $\mathrm{M_Z}$, α	$1.18231(85)_{\rm i}(33)_{\rm p}$	$1.14642(78)_{\rm i}(33)_{\rm p}$	$1.18288(85)_{\rm i}(33)_{\rm p}$
$\mathrm{G_F}$, $\mathrm{M_Z}$, α	$1.18154(4)_{\rm i}(21)_{\rm p}$	$1.14570(4)_{\rm i}(22)_{\rm p}$	$1.18211(4)_{\rm i}(21)_{\rm p}$

- Fermi constant: 0.9σ tension with $6\text{x}10^{-4}$ relative difference

- agreement of electroweak vs muon mass scales

O. T. and Richard J Hill, PLB2020, 1911.01493

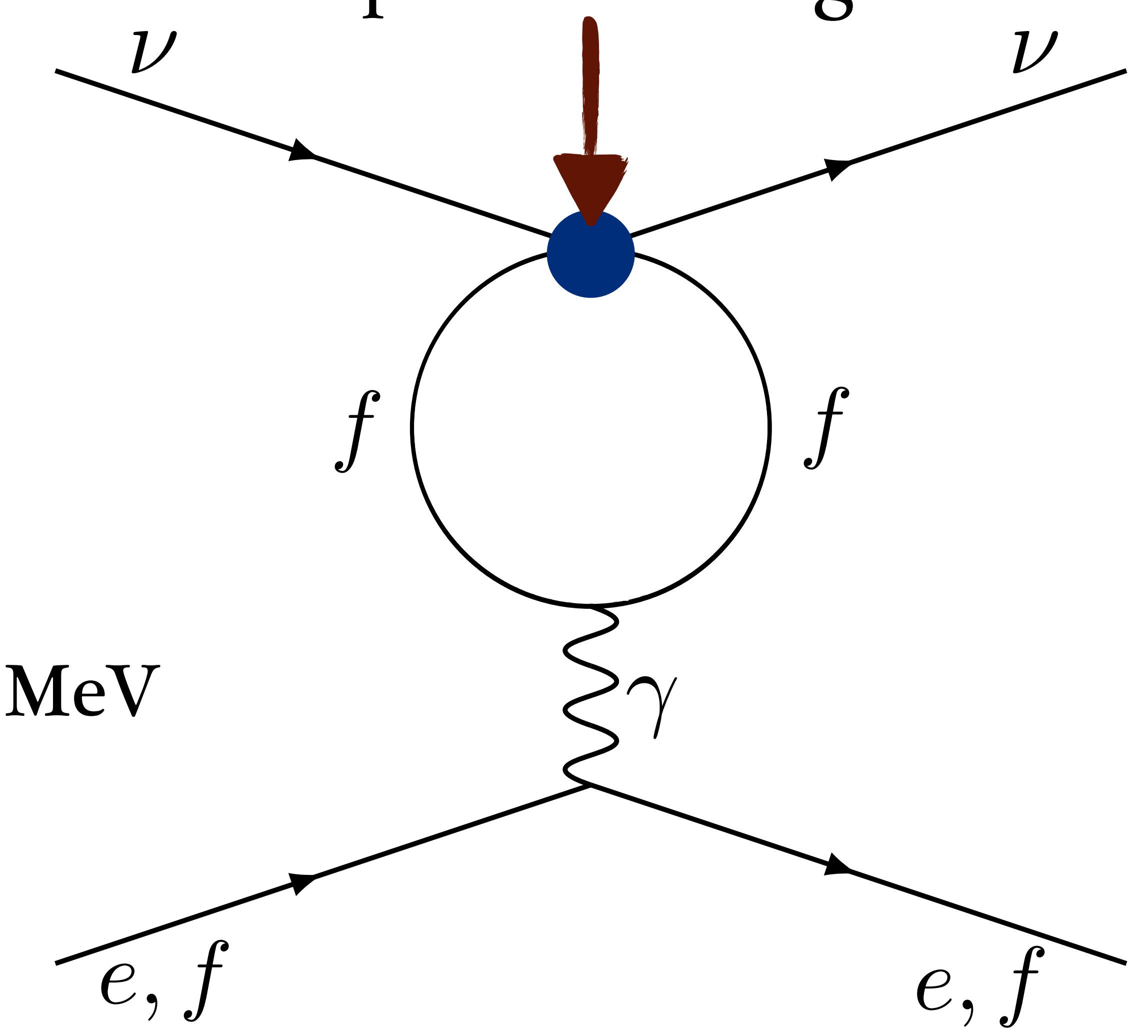
Running to low scales

M_Z - integrate out top, Z , W, h

% running effects

- only one EFT coupling changes with scale

operator mixing



m_b

m_τ - integrate out GeV particles

m_c

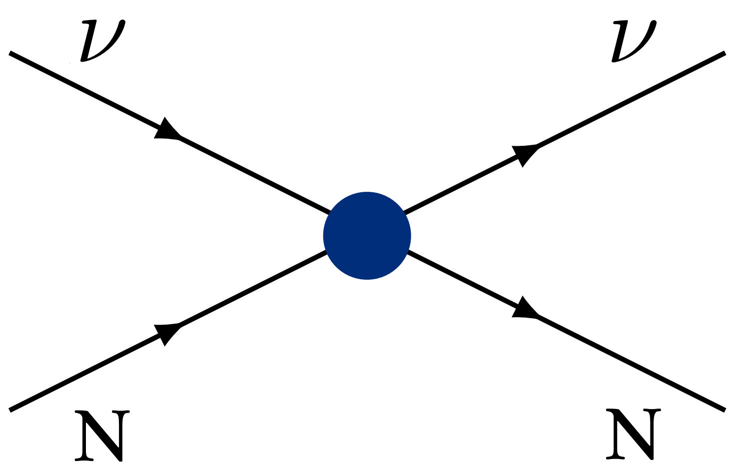
- α_s becomes too strong

- hadronic physics down to 140 MeV

m_π - theory with leptons

- precise mapping from electroweak to hadronic scales
- only 1 effective coupling changes with scale

CEvNS cross section on spin-0 nuclei



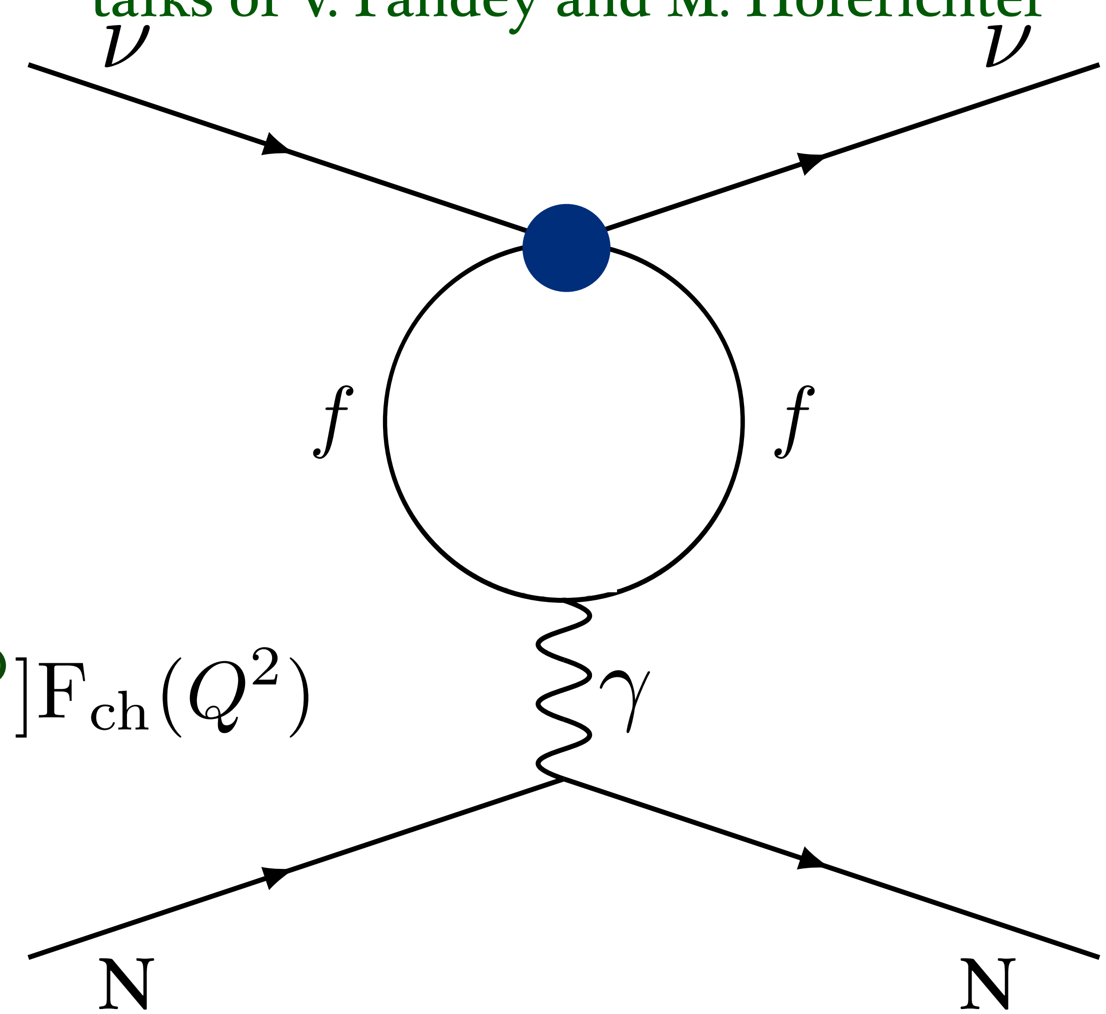
- tree-level cross sections

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

talks of V. Pandey and M. Hoferichter

- effect of radiative corrections

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



- radiative corrections enter with a nucleus charge form factor

Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop

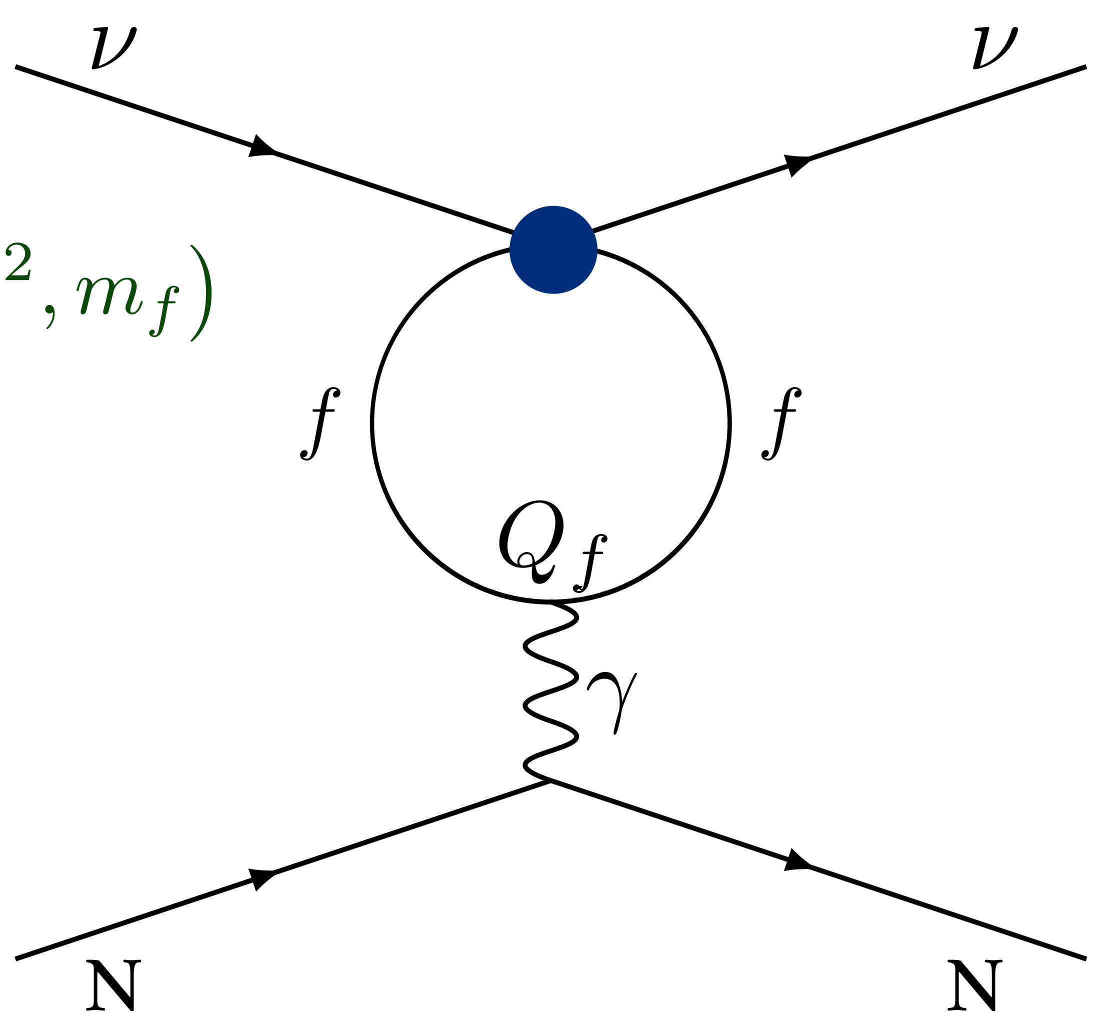
$$\mathcal{L}_{\rm eff}^{f} = -\bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{f}\gamma^\mu (c_{\rm L}^{f}\mathrm{P_L} + c_{\rm R}^{f}\mathrm{P_R}) f$$

- 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

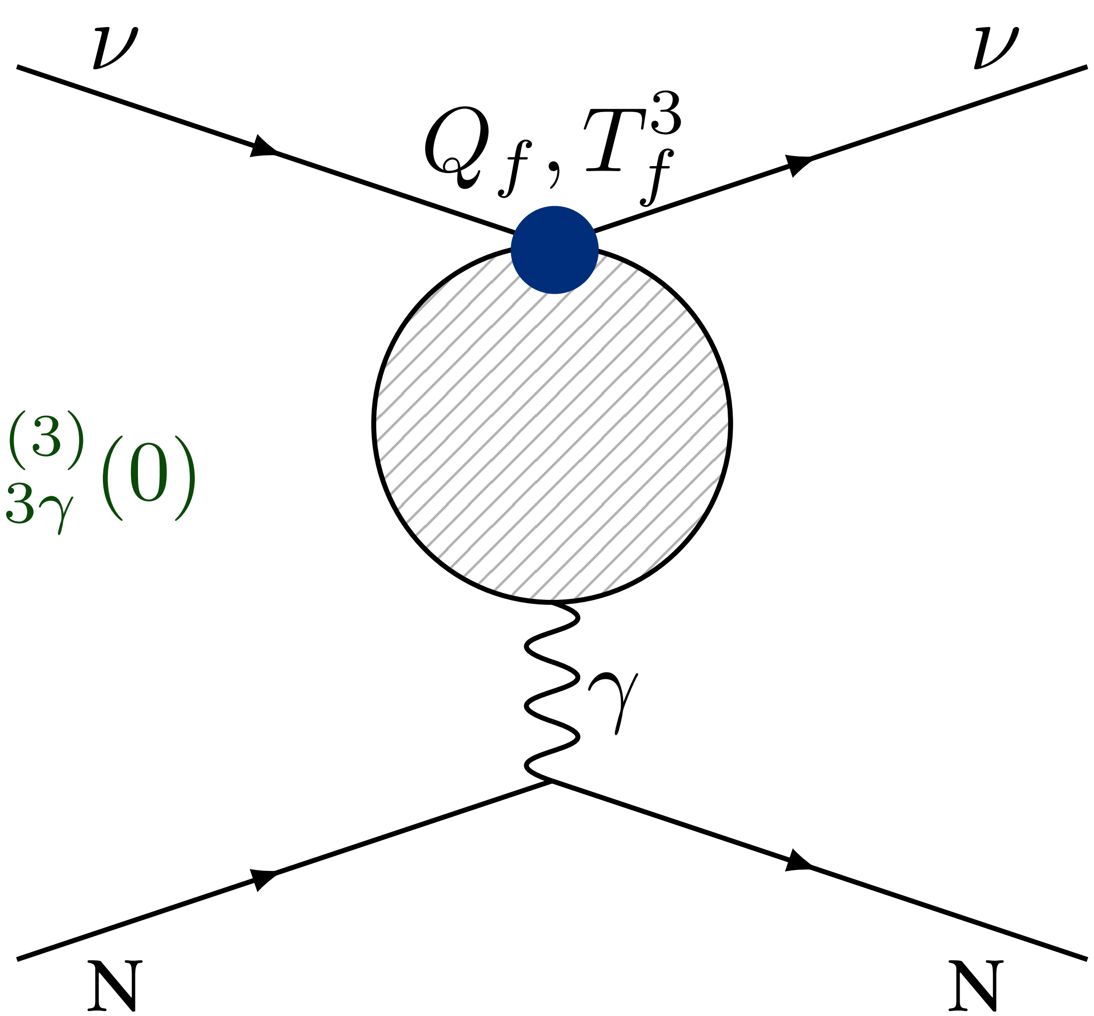
- description in terms of quarks is invalid at CEvNS kinematics

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

- light quarks

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

- flavor independent



- hadronic correlators at zero momentum transfer

Light-quark contribution

- vector-vector correlation functions in terms of quark contributions

$$\Pi_{\gamma\gamma} = \sum_{i,j} Q_i Q_j \Pi^{ij} \qquad \Pi_{3\gamma} = \sum_{i,j} T_i^3 Q_j \Pi^{ij}$$

- SU(3)f approximation

$$\Pi_{3\gamma} = \Pi_{\gamma\gamma}$$

- SU(2)f approximation

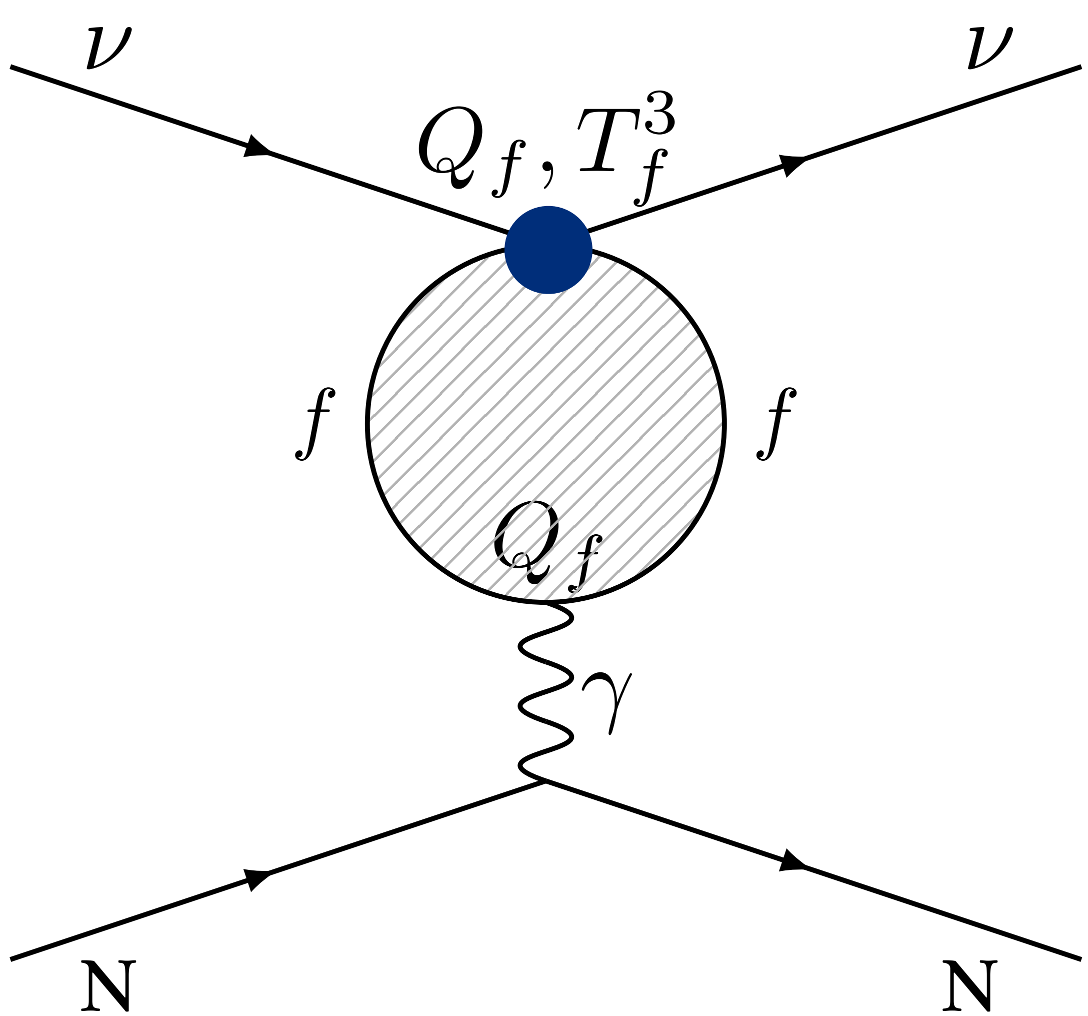
$$\Pi_{3\gamma} = \frac{9}{10}\Pi_{\gamma\gamma}$$

- our choice

$$\Pi_{3\gamma}^{(3)} = (1 \pm 0.2)\,\Pi_{\gamma\gamma}^{(3)}$$

- with $\Pi_{\gamma\gamma}^{(3)}(0)$ from

Erler et al (2018), 1712.09146



- non-perturbative light-quark contribution

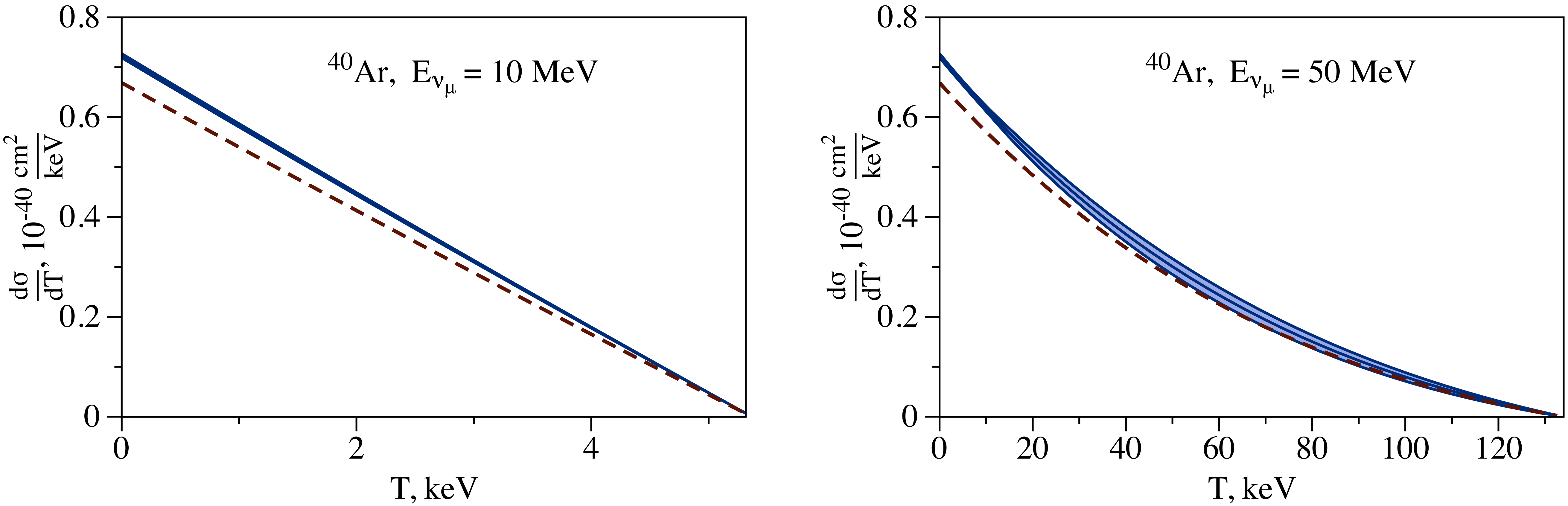
Total and differential cross section

- prompt neutrinos from pion decay-at-rest source

$$\sigma_{\nu_\mu} = (15.19 \pm 0.24) \cdot 10^{-40}\ \text{cm}^2, \qquad \sigma_{\nu_e} = (15.01 \pm 0.24) \cdot 10^{-40}\ \text{cm}^2$$

point-nucleon form factors:
J. Yang et al. (2019), C. Payne et al. (2019), M. Hoferichter et al. (2020), N. Van Dessel et al. (2020)

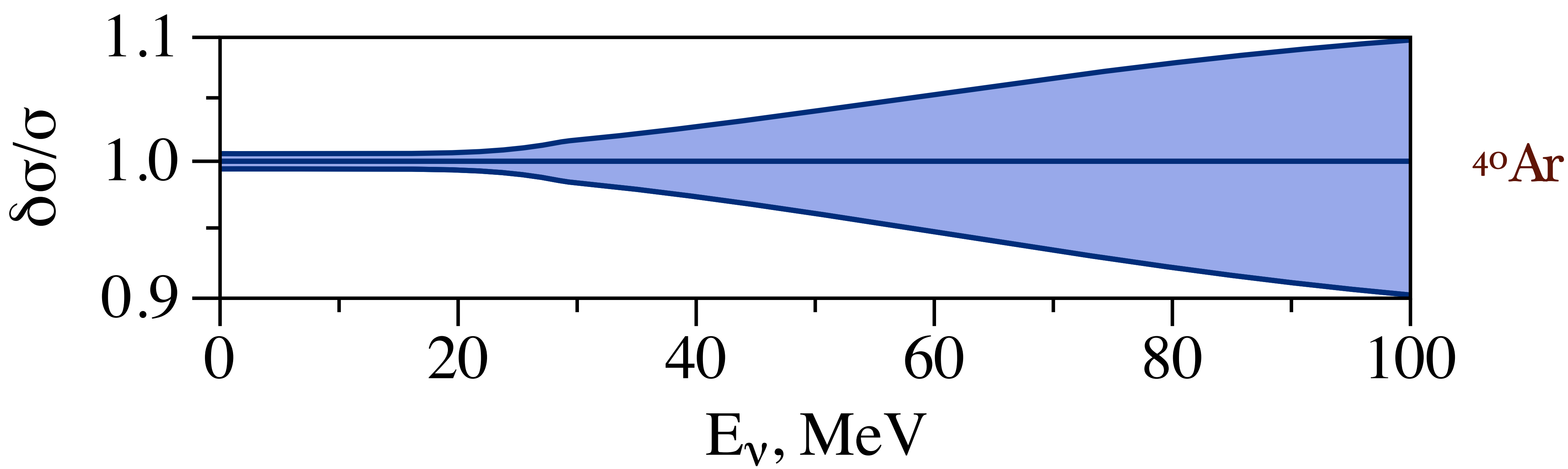
- recoil nucleus energy spectrum: one-loop vs tree level



- % effect of radiative corrections on cross sections
- averaging over radiatively corrected flux ongoing

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

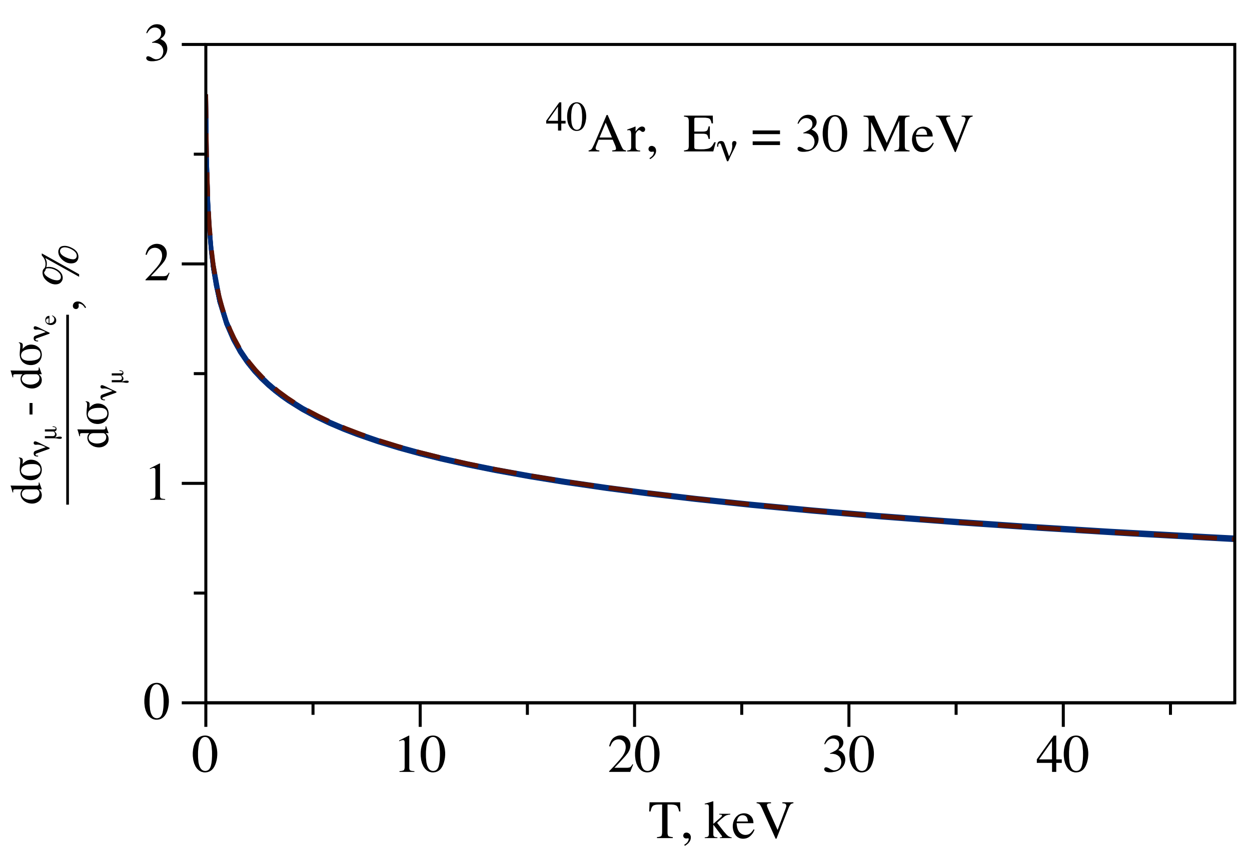
- hadronic error 0.6% at low energy, nuclear error at higher energy

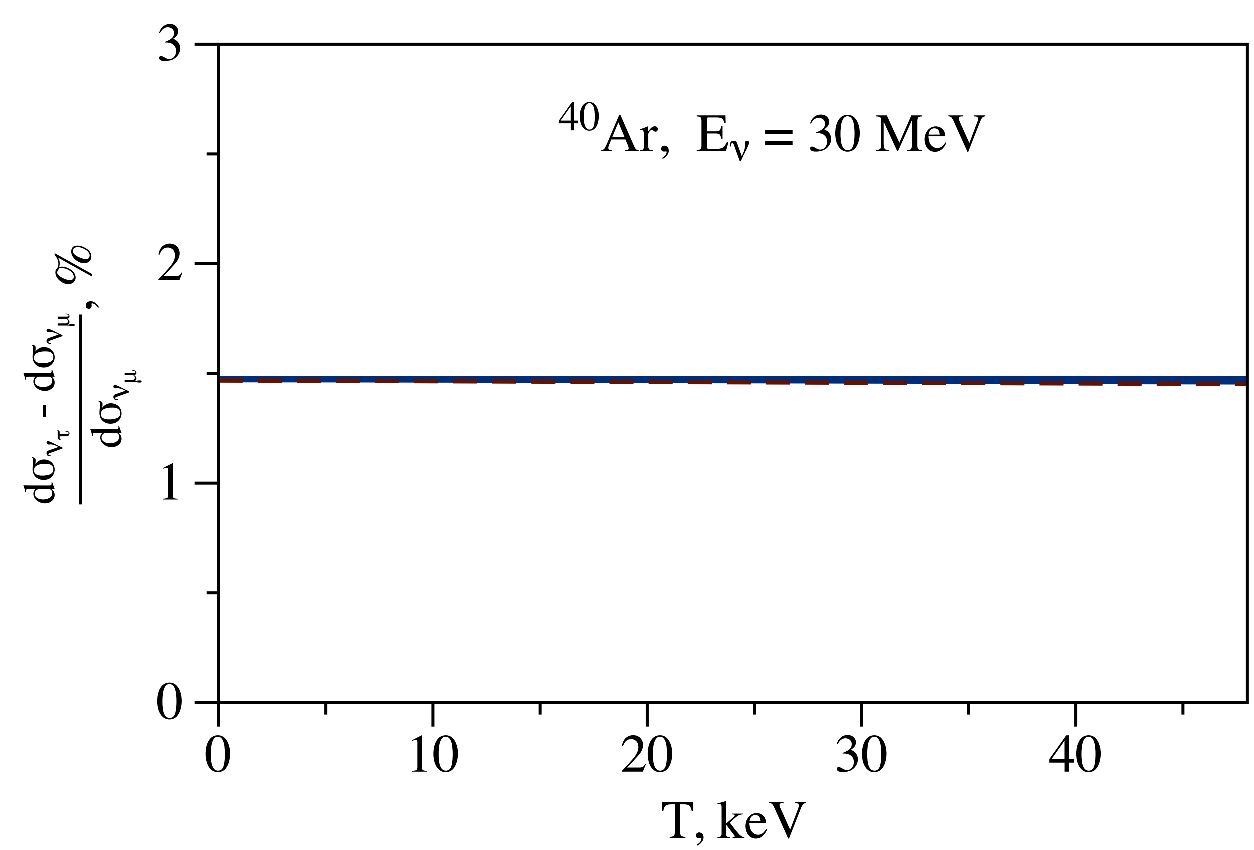
Flavor difference

- well described by point-nucleus limit

$$\lim_{R_p, R_n \to 0} \frac{d\sigma_{\nu_\ell} - d\sigma_{\nu_{\ell'}}}{d\sigma_{\nu_\ell}} = 4 \frac{\alpha_0}{\pi} \frac{Z}{Q_{\mathrm{W}}} \left[\Pi \left(Q^2, m_\ell \right) - \Pi \left(Q^2, m_{\ell'} \right) \right]$$

- kinematic dependence: full result vs point-nucleus limit

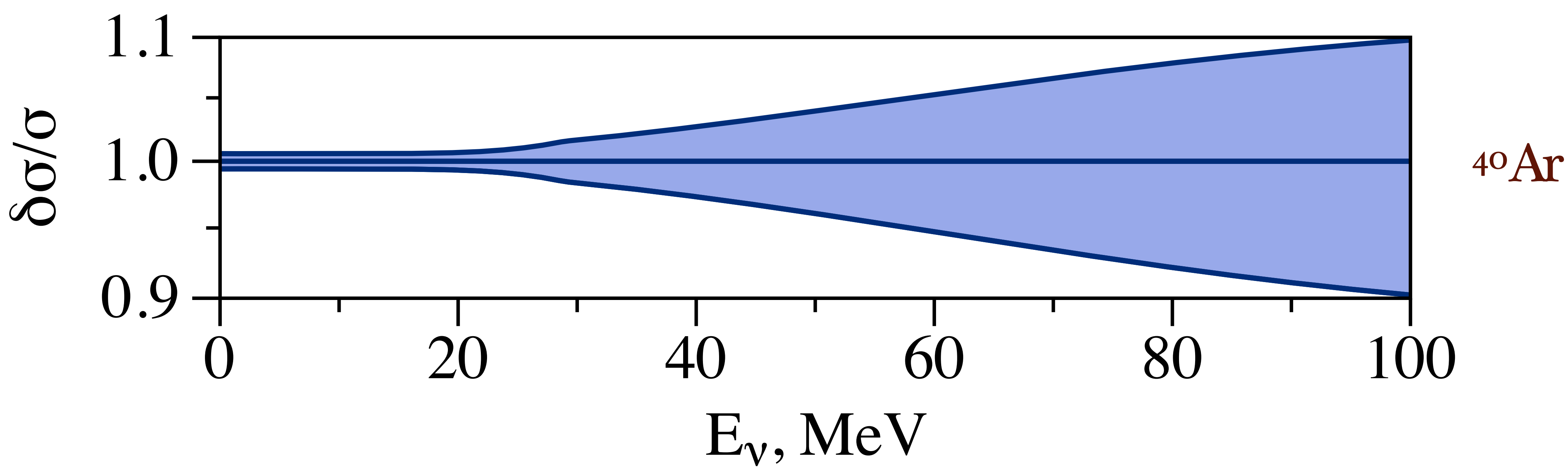




- up to factor 3-6 change in electron-muon asymmetry

Flavor difference errors

- relative cross section error

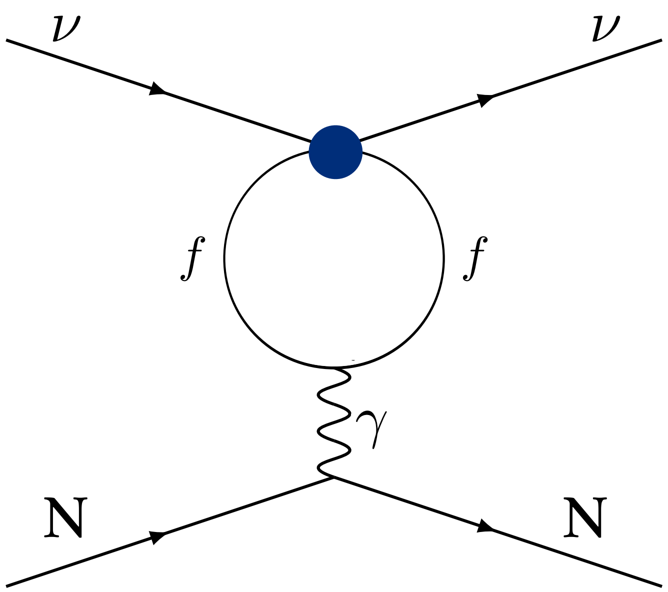


- sources of uncertainty for muon-tau asymmetry (%)

E_ν, MeV	Nuclear	Nucleon	Hadronic	Quark	Perturbative	Total
50	0.43	0.007	0.28	0.07	0.002	0.52
30	0.17	0.003	0.28	0.07	0.002	0.34
10	0.02	0.0003	0.28	0.07	0.002	0.29

- nuclear errors largerly cancel in flavor asymmetry

Takeaway messages



radiative corrections to CEvNS formulated in EFT framework

- lepton loops: CEvNS is flavor dependent at percent level
  S. Sakakibara and L. M. Sehgal (1979)
- kinematic dependence of radiative corrections at percent level
  L. M. Sehgal (1985)
- quark loops: no constituent quarks as degrees of freedom
  Weinberg angle: F. Jegerlehner (1985)
- cross sections and flavor differences with error budget on ^{40}Ar
  this work
- hadronic errors dominate at low energies and momentum transfer
  this work

Applications in talk of Ryan Plestid

Thanks for your attention !!!

This presentation is based upon work
that is supported by the Visiting Scholars Award Program
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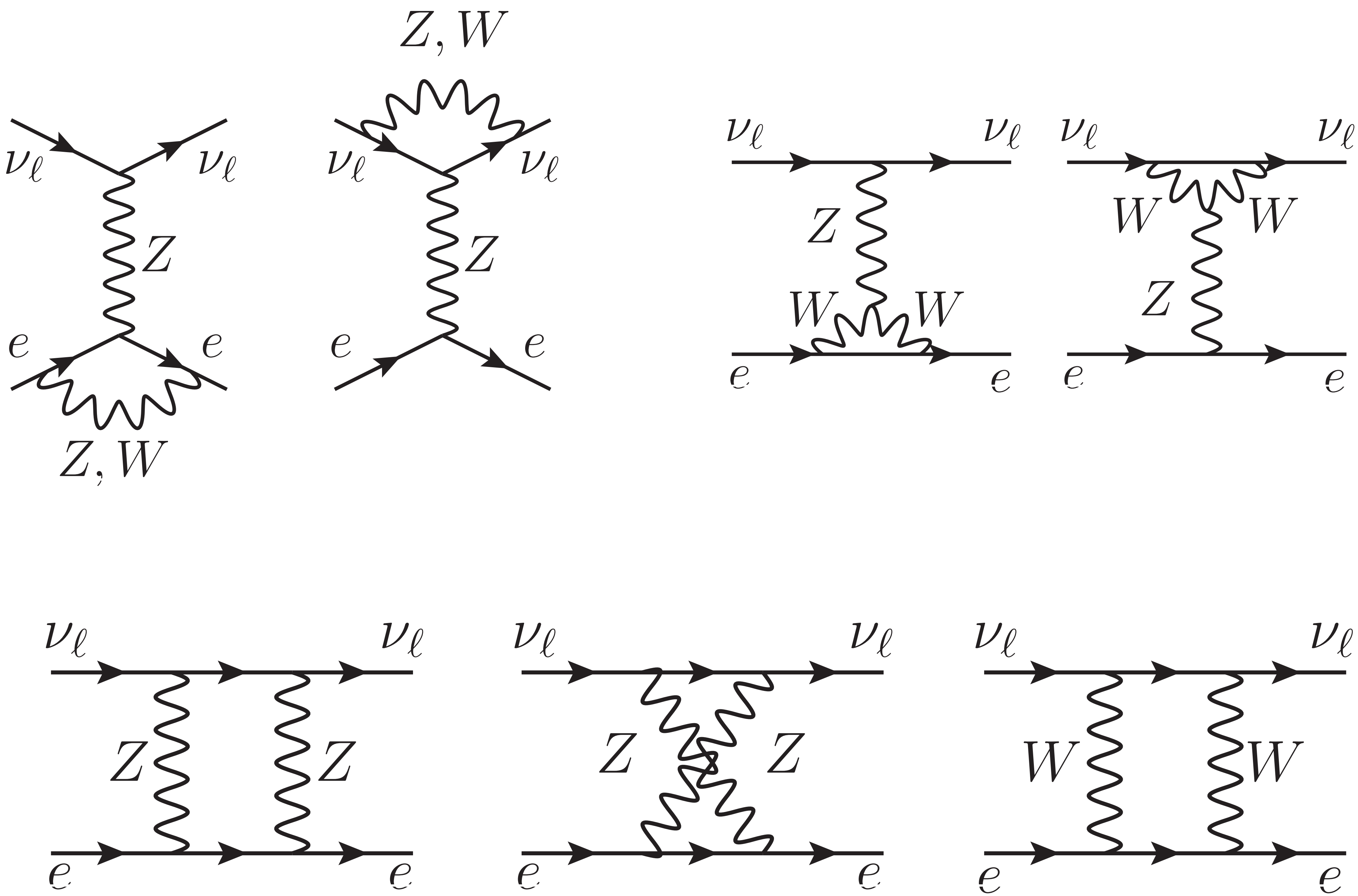
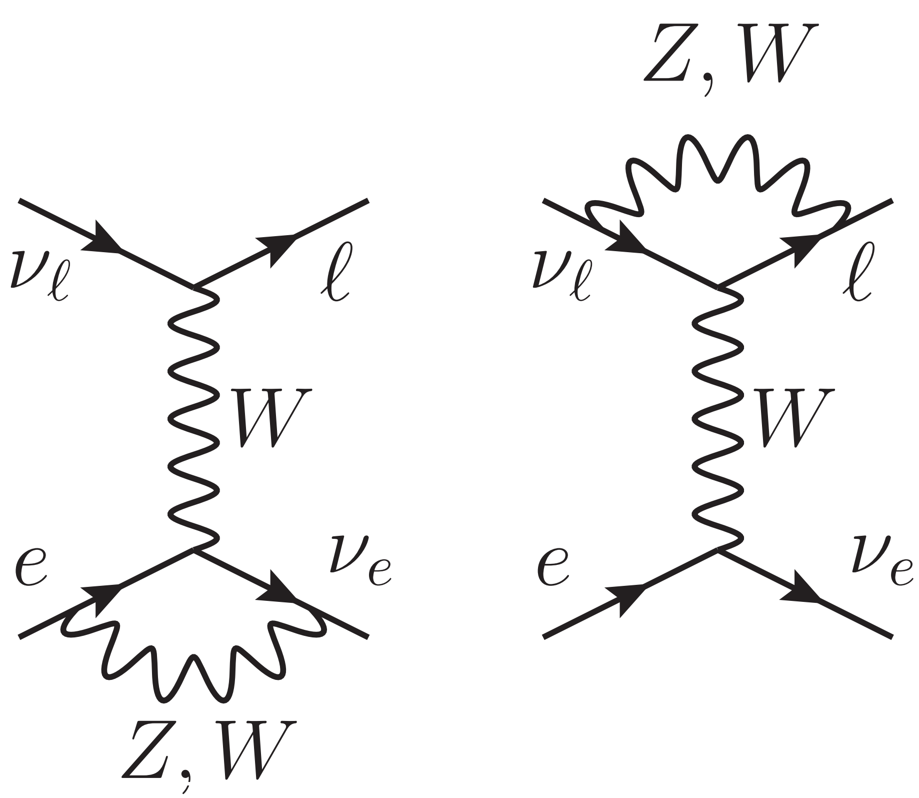
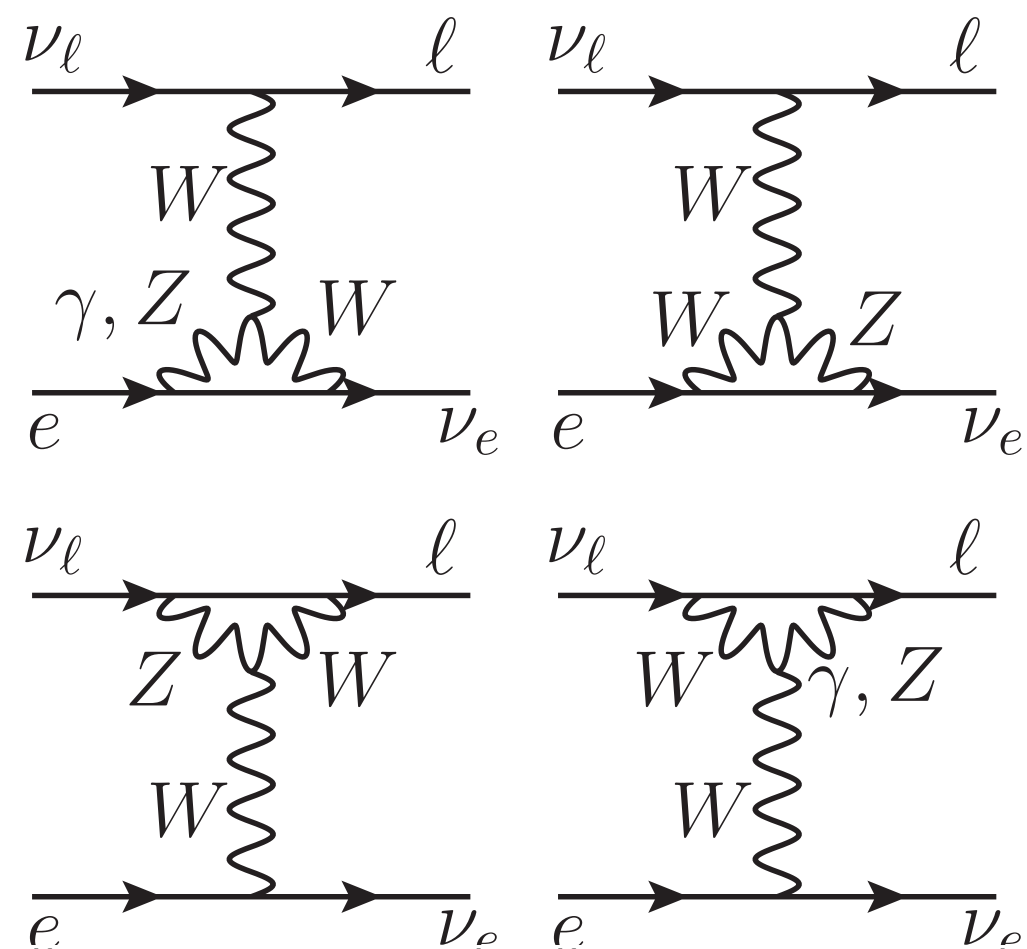
Neutral current in SM



- contribution to effective couplings

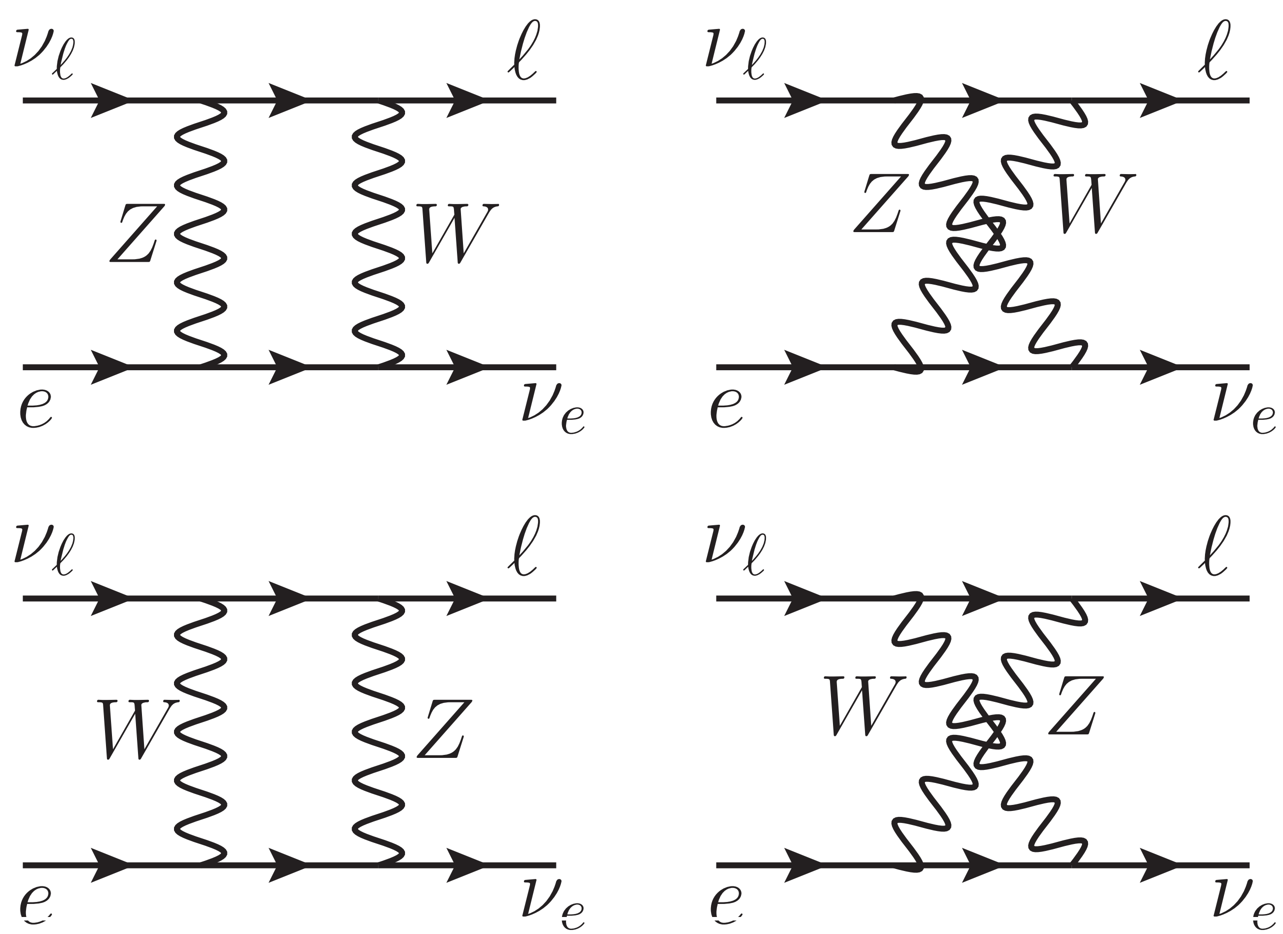
Charged current in SM. Vertexes





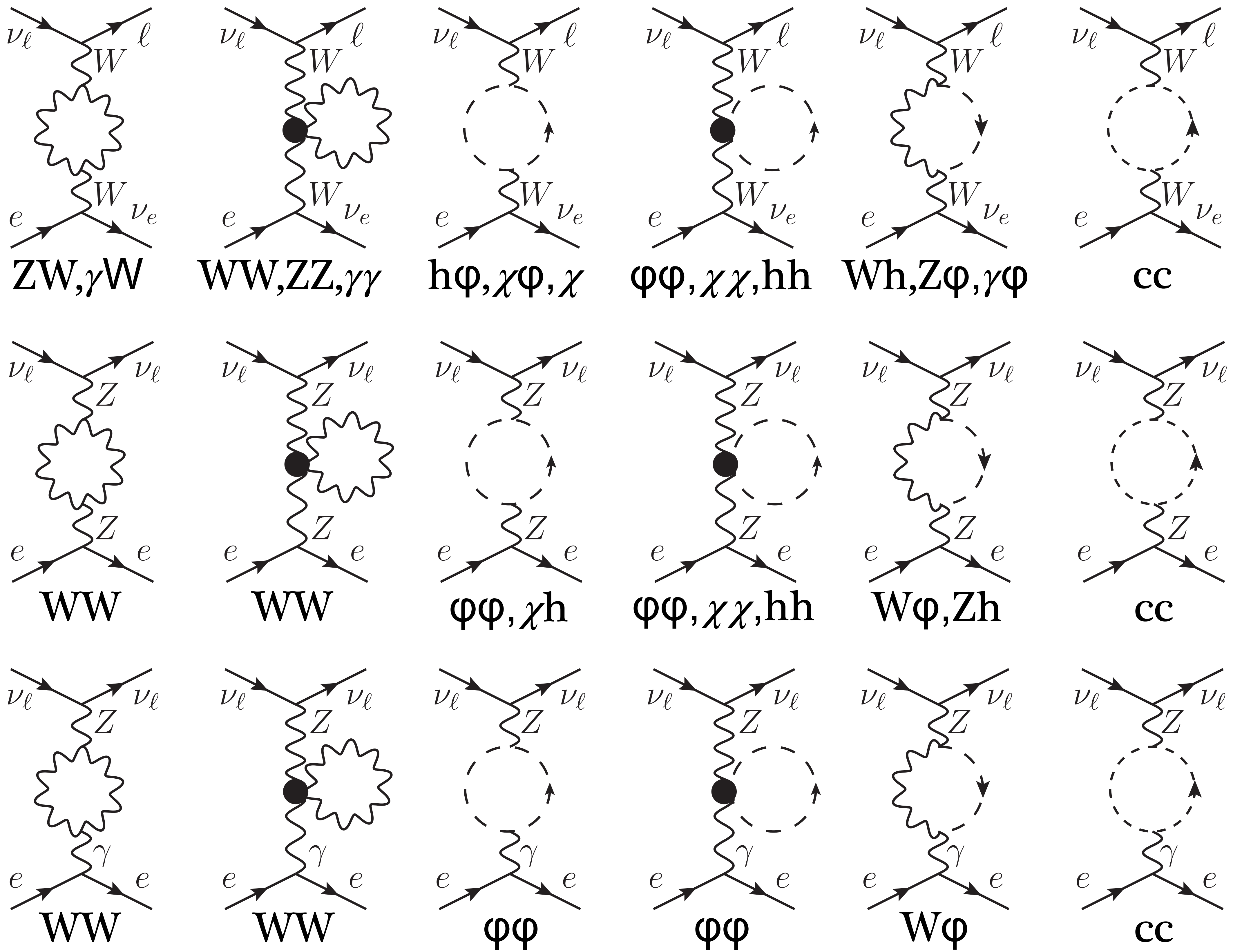
- contribution to effective couplings

Charged current in SM. Boxes

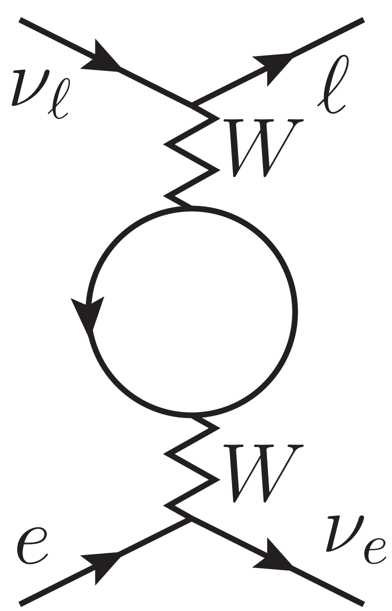


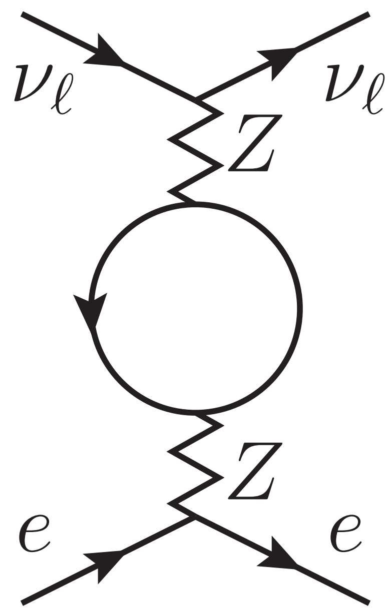
- contribution to effective couplings

Self energy and γZ mixing. Boson loops

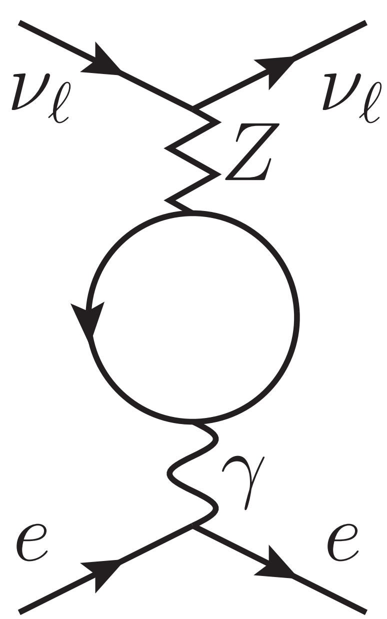


Self energy and γZ mixing. Fermion loops



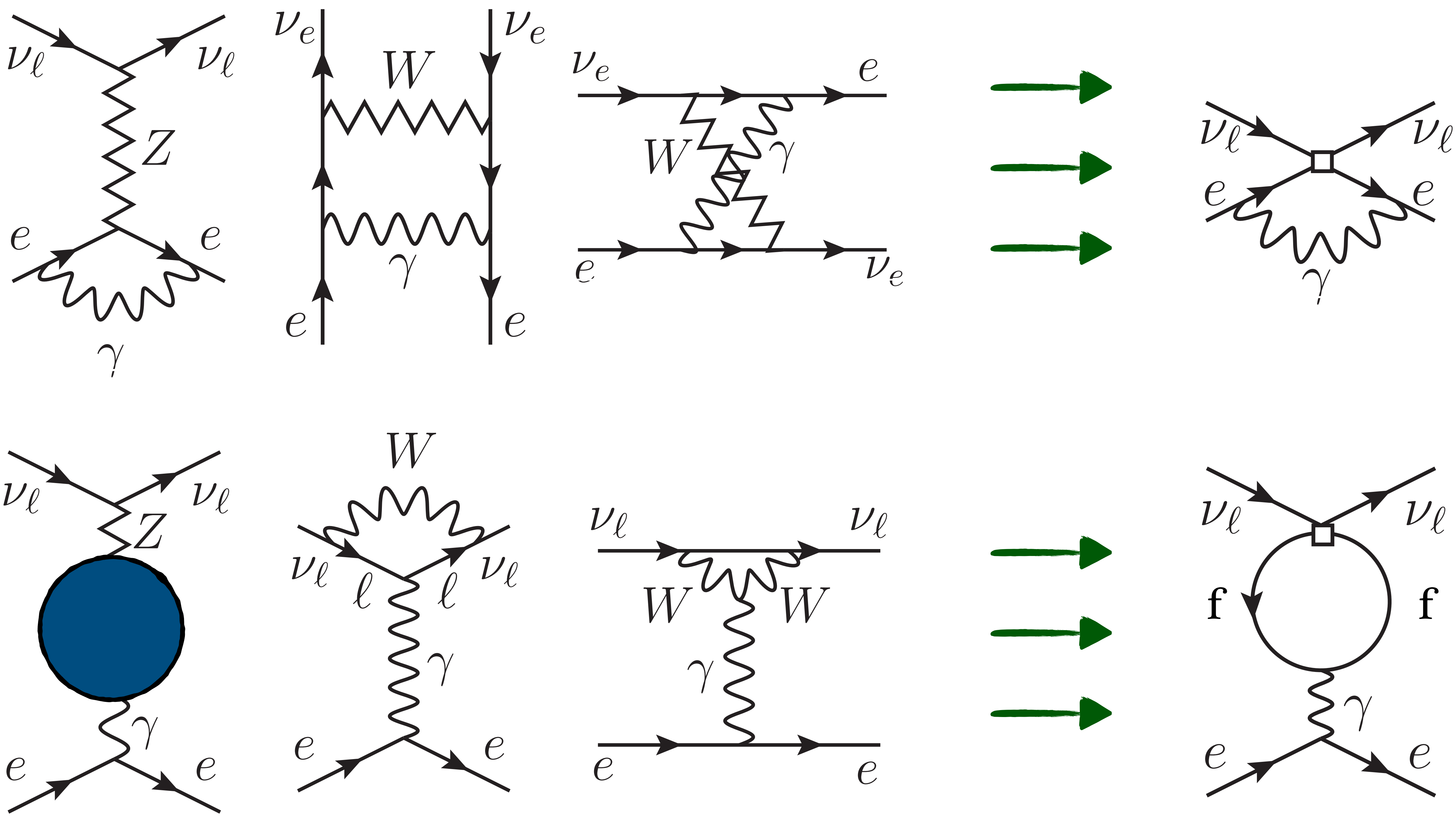


- vanishing contribution to matching besides loops with t quark
- finite contribution to self energy pole vs $\overline{\text{MS}}$ masses
- do not consider Higgs tadpoles (hVV): matching vs self energy cancellation



- gauge-independent contribution

Matching at one loop → EFT side



- cancellation of infrared and collinear singularities