RADCOR 2019

Centre des Congres du Palais des Papes

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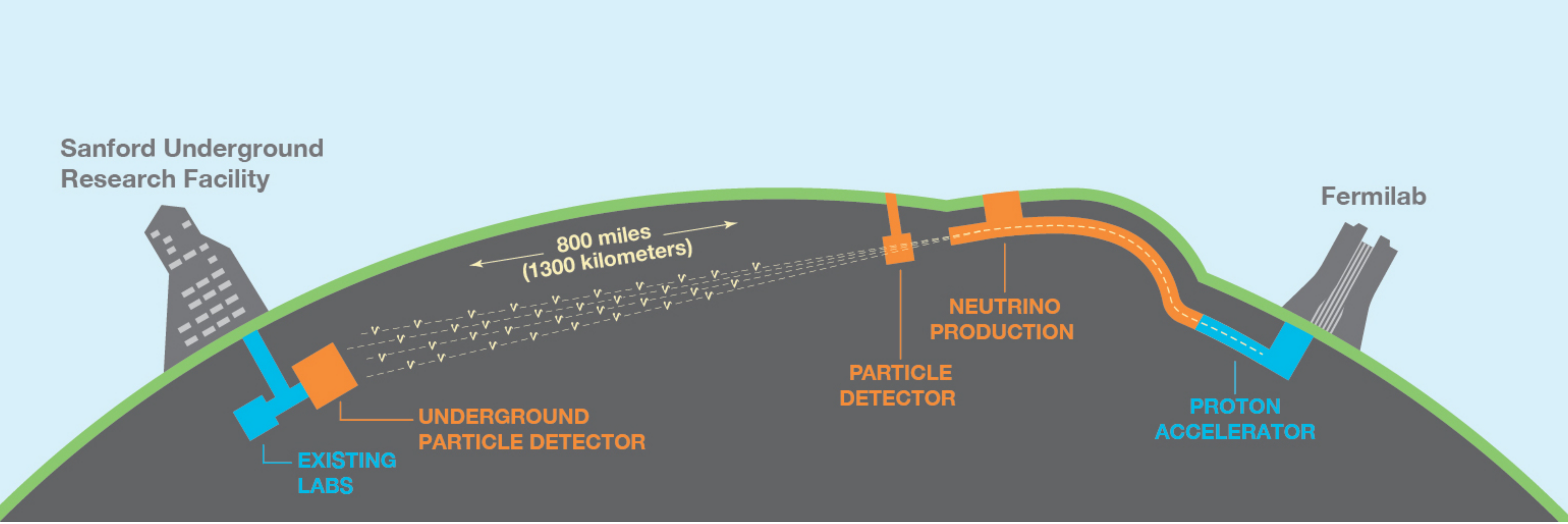
Elastic neutrino-electron scattering in effective field theory

University of Kentucky

Oleksandr Tomalak

Neutrino experiments

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



- measurement of ν_μ disappearance and ν_e appearance from count rates

$$N_\nu \sim \int \mathrm{d}\omega \Phi_\nu(\omega) \times \sigma(\omega) \times R(\omega, \omega_{\mathrm{rec}})$$

- determination of neutrino fluxes:
one of the main goals of Near Detector

Elastic neutrino-electron scattering

- historic channel in discovery of weak neutral currents
  Gargamelle (1973)
- measurement of total cross section and Weinberg angle
  CHARM (1988), CHARM-II (1994), BNL-E734 (1990), LAMPF (1993), LSND (2001)
- solar neutrino studies
  Kamiokande, SNO, Super-Kamiokande I-IV, Borexino, Hyper-Kamiokande
- reactor antineutrino studies
  Savannah river (1976), Krasnoyarsk (1990), Rovno (1993), MUNU (2005), TEXONO (2010), GEMMA (2012)

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- small cross section scales as electron mass m:

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

- scattering on atomic electrons: standard candle to constrain flux

  uncertainty from 9% to 6% and from 7.5% to 4%

  MINERvA (2016, 2019), NOvA analysis is ongoing

> - relatively clean tool to constrain neutrino flux in DUNE
> - goal: EFT-based calculation with accuracy below %

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

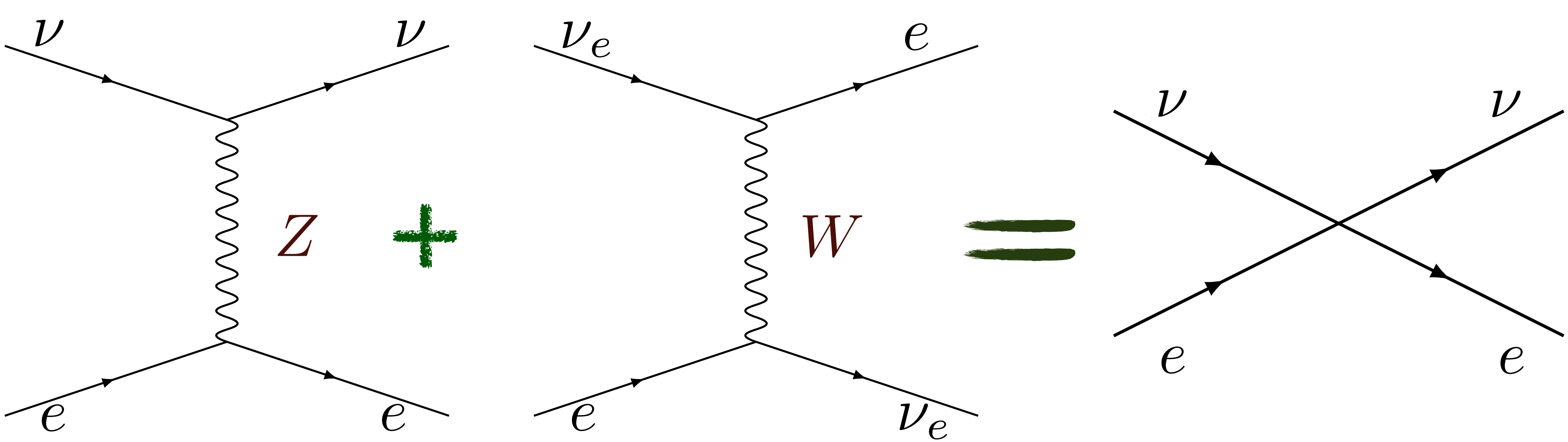
$$\mathcal{L}_{\text{eff}} = -\bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{e}\gamma^\mu(c_\mathrm{L}\mathrm{P_L} + c_\mathrm{R}\mathrm{P_R})e$$

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

Weinberg (1967), 't Hooft (1971)

- projectors on chiral states: $\mathrm{P_L} = \dfrac{1-\gamma_5}{2} \qquad \mathrm{P_R} = \dfrac{1+\gamma_5}{2}$

neutral current | charged current



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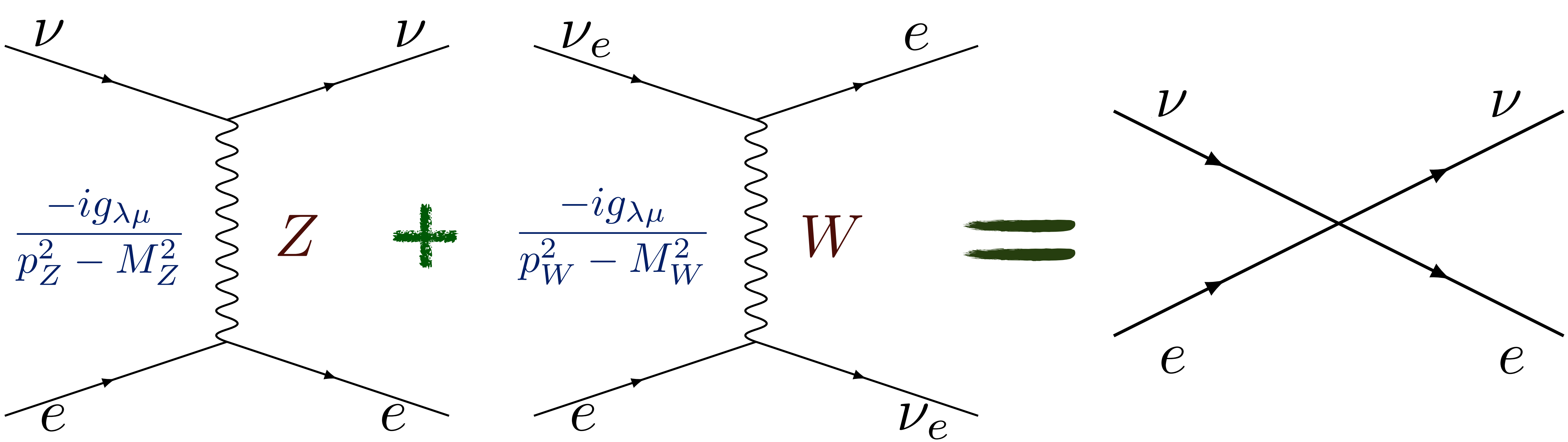

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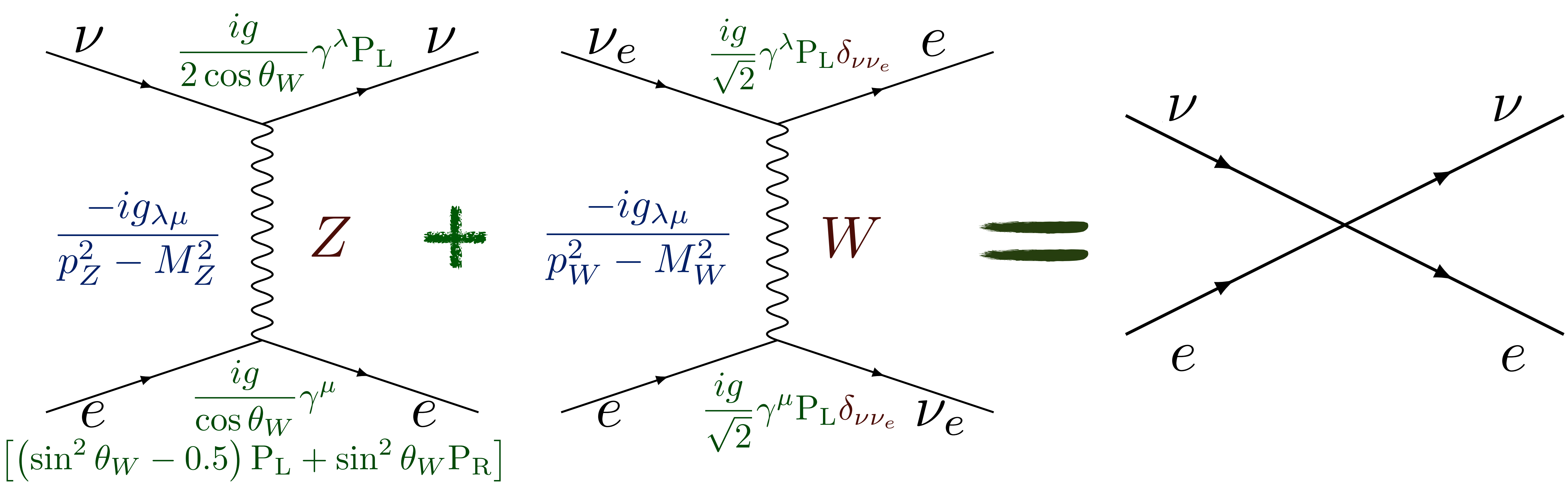

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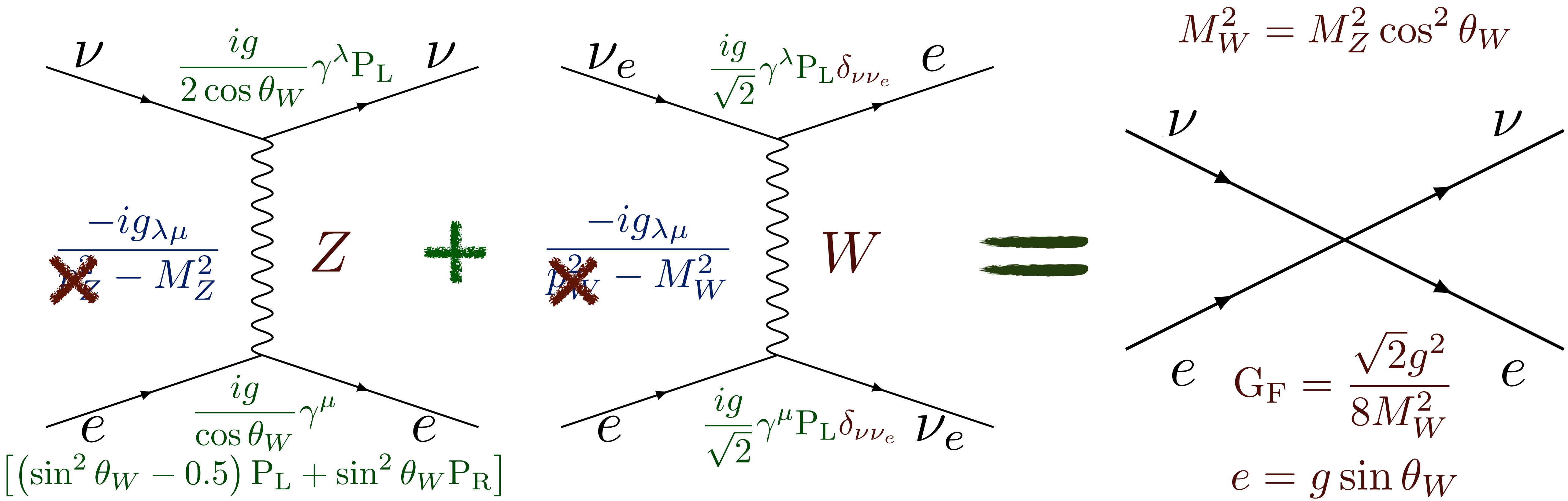

- integrate out W and Z at tree level

Neutrino scattering in EFT. Matching

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Weinberg (1967), 't Hooft (1971)

- consider only leading in $\mathrm{G_F}$ terms: loop corrections in α, α_s

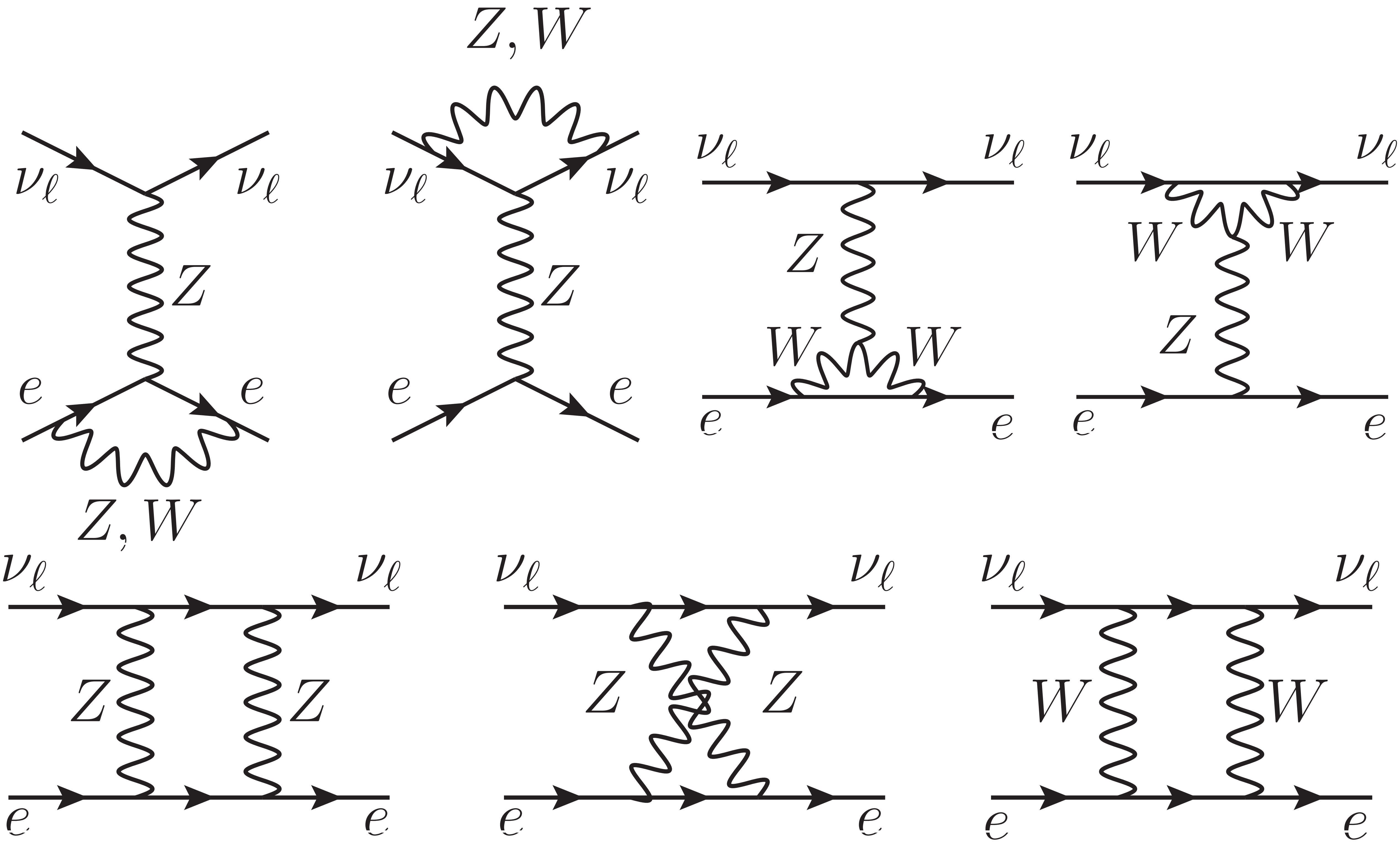
- matching of amplitudes, renormalized in $\overline{\mathrm{MS}}$ scheme:

$$\mathcal{M}^{\rm SM}(\mu) = \mathcal{M}^{\rm EFT}(\mu) \qquad \mu = M_Z$$

- neglect fermion masses besides top quark

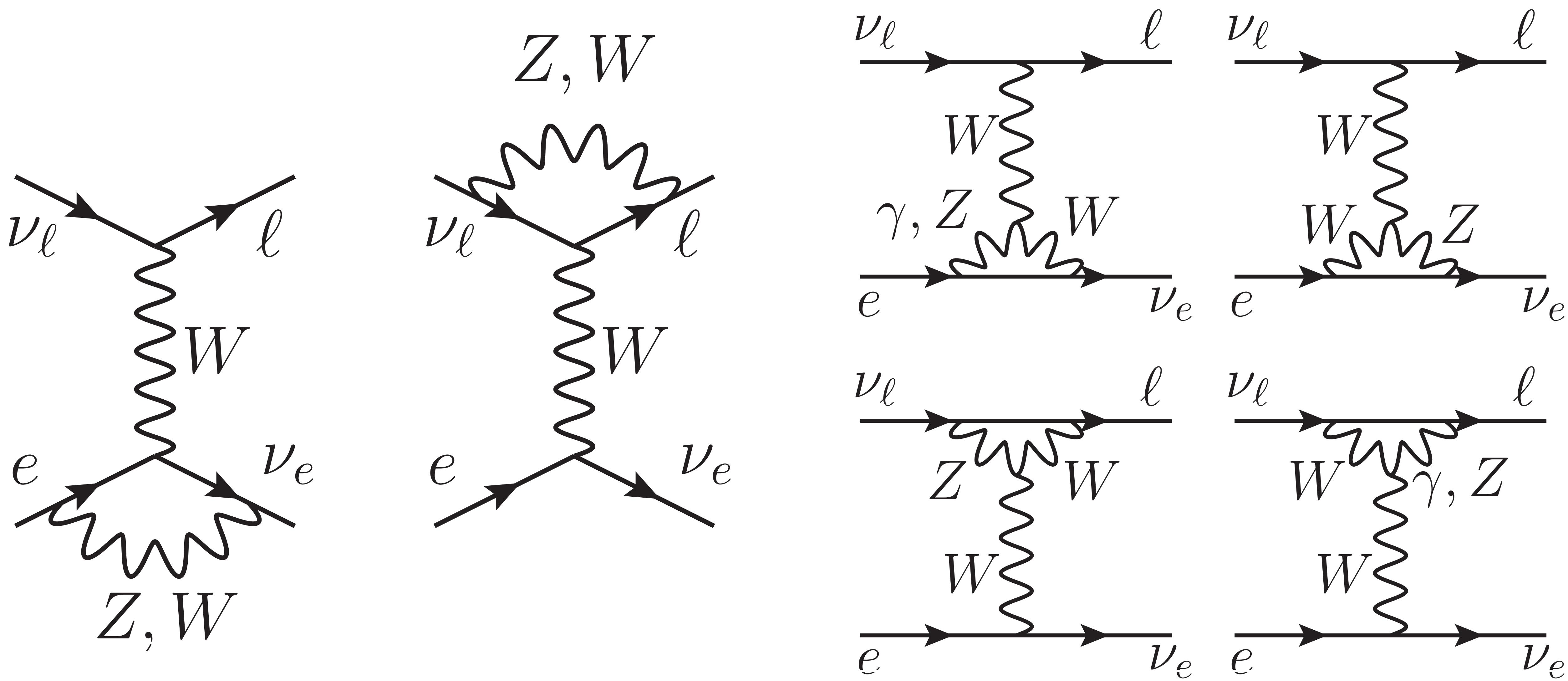
$$\mathrm{G_F} = \frac{\sqrt{2}g^2}{8M_W^2}$$

Neutral current in SM



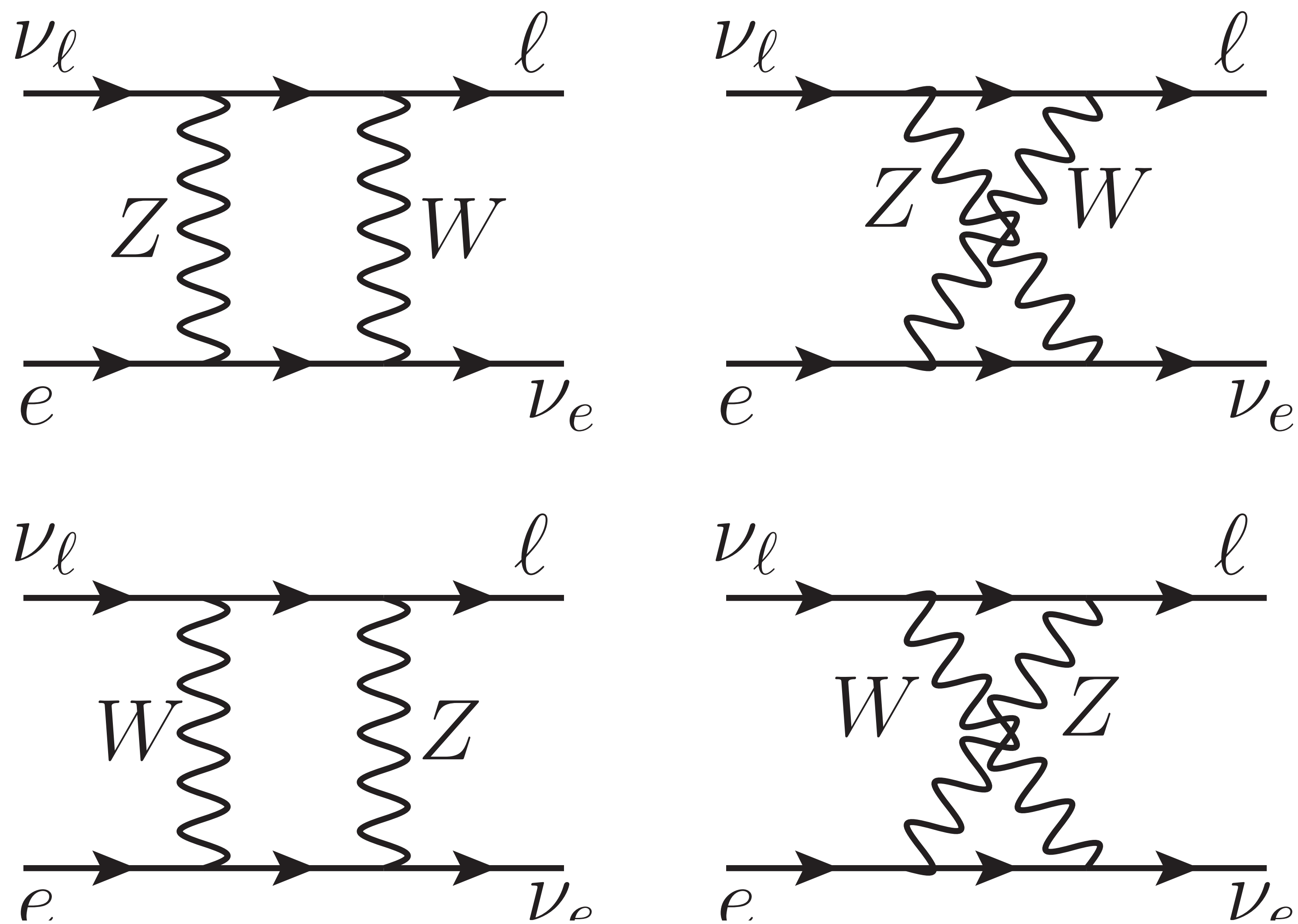
- contribution to effective couplings

Charged current in SM. Vertexes



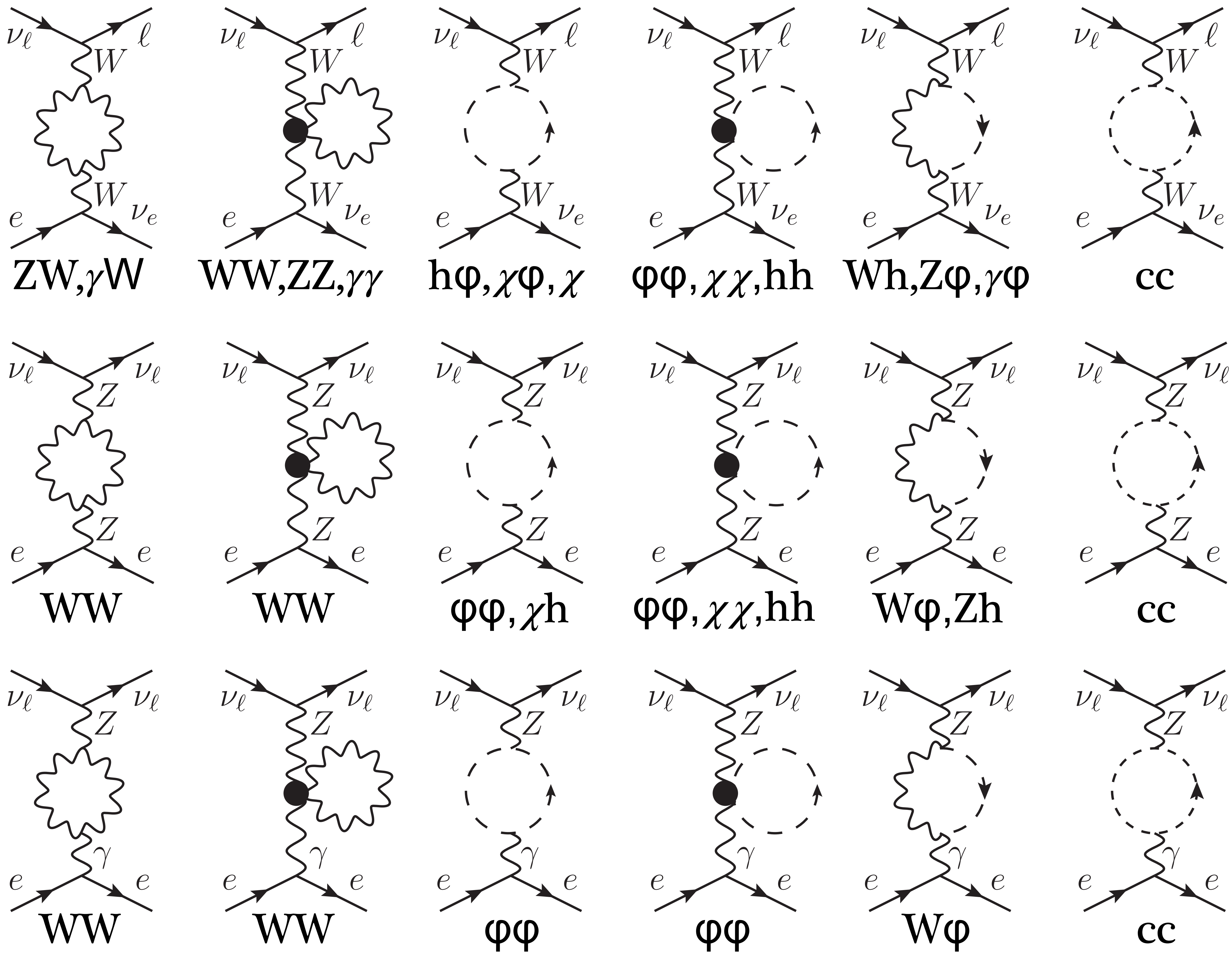
- contribution to effective couplings

Charged current in SM. Boxes

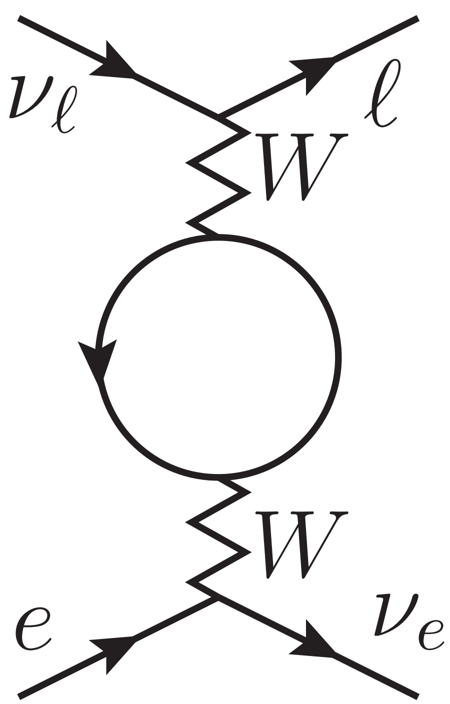


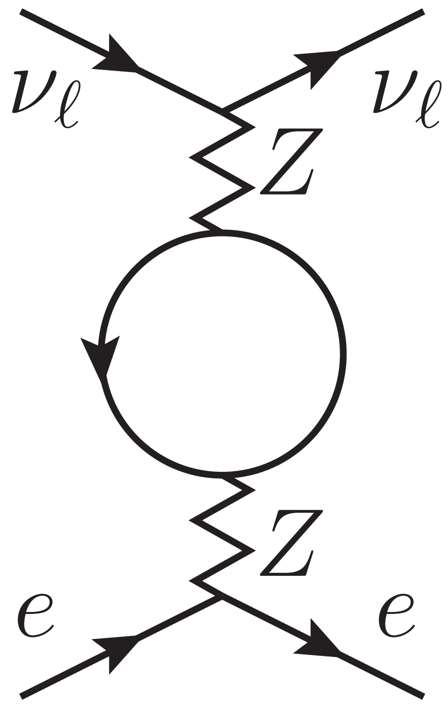
- contribution to effective couplings

Self energy and γZ mixing. Boson loops

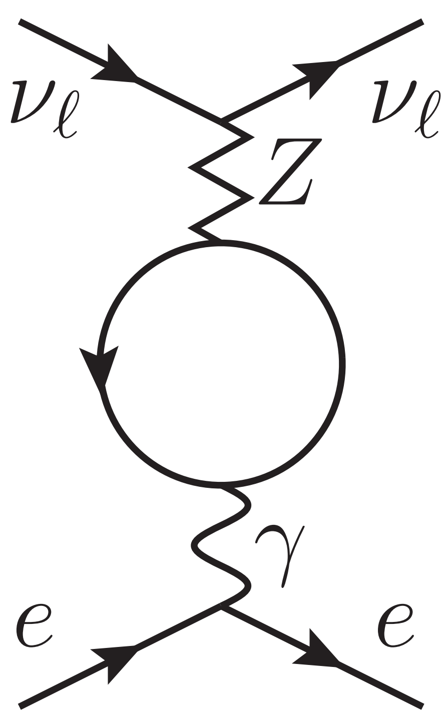


Self energy and γZ mixing. Fermion loops



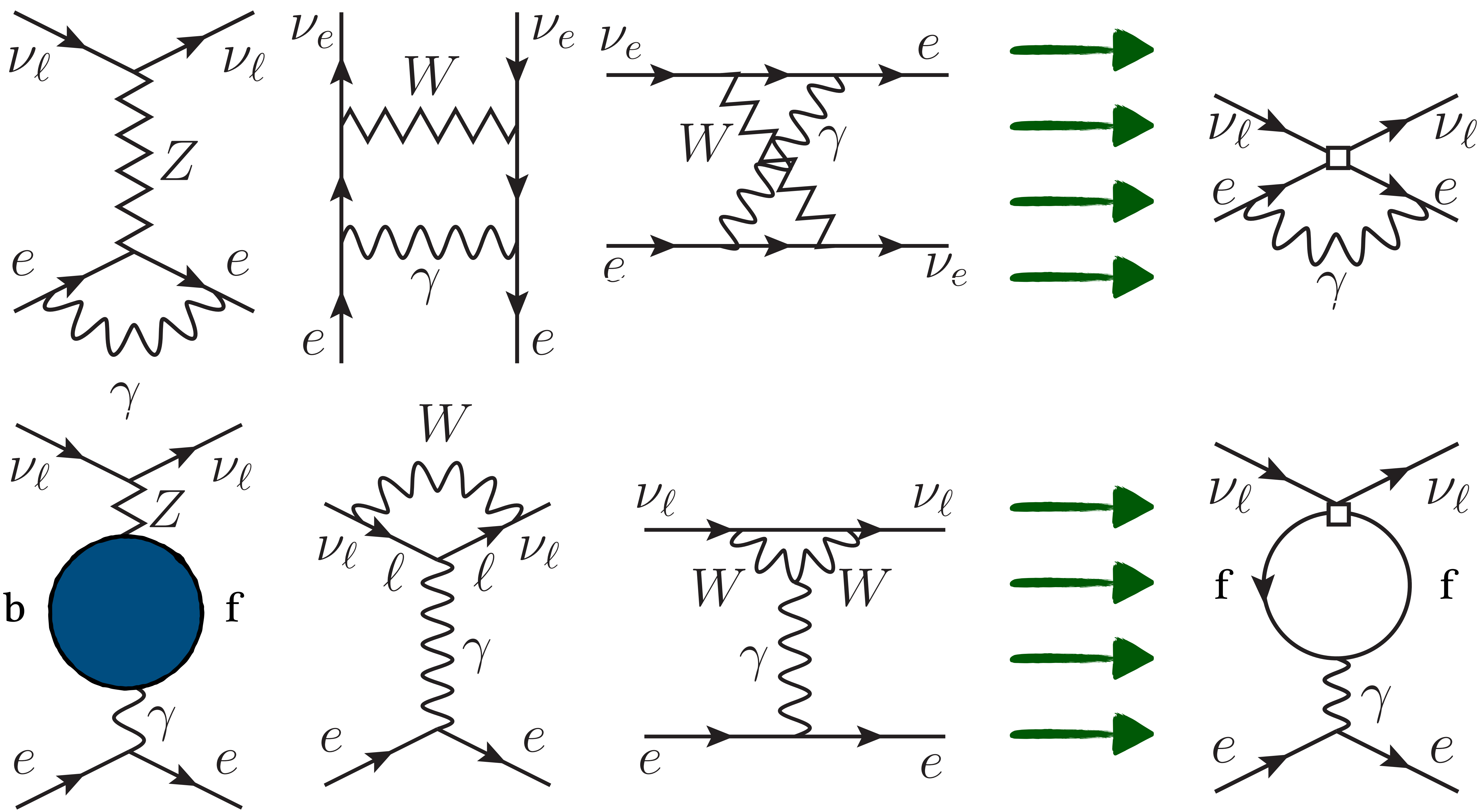


- vanishing contribution to matching besides loops with t quark
- finite contribution to self energy pole vs $\overline{\text{MS}}$ masses
- do not consider Higgs tadpoles (hVV): matching vs self energy cancellation



- gauge-independent contribution
- cancels in matching conditions

Matching at one loop → EFT side



- cancellation of infrared and collinear singularities
- Z and W Z-factors are absent in EFT

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

Weinberg (1967), 't Hooft (1971)

- consider only leading in $\mathrm{G_F}$ terms: loop corrections in α, α_s

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

$$\mathcal{M}^{\rm SM}(\mu) = \mathcal{M}^{\rm EFT}(\mu) \qquad \mu = M_Z$$

- the same tree-level operators after one-loop matching

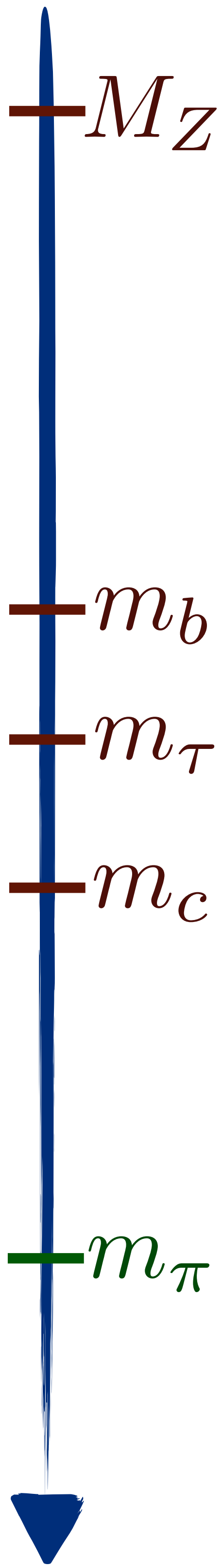
- exploit $\mathrm{G_F}$ for one combination of electroweak parameters

$$\mathrm{G_F} = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2} \qquad \mathrm{G_F} = \frac{\sqrt{2}g^2}{8M_W^2}$$

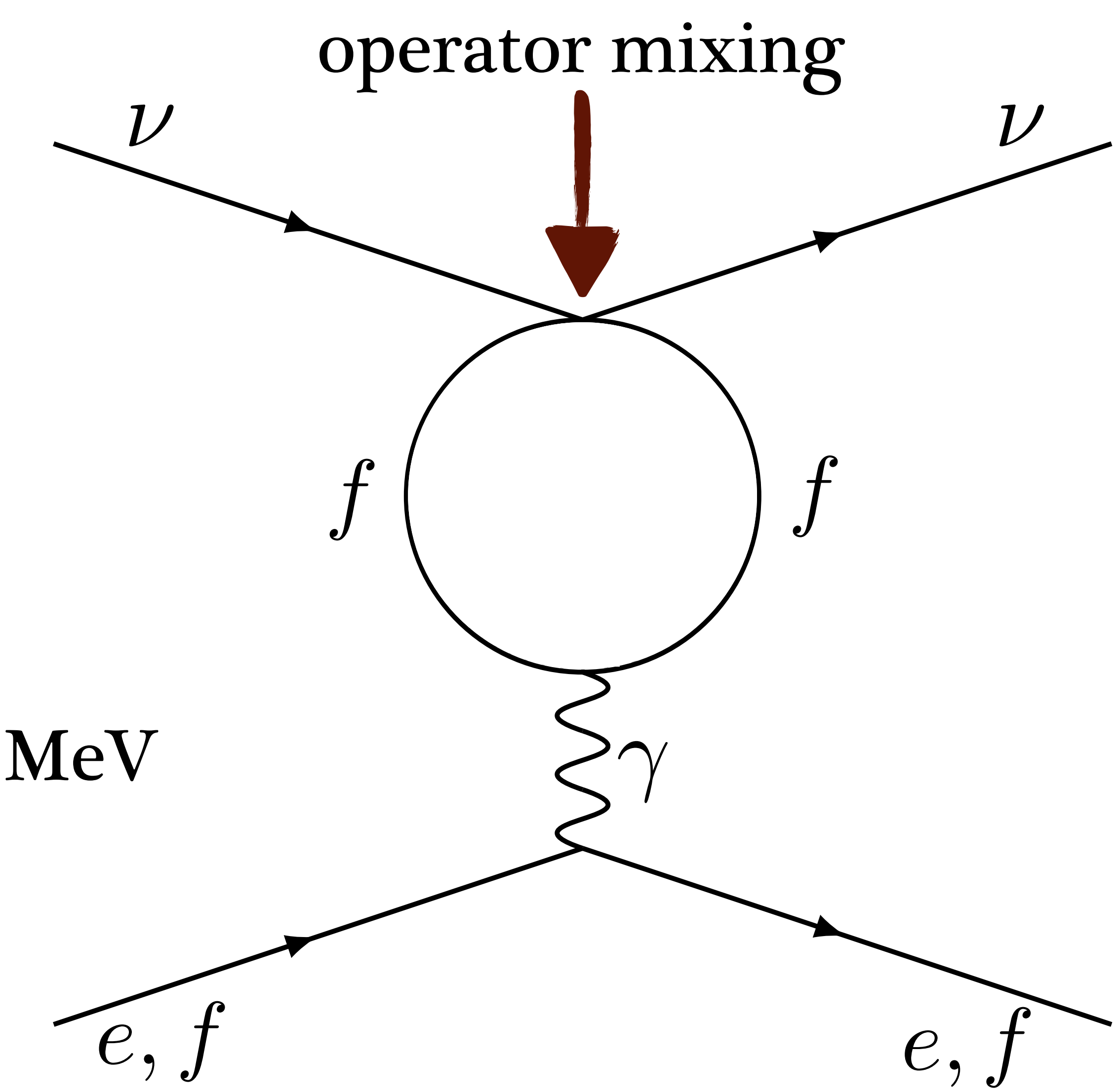
MULAN (2012)

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

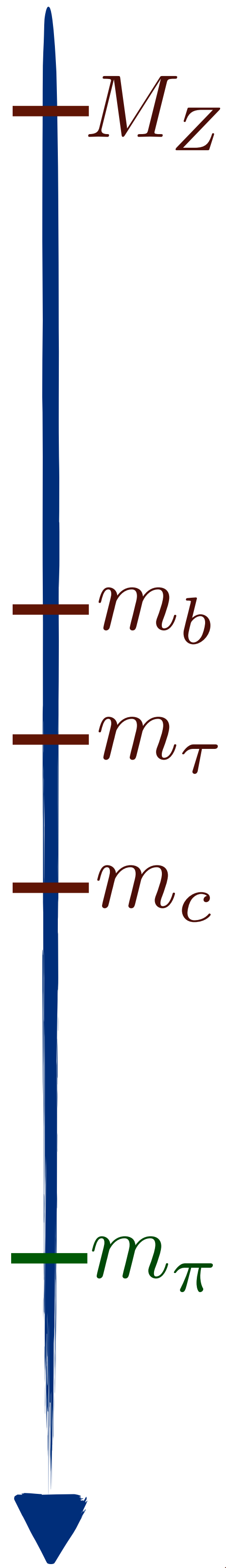
Running to low scales



- integrate out top at Z scale
- PDG running for α, α_s
- 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



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

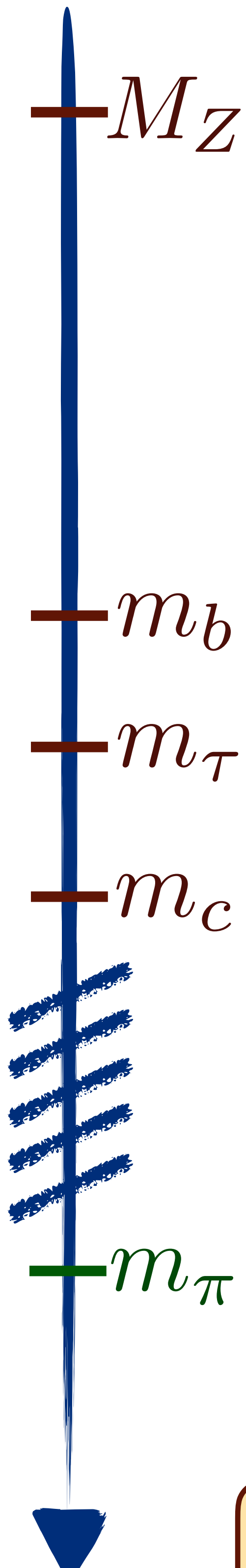
- chirally-symmetric universal running + flavor symmetry provide 9 constraints on running in the theory:

$$c_{\mathrm{R}}^{b}(\mu) - c_{\mathrm{R}}^{d}(\mu) = 0,$$
$$c_{\mathrm{L}}^{\nu_e e}(\mu) - c_{\mathrm{L}}^{\nu_\mu e}(\mu) = 2\sqrt{2}\mathrm{G_F},$$
$$c_{\mathrm{L}}^{\nu_\mu e}(\mu) - c_{\mathrm{R}}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}},$$
$$c_{\mathrm{L}}^{u}(\mu) - c_{\mathrm{R}}^{u}(\mu) = \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{u},$$
$$c_{\mathrm{L}}^{d}(\mu) - c_{\mathrm{R}}^{d}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{d},$$
$$c_{\mathrm{L}}^{b}(\mu) - c_{\mathrm{R}}^{b}(\mu) = -\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{b},$$
$$c_{\mathrm{L}}^{d}(\mu) - c_{\mathrm{L}}^{b}(\mu) + c_{\mathrm{R}}^{d}(\mu) - c_{\mathrm{R}}^{b}(\mu) = \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{b} - \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{d},$$
$$4c_{\mathrm{R}}^{d}(\mu) + 2c_{\mathrm{R}}^{u}(\mu) = 2\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{d} - \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{u} - \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{q},$$
$$6c_{\mathrm{R}}^{d}(\mu) - 2c_{\mathrm{R}}(\mu) = 3\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{d} - \sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}} - 2\sqrt{2}\tilde{\mathrm{G}}_{\mathrm{F}}^{l}.$$

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

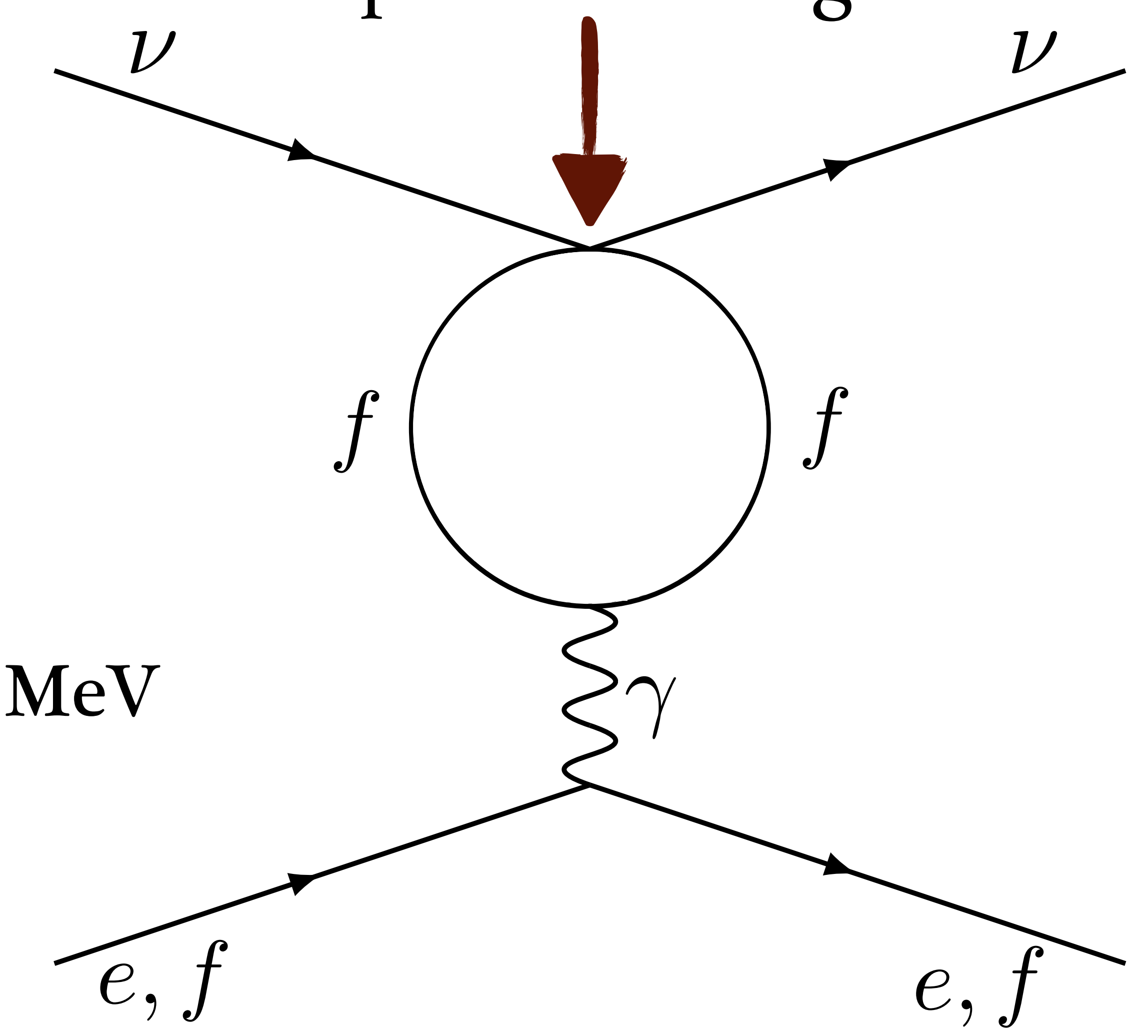
- only 1 effective coupling changes with scale

Running to low scales



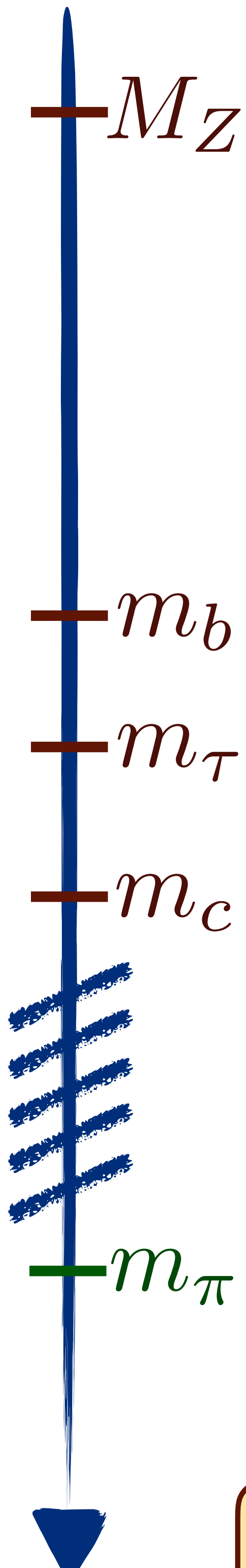
- integrate out top at Z scale
- PDG running for α, α_s
- only one EFT coupling changes with scale
- integrate out GeV particles
- α_s becomes too strong
- hadronic physics down to 140 MeV
- theory with leptons

operator mixing



- precisely known from electroweak to hadronic scales
- only 1 effective coupling changes with scale

Running to low scales



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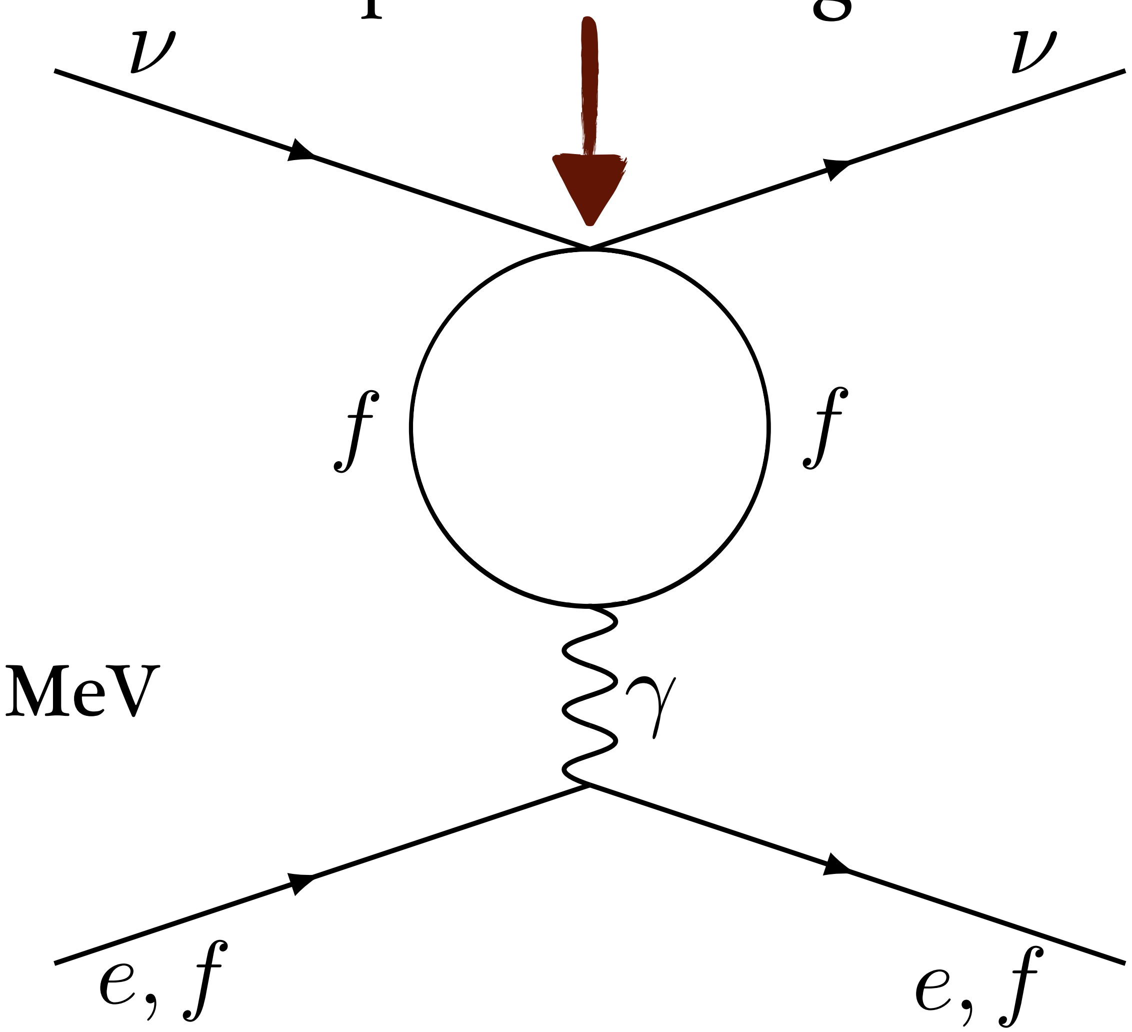
$$c_L^{\nu_e e}: \quad 2.388 \to 2.398$$
$$c_L^{\nu_\mu e}: -0.911 \to -0.901 \quad \text{\% effect}$$
$$c_R: \quad 0.759 \to 0.769$$

operator mixing



- precisely known from electroweak to hadronic scales
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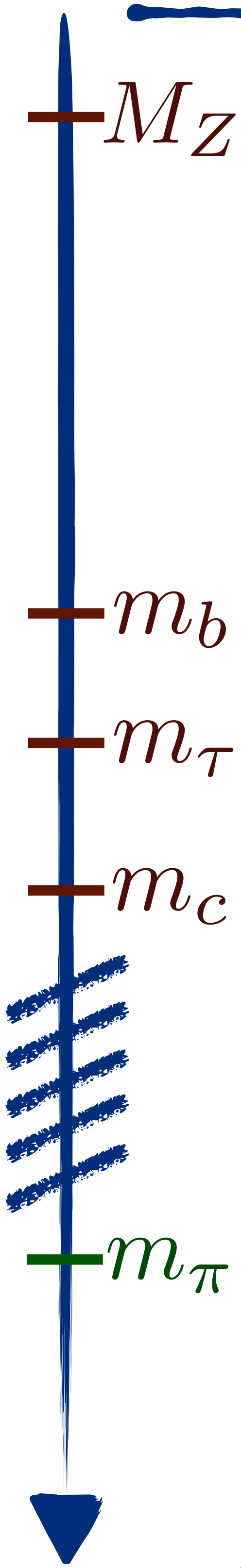
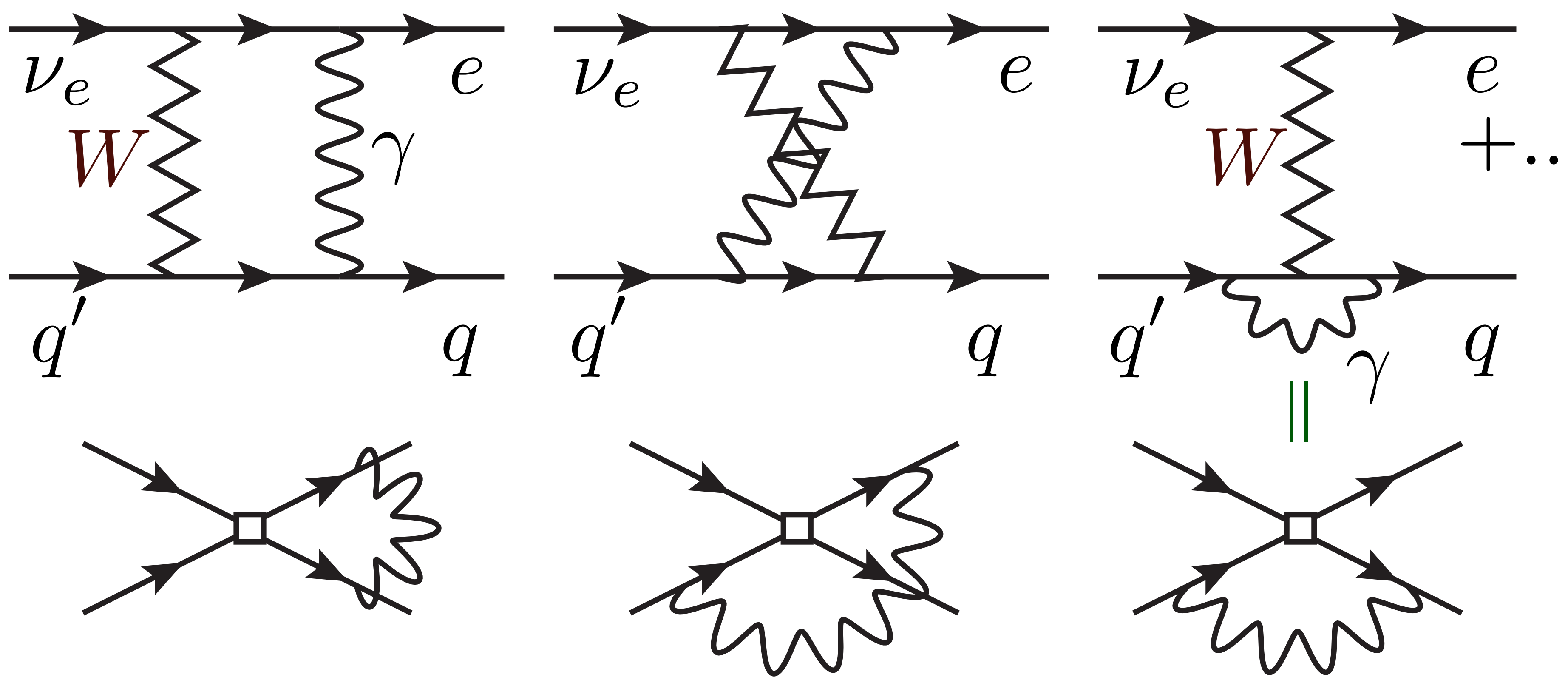
Semileptonic operators and muon decay



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

- Fermi coupling is scale independent



scheme independent

scheme dependent for quarks

- NDR scheme for γ_5 with a=-1 for evanescent operators E

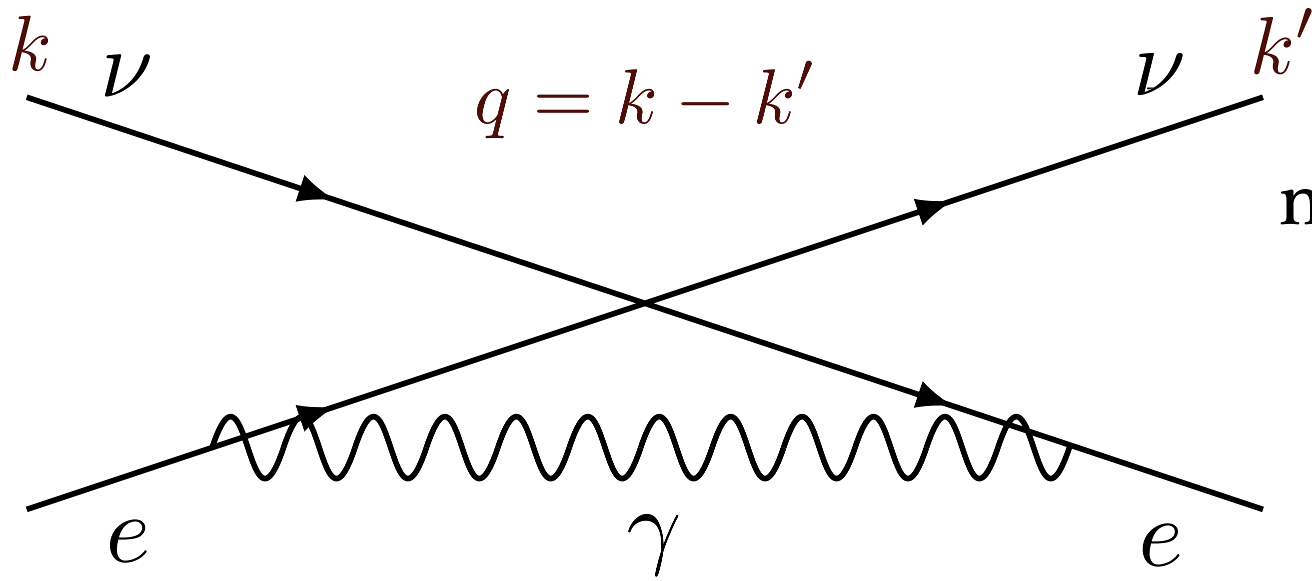
$$\gamma^\alpha \gamma^\beta \gamma^\mu \mathrm{P_L} \otimes \gamma_\mu \gamma_\beta \gamma_\alpha \mathrm{P_L} = 4\left(1 + a\left(4 - d\right)\right) \gamma^\mu \mathrm{P_L} \otimes \gamma_\mu \mathrm{P_L} + \mathrm{E}\left(a\right)$$

Buras and Weisz (1990)

- Wilson coefficient of semileptonic operator depends on scale

- scheme dependence of 1-loop matching and 2-loop running

Virtual QED corrections. Vertex



neutrino energy

ω

momentum transfer

$Q^2 = -q^2$

- up to suppressed by neutrino mass terms:

$$\bar{e}\gamma^\mu e \to \frac{\alpha}{\pi}\bar{e}\left[f_1\left(Q^2\right)\gamma^\mu + f_2\left(Q^2\right)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right]e$$

$$\bar{e}\gamma^\mu\gamma_5 e \to \frac{\alpha}{\pi}\left[f_1\left(Q^2\right) - f_2\left(Q^2\right)\right]\bar{e}\gamma^\mu\gamma_5 e$$

- infrared divergence cancels with radiation of real soft photon

- factorizable in limit of small electron mass: $f_2 = 0$

- given in terms of QED form factors at one loop

Virtual QED corrections. Fermion loop

- charged fermions contribute to elastic scattering at one loop:

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

- adds vector contribution:

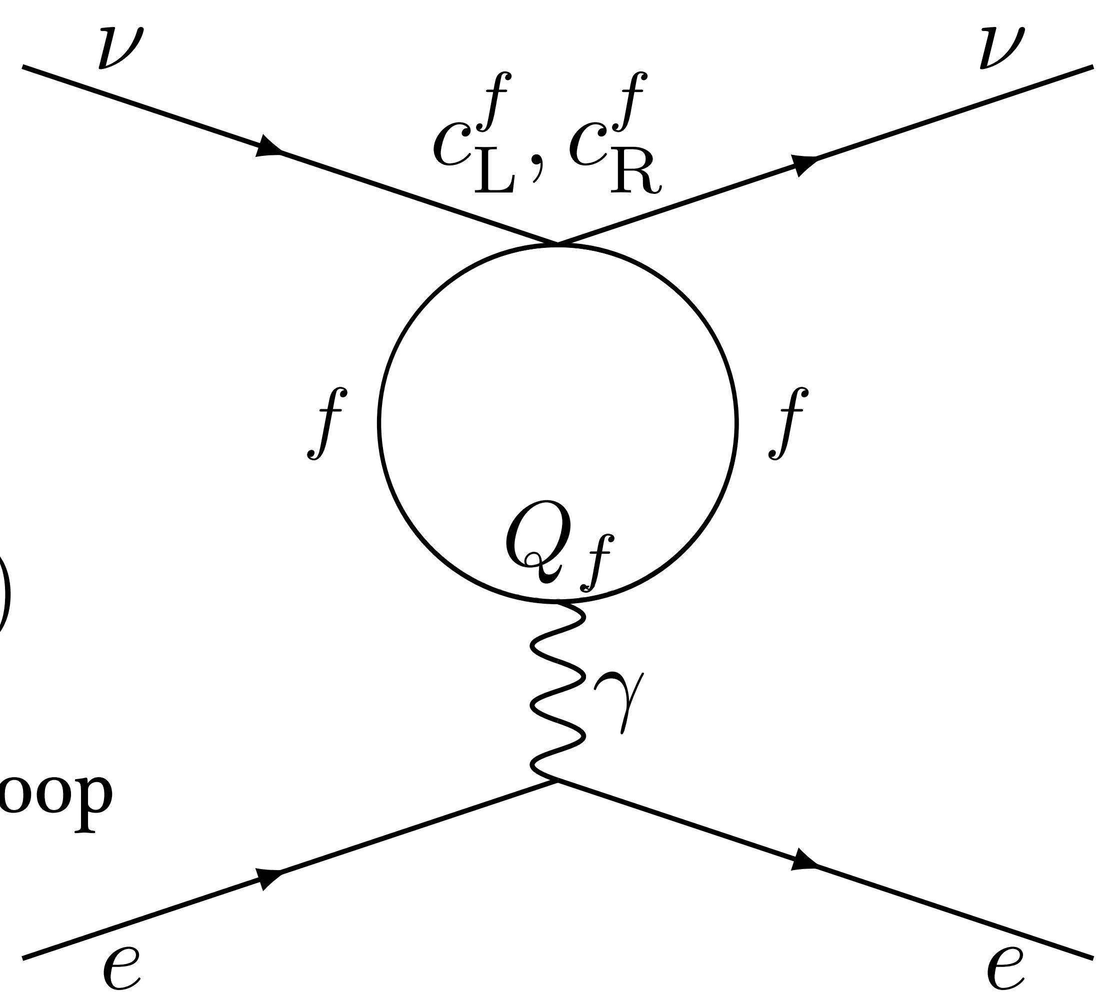
$$c^{f}\,\bar{\nu}\gamma_{\mu}\mathrm{P_L}\nu \cdot \bar{e}\gamma^{\mu}e$$

- fermion-dependent correction:

$$c^{f} = -\frac{\alpha}{2\pi}Q_{f}\left(c_{\mathrm{L}}^{f} + c_{\mathrm{R}}^{f}\right)\Pi\left(Q^{2}, m_{f}\right)$$

account for one gluon in quark loop

use MS masses for heavy quarks



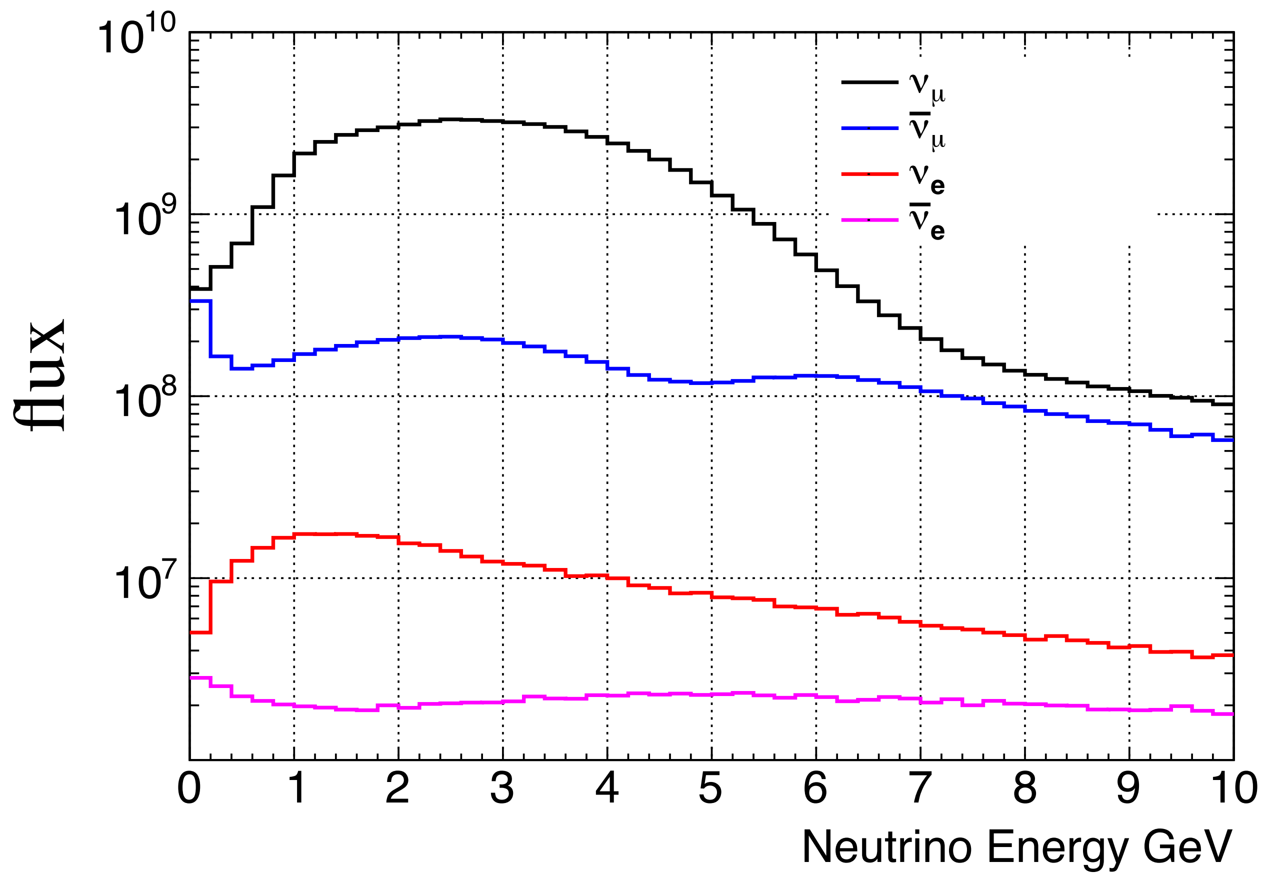
- given in terms of photon vacuum polarization
- sum over all particles with corresponding couplings

Main theoretical uncertainty

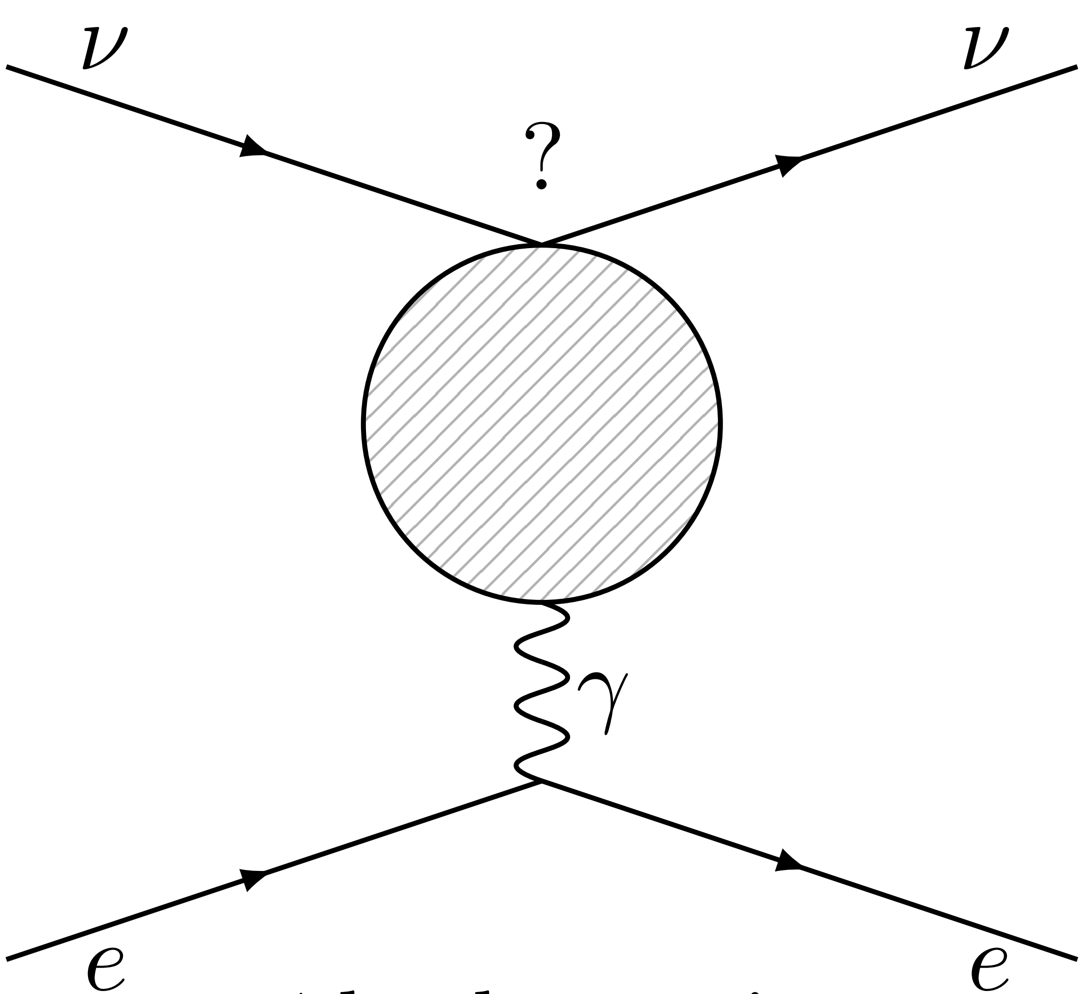
- momentum transfer is suppressed by electron mass:

$$Q^2 < 2m\omega \ll \Lambda^2_{\rm QCD}$$

- description in terms of quarks is questionable:



DUNE, CDR (2015)



% level correction

- hadronic correction is the main error in theory

Light-quark contribution

- virtual-loop scale is well below muon and hadron masses:

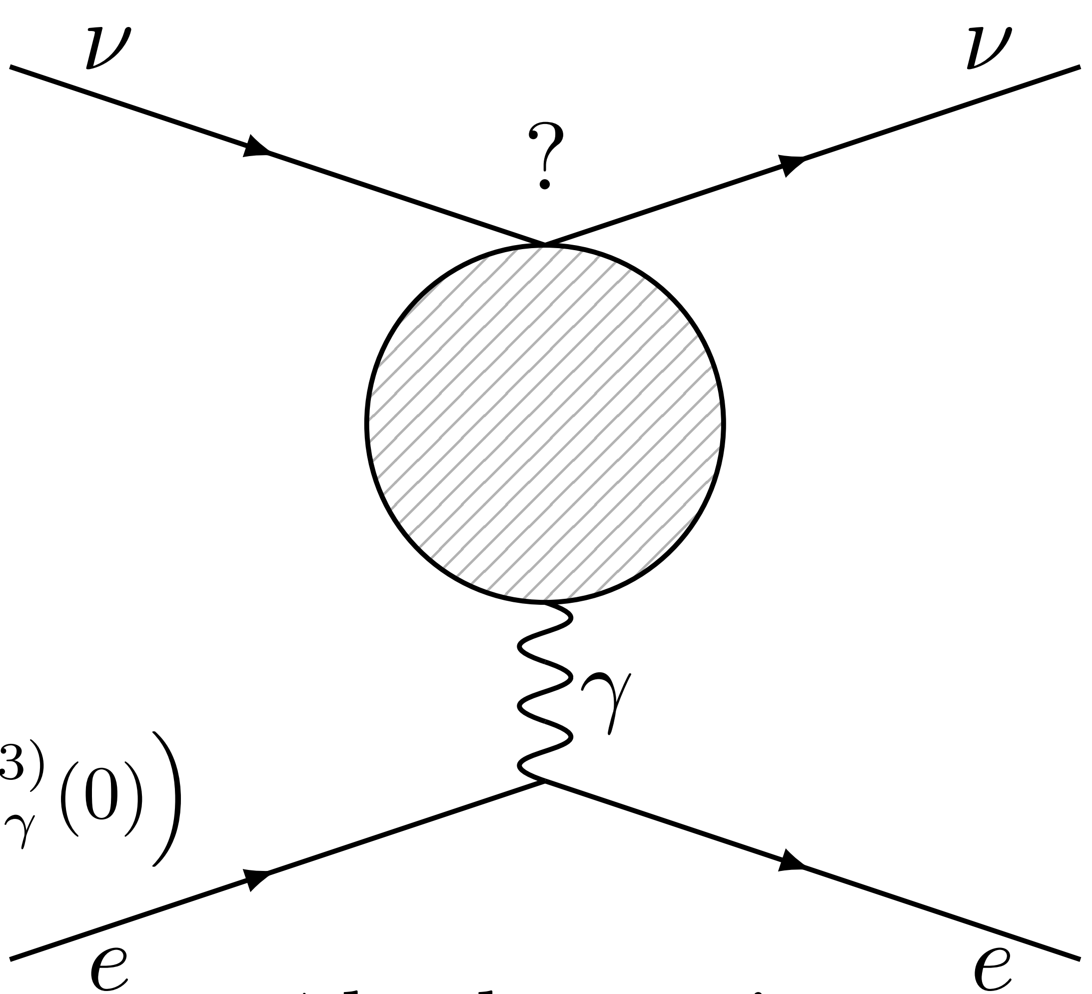
$$Q^2 < 2m\omega \ll \Lambda^2_{\mathrm{QCD}}$$

- adds vector contribution:

$$c^f \, \bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{e}\gamma^\mu e$$

- fermion-dependent correction:

$$c^f = \frac{\sqrt{2}\alpha \mathrm{G_F}}{\pi} \left(2\sin^2\theta_W \hat{\Pi}^{(3)}_{\gamma\gamma}(0) - \hat{\Pi}^{(3)}_{3\gamma}(0)\right)$$



% level correction

- hadronic correlators at zero momentum transfer

Light-quark contribution

- vector-vector correlation functions in terms of quark contributions

$$\hat{\Pi}^{(3)}_{\gamma\gamma} = \sum_{i,j} Q_i Q_j \Pi^{ij} \qquad \hat{\Pi}^{(3)}_{3\gamma} = \sum_{i,j} T^3_i Q_j \Pi^{ij}$$

- SU(3)$_f$ $\hat{\Pi}^{uu} = \hat{\Pi}^{dd} = \hat{\Pi}^{ss}$

$$\hat{\Pi}^{(3)}_{3\gamma} = \hat{\Pi}^{(3)}_{\gamma\gamma}$$

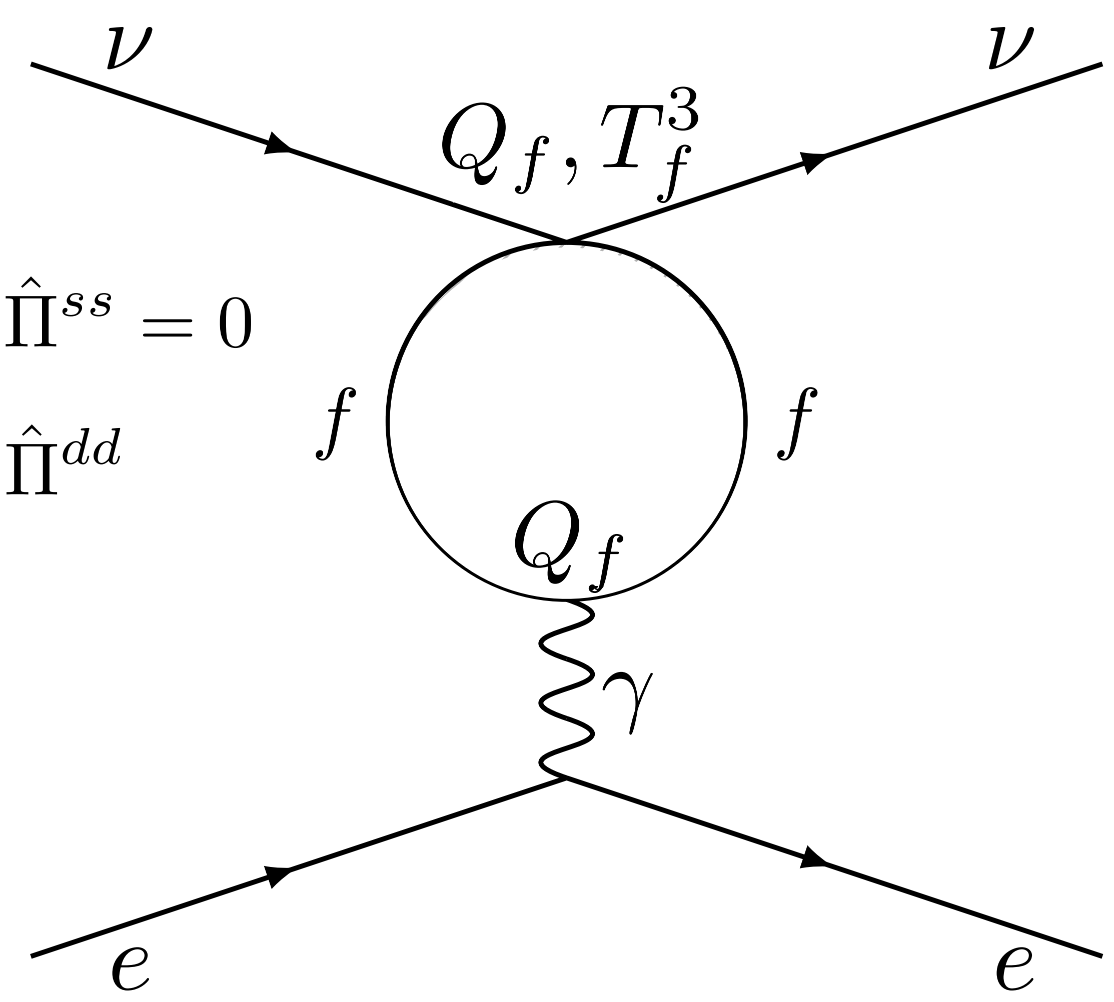
- SU(2)$_f$ + OZI $\hat{\Pi}^{ud} = \hat{\Pi}^{us} = \hat{\Pi}^{sd} = \hat{\Pi}^{ss} = 0$

$$\hat{\Pi}^{(3)}_{3\gamma} = \frac{9}{10}\hat{\Pi}^{(3)}_{\gamma\gamma} \qquad \hat{\Pi}^{uu} = \hat{\Pi}^{dd}$$

- our choice:

$$\hat{\Pi}^{(3)}_{3\gamma} = (1 \pm 0.2)\,\hat{\Pi}^{(3)}_{\gamma\gamma}$$

- with $\hat{\Pi}^{(3)}_{\gamma\gamma}(0)$ from Erler et al (2018)



- non-perturbative light-quark contribution

EFT with leptons

- virtual-loop scale is well below muon and hadron masses:

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

- QCD degrees of freedom: vector contribution to effective couplings

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

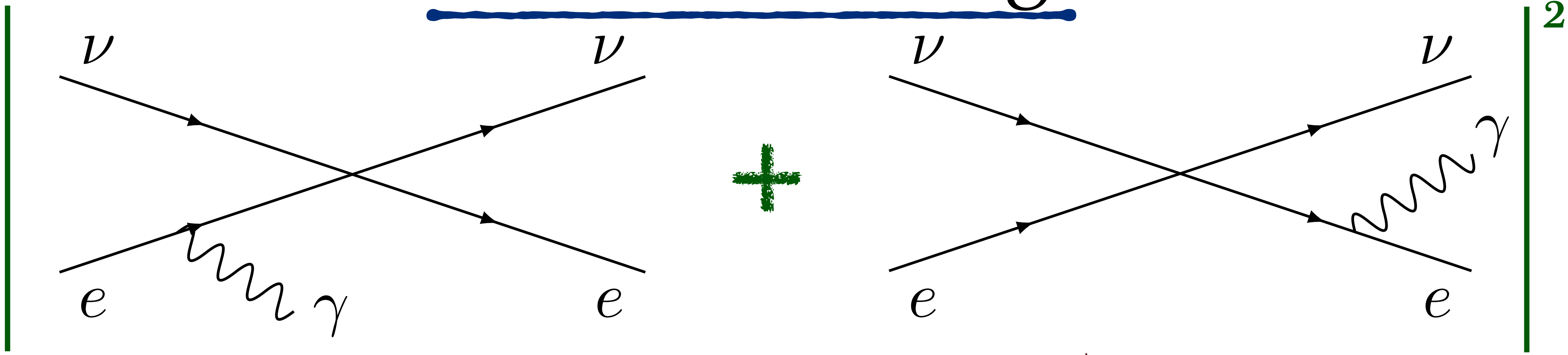
- theory with electron, muon and neutrinos only

	$c_{\mathrm{L}}^{\nu_e e}$	$c_{\mathrm{L}}^{\nu_\mu e}$	$c_{\mathrm{R}}^{\nu_e e}$	$c_{\mathrm{R}}^{\nu_\mu e}$
μ = 2 GeV	2.4064(28)	-0.8926(28)	0.7773(28)	0.7773(28)
$\mu = m_\mu$	2.3997(29)	-0.8994(29)	0.7706(29)	0.7706(29)
$\mu = m_e$	2.3865(29)	-0.8988(29)	0.7575(29)	0.7711(29)

- three right-handed couplings below the muon mass !!!

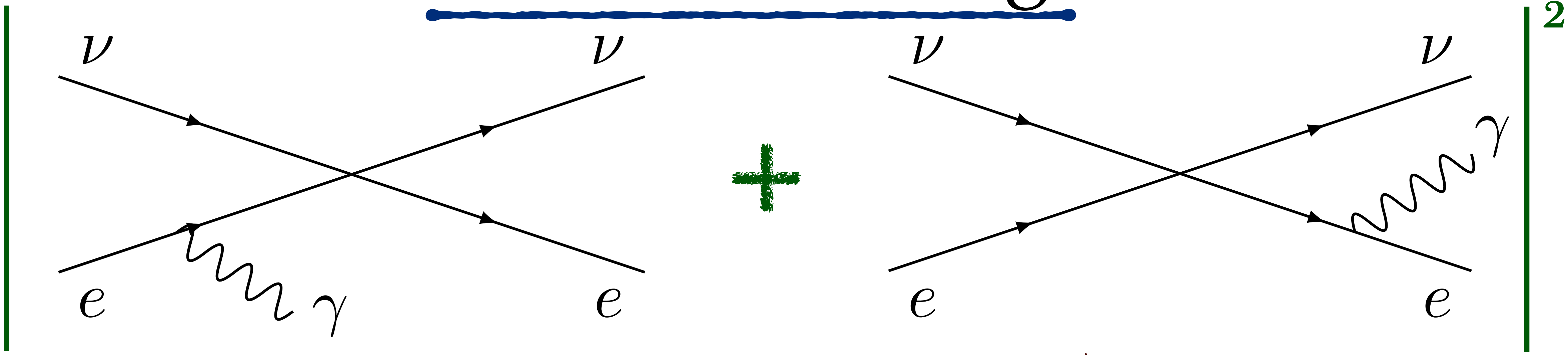
- neutrino-electron scattering is described by EFT with leptons only

Bremsstrahlung



- soft Bremsstrahlung: $E_\gamma < \varepsilon$ $\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e \gamma} = \delta_s \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}$

Bremsstrahlung

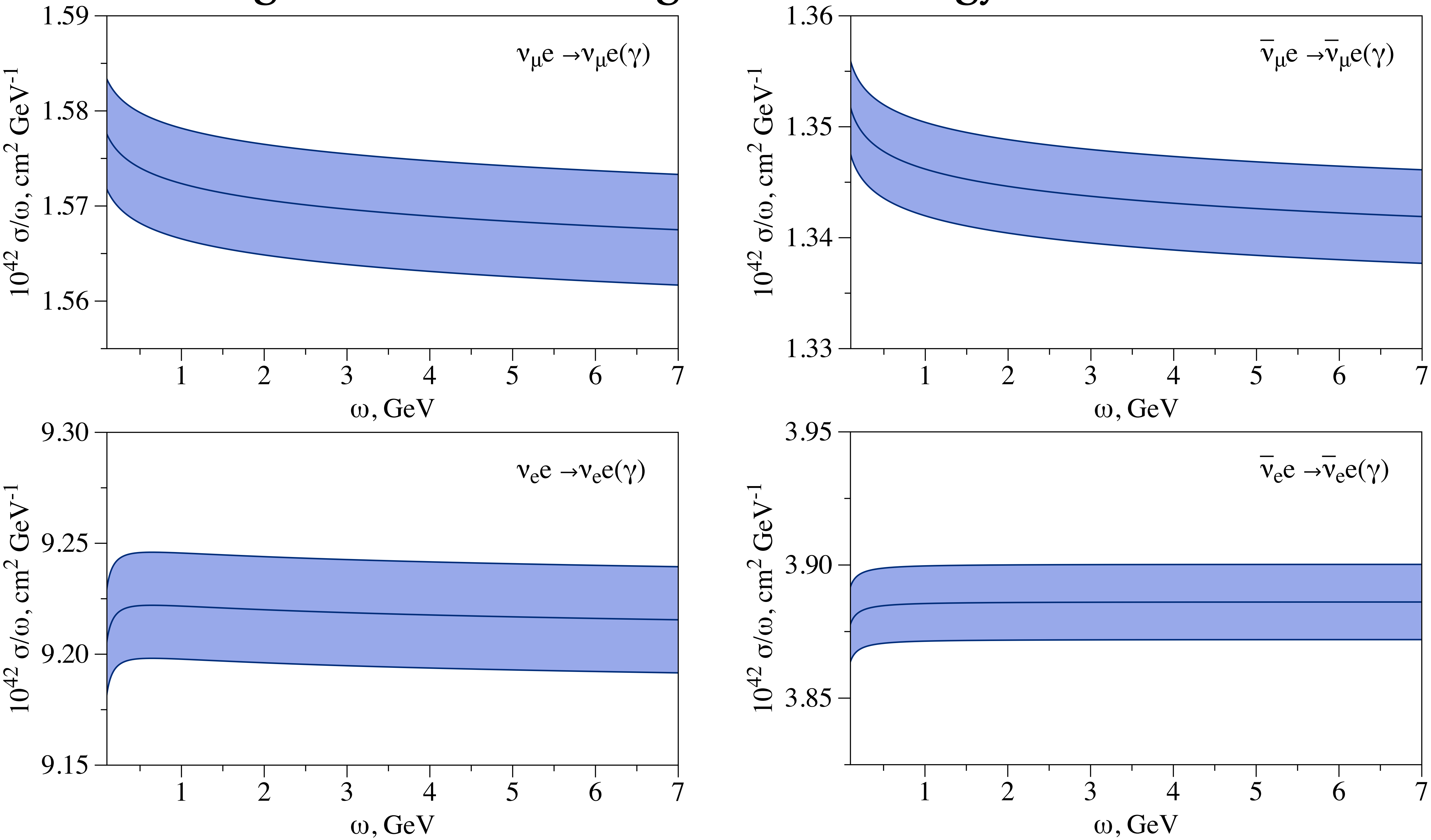


- soft Bremsstrahlung: $E_\gamma < \varepsilon$ $\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e \gamma} = \delta_s \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}$
- soft-photon correction — Lee and Sirlin (1964)
- integration technique — Ram (1967)
- EW correction — Aoiki, Hioki, Kawabe, Konuma and Muta (1980)
- electron energy spectrum and numerically total — Aoiki and Hioki (1981)
- electron energy spectrum and EW, small m — Sarantakos, Sirlin and Marciano (1982)
- electromagnetic energy spectrum and total — Bardin and Dokuchaeva (1983-1985)
- numerically electron and electromagnetic spectra — Passera (2000)

- exactly calculable radiation

Absolute cross section

- linear growth with incoming neutrino energy ω

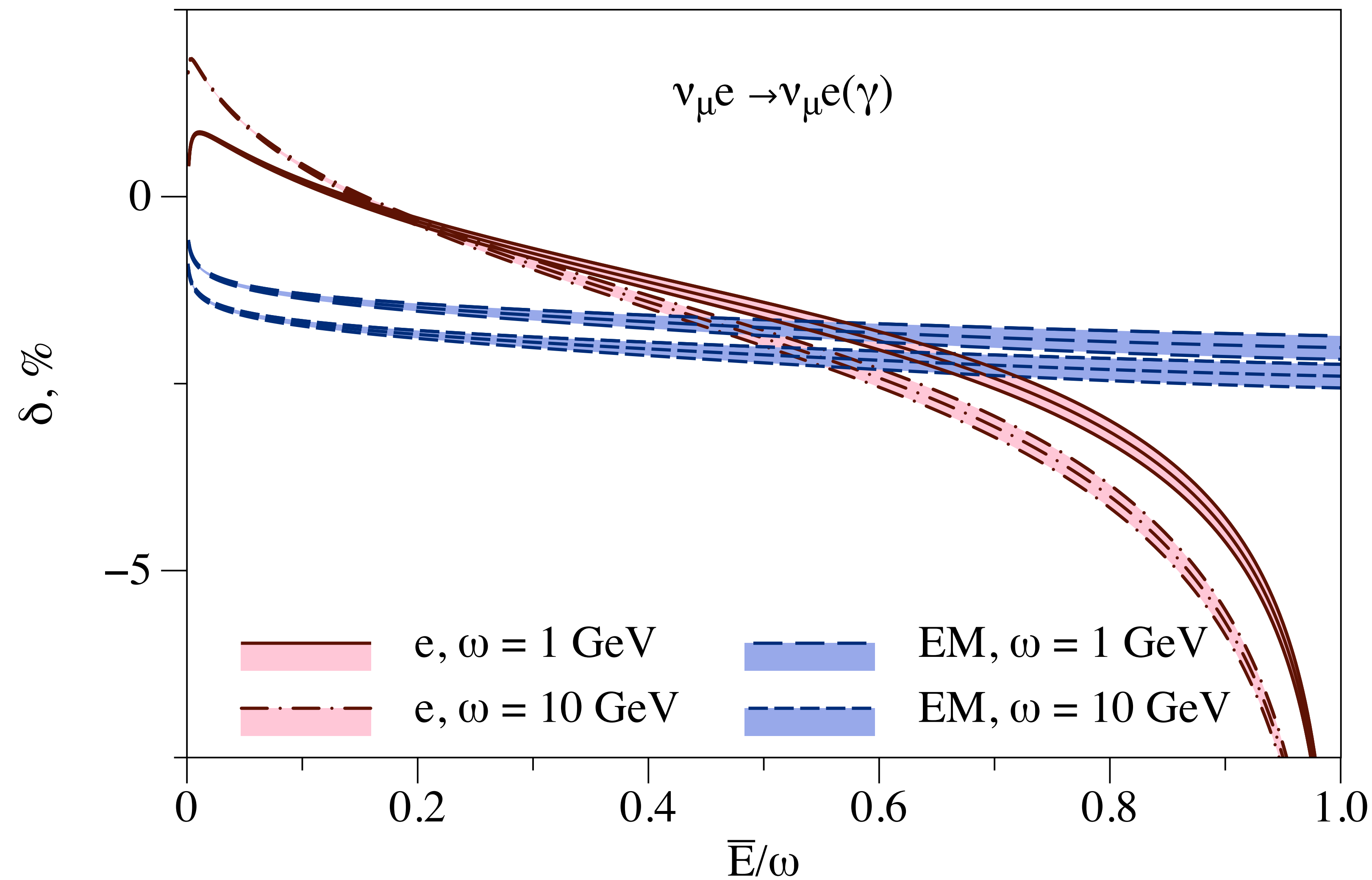


- analytic results and first error estimate at level 0.2-0.4%

Electron vs electromagnetic (EM) spectra

- relative correction depends on $\overline{\text{MS}}$ scale μ: $\mu_0/\sqrt{2} \leq \mu \leq \sqrt{2}\,\mu_0$

$$\delta = \frac{\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e\to\nu e\gamma} + \mathrm{d}\sigma_{\mathrm{NLO}}^{\nu e\to\nu e} - \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e\to\nu e}}{\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e\to\nu e}}$$

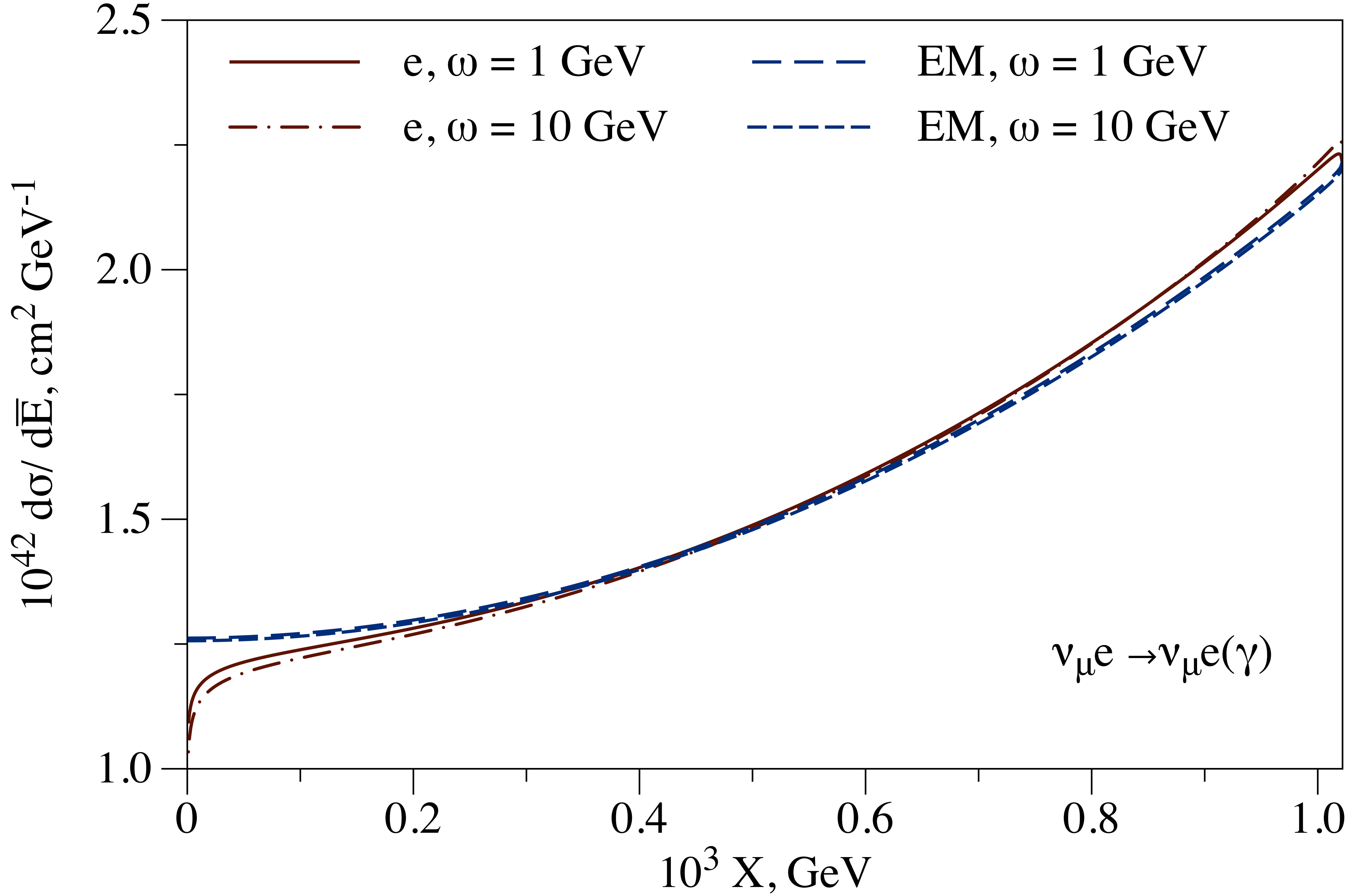


$\mu_0 = 2$ GeV

- total correction: Sudakov logarithms cancel
- dramatic difference in radiative corrections

Electron vs electromagnetic (EM) spectra

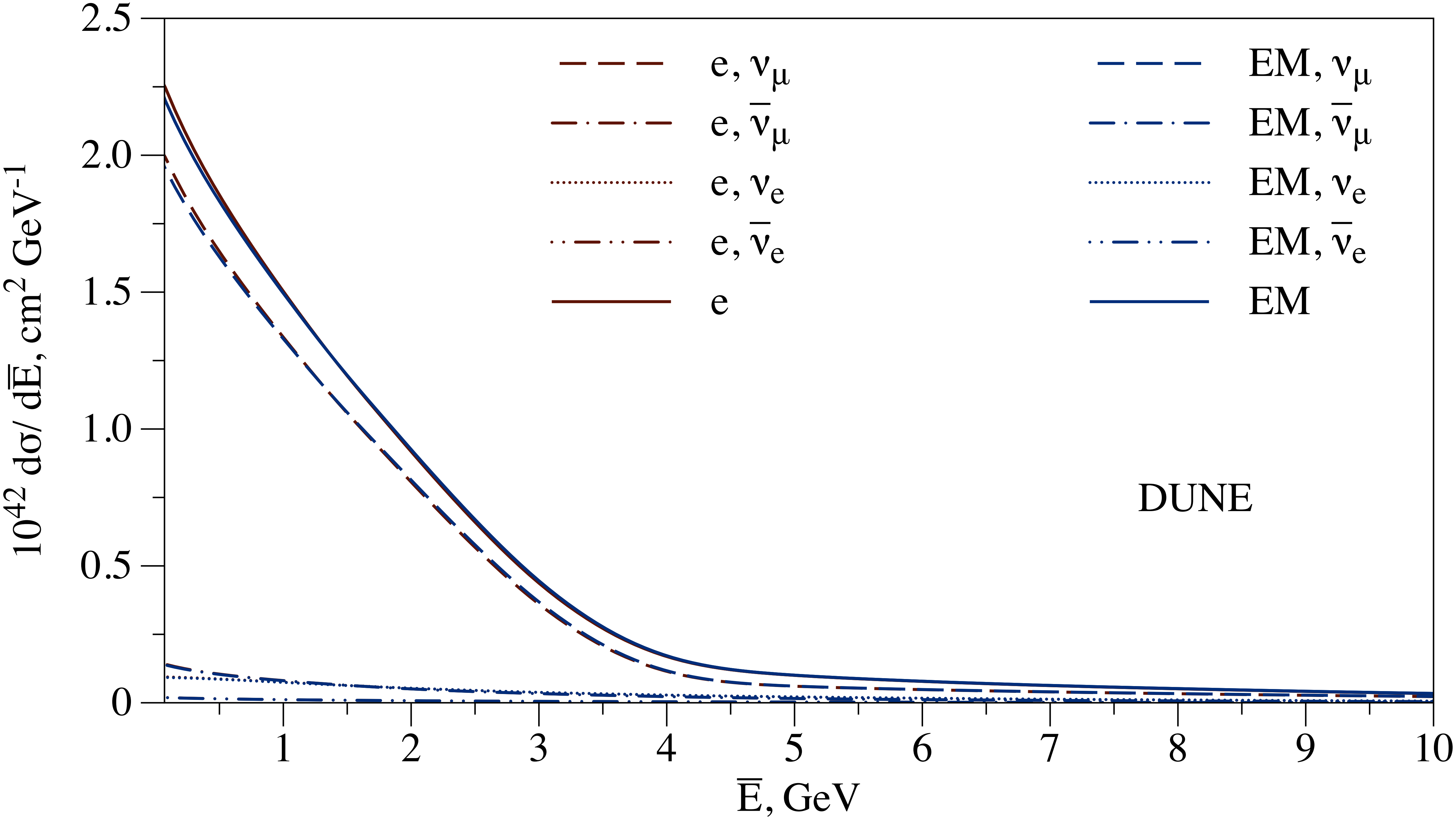
- resulting spectrum: $X = 2m\left(1 - \frac{\bar{E}}{\omega}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$



- dramatic difference in radiative corrections: cut dependence

Experimental energy spectrum

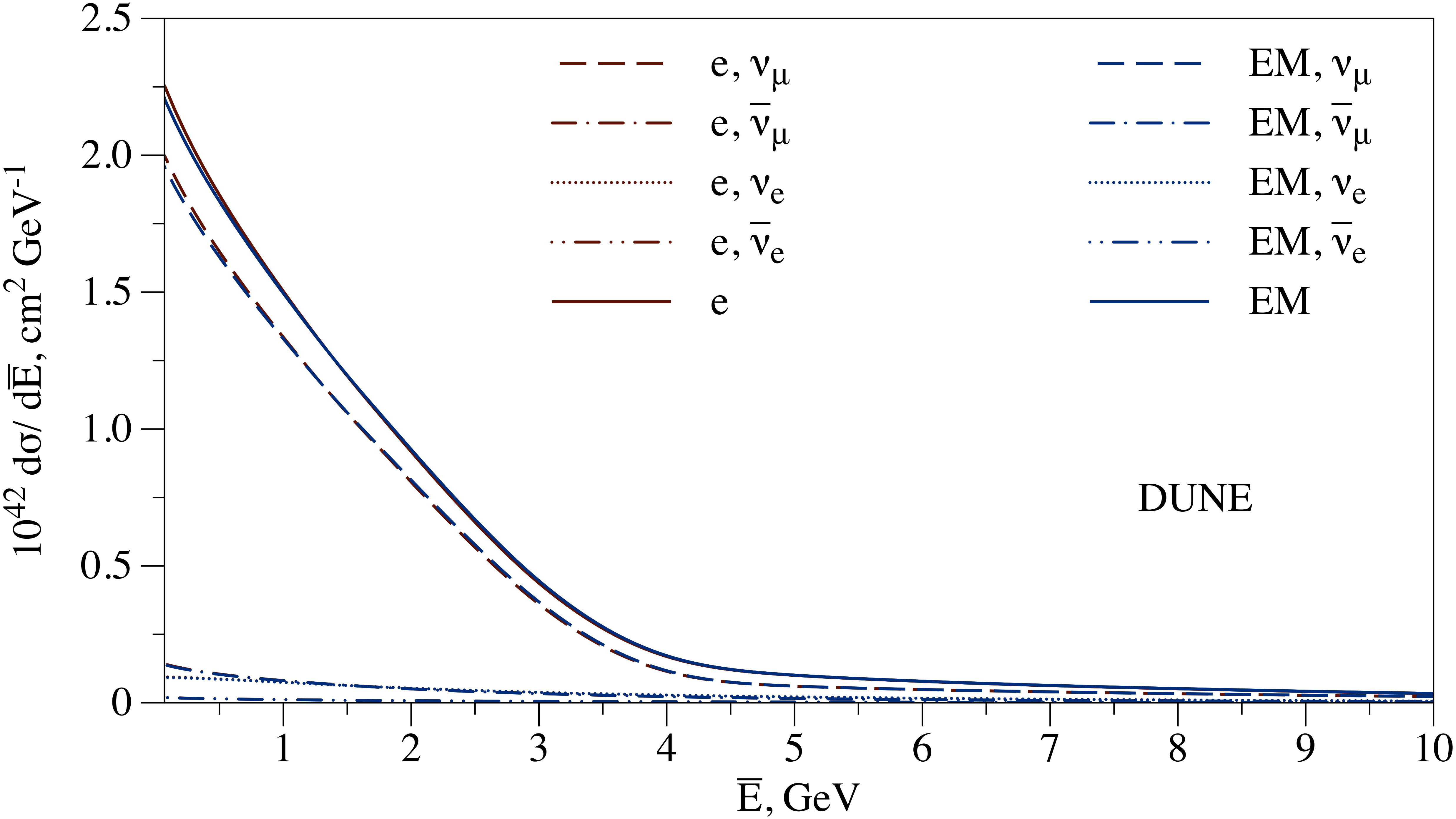
- average over beam flux and sum over flavors:



- 1-3 % difference at low recoil energy

Comparison to MINERvA and GENIE

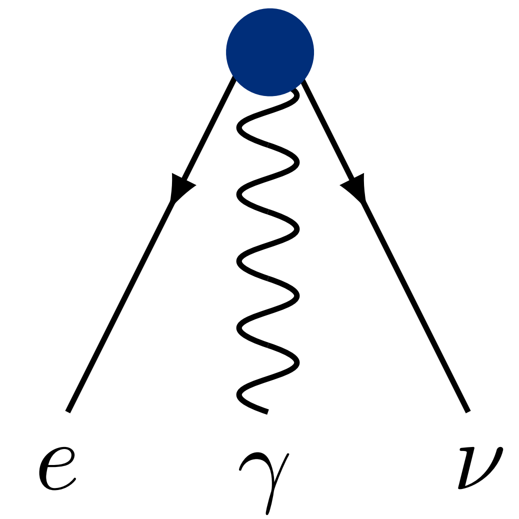
- average over beam flux and sum over flavors:



- 1-3 % difference at low recoil energy

Bremsstrahlung cross sections

- distributions under consideration:



E_e, E_γ, θ_e

$E_{\rm EM}, \theta_\nu$ $E_{\rm EM}, \theta_e$ E_e, θ_e E_e, E_γ E_γ, θ_γ

$E_{\rm EM}$ E_e E_γ

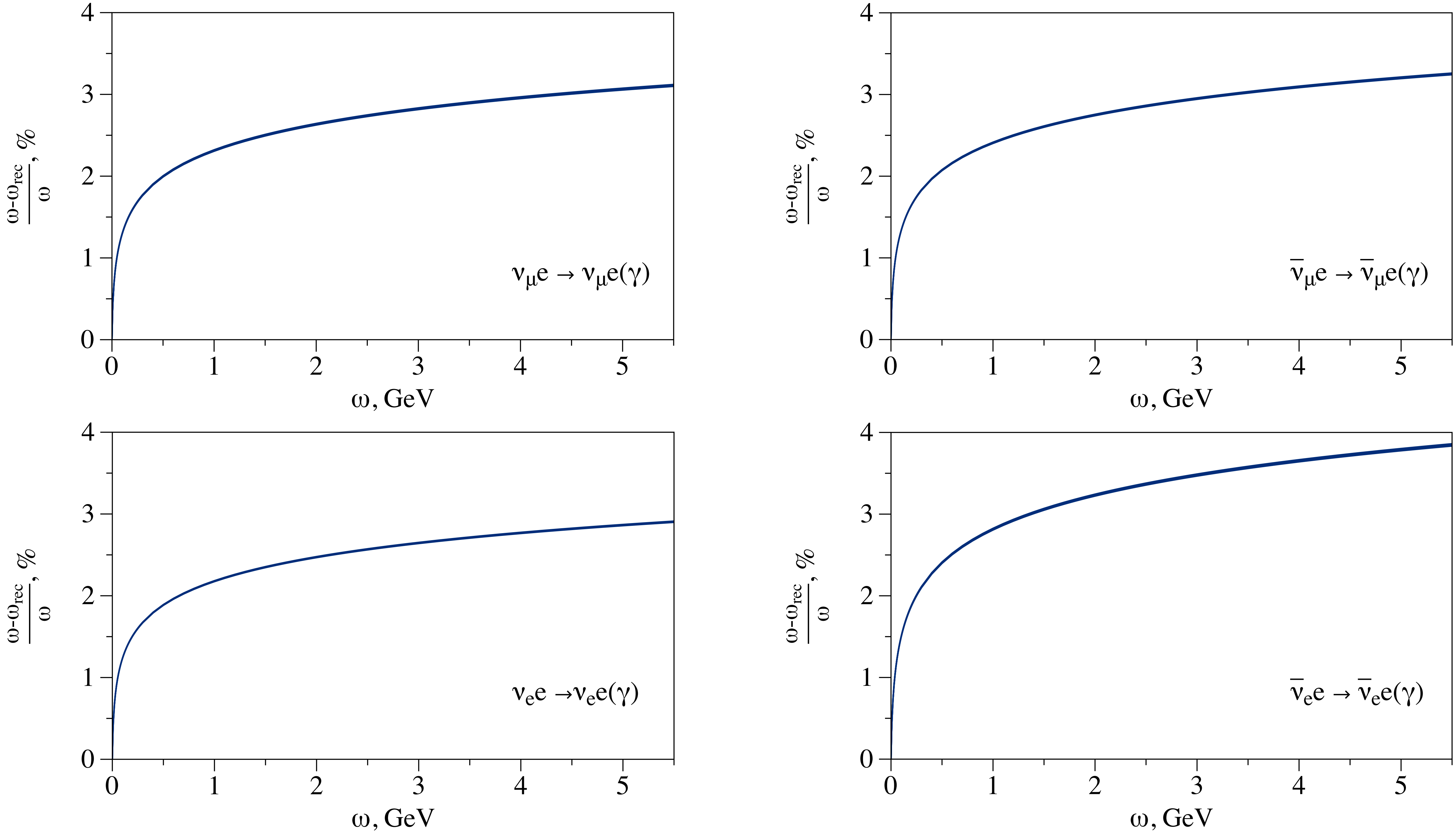
total cross section

O. T. and Richard J Hill (2019)

- analytical form for finite and small electron mass

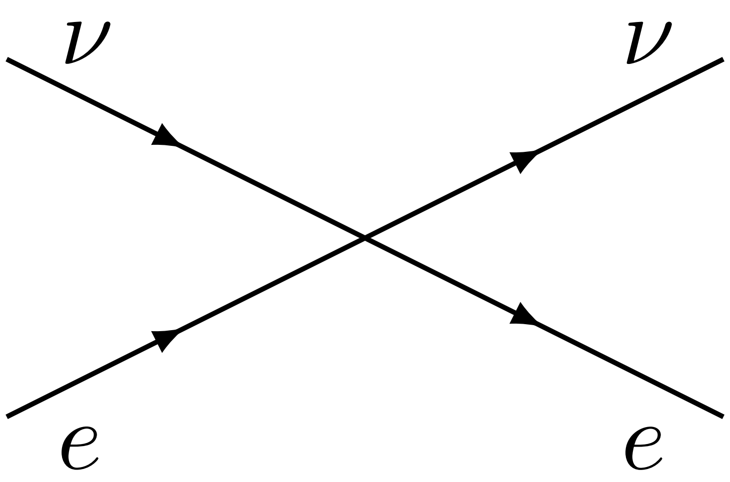
Neutrino energy reconstruction

- reconstruct from elastic kinematics: $\omega_{\rm rec} = \dfrac{m|\vec{p}_e|}{(E_e+m)\cos\theta_e - |\vec{p}_e|}$



- radiative corrections are crucial in energy reconstruction

Conclusions



best tool to constrain neutrino flux

- EFT of neutrino-electron and neutrino-quark scattering:

  left- and right-handed couplings at subpermille level

- absolute cross section at permille level and first error analysis

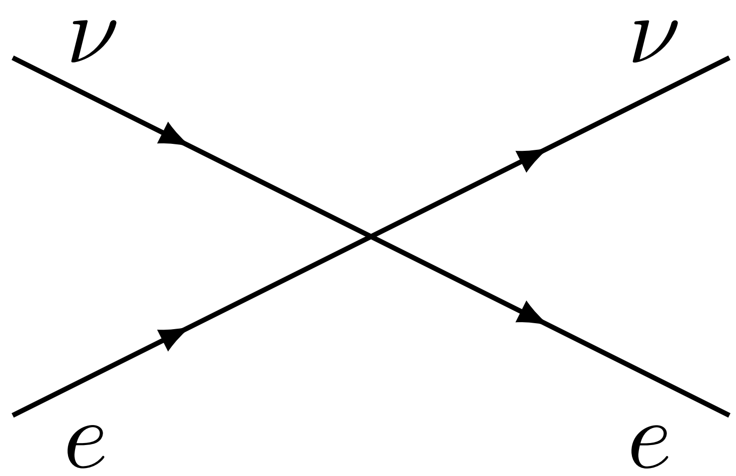
  main source of uncertainty: loops with hadrons

- energy spectra and bremsstrahlung cross sections:

  new and known results in analytical form

- application to neutrino energy reconstruction

Outlook



- implement framework and results in modern event generators

- study hadronic uncertainty with dispersive methods

- pin down the uncertainty on lattice; connection to running α, g-2

- constrain light-quark contribution at DUNE

- application to solar neutrinos and reactor antineutrinos

Thanks for your attention !!!

Proposal for flux determination in DUNE

- determination of neutrino fluxes:

  one of the main goals of Near Detector

	relative	normalization
ν_μ mode	$\nu_\mu p \to \mu^- p \pi^+$	$\nu_\mu e^- \to \nu_\mu e^-$
$\bar{\nu}_\mu$ mode	$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	$\bar{\nu}_\mu p \to \mu^+ n$

according to H. Duyang et al. (2019)

- neutrino-electron scattering plays a role of additional constraint

- νe is required for absolute normalization of ν_μ component

Leading unaccounted correction

- sum of possible permutations of gluon lines
  has zero anomalous dimension
  contributes with α_s^2 contribution to vacuum polarization