

PIKIMO-8

University of Cincinnati
Cincinnati, OH, USA

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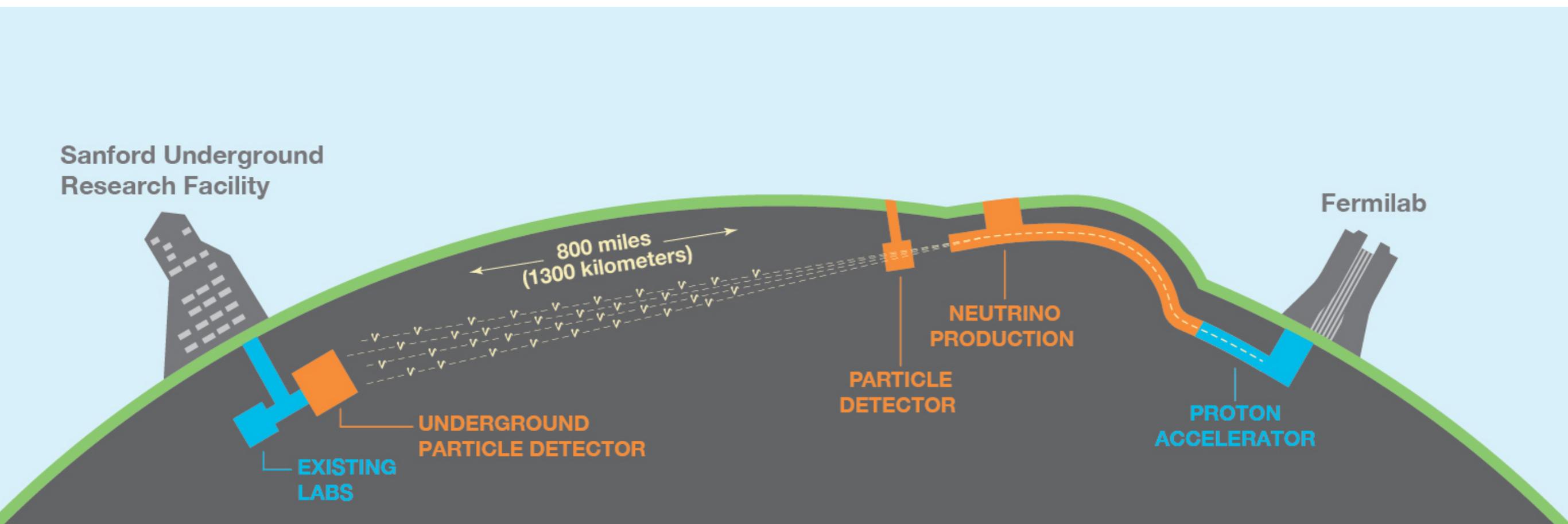
Neutrino-electron scattering in effective field theory



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

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

- near detector: determine flux and cross sections

Neutrino-electron scattering

- small cross section scales as target mass m:
 10^{-4} - 10^{-3} of cross section on nucleons and nuclei
 - scattering on atomic electrons free from structure effects
 - standard candle to constrain flux:
normalization uncertainty from 7.5% to 4%
MINERvA (2016, 2019), NOvA analysis is ongoing
 - huge statistics of DUNE near detector vs MINERvA
5000-7000 events in a year vs 810 events in total
normalization uncertainty from 8% to 2%
Ch. Marshall et al. (2019)
- goal: EFT-based calculation with accuracy below %

Neutrino scattering in EFT. Matching

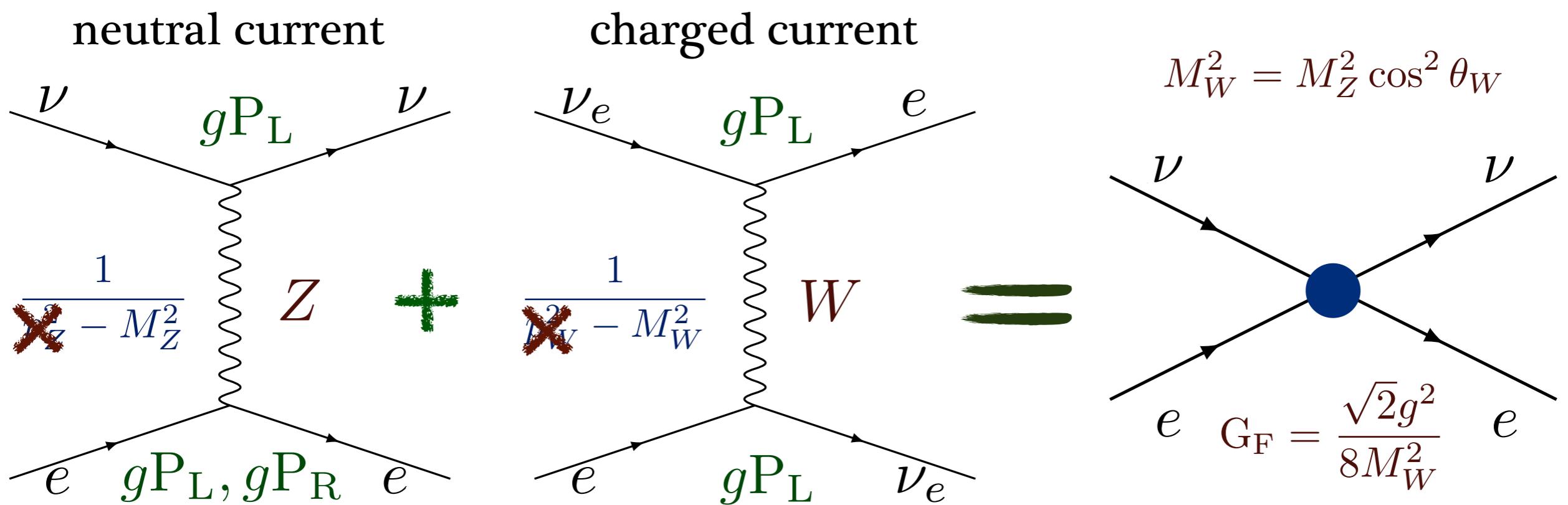
- tree-level matching to low-energy EFT:

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

$$c_R = 2\sqrt{2}G_F \sin^2 \theta_W \quad c_L = 2\sqrt{2}G_F (\sin^2 \theta_W - 0.5 + \delta_{\nu,\nu_e})$$

Weinberg (1967), 't Hooft (1971)

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



- integrate out W and Z at tree level

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

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Weinberg (1967), 't Hooft (1971)

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

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

- no additional operators after one-loop matching
- G_F : combination of parameters is precisely measured

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

MULAN (2012)

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

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

Running to low scales

M_Z - integrate out top, Z , W, h

- PDG running for α, α_s
- only one EFT coupling changes with scale

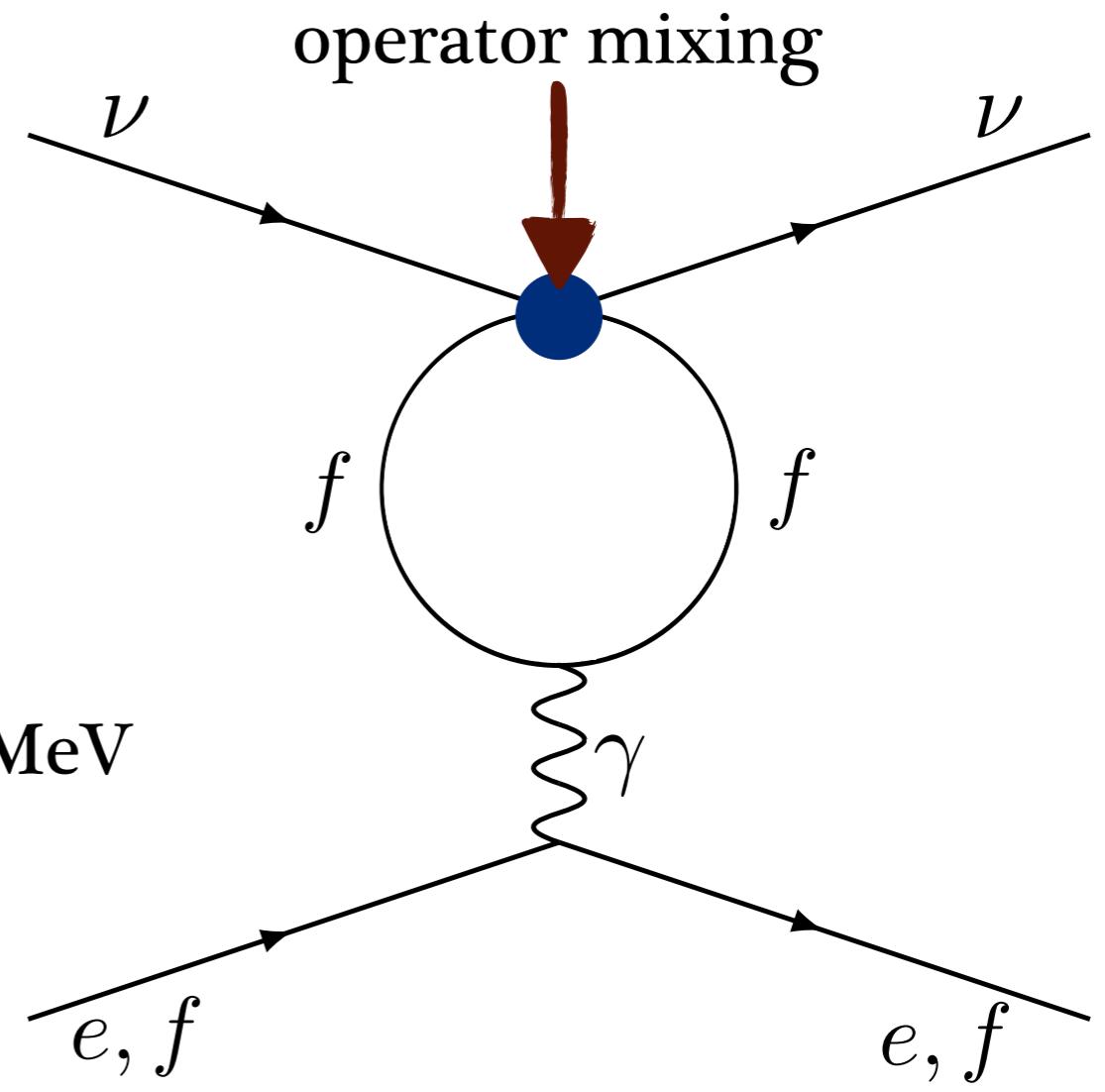
m_b

m_τ - integrate out GeV particles

m_c

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

m_π - theory with leptons



Running to low scales

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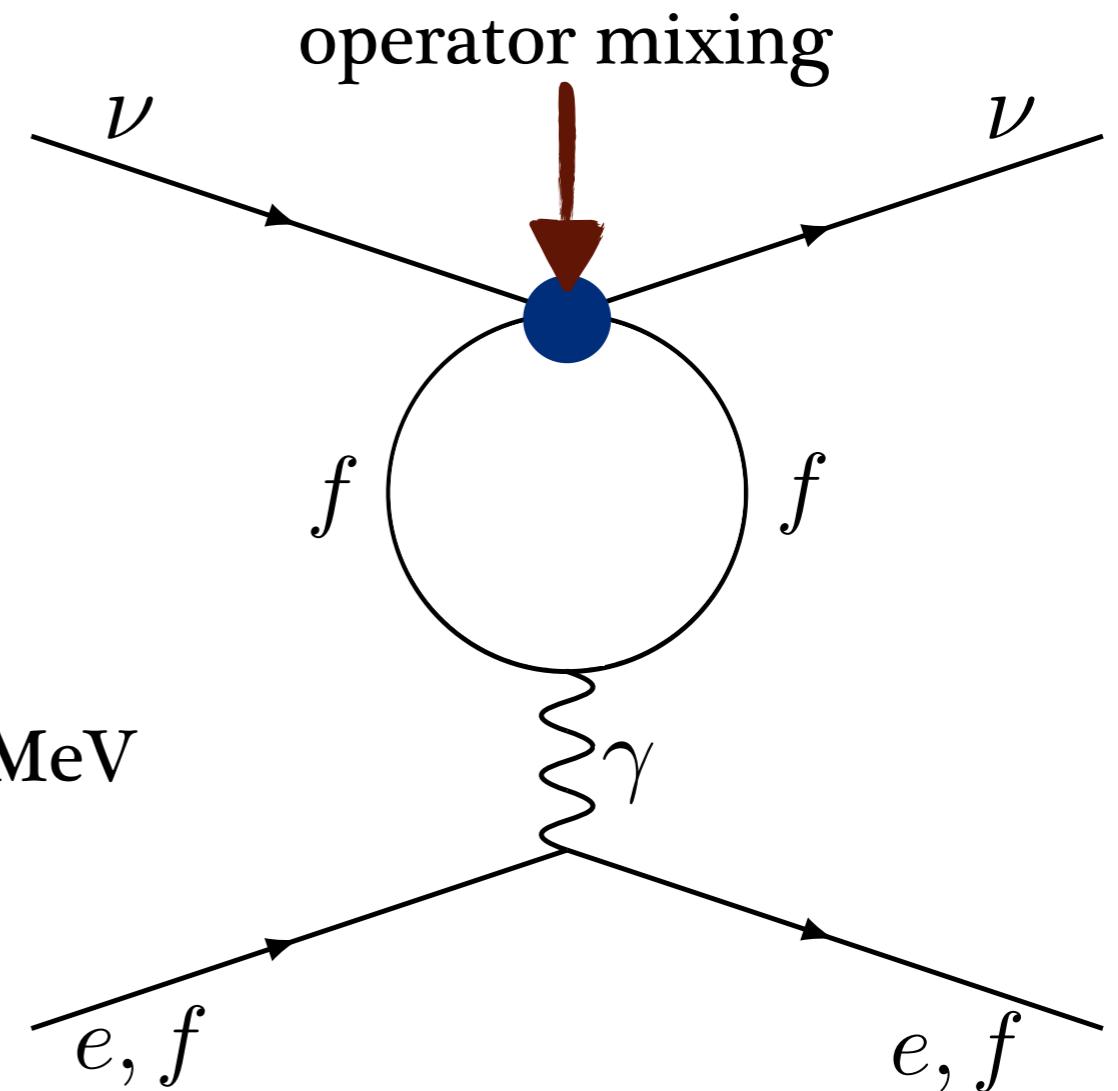
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m_π

- theory with leptons



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

Running to low scales

M_Z - integrate out top, Z , W, h

- PDG running for α, α_s
- only one EFT coupling changes with scale

$$c_L^{\nu_e e} : 2.388 \rightarrow 2.398$$

$$c_L^{\nu_\mu e} : -0.911 \rightarrow -0.901 \quad \% \text{ effect}$$

$$c_R : 0.759 \rightarrow 0.769$$

operator mixing

m_b

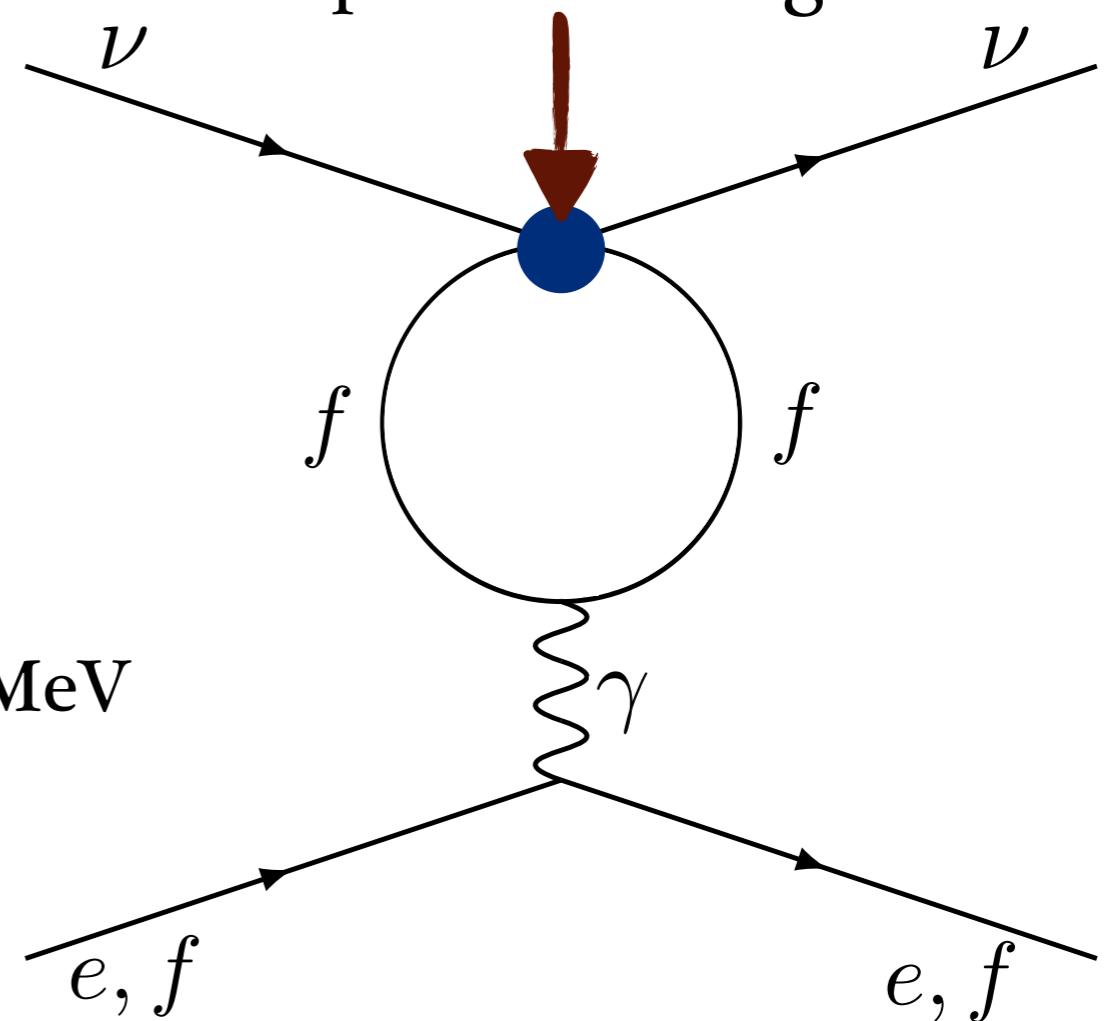
m_τ - integrate out GeV particles

m_c

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

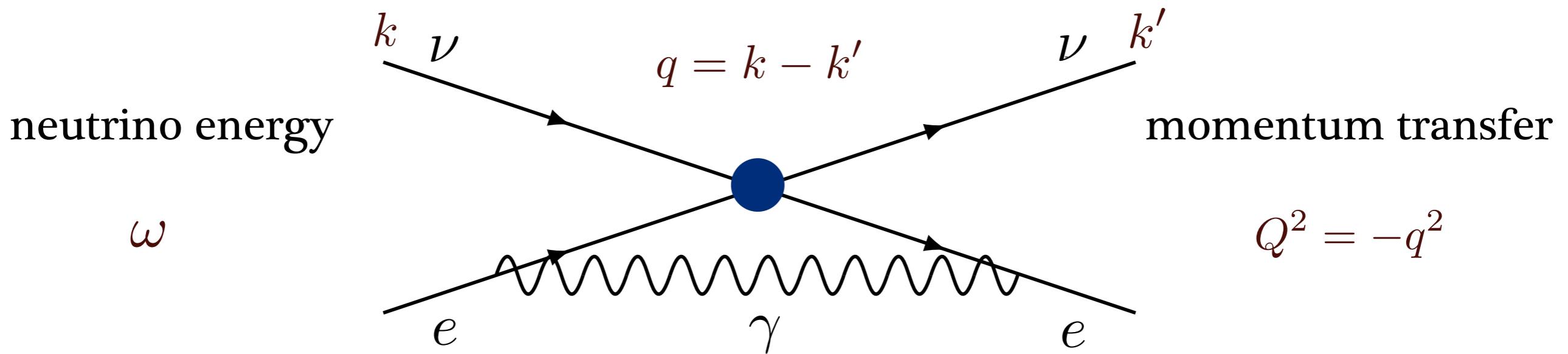
m_π

- theory with leptons



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

Virtual QED corrections. Vertex



- up to suppressed by neutrino mass terms:

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

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

- 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 f_1, f_2 at one loop

Virtual QED corrections. Fermion loop

- all charged fermions contribute to elastic scattering at one loop:

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

- adds vector contribution:

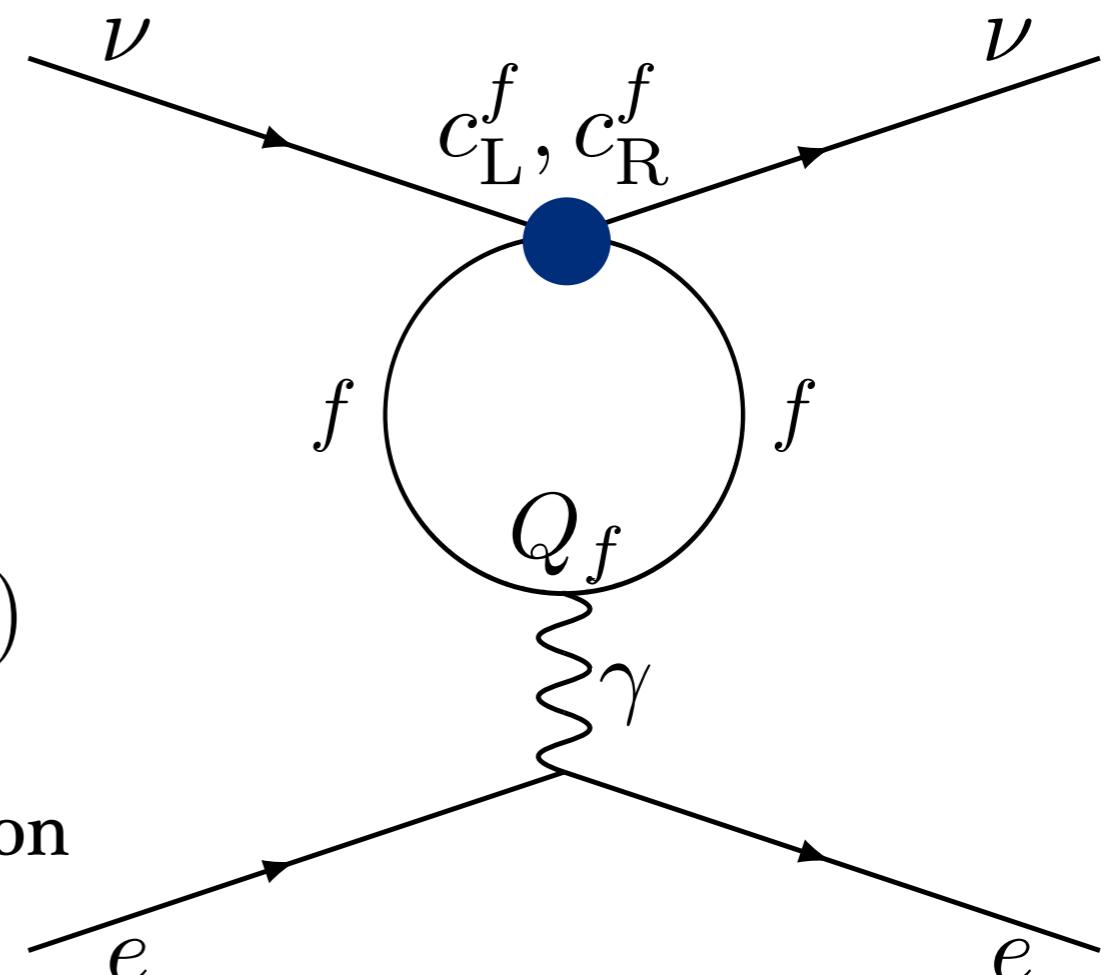
$$c^f \bar{\nu} \gamma_\mu P_L \nu \cdot \bar{e} \gamma^\mu e$$

- leptons and heavy quarks:

$$c^f = -\frac{\alpha}{2\pi} Q_f \left(c_L^f + c_R^f \right) \Pi(Q^2, m_f)$$

include two-loop $\mathcal{O}(\alpha\alpha_s)$ correction

from gluon exchanges



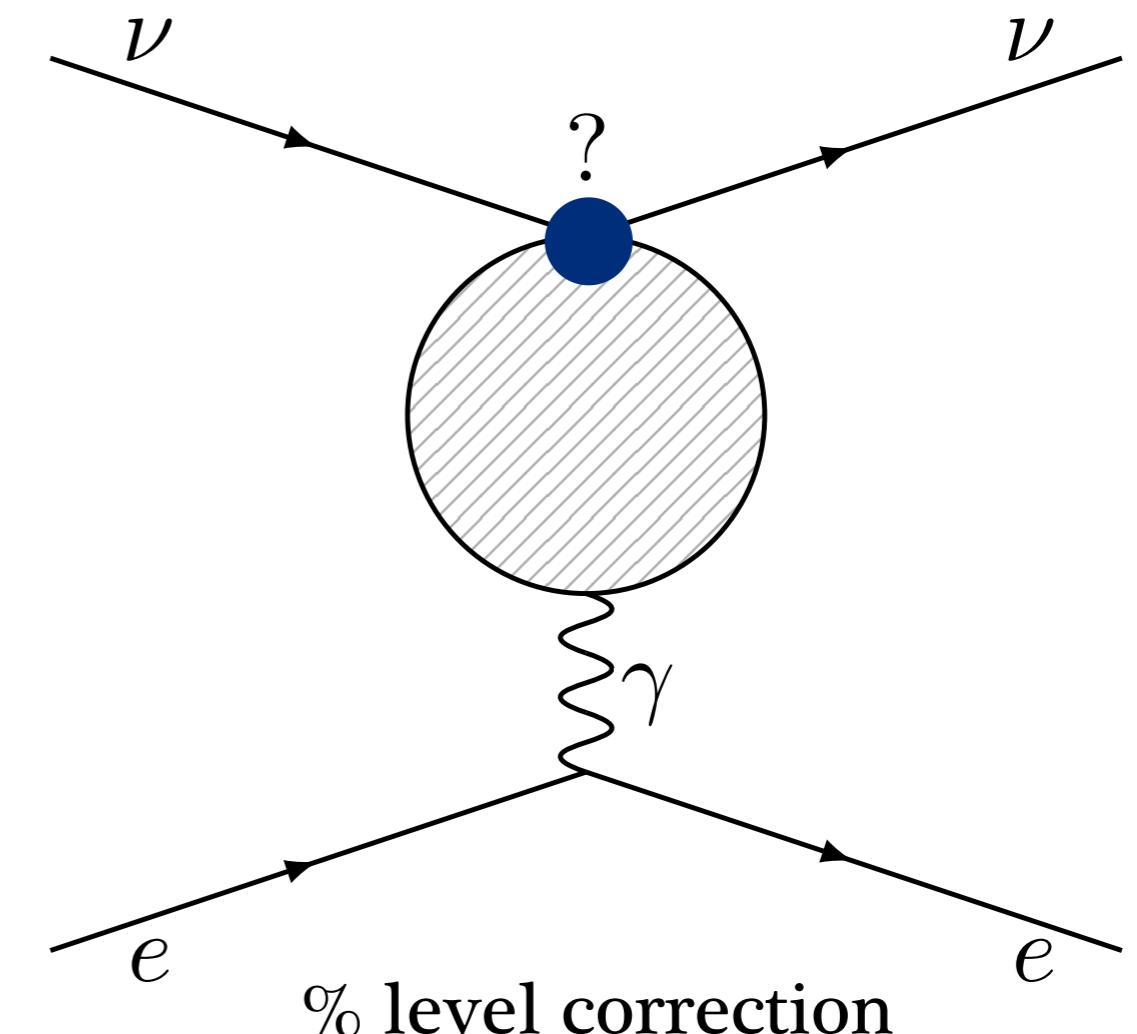
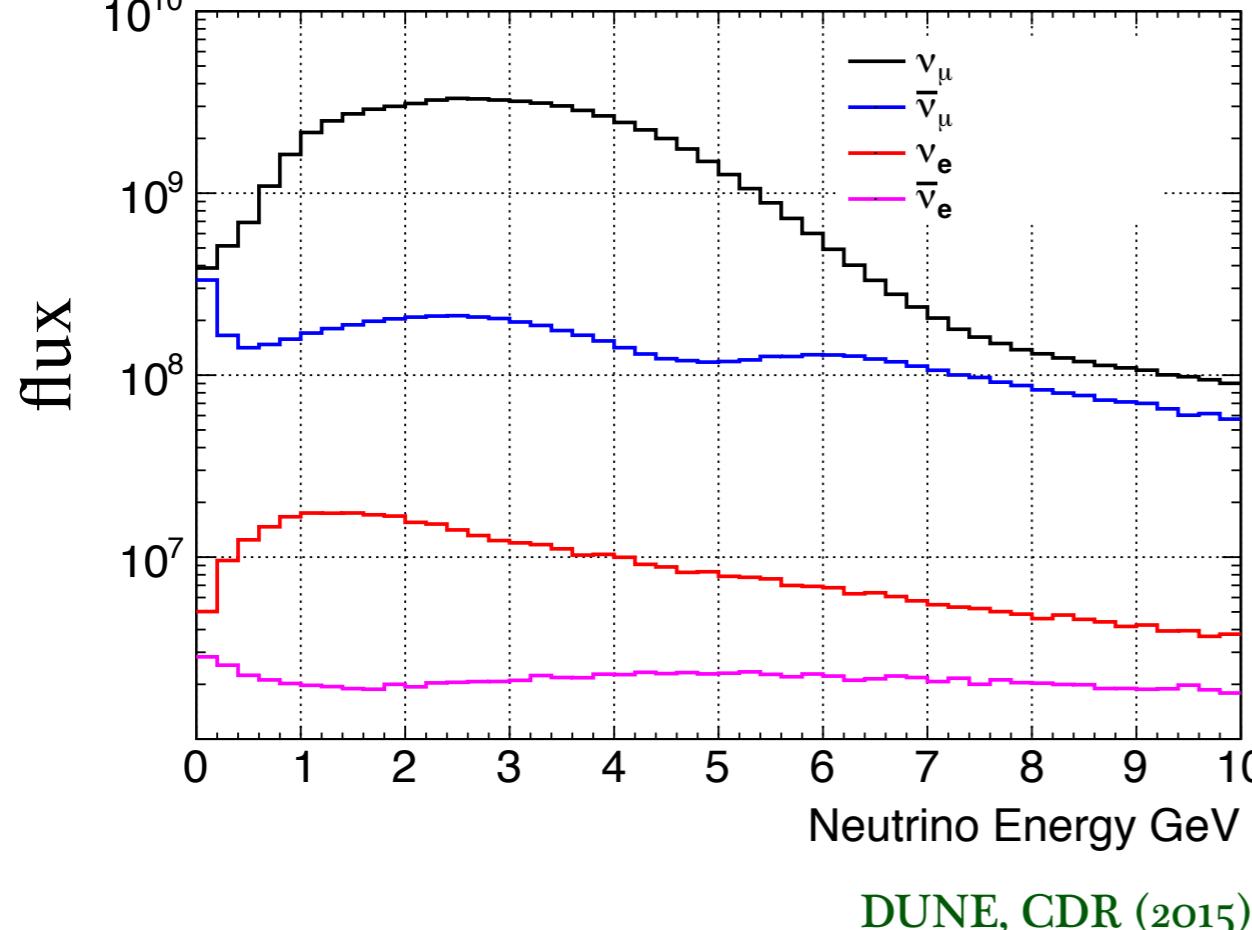
- given in terms of photon vacuum polarization

Main theoretical uncertainty

- momentum transfer is suppressed by electron mass:

$$Q^2 < 2m\omega \ll \Lambda_{\text{QCD}}^2$$

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



- hadronic correction is the main error in theory

Light-quark contribution

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

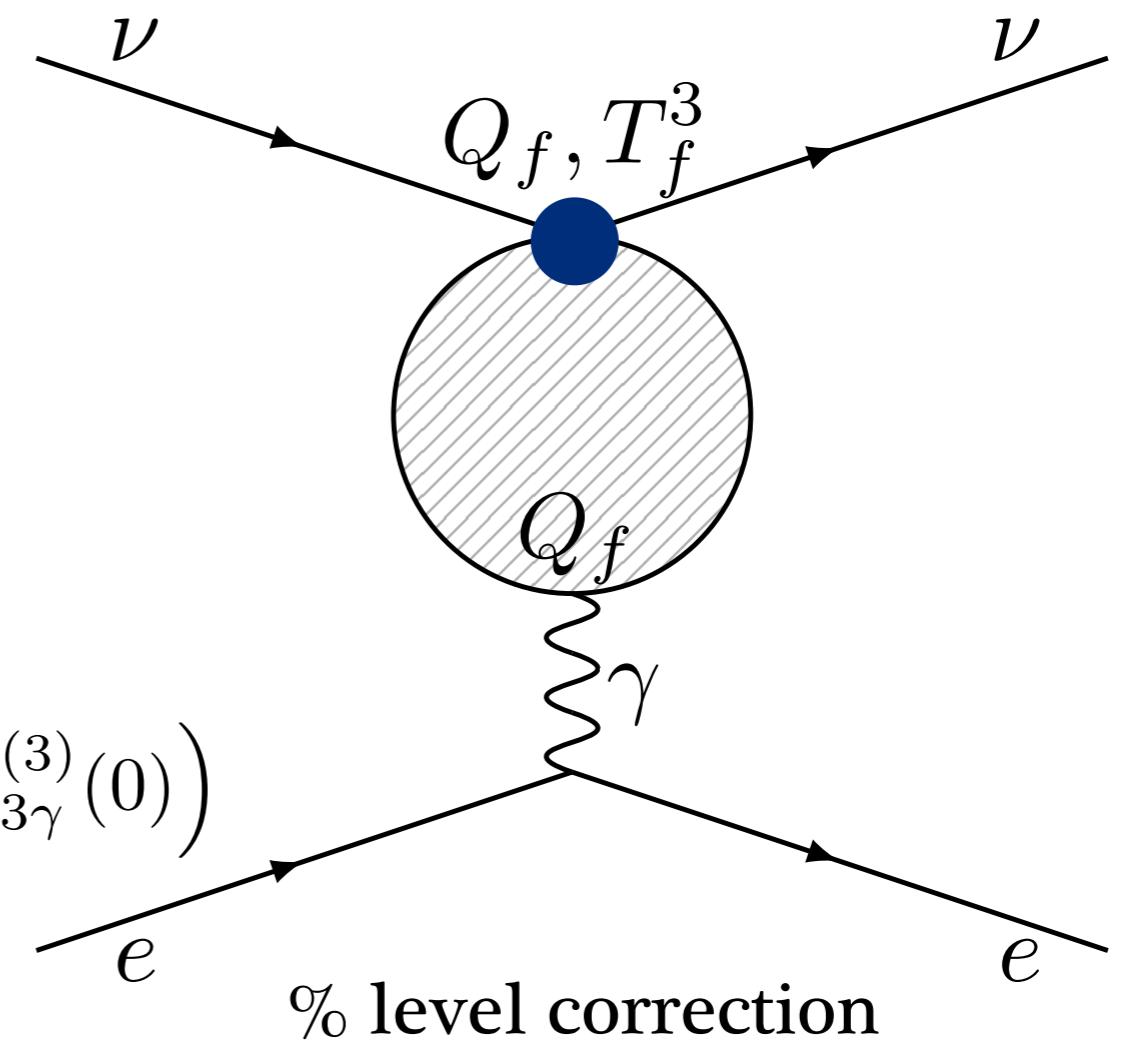
$$Q^2 < 2m\omega \ll \Lambda_{\text{QCD}}^2$$

- adds vector contribution:

$$c^h \bar{\nu} \gamma^\mu P_L \nu \cdot \bar{e} \gamma_\mu e$$

- light quarks

$$c^h = \frac{\sqrt{2}\alpha G_F}{\pi} \left(2 \sin^2 \theta_W \Pi_{\gamma\gamma}^{(3)}(0) - \Pi_{3\gamma}^{(3)}(0) \right)$$



- hadronic correlators at zero momentum transfer

Light-quark contribution

- vector-vector correlation functions in terms of quark contributions

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

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

- SU(3)_f approximation:

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

- SU(2)_f approximation:

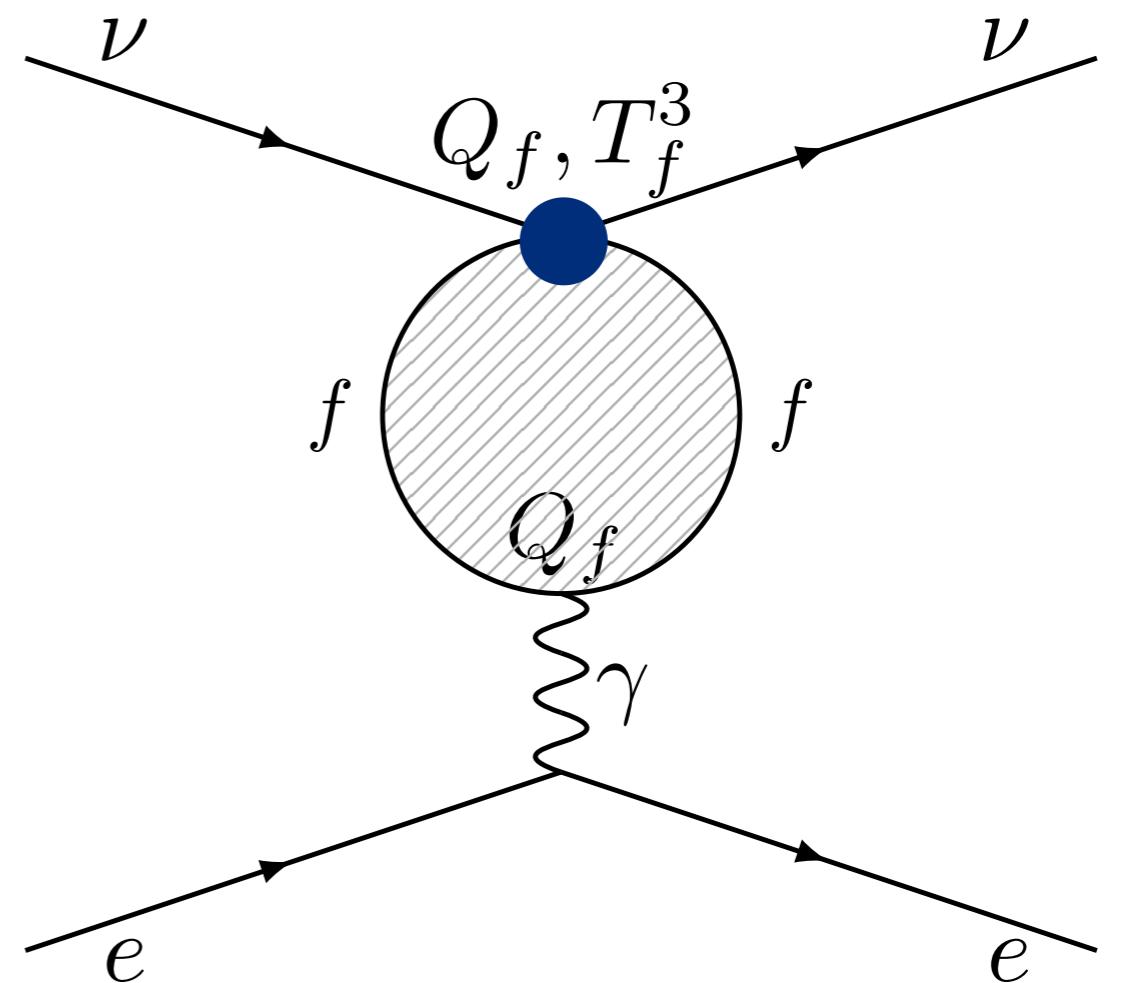
$$\Pi_{3\gamma} = \frac{9}{10} \Pi_{\gamma\gamma}$$

- our choice:

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

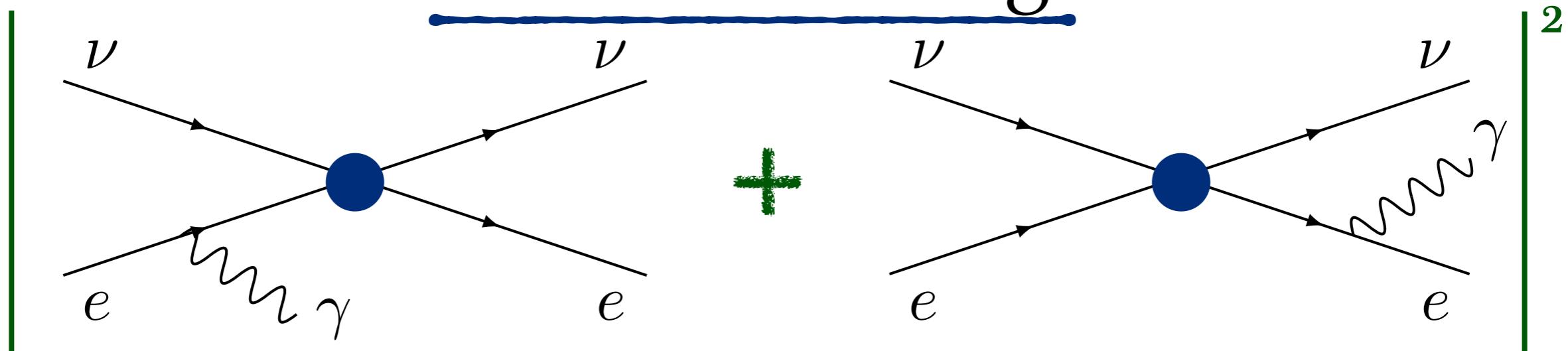
- with $\Pi_{\gamma\gamma}^{(3)}(0)$ from

Erler et al (2018)



- non-perturbative light-quark contribution

Bremsstrahlung

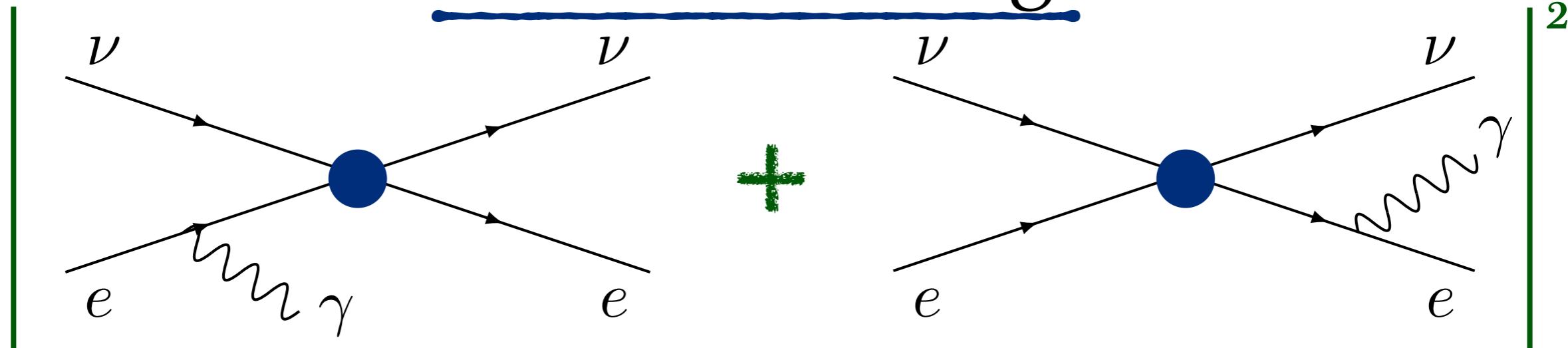


- soft Bremsstrahlung:

$$E_\gamma < \varepsilon$$

$$d\sigma_{\text{LO}}^{\nu e \rightarrow \nu e \gamma} = \delta_s d\sigma_{\text{LO}}^{\nu e \rightarrow \nu e}$$

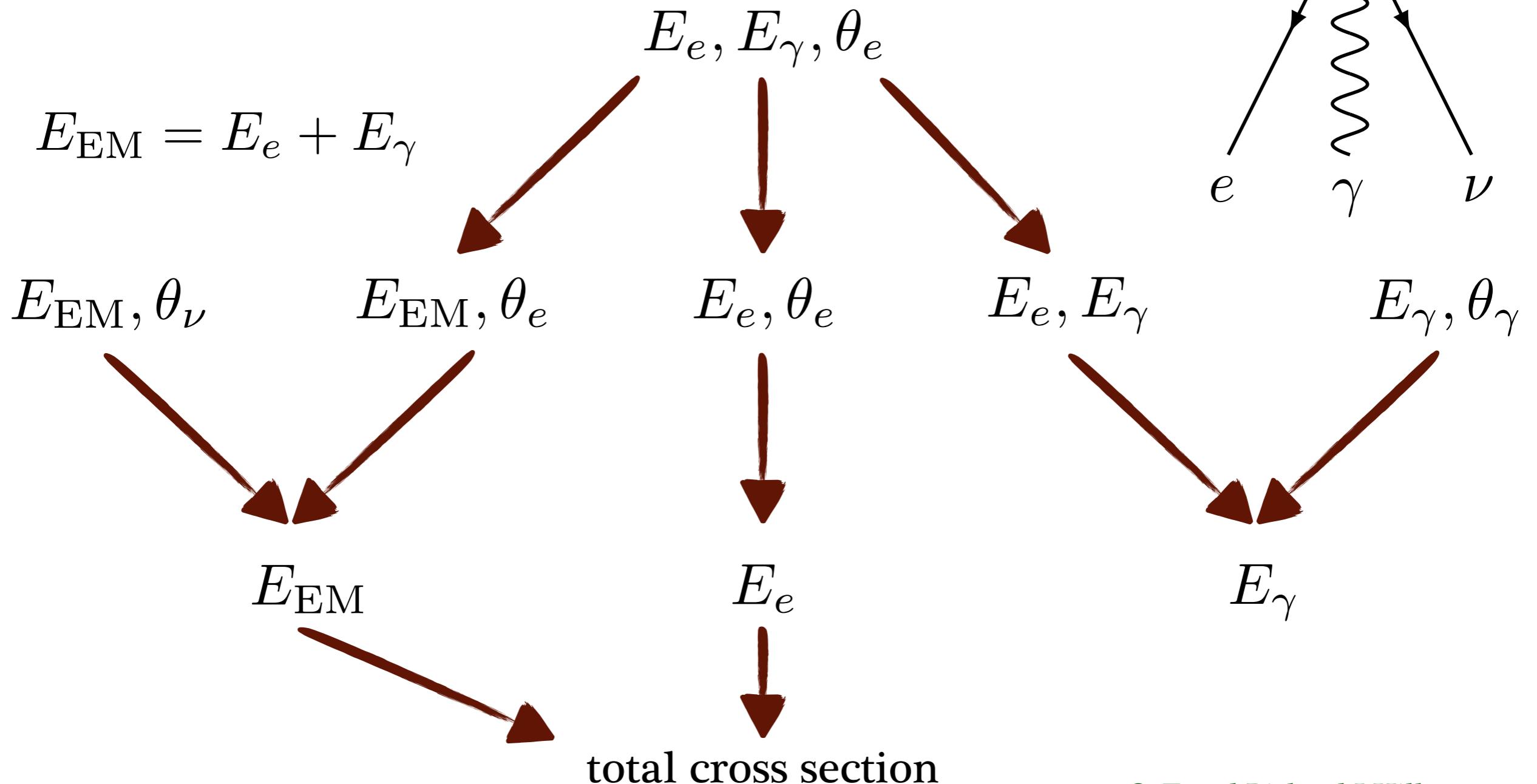
Bremsstrahlung



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

Bremsstrahlung cross sections

- distributions under consideration:

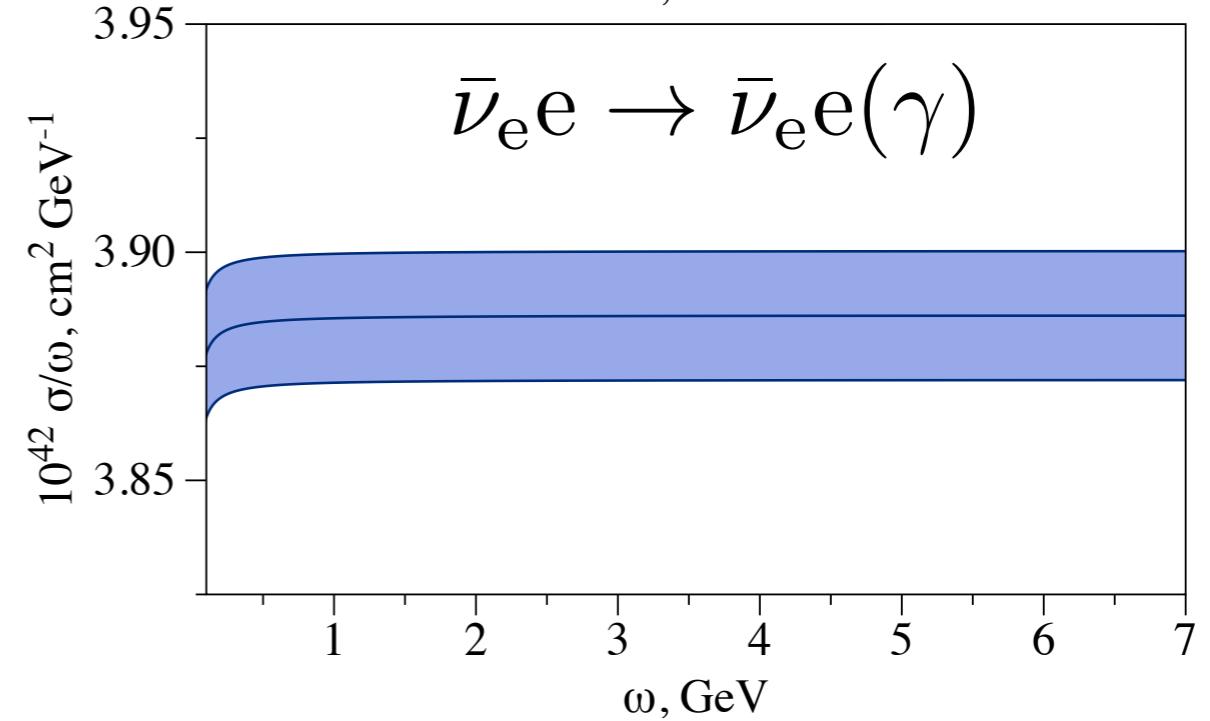
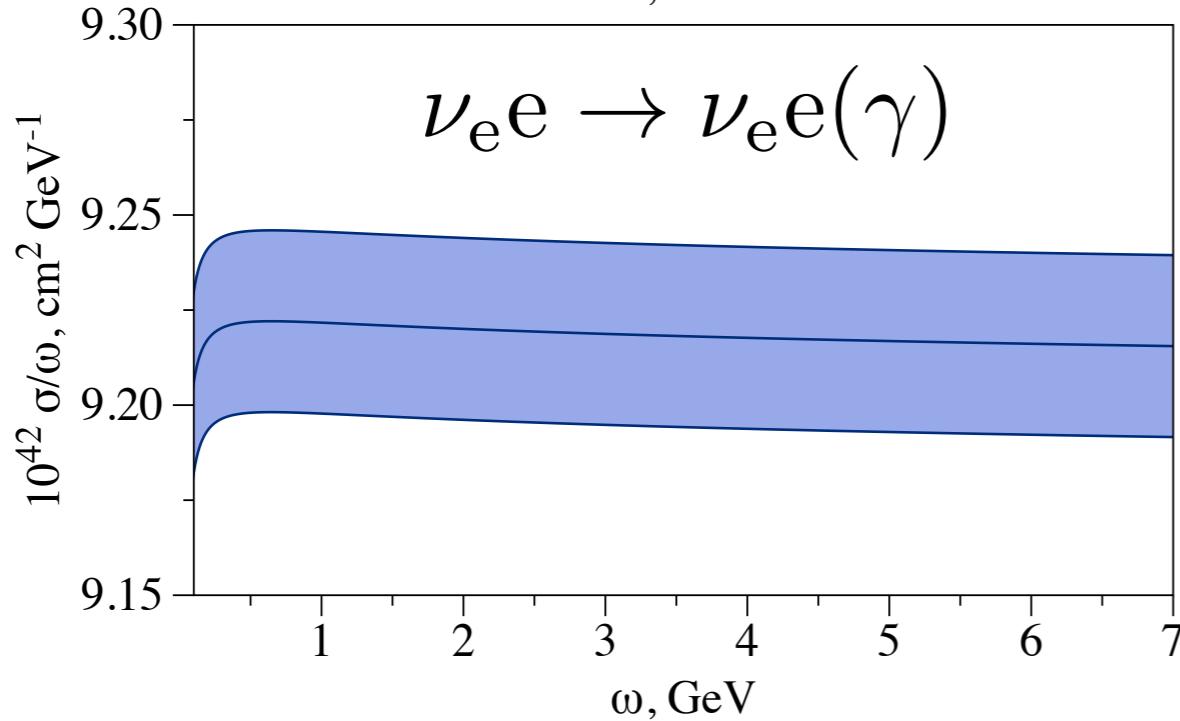
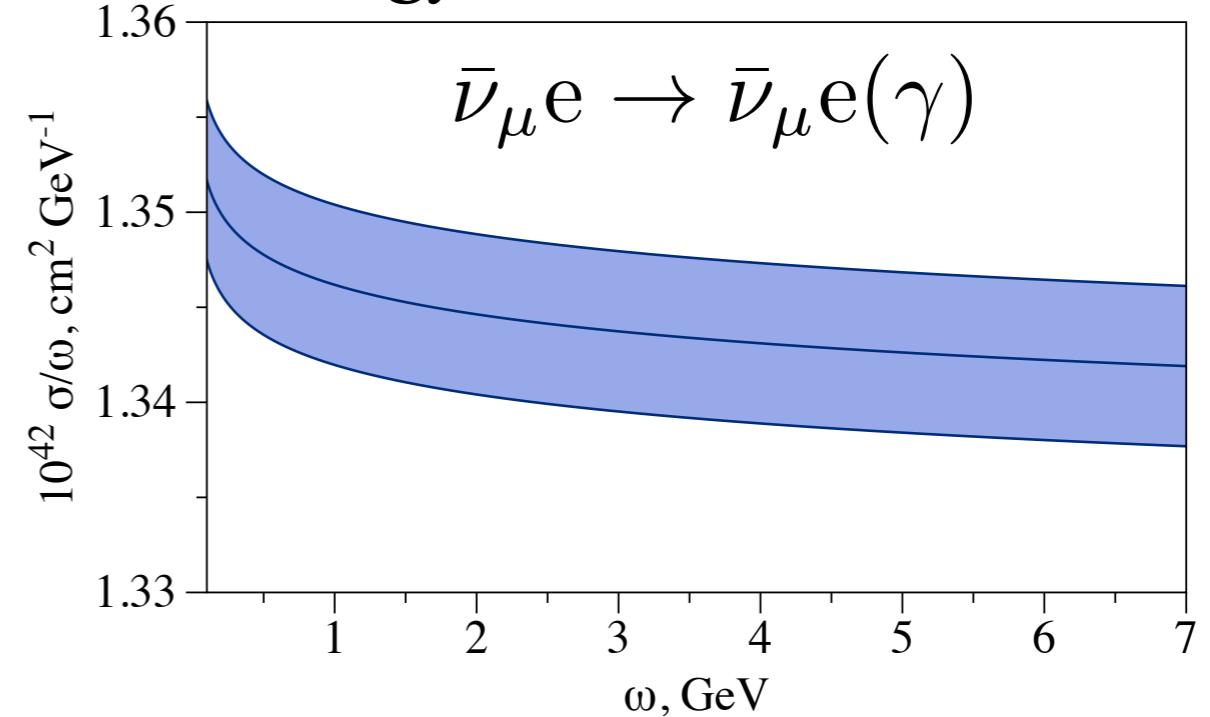
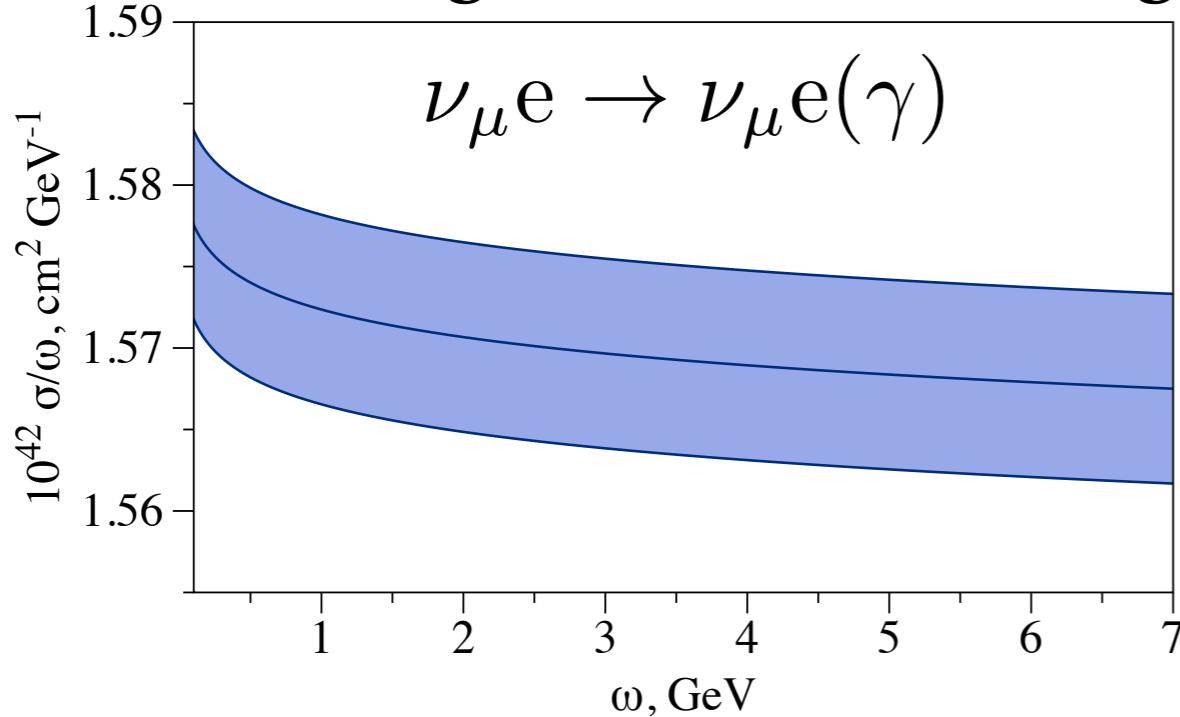


O. T. and Richard J Hill, 1907.03379

- analytical form for finite and small electron mass

Absolute cross section

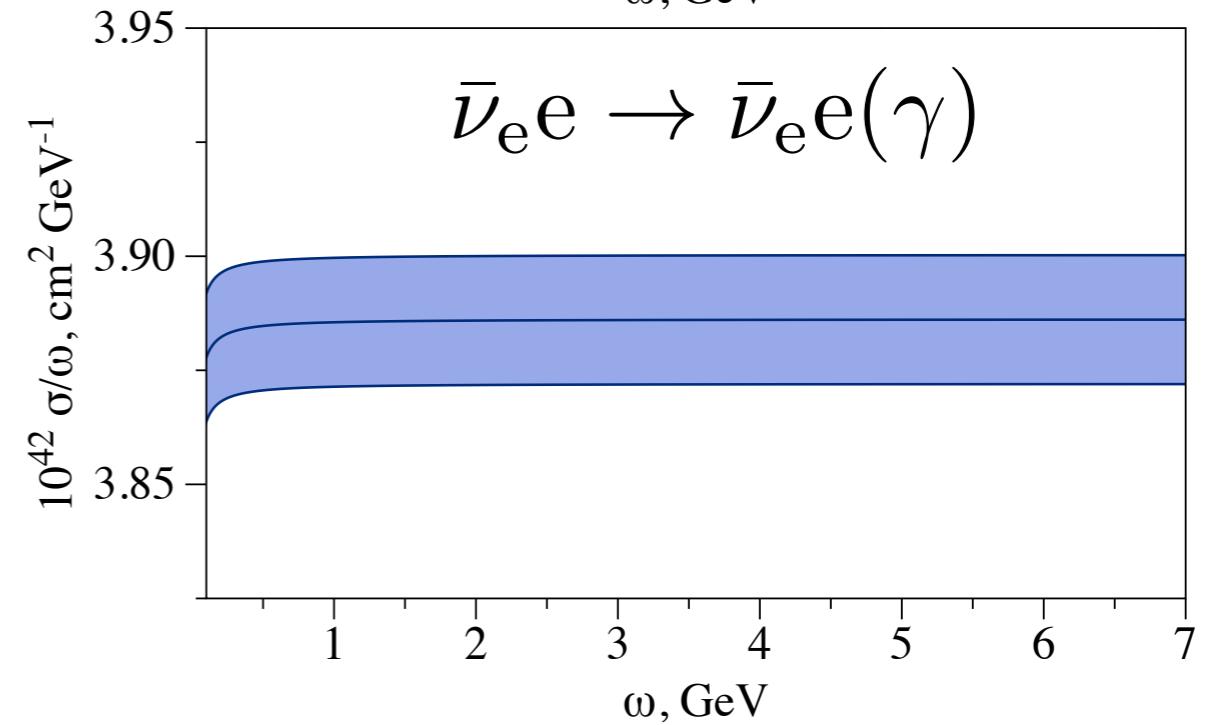
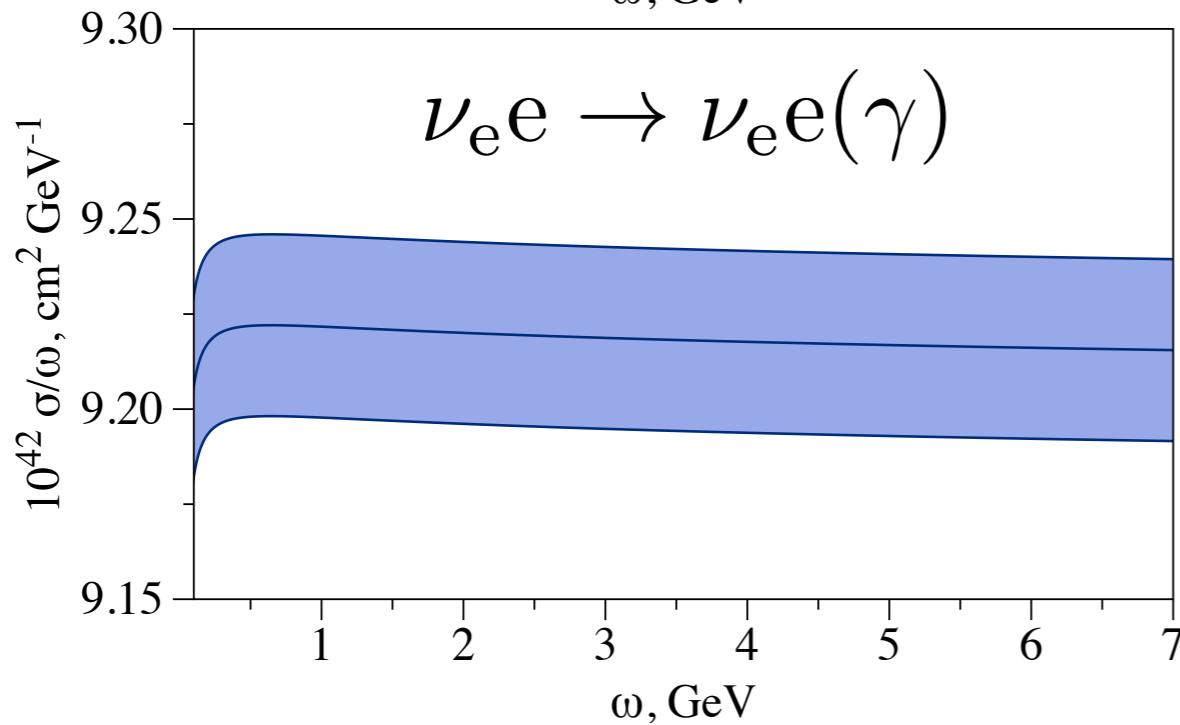
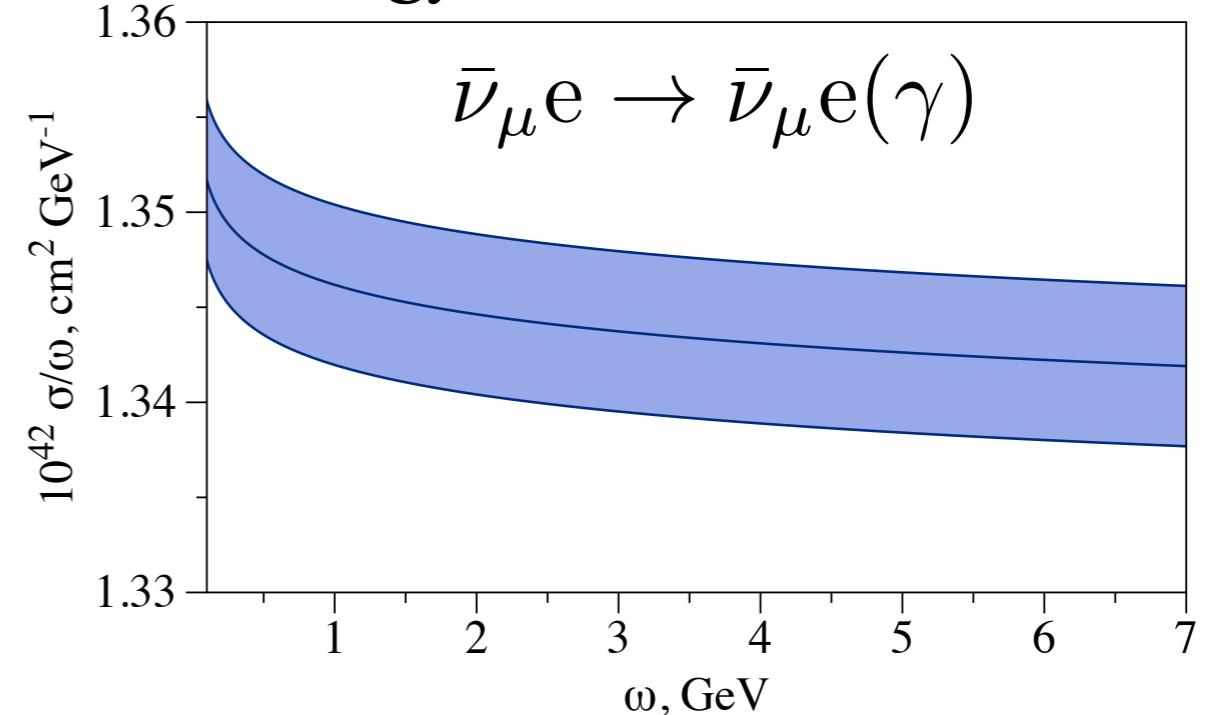
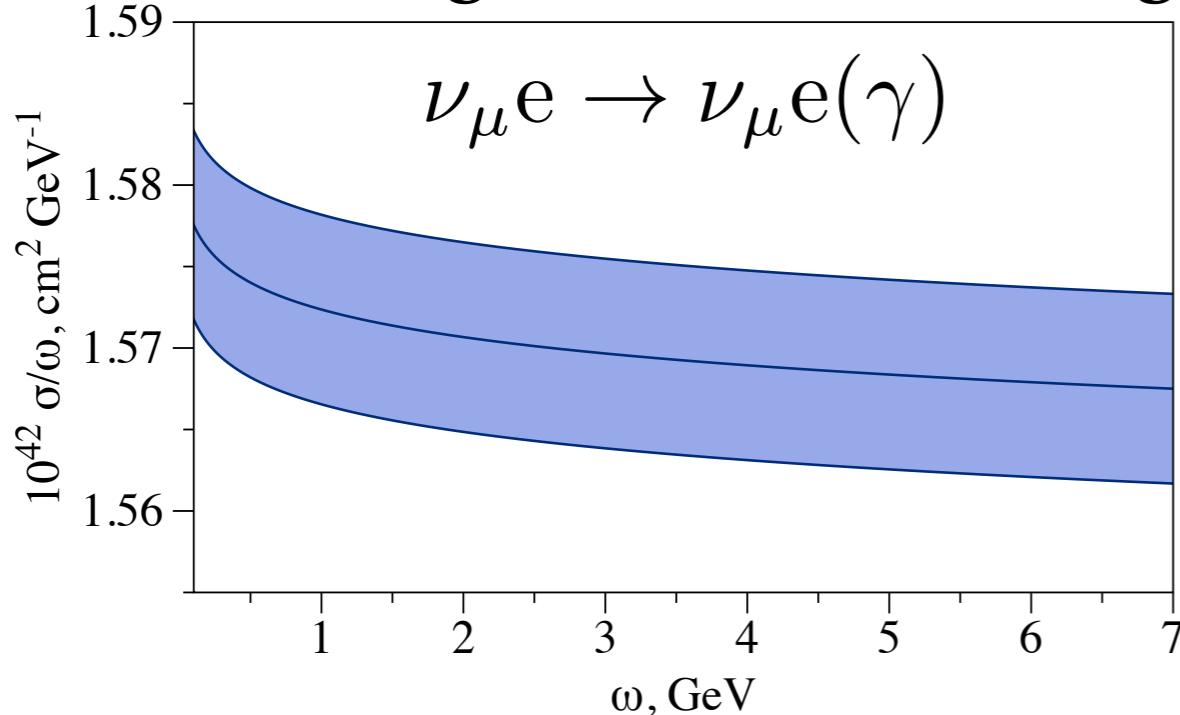
- linear growth with incoming neutrino energy ω



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

Absolute cross section

- linear growth with incoming neutrino energy ω

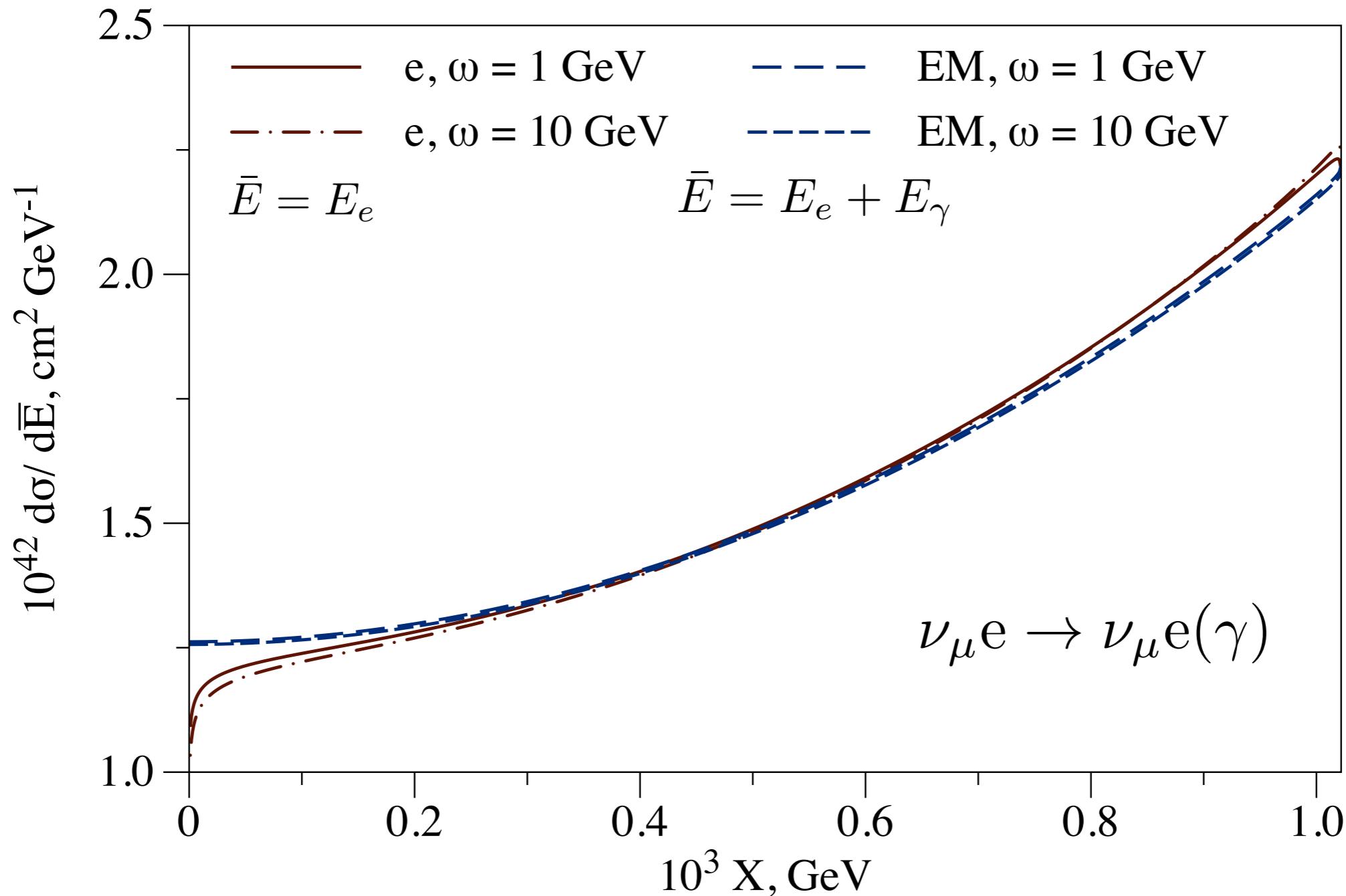


- uncertainty 0.2-0.4% is of order DUNE statistical error

Electron vs electromagnetic (EM) spectra

- resulting spectrum:

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

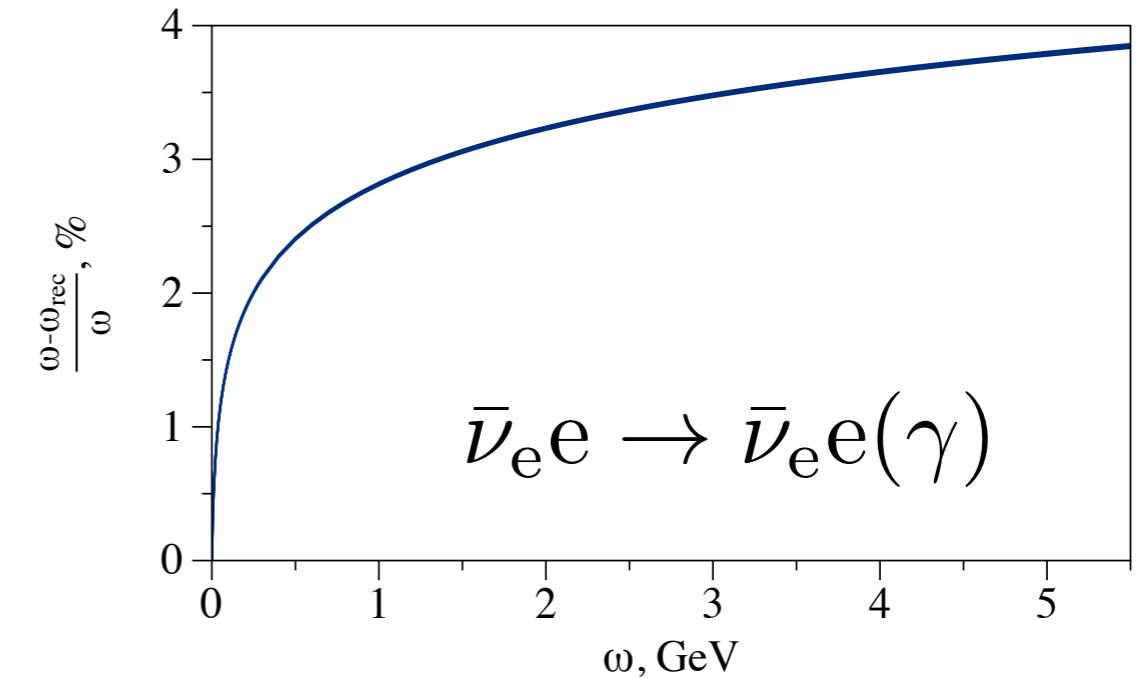
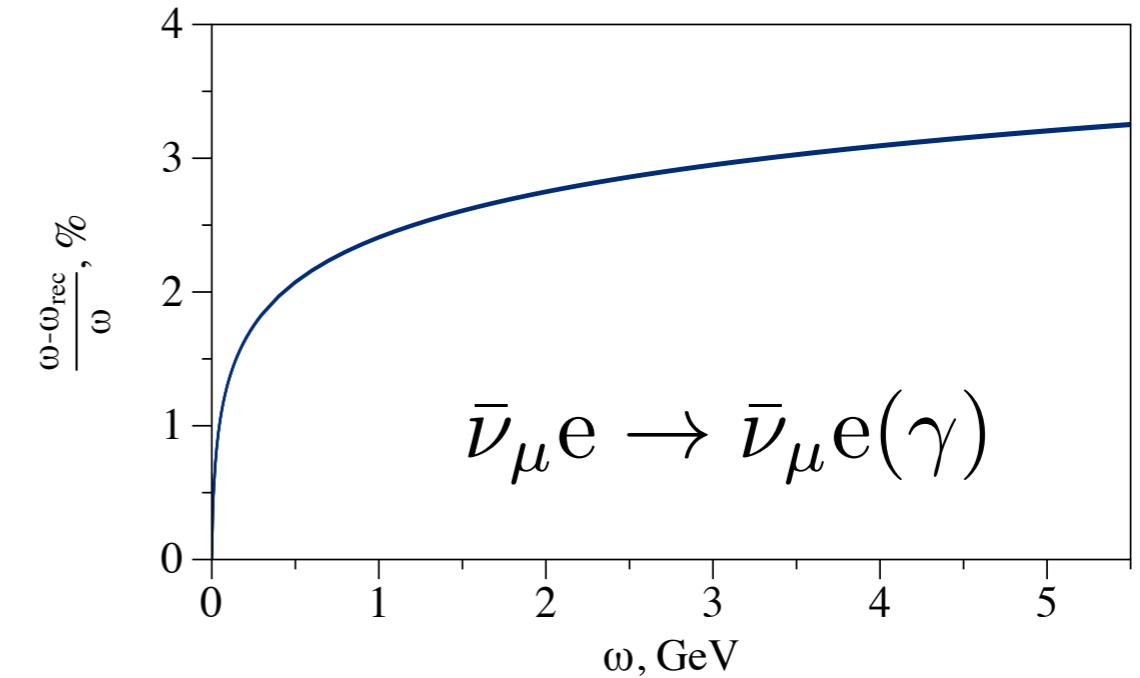
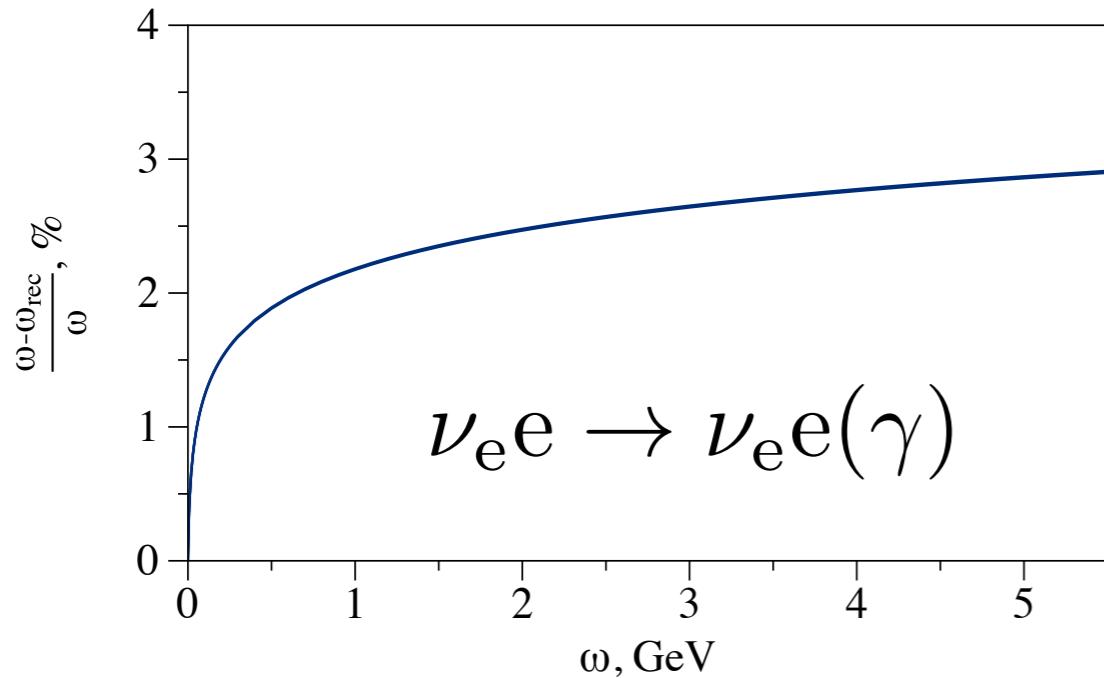
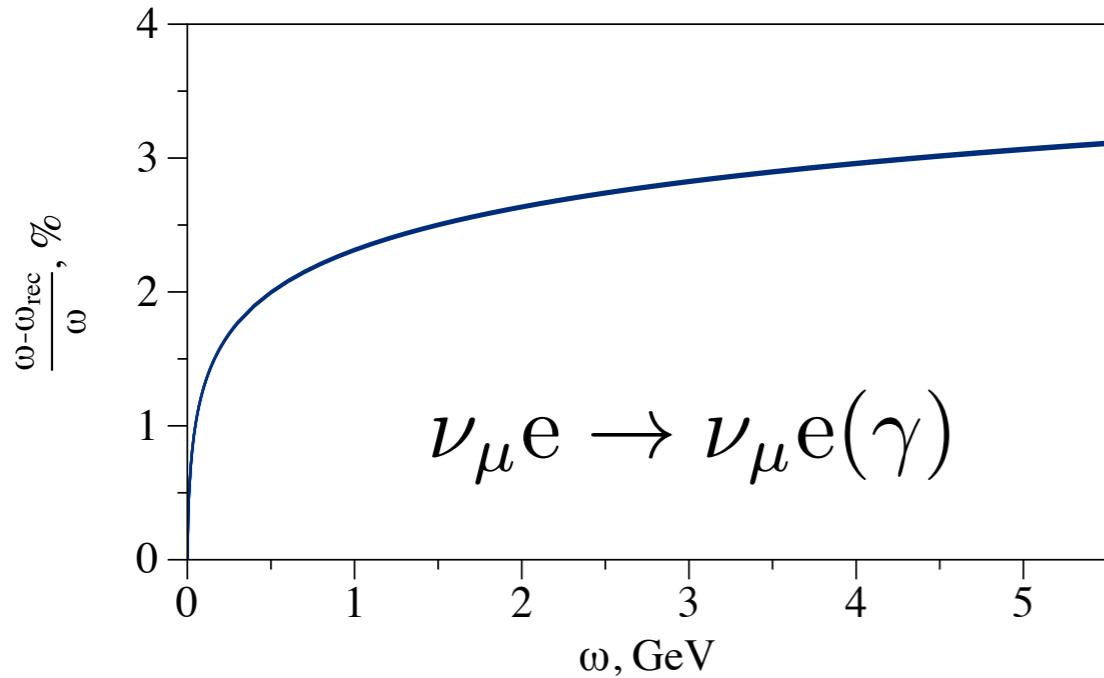


- cut dependence after radiative corrections

Neutrino energy reconstruction

- reconstruct from elastic kinematics:

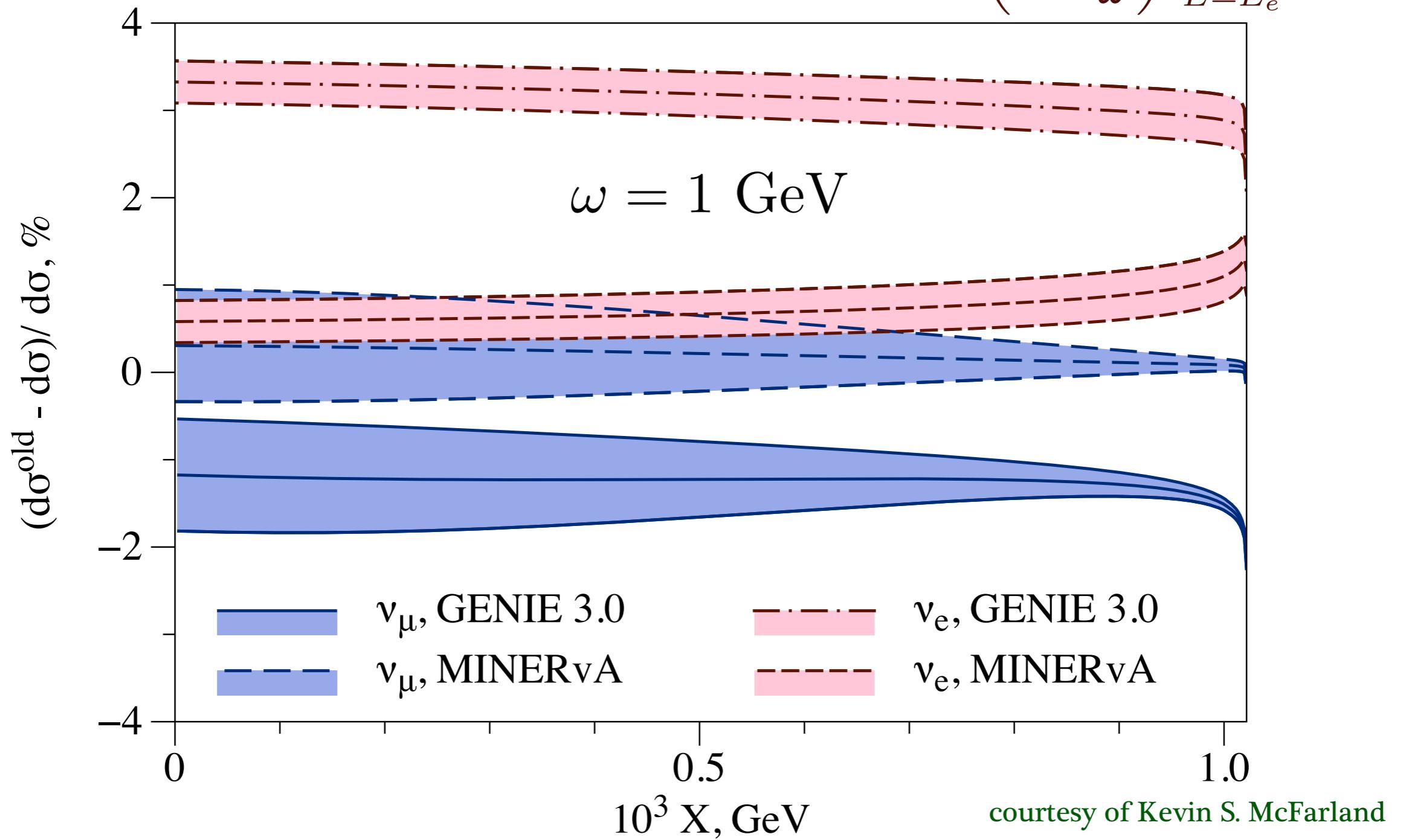
$$\omega_{\text{rec}} = \frac{m|\vec{p}_e|}{(E_e + m) \cos \theta_e - |\vec{p}_e|}$$



- radiative corrections change energy reconstruction

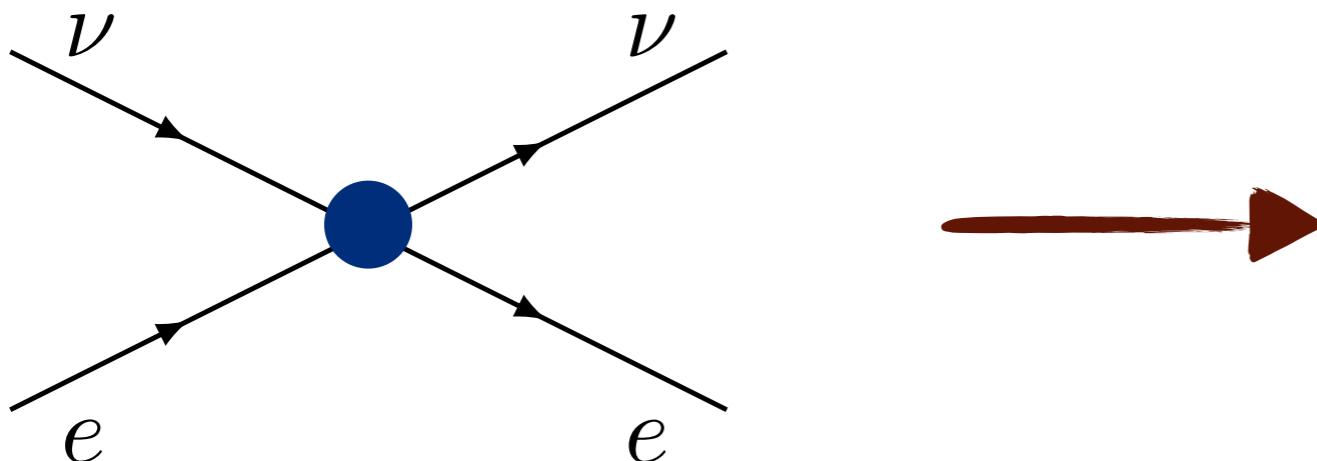
Comparison to GENIE

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



- correct description and definite improvement at GeV energies

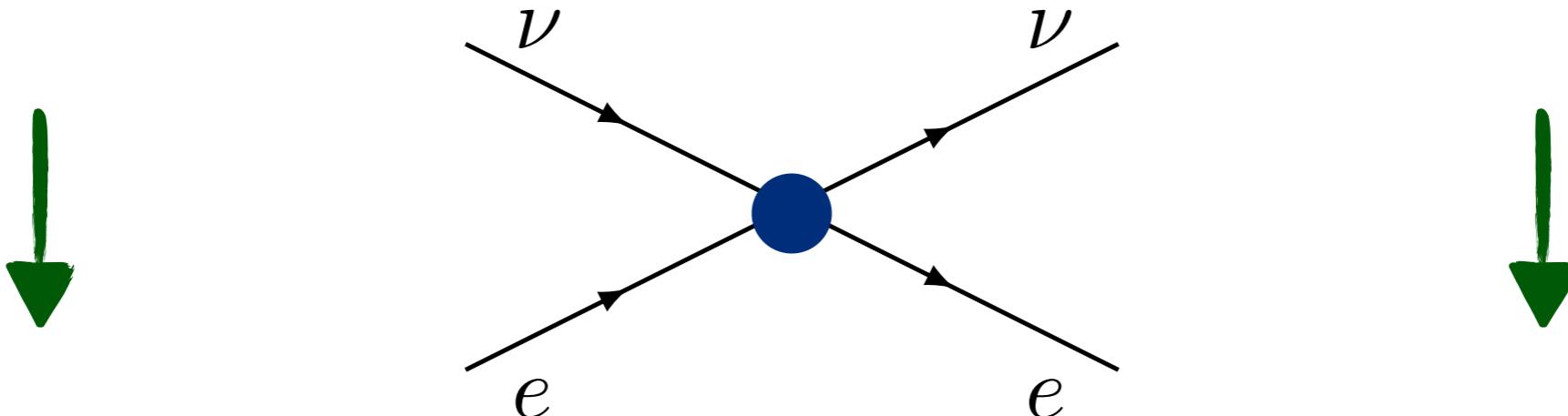
Conclusions



powerful constraint
on 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 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 $\alpha, g-2$
- constrain light-quark contribution at DUNE
- application to solar neutrinos and reactor antineutrinos

Thanks for your attention !!!

This presentation is based upon work
that is supported by the Visiting Scholars Award Program
of the Universities Research Association

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

$$\mathcal{L}_{\text{eff}} = -\bar{\nu}\gamma_\mu P_L \nu \cdot \bar{e}\gamma^\mu (c_L P_L + c_R P_R) e$$
$$c_R = 2\sqrt{2}G_F \sin^2 \theta_W \quad c_L = 2\sqrt{2}G_F (\sin^2 \theta_W - 0.5 + \delta_{\nu,\nu_e})$$

Weinberg (1967), 't Hooft (1971)

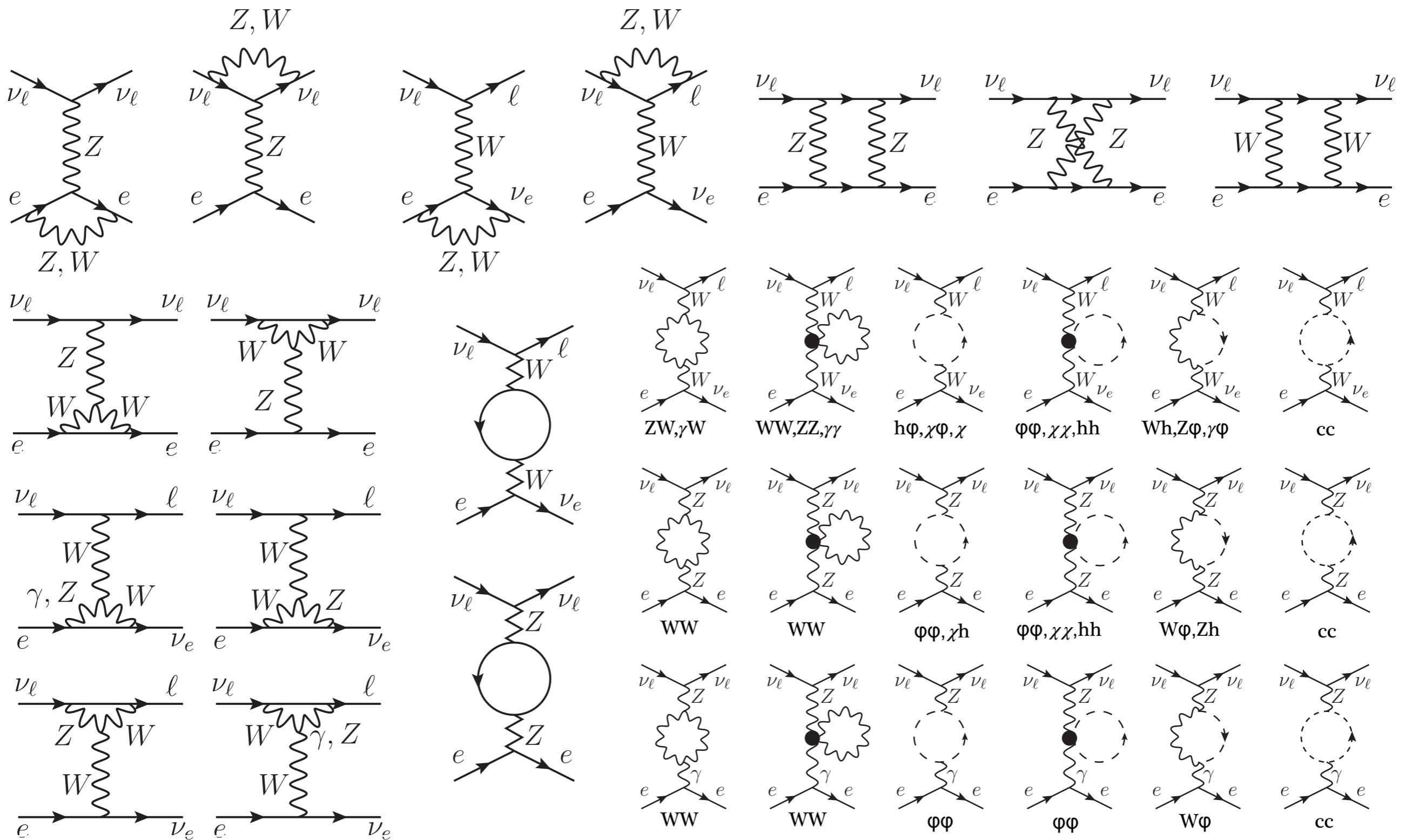
- consider only leading in G_F terms: loop corrections in α, α_s
- matching of amplitudes at EW scale, renormalized in $\overline{\text{MS}}$ scheme:

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

- neglect fermion masses besides top quark

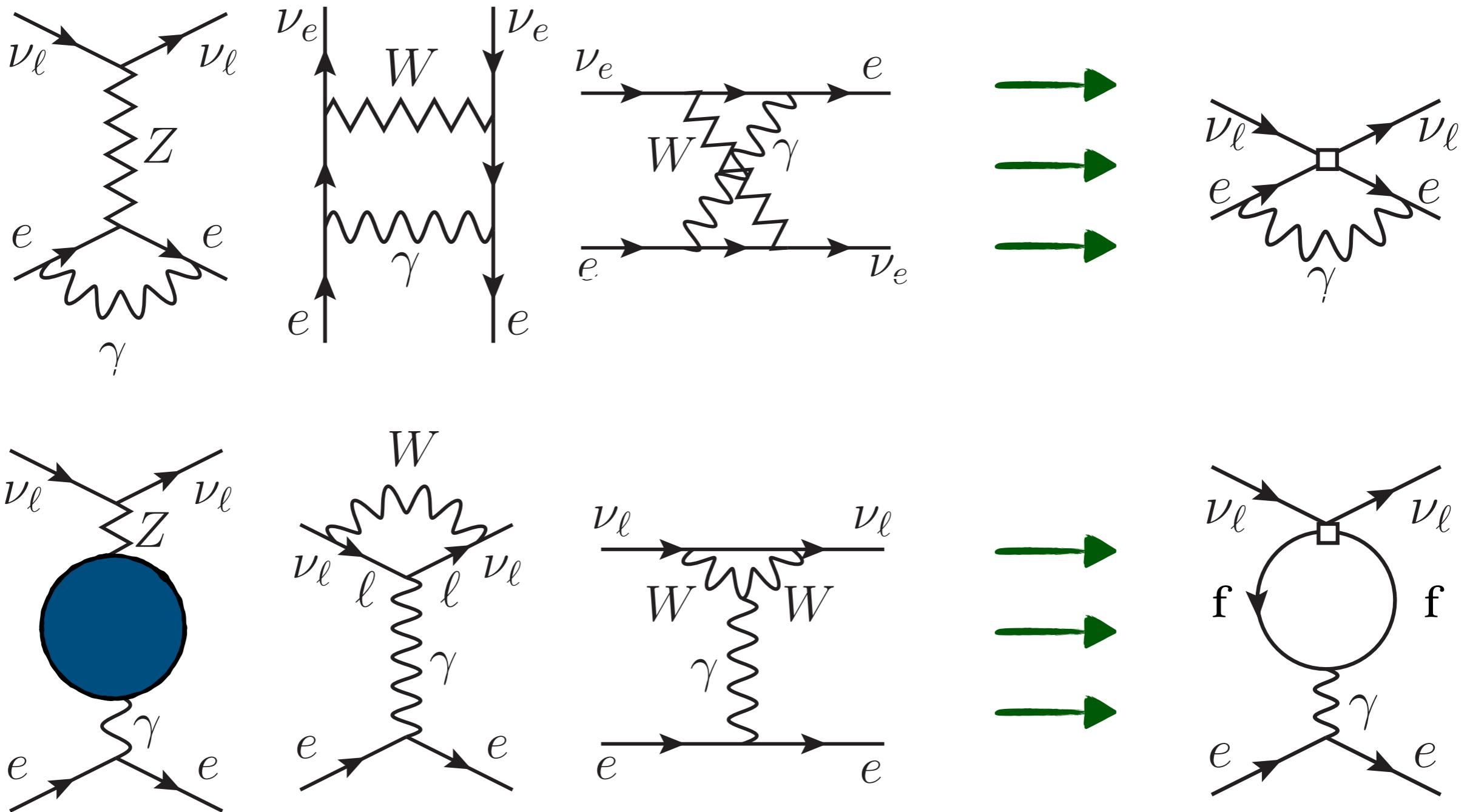
$\alpha \frac{m^2}{M_W^2}$ suppression

Contributions in SM



- contribution to effective couplings

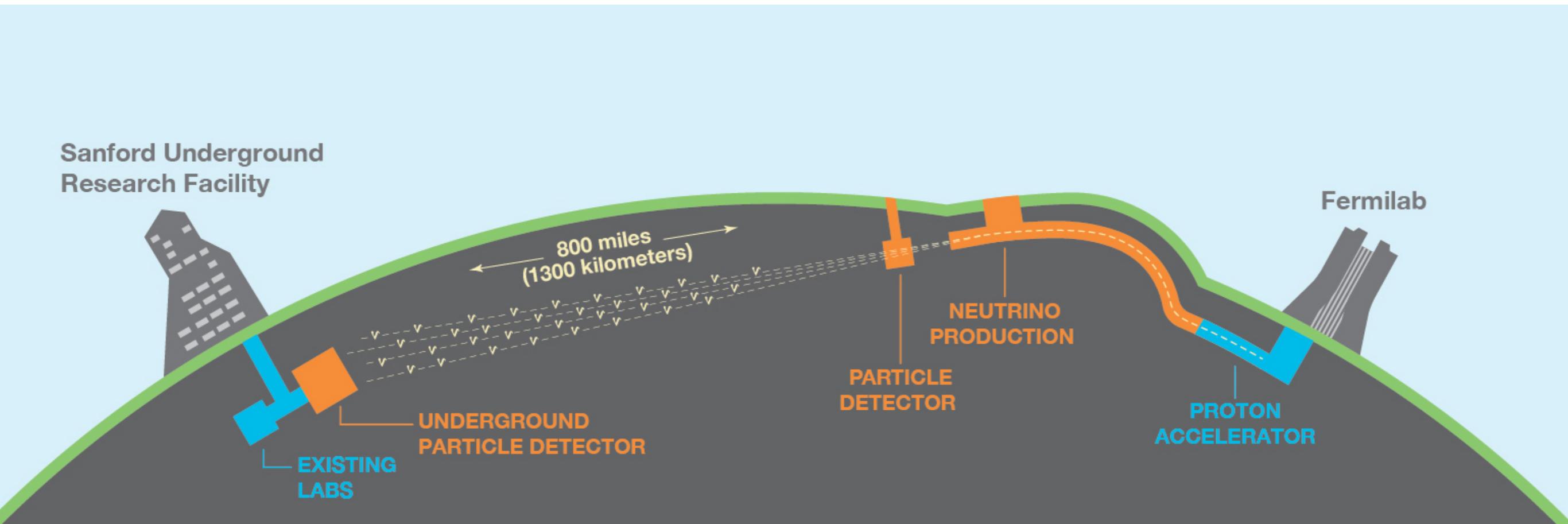
Matching at one loop \rightarrow EFT side



- cancellation of infrared and collinear singularities

Questions in neutrino physics

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



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

Scale-independent combinations

— M_Z

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

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

$$c_R^b(\mu) - c_R^d(\mu) = 0,$$

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

$$c_L^{\nu_\mu e}(\mu) - c_R(\mu) = -\sqrt{2}\tilde{G}_e,$$

$$c_L^u(\mu) - c_R^u(\mu) = \sqrt{2}\tilde{G}_u,$$

$$c_L^d(\mu) - c_R^d(\mu) = -\sqrt{2}\tilde{G}_d,$$

$$c_L^b(\mu) - c_R^b(\mu) = -\sqrt{2}\tilde{G}_b,$$

$$3c_L^u(\mu) + 2c_L^{\nu_\mu e}(\mu) = \sqrt{2}G_u,$$

$$-3c_L^d(\mu) + c_L^{\nu_\mu e}(\mu) = 2\sqrt{2}G_d.$$

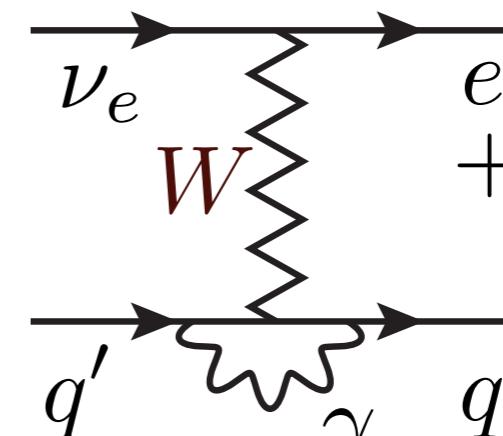
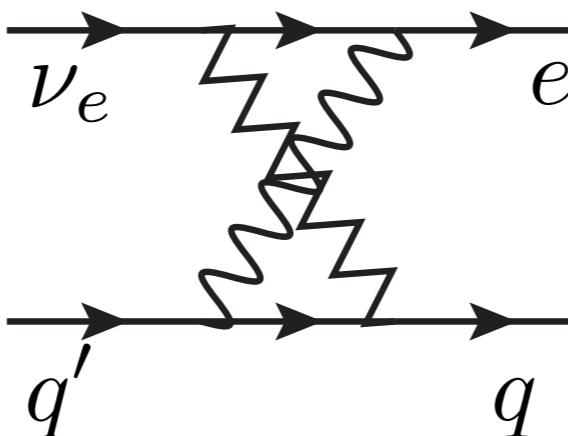
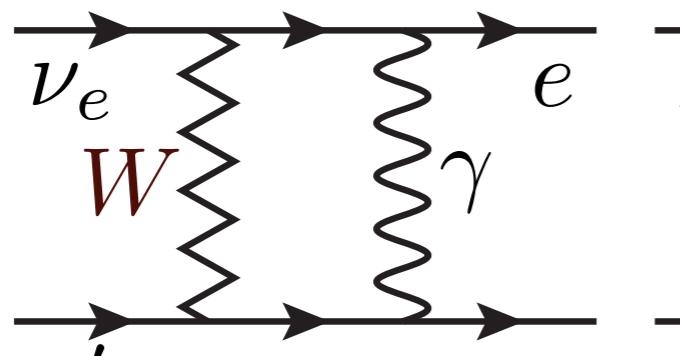
- one Fermi coupling and one c_R at leading order

- only 1 effective coupling changes with scale

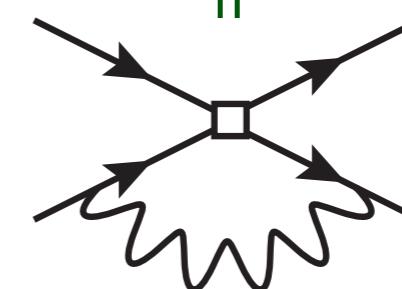
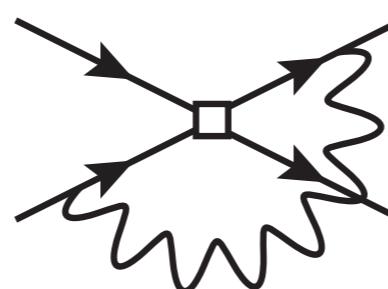
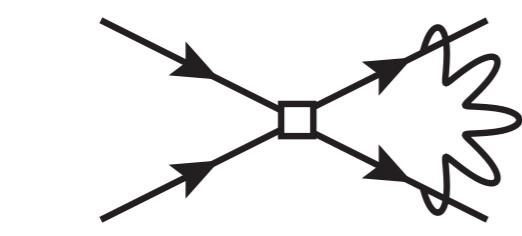
Semileptonic operators and muon decay

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

- Fermi coupling is scale independent



scheme
independent



scheme
dependent
for quarks

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

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

Buras and Weisz (1990)

- Wilson coefficient of semileptonic operator depends on scale

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

EFT with leptons

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

$$Q^2 < 2m\omega \ll \Lambda_{\text{QCD}}^2$$

- QCD degrees of freedom: vector contribution to effective couplings

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

- theory with electron, muon and neutrinos only



	$c_L^{\nu_e e}$	$c_L^{\nu_\mu e}$	$c_R^{\nu_e e}$	$c_R^{\nu_\mu e}$
$\mu = 2 \text{ GeV}$	2.4064(28)	-0.8926(28)	0.7773(28)	0.7773(28)
$\mu = m_\mu$	2.3996(29)	-0.8994(29)	0.7705(29)	0.7705(29)
$\mu = m_e$	2.3864(29)	-0.8989(29)	0.7573(29)	0.7711(29)

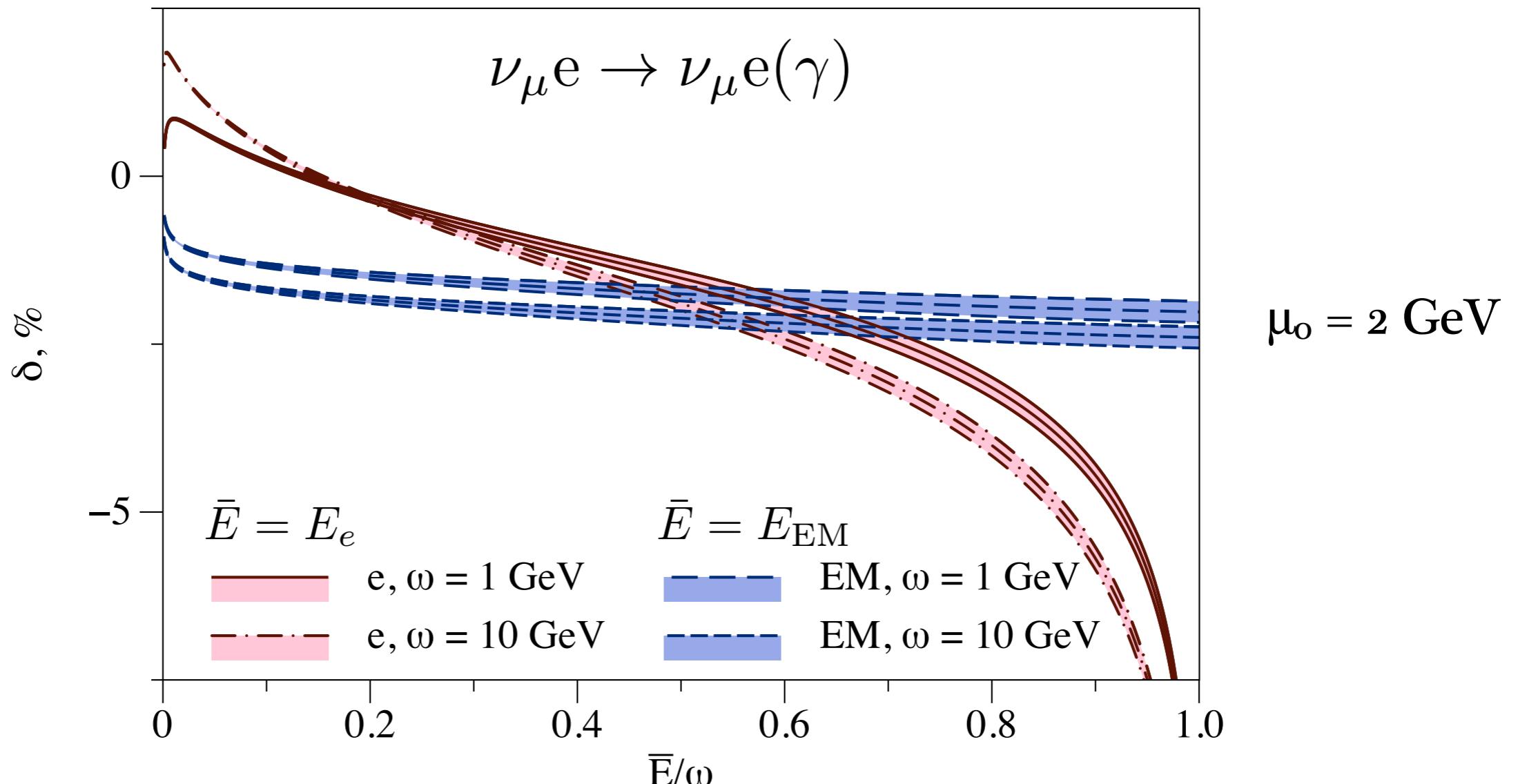
- three distinct L and R couplings below the muon mass !!!

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

Electron vs electromagnetic (EM) spectra

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

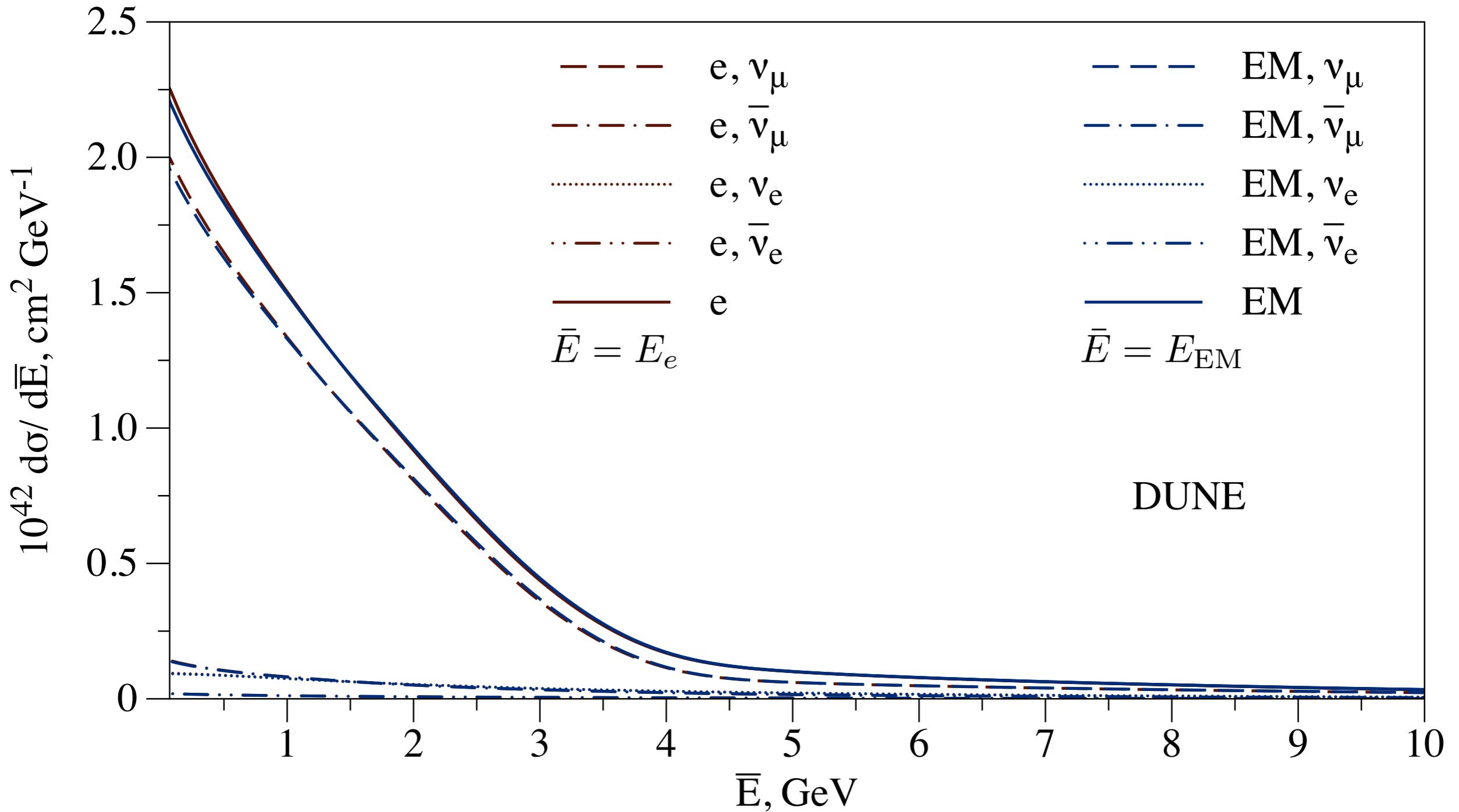
$$\delta = \frac{d\sigma_{\text{LO}}^{\nu e \rightarrow \nu e \gamma} + d\sigma_{\text{NLO}}^{\nu e \rightarrow \nu e} - d\sigma_{\text{LO}}^{\nu e \rightarrow \nu e}}{d\sigma_{\text{LO}}^{\nu e \rightarrow \nu e}}$$



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

Experimental energy spectrum

- average over beam flux and sum over flavors:



Proposal for flux determination in DUNE

- determination of neutrino fluxes:

one of the main goals of Near Detector

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

according to H. Duyang et al. (2019)

- neutrino-electron scattering plays a role of additional constraint

- ve 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

