New Perspectives 2019

Fermilab, USA

10 June, 2019

Elastic neutrino-electron scattering within the effective field theory

University of Kentucky

Oleksandr Tomalak

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

- standard candle to constrain neutrino flux:
  uncertainty from 9% to 6%
  MINERvA (2016), MINERvA and NOvA analyses ongoing

- relatively clean tool to constrain neutrino flux in DUNE
- EFT-based calculation with % accuracy was absent

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

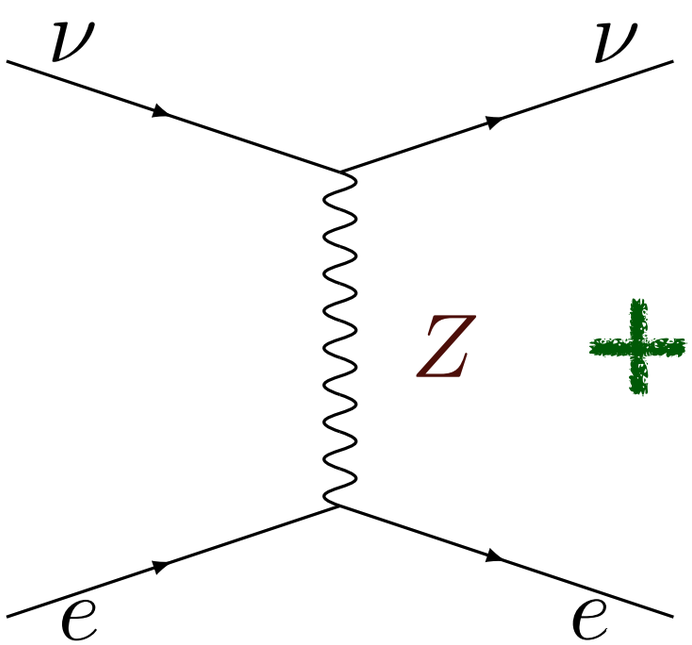
$$\mathcal{L}_{\text{eff}} = -\bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{e}\gamma^\mu(c_\mathrm{L}\mathrm{P_L} + c_\mathrm{R}\mathrm{P_R})e$$

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

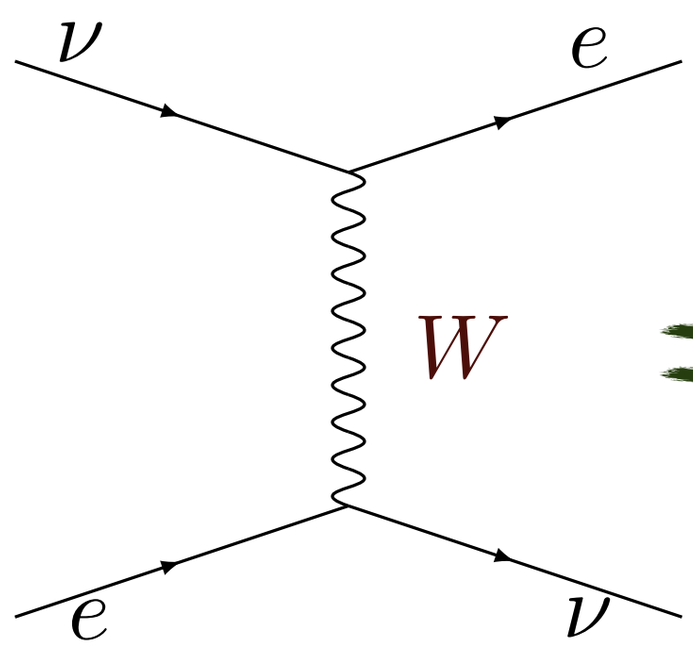
Weinberg (1967), 't Hooft (1971)

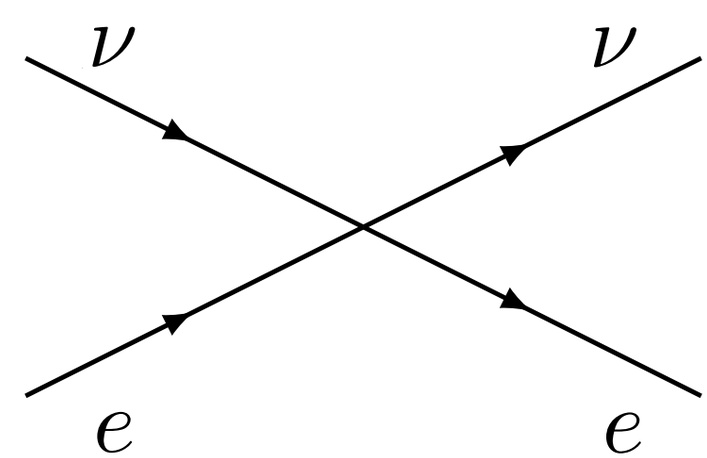
- projectors on chiral states: $\mathrm{P_L} = \dfrac{1-\gamma_5}{2}$ $\quad \mathrm{P_R} = \dfrac{1+\gamma_5}{2}$

neutral current



charged current





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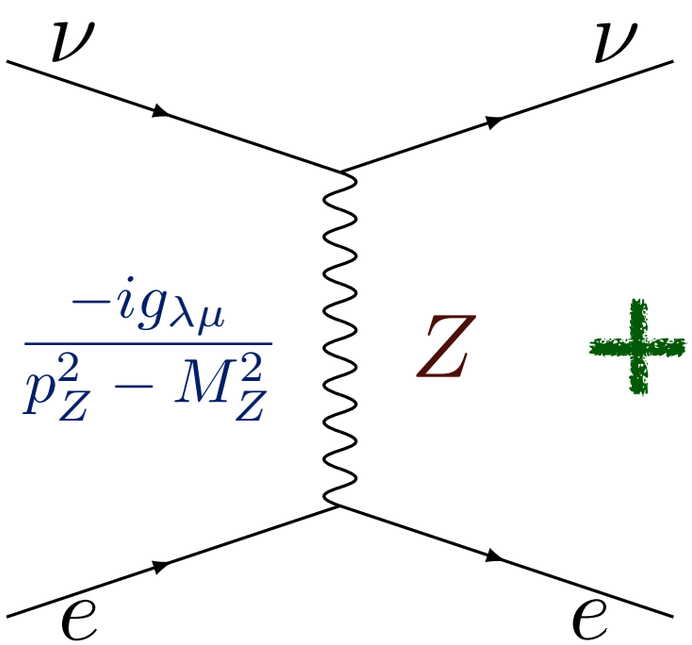

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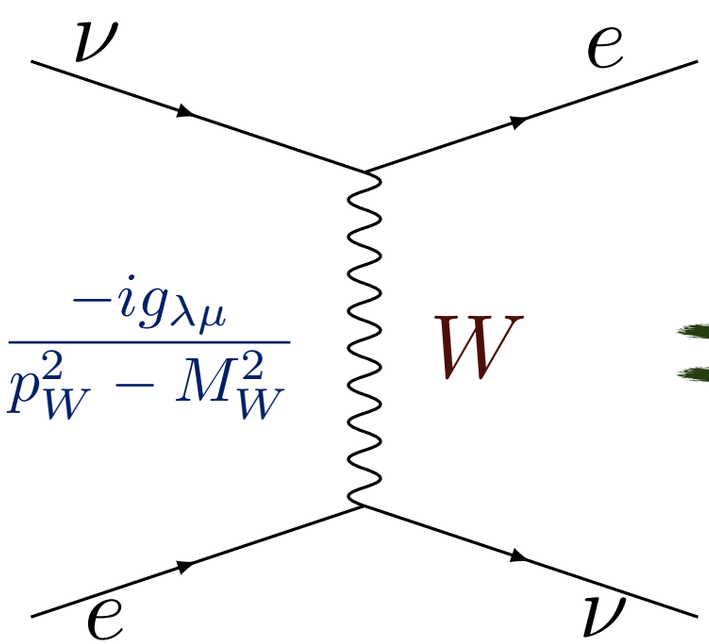

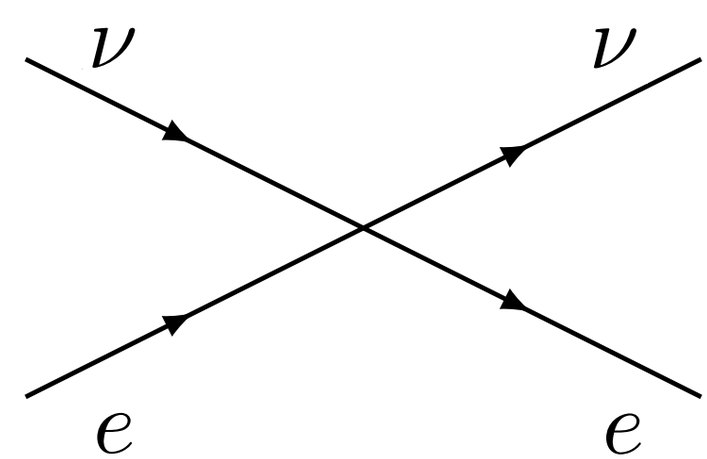

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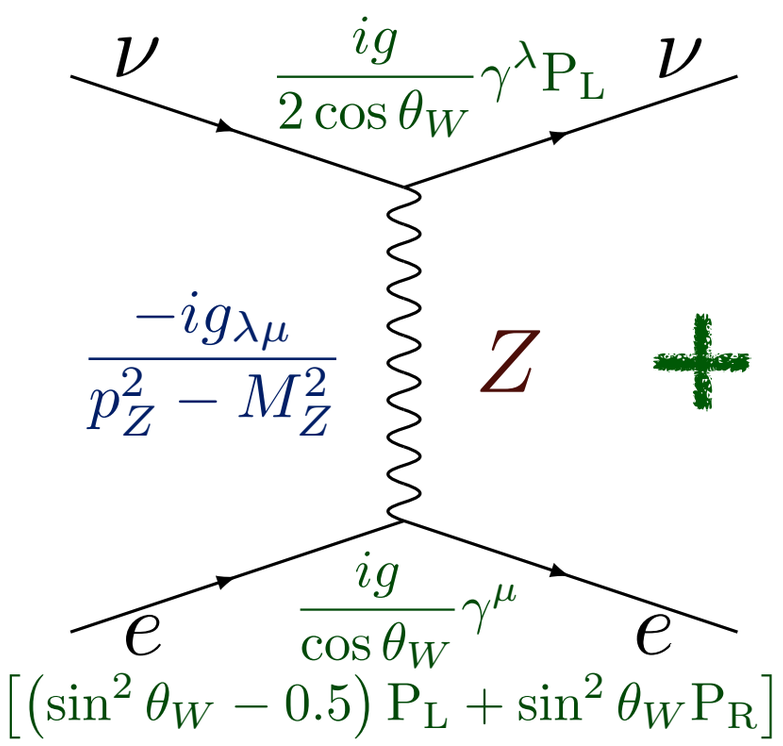

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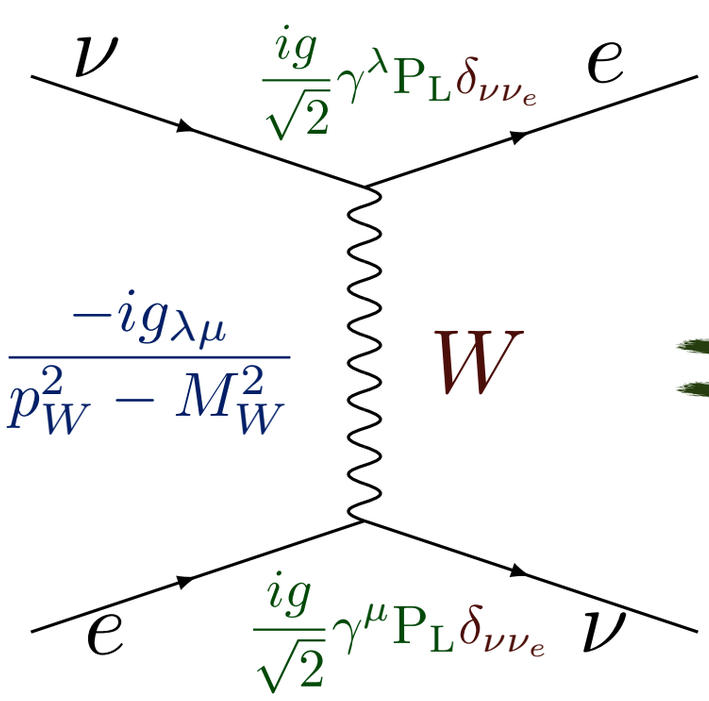

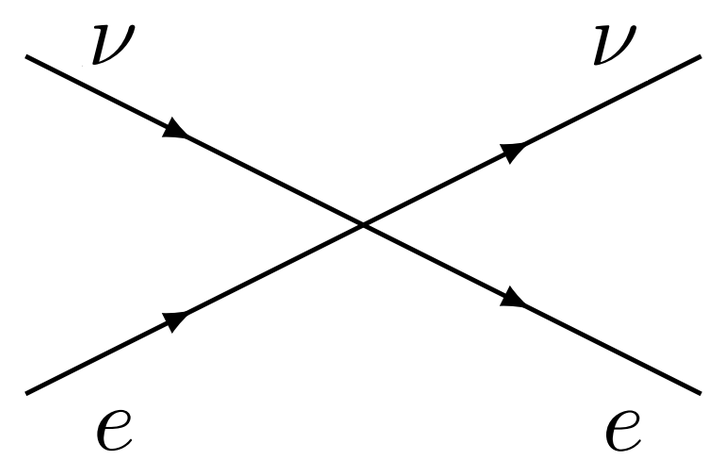

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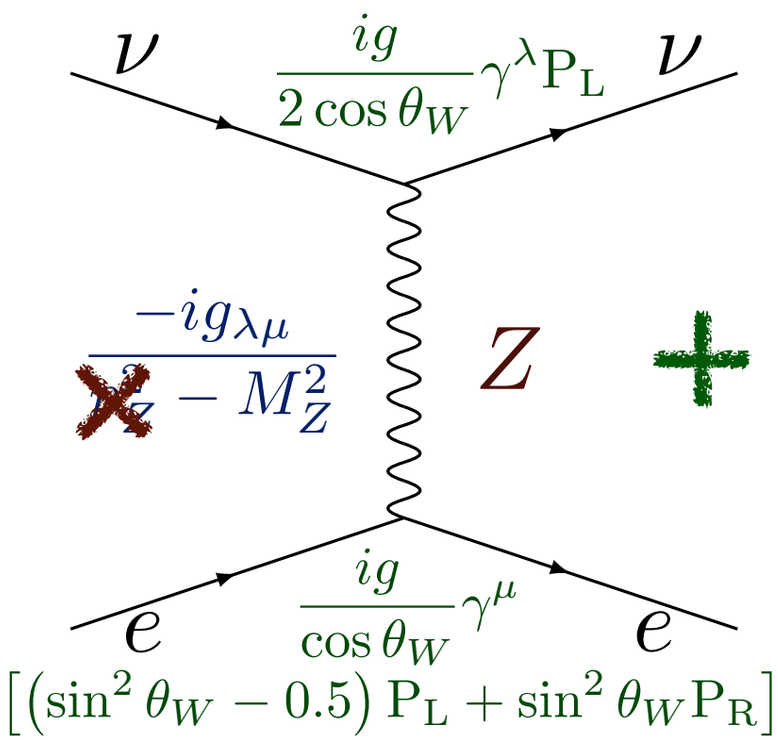

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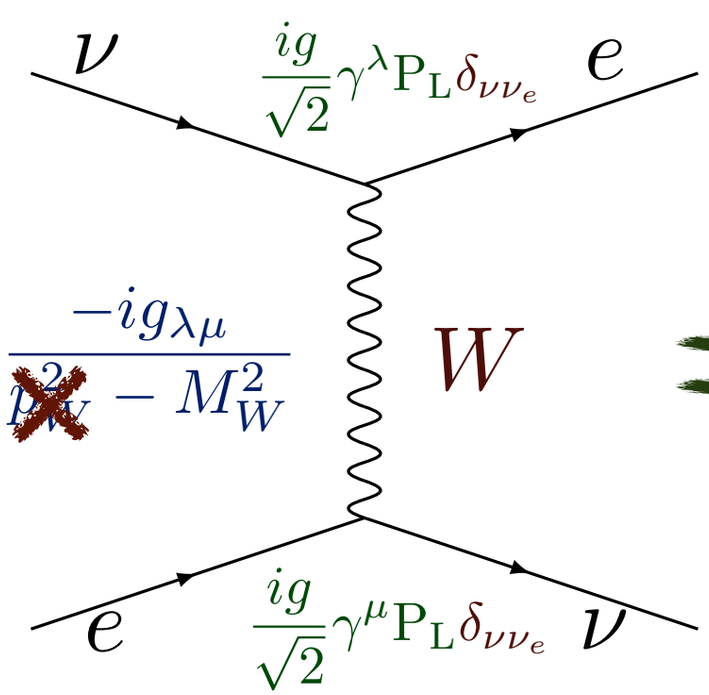
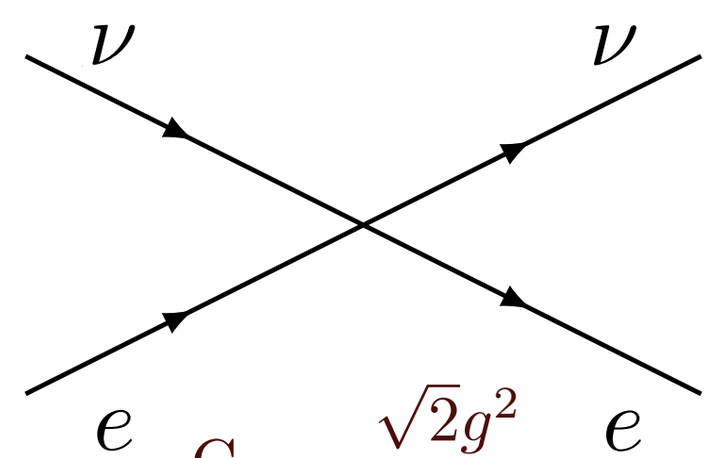


$$M_W^2 = M_Z^2\cos^2\theta_W$$



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

$$e = g\sin\theta_W$$

- integrate out W and Z at tree level

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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:

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

- SM symmetries and universality leave 8 couplings to determine:

  3 for leptons and 5 for quarks besides top

- 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 $\alpha\alpha_\mathrm{s}$: left- and right-handed couplings
- muon lifetime measurement improves precision

Running to low scales

M_Z - integrate out top at Z scale

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

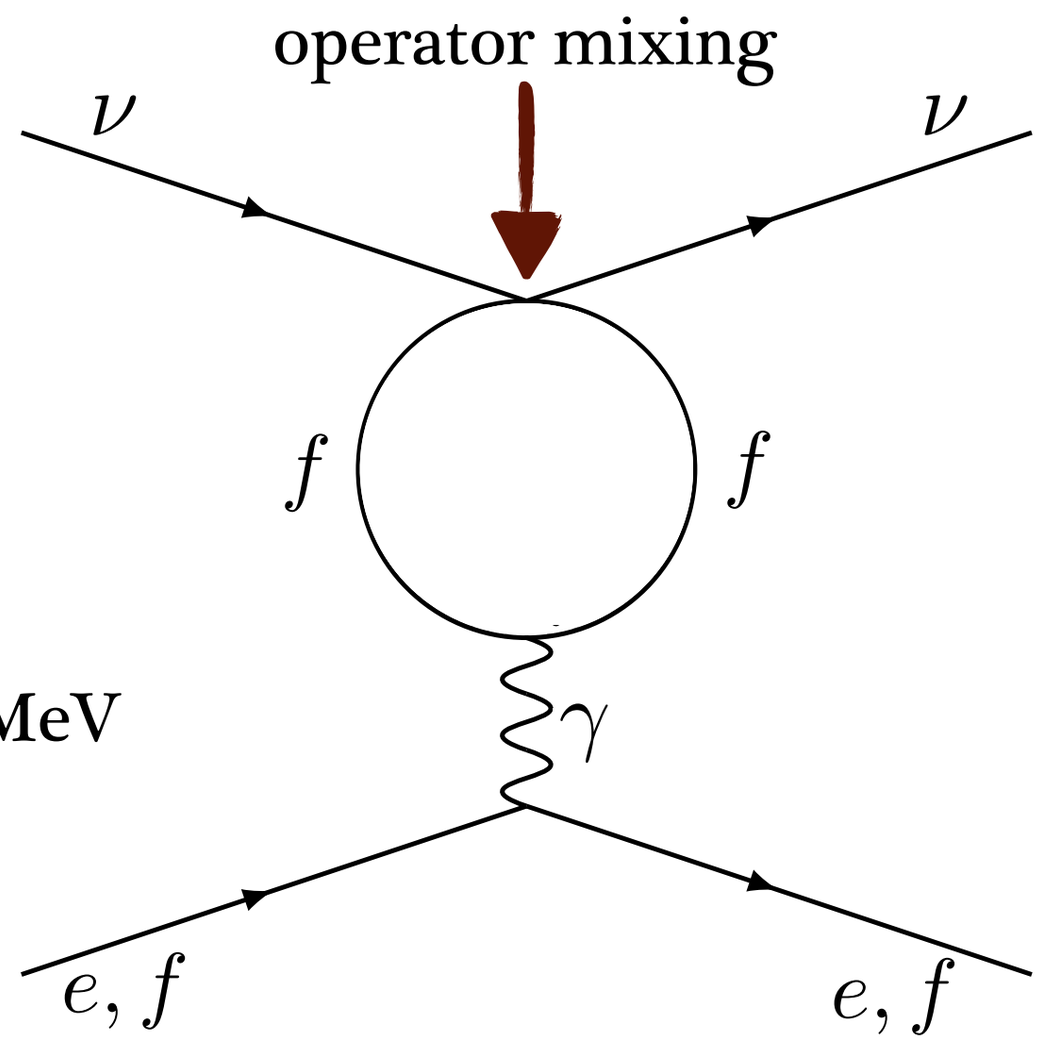
m_b

m_τ - integrate out GeV particles

m_c

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

m_π - theory with leptons: one unknown coupling



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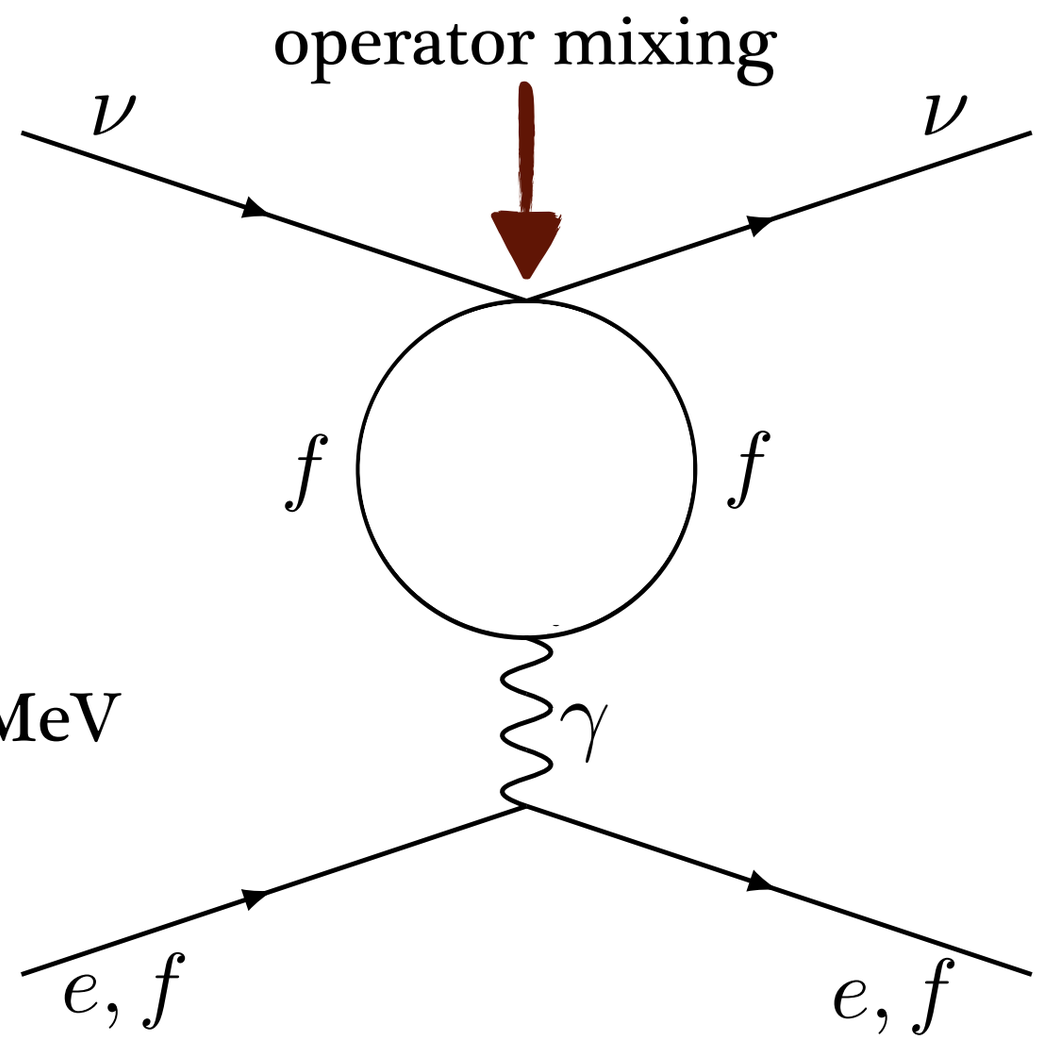

- known from electroweak to hadronic scales
- after diagonalization, only 1 effective coupling changes with scale

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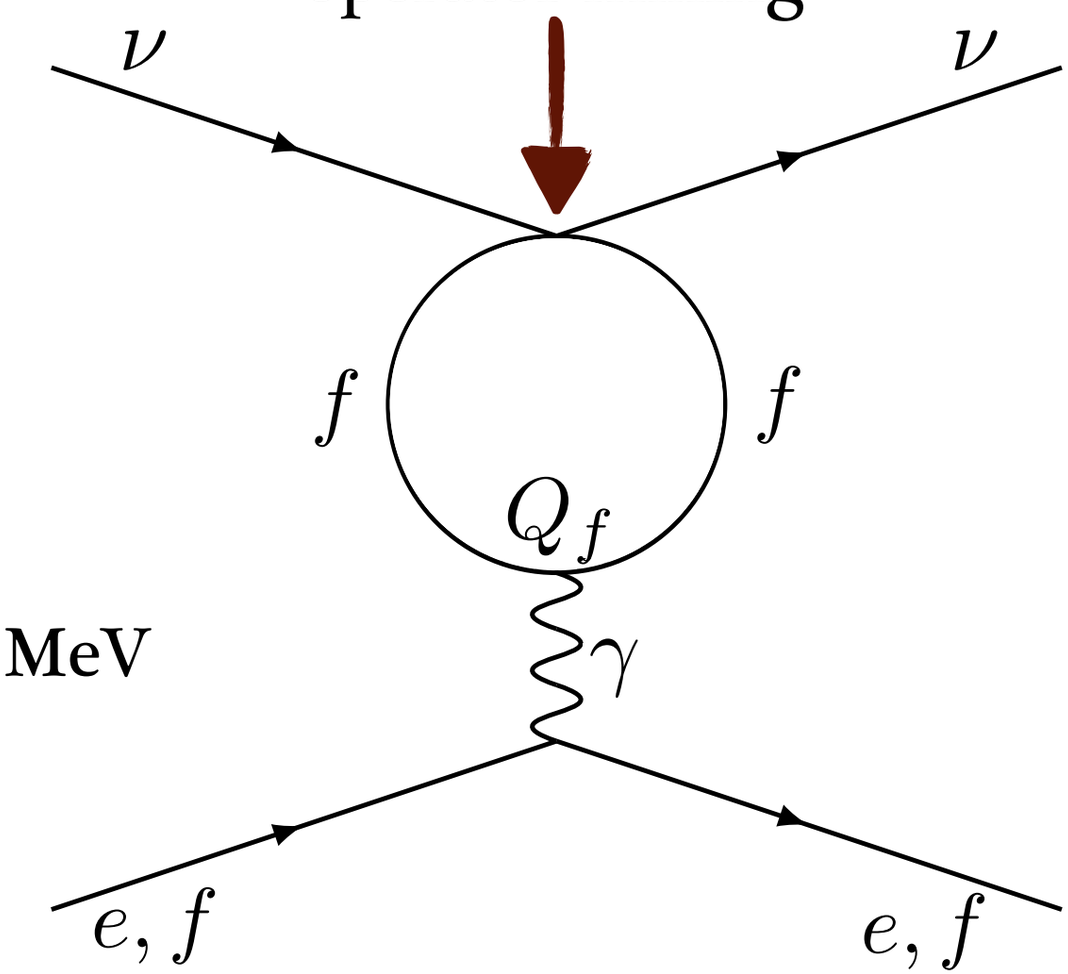
m_π

- theory with leptons: one unknown coupling

$$c_L^{\nu_e e} : \quad 2.387 \to 2.397$$
$$c_L^{\nu_\mu e} : -0.912 \to -0.902$$
$$c_R \quad : \quad 0.758 \to 0.768$$

operator mixing



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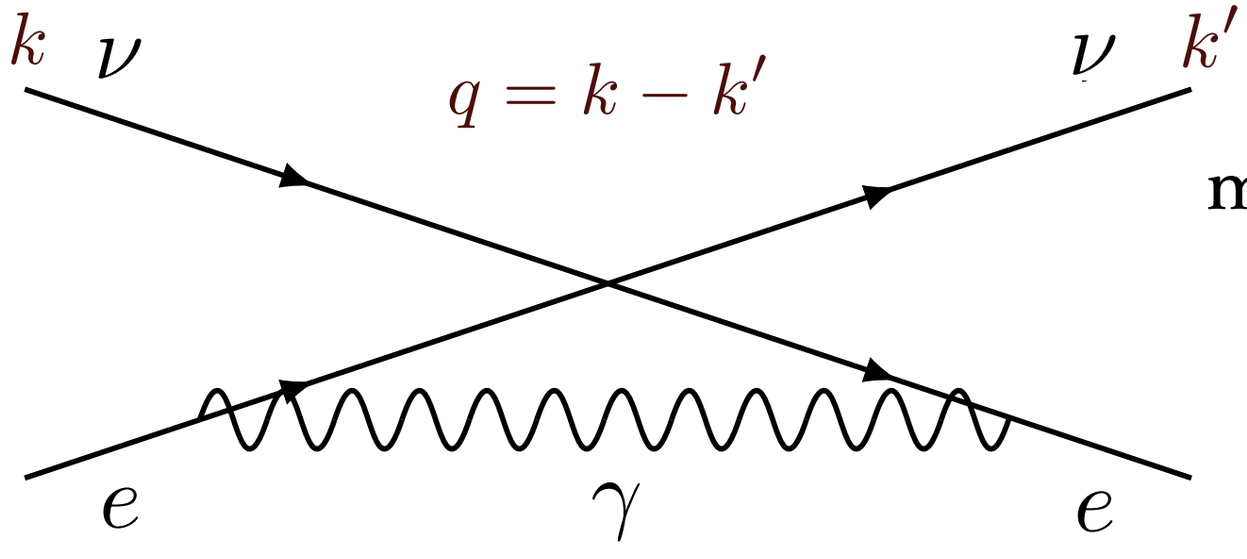
Virtual QED corrections. Vertex



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:

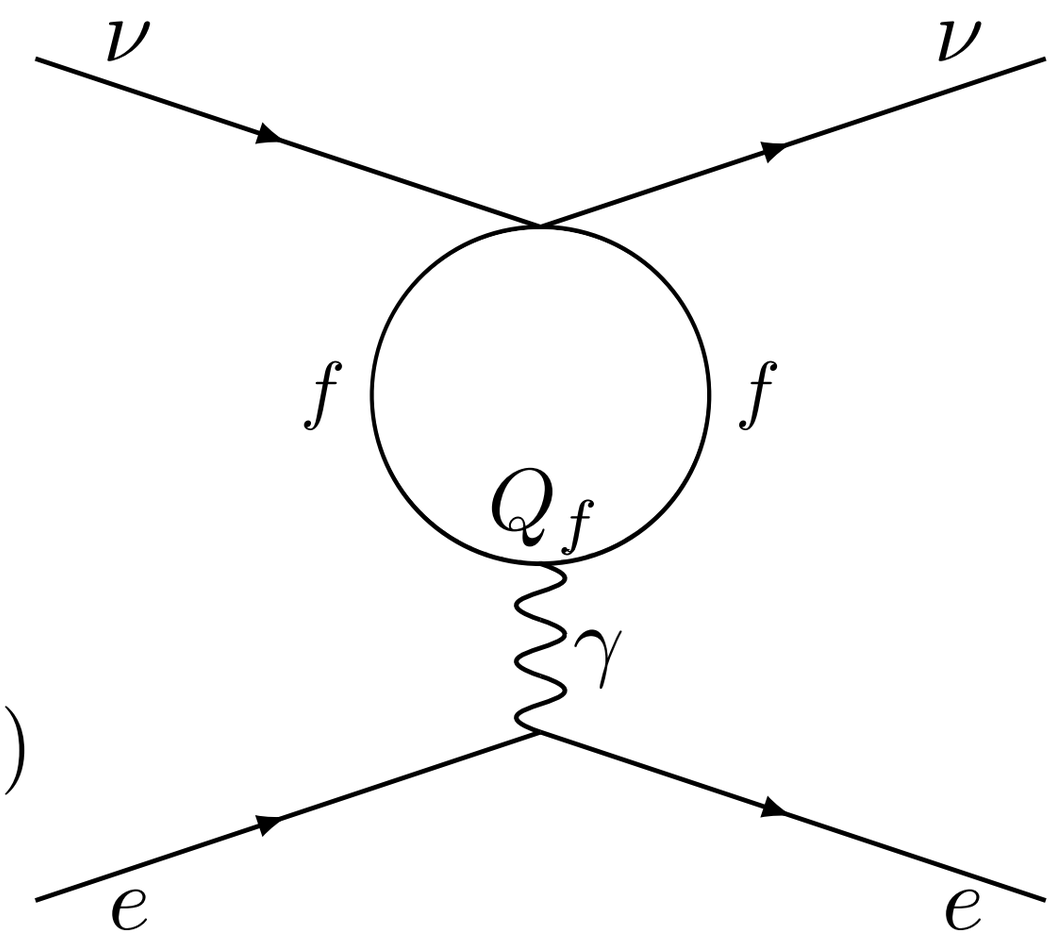
$$\mathcal{L}_{\text{eff}}^{f} = -\bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{f}\gamma^\mu (c_{\mathrm{L}}^{f}\mathrm{P_L} + c_{\mathrm{R}}^{f}\mathrm{P_R}) f$$

- adds vector contribution:

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

- fermion-dependent correction:

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



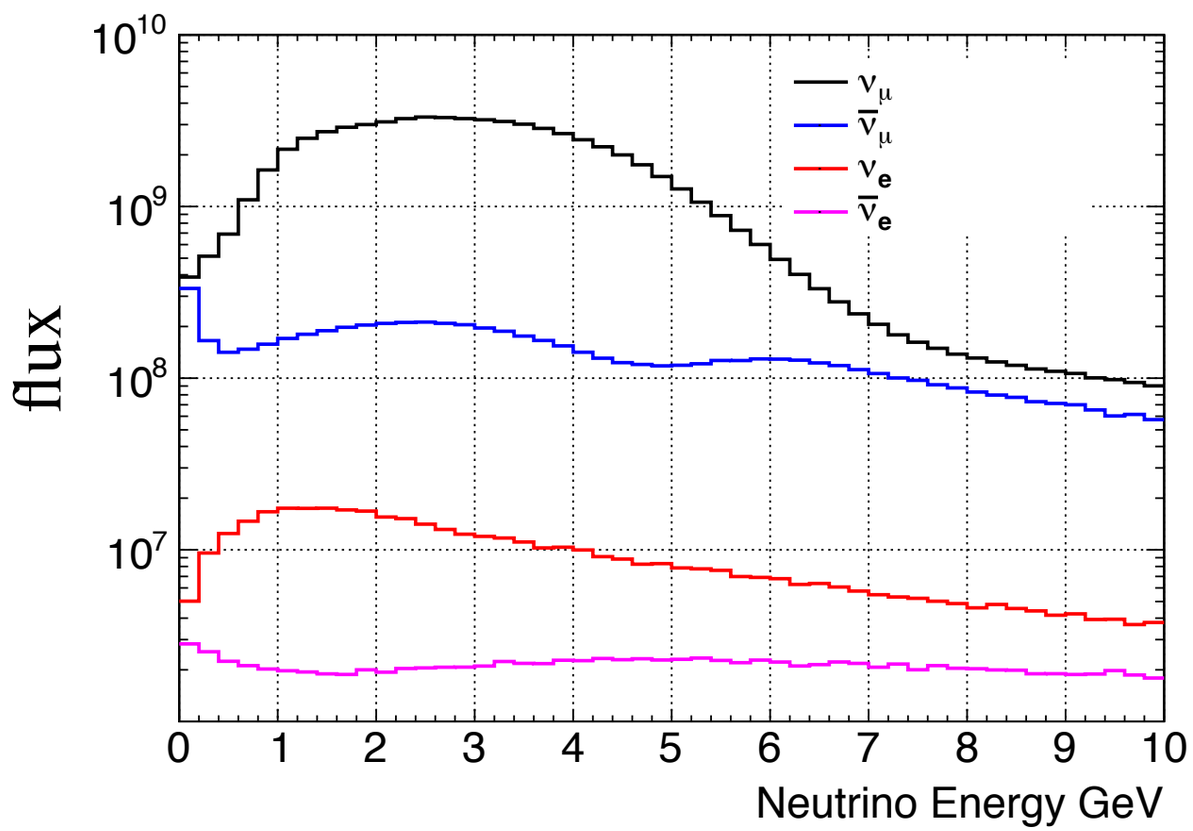
- given in terms of photon vacuum polarization
- sum over all particles with corresponding couplings

Main theoretical uncertainty

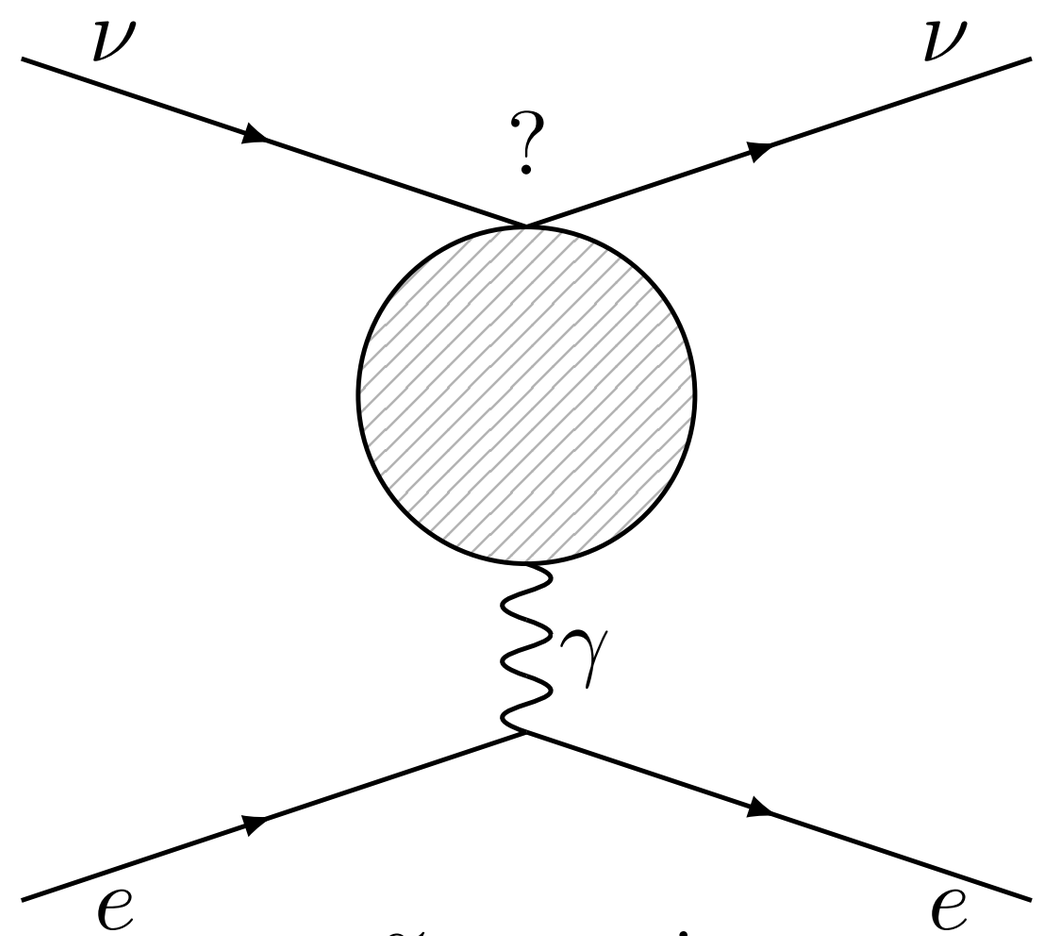
- momentum transfer is suppressed by electron mass:

$$Q^2 < 2m\omega \lesssim 0.007 \text{ GeV}^2$$

- description in terms of quarks is questionable:



DUNE, CDR (2015)



$\lesssim$ 3 % correction

- hadronic correction is unknown: estimate in model with quarks

Uncertainty-free measurements

- virtual-loop scale is well below muon mass:

$$Q^2 < 2m\omega \lesssim 0.007\ \mathrm{GeV}^2$$

effective field theory description:

- only electrons in theory
- one independent low-energy coupling c_R

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what can we do?

statistical significance

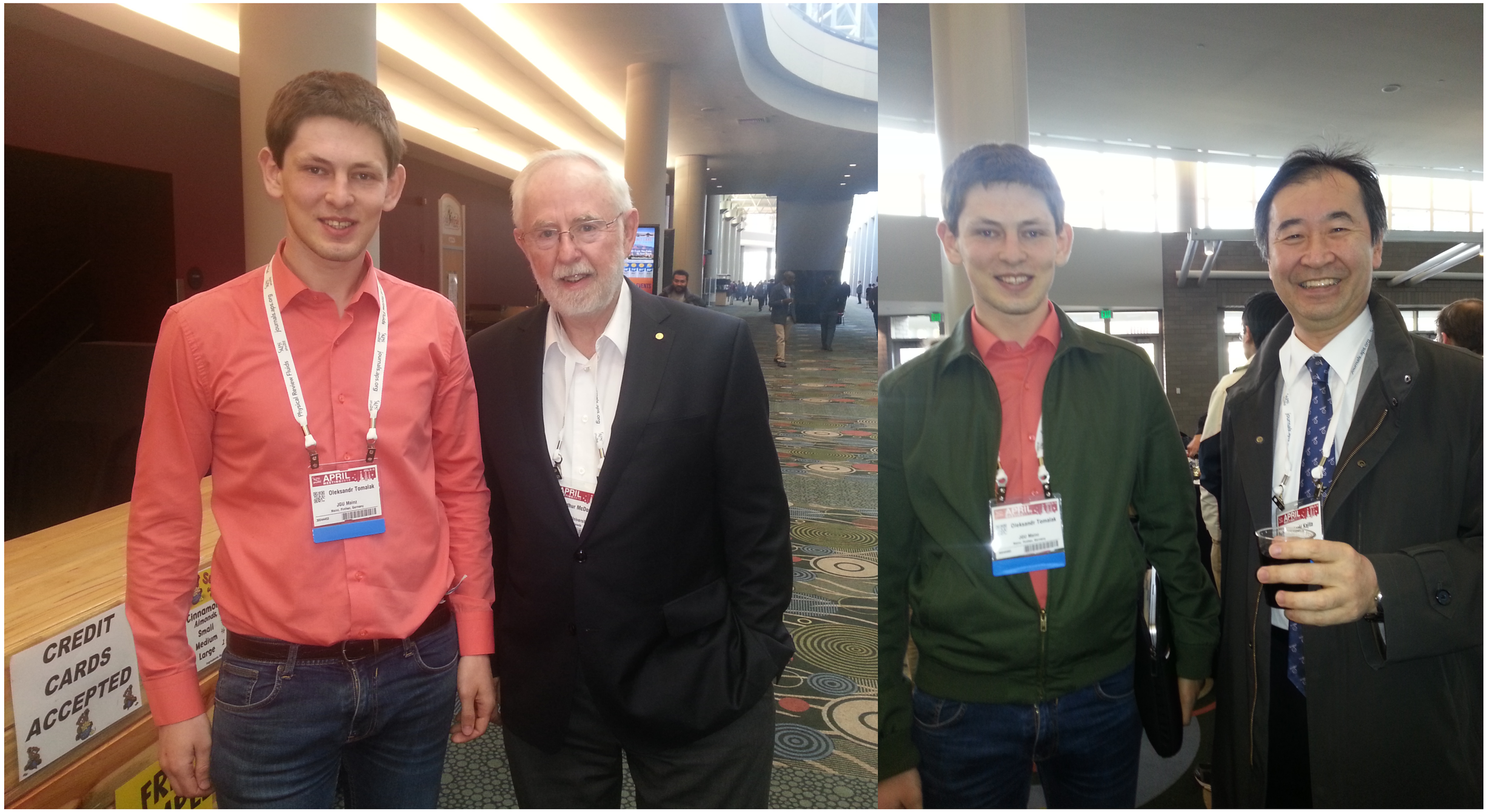
complementary measurement

fix unknown coupling c_R from various distributions

measure spin asymmetry on polarised electron target

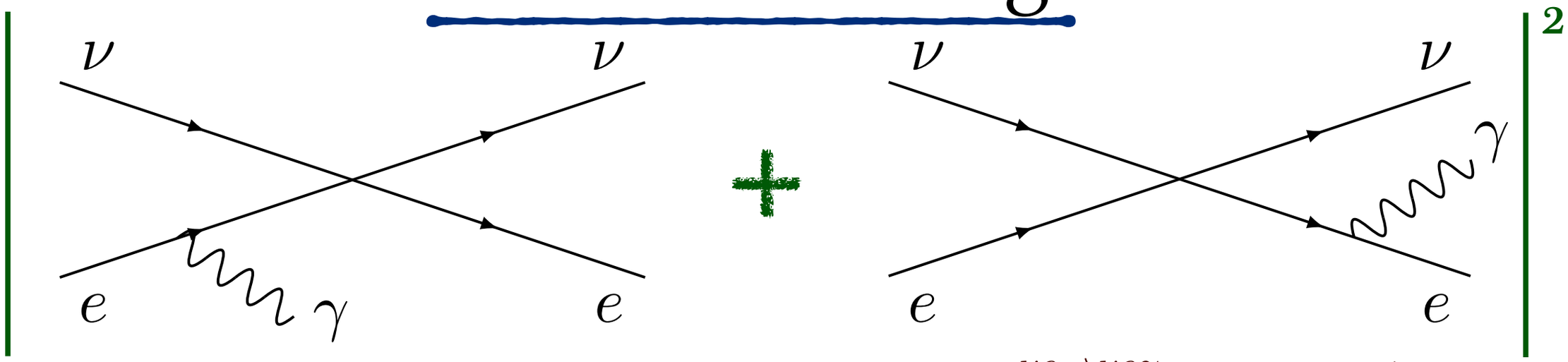
- only one coupling has to be fixed

Low-energy frontier



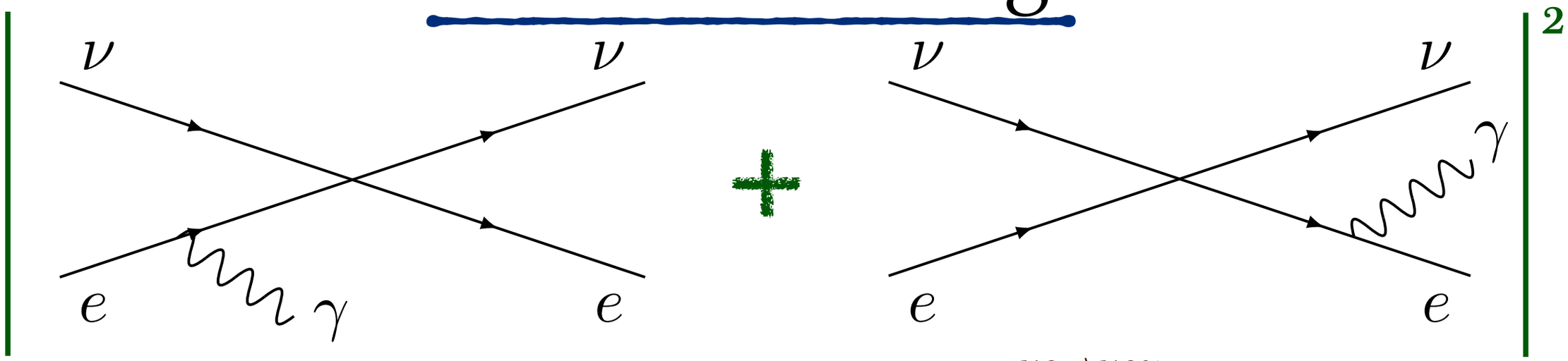
- application to solar neutrinos and reactor antineutrinos

Bremsstrahlung



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

Bremsstrahlung



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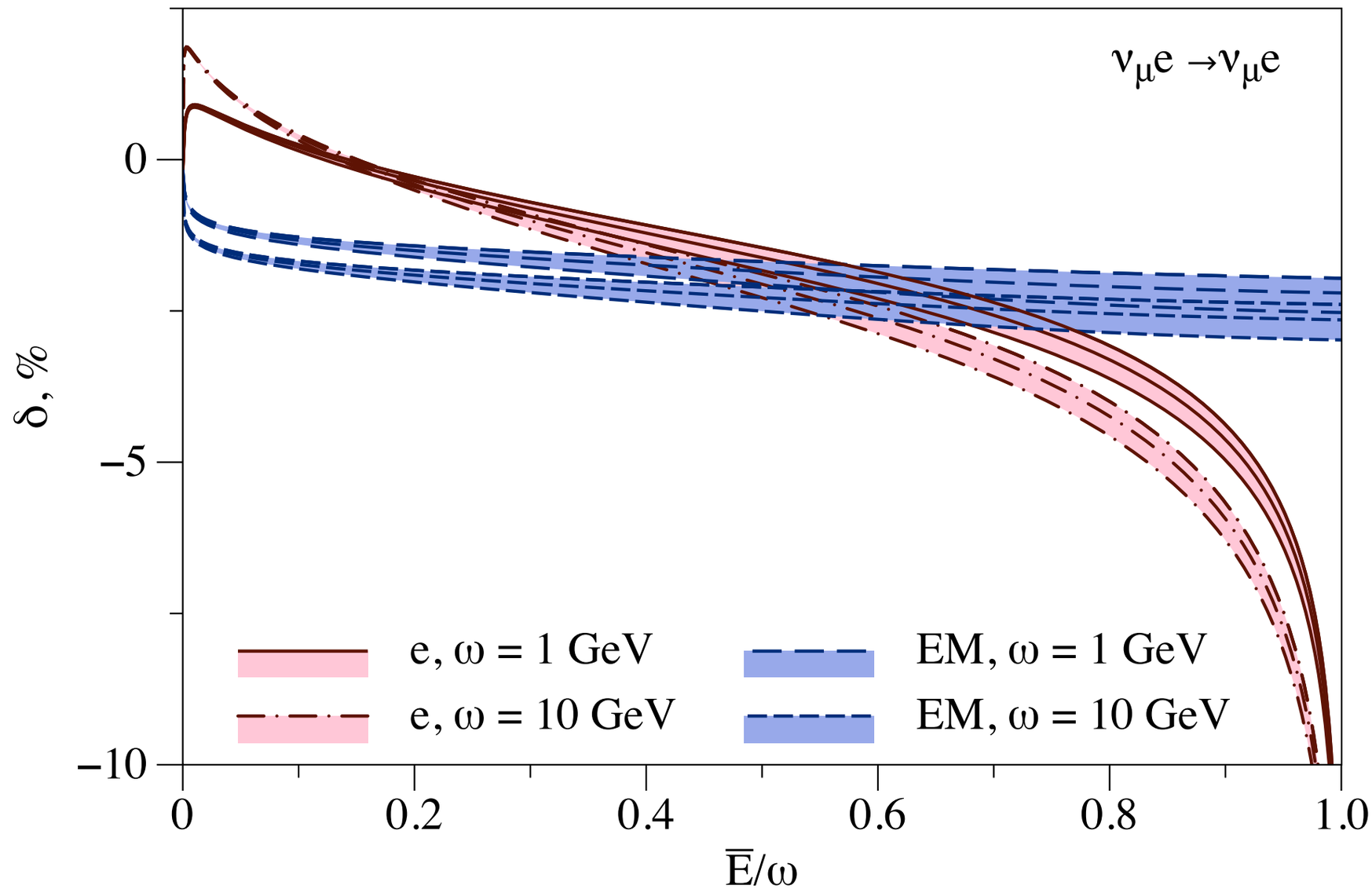
- soft-photon correction Lee and Sirlin (1964)
- integration technique Ram (1967)
- EW correction Aoiki, Hioki, Kawabe, Konuma and Muta (1980)
- electron energy spectrum and numerically total Aoiki and Hioki (1981)
- electron energy spectrum and EW, small m Sarantakos, Sirlin and Marciano (1982)
- electromagnetic energy spectrum and total Bardin and Dokuchaeva (1983-1985)
- numerically electron and electromagnetic spectra Passera (2000)

- exactly calculable radiation

Electron vs electromagnetic (EM) spectra

- relative correction depends on $\overline{\mathrm{MS}}$ scale μ: $m_c \leq \mu \leq m_b$

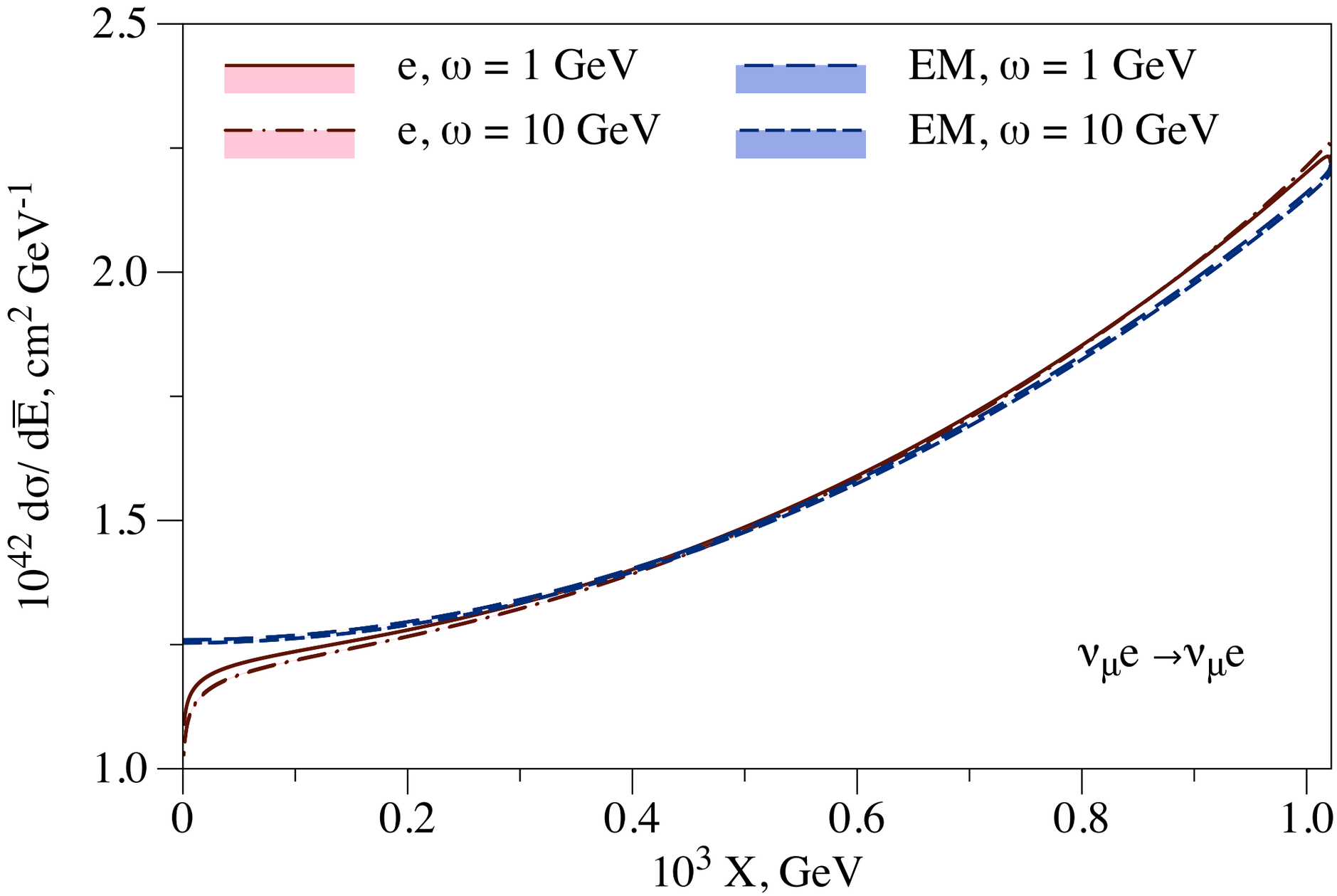
$$\delta = \frac{\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e \gamma} + \mathrm{d}\sigma_{\mathrm{NLO}}^{\nu e \to \nu e} - \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}}{\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}}$$



- dramatic difference in radiative corrections

Electron vs electromagnetic (EM) spectra

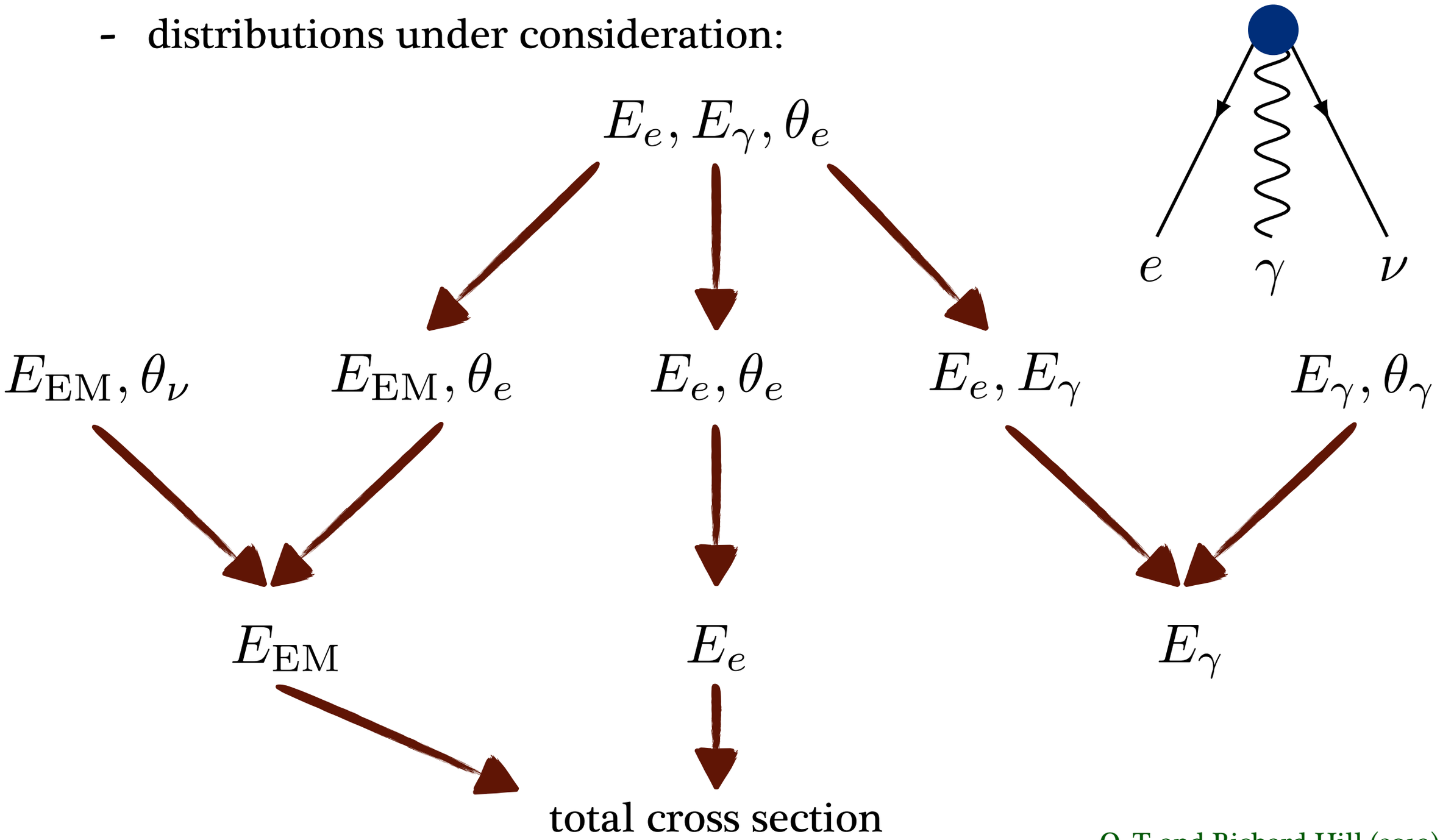
- resulting spectrum: $X = 2m\left(1 - \frac{\bar{E}}{\omega}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$



- dramatic difference in radiative corrections: cut dependence

Bremsstrahlung cross sections

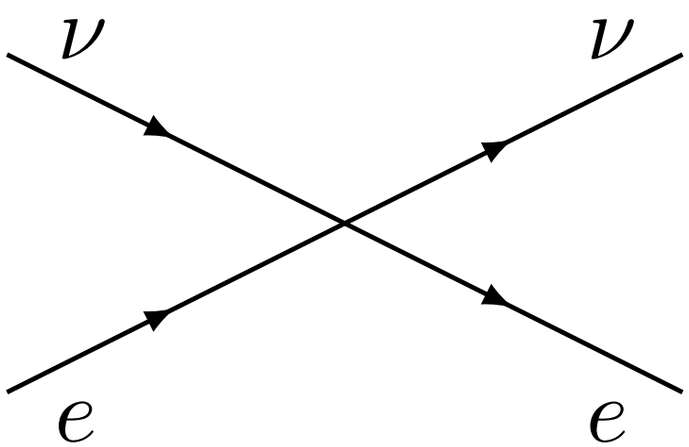
- distributions under consideration:



O. T. and Richard Hill (2019)

- analytical form for finite and small electron mass

Conclusions



best tool to constrain neutrino flux

- EFT of neutrino-electron and neutrino-quark scattering ($\mu \gtrsim m_c$):

  left- and right-handed couplings at subpermille level

- energy spectra and bremsstrahlung cross sections:

  new and known results in analytical form

- main source of uncertainty and how to avoid it:

  loops with hadrons at low energy and momentum transfer

- all results will be available to experimental collaborations soon

Thanks for your attention !!!

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	$\bar{\nu}_\mu p \to \mu^+ p \pi^-$	$\bar{\nu}_\mu p \to \mu^+ n$

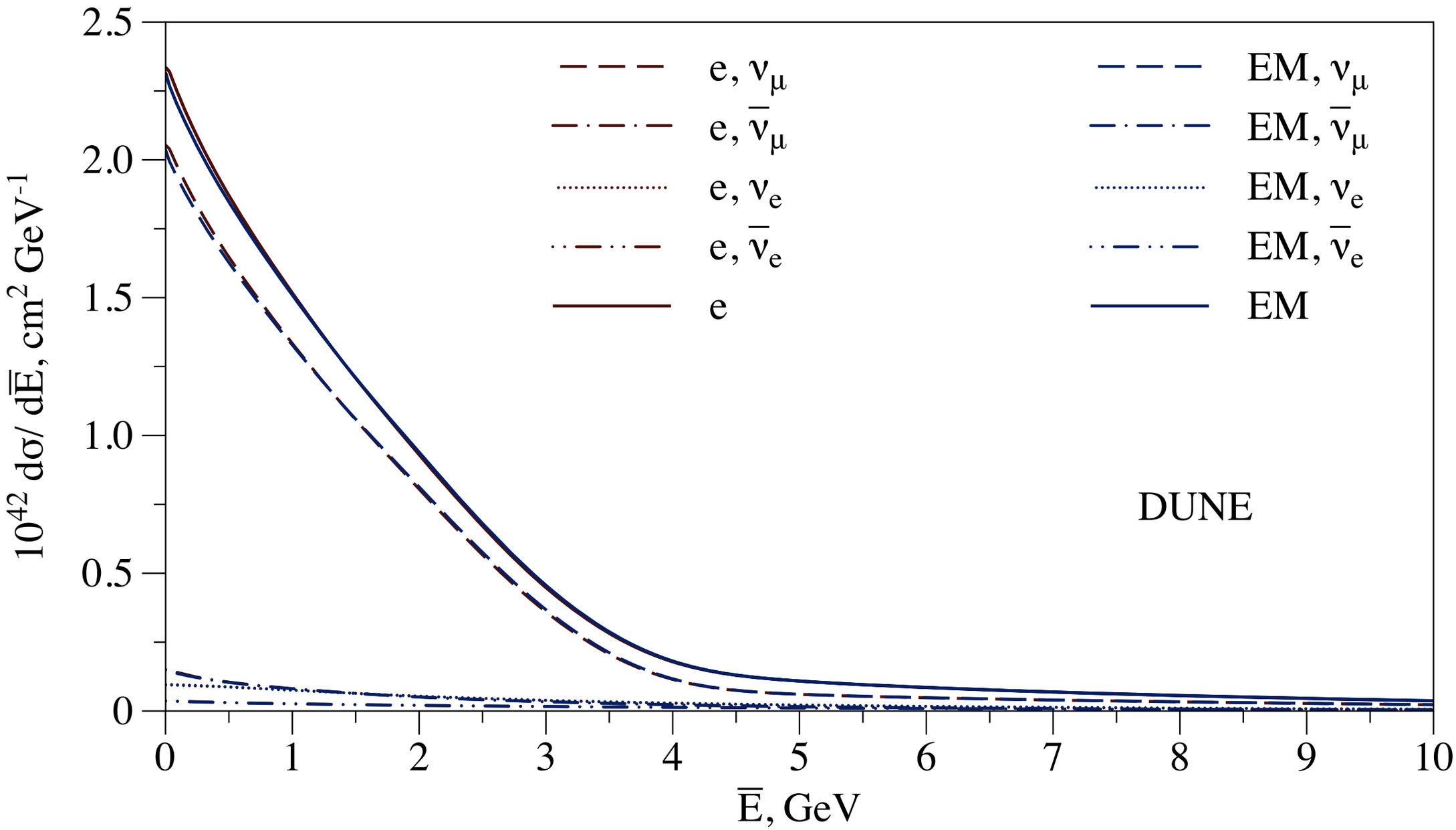
according to H. Duyang et al., arXiv: 1902.09480v2 (2019)

- neutrino-electron scattering plays a role of additional constraint

- νe is required for absolute normalization of ν_μ component

Experimental energy spectrum

- average over beam flux and sum over flavors:



- 1-3 % difference at low recoil energy