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# Elastic neutrino-electron scattering within the effective field theory

University of Kentucky

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# 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% 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:

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

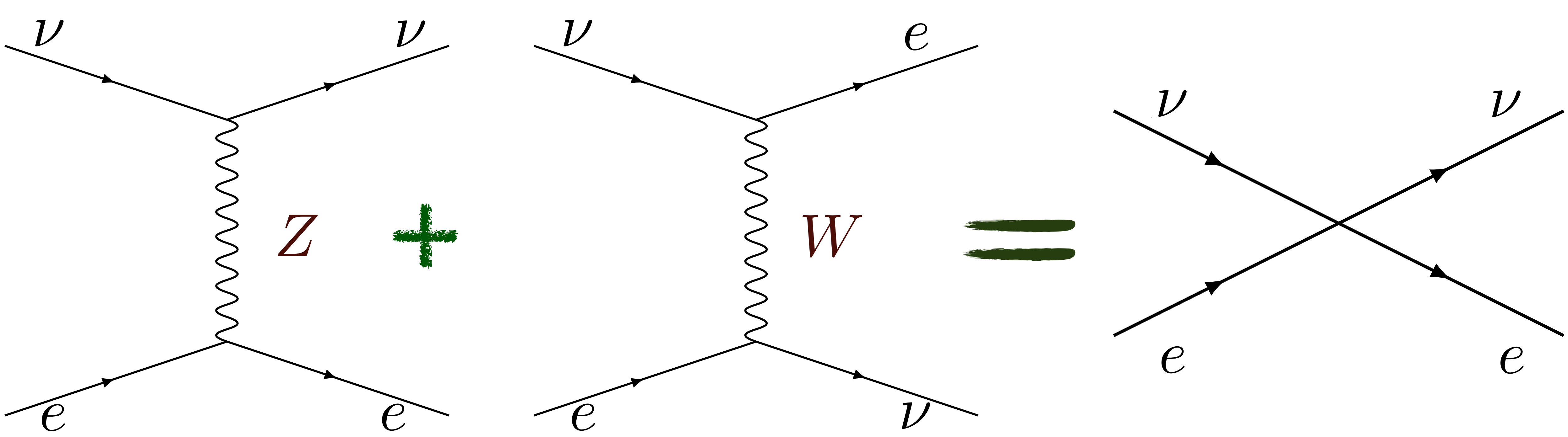
$$c_{\rm R} = 2\sqrt{2}\mathrm{G_F}\sin^2\theta_W \quad c_{\rm L} = 2\sqrt{2}\mathrm{G_F}\left(\sin^2\theta_W - 0.5 + \delta_{\nu,\nu_e}\right)$$

Weinberg (1967), 't Hooft (1971)

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

neutral current

charged current



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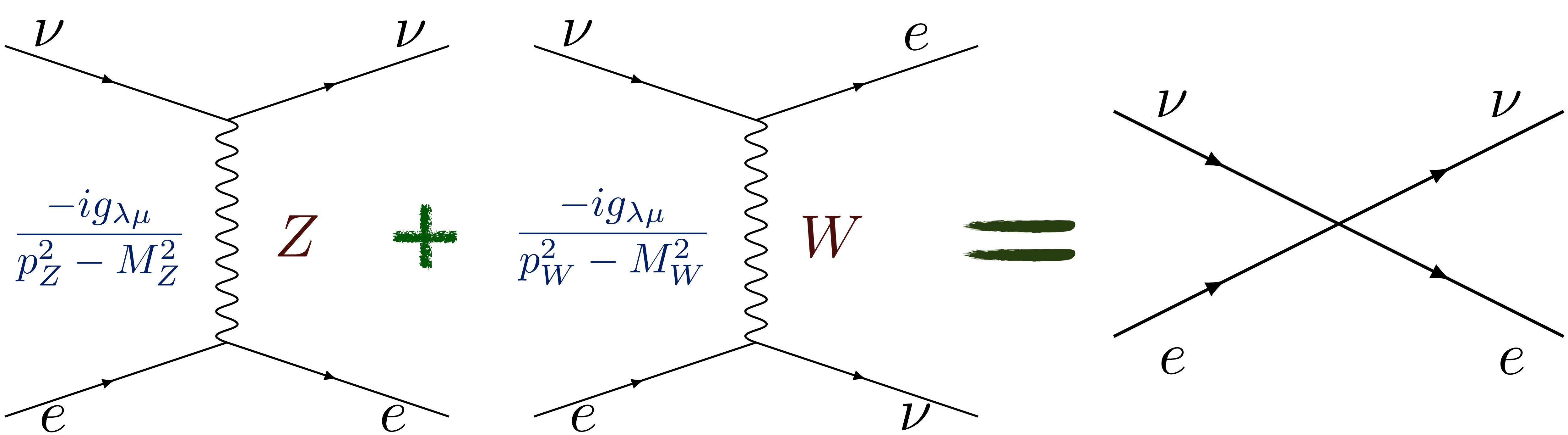

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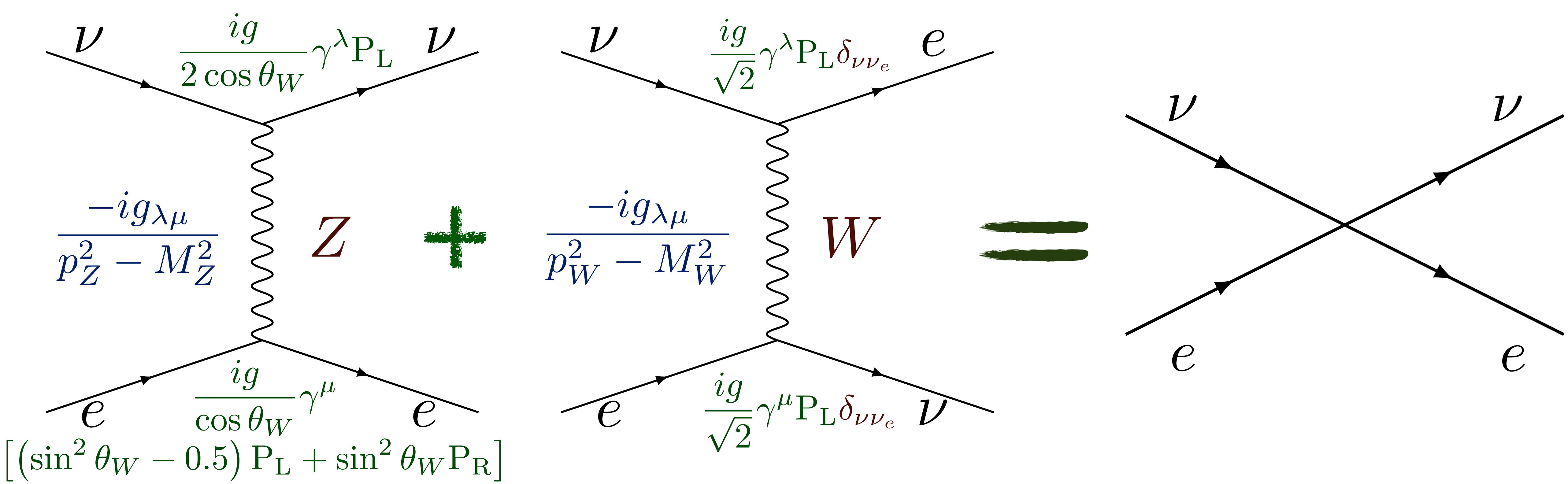

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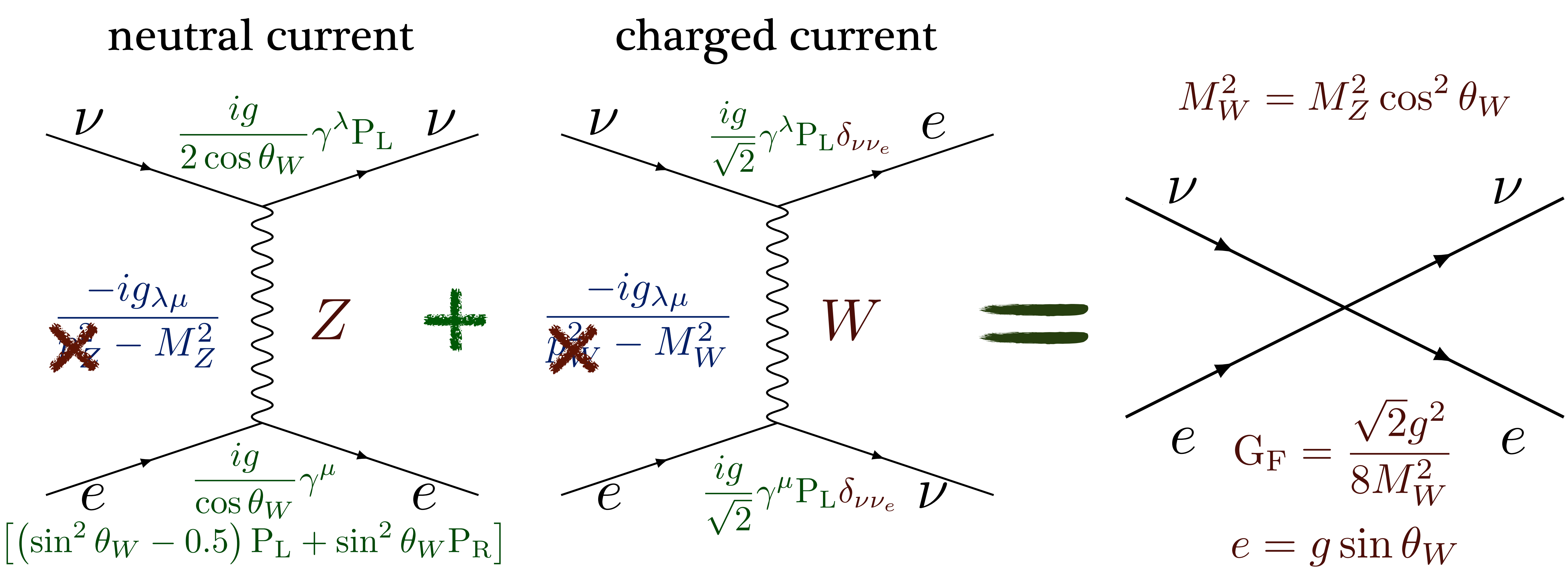


- integrate out W and Z at tree level

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Weinberg (1967), 't Hooft (1971)

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

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

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

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

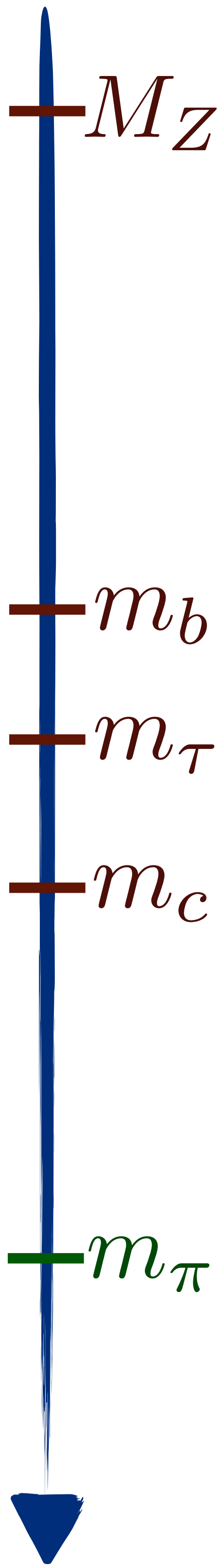
- exploit $\mathrm{G_F}$ for one combination of electroweak parameters

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

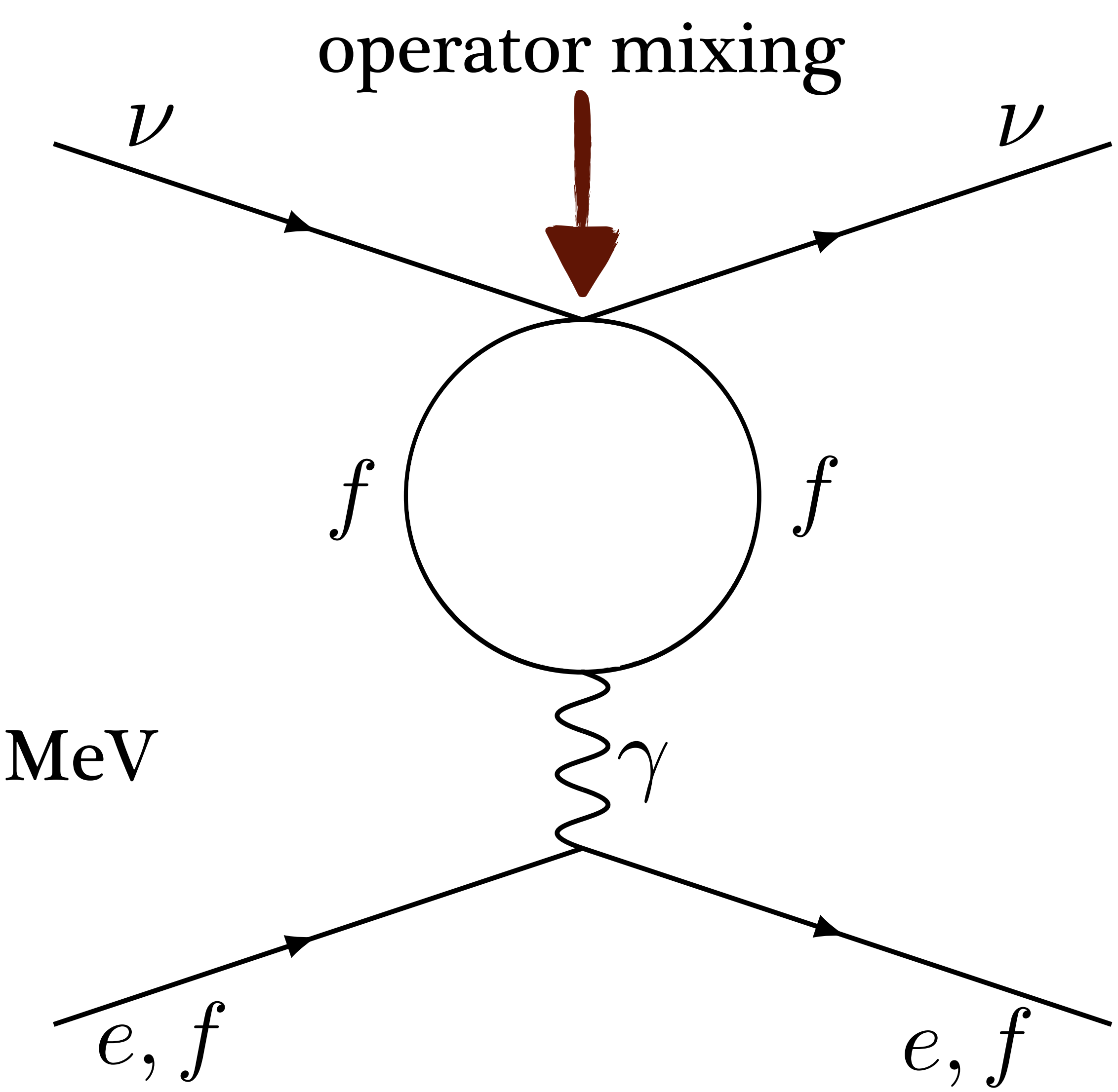
MULAN (2012)

- 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 $\alpha$, $\alpha_s$
- only one EFT coupling changes with scale
- integrate out GeV particles
- $\alpha_s$ becomes too strong
- hadronic physics down to 140 MeV
- theory with leptons



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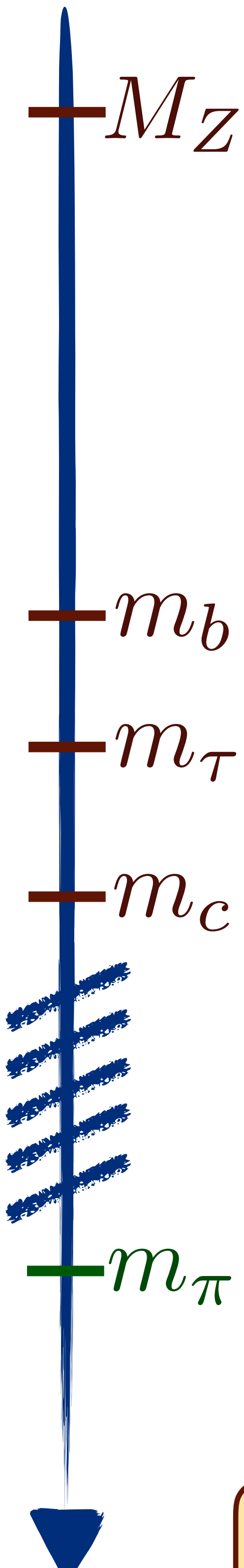


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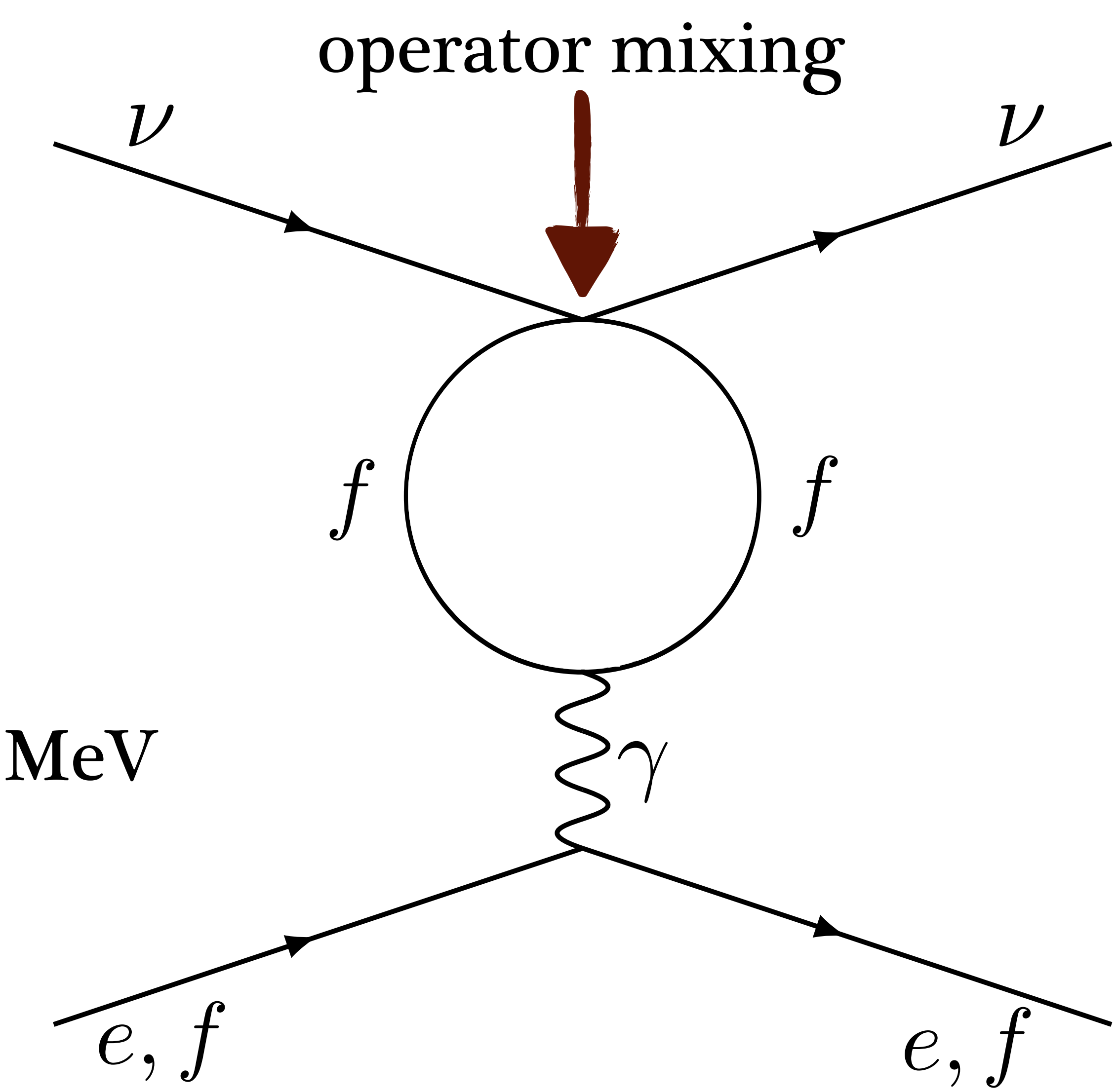


- precisely known from electroweak to hadronic scales
- only 1 effective coupling changes with scale

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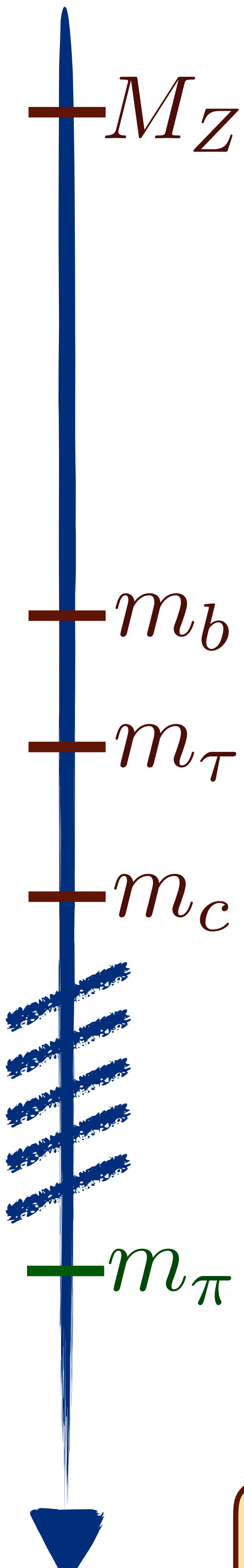


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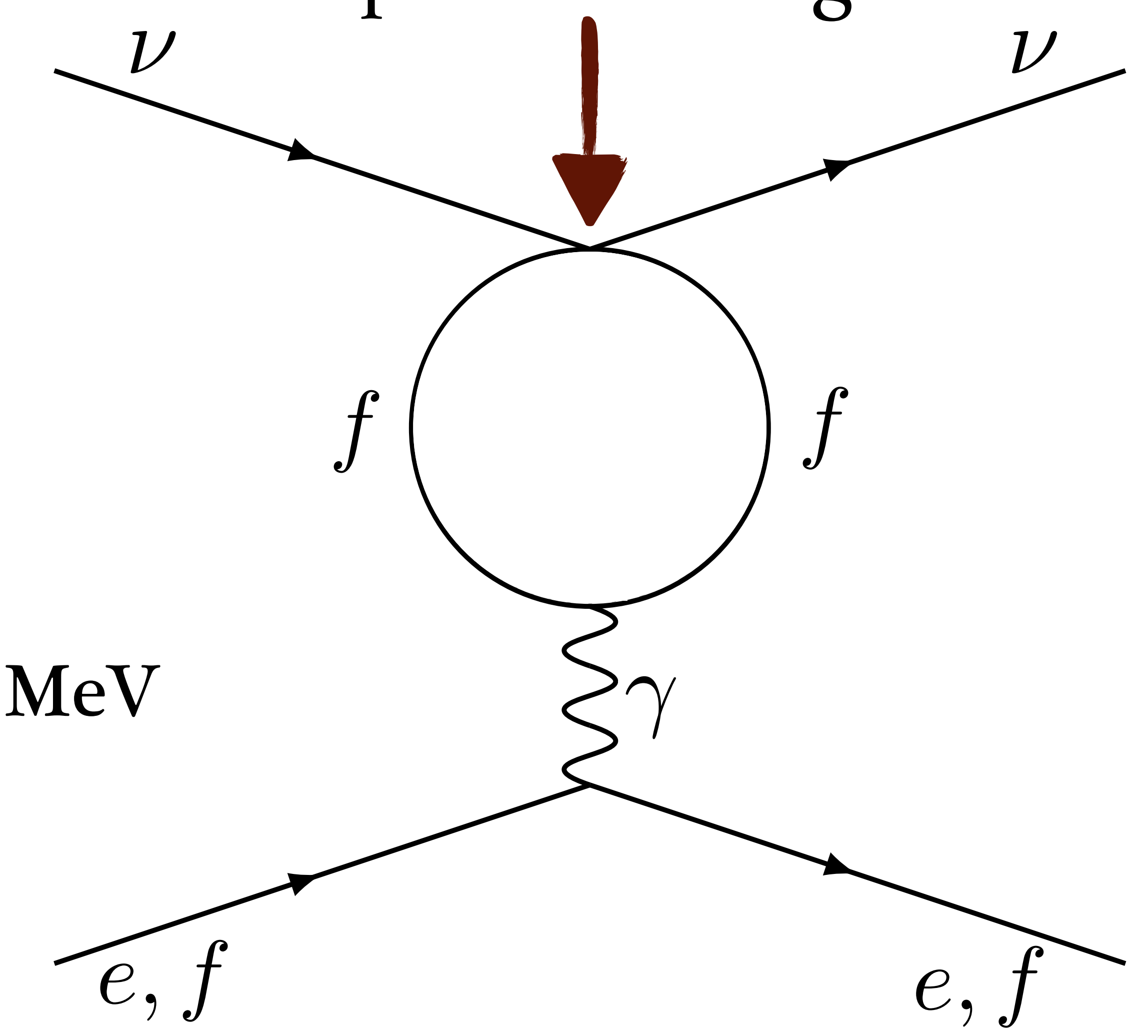
$c_L^{\nu_e e}$ : $2.388 \to 2.398$

$c_L^{\nu_\mu e}$ : $-0.911 \to -0.901$ % effect

$c_R$ : $0.759 \to 0.769$

operator mixing

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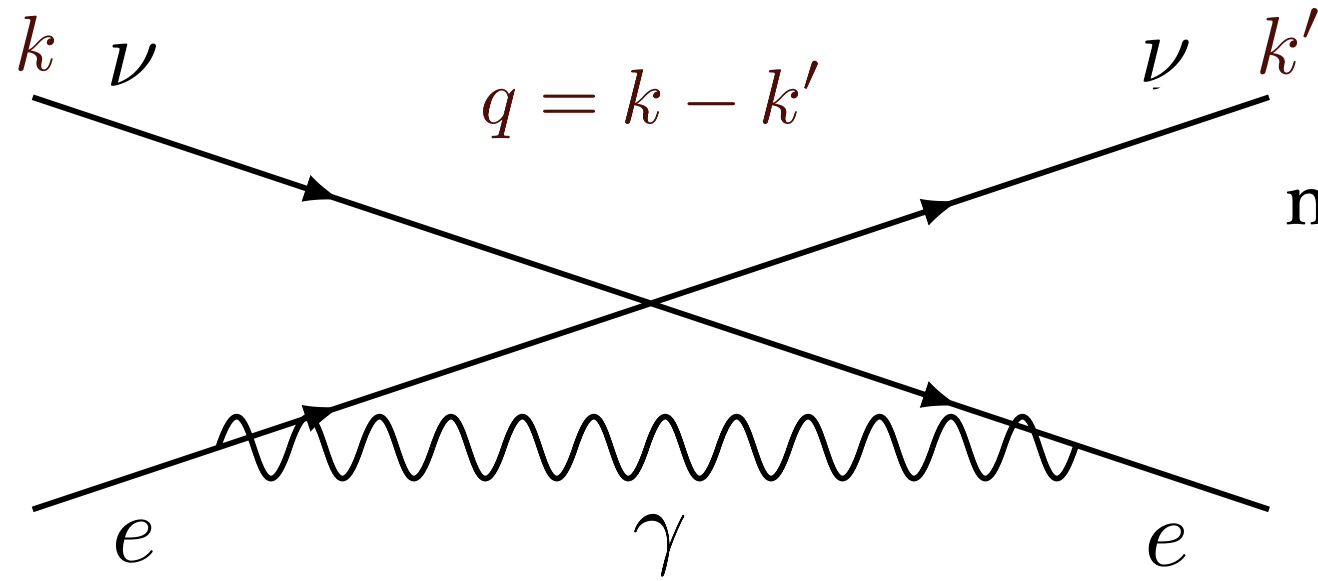
# Virtual QED corrections. Vertex

neutrino energy $\omega$




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:

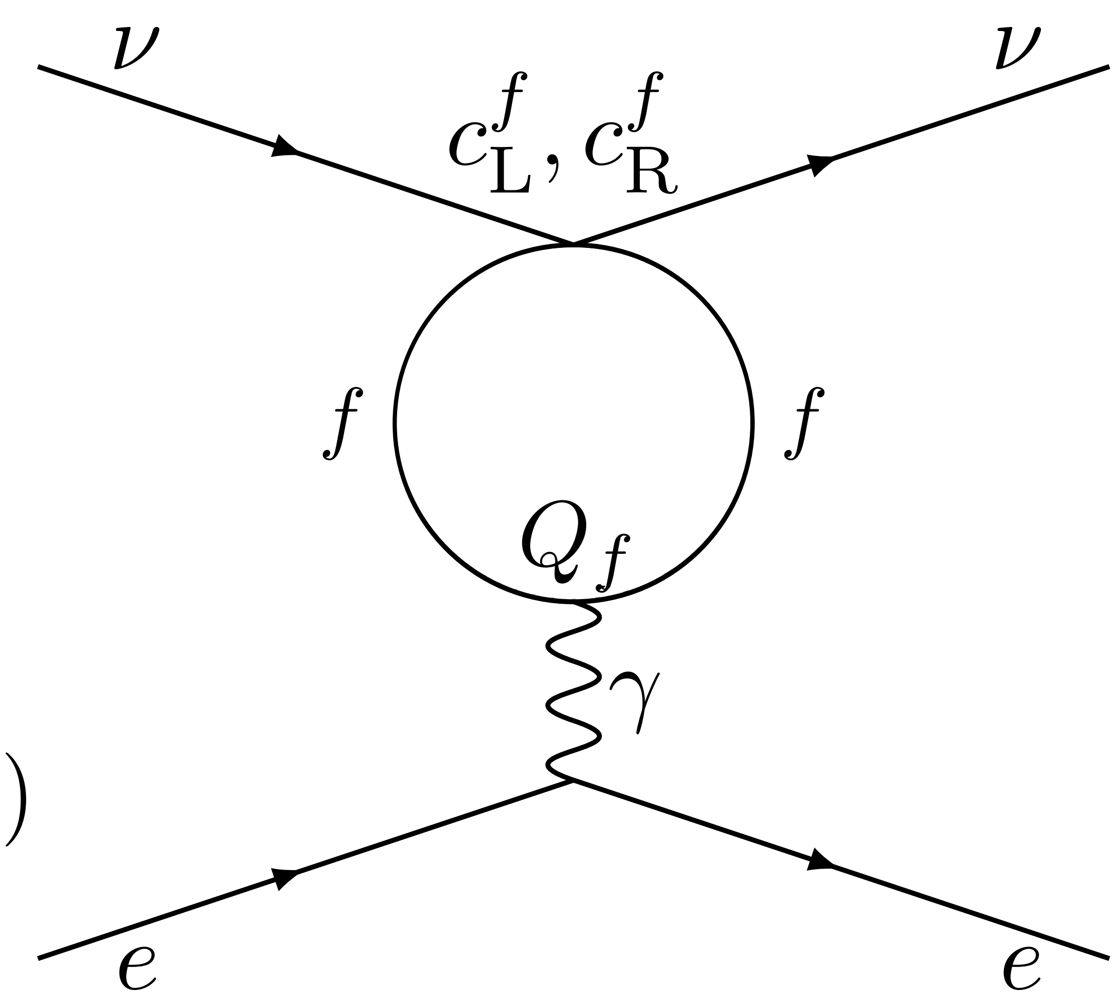
$$\mathcal{L}_{\text{eff}}^{f} = -\bar{\nu}\gamma_{\mu}\mathrm{P_L}\nu \cdot \bar{f}\gamma^{\mu}(c_{\mathrm{L}}^{f}\mathrm{P_L} + c_{\mathrm{R}}^{f}\mathrm{P_R})f$$

- adds vector contribution:

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

- fermion-dependent correction:

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



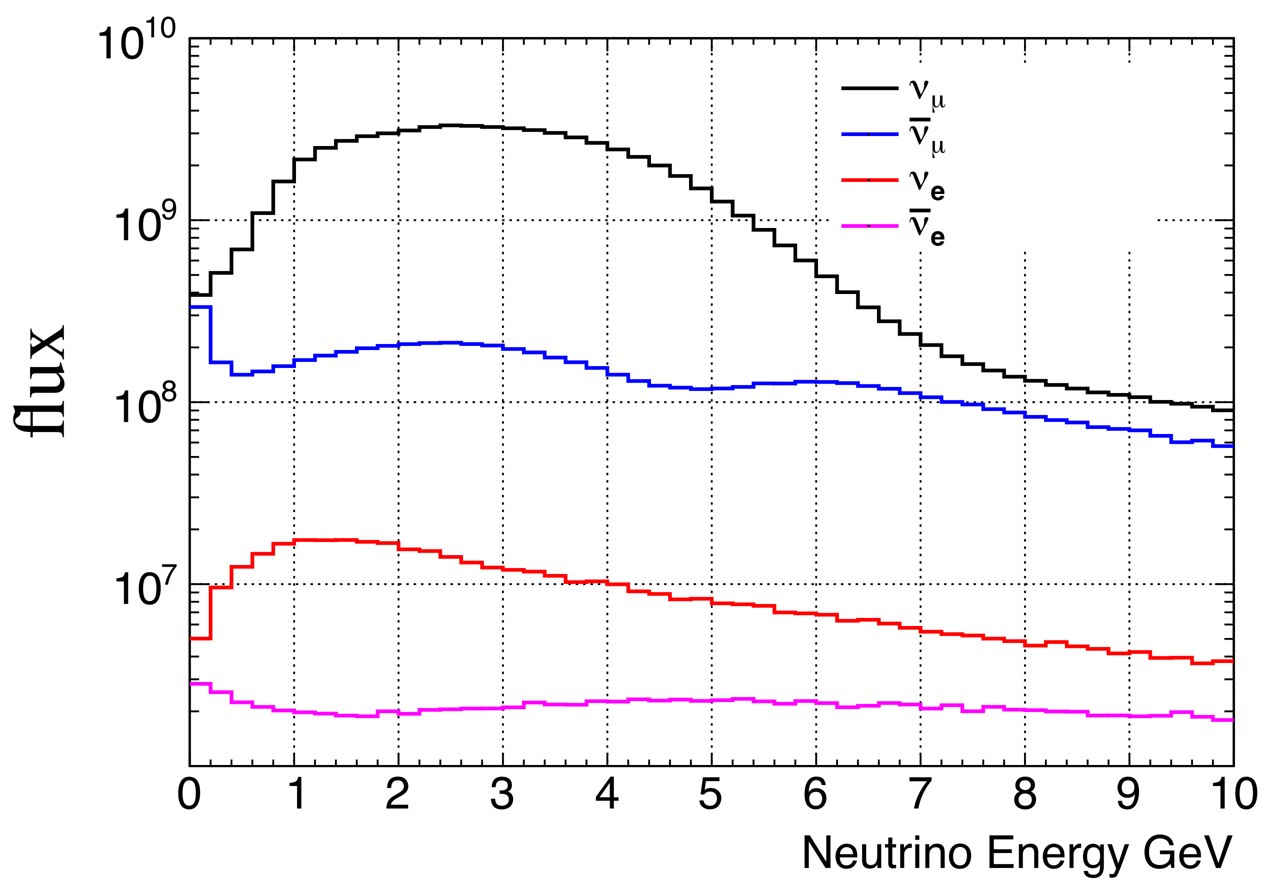

- given in terms of photon vacuum polarization
- sum over all particles with corresponding couplings

# Main theoretical uncertainty

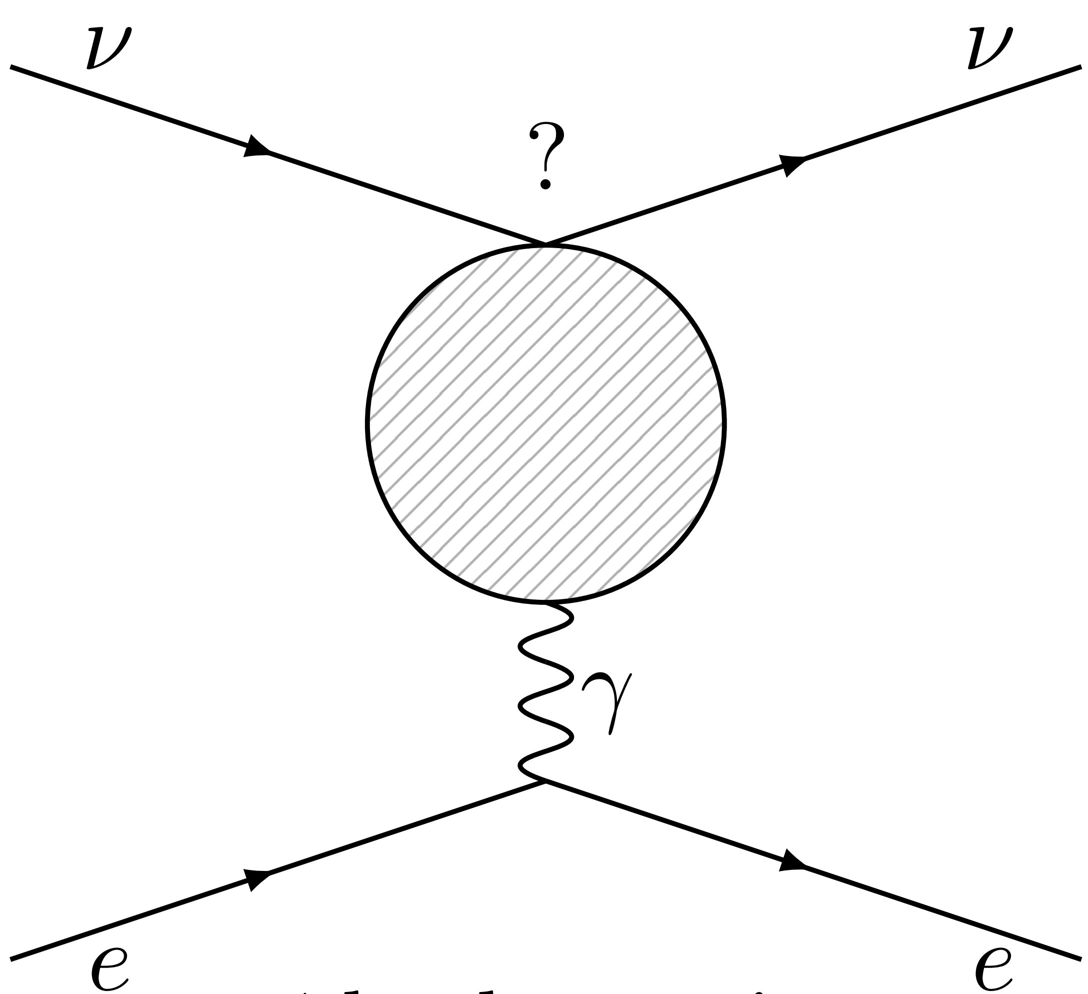
- momentum transfer is suppressed by electron mass:

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

- 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:

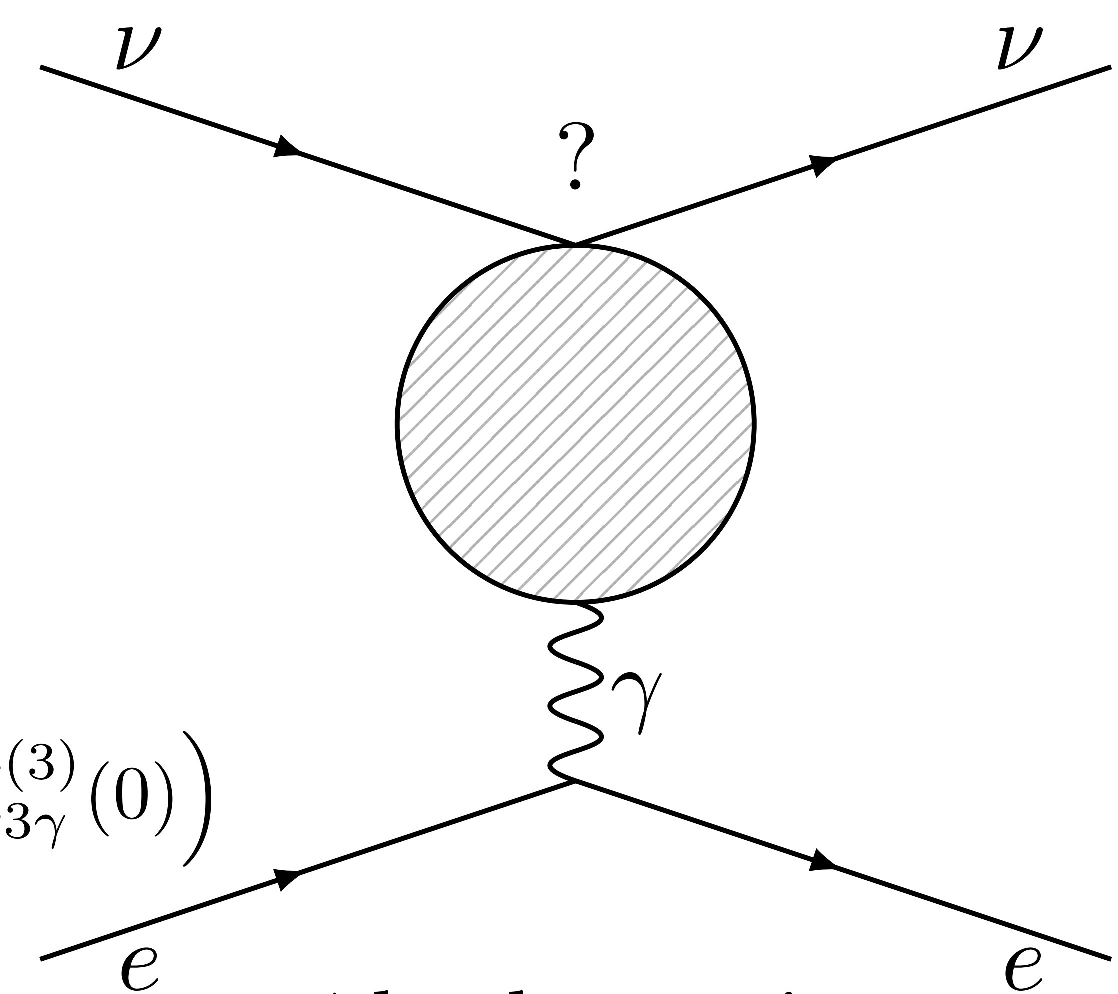
$$Q^2 < 2m\omega \lesssim 0.007\ \mathrm{GeV}^2$$

- 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

- EFT with leptons only

# Light-quark contribution

- vector-vector correlation functions:

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

- SU(3)f symmetry:

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

- SU(2)f symmetry:

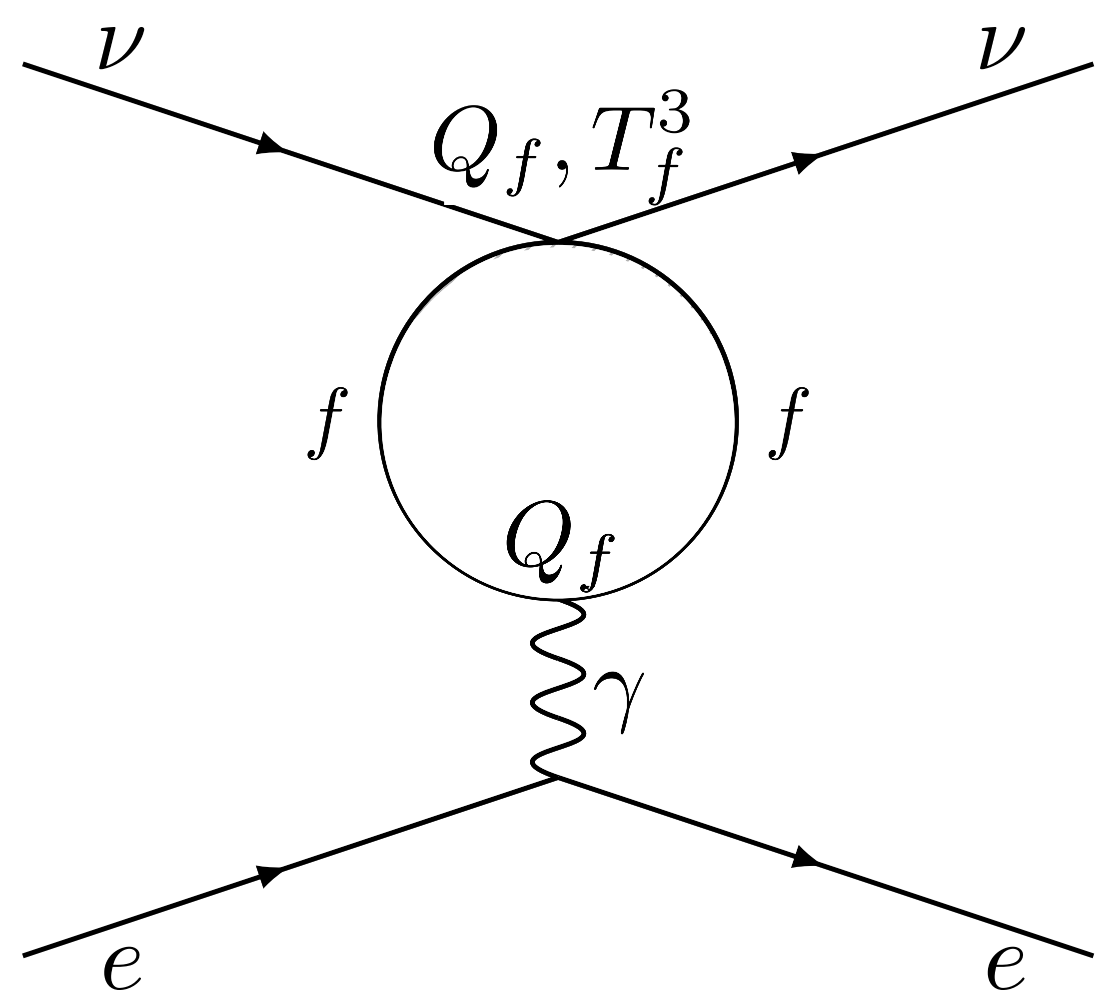
$$\hat{\Pi}^{(3)}_{3\gamma} = \frac{9}{10}\hat{\Pi}^{(3)}_{\gamma\gamma}$$

- our choice:

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

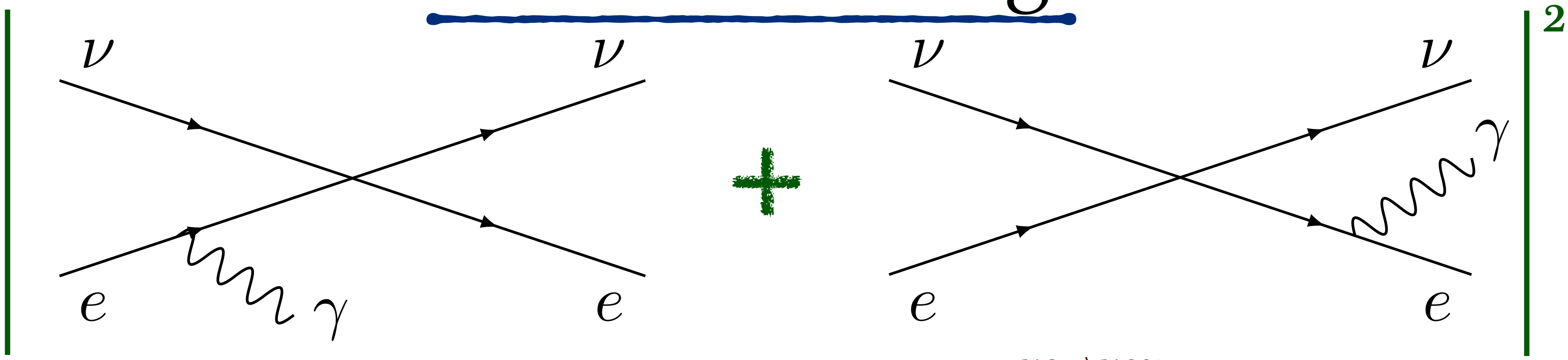
- with $\hat{\Pi}^{(3)}_{\gamma\gamma}\,(0)$ from

Erler et al (2018)



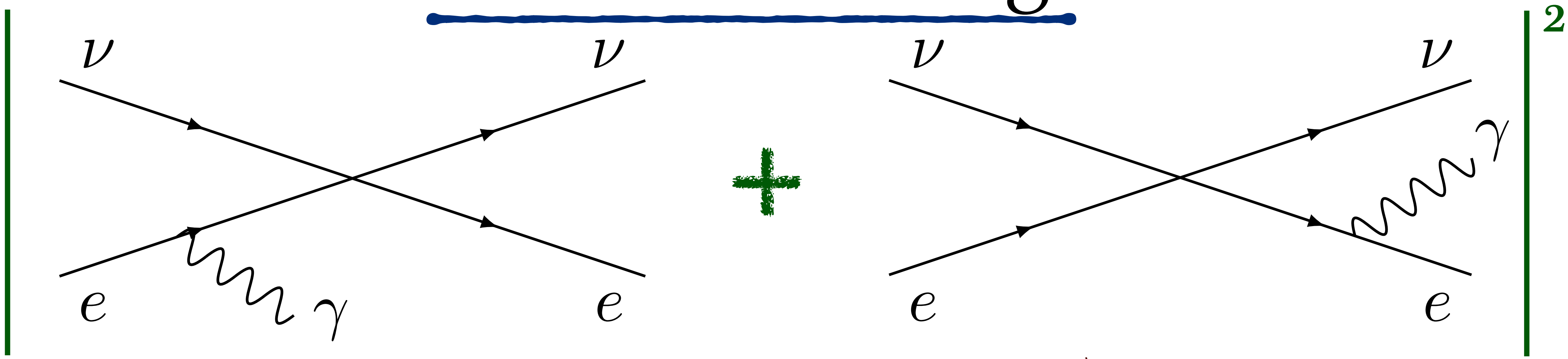

- non-perturbative light-quark contribution
- EFT with leptons only

# 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

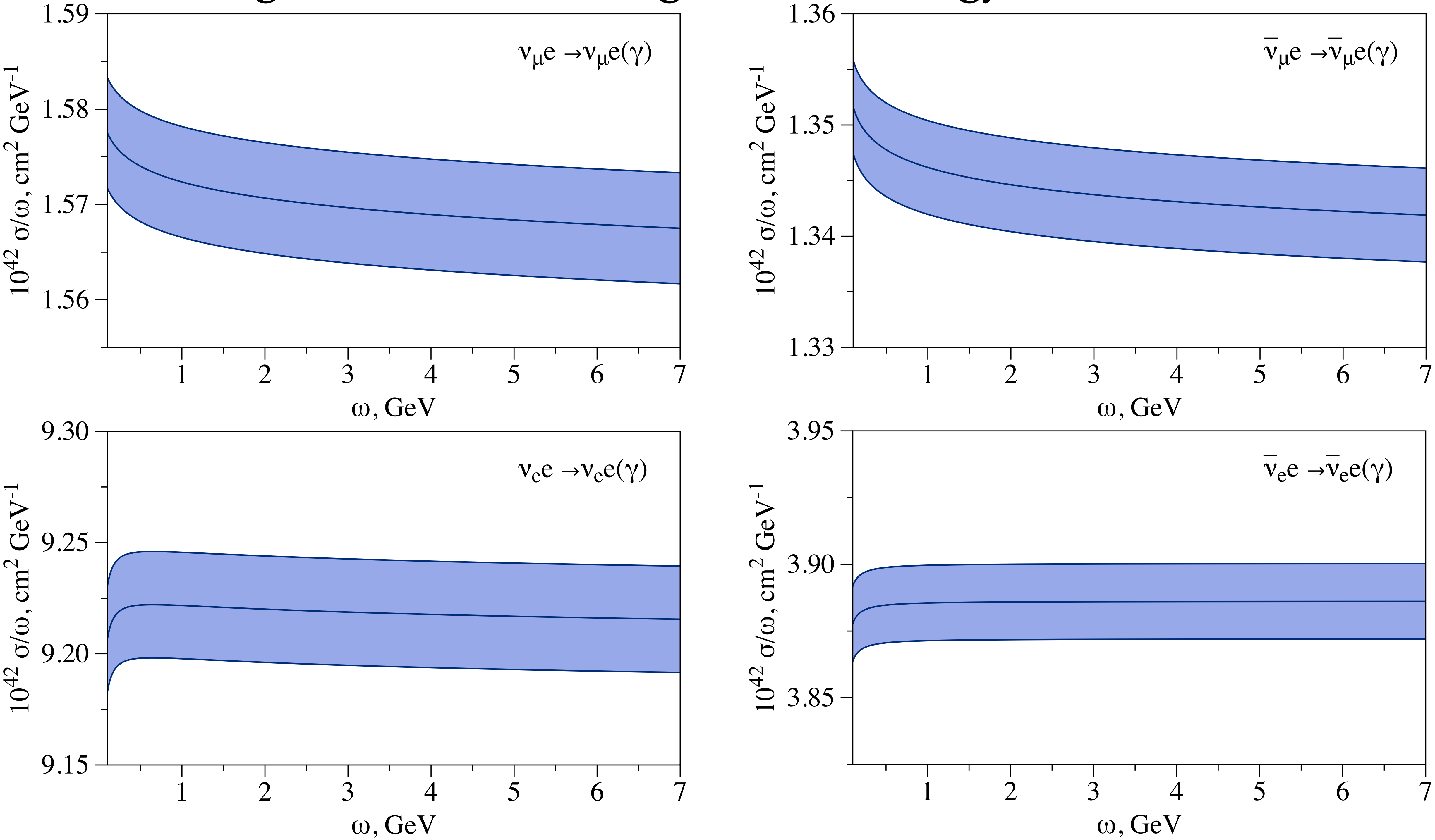



- soft Bremsstrahlung: $E_\gamma < \varepsilon$ $\mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e \gamma} = \delta_s \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}$
- soft-photon correction — Lee and Sirlin (1964)
- integration technique — Ram (1967)
- EW correction — Aoiki, Hioki, Kawabe, Konuma and 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

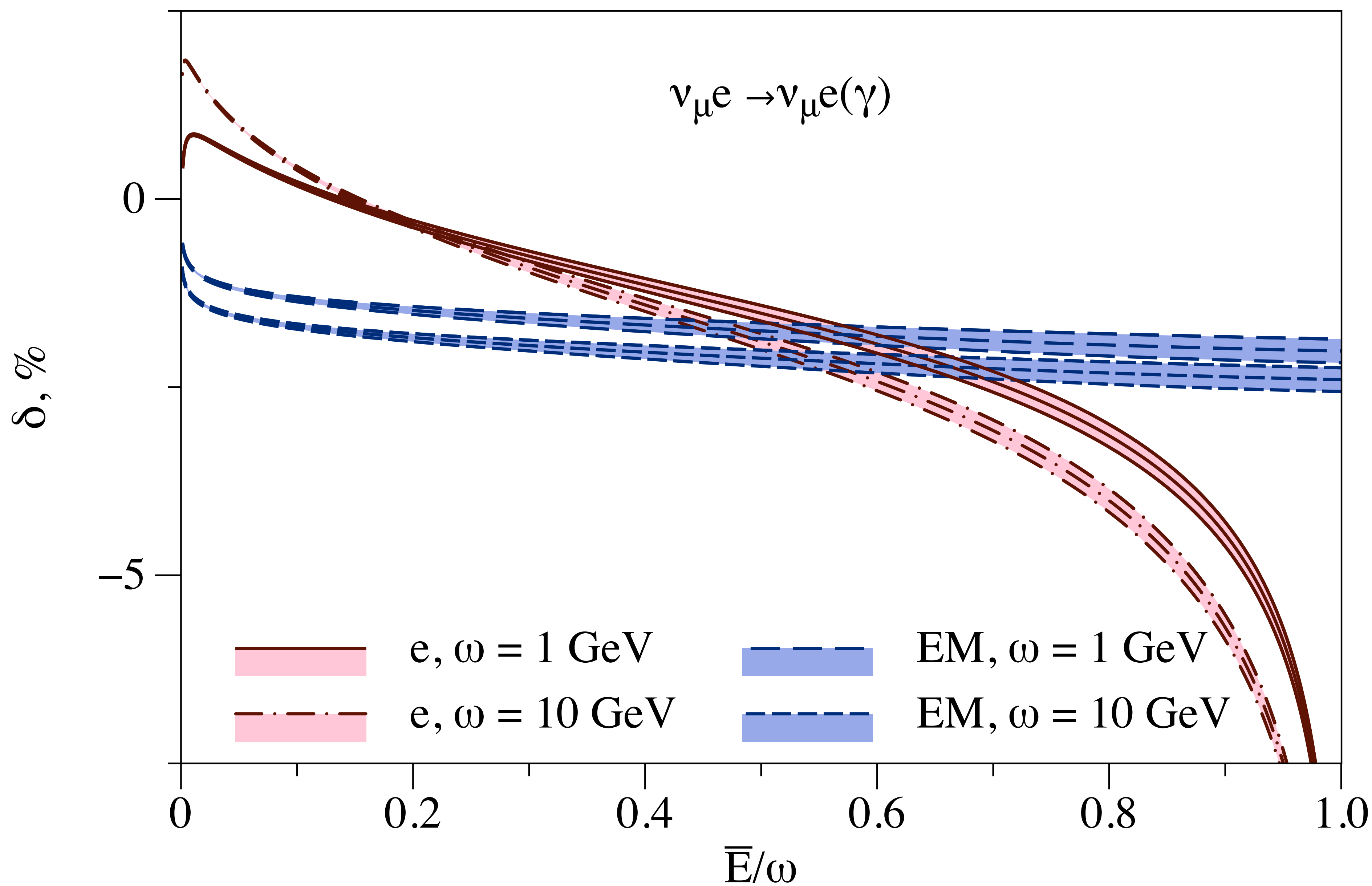



- analytic results and first error estimate at level 0.2-0.4%

# Electron vs electromagnetic (EM) spectra

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

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

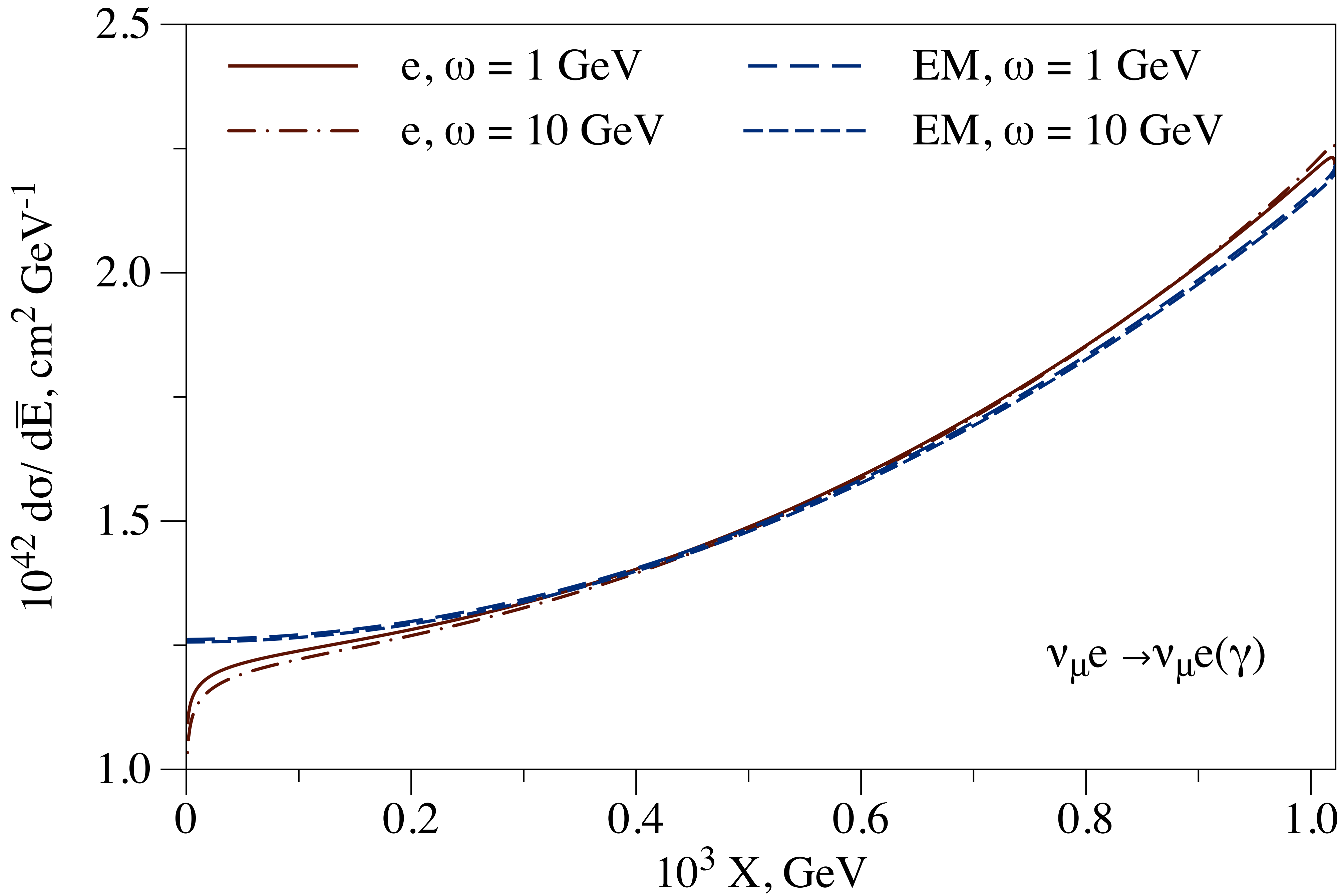



$\mu_0$ = 2 GeV

- dramatic difference in radiative corrections

# Electron vs electromagnetic (EM) spectra

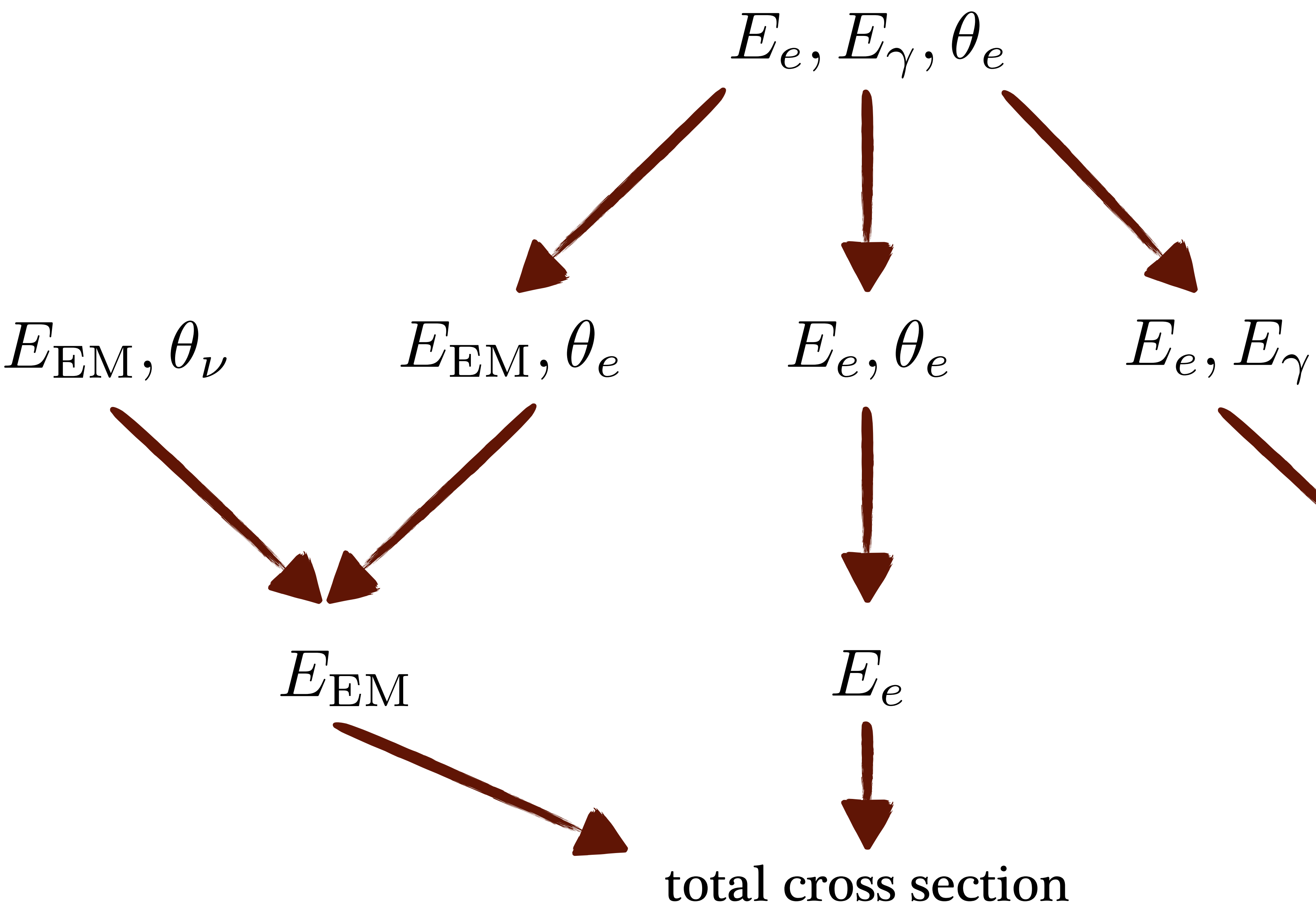
- resulting spectrum: $X = 2m\left(1 - \frac{\bar{E}}{\omega}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$

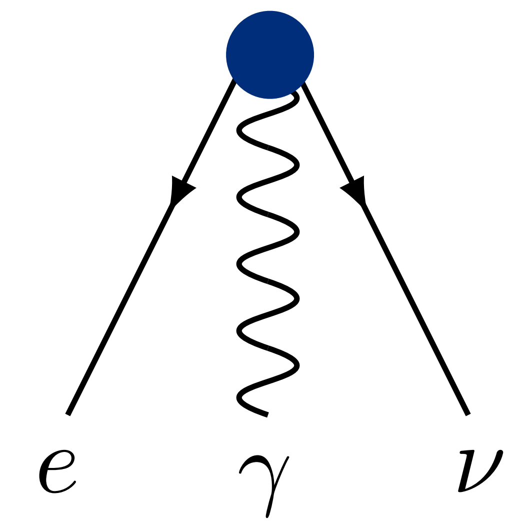



- dramatic difference in radiative corrections: cut dependence

# Bremsstrahlung cross sections

- distributions under consideration:



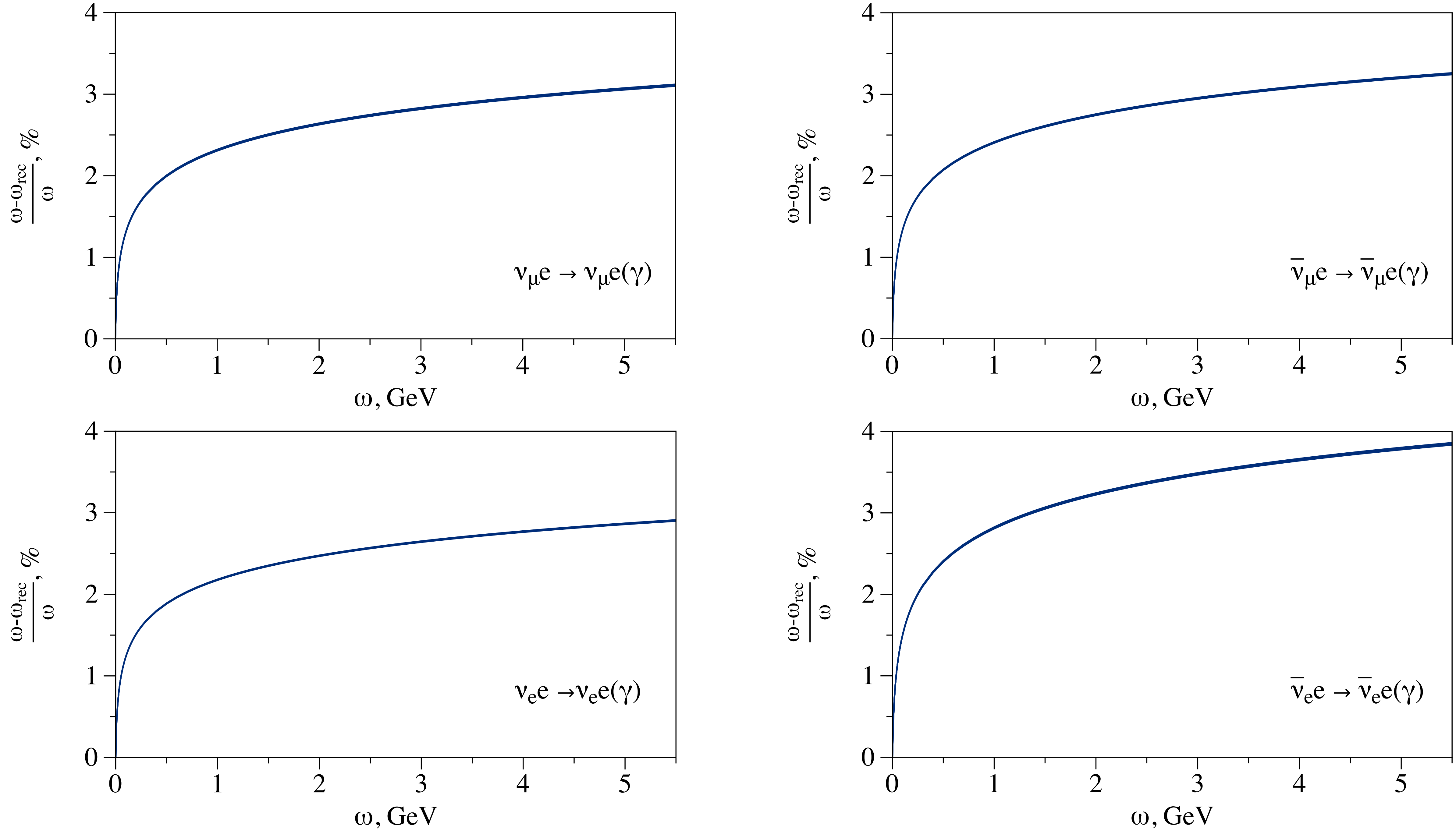




O. T. and Richard Hill (2019)

- analytical form for finite and small electron mass

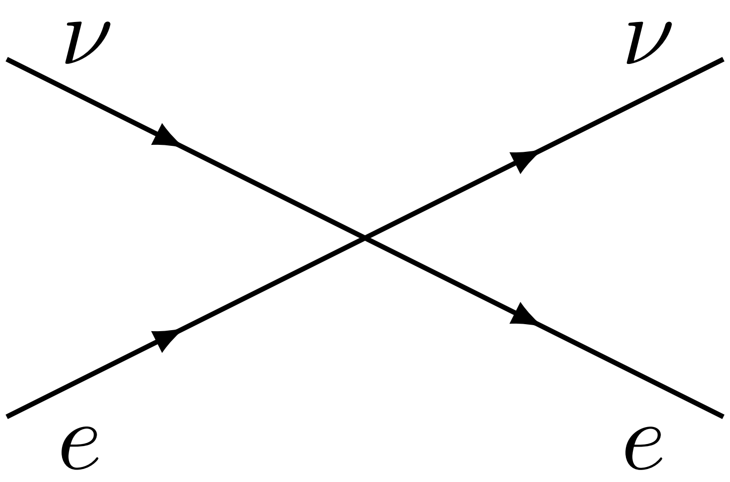
# Neutrino energy reconstruction

- 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 error analysis

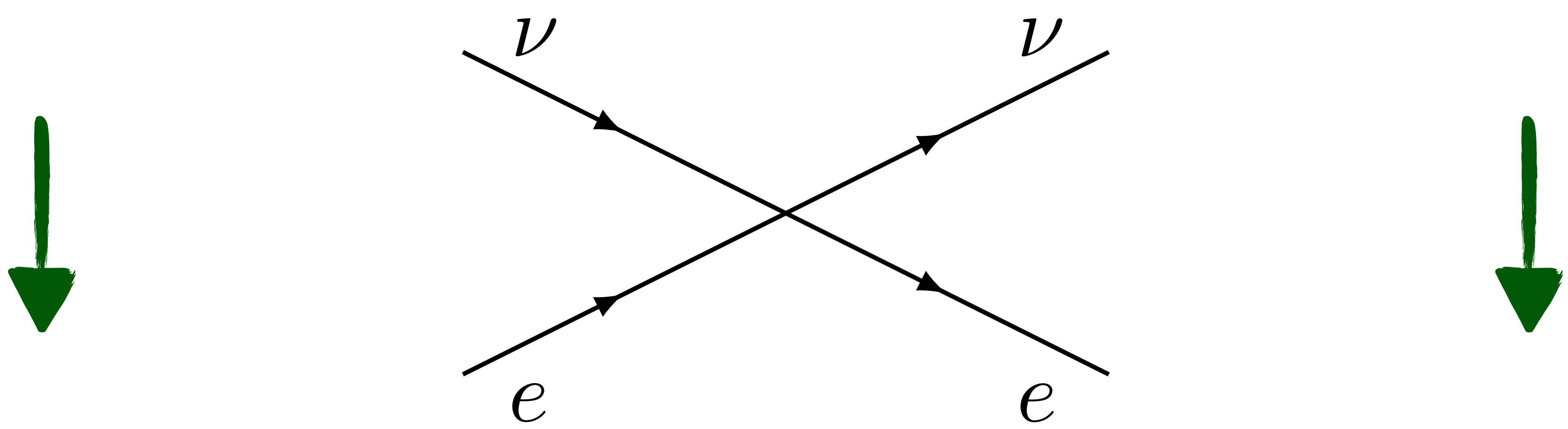
  main source of uncertainty: loops with hadrons

- 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 $\alpha$, g-2

- constrain light-quark contribution at DUNE

- application to solar neutrinos and reactor antineutrinos

Thanks for your attention !!!

# Flux determination in DUNE

- determination of neutrino fluxes:

  one of the main goals of Near Detector

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

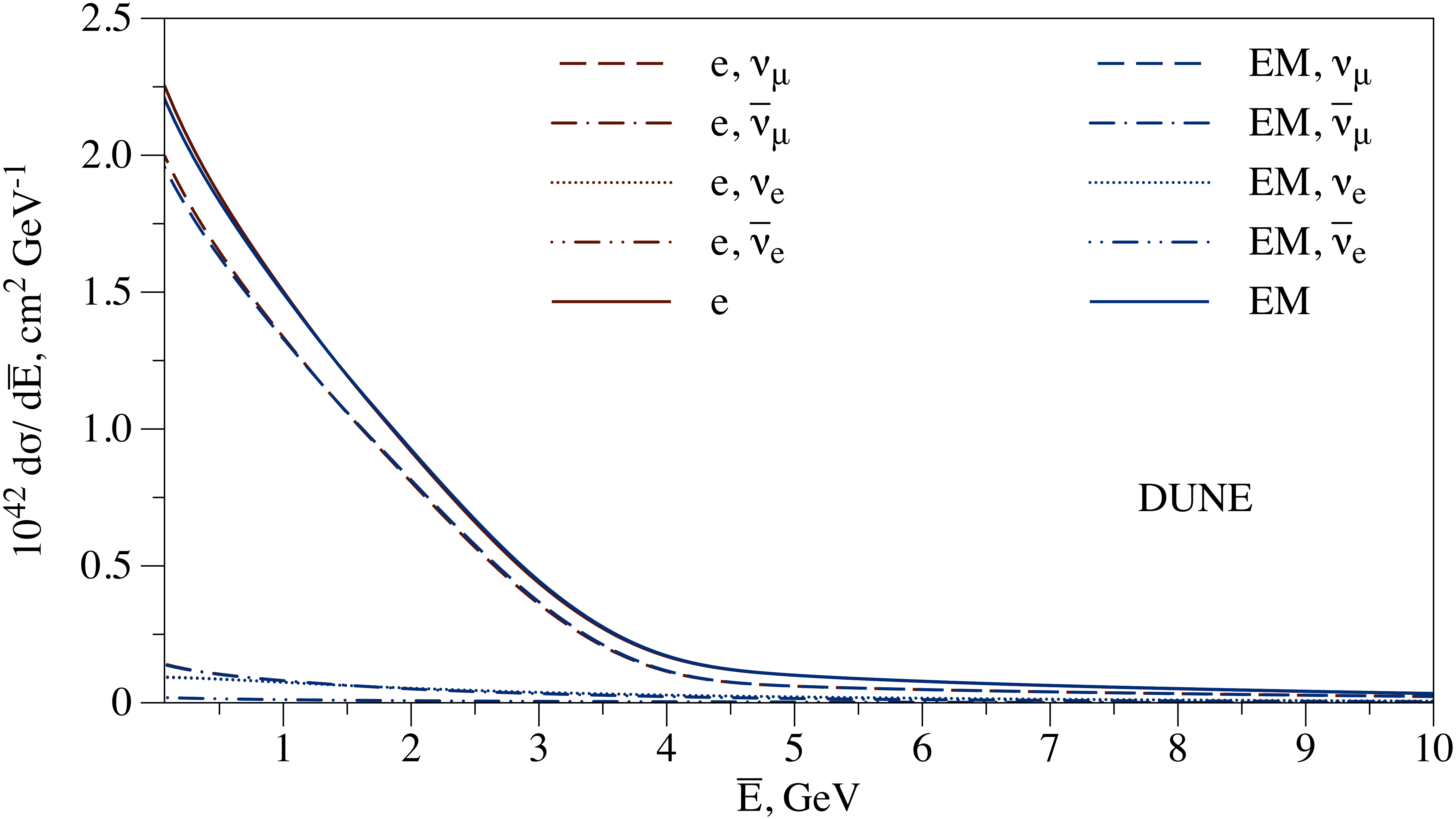
according to H. Duyang et al. (2019)

- neutrino-electron scattering plays a role of additional constraint

- $\nu e$ is required for absolute normalization of $\nu_\mu$ component

# Experimental energy spectrum

- average over beam flux and sum over flavors:




- 1-3 % difference at low recoil energy