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How well do we know neutrino-electron scattering?
EFT approach for neutrino interactions

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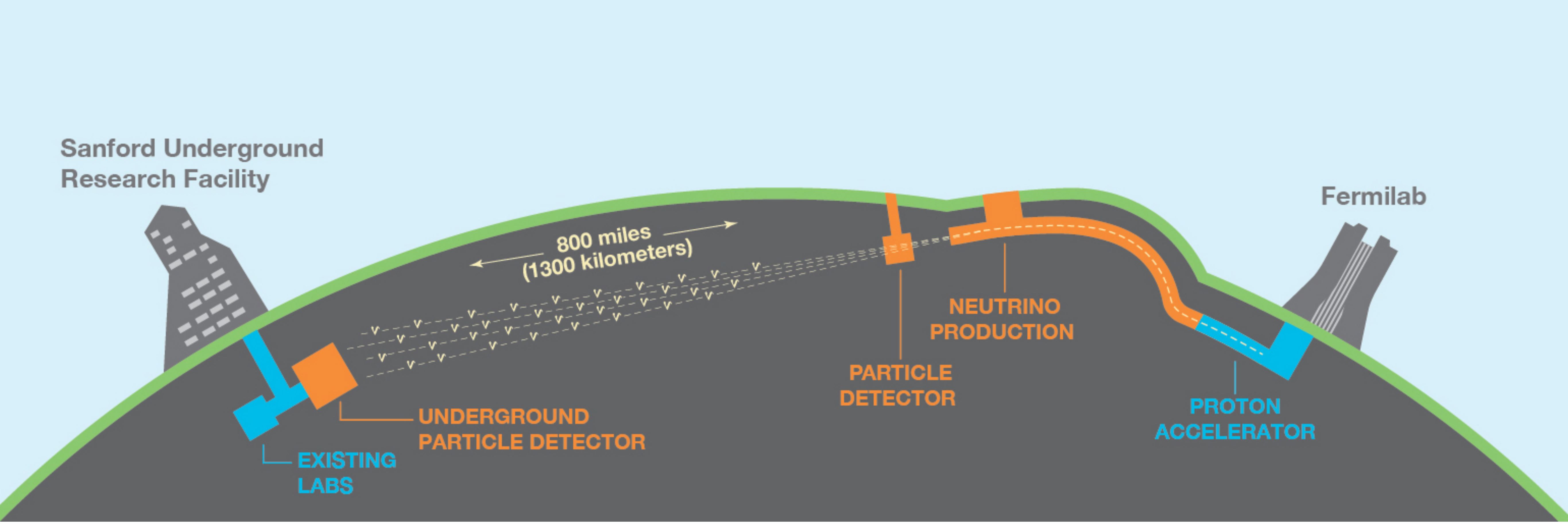
O.T. and R. J. Hill, Phys. Rev. D 101, 033006 (2020), arXiv:1911.01493, arXiv:1911.03528

Neutrino experiments

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



- measurement of ν_μ disappearance and ν_e appearance from count rates

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

- 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 events in a year vs 1180 events in total

  normalization uncertainty: from 8% to 2%

  Ch. Marshall et al. (2019)

- need: EFT-based calculation with accuracy below %

Neutrino scattering in EFT. Matching

- tree-level matching to low-energy EFT:

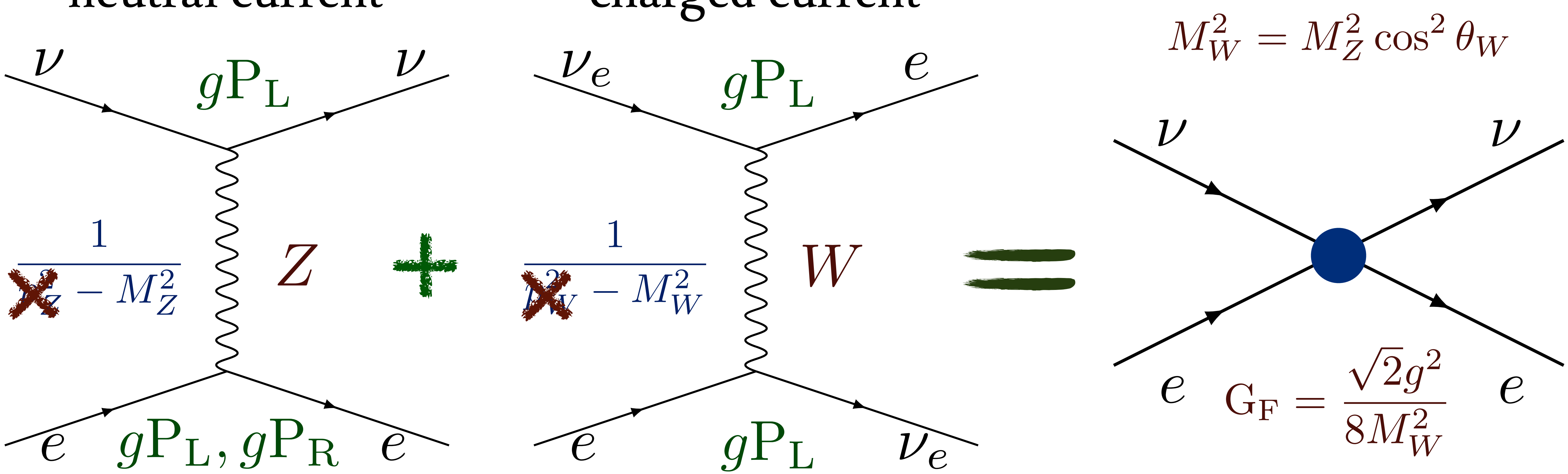
$$\mathcal{L}_{\rm eff} = -\bar{\nu}\gamma_\mu \mathrm{P_L}\nu \cdot \bar{e}\gamma^\mu(c_{\rm L}\mathrm{P_L} + c_{\rm R}\mathrm{P_R})e$$

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

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



- modern event generators are based on 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 $\mathrm{G_F}$ terms: loop corrections in α, α_s

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

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

- no additional operators after one-loop matching

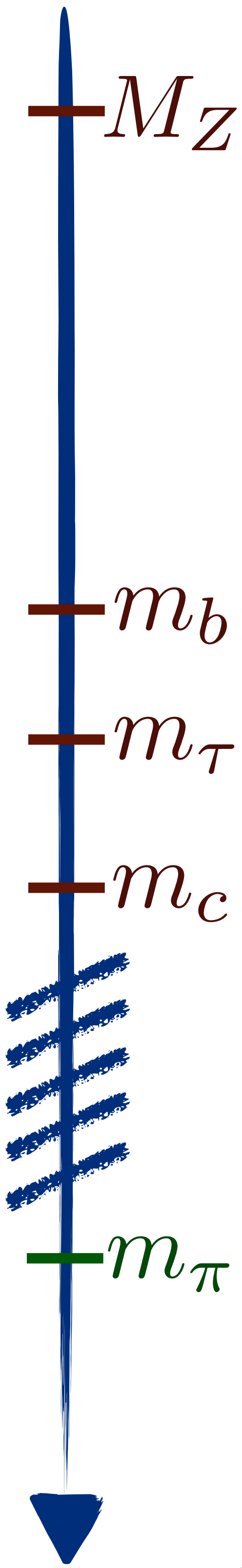
- $\mathrm{G_F}$: combination of parameters is precisely measured

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

MULAN (2012)

- matching at order $\alpha\alpha_\mathrm{s}$: left- and right-handed couplings

Running to low scales



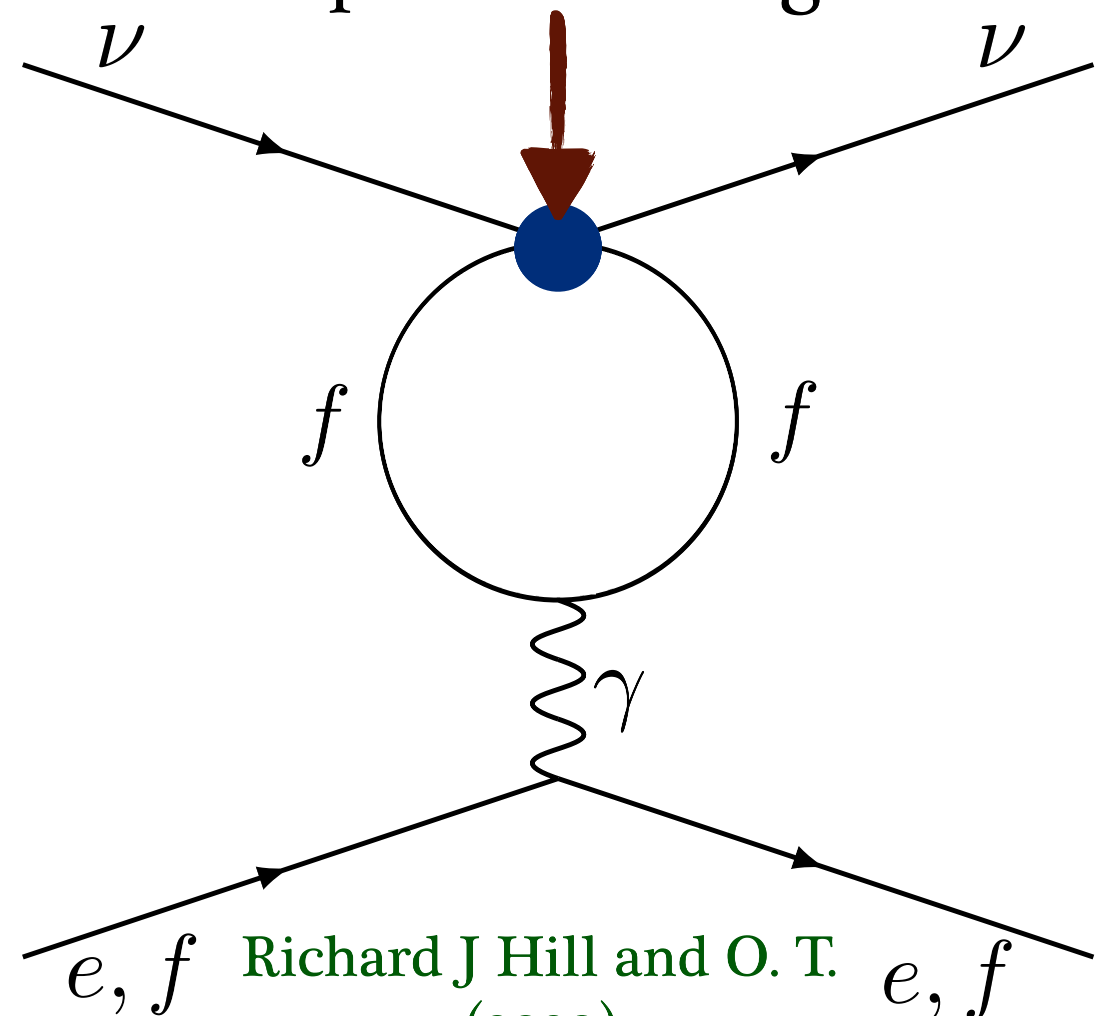
- integrate out top, Z , W, h
- only one EFT coupling changes with scale
- integrate out GeV particles
- α_s becomes too strong
- hadronic physics > 140 MeV
- theory with leptons

$c_{\rm L}^{\nu_e e}$: $2.388 \to 2.398$

$c_{\rm L}^{\nu_\mu e}$: $-0.911 \to -0.901$ % effect

$c_{\rm R}$: $0.759 \to 0.769$

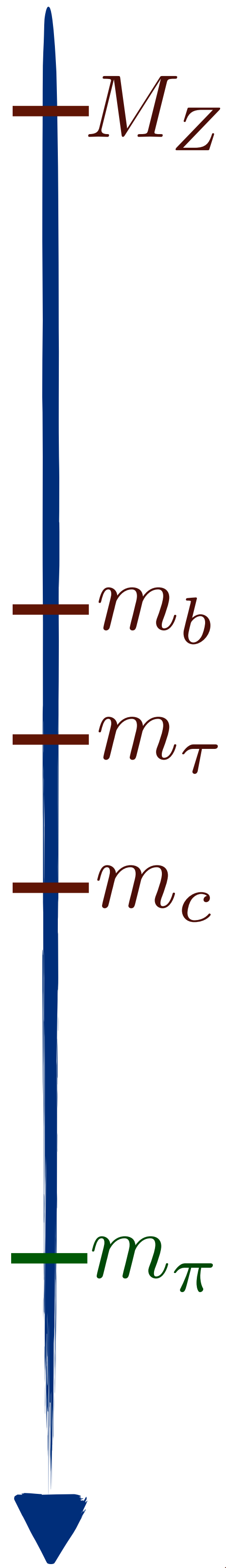
operator mixing



Richard J Hill and O. T. (2020)

- precise mapping from electroweak to hadronic scales

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:

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

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

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

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

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

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

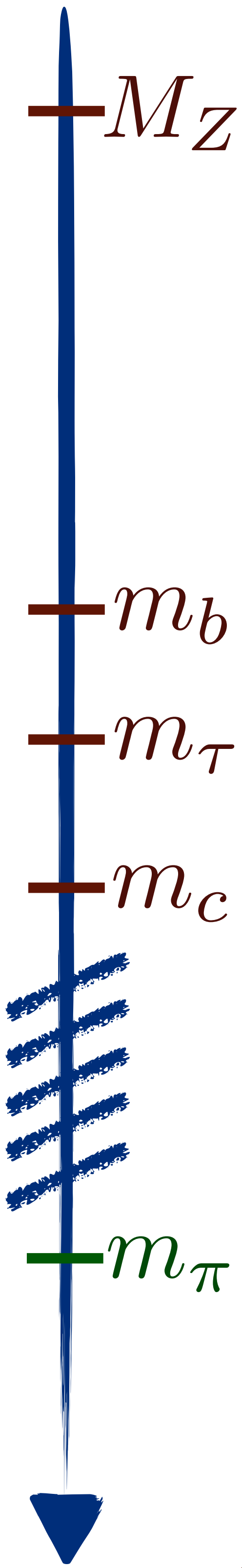
$$3c_{\mathrm{L}}^{u}(\mu) + 2c_{\mathrm{L}}^{\nu_\mu e}(\mu) = \sqrt{2}\mathrm{G}_u,$$

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

- 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	$1.16713(83)_\mathrm{i}(12)_\mathrm{p}$	$1.18161(85)_\mathrm{i}(33)_\mathrm{p}$	$1.16917(83)_\mathrm{i}(32)_\mathrm{p}$
$\mathrm{G_F}$, $\mathrm{M_Z}$, α	$1.1663787(6)_\mathrm{i}$	$1.18083(4)_\mathrm{i}(21)_\mathrm{p}$	$1.16841(4)_\mathrm{i}(20)_\mathrm{p}$

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

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

- agreement of electroweak vs muon mass scales

Richard J Hill and O. T. (2020)

Main theoretical uncertainty

- momentum transfer is suppressed by electron mass:

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

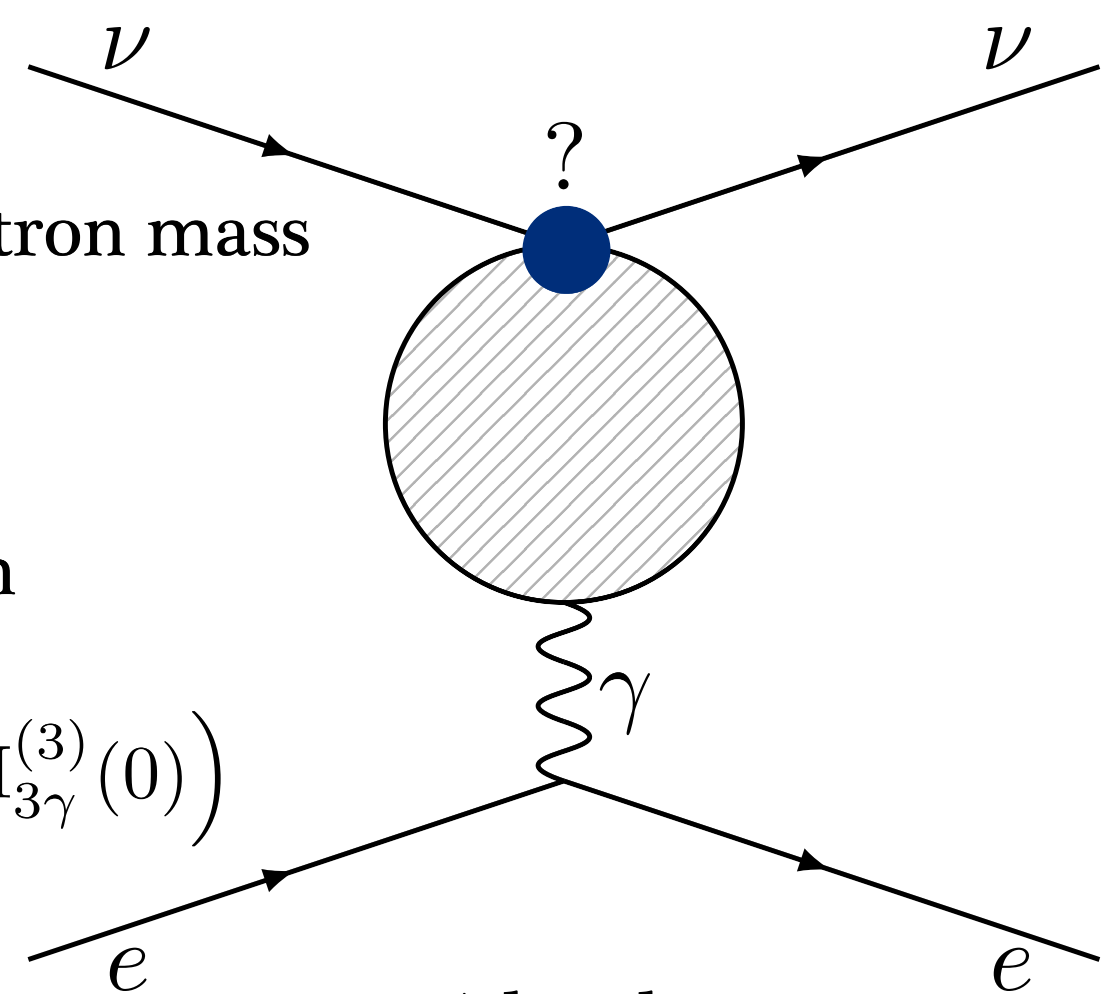
- description in terms of quarks is invalid for GeV neutrino energies

- kinematics is suppressed by electron mass

$$s, Q^2 \lesssim 2mE_\nu \ll \Lambda^2_{\mathrm{QCD}}$$

- QCD: short-distance contribution

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



- non-perturbative light-quark contribution

% level

- hadronic correction is the main error in theory

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

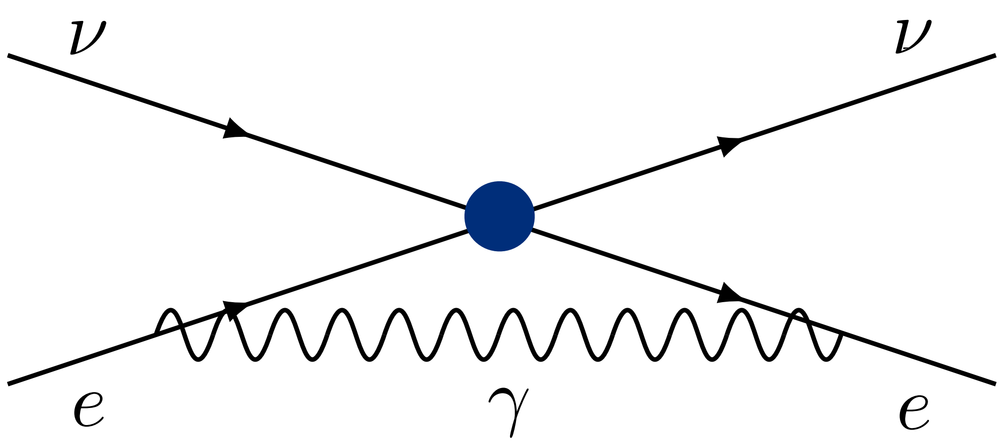
	$c_{\mathrm{L}}^{\nu_e e}$	$c_{\mathrm{L}}^{\nu_\mu e}$	$c_{\mathrm{R}}^{\nu_e e}$	$c_{\mathrm{R}}^{\nu_\mu e}$
μ = 2 GeV	2.4064(28)	-0.8926(28)	0.7773(28)	0.7773(28)
$\mu = \mathrm{m}_\mu$	2.3997(29)	-0.8994(29)	0.7706(29)	0.7706(29)
$\mu = \mathrm{m}_e$	2.3865(29)	-0.8988(29)	0.7575(29)	0.7711(29)

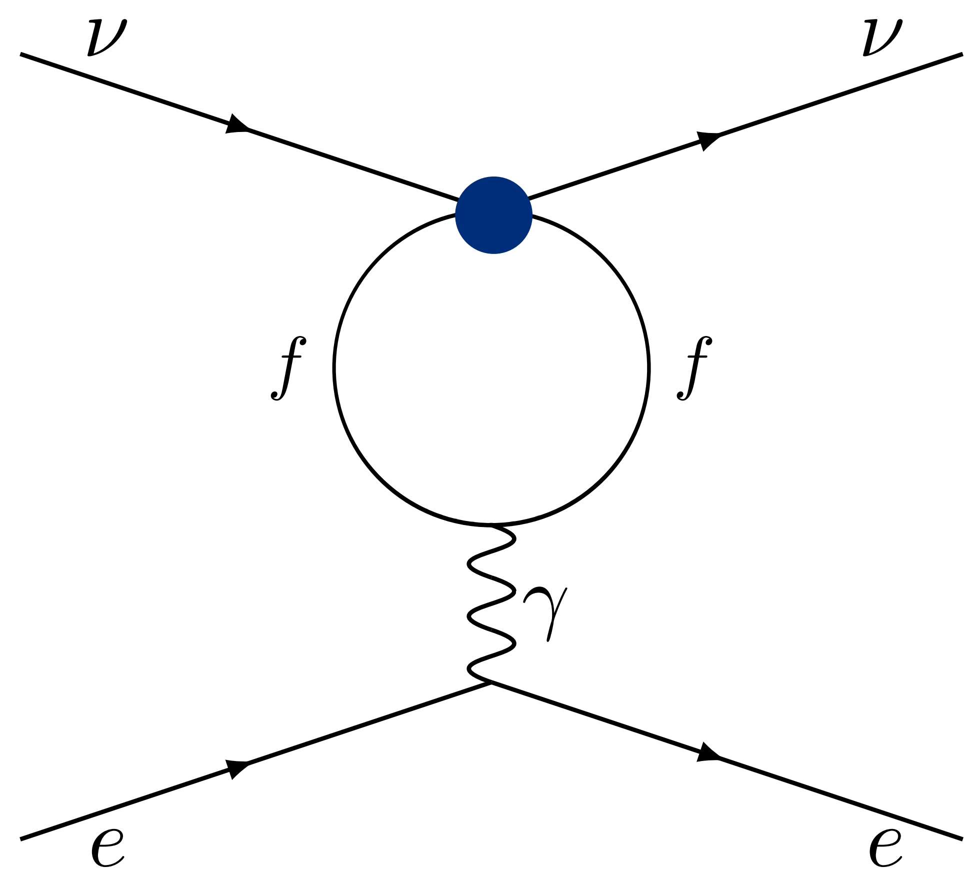
- three distinct L and R couplings below the muon mass !!!

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

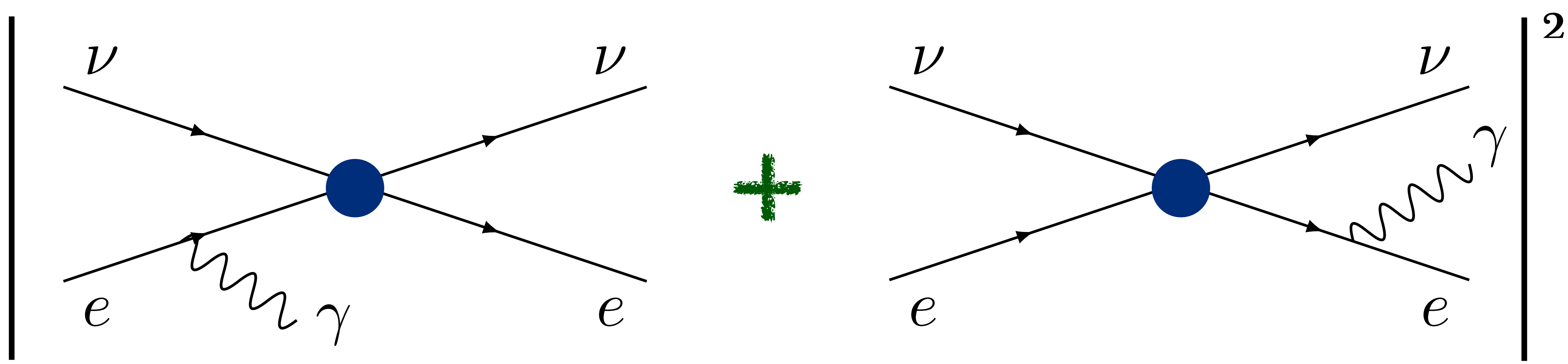
Radiative corrections in four-Fermi theory

- virtual corrections:



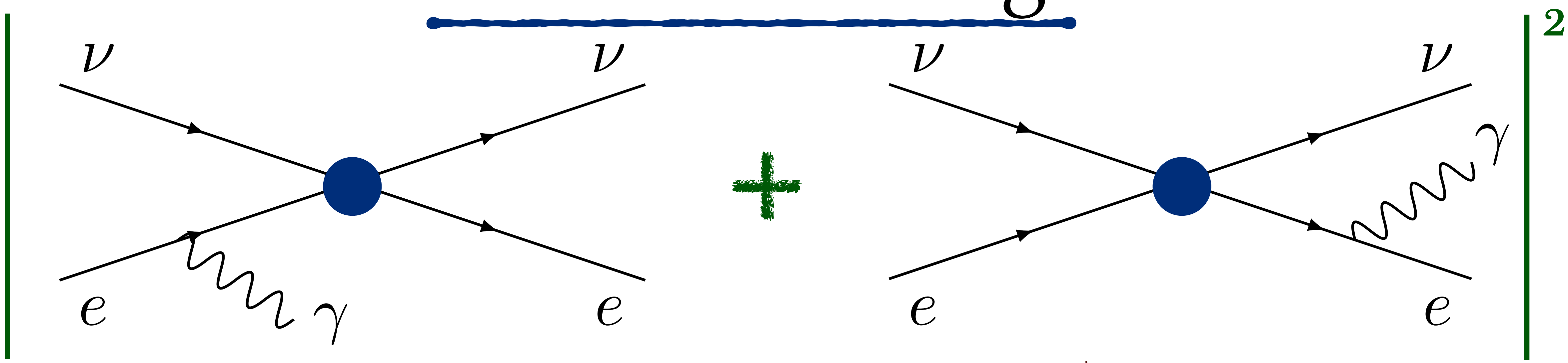


- real radiation:



- only few QED corrections are present in effective theory

Bremsstrahlung

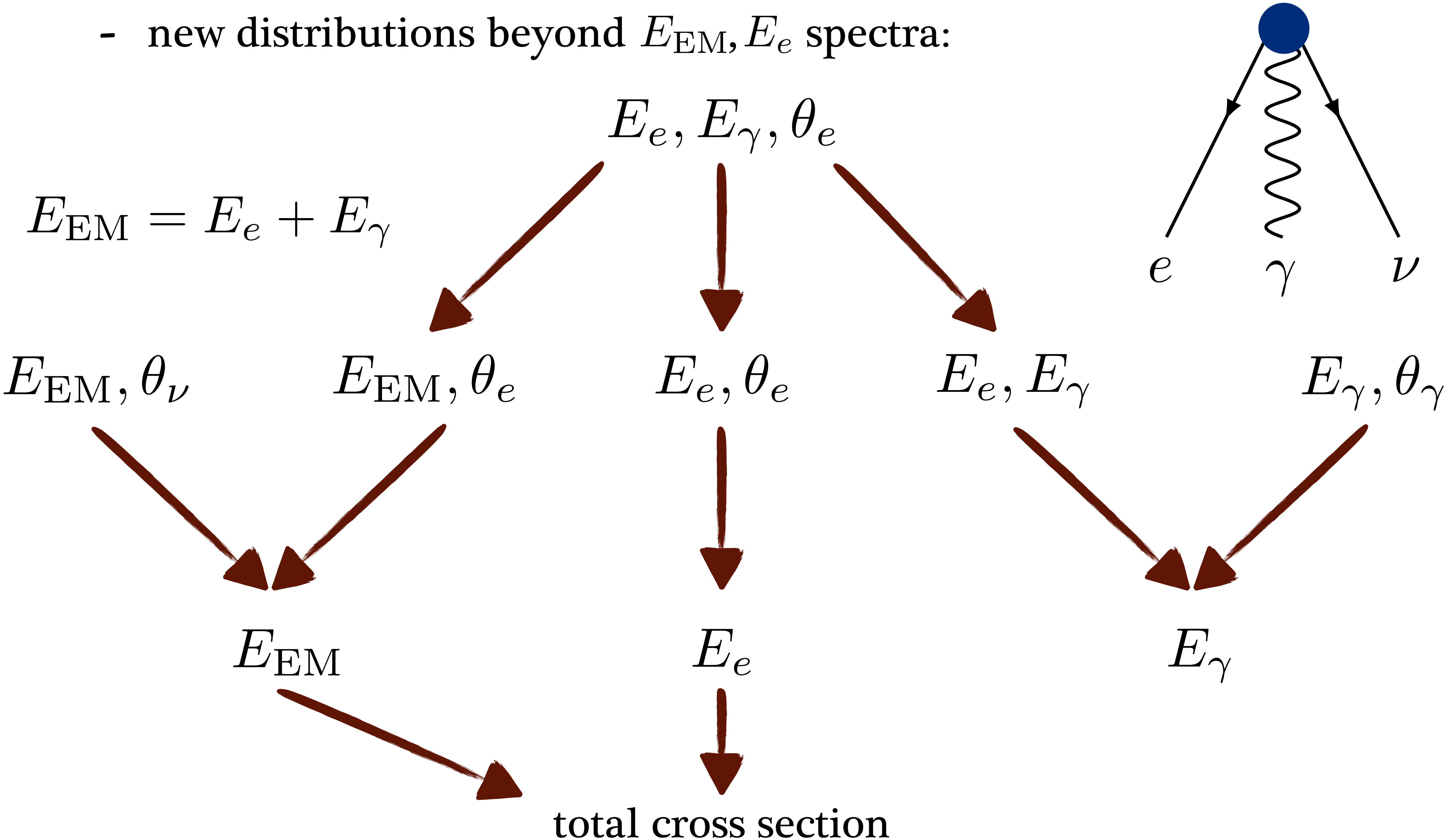


- soft Bremsstrahlung: $E_\gamma < \varepsilon$ $\quad \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e \gamma} = \delta_s \mathrm{d}\sigma_{\mathrm{LO}}^{\nu e \to \nu e}$
- soft-photon correction — Lee and Sirlin (1964)
- integration technique — Ram (1967)
- EW correction — Aoiki, Hioki, Kawabe, Konuma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

- new distributions beyond $E_{\rm EM}, E_e$ spectra:

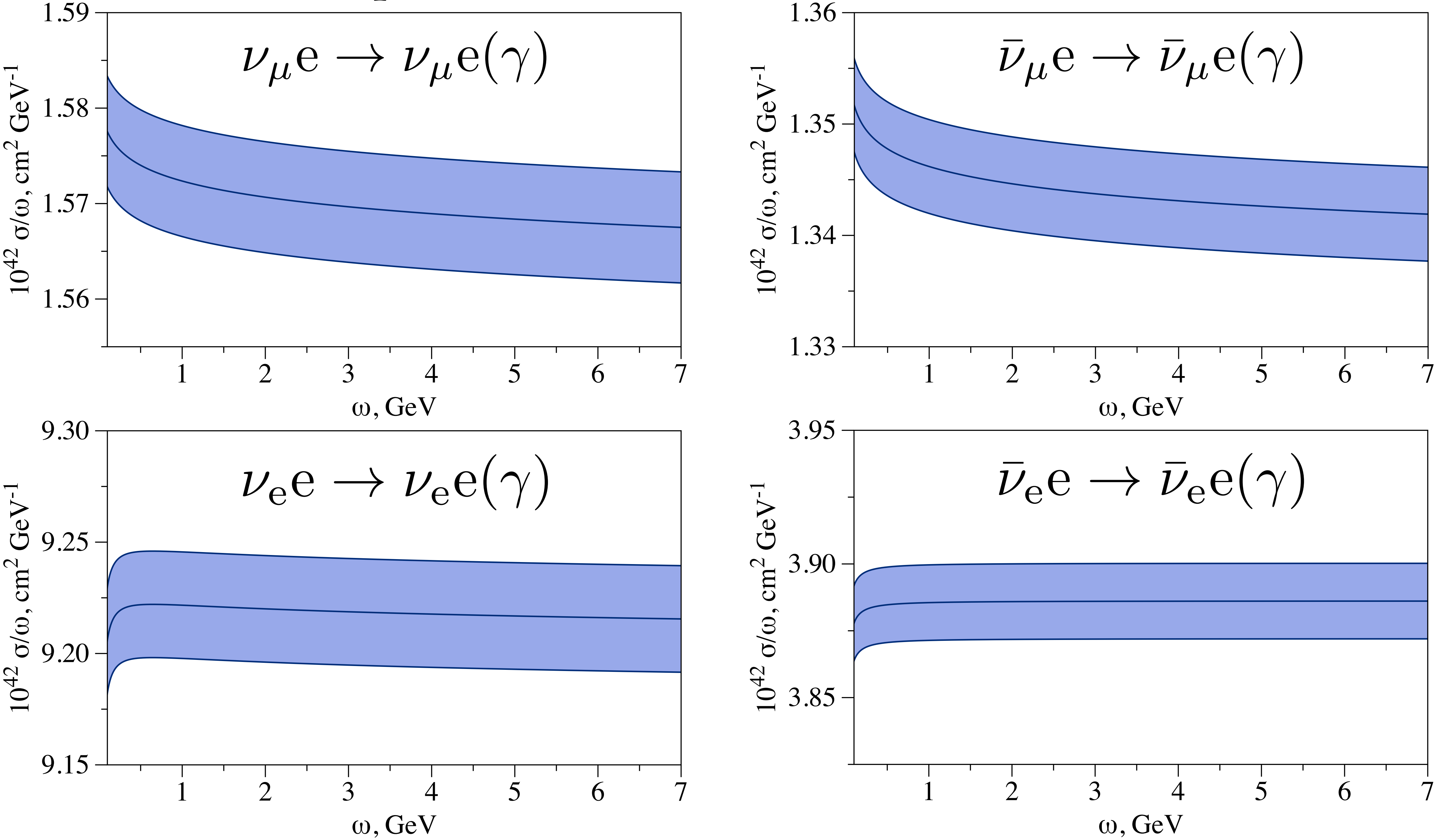


O. T. and Richard J Hill (2020)

- analytical form for finite and small electron mass

Absolute cross section

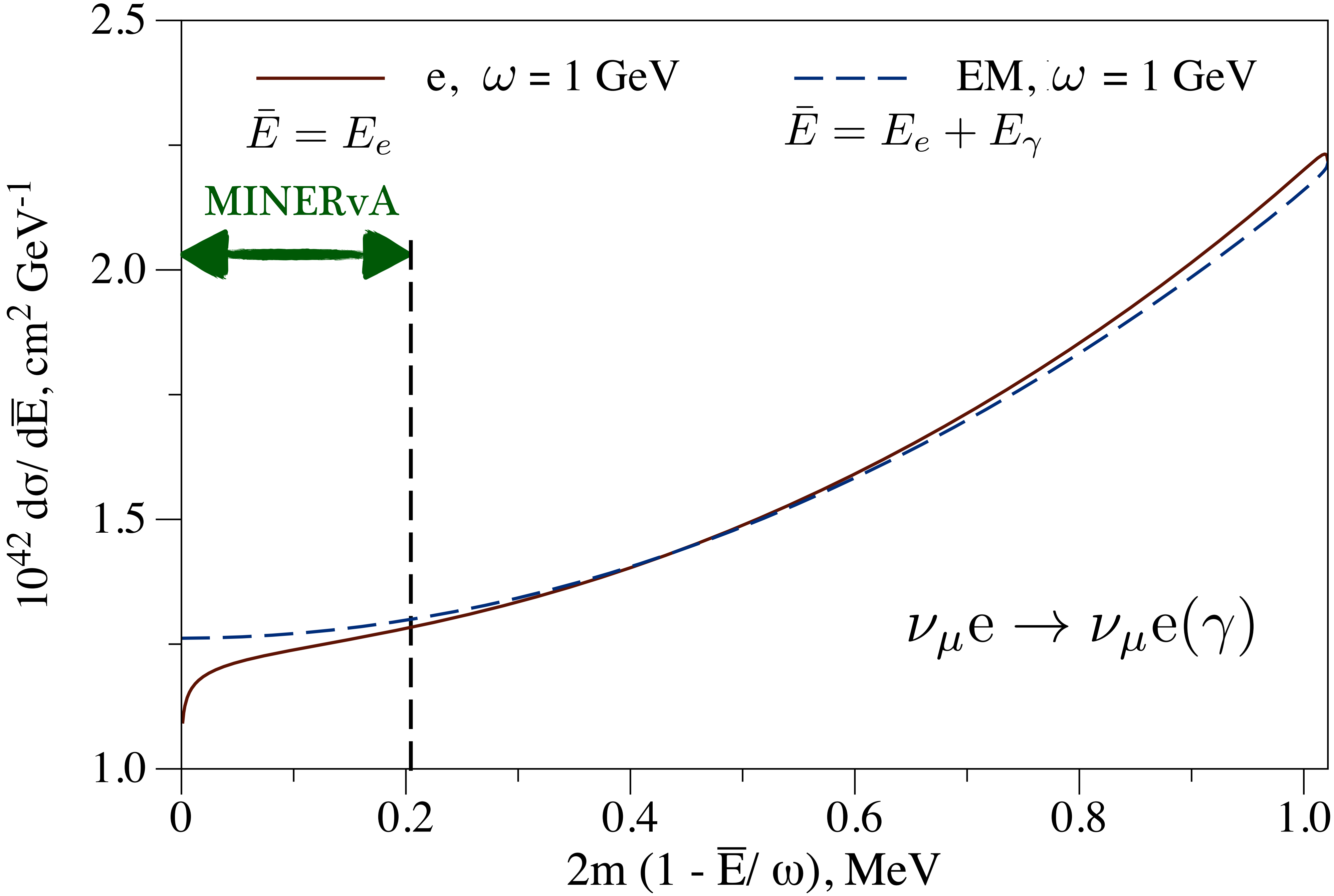
- hadronic loops introduce the main error



- error 0.2-0.4% of order DUNE statistical error

Electron vs electromagnetic (EM) spectra

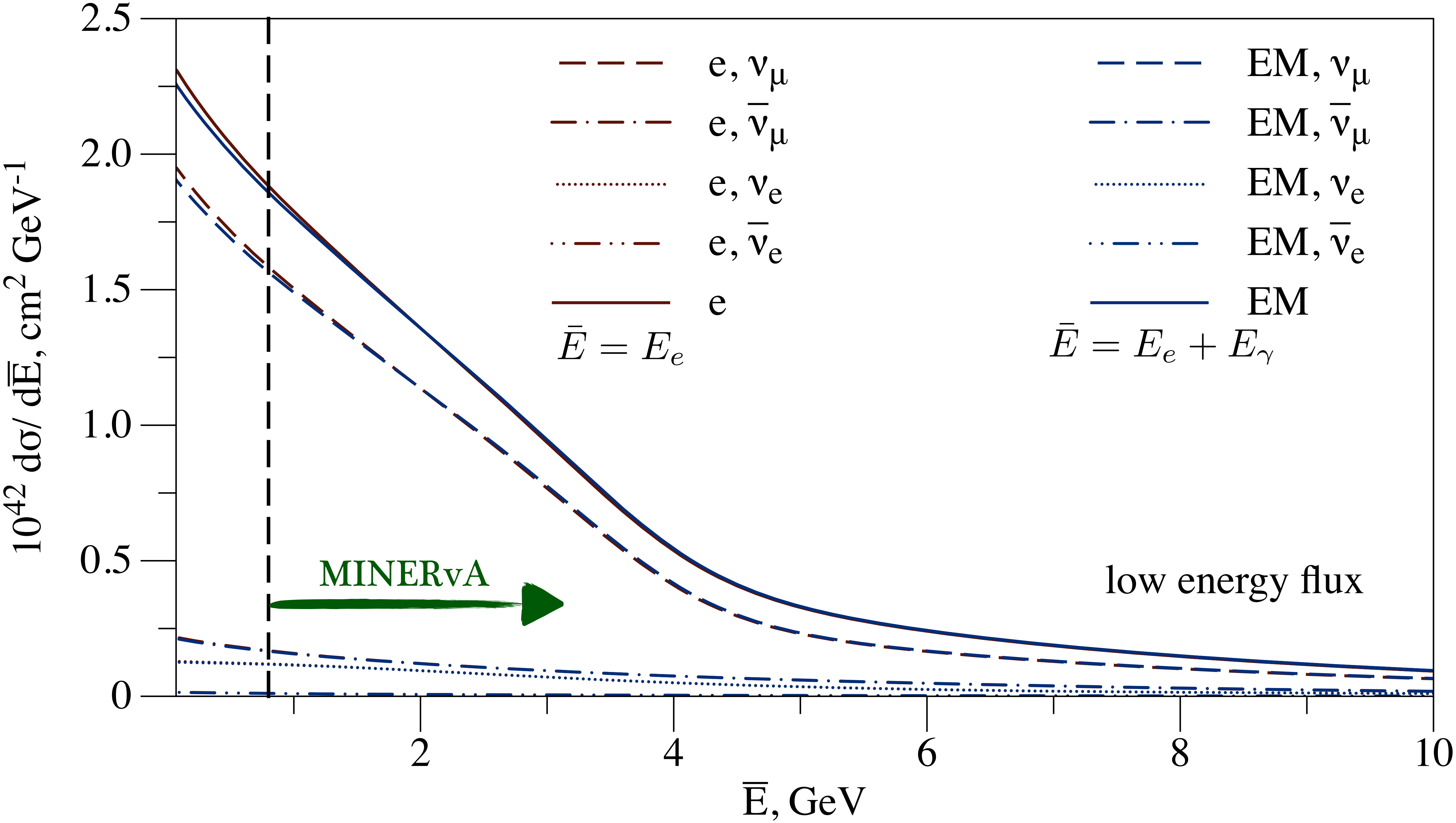
- experimentally convenient variable $2m\left(1-\frac{\bar{E}}{\omega}\right) \underset{\bar{E}=E_e}{\approx} E_e\theta_e^2$



- cut dependence after radiative corrections

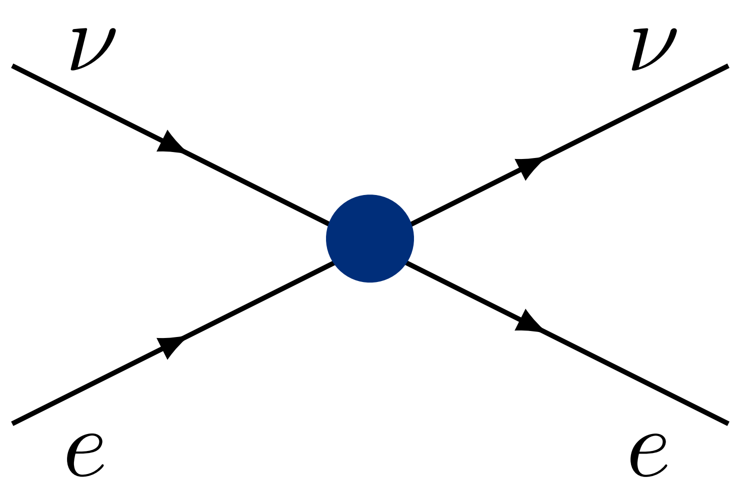
Experimental energy spectrum

- average over beam flux and sum over flavors:



- 1-3 % difference at low recoil energy

Conclusions



powerful constraint on neutrino flux

- precision four Fermi effective theory: basis for computations with sub-percent accuracy in neutrino interactions
- total and differential neutrino-electron cross sections evaluated from theory with first error analysis
- dominant hadronic uncertainty at the level 0.2-0.4% could be further reduced by lattice QCD
- energy spectra and bremsstrahlung cross sections: new results in analytical form

Thanks for your attention !!!