CIPANP 2022:
14th Conference on the Intersection of Particle and Nuclear Physics

31 August, 2022

An Overview of Cross Sections in Neutrino Physics

Los Alamos
NATIONAL LABORATORY

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LA-UR-22-28913

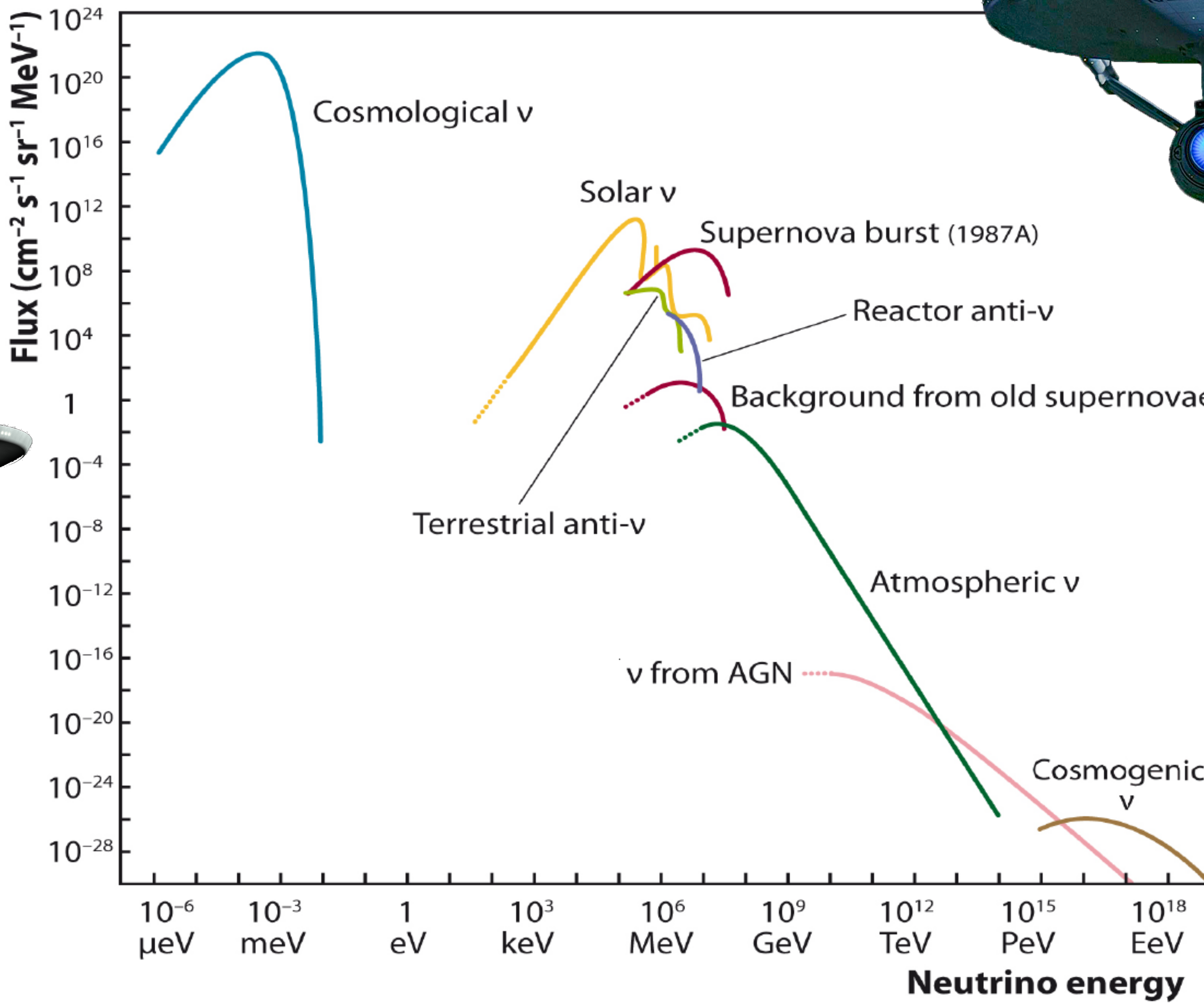
1) Neutrino sources across energy scales

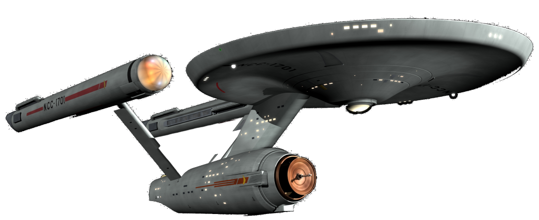
2) Cross sections on electrons, nucleons, and nuclei

3) Radiative corrections in neutrino physics

Neutrino interactions across energy scales

Nature sources

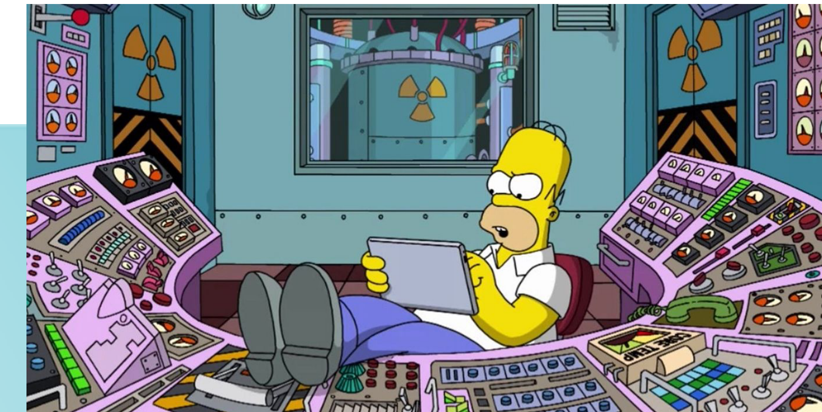


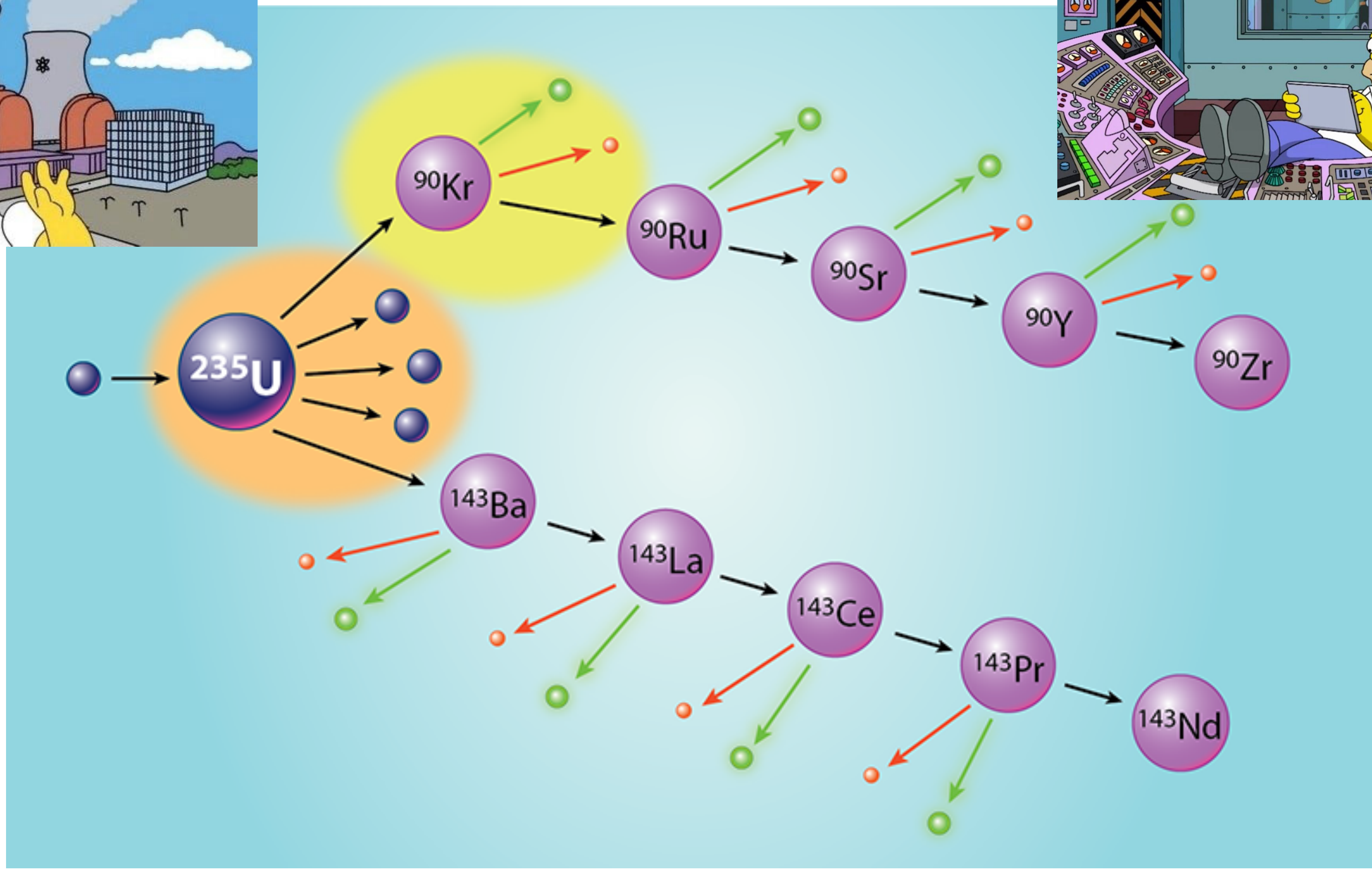


U.F. Katz, Ch. Spiering, Prog. Part. Nucl. Phys. 67, 651-704 (2012)

- cosmological, cosmogenic, supernova background: to be detected

Reactor (anti)neutrinos





A. Bernstein, N. Bowden, B.L. Goldblum, P. Huber, I. Jovanovic, J. Mattingly, Rev. Mod. Phys. 92, 011003 (2020)

- first detected neutrinos; antineutrinos from nuclear beta decays

Artificial neutrinos: accelerator

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

$\pi^+ \to \mu^+ \nu_\mu$

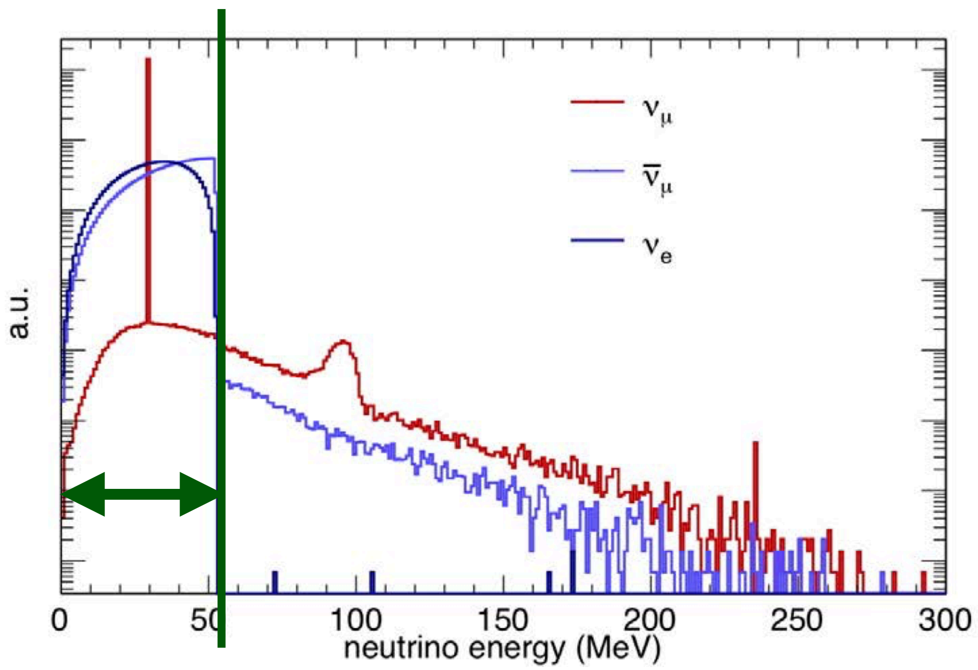
$K^+ \to \mu^+ \nu_\mu$

$K^+ \to \pi^0 e^+ \nu_e$ $\quad K_L^0 \to \pi^\pm e^\mp \nu_e$

$K^+ \to \pi^0 \mu^+ \nu_\mu$ $\quad K_L^0 \to \pi^\pm \mu^\mp \nu_\mu$

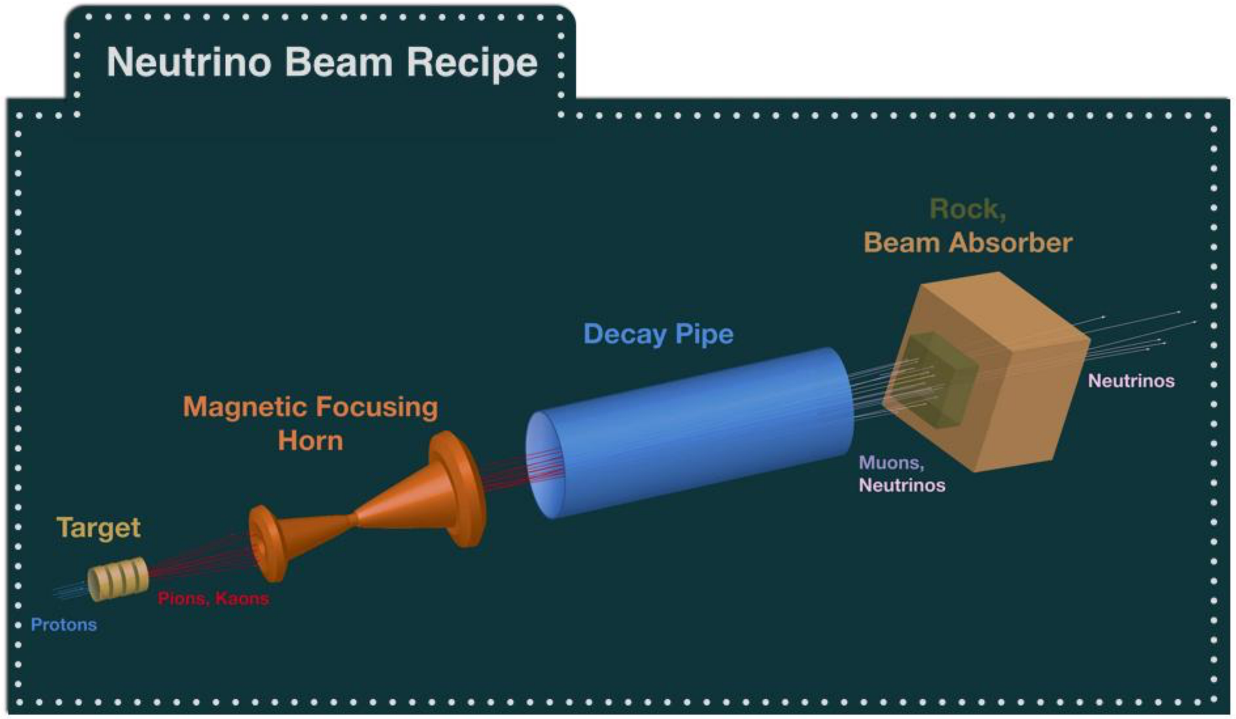
decay at rest

decay in flight



Akimov et al., Science 357 6356, 1123-1126 (2017)

Coherent and CCM



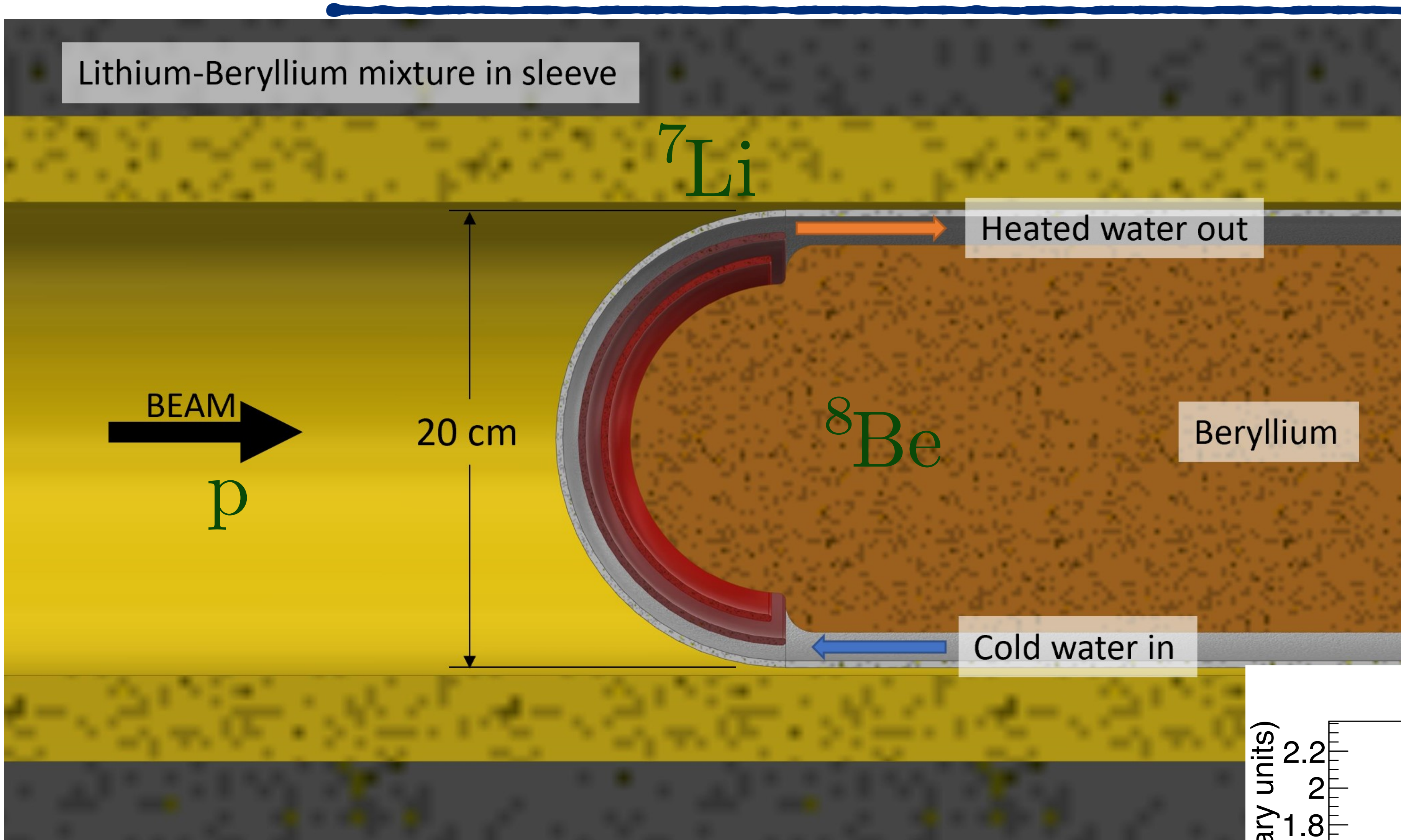
www.fnal.gov

T2K, NOvA, MiniBooNE, MicroBooNE
MINERvA, MINOS, NuTeV
SBN, DUNE, HyperK, ESSnuSB

meson decay: monochromatic line

- precise measurements of neutrino properties, EW, and BSM search
- physics program relies on neutrino cross sections in MeV-TeV range

Artificial neutrinos: IsoDAR

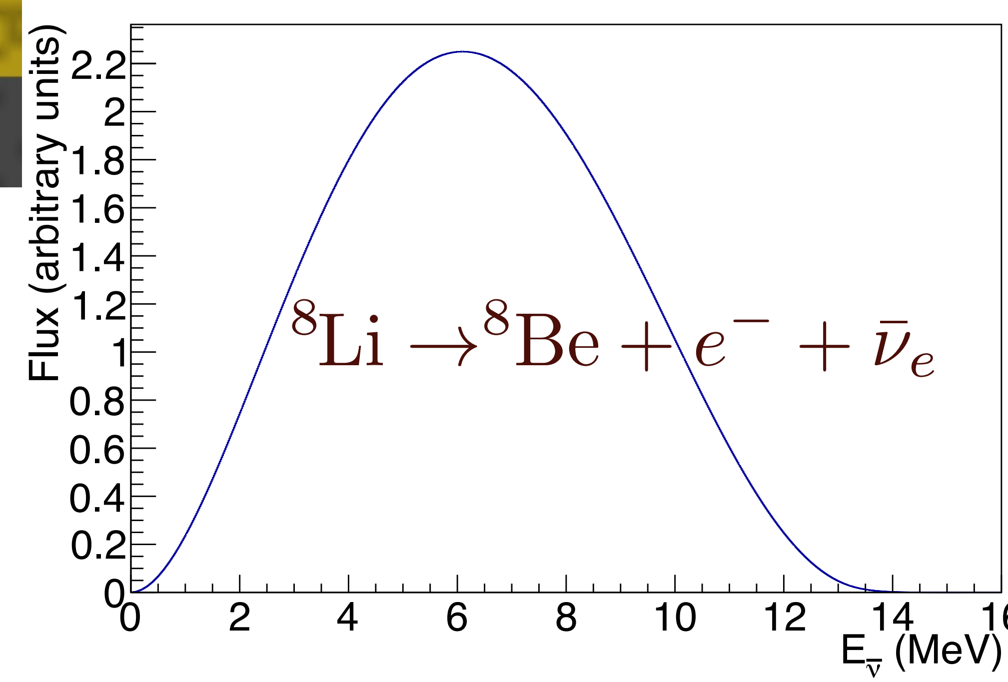


$$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$$

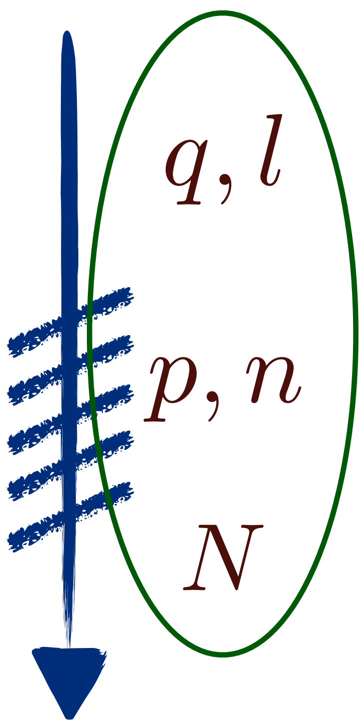
$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$

$$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$$

J.R. Alonso et al., IsoDAR@Yemilab, 2022



- well-understood fluxes and cross sections at low energies



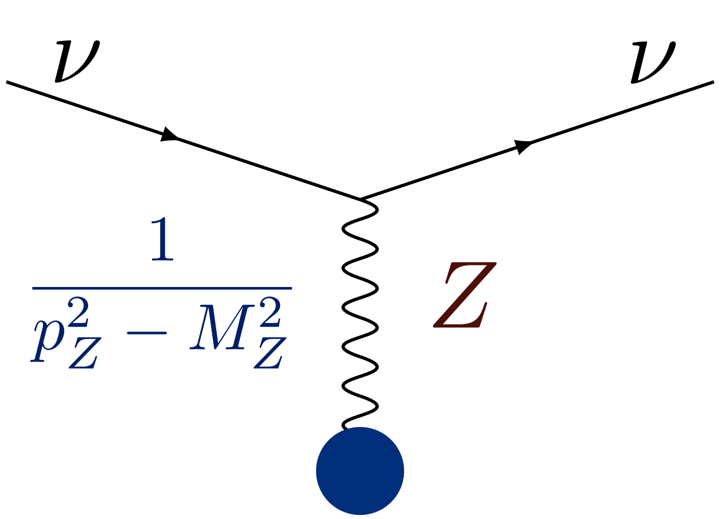
Cross sections on electrons, nucleons, and nuclei

Neutral- and charged-current processes

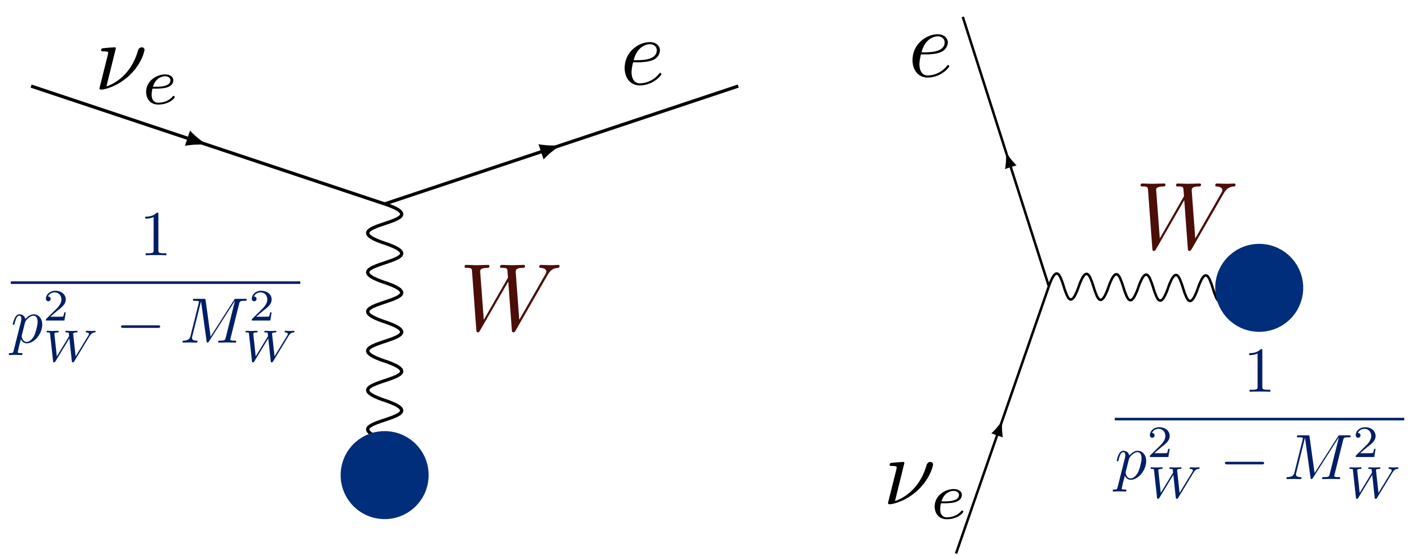
- cross sections determine neutrino-induced events

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

neutral current



charged current



- contact interactions at GeV energy scale and below

> - charged current (only): threshold to produce lepton and recoil
> - neutral current: no thresholds

Neutral- and charged-current processes

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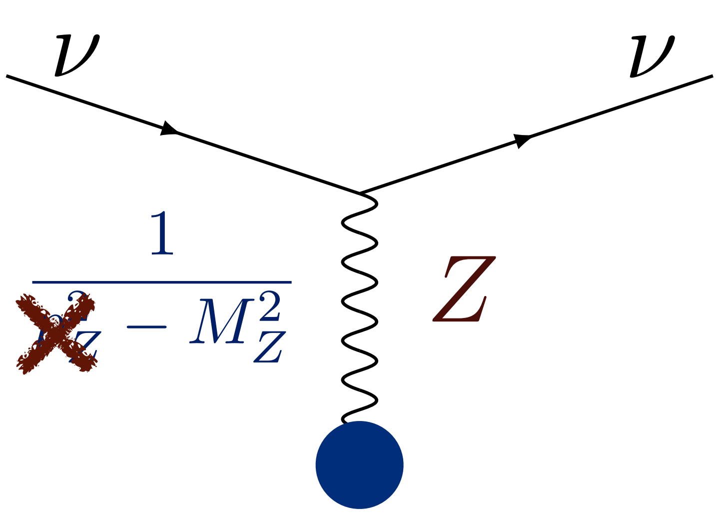
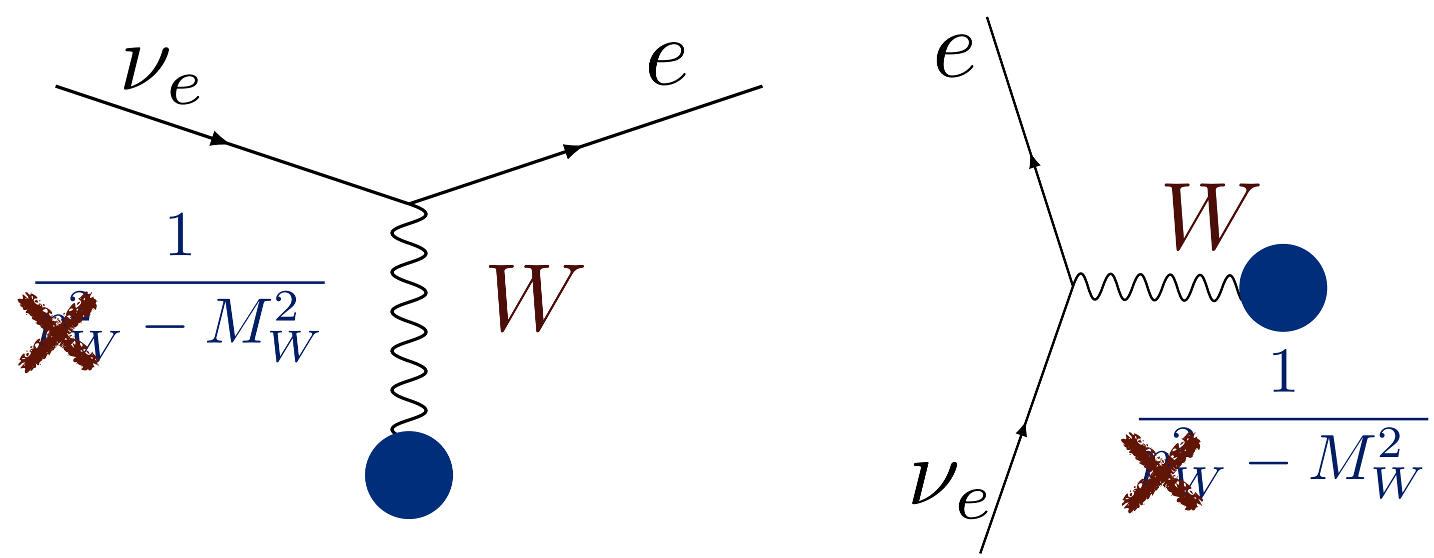
neutral current



charged current



- contact interactions at GeV energy scale and below

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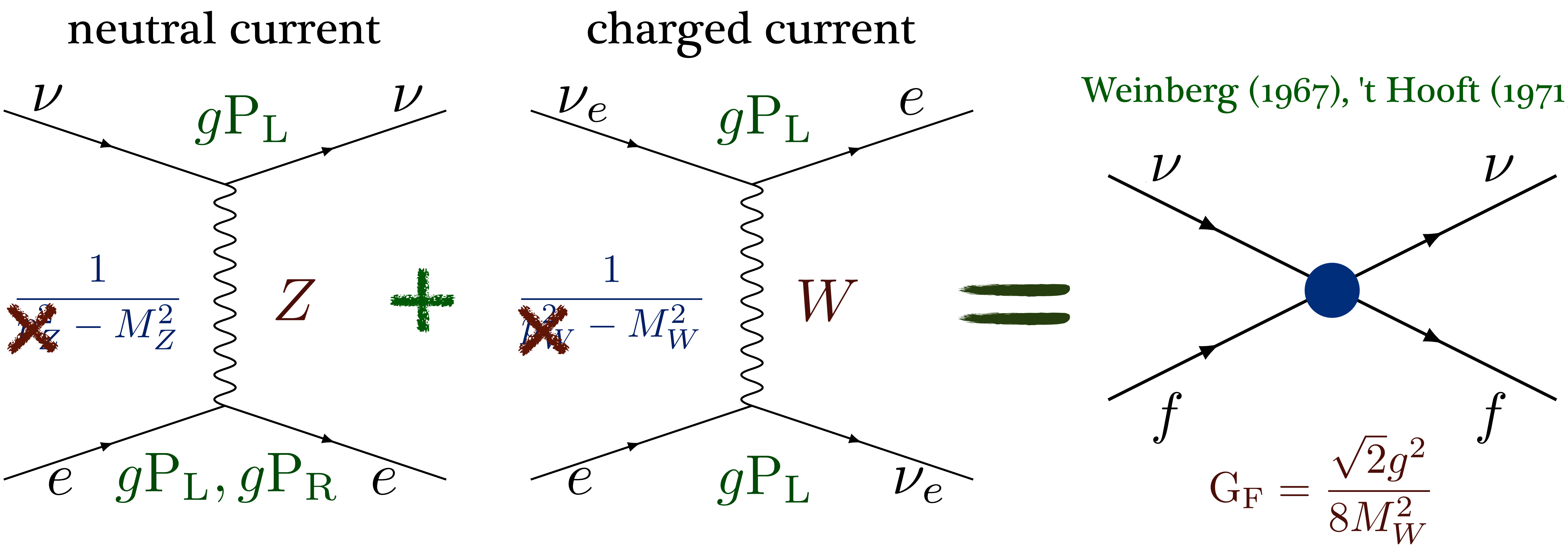
> - neutral current: no thresholds

Neutrino-electron scattering

- Fermi theory at GeV energies and below, $\sigma \sim m$

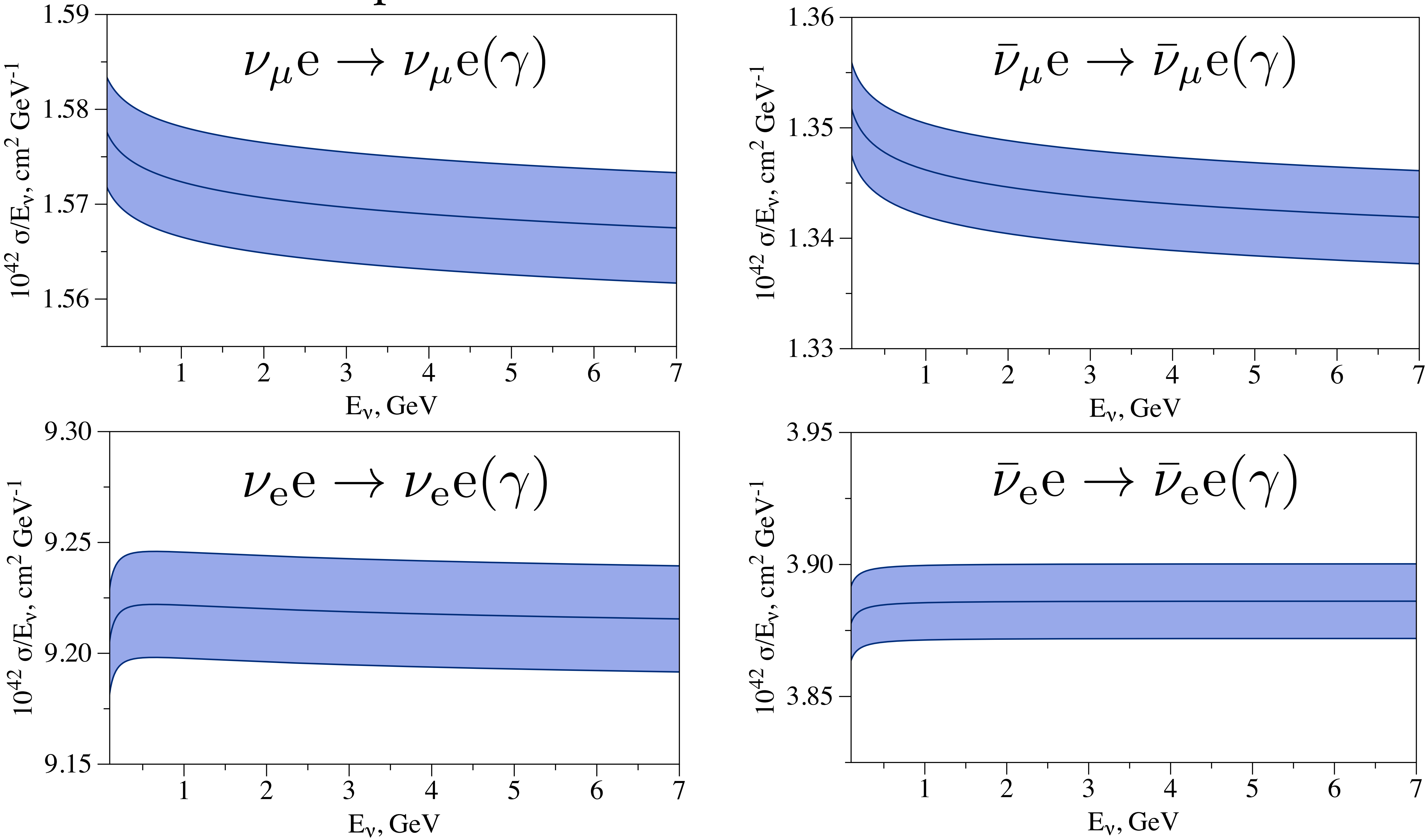


- s-channel resonant enhancement at vector-boson pole (PeV scale)

- historically: precise EW physics and BSM searches
- channel for in-situ flux constraints at accelerator experiments
- solar neutrinos@Super-K, SNO, Borexino
- recent observation of Glashow resonance by IceCube

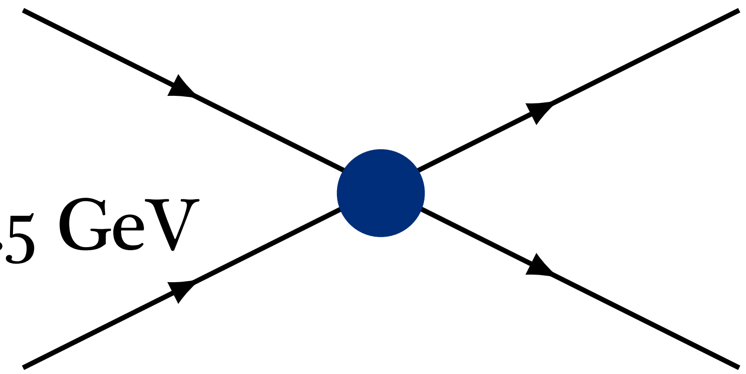
Absolute cross section

- hadronic loops introduce the main error

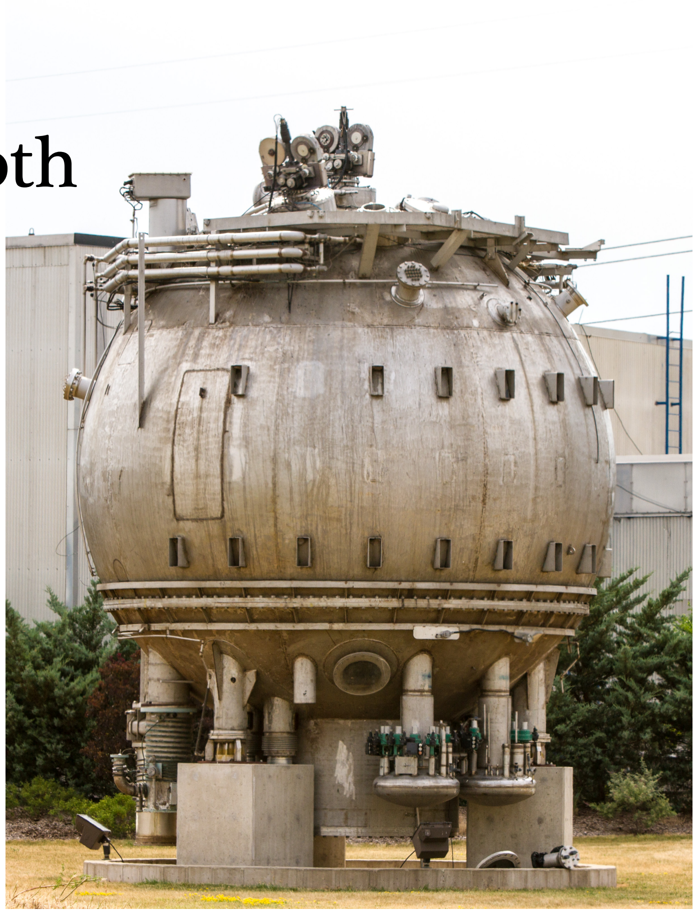


- quadratic dependence -> linear dependence -> resonance

Neutrino-nucleon scattering (CC)



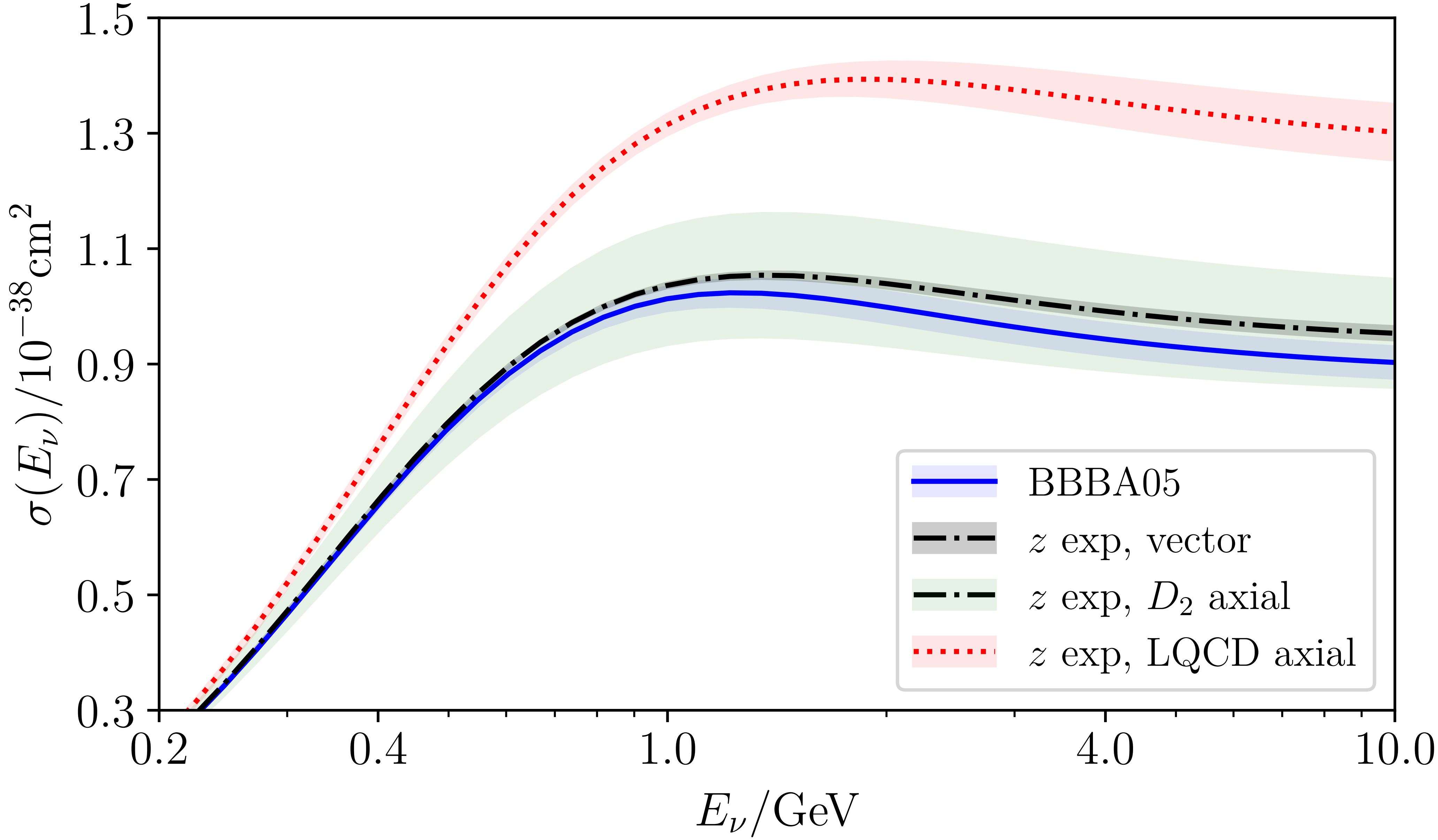
- 4-Fermi theory + ChPT @ and < pion-mass scale
- production thresholds: muon ~ 110 MeV, tau ~ 3.5 GeV
- only electron flavor for supernova, solar, and reactor neutrinos
- data from deuterium bubble chambers in 1980th
- CH_2-C subtraction results are anticipated
- provide nucleon axial form factor
- target for many lattice QCD groups



Fermilab bubble chamber, Richard Drew

- elastic scattering -> pion production -> deep inelastic scattering

Neutrino-nucleon scattering (CC)

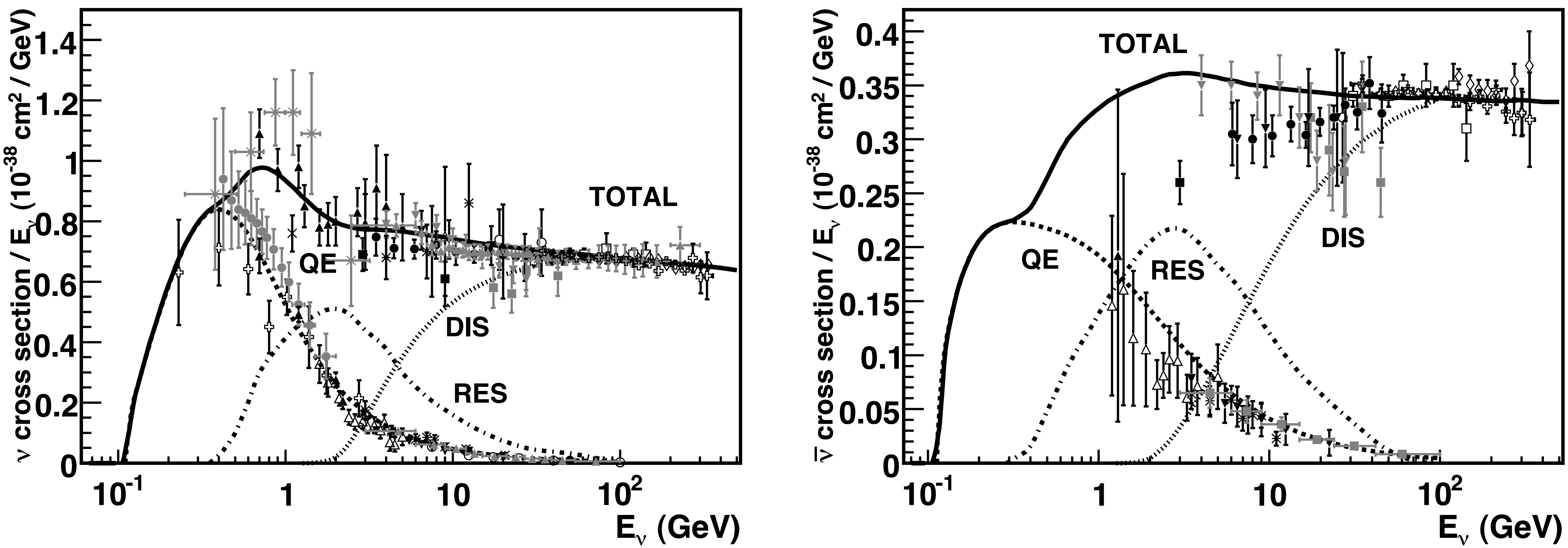


A.S. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. of 72, 010622-120608 (2022)
A.S. Meyer, M. Betancourt, R. Gran, and R.J. Hill, PRD (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill, and O. T. , PRD (2021)

- knowledge of vector structure stops a progress in studies of axial
- acknowledged discrepancy: lattice QCD <-> experimental data

Neutrino-nucleus scattering

- NC scattering across all energies -> neutrino floor
- CC with electron flavor for supernova, solar, and reactor neutrinos
- same open channels as at nucleon level



Formaggio and Zeller (2013)

- binding effects, Fermi motion, Pauli blocking
- meson exchange, 2p-2h, final-state interaction

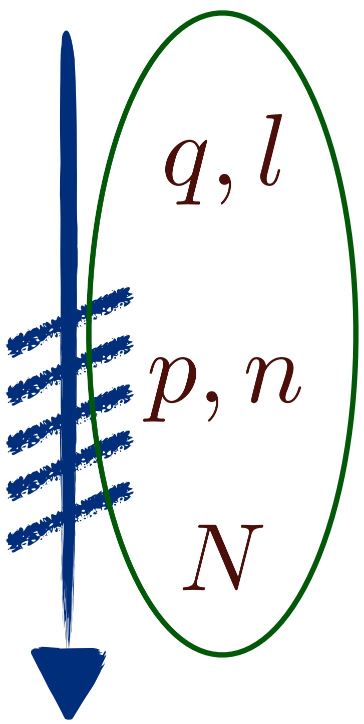
Neutrino cross sections at CIPANP-2022

Wednesday, August 31

- Maria Martinez-Casales: A Consideration of NOvA Cross Sections
- Nina Coyle: Neutrino Cross Sections and New Physics Searches
- Joshua Barrow: $e4\nu$, $\mu4\nu$: Brightening Future of Neutrino Oscillation Measurements
- Yin Lin: Neutrino-nucleon quasi-elastic scattering from lattice QCD

Other days

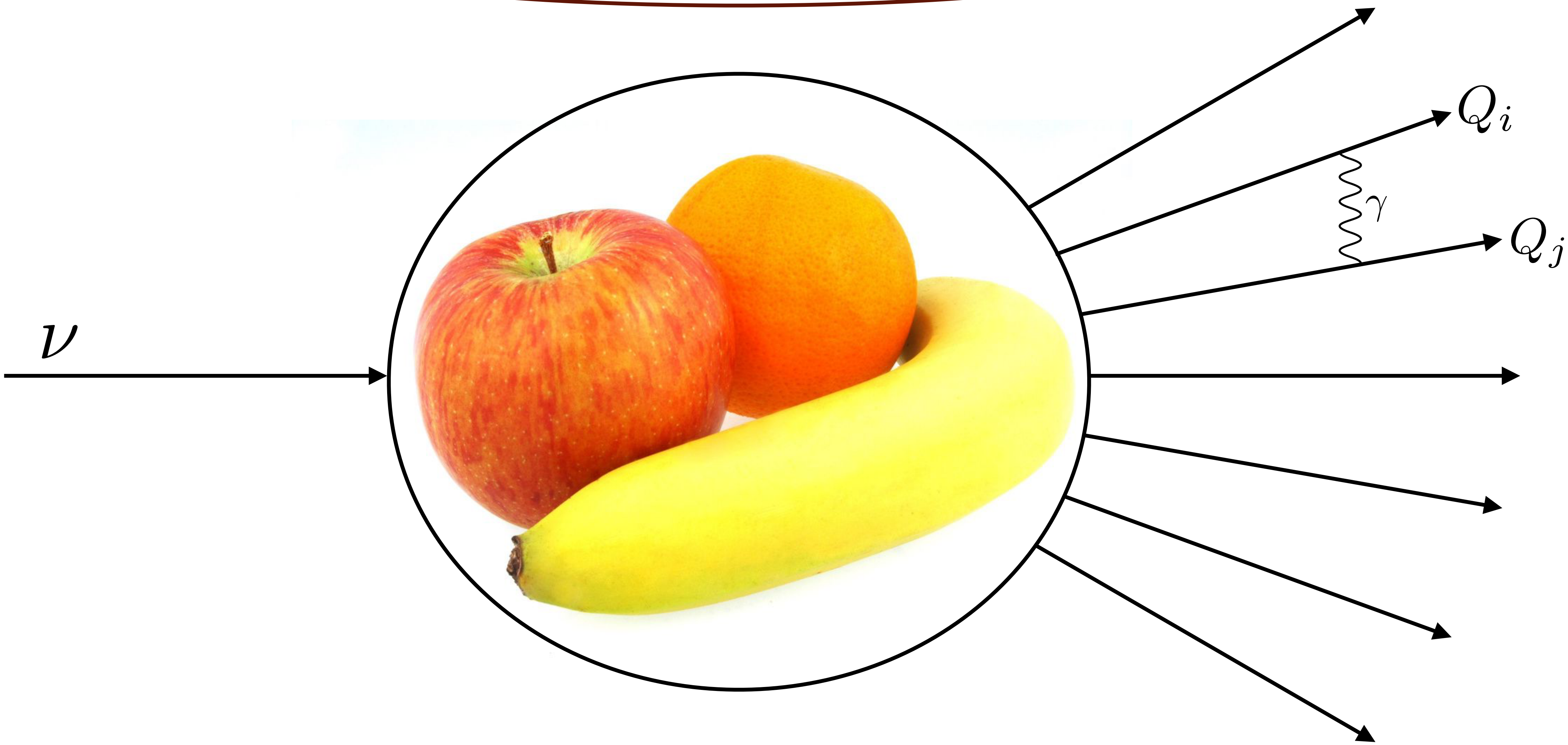
- Alejandro Ramirez Delgado: Neutrino-induced production in C, CH, Fe and Pb at $E_\nu \sim 6$ GeV
- Camilo Mariani: Electron Scattering Cross-Sections for Neutrinos@JLab
- Vishvas Pandey: Theory Overview of Coherent Elastic and Inelastic Neutrino-Nucleus Scattering
- Michael Wagman: Precise Lattice Calculations for Neutrino Scattering



Radiative corrections in neutrino physics (at MeV-GeV energies)

Electroweak corrections

$$m_e, m_\mu, M, E_\nu \ll M_W, M_Z, m_t, m_H$$



$$\frac{\alpha}{\pi} \sim 0.2\ \% \text{ multiplied by } \frac{1}{\sin^2\theta_W},\ \ln\frac{M_Z}{M},\ \ln\frac{M_t}{M},\ldots$$

- electroweak corrections can be included in low-energy interactions couplings of effective Lagrangian are precisely determined

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

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

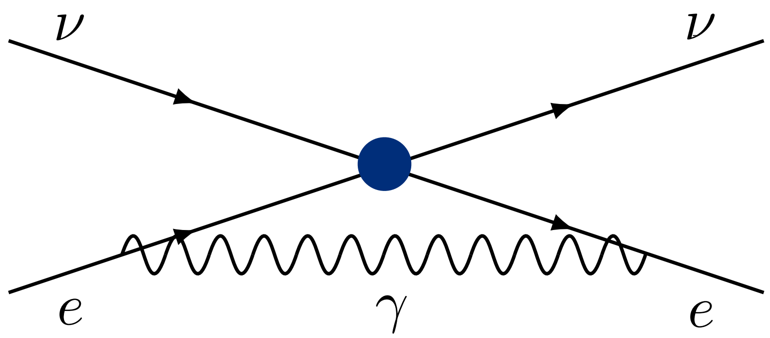
Neutrino-lepton, neutrino-quark scattering

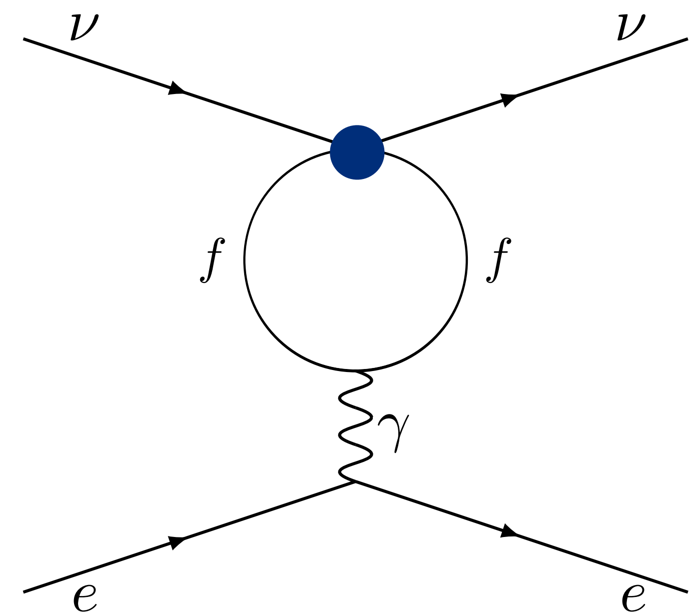
O.T. and Richard J Hill, Phys. Lett. B 805, 3, 135466 (2020)

known at permille level ✓

leading in $\mathrm{G_F}$ terms with loop expansion in α, α_s within Standard Model

poster at Neutrino 2020: https://youtu.be/mrW4aYjP57w



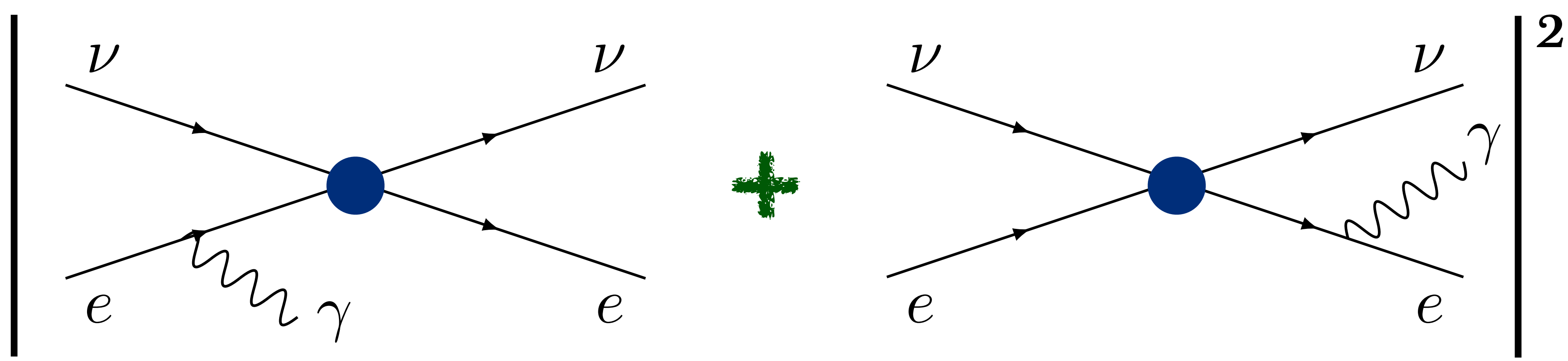


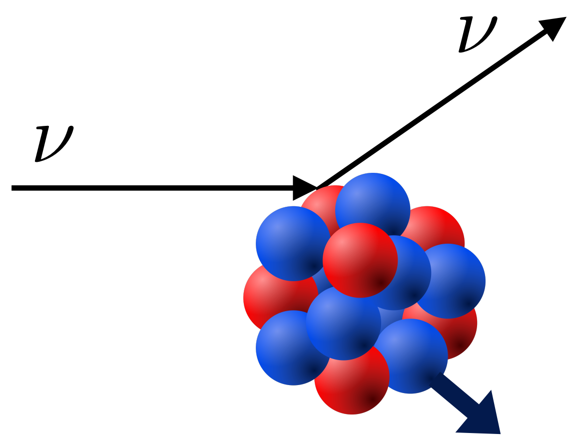
Neutrino-electron scattering

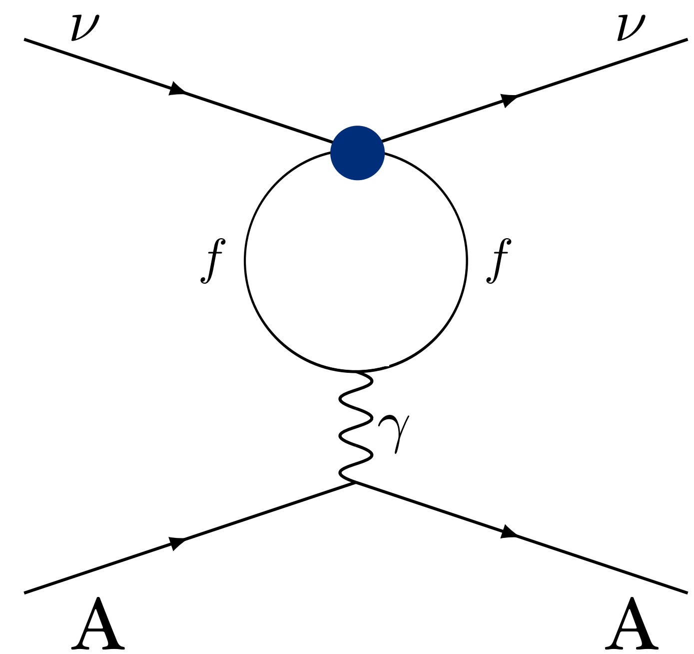
O.T. and Richard J Hill, Phys. Rev. D 101 3, 033006 (2020)

percent-level predictions for MINERvA

known analytically at permille level for NOvA and DUNE, solar ν







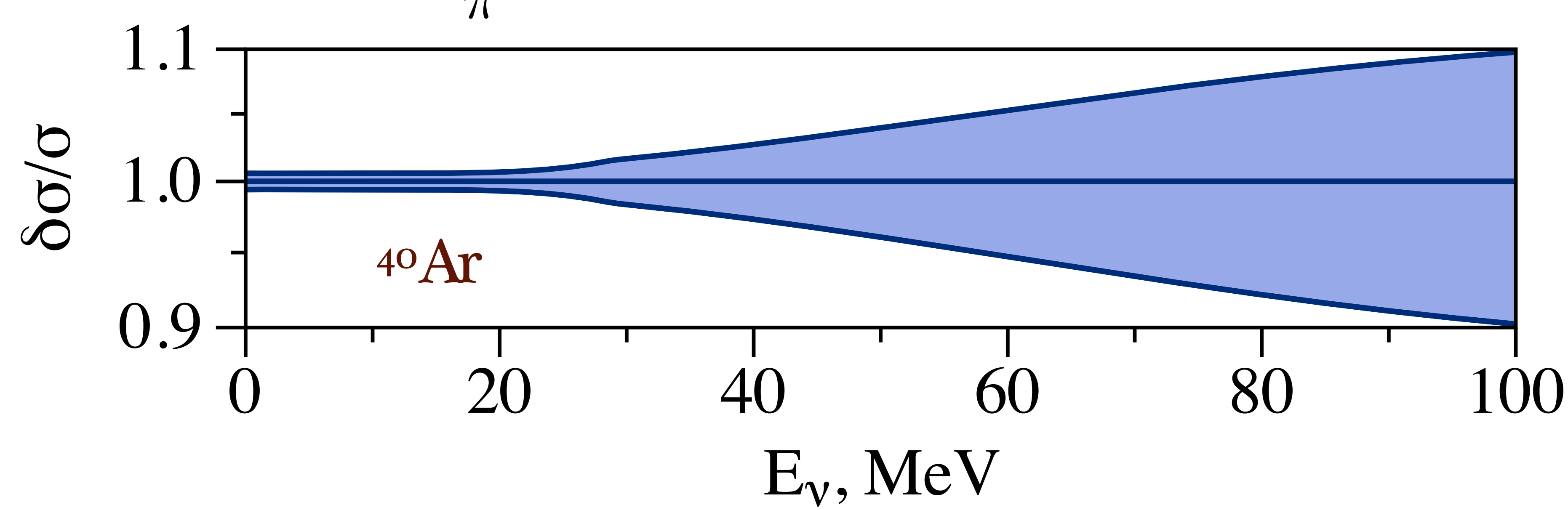
Coherent elastic neutrino-nucleus scattering

O.T., Pedro Machado, Vishvas Pandey and Ryan Plestid, JHEP 2102, 097 (2021)

$$\mathrm{F_W}\left(Q^2\right) \to \mathrm{F_W}\left(Q^2\right) + \frac{\alpha}{\pi}[\delta^{\nu_\ell} + \delta^{\mathrm{QCD}}]\mathrm{F_{ch}}(Q^2)$$

flavor-dependent
at percent level

for Coherent and CCM



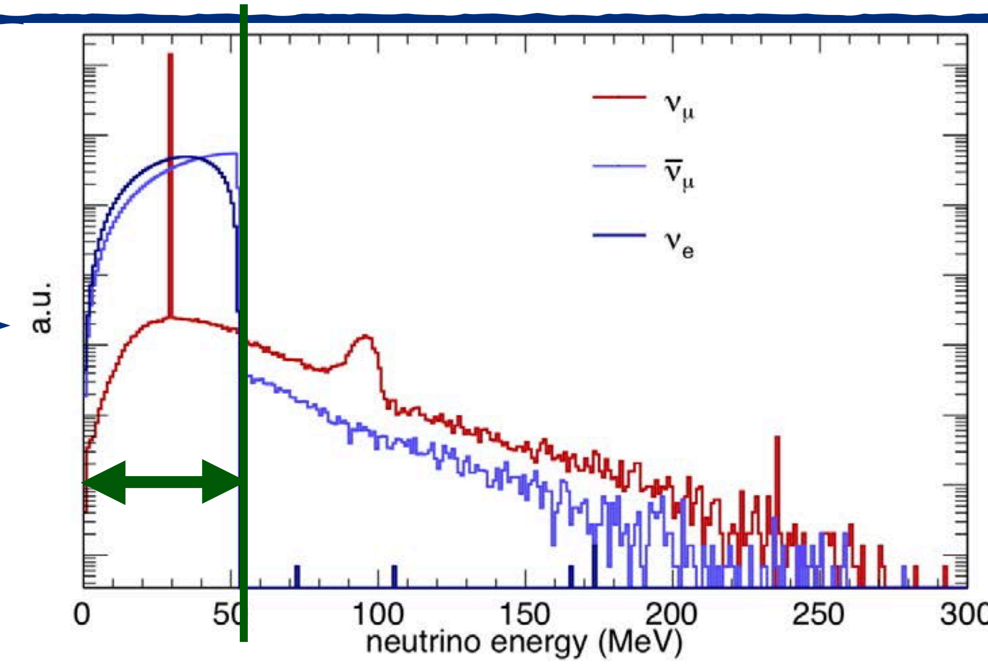
Neutrinos from muon, pion and kaon decays

flavor-dependence at tree-level

energy spectra from πDAR

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



Akimov et al., Science 357 6356, 1123-1126 (2017)

O. T., Phys. Lett. B 829, 137108 (2022)

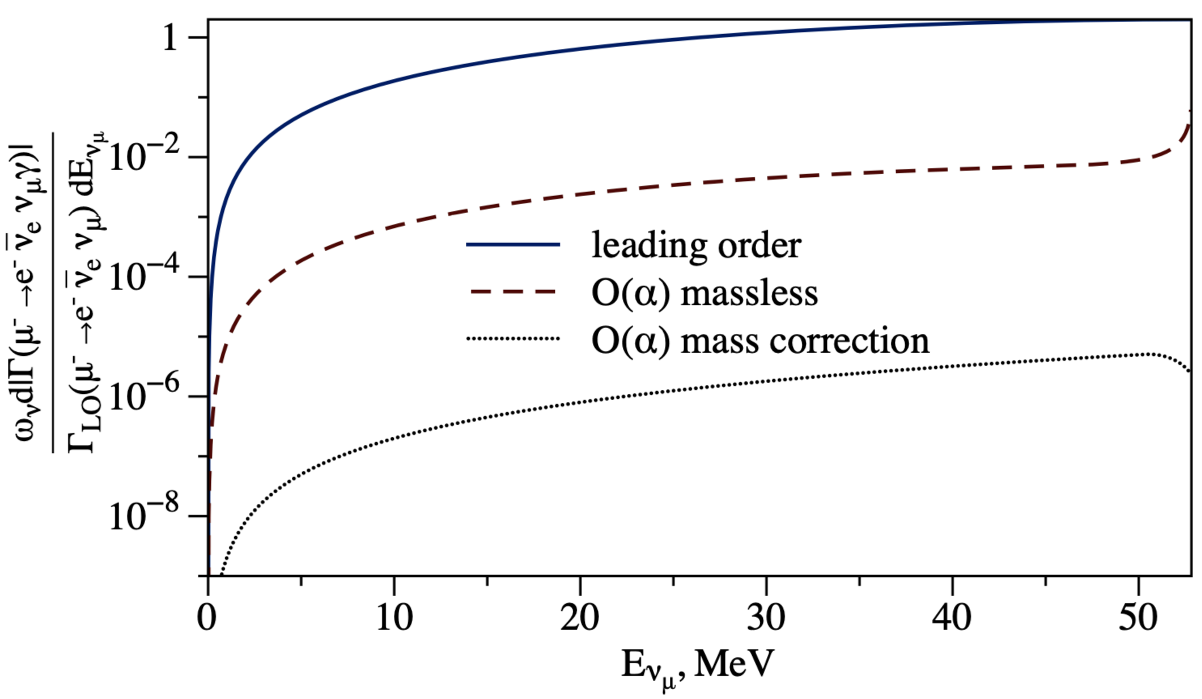
$$\pi^+ \to \mu^+ \nu_\mu \gamma$$

$$K^+ \to \mu^+ \nu_\mu \gamma$$

< 0.1 ‰

flavor-dependence is clarified to permille level analytically ✓

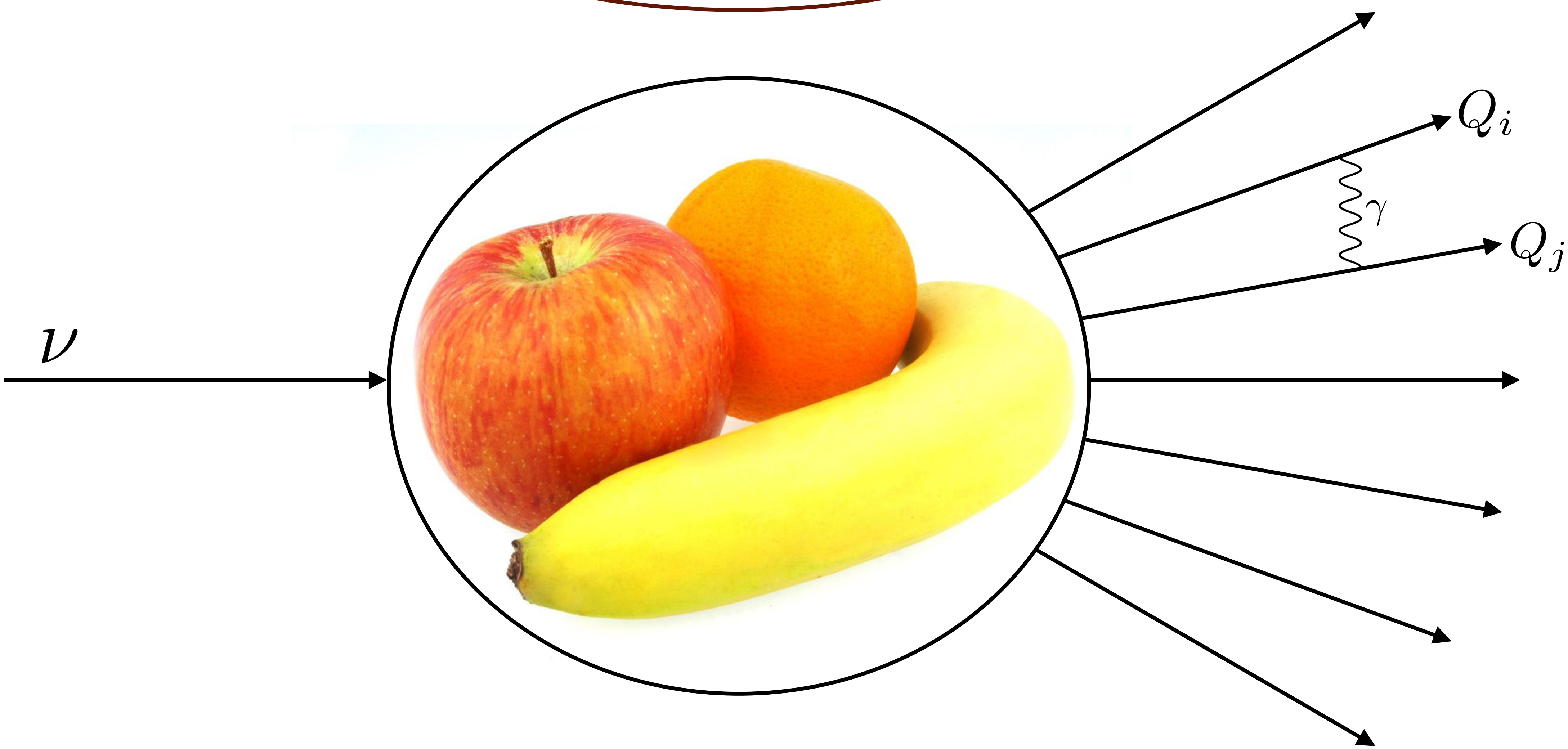
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$$ 3-4 ‰



first QED/EW form factors with different mass

QED corrections

$$m_e \ll m_\mu \ll E_\nu$$



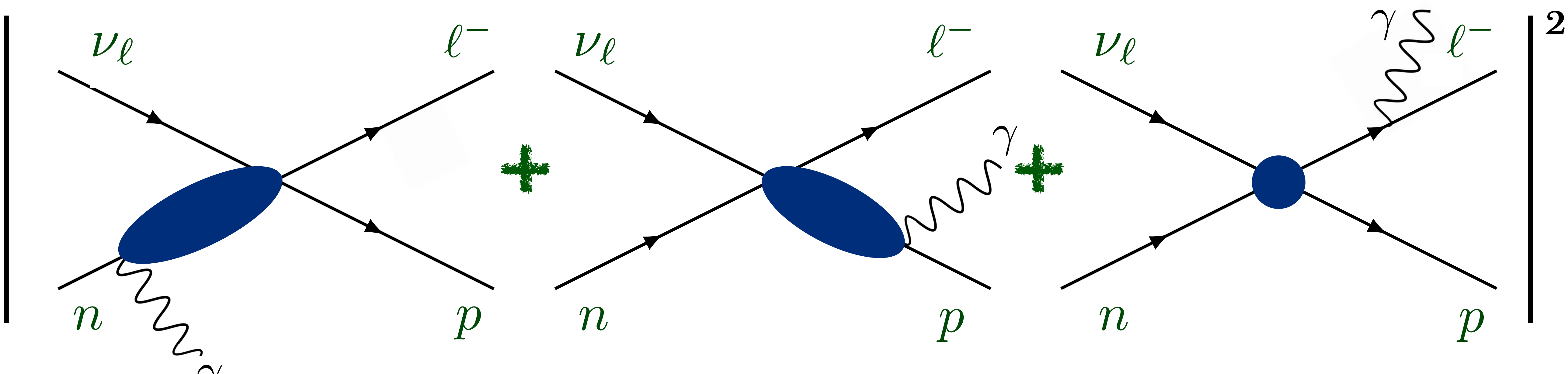
$$\frac{\alpha}{\pi} \sim 0.2\ \% \text{ multiplied by } \ln\frac{E_\nu}{m_e} \sim 6-10 \text{ or } \ln^2\frac{E_\nu}{m_e} \sim 36-100$$

- scale separation introduces large flavor-dependent QED logarithms factorization for radiative corrections with model for hard function

Charged-current elastic scattering on nucleons

precise predictions for flavor ratios and radiative corrections

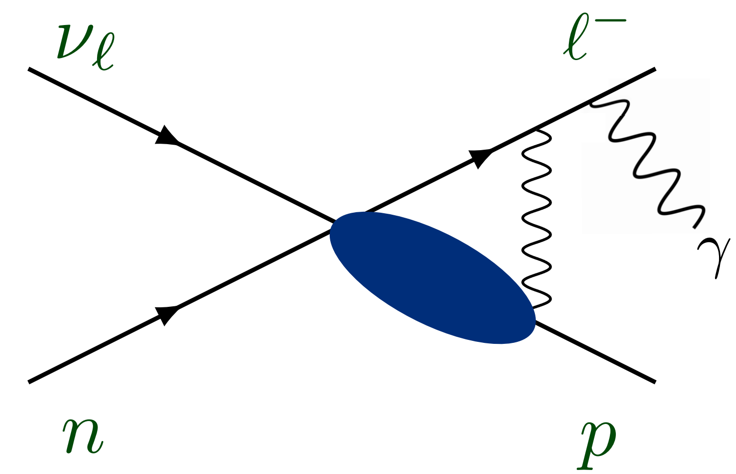
in exclusive and inclusive observables with GeV neutrino beams



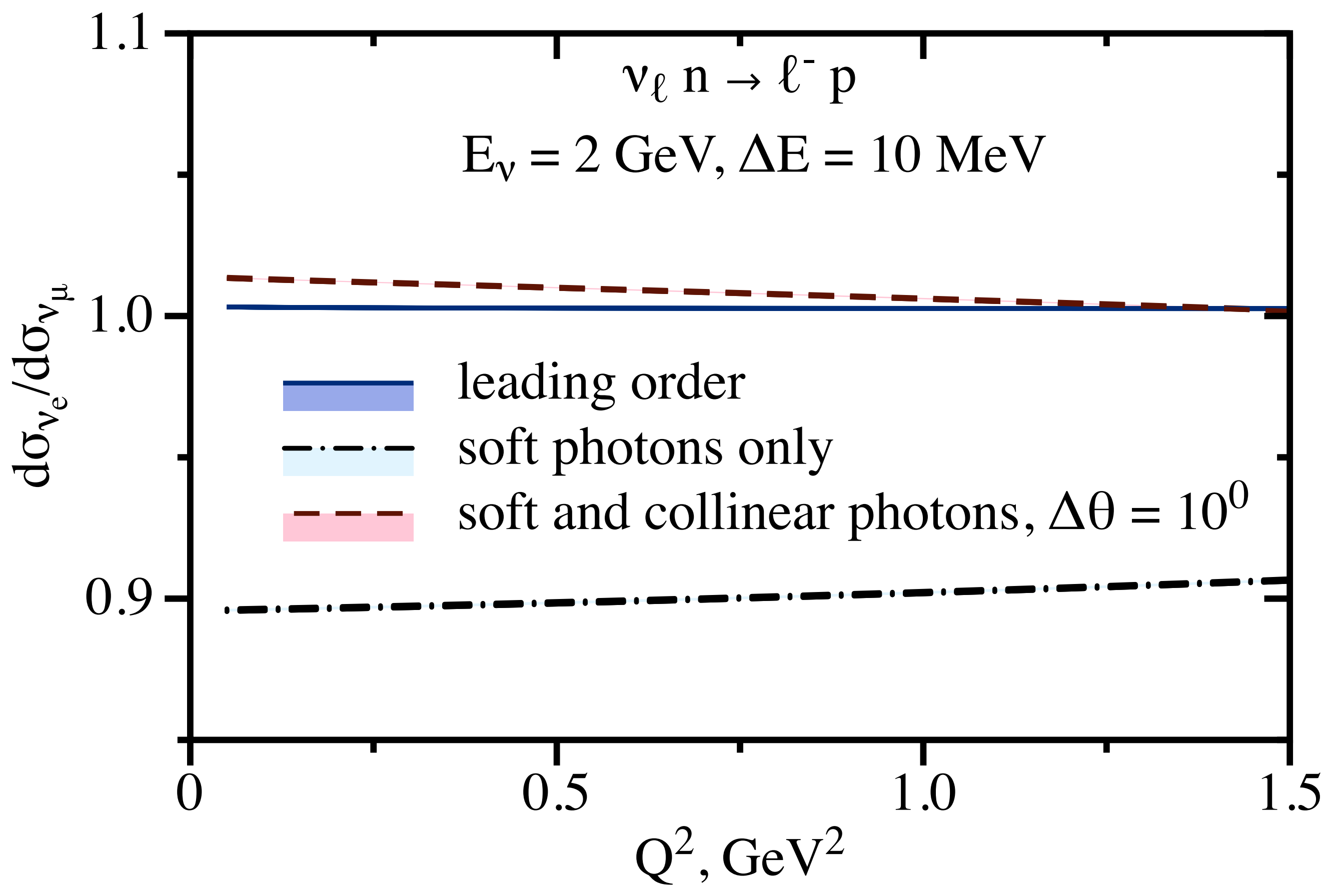
Charged-current scattering on nucleons

- theory and 1st-ever complete calculation
  10-20% hadronic uncertainties
  cancel for e/μ ratio

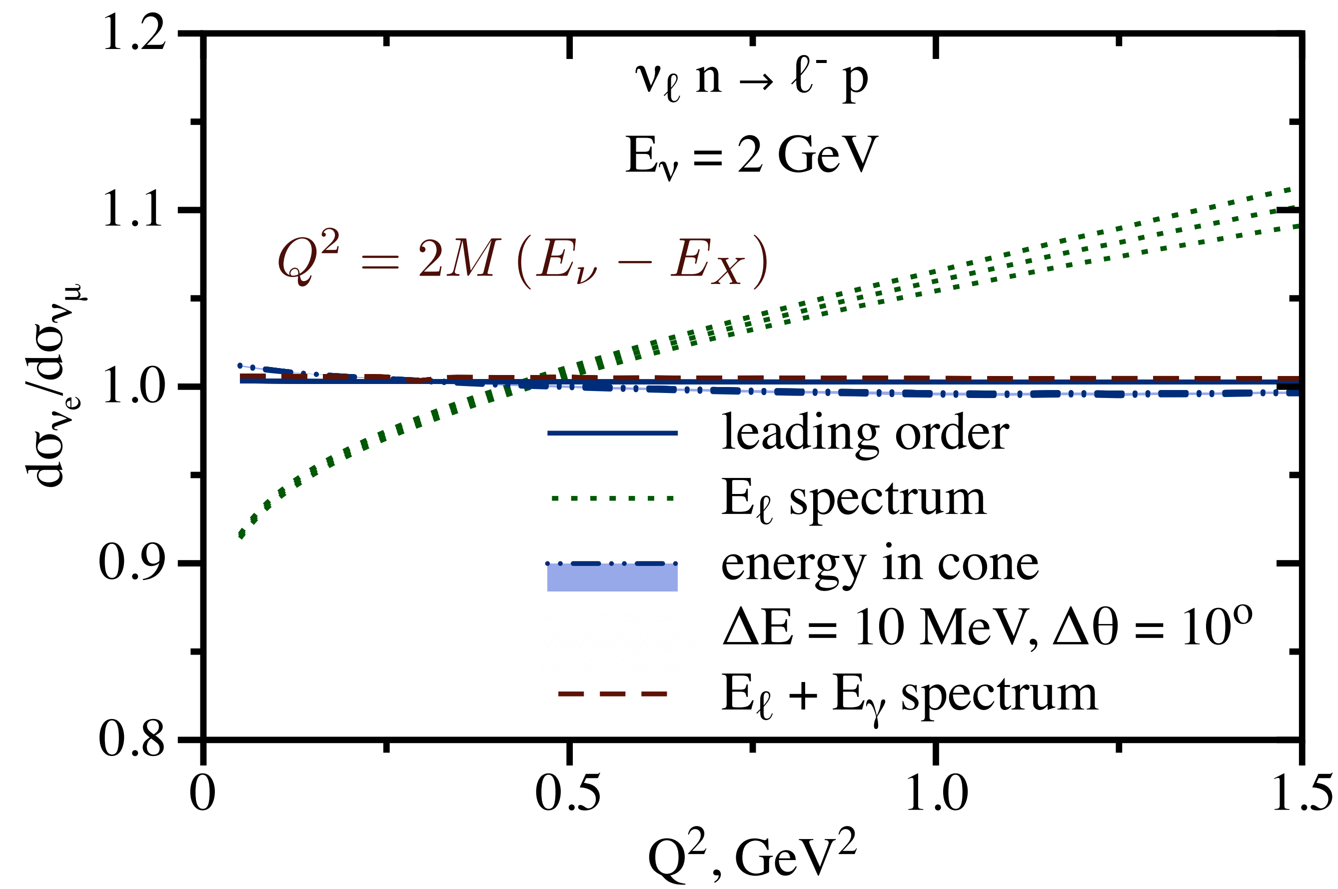
O. T., Qing Chen, Richard J. Hill, Kevin S. McFarland, and Clarence Wret (2021, 2022)



exclusive



inclusive



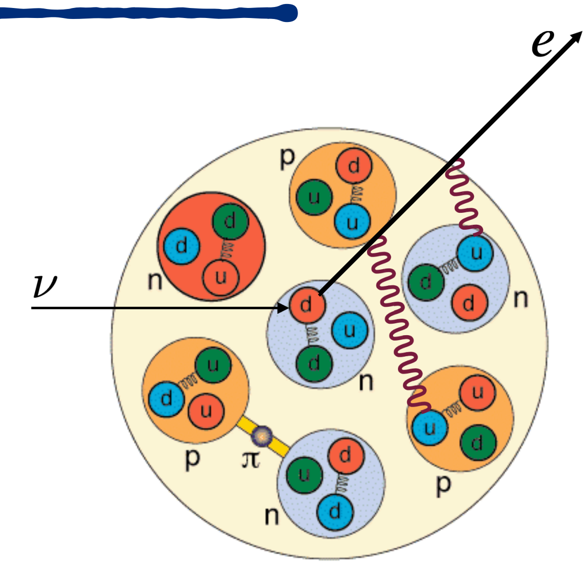
- critical dependence on details of experimental analysis
- predict σ_{ν_e} from σ_{ν_μ} measurements with neutrino beam

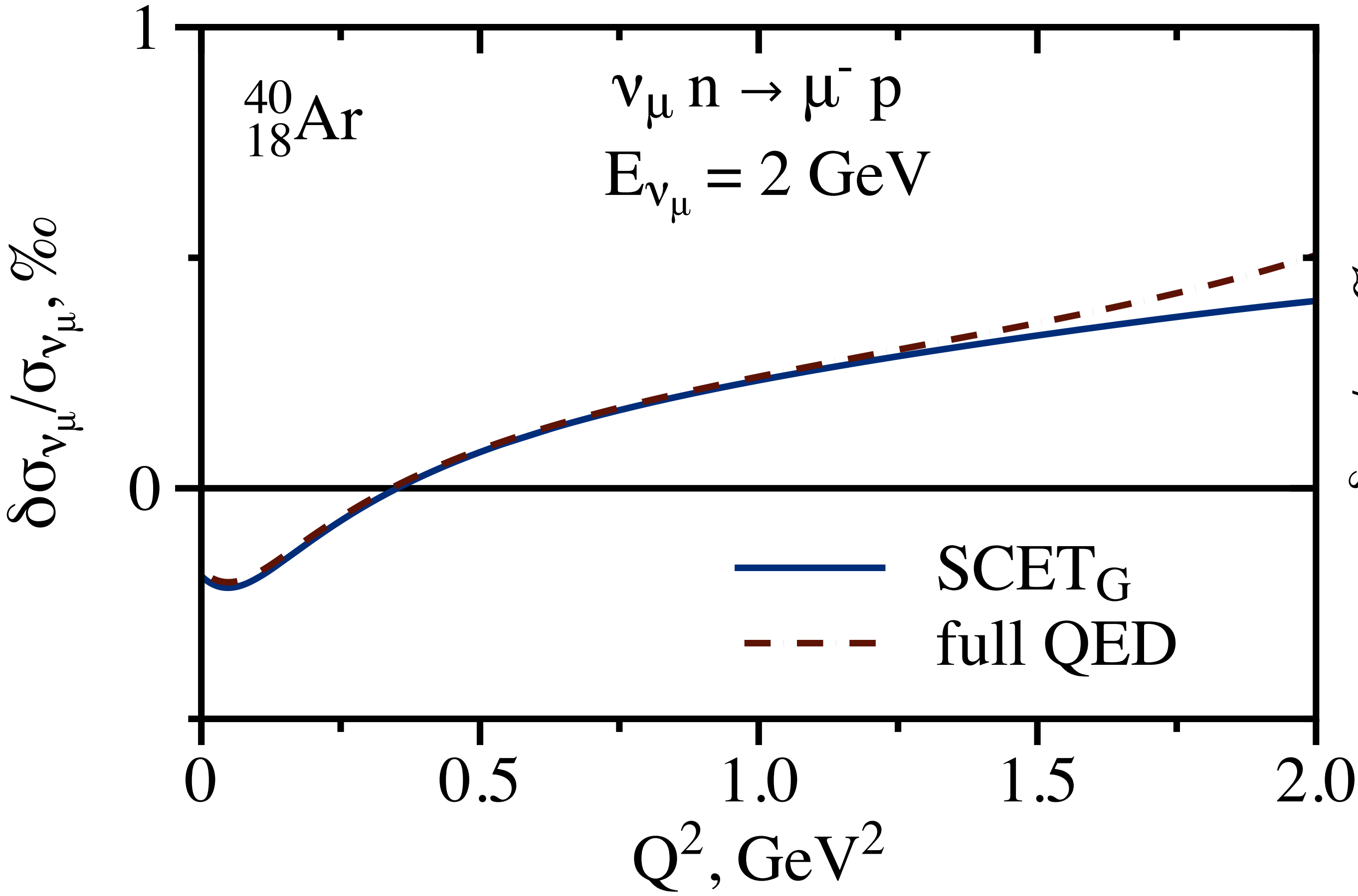
QED nuclear medium effects

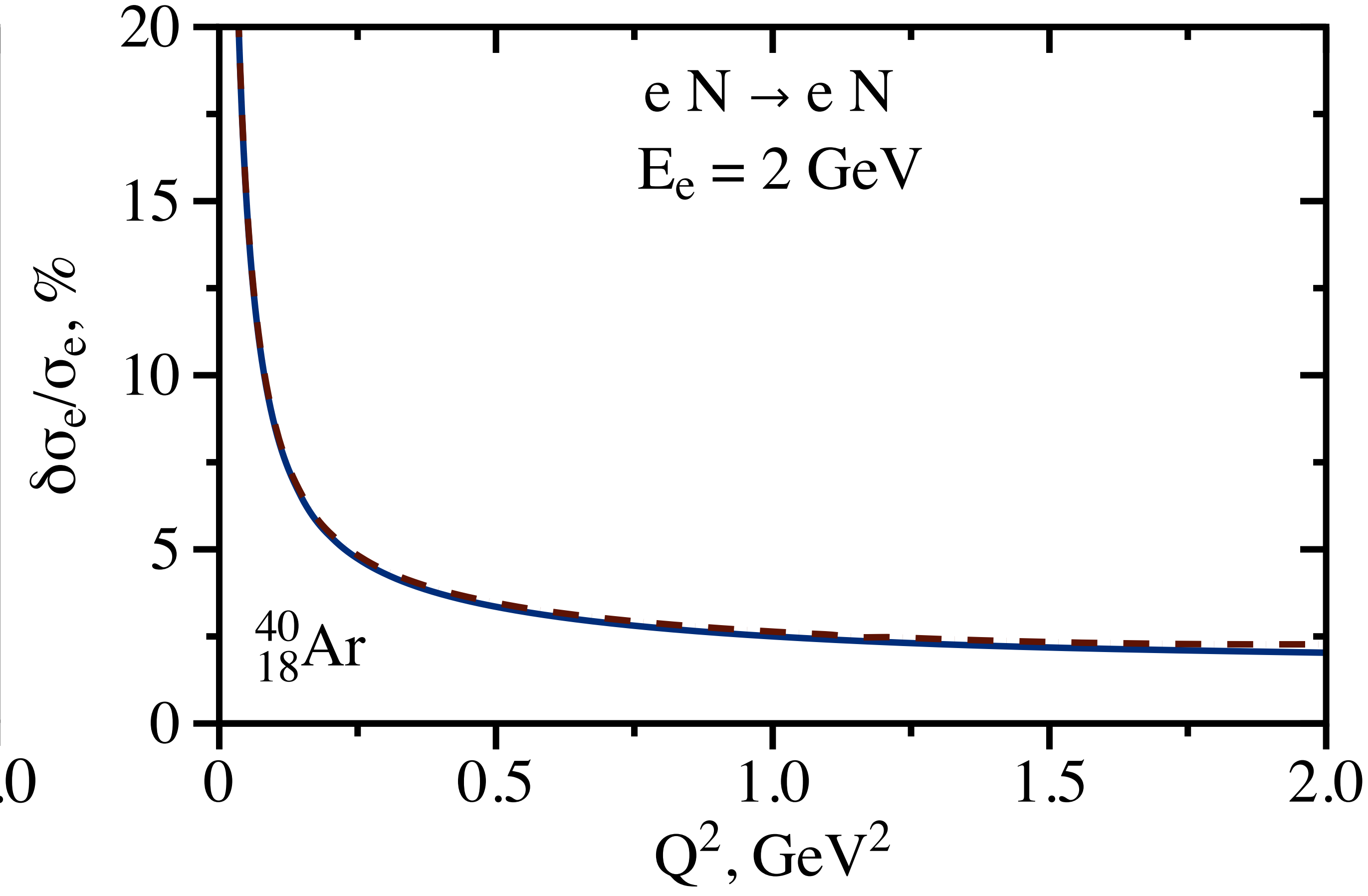
- theory and 1st-ever estimate by two methods:

SCET$_G$: Soft-collinear effective theory (Glauber)
QED: quantum electrodynamics

O. T. and Ivan Vitev (2022)







- permille-level for ν_e A -> eA', percent-level for eA -> eA
- critical new effect for electron scattering experiments

Conclusions

- neutrino cross sections is the main tool to access neutrinos
- various production and interaction mechanisms at all energy scales
- interplay of nuclear and particle physics, astrophysics and cosmology
- radiative corrections (1-20%) for consistent uncertainty estimates
- radiative corrections for precise flux determinations
- QED nuclear effects in neutrino and electron scattering
- total and differential νe, CEvNS, $\nu_\ell n \to \ell^- p$ and $\bar{\nu}_\ell p \to \ell^+ n$ flavor ratios evaluated from theory with rigorous error analysis

$$\nu e^- \to \nu e^- \, (\gamma)$$

$\pi^+ \to \mu^+ \nu_\mu (\gamma)$ $K^+ \to \mu^+ \nu_\mu (\gamma)$ $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu (\gamma)$

Thanks for your attention !!!

$\bar{\nu}_\ell p \to \ell^+ n \, (\gamma)$ $\nu_\ell n \to \ell^- p \, (\gamma)$

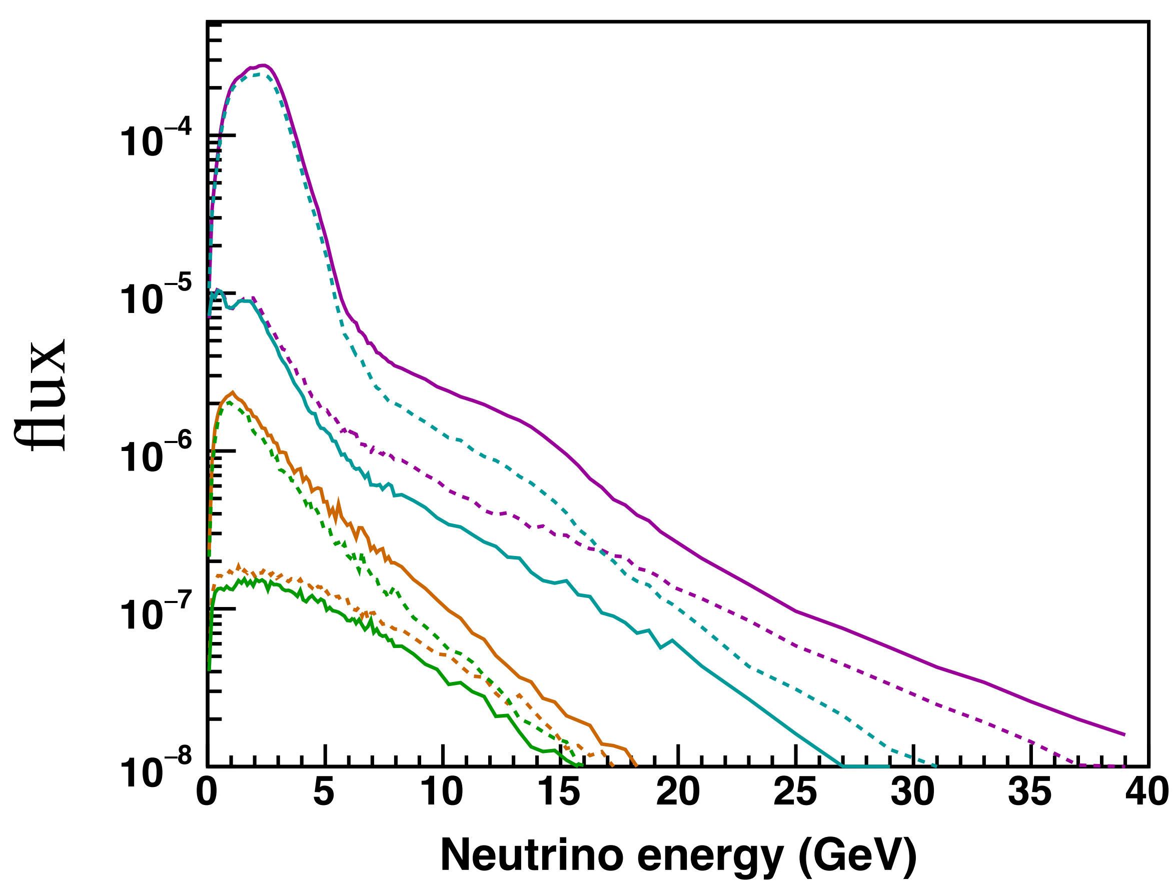
$$\nu \; {}^{40}\mathrm{Ar} \to \nu \; {}^{40}\mathrm{Ar} \, (\gamma)$$

Main theoretical uncertainty

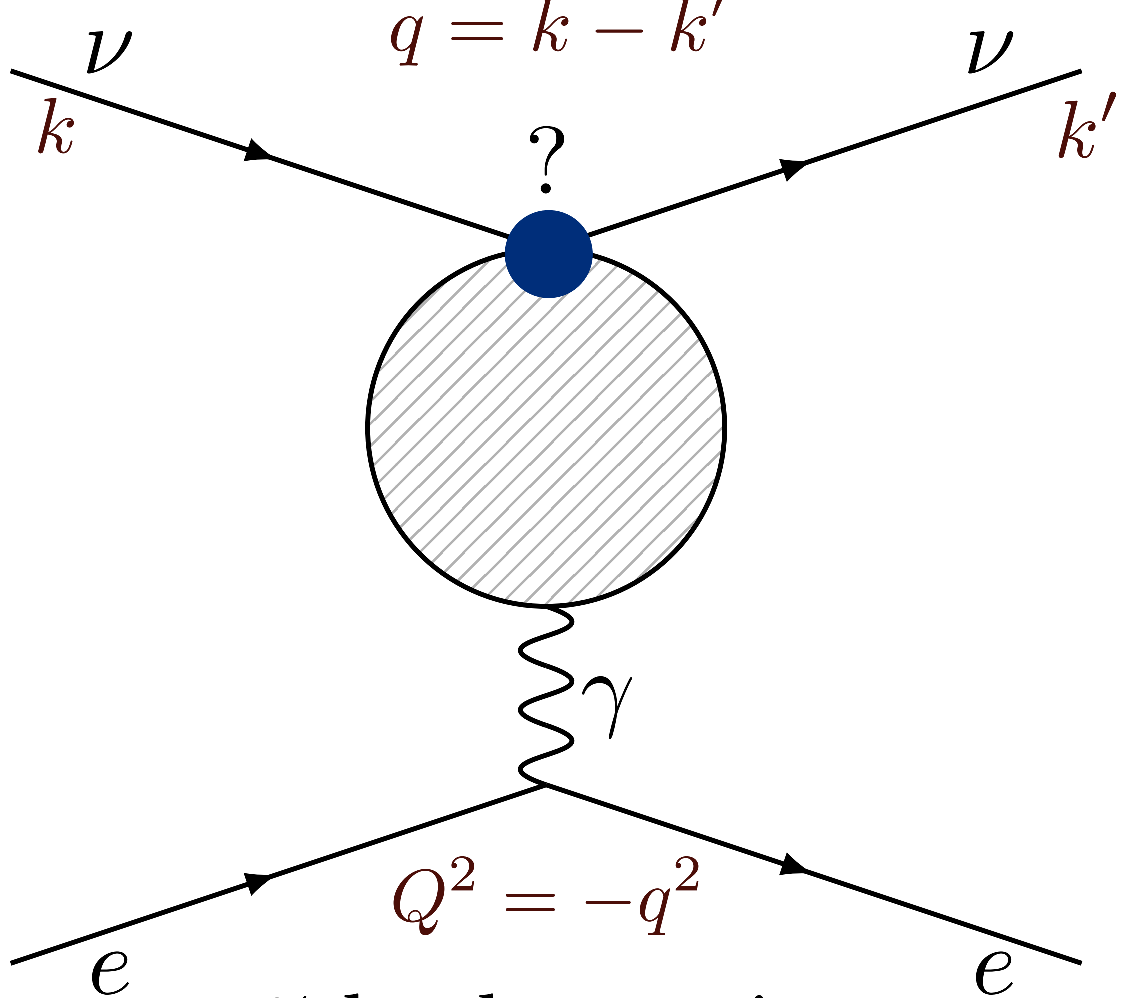
- kinematics is suppressed by electron mass:

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

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



Ch. Marshall et al, Phys.Rev.D 101 3, 032002 (2020)



% level correction

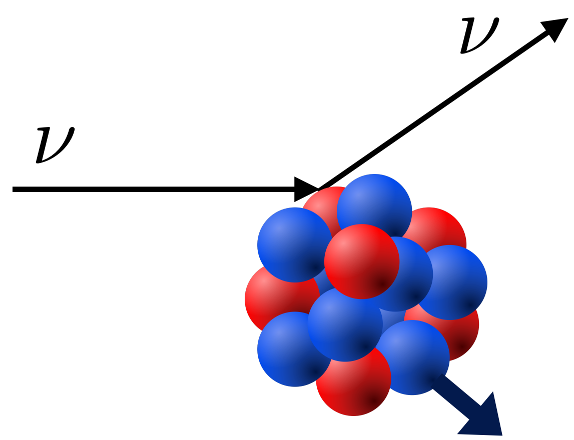
- hadronic correction is the main error in theory

Coherent elastic neutrino-nucleus scattering

- at low neutrino energies (<50 MeV) nuclear state is unchanged

  nucleus recoils as a whole

  Stodolsky (1966), Freedman (1974), Kopeliovich and Frankfurt (1974)



recoil nucleus energy T

- large cross section scales as squared number of neutrons N^2

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M_A}{4\pi}\left(1 - \frac{M_A T}{2E_\nu^2}\right)\left(N - \left(1 - 4\sin^2\theta_W\right)Z\right)^2$$

- first detection in 2017 at SNS, measured on CsI and Ar

  COHERENT, Science 357 (2017) 6356, 1123-1126

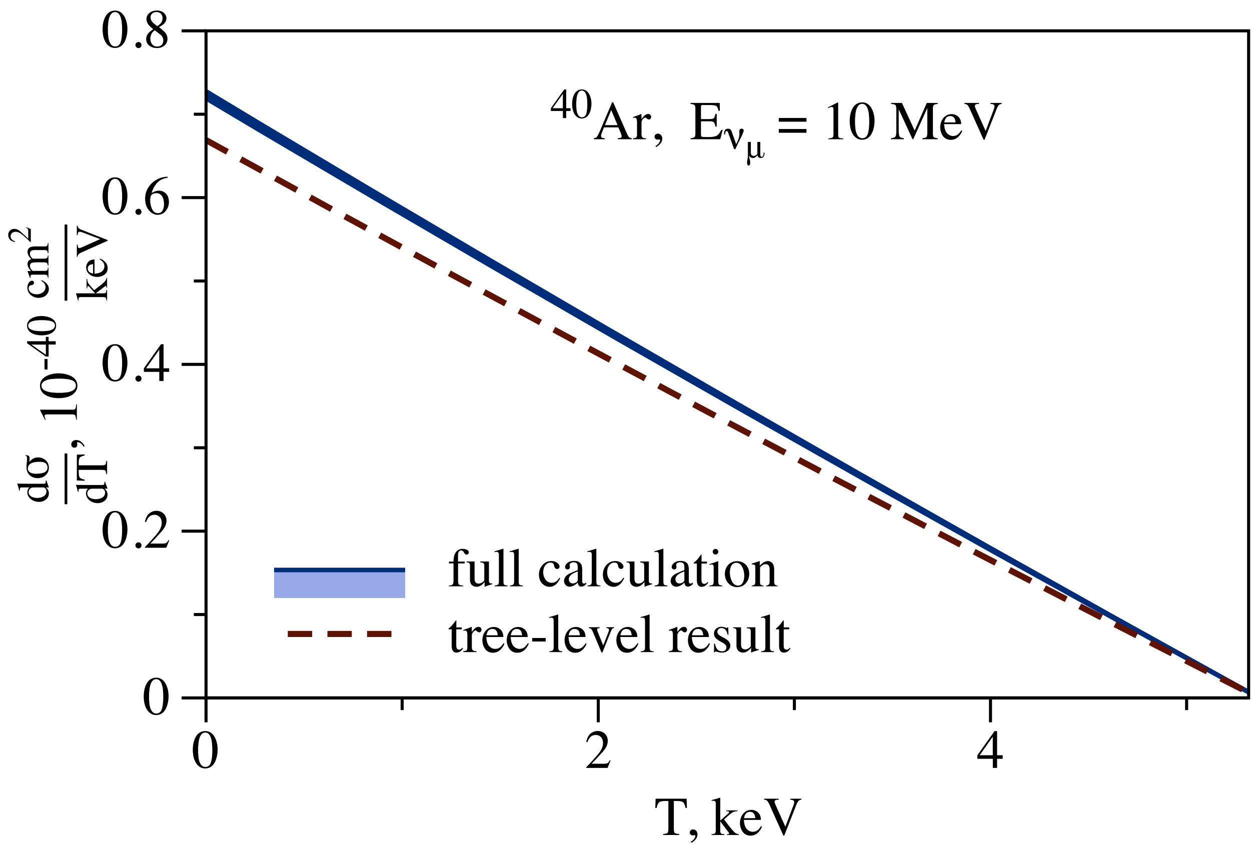
- rapidly developing field nowadays

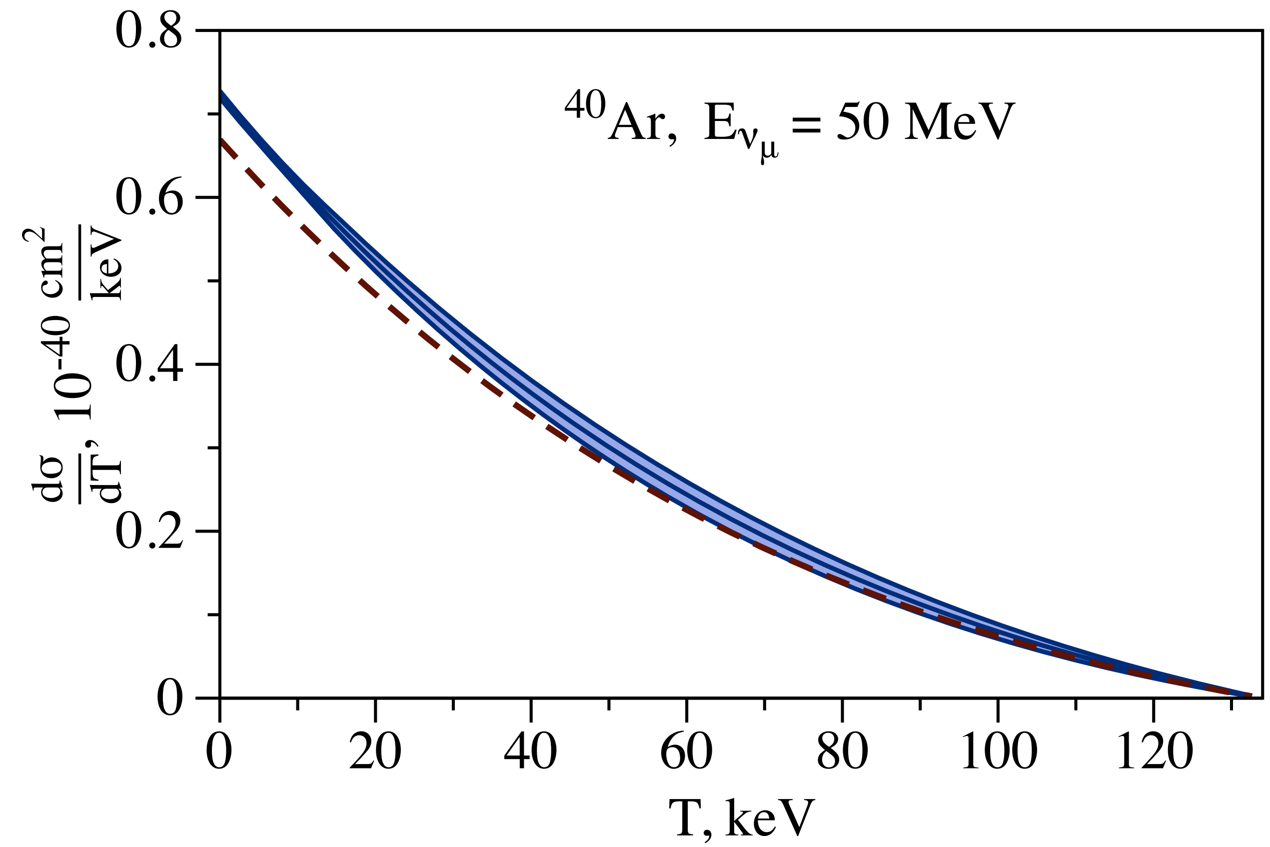
- CEvNS enters precision era with πDAR sources

Total and differential cross section

- recoil nucleus energy spectrum: one-loop vs tree level

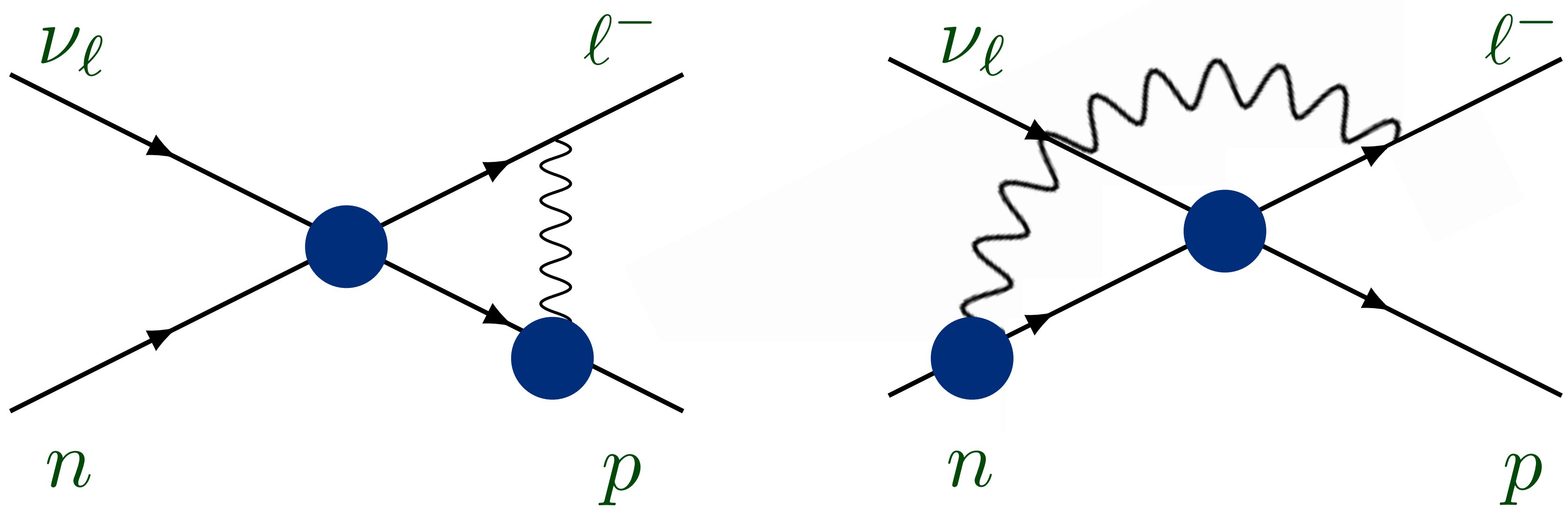
nuclear models for point-nucleon form factors:
Yang et al. (2019), Payne et al. (2019), Hoferichter et al. (2020), Van Dessel et al. (2020)





- % effect of radiative corrections on cross sections

Hadronic model at GeV scale



- exchange of photon between the charged lepton and nucleons

- assume onshell form for each interaction with dipole form factors

discussed for neutrino-nucleon scattering: Graczyk (2013)

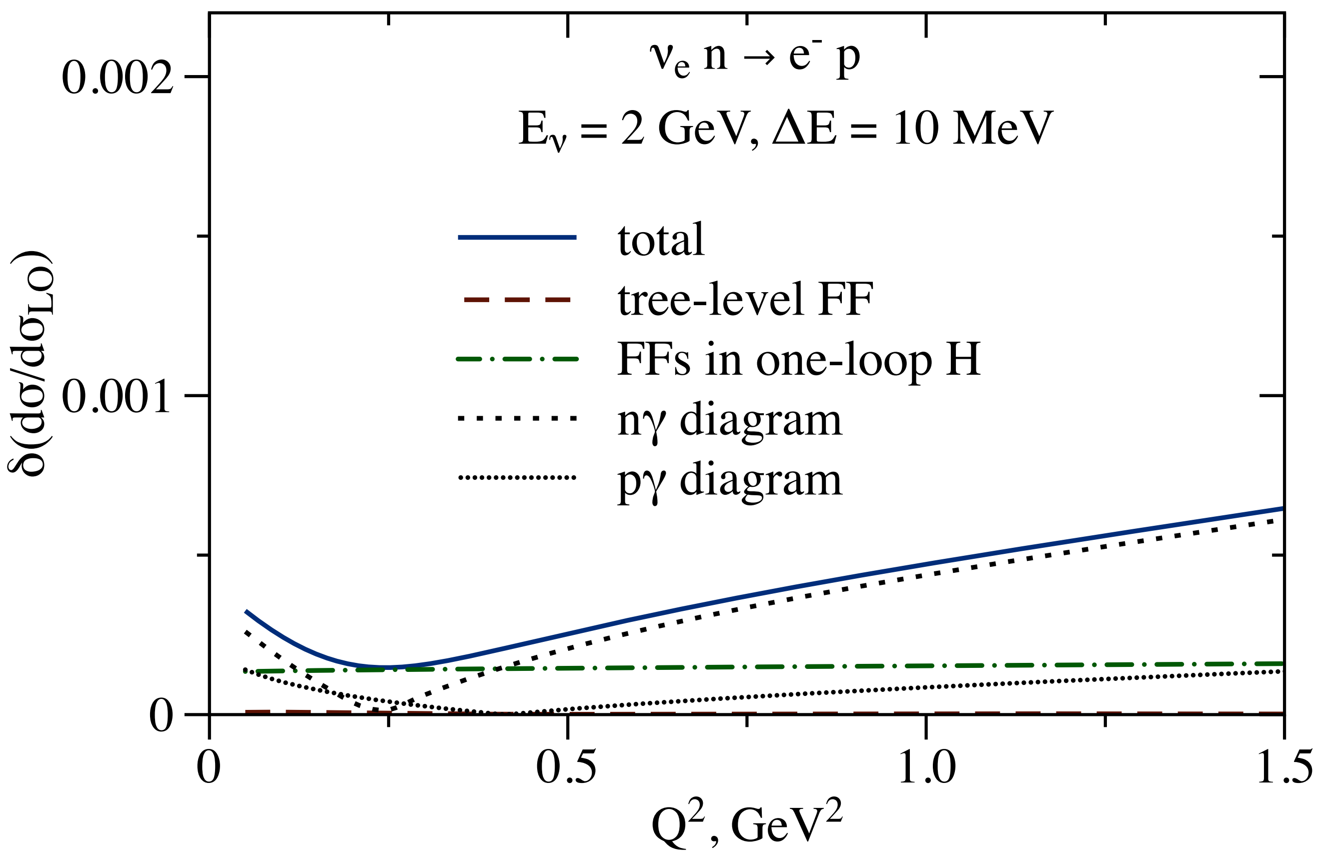
- add self energy for charged particles

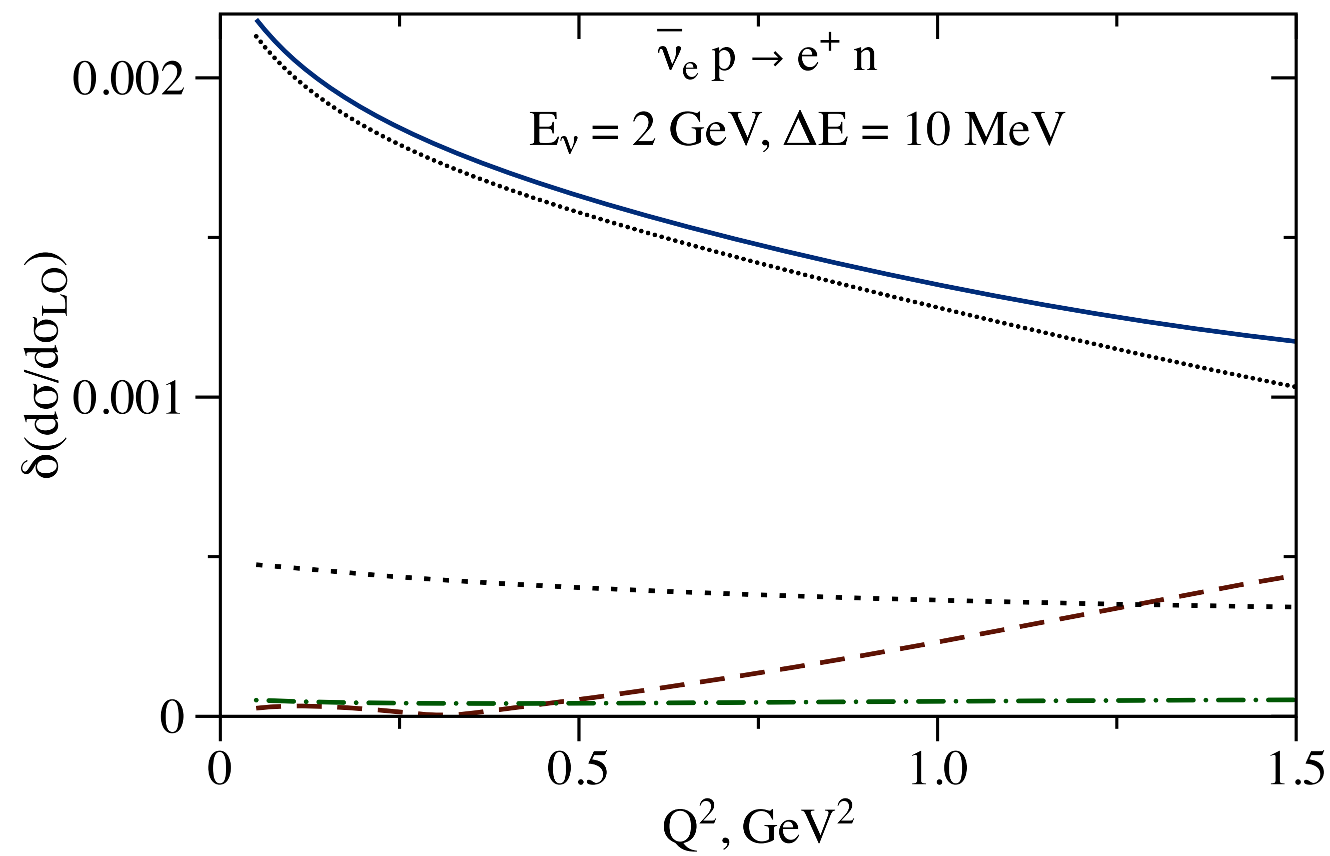
- reproduce soft and collinear regions of SCET

- best determination of hard function

Error budget

- uncertainties from hard function



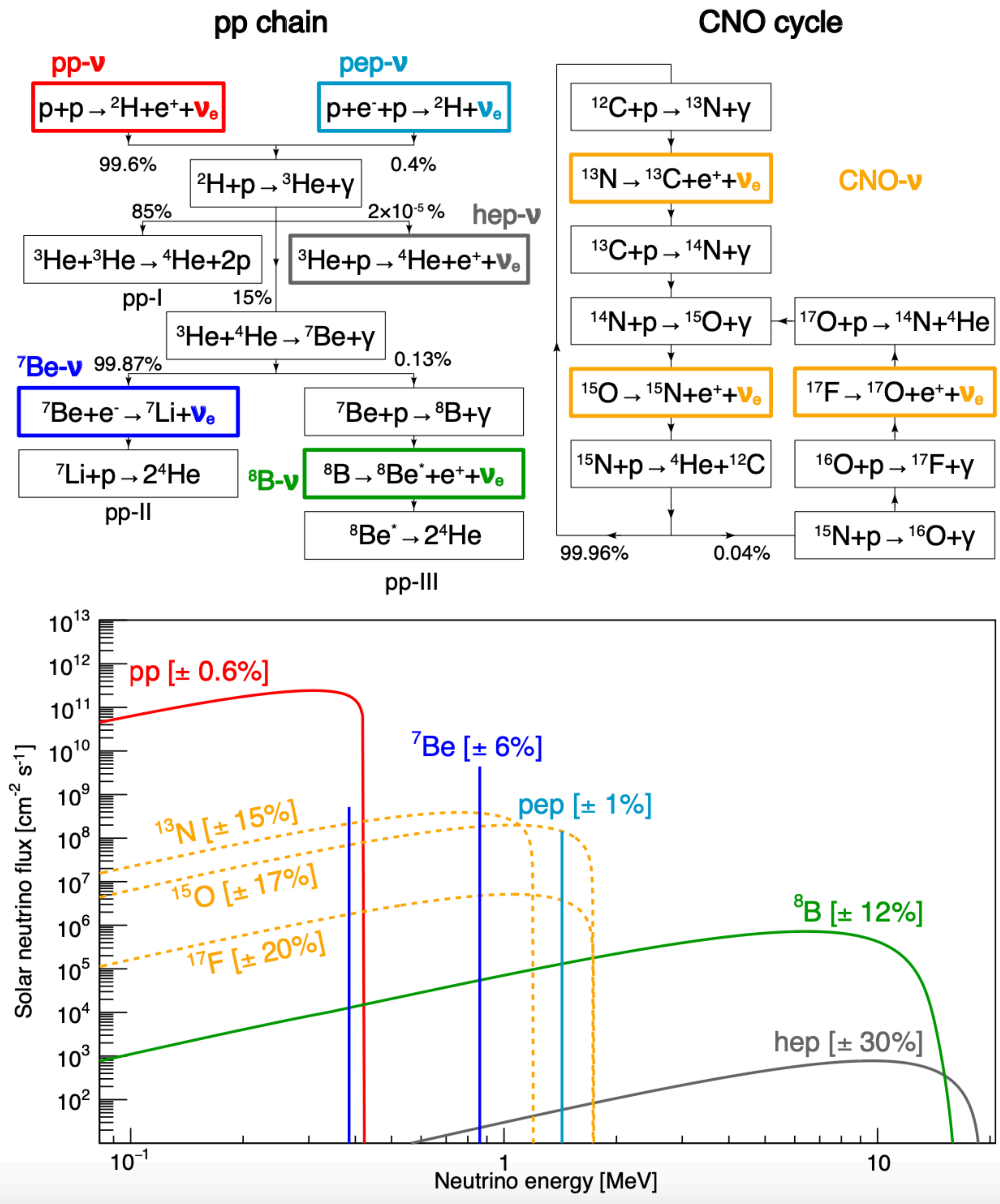


- nucleon form factors

Meyer, Betancourt, Gran and Hill (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T. (2020)

- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result


pp chain
CNO cycle
pp-ν
pep-ν
p+p → ²H+e⁺+νe
p+e⁻+p → ²H+νe
99.6%
0.4%
²H+p → ³He+γ
85%
2×10⁻⁵ %
hep-ν
³He+³He → ⁴He+2p
³He+p → ⁴He+e⁺+νe
pp-I
15%
³He+⁴He → ⁷Be+γ
⁷Be-ν
99.87%
0.13%
⁷Be+e⁻ → ⁷Li+νe
⁷Be+p → ⁸B+γ
⁷Li+p → 2⁴He
⁸B-ν
⁸B → ⁸Be*+e⁺+νe
pp-II
⁸Be* → 2⁴He
pp-III
¹²C+p → ¹³N+γ
¹³N → ¹³C+e⁺+νe
CNO-ν
¹³C+p → ¹⁴N+γ
¹⁴N+p → ¹⁵O+γ
¹⁷O+p → ¹⁴N+⁴He
¹⁵O → ¹⁵N+e⁺+νe
¹⁷F → ¹⁷O+e⁺+νe
¹⁵N+p → ⁴He+¹²C
¹⁶O+p → ¹⁷F+γ
¹⁵N+p → ¹⁶O+γ
99.96%
0.04%
pp [± 0.6%]
⁷Be [± 6%]
pep [± 1%]
¹³N [± 15%]
¹⁵O [± 17%]
¹⁷F [± 20%]
⁸B [± 12%]
hep [± 30%]
Solar neutrino flux [cm⁻² s⁻¹]
Neutrino energy [MeV]
10⁻¹
1
10

2105.13858