NREC 2026

Workshop

16 April, 2026

Radiative corrections in (anti)neutrino-nucleon scattering and nucleon structure

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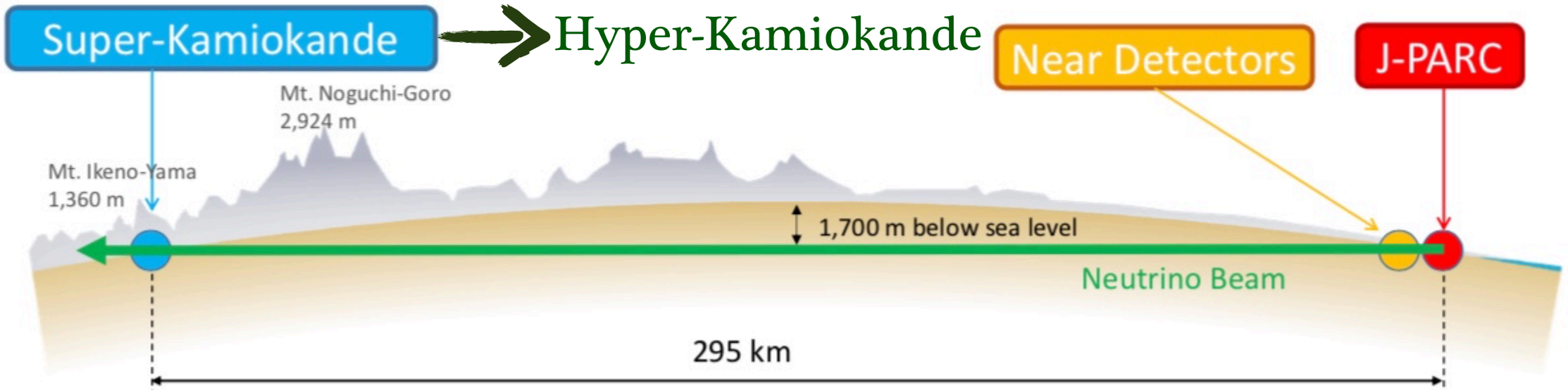
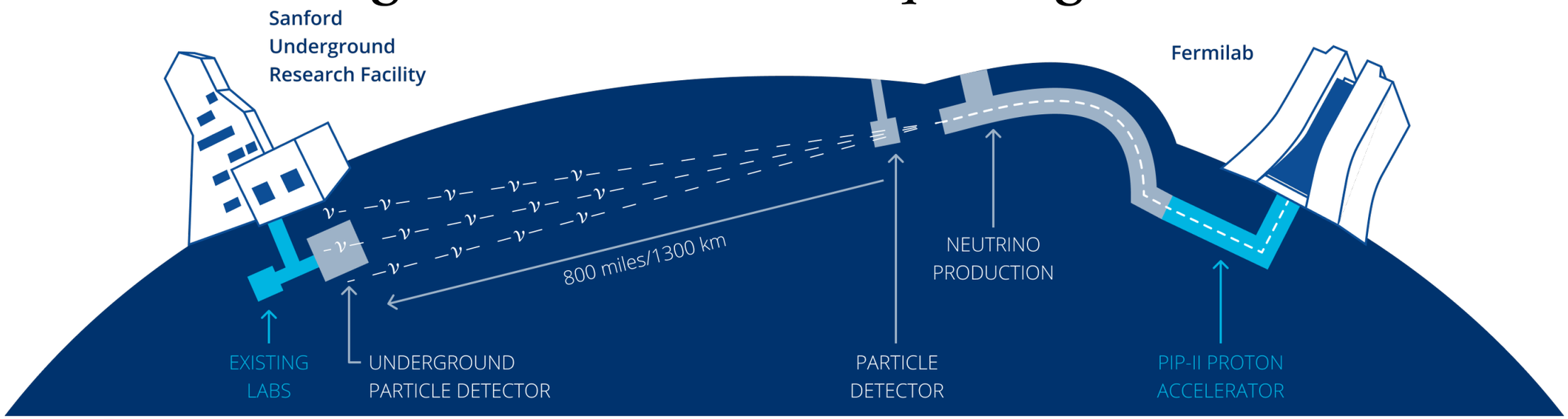
Sasha Tomalak

CP violation and mass hierarchy@laboratory

650 m under rocks in mountain, 260000t of pure water

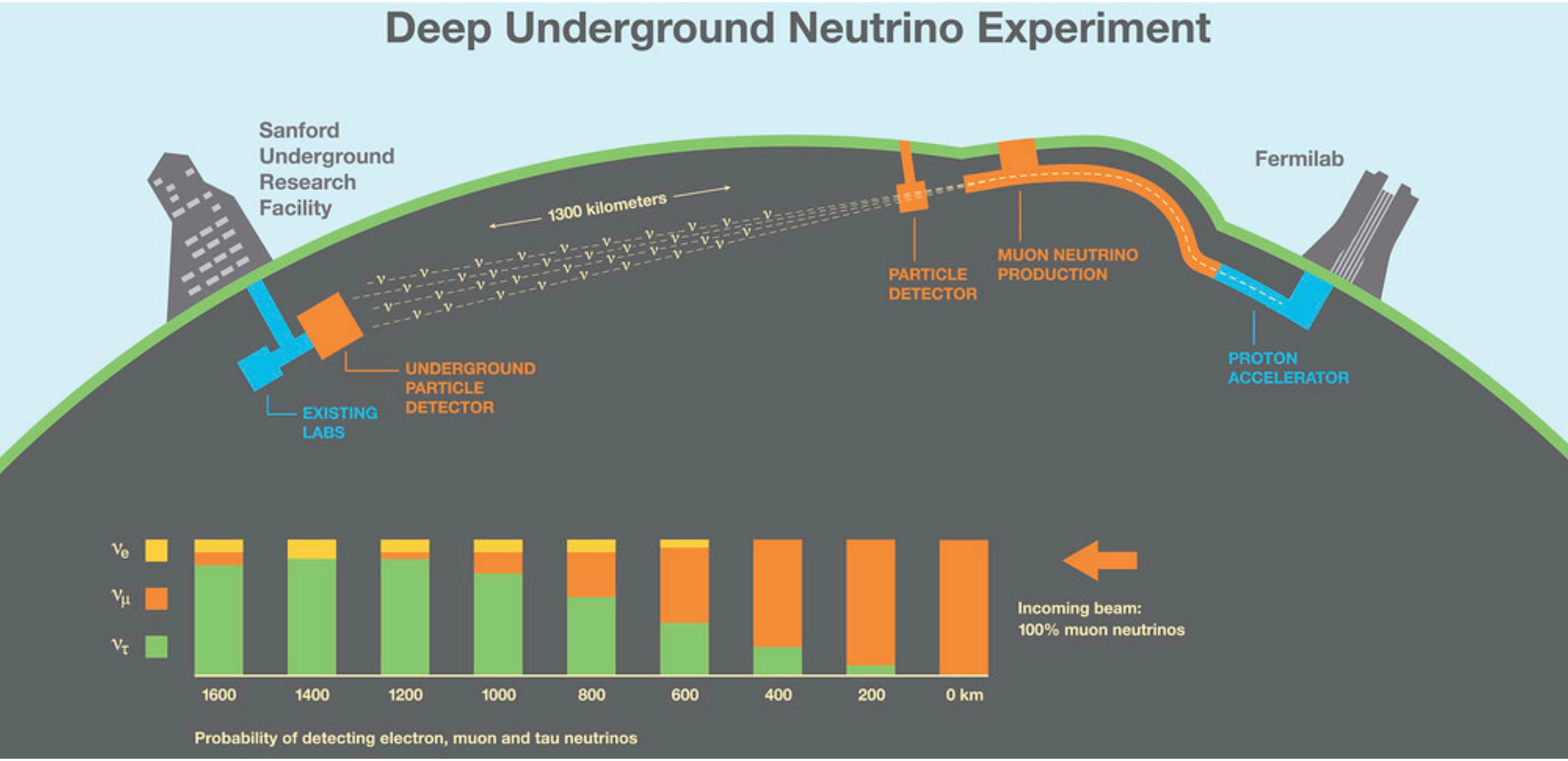


1.5 km underground, 4x70000t of liquid argon



- CP violation in PMNS and mass hierarchy in next 10-20 years !!!

Neutrino experiments

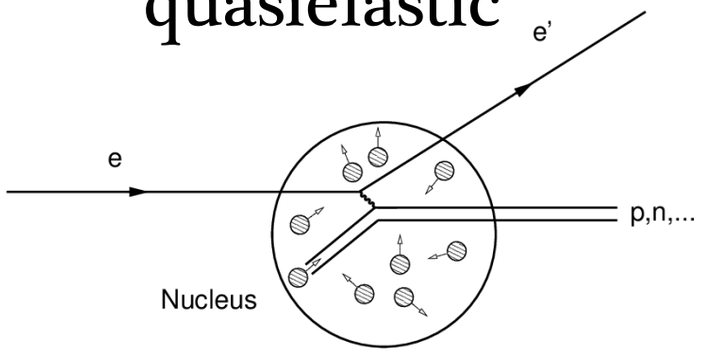


$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu\left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

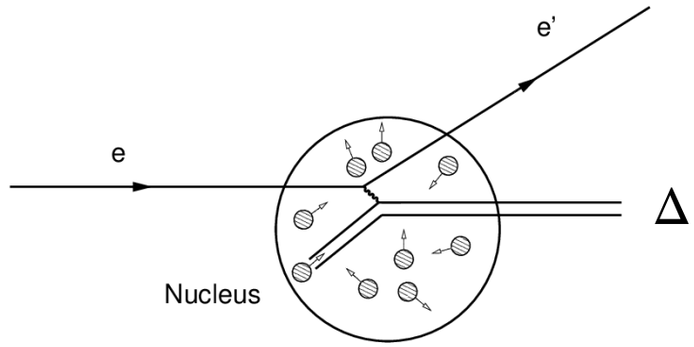
- precise neutrino physics: need in cross sections

Interaction mechanisms

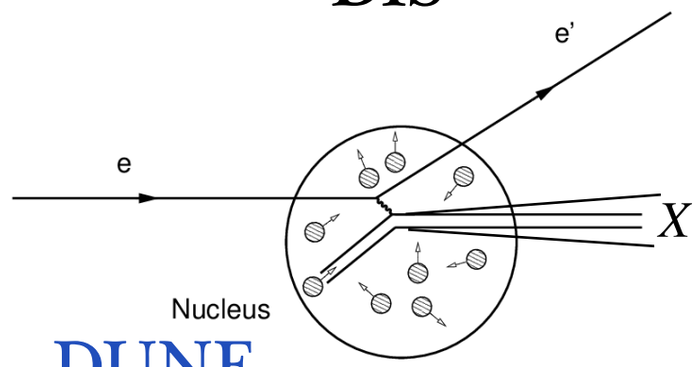
quasielastic



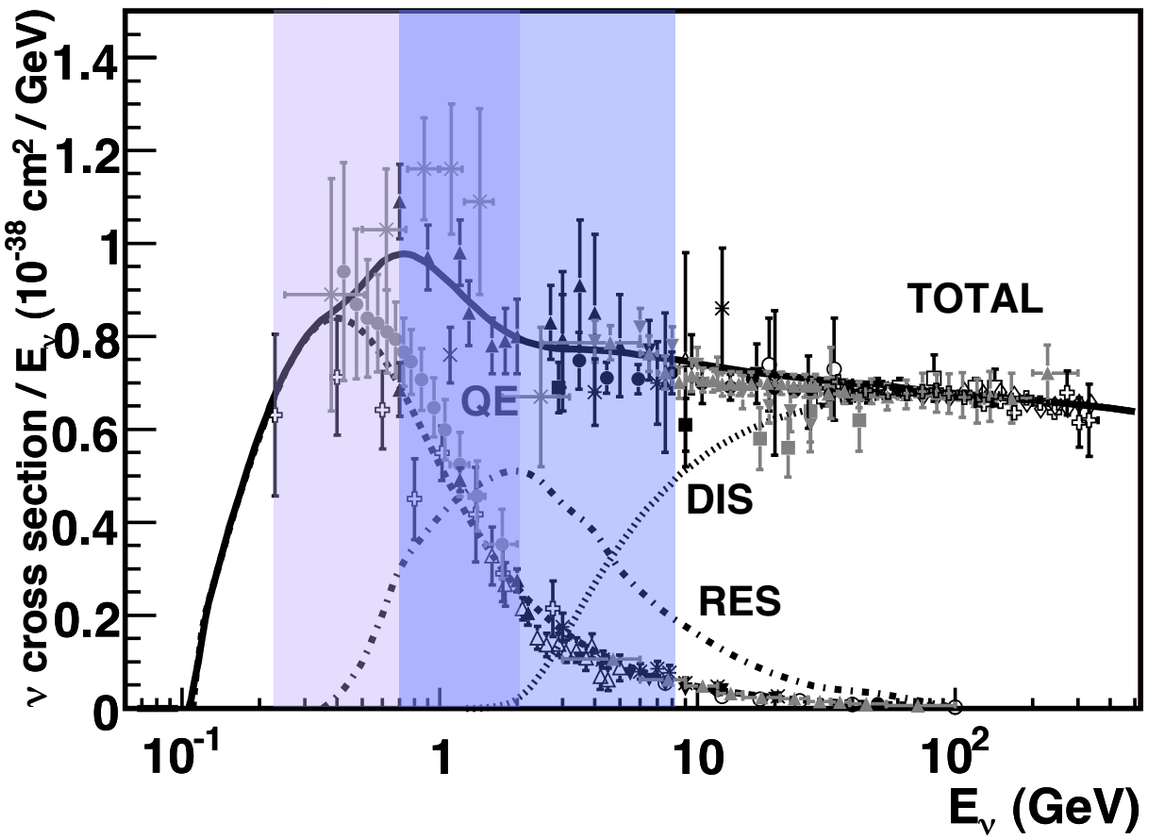
resonance



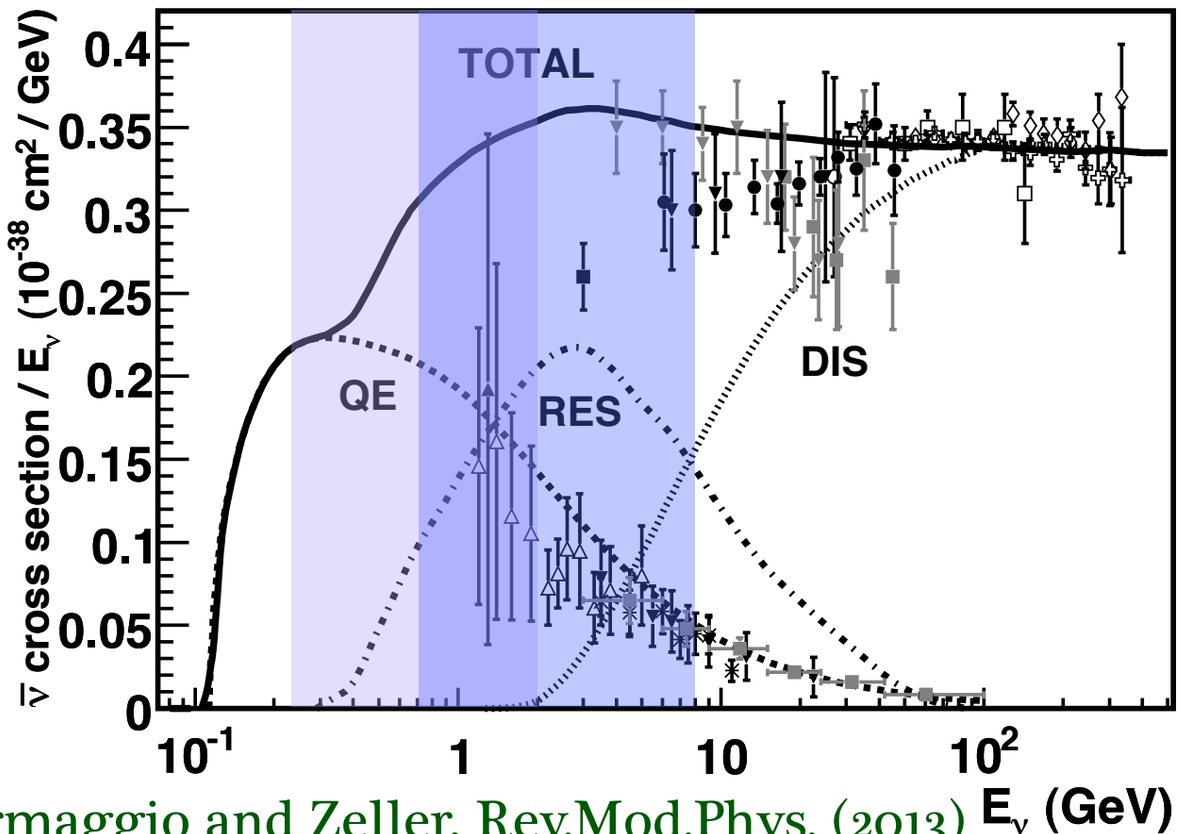
DIS



Hyper-K



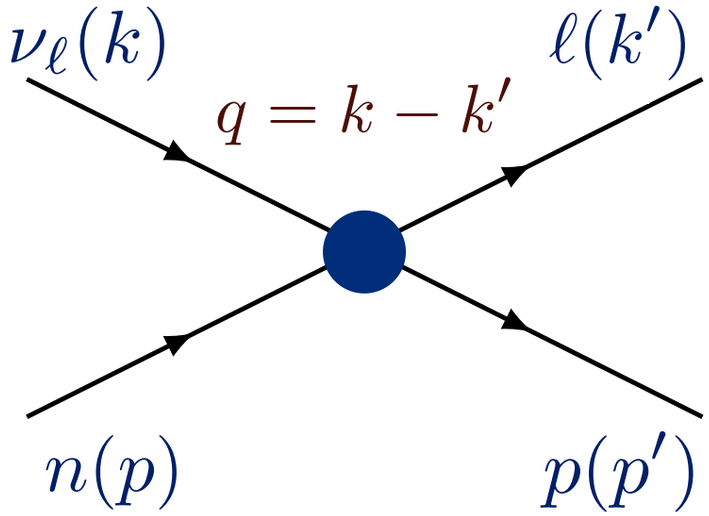
DUNE



Formaggio and Zeller, Rev.Mod.Phys. (2013)

- significant overlap with prior and modern JLab energy range
- DUNE experimental program requires 3-5 % precise cross sections

Elastic scattering on free nucleon



neutrino energy E_ν

momentum transfer $Q^2 = -q^2$

contact interaction at GeV energies

- assuming isospin symmetry, nucleon current:

$$\Gamma^\mu\left(Q^2\right) =< p|\bar{u}\left(\gamma^\mu - \gamma^\mu\gamma_5\right) d|n >$$

$$\Gamma^\mu(Q^2) = \gamma^\mu F_D^V(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_P^V(Q^2) + \gamma^\mu\gamma_5 F_A(Q^2) + \frac{q^\mu}{M}\gamma_5 F_P(Q^2)$$

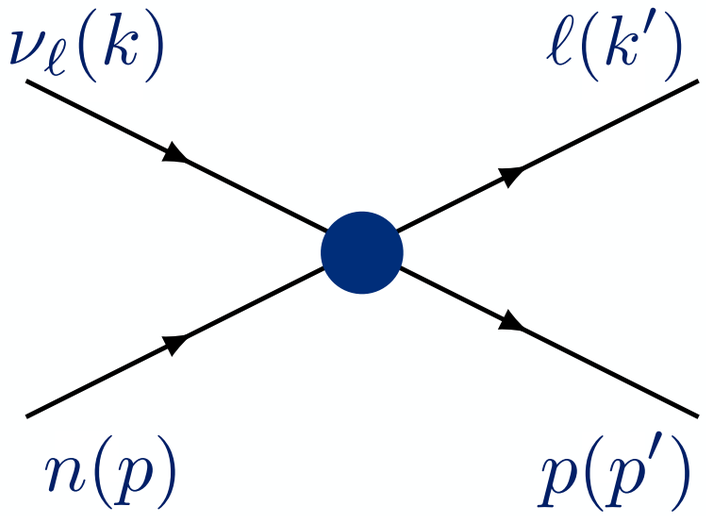
form factors: isovector Dirac and Pauli axial and pseudoscalar

$$F_{D,P}^V = F_{D,P}^p - F_{D,P}^n$$

tree-level amplitude

$$\mathrm{T} = \frac{\mathrm{G_F}V_{ud}}{\sqrt{2}}(\bar{\ell}(k')\gamma_\mu\left(1-\gamma_5\right)\nu_\ell(k))(\bar{p}(p')\Gamma^\mu(Q^2)n(p))$$

Elastic scattering on free nucleon



$$\nu = E_\nu/M - \tau - r^2$$

$$r = \frac{m_\ell}{2M} \qquad \tau = \frac{Q^2}{4M^2}$$

unpolarized cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \sim \frac{M^2}{E_\nu^2}\left(\left(\tau + r^2\right) A(Q^2) - \nu B(Q^2) + \frac{\nu^2}{1+\tau} C(Q^2)\right)$$

Llewellyn Smith (1972)

- structure-dependent functions

$$A = \tau\left(G_M^V\right)^2 - \left(G_E^V\right)^2 + (1+\tau)F_A^2 - r^2\left(\left(G_M^V\right)^2 + F_A^2 - 4\tau F_P^2 + 4F_A F_P\right)$$

$$B = \pm 4\tau F_A G_M^V \qquad C = \tau\left(G_M^V\right)^2 + \left(G_E^V\right)^2 + (1+\tau)F_A^2$$

- pseudoscalar form factor contribution is suppressed by lepton mass
- cross section is sensitive to both vector and axial contributions

Elastic scattering on free nucleon

- only 3 experiments performed with deuterium bubble chamber

direct access to form-factor shape

ANL 1982: 1737 events

BNL 1981: 1138 events

FNAL 1983: 362 events

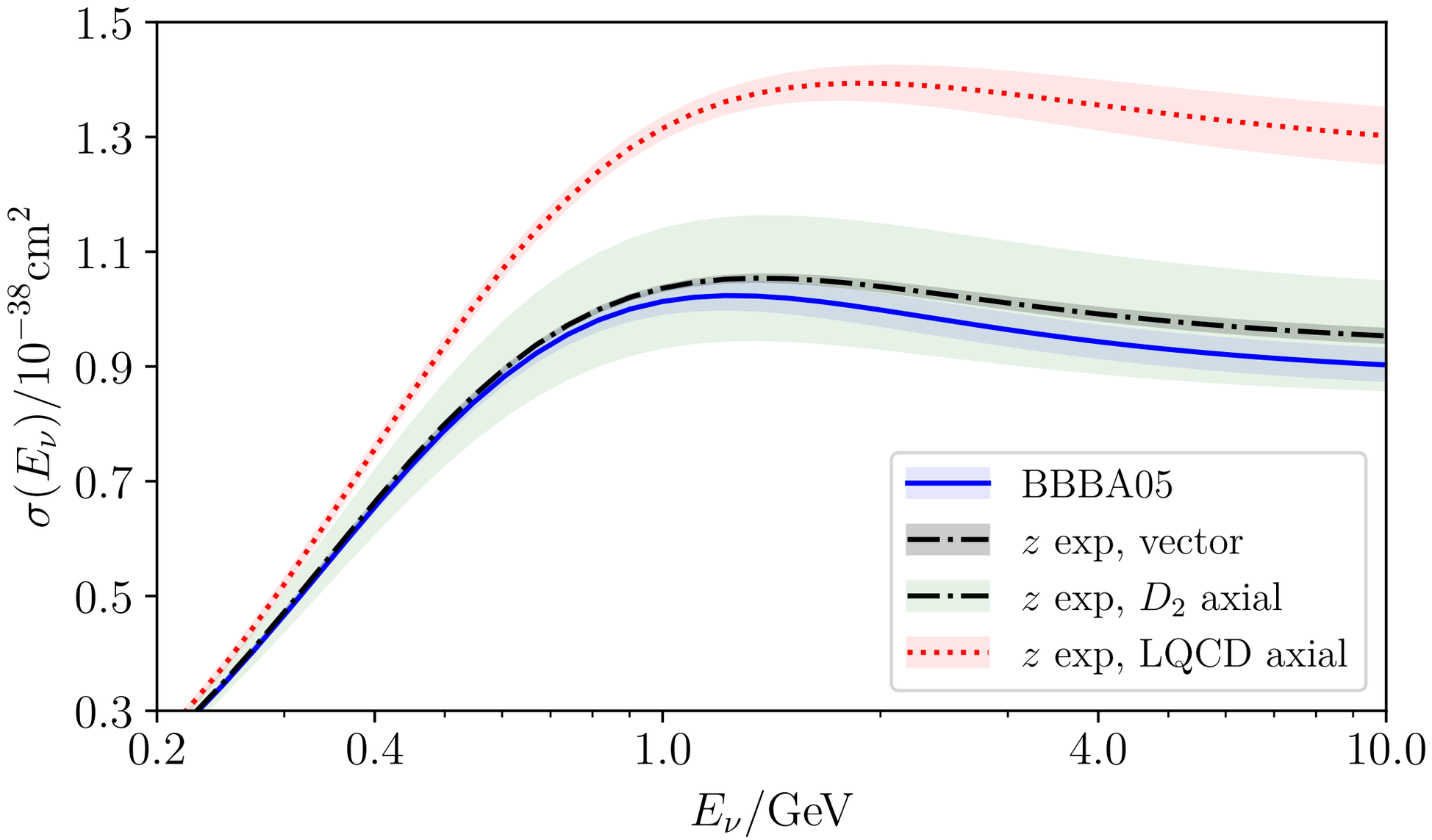
world data: ~3200 events

Fermilab bubble chamber, Richard Drew

- axial form factor extracted based on electromagnetic structure

A.S. Meyer, M. Betancourt, R. Gran and R.J. Hill, PRD (2016)

Neutrino-nucleon scattering (CC)

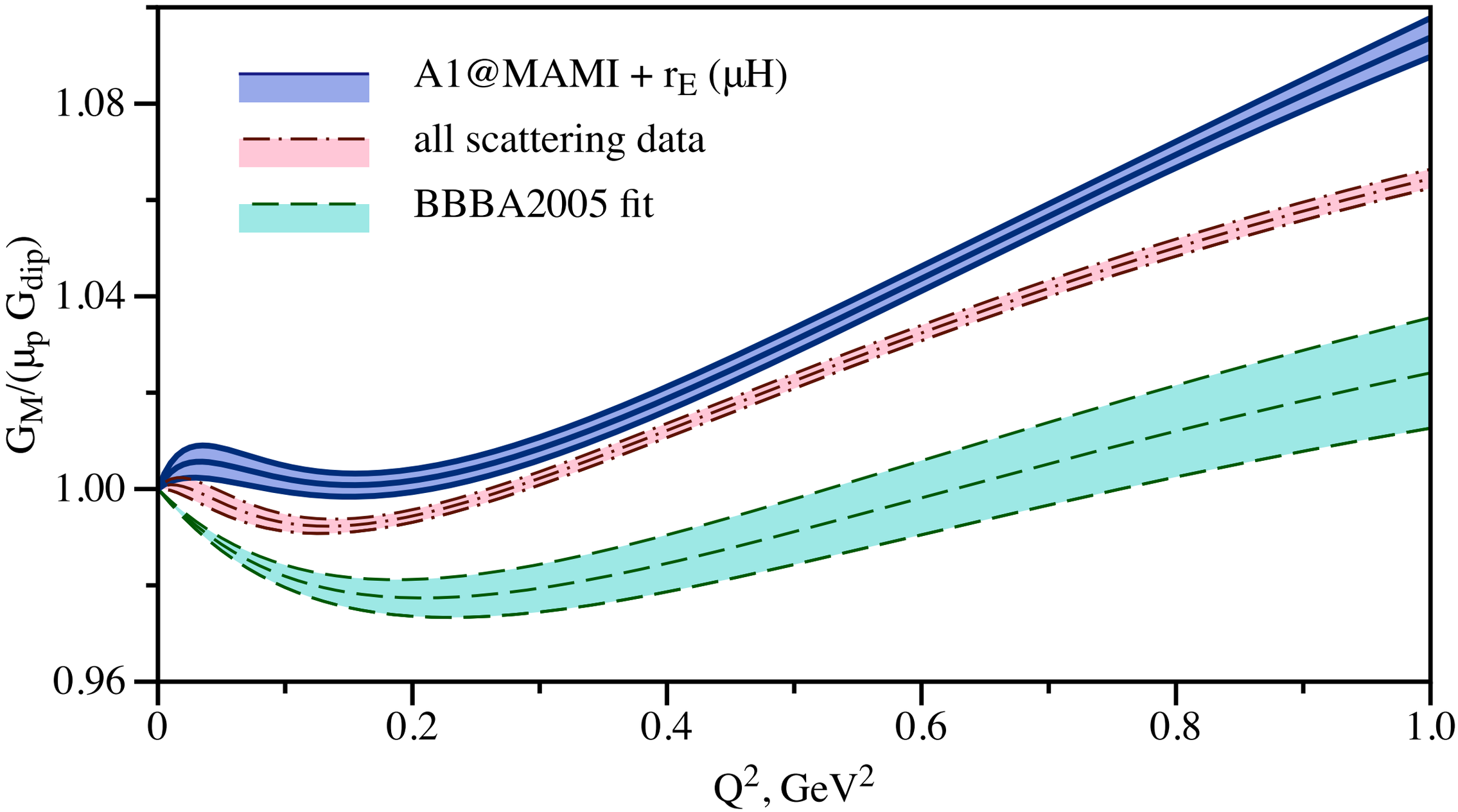


A.S. Meyer, A. Walker-Loud, C. Wilkinson, Ann. Rev. of 72, 010622-120608 (2022)
A.S. Meyer, M. Betancourt, R. Gran, and R.J. Hill, PRD (2016)
Kaushik Borah, Gabriel Lee, Richard J. Hill, and O.T. , PRD (2021)

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

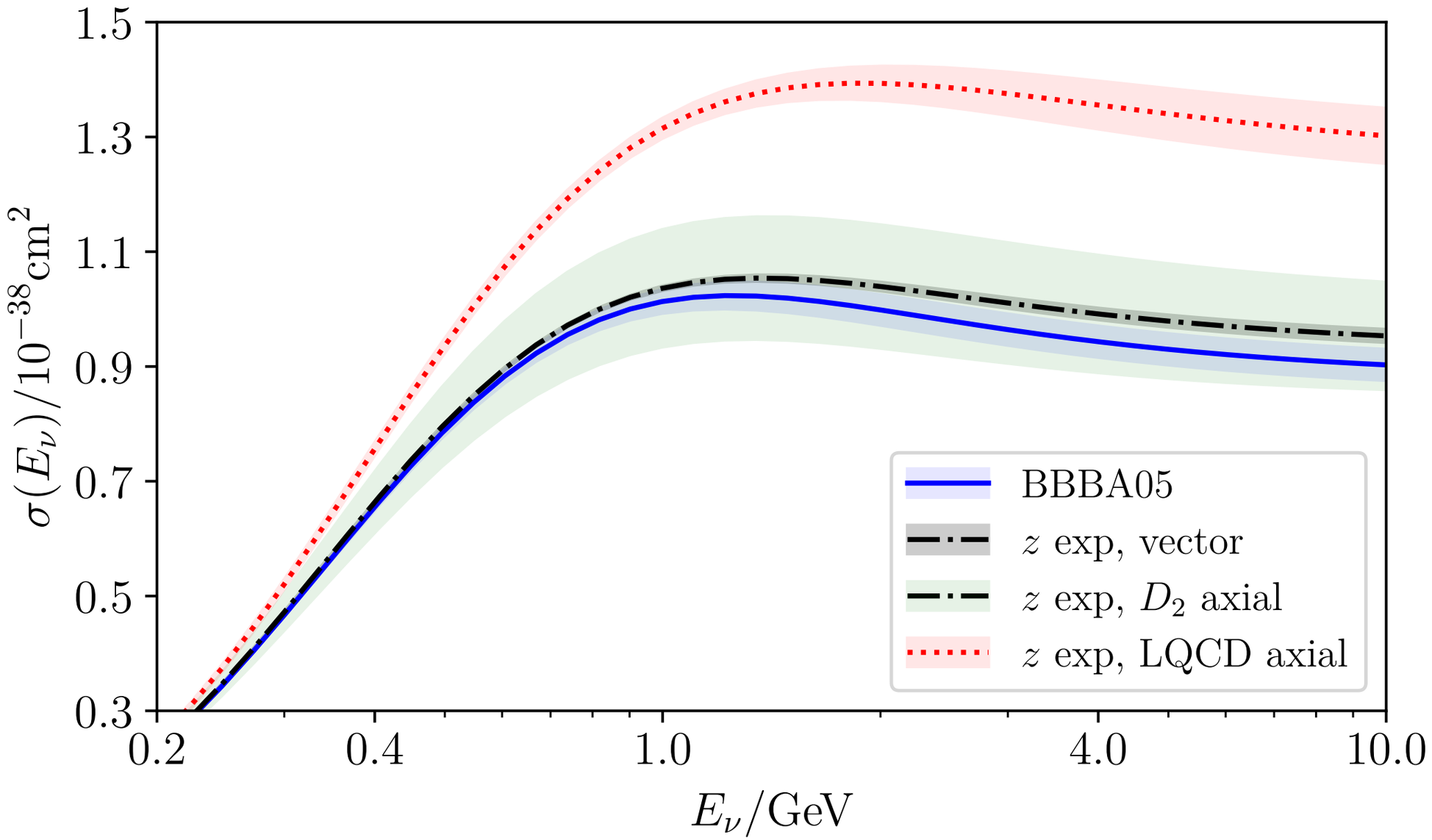
Origin of difference

- fits of proton magnetic form factor:



- proton magnetic form factor has to be precisely measured again

Neutrino-nucleon scattering (CC)



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- knowledge of vector structure stops a progress in studies of axial
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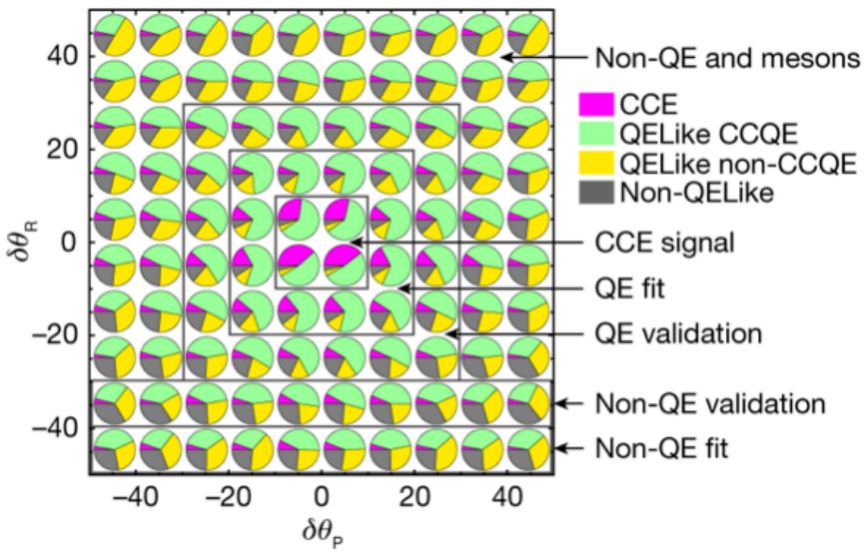
MINERvA result with free protons

- idea of scattering on molecular hydrogen realized !!!

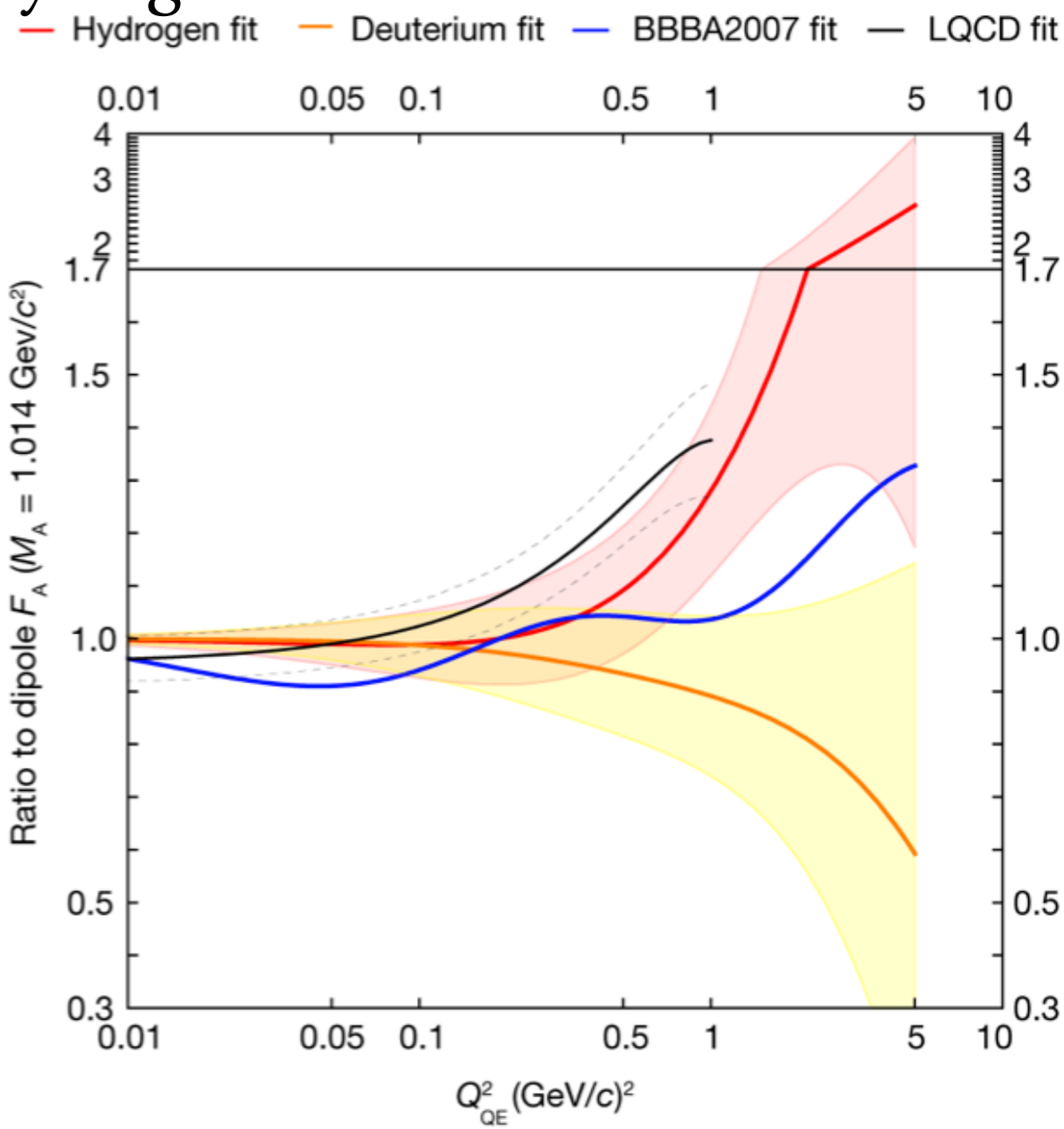
$$\overline{\nu}_\mu p \to \mu^+ n$$

kinematic selection



5580 events over
12500 background

background nuclear events
constrained by scattering of ν

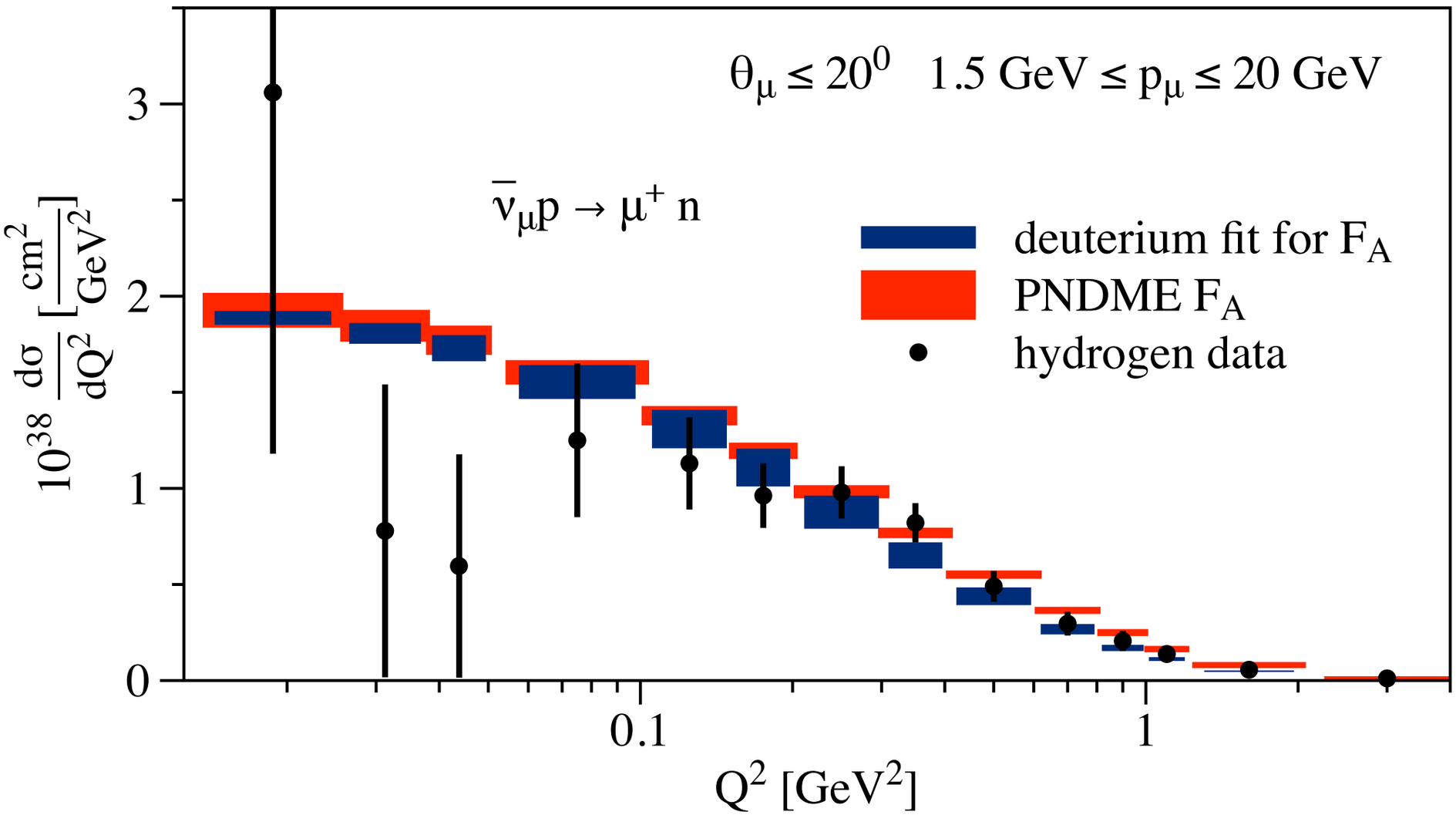


- 1st measurement of axial form factor on “free” protons $\overline{\nu}_\mu p \to \mu^+ n$

T. Cai et al., MINERvA Collaboration, Nature (2023)

Lattice QCD vs MINERvA

- PNDME 2023 axial-vector form factor as representative of lattice QCD



- $\lesssim 1\sigma$ agreement for each bin besides two at small Q^2

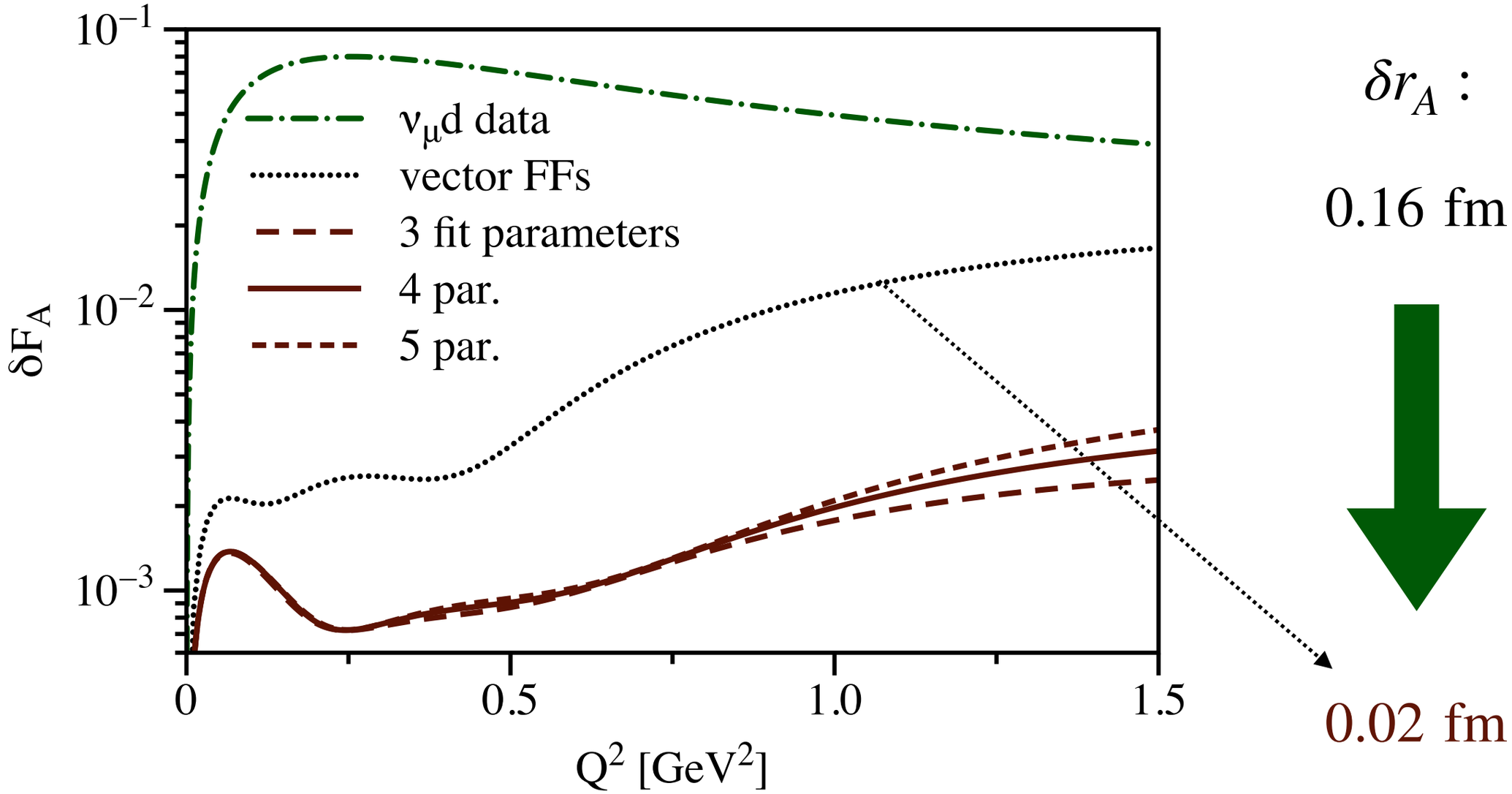
- 2-3σ tension between lattice QCD and deuterium data
- MINERvA hydrogen data consistent with LQCD and deuterium

O.T., Rajan Gupta, and Tanmoy Bhattacharya, PRD (2023)

DUNE projections

- estimates for 700 kg of H in Straw Tube Tracker at near detector

H. Duyang, B. Guo, S. R. Mishra, and R. Petti, PLB (2019)



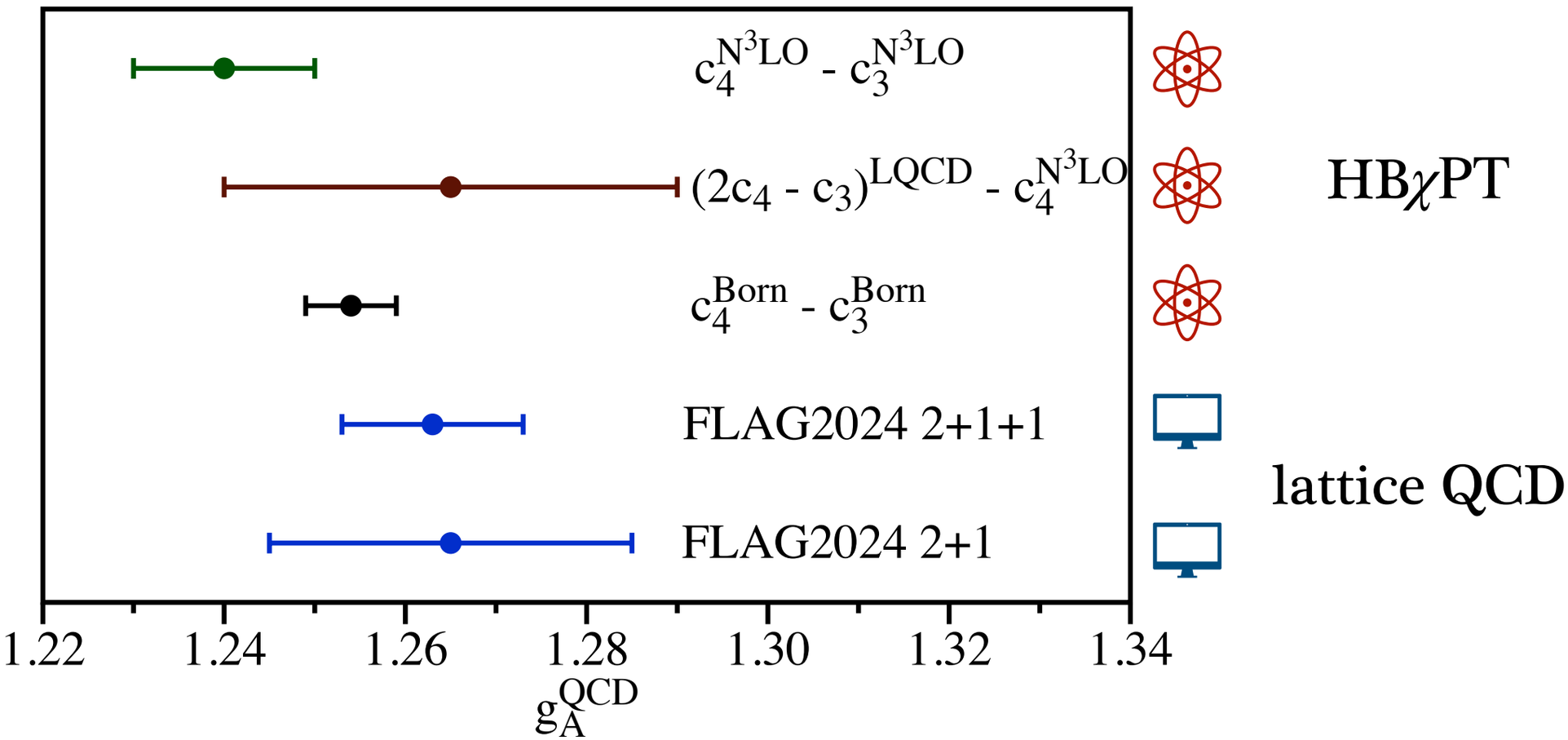
- order of magnitude improvement in axial form factor and radius
- DUNE will probe vector form factors and isospin symmetry

Roberto Petti, O.T., and Richard J. Hill, letter in PRD (2024)

Nucleon axial-vector charge

- effective field theory approach to low-energy charged currents

Standard Model -> LEFT -> HBχPT -> πEFT



O.T. and Yi-Bo Yang, Universe (2026)
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., PRD (2024) and PRD (2025)
V. Cirigliano, J. de Vries, L. Hayen, E. Mereghetti, and A. Walker-Loud, PRL (2022)

- first consistent at 0.1%-level QED radiative corrections

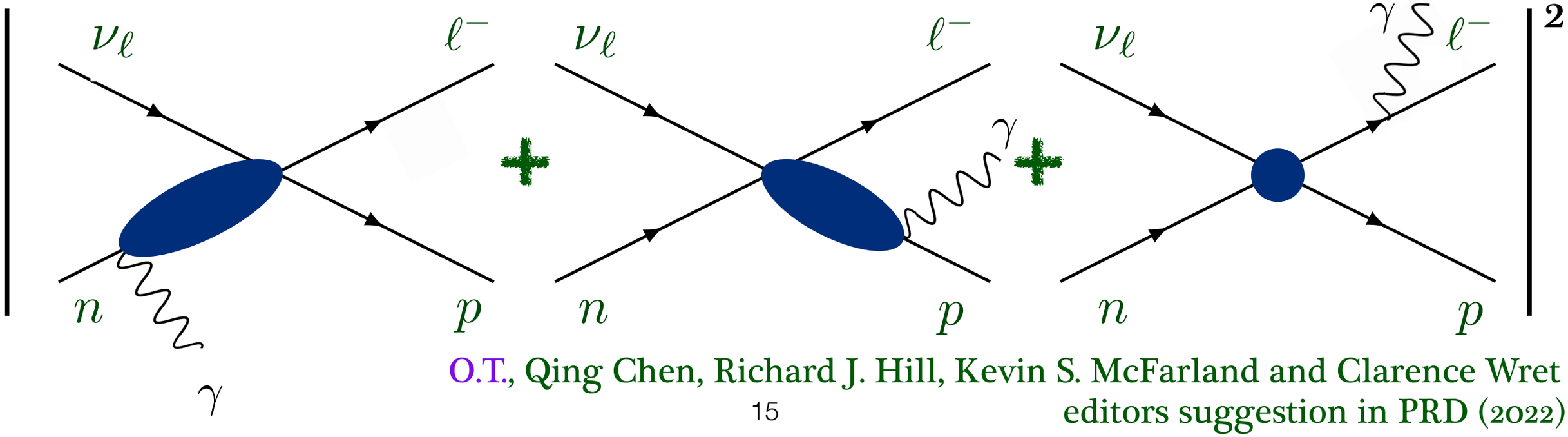
factorization for radiative corrections with model for hard function

Charged-current elastic scattering on nucleons

O.T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. (2022)

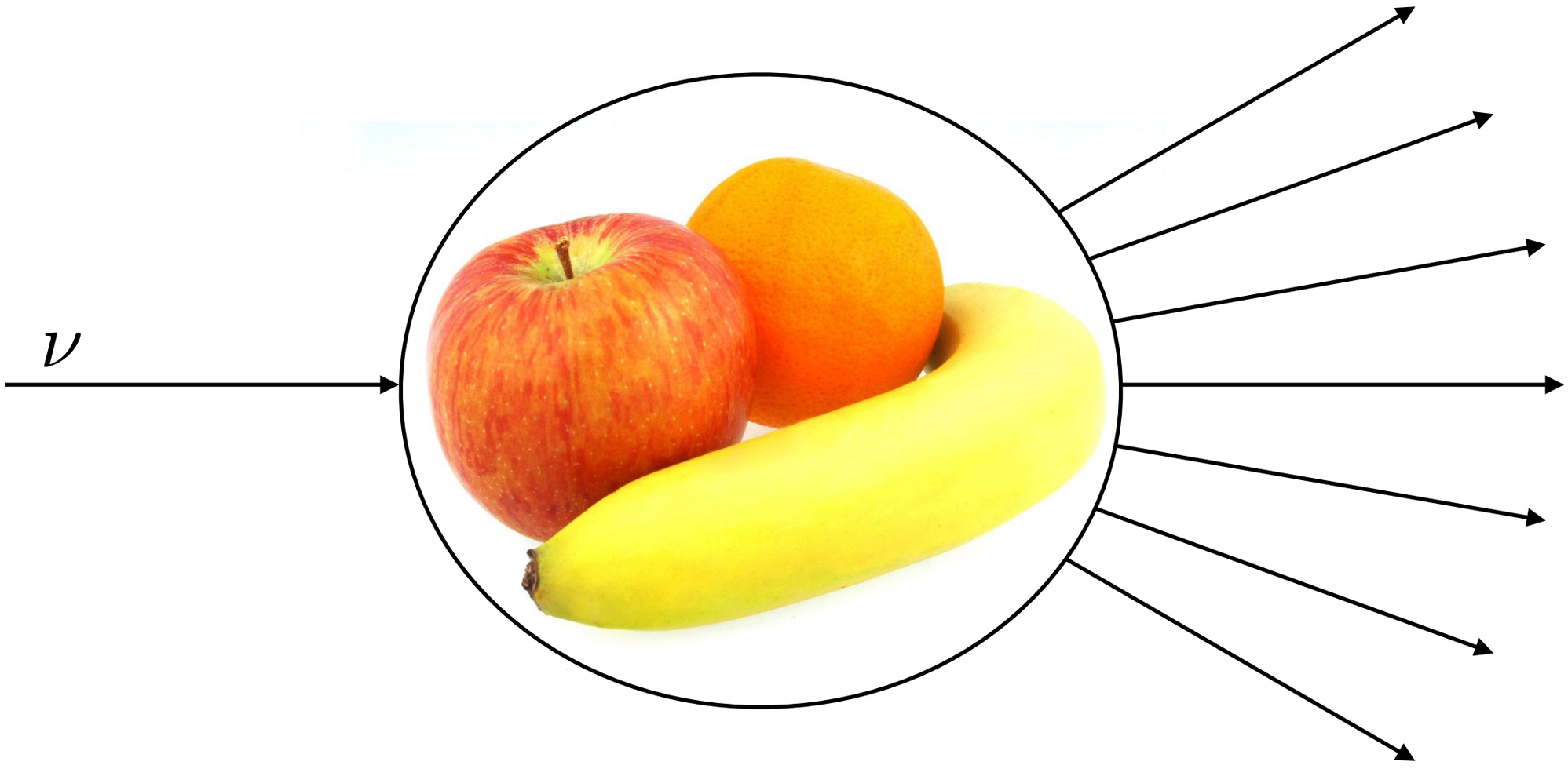
precise predictions for flavor ratios and radiative corrections

in exclusive and inclusive observables with GeV neutrino beams

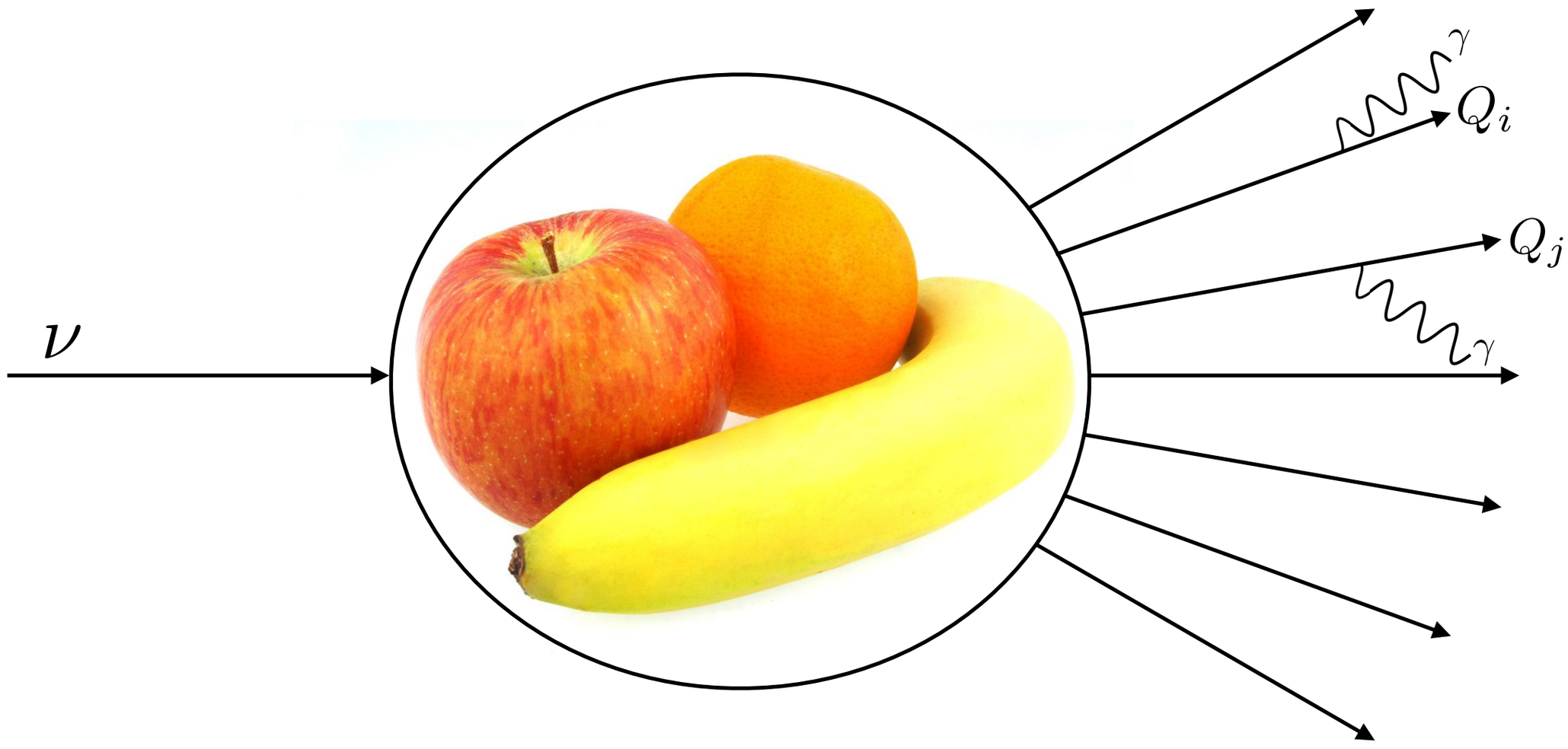


O.T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret
editors suggestion in PRD (2022)

Neutrino interactions

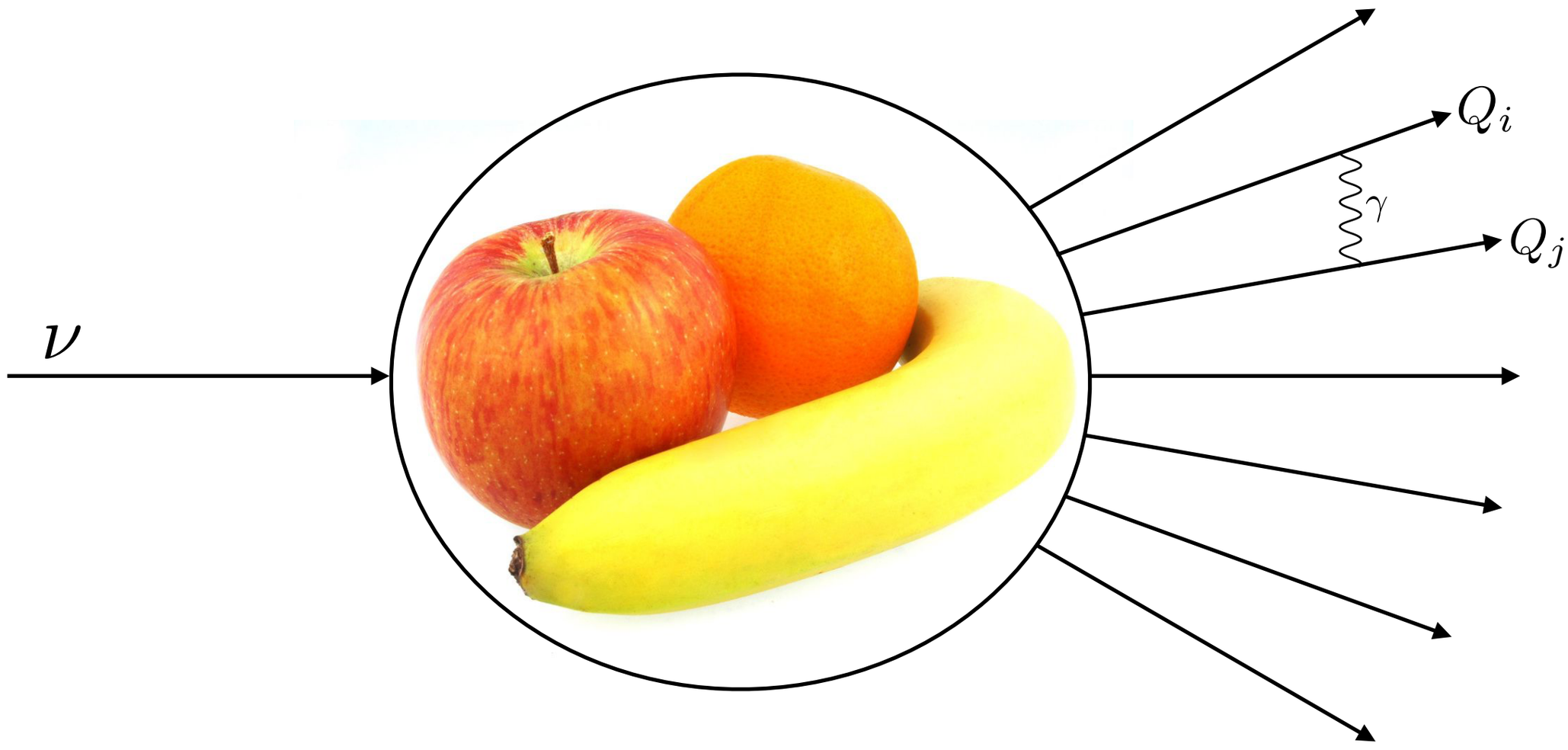


QED corrections



- all charged particles couple to real and virtual photons

QED corrections



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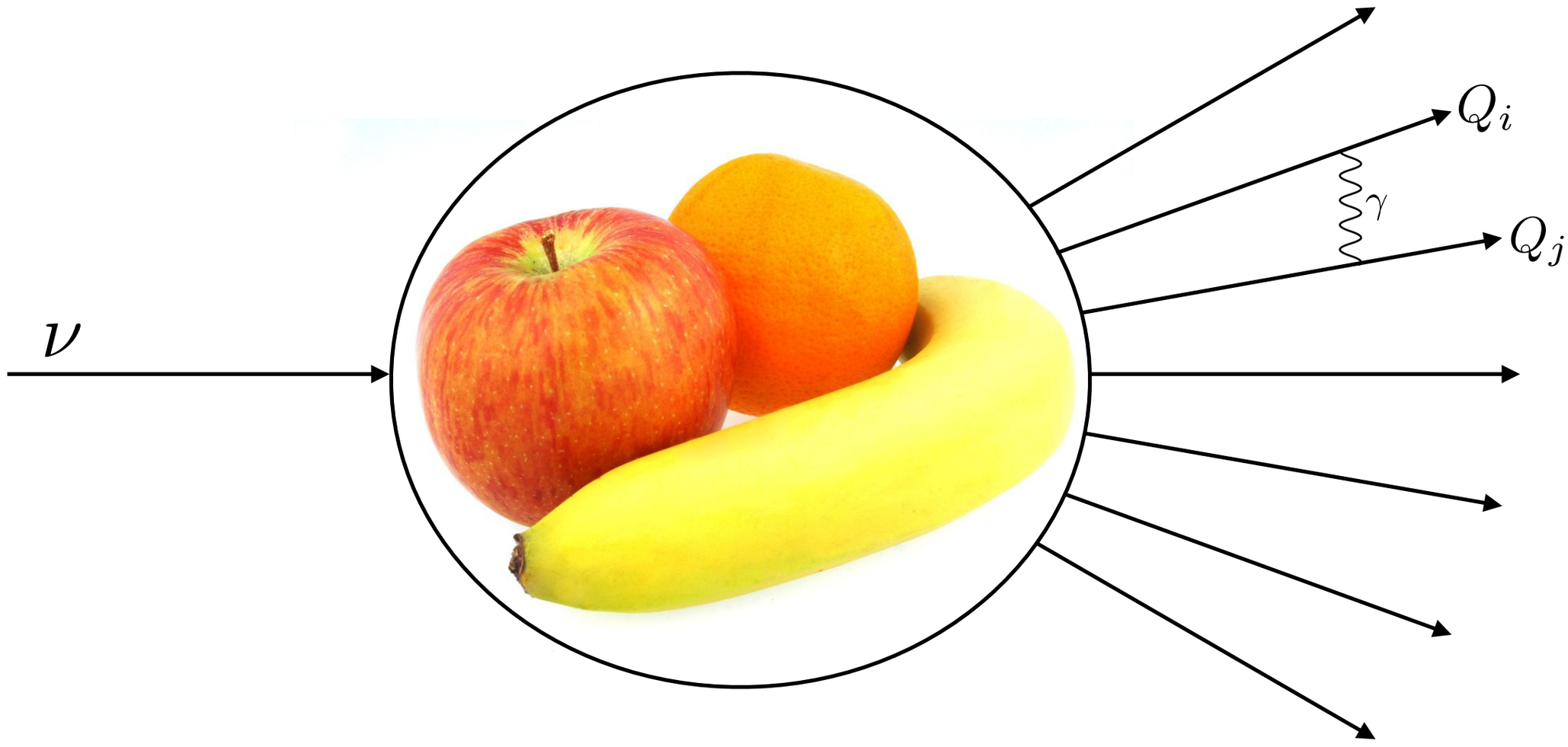
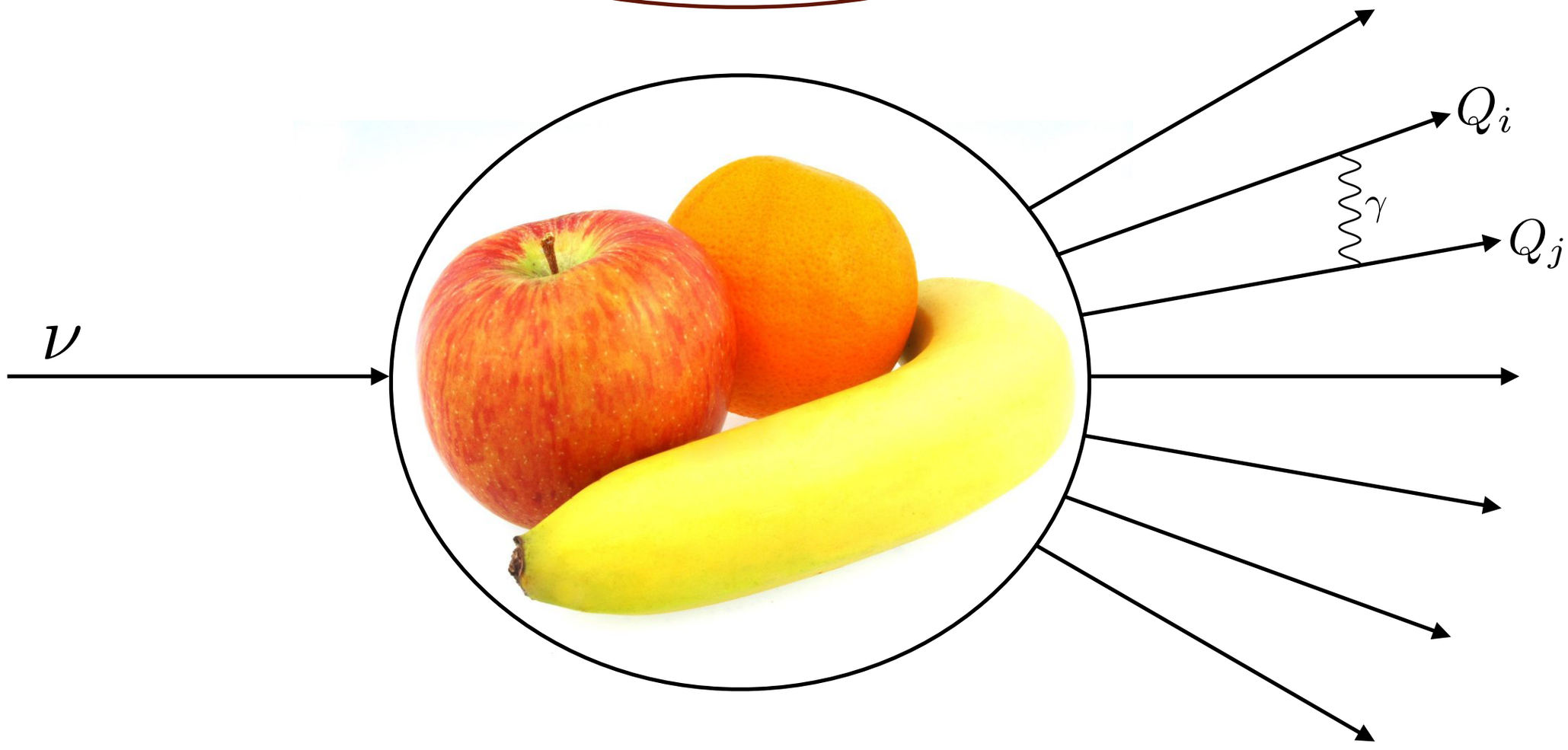
QED corrections



- $\frac{\alpha}{\pi} \sim 0.2\ \%$ suppression by electromagnetic coupling constant

QED corrections

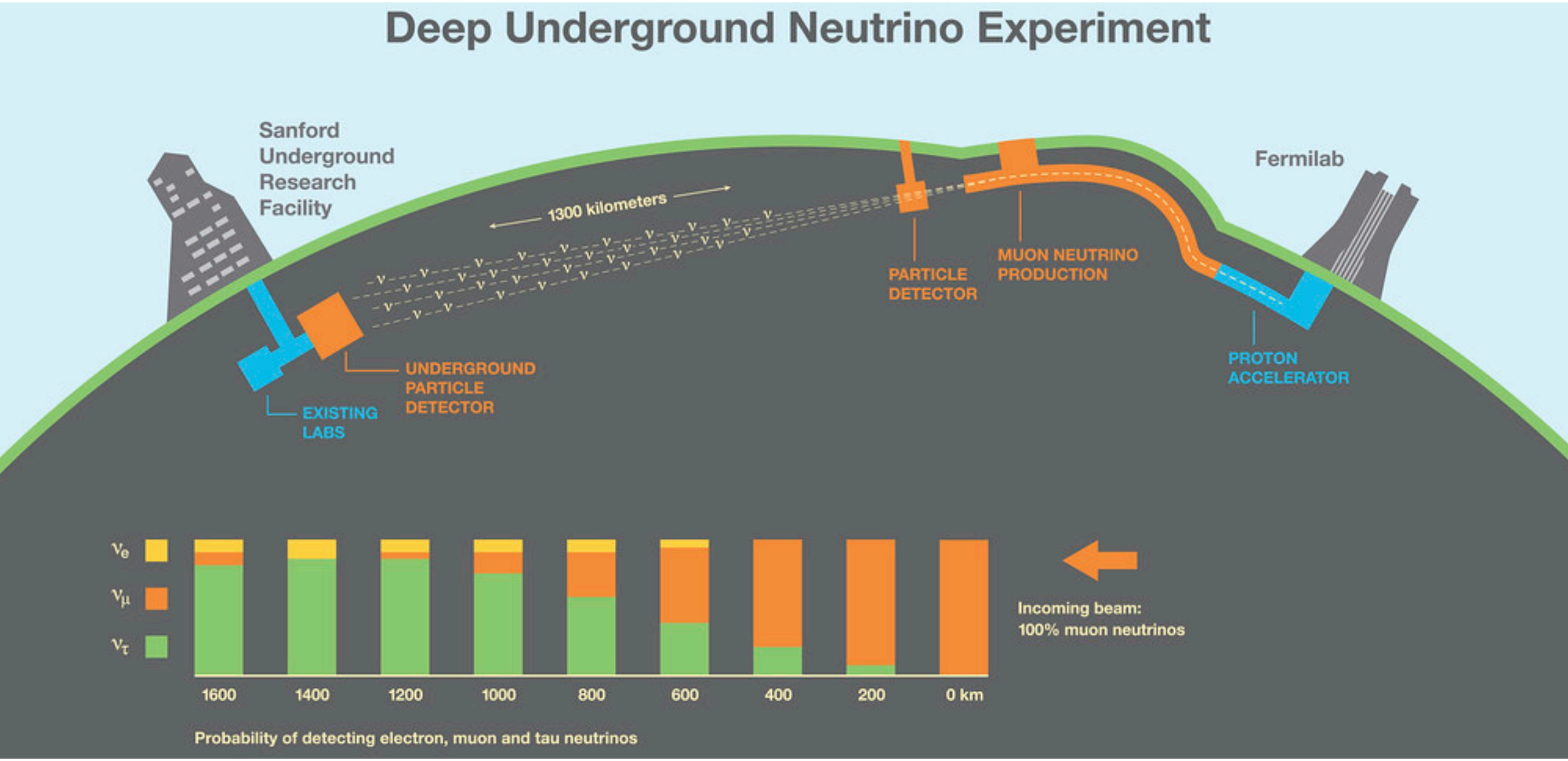
$$m_e \ll m_\mu \ll E_\nu$$



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

- scale separation introduces large flavor-dependent QED logarithms

Neutrino experiments

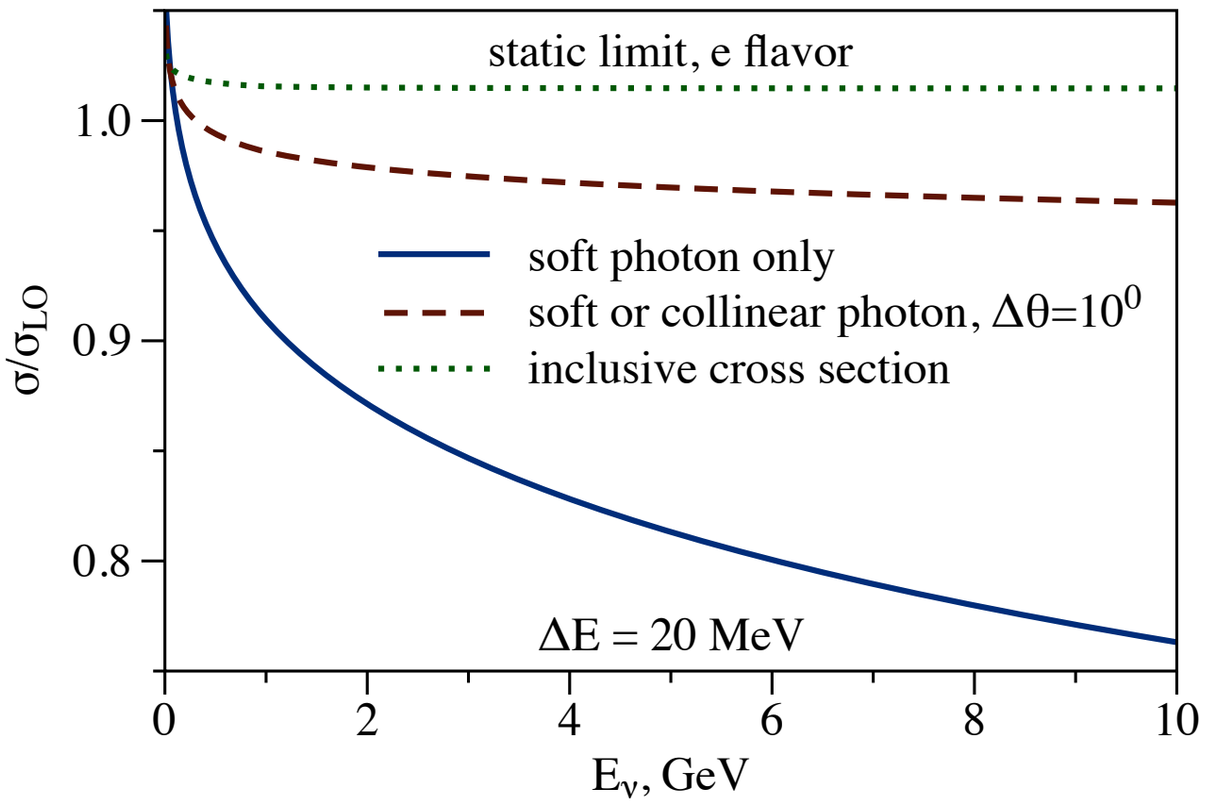


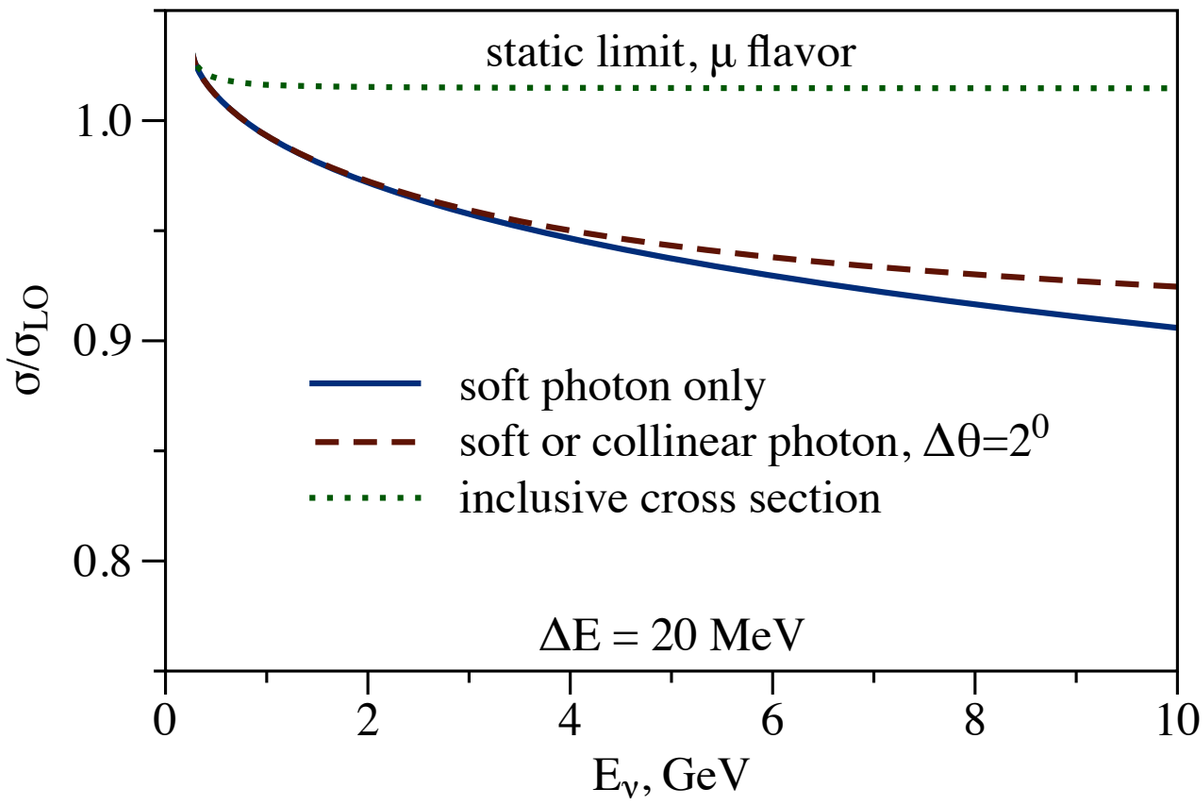
$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu\left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

- precise neutrino physics: need in cross sections

Static nucleon limit

- formal limit of infinitely heavy nucleus $m_\ell \ll E_\ell \ll M$
- provides correct soft and collinear logarithms
- soft-photon energy < 20 MeV, jet size: 10^0 for electron and 2^0 for muon

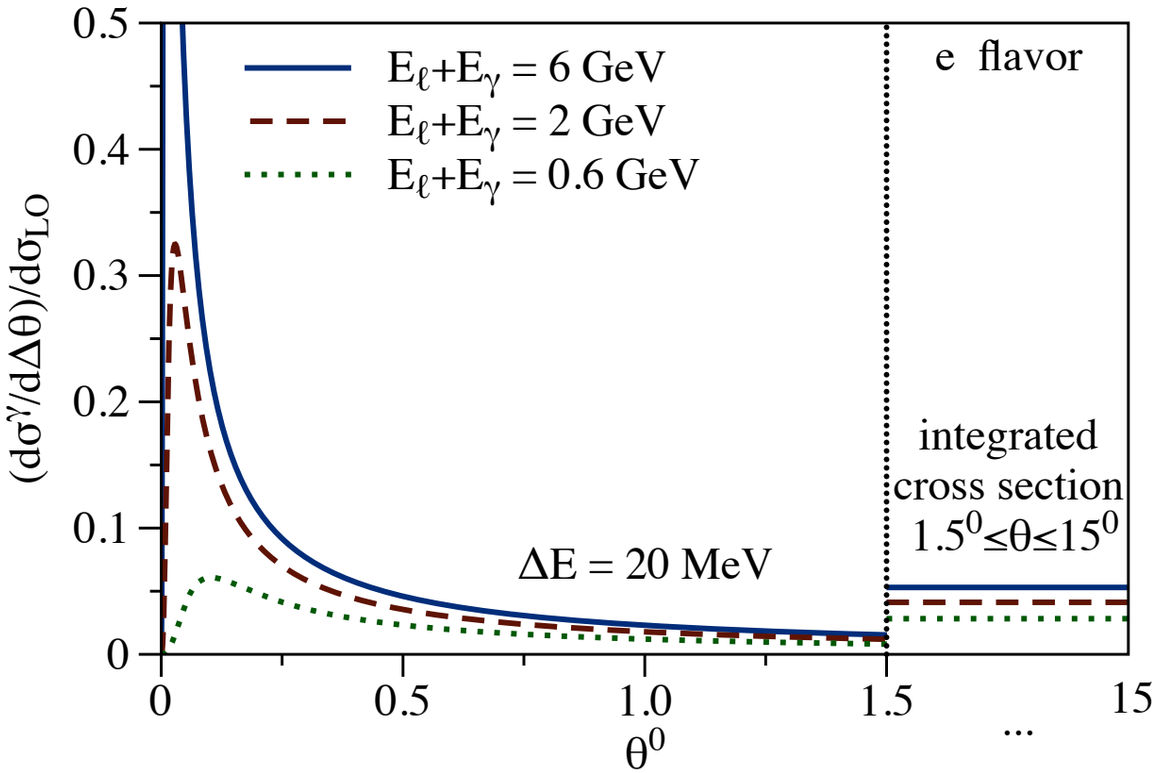


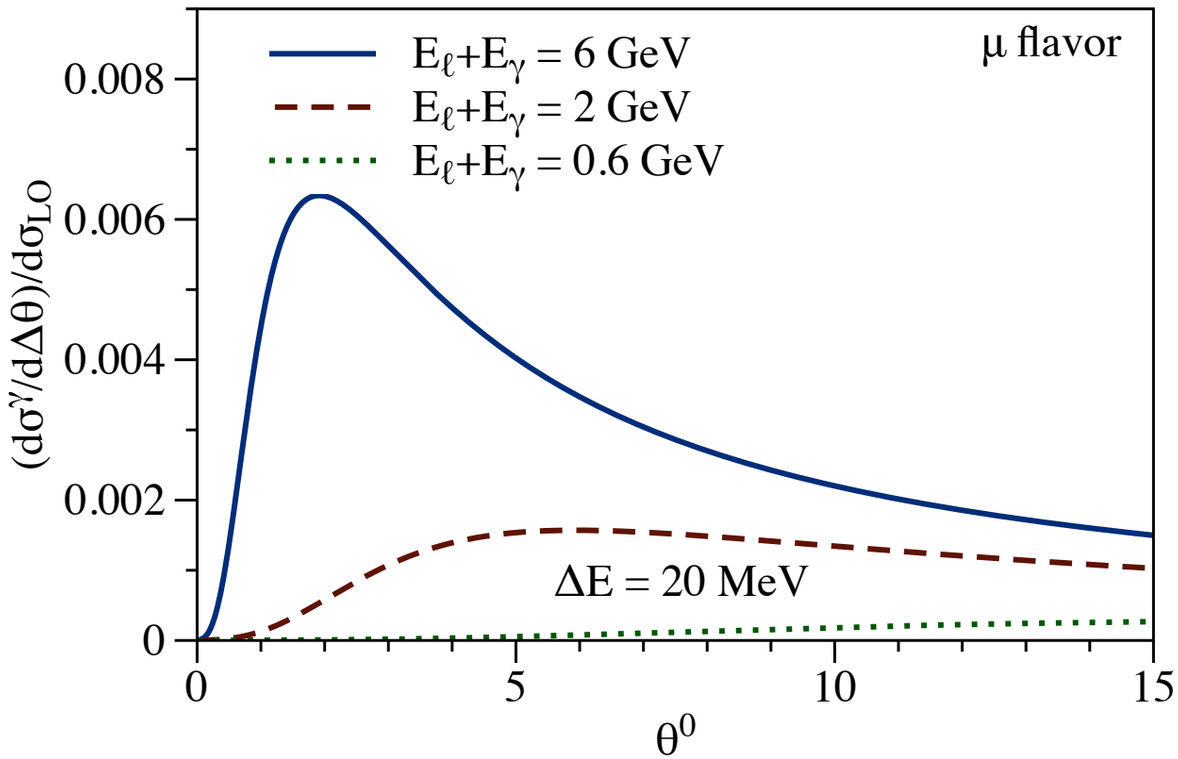


- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- collinear observable: cancellation of virtual vs real logs
- inclusive observables ($+\gamma$): few % level, flavor independent

Electron vs muon jets

- factorization for radiation of collinear photons
- cone angle is defined to lepton direction
- photons of energy > 20 MeV, fixed energy in the cone





- flavor-dependent effect, same for $\nu_\ell n \to \ell^- p$ vs $\bar{\nu}_\ell p \to \ell^+ n$
- forward-peaked radiation for electron flavor
- negligible radiation for muons with shifted peak position

Factorization approach

- cross section is given by factorization formula

$$\mathrm{d}\sigma \sim S\left(\frac{\Delta E}{\mu}\right) J\left(\frac{m_\ell}{\mu}\right) H\left(\frac{M}{\mu}\right)$$

- determine hard function at hard scale by matching experiment or hadronic model to the theory with heavy nucleon

- soft and collinear functions are evaluated perturbatively

SCET power expansion parameter

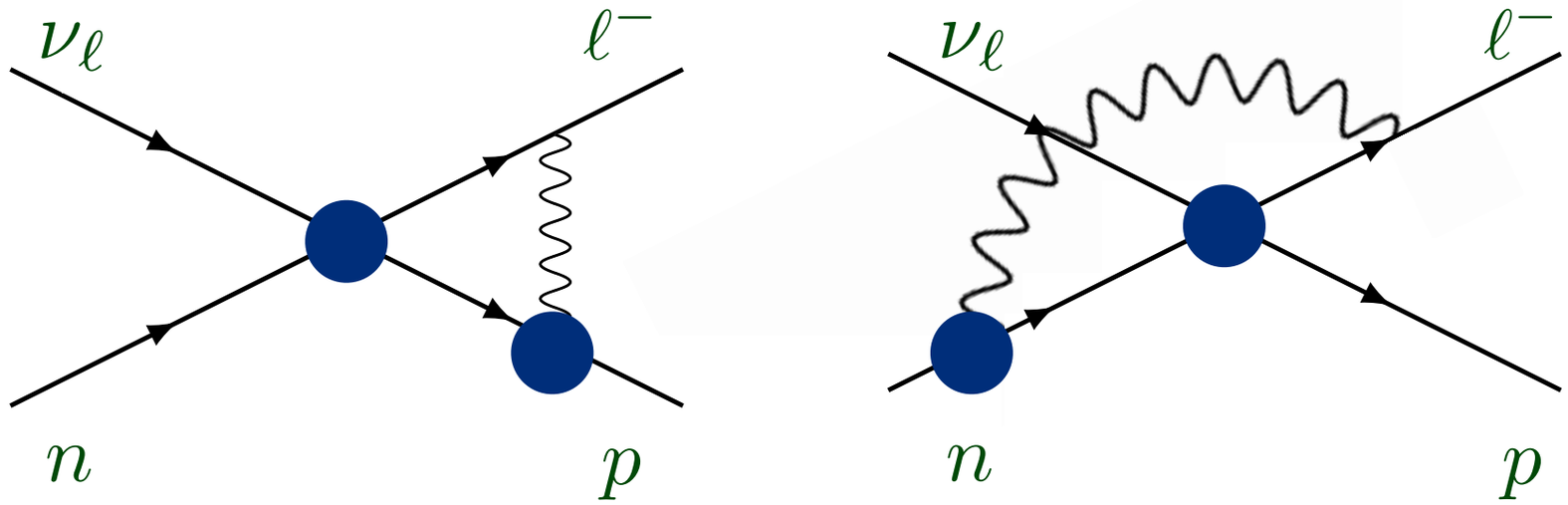
$$\lambda \sim \frac{m_\mu^2}{E_\nu^2} \sim (\Delta\theta)^2 \sim \frac{\Delta E}{E_\nu}$$

$\ln \lambda$ enhancements

O.T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun. (2022)

O.T., Qing Chen, Richard J. Hill, Kevin S. McFarland and Clarence Wret editors suggestion in PRD (2022)

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, PLB (2013)

- add self energy for charged particles

- reproduce soft and collinear regions of SCET

- best determination of hard function

Factorization approach

- cross section is given by factorization formula

$$\mathrm{d}\sigma \sim S\left(\frac{\Delta E}{\mu}\right) J\left(\frac{m_\ell}{\mu}\right) H\left(\frac{M}{\mu}\right)$$

- determine hard function at hard scale by matching experiment or hadronic model to the theory with heavy nucleon

- RGE evolution of the hard function to scales $\Delta E, m_\ell$

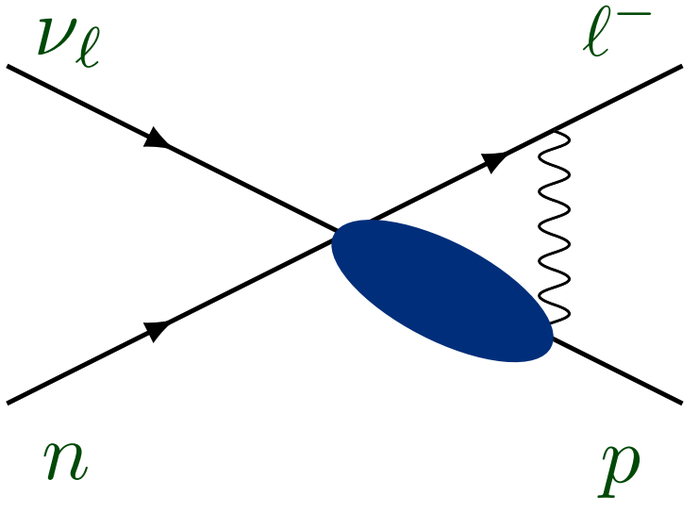
- soft and collinear functions are evaluated perturbatively

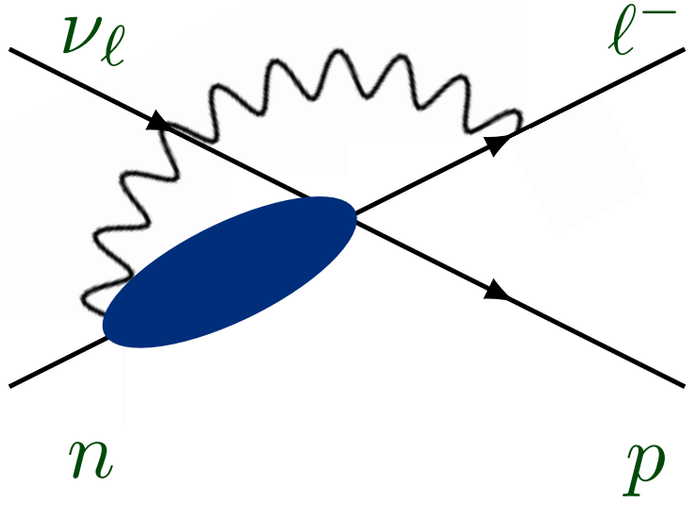
- calculate cross section at low energies accounting for all large logs

ep scattering with soft radiation only: Richard J. Hill, PRD (2016)

- soft and collinear functions determined analytically
- hard function describes physics at GeV energies

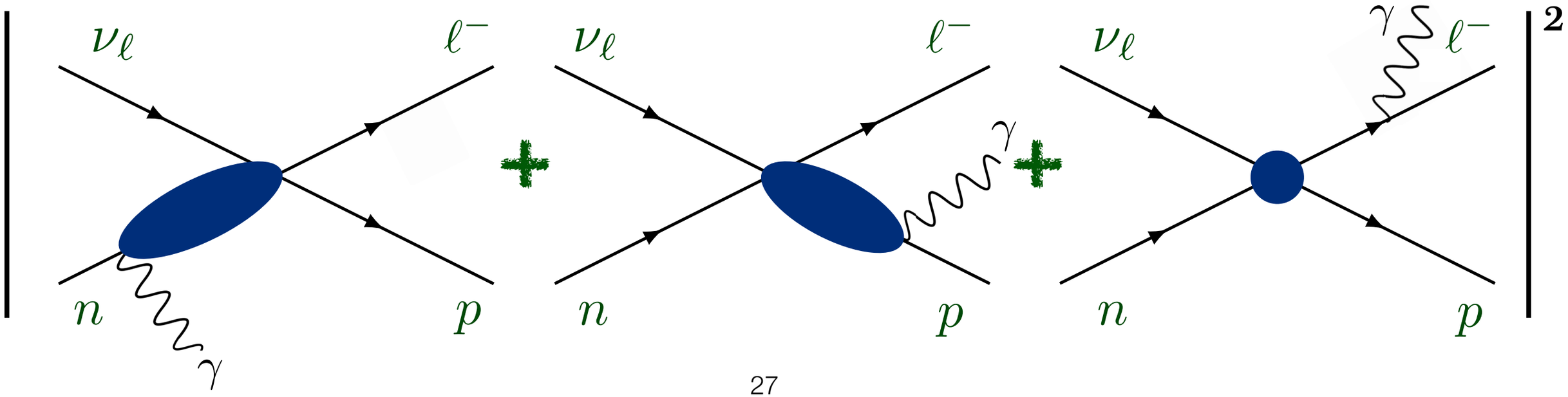
Inclusive observables





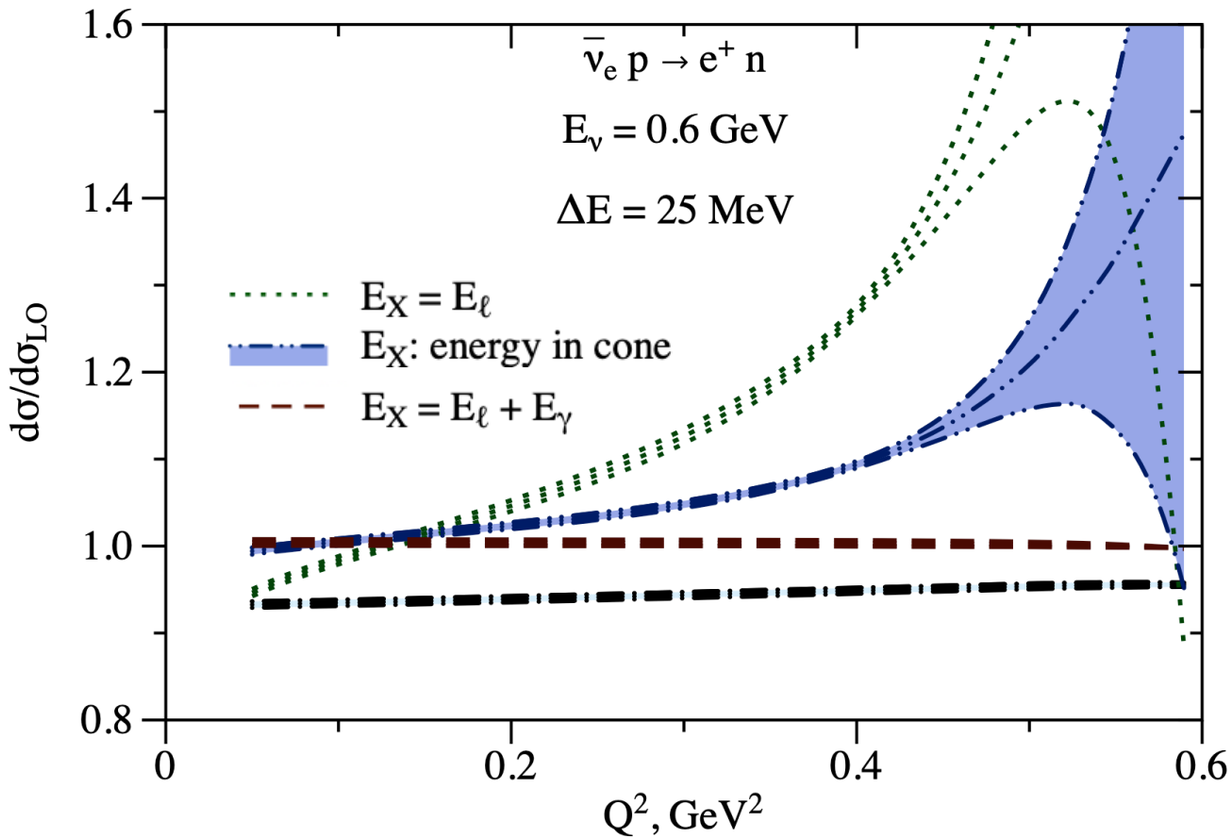
- the same gauge-invariant model for the real radiation

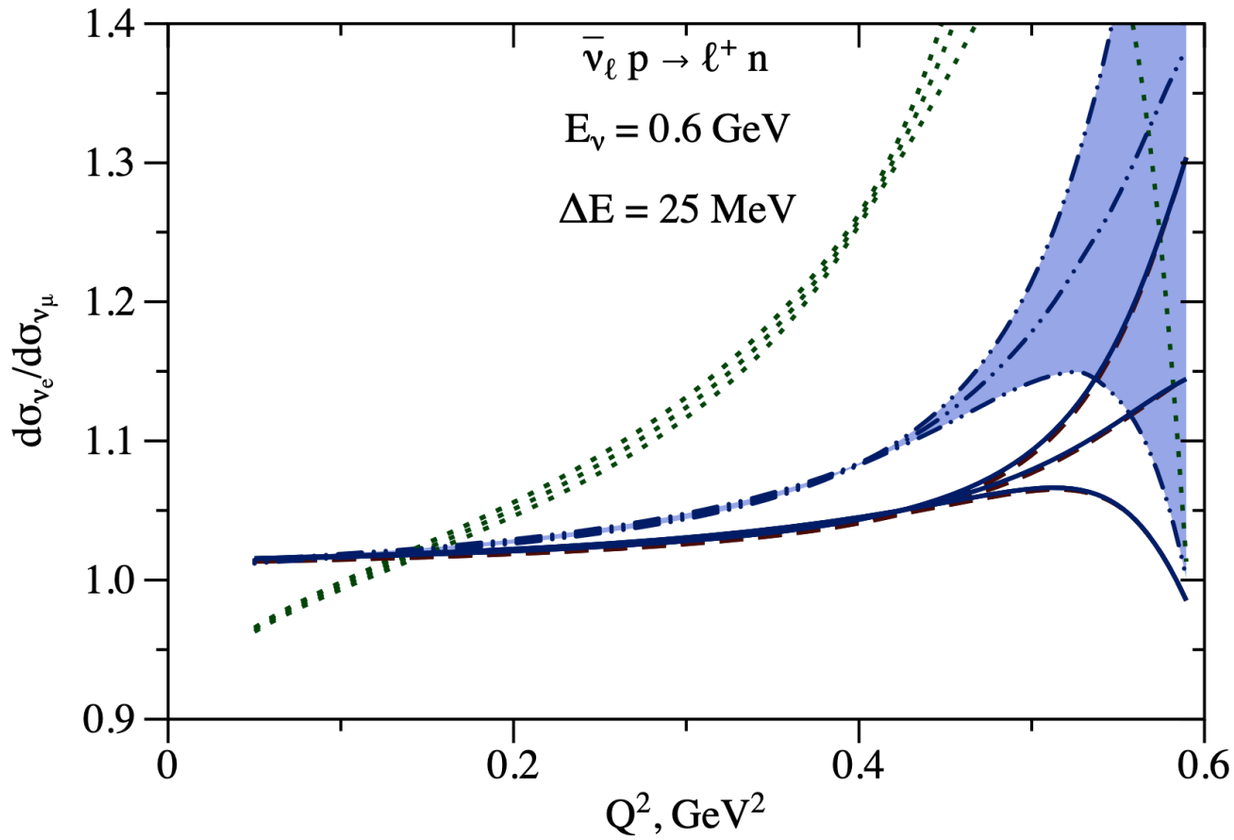
- arbitrary hard photons are part of the observable



Inclusive observables

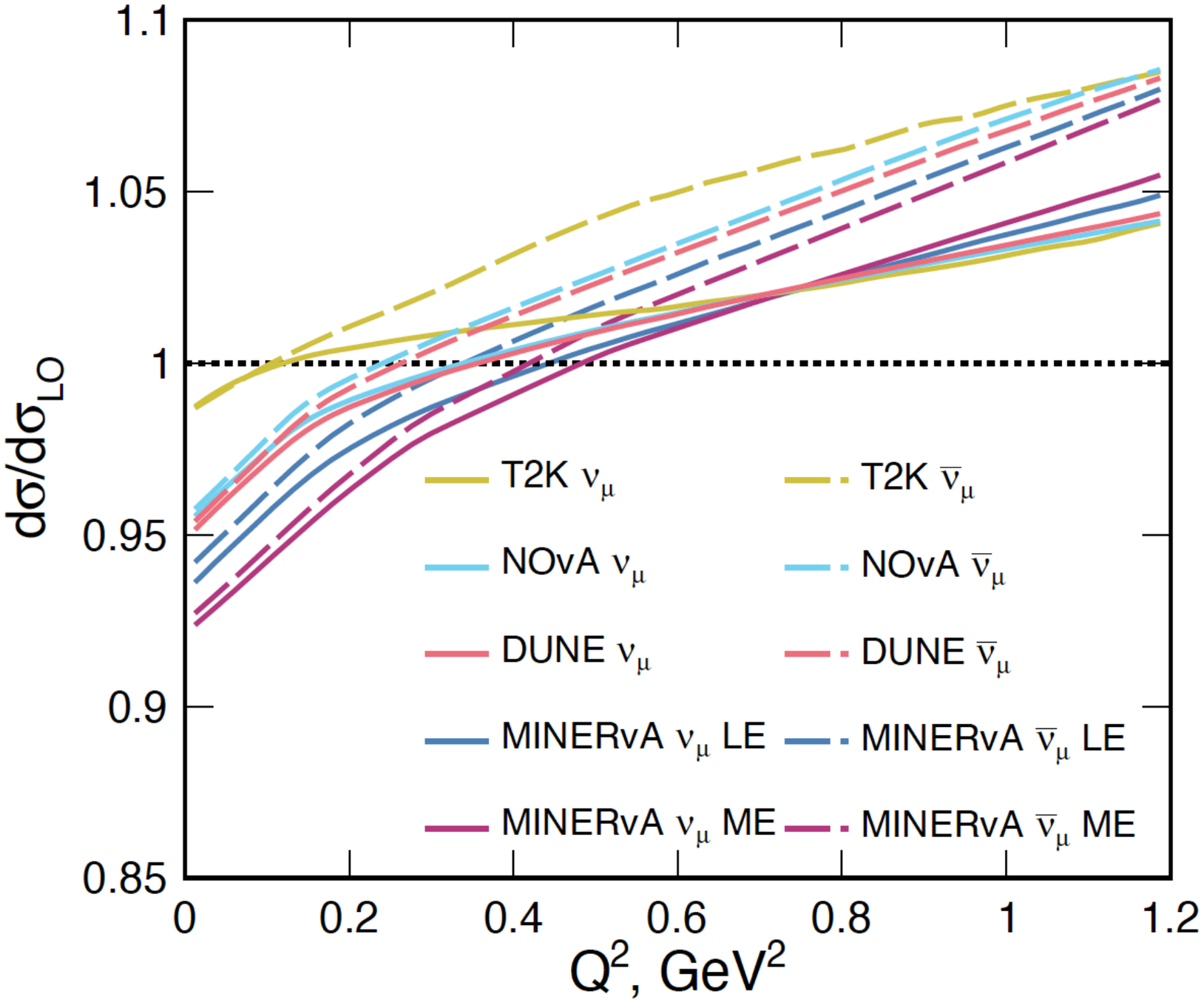
- kinematics $Q^2 = 2M\,(E_\nu - E_X)$ is reconstructed with 3 different E_X





- dependence on reconstruction of kinematics and cuts
- precise prediction for ratios $\sigma_{\nu_e}/\sigma_{\nu_\mu}$

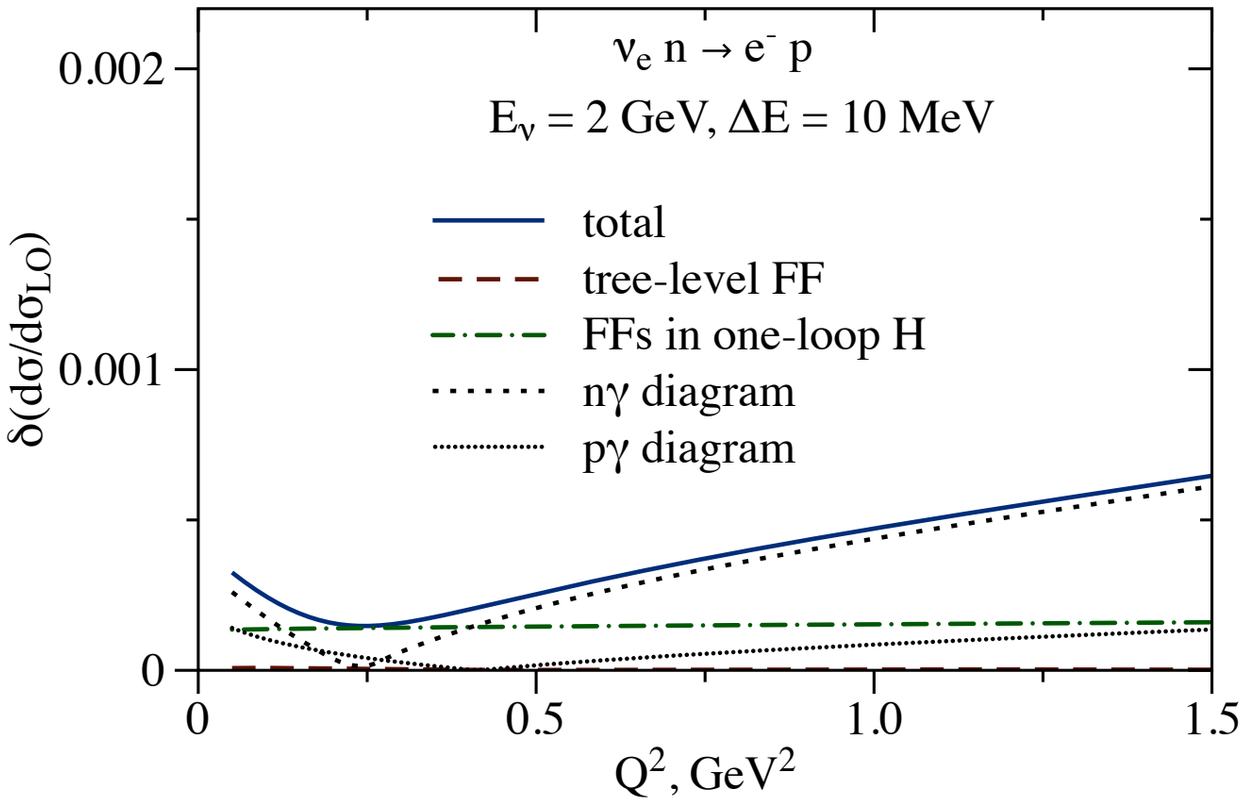
Comparison to data

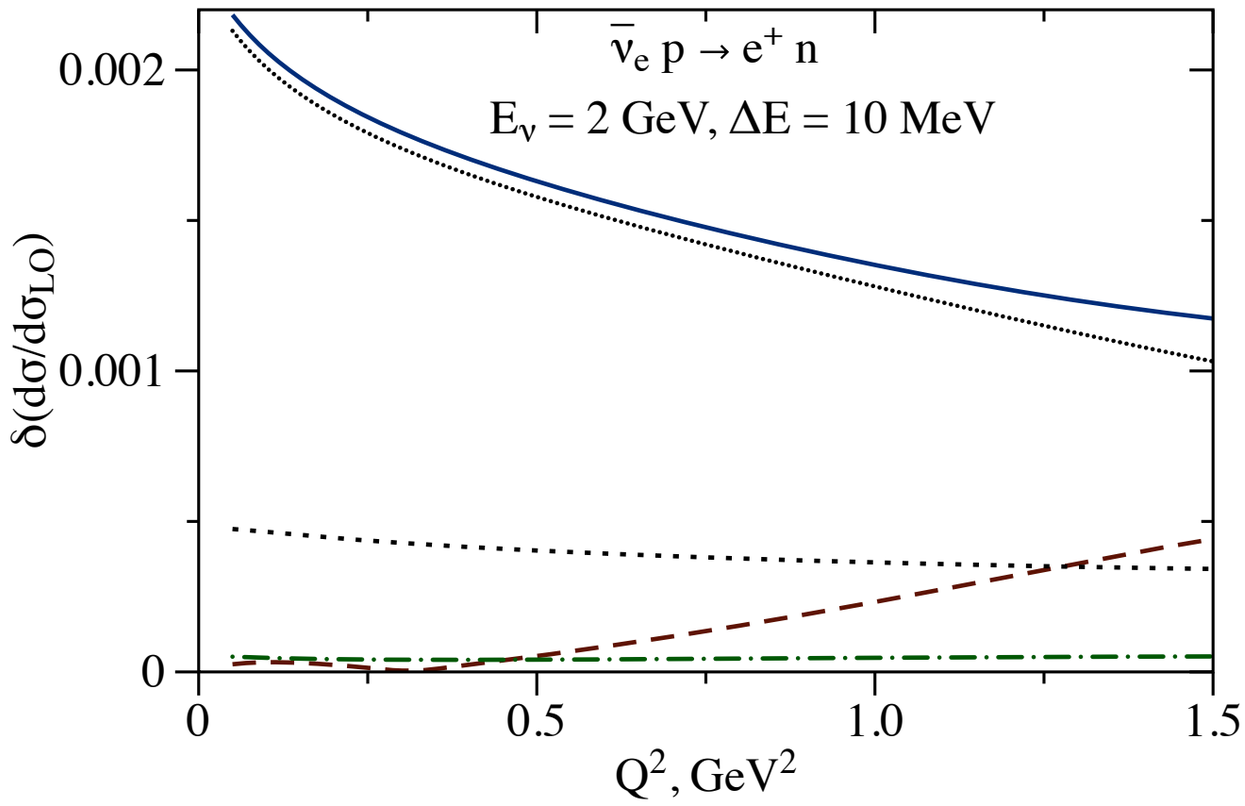


- lepton energy spectra with lepton kinematics
- NEUT generator + flux averaging

Error budget

- uncertainties from hard function





- nucleon form factors

Meyer, Betancourt, Gran and Hill, PRD (2016)

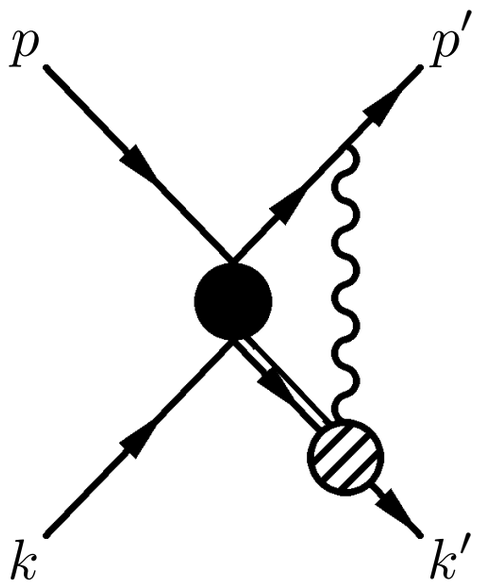
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T., PRD (2020)

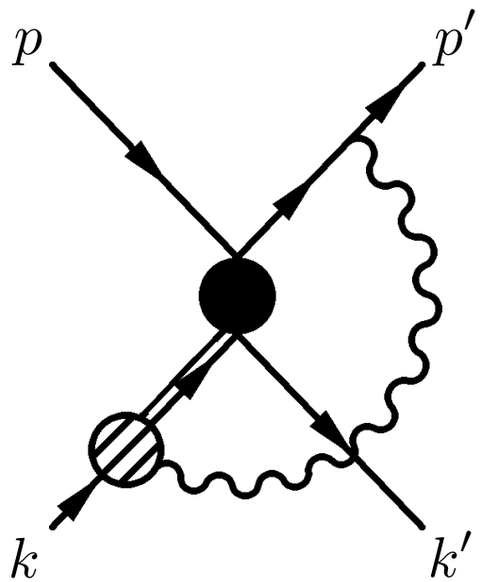
- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result

Δ resonance contribution

- vector part with magnetic transition only; pQCD for axial-vector





$$C_5^A\left(Q^2\right) \lesssim \frac{\ln Q^2}{Q^6}$$

- free from soft singularities ⟶ flavor-independent

- expected collinear limit

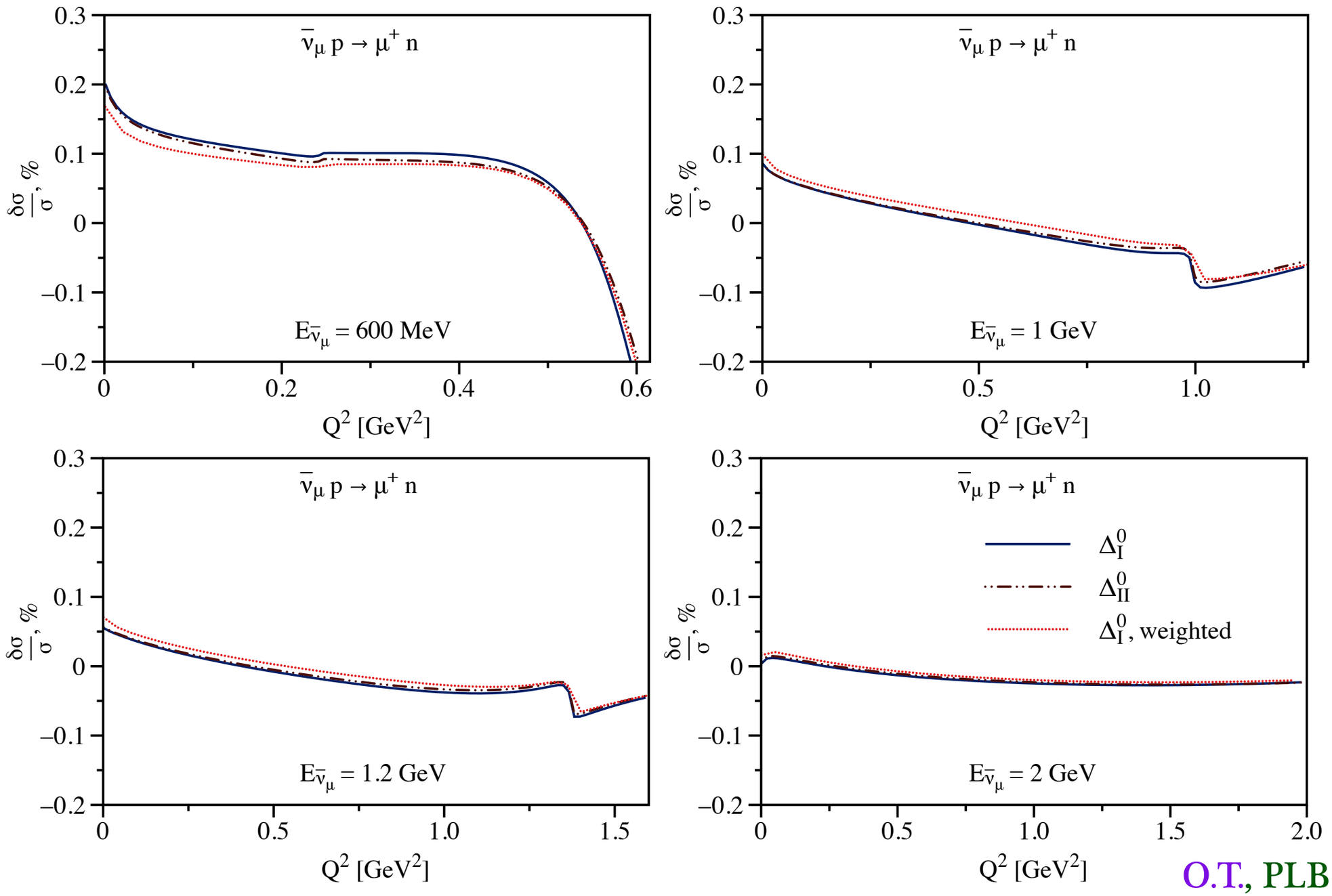
$$g_M, g_E, f_A, f_{A3} \sim \text{const}$$
$$f_P,\ f_3,\ f_R,\ f_T \sim \ln m$$

O.T., PLB (2026)

- expected infrared behavior

Δ resonance contribution

- width of Δ resonance included

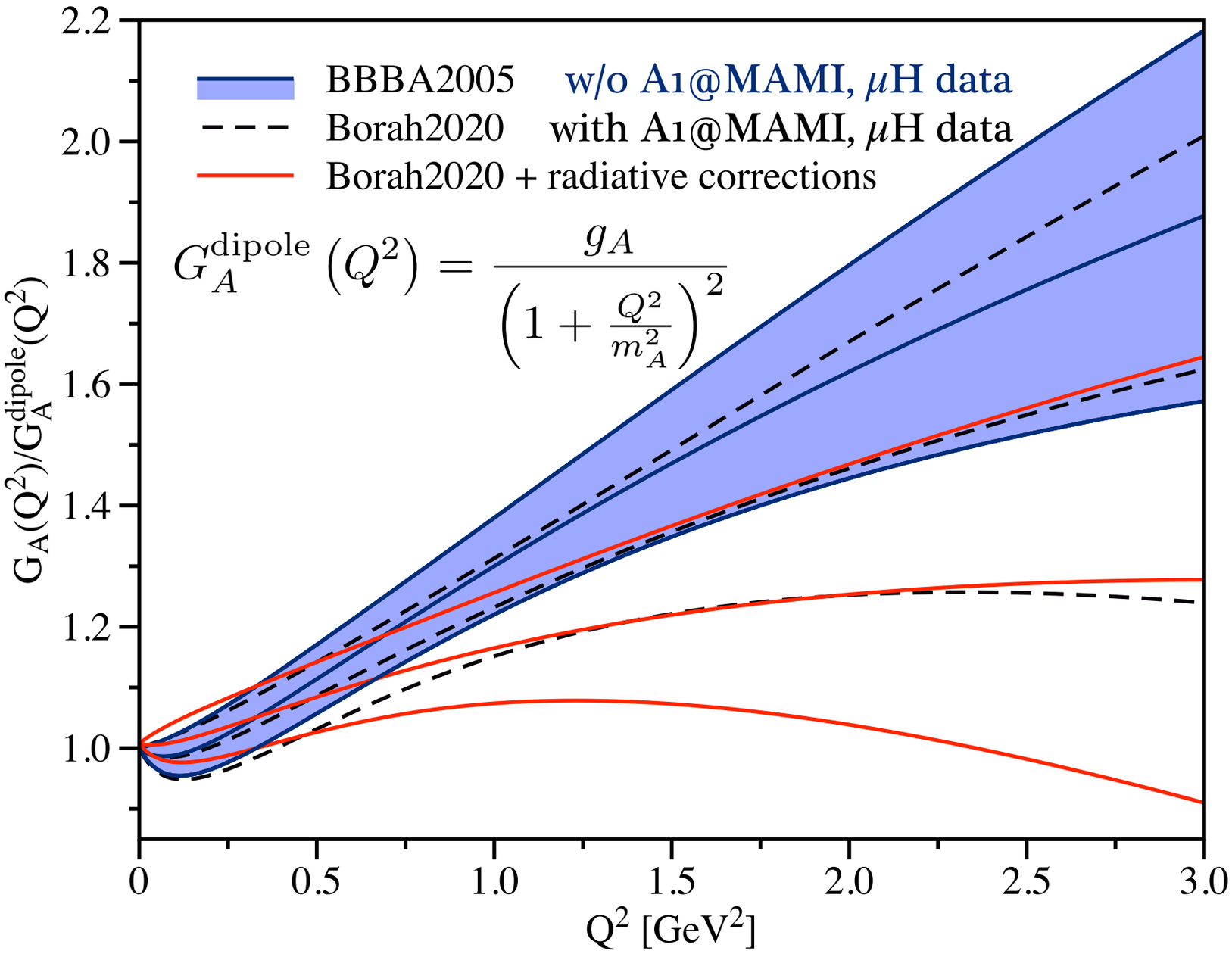


O.T., PLB (2026)

- in agreement with conservative error estimates of inelastic states

Nucleon axial-vector form factor

- first extraction of axial-vector form factor with QED

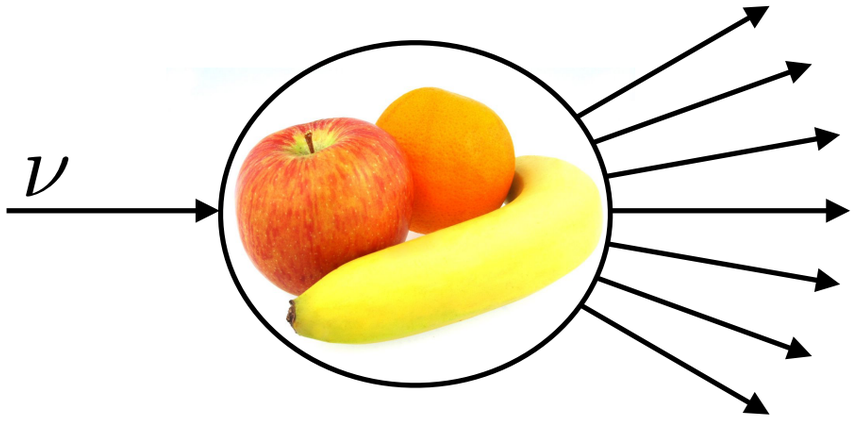


inclusive fixed order

O.T., Aaron S. Meyer, Clarence Wret, Tejin Cai, Richard J. Hill, Kevin S. McFarland, PRD (2026)

- first consistent at 1%-level QED radiative corrections

Conclusions



QED radiative corrections
in EFT framework

- radiative corrections to (anti)neutrino-nucleon cross sections formulated in factorization framework

- charged-current elastic electron vs muon cross-section ratios evaluated from theory with sub-percent uncertainty

- nucleon axial-vector form factor and radius extracted accounting for radiative corrections

Thanks for your attention !!!