NuPhyR 2025

Zhuhai, Guangdong, China

30 November, 2025

Charged-current (anti)neutrino scattering cross sections and radiative corrections

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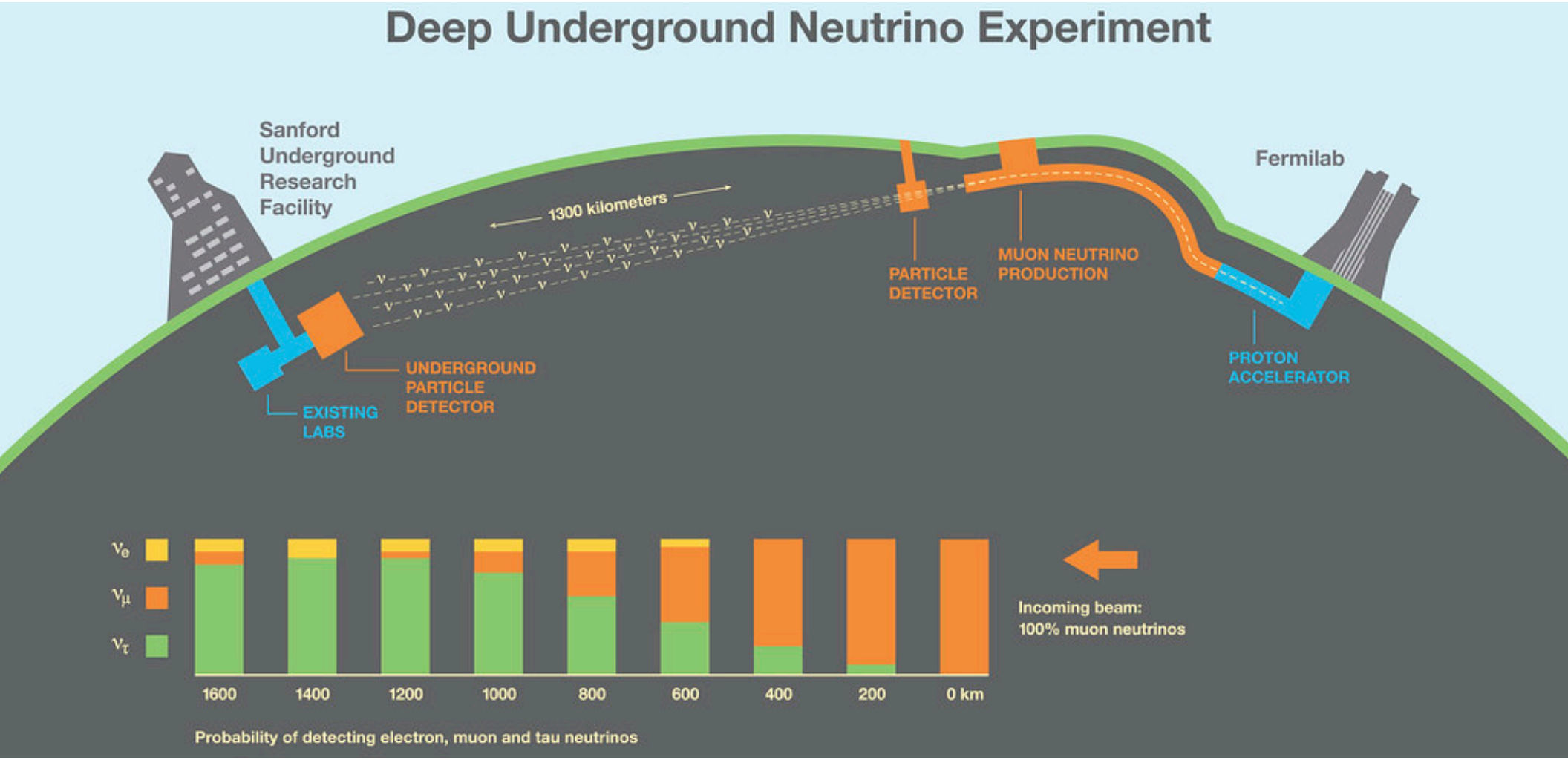
Neutrino experiments

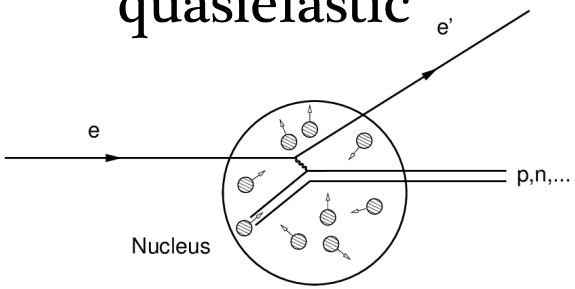


$$N_\nu \sim \int \mathrm{d}E_\nu \Phi_\nu\left(E_\nu\right) \times \sigma\left(E_\nu\right) \times R\left(E_\nu, E_\nu^{\mathrm{rec}}\right)$$

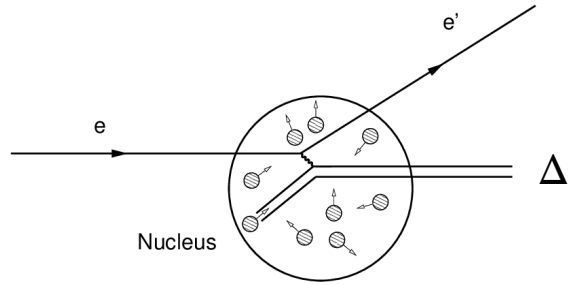
- precise neutrino physics: need in cross sections

Interaction mechanisms

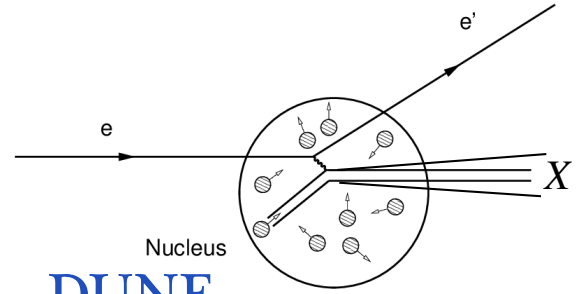
quasielastic



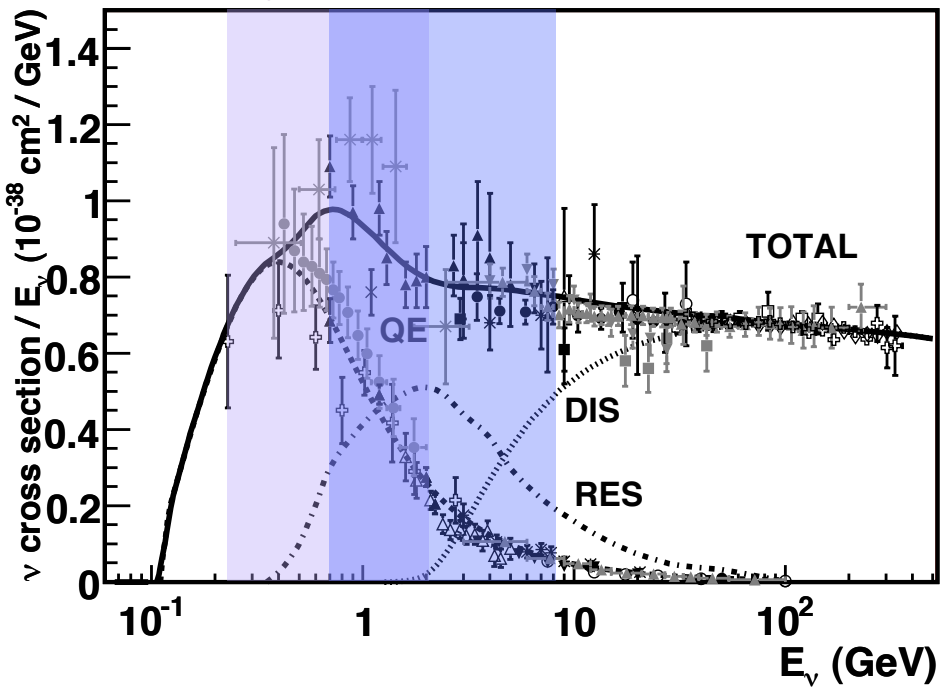
resonance



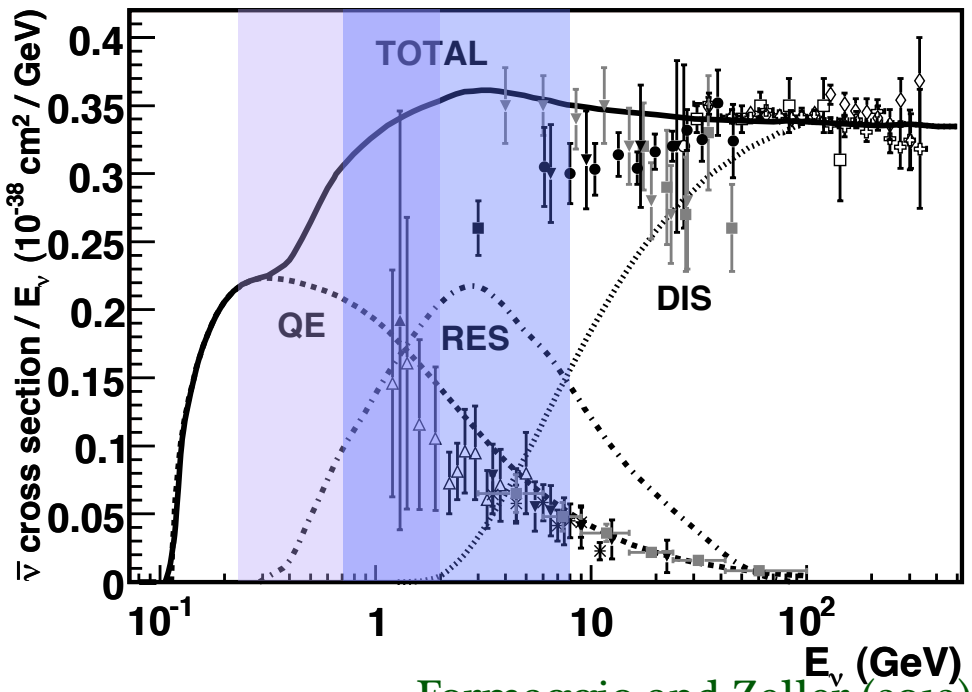
DIS



Hyper-K



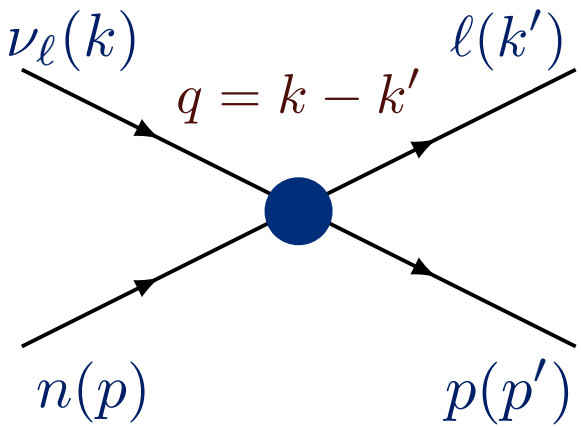
DUNE



Formaggio and Zeller (2013)

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

CCQE scattering on free nucleon



neutrino energy E_ν

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

contact interaction at GeV energies

- assuming isospin symmetry, nucleon current:

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

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

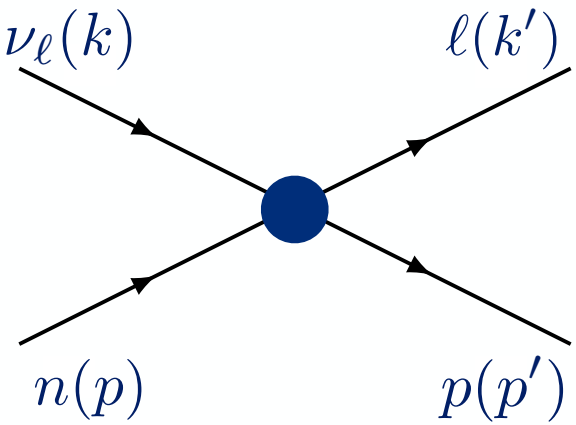
form factors: isovector Dirac and Pauli axial and pseudoscalar

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

tree-level amplitude

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

CCQE 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

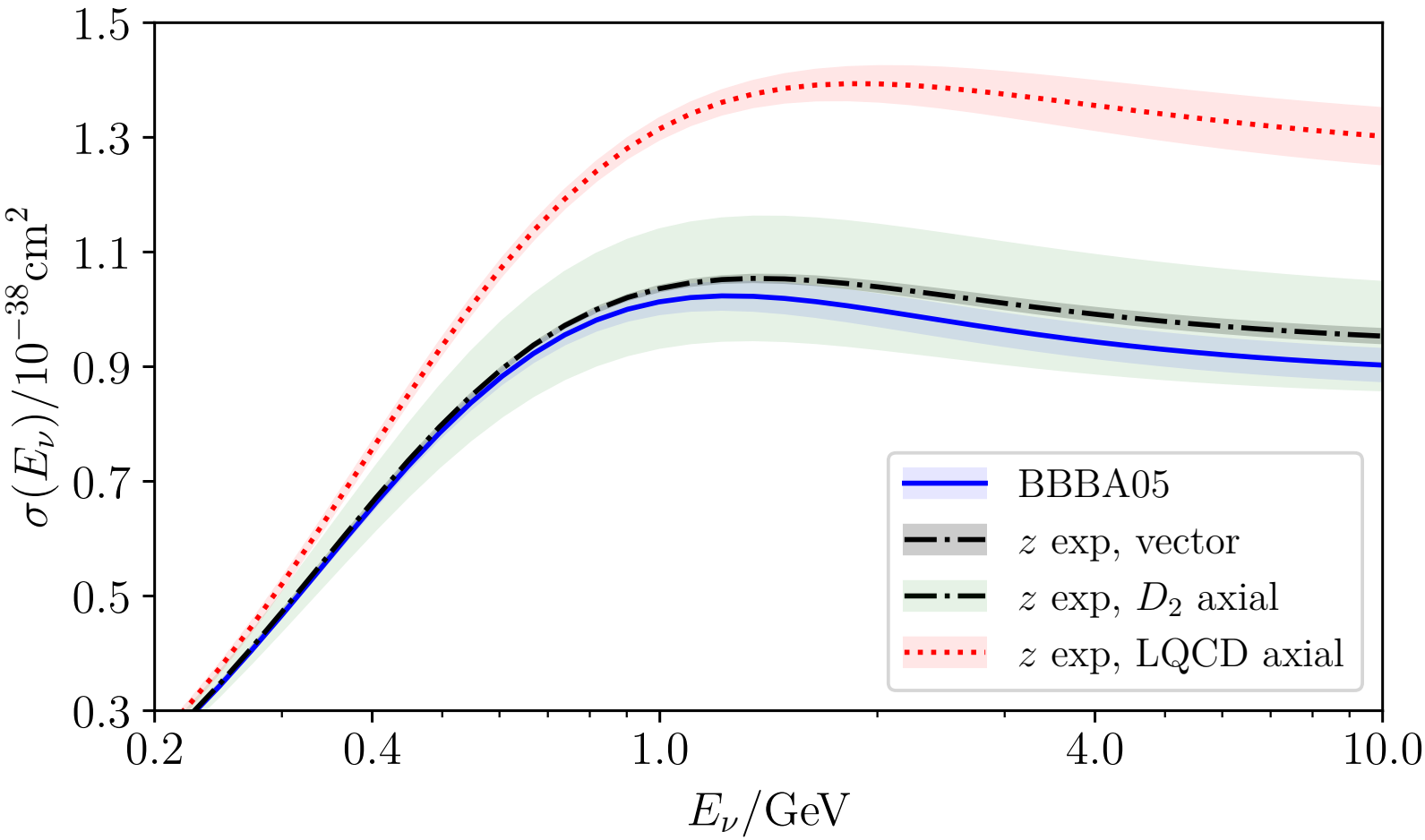
world data: ~3200 events

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 (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)

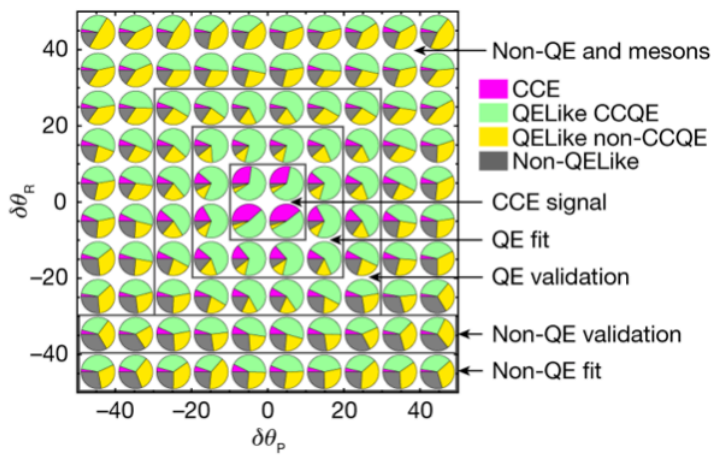
- knowledge of vector structure stops a progress in studies of axial
- acknowledged discrepancy: lattice QCD <-> experimental data

MINERvA result with free protons

- idea of scattering on molecular hydrogen realized !!!

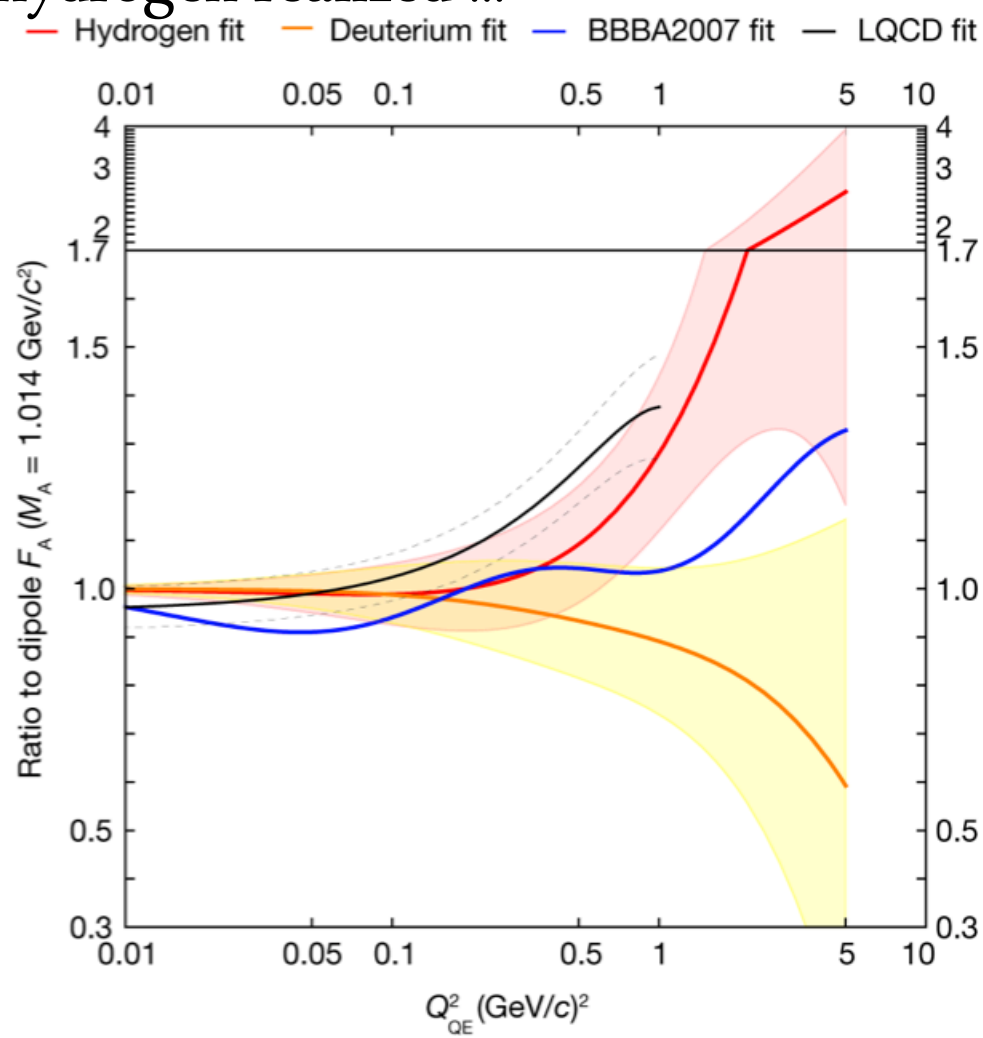
$$\overline{\nu}_\mu p \to \mu^+ n$$

kinematic selection



5580 events over
12500 background

background nuclear events
constrained by scattering of ν

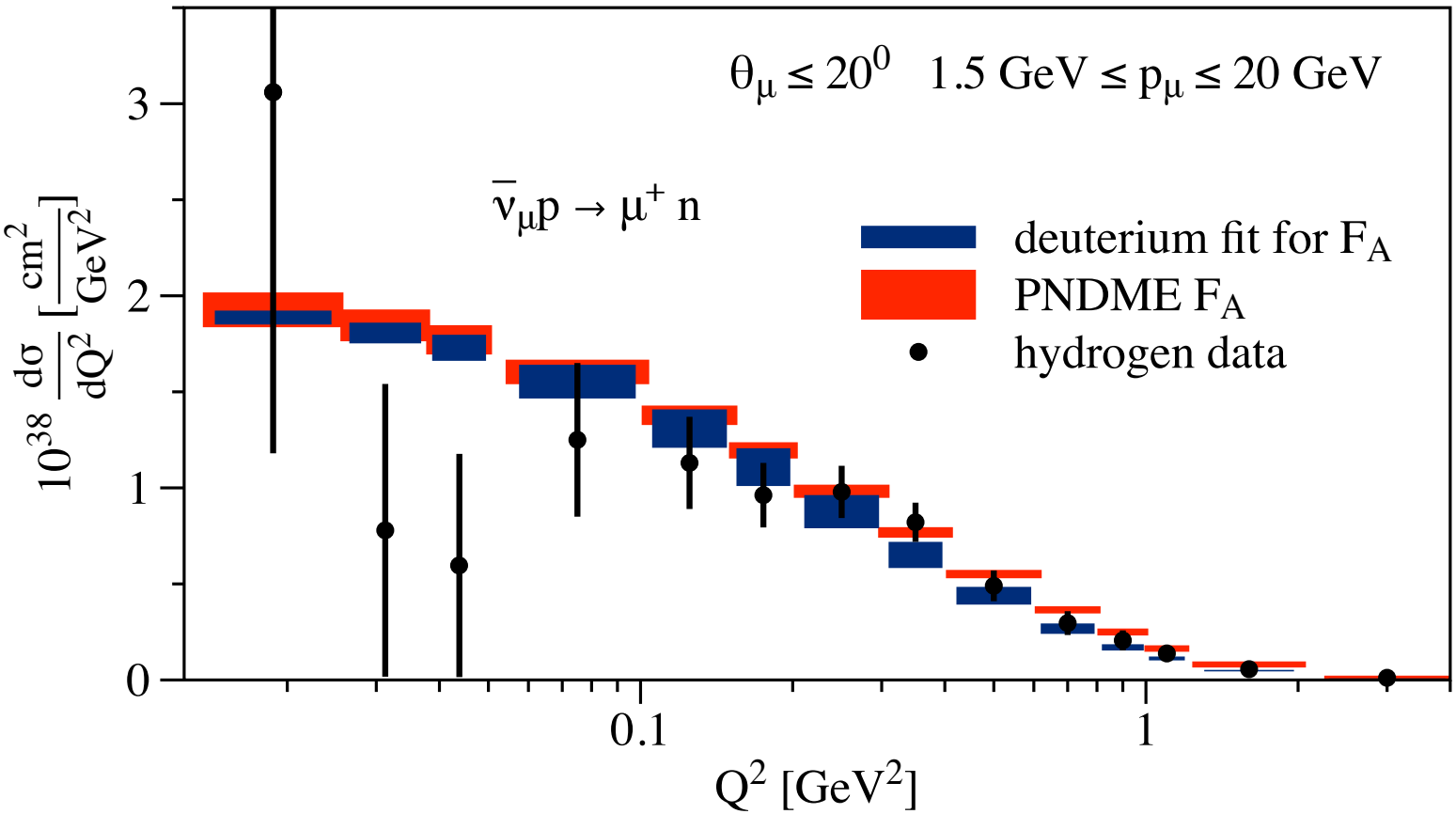


- 1st measurement of axial form factor on "free" protons $\overline{\nu}_\mu p \to \mu^+ n$

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

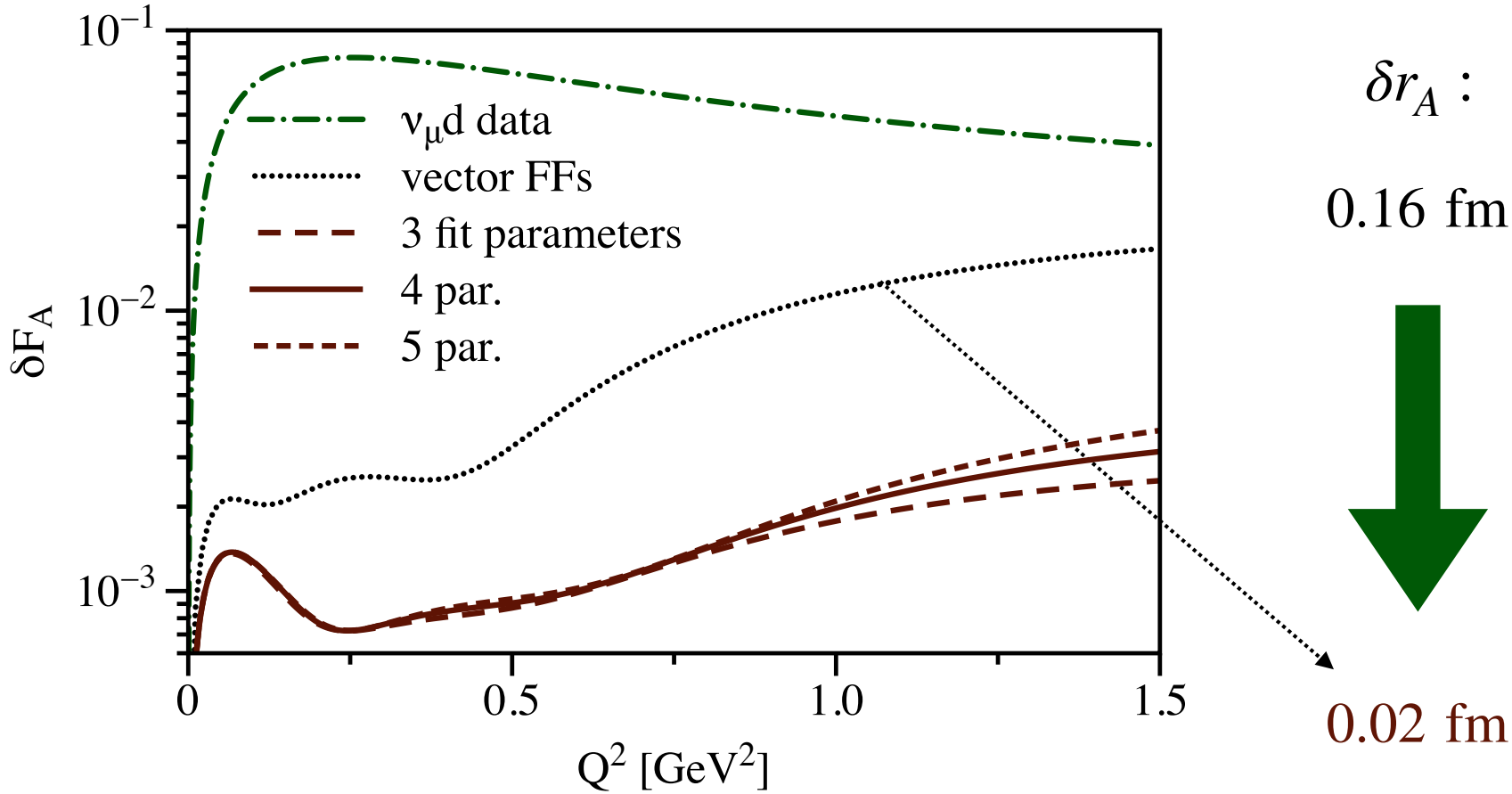
- 2-3σ tension between lattice QCD and deuterium data
- MINERvA hydrogen data consistent with LQCD and deuterium

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

DUNE projections

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

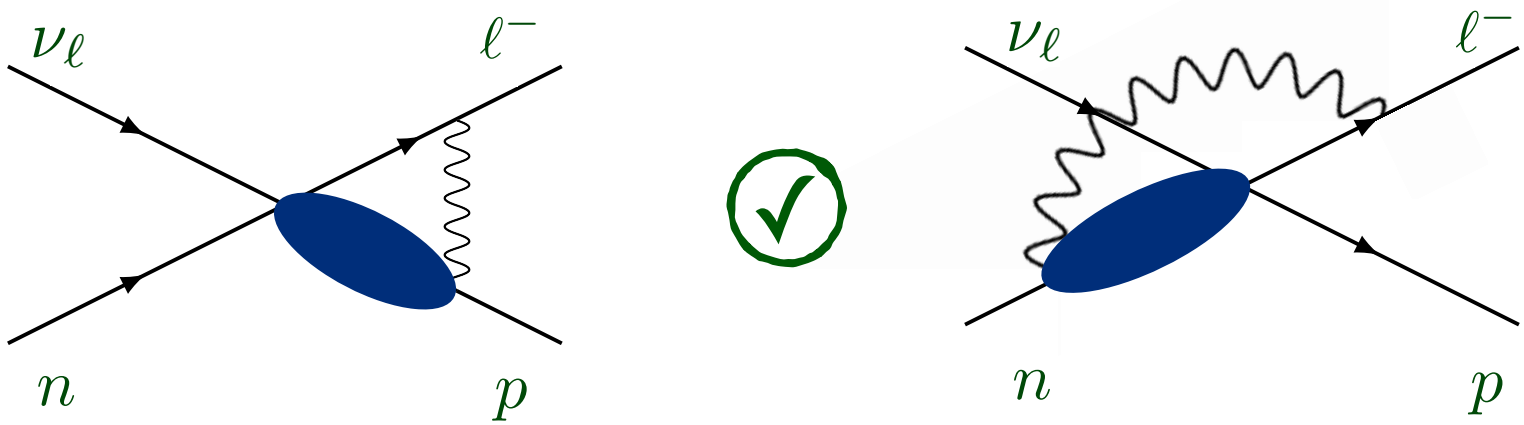
H. Duyang, B. Guo, S. R. Mishra, and R. Petti, PRD (2018)



- 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)

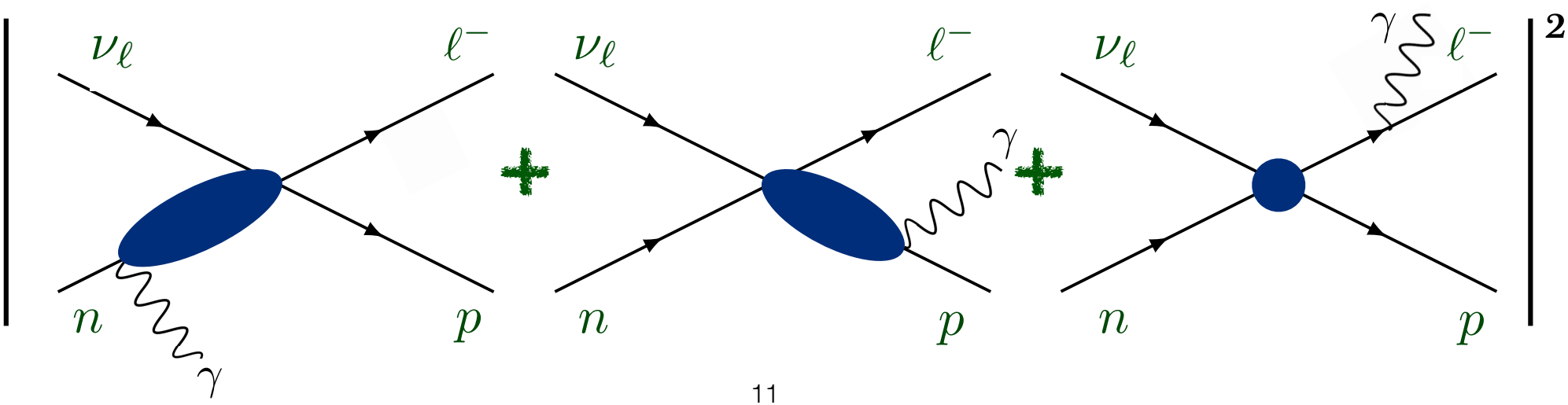
factorization for radiative corrections with model for hard function



Radiative corrections

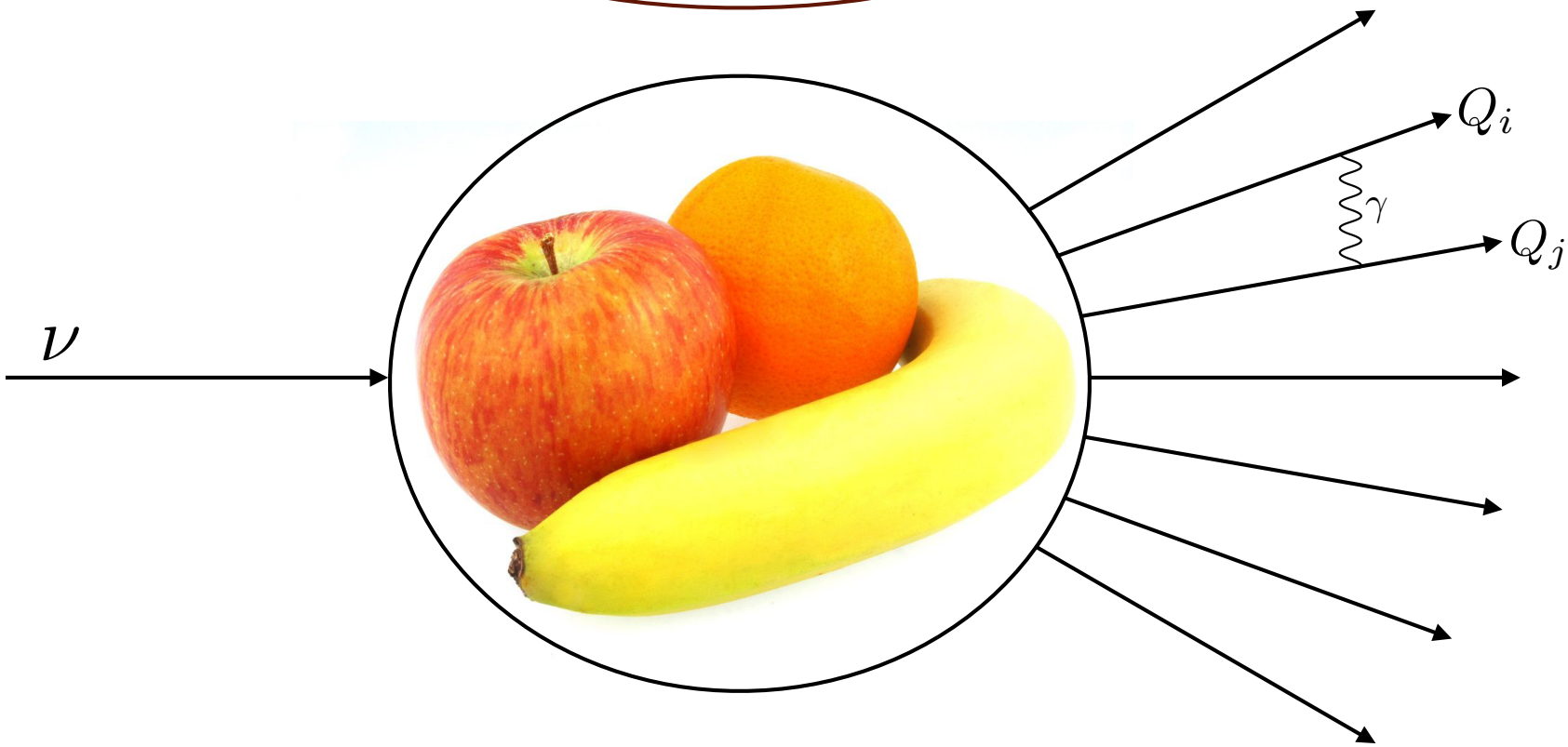
O.T., Qing Chen, Richard J. Hill and Kevin S. McFarland, Nature Commun (2022)

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



QED corrections

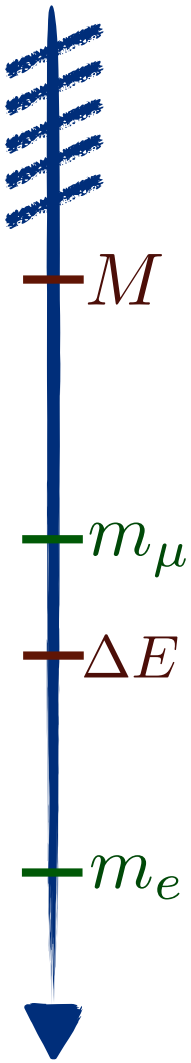
$$m_e \ll m_\mu \ll E_\nu$$



$\frac{\alpha}{\pi} \sim 0.2\ \%$ 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

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

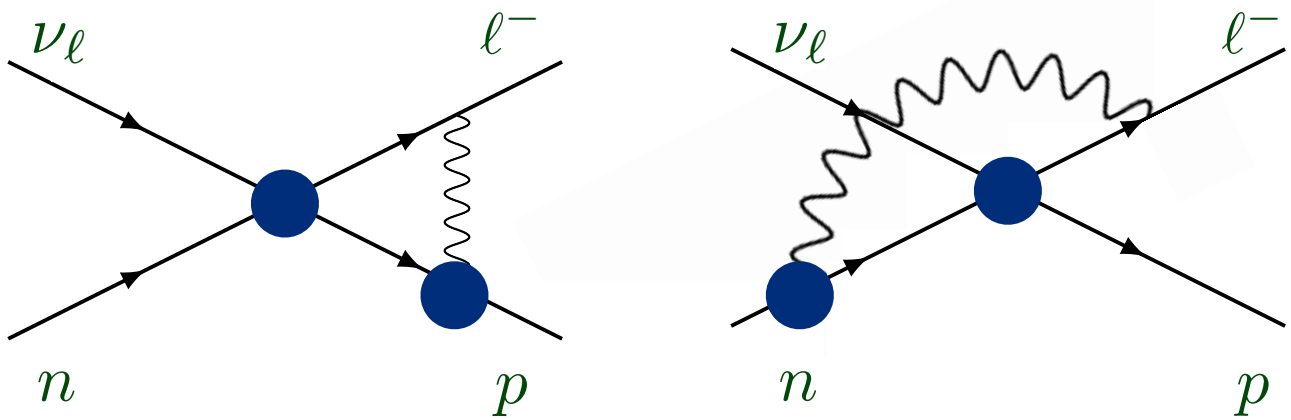
SCET power expansion parameter

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

$\ln\lambda$ enhancements

power corrections are large at lowest muon (anti)neutrino E @ SBND

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, Phys. Lett. B (2013)

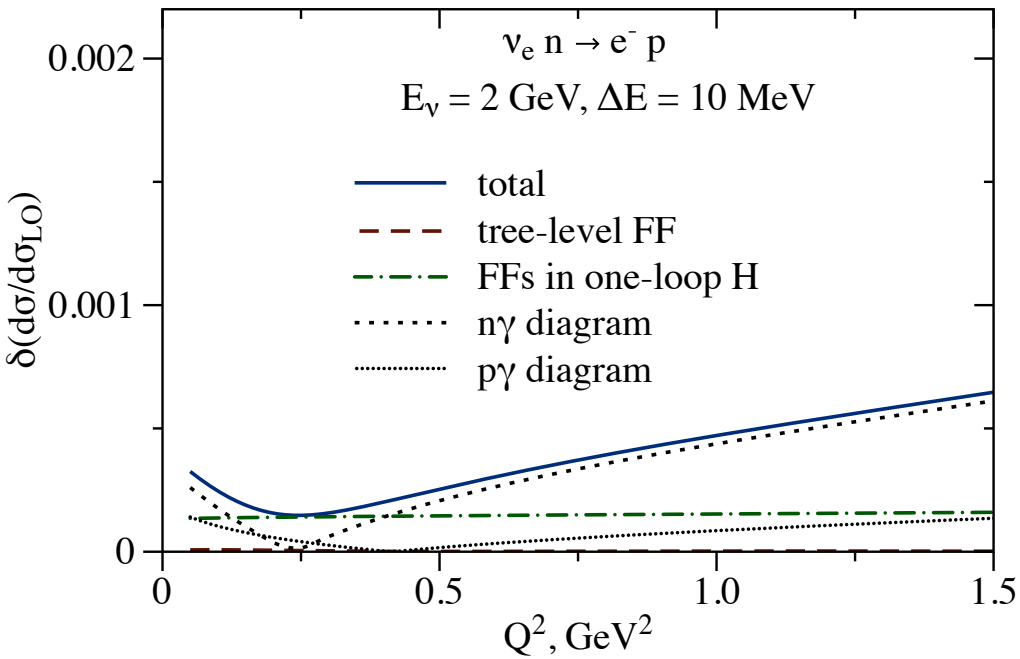
- add self energy for charged particles

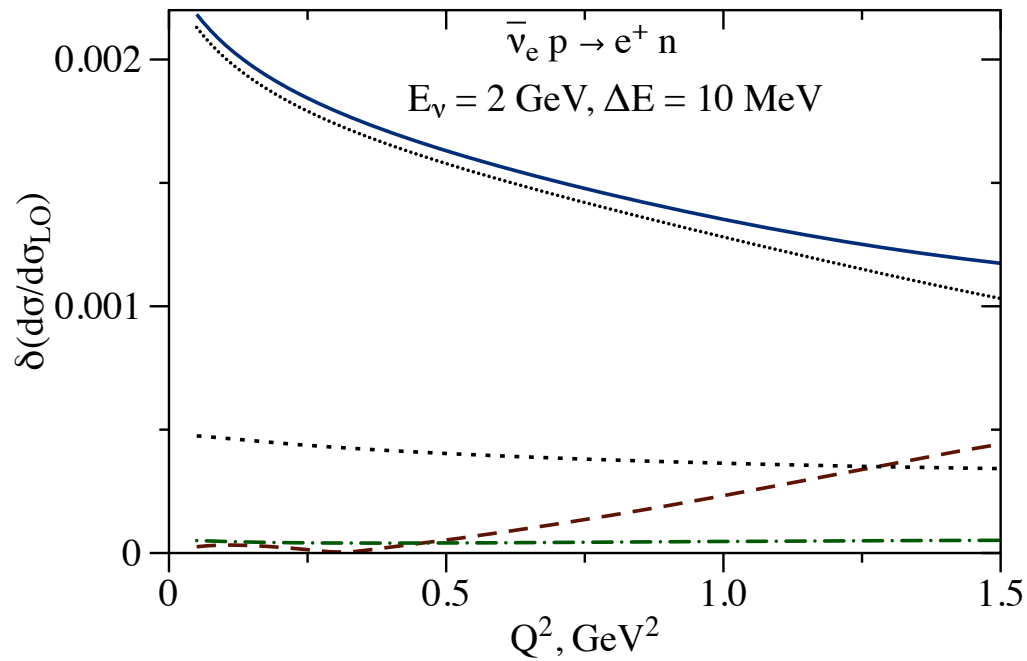
- reproduce soft and collinear regions of SCET

- best determination of hard function

Error budget

- uncertainties from hard function





- nucleon form factors

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

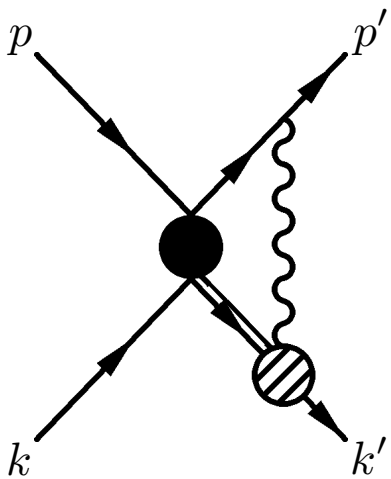
Kaushik Borah, Gabriel Lee, Richard J. Hill and O.T., PRD (2020)

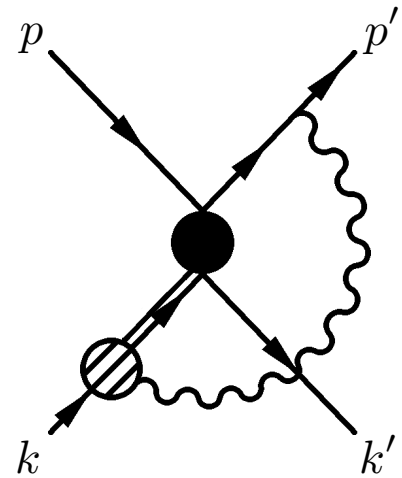
- add perturbative uncertainty by variation of scale

- uncertainty of permille level for the ratio to LO result

Δ resonance contribution

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





- free from soft singularities → flavor-independent

- expected collinear limit

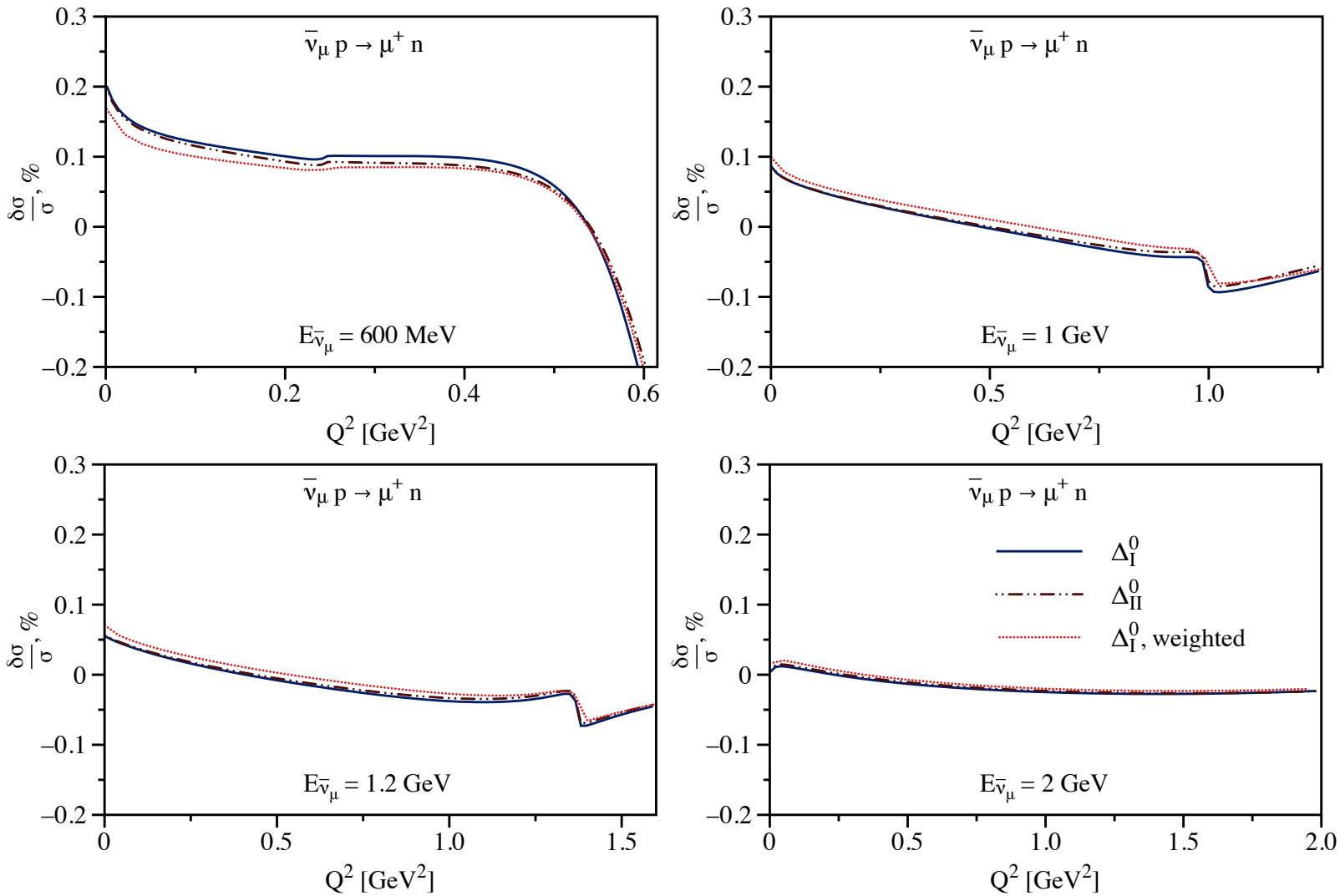
$$g_M, g_E, f_A, f_{A3} \sim \text{const}$$
$$f_P,\ f_3,\ f_R,\ f_T \sim \ln m$$

- expected infrared behavior

O.T., arXiv (2025)

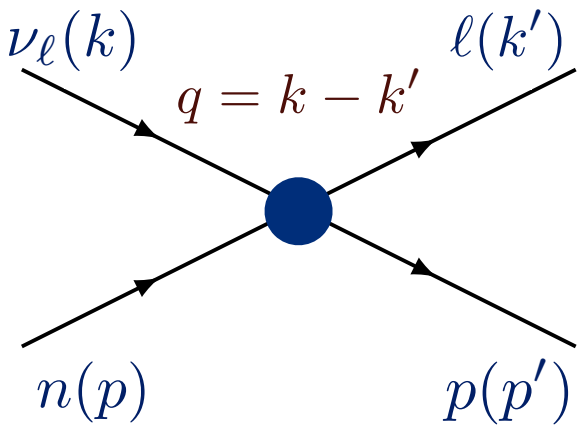
Δ resonance contribution

- width of Δ resonance included



- in agreement with conservative error estimates of inelastic states

Invariant amplitudes



averaged lepton momentum $K_\mu = \dfrac{k_\mu + k'_\mu}{2}$

averaged nucleon momentum $P_\mu = \dfrac{p_\mu + p'_\mu}{2}$

- four amplitudes for massless charged lepton

$$T^{m_\ell=0}_{\nu_\ell n\to\ell^- p} = \sqrt{2}\mathrm{G_F}V_{ud}\,\bar{\ell}^-\gamma^\mu\mathrm{P_L}\nu_\ell\,\bar{p}\left(\gamma_\mu\left(g_M + f_A\gamma_5\right) - \left(f_2 + f_A^3\gamma_5\right)\frac{K_\mu}{M}\right)n$$

- four extra amplitudes for massive charged lepton

$$T^{m_\ell\neq0}_{\nu_\ell n\to\ell^- p} = -\sqrt{2}\mathrm{G_F}V_{ud}\frac{m_\ell}{M}\,\bar{\ell}^-\mathrm{P_L}\nu_\ell\,\bar{p}\left(f_3 + f_P\gamma_5 - \frac{f_R}{4}\frac{P_\mu}{M}\gamma^\mu\gamma_5\right)n$$

$$+\sqrt{2}\mathrm{G_F}V_{ud}\frac{m_\ell}{M}\frac{f_T}{4}\,\bar{\ell}^-\sigma^{\mu\nu}\mathrm{P_L}\nu_\ell\,\bar{p}\sigma_{\mu\nu}n$$

- 8 invariant amplitudes for charged-current elastic scattering

Constraints from MINERvA data

- scaling with lepton mass and dipole Q^2 dependence

$$\frac{1}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$$

- nucleon form factors from experimental data

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)

- rigorous error propagation to 68% confidence intervals

	$\mathfrak{Re}\,\bar{f}_3$	$\mathfrak{Re}\,\bar{f}_T$	$\mathfrak{Re}\,\bar{f}_{A3}$	$\mathfrak{Re}\,\bar{f}_R$
$\bar{\nu}p$ scattering	$88.4^{+33.5}_{-58.0}$	$-0.5^{+5.0}_{-4.8}$	$-1.0^{+0.4}_{-0.3}$ & $1.0^{+0.3}_{-0.4}$	$-80.1^{+40.6}_{-26.0}$
beta decay	0.0 ± 1.8	-9.3 ± 10.3	0.0 ± 0.075	

	$\mathfrak{Im}\,\bar{f}_3$	$\mathfrak{Im}\,\bar{f}_T$	$\lvert\mathfrak{Im}\,\bar{f}_{A3}\rvert$	$\lvert\mathfrak{Im}\,\bar{f}_R\rvert$
$\bar{\nu}p$ scattering	$-82.1^{+34.6}_{-23.8}$ & $82.1^{+23.8}_{-34.6}$	0.0 ± 4.9	$1.00^{+0.29}_{-0.43}$	$69.9^{+20.9}_{-30.9}$
beta decay	13.0 ± 54.0	-1.9 ± 15.4		

- improvements for tensor and scalar interactions

- first constraints on muon-specific interactions

Constraints from MINERvA data

- Lee-Yang Lagrangian

$$\mathcal{L}_{LY} = -C_S\ \bar{p}n\cdot\bar{\ell}\,(1-\gamma_5)\,\nu_\ell - C_P\ \bar{p}\gamma_5 n\cdot\bar{\ell}\gamma_5\,(1-\gamma_5)\,\nu_\ell$$
$$-\ C_V\ \bar{p}\gamma^\mu n\cdot\bar{\ell}\gamma_\mu\,(1-\gamma_5)\,\nu_\ell + C_A\ \bar{p}\gamma^\mu\gamma_5 n\cdot\bar{\ell}\gamma_\mu\gamma_5\,(1-\gamma_5)\,\nu_\ell$$
$$-\ C_T\ \bar{p}\sigma^{\mu\nu}n\cdot\bar{\ell}\sigma_{\mu\nu}\,(1-\gamma_5)\,\nu_\ell + \text{h.c.}$$

$$\mathfrak{Re}C_T = -1^{+14}_{-13}\times 10^{-4} \quad |\mathfrak{Im}C_T| \leq 1.3\times 10^{-3} \quad |\mathfrak{Im}C_S| = 45^{+13}_{-19}\times 10^{-3}$$

- quark-level Lagrangian

$$\mathcal{L}_q = -\frac{G_F V_{ud}}{\sqrt{2}}\left[\epsilon_S\bar{u}d\cdot\bar{\ell}\,(1-\gamma_5)\,\nu_\ell - \epsilon_P\bar{u}\gamma_5 d\cdot\bar{\ell}\,(1-\gamma_5)\,\nu_\ell\right.$$
$$+\ \epsilon_V\bar{u}\gamma^\mu d\cdot\bar{\ell}\gamma_\mu\,(1-\gamma_5)\,\nu_\ell + \epsilon_A\bar{u}\gamma^\mu\gamma_5 d\cdot\bar{\ell}\gamma_\mu\gamma_5\,(1-\gamma_5)\,\nu_\ell$$
$$\left.+\ \epsilon_T\bar{u}\sigma^{\mu\nu}d\cdot\bar{\ell}\sigma_{\mu\nu}\,(1-\gamma_5)\,\nu_\ell\right] + \text{h.c.}$$

- with lattice-QCD values for nucleon matrix elements

$$\mathfrak{Re}\left(\epsilon_T^{ud}\right)_{\mu\mu} = 7^{+68}_{-71}\times 10^{-3} \quad |\mathfrak{Im}\left(\epsilon_T^{ud}\right)_{\mu\mu}| \leq 7\times 10^{-2} \quad |\mathfrak{Im}\left(\epsilon_S^{ud}\right)_{\mu\mu}| = 9.1^{-3.8}_{+2.6}$$

- improvements for tensor and scalar interactions

- first constraints on muon interactions at nucleon and quark level

Conclusions

- general framework for elastic scattering on nucleons: 8 amplitudes

- QED radiative corrections in factorization framework

- Δ resonance contributions to hard function as inelastic correction

- MINERvA data vs deuterium data or lattice QCD: within 1σ

- MINERvA hydrogen data: update on tensor and scalar interactions

- axial-vector form factor and radius at DUNE: subpercent precision

MDPI

IMPACT FACTOR 2.6

Special Issue: Neutrino Oscillations and Interactions

Partial or Full Fee Wavers

universe

CITESCORE 5.2

Thanks for your attention !!!