IFIC scientific days
Neutrinos and Lepton flavor

Hadron Physics with Electroweak Probes

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Introduction

- Electroweak interactions open a doorway to fundamental properties of strong interacting matter

- ν cross sections are crucial to achieve the precision goals of oscillation experiments

- Need for neutrino interaction theory:
- Experiments (partially) rely on theory-based simulations for:
  - background subtraction
  - flux calibration
  - E_ν reconstruction
  - efficiency and acceptance determination
  - $\sigma(\nu_\mu)$ to $\sigma(\nu_e)$, target extrapolations

- Neutrino scattering mismodeling in event generators can lead to **systematic errors** even if tuned to the best (ND) data.

Baryon Chiral Perturbation Theory

- Effective field theory of QCD at low momenta and small quark masses
  - Allows to study light-quark mass dependence ⇔ Lattice QCD
- Power counting:
  - in powers of p, m_q
  - Order of a Feynman diagram: $D = 4L + \sum_k k V^{(k)} - 2I_\pi - I_N$
    - with explicit $\Delta(1232)$ $\delta = m_\Delta - m_N$ (different countings)

- In presence of baryons:
- Power-counting breaking (PCB) terms
  - because of N, Δ with masses that do not vanish in the χ limit
  - EOMS (Extended on mass shell) scheme Gegelia & Scherer
    - PCB terms absorbed by low-energy constants (LEC)
    - Covariance and analytic properties of loops preserved.

Baryon ChPT

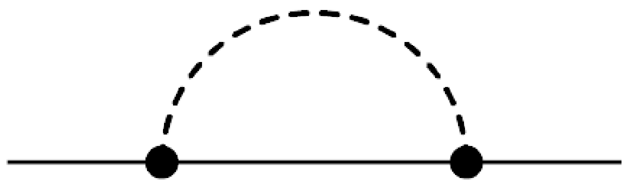
- Power-counting breaking (PCB) terms in EOMS
- Example: nucleon mass in SU(2)

O(p) $\mathcal{L}_1 = -\bar{\psi} M_0 \psi + \ldots \qquad M = M_0$

O(p²) $\mathcal{L}_2 = 4 c_1 m_\pi^2 \bar{\psi}\psi + \ldots \qquad M = M_0 - 4 c_1 m_\pi^2$

O(p³) Loops $M = M_0 - 4 c_1 m_\pi^2 + \boxed{\frac{1}{16\pi^2}\left(\frac{g_A}{f_\pi}\right)^2 m_\pi^2 M_0} + \ldots$

O(p²) !



EOMS: $c_1 \to c_1 + \frac{1}{64\pi^2}\left(\frac{g_A}{f_\pi}\right)^2 M_0$

Nucleon axial form factor

- Fundamental nucleon property

$$A_\alpha^a = \bar{u}(p')\left[\gamma_\alpha\gamma_5 F_A + \frac{q_\alpha}{m_N}\gamma_5 F_P\right]\frac{\tau^a}{2}u(p)$$

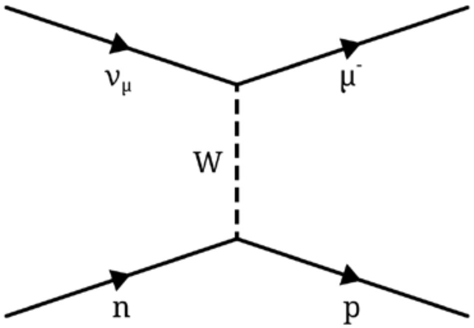
$$q = k - k' = p' - p$$

$$F_A(q^2) = g_A\left[1 + \tfrac{1}{6}\langle r_A^2\rangle q^2 + \mathcal{O}(q^4)\right]$$

$$Q^2 = -q^2 > 0$$

- Main source of uncertainty for QE scattering on nucleons:

$$\begin{aligned}
\text{CCQE}: \; \nu(k) + n(p) &\rightarrow l^-(k') + p(p') \\
\bar{\nu}(k) + p(p) &\rightarrow l^+(k') + n(p') \\
\text{NCE}: \; \nu(k) + N(p) &\rightarrow \nu(k') + N(p') \\
\bar{\nu}(k) + N(p) &\rightarrow \bar{\nu}(k') + N(p')
\end{aligned}$$



  - Largest contribution at T2K, MicroBooNE
  - Used for kinematic E_ν reconstruction

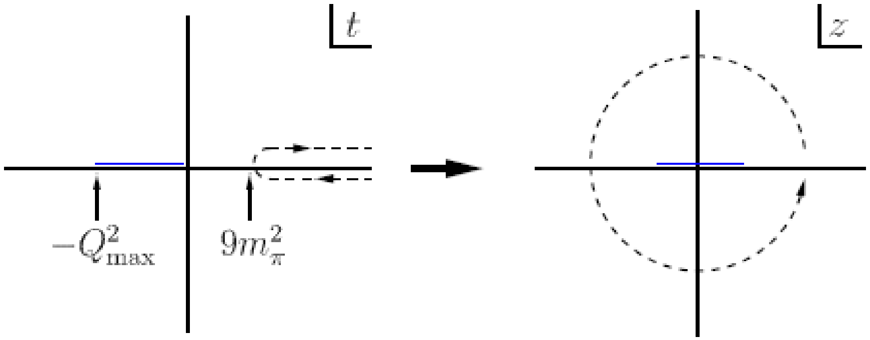
- Input in models of non-resonant inelastic reactions (meson production) and two-nucleon currents

Nucleon axial form factor

- What is known:
  - $F_A(0) = g_A \leftarrow \beta$ decay
  - $F_A(\infty) \sim Q^{-4} \leftarrow$ QCD
- Information:
  - Experiment: bubble chamber (ANL, BNL, FNAL) data
  - Lattice QCD
- Dipole ansatz: Bodek et al., EPJC 53 (2008)

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2} \qquad \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$

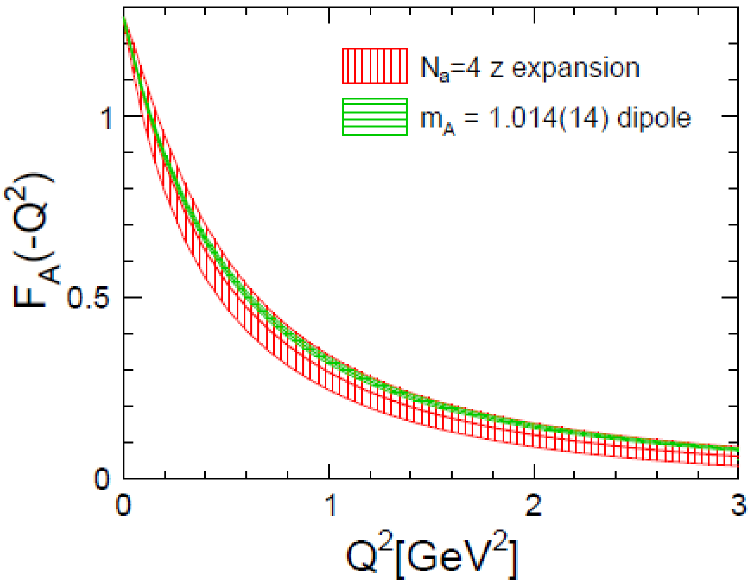
- z-expansion: Meyer et al., PRD 93 (2016)

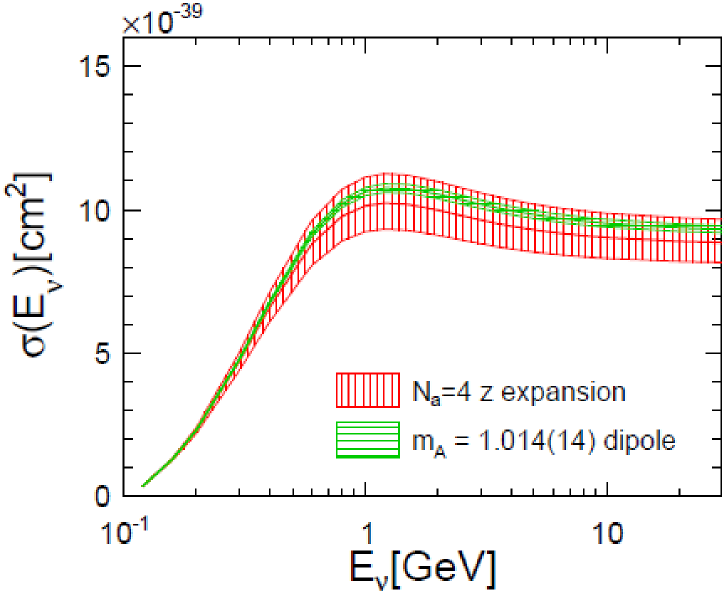


$$F_A(Q^2) = \sum_{k=0}^{\infty} a_k z(Q^2)^k$$

Empirical determination

- z-expansion Meyer et al., PRD 93 (2016) : Fit to ANL, BNL, FNAL data

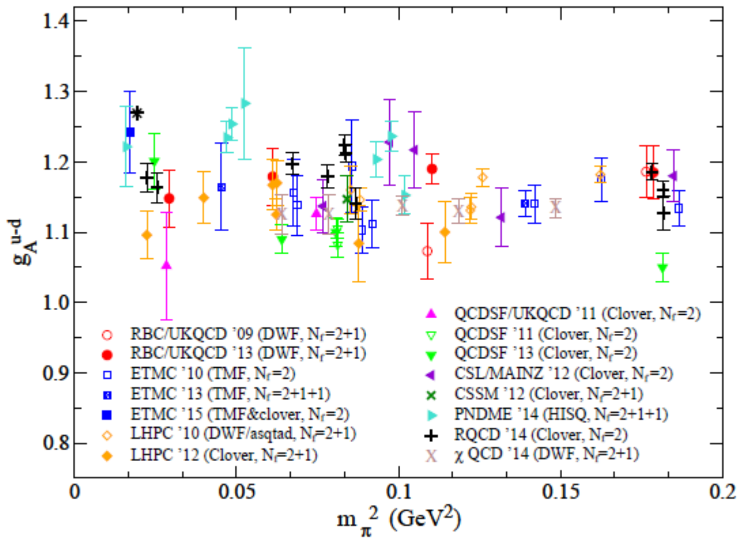




- $\langle r_A^2 \rangle$ = 0.46(22) fm^2 vs 0.453(12) fm^2 dipole Bodek et al., EPJC 53 (2008)
- At $E_\nu \sim 1$ GeV σ(CCQE) has $\approx$ 10 % error

F_A & LQCD

- g_A : lower than exp. values were once obtained



Constantinou, PoS CD15 (2015) 009

$g_A = 1.2754(13)_{exp}(2)_{RC}$

M. Gorchtein and C.-Y. Seng, JHEP 53 (2021

- Recent progress (for both g_A and F_A)
  - improved algorithms for a careful treatement of excited states
  - low pion masses

FLAG 2021
Flavour Lattice Averaging Group

$g_A = 1.246(28)$

Alexandrou et al., PRD 96 (2017); PRD103 (2021)
Capitani et al., Int. J. Mod. Phys. A 34 (2019)
Gupta et al., PRD 96 (2017); Park et al., PRD 105 (2022)
Chang et al., Nature 558 (2018)
Bali et al., JHEP 05 (2020)
Shintani, PRD 99; PRD 102(erratum) (2020)

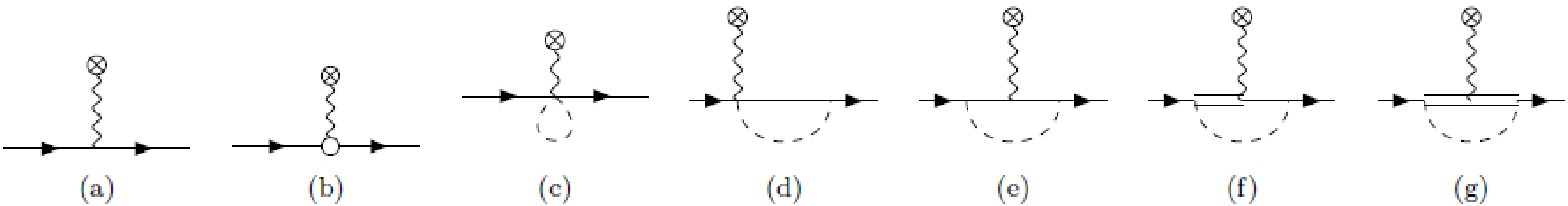
F_A & LQCD

- Baryon ChPT analysis: $Q^2 < 0.36$ GeV^2, $M_\pi < 400$ MeV , $M_\pi L > 3.5$
  - Model-independent extrapolations to the physical M_π

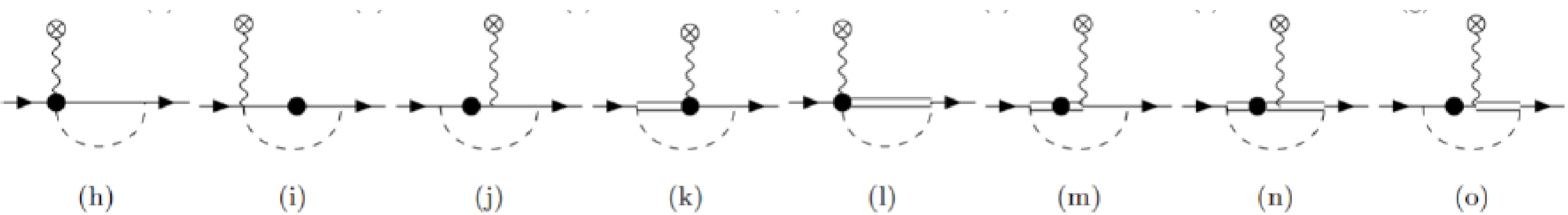
$$F_A(Q^2, M_\pi^2) = g + 4d_{16}M_\pi^2 + d_{22}Q^2 + F_A^{(\mathrm{loops})} + F_A^{(wf)}$$

- Up to O(p^3) Yao, LAR, Vicente Vacas, PRD 96 (2017)

$$\delta = m_\Delta - m_N \sim \mathcal{O}(p)$$



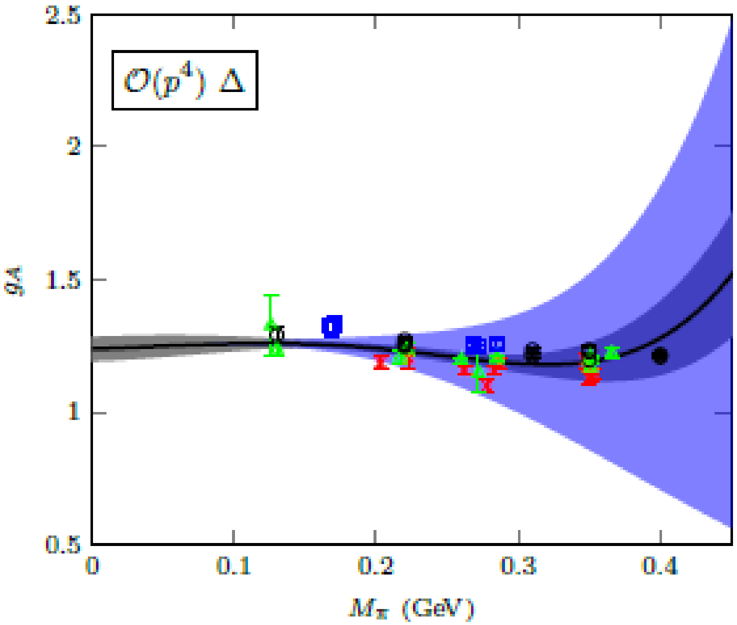
- Up to O(p^4) Alvarado, LAR, PRD 105 (2022); work in progress



- Differences between O(p^3) and O(p^4) are considerable (at larger M_π) and provide a measure of the systematic error arising from the truncation of the perturbative expansion.

g_A & LQCD

- Differences between O(p^3) and O(p^4) are considerable (at larger M_π) and provide a measure of the systematic error arising from the truncation of the perturbative expansion.
  - Best seen for $g_A(M_\pi)$ Alvarado, LAR, PRD 105 (2022)



$$\chi^2 = \sum_i \frac{\left(g_A(M_\pi^i, a_i) - g_A^i\right)^2}{(\Delta g_A^i)^2} + \chi^2_{\rm prior}$$

$$(\Delta g_A^i)^2 = (\Delta g_{A\,\rm LQCD}^i)^2 + (\Delta g_{A\chi}(M_\pi^i))^2$$

FLAG 2021 Flavour Lattice Averaging Group

- **g_A = 1.2600(120)** vs g_A = 1.2754(13)$_{\rm exp}$(2)$_{\rm RC}$ vs g_A = 1.2460(280)
- d_{16} = -0.88 $\pm$ 0.88 GeV^{-2} $\leftarrow$ M_π dependence of long range nuclear forces

F_A & LQCD

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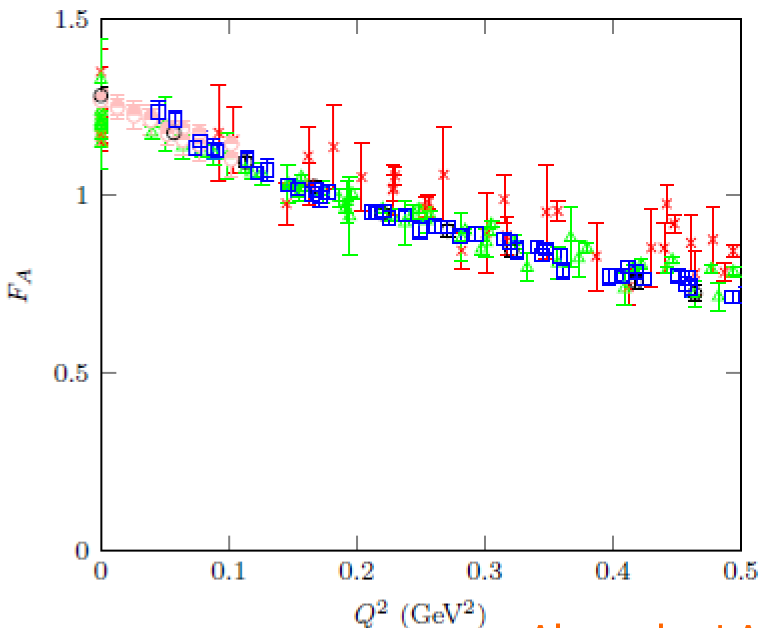
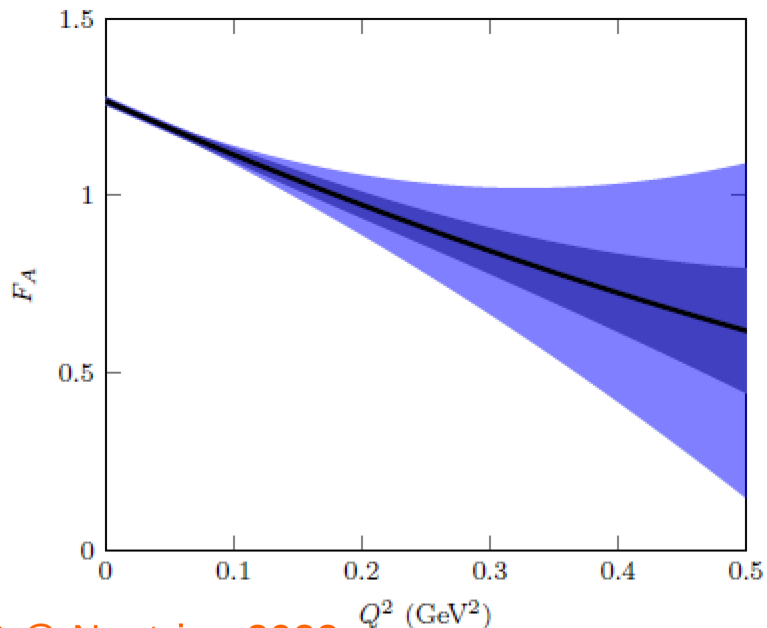
$M_\pi < 400$ MeV



M_π physical



Alvarado, LAR @ Neutrino 2022

$$F_A(q^2) = g_A \left[1 + \frac{1}{6}\langle r_A^2 \rangle q^2 + \mathcal{O}(q^4)\right]$$

Axial radius & LQCD

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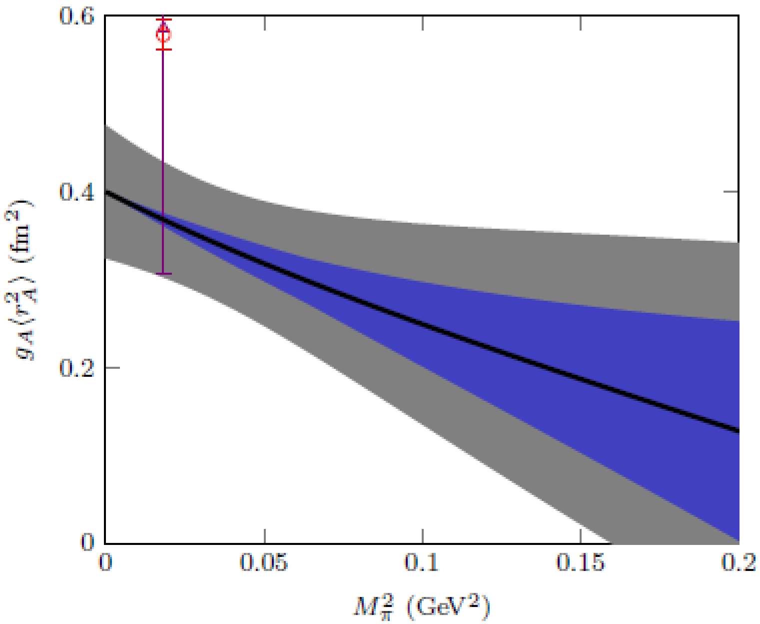
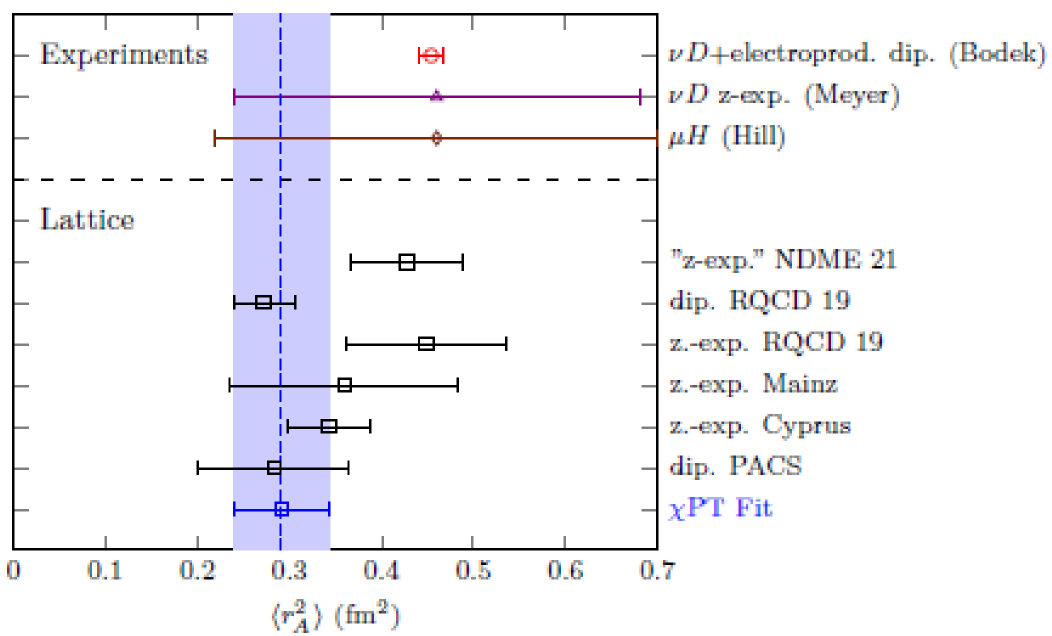


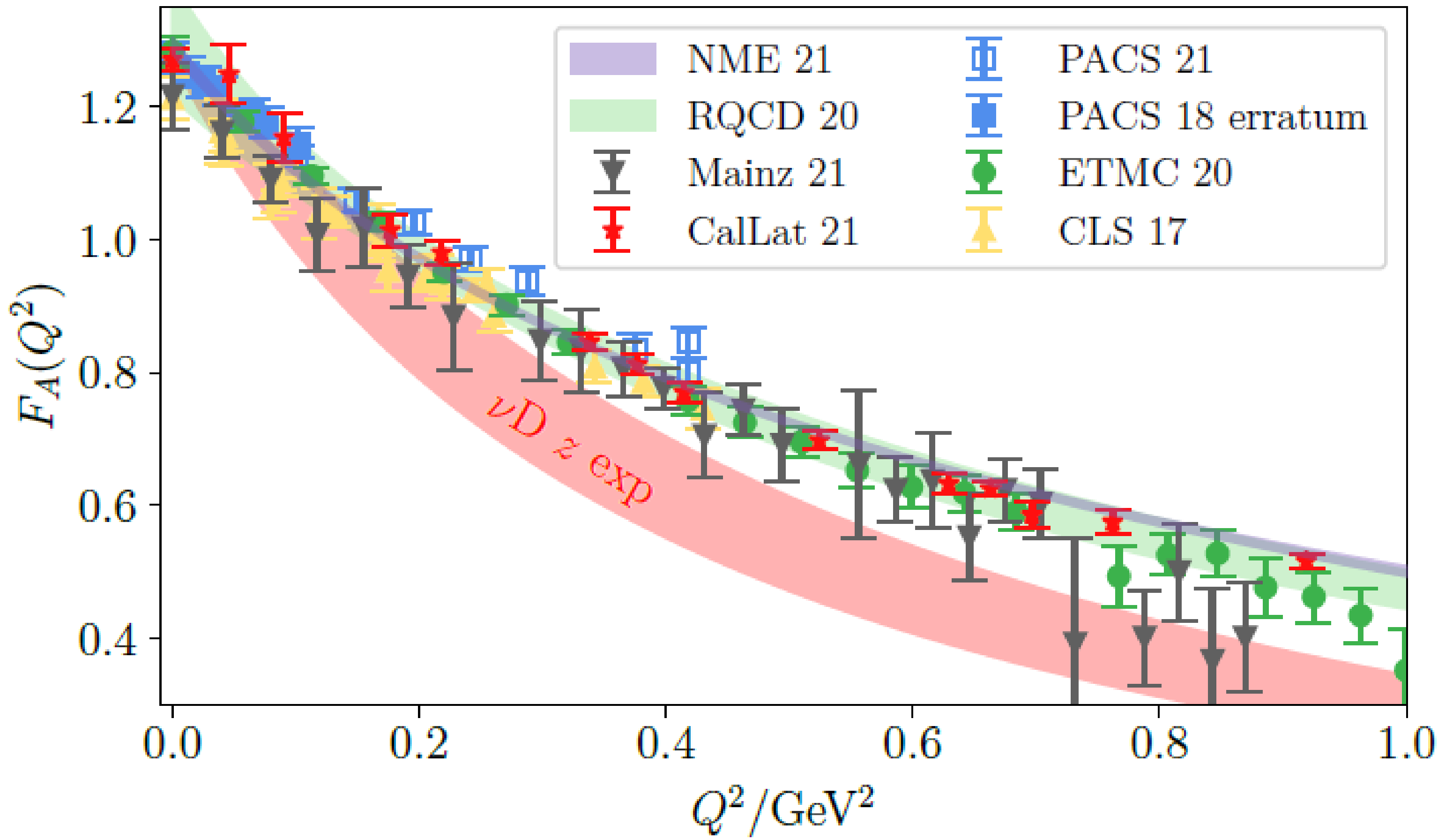


- Slope driven by loops with Δ

$\langle r_A^2 \rangle$(phys) = 0.291(52) fm^2

In tension with empirical determinations

F_A: Exp. vs LQCD



Meyer, Walker-Loud, Wilkinson, arXiv:2201.01839

- How reliable are old bubble chamber experiments?
- Do LQCD present results still hide uncontrolled systematics?

1π production on the nucleon

$$\nu_l \, N \to l \, \pi \, N'$$

- CC:
$$\nu_\mu \, p \to \mu^- \, p \, \pi^+ , \qquad \overline{\nu}_\mu \, p \to \mu^+ \, p \, \pi^-$$
$$\nu_\mu \, n \to \mu^- \, p \, \pi^0 , \qquad \overline{\nu}_\mu \, p \to \mu^+ \, n \, \pi^0$$
$$\nu_\mu \, n \to \mu^- \, n \, \pi^+ , \qquad \overline{\nu}_\mu \, n \to \mu^+ \, n \, \pi^-$$
  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction
- NC:
$$\nu_\mu \, p \to \nu_\mu \, p \, \pi^0 , \qquad \overline{\nu}_\mu \, p \to \overline{\nu}_\mu \, p \, \pi^0$$
$$\nu_\mu \, p \to \nu_\mu \, n \, \pi^+ , \qquad \overline{\nu}_\mu \, n \to \overline{\nu}_\mu \, n \, \pi^0$$
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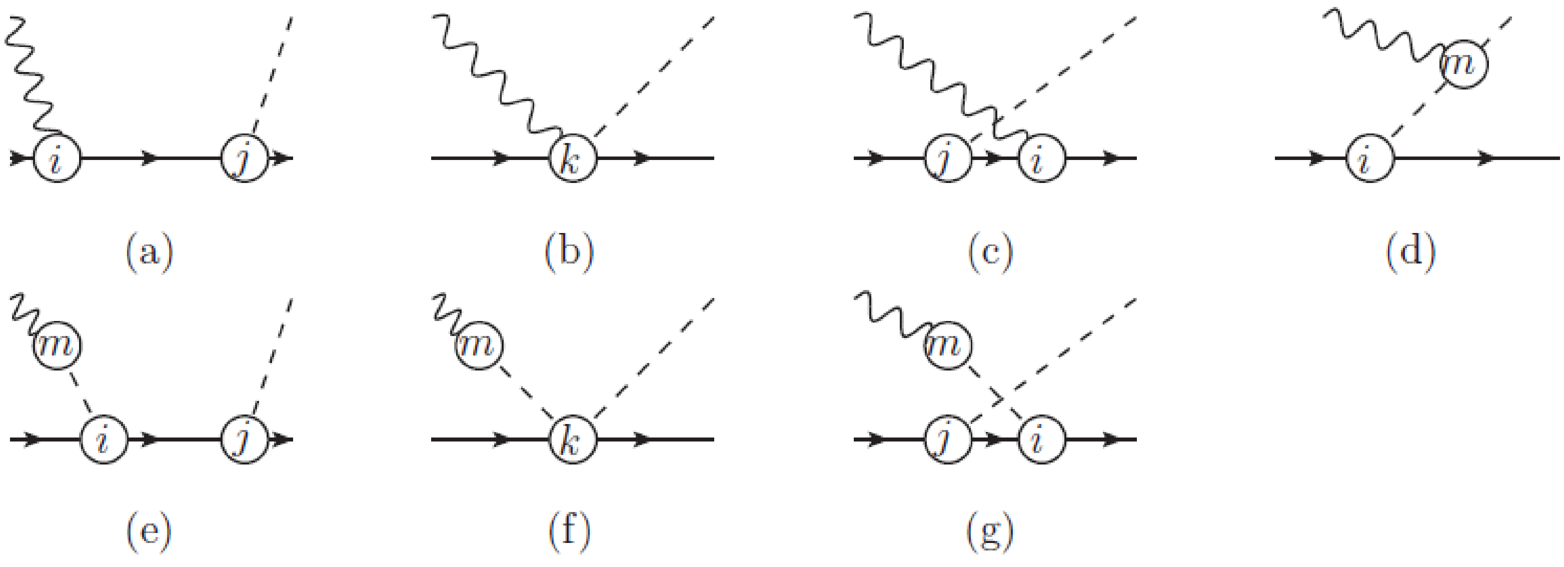
$$\nu_\mu \, n \to \nu_\mu \, p \, \pi^- , \qquad \overline{\nu}_\mu \, n \to \overline{\nu}_\mu \, p \, \pi^-$$
  - e-like background to $\nu_\mu \to \nu_e$

Weak pion production in ChPT

- First study in ChPT: Yao et al., PRD 98 (2018); PLB 794 (2019)
- Part of a comprehensive study of $\pi N \to N\pi$, $\gamma^* N \to N\pi$, $W^*, Z^* N \to N\pi$, ...
- EOMS, explicit $\Delta(1232)$, $O(p^3)$
- δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$ $\Rightarrow$ $$D = 4L + \sum_k kV^{(k)} - 2I_\pi - I_N - \frac{1}{2}I_\Delta$$
  - applicable at threshold: $p/\delta \approx \delta/\Lambda$



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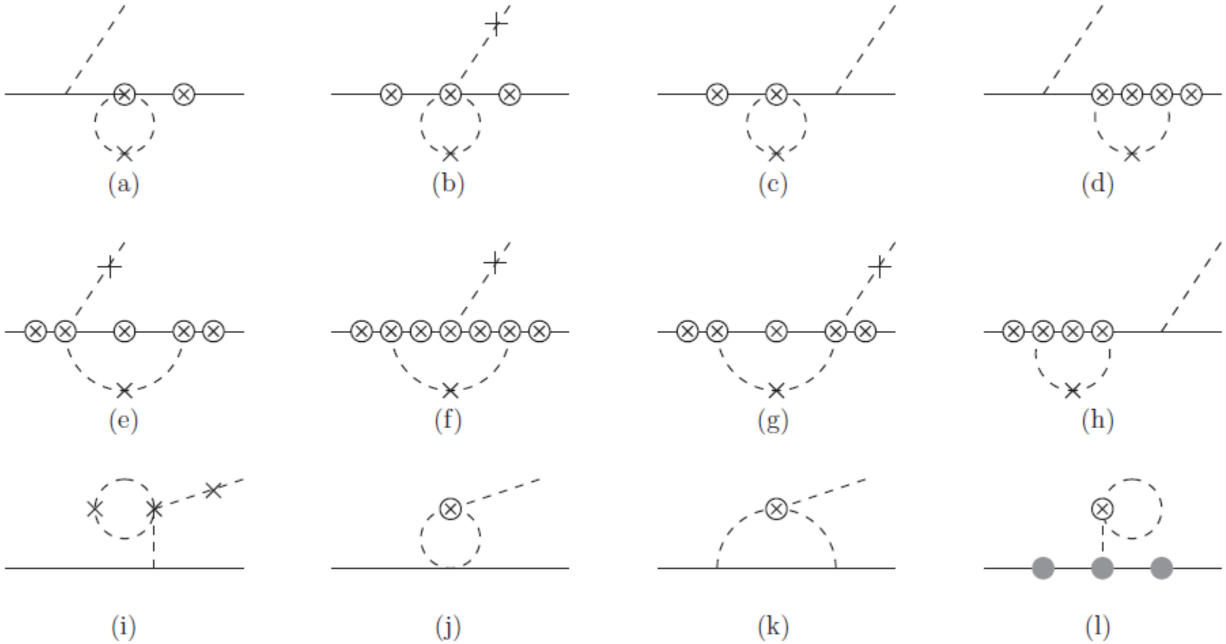

- Example: topology (b)

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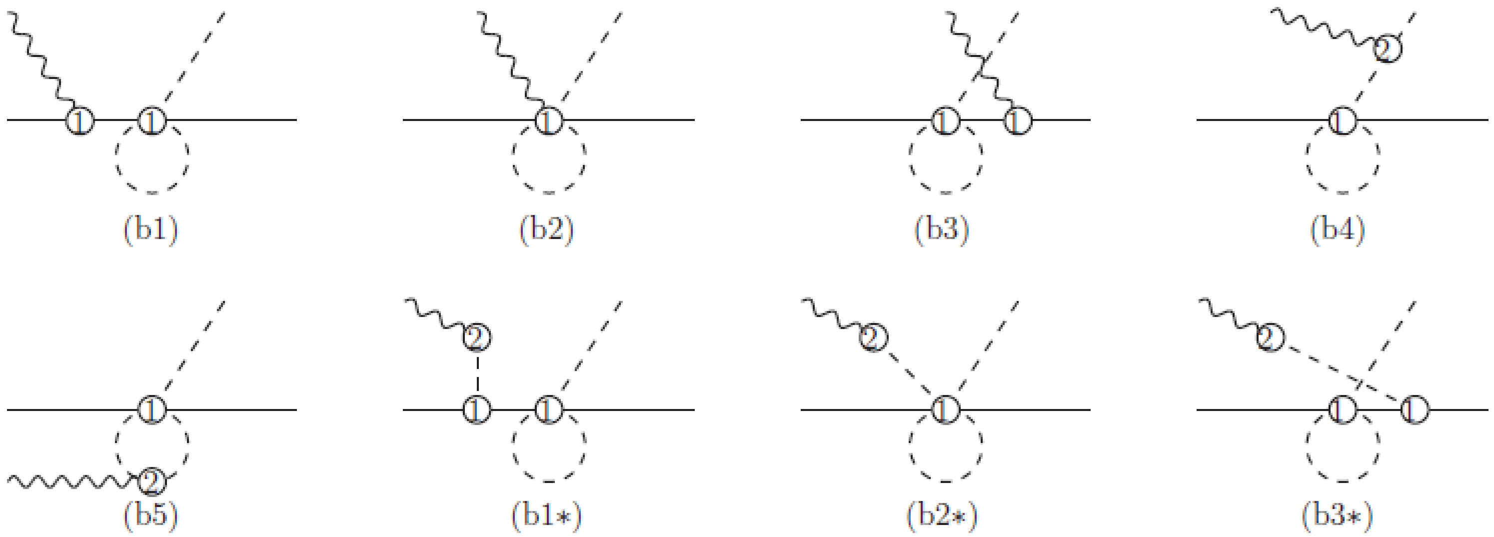

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- EOMS, explicit $\Delta(1232)$, O(p^3) in the δ-counting: $\delta = m_\Delta - m_N \sim O(p^{1/2})$

- LECs : 22 in total
  - 7 unknown:
    - 4 can be extracted from pion photo and electro-production
    - information about remaining 3 could be obtained from new close-to-threshold measurements of ν-induced π production on protons

- Valid only close to threshold
- Benchmark for phenomenological models
- “Standard candle” for flux monitoring?

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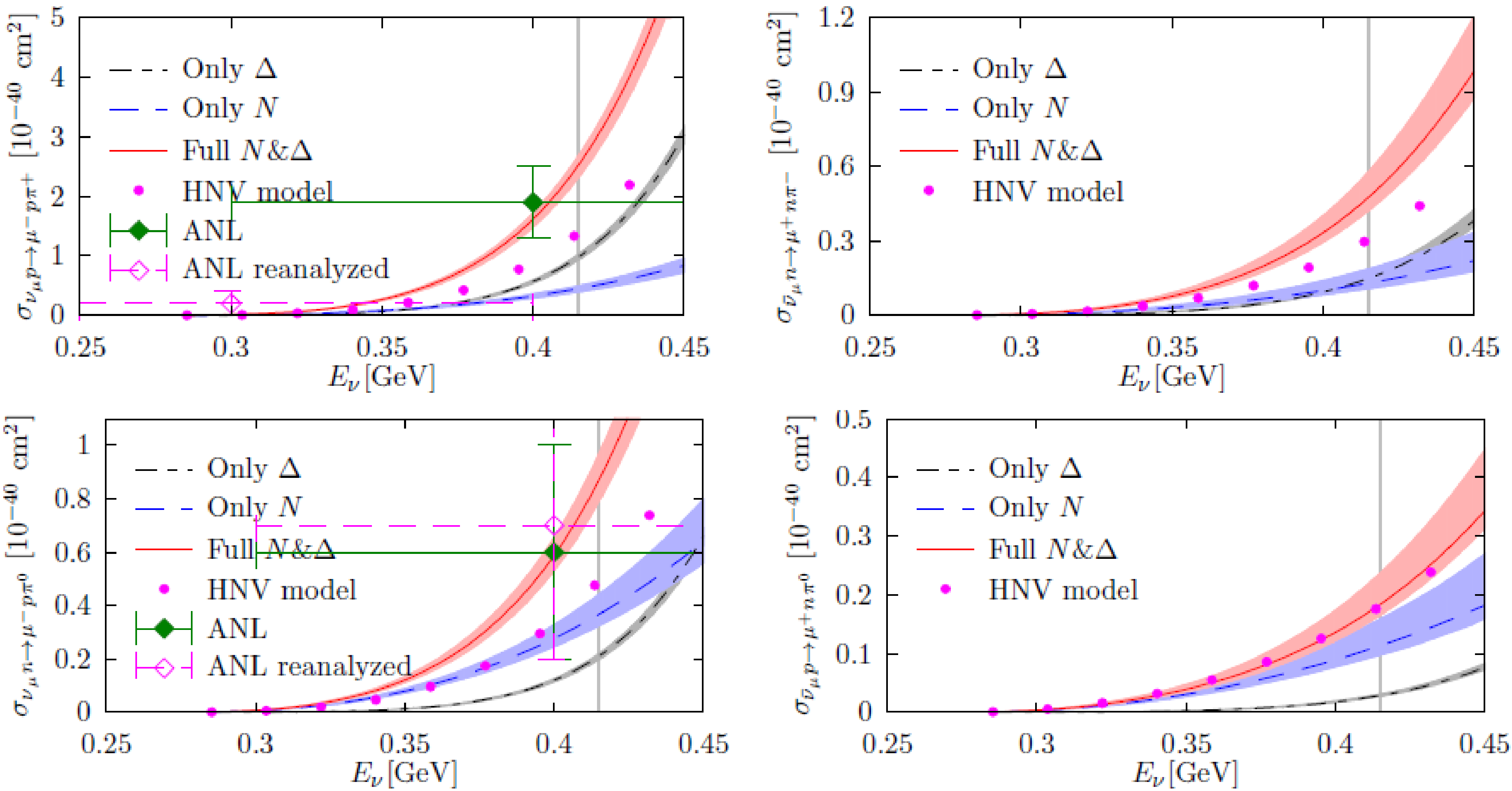

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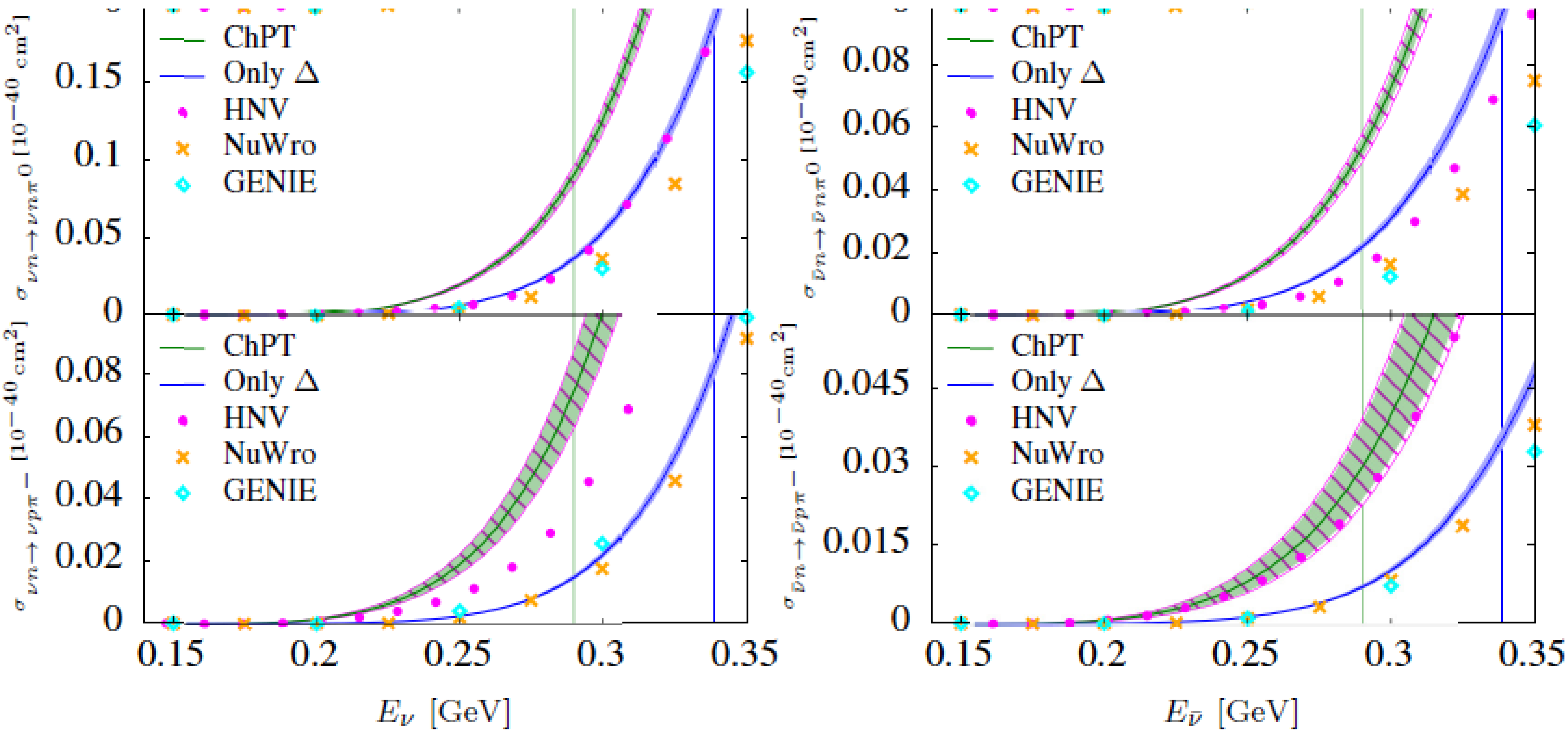

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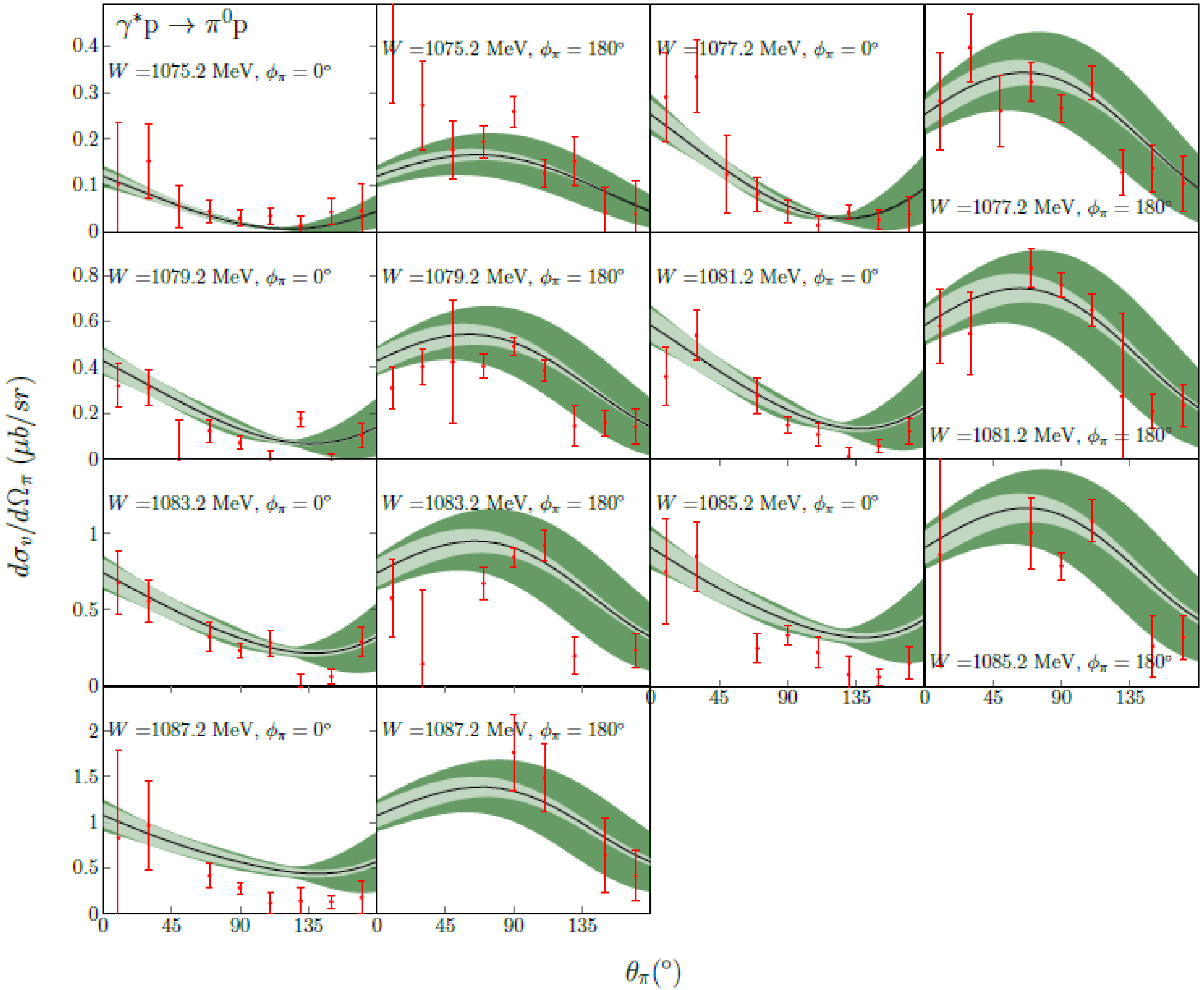
π photo & electroproduction

- Large and kinematically complete close to threshold data sets
- Several $O(p^3)$ LECs could be precisely determined

Guerrero Navarro, Vicente Vacas, PRD 102 (2020)



New measurements on H/D

- Several possibilities are currently under consideration:
  - Modern bubble chambers (small, modular) arXiv:2203.11319
  - High pressure TPC with hydrogen-rich gases (such as CH_4) Hamacher-Baumann, Lu, Martín-Albo, PRD 102 (2020)
  - "Solid Hydrogen" concept at the Straw Tube Tracker (STT) as part of the System for on-Axis Neutrino Detection (SAND) at the DUNE near-detector complex
    - extraction of CC pion production data on H by subtracting measurements on graphite (pure C) from those on a CH_2 plastic Duyang, Guo, Mishra, R. Petti, PLB 795 (2019)
    - Flux determination: using BChPT to have controlled errors LAR, R. Petti, work in progress

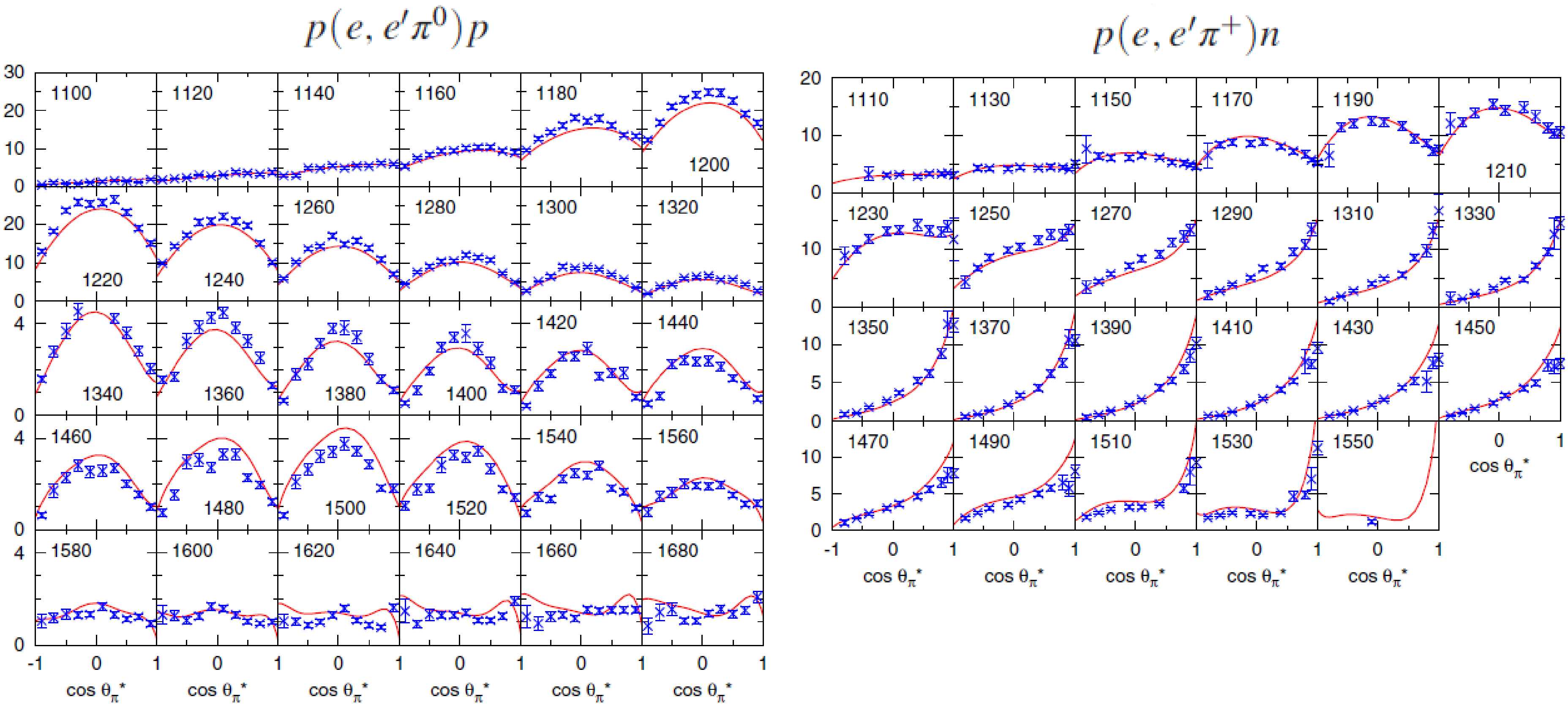
Summary

- ChPT allows to study neutrino-nucleon elastic and inelastic interaction processes in a systematic way but in a reduced kinematic region.
  - Assess fundamental properties of the nucleon
  - Study the light-quark mass dependence provided by LQCD
  - Better control of errors
  - Benchmark for phenomenological models
  - Help in neutrino-flux determination

- These studies
  - benefit from existing EM interaction data
  - require new measurements of neutrino-nucleon interactions

1π production on the nucleon

- Pheno models rely on (non-ν) data as input and/or validation
  - Vector current can be constrained with $\gamma N \to N \pi$, $e N \to e' N \pi$



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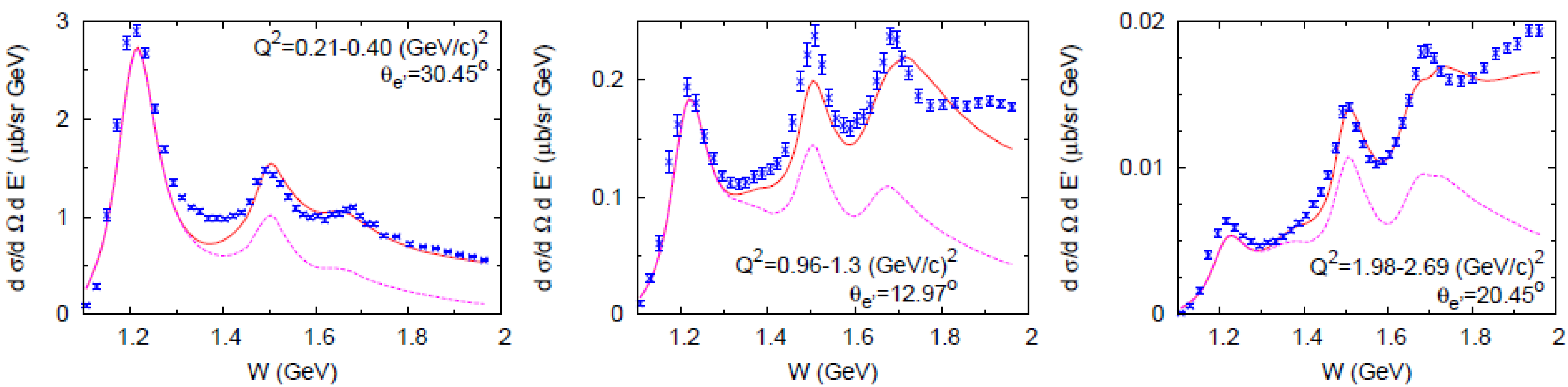
  - Axial current at $q^2 \to 0$ can be constrained with $\pi N \to N \pi$ (PCAC)

$$\left.\frac{d\sigma_{CC\pi}}{dE_l d\Omega_l}\right|_{q^2=0} = \frac{G_F^2 V_{ud}^2}{2\pi^2} \frac{2 f_\pi^2}{\pi} \frac{E_l^2}{E_\nu - E_l} \sigma_{\pi N}$$



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  - Very limited information about the axial current at $q^2 \neq 0$
    - Some on N-Δ(1232) from ANL and BNL data on
      $\nu_\mu d \to \mu^- \pi^+ p n$
    - Direct or indirect CCQE measurement on n/p
    - Lattice QCD