Should neutrino-nucleon cross sections be (re)measured?

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Introduction

- Do we want new more precise ν-nucleon cross section measuremens?
  - Relevant input for ν MC and theoretical models
  - New info about the axial structure of nucleons and other baryons
  - Radiative corrections
  - ChPT LECs, non-pole corrections to Goldberger-Treiman relations
  - New physics (perhaps combining c.s. & lepton/baryon polarization)
  - ...

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  - ...
- ... but who pays for it?

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  - Our letter to Santa should be compelling

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- Do we NEED new more precise ν-nucleon cross section measuremens?
  - Our letter to Santa should be compelling:
  - ν-nucleon cross section should be crucial for future oscillation measurements
  - Experimental projections: c.s. uncertainties $\Rightarrow$ oscillation errors
- Possible alternatives:
  - LQCD
  - (Polarized) electron scattering
  - H_2 enriched targets
  - ...

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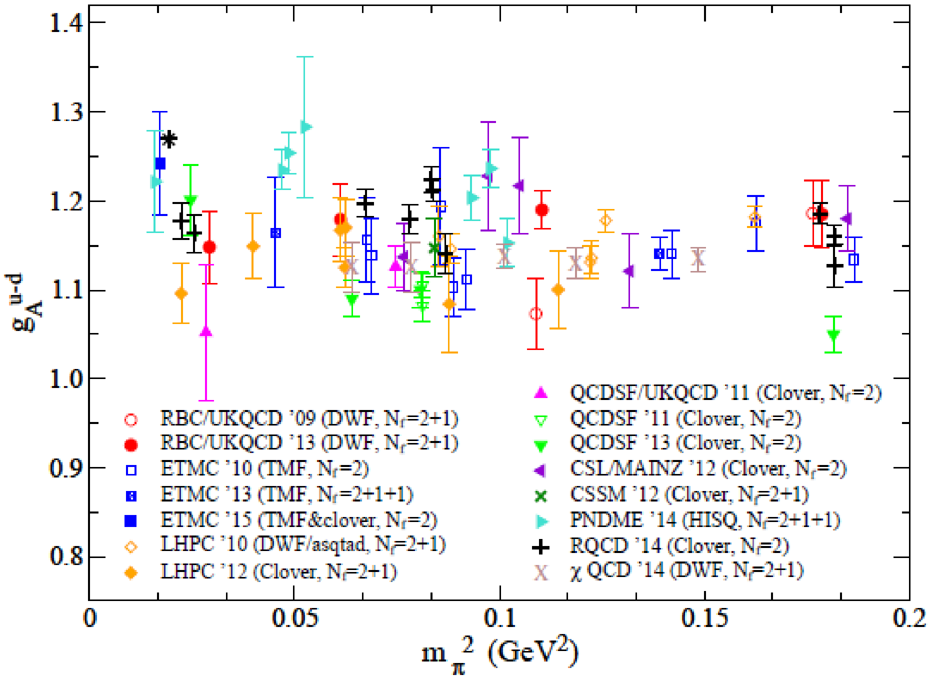
- It is not just the nucleon F_A (Q^2)
- Our ignorance regarding the transition axial N-X (X=Nπ, N$\pi\pi$, N K,...) at $Q^2 \neq 0$ is almost total
- These processes will be (among) the largest at DUNE

Outline

- Introduction
- Extraction of F_A from LQCD results using BChPT
- Extraction of F_A from ν-nucleon data using neural networks
- Pion production and resonance excitation

F_A from LQCD

- g_A : lower than exp. values have been recurrently obtained



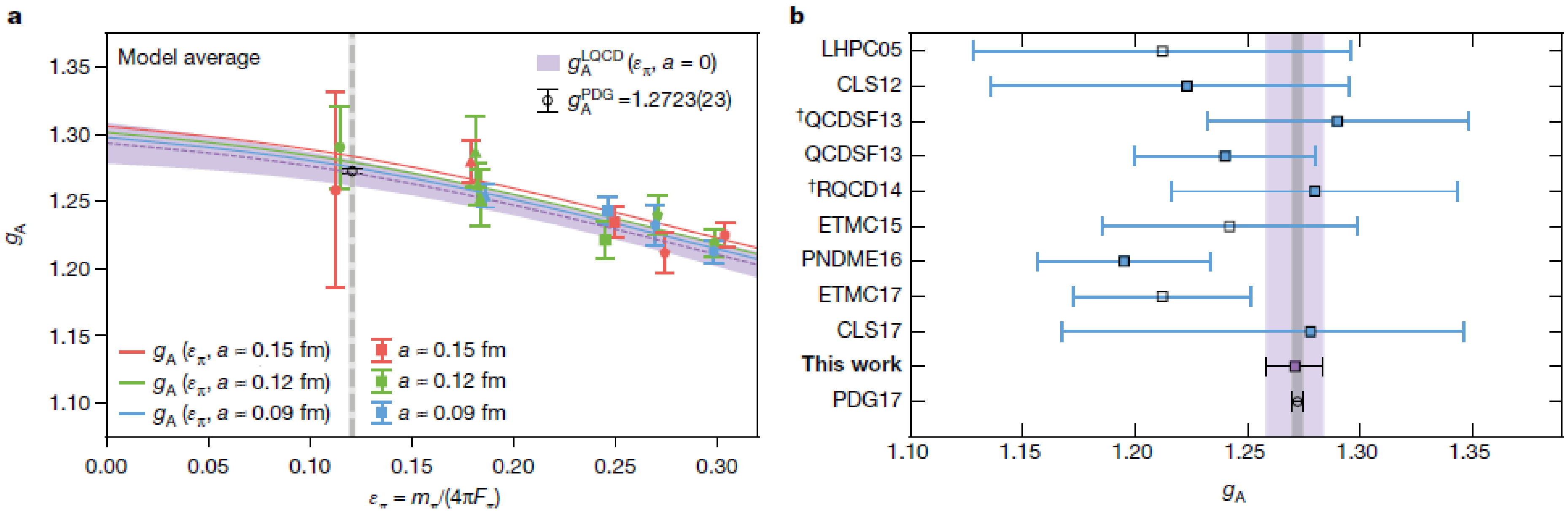
Constantinou, PoS CD15 (2015) 009

F_A from LQCD

- A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

  Chang et al., Nature 558 (2018)

  - unconventional method inspired by the Feynman–Hellmann theorem



F_A from LQCD

- Recent determinatons of F_A (Q^2, M_π):
  - improved algorithms for a careful treatement of excited states
  - low pion masses

Alexandrou et al., Phys. Rev. D 96 (2017)
Capitani et al., arXiv:1705.06186
Gupta, Phys.Rev. D96 (2017)

F_A in BChPT

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

- $F_A(Q^2, M_\pi)$ calculated using covariant ChPT
  Yao, LAR, Vicente Vacas, PRD 96 (2017)
- up to leading one-loop $O(p^3)$
  - standard power counting
- with explicit $\Delta(1232)$
  - $\delta = m_\Delta - m_N \sim O(p)$
- 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.

F_A in BChPT

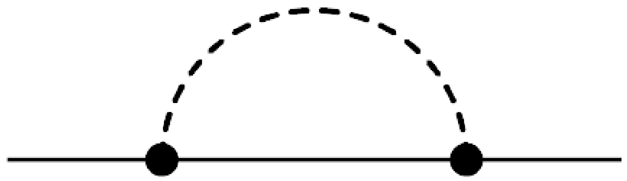
- Example: nucleon mass in SU(2)

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

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

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

O(p²) !



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

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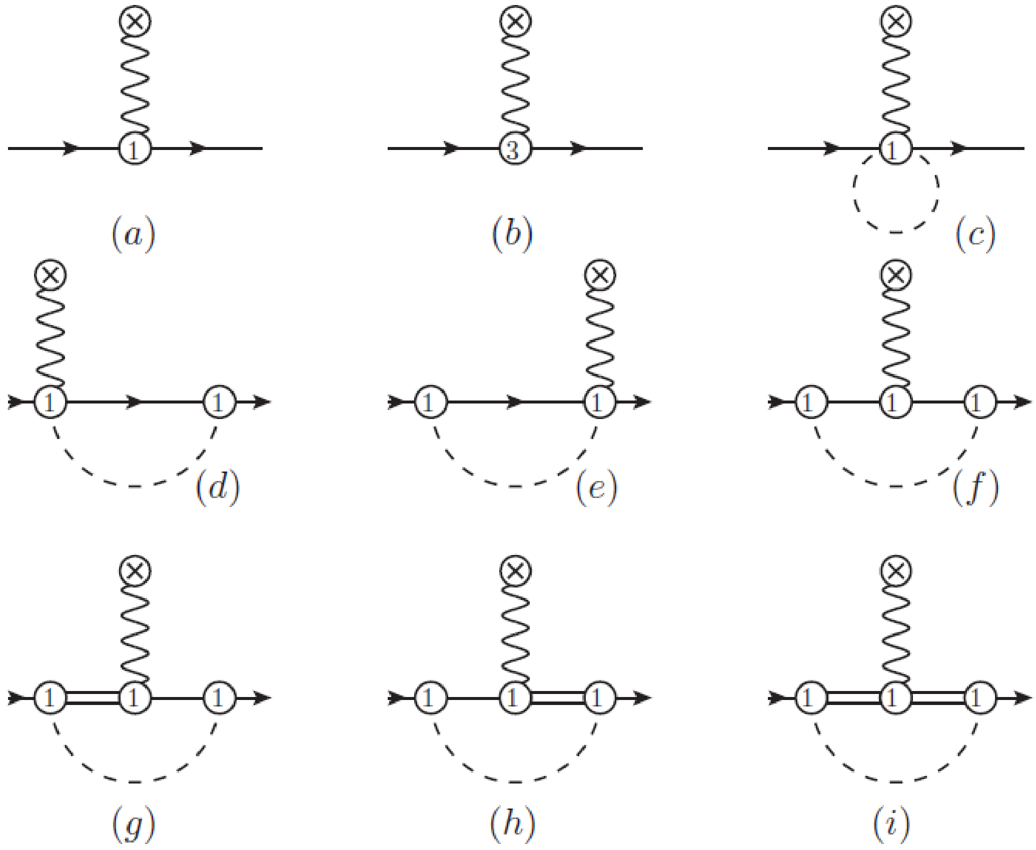

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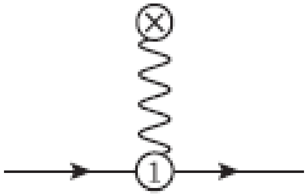
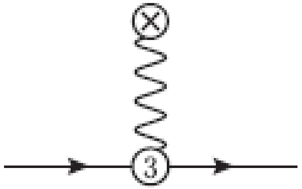


$$\mathcal{L}^{(1)}_{\pi N} \supset \bar{\Psi}\left(\frac{1}{2} g u^\mu \gamma_\mu \gamma^5\right)\Psi \ ,$$



$$\mathcal{L}^{(3)}_{\pi N} \supset \bar{\Psi}\left\{\frac{d_{16}}{2}\gamma^\mu\gamma_5\langle\chi_+\rangle u_\mu + \frac{d_{22}}{2}\gamma^\mu\gamma_5[D_\nu, F^-_{\mu\nu}]\right\}\Psi \ ,$$

F_A in BChPT

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

- $F_A(Q^2, M_\pi)$ calculated in covariant ChPT up to $O(p^3)$ with explicit $\Delta(1232)$

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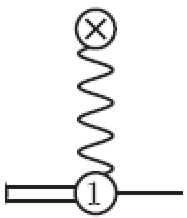
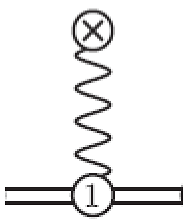


$$\mathcal{L}^{(1)}_{\pi N\Delta} = h_A\, \bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij}\omega^{\mu,j}\Psi + h.c.$$



$$\mathcal{L}^{(1)}_{\pi\Delta} \supset -\bar{\Psi}^i_\mu \xi^{\frac{3}{2}}_{ij}\left\{\frac{g_1}{2}\not{u}^{jk}\gamma_5 g^{\mu\nu}\right\}\xi^{\frac{3}{2}}_{kl}\Psi^l_\nu$$

- h_A , g_1 fixed in πN scattering Yao et al., JHEP 05 (2016)

F_A in BChPT

- $F_A(Q^2, M_\pi)$ calculated in covariant ChPT up to $O(p^3)$ with explicit $\Delta(1232)$

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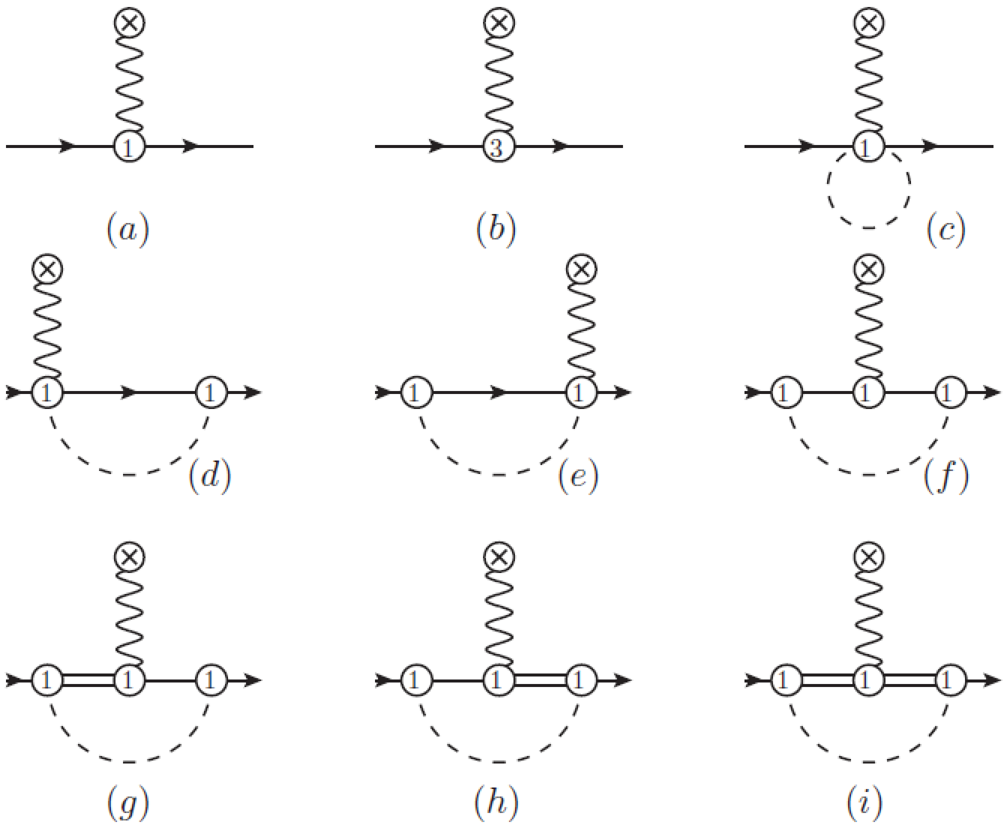

$$F_A(Q^2, M_\pi^2) = g + 4d_{16}M_\pi^2 + d_{22}Q^2 + F_A^{(c)} + F_A^{(f)} + 2\,F_A^{(g)} + F_A^{(i)} + F_A^{(wf)}$$

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- g, d_{16}, d_{22} are determined from a fit to LQCD data in both Q^2 and M_π

  Alexandrou et al., Phys. Rev. D 96 (2017)
  Capitani et al., arXiv:1705.06186
  Gupta, Phys.Rev. D96 (2017)

- Fit range:
  - M_π < ???
  - Q^2 < ???
- Explicit or implict $\Delta(1232)$?

F_A in BChPT

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- Fit range:
  - M_π < 400 MeV
    - reasonable
    - LQCD ensembles with M_π > 400 MeV increase χ^2
  - Q^2 < ???

- Explicit or implict $\Delta(1232)$?

F_A in BChPT

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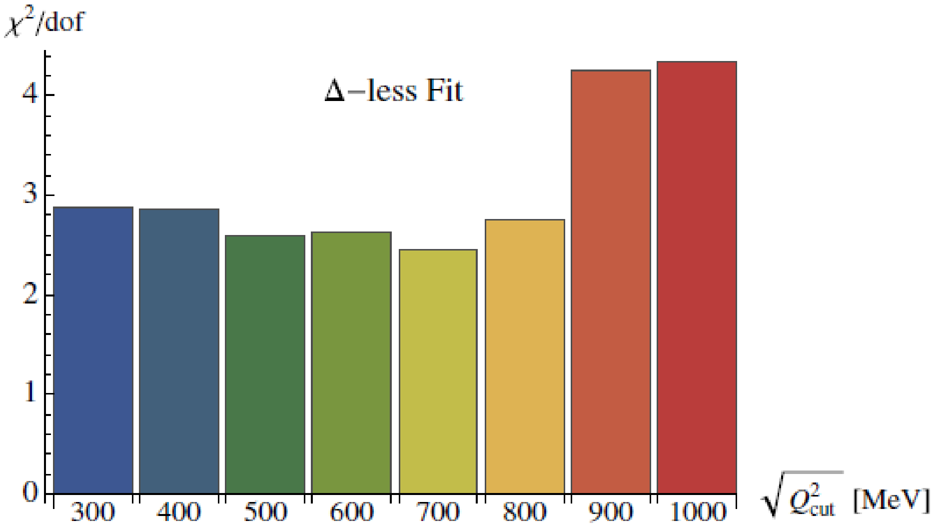

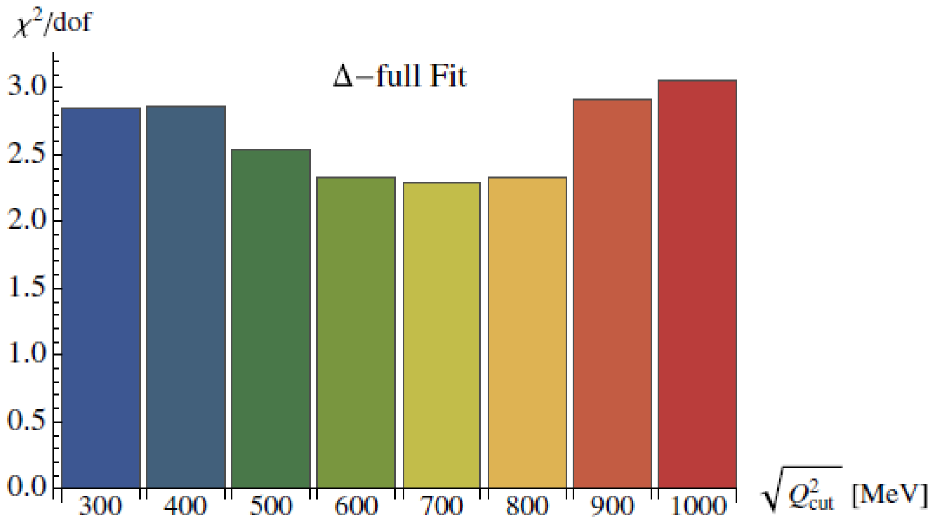

  - $Q^2 < 0.25\ (0.36)\ \text{GeV}^2$

- Explicit $\Delta(1232)$
  - better χ^2/dof

F_A in BChPT

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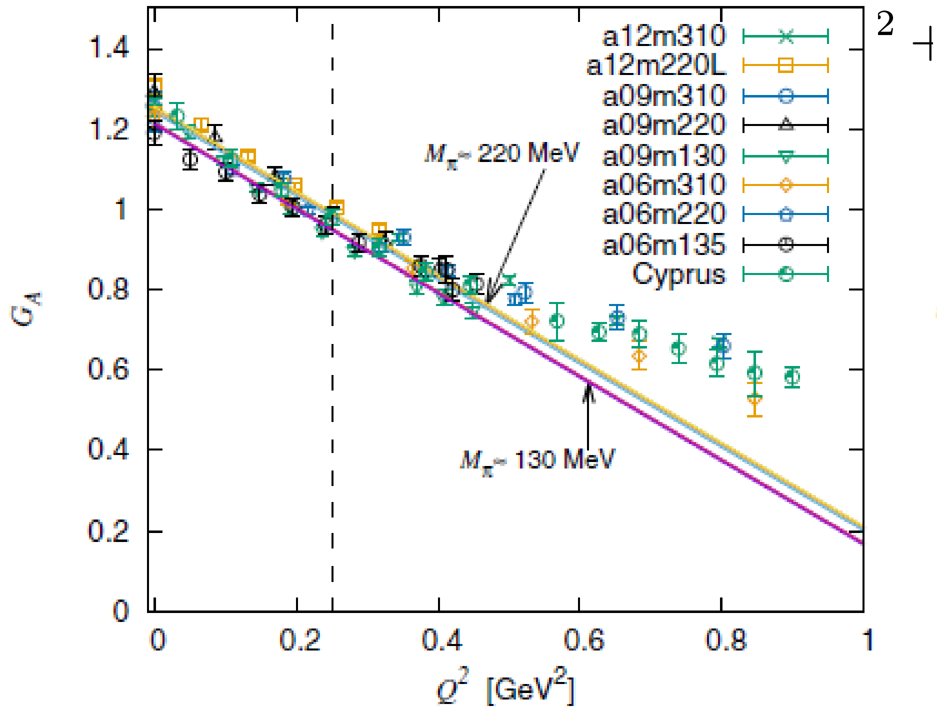

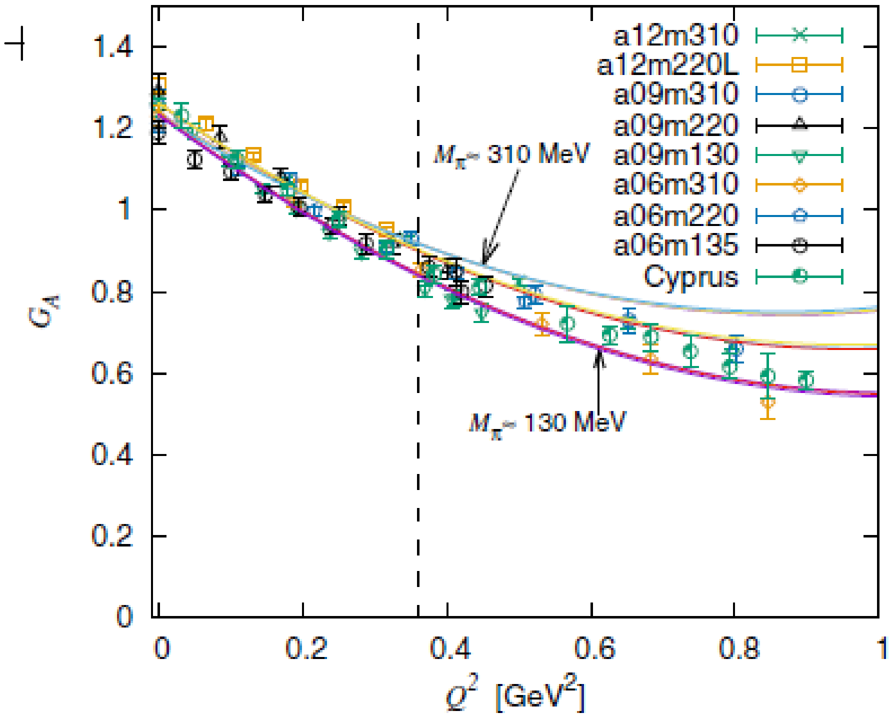

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F_A & LQCD

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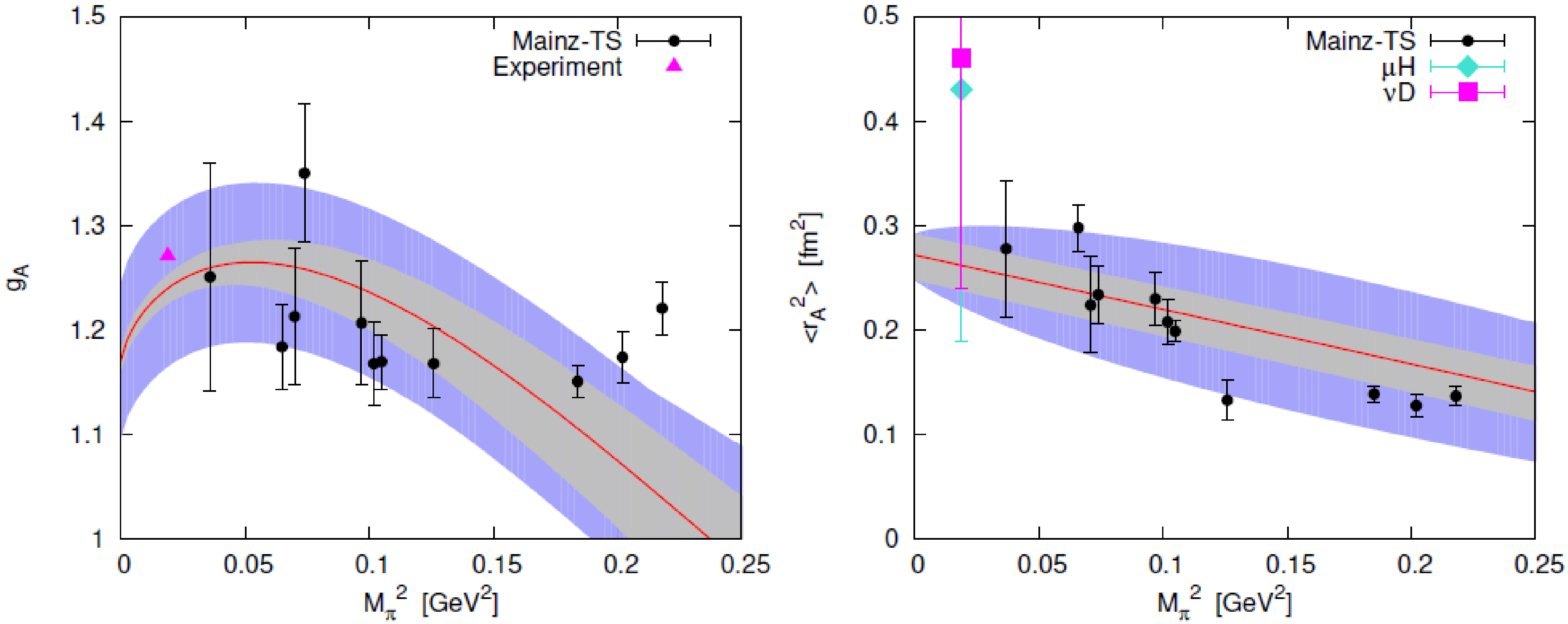
  Yao, LAR, Vicente Vacas, PRD 96 (2017)



- At the physical point: g_A = 1.237(74) , $<r_A^2>$ = 0.263(38) fm^2
- Mainz-TS points: z-expansion results from Capitani et al., arXiv:1705.06186, not used in the fit.

F_A & LQCD

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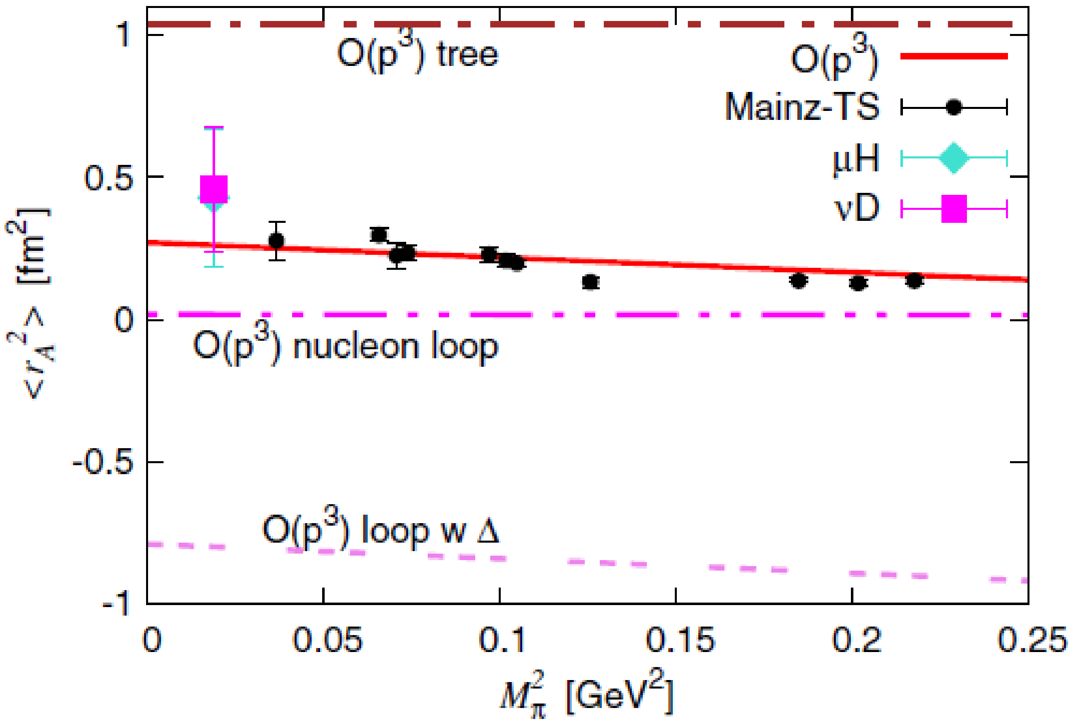
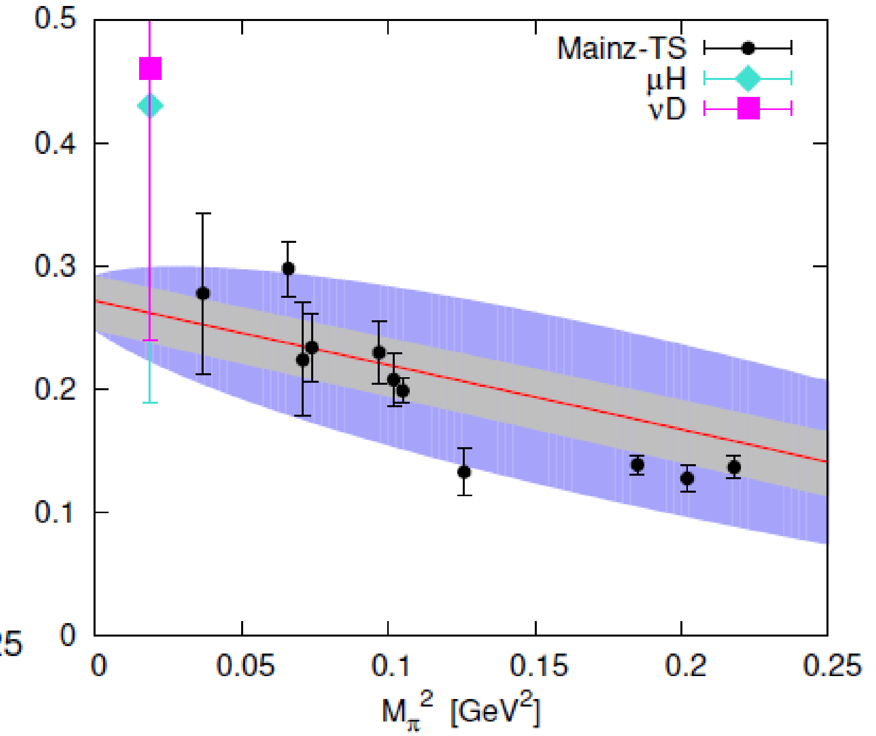
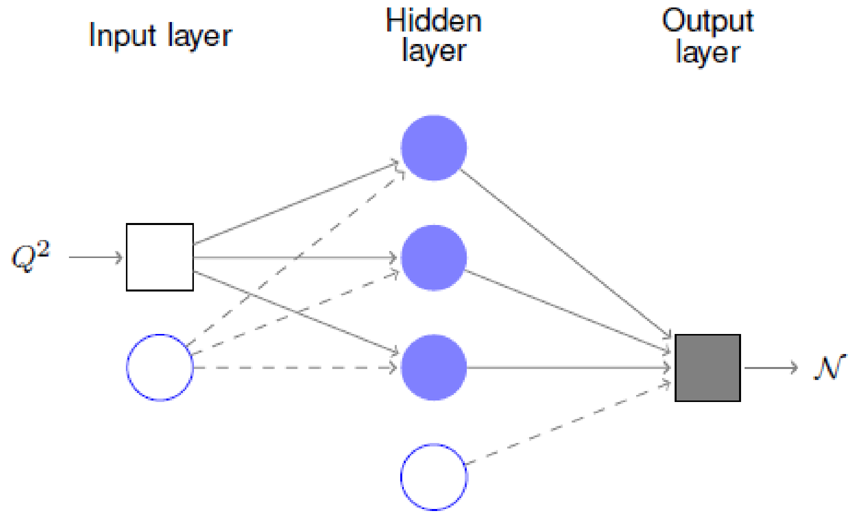




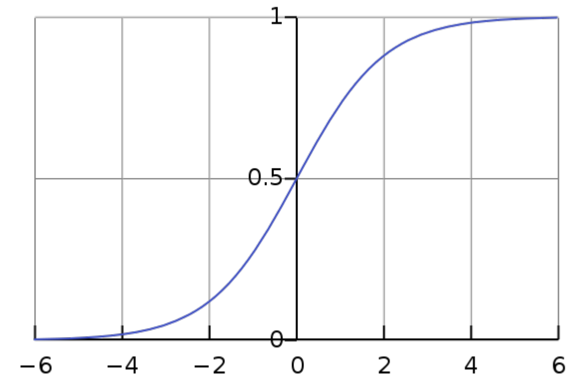
- At the physical point: $g_A = 1.237(74)$, $\langle r_A^2 \rangle = 0.263(38)$ fm^2
- Loops with $\Delta(1232)$ significantly improve $\langle r_A^2 \rangle$
- $O(p^5)$ might be needed to improve M_π dependence of $\langle r_A^2 \rangle$

Neural Networks for F_A

- Feed-forward NN in multilayer perceptron (MLP) configurations
- Non-linear map $\mathcal{N}$: $R^{in} \to R^{out}$



- For every unit: $y = f_{\mathrm{act}}\left(\sum_{i\in \mathrm{prev.\ layer}} w_i\, y_i\right)$
- Activation function: $f(x) = \dfrac{1}{1+\exp(-x)}$



  - except in bias units: $f(x) = 1$ and output: $f(x) = x$

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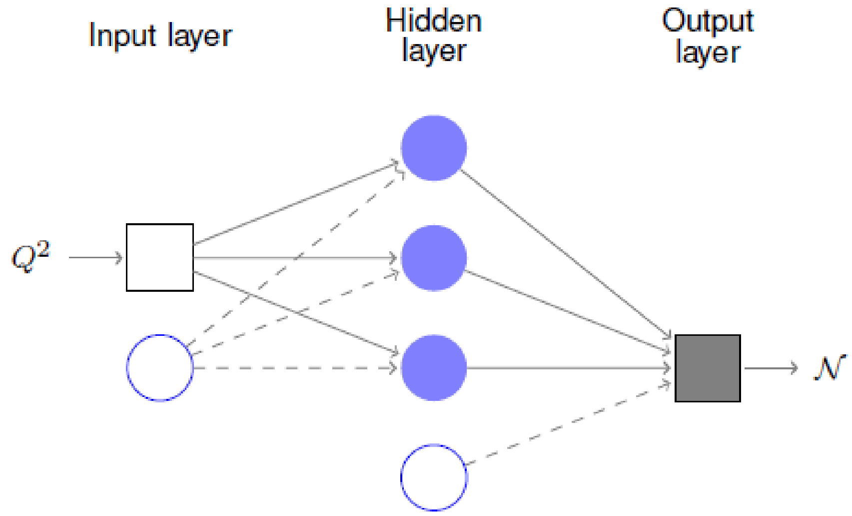

$$\mathcal{N}_M(Q^2;\{w_j\}) = \sum_{n=1}^{M} w_{2M+n}\, f\left(w_n Q^2 + w_{M+n}\right) + w_{3M+1}.$$

$$F_A(Q^2) = F_A^{\mathrm{dipole}}(Q^2) \times \mathcal{N}_M(Q^2;\{w_i\})$$ ← function of W=3 M +1 weights and Q^2

- Cybenko's theorem: for large enough M, can map arbitrarily well any continuous function and its derivative

Neural Networks for F_A

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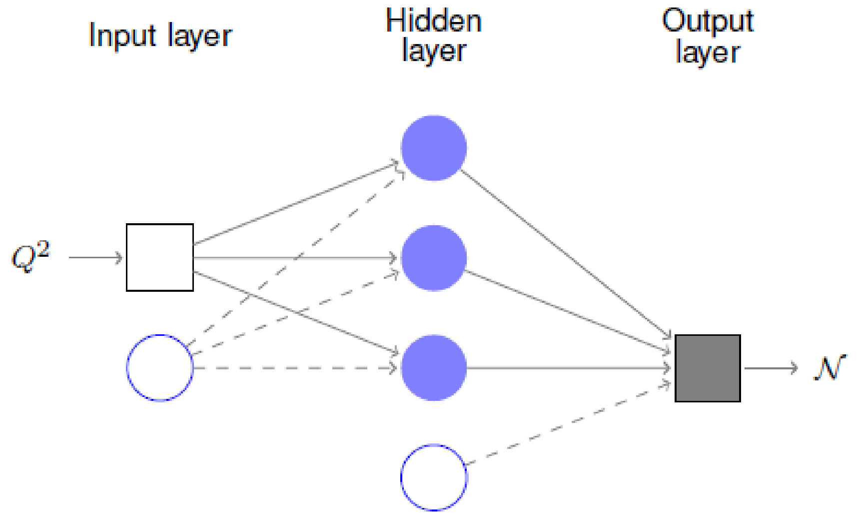

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$$F_A(Q^2) = F_A^{\text{dipole}}(Q^2) \times \mathcal{N}_M(Q^2; \{w_i\})$$ $\leftarrow$ function of W=3 M +1 weights and Q^2

- Bayesian inference to train the network, avoiding overfitting

Bayesian inference for NN

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

1. For a given $\mathcal{N}$: $\mathcal{P}(\{w_j\} \mid \mathcal{D}, \mathcal{N}) = \dfrac{\mathcal{P}(\mathcal{D} \mid \{w_j\}, \mathcal{N})\mathcal{P}(\{w_j\} \mid \mathcal{N})}{\mathcal{P}(\mathcal{D} \mid \mathcal{N})}$,

- Likelihood in terms of χ^2 :

$$\mathcal{P}(\mathcal{D} \mid \{w_j\}, \mathcal{N}) = \frac{1}{N_L} \exp(-\chi^2)$$

- Prior: weights w_j are Gaussian distributed

$$\mathcal{P}(\{w_j\}, \mathcal{N}) = \frac{1}{N_w} \exp\left(-\alpha \frac{1}{2} \sum_{i=1}^{W} w_i^2\right)$$

$\alpha \leftarrow$ regularizer

- Algorithm to find the optimal: $(\{w_j\}_{MP}, \alpha_{MP})$

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2. For $\mathcal{N}_{\text{1-M}}$: $\mathcal{P}(\mathcal{N} \mid \mathcal{D}) = \dfrac{\mathcal{P}(\mathcal{D} \mid \mathcal{N}) \mathcal{P}(\mathcal{N})}{\mathcal{P}(\mathcal{D})}$

- Assuming all NN configurations are equally suited to describe data:

  $\mathcal{P}(\mathcal{N}_1) = \mathcal{P}(\mathcal{N}_2) = \ldots = \mathcal{P}(\mathcal{N}_M)$ then $\mathcal{P}(\mathcal{N} \mid \mathcal{D}) \propto \mathcal{P}(\mathcal{D} \mid \mathcal{N})$

- In the Hessian approximation:

$$\mathcal{P}(\mathcal{D} \mid \mathcal{N}) = \int dw_1 \cdots dw_W \mathcal{P}(\mathcal{D} \mid \{w_j\}, \mathcal{N}) \mathcal{P}(\{w_j\} \mid \mathcal{N})$$

$$\ln \mathcal{P}\left(\mathcal{D} \middle| \mathcal{N}\right) \approx -\chi^2 - \alpha_{MP} \frac{1}{2} \sum_{i=1}^{W} \{w_i\}^2_{MP} - (\text{Occam's factor})$$

large for models with many parameters

Bayesian inference in hadronic and nuclear physics

- Resonance content of γ p $\to$ K$^+$ Λ

  De Cruz et al., PRL 108 (2012)
- Uncertainty Quantification in Nuclear Density Functional Theory

  McDonnell et al., PRL 114 (2015)
- Halo effective field theories

  Zhang et al., PLB 751 (2015)

- Bayesian neural-network analysis
  - Parametrization of EM nucleon form factors

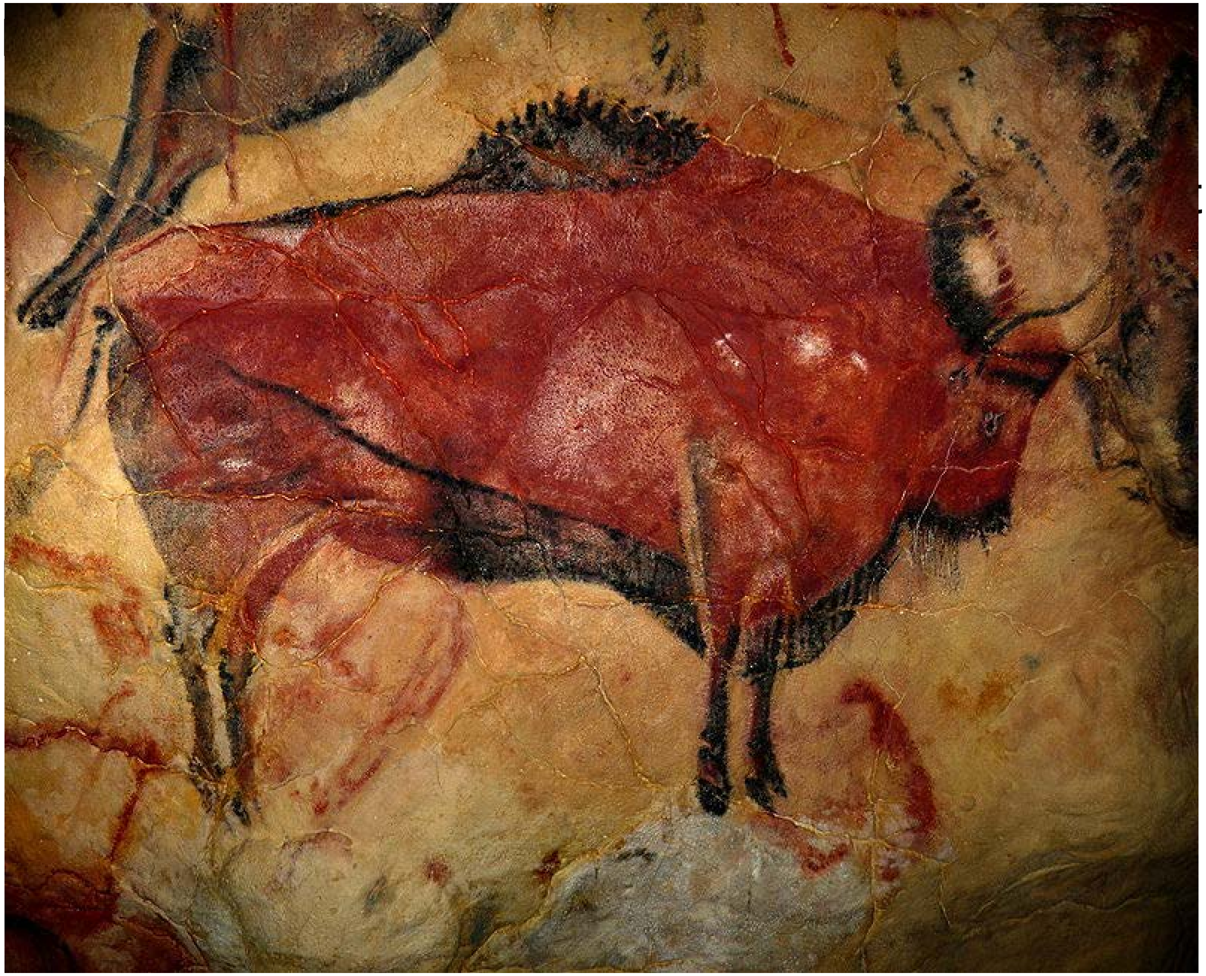
    Graczyk et al., JHEP 1009 (2010)
  - Proton radius

    Graczyk & Juszczak, PRC 90 (2014)

  - Nucleon axial form factor from new ν–nucleon data

    LAR, Graczyk, Saúl-Sala, arXiv:1805.00905

Bayesian inference in hadronic and nuclear physics



- ional Theory

- Nucleon axial form factor from ~~new ν–nucleon data~~ ANL data

LAR, Graczyk, Saúl-Sala, arXiv:1805.00905

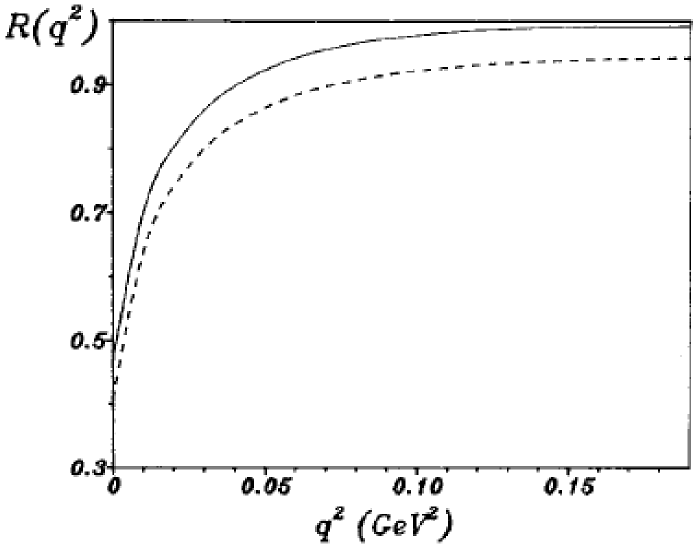
Bayesian NN analysis of ANL data

- LAR, Graczyk, Saúl-Sala, arXiv:1805.00905

$$\frac{d\sigma_{\nu n}}{dQ^2} = \frac{G_F^2 m_N^2}{8\pi E_\nu^2}\left[A(Q^2) + B(Q^2)\frac{(s-u)}{m_N^2} + C(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

- A, B, C are functions of $F^V_{1,2}$ and $F_{A,P}$
- $F^V_{1,2}$ assumed exact; F_P given in terms of F_A

$$\frac{d\sigma_{\nu d}}{dQ^2} = R(Q^2)\,\frac{d\sigma_{\nu n}}{dQ^2}$$



Singh, Arenhövel, Z. Phys. A 324 (1986)

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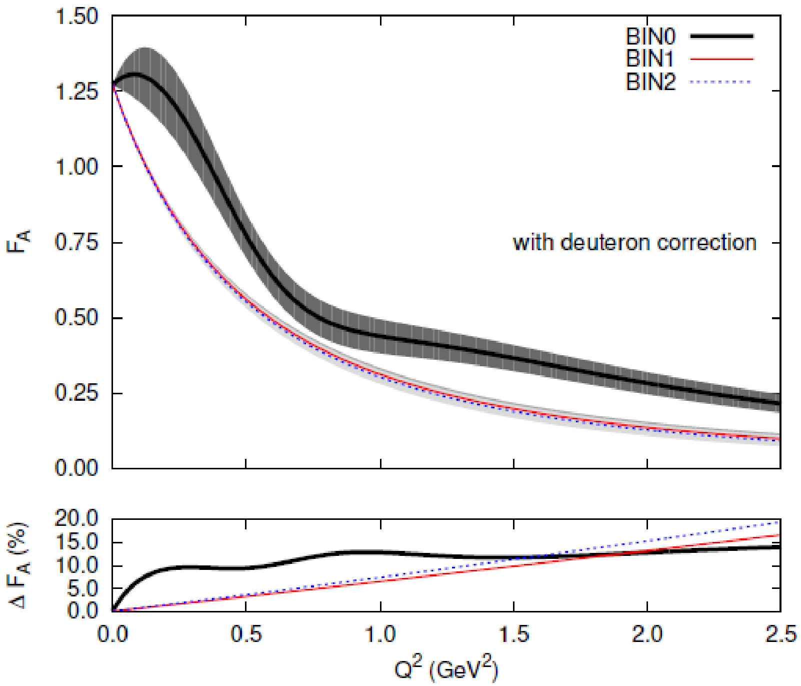
- A, B, C are functions of $F^V_{1,2}$ and $F_{A,P}$
- $F^V_{1,2}$ assumed exact; F_P given in terms of F_A
- Events: $N^{th}(Q^2) = \int_0^\infty dE_\nu \frac{d\sigma}{dQ^2}(E_\nu, F_A, Q^2)\phi(E_\nu)$
- Neutrino flux: $\phi(E_\nu) = p\,\frac{1}{\sigma(E_\nu, F_A)}\frac{dN}{dE_\nu}$

$\frac{dN}{dE_\nu}$ ← experimental E_ν distribution of observed events
Barish et al., PRD19 (1979)

- $$\chi^2 = \left(\frac{F_A(0) - g_A}{\Delta g_A}\right)^2 + \sum_{i=k}^{n_{\rm ANL}} \frac{\left(N_i - N_i^{th}\right)^2}{N_i} + \left(\frac{1-p}{\Delta p}\right)^2 \qquad \Delta p = 20\,\%$$

Bayesian NN analysis of ANL data

- Results:



- BIN0 results inconsistent with z-exp ones:
  - r_A^2 = -1.61 $\pm$ 0.24 fm^2 vs 0.46(22) fm^2 [νd] & 0.43(24) fm^2 [μ-capt.]

Meyer et al., PRD93 (2016)
Hill et al., arXiv:1708.08462

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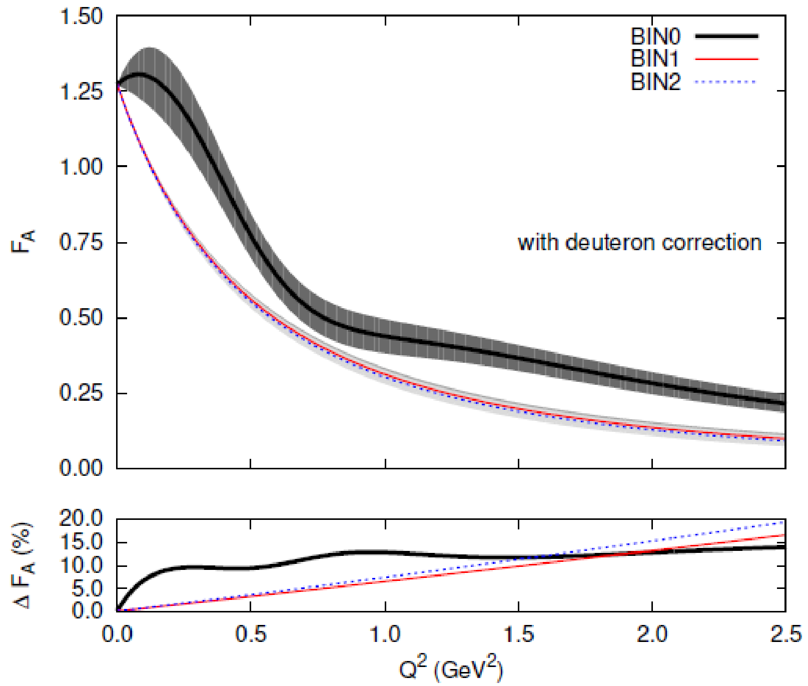

- BIN0 results inconsistent with z-exp ones:
  - r_A^2 = -1.61 $\pm$ 0.24 fm^2 vs 0.46(22) fm^2 [νd] & 0.43(24) fm^2 [μ-capt.]
- In a similar study of the proton EM radii:
- r^p_E = 0.899 $\pm$ 0.003 fm vs 0.870 $\pm$ 0.023 $\pm$ 0.012 fm

Graczyk, Juszczak, PRC 90 (2014)   Hill, Paz, PRD 82 (2010)

Bayesian NN analysis of ANL data

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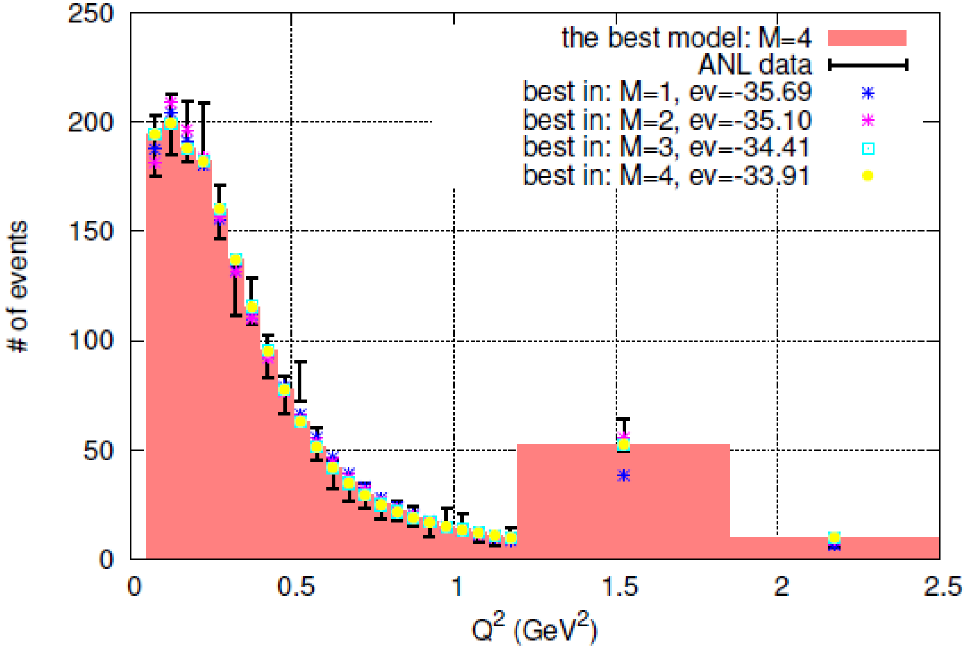
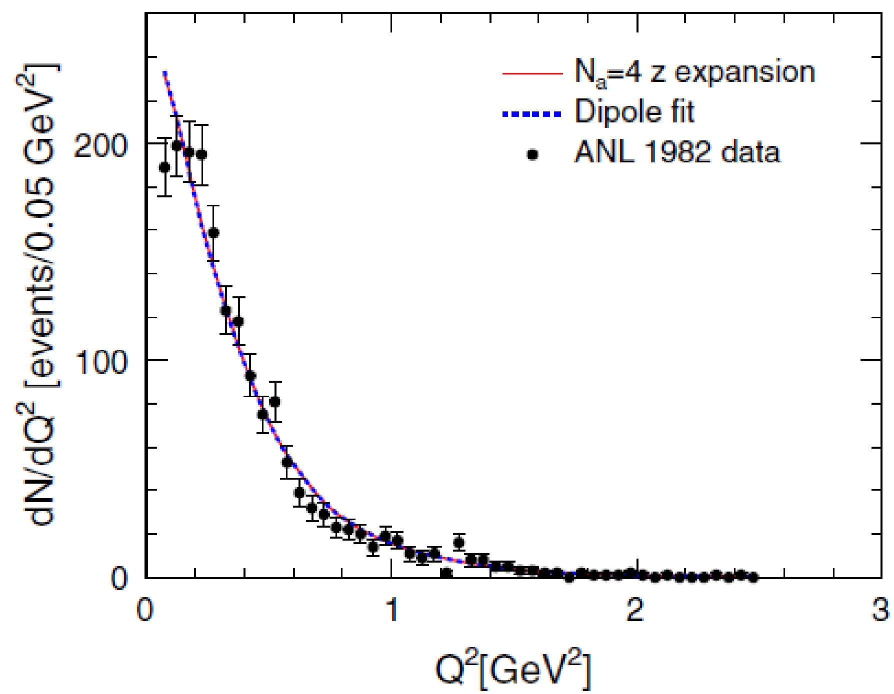


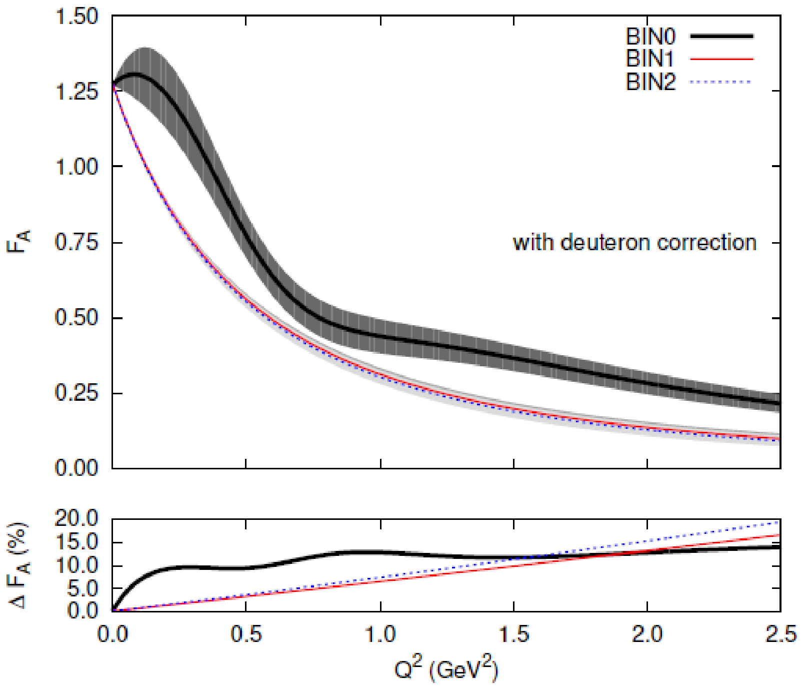


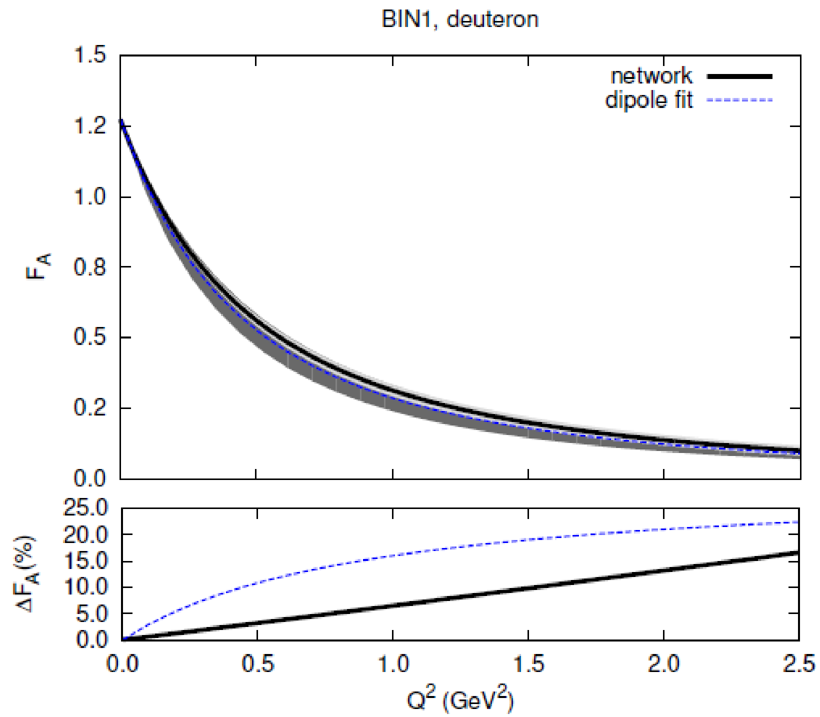
Meyer et al., PRD93 (2016)

- BIN0 results inconsistent with z-exp ones:
  - r_A^2 = -1.61 $\pm$ 0.24 fm^2 vs 0.46(22) fm^2 [νd] & 0.43(24) fm^2 [μ-capt.]
  - Deuteron corrections (important in the 1st,2nd bins)
  - Experimental efficiency issues at low Q^2

Bayesian NN analysis of ANL data

- Results:





- BIN1 results consistent with z-exp (and dipole) ones:
  - r_A^2 = 0.471 $\pm$ 0.015 fm² vs 0.46(22) fm² [νd] & 0.43(24) fm² [μ-capt.]

Meyer et al., PRD93 (2016)
Hill et al., arXiv:1708.08462

Dipole nucleon form factors?

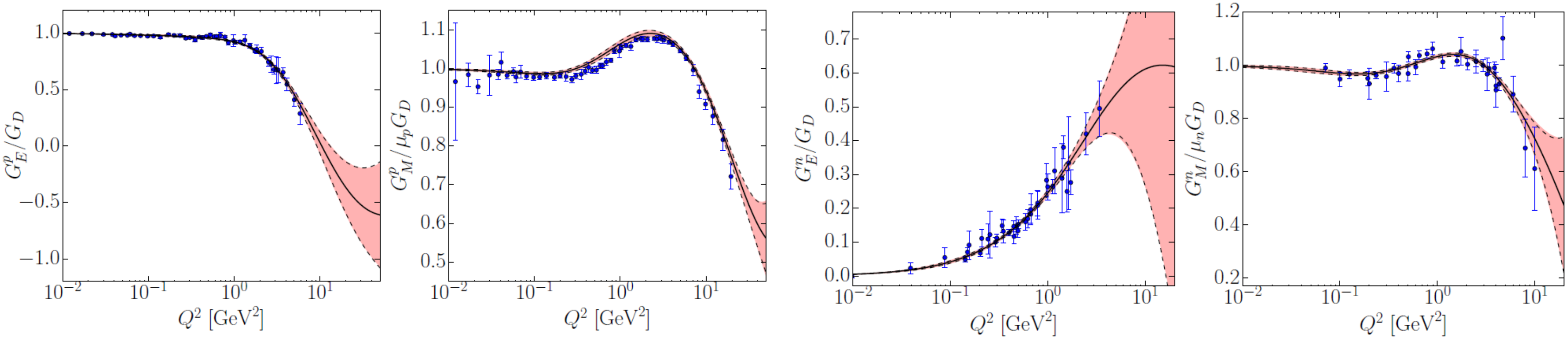
- A priori not theoretically justified
- z-expansion

$$F_A(q^2) = \sum_{k=0}^{\infty} a_k z(q^2)^k \qquad z(t, t_{\text{cut}}, t_0) = \frac{\sqrt{t_{\text{cut}} - t} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} - t} + \sqrt{t_{\text{cut}} - t_0}}$$

$a_k \sim k^{-4}$ while for the dipole ansatz $a_k \sim k$ at large k Meyer et al., PRD93 (2016)

Dipole nucleon form factors?

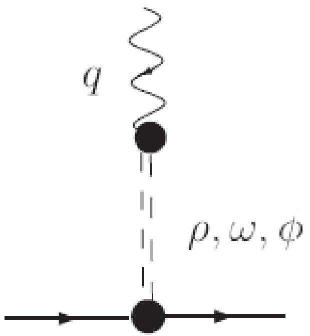
- EM form factors from (e,e’) scattering



Ye et al., arXiv:1707.09063

- Dipole behavior for $Q^2 \lesssim 1$ GeV^2
  - Exponential charge distributions (in the static limit)
  - In the VMD picture, a dipole might arise from two mesons with similar masses and opposite couplings

$$G_D = \left(1 + \frac{Q^2}{0.71\,\mathrm{GeV}^2}\right)^{-2}$$



Axial N-R transitions

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p')\left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu)\right)\gamma_5 + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu\right]u(p)$$

$$C_5^A(0) = \sqrt{\frac{2}{3}}g_{\Delta N\pi}$$ $\leftarrow$ off diagonal Goldberger-Treiman relation

$$\mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi}\bar{\Delta}_\mu(\partial^\mu\vec{\pi})\vec{T}^\dagger N \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(\Delta\to N\pi)$$

- Deviations from GTR arise from chiral symmetry breaking
  - expected only at the few % level

Axial N-R transitions

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu} q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu} q\cdot p - q_\alpha p_\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu} q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2} q_\alpha q_\mu \right] u(p)$$

$$C_5^A(0) = \sqrt{\frac{2}{3}}\, g_{\Delta N\pi}$$ ← off diagonal Goldberger-Treiman relation

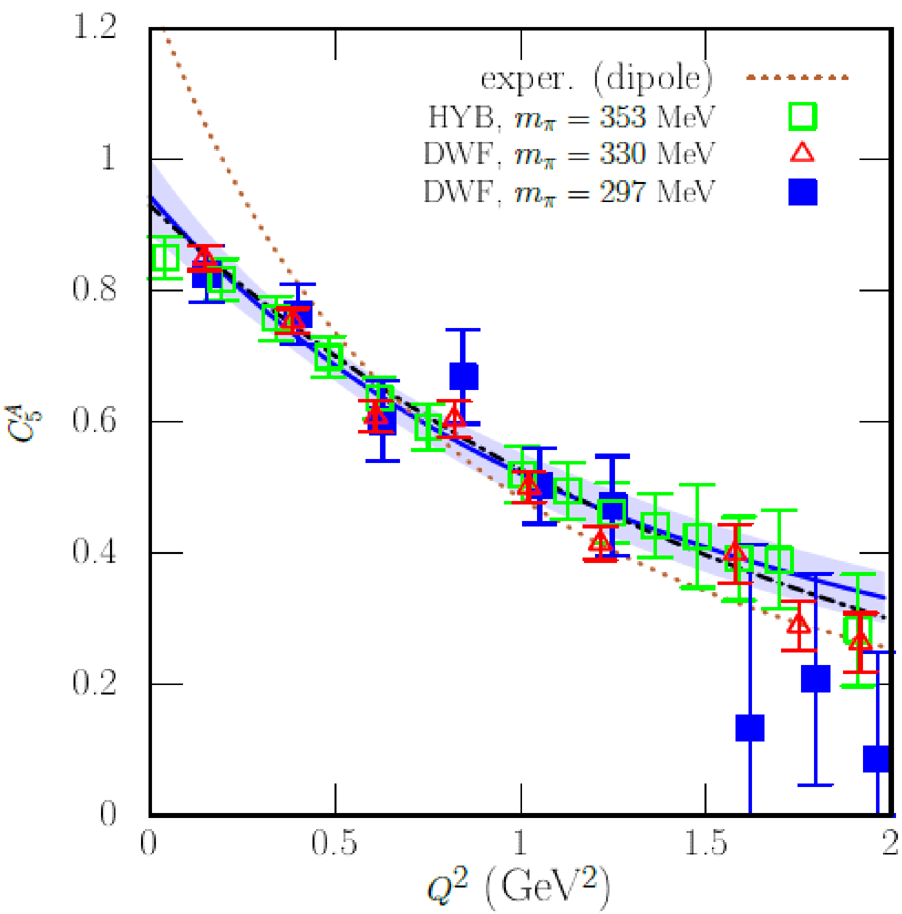
$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$ ↔ z-expansion for N-R transitions?

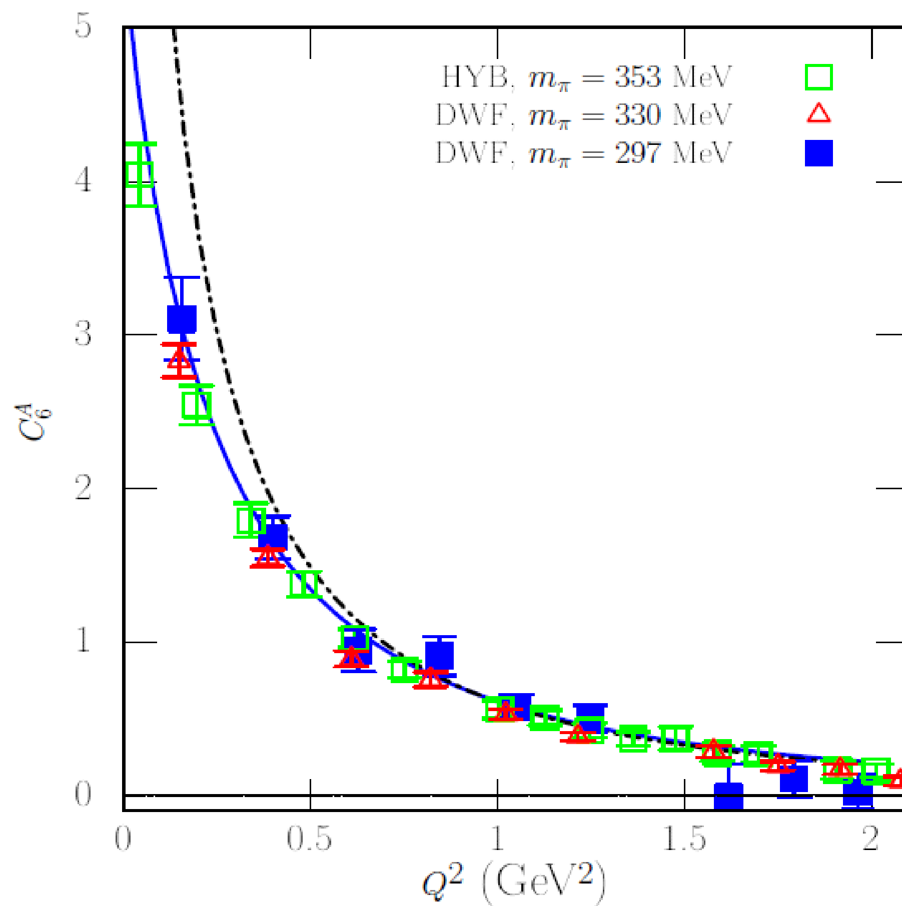
- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$
  - $M_{A\,\Delta}$ = 0.96 ± 0.07 GeV LAR, Hernandez, Nieves, Vicente Vacas, PRD 93 (2016)
  - ANL and BNL data do not constrain $C^A_{3,4}$: consistent with zero
    Hernandez et al., PRD81(2010)

Axial N-R transitions

- N-Δ axial form factors in LQCD

  Alexandrou et al., PRD83 (2011)



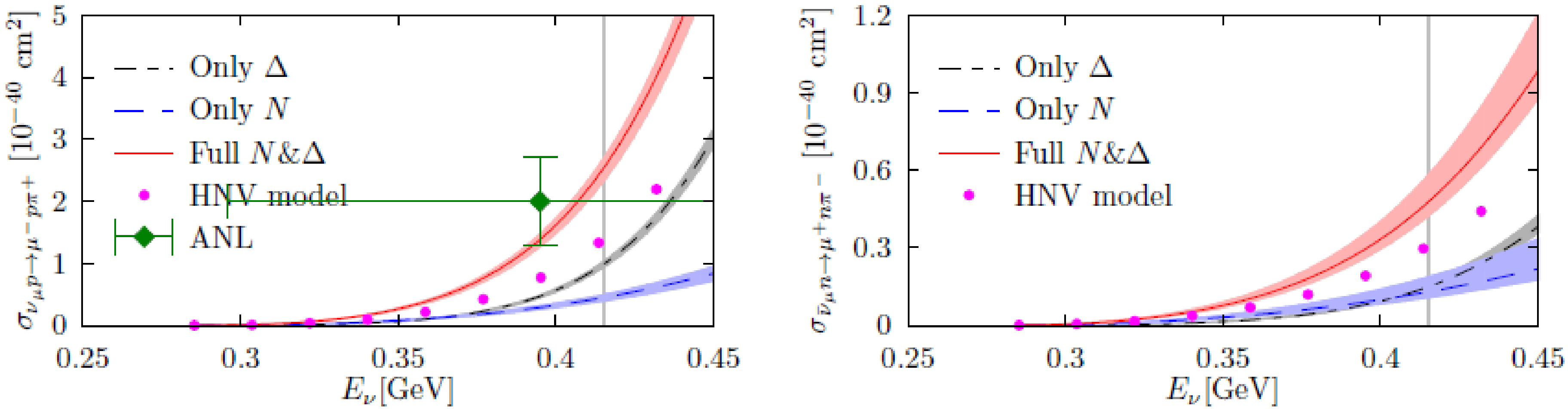


Axial N-R transitions

- Heavier resonances:
  - Goldberger-Treiman relations can be derived for leading couplings
  - No information about Q^2 dependence
  - Calculations assume dipole shapes with M_A = 1 GeV
  - No LQCD results

Weak pion production in BChPT

- Yao et al., arXiv:1806.09364
- First comprehensive study in ChPT
- EOMS
- Explicit $\Delta(1232)$
- $O(p^3)$
- $\delta = m_\Delta - m_N \sim O(p^{1/2})$
- Valid only close to threshold
- Benchmark for phenomenological models



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- Valid only close to threshold
- Benchmark for phenomenological models
- LECs :
  - 22 in total
  - 7 unknown (but not very relevant)
    - 4 of them can be extracted from pion electroproduction
  - information about remaining 3 LEC could be obtained from new close-to-threshold measurements of ν-induced π production on protons

Conclusions

- Do we want new more precise ν-nucleon cross section measuremens?
  - Relevant input for ν MC and theoretical models in general
  - New info about the axial structure of nucleons and other baryons
  - Radiative corrections
  - ChPT LECs, non-pole corrections to Goldberger-Treiman relations
  - New physics (perhaps combining c.s. & lepton/baryon polarization)
  - ...
- Do we NEED new more precise ν-nucleon cross section measuremens?
  - Our letter to Santa should be compelling:
  - ν-nucleon cross section should be crucial for future oscillation measurements
  - Experimental projections: c.s. uncertainties $\Rightarrow$ oscillation errors
- Possible alternatives:
  - LQCD
  - (Polarized) electron scattering
  - H_2 enriched targets
  - ...