NEUTRINO PLATFORM WEEK

Nucleon axial form factors:

how well are they known?

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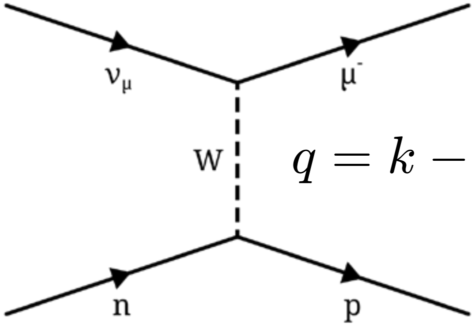
ν QE scattering on the nucleon

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



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

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

where $l^\alpha = \bar{u}(k')\gamma^\alpha(1-\gamma_5)u(k)$

$$J_\alpha = \bar{u}(p')\left[\gamma_\alpha F_1^V + \frac{i}{2m_N}\sigma_{\alpha\beta}q^\beta F_2^V - \gamma_\mu\gamma_5 F_A - \frac{q_\mu}{m_N}\gamma_5 F_P\right]u(p)$$

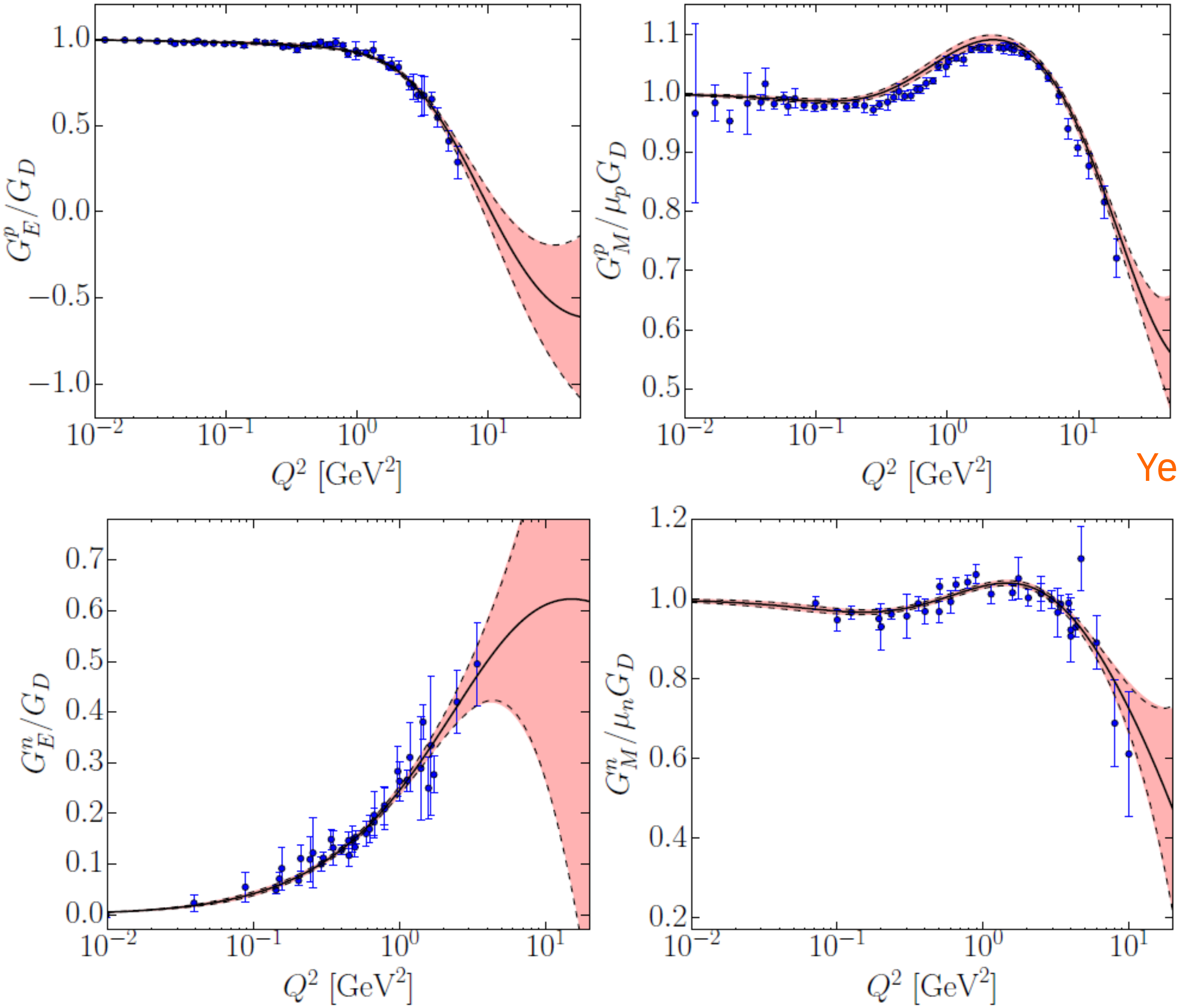
- Vector form factors: $F_{1,2}^V = F_{1,2}^p - F_{1,2}^n$

$$G_E = F_1 + \frac{q^2}{2m_N}F_2 \quad \leftarrow \text{electric}$$

$$G_M = F_1 + F_2 \quad \leftarrow \text{magnetic}$$

Nucleon form factors

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



Ye et al., arXiv:1707.09063

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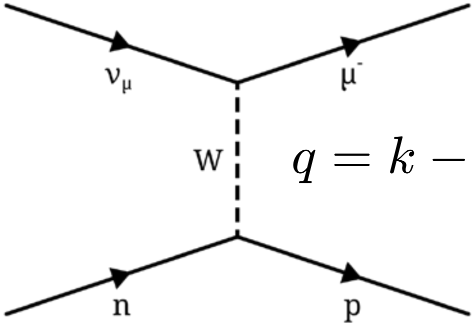

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- Axial form factors:

$$F_A(Q^2) = g_A F(Q^2)\,,\ F_P(Q^2) = \frac{2M^2}{Q^2+m_\pi^2}F_A(Q^2)\,,\ Q^2 = -q^2 > 0$$

g_A = 1.267 ← β decay (n lifetime)

PCAC

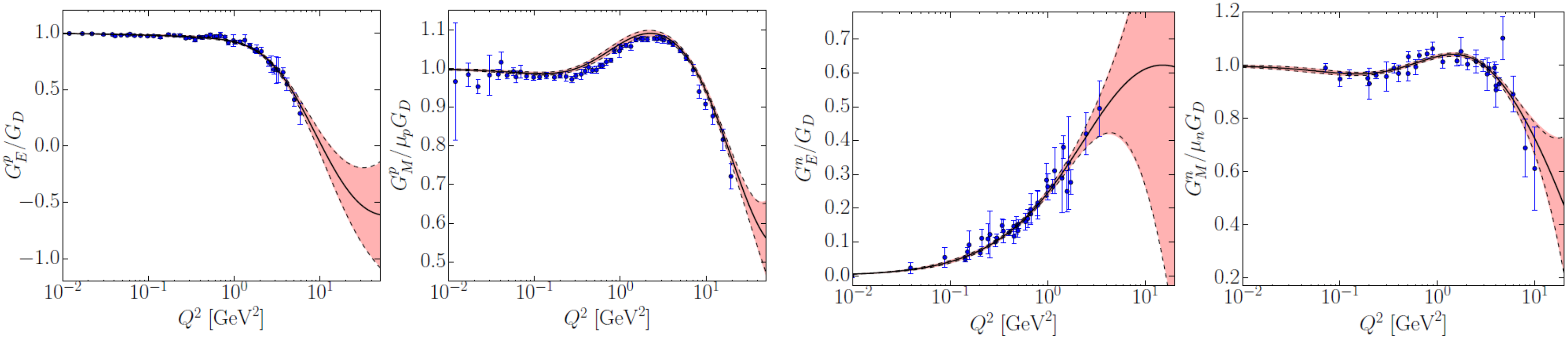
Nucleon axial form factor

$$F_A(Q^2) = g_A F(Q^2)$$

- $\nu_\mu \, d \to \mu^- \, p \, p$: fits to ANL, BNL, FNAL data
- Dipole ansatz: $F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$
  - M_A= 1.016 ± 0.026 GeV Bodek et al., EPJC 53 (2008)
  - A priori not theoretically justified

Nucleon form factors

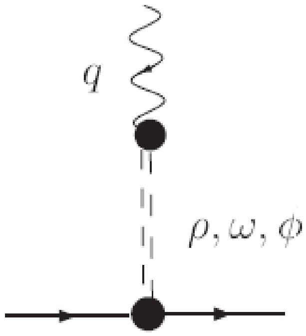
- EM form factors from (e,e') scattering



Ye et al., arXiv:1707.09063

- Dipole behavior for $Q^2 \lesssim 1$ GeV^2
  - A priori not theoretically justified
  - Exponential charge distributions (in the static limit)
  - In the VMD picture, a dipole might arise from two mesons with similar masses and opposite couplings

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



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  - M_A= 1.016 ± 0.026 GeV Bodek et al., EPJC 53 (2008)
  - A priori not theoretically justified
    - Leads to artificially small errors in M_A
    - Axial radius:

$$F_A(Q^2) = g_A \left(1 - \frac{1}{6}\langle r_A^2\rangle Q^2 + \cdots\right) \qquad \langle r_A^2\rangle = \frac{12}{{M_A}^2}$$

Nucleon axial form factor

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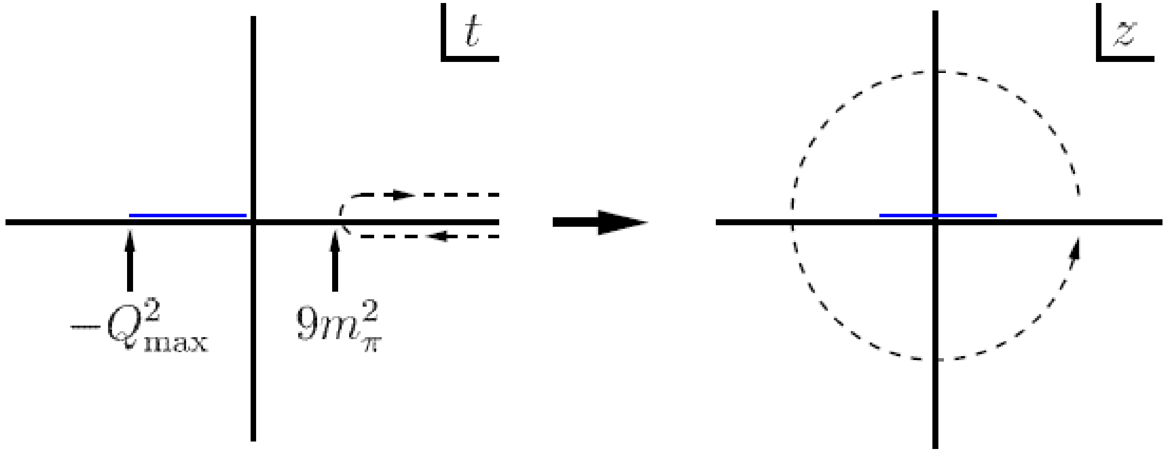
- Dipole ansatz: $F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$
- z-expansion: R. Hill, G. Paz, ...

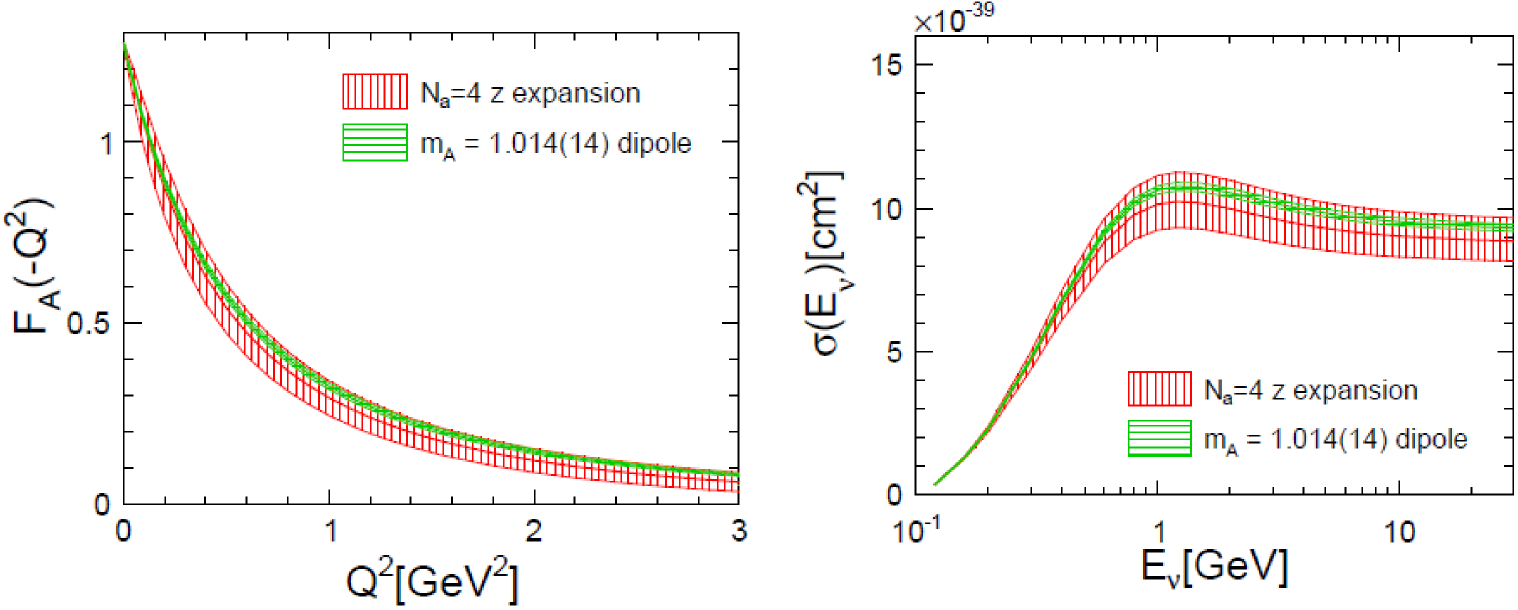


$$F_A(q^2) = \sum_{k=0}^{\infty} a_k z(q^2)^k \qquad z(t, t_{\mathrm{cut}}, t_0) = \frac{\sqrt{t_{\mathrm{cut}} - t} - \sqrt{t_{\mathrm{cut}} - t_0}}{\sqrt{t_{\mathrm{cut}} - t} + \sqrt{t_{\mathrm{cut}} - t_0}}$$

- For a given $Q2_{\mathrm{max}}$, t_0 can be chosen: $|z|$ is small (<1)

QE scattering on the nucleon

- 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 Bodek et al., EPJC 53 (2008)
- At $E_\nu \sim 1$ GeV σ(CCQE) has $\approx$ 10 % error
- More precise information about F_A is (probably) needed
  - Direct or indirect CCQE measurement on d/p

    Workshop at INT, Seattle, June 2018

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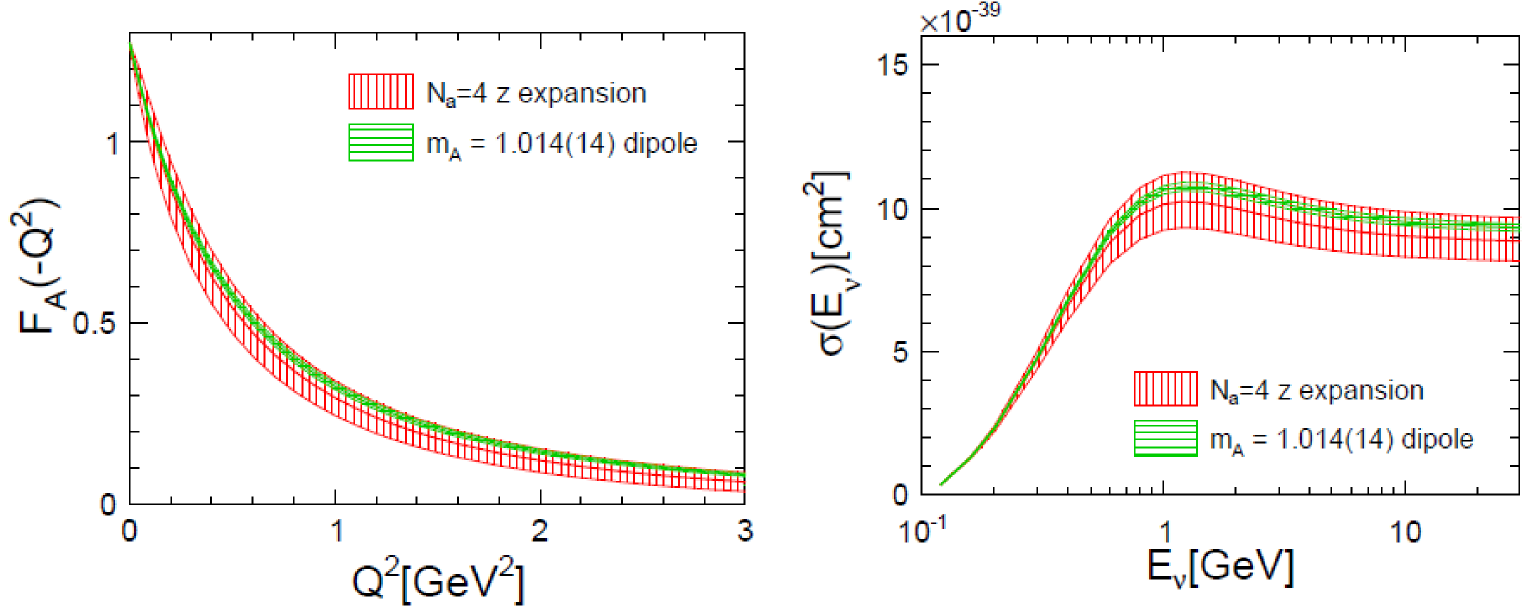

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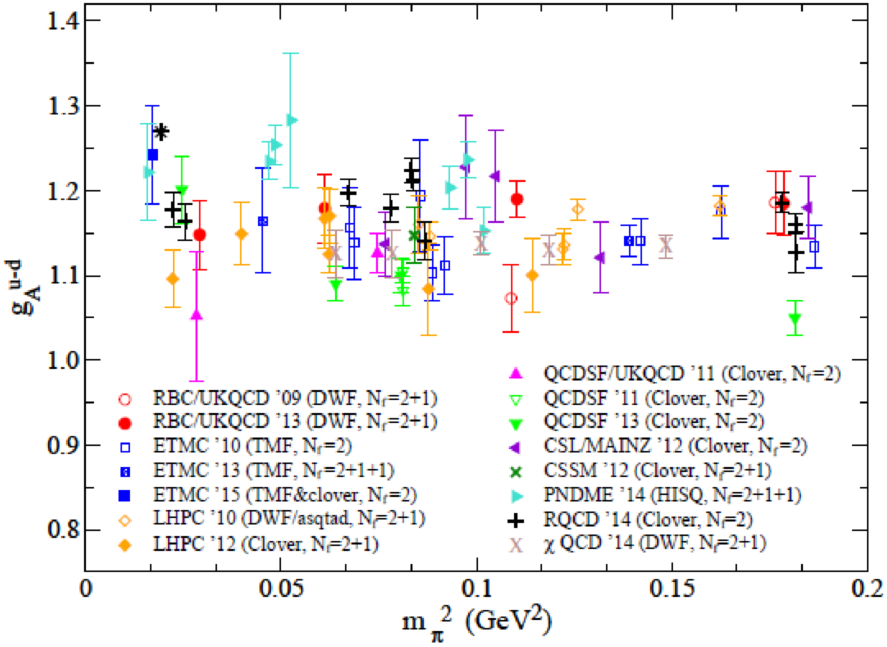
  - Lattice QCD

F_A & LQCD

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



Constantinou, PoS CD15 (2015) 009

- Recent progress:
  - 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 & LQCD

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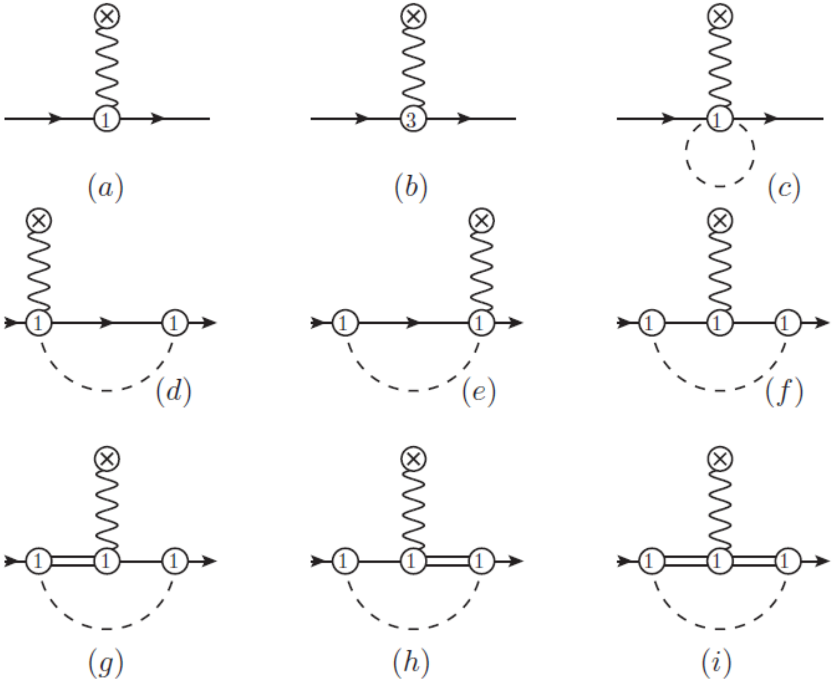
- Baryon ChPT analysis: Yao, LAR, Vicente Vacas, PRD 96 (2017)
  - $O(p^3)$, $Q^2 < 0.36\ \mathrm{GeV}^2$, $130\ \mathrm{MeV} < M_\pi < 473\ \mathrm{MeV}$, explicit $\Delta(1232)$



F_A & LQCD

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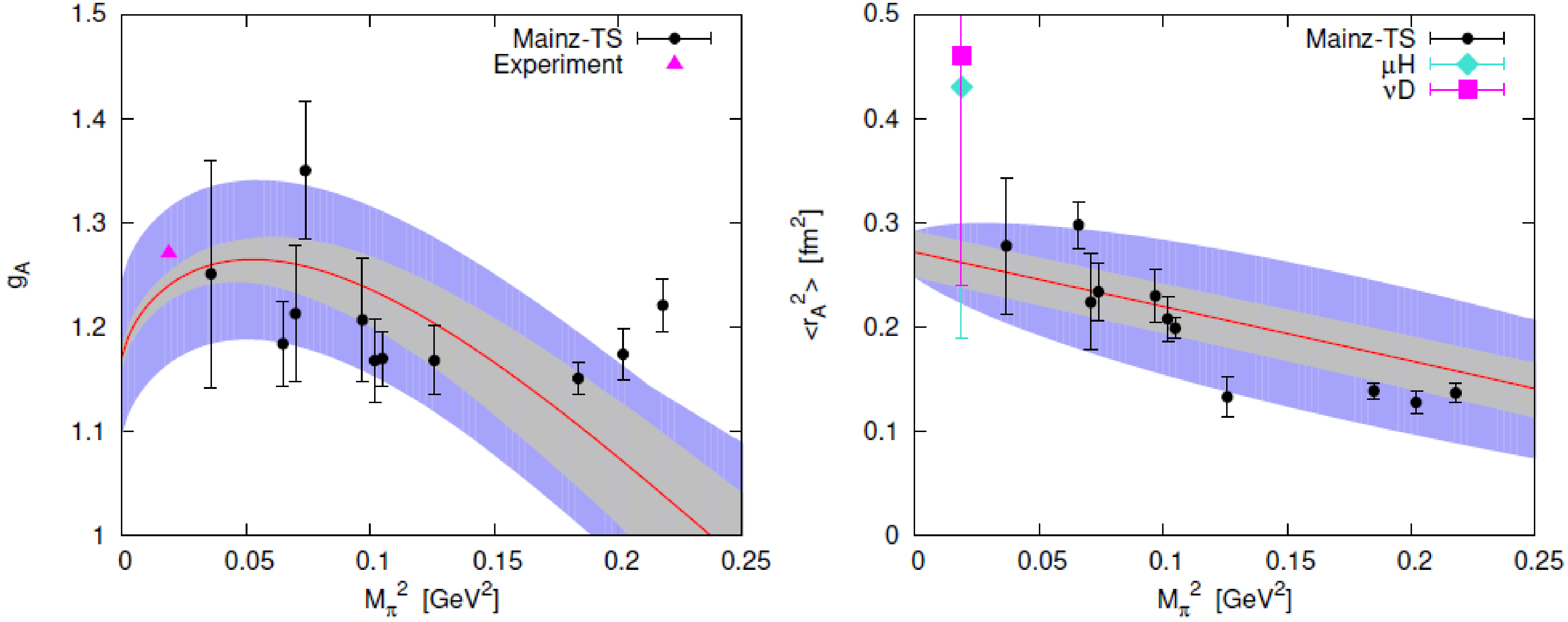

  - $g_A = 1.237(74)$, $\langle r_A^2 \rangle = 0.263(38)$ fm^2

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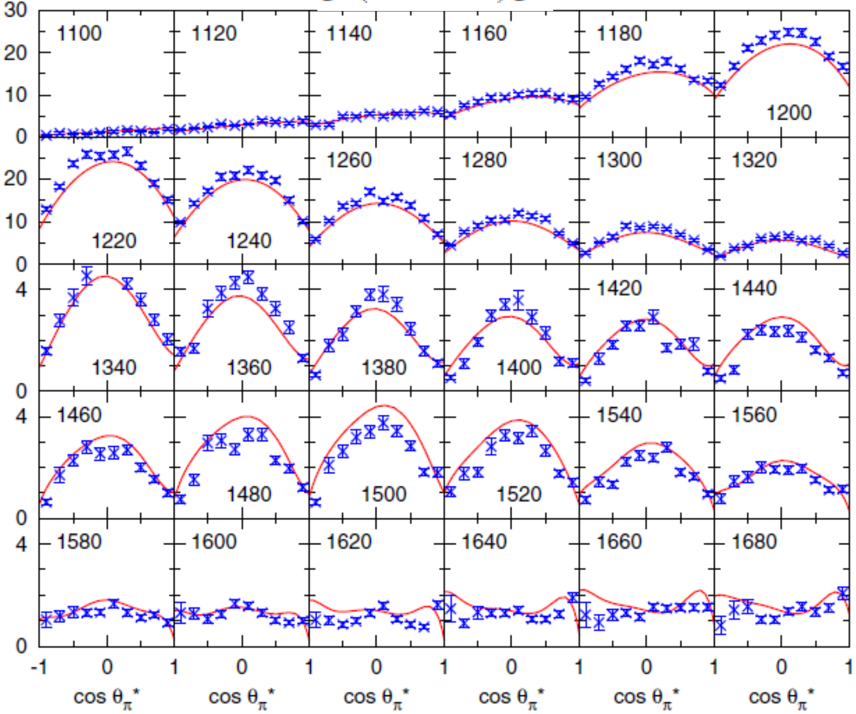
  - $g_A = 1.237(74)$, $\langle r_A^2 \rangle = 0.263(38)$ fm^2
- Improvements:
  - BChPT: $O(p^5)$ might be needed to improve M_π dependence
  - LQCD: excited states and finite volume corrections
    - Critical to reliably obtain F_A in LQCD

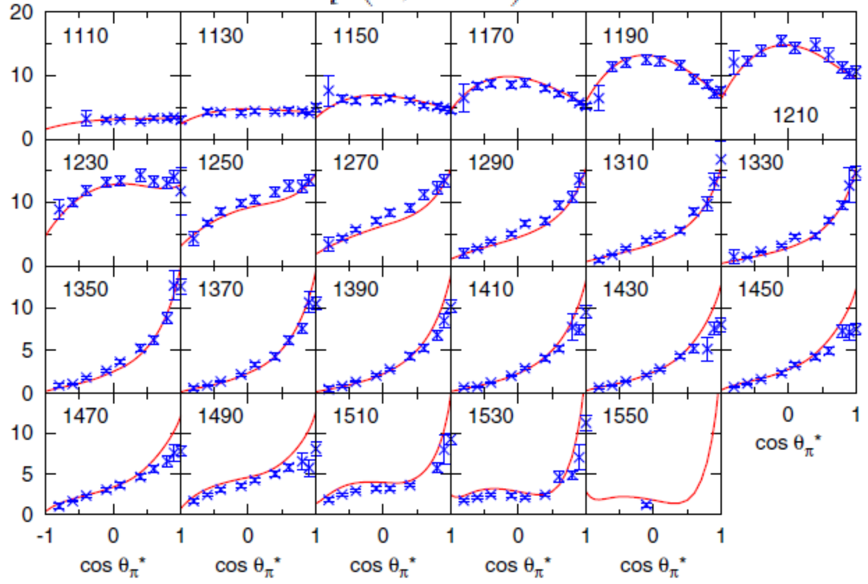
Inelastic channels

- For example: $\nu_l\, N \to l\, N'\, \pi$
  - Vector current can be constrained with $\gamma\, N \to N\, \pi$, $e\, N \to e'\, N\, \pi$

$p(e,e'\pi^0)p$



$p(e,e'\pi^+)n$



Nakamura, Kamano, Sato, PRD92 (2015)

  - Axial current at $q^2 \to 0$ can be constrained with $\pi\, N \to N\pi$ (PCAC)
  - Very limited information about the axial current at $q^2 \neq 0$

In summary

- Neutrino-nucleus c.s. mismodeling could lead to unacceptably large systematic uncertainties or biased measurements.
  - *Nuclear effects*
    - Multi-nucleon problem
    - initial state description: non-relativistic *ab-initio* calculations, spectral functions, mean fields, collective effects
    - final state interactions: (relativistic) NN, πN, ...
  - ν-nucleon interactions: insuffcently constrained