Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Neutrino-nucleon interactions

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NuINT school, Sao Paolo, Brazil
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Neutrino-nucleon interactions

A very birds-eye view

Some examples based on introductory works:
E.A. Paschos, Electroweak theory
M. Thomson, Modern particle physics

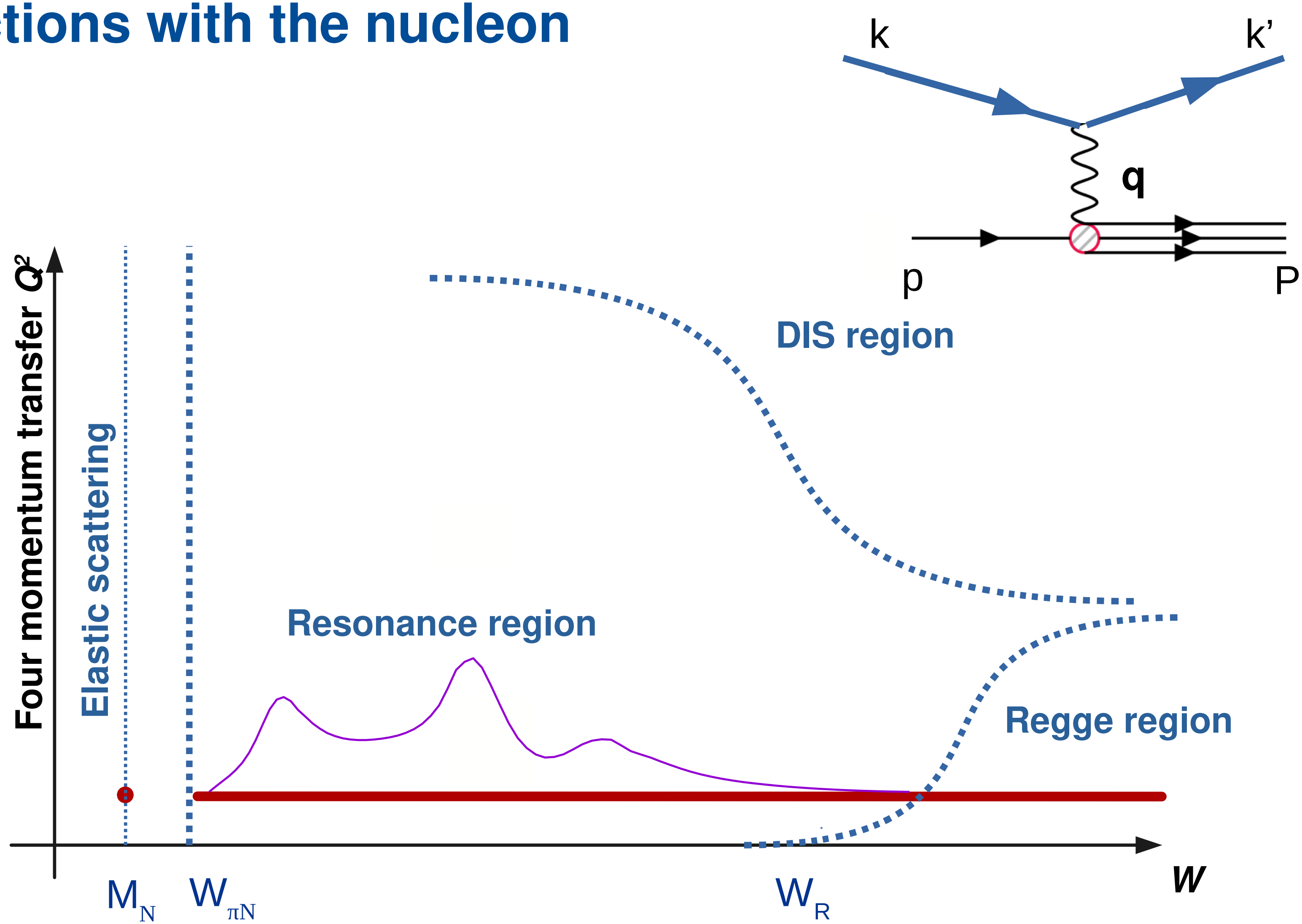
Recent research

And lectures from N. Rocco at the last NuSTEC school at Fermilab

For more in-depth overviews:

References in this presentation
&
NuSTEC White Paper : arxiv.org/abs/1706.03621
&
Snowmass 2021 white paper : arxiv.org/abs/2203.09030

Interactions with the nucleon

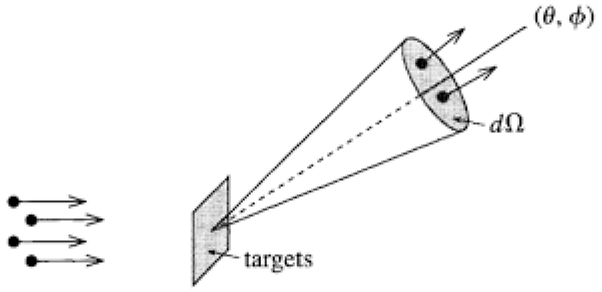


$$Q^2 = -q^2 = (k - k')^2$$

$$W^2 = P^2 = (q + p)^2 = Q^2 - 2M_N\omega + M_N^2$$

Interaction cross section

$$N_{\text{interaction}} = \text{flux} \int_{\Delta\Omega} \mathrm{d}\Omega \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}$$



[Taylor, ISBN:0486450139]

2 → N-2 exclusive scattering

$$p_1 + p_2 \to p_3 + p_4 + \quad \ldots \quad + p_n$$

flux | Phase space | Energy-momentum conservation

$$\mathrm{d}\sigma = \frac{1}{F} \prod_i^n \frac{\mathrm{d}\mathbf{p}_i}{(2\pi)^3 E_i} \delta^4(p_1 + p_2 - \sum_i^n p_i) (2\pi)^4 |\mathcal{M}|^2$$

$$F^2 = 16 \left((p_1 \cdot p_2)^2 - m_1^2 m_2^2 \right)$$

Interaction cross section: degrees of freedom

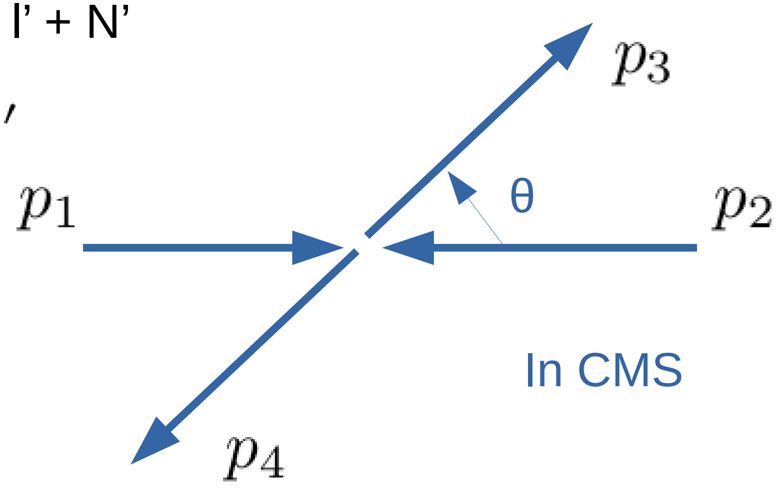
2 → N-2 exclusive scattering

$$p_1 + p_2 \to p_3 + p_4 + \quad \ldots \quad + p_n$$

$N_{d.o.f}$ = 4N - N (mass-shell conditions)
- 3 (choice of reference system)
- 3 (choice of coordinates)
- 4 (Energy-momentum conservation)

For Elastic lepton-nucleon scattering : l + N → l' + N'
2 → 2 : $N_{d.o.f}$ = 2 dof = $E_i, \quad \cos\theta_{l'}$

$$\frac{d\sigma(E)}{d\cos\theta} = \frac{1}{32\pi}\left(\frac{E'}{M_N E}\right)^2 |\mathcal{M}|^2$$



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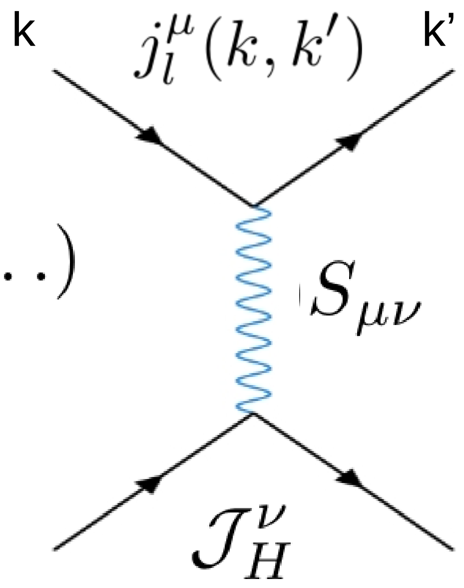
Matrix element for lepton-hadron scattering

Feynman rules for one-boson exchange:



$$\mathcal{M} = j_l^\mu(k,k') S_{\mu\nu}(q = k - k') \mathcal{J}_H^\nu(q, \ \ldots)$$

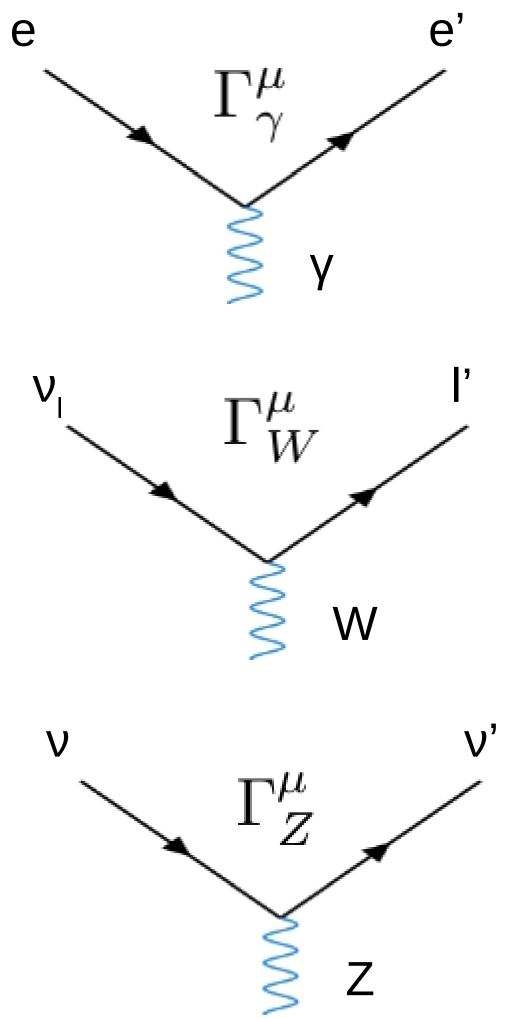
$$S_{\mu\nu}^{W/Z} = -i \frac{g_{\mu\nu} - q_\mu q_\nu / M_{W/Z}^2}{q^2 - M_{W/Z}^2} \approx -i \frac{g_{\mu\nu}}{M_{W/Z}^2}$$

$$S_{\mu\nu}^{\gamma} = \frac{-i g_{\mu\nu}}{q^2},$$

$$\overline{\sum}_{\lambda_l, \lambda_h} |\mathcal{M}|^2 = F_X^2 \overline{\sum} |j_l^\mu \mathcal{J}_\mu|^2 = F_X^2 \overline{\sum}_{\lambda_l} [j_l^\mu]^* j_l^\nu \sum_{\lambda_h} [\mathcal{J}_\mu]^* \mathcal{J}_\nu \equiv F_X^2 \ L^{\mu\nu} H_{\mu\nu}$$

Matrix element for lepton-hadron scattering

For one-boson exchange: $j_l^\mu = \overline{u}(k')\Gamma^\mu u(k)$



$$\Gamma_\gamma^\mu = e\gamma^\mu$$

$$\Gamma_Z^\mu = \frac{g}{4\cos\theta_W}\gamma^\mu\left(1-\gamma^5\right)$$

$$\Gamma_W^\mu = \frac{g}{2\sqrt{2}}\gamma^\mu\left(1-\gamma^5\right)$$

If you calculate the lepton tensor with Γ_W once
→ get all the other cases for free

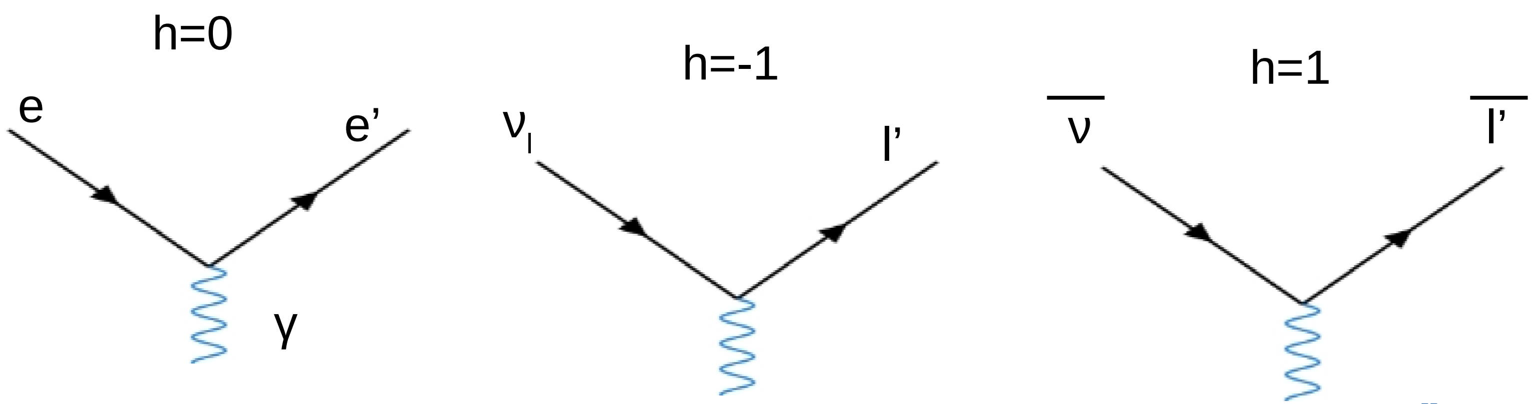
Matrix element for lepton-hadron scattering

For one-boson exchange:

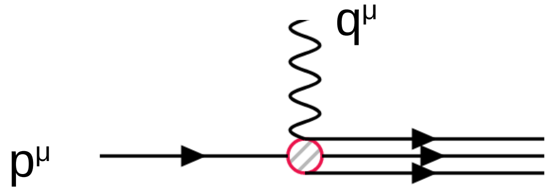
$$\overline{\sum}_{\lambda_l,\lambda_h} |\mathcal{M}|^2 = F_X^2\; L^{\mu\nu} H_{\mu\nu}$$

$$\mathcal{L}^{\mu\nu}(s,s') = \left[\overline{u}(k',s')\gamma^\mu(1\pm\gamma^5)u(k,s)\right]\left[\overline{u}(k',s')\gamma^\nu(1\pm\gamma^5)u(k,s)\right]^\dagger$$

$$\sum_{s,s'}\mathcal{L}^{\mu\nu}_{s,s'} \equiv \boxed{L^{\mu\nu}(k,k',h) = 4\left[k^\mu k'^\nu + k^\nu k'^\mu + g^{\mu\nu}(mm' - k\cdot k') \mp i h \epsilon^{\mu\nu\alpha\beta}k_\alpha k'_\beta\right]}$$

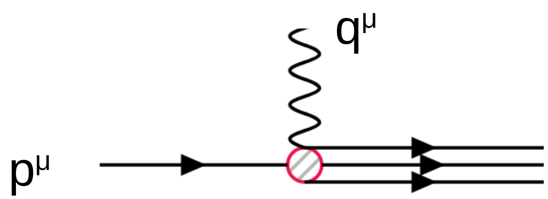


General expression for the (inclusive) hadron tensor



$$H^{\mu\nu} = -g^{\mu\nu}W_1 + \frac{P^\mu P^\nu}{M_N^2}W_2 + i\frac{\epsilon^{\mu\nu\alpha\beta}P_\alpha Q_\beta}{2M_N^2}W_3 + \frac{Q^\mu Q^\nu}{M_N^2}W_4 + \frac{P^\mu Q^\nu + P^\nu Q^\mu}{M_N^2}W_5$$

General expression for the inclusive hadron tensor



$$H^{\mu\nu} = -g^{\mu\nu} W_1 + \frac{P^\mu P^\nu}{M_N^2} W_2 + i \frac{\epsilon^{\mu\nu\alpha\beta} P_\alpha Q_\beta}{2 M_N^2} W_3 + \frac{Q^\mu Q^\nu}{M_N^2} W_4 + \frac{P^\mu Q^\nu + P^\nu Q^\mu}{M_N^2} W_5$$

$$L_{\mu\nu}(h=-1) H^{\mu\nu} = 2 E_i E_f \left[2 W_1 \sin^2 \frac{\chi}{2} + W_2 \cos^2 \frac{\chi}{2} \right. \\ - h \frac{W_3}{M_N} \left((E_i + E_f) \sin^2 \frac{\chi}{2} - \frac{m_f^2}{2 E_f} \right) \\ \left. + \frac{W_4}{M_N^2} m_f^2 \sin^2 \frac{\chi}{2} + \frac{W_5}{M_N} \frac{m_f^2}{E_f} \right]$$

Completely general and well-defined, but structure functions W_i depend on interaction

→ **Constraints come at level of the current**

$$\cos\chi = \frac{p_i p_f}{E_i E_f} \cos\theta_f$$

$W\,(q^2, p_\mu q^\mu)$

Elastic lepton-nucleon scattering: amplitude level

quarks nucleons

$$\overline{u}(p')\gamma^{\mu}(1-\gamma^{5})u(p) \rightarrow \overline{u}(p')\Gamma_{V}^{\mu} - \Gamma_{A}^{\mu}u(p)$$

Structure of vector and axial current

$$\Gamma_{V}^{\mu} = F_{1}(Q^{2})\gamma^{\mu} - \frac{F_{2}(Q^{2})}{2m_{N}}(\gamma^{\mu}\not{Q} - \not{Q}\gamma^{\mu})$$

$$\Gamma_{A}^{\mu} = F_{A}(Q^{2})\gamma^{\mu}\gamma^{5} + \frac{F_{P}(Q^{2})}{2m_{N}}Q^{\mu}\gamma^{5}$$

Elastic lepton-nucleon scattering

quarks — nucleons

$$\overline{u}(p')\gamma^\mu(1-\gamma^5)u(p) \rightarrow \overline{u}(p')\Gamma^\mu_V - \Gamma^\mu_A u(p)$$

Structure of vector and axial current

$$\Gamma^\mu_V = F_1(Q^2)\gamma^\mu - \frac{F_2(Q^2)}{2m_N}(\gamma^\mu \not{Q} - \not{Q}\gamma^\mu)$$

$$\Gamma^\mu_A = F_A(Q^2)\gamma^\mu\gamma^5 + \frac{F_P(Q^2)}{2m_N}Q^\mu\gamma^5$$

$$\begin{aligned}
W_1 &= -\tau\left(F_1+F_2\right)^2 - F_A^2(\tau+1), \\
W_2 &= F_1^2 + \tau F_2^2 + G_A^2, \\
W_3 &= G_A\left(F_1+F_2\right), \\
W_4 &= \frac{\tau-1}{4}F_2^2 - \frac{F_1F_2}{2} - F_P G_A M_N + \tau M_N^2 F_P^2, \\
W_5 &= \frac{W_2}{2},
\end{aligned}$$

e-N scattering

$$W_1 = -\tau\left(F_1+F_2\right)^2$$
$$W_2 = F_1^2 + \tau F_2^2$$

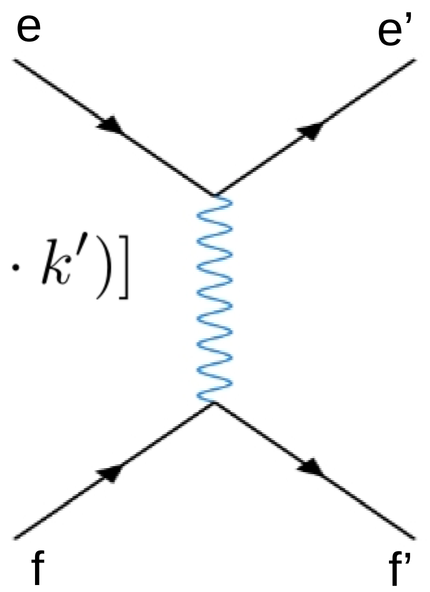
Relativistic electron scattering with Dirac fermion

$$\mathcal{J}^{\mu} = e\overline{u}(k', s')\gamma^{\mu}u(k, s)$$

= same as the lepton-current calculated previously

$$H^{\mu\nu}(k, k') = e^2 4\left[k^{\mu}k'^{\nu} + k^{\nu}k'^{\mu} + g^{\mu\nu}(mm' - k \cdot k')\right]$$

→ W1 = $Q^2/2$, $W_2 = 2\,M_p^{\,2}$



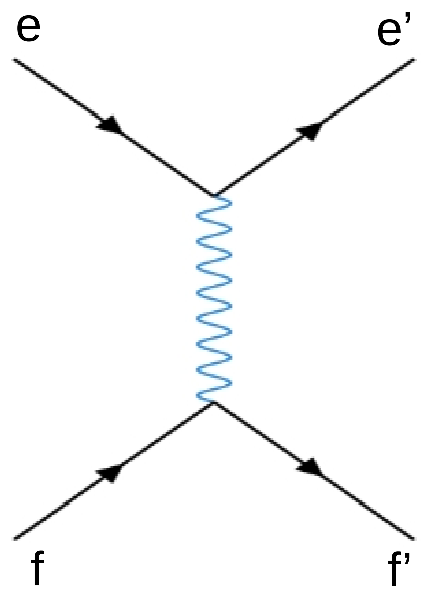
The differential cross section is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{e'}} = \left(\frac{\alpha}{Q^2}\right)^2 \left(\frac{E'}{E}\right)^2 \left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_p^2}\sin^2\frac{\theta}{2}\right]$$

Relativistic : $p_e/E_e = 1$

Relativistic electron scattering with Dirac fermion

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{e'}} = \left(\frac{\alpha}{Q^2}\right)^2 \left(\frac{E'}{E}\right)^2 \left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_p^2}\sin^2\frac{\theta}{2}\right]$$



Compare to the **Mott cross section**
= scattering off a spinless point-charge

$$\frac{\mathrm{d}\sigma_{Mott}}{\mathrm{d}\Omega} = \frac{\alpha^2}{(Q^2)^2}\left(\frac{E'}{E}\right)^2 \cos^2\frac{\theta}{2}$$

→ Dirac particle includes magnetic moment gives $\sin^2$ term

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Relativistic : $p_e/E_e = 1$

Electron scattering with nucleons

Spinless point charge:

$$\frac{d\sigma_{Mott}}{d\Omega} = \frac{\alpha^2}{(Q^2)^2}\left(\frac{E'}{E}\right)^2 \cos^2\frac{\theta}{2}$$

Point-like fermion with Dirac magnetic moment

$$\frac{d\sigma}{d\Omega_{e'}} = \left(\frac{\alpha}{Q^2}\right)^2 \left(\frac{E'}{E}\right)^2 \left[\cos^2\frac{\theta}{2} + \frac{Q^2}{2m_p^2}\sin^2\frac{\theta}{2}\right]$$

Nucleon:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right]\frac{1}{1+\tau}$$

$$1/\epsilon = 1 + 2(1+\tau)\tan^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4m_p^2}$$

$$G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2$$

Nucleon form factors: electron scattering

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right]\frac{1}{1+\tau}$$

Electric and Magnetic form factors of the nucleon

At small Q^2 : $G_E(Q^2)$ ~ $G_E(q)$ ~ 'the Fourier-transform of the charge density' (not strictly true)

Charge and magnetic moment of the nucleon:

$$G_E^p(0) = 1, \quad G_M^p(0) = \mu/\mu_B = 2.7928$$

→ Anomalous μ

$$G_E^n(0) = 0, \quad G_M^n(0) = \mu/\mu_B = -1.9130$$

Point-like fermion (no higher-order corrections)

$$G_E(0) = 1, \quad G_M(0) = \mu/\mu_B = 1$$

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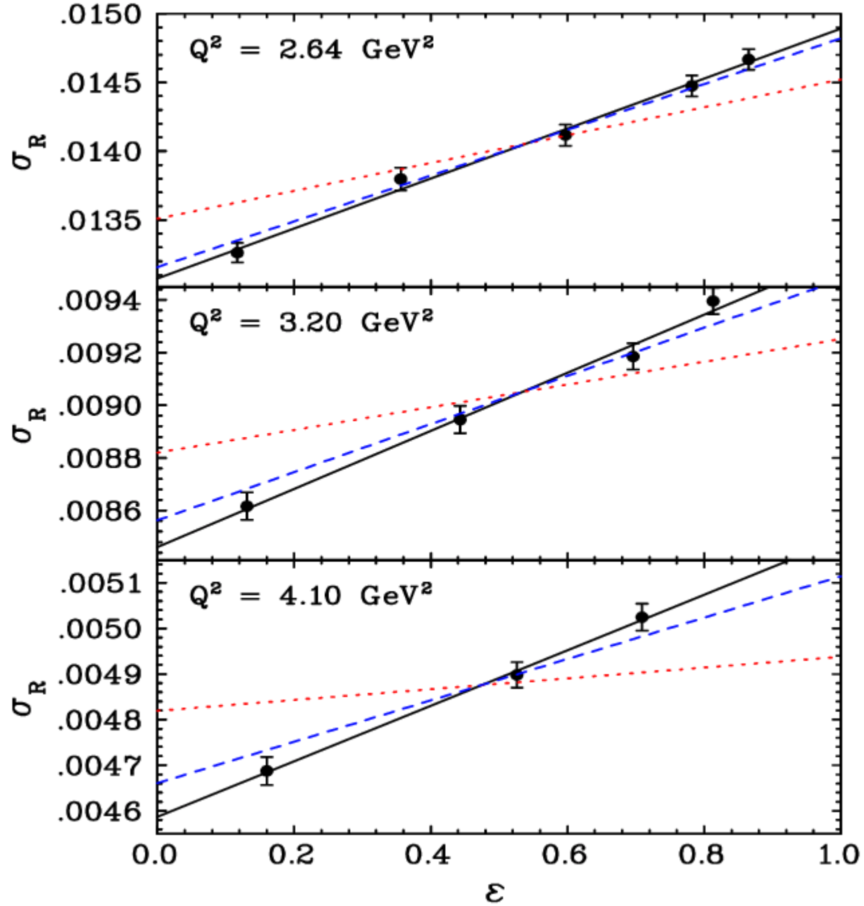
Nucleon form factors: measurement

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega}\left[G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right]\frac{1}{1+\tau}$$

$$1/\epsilon = 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$$

Measure the cross section
At different combinations of θ, E_i
with Q^2 = constant

→ Can separate electric and magnetic form factors



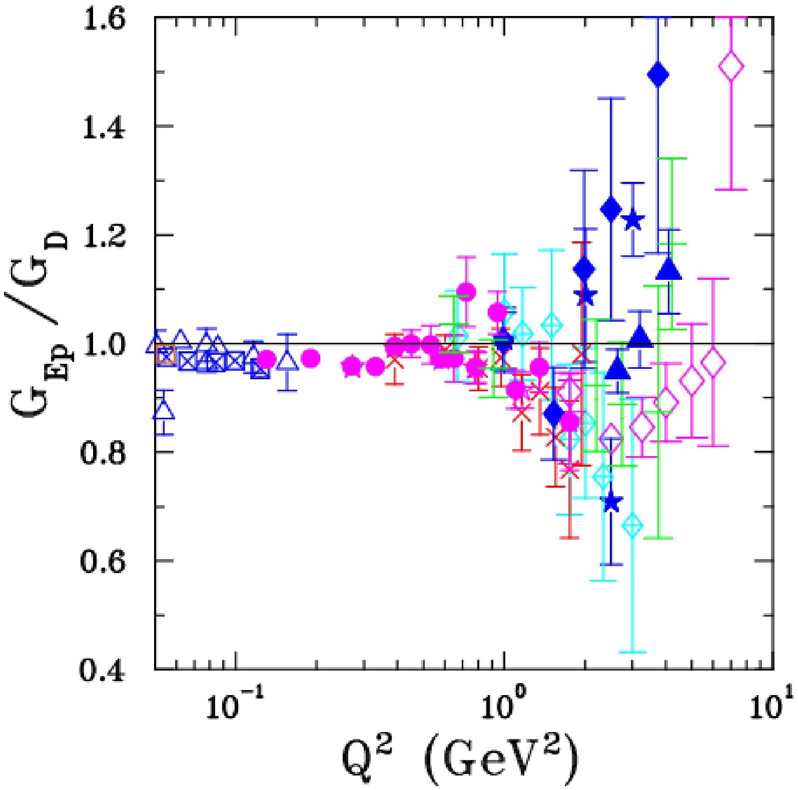
[Qattan et al.,PRL 94, 142301 (2005)]

Nucleon EM form factors

Early analysis found form-factors consistent with dipole-form

$$G_E^p(Q^2) = G_D(Q^2), \quad G_M^p(Q^2) = \mu^p G_D(Q^2), \quad G_M^n(Q^2) = \mu^n G_D(Q^2)$$

$$G_D(Q^2) = (1 + Q^2/M_V^2)^{-2}$$



[Prog.Part.Nucl.Phys. 59 (2007) 694-764]

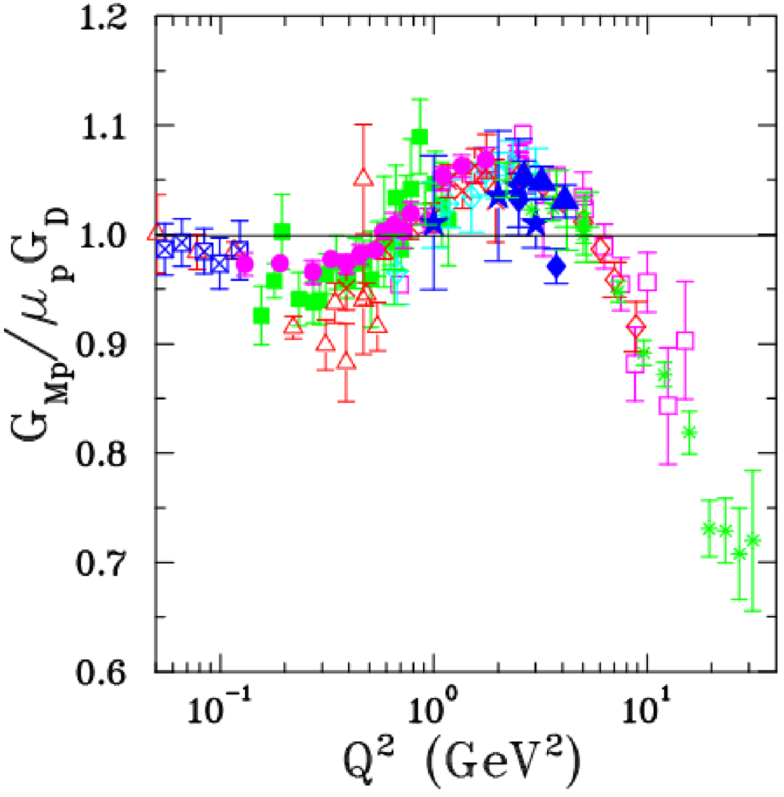
Nucleon EM form factors

Early analysis found form-factors consistent with dipole-form

Modern analyses: deviation from dipoles

Often used in generators:

- Kelly form [Phys. Rev. C 70, 068202]
- BBBA07 [Eur.Phys.J.C53:349-354,2008]
- Z-expansion [Phys. Lett B 777, 8-15]



[Prog.Part.Nucl.Phys. 59 (2007) 694-764]

Modern measurements and analyses are of high precision:
[Prog.Part.Nucl.Phys. 59 (2007) 694-764]
&
[Rev. Mod. Phys. 94, 015002]

Uncertainty is not dominant for neutrino experiments

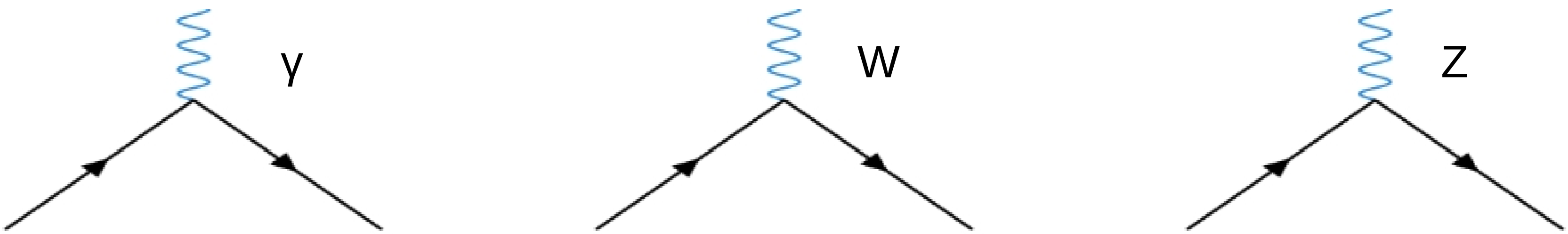
Nucleon form factors: vector and axial currents

The Dirac structure: 2 vector and 2 axial form factors

The vector current is assumed to be an isovector operator:

$$J^{\mu}_{EM} = \langle N | V^{\mu}_{3} + S^{\mu} | N \rangle$$

$$J^{\mu}_{CC\pm} = \langle N | V^{\mu}_{\pm} + A^{\mu}_{\pm} | N \rangle$$



V

$$F_i = F_i^V \tau_3 + F_i^S$$

$$F_i^V \tau_\pm$$

$$F_i^V \tau_3 - 2\sin^2\theta_W (F_i^V \tau_3 + F_i^s)$$

Vector form factors determined from e-p and e-n scattering

$$F_i^p = F_i^V + F_i^S, \quad F_i^n = F_i^S - F_i^V$$ (modulo factors 2)

Axial form factor

-Neutrino data is less precise
→ ANL/BNL/FNAL bubble chambers from 80's

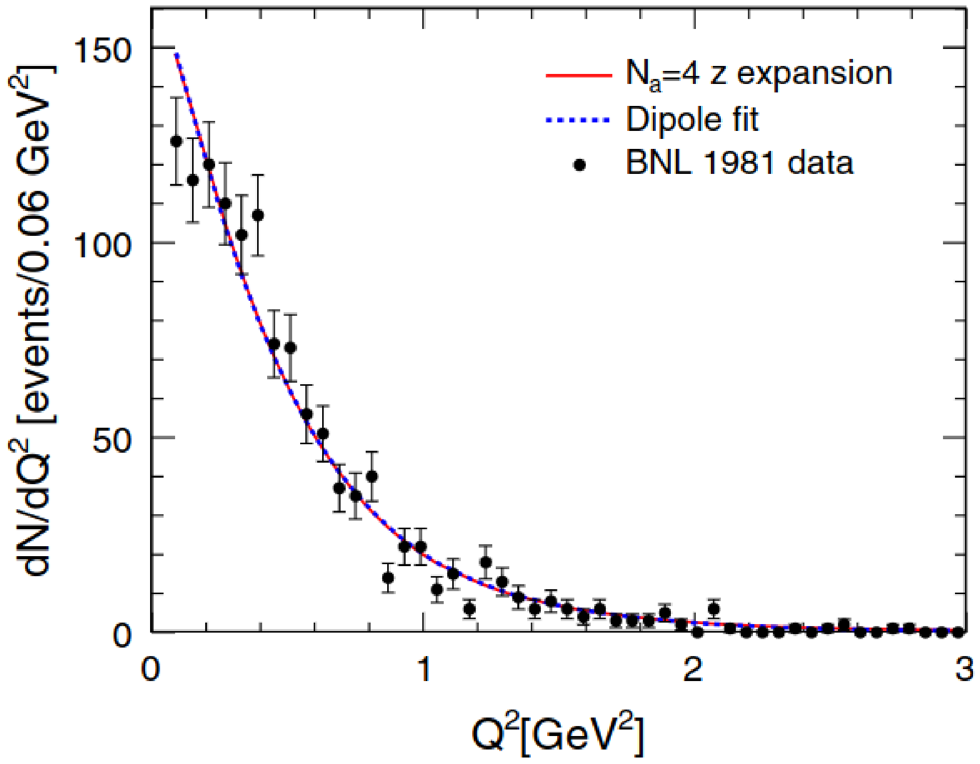
-Original fits done with dipole form:

$$G_A(Q^2) = g_A \left(1 + Q^2/M_A^2\right)^{-2}$$

$$M_A \approx 1 \text{ GeV}$$

- Modern analysis with Model-independent parametrization [Meyer et al. PhysRevD.93.113015] 'z-expansion'

[Meyer et al. PhysRevD.93.113015]



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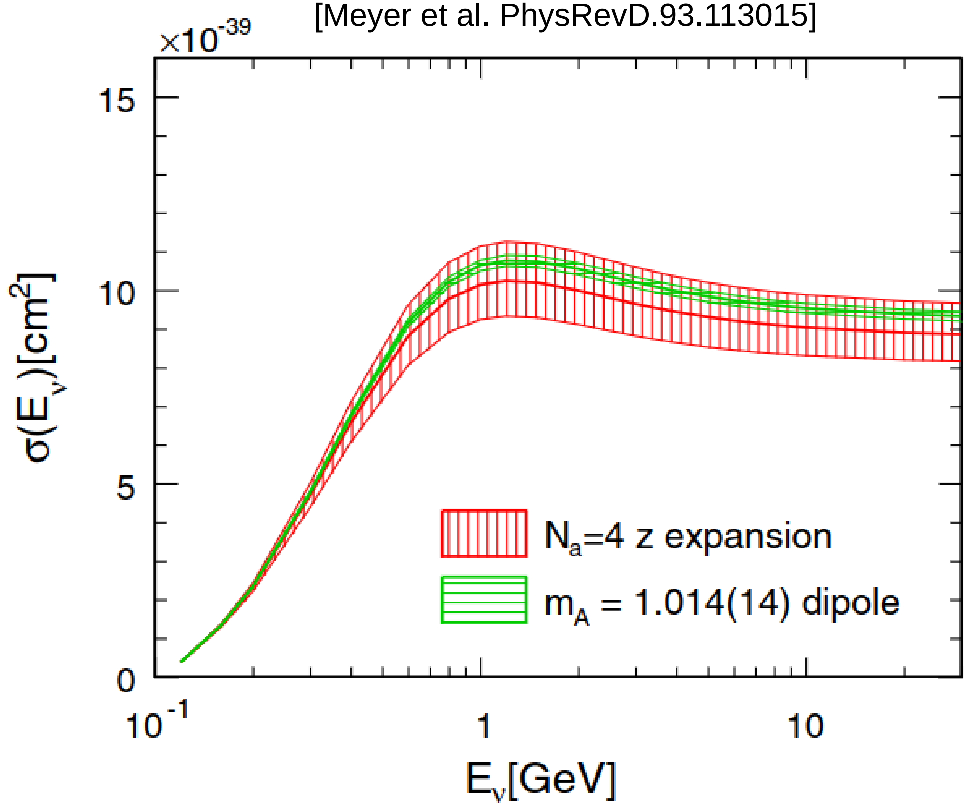
- More realistic error budget !

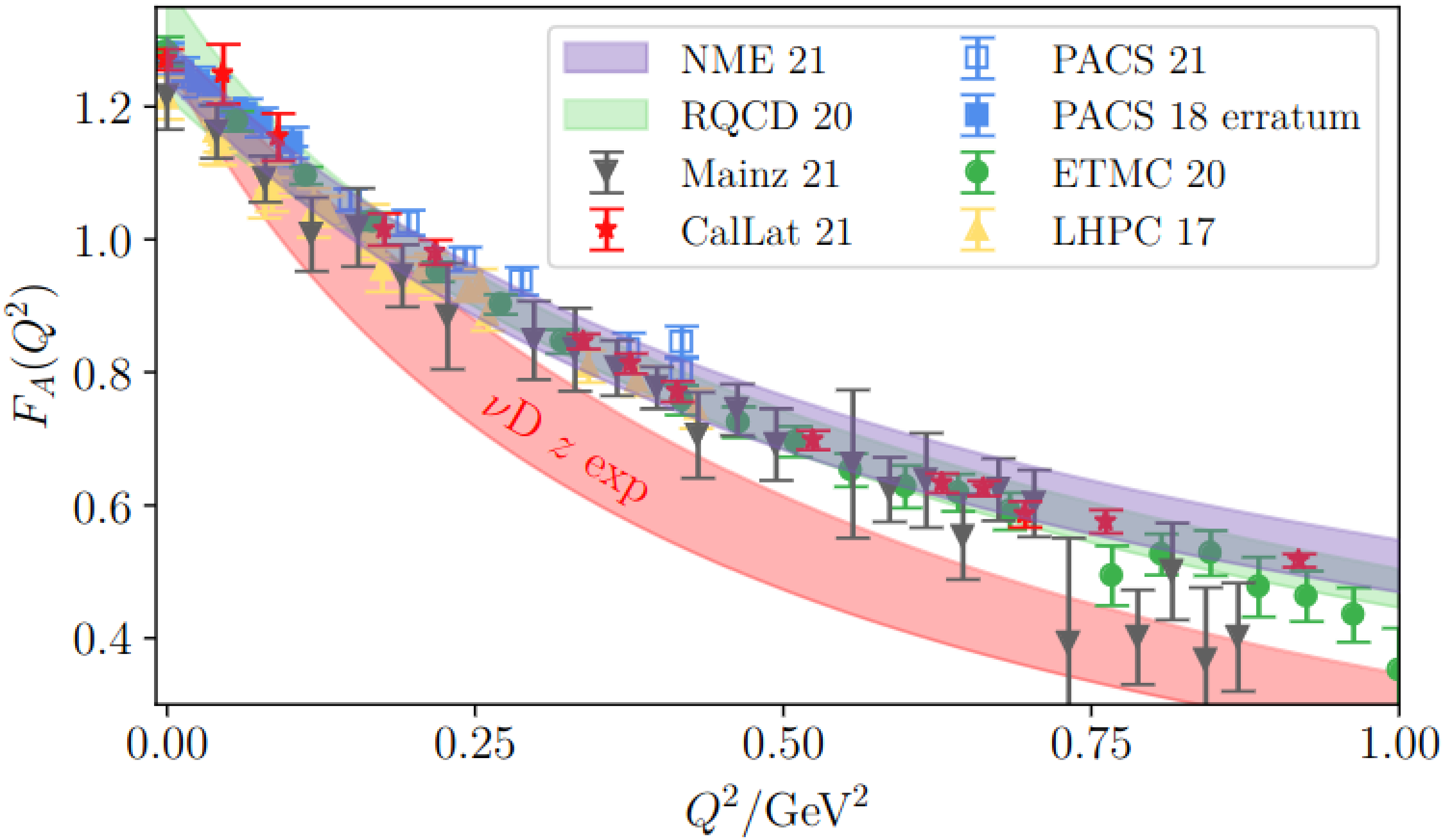
[Meyer et al. PhysRevD.93.113015]



Axial form factor: Lattice QCD

- Recent Lattice QCD calculations for the axial form factor

→ **deviation from deuteron bubble chamber data**



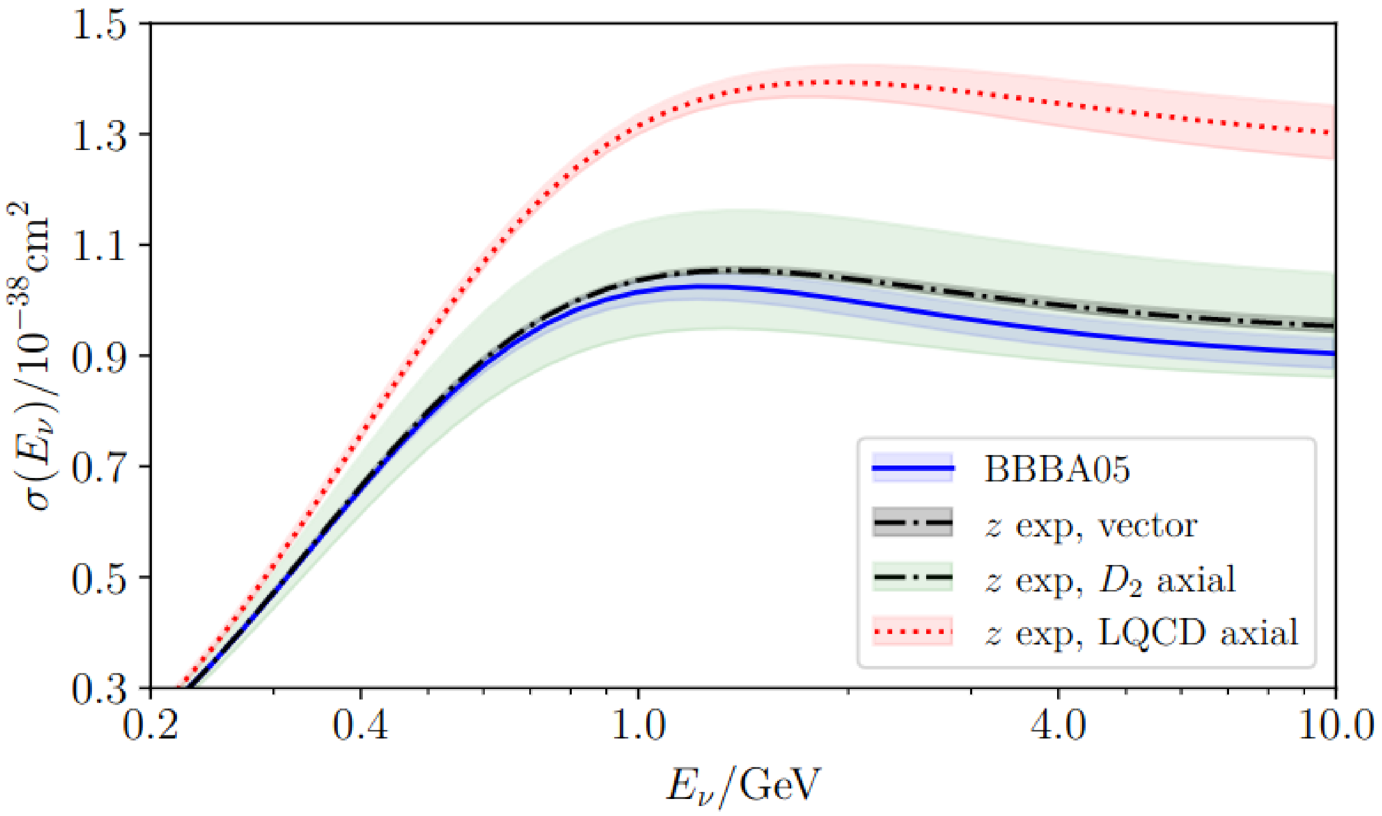
[Meyer et al. arxiv:2201.01839]

Axial form factor: Lattice QCD

- Recent Lattice QCD calculations for the axial form factor

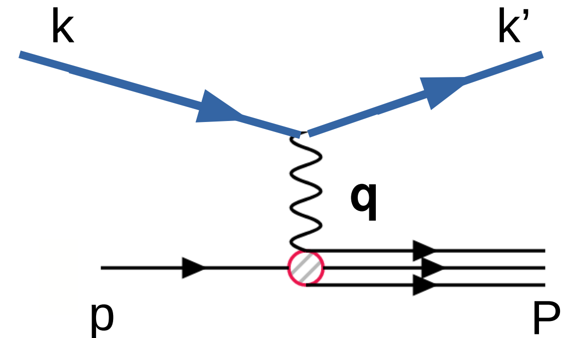
→ **Significant increase for the total elastic cross section**

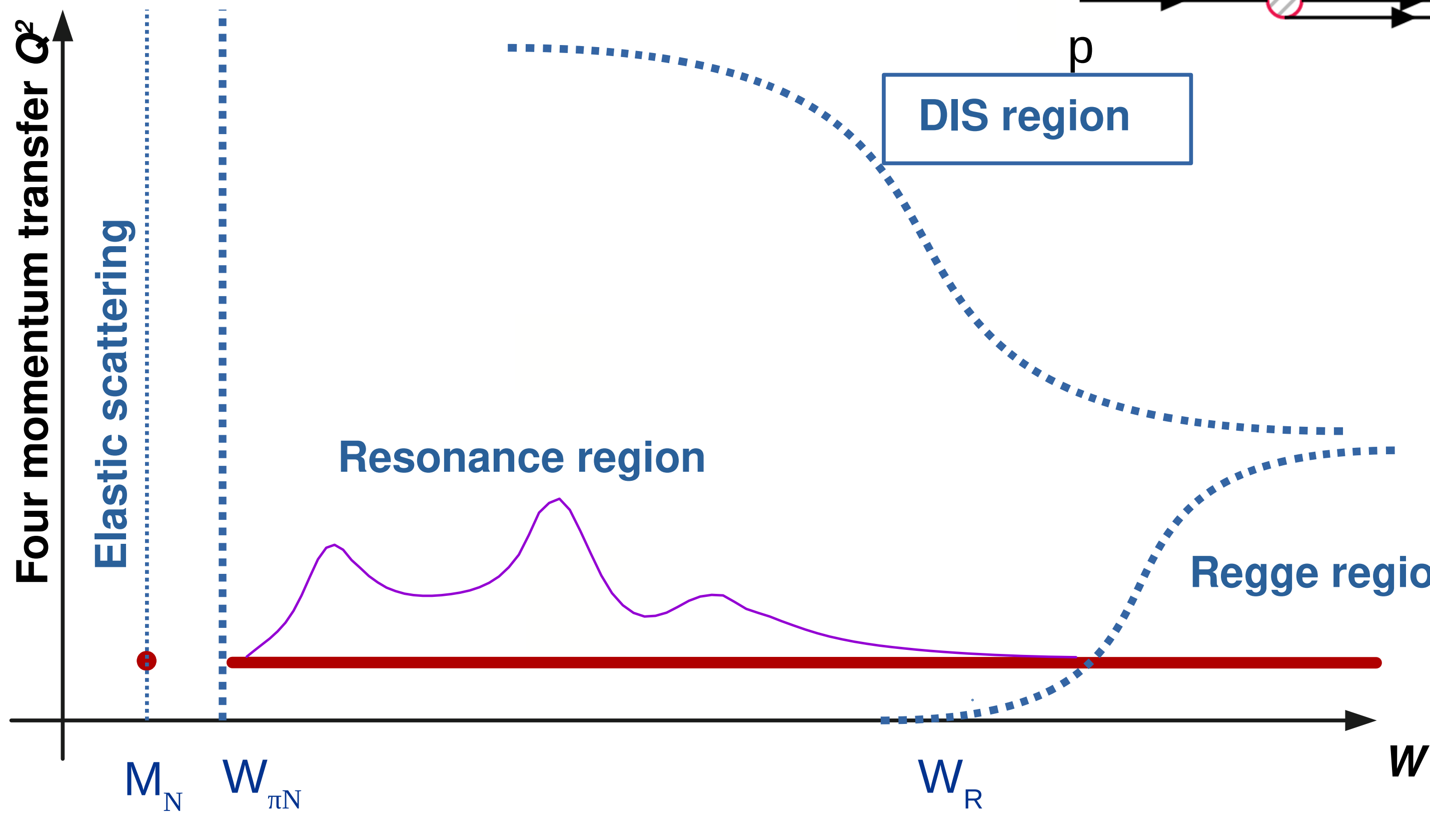
→ **Status currently unclear**



[Meyer et al. arxiv:2201.01839]

Interactions with the nucleon: DIS





$$Q^2 = -q^2 = (k - k')^2$$

$$W^2 = P^2 = (q + p)^2 = Q^2 - 2M_N\omega + M_N^2$$

Bjorken x : 0 < x < 1

$$x \equiv \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M_N(E - E')}$$

Deep inelastic scattering

$$H^{\mu\nu} = -g^{\mu\nu} W_1 + \frac{P^\mu P^\nu}{M_N^2} W_2 + i \frac{\epsilon^{\mu\nu\alpha\beta} P_\alpha Q_\beta}{2M_N^2} W_3 + \frac{Q^\mu Q^\nu}{M_N^2} W_4 + \frac{P^\mu Q^\nu + P^\nu Q^\mu}{M_N^2} W_5$$

$$W_i^{elastic}(q^2) \rightarrow W_i^{inelastic}(q^2, p \cdot q) = W_i(Q^2, x)$$

$$\frac{\mathrm{d}\sigma(E)}{\mathrm{d}Q^2} \rightarrow \frac{\mathrm{d}\sigma(E)}{\mathrm{d}Q^2 \mathrm{d}x}$$

Deep inelastic scattering

Bjorken scaling

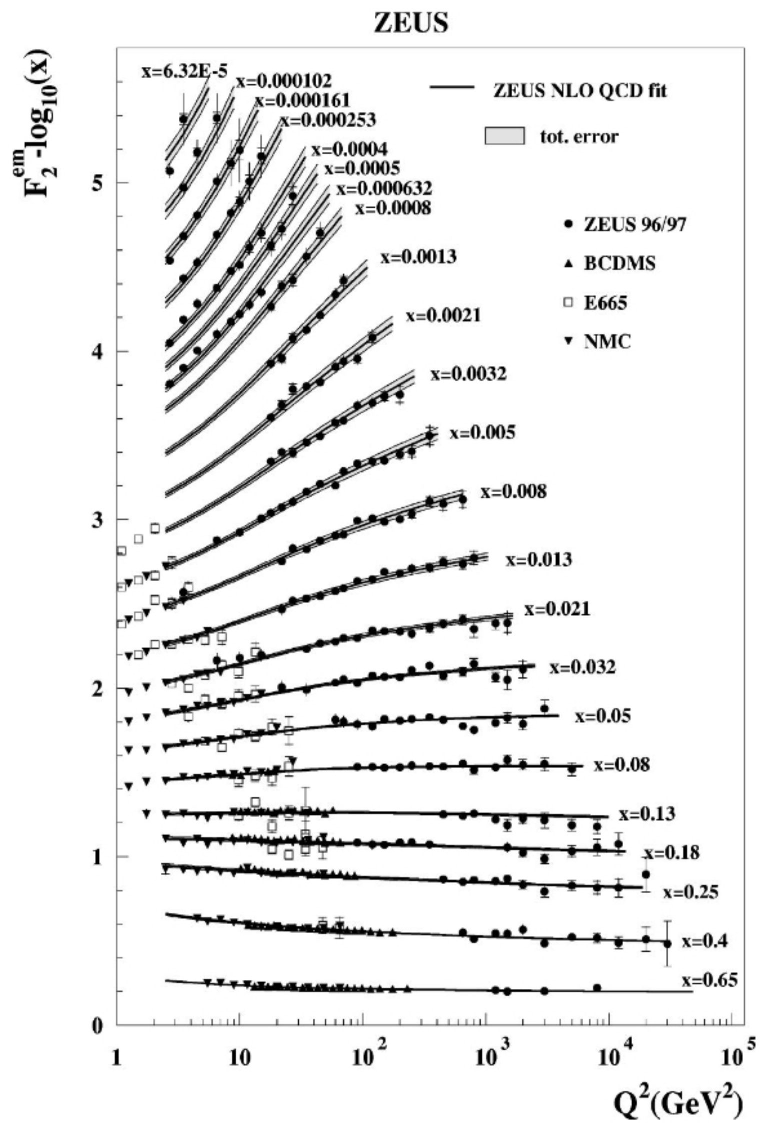
In the limit

$$\omega \to \infty, \quad Q^2 \to \infty, \quad 0 < x = \frac{Q^2}{2M_N\omega} < 1$$

Structure functions F_i become independent of Q^2

$$\omega W_{2,3}(x, Q^2) \equiv F_{2,3}(x, Q^2) \to F_{2,3}(x)$$

$$M W_1(x, Q^2) \equiv F_1(x, Q^2) \to F_1(x)$$



[Phys. Rev. D 67, 012007]

Deep inelastic scattering

Simple explanation of **Bjorken scaling** is the parton picture:
"Scattering of point-like fermions with momentum fraction x"

$$\frac{d\sigma^{\gamma}}{dx\,dQ^2} = 4\pi\left(\frac{\alpha}{Q^2}\right)^2\left[(1-y)+y^2/2\right]n_p(x)$$

$$\frac{d\sigma^{\gamma}}{dx\,dQ^2} = 4\pi\left(\frac{\alpha}{Q^2}\right)^2\left[(1-y)\frac{F_2(x,Q^2)}{x}+y^2F_1(x,Q^2)\right]n_p(x)$$

$$\rightarrow \underline{F_2 = 2xF_1} = xn_p(x)$$

Callan-Gross relation

See e.g. [E.A. Paschos, Electroweak theory]
[Thomson, Modern particle physics]

$$y = (k\cdot q)/(p\cdot k)$$

Deep inelastic scattering

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In practice

Rigorous factorization theorems
[Collins et al. Factorization of Hard Processes in QCD]

Higher order QCD + non-perturbative corrections

Relevance of and overlap with neutrino program:
[NuSTEC white paper, arXiv:1706.03621]

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Higher order QCD + non-perturbative corrections

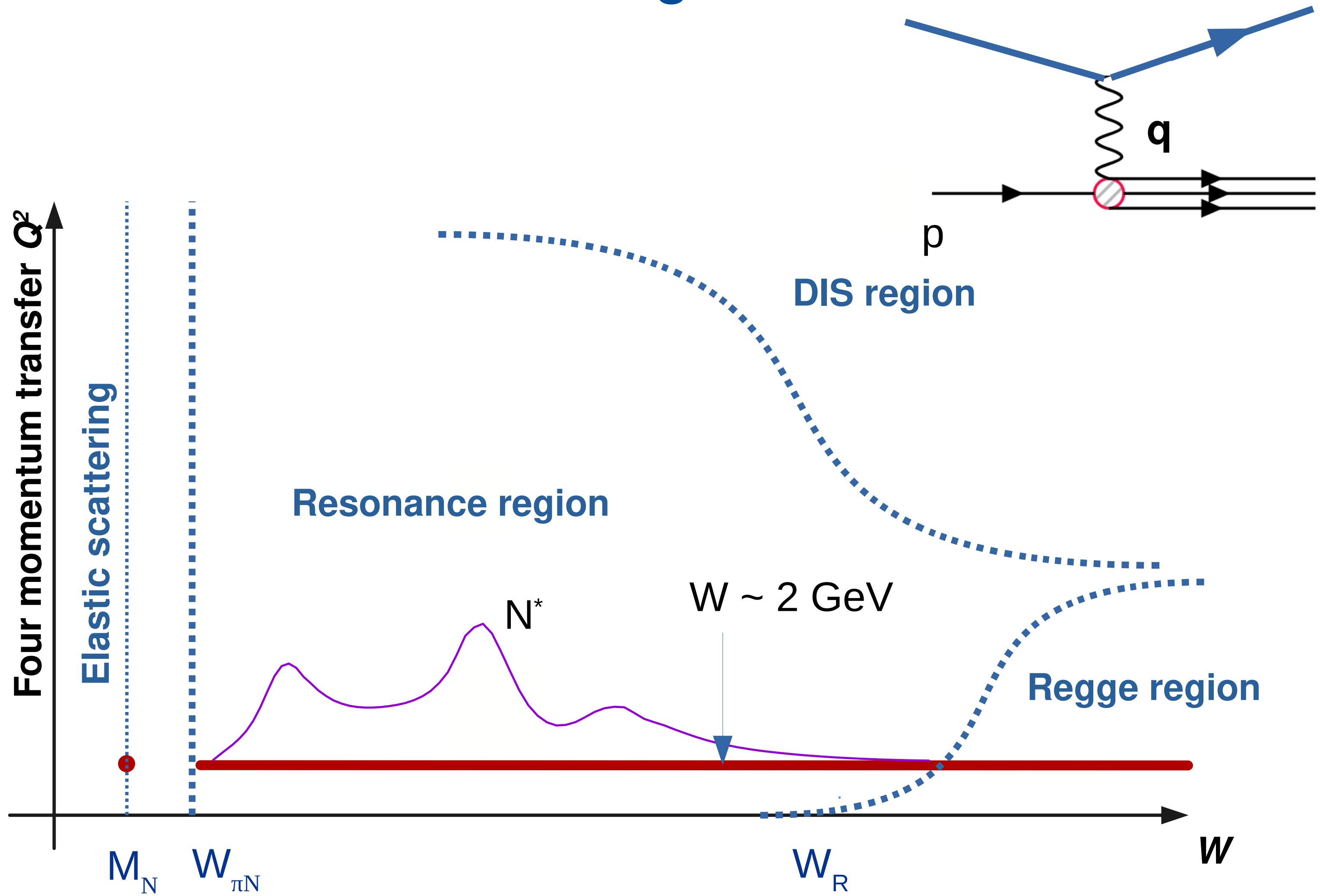
Relevance of and overlap with neutrino program:
[NuSTEC white paper, arXiv:1706.03621]

Neutrino generators use DIS at low Q^2 and W ~ 1.5 GeV

→ Often called 'Shallow inelastic scattering' (SIS)
'transition' between hadronic and parton degrees of freedom

→ Brings us to the resonance region

Interactions in the resonance region



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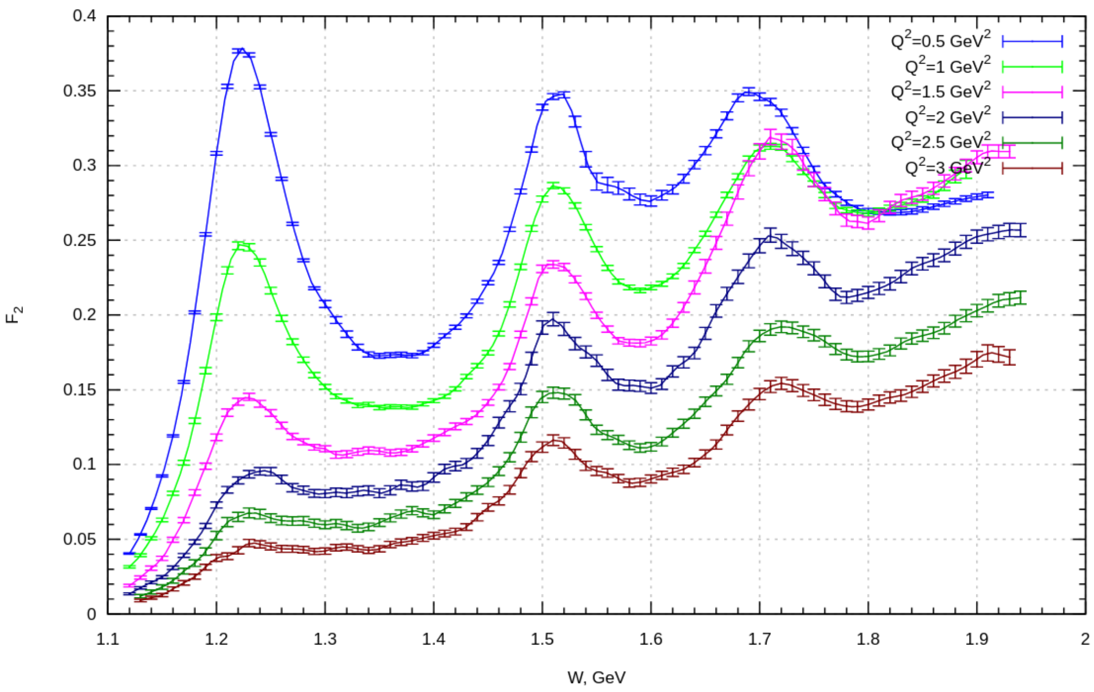
$$W^2 = P^2 = (q + p)^2 = Q^2 - 2M_N\omega + M_N^2$$

Interactions in the nucleon resonance region

- **Significant contribution to event rate in ~1 GeV experiments**



Proton F_2 structure functions (e,e') CLAS

From [clas.sinp.msu.ru/strfun/]

GENIE estimates for **SBND**:

~ 23 % of the signal has a pion

Of which **~80 %** in resonance region

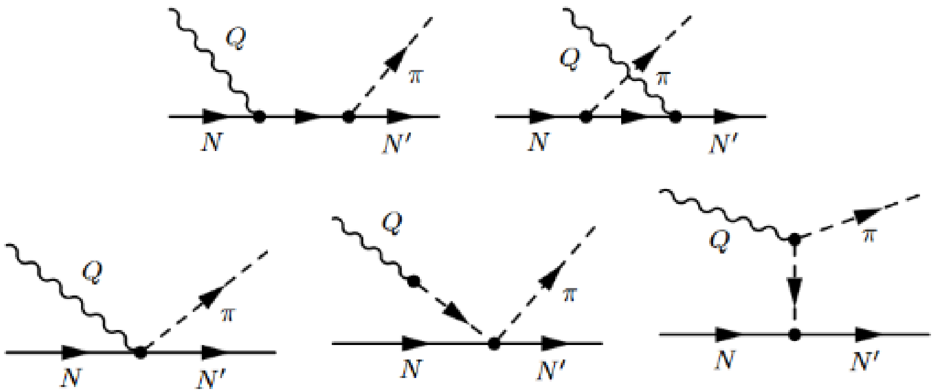
Non-perturbative, no factorization → Hadron d.o.f

Electro and photoproduction of pions

Much expertise from electromagnetic interactions with hadrons

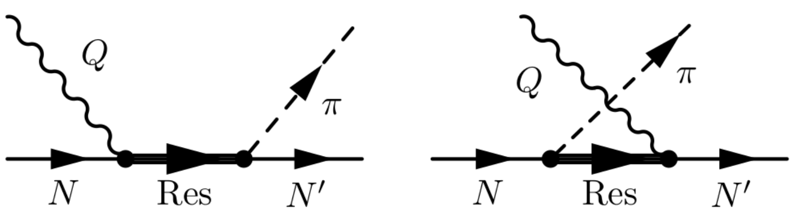
Many approaches available in the literature
- MAID07, CLAS analyses ('unitary isobar model')
- Julich-Bonn, ANL-Osaka, ... (Dynamical models)
- ...

Non-resonant



+

Baryon resonances



Electro and photoproduction

Much expertise from electromagnetic interactions with hadrons

Many approaches available in the literature
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- ...

Supported by a large amount of data!

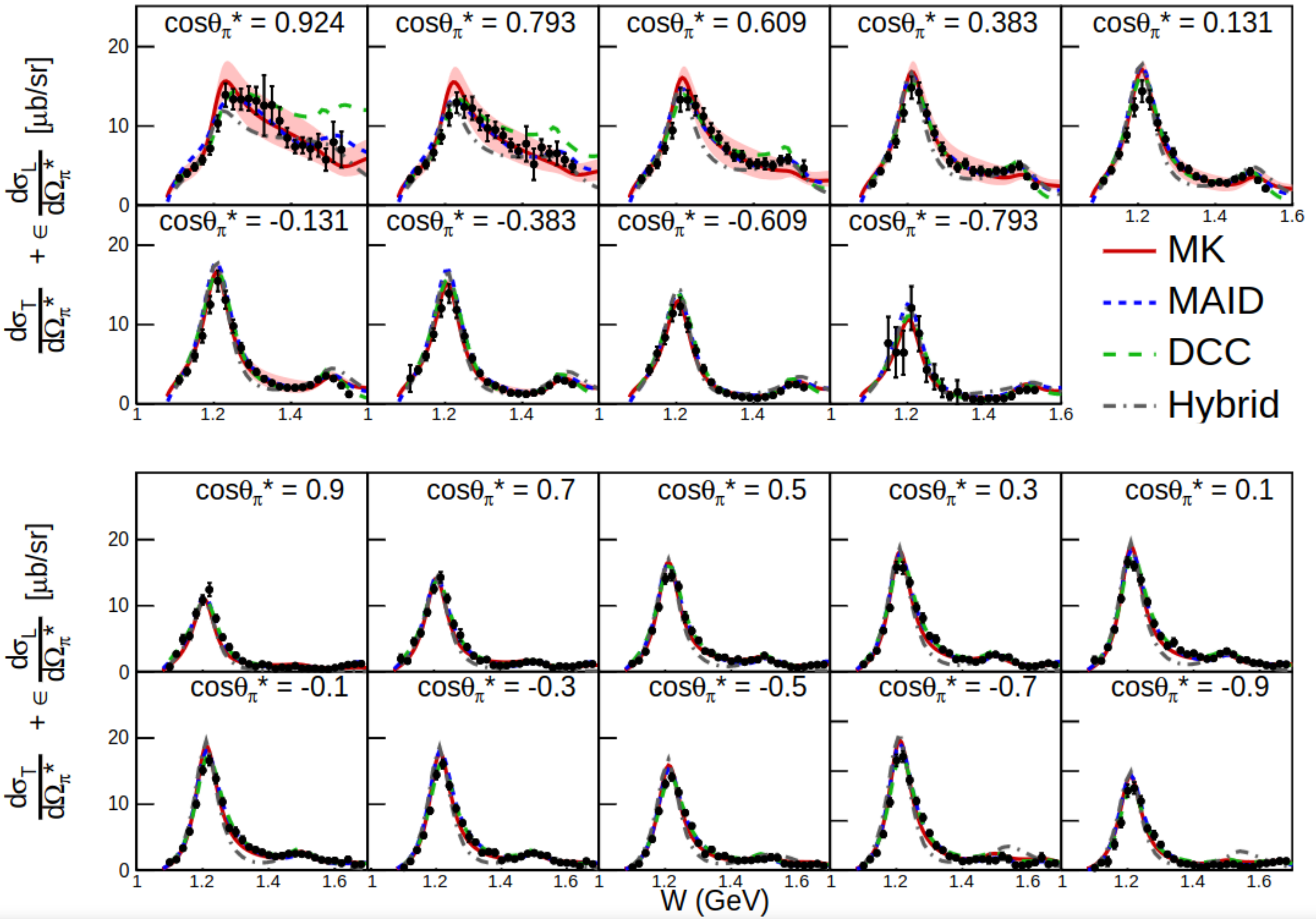
MAID07
~18 000 points for photon processes

[illegible] $n\pi^+$	[illegible] 0.4-0.65	[illegible] $d\sigma_{LT'}$
CLAS06 [46] $n\pi^+$	1110-1570 0.3-0.60	4179 $d\sigma$
CLAS06 [13] $p\pi^0$	1110-1390 3.0-6.0	8491 $d\sigma$
total $p\pi^0$, $n\pi^+$	1074-1975 0.1-6.0	68457 $d\sigma$, ...

Electron-proton data in MAID07

Electron-induced SPP: high quality proton target data

Figures from M. Kabirnezhad [arxiv:2203.15594]

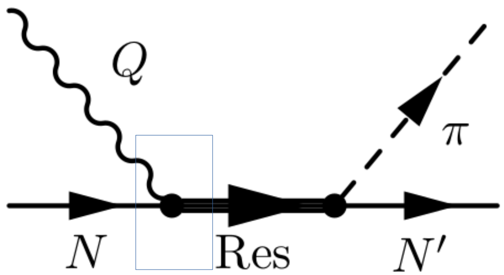


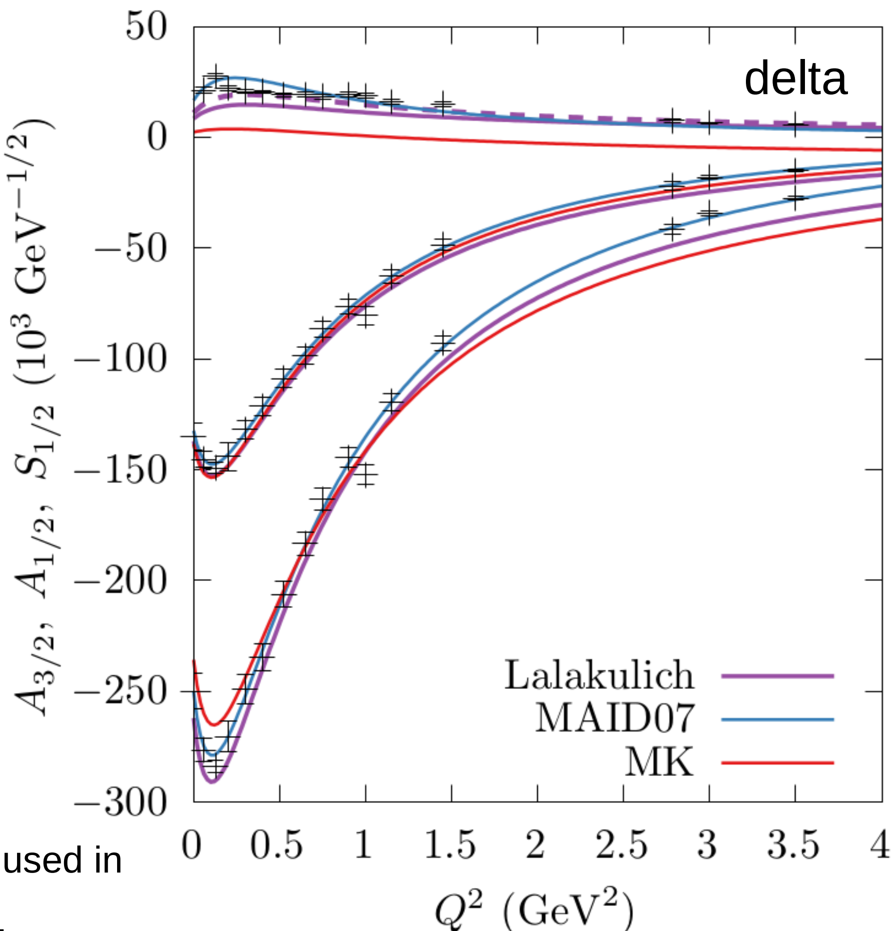
, CLAS data

Differential exclusive cross sections are abundant for large kinematic range

Form factors for resonance excitation extracted from data

Model of background + resonances can be used to determine γ*p→ R form-factors (model-dependent!)





Helicity amplitudes from CLAS and MAID07 analyses used in Neutrino pion production models :

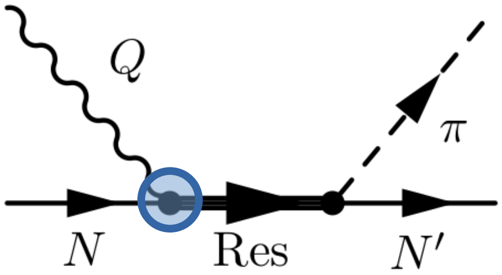
- Lalakulich et al [Phys. Rev. D74, 014009 (2006)]
- Hernandez et al. [Phys Rev D 77 053009 (2008)]
- Nikolakopoulos et al. [Phys Rev D 107, 05300 (2023)]

Axial couplings are not well constrained

The quality of neutrino-nucleon scattering data is not up to par

Spin 3/2 resonance:

$$\Gamma_A^{\beta\mu} = \frac{C_3^A}{M}\left(g^{\beta\mu}\not{Q} - Q^\beta\gamma^\mu\right) + \frac{C_4^A}{M^2}\left(g^{\beta\mu}Q\cdot k_R - Q^\beta k_R^\mu\right) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}Q^\beta Q^\mu,$$



→ 4 axial form-factors

Axial couplings are not well constrained

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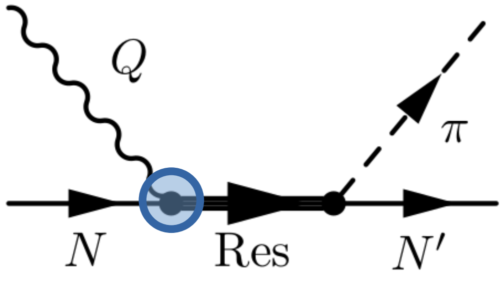

Constraints on $C_5^A(Q^2=0)$ and $C_6^A(Q^2=0)$, can be formulated from PCAC

No constraints on other form factors or Q^2 - dependence

Axial couplings are not well constrained

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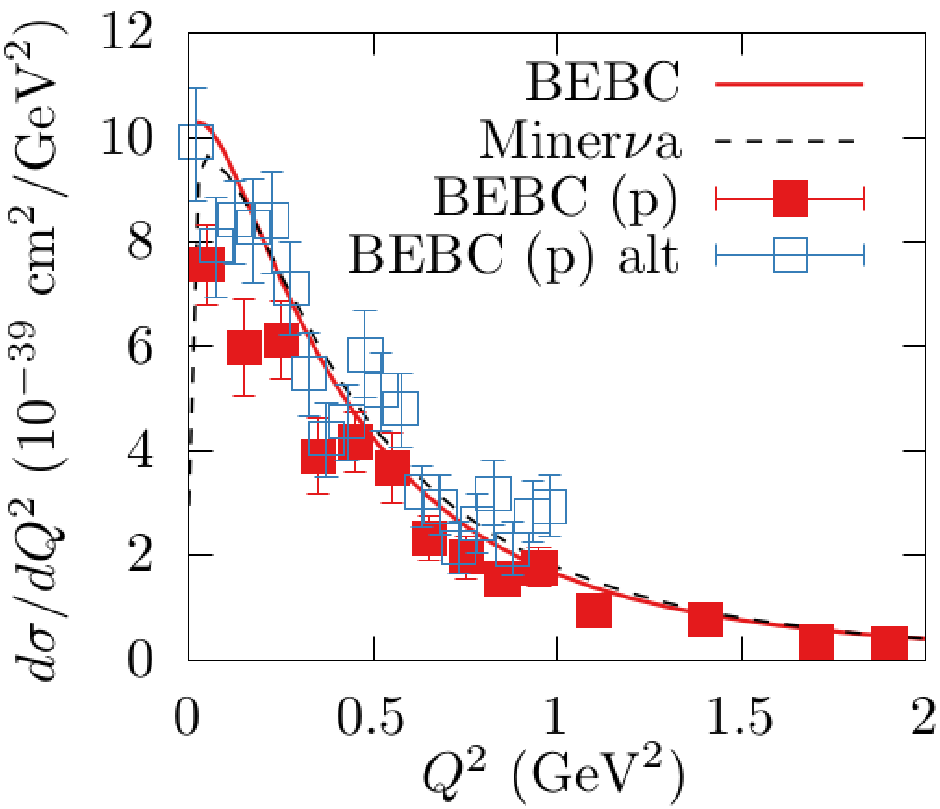
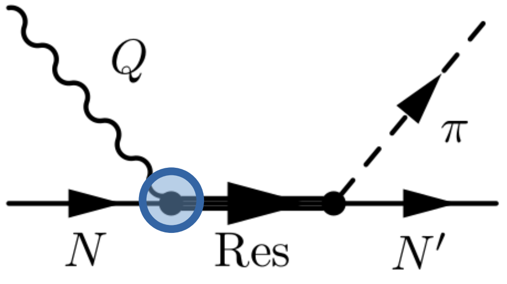




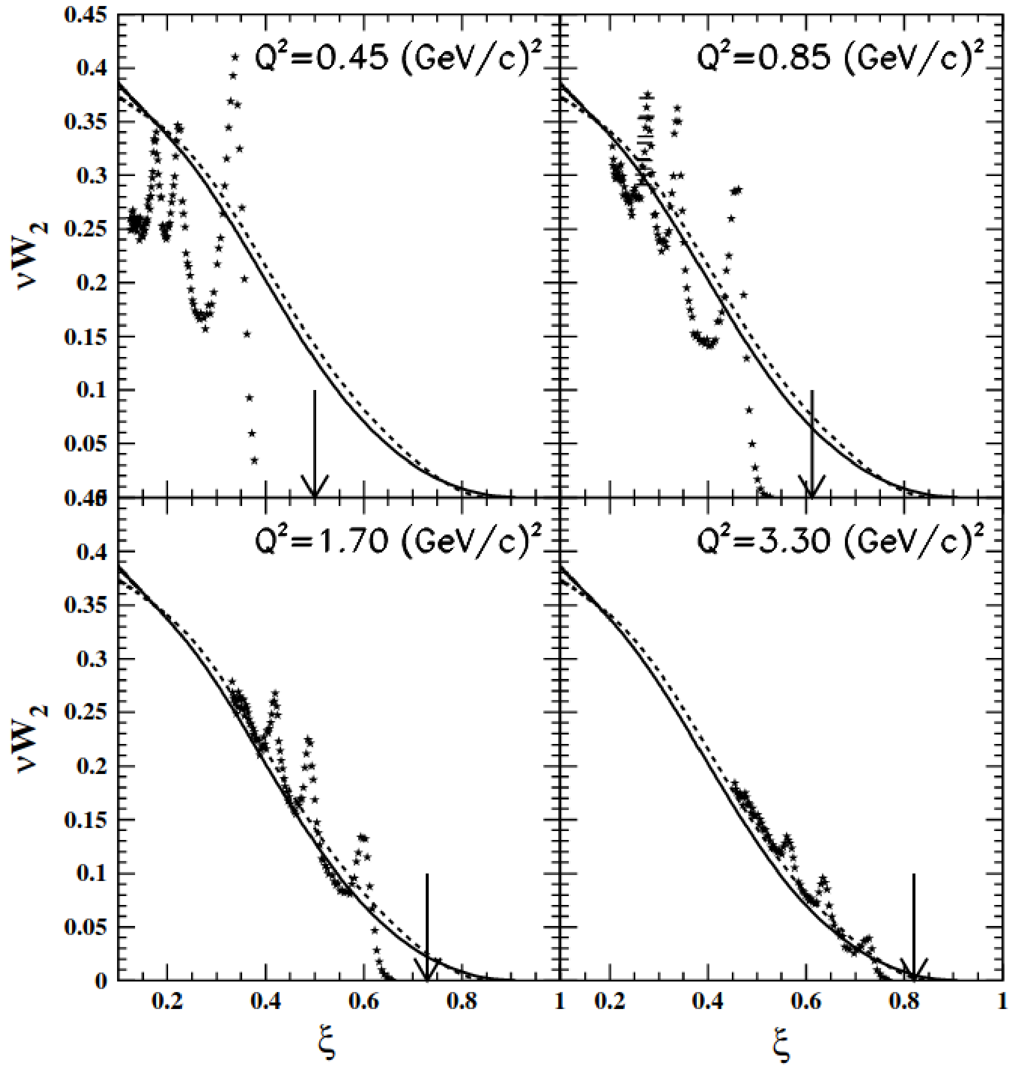
Data shows large uncertainties

Quark-hadron duality

[W. Melnitchouk et al. ,Phys. Rept. 406, 127–301 (2005), arXiv:hep-ph/0501217]

F_2 structure function
In electron scattering in RES region

Approaches and averages to
DIS structure function



[Niculescu et al. PRL85, 1186 (2000)]

Quark-hadron duality in neutrino interactions
[T. Sato EPJ:ST (2021) 230:4409-4418 (2022)]

F_2 structure function
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Approaches and averages to
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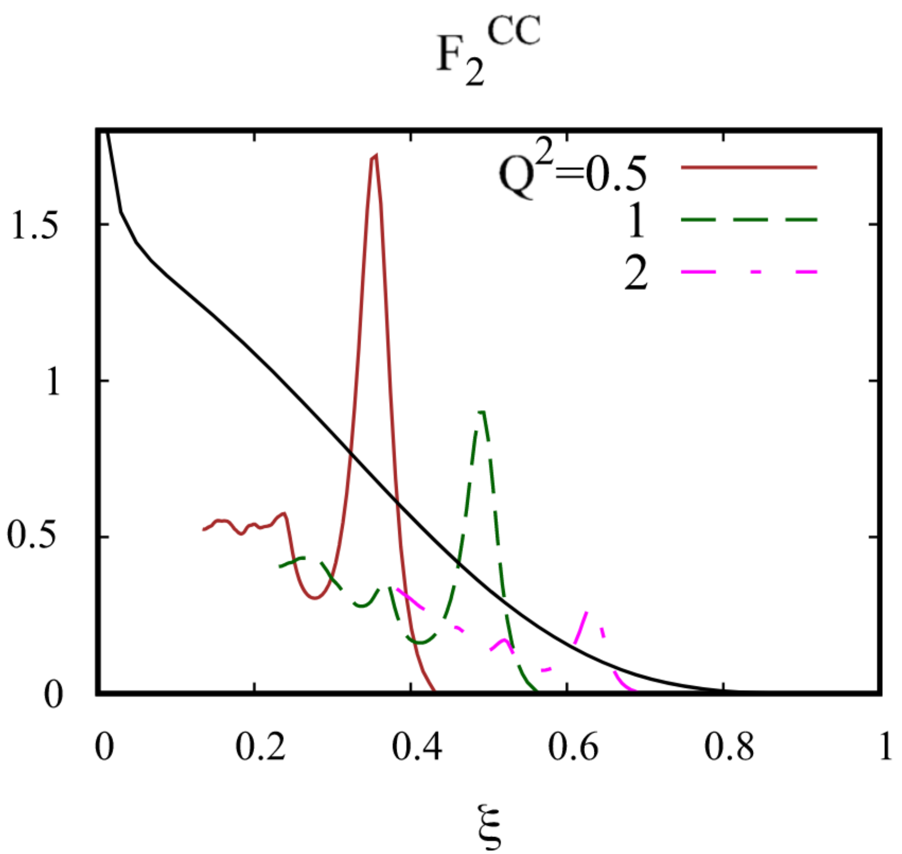
For CC ν scattering

- ANL-Osaka DCC model underestimates F_2 from DIS
- Modifying the Q^2-dependence of resonance axial form factor to that from electrons :

Improved agreement with DIS



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see also:
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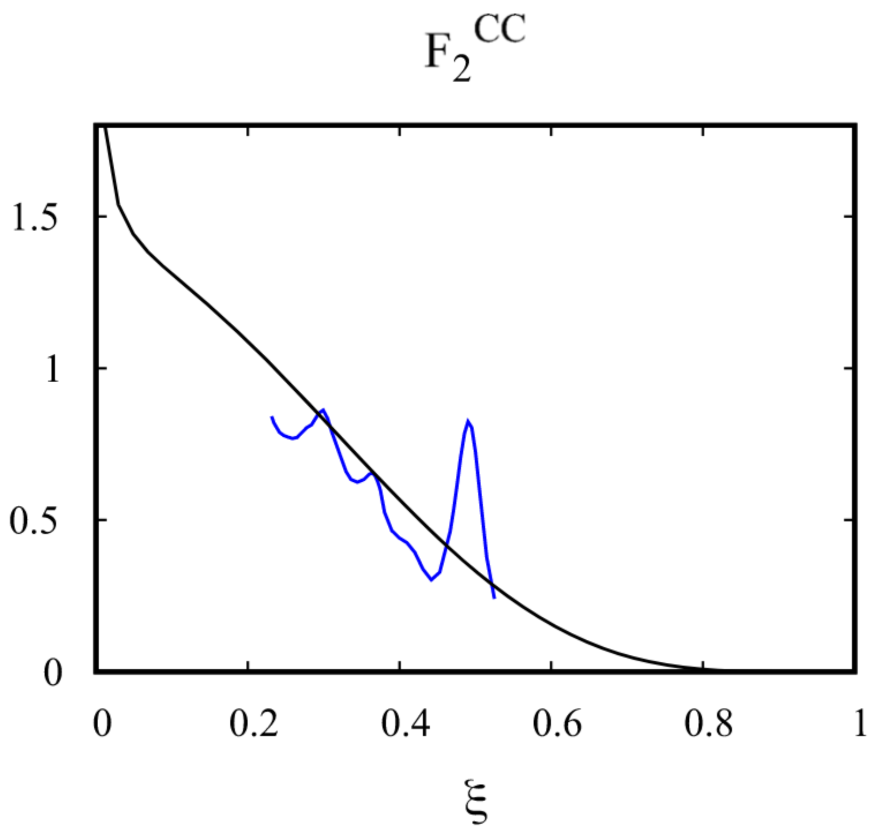

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Questions ? Answers ?