Electron scattering data and its use in constraning neutrino models

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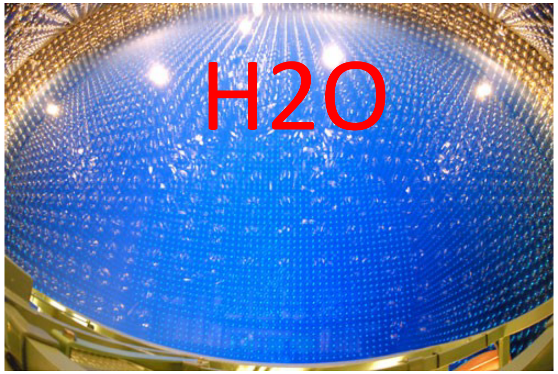
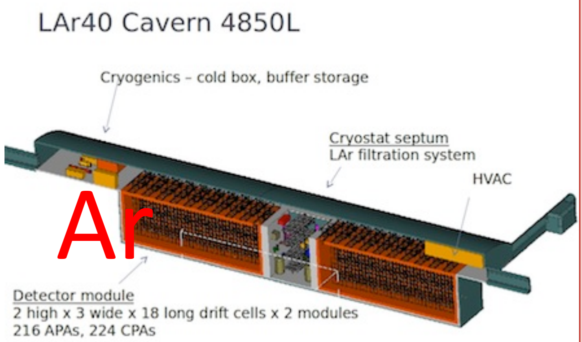
Outline

- Neutrino physics due to low amount of data need and should use electron scattering data to constrain our models of neutrino interactions.
  – Nucleon structure
  – Nuclear Structure
  – In medium modifications (PDFs, hadronization and FSI)

Nuclear cross sections and IA

- To boost statistics, **neutrino experiments use nuclear targets**, typically





- Neutrino-nucleus cross sections are typically computed using the *Impulse Approximation*
- *IA: Nuclear cross sections (νA) described by incoherent scattering off quasi-free nucleons*
- Descriptions of free nucleon cross section important! → Nucleon structure

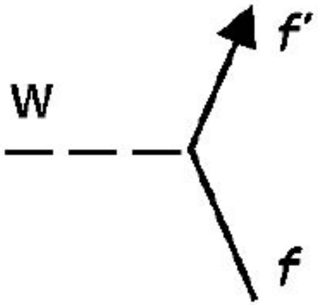
Nucleon structure measurements

- Elastic nucleon form factors measurements (→ neutrino QE)
- Structure function measurements (→ neutrino DIS)
- Study of resonance excitation (→ transition from QE to DIS)

Two types of interactions

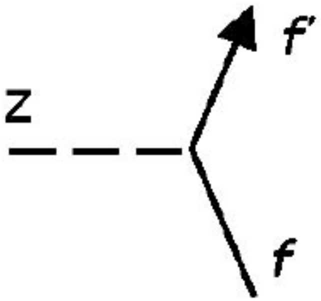
- Neutrino interact only via exchange of W and Z bosons

Charge Current



$$J_W^\mu = \bar{u}_{f'}\tau_+\gamma^\mu(1-\gamma^5)u_f$$

Neutral Current



$$J_Z^\mu = \bar{u}_f\gamma^\mu(g_V^f - g_A^f\gamma^5)u_f$$

$$\boxed{\begin{aligned} g_V^f &= T_3^f - 2Q^f\sin^2\theta_W \\ g_A^f &= T_3^f \end{aligned}}$$

Electron scattering data

- Electron scattering data provides information about the vector part of the interaction.
- All weak processes can be parametrized in term of vector and axial structure functions.
- They describe all kinematics distributions of the final state lepton, and are applicable at all energies for electron scattering as well as neutrino and antineutrinos

Electron scattering data

- Theoretical models must describe the vector parts of both longitudinal and transverse structure function of electron scattering measurements for the appropriate reactions at the level of a few percent.

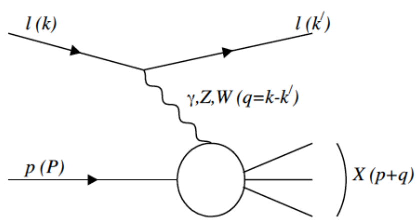
- Neutrino scattering data need to be used to constrain the axial structure functions

Neutrino cross sections

- All neutrino oscillation experiments require good knowledge of energy dependence of neutrino cross sections and kinematic distributions of the final state for the reaction:

$$\nu + nucleon \rightarrow \mu + X$$

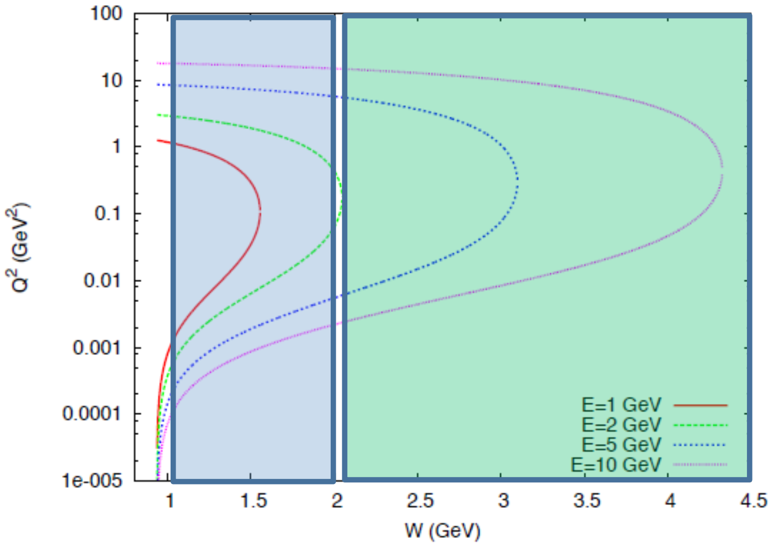
- We need to know neutrino cross section at low energies and on nuclear targets.



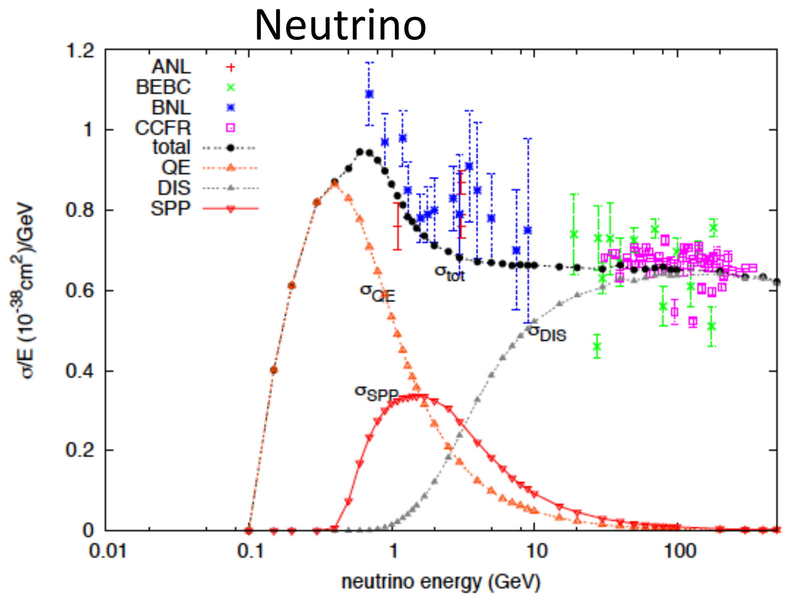
$W^2 = (p+q)^2 = M^2 + 2M\nu - Q^2$
ν = energy transfer to target
$y = \nu/E$=inelasticity
Q^2=square of the four momentum transfer
$x=Q^2/2M\nu$=fraction of momentum carried by quark)
$x=1$ for quasielastic scattering

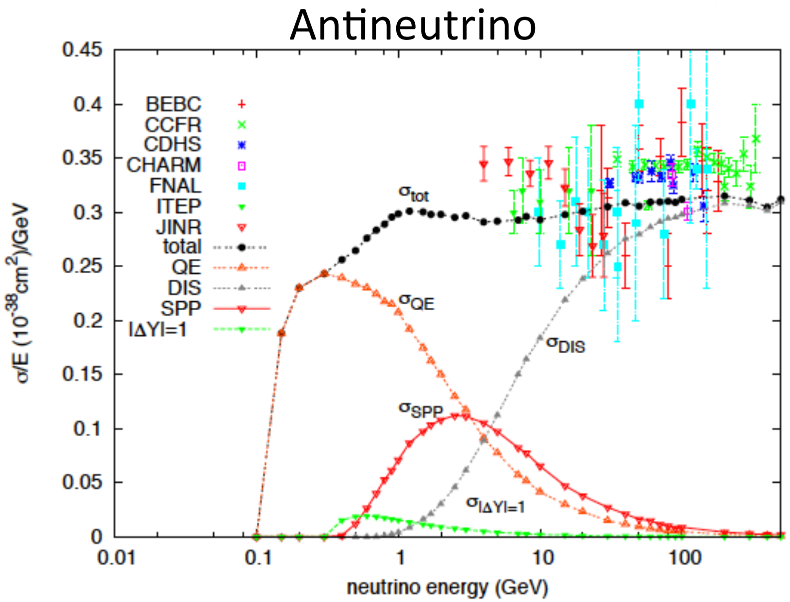
Neutrino cross section

- In electron and neutrino scattering we categorize cross section by the mass of the final state hadronic state: W
  - W= 0.983 GeV: (quasi-)elastic scattering
  - 1.1 < W < 1.9 GeV: inelastic scattering in the resonance region
  - W > 1.9 GeV: Inelastic scattering in the continuum



Neutrino cross section

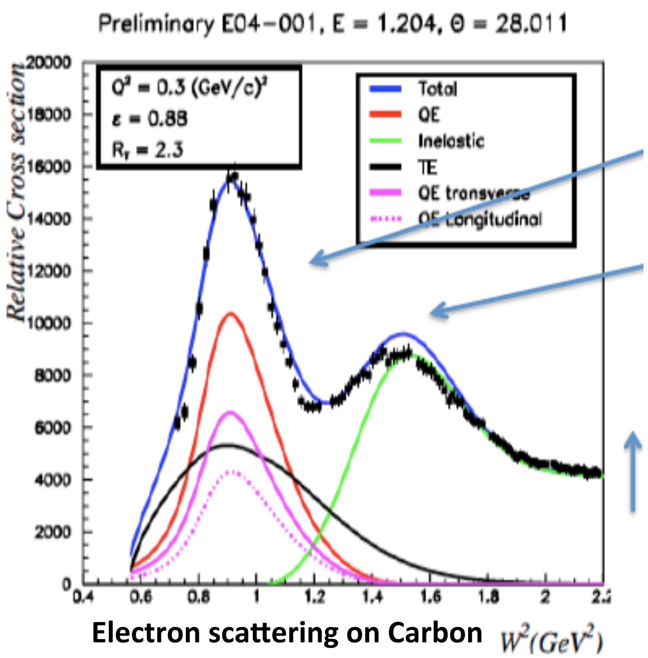




- All data points are for the ν_μ

Electron scattering

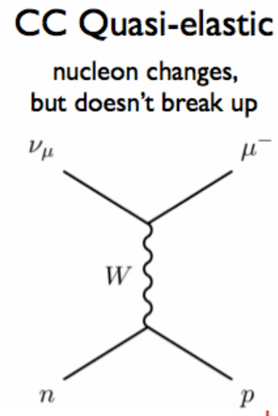
- The term quasielastic scattering means different things to the electron scattering community and to the neutrino scattering community.



Electron scattering on Carbon

- Electron scattering at x=1. W=M On Free nucleons => elastic scattering = Delta Function
- On nucleons bound in Nuclei -> Quasielastic scattering (quasi free)
- Δ resonance (1234)
- In neutrino physics QE scattering means
  - Neutrino charged current at X=1, W=M
  - On free nucleons → Quasielastic (neutrino → muon)
  - On nucleons bound in nuclei → quasielastic scattering (quasi free, same as for electron)

Quasi-elastic reaction and axial mass



$$\Gamma_\mu = \underbrace{\gamma_\mu F_1(Q^2) + i\sigma_{\mu\nu} q^\nu \frac{F_2(Q^2)}{2M}}_{V} + \underbrace{\gamma_\mu \gamma_5 F_A(Q^2) + \gamma_5 q_\mu \frac{F_P(Q^2)}{M}}_{-A}$$

CVC – for F_1 and F_2 we can use electromagnetic data

PCAC – F_A and F_P are not independent

$$F_P(Q^2) = \frac{2M^2 F_A(Q^2)}{m_\pi^{\ 2} + Q^2}$$

We need the axial form-factor; the standard dipole form

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^{\ 2}}\right)^2}$$

g_A =1.267 from β decay;
M_A a free parameter (the only one)

The value of axial mass is obtained from experimental data.

Quasi-elastic reaction

(-) for neutrinos (+) for antineutrinos

$$\frac{d\sigma^{\nu,\bar{\nu}}}{d|q^2|} = \frac{M^2 G^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + C(q^2)\frac{(s-u)^2}{M^4}\right]$$

$$\begin{aligned}
A &= \frac{(m^2-q^2)}{4M^2}\left[\left(4-\frac{q^2}{M^2}\right)F_A^2 - \left(4+\frac{q^2}{M^2}\right)(F_V^1)^2 - \frac{q^2}{M^2}(\xi F_V^2)^2\left(1+\frac{q^2}{4M^2}\right)\right.\\
&\left. - \frac{4q^2 F_V^1 \xi F_V^2}{M^2} - \frac{m^2}{M^2}\left((F_V^1+\xi F_V^2)^2 + (F_A + 2F_p)^2 + \left(\frac{q^2}{M^2}-4\right)F_p^2\right)\right],\\
B &= -\frac{q^2}{M^2}F_A(F_V^1+\xi F_V^2),\\
C &= \frac{1}{4}\left[F_A^2 + (F_V^1)^2 - \frac{q^2}{M^2}\left(\frac{\xi F_V^2}{2}\right)^2\right],
\end{aligned}$$

Elastic proton and neutron form factors
Determined from eN (CVC)

$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2}G_M^V(q^2)}{1-\frac{q^2}{4M^2}}$$

$$\xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1-\frac{q^2}{4M^2}}$$

$$G_E^V(q^2) = G_E^p(q^2) - G_E^n(q^2)$$

$$G_M^V(q^2) = G_M^p(q^2) - G_M^n(q^2)$$

- Electron nucleon and muon-nucleon scattering
  - Structure function description

$$\frac{d^2\sigma}{d\Omega dE'}(E_0, E', \theta) = \frac{4\alpha^2 E'^2}{Q^4}\cos^2(\theta/2)$$

$$\times \left[\mathcal{F}_2(x, Q^2)/\nu + 2\tan^2(\theta/2)\mathcal{F}_1(x, Q^2)/M\right]$$

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(x, Q^2) + \epsilon\sigma_L(x, Q^2)\right]$$

  - Transverse and longitudinal description

$$\Gamma = \frac{\alpha K E'}{4\pi^2 Q^2 E_0}\left(\frac{2}{1-\epsilon}\right)$$

$$\epsilon = \left[1 + 2(1 + \frac{Q^2}{4M^2x^2})tan^2\frac{\theta}{2}\right]^{-1}$$

$$K = \frac{Q^2(1-x)}{2Mx}$$

$$\mathcal{R}(x, Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{\mathcal{F}_2}{2x\mathcal{F}_1}(1 + \frac{4M^2x^2}{Q^2}) - 1 = \frac{\mathcal{F}_L}{2x\mathcal{F}_1}$$

- Terms of the structure functions

$F_1 = MW_1(x,Q^2)$ $\quad F_2 = \nu W_2(x,Q^2)$ $\quad F_3 = \nu W_3(x,Q^2)$

- Relation between the two descriptions

$$\mathcal{F}_1 = \frac{MK}{4\pi^2\alpha}\sigma_T,$$

$$\mathcal{F}_2 = \frac{\nu K(\sigma_L + \sigma_T)}{4\pi^2\alpha(1 + \frac{Q^2}{4M^2x^2})}$$

- Since R is small what is general used is a mixed description in terms of F_2, R, F_3

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi}\left(\left[1 - y\left(1 + \frac{Mx}{2E_\nu}\right) + \frac{y^2}{2}\left(\frac{1 + (\frac{2Mx}{Q})^2}{1+R}\right)\right]\mathcal{F}_2 \pm \left[y - \frac{y^2}{2}\right]x\mathcal{F}_3\right)$$

- Relations between electric and magnetic form factors and structure functions for elastic electron scattering

$$W_{1p}^{elastic} = \delta(\nu - \frac{Q^2}{2M})\tau|G_{M_p}(Q^2)|^2$$

$$W_{1n}^{elastic} = \delta(\nu - \frac{Q^2}{2M})\tau|G_{M_n}(Q^2)|^2$$

- And

$$W_{2p}^{elastic} = \delta(\nu - \frac{Q^2}{2M})\frac{[G_{E_p}(Q^2)]^2 + \tau[G_{M_p}(Q^2)]^2}{1+\tau}$$

$$W_{2n}^{elastic} = \delta(\nu - \frac{Q^2}{2M})\frac{[G_{E_n}(Q^2)]^2 + \tau[G_{M_n}(Q^2)]^2}{1+\tau}$$

$$R_{p,n}^{elastic}(x=1,Q^2) = \frac{\sigma_L^{elastic}}{\sigma_T^{elastic}} = \frac{4M^2}{Q^2}\left(\frac{G_E^2}{G_M^2}\right)$$

- $G_M{}^p$ and $G_M{}^n$ contribute to the transverse virtual photon-absorption cross section and $G_E{}^p$ and $G_E{}^n$ contribute to the longitudinal cross section

- FOR elastic/QE scattering
- **Transverse cross section is on magnetic moment distribution FF**
- **Longitudinal cross section is on electric charge distribution FF**

- For neutrino QE scattering: vector form factors are known from electron scattering
- But we also have axial form factors

$$W_{1\text{-Qelastic}}^{\nu\text{-vector}} = \delta\left(\nu - \frac{Q^2}{2M}\right)\tau|\mathcal{G}_M^V(Q^2)|^2,$$

$$W_{1\text{-Qelastic}}^{\nu\text{-axial}} = \delta\left(\nu - \frac{Q^2}{2M}\right)(1+\tau)|\mathcal{F}_A(Q^2)|^2,$$

$$W_{2\text{-Qelastic}}^{\nu\text{-vector}} = \delta\left(\nu - \frac{Q^2}{2M}\right)|\mathcal{F}_V(Q^2)|^2,$$

$$W_{2\text{-Qelastic}}^{\nu\text{-axial}} = \delta\left(\nu - \frac{Q^2}{2M}\right)|\mathcal{F}_A(Q^2)|^2,$$

$$W_{3\text{-Qelastic}}^{\nu} = \delta\left(\nu - \frac{Q^2}{2M}\right)|2\mathcal{G}_M^V(Q^2)\mathcal{F}_A(Q^2)|$$

- Where

$$\mathcal{G}_E^V(Q^2) = G_E^p(Q^2) - G_E^n(Q^2),$$
$$\mathcal{G}_M^V(Q^2) = G_M^p(Q^2) - G_M^n(Q^2).$$

- and

$$|\mathcal{F}_V(Q^2)|^2 = \frac{[\mathcal{G}_E^V(Q^2)]^2 + \tau[\mathcal{G}_M^V(Q^2)]^2}{1+\tau}.$$

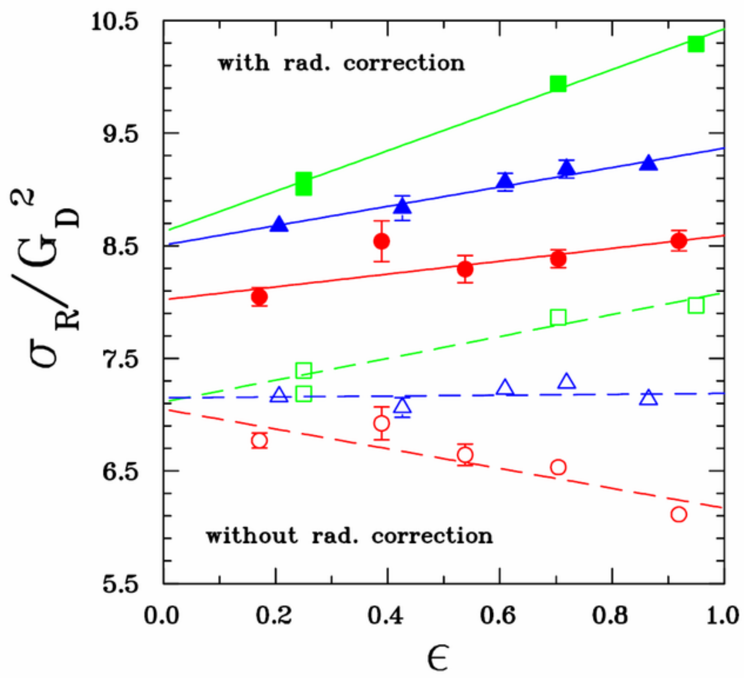
$$\sigma_T^{\text{vector}} \propto \tau|\mathcal{G}_M^V(Q^2)|^2; \qquad \sigma_T^{\text{axial}} \propto (1+\tau)|\mathcal{F}_A(Q^2)|^2$$
$$\sigma_L^{\text{vector}} \propto (\mathcal{G}_E^V(Q^2))^2; \qquad \sigma_L^{\text{axial}} = 0.$$

Nucleon form factor measurements

- Rosenbluth separation

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2 E_e^{'}\cos^2\frac{\theta_e}{2}}{4E_e^3\sin^4\frac{\theta_e}{2}}\left[G_e^2+\frac{\tau}{\varepsilon}G_m^2\right]\left(\frac{1}{1+\tau}\right)$$

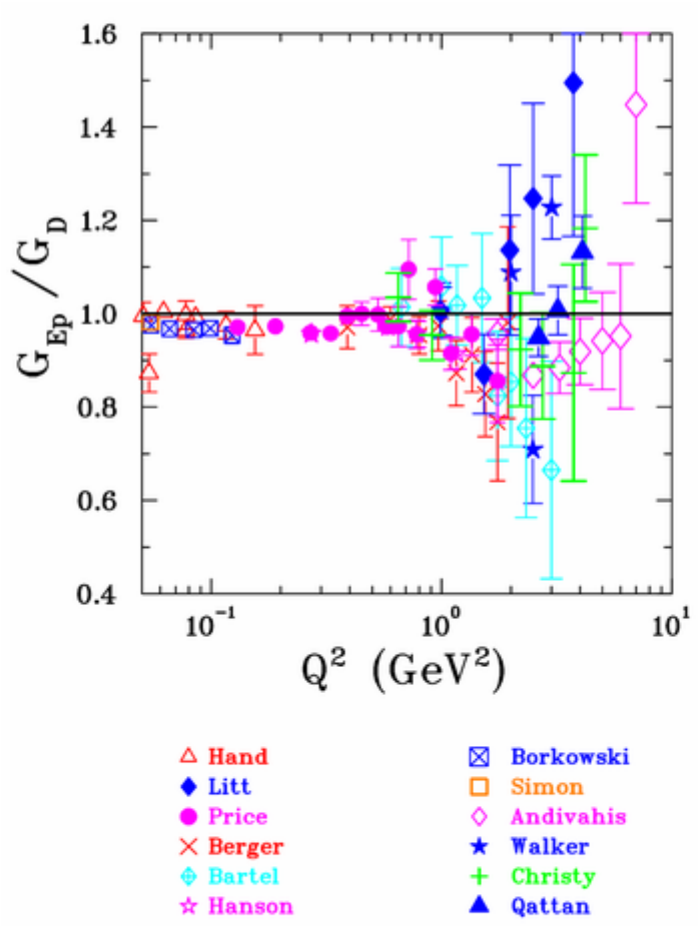
$\sigma_R=\varepsilon/\tau(G_E^2+G_M^2)$

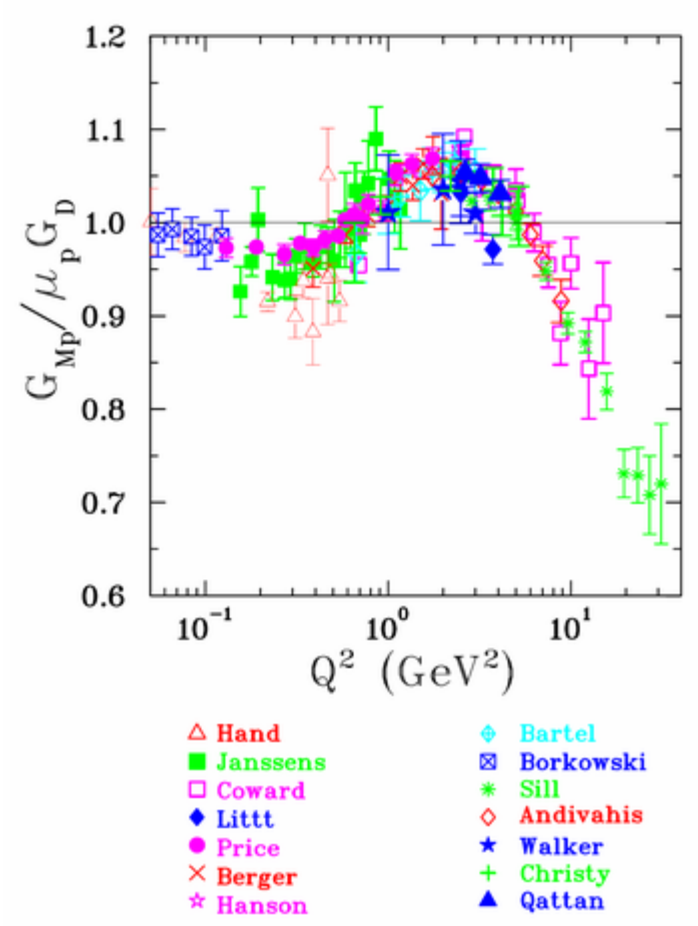


- Fix Q2, measure cross section as function of polarization ε
- Linear fit: Slope and offset give elastic form factors

- Problems:
  - Cross section measurement limited by systematics
  - Polarization-dependent modification due to >1 photon contributions
  - G_M term dominates at large Q^2 (poor determination of G_E)

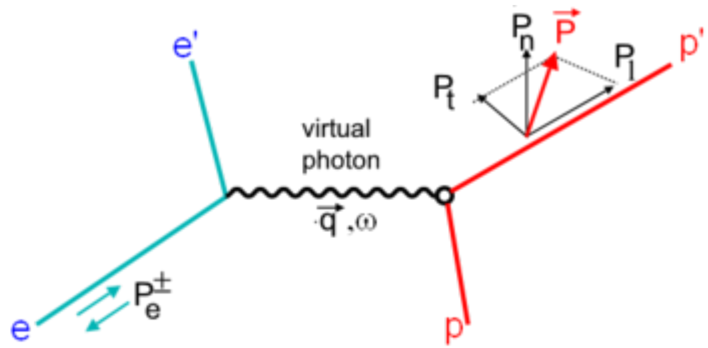
Rosenbluth separation – form factors

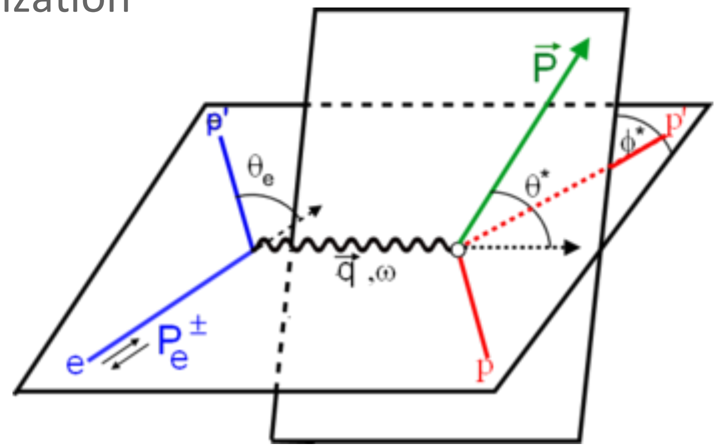




Nucleon form factor measurements

- Polarization measurements
  - First proposed by A.I.Akhiezer et al, Sov.Phys.JETP 6, 588 (1958)
  - First used at MIT-Bates by Milbrath et al., Phys.Rev.Lett.80, 452 (1998)
- A polarized electron will transfer its polarization to the recoil nucleon
  - Measuring the recoil nucleon polarization





$$\frac{G_e}{G_m} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

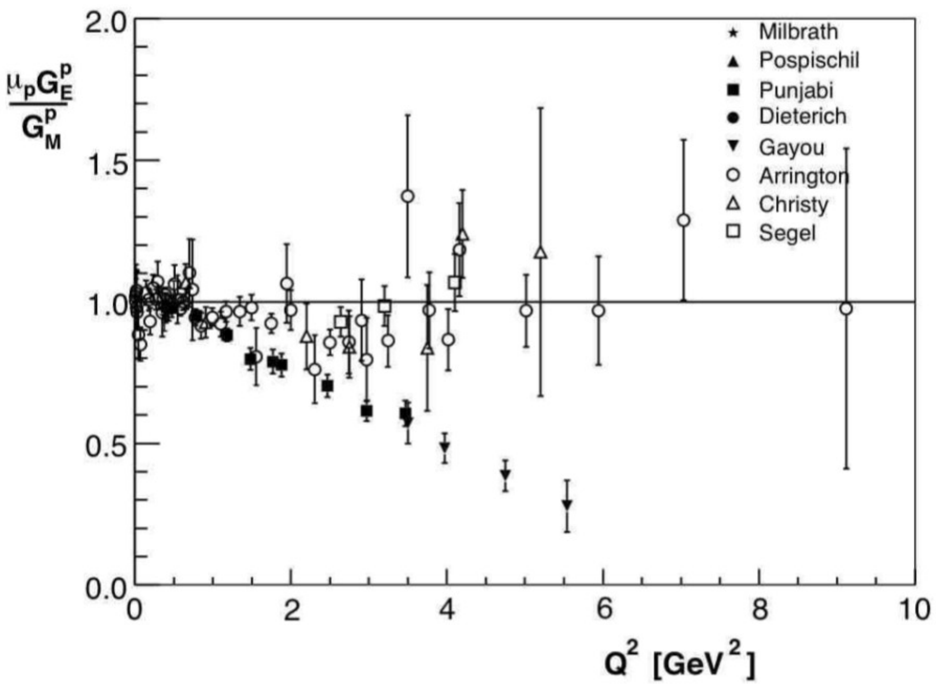
Recent experiments at JLAB (Hall A) → $Q^2 <$ ~6 GeV^2

•M.K.Jones et al., Phys.Rev.Lett.84, 1398 (2000)

•O.Gayou et.al., Phys.Rev.Lett.88,092301 (2002)

- Equivalently: measure the polarized electron asymmetry in scattering off polarized targets

`Rosenbluth' & `Polarization' Results: GEp/GMp



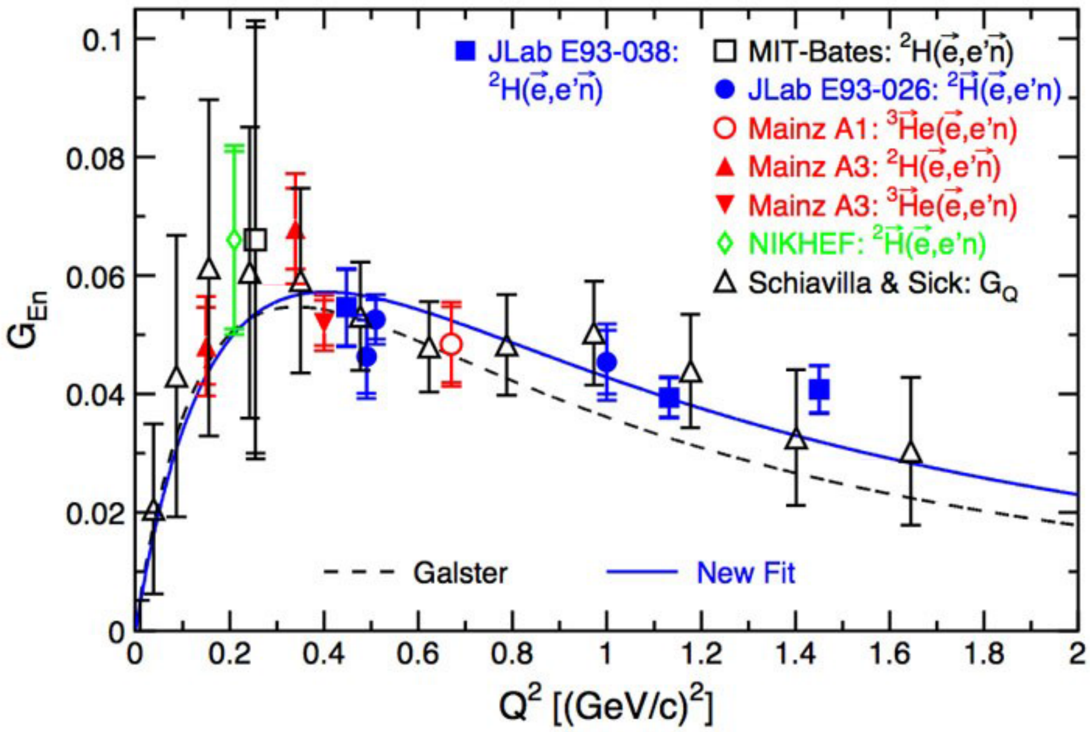
Form factor scaling ?

Hyde-Wright and De Jagger, Ann.Rev.Nucl.Part.Sci 2004 54:217

- Polarization measurements (closed markers)
- Rosenbluth measurements
- Include:
  - Arrington et al re-analysis of SLAC data Phys.Rev.C 68: 034325 (2003)
  - Christy et al re-analysis of JLAB data Phys.Rev.C70:015206 (2004)
  - Results from a new JLAB experiment @ Hall A Qattan et al, PRL94:142301(2005)
- Methods self-consistent
  - but disagree with each-other
- Polarization results seen more reliable
  - 2 photon contributions at Rosenbluth?

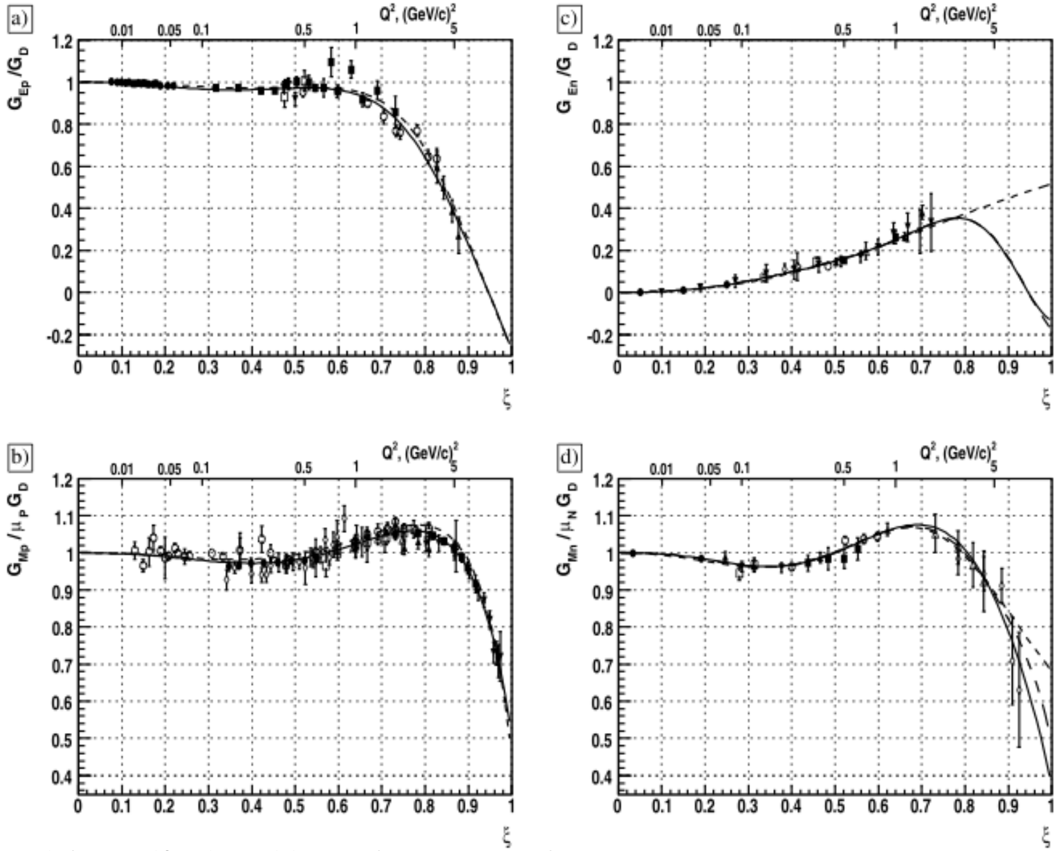
G_Ep decreases with Q^2 faster than dipole form factors

Recent Results: G_{En}



H. Zhu et al., PRL 87 (2001) 081801
R. Madey et al., PRL 91 (2003) 122002
G. Warren et al., PRL 92 (2004) 042301
B. Plaster et al., PRC 73 (2006) 025205

New form factor parametrizations



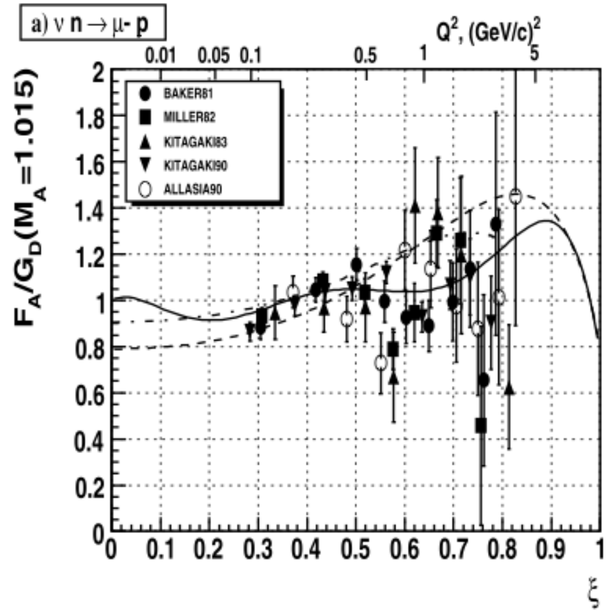
Bodek, Bradford, Budd, Avvakumov, Eur.Phys.J.C53:349-354,2008

$$G\left(Q^2\right) = \frac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n} b_k \tau^k}, \qquad \tau = \frac{Q^2}{4M^2},$$

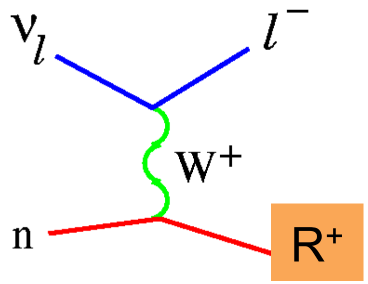
Improving accuracy of νN CCQE

- BBBA07, Eur.Phys.J.C53:349-354,2008.
- BBA05, Nucl.Phys.B. 159 (2006)
- J.J.Kelly, PRC 70, 068202 (2004

Re-extraction of axial form factor



Resonant region W<1.9 GeV



- Charge Current

$$\begin{aligned}
\nu + p &\rightarrow \mu^- + (\Delta^{++} \hookrightarrow p + \pi^+) \\
\nu + n &\rightarrow \mu^- + (\Delta^{+} \hookrightarrow p + \pi^0) \\
\nu + n &\rightarrow \mu^- + (\Delta^{+} \hookrightarrow n + \pi^+)
\end{aligned}$$

$$\begin{aligned}
\bar{\nu} + p &\rightarrow \mu^+ + (\Delta^{0} \hookrightarrow n + \pi^0) \\
\bar{\nu} + p &\rightarrow \mu^+ + (\Delta^{0} \hookrightarrow p + \pi^-) \\
\bar{\nu} + n &\rightarrow \mu^+ + (\Delta^{-} \hookrightarrow n + \pi^-)
\end{aligned}$$

- Neutral Current

$$\begin{aligned}
\nu(\bar{\nu}) + p &\rightarrow \nu(\bar{\nu}) + (\Delta^{+} \hookrightarrow p + \pi^0) \\
\nu(\bar{\nu}) + p &\rightarrow \nu(\bar{\nu}) + (\Delta^{+} \hookrightarrow n + \pi^+) \\
\nu(\bar{\nu}) + n &\rightarrow \nu(\bar{\nu}) + (\Delta^{0} \hookrightarrow p + \pi^-) \\
\nu(\bar{\nu}) + n &\rightarrow \nu(\bar{\nu}) + (\Delta^{0} \hookrightarrow n + \pi^0)
\end{aligned}$$

Cross section

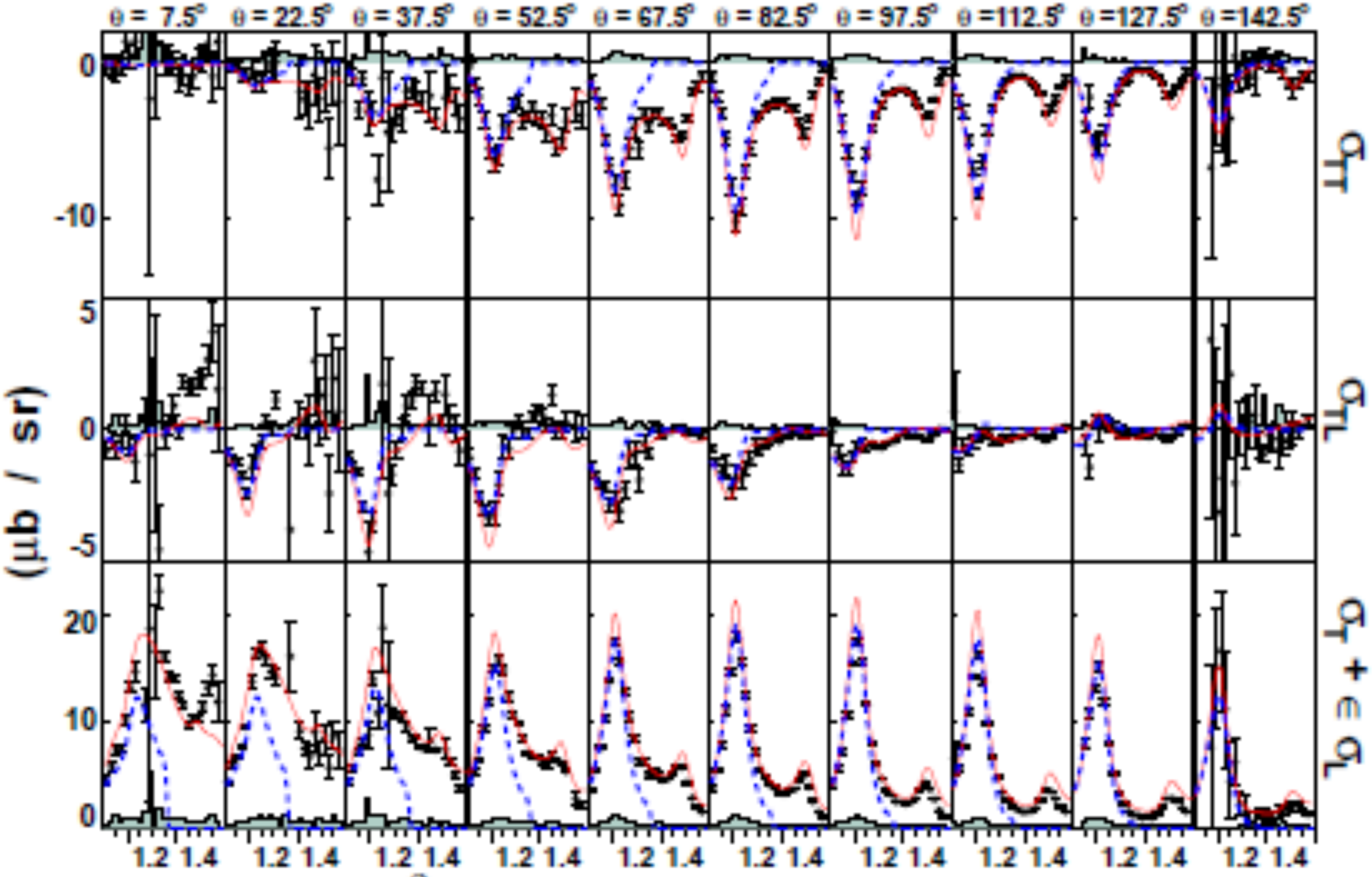
- In the Rarita-Swinger formalism
  - Hadronic current $< \Delta^{++}|J^{\nu}|p >= \sqrt{3}\bar{\psi}_{\lambda}(P)d^{\lambda\nu}u(p),$

$$
\begin{aligned}
d^{\lambda\nu} &= g^{\lambda\nu}\left[\frac{C_3^V}{M}\not{q} + \frac{C_4^V}{M^2}(Pq) + \frac{C_5^V}{M^2}(pq) + C_6^V\right]\gamma_5 - q^{\lambda}\left[\frac{C_3^V}{M}\gamma^{\nu} + \frac{C_4^V}{M^2}P^{\nu} + \frac{C_5^V}{M^2}p^{\nu}\right]\gamma_5 \\
&+ g^{\lambda\nu}\left[\frac{C_3^A}{M}\not{q} + \frac{C_4^A}{M^2}(Pq)\right] - q^{\lambda}\left[\frac{C_3^A}{M}\gamma^{\nu} + \frac{C_4^A}{M^2}P^{\nu}\right] + g^{\lambda\nu}C_5^A + q^{\lambda}q^{\nu}\frac{C_6^A}{M^2} \qquad (2.136)
\end{aligned}
$$

  - Hadronic tensor $H_{\Delta}^{\nu\mu} = \frac{1}{2}Tr\left[(\not{p}+M)\,\tilde{d}^{\nu\alpha}\Lambda_{\alpha\beta}d^{\beta\mu}\right],$ $\tilde{d}_{\nu\alpha} = \gamma_0 d_{\nu\alpha}^{\dagger}\gamma_0.$
  -
  - $\Lambda_{\alpha\beta}$ is a projection operator for spin 3/2

$$
\Lambda_{\alpha\beta} = -\left(\gamma^{\mu}P_{\mu} + \sqrt{P^2}\right)\left(g_{\alpha\beta} - \frac{2}{3}\frac{P_{\alpha}P_{\beta}}{P^2} + \frac{1}{3}\frac{P_{\alpha}\gamma_{\beta} - P_{\beta}\gamma_{\alpha}}{\sqrt{P^2}} - \frac{1}{3}\gamma_{\alpha}\gamma_{\beta}\right).
$$

CLAS data, $p(e, e'n)\pi^{+}$, $Q^{2} = 0.3$

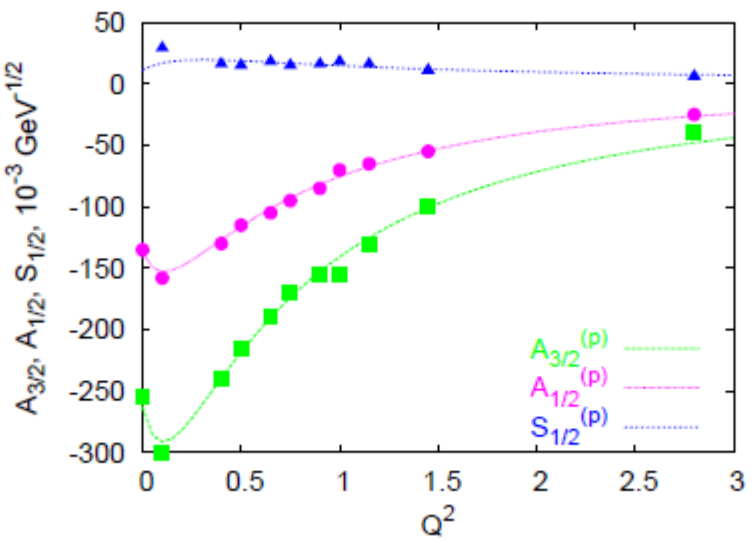


More data $0.25 < Q^{2} < 0.65$

Comparison to MAID2003, Sato-Lee models.

Cross section

- Vector form factor C^V_i are related to the EM form factors
- Paschos-Lalakulich model tuned to agree with MAID wrt $\Delta(1232)$ helicity amplitudes.



$$C_3^V = \frac{2.13}{D_V} \cdot \frac{1}{1+Q^2/4M_V^2}$$

$$C_4^V = \frac{-1.5}{D_V} \cdot \frac{1}{1+Q^2/4M_V^2},$$

$$C_5^V = \frac{-0.58}{D_V} \cdot \frac{1}{1+Q^2/0.76M_V^2}$$

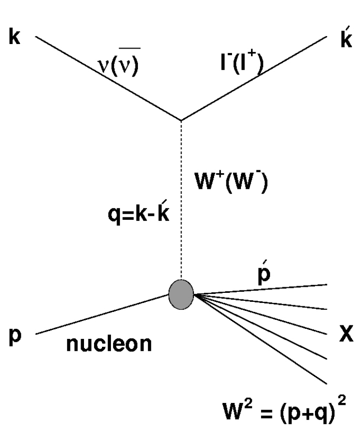
where

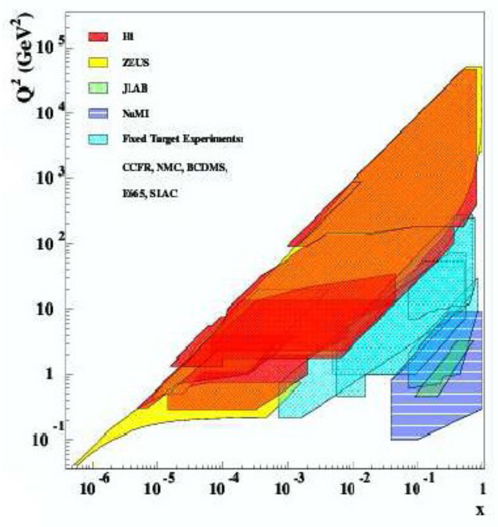
$$D_V = (1 + Q^2/0.71\ \mathrm{GeV}^2)^2$$

Coincide with the "magnetic dominance" values with 4% accuracy

Neutrino DIS scattering: Formalism

$$\frac{1}{E_\nu}\frac{d^2\sigma^{\nu|\bar{\nu}|}}{dxdy} = \frac{G_F^2 M}{\pi\left|1+Q^2/M_W^2\right|^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}\right)F_2^{\nu|\bar{\nu}|} \pm \left(y-\frac{y^2}{2}\right)xF_3^{\nu|\bar{\nu}|}\right]$$





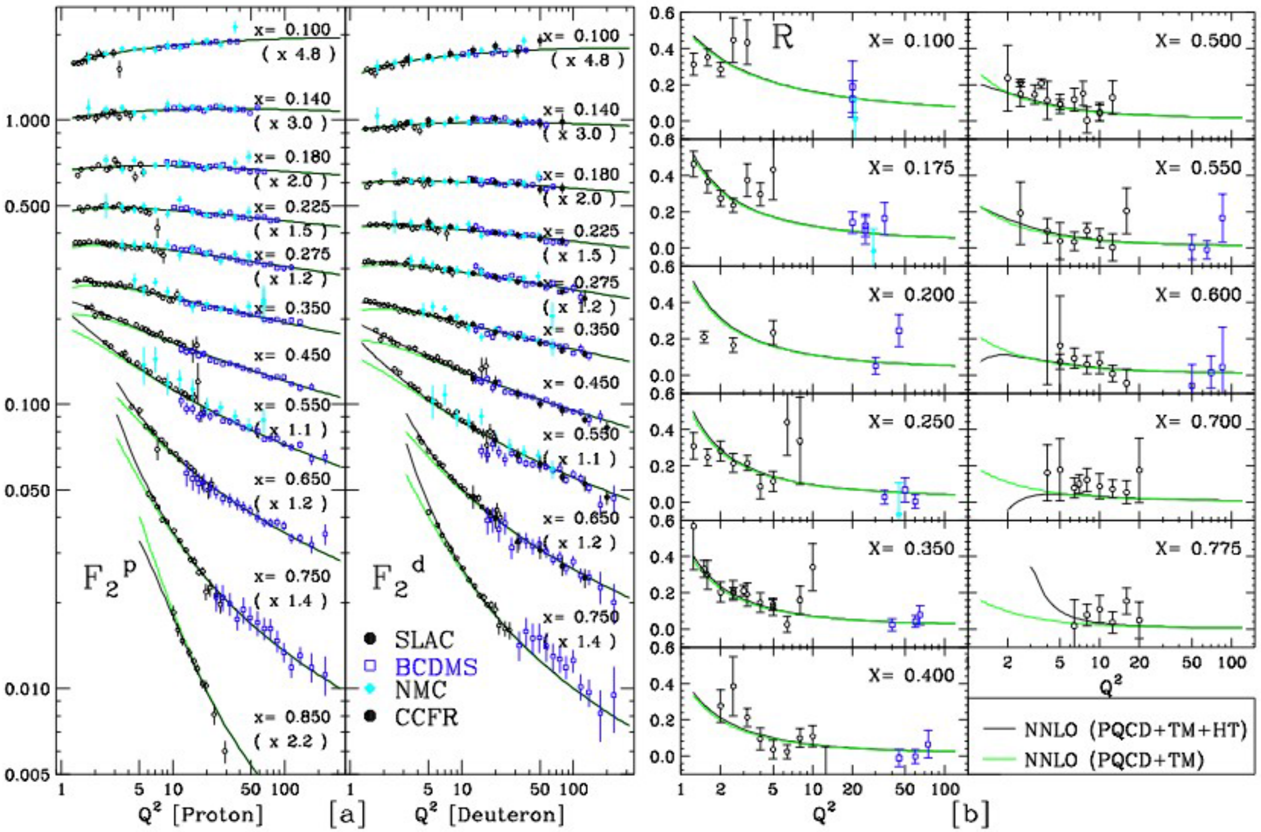
F2, xF3 combinations of PDFs:
in LO:

$$\begin{aligned} F_1(x,Q^2) &= \sum_{i=u,d,\ldots}[q_i(x)+\bar{q}_i(x)] \\ F_2(x,Q^2) &= 2x\sum_{i=u,d,\ldots}[q_i(x)+\bar{q}_i(x)] \\ F_3(x,Q^2) &= 2x\sum_{i=u,d,\ldots}[q_i(x)-\bar{q}_i(x)] \end{aligned}$$

$$R=\frac{\sigma_L}{\sigma_T}$$

$$R=\frac{F_L}{2xF_1}=\frac{F_2}{2xF_1}(1+Q^2/\nu^2)-1,$$

`The triumph of NNLO pQCD' *

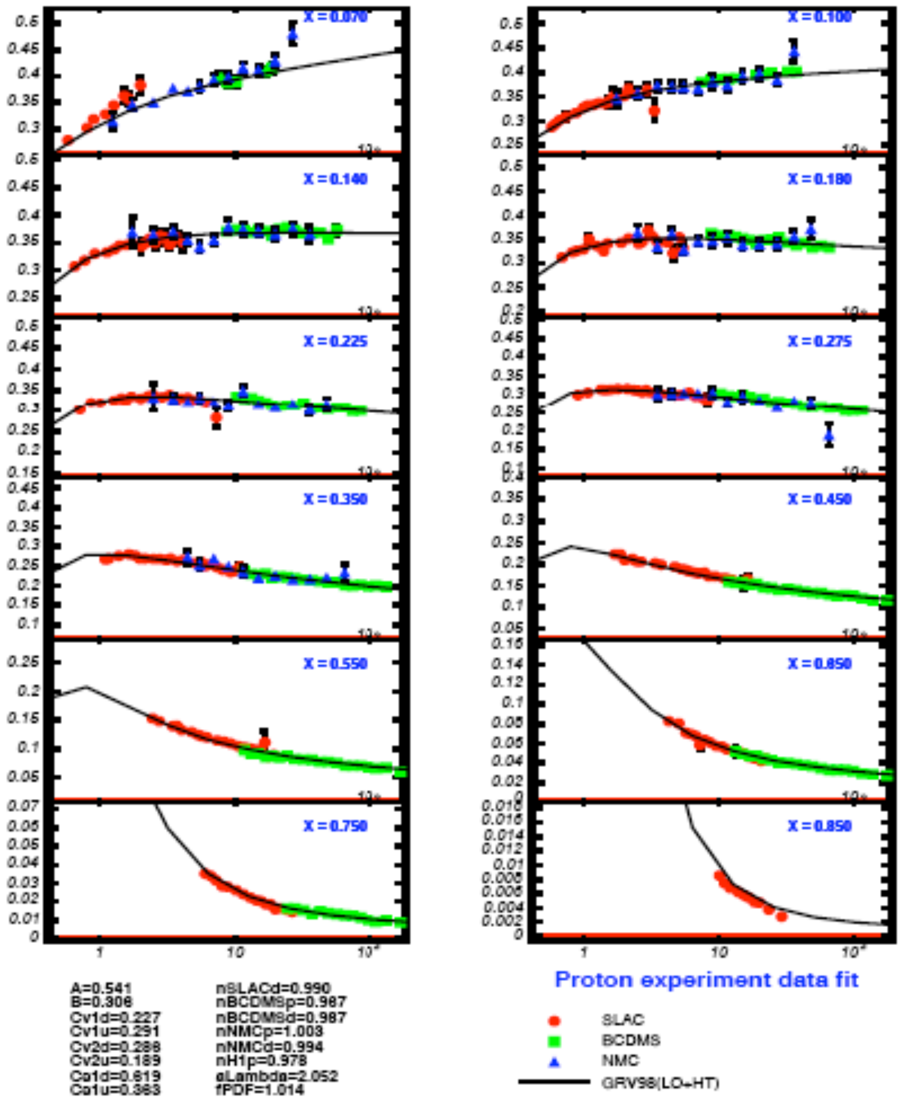


Next to next to leading order (NNLO) perturbative QCD with target-mass corrections

Shown data from
- SLAC
- BCDMS
- NMC

Plot & remark from A.Bodek's Panofsky prize 2004 talk, Nucl.Phys.Proc.Suppl.139:165-192,2005

Effective LO models for Monte Carlos



Effective model for Monte Carlos

LO pdfs (GRV98LO)

New scaling variable

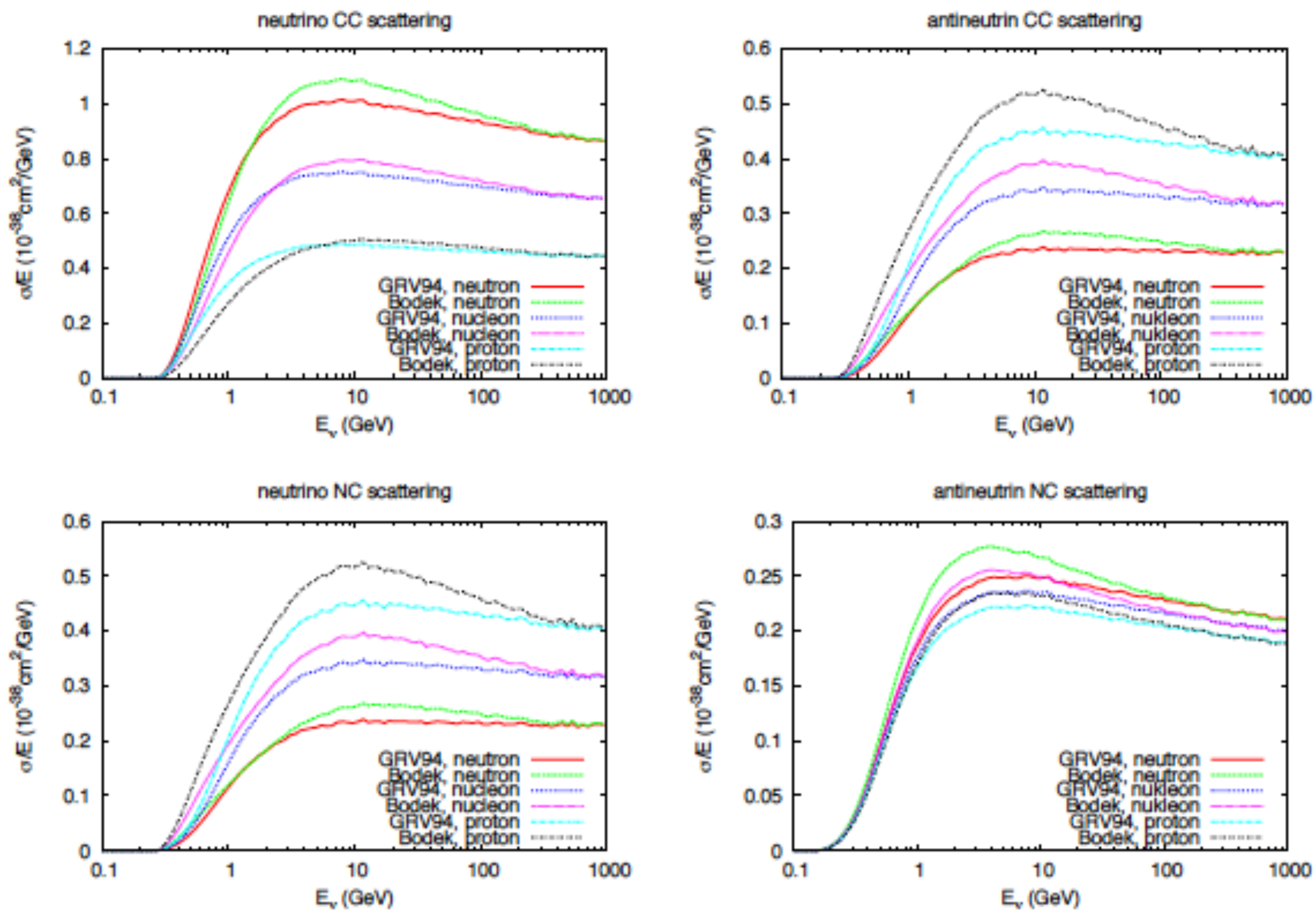
$$\xi_w = \frac{2x(Q^2 + {M_f}^2 + B)}{Q^2[1 + \sqrt{1 + (2Mx)^2/Q^2}] + 2Ax}$$

absorbs TM, HT, higher order corrections

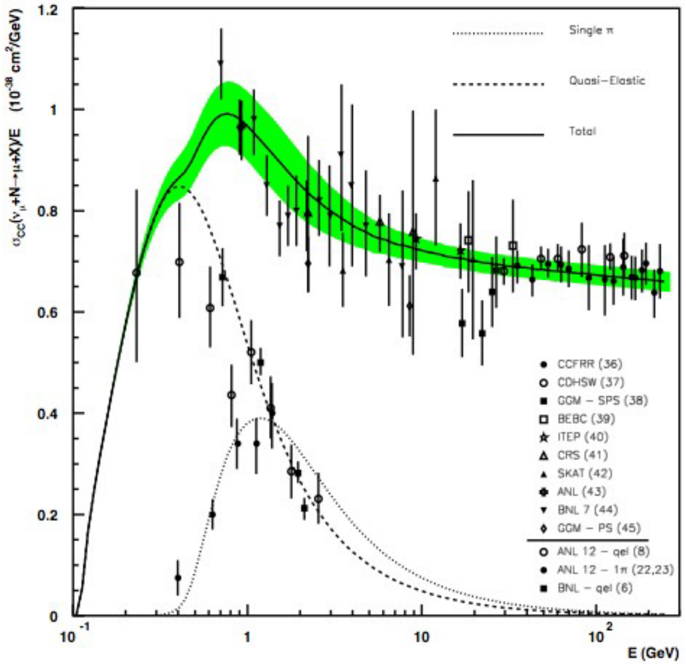
"K factors" for valence & sea PDFs

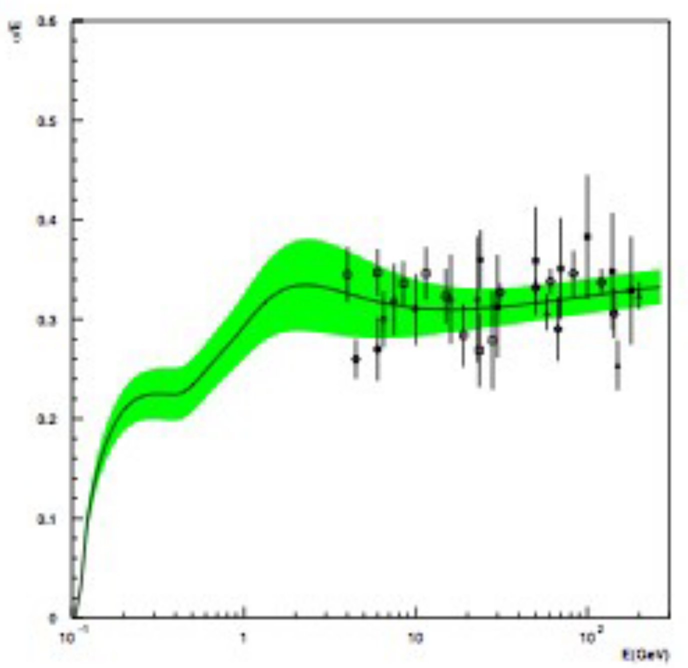
Bodek and Yang, Nucl.Phys.Proc.Suppl.139:113-118,2005

New PDFs with Bodek-Yang modifications for structure functions



Application to MINOS



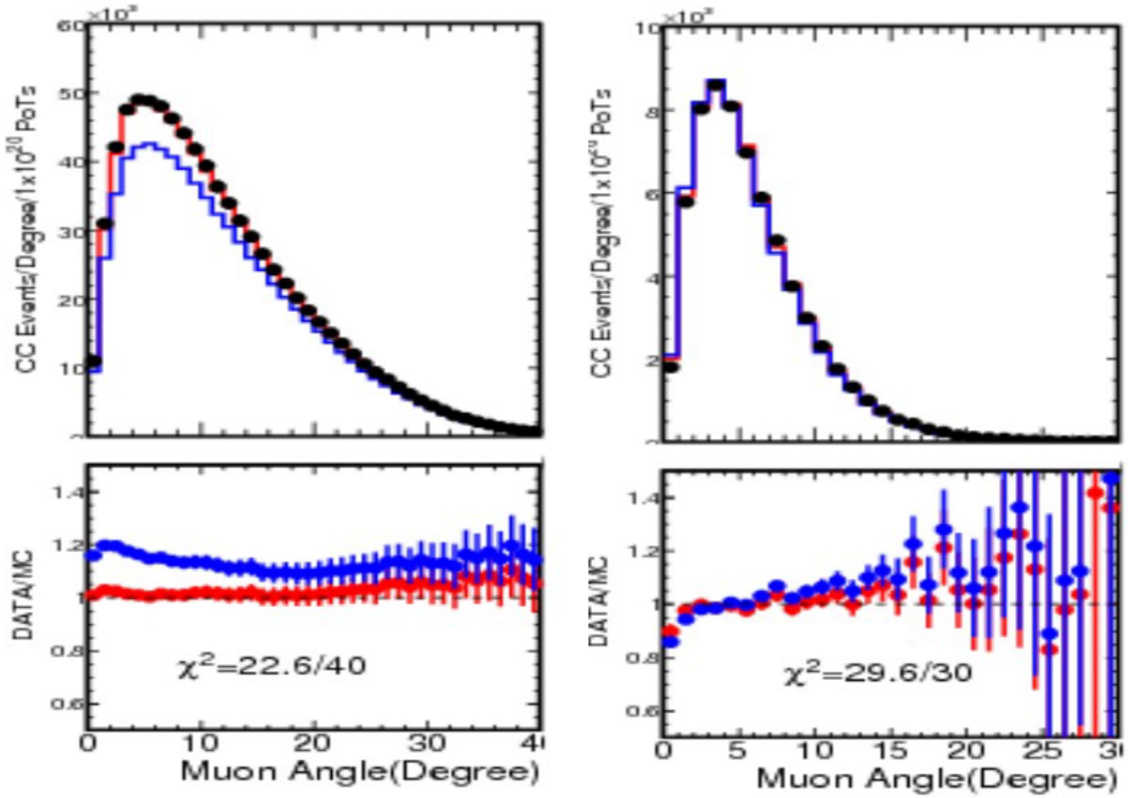


R at low Q^2 ?

$xF_3 \rightarrow \xi_\omega F_3$

Tuning factor: asymptotic cross section (x~1.032)

Experience from MINOS

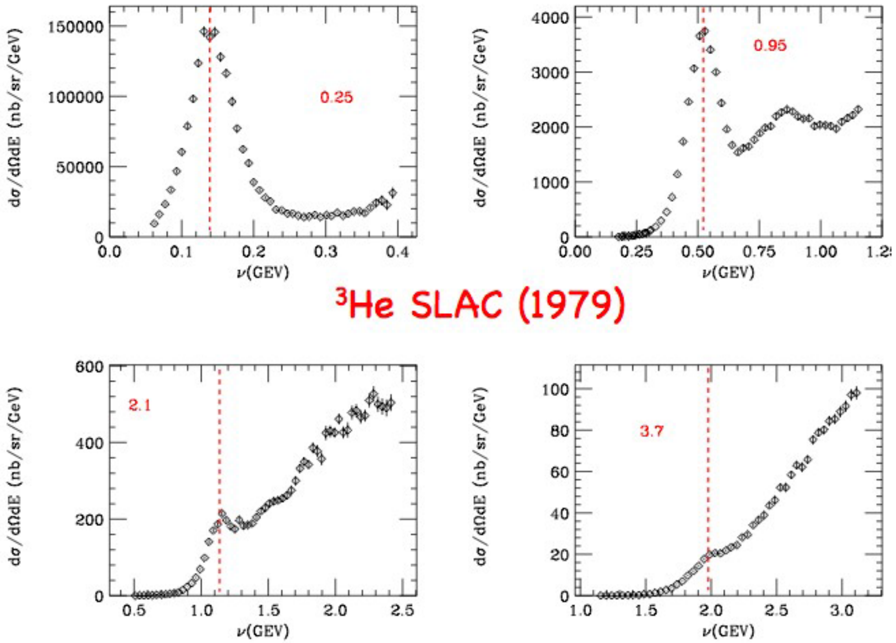


- Measured muon angle →
- Sensitive to x, Q^2 distributions
- **Excellent agreement with data**

Debdatta Bhattacharya (Pittsburgh U.)
FERMILAB-THESIS-2009-11, Mar 2009

QE → DIS

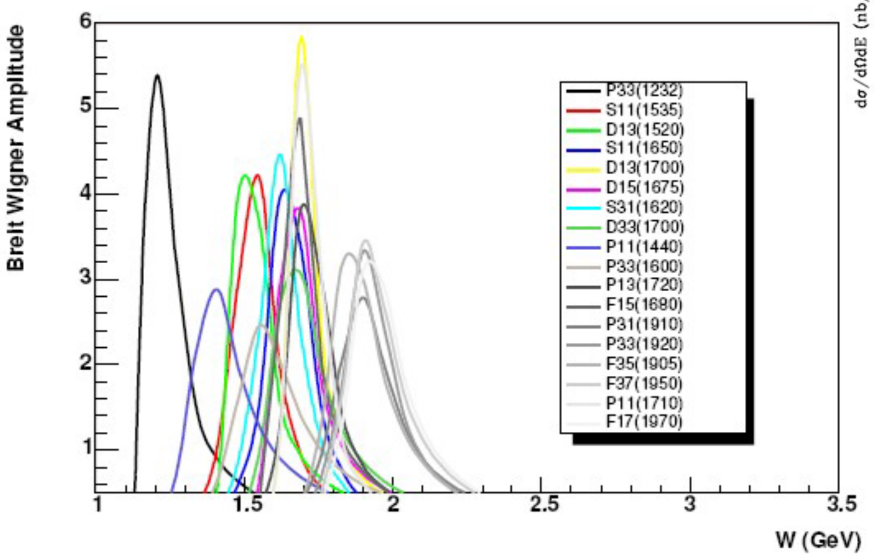
Transition from QE → DIS has been mapped out in detail using electron scattering data



^{3}He SLAC (1979)

Transition from νQE → νDIS difficult to model

- ~18 baryon resonances up to W = 2 GeV
- Non-resonance backgrounds

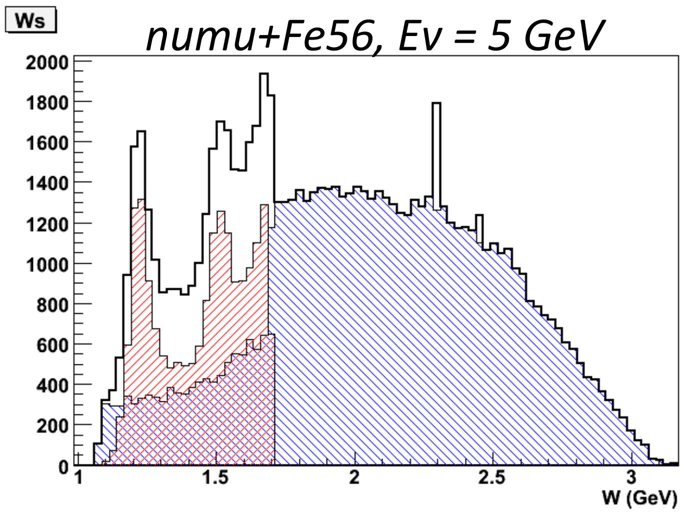


Cross section tuning in the ~GeV range

- Duality-inspired Bodek-Yang model: Valid all the way down to photo-production threshold.
- Includes resonances `on average'
- No resonance structure but, for nuclear targets, structure largely washed-out due to Fermi motion

- Many potential options available for vMC's:

- QE + BodekYang (W > MNuc)
- QE + Delta + BodekYang (W > MDelta+width)
- QE + Delta + higher RES + non RES bkg +
  + BodekYang (W > ~2 GeV)

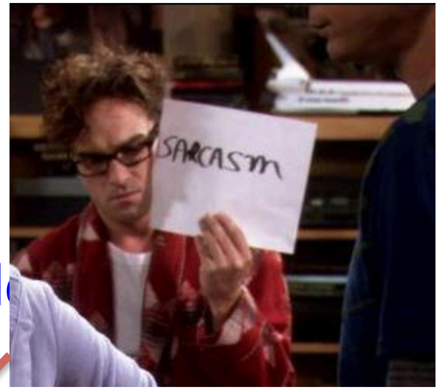


From free nucleon to nuclear targets

- Scattering is smeared by Fermi motion (large x)
- Internal structure of nucleons modified by medium (e.g. EMC effect)
- Nucleons can shadow each other at low Q2 (small x)
- For QE scattering at very low Q2 there should be Pauli suppression since final state cannot occupy the same state as the other nucleon(Q2<0.1GeV2)
- For QE transverse scattering (magnetic) there can be scattering from additional current in the nucleus (e.g MEC)
- For QE longitudinal (electric) scattering - since change is conserved the integral over longitudinal scattering should be conserved -besides the small distortion of the internal structure (form factor), and Pauli suppression (Q2<0.1 GeV2)

Electron scattering data can be used to study all of these nuclear effects

Nuclear structure



Electron-scattering is ideal for studying nucl

- Interaction well understood (QED)
- Electron is a `weak probe': Virtual photon doesn't disturb the nuclear target (even at large Q2)

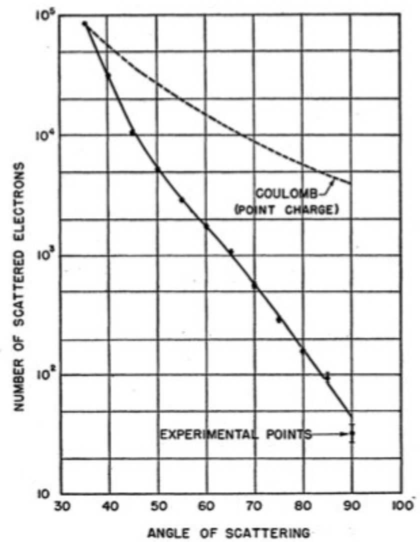


FIG. 3. Typical angular distribution obtained at 116 Mev with a 0.002-inch gold foil. The gold foil was oriented at 45° with respect to the incident beam for all angular settings of the spectrometer magnet.

Scattering of High-Energy Electrons and the Method of Nuclear Recoil*†

R. HOFSTADTER, H. R. FECHTER, AND J. A. MCINTYRE
Department of Physics and Microwave Laboratory, Stanford University, Stanford, California
(Received April 29, 1953)

IN an effort to exhibit the finite dimensions and charge distribution within atomic nuclei, an electron scattering program has been initiated. The external electron beam of the Stanford

Phys. Rev. 91, 422 - 423 (1953)

Mapping out the nuclear structure

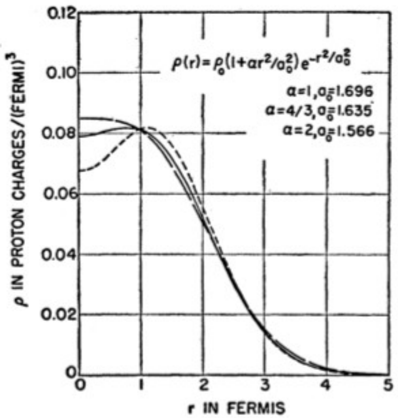


FIG. 36. The charge distribution for Model XI for three values of α. All three charge distributions fit the experimental data equivalently. $\alpha=4/3$ has some theoretical justification.

Charge distributions

$$k_F = \left(\frac{3\pi^2}{2}\rho\right)^{1/3}$$

Energy levels

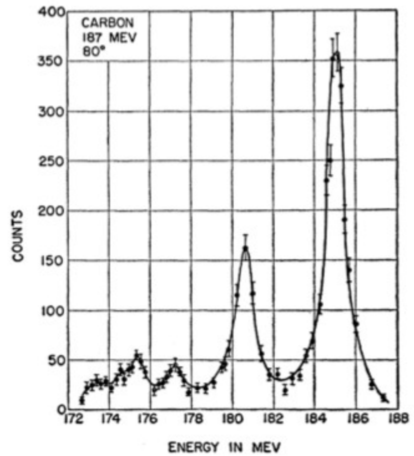


FIG. 11. The elastic scattering peak from carbon near 185 Mev and the inelastic scattering peaks from excited states of carbon.

Nucleon momentum distributions via "electro-disintegration"

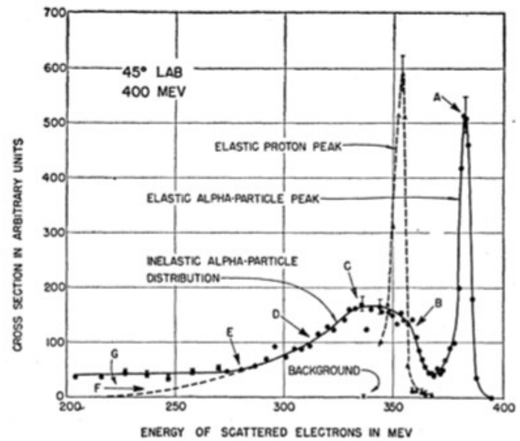
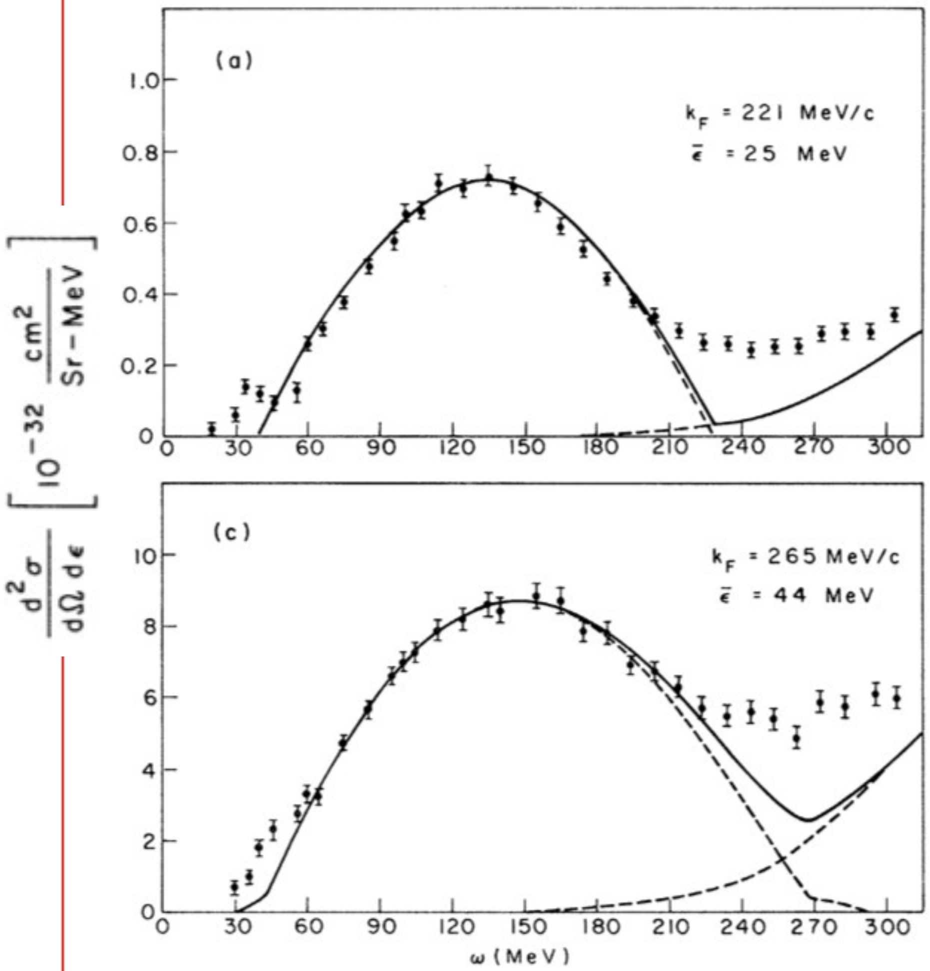


FIG. 12. Electrodisintegration of the alpha particle at 400 Mev

R.Hofstadter, Rev.Mod.Phys.28, 214 (**1956**)

Electron quasielastic data → kF, epsilon



Moniz et al., Phys.Rev.Lett. 26 (1971)

Just as quasi-elastic scattering on quarks (DIS) tells us about PDFs →
Quasi-elastic scattering on nucleons tells us about the nucleon momentum distributions

Nucleus	k_F (MeV/c)[a]	$\bar{\epsilon}$ (MeV)[b]
$_3Li^6$	169	17
$_6C^{12}$	221	25
$_{12}Mg^{24}$	235	32
$_{20}Ca^{40}$	251	28
$_{28}Ni^{58.7}$	260	36
$_{39}Y^{89}$	254	39
$_{50}Sn^{118.7}$	260	42
$_{73}Ta^{181}$	265	42
$_{82}Pb^{208}$	265	44

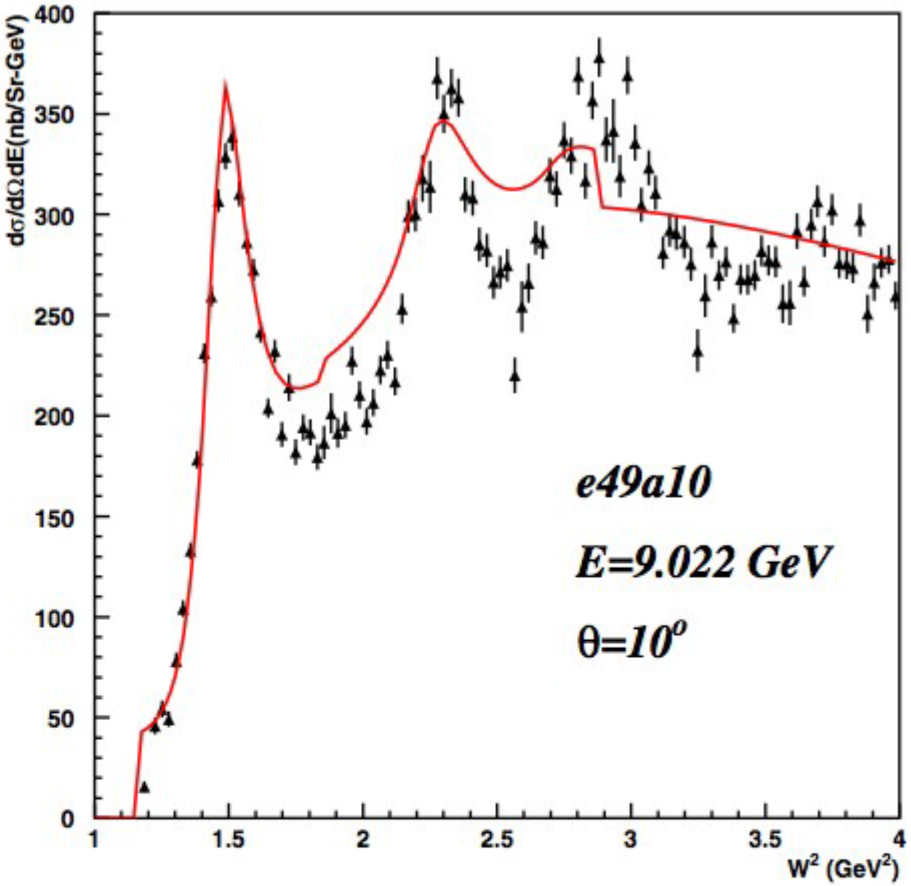
Quasi-elastic electron scattering is the source of all these "usual numbers" entering into the FGM models of neutrino MCs.

Honorable mentions

- Electron scattering data is use in modelling other elements of neutrino cross section
  - Nuclear effects: Spectral Function, Local Density Approximation, Optical potential
  - Hadronization: creation of final state hadrons form the available hadronic invariant mass
  - Final State Interactions
  - …

backup

Cross section tuning in the ~GeV range



- Gallagher, Nucl.Phys.B(Proc.Suppl.) 159 (2006) 229-234
- **On MINOS (neugen3/GENIE) we exercised the various schemes using electron scattering data**
- **(then tuned selected scheme to world's total, exclusive 1pi and exclusive 2pi data)**