Final State Nucleons for Neutrino - Nucleus Interactions

Thomas Jefferson National Accelerator Facility May 14th, 2015

Semi-inclusive neutrino-nucleus reactions

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SUMMARY

- Definition of semi-inclusive
- Motivation
- Kinematics: lepton and transfer variables, the space of residual nucleus variables
- Dynamics: generalized Rosenbluth factors and hadronic response functions, tensor contraction and cross-sections
- Remarks on incident neutrino kinematics and nuclear dynamics
- Summary

DEFINITION

- In semi-inclusive charged current neutrino-nucleus reactions (anti)neutrinos interact with a nuclear target and the final charged lepton is detected in coincidence with a another particle.

$$X(\nu_\ell, \ell^- x) \qquad X(\bar{\nu}_\ell, \ell^+ x)$$

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$$X(\nu_\ell, \ell^- x) \qquad X(\bar{\nu}_\ell, \ell^+ x)$$

- Case of most interest: nucleon emission

$$^{A}_{Z}X(\nu_\ell, \ell^- p)^{A-1}_{Z}Y \qquad ^{A}_{Z}X(\nu_\ell, \ell^- n)^{A-1}_{Z+1}Y$$

$$^{A}_{Z}X(\bar{\nu}_\ell, \ell^+ n)^{A-1}_{Z-1}Y \qquad ^{A}_{Z}X(\bar{\nu}_\ell, \ell^+ p)^{A-1}_{Z-2}Y$$

MOTIVATION

- An increasing number of neutrino experiments allow for semi-inclusive measurements (ArgoNeuT, MicroBooNE: μ and p).

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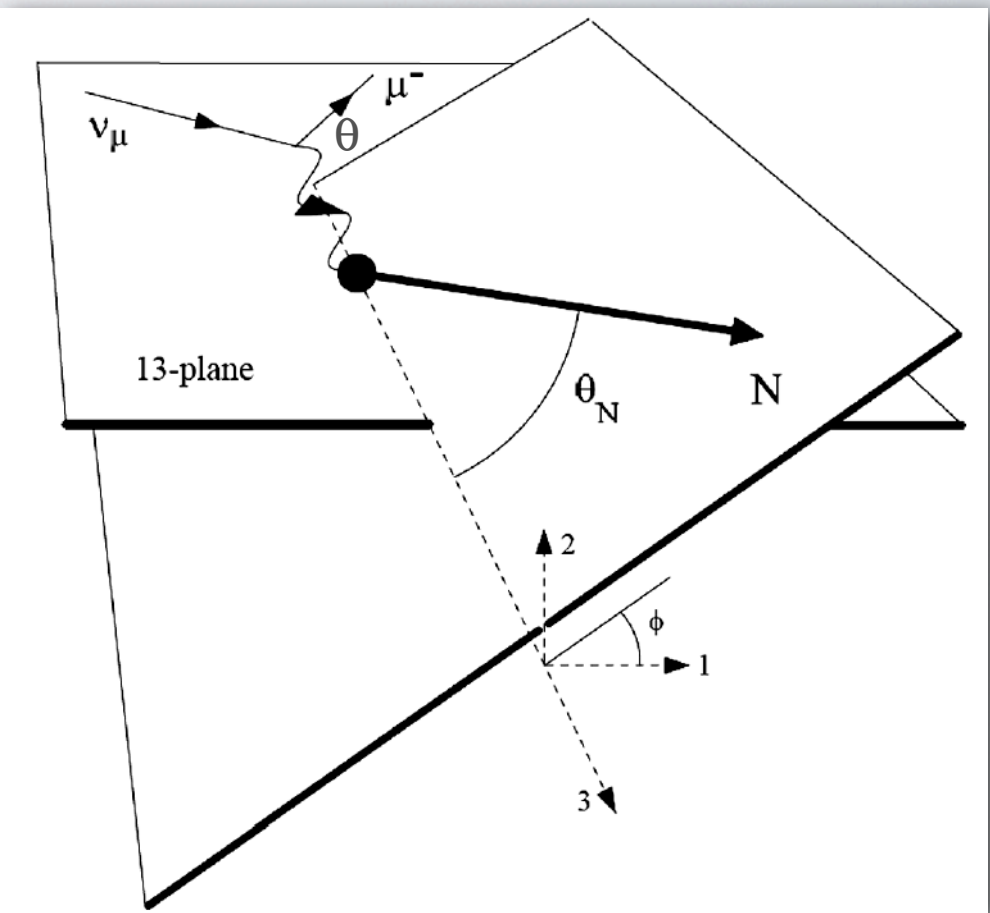
- Hadronic structure studies.

KINEMATICS

- Leptonic variables: k, k', θ
- Exchange variables: q, ω
- Detected hadron variables: p_N, θ_N, ϕ



KINEMATICS

- Detected hadron variables:
  p_N, θ_N, ϕ

$$\mathbf{p} \equiv -\mathbf{p}_{A-1} = \mathbf{p}_N - \mathbf{q}$$

$$p = |\mathbf{p}_m|$$

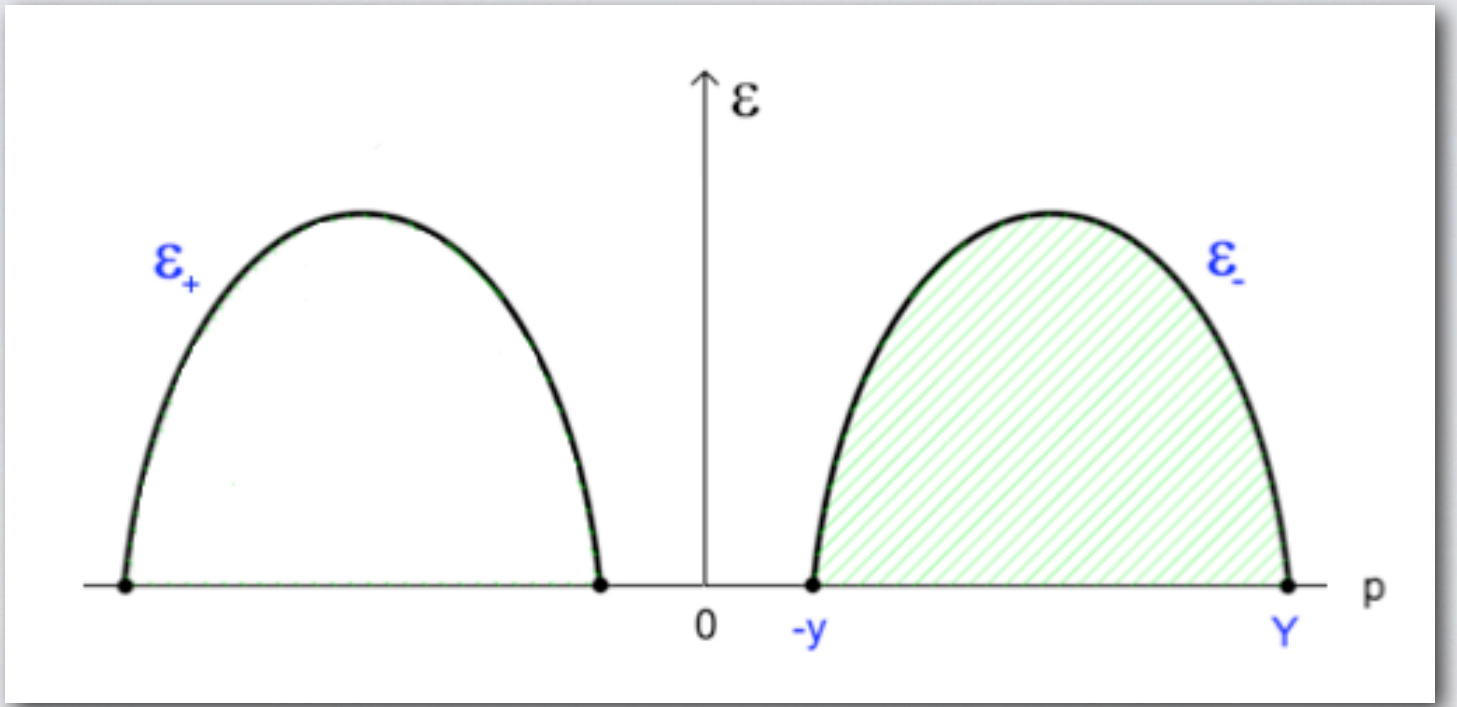
$$\mathcal{E} \equiv E_{A-1} - E^0_{A-1} = \omega - E_s + m_N - \sqrt{m_N^2 + p^2 + q^2 + 2pq\cos\theta_{pq}} - \sqrt{{W^0_{A-1}}^2 + p^2} + W^0_{A-1}$$

$$\mathcal{E} \approx E_m - E_s$$

KINEMATICS

(ε,p) plane: allowed region

For q, ω fixed, with $\omega < \omega_{QE}$ ($\Rightarrow$ y < 0, x > 1)



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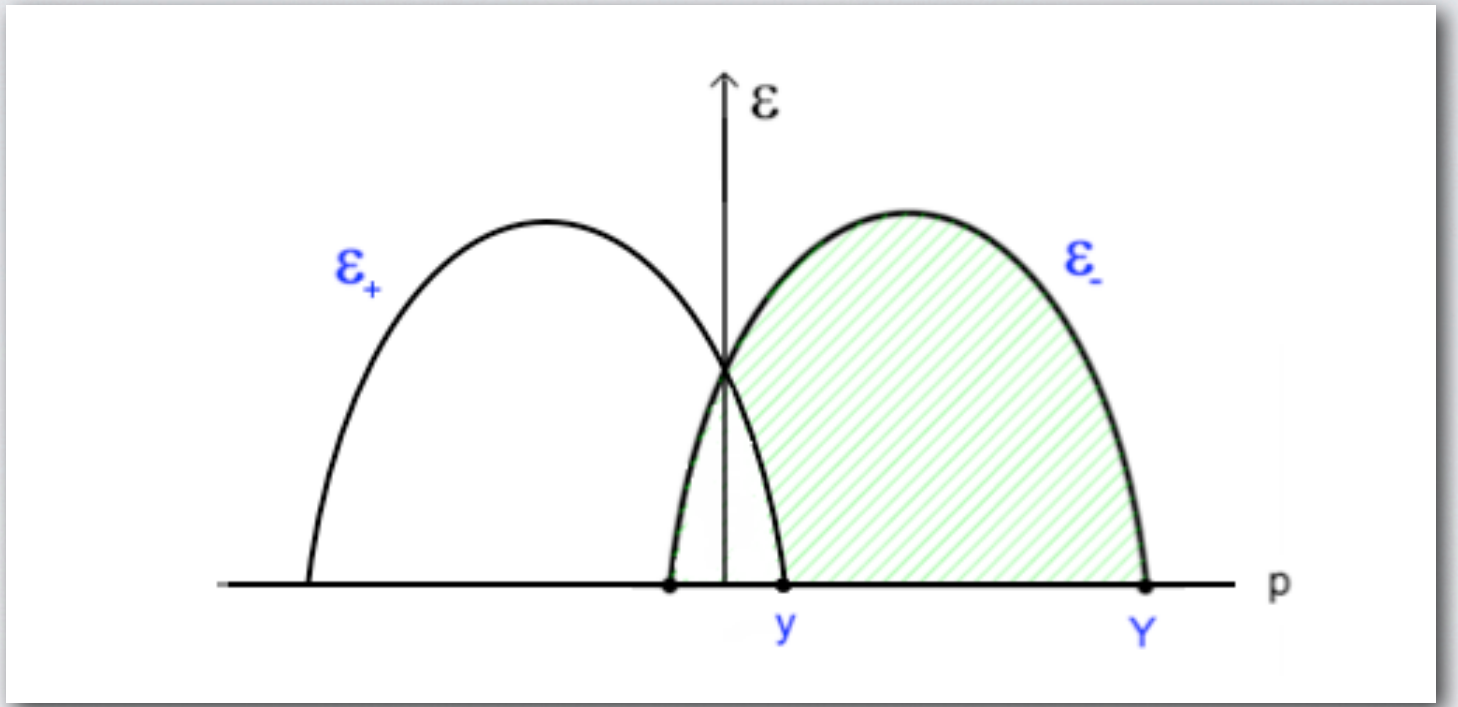
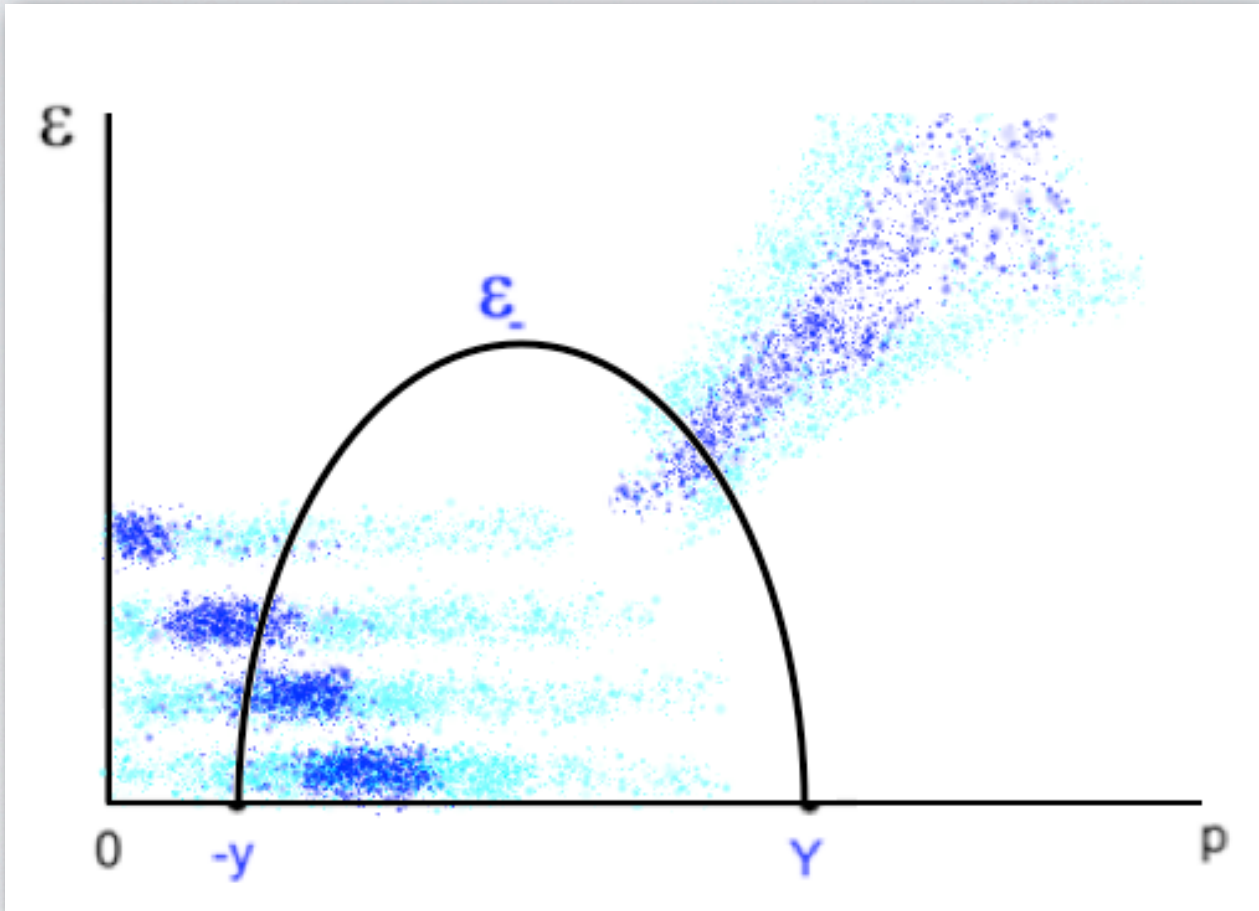
(ε,p) plane: allowed region

For q, ω fixed, with $\omega > \omega_{QE}$ ($\Rightarrow$ y > 0, x < 1)



KINEMATICS

(ε,p) plane: residual system distribution



DYNAMICS

Leptonic and hadronic tensors:

$$d\sigma \sim \eta_{\mu\nu} W^{\mu\nu} \sim \eta^s_{\mu\nu} W^{\mu\nu}_s + \chi \eta^a_{\mu\nu} W^{\mu\nu}_a$$

$$\eta_{\mu\nu} \equiv 2mm' \overline{\sum_{if}} j^*_\mu j_\nu$$

$$W^{\mu\nu} \equiv \overline{\sum_{if}} J^{\mu *}_{fi}(\mathbf{q}) J^\nu_{fi}(\mathbf{q})$$

DYNAMICS

Leptonic and hadronic tensors contraction:

$$\eta^s_{\mu\nu} W^{\mu\nu}_s = v_0 \{ [\hat{V}_{CC} W^{CC} + \hat{V}_{CL} W^{CL} + \hat{V}_{LL} W^{LL} + \hat{V}_T W^T + \hat{V}_{TT} W^{TT} + \hat{V}_{TC} W^{TC} + \hat{V}_{TL} W^{TL}] + [\hat{V}_{\underline{T}T} W^{\underline{T}T} + \hat{V}_{\underline{T}C} W^{\underline{T}C} + \hat{V}_{\underline{T}L} W^{\underline{T}L}] \}$$

$$\eta^a_{\mu\nu} W^{\mu\nu}_a = v_0 \{ [\hat{V}_{T'} W^{T'} + \hat{V}_{TC'} W^{TC'} + \hat{V}_{TL'} W^{TL'}] + [\hat{V}_{\underline{C}L'} W^{\underline{C}L'} + \hat{V}_{\underline{T}C'} W^{\underline{T}C'} + \hat{V}_{\underline{T}L'} W^{\underline{T}L'}] \}$$

DYNAMICS

Generalized Rosenbluth factors from the leptonic tensor:

$$\hat{V}_{CC} \quad \hat{V}_{CL} \quad \hat{V}_{LL} \quad \hat{V}_{T} \quad \hat{V}_{TT} \quad \hat{V}_{TC} \quad \hat{V}_{TL}$$

$$\hat{V}_{T'} \quad \hat{V}_{TC'} \quad \hat{V}_{TL'}$$

DYNAMICS

Generalized Rosenbluth factors from the leptonic tensor:

$$\hat{V}_{CC} = \frac{1}{2}\{(a_V^2 + a_A^2) - [a_V^2(\delta - \delta')^2 + a_A^2(\delta + \delta')^2]\tan^2\tilde{\theta}/2\}$$

$$\delta \equiv \frac{m}{\sqrt{|Q^2|}} \qquad \delta' \equiv \frac{m'}{\sqrt{|Q^2|}}$$

DYNAMICS

Response functions from the hadronic tensor:

W^{CC} W^{CL} W^{LL} W^{T} W^{TT} W^{TC} W^{TL}

$W^{T'}$ $W^{TC'}$ $W^{TL'}$

DYNAMICS

Response functions from the hadronic tensor:

For inclusive cross-sections:

W^{CC} W^{CL} W^{LL} W^{T} ~~W^{TT}~~ ~~W^{TC}~~ ~~W^{TL}~~

$W^{T'}$ ~~$W^{TC'}$~~ ~~$W^{TL'}$~~

ϕ dependence

DYNAMICS

General differential cross-section:

$$d\sigma_\chi = \frac{G^2\cos^2\theta_c}{2(2\pi)^5}\frac{m_N W_{A-1} v_0}{k\varepsilon' E_N E_{A-1}}\mathcal{F}_\chi^2 d^3\mathbf{k}' d^3\mathbf{p_N} d^3\mathbf{p_{A-1}}\delta^4(K + P_A - K' - P_{A-1} - P_N).$$

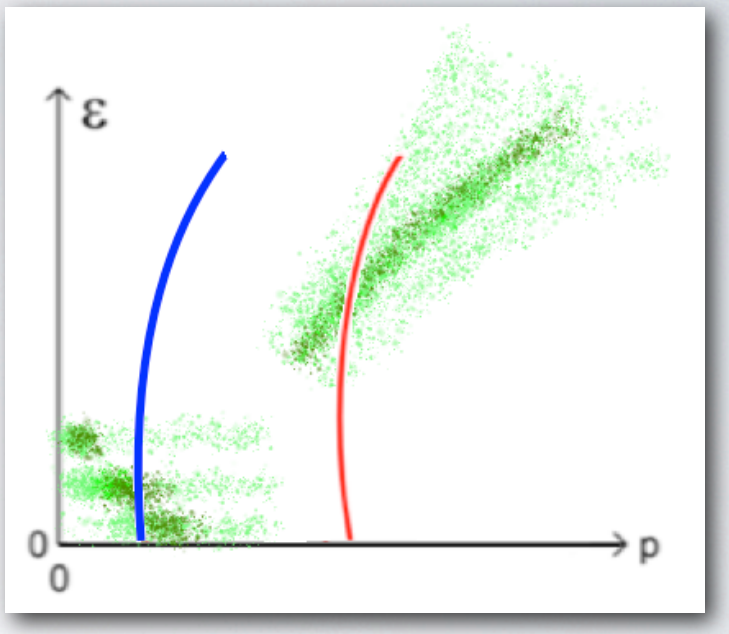
Integration over the unobserved residual system variables:

$$\frac{d\sigma_\chi}{dk' d\Omega_{k'} d\Omega_{p_N}} = \frac{G^2\cos^2\theta_c}{2(2\pi)^5}\frac{m_N W_{A-1}}{M_A^0}\frac{p_N k'^2 v_0}{k\varepsilon' F_{\text{rec}}}\mathcal{F}_\chi^2,$$

REMARKS

In practice, one performs an integration of the cross-section over the incoming neutrino energy weighted with the neutrino flux.

For a given set of values of the semi-inclusive variables (k', θ, p_N, θ_N, ϕ), a range of incident neutrino energy corresponds to a curve in the (ε,p)-plane.



The nuclear target modeling is more demanding than in the inclusive case: (ε,p)-dependence needed. The possibility of kinematic discrimination would allow for the calibration of nuclear models.

REMARKS

Determination of the incident neutrino momentum

- From momentum conservation:

$$k = k' \cos\theta \pm \left\{ \left[p_N \cos\theta_N \pm \left(p^2 - p_N^2 \sin^2\theta_N \right)^{1/2} \right]^2 - k'^2 \sin^2\theta \right\}^{1/2}$$

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- From energy conservation:

$$\epsilon = \epsilon' + E_N - M_A^0 + E_{A-1} \quad \Rightarrow$$

$$k = \left\{ \left[(k'^2 + m'^2)^{1/2} + (p_N^2 + m_N^2)^{1/2} - M_A^0 + \mathcal{E} + (p^2 + W_{A-1}^{(0)\,2})^{1/2} \right]^2 - m^2 \right\}^{1/2}$$

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For the particular case of deuteron target: $W_{A-1}^{(0)} = m_p, \;\; \mathcal{E} = 0$

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- The masses of the incoming and outgoing leptons are kept.
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- Components of the leptonic and hadronic tensors are given in terms of chargelike, longitudinal and transverse projections of the electroweak current and organized into VV, AA and VA contributions.

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- The masses of the incoming and outgoing leptons are kept.
- Scattering of both neutrinos and antineutrinos (different sign of V-A interference contributions).
- General hadronic target and hadronic products (detected particle and residual system).
- Components of the leptonic and hadronic tensors are given in terms of chargelike, longitudinal and transverse projections of the electroweak current and organized into VV, AA and VA contributions.
- Formalism valid for charged-current and neutral current weak interactions; in the latter case, integrate over the unobserved outgoing neutrino variables (u-channel inclusive, different from t-channel inclusive).

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- Transformation of hadronic variables to the (ε,p) variables, which are best suited to characterizing the nuclear dynamics.
- Translation of a neutrino energy range onto the (ε,p)-plane: kinematical discrimination of nuclear dynamics.
- Determination of the incident neutrino kinematics in semi-inclusive measurements (special case of deuteron).

A BRIEF DETOUR TO A DIFFERENT PROCESS:

ELASTIC NEUTRINO SCATTERING

- From semi-inclusive to inclusive
- From (mainly) charged-current to neutral-current
- From quasi-elastic to elastic
- From detection of ejected particles to detection of target recoil

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In elastic neutrino scattering the target nucleus remains in its ground state. In general, the main contribution is the **coherent scattering**, proportional to N^2 and valid when $q \lesssim 1/R \approx 160\ A^{-1/3}$ MeV; it is the only contribution for even-even targets.

A BRIEF DETOUR TO A DIFFERENT PROCESS:

ELASTIC NEUTRINO SCATTERING

- Relationship between coherent electron-nucleus and coherent neutrino-nucleus cross-sections in PWBA:

$$\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)} = \left[\frac{(a_V^\nu)^2 + (a_A^\nu)^2}{2\,(a_A^e)^2}\right] \mathcal{A}^2_{(e,e)} \left(\frac{d\sigma}{d\Omega}\right)_{(e,e)}$$

where the parity-violating elastic electron scattering asymmetry is defined as

$$\mathcal{A}_{(e,e)} = \frac{\left(\frac{d\sigma}{d\Omega}\right)^{h=+1} - \left(\frac{d\sigma}{d\Omega}\right)^{h=-1}}{\left(\frac{d\sigma}{d\Omega}\right)^{h=+1} + \left(\frac{d\sigma}{d\Omega}\right)^{h=-1}}$$

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- Deviations from this prediction:

  - Coulomb distortion.

  - Effect of higher order corrections.

  - Different coupling of Z^0 to neutrinos and charged leptons.

  - Other effects affecting differently neutrinos and charged leptons.

A BRIEF DETOUR TO A DIFFERENT PROCESS:

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- Relationship between relative uncertainties:

$$\mathcal{E}_{\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)}} \approx 2\,\mathcal{E}_{\mathcal{A}_{(e,e)}}$$

A BRIEF DETOUR TO A DIFFERENT PROCESS:

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- Relationship between relative uncertainties:

$$\mathcal{E}_{\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)}} \approx 2\,\mathcal{E}_{\mathcal{A}_{(e,e)}}$$

to which the PV experiment statistical contribution is:

$$\mathcal{E}^{stat.}_{\left(\frac{d\sigma}{d\Omega}\right)_{(\nu,\nu)}} \approx 2\,\mathcal{X}_{PV}^{-\frac{1}{2}}\,\mathcal{F}_{PV}^{-\frac{1}{2}}$$

A BRIEF DETOUR TO A DIFFERENT PROCESS:

ELASTIC NEUTRINO SCATTERING

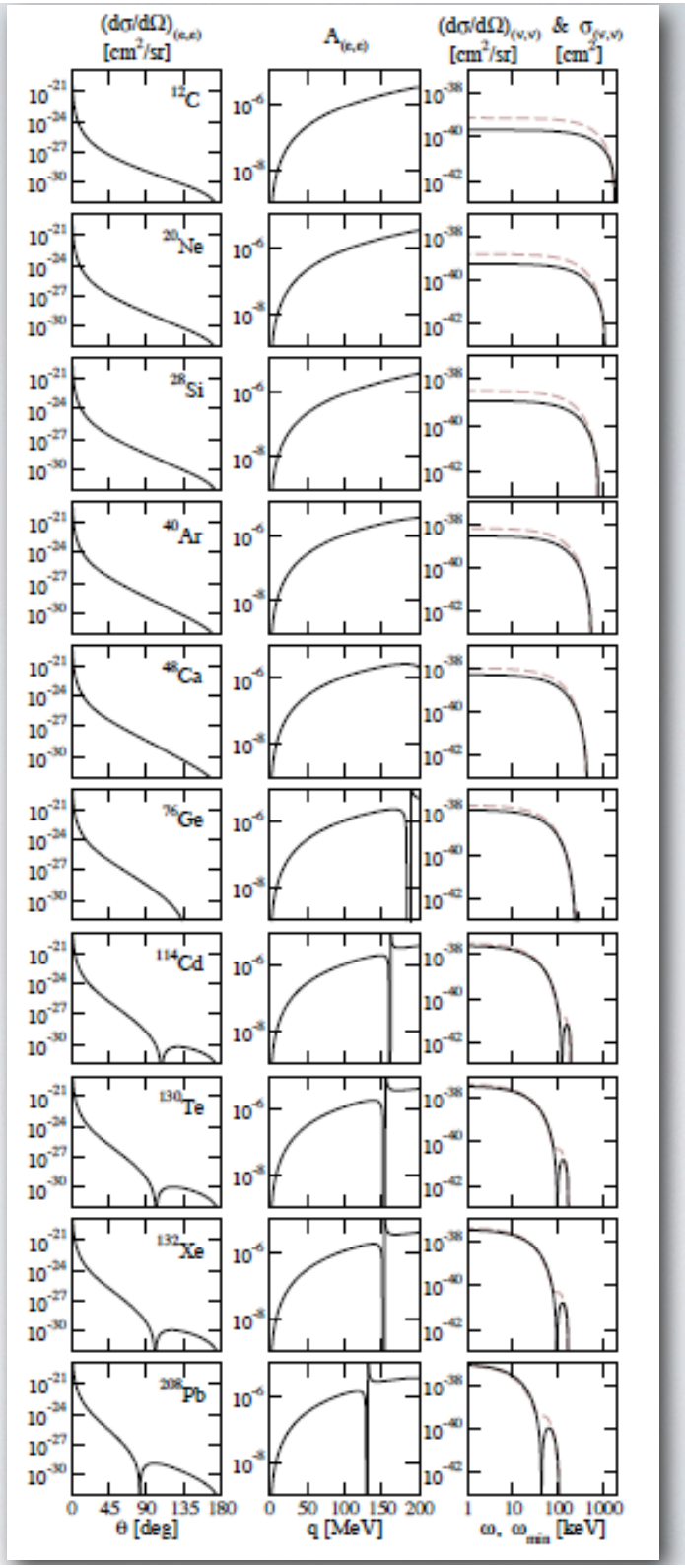
- For measurements at different kinematic conditions:

$$\left(\frac{d\sigma(k_\nu,\theta_\nu)}{d\Omega}\right)_{(\nu,\nu)} = \mathcal{K}(k_\nu,k_e,\theta_e)\ \ \mathcal{A}^2_{(e,e)}(\widehat{k}_e,\widehat{\theta}_e)\ \ \left(\frac{d\sigma(k_e,\theta_e)}{d\Omega}\right)_{(e,e)}$$

$$\mathcal{K} = \frac{k_e^2\,(k_\nu-\omega_e)^2\,[2\,k_\nu^2-\omega_e\,(2\,k_\nu+M_A)]}{k_\nu^2\,(k_e-\omega_e)^2\,[2\,k_e^2-\omega_e\,(2\,k_e+M_A)]}$$

ELASTIC NEUTRINO SCATTERING

Preliminary results,
starting point



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EXTRA MATERIAL

Generalized Rosenbluth factors

$$\hat{V}_{CC} = \frac{1}{2}\{(a_V^2 + a_A^2) - [a_V^2(\delta - \delta')^2 + a_A^2(\delta + \delta')^2]\tan^2\tilde{\theta}/2\},$$

$$\hat{V}_{CL} = -\frac{1}{2}(a_V^2 + a_A^2)\left[\nu - \frac{1}{\rho'}(\delta^2 - \delta'^2)\tan^2\tilde{\theta}/2\right],$$

$$\hat{V}_{LL} = \frac{1}{2}\left\{(a_V^2 + a_A^2)\left[\nu^2 - \frac{1}{\rho'}(2\nu - \rho\rho'(\delta^2 - \delta'^2))(\delta^2 - \delta'^2)\tan^2\tilde{\theta}/2\right] + [a_V^2(\delta - \delta')^2 + a_A^2(\delta + \delta')^2]\tan^2\tilde{\theta}/2\right\},$$

$$\hat{V}_T = \frac{1}{2}(a_V^2 + a_A^2)\left\{\left[\frac{1}{2}\rho + \tan^2\tilde{\theta}/2\right] + \left(\frac{\nu}{\rho'}(\delta^2 - \delta'^2) - \frac{1}{2}\rho(\delta^2 - \delta'^2)^2\right)\tan^2\tilde{\theta}/2\right\} - (a_V^2 - a_A^2)\delta\delta'\tan^2\tilde{\theta}/2,$$

$$\hat{V}_{TT} = \frac{1}{2}(a_V^2 + a_A^2)\left\{-\frac{1}{2}\rho + \left[(\delta^2 + \delta'^2) - \frac{\nu}{\rho'}(\delta^2 - \delta'^2) + \frac{1}{2}\rho(\delta^2 - \delta'^2)^2\right]\tan^2\tilde{\theta}/2\right\},$$

$$\hat{V}_{TC} = -\frac{1}{2}(a_V^2 + a_A^2)\frac{1}{\rho'}\tan\tilde{\theta}/2 \times \left(\frac{1}{2} - \frac{1}{\rho}[(\delta^2 + \delta'^2) - \frac{\nu}{\rho'}(\delta^2 - \delta'^2) + \frac{1}{2}\rho(\delta^2 - \delta'^2)^2]\tan^2\tilde{\theta}/2\right)^{1/2},$$

Generalized Rosenbluth factors

$$v_0 \equiv (\varepsilon + \varepsilon')^2 - q^2.$$

$$\nu \equiv \frac{\omega}{q},$$

$$\rho \equiv \frac{|Q^2|}{q^2} = 1 - \nu^2; \qquad \rho' \equiv \frac{q}{\varepsilon + \varepsilon'},$$

$$\delta \equiv \frac{m}{\sqrt{|Q^2|}}; \qquad \delta' \equiv \frac{m'}{\sqrt{|Q^2|}},$$

$$\tan^2\tilde{\theta}/2 = \frac{|Q^2|}{v_0} = \frac{\rho\rho'^2}{1 - \rho'^2}.$$

$$\hat{V}_{TL} = -(\nu - \rho\rho'(\delta^2 - \delta'^2))\hat{V}_{TC},$$

$$\hat{V}_{\underline{T}T} = 0,$$

$$\hat{V}_{\underline{T}C} = 0,$$

$$\hat{V}_{\underline{T}L} = 0,$$

$$\hat{V}_{T'} = a_V a_A \frac{1}{\rho'}(1 + \nu\rho'(\delta^2 - \delta'^2))\tan^2\tilde{\theta}/2,$$

$$\hat{V}_{TC'} = -a_V a_A \tan\tilde{\theta}/2 \times \left[\frac{1}{2} - \frac{1}{\rho}\left[(\delta^2 + \delta'^2) - \frac{\nu}{\rho'}(\delta^2 - \delta'^2) + \frac{1}{2}\rho(\delta^2 - \delta'^2)^2\right]\tan^2\tilde{\theta}/2\right]^{1/2},$$

$$\hat{V}_{TL'} = -\nu\hat{V}_{TC'},$$

$$\hat{V}_{\underline{C}L'} = 0,$$

$$\hat{V}_{\underline{T}C'} = 0,$$

$$\hat{V}_{\underline{T}L'} = 0.$$

Generalized Rosenbluth factors,

ERL

$$v_{CC} = 1,$$

$$v_{CL} = -\nu,$$

$$v_{LL} = \nu^2,$$

$$v_T = \frac{1}{2}\rho + \tan^2\theta/2,$$

$$v_{TT} = -\frac{1}{2}\rho,$$

$$v_{TC} = -\frac{1}{\sqrt{2}\rho'}\tan\theta/2,$$

$$v_{TL} = -\nu v_{TC},$$

$$v_{T'} = \tan\theta/2\sqrt{\rho + \tan^2\theta/2},$$

$$v_{TC'} = -\frac{1}{\sqrt{2}}\tan\theta/2,$$

$$v_{TL'} = -\nu v_{TC'}.$$