Charged-current interactions of Kaon-decay-at-rest neutrinos

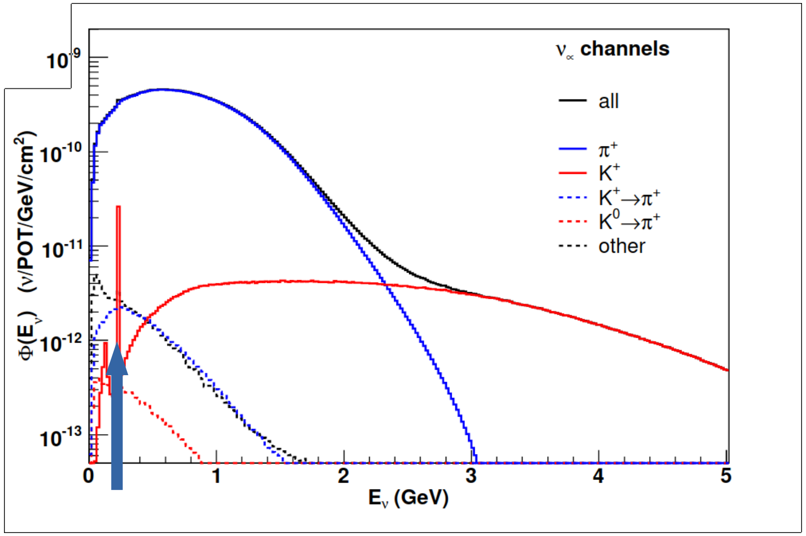
Alexis Nikolakopoulos

Based on work with N. Jachowicz, V. Pandey & J. Spitz

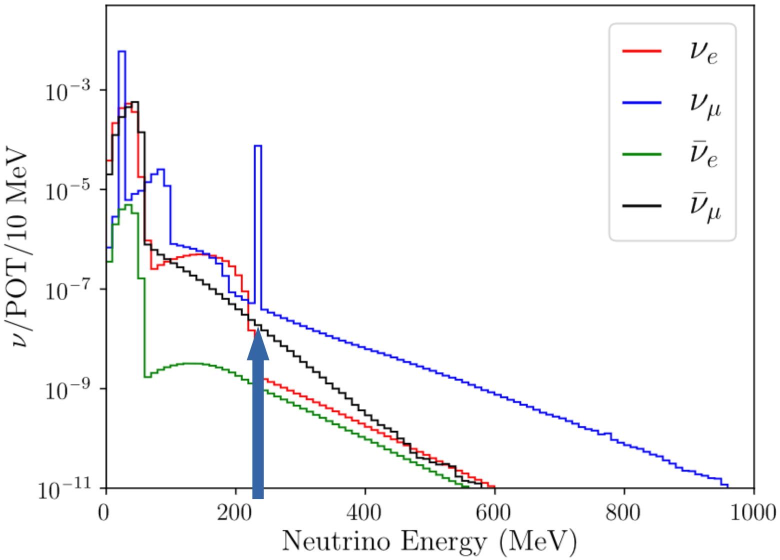
Interplay of Nuclear, Neutrino and BSM Physics at Low-Energies
INT, University of Washington, 20 April 2023

Muon neutrinos from stopped Kaon's in the absorber

MiniBooNE



JSNS[2]



KDAR produces ν_μ with E_ν = 236 MeV

What I will talk about

Opportunity of study of the nuclear response with monoenergetic ν_μ

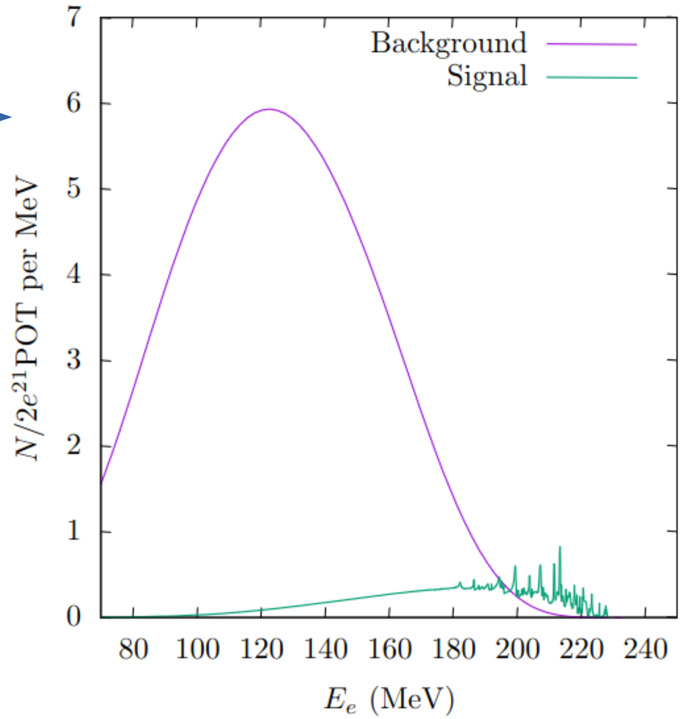
1. Angular dependence of electroweak nuclear response
2. Complementary electron scattering data
3. Measurements of KDAR ν_μ cross sections

What I will NOT talk about

KDAR ν_μ oscillations on short-baselines to study MB excess

[J Spitz, PRD 85 093020]

Electron appearance in ν_μ from KDAR
Background from ν_e decays
In LarTPC



[Phys. Rev. C 103, 064603 (2021)]

What I will NOT talk about

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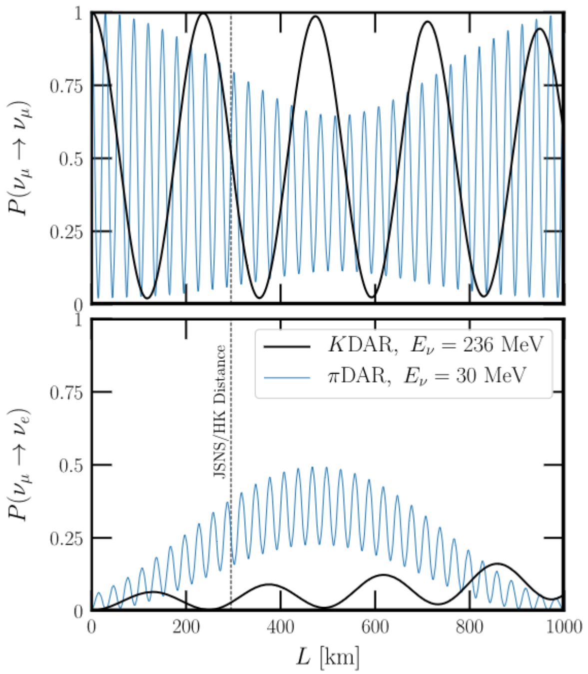
Long-baseline $\nu_\mu \rightarrow \nu_e$ oscillations with KDAR ν_μ from J-PARC MLF in HyperK

[R. Harnik, K.J. Kelly, P. Machado, PRD 101, 033008 (2020)]

'standard' 3ν oscillations at a fixed E/L



Fermilab

What I will NOT talk about

KDAR ν_μ oscillations on short-baselines to study MB excess

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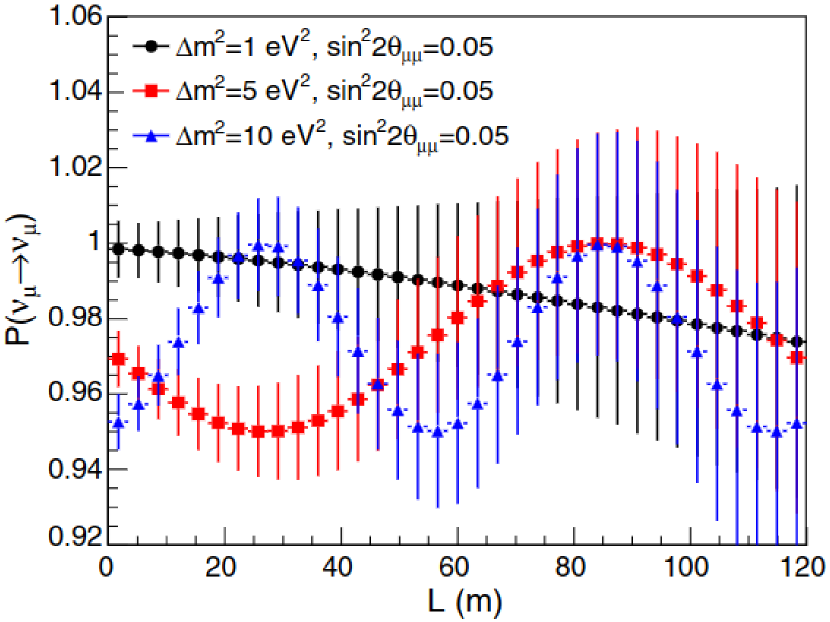
"Kpipe": A proposed 120 m long detector at JPARC MLF to search
For ν_μ dissapearance at short-baseline

[S. Axani, G. Collin, J. M. Conrad, M. H. Shaevitz, J. Spitz, and T. Wongjirad PRD 92, 092010]



Some generalities

$$\frac{\mathrm{d}\sigma_X}{\mathrm{d}E_f \mathrm{d}\cos\theta_f} = \frac{F_X^2 E_f k_f}{2\pi} \times \left[(V_{CC} R_{CC} + V_{CL} R_{CL} + V_{LL} R_{LL}) + (V_T R_T + h V_{T'} R_{T'}) \right].$$

$$J^\mu(q) = \int d\vec{r} e^{-i\vec{q}\cdot\vec{r}} \mathcal{J}^\mu(\mathbf{r}),$$

$$\mathcal{M}_{JM} = \int d\vec{r} [j_J(qr) Y_{JM}(\Omega_r)] \mathcal{J}^0(\vec{r})$$

$$\mathcal{L}_{JM} = \frac{i}{q} \int d\vec{r} \left[\vec{\nabla} (j_J(qr) Y_{JM}(\Omega_r)) \right] \cdot \vec{\mathcal{J}}(\vec{r})$$

$$\mathcal{T}_{JM}^{el} = \frac{1}{q} \int d\vec{r} \left[\vec{\nabla} \times j_J(qr) \vec{\mathcal{Y}}_{J(J,1)}^M(\Omega_r) \right] \cdot \vec{\mathcal{J}}(\vec{r})$$

$$\mathcal{T}_{JM}^{mag} = \int d\vec{r} \left[j_J(qr) \vec{\mathcal{Y}}_{J(J,1)}^M(\Omega_r) \right] \cdot \vec{\mathcal{J}}(\vec{r}).$$

For 1-boson exchange
(No coulomb, radiation)

Separation in lepton factors
V(E,E',cosθ,m$_l$)

And nuclear responses
R(ω, q)

ω = E – E', q = | ***k*** – ***k'*** |

Some generalities

$$\frac{\mathrm{d}\sigma_X}{\mathrm{d}E_f \mathrm{d}\cos\theta_f} = \frac{F_X^2 E_f k_f}{2\pi} \times \left[(V_{CC}R_{CC} + V_{CL}R_{CL} + V_{LL}R_{LL}) + (V_T R_T + hV_{T'}R_{T'})\right].$$

$$R_{CC} = \sum_{J\geq 0}\sum_{J_f,J_i} |\langle J_f \| \mathcal{M}_J \| J_i\rangle|^2,$$

$$R_{LL} = \sum_{J\geq 0}\sum_{J_f,J_i} |\langle J_f \| \mathcal{L}_J \| J_i\rangle|^2,$$

$$R_{CL} = \sum_{J\geq 0}\sum_{J_f,J_i} 2\mathrm{Re}\left[\langle J_f \| \mathcal{M}_J \| J_i\rangle \langle J_f \| \mathcal{L}_J \| J_i\rangle^*\right],$$

$$R_T = \sum_{J\geq 1}\sum_{J_f,J_i} |\langle J_f \| \mathcal{T}_J^{el} \| J_i\rangle|^2 + |\langle J_f \| \mathcal{T}_J^{mag} \| J_i\rangle|^2,$$

$$R_{T'} = \sum_{J\geq 1}\sum_{J_f,J_i} 2\mathrm{Re}\left[\langle J_f \| \mathcal{T}_J^{el} \| J_i\rangle \langle J_f \| \mathcal{T}_J^{mag} \| J_i\rangle^*\right],$$

→ Pure VA-interference

For 1-boson exchange (No coulomb)

Separation in lepton factors $V(E,E',\cos\theta,m_l)$

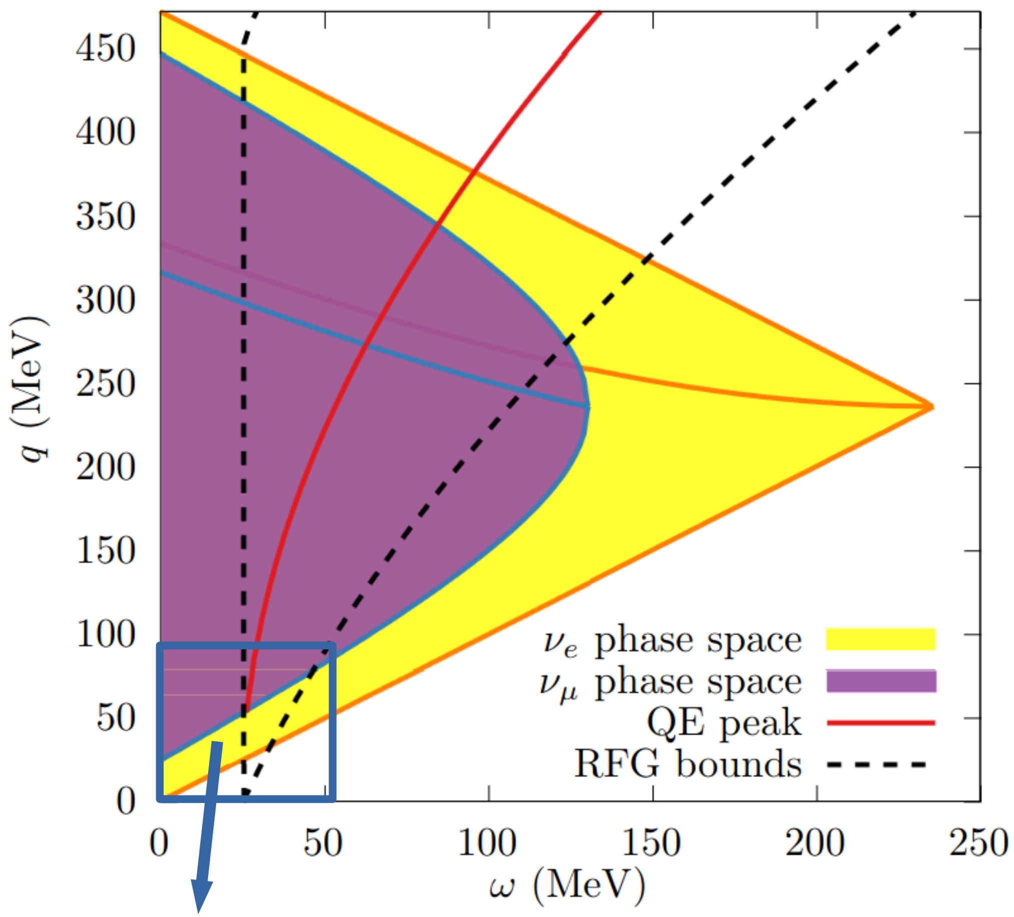
And nuclear responses $R(\omega, q)$

$\omega = E - E'$, $q = |\,\mathbf{k} - \mathbf{k'}\,|$

$R_X = R_X^{AA} + R_X^{VV}$

$R_{X'} = R^{VA}_{X'}$

KDAR phase space in energy- momentum transfer: Charged-current



Phase space for πDAR ν_e

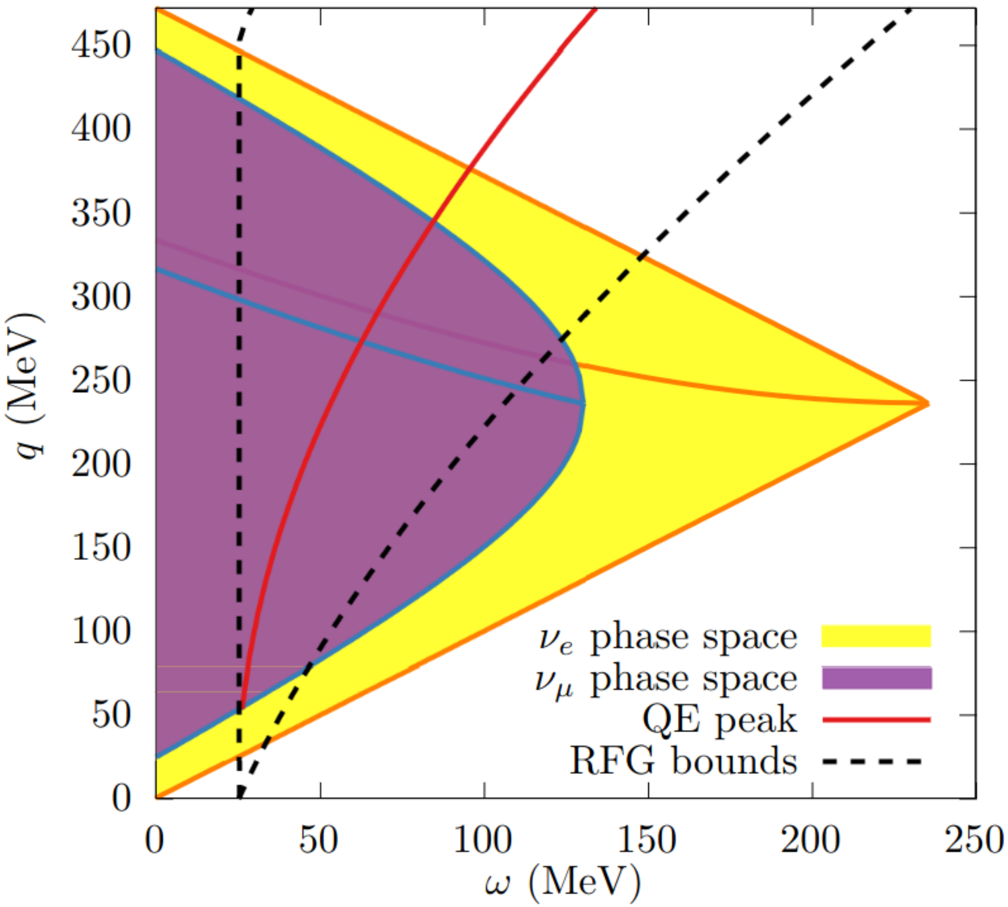
KDAR ν_μ live in a 'transition region' between 'QE' scattering and low-energy excitations

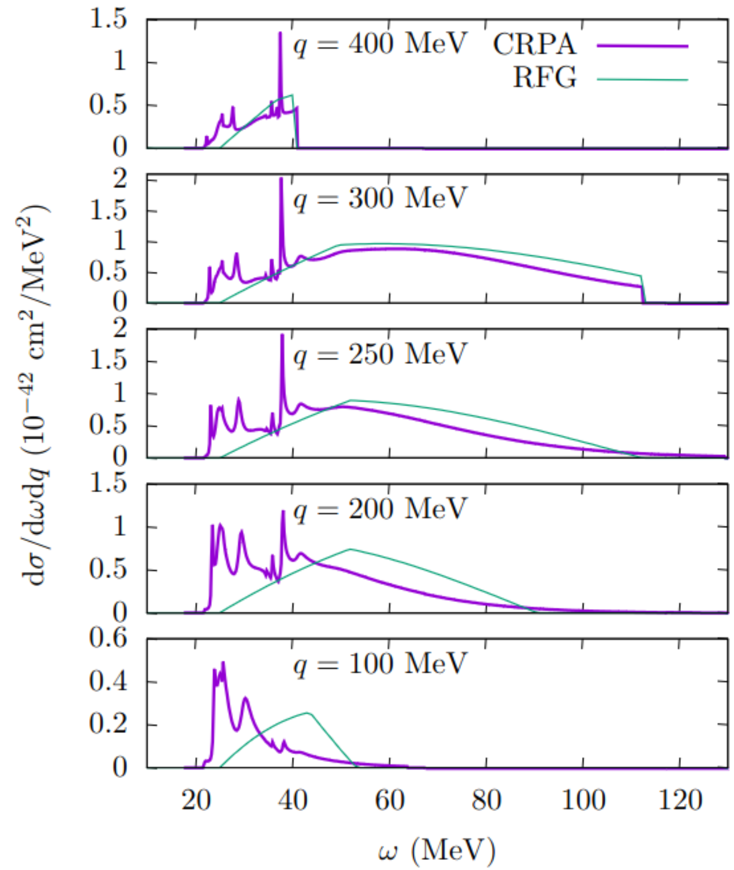
Monoenergetic **CC** scattering → muon as a clear observable

Can use the muon angle to probe momentum transfer

KDAR phase space in energy- momentum transfer: Charged-current

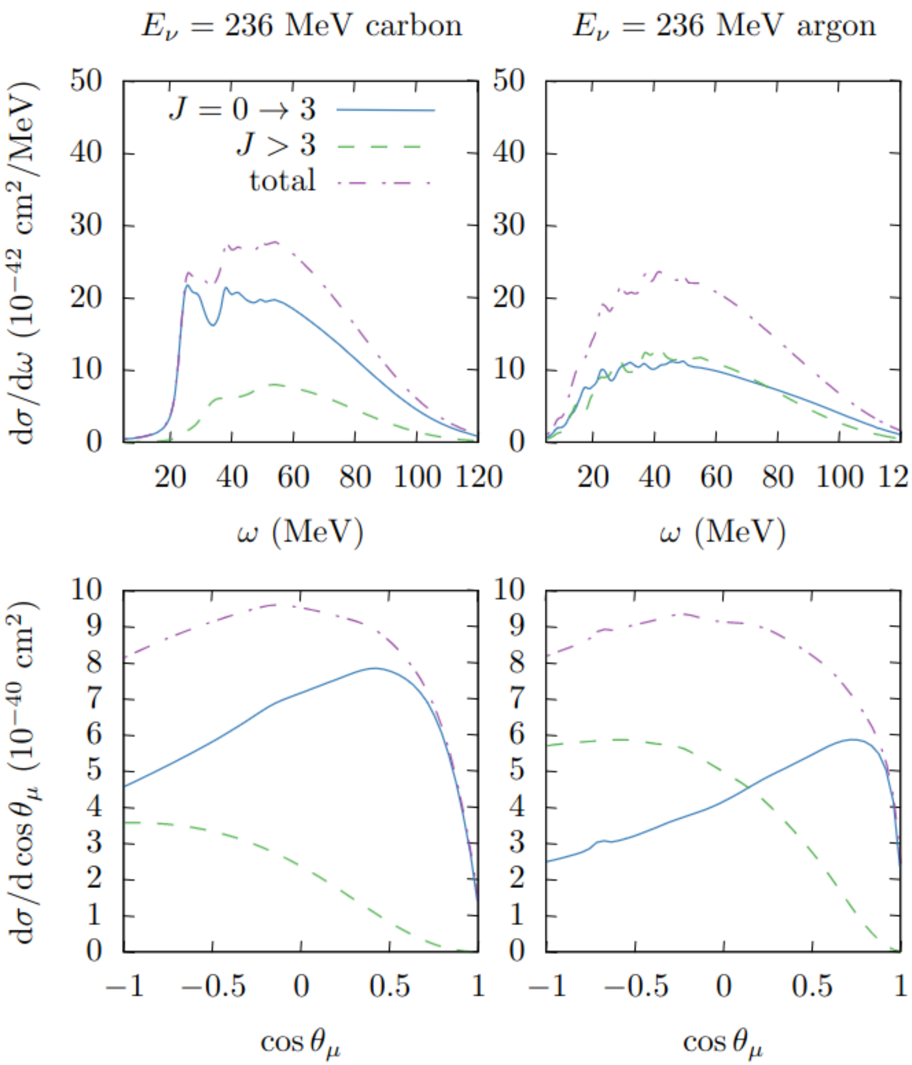
'Transition region'



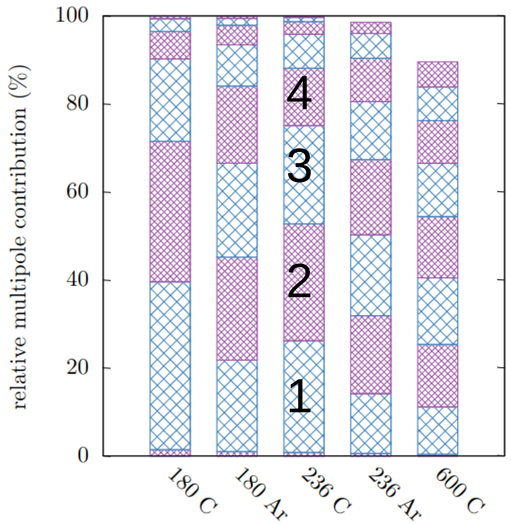


Momentum transfer q ↔ $cos\theta_\mu$ → Inclusive measurements with angular resolution?

Angular dependence of multipole contributions



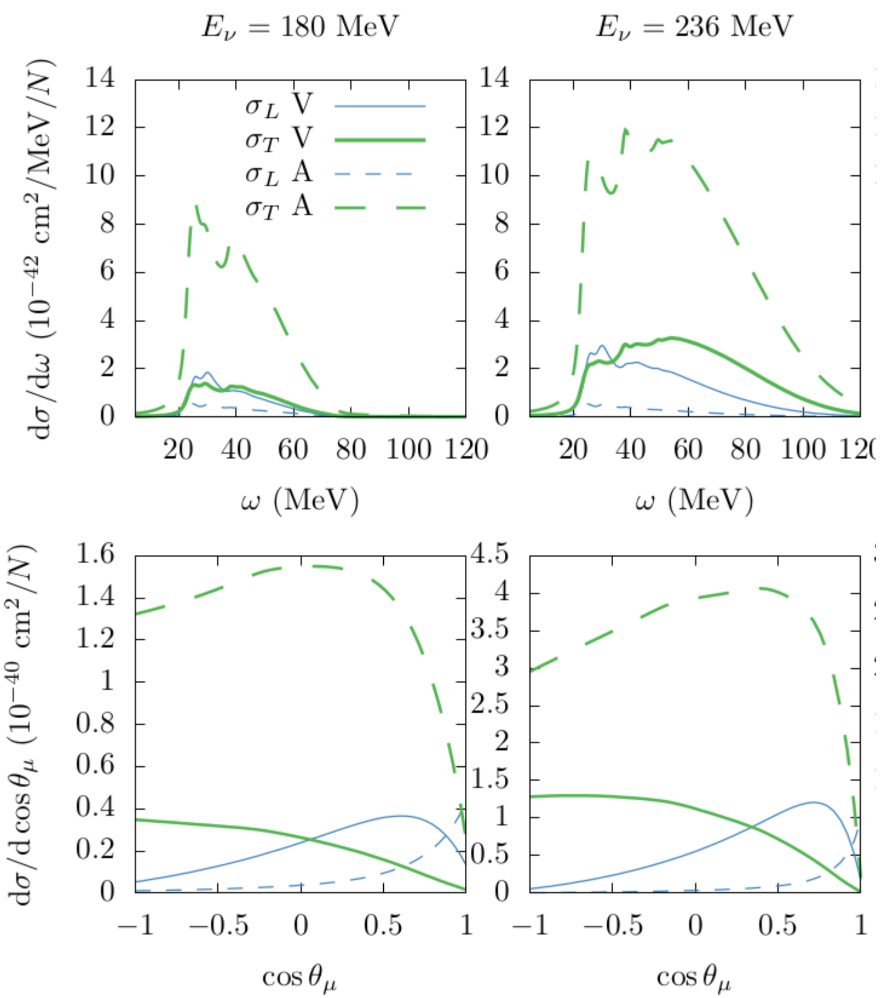
Multipole contributions



Carbon CS ~ 6 MPs
Argon CS ~ 9 MPs

Carbon: separate low-w structure
From ~3 MP at forward angles

Vector and Axial-vector contributions



$$V_{CC} = 1 + \frac{k_l}{E_l}\cos\theta_l,$$

$$V_{CL} = -\left(\frac{\omega}{q}V_{CC} + \frac{m_l^2}{E_l q}\right),$$

$$V_{LL} = V_{CC} - \frac{2E_i E_l}{q^2}\left(\frac{k_l}{E_l}\right)^2 \sin^2\theta_l,$$

$$V_T = 2 - V_{CC} + \frac{E_i E_l}{q^2}\left(\frac{k_l}{E_l}\right)^2 \sin^2\theta_l,$$

$$V_{T'} = \frac{E_i + E_l}{q}(2 - V_{CC}) - \frac{m_l^2}{E_f q}.$$

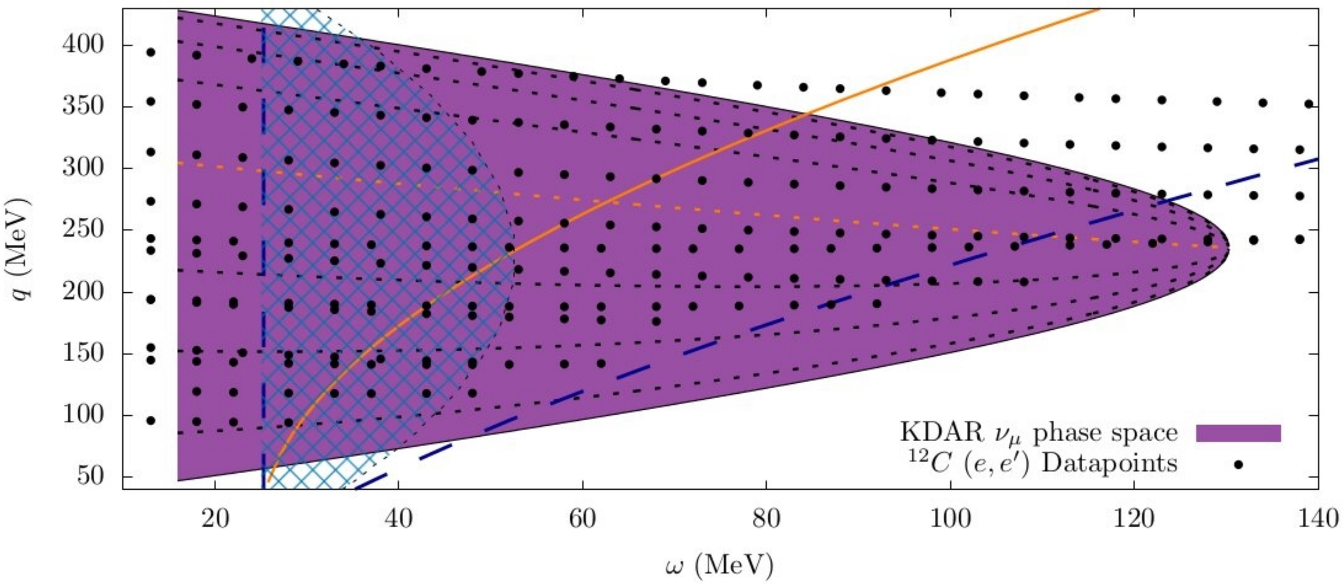
$$\frac{\mathrm{d}\sigma_X}{\mathrm{d}E_f \mathrm{d}\cos\theta_f} = \frac{F_X^2 E_f k_f}{2\pi} \times \left[(V_{CC}R_{CC} + V_{CL}R_{CL} + V_{LL}R_{LL}) + (V_T R_T + hV_{T'}R_{T'})\right].$$

σ_L ← $(V_{CC}R_{CC} + V_{CL}R_{CL} + V_{LL}R_{LL})$

σ_T ← $(V_T R_T + hV_{T'}R_{T'})$

Forward-backward separation L T

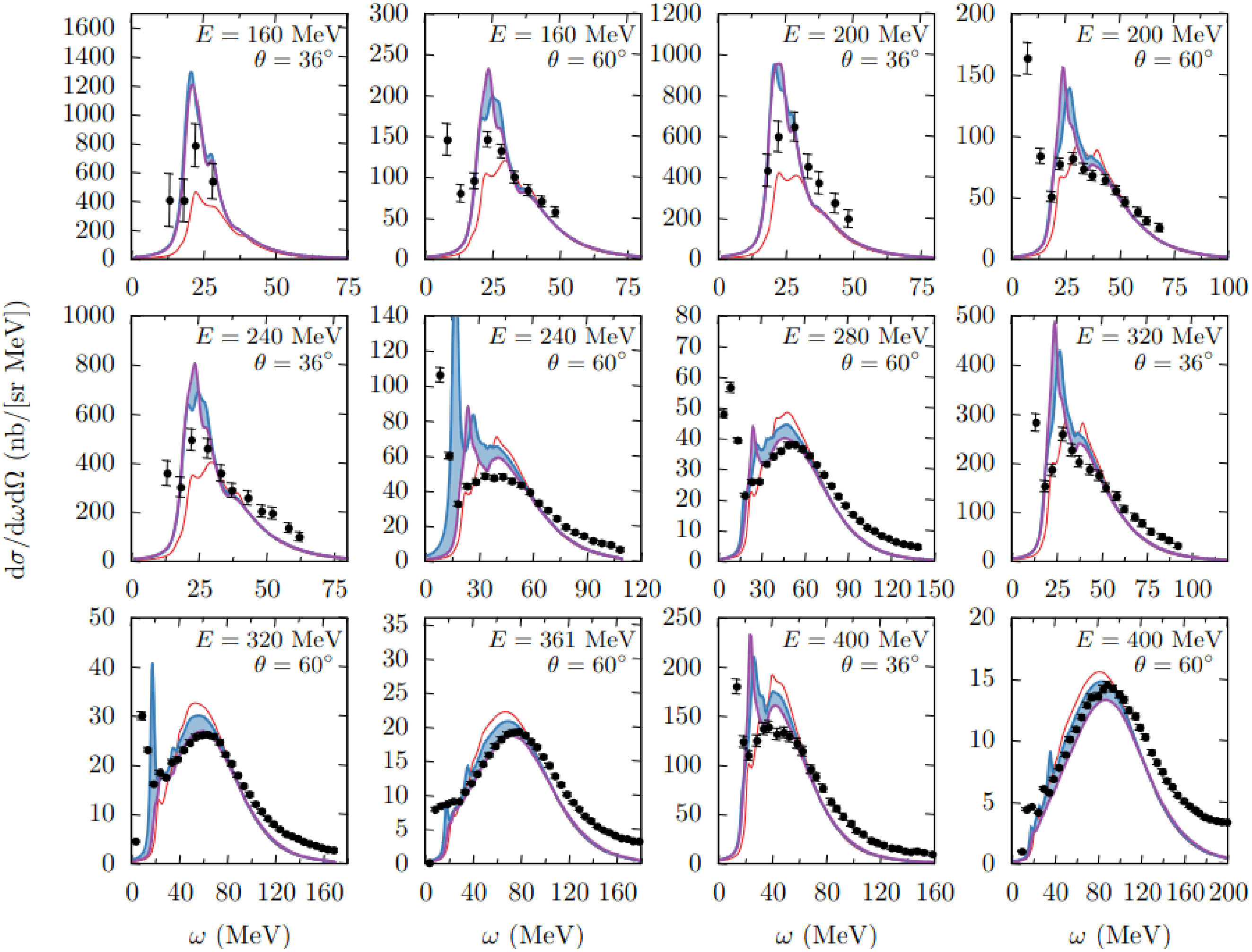
Electron scattering in KDAR phase-space



Available phase space almost fully covered by (e,e') scattering on ^{12}C
→ Can probe nuclear phase space with both e and ν!

+New ^{40}Ar data from Mainz (E=240, **θ=20º**), see talk J. Sobczyk

Electron scattering in KDAR phase-space: ^{12}C
HF-CRPA calculations (N. Jachowicz talk)



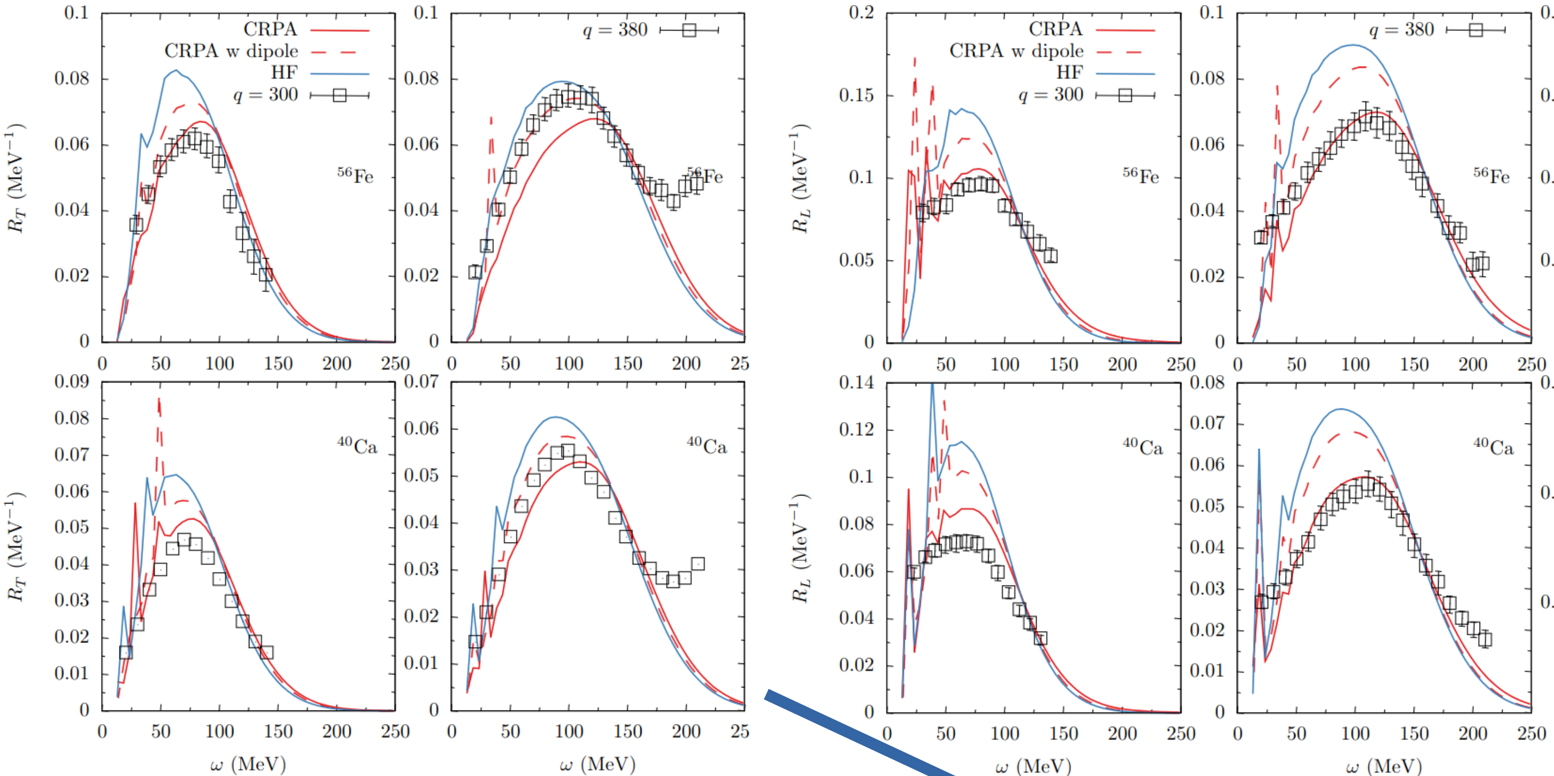
Sk-HF
CRPA w cut-off
CRPA

Cut-off FF in residual interaction Included

Low-q : prefer no FF
High-q : FF needed

Electron scattering in KDAR phase-space: Heavier targets

R_T R_L



Fe

Ca

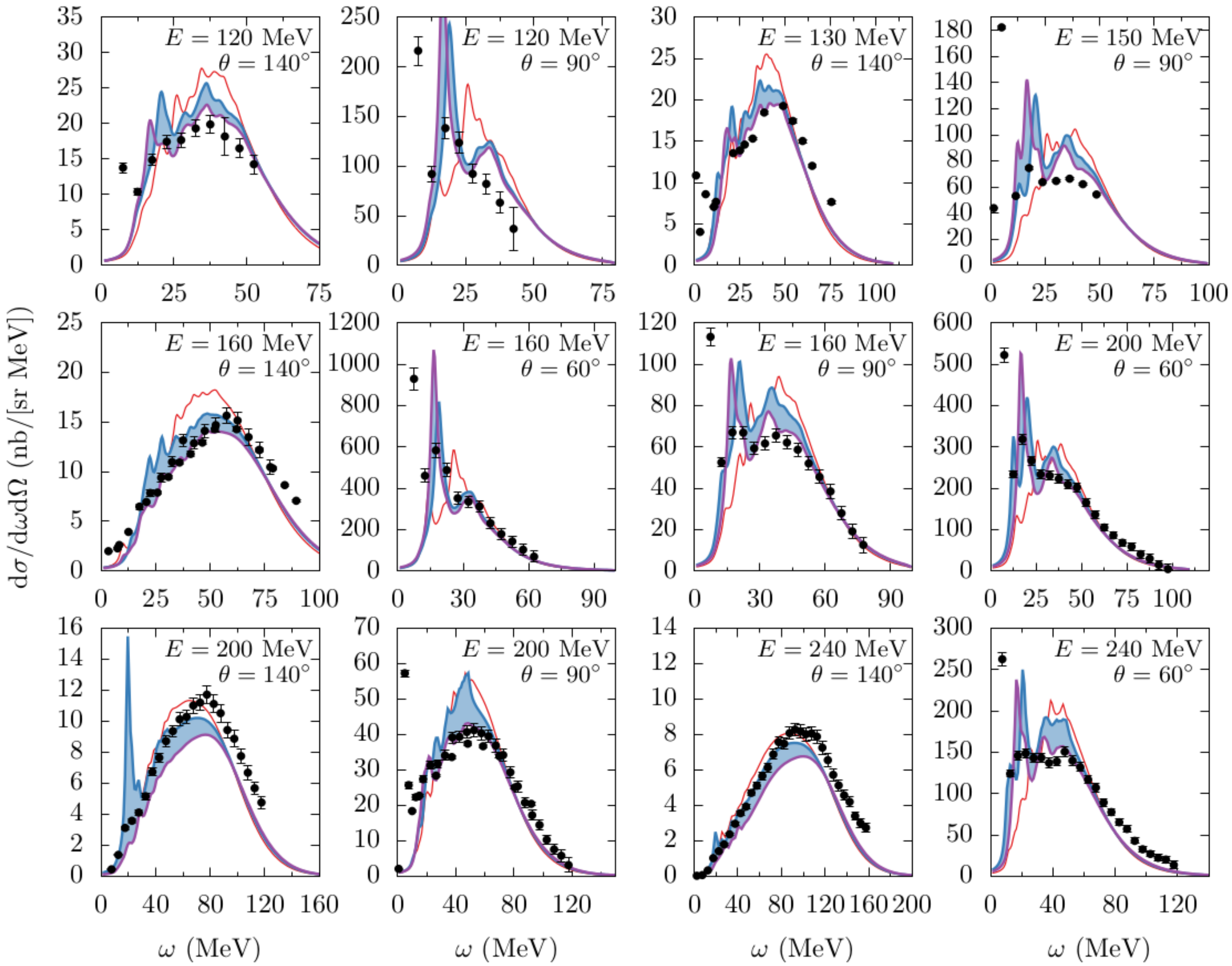
Low-q: no FF, high-q : FF needed ?

R_T behaviour

$$\frac{d\sigma}{d\omega d\Omega} = \sigma_{\mathrm{Mott}} \left[\frac{Q^4}{q^4} R_L + \left(\frac{Q^2}{2q^2} + \tan^2 \frac{\theta_l}{2} \right) R_T \right]$$

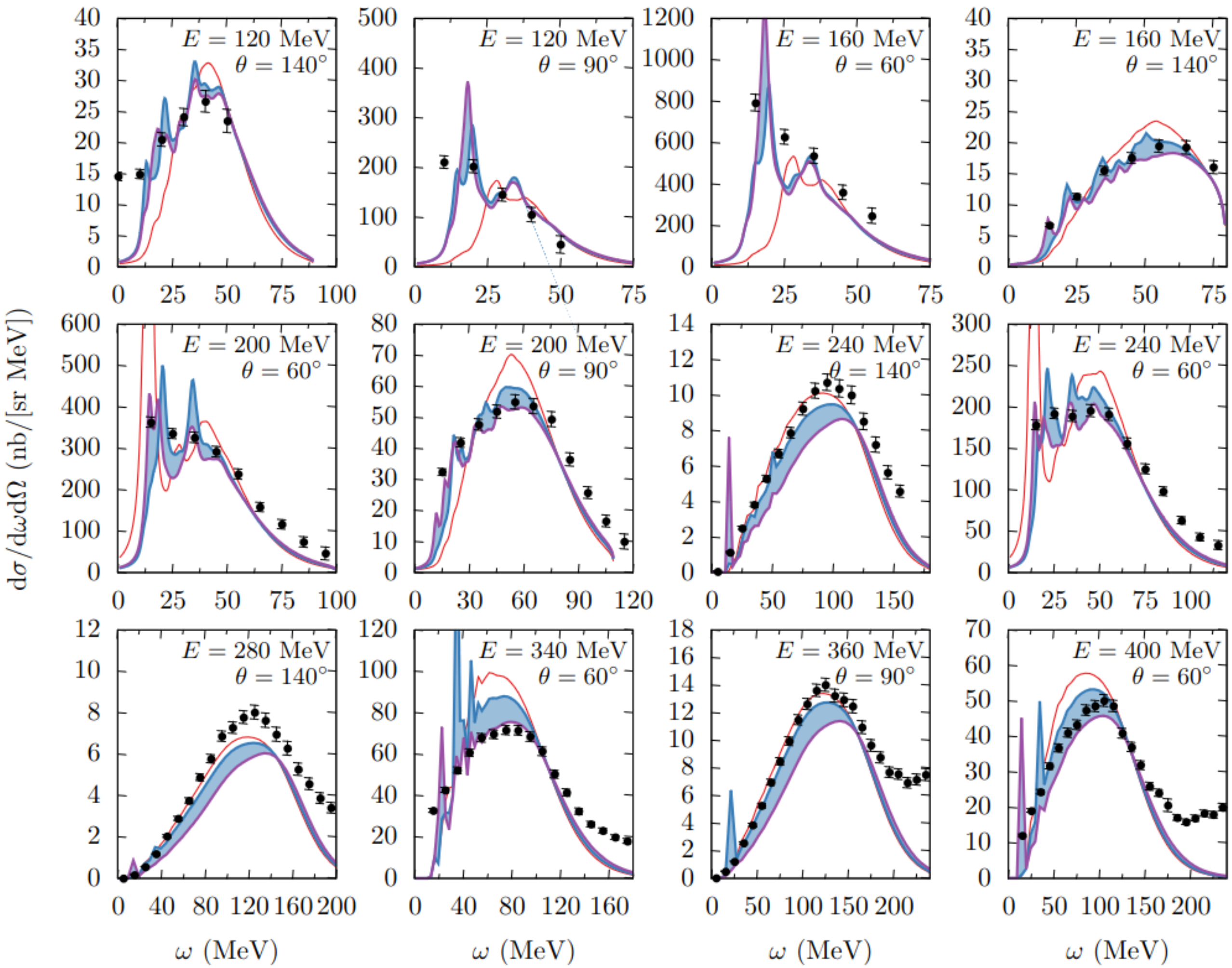
Electron scattering in KDAR phase-space: ^{40}Ca

More detailed information from directly comparing to the cross section



Sk-HF
CRPA w cut-off
CRPA

Electron scattering in KDAR phase-space: ^{56}Fe



Sk-HF
CRPA w cut-off
CRPA

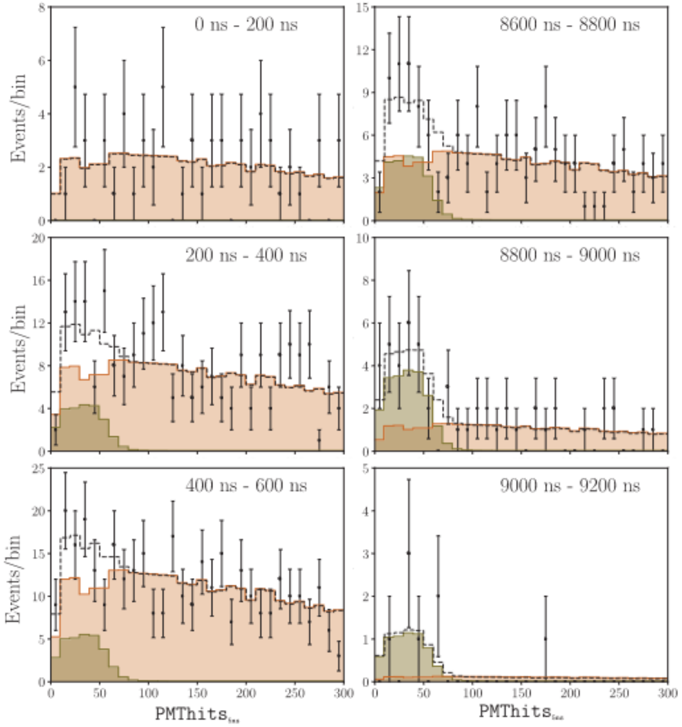
Robust results for ^{12}C, ^{40}Ca, ^{56}Fe

Measurements of KDAR muon neutrino interactions

MiniBooNE

PRL 120, 141802 (2018)

Isolate KDAR ν_μ from NuMI absorber

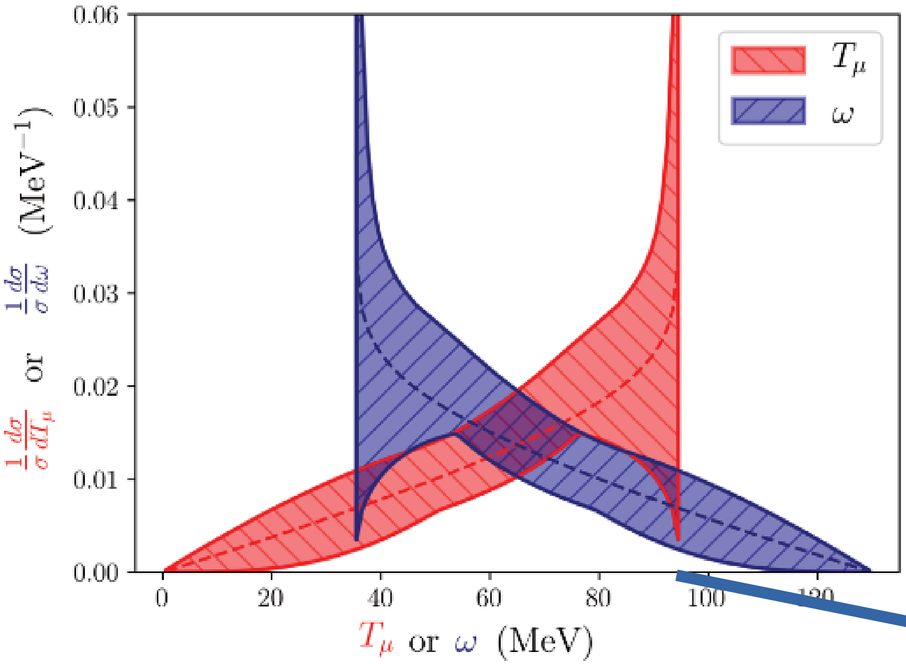


Timing info to separate from in-flight

Fermilab

MiniBooNE shape measurement

PRL 120, 141802 (2018)



MiniBooNE performs a 'template-based' analysis

$$x^{a-1}(1-x)^{b-1}\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}, \qquad x = \frac{T_\mu}{T_\mu^{max}}$$

Testing the consistency of the parametrized spectrum shape with the signal

Depends on parameter T_μ^{max}

MB prefers T_μ^{max} = 95 MeV

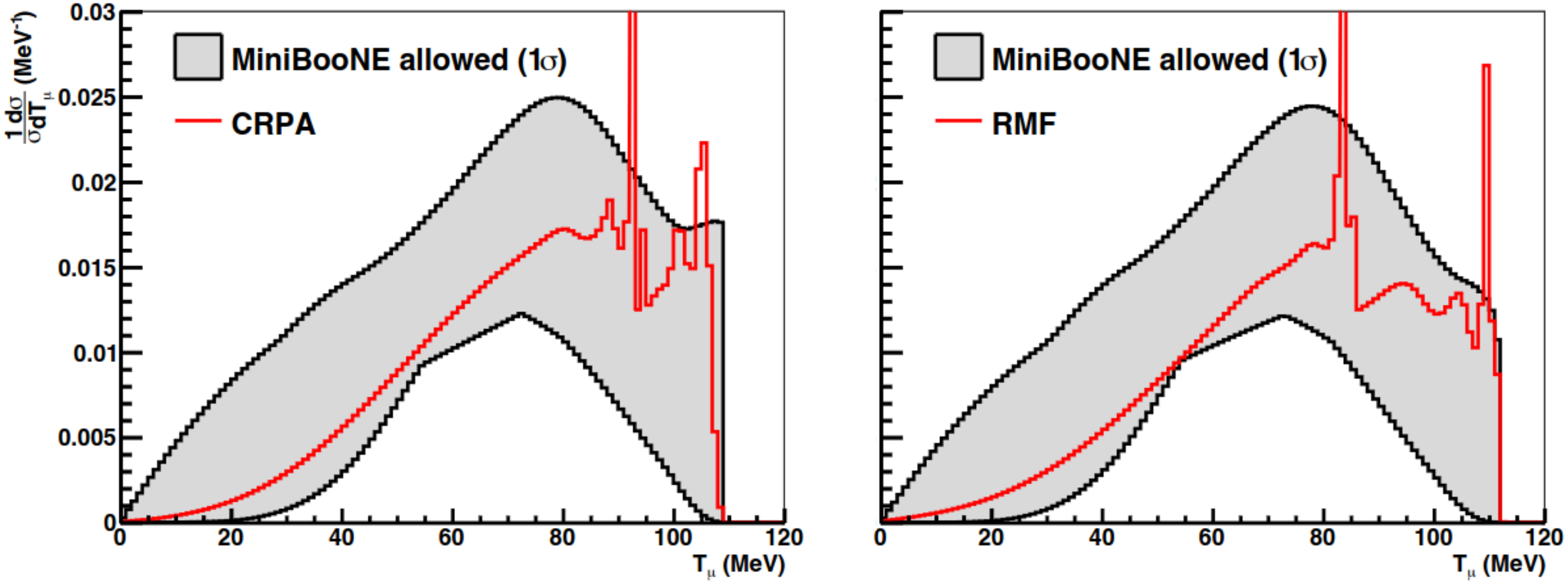
In principle $T_\mu^{max} = E_\nu - m_\mu \approx 130$ MeV

Fermilab

MiniBooNE shape measurement

PRL 120, 141802 (2018)

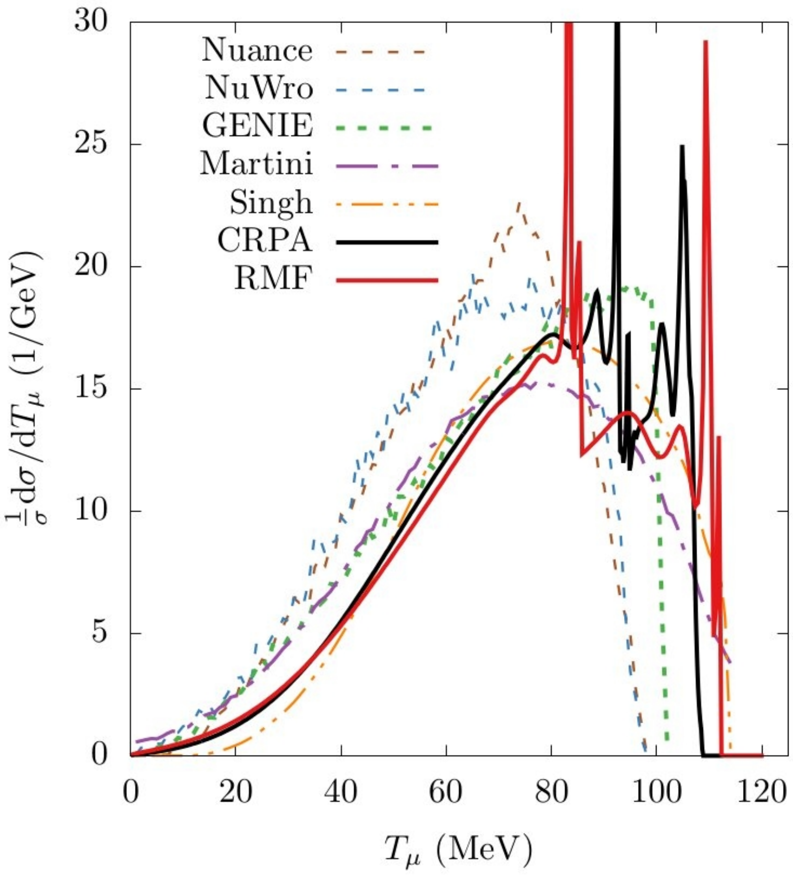
$$x^{a-1}(1-x)^{b-1}\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}, \qquad x = \frac{T_\mu}{T_\mu^{max}}$$



Comparison to MB best fit template as function of endpoint (online tool)

Note: Best fit shape changes with the 'endpoint'

MiniBooNE comparison: Model comparisons

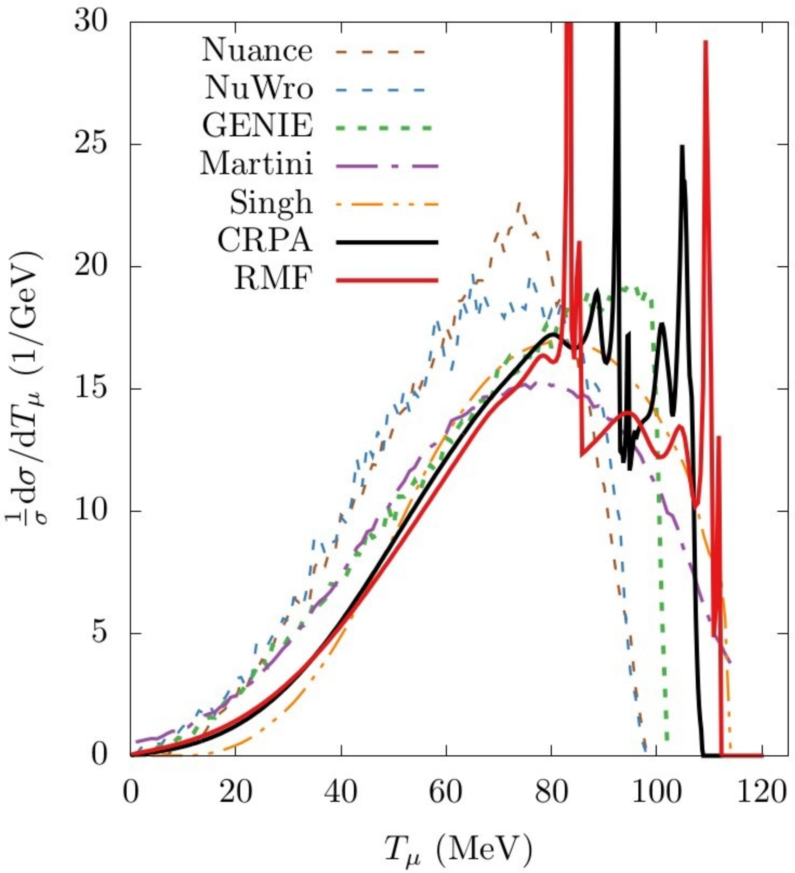


Model	$\Delta\chi^2$	χ^2 Prob.	σ $(10^{-39}cm^2)$
Nuance	2.64	0.45	1.4
NuWro	2.07	0.56	1.3 + 0.4 (np-nh)
GENIE	0.95	0.81	1.75
Martini	2.15	0.54	1.3 + 0.2 (np-nh)
Singh	3.90	0.27	0.91
CRPA	3.20	0.36	1.58
RMF	3.49	0.27	1.56
RFG	1.69	0.64	1.66
RFG34	4.16	0.25	1.38
MB data	-	-	2.7 ± 1.2

χ^2 basically driven by endpoint

Shape-only comparisons of different models

MiniBooNE comparison: Model comparisons & Total cross sections



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Total cross sections

Most ~ 1.5 – 1.7 10^{-39} cm2/N

RFG34 & NUANCE ~ 1.4 10^{-39} cm2/N

Singh ~ 0.91 10^{-39} cm2/N

see also [Prog.Part.Nucl.Phys. 129 (2023) 104019]

Fermilab

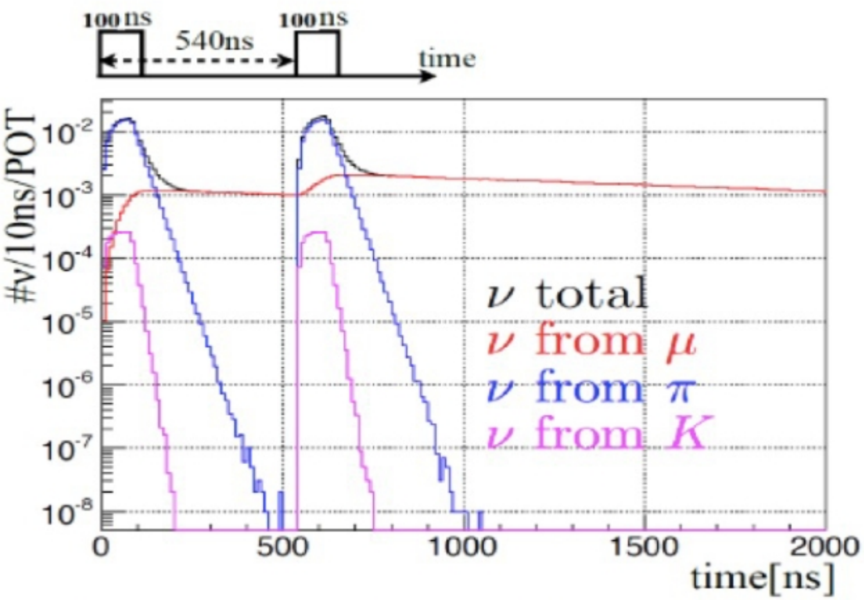
JSNS^2 measurement on carbon (from Hyoungku Jeon talk NuFACT22)

Measure the total visible energy:

$$E_{vis} = E_{\nu} - m_{\mu} - T_X$$

Invisible energy e.g. neutrons

Sensitive to specific decay channel of nucleus



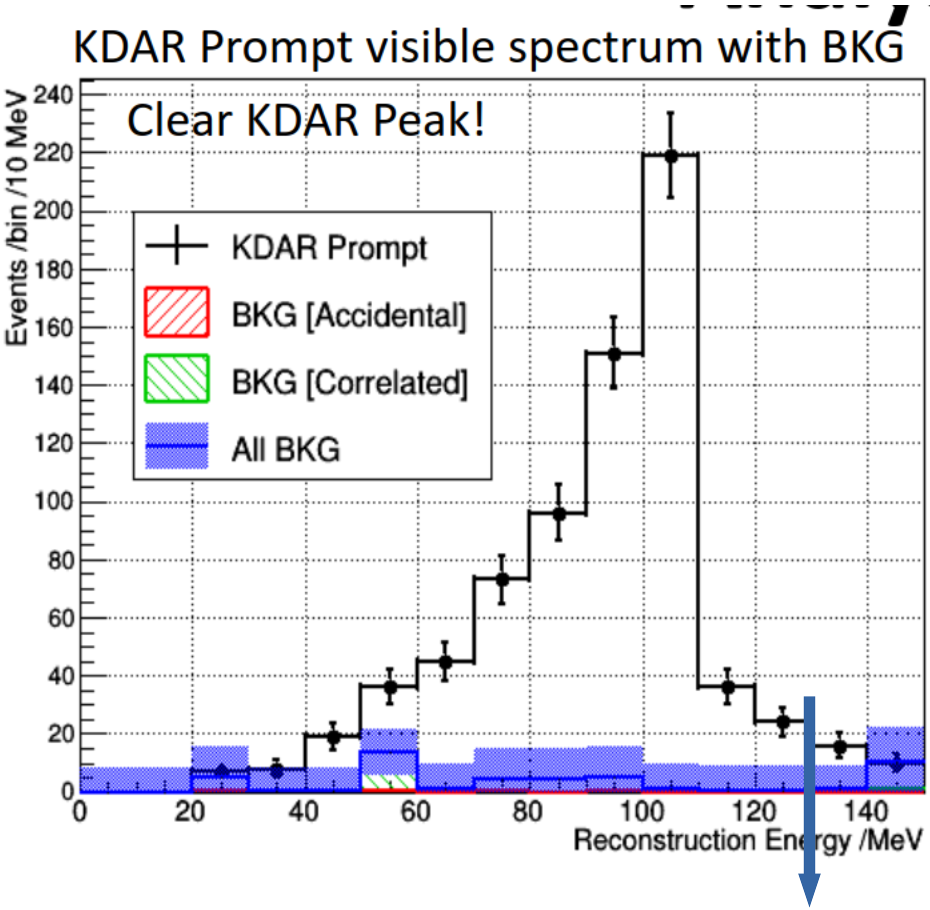
- The time distribution of neutrinos from pion, muon and kaon decays.
- the neutrino from kaon is concentrated at the proton beam bunch timing.

$JSNS^2$ measurement
(from Hyoungku Jeon talk NuFACT22)

Measure the total visible energy:

$E_{vis} = E_\nu - m_\mu - T_X$

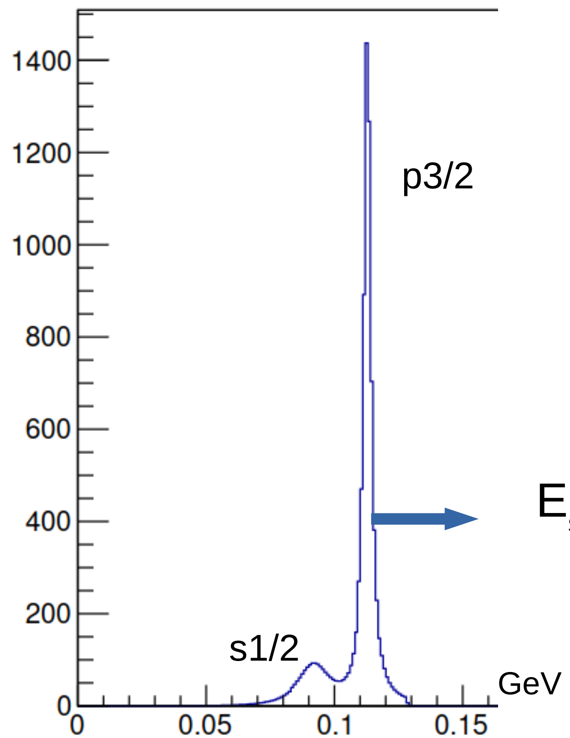
Sensitive to specific decay channel of nucleus



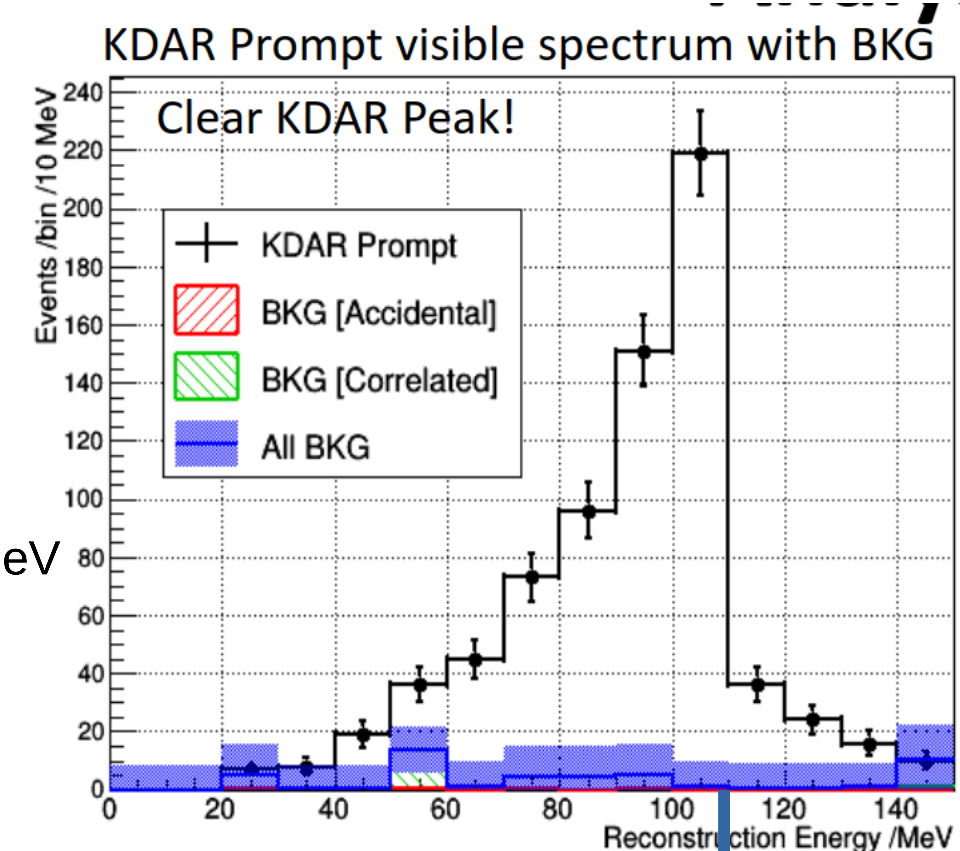
$E_{vis}^{max} = E_\nu - m_\mu$

JSNS^2 measurement

Missing energy spectrum (ν,μ p)



$E_s \approx 16$ MeV



$E_\nu - m_\mu - E_s$

RMF calculation exclusive (no FSI)
w Benhar spectral function

Clear smearing of spectrum in data
Need good final-state approach

Conclusions

- KDAR ν_μ provide charged-current signal with E_ν = 236
  → muon kinematics as a 'clean' observable

- Muon angle dependence carries information on responses and separates low- energy excitations from 'QE'-region

- Large body of electron scattering information in the KDAR phase space
  → Combined data constraints from *e* and ν probe axial current

- HF-CRPA calculations provide robust results for different nuclei in this kinematic region
  → Exact treatment of the continuum provides smooth behaviour over regimes

- KDAR measurements of MiniBooNE: inclusive energy spectrum
- KDAR measurements of JSNS^2 : missing energy distribution
  → Requires control over 'FSI' and deexcitations
  → Where does the FSI picture change ?