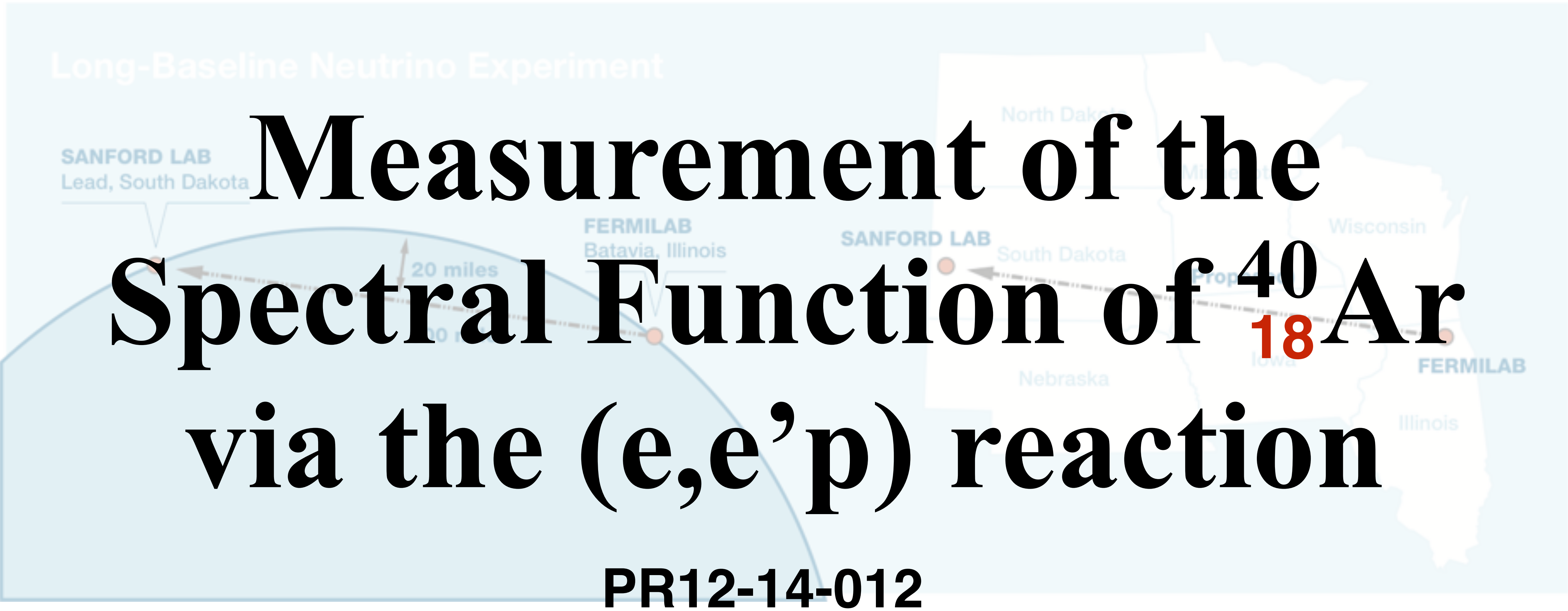
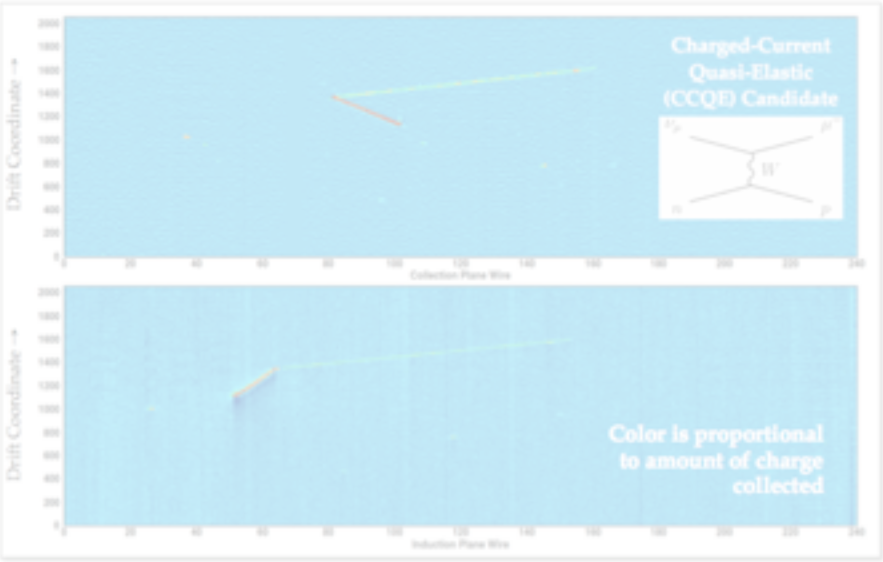
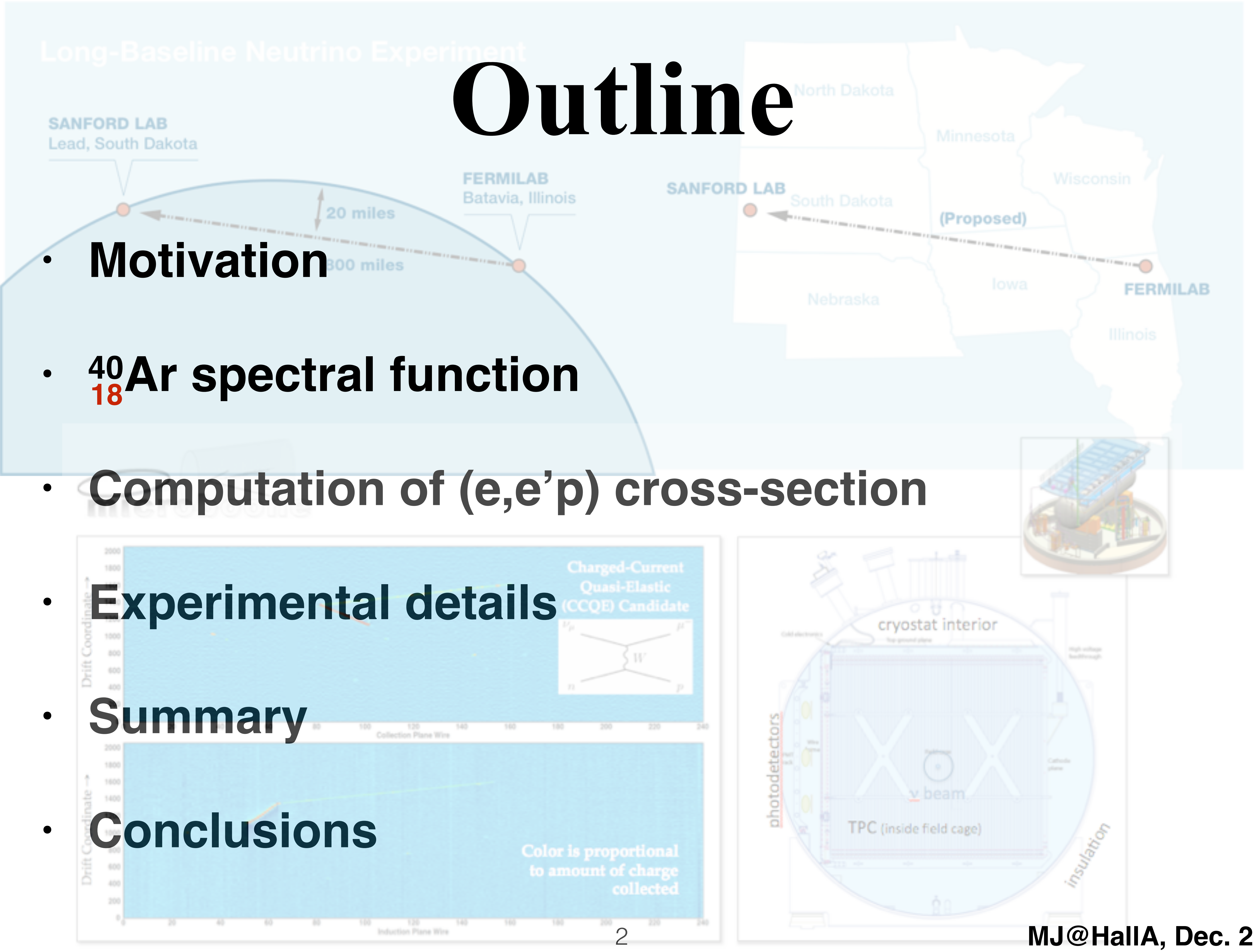


Measurement of the Spectral Function of $^{40}_{18}$Ar via the (e,e'p) reaction

PR12-14-012
Chun-Min Jen@Virginia Tech (12/09/14')
2014 Winter Hall-A Collaboration Meeting



Outline



- Motivation
- $^{40}_{18}$Ar spectral function
- Computation of (e,e’p) cross-section
- Experimental details
- Summary
- Conclusions

Motivation

Why do neutrino people need to borrow electron beam time?

- the ***quantitative*** description of the response to the ***electro-weak interaction*** is required in order to accurately explain the the signals detected in accelerator based neutrino scattering experiments.

- various ***nuclear effects*** play a crucial role in the interpretation of data.

Why Neutrino Experiments (just "Counting" Experiments) are Relatively Much More Challenging than Electron Experiments?

○ beam : neutrino energies are needed to be quantified.

○ interaction : interaction type is needed to be classified.

Neutrino Beam Energy Reconstruction

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

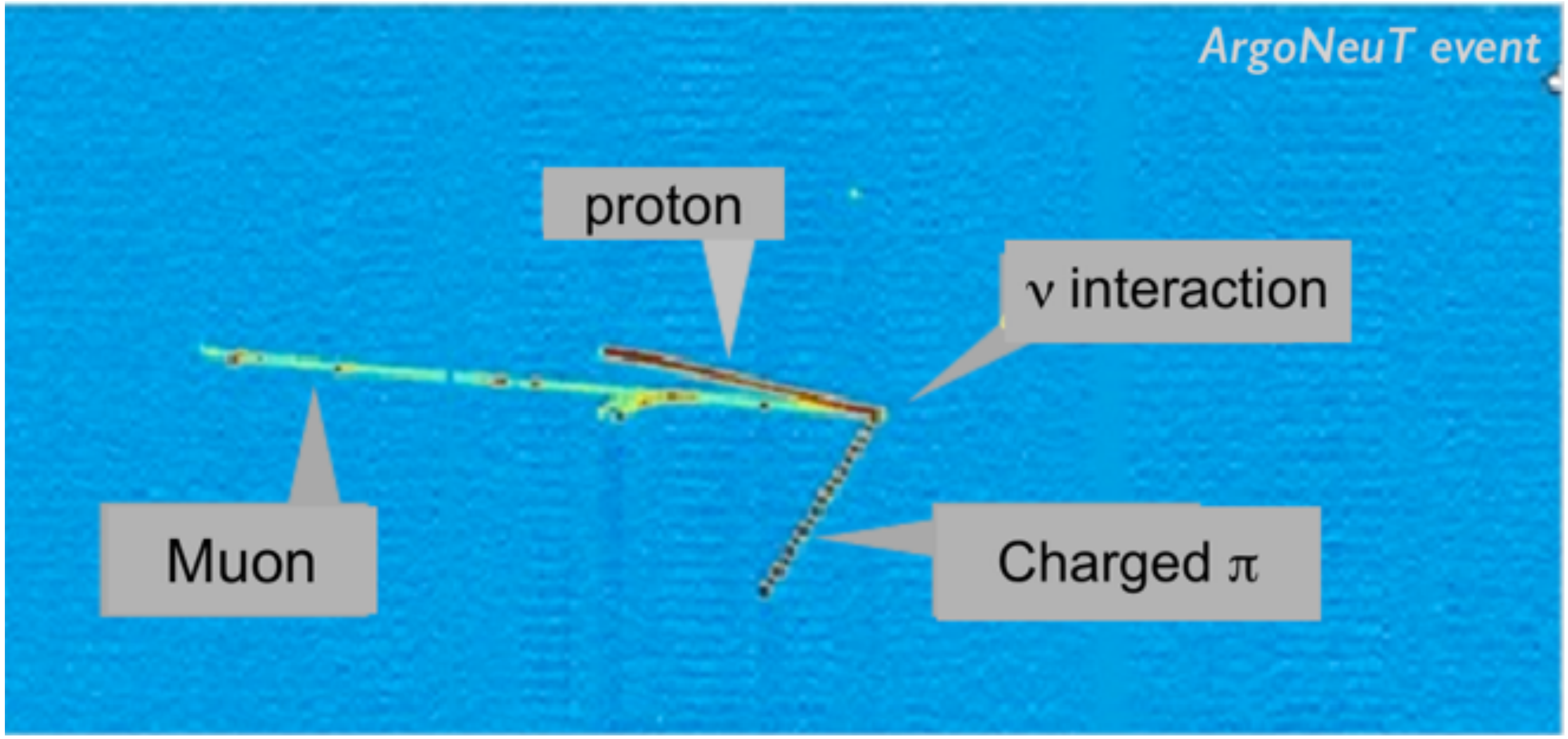
- ***Nature*** (unknown)
- ***Distance*** between near and far detectors - fixed (well-known)
- ***Reconstructed Neutrino Beam Energies*** (known but not precise enough due to ***many reasons***)

why neutrino experiments are very challenging?

1. beam energies (also, a range of Q^2) at the target (interaction vertex) are not fixed to one value.

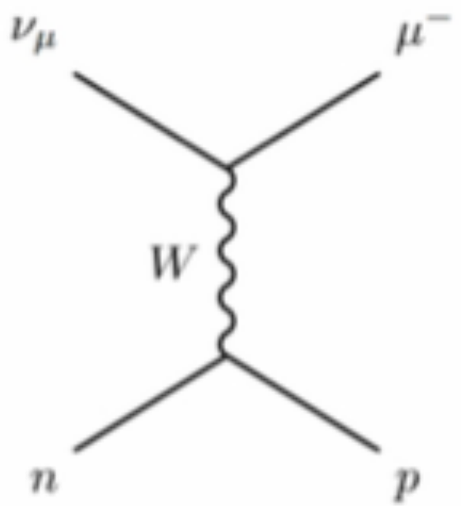
2. neutrino energy reconstruction involves the precise understanding of various nuclear effects, including final-state interaction to account for hadron re-interactions.

Neutrino Interaction Vertex Reconstruction



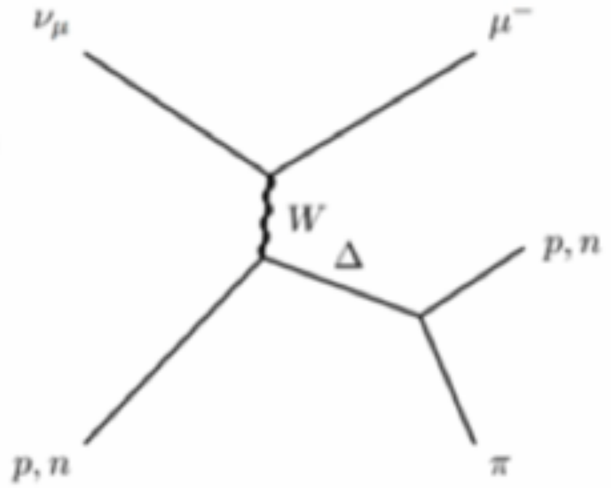
CC Quasi-elastic

nucleon changes,
but doesn't break up



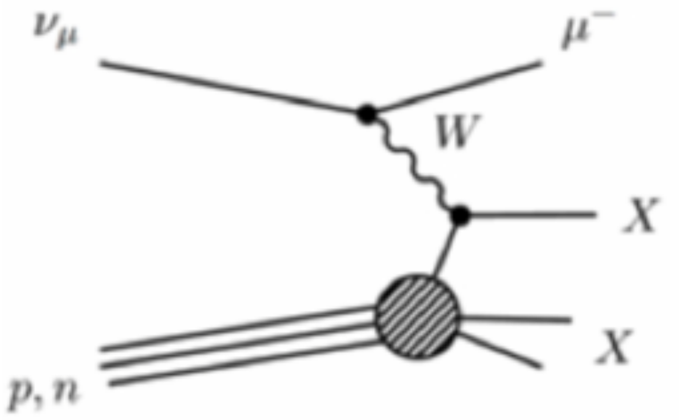
CC Single pion

nucleon excites to
resonance state



CC Deep Inelastic

nucleon breaks up



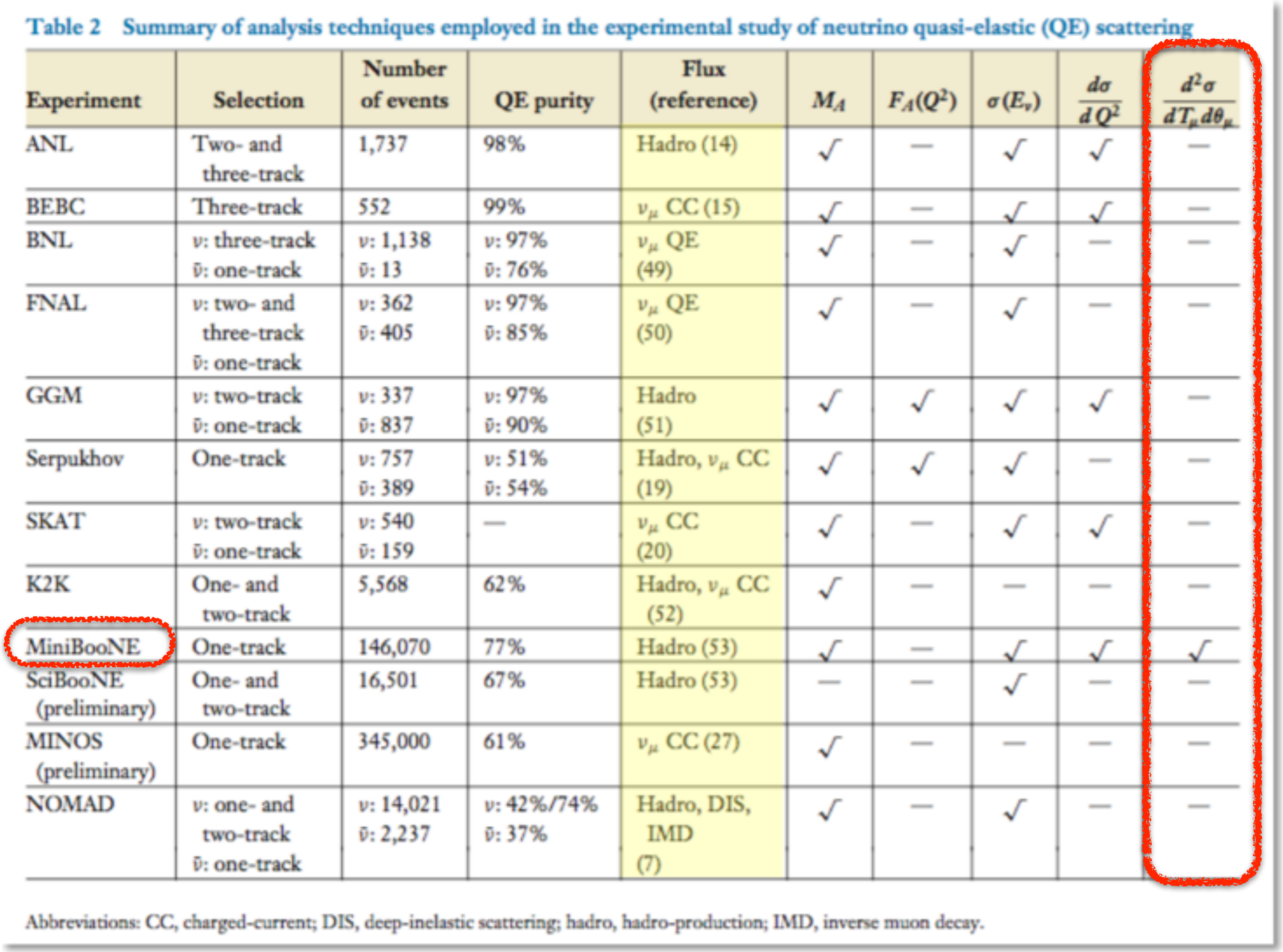


Table 2 Summary of analysis techniques employed in the experimental study of neutrino quasi-elastic (QE) scattering

Experiment	Selection	Number of events	QE purity	Flux (reference)	M_A	$F_A(Q^2)$	$\sigma(E_\nu)$	$\frac{d\sigma}{dQ^2}$	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$
ANL	Two- and three-track	1,737	98%	Hadro (14)	✓	—	✓	✓	—
BEBC	Three-track	552	99%	ν_μ CC (15)	✓	—	✓	✓	—
BNL	ν: three-track $\bar{\nu}$: one-track	ν: 1,138 $\bar{\nu}$: 13	ν: 97% $\bar{\nu}$: 76%	ν_μ QE (49)	✓	—	✓	—	—
FNAL	ν: two- and three-track $\bar{\nu}$: one-track	ν: 362 $\bar{\nu}$: 405	ν: 97% $\bar{\nu}$: 85%	ν_μ QE (50)	✓	—	✓	—	—
GGM	ν: two-track $\bar{\nu}$: one-track	ν: 337 $\bar{\nu}$: 837	ν: 97% $\bar{\nu}$: 90%	Hadro (51)	✓	✓	✓	✓	—
Serpukhov	One-track	ν: 757 $\bar{\nu}$: 389	ν: 51% $\bar{\nu}$: 54%	Hadro, ν_μ CC (19)	✓	✓	✓	—	—
SKAT	ν: two-track $\bar{\nu}$: one-track	ν: 540 $\bar{\nu}$: 159	—	ν_μ CC (20)	✓	—	✓	✓	—
K2K	One- and two-track	5,568	62%	Hadro, ν_μ CC (52)	✓	—	—	—	—
MiniBooNE	One-track	146,070	77%	Hadro (53)	✓	—	✓	✓	✓
SciBooNE (preliminary)	One- and two-track	16,501	67%	Hadro (53)	—	—	✓	—	—
MINOS (preliminary)	One-track	345,000	61%	ν_μ CC (27)	✓	—	—	—	—
NOMAD	ν: one- and two-track $\bar{\nu}$: one-track	ν: 14,021 $\bar{\nu}$: 2,237	ν: 42%/74% $\bar{\nu}$: 37%	Hadro, DIS, IMD (7)	✓	—	✓	—	—

Abbreviations: CC, charged-current; DIS, deep-inelastic scattering; hadro, hadro-production; IMD, inverse muon decay.

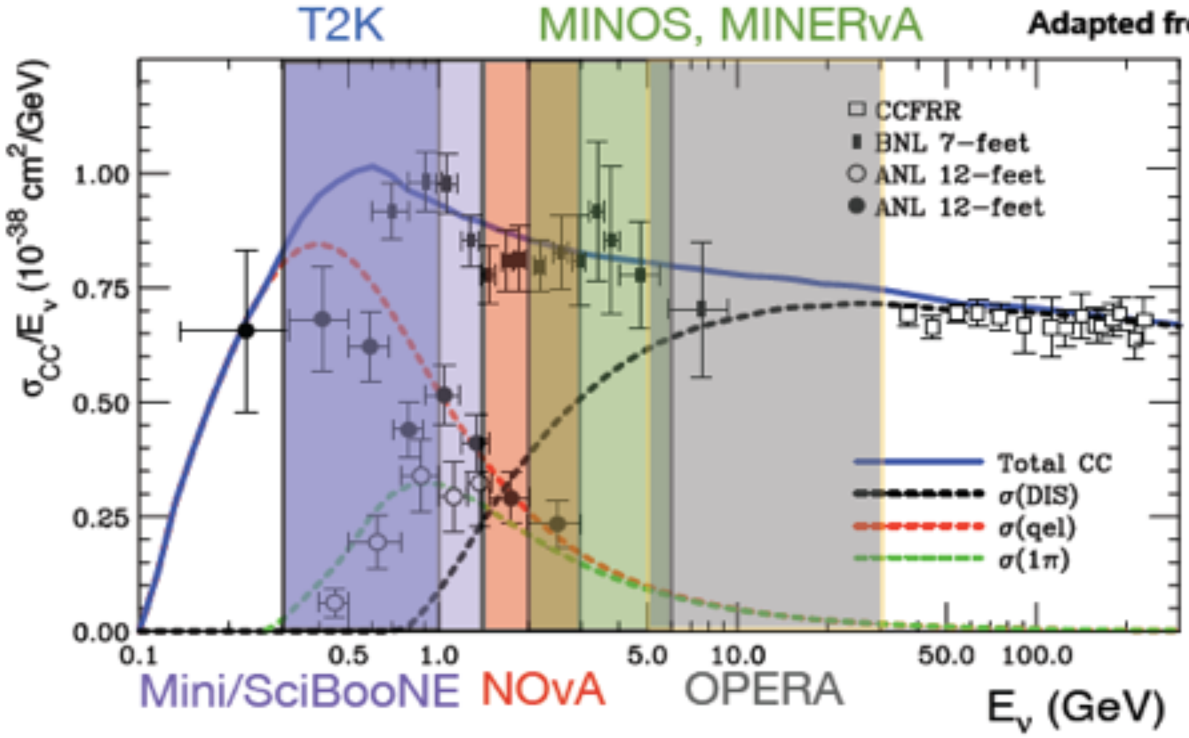
(Ann. Rev. Nucl. Part. Sci, 61, 355, 2011)

1. less likely to be influenced by FSI
2. w/o any need to struggle with (very tough work!!!) the neutrino energy reconstruction

despite the merits in the double differential (not the "total") cross-section measurements, we still need an accurate nuclear structure model to give us a "correct" description of the charged lepton kinematics. (in slide 13)

- from the ***experimenters***' view: **E_i : reconstructed energy**

$$N_i^{\text{type}} = \sigma^{\text{type}}(E_i)\phi(E_i)P_{\mu\mu}(E_i)$$



Adapted from P. Lipari, NuInt01

- **QE**

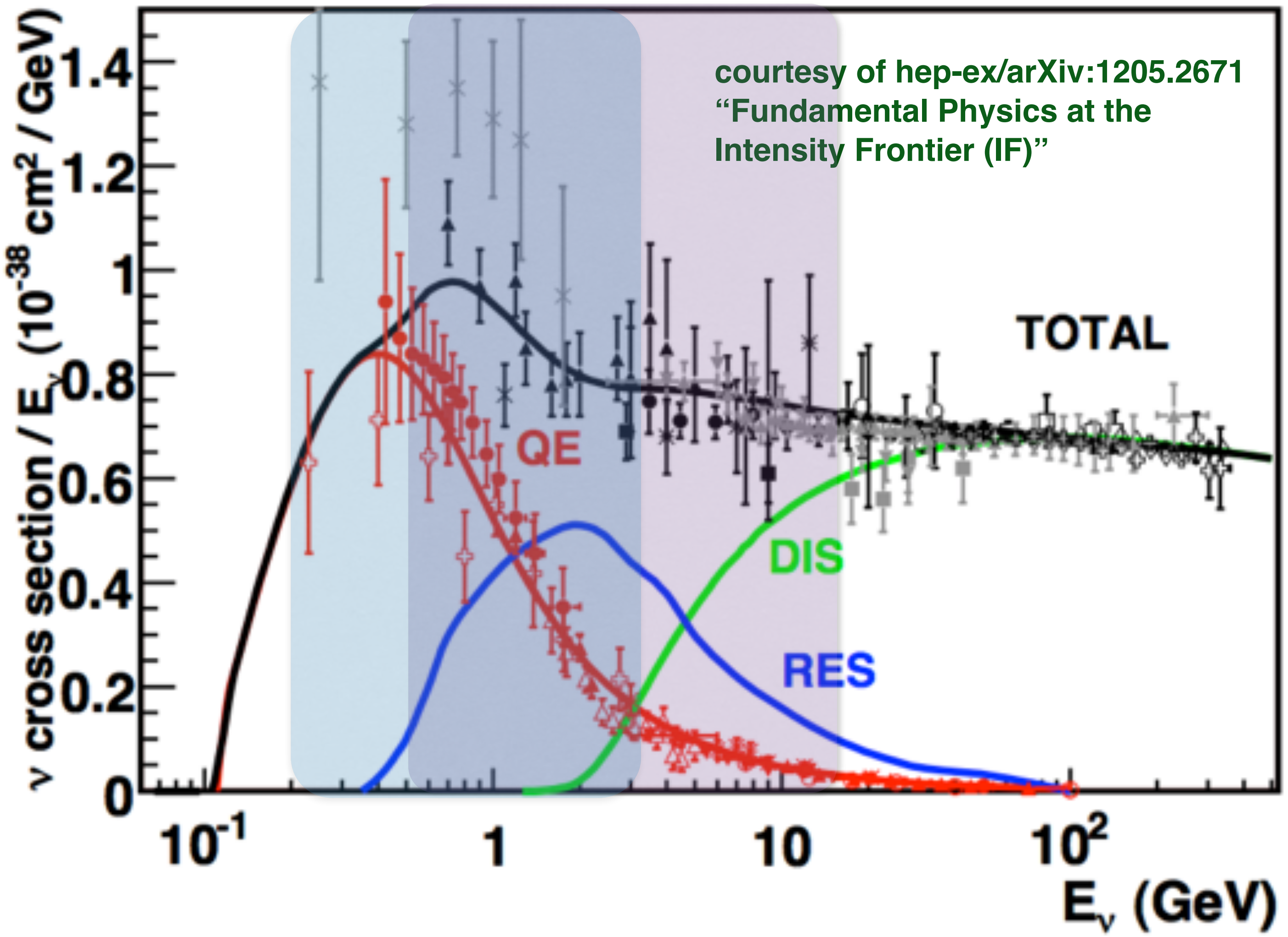
  (BNL, FNAL)

lower energy beams

- **hadro-production**

  (ANL, GGM, MB, SB)

MicroBooNE & LBNE/F beam flux



courtesy of hep-ex/arXiv:1205.2671 “Fundamental Physics at the Intensity Frontier (IF)”

higher energy beams

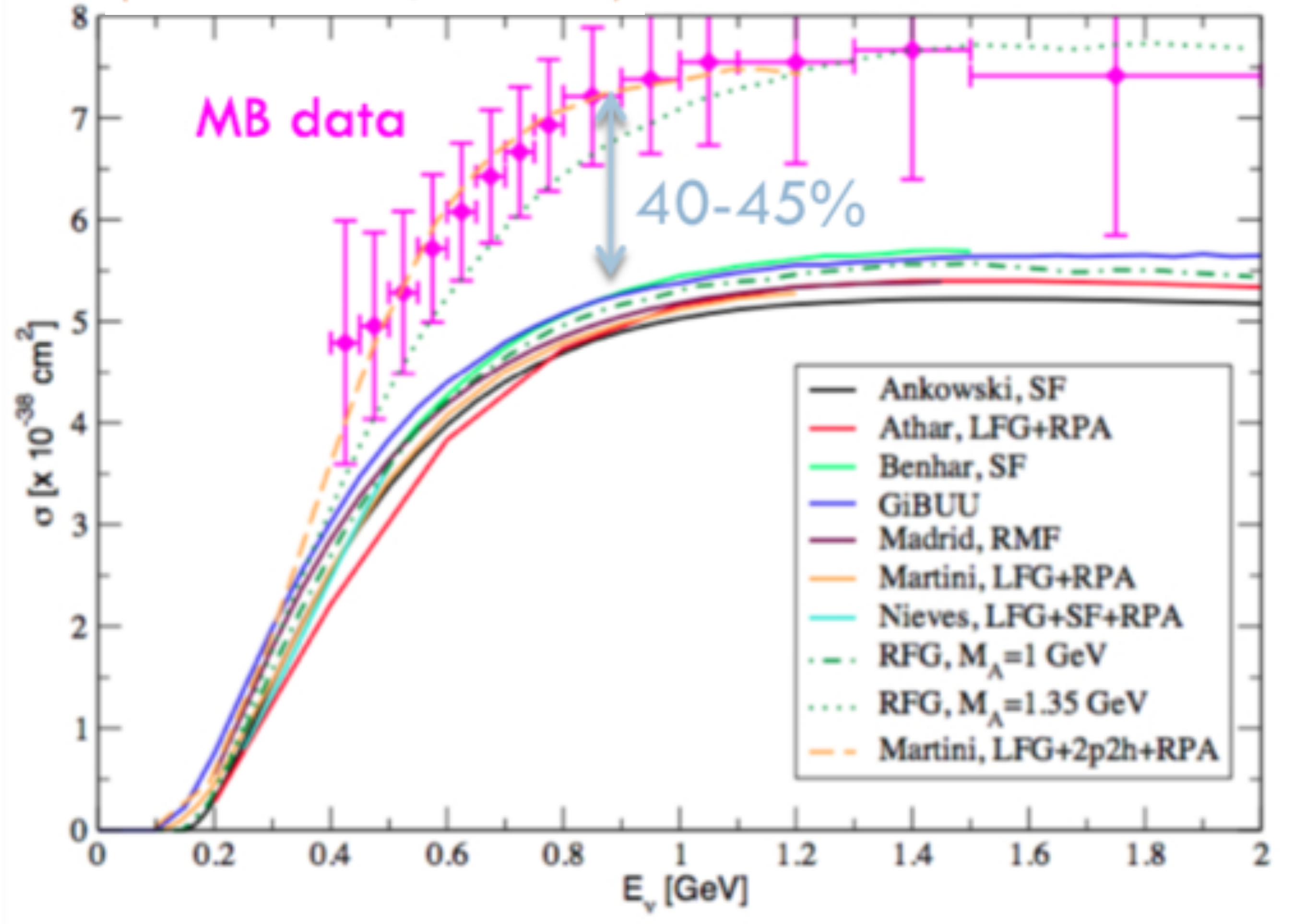
- **total CC**

  (BEBC, Serpukhov, SKAT, K2K, MINOS, NOMAD)

- **IMD**

  (NOMAD)

(L. Alvarez-Ruso, NuFact11)



a lot of models and event generators are currently on the market. they give you different predictions.

- **nuclear structure models**
- **QE interaction models**
- **vector and axial form factors**

courtesy of NuINT09' proceeding :
Comparison of Models of Neutrino-Nucleus Interactions
S. Boyd, S. Dytman, E. Hernandez, J. Sobczyk and R. Tacik

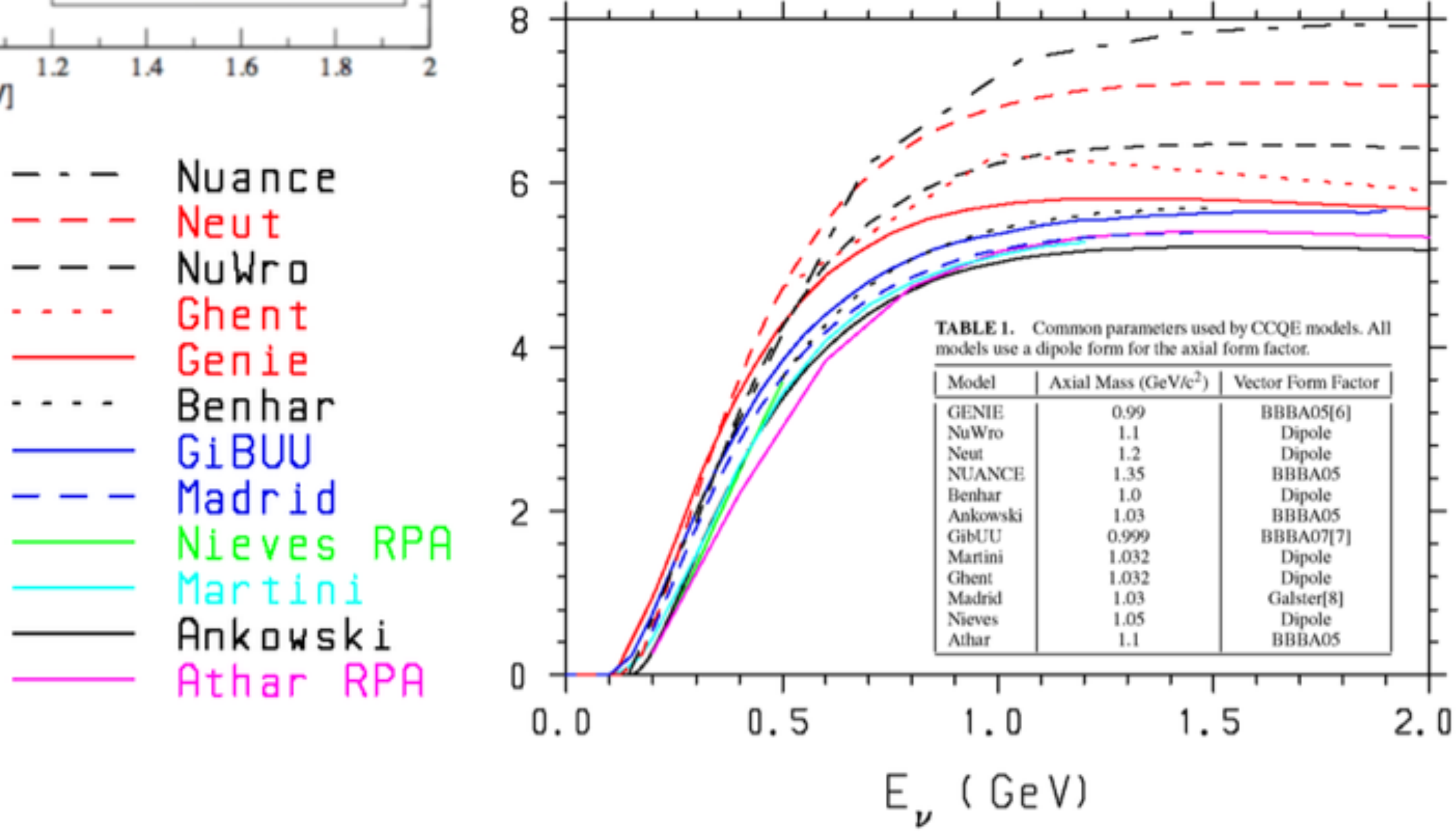


TABLE 1. Common parameters used by CCQE models. All models use a dipole form for the axial form factor.

Model	Axial Mass (GeV/c^2)	Vector Form Factor
GENIE	0.99	BBBA05[6]
NuWro	1.1	Dipole
Neut	1.2	Dipole
NUANCE	1.35	BBBA05
Benhar	1.0	Dipole
Ankowski	1.03	BBBA05
GibUU	0.999	BBBA07[7]
Martini	1.032	Dipole
Ghent	1.032	Dipole
Madrid	1.03	Galster[8]
Nieves	1.05	Dipole
Athar	1.1	BBBA05

${}^{40}_{18}$Ar Spectral Function

RFG (an approximation of Spectral Function)

$$P(|\vec{\mathbf{p}}|, E) = \frac{3}{4\pi k_F^3}\,\theta(k_F - |\vec{\mathbf{p}}|)\,\delta(\sqrt{m^2 + |\vec{\mathbf{p}}|^2} - m - E_B + E)$$

step function (no structure)

Spectral Function (one particle one hole)

$$P(|\vec{\mathbf{p}}|, E) = |<^{40} Ar|^{39} Ar, p > |^2\,\delta(E_{^{40}Ar} - E_{^{39}Ar} - m_n + E)$$

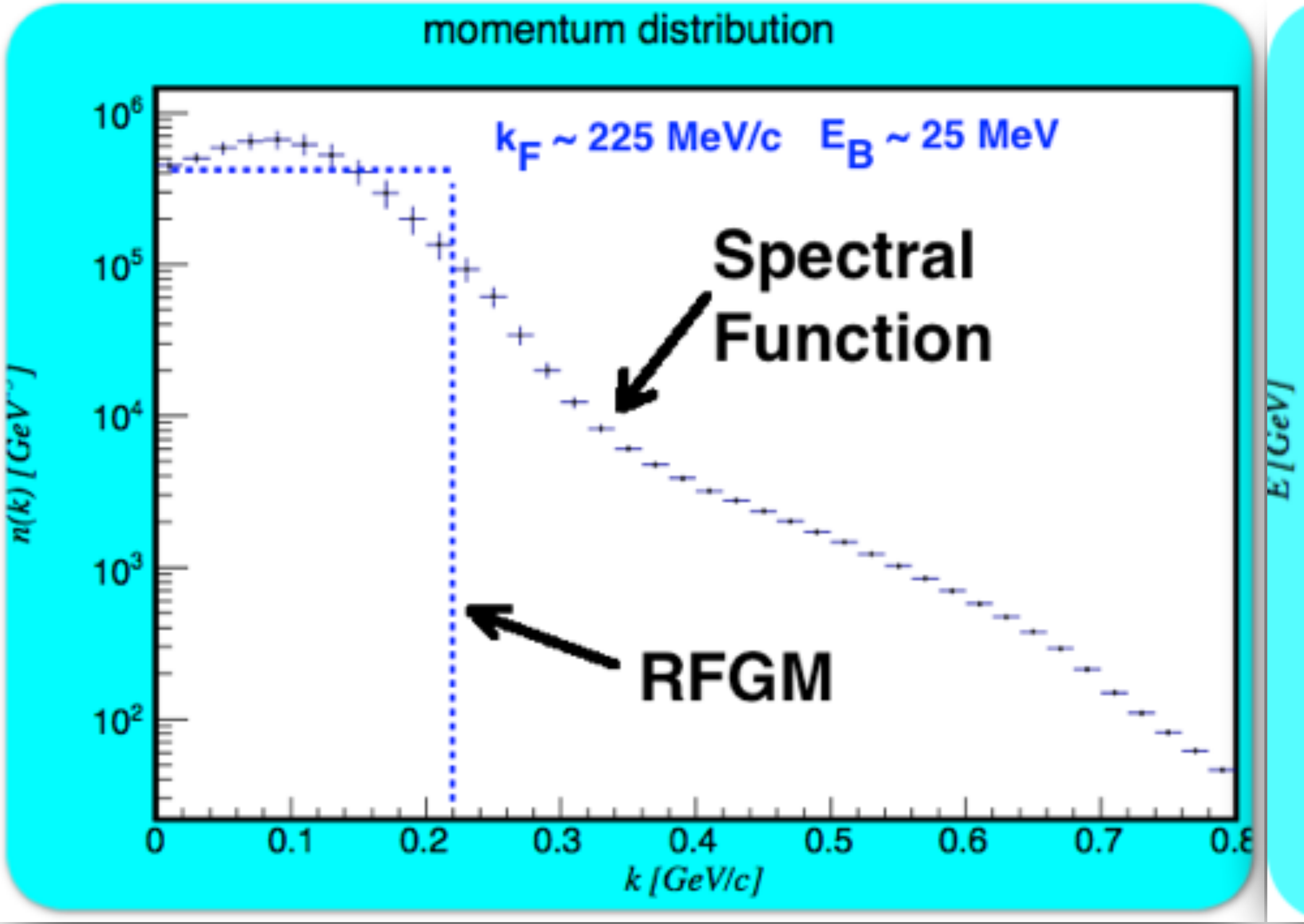
probability amplitude if knocking out one nucleon

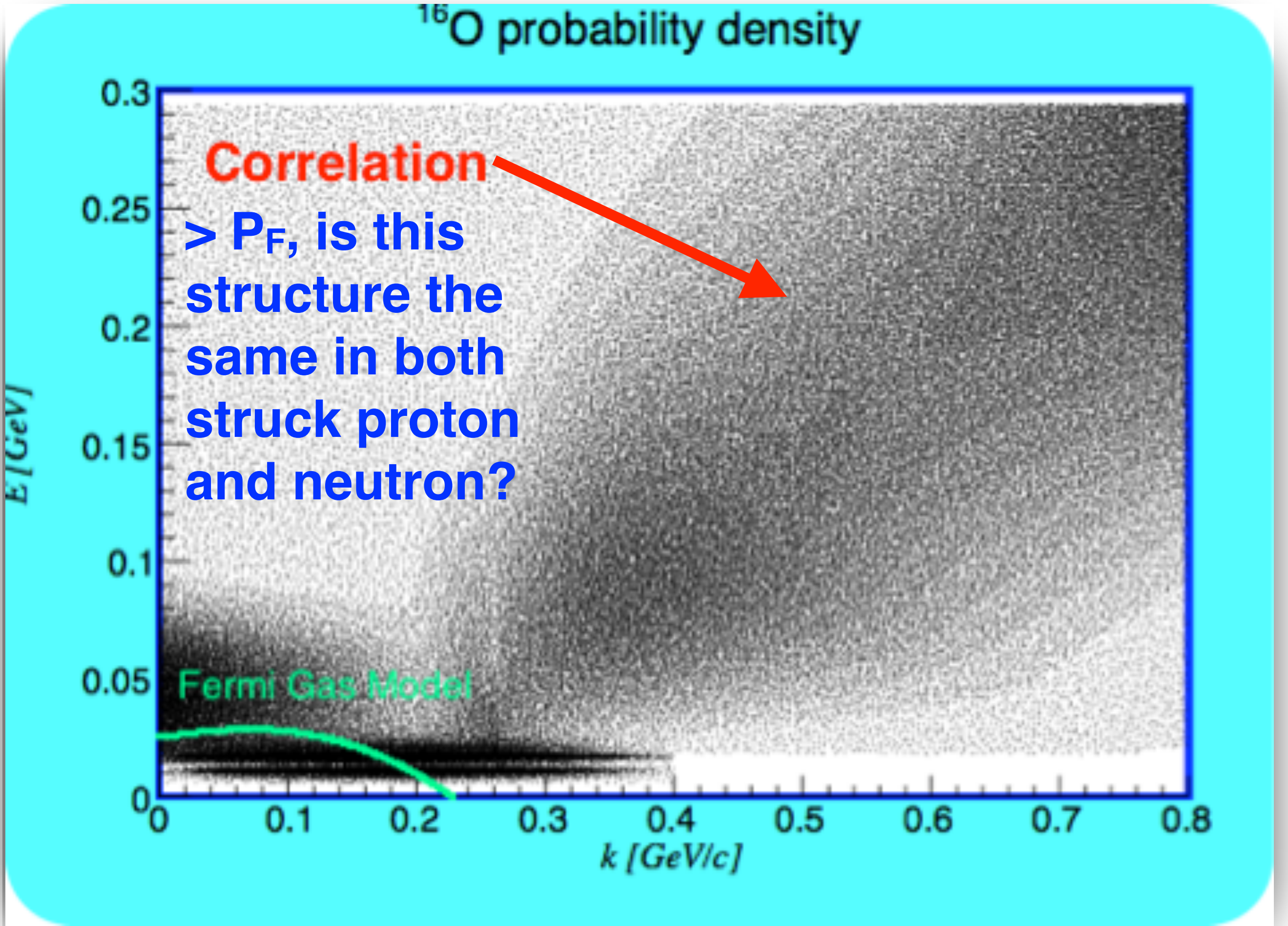
p : missing momentum, E : missing (excitation) energy

$$\mathbf{p}_m = \mathbf{p} - \mathbf{q}$$

$$\omega + M_A = \sqrt{(M_A - m + E_m)^2 + |\mathbf{p}_m|^2} + \sqrt{\mathbf{p}^2 + m^2} \to E_m \approx \omega - T_{\mathbf{p}}$$

$^{40}_{18}$Ar Spectral Function





> P_F, is this structure the same in both struck proton and neutron?

Spectral Function tells you:

- the initial-state nucleon's momentum distribution is not uniform and extends above the Fermi momentum (k_F);

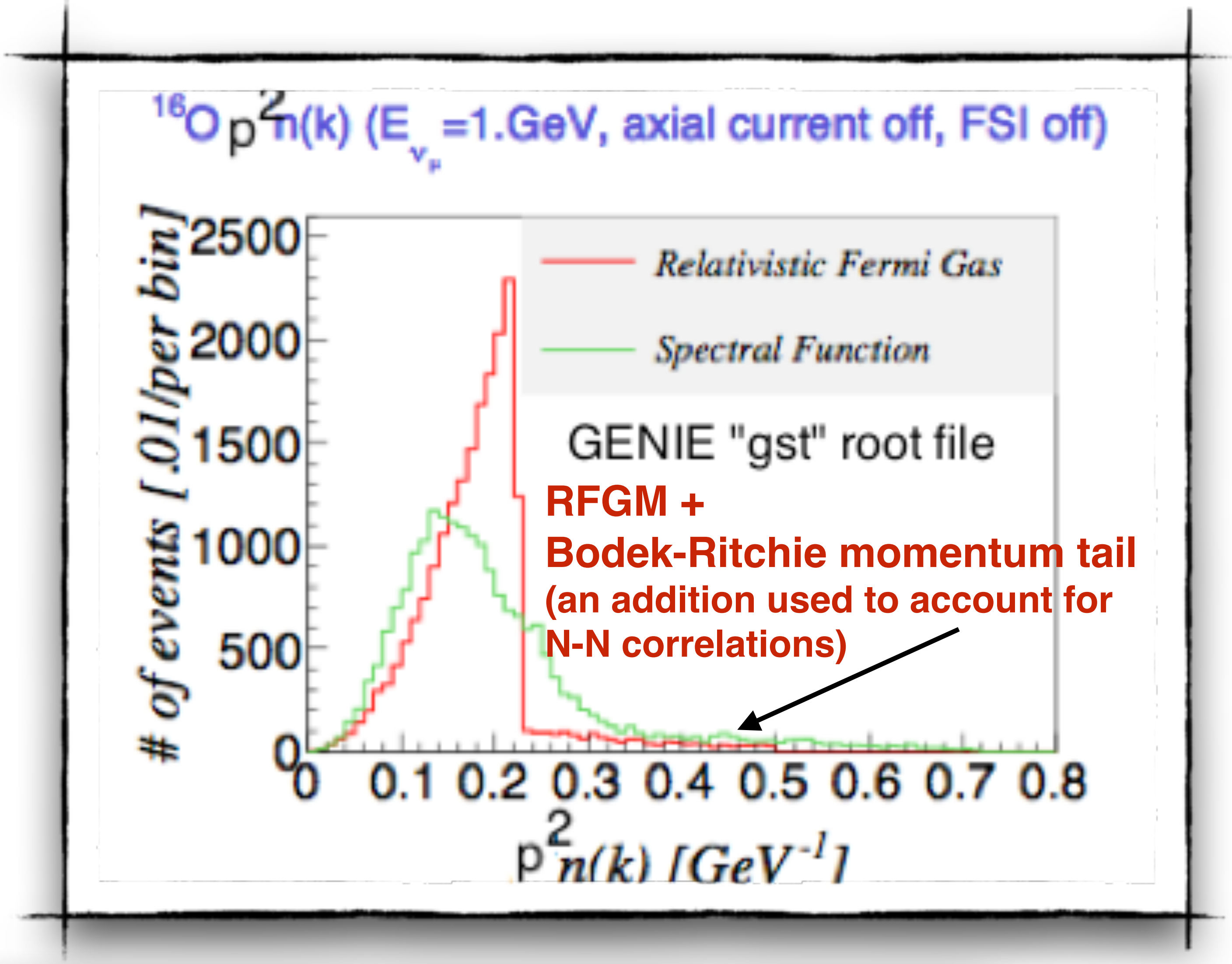
- the removal energy (E_b) of each nucleon is correlated to its momentum and is not an average constant;

${}^{40}_{18}$Ar Spectral Function and Cross-Section

$$e + A \rightarrow e' + p + (A-1)_n$$

$$\frac{d\sigma_A}{dE_{e'}d\Omega_{e'}\boxed{dE_p d\Omega_p}} = K\,\sigma_{ep}\,P(p_m, E_m)$$

- in RFGM, nucleons sitting around Fermi sea are most likely to interact with beam particles
- Spectral Function, however, tells you “the probability” of nucleons from different shells to interact with beam particles.



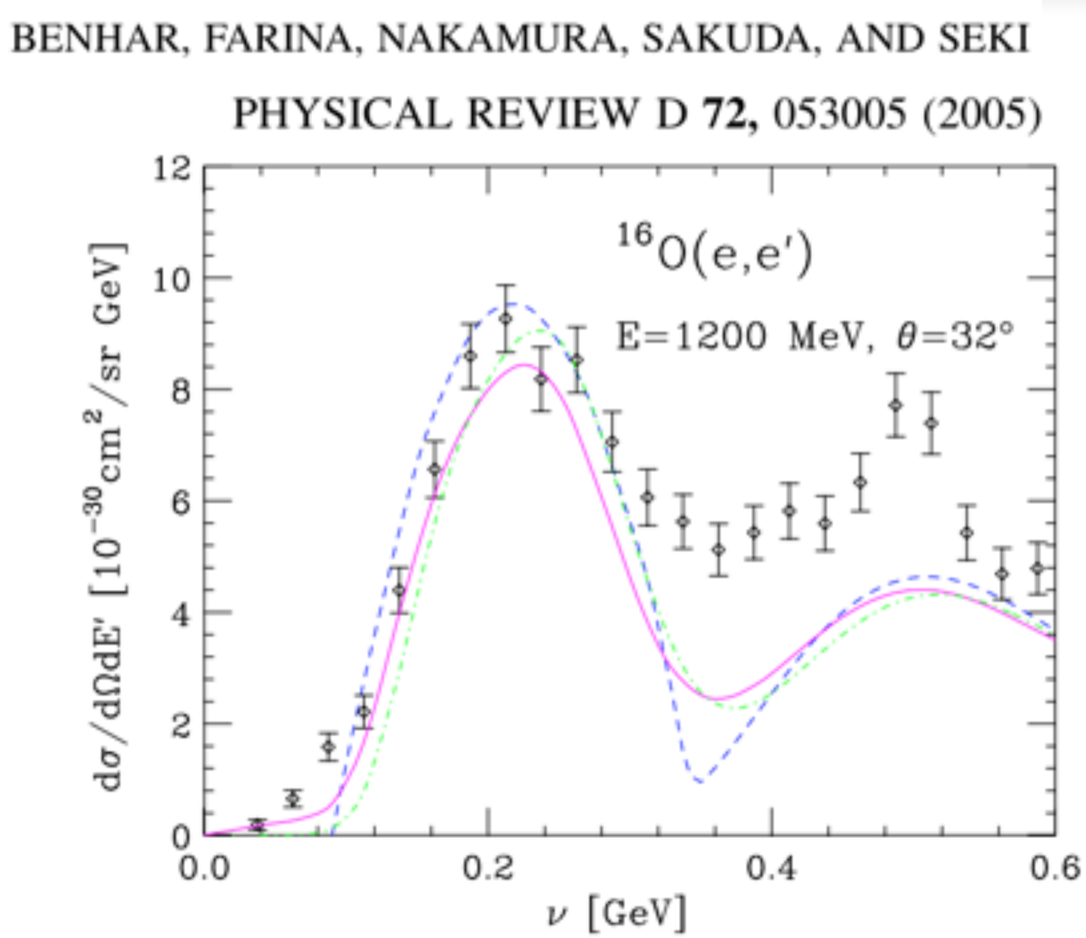
GENIE "gst" root file

RFGM +
Bodek-Ritchie momentum tail
(an addition used to account for N-N correlations)

$$\left(\frac{d^2\sigma}{d\omega d\Omega_{k'}}\right)_A = \int \underset{p^2dp}{\boxed{d^3p}}\,dE\,\boxed{\left(\frac{d^2\sigma}{d\omega d\Omega_{k'}}\right)_N}\,\boxed{P(|\mathbf{p}|, E)}$$
$$\times\ \delta(\omega + M_A - \sqrt{|\mathbf{p}+\mathbf{q}|^2 + m^2} - E_{A-1})\ .$$

Motivation

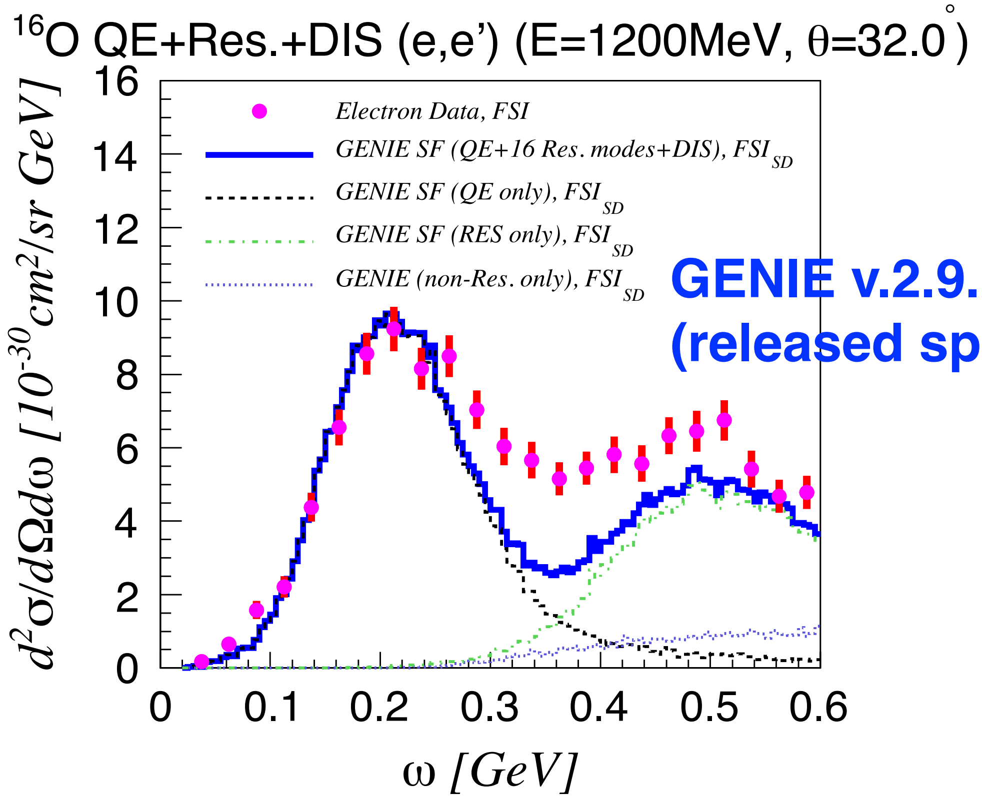
- the **Spectral Function** possesses the reliable capability of providing the fully realistic description of the initial-state nucleon kinematics. we are thus able to obtain the accurately computed cross-sections for ***all interaction channels*** (QE, RES, COH, DIS, MEC/2p2h).



BENHAR, FARINA, NAKAMURA, SAKUDA, AND SEKI

PHYSICAL REVIEW D **72,** 053005 (2005)

GENIE Neutrino Monte Carlo Generator

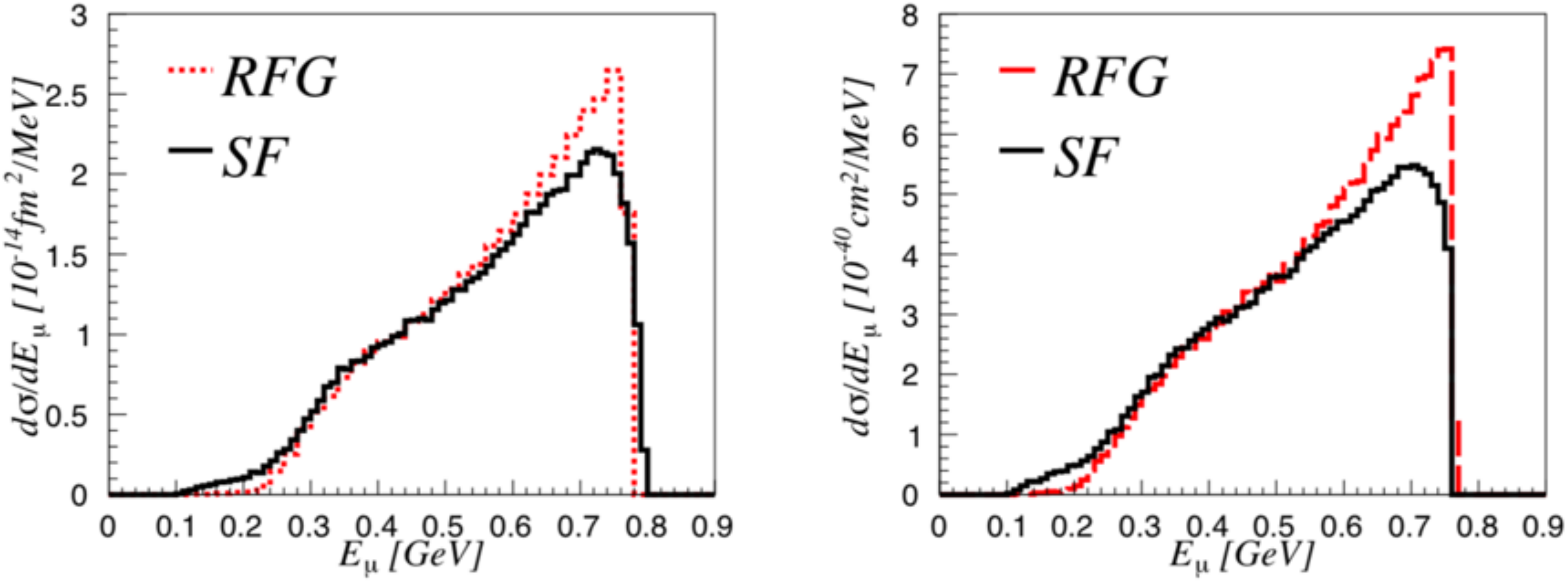


GENIE v.2.9.2 (released spring 2015)

courtesy of PRD 90, 093004 (2014) ***1p1h SF (at this stage)***

M. Jen, A. M. Ankowski, O. Benhar, A. P. Furmanski, L. N. Kalousis, C. Mariani

Example -



(a) $\nu + \mathrm{O} \rightarrow \mu + X$, with no Pauli blocking, and no FSI

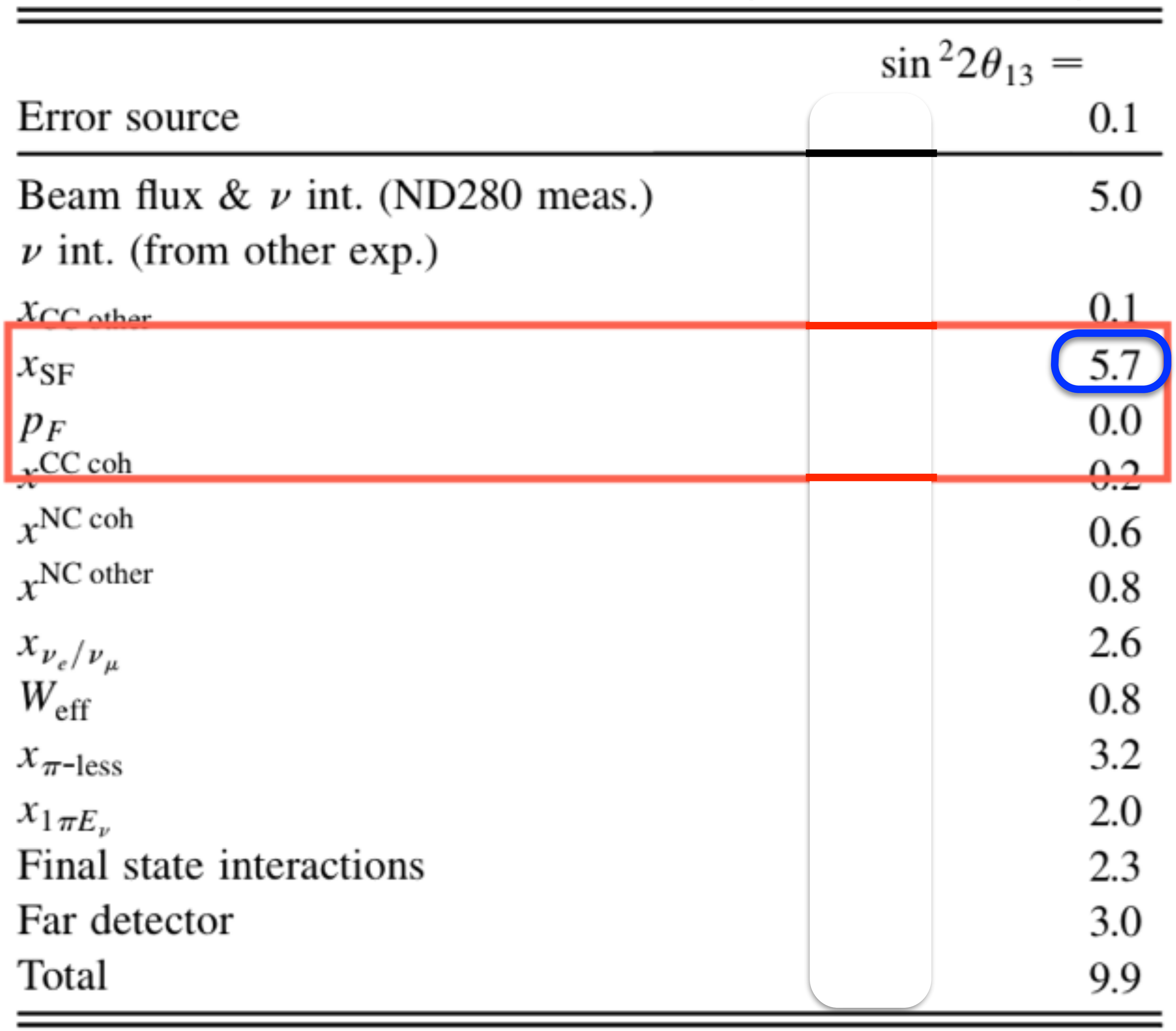
(b) $\nu + \mathrm{Ar} \rightarrow \mu + X$, with both Pauli blocking and FSI included

FIG. 11. (Color online). Comparison of the differential CCQE cross sections $d\sigma/dE_\mu$ of (a) oxygen and (b) argon at neutrino energy $E_\nu = 800$ MeV, obtained using GENIE 2.8.0 + νT with RFGM and SF.

courtesy of PRD 90, 093004 (2014) ***1p1h SF (at this stage)***
M. Jen, A. M. Ankowski, O. Benhar, A. P. Furmanski, L. N. Kalousis, C. Mariani

Motivation

courtesy of PRD 88, 032002 (2013)
Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam (T2K Collaboration)

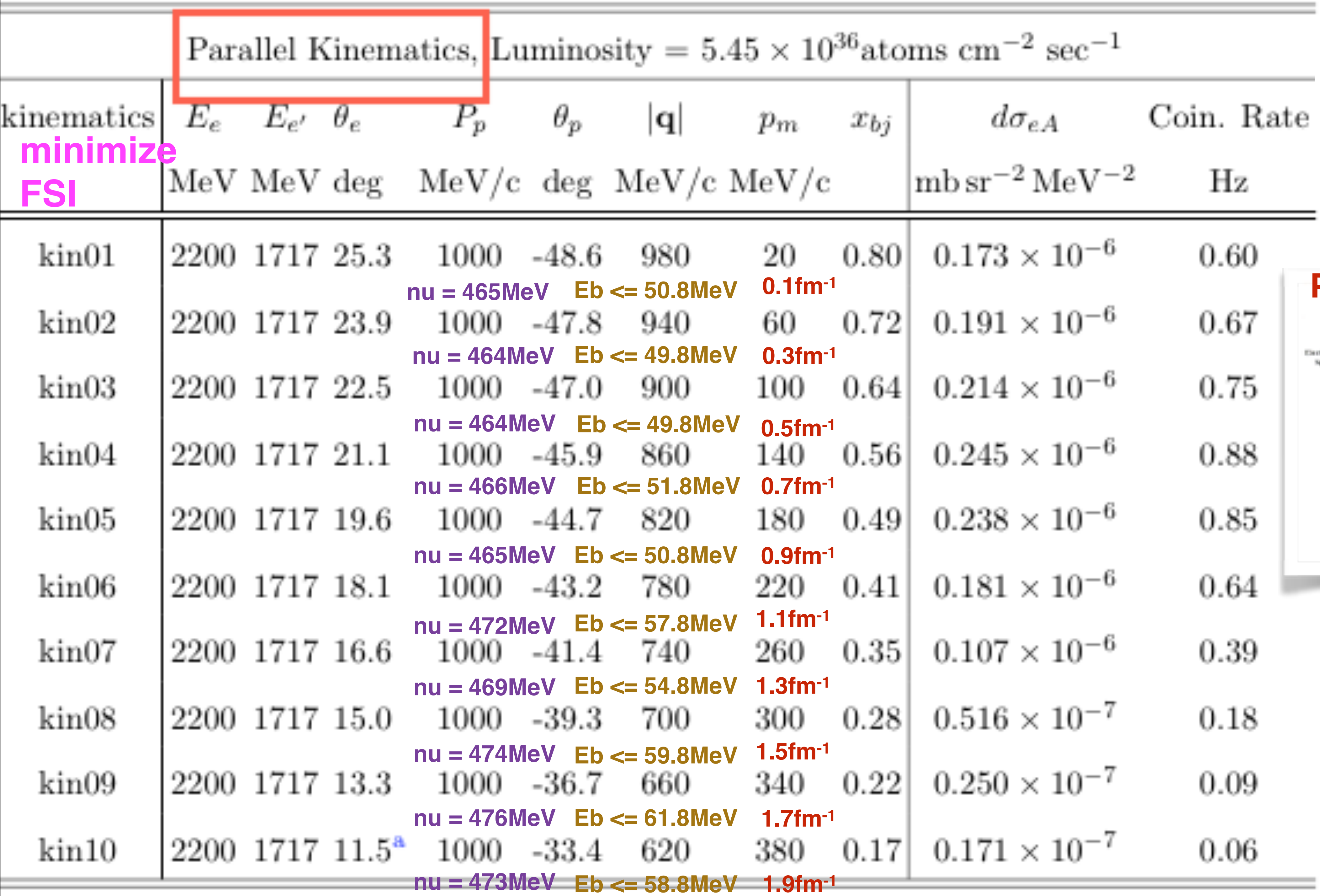


Error source	$\sin^2 2\theta_{13} = 0.1$
Beam flux & ν int. (ND280 meas.)	5.0
ν int. (from other exp.)	
$x_{\text{CC other}}$	0.1
x_{SF}	5.7
p_F	0.0
$x^{\text{CC coh}}$	0.2
$x^{\text{NC coh}}$	0.6
$x^{\text{NC other}}$	0.8
x_{ν_e/ν_μ}	2.6
W_{eff}	0.8
$x_{\pi\text{-less}}$	3.2
$x_{1\pi E_\nu}$	2.0
Final state interactions	2.3
Far detector	3.0
Total	9.9

major one

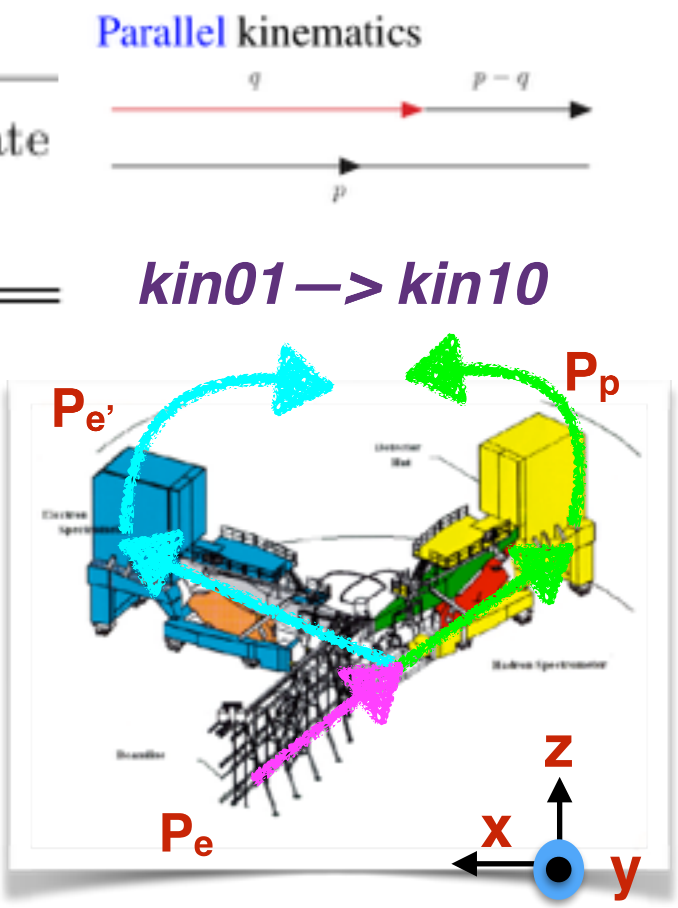
courtesy of Omar Benhar's calculation

Kinematical Range for $^{40}_{18}$Ar and Proposed Kinematical Setup



Parallel Kinematics, Luminosity = 5.45×10^{36} atoms cm^{-2} sec^{-1}

kinematics	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	p_m	x_{bj}	$d\sigma_{eA}$	Coin. Rate
minimize FSI	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c		mb sr^{-2} MeV^{-2}	Hz
kin01	2200	1717	25.3	1000	-48.6	980	20	0.80	0.173×10^{-6}	0.60
				nu = 465MeV		Eb <= 50.8MeV	0.1fm^{-1}			
kin02	2200	1717	23.9	1000	-47.8	940	60	0.72	0.191×10^{-6}	0.67
				nu = 464MeV		Eb <= 49.8MeV	0.3fm^{-1}			
kin03	2200	1717	22.5	1000	-47.0	900	100	0.64	0.214×10^{-6}	0.75
				nu = 464MeV		Eb <= 49.8MeV	0.5fm^{-1}			
kin04	2200	1717	21.1	1000	-45.9	860	140	0.56	0.245×10^{-6}	0.88
				nu = 466MeV		Eb <= 51.8MeV	0.7fm^{-1}			
kin05	2200	1717	19.6	1000	-44.7	820	180	0.49	0.238×10^{-6}	0.85
				nu = 465MeV		Eb <= 50.8MeV	0.9fm^{-1}			
kin06	2200	1717	18.1	1000	-43.2	780	220	0.41	0.181×10^{-6}	0.64
				nu = 472MeV		Eb <= 57.8MeV	1.1fm^{-1}			
kin07	2200	1717	16.6	1000	-41.4	740	260	0.35	0.107×10^{-6}	0.39
				nu = 469MeV		Eb <= 54.8MeV	1.3fm^{-1}			
kin08	2200	1717	15.0	1000	-39.3	700	300	0.28	0.516×10^{-7}	0.18
				nu = 474MeV		Eb <= 59.8MeV	1.5fm^{-1}			
kin09	2200	1717	13.3	1000	-36.7	660	340	0.22	0.250×10^{-7}	0.09
				nu = 476MeV		Eb <= 61.8MeV	1.7fm^{-1}			
kin10	2200	1717	11.5[a]	1000	-33.4	620	380	0.17	0.171×10^{-7}	0.06
				nu = 473MeV		Eb <= 58.8MeV	1.9fm^{-1}			



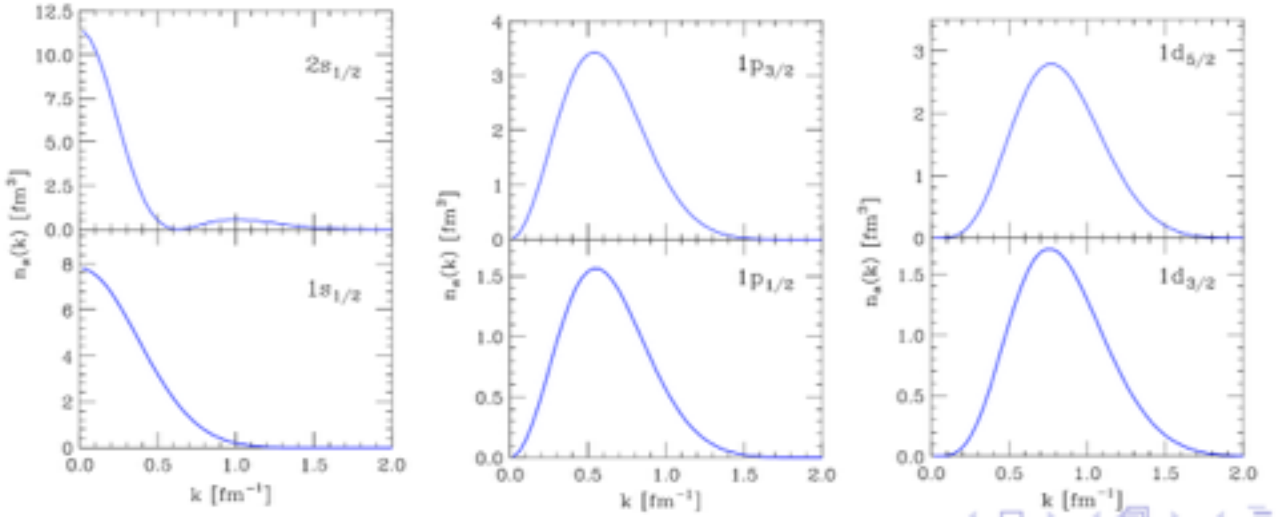
scan the struck nucleon's angles

by moving LHRS & RHRS

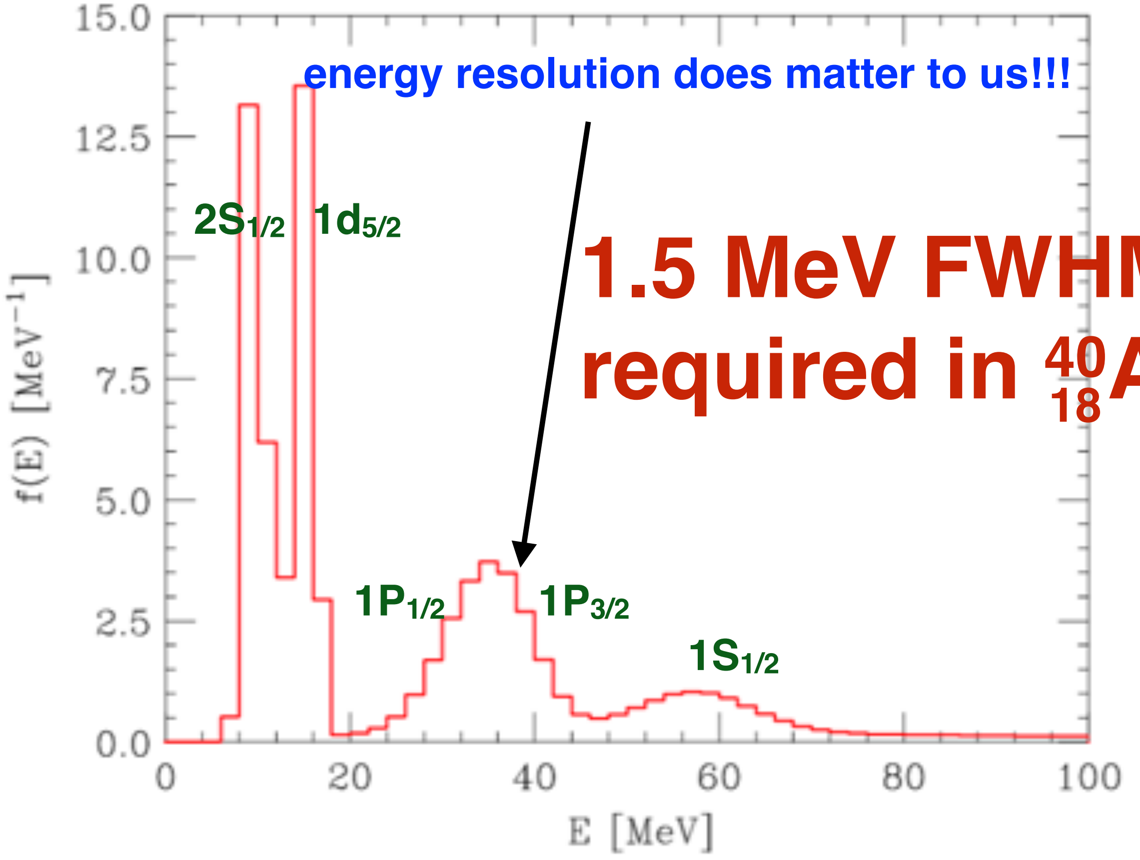
courtesy of
Omar Benhar's
calculation

Kinematical Range for $^{40}_{18}$Ar and Proposed Kinematical Setup

^{40}Ca momentum distribution of shell states



^{40}Ca missing (removal) energy of shell states

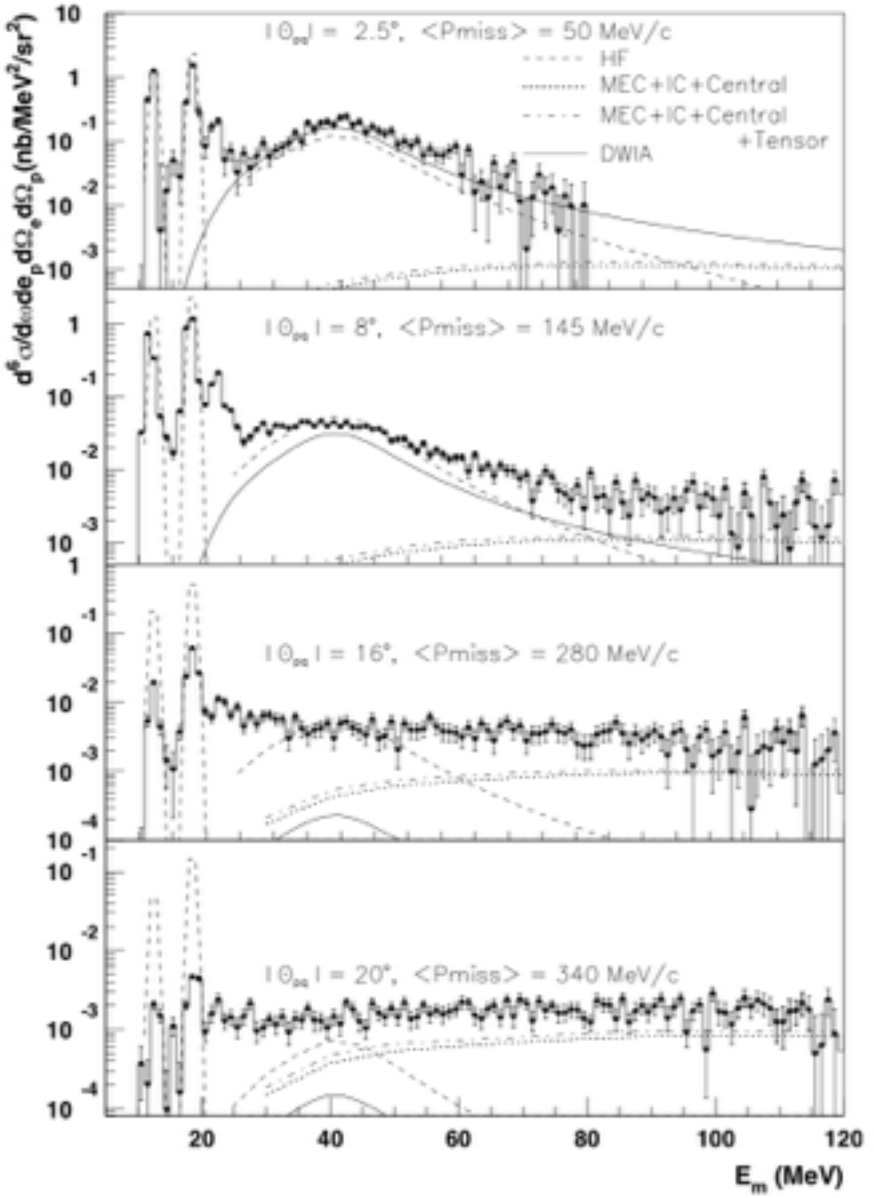


energy resolution does matter to us!!!

1.5 MeV FWHM required in $^{40}_{18}$Ar(e,e'p)

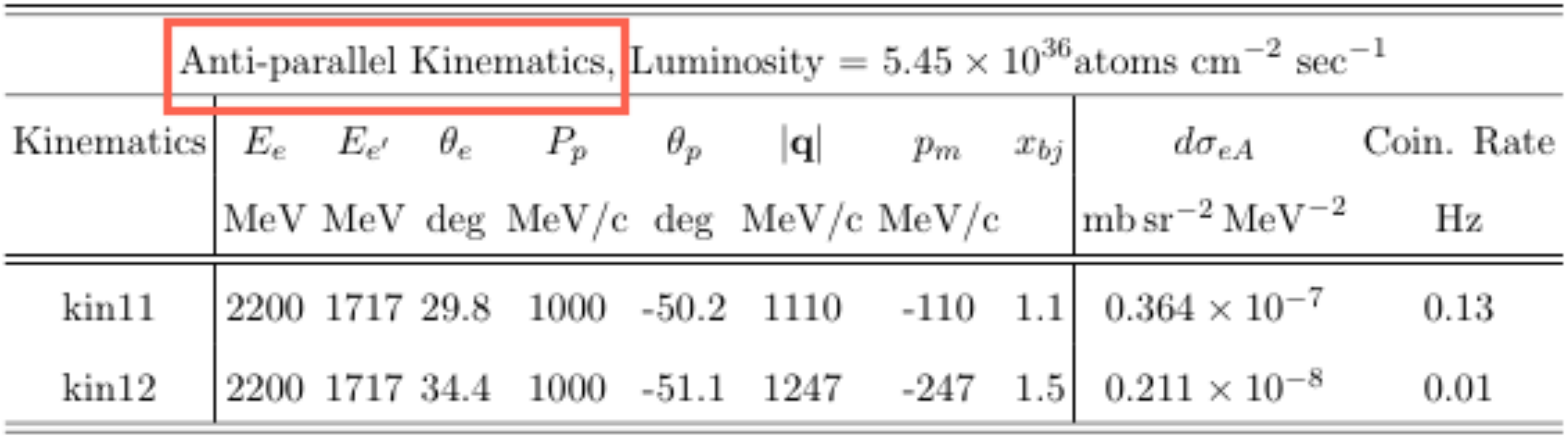
$^{16}O(e,e'p)X$, E_e = 2.4 GeV

E89-003 (waterfall target): achieved resolution was 0.9 MeV FWHM



Kinematical Range for ${}^{40}_{18}\mathrm{Ar}$ and Proposed Kinematical Setup

courtesy of Omar Benhar's calculation

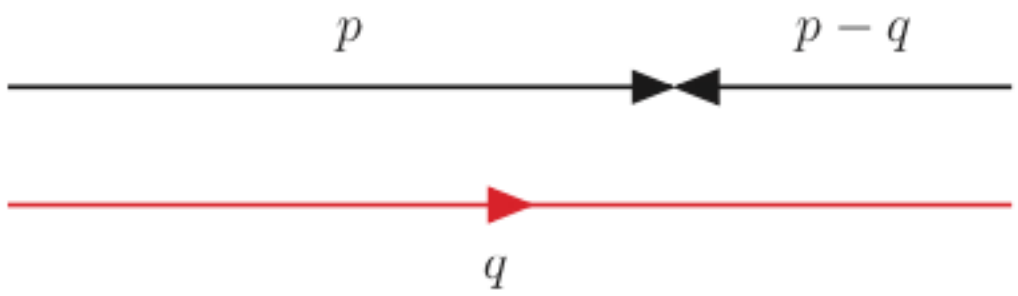


Anti-parallel Kinematics, Luminosity = 5.45×10^{36} atoms cm^{-2} sec^{-1}

Kinematics	E_e	$E_{e'}$	θ_e	P_p	θ_p	$\|\mathbf{q}\|$	p_m	x_{bj}	$d\sigma_{eA}$	Coin. Rate
	MeV	MeV	deg	MeV/c	deg	MeV/c	MeV/c		mb sr^{-2} MeV^{-2}	Hz
kin11	2200	1717	29.8	1000	-50.2	1110	-110	1.1	0.364×10^{-7}	0.13
kin12	2200	1717	34.4	1000	-51.1	1247	-247	1.5	0.211×10^{-8}	0.01

maximum FSI

Antiparallel kinematics



- cross-check structure functions extracted from both parallel and anti-parallel kinematics
- estimate the significance of FSI using data from the anti-parallel kinematics setting

Experimental Details

- unpolarized electron beam at ~100uA (raster size = 2x2 mm^2)
- cryogenic $^{40}_{18}$Ar ($E_{deposited}$ = 160 W) gas target at P = 10 atm
  - thickness = 10 mil
  - cell diameter = 6.28 cm
  - low background : thin Al window ($E_{deposited}$ = 30 W)
  - constant density : rapid and uniform flow at 216 g/s with P = 10 atm and T = 130K
  - long length (15 cm) to avoid data with z_{tgt} resolution
  - average density loss ~ 3.9 %
- HRS acceptance requires

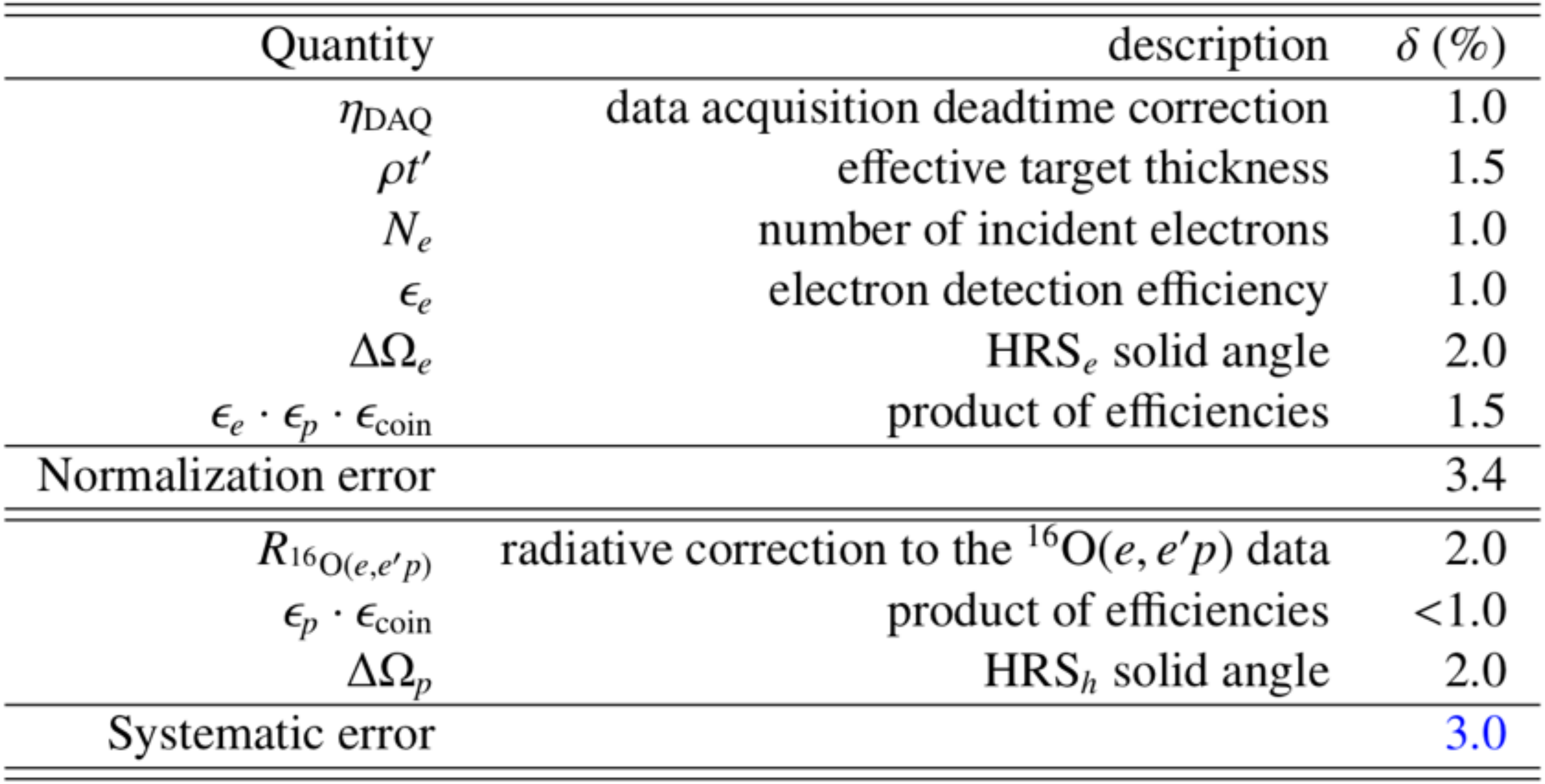
$$\delta p/p = 3.5\% \ , \ \delta\phi = 20\ mr \ , \ \delta\theta = 40\ mr$$

Experimental Details

- Calibration requires:
  - detector configuration - PMT gain factor update
  - HRS pointing - optics matrix update (studies of momentum and scattering angles at the target included)
  - target/HRS/detector acceptance update
- Selections include:
  - beam trip
  - end-cap background removal
  - final state particle identification (PID)

Summary

- ★ Statistical uncertainties are estimated at 3% **~ systematics error**
- ★ Breakdown of systematics uncertainties



Quantity	description	δ (%)
η_{DAQ}	data acquisition deadtime correction	1.0
$\rho t'$	effective target thickness	1.5
N_e	number of incident electrons	1.0
ϵ_e	electron detection efficiency	1.0
$\Delta\Omega_e$	HRS$_e$ solid angle	2.0
$\epsilon_e \cdot \epsilon_p \cdot \epsilon_{\mathrm{coin}}$	product of efficiencies	1.5
Normalization error		3.4
$R_{^{16}\mathrm{O}(e,e'p)}$	radiative correction to the ^{16}O$(e, e'p)$ data	2.0
$\epsilon_p \cdot \epsilon_{\mathrm{coin}}$	product of efficiencies	<1.0
$\Delta\Omega_p$	HRS$_h$ solid angle	2.0
Systematic error		3.0

Conclusion

- Spectral function formalism allows for a clear cut description of both the reaction mechanisms and the dynamics of the nuclear target;
- The usage of realistic spectral function will play a critical role to reduce the systematics of neutrino interactions in high-precision oscillation (appearance and disappearance) analysis.

“Thank you for your attention.”

– any comments?