Neutrino Interaction Physics

Lecture 1: Introduction of neutrino interactions
1. Overview
2. Neutrino lepton scattering
3. Neutrino DIS physics
4. Neutrino nucleus reactions

Lecture 2: Neutrino interactions for long baseline oscillation experiments
1. Overview
2. CCQE interaction
3. Baryonic resonances
4. DIS and hadronization
5. Simulation, systematics

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Oct. 17, 2017

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Alexander 2016 J.Phys.:Conf. Ser. 718(2016)062076

2. Neutrino-electron scattering

Neutrino – electron differential cross section

T=recoil electron kinetic energy

E=neutrino energy

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E-T}{E}\right)^2 - C_L C_R \frac{m_e T}{E^2}\right]$$

Neutrino – electron differential cross section with neutrino magnetic moment

($\mu_\nu < 3\text{x}10^{-11}\ \mu_B$)

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E-T}{E}\right)^2 - C_L C_R \frac{m_e T}{E^2}\right] + \frac{\pi\alpha\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E}\right)$$

Neutrino – electron total cross section

$$\sigma(E) = \frac{2G_F^2 m_e E}{\pi}\left[c_L^2 + \frac{1}{3}c_R^2 - \frac{1}{2}C_L C_R \frac{m_e}{E}\right]$$

	C_L	C_R
ν_e - e^-	$\frac{1}{2}+\sin^2\theta_w$	$\sin^2\theta_w$
$\bar{\nu}_e$ - e^-	$\sin^2\theta_w$	$\frac{1}{2}+\sin^2\theta_w$
ν_μ - e^-	$-\frac{1}{2}+\sin^2\theta_w$	$\sin^2\theta_w$
$\bar{\nu}_\mu$ - e^-	$\sin^2\theta_w$	$-\frac{1}{2}+\sin^2\theta_w$

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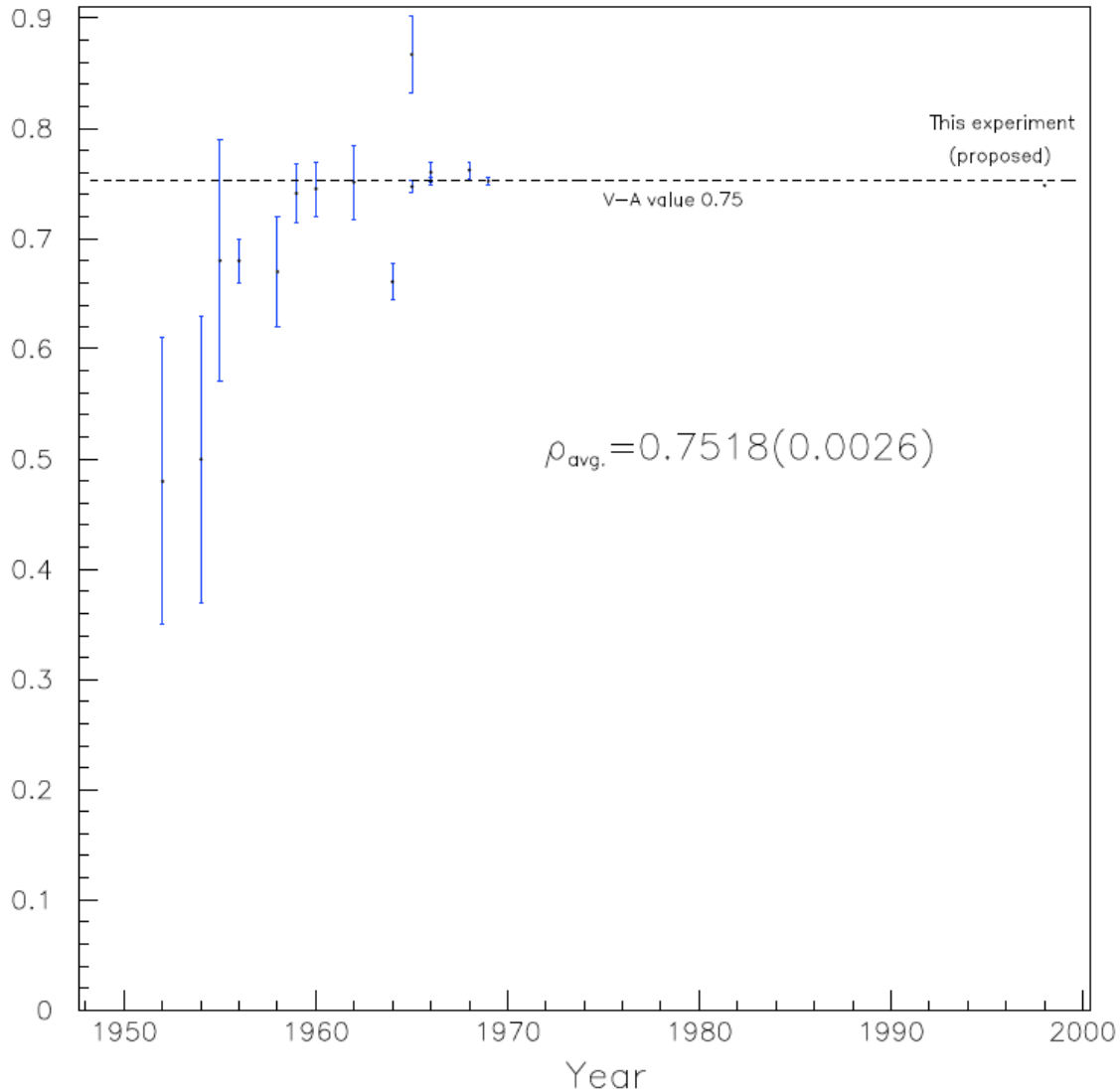
Lee, PhD thesis, Virginia Tech (2001)

2. Time dependence of muon decay Michel parameter ρ



3. Neutrino-DIS cross section

Neutrino – single d-quark cross section

$$\frac{d\sigma}{dy}(\nu d \to \mu u) = \frac{G_F^2 xs}{\pi}$$

Neutrino – d-quark cross section

$$\frac{d\sigma}{dy}(\nu d \to \mu u) = \int_0^1 \frac{G_F^2 xs}{\pi} d(x)dx$$

Neutrino-nucleon DIS cross section

$$\frac{d\sigma}{dy}(\nu N \to \mu X) = \int_0^1 \frac{G_F^2 xs}{\pi} [(d(x) + s(x) \dots) + [\bar{u}(x) + \bar{c}(x) \dots](1-y)^2]dx$$

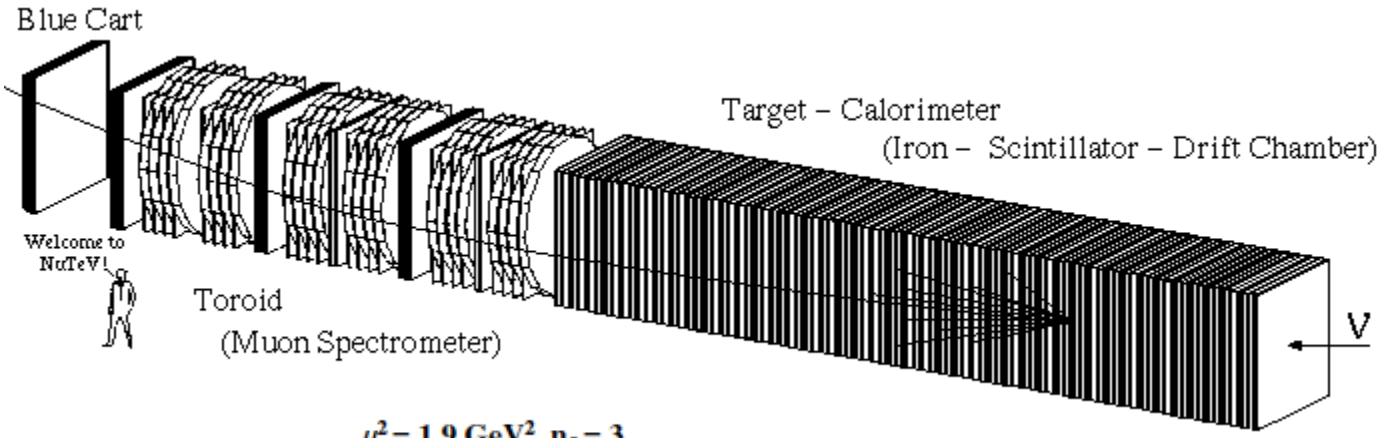
Neutrino-nucleus DIS cross section with isoscalar assumption

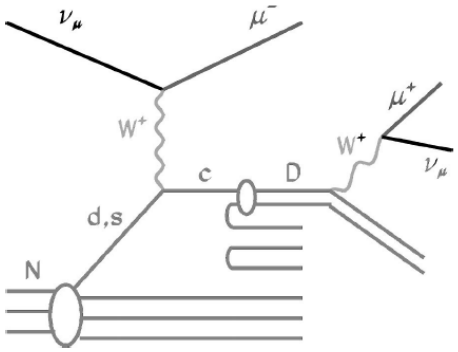
$$\frac{d\sigma}{dy}(\nu A \to \mu X) = A \int_0^1 \frac{G_F^2 xs}{\pi} [Q(x) + \bar{Q}(x)(1-y)^2]dx$$

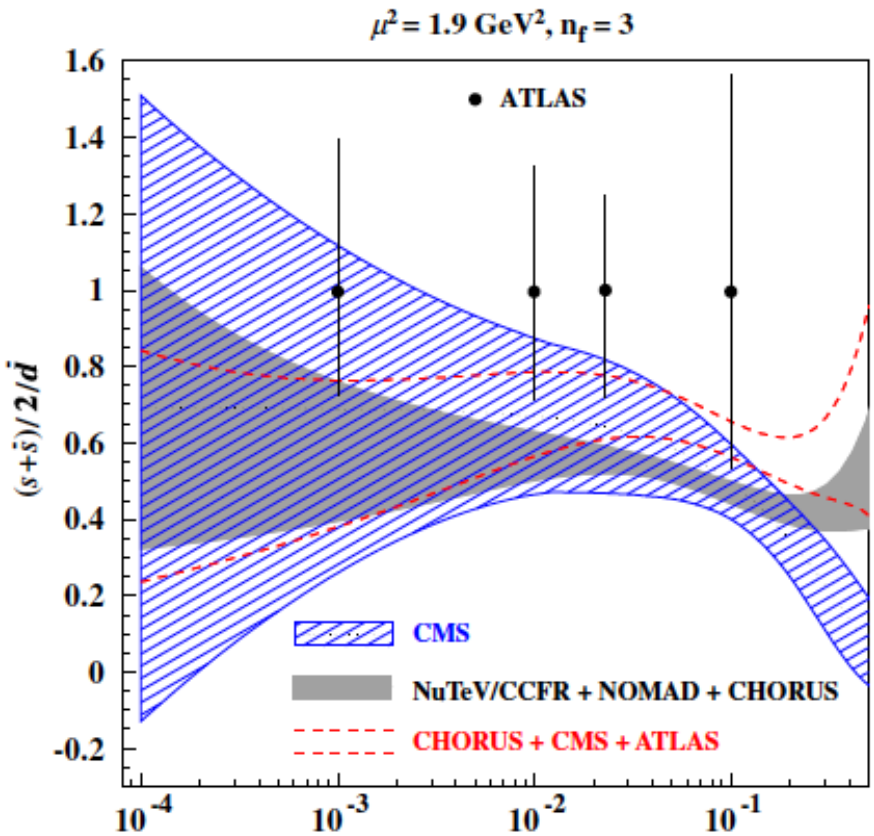
$$u^p(x) + u^n(x) = d^n(x) + d^p(x) = u(x) + d(x) \equiv Q(x)$$
$$\bar{u}^p(x) + \bar{u}^n(x) = \bar{u}^n(x) + \bar{u}^p(x) = \bar{u}(x) + \bar{d}(x) \equiv \bar{Q}(x)$$

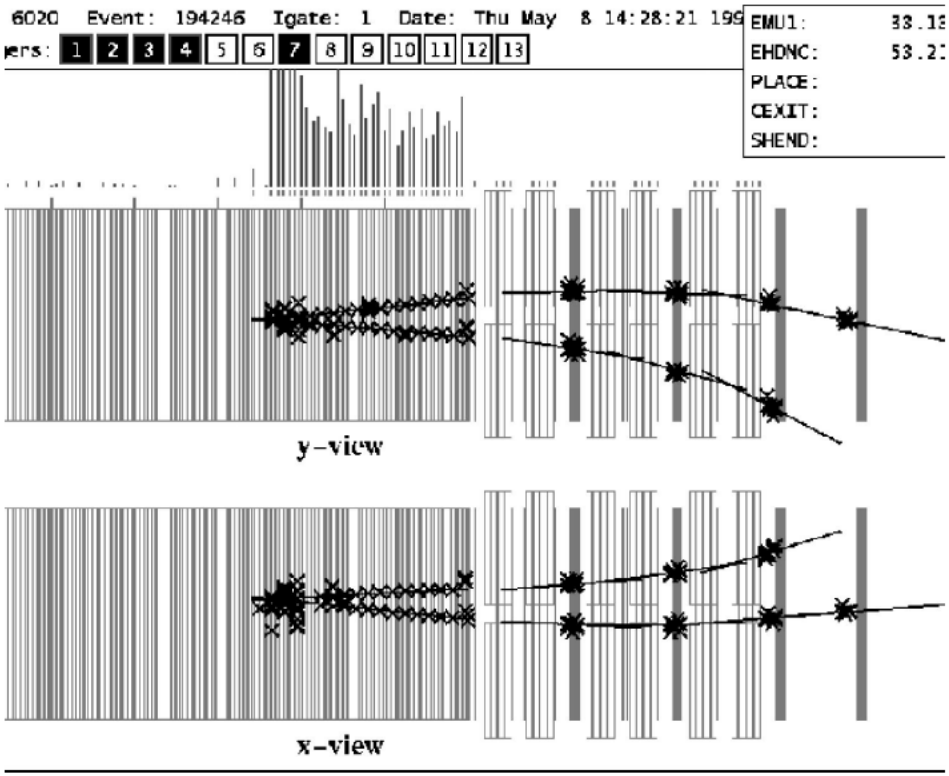
NuTeV, PRD64(2001)112006
Alekhin et al.,PRD91(2015)094002

3. Di-muon production



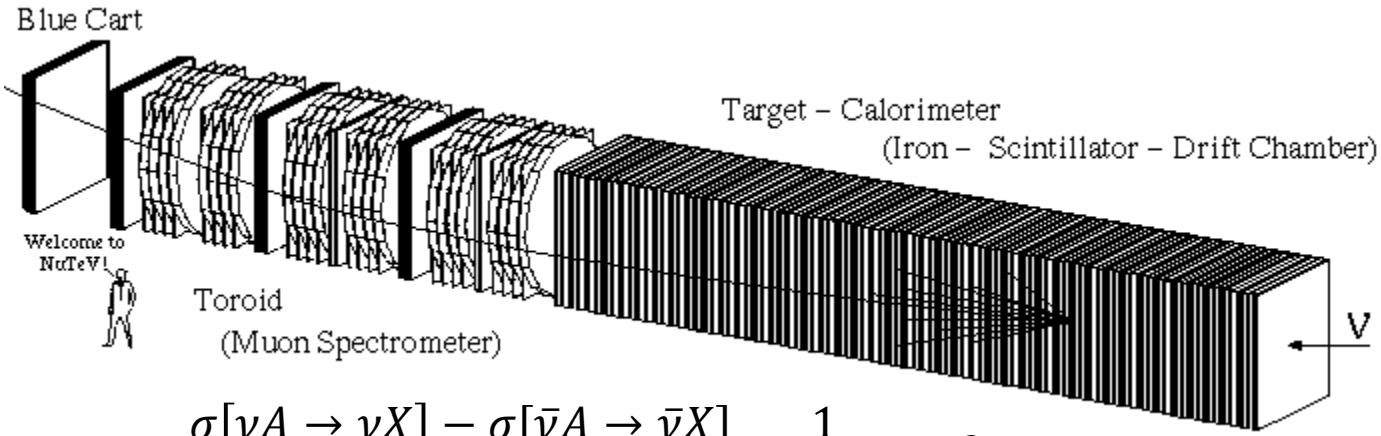






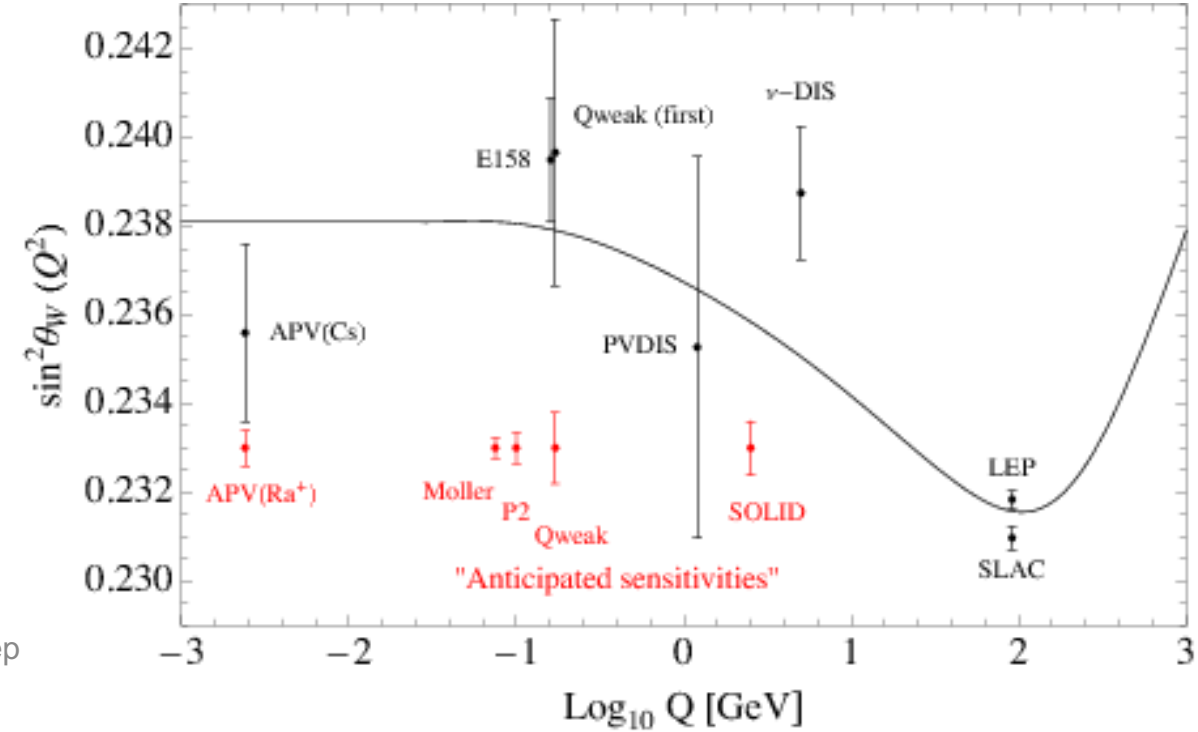
NuTeV, PRL88(2002)091802

3. Paschos-Wolfenstein ratio and NuTeV anomaly



Manny Paschos (Dortmund)

$$R_{PW} = \frac{\sigma[\nu A \to \nu X] - \sigma[\bar{\nu} A \to \bar{\nu} X]}{\sigma[\nu A \to \mu X] - \sigma[\bar{\nu} A \to \mu^+ X]} = \frac{1}{2} - sin^2\theta_W$$



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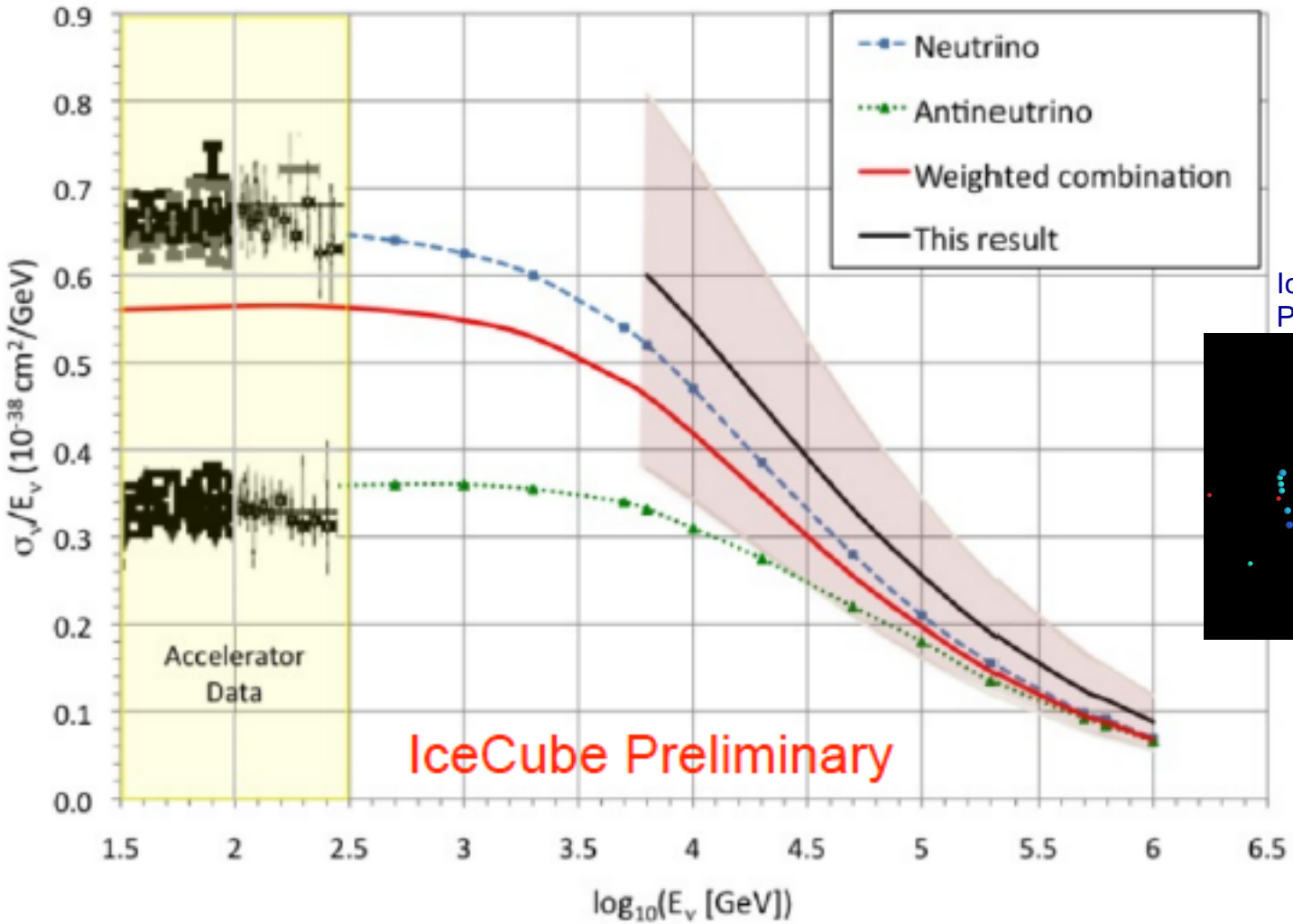
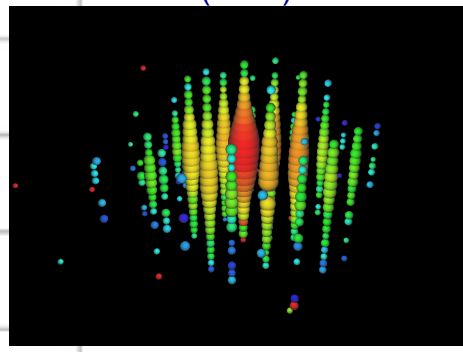
Tep

3. Neutrino DIS saturation



IceCube collaboration
PRL111(2013)021103



Cleveland et al.,Astrophys.J.496(1998)505
Pontecorvo,Phys.Lett.28B(1969)493

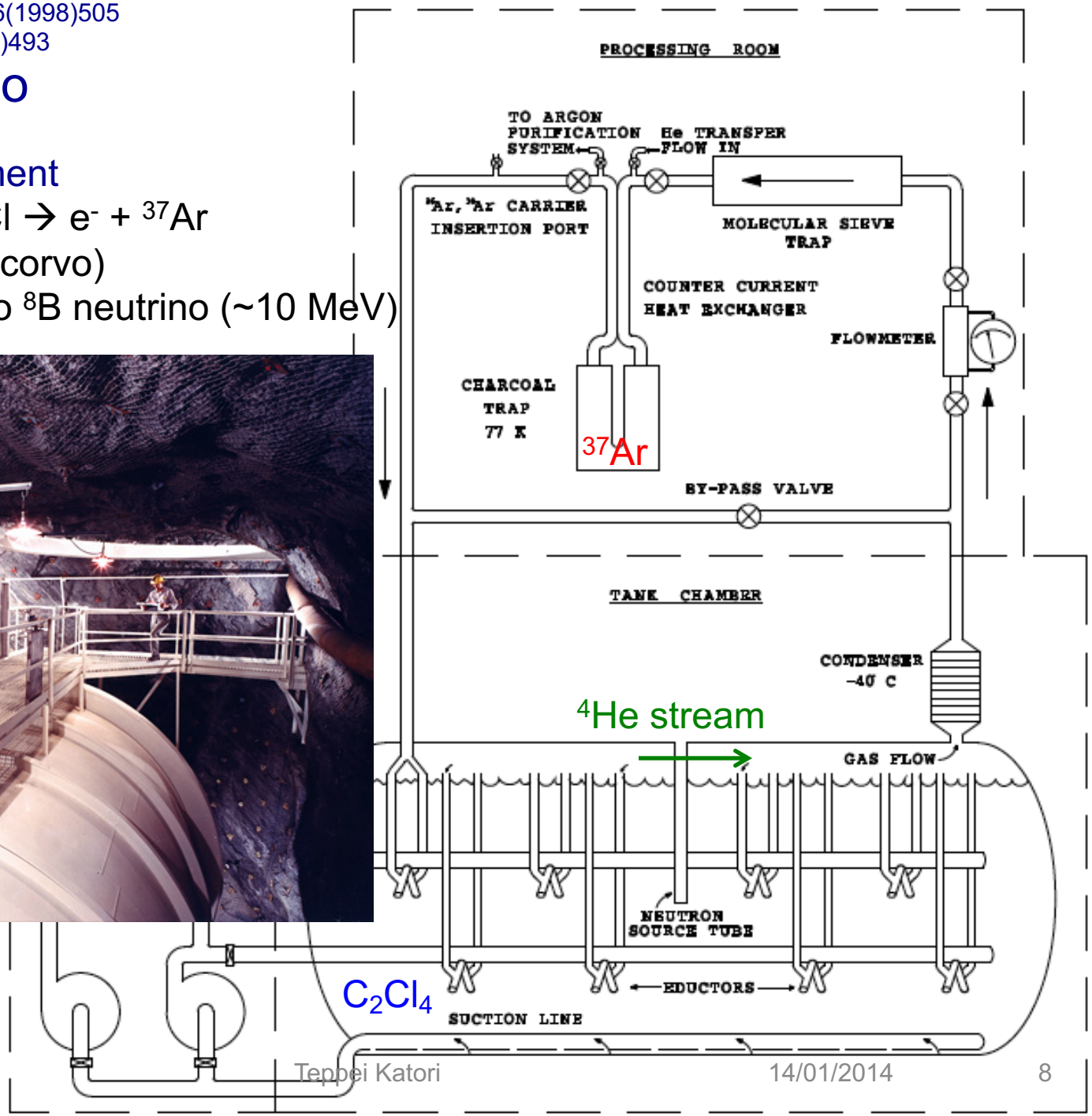
4. Solar neutrino

Homestake experiment

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

(proposed by Pontecorvo)

- mainly sensitive to ^{8}B neutrino (~10 MeV)



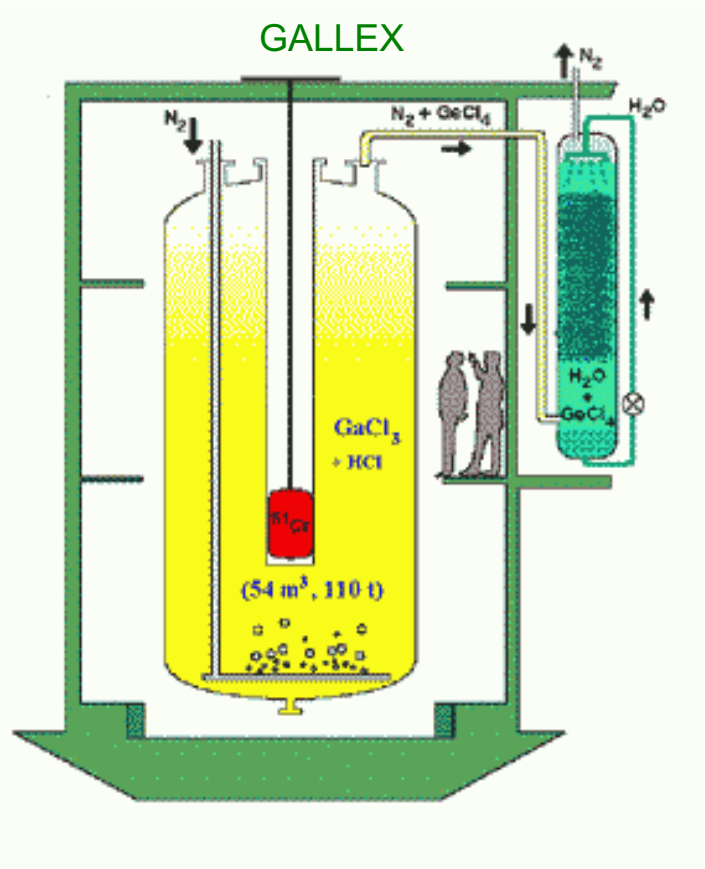
GALLEX, PLB490(2000)16;SAGE, J.Expt.Theor.Phys.95(2002)181
Borexino, PRL 108(2012)051302

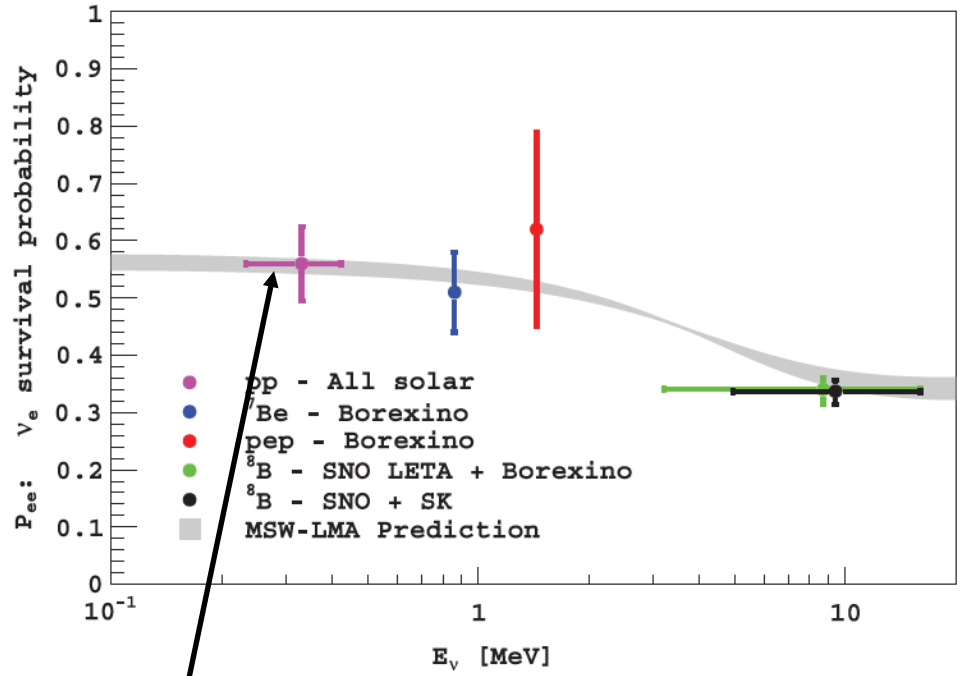
4. Solar neutrino

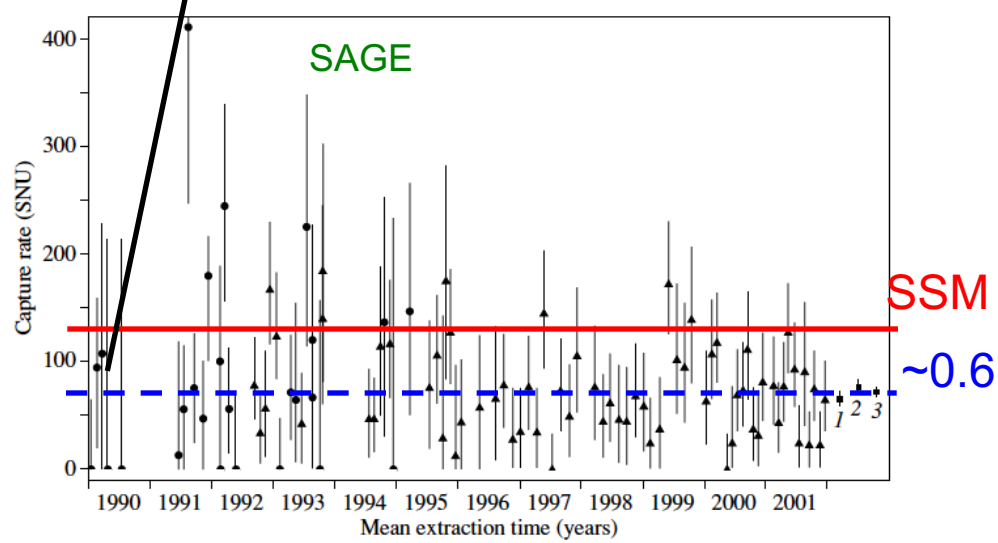
Gallium experiment

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

- Sensitive to pp-neutrino (0.42 MeV), 90% of total solar neutrino flux.
- Both experiments observed deficit, but higher than Homostake result





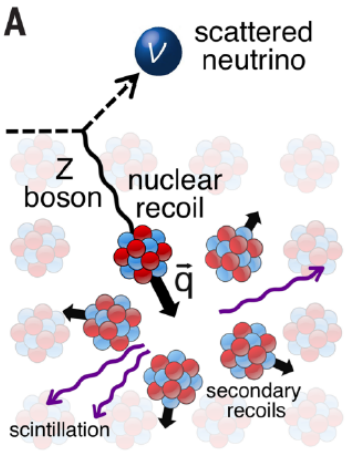


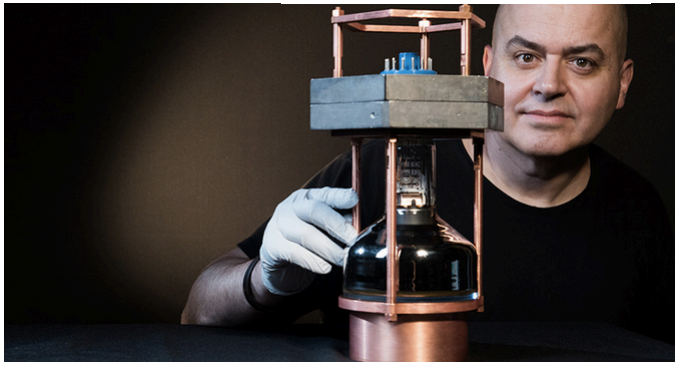
COHERENT, Science10.1126/science.aao0990 (2017).

4. Neutrino-Nucleus coherent scattering

Low energy neutrinos from neutron sources at SNS (spallation neutron source), ORNL (Oak Ridge National Lab)

$$\nu + A \rightarrow \nu + A$$





Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

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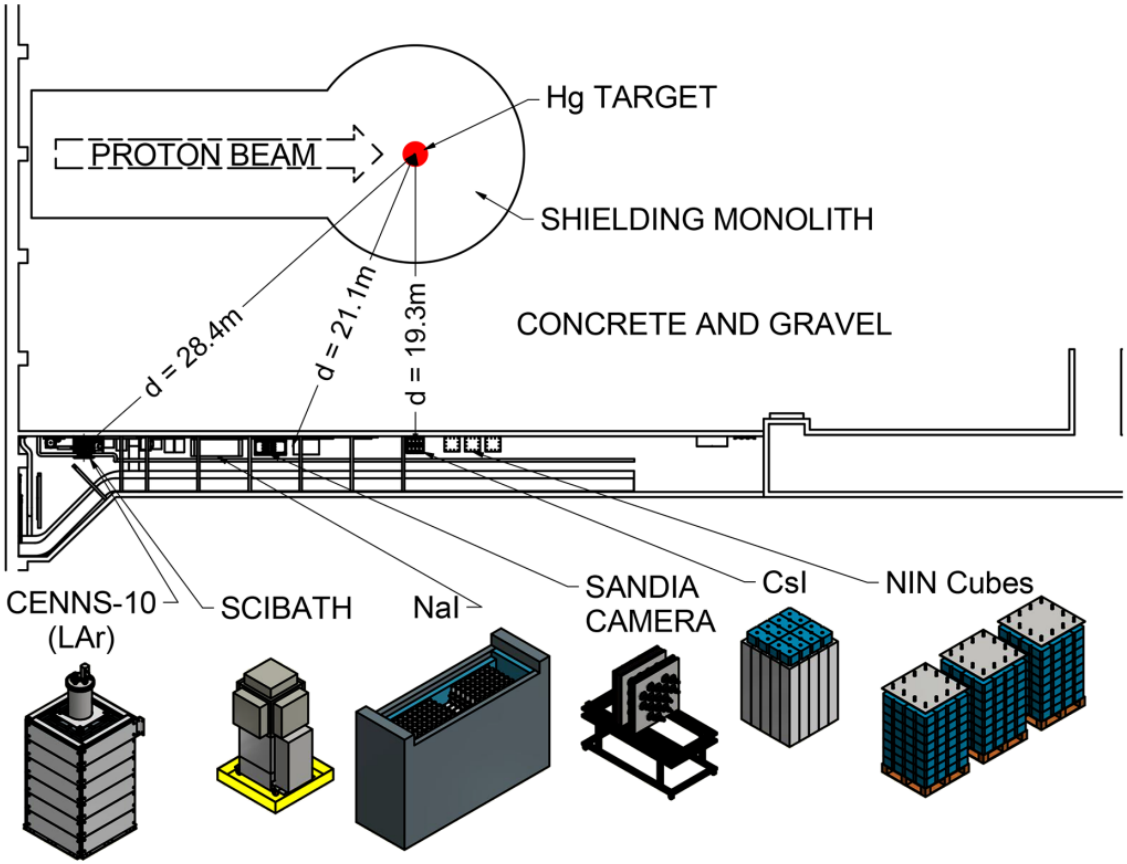

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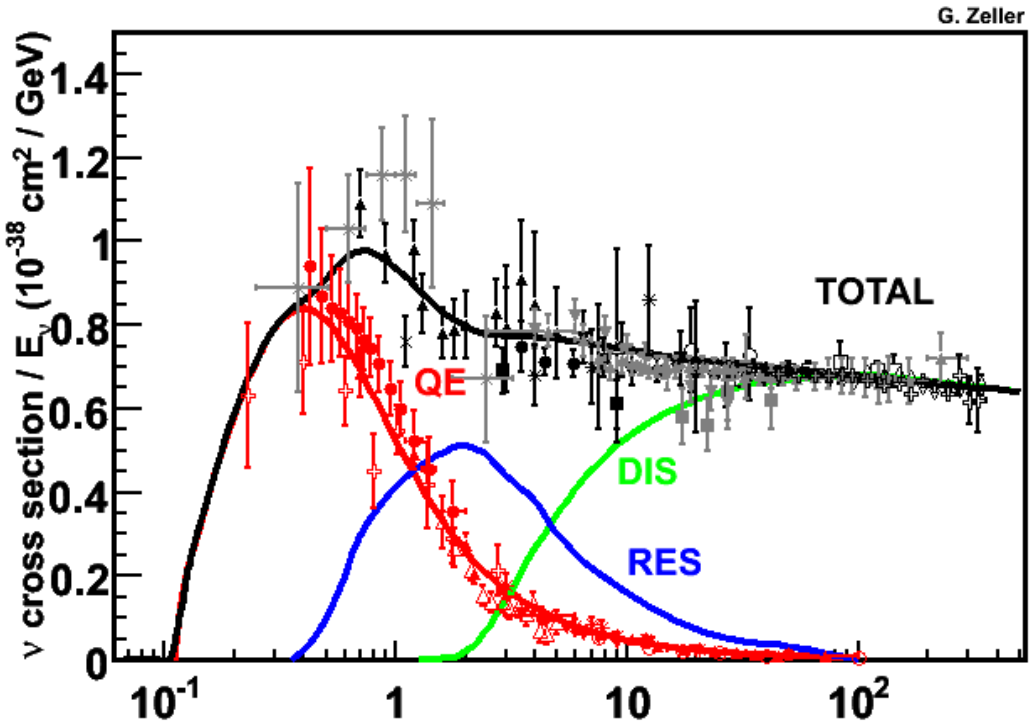
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE…



ν_μCC cross section per nucleon E_ν (GeV)

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$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

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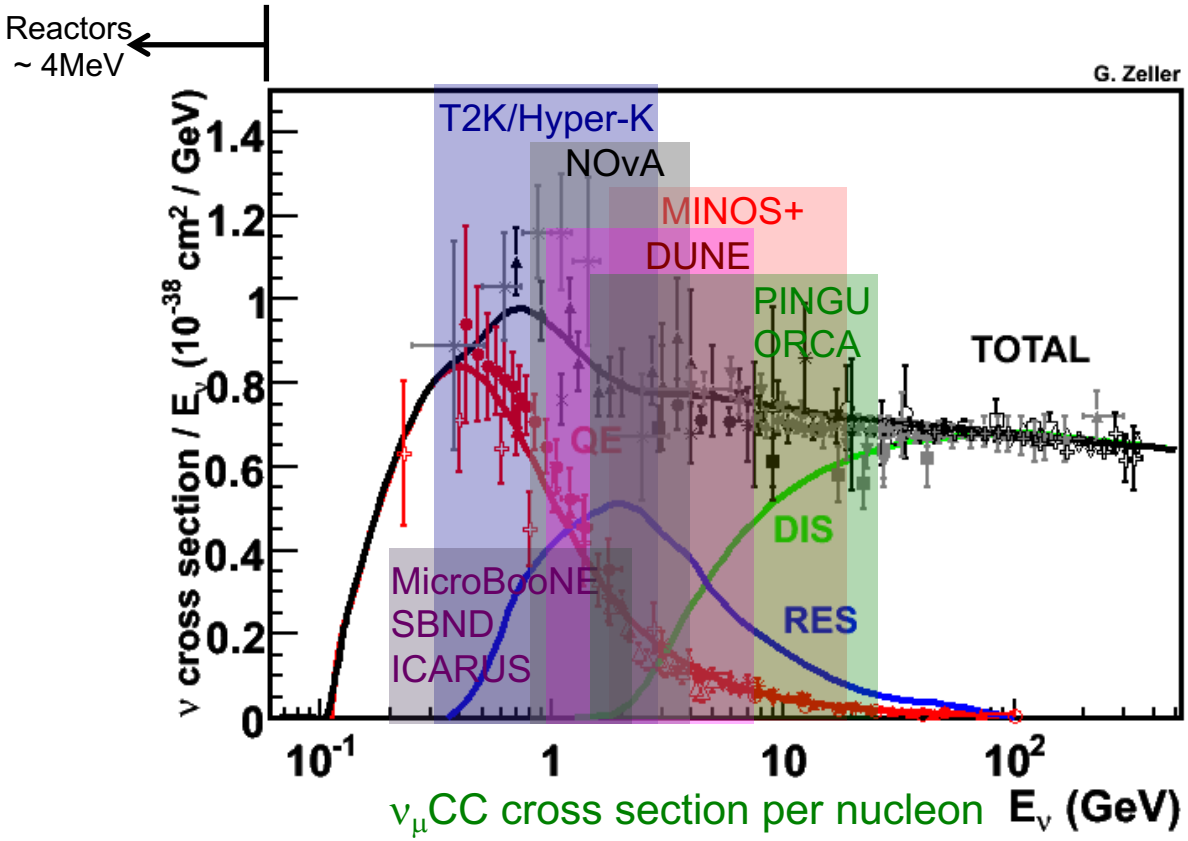

ν_μCC cross section per nucleon

Queen Mary University of London

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$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Conclusion

Neutrinos interact by weak force

ν-l scattering : test of weak theory

- Neutrino-electron scattering
- Muon decay

ν-q scattering : test of weak theory, test of quark model

- DIS cross sections
- Di-muon production
- Paschos-Wolfenstein ratio

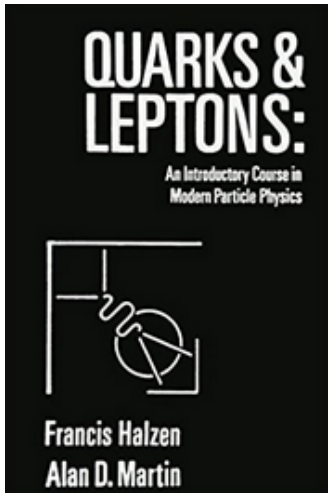
ν-A scattering :

- Neutrino nuclear capture by Cl and Ga, important for solar neutrinos
- Neutrino coherent scattering, important for supernova
  (first observation, Aug. 2017)

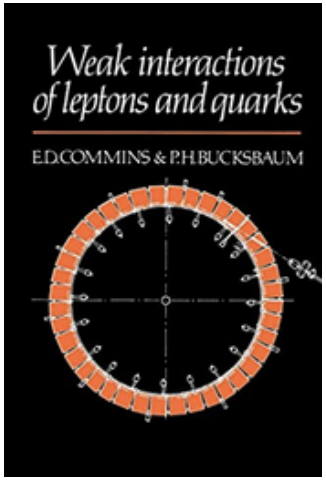
ν-N scattering : important reactions for long baseline neutrino oscillation experiment

- (T2K, NOvA, DUNE, Hyper-Kamiokande)

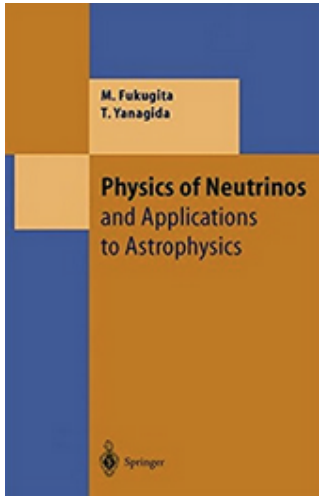
References



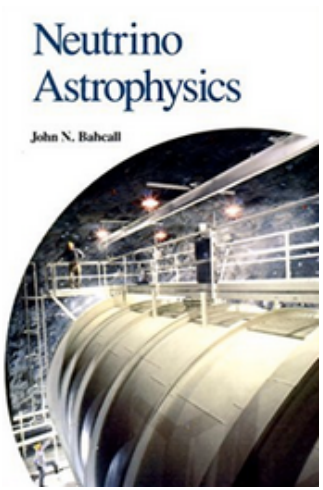
Quarks and Leptons (Halzen and Martin)
- classic
- show many calculations
- solutions for all exercises



Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- classic
- show more details of weak interaction calculations
- too many typos



Physics of Neutrinos (Fukugita and Yanagida)
- modern
- very intense
- from solar neutrinos to SUSY



Neutrino astrophysics (Bahcall)
- more likely a novel, honorable mentioning