Some Nuclear Physics with Solar Neutrinos

Solar neutrino experiments are big ‘consumers’ of nuclear physics information, e.g.:

- CC flux, CC/ES ratio: ν oscillations evidence
- NC flux, ν oscillations
- hep flux prediction
- solar physics calculations (pp, SSM)

Now we find SNO is also a ‘producer’ and we can learn about the semileptonic weak interaction of the deuteron and

L_{1A} the weak axial exchange-current term

ν Reactions in Heavy Water

CC

$$\nu_e + d \Rightarrow p + p + e^-$$

- “Charged Current”
- ν_e only.

NC

$$\nu_x + d \Rightarrow p + n + \nu_x$$

-“Neutral Current”
- Equal cross section for all active ν types

ES

$$\nu_x + e^- \Rightarrow \nu_x + e^-$$

-“Elastic Scattering”
-Mainly sensitive to $\nu_{e,}$, some sensitivity to ν_μ and ν_τ

Neutrino-deuteron interactions

Standard NP Approach:

Potential model
Higher-order corrections
with mesons, Δ's

NSGK, PRC63, 034617 (2001)
NSA+, NP A707, 561 (2002)

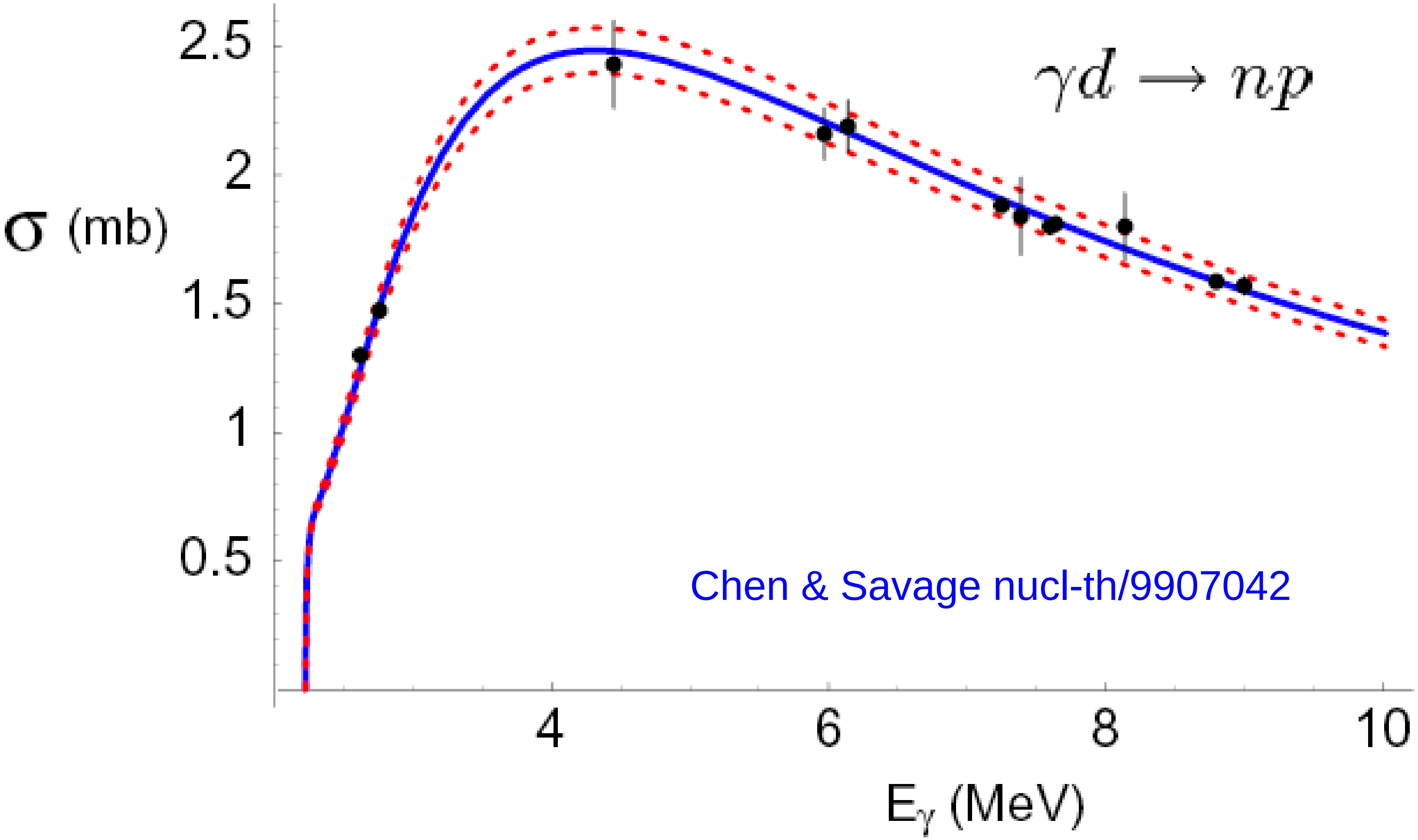
EFT (pionless)

$$Q \equiv \frac{(1/a, \gamma, p)}{\Lambda}$$

Expansion of interactions in power series.
Scattering length a, deuteron binding γ, momentum p are all small compared to pion mass Λ (lowest non-nucleonic excitation)

BCK, PRC 63, 035501 (2001)

An example - deuteron photodisintegration in EFT



El : NNNLO; M1: NLO

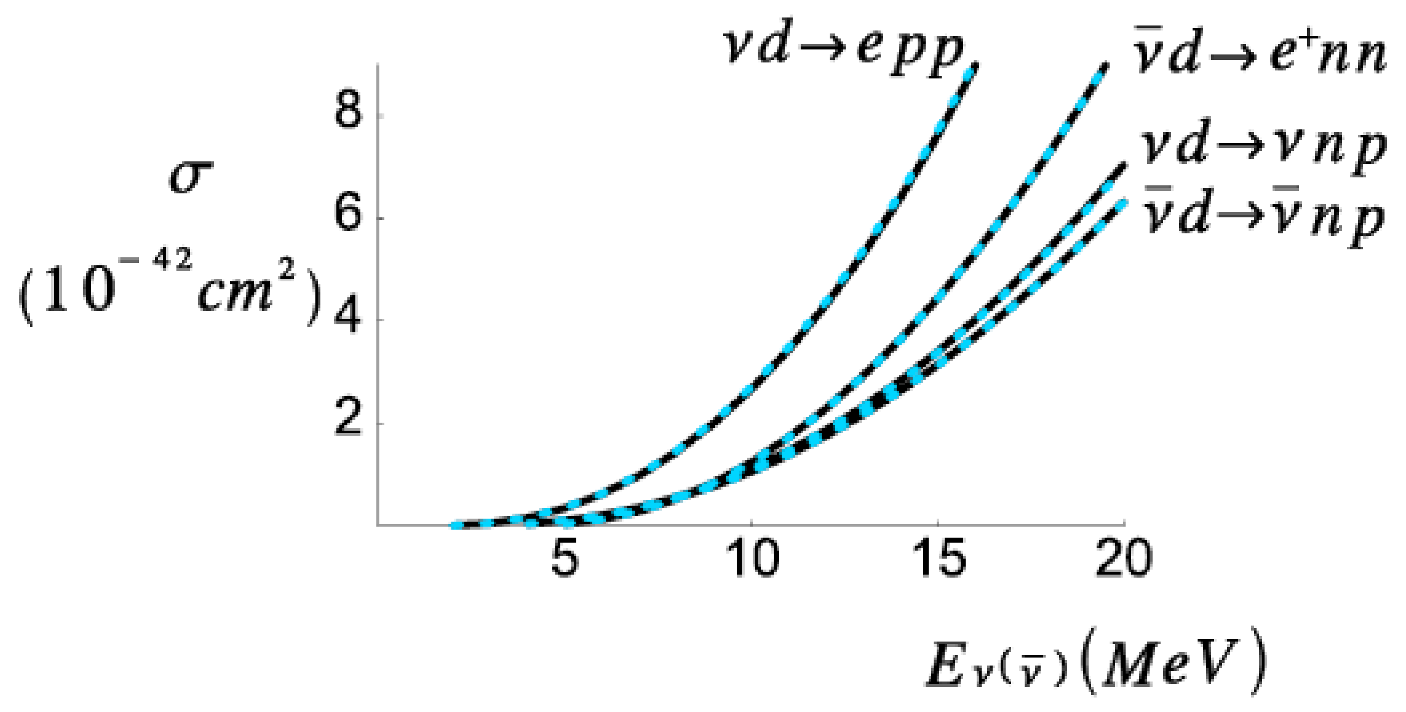
EFT gives general results

- Leading order & NLO cross sections model-independent
- Cross sections are analytic expressions
- All observable parameters (doubly differential cross sections, angular distributions, neutrino and antineutrino, CC & NC)
- First undetermined term is in NNLO. Term is the weak axial two-body current, called $L_{1,A}$

$$
\begin{aligned}
\nu_e + d &\rightarrow p + p + e^- && \text{(CC)},\\
\nu_x + d &\rightarrow p + n + \nu_x && \text{(NC)},\\
\nu_x + e^- &\rightarrow \nu_x + e^- && \text{(ES)}.
\end{aligned}
$$

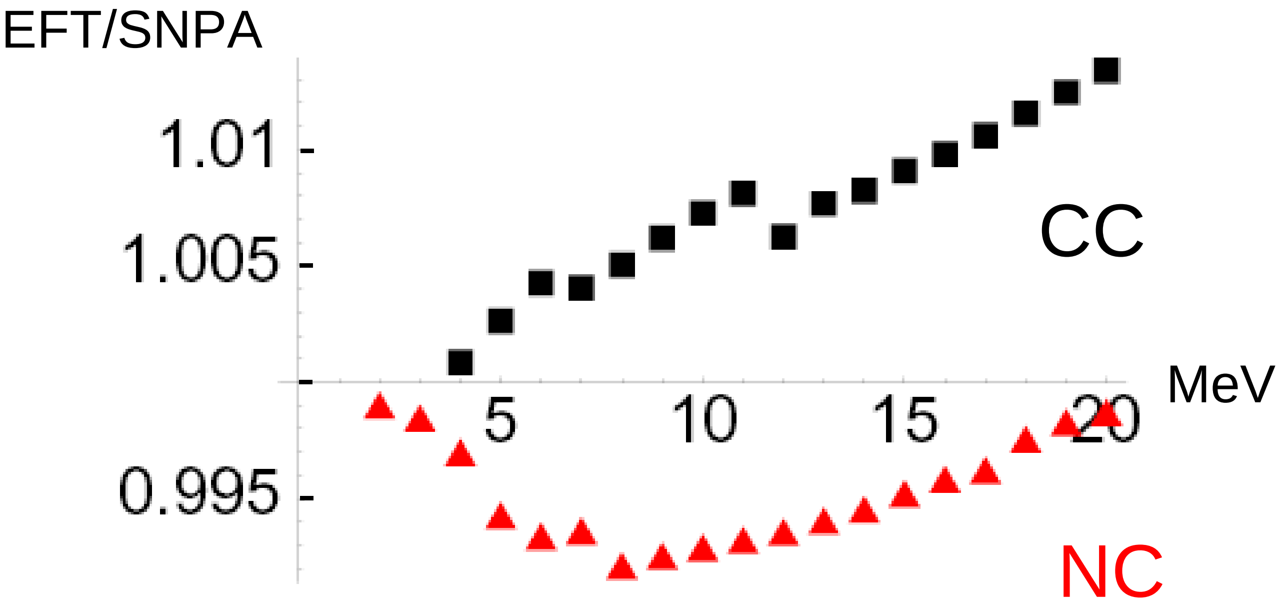
Depend on L1A

L1A can be fit to SNPA calculations



A SINGLE choice of L_{1A} produces this agreement!

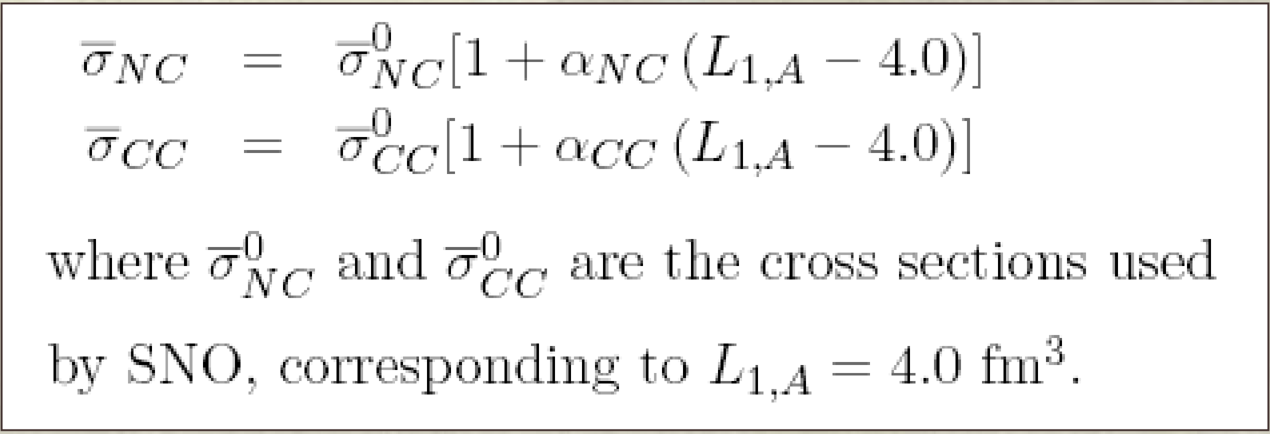
EFT compared to Standard Nuclear Physics Approach



Ratio of Butler et al. (BCK) EFT with $L_{1A} = 4.0\ \mathrm{fm}^3$ to Nakamura et al. (NSA+)

Dependence of σ_{NC}, σ_{CC} on L_{1A}

The cross-sections may be written to NNLO in the form:



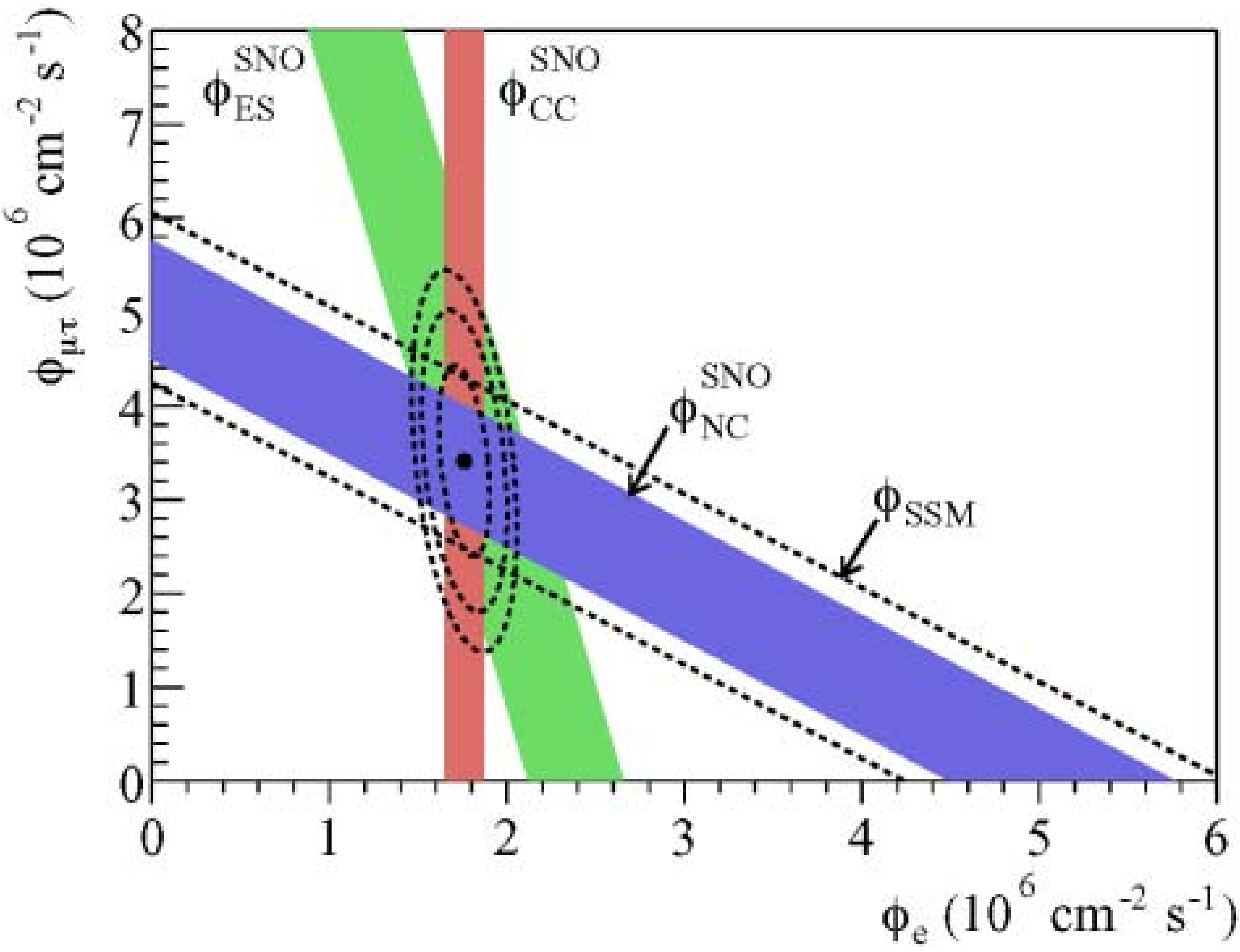
$$\begin{aligned}\overline{\sigma}_{NC} &= \overline{\sigma}^{0}_{NC}[1+\alpha_{NC}\,(L_{1,A}-4.0)]\\ \overline{\sigma}_{CC} &= \overline{\sigma}^{0}_{CC}[1+\alpha_{CC}\,(L_{1,A}-4.0)]\end{aligned}$$

where $\overline{\sigma}^{0}_{NC}$ and $\overline{\sigma}^{0}_{CC}$ are the cross sections used by SNO, corresponding to $L_{1,A} = 4.0\ \mathrm{fm}^3$.

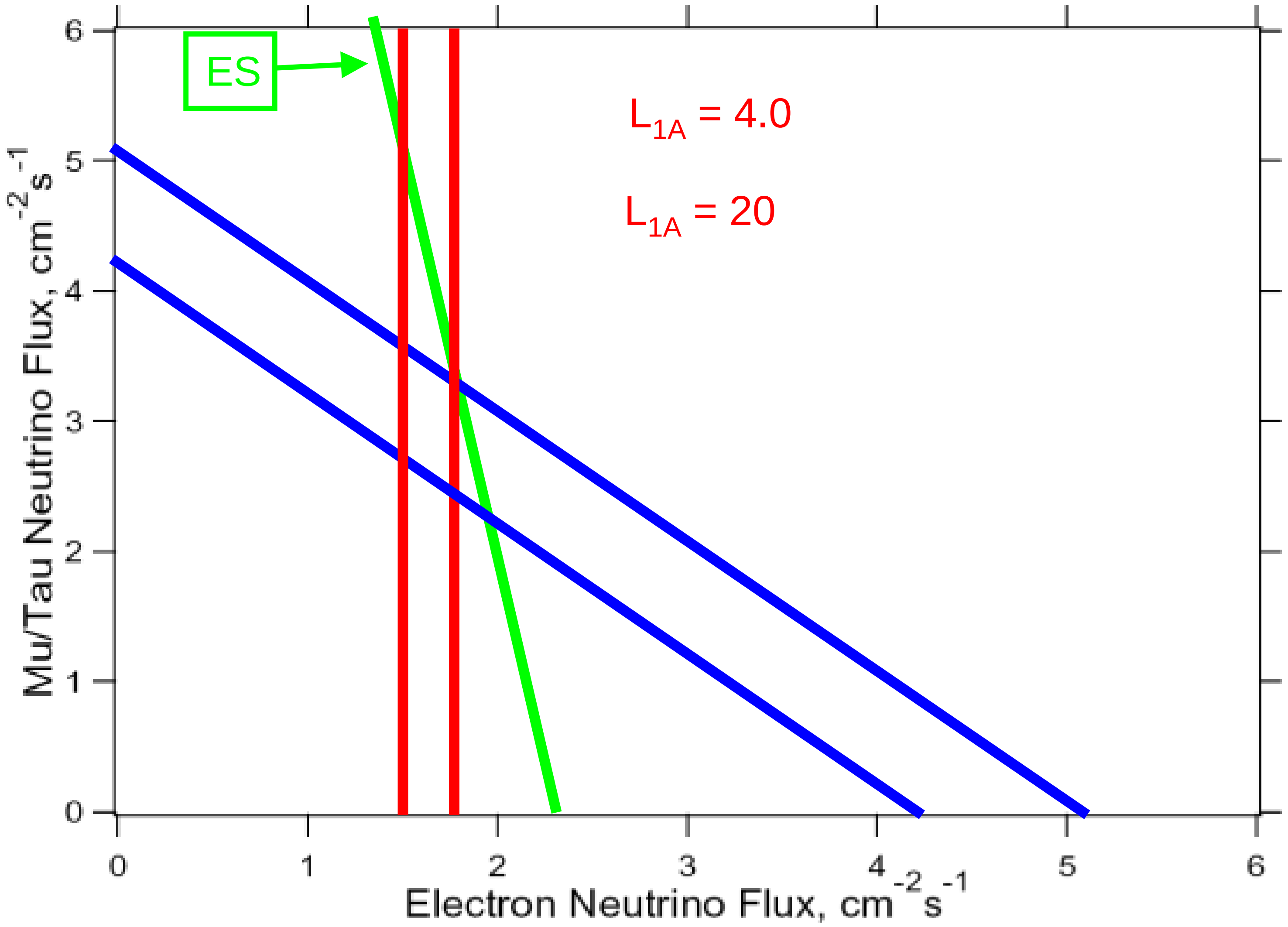
The coefficients α_{NC} and α_{CC} come from EFT and are small,

$\alpha_{NC} = 0.013$

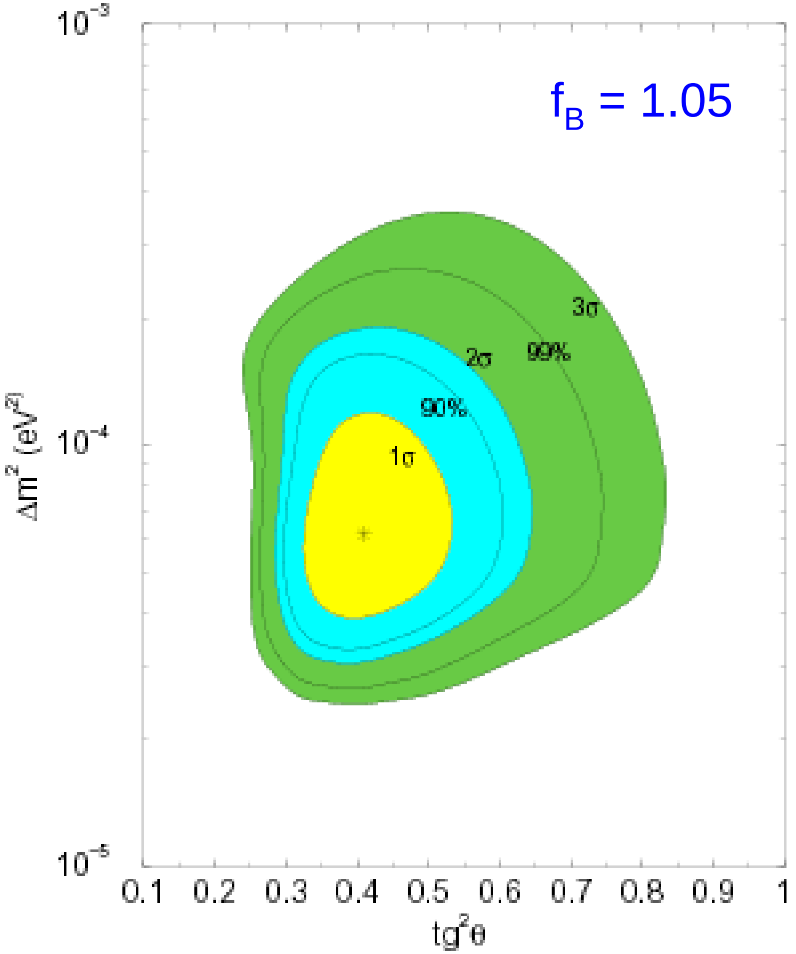
$\alpha_{CC} = 0.010$



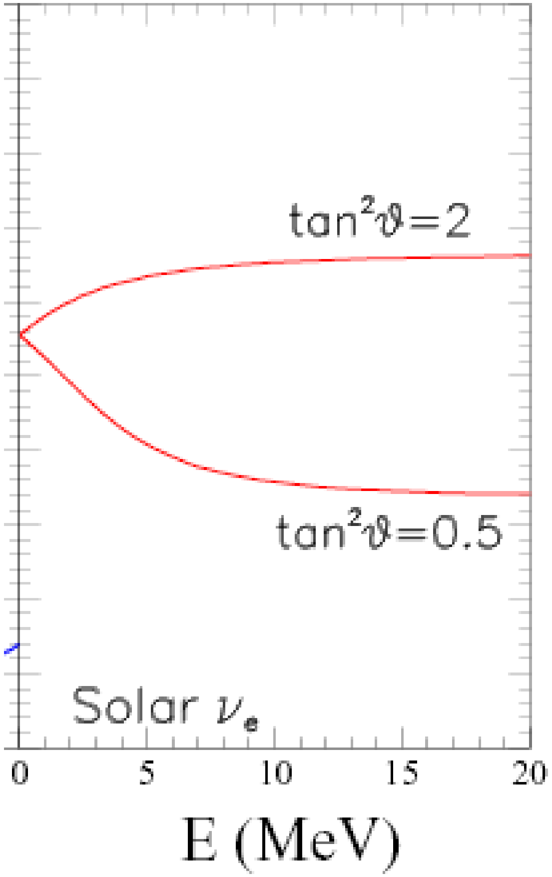
With only 2 fluxes (e and $\mu\tau$) and 3 data (NC, CC, ES) the fit is overconstrained. J-W. Chen's Proposal: Extract a third parameter (L_{1A}).

ES
$L_{1A} = 4.0$
$L_{1A} = 20$
Mu/Tau Neutrino Flux, $cm^{-2}s^{-1}$
Electron Neutrino Flux, $cm^{-2}s^{-1}$
0
1
2
3
4
5
6
0
1
2
3
4
5
6

Oscillation solutions actually have not just 2 parameters ϕ_e and $\phi_{\mu\tau}$, but 3 (such as Δm^2, $\tan^2\theta$, and ϕ_B) because the shape of the CC spectrum is in general distorted.



de Holanda & Smirnov hep-ph/0205241
Bahcall et al. hep-ph/0212147



What is the “CC flux” in this case?

Effective Cross Section

Detector resolution

$$\sigma_X(E_\nu, T_{min}) = \int_{T_{min}} dT \int dT' \frac{d^2\sigma_X(E_\nu, T')}{dE_\nu dT'} r(T, T')$$

Integrate above the experimental threshold

True Double Differential Cross Section for $E_\nu \rightarrow T'$

Effective cross section is a function of the neutrino energy and the threshold only

4 Reactions

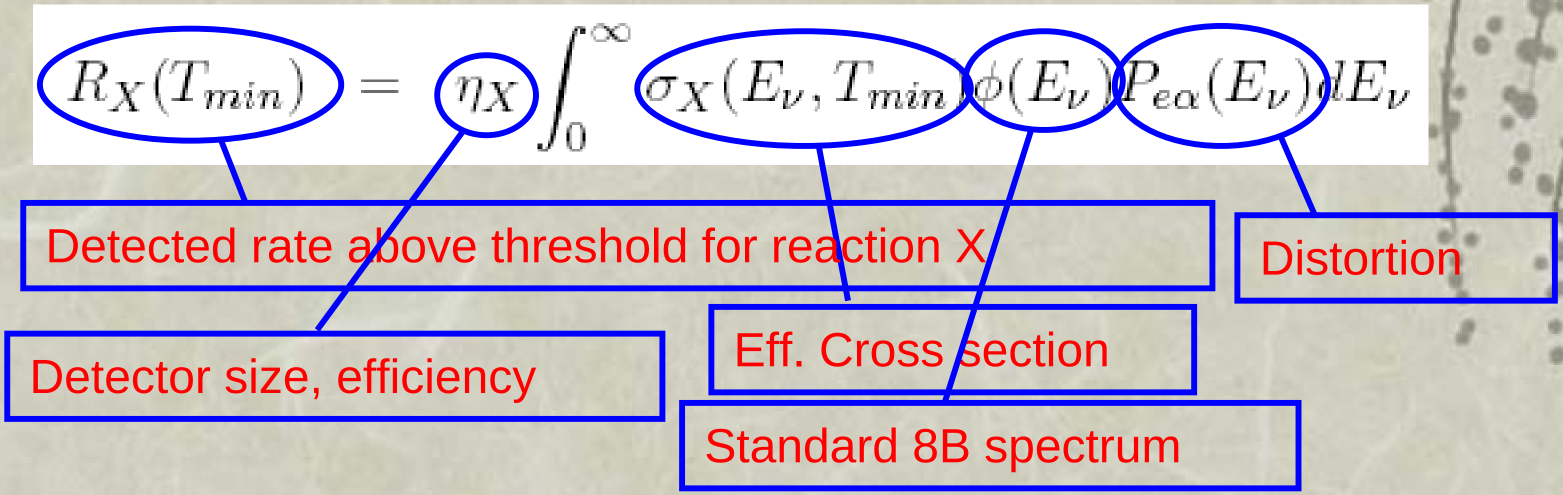
There are 4 kinds of interaction “X”:

X = NC Neutral Current on d

X = CC Charged Current on d

X = e ν_e electron elastic scatt. (CC)

$X = \mu\tau\nu_{\mu\tau}$ electron elastic scatt. (NC)



$$R_X(T_{min}) = \eta_X \int_0^\infty \sigma_X(E_\nu, T_{min}) \phi(E_\nu) P_{e\alpha}(E_\nu) dE_\nu$$

Detected rate above threshold for reaction X

Distortion

Detector size, efficiency

Eff. Cross section

Standard 8B spectrum

Detected Rate

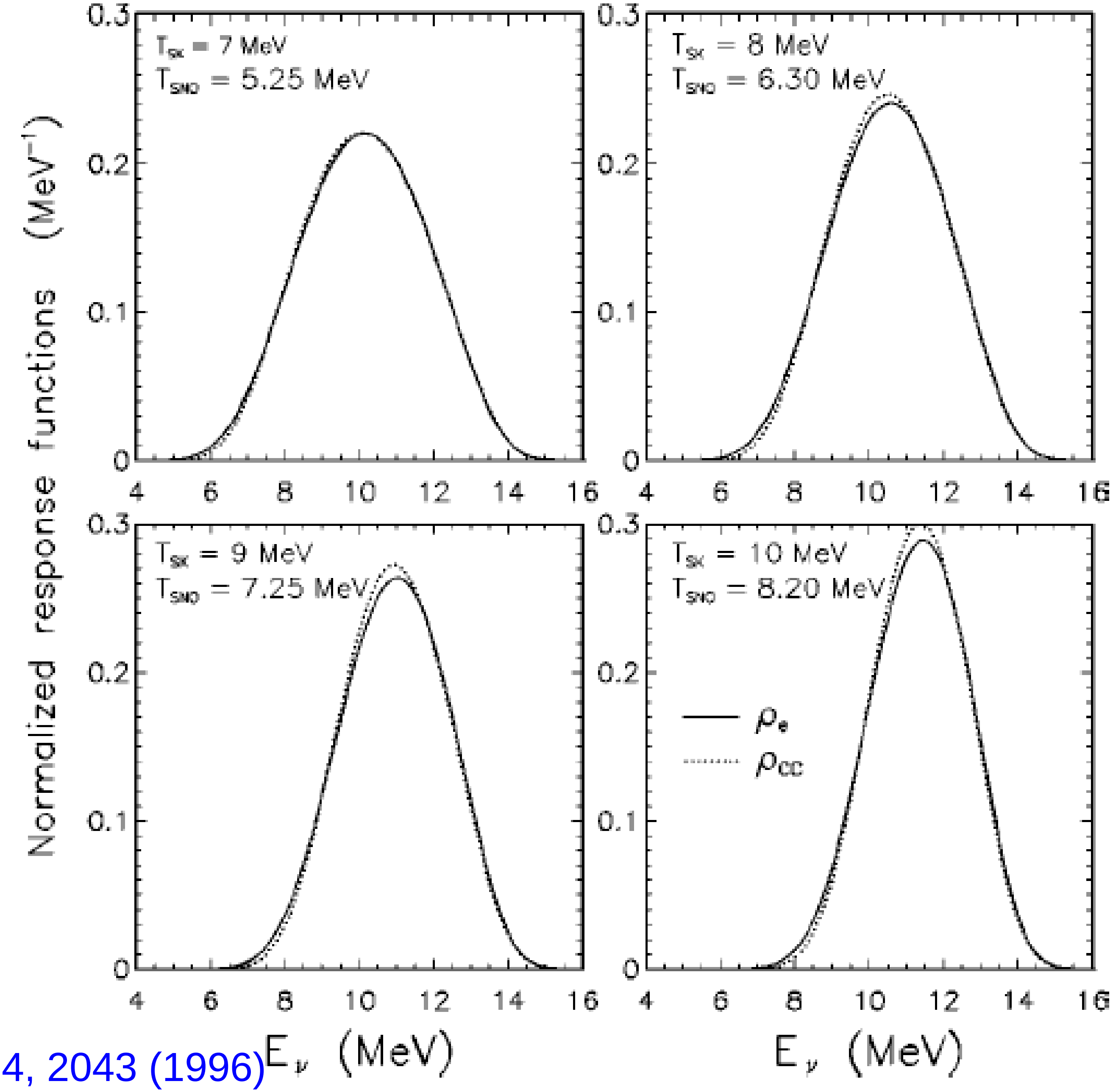
$$\begin{aligned} R_X(T_{min}) &= \eta_X \int_0^\infty \sigma_X(E_\nu, T_{min})\phi(E_\nu)P_{ea}(E_\nu)dE_\nu \\ &= \Phi_B \bar{\sigma}_X(T_{min}) \int \rho_X(E_\nu, T_{min})P_{ea}(E_\nu)dE_\nu \end{aligned}$$

"Response Function"

Standard ^{8}B Neutrino Spectrum

$$\begin{aligned} \rho_X(E_\nu, T_{min}) &= \frac{\sigma_X(E_\nu, T_{min})\phi(E_\nu)}{\int \sigma_X(E_\nu, T_{min})\phi(E_\nu)dE_\nu} \\ \bar{\sigma}_X(T_{min}) &= \eta_X \frac{\int \sigma_X(E_\nu, T_{min})\phi(E_\nu)dE_\nu}{\int \phi(E_\nu)dE_\nu}, \\ \Phi_B &= \int \phi(E_\nu)dE_\nu \end{aligned}$$

Response Functions of SNO and SK can be made equal by choosing T_{min}



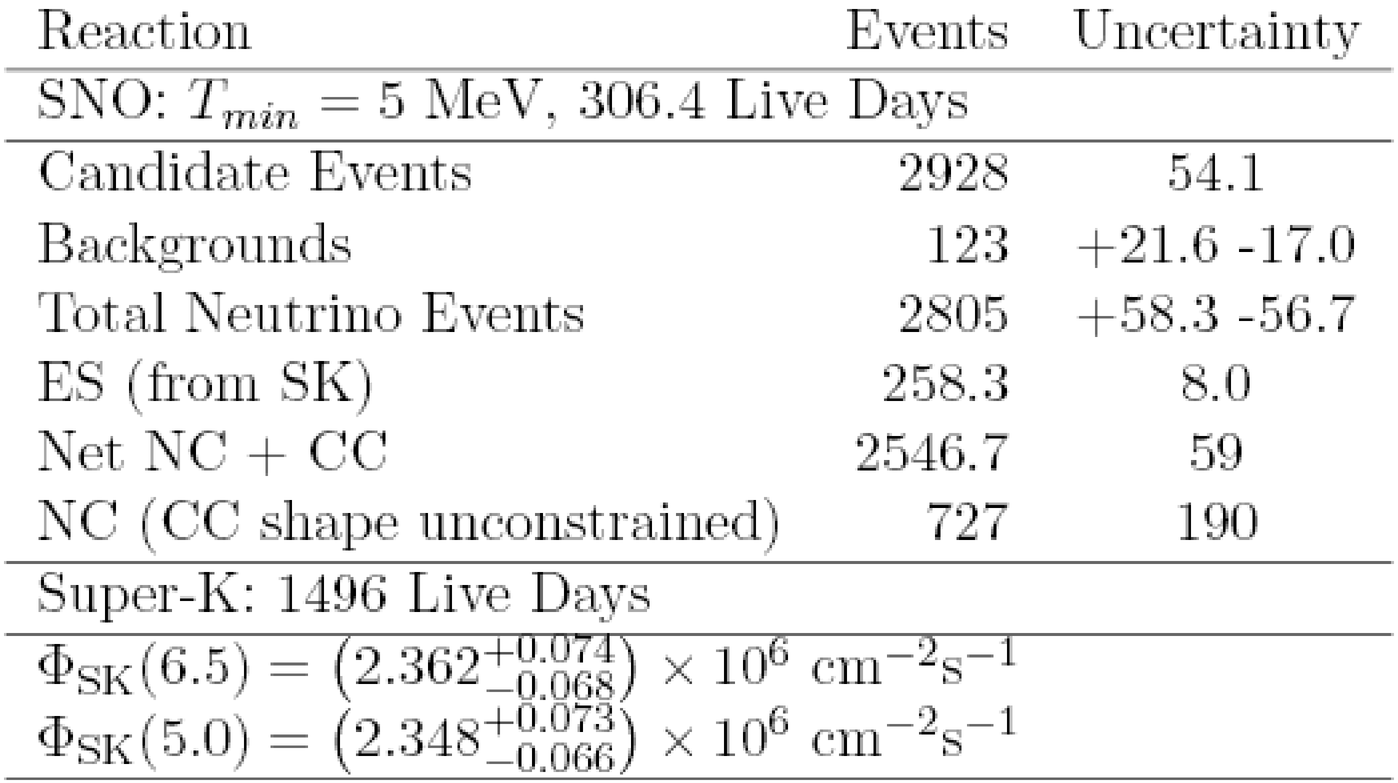
Kwong & Rosen PRD 54, 2043 (1996)
Villante et al., PRD 59, 013006 (1998)

The 3 experimental rates and 3 undetermined parameters

$$
\begin{aligned}
R_{NC} &= \boxed{\Phi_{\nu_x}}\,\overline{\sigma}^0_{NC}[1+\alpha_{NC}\,(\boxed{L_{1,A}}-4.0)]\ , \\
R_{CC} &= \Phi_{\nu_x}\overline{\sigma}^0_{CC}[1+\alpha_{CC}\,(L_{1,A}-4.0)]\boxed{\int_0^\infty \rho(E,T_{min})P_{e\alpha}dE}, \\
R_{ES} &= \Phi_{\nu_x}\overline{\sigma}_e\left[\frac{\overline{\sigma}_{\mu,\tau}}{\overline{\sigma}_e}+\left(1-\frac{\overline{\sigma}_{\mu,\tau}}{\overline{\sigma}_e}\right)(1+\epsilon)\int_0^\infty \rho(E,T_{min})P_{e\alpha}dE\right]\ .
\end{aligned}
$$

By selecting T_{min} appropriately for the CC and ES cases, we make the functions ρ and hence the integrals equal. For CC, T_{min} = 5.0 MeV, for ES, T_{min} = 6.8 MeV.

Experimental Inputs from SNO & SK



Reaction	Events	Uncertainty
SNO: $T_{min} = 5$ MeV, 306.4 Live Days		
Candidate Events	2928	54.1
Backgrounds	123	+21.6 -17.0
Total Neutrino Events	2805	+58.3 -56.7
ES (from SK)	258.3	8.0
Net NC + CC	2546.7	59
NC (CC shape unconstrained)	727	190
Super-K: 1496 Live Days		
$\Phi_{\mathrm{SK}}(6.5) = (2.362^{+0.074}_{-0.068}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		
$\Phi_{\mathrm{SK}}(5.0) = (2.348^{+0.073}_{-0.066}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$		

Q. R. Ahmad et al., PRL 89, 011301 (2002);
S. Fukuda et al., PL B539, 179 (2002).

Experimental Systematic Errors on Fluxes

Error Source	**CC Error** (%)	**NC Error** (%)
Energy Scale	-4.2/+4.3	-6.2/+6.1
Energy Resolution	-0.9/+0.0	-0.0/+4.4
Energy Scale Non-Linearity	±0.1	±0.4
Vertex Accuracy	-2.8/+2.9	±1.8
Vertex Resolution	±0.0	±0.1
Angular Resolution	±0.2	±0.3
Live Time	±0.1	±0.1
Trigger Efficiency	0.0	0.0
Cut Acceptance	-0.2/+0.4	-0.2/+0.4
Neutron Capture	± 0.0	+4.0/-3.6
Residual Backgrounds ($R_{fit} \lesssim 550$ cm)		
Photodisintegration	± 0.1	-2.5/+2.6
Cherenkov	-0.2/+0.3	+3.0/-1.8
Experimental Uncertainty	**-5.2/+5.2**	**+8.5/-9.1**

Results of fit

Chen, Heeger & HR, PRC 67, 025801 (2003), nucl-th/0210073

$$\begin{aligned} L_{1,A} &= 4.0 \pm 4.7(\mathrm{stat.}) \pm 4.5(\mathrm{syst.})\ \mathrm{fm}^3 \\ \Phi_{\nu_x} &= (6.4 \pm 1.4 \pm 0.6) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \\ \int_0^\infty \rho(E, T_{min} = 5.0) P_{ea} dE &= 0.25^{+0.12}_{-0.07} \pm 0.03 \end{aligned}$$

The integral is 4.2 σ from unity (the Standard Model value)

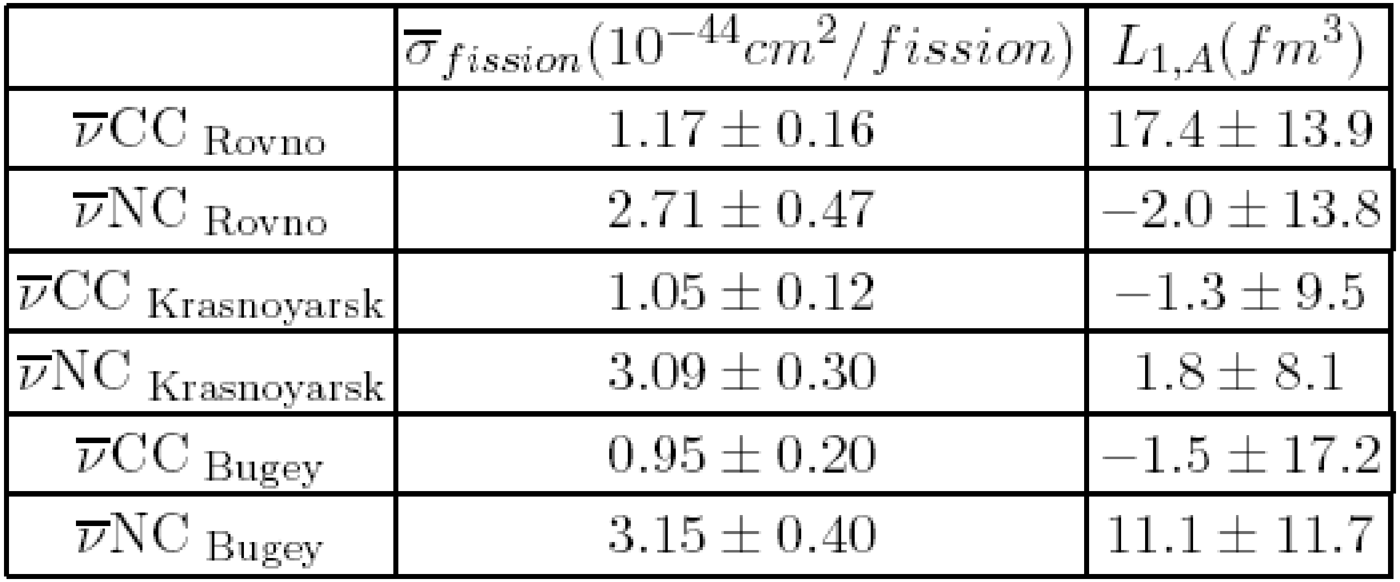
With L_{1A} as a fit parameter, null hypothesis fails at 4.3 σ.

Using reactor value for L_{1A}, 5.1 σ (SNO only), or 5.3 σ (SNO & SK).
[Ahmad et al.: 5.3, 5.5]

Determinations of L_{1A}

Process	L_{1A} (fm^3)	Reference
CC, NC, ES	4.0 ± 6.3	This work
Reactor antineutrinos	3.6 ± 4.6	Butler et al. nucl-th/0206026
Tritium β decay	4.2 ± 0.1	Schiavilla et al. PRC 58, 1263 (1998); Park et al. nucl-th/0106025 & nucl-th/0208055; Ando et al. nucl-th/02026001
Solar *pp* reaction	4.8 ± 5.9	Brown et al. nucl-th/0207008
Potential model	4.0	Nakamura et al. NP A707, 561 (2002)

L_{1A} from Reactor Antineutrino Experiments

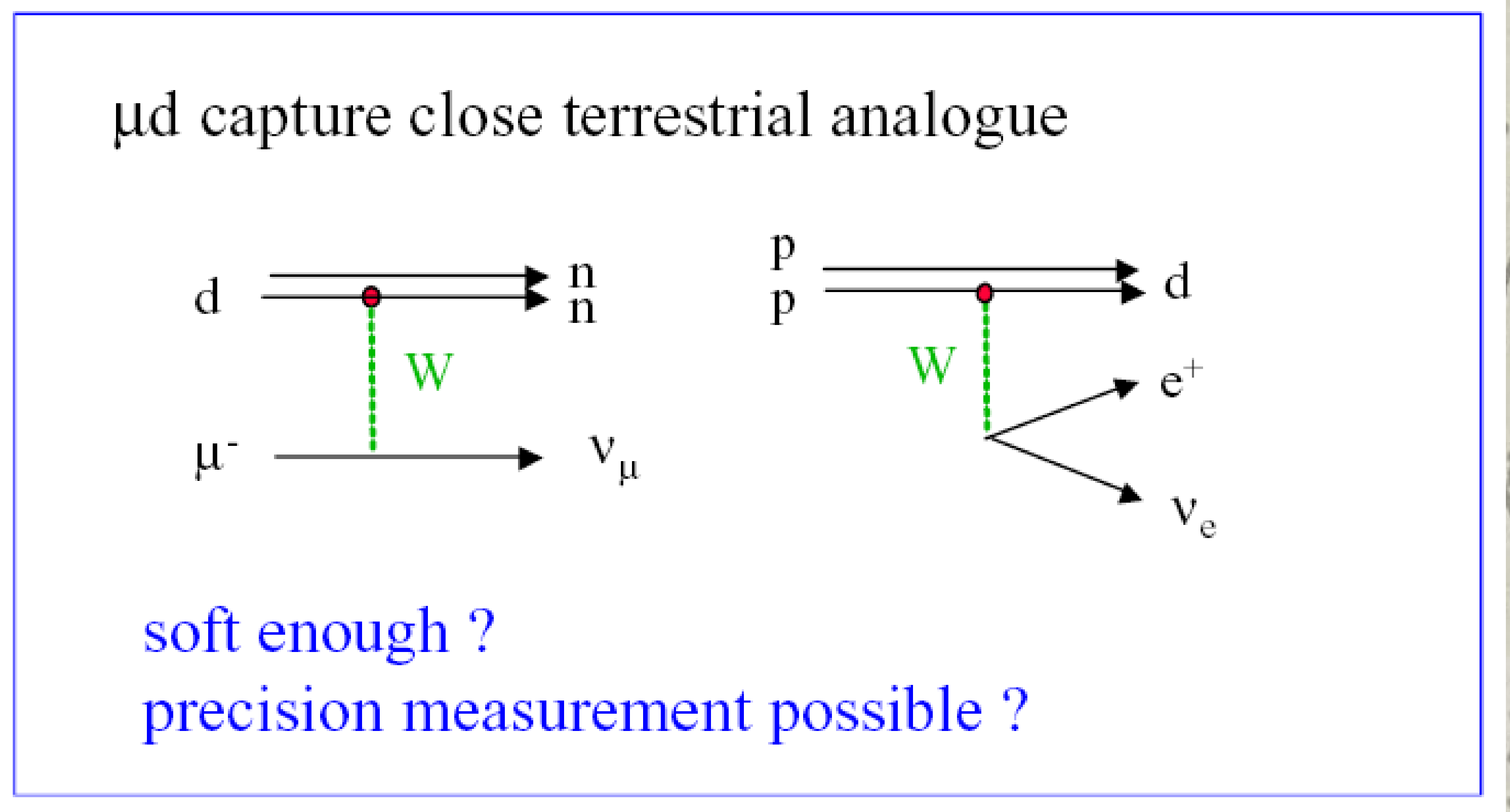


	$\overline{\sigma}_{fission}(10^{-44}cm^2/fission)$	$L_{1,A}(fm^3)$
$\overline{\nu}$CC Rovno	1.17 ± 0.16	17.4 ± 13.9
$\overline{\nu}$NC Rovno	2.71 ± 0.47	-2.0 ± 13.8
$\overline{\nu}$CC Krasnoyarsk	1.05 ± 0.12	-1.3 ± 9.5
$\overline{\nu}$NC Krasnoyarsk	3.09 ± 0.30	1.8 ± 8.1
$\overline{\nu}$CC Bugey	0.95 ± 0.20	-1.5 ± 17.2
$\overline{\nu}$NC Bugey	3.15 ± 0.40	11.1 ± 11.7

Butler, Chen & Vogel, PL B549, 26 (2002)
Rovno: Vershinsky et al., JETP Lett. 53, 513 (1991)
Krasnoyarsk: Kozlov et al., Phys. Atom. Nucl. 63, 1016 (2000)
Bugey: Riley et al., PRC 59, 1780 (1998).

Possibility of a Precision Measurement

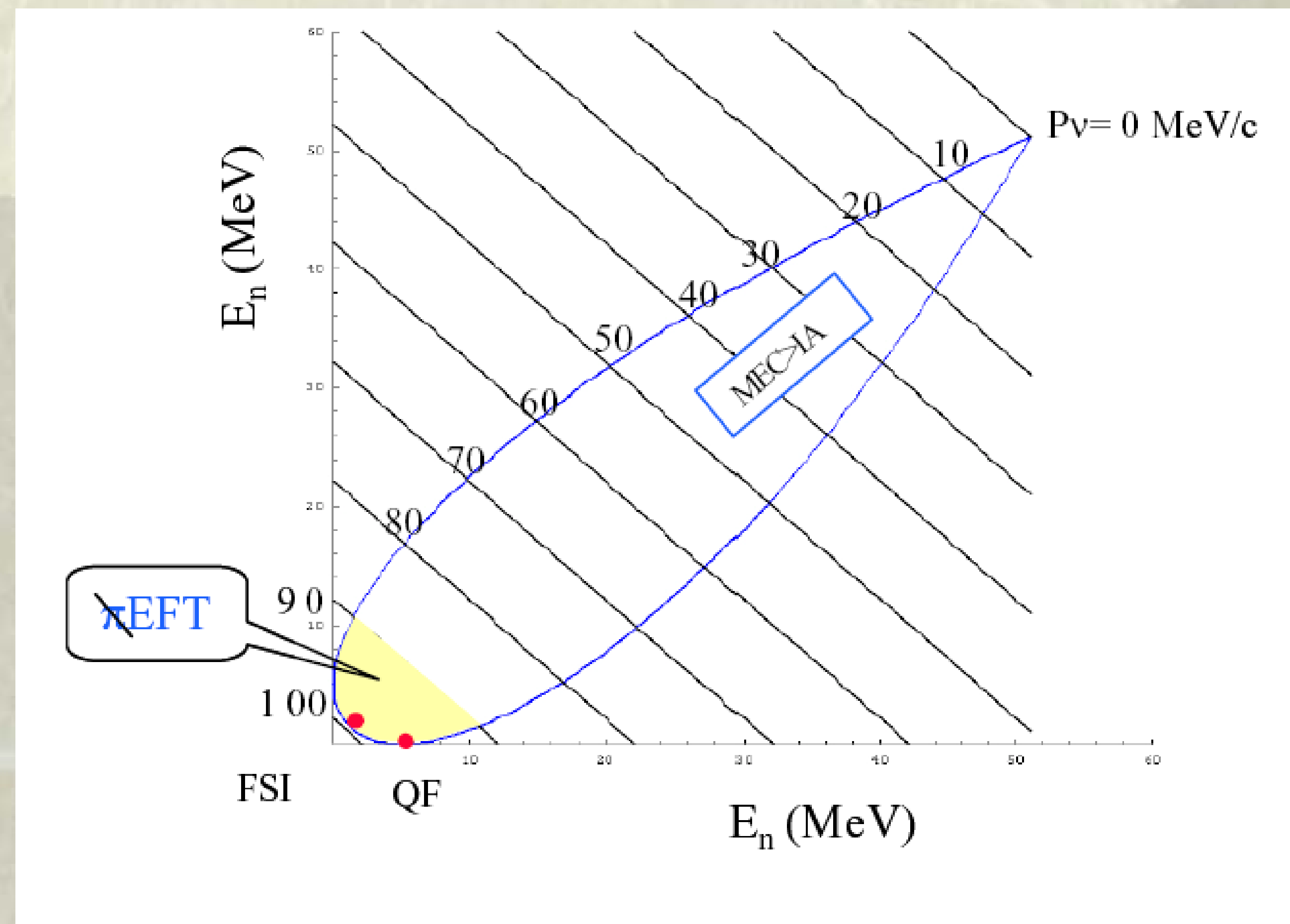
(Peter Kammel et al. at PSI)



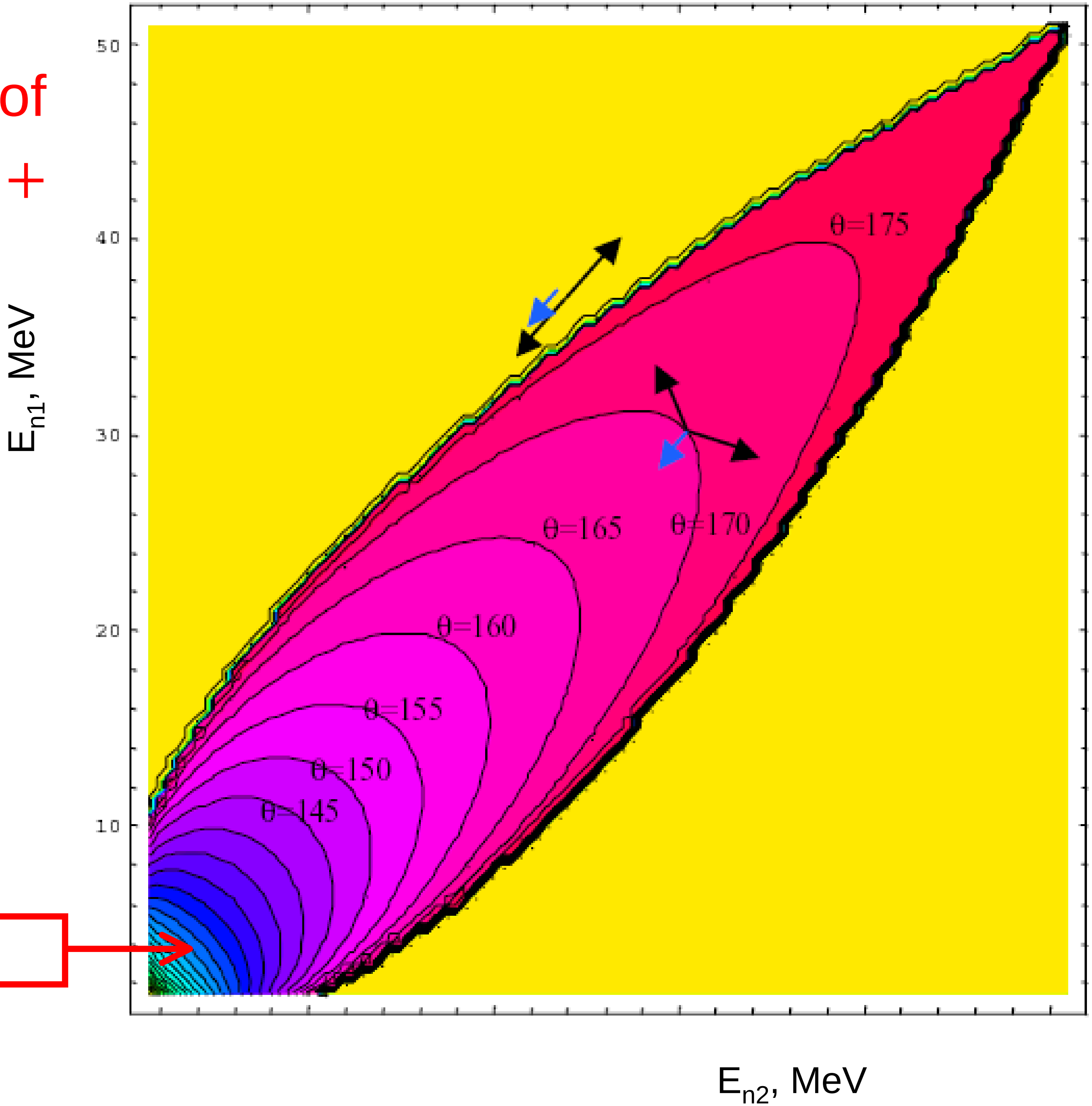
μd capture close terrestrial analogue

soft enough ?
precision measurement possible ?

3-body decay Dalitz Plot

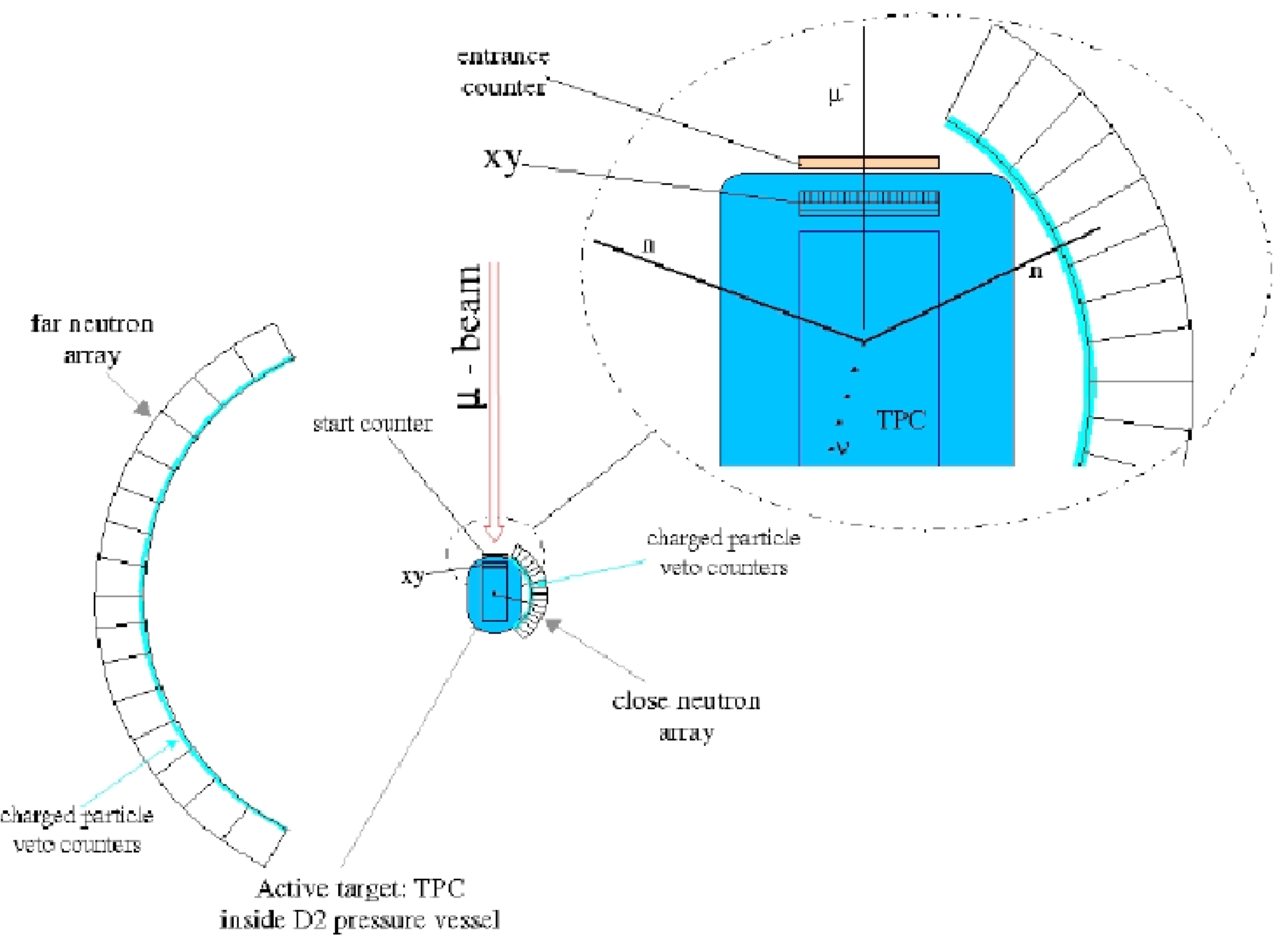


Kinematics of $\mu + d \rightarrow 2n + \nu_\mu$



EFT applies

Experimental arrangement at PSI



Conclusions

- L_{1A} serves as a fundamental parameter describing semileptonic weak processes in the 2-nucleon system.
- SNO, or SNO+SK, provide a new experimental determination of L_{1A}
- Resulting value agrees well with theory and with other experiments.
- SNO's conclusions re oscillations are not significantly theory dependent.
- Future results with SNO and with μ+d capture will improve precision on L_{1A}