Theoretical evaluation of the IBD cross section

Giulia Ricciardi

Università degli Studi di Napoli Federico II

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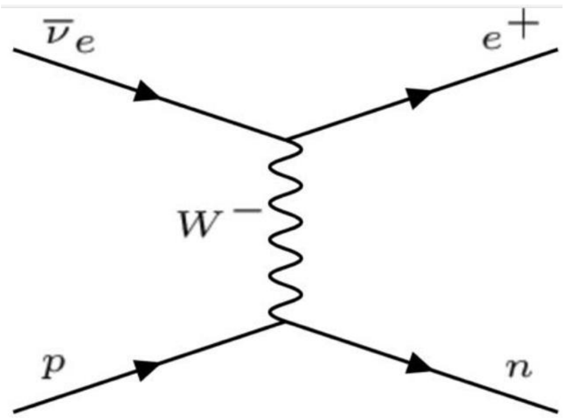
Inverse beta decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



by far the most important mechanism of interaction of low-energy antineutrinos

precision of theoretical cross section crucial for high statistics experiments

- Calculation of the amplitude
- Theoretical uncertainties
- Experimental relevance

THE SIX FORM FACTORS

Neutrino interactions with a free nucleon:

- ❑ same basic characteristics of neutrino-lepton interactions
- ❑ generic Lorentz invariant hadronic current

$$\mathcal{M} = \bar{v}_\nu \gamma^a (1-\gamma_5) v_e \quad \mathrm{X} \quad \bar{u}_n \left(f_1 \gamma_a + g_1 \gamma_a \gamma_5 + i f_2 \sigma_{ab} \frac{q^b}{2M} + g_2 \frac{q_a}{M} \gamma_5 + f_3 \frac{q_a}{M} + i g_3 \sigma_{ab} \frac{q^b}{2M} \gamma_5 \right) u_p$$

$$M = (m_n + m_p)/2.$$

SECOND CLASS CURRENTS

$$\bar{u}_n\left(f_1\gamma_a + g_1\gamma_a\gamma_5 + if_2\sigma_{ab}\frac{q^b}{2M} + g_2\frac{q_a}{M}\gamma_5 + f_3\frac{q_a}{M} + ig_3\sigma_{ab}\frac{q^b}{2M}\gamma_5\right)u_p$$

SCC

G-parity $G = Ce^{i\pi I_2}$

$GV_\mu G^{-1} = V_\mu\,, \quad GA_\mu G^{-1} = -A_\mu$ First Class Standard Model

$GV_\mu G^{-1} = -V_\mu\,, \quad GA_\mu G^{-1} = A_\mu$ Second Class

SCC absent if SU(3) symmetry holds (or charge symmetry & time reversal)

(Weinberg, Ankovski, Giunti, Ivanov, …)

THE CROSS SECTION

$$\overline{|\mathcal{M}^2|} = A_{\bar{\nu}}(t) - (s-u)B_{\bar{\nu}}(t) + (s-u)^2 C_{\bar{\nu}}(t)$$

Including the SCC currents

G.R., Vissanii & Vignaroli

$$\frac{d\sigma}{dt} = \frac{G_F^2 \cos^2\theta_C}{64\pi(s-m_p^2)^2}\overline{|\mathcal{M}^2|}$$

$$\cos\theta_C = V_{\rm ud}$$

$$d\sigma(E_\nu, E_e) \to d\sigma(E_\nu, E_e)\left[1 + \frac{\alpha}{\pi}\left(6.00 + \frac{3}{2}\log\frac{m_p}{2E_e} + 1.2\left(\frac{m_e}{E_e}\right)^{1.5}\right)\right]$$

Including radiative corrections

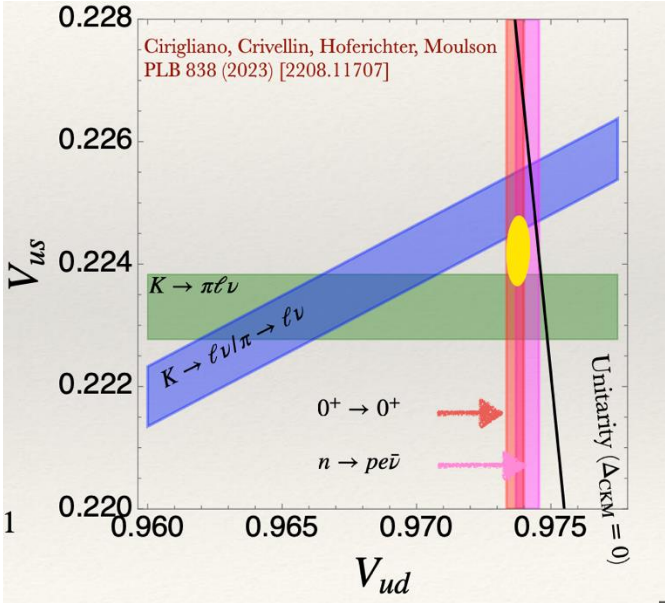
Towner, Beacom & Parke, Kurylov, Ramsey-Musolf & Vogel

CABIBBO ANGLE ANOMALY

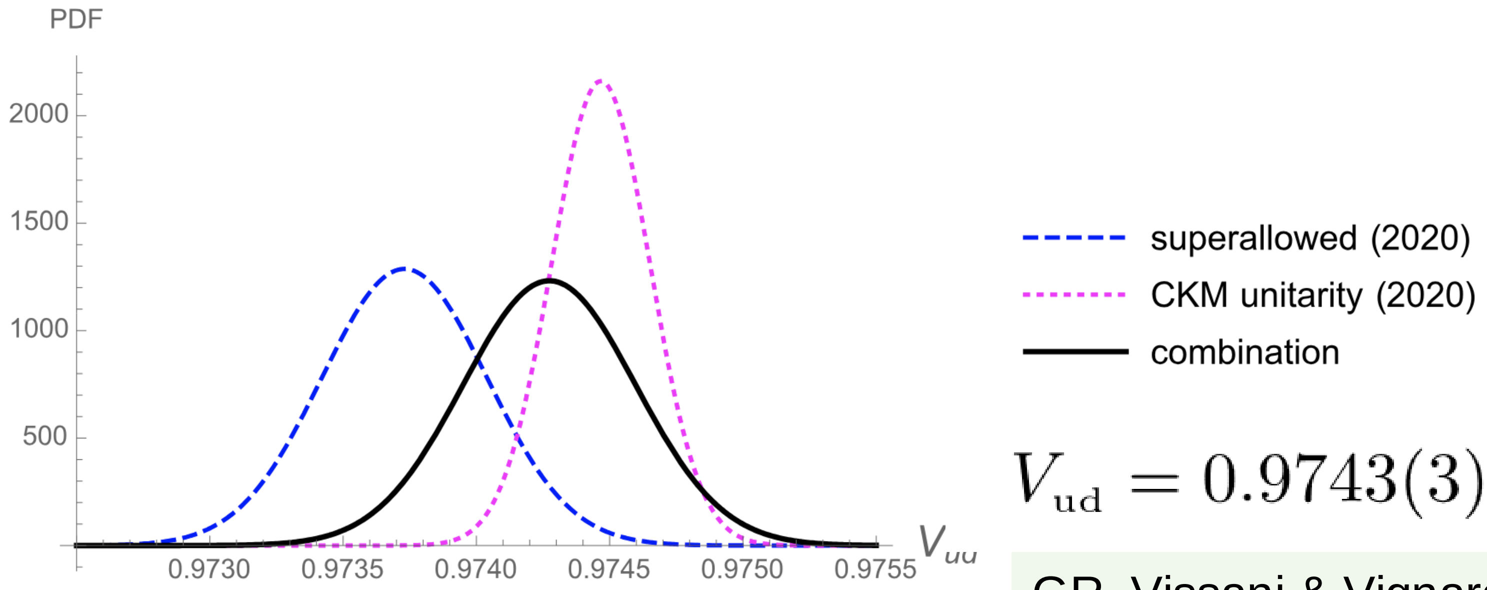
V_{ud}

- ✓ Super-allowed nuclear transitions $0^+ \to 0^+$ ⟶ $V_{\rm ud}({\rm s.a.}) = 0.9737(3)$
- ✓ CKM unitarity $V_{\rm us} = 0.2245(8)$ $V_{\rm ub} = 3.82(24) \times 10^{-}$ ⟶ $V_{\rm ud}({\rm unit}) = 0.9745(2)$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$



From talk by Andre Walker-Loud



$$V_{\rm ud} = 0.9743(3)$$

GR, Vissani & Vignaroli

NEUTRON LIFETIME

$$\frac{1}{\tau_{\rm n}} = \frac{V_{\rm ud}^2\,(1+3\lambda^2)}{4906.4 \pm 1.7{\rm s}}.$$

$$q^2 = 0$$

$$\lambda = -\frac{g_1(0)}{f_1(0)}$$

vector-axial/vector form factor at $q^2 = 0$

$$\bar{u}_n\left(f_1\gamma_a + g_1\gamma_a\gamma_5 + if_2\sigma_{ab}\frac{q^b}{2M} + g_2\frac{q_a}{M}\gamma_5 + f_3\frac{q_a}{M} + ig_3\sigma_{ab}\frac{q^b}{2M}\gamma_5\right)u_p$$

$$\tau_{\rm n}({\rm SM}) = 878.38 \pm 0.89 \text{ s.}$$

Czarnecki, Marciano & Sirlin 2019

- ✓ **ultra-cold neutrons** are trapped their number is measured over time, determining the total average lifetime

$$\tau_{\rm n}({\rm tot}) = 878.52 \pm 0.46 \text{ s}$$

- ✓ the products of the single decay channel predicted by the standard model are observed, using **beam neutrons**

$$\tau_{\rm n}({\rm beam}) = 888.0 \pm 2.0 \text{ s}$$

AXIAL FORM FACTOR AT $q^2 = 0$

$$\lambda = -\frac{g_1(0)}{f_1(0)}$$

Direct measure of vector-axial form factor from polarized neutrons

Eight different measurements available; more precise PERKEO-III (2019)

See also talk by
Andre Walker-Loud

average $\lambda = 1.2755(5)$ $\quad S = \sqrt{\frac{\chi^2_{\rm min}}{N-1}}$ $\quad S = 2.3$

- ✓ excluding the four measurements prior to 2002 $\quad S = 0.7$
- ✓ include them, but enlarging their error by a factor 2 $\quad S = 1.2$

$$\Sigma^2 = \begin{pmatrix} (\delta V_{\rm ud})^2 & , & \rho\, \delta V_{\rm ud}\, \delta\lambda \\ \rho\, \delta V_{\rm ud}\, \delta\lambda & , & (\delta\lambda)^2 \end{pmatrix}$$

Independent V_{ud}, λ

$$\begin{cases} V_{\rm ud} = 0.97427(32) \\ \lambda = 1.27601(52) \\ \rho = 0 \end{cases}$$

Constraints from τ_n

$$\begin{cases} V_{\rm ud} = 0.97425(26) \\ \lambda = 1.27597(42) \\ \rho = -0.53 \end{cases}$$

FORM FACTORS $q^2 \neq 0$

Form factor linear expansion (at lower energies) *in lieu* of modelling
(e.g. double dipole is untested at small E_ν)

$$\frac{F(Q^2)}{F(0)} \equiv 1 - \frac{\langle r^2 \rangle \; Q^2}{6} + \mathcal{O}(Q^4) \qquad Q^2 = -t > 0.$$

VECTOR FORM FACTORS

$$\bar{u}_n \left(f_1 \gamma_a + g_1 \gamma_a \gamma_5 + i f_2 \sigma_{ab} \frac{q^b}{2M} + g_2 \frac{q_a}{M} \gamma_5 + f_3 \frac{q_a}{M} + i g_3 \sigma_{ab} \frac{q^b}{2M} \gamma_5 \right) u_p$$

$$f_1 \approx 1 + \frac{(2.41 \pm 0.02)\ t}{\mathrm{GeV}^2} \qquad f_2 \approx \xi \left(1 + \frac{(3.21 \pm 0.02)\ t}{\mathrm{GeV}^2} \right)$$

Lin, Hammer & Meissner 21

$(e^- N \to e^- N)$

Negligible source of uncertainty to the cross section

AXIAL FORM FACTOR

✓ Dipole approximation

$$g_1 = g_1(0)/(1 - t/M_A^2)^2$$

$$M_A = 1.014 \pm 0.014\ \text{GeV}$$

Average: Bodek et al. 2008

M_A [GeV]	
1.07(11)	NOMAD [43]
1.08(19)	NOMAD [43]
$1.19^{+0.09(0.12)}_{-0.10(-0.14)}$	MINOS [44]
0.99	MINERνA [45, 46]
1.20(12)	K2K [47]
1.36(6)	MiniBooNE [41]
1.31(3)	MiniBooNE [41]
$1.26^{+0.21}_{-0.18}$	T2K [42]

✓z-expansion

based on a conformal mapping: building the largest possible range of convergence for the form factors

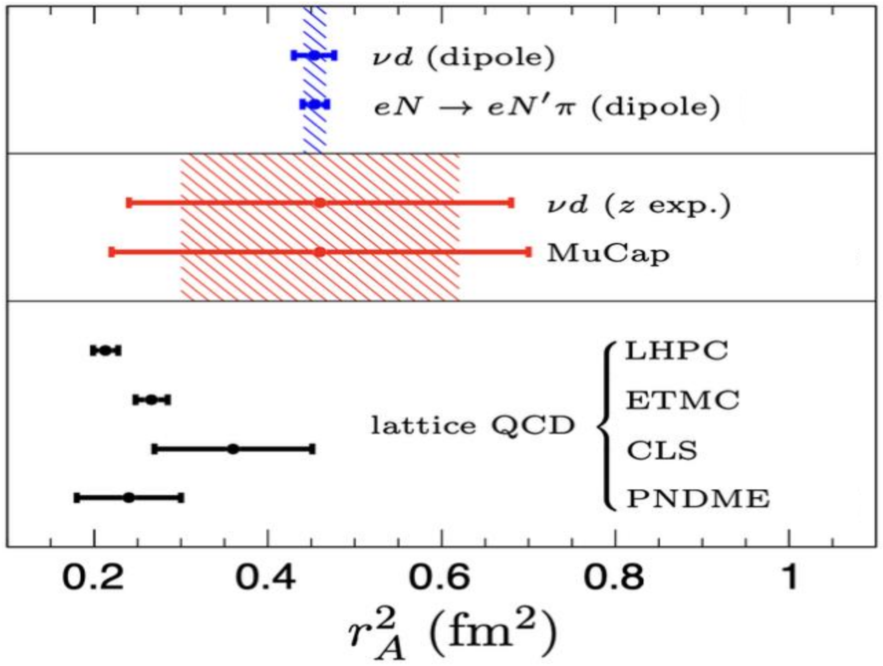
z-expans. M_A [GeV]	dipole approx. M_A [GeV]	
$0.85^{+0.22}_{-0.07} \pm 0.09$	1.29 ± 0.05	(ν_μ) MiniBooNE [50]
$0.84^{+0.12}_{-0.04} \pm 0.11$	$1.27^{+0.03}_{-0.04}$	$(\bar{\nu}_\mu)$ MiniBooNE [51]
$0.92^{+0.12}_{-0.13} \pm 0.08$	1.00 ± 0.02	(π) MiniBooNE [50]

$$\frac{g_1(Q^2)}{g_1(0)} \equiv 1 - \frac{\langle r_A^2 \rangle \, Q^2}{6} + \mathcal{O}(Q^4)$$

low SN & reactor neutrino energies

$$M_A^2 \equiv -2\frac{g_1{}'(0)}{g_1(0)} = \frac{12}{\langle r_A^2 \rangle}$$

Dipole approximation



νN direct measurements of charged current interactions

MuCap muon capture on proton

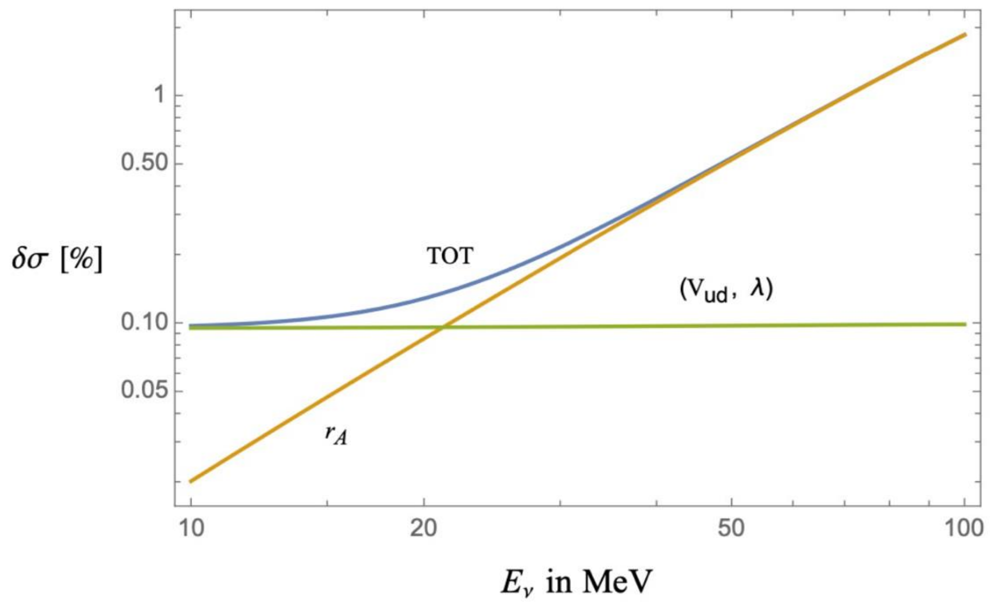
$e \rightarrow \pi$ single pion production by electrons on nucleons

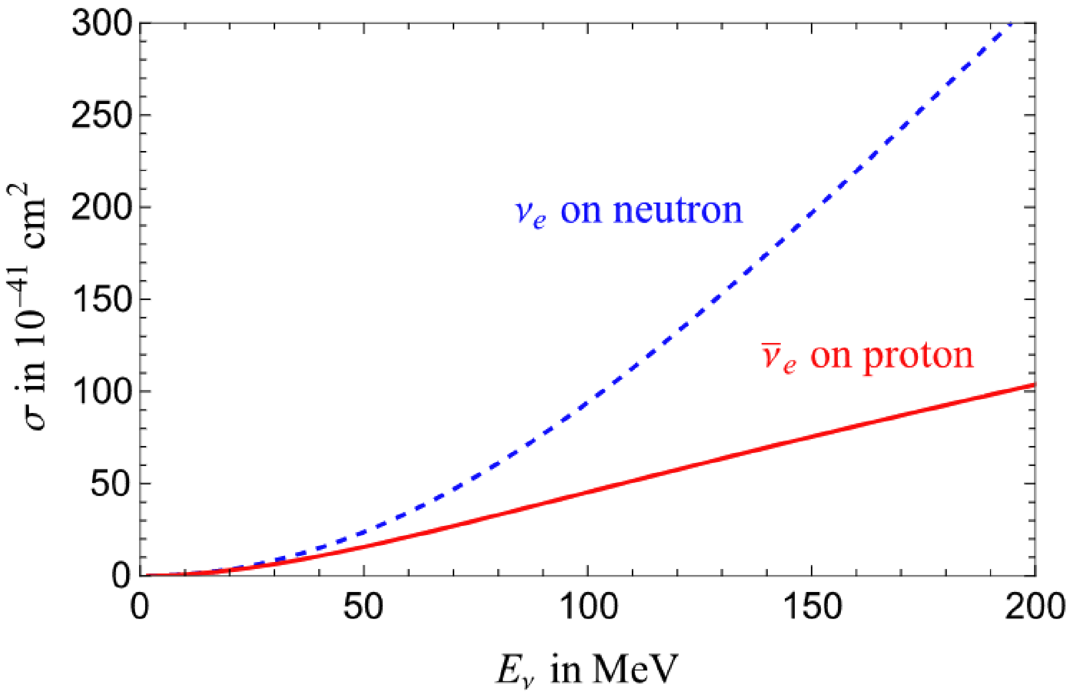
$$r_A^2 = \begin{cases} 0.454 \pm 0.012 \text{ fm}^2 & \nu\text{N(dipole) \& e} \rightarrow \pi \\ 0.46 \pm 0.16 \text{ fm}^2 & \nu\text{N \& } \mu\text{Cap}, \end{cases}$$

Bodek et al 2008

Hill et al 2018

CROSS SECTION & TOTAL UNCERTAINTY





$\delta\sigma(V_{\rm ud}) = 0.66$ ‰
$\delta\sigma(\lambda) = 0.68$ ‰

$\delta\sigma = 0.94$ ‰

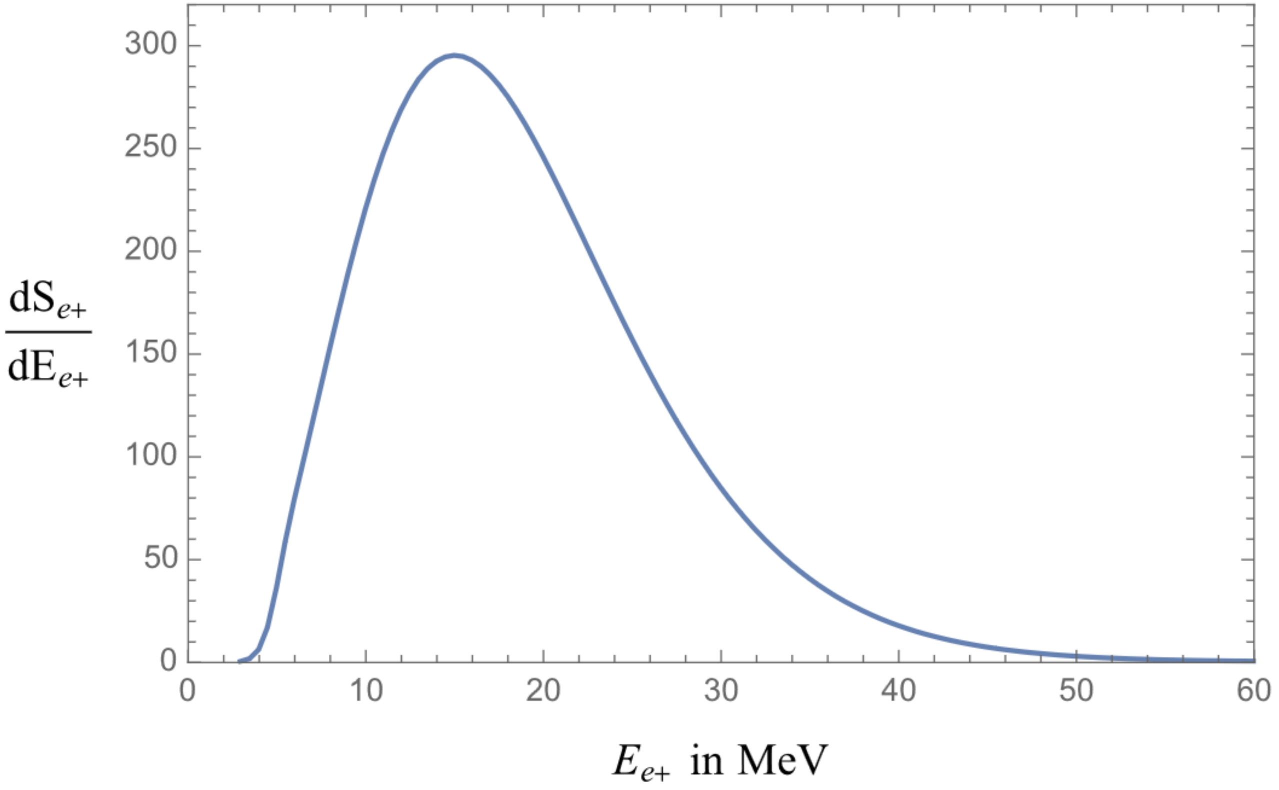
$\delta\sigma(V_{\rm ud}) = 0.53$ ‰
$\delta\sigma(\lambda) = 0.55$ ‰

$\delta\sigma = 0.52$ ‰

G.R:, Vissani & Vignaroli

POSITRON SPECTRUM IN SUPERKAMIOKANDE

$$\frac{dS_e}{dE_e} = N_p \int_{E_\nu^{max}}^{E_\nu^{min}} dE_\nu \frac{dF}{dE_\nu}(E_\nu) \frac{d\sigma}{dE_e}(E_\nu, E_e)\, \epsilon(E_e)$$



Time integrated flux (≡fluence)

$$\frac{dF}{dE_\nu} = \frac{\varepsilon}{4\pi D^2} \frac{E_\nu^2\, e^{-E_\nu/T}}{6T^4}$$

Vissani 2015

$$\varepsilon = 5 \times 10^{52} \text{ erg}$$

$\langle E_\nu \rangle = 3T$ $\quad T = 4$ MeV

$$N_p = 2.167 \times 10^{33}$$

G.R., F Vissani & N. Vignaroli, *JHEP* 08 (2022) 212

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

DSNB: Diffuse neutrino flux from past core-collapse supernovae

Existing and future large water-Cherenkov and LS detectors have good potential to observe the DSNB signal (up to a few tens of MeV) via IBD (primary observation channel)

- ✓ Putting Gd into Super-K enables highly efficient neutron tagging & provides powerful background rejection
- ✓ LS detectors such as JUNO have intrinsically high neutron tagging efficiencies for neutron capture on free protons

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = N_p \times \sigma_\nu(E_\nu) \times c \int_0^\infty \frac{\mathrm{d}N(E'_\nu)}{\mathrm{d}E'_\nu} \times \frac{\mathrm{d}E'_\nu}{\mathrm{d}E_\nu} \times R_{\mathrm{SN}}(z) \times \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z$$

$$\langle E_\nu \rangle = 15 \text{ MeV}$$

R_{SN} Core collapse SN rate

$E_\nu = E'_\nu/(1+z)$ red-shifted neutrino energy upon detection

$$|\mathrm{dt/dz}|^{-1} = H_0(1+z)[\Omega_\Lambda + \Omega_m(1+z)^3]^{\frac{1}{2}}$$

JUNO collab Prog.Part.Nucl.Phys. 123 (2022) 103927

REACTOR ANTINEUTRINO EVENTS

$$N_{ev} = \epsilon \, N_p \, \tau \sum_{r=1}^{N_{react}} \frac{P_r}{4\pi L_r^2} < LF_r > \times \int dE_{\bar{\nu}_e} \sum_{i=1}^{4} \frac{p_i}{Q_i} \phi_i(E_{\bar{\nu}_e}) \sigma(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}, \hat{\theta}, L_r),$$

where ϵ is the detection efficiency, N_p is the number of target protons, and τ is the data-taking time. The index r cycles over the number of reactors considered: P_r is the nominal thermal power, L_r is the reactor-detector distance, $< LF_r >$ indicates the average Load Factor (LF) [3] in the period τ, $E_{\bar{\nu}_e}$ is the antineutrino energy. The index i stands for the different nuclear-fuel components (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu), p_i is the power fraction, Q_i is the energy released per fission of the component i, and $\phi_i(E_{\bar{\nu}})$ is the antineutrino energy spectrum originated by the fission of component i. $\sigma(E_{\bar{\nu}_e})$ is the inverse-beta-decay cross section. P_{ee} is the energy-dependent survival probability of electron antineutrinos traveling the baseline L_r, for mixing parameters $\hat{\theta} = (\delta m^2, \Delta m^2, \sin^2\theta_{12}, \sin^2\theta_{13})$.

JUNO collab., J.Phys.G 43 (2016) 3, 030401

CONCLUSIONS

- ✓ Improved determination of the cross section and assessment of uncertainty
  - ❑ Impact on od SCC current negligible on cross sections
  - ❑ At lower energy
    overall uncertainty at the 1 permil level
    (from Cabibbo angle and axial coupling)
  - ❑ At higher energies
    uncertainty grows up to percent level
    (from axial form factor)

- ✓ important for current and future high statistic experiments
e.g. SN observations, DSNB, …