Search for neutron-antineutron oscillations at the Sudbury Neutrino Observatory

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LLNL, Rare Event Detection Group
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Presenting results from:

PHYSICAL REVIEW D **96,** 092005 (2017)

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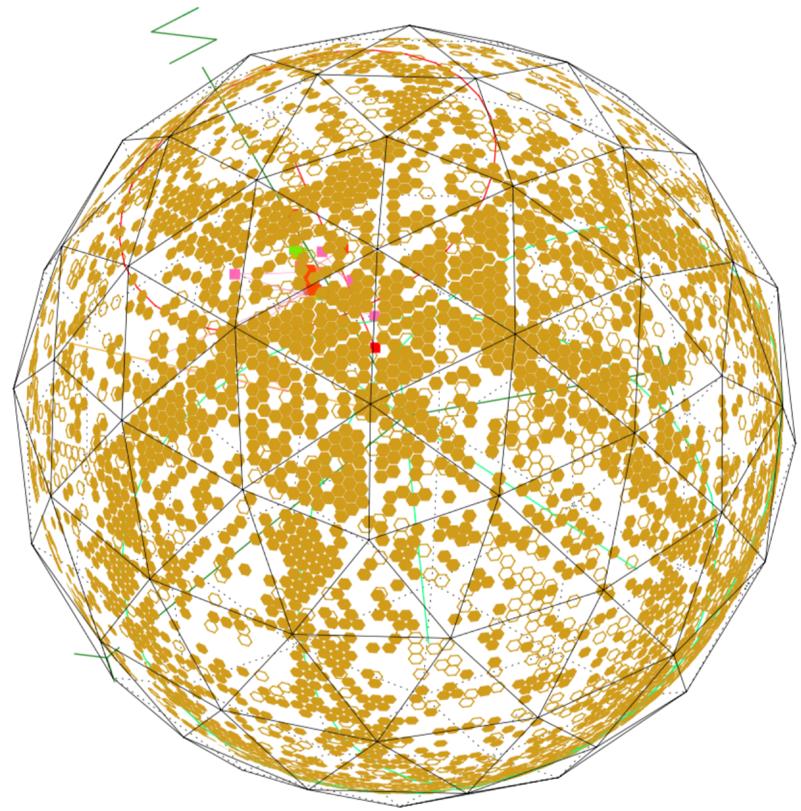


Simulation of a neutron-antineutron oscillation event in SNO

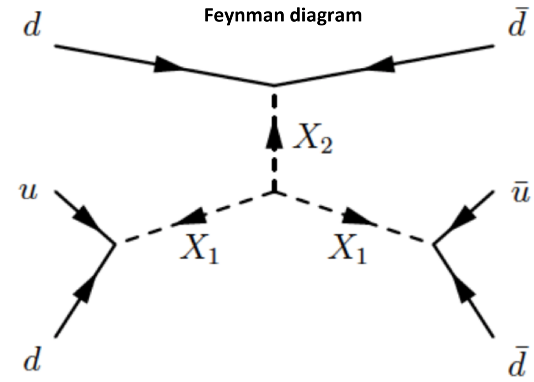
Unsolved mystery of the universe: why is there more matter than antimatter?

Sakharov conditions for matter/antimatter imbalance

(1) The baryon number **B** must be violated

(2) C-symmetry and CP-symmetry violation

(3) Interactions out of thermal equilibrium



$$\delta m_{n\bar{n}} = \frac{1}{\tau_{n\bar{n}}} = \langle \bar{n} | L_{\Delta B=2} | n \rangle = \frac{1}{M^5} \langle \bar{n} | UDDUDD | n \rangle \sim \frac{\Lambda^6}{M^5}$$

$\Lambda \approx 200$ MeV
$\tau \approx 10^8$ s
$M > 10^6$ GeV

Observing a neutron oscillating to a antineutron, a process that violates only **the baryon number,** provides a potential mechanism for Baryogenesis

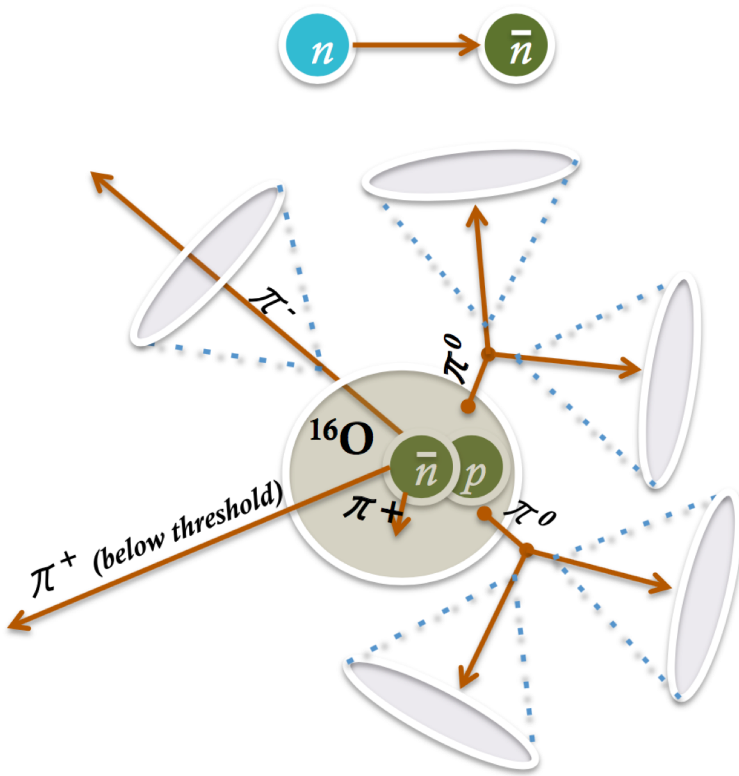
Diagrams and values taken from Ed Kearns, BLV 2017

Two possible type of experiments

Free neutron beams

free : τ_{free} >0.86 × 10^8 s at 90% C.L

Neutron bound in nuclei



SuperKamiokande (^{16}O):

$$T_{\text{intranuclear}} > 19 \times 10^{31} \text{ yr at 90\% C.L.}$$

Soudan II (^{56}Fe):

$$T_{\text{intranuclear}} > 7.2 \times 10^{31} \text{ yr at 90\% C.L.}$$

In this presentation: SNO (^2H)

The nnbar oscillation time is suppressed in the intranuclear environment

Neutron-antineutron oscillations in nuclei – an experimentalist's perspective

The oscillation probability of a neutron to an antineutron can be evaluate in **analogous** ways to **neutrino oscillation** probability.

A small *δm* perturbation allows the neutron and antineutron to oscillate between each state

Paris potential is used for deuteron to evaluate suppression factor *R* [$(2.48\pm0.08)\times10^{22}$ s^{-1}].

Optical potential used for heavier nuclei; newer calculations for Heavier nuclei showed a decrease of the suppression factor by a factor of 2

If $|\psi_{\bar{n}p}|^2 = e^{-\Gamma_R t}$ **and**

$$i\frac{\partial}{\partial t}\begin{pmatrix} np \\ \bar{n}p \end{pmatrix} = \begin{pmatrix} 0 & \delta m \\ \delta m & \Delta - i\frac{\Gamma_R}{2} \end{pmatrix}\begin{pmatrix} np \\ \bar{n}p \end{pmatrix}$$

$$\Gamma_R \gg \Delta \longrightarrow |\psi_{np}|^2 \approx e^{-4\frac{\delta m^2}{\Gamma_R}t}$$

Since $\delta m = 1/\tau_{n\bar{n}}$,

$$T_{\text{intranuclear}} = \tau_{n\bar{n}}^2 R$$

Measurable in detector

Evaluated from nuclear models

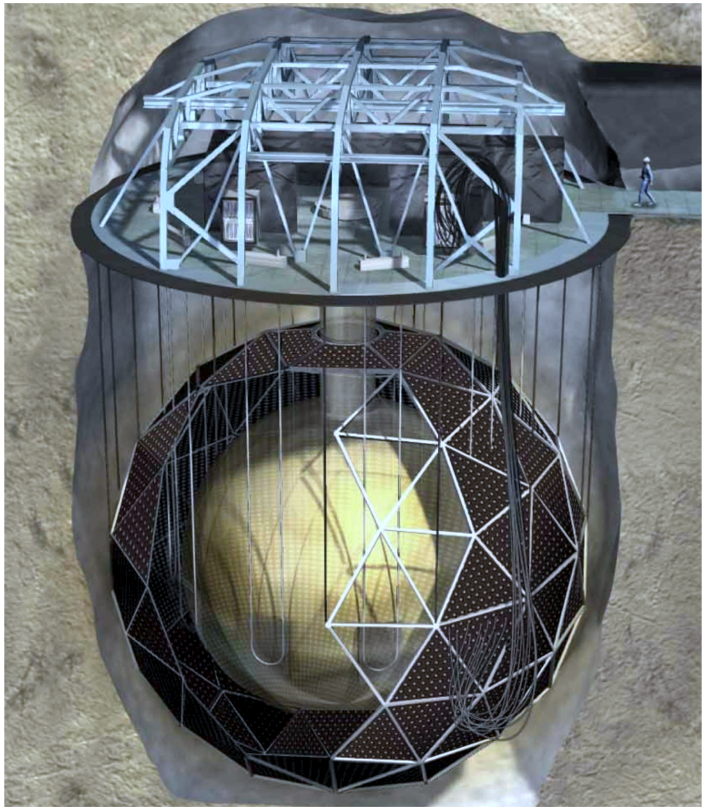
The Sudbury Neutrino Observatory (SNO)

SNO was a heavy water ($^{2}\mathbf{H}_2O$ or $\mathbf{D}_2O$) Cherenkov imaging detector that was in operation from November 2, 1999 to November 28, 2006

The main focus of SNO was the neutrino oscillation observation, for which it was awarded the Nobel prize in 2015

For better physics characterization, the experiment was divided into three operational phases:

- Phase I : D_2O
- Phase II : D_2O+NaCl
- Phase III: D_2O+Proportional counter arrays



Exposure to neutron-antineutron oscillations for the operational phases of SNO

Phase I : D_2O (50% blinded)

350.43 ± 0.01 days; $(6.021\pm0.007)\times10^{31}$ deuterons

Phase II : D_2O+NaCl (85% blinded)

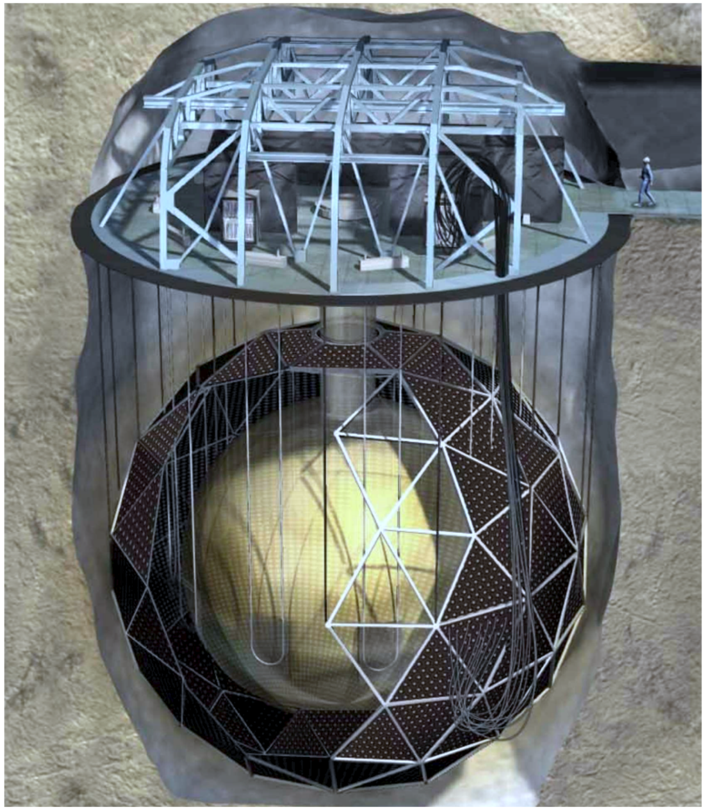
499.42 ± 0.01 days; $(6.021\pm0.007)\times10^{31}$ deuterons

Phase III: D_2O+Proportional counter arrays (80% blinded)

392.56 ± 0.01 days; $(6.015\pm0.007)\times10^{31}$ deuterons

Total exposure

$$\text{neutron exposure (D)} = 2.047 \times 10^{32}\ \text{n} \cdot \text{yr}$$
$$\text{neutron exposure } (^{16}\text{O}) = 8.190 \times 10^{32}\ \text{n} \cdot \text{yr}$$

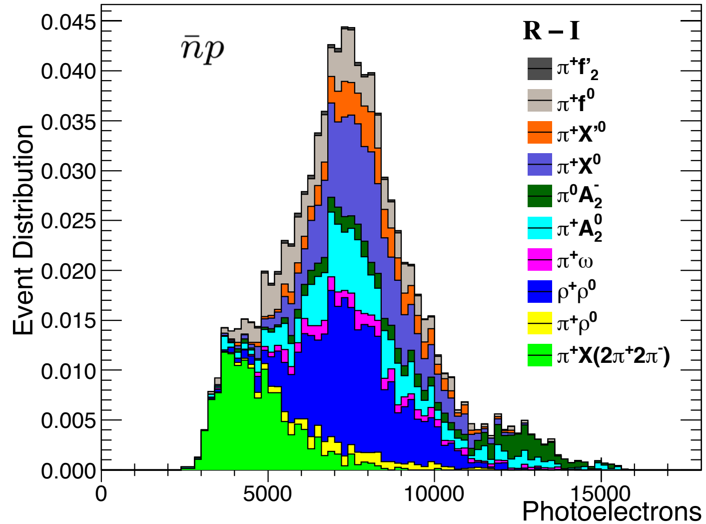


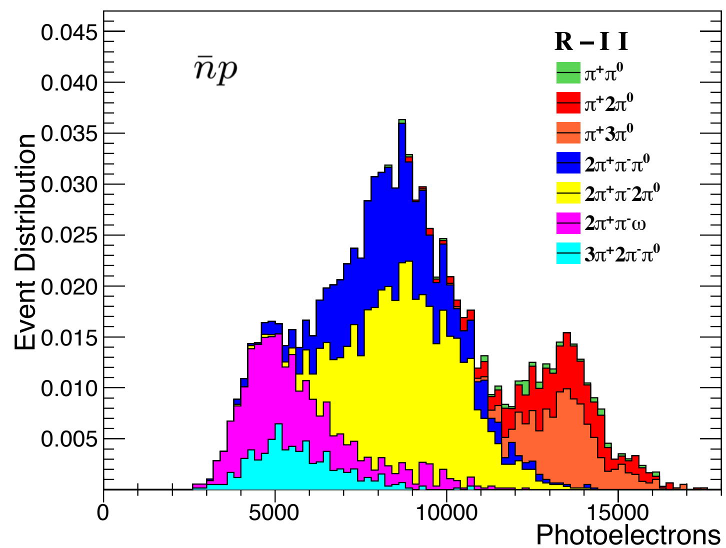
Signal: Visible energy of nnbar events and decay modes under consideration

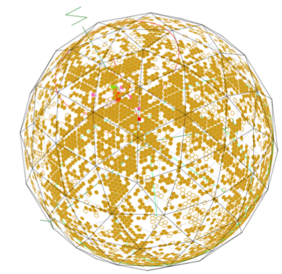
- **Momentum regime I (at rest)**
A study of channels of an antiproton colliding with a neutron near rest showed a majority of 2-body intermediate states*. These intermediate states can then decay into channels including multiple pions.

- **Momentum regime II (~ 250 MeV)** :
Alternative interaction channels [**] for n̄p annihilation have also been modeled using beam data of p̄n collisions at momenta comparable to the ^{16}O

Both models are investigated and **give similar results.** Weighted average of both is used in analysis







Multiple rings
Mainly pion final states

Energy Range
2,000 pe ~ 250 MeV
18,000 pe ~ 2.0 GeV

*R. Bridges et al., Phys. Rev. Lett. 56, 215 (1986)
**K. Abe et al., Phys. Rev. D 91, 072006 (2015)

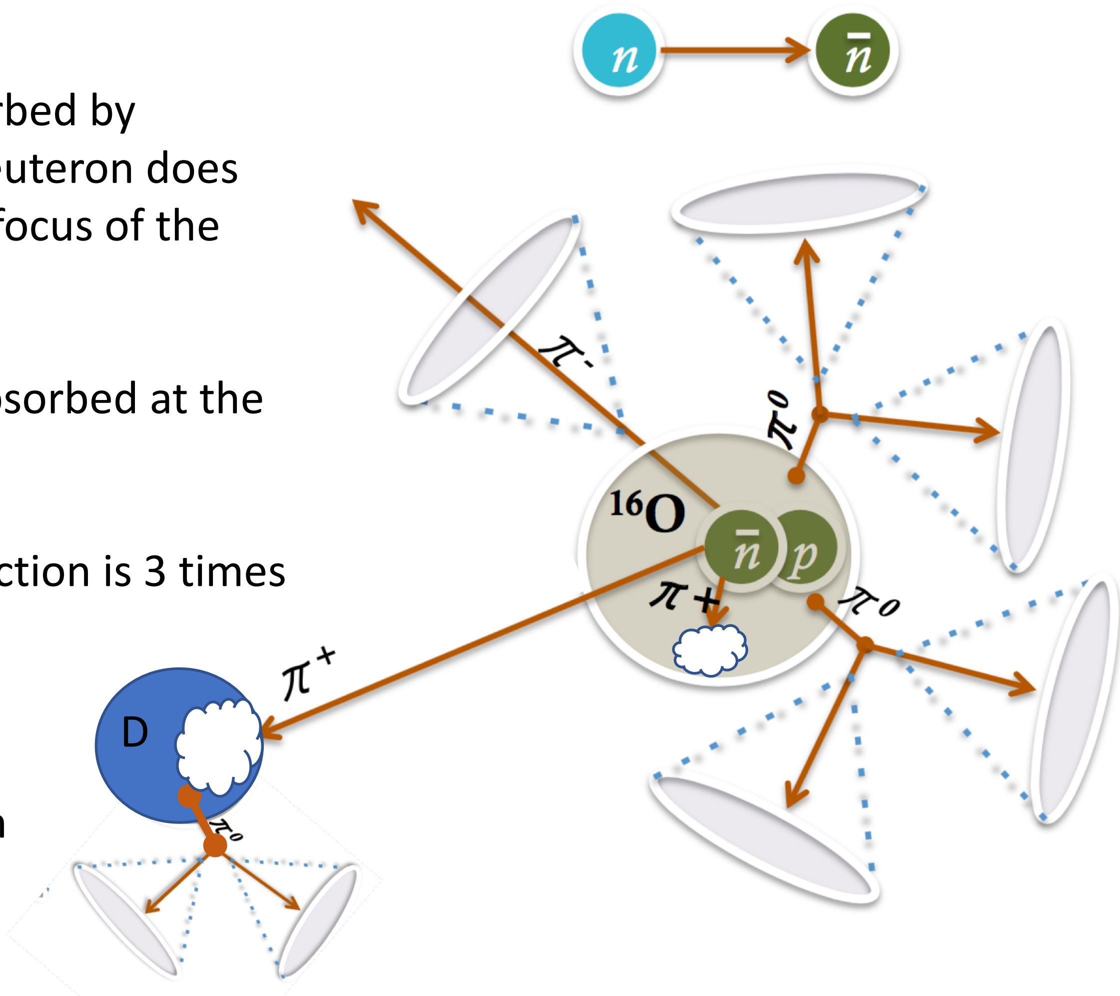
Signature consists of multiple particles that will create rings within the detector

In ^{16}O, ~23% of pions are absorbed by surrounding nuclear media. Deuteron does not suffer from this and is the focus of the analysis

In D_2O, π- and π+ may be re-absorbed at the same rate

Mean free path for pion interaction is 3 times lower in D_2O compared to H_2O

Vertex reconstruction, invariant mass and momentum reconstruction is challenging



Analysis concentrates on identifying ring behavior of events for nnbar in the deuteron

Backgrounds to neutron-antineutron oscillations - atmospheric neutrinos

Nuance models and Bartol prediction are used. Bartol prediction are corrected by **scaling correction (1.22 ± 0.09)** based on prior atmospheric neutrino measurement at SNO

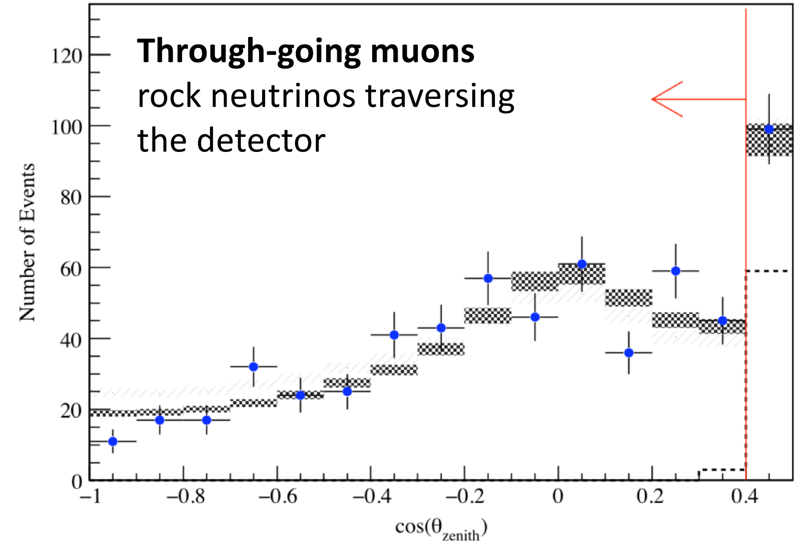
$$
\begin{array}{lllll}
\nu_{cc}: & \nu_l N & \to lN & \text{Quasi-elastic CC} & \\
 & \nu_l N & \to lN' & \text{Deep-inelastic CC} & \\
 & \nu_l N & \to lN' & \text{Cabibbo-suppressed CC} & \\
\nu_{nc}: & \nu_l N & \to \nu_l N' & \text{Deep-inelastic NC} & \\
\nu_{\pi}: & \nu_l N & \to l\Delta \to lN'\pi & \text{CC pion creation} & \\
 & \nu_l N & \to \nu_l\Delta \to \nu_l N'\pi & \text{NC pion creation} & \\
\nu_X: & \nu_l N & \to l(\nu_l)X & \text{CC(NC) } n\pi & \\
\nu_{otr}: & \nu_l N & \to l(\nu_l)X & \text{ES, IMD, PNP} & (5)
\end{array}
$$

where $l = \{e, \mu, \tau\}$, $N = \{p, n\}$ and $X = \{\rho, \eta, \Sigma, ...\}$

Neutrino CC/NC pion creation mode will also create multiple ring

Energy Range for analysis
2,000 pe ~ 250 MeV
18,000 pe ~ 2.0 GeV

PHYSICAL REVIEW D 80, 012001 (2009)



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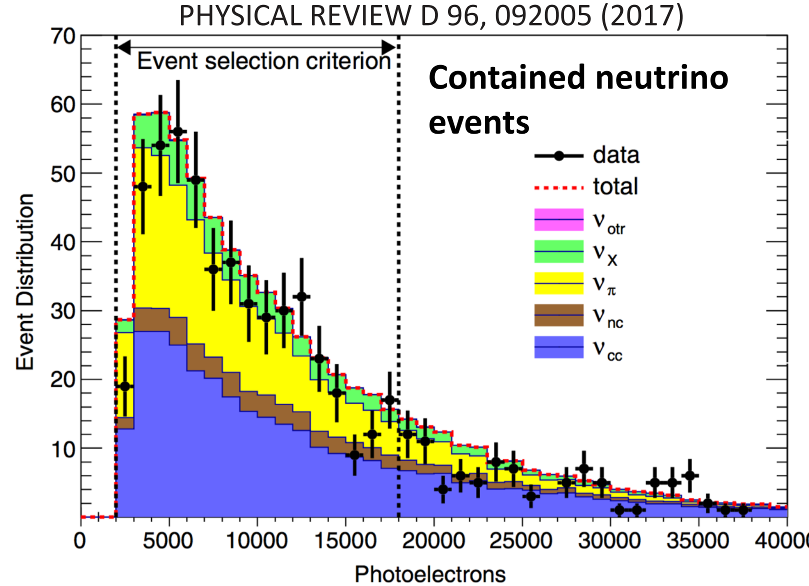
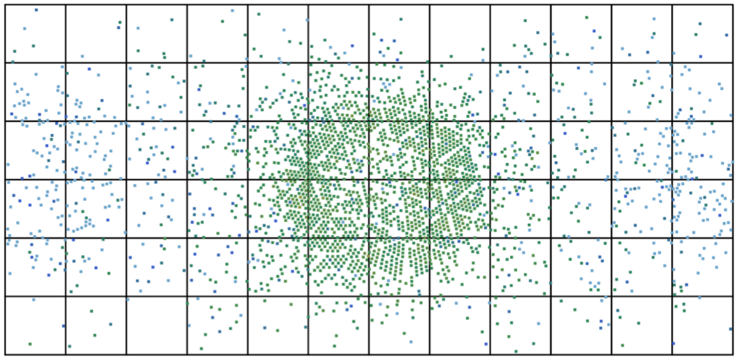


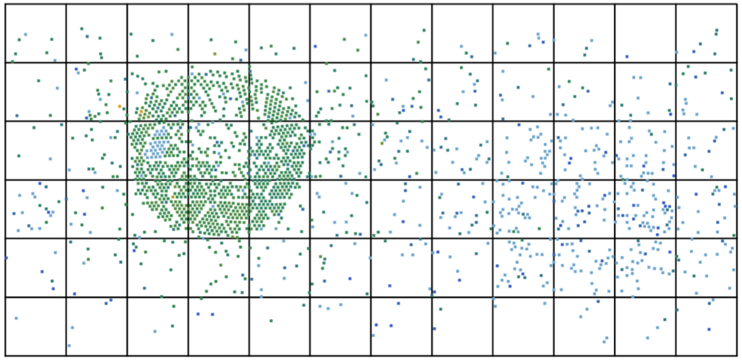
How to count and characterize rings?

How is →

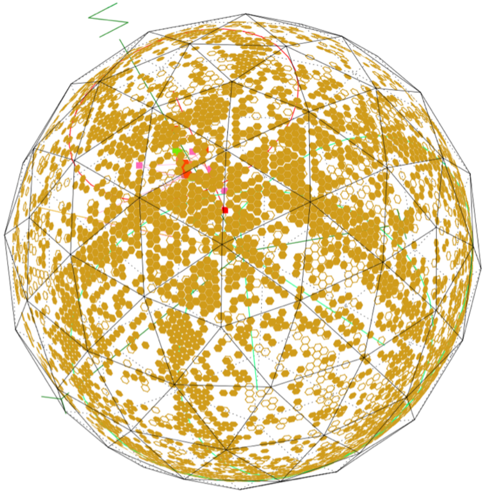


electron-like event

different from →



muon-like event



Simulation of a neutron-antineutron oscillation event in SNO

How do we identify and reconstruct these rings?

Ring counting is automated via an inhouse multiple ring finding algorithm based on a modified Hough transform method

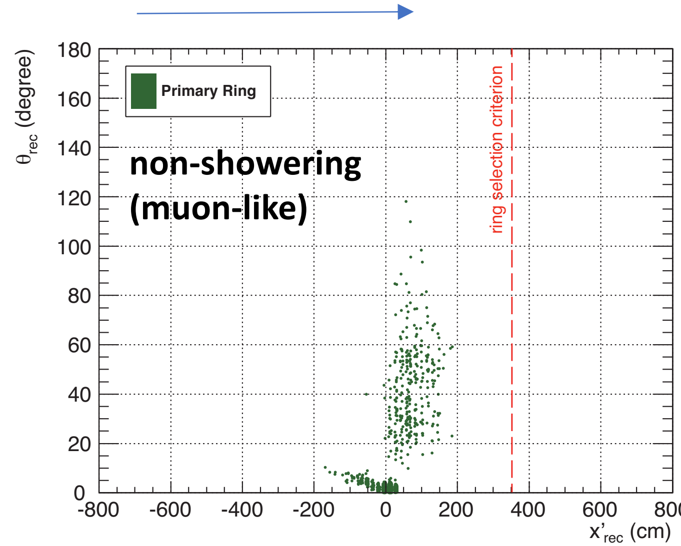
Charged pion reconstruction performances

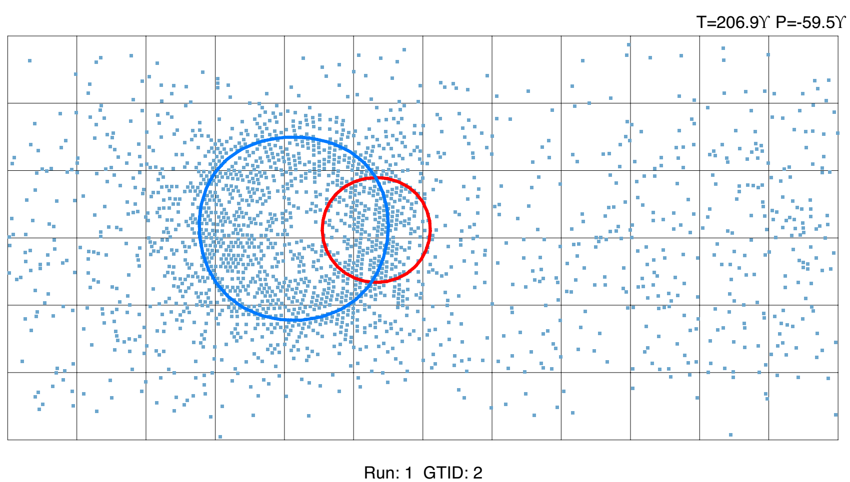
Reconstruction of π+ simulated at the origin of the detector using a **electron-like** and **muon-like** expectation, highlighting the complexity of single pion reconstruction.

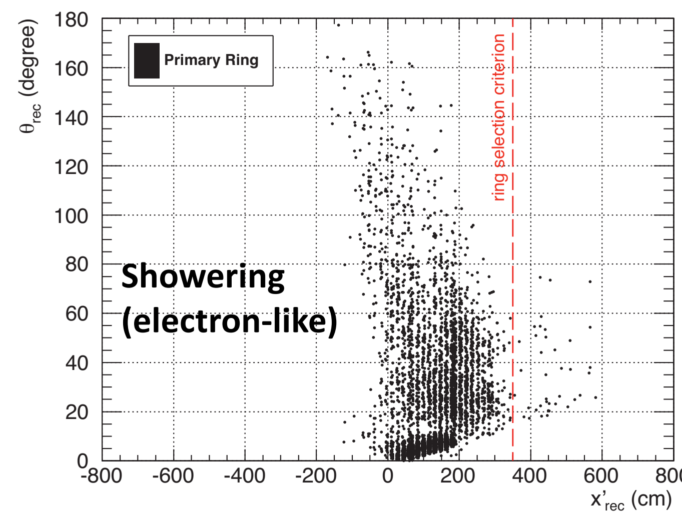
Visual validation shows good reconstructed ring for events below $x'_{rec} < 350$ cm (ring size requirement)

Due to greater ring finding efficiency, only electron-like expectations are used to identify rings

(x′,θ) = (0,0)

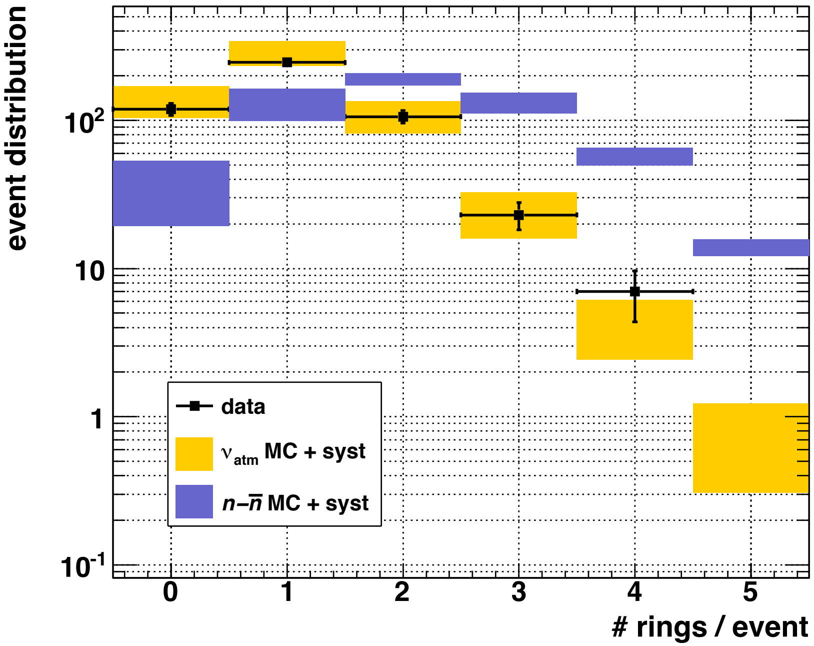


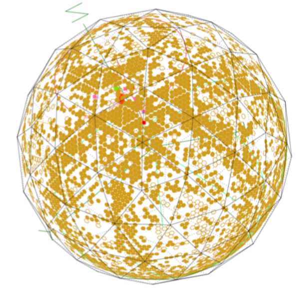




Ring result after box opening is consistent with background expectation

Ring distribution of contained events





Simulation of a neutron-antineutron oscillation event in SNO

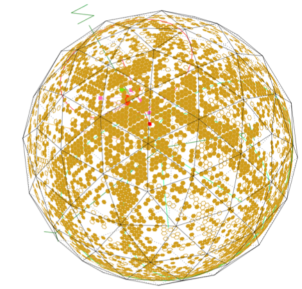
11.7% systematics uncertainty on detection efficiency and overall background systematics of 24.5%

$$\sigma_{\mathrm{bkgd}} = \sqrt{\sigma^2_{\Phi^{\mathrm{atmo}}_{\mathrm{osc}}} + \left(\frac{\sum_i T_i \sigma_{\Phi_i^{\mathrm{atmo}}}}{\sum_i T_i}\right)^2 + \left(\frac{\sum_i T_i \sigma_{\epsilon_i^{\mathrm{atmo}}}}{\sum_i T_i}\right)^2 \ldots}$$

$$\sigma_{signal} = \frac{\sum_i T_i \sigma_{\epsilon_i^{n-\bar{n}}}}{\sum_i T_i}$$

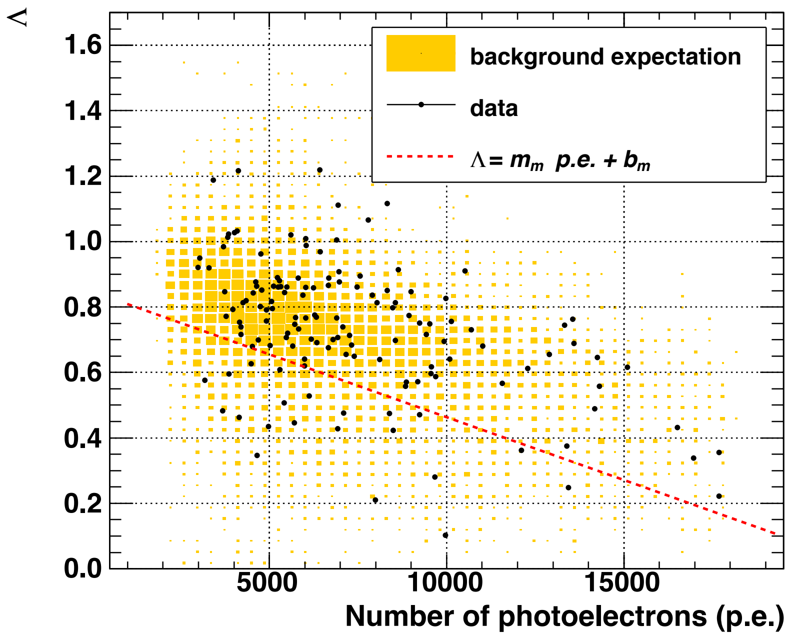
Uncertainty	Phase independent $\Phi^{\mathrm{atmo}}_{\mathrm{osc}}$	Phase I $\Phi^{\mathrm{atmo}}_{\mathrm{I}}$	Phase I $\epsilon^{\mathrm{atmo}}_{\mathrm{I}}$	Phase I $\epsilon^{n-\bar{n}}_{\mathrm{I}}$	Phase II $\Phi^{\mathrm{atmo}}_{\mathrm{II}}$	Phase II $\epsilon^{\mathrm{atmo}}_{\mathrm{II}}$	Phase II $\epsilon^{n-\bar{n}}_{\mathrm{II}}$	Phase III $\Phi^{\mathrm{atmo}}_{\mathrm{III}}$	Phase III $\epsilon^{\mathrm{atmo}}_{\mathrm{III}}$	Phase III $\epsilon^{n-\bar{n}}_{\mathrm{III}}$
Measurement uncertainties										
photoelectrons	—	1.5%	0.2%	0.1%	1.8%	0.3%	0.1%	1.7%	0.3%	0.1%
MRF calibration	—	—	16.7%	6.5%	—	14.4%	5.6%	—	15.4%	8.3%
$\cos\theta_{\mathrm{ring}}$	—	—	8.4%	1.4%	—	8.1%	1.6%	—	9.2%	2.2%
Model uncertainties										
ν_{atmo} models	—	—	6.5%	—	—	6.5%	—	—	6.5%	—
$\bar{n}p$ modeling	—	—	—	9.4%	—	—	9.4%	—	—	9.4%
External input uncertainties										
$\phi_{\mathrm{normalization}}$ (SNO)	7.4%	—	—	—	—	—	—	—	—	—
$\Delta m^2_{\mathrm{MINOS}}$	<0.01%	—	—	—	—	—	—	—	—	—
$\sin^2 2\theta_{\mathrm{SK}}$	0.7%	—	—	—	—	—	—	—	—	—
Δ Resonance (20%)	—	8.0%	10.6%	—	8.4%	11.5%	—	8.5%	10.9%	—
$\bar{\nu}/\nu$ ratio (SK)	—	1.4%	1.4%	—	1.5%	1.5%	—	1.5%	1.5%	—
Total	7.4%	8.3%	22.5%	11.5%	8.7%	21.2%	11.1%	8.8%	22.0%	12.7%

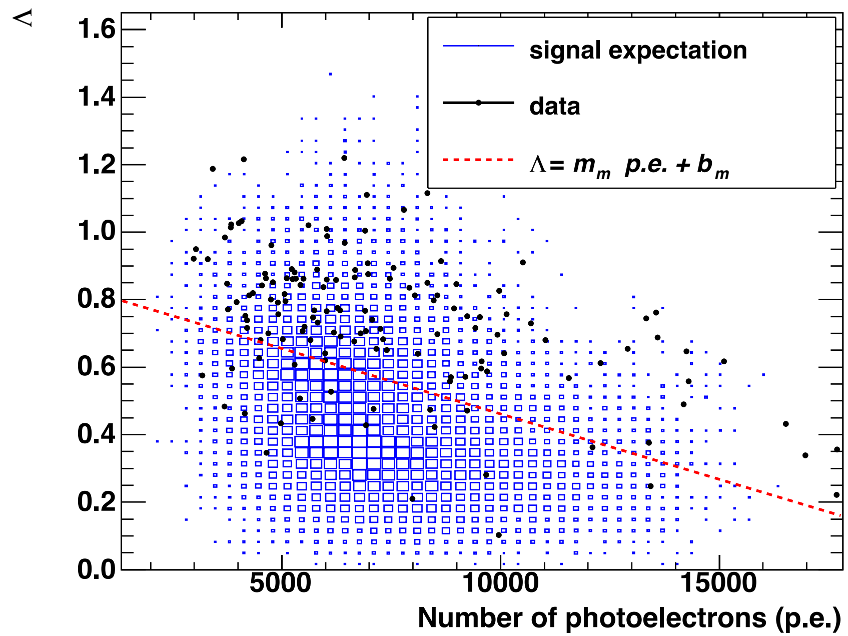
Isotropy-photoelectron phase space is consistent with background expectation



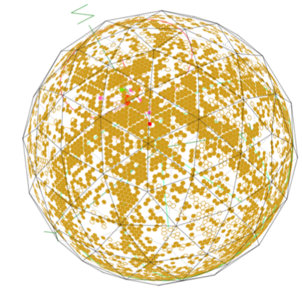
Simulation of a neutron-antineutron oscillation event in SNO

$$\vec{\Lambda} = \sum_{i=1}^{N} \frac{\mathrm{PMT}_{\mathrm{ring}}^{\,i}}{\mathrm{Nhits}} \cdot \hat{x}_c^{\,i}$$



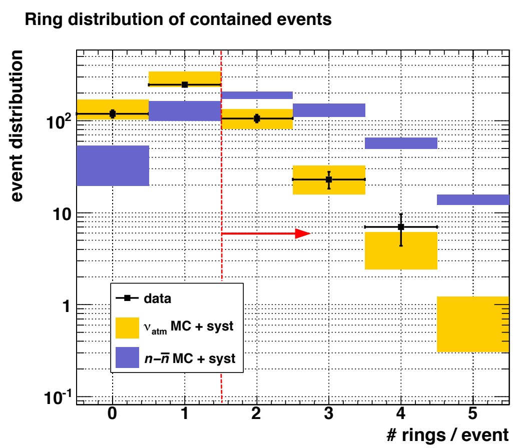


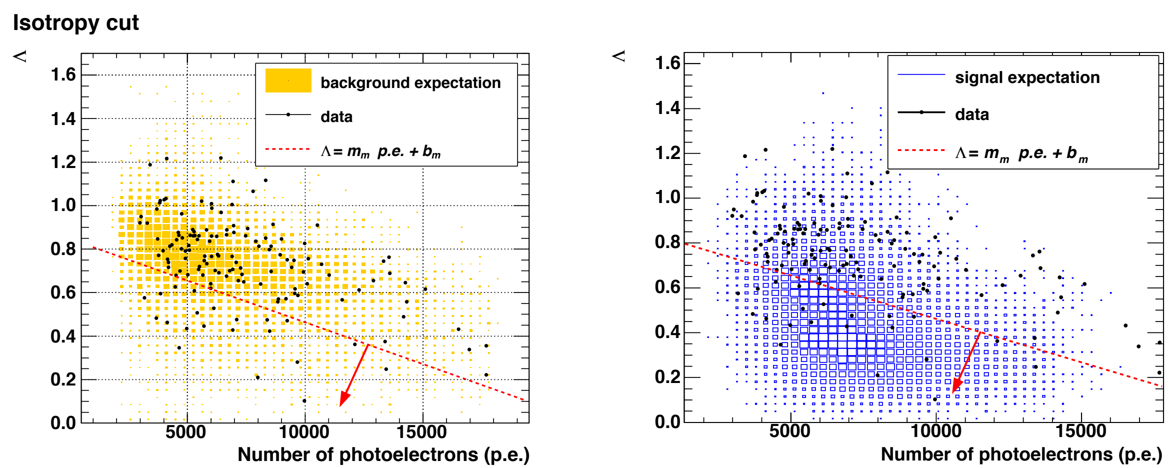
Results after Multi-Ring and Isotropy-Cut criteria



Simulation of a neutron-antineutron oscillation event in SNO

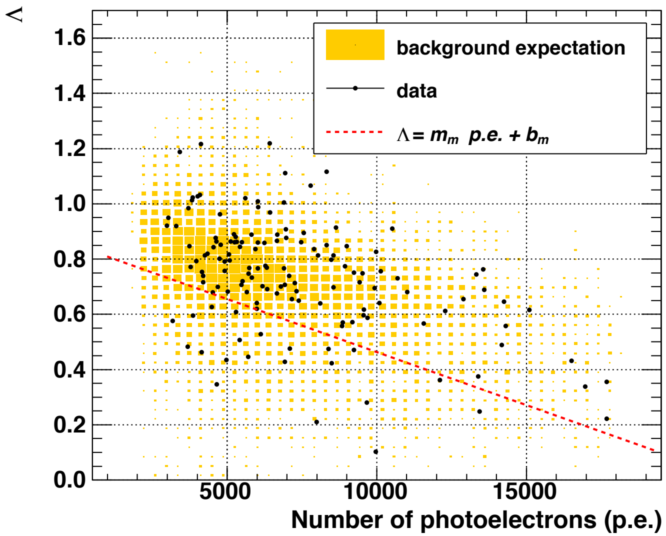
Phase	x_{cont}	b_{cont}	x_{MR}	b_{MR}	x_{IC}	b_{IC}
Phase I	143	154.1	43	38.1	**8**	**7.8**
Phase II	188	228.2	54	57.8	**10**	**12.2**
Phase III	170	179.4	39	41.9	**5**	**10.5**
total	501	561.7	136	137.8	**23**	**30.5**

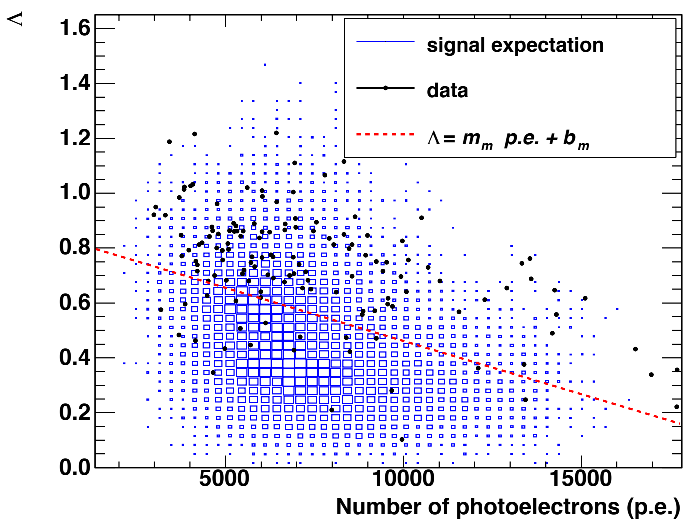




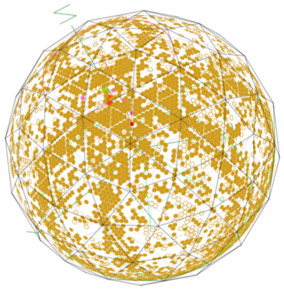
Statistical map of Λ-photoelectron phase space shows data consistent with statistical fluctuations

Isotropy cut





$$\vec{\Lambda} = \sum_{i=1}^{N} \frac{\mathrm{PMT}^{\,i}_{\mathrm{ring}}}{\mathrm{Nhits}} \cdot \hat{x}_c^{\,i}$$



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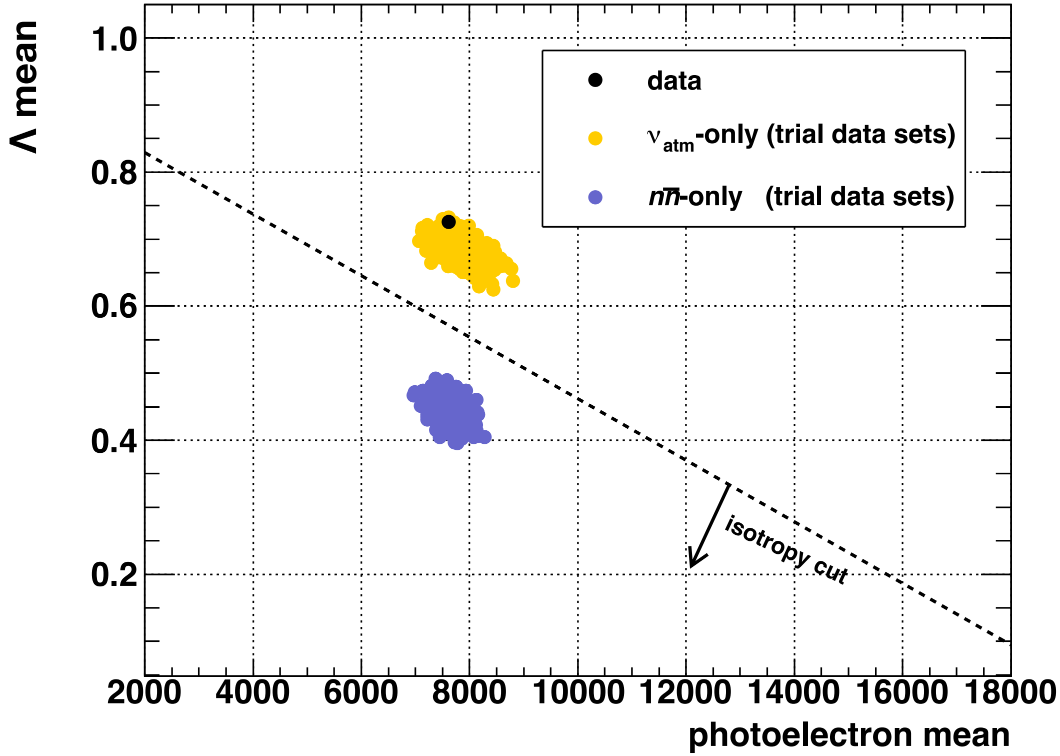


Results for neutron-antineutron oscillation search in deuteron for SNO using the profile likelihood method

Likelihood includes systematic uncertainties

$$L(\mu, b, \epsilon | x, b_o, \epsilon_o) = P_P(x|\mu, \epsilon, b) P_G(\epsilon|\epsilon_0, \sigma_\epsilon) P_G(b|b_0, \sigma_b)$$

Profile likelihood method

$$\mathcal{L}(\mu|x, b_o, \epsilon_o) = \frac{\sup(L(\mu, \hat{\hat{b}}(\mu), \hat{\epsilon}(\mu)|x, b_o, \epsilon_o))}{\sup(L(\hat{\mu}, \hat{b}, \hat{\epsilon}|x, b_o, \epsilon_o))}$$

Intranuclear to free neutron-antineutron relation

$$\tau_{\text{free}} = \sqrt{T_{\text{intranuclear}} \cdot \left(\frac{3.16 \times 10^7 \text{ s/year}}{R} \right)}$$

SNO Phase	Exposure 10^{31} n-yr	ϵ_{tot} (%)	Observed	Bkgd	UL (B/UB)	$T_{\text{intranuclear}}$ 10^{31} yr	R 10^{23} s^{-1}	τ_{free} 10^8 s (B/UB)
Phase I	5.78	55.0	8	7.8	(6.66 / 6.66)	(0.48 / 0.48)	0.248	(0.78 / 0.78)
Phase II	8.23	55.8	10	12.2	(5.91 / 5.52)	(0.78 / 0.83)	0.248	(1.00 / 1.03)
Phase III	6.47	50.9	5	10.5	(3.09 / 0.63)	(1.06 / 5.25)	0.248	(1.16 / 2.59)
Combined Phases	20.47	54.0	23	30.5	(9.38 / 7.46)	(1.18 / 1.48)	0.248	(1.23 / 1.37)

Conclusion

SNO finds a limit of
$T_{intranuclear}$ > 1.48 x10^{31} years at 90% CL, corresponding to τ_{free} > 1.37x10^{8} s at 90% unbounded

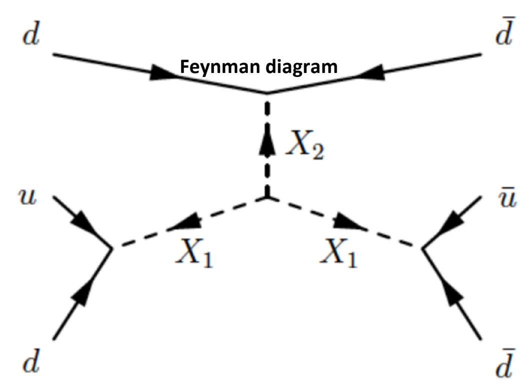
First limit using deuteron as a target. The absence of surrounding nucleon helped reduce systematics

Future Heavier nuclei searches would benefit in final interaction state characterization (Michel electron, neutron evaporation, radionuclide tagging)

As a probe..

δm < 30 yev at 90% CL (y: yocto = 1x10^{-24})

$$\delta m_{n\bar{n}} = \frac{1}{\tau_{n\bar{n}}} = \langle \bar{n} | L_{\Delta B=2} | n \rangle = \frac{1}{M^5} \langle \bar{n} | UDDUDD | n \rangle \sim \frac{\Lambda^6}{M^5}$$



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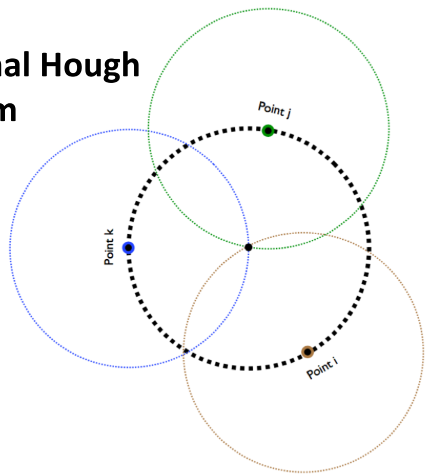
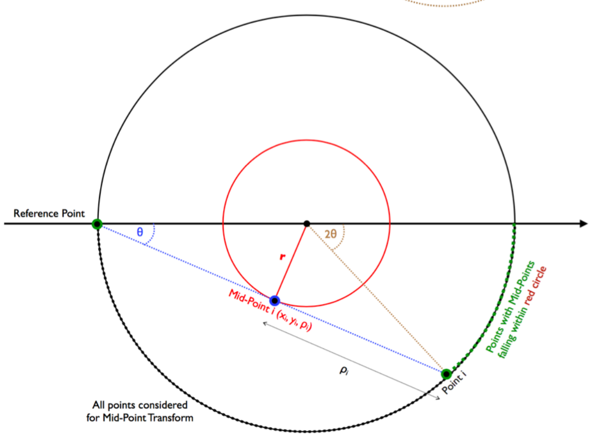
Backup

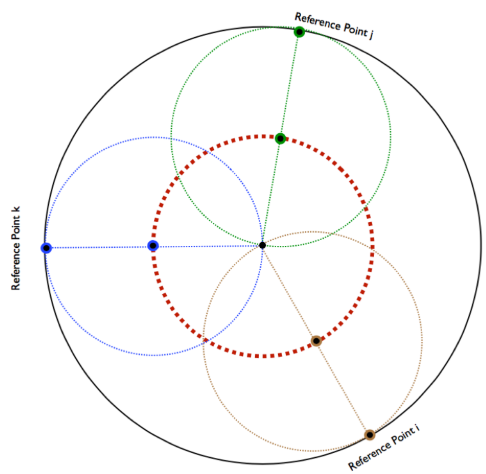
Ring counting is automated via an inhouse multiple ring finding algorithm

Part 1
Populate phase-space with ring candidates

Traditional Hough transform

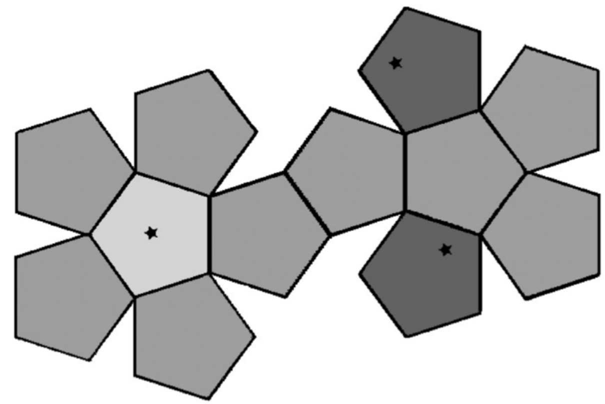






Mid-point pair transform

Part 2
Separation of candidates into multiple phase space



Part 3
Validation of ring candidates