Neutrino event reconstruction with neutron detection in SK-Gd

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Exploration of Particle Physics and Cosmology with Neutrinos

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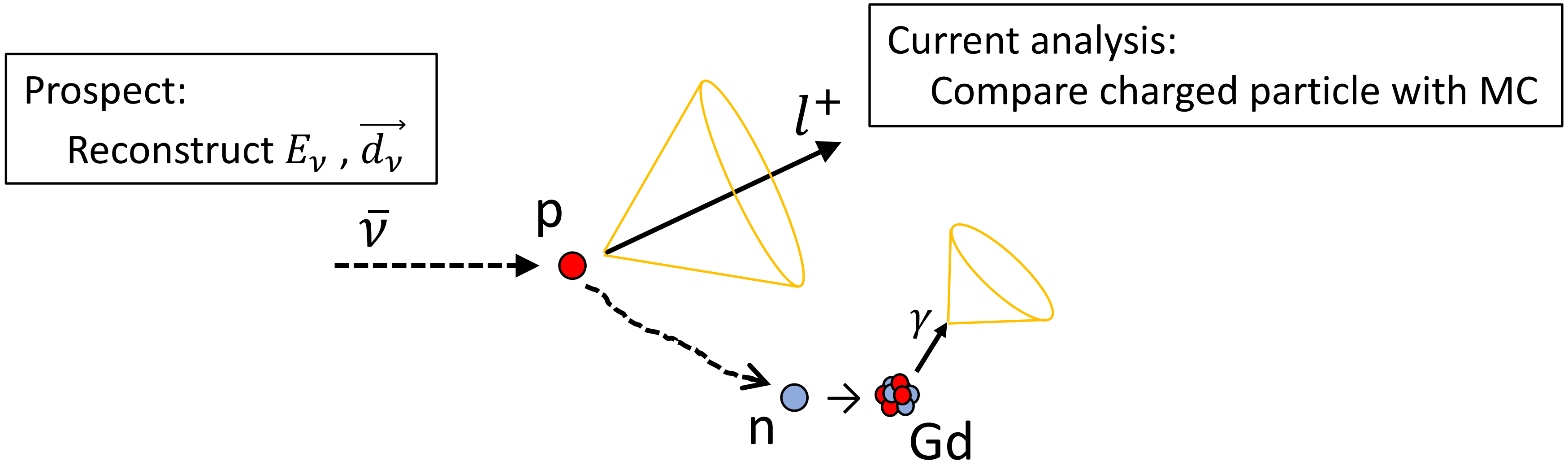
Purpose

- Measure neutrino oscillation parameters, especially mass ordering, δ_{CP}, θ_{23} octant by reconstructing atmospheric neutrino better using neutron tagging.
- $\overrightarrow{d_\nu}$ and E_ν reconstructions in this talk.



+ Nuclear effect or hadronic interaction can generate secondary neutrons.

SK-Gd

- Super-Kamiokande detector started “SK-Gd” phase with 0.011% Gd loaded in 2020.

Thermal neutron
- ~50% → p(n,γ) → 2.2 MeV γ — efficiency ~25%
- ~50% → Gd(n,γ) → multiple γ (total 8 MeV) — efficiency ~80%

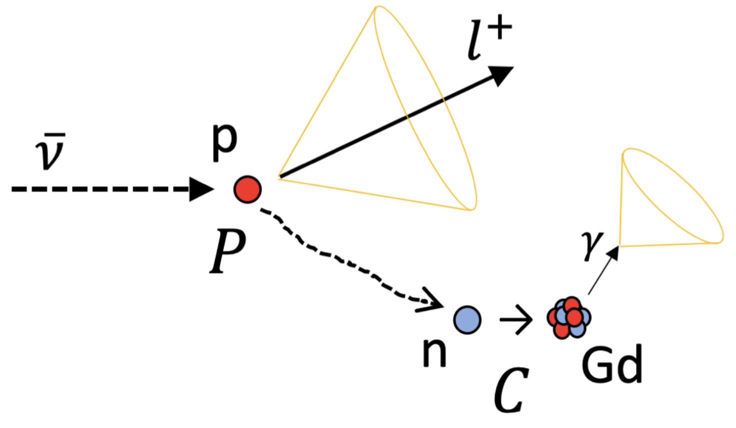
- **<u>Higher efficiency</u>** and **<u>better vertex resolution</u>** of neutron are expected with Gd(n,γ).
- Tagging efficiency will be higher with higher Gd concentration.

Neutrino reconstruction with neutron

- $\overrightarrow{p_n}$ is estimated from $\overrightarrow{PC}$ (neutron displacement).

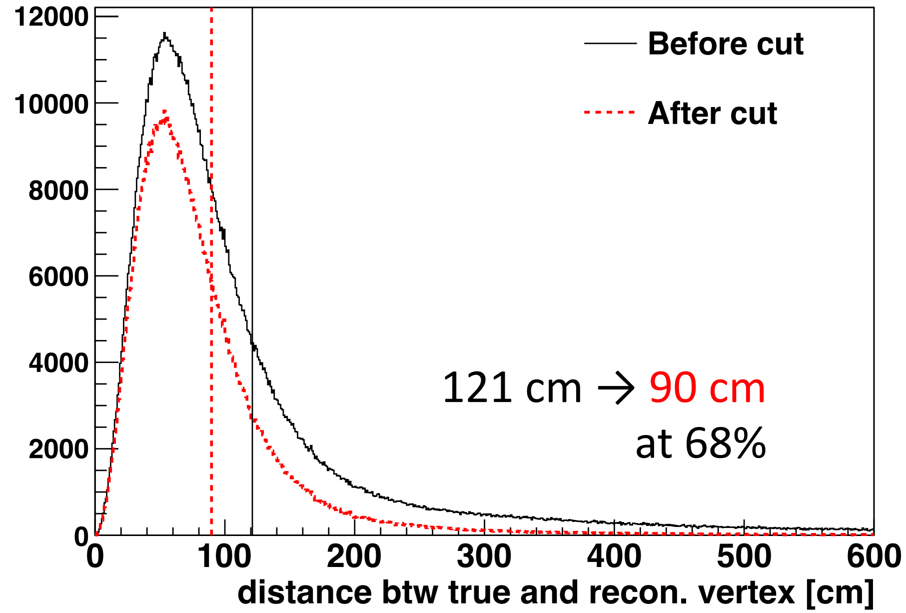
→ Reconstruct $\overrightarrow{d_\nu}, E_\nu$ with charged particle information.

- So far, the algorithm is developed and tested only in MC.



Procedure

- Search for neutrons in atmospheric MC,
  [4 μs, 534 μs] after primary reaction.
- Select neutron signals with good reconstruction：
  quality parameter > 0.2
  # of hit PMT in 14 ns ≥ 12
- 36% of tagged signals are removed.

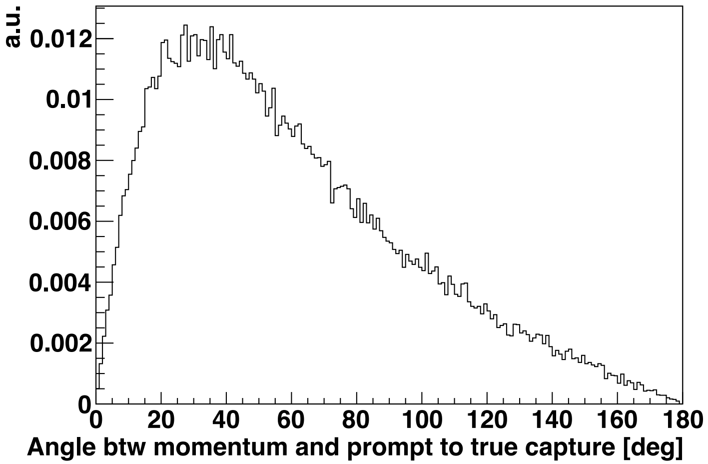


- Selected neutron is seen in 39% of atmospheric 1-ring events.

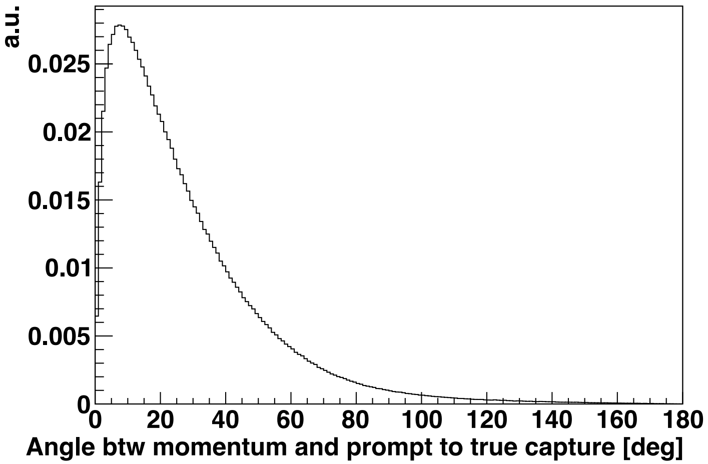
Neutron direction

- Initial direction and capture vertex of neutrons are correlated.

$p_n < 150$ MeV/c



500 MeV/c $< p_n <$ 2000 MeV/c



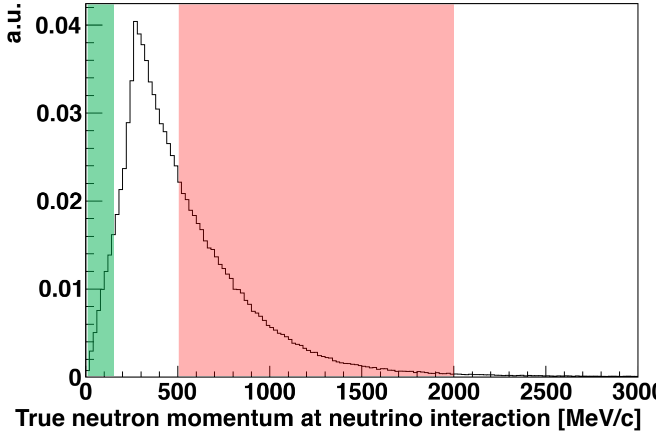
Angle btw initial direction and displacement $\overrightarrow{PC_{\mathrm{true}}}$

Test in MC with 1 neutron.
Initial momentum p_n is uniform.

→ Assume neutron is emitted in the same direction as $\overrightarrow{PC}$:

$$\overrightarrow{p_n} \propto \overrightarrow{PC}$$

Neutron momentum generated in atmospheric neutrino MC



Neutron momentum estimation

- Estimate neutron momentum from travel length $|\overrightarrow{PC}|$.
- In multiple neutron events, their vector sum $|\sum \overrightarrow{PC_i}|$ is used.
- Try two ways to estimate p_n from $|\overrightarrow{PC}|$:

(linear) $p_n \propto |\overrightarrow{PC}|$

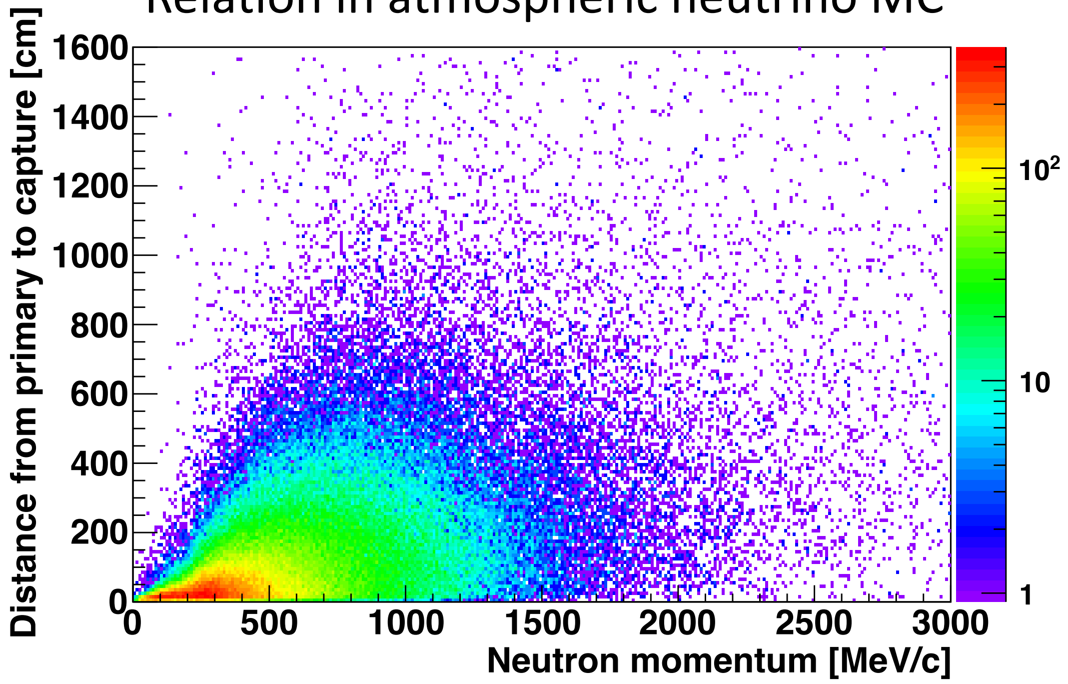
$$p_n = a \times |\overrightarrow{PC}|$$
$$\text{if } p_n > u, \quad p_n = u$$

Set upper limit u to prevent overestimate.

(log) $\log p_n \propto |\overrightarrow{PC}|$

$$\log_{10} \frac{p_n}{p_0} = \frac{|\overrightarrow{PC}|}{b}$$

Relation in atmospheric neutrino MC



Neutrino direction reconstruction

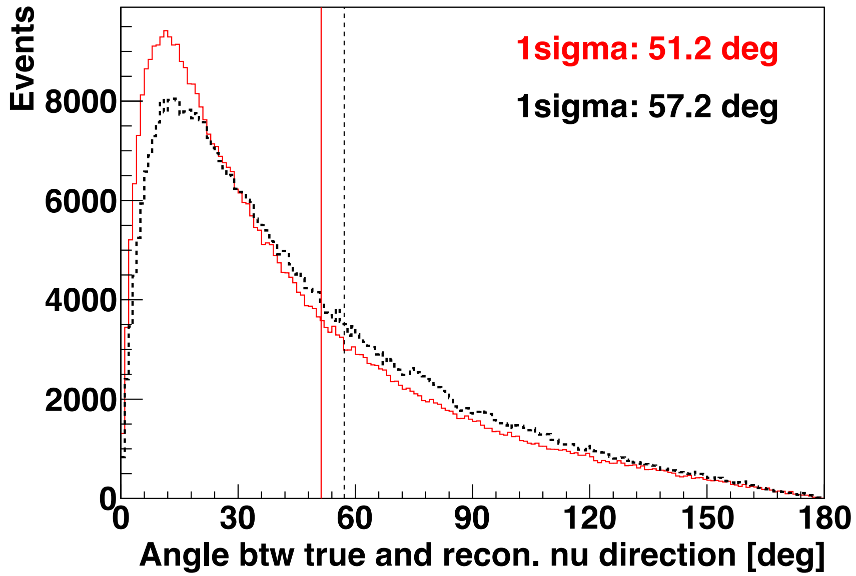
- Reconstruct direction as $\overrightarrow{p_\nu} = \overrightarrow{p_l} + \overrightarrow{p_n}$.
- Searched for optimal conversion parameters in 1-ring events.

(linear)

[deg]		a [MeV/c/cm] 1	1.5	2	2.5	3	4	5
u [MeV/c]	∞	51.8	51.5	51.8	52.8	54.0	56.8	59.3
	1000	51.8	51.3	51.7	52.5	53.5	55.5	57.3
	700	51.8	**51.2**	51.5	52.0	52.8	54.2	55.5

(log)

[deg]		b [cm] 1600	1400	1200	1000	800	600	400
p_0 [MeV/c]	100	52.8	52.7	52.5	52.2	52.0	51.8	52.8
	200	**51.2**	**51.2**	51.3	51.5	51.8	53.0	56.5
	300	52.5	52.7	53.0	53.7	54.8	56.8	61.2



— : This method
— : Assume ring direction

Best resolution is same in both conversions.
→ Resolution is almost independent of the expression of conversion.

Neutrino energy reconstruction

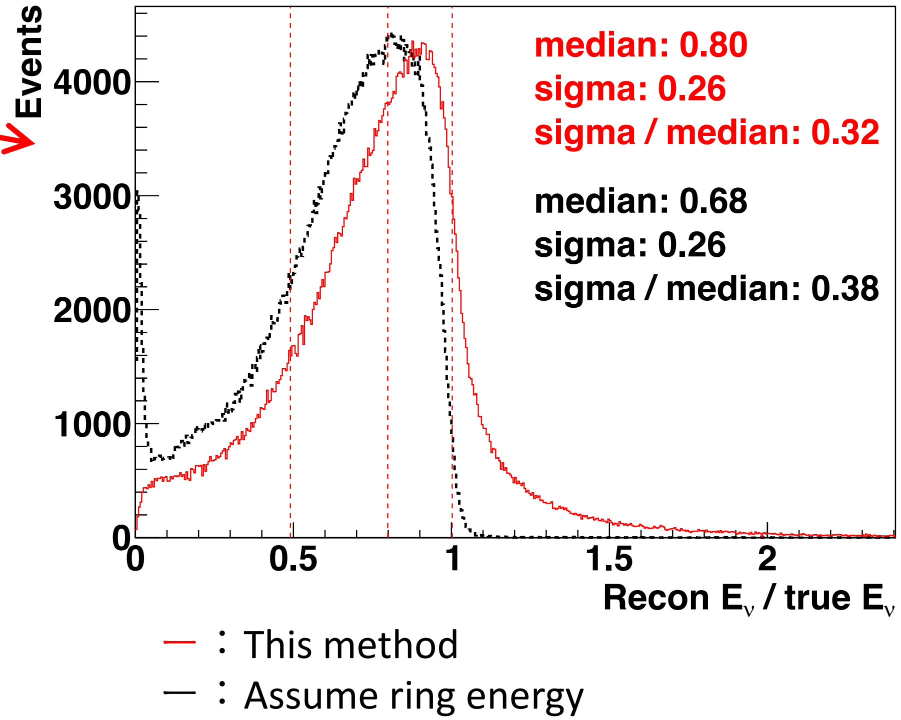
- As $|\vec{p_l} + \vec{p_n}|$ is more sensitive to neutron direction, reconstruct energy as $E_\nu = E_l + K_n$.
- Minimize $\sigma/\tilde{r}$ where $\tilde{r}$: median, σ : 68% width of $E_{\mathrm{recon}}/E_{\mathrm{true}}$.

(linear)

[%]		a [MeV/c/cm] 1	1.5	2	2.5	3	4	5
u [MeV/c]	∞	35	34	33	**32**	33	37	44
	1000	36	34	33	**32**	**32**	33	34
	700	36	35	34	33	33	33	33

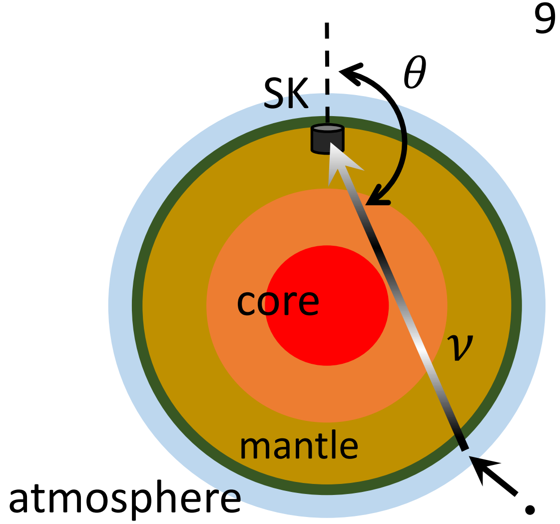
(log)

[%]		b [cm] 1600	1400	1200	1000	800	600	400
p_0 [MeV/c]	100	37	37	36	36	36	35	33
	200	35	35	34	34	33	**32**	40
	300	33	33	**32**	**32**	**32**	35	56



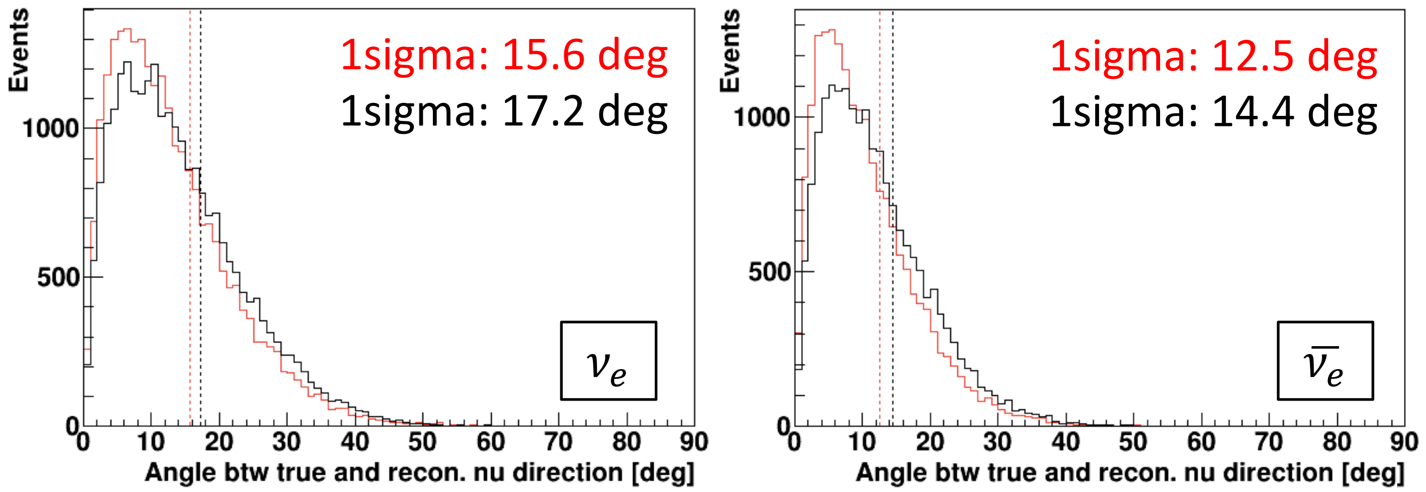
Succeeded in getting more precise value while keeping σ .

Effect on oscillation analysis

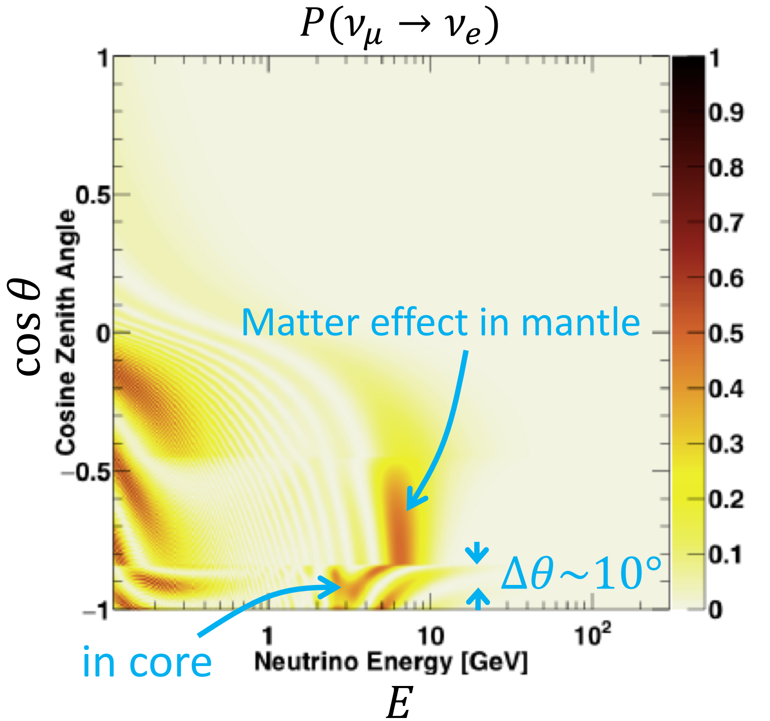


- Sensitivity study is just started.
- As a rough estimation of the effect on mass ordering determination, consider observing enhancement pattern in $\nu_e/\overline{\nu_e}$.
- To identify the change at $\cos\theta = -0.84$, required θ resolution is ~10°.

→ **Achievement is close to the requirement !**



Improvements in $\nu_e/\overline{\nu_e}$ angular resolution ($E_{\text{vis}} > 1.33$ GeV)



Summary and prospects

- I developed a new algorithm to reconstruct neutrino direction & energy using neutron tagging vertex.
- Neutron momentum is estimated from its displacement, and improvements in neutrino reconstruction are:

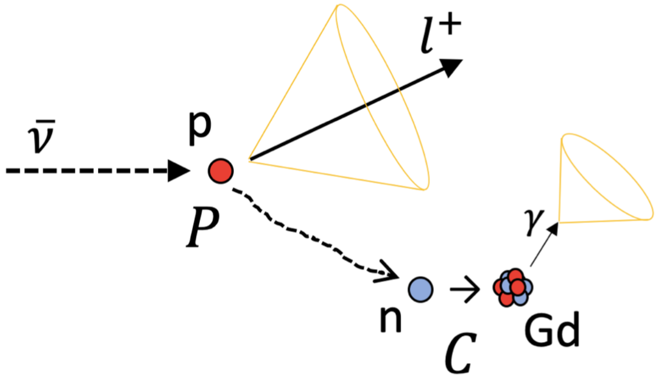
  57.2° → 51.2° in direction / 38% → 32% in energy

  This method is applied in 39% of 1-ring events.
- The achieved angular resolution in high energy is close to the requirement for a strong evidence of mass ordering determination.

- Information of # of neutrons in a event can also be used for neutrino energy reconstruction.
- The method will be tested with real data of T2K events.

Backup

中性子情報を用いたニュートリノ再構成

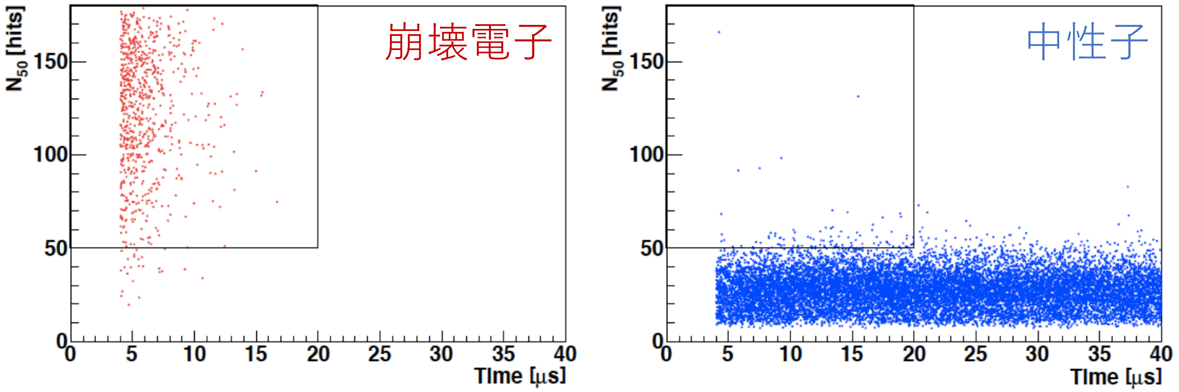


- ニュートリノ反応位置 P から中性子捕獲位置 C までの変位 $\overrightarrow{PC}$ から中性子の運動量を見積もる。

  → 荷電レプトンの情報と合わせてニュートリノの方向とエネルギーを再構成

- 大気ニュートリノ MC 中で、ニュートリノ反応の後 [4 μs, 534 μs] の範囲で中性子信号を探索した。

  崩壊電子の信号も含まれる
  → 検出時間、PMTヒット数で除去

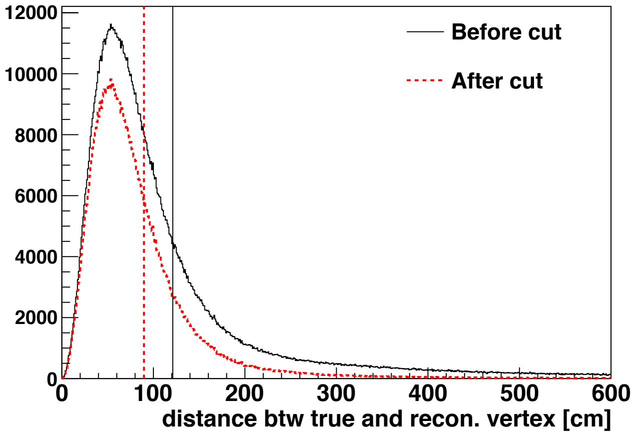


- 捕獲位置の再構成精度が悪い信号を除去：

  (CapVtx1) 再構成の quality > 0.2

  (CapVtx2) 14 ns 間でのPMTヒット数 ≥ 12

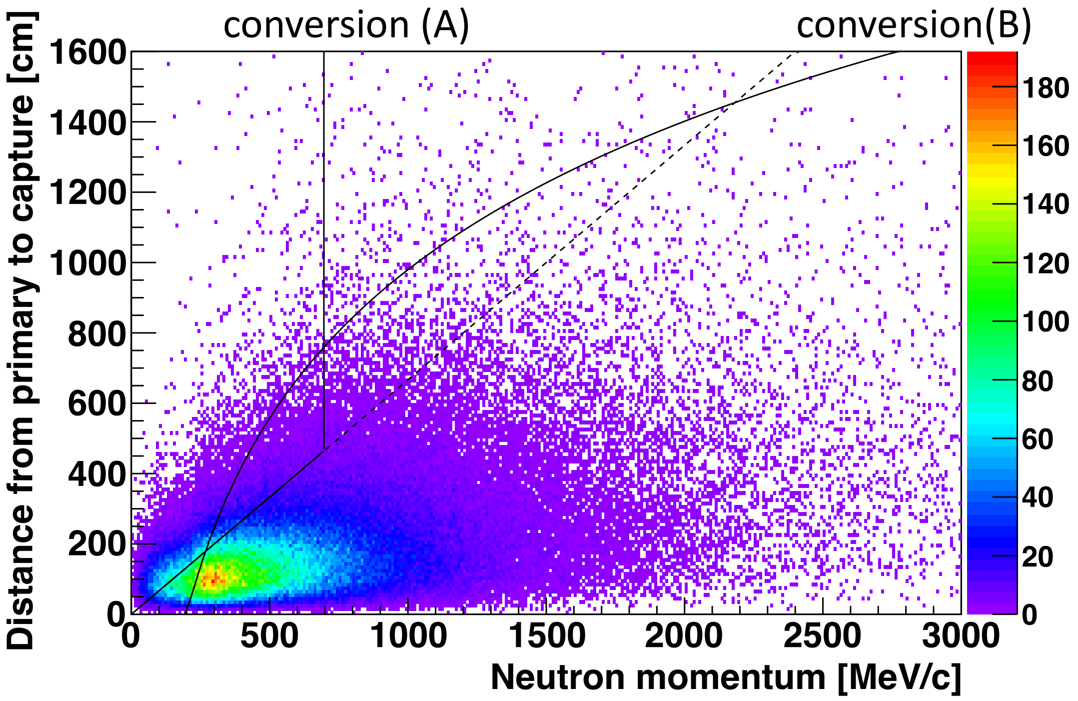
検出された中性子信号の36%が除去された。



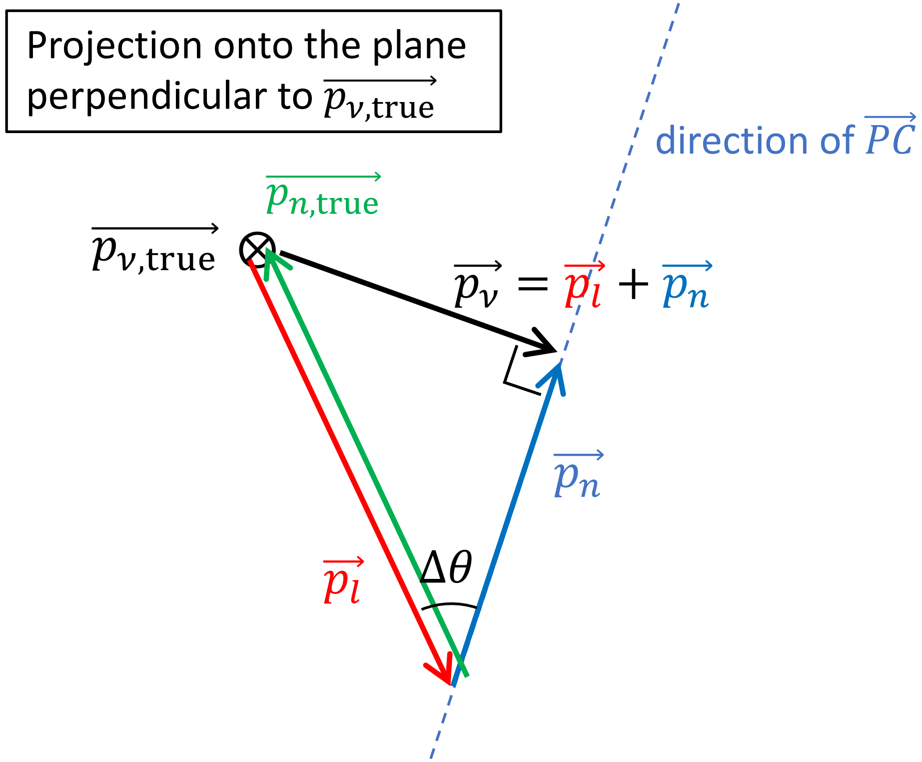
再構成精度は
121 cm → 90 cm
に改善

Interpretation of conversions

- The optimal conversions give smaller neutron momentum than the true value.
- In the plane perpendicular to $\overrightarrow{p_{\nu,\mathrm{true}}}$, when reconstructed neutron direction is shifted by $\Delta\theta$, the best reconstruction of neutrino direction is realized at $p_n = p_{n,\mathrm{true}} \cos \Delta\theta$.



Use reconstructed vertex



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- Estimate neutron momentum from travel length $|\overrightarrow{PC}|$.
- In multiple neutron events, their vector sum $|\sum \overrightarrow{PC_i}|$ is used.
- Try two ways to estimate p_n from $|\overrightarrow{PC}|$:

(A) $p_n \propto |\overrightarrow{PC}|$

$$\begin{gathered} p_n = a \times |\overrightarrow{PC}| \\ \text{if } p_n > u, \quad p_n = u \end{gathered}$$

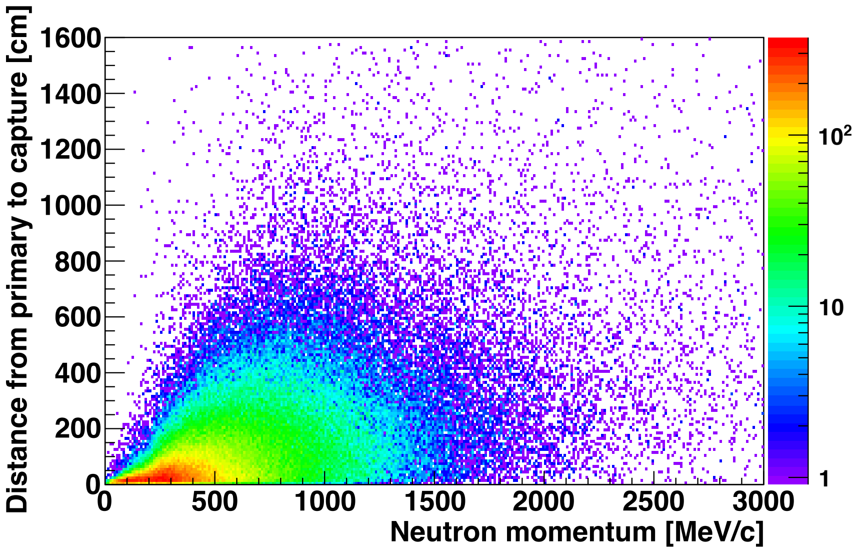
Set upper limit u to prevent overestimate.

(B) $\log p_n \propto |\overrightarrow{PC}|$

- Energy loss in a elastic collision $\propto K_n$
- Scattering cross section is approximately constant in $p_n \gtrsim 300$ MeV/c

→ Travel length of a neutron ∝ # of collisions $\propto \log K_n$

$$\log_{10} \frac{p_n}{p_0} = \frac{|\overrightarrow{PC}|}{b}$$



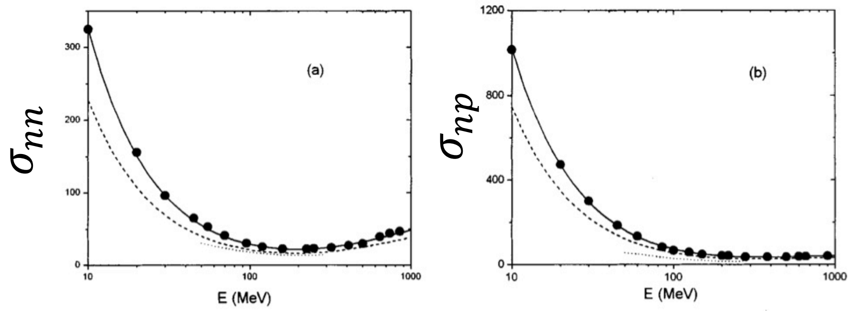


FIG. 1. Nucleon-nucleon cross section as a function of incident energy. (a) Neutron-neutron interaction cross section. (b) Neutron-proton interaction cross section. Solid circles indicate experimental free-space nucleon-nucleon cross section. Solid and dashed curves indicate the result of present formula at $\rho=0$ and ρ_0, respectively. For comparison, results of the LM formula at $\rho=\rho_0$ are shown by dotted lines.

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