# Study for the Neutrino Coherent Pion Production Experiment

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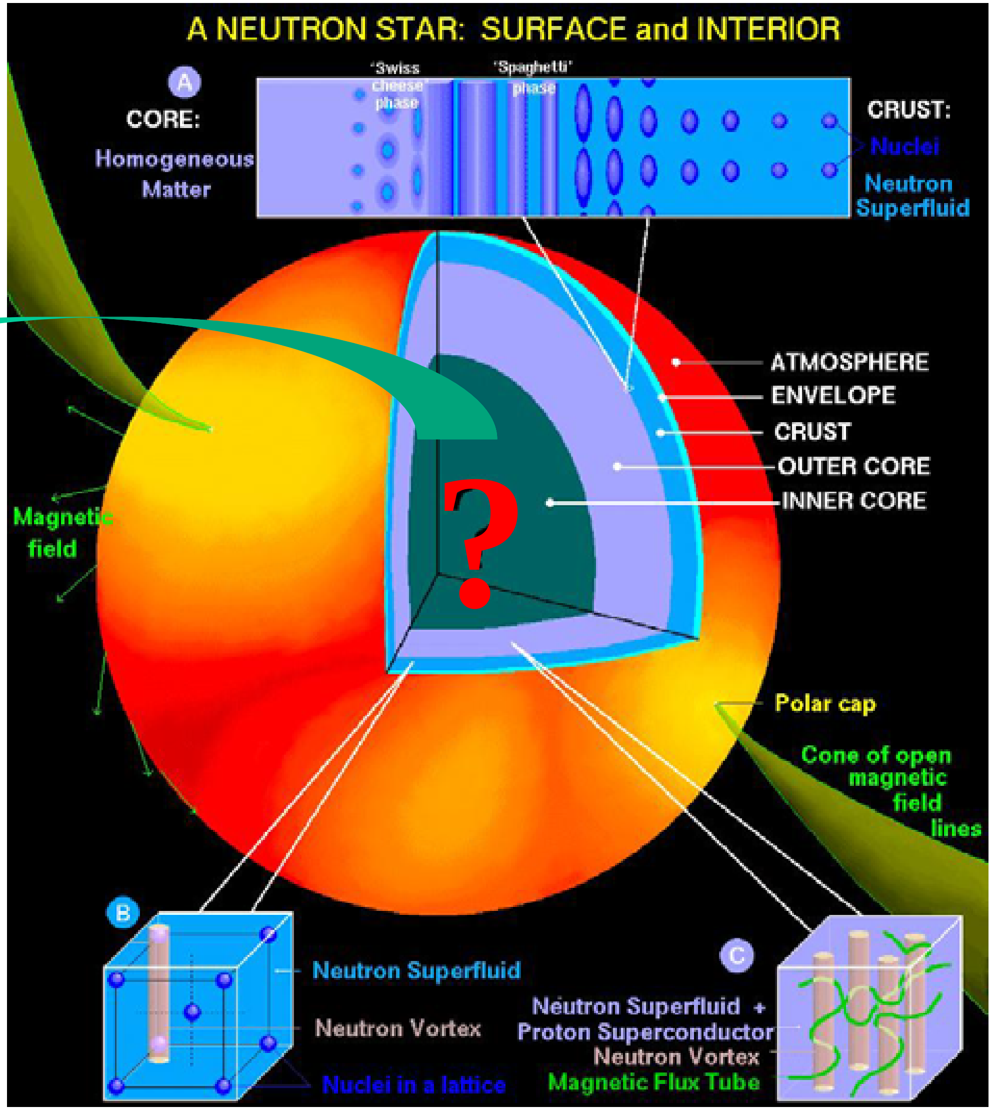
Contents

# Phase Transition in Nuclear Matter

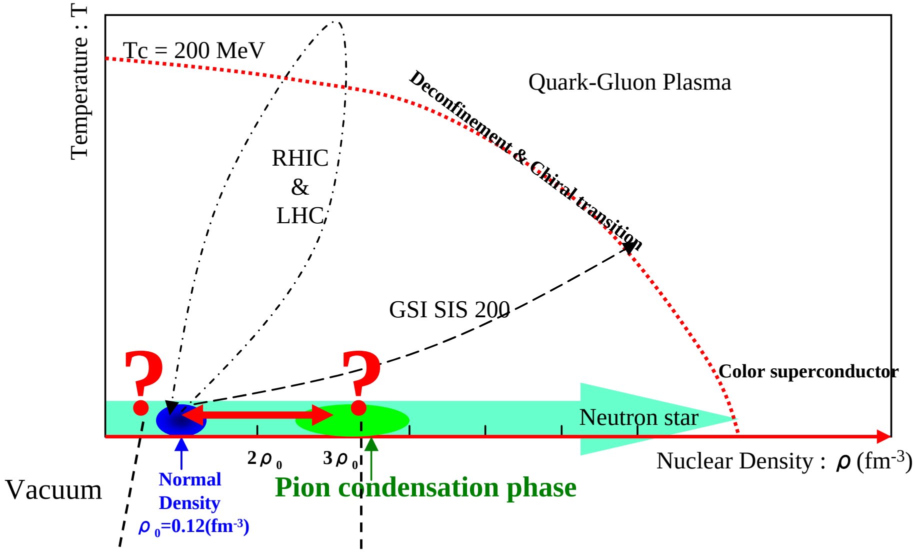
**Phase transition of nuclear matter**

- **Pion condensation**
  ~ Bose-Einstein condensation in the high density nuclear matter
- **Kaon condensation**
- **…..**

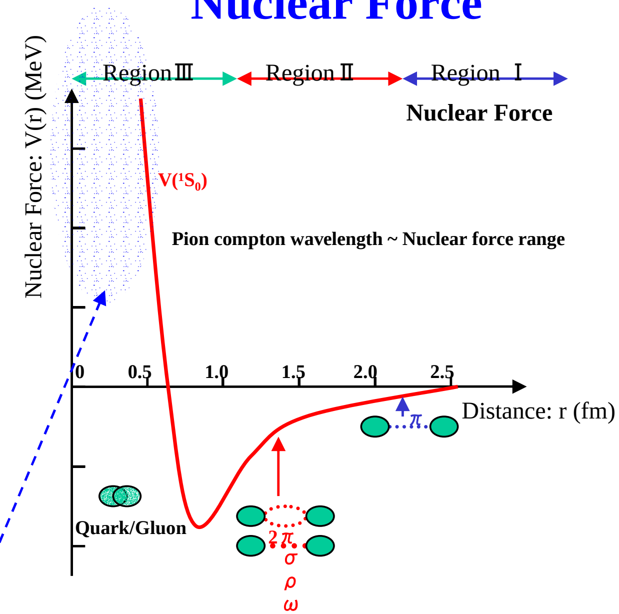


# Physics motivation

## Phase Transition




## Nuclear Force




- **Critical density** of phase transition into **Pion Condensation** phase
- **Precursor** of Pion Condensation ~ Enhancement of Nuclear **Response Function** related pion

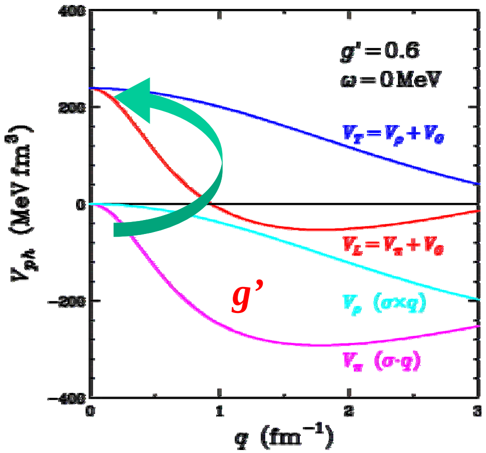
**Study on Short range component of Nuclear Force with Neutrino Beam**

# Nuclear force and Pion condensation

- Nuclear force ~ short range correlation of the nuclear interaction
  - *$1\pi + 1\rho + g'$ (short range: phenomenological parameter)*

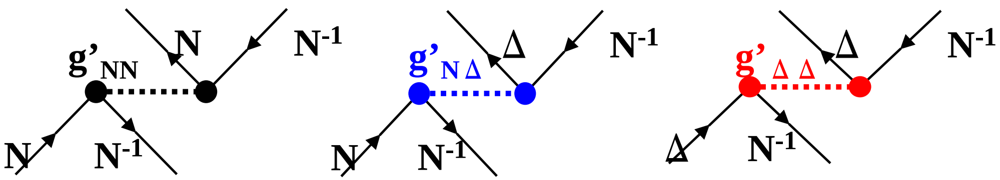
$$V_{ph}^{longitudinal} = 4\pi f^2 \left( g'_{NN} + \frac{k^2}{\omega^2 - k^2 - m_\pi^2} \right) (\sigma_1 \cdot k)(\sigma_2 \cdot k) \tau_1 \cdot \tau_2$$

$$V_{ph}^{transverse} = 4\pi f^2 \left( g'_{NN} + \frac{f_\rho^2}{f^2} \cdot \frac{k^2}{\omega^2 - k^2 - m_\rho^2} \right) (\sigma_1 \times k)(\sigma_2 \times k) \tau_1 \cdot \tau_2$$

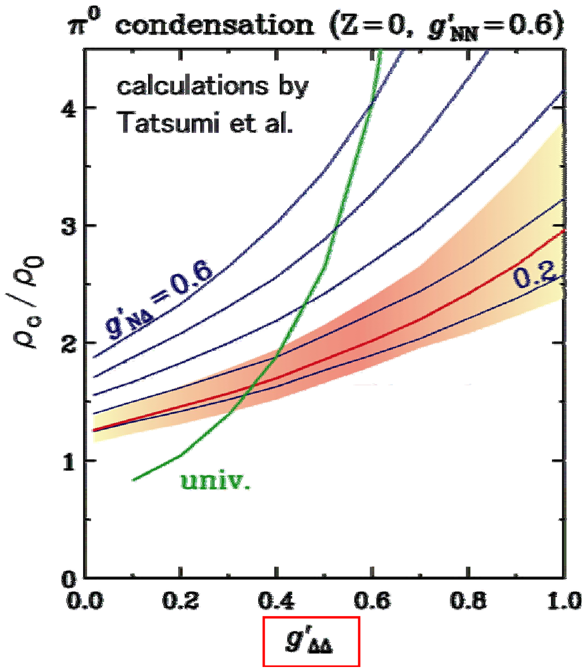



- Landau-Migdal parameters: ***g'~ g'$_{NN}$・ g'$_{N\Delta}$, g'$_{\Delta\Delta}$***

***g'$_{NN}$*** $\sigma_1 \cdot \sigma_2 \tau_1 \cdot \tau_2$ ***g'$_{N\Delta}$*** $\sigma_1 \cdot S_2 \tau_1 \cdot T_2$ ***g'$_{\Delta\Delta}$*** $S_1 \cdot S_2 T_1 \cdot T_2$




**Well known from Gamow-Teller resonance** **Known from Quasi-free scattering** **Unknown**



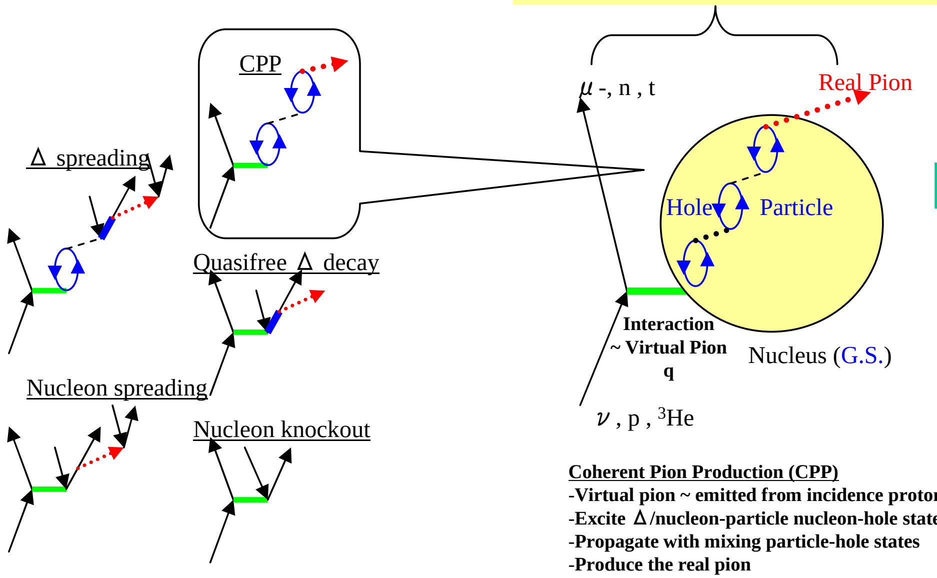

- Critical density of Pion condensation phase transition
  - *Sensitive to **g'$_{\Delta\Delta}$***
  - *Determine the **g'$_{\Delta\Delta}$** from **Coherent Pion Production***

# Coherent Pion Production

$$A(\nu, \mu^- \pi^+)A(\text{Ground State}) \Rightarrow \text{Nuclear Force} \sim g'_{\Delta\Delta}$$

Inclusive measurement

Coincidence measurement of neutron and pion




**Coherent Pion Production (CPP)**
- Virtual pion ~ emitted from incidence proton beam
- Excite Δ/nucleon-particle nucleon-hole states
- Propagate with mixing particle-hole states
- Produce the real pion
- Target nucleus is left in the Ground State (G.S.)

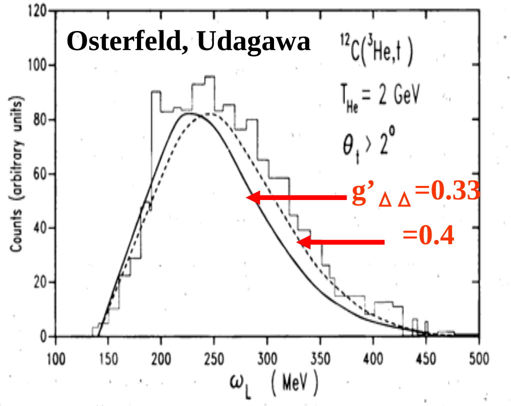
Observables

- **Cross section**
- **Spectrum shape**
- **Peak position :**

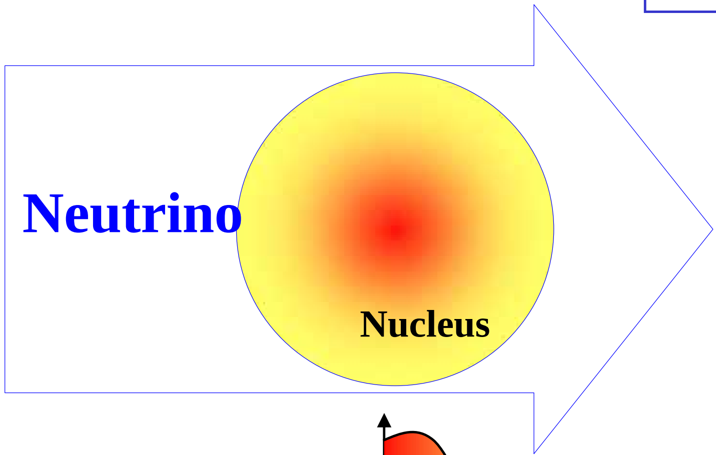
$$\Delta E \approx g'_{\Delta\Delta}\frac{hcf_{\pi N\Delta}}{m_\pi^{2}}\rho_0$$

↓

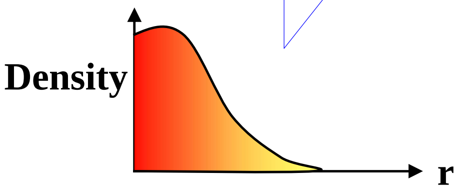
**Depend on g' ΔΔ**



# Neutrino Beam

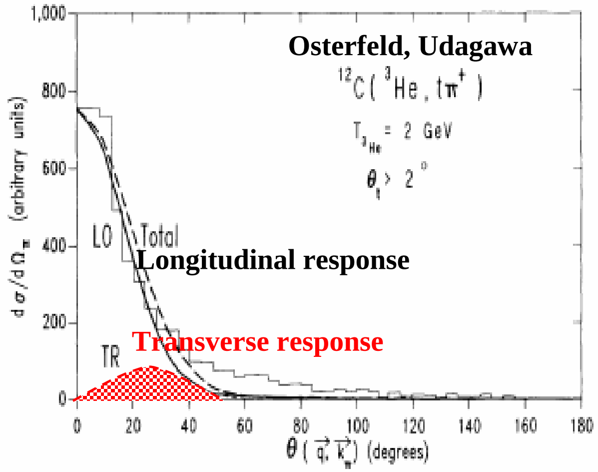


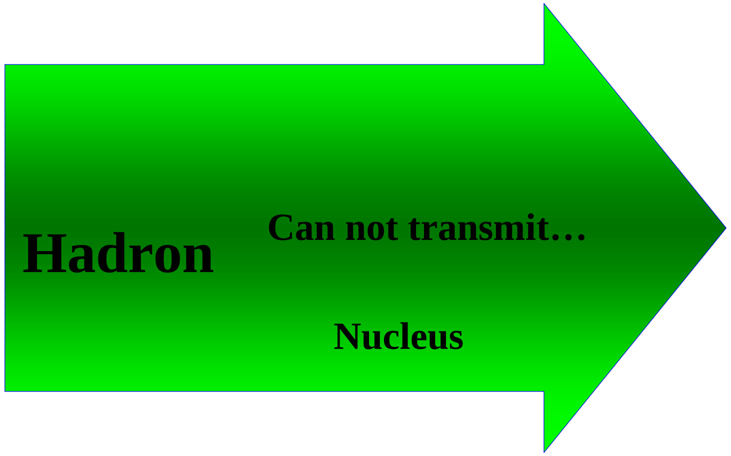

- **Weak interaction**
- **Can prove the interior of nucleus**
- **Cross section ~ behave volume like**
- **No distortion/absorption**
- **Adler's theorem : M~T( $\pi$ (q)+N→X)**




**Cross section, shape and peak position ~ $g'_{\Delta\Delta}$**

**Neutrino**
**→ Good Probe to study the interior of the nucleus**
**⇒ keep the information of nuclear interior**




- **Strong interaction**
- **Reaction ~ peripheral**
- **Sensitive to nuclear surface**
- **Distortion/Absorption effects**

**⇒can investigate residual interaction with high accuracy**

# Electron/Photon induced CPP

**Suggested by Prof. M. Sakuda**

- Longitudinal Response

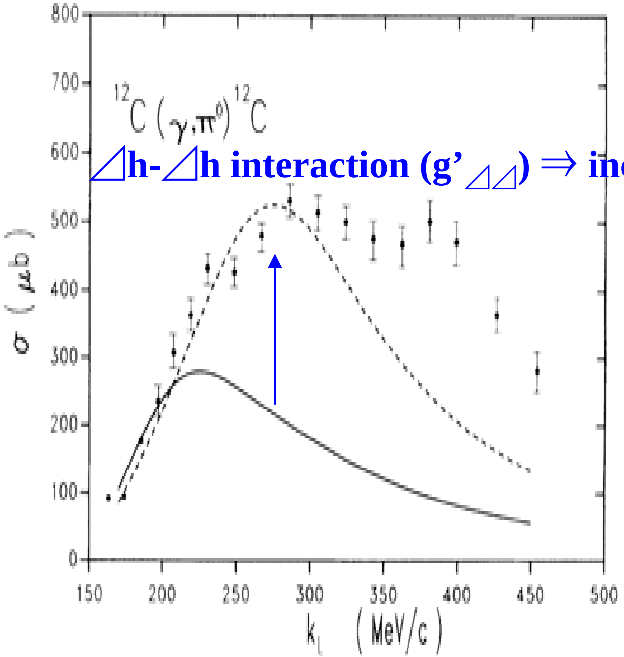
$$R_L \propto \left| \langle n | \sigma \cdot \mathbf{q} | 0 \rangle \right|^2$$

  - Enhancement and Softening

- Transverse Response

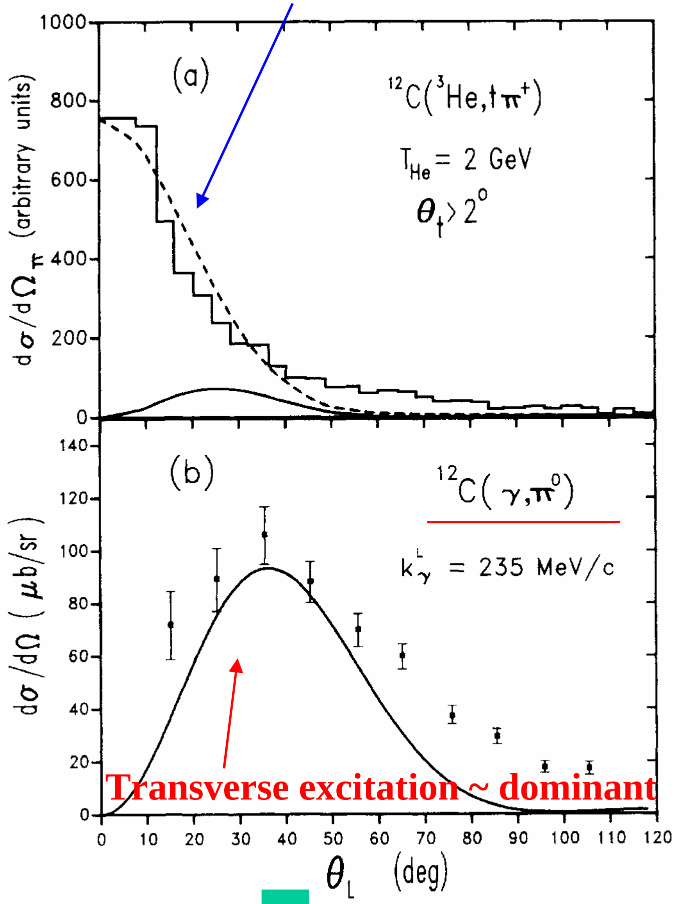
$$R_T \propto \left| \langle n | \sigma \times \mathbf{q} | 0 \rangle \right|^2$$

  - Quenching and Hardening




**⊿h-⊿h interaction (g'$_{⊿⊿}$) ⇒ include**

**Mixture of longitudinal and transverse responses**

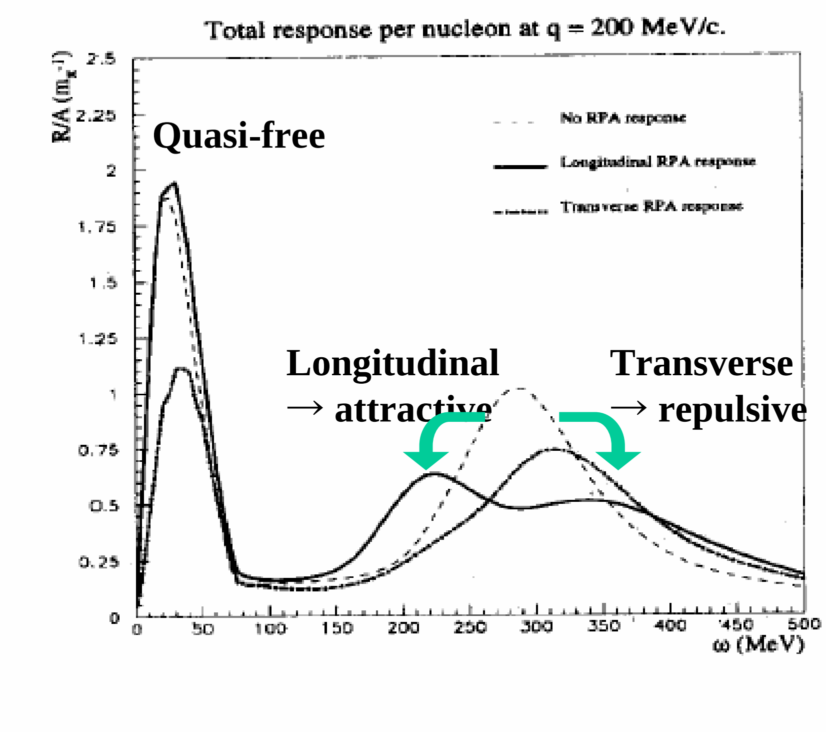


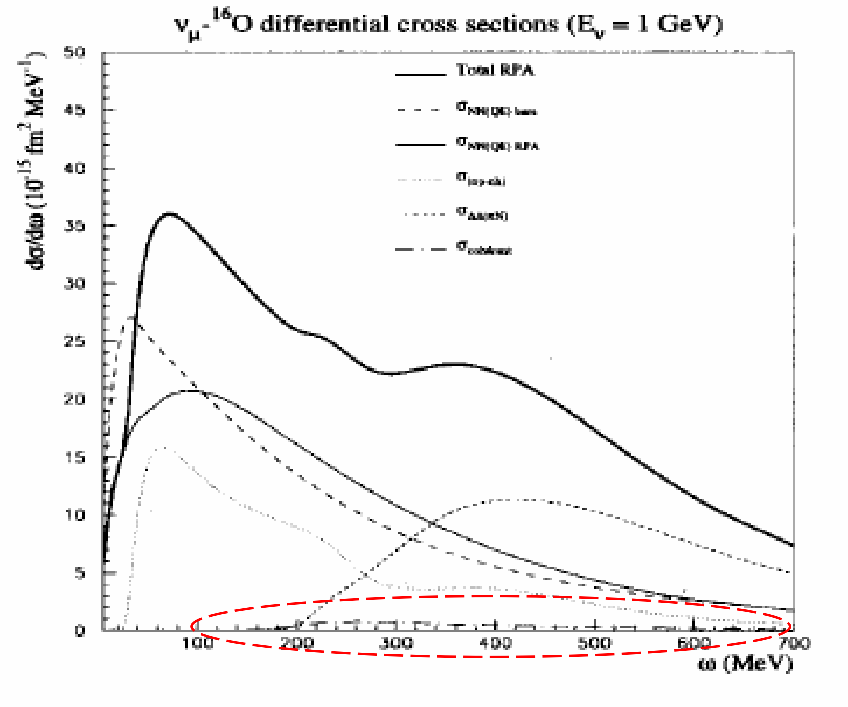

**Transverse excitation ~ dominant**

**Can extract Longitudinal response strength by reducing the Transverse component measured by e/ γ induced CPP**

# Neutrino induced CPP

**J.Marteau**

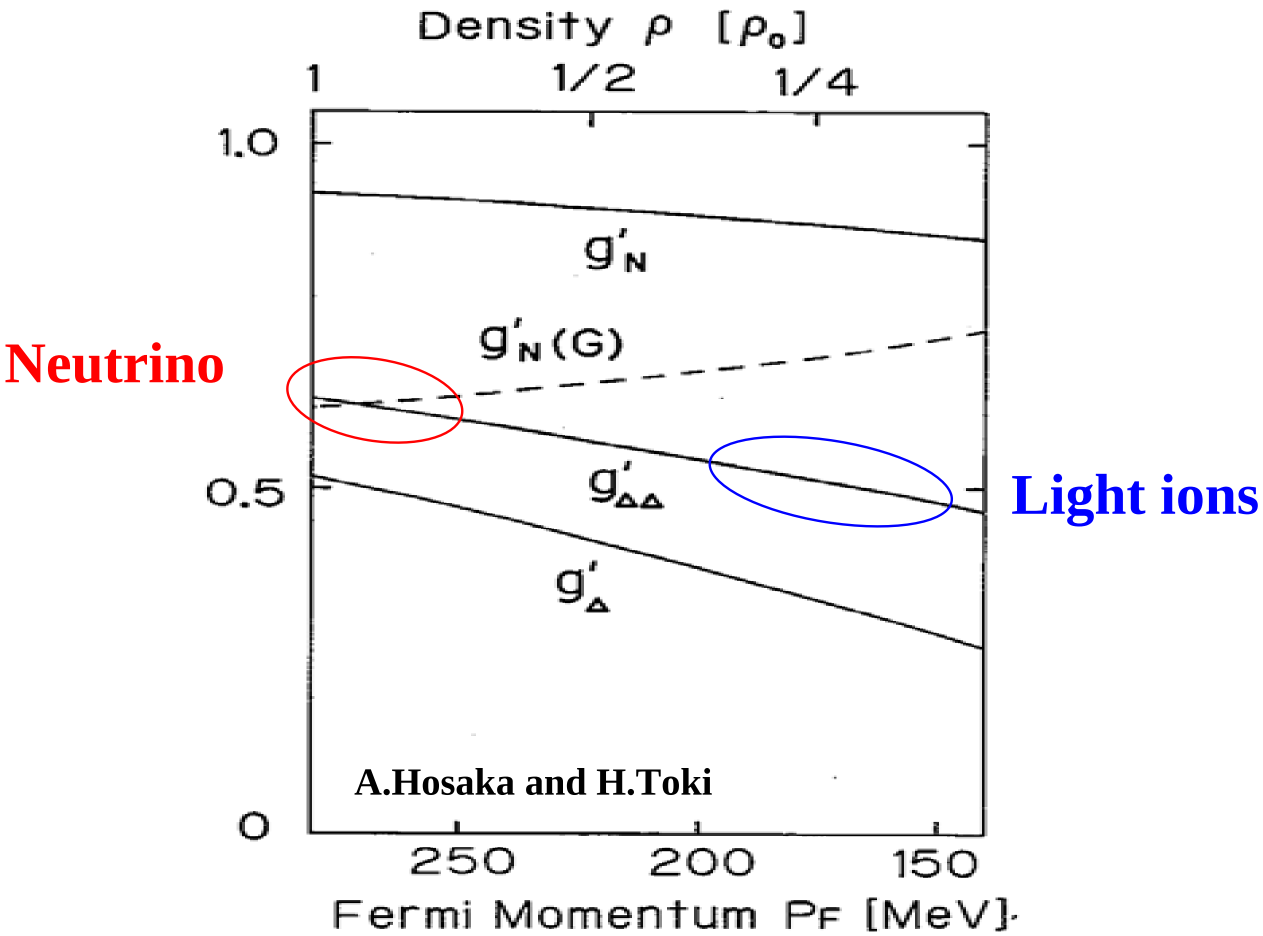



●**Peak ⇒g' Δ Δ**

●**Strength⇒ Precursor of pion condensation**

# Density dependence of g’



# Coherent Pion Production at RCNP

$g'_{DD}$ ~ extract from Coherent Pion Production

**p + A → n + $\pi^+$ + A (g.s.)**

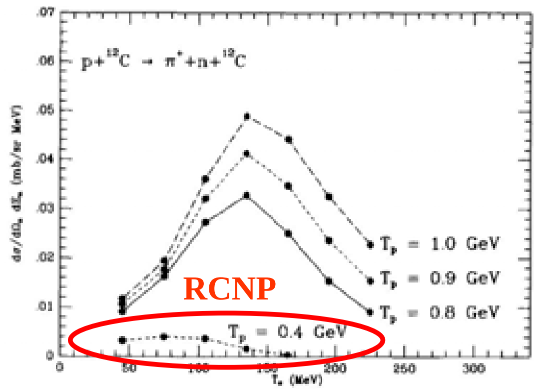
1. Peak shift from N-**D** residual interaction
   - $\Delta E \approx g'_{\Delta\Delta}(\hbar c f_{\pi N D}/m_{p}^{2})\, \rho_0$
2. Longitudinal response function ($R_L$) ~ dominant at 0 degree
   - $\mathbf{s}_{cpp}(0°) \rightarrow R_L \rightarrow g'$ ($g'_{NN}$, $g'_{ND}$, $g'_{DD}$)

CPP status

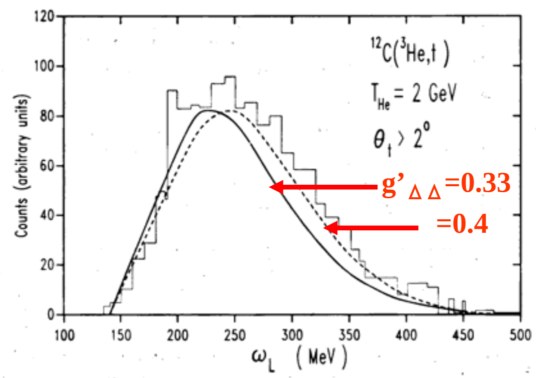
- Saclay $^{12}C(3He,t\pi^+)^{12}C$(G.S.)~resolution poor/shutdown
- LAMPF $^{12}C(p,n\pi^+)^{12}C$(G.S.)~ test experiment / shutdown
- RCNP $^{12}C(p,n\pi^+)^{12}C$(G.S.)~ in progress

Experiment

- Beam ~ proton 400MeV un-polarized ⊿E~100keV
- Target ~ $^{12}C$ (100mg/cm$^2$)
- Detector
  - *Netron detector ~ ⊿E~300 keV*
  - *$\pi$ detector ~ ⊿E~1 MeV*
- Identification of CPP
  - select the ground state of residual nucleus




**coherent pion cross section[2].**



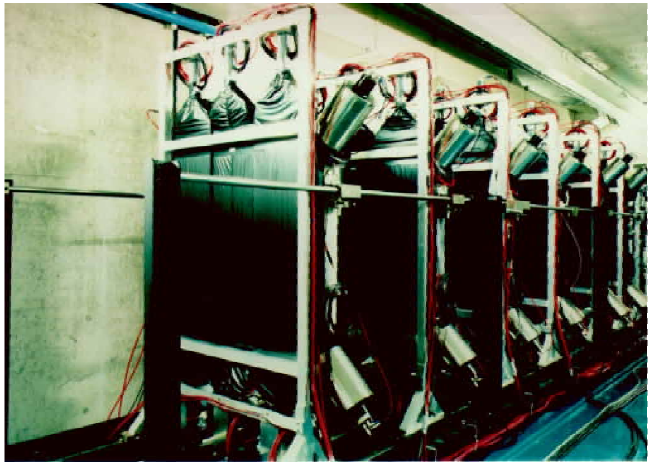

correlation of cross section and $g'_{\Delta\Delta}$[3].

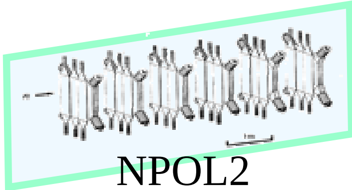

**[2] E. Oset, Nucl. Phys. A 592 (1995) 472.**

**[3] T. Udagawa et al., Phys. Rev. C 49 (1994) 6.**

# CPP Experiment

**Neutron Counter**





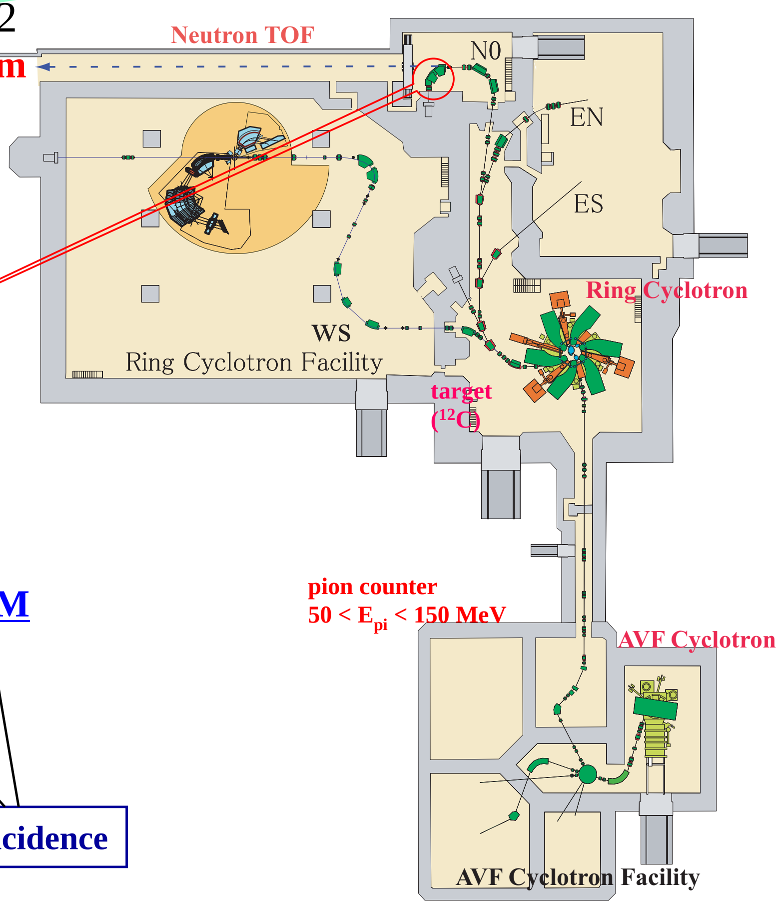
NPOL2

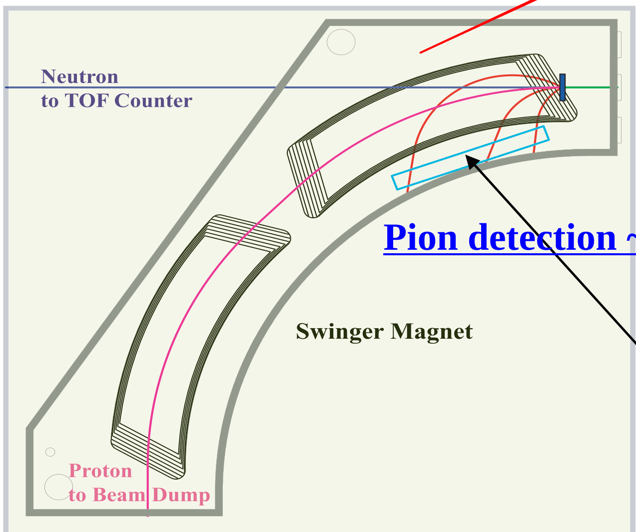
**100 m**

**Position sensitive Neutron Counter (liq Sci.)**

**Energy resolution : 300 keV**

**Detection efficiency : 20 %**

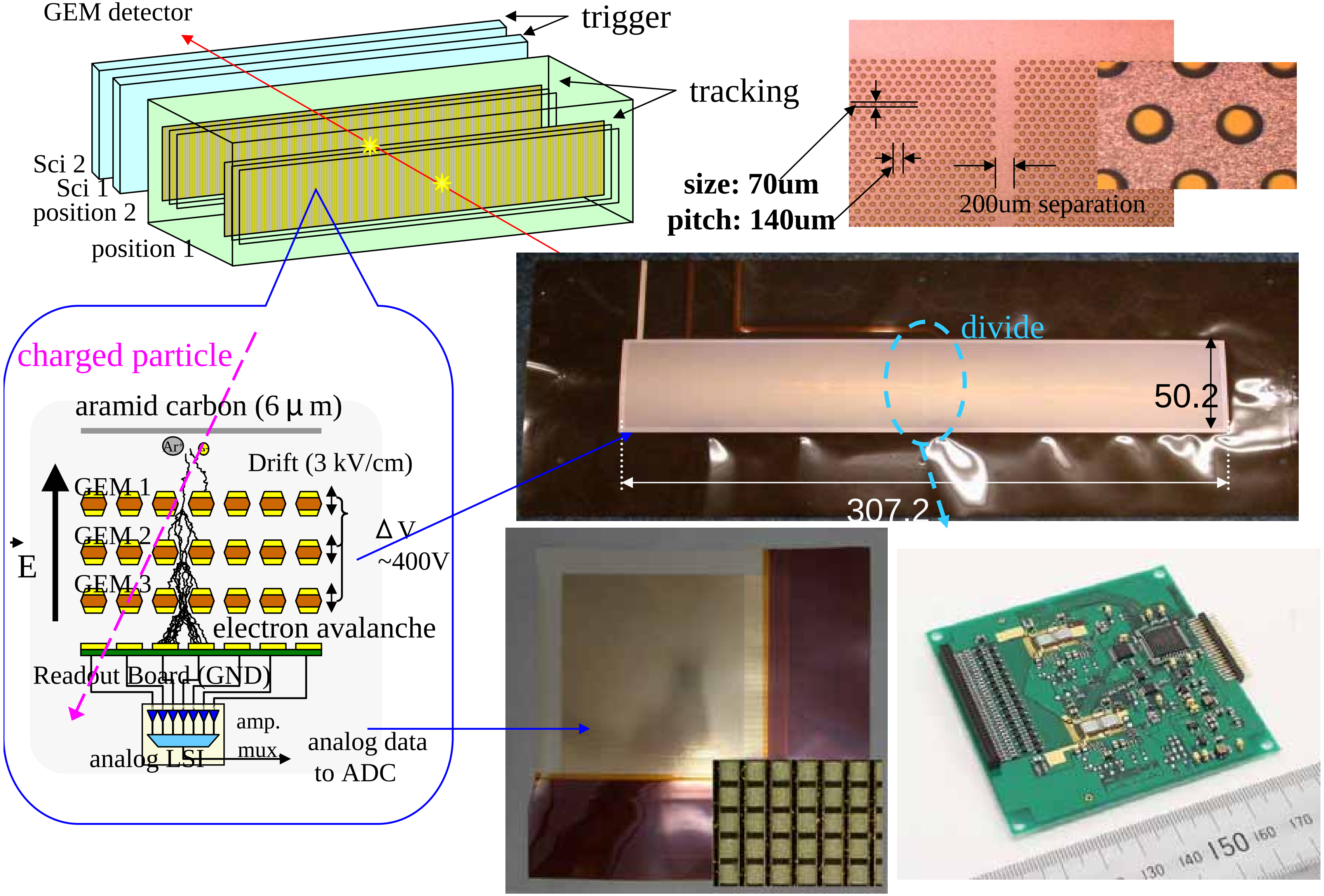


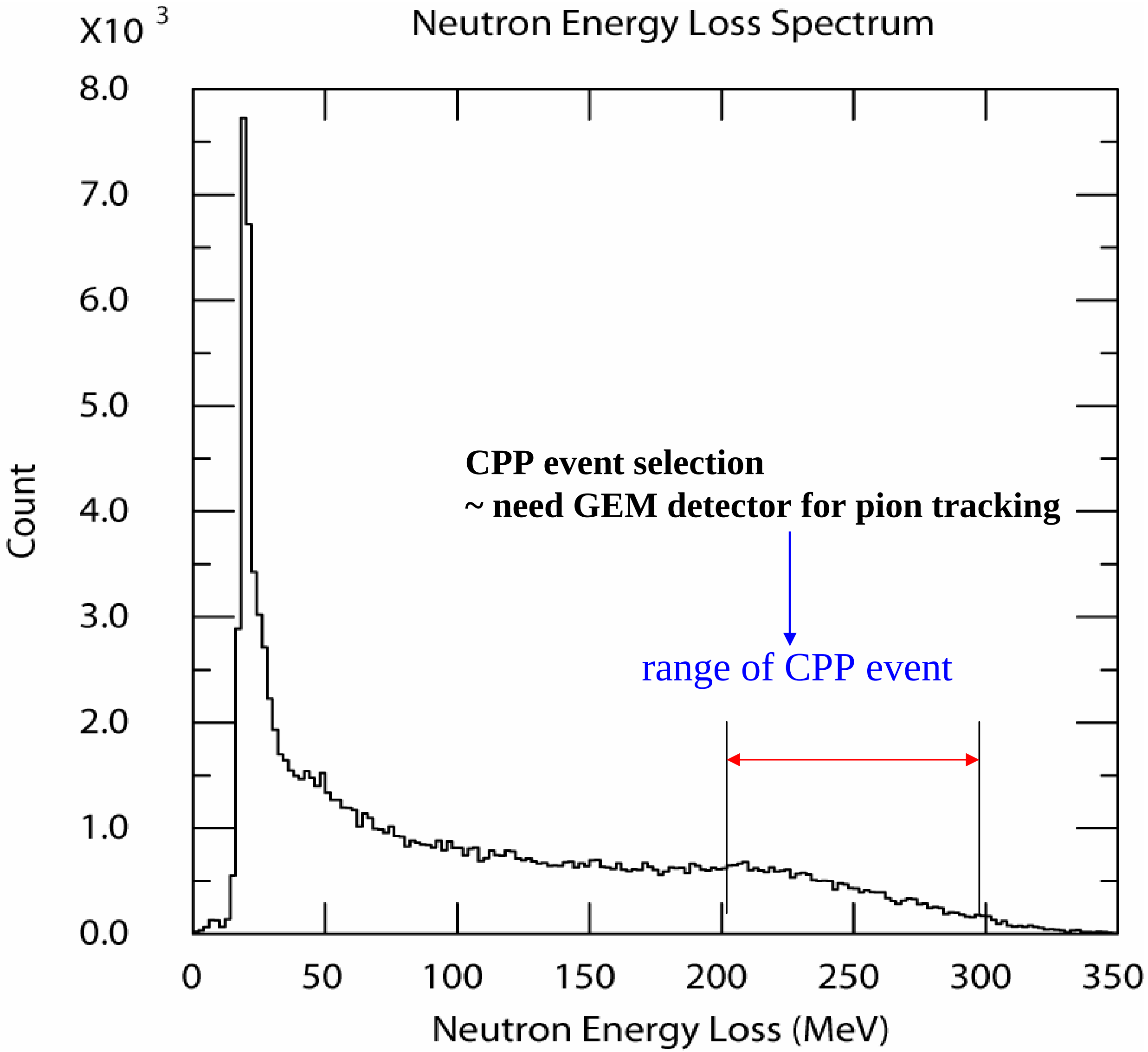

**Pion detection ~ GEM**

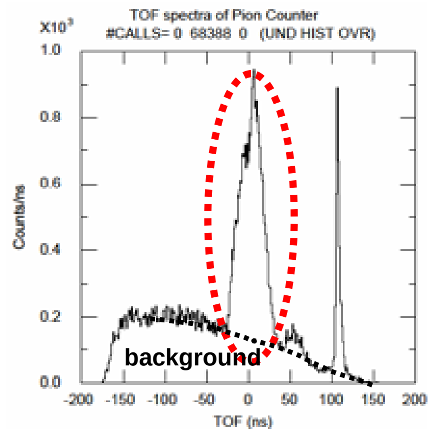
**coincidence**

# Tracking Detector: Gas Electron Multiplier

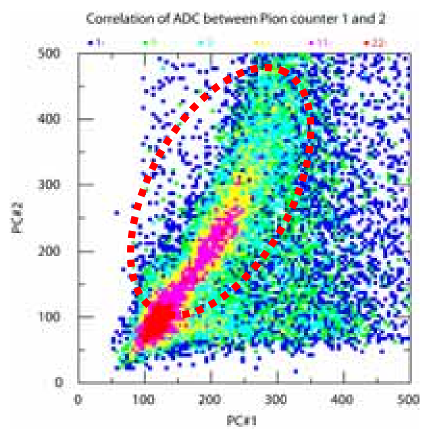


# Experimental status



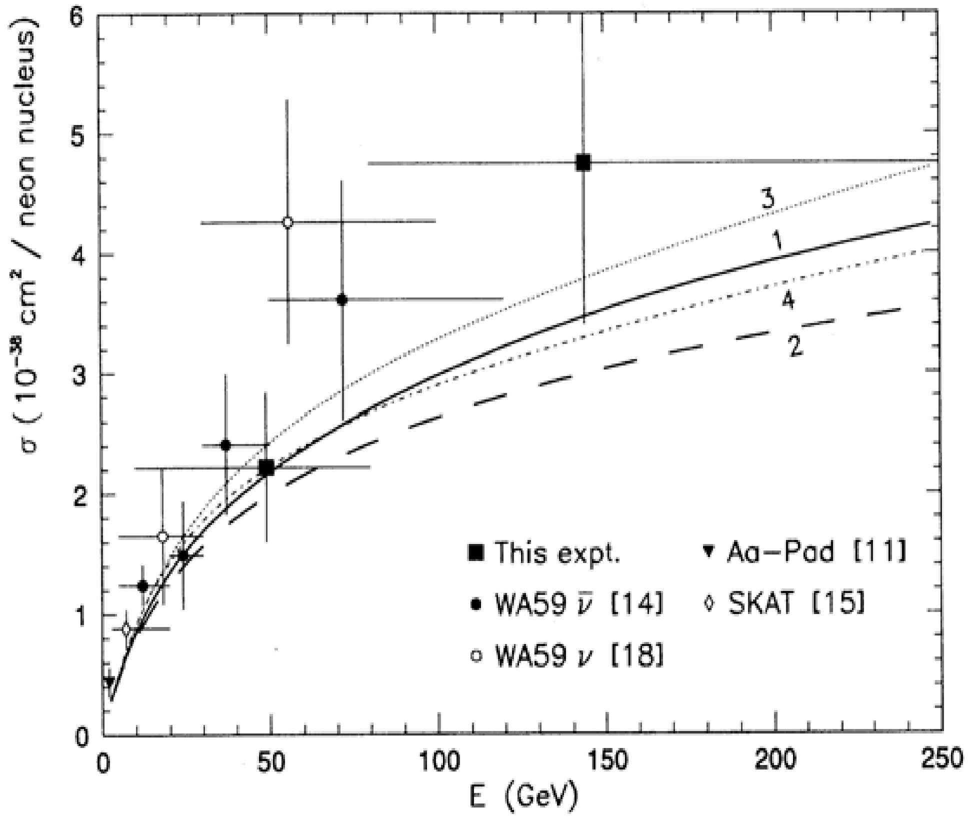

TOF spectrum of pion counter



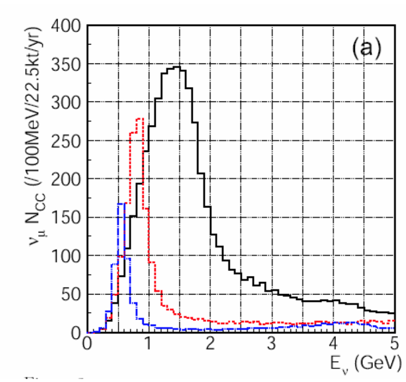

Trigger sci.

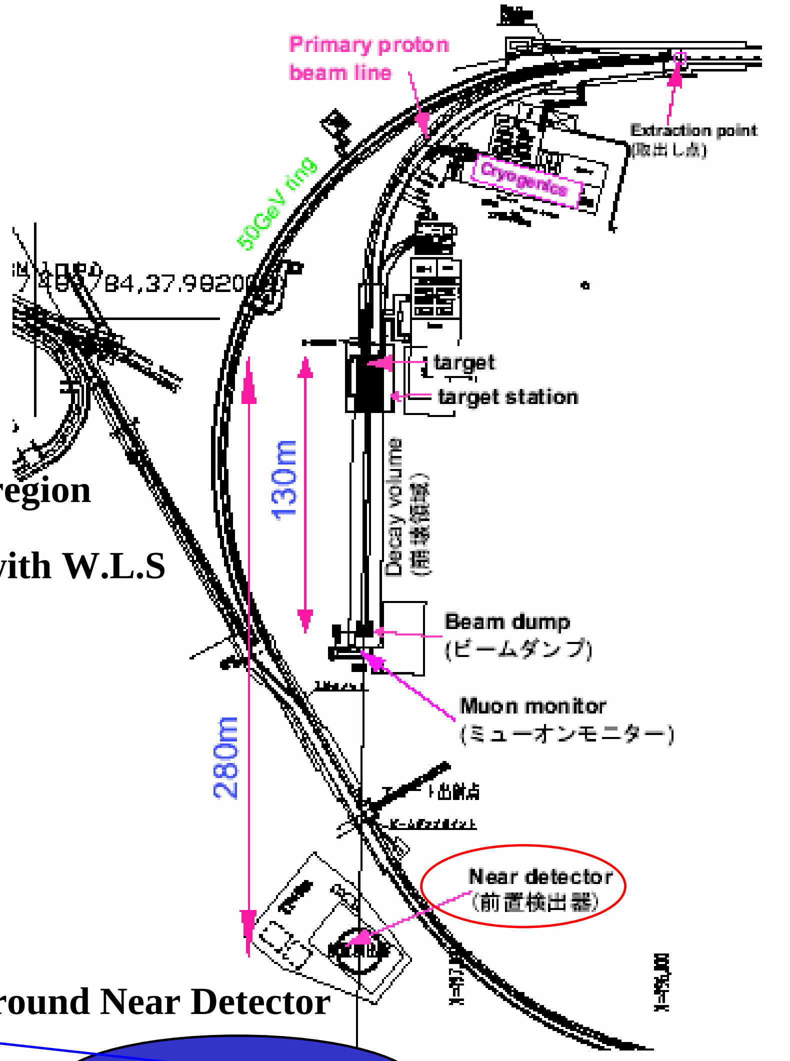
# Neutrino induced CPP

**Coherent Pion Production data ~ poor**
**First data from K2K ~ GeV energy region ⇒ NO eveidence of CPP**



# Neutrino Beam at J-PARC




**Beam energy ~ 1 GeV**

**→ suitable for Nuclear Physics in the ⊿ resonance region**

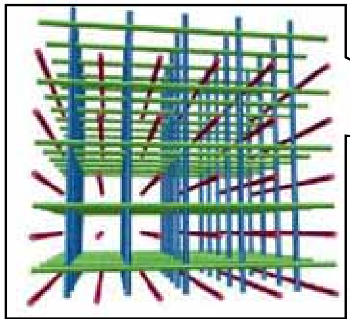
**Detector ~ LOI(AGS neutrino beam) ~ Liquid Sci. with W.L.S**

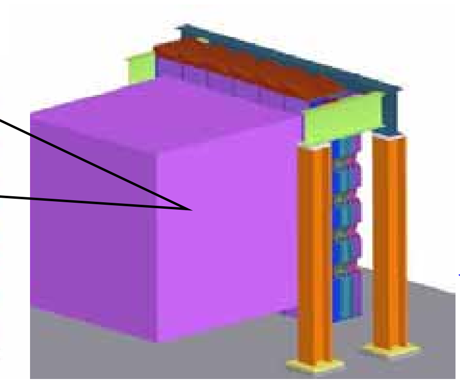
**Target**

**●Proton**

**●Carbon !**

**●Heavy Nucleus**





**Around Near Detector**

# Neutrino induced CPP

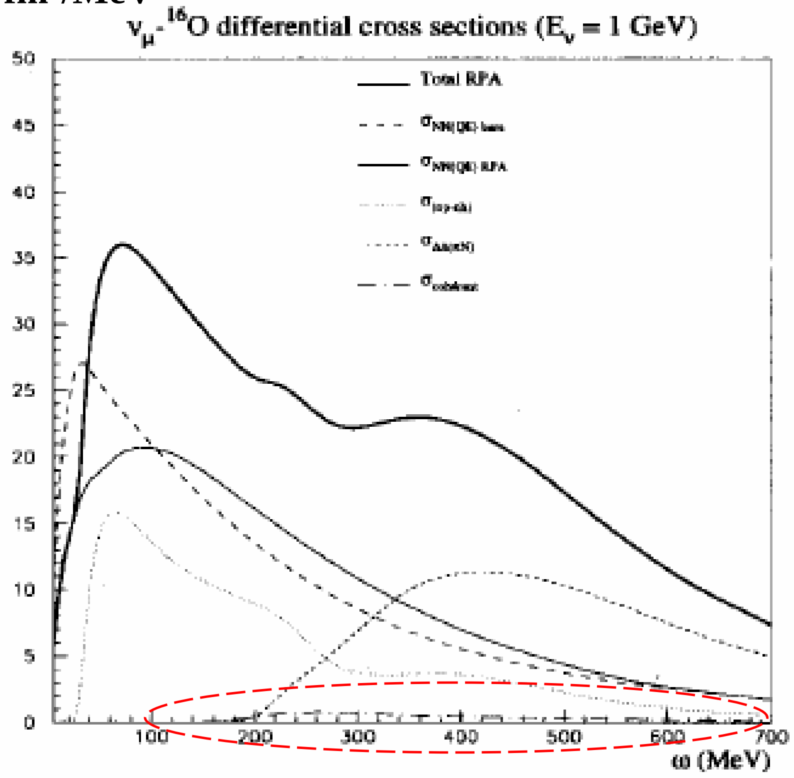
**E=1 GeV → Δ resonance region ~ π , Δ propagation in the interior of nucleus**

**LOI (AGS neutrino beam)**

| $\nu$ interaction type | $\nu_\mu$ $10^{20}$ POT 1 ton | $\overline{\nu_\mu}$ $10^{20}$ POT 1 ton | $\nu_e + \overline{\nu_e}$ $10^{20}$ POT 1 ton |
|---|---|---|---|
| CC QE, $\nu_\mu n \to \mu^- p$ | 11,395 | 184 | 56 |
| NC EL, $\nu_\mu N \to \nu_\mu N$ | 4,993 | 86 | 22 |
| CC $\pi^+$, $\nu_\mu p \to \mu^- p \pi^+$ | 3,293 | 24 | 24 |
| CC $\pi^0$, $\nu_\mu n \to \mu^- p \pi^0$ | 725 | 11 | 6 |
| CC $\pi^+$, $\nu_\mu n \to \mu^- n \pi^+$ | 646 | 10 | 6 |
| NC $\pi^0$, $\nu_\mu p \to \nu_\mu p \pi^0$ | 606 | 10 | 5 |
| NC $\pi^+$, $\nu_\mu p \to \nu_\mu n \pi^+$ | 370 | 6 | 3 |
| NC $\pi^0$, $\nu_\mu n \to \nu_\mu n \pi^0$ | 454 | 8 | 3 |
| NC $\pi^-$, $\nu_\mu n \to \nu_\mu p \pi^-$ | 290 | 5 | 2 |
| CC DIS, $\nu_\mu N \to \mu^- X$ | 176 | 0 | 1 |
| NC DIS, $\nu_\mu N \to \nu_\mu X$ | 64 | 0 | 0 |
| CC coh $\pi^+$, $\nu_\mu A \to \mu^- A \pi^+$ | 539 | 22 | 3 |
| NC coh $\pi^0$, $\nu_\mu A \to \nu_\mu A \pi^0$ | 349 | 14 | 2 |
| other | 464 | 14 | 1 |
| total | 24,364 | 394 | 134 |

Table 3.1: *Number of events expected at 50 m with a 25 m decay length for $1 \times 10^{20}$ POT per ton detector. These predictions do not include final state effects and assume 100% detection/reconstruction efficiency.*

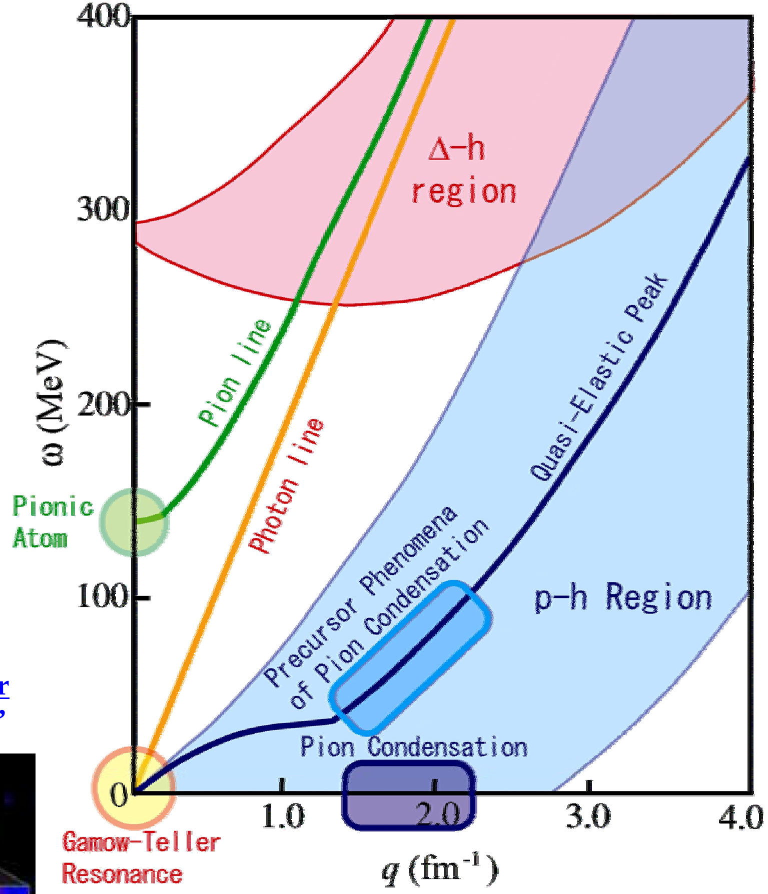
**$10^{-15}$ fm$^2$/MeV**



# Summary

Nuclear physics with Neutrino Beam

- ●Understand Neutrino-Nucleus reaction mechanism
- ●New probe ~ Neutrino at J-PARC
  - ➢E ν ~1 GeV : ⊿ properties in nucleus
- ●Coherent Pion Production
  - **➢Neutrino Beam**
  - **~ Probe the interior of the nucleus**
  - **➢ Proton/3He Beam**
  - **~ Prove the surface, Reaction mechanism**
  - **➢Electron Beam**
  - **~ Transverse response function**
- ●Physics discussion, Detector design

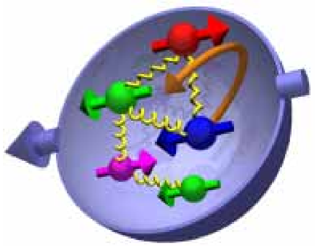


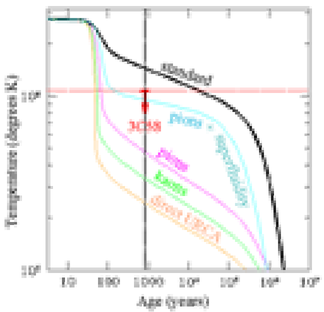

<u>**Strange Quark Content in the Nucleon**</u>

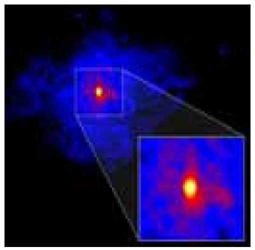
*_by T.-A. Shibata, N.Saito, Y.Miyachi*

<u>**Phase transitions in the neutron star**</u>

**~ cooling mechanism ~ depend on g'**





# Neutrino Beam