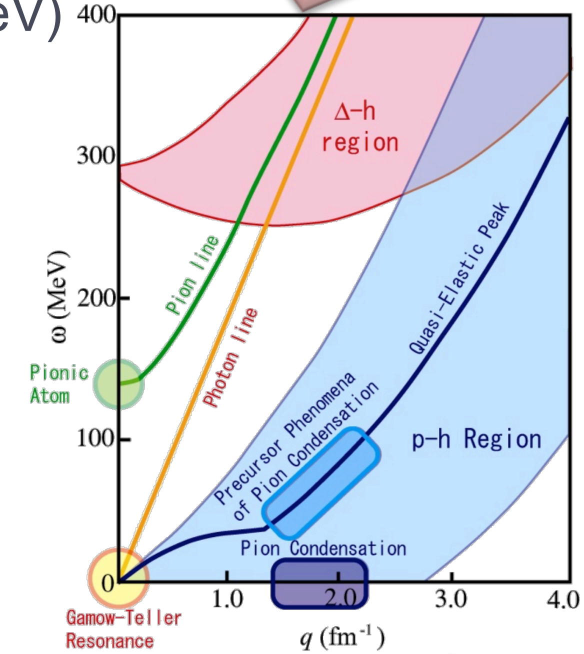
コヒーレント中間子生成とデルタ領域のスピン・アイソスピン物理

九州大学
若狭　智嗣（九大院理）
東北大学
酒見　泰寛（東北大CYRIC）

Introduction
(Same as summary)

- **Spin-isospin responses have been widely studied via**
  - GT at small q&ω
    - (3He,t), (p,p'), (p,n)
  - QES at large q (1-2 fm^{-1}) and medium ω (100 MeV)
    - (p,n) (as well as (p,p'))
  - Spin-longitudinal at wide q and small ω
    - (p,n), (p,p') (Dispersion matching)
  - Pionic atoms at small q and large ω (m_π)
    - (d,^{3}He), (p,^{2}He)
- **In progress**
  - GT at small q and medium ω
    - ICHO/SHARAQ at RIBF by U-Tokyo
- **NOT sufficiently explored region**
  - Δ region at large ω (200-400 MeV)

Unexplored (target) region



Goal: Understand spin-isospin responses in wide (q,ω) in a unified way

HowTo:* 1. *Polarization transfer observables of (p,n)
2. *Coherent Pion Production (CPP) via (p,nπ$^+$)*

} with GeV "pol." beam

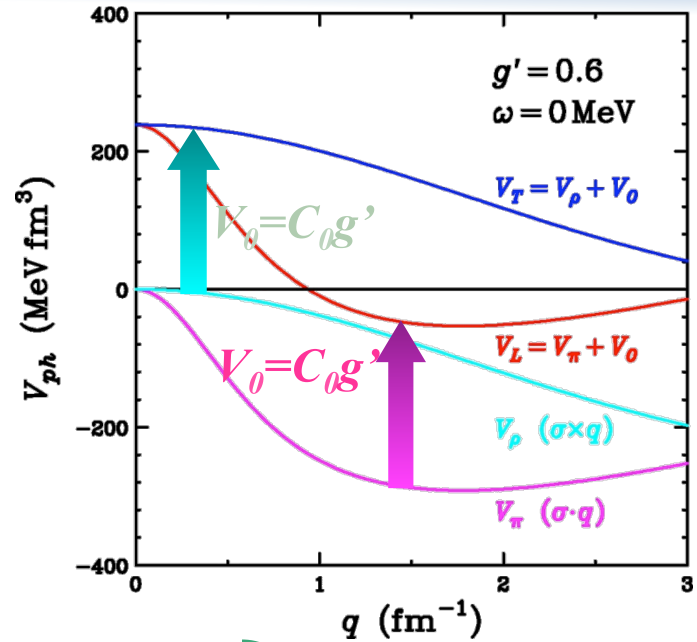
Nuclear Correlations and Δ Effects

- π+ρ+g′ model

$$V^{\mathrm{eff}}(\mathbf{q},\omega) = V_{\mathrm{LM}} + V_{\pi}(\mathbf{q},\omega) + V_{\rho}(\mathbf{q},\omega)$$

- Landau-Migdal parameters:g′

$$V_{LM} = C_0\Big[g'_{NN}(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2) + \left\{\frac{f_{\pi N\Delta}}{f_{\pi NN}} g'_{N\Delta}\Big((\sigma_1\cdot S_2)(\tau_1\cdot T_2) + (\sigma_1\cdot S_2^+)(\tau_1\cdot T_2^+)\Big) + \frac{f^2_{\pi N\Delta}}{f^2_{\pi NN}} g'_{\Delta\Delta}(S_1\cdot S_2^+)(T_1\cdot T_2^+)\right\} + (1\leftrightarrow 2)\Big]$$



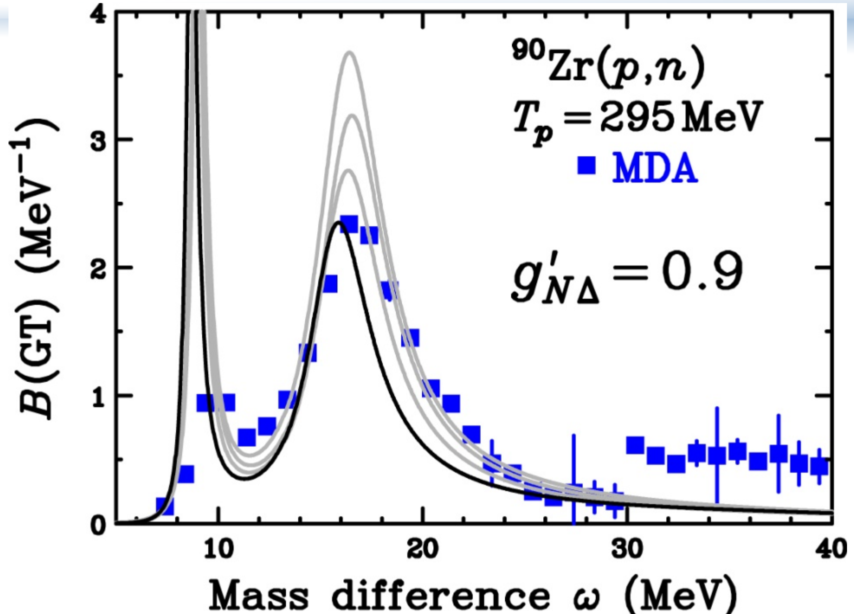
- g'_{NN}: Repulsion at $q=0$ — *Exp.*
  - Energy of GTGR
- $g'_{N\Delta}$: Coupling between N and Δ at $q=0$ — *Exp.*
  - GT quenching

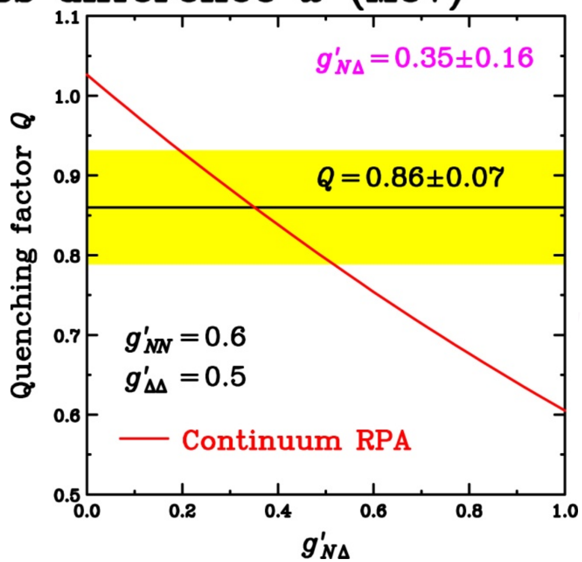
g's affect V^{eff} at large q

- $g'_{\Delta\Delta}$:Few experimental information
  - PT and CPP measurements are sensitive to $g'_{\Delta\Delta}$

GT Strength and Landau-Migdal Parameters

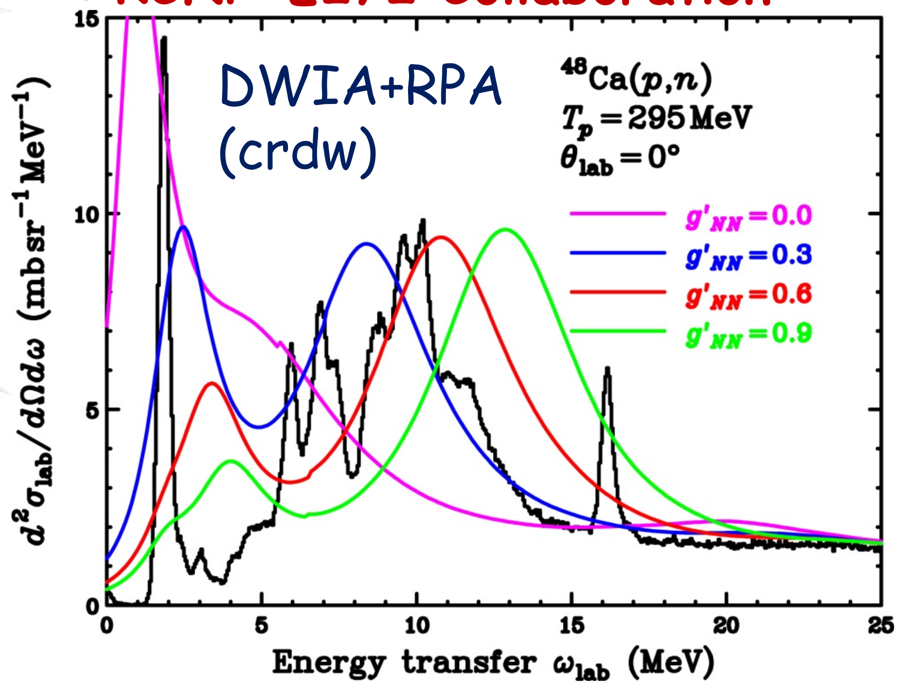
- g′ Dependence of GTGR
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - Strongly depends on g'_{NN}
      - $g'_{NN}=0.6\pm0.1$
    - Weak $g'_{N\Delta}$ dependence
  - GTGR strength
    - Quenched with $g'_{N\Delta} > 0$
- $g'_{N\Delta}$ Dependence of Q
  - *Q=0.86±0.07(quadratic sum of errors)*
  - Q evaluated in RPA
    - Strongly depends on $g'_{N\Delta}$
      - $g'_{N\Delta}=0.35\pm0.16$





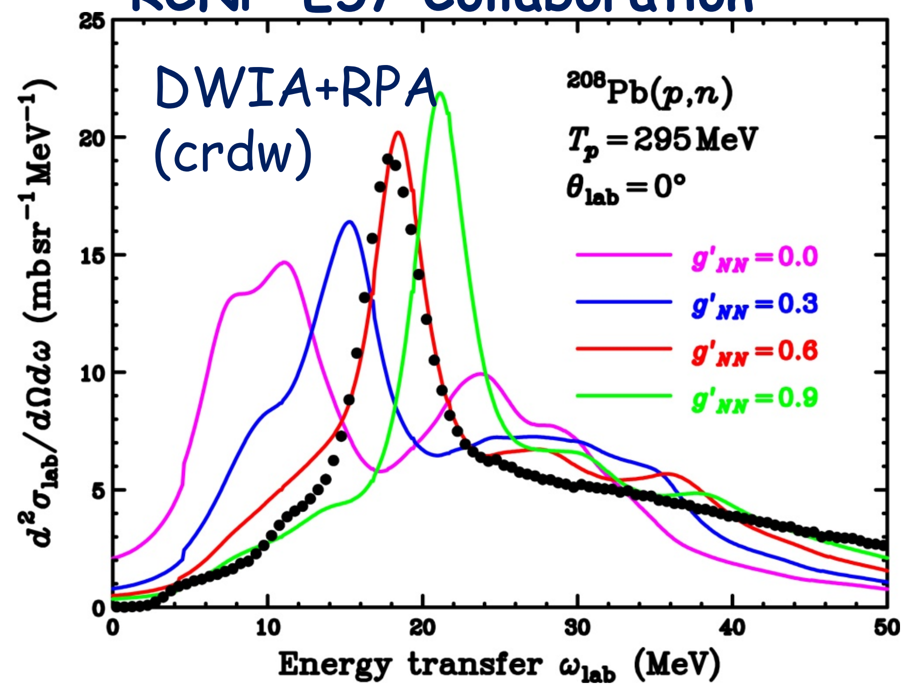
GT Strength and g'_{NN} for ^{48}Ca and ^{208}Pb

M. Sasano et al.
RCNP-E272 Collaboration



g'_{NN}=0.5 for ^{48}Ca

T.W. et al.
RCNP-E57 Collaboration



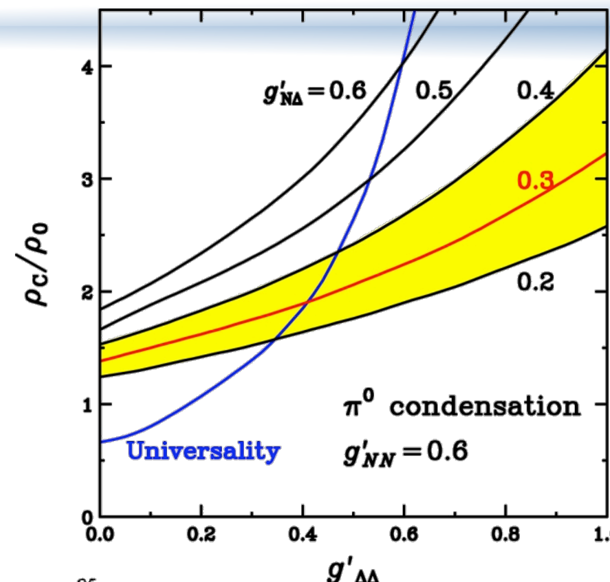
g'_{NN}=0.6 for ^{208}Pb

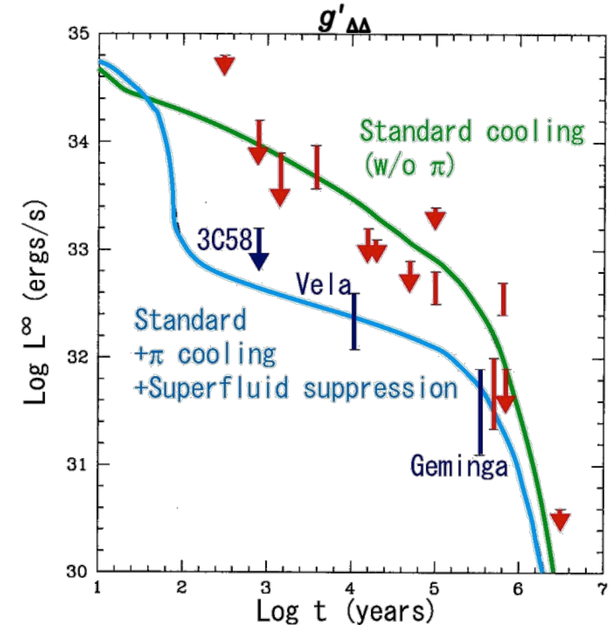
g'_{NN}=0.5-0.7 at q=0 (Common for A=48-208)

Pion Condensation in Neutron Star

-EOS and Pion Cooling-

- Under universality ansatz
  - $g'_{NN}=g'_{N\Delta}=g'_{\Delta\Delta}=0.6\sim0.7$
  - Critical density: $\rho_c \sim 4\rho_0$
  - Pion condensation "does not" occur
- With new information on g′
  - Universality ansatz "does not" hold
    - $g'_{NN}=0.6\pm0.1,\ \ g'_{N\Delta}=0.35\pm0.16$
  - $\rho_c \sim 2\rho_0$ (for $g'_{\Delta\Delta}=0.5$)
    - Pion condensation would be realized in N.S. (3C58 etc.)
    - π-cond. accelerates NS cooling



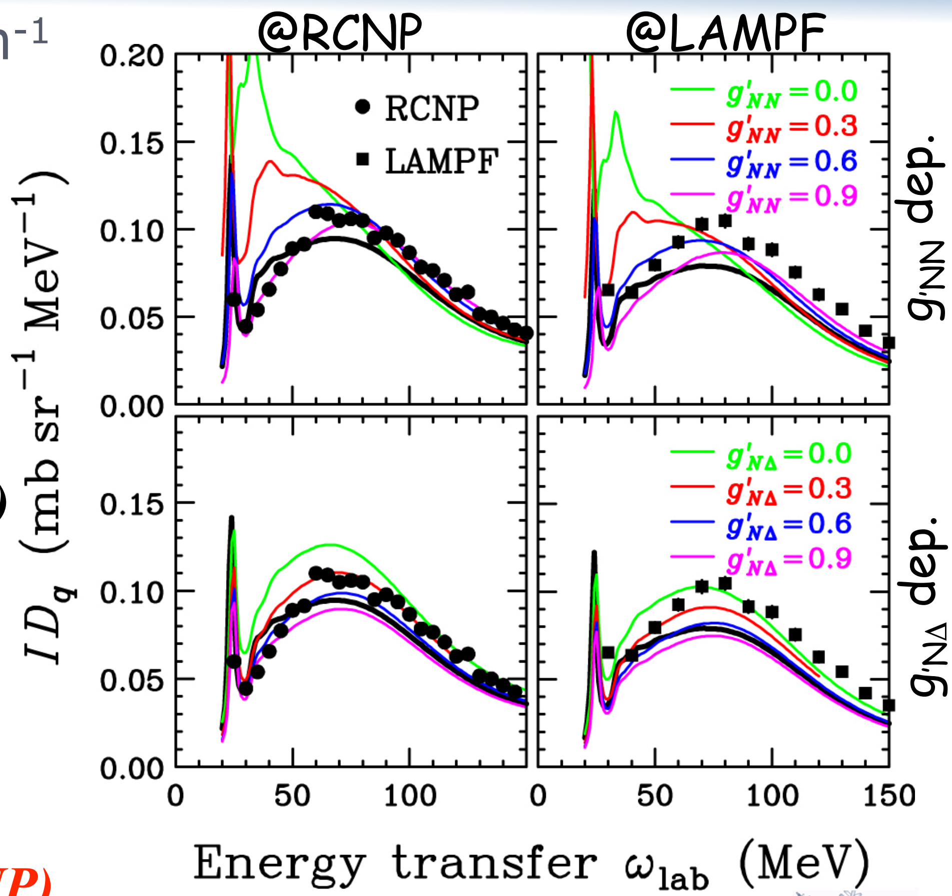


Critical density ρ_0 is sensitive to $g'_{\Delta\Delta}$
→ Experimental determination $g'_{\Delta\Delta}$ is important

Pionic Enhancement in QES

Precursor of Pion Condensation

- Pionic ID_q (^{12}C,^{40}Ca) at q=1.7 fm^{-1}
  - RCNP data
    - *θ=22°,T_p=346 MeV*
  - LAMPF data
    - *θ=18°,T_p=494 MeV*
- Pionic Enhancement
  - Exp. Data > Free ***(w/o Correlation)***
  - RPA is sensitive to ***g'_{NN}*** and ***$g'_{N\Delta}$***
  - RPA is insensitive to ***$g'_{\Delta\Delta}$***
- Landau-Migdal Parameters
    - ***g'_{NN} ~ 0.7***
    - ***$g'_{N\Delta}$ = 0.2(LAMPF) − 0.4(RCNP)***
  - Consistent with g's deduced from GT
    - ***g'_{NN}=0.6±0.1, $g'_{N\Delta}$=0.35±0.16***
  - *q-dependence of g's is weak*

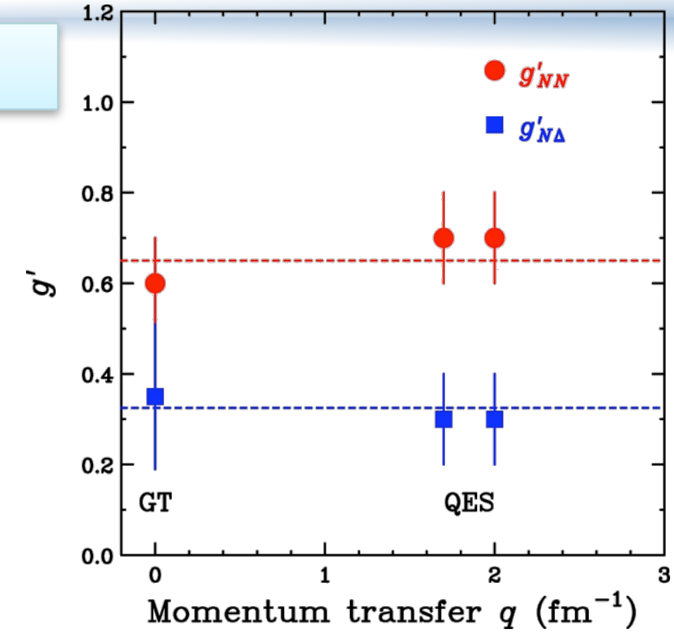


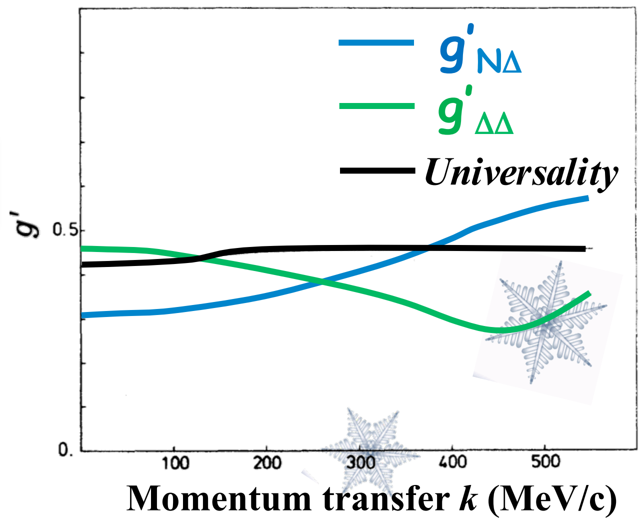
T. Wakasa et al.
Phys. Rev. C 69, 054609 (2004)
T. N. Taddeucchi et al.
Phys. Rev. Lett. 73, 3516 (1994)

Summary of our previous experiments

—Remaining subjects—

- $g'_{NN} > g'_{N\Delta}$ (universality does NOT hold)
- q-dependence of g'_{NN} and $g'_{N\Delta}$
    - q=0 from GT
    - q=1.7 and 2.0 fm^{-1} from QES
  - q-dependence of g' is weak
    - Consistent with theoretical predictions
      - W.H.Dickhoff et al. Phys. Rev. C 23, 1154 (1981)
  - Small $g'_{N\Delta}$ produces largely attractive spin-longitudinal (pionic) residual interaction
    - Pion condensation in N.S. : More likely
- NO information on $g'_{\Delta\Delta}$ (Last unknown)
  - $g'_{\Delta\Delta}$ is important to determine ρ_C for pion condensation
  - ***CPP and PT measurements are promising to determine $g'_{\Delta\Delta}$ experimentally***

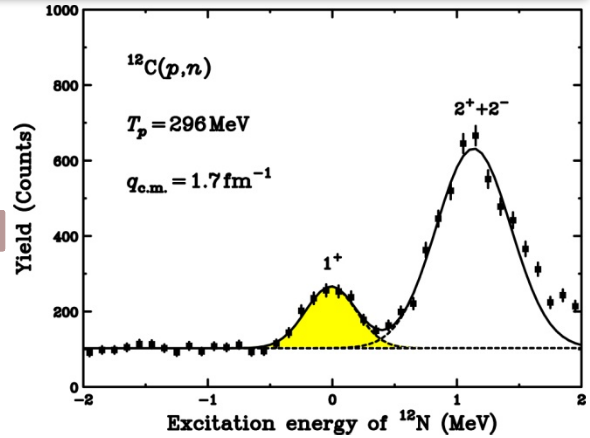


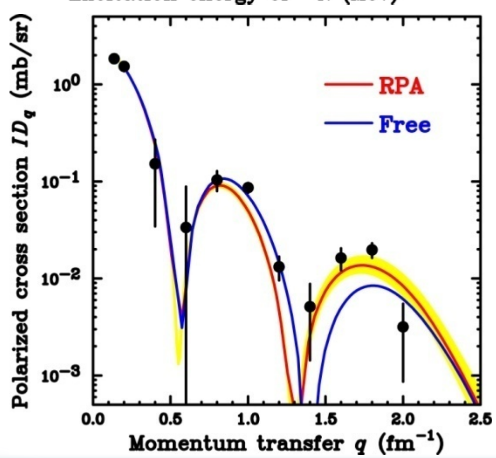


Other evidences for pionic correlations and enhancements observed at RCNP

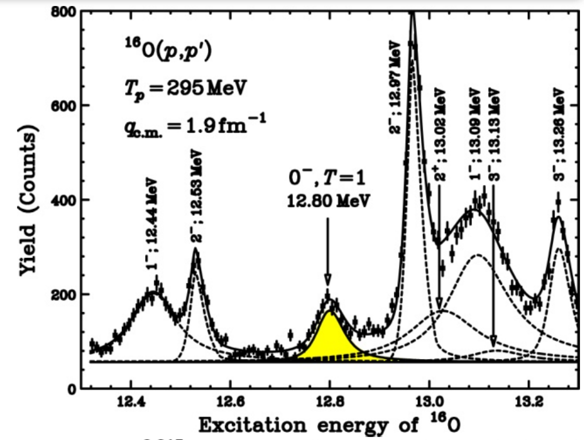
$^{12}C(p,n)^{12}N(g.s.,1^+)$ at 296 MeV
M.Dozono, T.W. et al., PLB 656(2007)38.

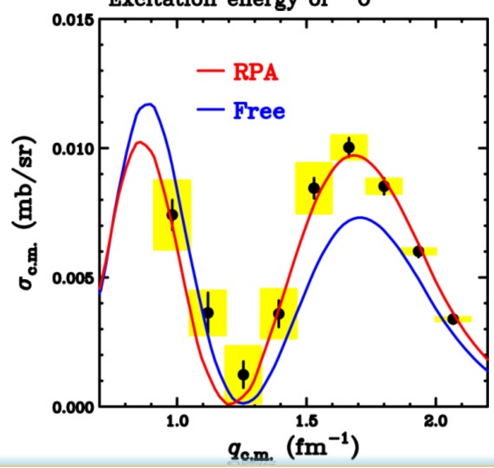
PTO (D_{ij})





$^{16}O(p,p')^{16}O(0^-,T=1)$ at 295 MeV
T.Wakasa et al., PLB 632(2007)485.

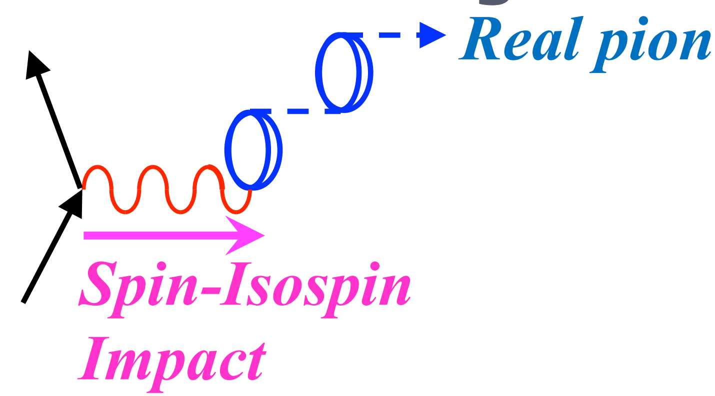




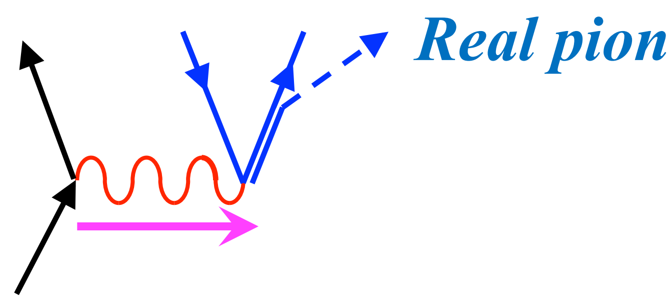
High resolution and/or PTO(D_{ij}) measurements are important and powerful

Physical Processes Important in Δ Region

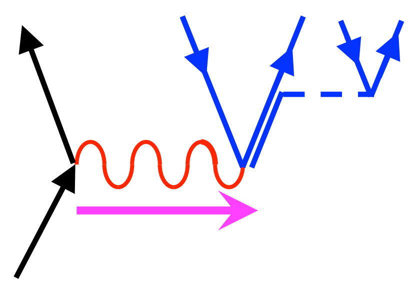
- **Spin-isospin responses important in Δ region**
  - Coherent Pion Production
    - Pions in final state



  - Quasi-free Δ decay
    - Δ (in Δ-h) decays into π + N
    - Pions in final state



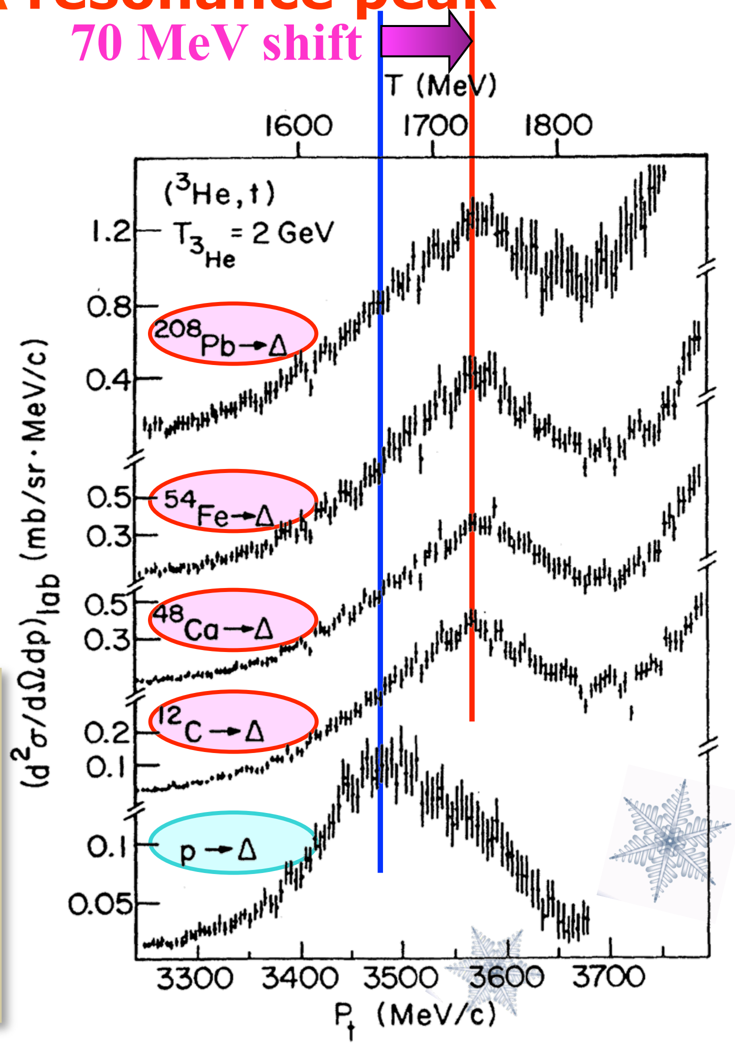
  - Δ spreading
    - Δ (in Δ-h) interacts with N (Δ conversion process)
      - Δ + N → N + N
    - No pions in final state



Inclusive Charge-Exchange Spectra in GeV region

Signatures of CPP process in previous exp. ?

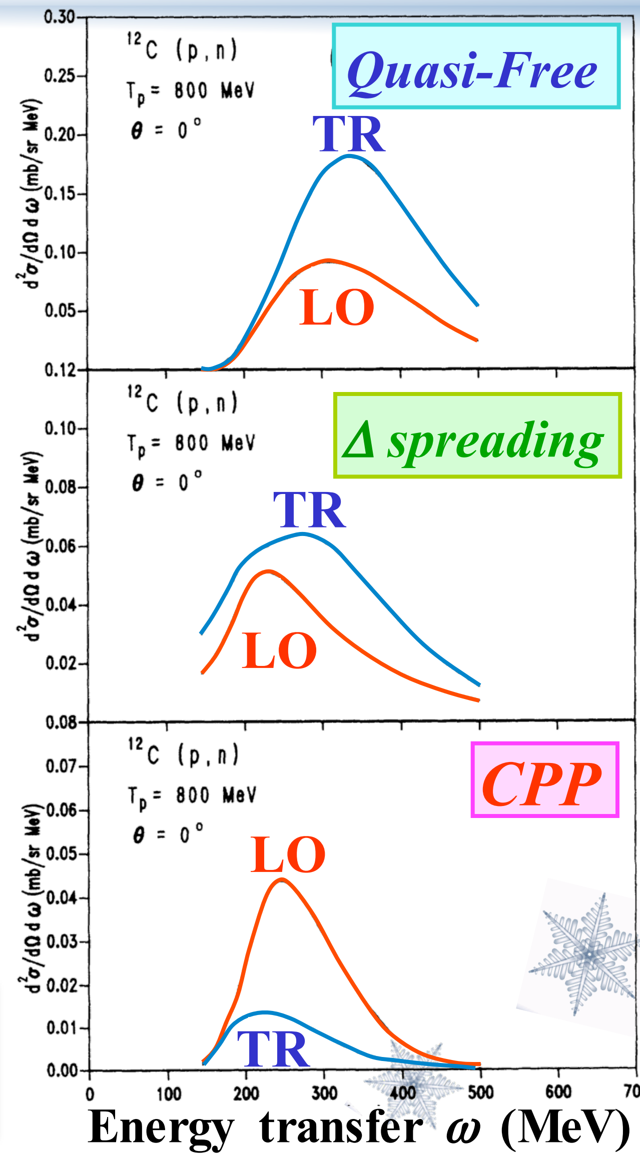
- **CPP has been considered as a reason of**
  the downward energy shift of the Δ resonance peak
  - (^{3}He,t) at 2 GeV
    - *D. Contardo et al. PLB168,331 (1986)*
  - $p(^3He,t)$ peaks at T_t=1675 MeV (ω=325 MeV)
    - Shift from $m_\Delta - m_N$=294 MeV is due to the q-dependence of form factors.
  - $A(^3He,t)$ peaks at T_t=1745 MeV (ω=255 MeV)
    - 70 MeV shift from $p(^3He,t)$
      - 40 MeV shift is due to change in the Δ self-energy (mass) in nuclear mean field
      - Leaving 30 MeV shift would be due to nuclear correlation effects including CPP



Sensitivity to pionic correlations

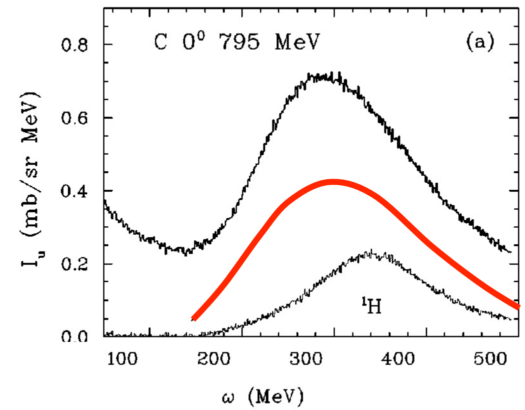
—*Ratio of spin-longitudinal and spin-transverse modes*—

- **Real (Experimental) impact is spin-isospin interaction via (p,n)**
  - NOT a pure (virtual) pion
  - Excite several J^{π} modes
    - Spin-longitudinal (LO:pionic)
    - Spin-transverse (TR:non-pionic)
- **Theoretical calculations**
  - ^{12}C(p,n) at 800 MeV and 0°
  - Residual int. with $g'_{NN}=0.6$, $g'_{N\Delta}=g'_{\Delta\Delta}=0.33$
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1994)
  - TR (non-pionic) modes are dominant in Quasi-free and Δ-spreading
    - PT measurements are needed to study LO (pionic) modes
  - LO (pionic) is dominant in CPP
    - ***Sensitive to pionic correlations in nuclei***

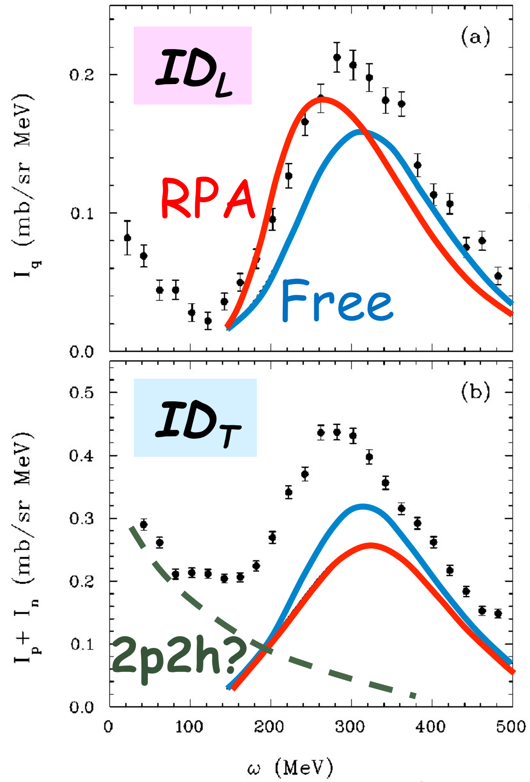


PT Observables in Δ region

$^{12}C(p,n)$ at 795 MeV (LAMPF)



- **Unpolarized cross section**
  - Peak shift to lower ω
    ⇒ Nuclear correlation ?
  - Significant enhance from DWIA+RPA
    - Same as QES (@q=1.7fm-1)
    - Same reason ?
- **Polarized cross section**
  - Spin-longitudinal ID_L
    - Consistent with DWIA+RPA
      $g'_{NN}=0.6$, $g'_{N\Delta}=g'_{\Delta\Delta}=0.4$
  - Spin-transverse ID_T
    - Significant enhancement
    - Contribution from 2p2h etc. ?



D.L.Prout et al., PRL 76(1996)4488.

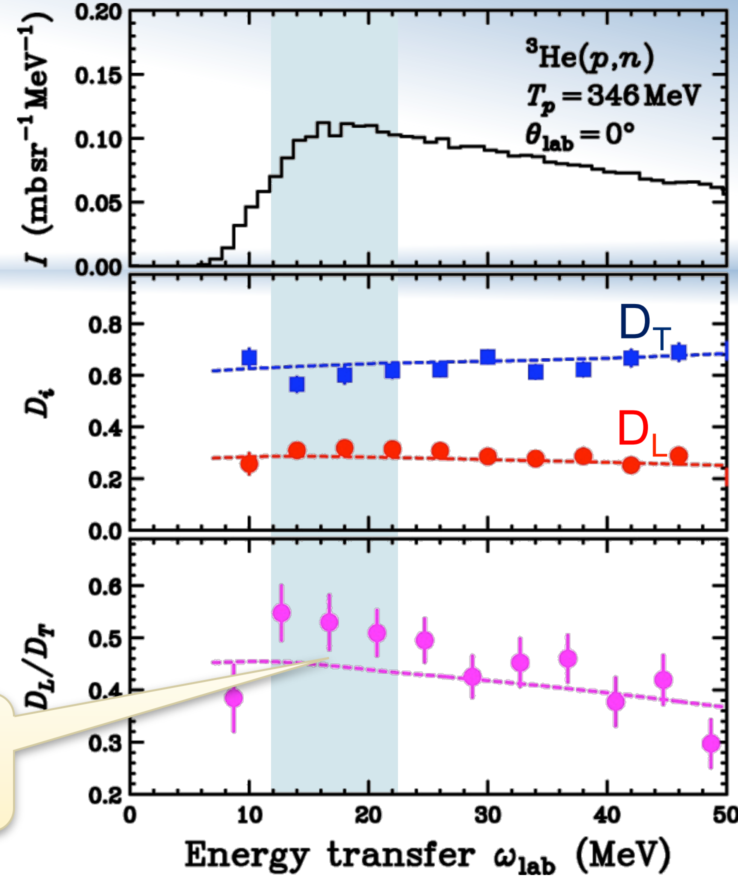
Simultaneous measurement/interpretation(DWIA+RPA) for GT and Δ region on $^{90}Zr/^{208}Pb(p,n)$ is very interesting

Power of PTO

Three Nucleon Force for T=3/2

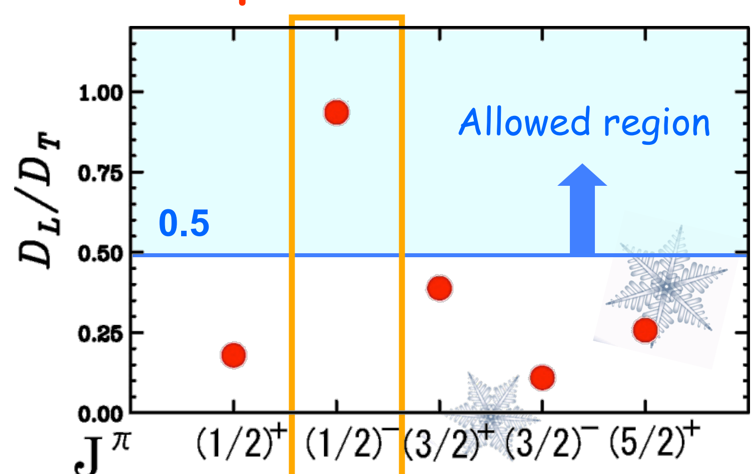
E.Ihara at Kyushu (RCNP-E300)

- **3N system with T=3/2**
  - NO bound/resonance state
    - Faddeev calc. with 2NF
  - If a resonance exists
    ⇒ Evidence for 3NF with T=3/2
- **$^3He(p,n)$ at 0 degrees**
  - Large B.G. from QES
  - Shape (c.s.) of QES is complicated
    - Pauli blocking, q-distribution, etc.
    - B.G. subtraction is difficult
  - PT observables are sensitive to Jp



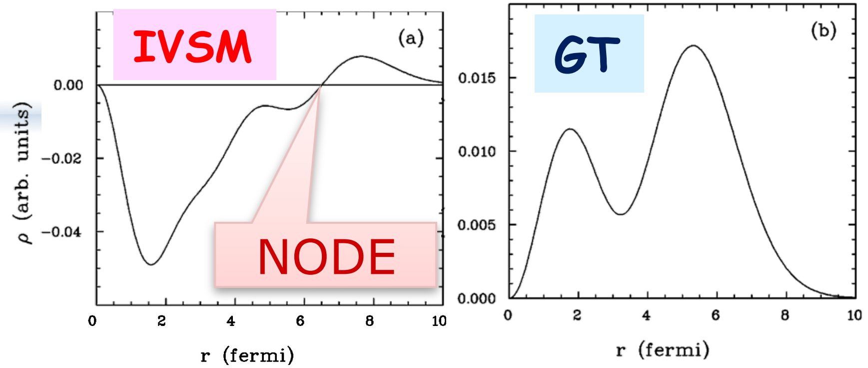
If strength with J^π is concentrated as resonance
⇒ Evidence will be clearly observed in PTO

DWIA prediction



Physics with GeV Polarized Beams

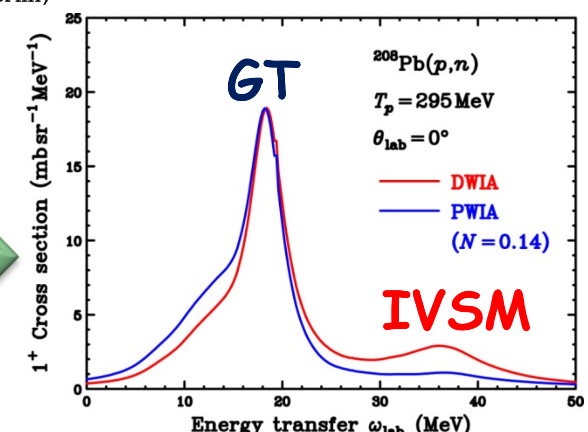
Isovector (Spin) Monopole Resonance



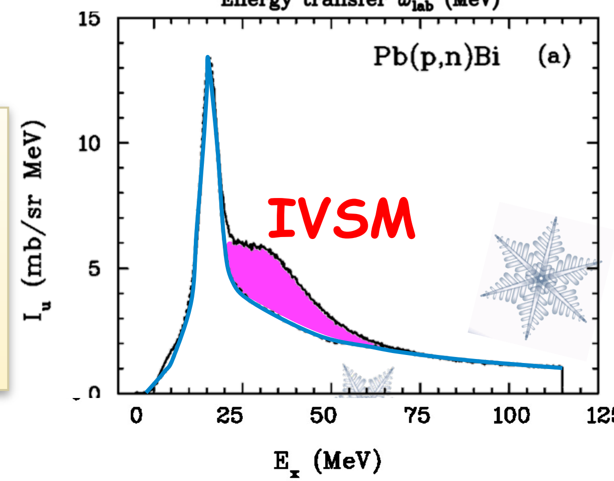
- **Isovector (spin) monopole**

$$O_{IVSM} = \sum_i r_i^2 \sigma_i \tau_i \qquad O_{IVM} = \sum_i r_i^2 \tau_i$$

  - A node at nuclear surface
    - Excited by surface probe
    - NOT excited by volume probe (Insensitive at RCNP energies)



- **Evidence for IVSM is observed at LAMPF**
  - 795 MeV at LAMPF (Surface-like)
  - 200 MeV at IUCF (Volume-like)



▪IVSM is clearly excited by (p,n) at ～GeV
▪PT observables are useful to assign $J^\pi=1^+$
(PT observables are sensitive to J^π)

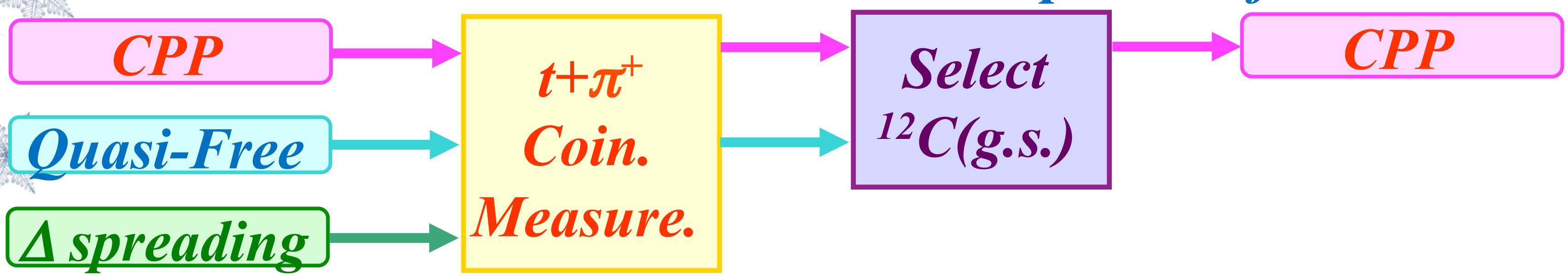
D.L.Prout et al., PRC 63(2000)014603

How to distinguish CPP from other processes

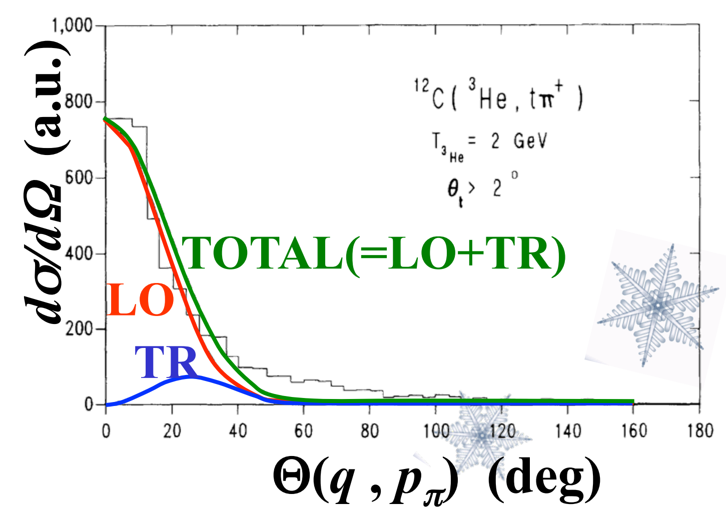
- **Main processes in Δ region are**
  - Coherenet Pion Production
  - Quasi-Free Δ decay
  - Δ spreading

Pions in final state (Coherenet Pion Production, Quasi-Free Δ decay)

No pions in final state (Δ spreading)

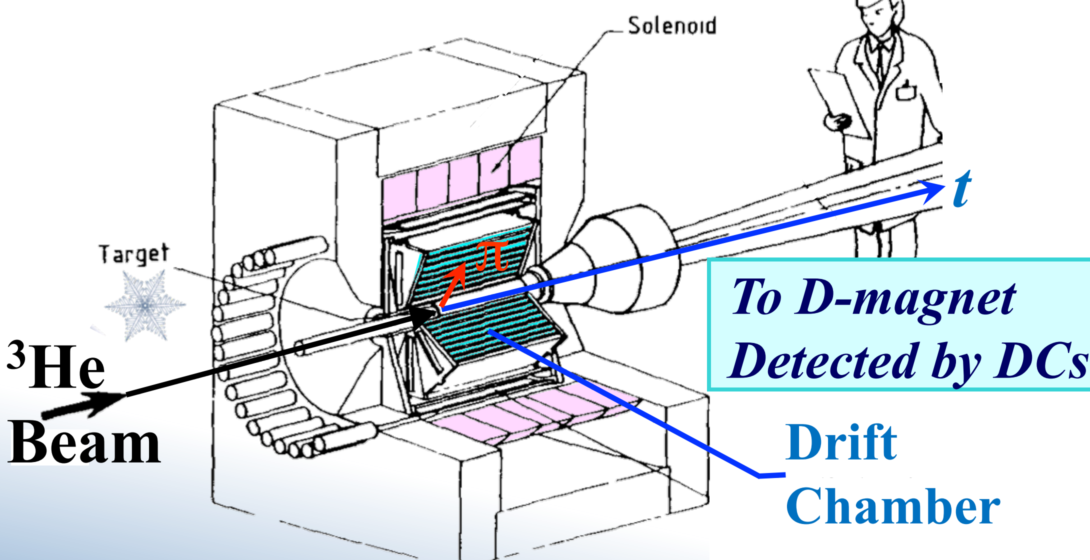


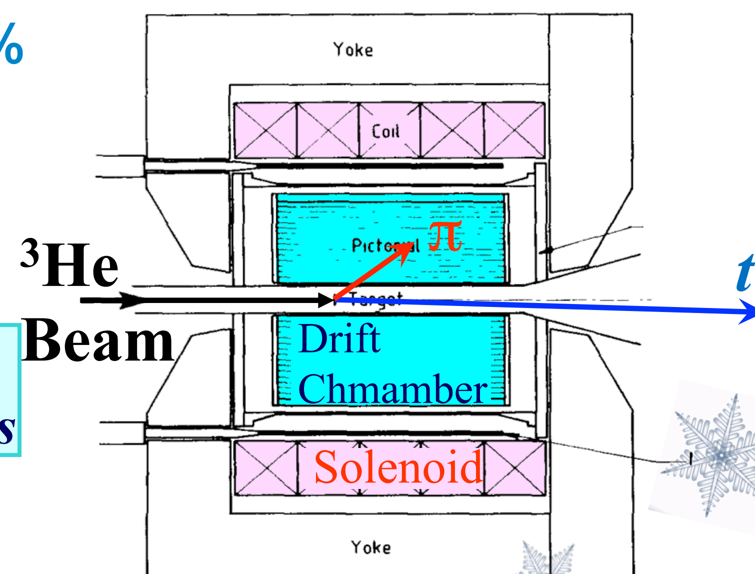
- **Measure correlation between momentum-transfer q and momentum $p_{\pi+}$ of pion**
  - Strong (parallel) correlation has been expected
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1995)



CPP Experiment at Saturne

- $^{12}C(^{3}He,t\pi^{+})^{12}C$(g.s.) at 2 GeV and $\theta_t \sim 0°$
  - T_t=2GeV: Dispersion matching was tried
    - poor energy resolution?
  - θ_{3He} = -1° ~ 4°
    - Analyzed by D-magnet and detected by DCs
    - Poor energy resolution of 15 MeV
  - θ_π=20° ~ 132°
    - Analyzed and detected by CDC
    - Poor momentum resolution of 10%

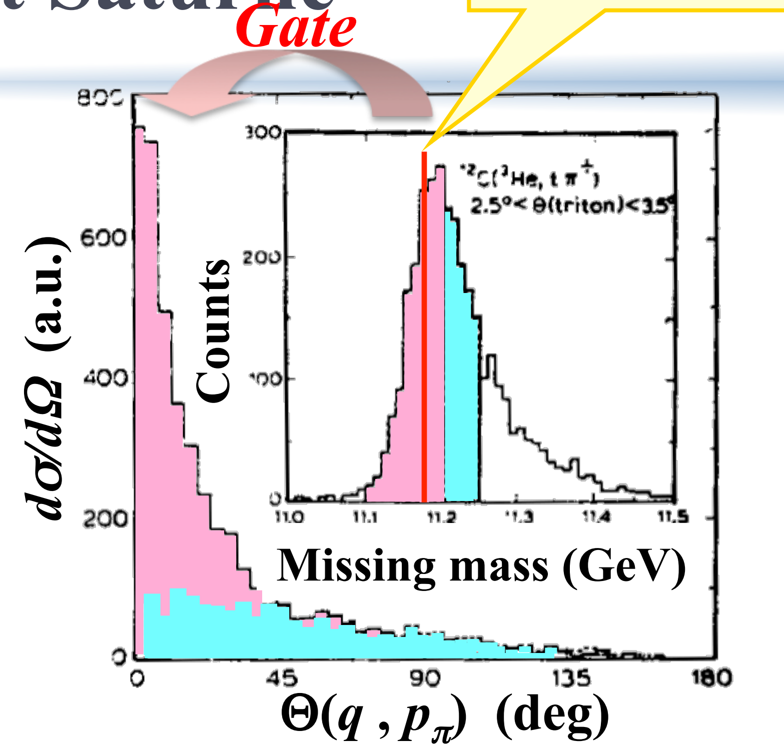


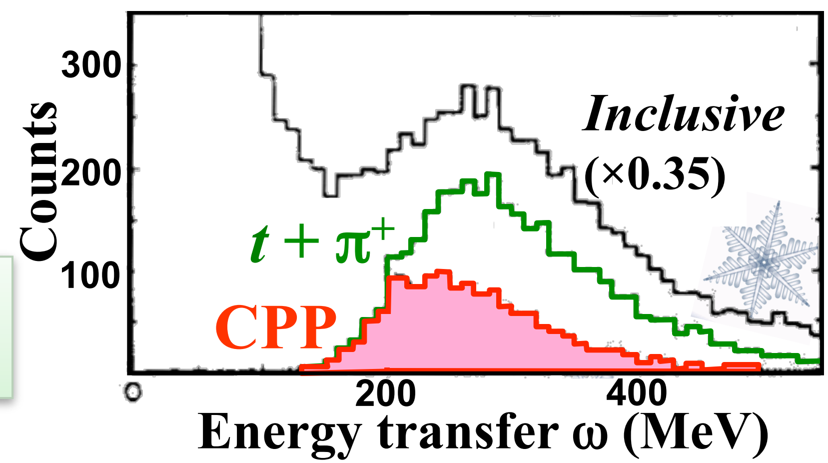


Results of CPP Experiment at Saturne

- **Poor missing mass resolution of 25 MeV (FWHM)**
  - Could not separate ^{12}C(g.s.) (CPP) from excited states
- **Strong (parallel) correlation between q and p_π**
  - *Signature of CPP*
  - Consistent with theoretical prediction
- **Downward energy shift of the Δ resonance peak for CPP**
  - *Signature of (attractive) pionic correlations in nuclei*

High resolution (g.s. separated) measurement are highly desired

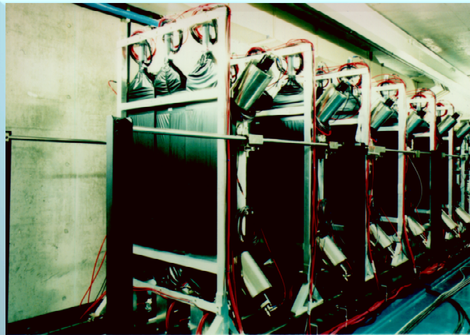




CPP Experiment at RCNP

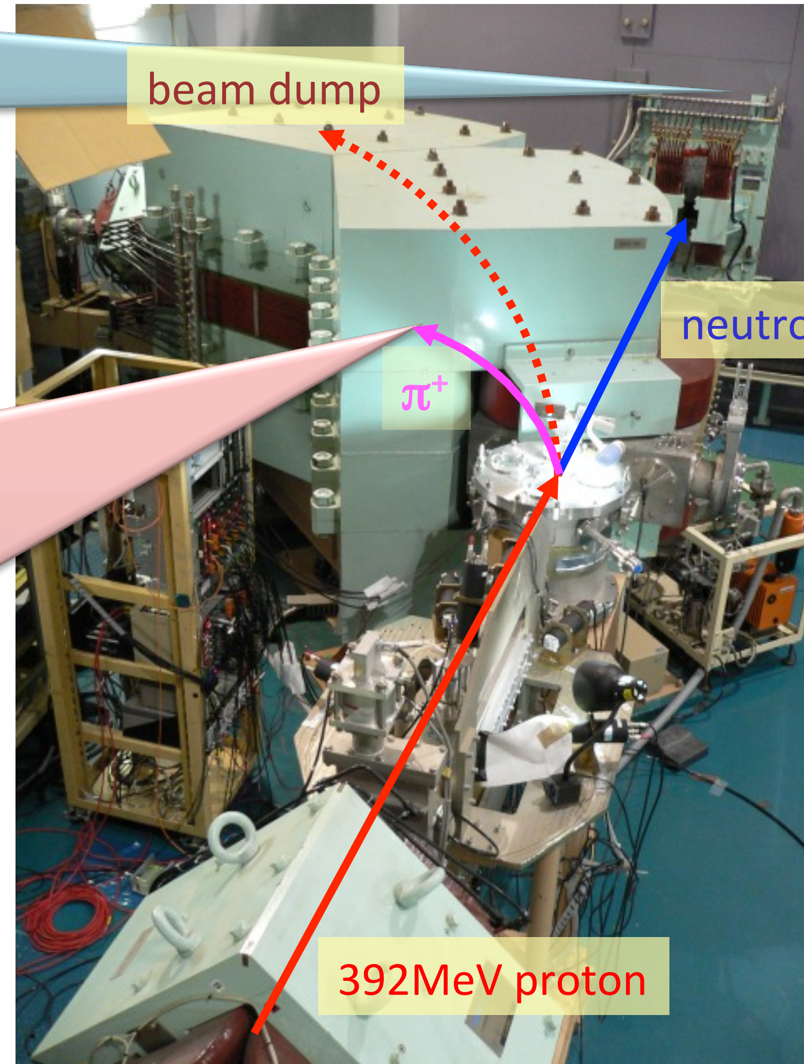
$^{12}C(p,n\pi^{+})^{12}C(g.s.)$ at 400 MeV

K.Fujita, Y.Sakemi et al.

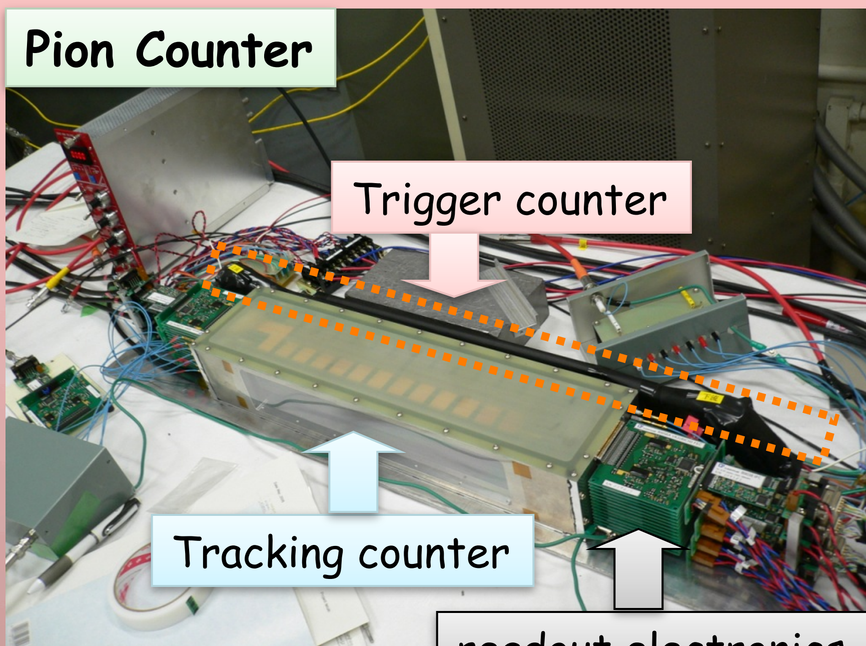


NPOL2

$\Delta E = 300$ keV, $\varepsilon = 15\%$



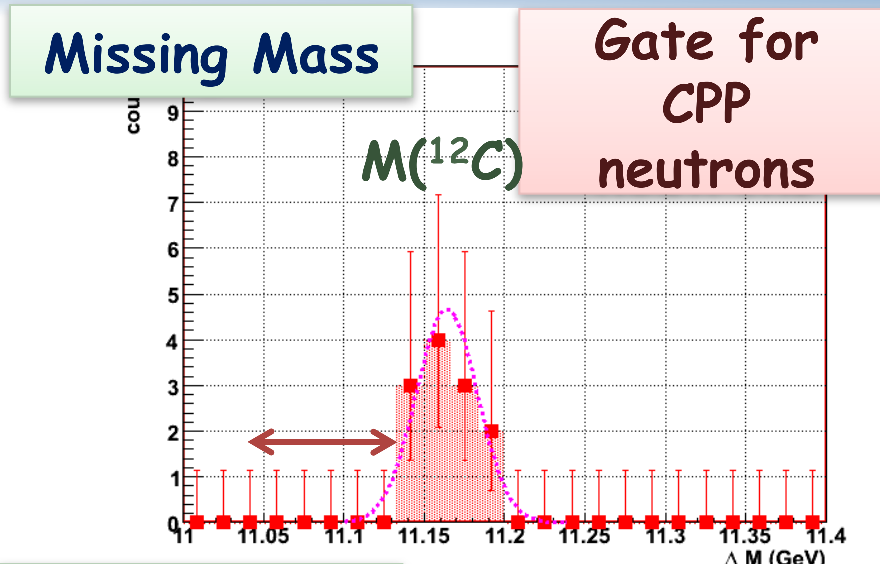
GEM Counter (NEW!!)

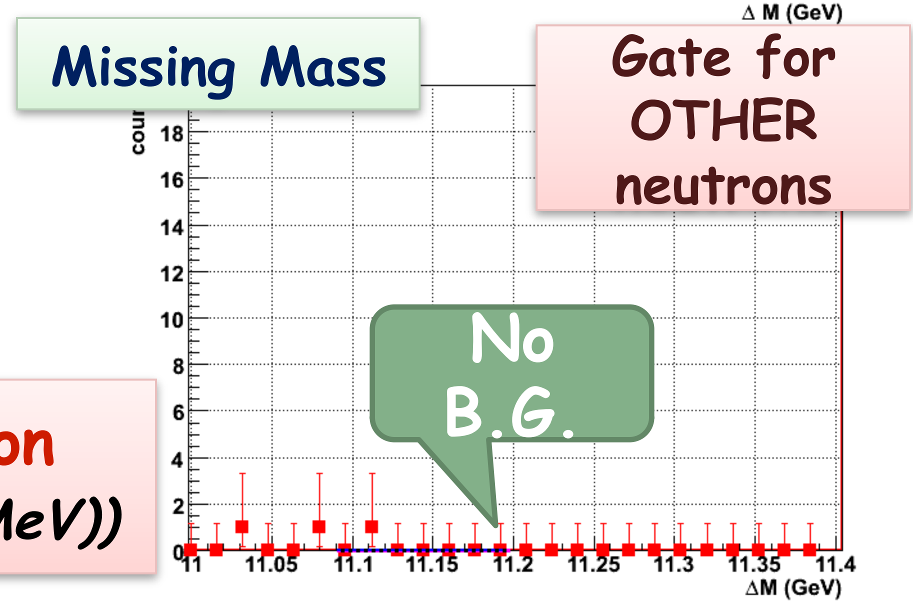


Neutron+Pion "True" Coincidence

K.Fujita, Y.Sakemi et al.

- **Missing mass spectrum**
  - From neutron/pion momenta
  - Peak at $\Delta M = M(^{12}C)$
    - $M(^{12}C) = 11.175$GeV
  - Signagure for CPP events
- **Energy resolution**
  - 9 MeV (before correction)
    - << 25 MeV at Saturne
      - Magnetic field of swinger
      - Pulse-height correction for neutron counter





⇒ **3-4 MeV after full correction**

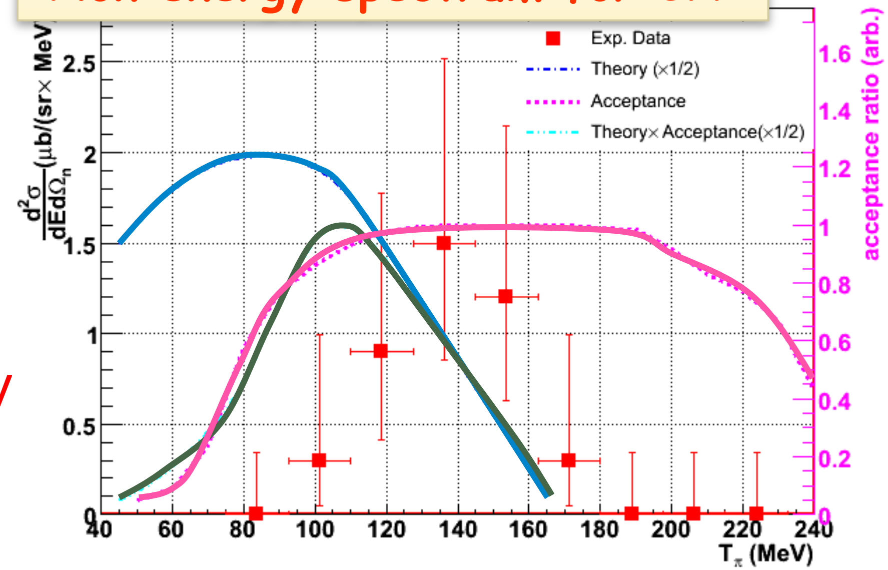
(Not sufficient to resolve 2^+(4.4MeV))

Preliminary Results for CPP at RCNP

K.Fujita, Y.Sakemi et al.

- **Selection of CPP**
  - 11.14 GeV < ΔM < 11.19 MeV
  - Including both
    - ^{12}C(g.s.) (CPP)
    - ^{12}C(4.4MeV,2^+)
- **Pion energy**
  - Exp. (GEM pion counter)
    - Less acceptance at T_π<120 MeV
  - Theory (Universality of g'=0.6)
    - Peak at T_π=90 MeV

Pion energy spectrum for CPP



Acceptance effects are large (significant)

- **Preliminary results for CPP peak**
  - Exp. (140 MeV) > Theory (110 MeV) after acceptance correction

$g'_{\Delta\Delta}$ would be larger than $g'_{\Delta\Delta}$=0.6 (universality)
(More experimental and theoretical works are needed!!)

Summary

- "Unified" understanding of spin-isospin responses of nuclei is very interesting and challenging
- **N-D coupling affects the phenomena in both**
  N-region and Δ-region (ω = 300 MeV)

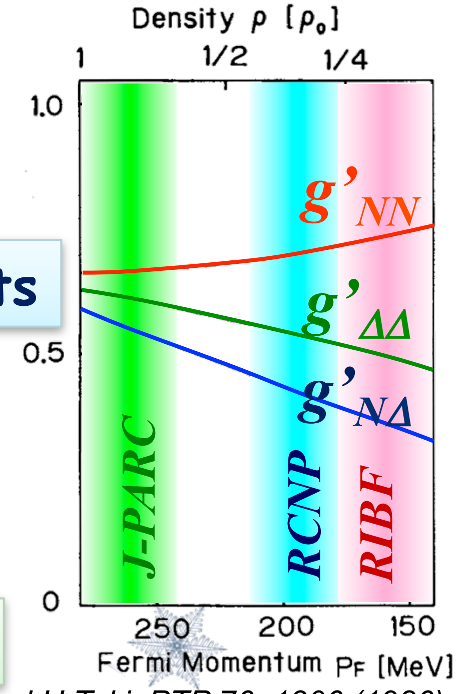
$g'_{N\Delta}$ determined in N-region is adequate in Δ-region ?

- Experiments
  - Polarization transfer measurements
    - Transferred spin and J^{π} determination
  - CPP measurements
    - Sensitive to spin-longitudinal (pionic) mode

Polarized GeV beams as well as excellent equipments

- Other facilities
  - ICHO/SHARAQ at RIBF
  - $^{12}C(\nu_{\mu},\mu^{-}\pi^{+})^{12}C$(g.s.) at J-PARC
  - *First ν-CPP data from K2K: no-evidence for CPP*

Density dependence of g' could be investigated (?)

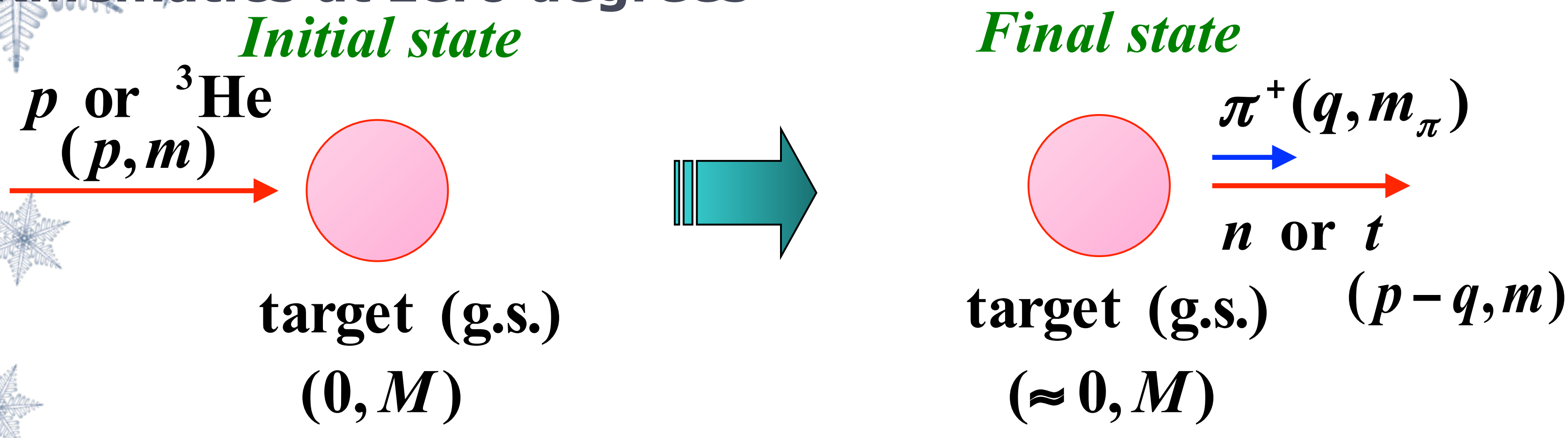


A.Hosaka and H.Toki, PTP 76, 1306 (1986)

Backup Slides

Kinematics of Coherent Pion Production Process

- **Kinematics at zero degrees**



- **Momentum transfer q for Coherenet Pion Production (CPP)**
  - Neglect the recoil energy (~ 1 MeV)

$$\frac{p^2}{2m} = \frac{(p-q)^2}{2m} + \frac{q^2}{2m_\pi}$$

$$q = \frac{2pm_\pi}{M + m_\pi} \approx \frac{2pm_\pi}{M}$$

$$\begin{cases} q = 1.8 \text{ fm}^{-1} & \text{for } (p,n) \text{ at } 800 \text{ MeV} \\ q = 1.6 \text{ fm}^{-1} & \text{for } (^3\text{He}, t) \text{ at } 2 \text{ GeV} \end{cases}$$

CPP is a process with large momentum transfers of q=1.5-2.0 fm^{-1}

Pionic Correlations in Δ-h States

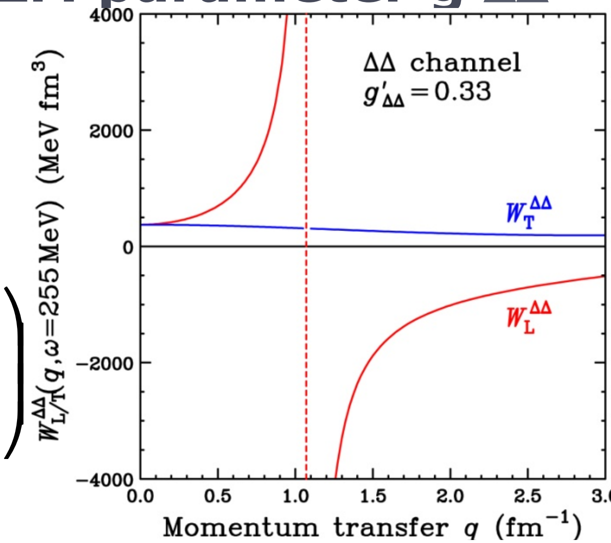
- **Residual interaction W is specified by LM parameter g′ΔΔ**

π - exchange

$$\text{LO } (S\cdot q\,T)\quad W_L^{\Delta\Delta} = \frac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + \frac{q^2}{\omega^2 - q^2 - m_\pi^2}\Gamma_{\pi N\Delta}^2 \right)$$

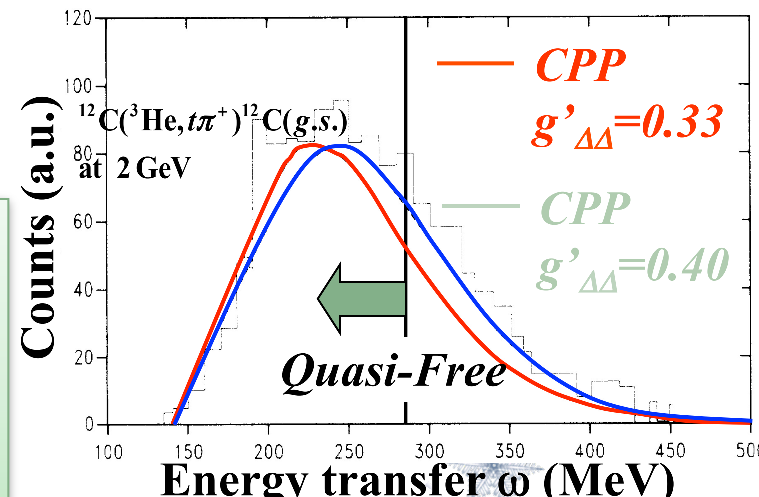
$$\text{TR } (S\times q\,T)\quad W_T^{\Delta\Delta} = \frac{f_{\pi N\Delta}^2}{m_\pi^2}\left(g'_{\Delta\Delta} + C_\rho \frac{q^2}{\omega^2 - q^2 - m_\rho^2}\Gamma_{\rho N\Delta}^2 \right)$$

Short - range repulsion ρ - exchange



- **Spin-longitudinal interaction is largely attractive at large momentum transfers**
  - This attraction leads to a collective pionic mode (CPP) at lower ω

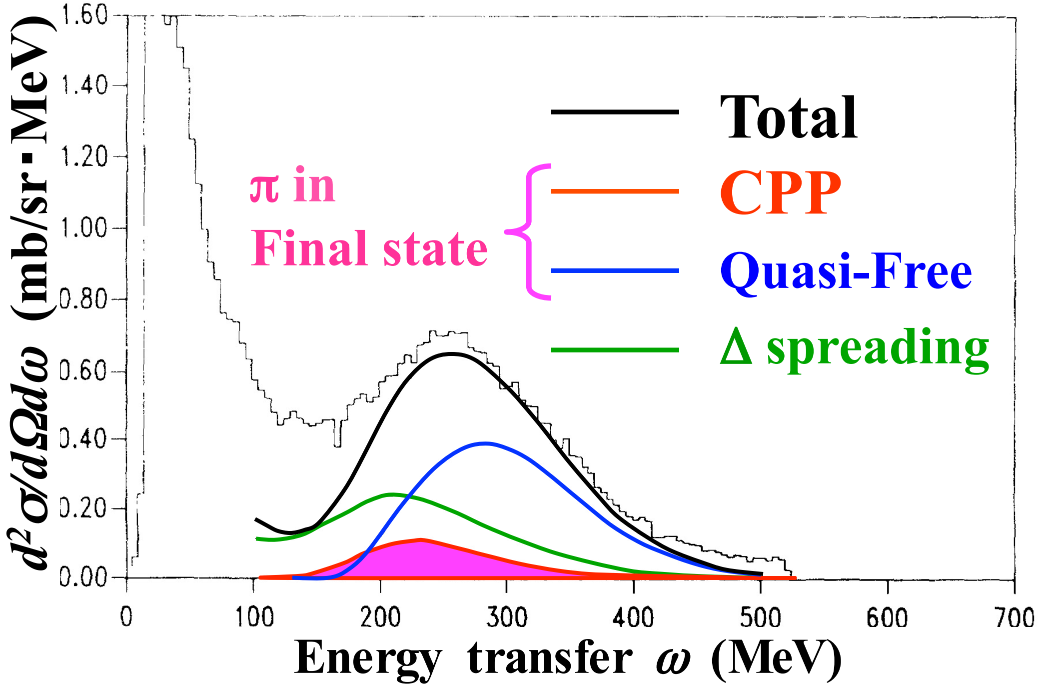
$$\Delta E \approx \Delta g'_{\Delta\Delta}\left(\frac{\hbar c f_{\pi N\Delta}^2}{m_\pi^2}\right)\rho_0 \;\Rightarrow\; \textit{Determine } g'_{\Delta\Delta}$$



B.Korfgen et al., Phys. Rev. C 50, 1637 (1994)

Fraction of CPP and other processes in Δ region

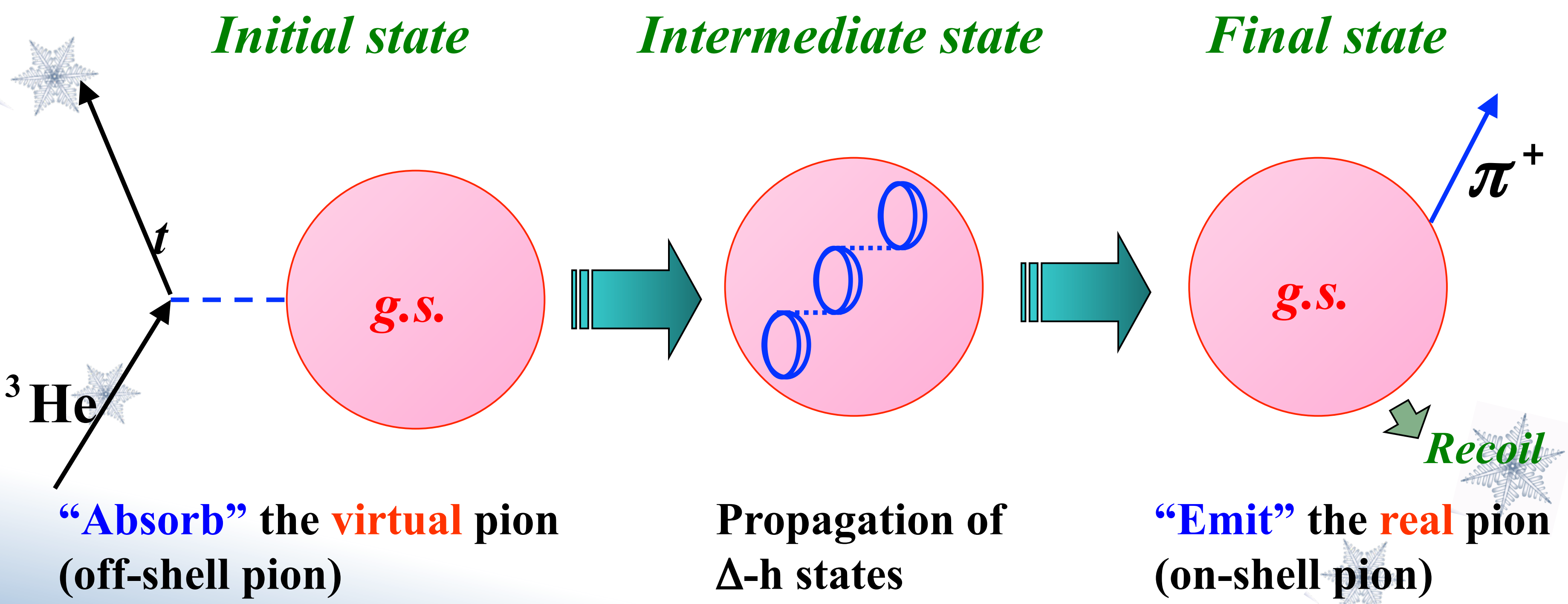
- **Experimental Data**
  - $^{12}C(^{3}He,t)$ at 2 GeV and 0°
    - D.Contardo et al.
      Phys. Lett. B 168, 331 (1986)
  - Clear Δ-resonance peak at ω=260 MeV
- **Theoretical calculations**
  - Residual interaction with g'_{NN}=0.6 and $g'_{N\Delta}$=$g'_{\Delta\Delta}$=0.33
    - T.Udagawa et al.
      Phys. Rev. C 49, 3162 (1994)
  - CPP peaks at lower w compared with QF
    - *Pionic correlation effect*
  - CPP is 10-20% of the total strength



Inclusive is NOT sensitive to CPP (Pionic correlations)
→Exclusive measurement is important!

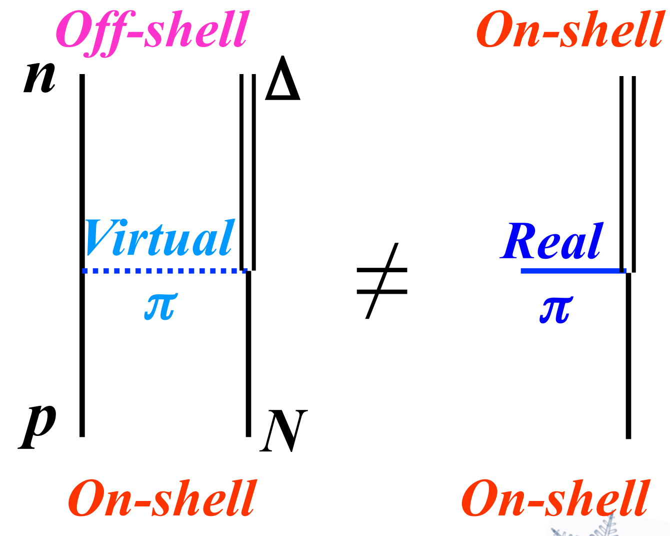
What is "Coherent Pions (mesons)"

- **Coherent Pions in Charge-Exchange Reactions**
  - Target nucleus is left to the g.s.
    - $p + A(g.s.) \rightarrow n + \pi^{+} + A(g.s.)$
    - $^{3}He + A(g.s.) \rightarrow t + \pi^{+} + A(g.s.)$



What is interesting ?

- **Virtual pion (elastic) scattering (by Ericson)**
  - Elastic means the target nucleus is left to the g.s.
  - Nuclear response can be studied in wide (q,ω) region where we cannot access with real pions
- **Information on Elementary Process**
  - Off-shell properties of t-matrix for NN→NΔ
  - Would be useful for Fujita-Miyazawa type 3NF (with Delta excitation)
- **Nuclear Structural points of view**
  - Pions in nuclear mean field are absorbed by the projectile



→ **Sensitive to the nuclear correlations (many body effects)**
(Difference from the simple Fermi-Gas model w/o correlations)

Inclusive process and pionic correlations

- ***Is the downward energy shift of the Δ resonance peak*** **<u>a "direct" signature of pionic correlations</u> (attractive $W_L^{\Delta\Delta}$)?**
  - Answer is "No". Because inclusive cross sections includes both
    - Spin-longitudinal (pionic) modes
    - Spin-transverse (non-pionic, ρ-mesonic) modes

- **How to separate these two modes "experimentally"**
  - Measure a complete set of polarization transfer observables
    - Measure spin transfer $\boldsymbol{S}$ with its direction
    - Separate σ into $\boldsymbol{S}\cdot\boldsymbol{q}$ and $\boldsymbol{S}\times\boldsymbol{q}$ components

Spin-transfer measurement is a unique feature at RCNP

  - Measure π decay of Δ in coincidence with the ejectile
    - Exclusive measurement
    - Extract pionic $\boldsymbol{S}\cdot\boldsymbol{q}$ component