コヒーレントπ中間子生成による核力短距離相関の研究

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- Proton induced CPP at RCNP
- Neutrino beam at J-PARC
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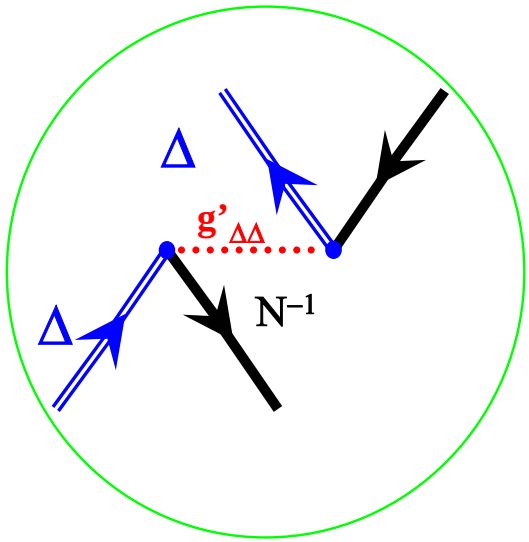
ΔΔ interaction in the nuclear medium
~ short range correlation of Δ-hole: $g'_{\Delta\Delta}$



Short range correlation ~ Landau-Migdal parameters : $g' = g'_{NN}, g'_{N\Delta}, g'_{\Delta\Delta}$

Phase transition of Nuclear matter ~ Pion condensation…

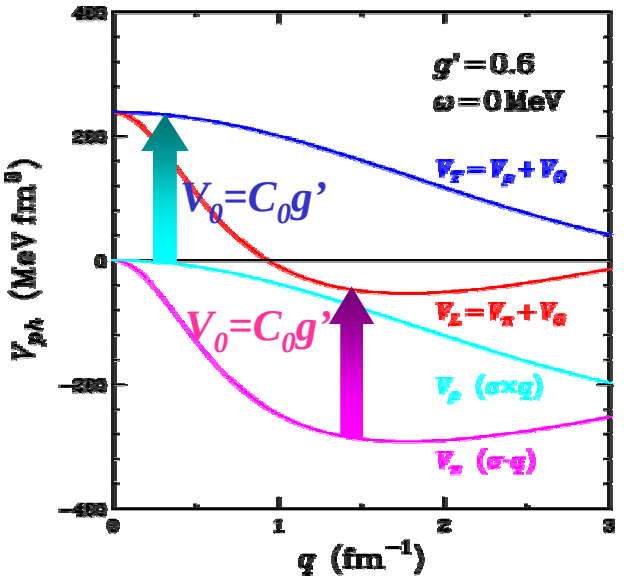
Nuclear Correlations and Δ Effects

- π+ρ+g' model

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

- Landau-Migdal parameters:g'

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



– g'_{NN}: Repulsion at $q=0$
  - Energy of GTGR

Exp.

– $g'_{N\Delta}$: Coupling between N and Δ at $q=0$
  - GT quenching

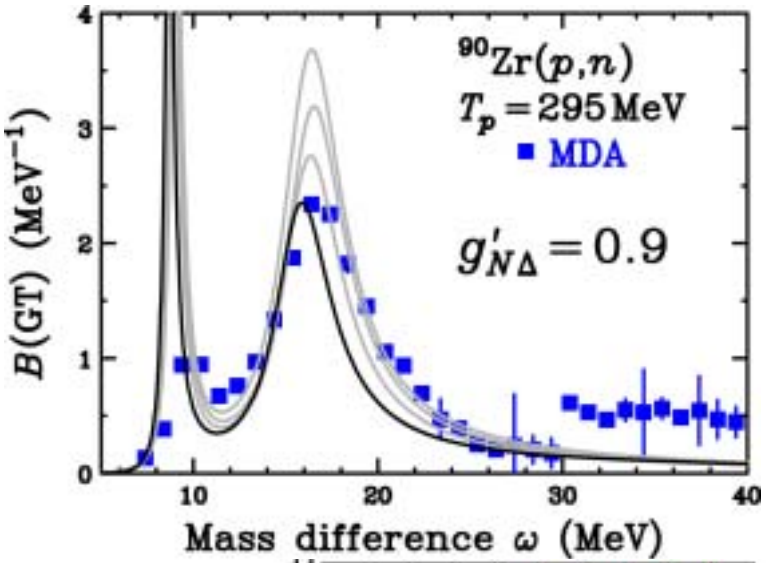
Exp.

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

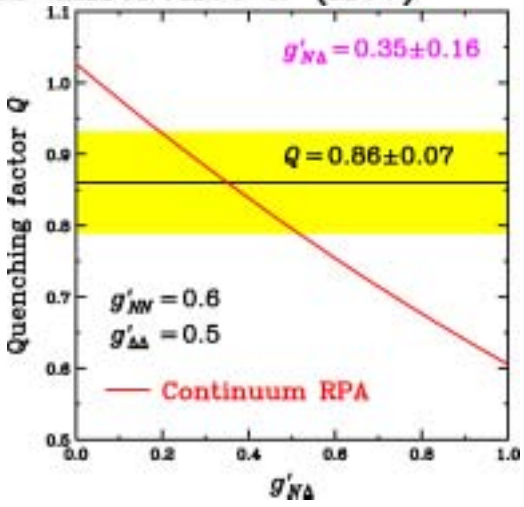
– $g'_{\Delta\Delta}$:Few experimental information
  - Coherent pion production is sensitive to $g'_{\Delta\Delta}$

GT Strength and Landau-Migdal Parameters

- **g' Dependence of GTGR**
  - RPA(1p1h) by Ichimura group
  - GTGR peak position
    - Strongly depends on g'_{NN}
      - $g'_{NN}=0.6 \pm 0.1$
    - Weak $g'_{N\Delta}$ dependence
  - GTGR strength
    - Quenched with $g'_{N\Delta} > 0$



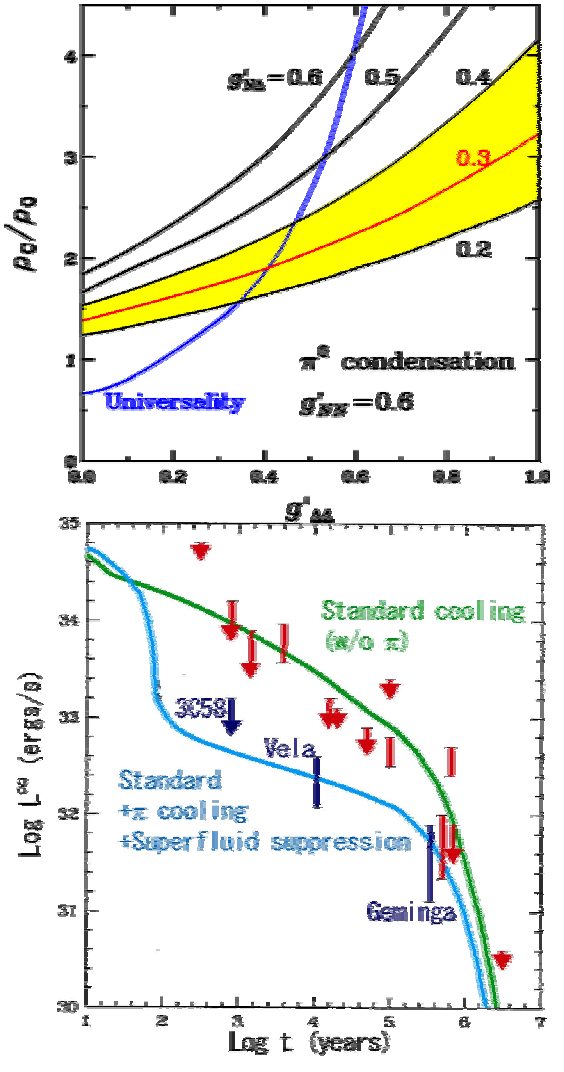
- **$g'_{N\Delta}$ Dependence of Q**
  - *Q=0.86 ±0.07(quadratic sum of uncertainties)*
  - Q evaluated in RPA
    - Strongly depends on $g'_{N\Delta}$
      - $g'_{N\Delta}=0.35 \pm 0.16$



Pion Condensation in Neutron Star
-EOS and Pion Cooling-

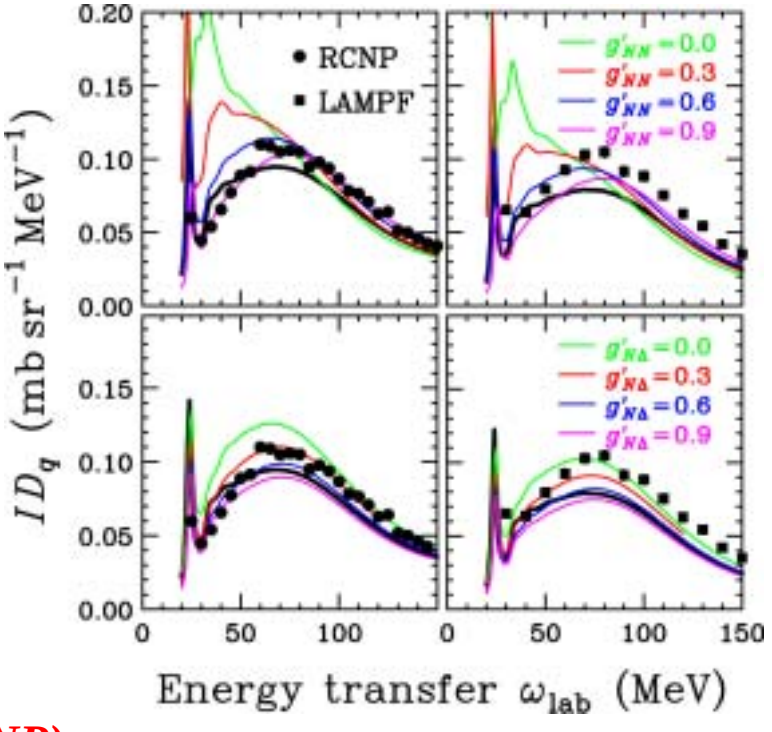
- **Under universality ansatz**
  - $g'_{NN}=g'_{N\Delta}=g'_{\Delta\Delta}=0.6\sim0.7$
  - Critical density:$\rho_c\sim4\rho_0$
  - Pion condensation "does not" occur
- **With new information on g'**
  - Universality ansatz "does not" hold
    - $g'_{NN}=0.6\pm0.1,\ g'_{N\Delta}=0.35\pm0.16$
  - $\rho_c\sim2\rho_0$ (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

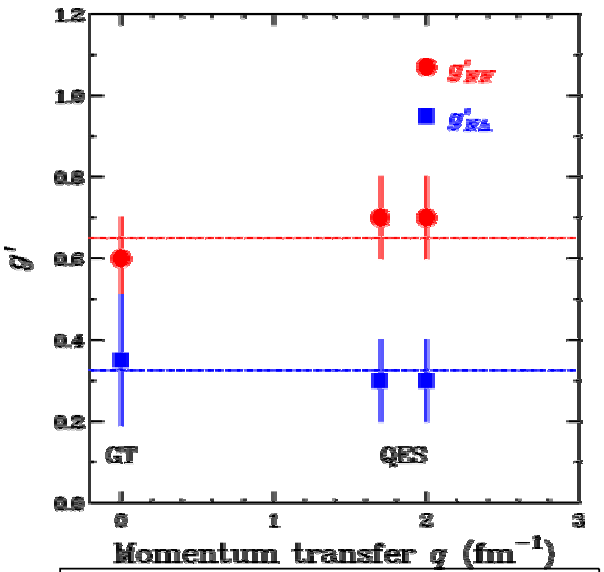
- **Pionic ID_q (^{12}C,^{40}Ca) at q=1.7 fm^{-1}**
  - RCNP data
    - ***θ=22 °, T_p=346 MeV***
  - LAMPF data
    - ***θ=18 °, T_p=494 MeV***
- **Pionic Enhancement**
  - Exp. Data > Free ***(w/o Correlation)***
  - RPA is sensitive to ***g'$_{NN}$*** and ***g'$_{NΔ}$***
  - RPA is insensitive to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

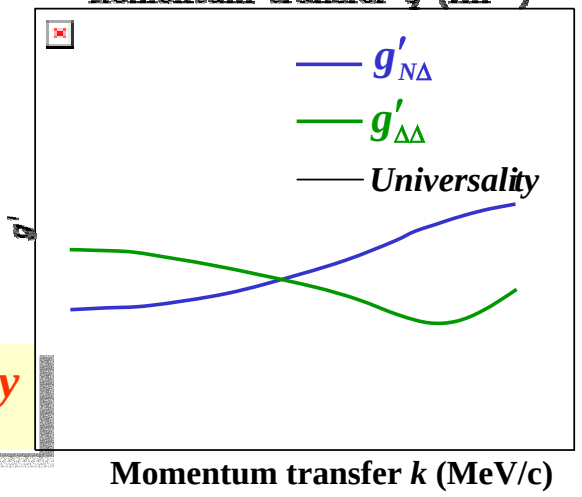


T. Wakasa et al.
Phys. Rev. C 69, 054609 (2004)
T. N. Taddeucchi et al.
Phys. Rev. Lett. 73, 3516 (1994)

Summary of previous experiments
―*Remaining subjects*―

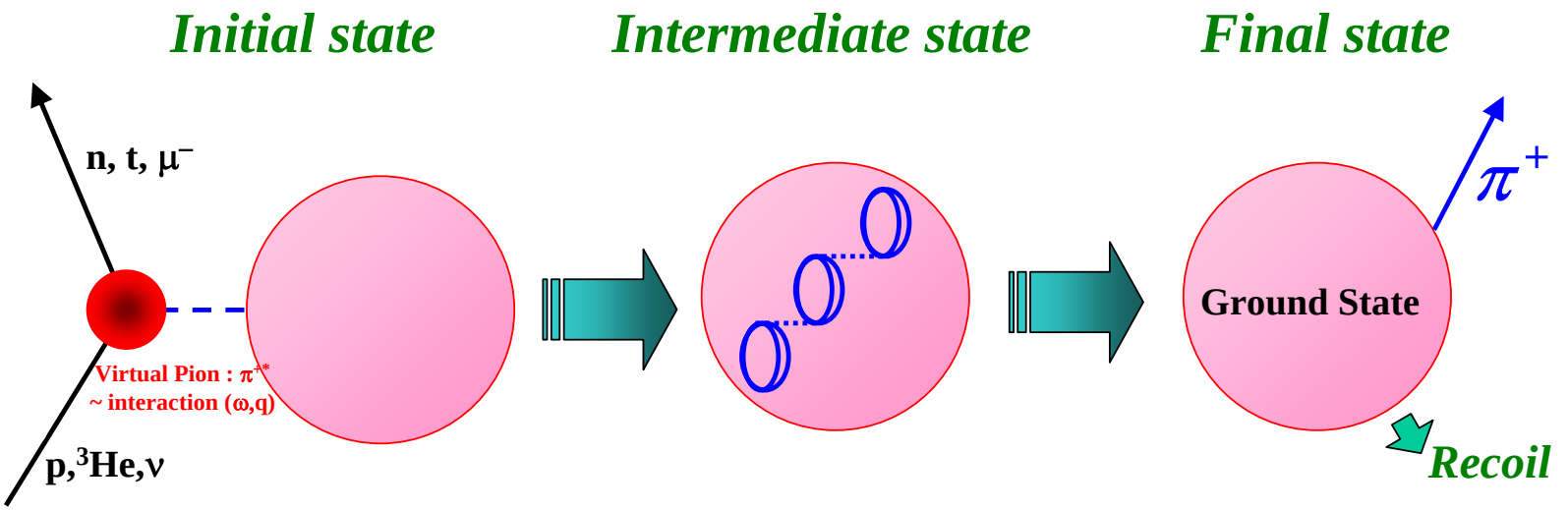
- **$g'_{NN} > g'_{N\Delta}$ (universality does NOT hold)**
- **q-dependence of g'_{NN} and $g'_{N\Delta}$**
  - q=0 from GT
  - q=1.7 and 2.0 fm^{-1} from QES
  - q-dependence of g' is weak
    - Consistent with theoretical predictions
      - W.H.Dickhoff et al. Phys. Rev. C 23, 1154 (1981)
  - Small $g'_{N\Delta}$ 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 is promising to determine $g'_{\Delta\Delta}$ experimentally***





What is "Coherent Pions (mesons)"

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



"Absorb" the virtual pion (off-shell pion)

Propagation of Δ-h states

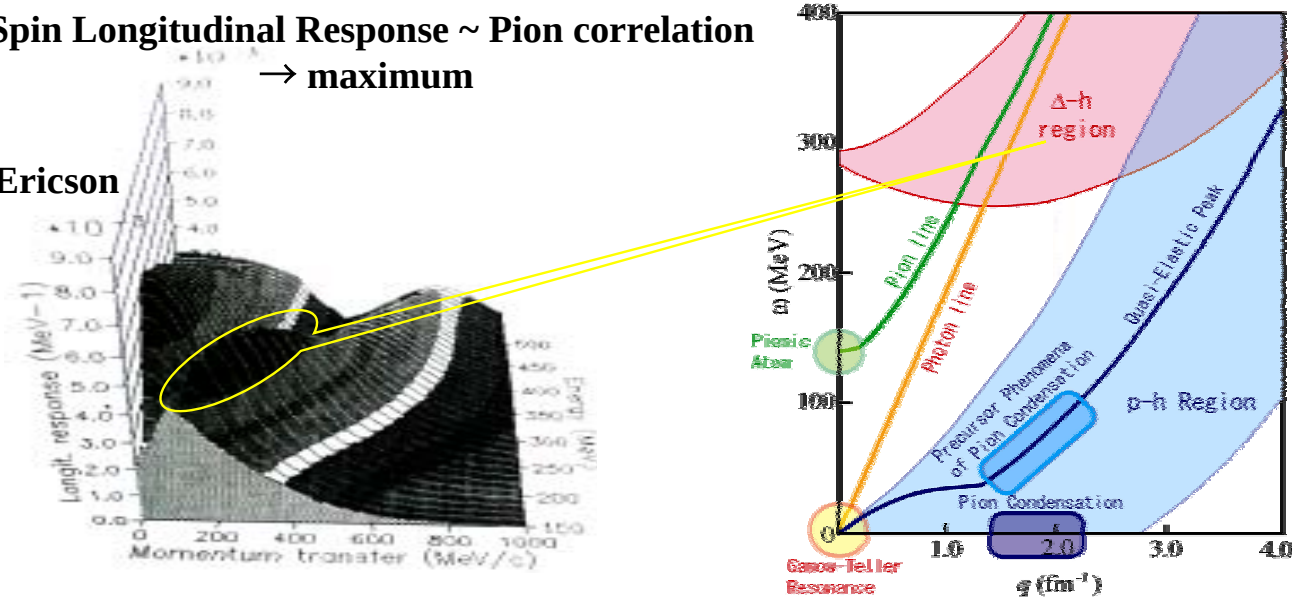
"Emit" the real pion (on-shell pion)

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,w) region where we cannot access with real pions

Spin Longitudinal Response ~ Pion correlation
→ maximum

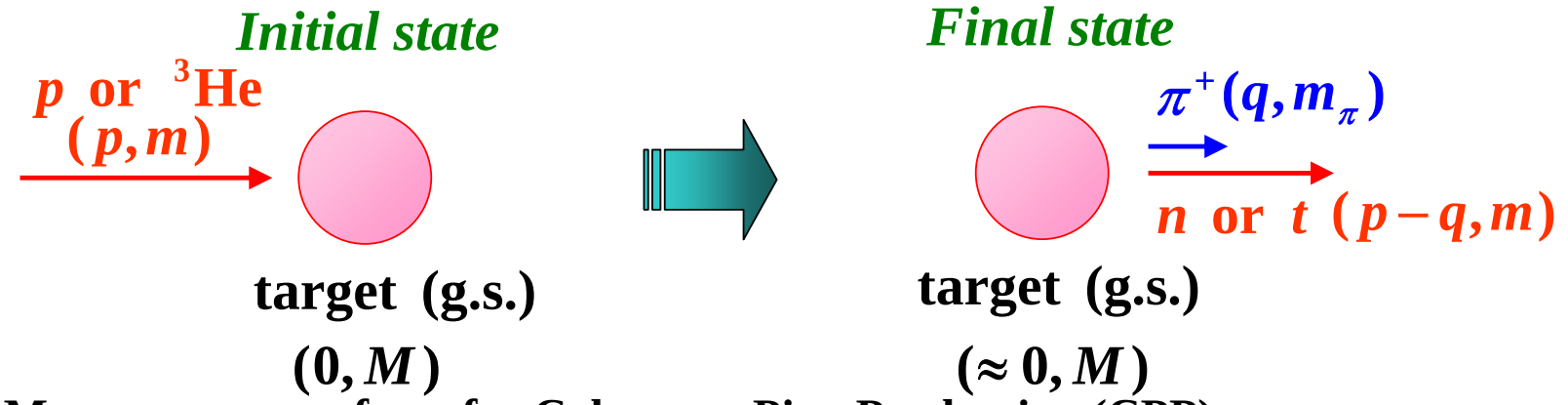
M.Ericson



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

Kinematics of Coherent Pion Production Process

- **Kinematics at zero degrees**



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

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

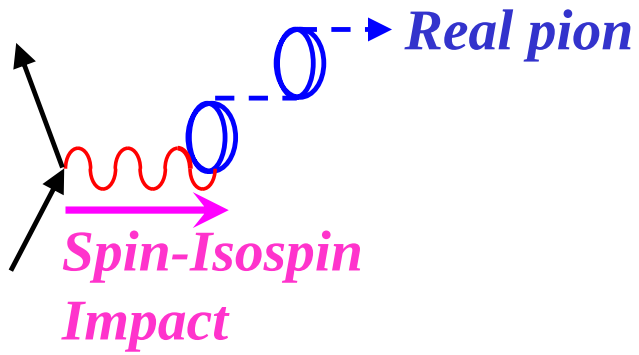
$$q = \frac{2pm_\pi}{M+m_\pi} \approx \frac{2pm_\pi}{M}$$

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

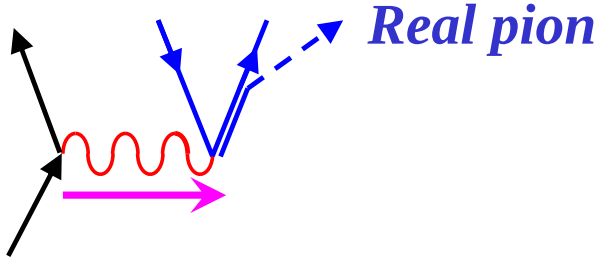
CPP is a process with large momentum transfers of q=1.5-2.0 fm^{-1}

Theoretical investigation for A(p,n) and CPP

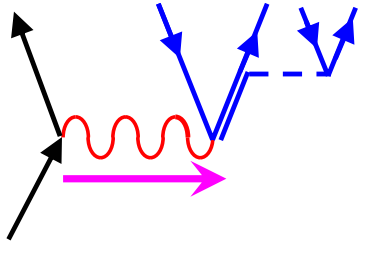
- **Physical processes important in Δ region**
  - Coherent Pion Production
    - Pions in final state



  - 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



Pionic Correlations in Δ-h States

- **π and ρ-meson exchange in nuclear mean field**
  - π+ρ+g' model interaction between Δ-h states

$$V_{\text{eff}}^{\Delta\Delta} = V_L^{\Delta\Delta}(q,\omega) + V_T^{\Delta\Delta}(q,\omega)$$

$$V_L^{\Delta\Delta}(q,\omega) = W_L^{\Delta\Delta}\left[\left\{(T_1\cdot T_2^*)(S_1\cdot\hat{q})(S_2^*\cdot\hat{q}) + (T_1\cdot T_2)(S_1\cdot\hat{q})(S_2\cdot\hat{q})\right\} + h.c.\right]$$

Spin-longitudinal $(S\cdot q\ T)$ channel
π-exchange + short-range repulsion (g')

$$V_T^{\Delta\Delta}(q,\omega) = W_T^{\Delta\Delta}\left[\left\{(T_1\cdot T_2^*)(S_1\times\hat{q})(S_2^*\times\hat{q}) + (T_1\cdot T_2)(S_1\times\hat{q})(S_2\times\hat{q})\right\} + h.c.\right]$$

Spin-transverse $(S\times q\ T)$ channel
ρ-exchange + short-range repulsion (g')

***S* and *T* : Spin and Isospin transition operator from N to Δ**

Pionic Correlations in Δ-h States

- **Residual interaction W is specified by LM parameter g'$_{\Delta\Delta}$**

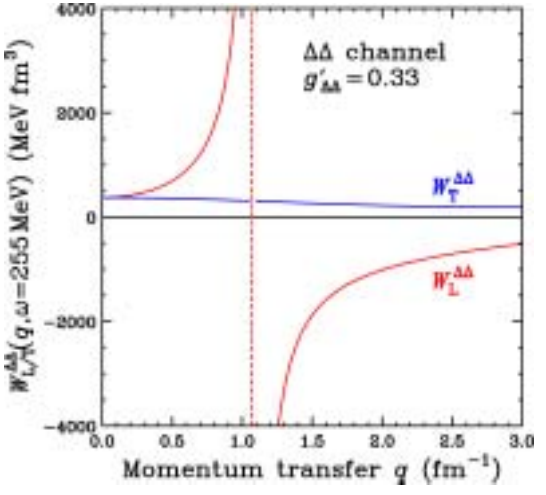
π - exchange

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

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

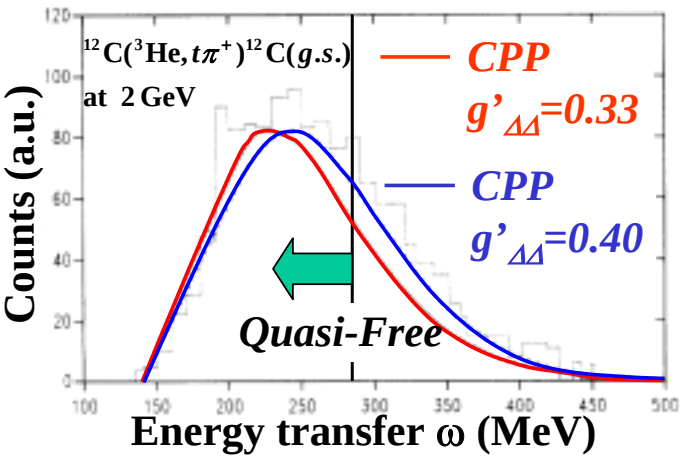
Short - range repulsion

ρ - exchange



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

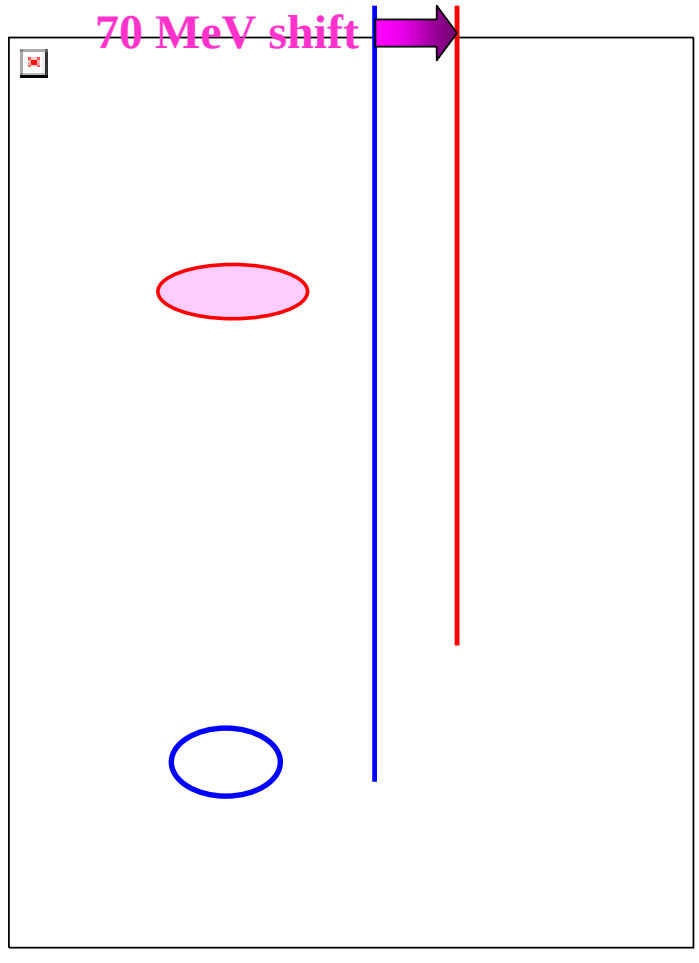
$$\Delta E \approx \Delta g'_{\Delta\Delta}\left(\frac{\hbar c f_{\pi N\Delta}^2}{m_\pi^2}\right)\rho_0 \Rightarrow \textit{Determine } g'_{\Delta\Delta}$$



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

Signatures of CPP process in previous experiments

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



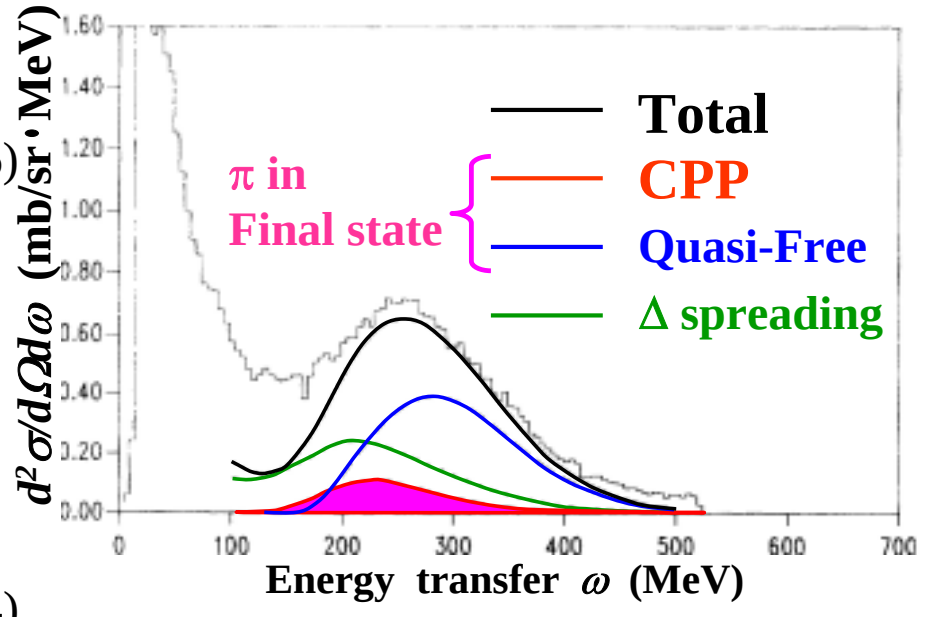
Inclusive process and pionic correlations

- **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 ***S*** with its direction
    - Separate s into $\boldsymbol{S}\cdot\boldsymbol{q}$ and $\boldsymbol{S}\times\boldsymbol{q}$ components
  - Measure π decay of Δ in coincidence with the ejectile
    - Exclusive measurement
    - Extract pionic $\boldsymbol{S}\cdot\boldsymbol{q}$ component

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 w=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

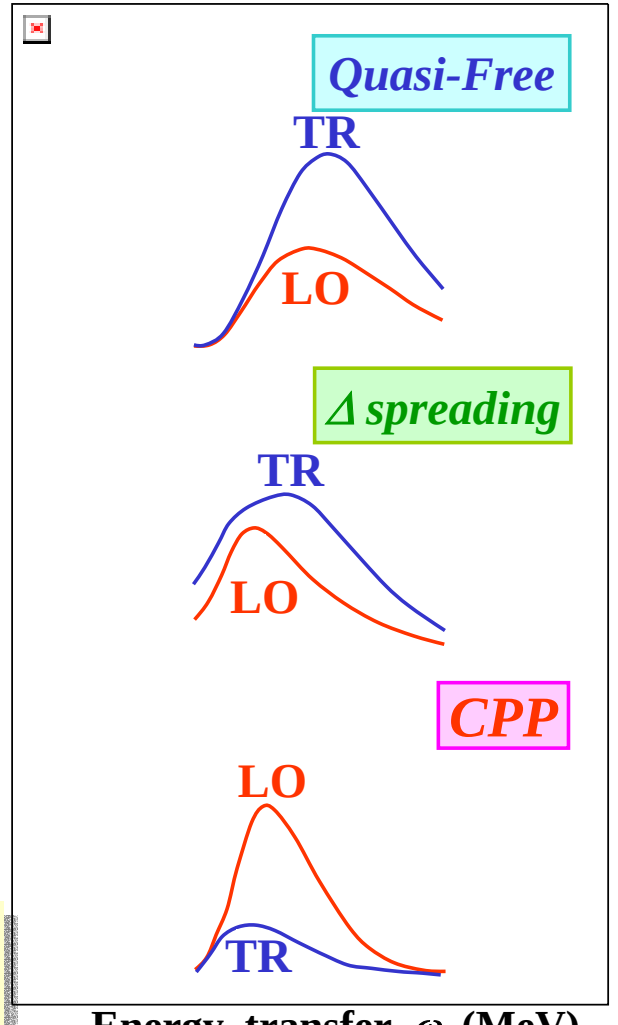


Inclusive is NOT sensitive to CPP (Pionic correlations)

→Exclusive measurement is important!

Sensitivity to pionic correlations
―*Ratio of spin-longitudinal and spin-transverse modes*―

- **Real (Experimental) impact is spin-isospin interaction via (^{3}He,t)**
  - **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 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)
  - 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***

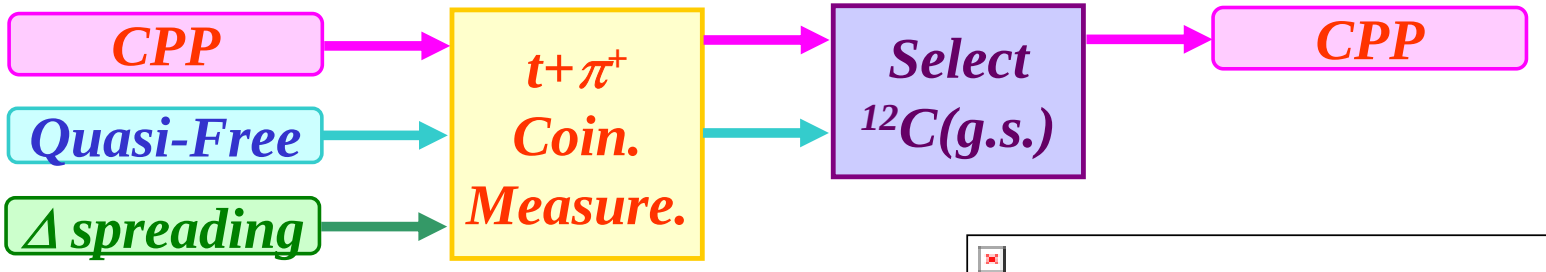


How to distinguish CPP from other processes

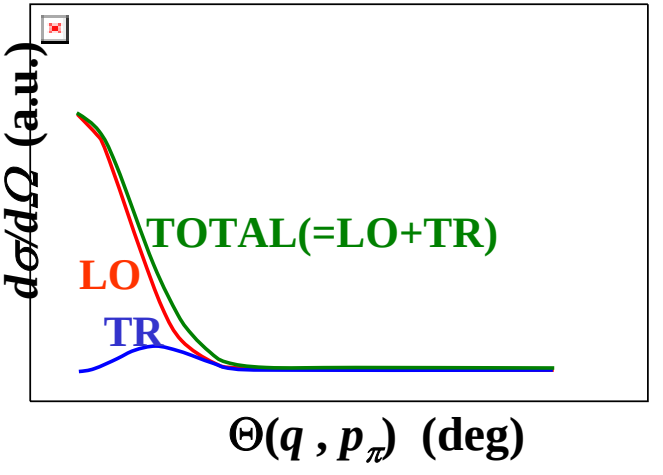
- **Main processes in Δ region are**
  - Coherenet Pion Production
  - Quasi-Free Δ decay
  - Δ spreading

Pions in final state

No pions in final state

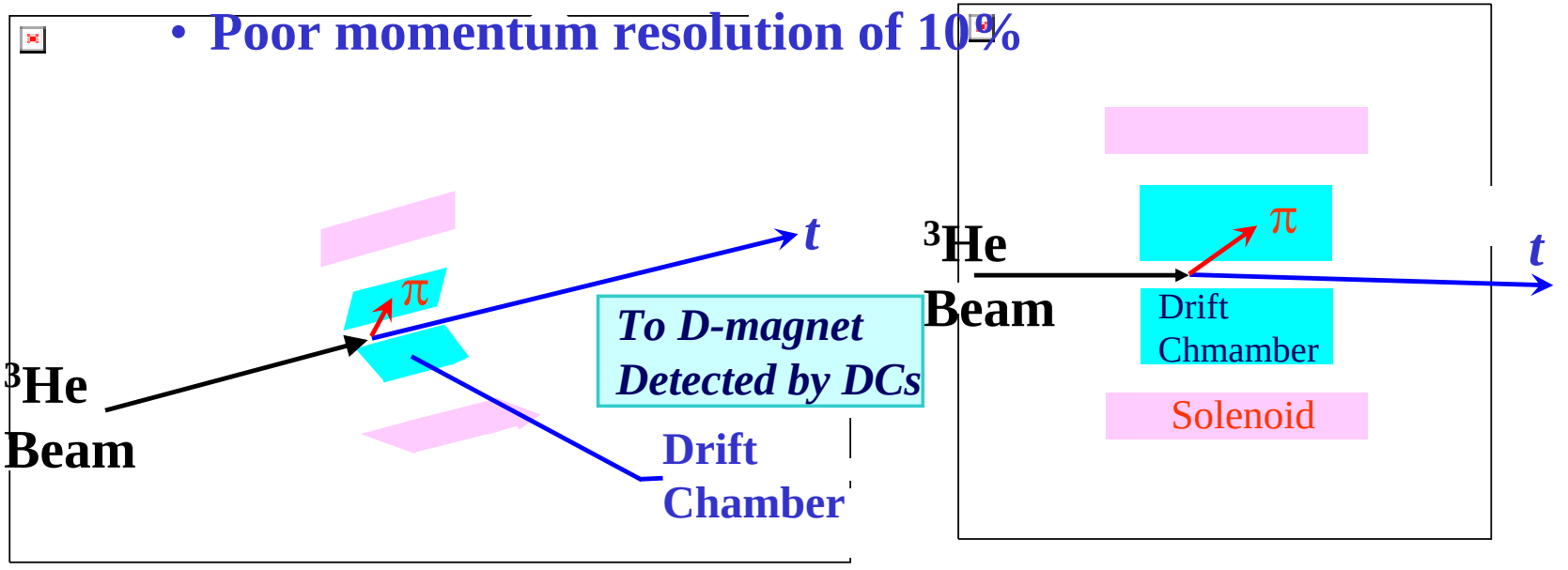


- **Measure correlation between momentum-transfer q and momentum $p_{\pi+}$ of pion**
  - Strong (parallel) correlation has been expected
    - T.Udagawa et al. Phys. Rev. C 49, 3162 (1995)



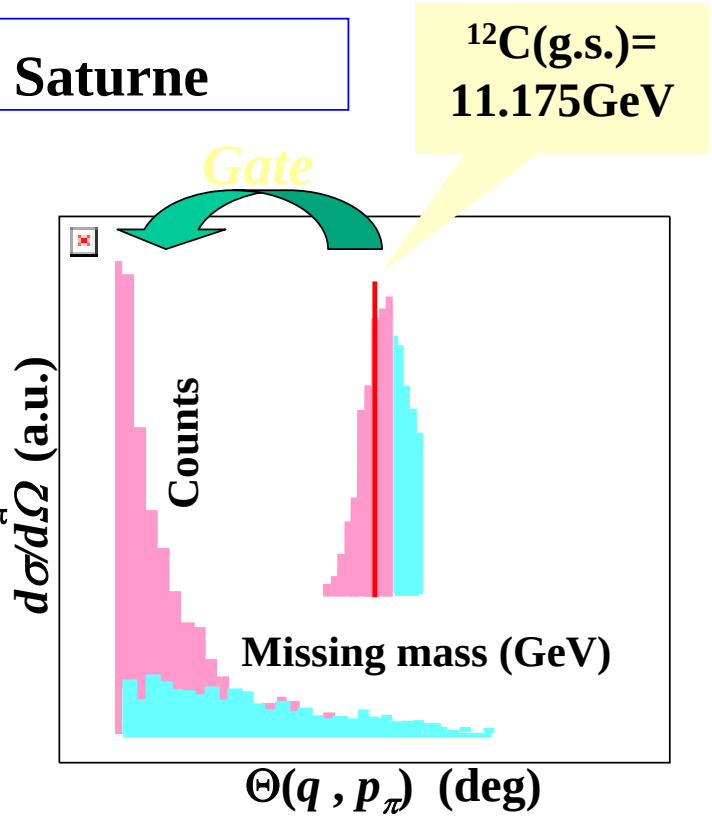
CPP Experiment at Saturne

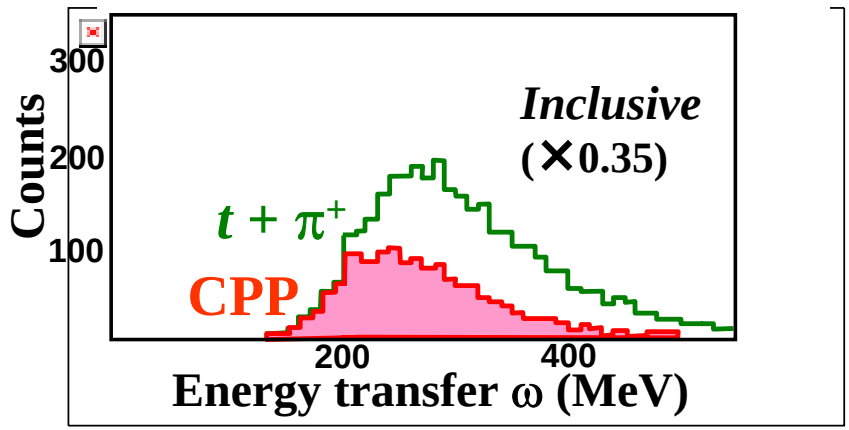
- **$^{12}C(^3He,tp^+)^{12}C(g.s.)$ at 2 GeV and $q_t \sim 0°$**
  - T_t=2GeV: Dispersion matching was tried
    - poor energy resolution?
  - q_{3He} = -1° ~4°
    - Analyzed by D-magnet and detected by DCs
    - **Poor energy resolution of 15 MeV**
  - q_p=20° ~132°
    - Analyzed and detected by CDC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



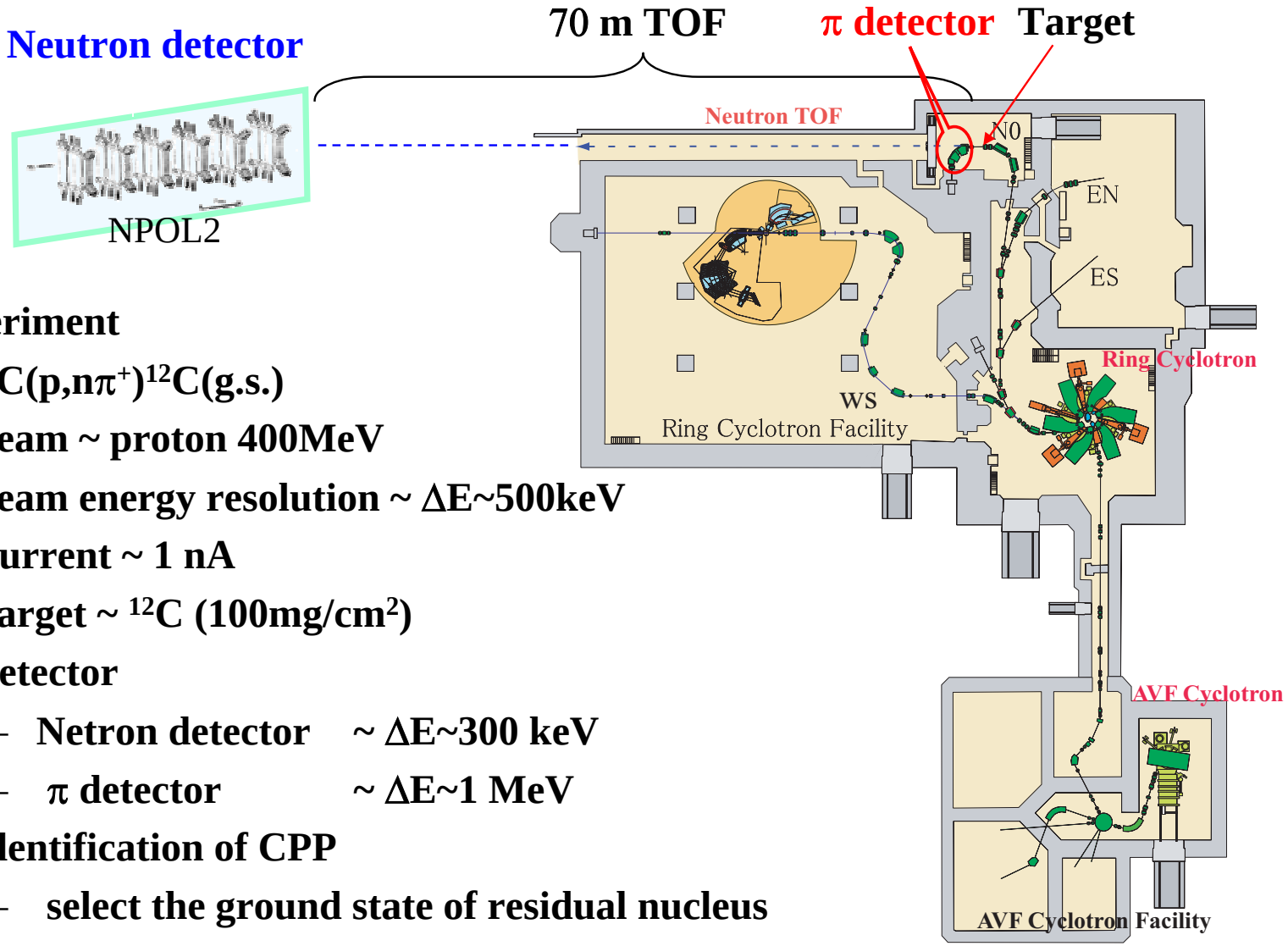
Results of CPP Experiment at Saturne

- **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 D resonance peak for CPP**
  - ***Signature of (attractive) pionic correlations in nuclei***





Proton induced CPP at RCNP

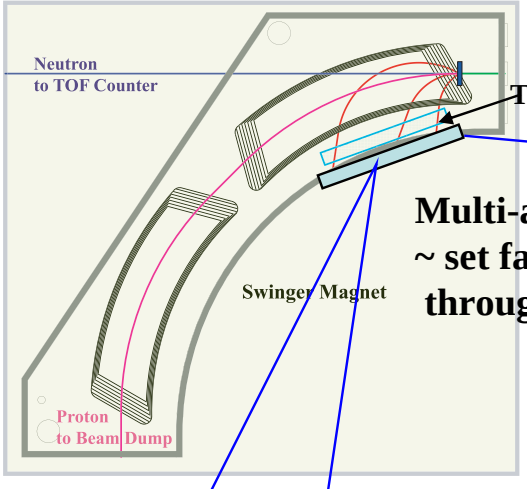


Experiment

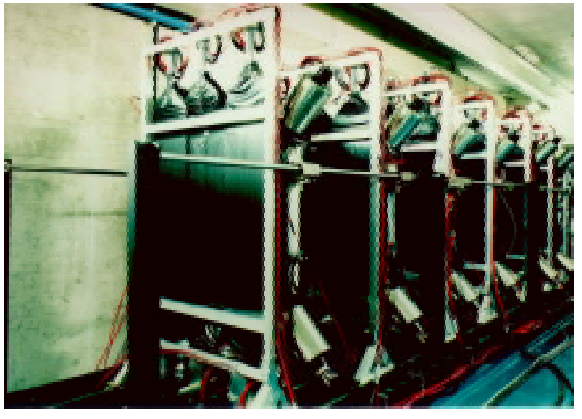
- $^{12}C(p,n\pi^{+})^{12}C(g.s.)$
- Beam ~ proton 400MeV
- Beam energy resolution ~ ΔE~500keV
- Current ~ 1 nA
- Target ~ ^{12}C (100mg/cm^2)
- Detector
  - Netron detector ~ ΔE~300 keV
  - π detector ~ ΔE~1 MeV
- Identification of CPP
  - select the ground state of residual nucleus

Experimental setup

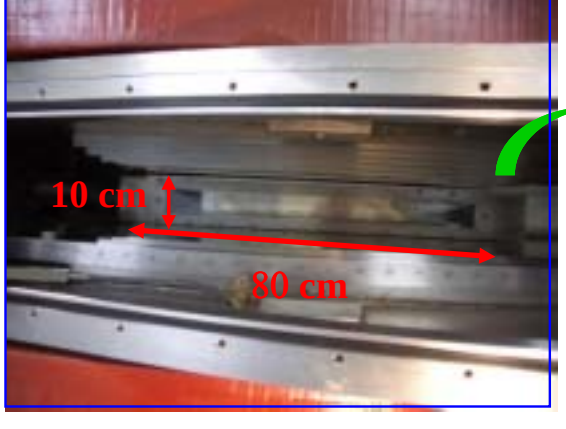
Charged particle detector in the sweeping magnet

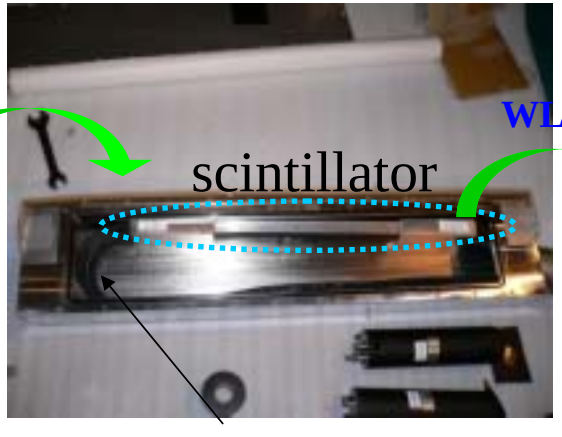


Neutron Counter



Position sensitive Neutron Counter (liq Sci.)
TOF length ~ 70 m
Energy resolution : 300 keV
Detection efficiency : 15 % @150~400 MeV

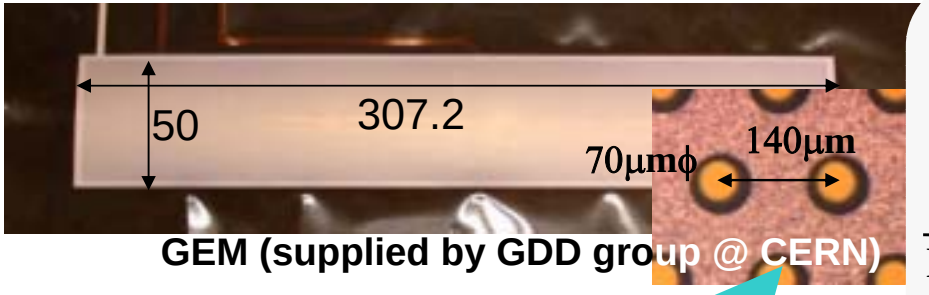




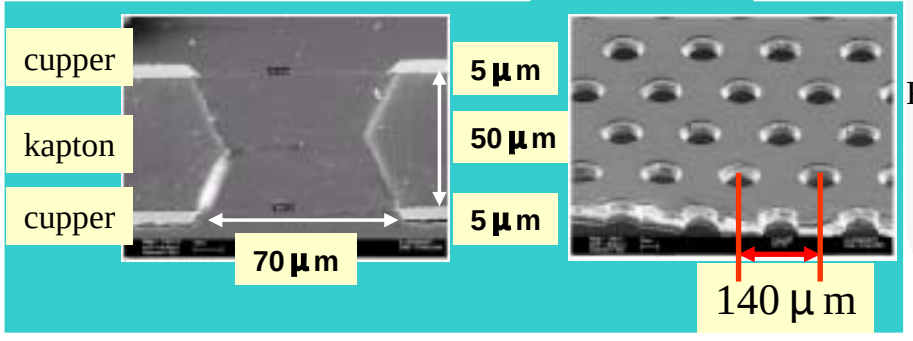
Gas Electron Multiplier (GEM) detector

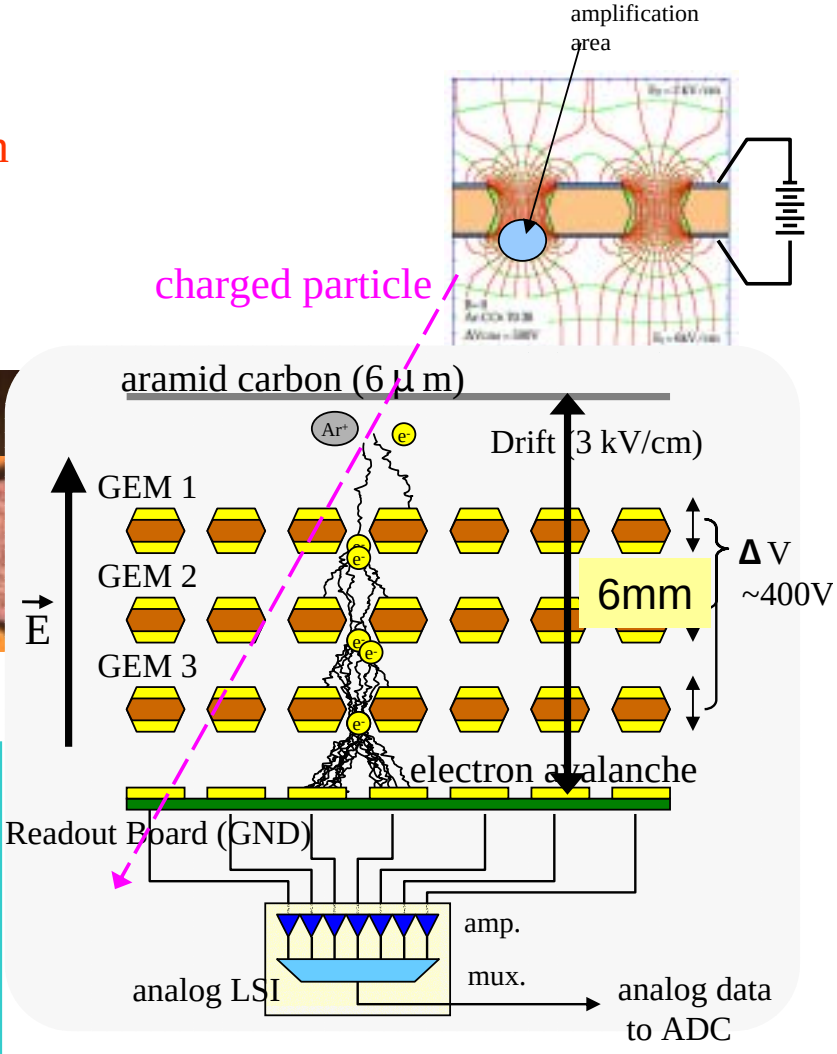
—For charged particle (π^+…) detection in magnet—

- **Detector components**
  - Three layers of GEM foil: High gain
  - 2-dim. Readout board: High resolution
- **Specification**
  - High position resolution: 100 mm
  - Effective area: 300 × 50 mm



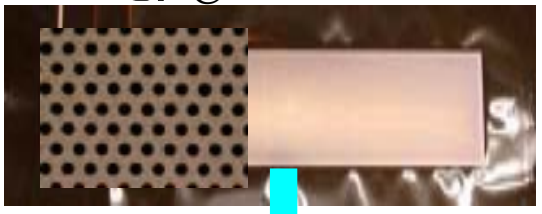
GEM (supplied by GDD group @ CERN)



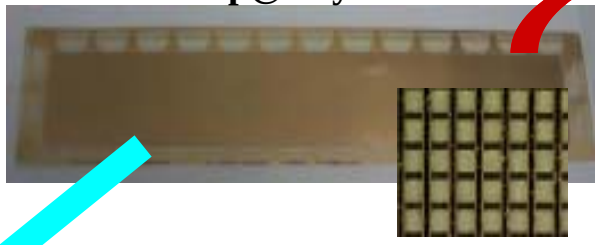


Pion tracking detector

GEM電極@CERN



Readout strip@Raytech



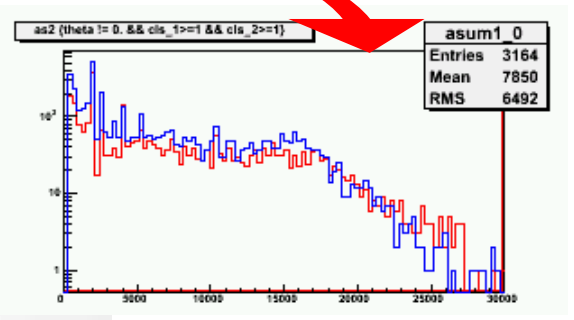
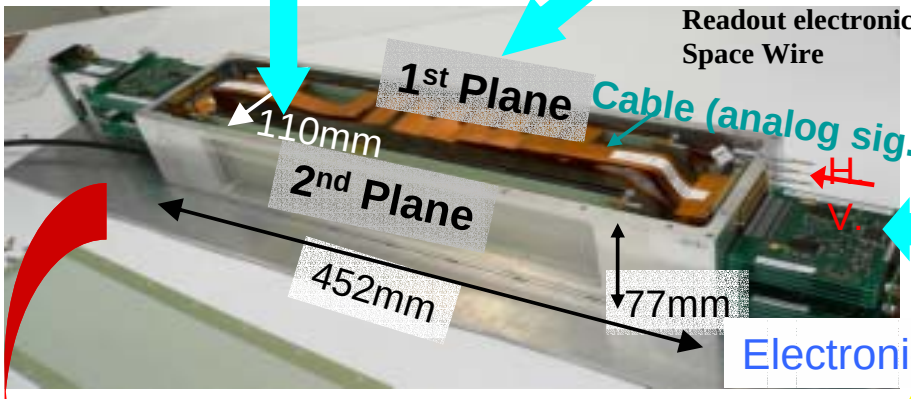
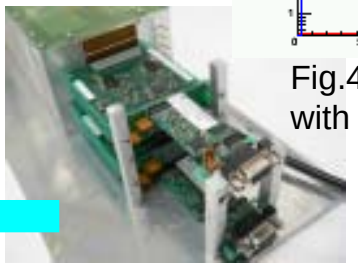
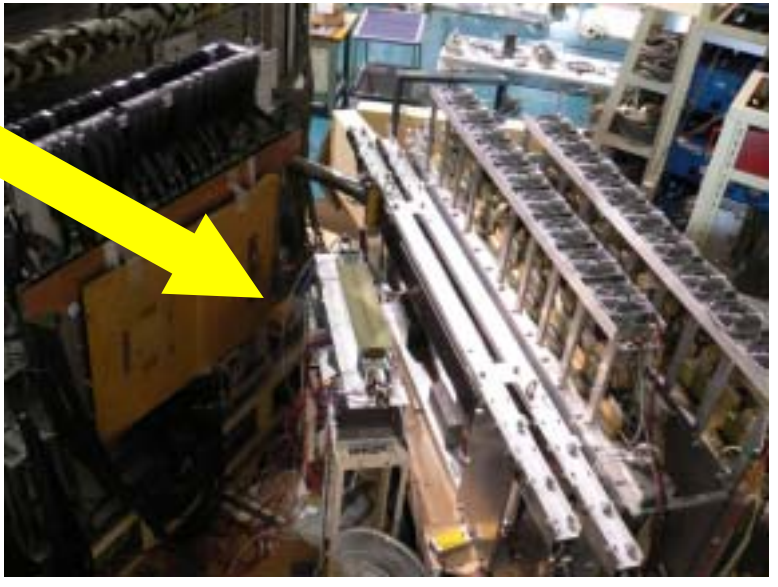


Fig.4: ADC spectrum
with V_{gem}=410(blue), 417(red)V





Electronics



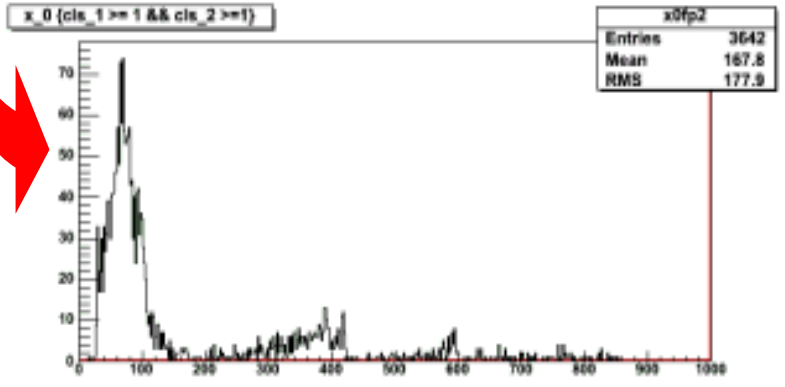
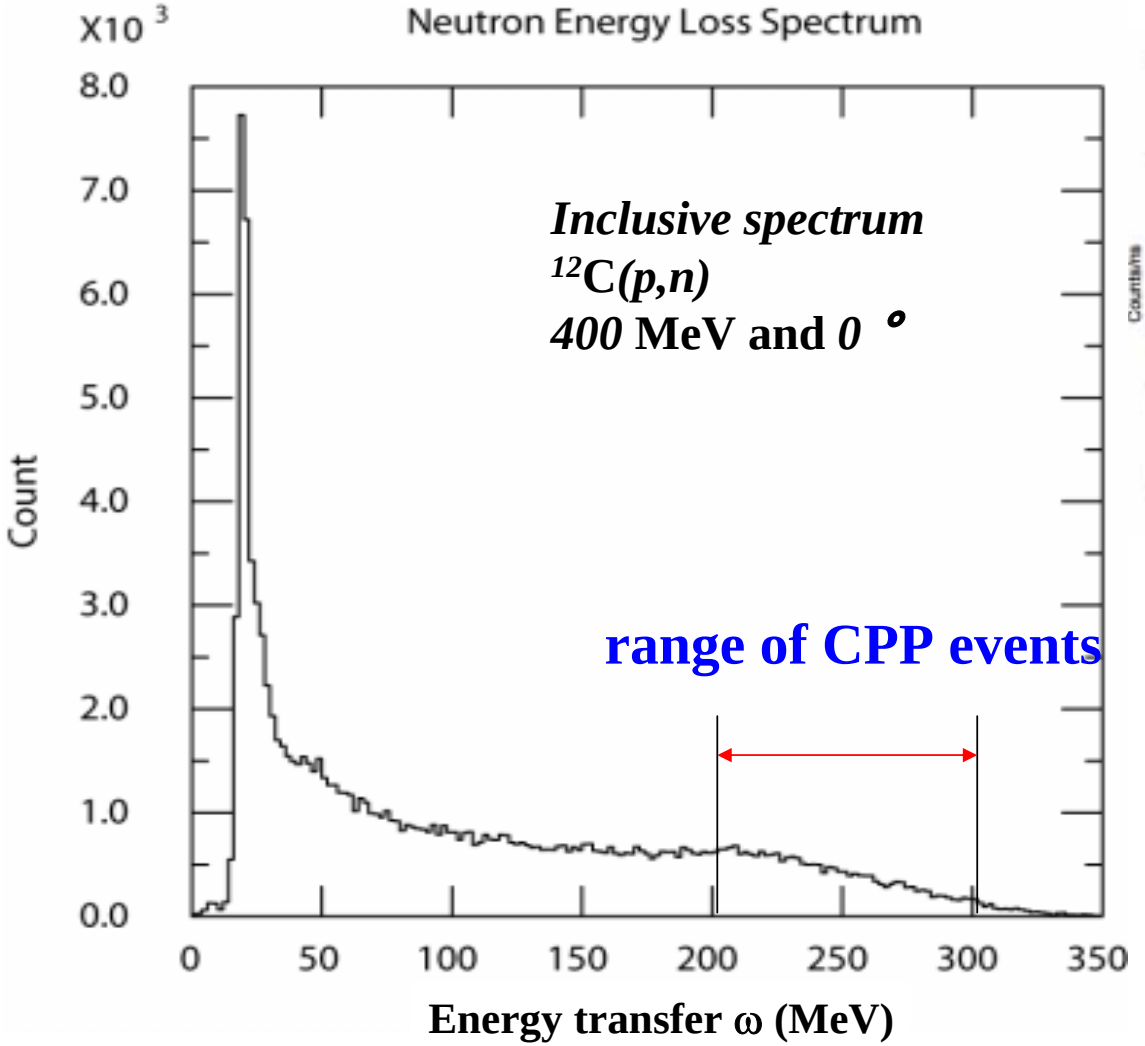
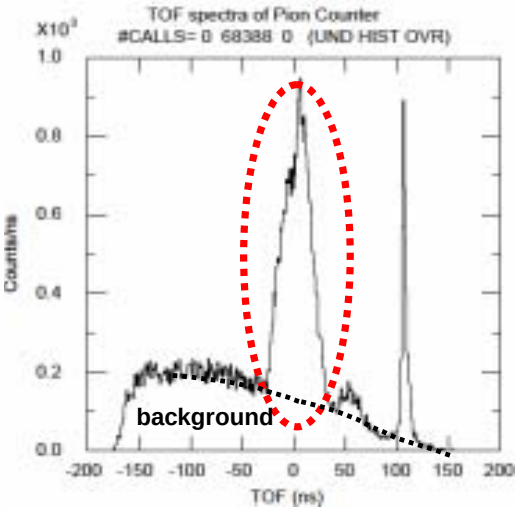


Fig.2: position on focal plane

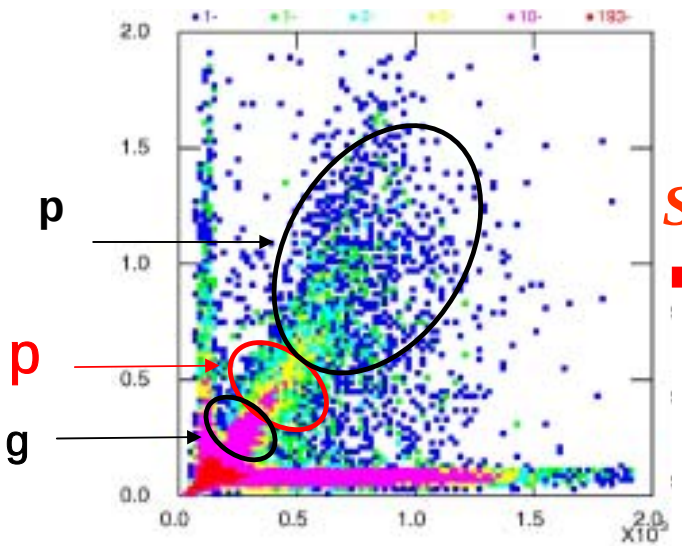
CPP Test Experiment





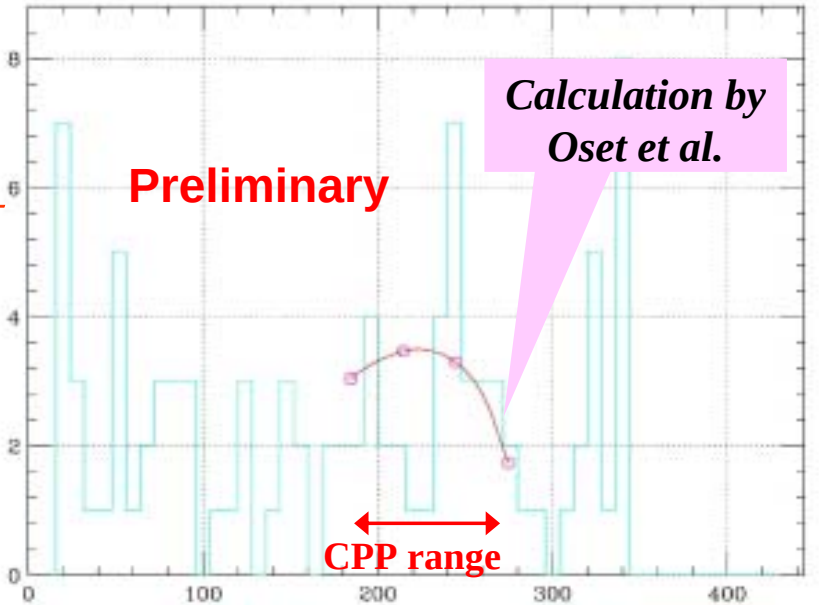
TOF spectrum of pion counter

Present status of CPP experiment



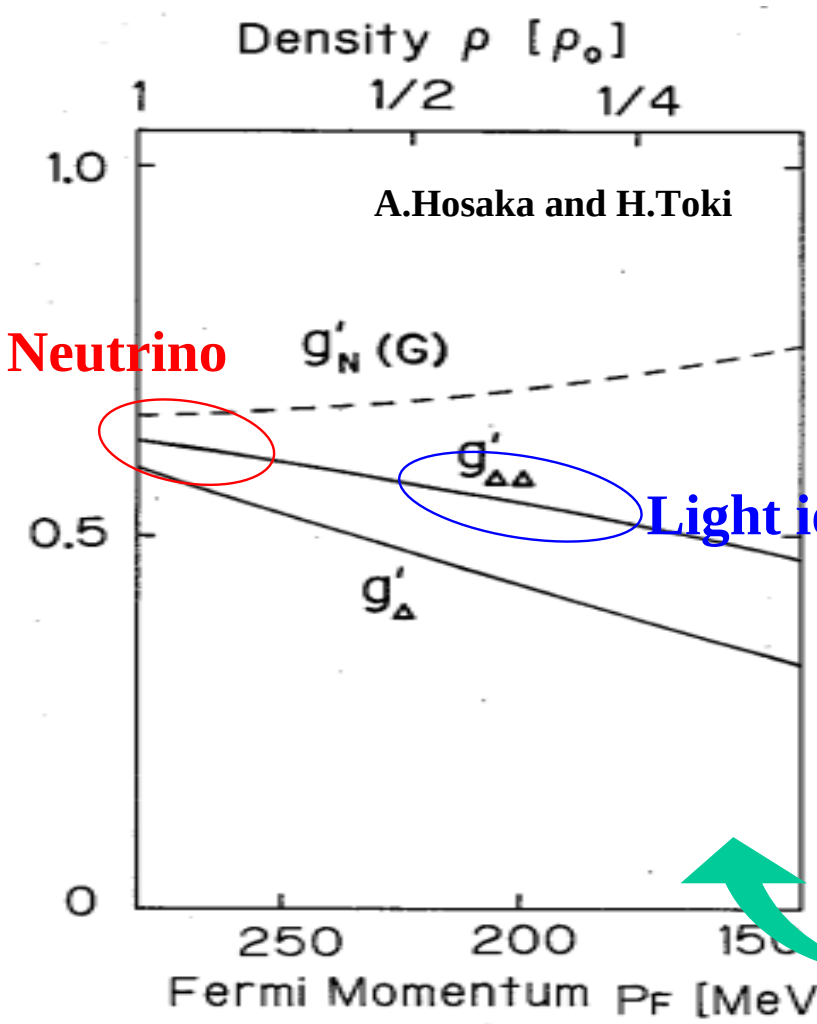
Select π^+

Cut
E/TOF



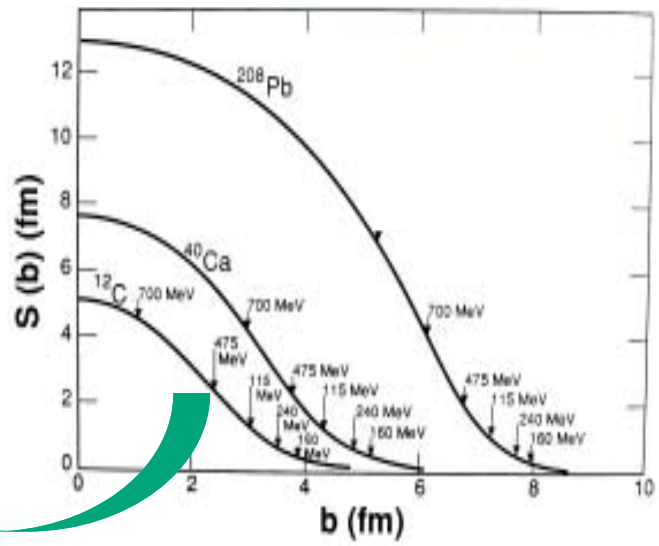
- **Neutron energy spectrum**
  - ***CPP region ~ enhancement ? ~ detailed analysis continued***
  - ***Poor resolution for π***
- **Background ~ study in progress**
  - ***beam halo ~ beam optics tuning***
  - ***Edge scattered high energy protons* ~ almost same flight time as pions**
- **Future measurement**
  - ***High resolution with GEM***
  - ***High statistics data***

Density dependence of g'



profile function ~ one mean free path

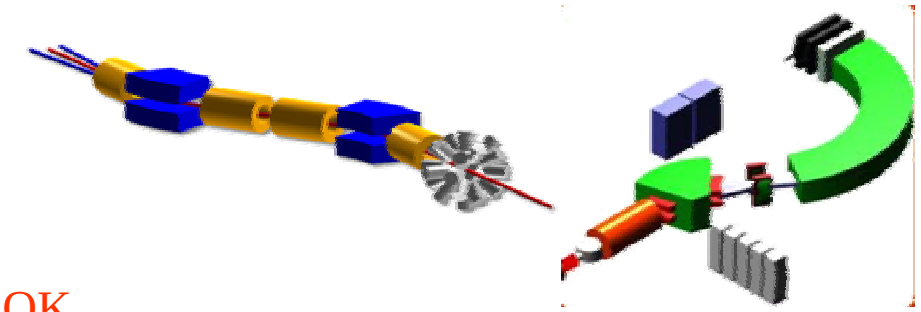
$S(b) \sim \lambda \sim (A\rho\sigma)^{-1}$



CPP Experiment at RIBF with $^{3}He^{++}$ Primary Beam

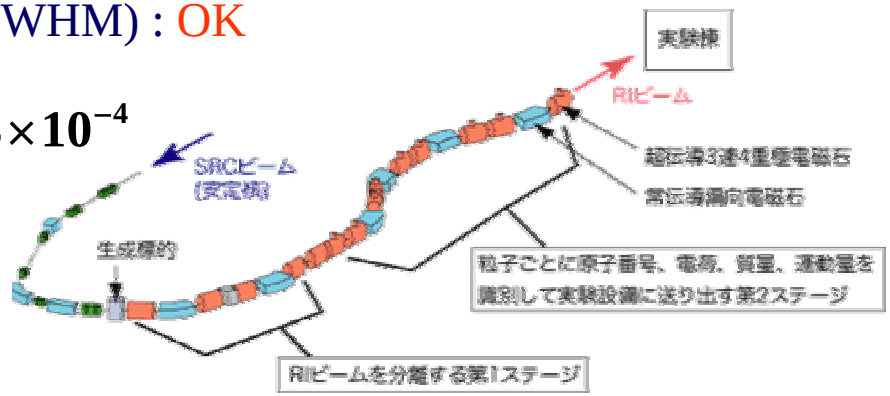
Proposed by Dr. Wakasa

- **High resolution beam**
  - 400 MeV/n $^{3}He^{++}$: Dp=0.03% (s) → DE=1.4 MeV (FWHM) : OK
- **High resolution triton measurement**
  - Requirement: DE ～ 2 MeV and q < 2.5 ° including 0 °
  - Facility (not studied)
    - Zero-degree Spectrometer
    - SHARAQ
  - Big-RIPS
    - Dq = ±40 mrad = ±2.3 °：OK
    - D = 2.3 m → DE = 1.7 MeV (FWHM) : OK



$$\frac{\Delta p}{p} = \frac{1}{R} = \left|\frac{M_x}{D}\right| \Delta x_0 = 4.3 \times 10^{-4}$$

$$(M_x = 1,\ \Delta x_0 = 1\,\mathrm{mm})$$

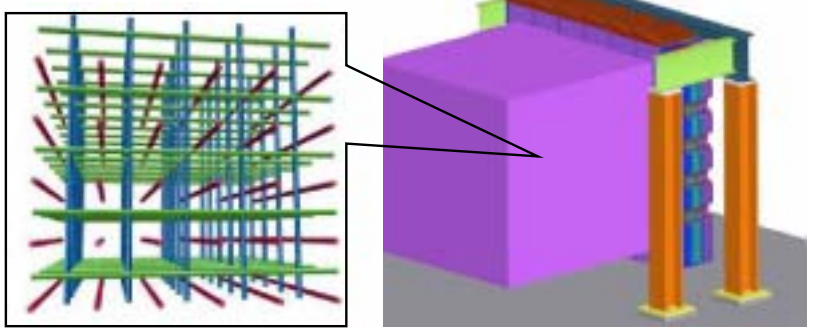


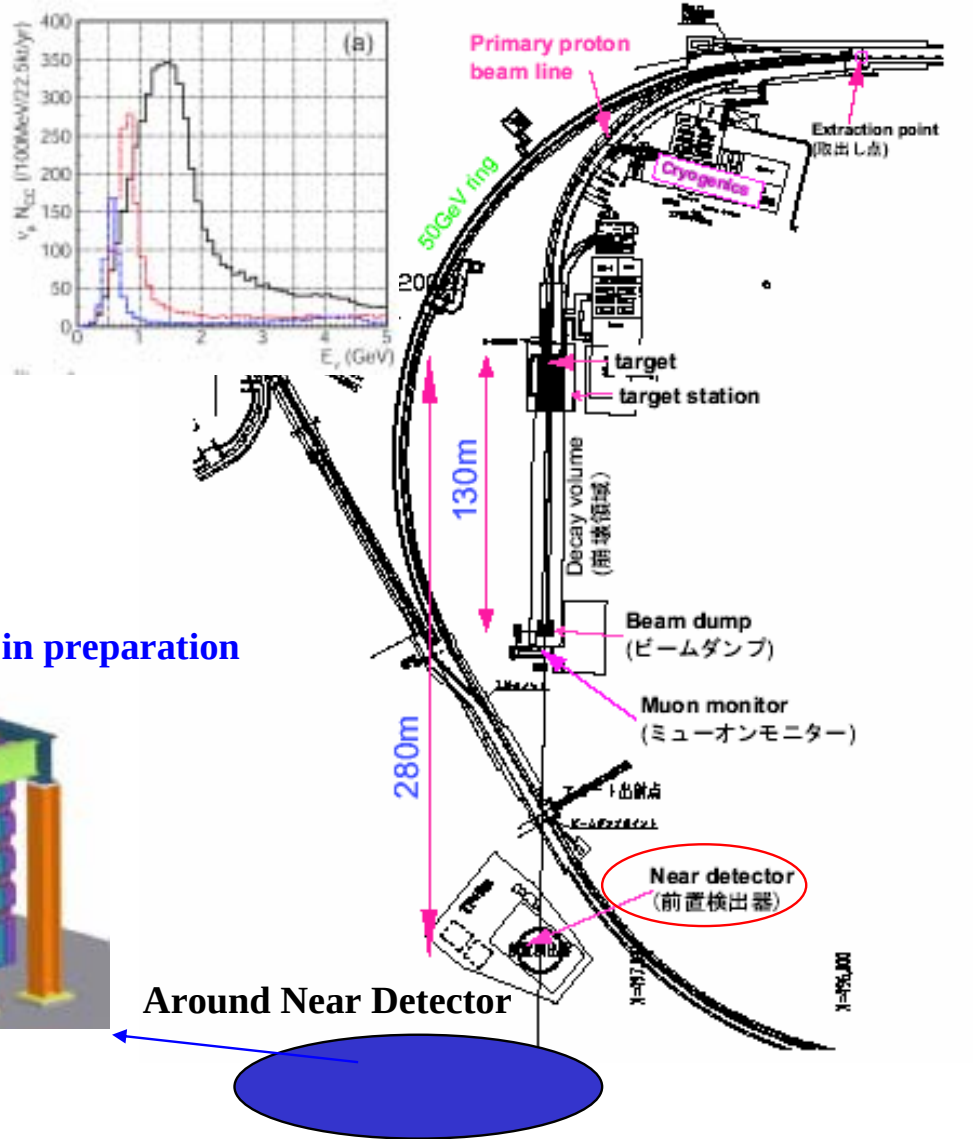
Neutrino Beam at J-PARC

Beam energy ~ 1 GeV
→ suitable for Nuclear Physics in the Δ resonance region

Detector ~ Liquid Sci. with W.L.S
Target
- **Proton**
- **Carbon !**
- **Heavy Nucleus**

Physics and Detector design ~ LOI ~ in preparation





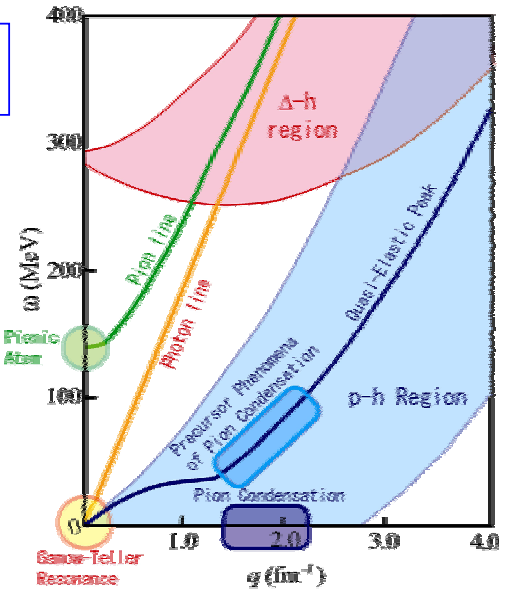
Summary

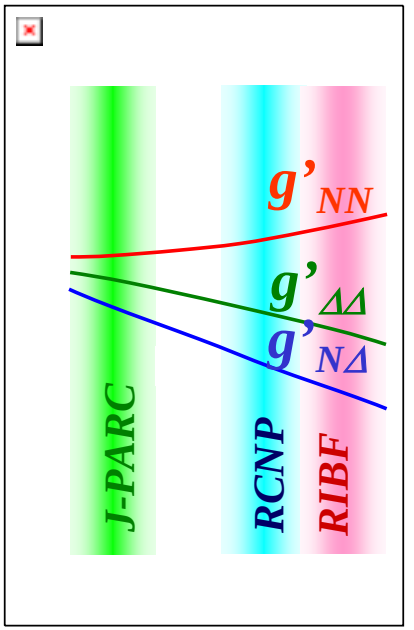
- **CPP is a promising tool to obtain the information on $g'_{\Delta\Delta}$**

- **Test experiment at RCNP ~ performed**
  - **CPP signature ? ~ should be studied further**
  - **High resolution measurement with GEM**
  - **High statistics data ~ accumulation run**

- **Need theoretical calculation on CPP**

- **CPP experiments are performed/proposed at several places.**
  - **$^{12}C(\nu_\mu,\mu^-\pi^+)^{12}C$(g.s.) at J-PARC (W.G., Sakemi)**
    - ***First ν-CPP data from K2K:no-evidence for CPP***
    - ***can be performed with ΔS experiment***
  - **$^{12}C(^3He,t\pi^+)^{12}C$(g.s.) at RIBF (Dr. Wakasa)**
  - ***Density dependence of g' can be investigated***





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