Pionic and Tensor Correlations Studied by High Resolution and Polarization Transfer Measurements

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Outline

Spin-isospin responses and residual interactions

- Short-range correlations → GTR
- Pionic correlations → *Significantly attractive at large q ?*
- Tensor correlations → *Significant effects on QES and SDR ?*

High-resolution Spectroscopy for $^{16}O(p,p')$

- Construction of WS beam line for dispersion matching
  - *Pure pionic 0^- state was separated with ΔE=40 keV resolution*
- Precursor of pion condensation in pure pionic 0^- state

Tensor correlations in SDR for $^{208}Pb(p,n)$

- Spin-parity decomposition ($J^\pi = 0^-, 1^-, 2^-$) of SD strengths
  - *Complete polarization transfer data were measured*
- J^π-dependent tensor force effects on SD strengths

Summary

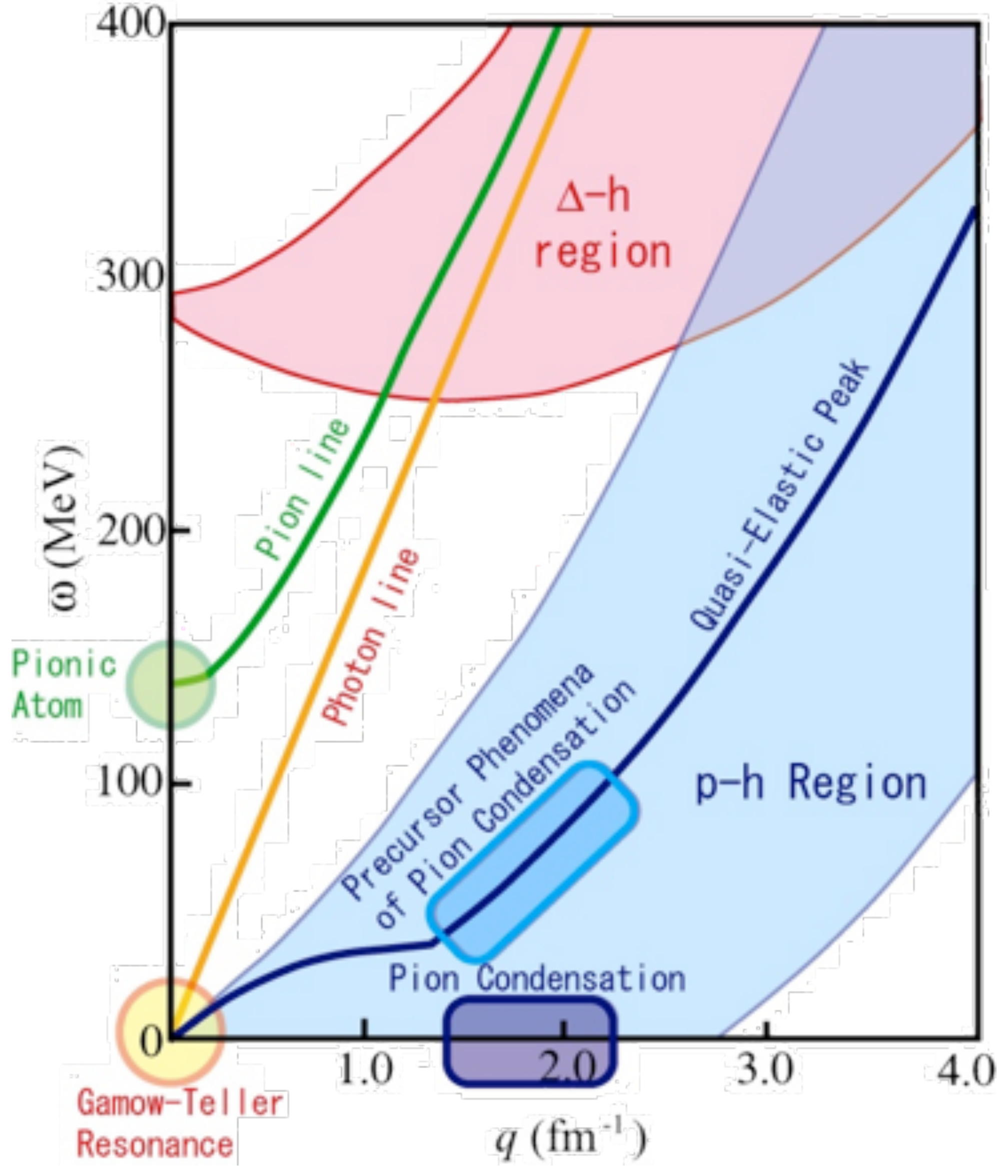
Spin-isospin modes in nuclei

Spin-isospin responses have been widely studied by

- GT/M1 at q ~ 0 and small ω
  - (p,n), (^{3}He,t), (p,p')
- **SDR at small q and small ω**
  - (p,n), (d,^{2}He)
- QES at large q (1~2 fm^{-1}) and medium ω
  - (p,n)
- **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

- Spin-isospin responses in unstable nuclei



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

- Pionic correlations at large q
- Tensor correlations in wide q

} **This talk** *(based on RCNP high-res./pol. data)*

Pionic enhancement in QES

T.N.Taddeucci et al., PRL 73, 3516 (1994)./T.W. et al., PRC 59, 3177 (1999)

Effective interaction at large q

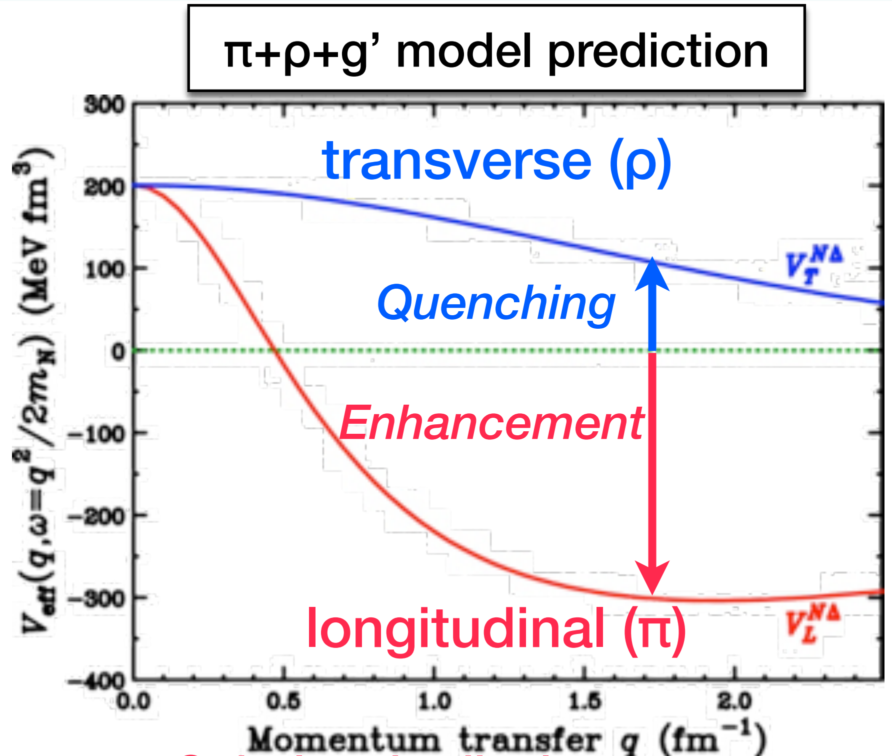
- Attractive spin-longitudinal V_L
  - Especially for NΔ with small $g'_{N\Delta}$

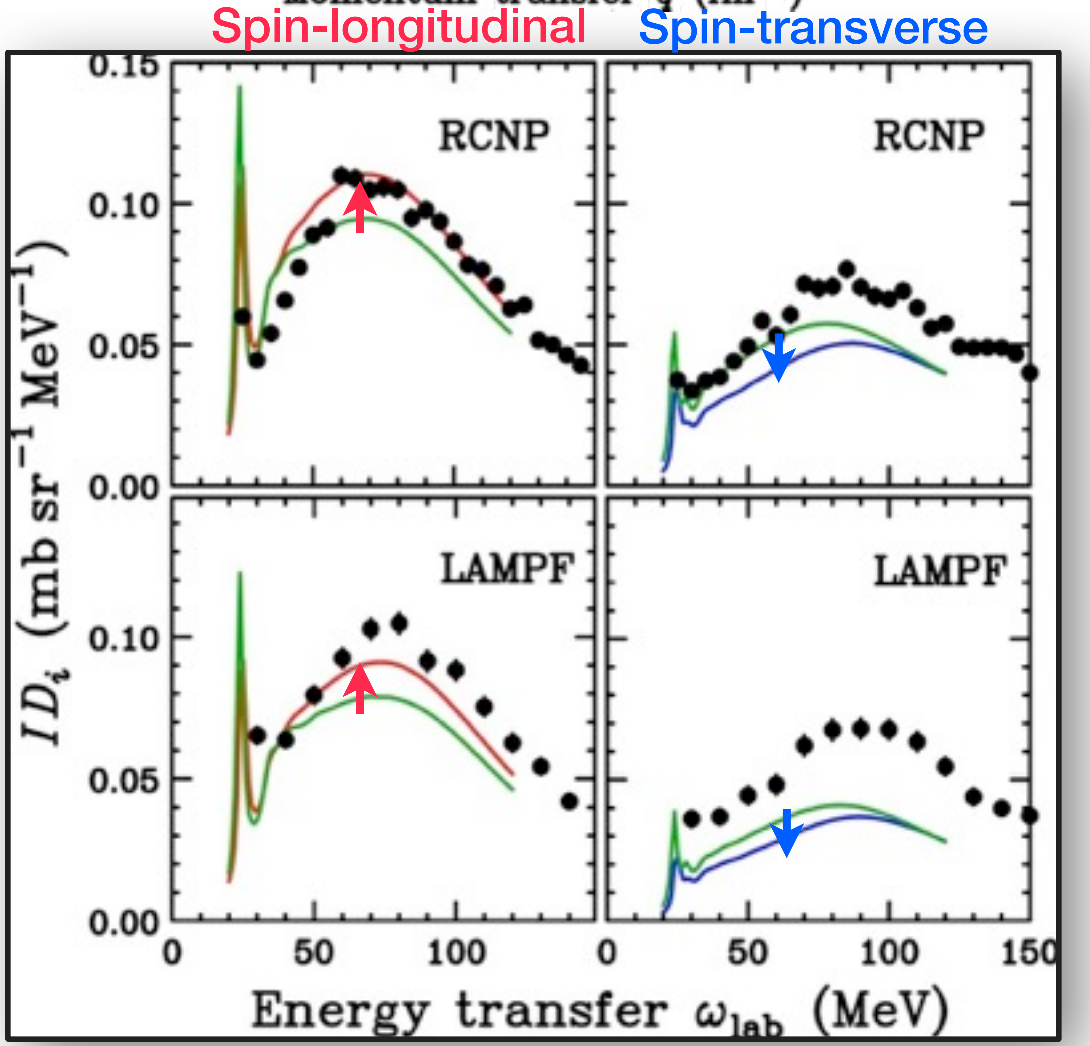
Quasi-elastic scattering at large q

- Spin-longitudinal (π) mode
  - *Enhancement* by *attractive* π-corr.
- Spin-transverse (ρ) mode
  - *Quenching* by *repulsive* ρ-corr.

RCNP/LAMPF data at q=1.7fm^{-1}

- Spin-longitudinal mode
  - Exp. = RPA > Free (w/o corr.)
  - ***Pionic enhancement in nuclei***
- Spin-transverse mode
  - Exp. > Free > RPA
  - ***Attractive ρ-correlations?***





New experiment for pionic correlations

Results of quasi-elastic scattering

- Enhancement of spin-longitudinal OK
- Quenching of spin-transverse NG
- *Is enhancement really due to attractive pionic correlations ?*
  - Spin-longitudinal/transverse modes were separated with D_{ij}
  - Simple reaction mechanism was assumed → more systematic data desired

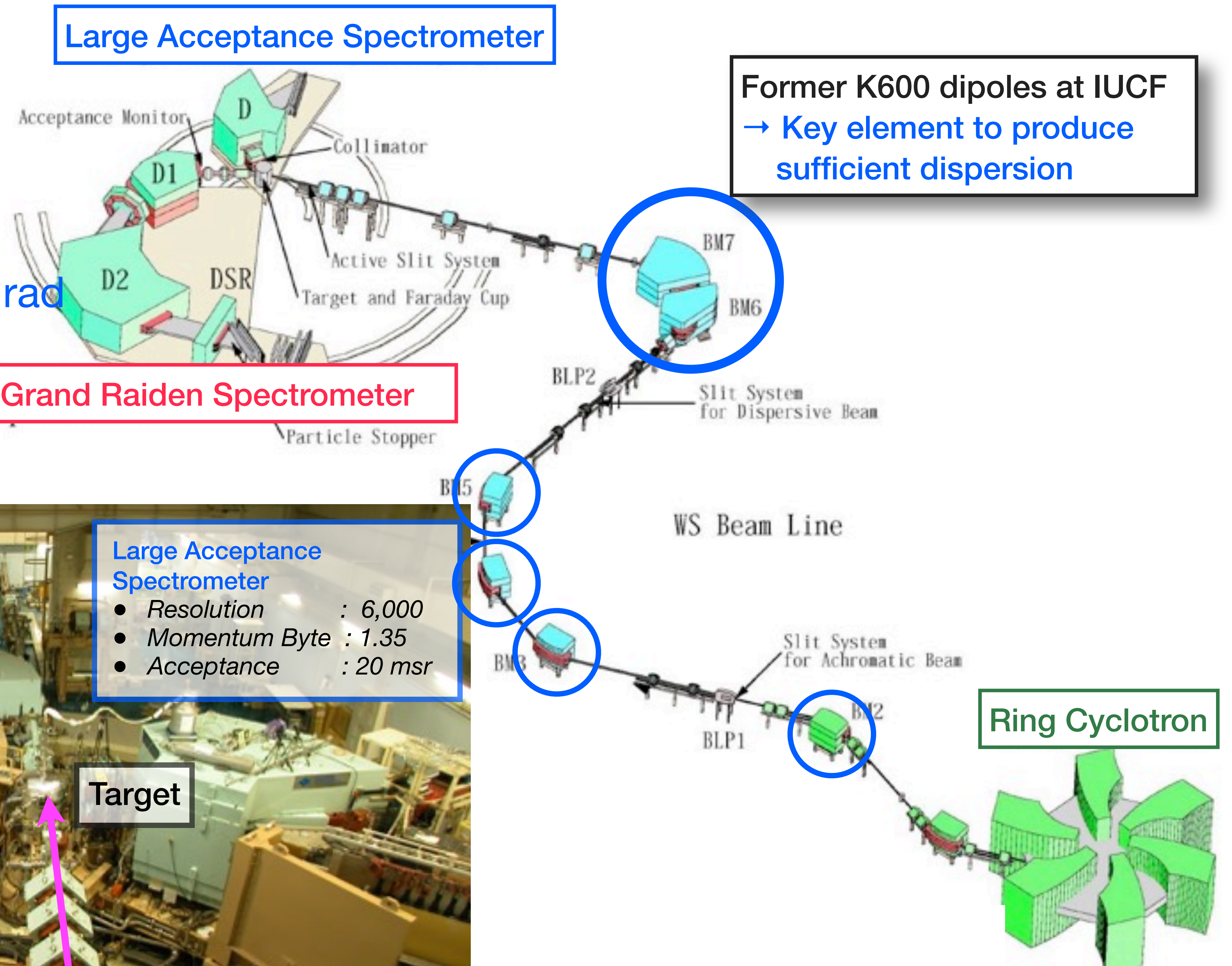
New experiment at RCNP

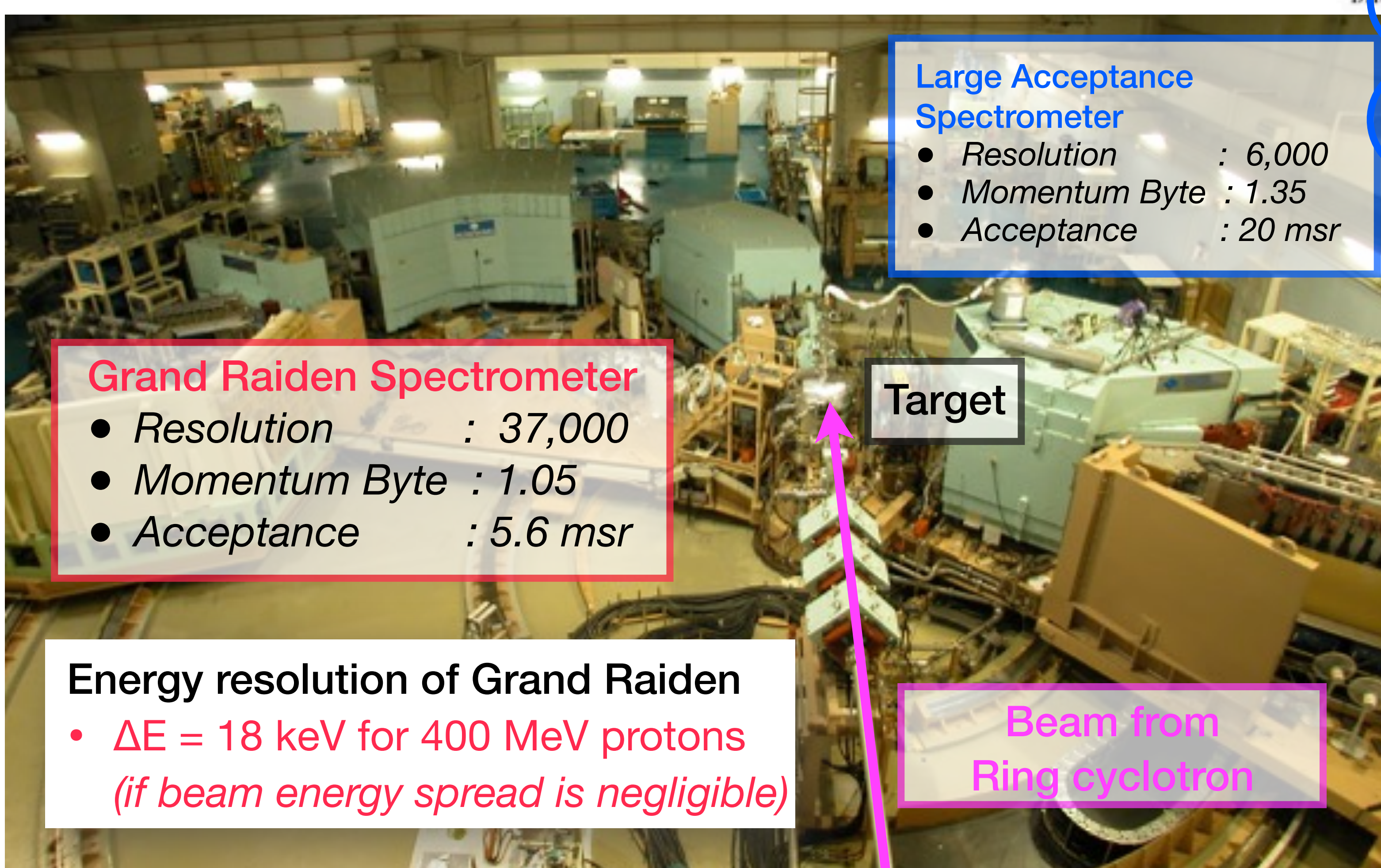
- Measure σ of $^{16}O(p,p')^{16}O(0^-,T=1)$
  - *Pure spin-longitudinal mode* → Separation with D_{ij} is not required
  - Require ΔE～40 keV for separating 0^- state from other states
    - Beam energy spread is typically ～100 keV
    - Dispersion matching is required to cancel the effect of beam energy spread

WS beam line at RCNP (2000～)

Specifications

- Bending angle: 270°
- Dispersion: 37.1 m
- Angular dispersion: 20.0 rad
- ***Complete matching with Grand Raiden***





Pionic enhancement in $^{16}O(p,p')^{16}O(0^-,T=1)$

Isovector $J^\pi=0^-$ excitations

- Carry π-like quantum number
- *Pure information on pionic mode*

Experiment: $^{16}O(p,p')^{16}O(0^-,T=1)$

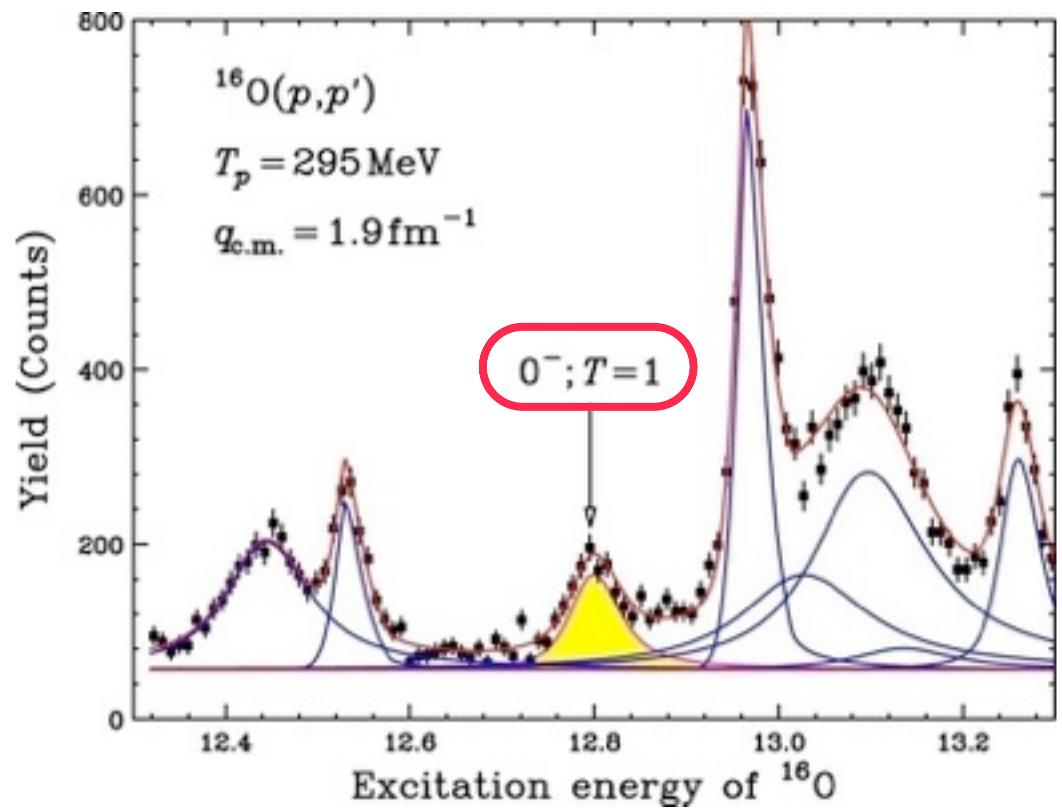
- ΔE = 30 keV by dispersion matching
  - *Clearly resolve 0^- state*
- $q_{c.m.}$ = 0.9 - 2.1 fm^{-1}

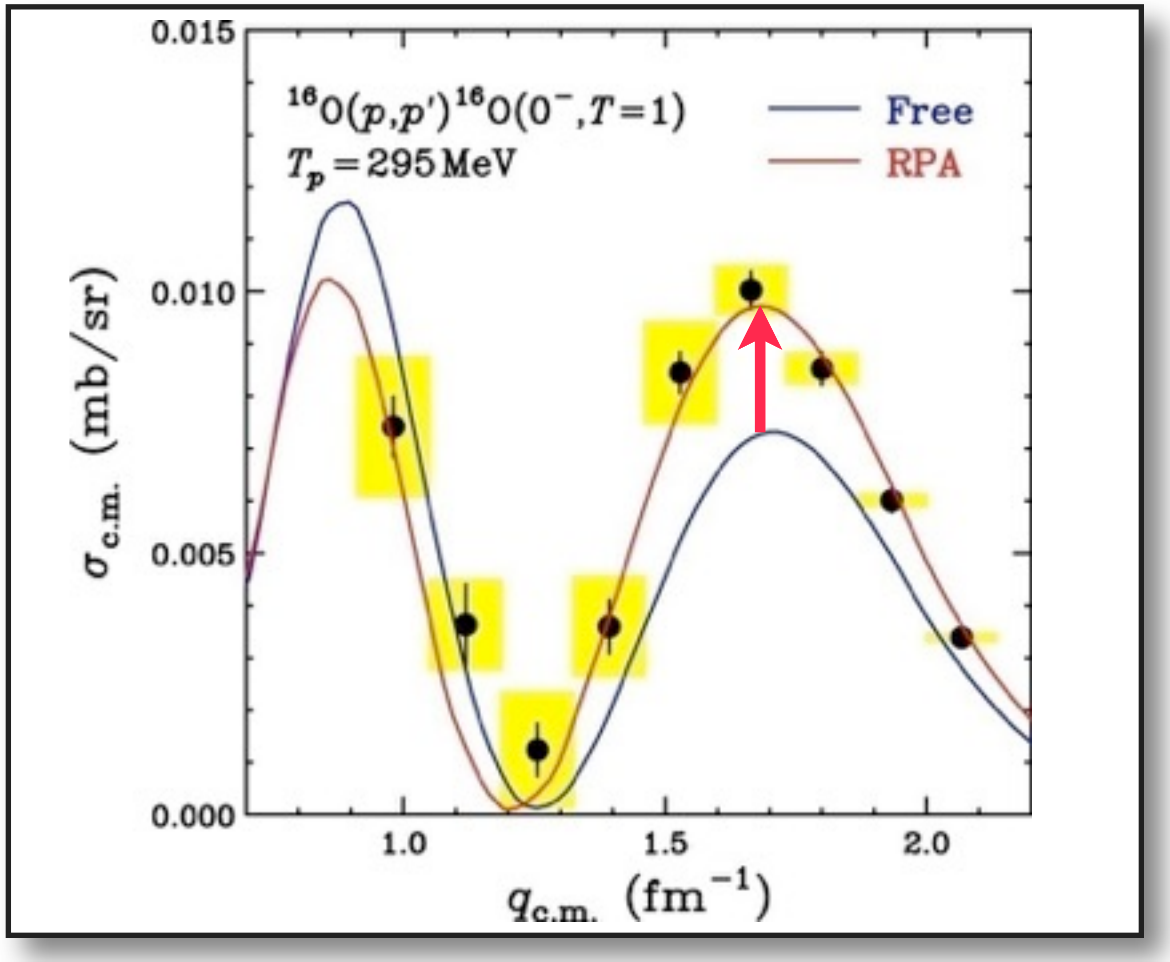
Comparison with theory

- Blue : without correlation (Free)
  - Significant enhancement
- Red : with RPA correlation

Data supports pionic enhancement

- Signature of ***precursor for pion condensation*** in pure pionic mode





Possible origin for spin-transverse enhancement

Pionic enhancement has been confirmed in pure pionic $^{16}O(p,p')^{16}O(0^-,T=1)$

- Consistent with spin-longitudinal enhancement in quasi-elastic scattering
- Spin-longitudinal (π) mode could be understood in a standard model (π+ρ+g')

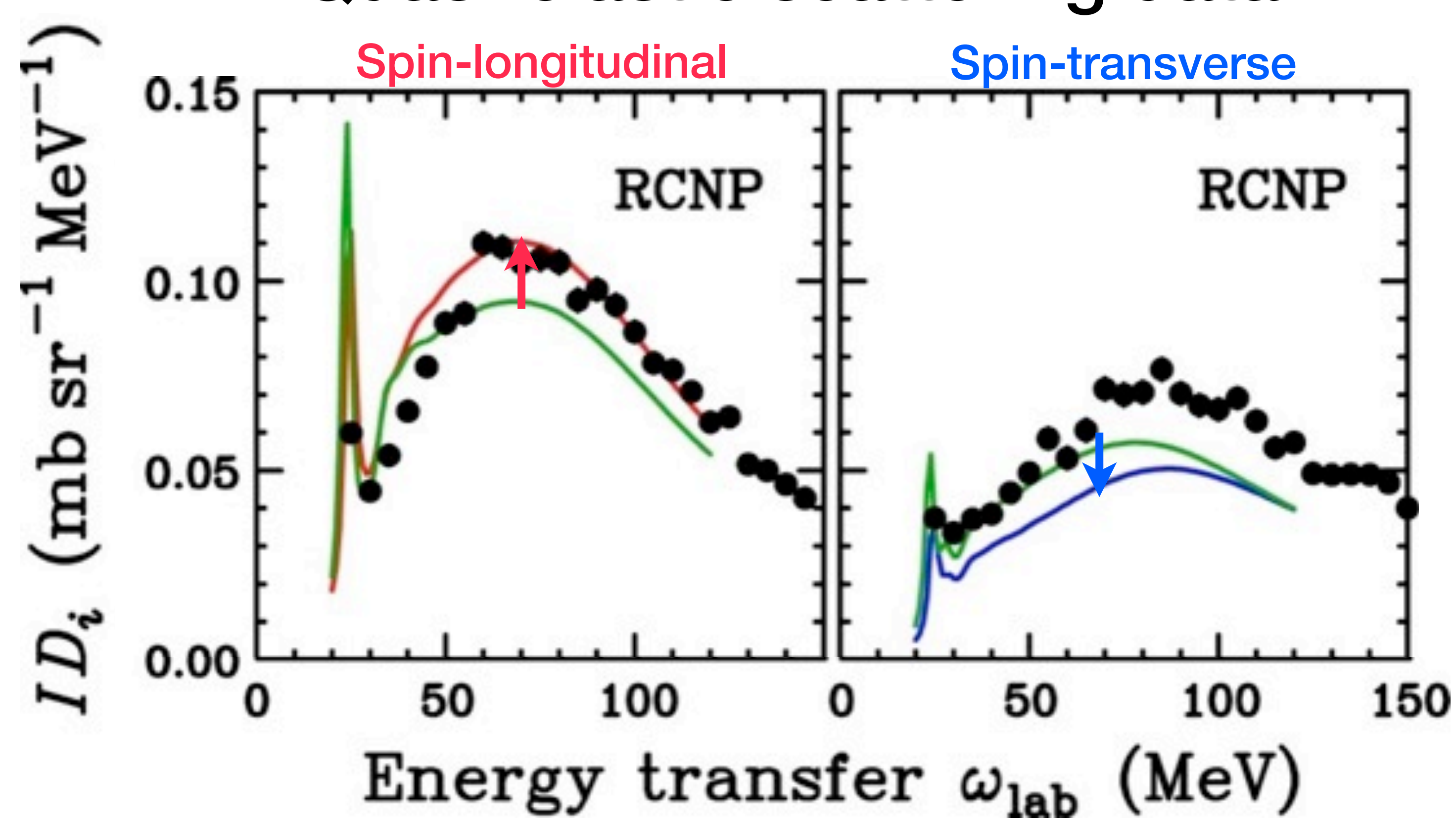
Experimental spin-longitudinal/transverse separation is reasonable

- Spin-transverse (ρ) mode in quasi-elastic scattering is *enhanced (not quenched)*

Possible origin/explanation

- Attractive interaction
- Tensor correlations

Quasi-elastic scattering data

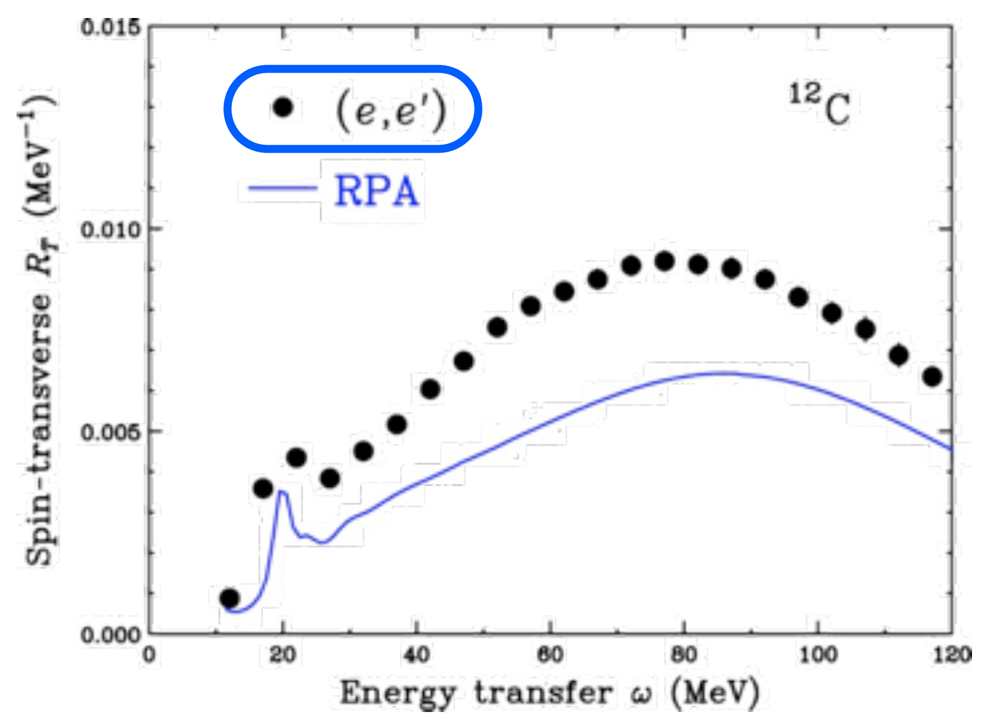


Short-range tensor correlations

C.J.Horowitz et al., PRC 50, 2540 (1994) / M.Ichimura et al., PPNP 56, 446 (2006).

Spin-transverse (e,e') response

- Enhancement from RPA
  - Higher-order (2p2h) effects
  - MEC



Different g' for π and ρ-modes

$$g'_\pi(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + g'_\rho(\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})$$

spin-longitudinal (π) spin-transverse (ρ)

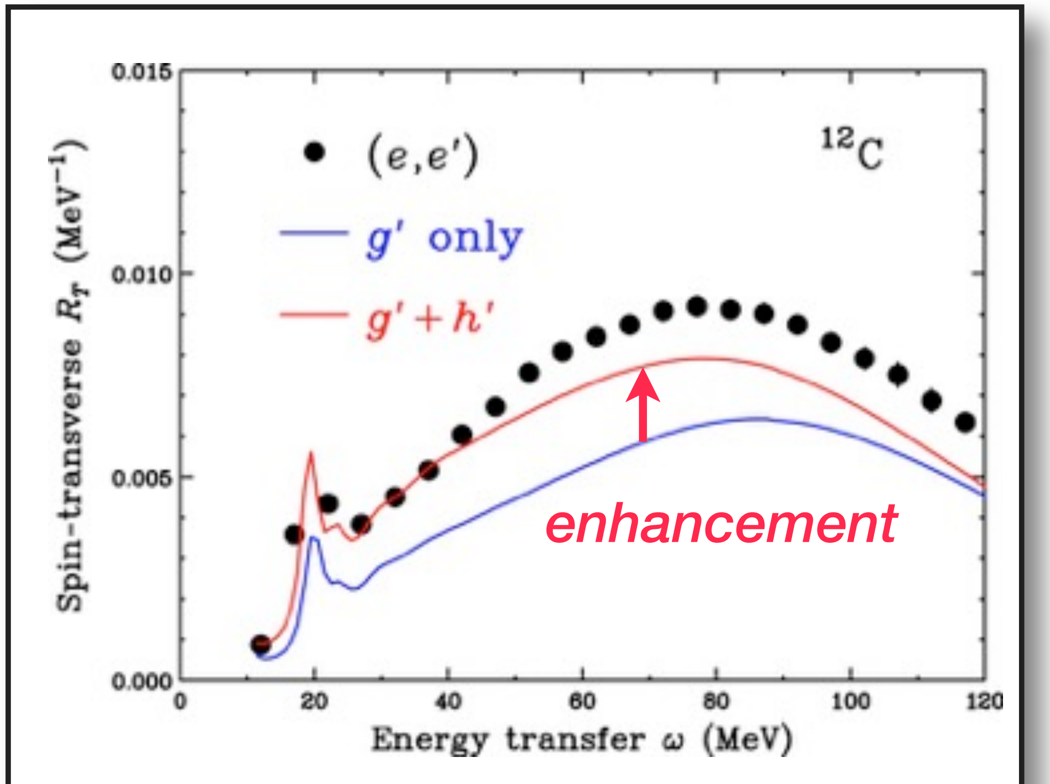
$$= [g' + 2h'](\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + [g' - h'](\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})$$

$$= g'\sigma_1 \cdot \sigma_2 + h' S_{12}(\hat{q})$$

Central *Short-range tensor*

Short-range tensor h'

- Spin-longitudinal (π) : $g'_\pi = g' + 2h'$
- Spin-transverse (ρ) : $g'_\rho = g' - h'$
- ***h' effects are attractive for ρ-mode***



Reasonably reproduce (e,e') response with h'

- Under-estimation at large ω would be 2p2h effects

Short-range tensor correlations in QES

Short-range tensor h'

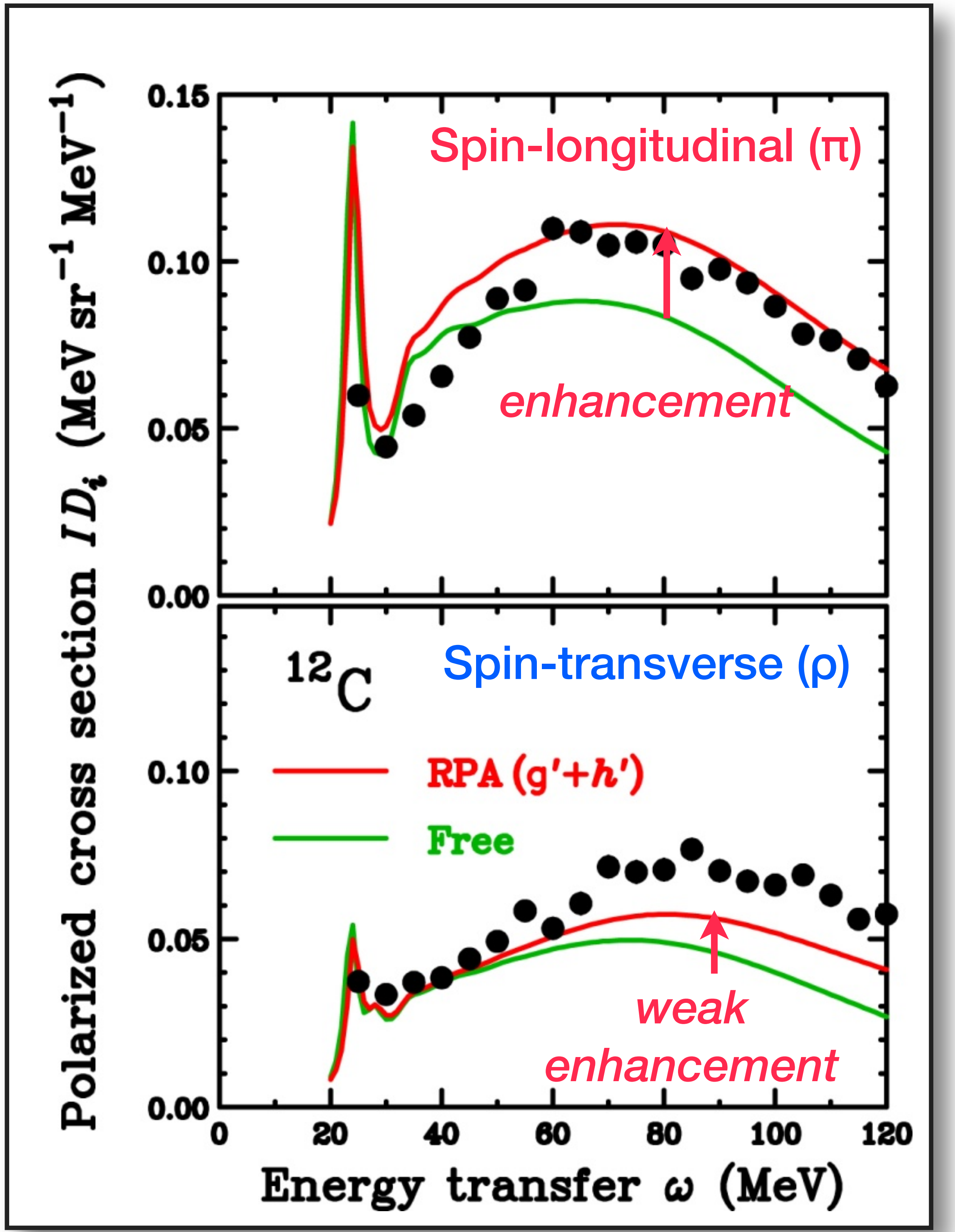
- Determined by (e,e') response
- Parameter-*free* calculations

Spin-longitudinal (π) mode

- g' (central) values are adjusted within errors
  - $g'_{NN} = 0.6 \rightarrow 0.5$
  - $g'_{N\Delta} = 0.35 \rightarrow 0.2$
- π + g'(less repulsive) + h'(repulsive)
  - **Net attractive effects for π-mode**
  - Enhancement of π-mode

Spin-transverse (ρ) mode

- ρ + g'(less repulsive) + h'(*attractive*)
  - **Repulsive effects by g' are *cancelled* by h'**
  - Weak enhancement of ρ-mode



Short-range tensor correlations can provide better descriptions for QES at large q
- Discrepancy at large ω → Higher order effects not included by h' ?

Tensor correlation effects on SDR

Spin-dipole resonance (SDR)

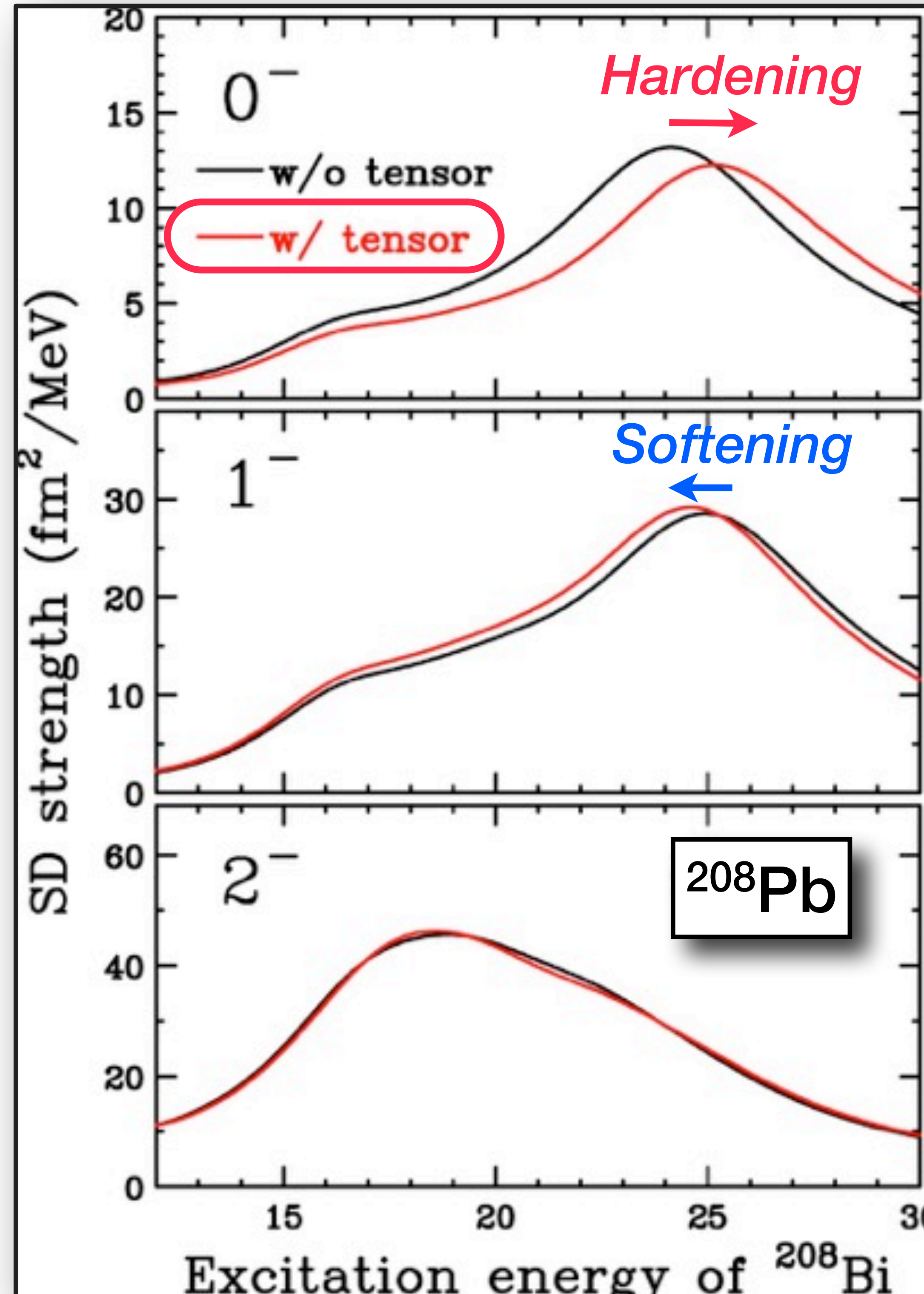
- Three different J^π
  - 0^- : Pure spin-longitudinal
  - 1^- : Pure spin-transverse
  - 2^- : mixed
- Typical q ~ 0.4 fm^{-1} (^{208}Pb)
  - *Tensor correlations might be important*

Tensor correlations

$$h' S_{12}(\hat{q}) = \underbrace{2h'(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q})}_{\text{longitudinal } (\pi)}$$

$$\underbrace{-h'(\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})}_{\text{transverse } (\rho)}$$

- Spin-longitudinal : repulsive
  - *Hardening* for 0^-
- Spin-transverse : attractive
  - *Softening* for 1^-



J^π dependent effects by tensor correlations are expected in SDR

Tensor force effects on SD strengths

Tensor force/correlation

- h’ treats tensor force for np (n-particle/p-hole)
- ***How about tensor force effects for nn/pp ?***

HF+RPA prediction for ^{208}Pb

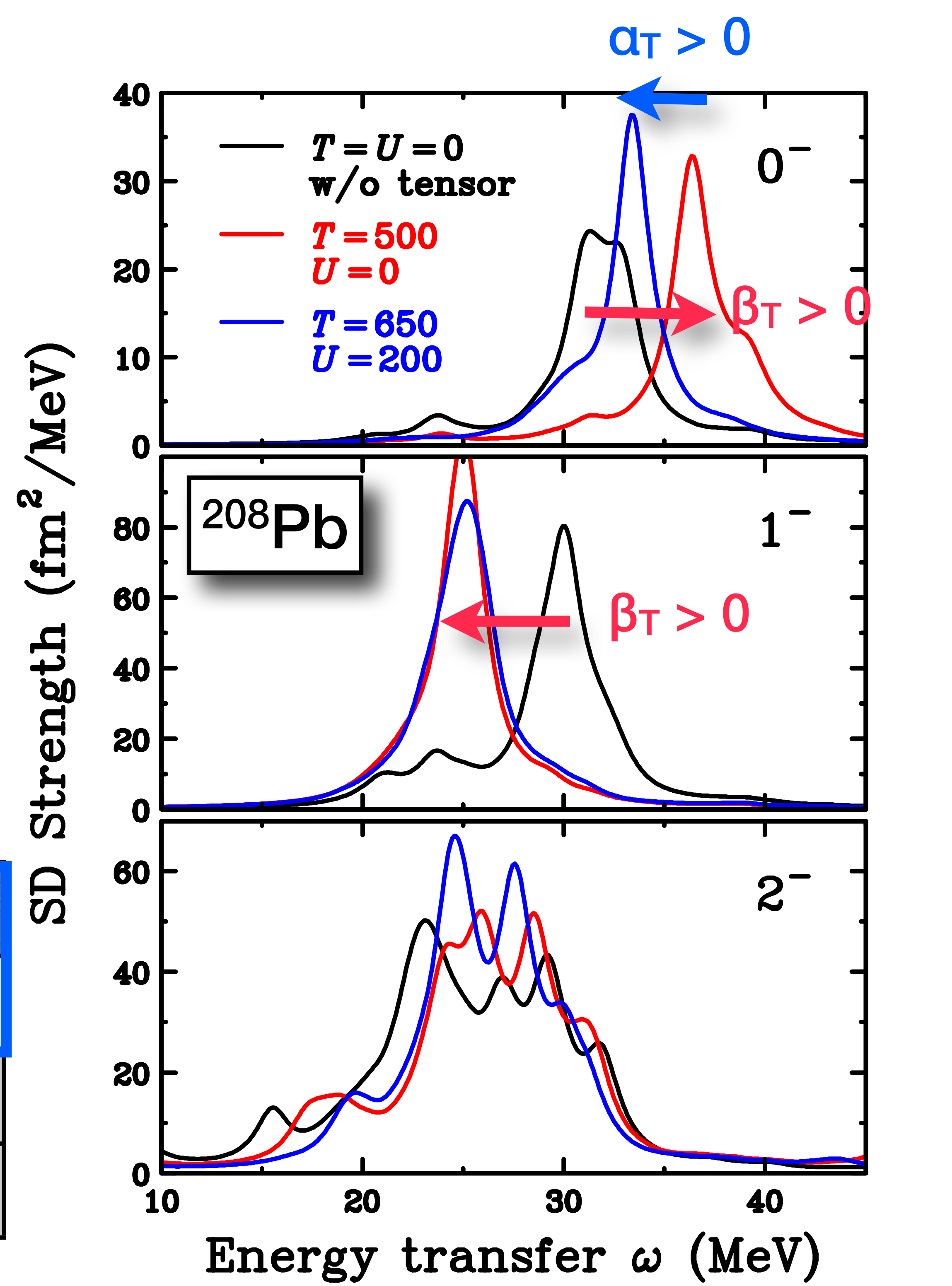
- RPA : Tensor effects depend on J^{π}

$$V^T \propto \beta_T + \alpha_T$$

β_T for *np* ↕ h'

α_T for *nn/pp*

	$\beta_T > 0$	$\alpha_T > 0$	$\alpha_T < 0$
0^-	hardening	softening	hardening
1^-	softening	insensitive	
2^-	insensitive		



Separated SD strengths would constrain both α_T and β_T *(nn/pp and np)*

This “experimental” work for ^{208}Pb(p,n)

New data and analysis for ^{208}Pb(p,n)

- Cross sections and analyzing powers at θ = 0.0° ∼ 10.0° (11 angles)
- Complete sets of polarization transfers at θ = 0.0° ∼ 7.0° (5 angles)

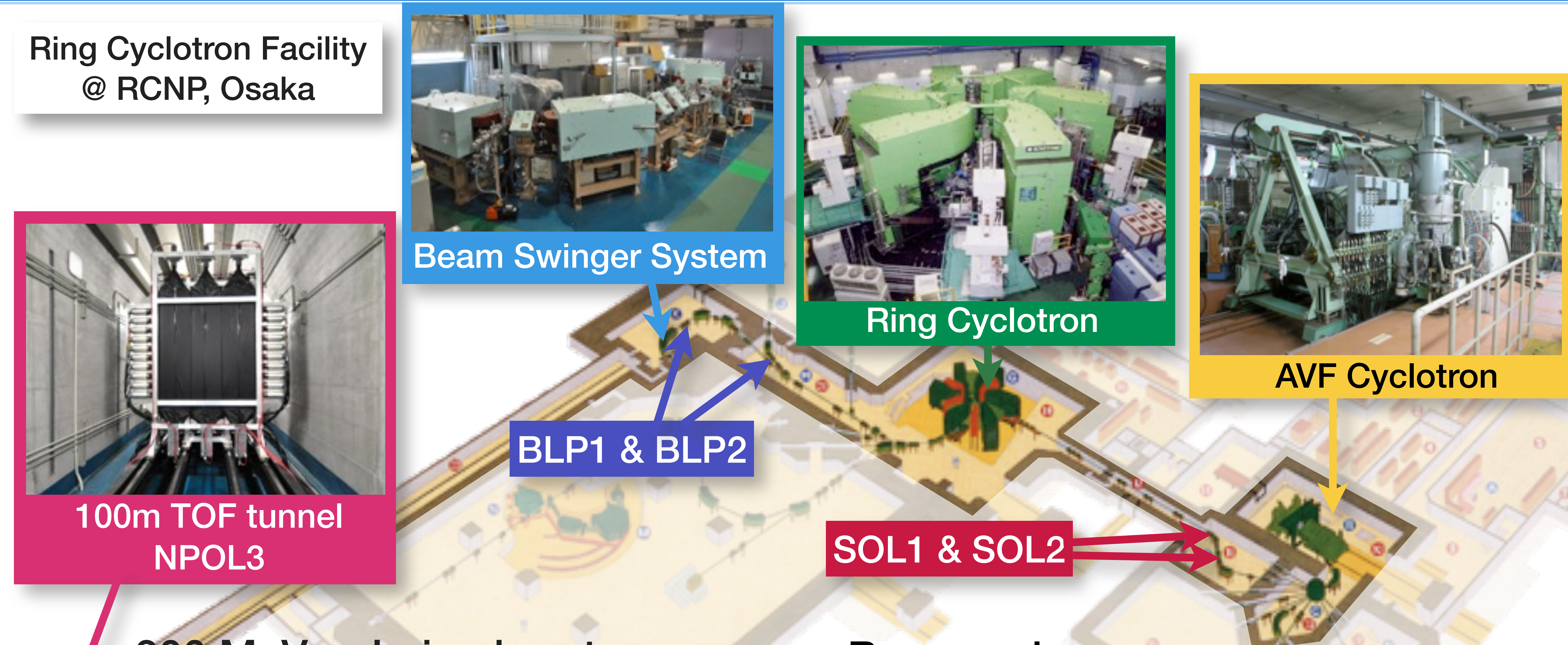
Goal

- Spin-parity J^{π} separated SD strengths for ^{208}Pb
  - Distribution of separated SD strengths
    - Tensor correlation effects on SD strengths

Tools

- Polarization transfer D_{ij}
  - Sensitive to ΔJ^{π} (0^-, 1^-, 2^-) → *advantage to high-resolution (^{3}He,t)*
- Multipole decomposition analysis (MDA) with polarization transfer D_{ij}
  - Based on reliable DWIA+RPA calculations

Experimental scheme and approach



300 MeV polarized protons

- Smallest distortion

Beam polarization

- Controlled by two solenoids
- Measured by two BLPs (p+p)

Beam swinger

- Θ = 0° - 10°

Neutron measurement

- NPOL3 with 70m TOF
- D_{ij} measurement with NSR

Experimentally identify J^{π} from cross section σ(θ) and spin transfer D_{ij}(θ)

Separation of SDR into each J^{π}

Separation of SDR (L=1) into 0^-, 1^-, 2^- is important

- Tensor effects depends on J^{π}

Normal multipole decomposition

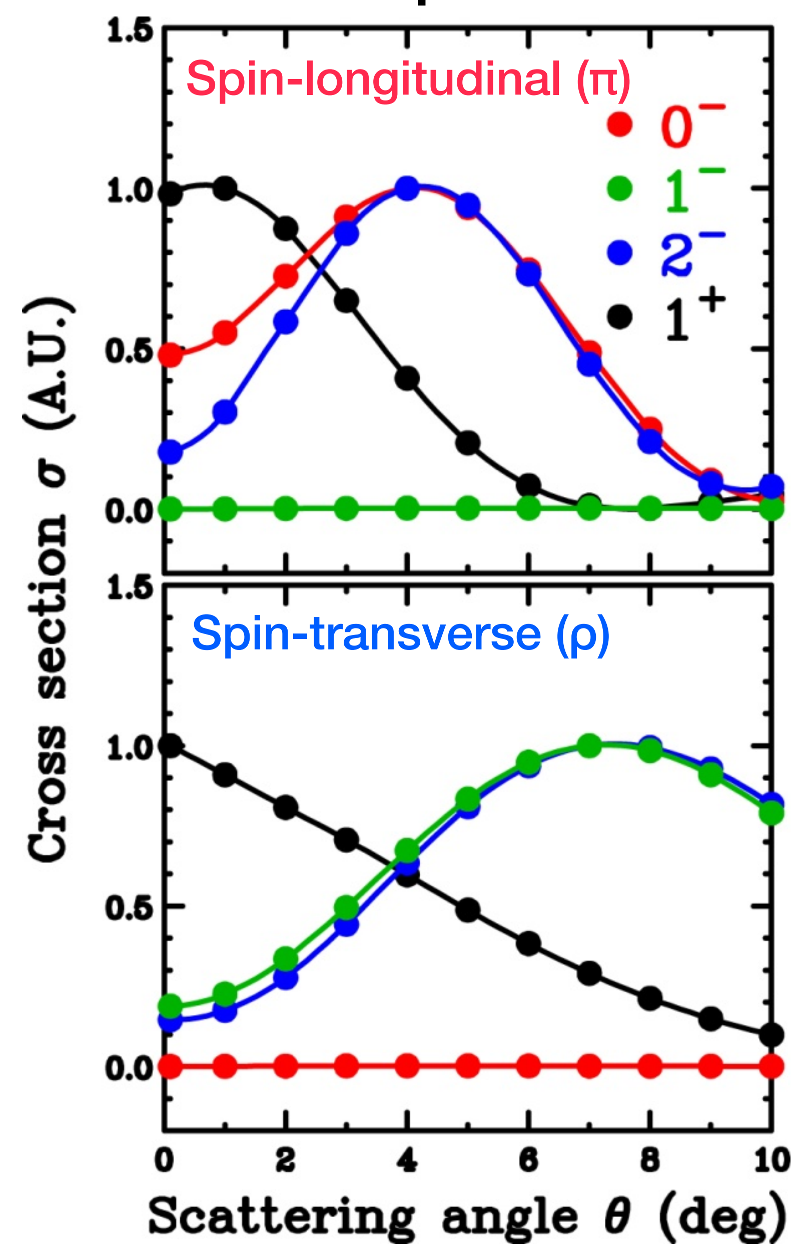
- Separate into each L component
  - Works very well to extract GT (L=0)
- Could NOT separate into J^{π} with same L
  - Angular distributions are governed by L

Idea to separate SDR into each J^{π}

- Polarization observables are sensitive to J^{π}
- Separate c.s. into longitudinal (π) - transverse (ρ)
  - 0^-: Spin-longitudinal (π) only
  - 1^-: Spin-transverse (ρ) only
  - 2^-: Both

Multipole decomposition for longitudinal (π) and transverse (ρ) c.s.
→ Can separate/specify not only L, but also J^{π}

DWIA prediction



Results of multipole (L and J^π) decomposition for ^{208}Pb

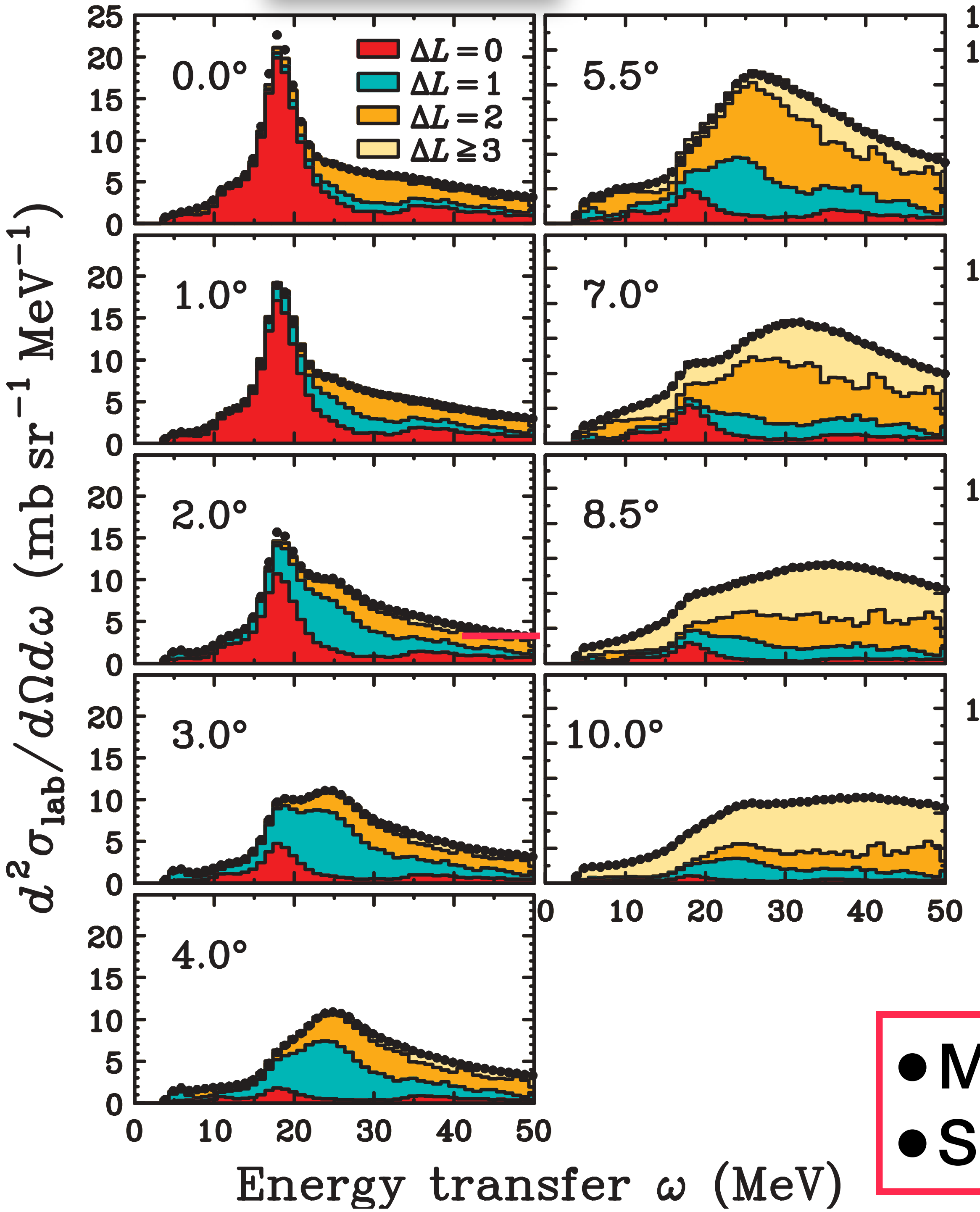
non-spin-flip $\Delta S = 0$

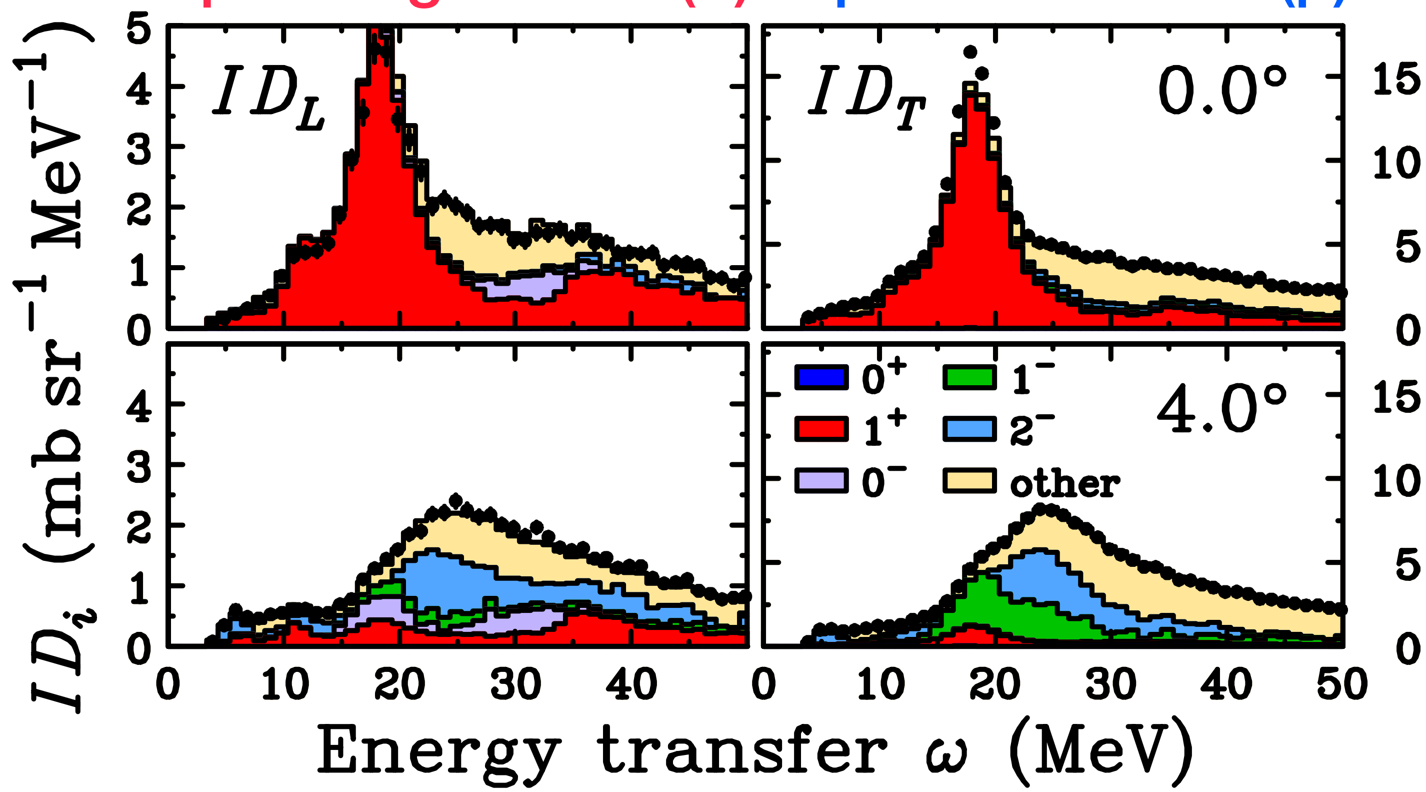
spin-flip $\Delta S = 1$

$$I = ID_0 + ID_L + ID_T$$

I(θ) → ΔL

Spin-longitudinal (π) Spin-transverse (ρ)





ΔL=0: 1^+	ΔL=0: 1^+
ΔL=1: 0^- and 2^-	ΔL=1: 1^- and 2^-

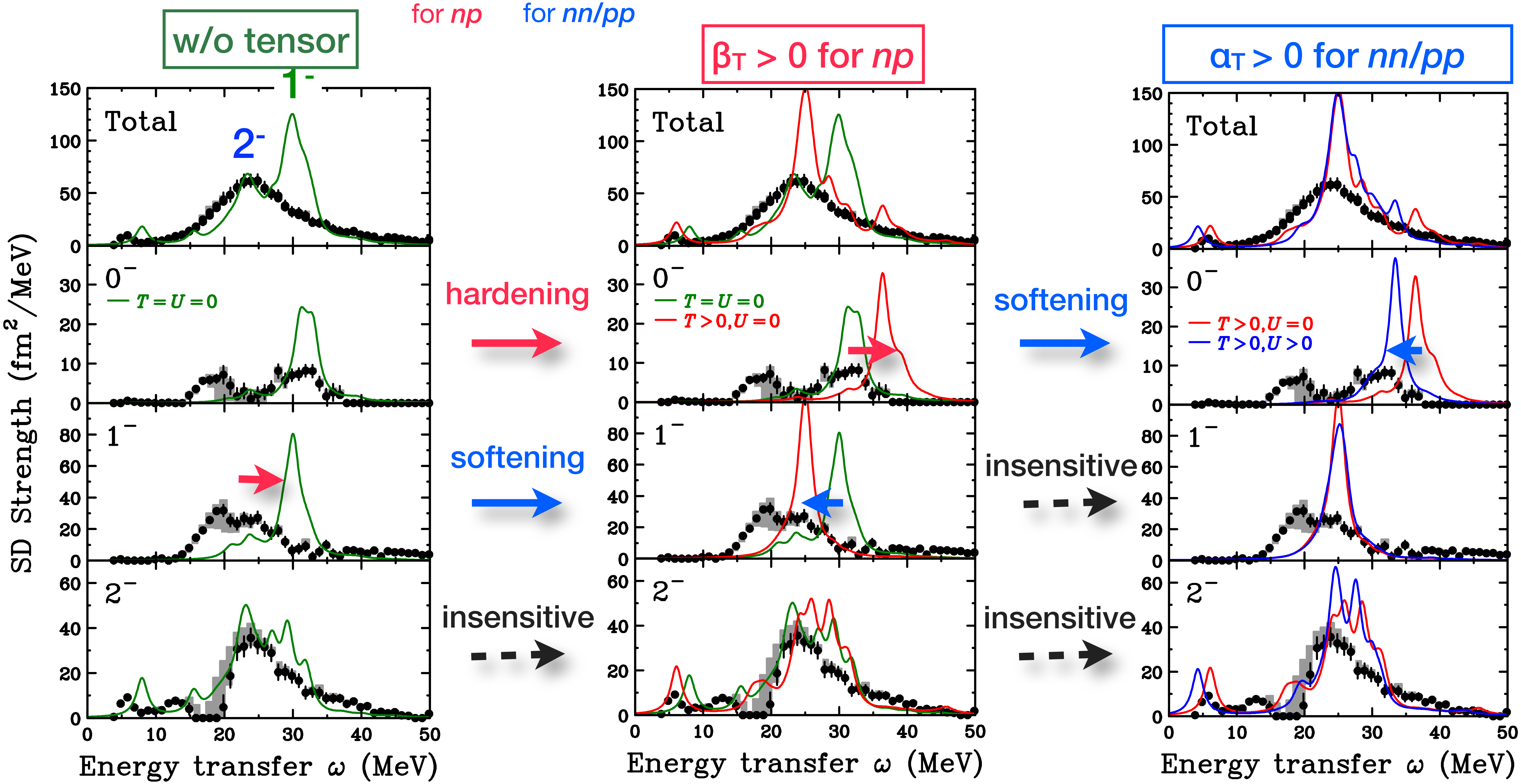
ID_L and ID_T → ΔJ^π

- Multipole (J^π) decomposition is successful
- SD strength is *separated* into 0^-, 1^-, and 2^-

Tensor force effects on SDR

Tensor force : $V^T \propto \beta_T + \alpha_T$ → J^π dependent effects on SDR

β_T for *np*, α_T for *nn/pp*



- Softening on 1- is reproduced by $\beta_T>0$ (tensor for np)
- Tensor effect on 0- is weak
  - Hardening by $\beta_T>0$ should be cancelled by softening by $\alpha_T>0$

•$\beta_T \sim 200$ MeV fm^5

•$\alpha_T \sim 100$ MeV fm^5

Conclusion and Outlook

Correlations in spin-isospin responses at large q

- Signature of pionic enhancement a precursor of pion condensation
  - Pure π-mode in ^{16}O is separated experimentally ***by dispersion matching technique***
- Enhancement in spin-transverse mode is partly explained by short-range tensor h'

SDR strength

- **First exp./theor. findings for tensor force effects in GR**
- ***Softening*** effect for 1^-
  - ***Positive*** β_T ～200 [MeV fm^5] tensor force for np
- ***Small effect*** for 0^-
  - ***Positive*** α_T ～100 [MeV fm^5] tensor force for nn/pp
- Similar to β_T=238 [MeV fm^5] and α_T=135 [MeV fm^5] by low-q limit of G-matrix calc.

Outlook

- Systematic measurements of SDR (in neutron-proton asymmetric nuclei, isospin dep.)
- Absolute values for SD strengths
  - Sum-rule will give information on neutron skin and/or quenching
  - Calibration of $\hat{\sigma}_{SD}$ with RI beams