Electroweak pion-production on nuclei within DCC approach

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ANL-Osaka DCC model

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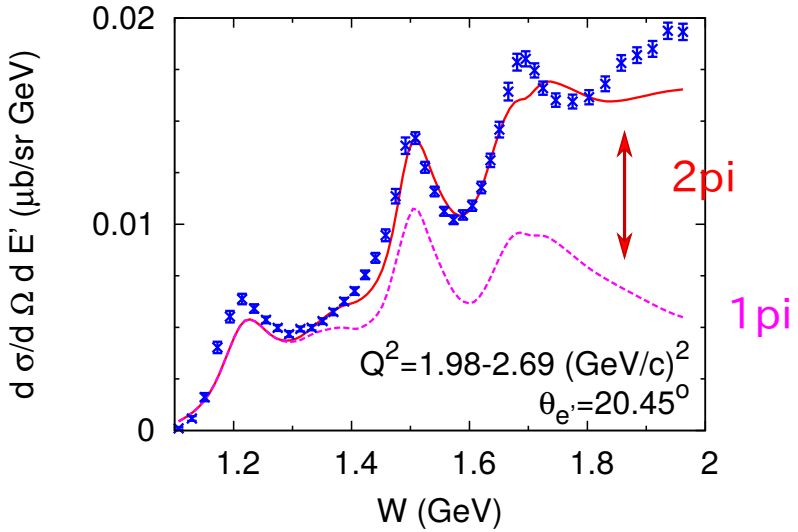
- Primary objective: investigate spectrum and structure of nucleon resonances(Δ, N^*)
- Coupled channel reaction model for pion, photon, electron and neutrino induced meson production reaction on nucleon.
- Realistic amplitudes for πN, ηN, $\pi\pi N(\rho N, \sigma N, \pi\Delta)$, $K\Lambda, K\Sigma$ productions up to $W < 2GeV$

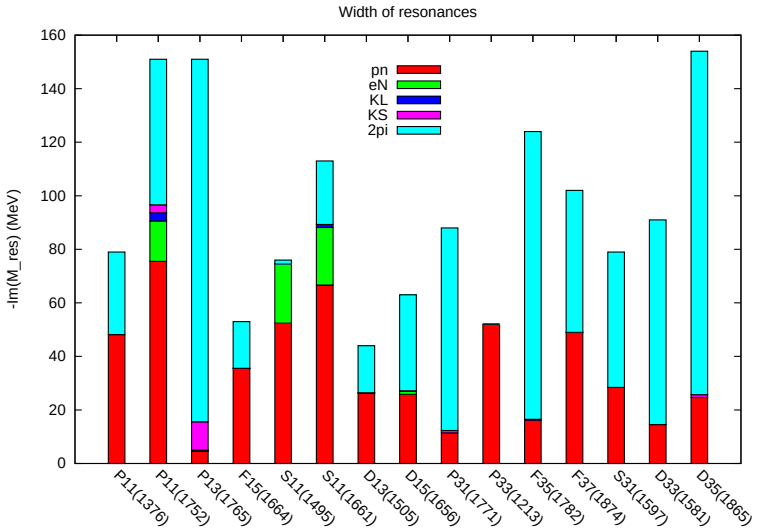
https://www.rcnp.osaka-u.ac.jp/~anl-osk/ (passwd anlosaka2022)

https://www.phy.anl.gov/theory/research/anl-osaka-pwa/

$e + p \to e' + X(E_e = 5.498GeV)$

'Width/2' of N^*, Δ (π red,2π light blue)



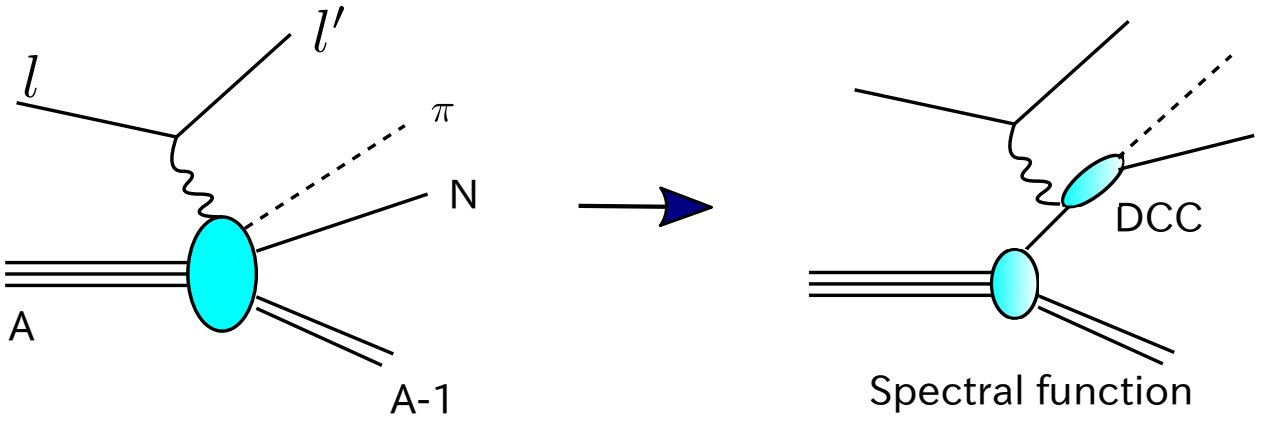


Note:

- Limitation: $m_N + m_\pi < W < 2GeV$ and $0 < Q^2 < 3GeV^2$
- to be improved:
  - multi-pion production for higher W
  - Axial vector form factor
  - Iso-vector/Iso-scalar decomposition of N^* transition form factors

Application of DCC model for nuclear EW reactions

Examine (e, e') and (ν, μ) reactions on ^{12}C and d within DCC model



based on collaboration with N. Rocco, A. Lovato, T. -S. H. Lee, O. Benhar

Application of DCC model for nuclear EW reactions

Nuclear hadron tensor (nuclear $W_A^{\mu\nu}$) using spectral function $P(\boldsymbol{p}, E)$

$$W_A^{\mu\nu} = \int d\boldsymbol{p} dE \; P(\boldsymbol{p}, E) \; w^{\mu\nu}(p^\mu, \tilde{q}^\mu)$$

where nucleon's hadron tensor $w^{\mu\nu}$(similar expression for CC)

$$w^{\mu\nu}(p^\mu, \tilde{q}) = (-g^{\mu\nu} + \frac{\tilde{q}^\mu \tilde{q}^\nu}{\tilde{q}^2}) W_1(\tilde{W}, \tilde{Q}^2) + \frac{W_2(\tilde{W}, \tilde{Q}^2)}{M_N^2} (p^\mu - \frac{p \cdot \tilde{q}}{\tilde{q}^2} \tilde{q}^\mu)(p^\nu - \frac{p \cdot \tilde{q}}{\tilde{q}^2} \tilde{q}^\nu)$$

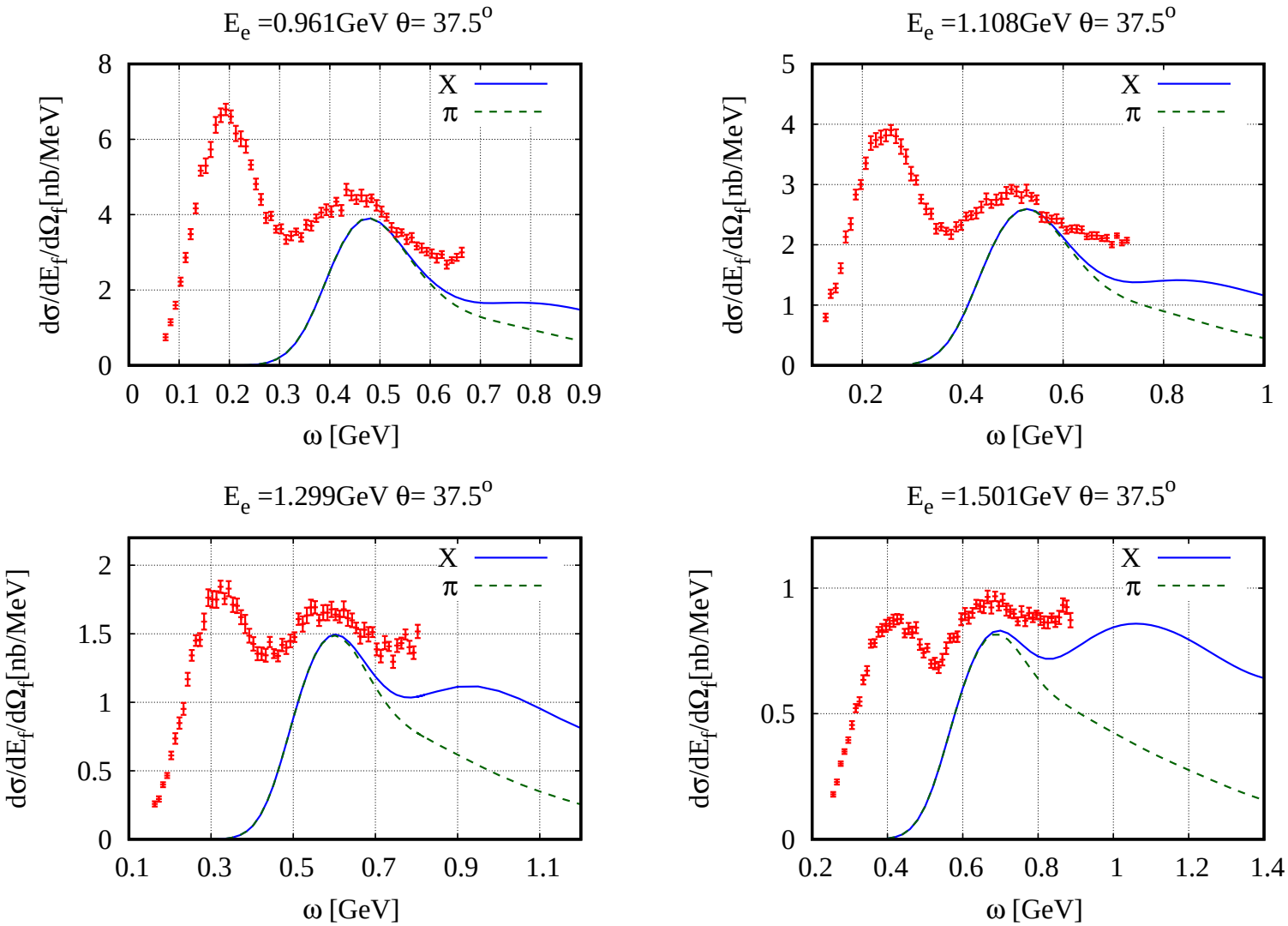
- $(e, e'\pi)$ and $(e, e'X)$ including 2π can be easily calculated by using W_i of DCC model.
- Effective energy transfer(O. Benhar et al. PRD72,053005(2005))

  $q^\mu \to \tilde{q}^\mu = (\tilde{\omega}, \boldsymbol{q})$ with $E_{hadron} = \tilde{\omega} + E_p = \omega + M_A - \sqrt{(M_A - M_N + E)^2 + \boldsymbol{p}^2}$

  $\tilde{W} = \sqrt{(p + \tilde{q})^2}$ with $p^\mu = (E_p, \boldsymbol{p})$ and $E_p = \sqrt{M_N^2 + \boldsymbol{p}^2}$
- nuclear effects such as pion absorption, medium modification of resonance are not included.

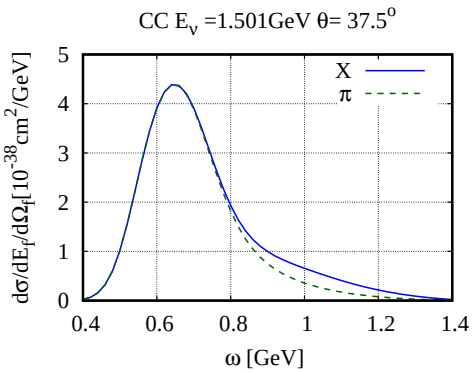
Double differential cross section $^{12}C(e, e'X)$

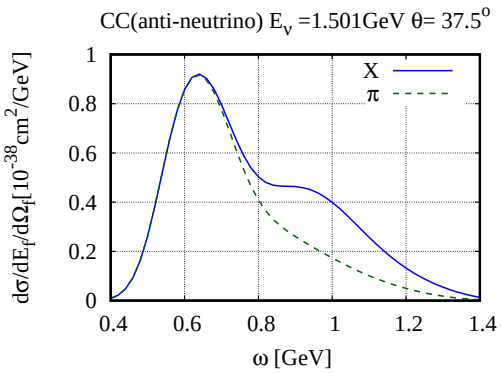
inclusive cross section $d\sigma/dE_{e'}/d\Omega_{e'}$ of $e + ^{12}C \to e' + X$

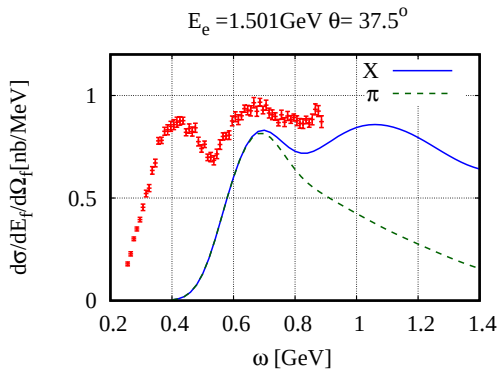


Double differential cross section EM CC

$\nu_\mu + {}^{12}C \to \mu^- + X$ $\bar{\nu}_\mu + {}^{12}C \to \mu^+ + X$ $e + {}^{12}C \to e' + X$





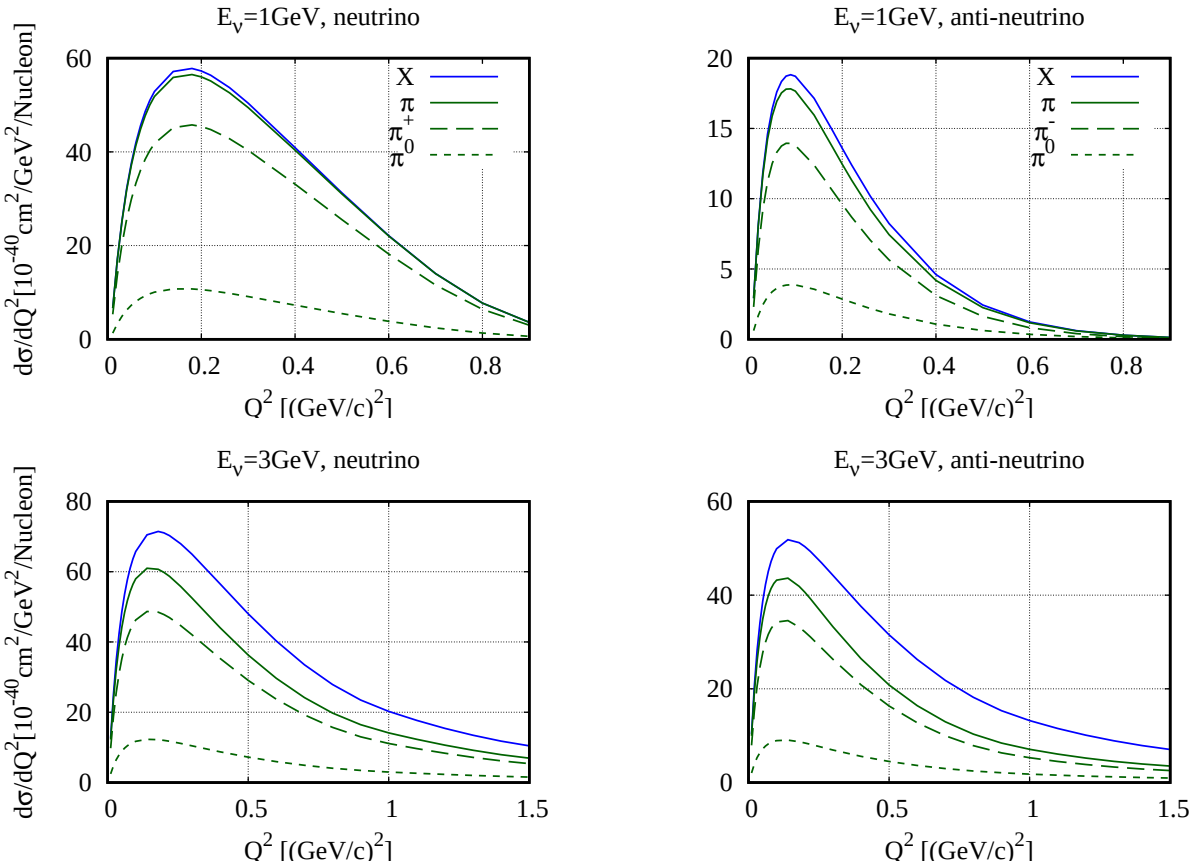


- ν_μ CC: single pion(mostly Delta) dominated
- $\bar{\nu}_\mu$ CC: appreciable contribution of 2π

$d\sigma/dQ^2$ neutrino/anti-neutrino-^{12}C

$$(\frac{d\sigma}{dQ^2}(^{12}C) + \frac{d\sigma}{dQ^2}(p))/13$$

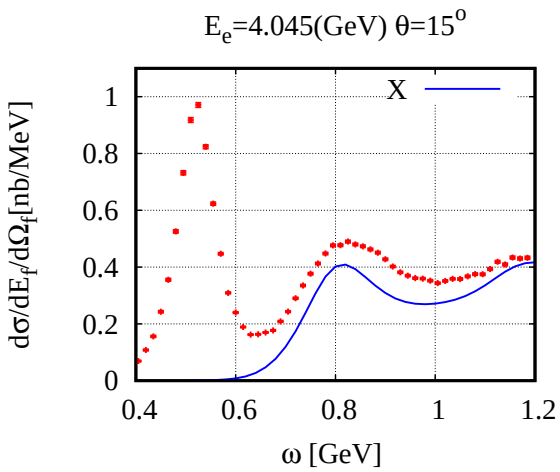
all final state(solid blue), pion(solid green), Charged pion(long dash), Neutral pion(short dash),



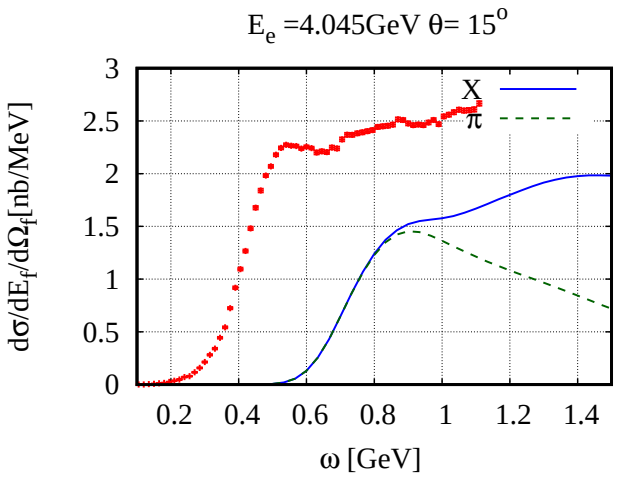
- 1GeV: almost single pion(green $\sim$ blue)
- 3GeV: appreciable contribution of 2π (blue -green)

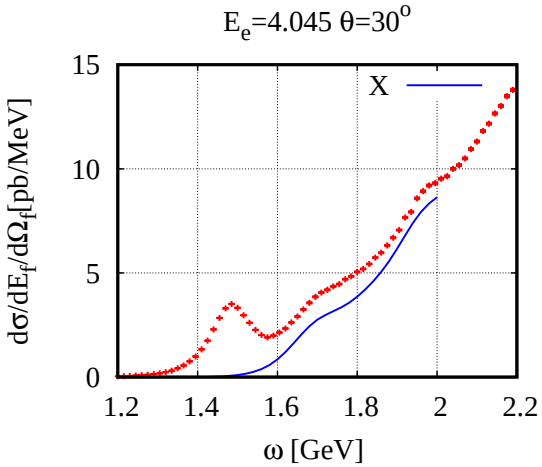
Double differential cross section $d(e,e'X)$ and $^{12}C(e,e'X)$

$e + d \to e' + X$

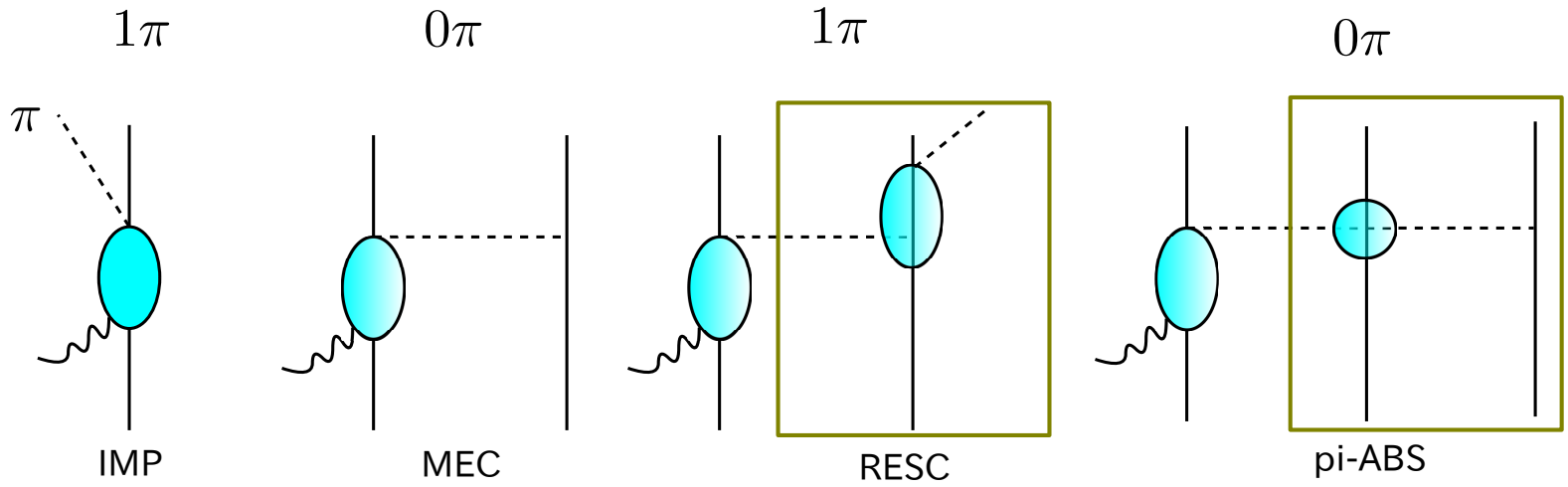


$^{12}C + d \to e' + X$



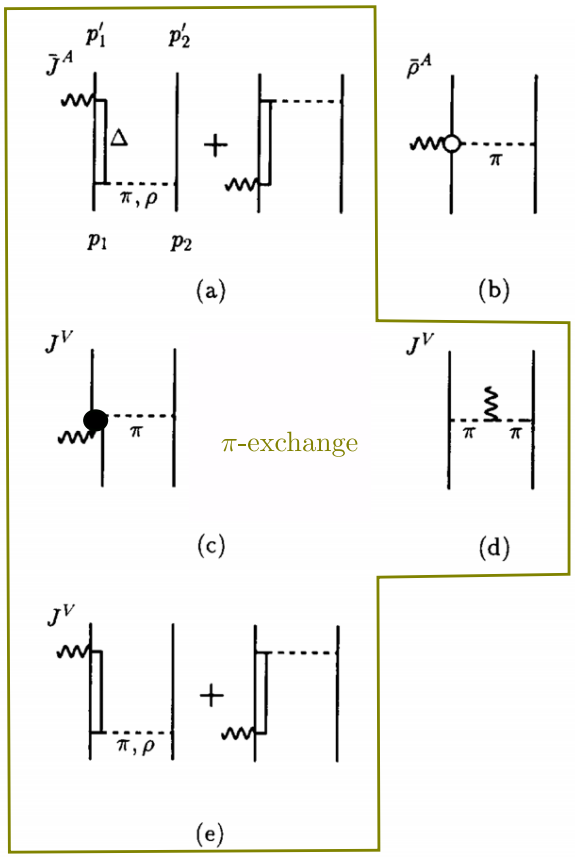


Nuclear pion production



- pion absorption by N $\sim$ MEC
- MEC: effective operator within nucleon Fock-Space by elimination non-nucleon degrees of freedom. When energy of the system is above pion production threshold, MEC might be modified.
- DCC amplitudes may be used for each mechanism

MEC

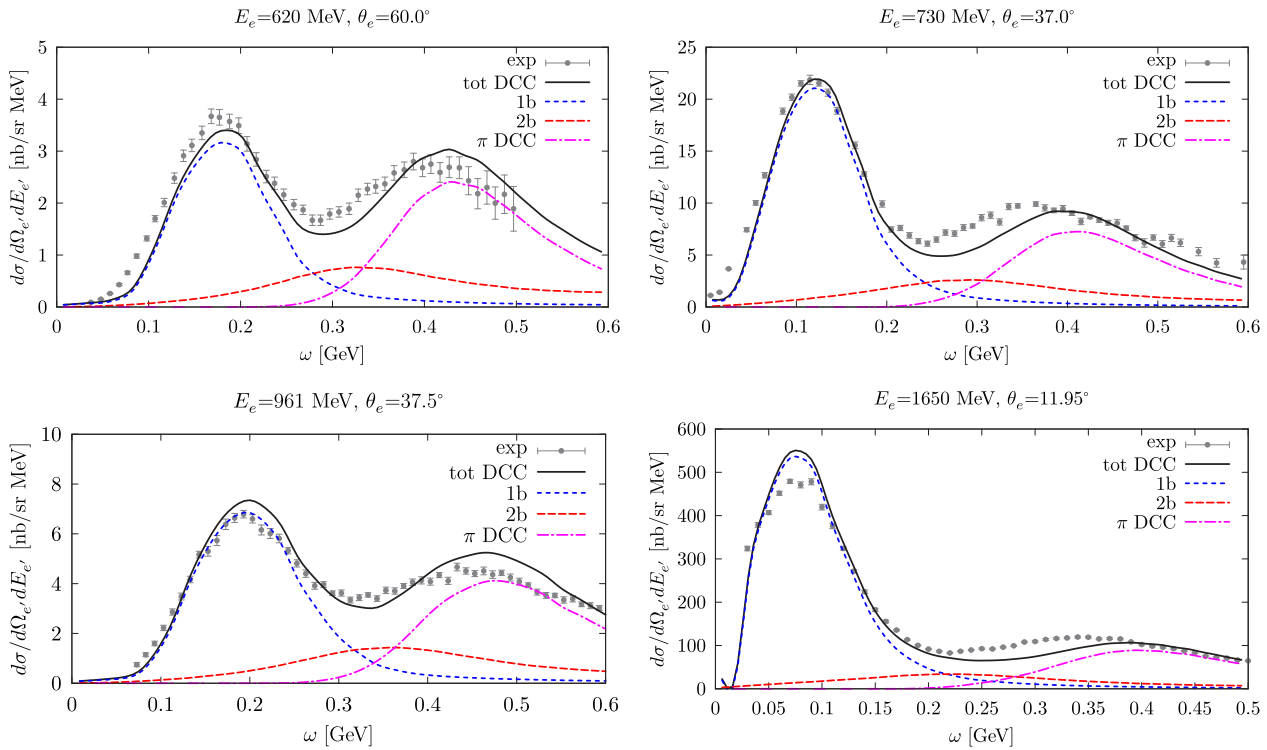


- MEC diagrams for muon capture $\pi + \rho$
  (M. Doi, T. Sato, H. Ohtsubo, M.Morita NPA511(1990)507)
- (1body + 2body + πDCC) is studied for $e - {}^{12}C, \nu - {}^{12}C$

  N. Rocco,S.X. Nakamura,T.-S.H.Lee, A. Lovato Phys. Rev. C100,045503 (2019)
  pion exchange, medium effect in Delta propagator

Double differential cross section $^{12}C(e, e'X)$

N. Rocco, S.X. Nakamura, T.-S.H.Lee, A. Lovato Phys. Rev. C100,045503 (2019)



- reasonable agreement with data
- $W^{\mu\nu}$ is calculated directly from $< \pi N|J^{\mu}|N >$.

Discussion

Possible contribution of ANL-Osaka model for lepton-nucleus reaction

- Q^2 and W dependence of MEC/Pion absorption

  Use pion/meson production amplitudes of ANL-Osaka model

  analysis of $d(e,e')$ reactions

  possible MEC for 1pi process

- Modification of propagation of nucleon resonances inside nuclei

  simple parametrization of ANL-Osaka amplitudes of pion and $\rho, \sigma, \pi\Delta$ for major partial waves($P_{33}, D_{13}, ..$).

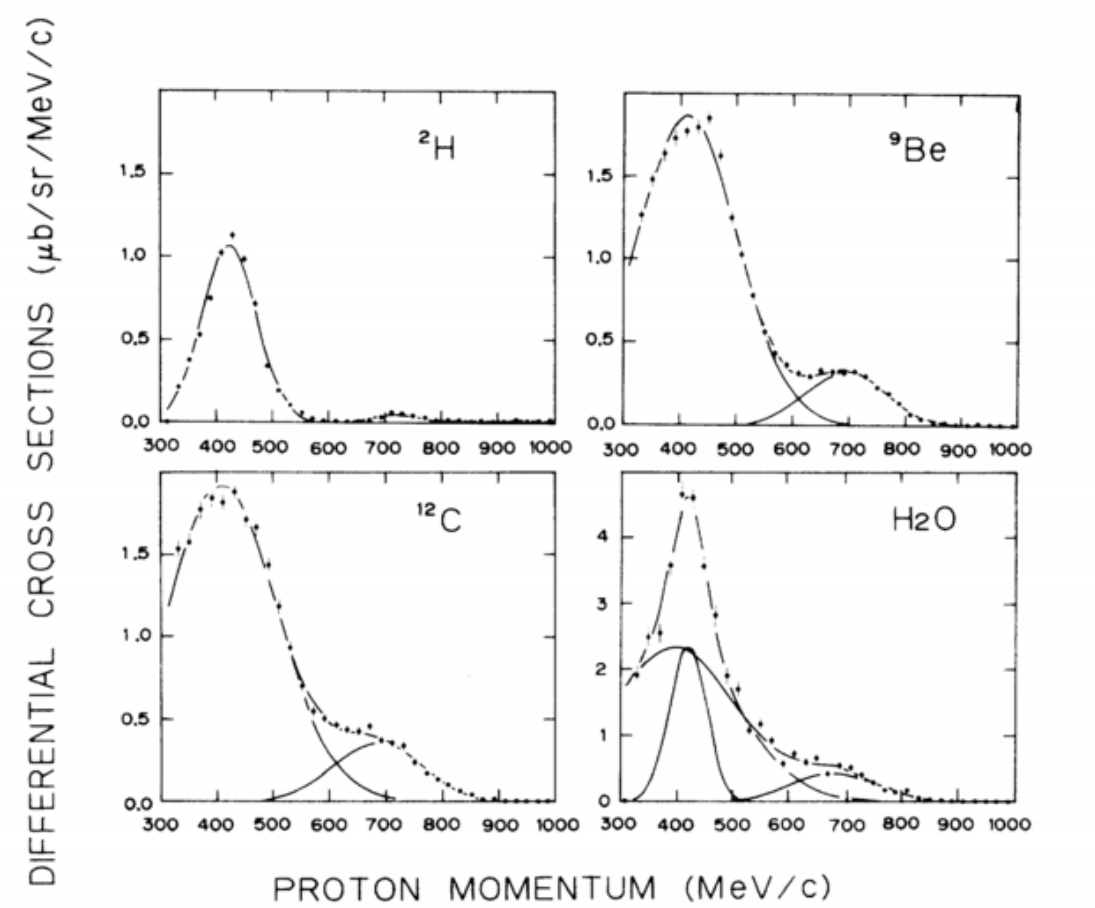
  Example:Mittag-Leffler expansion using uniformization variable for $P33$

  W. Yamada, O. Morimatsu, PRC102, 055201 (2020)
  W. Yamada, O. Morimatsu, T. Sato, K.Yazaki, PRD105, 014034(2022)

- Axial vector response, form factors

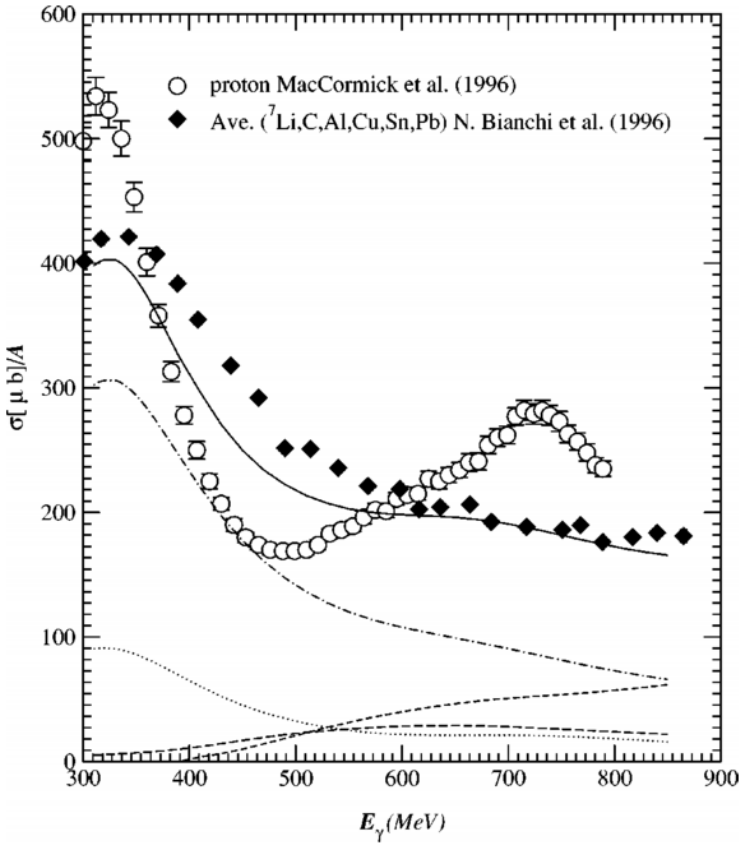
  Examine $p(e,e'\ \ \text{soft}\pi)X$ as a possible 'axial vector' probe.

- signal on two-body photo absorption



$A(\gamma, p)X$ at $E_\gamma = 375MeV$,Kanazawa et al. PRC 35,1828 (1987)

- Medium effects in N^* region



Nuclear Photo absorption cross section
(M. Hirata et al., PRC66,014612(2002))