# Simulation of Single-Pion Production Reactions Using the ANL-Osaka DCC Model in the NEUT Neutrino Event Generator

- Introduction to NEUT Single-Pion Productions
- Implementation of DCC model into NEUT
- Investigation of nuclear models

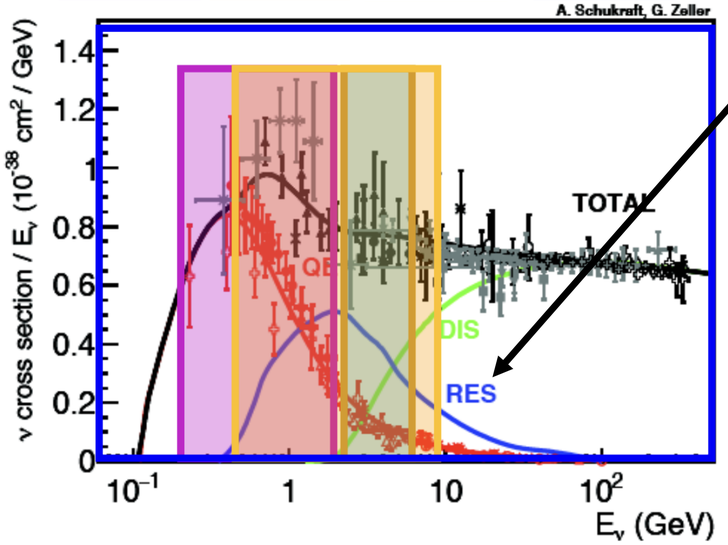
**Seisho Abe (安部 清尚)**
seisho.abe@riken.jp
RIKEN Nishina Center / ICRR, UTokyo

The 15th International Workshop on the Physics of Excited Nucleons – 9th September, 2026

# Role of Single-Pion Production (SPP) in ν physics

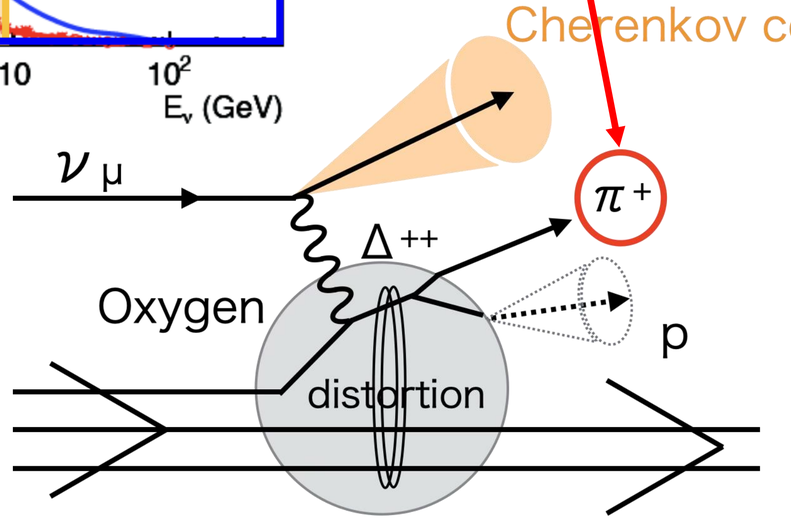
## sub-dominant channel in ν osc. exp.

T2K NOνA DUNE ATM ν

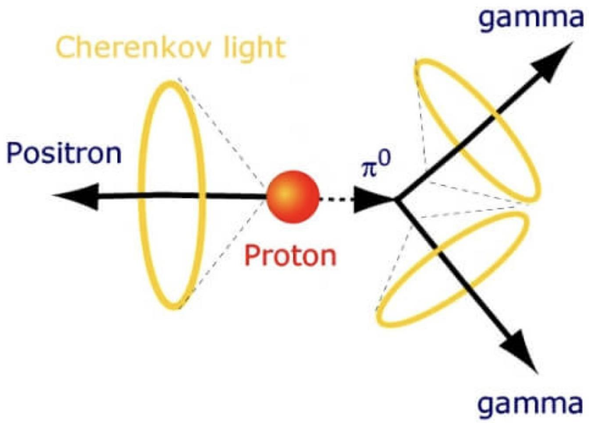



SPP

Key: π absence/presence, and its kinematics

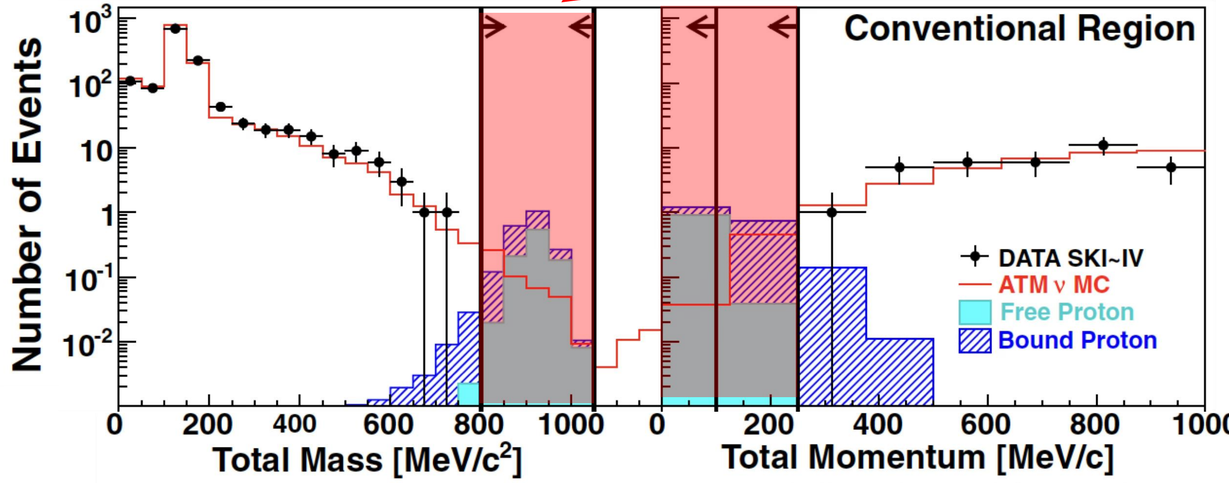



## Major BG in nucleon decay search.




Select “back-to-back” events, but atm. ν BG remains.

**signal region**




*Partially adapted from Phys. Rev. D 102, 112011 (2020)*

- Neutrino experiments are entering into a high-precision era.
  - c.f.) Hyper-Kamiokande, DUNE, JUNO, etc.
- **Precise prediction of SPP by event generator is required.**

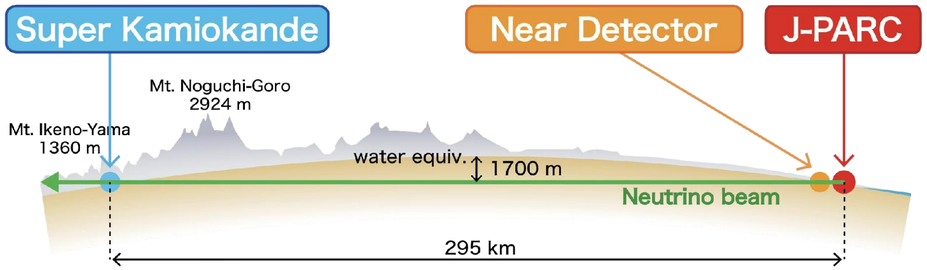
# NEUT neutrino event generator

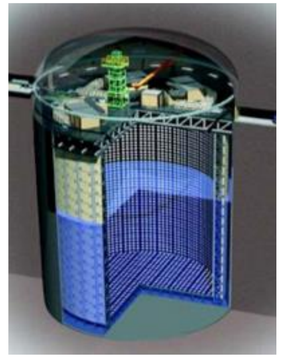
- Born for the Kamiokande experiment (NOT Super-K) in the 1980s.

*Y. Hayato and L. Pickering,*
*Eur. Phys. J. Special Topics 230, 4469 (2021).*

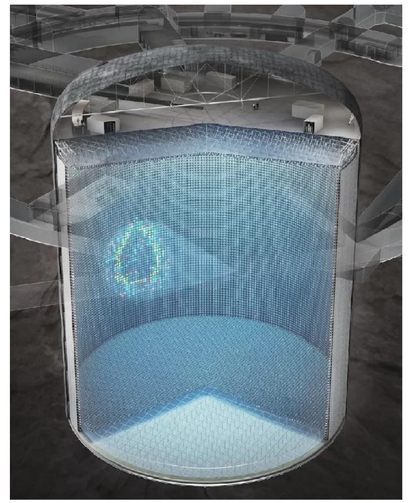
```
(Creation Date and Author)
  1983.??.?? ; M.NAKAHATA
  1987.08.?? ; N.SATO     FOR TAU
  1988.08.31 ; T.KAJITA   DATA UPDATE
  1988.09.06 ; T.KAJITA   R1314 IS ADDED
```

- Mainly used in experiments in Japan: Super-K and T2K.
  - The primary target is **water**, but it can be used for carbon, iron, etc.



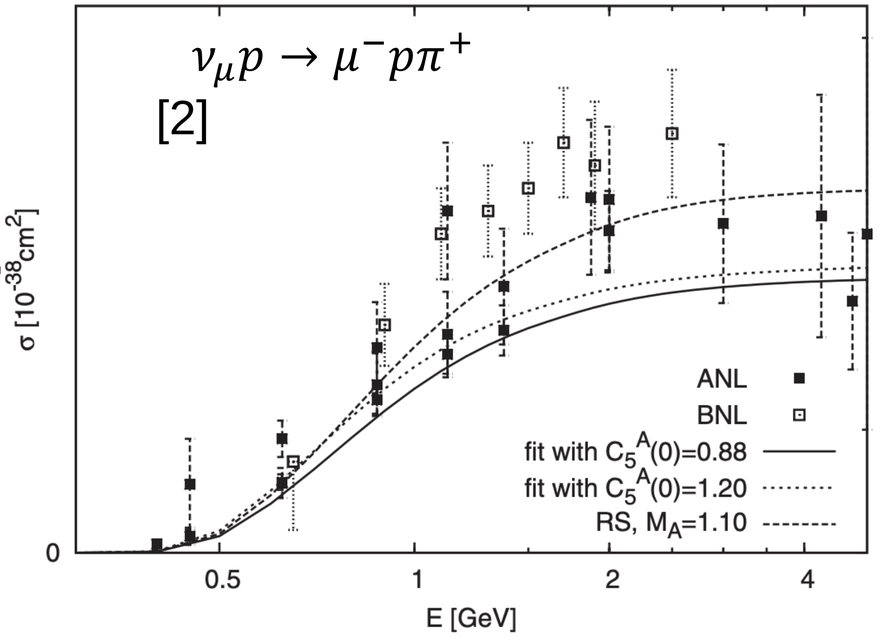
- Not open to public yet.
  - Contact us if you are interested in.
  - We have started discussion to make it public among developers.



- Aiming for Hyper-K and other next-generation neutrino experiments, we keep developing NEUT.

# SPP in NEUT

- Rein-Sehgal (RS) model has been used for long-time.
  - with Graczyk-Sobczyk form factor
  - with Berger-Sehgal lepton mass effects.
  - It accounts for interference among resonances.
  - Nonresonant background is included incoherently.
    - Interference terms are not included.




- **Several state-of-the-art SPP models were (are being) implemented.**
  - ANL-Osaka Dynamical Coupled-Channels (DCC) model
  - MK model and HNV model ← ongoing

*[1] D. Rein and L. M. Sehgal, Ann. Phys. (N.Y.) 133, 79 (1981).*
*[2] Graczyk-Sobczyk, PRD 77, 053001 (2008).*
*[3] C. Berger and L. M. Sehgal, Phys. Rev. D 76, 113004 (2007).*
*[4] S. X. Nakamura et al., Phys. Rev. D 92, 074024 (2015).*

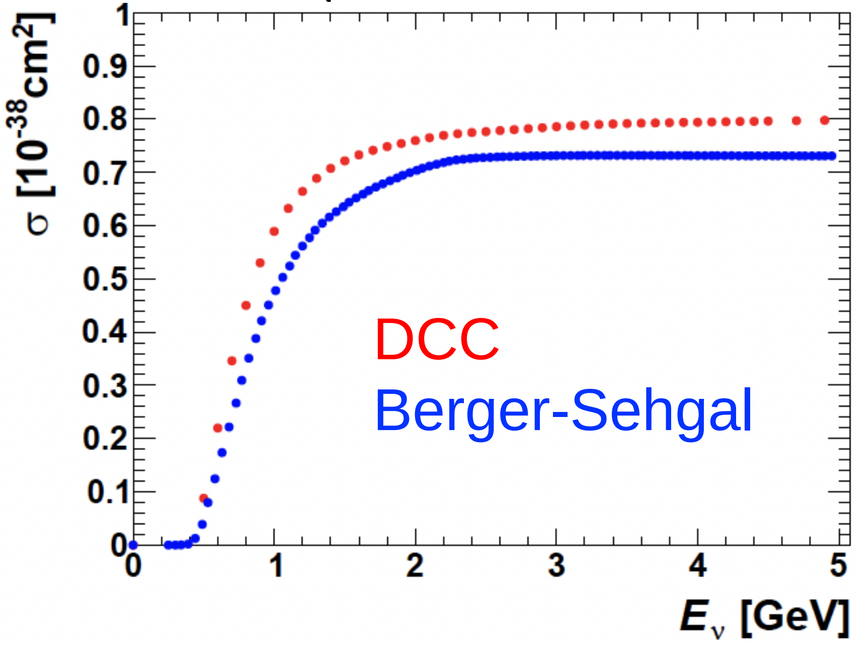
# Previously, the ANL-Osaka DCC model in NEUT



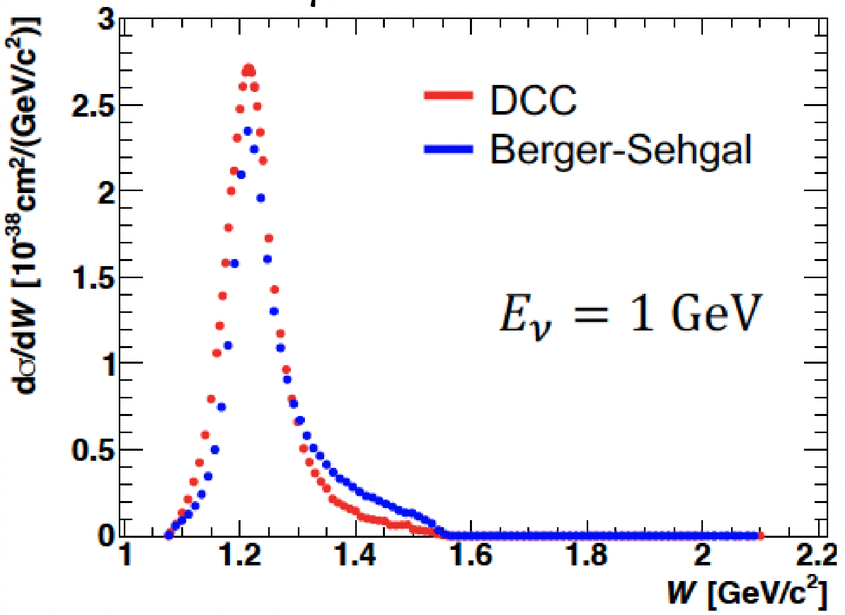
- Initial implementation to NEUT was conducted [5].
- DCC has larger Xsec than Berger-Sehgal for $\nu_\mu p \to \mu^- p \pi^+$.
  - The relation varies depending on the channel.
- Implemented also for electron-pion production [6].

*[5] K. Yamauchi et al., Proc. Sci. TAUP2023 (2024) 340*
*[6] S. Abe, PRD 111, 033006 (2025).*

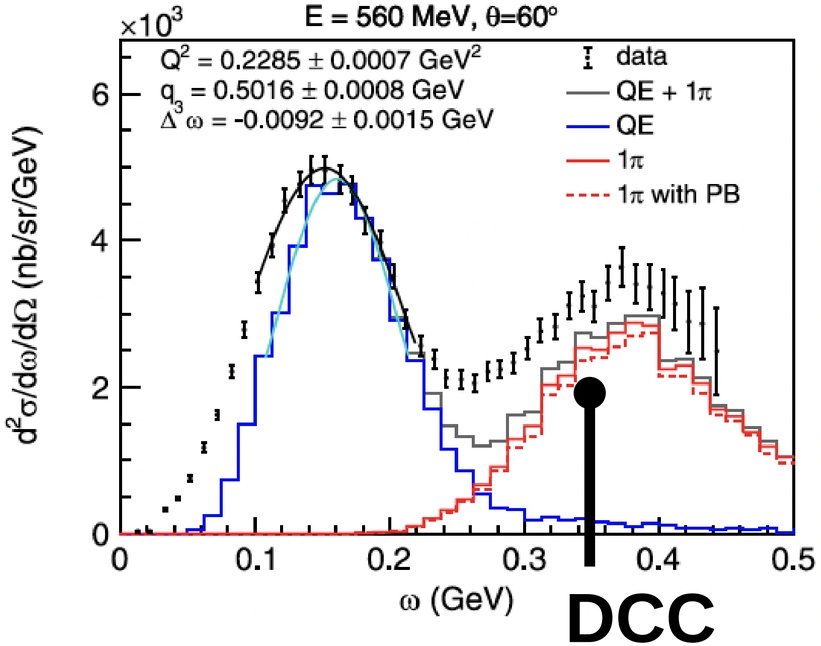
$\nu_\mu p \to \mu^- p \pi^+$




$\nu_\mu p \to \mu^- p \pi^+$




$(e, e')$



# Recent updates on DCC model in NEUT

**Previous**

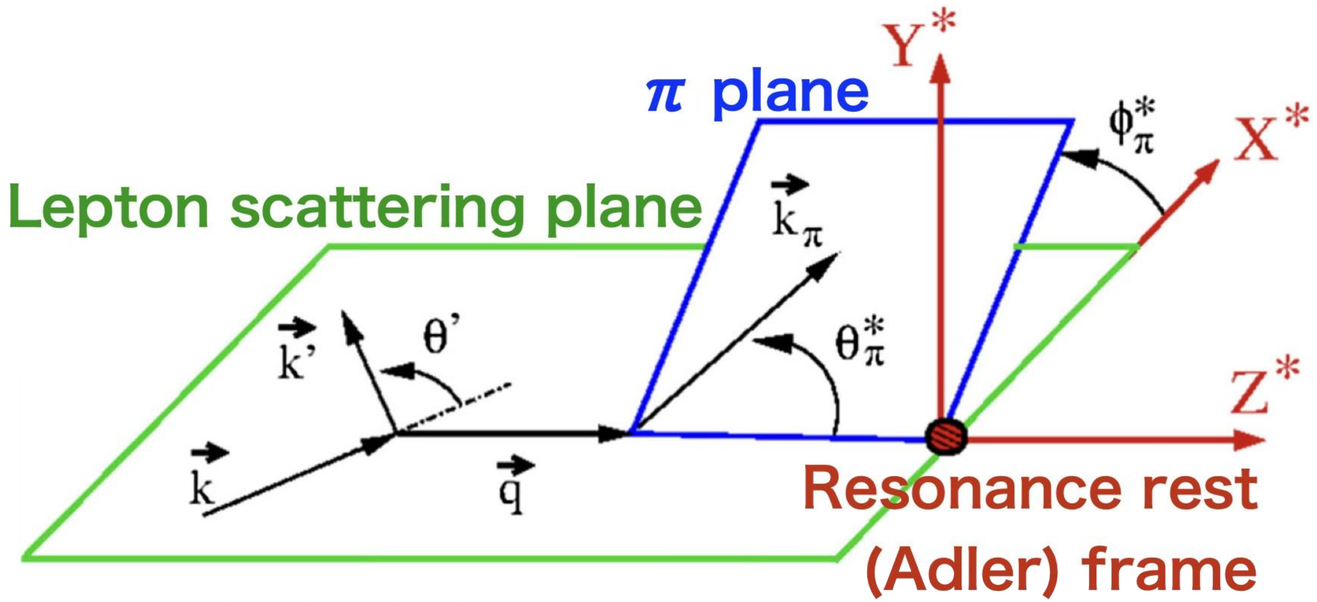
$$\frac{d^2\sigma}{dWdQ^2}(E_\nu)$$

- Isotropic $\cos\theta_\pi^*$ and $\phi_\pi^*$ (Adler angels) distributions are assumed.
- Tabulated structure functions are used.

**New**

$$\frac{d^4\sigma}{dWdQ^2 d\cos\theta_\pi^* d\phi_\pi^*}(E_\nu)$$

- $\cos\theta_\pi^*$ and $\phi_\pi^*$ are calculated & sampled as well.
- Achieved by having the tabulated multiple amplitude.
- Preliminary results were shown in NuInt2026. Completed implementation after that.




- Additional dimensions make event sampling slow.
- But, after optimization, it's sufficiently fast.
  - ~10 min/100k evts.
  - c.f.) previous: ~2-3 min/100k evts.

*J. E. Sobczyk et al., Phys. Rev. D 98, 073001 (2018).*

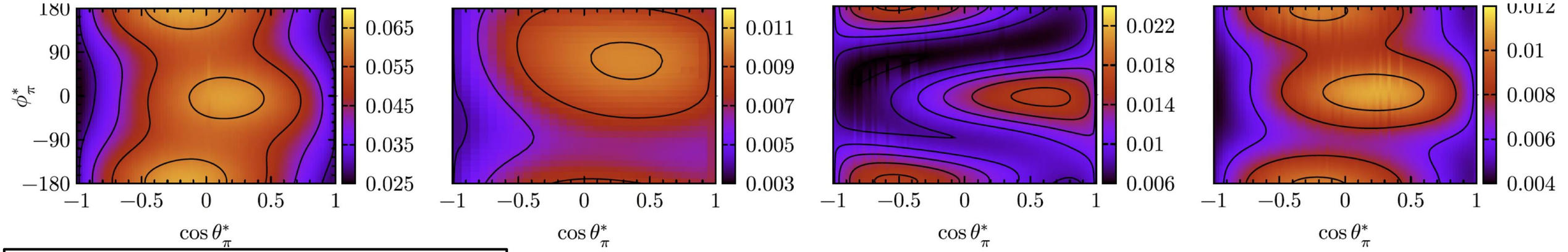
# Adler angle sampling in NEUT



Theoretical calculation: PRD 98, 073001 (2018)

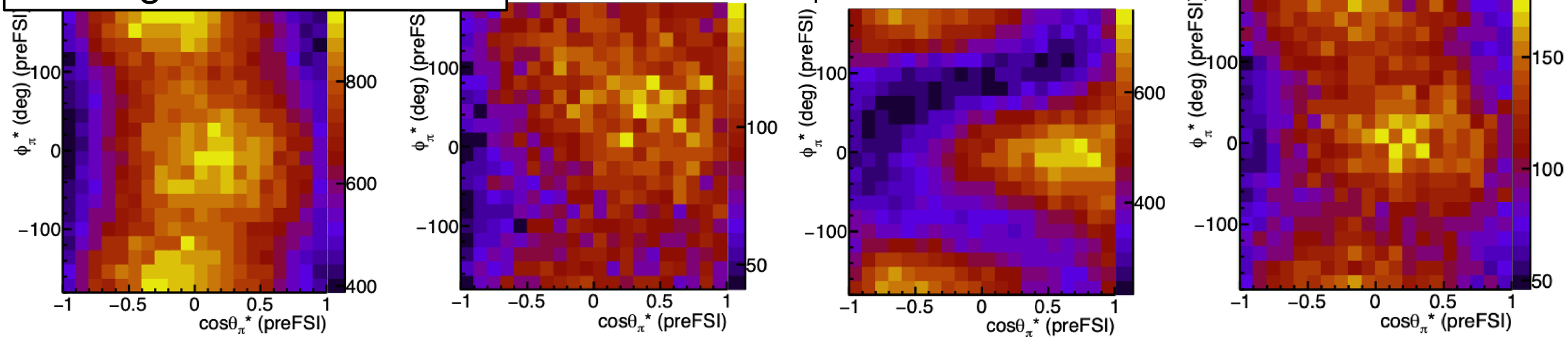
Ev = 1 GeV.

$\nu_\mu p \to \mu^- p \pi^+$ $\nu_e \mathrm{n} \to \mathrm{e}^- \mathrm{n} \pi^+$ $\bar{\nu}_e n \to e^+ n \pi^-$ $\nu_e p \to \nu_e p \pi^0$




NEUT generated events

Z-axis : nunmbe of events per bin

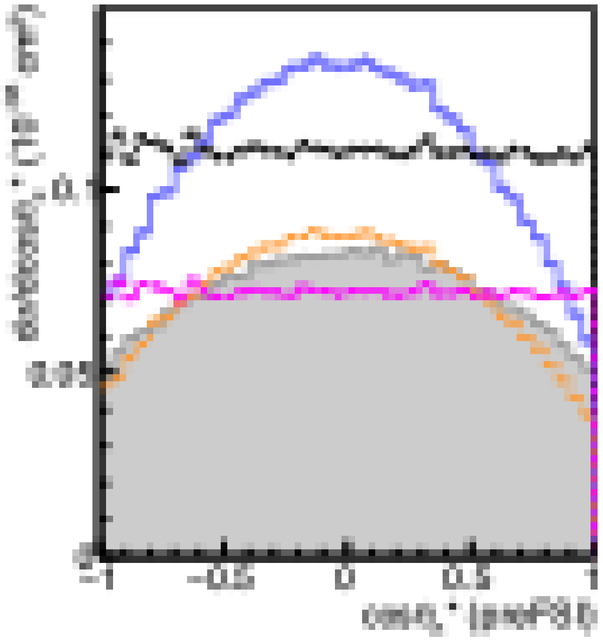


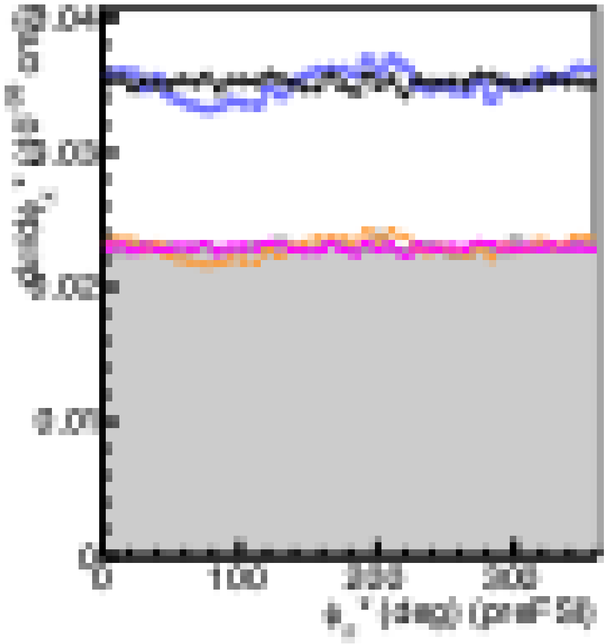

- **Successful implementation.**

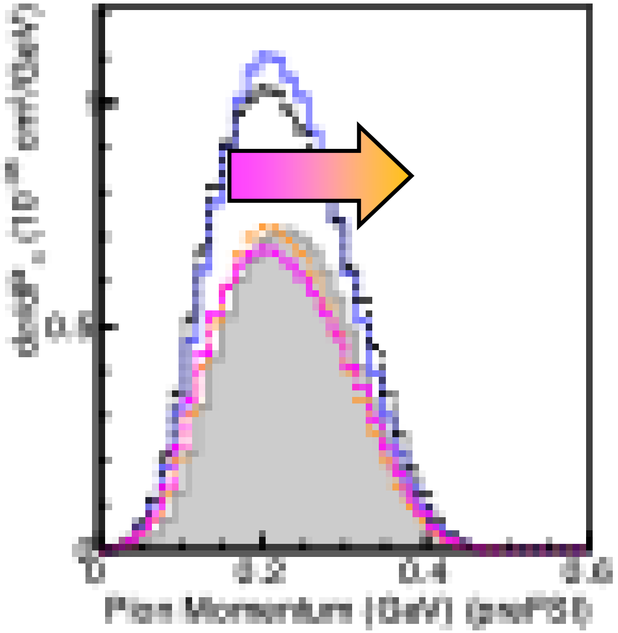
# DCC vs Berger-Sehgal

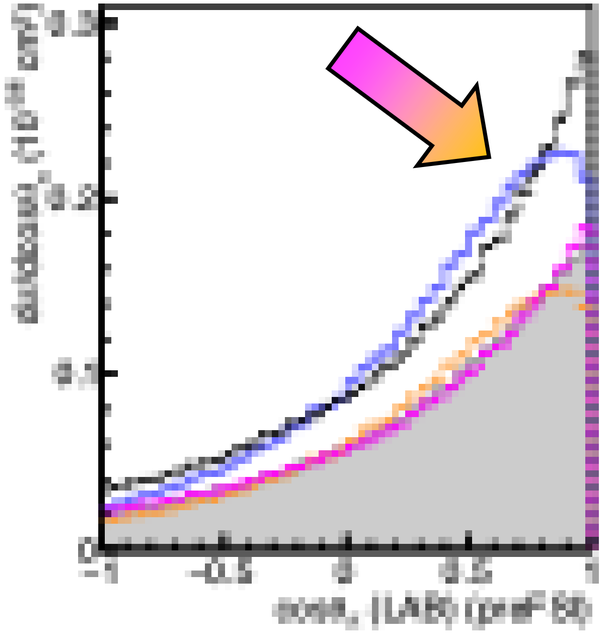
$\nu_\mu p \to \mu^- p \pi^+$. Ev = 600 MeV.

- Berger-Sehgal (BS)
- New DCC (aniso)
- Previous DCC (iso)
- New DCC (aniso). *Norm to BS.*
- Previous DCC (iso). *Norm to BS*.







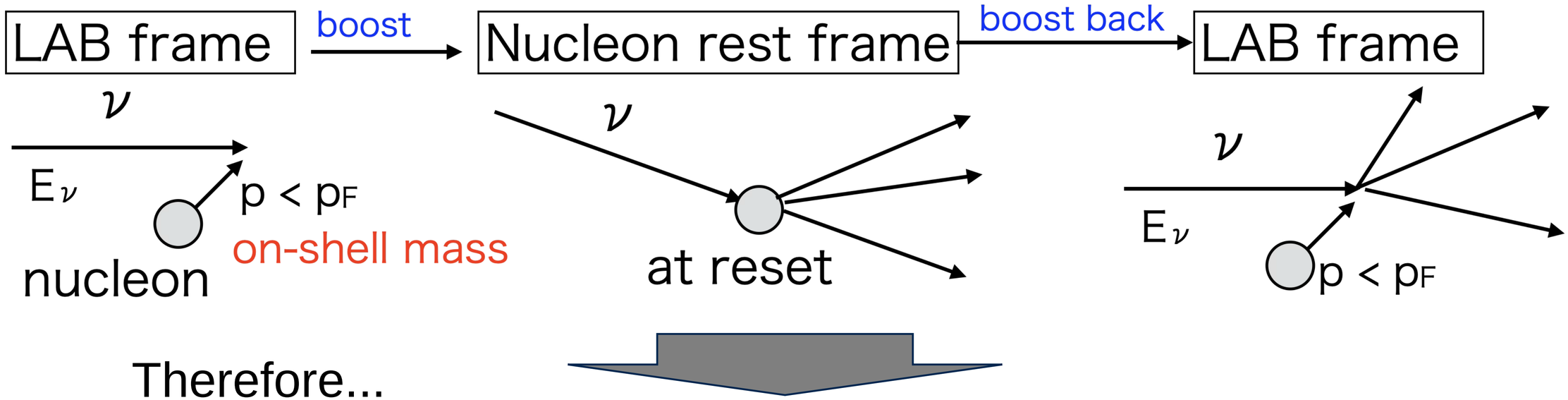



- Inclusion of Adler angle dist.
  Distorts pion kinematics.
  - Momentum: slightly larger.
  - Angle: Forward pions are reduced.

# Investigation on nuclear model in SPP

# Relativistic Fermi gas (RFG) model in NEUT SPP

- All SPP models in NEUT are based on this RFG nuclear model.
- Assumption:
  - The target nucleon moves below the Fermi surface $\mathrm{p}_F$.
  - The target nucleon has **on-shell mass**.

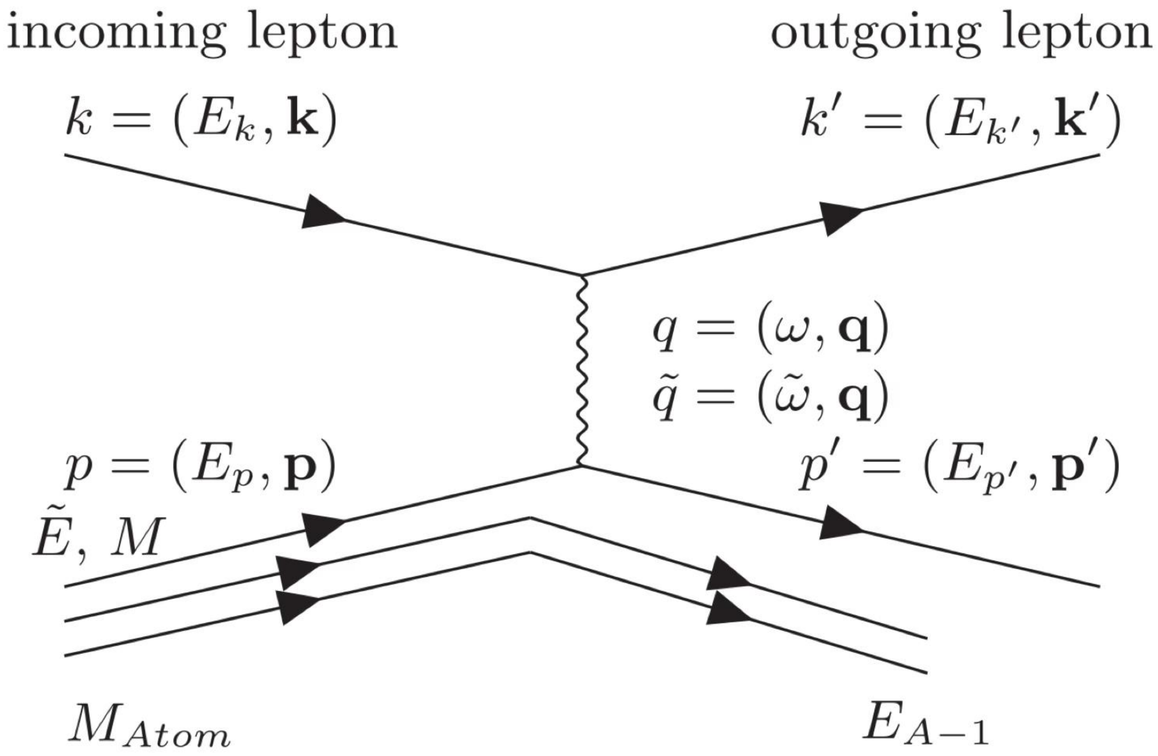



Therefore...

- The total energy of outgoing particles exceeds $E_\nu$.
  - It looks as if it has gained energy.
- Naively expected to be critical in the calorimetric variable 🤔

# Removel energy in Fermi gas models in NEUT SPP

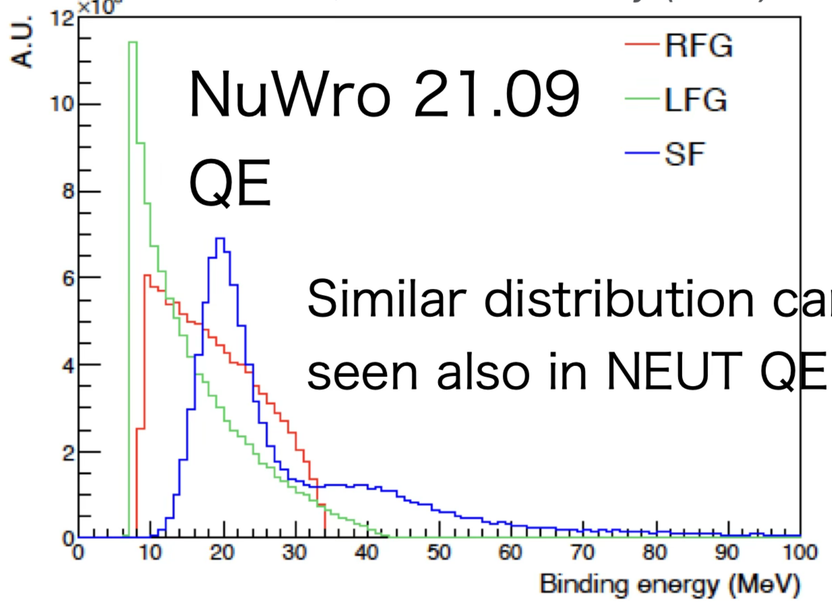
- QE: $E_k + M - E_{k'} - E_{p'}$ neglecting nuclear recoil E.



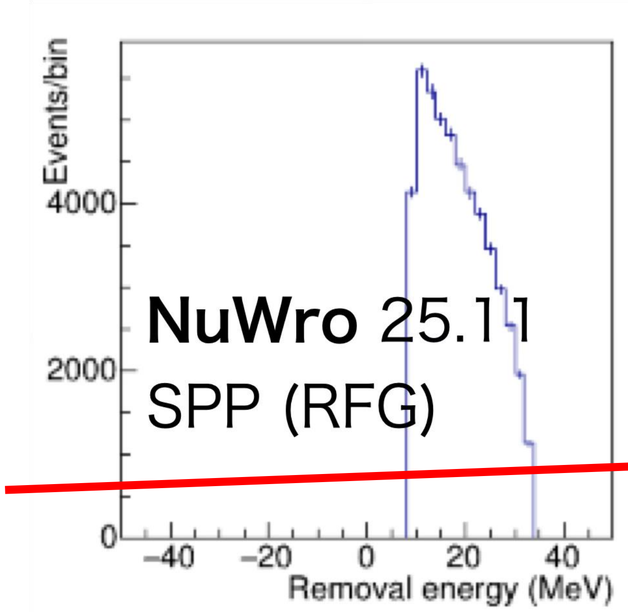

- SPP: $E_k + M - E_{k'} - E_{p'} - E_\pi$.

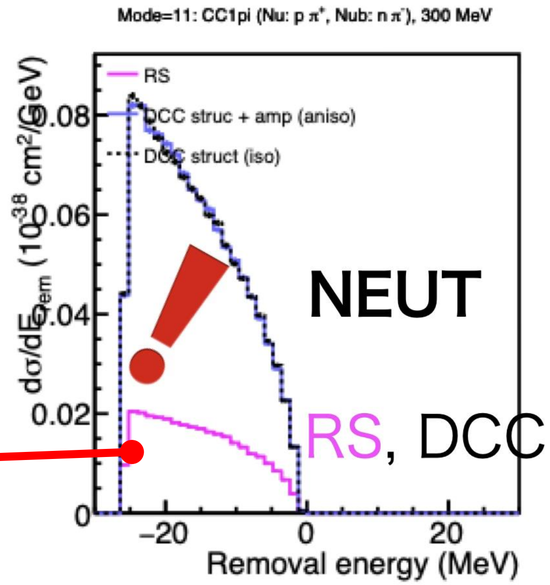
- **NEUT SPP gives unphysical negative removal energies.**

*S. Abe, Ph.D. thesis, Tohoku University (2023)*




Similar distribution can be seen also in NEUT QE



# Implement ad-hoc “binding energy"

- The same approach as NuWro is taken this time.
- Introduce binding energy $E_b$ and effective mass $M_{eff}$.

Binding energy (Eb)

$$p_N = (E, \mathbf{p}) \qquad E = \sqrt{\mathbf{p}^2 + M^2}$$

on-shell mass

$$p'_N = (E', \mathbf{p}) \qquad E' = E - E_b$$

$$E_b = \begin{cases} 34 \text{ MeV} & \text{RFG} \\ E_{Fermi} + 7 \text{ MeV} & \text{LFG} \end{cases}$$

$$E_{Fermi} = \sqrt{\mathbf{p}_{Fermi}^2 + M^2} - M$$

$\mathbf{p}_{Fermi}$: Radius dependent Fermi mom.

$$M_{eff} = \sqrt{E'^2 - \mathbf{p}^2} = \sqrt{(E - E_b)^2 - \mathbf{p}^2} \sim M - E_b$$

- This effective mass is used for calculating $W$ and $Q^2$.
- It requires more energy transfer.
- **Note: The in-medium effect and distortions are not considered.**

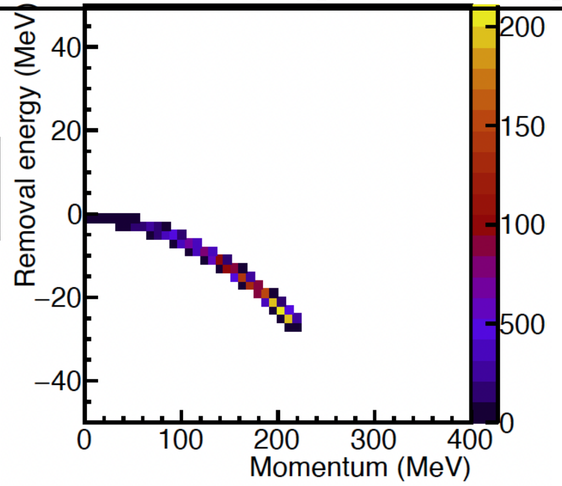
# Target nucleon profile (Removal E and momentum)

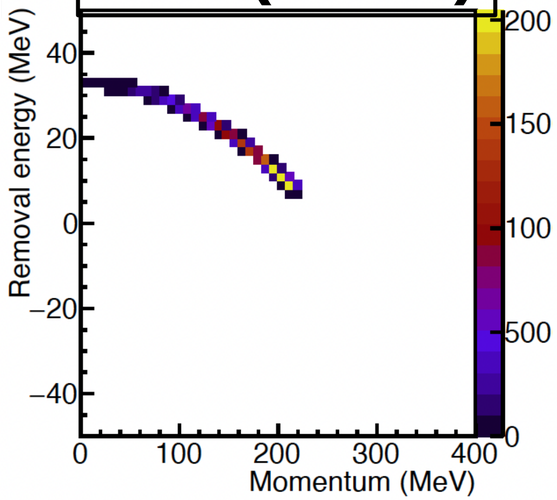


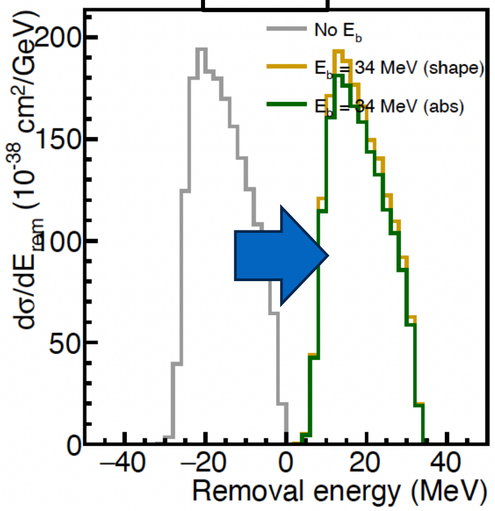
- Two Fermi Gas models (RFG and LFG) are implemented.

**Previous (w/o Eb)** | **New (w/ Eb)** | **1D**

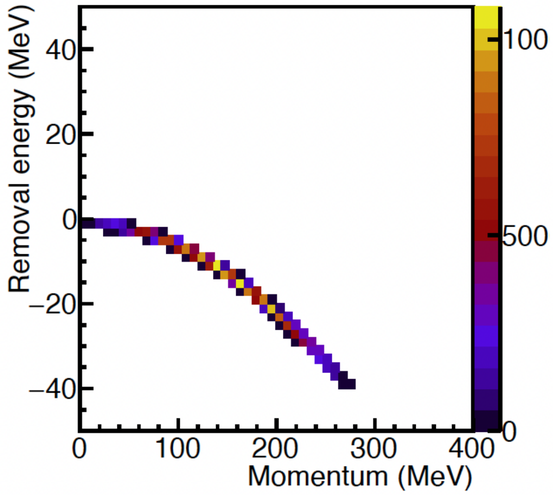
**RFG**

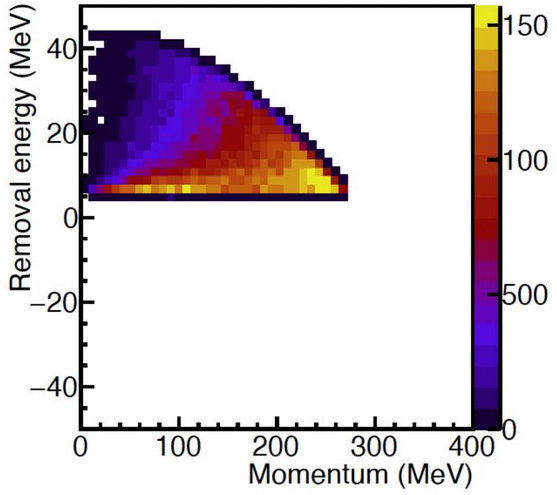


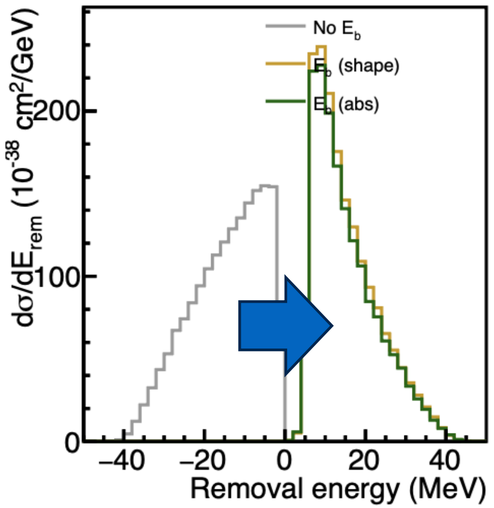



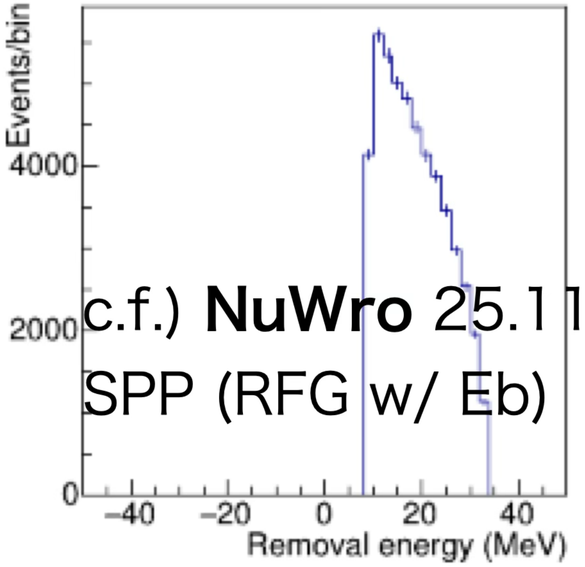




**LFG**

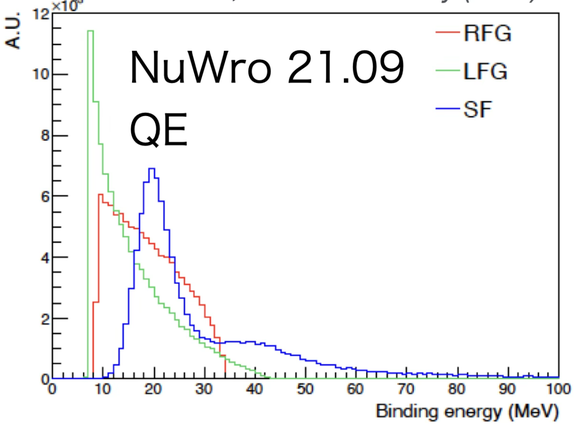



*S. Abe, Ph.D. thesis, Tohoku University (2023)*



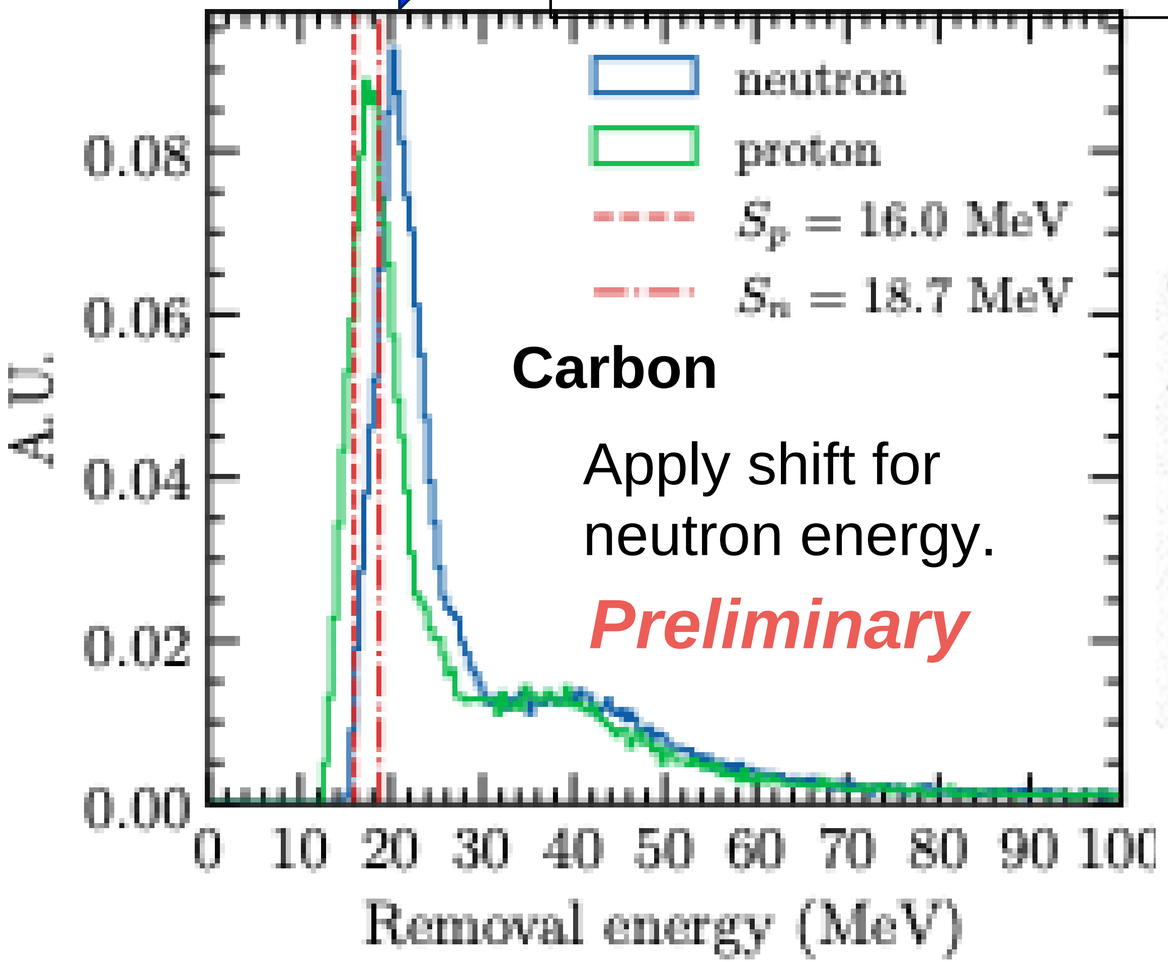

- Well known distributions → Sucessful implementation.

# Target nucleon profile (Removal E and momentum)

- **Spectral Function (SF) is implemented.**

$$P_{\text{neutron}}(\mathbf{p}, \tilde{E}) = P_{\text{proton}}(\mathbf{p}, \tilde{E} - \Delta\tilde{E}),$$

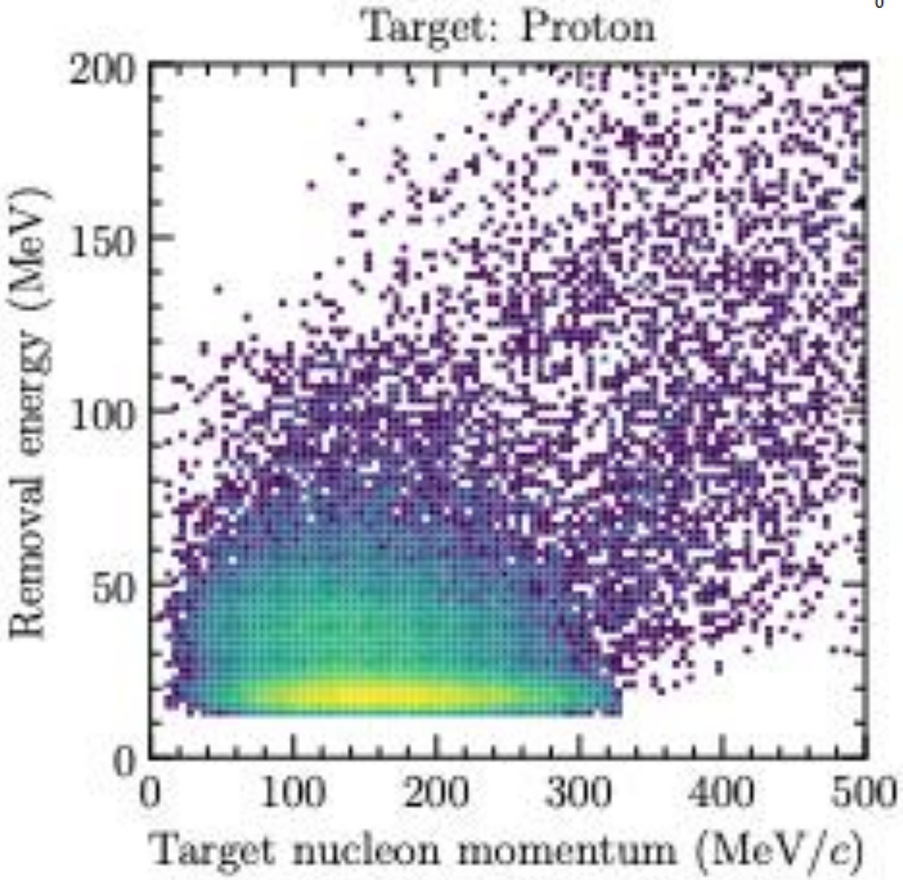
$\tilde{E}$: Removal energy
$\Delta\tilde{E}$: Correction for neutron. 2.76 MeV for carbon.



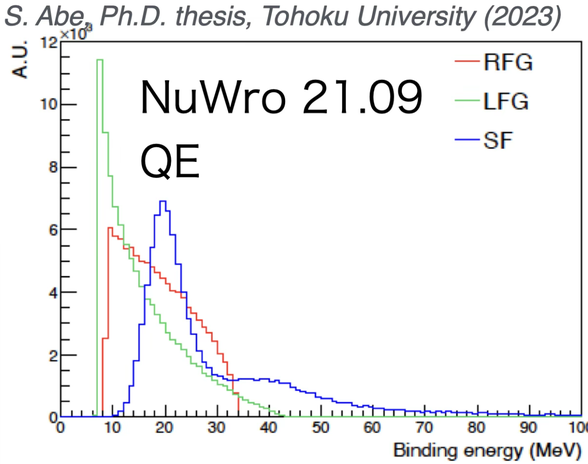

**Carbon**

Apply shift for neutron energy.

***Preliminary***




*S. Abe, Ph.D. thesis, Tohoku University (2023)*

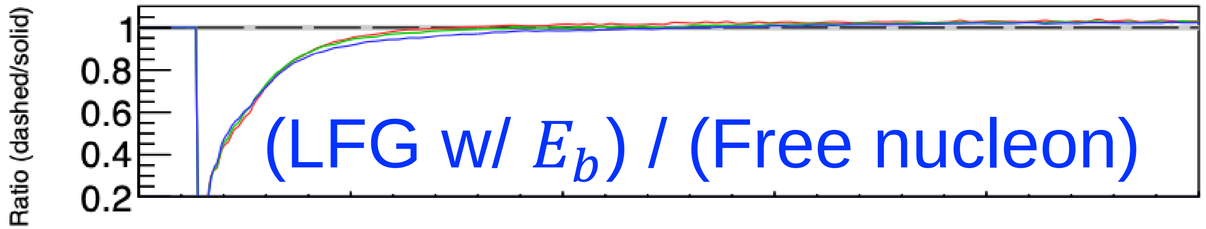


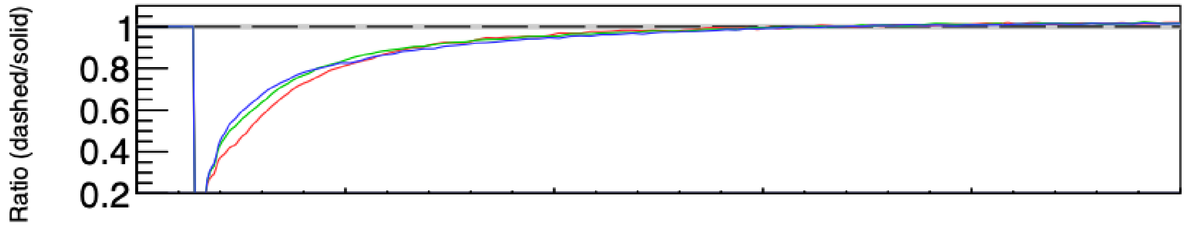
# Impact on total Xsec

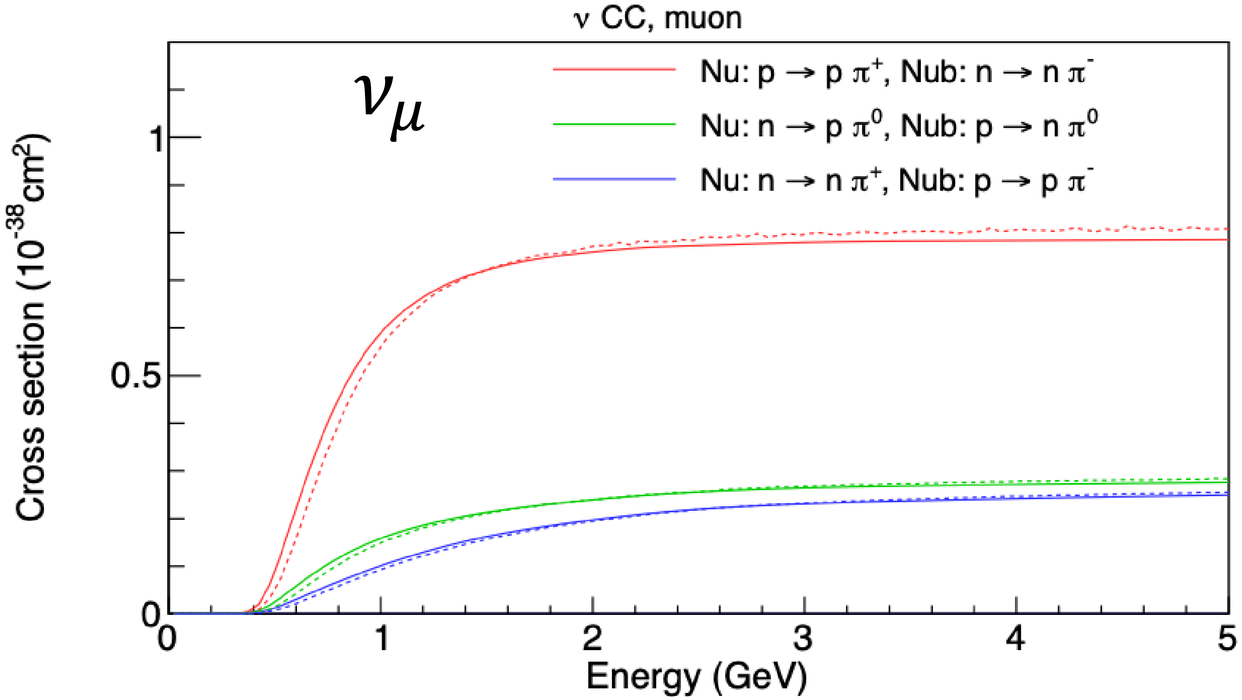
- The total Xsec is suppressed by the $E_b$ at low-Ev.

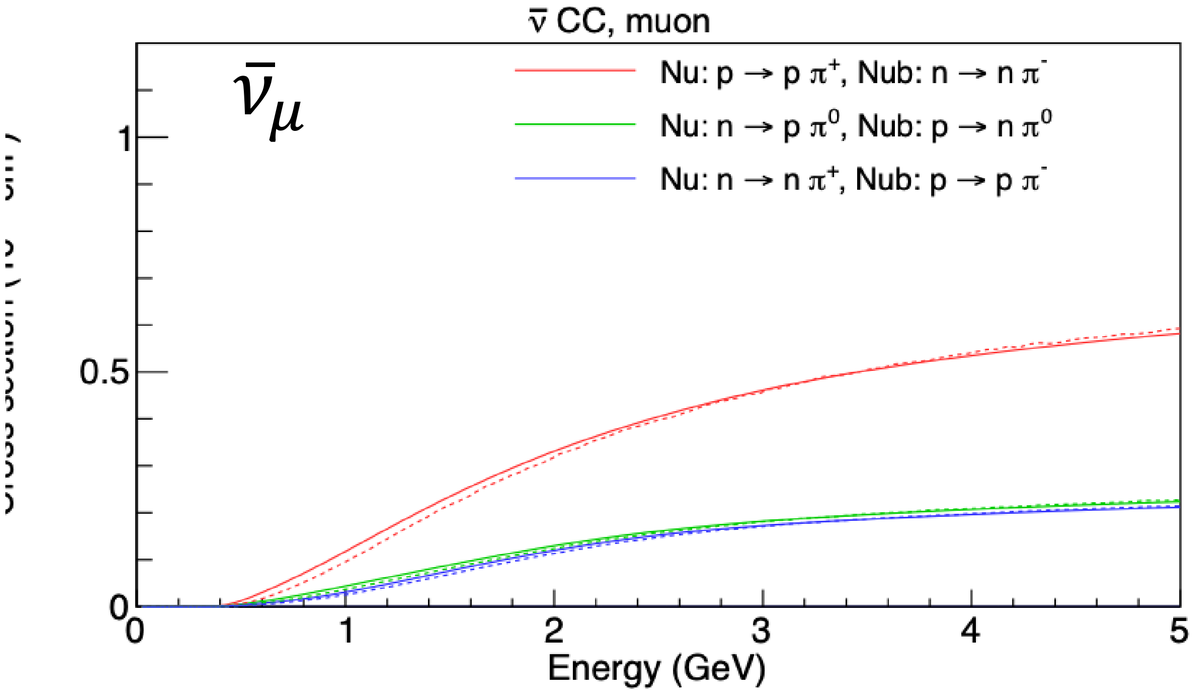
**Dashed: LFG w/ $E_b$**
**Solid: Free nucleon.**

**Xsec of LFG is ~60-70% of free nucleon** at Ev=600 MeV.



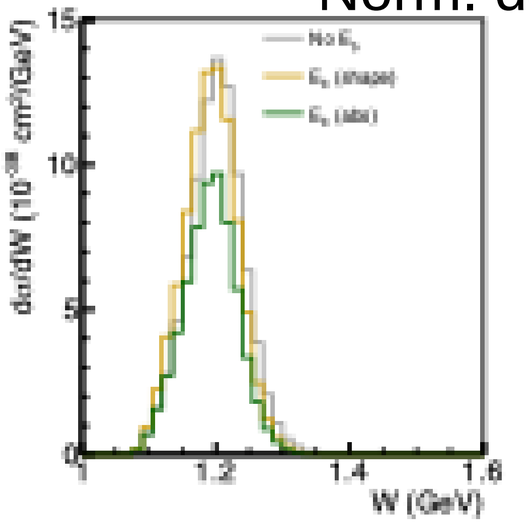



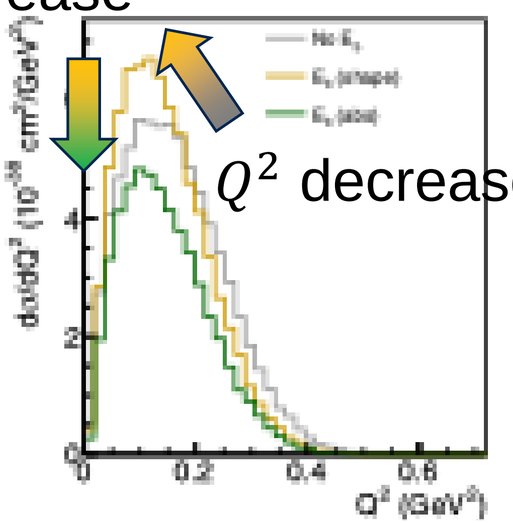
# Impact on differential Xsec (pre-FSI)

w/o Eb
w/ Eb (normalized to w/o Eb)
w/ Eb

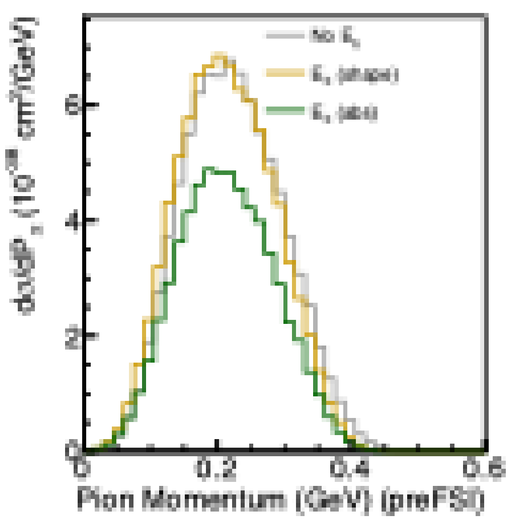
$\nu_\mu p \rightarrow \mu^- p \pi^+$ at 600 MeV.
**LFG** (RFG gives similar trend)

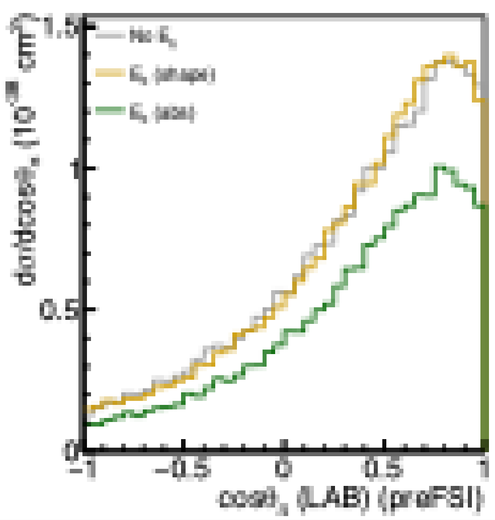
Norm. decrease

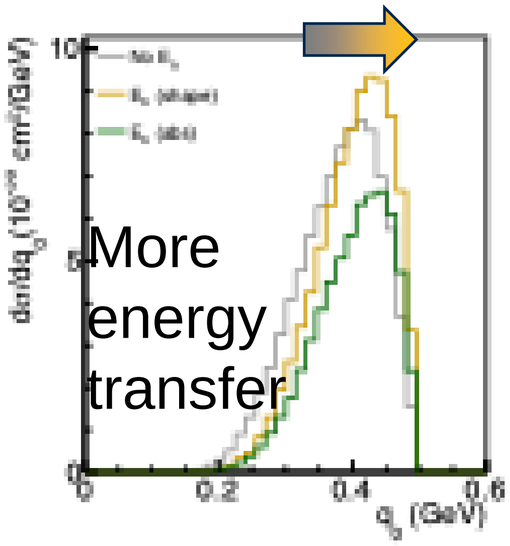


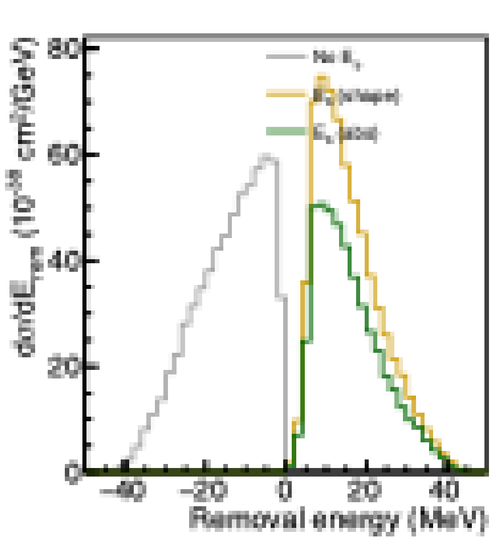

$Q^2$ decrease

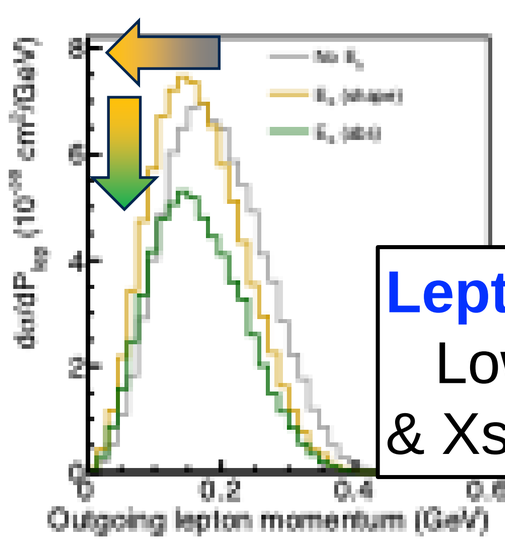



More energy transfer



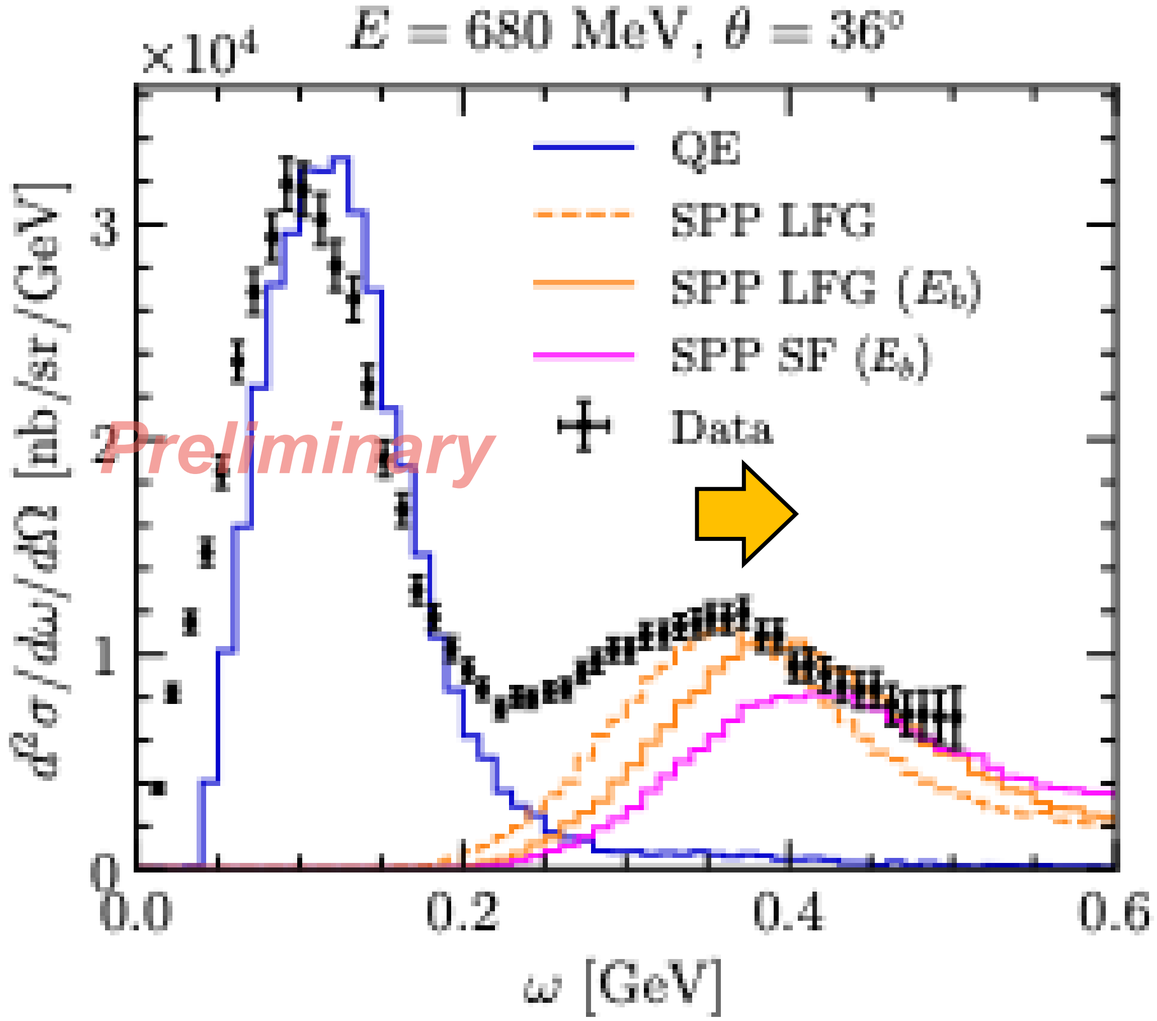

**Pion has little change** in shape under this nuclear model.

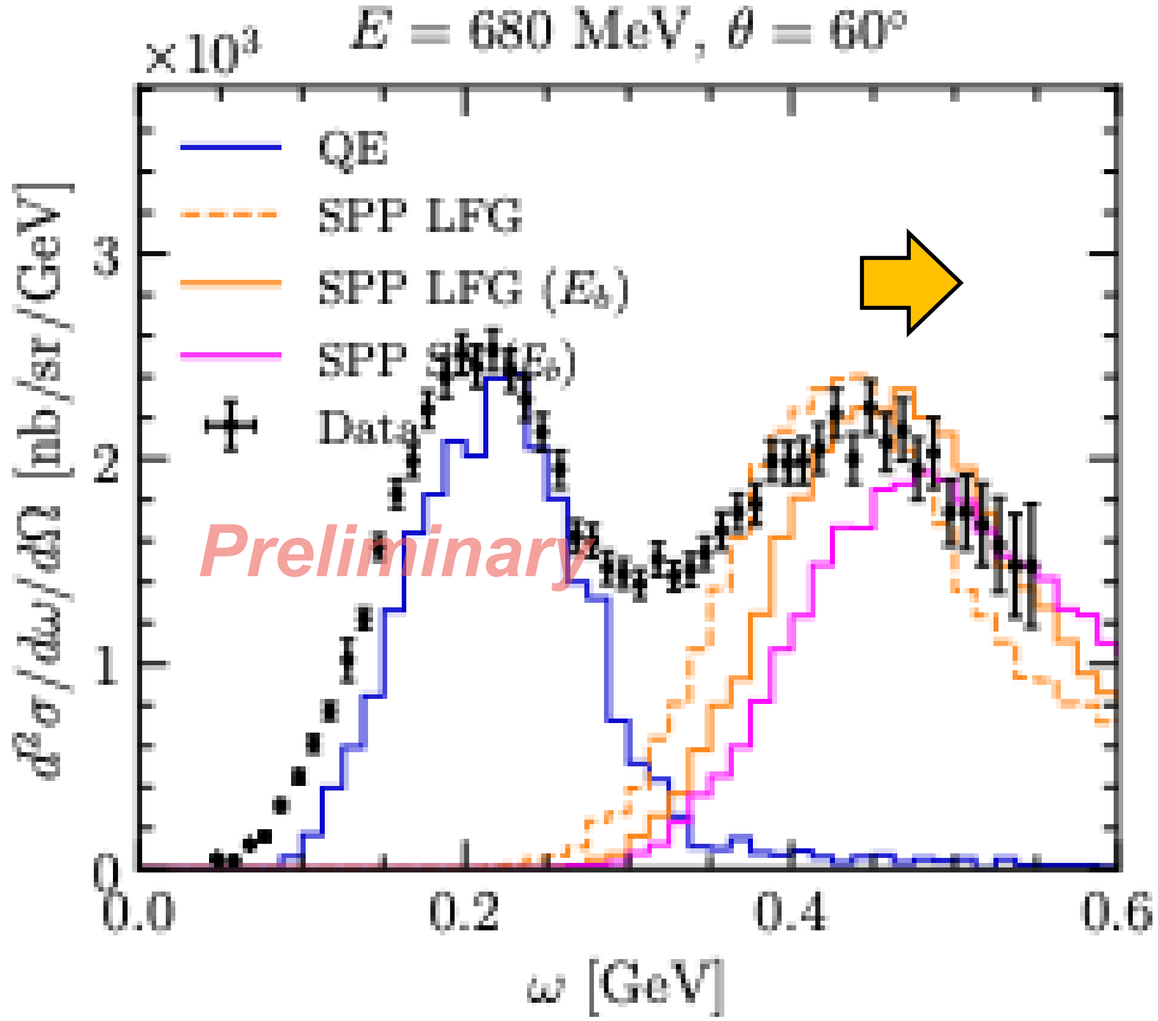
**Lepton changes drastically:**
Lower lepton momentum
& Xsec suppression by ~30%

# Impact on (e,e')



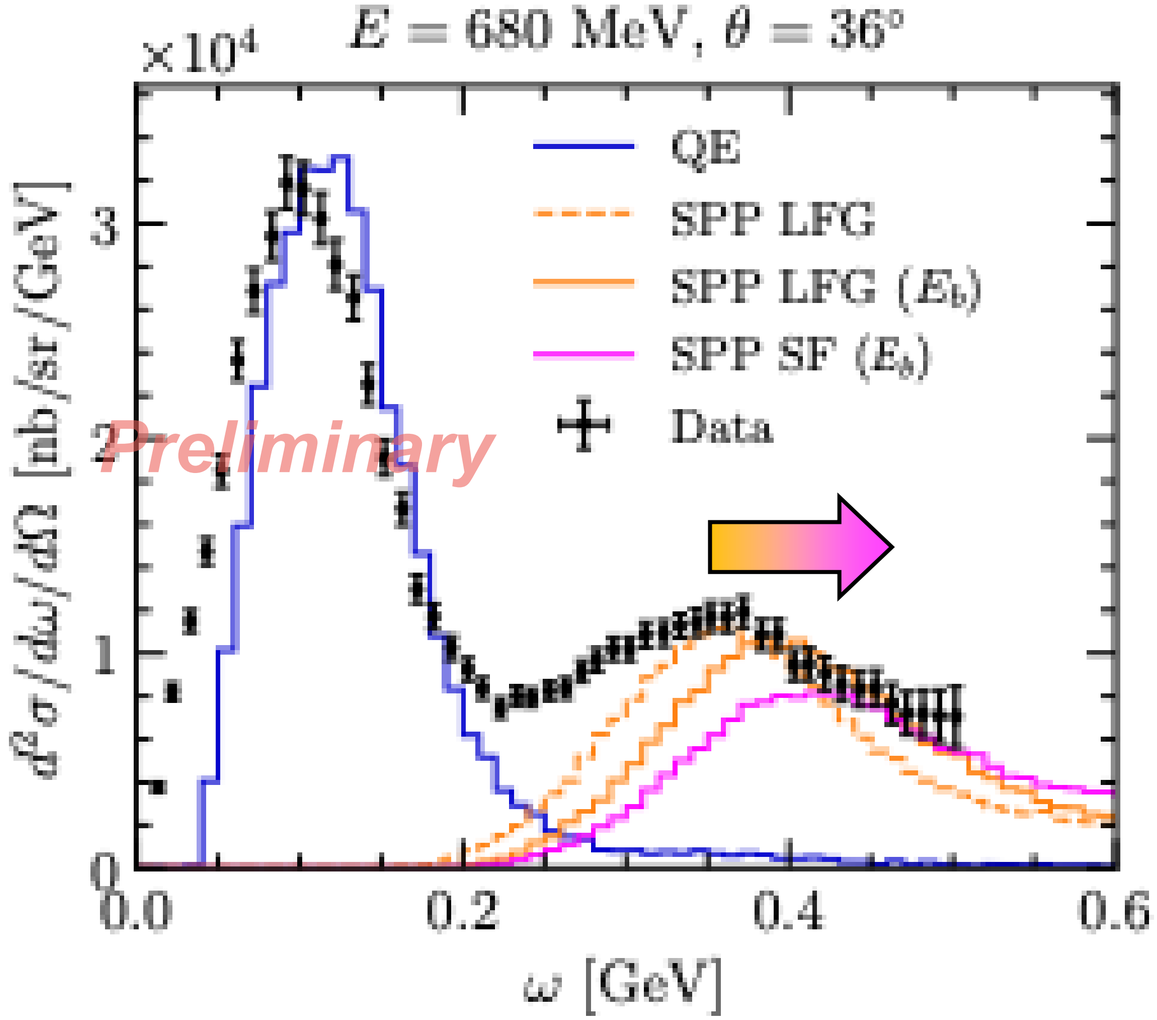
- Incorporating binding energy $E_b$ shifts the peak in energy transfer $\omega$.

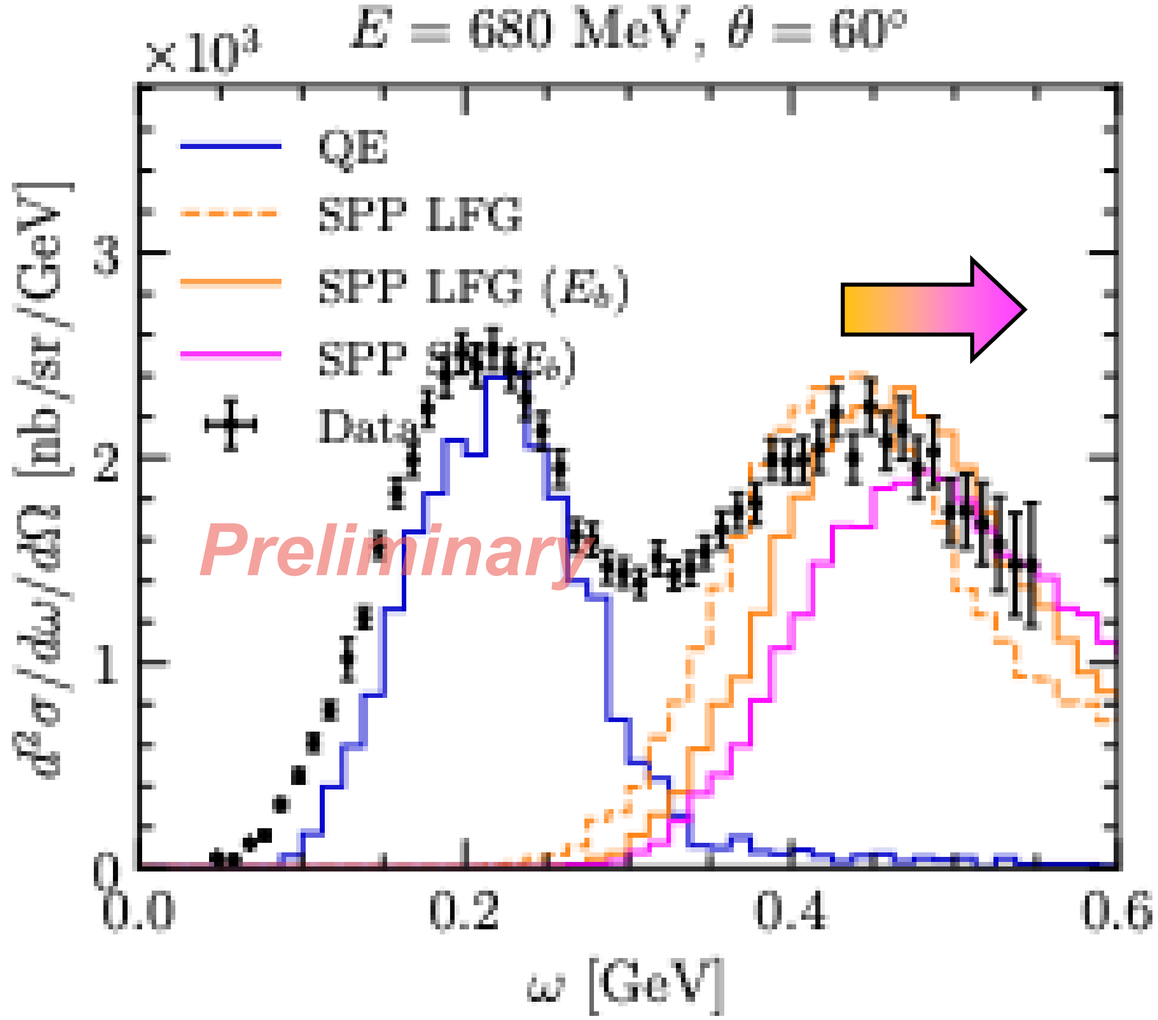


# Impact on (e,e')

- Incorporating binding energy $E_b$ shifts the peak in energy transfer $\omega$.
- SF peaks at more larger $\omega$. Peak height become a little small.
  - Roughly consistent behavior with Noemi et al., PRC 100, 045503 (2019).



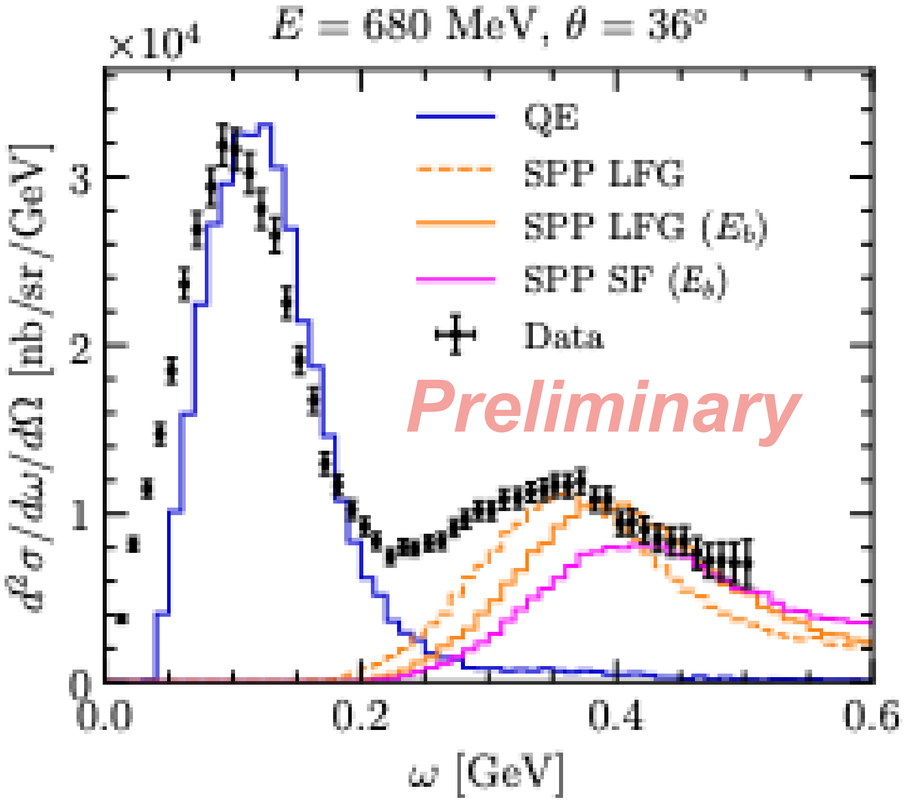



# Challenge 1: Distortion and in-medium effect

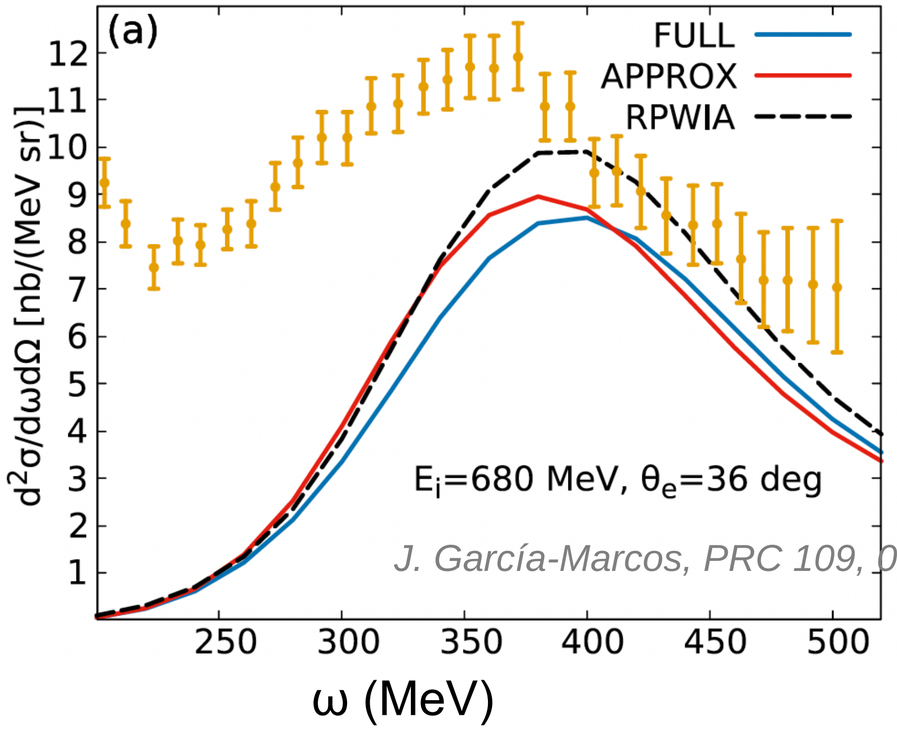


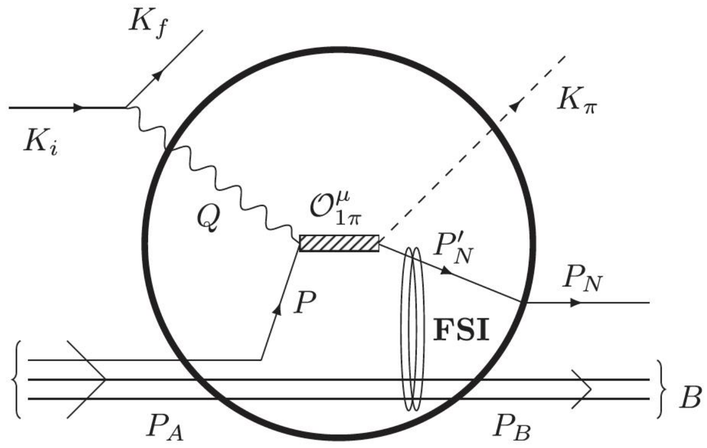
- **Distortion and in-medium effects should give non-negligible impact, but are absent in NEUT.**
- Is there any way to apply the distortion or in-medium effect to NEUT-DCC?
  - An ad-hoc method would be sufficient for the first step...?

**NEUT simulation**




**c.f.) RDWIA based on ED-RMF**



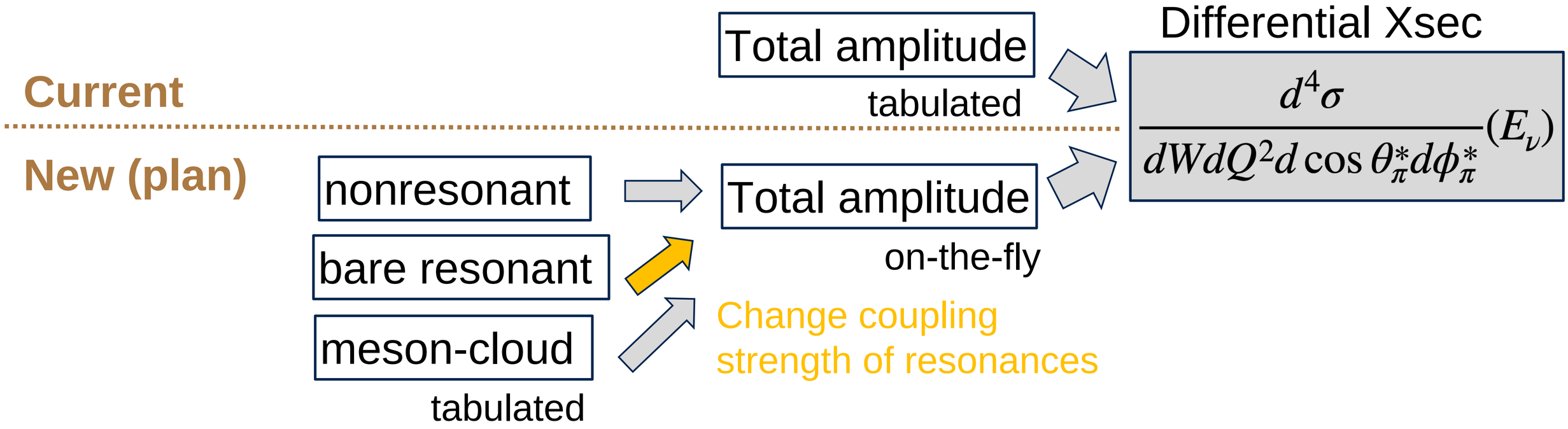

*J. García-Marcos, PRC 109, 024608 (2024).*

# Challenge 2: Reweighing



- DCC multipole amplitude is tabulated.
- Therefore, it's impossible to evaluate model uncertainty by "reweight".

- **Start discussion how to achieve "reweight" in NEUT-DCC.**
  - The amplitude has several terms.
    - nonresonant, bare resonant, and meson-could.
  - By splitting these, part of reweighting is feasible.



# Summary



- NEUT has more SPP model choise rather than RS recently.
- **Full DCC model, including Adler angle sampling, was implemented.**

- NEUT SPP models were based on naive nuclear models.
- **Newly introduced binding energy, the same approach as NuWro.**
  - SF, LFG, and RFG are implemented.
  - Significant impact on lepton kinematics is observed.
  - Impacts on SK/T2K/HK observables are to be investigated.

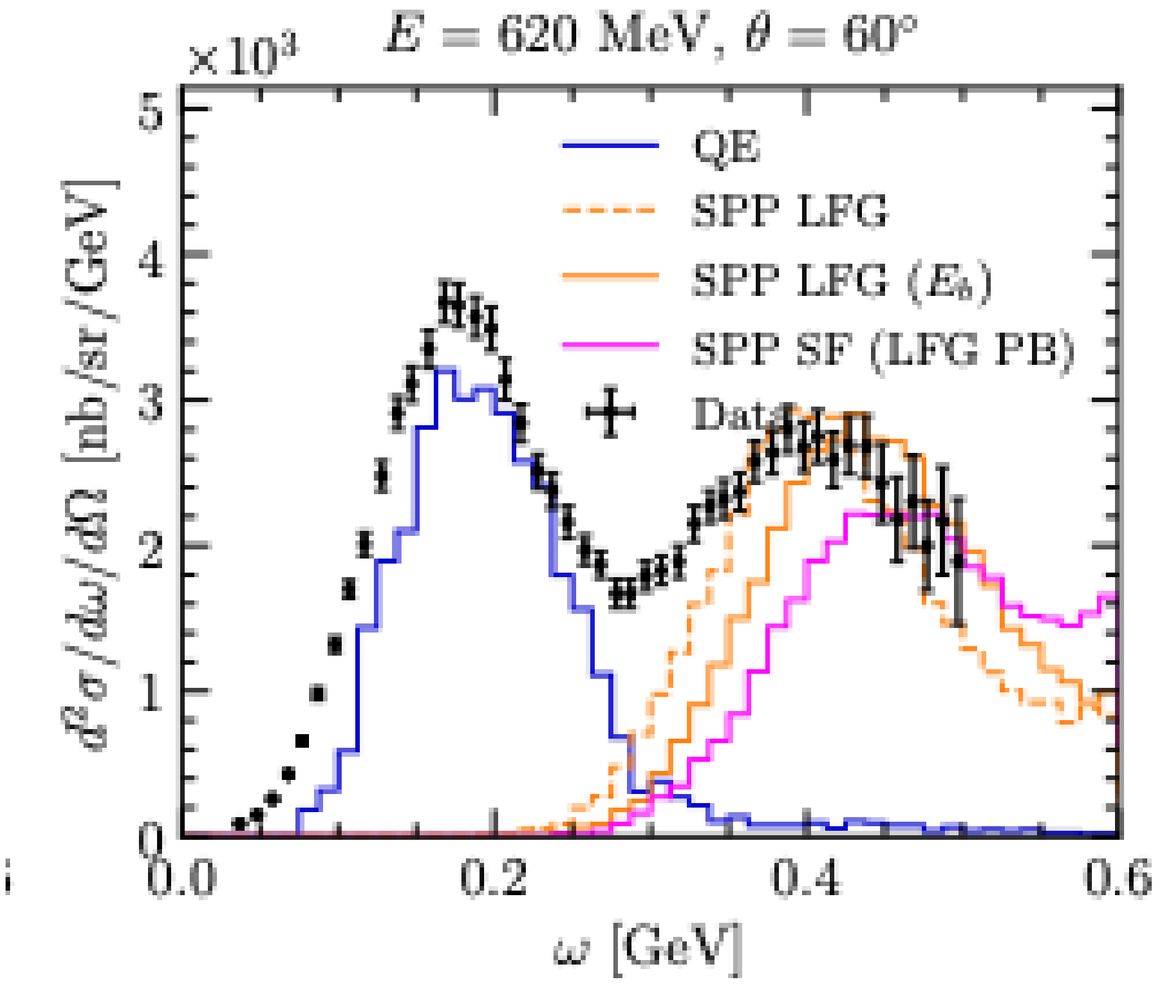
- There are big challenging topics!
  - NEUT-DCC reweighting for uncertainty estimation.
  - Nuclear effects (distortion and in-medium effects of delta) for high-precision prediction.

# backup

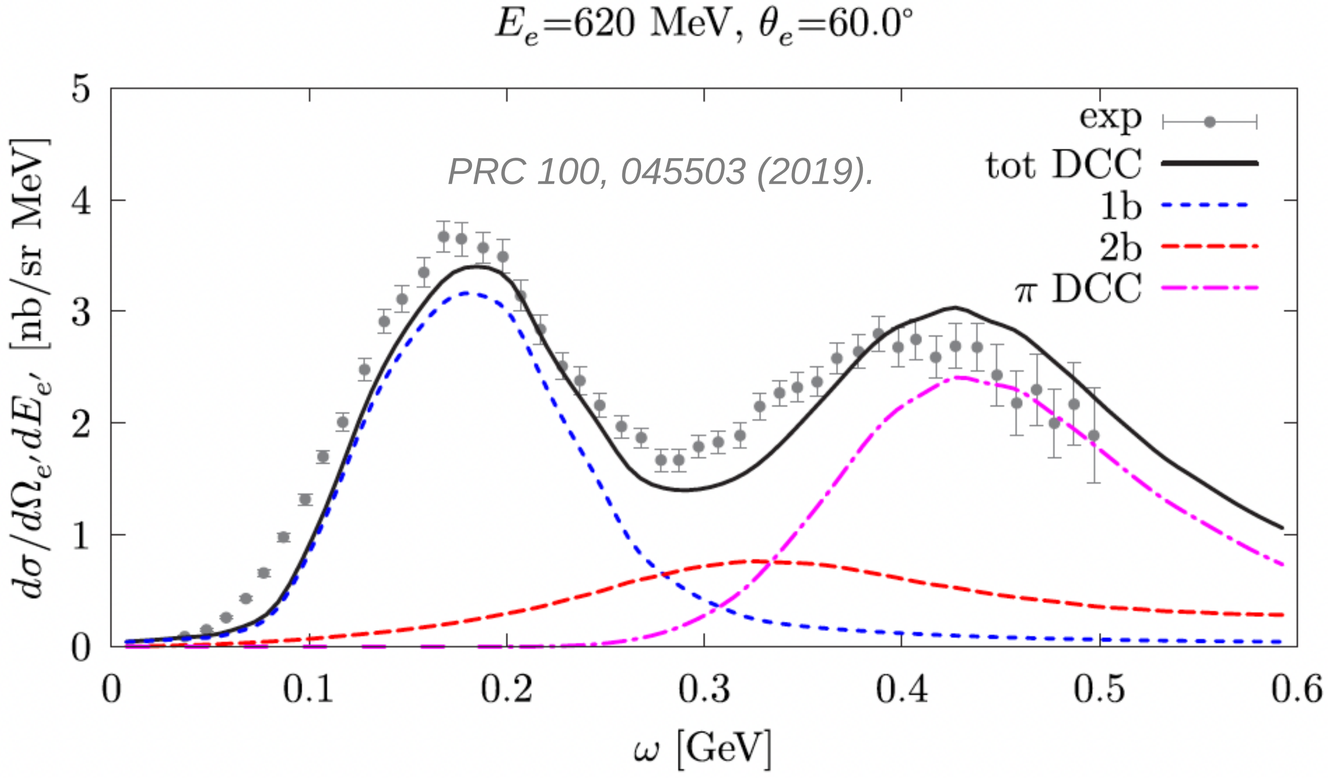
# Comparison with other calculation: 620 MeV, 60°



NEUT-DCC



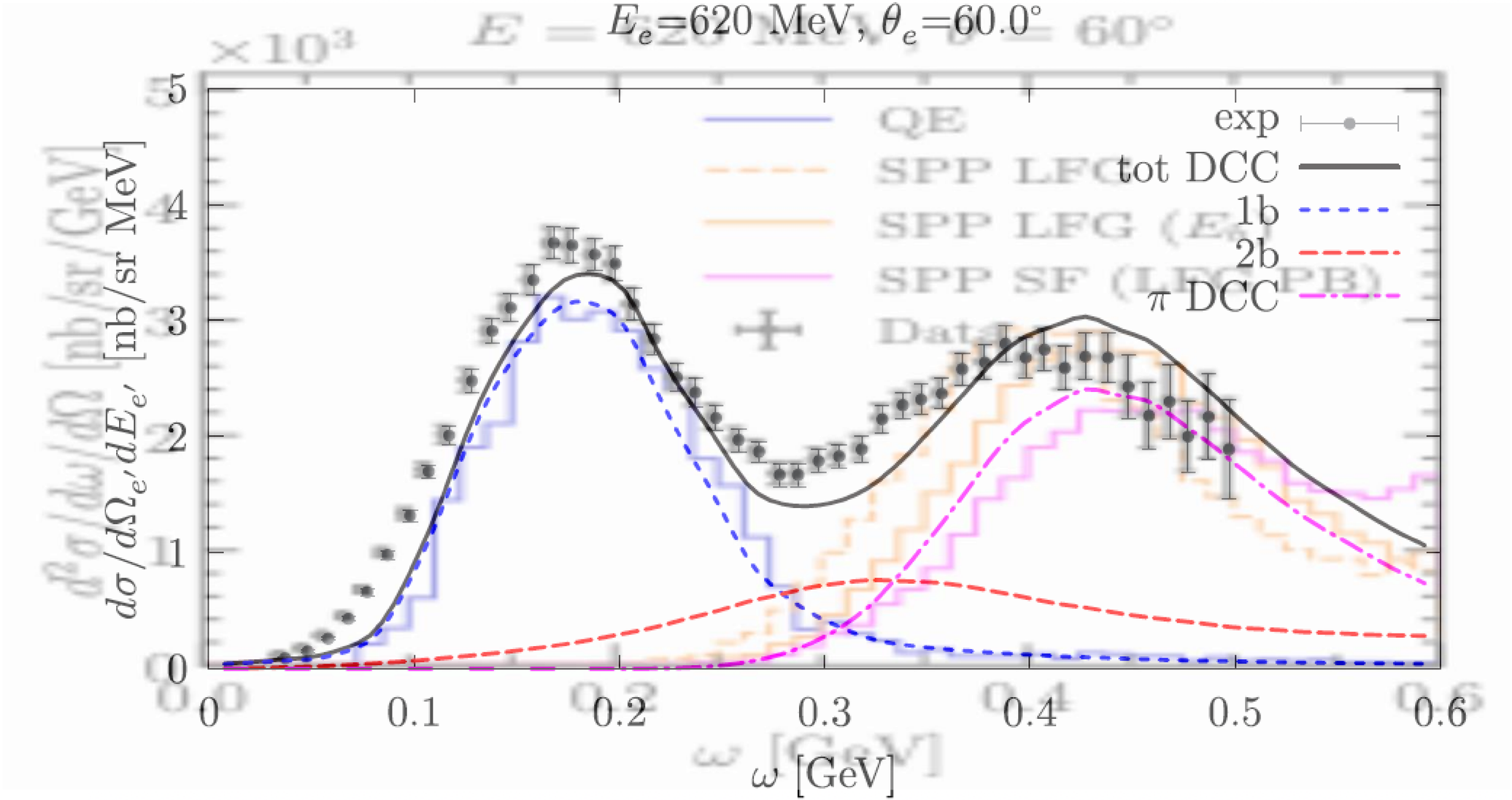

N. Rocco et al. DCC with SF



# Comparison with other calculation: 620 MeV, 60°

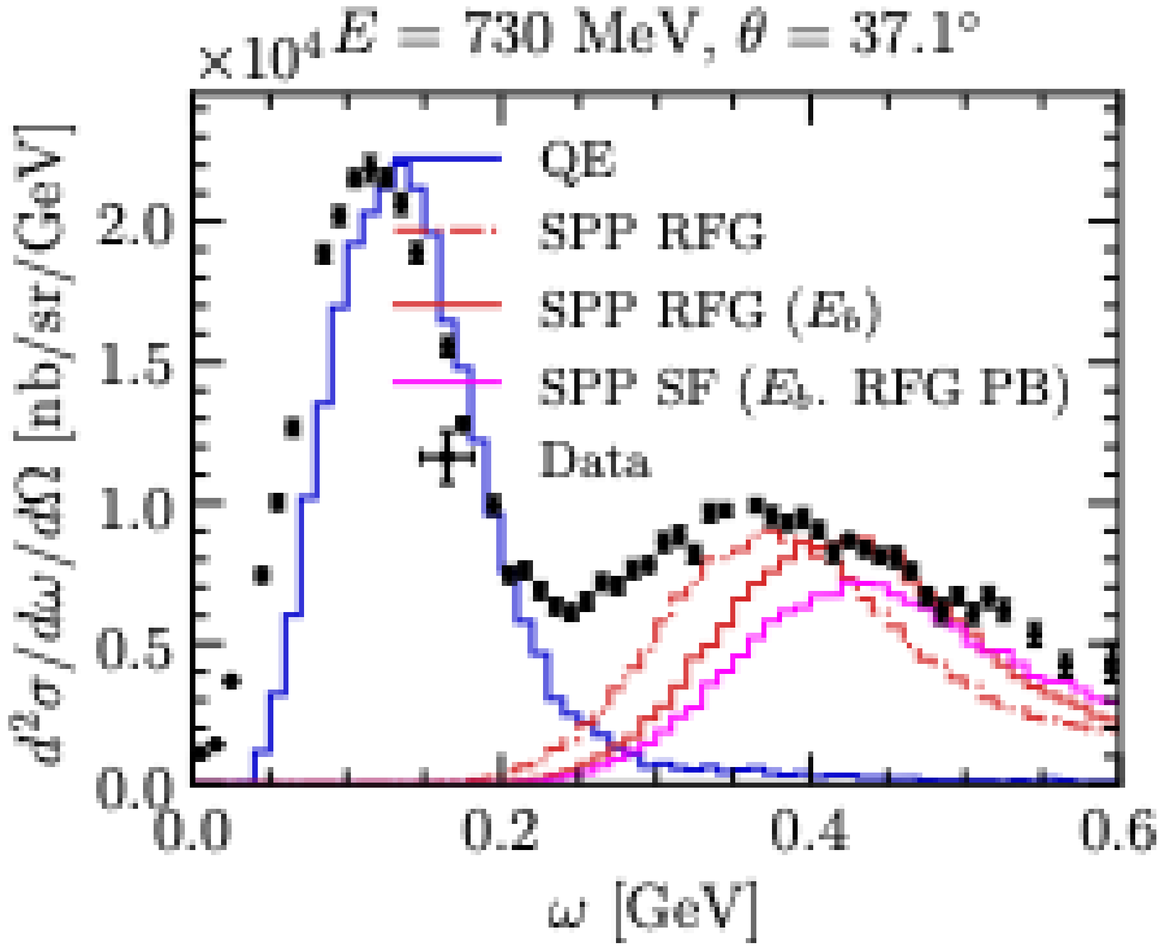


*PRC 100, 045503 (2019).*



# Comparison with other calculation: 730 MeV, 37°






## N. Rocco et al. DCC.

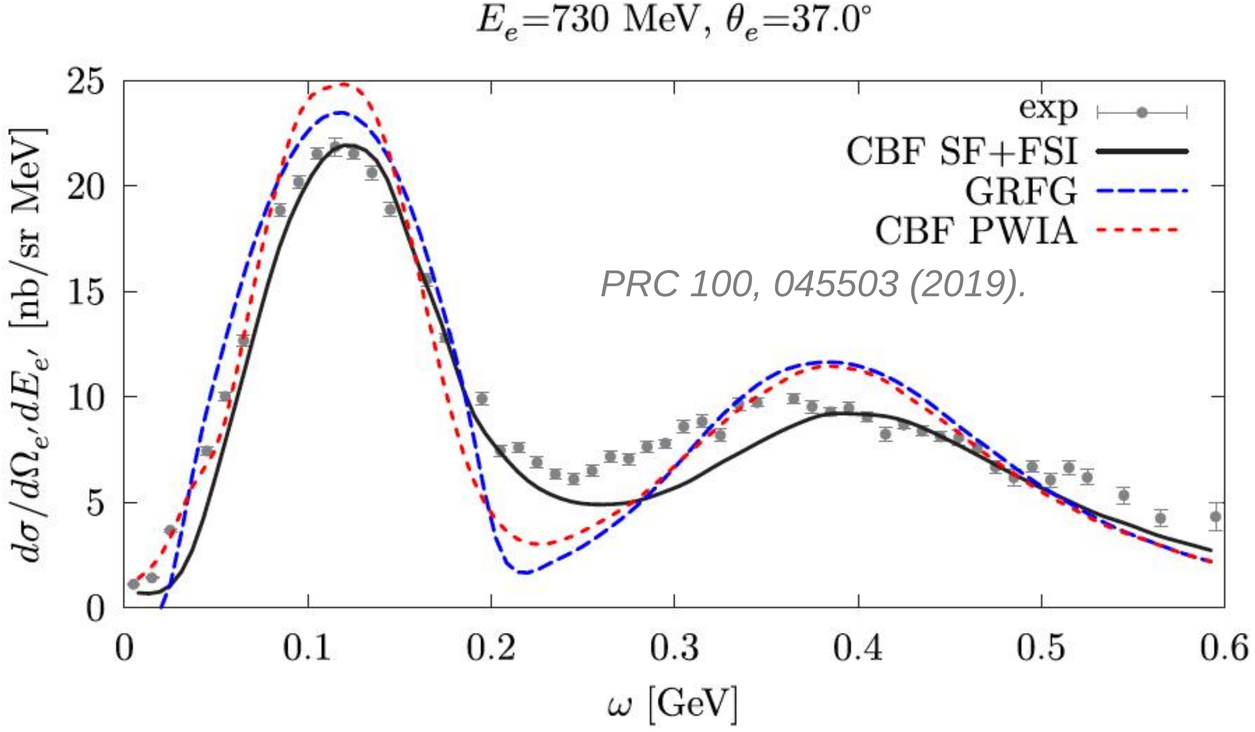



FIG. 10. Electron-$^{12}$C double-differential cross section. The dashed (blue) line has been obtained within the GRFG model. The short-dashed (red) and solid (black) curves have been obtained using the SF of Ref. [39] within the PWIA and IA with FSI corrections, respectively.

RFG **w/o Eb**

**SF PWIA (probably QE only)**