Modeling pion production for GeV neutrino experiments

The 23rd International Conference on Few-Body Problems in Physics

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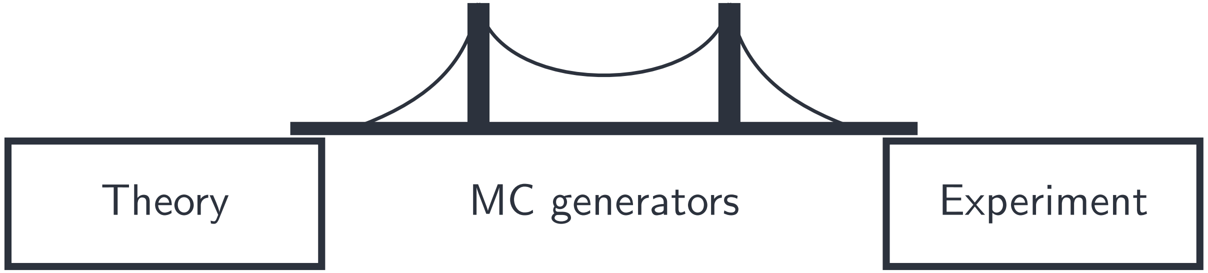
Introduction

Neutrino generators are bridges between theory and experiment.



Credit: Tomasz Golan, Link

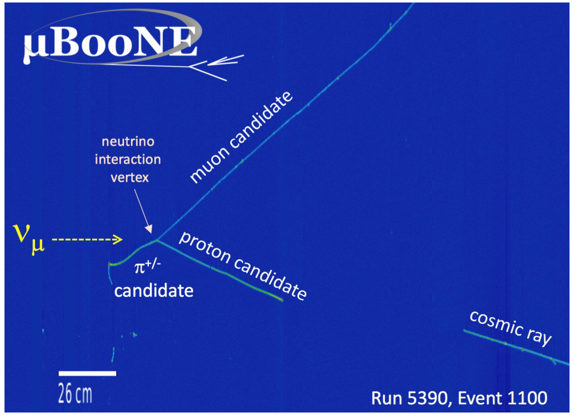


Figure 1: An example of a CC$\pi^{\pm}$ event from MicroBooNE, Link to source

- From neutrino to the 4-momenta of final state particles.
- Neutrino experiments relays on MC generators.
- Combination of multiple models:
  - Nucleus model (nuclear ground state/fermi motion/pauli blocking)
  - Interaction model ($\nu + p/n \rightarrow l + N + X$)
  - Final State Interaction, FSI (π absorption/production/charge exchange···)

How are neutrino generators working in GeV region?

- There are still tensions between different models and data.
  - In the GeV region, RES[1] and DIS kick in, the final state gets more complicated.
  - Any **mis-modeling** can lead to **mis-reconstruction**.

- Properly model the final state in those region is crucial for the experiments in this region. (reconstruction, background estimation, etc.)
- Xianguo Lu's talk in this morning provides a lot information on the importance of modeling interaction.

- Generators to discuss here:
  - NuWro
  - GENIE
  - GiBUU

[1] Inelastic process with meson production though resonances

Challenges

RES Channel

- Neutrino excites a nucleon to a resonance state, which decays to give a nucleon and a meson.
- For low-W: dominated by $\Delta(1232)$ resonance, final state follows iso-spin rule:

$$\sigma(\nu p \to \ell^- p\pi^+) : \sigma(\nu n \to \ell^- p\pi^0) : \sigma(\nu n \to \ell^- n\pi^+) = 9 : 2 : 1$$

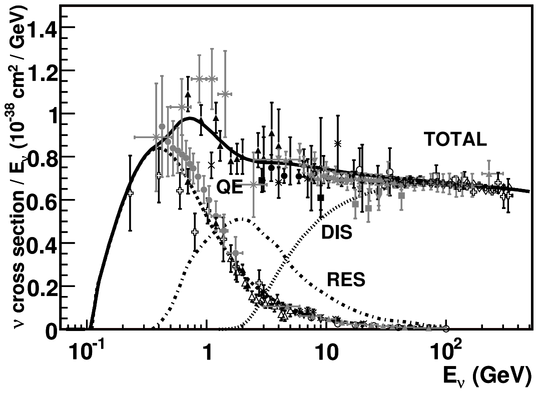
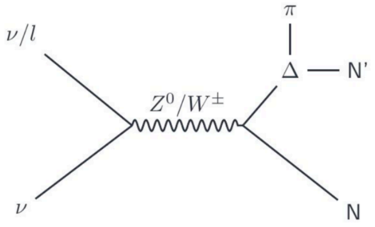


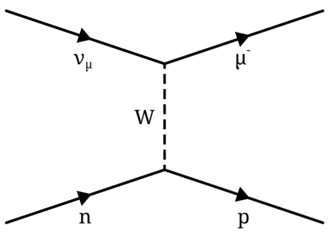
Figure 2: Inclusive per nucleon cross section of ν on isoscalar target, figure from Qian, PPNP, 83, 1-30 (2015)

A full π production model should describe:

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}W\,\mathrm{d}Q^2\,\mathrm{d}^2\Omega_\pi}$$



π production via Δ resonance
Credit: Tomasz Golan, Link

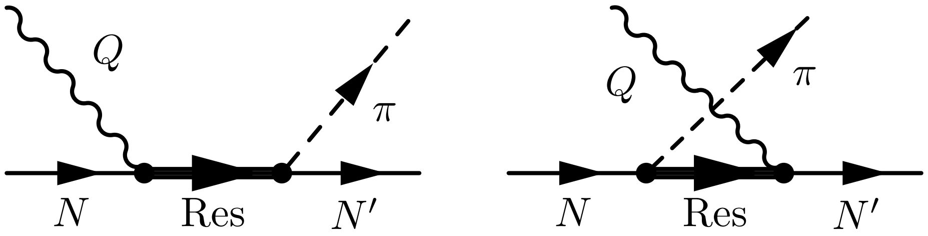


Quasi-Elastic Scattering, for comparison

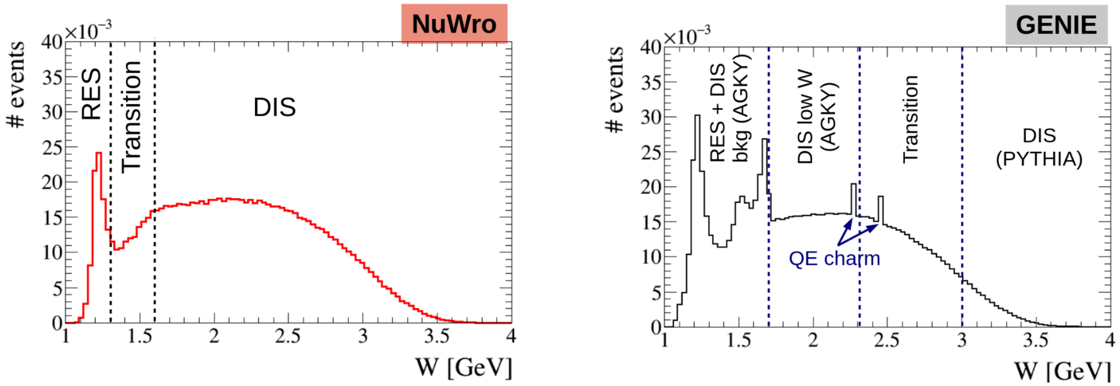
Challenges

And resonance contribution gets complicated when $W > 1.4\,\mathrm{GeV}$

- Leaves $\Delta(1232)$ dominating region $\rightarrow$ Other N^*s contribute significantly.
- More inelastic channels like 2π start to show up.
- Ideally those contributions should be added coherently.
- The non-resonant background also starts to contribute significantly.



Credit: Kajetan Niewczas, Link



2 GeV 3 GeV

GiBUU	RES + background contribution	Low-W DIS: Cross section from Bosted and Christy Kinematics from PYTHIA6	PYTHIA6

Figure 3: Overview of model composition in different generators. upper plot credit: Kavli IPMU, link

All models have RES region, transition region and DIS (PYTHIA) region.

NuWro

The Δ Production-Decay Model

$$\nu + \mathrm{N} \to l^- + (\Delta \to \mathrm{N}' + \pi)$$

- Default model for NuWro for RES.
- Δ excitation via *Adler-Rarita-Schwinger formalism*.
- Axial form factor extracted from bubble chamber data. Graczyk, K. M. *et al.* "C_5^V axial form factor from bubble chamber experiments"
- Δ decay: angular distribution $f_\Delta(\Omega_\pi^*)$ in Adler frame is from ANL/BNL data. (The only data available at that time.)

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}W\,\mathrm{d}Q^2\,\mathrm{d}^2\Omega_\pi^*} = \frac{\mathrm{d}^2\sigma}{\mathrm{d}W\,\mathrm{d}Q^2} f_\Delta(\Omega_\pi^*)$$

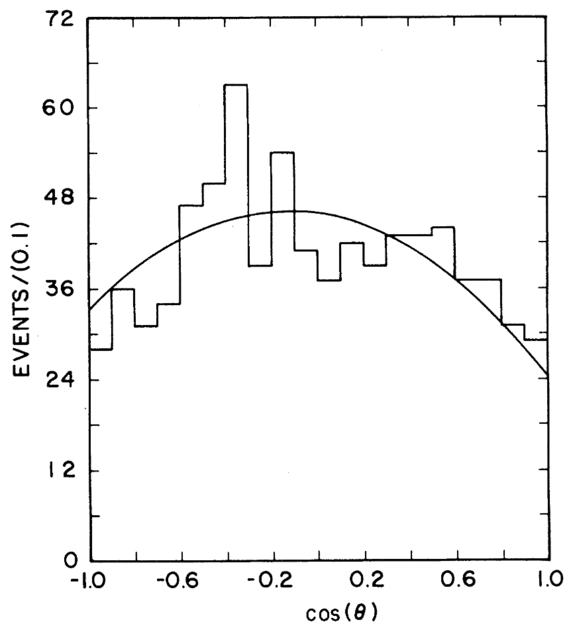


FIG. 15. Distribution of events in the pion polar angle cosθ for the final state $\mu^- p\pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

Figure 4: Δ decay angular distribution from ANL. Radecky, G. M. *et al.* Phys. Rev. D 25, 1161 (1982)

Non-resonant Background and more inelastic channel in NuWro with Δ Production-Decay Model

- Extracted from DIS contribution. (**quark-hadron duality**)
- PYTHIA6 hadronization and Bodek-Yang cross section.
  - Multiplied with a scaling factor to combine with Δ contribution for single π production channel.
  - For more inelastic channel, directly contribute to the cross section.
  - Implemented by adding a transition region.

Transition region for NuWro

- **quark-hadron duality**: aims to include contribution from heavier resonance contribution to the region beyond Δ region ($W > 1.3\,\mathrm{GeV}$).
- the full cross section in RES/DIS region is defined as:

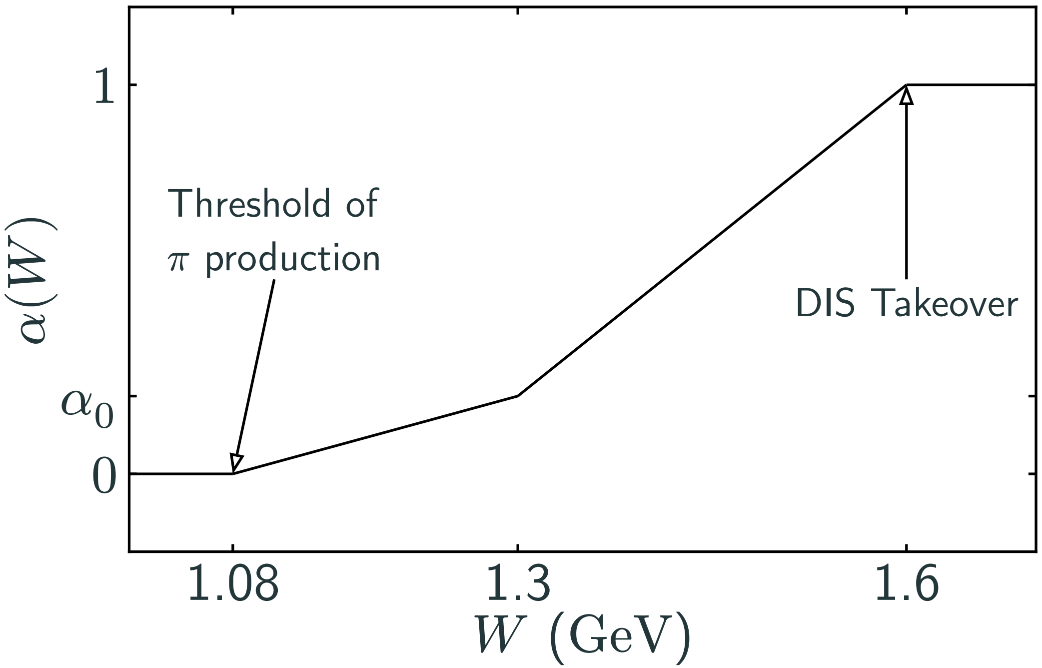
$$\sigma = \sigma^{\mathrm{SPP}} + \sigma^{\text{non-SPP, PYTHIA}},$$

  The "non-SPP" stands for the more inelastic channel contribution including multi-π production.
- The single pion production part:

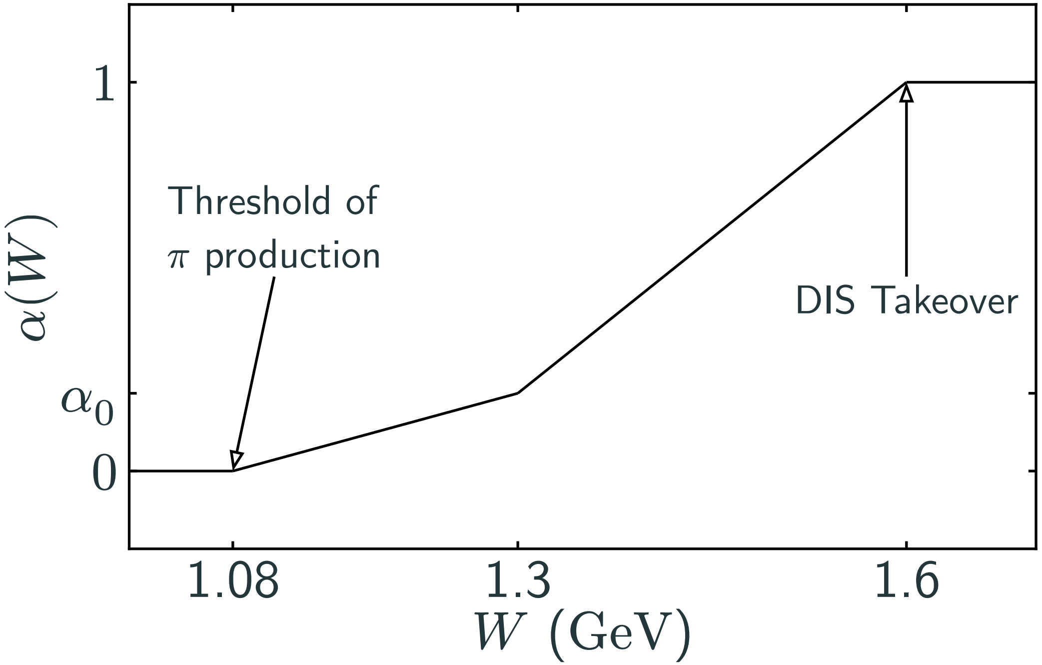
$$\sigma^{\mathrm{SPP}} = [1 - \alpha(W)]\sigma^{\Delta} + \alpha(W)\sigma^{\text{PYTHIA, SPP}},$$

  $\sigma^{\text{PYTHIA, SPP}}$ stands for the contribution from the DIS formalism in PYTHIA6.

- The $\alpha(W)$ describes the non-resonant contribution and transition behavior.



- The $\alpha(W)$ describes the non-resonant contribution and transition behavior.



I would not trust PYTHIA for anything with less than 6 pions

S. Prestel, "The LUND hadronization model"

The model works great... until it doesn't (when high W contributes to the prediction)

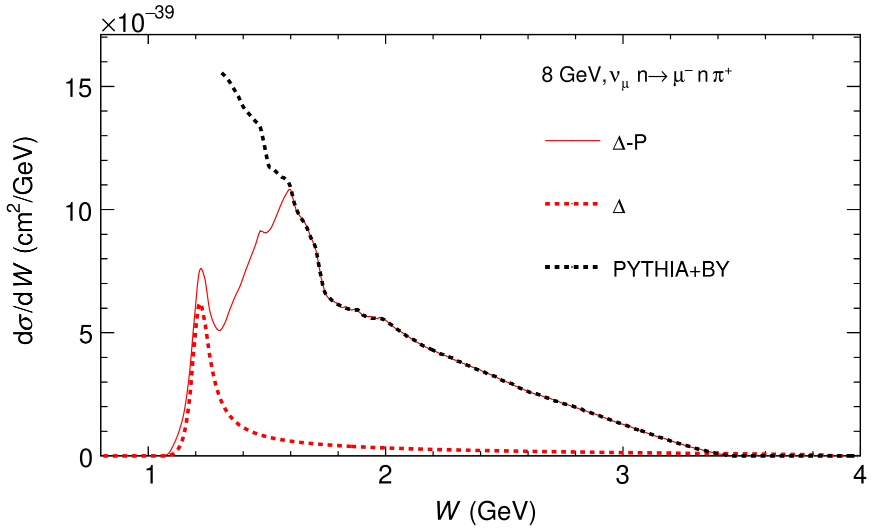


Figure 5: The single pion production prediction from **NuWro Δ model** for $8\,\mathrm{GeV}$ neutrino on n. Δ-P refers the full model with background contribution. Yan *et al.* arXiv:2405.05212 [hep-ph]

- Heavy usage of PYTHIA6 at lower W region $\to$ over-prediction.
- Peak around $W = 1.6\,\mathrm{GeV}$ is from transition.

Addressing the issue: Hybrid Model in NuWro

- LEM model that describes resonances contribution (incl. Δ, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$)
  - Similar to Valencia model.
- Background contribution from tree level diagrams calculation (ChPT based).
- Reggeized ChPT-background higher W.
  - Replace t-channel meson exchange with Regge propagator.
- **Coherent** addition of all components.

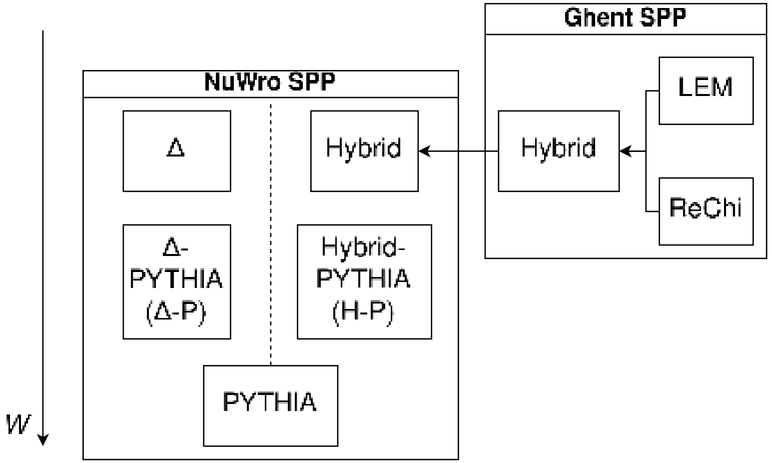


Figure 6: The structure of the Hybrid model. Yan *et al.* arXiv:2405.05212 [hep-ph]

NuWro

- Produces 4-fold differential cross section $\frac{\mathrm{d}^4\sigma}{\mathrm{d}W\,\mathrm{d}Q^2\,\mathrm{d}^2\Omega_\pi}$.
- Allowed minimal usage of PYTHIA6 for SPP:
  - Compared with the case for Δ model, α_0 can be always set to 0: no more DIS contributed SPP in Δ region.
  - Transition region can be pushed to very high W.

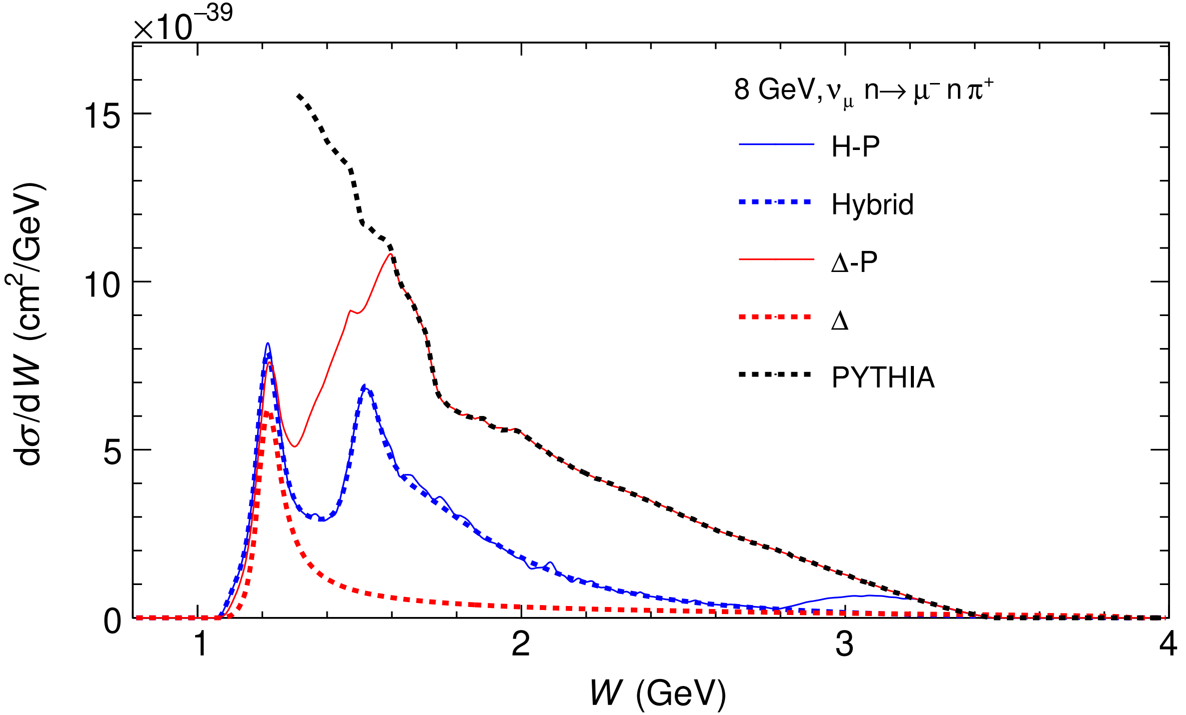
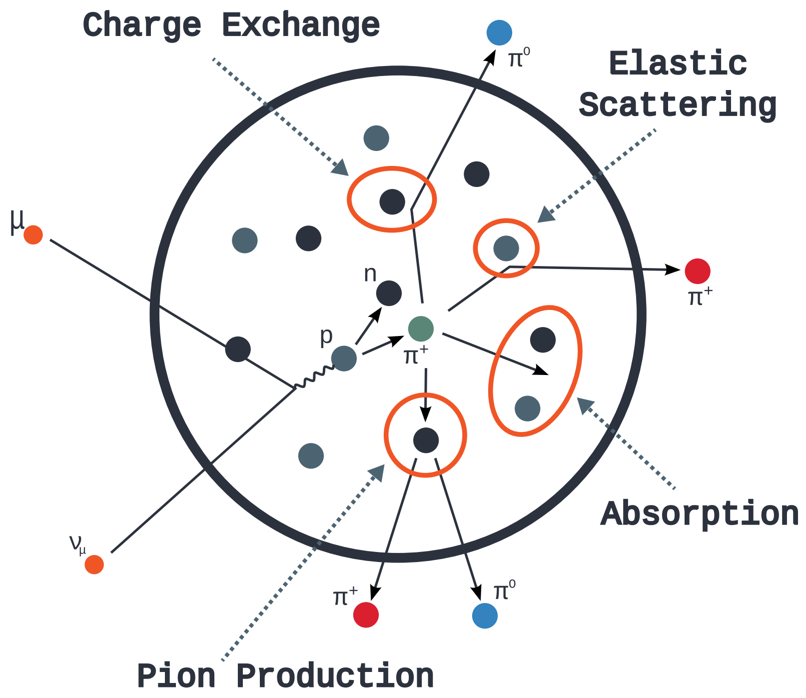


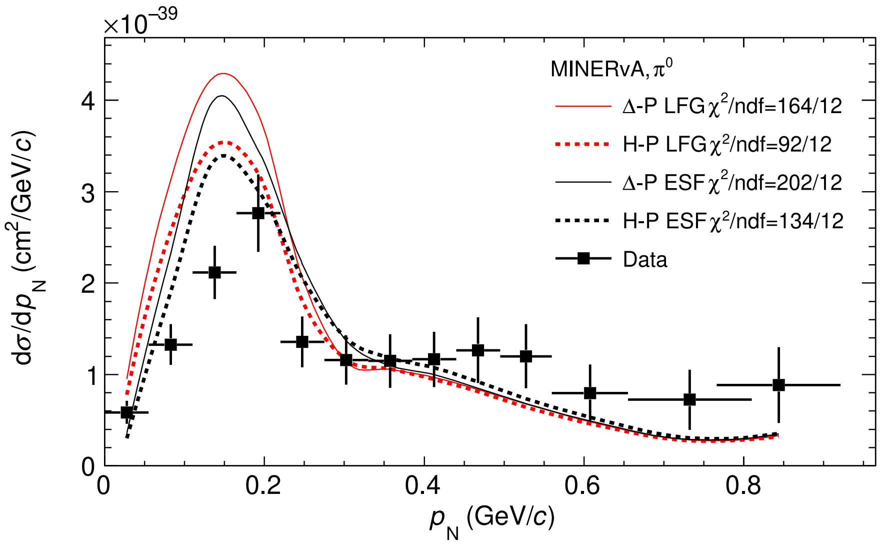
Figure 7: The $\frac{d\sigma}{dW}$ result comparison between the Δ model and the Hybrid model. Yan *et al.* arXiv:2405.05212 [hep-ph]

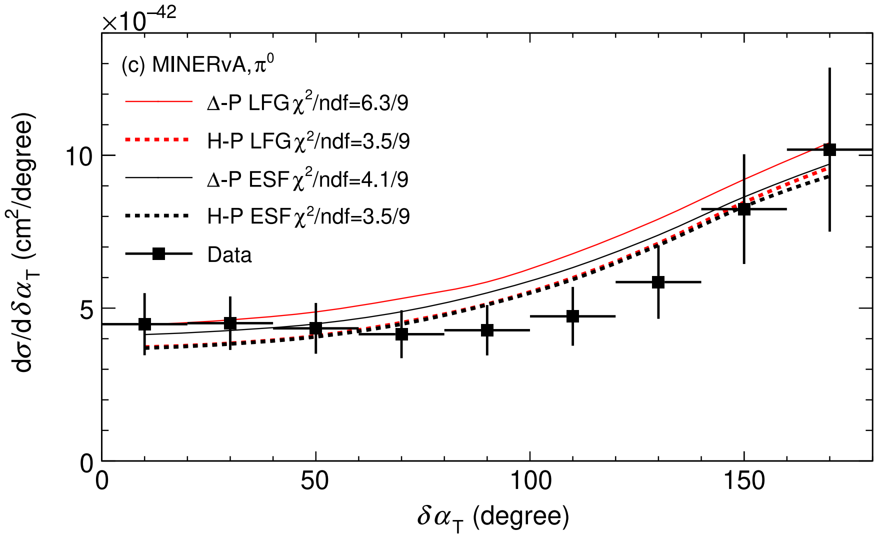
And when comparing with data, Final State Interaction (FSI) will be needed:



Credit: Tomasz Golan, Link

- π created at primary vertex will interact with the nucleus.
- Modeled by intranuclear cascade.
  - low energy π: Oset *et al.*
  - High energy π: From scattering experiments.
  - Angular distribution from SAID model.

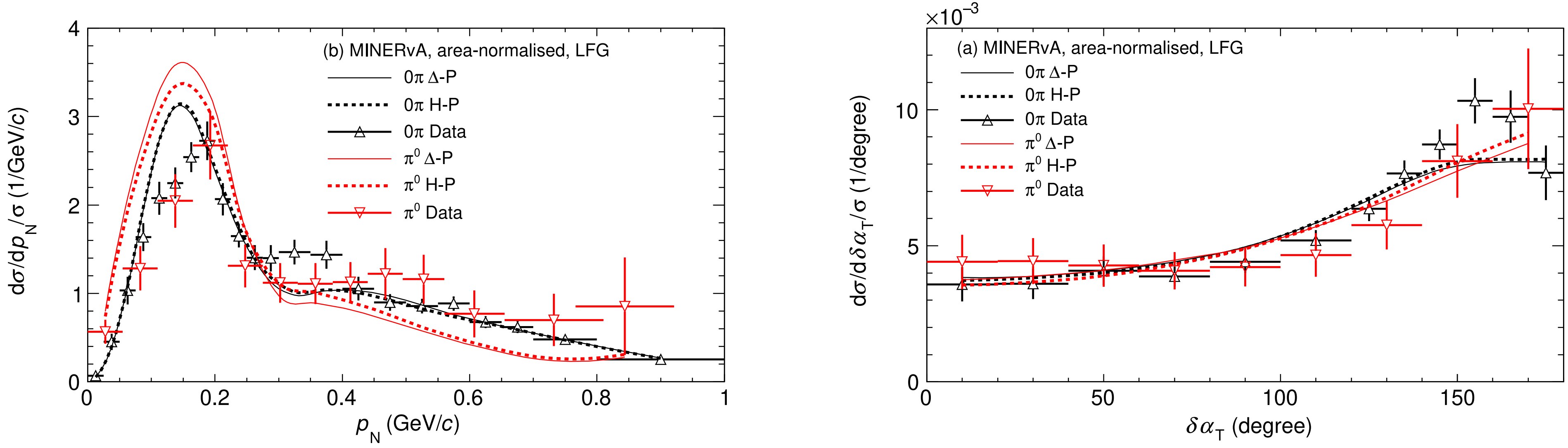




Model to data comparisons against MINERvA TKI measurements, the hybrid model showed significant improvements in χ^2

For the definitions of p_n and $\delta\alpha_T$, please refer to Xiangguo Lu's talk in this morning.

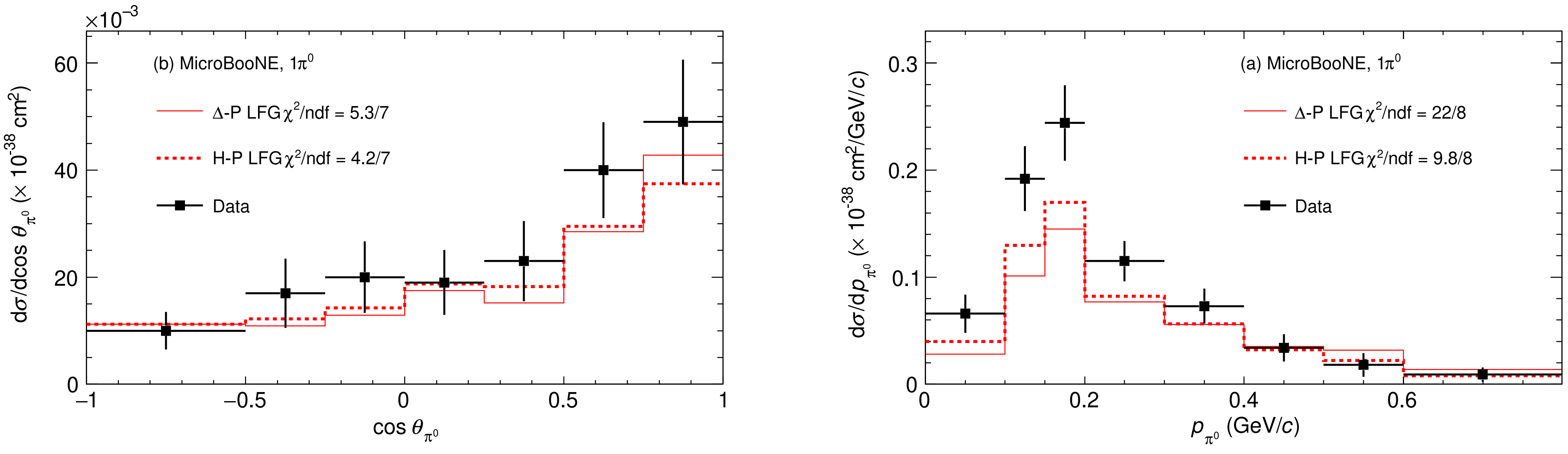
Yan *et al.* `arXiv:2405.05212 [hep-ph]`, data from MINERvA collaboration *Phys. Rev. D 102 (2020) 072007*



The shape agreements against 0π and π^0 is also improved in new model. Also note that, changes in π production model don't change prediction in 0π channel, which is QEL dominated.

Yan *et al.* `arXiv:2405.05212 [hep-ph]`, data from MINERvA collaboration *Phys. Rev. D 102 (2020) 072007*

NuWro



Model to data comparisons against MicroBooNE CC1π^0 measurements, the hybrid model showed improvements in the distribution of $p_{\pi^0}\chi^2$

Yan *et al.* `arXiv:2405.05212 [hep-ph]`, data from MicroBooNE Collaboration, `arXiv:2404.09949 [hep-ex]`

GENIE

GENIE

Model composition for GENIE relating to π production

- GENIE provide a comprehensive model for neutrino interaction.
- Many choices to describe the resonances
  - Resonance contribution stops at $W = 1.7\,\mathrm{GeV}$
- The non-resonant background is modeled using the AGKY model.
- Contains linear transition region from AGKY to PYTHIA6

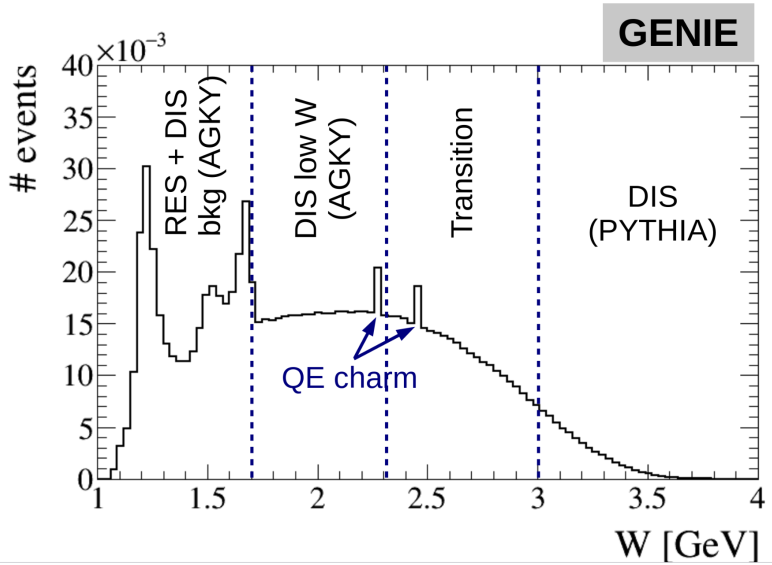


Figure 11: Kavli IPMU "Generators for the SIS/DIS region"

Possible choices for the resonance model in GENIE

- Rein-Sehgal
  - Original paper models 18 resonances, 16 are included in GENIE
  - Lepton mass related effects not included originally, but kinematics related effects are included.
  - $M_A = 1.2\,\mathrm{GeV}$
- Berger-Sehgal
  - Upgrade of Rein-Sehgal model.
  - Lepton mass contribution added.
  - Default for `G18_10` and later tunes.
- Berger-Sehgal-Kuzmin-Lyubushkin-Naumov
- ...

The low-W model for SIS/DIS region: AGKY model:

- AGKY is a Koba-Nielsen-Olesen (KNO) Scaling based hadronization model, T. Yang, *et al.* Eur. Phys. J. C 63, 1 (2009):

$$\langle n_{\mathrm{ch}} \rangle = a_{\mathrm{ch}} + \beta_{\mathrm{ch}} \ln \frac{W^2}{\mathrm{GeV}^2/c^4}$$

$$\langle n_{\pi^0} \rangle \approx 0.5 \langle n_{\mathrm{ch}} \rangle$$

$$\langle n \rangle P(n) = f\left(\frac{n}{\langle n \rangle} \right)$$

$$f\left(\frac{n}{\langle n \rangle} \right) \overset{\text{parameterize}}{=} L\left(\frac{n}{\langle n \rangle} \right) = \frac{2e^{-c} c^{c\frac{n}{\langle n \rangle}+1}}{\Gamma\left(\frac{n}{\langle n \rangle} + 1 \right)}$$

- Parameters in AGKY (α, β, c) model was initially from fitting to bubble chamber data.

GENIE

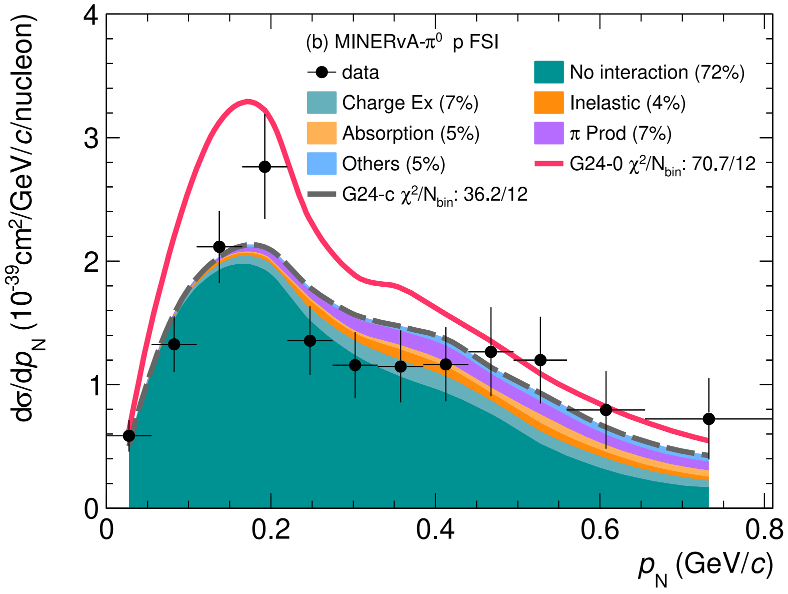
Tunning effort within GENIE

- Start with comprehensive model, with internal uncertainties.
- Fit those uncertain parameters to experimental data.

Tunning itself is a long story, involving too many aspects, but there are many great document about it.

- Global CC inclusive, 1π, and 2π data sets
  - Tune the Shallow inelastic region
  - Phys. Rev. D 104, 072009 (2021)
- Average charged multiplicity data
  - AGKY and PYTHIA
  - Phys. Rev. D 105, 012009 (2022)
- Nuclear tunes
  - Phys. Rev. D 106, 112001 (2022)
  - And FSI tunes!

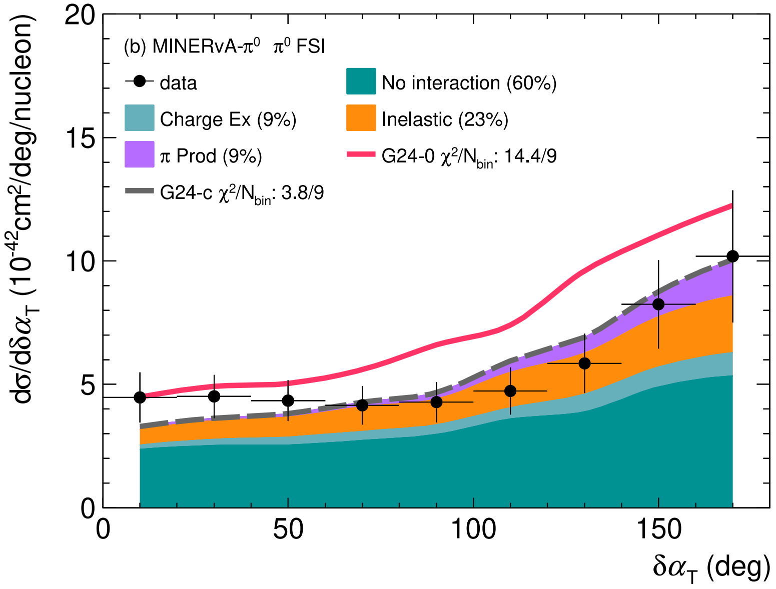
And FSI can also be tunned



Weijun Li, *et al.* `arXiv:2404.08510 [hep-ex]` PRD in press
G24-0 refers to original GENIE G24 model and G24-c refers to the tunned result.

- Some tension against data can be resolved by tuning FSI.
- The work tunned GENIE hA (effective intranuclear transport model) against T2K and MINERvA TKI data.
  - TKI is sensitive to FSI.
- Only tunned factors for fermi motion and scaling factor for re-scattering. (Not the interaction model)
- Improved agreements with the data.

And FSI can also be tunned



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GIBUU

The tool shared between few-body community and neutrino community: GiBUU

Powerful tool of GiBUU: Connect neutrino scattering prediction to electron scattering prediction

- Cross section predictions are connected with **structural functions** $W_i = W_i(Q^2, W)$, with the formalism of GiBUU, the neutrino (anti-neutrino) nucleon scattering cross section is:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_l\,\mathrm{d}\Omega} = \frac{G^2}{2\pi^2}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 E_l^2\left[2W_1(Q^2,W)\sin^2\frac{\theta}{2} + 2W_2(Q^2,W)\cos^2\frac{\theta}{2}\right.$$
$$\left.\mp W_3(Q^2,W)\frac{E+E_l^2}{m}\sin^2\frac{\theta}{2}\right]$$

The $W_3(Q^2, W)$ donates the interference term between vector contribution and axial contribution, thus only preset in neutrino/anti-neutrino scattering.

GiBUU

- GiBUU uses the connection between electron scattering and neutrino scattering to model **2p2h** and **background** contribution:

$$W_1^\nu = \left[1 + \left(\frac{2m}{\boldsymbol{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1) W_1^e,$$

$$W_3^\nu = 2\left(\frac{2m}{\boldsymbol{q}}\right)^2 \frac{G_A(Q^2)}{G_M(Q^2)} 2(\mathcal{T}+1) W_1^e,$$

- The functions W^e are fit by Bosted and Christy to electron scattering data.
- The resonance contribution for neutrino scattering is modeled using vector form factors from the MAID2007 analysis and axial from PCAC method.

- GiBUU uses the connection between electron scattering and neutrino scattering to model **2p2h** and **background** contribution:

nucleon mass

$$W_1^\nu = \left[1 + \left(\frac{2m}{\boldsymbol{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1) W_1^e,$$

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3 momentum transfer

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GiBUU

- GiBUU uses the connection between electron scattering and neutrino scattering to model **2p2h** and **background** contribution:

Axial coupling factor

$$W_1^\nu = \left[1 + \left(\frac{2m}{\boldsymbol{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1)W_1^e,$$

$$W_3^\nu = 2\left(\frac{2m}{\boldsymbol{q}}\right)^2 \frac{G_A(Q^2)}{G_M(Q^2)} 2(\mathcal{T}+1)W_1^e,$$

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$$W_1^{\nu} = \left[1 + \left(\frac{2m}{\boldsymbol{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1) W_1^e,$$

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EM isovector coupling factor

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$$W_1^{\nu} = \left[1 + \left(\frac{2m}{\boldsymbol{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1)W_1^e,$$

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Isospin for the nucleus

- The functions W^e are fit by Bosted and Christy to electron scattering data.
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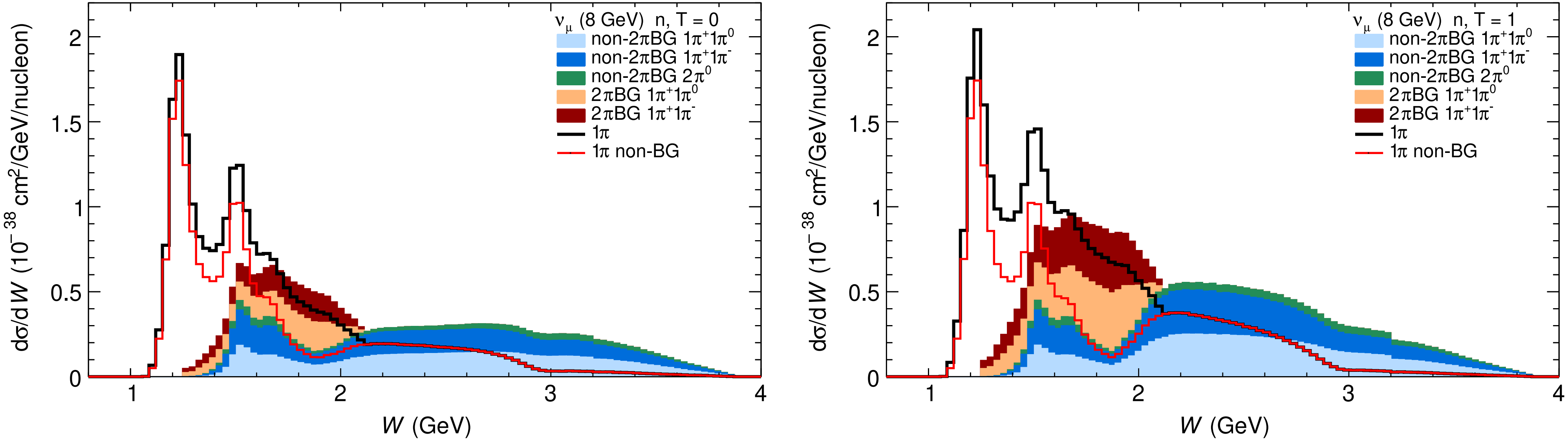


Figure 14: The demonstration of the affection affection of $\mathcal{T}$ factor.

The $\mathcal{T}$ factor scales the

- Backround contribution
- Part of DIS with cross section modeled by Bosted and Christy fit

by a factor of $\mathcal{T} + 1$.

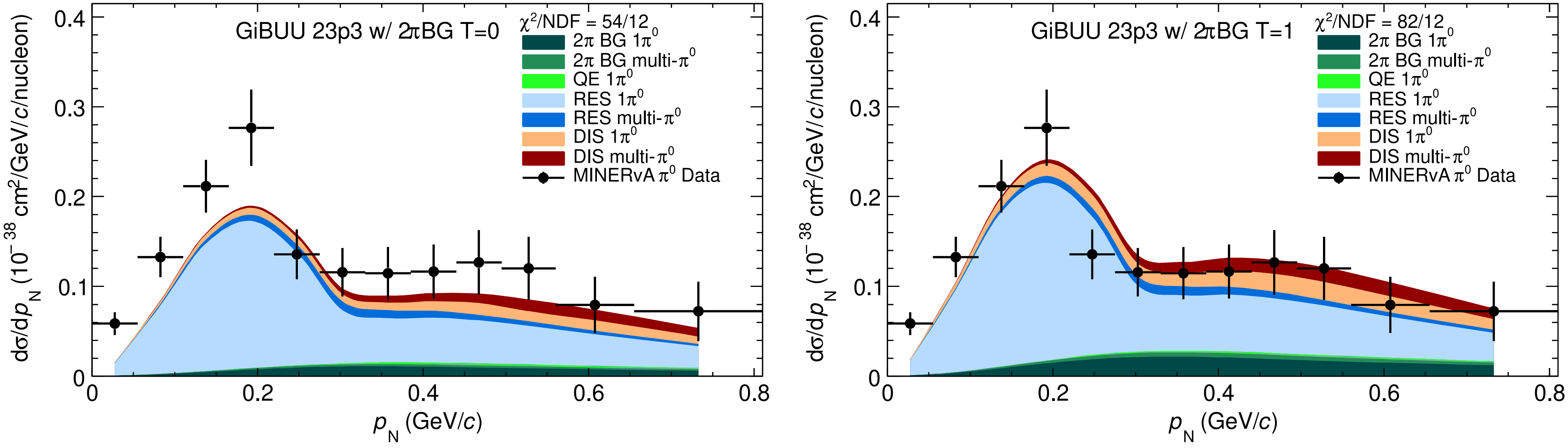


Figure 15: Comparison with MINERvA TKI with different T parameter.

For experiments with C target, the result from $\mathcal{T} = 0$ (physical for C-12) yields better agreement with data.

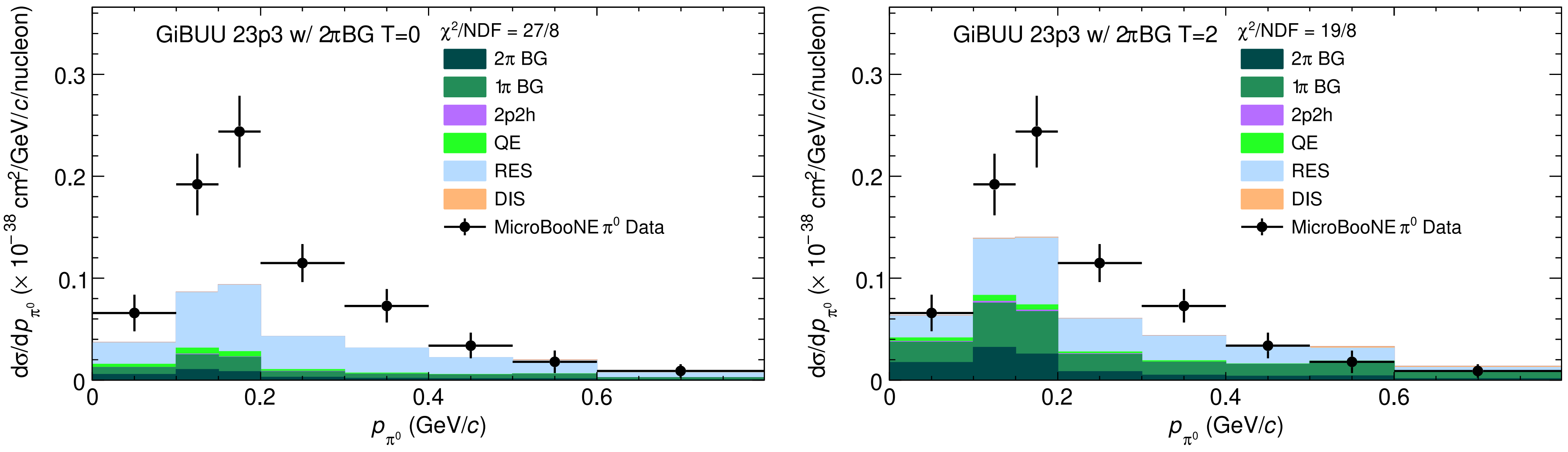


Figure 16: Comparison with MicroBooNE CCπ^0 data with different T parameter.

For experiments with Ar target, the result from $\mathcal{T} = 2$ (physical for Ar-40) yields better agreement with data.

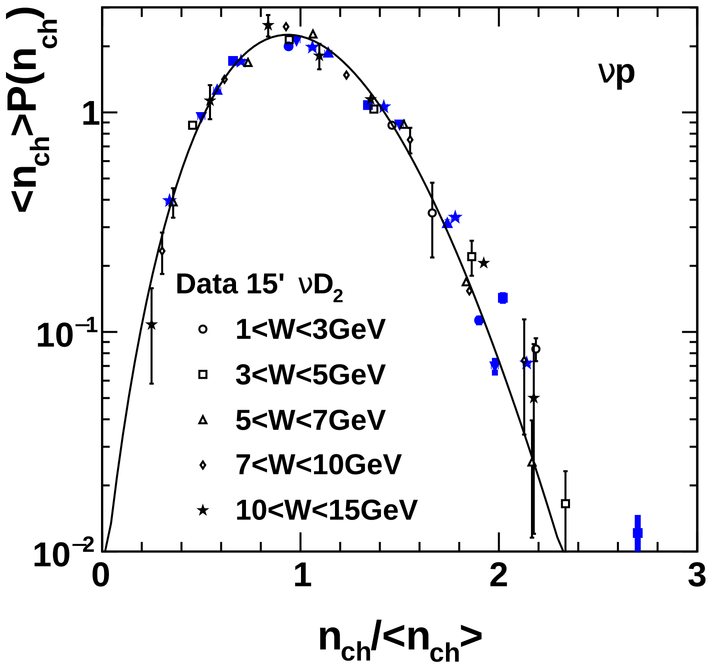
Summary

Summary

- This is a brief summary of the strategy of different neutrino generators employed pion production related process.
- There are some aspects related to nucleus effect not covered here:
  - Fermi motion model
  - In medium effect of the resonances
- The π production related region is a region with many challenges, but also with many opportunities.
- Many efforts being done to improve the GeV generators, getting them prepared for **next generation neutrino experiments**.
  - Soon to be running: atmospheric neutrino at JUNO
  - Long term: accelerator neutrino at DUNE and Hyper-K
- Systematic studies of neutrino pion production with dedicated data are much required.

Thank you!

Backup



Júlia Tena-Vidal, *et al.* Phys. Rev. D 105, 012009

$n_{\mathrm{ch}}\langle n_{\mathrm{ch}}\rangle$ follows a distribution for different W.

Idea

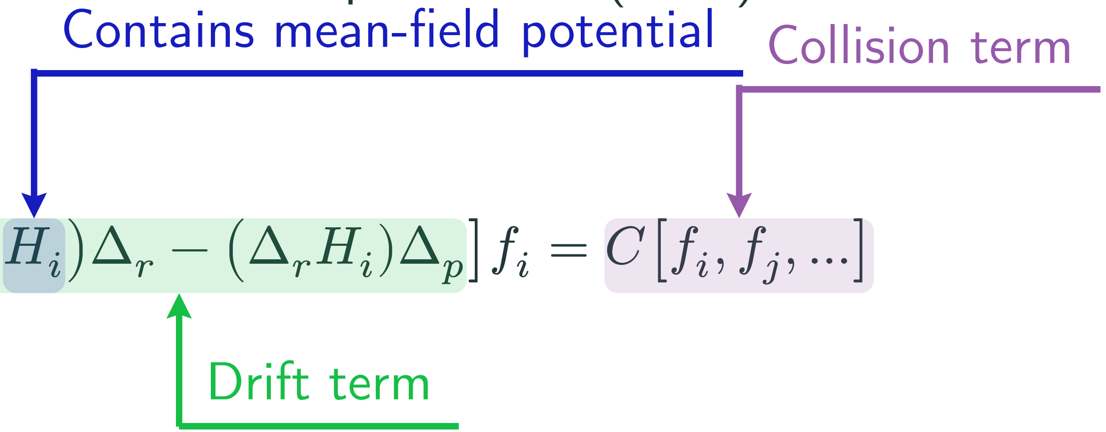
- pQCD, hard qq scattering scattering
- Creates a string
- String breaks, hadronization
- Phenomenological fragmentation function

$$f(z) \propto \frac{(1-z)^a}{z} \exp\left(-\frac{bm_\perp^2}{z}\right)$$

- Fit to data (e.g. to HERMES)

FSI for GiBUU

- Different from all other generators: transport model (BUU) instead of cascade.



$$[\partial_t + (\Delta_p H_i)\Delta_r - (\Delta_r H_i)\Delta_p] f_i = C[f_i, f_j, ...]$$

With Test particle to describe nucleus state:

$$f \sim \sum_i \delta(\vec{r} - \vec{r}_i(t))\delta(\vec{p} - \vec{p}_i(t))$$

propagates phase-space distributions, not particles.

Regge

Replace:

$$\frac{1}{t - m_\pi}$$

to

$$\mathcal{P}_\pi(t, s) = -\alpha'_\pi \varphi_\pi(t) \Gamma[-\alpha_\pi(t)] (\alpha'_\pi s)^{\alpha_\pi(t)}$$

- Based on crossing symmetry
- Amplitude can be expanded in a Legendre series
- Do intergral on complex plane
- See This talk