The Study of Single Signal Events from Atmospheric Neutrino Interaction with LS

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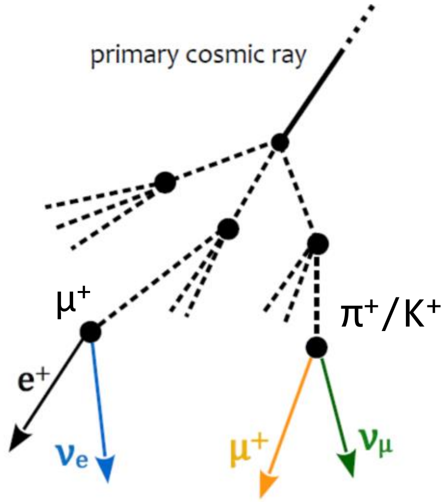
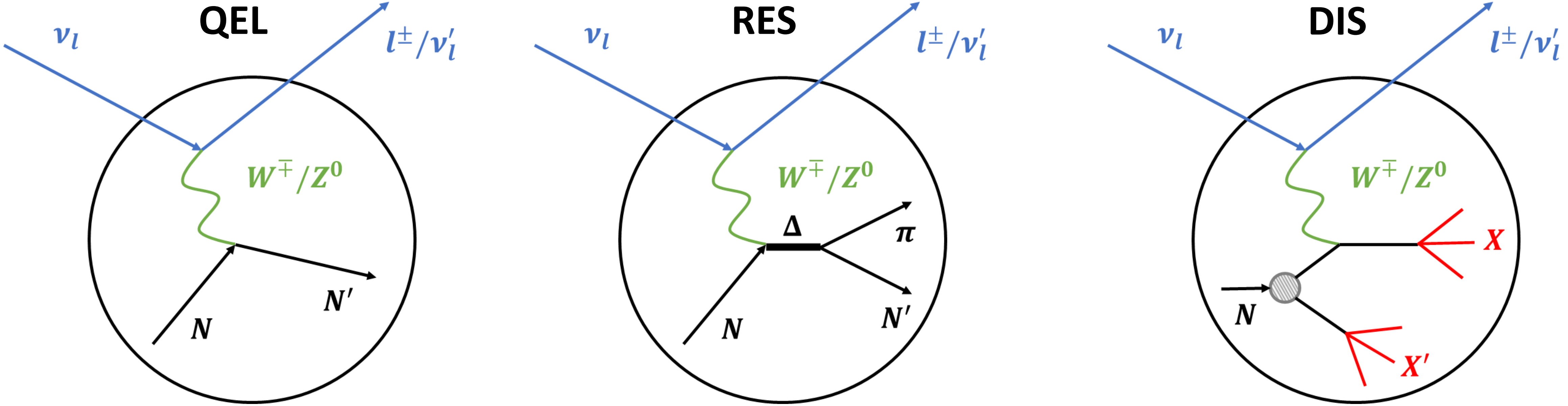
I. Motivation

Atmospheric ν Interaction with LS

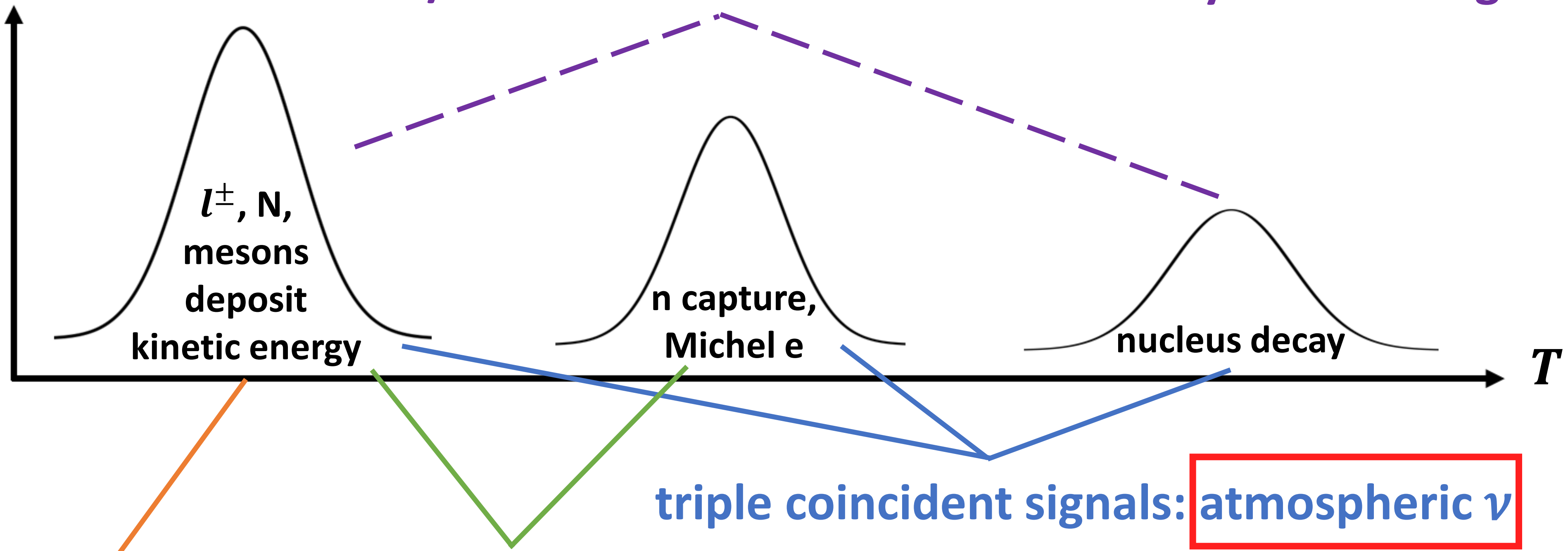


- Liquid scintillator (LS) detector can detect atmospheric ν: KamLAND, **JUNO**
  - Lower E_{thr}, and better σ_E than water Cherenkov detector
  - Good neutron tagging efficiency
- In LS detector, ν interact with H (free) and C (bound)



Different Kinds of Signal

Hard to select/exclude due to natural radioactivity and cosmogenic isotopes



triple coincident signals: atmospheric ν

double coincident signals: reactor ν, core-collapse supernova ν (IBD), DSNB, atmospheric ν

single signals: solar ν, core-collapse supernova ν (νp), atmospheric ν

Why atmospheric ν?

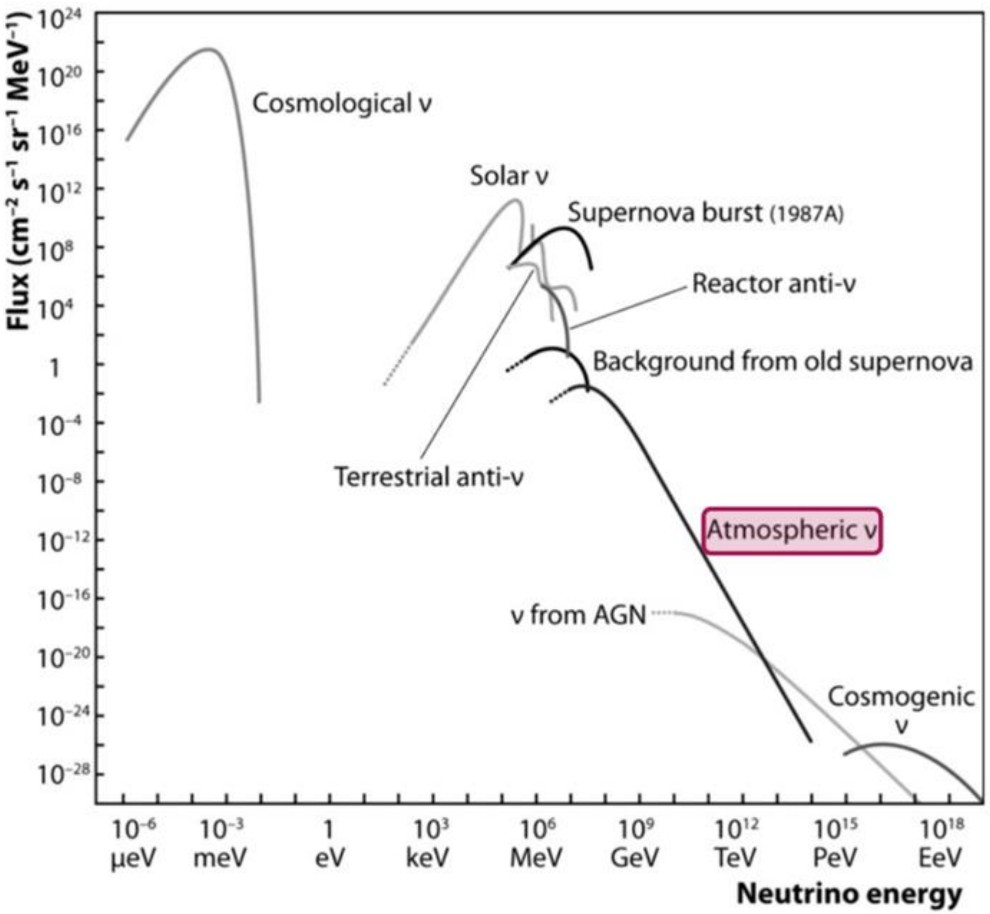
- Large LS detector (e.g., JUNO) can detect sufficient **atmospheric ν events**:

  Wide energy range, all flavors

  → Contain single, double [Jie Cheng, *arXiv*:2404.07429], and triple signals [Jie Cheng, *Phys.Rev.D* 103 (2021) 5, 053002]

- Relatively pure **single signals** from atmospheric ν, especially NC at low energy

  1. Separated energy window to other ν sources
  2. As the signal, new data to constrain NC model
  3. As the background of solar ν and new physics, e.g., boosted dark matter



II. Single Signals from νN Interaction in LS

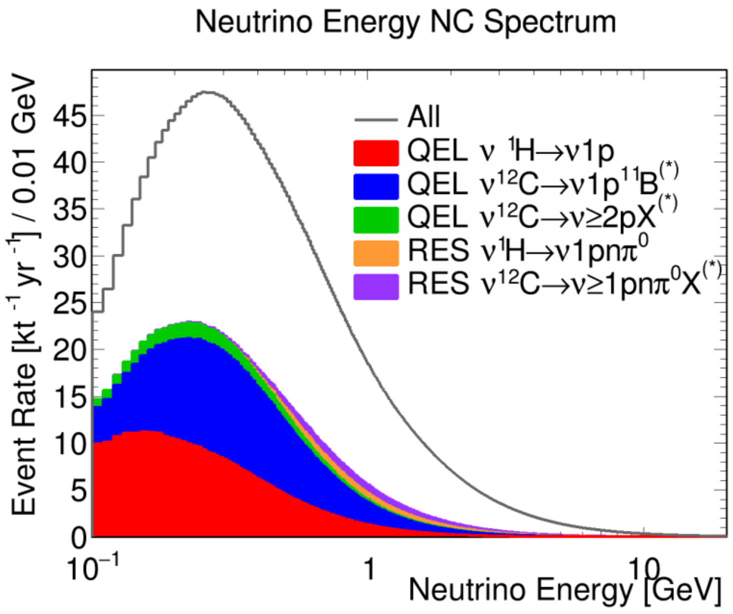
Processes to Form Single Signals

- No particles w/ delay signals (e.g., n, $\mu^{\pm}/\pi^{\pm}$)
- **Neutral Current (NC):**
  - **QEL:**
    - $\boldsymbol{\nu} + {}^{1}\mathbf{H} \rightarrow \boldsymbol{\nu} + \mathbf{p}$
    - $\boldsymbol{\nu} + {}^{12}\mathbf{C} \rightarrow \boldsymbol{\nu} + \boldsymbol{n}\mathbf{p} + \mathbf{X}^{(*)}$ (1p^{11}B$^{(*)}$, 2p^{10}Be$^{(*)}$, 3p^{9}Li$^{(*)}$, 4p^{8}He$^{(*)}$, …)

Just recoil proton!

Potentially good channel to constrain model

  - RES:
    - $\nu + {}^{1}\mathrm{H} \rightarrow \nu + \mathrm{p} + n\pi^{0}$
    - $\nu + {}^{12}\mathrm{C} \rightarrow \nu + n\mathrm{p} + n\pi^{0} + \mathrm{X}^{(*)}$



- Charge Current (CC):
  - QEL:
    - $\nu + {}^{12}\mathrm{C} \rightarrow \mathrm{e}^{\pm} + n\mathrm{p} + \mathrm{X}^{(*)}$ (e^{-}1p^{11}C$^{(*)}$, e^{+}1p^{11}Be$^{(*)}$, …)
  - RES
    - $\nu + {}^{12}\mathrm{C} \rightarrow \mathrm{e}^{\pm} + n\mathrm{p} + n\pi^{0} + \mathrm{X}^{(*)}$

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Nuclear Effect of νC Interaction

- NC QEL: $\nu + {}^{1}\mathrm{H} \rightarrow \nu + \mathrm{p}$, $\boldsymbol{\nu + {}^{12}\mathrm{C} \rightarrow \nu + np + \mathrm{X}^{(*)}}$

Affect by nuclear effects, i.e., nuclear model, final state interaction (FSI)

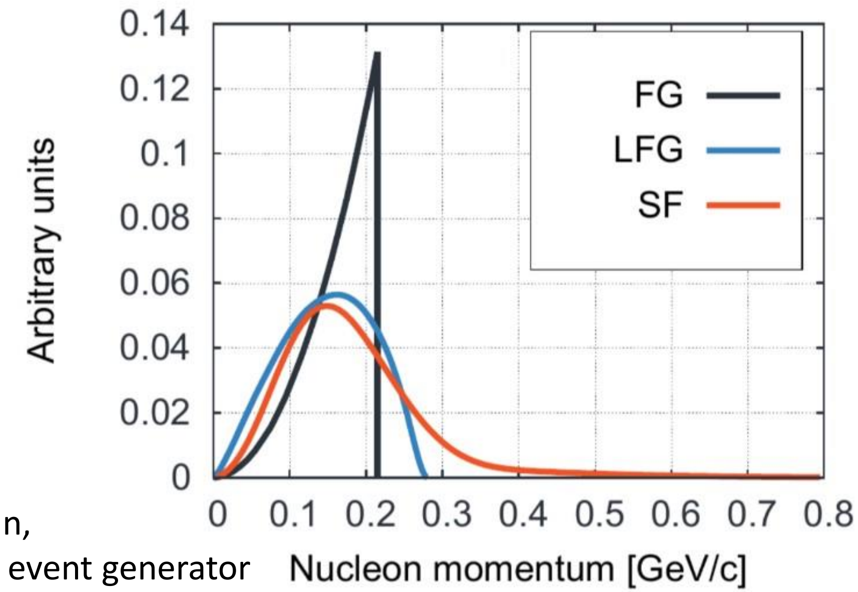
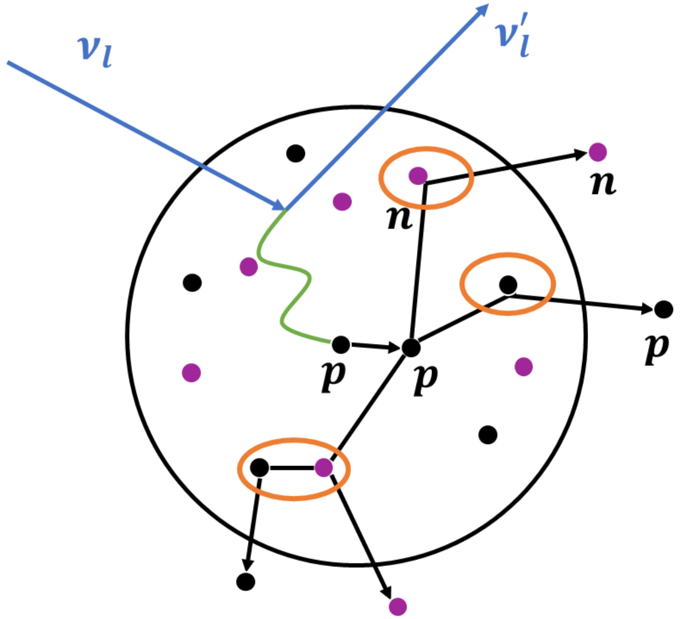


Fig from Tomasz Golan,
NuWro- neutrino MC event generator



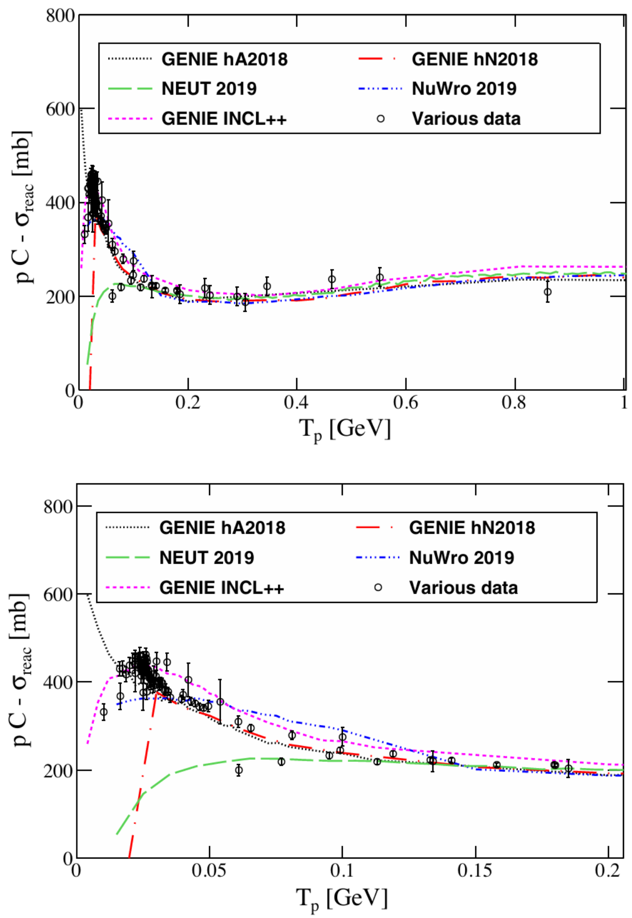
The leading proton smeared by **Fermi motion**, transferred momentum to other nucleons and knocked them out during **FSI**.

Comparison of Interaction Models

Models	Nuclear Model	M_A [GeV]	FSI
GENIE	**LFG**	**0.99**	**hN (Cascade)** ← **baseline**
GENIE	LFG	0.99	hA (Empirical)
GENIE	BRRFG	0.99	hN (Cascade)
NuWro	LFG	1.03	Cascade
NuWro	SF	1.03	Cascade

GENIE hA: a single interaction based on data

GENIE hN and NuWro cascade: multiple interactions



S. Dytman, et. al., *Phys. Rev. D* **104**, 053006

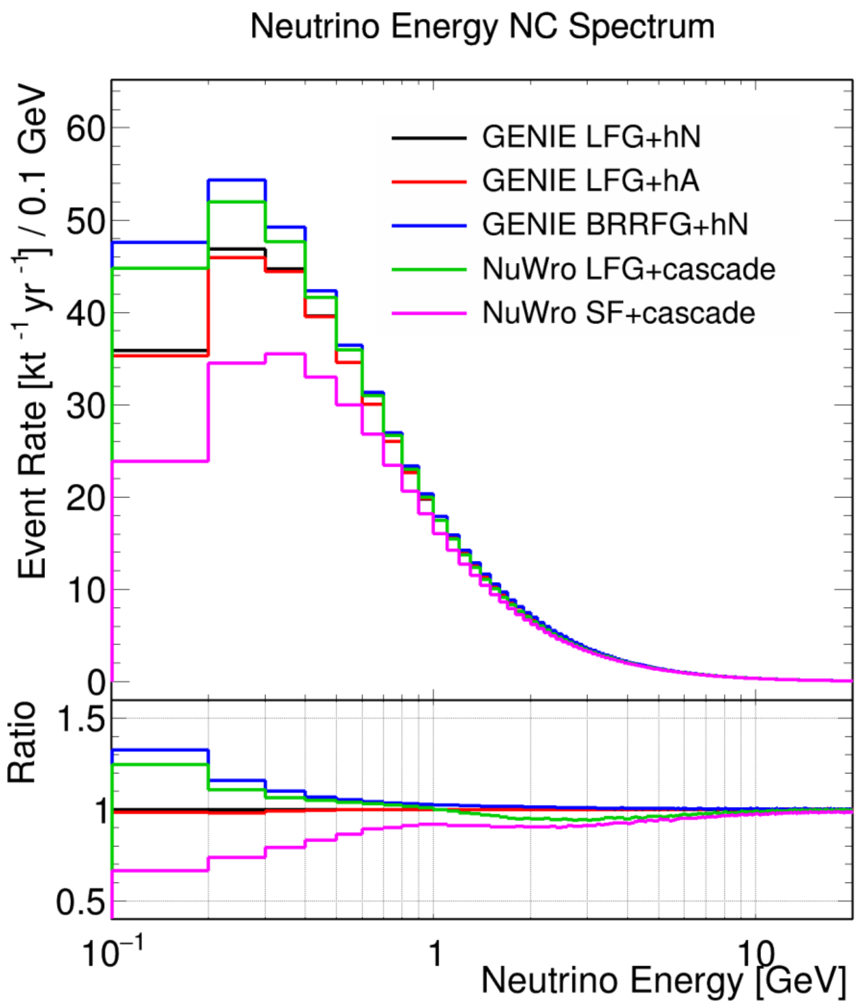
NC free nucleon QEL Cross Section

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M_p^2}{8\pi E_\nu^2}\left(A \pm B\frac{s-u}{M_p^2} + C\frac{(s-u)^2}{M_p^4}\right)$$

- $s - u = 4M_p E_\nu - Q^2$
- $A = \frac{Q^2}{M_p^2}\left(G_A^2\left(1+\frac{Q^2}{4M_p^2}\right) - F_1^2\left(1-\frac{Q^2}{4M_p^2}\right) + F_2^2\left(1-\frac{Q^2}{4M_p^2}\right)\frac{Q^2}{4M_p^2} + F_1F_2\frac{Q^2}{M_p^2}\right)$
- $B = \frac{Q^2}{M_p^2} G_A(F_1 + F_2)$
- $C = \frac{1}{4}\left(G_A^2 + F_1^2 + F_2^2\frac{Q^2}{4M_p^2}\right)$
- $G_A(Q^2) = \frac{1}{2}\frac{g_A(0)}{(1+Q^2/M_A^2)^2}(1+\eta)$

Larger M_A → larger σ

Comparison of Interaction Models

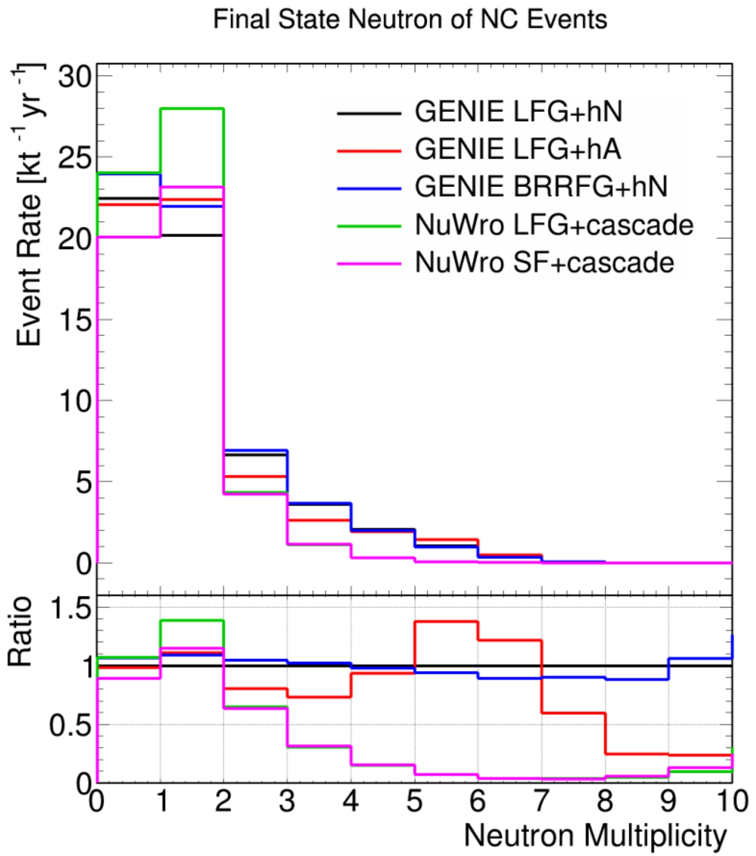


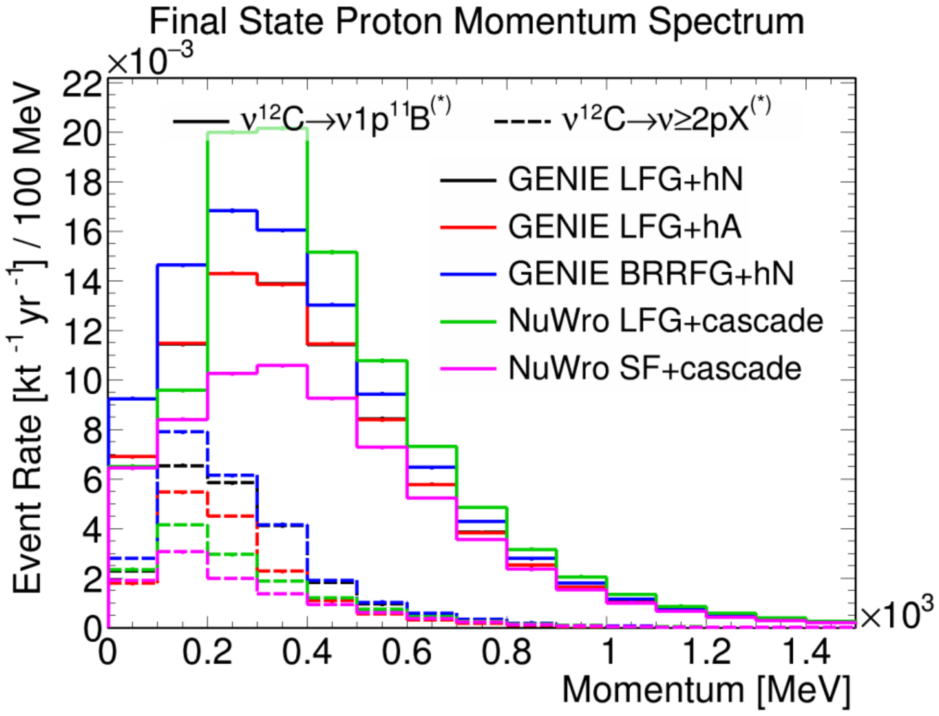
- Different nuclear models influence a lot, especially in low energy range.
- Larger M_A with higher rate as expected.

GENIE events with zero momentum nucleons are removed → Slightly different between LFG+hN/hA

Comparison of Interaction Models

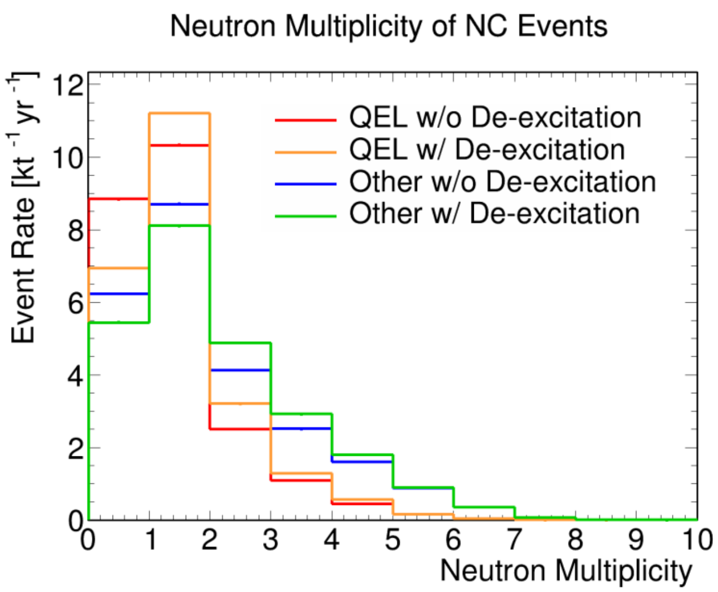
- ~10% max differences of events w/o n.
- Proton momentum of NC 1p^{11}B events are affected a lot.

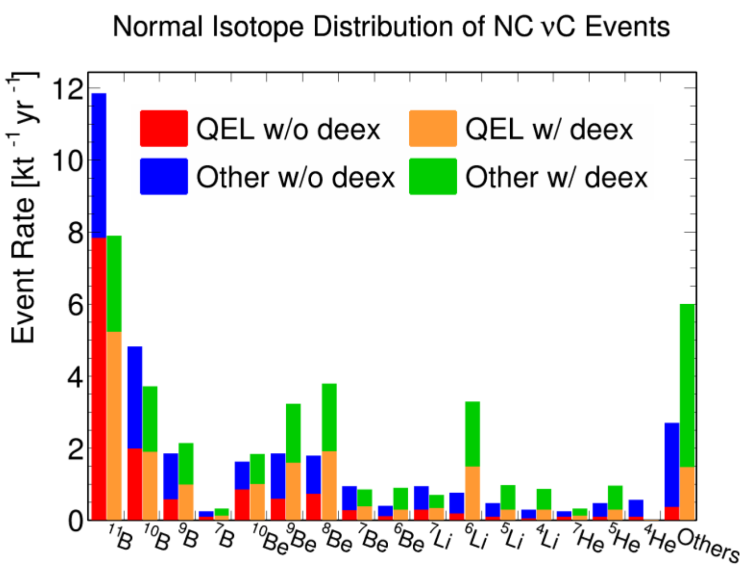


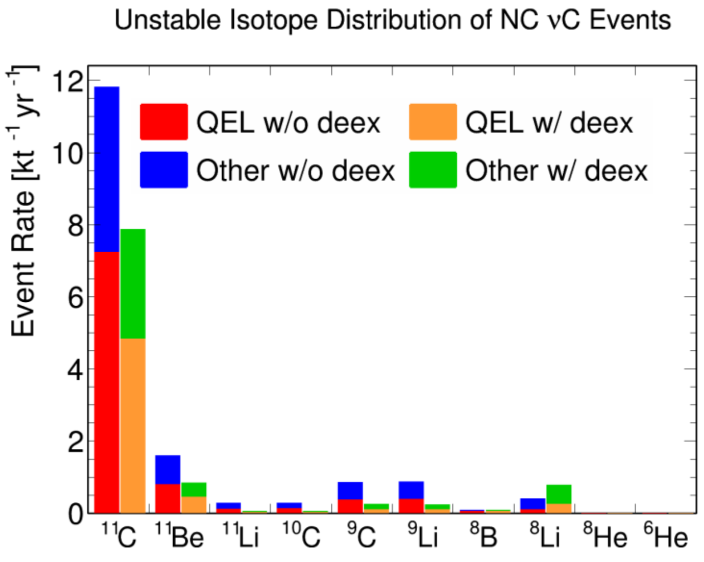


III. De-excitation Effect of Single Signals

- Remnant excited nucleus: de-excitation with additional γ, n, p.
- After de-excitation:
  - Less events w/o n, especially NC QEL
  - Less remnant nuclei w/ $T_{\frac{1}{2}} \in [1\ \mathrm{ms}, 1\mathrm{h}]$, unstable but hard to exclude

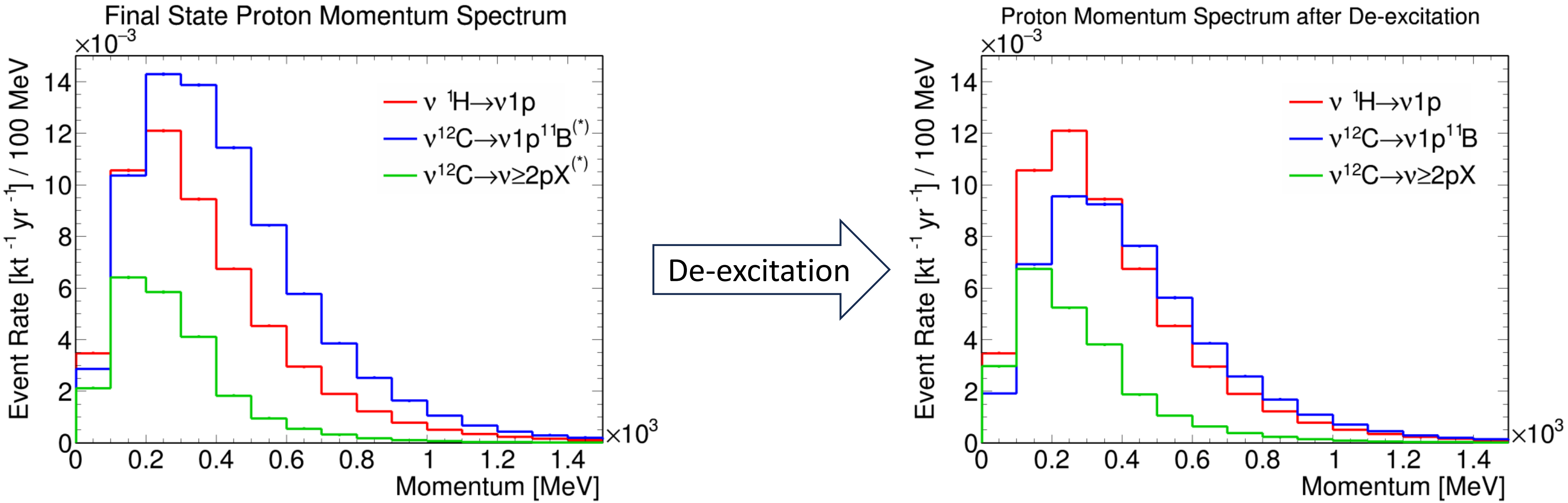






- νH not effected by de-excitation
- Master effect: less NC 1p^{11}B events after de-excitation → less available single signal

NC QEL Channel	Event Rate [kton^{-1}·yr^{-1}]
$\nu\ ^1\mathrm{H} \rightarrow \nu\mathrm{p}$	5.53→5.53
$\nu\ ^{12}\mathrm{C} \rightarrow \nu\mathrm{p}^{11}\mathrm{B}$	7.83→5.22
$\nu\ ^{12}\mathrm{C} \rightarrow \nu \geq 2\mathrm{pX}$	2.26→2.33

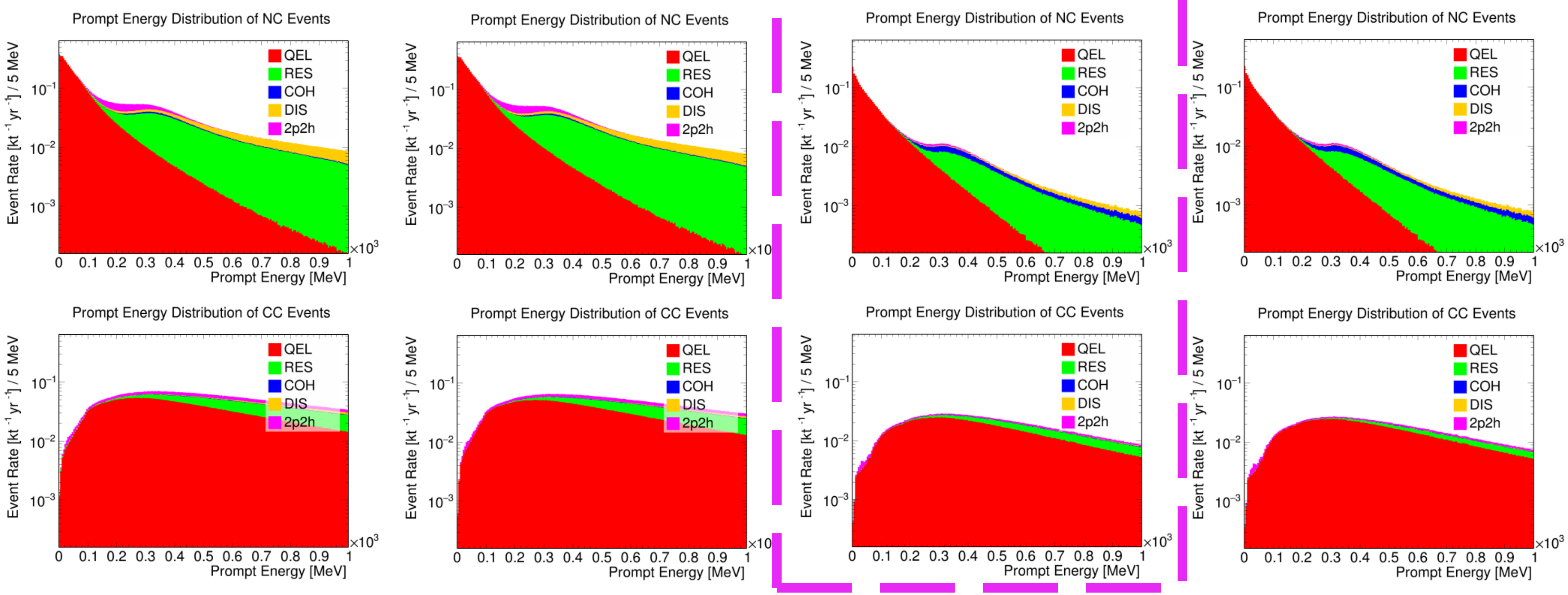


IV. Detector Response of Single Signals

Single Signals Selection Criterion

- Prompt Energy: particles deposit the kinetic energy quickly in first 1e3 ns.
- Exclusion of captured n mainly remained the QEL events

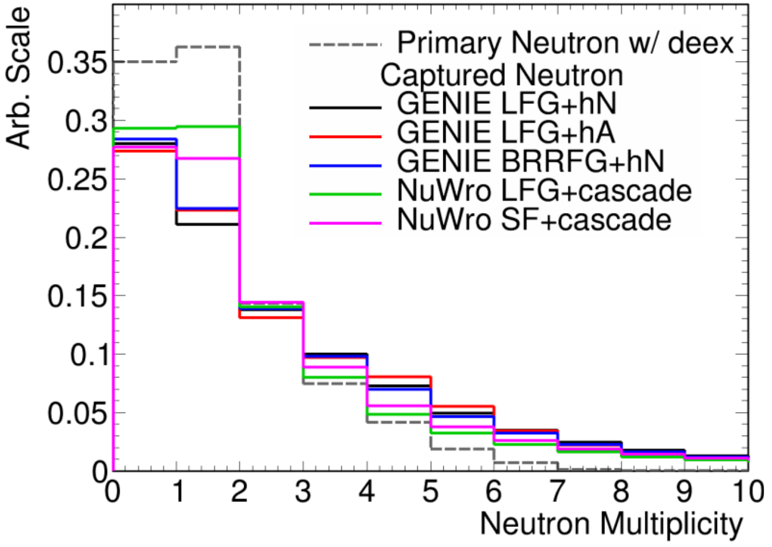
All Events | **FC Cut** | **Captured n Cut** | **Michel e Cut**



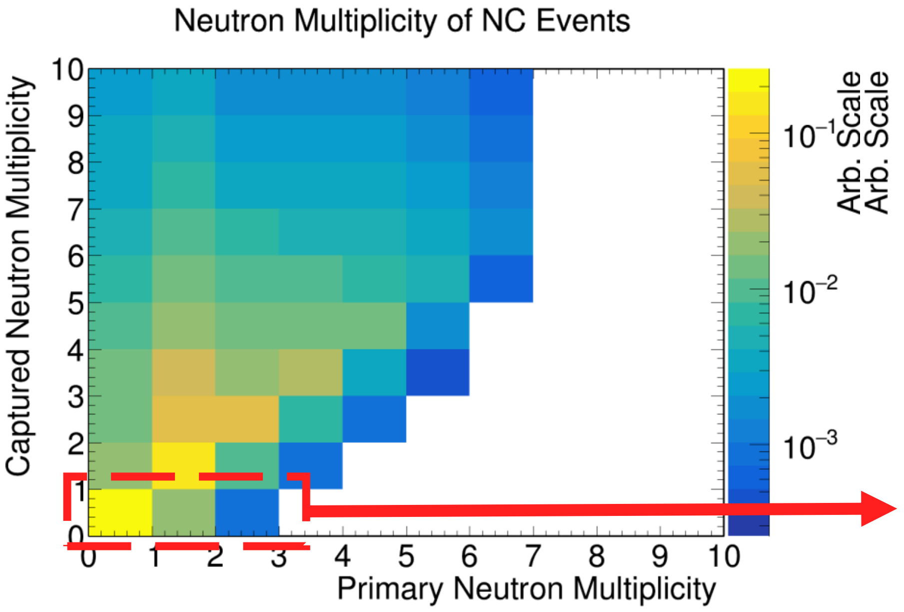
FC: no energy loss outside center detector

Neutron in Secondary Interaction

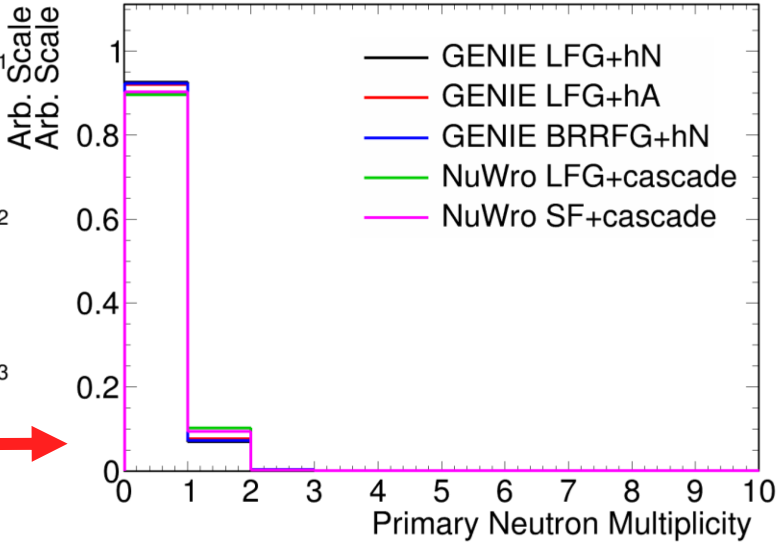
- ~7% less single signal after SI



- Many captured neutrons are produced by secondary interaction (SI)

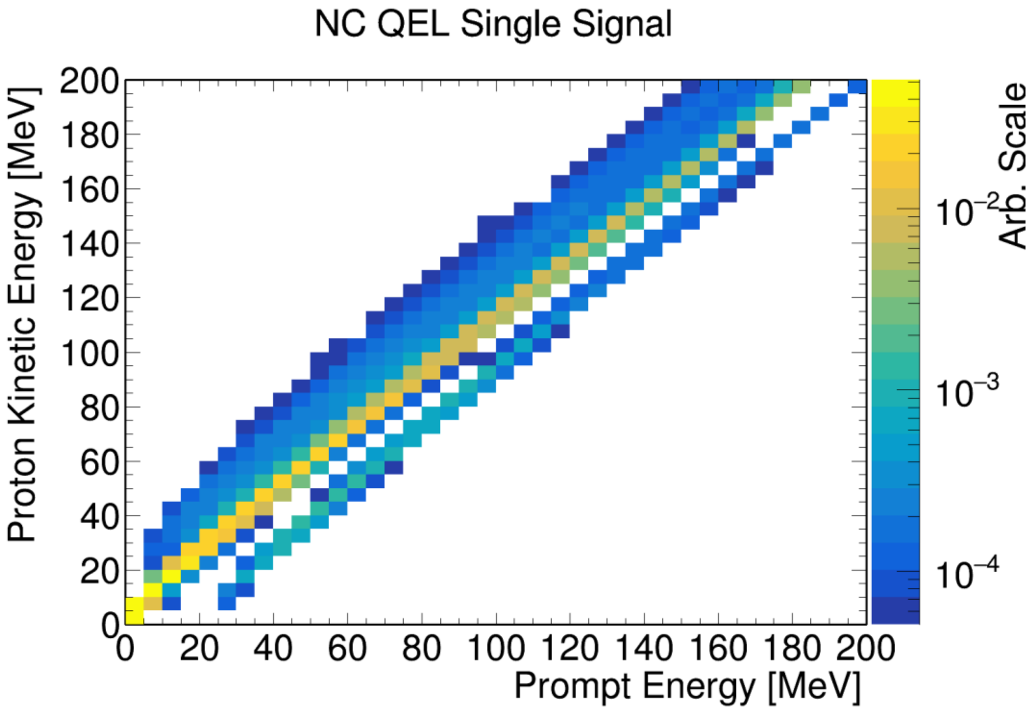


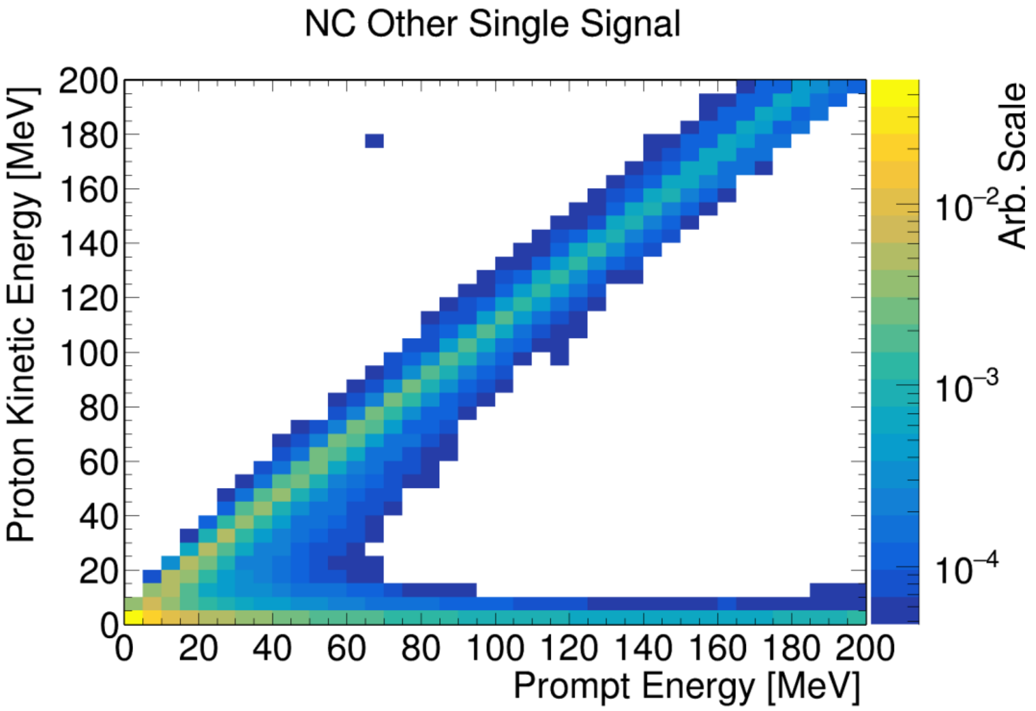
- ~7% of NC single signals with uncaptured primary neutrons (single-like)



Proton $E_{\mathrm{k}} \rightarrow E_{\mathrm{prompt}}$

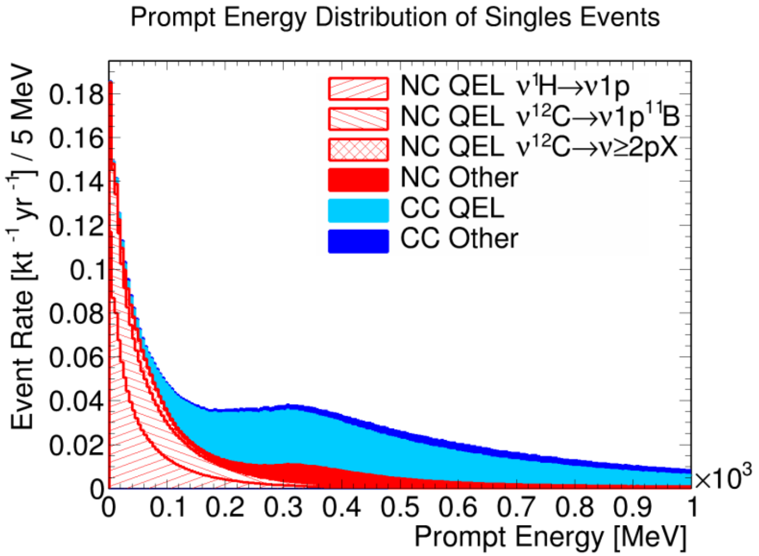
- NC QEL single signals: a relatively good linear relationship between proton kinetic energy and prompt energy

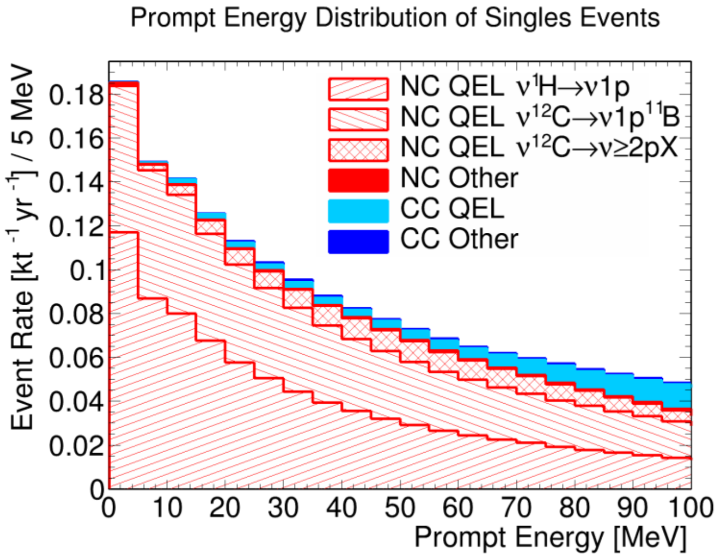


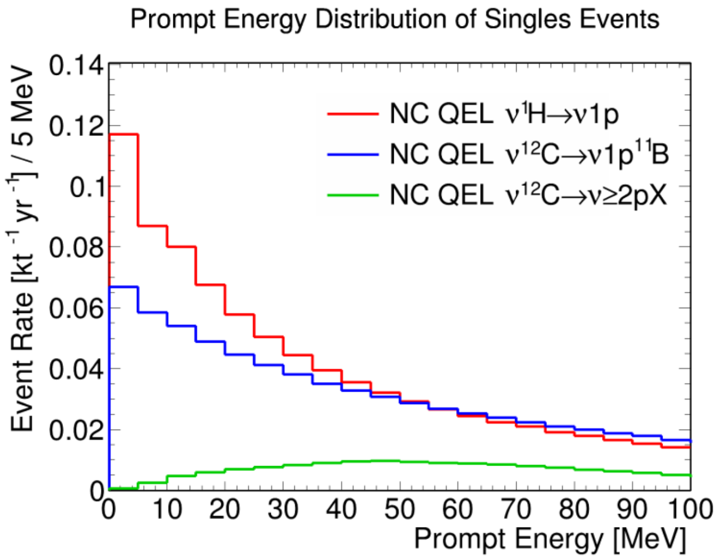


V. Available Spectrum of Single Signals

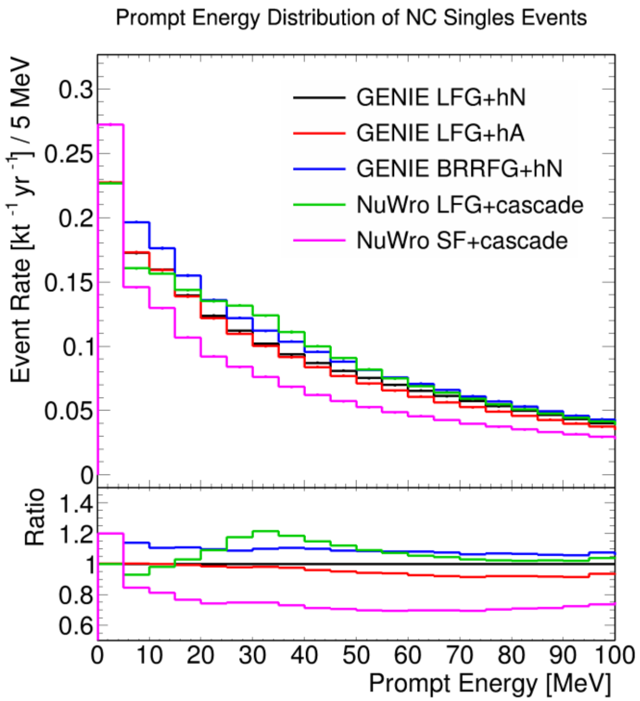
- $E_{\mathrm{prompt}} < 100\ \mathrm{MeV}$: main NC QEL events, especially w/ 1 recoil proton.
- Less NC $1p^{11}B$ events after selection
- Flatter E_{prompt} spectrum due to nuclear effect.
- Nuclear model affects more in low energy range of singles w/ 1 recoil proton.

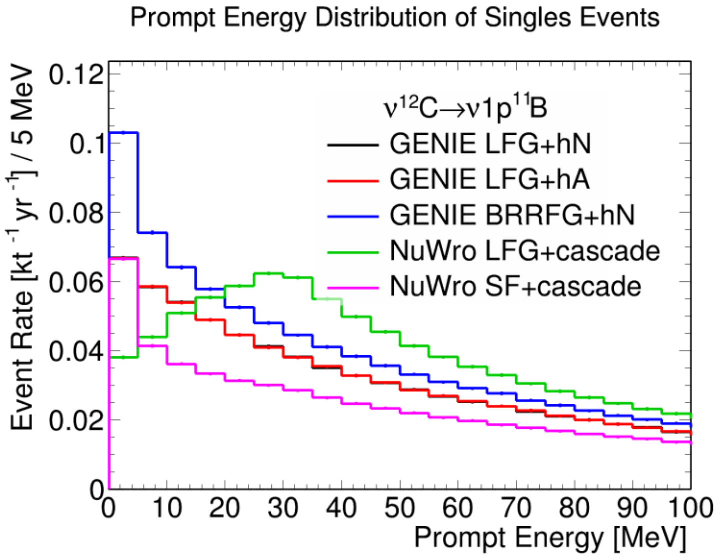


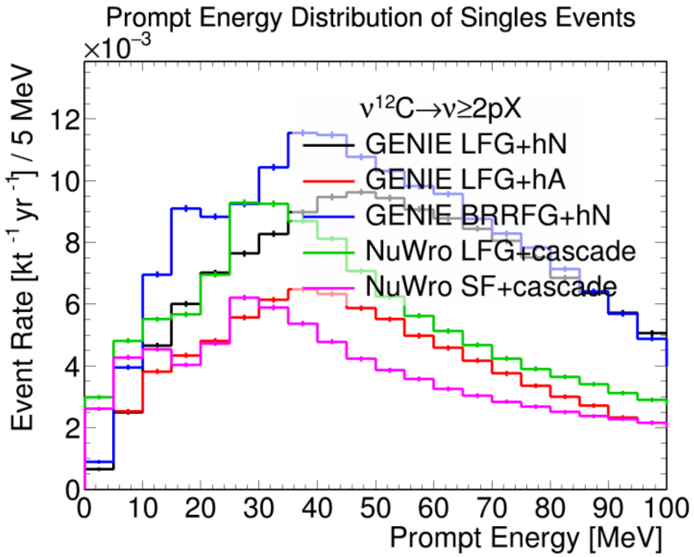




- Expected NC singles spectrums show different between GENIE and NuWro, especially NuWro SF model.
- NuWro LFG model expects a quite different NC 1p^{11}B singles spectrum
- Validate and constrain the models for LS experiments.







Summary

- Single signals from atmospheric ν events with recoil proton, γ, π^0, $e^\pm$
  - Especially **NC QEL with just recoil proton**
- Nuclear model, QEL, and FSI combine to influence the single signals
- De-excitation is an important factor: ~30% less $\nu\,^{12}\mathrm{C} \to \nu \mathrm{p}\,^{11}\mathrm{B}$
- Available single signals suffer slight lost and are mimicked by a few events with primary neutron due to SI
- $E_{\mathrm{prompt}} < 100\ \mathrm{MeV}$ relatively pure single signal events from **NC QEL with just recoil proton**
- Potentially good data to validate and to constrain νN interaction models

Thank you for your attention!