First combined tuning on transverse kinematic imbalance data with and without pion production constraints

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Abstract

We present the first combined tuning, using GENIE, of four transverse kinematic imbalance (TKI) measurements of neutrino-hydrocarbon scattering, both with and without pion final states, from the T2K and MINERvA experiments. As a proof of concept, we have simultaneously tuned the initial state and final-state interaction models (SF-CFG and hA, respectively), producing a new effective model that more accurately describes the data. The work is available on arXiv: 2404.08510, and all references are the same as in the paper for consistency.

TKI Measurements

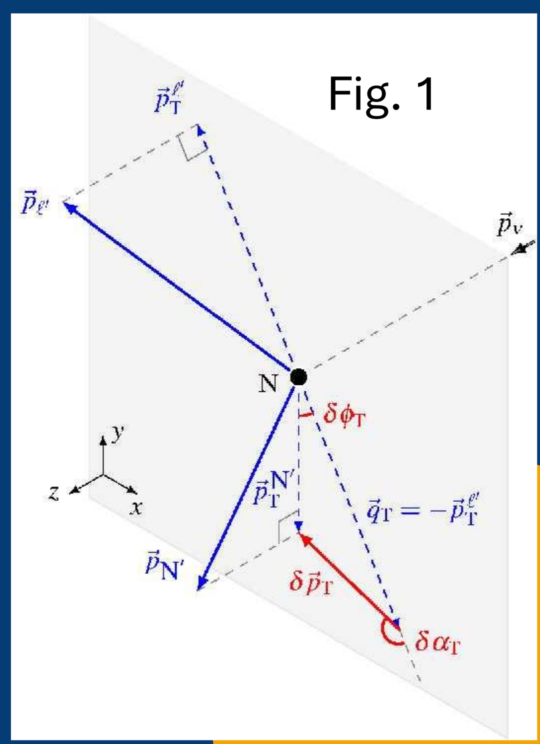


Fig. 1

- The Transverse Kinematic Imbalance (TKI) observables, as shown in Fig.1, are sensitive to initial nuclear states and hadronic final-state interactions (FSIs).
- Survey 4 TKI data-sets: T2K 0π [18], T2K π^+ [19], MINERvA 0π [20, 21], and MINERvA π^0 [14] measurements.
- Predictions made with G24_20i_00_000 (G24-0) shown in red lines in Fig.7
- Relatively good agreement except MINERvA-π^0
- Different combinations of TKI observables tried in tuning, as shown in Table III

Observables	No. of bins	Combi-Superset	Combi-Best-AllPar	Combi-Best-RedPar
		T2K-0π		
$\delta\alpha_T$	8	✓		✓
δp_T	8	✓	✓	✓
$\delta\phi_T$	8	✓		
		T2K-π^+		
$\delta\alpha_T$	3	✓		✓
p_N	4	✓	✓	✓
δp_{TT}	5	✓		✓
		MINERvA-0π		
$\delta\alpha_T$	12	✓		✓
p_N	24	✓	✓	✓
δp_T	24	✓	✓	
$\delta\phi_T$	23	✓		
p_p	25			
θ_p	26			
δp_{Tx}	32			
δp_{Ty}	33			
		MINERvA-π^0		
$\delta\alpha_T$	9	✓		✓
p_N	12	✓	✓	✓
δp_{TT}	13	✓		✓

Table III

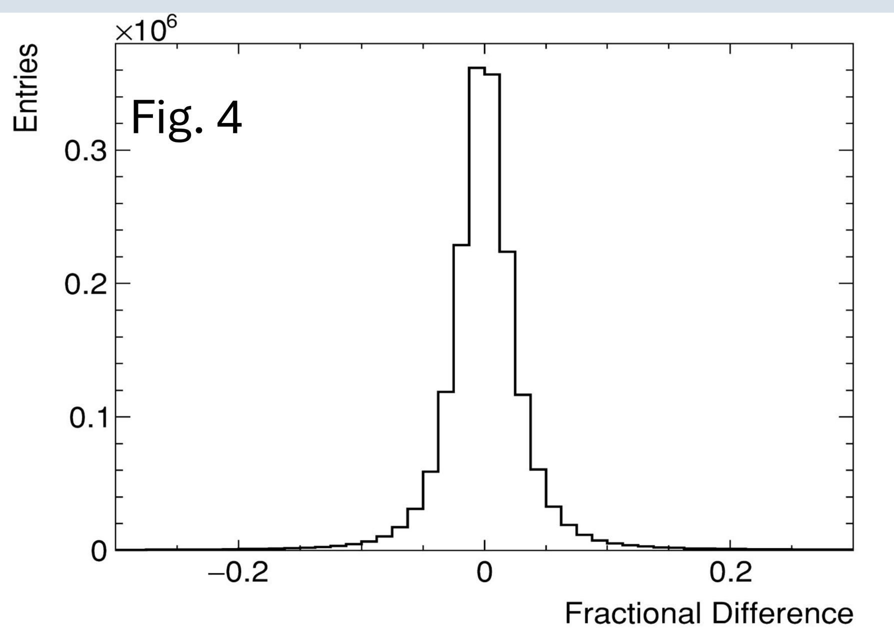
GENIE Model Selection

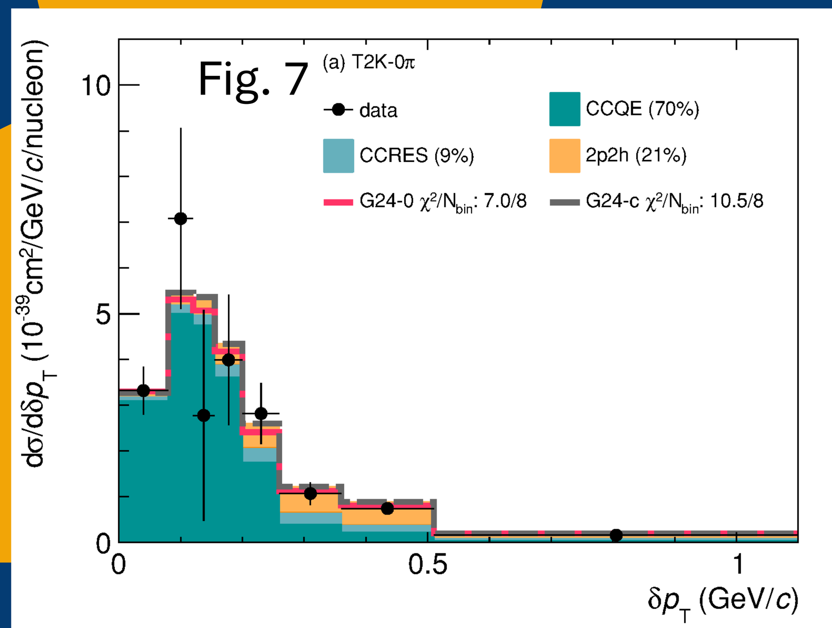
Table II **Base model: G24_20i_00_000**

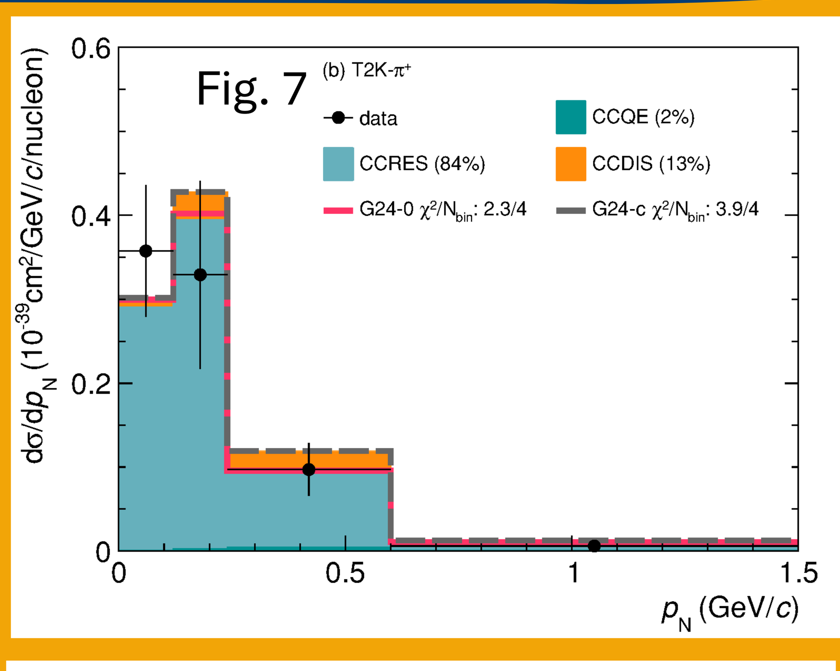
Simulation component	Model
Nuclear state	SF-CFG [8, 38, 39]
QE	Valencia [41]
2p2h	SuSAv2 [43]
QE $\Delta S = 1$	Pais [44]
QE $\Delta C = 1$	Kovalenko [45]
Resonance (RES)	Berger-Sehgal [46]
Shallow/Deep inelastic scattering (SIS/DIS)	Bodek-Yang [47]
DIS $\Delta C = 1$	Aivazis-Tung-Olness [48]
Coherent π production	Berger-Sehgal [49]
Hadronization	AGKY [50]
FSI	INTRANUKE hA [51]

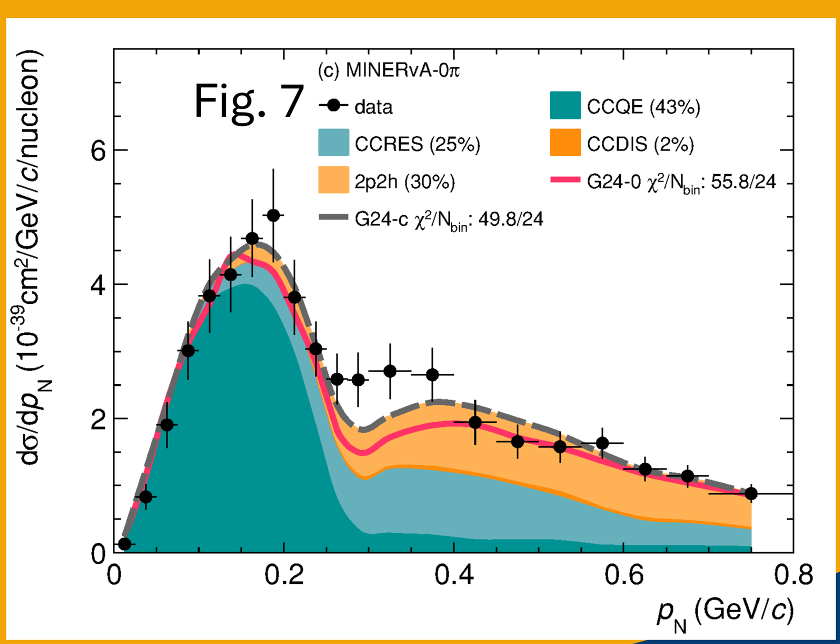
Methodology

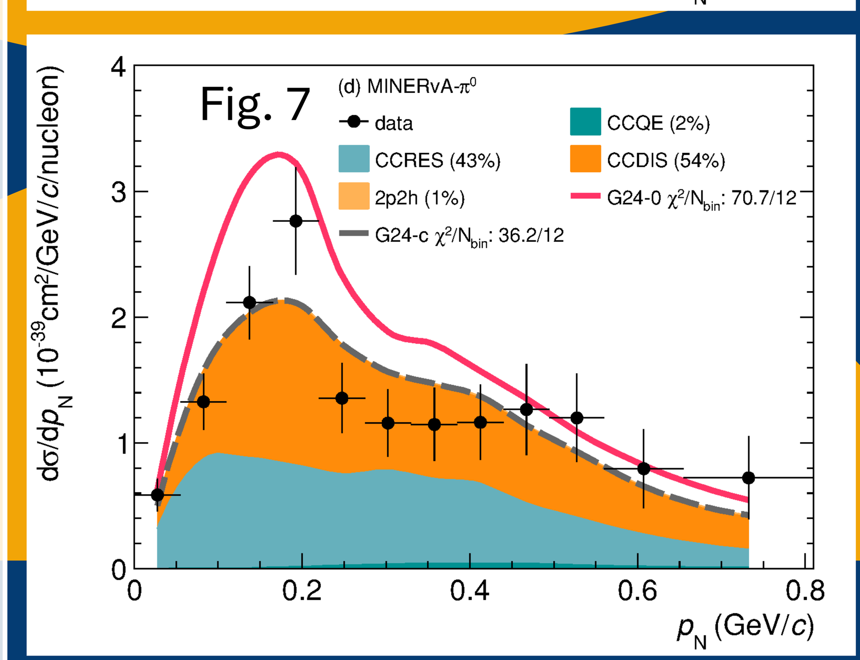
- Tuning all 2 SF-CFG and 12 hA parameters, the most relevant ones are:
  - R_{SRC}
  - $S_{\lambda}^{\pi^0}$
  - FSI scales, $S_{FSI}^{\pi/N}$, for each fate: charge exchange (CEX), inelastic (INEL), absorption (ABS) and pion production (PIPD).
- Randomly sample points in the model parameter space to run full simulations.
- Use Professor [52] to parameterize simulation output for each bin with a degree 4 polynomial.
- Apply Norm-Shape (NS) transformation prescription [53, 54] to circumvent Peelle's Pertinent Puzzle [55].
- Good reproduction of MC predictions, as shown in Fig. 4.
- Find the extremal point from a chi2 minimization between the parameterized approximation and data
- Apply priors to penalize large deviation from default values

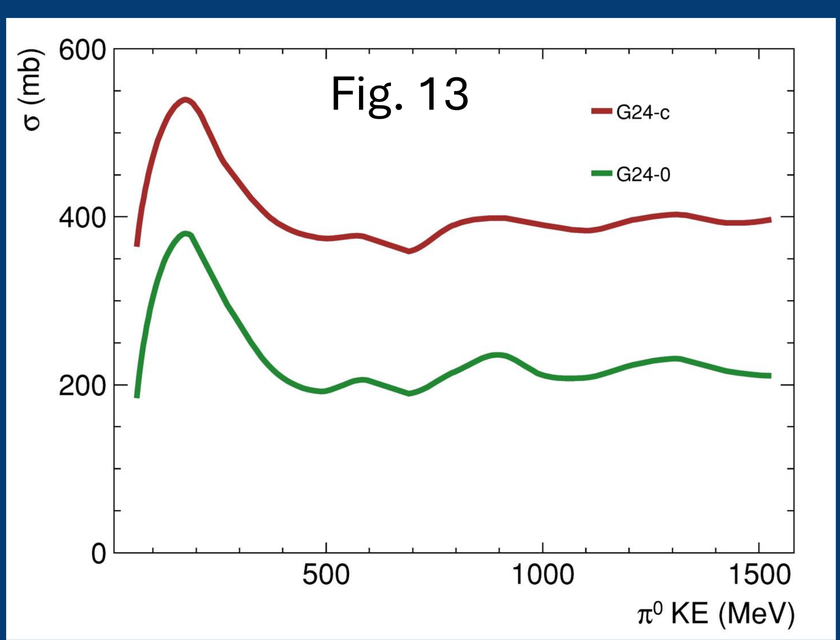










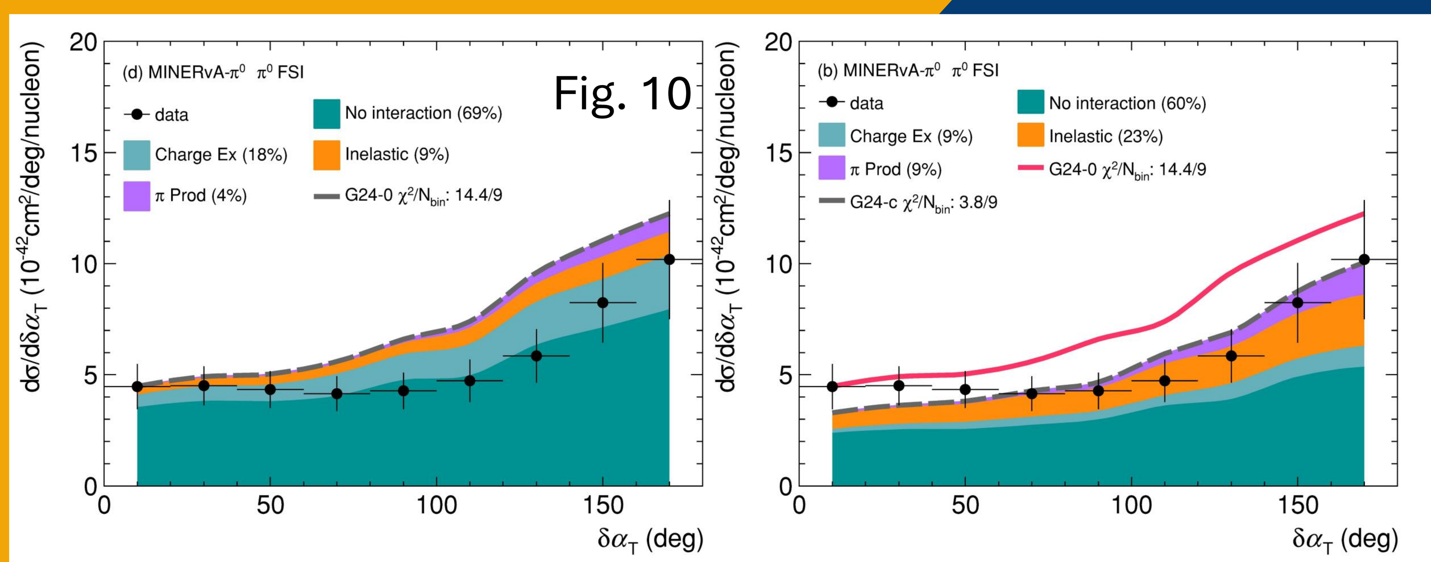


Result

- A new tune, G24_20i_06_22c (G24-c), is produced with values shown in Table V
- Achieve simultaneous good descriptions of both pion-less and pion production samples, as shown as the stacked histogram in Fig. 7
- Reduction in MINERvA π^0 cross-section mainly comes from large suppression of S_{CEX}^{π} and $S_{\lambda}^{\pi^0}$, as shown in Fig. 10

Parameter	Nominal (G24-0)	RedPar (G24-c)	AllPar (G24-t)
	SF-CFG		
R_{SRC}	0.12	0.15 ± 0.08	0.30 ± 0.05
E_{RM}^{C}	0.01	0.01	0.011 ± 0.003
	hA		
$S_{\lambda}^{\pi^\pm}$	1.0 ± 0.2	1.0	1.11 ± 0.16
$S_{\lambda}^{\pi^0}$	1.0 ± 0.2	0.22 ± 0.07	0.17 ± 0.06
S_{λ}^{N}	1.0 ± 0.2	1.0	1.20 ± 0.12
S_{CEX}^{π}	1.0 ± 0.5	0.26 ± 0.12	1.53 ± 0.37
S_{CEX}^{N}	1.0 ± 0.4	1.43 ± 0.34	1.41 ± 0.38
S_{INEL}^{π}	1.0 ± 0.4	1.0	0.67 ± 0.30
S_{INEL}^{N}	1.0 ± 0.4	1.0	1.26 ± 0.48
$S_{ABS}^{\pi^\pm}$	1.0 ± 0.2	1.0	1.59 ± 0.31
$S_{ABS}^{\pi^0}$	1.0 ± 0.2	1.0	0.90 ± 0.28
S_{ABS}^{N}	1.0 ± 0.2	0.25 ± 0.28	0.28 ± 0.27
S_{PIPD}^{π}	1.0 ± 0.2	1.0	1.12 ± 0.30
S_{PIPD}^{N}	1.0 ± 0.2	2.05 ± 0.48	1.27 ± 0.48
	χ^2 for combi		
untuned		231.75	161.26
tuned		174.84	122.53
diff		-56.91	-38.73
	χ^2 for vald		
untuned		229.5	299.99
tuned		214.7	263.41
diff		-14.8	-36.58
	χ^2 for combi+vald		
untuned		461.25	461.25
tuned		389.54	385.94
diff		-71.71	-75.31

Table V



Discussion and Outlook

- G24-c seems to suggest extreme values, but the effect of the parameter change is less effective than the change in the parameter suggests.
- For the individual FSI fate cross section, renormalization after scaling reduces the effective change for the particular fate
- Effect of $S_{\lambda}^{\pi^0}$ on the total π^0-C scattering cross section is plotted in Fig. 13. A 48% peak magnitude increase, considerably less than $S_{\lambda}^{\pi^0}$ = 0.22 seemingly suggests.
- π^0 FSI parameter values are calculated from charged pion data assuming isospin symmetry, so this modification does not violate any existing agreement with hadron scattering data
- Agreement of G24-c with most of the non-TKI neutrino datasets available is unchanged after the tune, thereby demonstrating the physicality of the tune.
- In conclusion, G24-c is a valid and effective model that can be used as a starting point for an analysis and is available in the latest GENIE release.
- Include more sophisticated models, such as resonance production, in future tunes

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