Tuning of generators and the path towards DUNE and Hyper-K

"Neutrino Interactions and the next generation of neutrino experiments"

ECT* Workshop, Torino

Julia Tena Vidal at Tel Aviv University

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

Genie

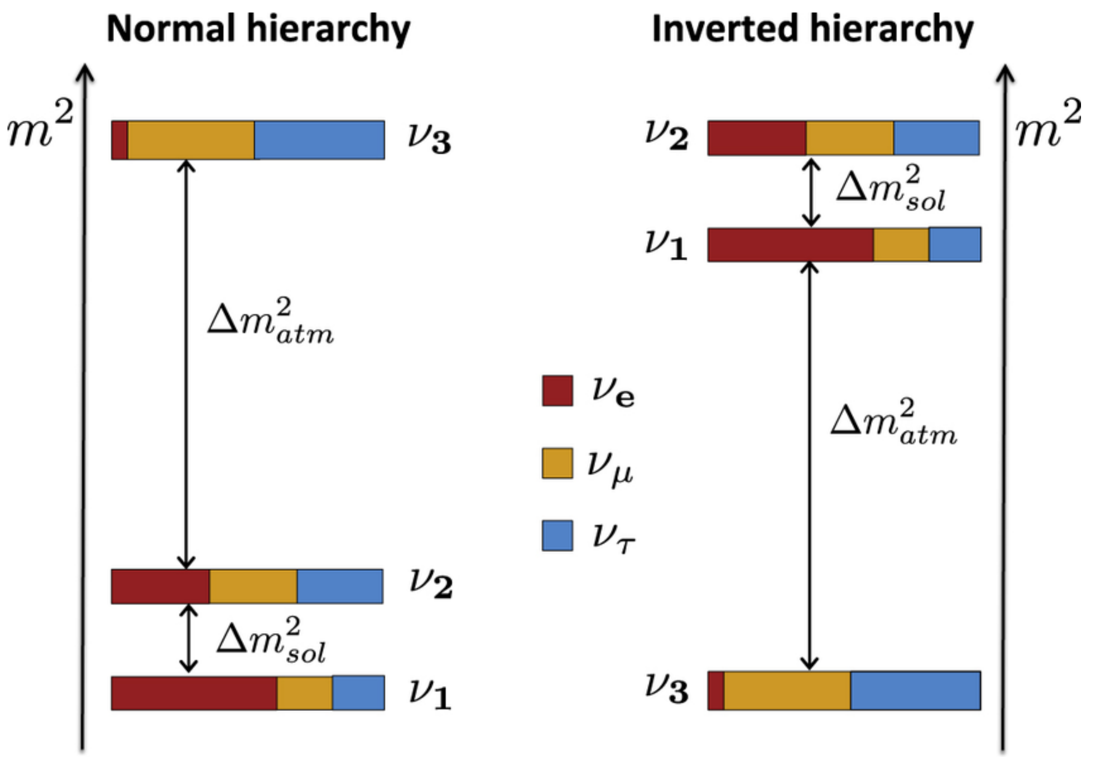
The TAU Neutrino Group

Long-baseline neutrino experiments goals

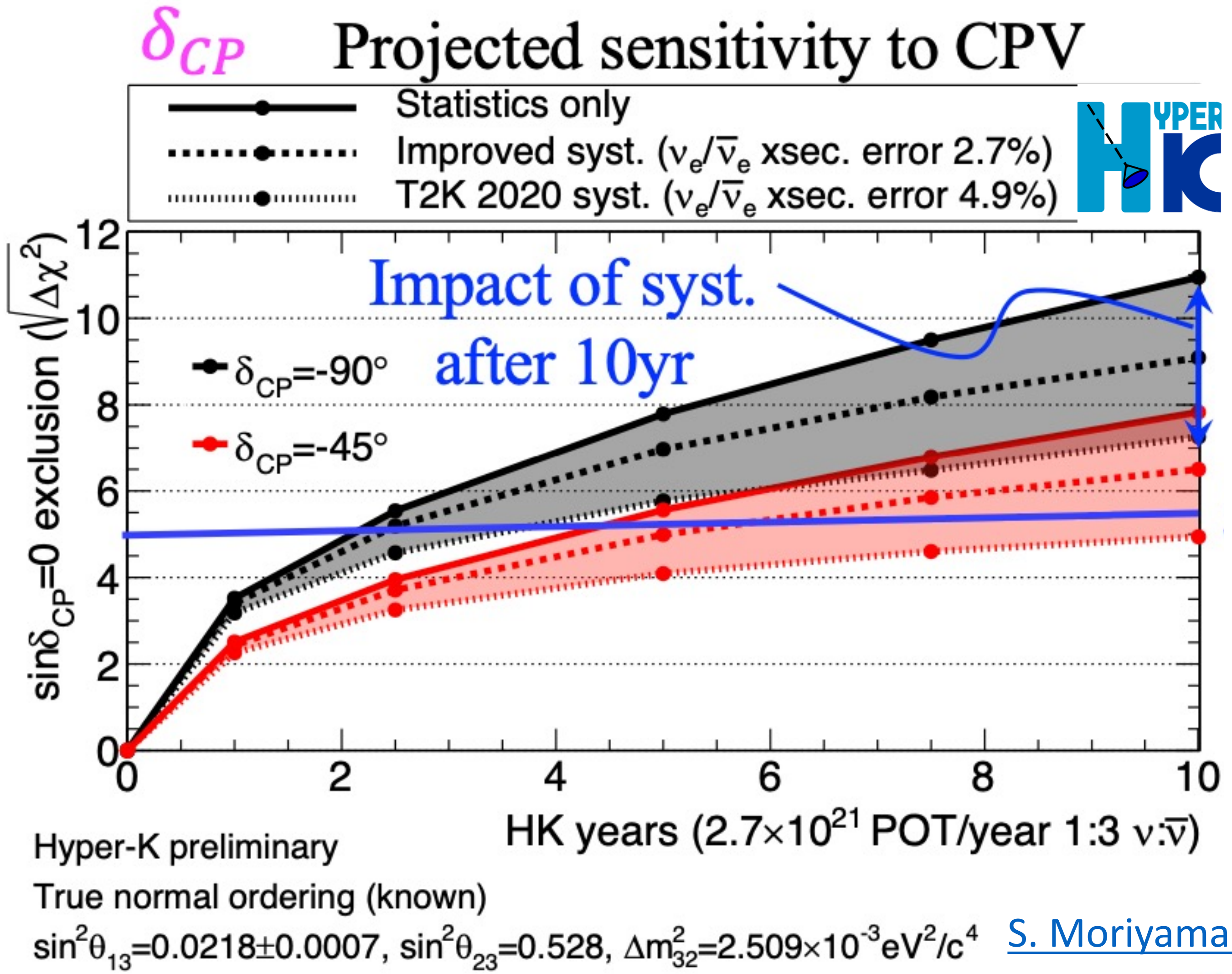
The next generation of neutrino experiments aim to measure neutrino oscillations with **unprecedented precision**

- Determine the neutrino mass ordering
- Measure δ_{CP} and determine if CP is violated
- Determine the octant of θ_{23}

Reducing modelling systematics is key to achieve these goals



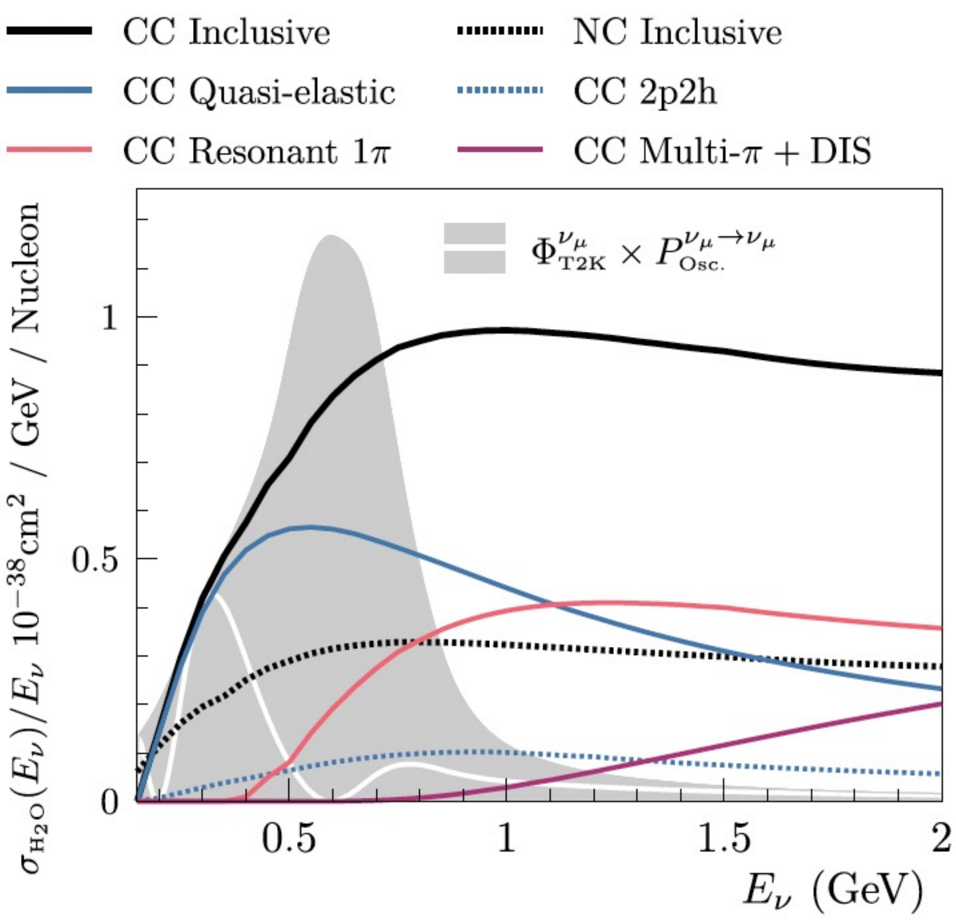
The δ_{CP} haunt: Hyper-K and DUNE



S. Moriyama at Neutrino 2024

Hyper-K

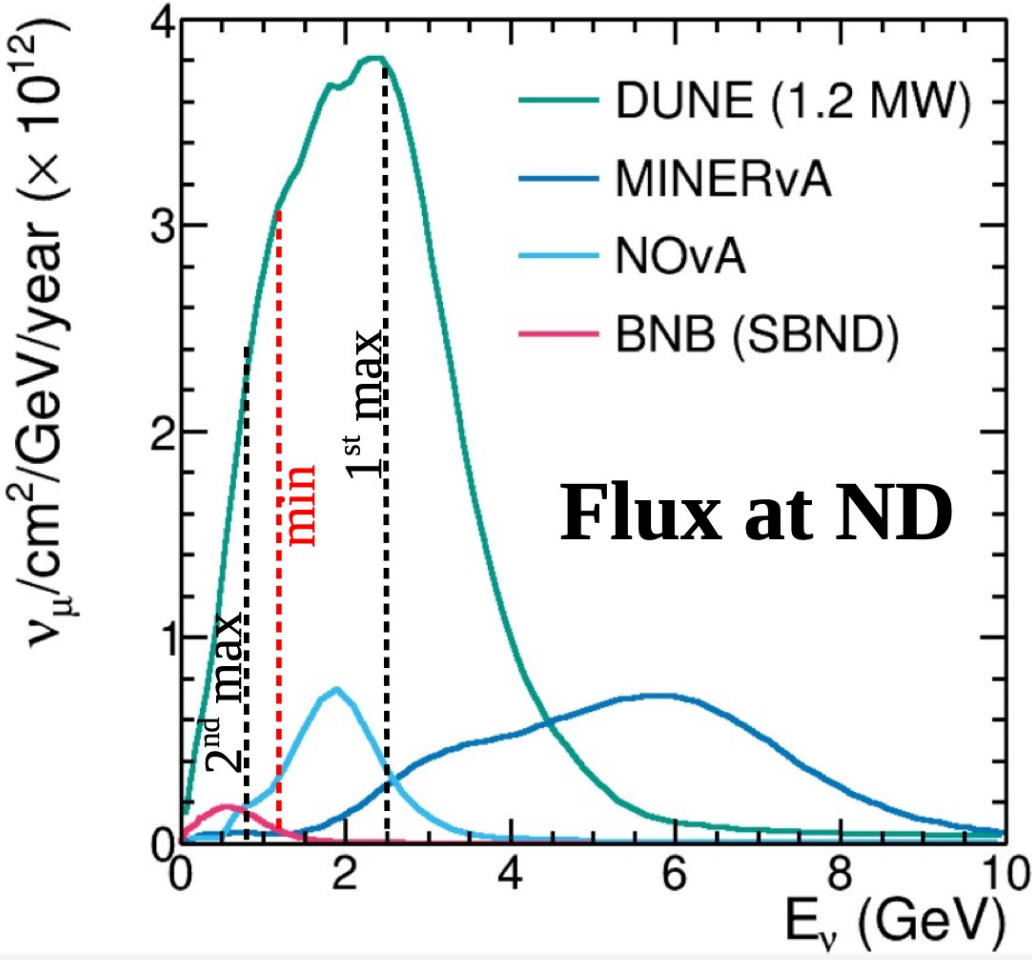
- **Beam – JPark**
  - 100 MeV – 10 GeV
  - Peaks at 0.6 GeV
- **Far detector**
  - Hyper-K – Water, 295 km from ND
  - Physics in 2028
- **Intermediate Detector**
  - IWCD – water
- **T2K detectors - operative**
  - Same flux as HK
  - INGRID (on axis) – CH, iron target
  - ND280 Upgrade (2.5° off axis) – CH target, H_2O
  - WAGASCI (1.5° off axis), H_2O and scintillator



Plot from L. Pickering

DUNE

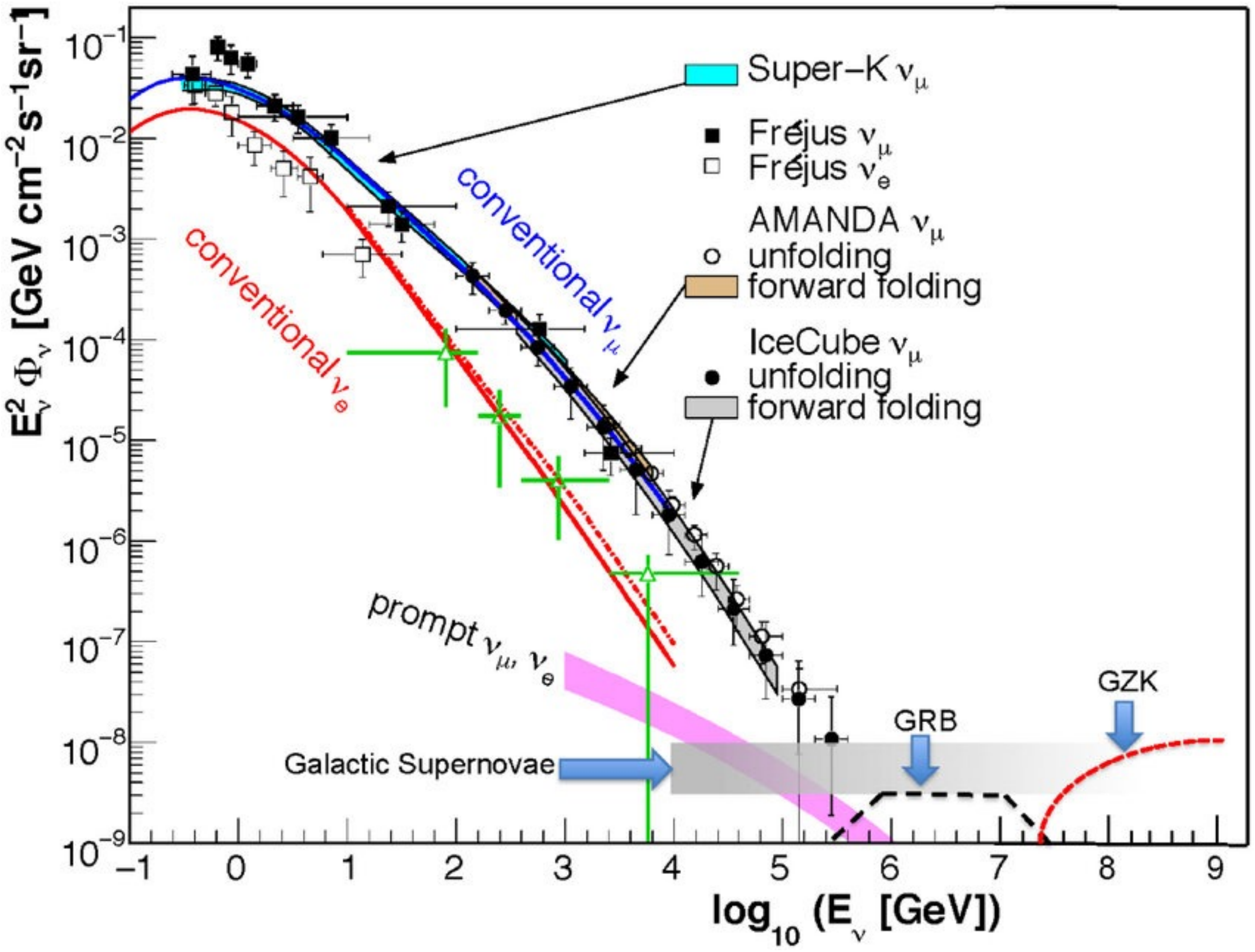
- **Beam**
  - LBNF beamline
  - Peaks at 2.5 GeV
- **Far detector**
  - Operative from 2028-2029
  - Argon
  - 1300 km, 1.5 km underground
- **Near detector**
  - Operative 2031
  - At 575 m from source
  - NDLAr, SAND, (*) NDGar
  - Argon, CH2 & C targets



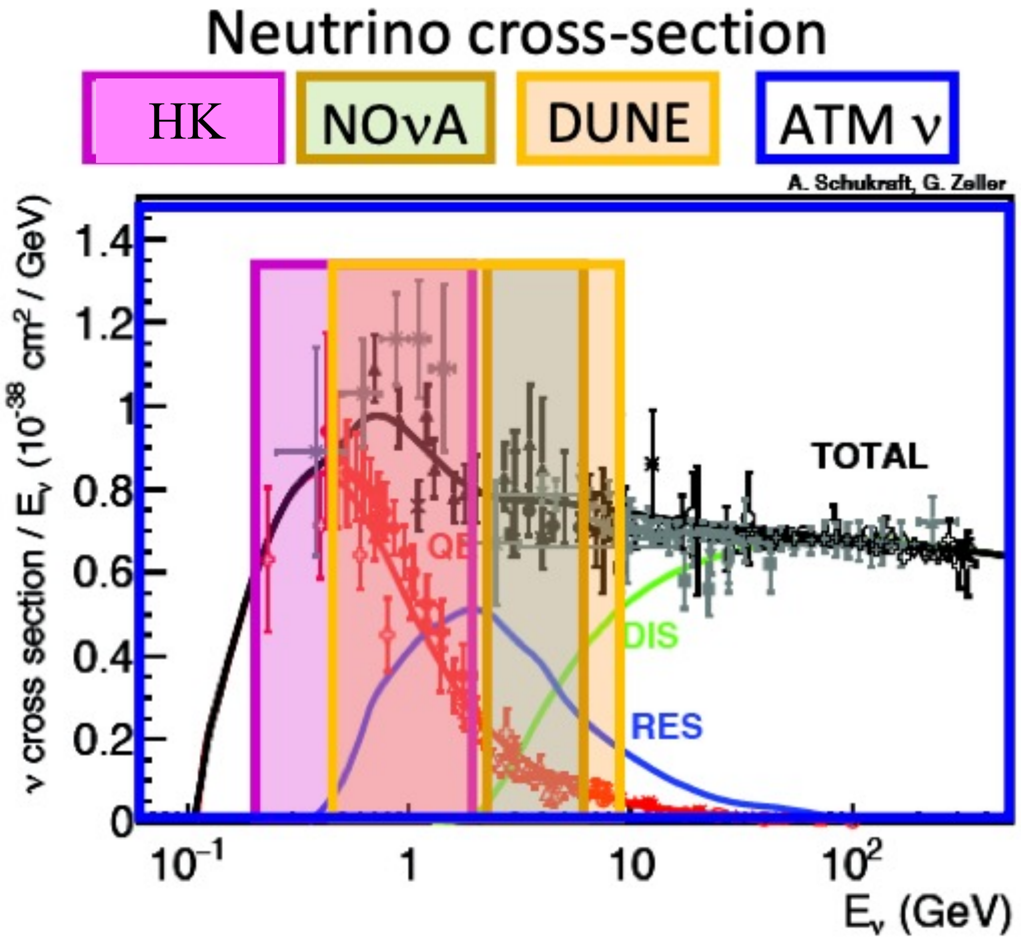
C. Marshall at Neutrino 2024

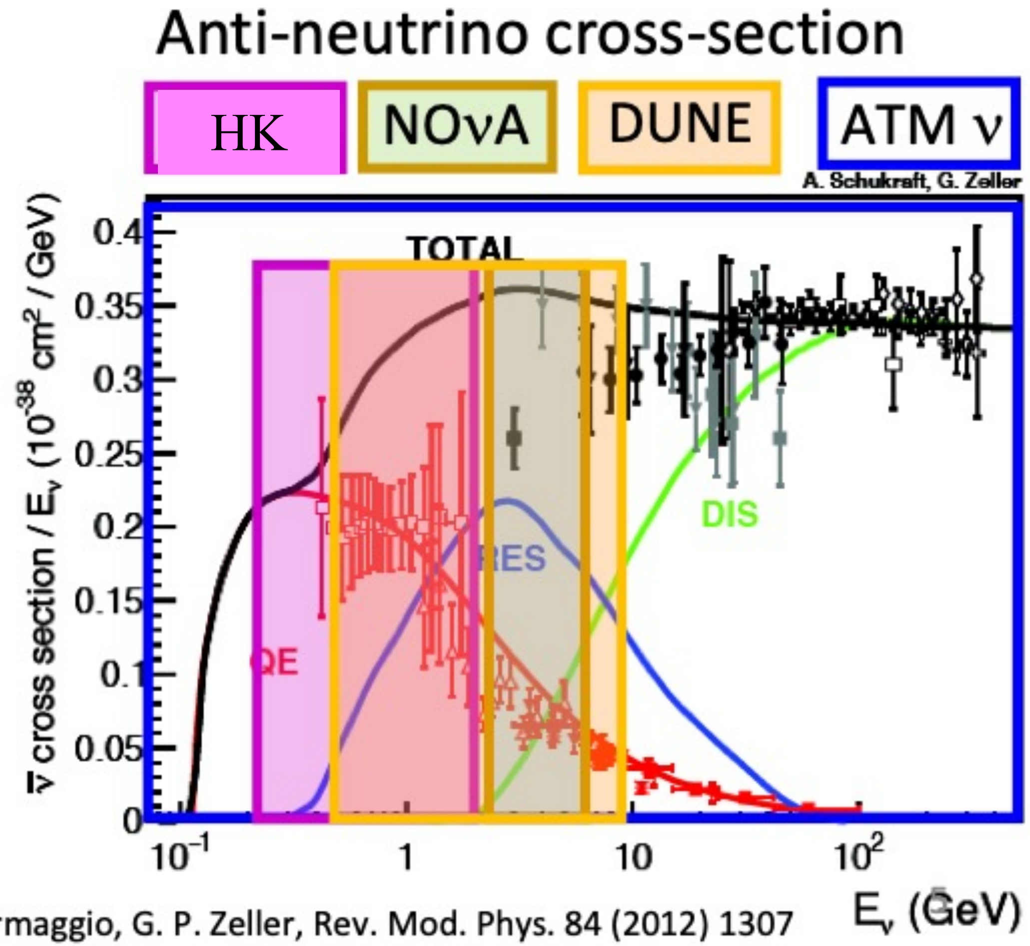
Atmospherics program

- Both Hyper-K and DUNE will measure atmospheric neutrinos
- Wider energy range
  - 100 MeV-TeV
- Wide travel distance (baseline)
- All flavours (ν_μ, ν_e,$\bar{\nu}_\mu$, $\bar{\nu}_e$)



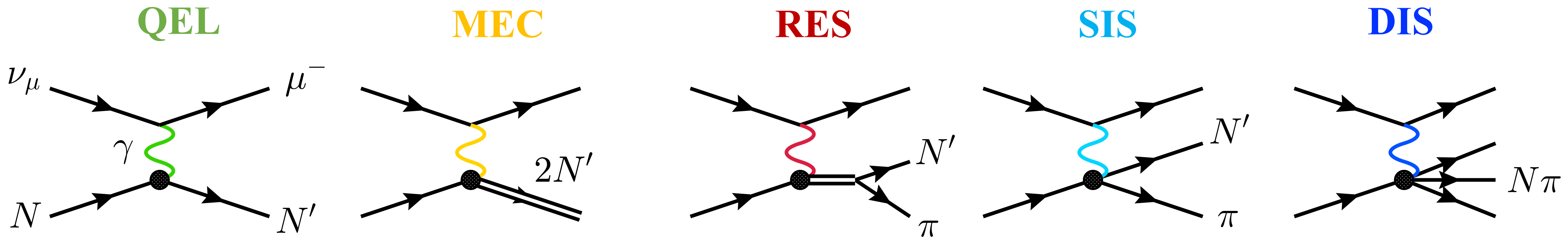
Simulating νA interactions





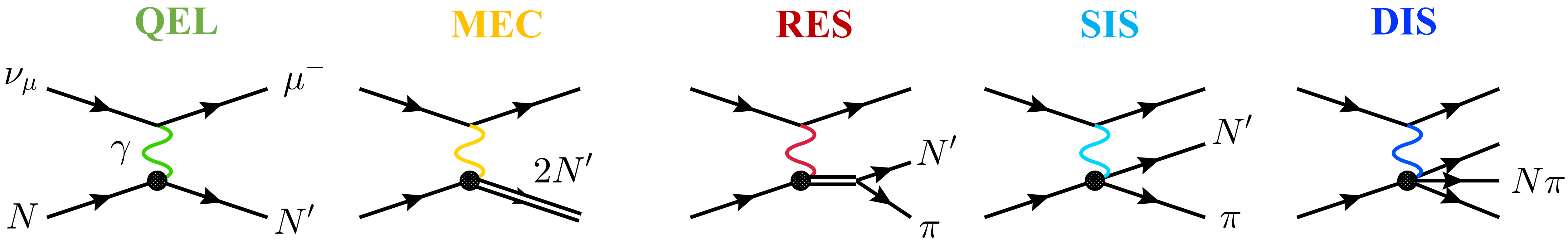
J. A. Formaggio, G. P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Event generators and cross-section models



- Cross-section modelling is the starting-point of all neutrino event generators
- Theoretical approach to model each mechanism preferred
  - but we still relay on **empirical models and approximations** to complete the picture
- Model constrains from experimental data - νN, νA, eN, eA, hA
  - Neutrino data essential to constrain the axial part of models, nuclear effects
  - Electron-scattering key to constrain nuclear model, FSI, vector part
    - See Adi Ashkenazi's talk

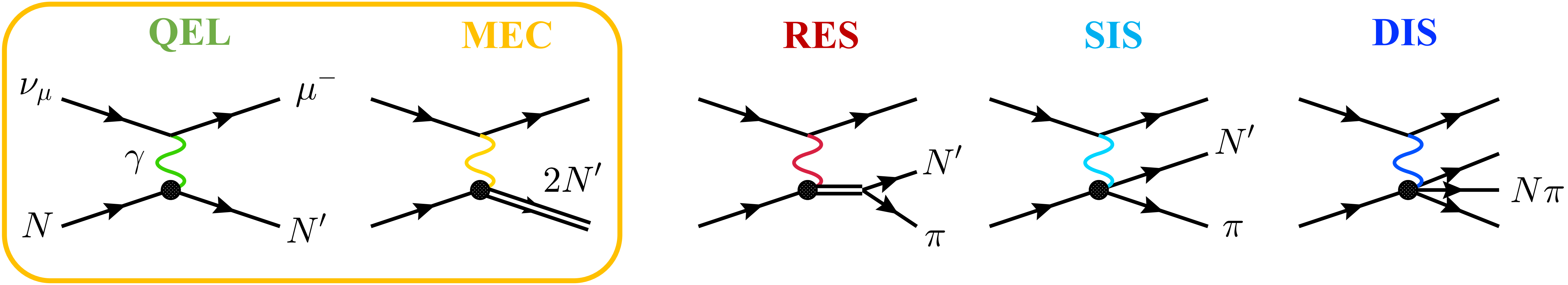
Event generators and cross-section models



Limitations for event generators:

- Models are specific to an interaction mechanism
- Limited phase space coverage → Empirical models needed to complete picture
- Models predict lepton kinematics → + assumptions to describe hadron production
- Nuclear effects → factorized out
- Missing model uncertainties → See talk by Raul Gonzalez and Joanna Sobczyk

Event generators and cross-section models



~50% (*) events for T2K/HK

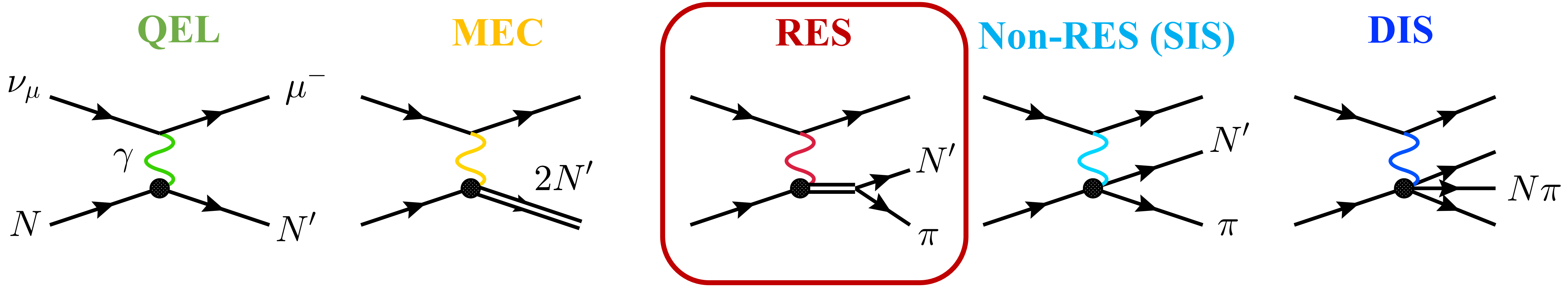
~25% events for DUNE

Huge theory effort: Overview of CC0pi modelling by Raul Gonzalez Jimenez

Fast growing database (CC0π) – T2K, MINERvA, MicroBooNE…

(*) Computed with GENIE G18_10a, Thanks to S. Dolan

Event generators and cross-section models



~35% RES events for T2K/HK

~41% RES events for DUNE

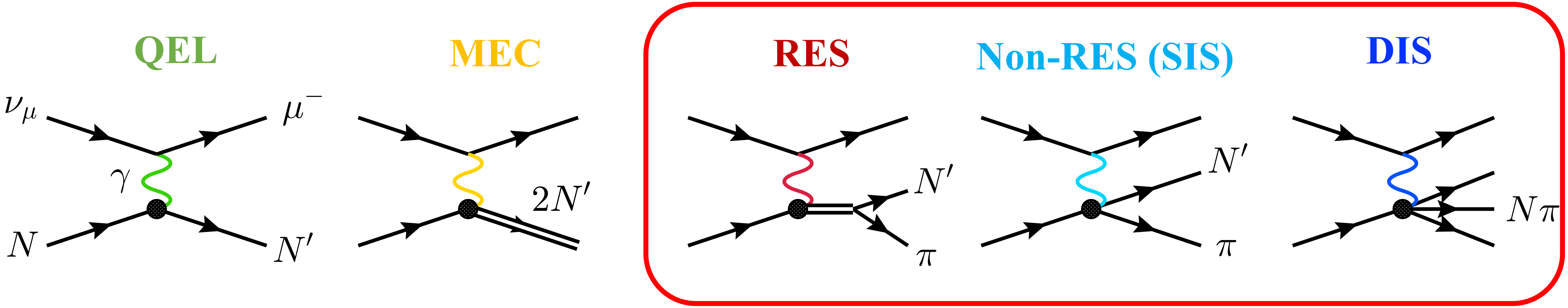
Key input for DUNE

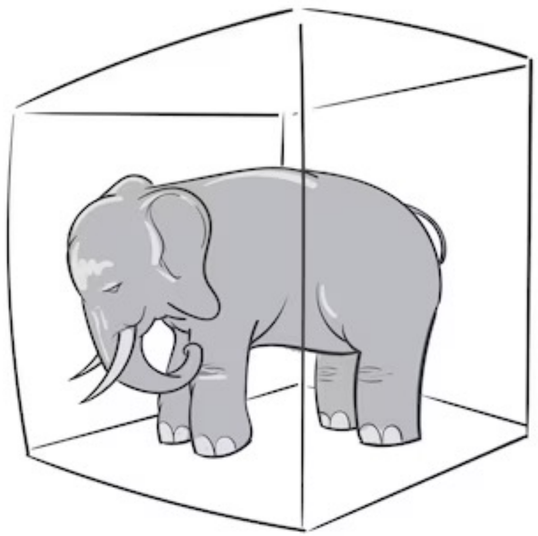
Most generators use the Berger-Sehgal model – resonances added coherently

(w/o non-RES!)

(*) Computed with GENIE G18_10a

Event generators and cross-section models



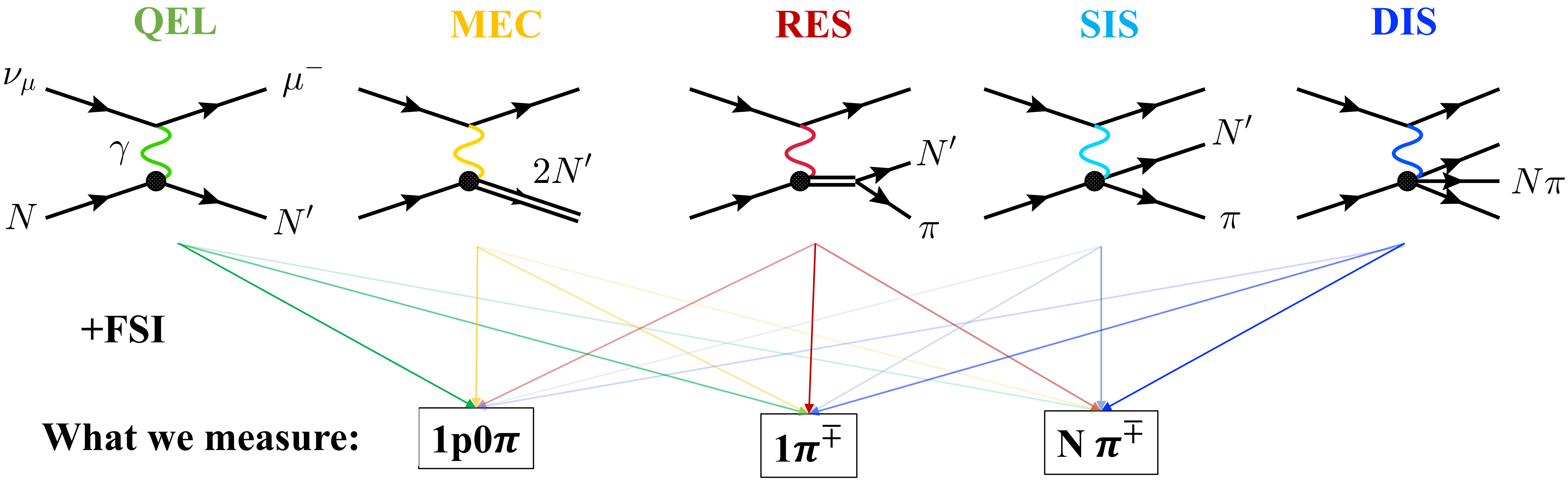


~13% SIS+DIS events for T2K/HK

~30% SIS+DIS events for DUNE

- Most models ignore RES/SIS interference!
  - Minoo Kabirnezhad's single pion production model accounts for it
- SIS/DIS modelling linked to hadronization
  - See Uncertainties in SIS and hadronization talk

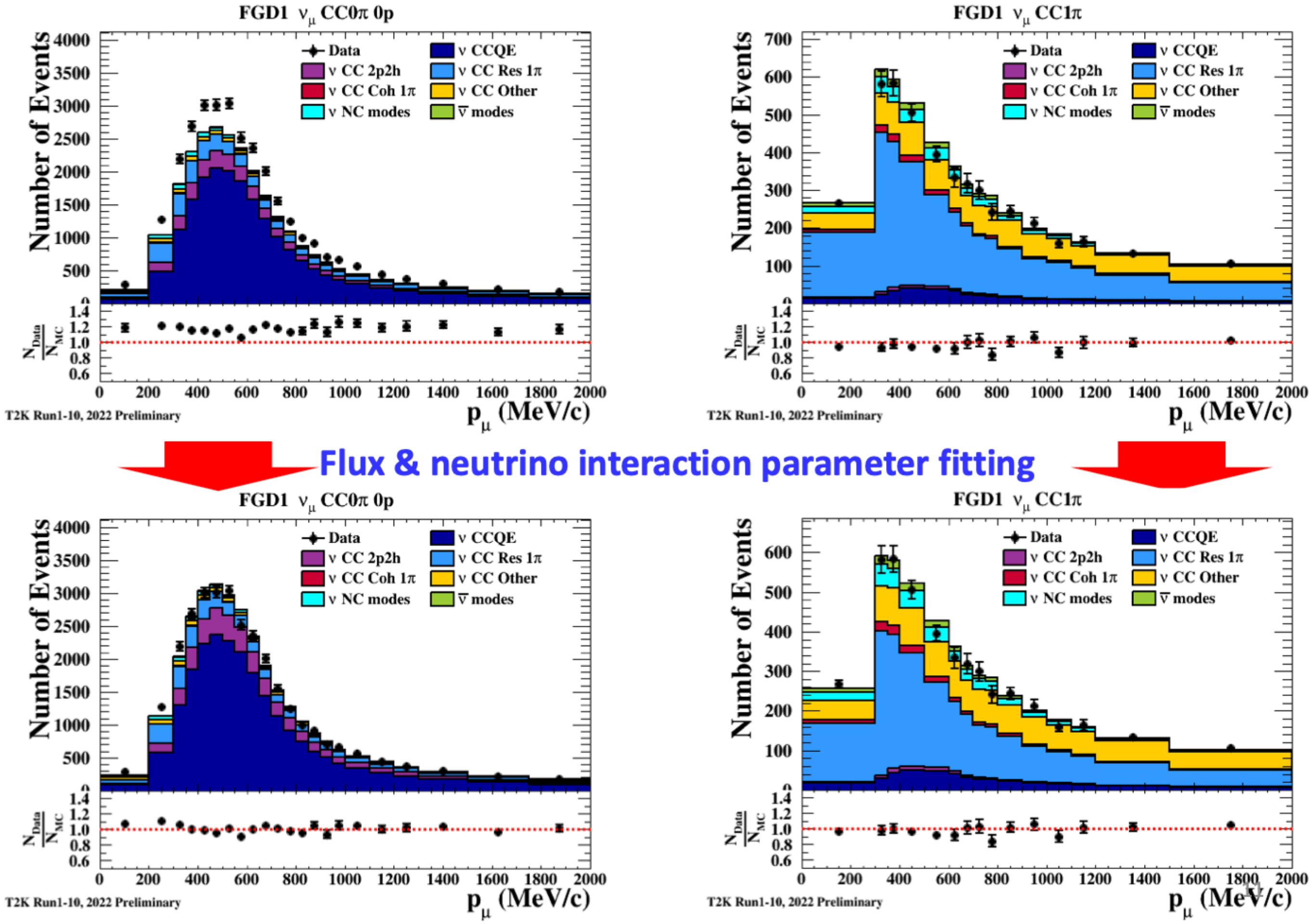
Event generators and nuclear effects



Generators allow experimentalist to compare theory models to data

Why tuning event generators?

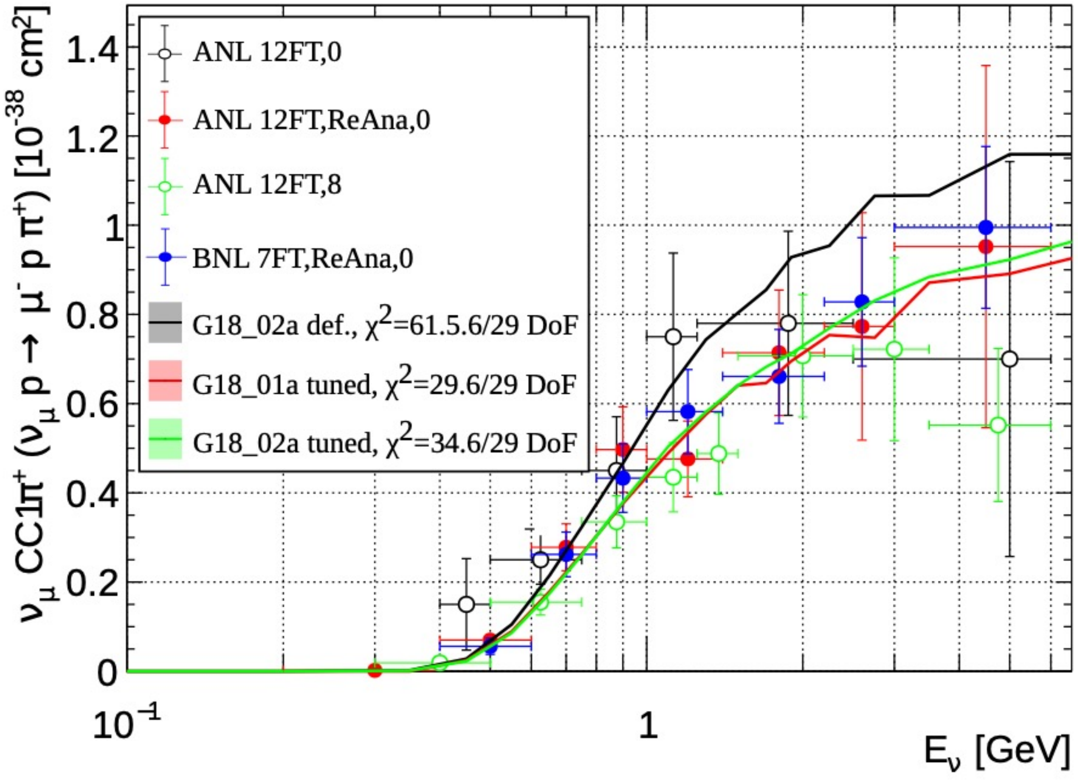
T2K ~ Constraints from near detector measurements



1. Apply constrains from near detector data to far detector
2. Background control samples

Y. Hayato

Why tuning event generators?



(a) Comparison of ν_μ CC $1\pi^+$ data on proton against the *default* and tuned CMCs.

1. Apply constrains from near detector data to far detector
2. Background control samples
3. Optimize baseline model with data
4. Constrain empirical models
5. Minimize double-counting in transition regions
6. Data-driven constrains and uncertainties
7. Highlight model limitations
8. Quantify/resolve tensions between experiments

Empirical aspects of the GENIE event generator

Data-driven models

- **Parameterization of vector and axial QEL and RES form factors**
  - Fits to e-N and ν-N data
- **Low-W AGKY Hadronization**
  - “Tuned” to ν-N data
- **GENIE hA 2018**
  - Fates and mean-free-path
- **Ground state model**
  - Binding-energy
  - High-momentum tail

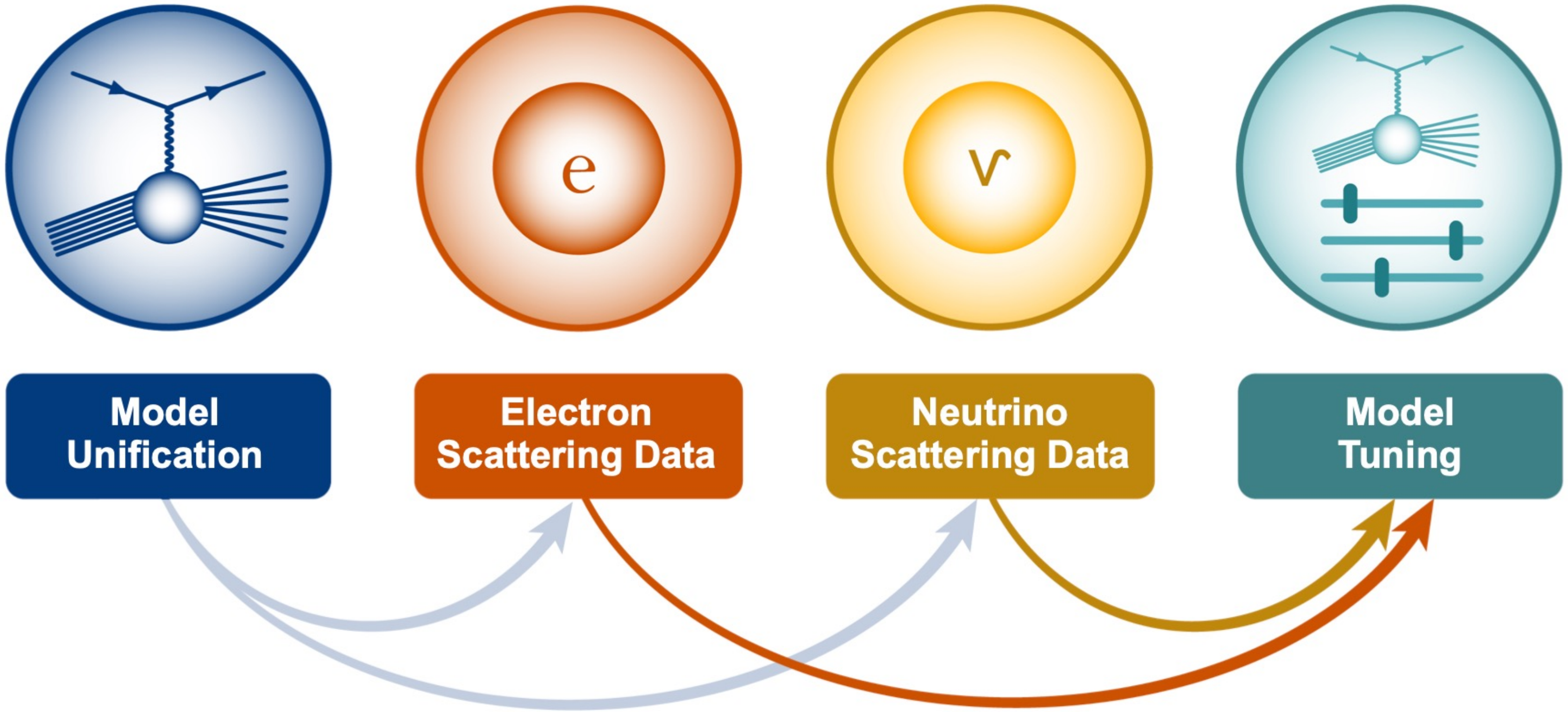
Transition regions

- **Shallow Inelastic Scattering**
  - Simplistic RES model
  - Empirical non-resonant background (NRB)
  - Coupled to low-W AGKY
  - Tuned to ν-N data
- **AGKY Hadronization model**
  - Low-W to high-W hadronization (PYTHIA)
  - Low-W parameters extracted from H data

Inclusive cross-section models

- Lepton kinematics only
- **2p2h inclusive models:**
  - Valencia and SuSAv2
  - Theory-driven models
  - Pre-computed hadron tensors for isoscalar nuclei
  - Used in exclusive final-states
- **π kinematics:**
  - Rein-Sehgal and Berger-Sehgal RES models
  - π-kinematics after decay

Towards a global tune



Towards a (global) tune

DISCLAIMER: we are not quite there, yet!

- **Tensions between datasets**
  - Same experiment different observables
    - i.e. lepton vs hadron kinematics
  - Same experiment different topologies
    - 1p0π vs Nπ data
  - Different experiments – different experimental setup, beam energy, target, analysis requirements…
    - NOvA, T2K, MINERvA, MicroBooNE, ICARUS, SBND…
- **Experiments use different analysis approaches**
  - Missing systematics (i.e. bubble chamber data)
  - Uncorrelated data with systematics
  - Data releases with full correlation matrices

Towards a (global) tune

- **Electron-scattering constraints – work in progress**
  - Need consistent implementation in generators
    - Not always available
  - Excellent data – mostly inclusive
    - New inclusive data on Argon from e4nu collaboration
  - Exclusive data from e4nu collaboration
    - $1p0\pi$, (*) Ongoing: $1p1\pi$, 1π, 2N
    - see Adi Ashkenazi's talk
- **Error propagation and characterization**
  - How to propagate uncertainty from non-reweightable parameters? Do we trust the uncertainty?

Towards a (global) tune

- **Many event generators on the market**
  - GENIE, NEUT, NuWro, GiBBU, Achilles
    - I am a GENIE author - this talk is focused on GENIE but same methods can be applied to all event generators
- **Each have different models and implementations**
  - Different degrees of freedom to tune
  - Different meanings behind the “same” parameters
- **Experiments use different parameterizations from those in the generators**
  - Implemented in ReWeight

Review of MC tuning methods

GENIE's interaction model parameters can be tuned using different methods:

GENIE Reweight ("RWG")

- Nominal prediction build using full event information
    - Can construct any type of prediction
- Reweight is used to emulate parameter impact on the nominal prediction
- Most used in experients
- **Limited to reweightable models**

GENIE-Professor based tunes

- Prediction is build using full event information
    - Can construct any type of prediction
- Professor-build response function using brute-force parameter scans
    - Parameters are defined in the event generator
- LHC community
- **Can tune all aspects of your event generator!**

GENIE Reweight

- Nominal prediction is reweighted to emulate parameter impact

$$w = \sigma'(\vec{p} + \Delta\vec{p}) \Big/ \sigma(\vec{p})$$

  - σ is the baseline cross-section
  - σ' is the cross section after parameter variations
- No need to re-generate the events
- Each parameter can have a ”dial” or “knob” which produces weights
  - Must be able to express the weight as a function of the dial
  - Several knobs are already available on GitHub:
    - I.e: shape and normalization parameters, resonance decay knobs, hA knobs, etc.
- Most-common technique used in neutrino experiments
  - Commonly used to tune event generators (T2K, NOvA, SBN, MINERvA)
  - Tunes to near-detector data or external data (i.e. MicroBooNE tune)

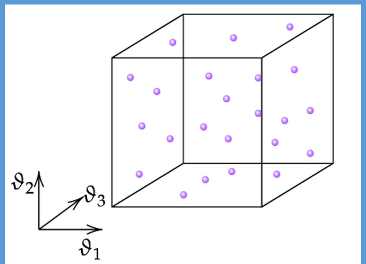
https://github.com/GENIE-MC/Reweight

GENIE Reweight

- Most the effort by the experimentalist is to **implement new reweighting schemes**
  - New knobs can be added by the user
  - Reweighting several important simulation aspects is non-trivial or possible, such as FSI cascade models or hadronization
  - This **limits the physics** that can be tuned with this technique
  - **Approximations** are needed
- It doesn't provide a comprehensive parameterization of the underlying model configuration
  - ReWeight behaviour should be specific to the configuration
  - Lack of rich parameter constraints - estimates
- The reweight prediction cannot be easily run out of the generator
  - Reweighted parameter does not exist in generator
  - Users must run reweight packages on top of the nominal GENIE predictions

GENIE-Professor based tunes

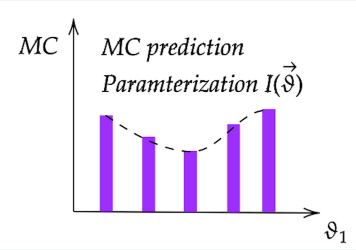
The GENIE-Professor method is based on a brute force approach



Brute-force scan of Monte Carlo response function

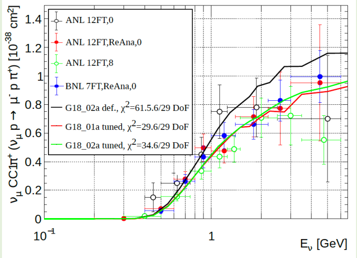
- Predictions are constructed in specific points of the parameter space
- No limitation on number of parameters to tune
- The response function is computed for the datasets of interest

https://professor.hepforge.org



Parameterisation of response function

- The predictions are then interpolated using N-dimensional polynomials as a function of the parameter space
- Handled by the standard Professor software [The European Physical Journal C volume 65, 331 (2010)]
- The parameterization is not exact. Validation tools are used.



Minimization of the MC response function parameterization

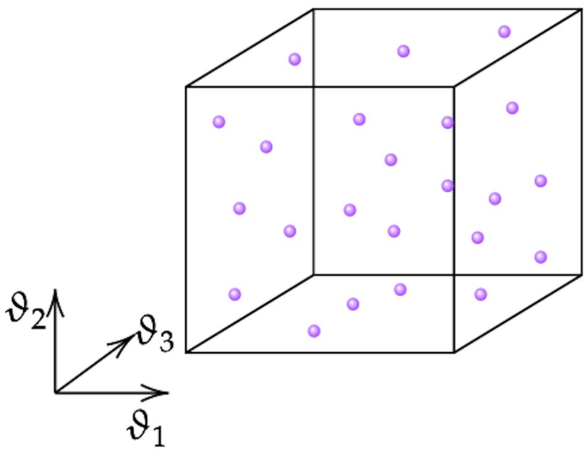
- Developed entirely by GENIE with emphasis on neutrino experiments demands
- Multi-dimensional parameter priors (uncorrelated and correlated), weights, nuisance parameters
- Can handle bin-to-bin correlation as well as correlation between experiments
- Proper treatment of highly correlated datasets with Peelle's Pertinent Puzzle resolution

Sampling of the phase-space

- Once the set of parameters is selected $(\vartheta_1, \vartheta_2, \dots, \vartheta_{N_\vartheta})$, the next step is to define the parameters phase-space
  - Ideally, the best-fit result should lie around the middle of the phase-space
  - Trial and error!
- To parameterize the response-function with an N-dimensional polynomial, we uniformly sample the phase space with

$$N_{MC\ Samples} = \frac{(N_\vartheta + N)!}{N_\vartheta!\, N!} \cdot 1.5$$

N_ϑ dimensions phase-space



N_ϑ	4th order polynomial	5th order polynomial
2	22	31
5	189	378
10	1500	4500
13	3570	12852

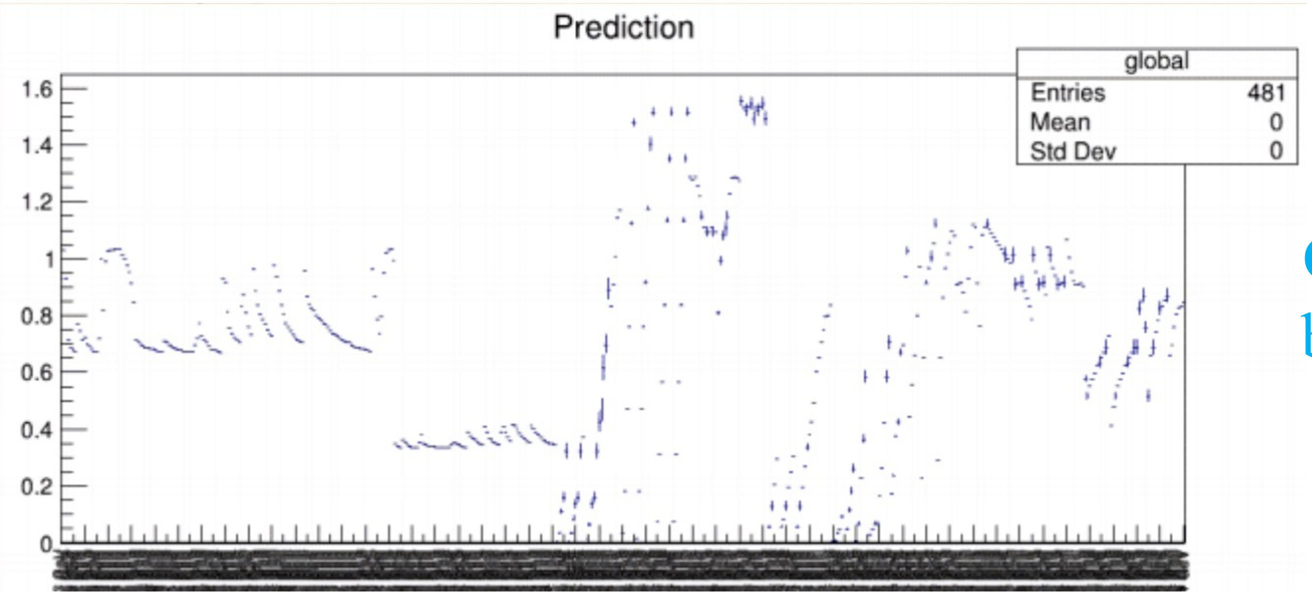
The generation of all the samples is the most expensive CPU expensive step
It can be easily parallelized to minimize computing time
It happens before the actual fit (which takes few minutes to run)

Definition of Observable

- The observable and its binning is data dependent

Example

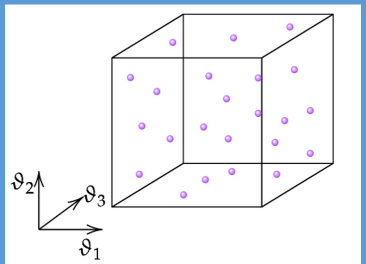
- Prediction histogram associated to thirty-three datasets [PhysRevD.104.072009]
  - The observable corresponds to a series of GENIE Predictions for ν_μ and anti- ν_μ CC inclusive, QEL, single-pion and two-pion production associated to ANL 12 ft, BNL 7ft, BEBC and FNAL bubble chamber data
- This prediction is computed with a single parameter set of our sampled phase space



Observable and binning defined by data release

GENIE-Professor based tunes

The GENIE-Professor method is based on a brute force approach



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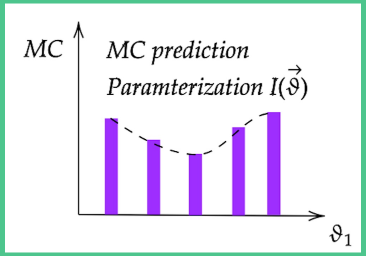

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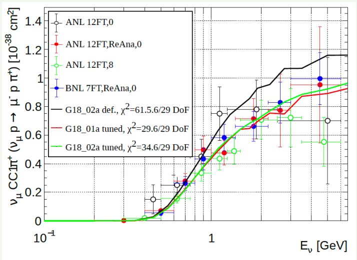

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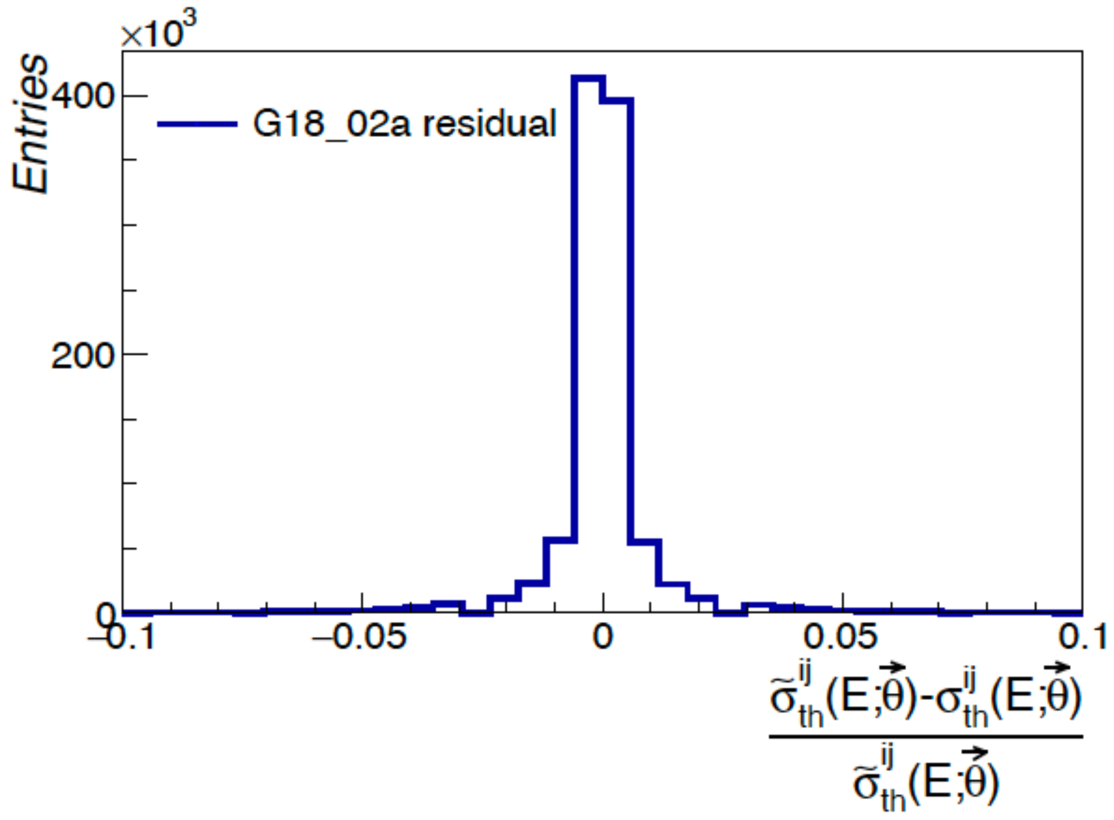
Parameterization of response function

- For each bin, we **parameterize the observable mean value and error** dependency on the parameters
- The parameterization is fit against the brute force scan
- The parameterization is an **approximation**
- We have tools to access its validity
  - Residual: True prediction - parameterization bin-by-bin



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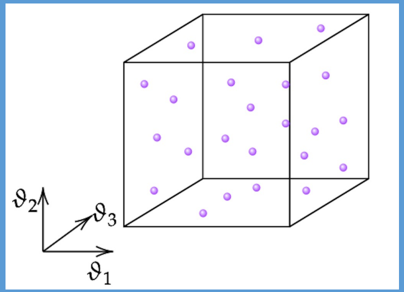

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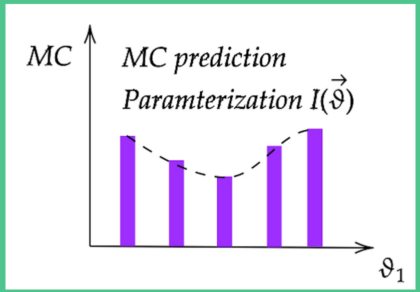

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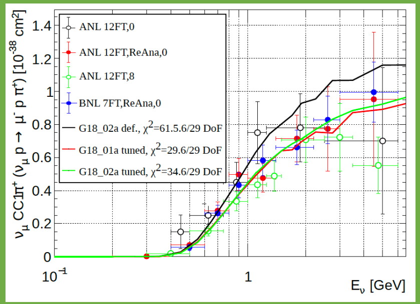

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  - Norm-shape transformation
  - Proper treatment of highly correlated datasets with Peelle's Pertinent Puzzle resolution

GENIE-Professor based tunes

Free nucleon tunes

(*) Ongoing work

- Constrain nucleon cross sections – core of νA models
- Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3 [PhysRevD.104.072009] with νH and D data
- **(*) e-N tuning with inclusive electron scattering data (J.Tena-Vidal @ GENIE Collaboration)**

Nuclear model tunes

- Nuclear ground state, 1p1h+2p2h models, FSI
- Neutrino-nucleus CC0π cross-section tuning in GENIE v3 [PhysRevD.106.112001] with MINERvA, MiniBooNE and T2K data
- **TKI tune with CC0π and CC1π data from MINERvA and T2K** **(Weijun Li, M.Roda, Xianguo Lu, C.Andreopoulos, J. Tena-Vidal),** Acceptedto Phys.Rev.D

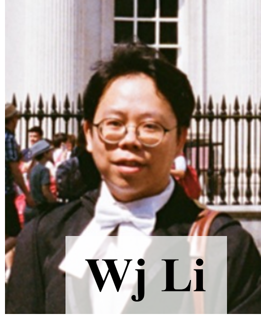
Hadronization tune

- Hadronization Model Tuning in GENIE v3 [PhysRevD.105.012009] using bubble chamber data
- First tune using neutrino data to constrain non-reweightable parameters

Uncertainty characterization and propagation

- **(*) Reweight upgrade to fully support GENIE tunes** **(Qiyu Yan, Marco Roda, Xianguo Lu, Costas Andreopoulos, Julia Tena-Vidal)**

TKI CC0π + CC1π data



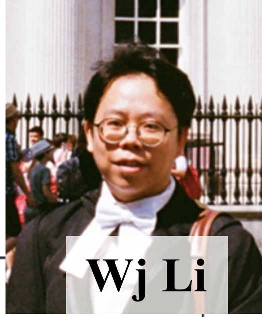
- New tune focused on TKI observables
  - Exploit the conservation of momentum in neutrino interactions
  - Constraints on nuclear aspects of the simulation
- The work is based on four datasets:
  - T2K 0π and 1π^+
  - MINERvA 0π and Nπ^0
- All signal definitions require at least a proton in the final state

Predictions computed with G24 20i 00 000

Simulation component	Model
Nuclear state	SF-CFG [8, 38, 39]
QE	Valencia [41]
2p2h	SuSAv2 [44]
QE $\Delta S = 1$	Pais [45]
QE $\Delta C = 1$	Kovalenko [46]
Resonance (RES)	Berger-Sehgal [47]
Shallow/Deep inelastic scattering (SIS/DIS)	Bodek-Yang [48]
DIS $\Delta C = 1$	Aivazis-Tung-Olness [49]
Coherent π production	Berger-Sehgal [50]
Hadronization	AGKY [51]
FSI	INTRANUKE hA [52]

TABLE II: Model components of G24-0. Processes with non-trivial ΔS and ΔC are those with strangeness and charm production, respectively.

TKI CC0π + CC1π data



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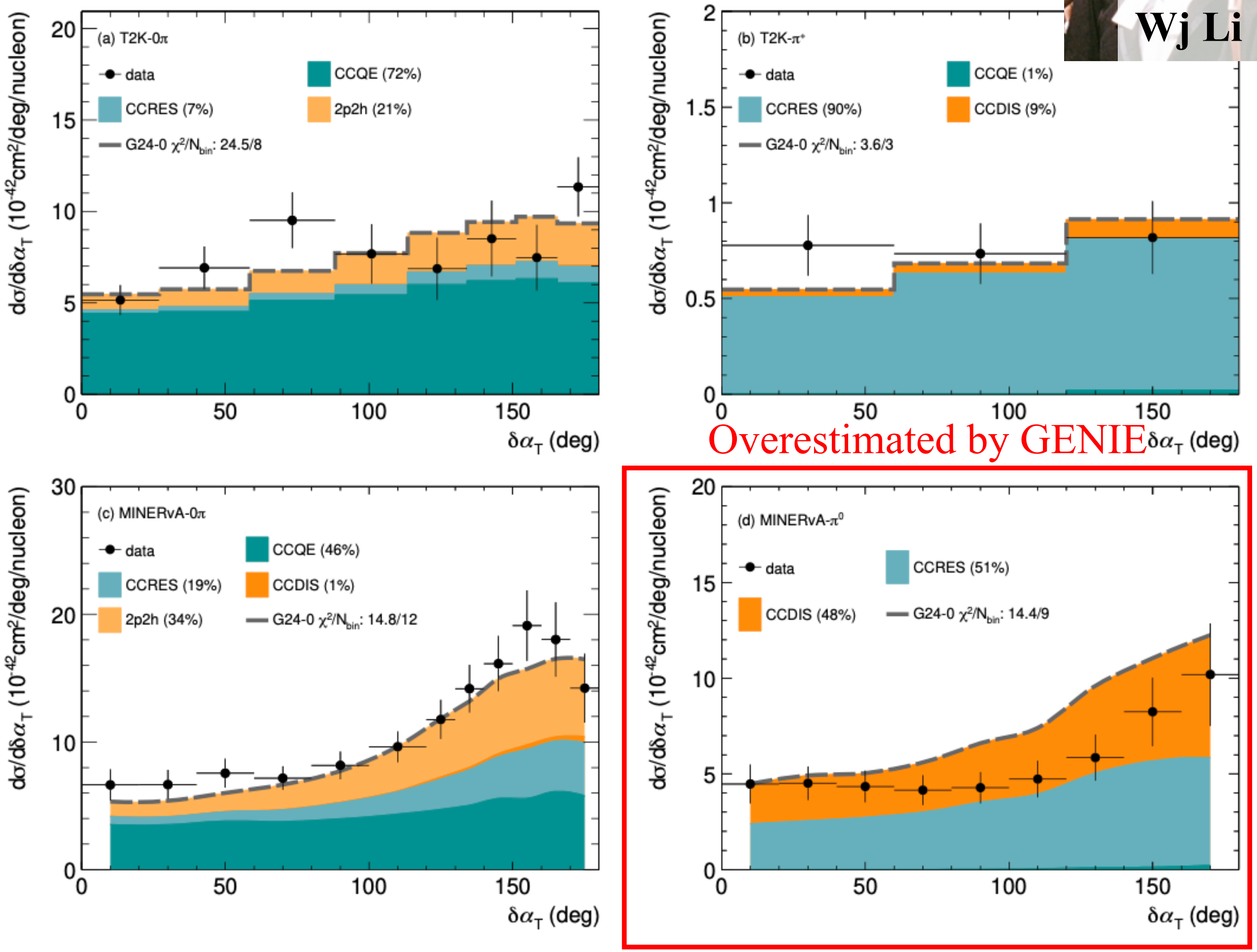


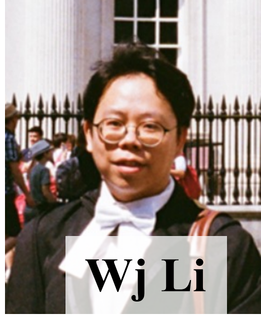
Predictions computed with G24 20i 00 000

TKI CC0π + CCπ data

Final tune

- Not all observables guarantee the best output
  - $\delta\phi_T$ strongly depends on beam energy
  - δp_T and p_N strongly correlated
- Propose a total of 26 combinations to be used for tuning
- The remaining observables are used as validation
  - $p_p, \theta_p, \delta p_{Tx}, \delta p_{Ty}$ MINERvA-0π

Observables	No. of bins	Combi-Superset	Combi-Best-AllPar	Combi-Best-RedPar
T2K-0π				
$\delta\alpha_{\mathrm{T}}$	8	✓		✓
δp_{T}	8	✓	✓	✓
$\delta\phi_{\mathrm{T}}$	8	✓		
T2K-π^+				
$\delta\alpha_{\mathrm{T}}$	3	✓		✓
p_{N}	4	✓	✓	✓
δp_{TT}	5	✓		✓
MINERvA-0π				
$\delta\alpha_{\mathrm{T}}$	12	✓		✓
p_{N}	24	✓	✓	✓
δp_{T}	24	✓	✓	
$\delta\phi_{\mathrm{T}}$	23	✓		
p_{p}	25			
θ_{p}	26			
δp_{Tx}	32			
δp_{Ty}	33			
MINERvA-π^0				
$\delta\alpha_{\mathrm{T}}$	9	✓		✓
p_{N}	12	✓	✓	✓
δp_{TT}	13	✓		✓



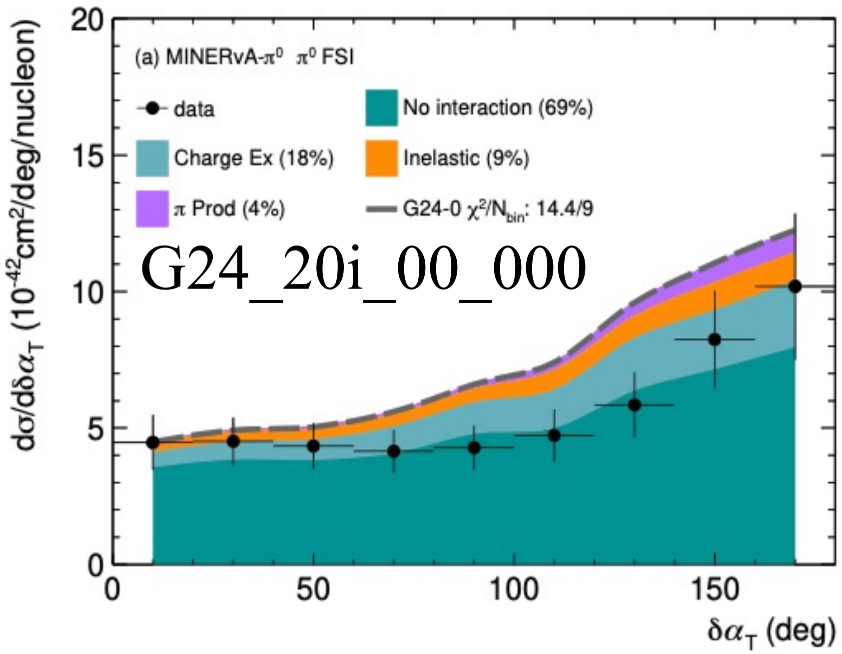
Model Parameters

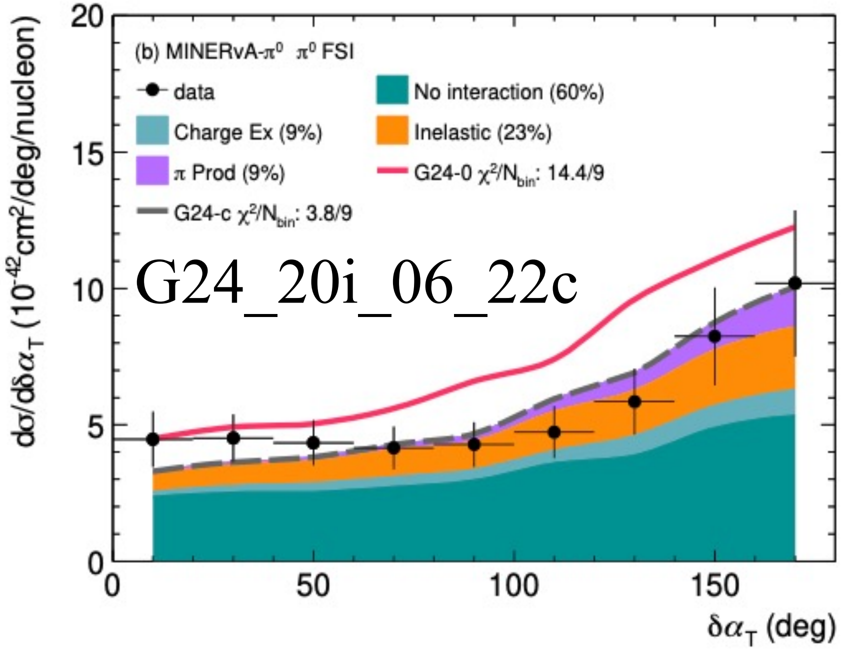
- Many modelling aspects are relevant
  - Ground state, FSI, 1p1h, 2p2h, RES, DIS
- In this work, we focus on:
  - SF-LFG parameters (2)
  - FSI parameters (12 for hA)
  - The role of the rest is not included – approximation, CPU intensive
- A first tune is performed to identify the relevant parameters
  - Some of the tuned parameters are close to their default values - removed
  - A 6-parameter RedPar tune is again run on the 26 combinations

Parameter	Nominal (G24-0)	Range In Tuning	RedPar (G24-c)
		SF-LFG	
R_{SRC}	0.12	(0.0, 0.5)	✓
$E^{\mathrm{C}}_{\mathrm{RM}}$	0.01	(0.0, 0.2)	
		hA	
$S^{\pi^\pm}_\lambda$	1.0 ± 0.2	(0.0, 3.0)	
$S^{\pi^0}_\lambda$	1.0 ± 0.2	(0.0, 3.0)	✓
S^{N}_λ	1.0 ± 0.2	(0.0, 3.0)	
S^{π}_{CEX}	1.0 ± 0.5	(0.0, 3.0)	✓
$S^{\mathrm{N}}_{\mathrm{CEX}}$	1.0 ± 0.5	(0.0, 3.0)	✓
S^{π}_{INEL}	1.0 ± 0.4	(0.0, 3.0)	
$S^{\mathrm{N}}_{\mathrm{INEL}}$	1.0 ± 0.4	(0.0, 3.0)	
$S^{\pi^\pm}_{\mathrm{ABS}}$	1.0 ± 0.2	(0.0, 3.0)	
$S^{\pi^0}_{\mathrm{ABS}}$	1.0 ± 0.2	(0.0, 3.0)	
$S^{\mathrm{N}}_{\mathrm{ABS}}$	1.0 ± 0.2	(0.0, 3.0)	✓
S^{π}_{PIPD}	1.0 ± 0.2	(0.0, 3.0)	
$S^{\mathrm{N}}_{\mathrm{PIPD}}$	1.0 ± 0.2	(0.0, 3.0)	✓

Results

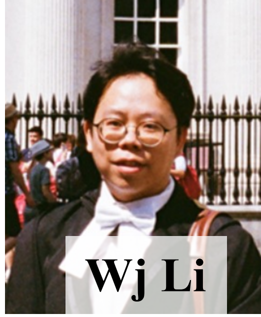
- Large suppression of $S_{\lambda}^{\pi^0}$, but increase in R_{SRC} and S_{CEX}^{π} instead
- Raises R_{SRC} to a larger extent such that RES interaction increases appreciably
- Reduction in χ^2 for vald
- Full covariance for tuned parameters





Parameter	Nominal (G24-0)	RedPar (G24-c)
		SF-LFG
R_{SRC}	0.12	0.15 ± 0.08
$E_{\mathrm{RM}}^{\mathrm{C}}$	0.01	0.01
		hA
$S_{\lambda}^{\pi^{\pm}}$	1.0±0.2	1.0
$S_{\lambda}^{\pi^{0}}$	1.0±0.2	0.22 ± 0.07
S_{λ}^{N}	1.0±0.2	1.0
S_{CEX}^{π}	1.0±0.5	0.26 ± 0.12
$S_{\mathrm{CEX}}^{\mathrm{N}}$	1.0±0.4	1.43 ± 0.34
S_{INEL}^{π}	1.0±0.4	1.0
$S_{\mathrm{INEL}}^{\mathrm{N}}$	1.0±0.4	1.0
$S_{\mathrm{ABS}}^{\pi^{\pm}}$	1.0±0.2	1.0
$S_{\mathrm{ABS}}^{\pi^{0}}$	1.0±0.2	1.0
$S_{\mathrm{ABS}}^{\mathrm{N}}$	1.0±0.2	0.25 ± 0.28
S_{PIPD}^{π}	1.0±0.2	1.0
$S_{\mathrm{PIPD}}^{\mathrm{N}}$	1.0±0.2	2.05 ± 0.48
		combi
untuned		231.75
tuned		174.84
diff		-56.91
		vald
untuned		229.5
tuned		214.7
diff		-14.8
		combi+vald
untuned		461.25
tuned		389.54
diff		-71.71

TKI tune - Discussion



- 30% decrease in total π^0 cross section, ($S_\lambda^{\pi^0}$ =1→ 0.22)
- Pion FSI uncertainty strongly correlated with RES modelling
  - Not considered in the tune
- RES model will be included in future iterations
  - Hard to decouple correlations
  - Electron-data might be key to break the degeneracy

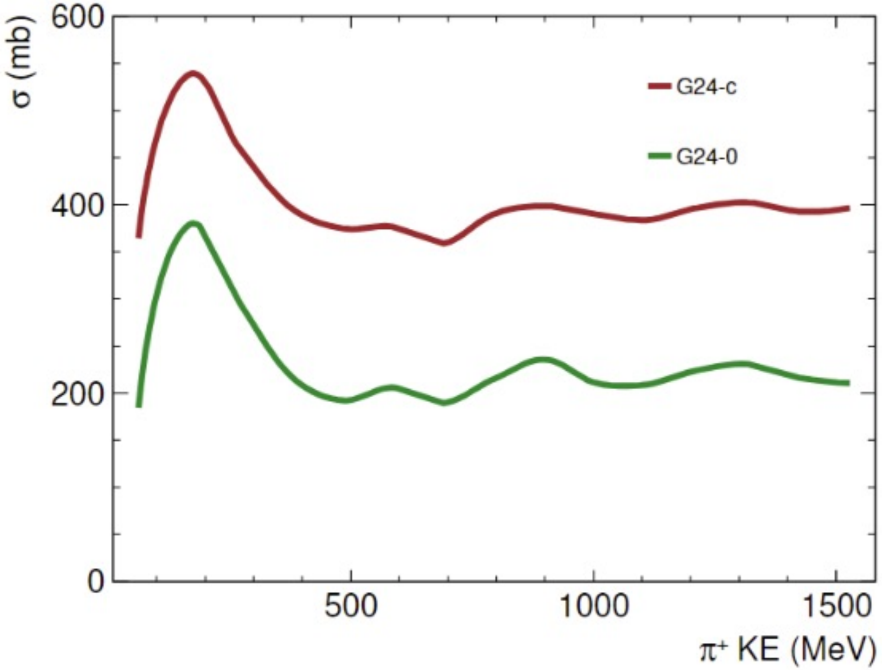


FIG. 14: Change in MC prediction for π^0 cross section between G24-0 and G24-c.

How to propagate the uncertainties? Conventional reweight

- Conventionally the weight from reweight package is calculated from the ratio of differential cross sections.
  - Require re-evaluation of cross section model, thus **highly model dependent**
  - Require **continuous maintenance** to in-cooperate with the model update and **separate implementation** for different parameters.
  - Not feasible approach for all simulation aspects

New: Professor based reweight

$$w_{\sigma}^{evt} = \frac{d^n\bar{\sigma}'_\nu / dK^n}{d^n\sigma_\nu / dK^n}$$

Conventional reweight: analytical weight calculator

↓

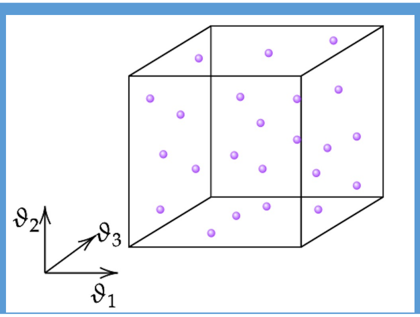
Professor-based reweight: MC response function

- **Brute force** is used to extract the information of model response to parameters
  - Using Professor response function
  - No need to implement a new reweight for each model
  - Can reweight any modelling aspect

New: Professor based reweight

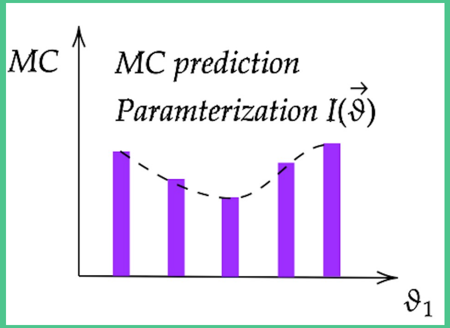
- Weight is assigned according to differential cross sections in terms of an observable
  - Used to build the professor N-dimensional response function
- The observable can be any property of an event
  - **Decided by the user**
  - Change of mentality – What observables are needed for a given parameter?
  - Including initial, intermediate and final state information

Workflow



Brute-force scan of MC response function

- Select parameters of interest from event generator
- No limitation on number of parameters



Parameterisation of response function

- **Determine the M observables to be used in the reweight**
  - Observable definition is independent of data – **User choice**
  - Can be process, topology specific
- **Construct the M-dimensional predictions for the observables of interest**
- Interpolate the predictions using N-dimensional polynomials as a function of the parameter space - **Handled by the standard Professor software**

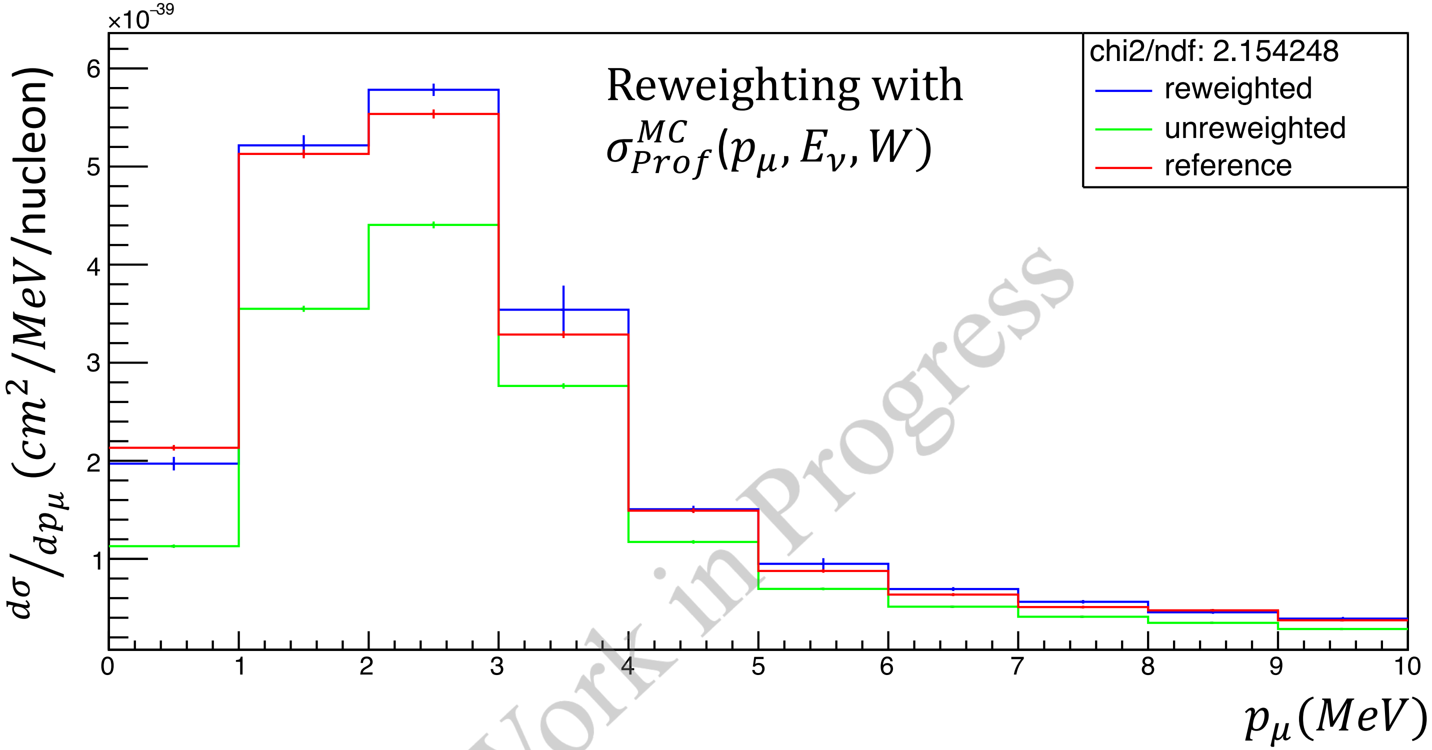
Professor-Based Reweight

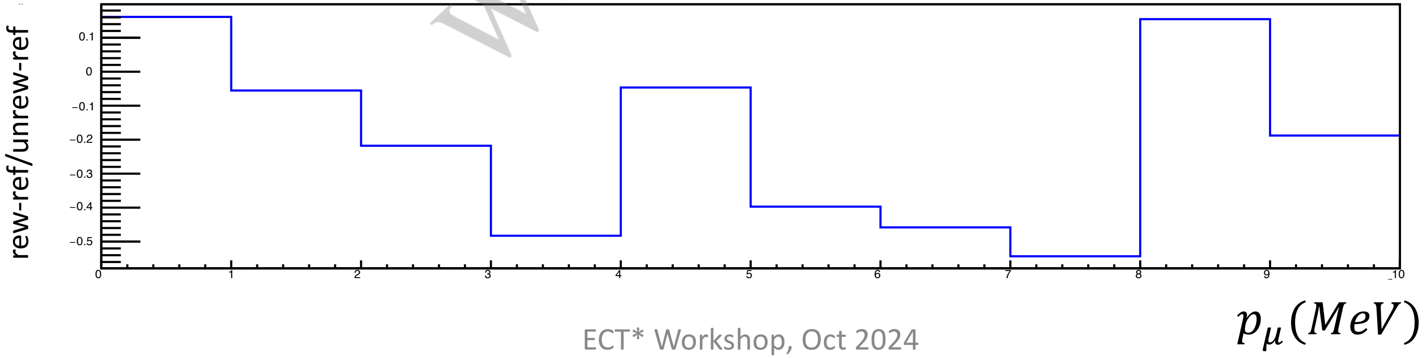
- Read professor-interpolation of MC response function – available in GitHub
- Use standard GENIE-Reweight to reweight new parameters – available in GitHub
- For each event, compute weight using MC response function given M observables

Proof of concept

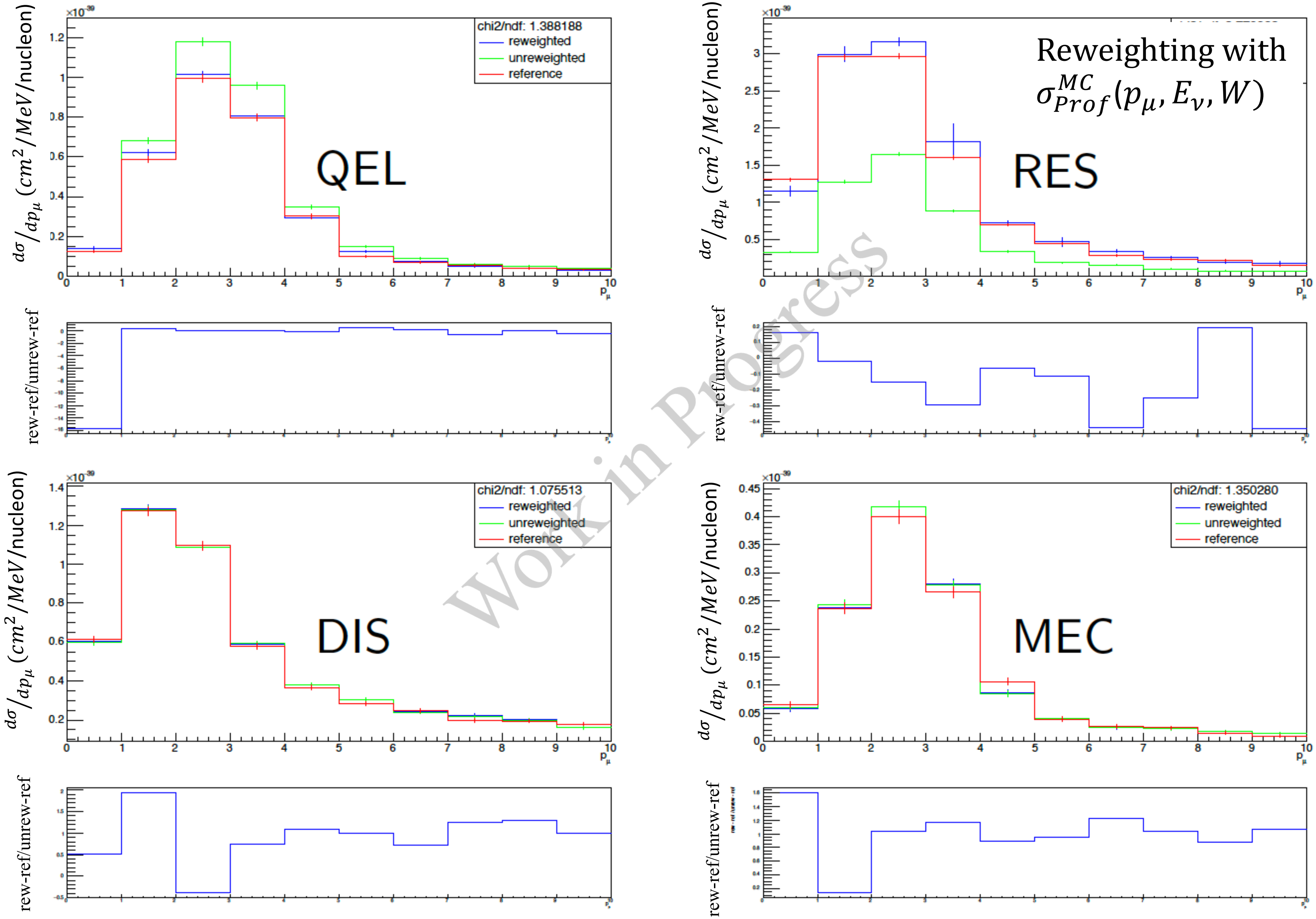
- Use p_μ, E_ν, W distributions to perform reweighting
- Simulation and spline generation is on all CC events with MINERvA flux
- Only $\bar{\nu}_\mu$ on 12C samples are plotted
- Varied parameters
  - $M_A^{QE} \in [0.0397, 1.969]\ GeV$
  - $M_A^{RES} \in [0.0219, 1.972]\ GeV$
- Selected samples
  - 35 samples for generating the spline
  - 2 samples for testing
    - Unweighted: $M_A^{QE} = 0.995\ GeV, M_A^{RES} = 1.089\ GeV$, default in G18_10a_02_11b
    - Reference and reweight target: $M_A^{QE} = 0.77\ GeV, M_A^{RES} = 1.64\ GeV$
- 4-order polynomial spline generated by Professor

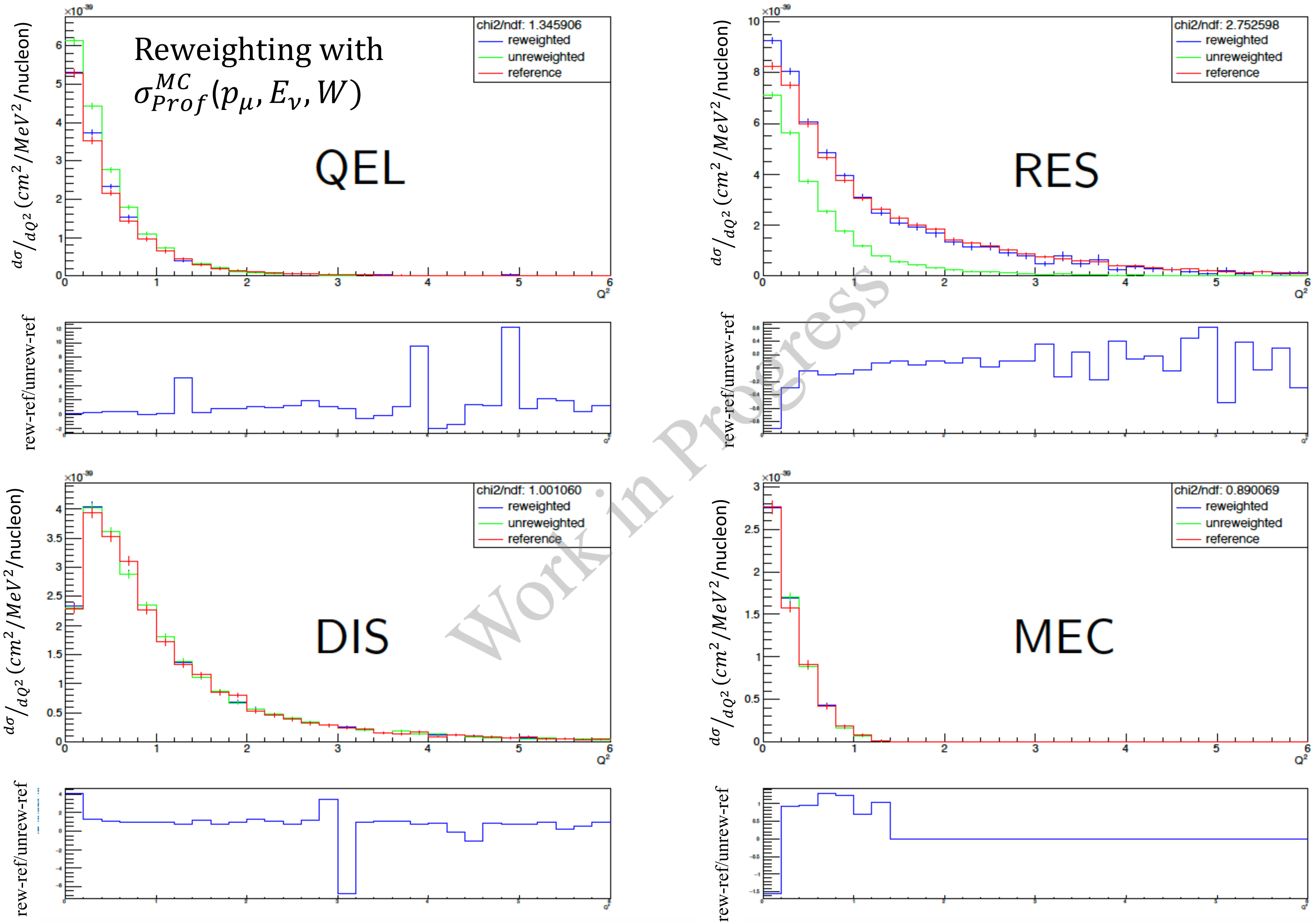
Proof of concept





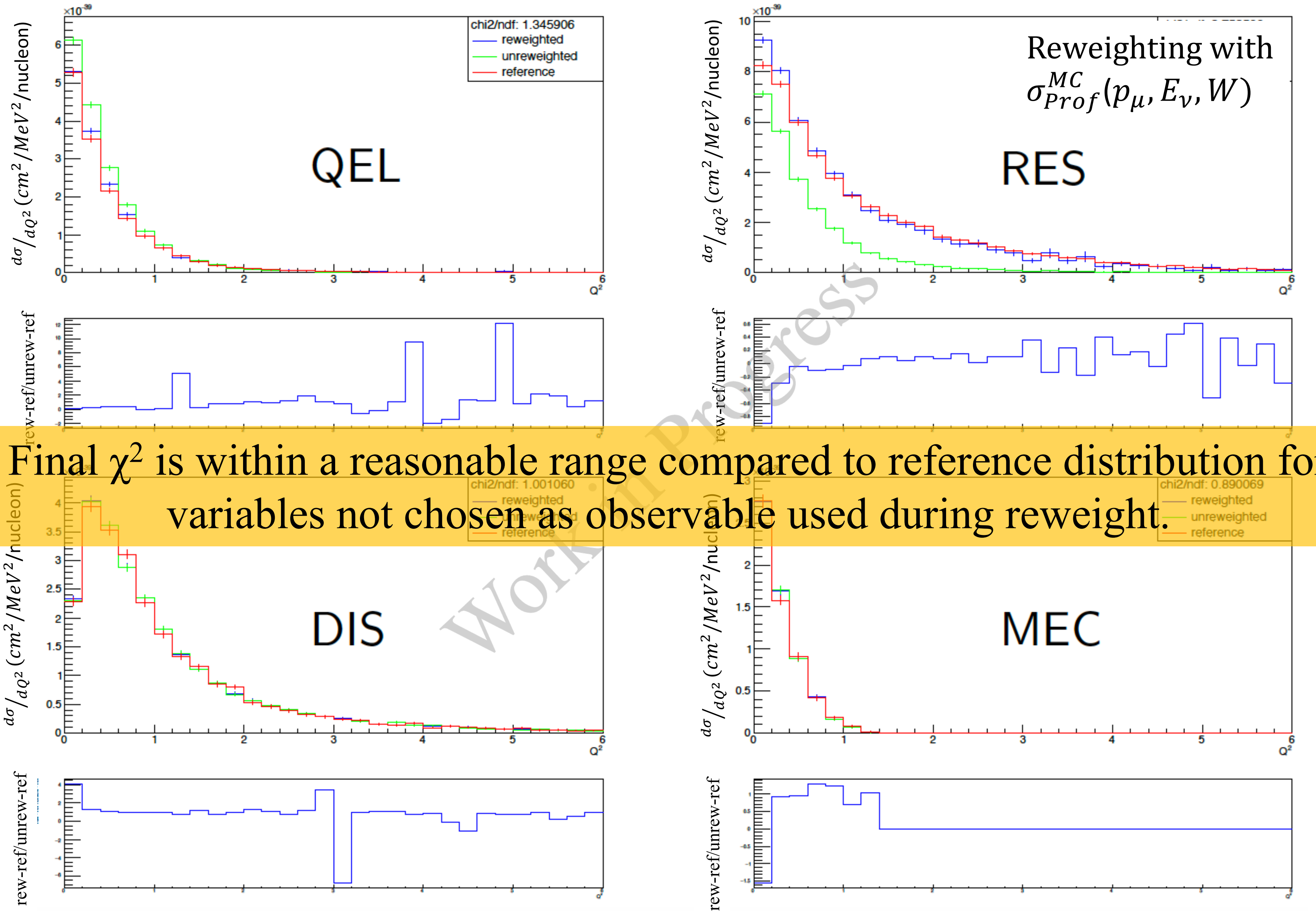
Reweighting with $\sigma^{MC}_{Prof}(p_\mu, E_\nu, W)$




Reweighting with
$\sigma^{MC}_{Prof}(p_\mu, E_\nu, W)$
QEL
RES
DIS
MEC
chi2/ndf: 1.345906
chi2/ndf: 2.752598
chi2/ndf: 1.001060
chi2/ndf: 0.890069
reweighted
unreweighted
reference
$d\sigma/_{dQ^2}\,(cm^2/MeV^2/\text{nucleon})$
rew-ref/unrew-ref
Q²
Work in Progress


Qiyu Yan

Reweighting with $\sigma^{MC}_{Prof}(p_\mu, E_\nu, W)$



Final χ^2 is within a reasonable range compared to reference distribution for variables not chosen as observable used during reweight.

Takeaways

HK and DUNE need dedicate efforts to characterize and reduce modelling systematic uncertainties - Ongoing effort from experimentalist, theorist and neutrino event generator experts

Tuning MC event generators is essential for the next generation of neutrino experiments - Different experiments have different needs:

- HK modelling systematics dominated by pion-less uncertainties. DUNE modelling systematics dominated by pion-production uncertainties

- Non-trivial task – a lot of work needed to achieve a global tune with well defined uncertainties

Many methods available:

- Reweight is the most used and well adopted for experimental analyses - model dependent, parameters tuned not necessarily in generators
- Reweighting several important simulation aspects is non-trivial or possible, such as FSI cascade models or hadronization

Takeaways

The GENIE Collaboration is building a Global analysis framework based on the Professor concept

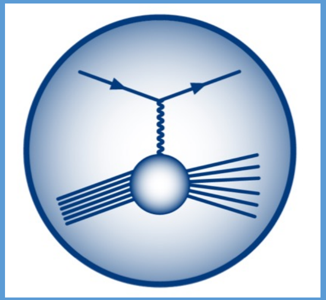
- Neutrino, electron and hadron-nucleus data
- Most emphasis on neutrino tunes – latest results show compatibility between T2K and MINERvA's CC0π and CC1π data

The GENIE Collaboration is working towards a new reweight scheme

- Based on Professor brute force strategy - exploits full MC response function
- First results demonstrate that reweight by observable is doable
- Change in paradigm – users need to decide on relevant observables for a given set of systematics
- **Generator parameters directly used in reweight calculation**
    - No need for additional coding! – Can reweight any modelling aspect of your event generator

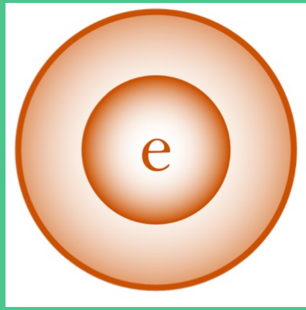
Backup slides

Towards a global tune



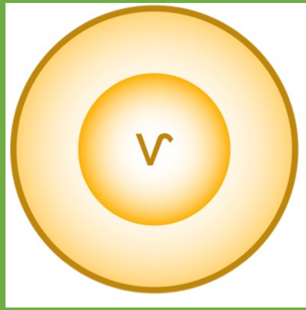
Model unification

- Ideally, models have clear V-A separation, with specific parameters
  - Not available in all event generators
- Identify modelling aspects common between e and ν



Tune your generator against electron-scattering data

- Turn off axial components
- Clear A-V separation might not be available
- Still useful to constrain base-model and focus on FSI aspects
- Exclusive data will avoid degeneracies in your tune – e4nu measurements!



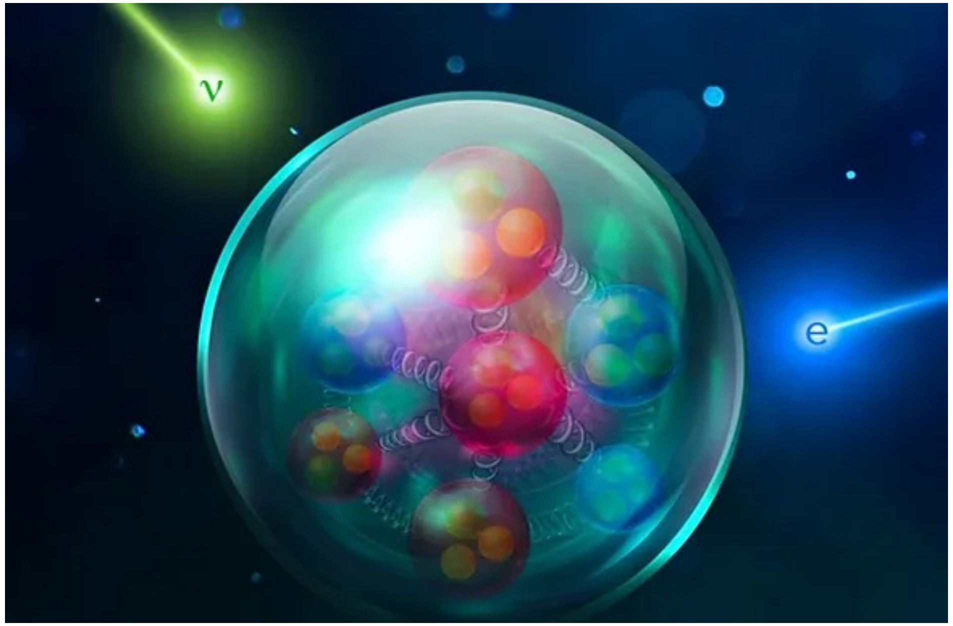
Propagate tune results to neutrino tune

- More e-A measurements
  - Results from the electron tune can be imposed as priors to avoid bias
- Constrain FSI and nuclear model with electron data
- Ideally, also axial part, but this might be tricky for some models

Tuning of e $-A$ interaction models

Complications:

- Much higher statistics than neutrinos!
- A common tune would bias the results in favor of electron data
- Most models don't have parameters specific to electrons
- Clear V-A separation not always easy
  - I.e: Non-resonance background model



Review of MC tuning methods

GENIE's interaction model parameters can be tuned using different methods:

GENIE Reweight ("RWG")

- Nominal prediction build using full event information
  - Can construct any type of prediction
- Reweight is used to emulate parameter impact on the nominal prediction
- **Limited to reweightable models**

Monte Carlo prediction

Analytical response function

GENIE-Professor based tunes

- Prediction is build using full event information
  - Can construct any type of prediction
- Professor-build response function using brute-force parameter scans
  - Parameters are defined in the event generator
- **Can tune all aspects of your event generator!**

Monte Carlo prediction

Monte-Carlo parameterized response function

GENIE's Alternative - Professor

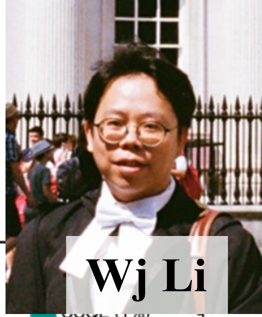
- Model fitting and data-driven uncertainty quantification
- Curated data-base
  - Neutrino-scattering
  - Electro-scattering
  - Hadro-nucleus scattering
- Applicable to all modelling aspects
  - Can tune non-reweightable models
- Easily to replicate whenever new models are included
- Available out-of-the box for all users
  - Complex configurations are handled with tune tags: Example of nuclear tune configuration (GPRD18_10a)
- New Professor-based reweight for uncertainty propagation

Based on the **Professor concept**
- Developed by LHC community
- Concept applied to neutrinos for the first time by GENIE

Requirements

- Reweight tool will read polynomial coefficients for each bin, and binning structure file and information describing how the observable is defined.
- For each event to be reweighted, calculate the exact observable used to define differential cross section, locate which bin this event should belong to.
- Use the polynomial for the bin located, calculate differential cross section at different systematic parameters sets.
- Weight will be defined as the ratio of the two differential cross section.

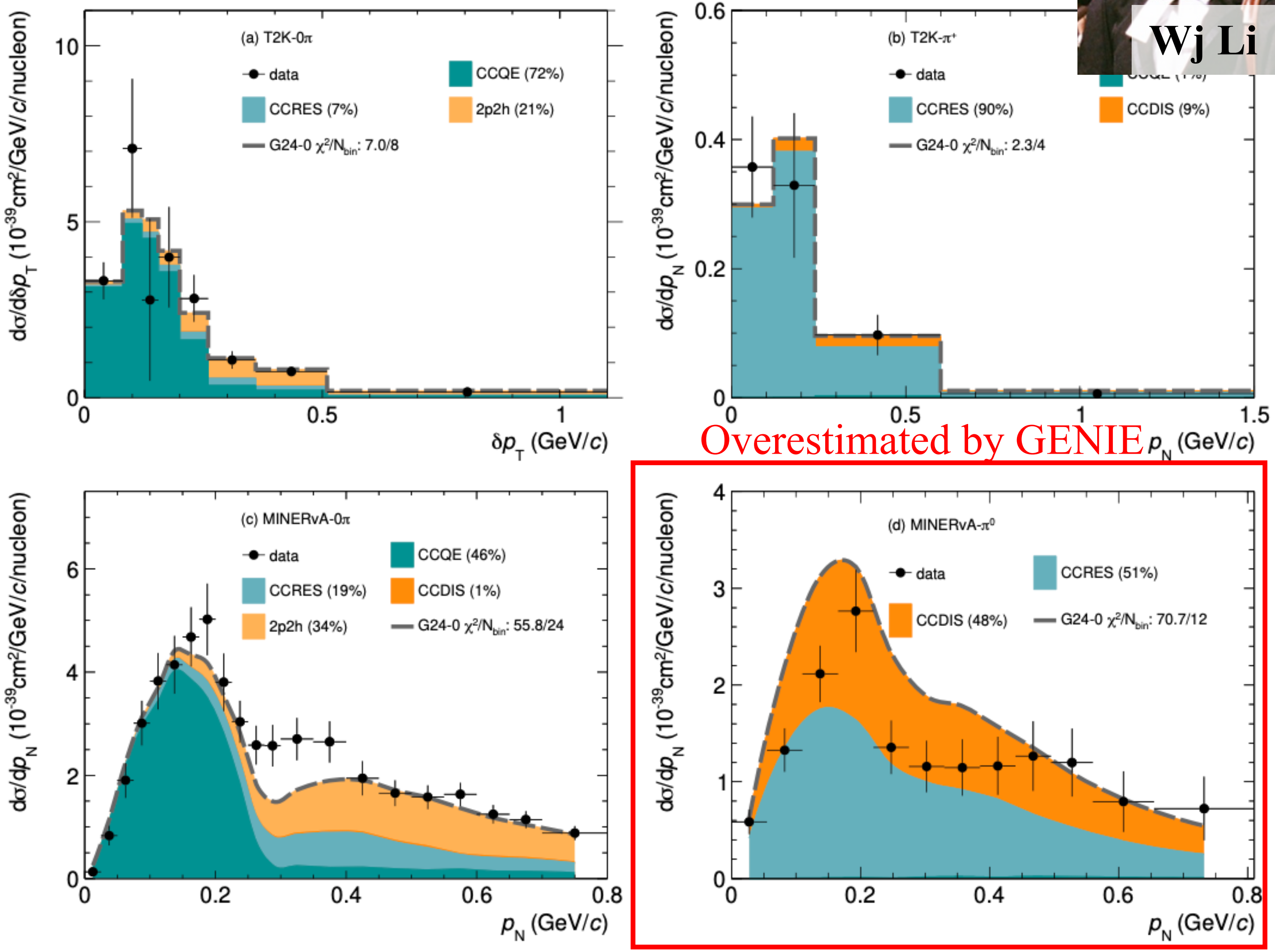
TKI CC0π + CCπ data



- First TKI oriented GENIE tune
  - Exploit the conservation of momentum in neutrino interactions
  - Constraints on nuclear aspects of the simulation
- Using CC0π + CCπ data
  - T2K 0π
  - T2K 1π+
  - MINERvA 0π
  - MINERvA Nπ0

Correlations used Norm-Shape (NS) transformation

- All signal definitions require at least a proton in the final state



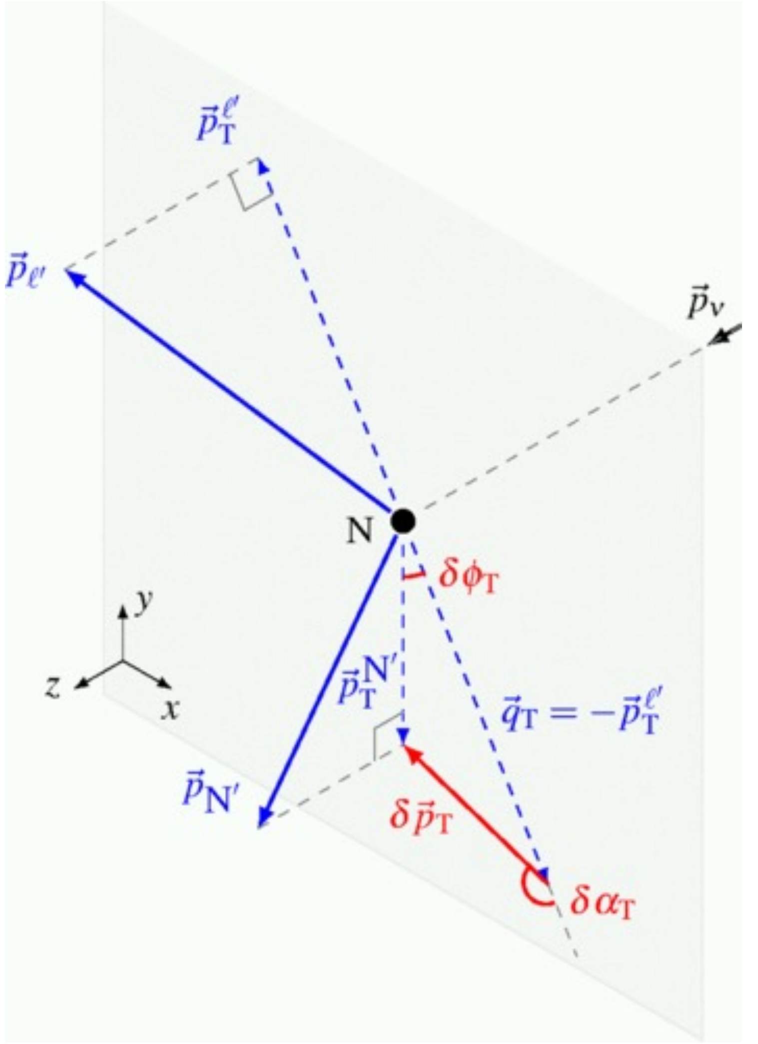
Predictions computed with G24 20i 00 000

TKI tune - Discussion

- Decrease in S_{ABS}^{N} can be interpreted as a convenient way to increase all the other fates rather
  - It does not necessarily indicate a decrease of nucleon absorption
- FSI fates should be interpreted collectively
  - Effective FSI model!
- RES model held fixed, all discussions are conditioned on this restriction.

TKI CC0π + CC1π tune

- Kinematic observables centred around the conservation of momentum in neutrino interactions.
- The imbalance between the observed transverse momentum of the final-state particles and the expected transverse momentum in a neutrino interaction
- Sensitive to initial nuclear states and hadronic FSIs



CC0π Tune

[PhysRevD.106.112001]

- Focus on QEL, MEC, RES parameters
  - QEL: Two parameters to control normalization and strength of RPA correction, and M_A^{QEL}
  - MEC: normalization and shape parameter
  - RES: overall scaling parameter with priors from free nucleon tune
- FSI parameters **not included** at this stage
- Goals:
  - Investigate tensions between experiments in quantitative way
  - Energy dependence of the cross section
  - Differences between neutrino and antineutrino data

CC0π Tune Results

G10a: MiniBooNE ν_μ CC0π

G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π

G20a: T2K ND280 ν_μ CC0p0π

G30a: MINERvA ν_μ CC0π

G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π

G35a: MINERvA ν_μ CCNp0π

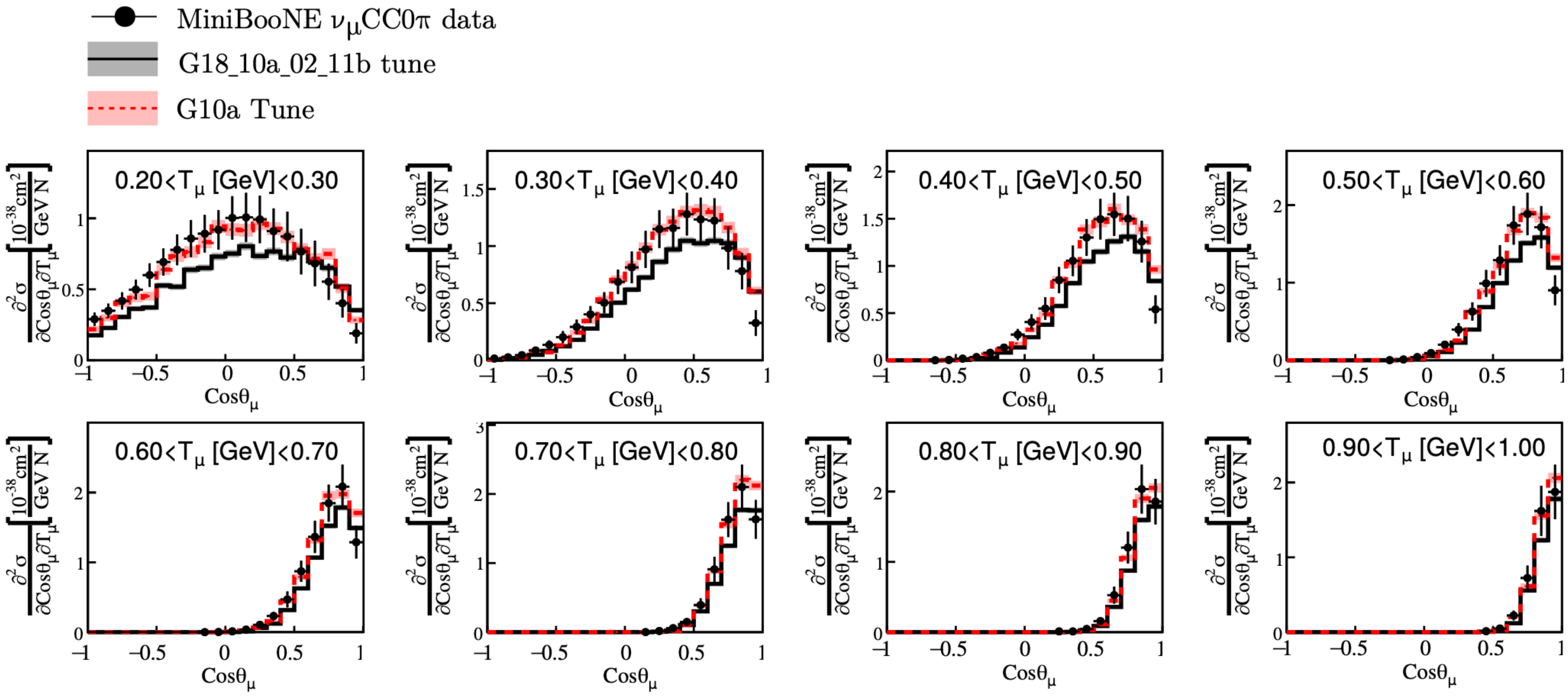
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
S_{RES}	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02
S_N^{2p2h}	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5
S_Δ^{2p2h}	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2
S_{PL}^{2p2h}	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1
χ^2	89/130	77/71	60/55	61/137	67/53

All tunes:

- Respect free nucleon priors
- Prefer RPA corrections
- Enhance the CCQEL(~20%) and CCMEC cross section

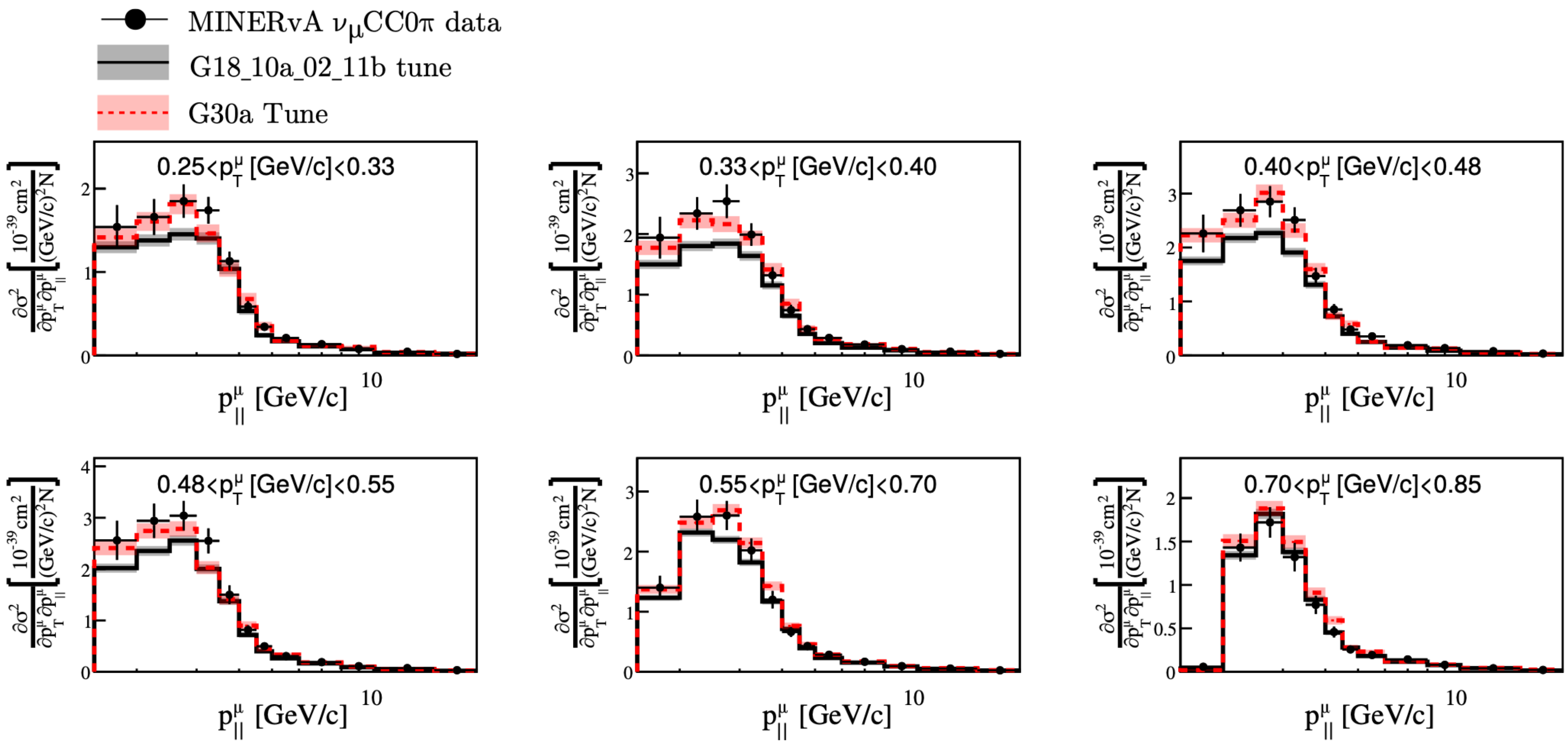
CC0π Tune Results

The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement



CC0π Tune Results

The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement



CC0π Tune Results

Differences:

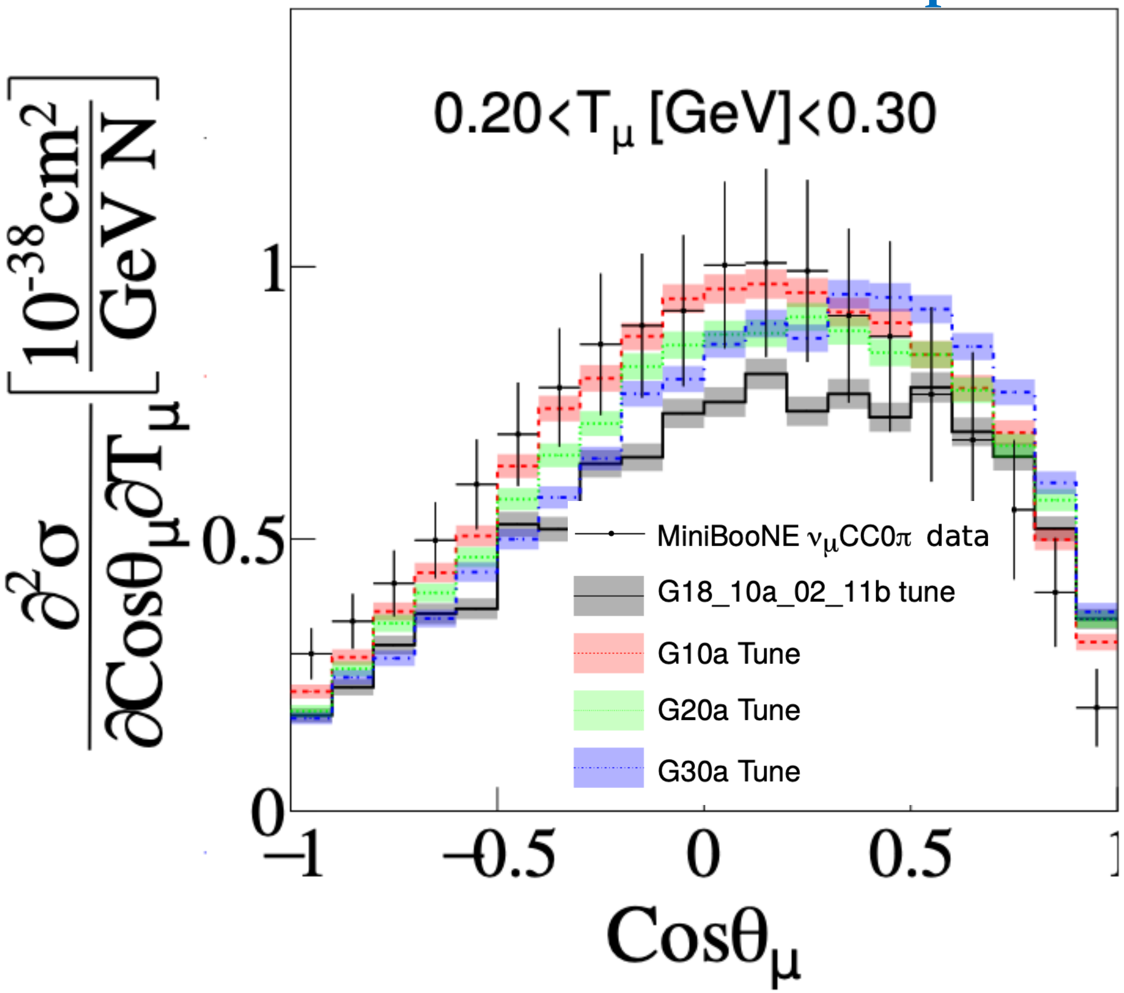
- MiniBooNE + T2K enhance MEC at $W = M_N$
- MINERva's tunes enhance both MEC peaks
- **Clear energy dependence on cross section shape**
- **Anti-neutrino tunes predict a higher cross-section**
- Same observations by recent MINERvA measurements using high energy beam

G10a: MiniBooNE ν_μ CC0π
G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π
G20a: T2K ND280 ν_μ CC0p0π
G30a: MINERvA ν_μ CC0π
G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π
G35a: MINERvA ν_μ CCNp0π

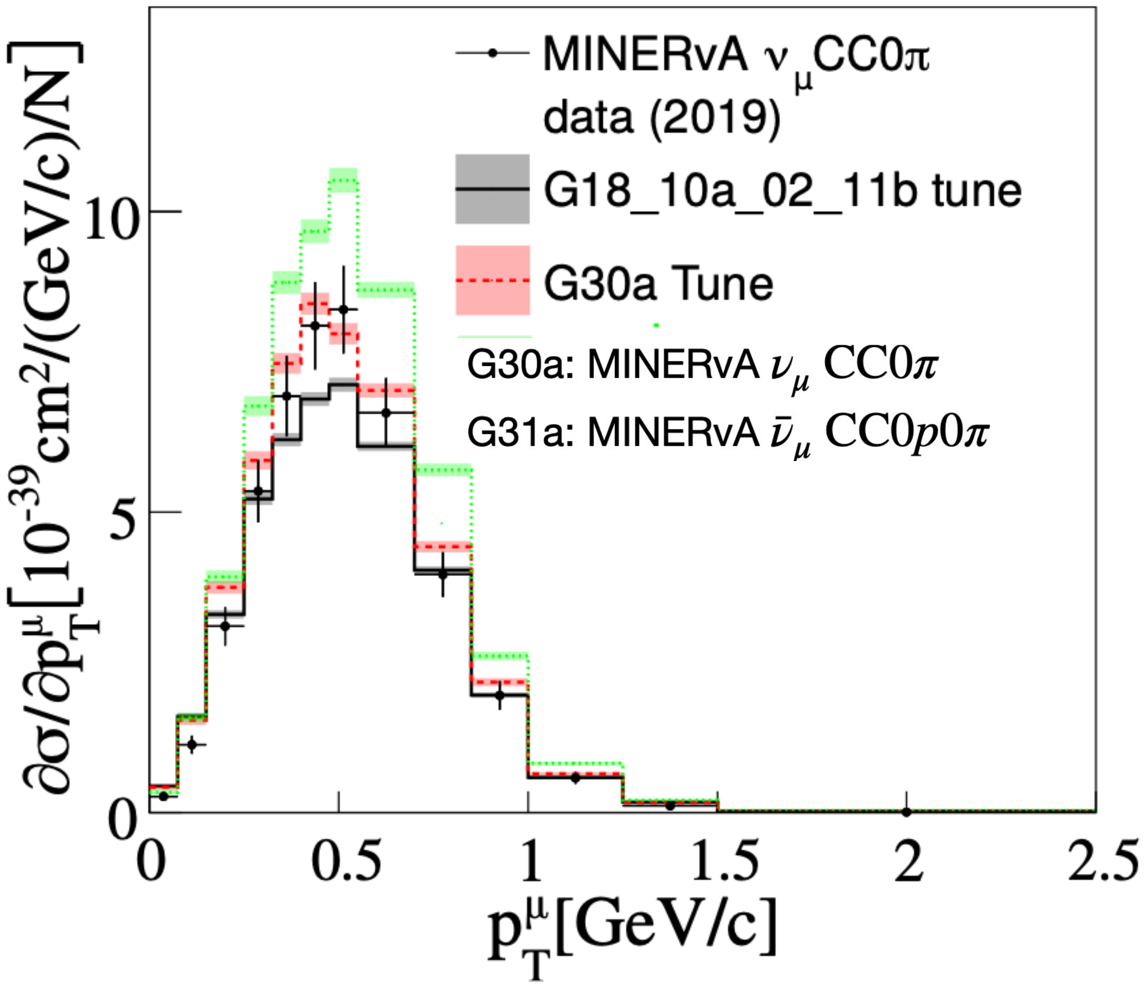
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
M_A^{QEL}(GeV/c^2)	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\ RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
S_{RES}	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02
S_N^{2p2h}	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5
S_Δ^{2p2h}	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2
S_{PL}^{2p2h}	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1
χ^2	89/130	77/71	60/55	61/137	67/53

CC0π Tune Results

Clear energy dependence on cross section shape



Anti-neutrino tunes predict a higher cross-section

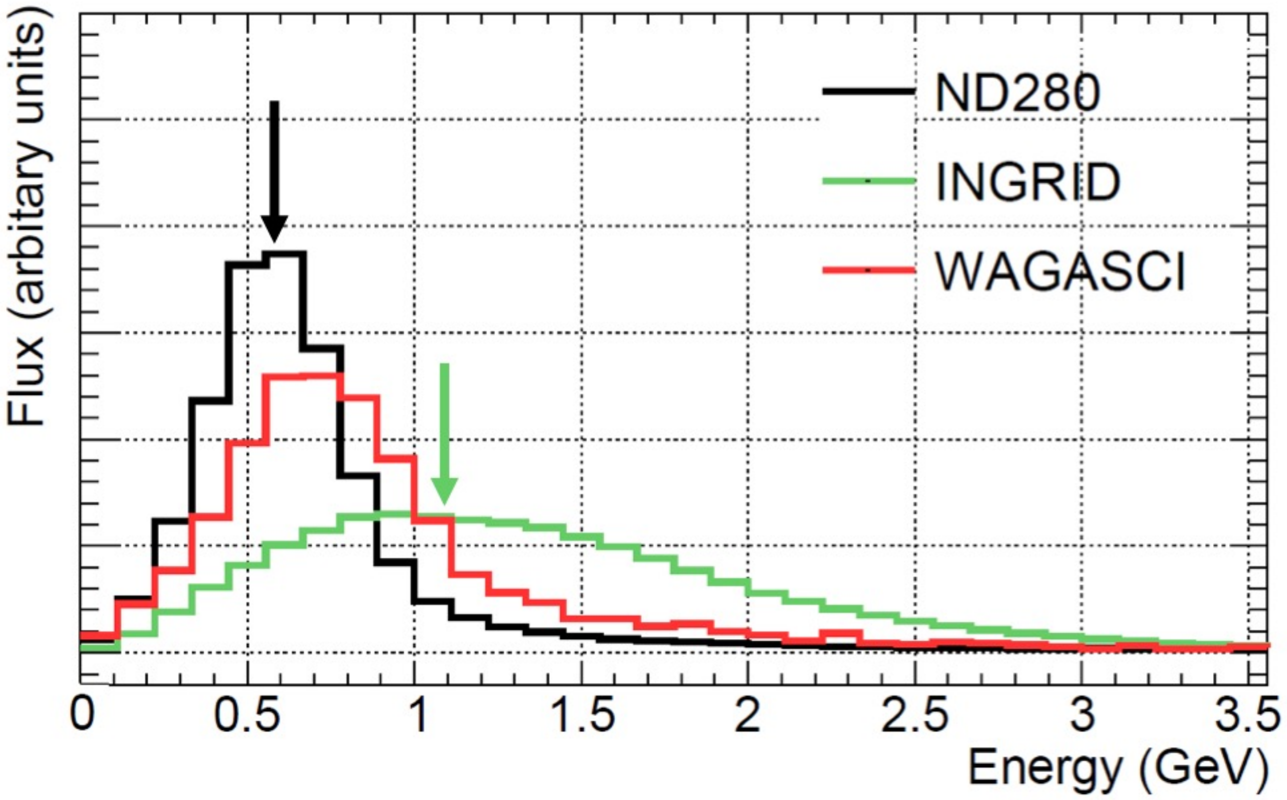


Predictions computed with G24_20i_00_000

Simulation component	Model
Nuclear state	SF-CFG [8, 38, 39]
QE	Valencia [41]
2p2h	SuSAv2 [44]
QE $\Delta S = 1$	Pais [45]
QE $\Delta C = 1$	Kovalenko [46]
Resonance (RES)	Berger-Sehgal [47]
Shallow/Deep inelastic scattering (SIS/DIS)	Bodek-Yang [48]
DIS $\Delta C = 1$	Aivazis-Tung-Olness [49]
Coherent π production	Berger-Sehgal [50]
Hadronization	AGKY [51]
FSI	INTRANUKE hA [52]

TABLE II: Model components of G24-0. Processes with non-trivial ΔS and ΔC are those with strangeness and charm production, respectively.

JPark Flux



2.5° off axis
on axis
1.5° off axis