Impact of Interaction Uncertainties on Neutrino-Nucleus Cross Section Measurements

Vishvas Pandey
Fermi National Accelerator Laboratory

14th International Workshop on Neutrino-Nucleus Interactions (NuInt 2024),
São Paulo, Brazil, April 15 - 20, 2024

Scope of this talk

- Charge from organizers: *We would like to invite you to give a plenary talk with the following title as part of the Impact of Uncertainties Working Group:*

  Impact of neutrino interaction uncertainties on neutrino cross-section measurements

- My reply: *Thank you so much for the invitation! I will be happy to present the talk with the title/scope you described, and am looking forward to it.*

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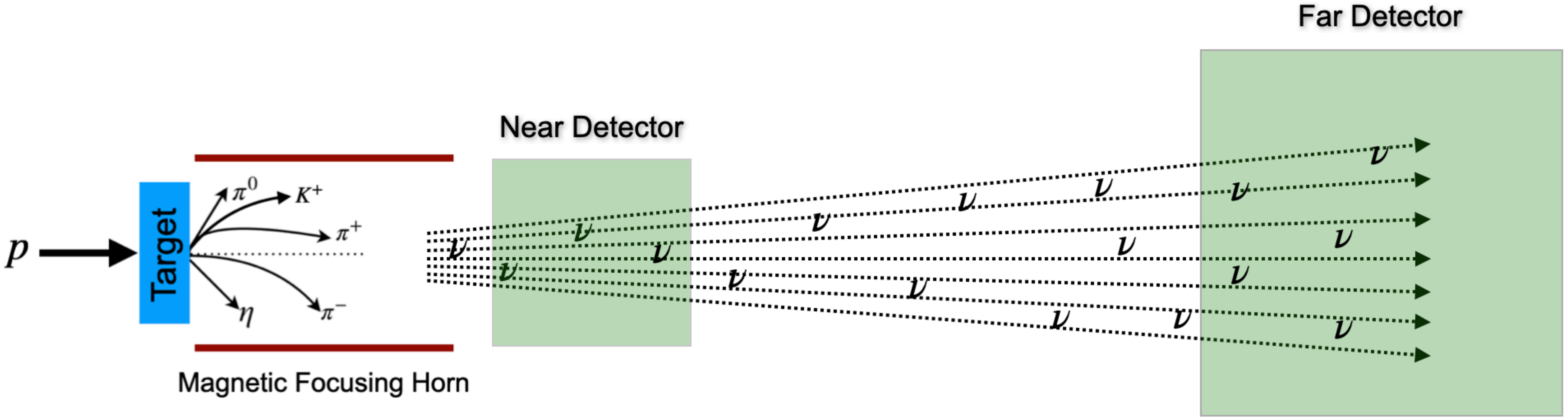
✦ On a serious note, this is a reminder that we have truly entered into a high-statistics neutrino cross section measurement era, and gearing toward the precision era in neutrino physics.

- A lot of us got into this business because we are interested in measuring neutrino oscillation parameters.

Clarence Wret's talk this morning



- **Extracting Oscillation Parameters:**

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu) = \sin^2 2\theta_{ij} \, \sin^2\left(\frac{\Delta m^2_{ij}}{4}\frac{L}{E_\nu}\right)$$

$$\frac{N^{\alpha\to\beta}_{FD}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma^i_\beta(E_\nu) \times P_{\nu_\alpha\to\nu_\beta}(E_\nu) \times \epsilon^i_\beta(E_\nu) \times S_i(E_\nu; E_{\nu,rec})}{N^\alpha_{ND}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma^i_\alpha(E_\nu) \times \epsilon^i_\alpha(E_\nu) \times S_i(E_\nu; E_{\nu,rec})}$$

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Neutrino-Nucleus Cross Sections: Motivations

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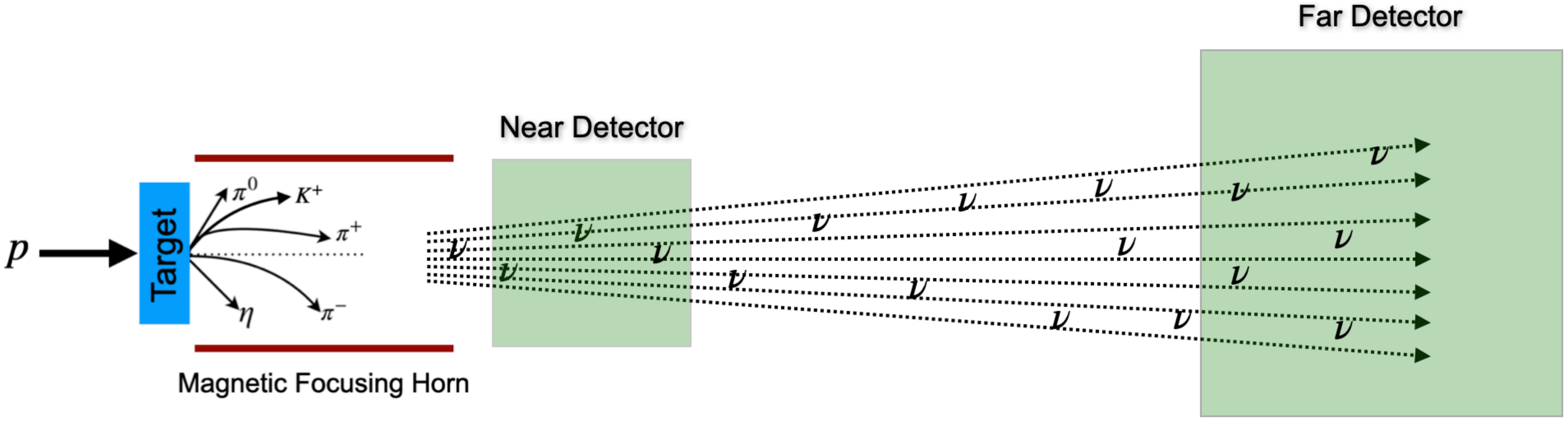

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- Near to far ratio does not cancel out neutrino interaction dependencies.

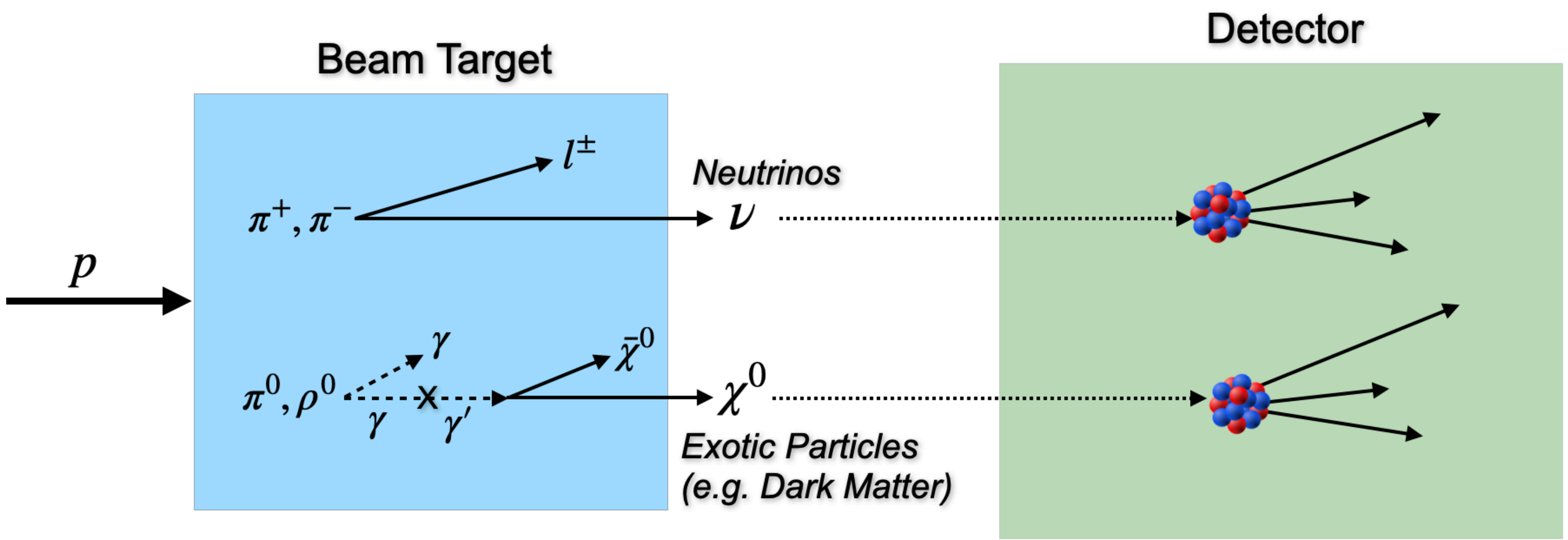
✦ Need to constrain neutrino-nucleus interaction physics in order to extract neutrino oscillation parameters.

✦ **Need more neutrino-nucleus cross section measurements!**

Neutrino-Nucleus Cross Sections: Motivations

- More recently, we started thinking about BSM physics signals at Neutrino Experiments.

Joachim Kopp's talk on Friday



- Typical BSM signatures include charged leptons ($e^\pm$, $\mu^\pm$), photons and hadrons in the final states.
- Neutrino-nucleus interaction products are the primary background.

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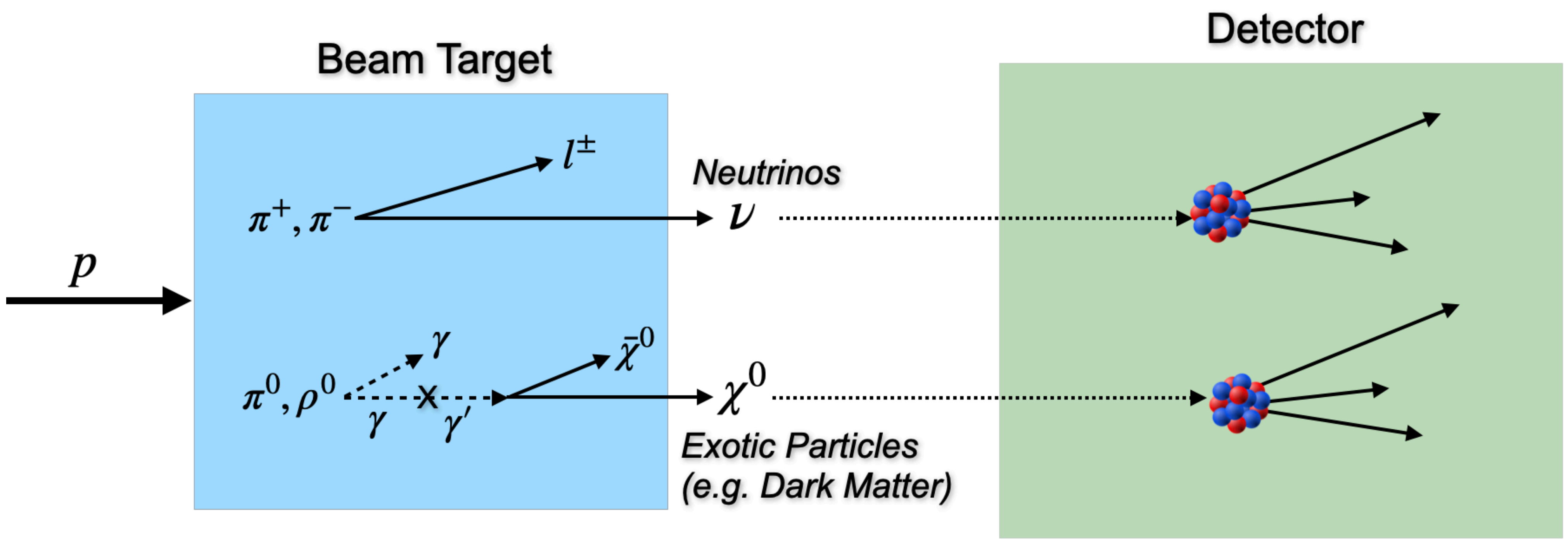

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Neutrino-Nucleus Cross Sections: High-Statistics Era

- Conclusions: Need more neutrino-nucleus cross section measurements!

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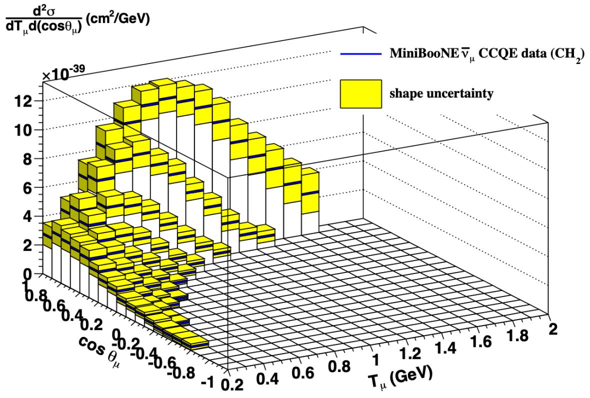
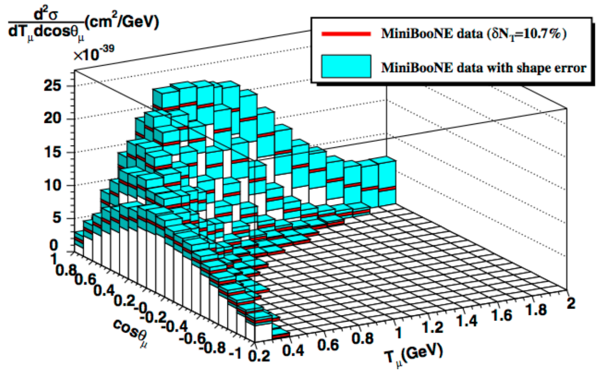


$\bar{\nu}_\mu$ CCQE



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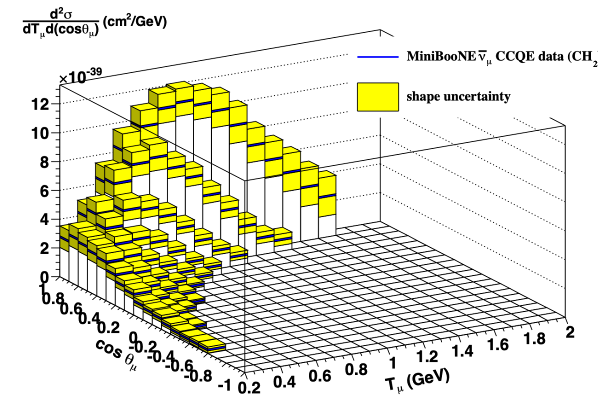

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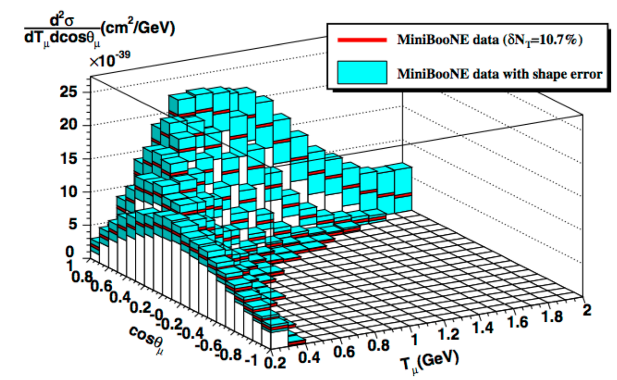

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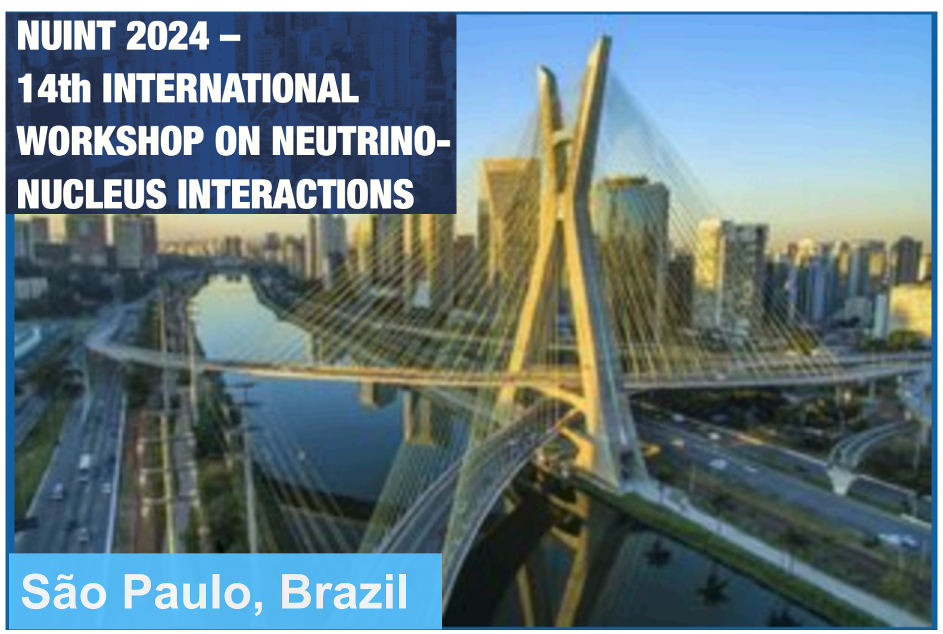
- Now, by the time we came back to Brazil, we are starting to live in an era of high-statistics multi-differential neutrino-nucleus cross section measurements.



Snowmass NF06 Report: arXiv:2209.06872 [hep-ex]

Experiment	Flavor	ν_μ Flux Peak (GeV)	Target	Detection
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NOvA	ν_μ,$\bar{\nu}_\mu$,ν_e, $\bar{\nu}_e$	2	CH_2	Tracking+Calorimetry
DUNE	ν_μ,$\bar{\nu}_\mu$,ν_e,$\bar{\nu}_e$	PRISM: 0.5-3	H,C,Ar	Tracking+Calorimetry
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MicroBooNE	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
SBND	ν_μ,ν_e	0.8 (PRISM: 0.6-0.8)	Ar	Tracking+Calorimetry
ICARUS	ν_μ,ν_e	0.3,0.8	Ar	Tracking+Calorimetry
MINERvA	ν_μ,$\bar{\nu}_\mu$,ν_e,$\bar{\nu}_e$	3.5,6	He, C, CH, H_2O, Fe, Pb	Tracking+Calorimetry
ANNIE	ν_μ,$\bar{\nu}_\mu$	0.6	CH, H_2O	Cherenkov
NINJA	ν_μ,$\bar{\nu}_\mu$,ν_e,$\bar{\nu}_e$,	1	CH, H_2O, Fe	Emulsion
FPF	ν_μ,$\bar{\nu}_\mu$,ν_e,$\bar{\nu}_e$, ν_τ, $\bar{\nu}_\tau$	700 GeV	W, Ar	Emulsion, Tracking+Calorimetry
nuSTORM	ν_μ,$\bar{\nu}_\mu$,ν_e,$\bar{\nu}_e$	PRISM: 0.8-3	CH,H_2O,Ar,TBD	Tracking+Calorimetry (TBD)

See T2K, MINERvA, MicroBooNE, NOvA, ICARUS, SBND, … cross section measurement talks throughout the week.

All Public MicroBooNE XS Measurements

- CC inclusive
  - 3D ν_μCC inclusive 0p/Np, BNB, arXiv:2402.19281, arXiv:2402.19216
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T2K cross-section publications (>20 articles in ≈ 10 years)

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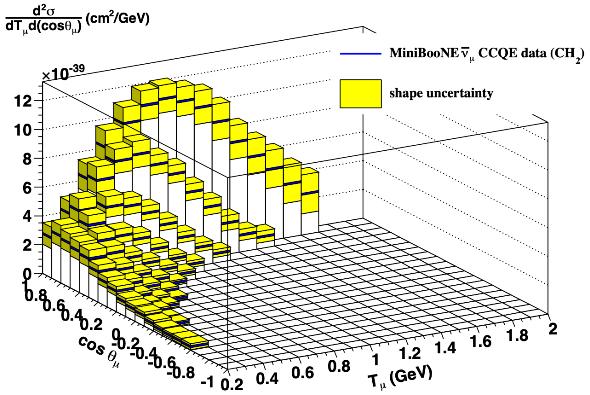

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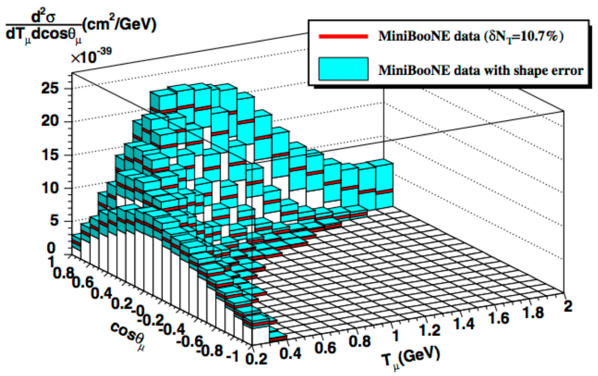

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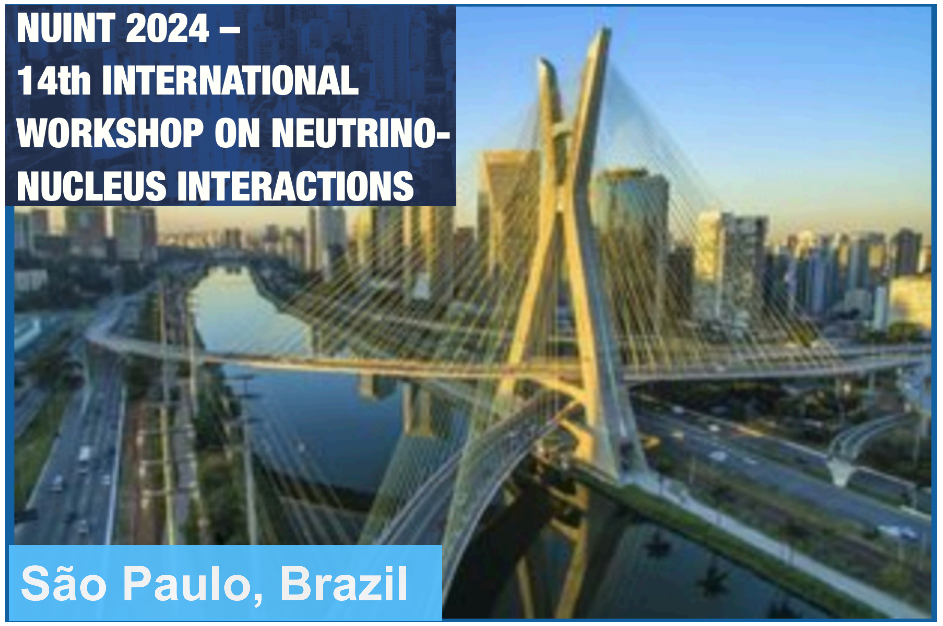

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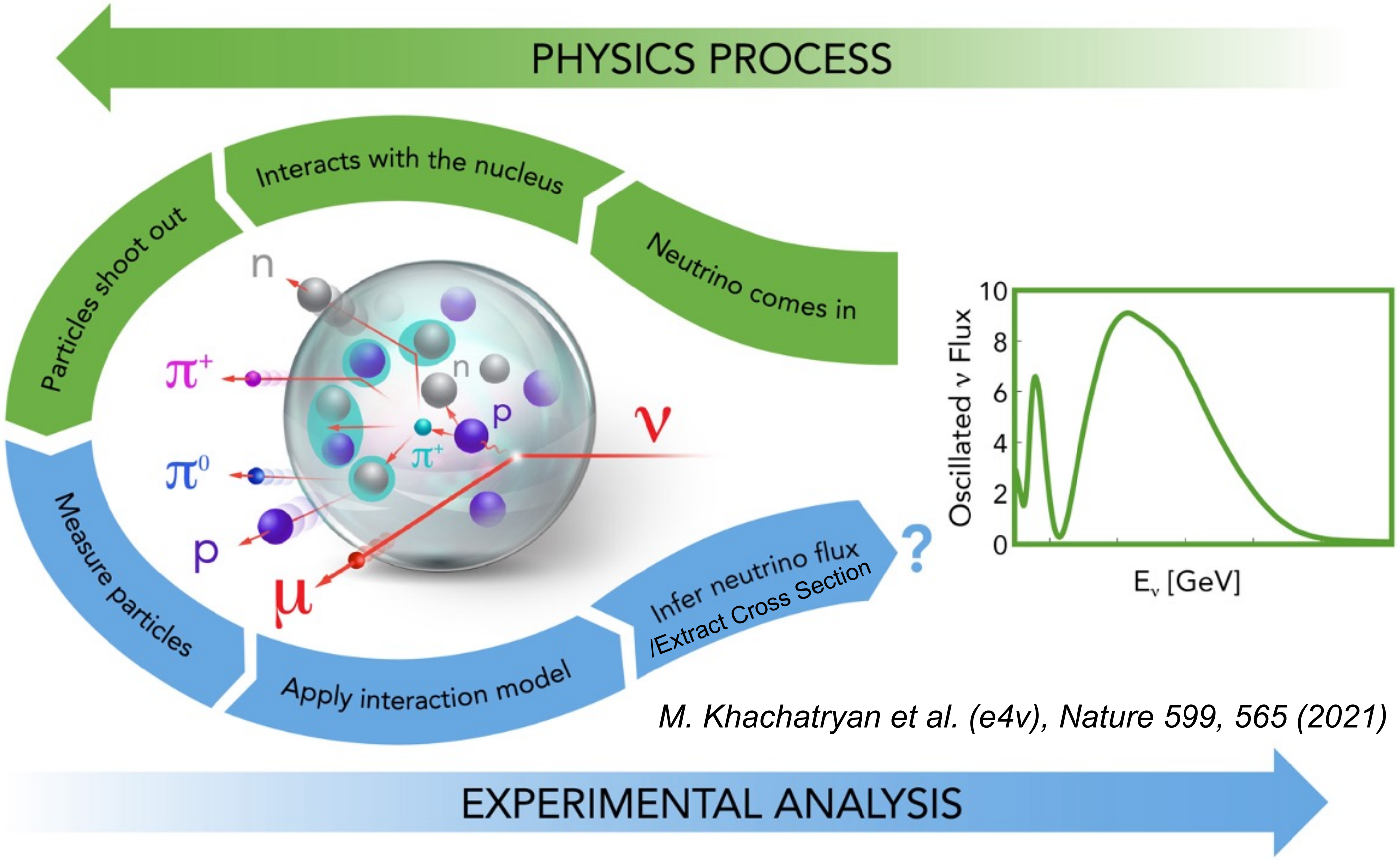
✦ Time to leverage high-statistics to perform clean and precise measurements and to constrain underlying neutrino-nucleus cross section physics.

Neutrino-Nucleus Cross Sections: Theory and Experiment



M. Khachatryan et al. (e4v), Nature 599, 565 (2021)

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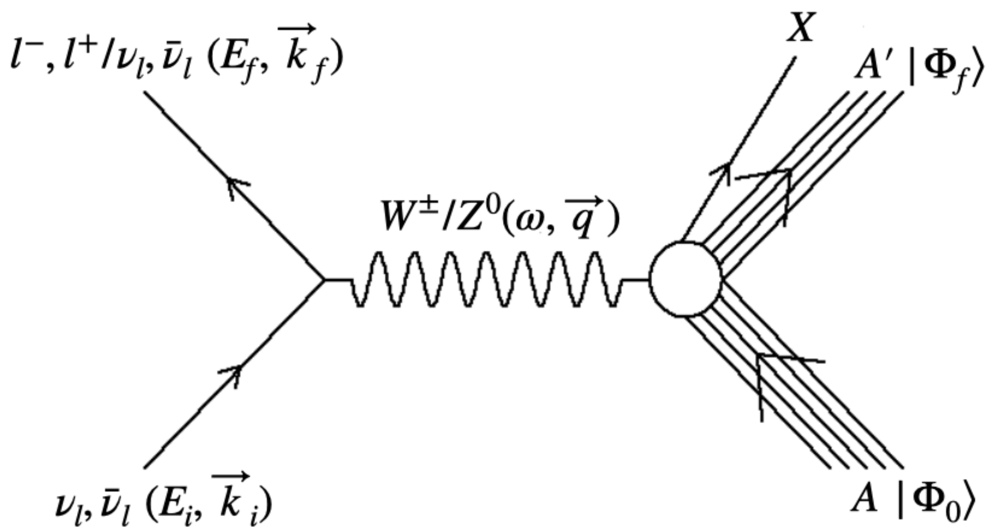
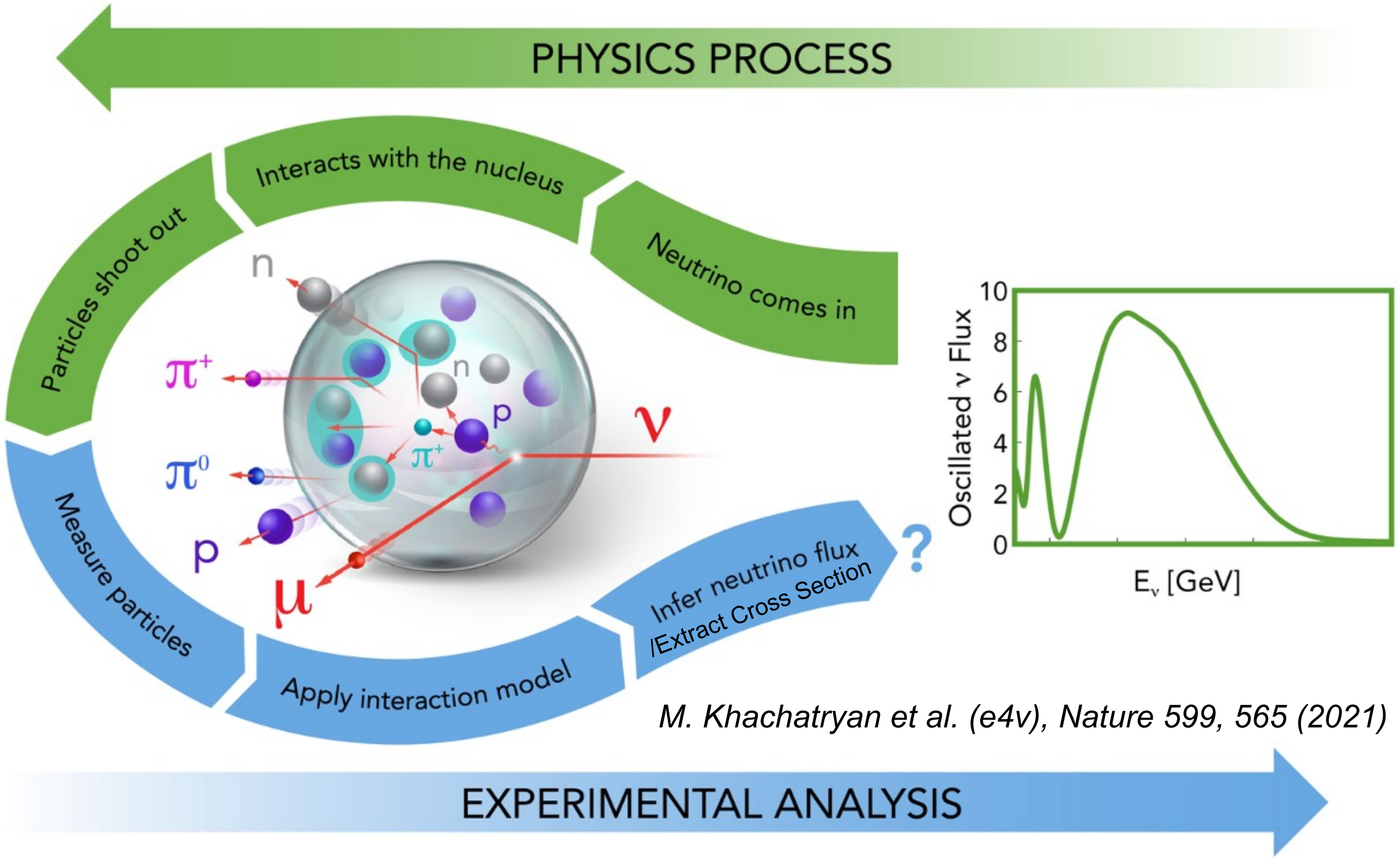


- Scattering Kinematics:

$$\omega = E_i - E_f, \quad q = |\vec{k}_i - \vec{k}_f|, \quad Q^2 = q^2 - \omega^2$$



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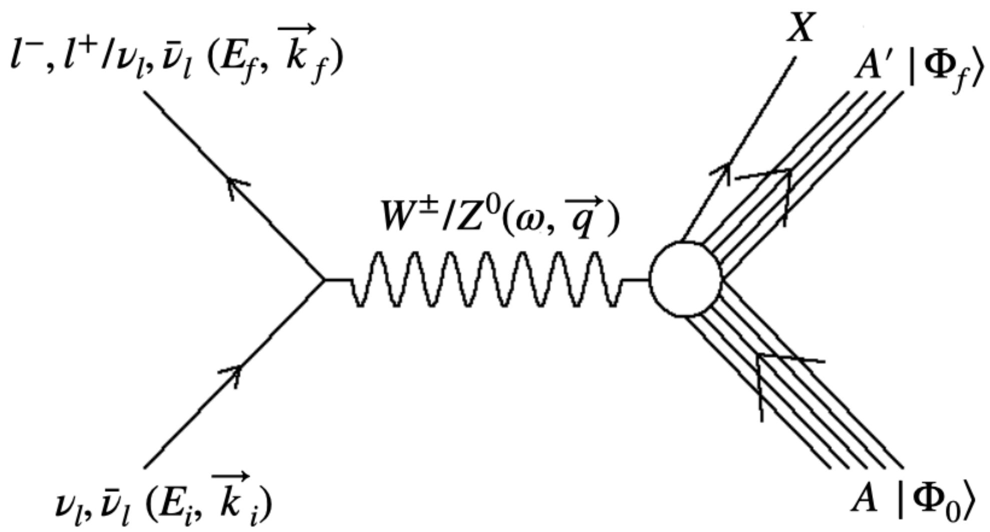

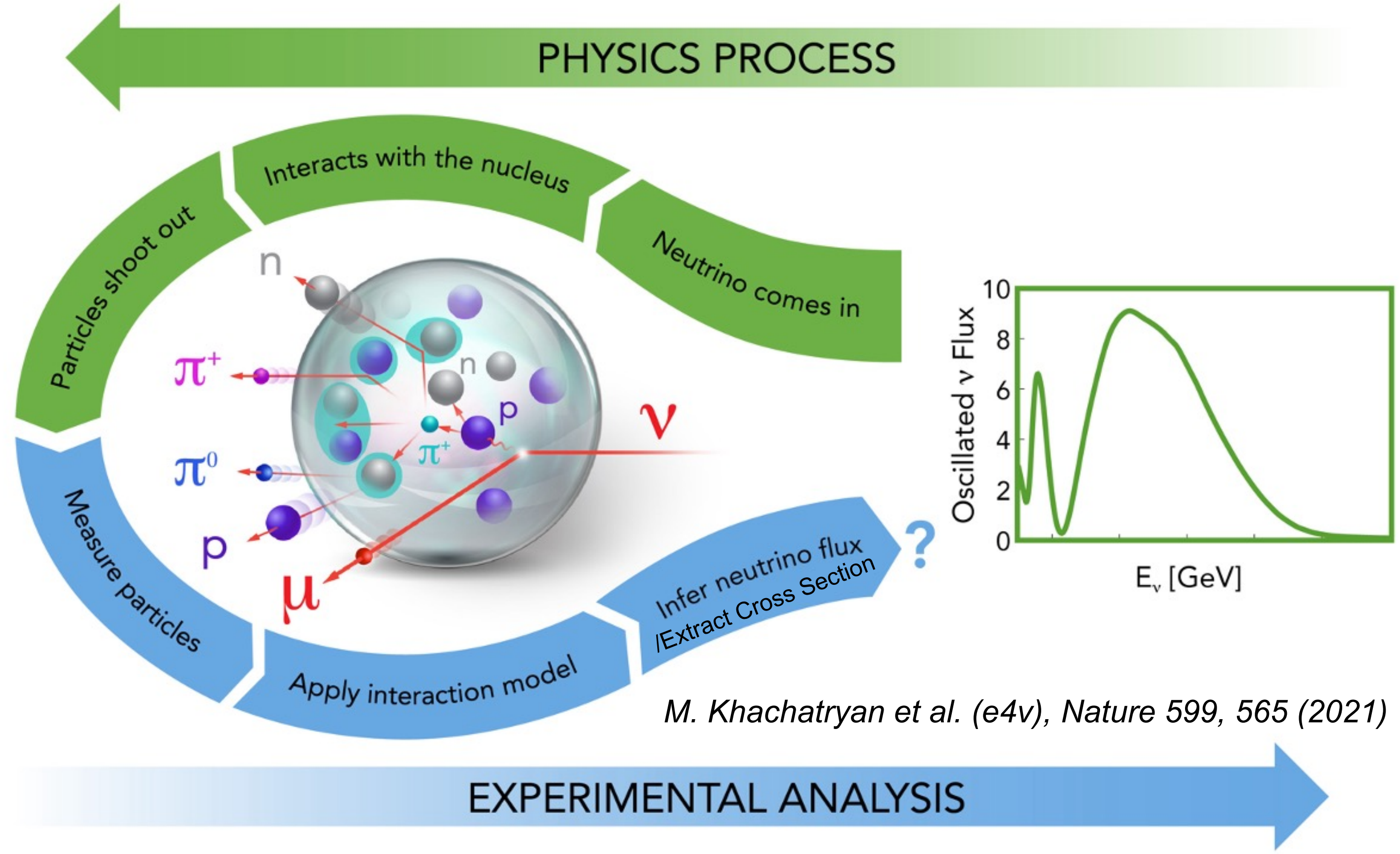

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- **Calculate neutrino-nucleus cross section**

$$d\sigma \propto \sum_{fi} |\mathcal{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$

- Leptonic Tensor: calculable analytically

$$L_{\mu\nu} = \sum_{fi} (\mathcal{J}_{l,\mu})^\dagger \mathcal{J}_{l,\nu}$$

- Hadronic Tensor: complicated multi-scale/many-body object, encodes all nuclear/nucleonic physics

$$W^{\mu\nu} = \sum_{fi} (\mathcal{J}_n^\mu)^\dagger \mathcal{J}_n^\nu$$

- Transition Amplitude:

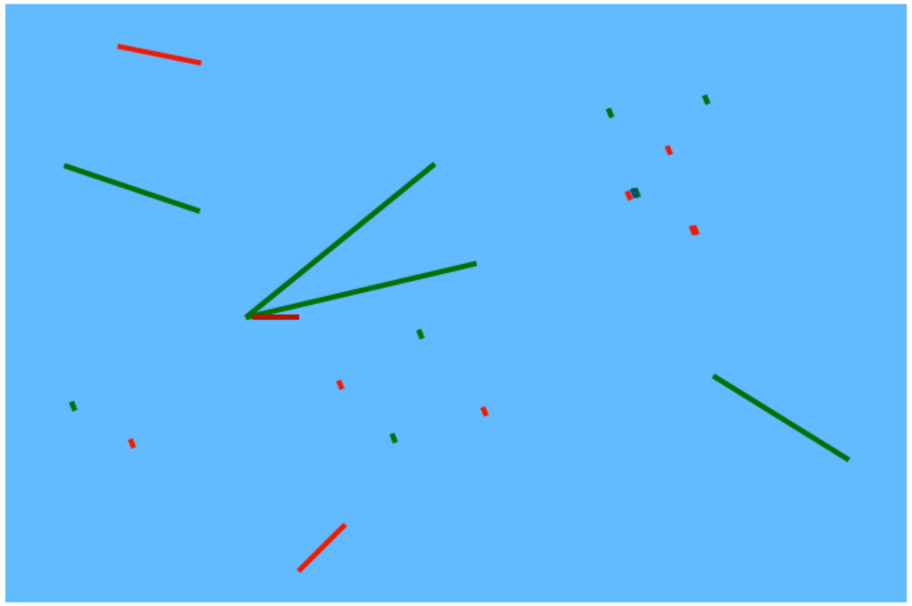
$$\mathcal{J}_n^\mu = \langle \Phi_f | \hat{J}_n^\mu(q) | \Phi_0 \rangle$$

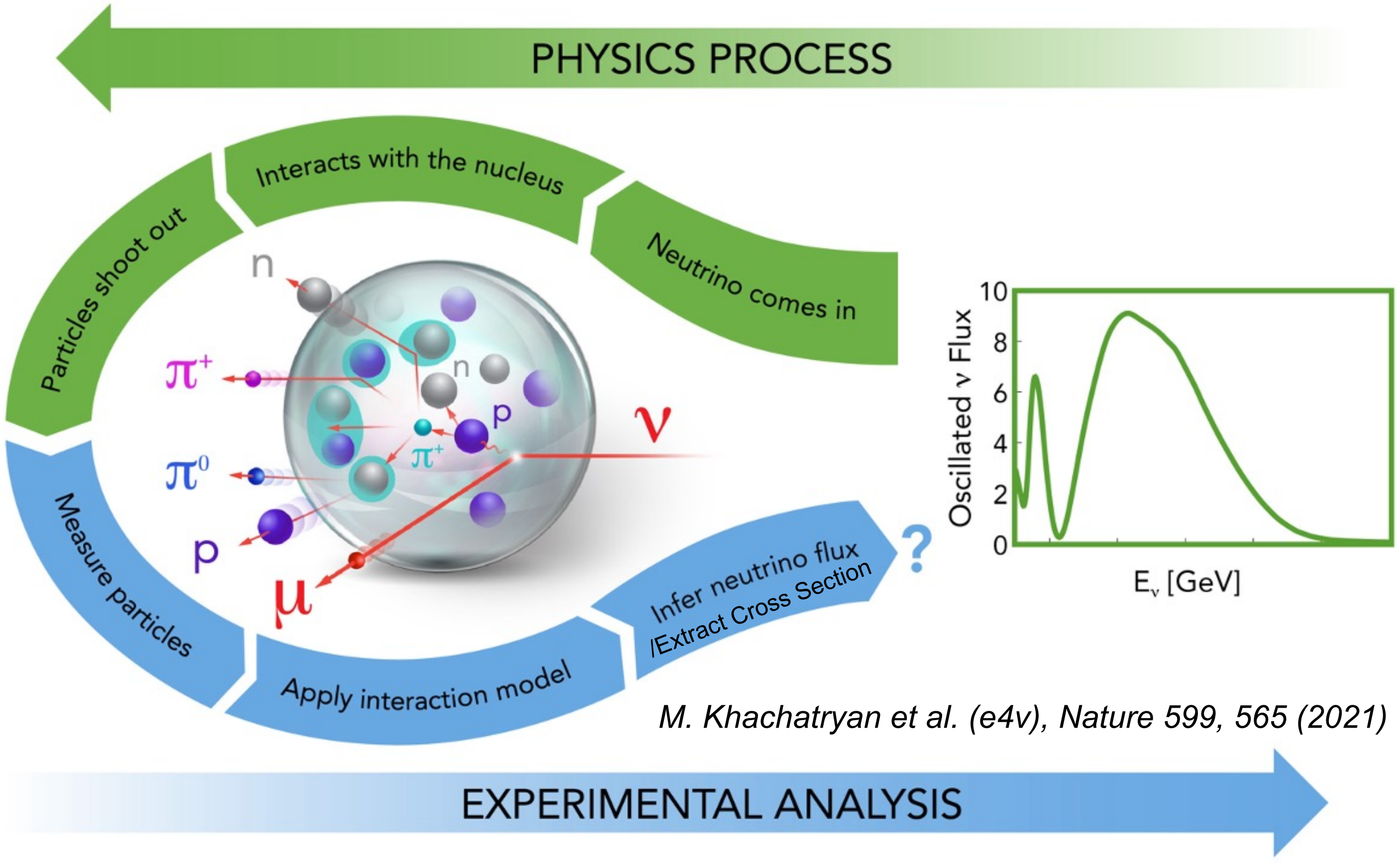
$|\Phi_0\rangle$: Initial state (e.g. ^{40}Ar ground state)

$|\Phi_f\rangle$: Final state (e.g. outgoing nucleons, pions, kaons, …)

Fermilab

- **Analysis happens left to right [Experimentalist's universe]**





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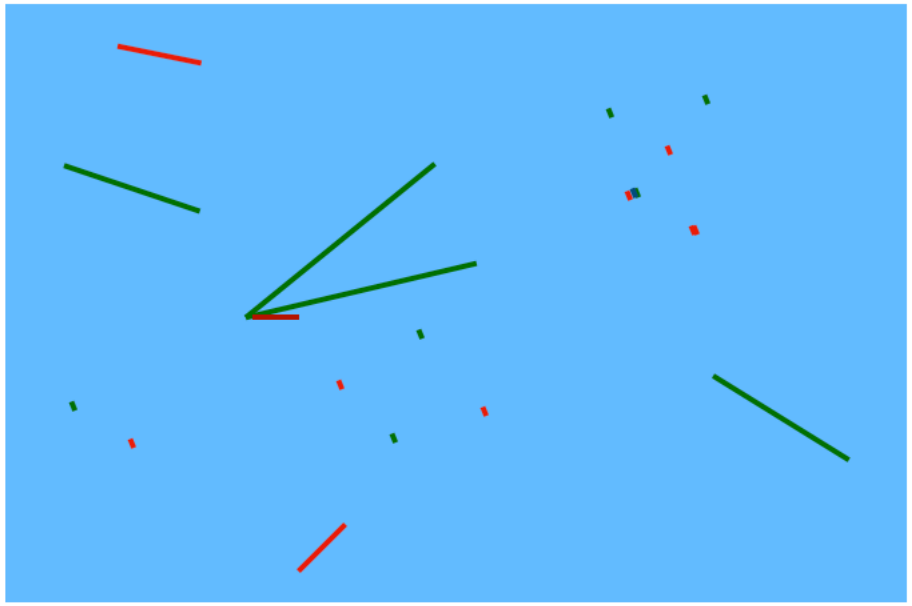

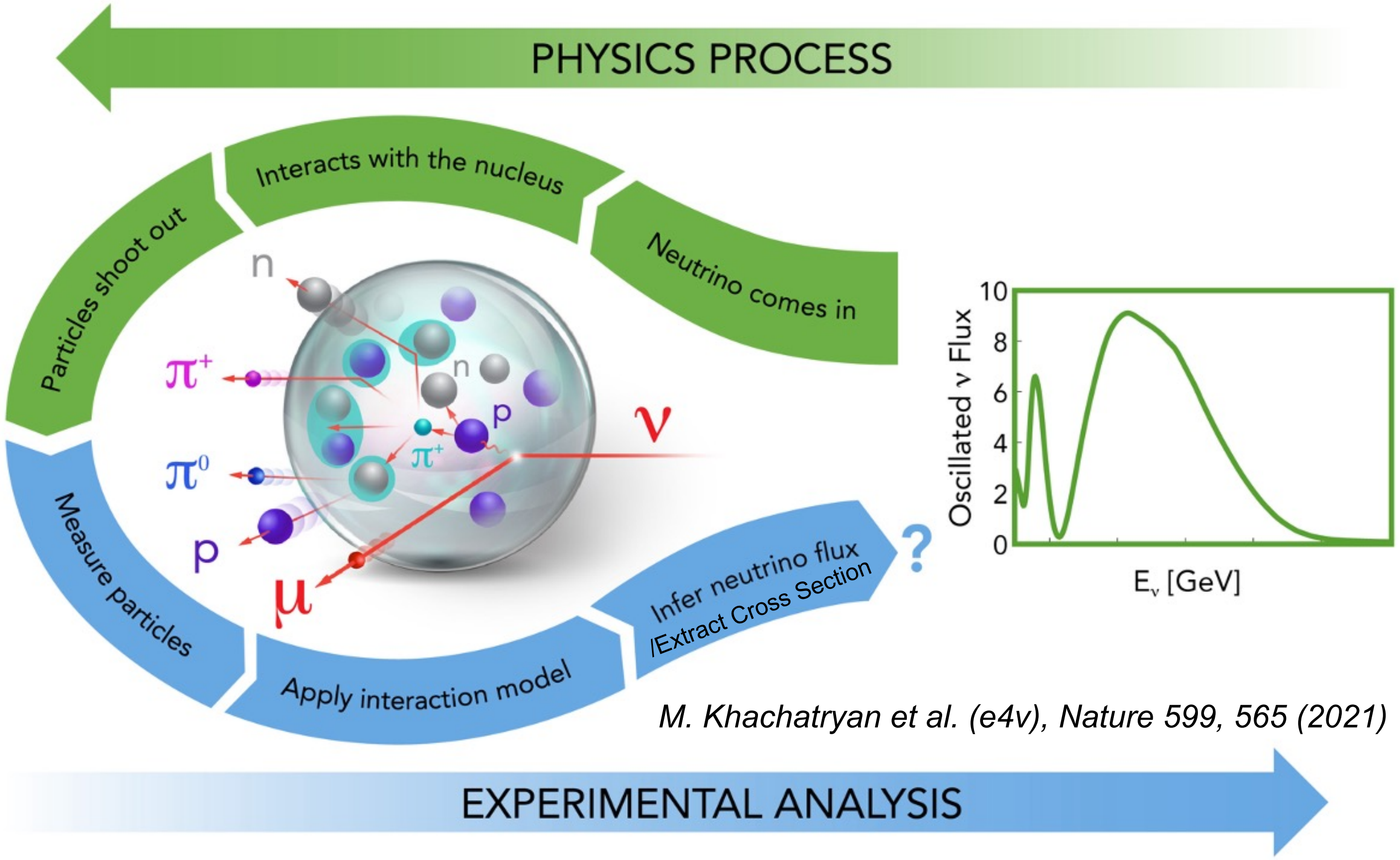

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- **Measure neutrino-nucleus cross section**
  - Define a signal/topology
  - Measure event rate
  - Extract Cross section in some observables x,

$$\frac{d\sigma}{dx_i} \propto \frac{\sum_j U_{ij}\,(N_j - B_j)}{\Phi_\nu\ T\ \epsilon_i\ \Delta x_i}$$

N: signal events, B: Background events, U: unfolding method
Φ: flux, T: number of targets, ϵ: efficiency

Neutrino-Nucleus Cross Sections: Theory and Experiment

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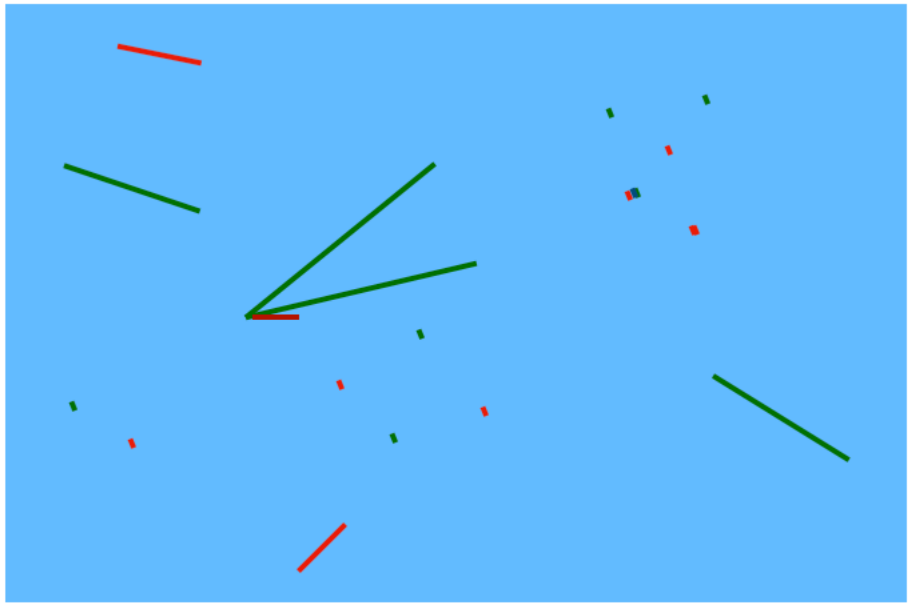

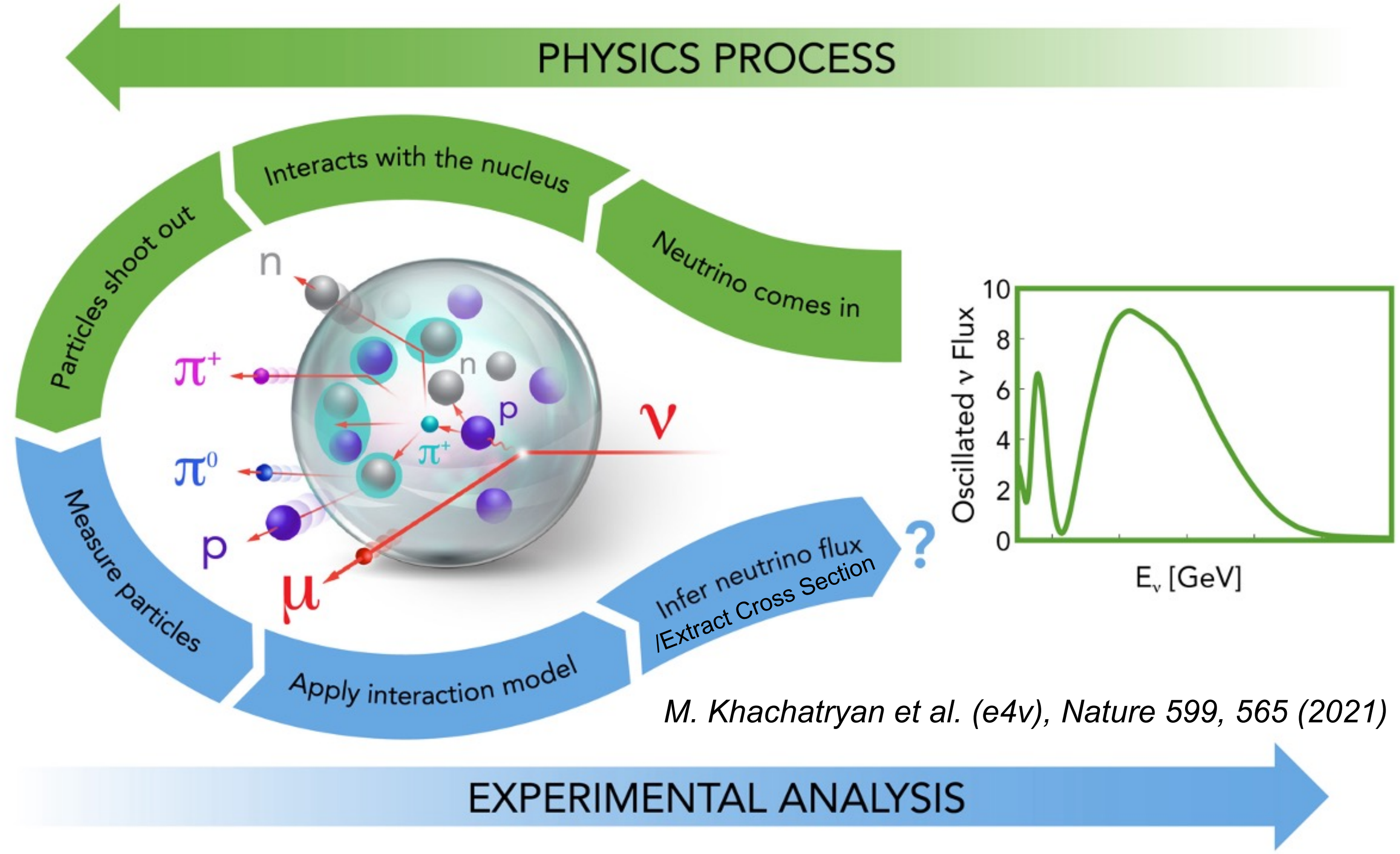

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- Primary source of uncertainty in cross section measurements:

  - <u>Flux Uncertainty</u>: all experiments are working on improving those using external hadron production data (past data and new data from NA61, EMPHATIC, etc.)

  - <u>Detector Systematics</u>: all experiments are working hard on this, experiment/detector specific

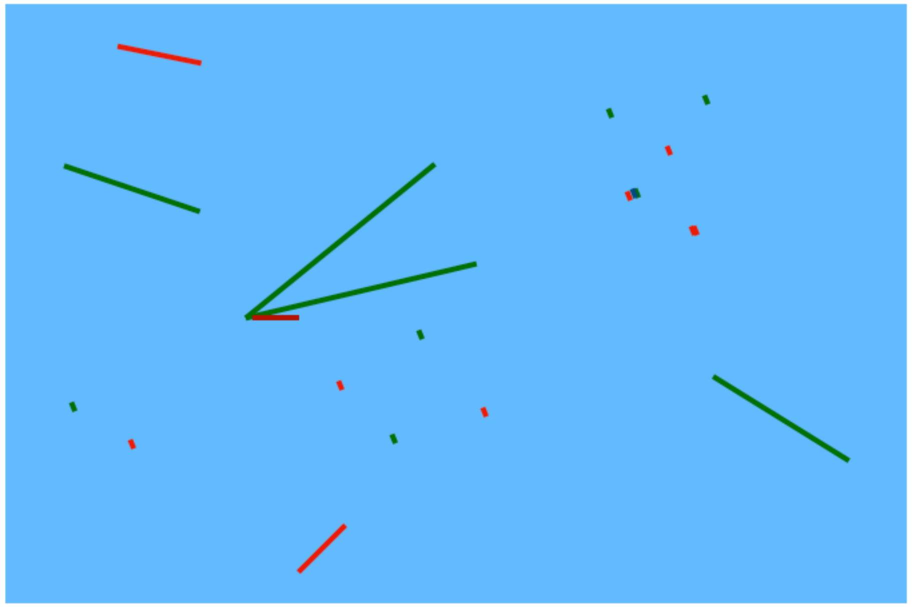
  - <u>Neutrino interaction uncertainties</u>: Let's talk about these!

Neutrino Interaction Uncertainties

- **Measure neutrino-nucleus cross section**
  - Extract Cross section in some observables x,

$$\frac{d\sigma}{dx_i} \propto \frac{\sum_j U_{ij}\,(N_j - B_j)}{\Phi_\nu\; T\; \epsilon_i\; \Delta x_i}$$

N: signal events, B: Background events, U: unfolding method
Φ: flux, T: number of targets, ϵ: efficiency



- **<u>Neutrino interaction uncertainties</u>:**
  - If x is not your direct observable (e.g. if its not p_μ or something), i.e. if you are building a non-observable variable like E_ν: then you are introducing some kind of model dependence.
  - If you are subtracting your background (B) using MC: then you are introducing some kind of model dependence.
  - Your efficiencies, purity, as well as unfolding methods couples to neutrino interaction model in a non-trivial way.
  - These are included using some reweighing tools, some generator (GENIE, NEUT, etc.) have their reweighing method and some experiments develop their reweighing tools (T2K, NOvA, etc.).

✦ None of our event generators (and models) predict the signal region well, but we need to trust them to predict the background (that often could be more complicated than signal), etc.

✦ Are we measuring what we want to measure?

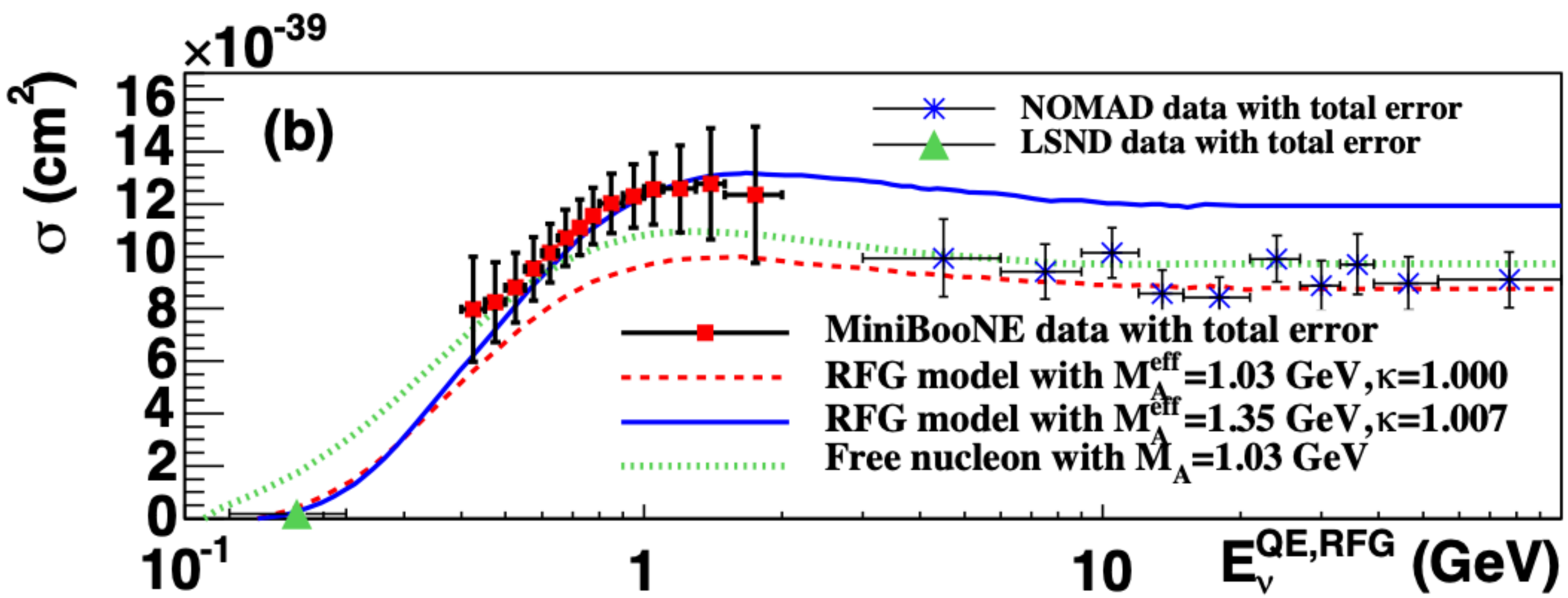
Deconstructing MiniBooNE CCQE-like Measurement

- Let's revisit the other MiniBooNE anomaly, "axial dipole mass anomaly"
  - MiniBonNE CCQE-like/CC 0pi measurement:

    Signal: 1 muon and no pion in the final state

  - Assuming a dipole form for the axial vector sector, with the world average value M_A = 1.014 ± 0.016 GeV in RFG-based model, the inclusive total and differential cross sections were underestimated.
  - Using a higher value of M_A = 1.35 ± 0.17, the RFG model can explain both the total and differential cross sections.

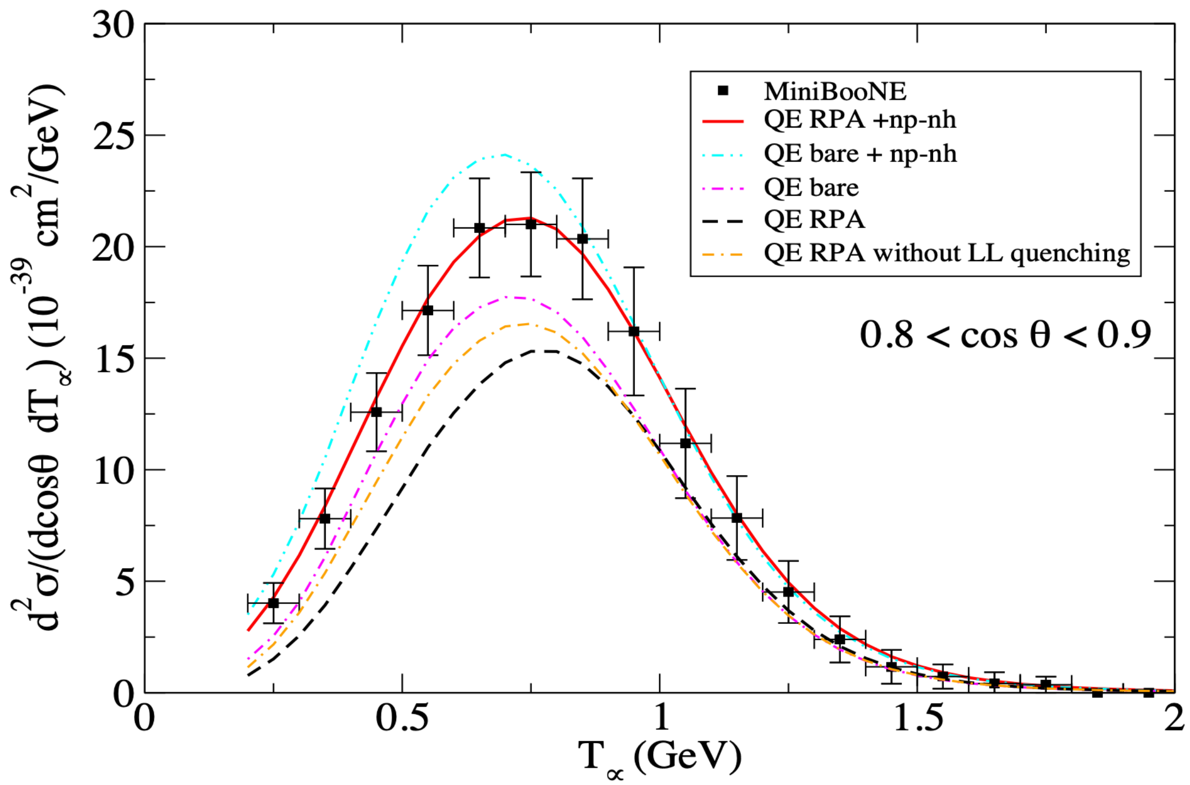
$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$



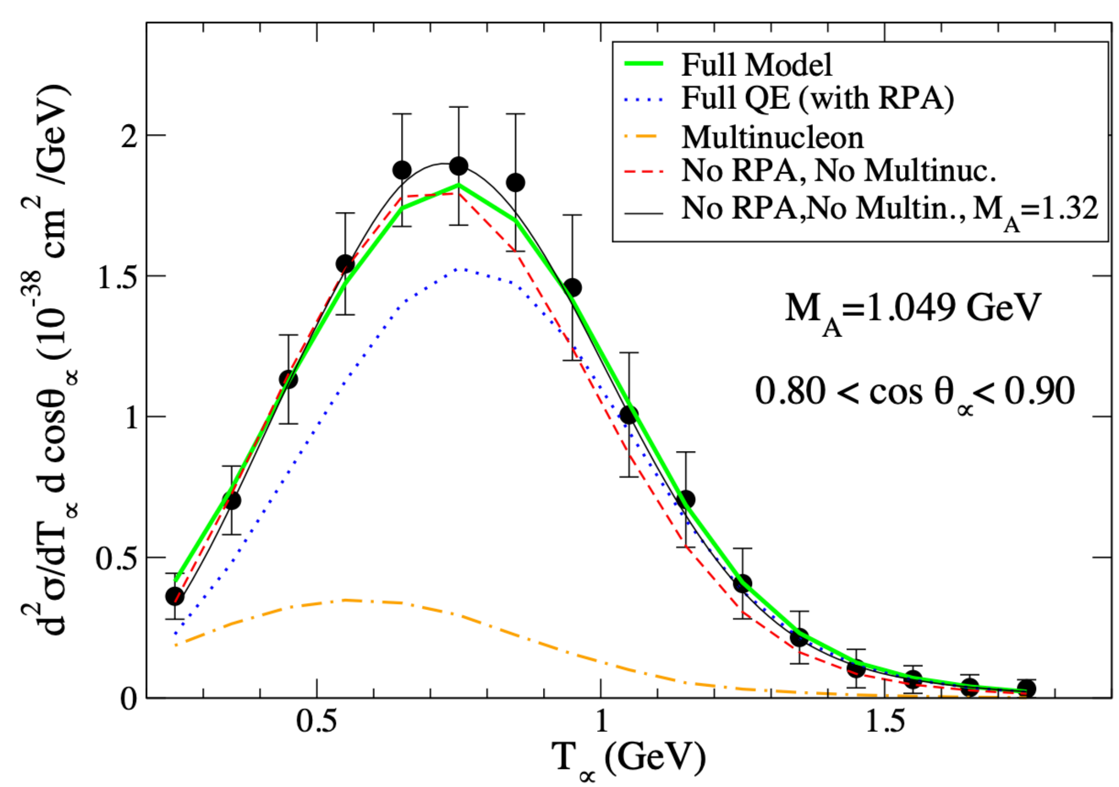
A. A. Aguilar-Arevalo, et al., Phys. Rev. D 81 (2010) 092005.

Deconstructing MiniBooNE CCQE-like Measurement

- Let's revisit the other MiniBooNE anomaly, "axial dipole mass anomaly"
  - MiniBonNE CCQE-like/CC 0pi measurement:
    Signal: 1 muon no pion in the final state
  - Martini et al. and then Nieves et al. could reproduced MiniBooNE cross section quite well with the world average axial mass, when 2p − 2h as well as the pion reabsorption effects were taken into account.
  - Turns out MiniBooNE signal could include: multi-nucleons in the final state (popularly known as 2p-2h) and neutrino induced pions that are reabsorbed in the nucleus due to final state interactions (FSI).



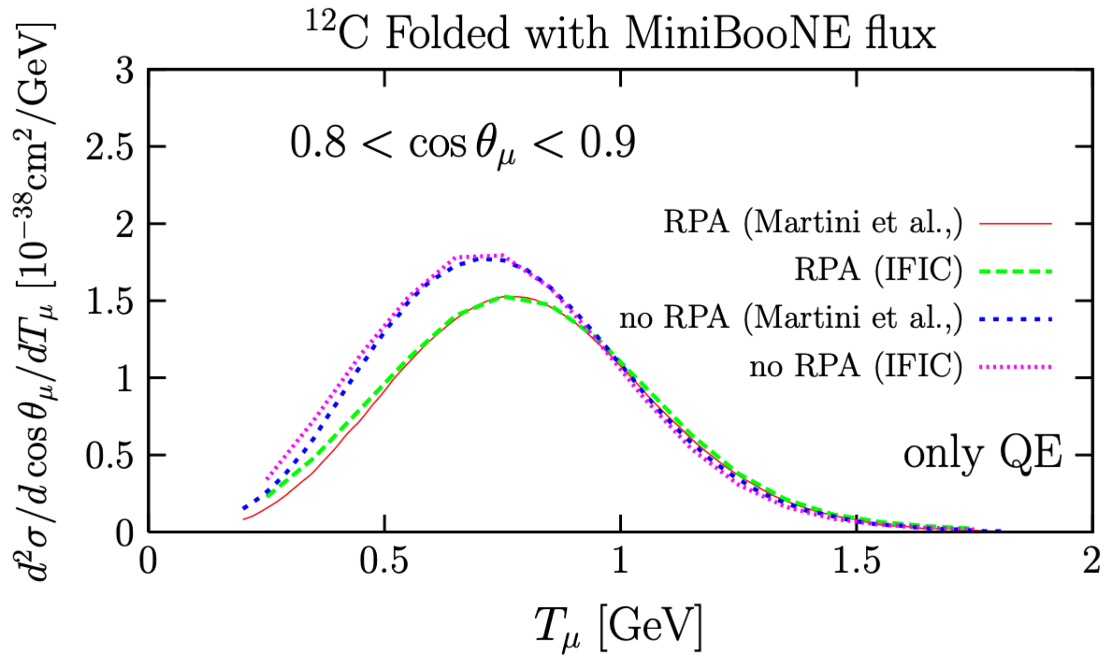
M. Martini, M. Ericson, G. Chanfray, Phys. Rev. C 84 (2011) 055502.

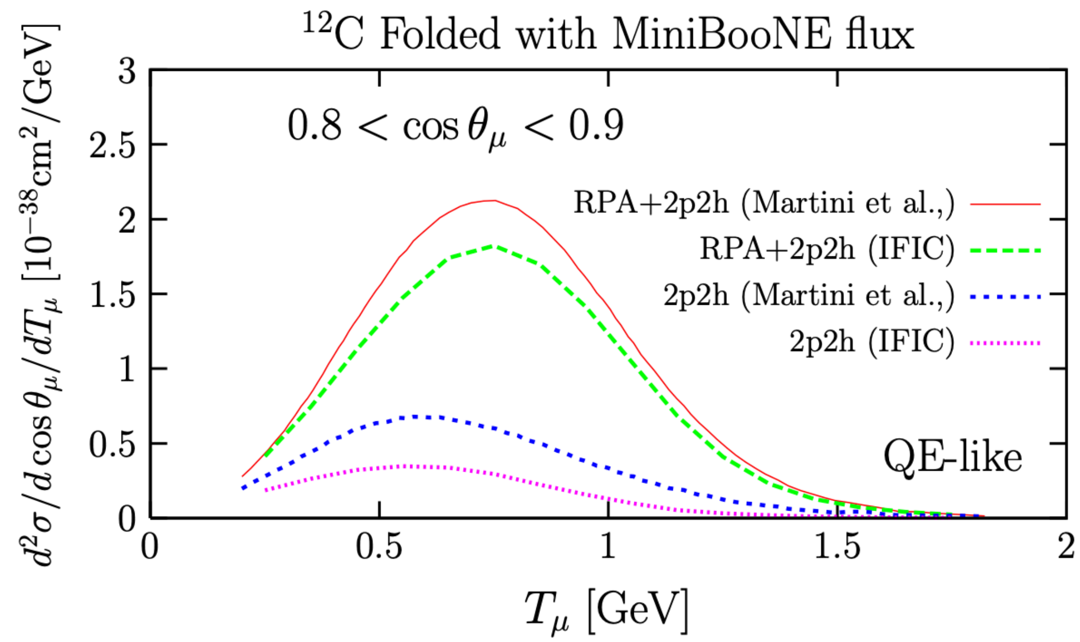


J. Nieves, I. Ruiz Simo, M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501.

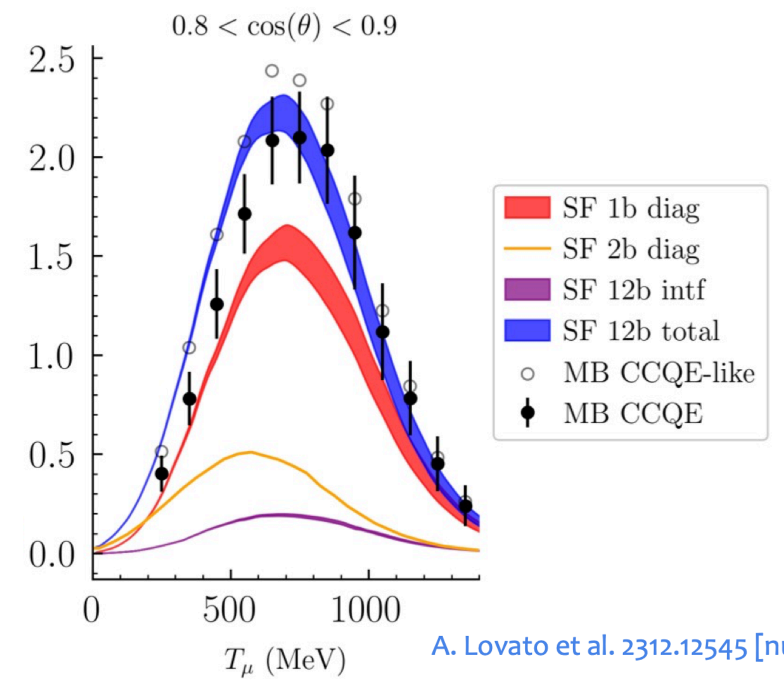
Deconstructing MiniBooNE CCQE-like Measurement

- However when you compare Martini et al. and Nieves et al. results
  - They compare well for bare QE and QE+RPA
  - But their 2p2h contribution is about a factor of 2 different





  - There is also one and two-body interference term that contributes to the signal



A. Lovato et al. 2312.12545 [nucl-th]

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Deconstructing MiniBooNE CCQE-like Measurement

- MiniBooNE's observed CCQE-like (1 muon and no pion) cross section included contribution from:

  - One-body current producing single nucleon knockout

  - Two-body current producing single and two nucleon knockout

  - One and two-body interference producing primarily single nucleon knockout

  - Delta current producing two nucleon knock out

  All of these should be taken into account in a consistent way in order to avoid double counting.

- But wait there is more …

Deconstructing MiniBooNE CCQE-like Measurement

- Enters LQCD description of axial form factor
  - **Axial Form Factor**

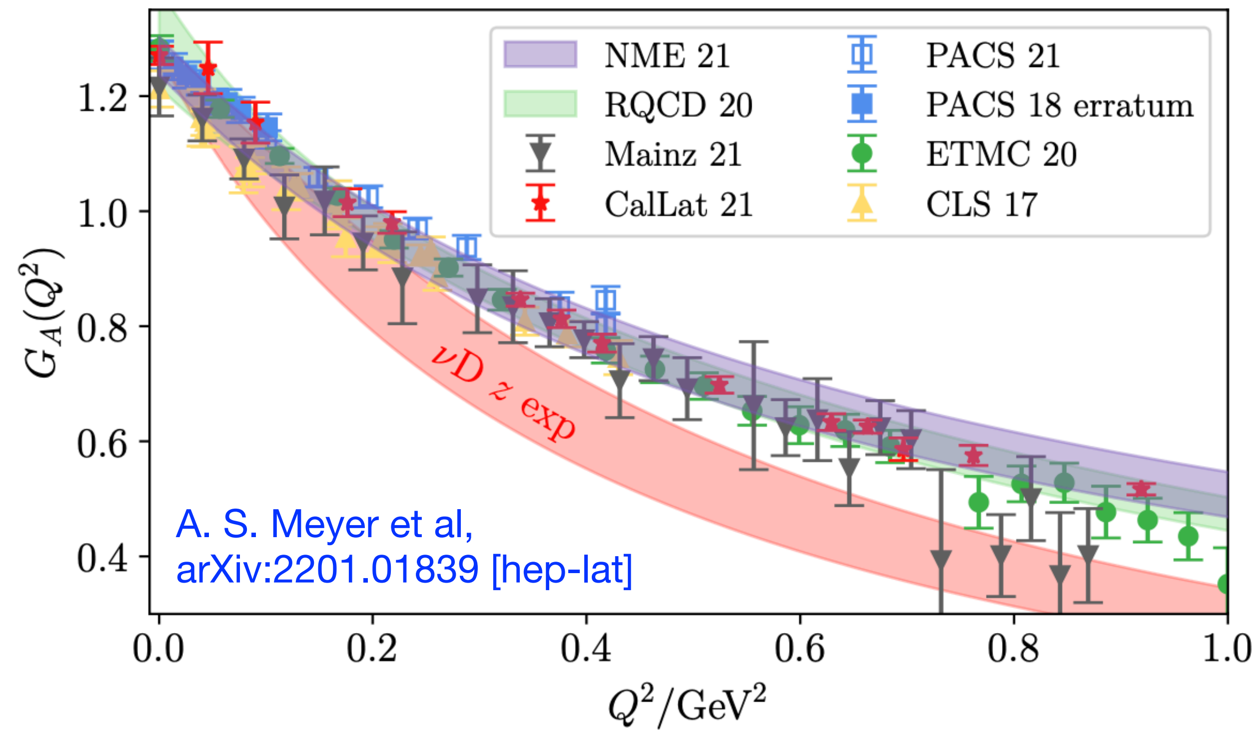
    - Historically parameterized as dipole form:

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

    - Modern description based on model independent z-expansion (only assumes basic field theory/ QCD properties)

$$F_A(Q^2) \approx \sum_{k=0}^{k_{\max}} a_k\, z(Q^2)^k \qquad \sum_{k=0}^{k_{\max}} a_k z(0)^k = g_A$$

    - LQCD form factor result higher at Q^2 > 0.3 GeV^2



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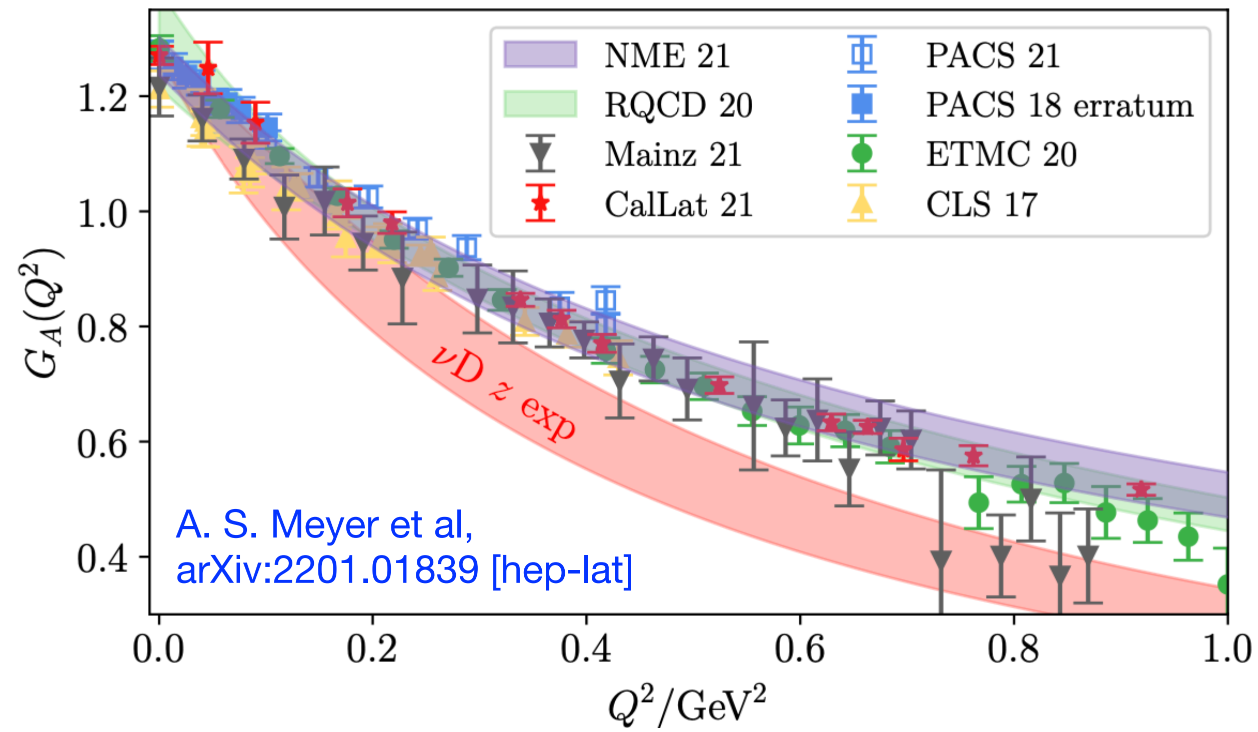
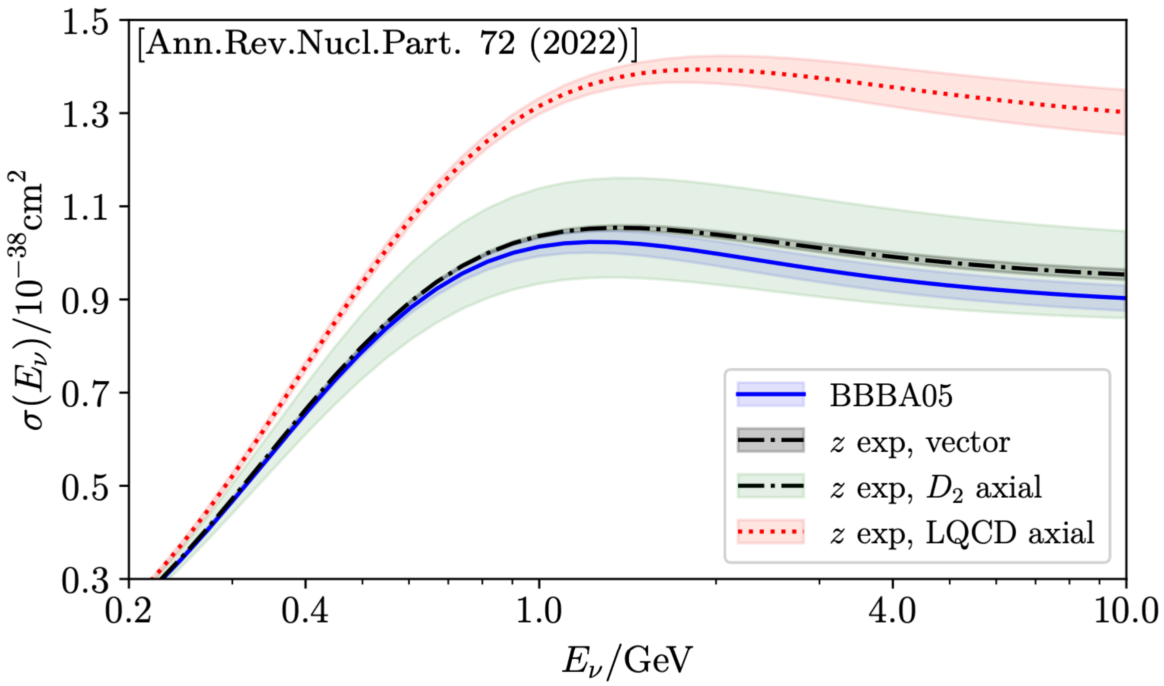
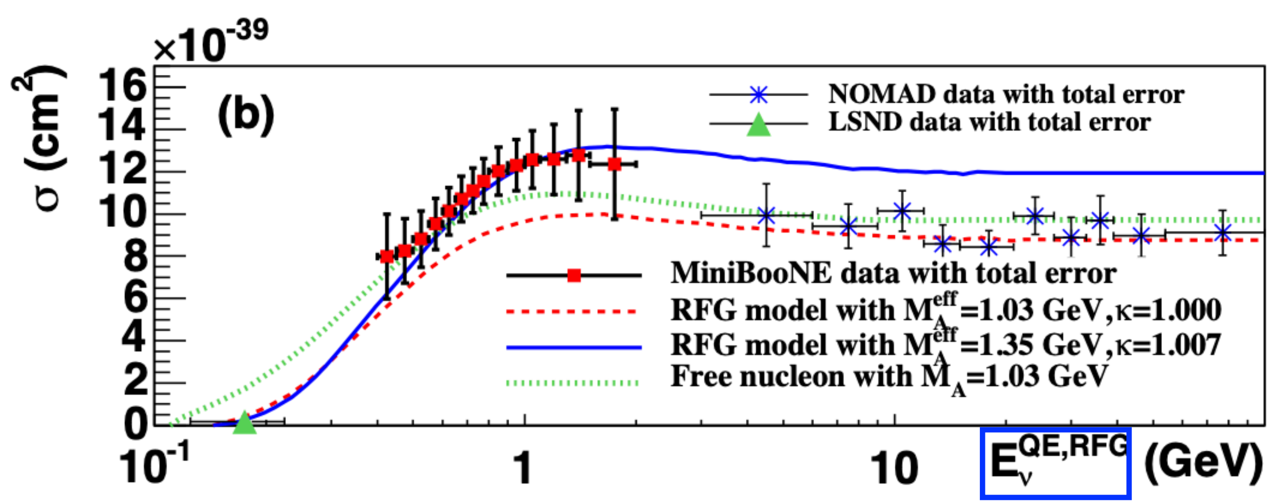
    - LQCD form factor result higher at Q^2 > 0.3 GeV^2
  - With LQCD Form Factor there is 30-40% enhancement to ν_μ CCQE cross section
  - Can not compare with model-dependent MiniBooNE measurement.







Deconstructing MiniBooNE CCQE-like Measurement

- We are (may be) starting to get a more clear picture of what actually contributes to MiniBooNE ν_μCCQE-like measurement.

- It requires tackling degeneracy between nucleon-level uncertainties and nuclear effects (interplay of one- and two-body current, pion absorption, …).

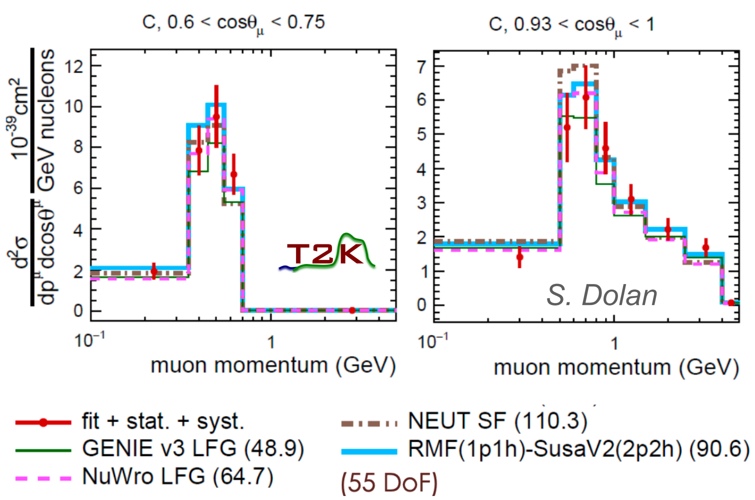
- LQCD is able to provide nucleon level form factors with complete error budgets and with few-percent precision, we should all be using it now.
  See Aaron Meyer's talk on Friday

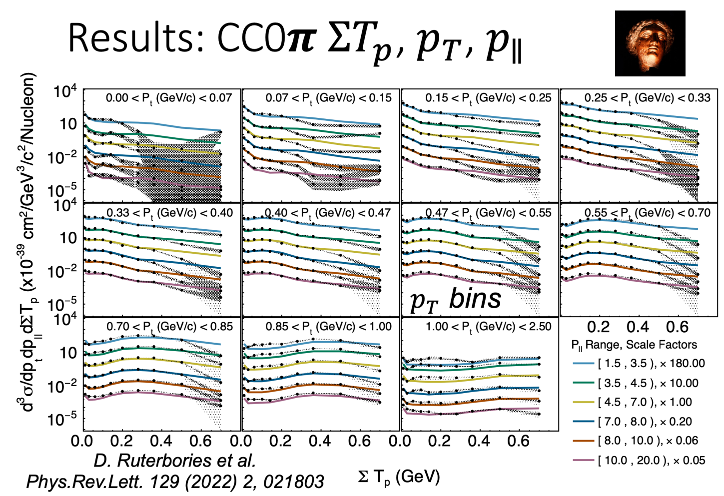
✦ If your model or event generator is tuned to MicroBooNE data, you need to be careful in inserting the LQCD form factor. You need to figure out how to disentangle axial form factor from nuclear effects in your existing model.

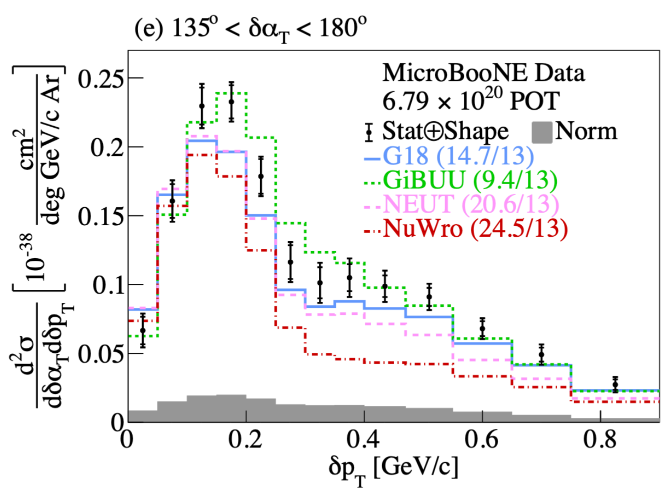
Measurements in High-Statistics Era

- The statistics and sophistication of neutrino-nucleus scattering data is expanding at an accelerating rate every year.
- Experiments and generators are also tuning MC in increasingly sophisticated ways.
- Great that it became norm to compare data to multiple generators but not sure how to draw any physics conclusion.

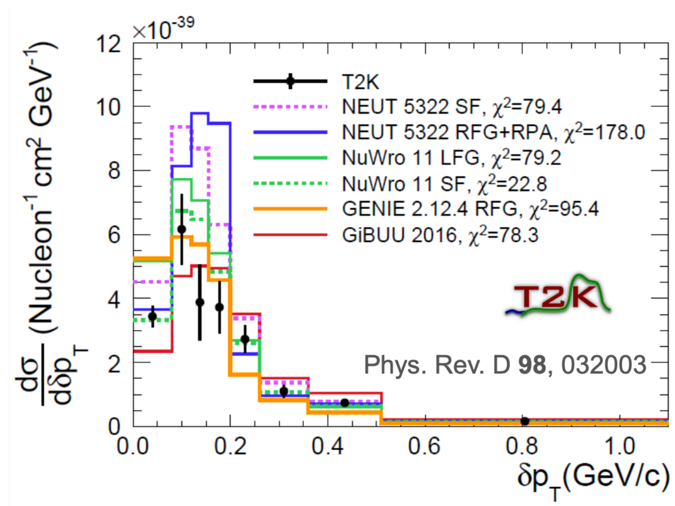
✦ We need to leverage high-statics to perform clean and precise measurements, make them accessible to theorists, in order to truly constrain underlying neutrino-nucleus cross section physics.







arXiv:2301.03700 [hep-ex]



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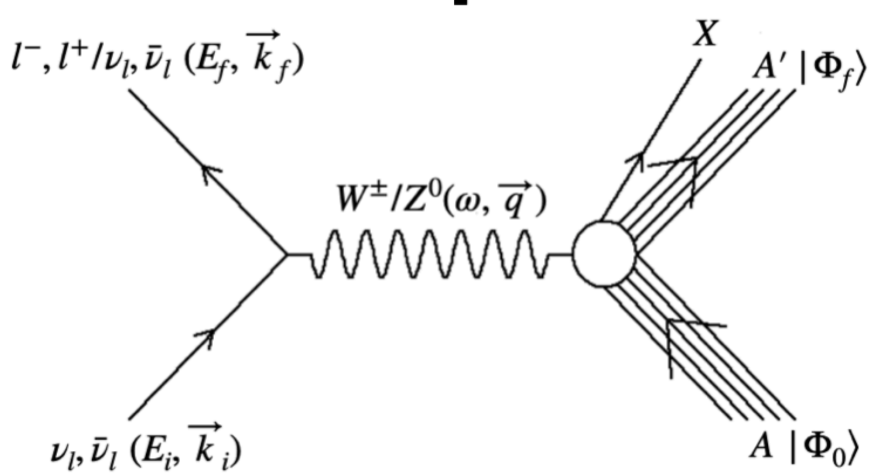
✦ This is achievable only with an iterative process between the two universes - at the end, its the same universe!

■ **Physics happens right to left [Theorist's universe]**

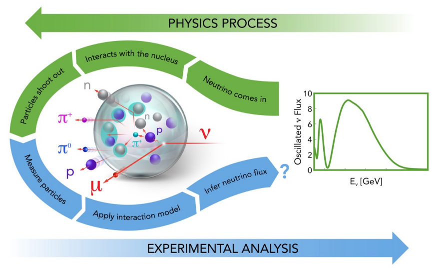


- Scattering Kinematics:

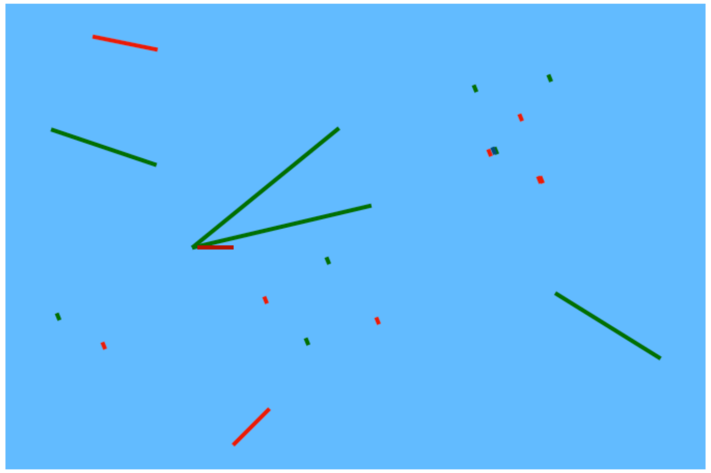
$$\omega = E_i - E_f, \quad q = |\vec{k}_i - \vec{k}_f|, \quad Q^2 = q^2 - \omega^2$$

■ **Calculate neutrino-nucleus cross section**

$$d\sigma \propto \sum_{fi} |\mathcal{M}|^2 \propto \frac{G_F^2}{2} L_{\mu\nu} W^{\mu\nu}$$



■ **Analysis happens left to right [Experimentalist's universe]**



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High-Statistics to High-Precision Era

✦ We need to make measurements more accessible.

- The threshold for comparing data to theory is increasing, theorists need to make apples to apples comparison, we need that in order to make physics conclusion. Theorists need:

  - Flux that was assumed in the measurement (preferably with error bars)
  - Final state topology
  - Full selected kinematics phase space (min and max momentum of all selected particles)
  - Covariance matrix, smearing matrix, unfolding matrix: with guidelines on how and when to apply them
  - Cross section data points

- Some variable, E_had, E_vis_, E_cal, are not straight forward for theorist to estimate - a more clear description of how they are estimated (in a appendix)

- New measurements from the same experiment should be put in context with the previous measurements, not clear when a new measurement supersedes a previous one

✦ We need to work on making our measurements as model-independent as possible

- Best to report cross sections primarily in direct observables?

Please see, recent NuXTract 2023 Workshop

High-Statistics to High-Precision Era

✦ We need clear data preservation plans.

- Community should be able to re-analyze data now and in future.

✦ From theory side, we need guidance on uncertainty quantification and predictions on semi-inclusive/exclusive processes.

- At nucleon level, we can start to use LQCD form factors (QE now, hopefully more in future) that comes with complete error budgets.
- For each model, we need a clear documentation/guidelines of the approximations used and their validity in specific kinematics and for specific processes.
- Theorists need to provide what effects are not considered in a given model, or which important assumptions should be revisited.

Please see, recent NuXTract 2023 Workshop

Summary and Path Forward

- Lots of data is here and more is expected in the next few years, need to think how to constructively improve the underlying physics.
- We need to leverage high-statics to perform clean and precise measurements, make them accessible to theorists, in order to truly constrain underlying neutrino-nucleus cross section physics.
- Need guidance from theorists on uncertainty quantification.
- Need to make data preservation plans which allow re-analysis.
- We need to make sure that we make high-statistics era into high-precision era! This NuInt is a great place to discuss constructively!

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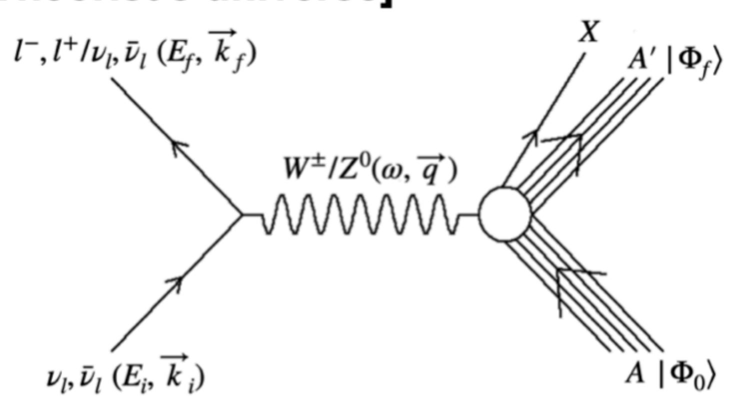

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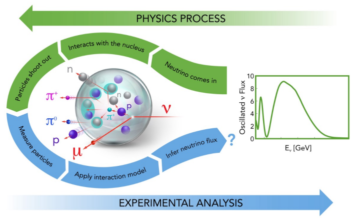

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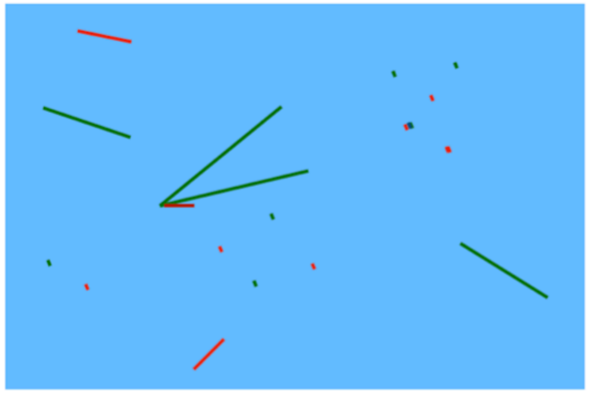

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