Experimental summary

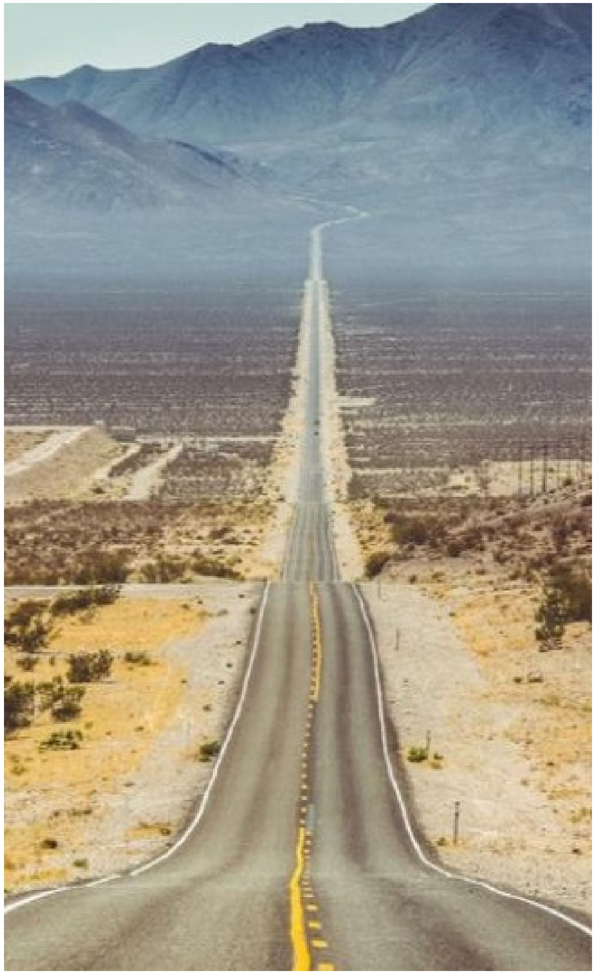
NuInt 2022, Seoul

29th October 2022

Callum Wilkinson

Outline

- Neutrino scattering measurement highlights
- Other highlights
- A word of caution
- Looking forwards
- What’s missing?



NuInt 2022: thought provoking discussion and scenery

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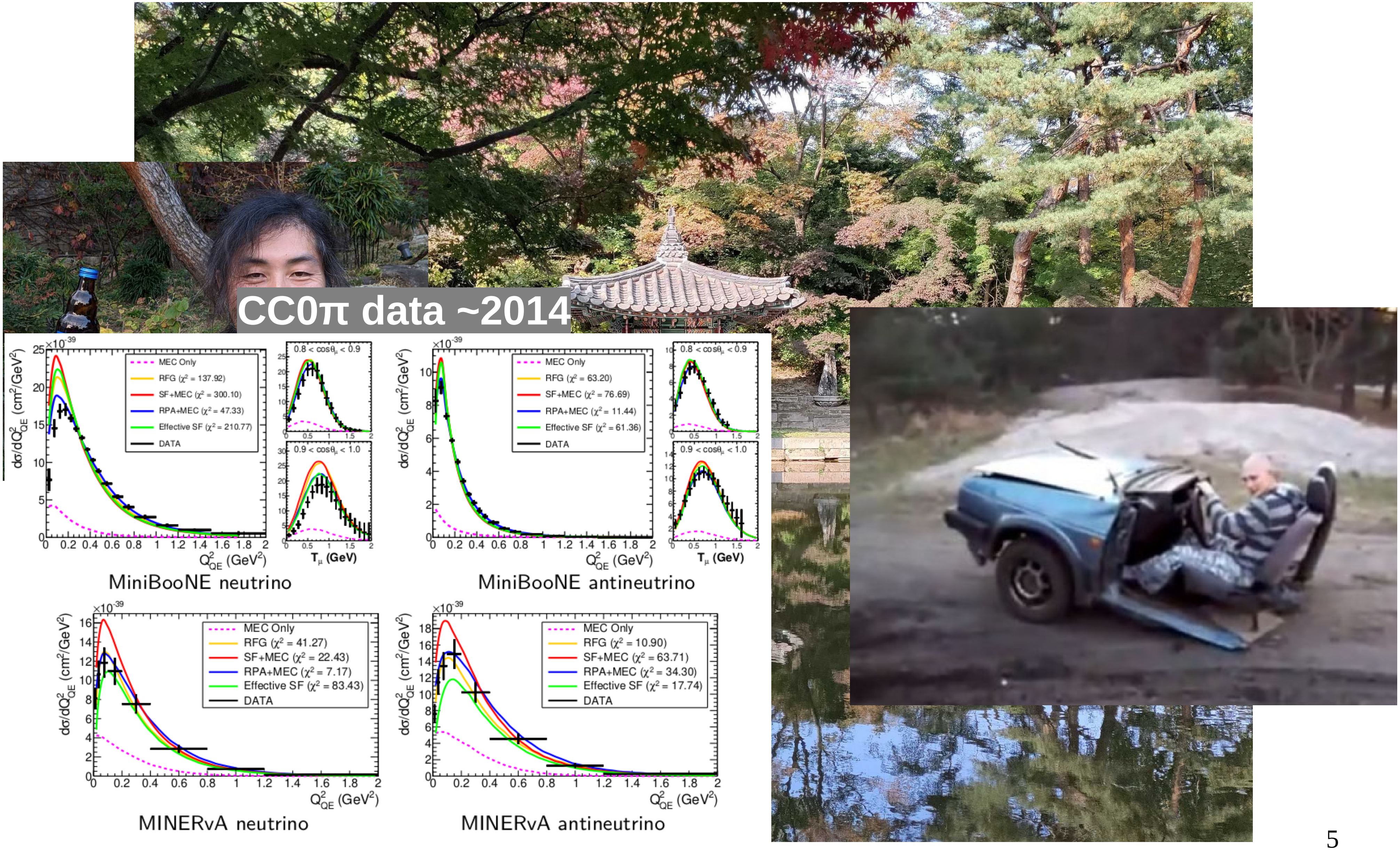


NuInt 2022: thought provoking discussion and scenery

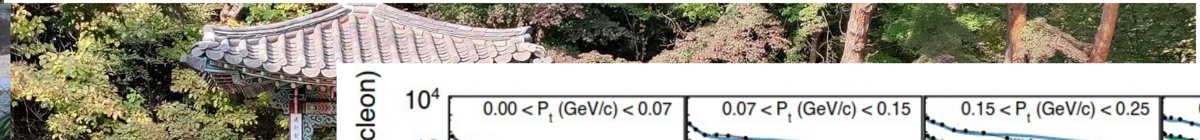
T2K cross-section publications (>20 articles in ≈ 10 years)

6 ν_μ or $\bar{\nu}_\mu$ CC inclusive
- PRD arXiv: 1302.4908
- PRD arXiv: 1801.05148
- PTEP arXiv: 1904.09611
- PRD arXiv: 1407.4256
- PRD arXiv: 1509.06940
- PRD arXiv: 1706.04257

3 ν_e or $\bar{\nu}_e$ CC inclusive
- PRL arXiv: 1407.7389
- PRD arXiv: 1503 .08815
- JHEP arXiv: 2002.11986

12 ν_μ or $\bar{\nu}_\mu$ CC0π
- PRD arXiv: 1602.03652
- PRD arXiv: 1708 .06771
- PRD arXiv: 1908.10249
- PRD arXiv: 2002.09323
- PRD arXiv: 2004.05434
- PRD arXiv: 1503.07452
- PRD arXiv: 1411.6264
- PRD arXiv: 1403.3140
- PRD arXiv: 1910.09439
- PRD arXiv: 1802.05078
- PRD arXiv: 2102.03346
- PTEP arXiv: 2004.13989

4 ν_μ or $\bar{\nu}_\mu$ CC1π
- PRD arXiv: 1605.07964
- PRL arXiv: 1604.04406
- PRD arXiv: 1909.03936
- PRD arXiv: 1704.07467



Wealth Of Results → Better Understanding of ν-Ar Interactions

CC inclusive
- ν_e CC inclusive @ NuMI (Wed.)
- ν_μ CC inclusive @ NuMI
- ν_μ CC inclusive @ BNB (Wed.)
- ν_e/ν_μ ratios @ NuMI
- E_ν, E_μ, hadronic energy @ NuMI & BNB

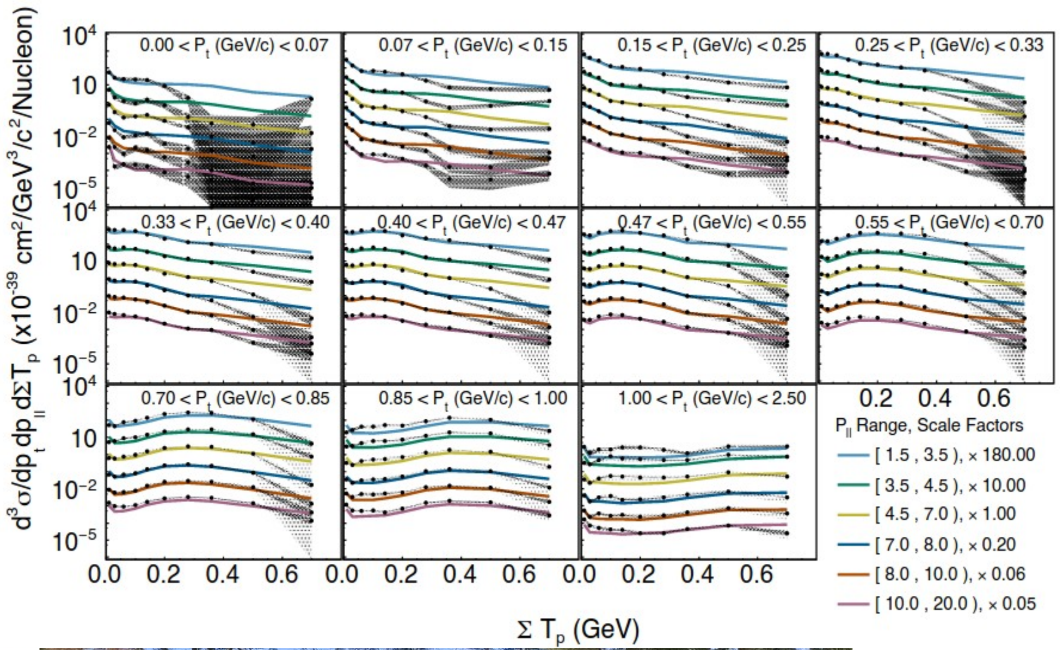
Much more coming from 30+ active analyses

Pion production
- ν_μ CC1π^+ @ BNB
- ν_μ CC-Coherent @ BNB
- ν_μ CCπ^0 @ BNB
- ν_μ NCπ^0 @ BNB (Fri.)
- ν_μ CC/NC π^0 @ BNB

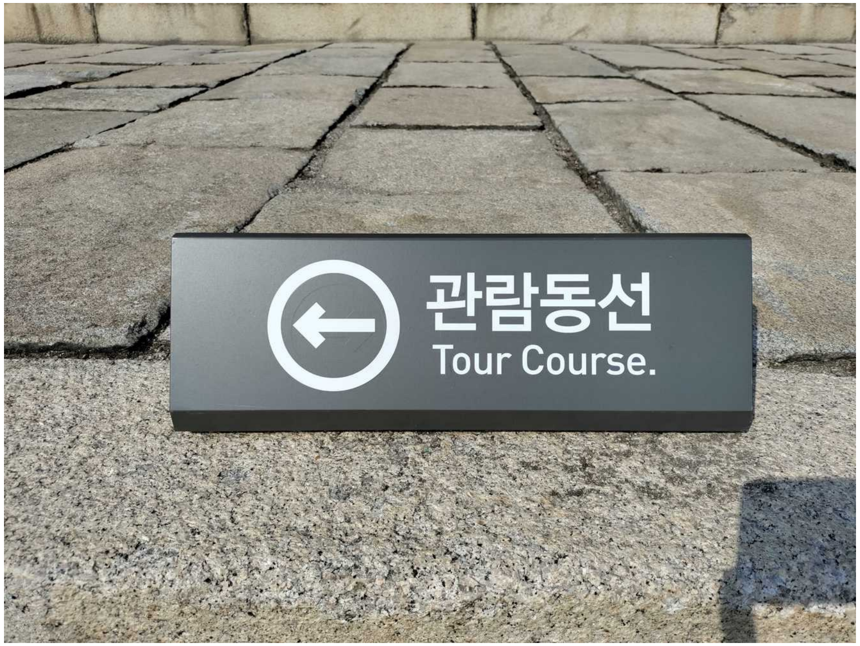
CC0π
- ν_μ Single Transverse Variables @ BNB (Wed
- ν_μ CC2p topologies @ BNB (Wed.)
- ν_μ CC0π inclusive @ BNB
- ν_μ CC0π0p @ BNB
- ν_e CC0πNp @ NuMI

μBooNE

Rare channels
- ν_μ CC Kaon @ BNB
- ν_μ CC Kaon @ NuMI
- η production @ BNB
- Hyperon (Λ,Σ) production @ NuMI (Fri.)
- MeV-scale Physics in MicroBooNE

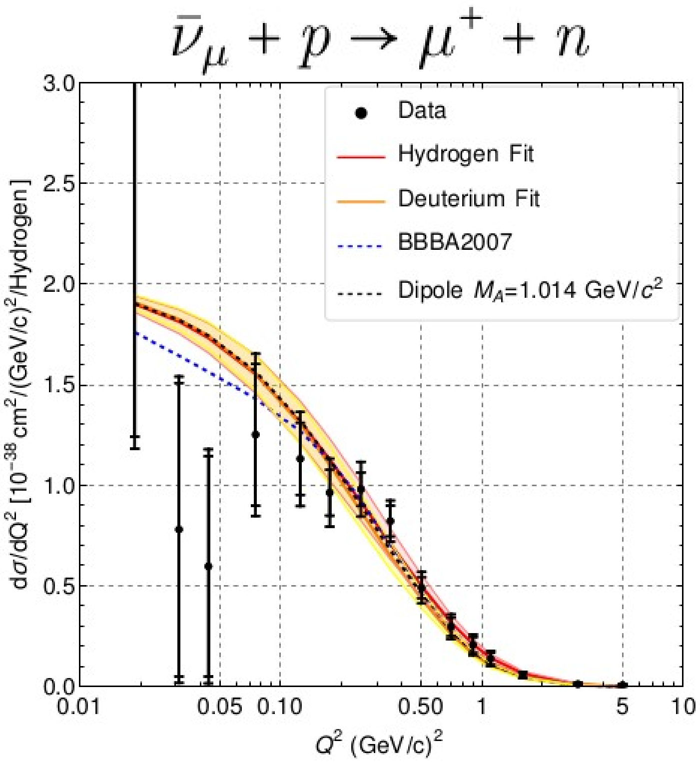


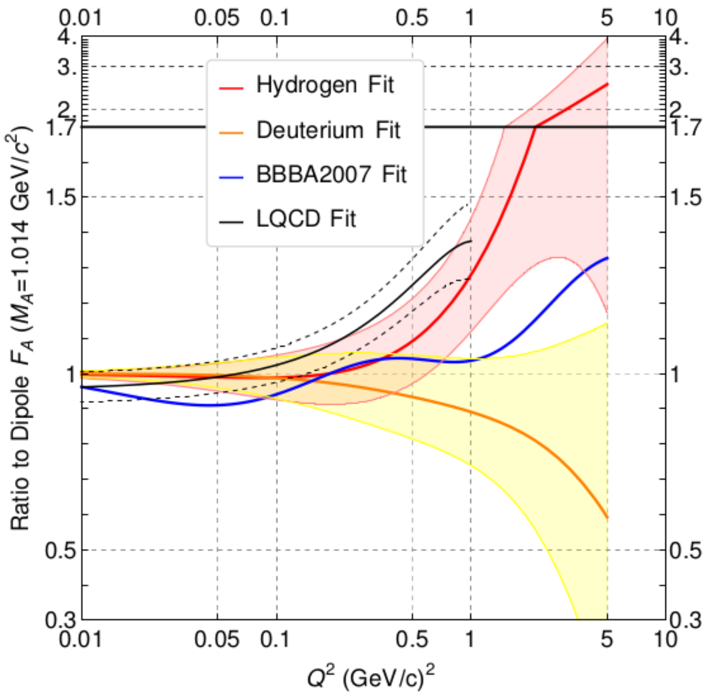
Neutrino scattering measurement highlights



MINERvA $\bar{\nu}_\mu$-H – Tejin Cai

- First new elementary target measurement since the 90's!
- Challenging neutron analysis, also important as proof of principle for future experiments
- Tension with older data and new theory results (LQCD) pose an interesting challenge for the community to solve



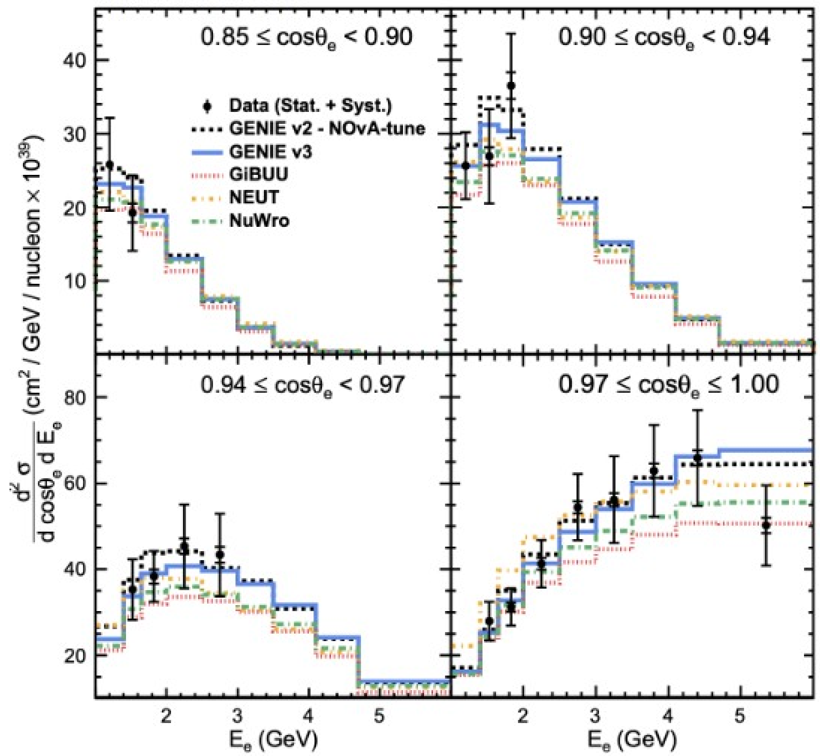


Electron neutrino cross sections

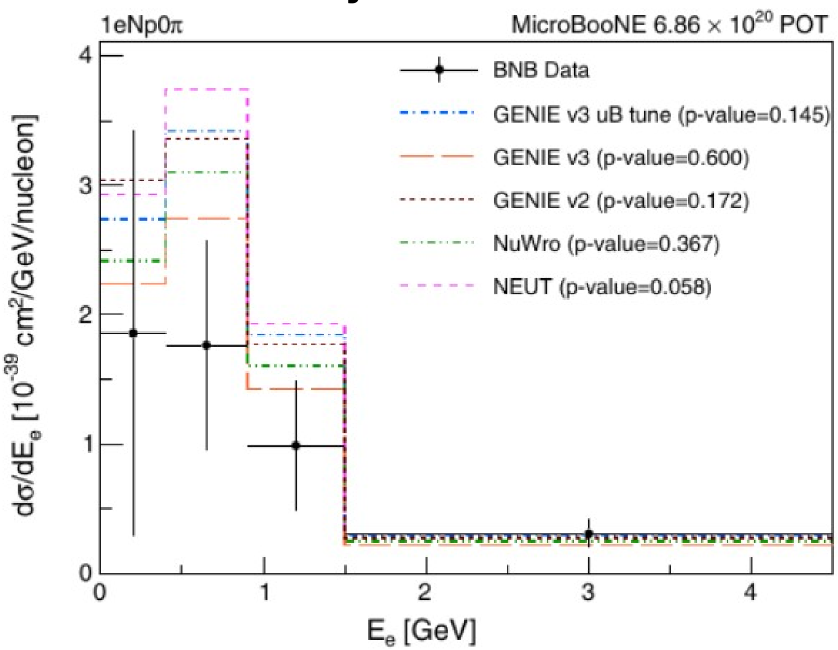
- Potentially vital tests of ν_e/ν_μ for oscillation measurements
- **NOvA:** double-differential(!) ν_e CC inclusive, $\bar{\nu}_e$ on the way!
- **MicroBooNE:** differential ν_e CC inclusive NuMI and ν_e CC0π BNB

arXiv:2206.10585

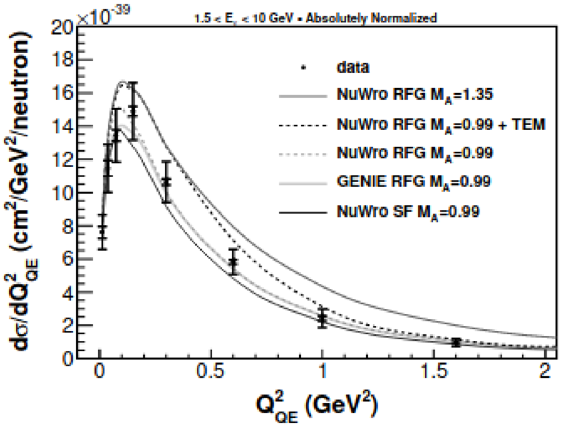
Derek Doyle



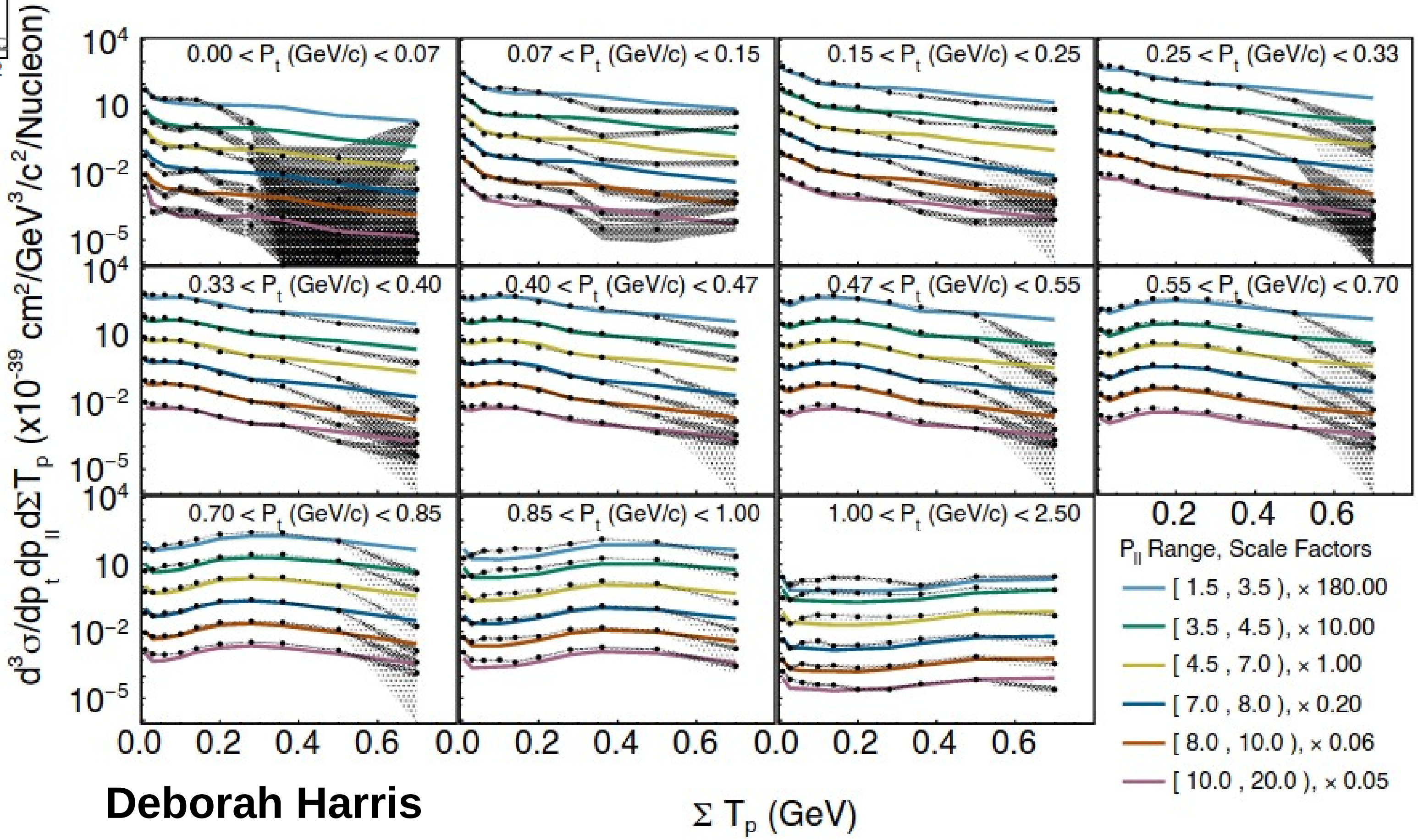
Andrej Szelc



MINERvA ν_μ C_8H_8 CC0π ($p_{||}$, p_T, ΣT_p)



A wealth of information about lepton/hadron correlations → hard to believe this is neutrino data!

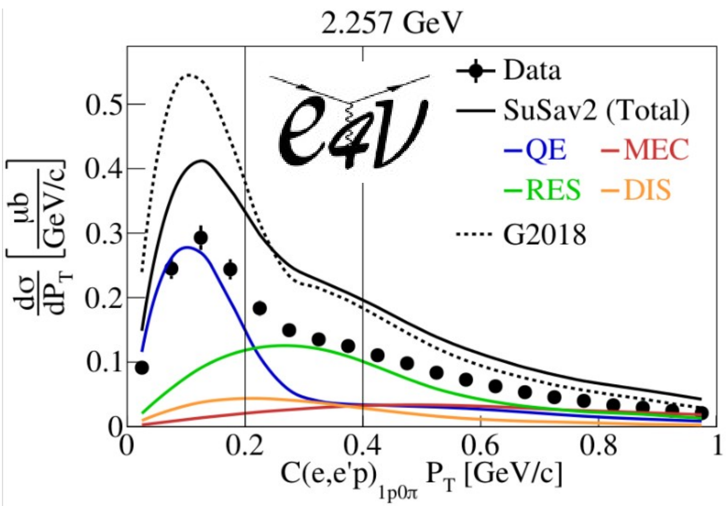


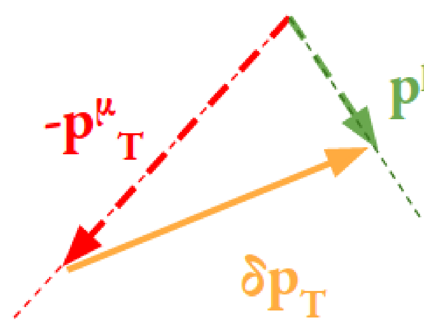
Deborah Harris

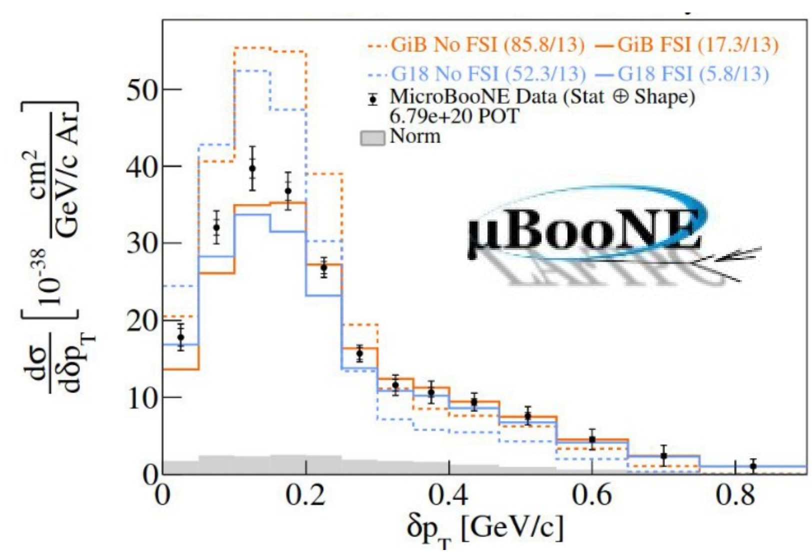
PRL 129 (2022) 2, 021803

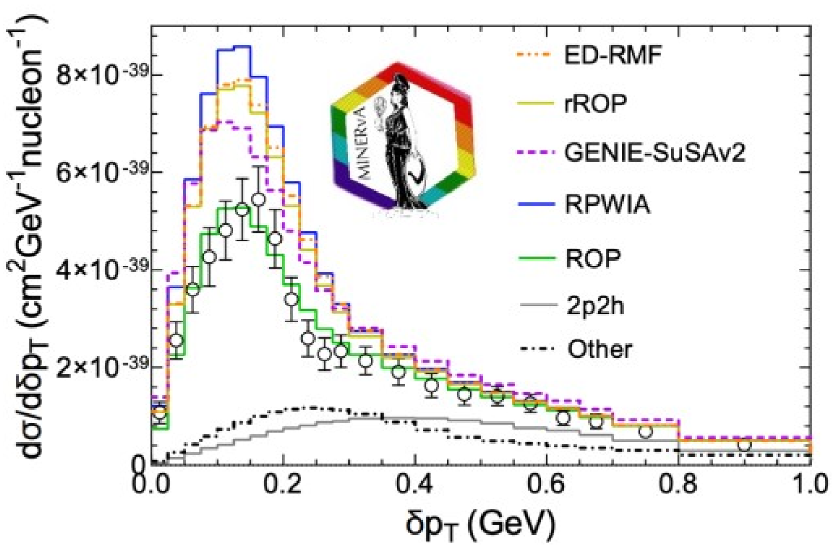
Lepton-hadron relationship across experiments

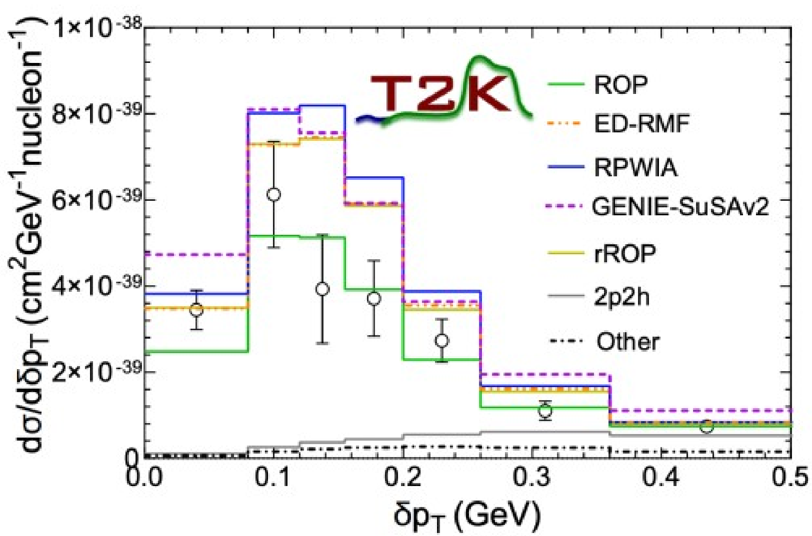
Also, first multi-differential TKI analysis from MicroBooNE!



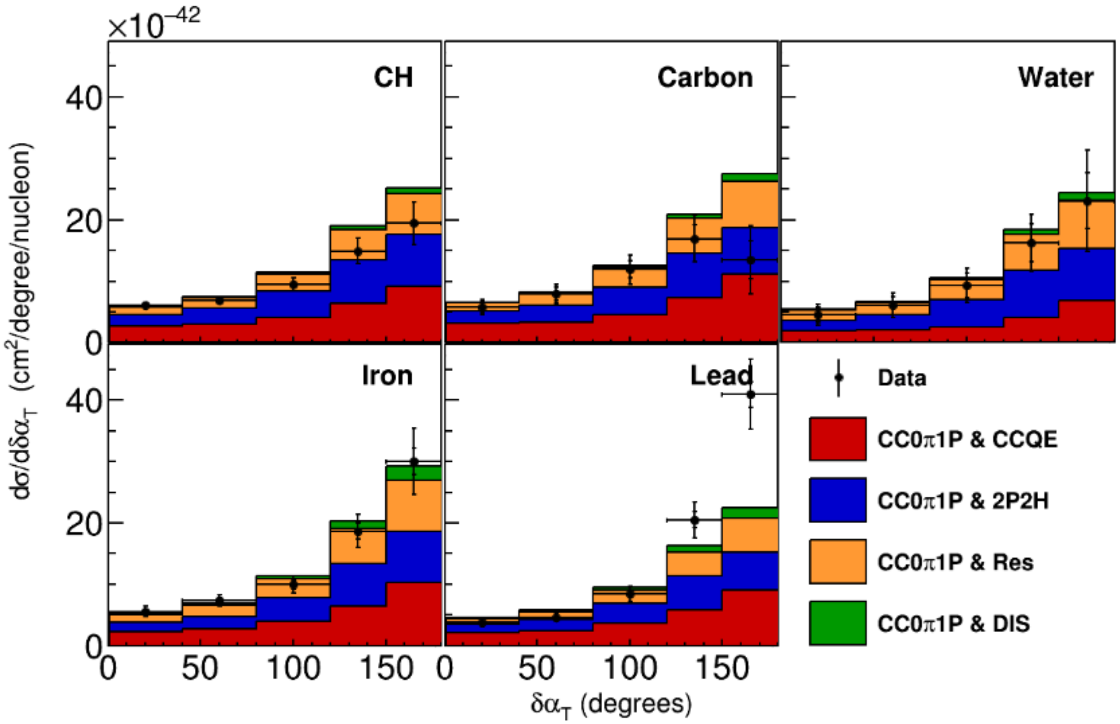


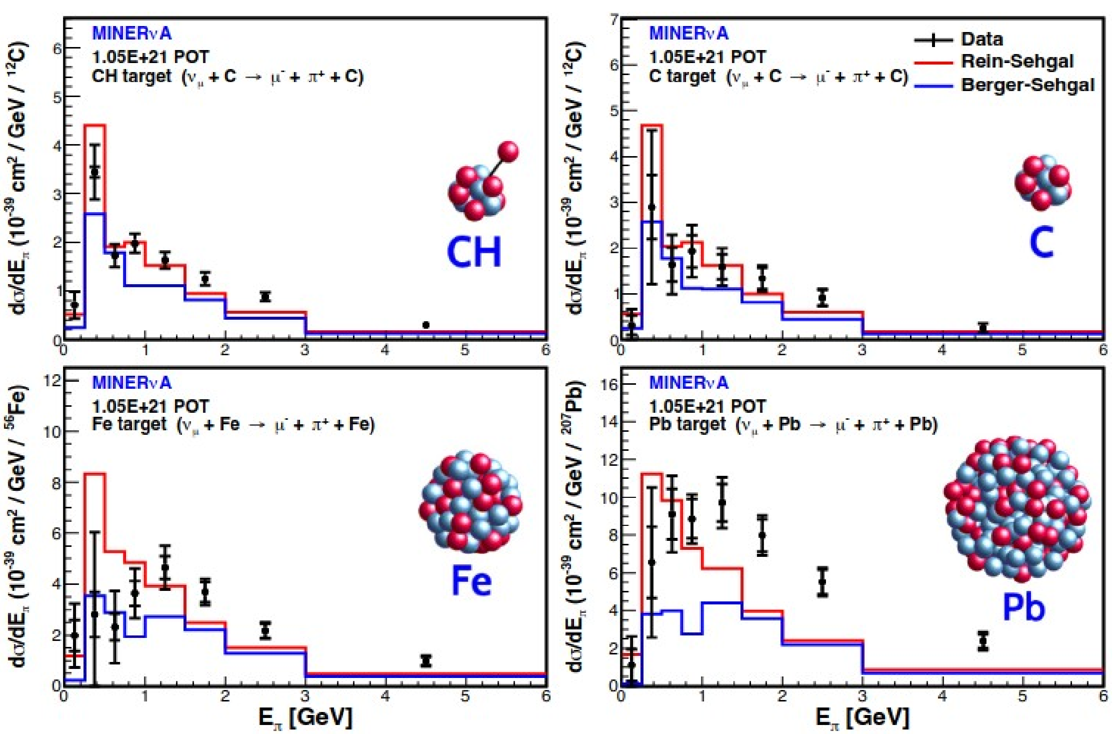






A-scaling



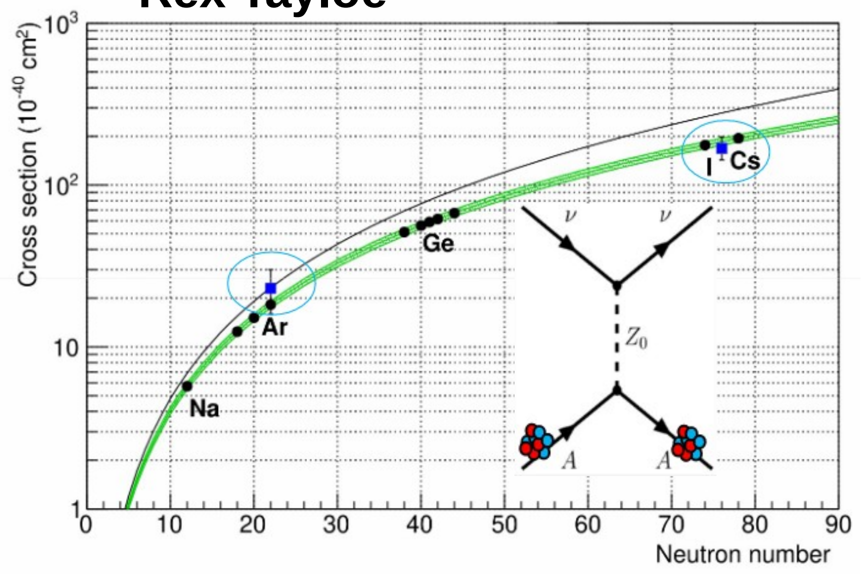


- A-scaling behaviour vital for LAr program as most data on hydrocarbons
- Significant new results from MINERvA exploring this
- TKI variables for different targets – Jeffrey Kleykamp
- Coherent pion production – Kevin McFarland

Less than a few-GeV neutrinos

- New measurement with LAr in CENNS-10 starts to explore the CEvNS A-scaling behaviour
- Exciting opportunities to use this tool to probe new physics
- Near future SNS plans and global reactor CEvNS effort underway!

Rex Tayloe



Dan Pershey

COHERENT CEvNS detectors

Target	Technology	Fid. Mass	Threshold	CEvNS?	Inelastics	First result
CsI[Na]	Scintillation	14.6	6.5 keV_{nr}	Yes		2017
Liquid Ar	Scintillation	24.4/610 kg	20 keV_{nr}	Yes	Yes	2020
Ge	Ionization	18 kg	0.4 keV_{ee}	Yes		
NaI[Tl]	Scintillation	3500 kg	13 keV_{nr}	Yes	Yes	
Pb	Scintillation	≈ 10 kg	100 keV_{ee}		Yes	2022
Th	Scintillation	TBD	TBD		Yes	
D2O	Chernkov	600 kg	TBD		Yes	

New for 2022!

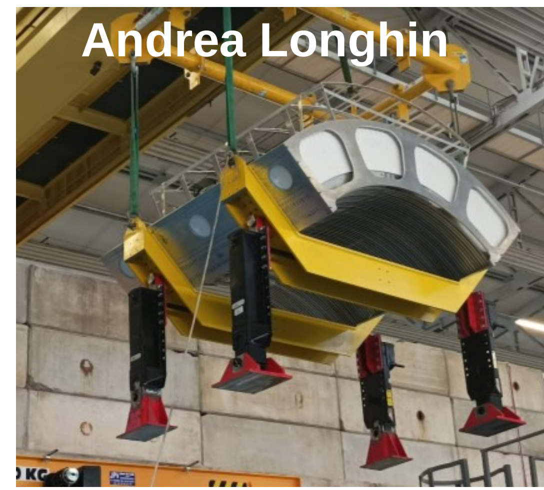
Other highlights

Flux measurements

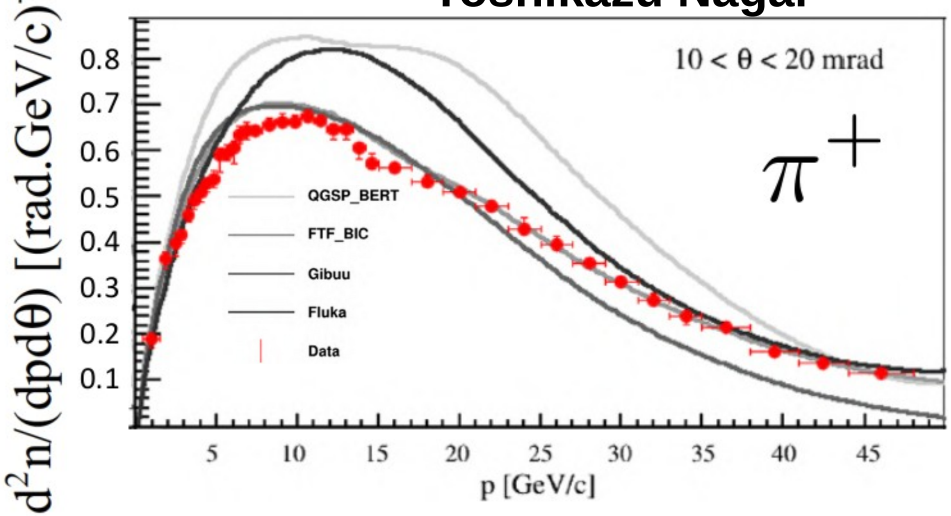
Flux uncertainties critical for precision XSEC or oscillation measurements

$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

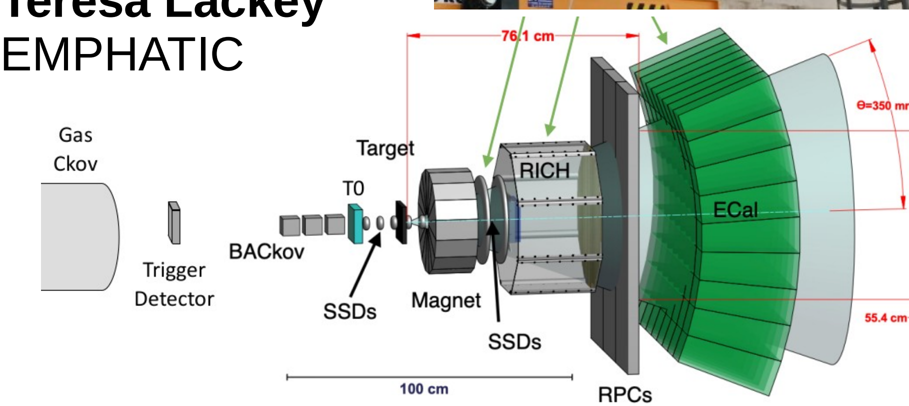
- Ongoing hadron-production efforts can deliver ~5% flux uncertainties through replica target efforts
- ENUBET concept reaching maturation → a potential path to ~1% uncertainties



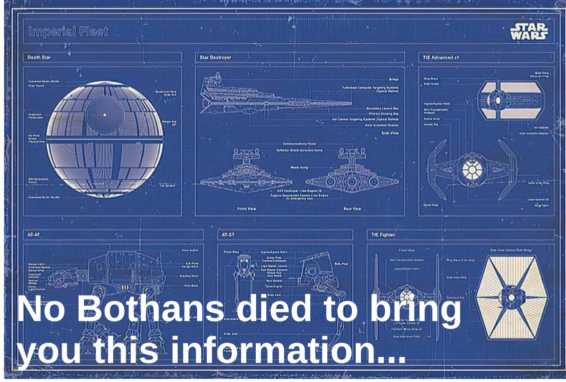
Yoshikazu Nagai



Teresa Lackey
EMPHATIC

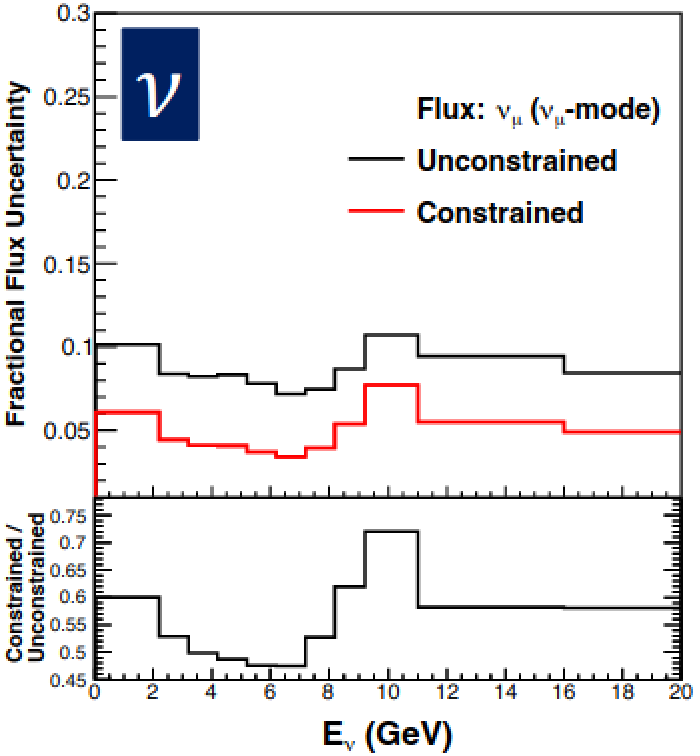


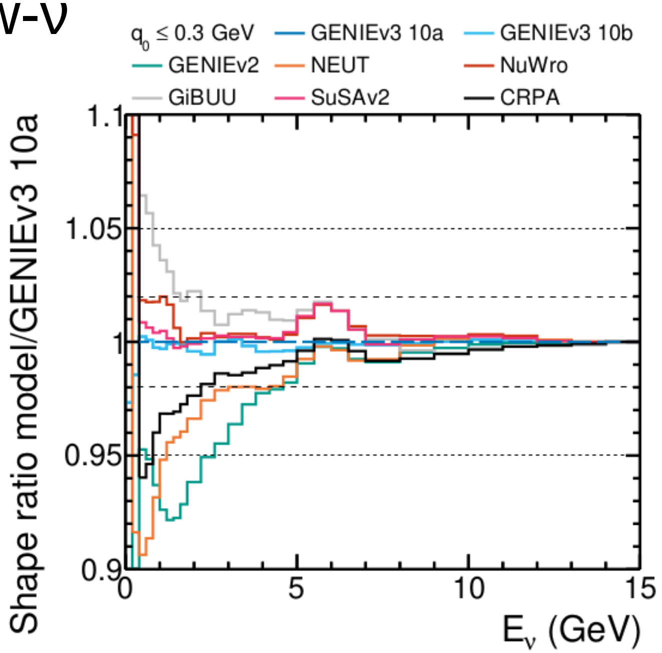
Multiple paths to precision



- In situ flux constraints are hugely important for next-generation program
- MINERvA is providing blueprints for how to leverage small well-known signals
- Important to explore and understand the utility of different methods
- Some limitations still to be understood for low-ν

Anežka Klustová

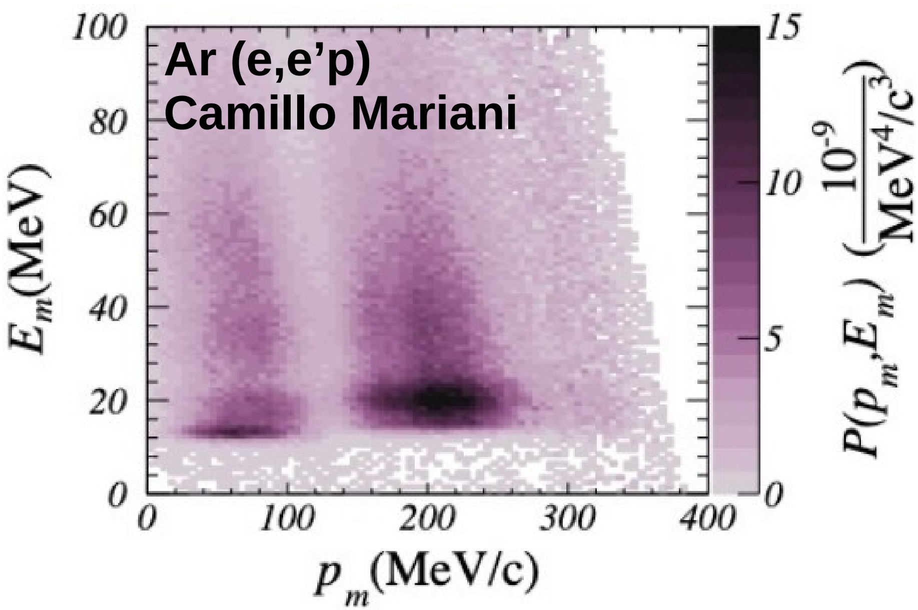




	$\bar{\nu}_\mu$-mode				ν_μ-mode			
	$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_μ	ν_e	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
a priori	7.76	7.81	11.1	11.9	7.62	7.52	12.2	11.7
ν_μ-mode νe^-	6.11	5.81	6.30	8.50	3.90	3.94	8.37	8.68
$\bar{\nu}_\mu$-mode νe^-	4.92	4.98	8.07	9.19	5.88	5.68	8.36	8.64
combined νe^-	4.68	4.62	5.56	7.80	3.56	3.58	7.15	7.84
combined νe^- + IMD	4.66	4.56	5.20	6.08	3.27	3.22	6.98	7.54

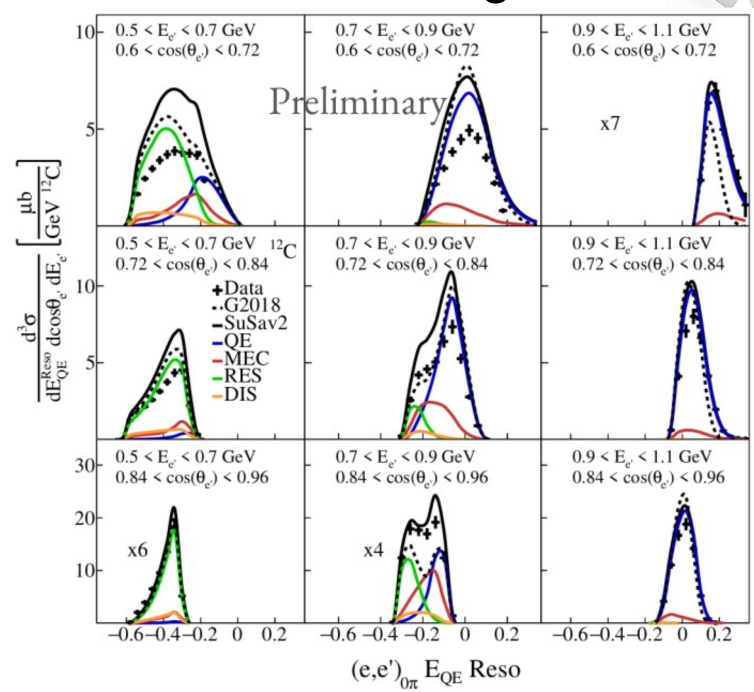
Supporting measurements

- Dedicated e-A scattering results are yielding rich results
- Valuable cross-check for ν-A scattering
- Ongoing work to develop generators to leverage them



Phys. Rev. D 105, 112002, (2022)

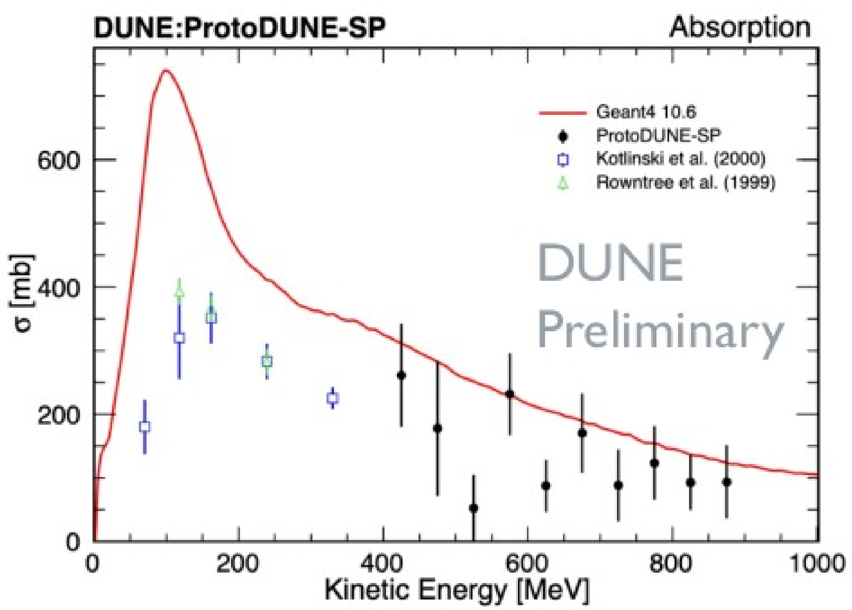
Noah Steinberg



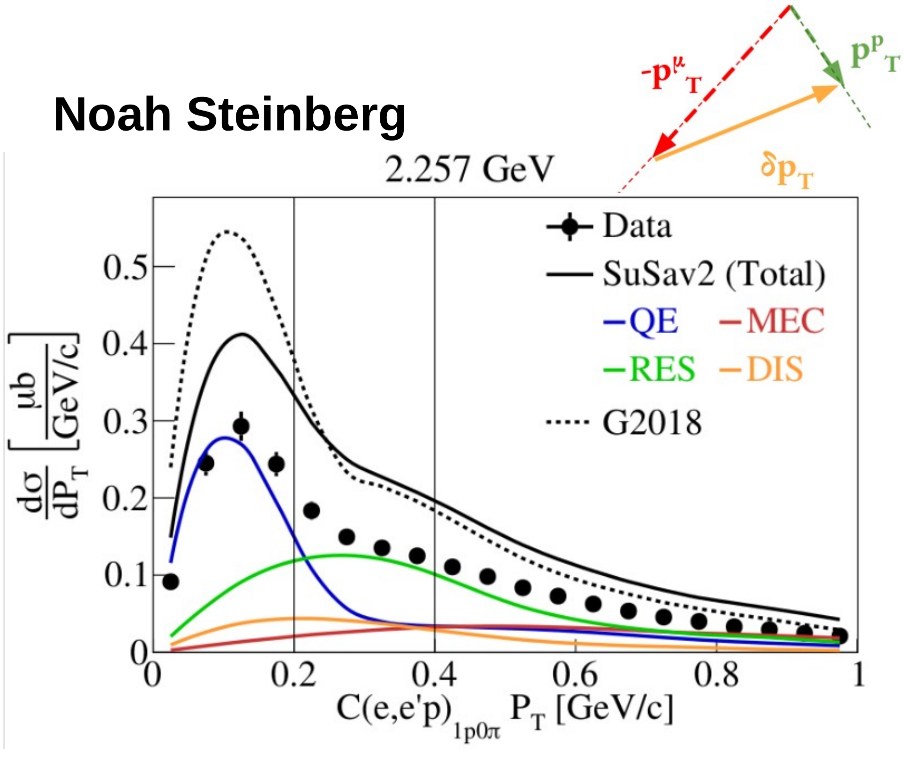
Supporting measurements limitations?

- How complex is the relationship between FSI in e-A and ν-A? -- is more theory work required?
- Similar questions for π-A scattering (although additionally useful for SI)

Laura Munteanu

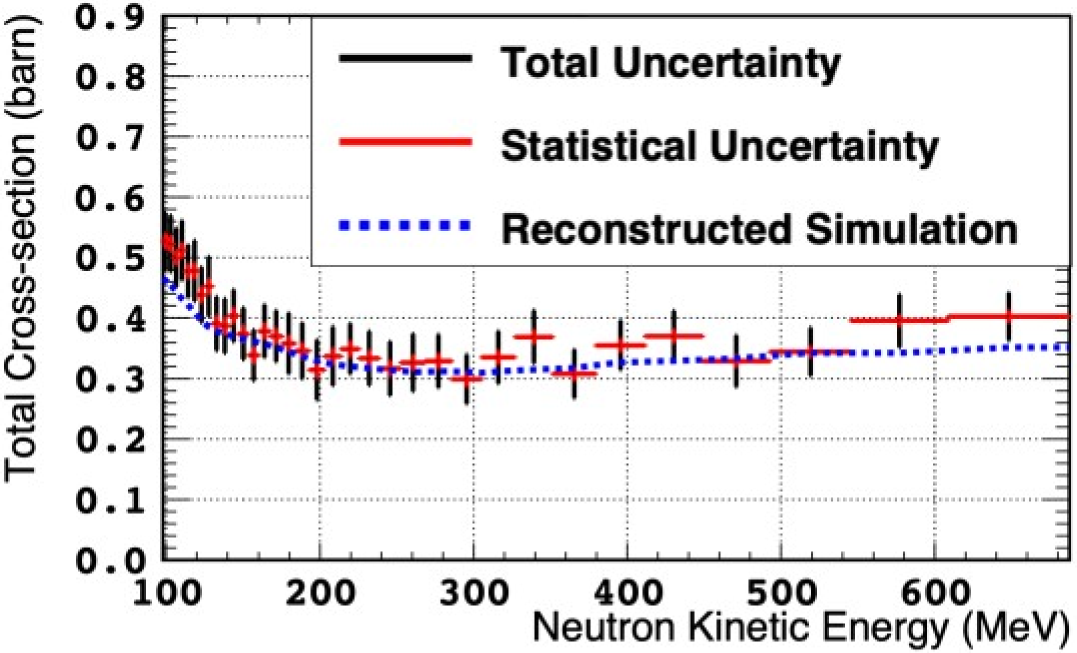


Noah Steinberg



Neutron measurements

- Neutron cross sections important for SI – several ongoing efforts to characterize them on different targets
- We also saw how important these inputs are for analyses that leverage neutrons (Tejin Cai)



Sunwoo Gwon (arXiv:2207.02685)

A word of caution

Data – MC tension

- More data is fantastic!
- Encouraging that it is now standard(ish) to compare many generators to data
- However, strong tensions are difficult to interpret – model selection challenging...
- Concomitant development of models is a challenge to avoid over-straining them

Theory → generator → data comparisons

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu - E_l} \Phi(E_\nu)$$

Theorists

Teppei Katori

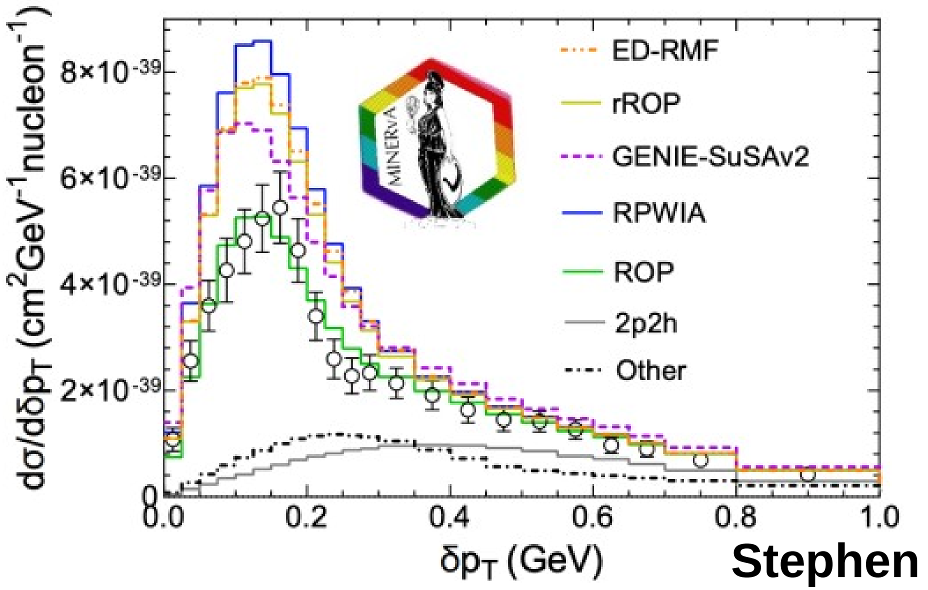
Experimentalists

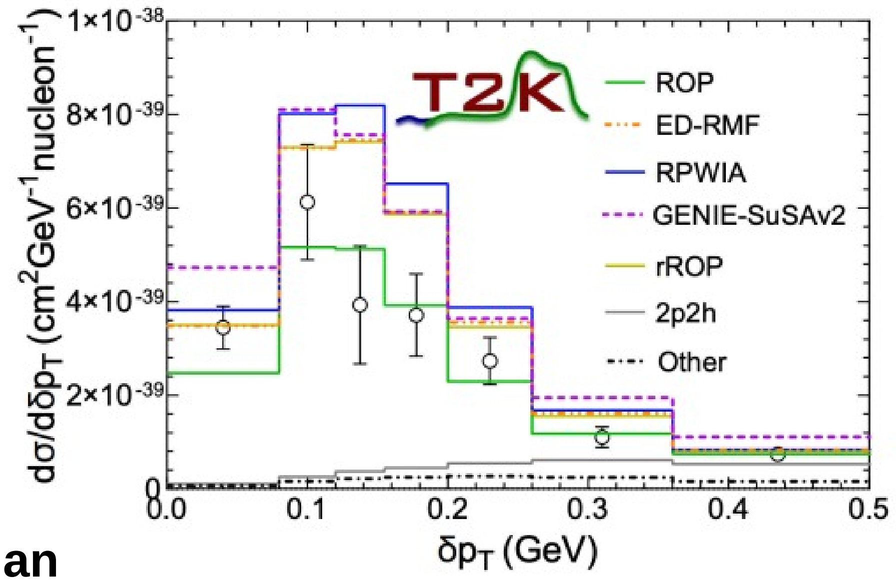
$$\frac{d^2\sigma}{dT_l cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

Are flux-averaged XSECs accessible for theorists?

Multiple channels and FSI adds significant burden...

Faster generator implementation cycle, but fast enough?



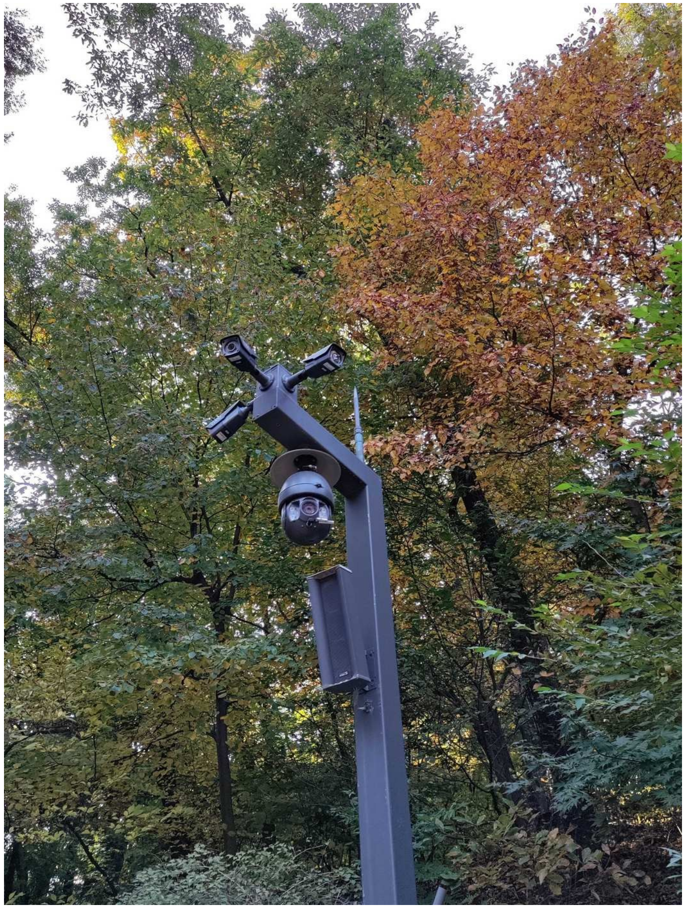


Stephen Dolan
arXiv:2207.02086

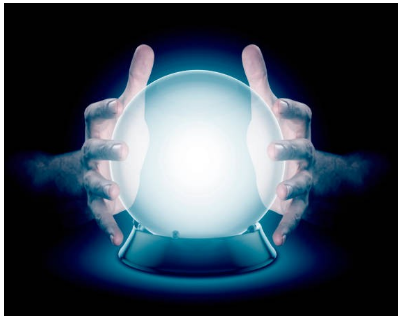
A word of caution II

Don't play Go with the LQCD guys...

Looking forwards



Continued emergence of "model fitters"



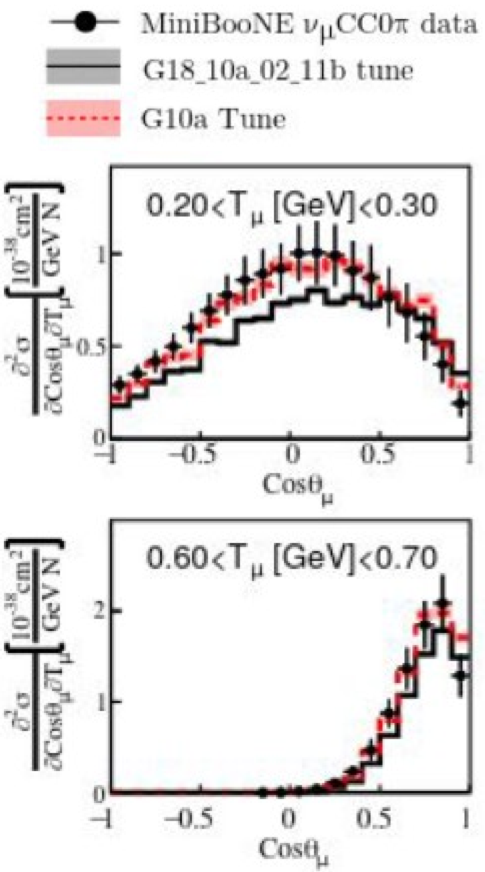
Prediction: in future NuInts, "global" fitters will have their own summary talk

Experiments and generators are tuning MC to data in increasingly sophisticated ways

Many examples at this workshop: GENIE, DUNE, T2K, NUISANCE, uBooNE, ...

Trying to understand the impact of our data on ν-A models, and the impact of other data in our analyses

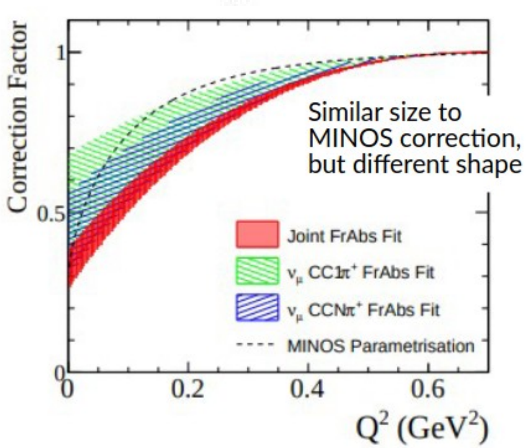
Continued emergence of "model fitters"

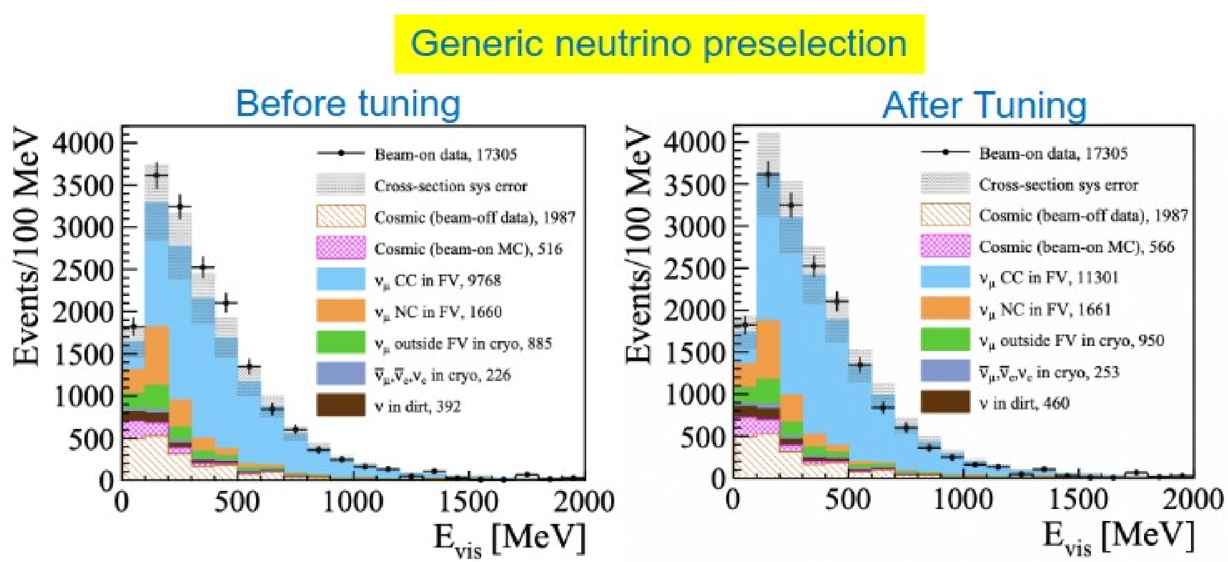


A glimpse of things to come, complements theory efforts

What data will be used for tuning in years to come?

What data won't we use?





Cause for concern: data longevity

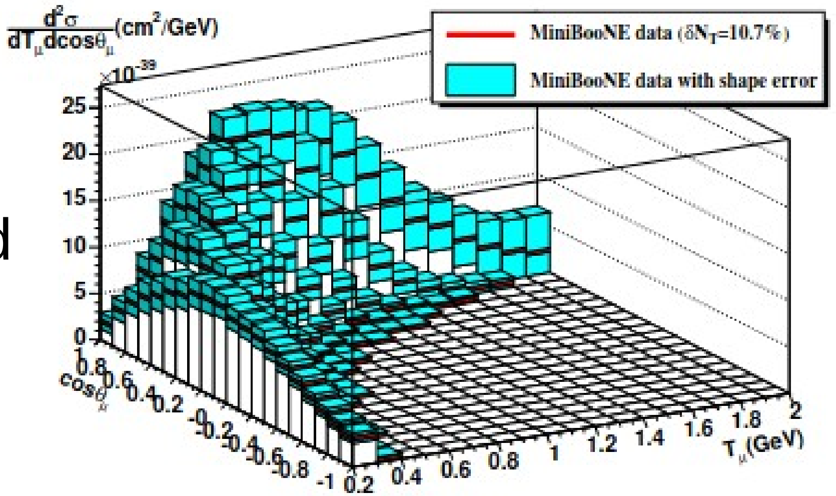
- Each measurement reflects a huge body of work, and I think “data producers” have two broad concerns:
  - How impactful will my data be?
  - How long will my data be used for?
- Debate around this topic is good, and is the context I think we should see discussions about variable choice in
- Data consumers have more control than data providers… that will mean the emerging “model fitting” groups
- E.g., PDG and PDF fitters developed procedures to select, or “deweight” problematic or untrusted datasets…

… I expect very robust debate when that starts happening

Thorough documentation: a MiniBooNE legacy

Extended lifetime through detailed descriptions of results:

- **Example:** the CC0π result we all know and love is in the appendix of the MiniBooNE paper
- We do not trust the CCQE-corrected "main result" of the paper



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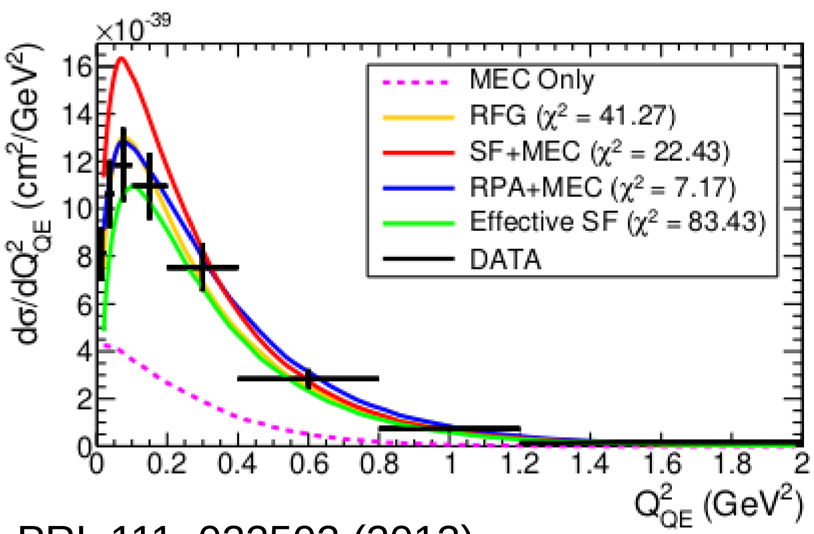


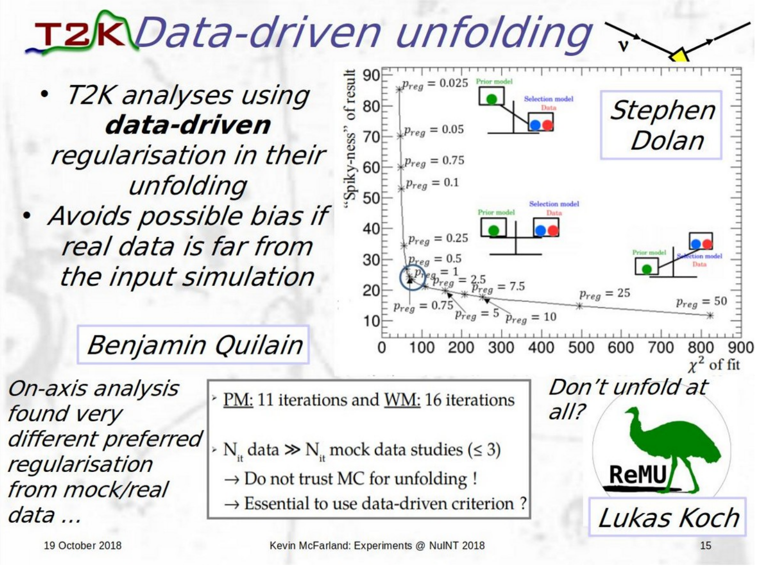
PRL 111, 022502 (2013)

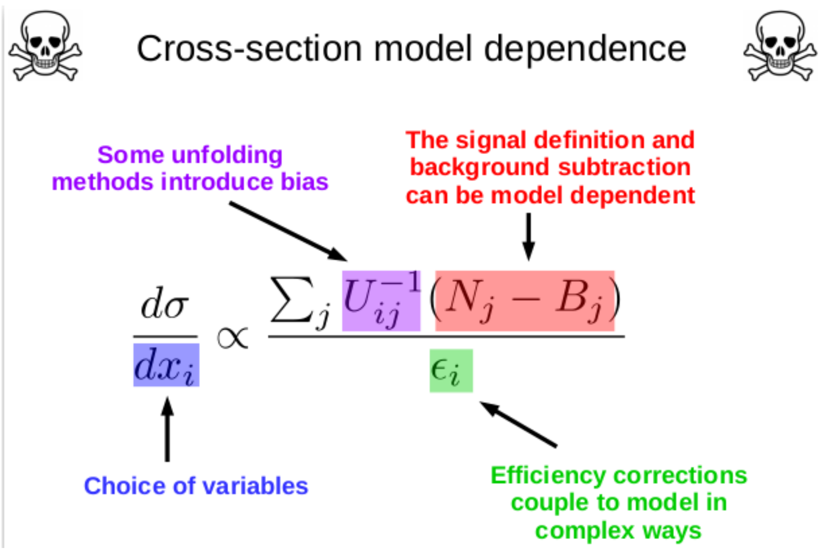
Discussions with the community can improve results:

- **Example:** MINERvA added a $\theta_\mu <$ 20° cut after publication
- Also, released neutrino—antineutrino correlations

How to tackle data longevity

- In NuInt2018, the related contentious(?) discussion was about unfolding methods
- Issue becomes more acute the more ambitious our measurements become
- Key issue is communication. This forum is good, but more time needed

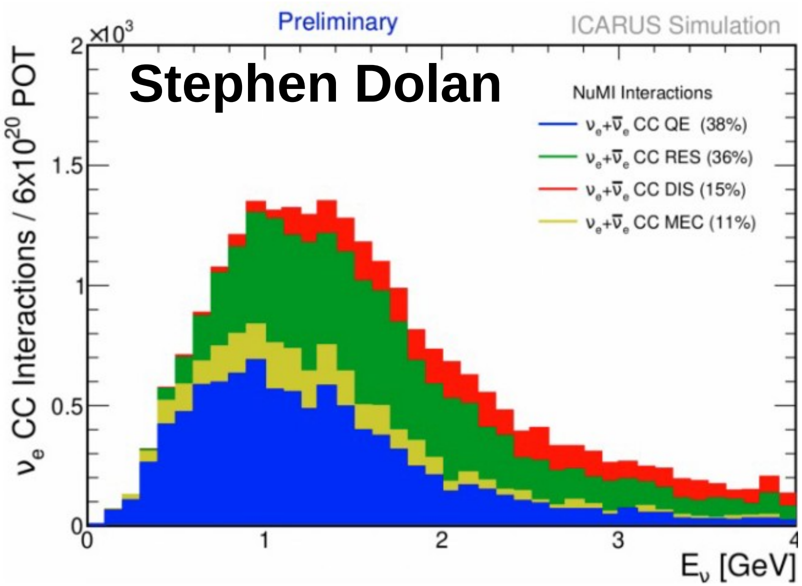




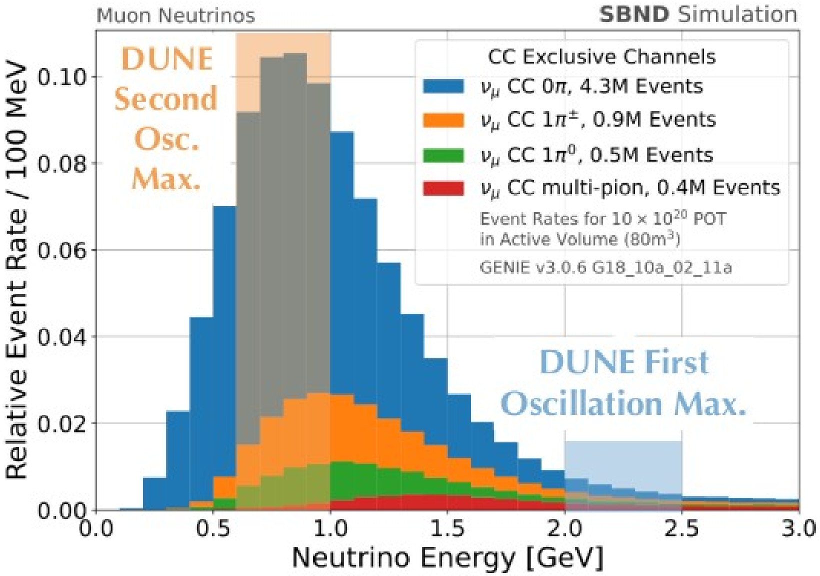
- Previous workshops (NuTion, Tensions) have helped – needs a champion… NuSTEC?
- Also of note: MINERVA data preservation! Public notes! Extensive supplementary material!

Anticipated measurements

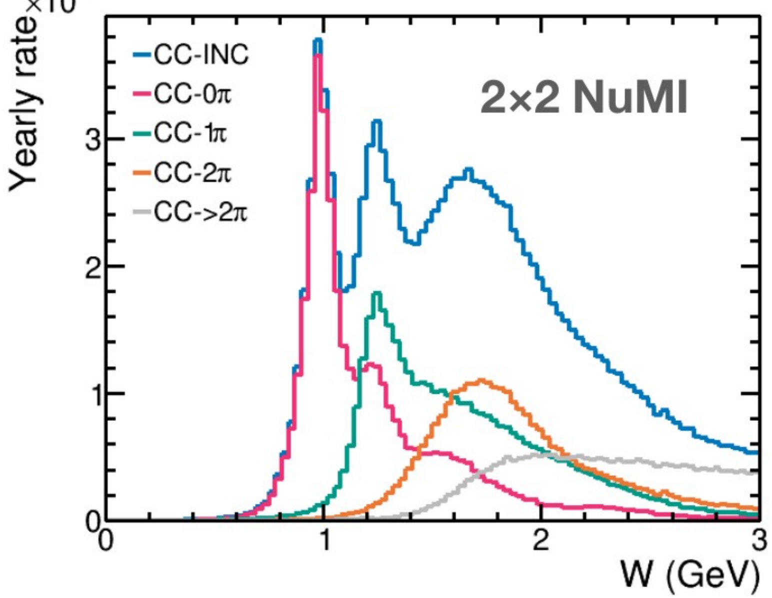
- Anticipate very high statistics results from SBND → **hugely important for DUNE program!**
- Additional great ideas leveraging various detectors and fluxes promises a rich LAr program



Lauren Yates

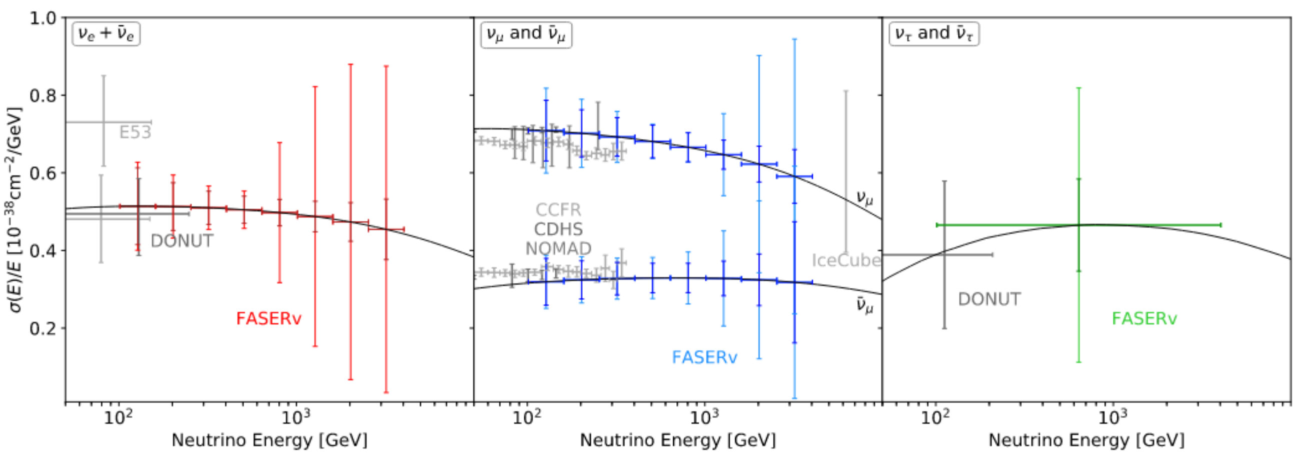


Yifan Chen

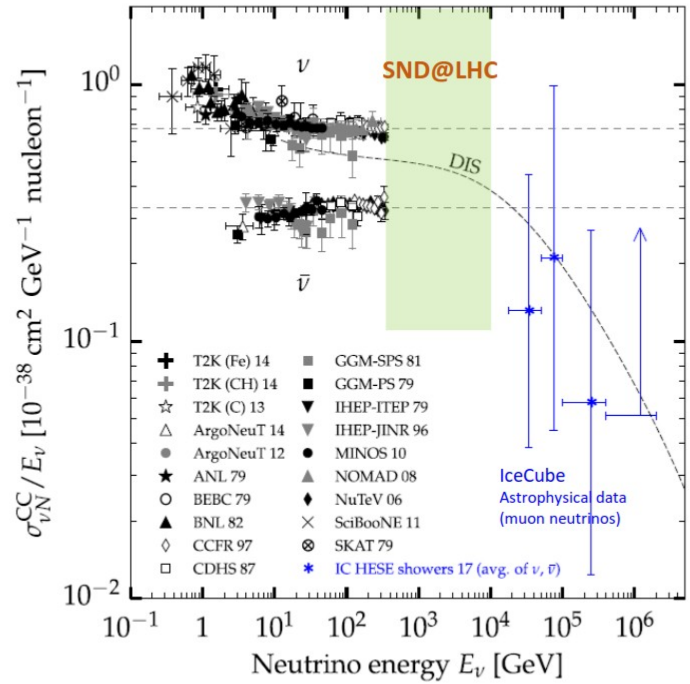


More than a few-GeV neutrinos

- FASERν and SND → Forward Physics Facility in HL-LHC
- Bridges a gap in our understanding of quite-high™ and ultra-high energy neutrinos
- An interesting connection between our community and the energy frontier



Daiki Hayakawa



Chun Sil Yoon

What’s missing?

What's missing?

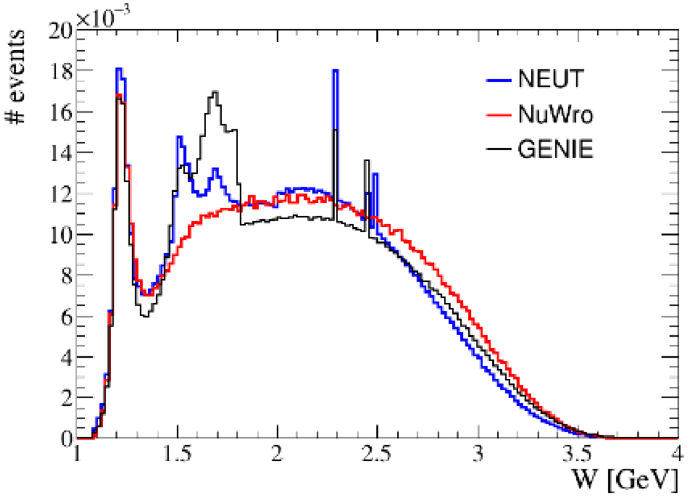
- I worry that DUNE phase space is not adequately covered by existing plans…

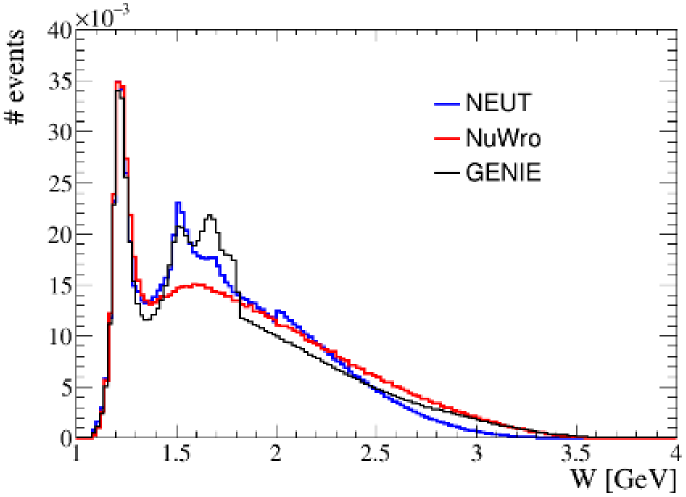
  … we may be in for a rocky ride

- Two areas stick out for me (please add your own!):

  1. Lack of $\bar{\nu}_\mu$ measurements
  2. SIS/DIS…

Neutrino **Christophe Bronner** Anti-neutrino





Why?

1) Lack of SBND antineutrino mode plans → something we should encourage as a community

2) Many challenges to making SIS/DIS measurements as discussed:

- Challenging events to reconstruct
- Issues of model dependence in the extraction

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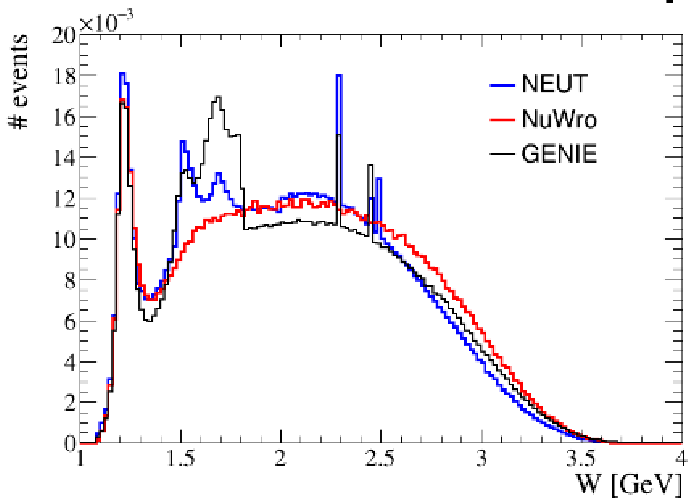
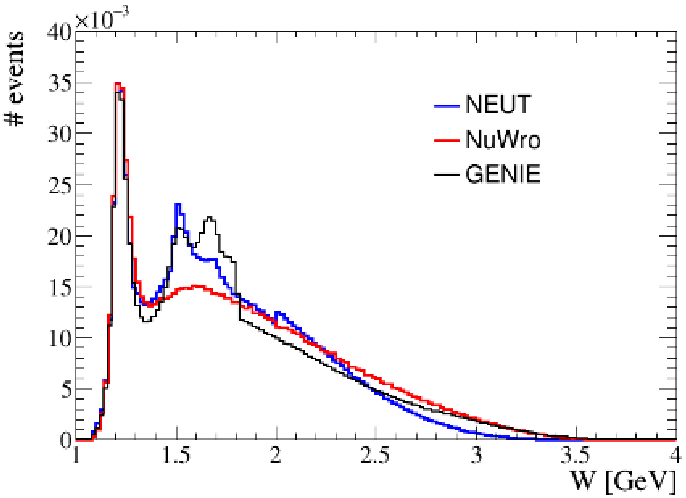




Generator support

- Theory → generator → experiment pipeline is improving, but this is a long effort
- Increasingly rely on generators to support more and more complex analysis
- Model dependence issues may lurk… are the generators sufficiently different for, e.g., FDS?
- Some progress:
  - New generator on the market – ACHILLES
  - Shared tools (e.g., GENIE flux driver for other events)
  - Ability to propagate custom tunes etc

Parting thoughts

Summary

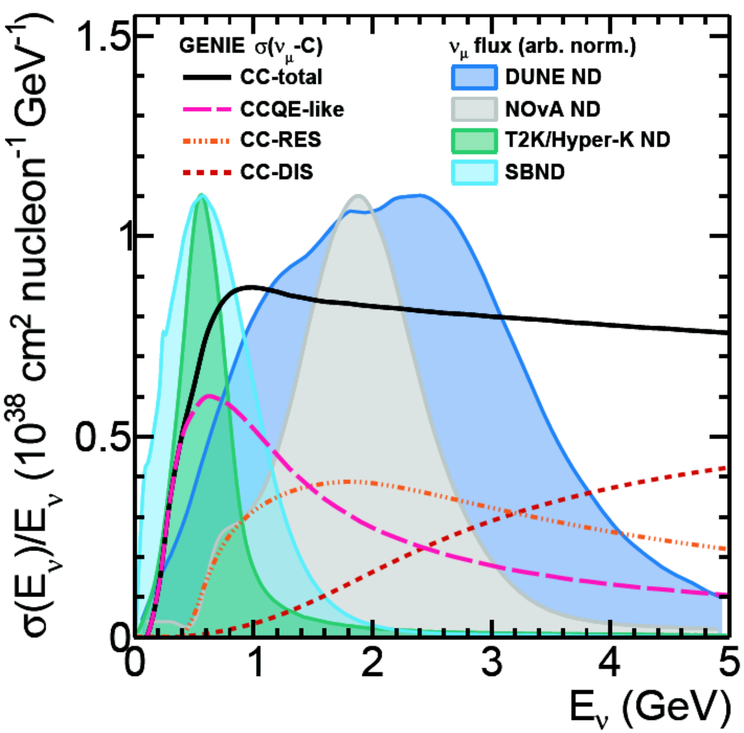
- A wealth of new data has been shown at this meeting!
- High statistics, multiple fluxes and targets, more hadron kinematics… ~~all~~ most of the things we say we need to constrain models
- Models do not do a good job of describing the majority of the data. A major challenge, maybe an opportunity
- We need to continue to support generator work, as the bridge between theory and experiments
- Ad hoc tuning efforts are becoming increasingly important for analysis and more sophisticated – potential for issues

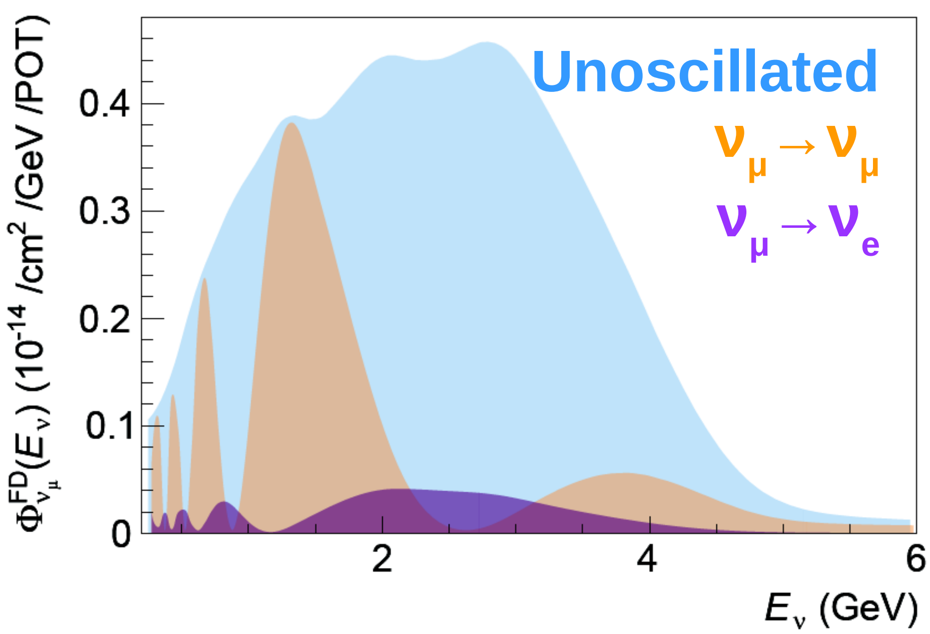
Thank you to the organizers for providing the forum for this fantastic workshop!

(Mostly) Providing input to a complex problem

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability

$$R(\vec{\mathbf{x}}) = \overbrace{\int dE \ \ \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \underbrace{ \times P(E_\nu; \nu_A \to \nu_B)}_{\text{Far}}$$



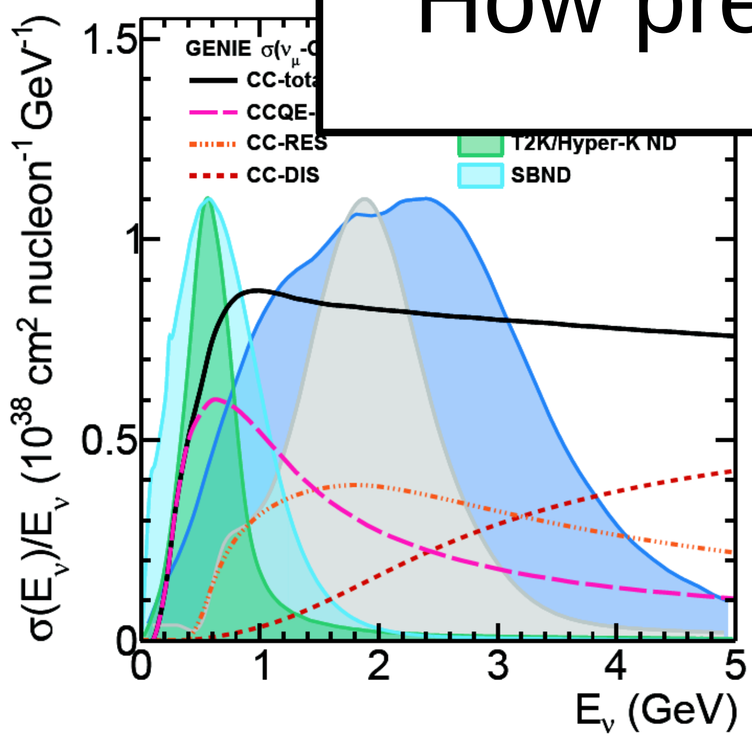


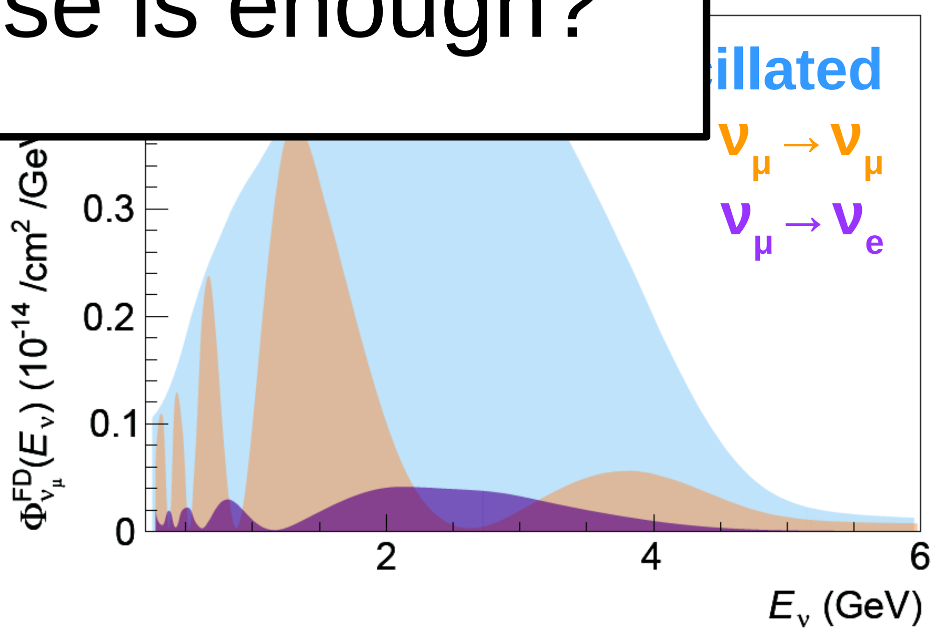
(Mostly) Providing input to a complex problem

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation p

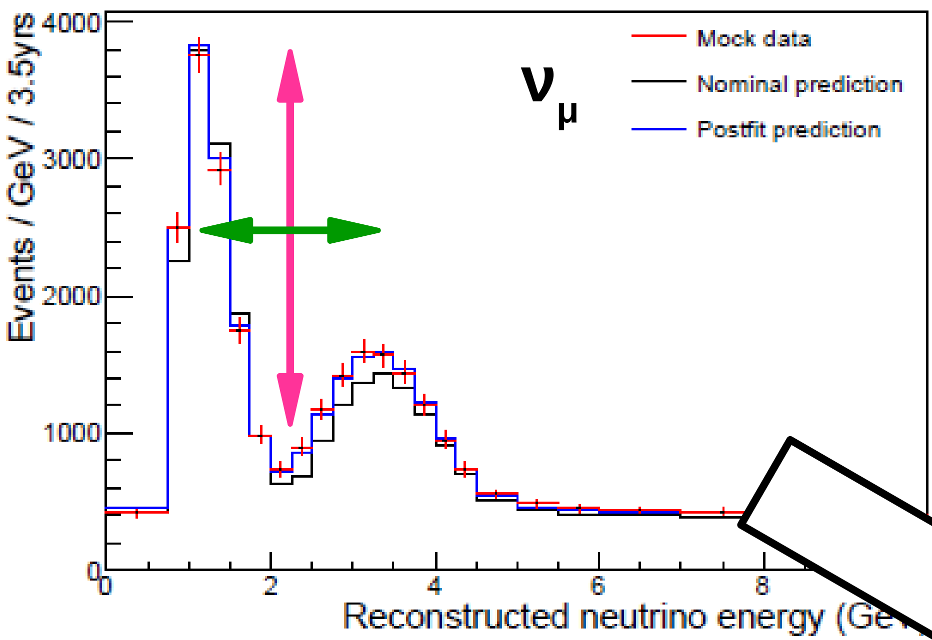
$$R(\vec{\mathbf{x}}) = \overbrace{\int dE \;\; \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \underbrace{\times P(E_\nu; \nu_A \rightarrow \nu_B)}_{\text{Far}}$$

How precise is enough?

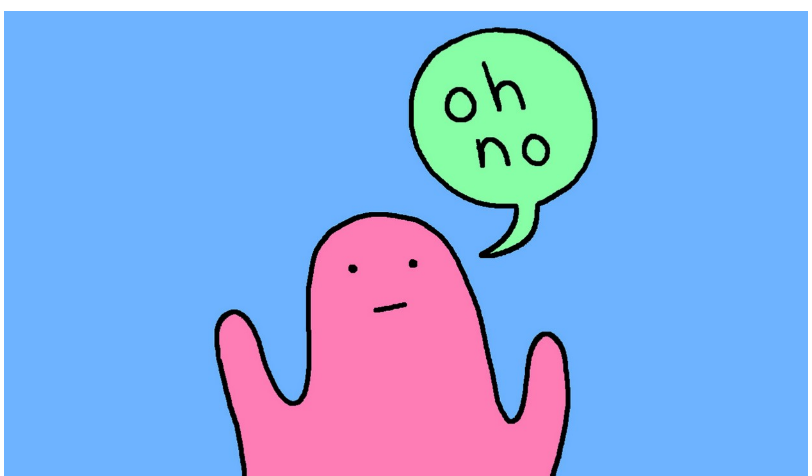




DUNE example: cross section mismodeling



- Shift 20% of proton energy to neutrons (for all Eν)
- Subtle impact on spectra, but large bias in oscillation parameters



90% confidence