Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

URA Early Career Award Talk:
Towards Precision Accelerator-Based Neutrino Physics

Laura Fields

2019 Fermilab Users Meeting

12 June 2019

Thank You

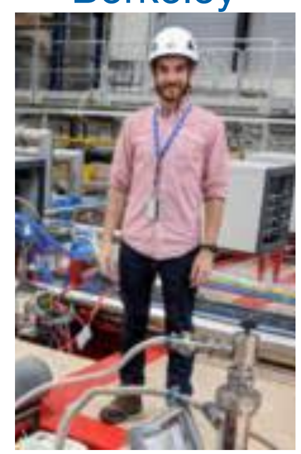
A big thank you to everyone who helped me be here today, and especially to the students and postdocs I've supervised/mentored as Fermilab Scientist:

Deepika Jena
Fermilab

Cheryl Patrick
UCL

Jake Calcutt
MSU

Peter Madigan
Berkeley



Nuruzzaman
Rutgers

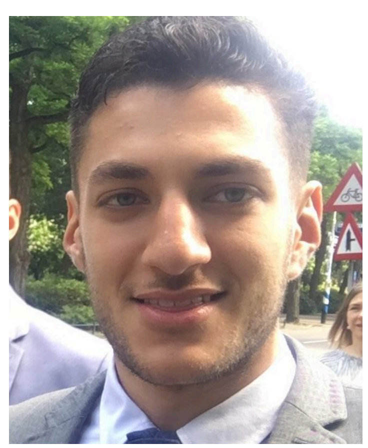
Aaron Bercellie
Rochester

Miguel Hernandez
Guanajuato

Ben Messerly
Pittsburgh

Amit Bashyal
OSU

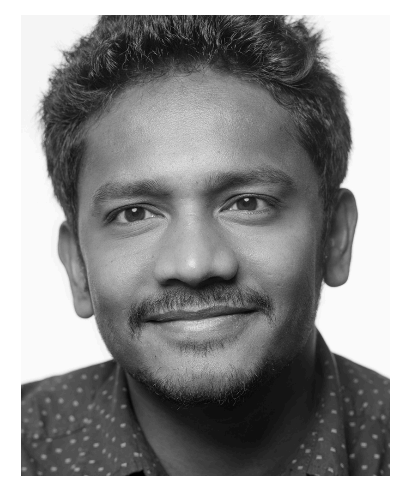
Rowan Zaki
Radboud



Tyler Rehak
Drexel

Tyler Johnson
Duke

Jogesh Rout
Jawaharlal Nehru



Nishat Fiza
IISER-Mohali

Looking Back on My Early Career Research So Far

On a day-to-day basis, the days since I became a Fermilab Associate Scientist in 2015 have often felt like this:

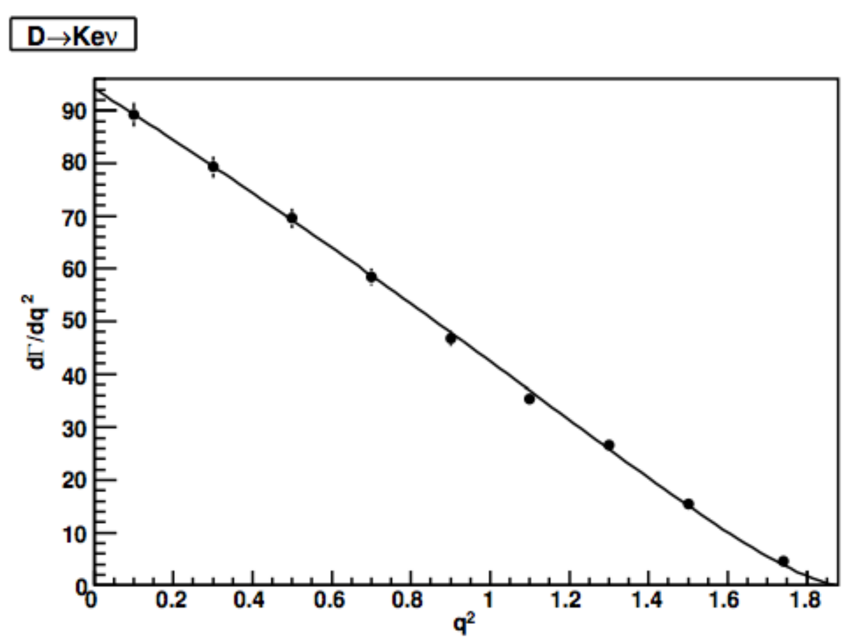
The Theme of My Early Career Research

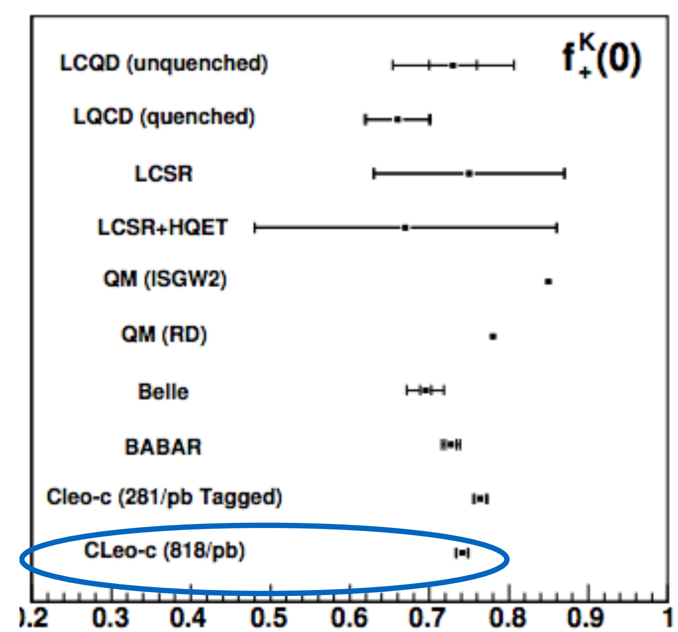
But stepping back to focus on wider timescales, my research has a different theme, that start in my early days of grad school:

Ritchie Patterson
(Cornell)

My PhD advisor is known for making very high precision measurements

That definitely appealed to me, and we went on to make some very precise measurements of charm semi-leptonic branching fractions

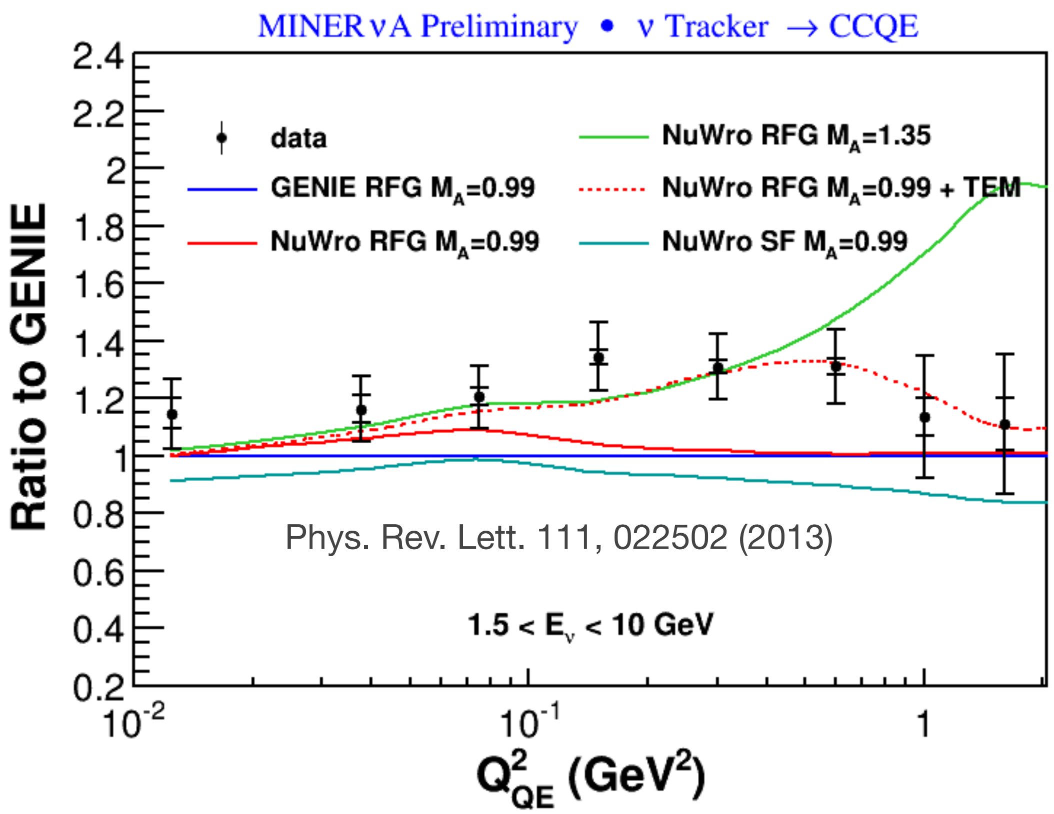


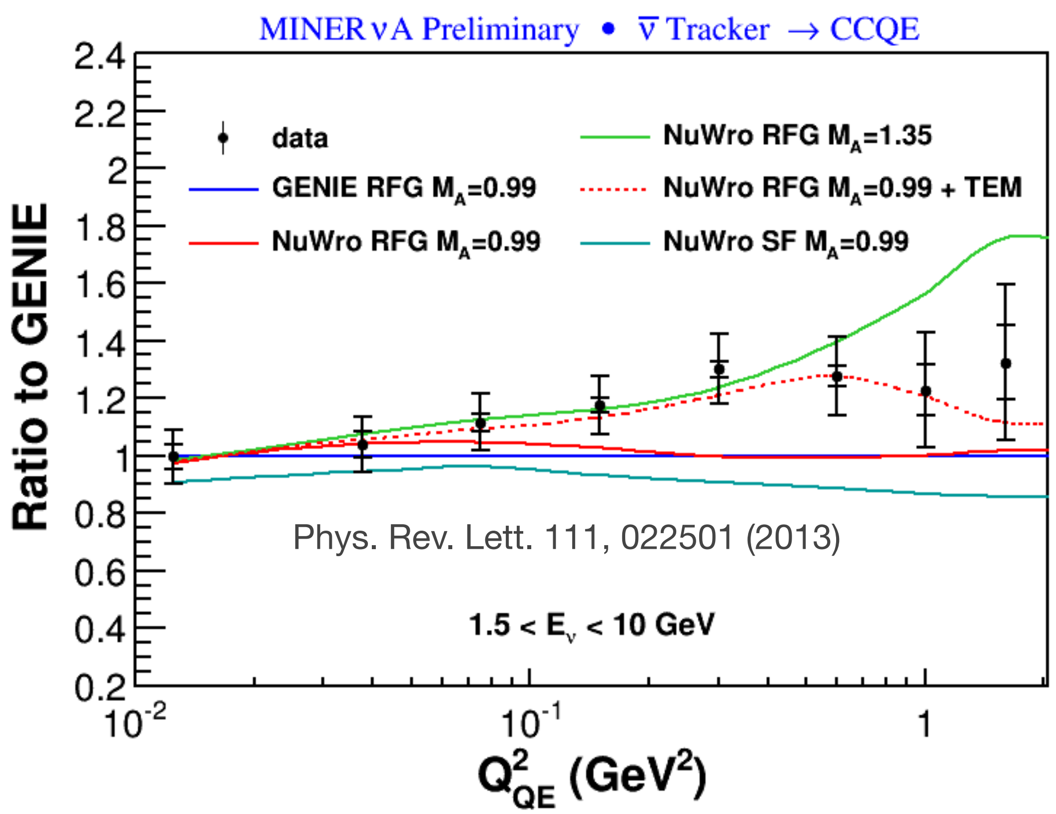


2%
Uncertainty!

The Theme of My Early Career Research

Then I joined the MINERvA experiment as a postdoc, and discovered that neutrino physics is really much harder than quark physics:





We were very happy to have 10-20% errors in our first measurements of neutrino interaction cross sections

Neutrino Physics Vs Quark Physics

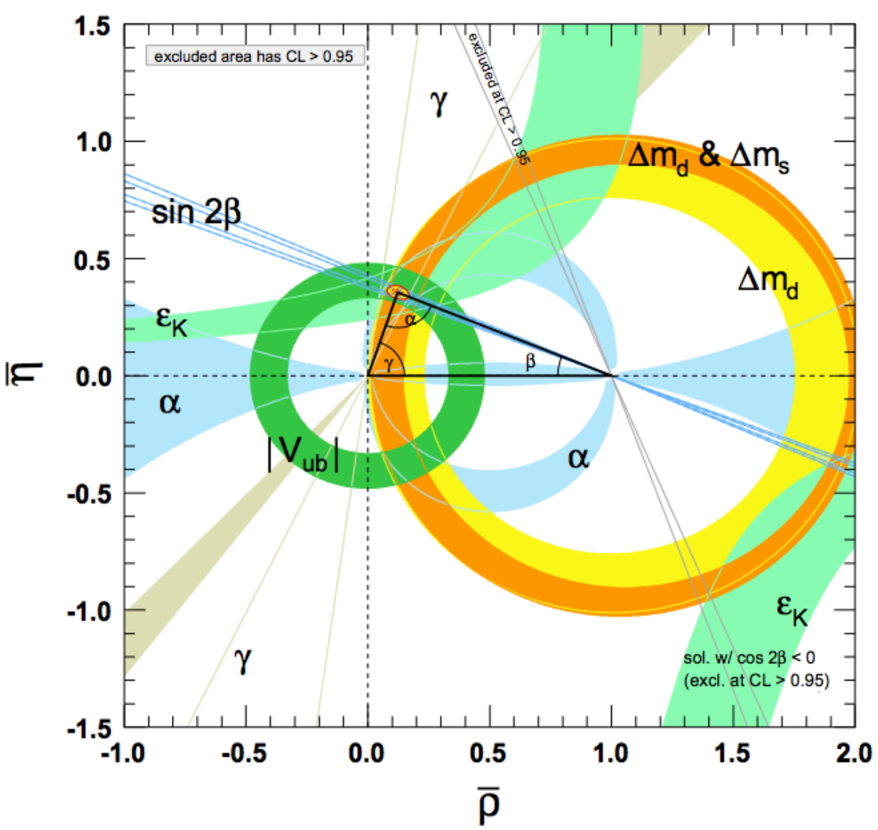
The goals of neutrino physics and quark physics are not hugely different:

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

CKM Quark Mixing Matrix

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \times \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})\ .$$

PMNS Neutrino Mixing Matrix



- Both are measuring parameters of mixing matrices, probing for inconsistencies with the standard model
- Neutrino physics is working towards the level of precision/overconstraint that has been achieved in quark mixing, but has a long way to go

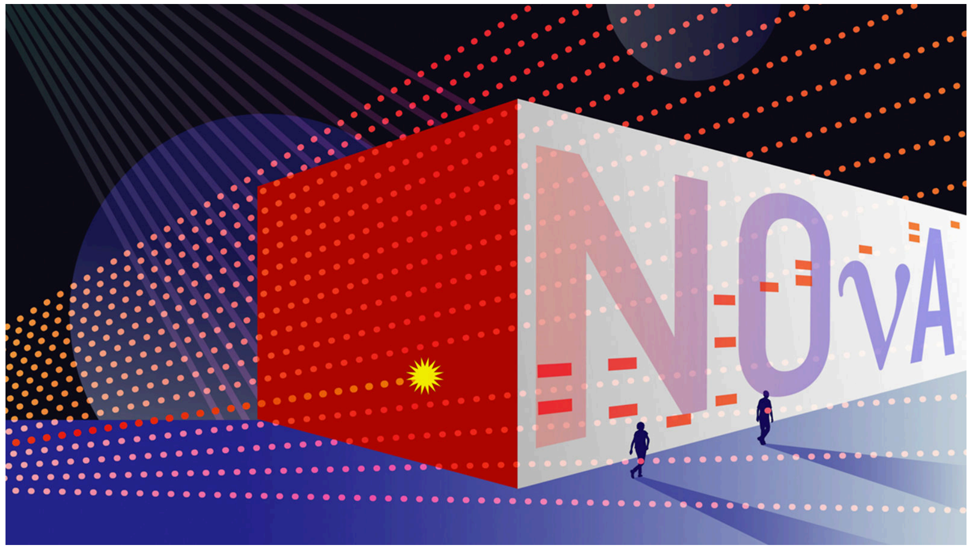
Plots/matrices from M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

What is Holding Neutrino Physics Back

Neutrino physics is really hard, in a zillion ways. For example:

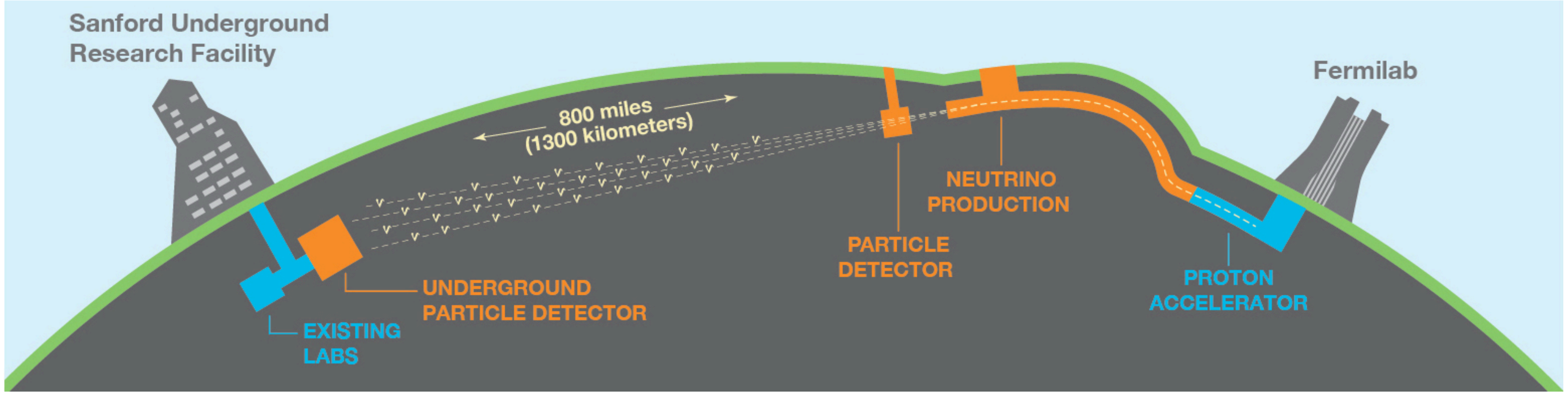
Neutrinos **interact super rarely**, so we need really, really intense beams and really big detectors

Creating beams of neutral particles is challenging, and the results results are difficult to control



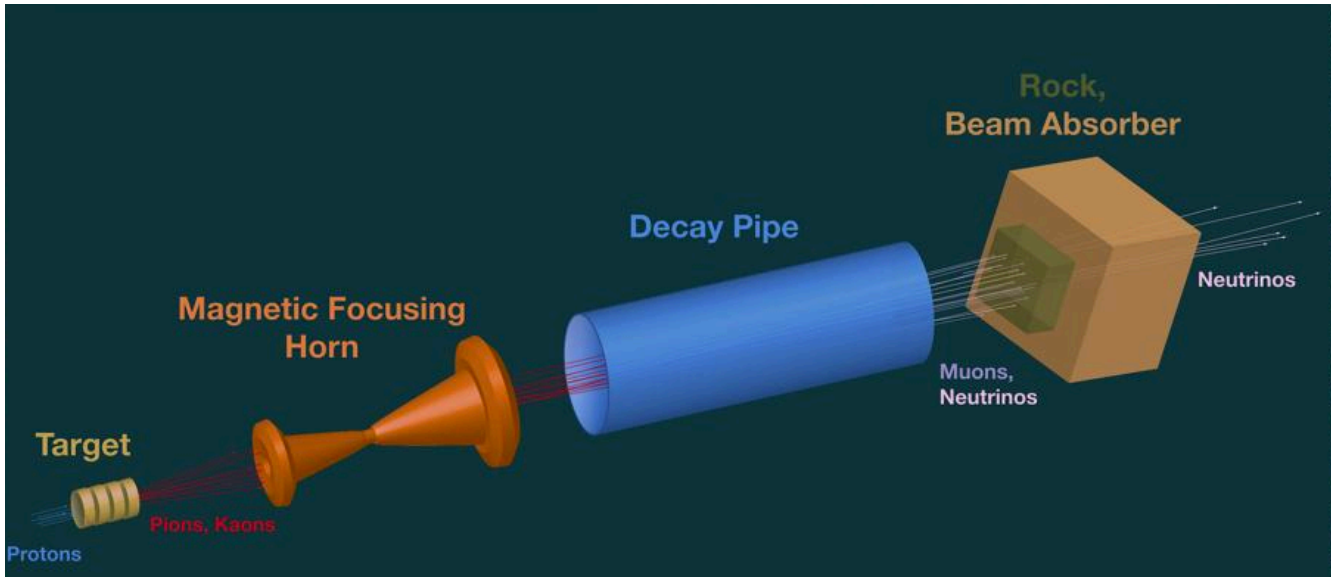
To study neutrino mixing with accelerator beams, we have **measure them after they have traveled long distances**, which means we need even bigger detectors

We observe **neutrinos when they interact with nuclei**, introducing complicated nuclear physics to our measurements



My Early Career Research

- Increase the precision of accelerator-based neutrino measurements is a global effort that involves thousands of people (including many of you!)
- The things that I focus on:

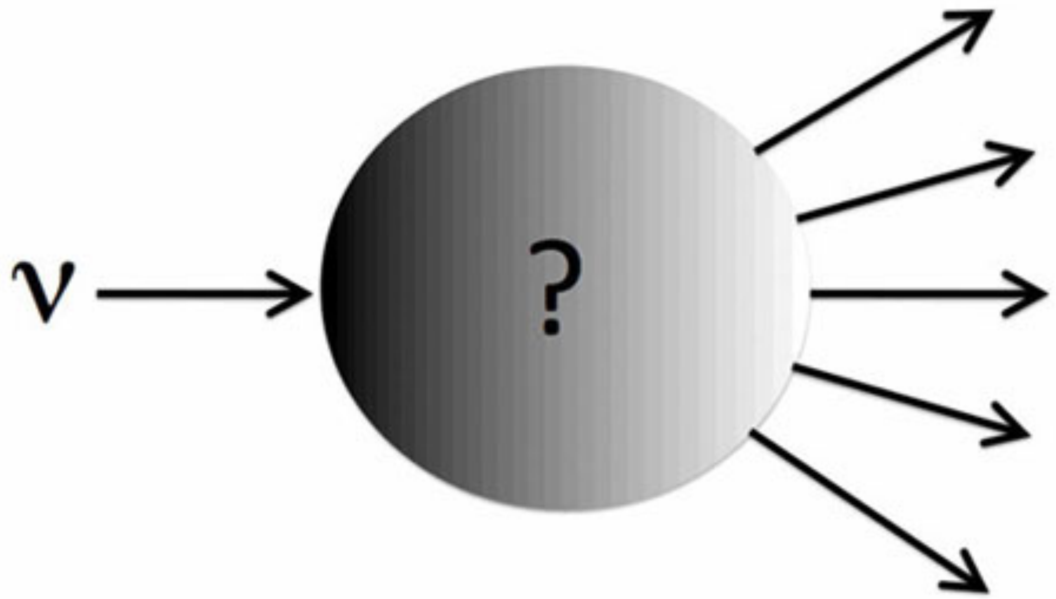


Neutrino Beams

- Designing neutrino beams to make precise measurements
- Measuring the number of neutrinos in the beam and their energy spectrum

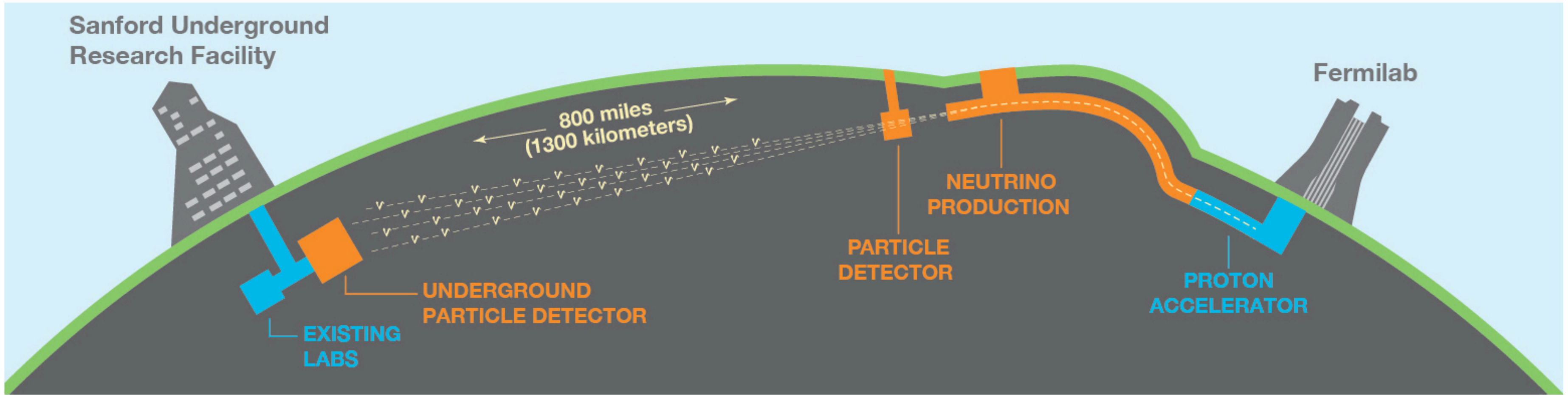
Neutrino Interactions

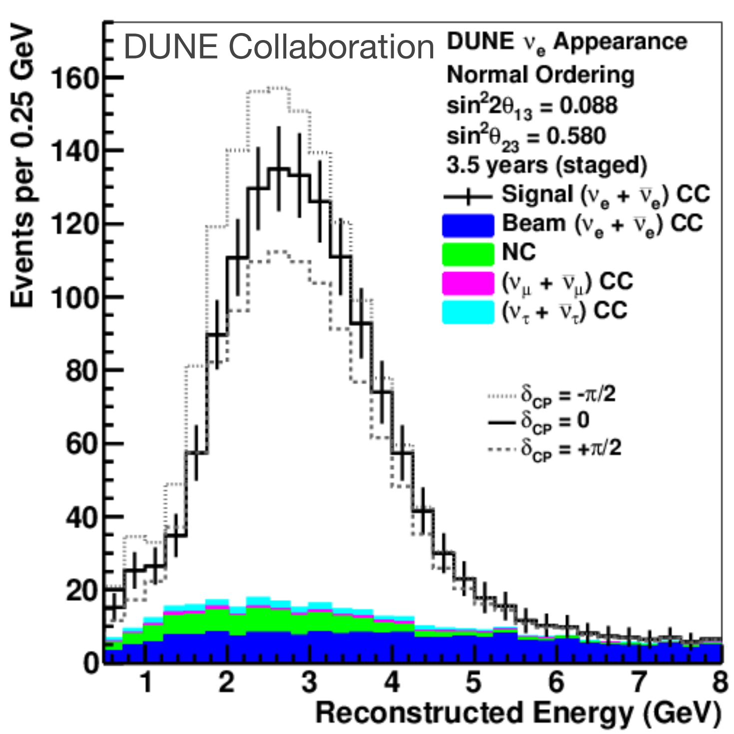
- Measuring and simulating neutrino-nucleus interactions, so that we can untangle neutrino oscillations from the interactions we measure



LBNF Beam Optimization

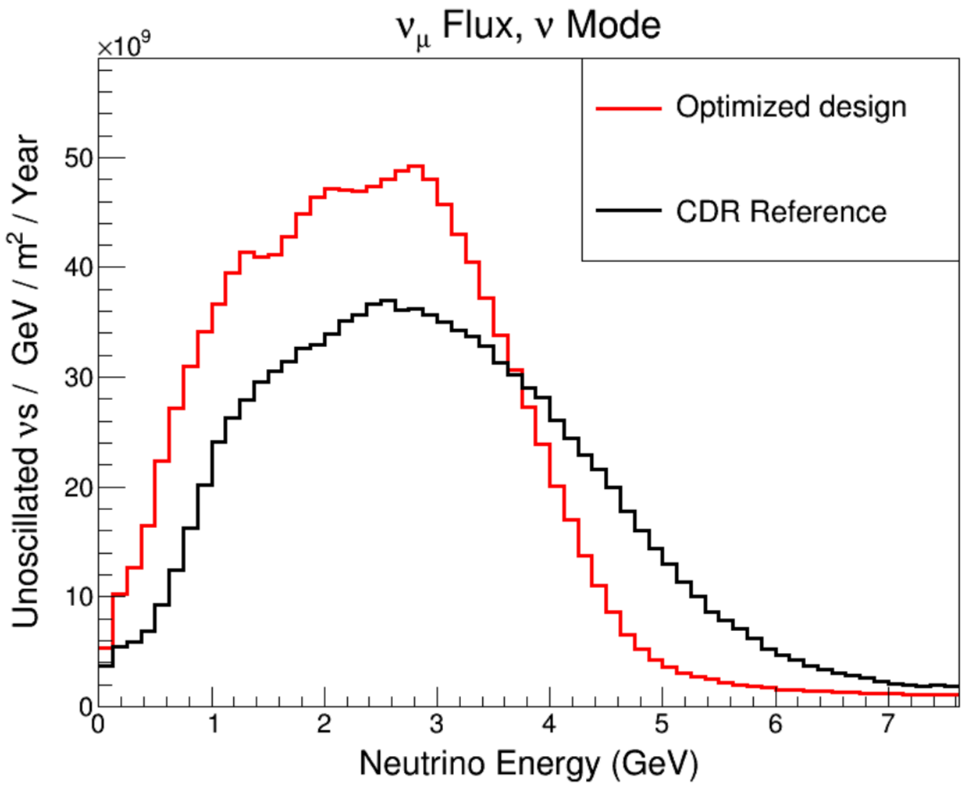
When I first joined Fermilab, I was working on developing a new design for the LBNF neutrino beam:





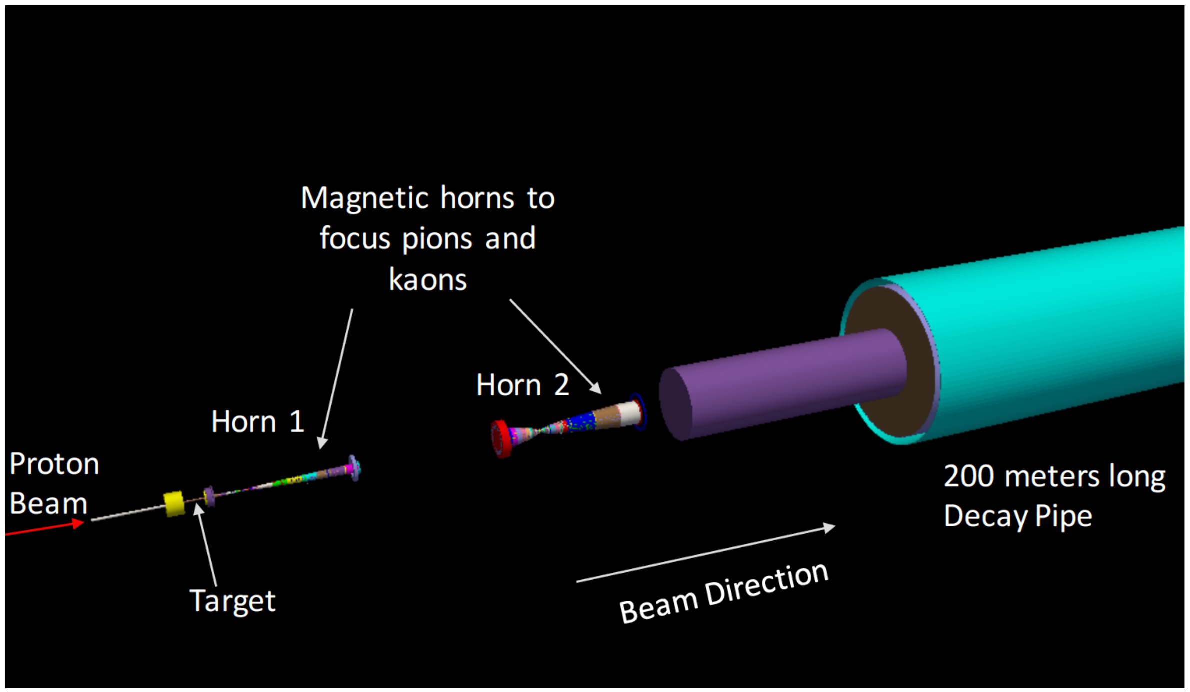
DUNE will search for CP violation by neutrinos by observing ~0.5-4 GeV muon neutrinos oscillating to electron neutrinos.

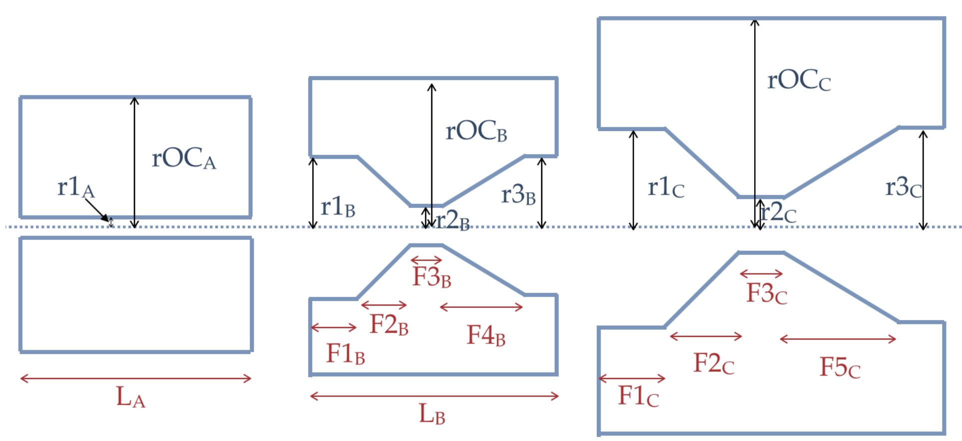
The optimized design I identified increase the muon neutrinos in this region by 36%



LBNF Beam Optimization

I identified that design using a genetic algorithm:





- We first developed a simulation that was similar to the previous design based one the (very successful!) NuMI experience
- But configured that simulation so that we could change a bunch of parameters:
  - Horn currents
  - Horn conductor shapes
  - Target length
  - Target transverse size
  - Primary proton beam energy

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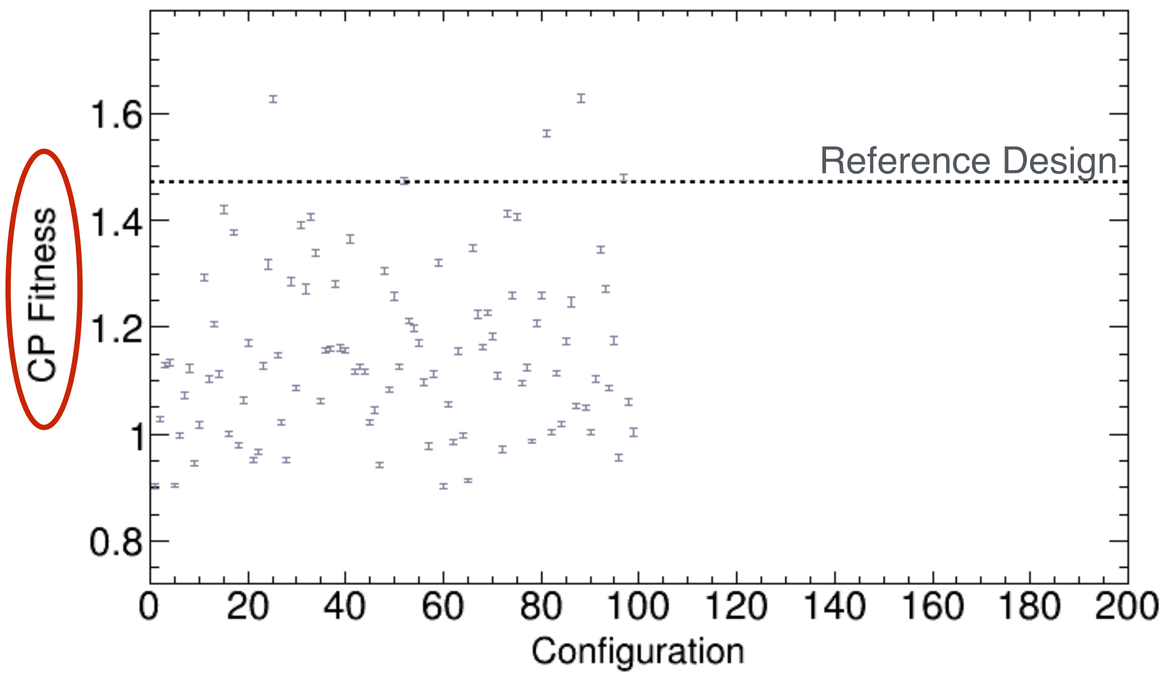
LBNF Beam Optimization

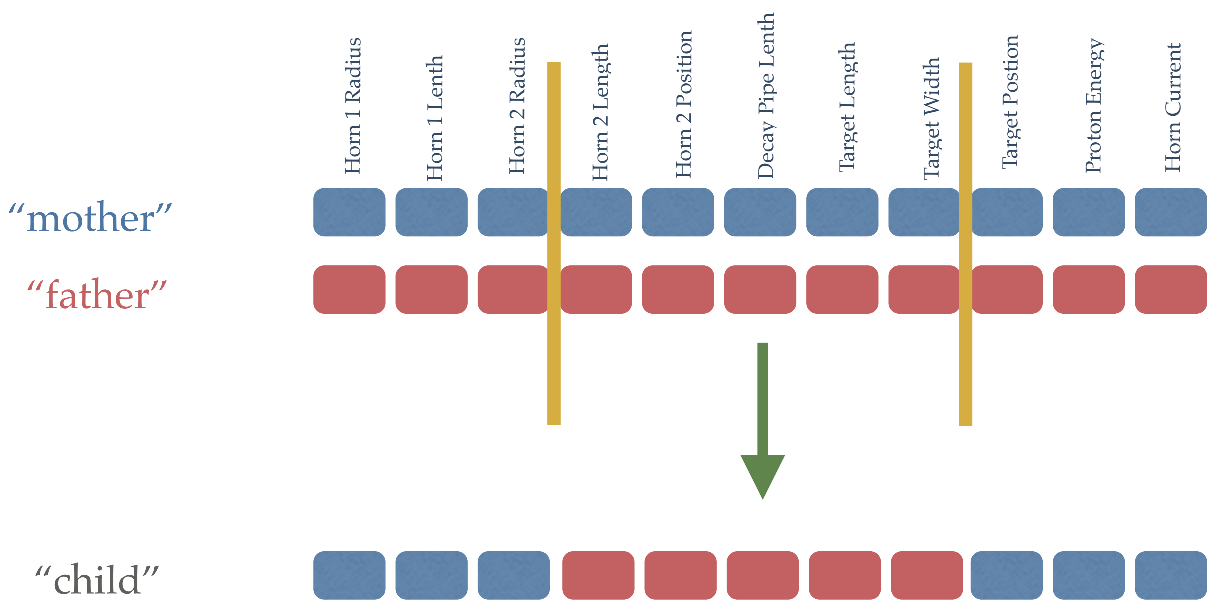
The genetic started with by simulating a bunch of random beams:

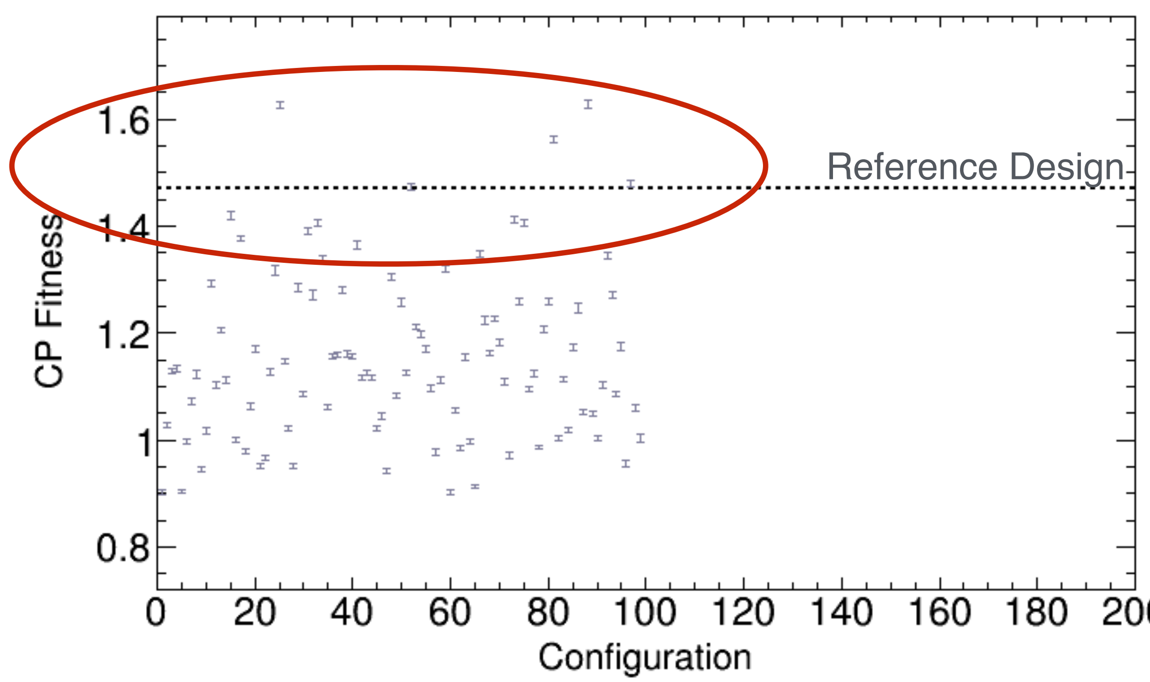
The quantity we chose to optimize was basically: how well will we measure CP violation after ~7 years of running



LBNF Beam Optimization

Then we create and simulate new beams using the best-performing random beams





To create a new beam, we choose two well-performing beams and mix together their parameters (similar to how the a human gets half of their traits from a mother and half from a father)

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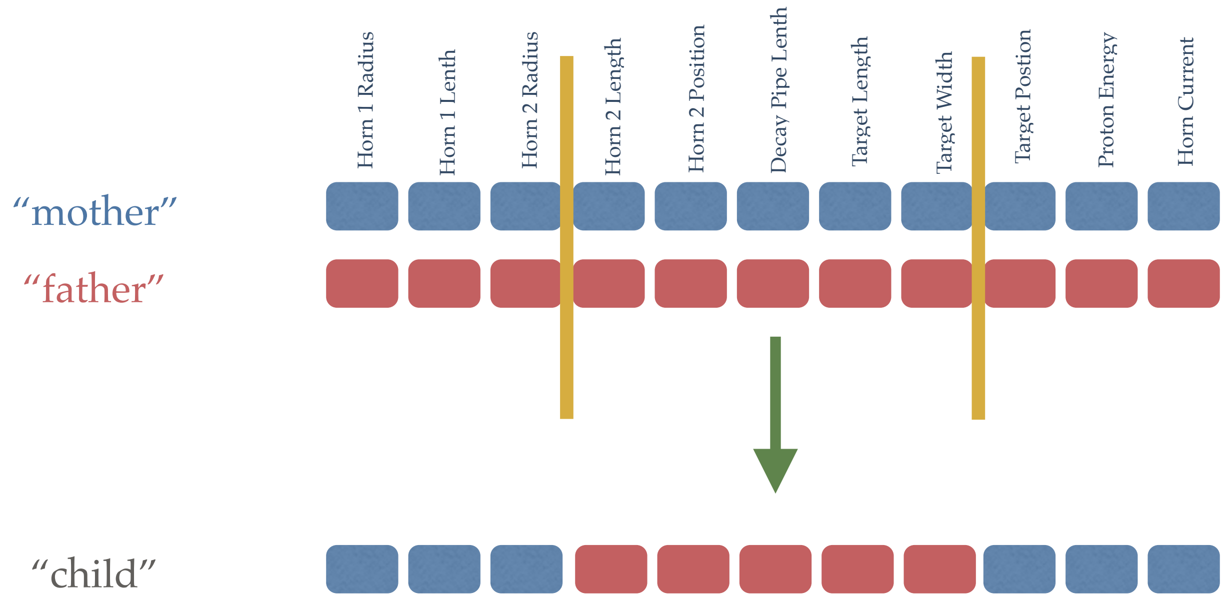
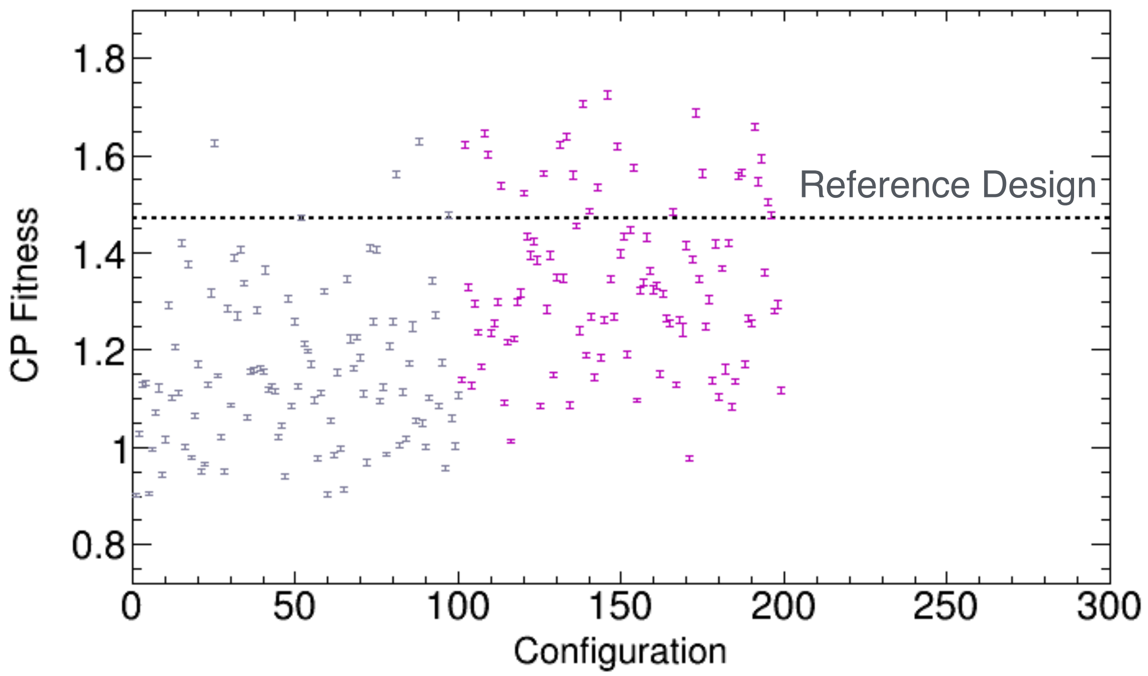
LBNF Beam Optimization

We immediately get beams that perform a lot better:





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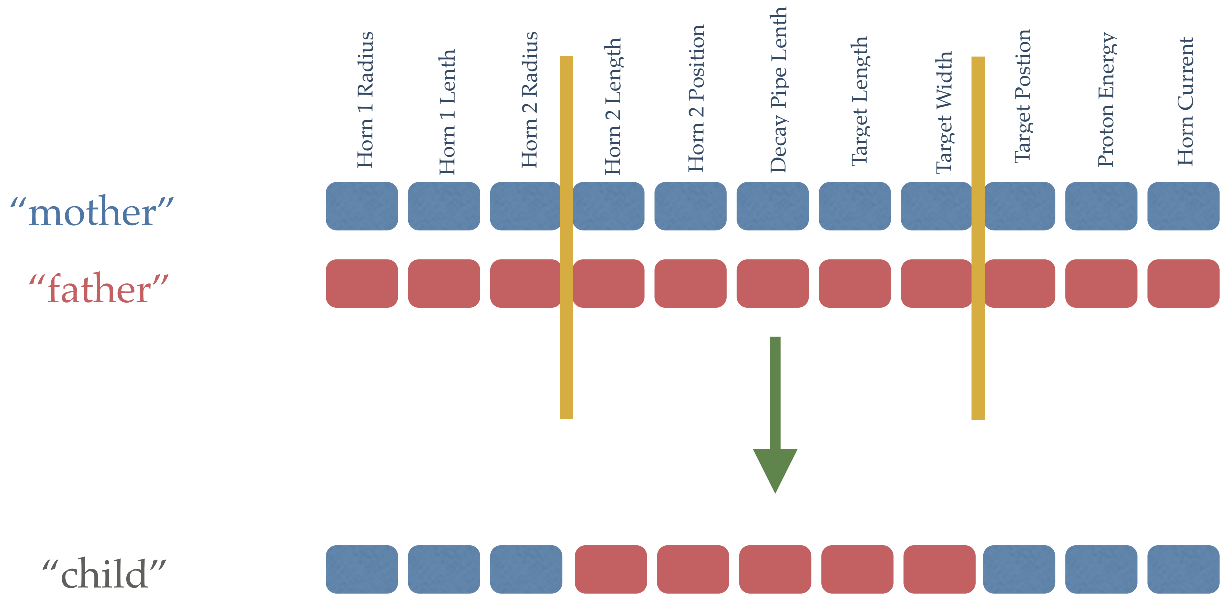

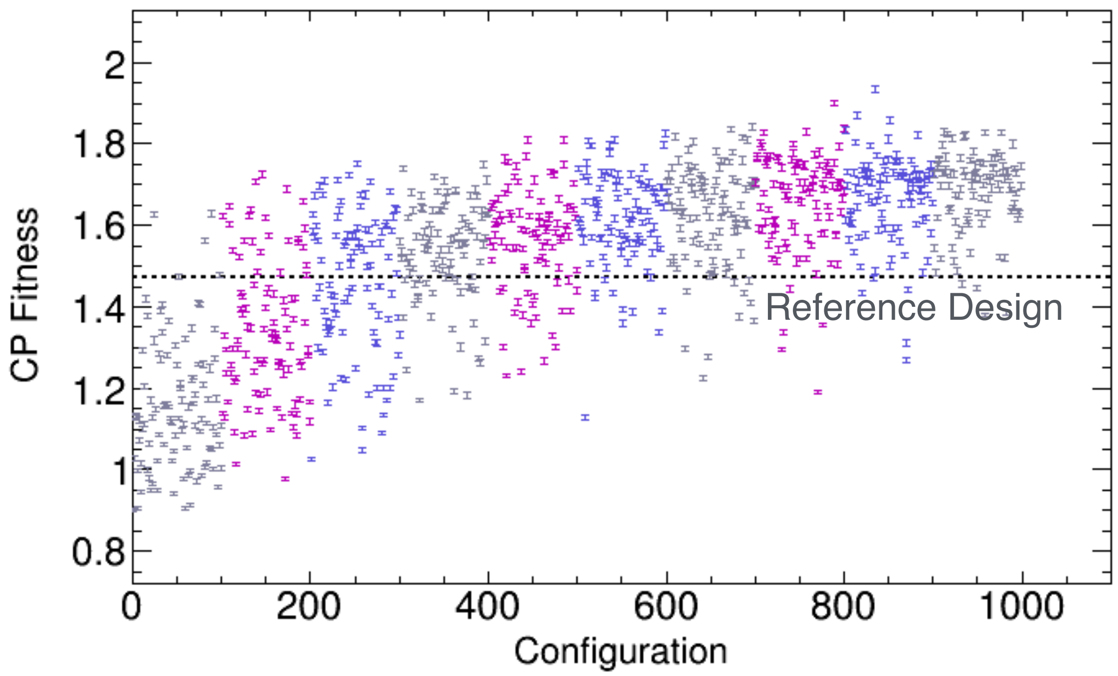

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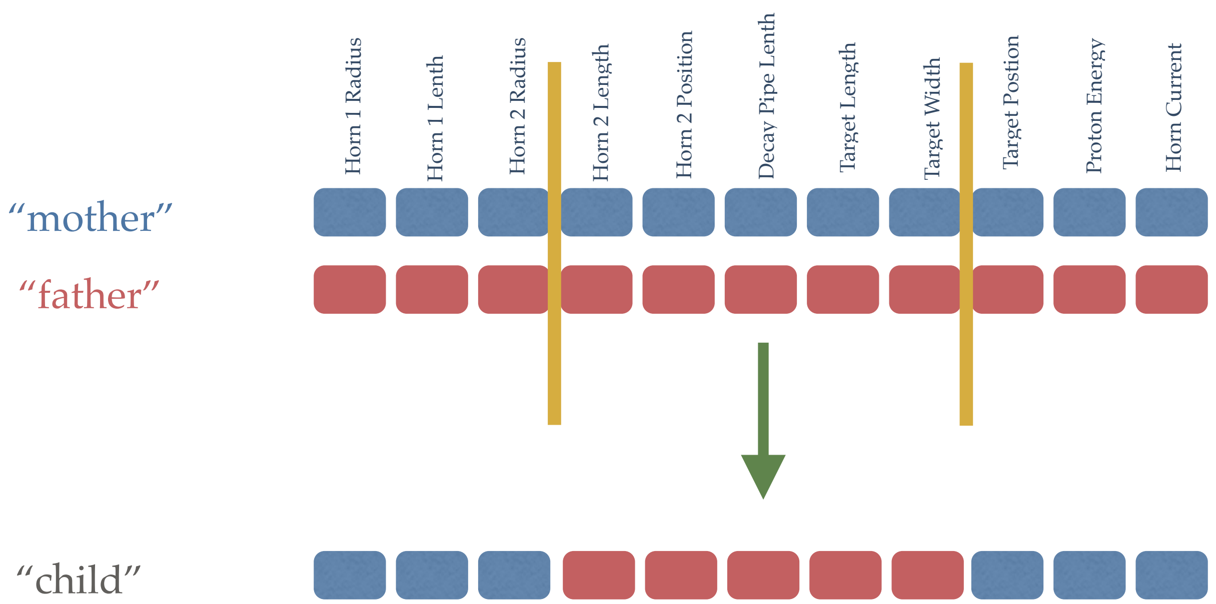
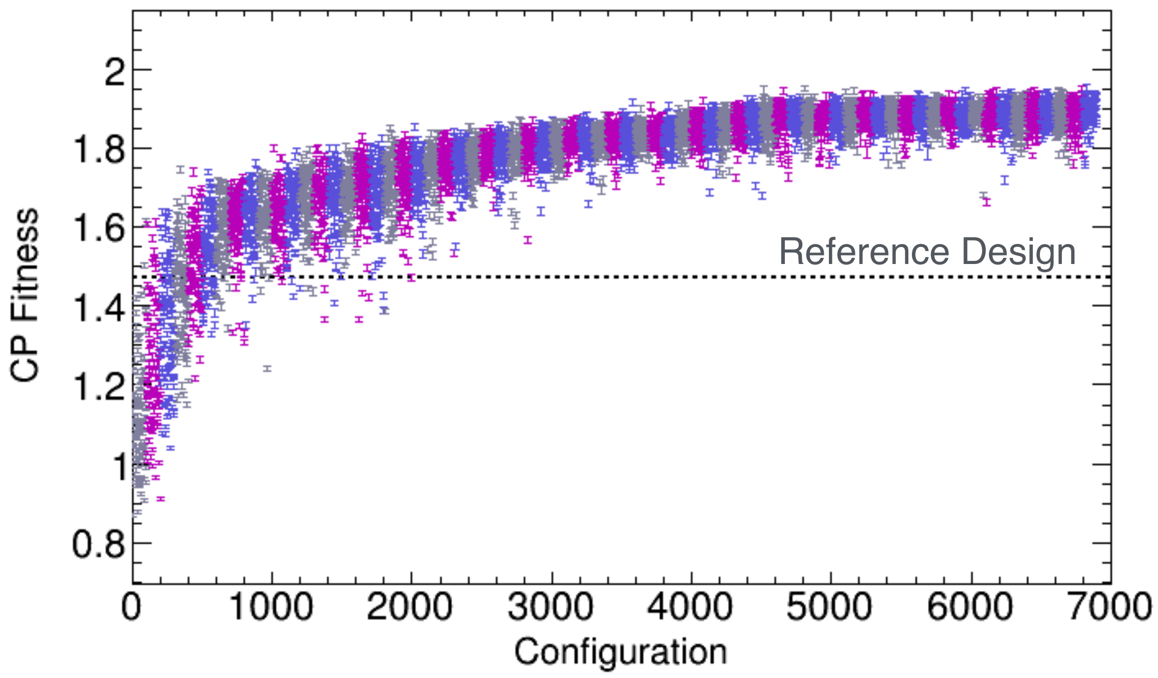




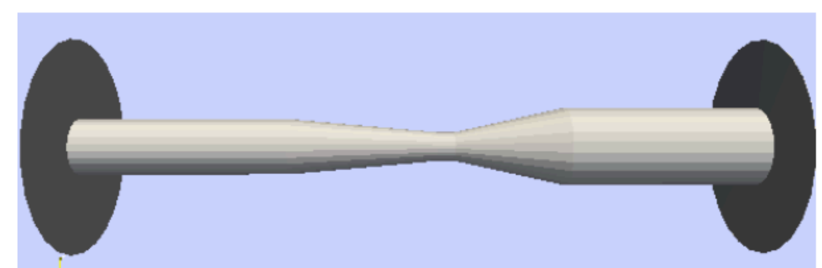
To create a new beam, we choose two well-performing beams and mix together their parameters (similar to how the a human gets half of their traits from a mother and half from a father)

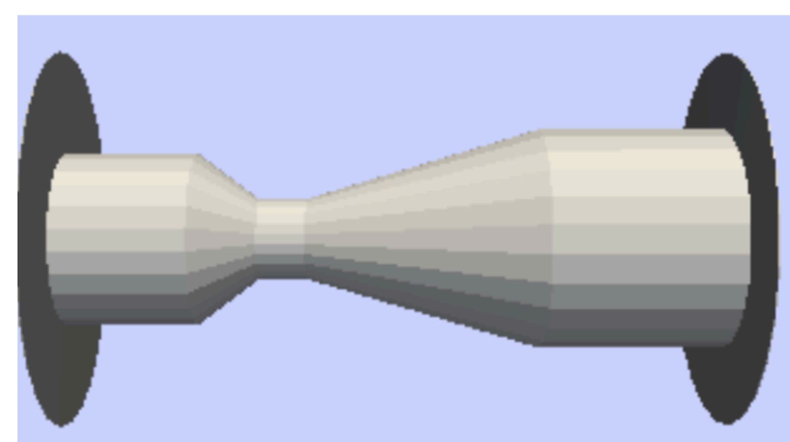
LBNF Beam Optimization

After doing this many times:

Key Features of final design

- Added an extra focusing horn
- Very long (4 m) second horn
- 2 m long target
- 300 kA horn currents





LBNF Beam Optimization

Some comparisons of the new and old beam designs:

	Optimized	Reference	Improvement vs Reference
Time to 3 sigma 75% CP sensitivity (kT MW y)	921	1577	42%
Time to 5 sigma 25% CP sensitivity (kT MW y)	293	419	30%
100 % MH coverage @ 400 kT MW y (# sigma)	6.21	4.69	33%
$\sin^2 2\theta_{13}$ resolution @ 1000 kT MW y	0.0036	0.0043	18%
$\sin^2 \theta_{23}$ resolution @ 1000 kT MW y	0.0027	0.0031	12%

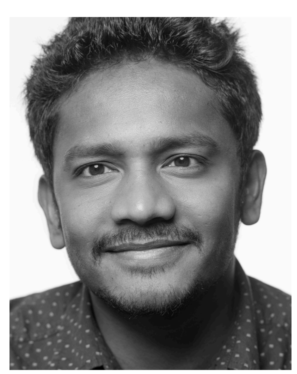
Equivalent to increasing mass of far detector by 70%, or 28 kTon!

17 kTon of Argon

Rowan Zaki
Radboud

Tyler Johnson
Duke

Jogesh Rout
Jawaharlal Nehru



Cory Crowley
Fermilab

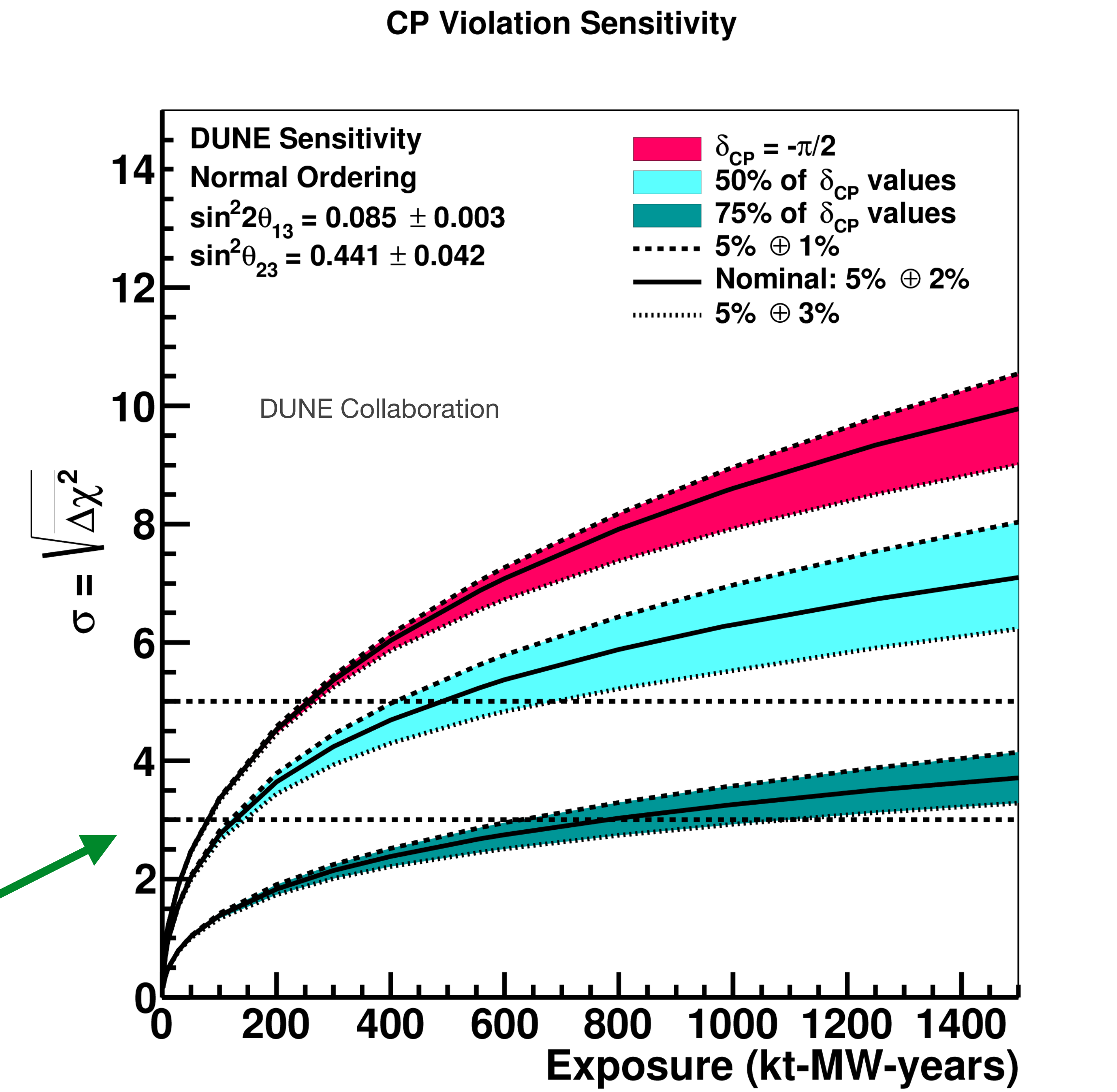
Chris Densham
RAL

Some of the engineers/students who contributed to the LBNF/DUNE beam optimization

DUNE Flux Uncertainties

The next challenge to DUNE precision: systematic uncertainty

- The beam optimization improves the statistical precision of DUNE
- DUNE's physics measurements will also be sensitive to systematic uncertainty
- These arise primarily because our measurements rely on a simulation, and when that simulation does not match reality, it will bias our measurements

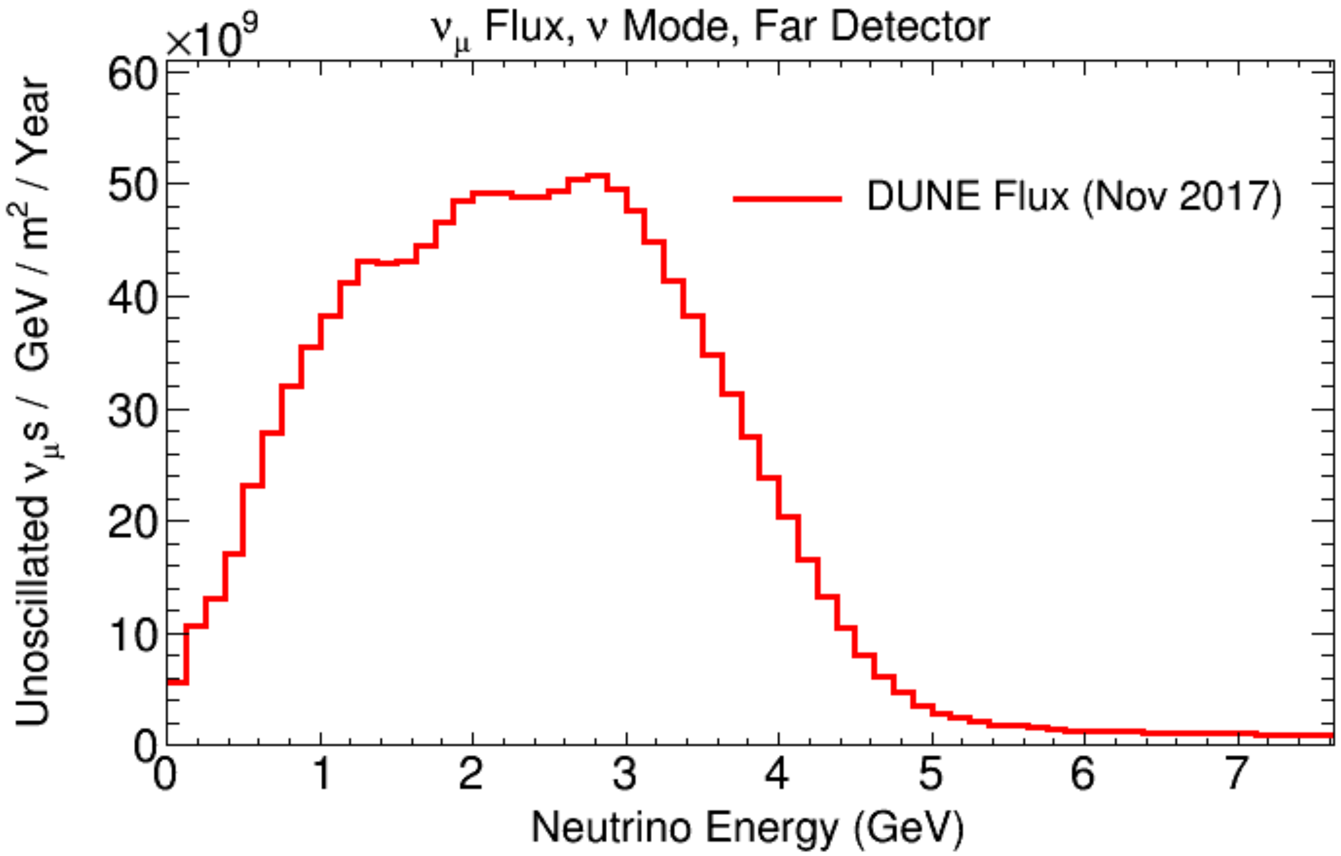


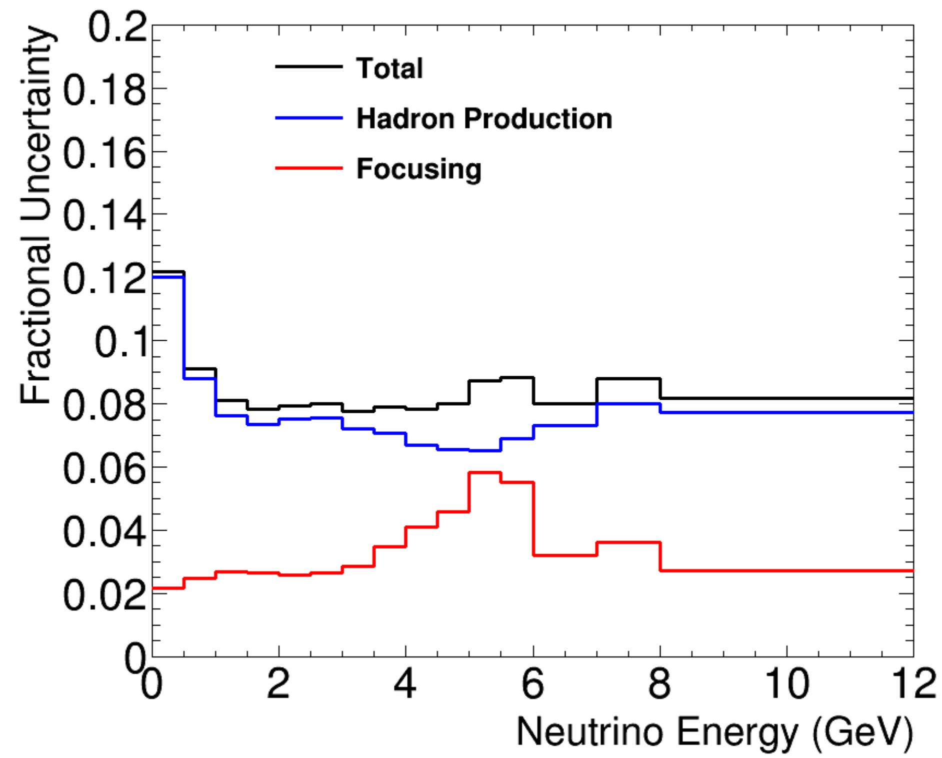
Time (in exposure) to several CP-violation measurement milestones

The width of the bands shows the difference in required exposure for several systematic uncertainty scenarios

DUNE Flux Uncertainties

Part of that systematic uncertainty comes from our simulation of the neutrino beam:





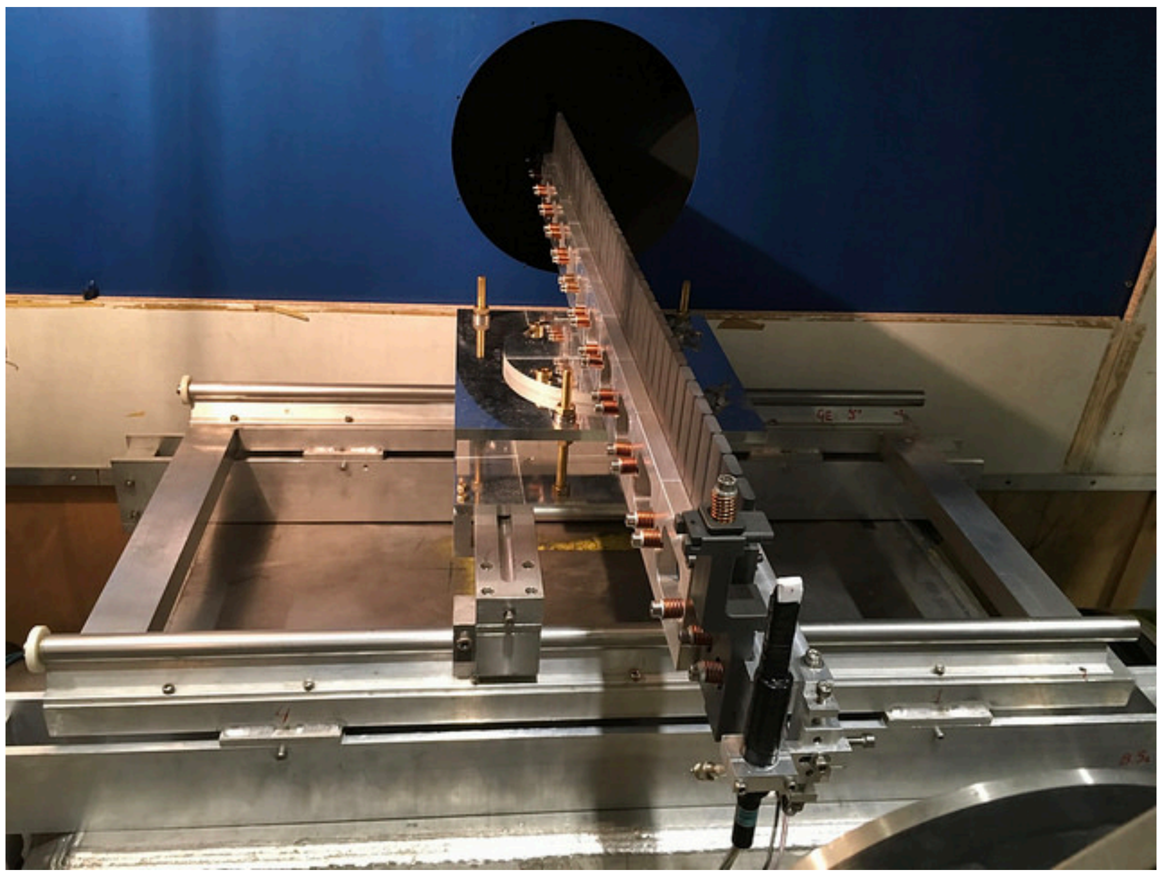
Along with a team of students, I produced the first estimates of neutrino flux uncertainties at the DUNE detectors, following path and code developed by MINERvA

Amit Bashyal
OSU

Peter Madigan
Berkeley

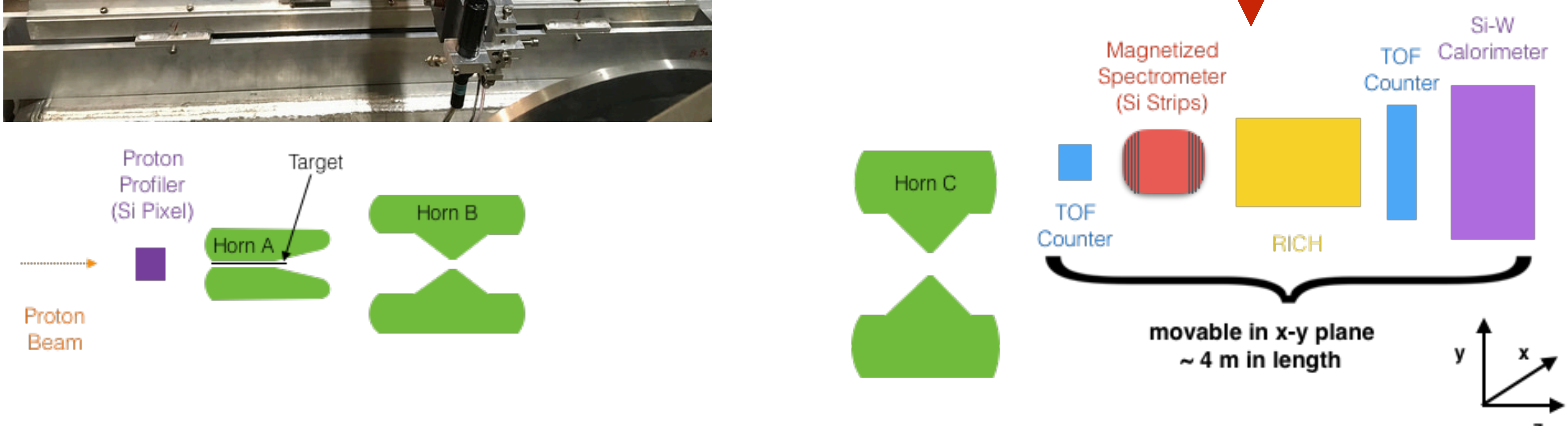
DUNE Flux Uncertainties

I am also working on lowering those uncertainties through hadron production measurements:



NuMI replica target installed in NA61 @ CERN

Strawman configuration of LBNF Spectrometer



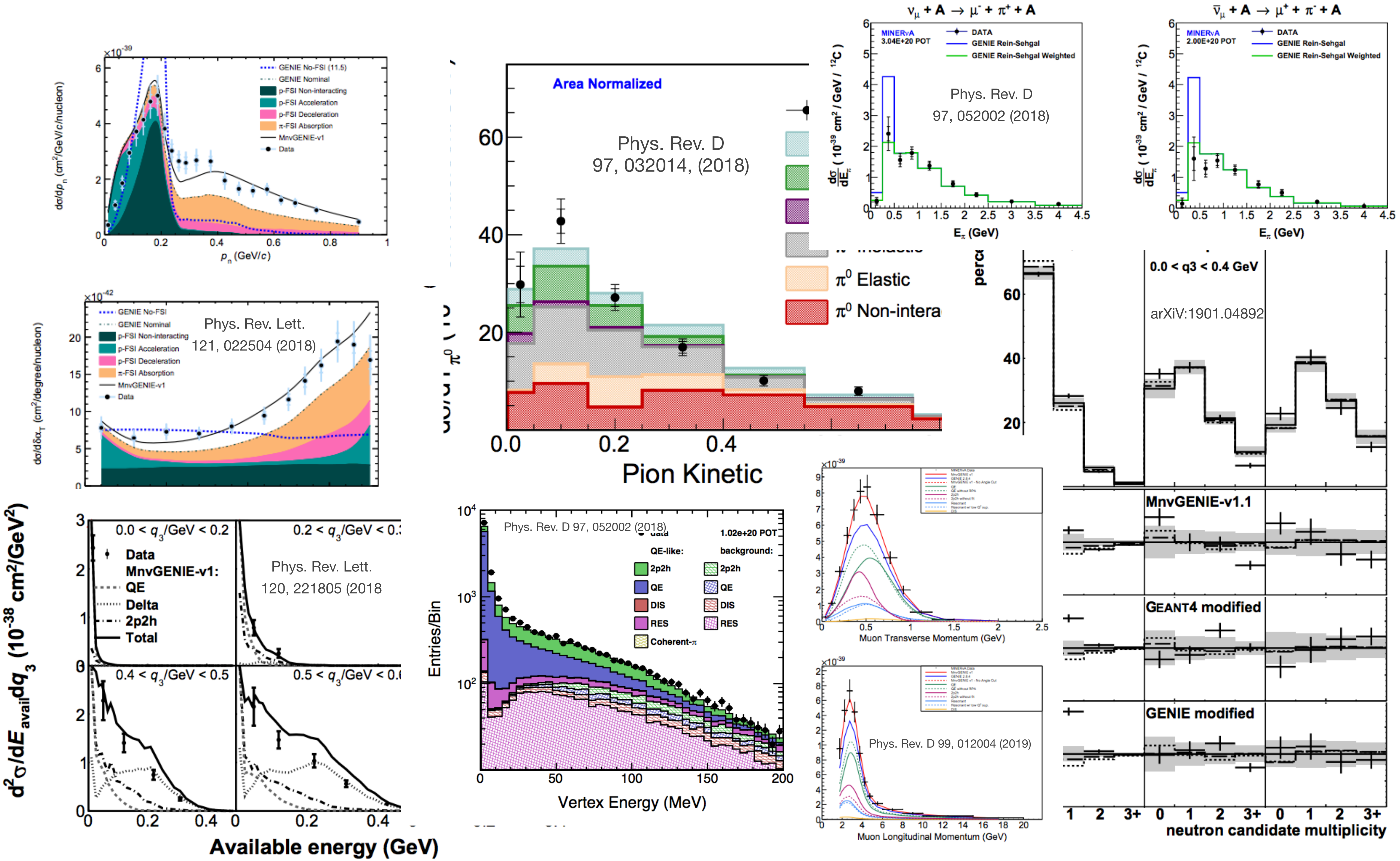
MINERvA

Another component of DUNE systematic uncertainty comes from our simulation of neutrinos interacting with Nuclei

MINERvA has been accumulating a large body of data illuminating neutrino-nucleus interactions since 2009

Please join the MINERvA end-of-run celebration tomorrow during the afternoon coffee break!

Some Recent MINERvA Measurements



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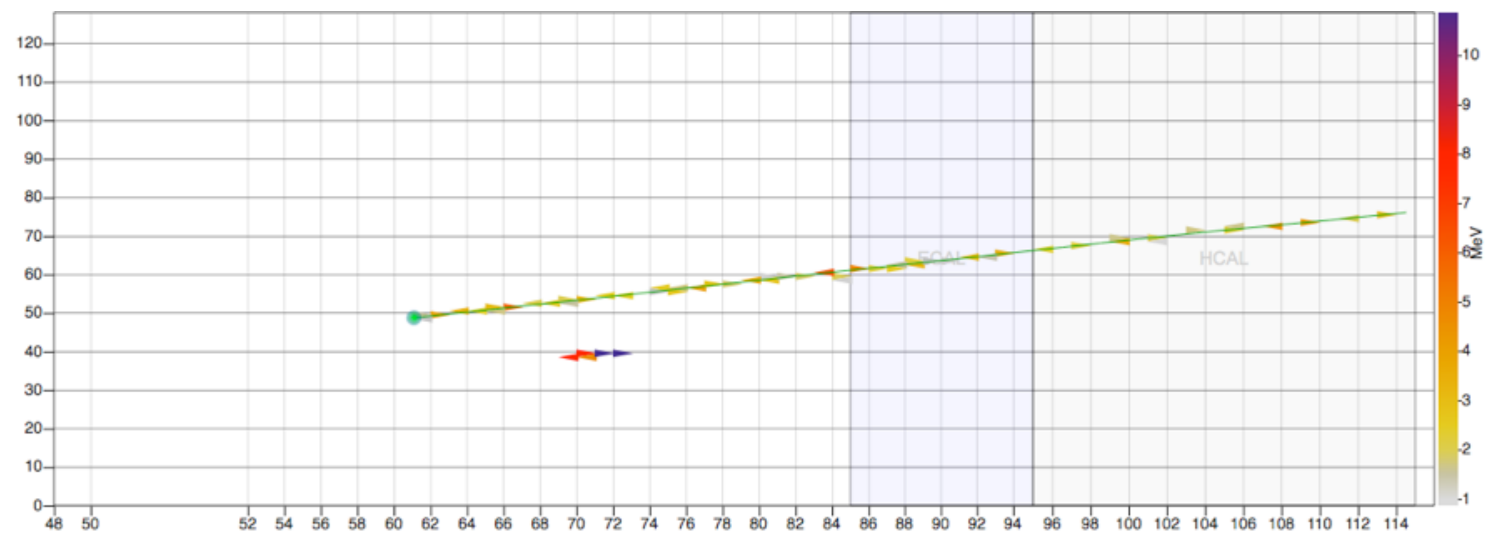
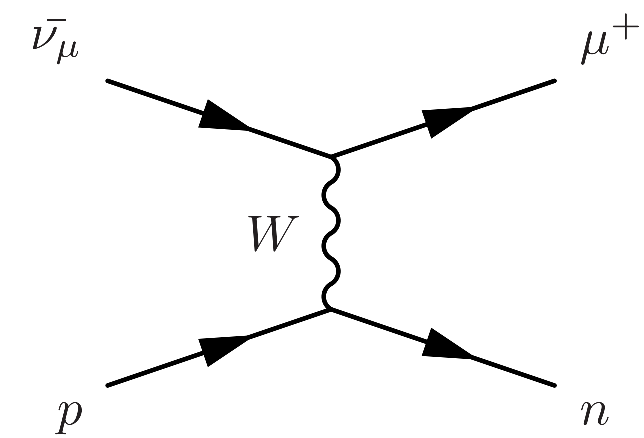
One MINERvA Measurement Close to My Heart

One of our recent measurements: Antineutrino quasi-elastic scattering

- A large portion of the rate in DUNE, NOvA and T2K
- Understanding differences between neutrinos and antineutrinos critical for measurements of CP violation

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$



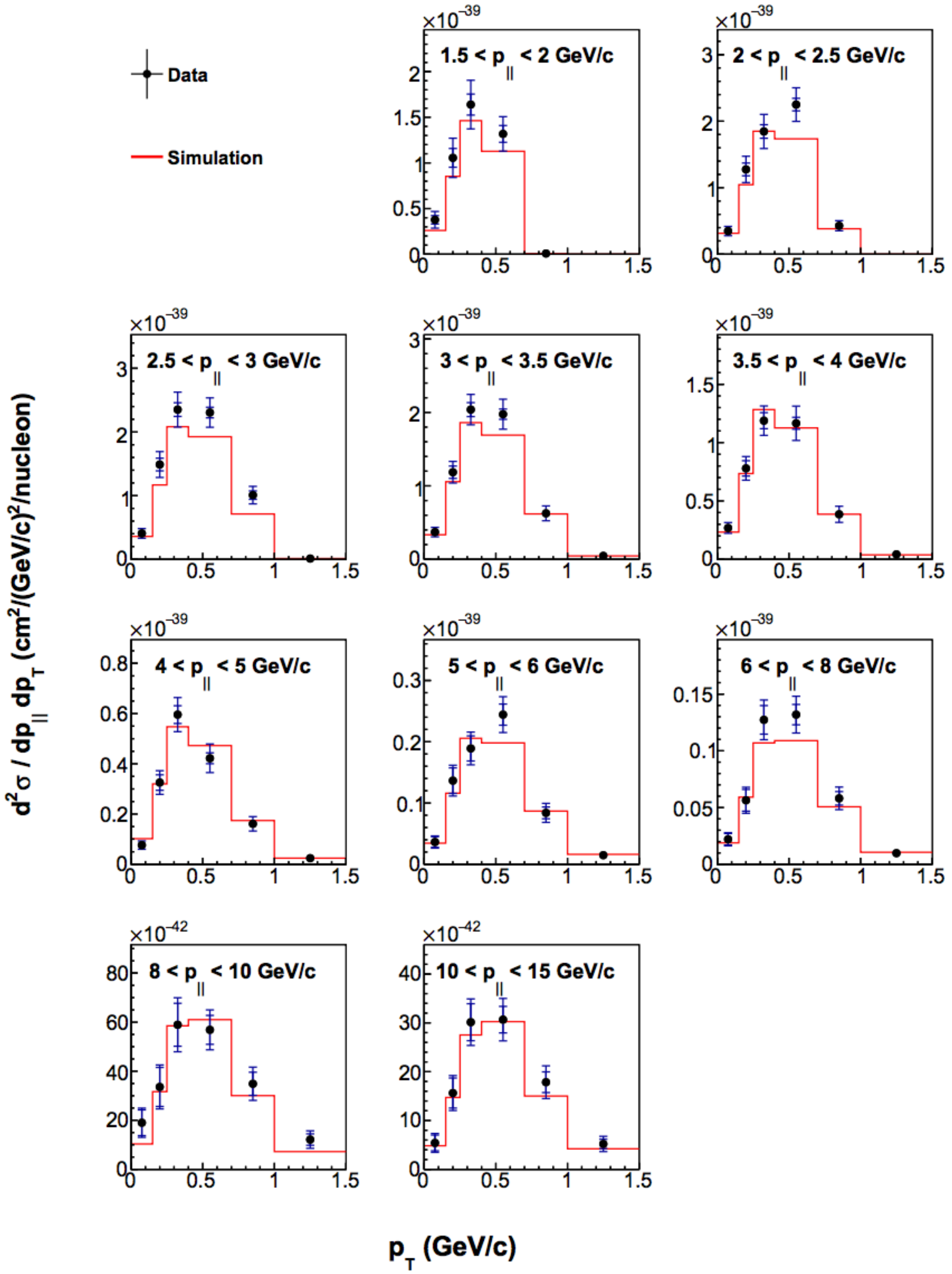


This was MINERvA's 7th(!) measurement of quasielastics; previous measurements taught us:

- There are **large problems** with the models of quasi-elastic scattering that had been used for decades
- The discrepancies appear to be coming from **effects associated with neutrino interactions occurring within dense nuclei**
- New treatments of **weak charge screening and interactions on multi-nucleon bound states** are necessary for good agreement with data

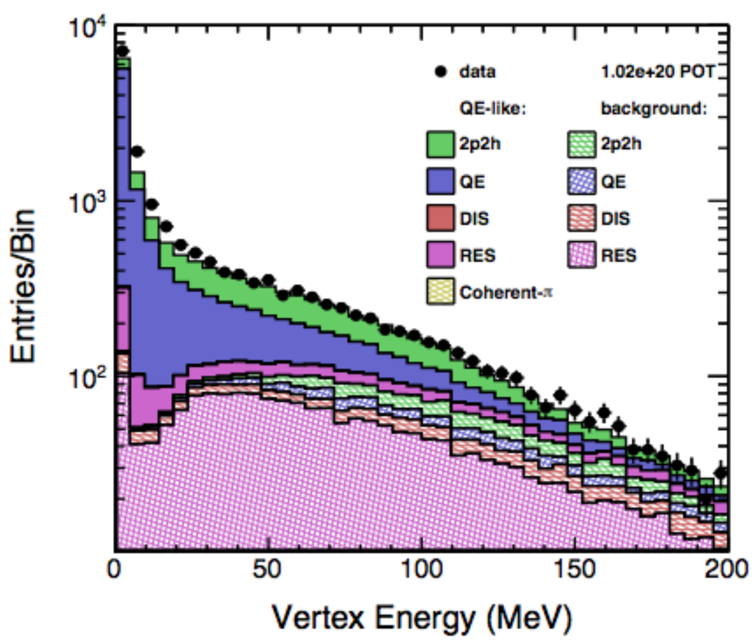
One MINERvA Measurement Close to My Heart

Cheryl Patrick
UCL



Phys. Rev. D 97, 052002 (2018)

- We produced a new double-differential measurement of muon kinematics and compared it to a model tuned with neutrino (not antineutrino) measurements
- We find that the model changes needed to model neutrino mode also agree well with antineutrino data
- There was no a priori reason to assume that this would be the case



Energy near the vertex in antineutrino quasi-elastic candidates; very sensitive to nuclear effects

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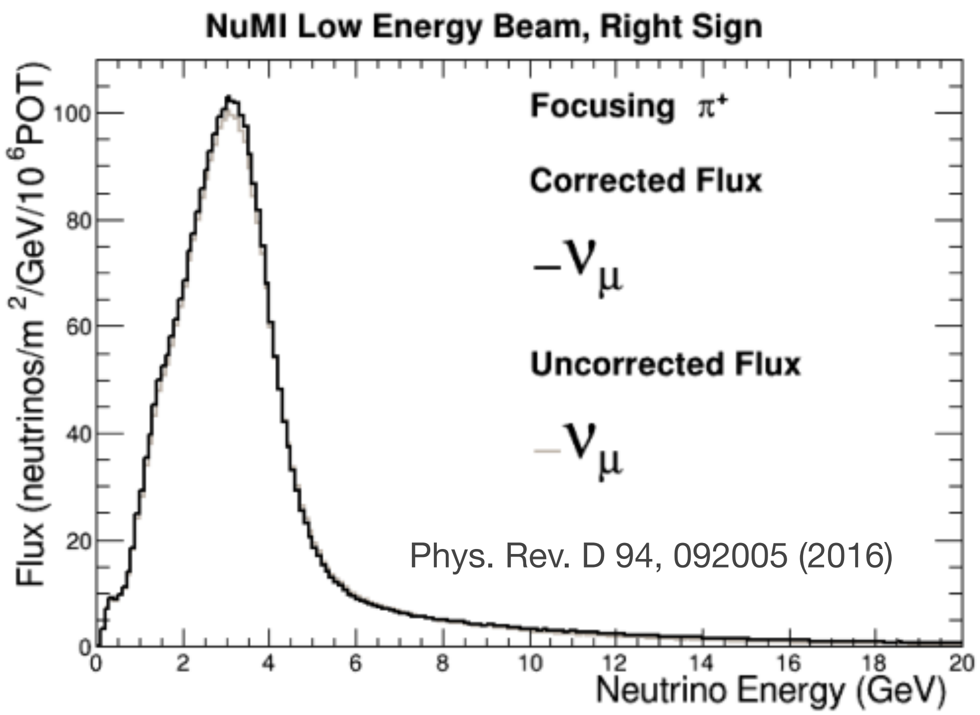
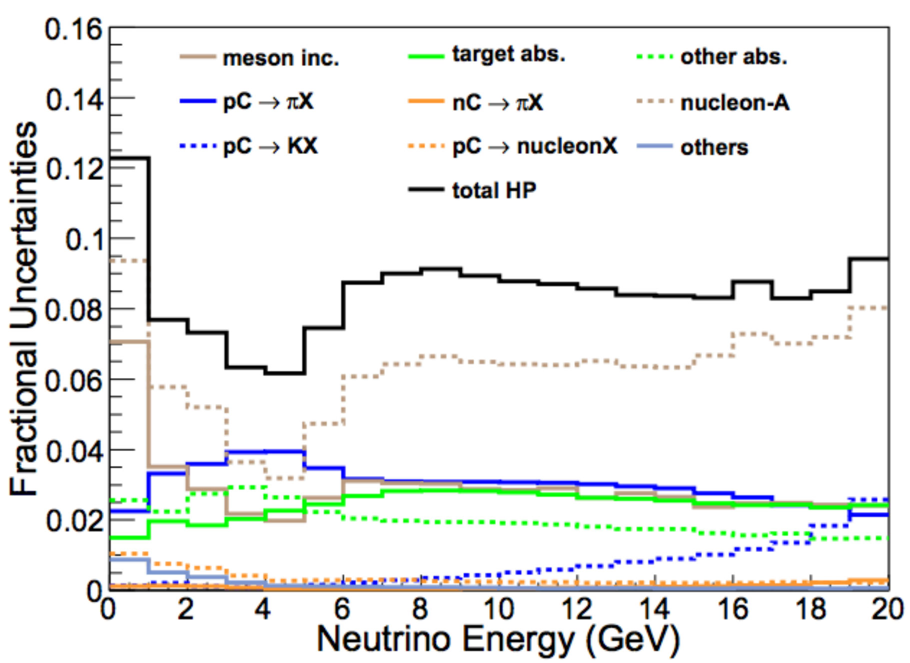
MINERvA Flux Uncertainties

MINERvA is also a leader in neutrino beam modeling:





- MINERvA has developed machinery ("PPFX") for tuning neutrino flux predictions using external hadron production data

Thanks Leo!

- This machinery is now used by several experiments.
- It was extended to produce the DUNE flux uncertainty estimates I mentioned earlier

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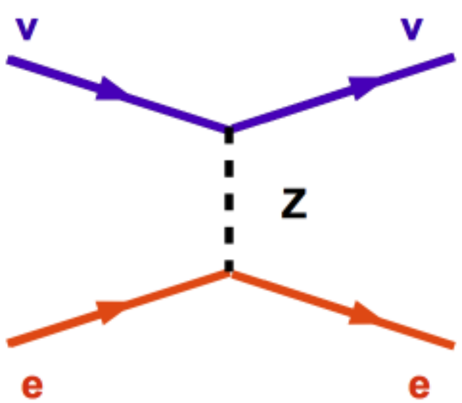
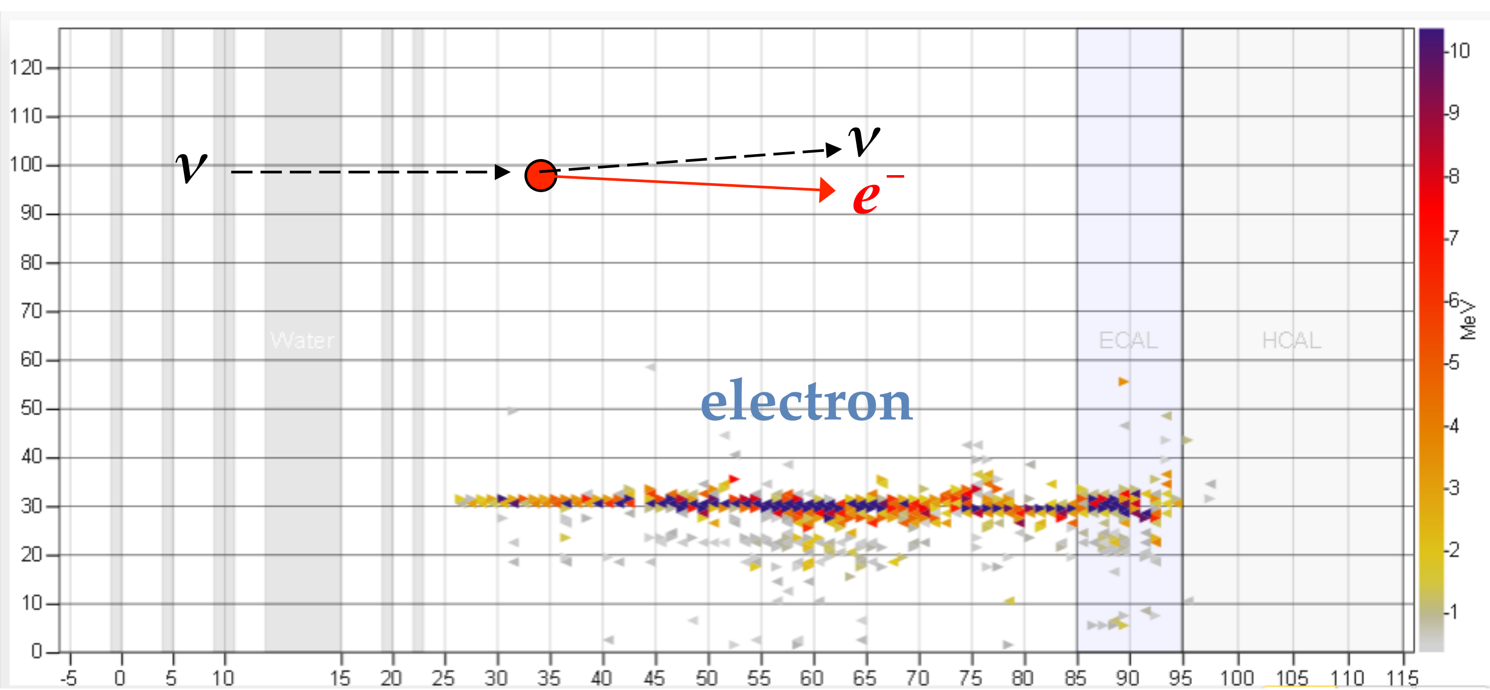
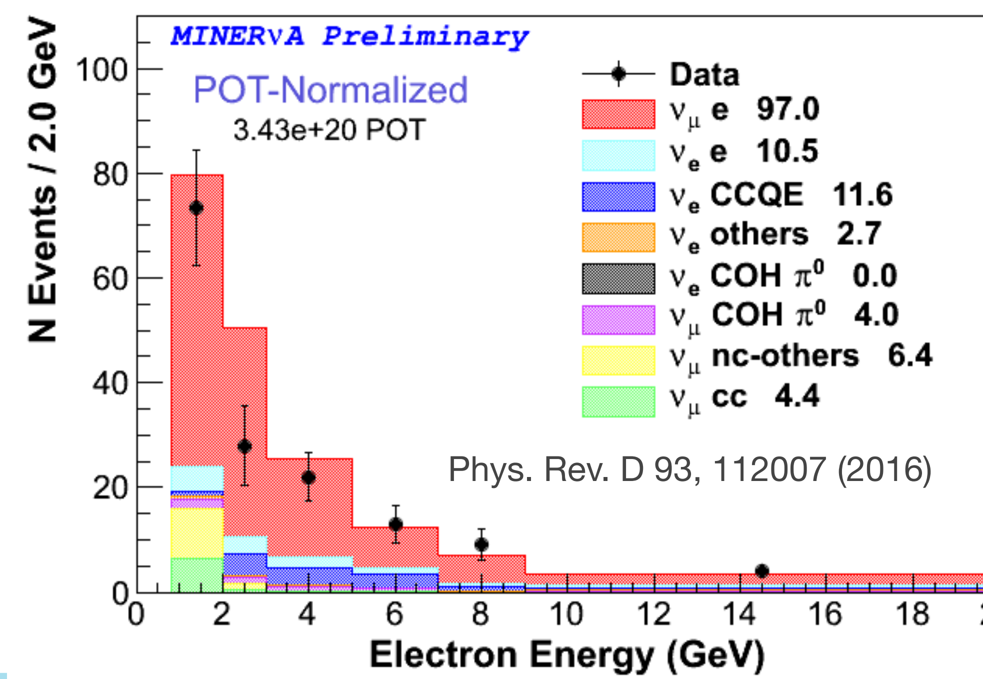
MINERvA Neutrino Electron Scattering

MINERvA has pioneered the use of neutrino electron scattering in measuring neutrino beams



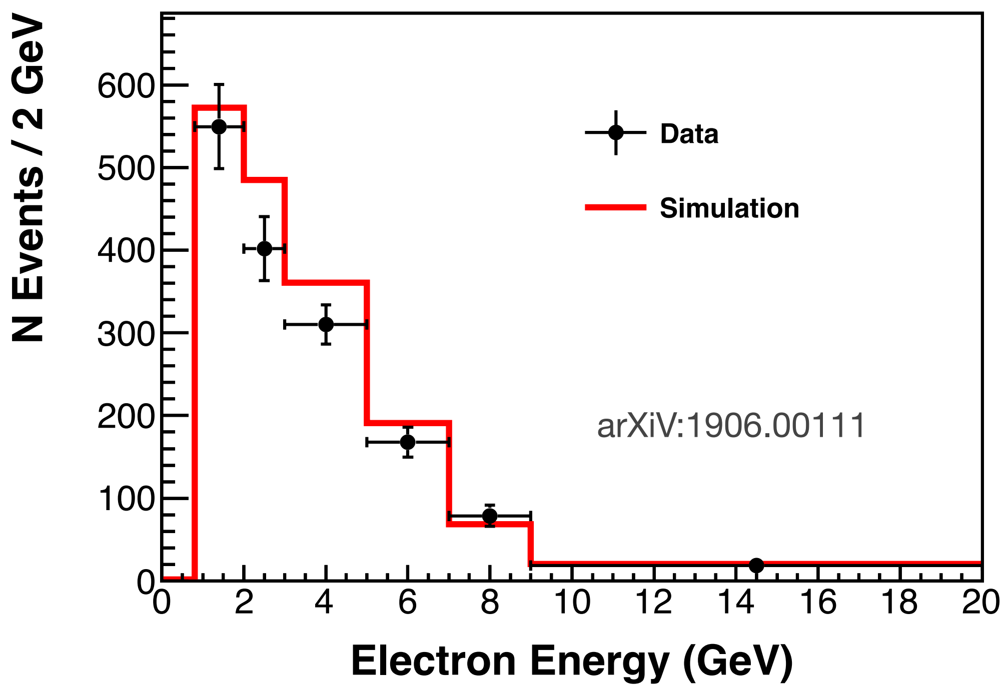
- Standard electroweak theory predicts it precisely
- Can be used as a standard candle to measure neutrino flux
- Signature is a single electron nearly collinear with beam -> good angular resolution is essential
- 1st measurement had 135 events, lowered flux uncertainty from 9% to 6%





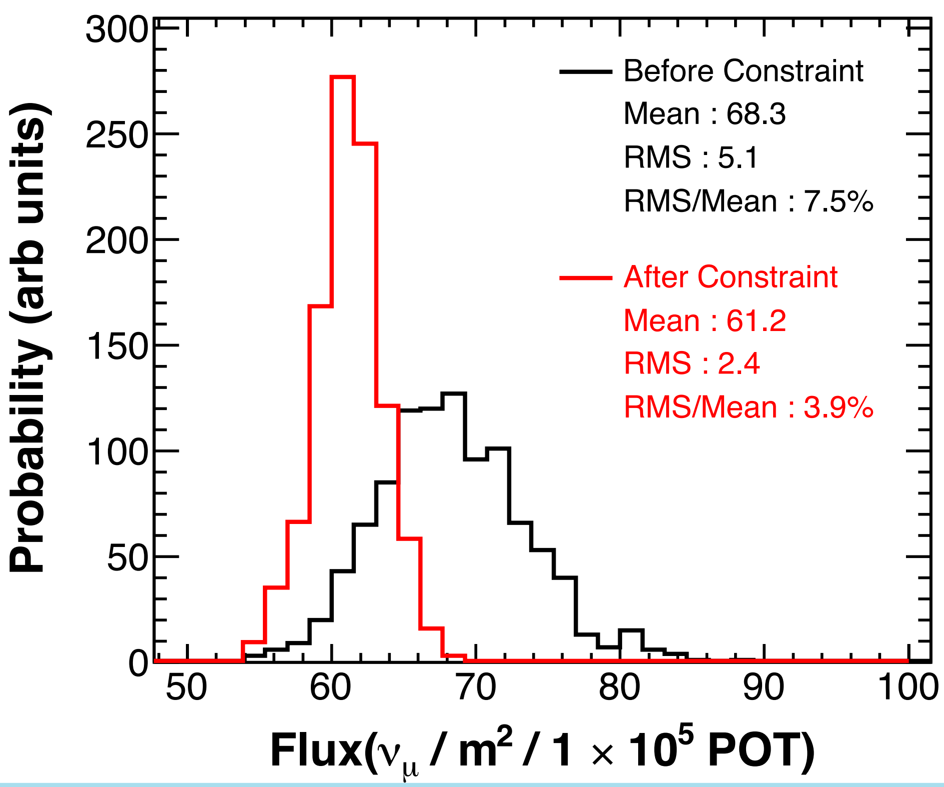
MINERvA Neutrino Electron Scattering

NEW! Measurement in the NuMI Medium Energy Beam:



Source	Uncertainty (%)
Beam	0.21
Electron Reconstruction	0.57
Interaction Model	1.68
Detector Mass	1.40
Total Systematic	2.27
Statistical	4.17
Total	4.75

- 1188 (order of magnitude more statistics) events after background subtraction and efficiency correction
- Lower systematic uncertainties (~2%!)
- Uncertainty on muon neutrino flux between 2 and 20 GeV lowered from 7.5% to 3.9%
- Meets the < 5% goal MINERvA set in its proposal!



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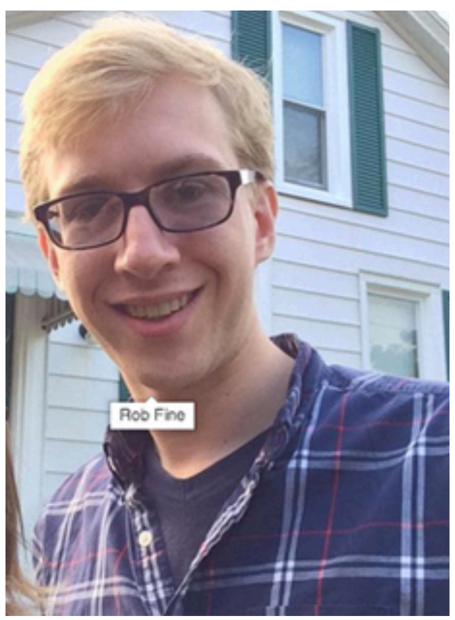
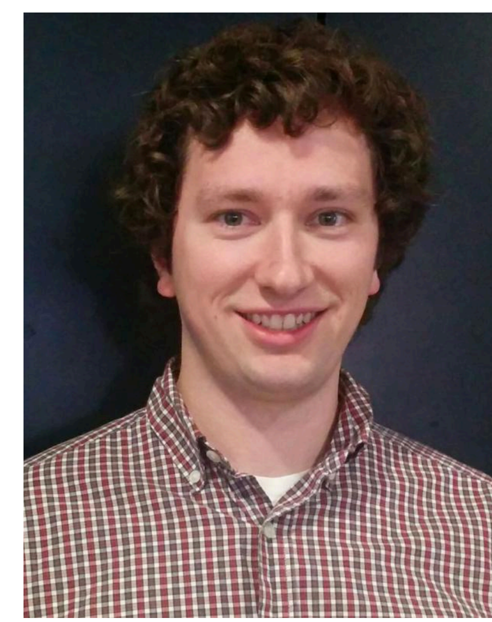
Conclusion

- **Precision measurement of neutrino** mixing (similar to what has been done with quark mixing) will potentially tell us a lot about the universe
- Neutrino physics faces **a lot of challenges** that quark physics doesn't
- Since joining Fermilab in 2015, I have concentrated on two of obstacles to precision accelerator-based neutrino measurements: **understanding of neutrino beams and neutrino-nuclear interactions** as a member of MINERvA and DUNE
- Hear more about MINERvA and DUNE tomorrow afternoon!



	15:10	**MINERvA: A neutrino-scattering experiment** *20'* Speaker: Rob Fine (University of Rochester)
15:30 - 16:00	MINERvA End-of-Operations Celebration	
16:00 - 18:00	Session VIII Convener: Dr. Gavin S. Davies (Indiana University)	
	16:00	**DUNE: Deep Underground Neutrino Experiment** *20'* Speaker: Dr. Chris Marshall (Lawrence Berkeley National Laboratory)



Thank You!