

Bryan Ramson (he/him/his), Pedro Machado, Lisa Kaufman
September 4, 2022
Neutrino Division
Fermilab

Join us at

INTERSECTIONS

~~May 30 - June 5, 2022~~

Lake Buena Vista, Fla

August 29-
September 4

14th Conference on the Intersections of Particle and Nuclear Physics
Neutrino Summary

The Conference at a Glance

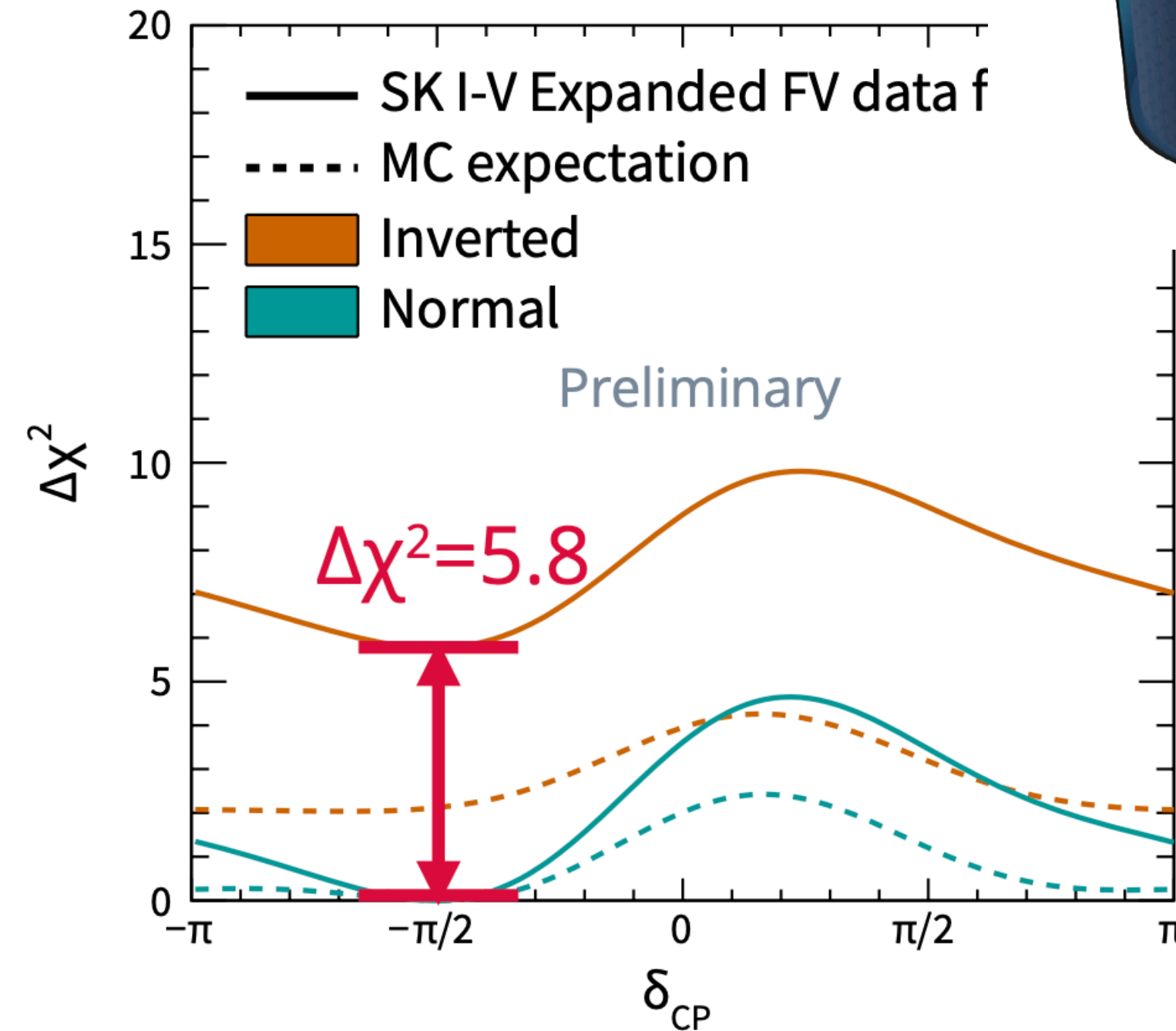
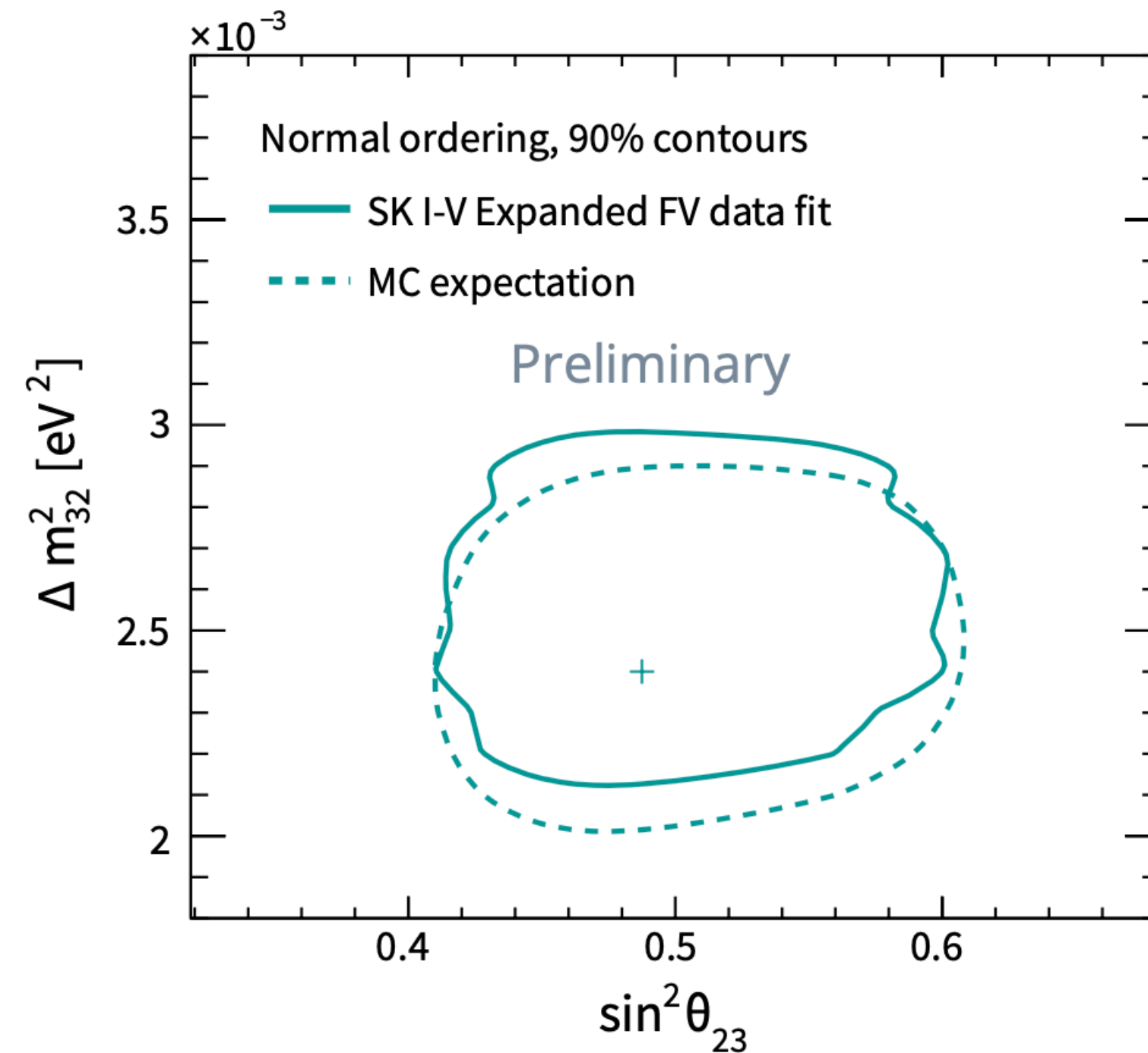
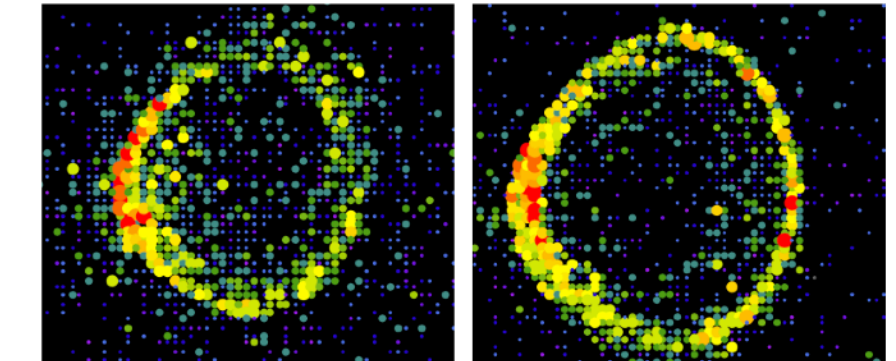
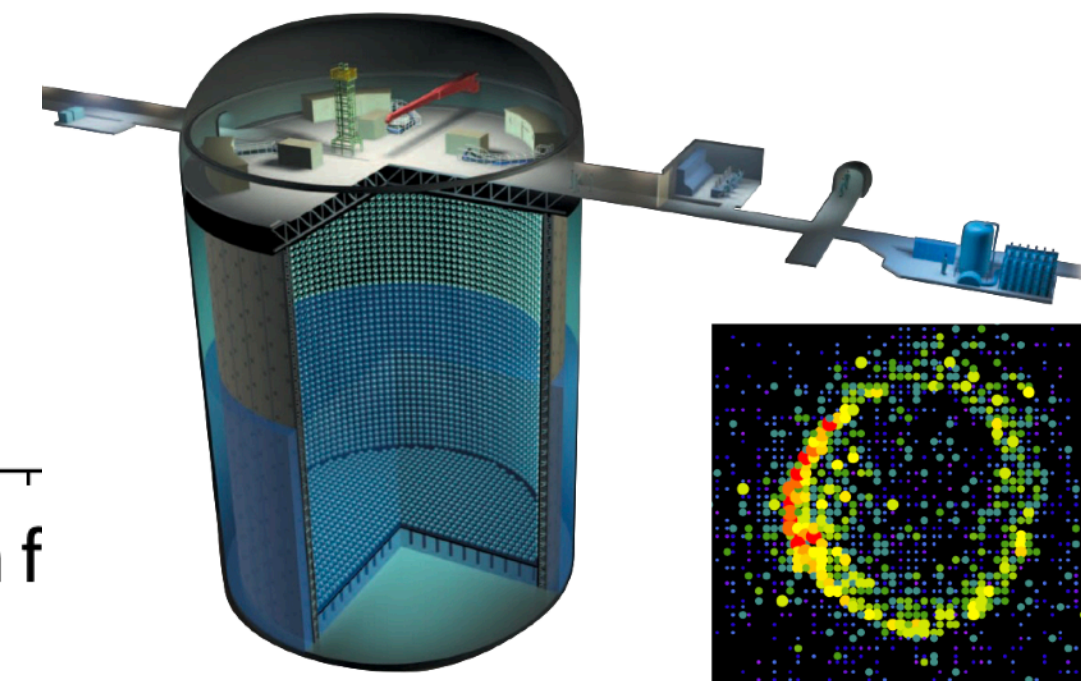
A Broad Range of Topics and Participants in Neutrinos!

- Five overarching topics:
 - “Standard” Oscillation Physics *and Beyond!*
 - Neutrino-Nucleus *Scattering and Cross Sections*
 - Neutrino *Anomalies and Dark Matter*
 - Neutrino *Astrophysics & Cosmology*
 - Neutrino *Properties (Majorana and Mass)*
- 27 Different Speakers gave 28 unique talks:
 - 23 different institutions
 - 4 countries represented institutionally
 - 5 feminine identifying and 21 masculine identifying (as far as I know...)
 - Nationality and ethnicity/race of speakers was reasonably diverse

“Standard” Oscillation Physics and Beyond

- Reports from:
 - Thomas Wester on Oscillations in Atmospheric Neutrinos from Super-Kamiokande
 - Denver Whittington on Oscillations in Accelerator Neutrinos from NOvA
 - Rupert Leitner on Reactor Neutrino Oscillations from Daya Bay
 - Tanaz Mohayai on Future Oscillations Experiments

Thomas Wester on Super-Kamiokande 2022 Results



Best fits	χ^2	$ \Delta m^2_{31} $ [eV ²]	$\sin^2\theta_{23}$	δ_{CP}
Normal	1000.42	2.4×10^{-3}	0.49	4.71
Inverted	1006.19	2.4×10^{-3}	0.49	4.71

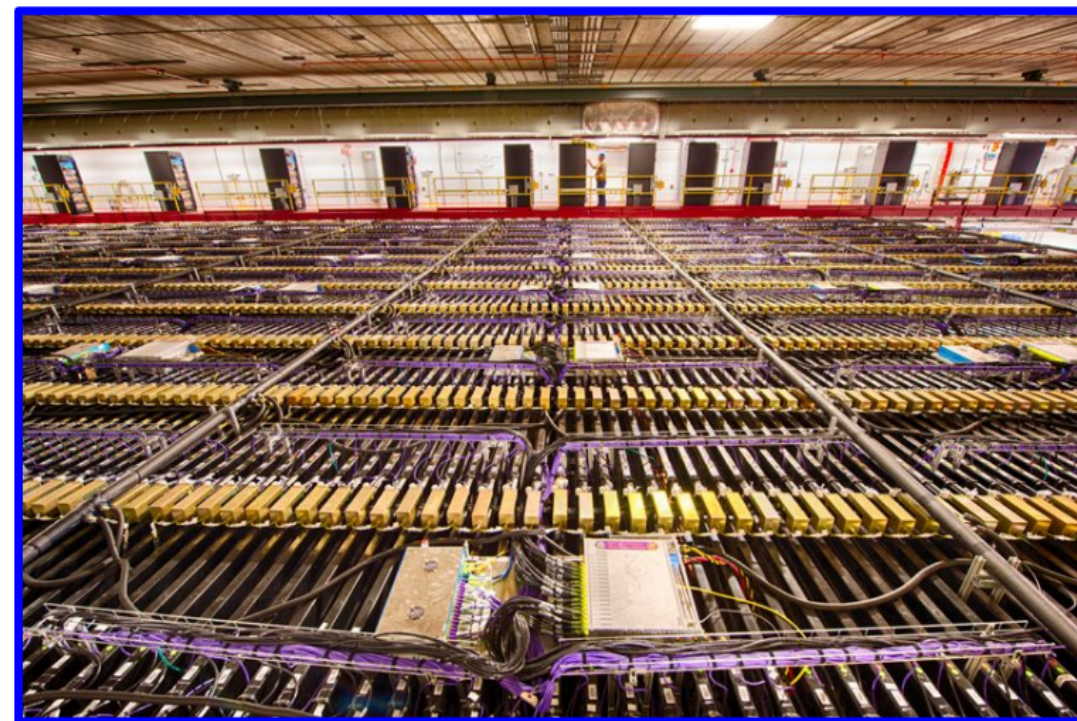
08/30/2022

SK Atmospheric Neutrino Oscillation • Thomas Wester • CIPANP 2022

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Identical values for θ_{23} and δ_{CP} fits slightly prefer the normal hierarchy!

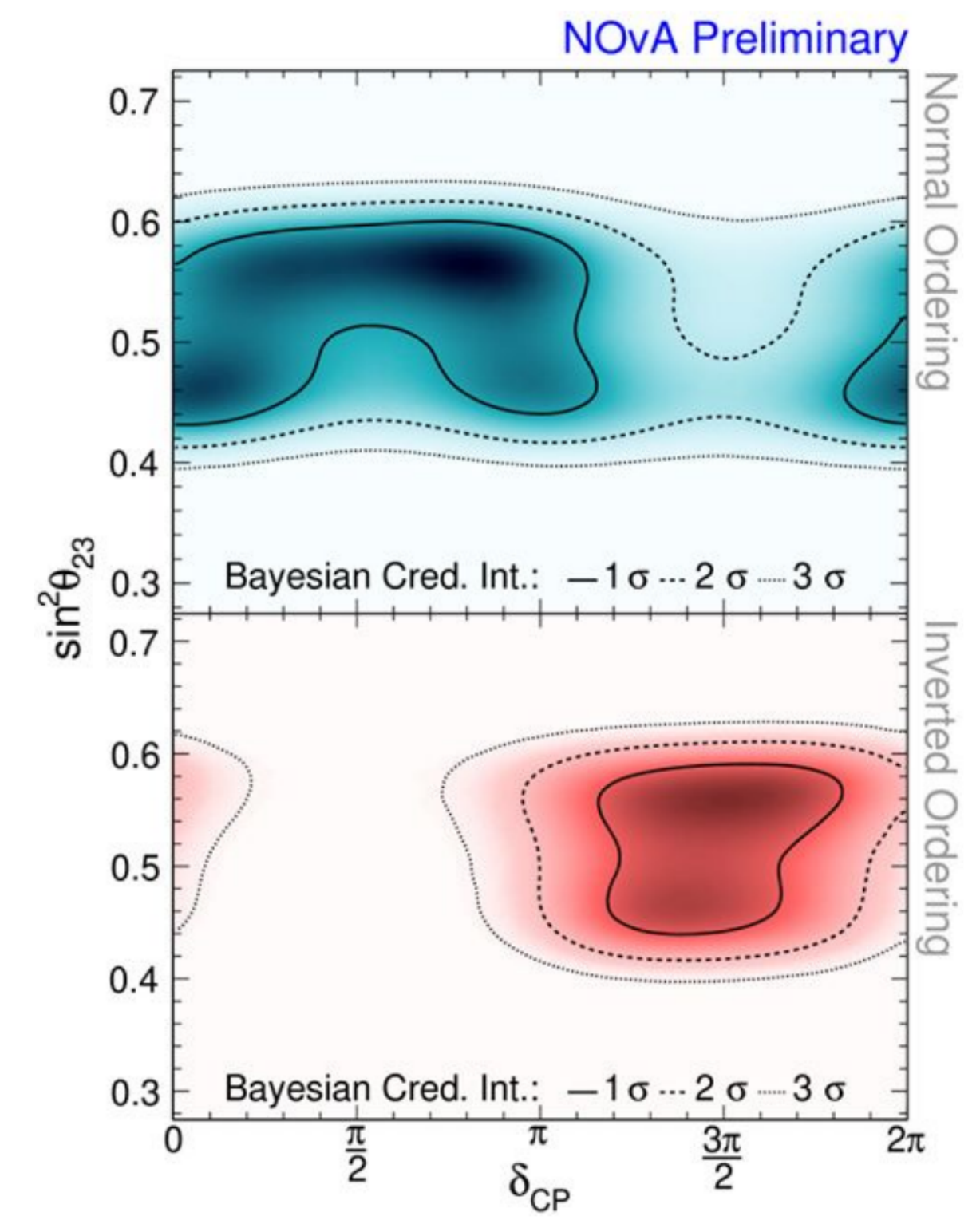
Denver Whittington on Oscillations in Accelerator Neutrinos from NOvA



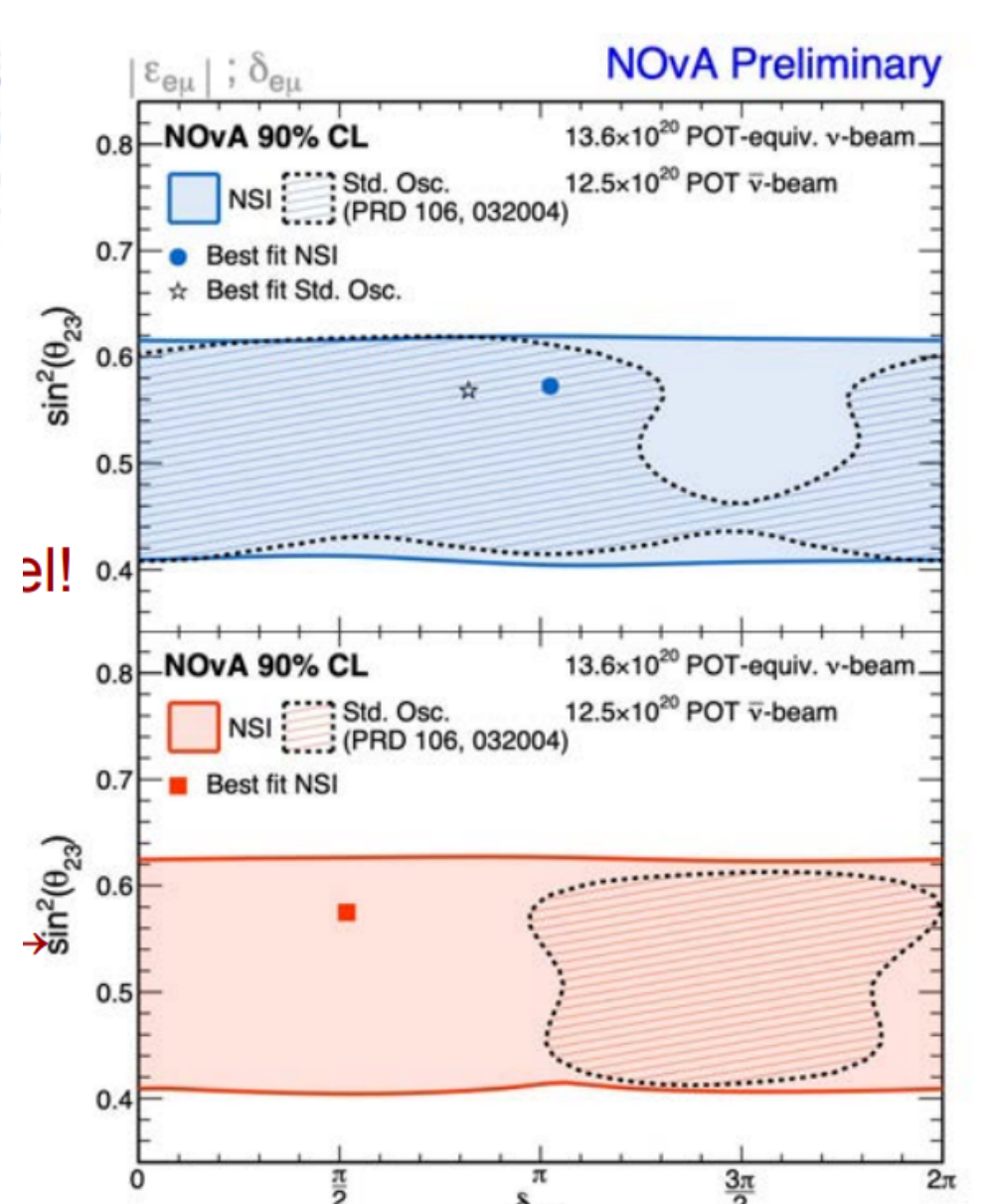
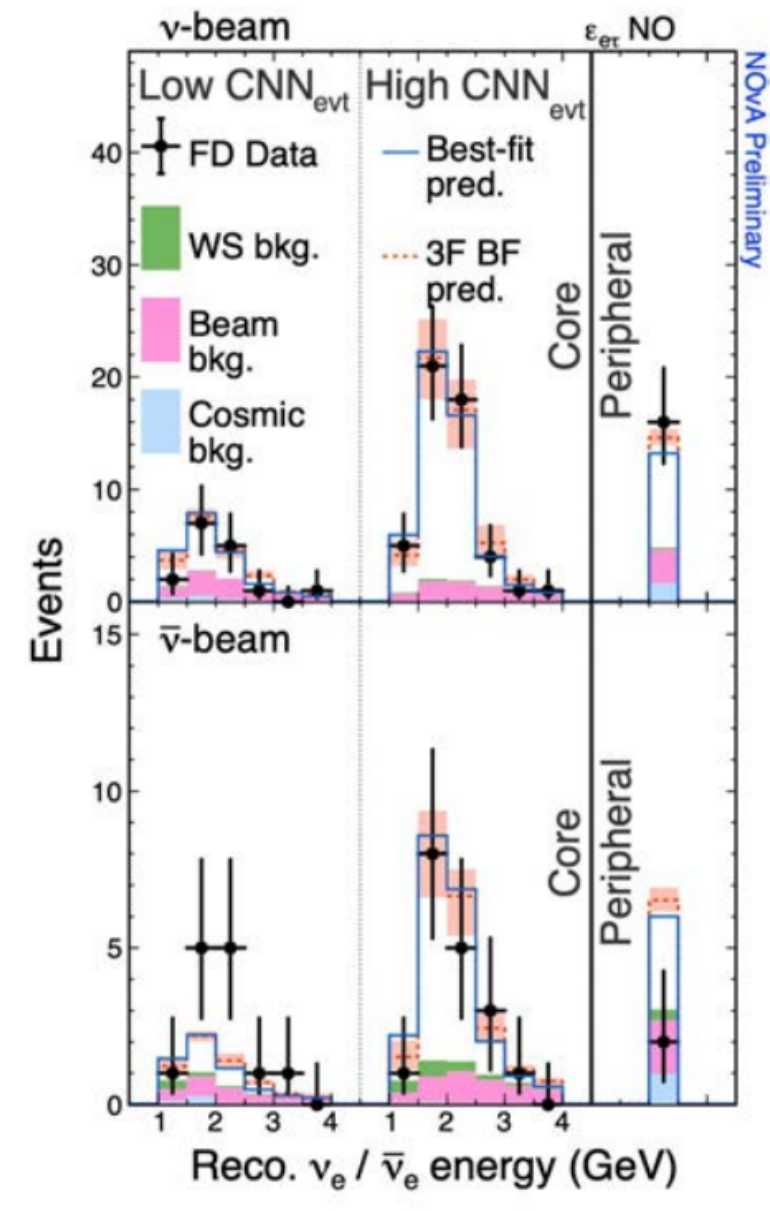
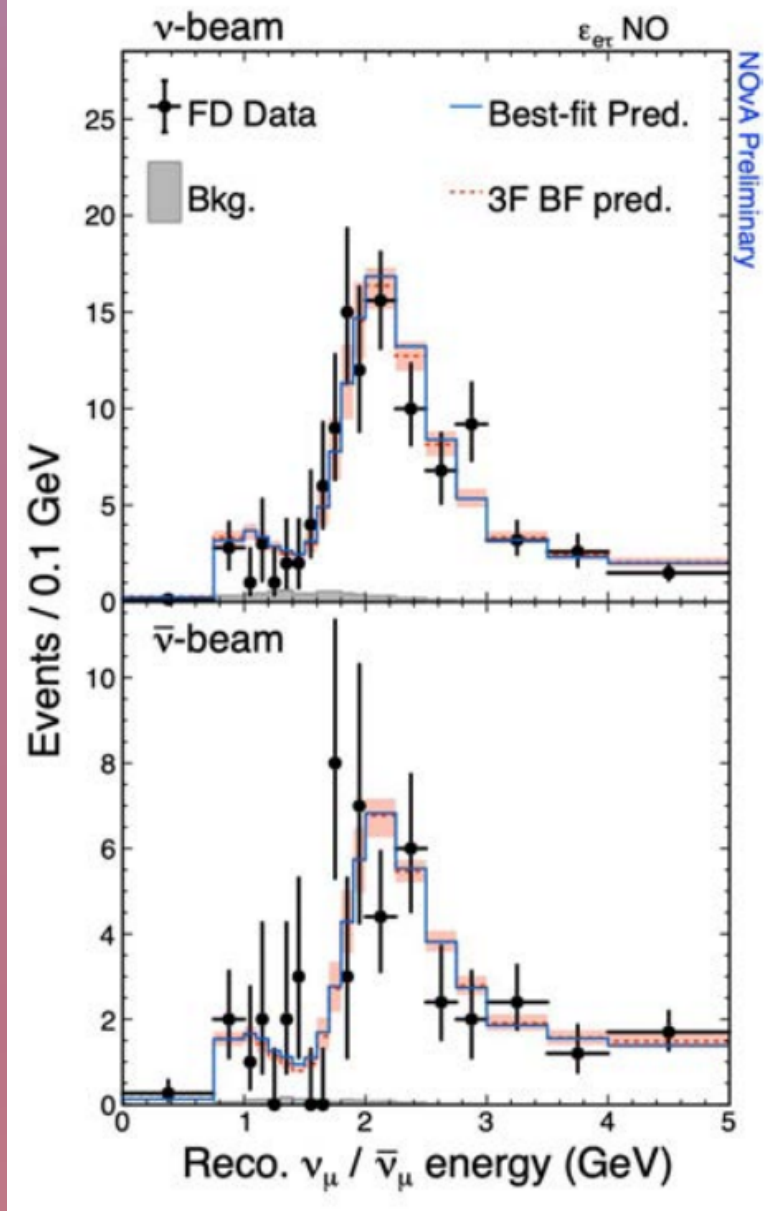
Markov Chain MC Bayesian Analysis
alternative statistical approach to previous frequentist analyses

- Allows results to be examined in new ways
- Conclusions the same as frequentist results
- Exclude (Inverted Ordering, $\delta = \pi/2$) at $> 3\sigma$

Best Fit
 Normal hierarchy
 $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2$
 $\sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03}$
 $\delta = 0.82\pi$ (frequentist results)



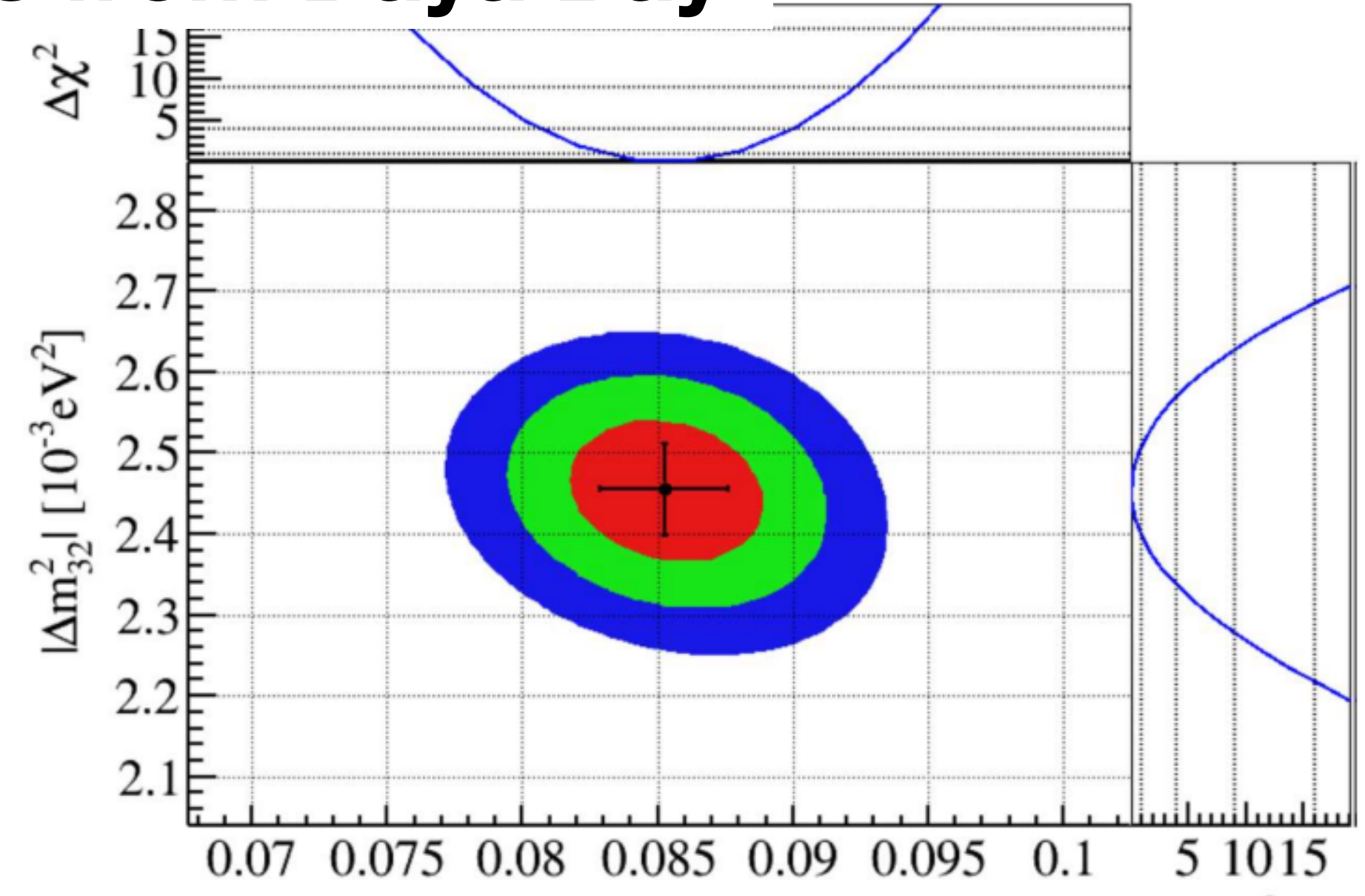
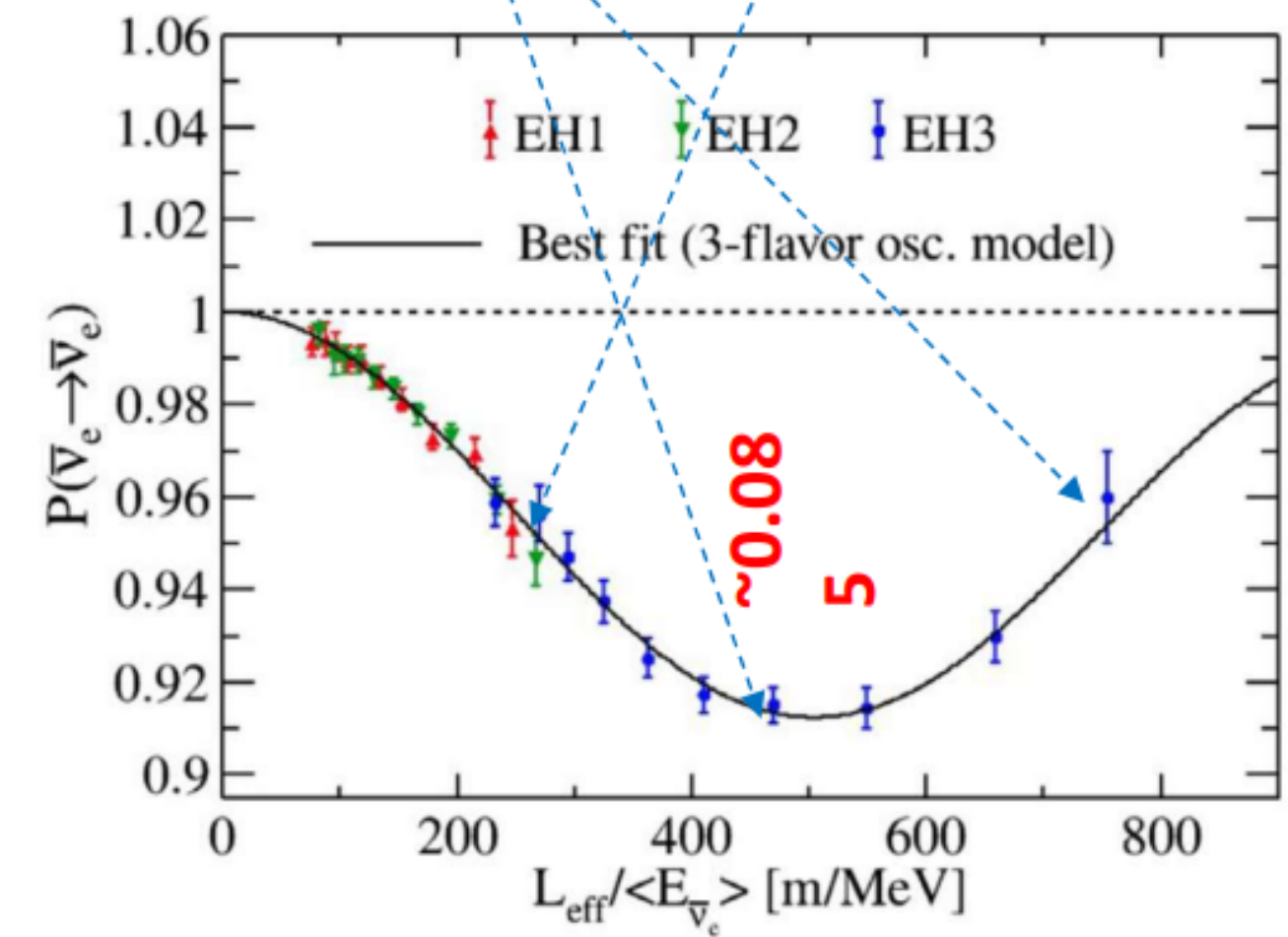
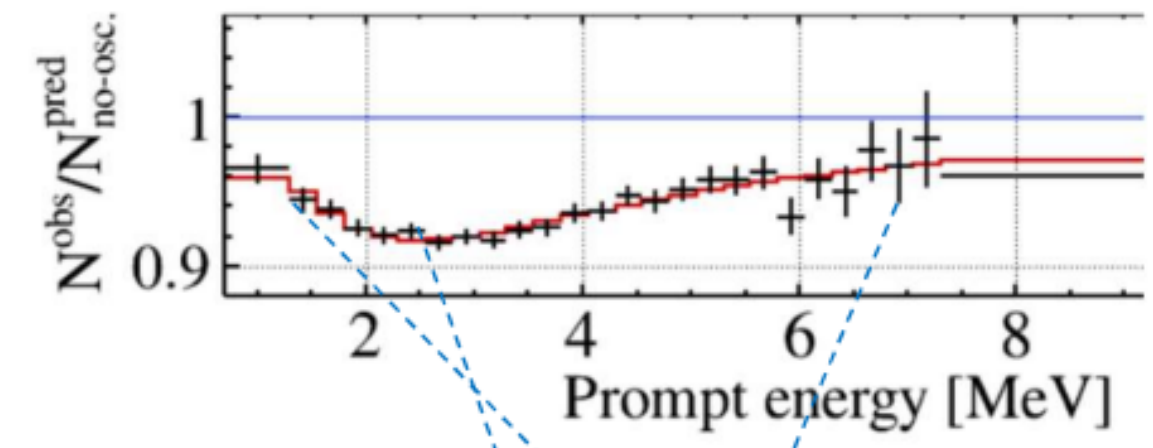
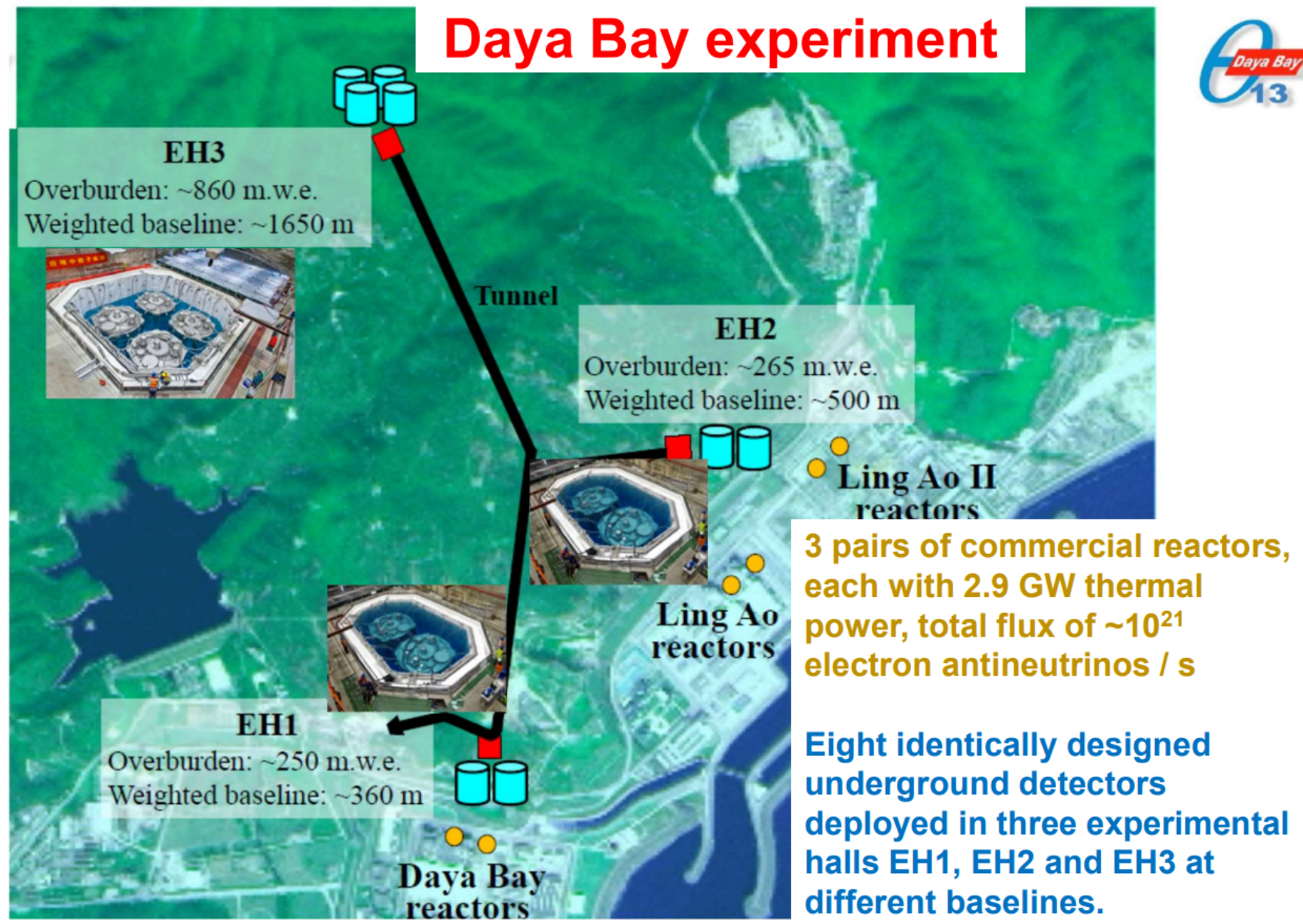
Recent Results from NOvA



Bayesian analysis agrees with frequentist analysis!
NSI Interactions Analysis consistent with standard oscillations analysis but would lead to major reinterpretation of the initial results.

Rupert Leitner on Latest Results in Reactor Neutrinos from Daya Bay

Daya Bay experiment



$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

Normal Mass Ordering

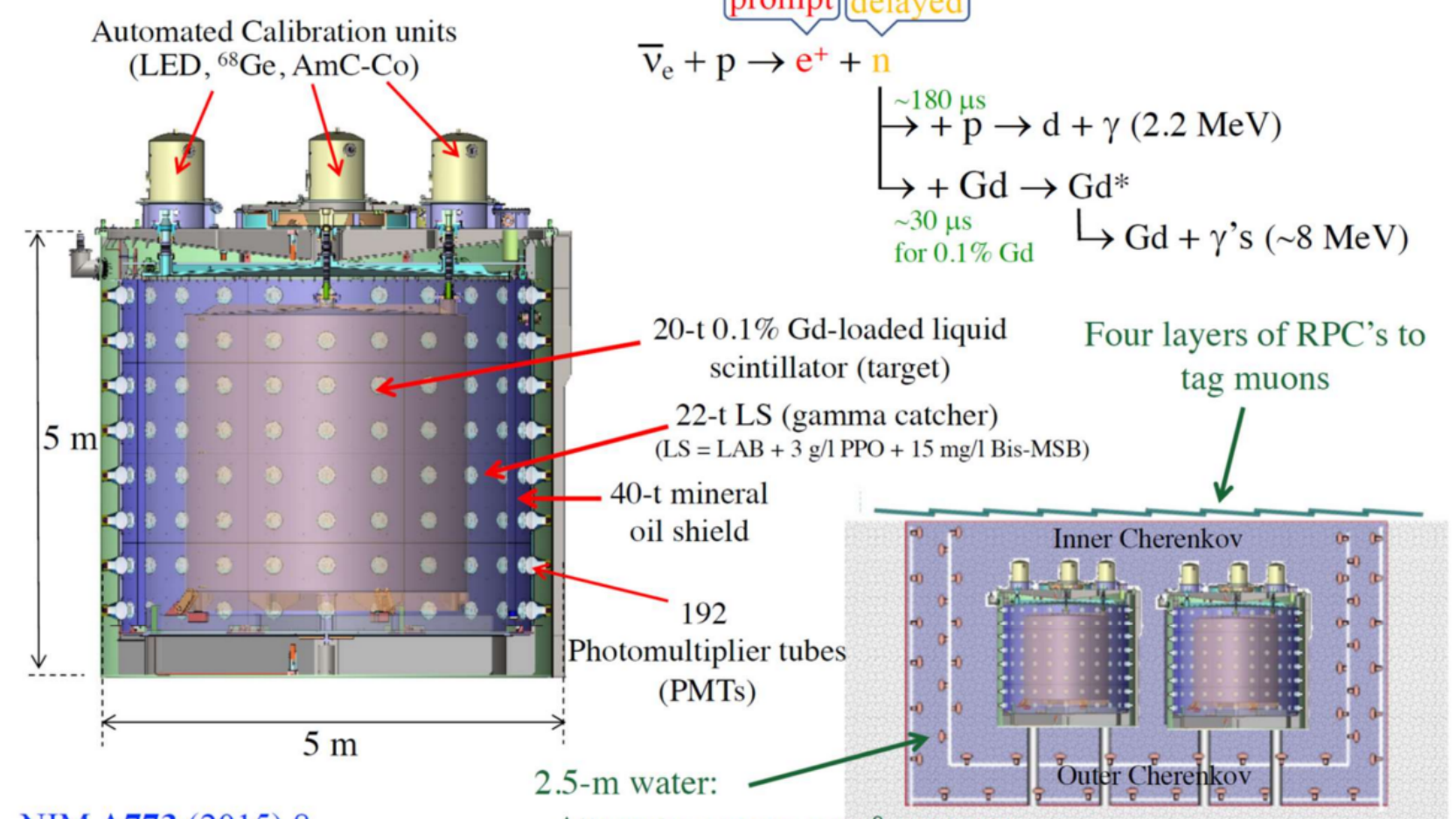
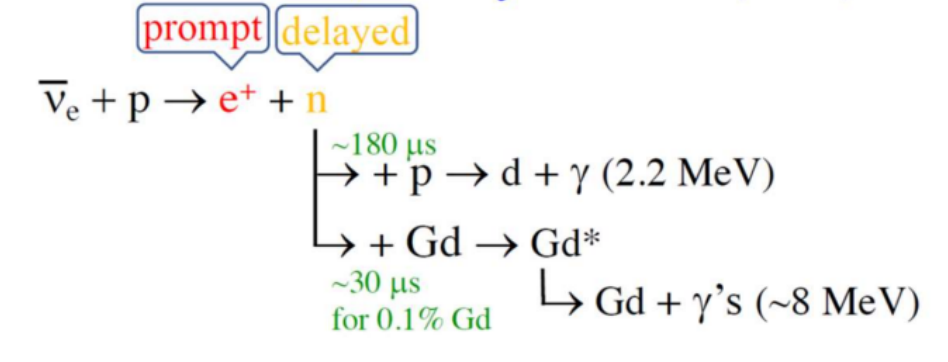
$$\Delta m_{32}^2 = +(2.454^{+0.057}_{-0.057}) \times 10^{-3} \text{eV}^2$$

Inverted Mass Ordering

$$\Delta m_{32}^2 = -(2.559^{+0.057}_{-0.057}) \times 10^{-3} \text{eV}^2$$

Detectors

- Detect inverse β -decay reaction (IBD):



NIM A773 (2015) 8
NIM A811 (2016) 133
30.08.2022

World's most precise measurements of θ_{13} and $|\Delta m_{32}^2|$ with the largest sample of reactor neutrinos to date!

Tanaz Mohayai on DUNE and T2HK/Hyper-K as well as emerging gaseous argon TPC

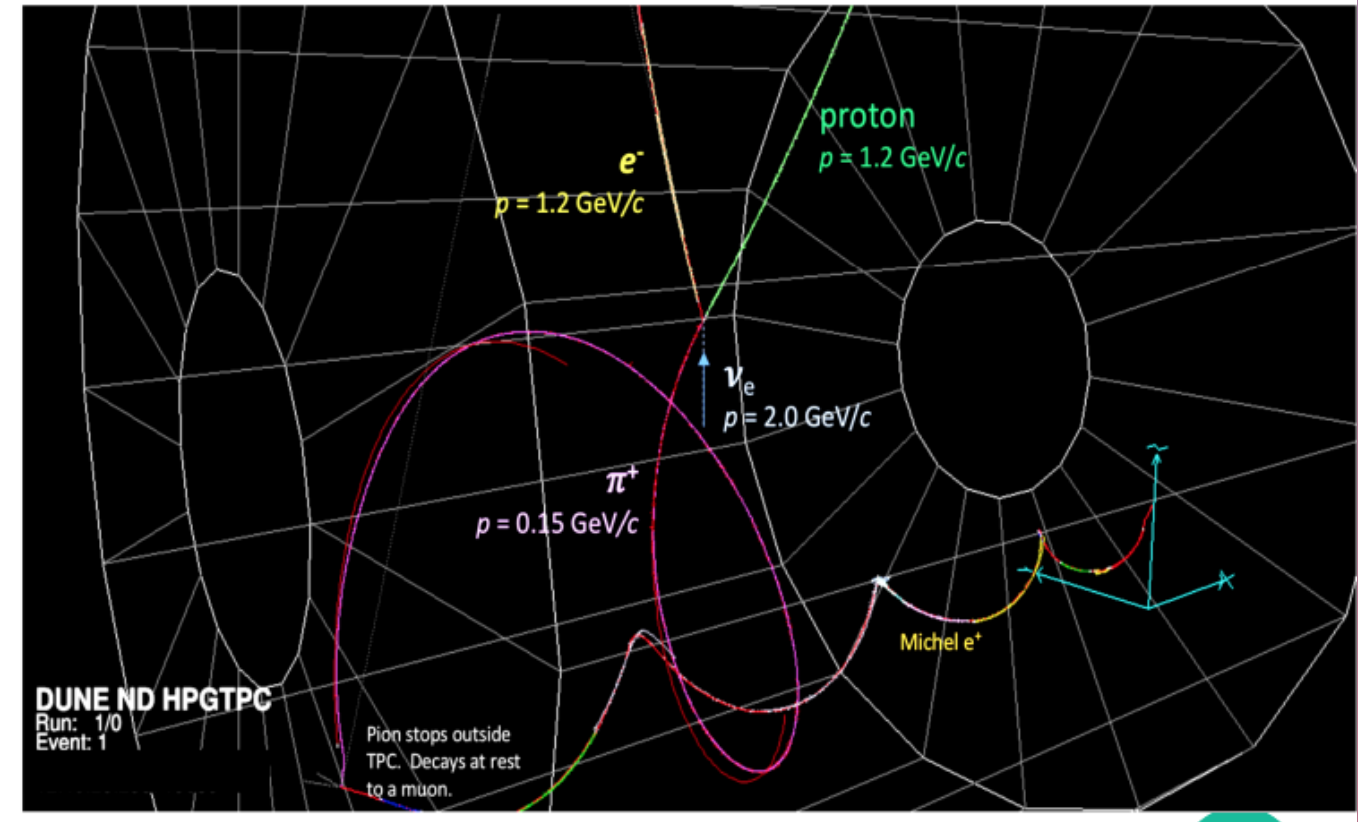
- Low threshold gas TPCs for long-baseline oscillation physics (e.g. ND-GAr in DUNE & gas TPCs in ND280):
 - ★ Low density, hence low detection threshold (e.g. lower than LArTPC), leads to high sensitivity to low energy **protons** or **pions**
 - ★ **Reveals discrepancies between neutrino event generators at low energies**, getting us closer to choosing a more accurate interaction models

Neutrino Beams of Two Future LBL Experiments

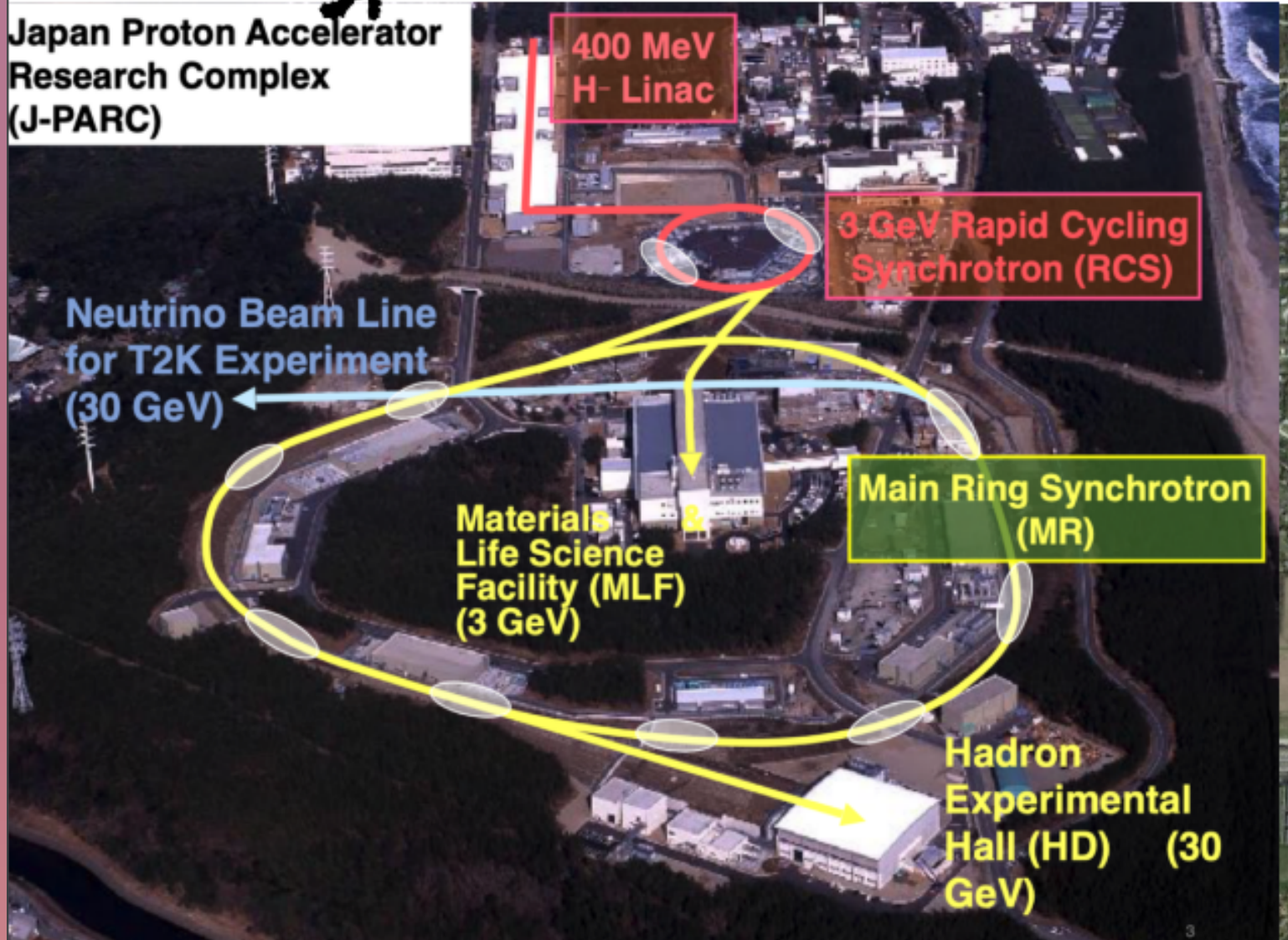
- T2HK/HyperK neutrino beam:
 - ★ At J-PARC, **1.3 MW beam power**
 - ★ Narrow-band beam, far detector placed off the beam axis to observe neutrino flux peaked at ~ 600 MeV + near detectors at on and off-axis locations

- DUNE neutrino beam:
 - ★ At Fermilab, **1.2 MW beam power, upgradable to 2.4 MW**
 - ★ Wide-band beam, far detector placed on-axis to observe a broad spectrum of neutrino fluxes (0.5-5 GeV) + movable near detector for on and off-axis ν -flux measurements (DUNE-PRISM)

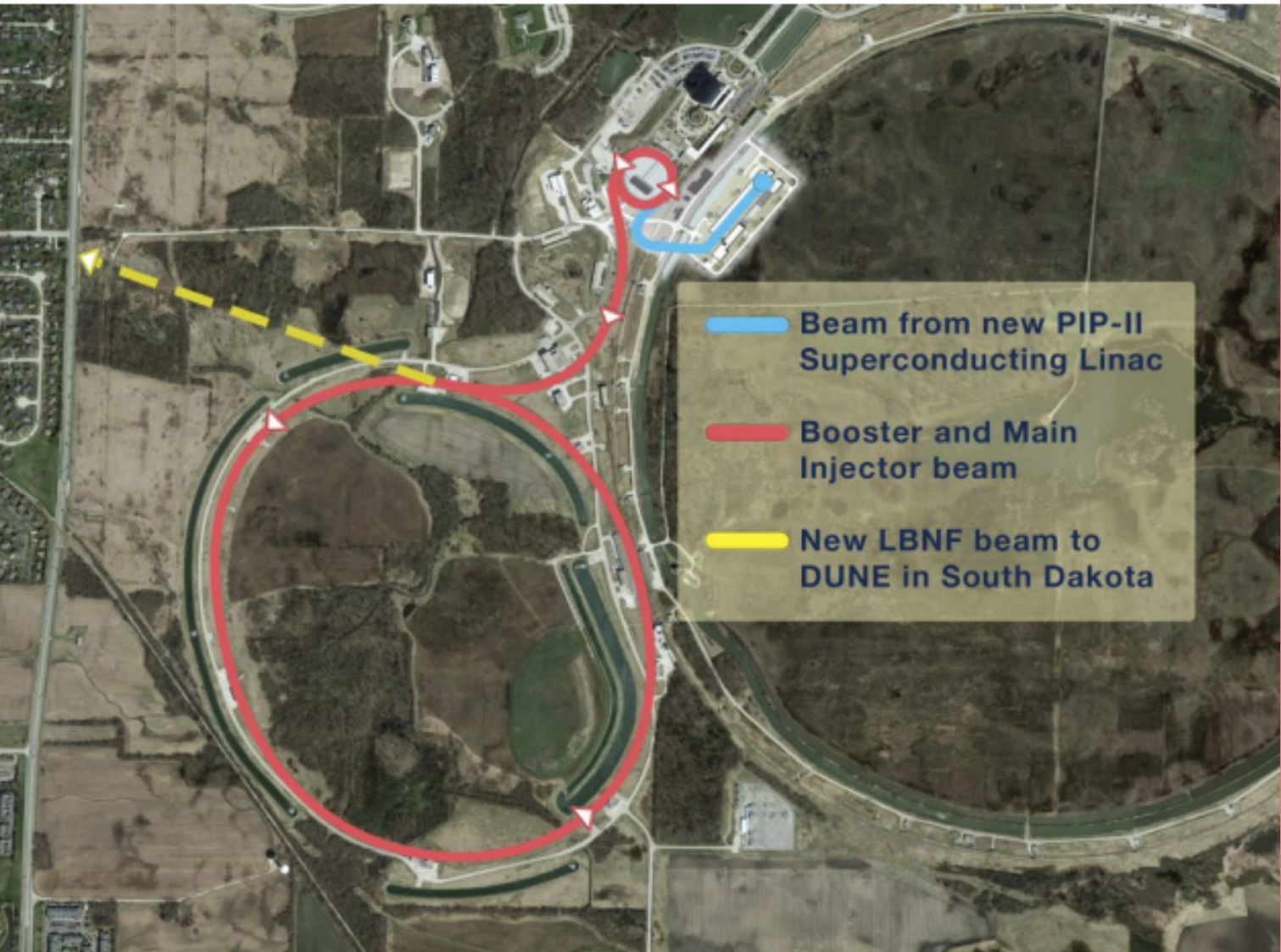
A detailed view of the ν -interaction vertex in ND-GAr near detector in DUNE



T2HK/HyperK Beam @ J-PARC



DUNE Beam @ Fermilab



T. A. Mohayai

The next generation of neutrino oscillation experiments is on the horizon!

Neutrino-Nucleus Cross-Sections and Scattering

- Reports from:
 - Vishvas Pandey and Oleksandr “Sasha” Tomalak on a Introductions to Neutrino Scattering
 - Josh Barrow on $\mu/e4\nu$
 - Maria Martinez-Casales on Cross Sections in NOvA
 - Camillo Mariani on electron-Argon scattering at JLab
 - Yin Lin on Contributions from Lattice QCD
 - Alejandro Ramirez Delgado on Coherent Pion Production in MINERvA
 - Nina Coyle on Cross-Section Tuning and Effects on New Physics
 - Ishaan Vohra on Smearing in Neutrino Simulation

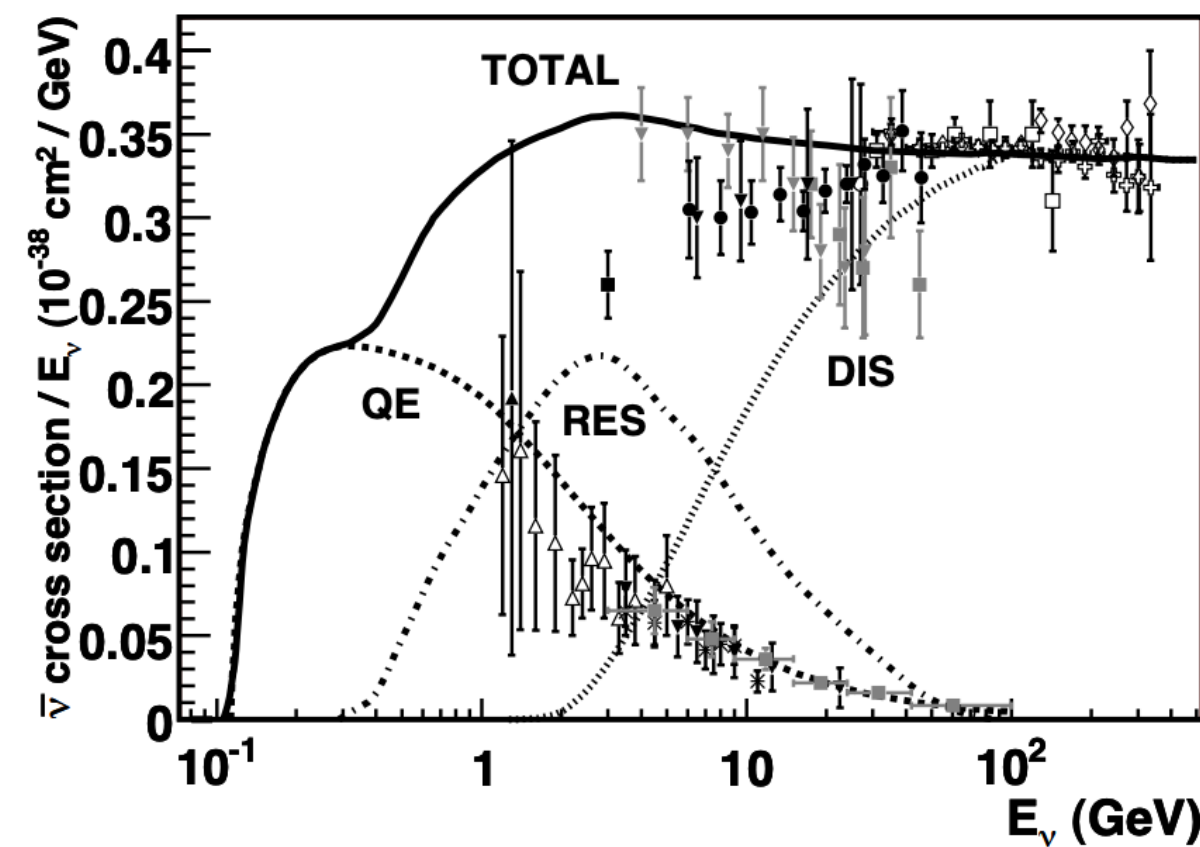
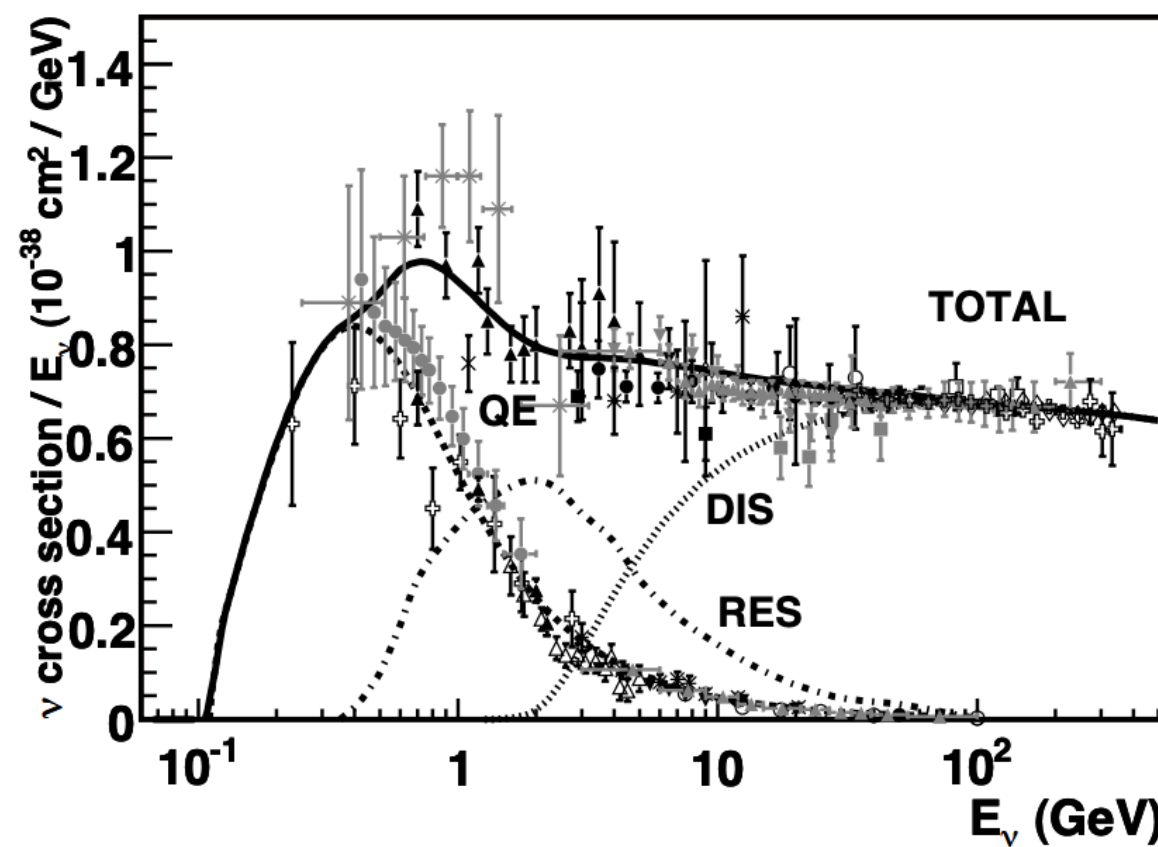
Introductions to Neutrino Scattering

Oleksandr “Sasha” Tomalak

Vishvas Pandey

Neutrino-nucleus scattering

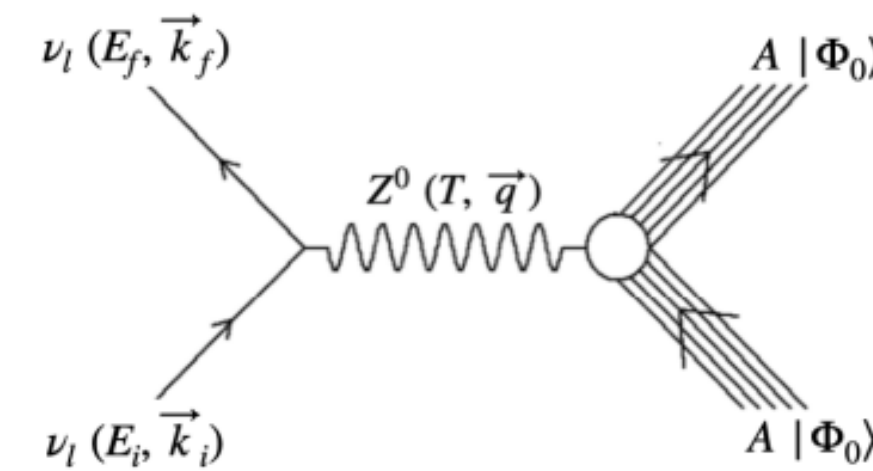
- NC scattering across all energies -> neutrino floor
- CC with electron flavor for supernova, solar, and reactor neutrinos
- same open channels as at nucleon level



Formaggio and Zeller (2013)

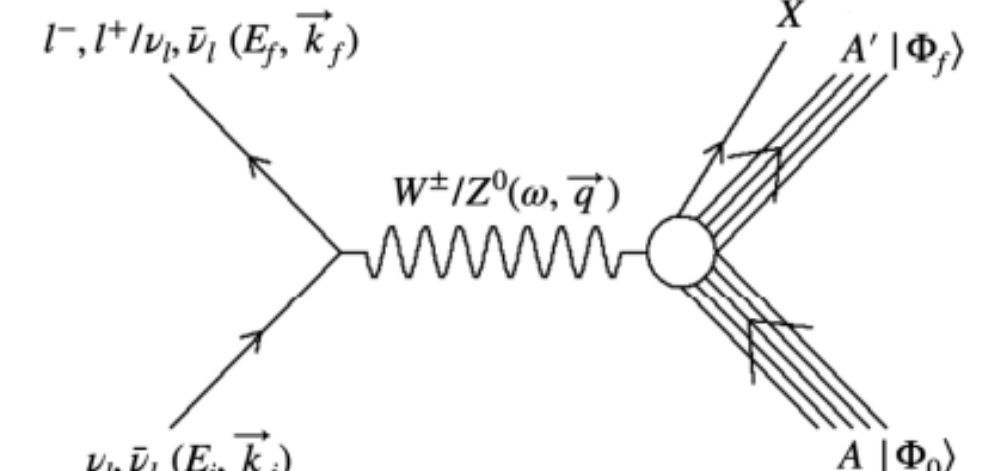
Low-energy Neutrinos-Nucleus Scattering

Coherent elastic [CEvNS]

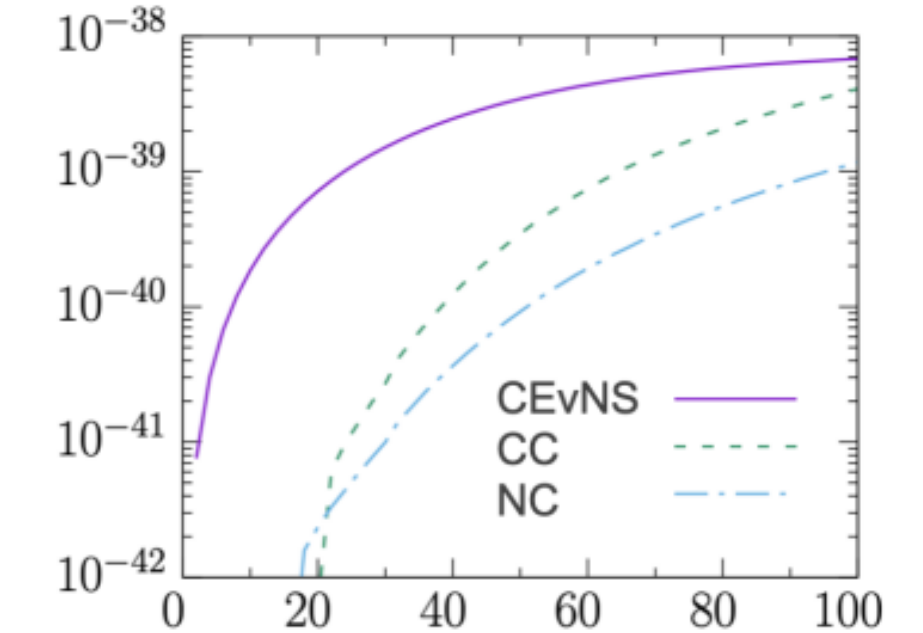
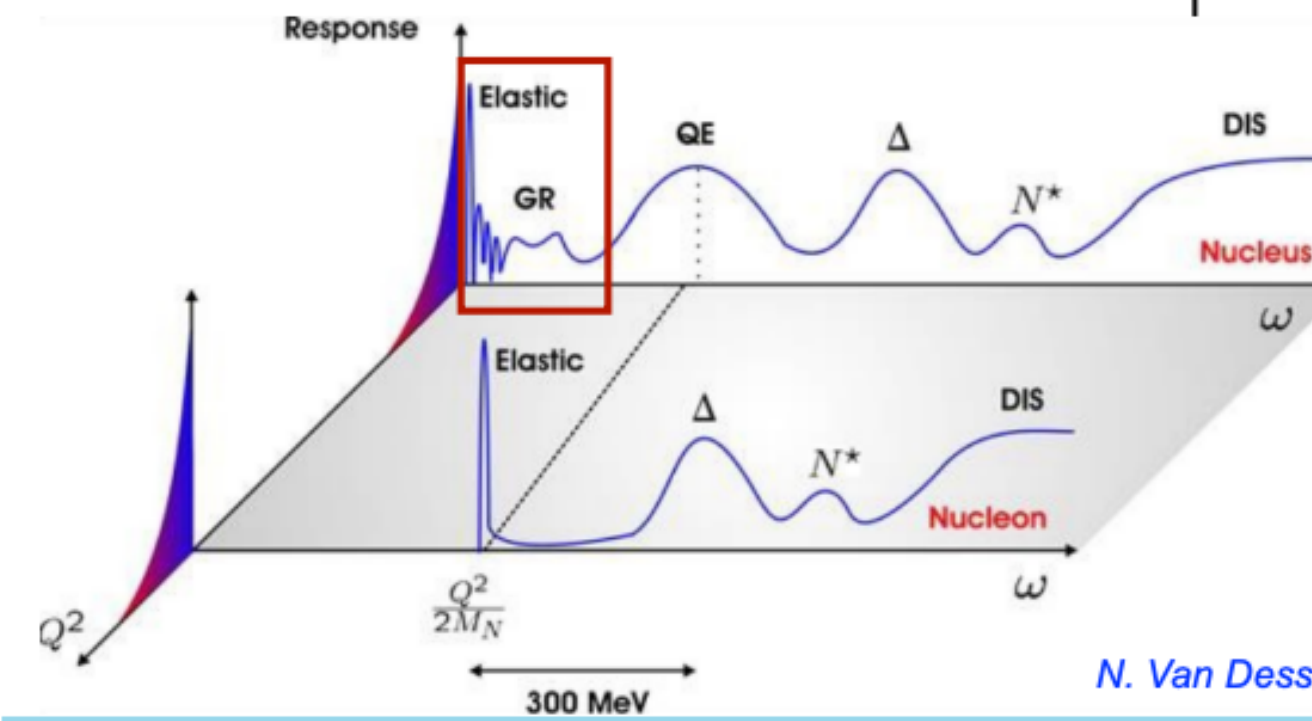


- Final state nucleus stays in its ground state
- Tiny recoil energy, large cross section
- Signal: keV energy nuclear recoil

Inelastic CC/NC



- Nucleus excites to states with well-defined excitation energy, spin and parity (J^π)
- Followed by nuclear de-excitation into gammas, n, p, and nuclear fragmentations.



N. Van Dessel, V. Pandey, H. Ray, N. Jachowicz, arXiv:2007.03658 [nucl-th]



Overlapping descriptions of the neutrino-nucleus scattering at different nuclear recoil energies outlines the fundamental difficulty of the problem!

Alejandro Ramirez Delgado on Coherent Pion Production at MINERvA

What Is Coherent Pion Production?



Features

- Coherence depends on the magnitude of the four-momentum transfer to the nucleus, $|t|$

$$|t| = \left| (p_\nu - p_l - p_\pi)^2 \right|$$

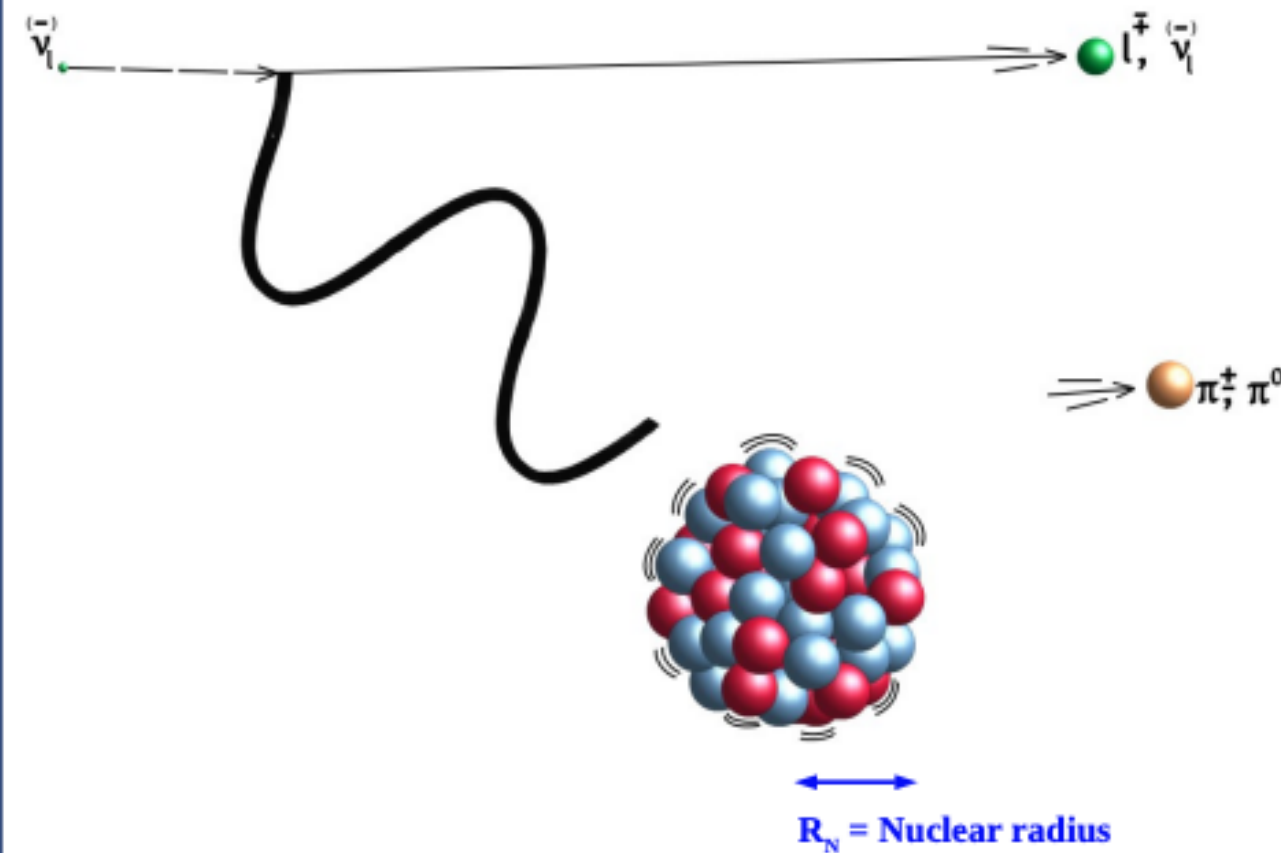
- There is a threshold $|t_{min}|$

$$|t_{min}| \simeq \left(\frac{Q^2 + m_\pi^2}{2E_\pi} \right)^2$$

- and a maximum $|t_{max}|$

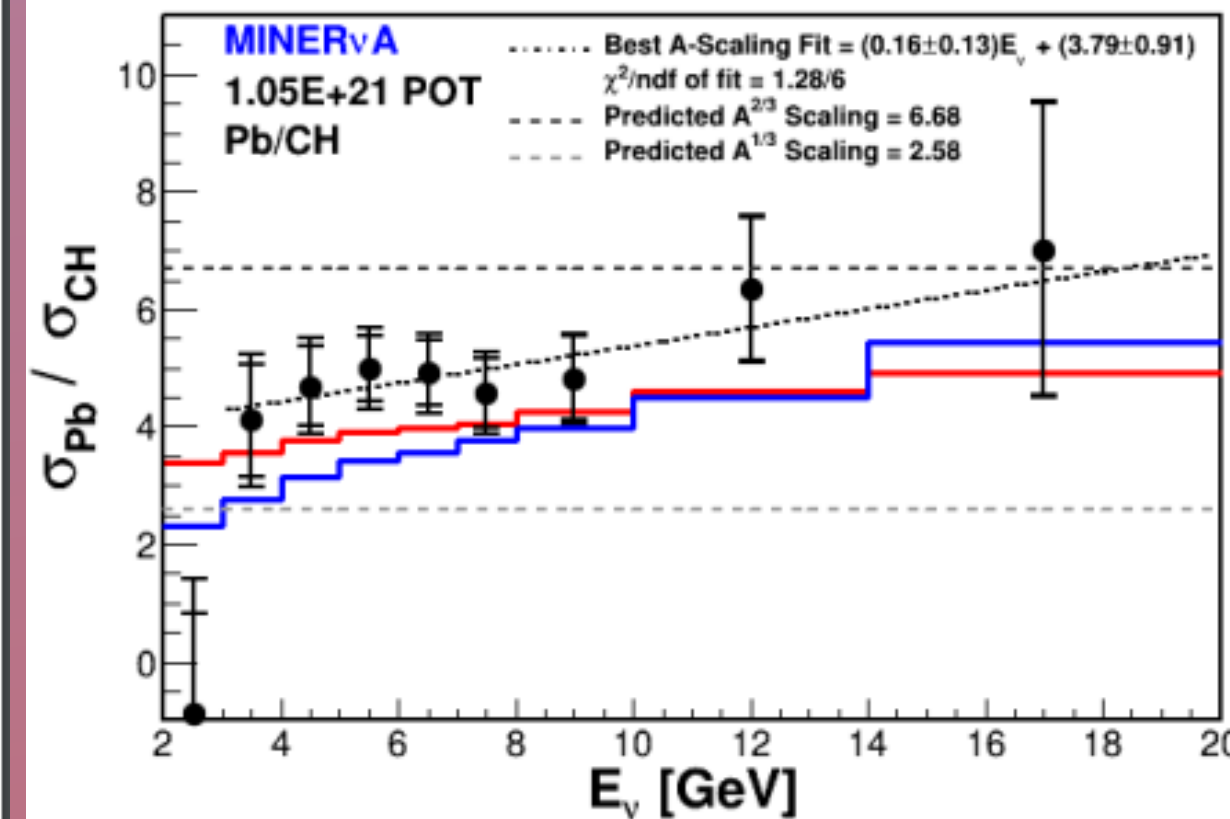
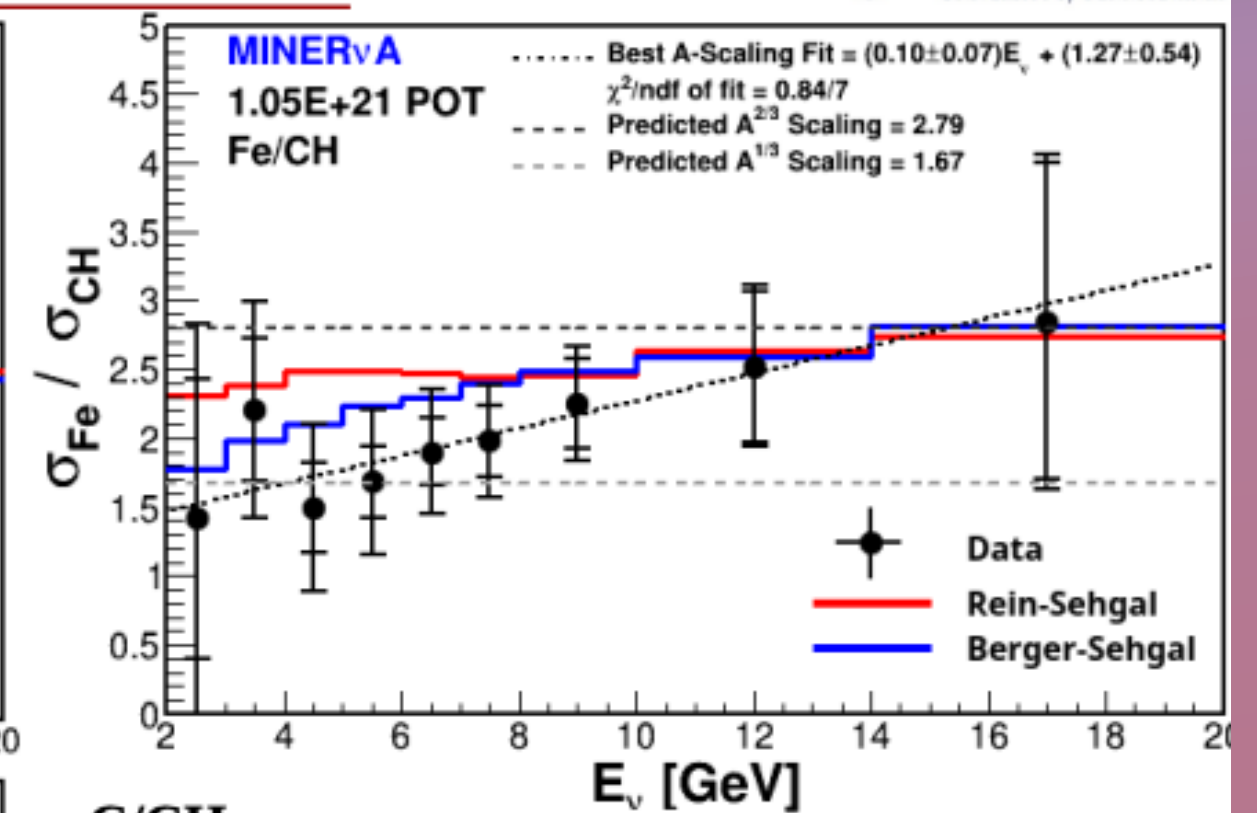
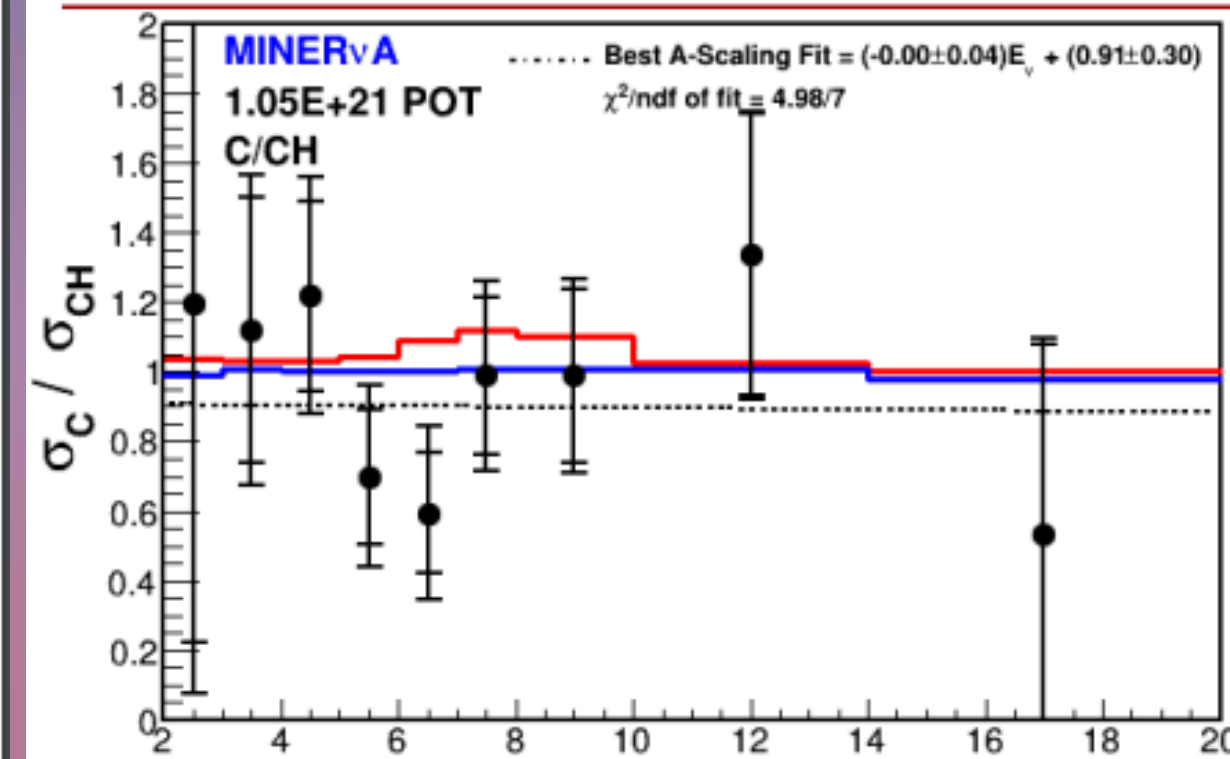
$$|t_{max}| \simeq 1/R_N^2$$

within which the interaction takes place.



Results: Cross Section Ratios

$$\sigma E_\nu$$



C/CH

- consistent with unity.

A-Scaling linear fit

Fe/CH

- Neither model does a good description.
- Closer to $A^{1/3}$ scaling for $E_\nu < 8$ GeV.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.

Pb/CH

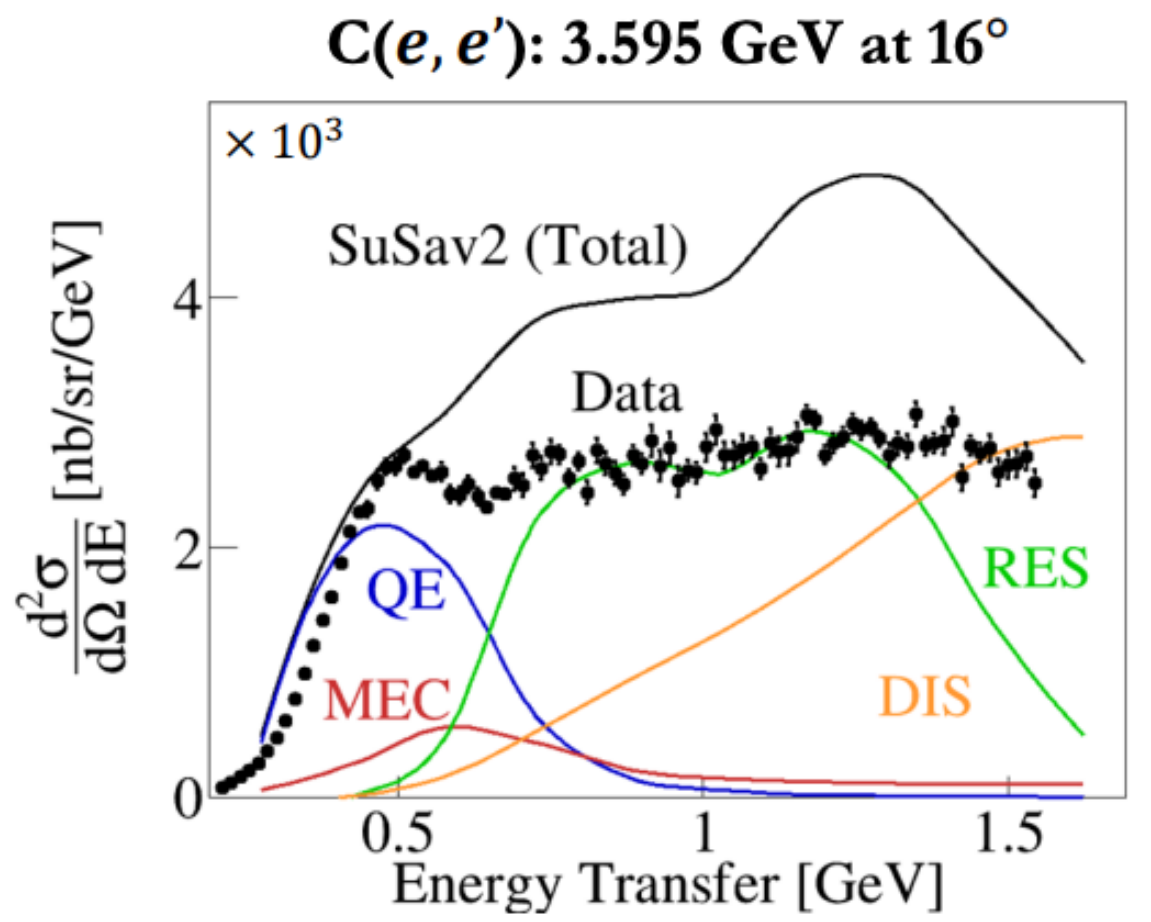
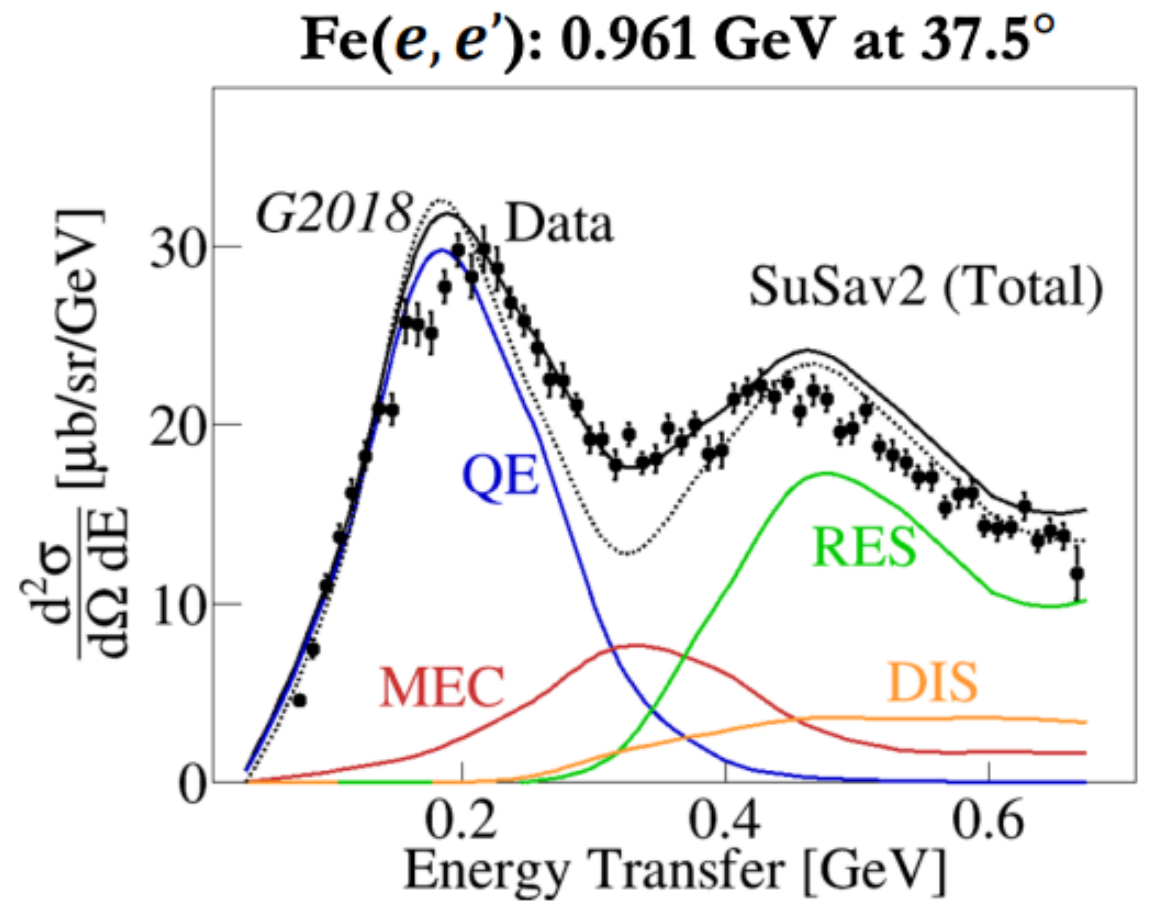
- Neither model does a good description.
- Closer to $A^{2/3}$ scaling for $E_\nu > 10$ GeV.
- Low E_ν A-scaling in between predictions.

MINERvA measurements show multiple cross-sections and comparisons using a fairly well understood process, good progress in cross-section measurements and measurements of nuclear structure

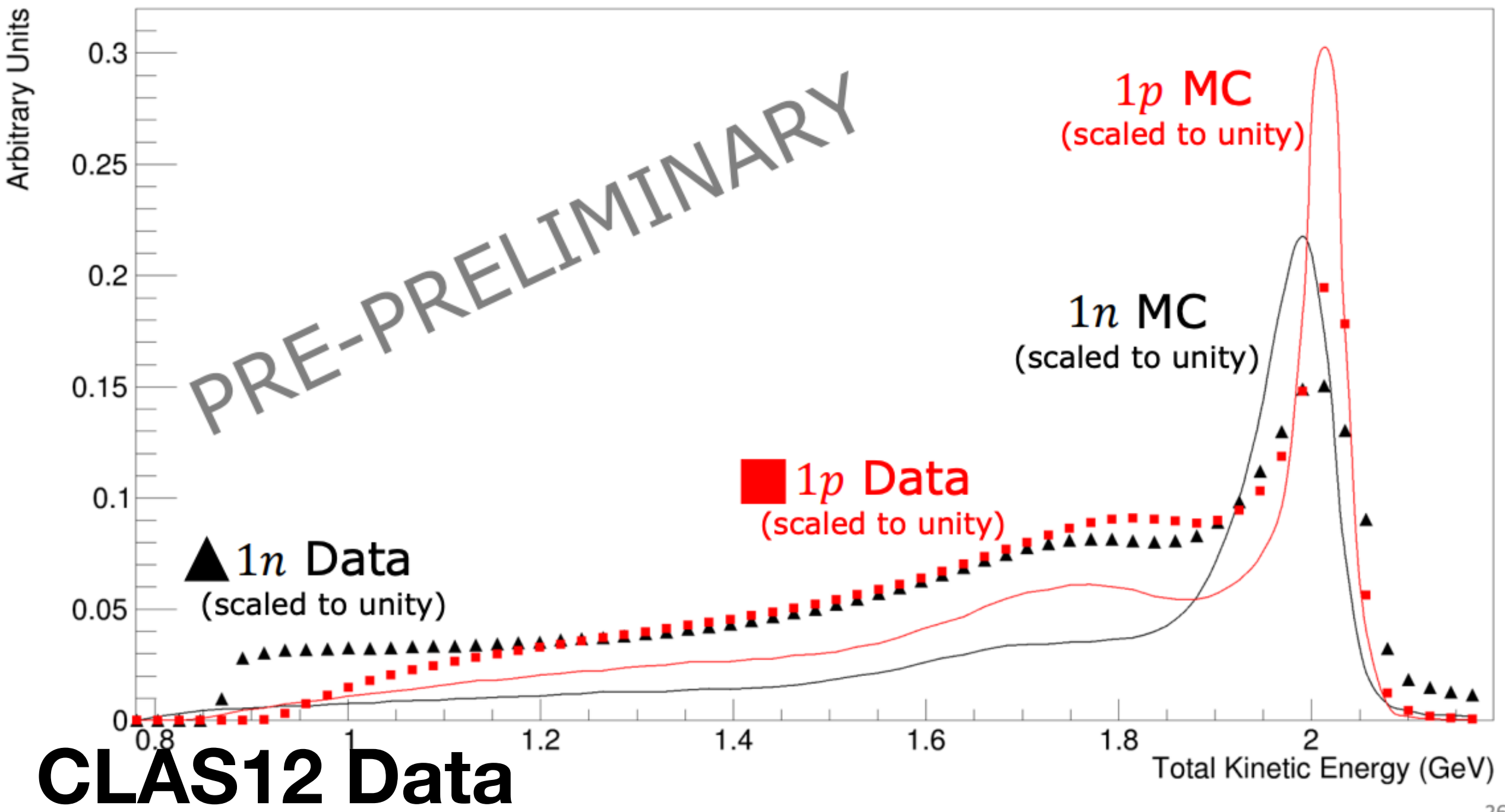
Josh Barrow on $e4\nu$

Inclusive $A(e, e')$ Data Comparisons

- Consistent $\{\nu_\ell, \ell\}$ modeling now implemented
 - Can compare to world inclusive QE electron scattering data
 - Any misconstrued behavior here won't work for ν s either!
- Much work to do!
 - Must build better models, constrain any free parameters!



Initial Comparisons to Simulation Showing Unphysical Differences?

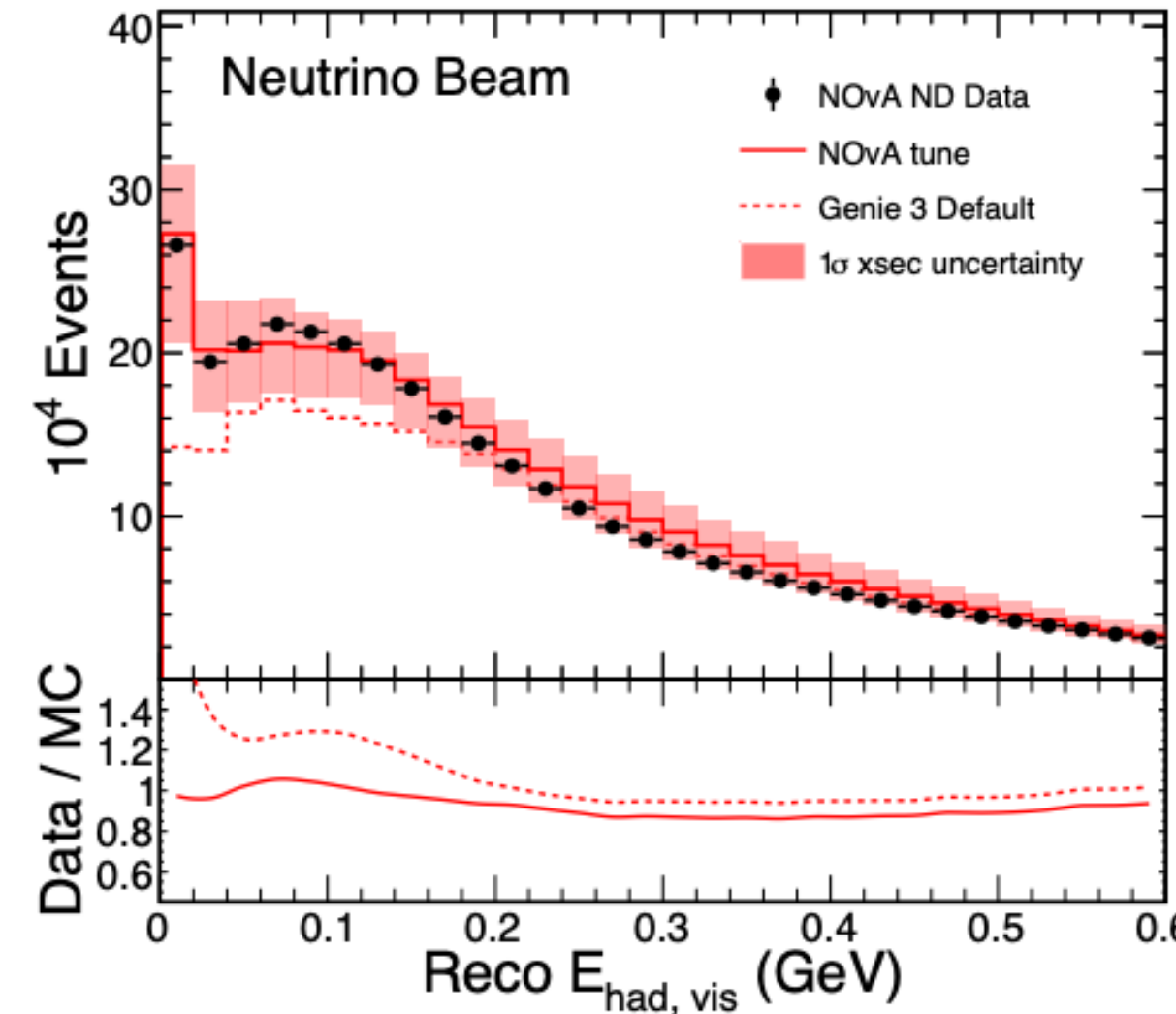


Useful but imperfect tools for inferring neutrino-nucleus scattering, shows there are a lot left to learn about nuclear and neutrino physics.

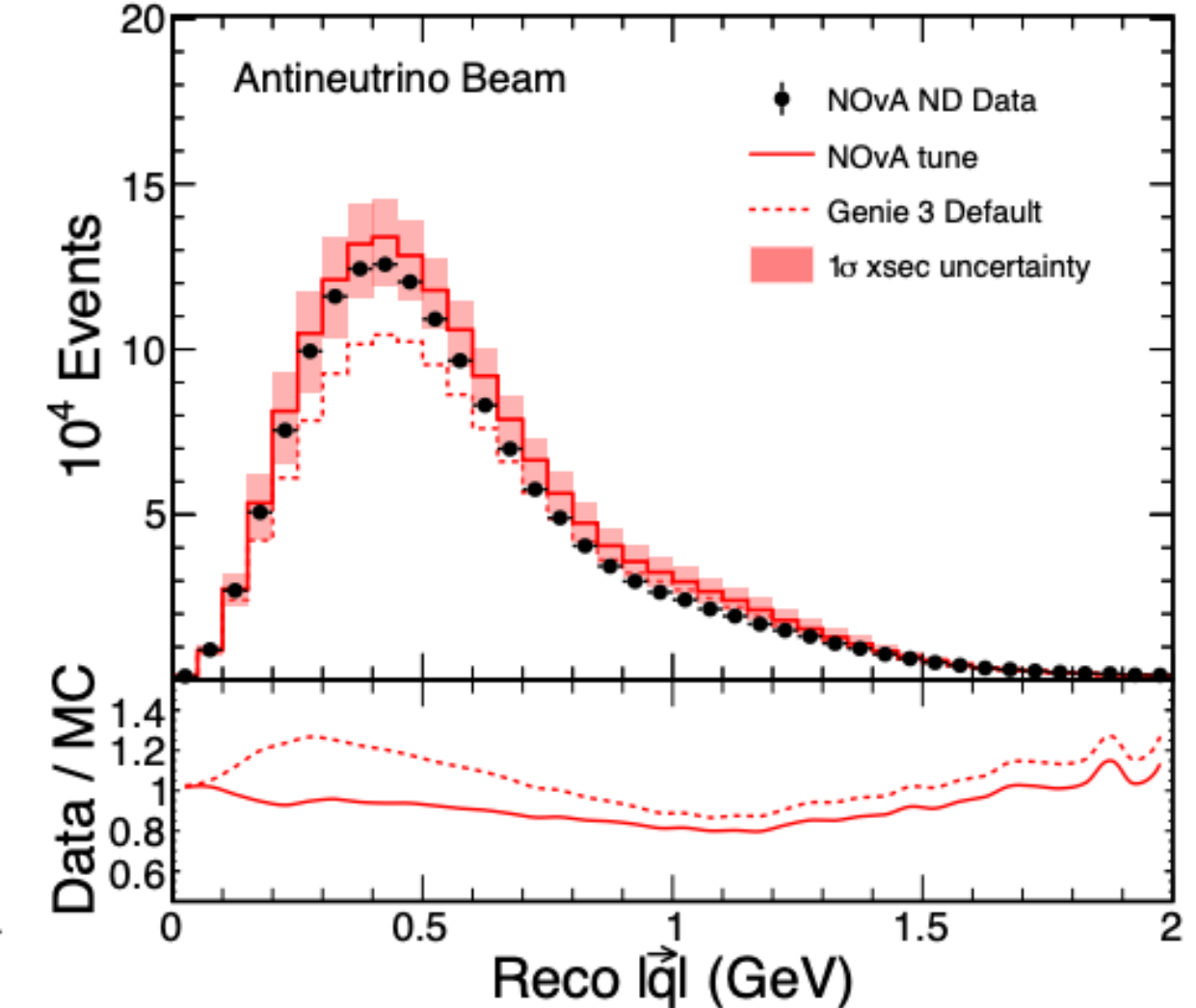
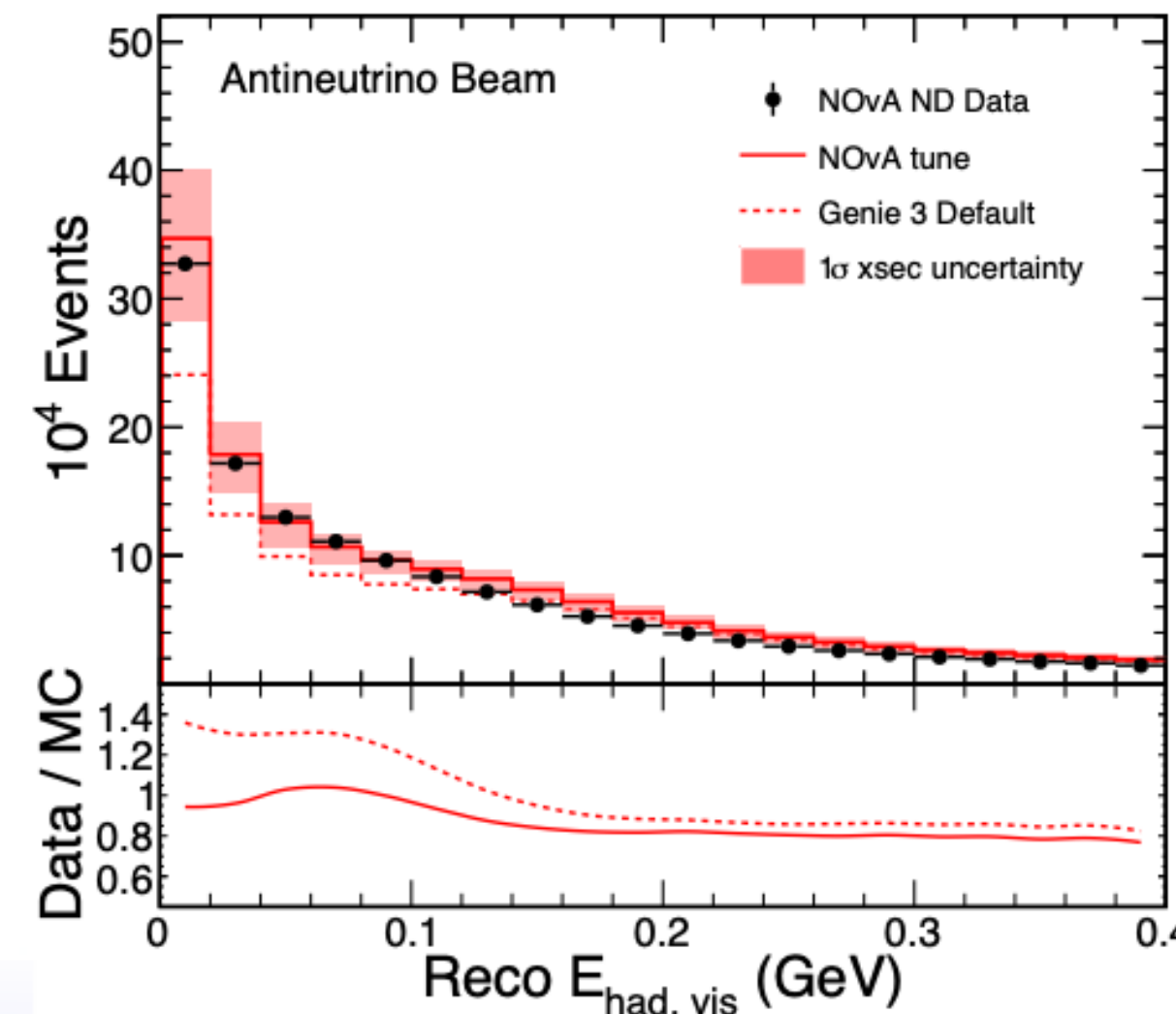
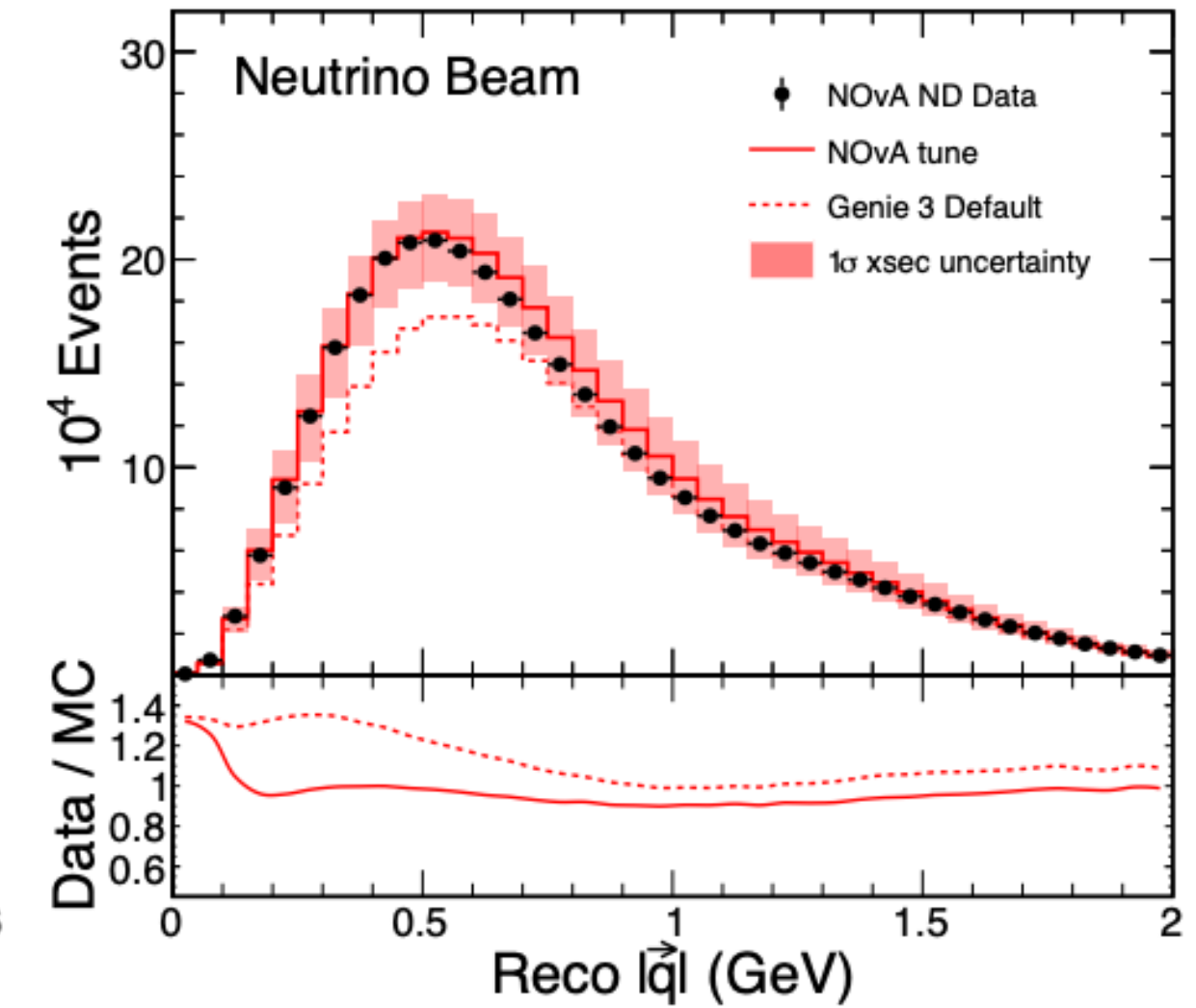
NOvA tune and uncertainties

- Central value agreement is good after FSI and MEC adjustments.
- Cross section uncertainties include custom MEC, FSI in addition GENIE uncertainties.
- These are adequate to take into account remaining differences.

NOvA Preliminary



NOvA Preliminary

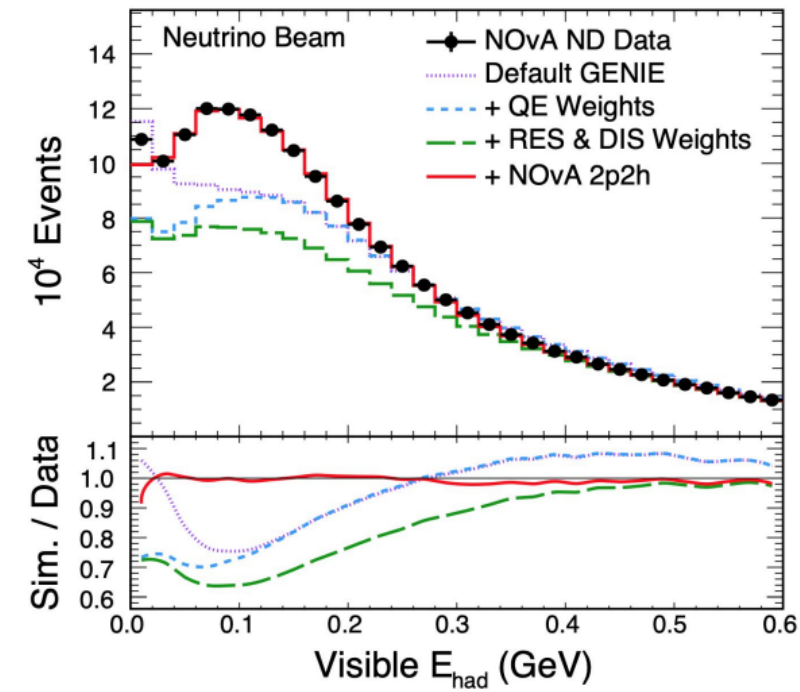
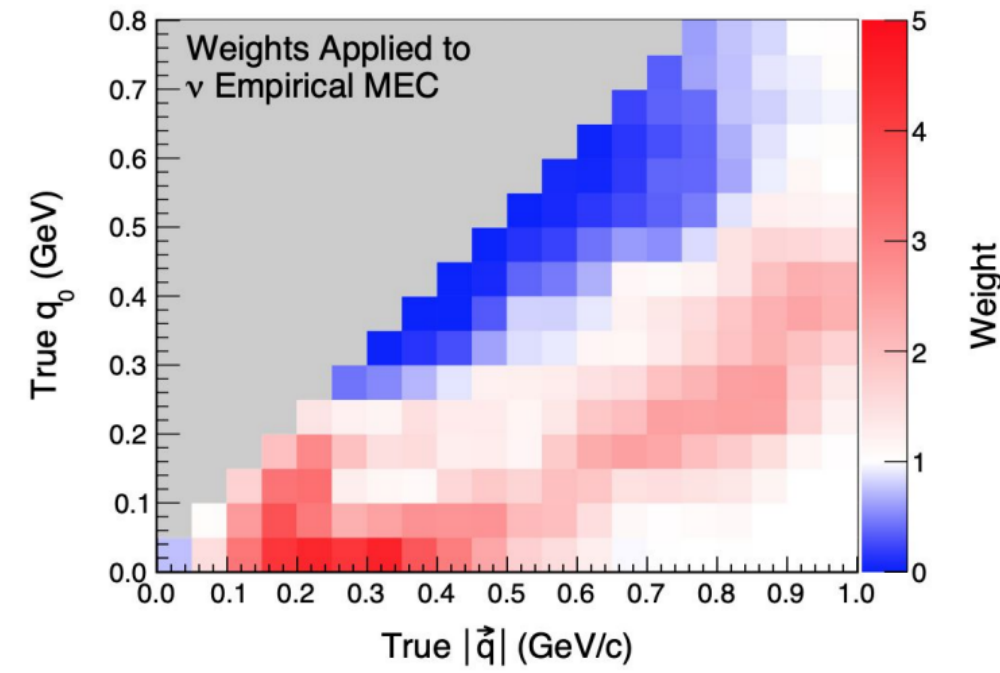


NOvA tunes its cross sections and FSI input for oscillations analyses to ND data, primarily using MEC.

Nina Coyle on Cross-Section Tuning and New Physics

Near detector tuning: NOvA

How to adjust for remaining discrepancy? Adjust the MEC contribution



NOvA collaboration, arXiv:2006.08727

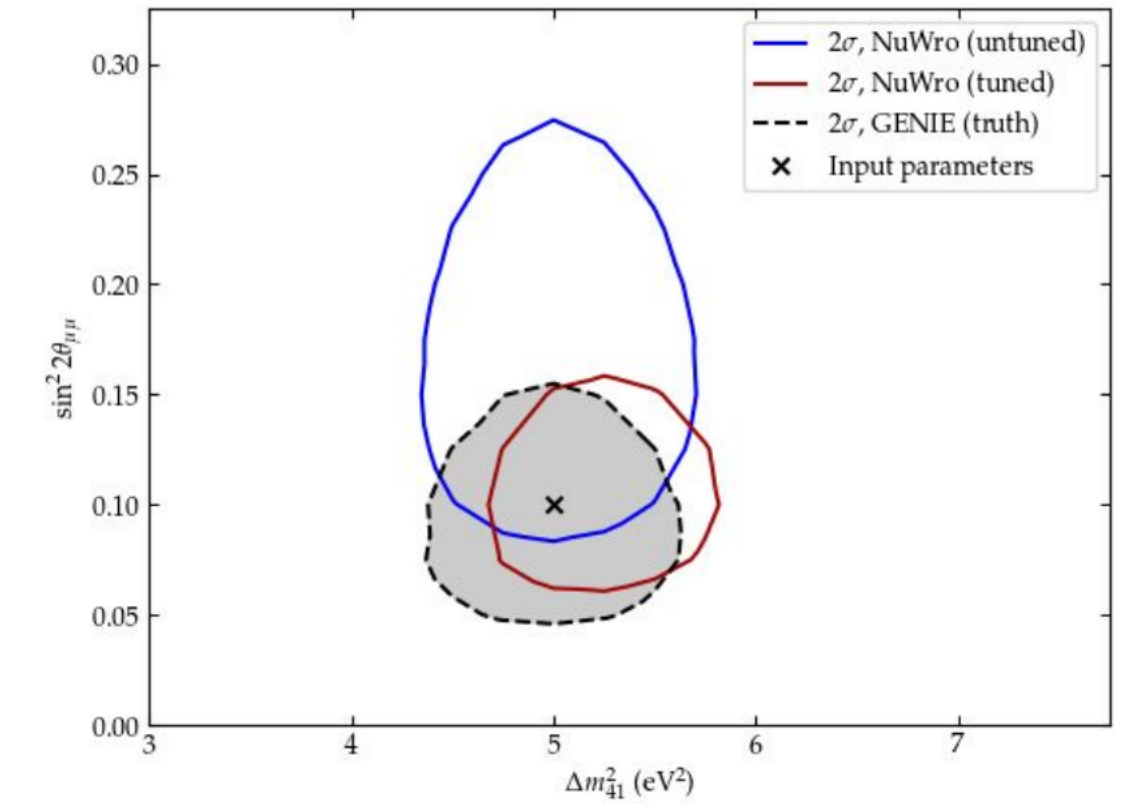
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Sterile neutrino signal: direct fit

- Two different generators: GENIE for data, NuWro for simulated model

- Direct fit to FD and ND rates

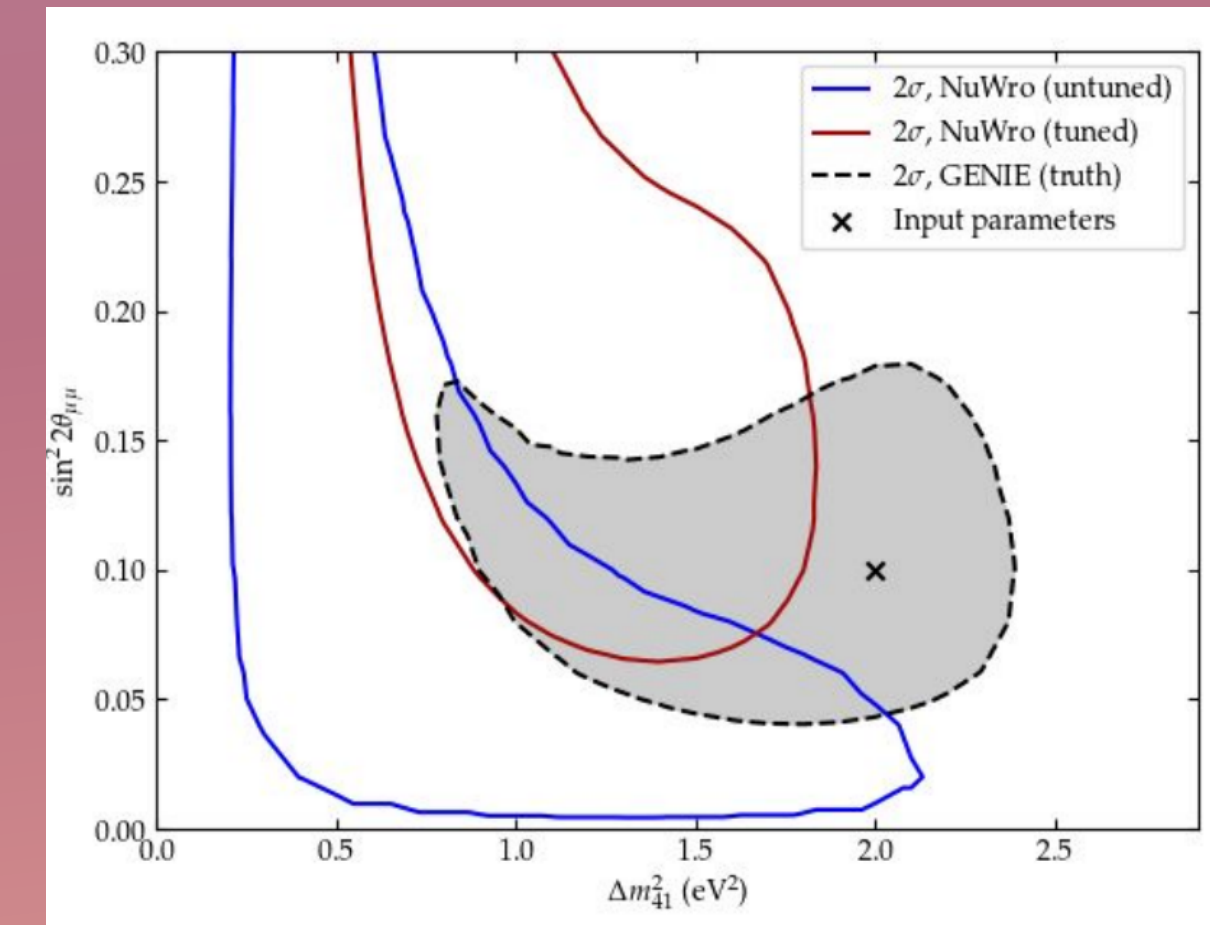
- Simultaneous fit and tune



N.C., Li, Machado, in preparation

Data driven tuning (like shown in the previous NOvA talk) has consequences!

Are we making ourselves insensitive to new physics?



(e, e'p) cross section

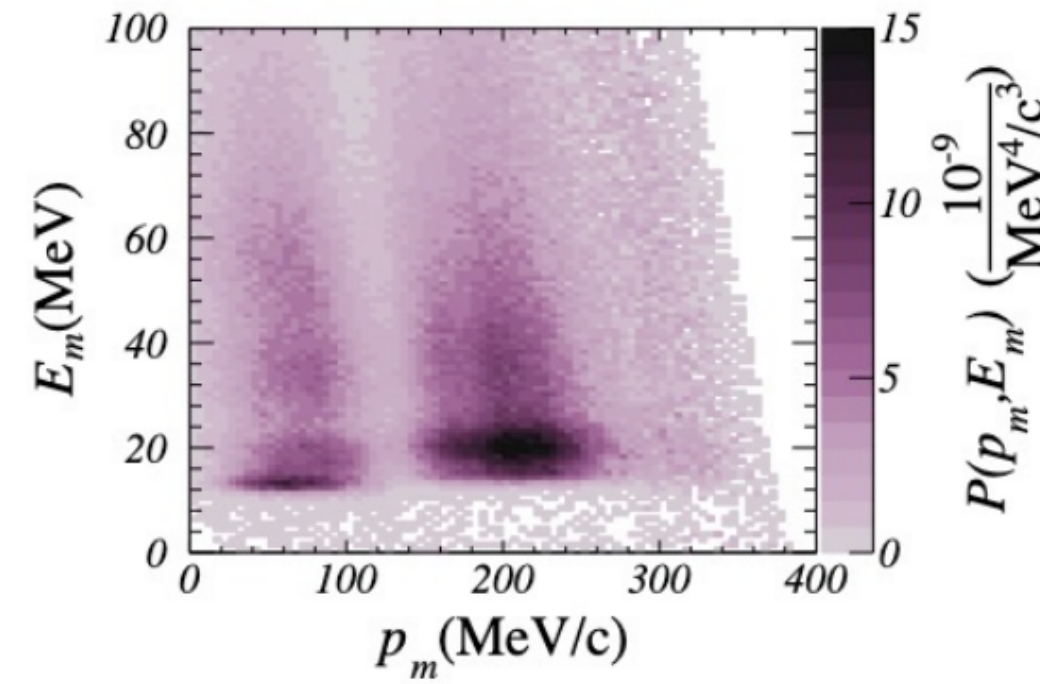
$$\frac{d^6 \sigma_{IA}}{d\Omega_{e'} dE_{e'} d\Omega_{p'} dE_{p'}} \propto \sigma_{ep} S(p_m, E_m) T(E_{p'})$$

elementary cross section \rightarrow σ_{ep}
 nuclear transparency \rightarrow $T(E_{p'})$
 spectral function \rightarrow $S(p_m, E_m)$

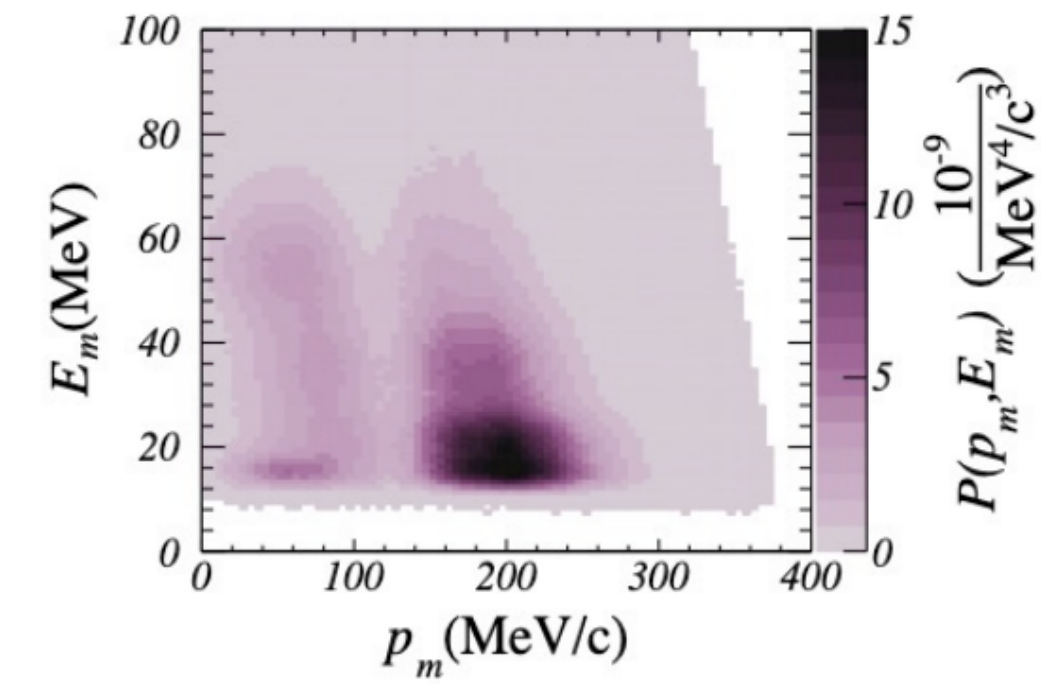
Camillo Mariani on e-scattering

CIPANP, 2022

Argon proton cross-sections and spectral response measured using CLAS data!
 Crucial for future Argon scattering experiments

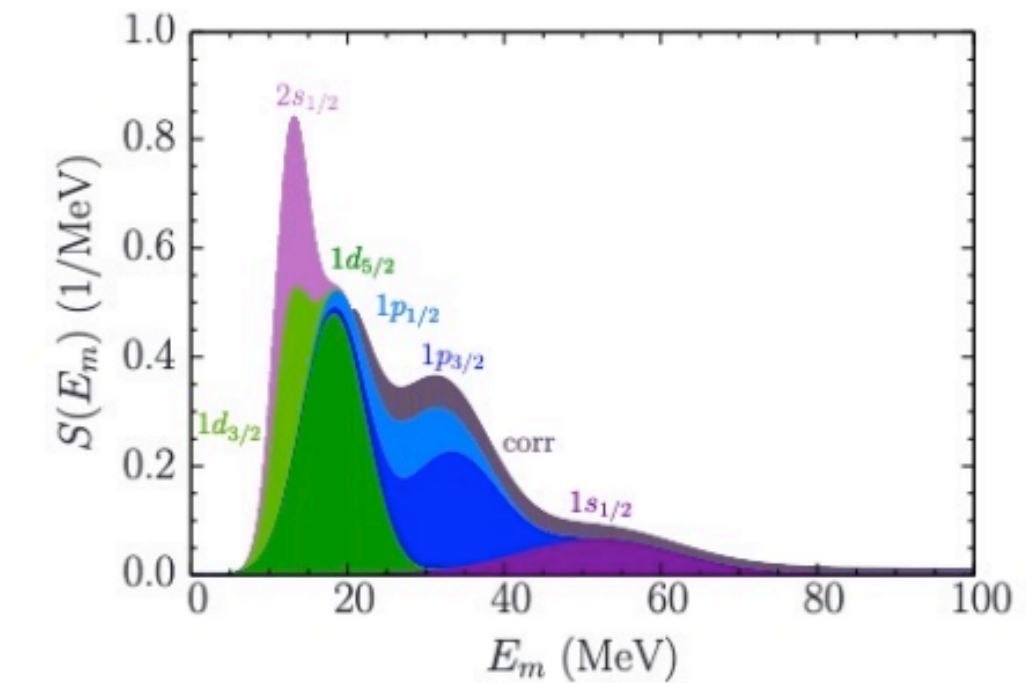
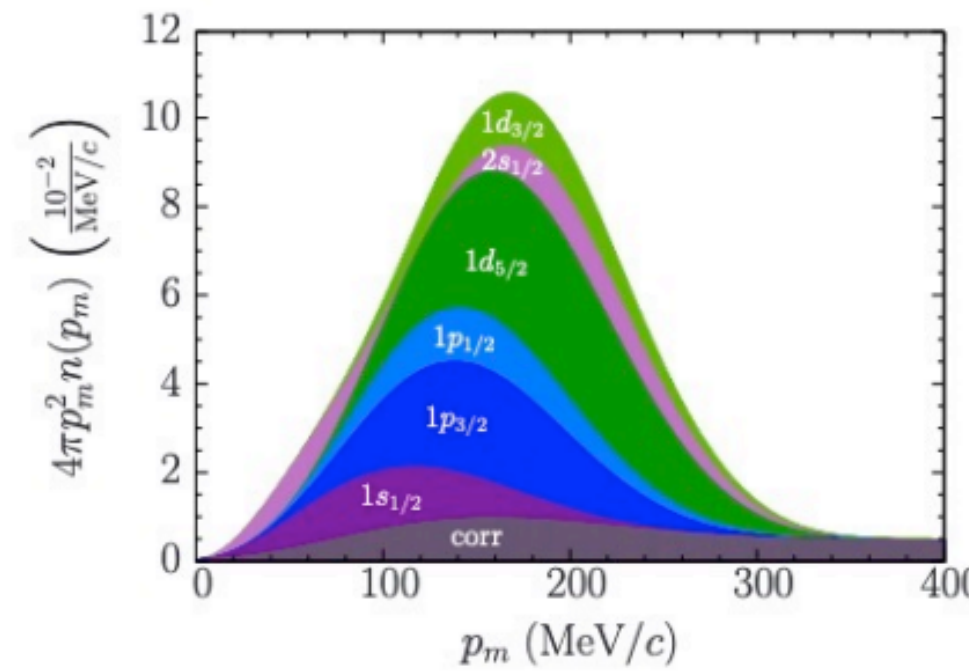


(a) Data



(b) MC

Ar (e, e'p) – Phys. Rev. D 105, 112002, (2022)



α	N_α	all priors	w/o p_m	w/o corr.
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 0.05	2.05 ± 0.23	2.52 ± 0.05
corr.	0	3.77 ± 0.28	3.85 ± 0.25	excluded
$\sum_\alpha S_\alpha$		17.02 ± 0.48	16.61 ± 0.57	14.12 ± 0.42
d.o.f		206	231	232
$\chi^2/\text{d.o.f.}$		1.9	1.4	2.0

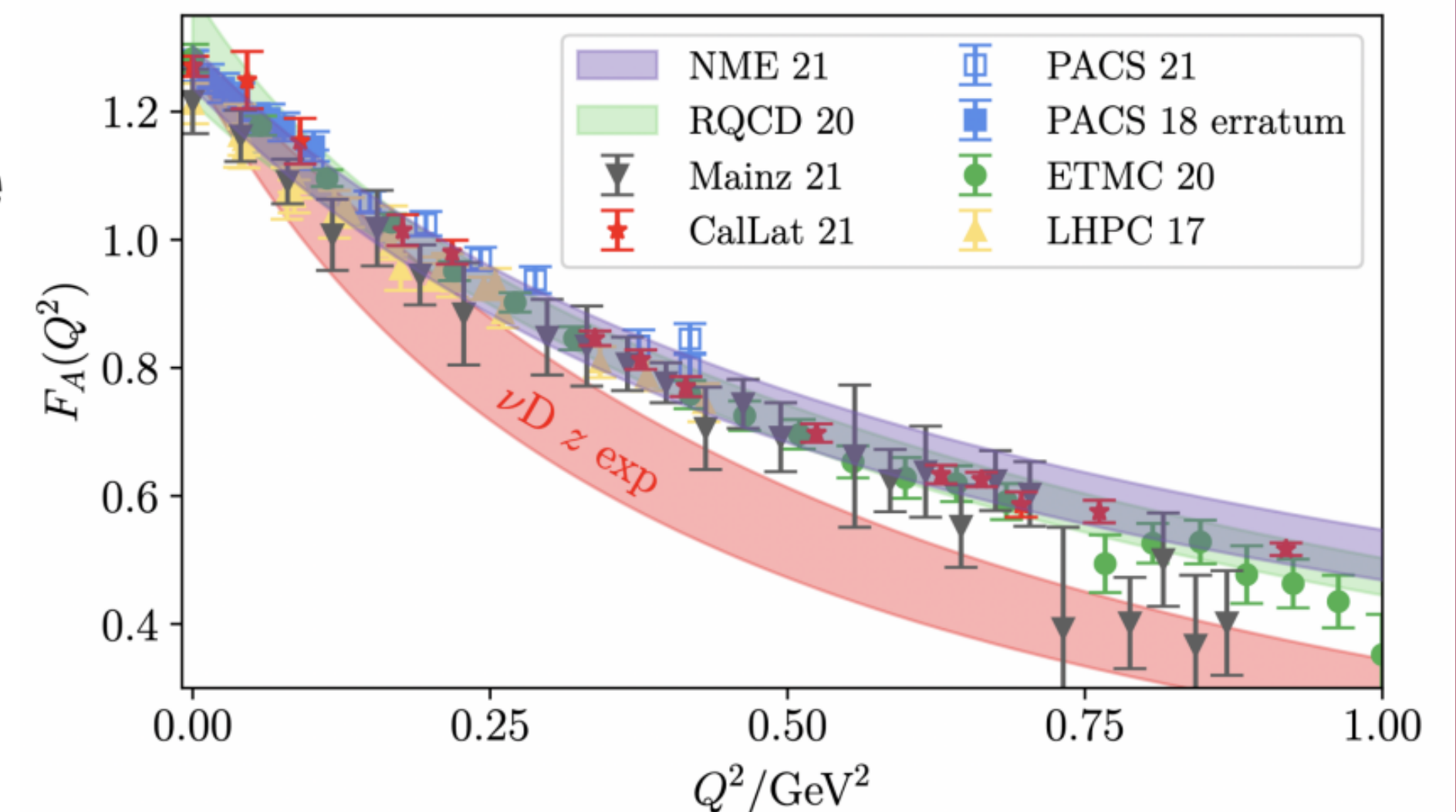
α	E_α (MeV)		σ_α (MeV)	
	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	12.53 ± 0.02	10.90 ± 0.12	1.9 ± 0.4	1.6 ± 0.4
$2s_{1/2}$	12.92 ± 0.02	12.57 ± 0.38	3.8 ± 0.8	3.0 ± 1.8
$1d_{5/2}$	18.23 ± 0.02	17.77 ± 0.80	9.2 ± 0.9	9.6 ± 1.3
$1p_{1/2}$	28.8 ± 0.7	28.7 ± 0.7	12.1 ± 1.0	12.0 ± 3.6
$1p_{3/2}$	33.0 ± 0.3	33.0 ± 0.3	9.3 ± 0.5	9.3 ± 0.5
$1s_{1/2}$	53.4 ± 1.1	53.4 ± 1.0	28.3 ± 2.2	28.1 ± 2.3
corr.	24.1 ± 2.7	24.1 ± 1.7	—	—

CIPANP, 2022

Summary

Yin Lin on Contributions from Lattice QCD

- Lattice QCD results on the nucleon axial form factors are converging
→ higher values at large Q^2
- Fully controlled systematics in the near future (new experiments?)
- Exploratory calculations of other processes (resonance transition form factors, hadronic tensors, and pdfs)



Lattice QCD now regularly provides testable predictions for neutrino nucleus scattering! Fascinating continued period of sustained growth!

What Is NuSmear?

- Energy smearing and angular smearing via parameterized model-based presets.
- Fast, generic, geometry-independent.
- Contribution package built onto the GENIE Monte Carlo event generator.
- Simulates energy and angular smearing between all flavors of neutrinos and nuclear targets within the MeV to PeV energy scales.



NuSmear

- Link to NuSmear GitHub pull request: <https://github.com/GENIE-MC/Generator/pull/222>

Program is up on GitHub,
and ready to be
implemented in simulations

Ishaan Vohra on NuSmear, a tool for smearing GENIE simulation

Validation of Smearing Performance

Energy Smearing - Complete MC Comparison

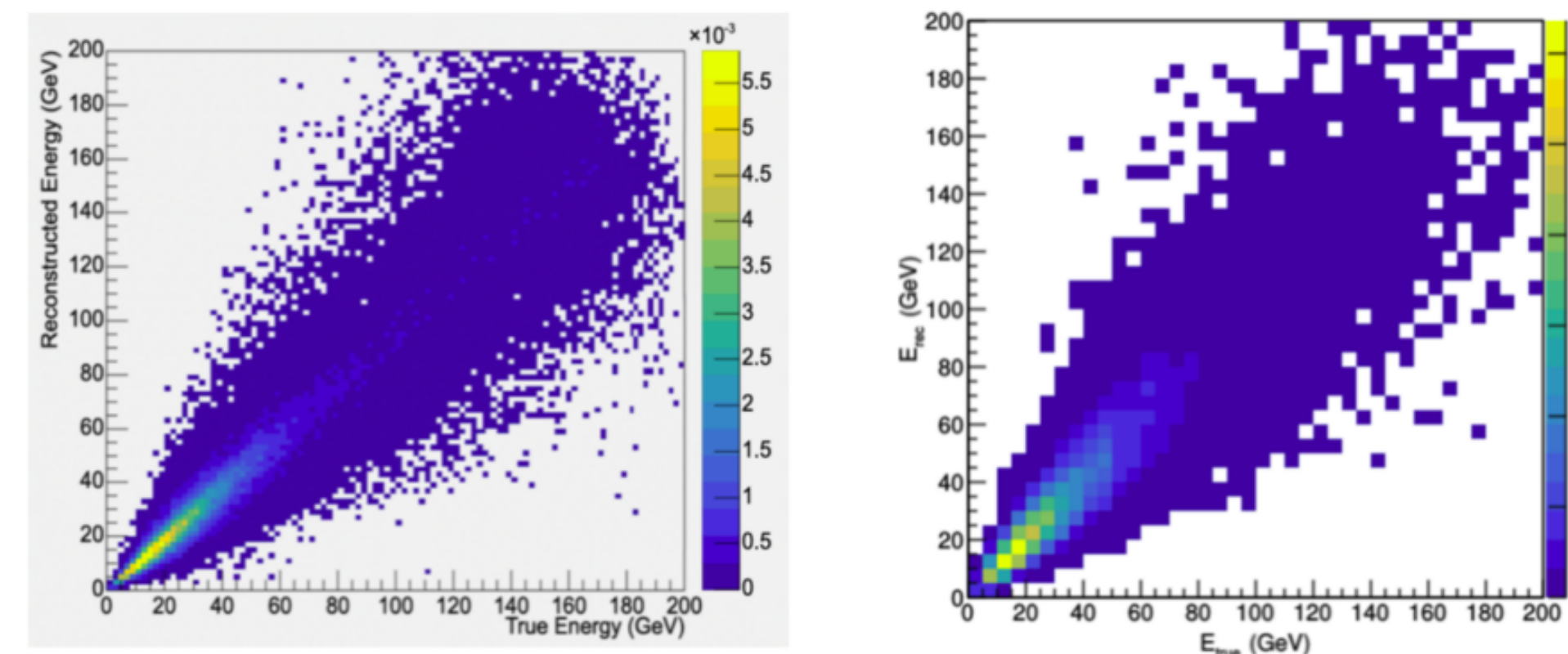
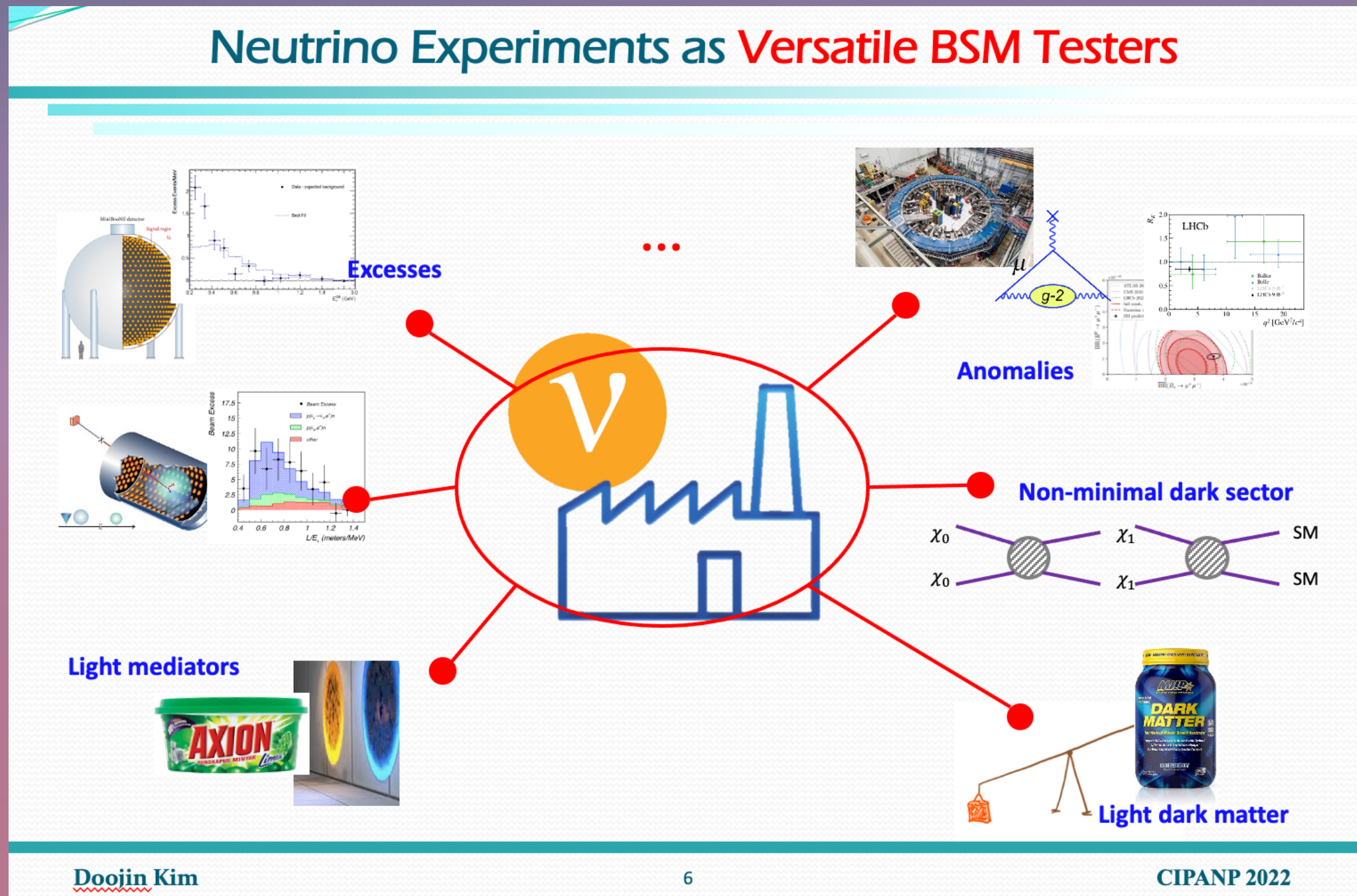


Figure 5: NuSmear Default (left) compared to complete Monte Carlo simulation (right) electron neutrino charged-current (CC) energy smearing matrices for the OPERA detector in the CNGS beam.

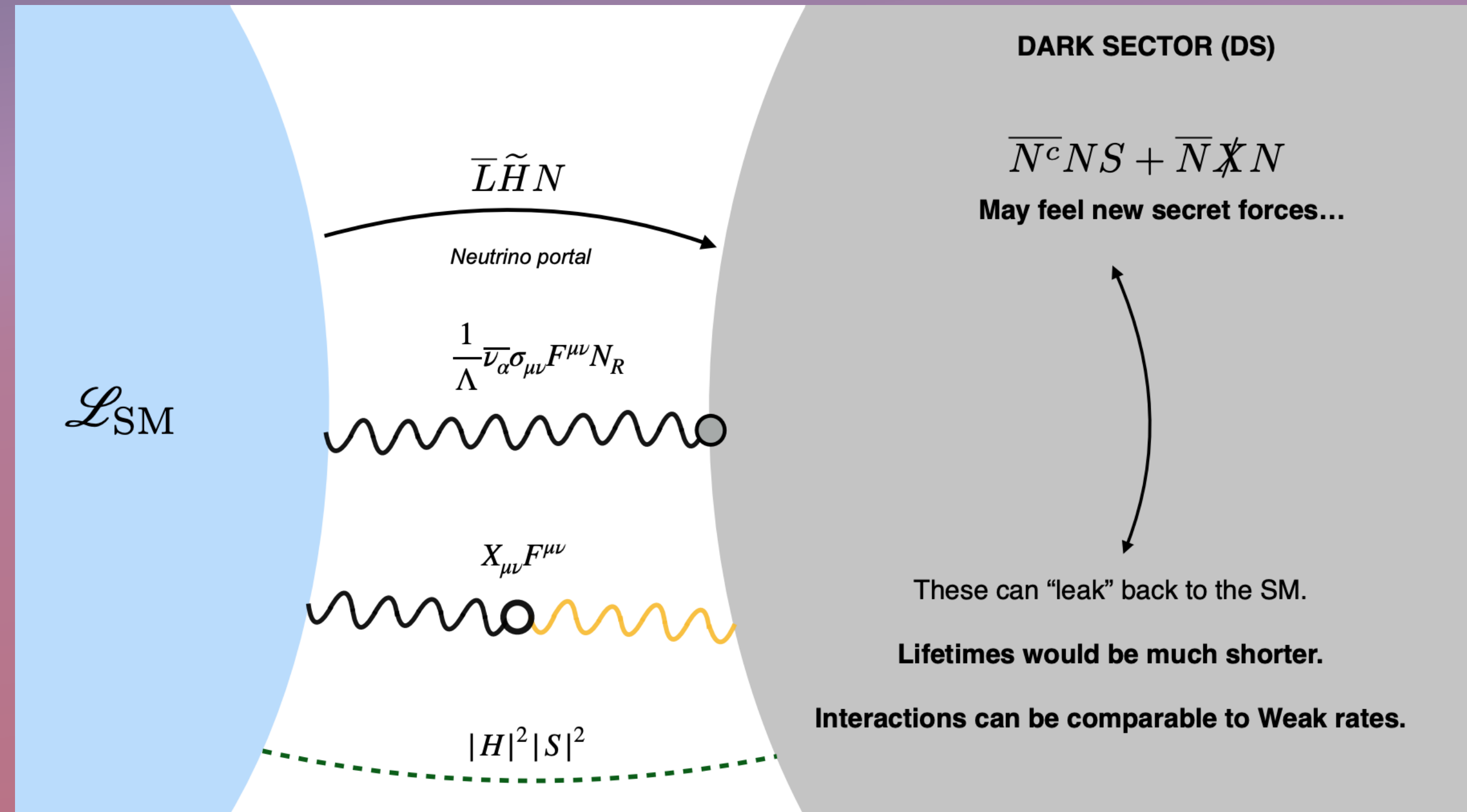
Neutrino Anomalies

- **Reports from:**
 - **Doojin Kim and Matheus Hostert on Neutrinos as Windows into Dark Sectors and BSM Physics**
 - **Josh Barrow on Results from MicroBooNE**
 - **Joseph Zennamo on the status of the Fermilab SBN Program**
 - **Tulasi Subedi on Reactor Neutrino Experiments**
 - **Stephan Friedrich on the Status of the BeEST Experiment**

Doojin Kim and Mateus Hostert on Neutrinos for Dark Matter and BSM Physics



Doojin Kim

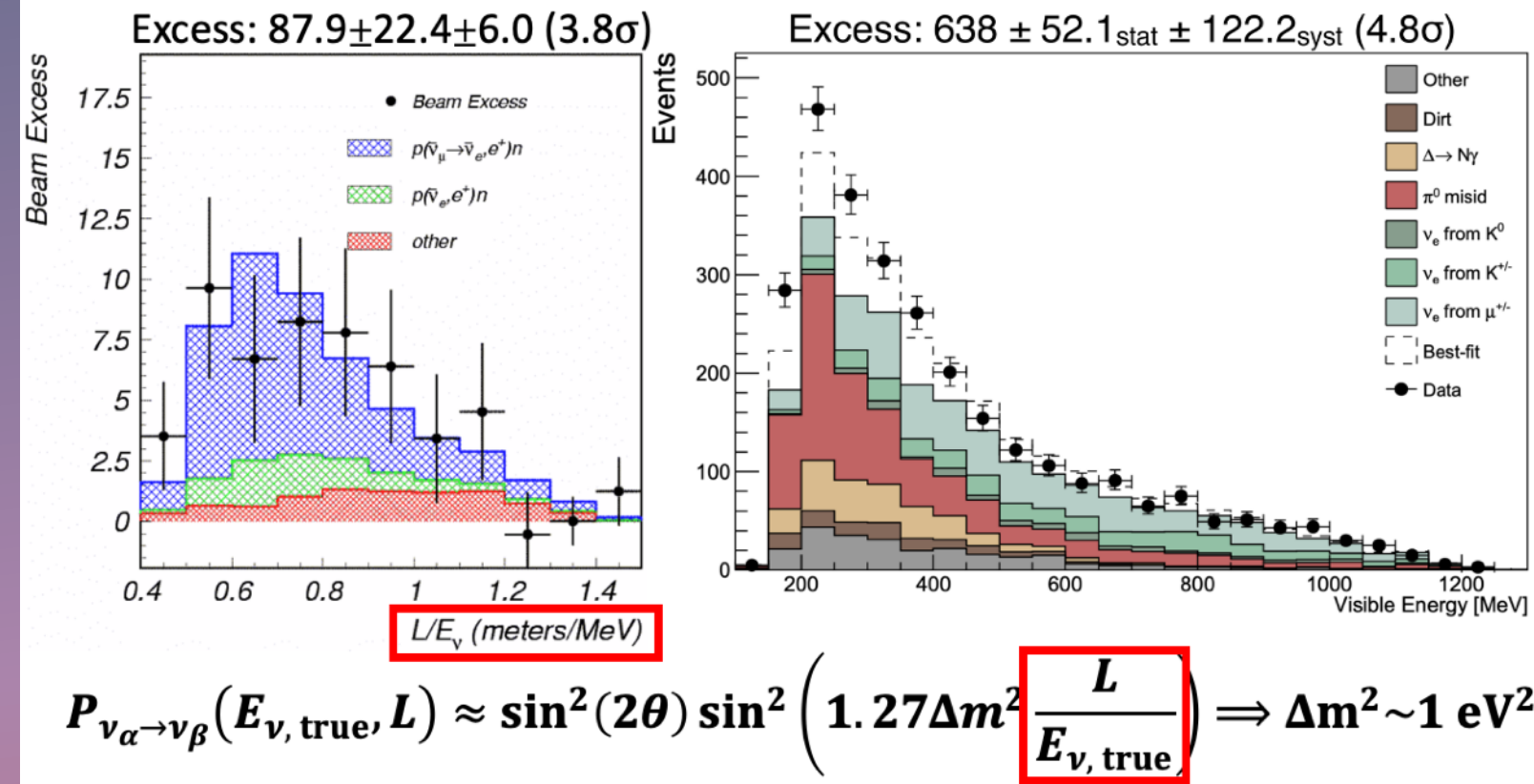


Mateus Hostert

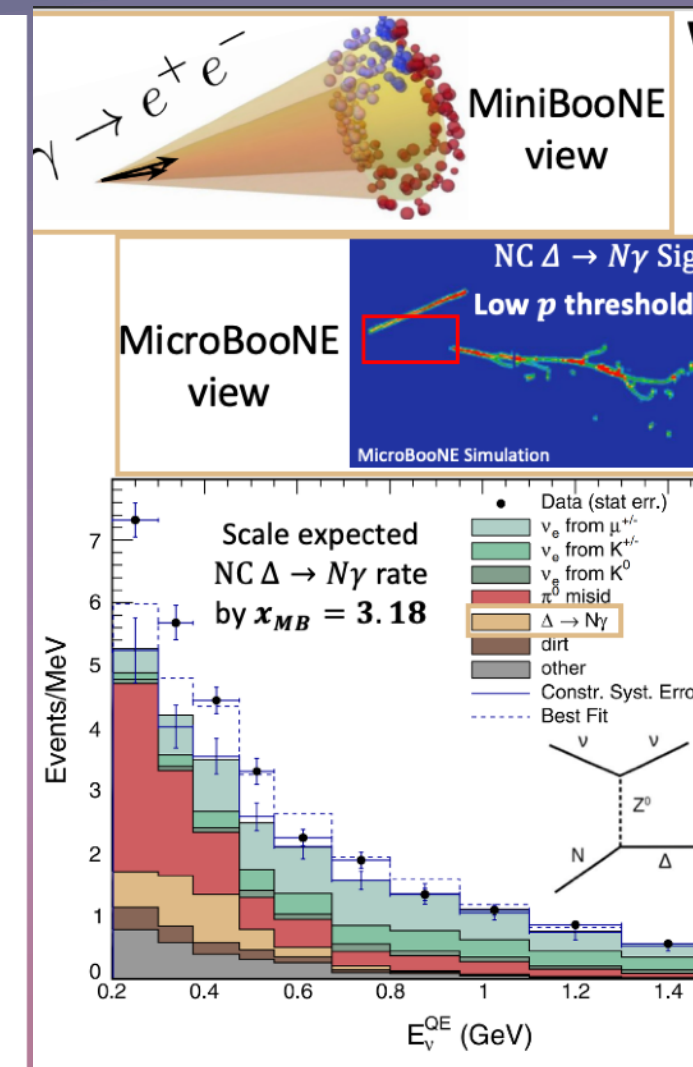
How can anomalies and sterile neutrinos serve as openings for BSM physics, Dark Matter or otherwise?

Josh Barrow on recent results from MicroBooNE on the LEE

Challenges to the Three Neutrino Paradigm Anomalies: The Low-Energy Excess



Adapted from Pedro Machado
Neutrino oscillation results from LSND
Updated MiniBooNE neutrino oscillation results with increased data and new background studies



Updated MiniBooNE neutrino oscillation results with increased data and new background studies

What Type of Excess from MiniBooNE?

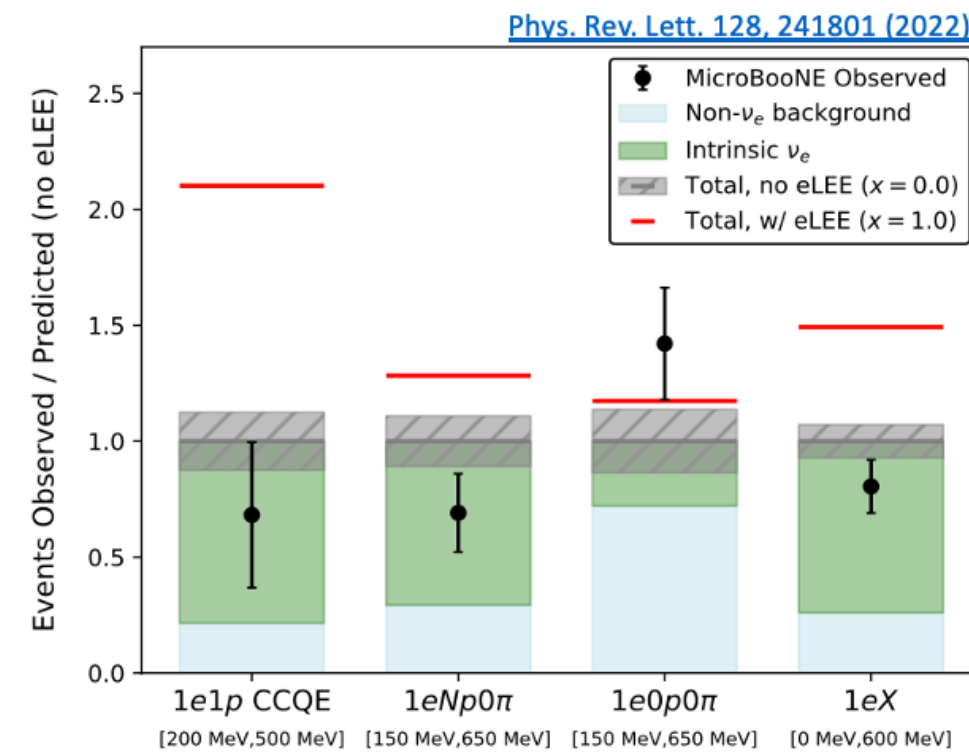
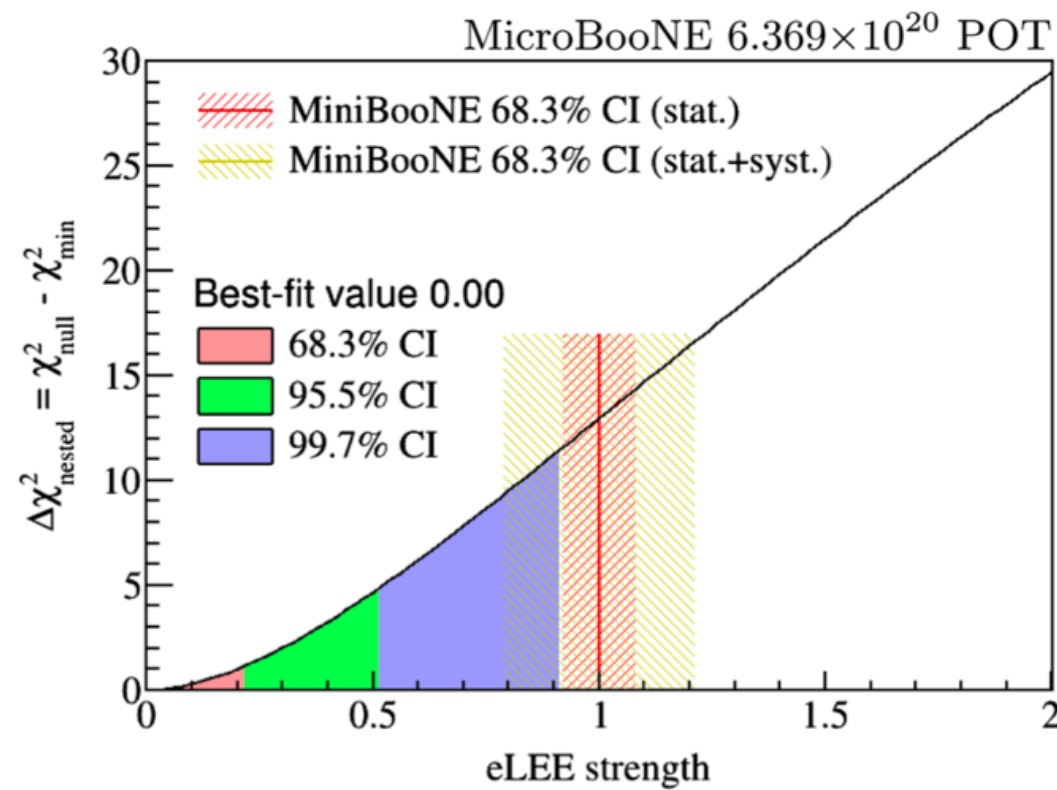
- **Photon-like excess:**
 - Mismodeled/unknown processes?
 - NC Δ resonance: $\Delta \rightarrow N\gamma$
 - Single γ LEE: **gLEE**
- **Electron-like excess:**
 - Oscillation-driven excess?
 - Energy-dependent ν_e -enhancement
 - ν_e LEE: **eLEE**
 - Derived from MiniBooNE empirically
- **Mismodeled/unknown processes?**
 - Collimated e^+e^- states?



Adapted from Jay Hyun Jo and Mark Ross-Lonegan

Adapted from Hanyu Wei

eLEE Search Results



- ν_e candidate rates are statistically consistent with those predicted
- Original **median LEE model** hypothesis:
 - “ ν_e events are *fully* responsible for the *median* MiniBooNE LEE”
 - **Rejected at > 97% CL**
 - This is $> 3\sigma$ in the fully inclusive channel, not true for $1e0p0\pi$

21 Adapted from Hanyu Wei

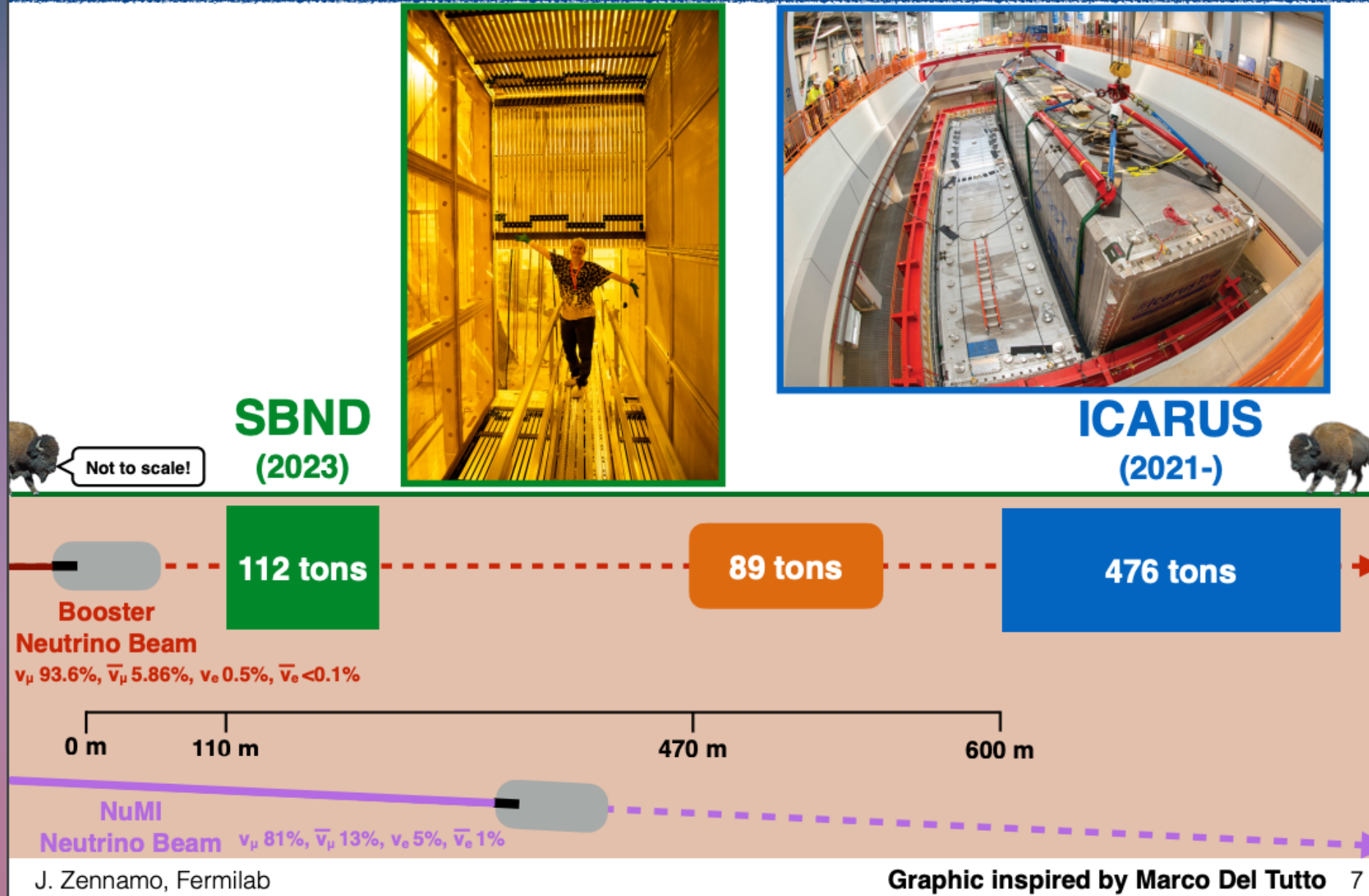
Summary

- MicroBooNE’s first LEE searches have found:
 - **No evidence for excessive ν_e production**
 - Disfavors pure ν_e excess as sole source of anomaly at 3σ
 - **No evidence for excessive NC $\Delta \rightarrow N\gamma$ production**
 - Disfavors pure Δ excess as sole source of anomaly at $\sim 2\sigma$
- Full 3 + 1 oscillation analyses seek out the sterile neutrino
 - **Runs 1-3 (50% of total dataset) are consistent with 3ν hypothesis**
 - Our statistics are soon to grow by a factor of 2!
 - Utilizing both BNB and NuMI datasets show great sensitivity promise
- **MiniBooNE anomaly still stands, with diminishing parameter space**
- Many searches on the way!
 - Expanded scope of sterile oscillation searches
 - Utilize deep learning methods for combined ν_e/ν_μ selections
 - Exotic e^+e^- pair production searches
 - Many other BSM particles and processes coming soon!

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Parameter space shrinking for your favorite explanation of the excess

Short-Baseline Neutrino Program at Fermilab

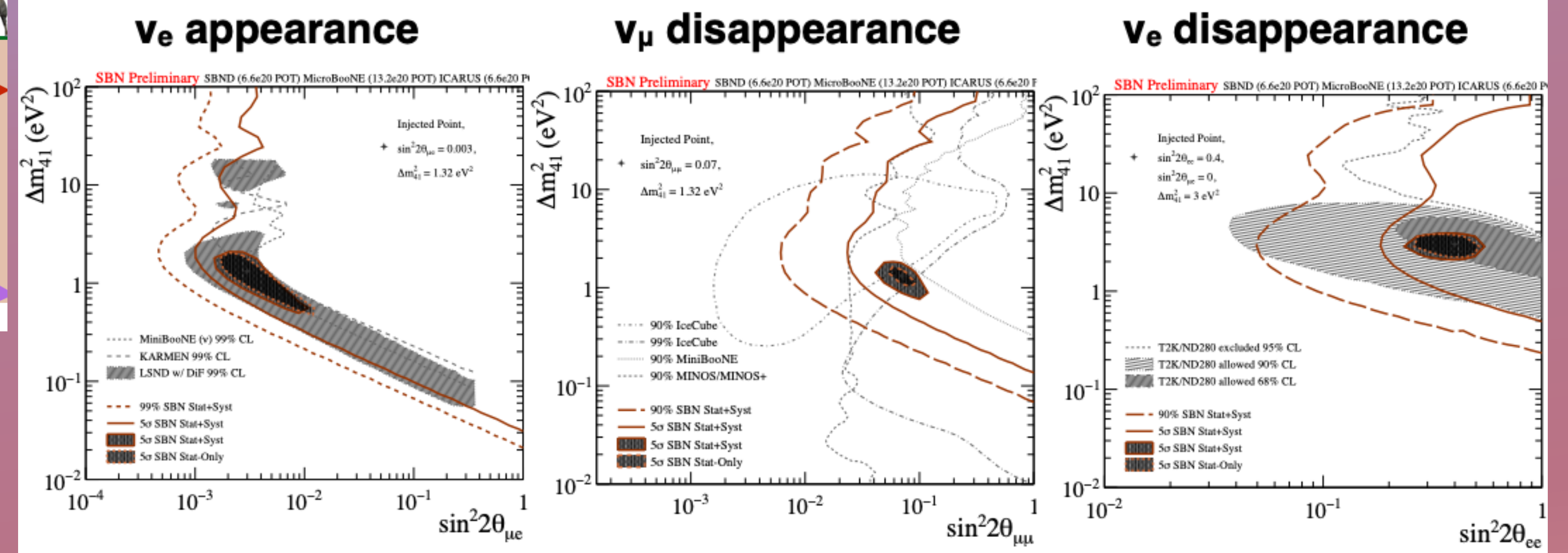


Joseph Zennamo updating us on the SBN program

The program suggests a definitive answer for the existence of sterile neutrinos

Searches for Sterile Neutrinos

Searches for sterile neutrinos with the SBN Program will definitively cover the LSND allowed region and stringently test the global allowed regions in three channels!



Conclusions

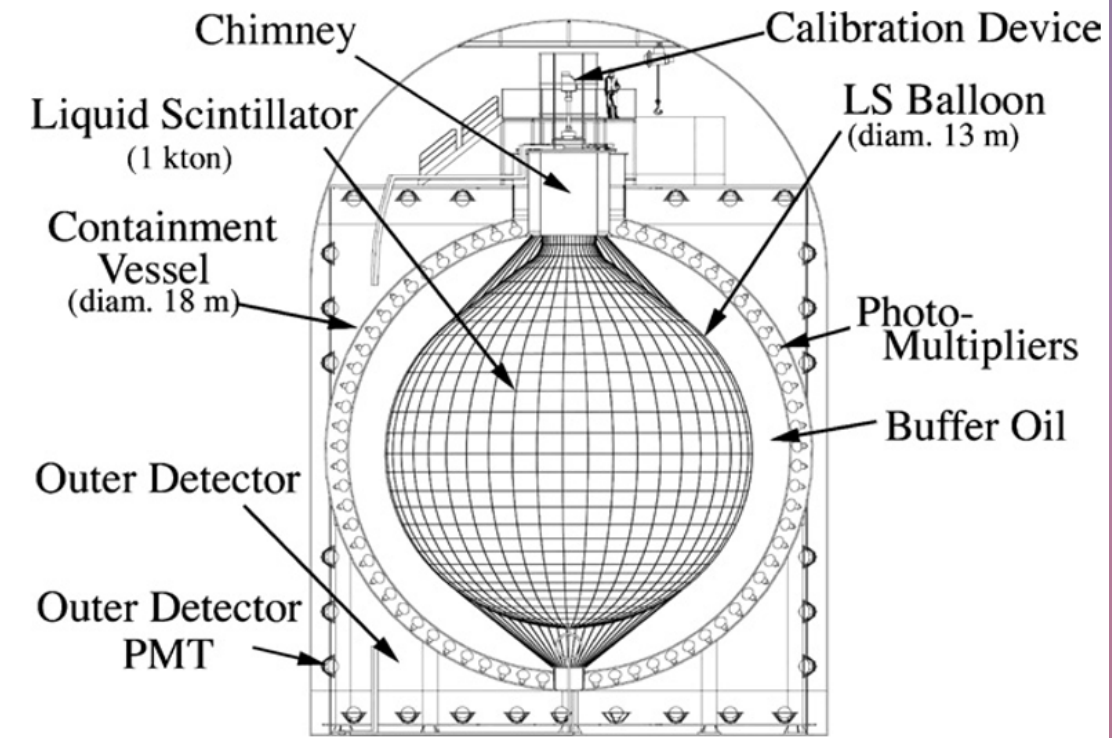
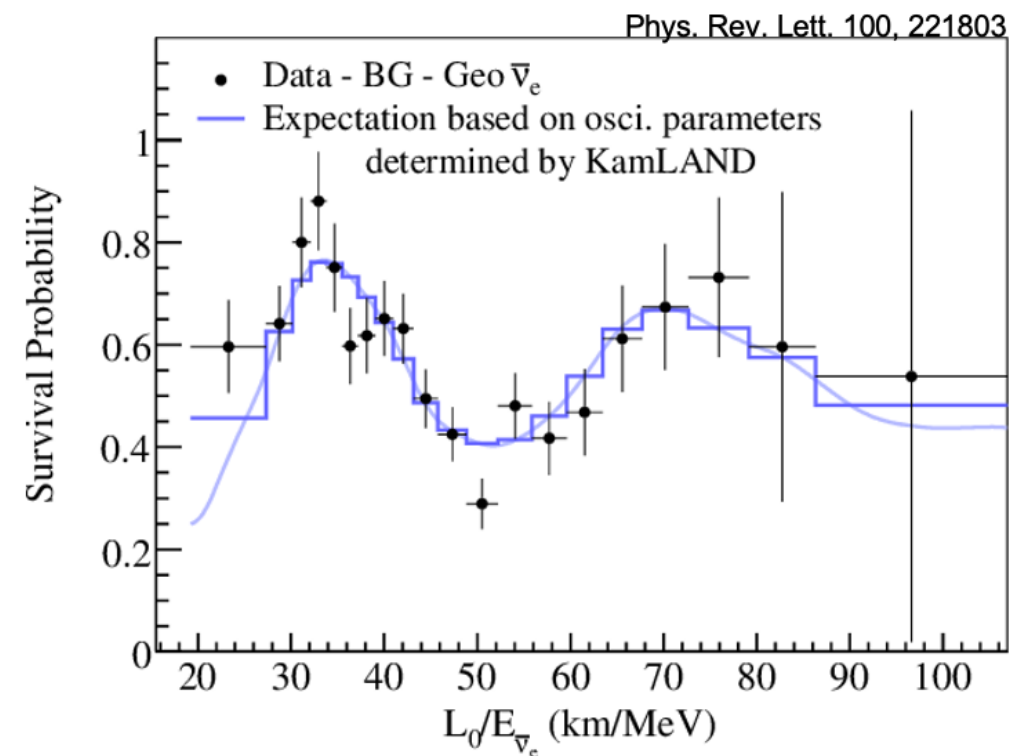
- SBND is finishing detector assembly, and ICARUS has started its physics running
- Stay tuned as the SBN Program launches itself toward an exciting physics program!
 - Including world-leading ν -Ar cross section measurements, definitive searches for eV-scale sterile neutrino oscillations, and other BSM physics

J. Zennamo, Fermilab

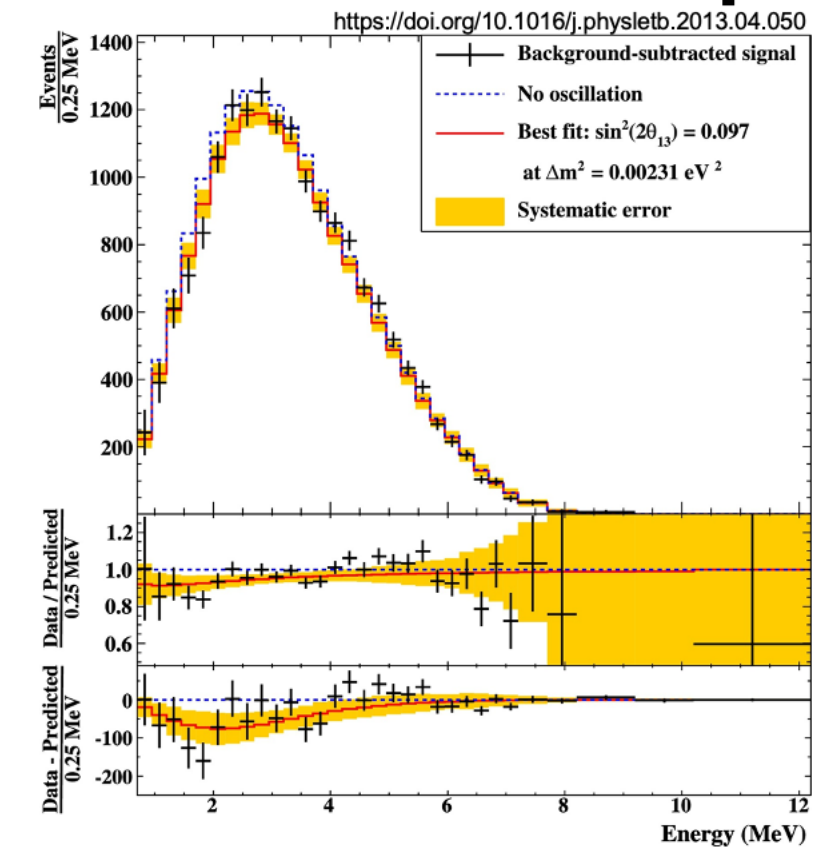
17

Neutrino Oscillations

The KamLAND experiment measured Δm_{21}^2 from reactor neutrino oscillations

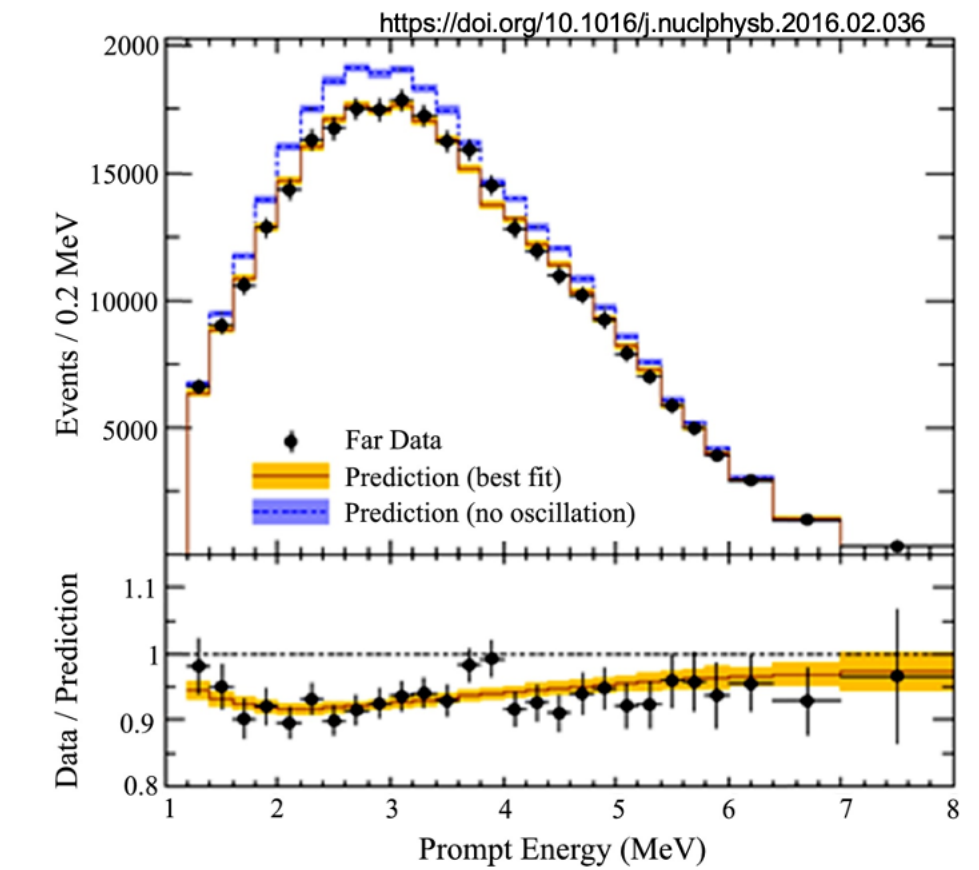


Double Chooz and RENO verified the parameter values



Double-Chooz

Independent of the absolute reactor flux and spectrum

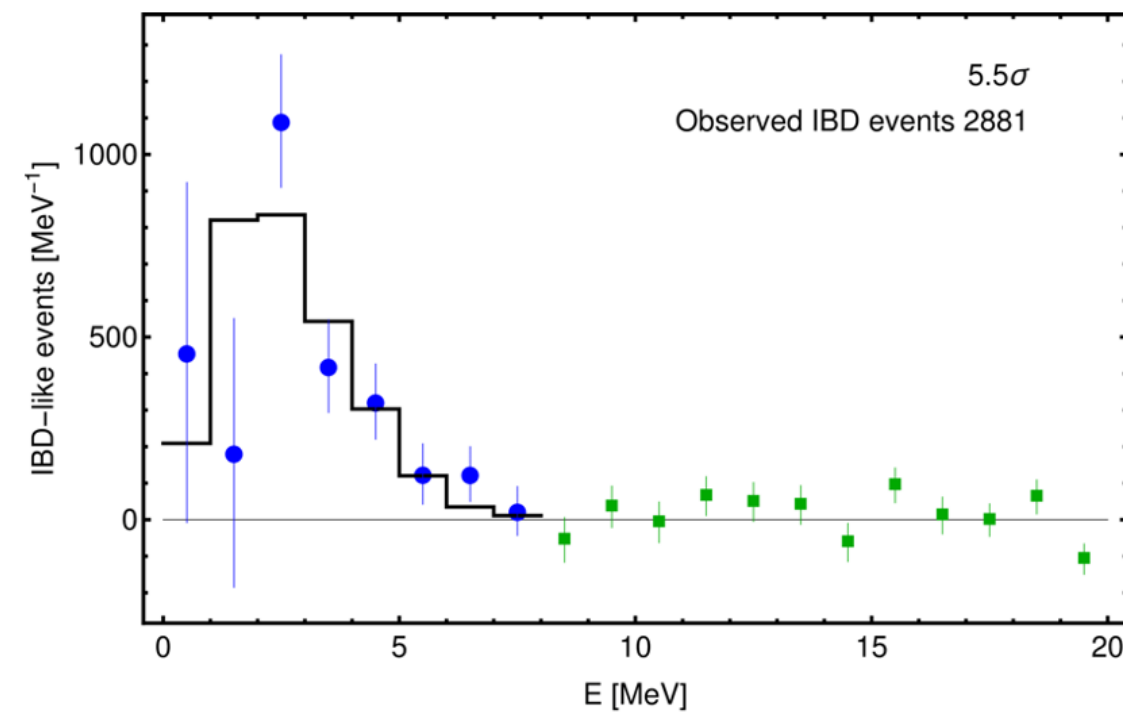


RENO

MiniCHANDLER Deployment



Deployed at North-Anna Nuclear Power Plant

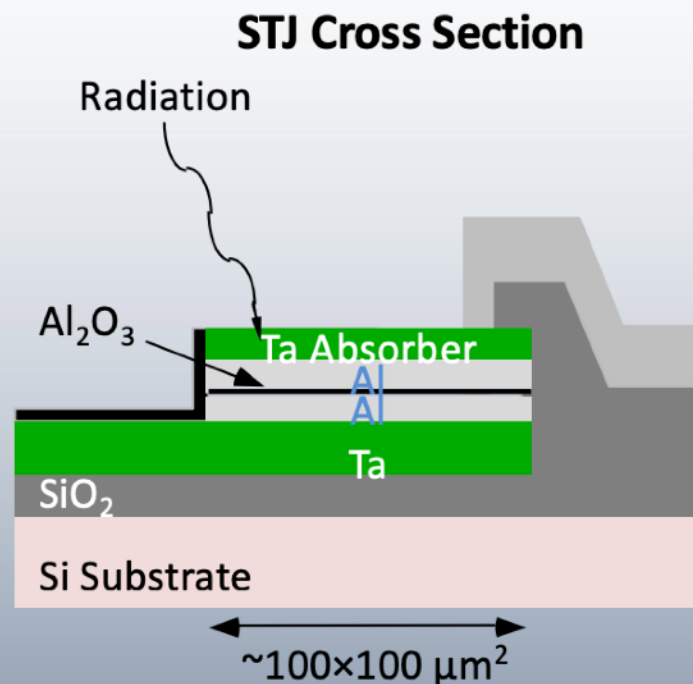


Detected antineutrinos with minimal shielding in a mobile platform at surface level environment

Tulasi Subedi gave an excellent introduction to Reactor Neutrino Experiments.

Thorough overview of important contributors, Daya Bay and JUNO not shown

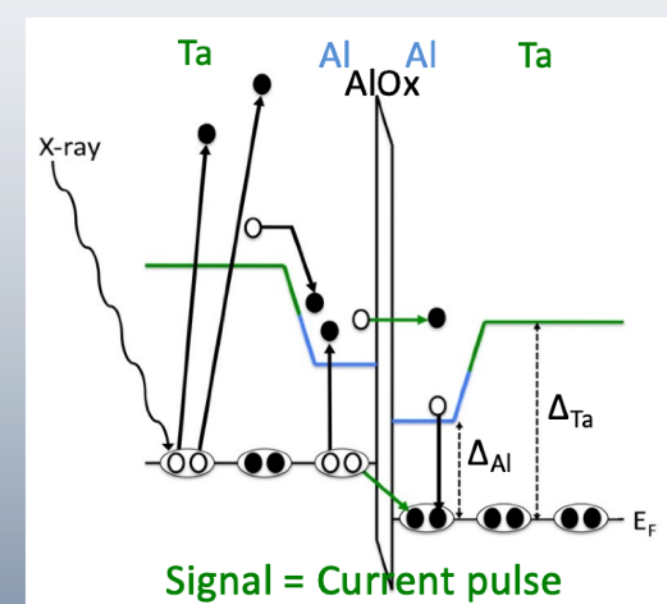
Superconducting Tunnel Junction (STJ) Radiation Detectors



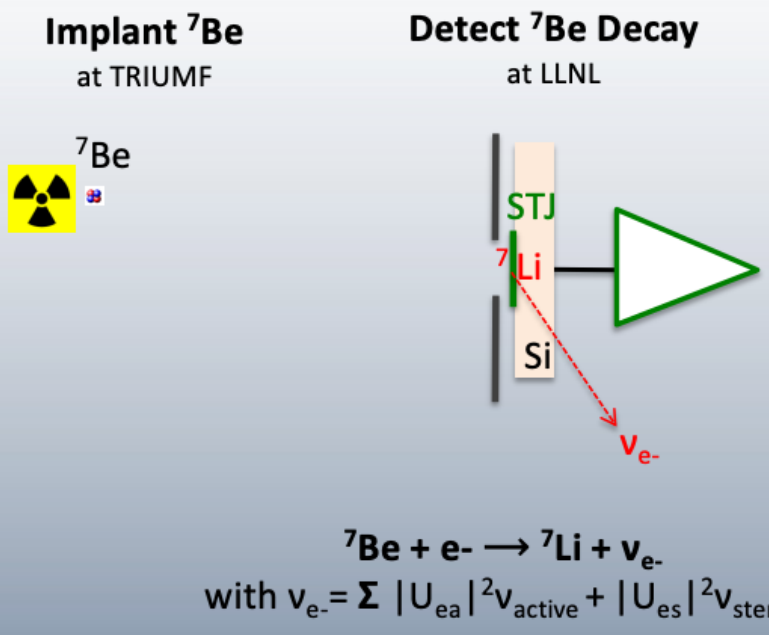
$$\text{Energy resolution } E_{\text{FWHM}} = 2.355 \sqrt{1.7\Delta \cdot E_{\text{X-ray}} \left(F + 1 + \frac{1}{n} \right)}$$

Small superconducting energy gap ($\Delta \approx 1\text{meV}$) \Rightarrow High resolution (<10 eV FWHM)
 Short excess charge life-time ($\sim\mu\text{s}$) \Rightarrow High count rate (>1,000 counts/s/pixel)

STJ Operating Principle

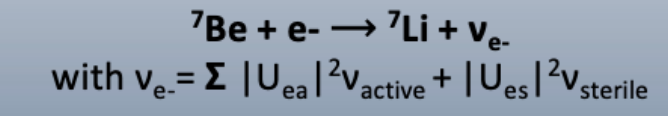


Be-7 Electron Capture in STJs: The BeEST Experiment



$$E_{\text{Li recoil}} = \frac{Q^2 - m_\nu^2 c^4}{2(Q - m_{\text{Li}} c^2)}$$

$\rightarrow 56.826(9)\text{eV}$ for $m_\nu \approx 0$



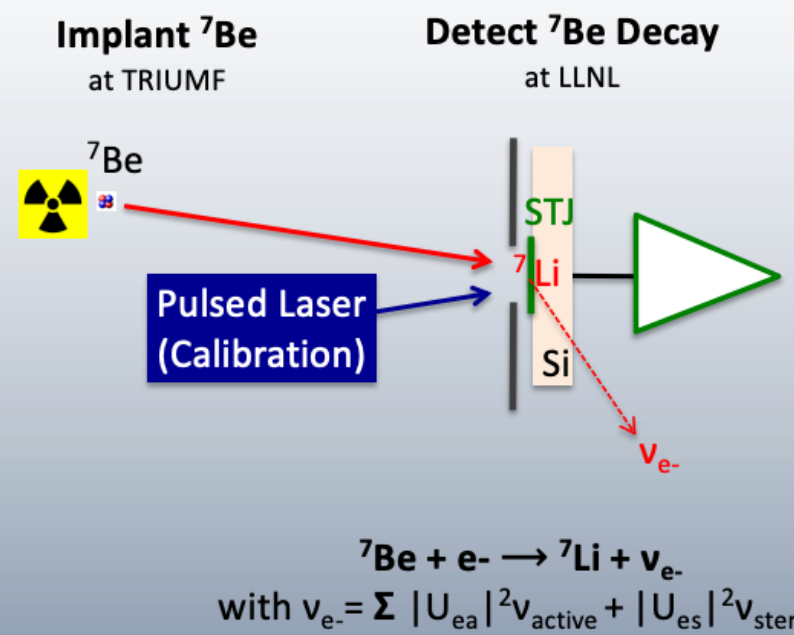
Heavy sterile neutrinos would reduce ⁷Li recoil energy.
 Look for shifted peaks in the recoil spectrum.



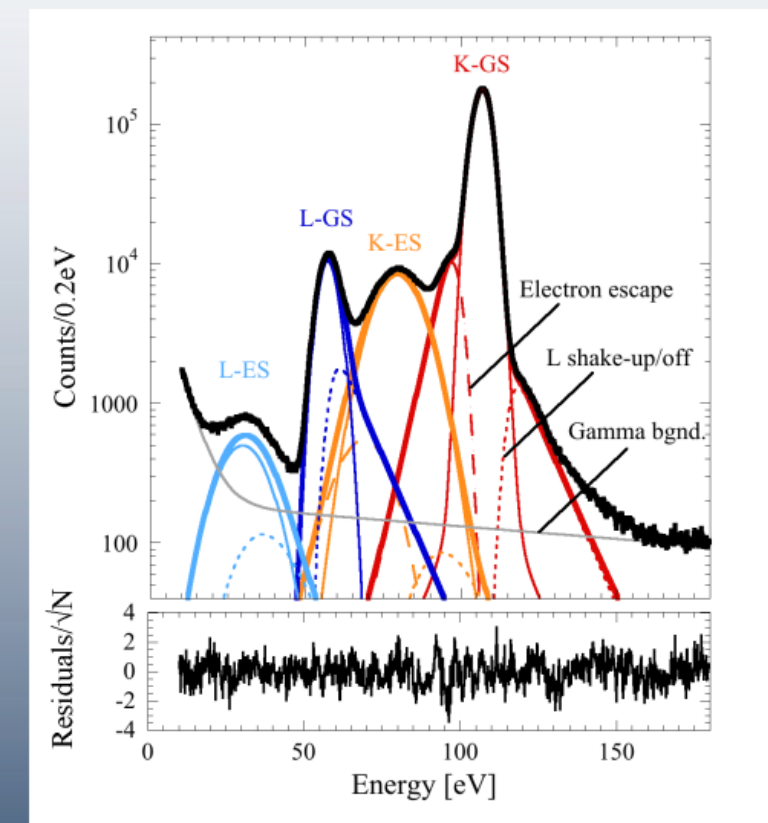
Stephan Friedrich walked us through the physics of BeEST

BeEST is a complementary and novel way of observing sterile neutrinos and dark matter.

The BeEST Sterile Neutrino Experiment



Data from 1 Ta-STJ Detector for 28 Days



- 4 primary peaks
 - 2 x K-capture, 2x L-capture
 - to ⁷Li ground state and to ⁷Li*
- 4 high-energy tails
 - Shake-off effects
- 2 low-energy tails
 - (Partial) Auger e- energy loss
- 1 broad background
 - 478 keV γ 's in substate

L/K Ratio = 0.070(7)

PRL 125, 032701 (2020)

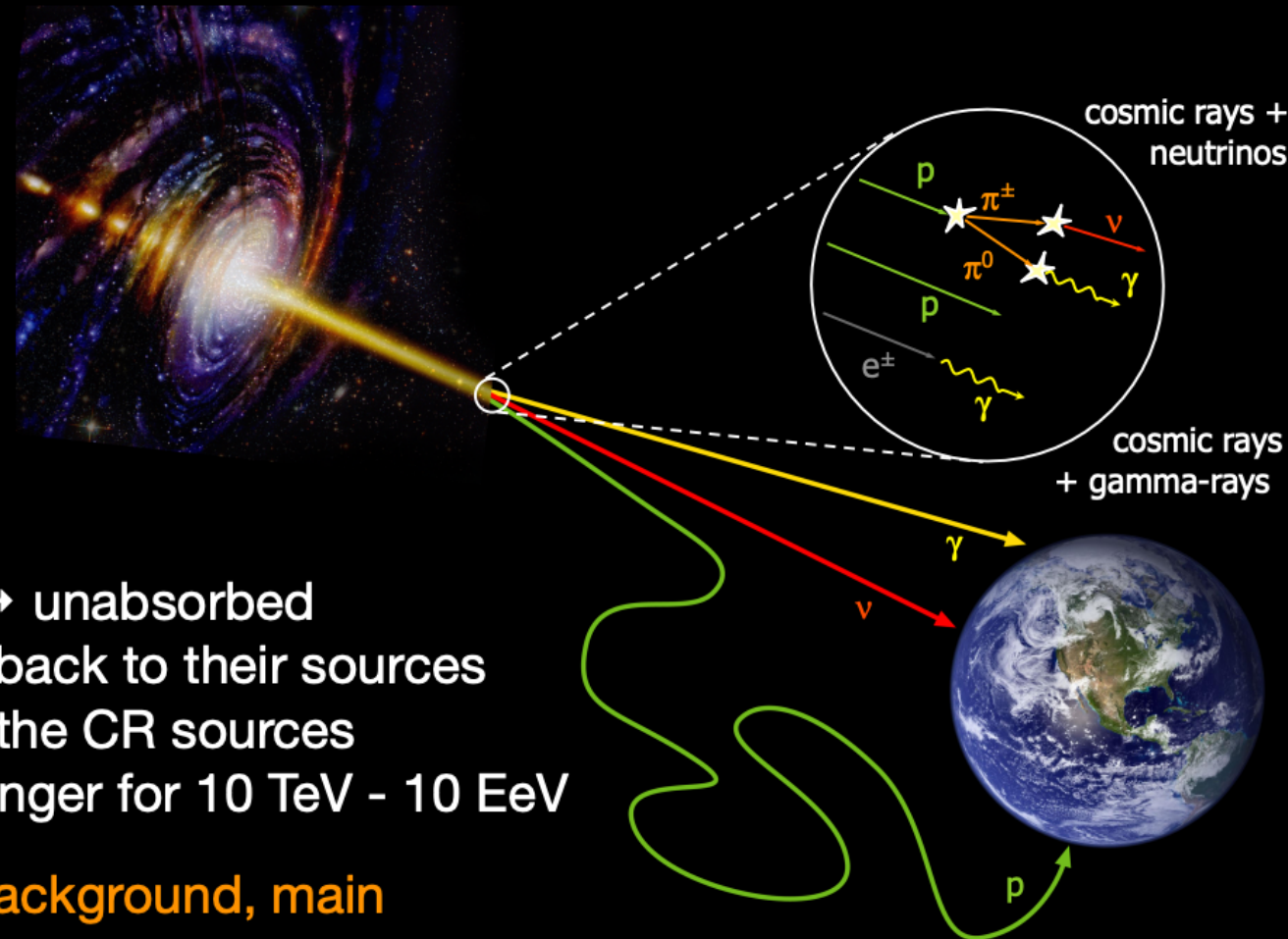
Neutrino Astrophysics & Cosmology

- **Reports from:**
 - **Ali Keirandish with a Theory Perspective on Neutrino Astrophysics**
 - **Amol Patwardhan on Neutrinos in Supernovae**
 - **Pooja Siwach on Oscillations in Supernova Simulations**
 - **Evan Grohs on Cosmological Neutrinos**

Neutrino Astrophysics

- Soon after discovery it was realized neutrinos are ideal cosmic messengers.

Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



- Neutrinos:
 - ✓ Hardly interact → unabsorbed
 - ✓ Neutral → point back to their sources
 - ✓ Smoking gun of the CR sources
 - ✓ Exclusive messenger for 10 TeV - 10 EeV

Low statistics and large background, main challenges for neutrino astronomy.

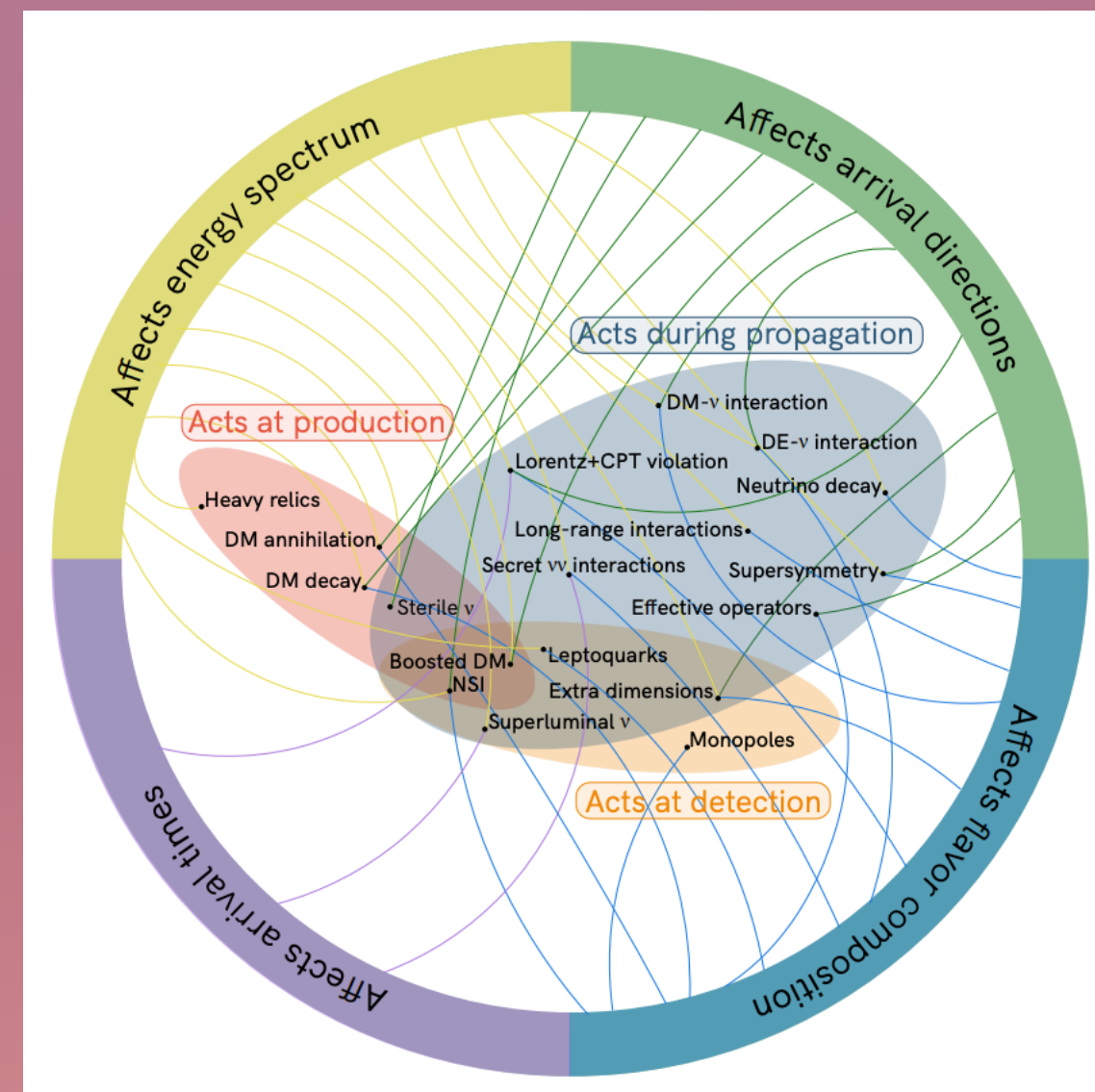
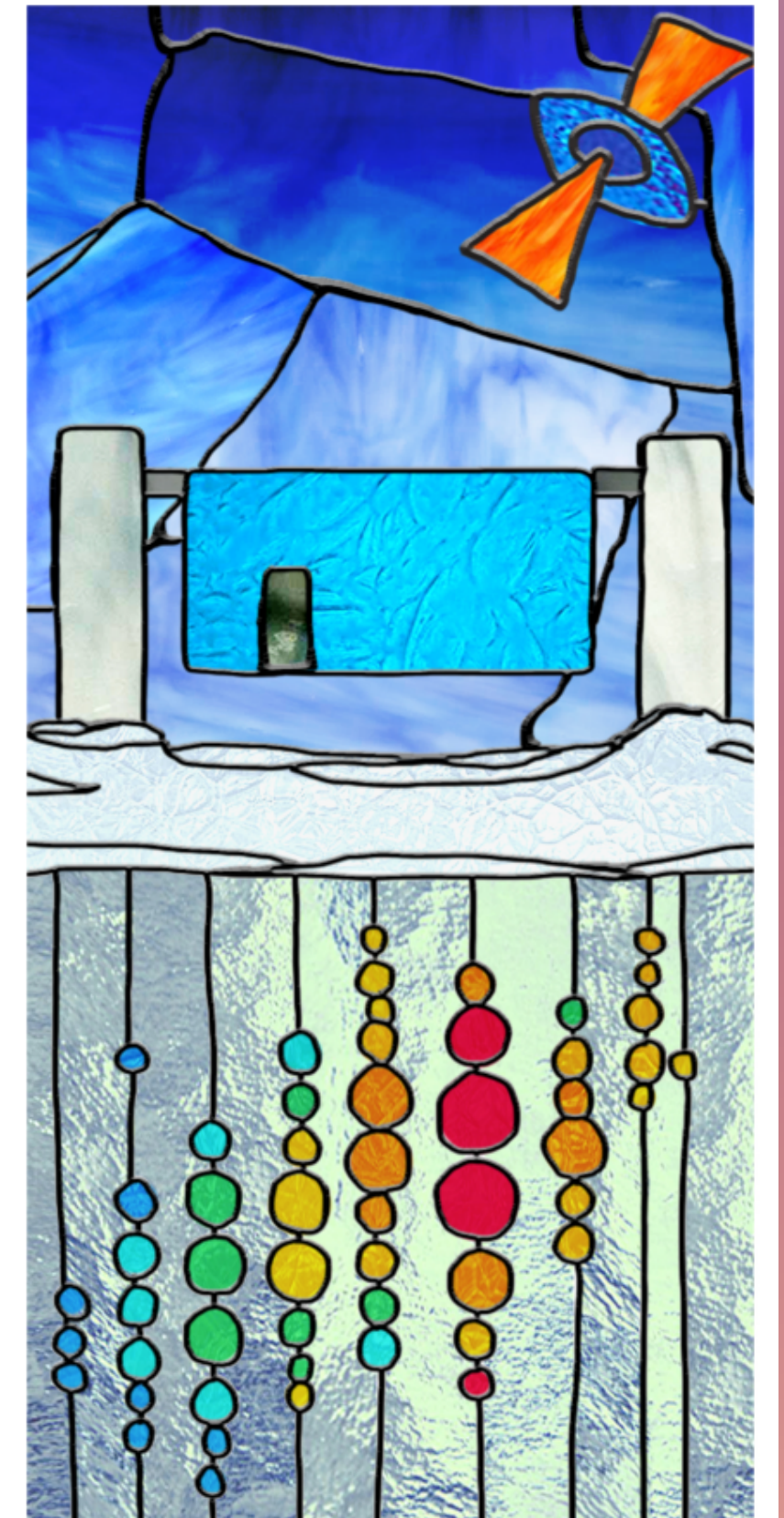
Ali Kheirandish | CIPANP 2022 | 2021 | 4

Ali Kheirandish with a Theory Perspective on Neutrino Astrophysics

High energy neutrino flux used to understand the universe and neutrinos!

Outlook

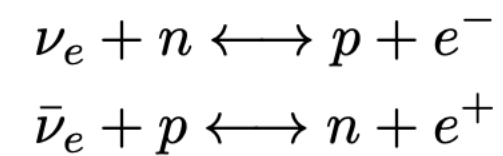
- After a decade of observation, signs of anisotropy are emerging in IceCube data.
 - ▶ Early indications points to active galactic nuclei as primary source of high-energy cosmic neutrinos.
- Identification of the origin of HE cosmic neutrinos will bring insight into the working of cosmic accelerators.
- The HE neutrino beam provided by cosmic accelerators offers unique opportunities to study neutrinos.
- Cosmic neutrinos provide complementary tests of physics beyond the Standard Model in the neutrino sector.



Ali Kheirandish | CIPANP 2022 | 2021 | 35

Core-collapse supernovae and neutrinos

- Neutrinos depositing $\sim 1\%$ of their energy behind the stalled shock front could revive the shock and explode the star
- ν -induced heating in the aftermath of explosion drives baryonic matter outflows from the surface of the nascent neutron star
- Charged-current weak processes govern the energy deposition and n/p ratio, a crucial input for nucleosynthesis



- Flavor asymmetric processes: thorough understanding of neutrino flavor evolution therefore required

Neutrino flavor equilibration and the νp -process

Amol Patwardhan

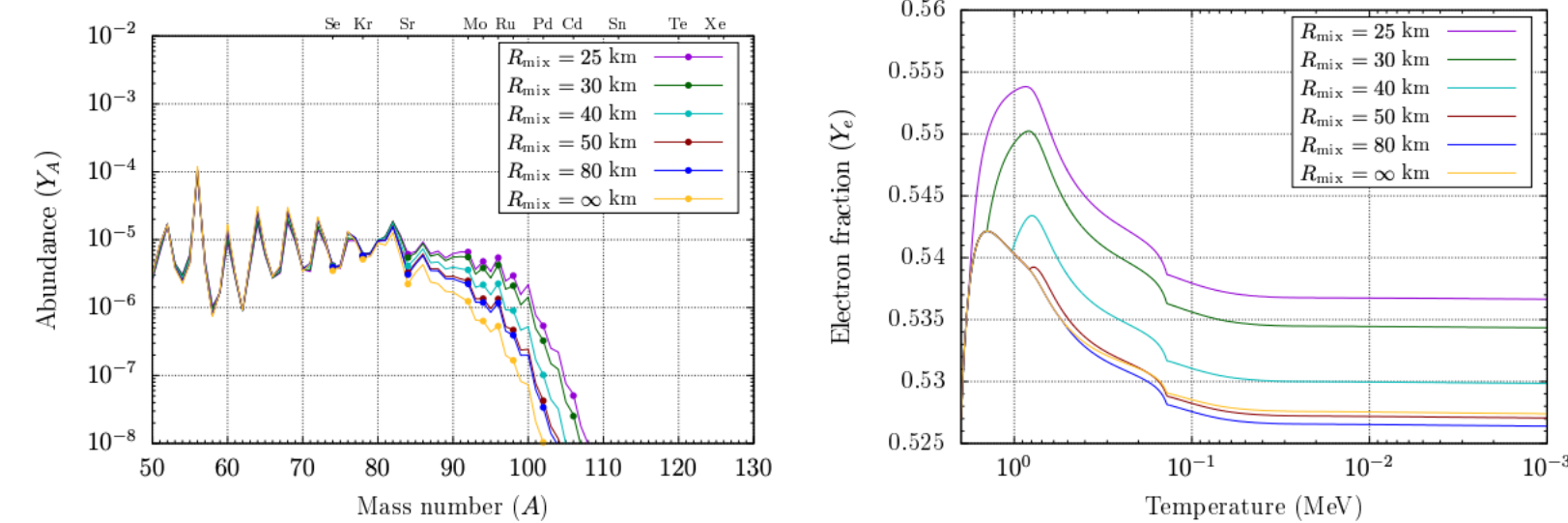
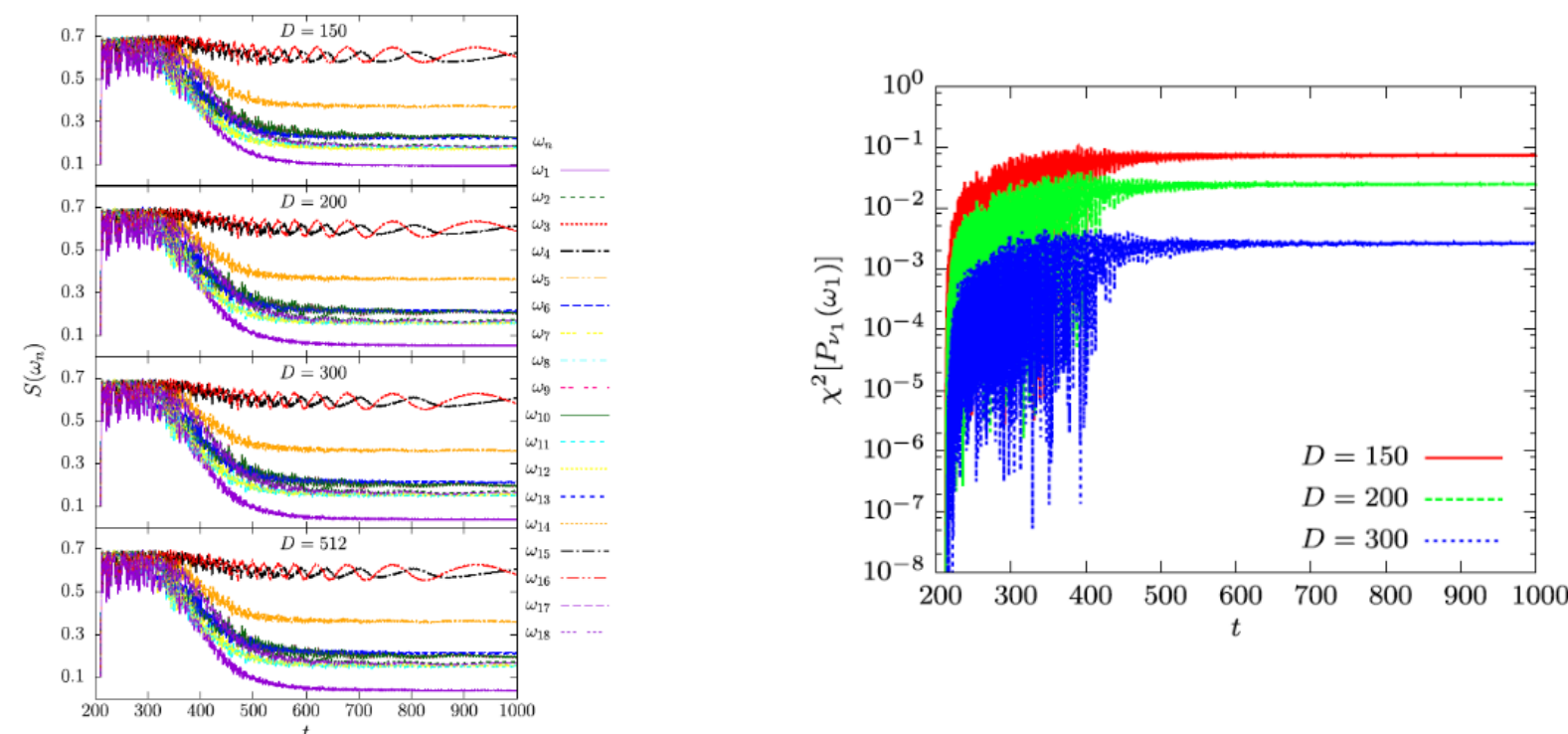


Figure: Nucleosynthesis calculations with different flavor equilibration radii R_{mix} . **Left:** Abundance vs Mass number. **Right:** Electron fraction vs Temperature.

[AVP, A. Friedland, P. Mukhopadhyay, and S. Xin, *in preparation*]
 In our model, we study these different regimes by varying the radius R_{mix} . Flavor equilibration is found to universally improve the νp -process efficacy, more so if it occurs closer to PNS.

Results



Pooja Siwach

Amol Patwardhan on Neutrinos in Supernovae

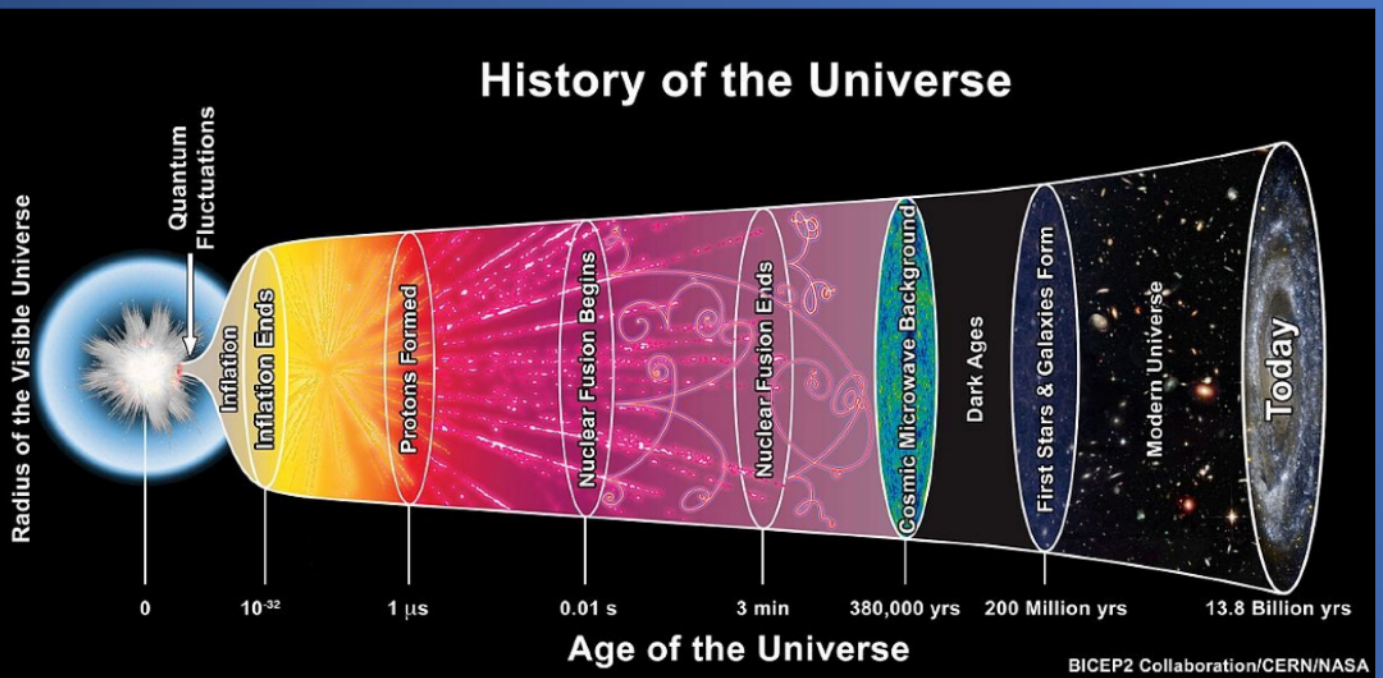
Considerable progress in understanding neutrino flavor interactions with nucleosynthesis!

Evan Grohs on Cosmological Neutrinos

Cosmology: Overview of Λ CDM

Universe begins from a "singularity" – hot Big Bang
 → Near Homogeneous, Isotropic spacetime geometry
 → Close to Thermal and Chemical Equilibrium
 → Subsequent Expansion and Cooling

$$H \equiv \frac{1}{a} \frac{da}{dt} = \sqrt{\frac{8\pi}{3m_{pl}^2} \rho}$$



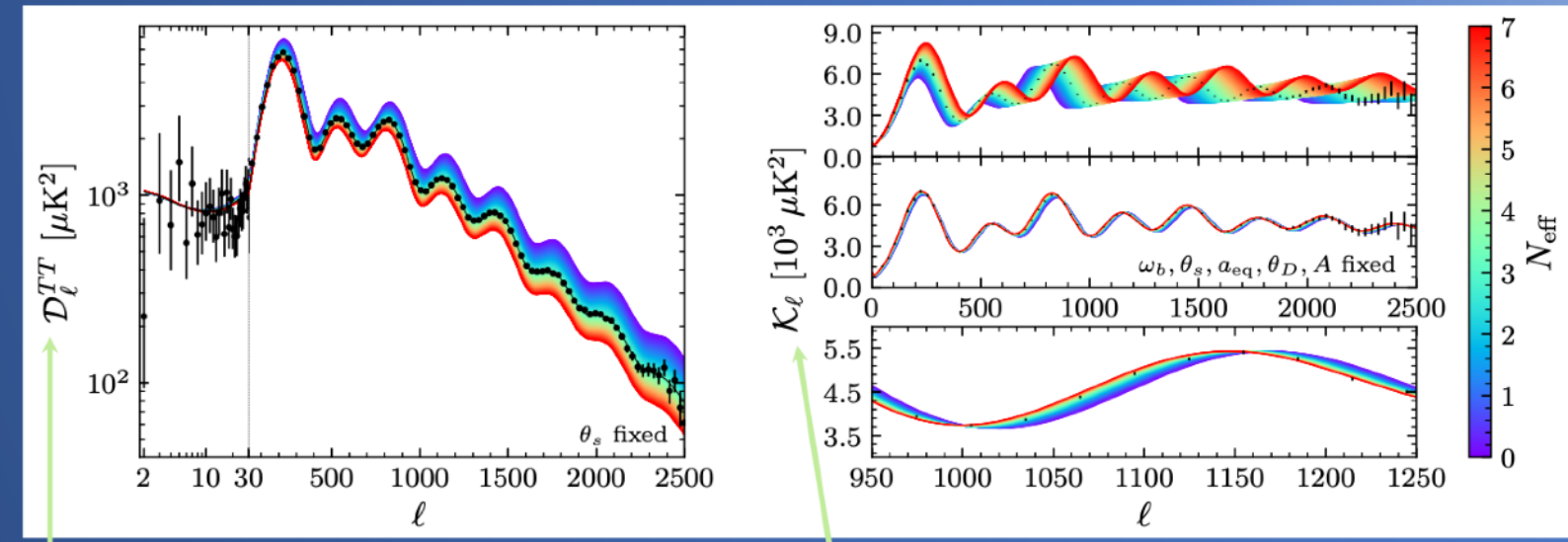
- Various epochs:
1. Planck epoch $\sim 10^{-44}$ s
 2. Grand Unification $\sim 10^{-38}$ s
 3. Inflation $\sim 10^{-32}$ s?
 4. Electroweak breaking $\sim 10^{-11}$ s
 5. Quark-Hadron transition $\sim 10^{-5}$ s
 6. BBN ~ 1 s – 3 mins.
 7. Atomic Recomb. $\sim 10^5$ yrs
 8. Structure ~ 100 Myr
 9. Reionization ~ 500 Myr
 10. Galaxies, stars, planets ~ 1 Gyr

Summary

1. Solid evidence for the existence of neutrinos in hot big bang cosmology
 - a. CMB and BAO show N_{eff} not equal to zero
 - b. BBN shows neutrinos have \sim thermal spectra
2. Future probes will show even more sensitivity to neutrino energy spectra
3. Generalized entropy formalism can capture out-of-equilibrium neutrino distributions
4. Abundance predictions require:
 - a. Neutrino spectra
 - b. Radiation energy density of the universe
 - c. Phasing between time and photon temperature

Effects of Radiation on CMB

Black points are Planck 2018 data values



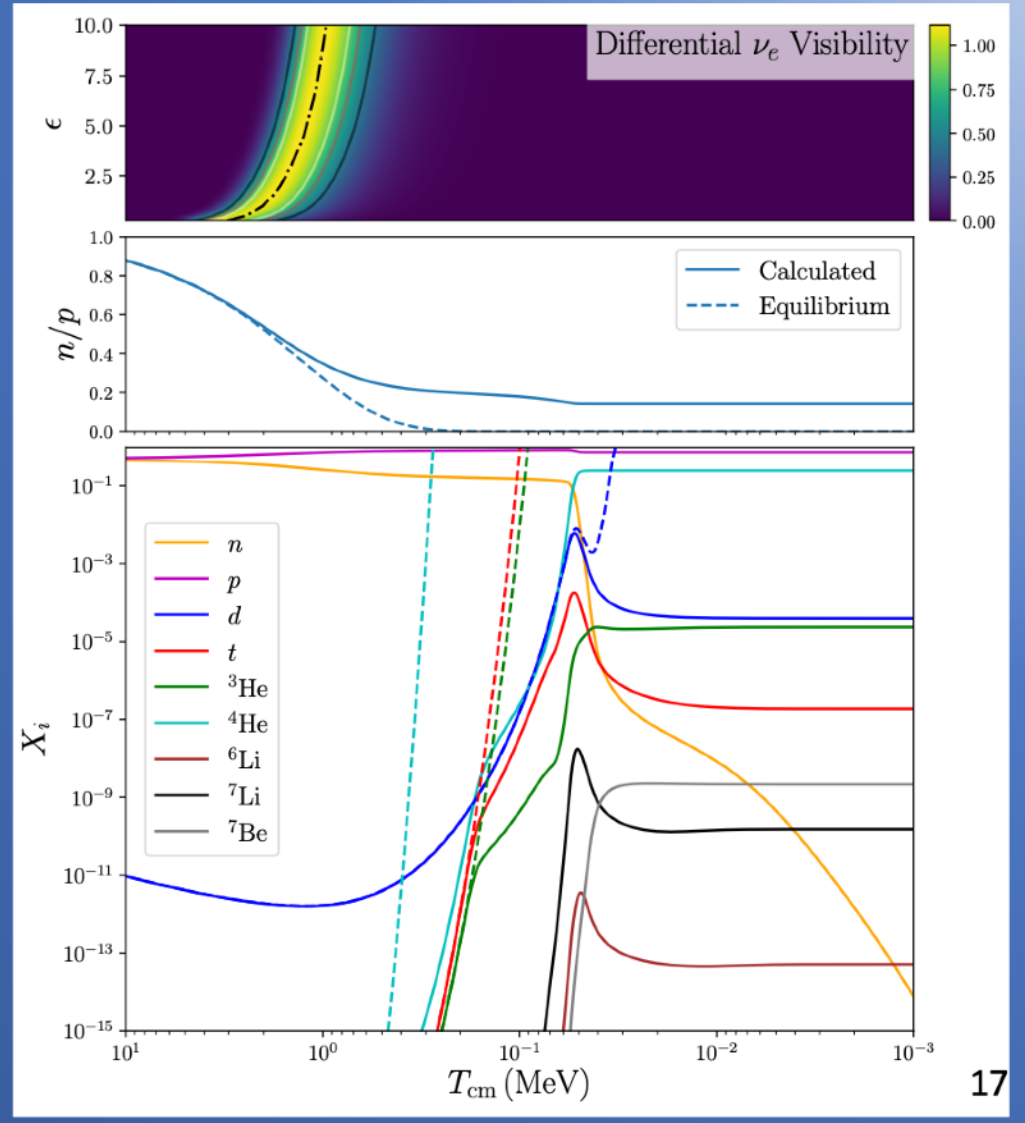
Temperature Power Spectrum: Non-photon radiation
 Non-damped Temperature Power Spectrum: Free-streaming radiation

Planck 2018: $N_{\text{eff}} = 2.92^{+0.18}_{-0.19} (1\sigma)$

Neutrino physics occurring during BBN

Coincident epochs during BBN:
 Weak Decoupling (Diff. Vis.)
 Weak Freeze-Out (n/p)
 Nuclear Freeze-Out (X_i)

Dashed lines: weak equilibrium or NSE



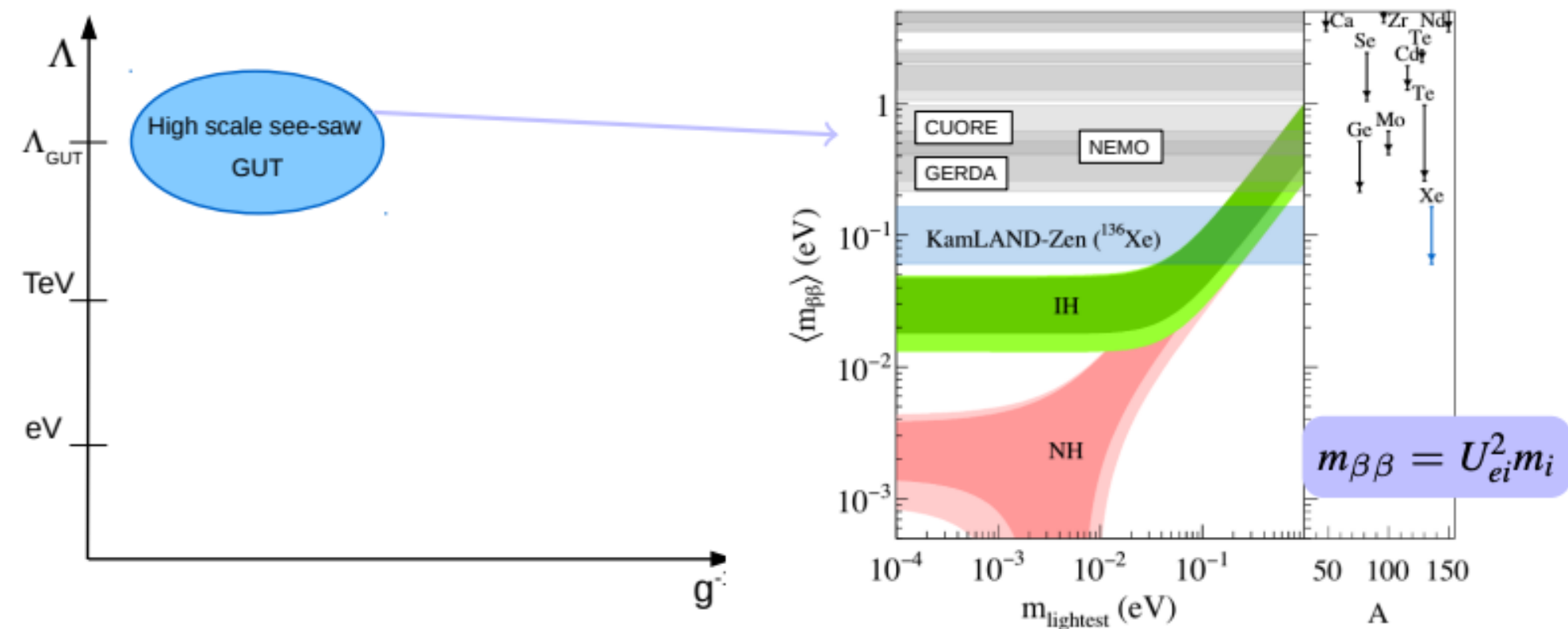
Effective neutrino flavor extracted from the CMB, Big Bang Nucleosynthesis

Neutrino Properties

- **Reports from:**
 - **Emanuele Mereghetti on the theory behind Neutrinoless Double Beta Decay**
 - **Ann-Kathrin Schuetz on Results from KATRIN, Project 8, and Neutrino Mass**
 - **Laxman Paudel and CJ Barton on the Majorana Demonstrator and LEGEND-1000**

Emanuele Mereghetti on the theory behind Neutrinoless Double Beta Decay

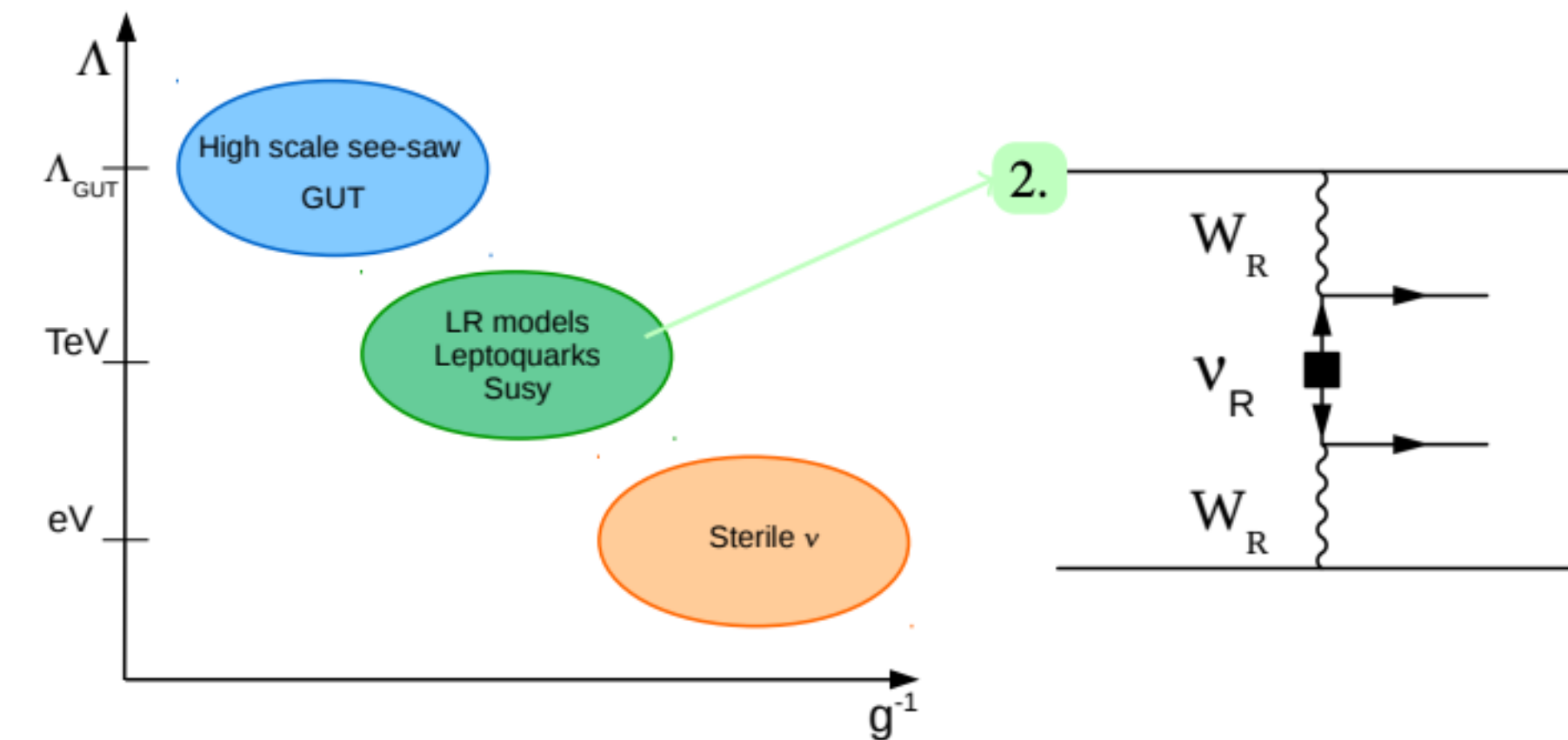
Introduction



$0\nu\beta\beta$ is the most sensitive probe of lepton number violation (LNV)

1. LNV originates at very high scales
direct connection between ν oscillations and $0\nu\beta\beta$
clear interpretative framework and goals

Introduction



$0\nu\beta\beta$ is the most sensitive probe of lepton number violation (LNV)

2. LNV at intermediate scales
 $0\nu\beta\beta$ is mediated by new particles, accessible at colliders?
3. very light and weakly coupled new physics

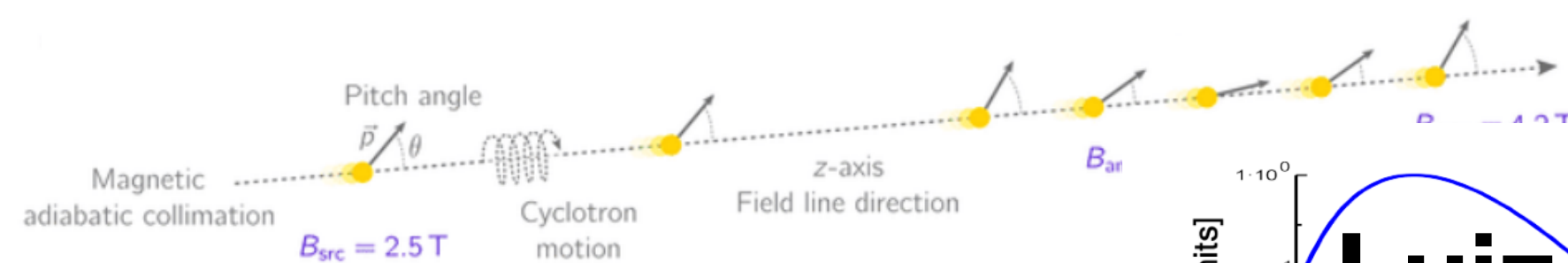
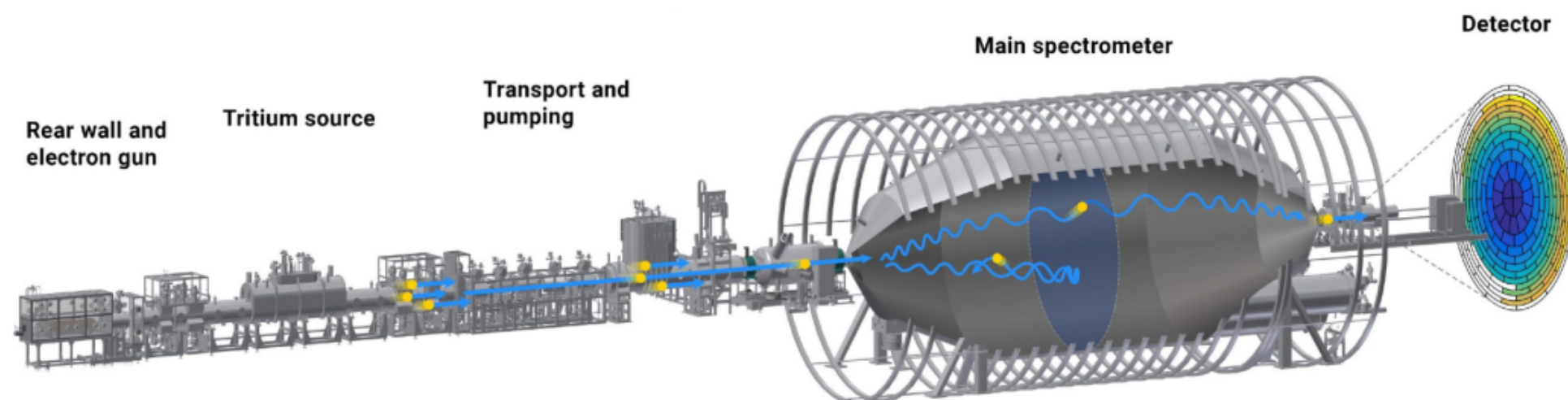
general framework to interpret $0\nu\beta\beta$ exp.?
with controlled uncertainties ?

Fantastic introduction to putting $0\nu\beta\beta$ decay in perspective!

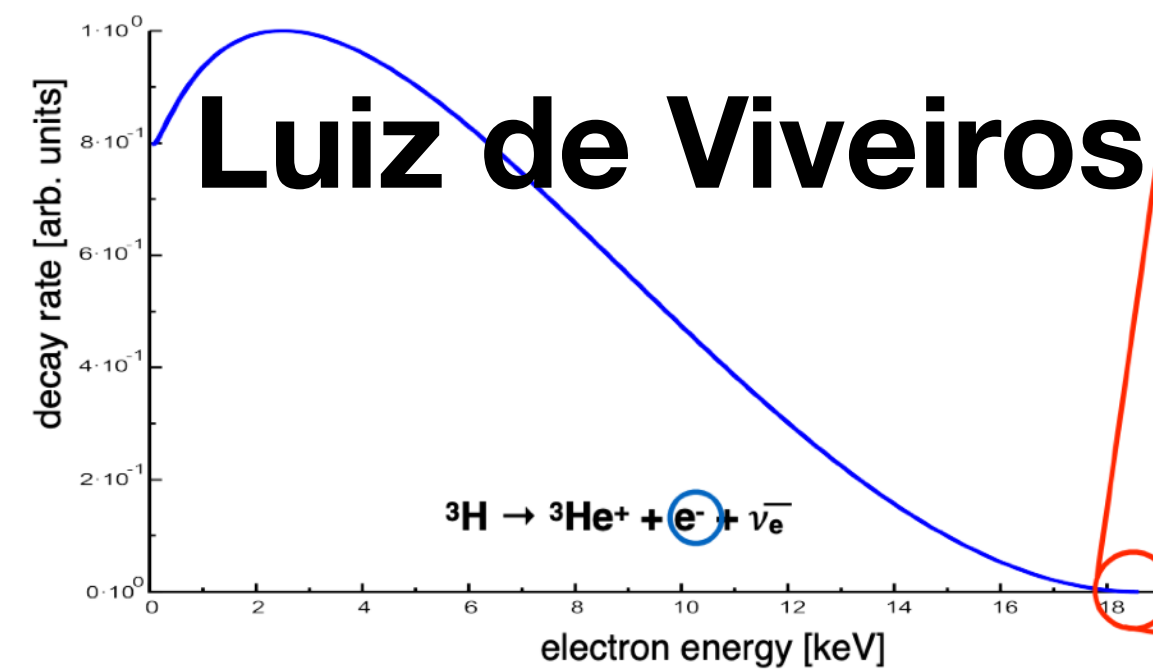
Ann-Kathrin Schuetz and Luiz de Viveiros on KATRIN, Project 8, and Neutrino Mass

KATRIN working principle

- Windowless gaseous T_2 source 10^{11} e-/s
- Tritium pumping & e- transport T_2 flow reduction $> 10^{14}$
- High-pass energy filters **MAC-E filter**
- Counting detector ~ 1 Mcps during calib runs

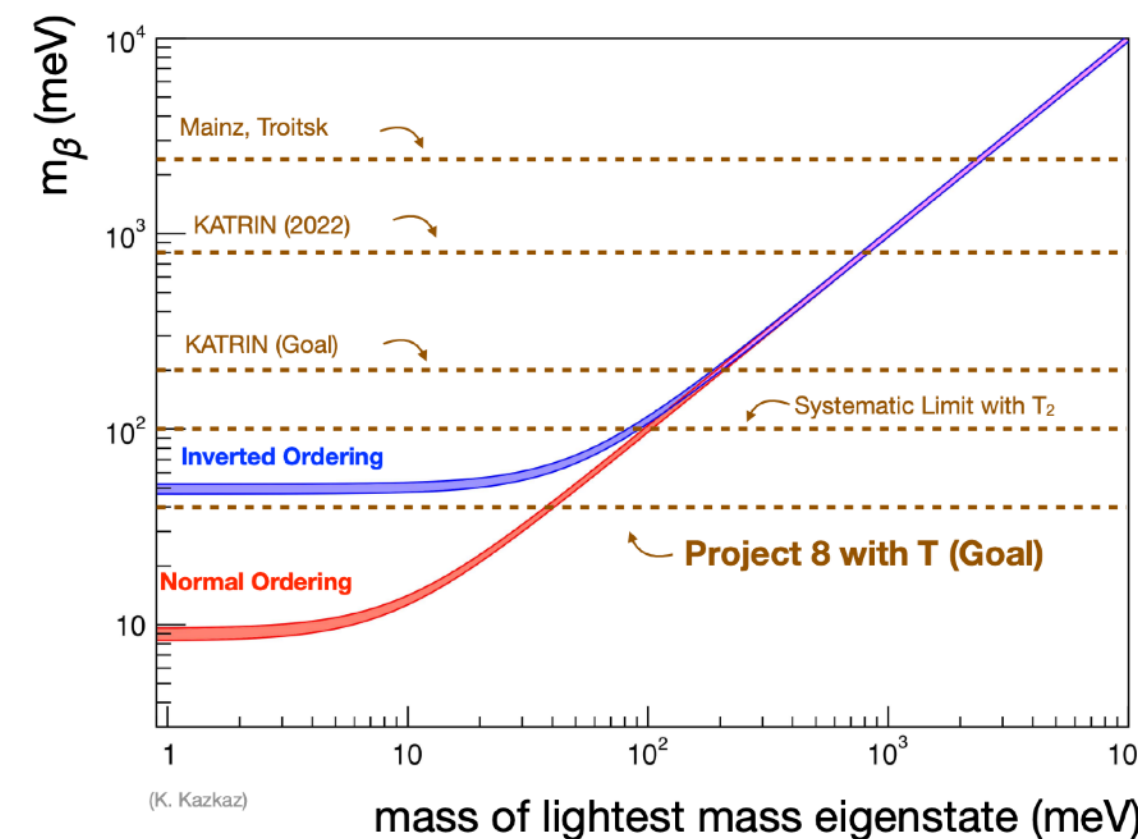


Full system description & commissioning paper: 2103.04755

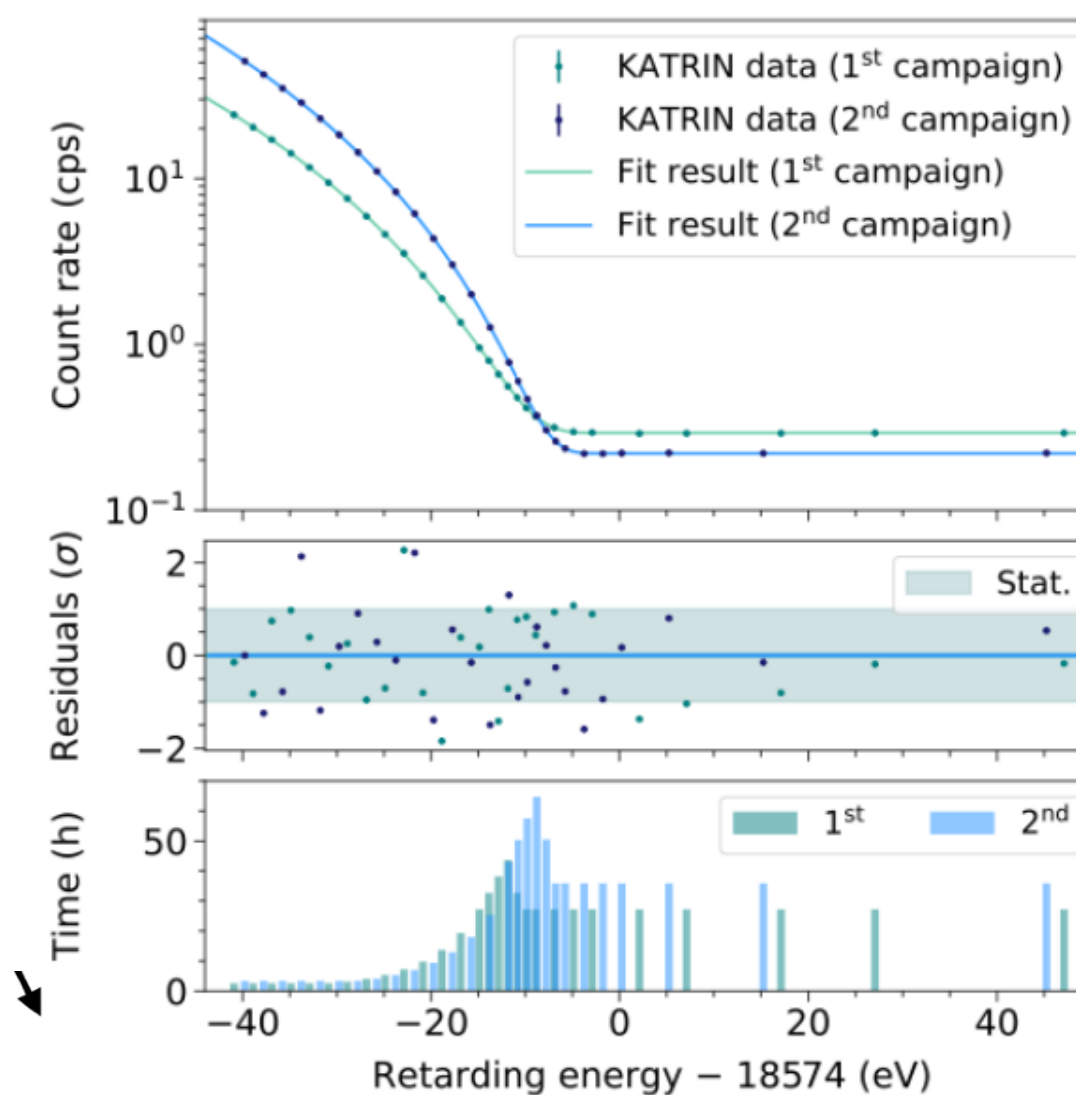
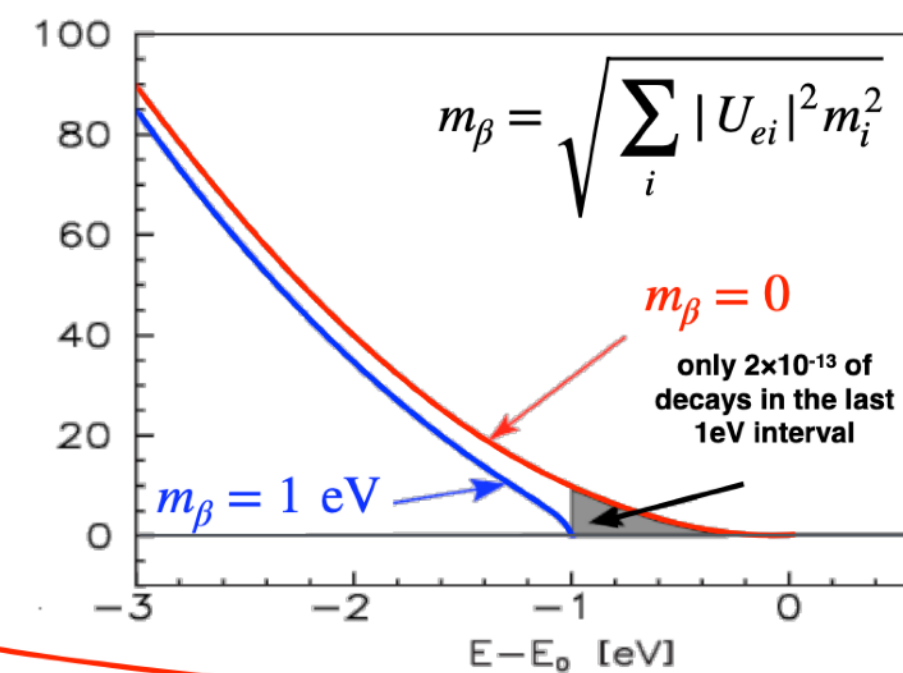


Results Combined 1st and 2nd campaign

Nature Phys.18, 160 (2022)



$m_\nu < 0.8$ eV (90% CL)



Best fit: $m_\beta^2 = 0.1 \pm 0.3$ eV²
 Limits LT and FC: $m_\beta < 0.8$ eV (90% CL)
 Limits Bayesian: $m_\beta < 0.73$ eV (90% CI)

9

Detectors act as high pass filters, rejecting low energy electrons and allowing precise understanding of the spectral shape close to the endpoint.

New results on model independent direct measurement of neutrino mass using beta decay electrons from tritium. First demonstration of super high precision Project 8.

Laxman Paudel and CJ Barton on Germanium based $0\nu\beta\beta$ detectors

Office of Science

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

Source and Detector: Array of p-type, point contact (PPC) detectors
30kg of 88% enriched ^{76}Ge crystals – 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors (ICPC) in final run

Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and Analysis Threshold: 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS

Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

Office of Science

MAJORANA DEMONSTRATOR 2022 $0\nu\beta\beta$ Result

Operating in a low background regime and benefiting from excellent energy resolution

Final enriched detector active exposure:
 $64.5 \pm 0.9 \text{ kg-yr}$

Background index at 2039 keV in lowest background configuration:
 $15.7 \pm 1.4 \text{ cts}/(\text{FWHM t yr})$

Background Index:
 $(6.2 \pm 0.6) \times 10^{-3} \text{ cts}/(\text{keV kg yr})$

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

See talk by W. Pettus on Sept 3rd in the plenary session at this meeting for an overview and final results of the MAJORANA DEMONSTRATOR.

Boosted Decision Tree analysis:
arXiv:2207.10710

Frequentist Limit:
Median $T_{1/2}$ Sensitivity: $8.1 \times 10^{25} \text{ yr}$ (90% C.I.)
65 kg-yr Exposure Limit: $T_{1/2} > 8.3 \times 10^{25} \text{ yr}$ (90% C.I.)

Bayesian Limit: (flat prior on rate)
65 kg-yr Exposure Limit: $T_{1/2} > 7.0 \times 10^{25} \text{ yr}$ (90% C.I.)

$m_{\beta\beta} < 113 - 269 \text{ meV}$

Using $M_{0\nu} = 2.66 - 6.34$

LEGEND overview

CJ Barton

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

MAJORANA	GERDA	Both
<ul style="list-style-type: none"> - Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.) - Low noise electronics improves PSD - Low energy threshold (helps reject cosmogenic background) 	<ul style="list-style-type: none"> - Liquid argon veto - Light nuclei shield, no lead 	<ul style="list-style-type: none"> - Clean fabrication techniques - Control of surface exposure - Development of large point-contact detectors - Lowest background and best resolution $0\nu\beta\beta$ experiments

First phase:

- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: $<0.6 \text{ c}/(\text{FWHM t y})$
- Discovery sensitivity at a half-life of 10^{27} years
- Currently taking commissioning data

Subsequent stages:

- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal $<0.03 \text{ cts}/(\text{FWHM t yr})$
- Location to be selected

See also the overview talk "The search of $0\nu\beta\beta$ and the LEGEND Experiment", W. Xu, session NN6 (Saturday @3:30)

Majorana Demonstrator Showed efficacy of Ge-based detectors!

LEGEND commissioning of 20% scale phase, combines best of Majorana Demonstrator with GERDA.

Join us at

INTERSECTIONS

Lake Buena Vista, Fla

~~May 30 - June 5, 2022~~

August 29-
September 4

Thanks for Coming!

