

WG1 Summary

NuFact 2022

The 23rd International Workshop on Neutrinos from Accelerators

Salt Lake City, Utah, United States
July 31st – Aug. 6th, 2022

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WG4: Muon Physics
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WG5: Neutrinos beyond PMNS
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And Ruiz (UC Louvain, Belgium)
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WG6: Detectors
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Mark Scott



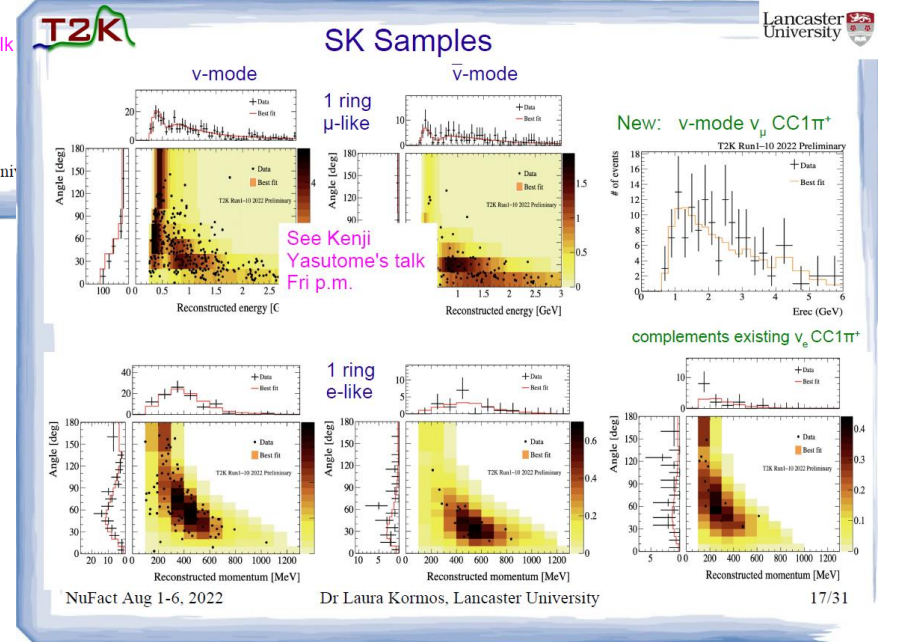
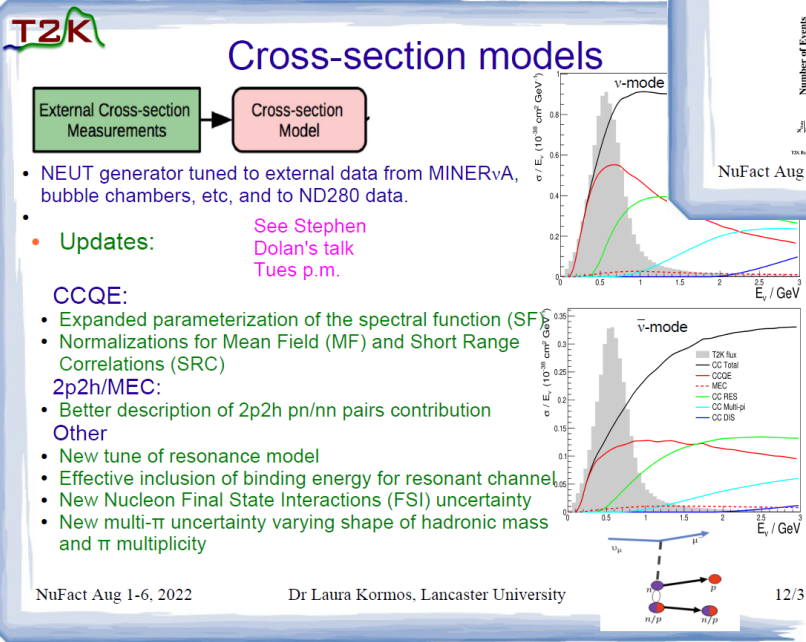
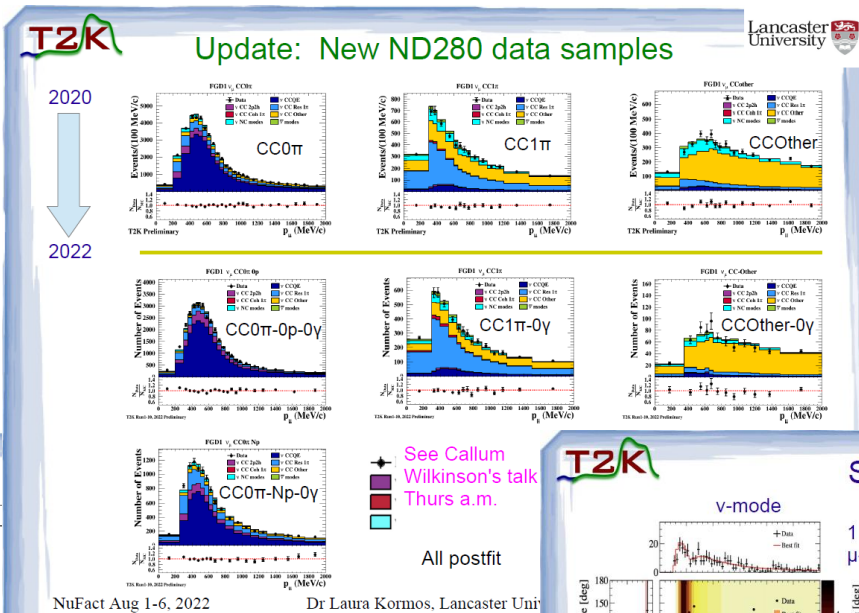
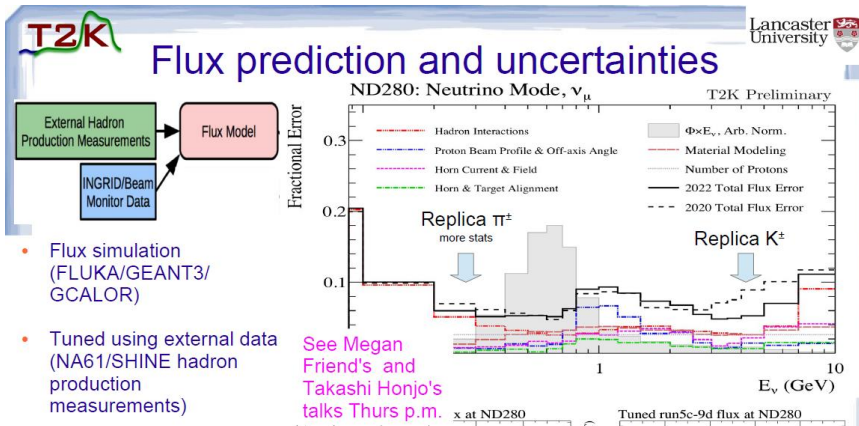
Adam Aurisano

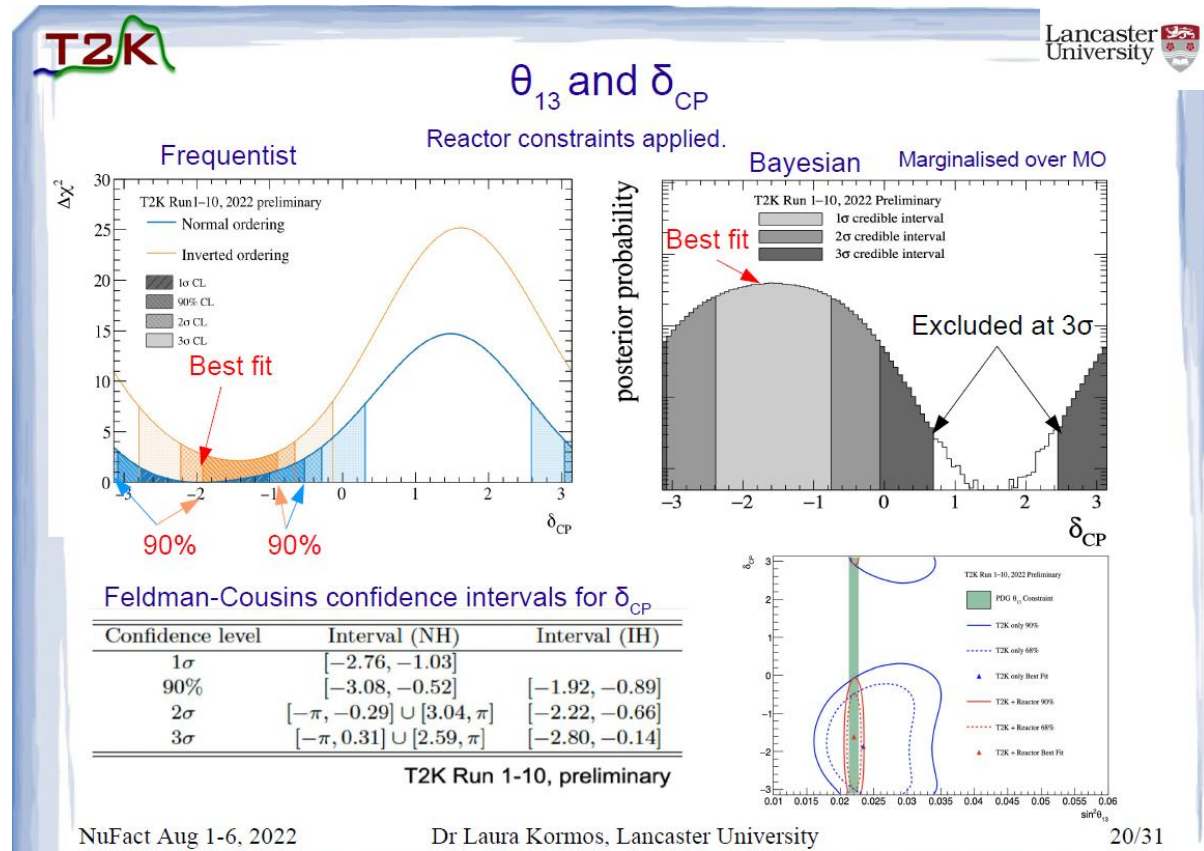


Jian Tang

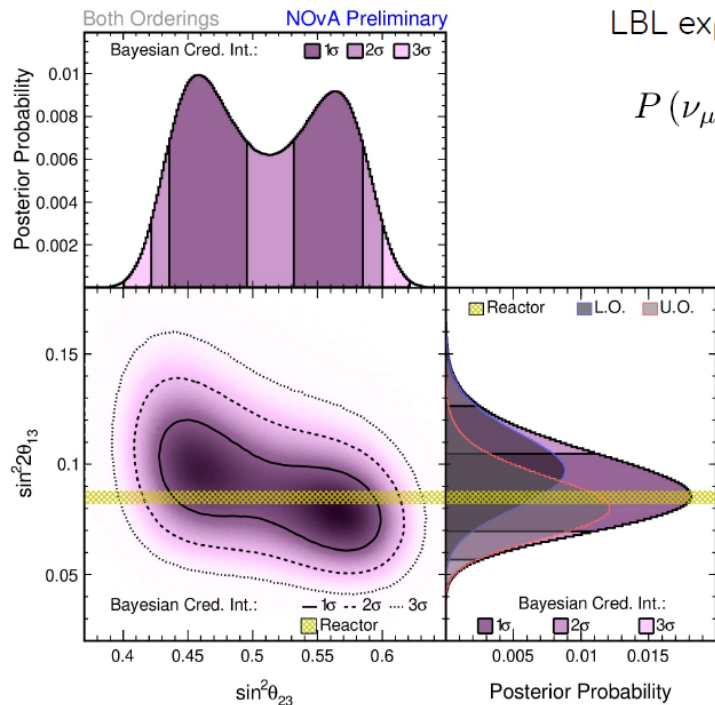
- Packed programme
- Interplay between WG1 and other WGs
- Lots of exciting work!
 - 44 total talks/virtual posters
 - Plenary talks
 - Current and future experiments
 - 4 joint sessions
 - WG1+WG2: constraining cross-section uncertainties/cross-section tuning
 - WG1+WG5: near-term BSM oscillation measurements
 - WG1+WG2+WG6: near detector constraints
 - WG1+WG6: machine learning strategies for reconstruction/selection
 - 4 WG1-only sessions
 - Details of current and future experiments
 - Programs to improve oscillation experiments
 - Exploration of BSM oscillation scenarios

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- Interplay between WG1 and other WGs
- Lots of exciting work!
- Biased highlights – any inaccuracies are mine
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PMNS measurements



LBL expts can't measure θ_{23} octant alone:

$$P(\nu_\mu \rightarrow \nu_e) \approx \underbrace{\sin \theta_{23} \sin 2\theta_{13} \sin \Delta_{31}}_{\text{correlated at first order!}} + \dots$$

Bayesian analysis enables **first NOvA-only measurement of θ_{13}** :

- Strong correlations with θ_{23} (as expected)
- Very good agreement with reactor value!
- (weak) θ_{23} octant preference driven by reactor constraint

$$\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$$

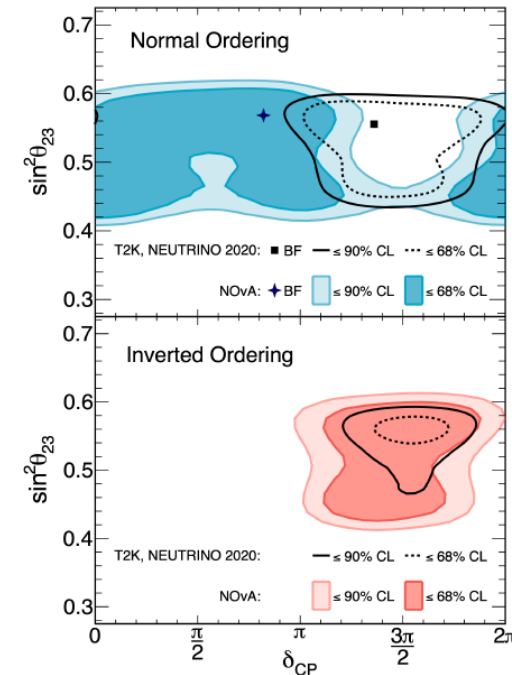
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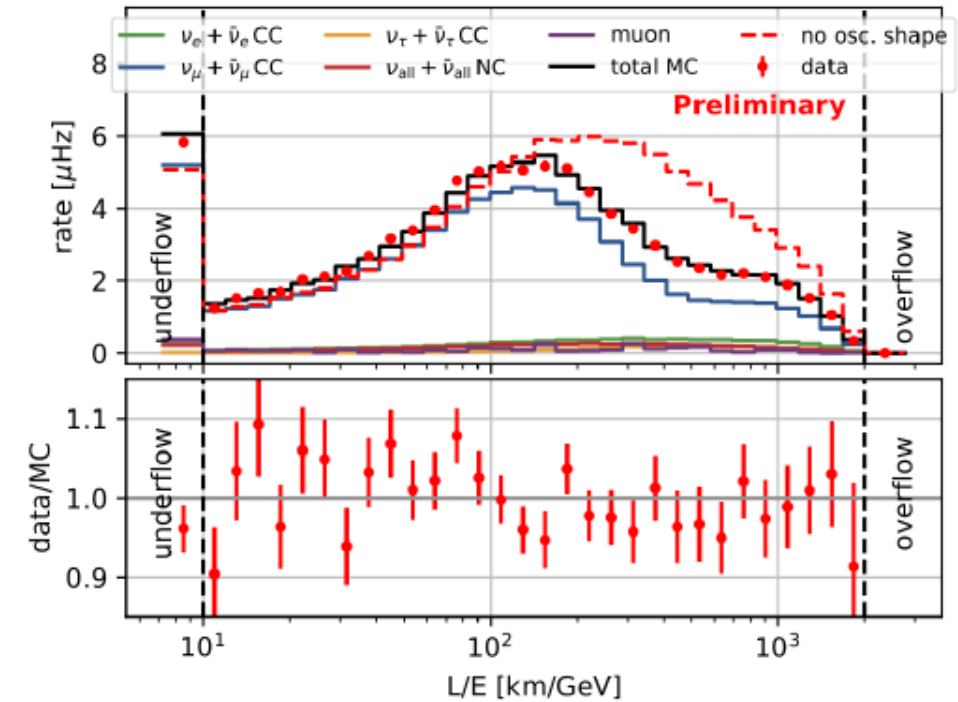
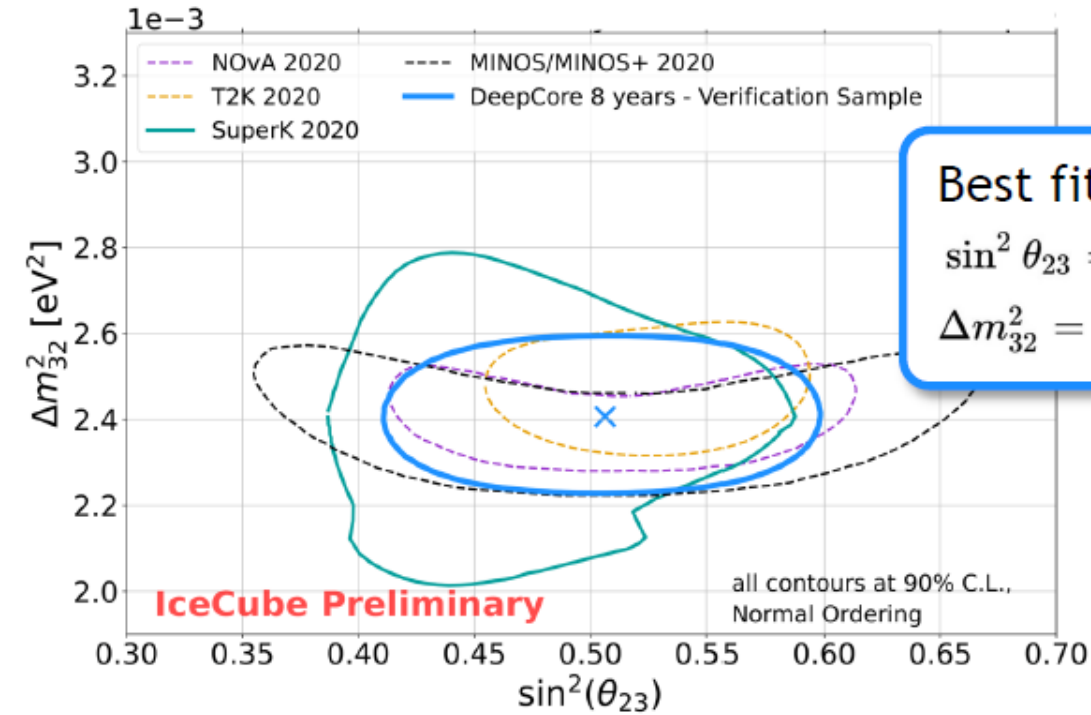
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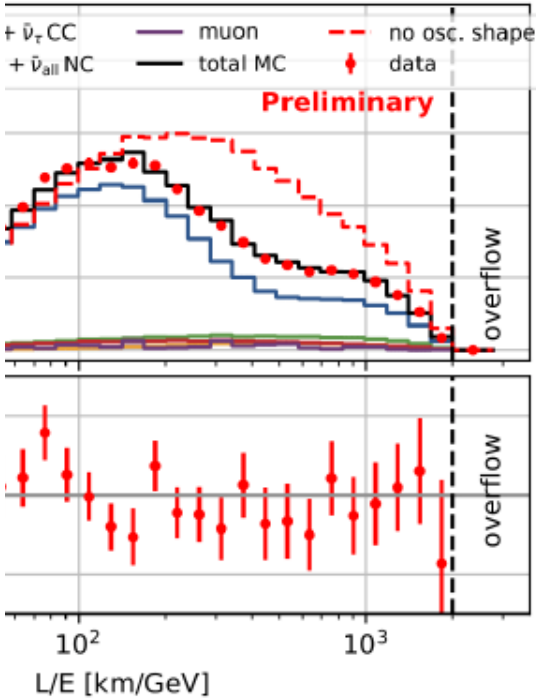
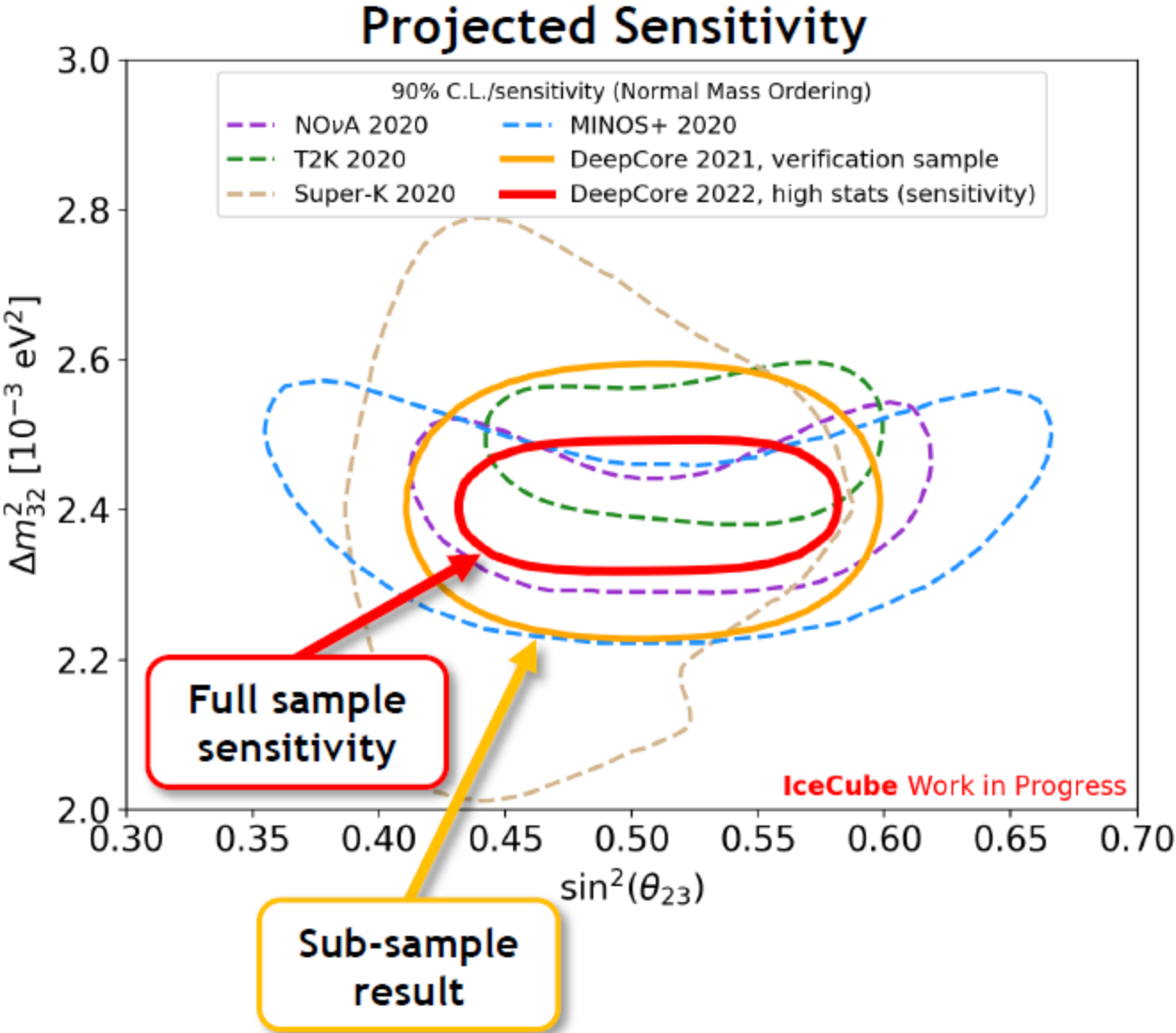
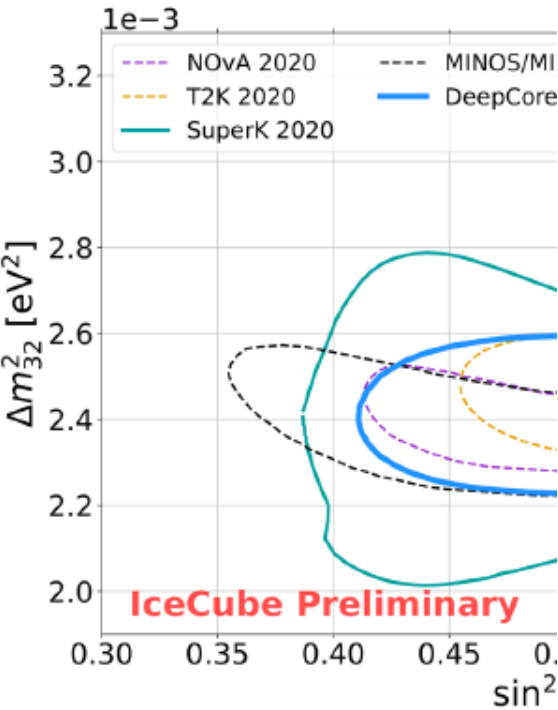
J. Walcott / Tufts University

PMNS measurements

- NOvA, T2K data preferences broadly compatible
 - Most probable regions (in NO) distinct, but significant 1 σ contour overlap
 - IO surfaces very similar
- Official joint fit results expected later in 2022





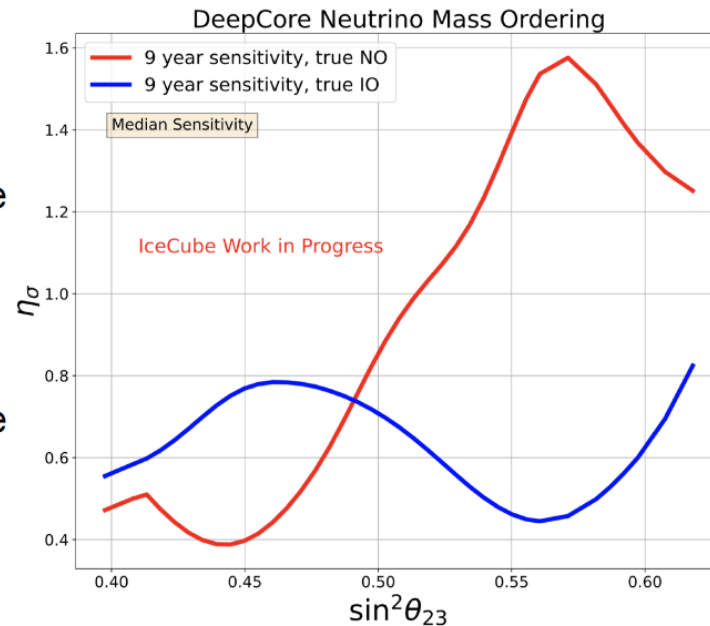


Slide 13

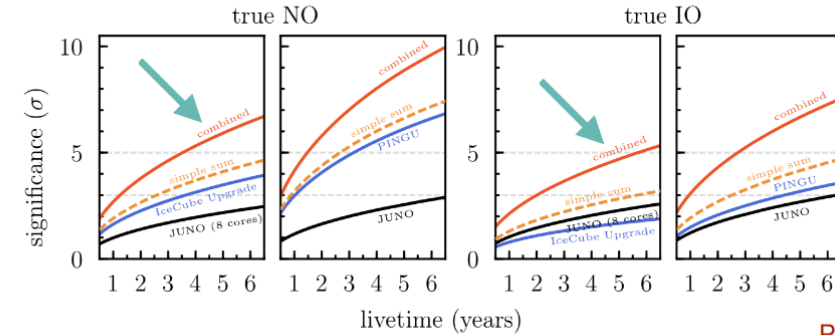
9-Year NMO Sensitivity

Key observations:

- Upper octant is most favorable for resolving the ordering provided NO is true
- Lower octant is most favorable for resolving the ordering provided IO is true



NMO with the Upgrade + JUNO



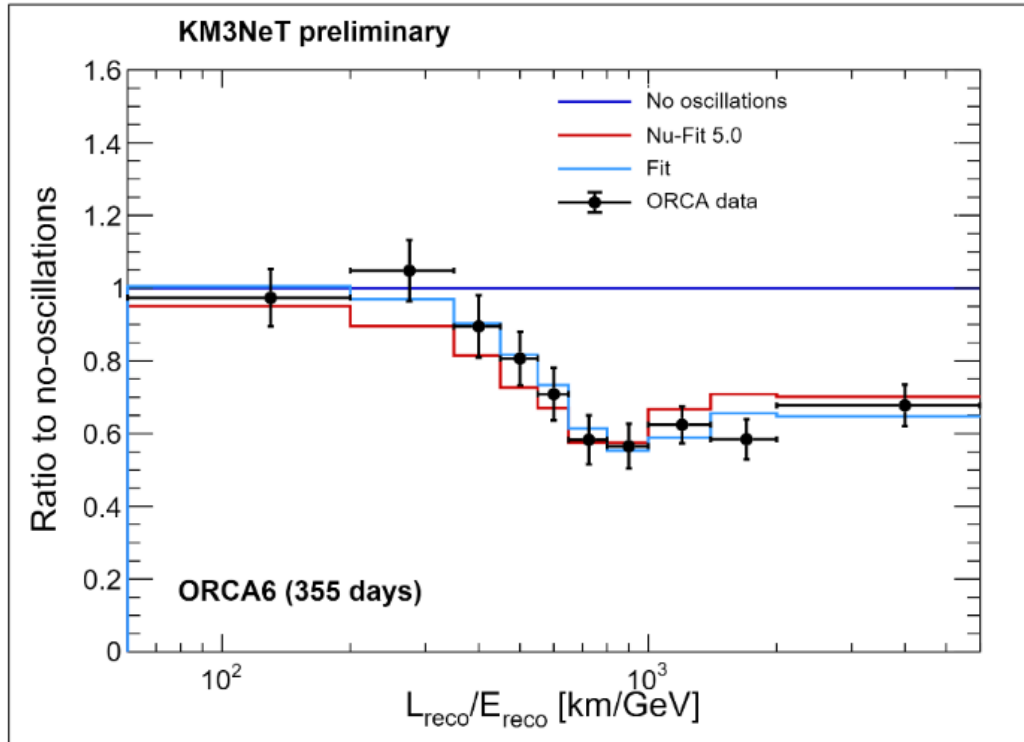
NO: $\theta_{23} = 49.6^\circ$

IO: $\theta_{23} = 49.8^\circ$

[PhysRevD.101.032006](https://arxiv.org/abs/PhysRevD.101.032006)

- 3σ projected NO sensitivity after four years of data-taking of **Upgrade only**
- **JUNO+Upgrade combined sensitivity:** same oscillation parameters in the fit for both experiments
- Synergy effect observed for JUNO+Upgrade combined sensitivity when fitting opposite orderings: IO to NO data and NO to IO data

- Challenging analysis – upgrades and combination with other experiments greatly increases sensitivity

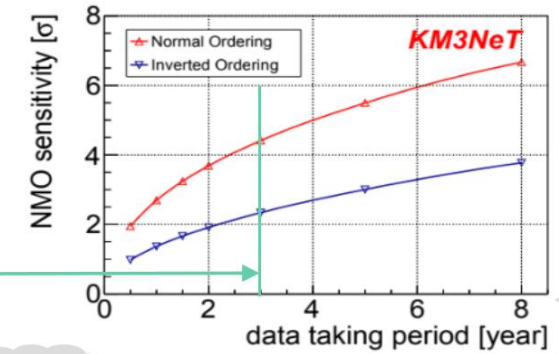
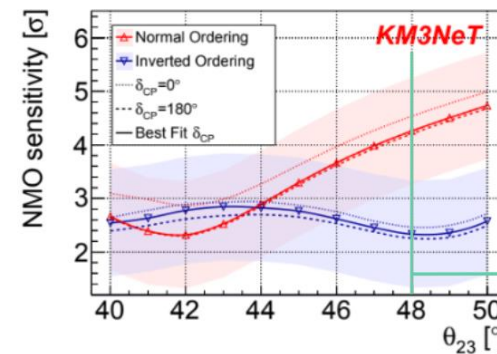
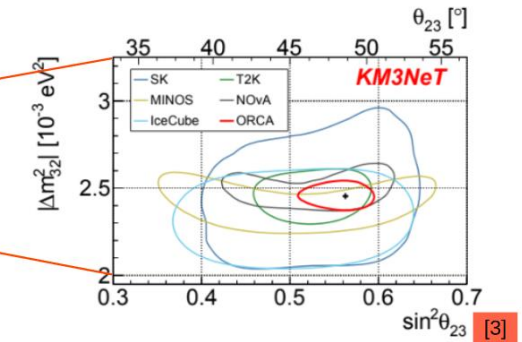
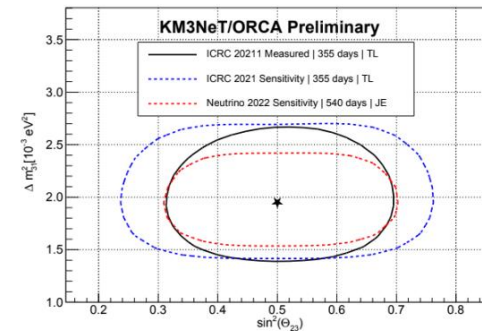


Johannes Schumann,
Fri AM

Oscillation Parameter Sensitivity

Updated oscillation parameter measurement with 6 strings

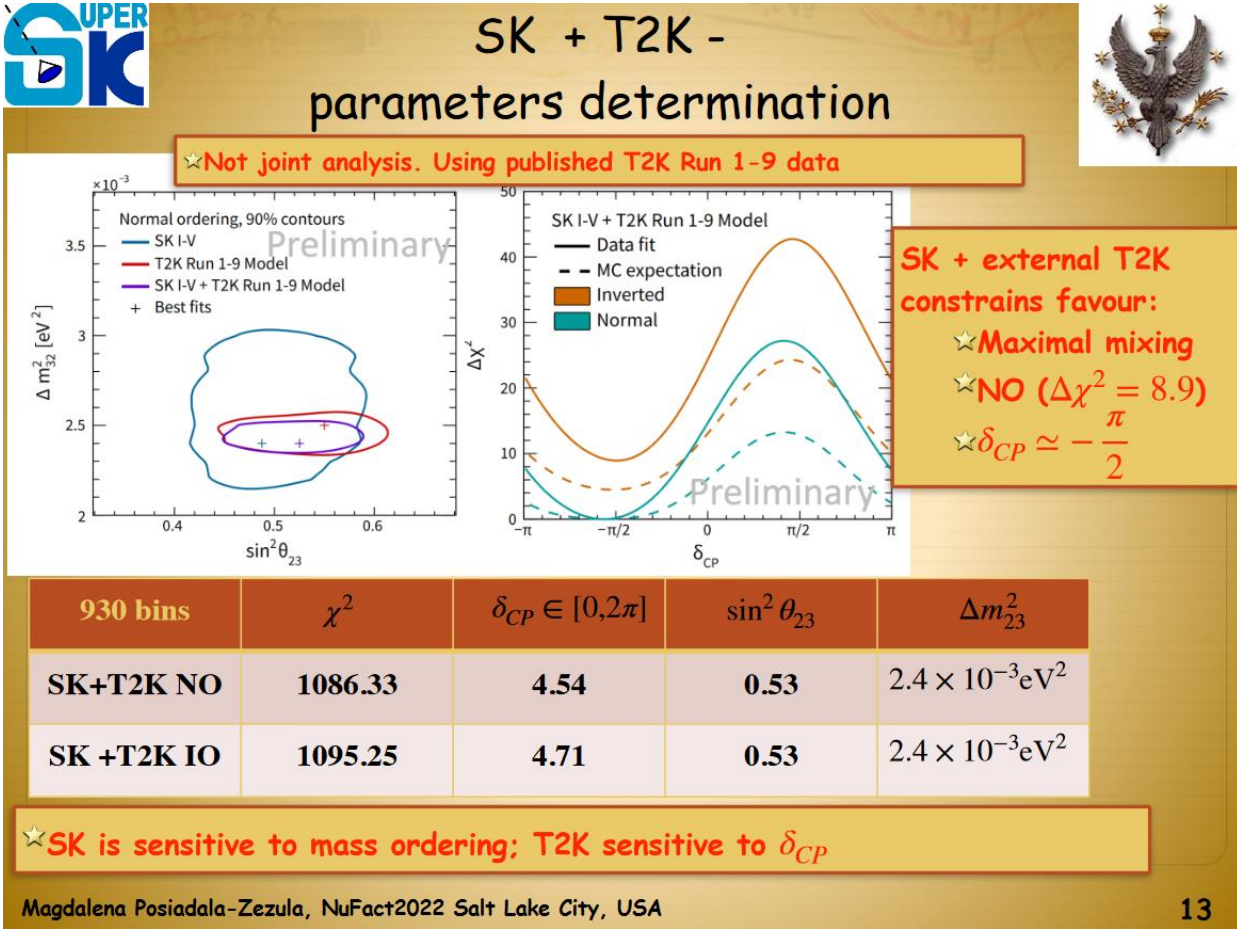
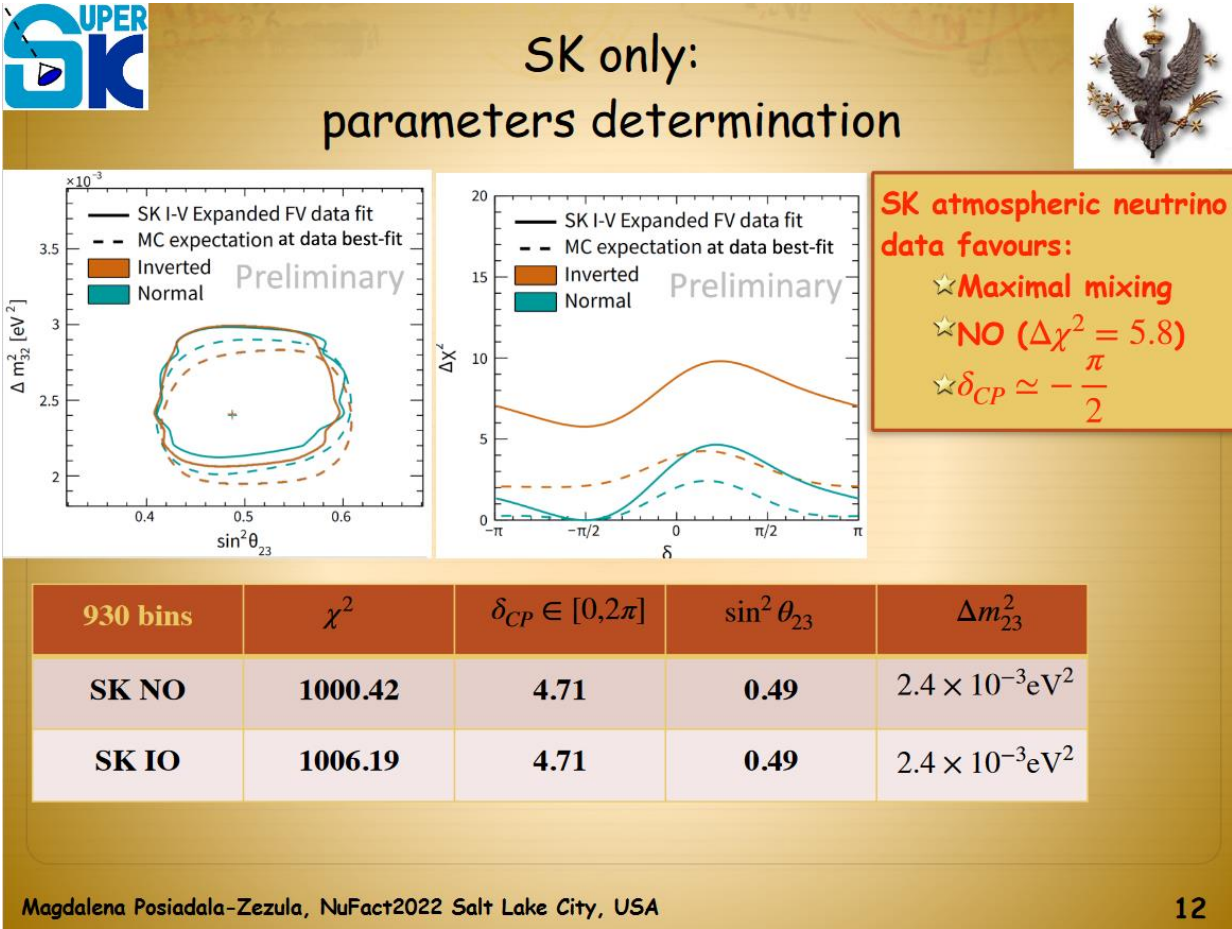
- Livetime increased from 355 days to 540 days
- Improved selection & particle identification
→ together: Sample increased by factor 4
- (Unblinding & Measurement update about to come)



3yrs

@ $\theta_{23} = 48^\circ$

[3]

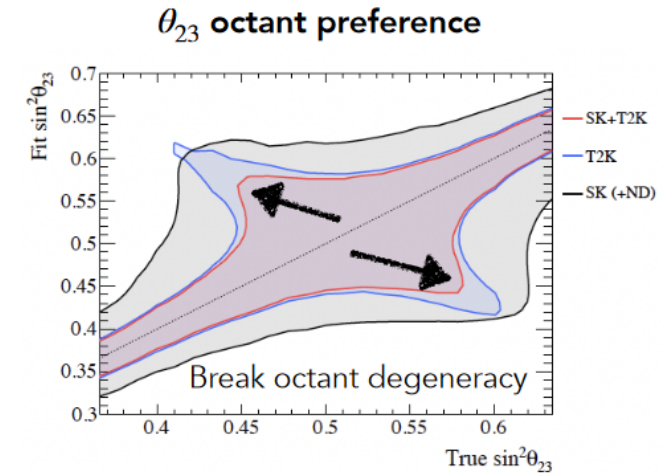
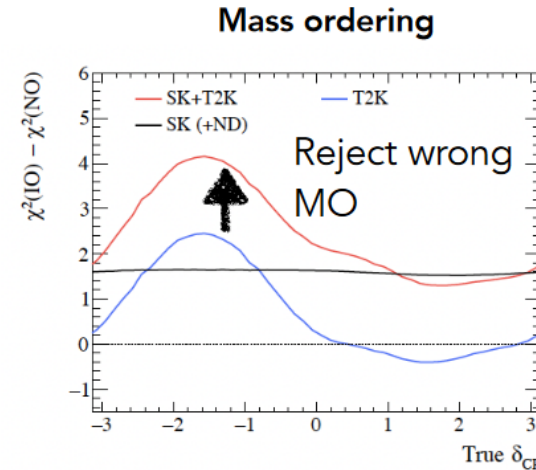
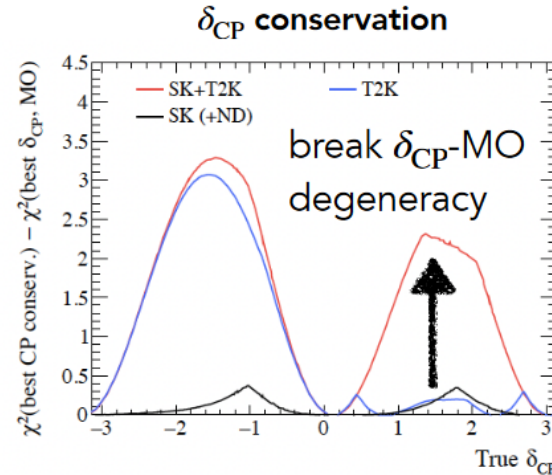


- Good individual sensitivity
- Statistical combination with other experiments improves both

Sensitivity results

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- Full joint analysis sensitivity
- Significant improvements
- Challenging!
- T2K + NOvA on the way



Run1-10 POT assumed (ν mode: 1.9664×10^{21} POT $\bar{\nu}$ mode: 1.6346×10^{21})

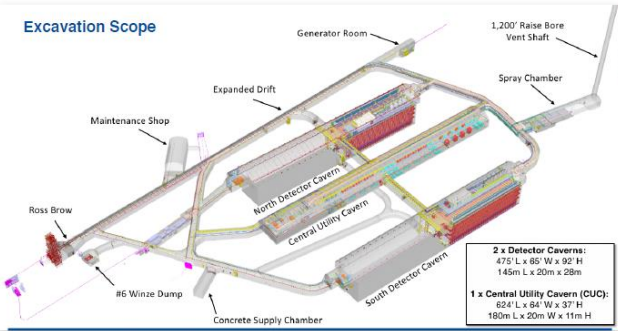
True values assumed in fits: $\sin^2 \theta_{23} = 0.528$, $\Delta m_{32}^2 = 2.509 \times 10^{-3} \text{eV}^2/c^4$, $\sin^2 \theta_{13} = 0.0218$, NO

- δ_{CP} conservation
 δ_{CP} -independent MO sensitivity from atmospheric samples breaks δ_{CP} -MO degeneracy.
Increase δ_{CP} sensitivity in the case $\delta_{CP} < 0$ in NO.
- MO & octant preference
Atmospheric samples being sensible to MO via mantle/core resonance significantly increase the power to reject wrong MO and to break the θ_{23} octant degeneracy.

Current experiment takeaways

- Mature experiments, complex analyses
 - Laying groundwork for future experiments
- Neutrino telescopes approaching (exceeding?) precision of accelerator experiments
- Still statistics limited but seeing impact of systematics (biases)
 - Multiplicity of experiments necessary
 - Combined analyses to remove degeneracies



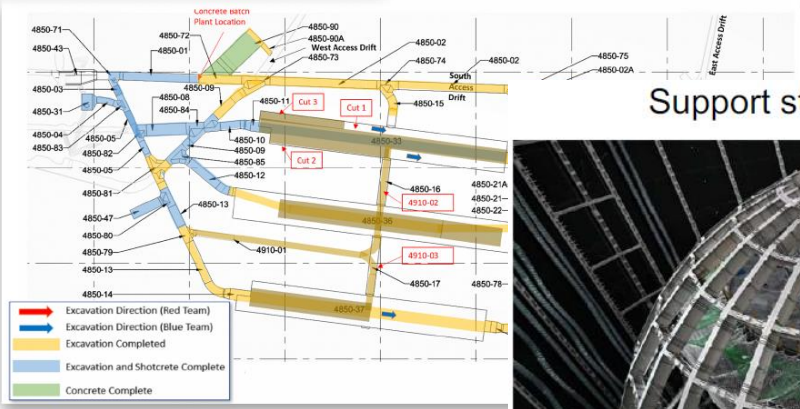


Far Site Status

- SURF far site excavation well underway
- North Cavern excavation began in May 2022
- Total excavated rock volume: 35% as of July 19, 2022



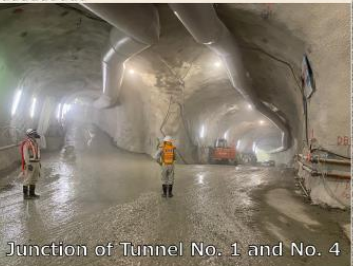
North Cavern



Support structure finished (June 2022)



more than a 1,000 words



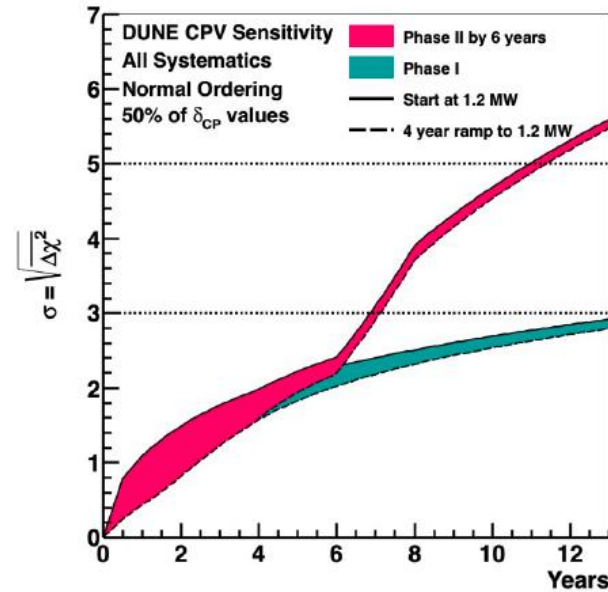
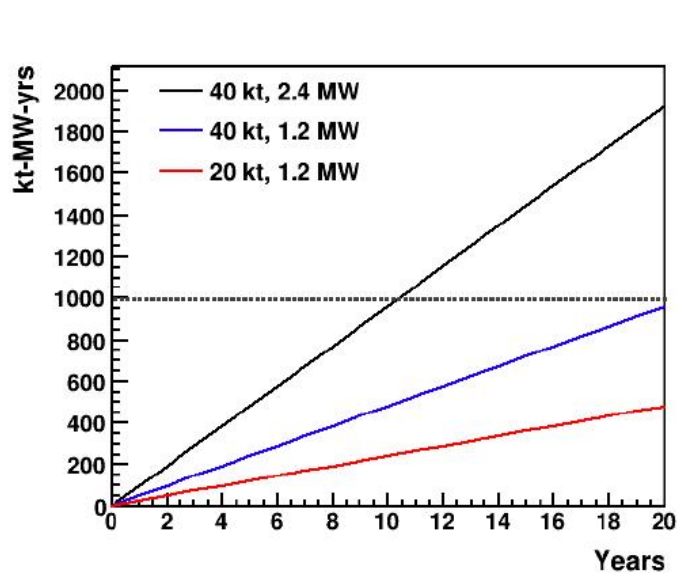
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Courtesy M. Shiozawa, ICRR and S. King, King's College

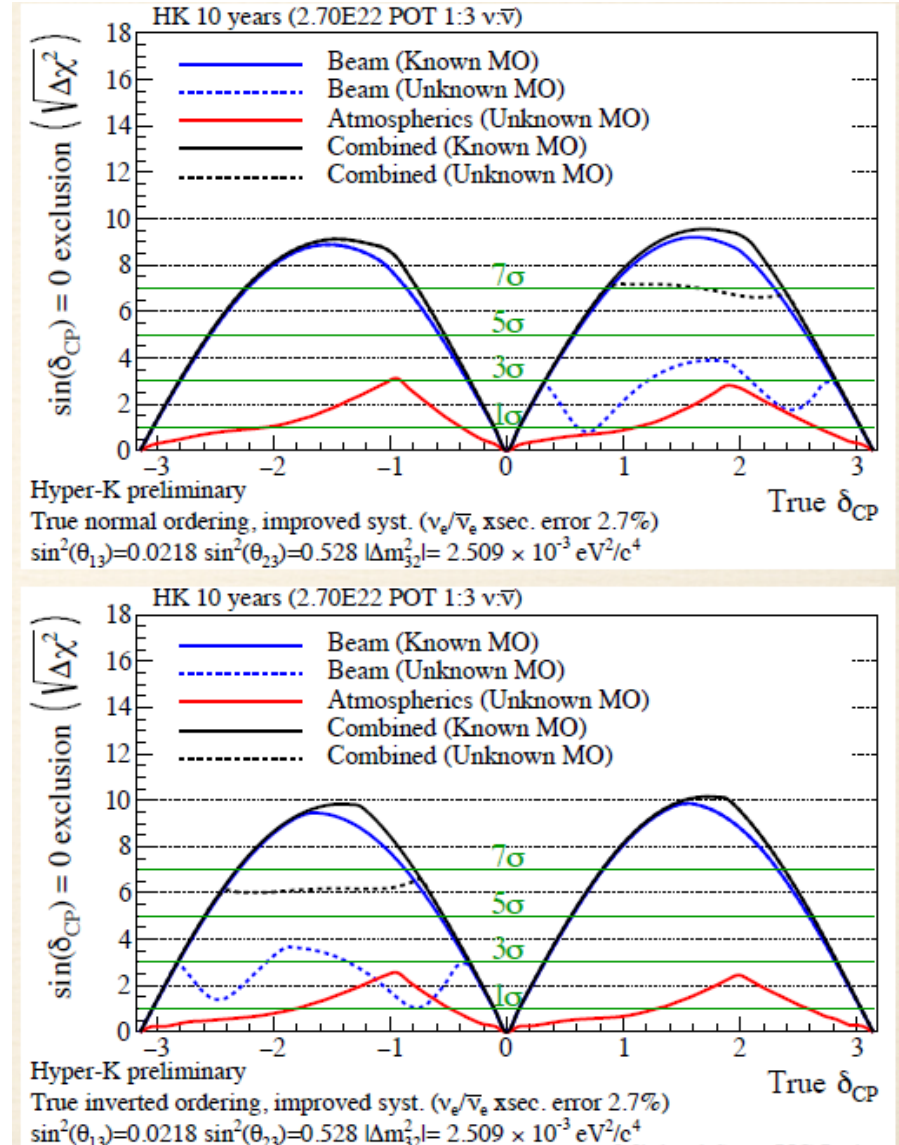
Sowjanya Gollapinni,
Mon PM

Livia Ludhova,
Mon PM

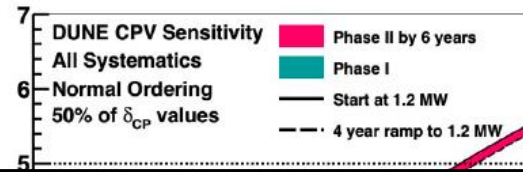
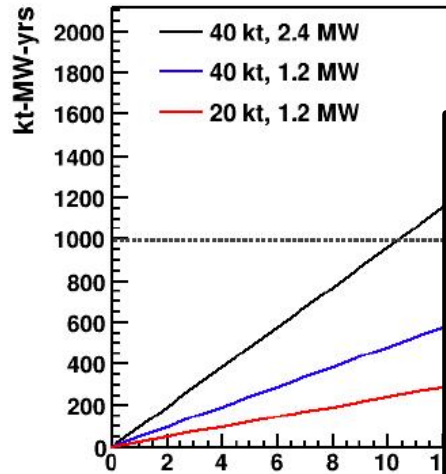
DUNE Phase II: Physics Potential



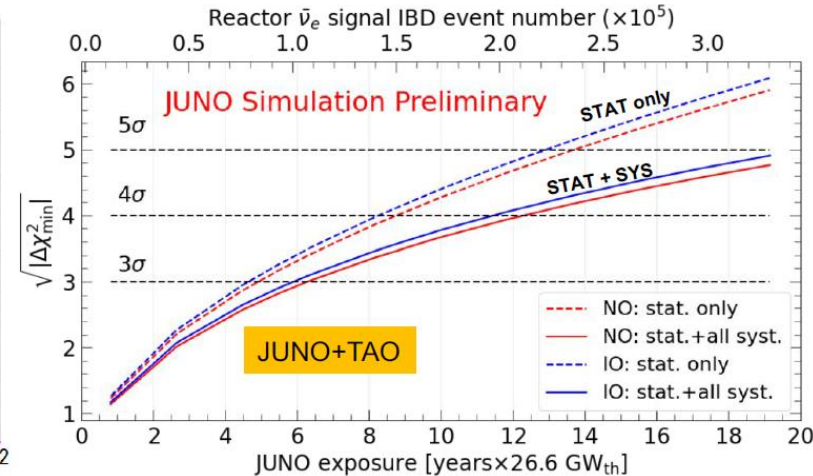
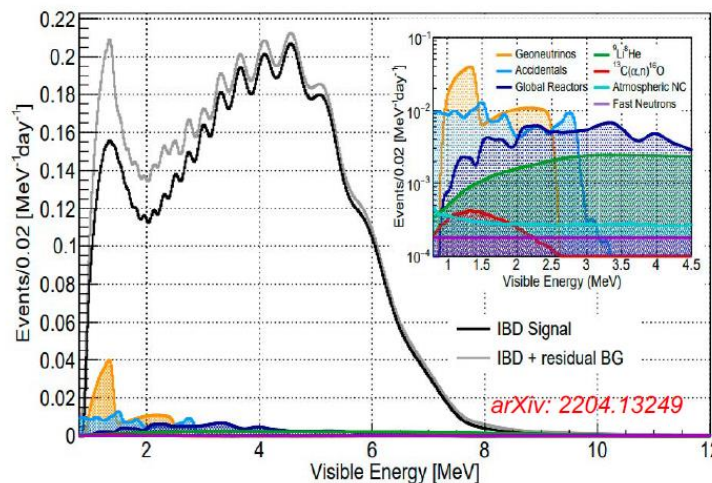
- O(1000) kt-MW-yr beam exposure needed to achieve full physics scope
- With phase-II, full precision physics results can be achieved in a decade (in 11-12 years)



DUNE Phase II: Physics Potential

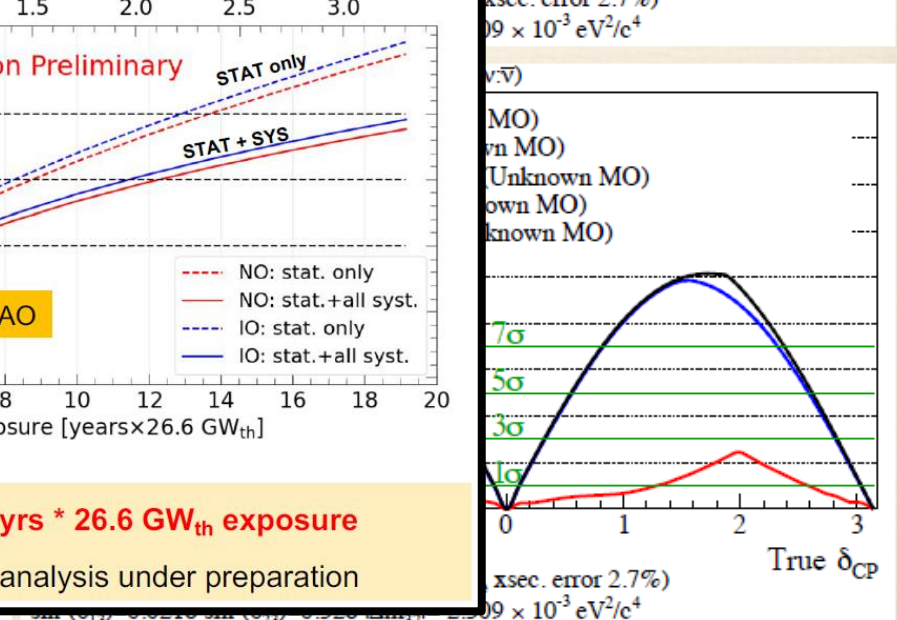
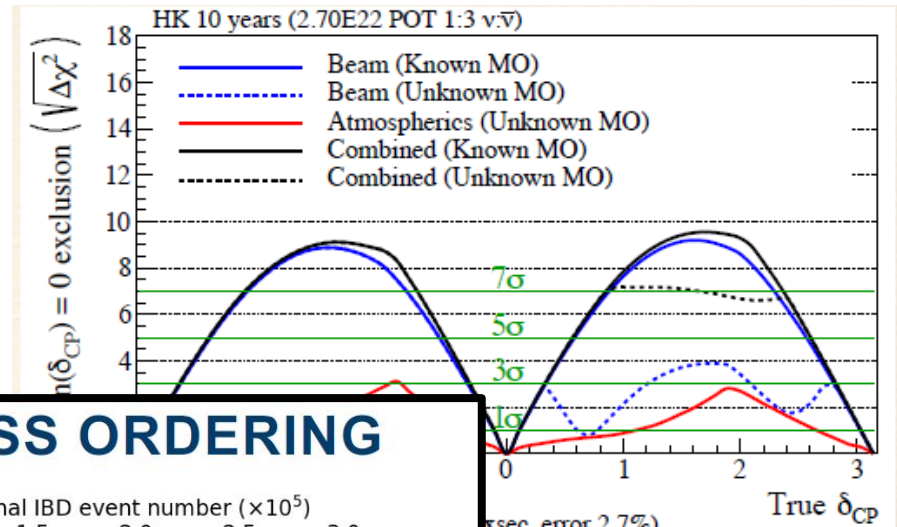


JUNO SENSITIVITY TO NEUTRINO MASS ORDERING



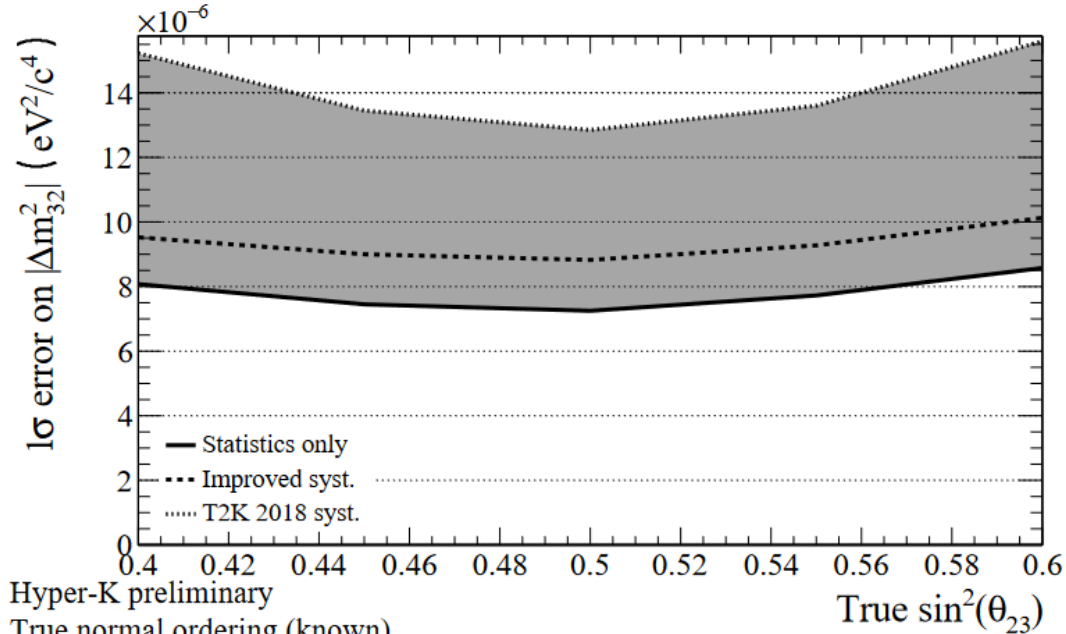
JUNO sensitivity on neutrino mass ordering: **3 σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Estimation of combined sensitivity with reactor + atmospheric neutrino analysis under preparation

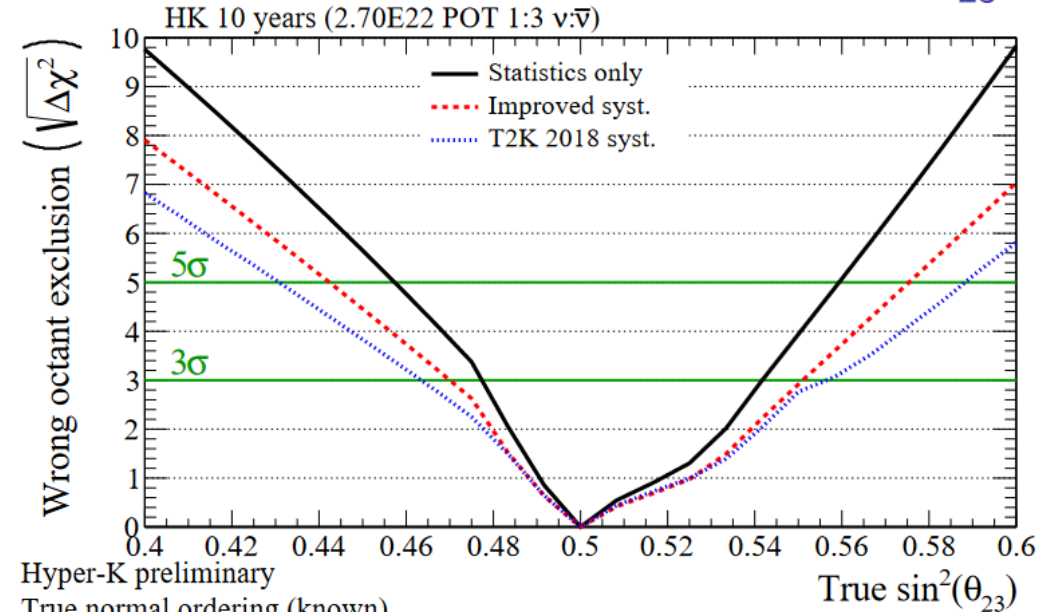


- O(1000) kt-MW-y
- With phase-II, full (11-12 years)

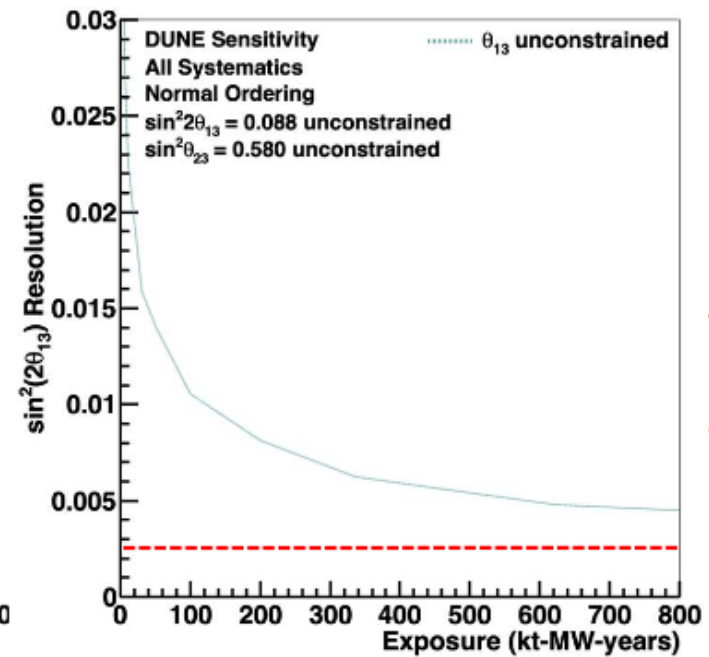
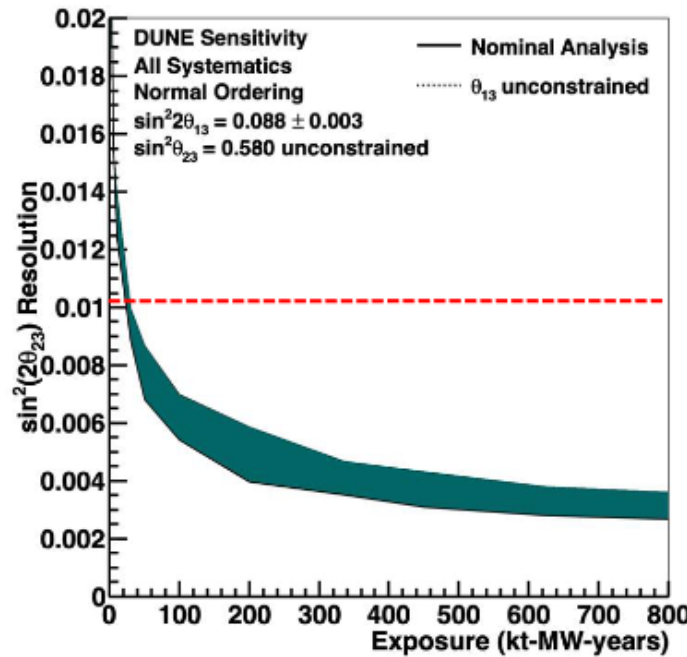
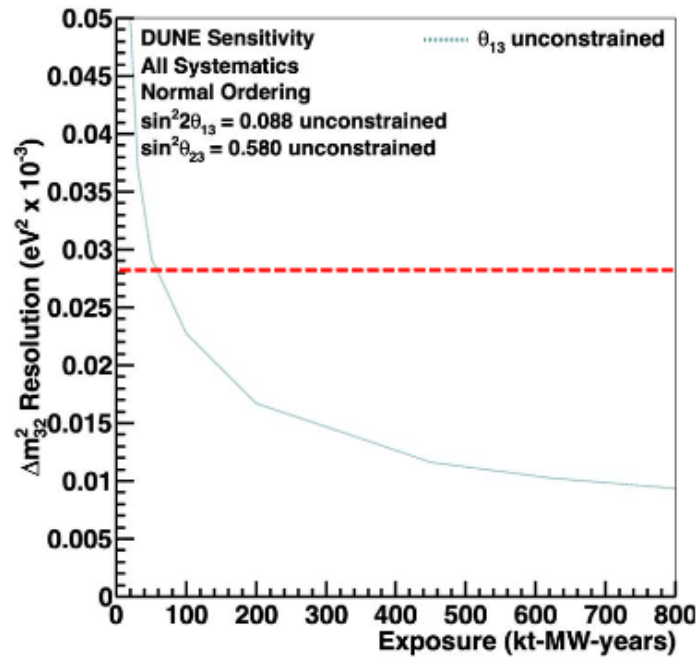
Measurement of Δm_{32}^2



Measurement of θ_{23} Octant

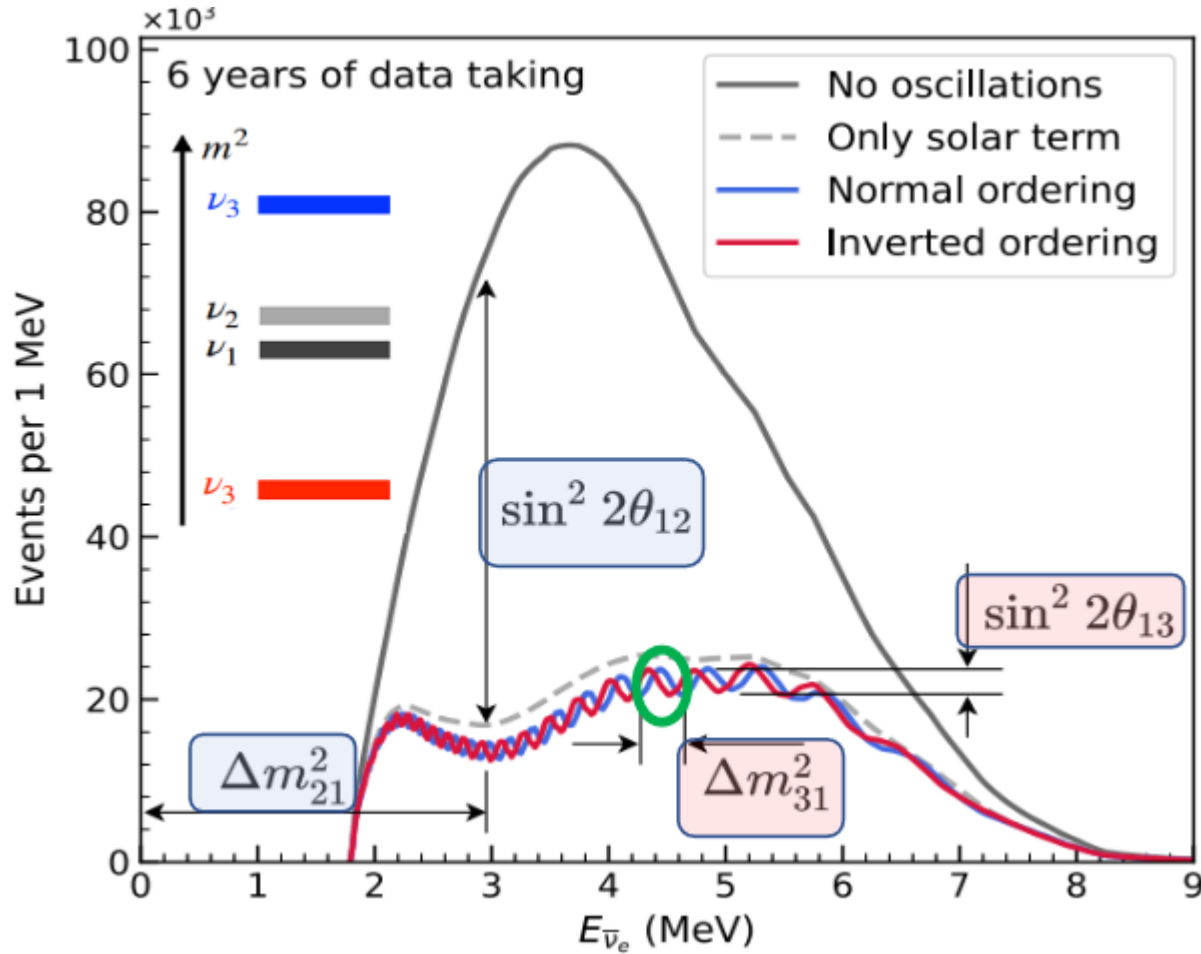


- Wrong θ_{23} octant can be excluded at 3σ for true $\sin^2 \theta_{23} < 0.47$ and true $\sin^2 \theta_{23} > 0.55$
- Systematics-limited measurement



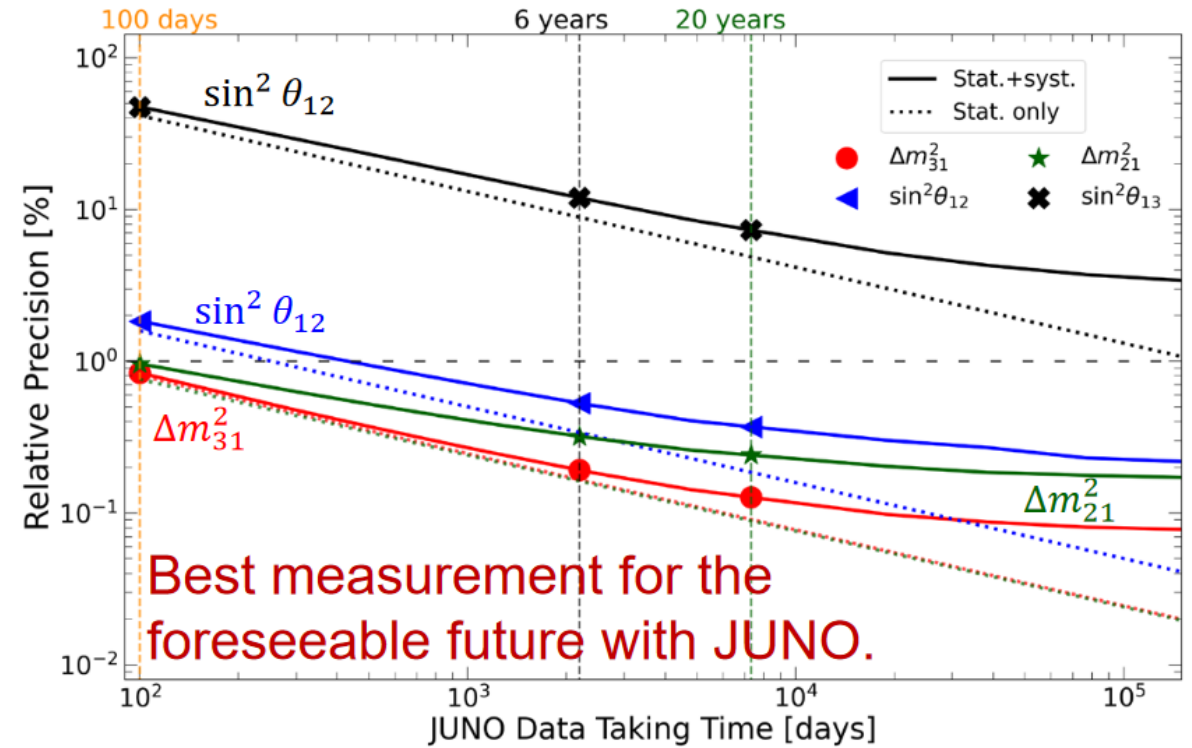
EPJC 80 (2020) 978

- Expected DUNE resolution vs exposure and **current global fit** (NuFit 5.0: JHEP 09 (2020) 178)
- Ultimate sensitivity approaches reactor θ_{13}
- Constrain δ_{CP} , Δm^2_{32} , θ_{23} , θ_{13} and MO with a single experiment



Precision of $\sin^2\theta_{12}$, Δm_{21}^2 , $|\Delta m_{31}^2|/|\Delta m_{32}^2| < 0.5\%$ in 6 yrs

	Central Value	PDG2020	100 days	6 years	20 years
Δm_{31}^2 ($\times 10^{-3}$ eV ²)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm_{21}^2 ($\times 10^{-5}$ eV ²)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2 \theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2 \theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)



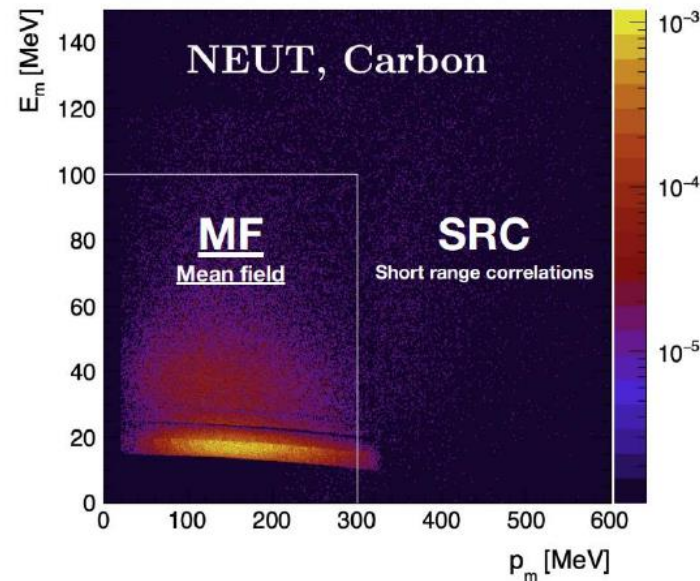
Future experiment takeaways

- Cannot hide behind low statistics anymore!
 - Many new experiments
 - High precision
 - Complementary
- What do oscillation analyses look like in this environment?
 - Starting to address this at existing experiments



Identifying the natural d.o.f.

- **Fermi motion and removal energy** in the mean field region:
 - Change **relative occupancy** of the shells (2 shells for C, 3 for O)
 - Change **shape of the momentum distribution** of each shell
 - Shift the **whole removal energy distribution**
 - Plausible alterations derived from $(e \rightarrow e', p)$ data
- **Short range correlations:**
 - **Normalisation of the SRC contribution** (high nucleon momentum tail, 2 nucleon final states)
 - NEUT predicts 5%, other models predict closer to 20%



Uncertainties

2(3) shell occupancy
uncertainties for C(O)

2 SRC normalisation
uncertainties (split for C/O)

Nucleon axial mass

3 Q^2 shape uncertainties*

4 removal energy shift
uncertainties (split C/O, p/n)

4 Pauli blocking uncertainties
(split C/O, p/n)

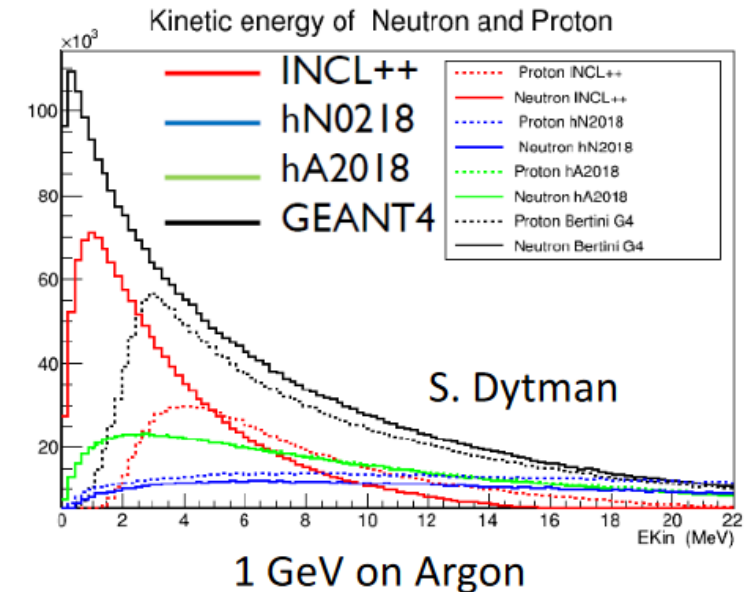
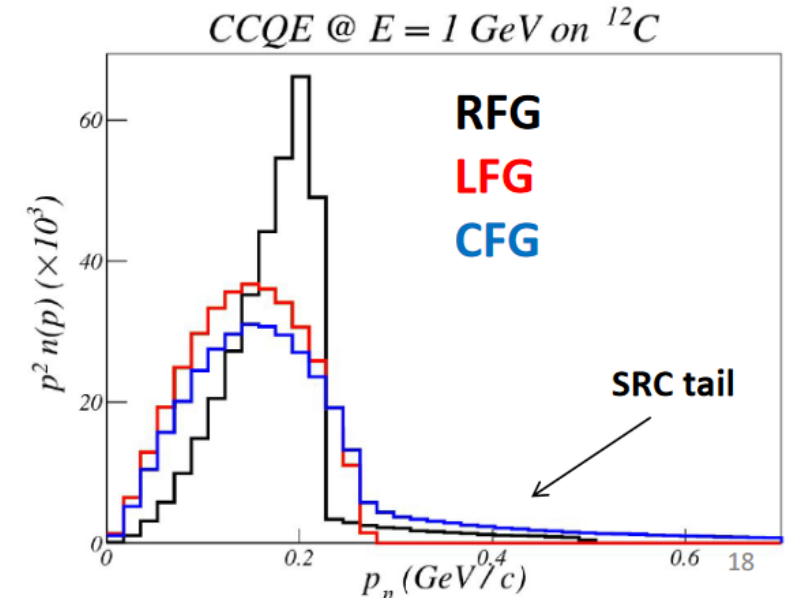
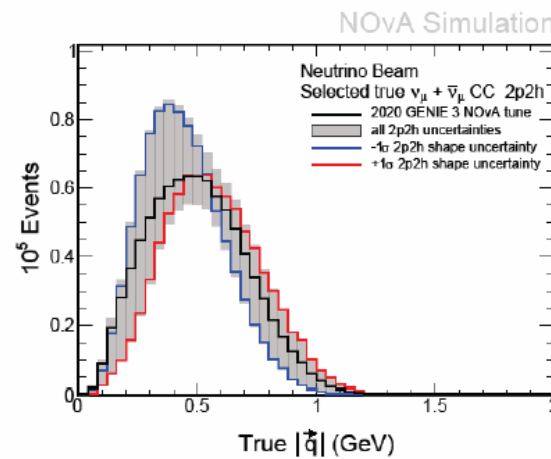
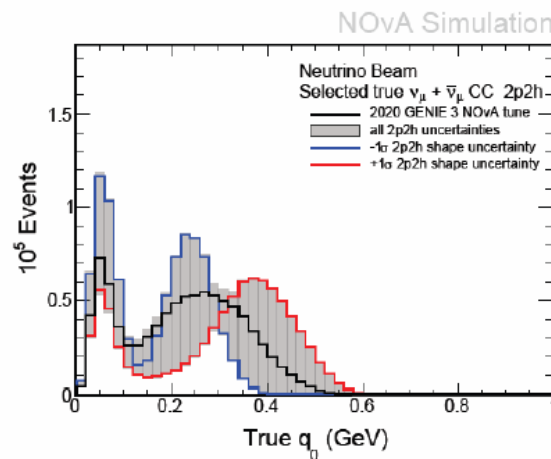
2 FSI correction uncertainties
(split C/O)

q_3 dependent removal energy
uncertainty

Stephen Dolan,
Tues PM

MEC uncertainty 3

- Want to **conservatively bracket** any **remaining uncertainty**
- If our other simulation were perfect, tuning to our ND data would correctly produce MEC. If our simulation is off, our resultant MEC model can be off
- To estimate, **shift our largest other cross-section uncertainties by 1σ in conjunction 'up' or 'down' in hadronic energy, then re-fit**. These are new $\pm 1\sigma$ uncertainties.



Presence of CC tau events over NC background

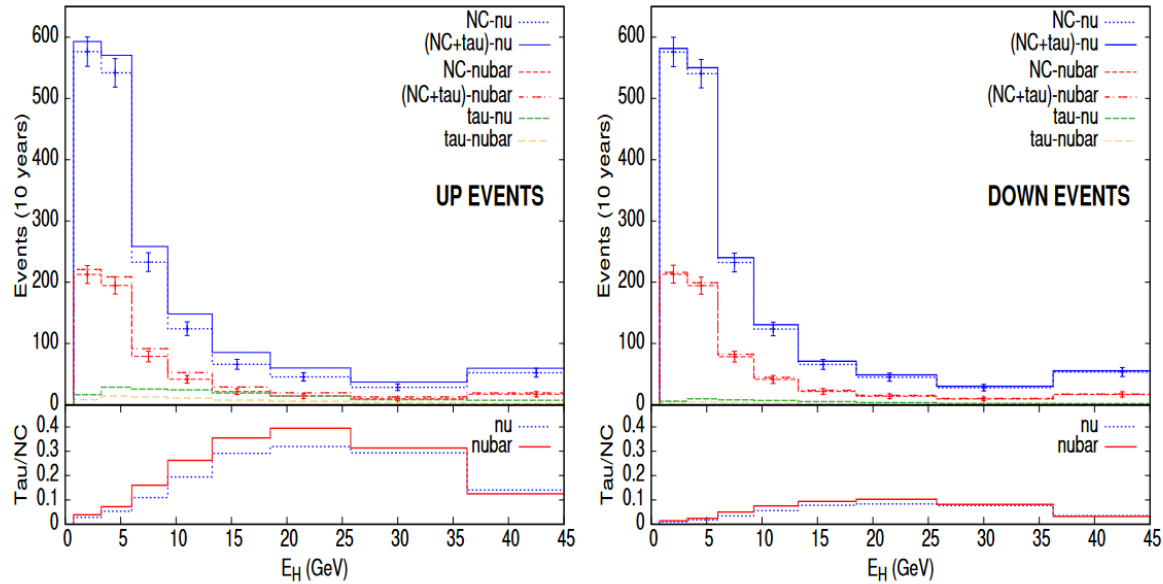
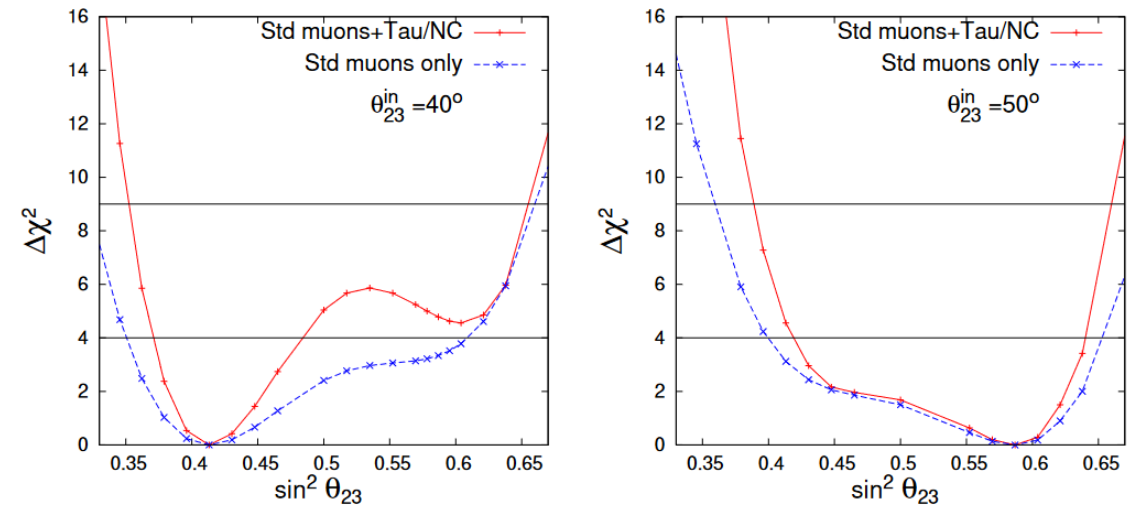


Figure: NC and CC-tau events in reconstructed E_{hadron} bins and the ratio of the CC tau events to the NC events.

Sensitivity to the octant of $\sin^2 \theta_{23}$ in combined analysis



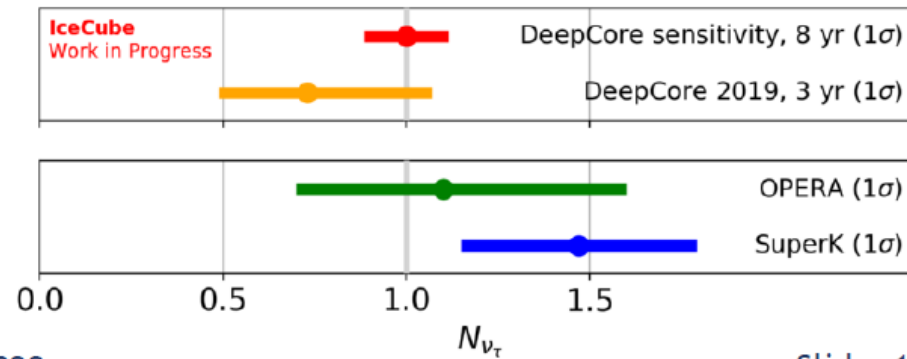
- Tau Neutrino Appearance

- DeepCore is above the tau lepton production threshold for ν_τ CC
- ν_τ appearance analysis fits a separate normalization N_{ν_τ}
- Expect a world leading measurement of the tau neutrino normalization

Kayla, Mon PM

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$|U_{e3}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2 = 1$$



NuFact 2022

Slide 15

Barbara, Tues PM

$$\begin{aligned} \frac{d^2\sigma_A}{dx dy} = & \frac{G_F^2 M_N E_\nu}{\pi(1 + \frac{Q^2}{M_W^2})^2} \left\{ \left[y^2 x + \frac{m_l^2 y}{2E_\nu M_N} \right] F_{1A}(x, Q^2) + \left[\left(1 - \frac{m_l^2}{4E_\nu^2} \right) - \left(1 + \frac{M_N x}{2E_\nu} \right) y \right] F_{2A}(x, Q^2) \right. \\ & \left. \pm \left[xy \left(1 - \frac{y}{2} \right) - \frac{m_l^2 y}{4E_\nu M_N} \right] F_{3A}(x, Q^2) + \frac{m_l^2 (m_l^2 + Q^2)}{4E_\nu^2 M_N^2 x} F_{4A}(x, Q^2) - \frac{m_l^2}{E_\nu M_N} F_{5A}(x, Q^2) \right\} \end{aligned}$$

Neutrino interactions modelling takeaway

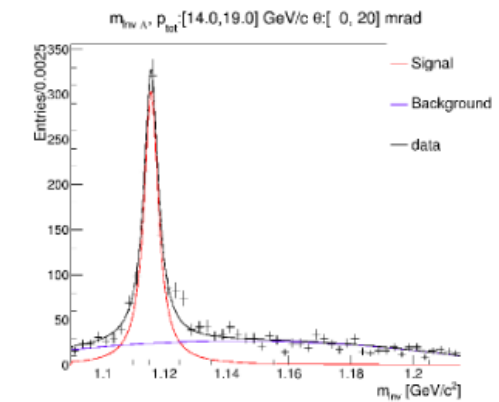
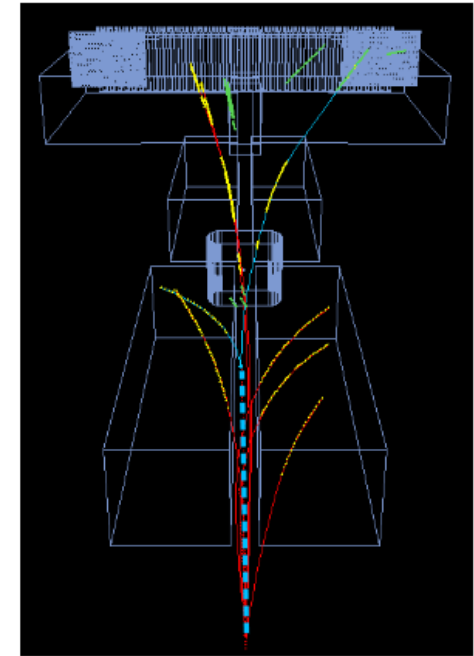
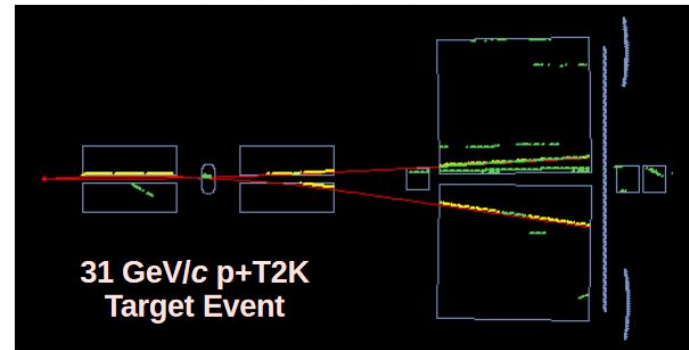
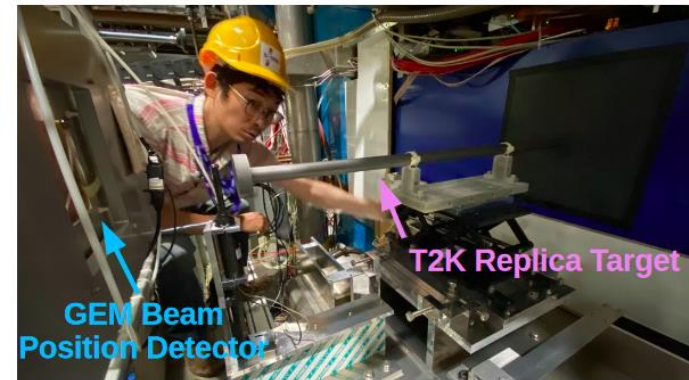
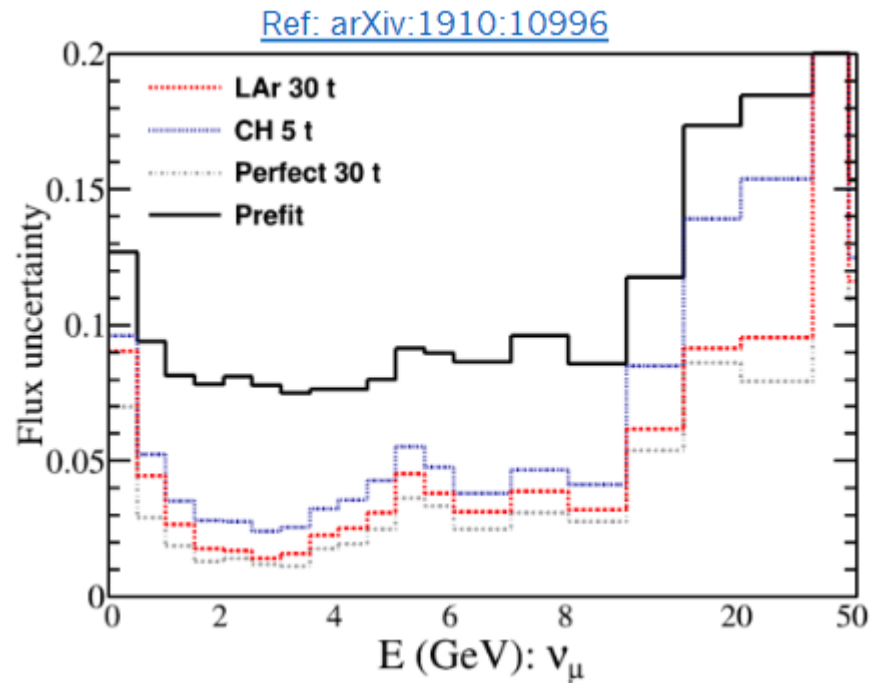
- Existing models do not provide enough freedom to predict neutrino scattering data well enough
 - Cannot fit individual interaction modes in isolation (degeneracy)
- Need a coherent approach to include **complete** models + uncertainties in generators
- Need to consider ν_τ cross-sections as well



Neutrino flux matters

- Flux uncertainties continue to be reduced

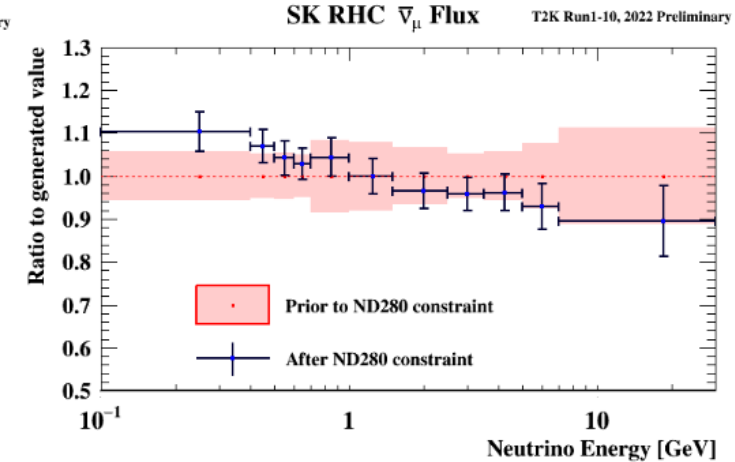
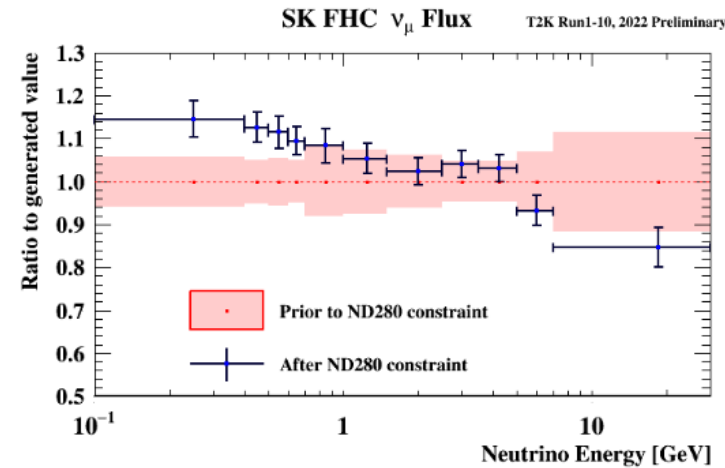
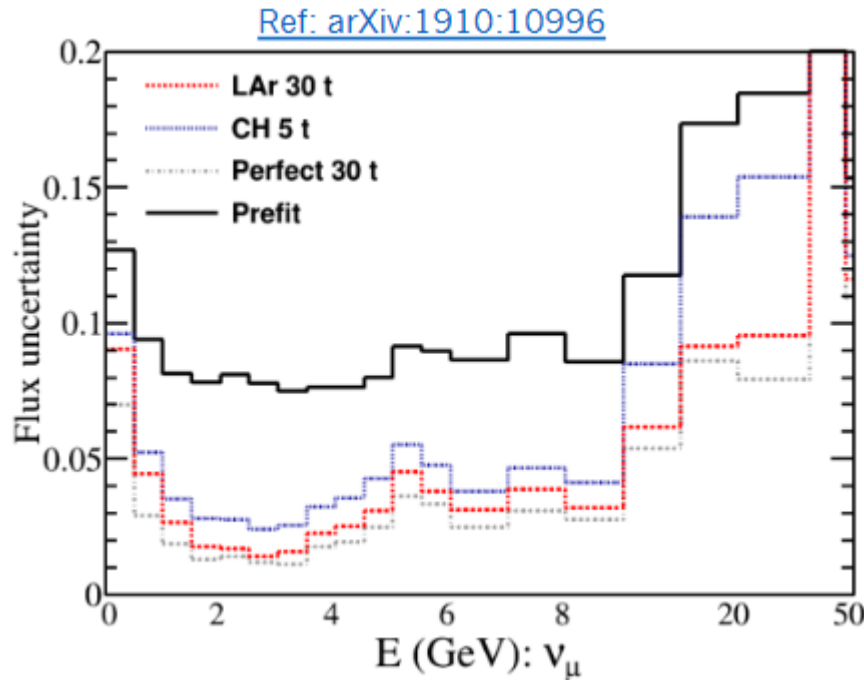
Brant Rumberger, Fri
PM



Zoya Vallari, Thu AM

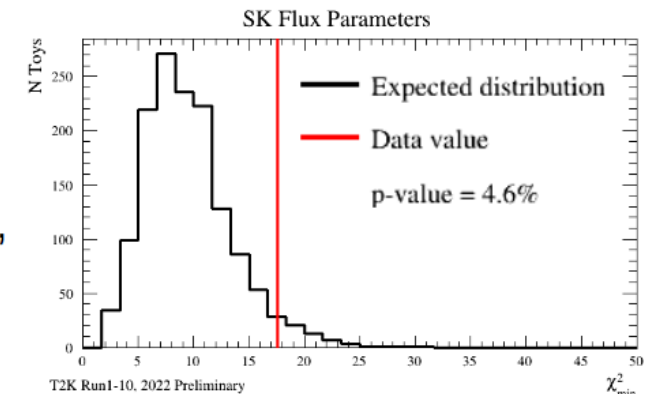
- Flux uncertainties continue to be reduced
- Signs of tension when compared to ND data?

Flux constraint

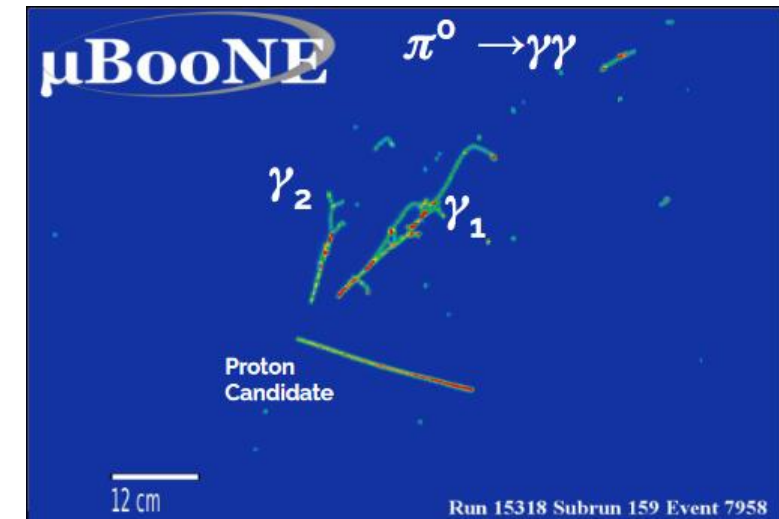


- Flux prediction at SK is updated using correlations with ND flux
- (Approximate) p-value* for flux is okay, despite parameters moving around

**Not a true p-value as correlations with other parameters are neglected*

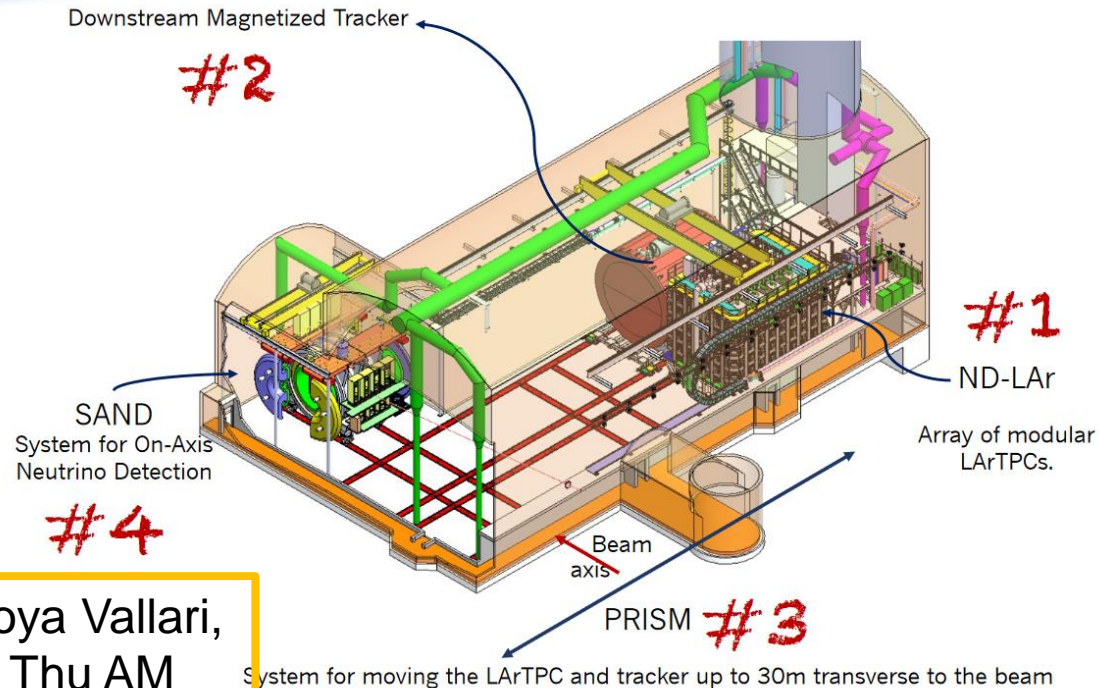


- Future long-baseline experiments with suites of near detectors
 - New technologies
 - Huge statistics



DUNE ND Overview

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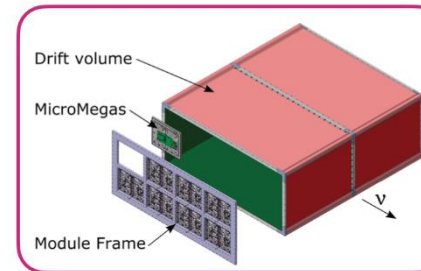
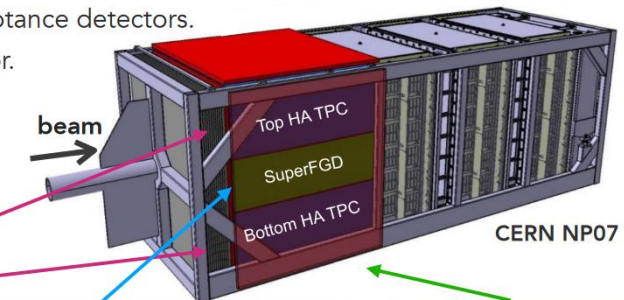


Zoya Vallari,
Thu AM

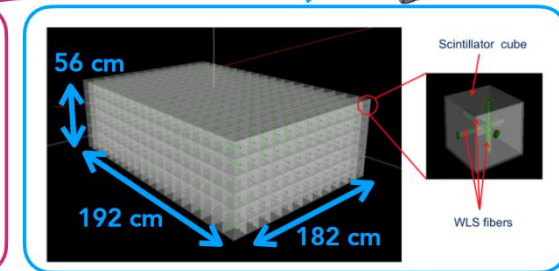
ND280 Upgrade

Aoi Eguchi, Thu AM

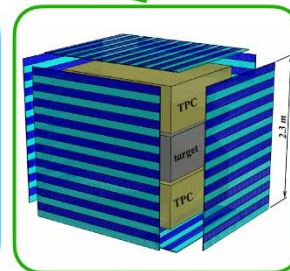
- Pi-0 detector will be replaced with new 4π acceptance detectors.
 - SuperFGD : fully active plastic scintillator.
 - High-Angle TPC: high resolution tracking of charged particles.
 - Time-of-Flight : Provide time information.
- Technical Design Report on [arXiv:1901.03750](https://arxiv.org/abs/1901.03750)



High-Angle TPC (HATPC)



Super Fine-Grained Detector (SuperFGD)



Time-of-Flight (TOF)

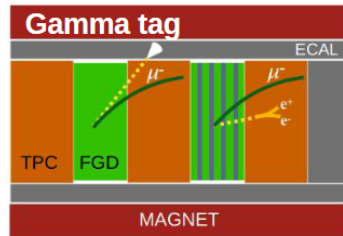
7

Higher precision through new samples

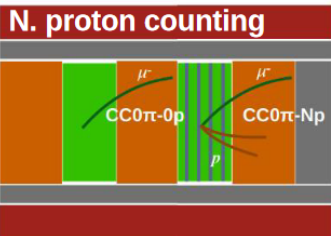
- Near detector data samples being split into more complex final states
- More sensitivity to individual neutrino interaction modes

Callum Wilkinson, Thu AM

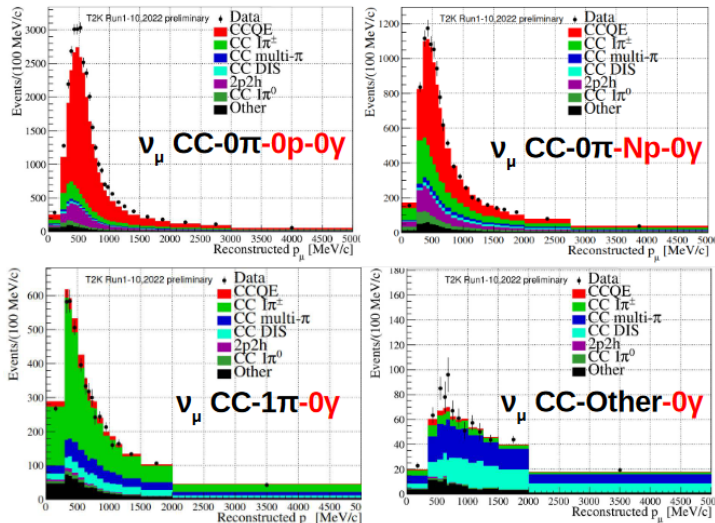
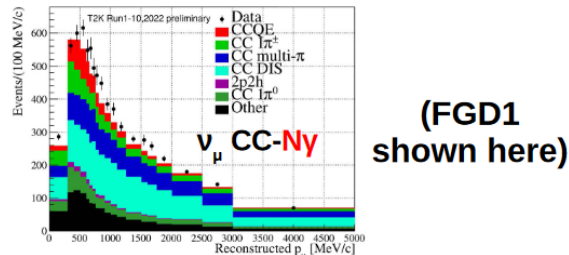
New(!) ν -mode samples ($\bar{\nu}$ -mode unchanged)



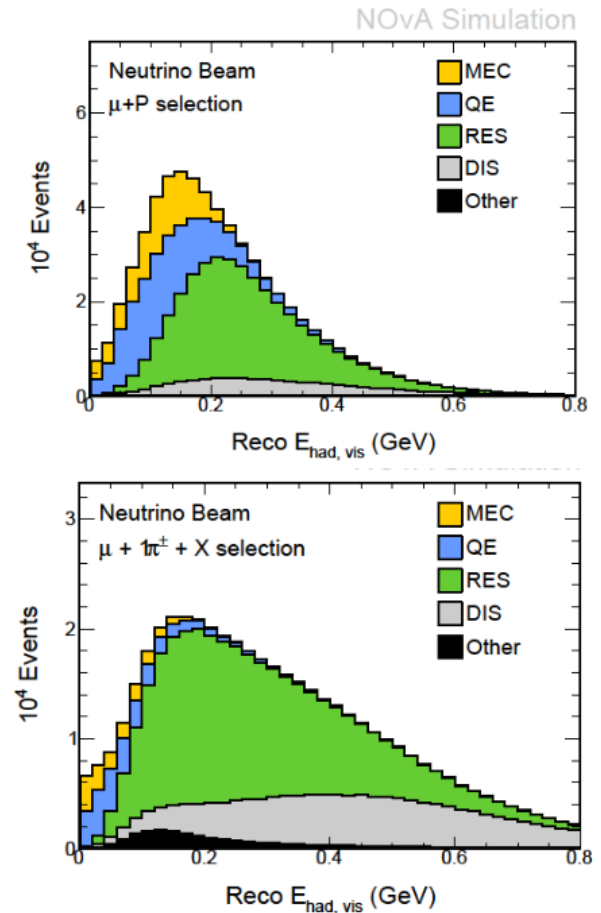
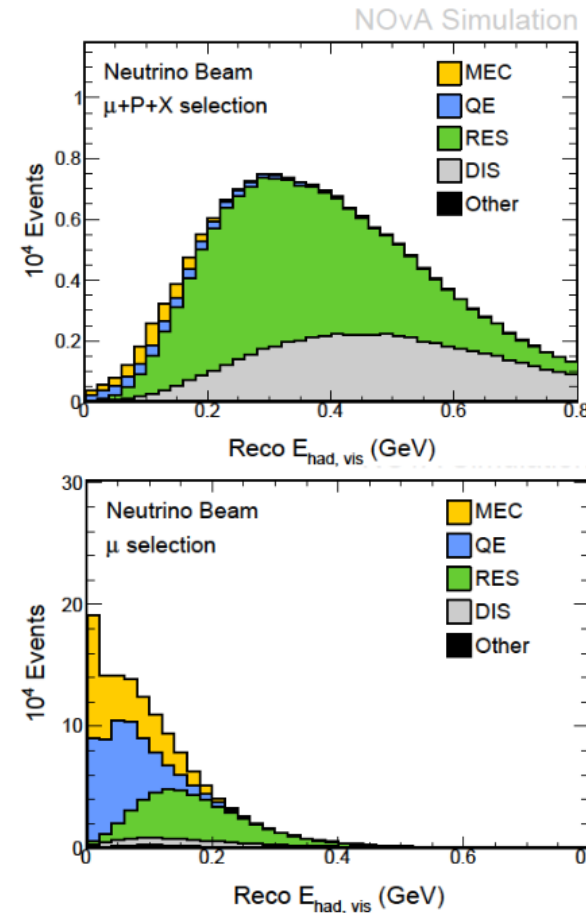
- Improves sample purities
- New (mostly DIS + multi- π) sample with FS π^0



- Subdivide CC0 π sample
- Constrain 2p2h + nuclear models



Kirk Bays, Tues PM



SBND-PRISM - Sterile Neutrino Oscillations - 2

$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

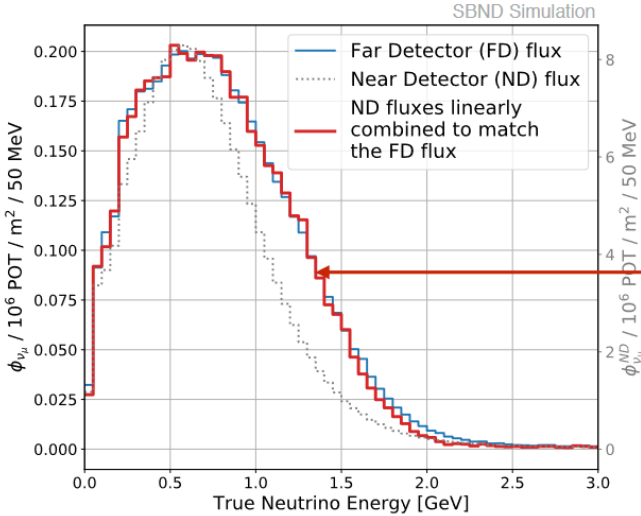
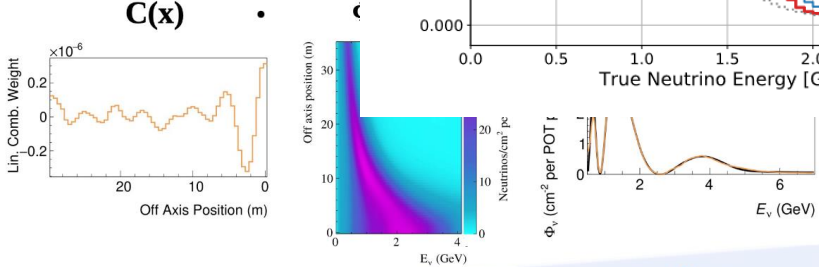
Can we make the two fluxes similar?

Yes!

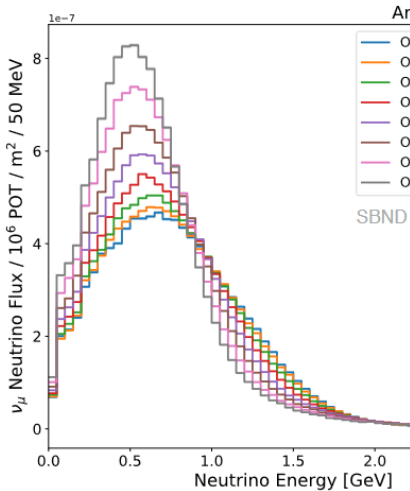
Michael Smy, Mon PM

PRISM

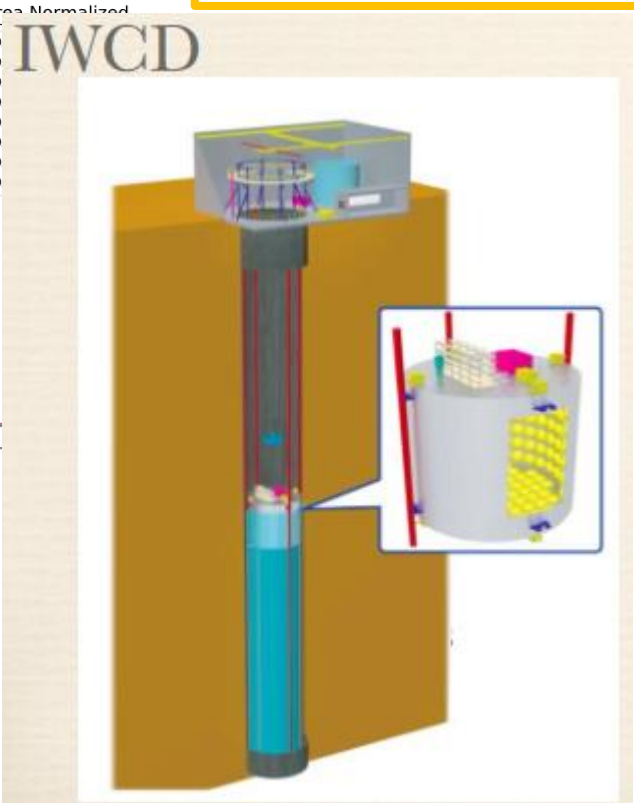
Using a linear combination of ND flux at various off-axis position, we can construct a prediction for the oscillated FD flux.



Fit a linear combination of the ND fluxes to reproduce the FD flux at the ND



Marco Del Tutto, Thu AM

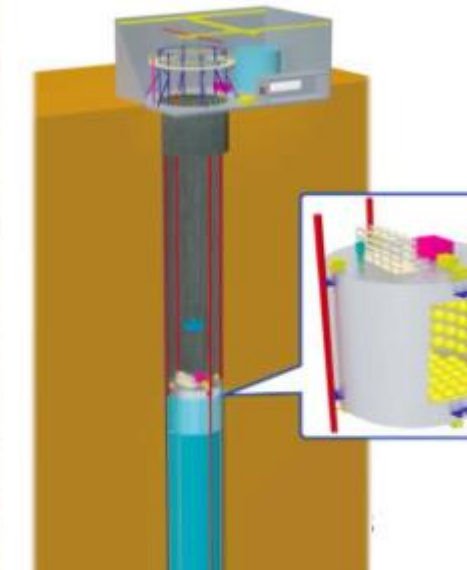


Zoya Vallari, Thu AM

$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

Yes!

IWCD



The diagram illustrates an Intelligent Well Completion (IWCD) system. It features a central production tube with multiple lateral branches. A detailed inset shows the internal structure of the wellhead, including valves and sensors.

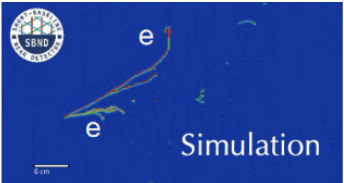
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Near detectors takeaway

- Huge increase in available information
 - More data
 - New technology
 - New techniques
 - New samples
- Require improvements in flux and interaction models
 - Closer work between theory and experiment
 - NuSTEC

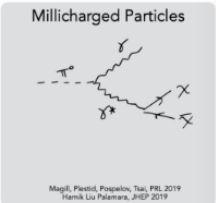


BSM Signatures in SBND



An SBND event display of a simulated dark neutrino event producing e^+e^- showers

Millicharged Particles



Hypothesized particles with **fractional electronic charge**, motivated by a cosmological anomaly (EDGES).
Could be a constituent of **Dark Matter**.
Produced by **neutral meson decay** in the BNB.

They would appear as **blips** or **faint tracks** pointing back to the target in SBND.

Projected SBND threshold: 50 keV
[MicroBooNE threshold: 100 keV]

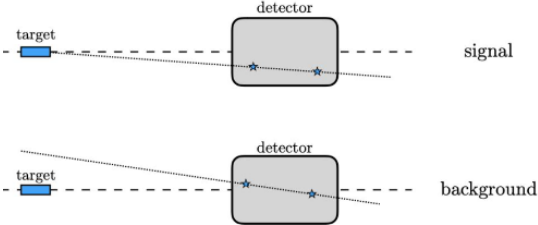
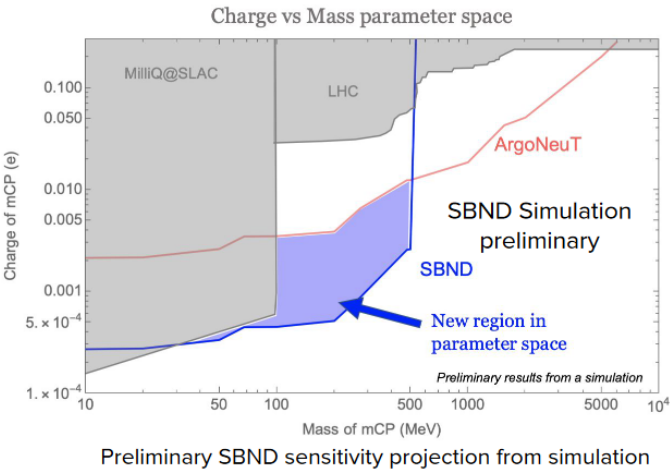


Image credit: ArgoNeuT, [arXiv:1902.03246v2](https://arxiv.org/abs/1902.03246v2)



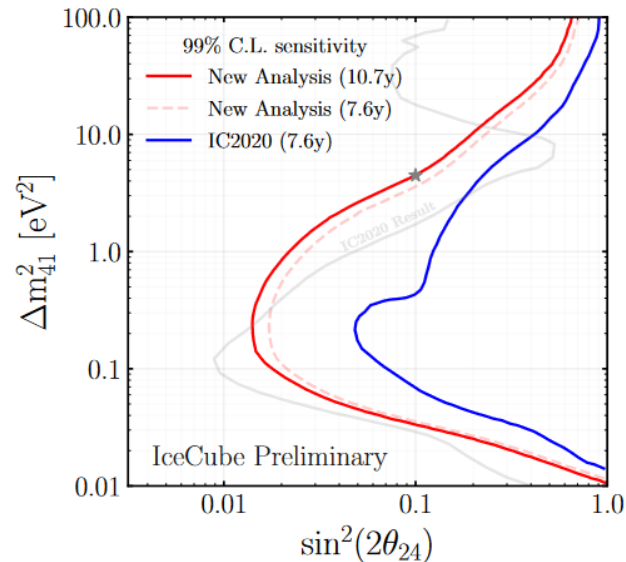
Preliminary SBND sensitivity projection from simulation



Supraja Balasubramanian, Tue PM

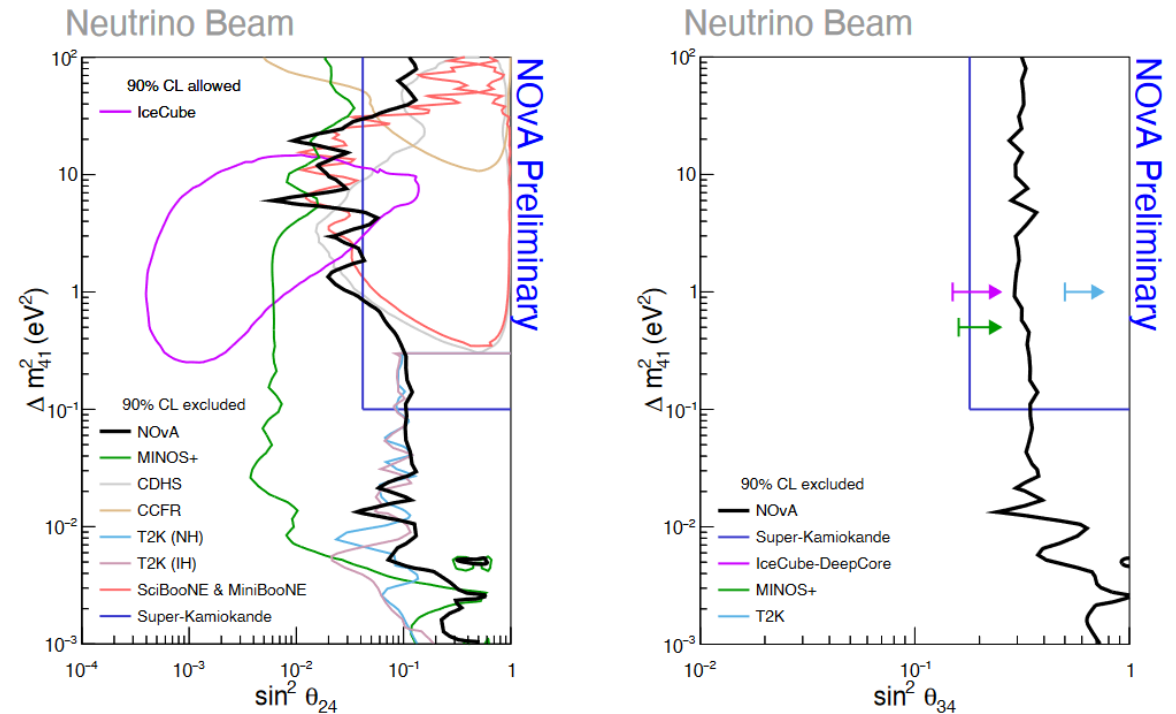
Prospects

- Sensitivities assuming $\theta_{34}=0$ in both analysis.
- Significant improvement in the 0.1-5 eV^2 region.
 - Most of the gain due to new event selection and energy reconstruction.
- Preferred region from previous analysis will be further studied.



Alfonso Garcia, Tue PM

90% CL contours



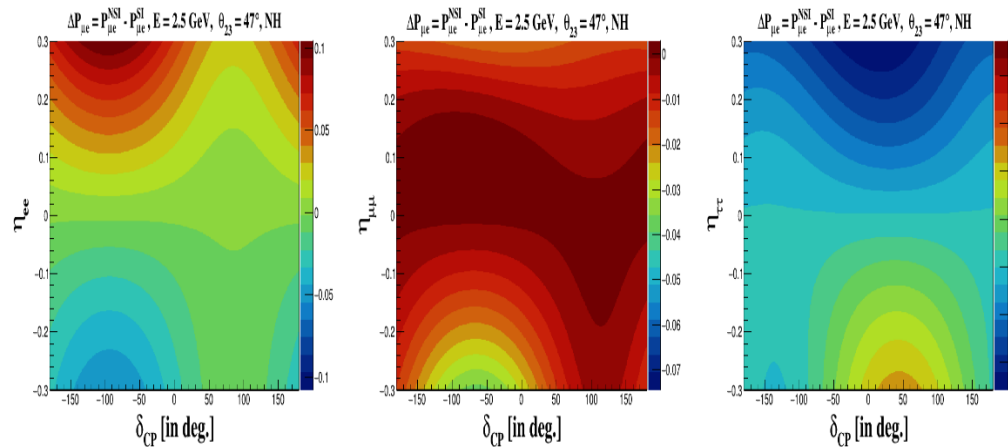
BSM neutrino oscillations at NOvA – V Hewes – NuFact 2022

V Hewes, Tue PM

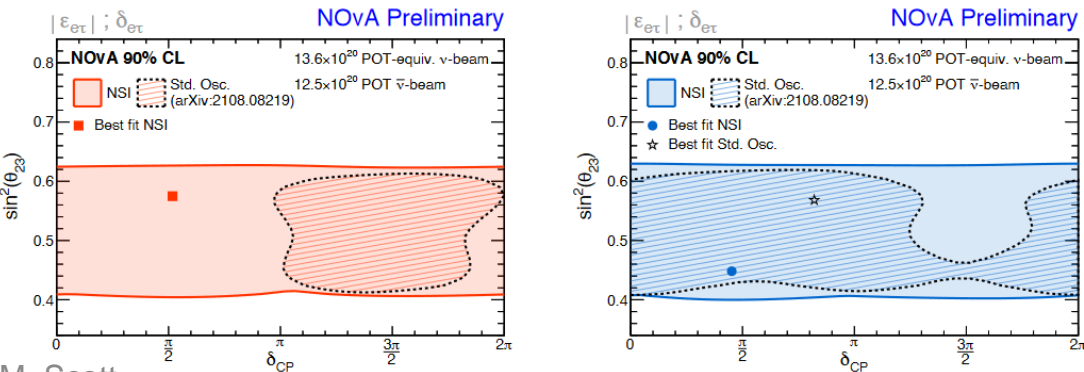
Results : $\Delta P_{\mu e}$ in $\delta_{CP}-\eta_{\alpha\beta}$ plane

Abinash M., Thu PM

$$\Delta P_{\alpha\beta} = P_{\alpha\beta}(\text{with SNSI}) - P_{\alpha\beta}(\text{without SNSI})$$

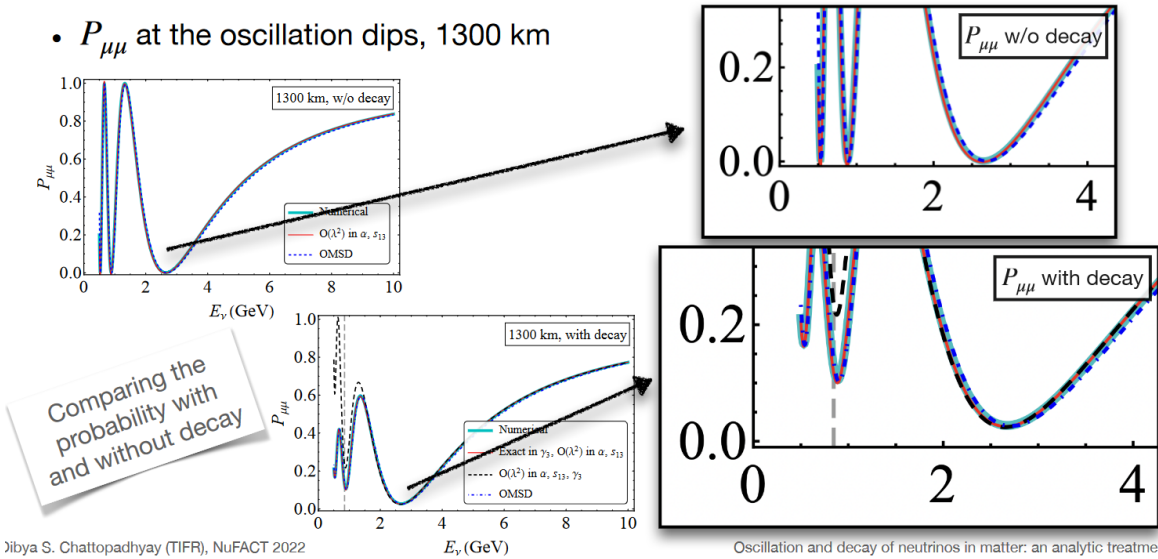


NSI $\epsilon_{e\tau}$ 90% CL limits



Increase of probability due to decay!

- $P_{\mu\mu}$ at the oscillation dips, 1300 km



Dibya S. Chattopadhyay (TIFR), NuFACT 2022

Oscillation and decay of neutrinos in matter: an analytic treatment

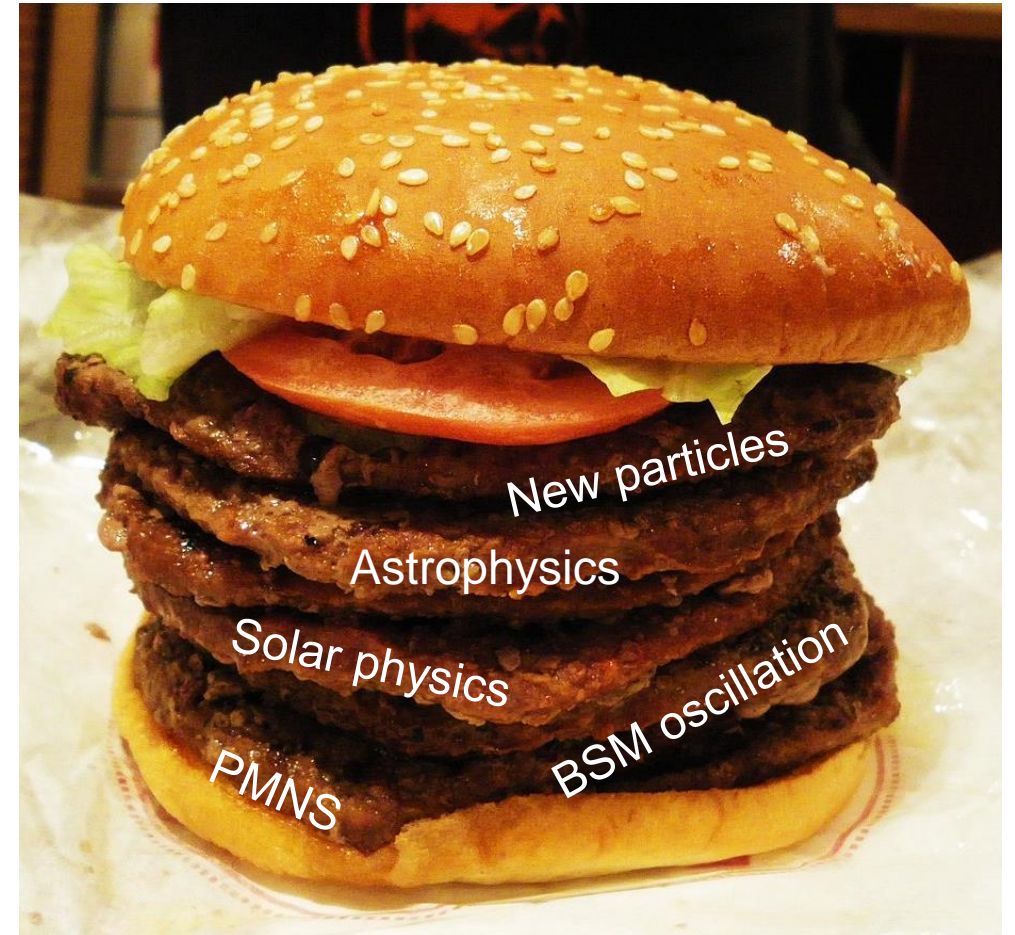
Dibya C., Thu PM

- BSM physics as sub-leading effect on PMNS oscillation
- Need multiple experiments (energies, baselines)

V Hewes, Thu PM

BSM takeaway

- Neutrino experiments are not just neutrino experiments
 - General-Purpose Detectors
- LAr has huge potential
 - Large sample size = rare events
- Next generation
 - Precision measurements to search for deviation from PMNS



Summary of the summary

- Community working to extract as much as possible from existing experiments
- More collaboration between experimentalists, phenomenologists and theorists necessary
- Combined measurements from different experiments needed to remove physics degeneracies
- More and more BSM searches
 - Relies on precision in oscillation measurements
- Challenging but about to have a wealth of data to work with!

**Thank you to all of the speakers, the other WG1
conveners and the LOC for making this
conference a success!**