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WG1 Summary



Mark Scott   Adam Aurisano   Jian Tang

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- Packed programme
- Interplay between WG1 and other WGs
- Lots of exciting work!

WG1 Program

- 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

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

WG1 Program

- 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
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  - Details of current and future experiments
  - Programs to improve oscillation experiments
  - Exploration of BSM oscillation scenarios

1 August 2022 NuFact 2022 - Adam Aurisano 10

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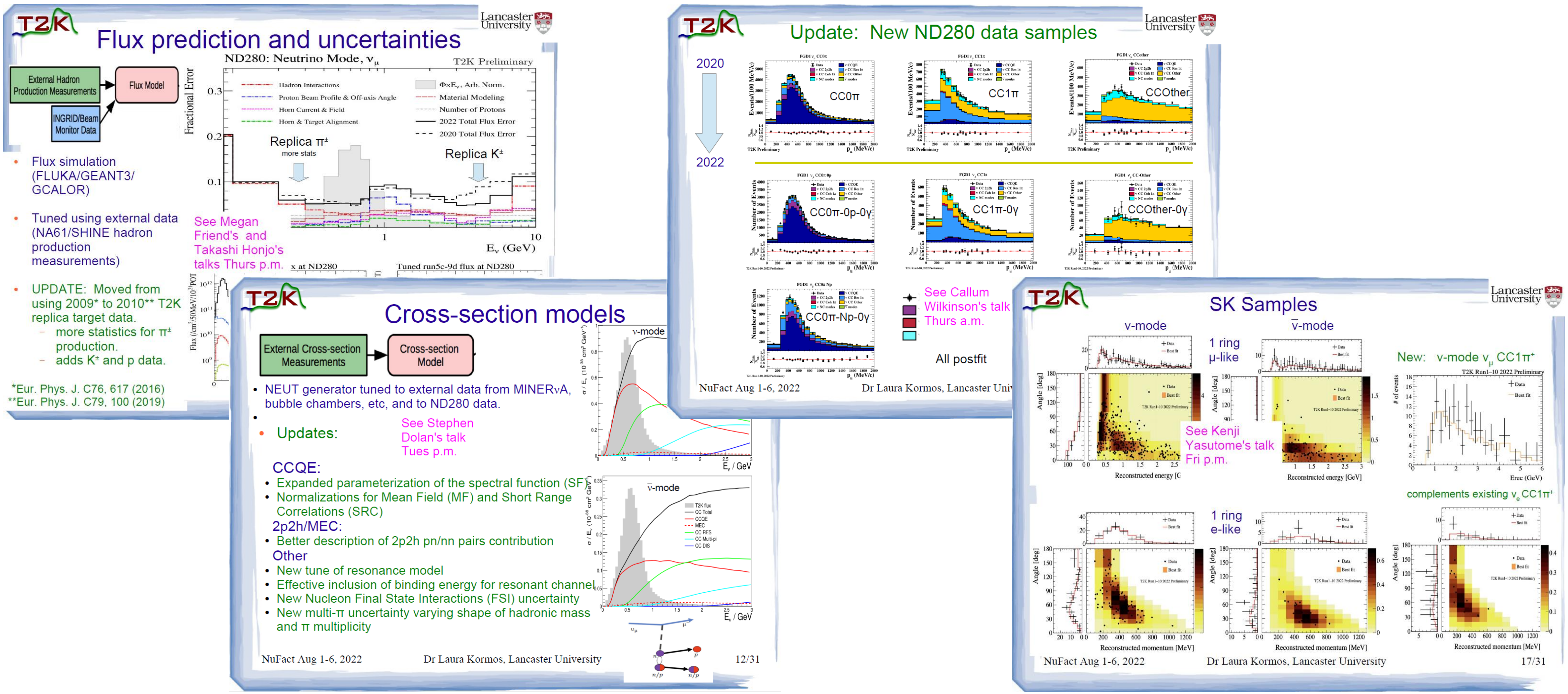
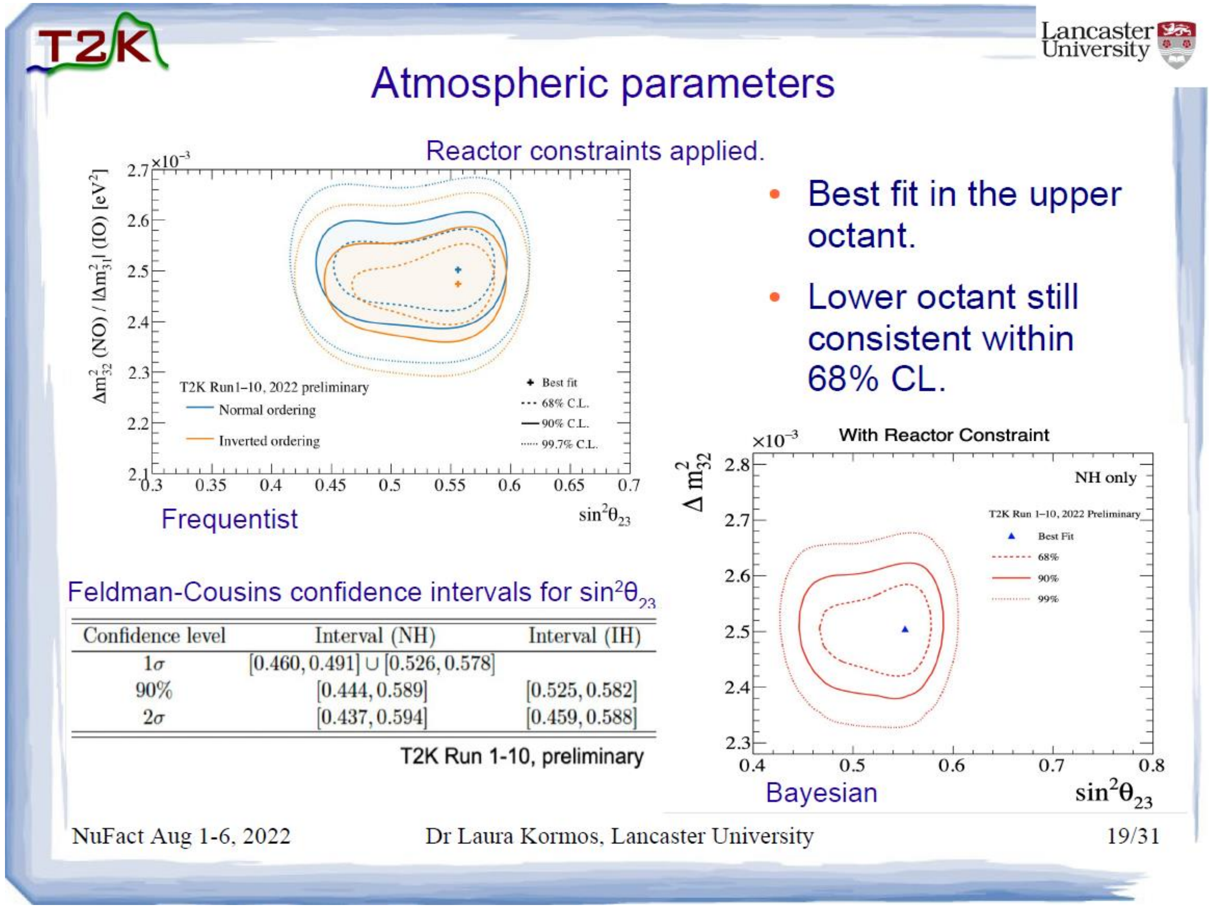
T2K Analysis Updates

Laura Kormos, Mon PM

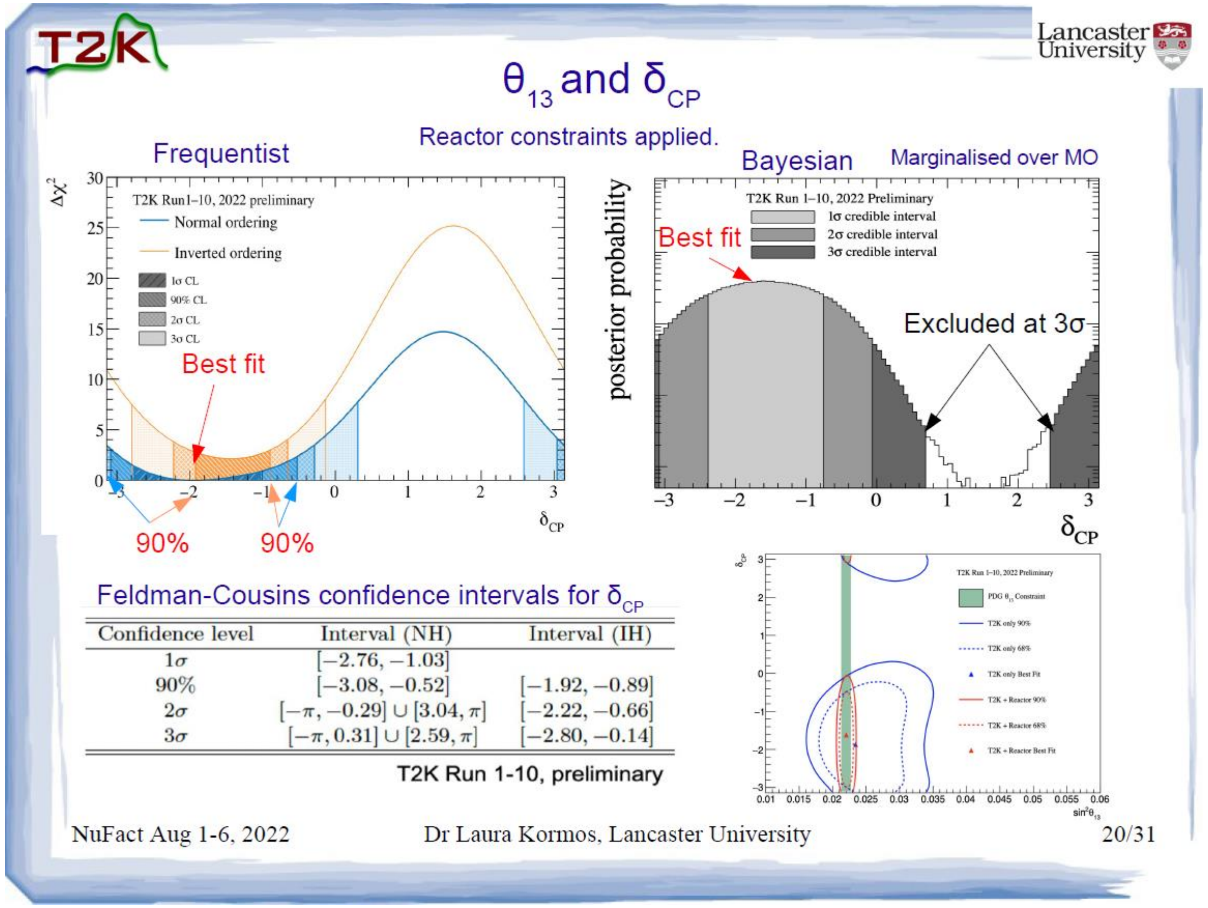


T2K Analysis Results

Laura Kormos, Mon PM



Confidence level	Interval (NH)	Interval (IH)
1σ	$[0.460, 0.491] \cup [0.526, 0.578]$	
90%	$[0.444, 0.589]$	$[0.525, 0.582]$
2σ	$[0.437, 0.594]$	$[0.459, 0.588]$

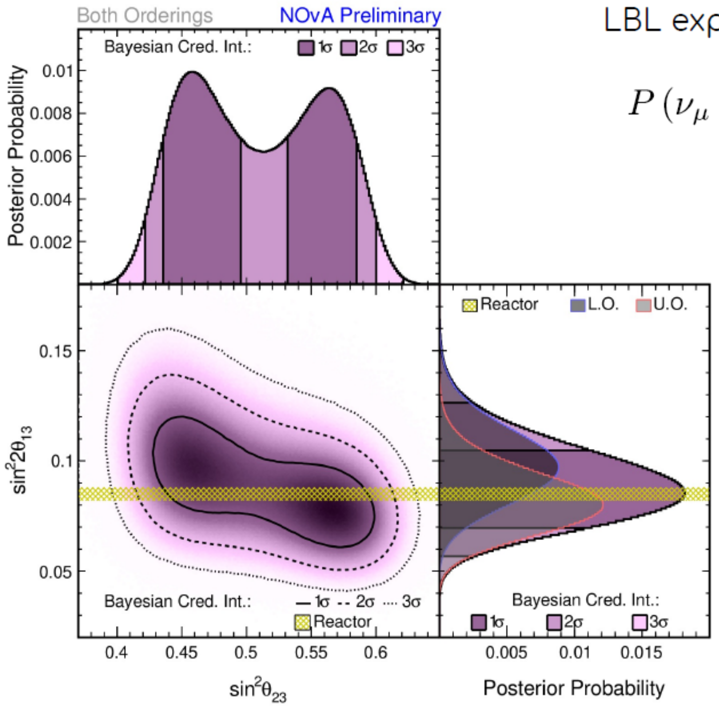


Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.76, -1.03]$	
90%	$[-3.08, -0.52]$	$[-1.92, -0.89]$
2σ	$[-\pi, -0.29] \cup [3.04, \pi]$	$[-2.22, -0.66]$
3σ	$[-\pi, 0.31] \cup [2.59, \pi]$	$[-2.80, -0.14]$

NOvA Analysis Results

Jeremy Walcott, Mon PM

PMNS measurements



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

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

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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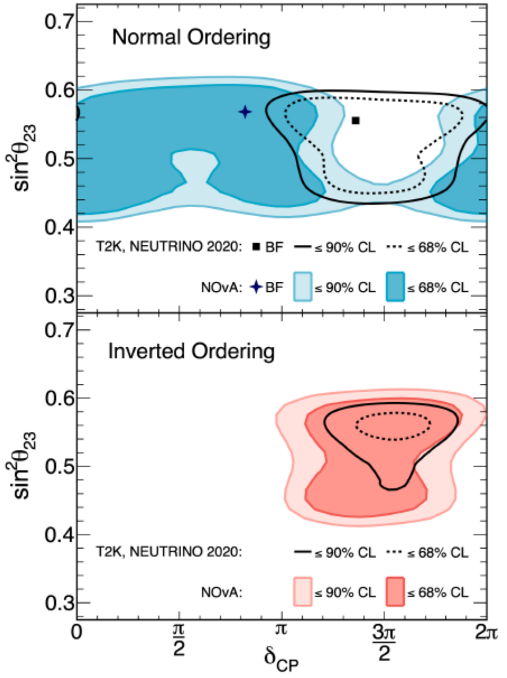
NuFact 2022 / Aug. 1, 2022 J. Wolcott / Tufts University

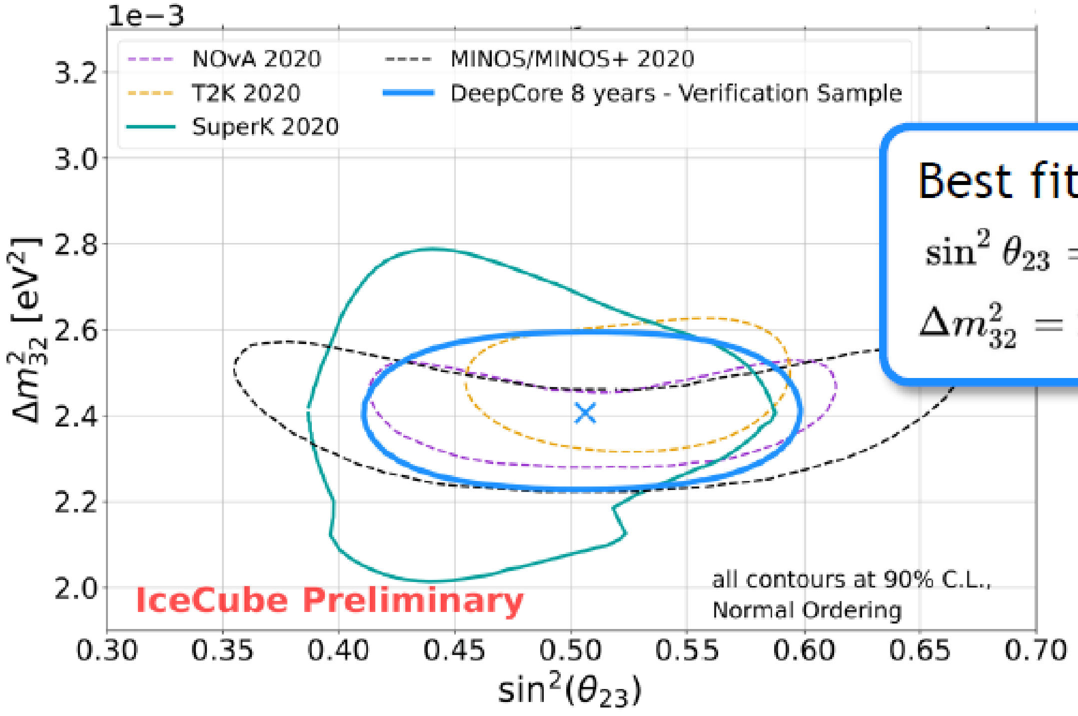
PMNS measurements

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



IceCube Analysis Results

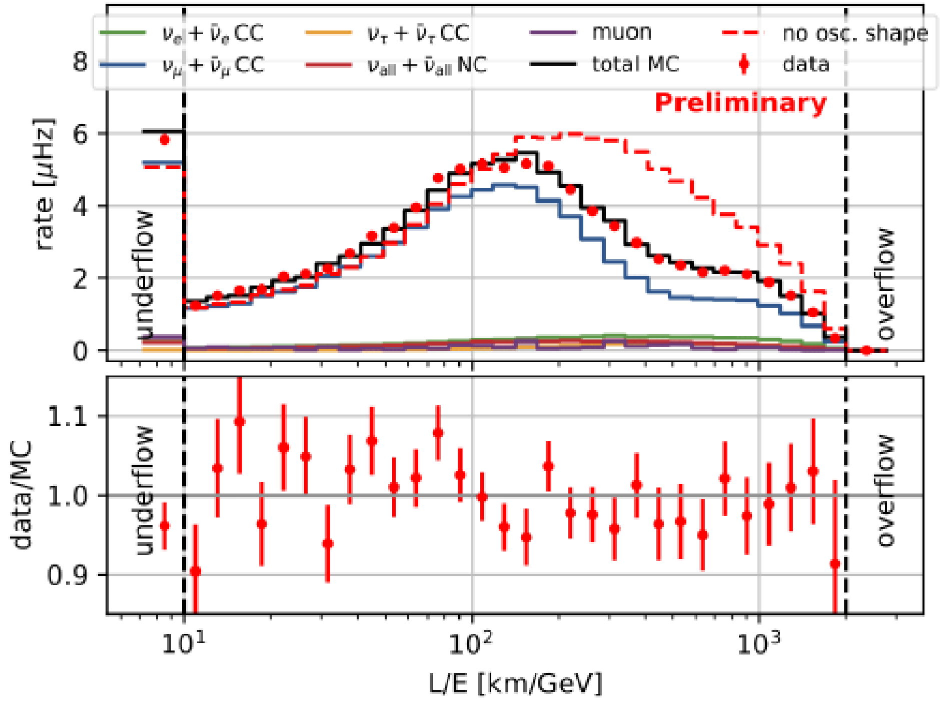
Kayla Leonard, Mon PM



Best fit point result:

$$\sin^2\theta_{23} = 0.505^{+0.051}_{-0.050}$$

$$\Delta m^2_{32} = 2.41^{+0.084}_{-0.084} \times 10^{-3} eV^2$$



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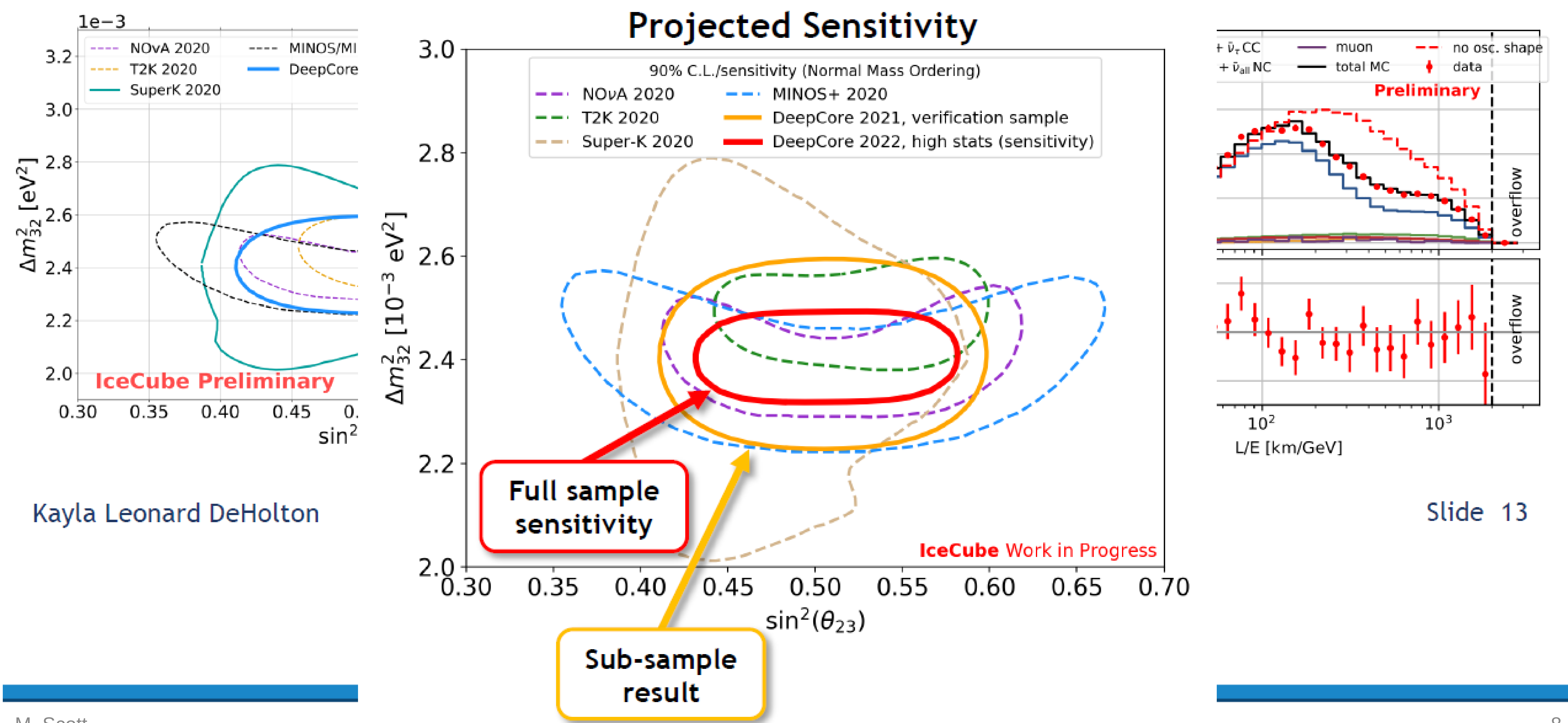
Kayla Leonard, Mon PM



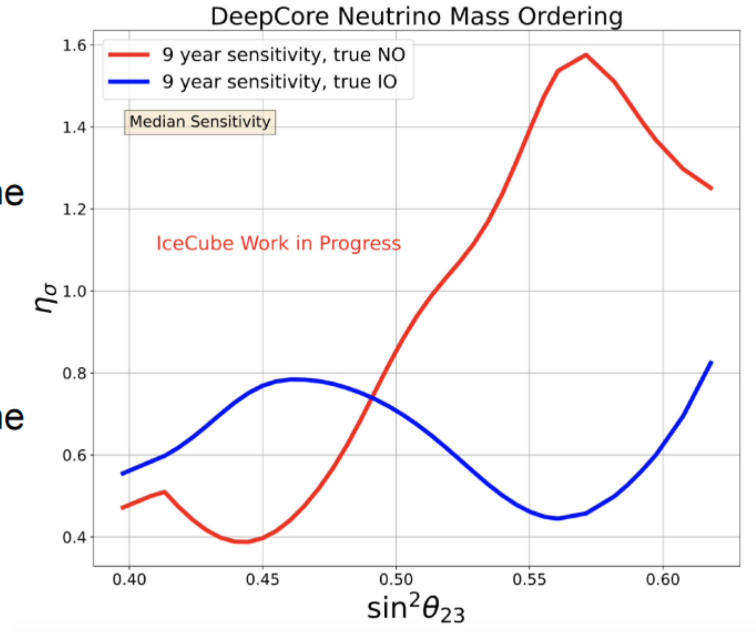
IceCube Analysis Results

Maria Rodriguez, Fri AM

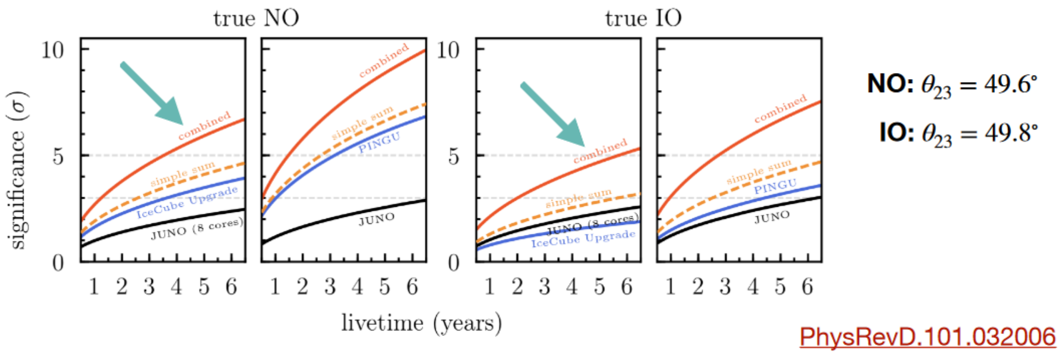
9-Year NMO Sensitivity

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

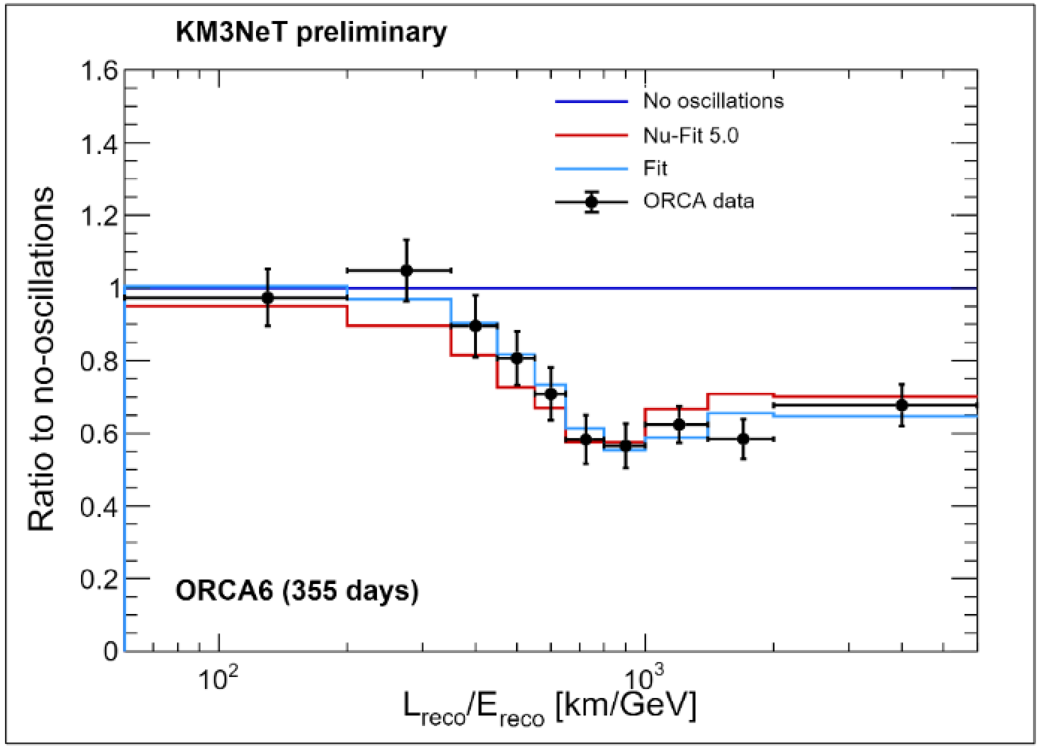


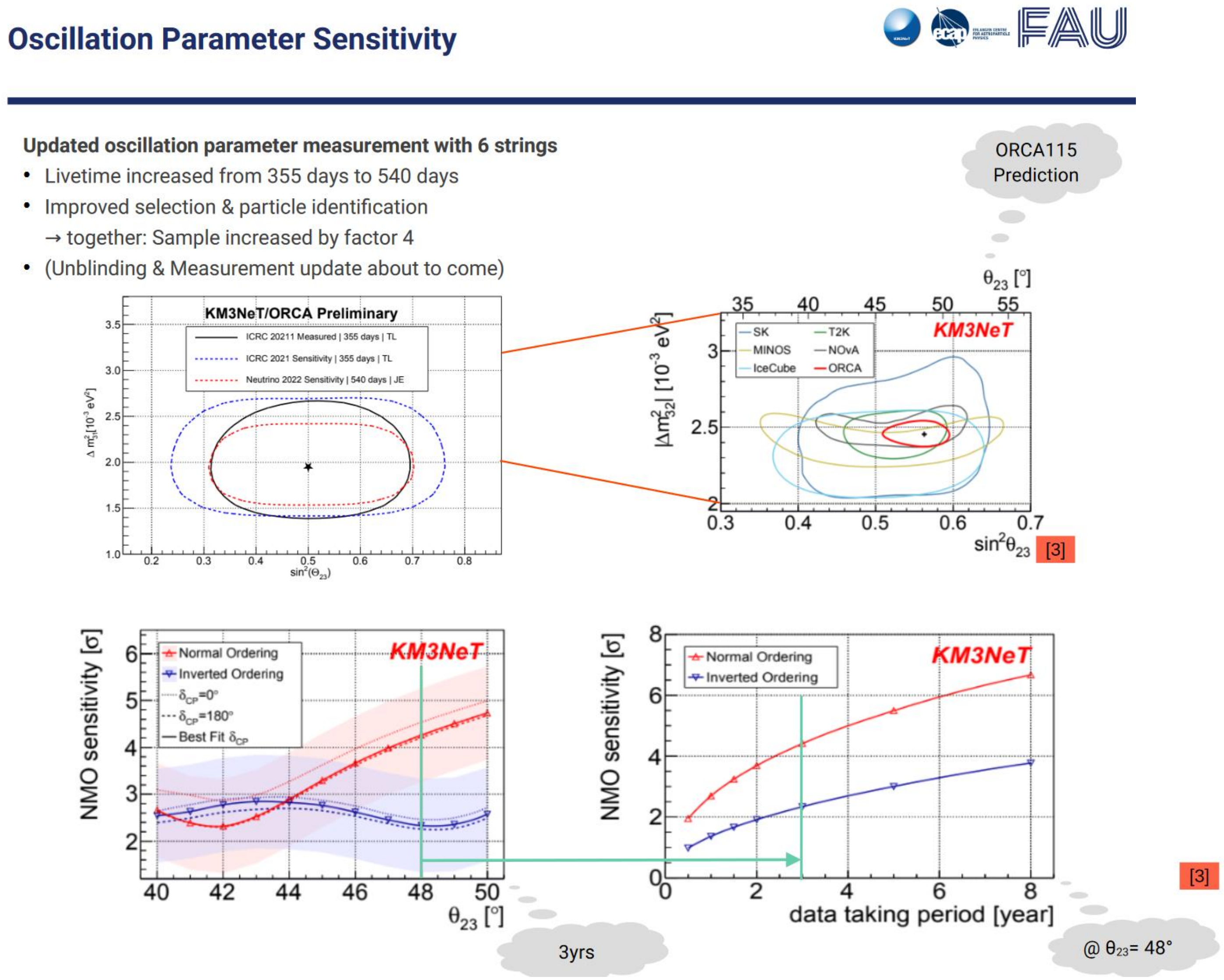
PhysRevD.101.032006

- 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

KM3NeT/ORCA



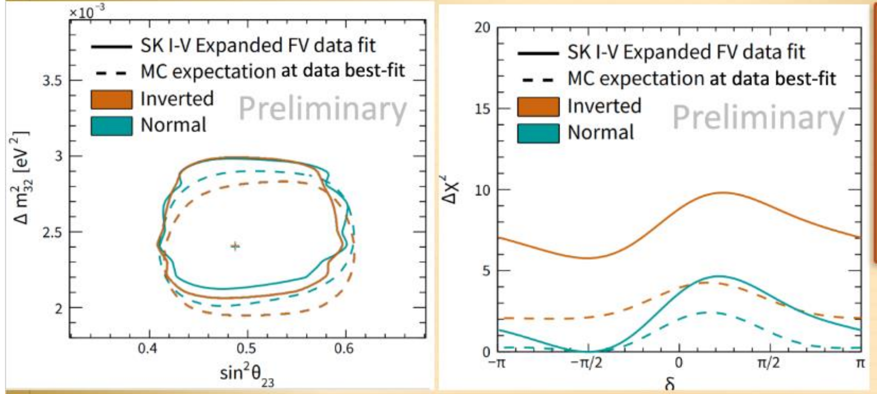


Johannes Schumann, Fri AM

Super-Kamiokande

Magda P-Z, Fri AM

SK only: parameters determination



SK atmospheric neutrino data favours:

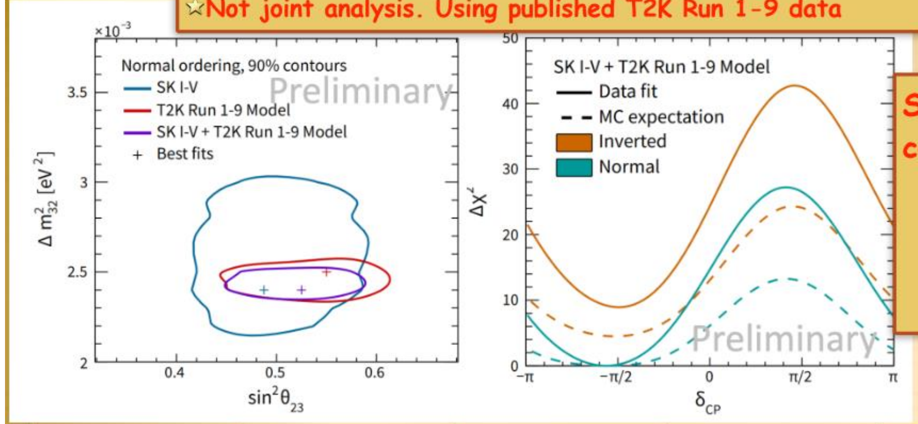
- Maximal mixing
- NO ($\Delta\chi^2 = 5.8$)
- $\delta_{CP} \simeq -\frac{\pi}{2}$

930 bins	χ^2	$\delta_{CP} \in [0,2\pi]$	$\sin^2\theta_{23}$	Δm^2_{23}
SK NO	1000.42	4.71	0.49	$2.4 \times 10^{-3} eV^2$
SK IO	1006.19	4.71	0.49	$2.4 \times 10^{-3} eV^2$

Magdalena Posiadala-Zezula, NuFact2022 Salt Lake City, USA 12

SK + T2K - parameters determination

Not joint analysis. Using published T2K Run 1-9 data



SK + external T2K constrains favour:

- Maximal mixing
- NO ($\Delta\chi^2 = 8.9$)
- $\delta_{CP} \simeq -\frac{\pi}{2}$

930 bins	χ^2	$\delta_{CP} \in [0,2\pi]$	$\sin^2\theta_{23}$	Δm^2_{23}
SK+T2K NO	1086.33	4.54	0.53	$2.4 \times 10^{-3} eV^2$
SK +T2K IO	1095.25	4.71	0.53	$2.4 \times 10^{-3} eV^2$

SK is sensitive to mass ordering; T2K sensitive to δ_{CP}

Magdalena Posiadala-Zezula, NuFact2022 Salt Lake City, USA 13

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

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T2K + Super-Kamiokande

Kenji Yasutome, Fri AM

Sensitivity results

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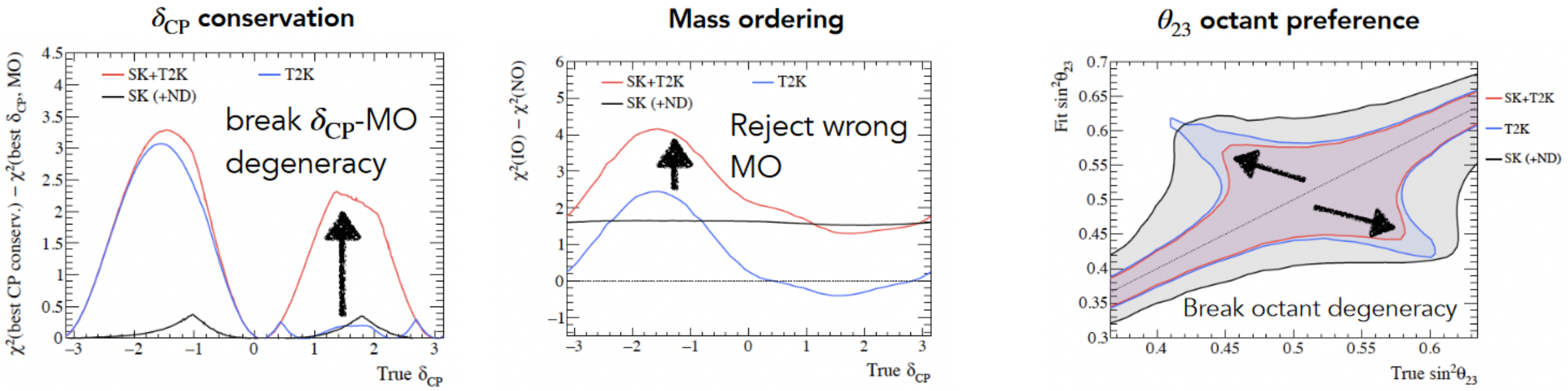
- Full joint analysis sensitivity
- Significant improvements
- Challenging!
- T2K + NOvA on the way



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

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

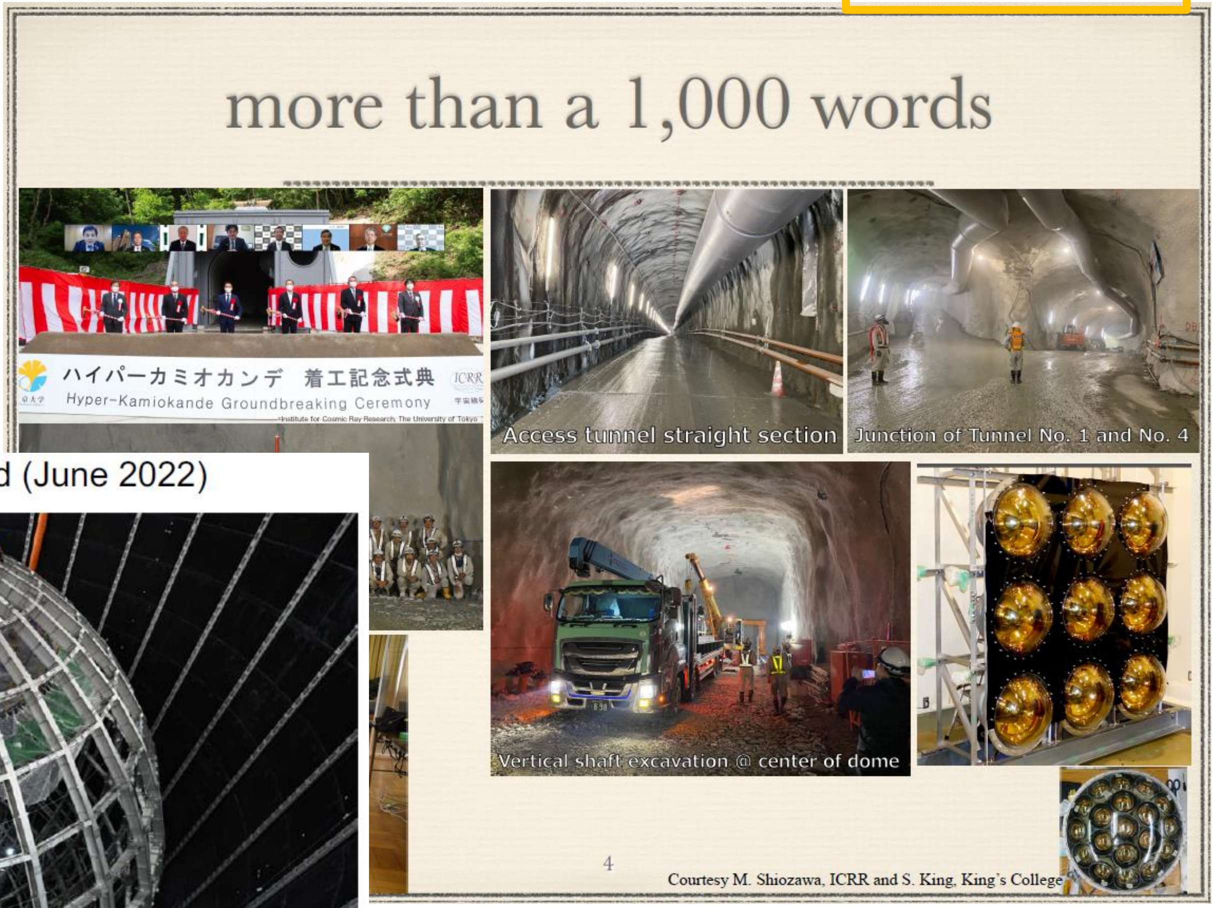
- δ_{CP} conservation
  δ_{CP}-independent MO sensitivity from atmospheric samples breaks δ_{CP}-MO degeneracy.
  Increase δ_{CP} sensitivity in the case $\delta_{CP} < 0$ in NO.
- MO & octant preference
  Atmospheric samples being sensible to MO via mantle/core resonance significantly increase the power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

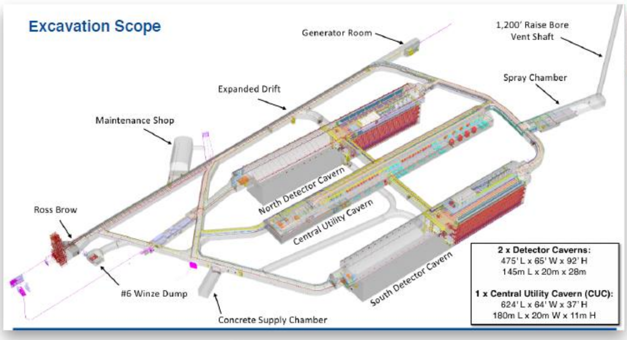
Next generation experiments

Michael Smy, Mon PM

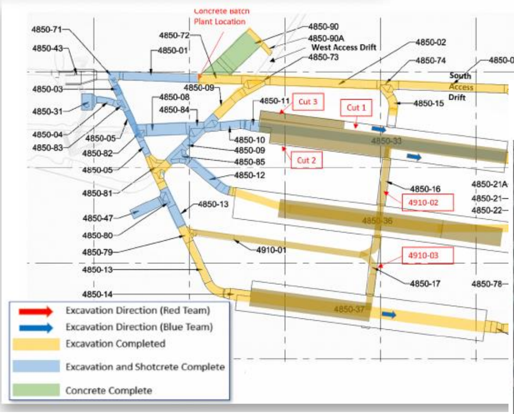


Far Site Status

- 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



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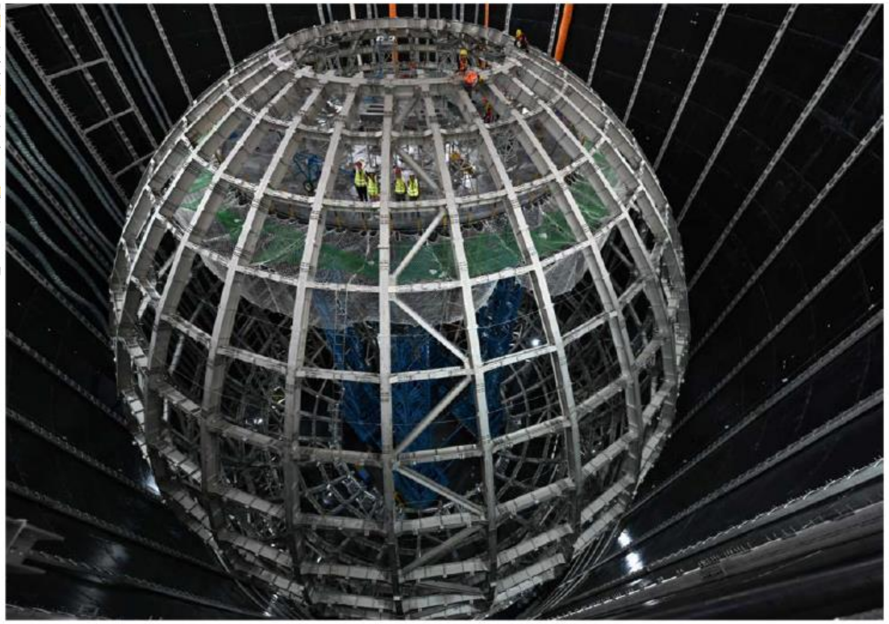
Support structure finished (June 2022)



Sowjanya Gollapinni, Mon PM

Livia Ludhova, Mon PM

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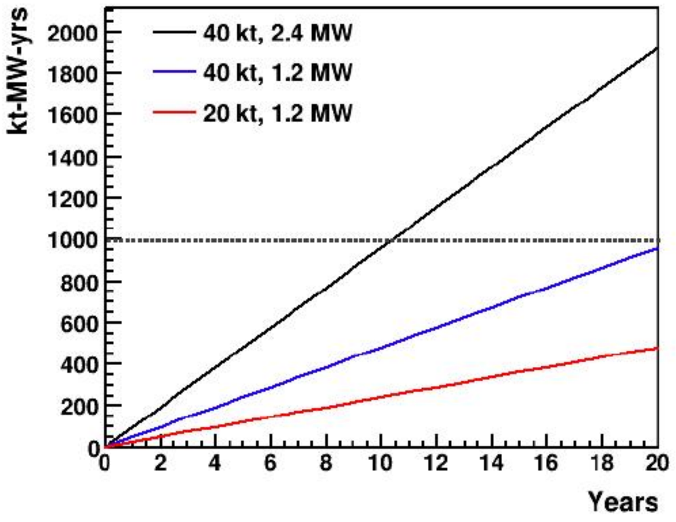
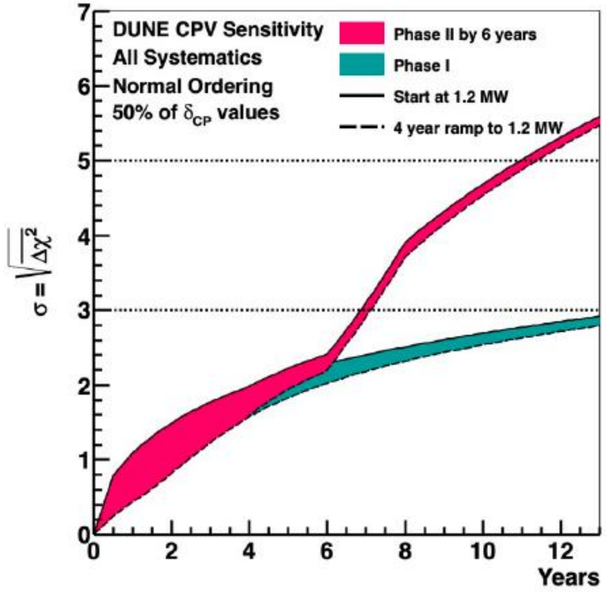
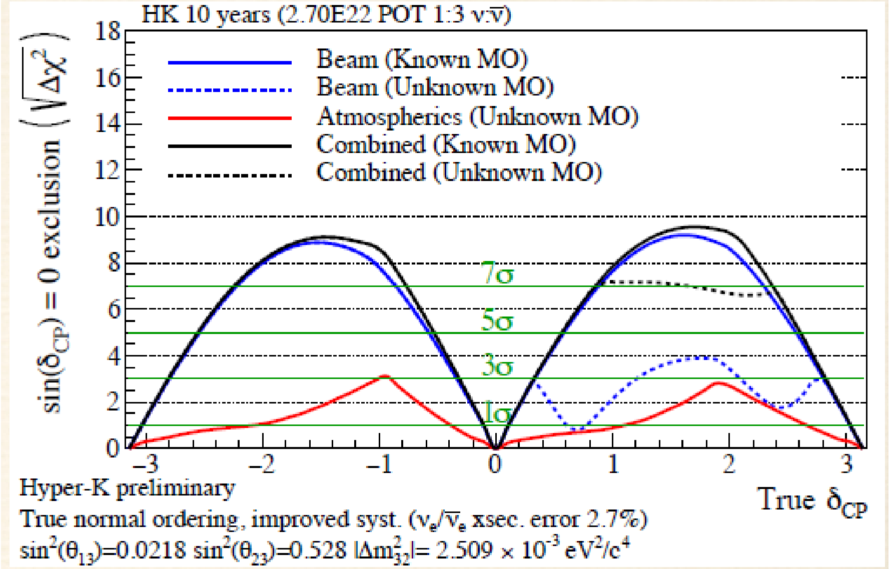
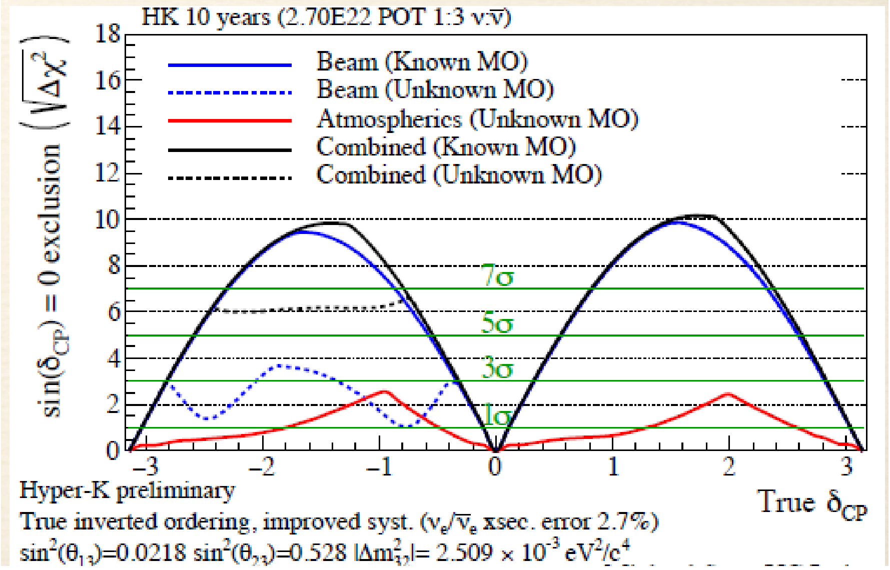
Next generation experiments

DUNE Phase II: Physics Potential









- O(1000) kt-MW-yrs 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)

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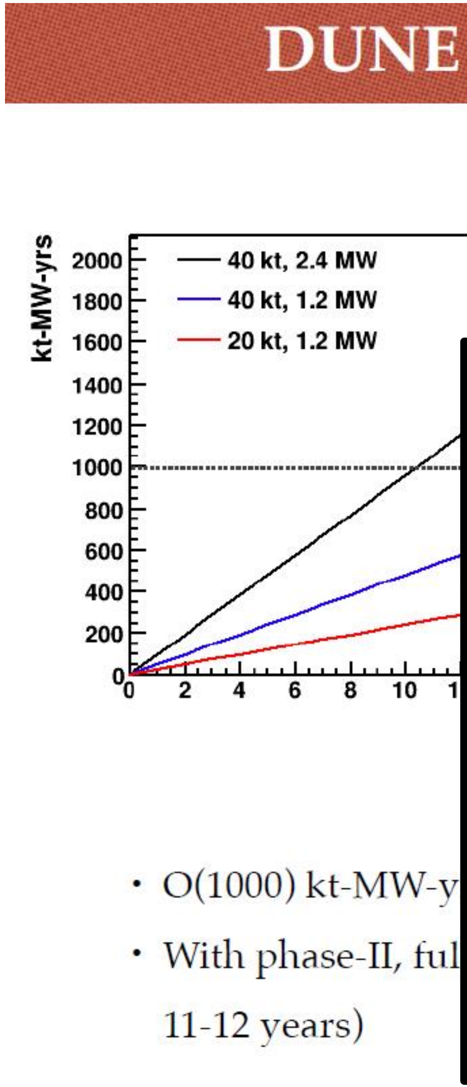
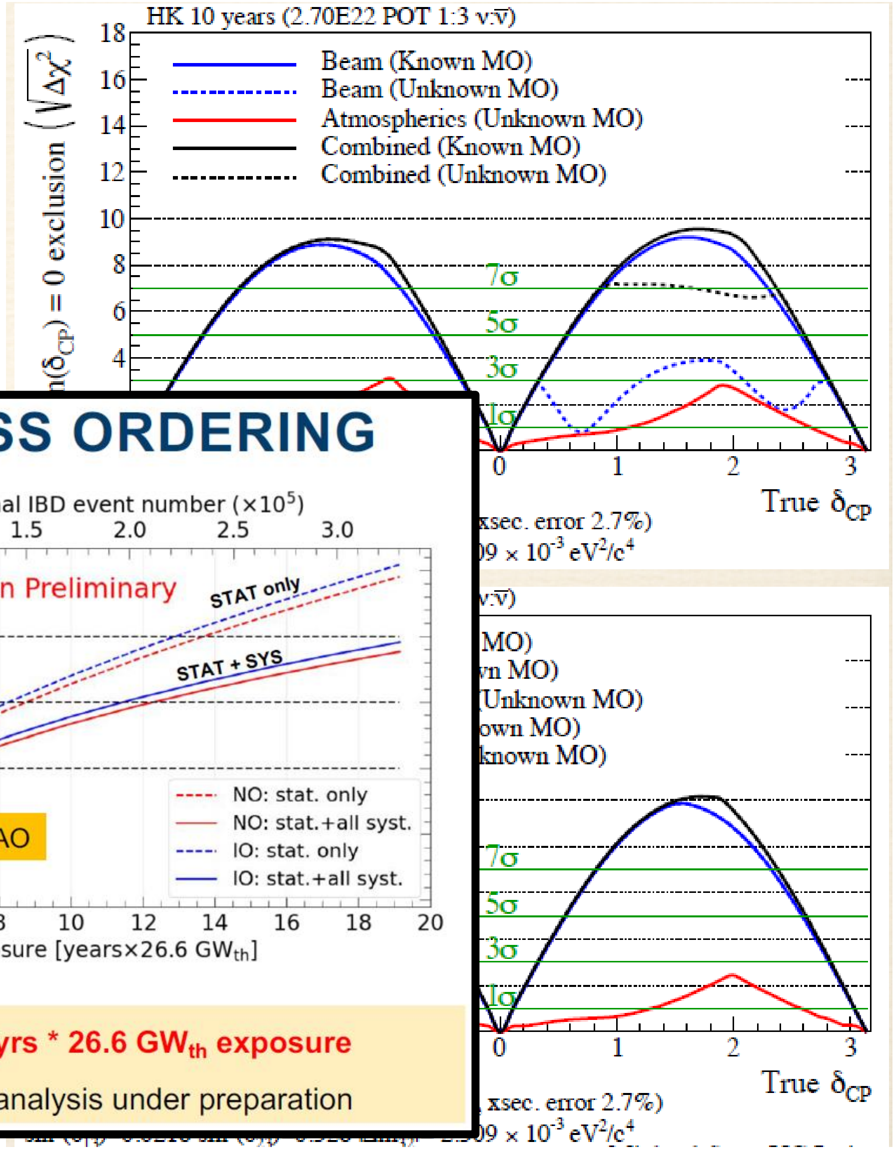
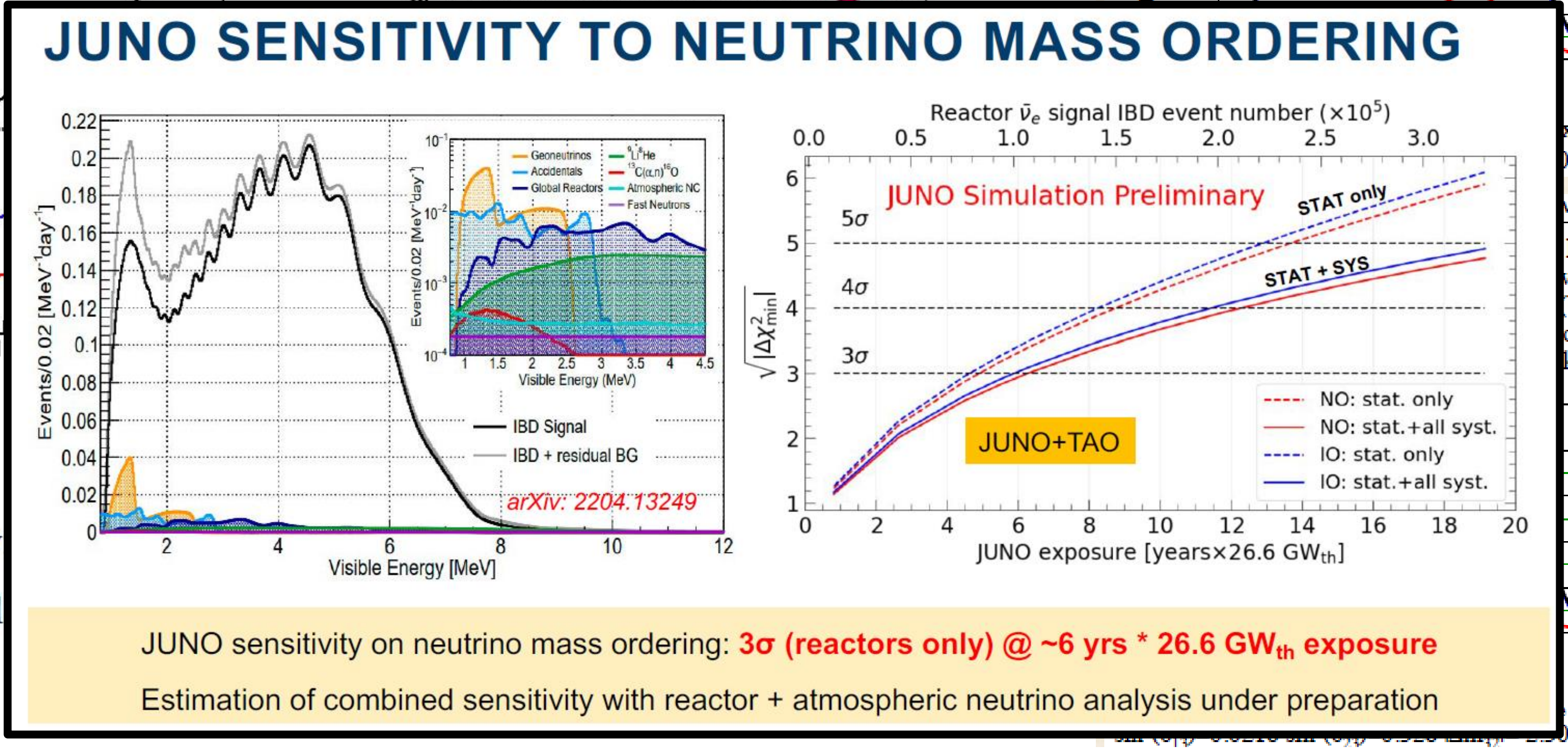
Next generation experiments







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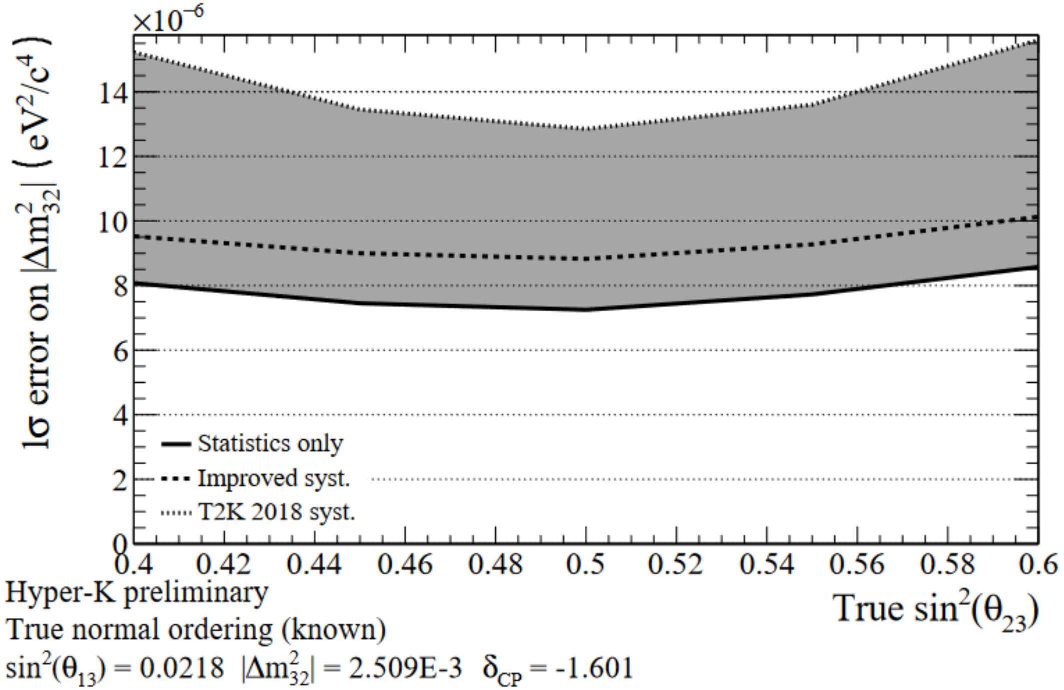
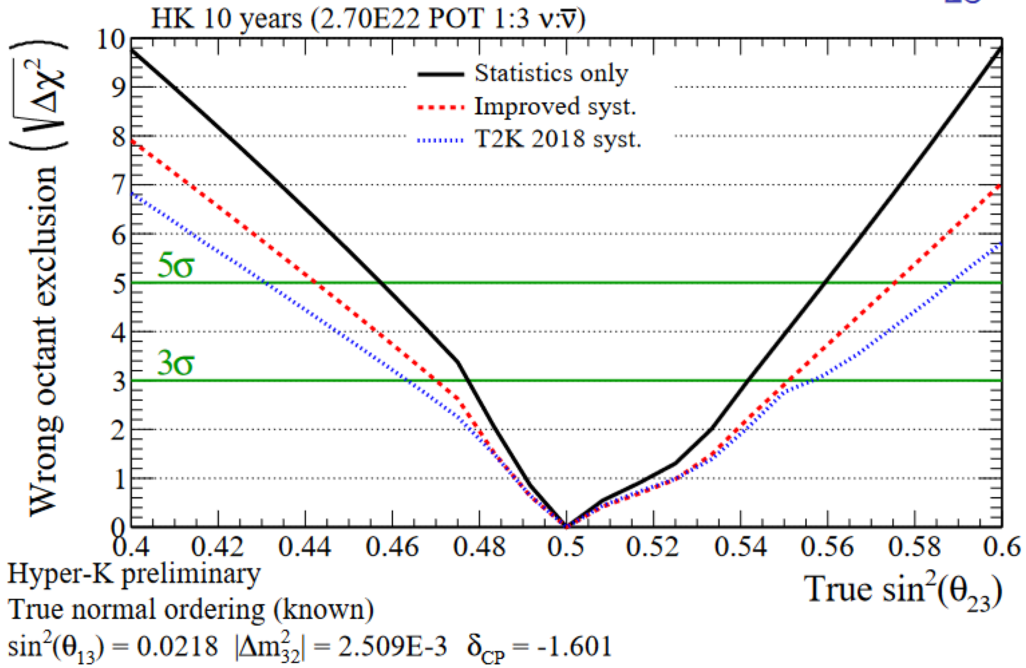
HK precision measurements

Megan Friend, Fri PM

Measurement of Δm^2_{32}



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

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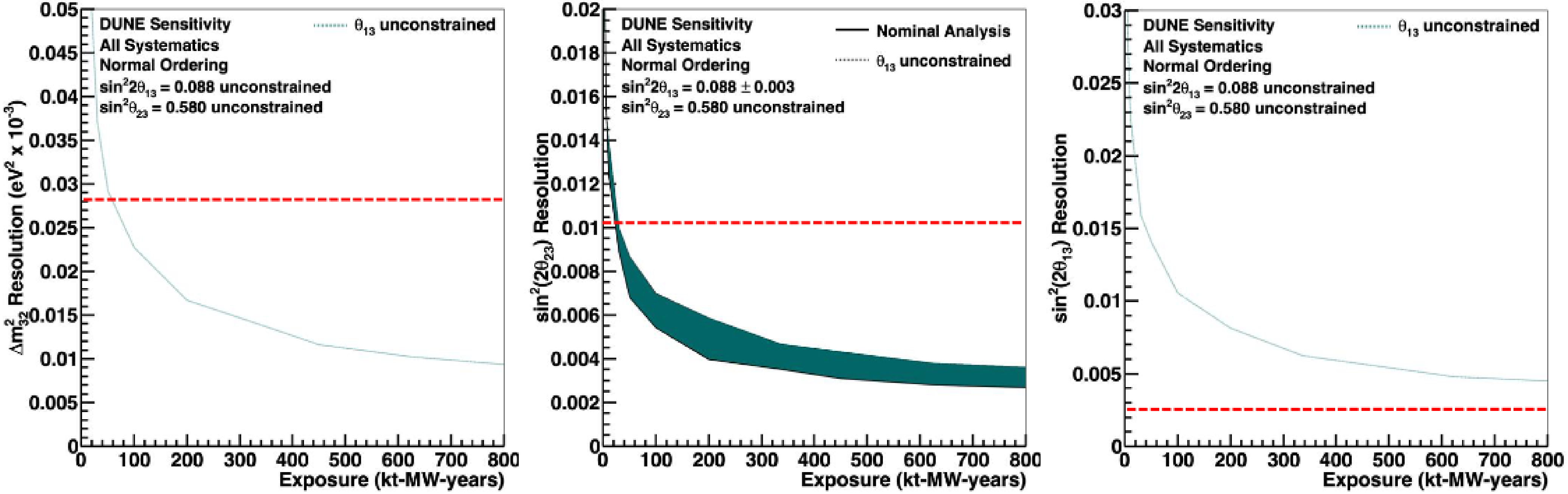
DUNE precision measurements

Callum Wilkinson, Fri PM



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

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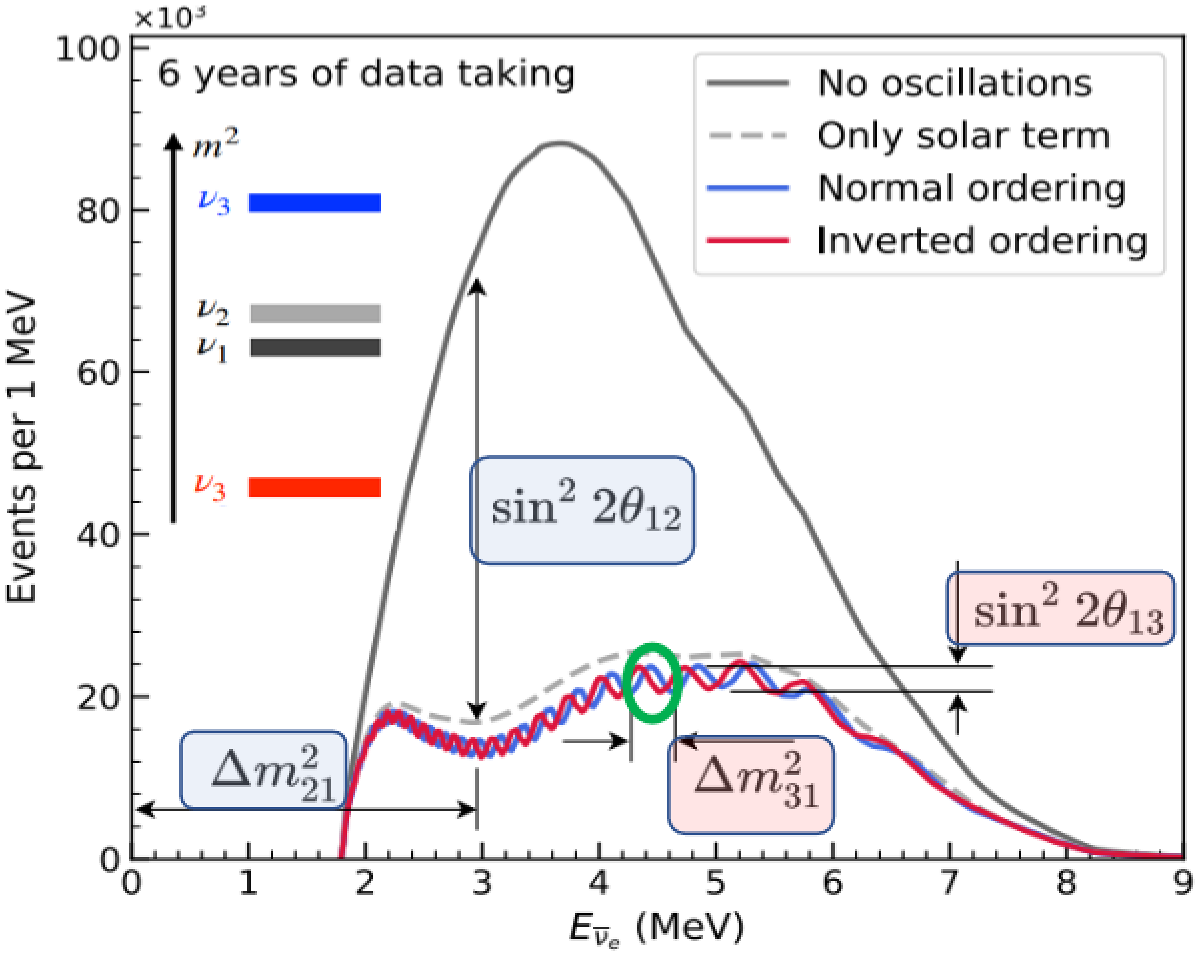
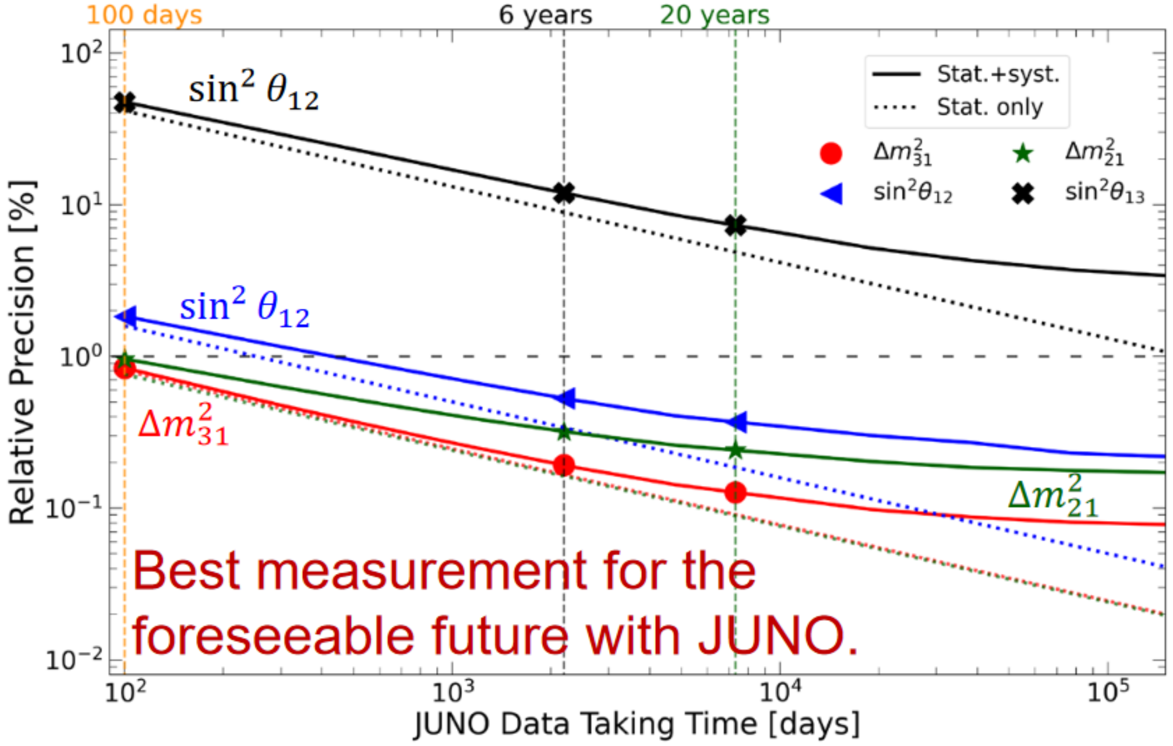
JUNO precision measurements

Jinnan Zhang, Fri PM



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

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ 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%)



Best measurement for the foreseeable future with JUNO.

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

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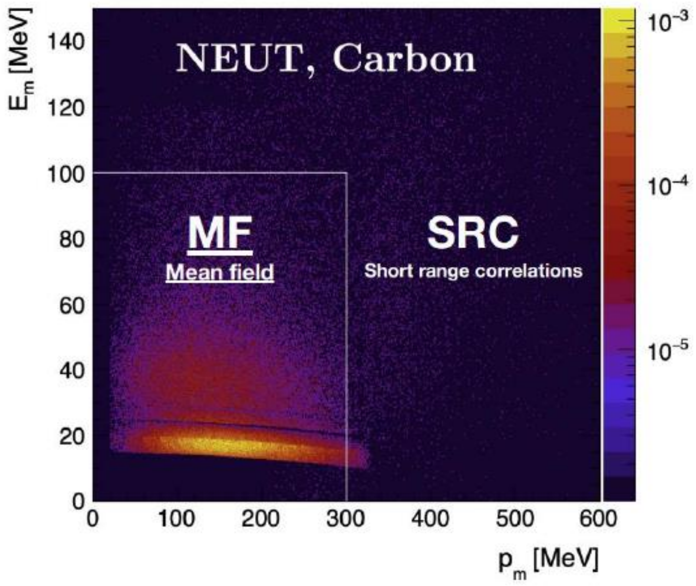
T2K Cross-section Updates

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 uncertainites for C(O)
2 SRC normalisation uncertaintes (split for C/O)
Nucleon axial mass
3 Q^2 shape uncertainties*
4 removal energy shift uncertainies (split C/O, p/n)
4 Pauli blocking uncertainies (split C/O, p/n)
2 FSI correction uncertainties (split C/O)
q_3 depedent removal energy uncertainty

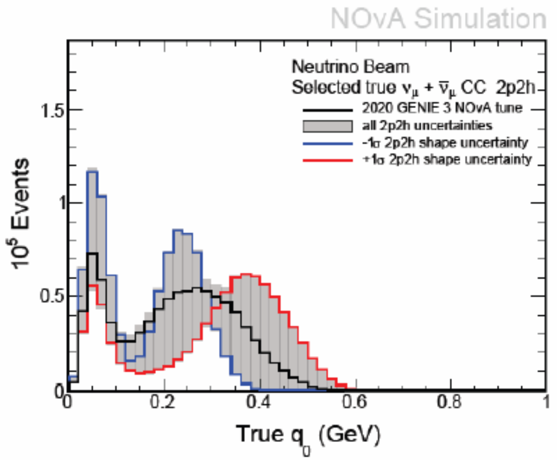
Stephen Dolan, Tues PM

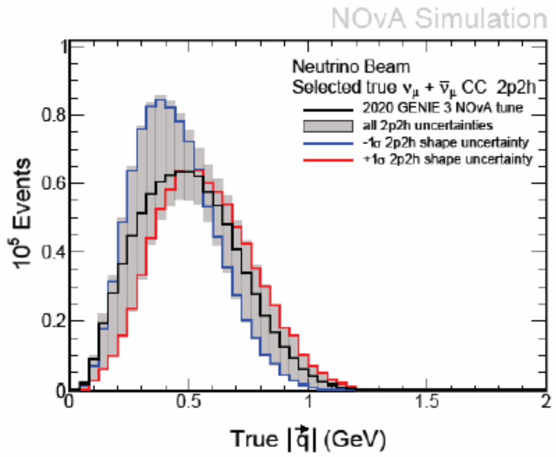
NOvA Cross-section Ideas

Kirk Bays, 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 conjuction** 'up' or 'down' in hadronic energy, **then re-fit**. These are new +/- 1σ uncertainties.





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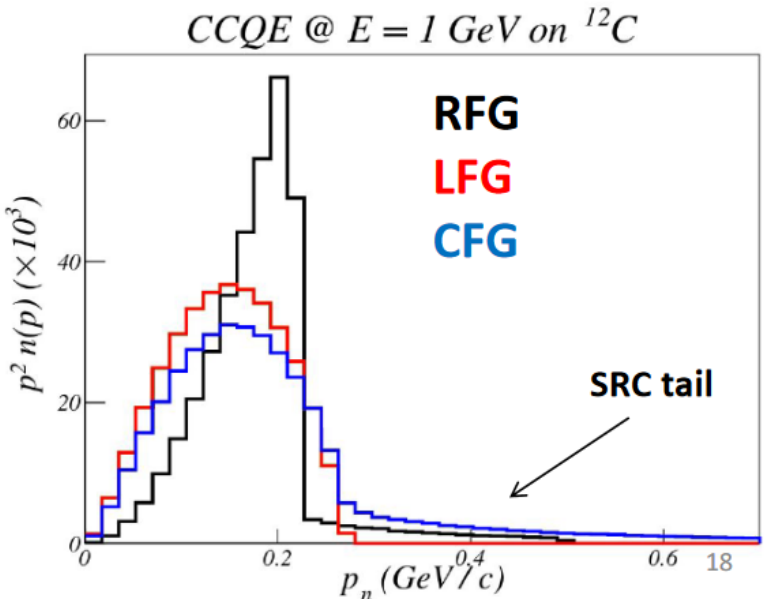

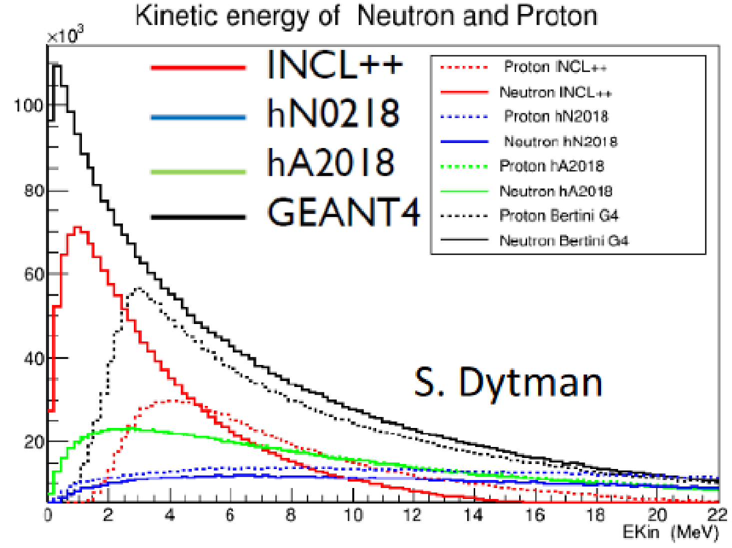

1 GeV on Argon

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Tau neutrinos @ INO

Thiru Senthil, Fri PM

Presence of CC tau events over NC background

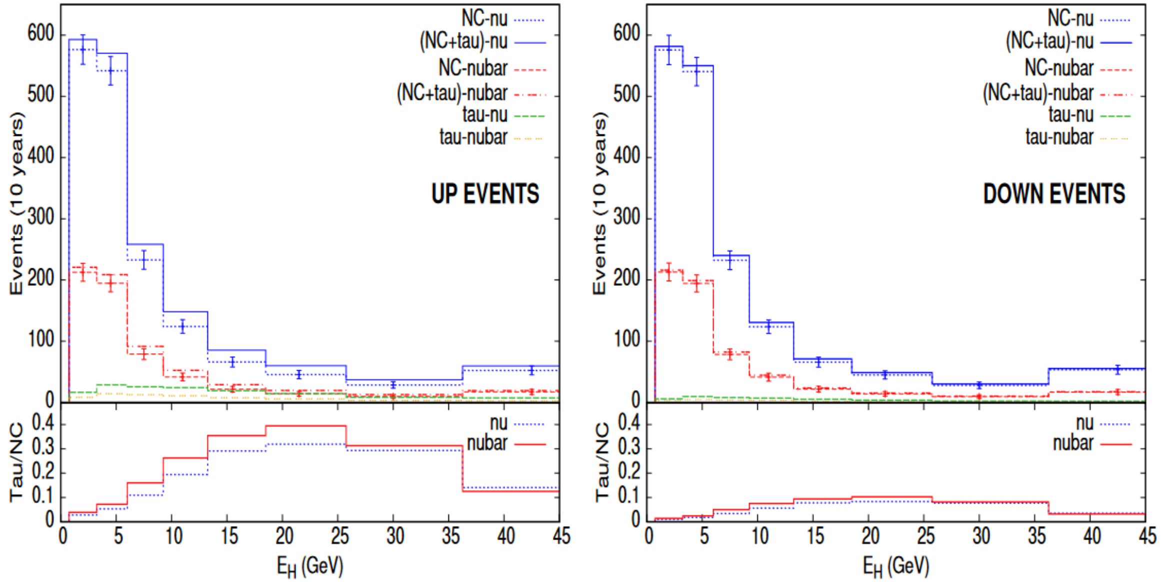
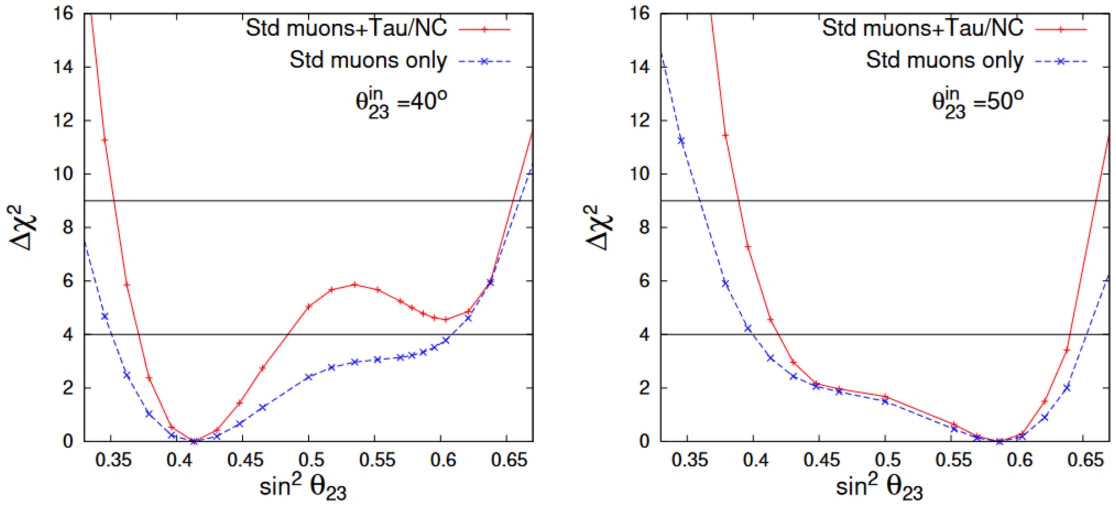


Figure: NC and CC-tau events in reconstructed E_{hadron} bins and the ratio of the CC tau events to the NC events.

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



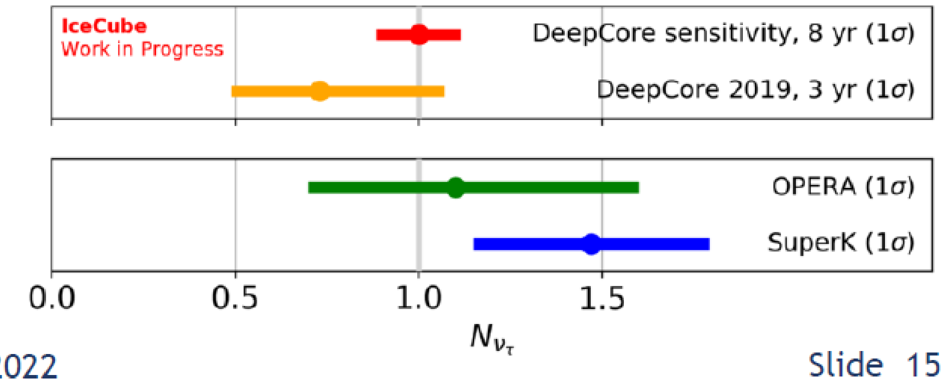
Tau neutrinos

- Tau Neutrino Appearance
  - DeepCore is above the tau lepton production threshold for $\boldsymbol{\nu_\tau}$ CC
  - $\boldsymbol{\nu_\tau}$ appearance analysis fits a separate normalization $\mathbf{N}_{\boldsymbol{\nu_\tau}}$
  - Expect a world leading measurement of the tau neutrino normalization

Kayla, Mon PM

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$|U_{e3}|^2 + |U_{\mu 3}|^2 + |U_{\tau 3}|^2 = 1$$



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

Barbara, Tues PM

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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

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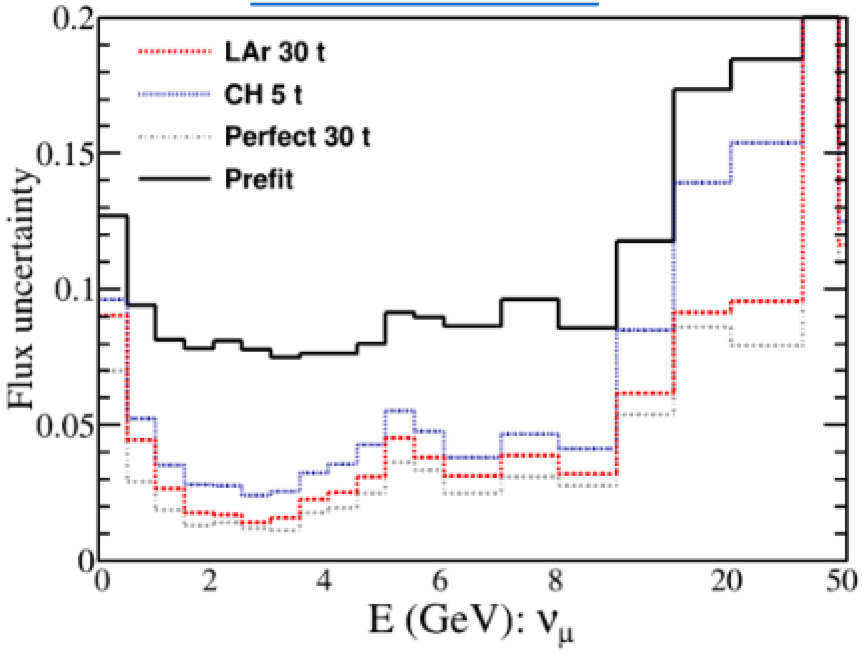
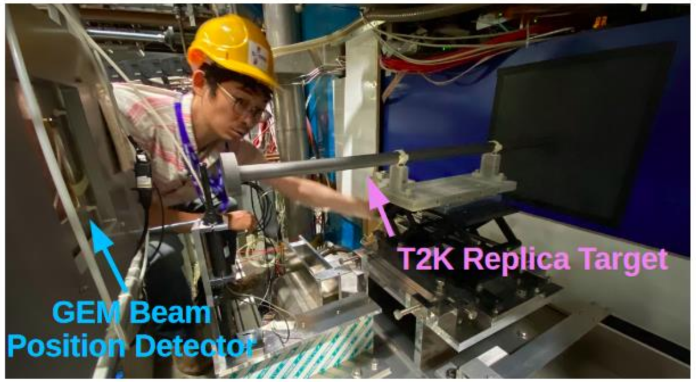
Neutrino flux matters

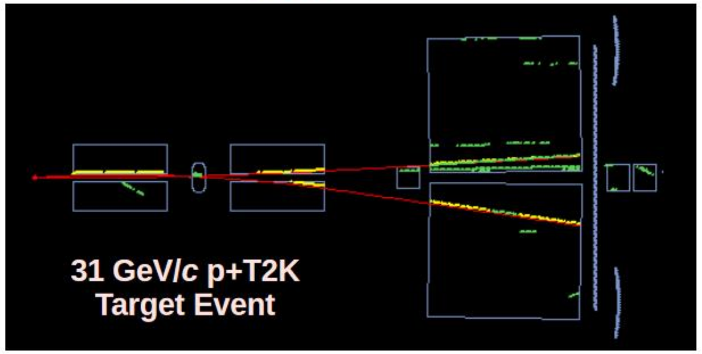
- Flux uncertainties continue to be reduced

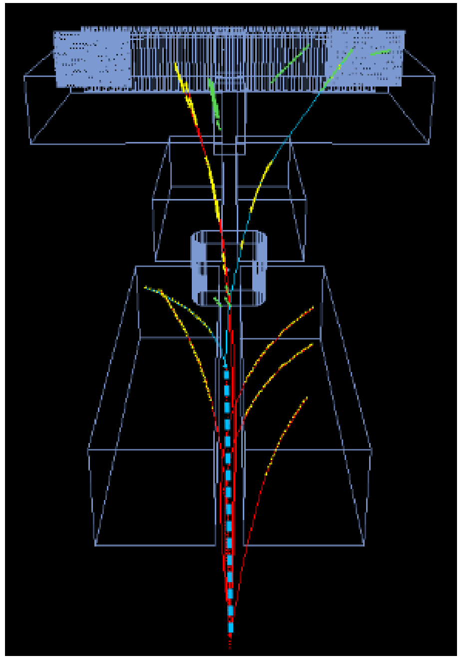
Brant Rumberger, Fri PM

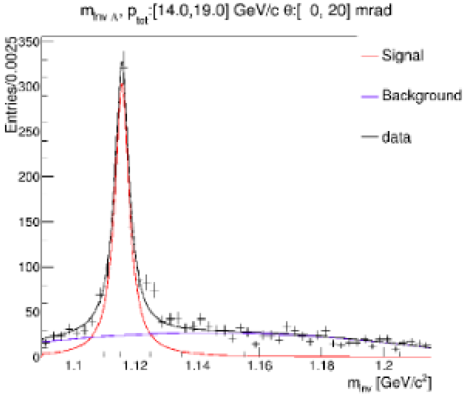
Ref: arXiv:1910:10996











Zoya Vallari, Thu AM

Neutrino flux matters

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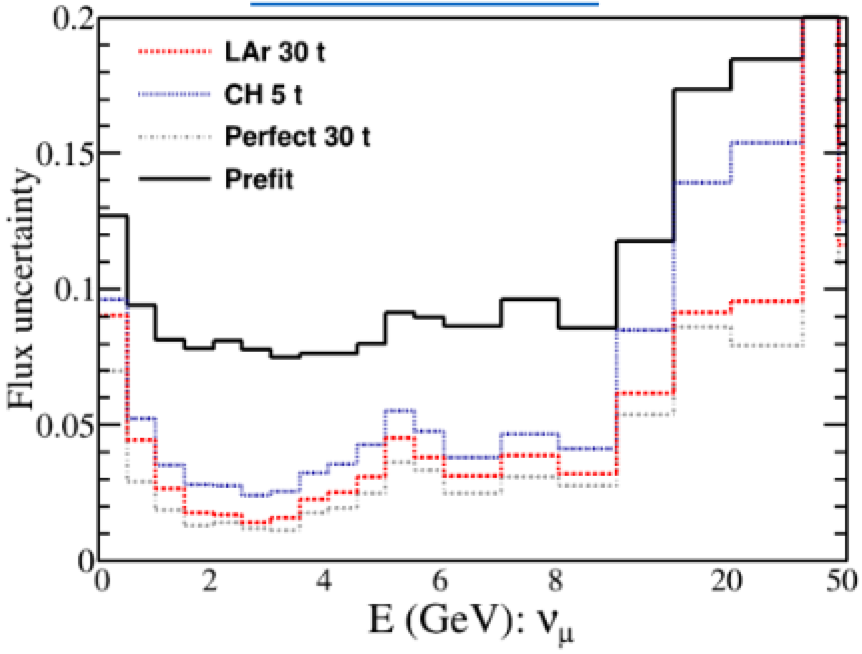
Callum Wilkinson, Thu AM

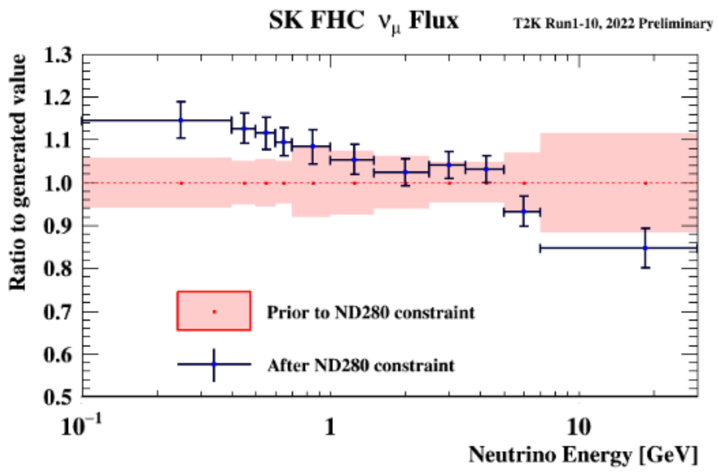
- Flux uncertainties continue to be reduced
- Signs of tension when compared to ND data?

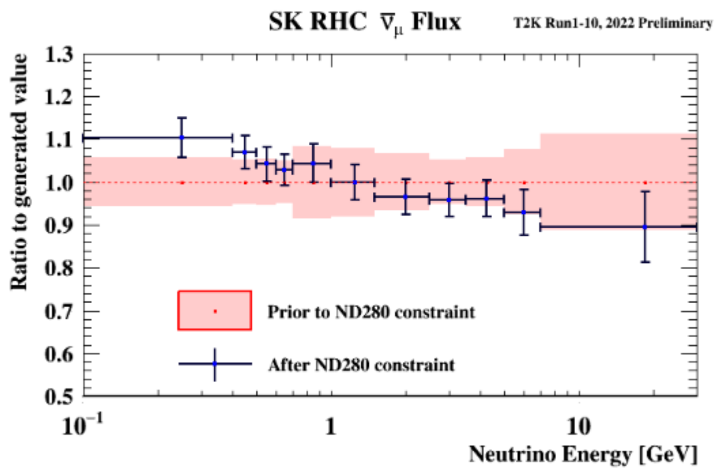
Ref: arXiv:1910:10996



Zoya Vallari, Thu AM

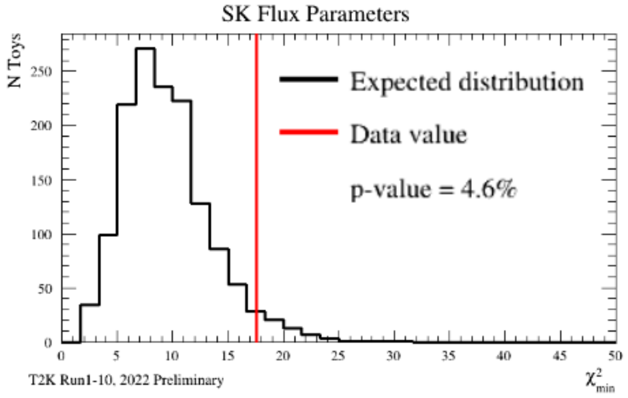
Flux constraint





- 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*



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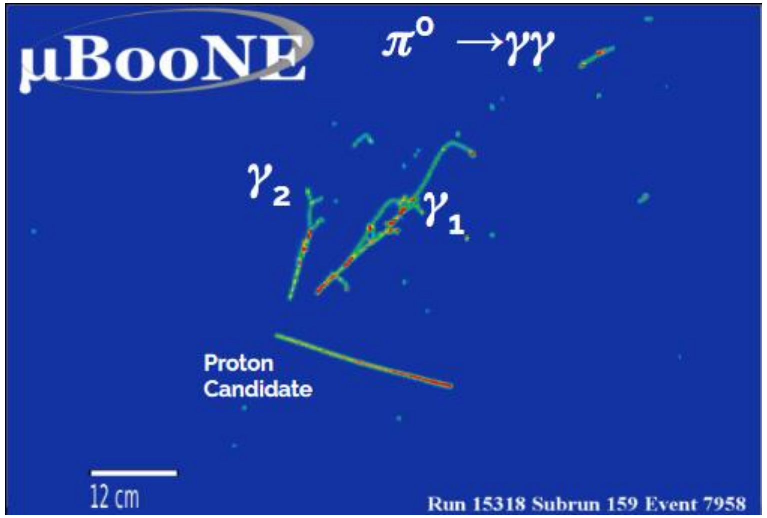
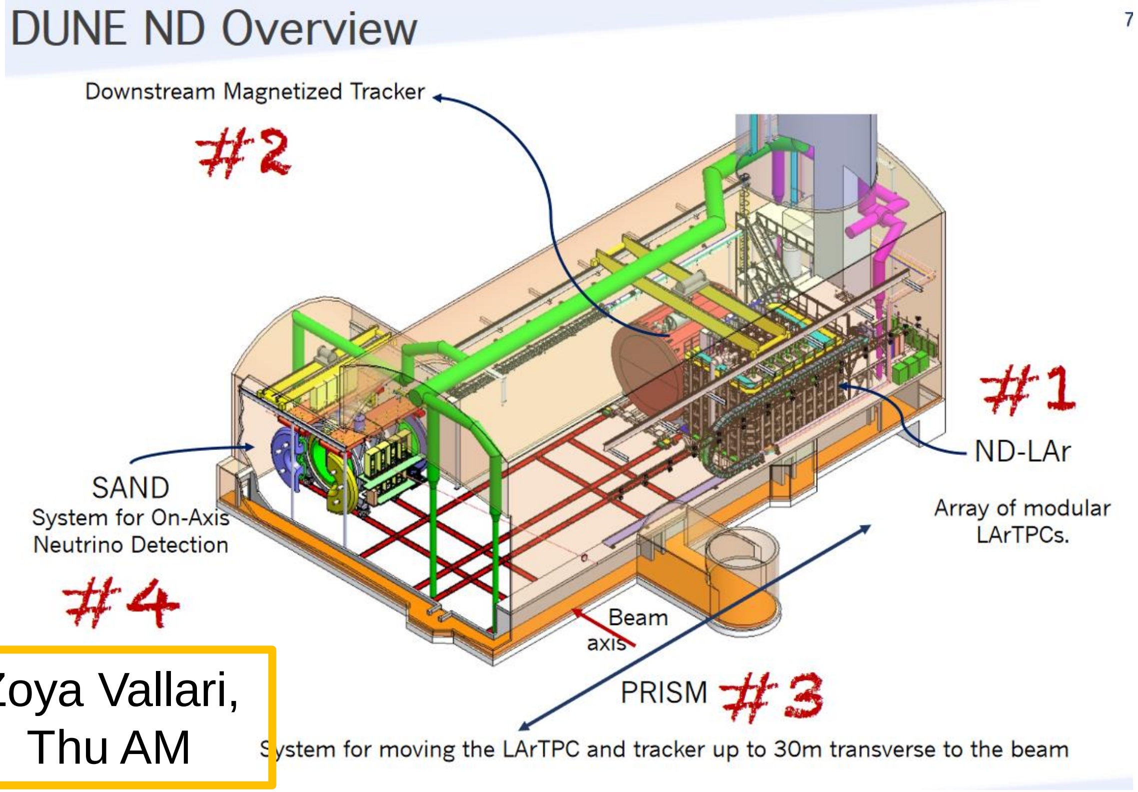
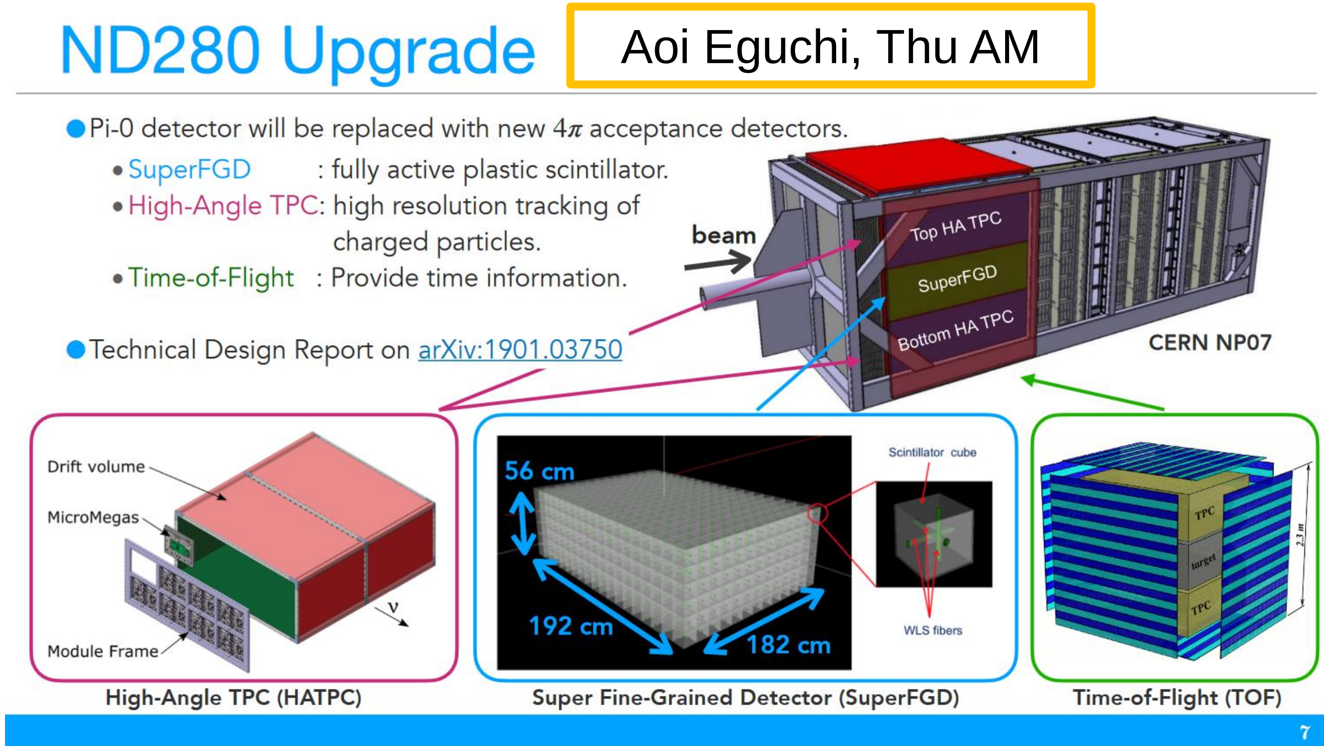
High precision with new detectors

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





Zoya Vallari, Thu AM



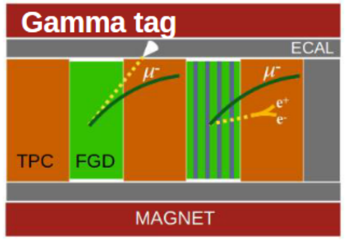
Aoi Eguchi, Thu AM

Higher precision through new samples

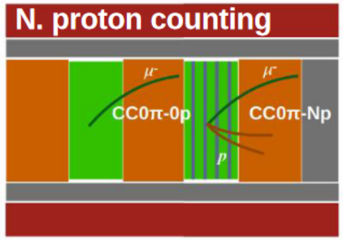
- Near detector data samples being split into more complex final states
- More sensitivity to individual neutrino interaction modes

Callum Wilkinson, Thu AM

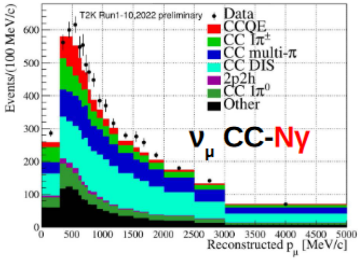
New(!) ν-mode samples ($\bar{\nu}$-mode unchanged)



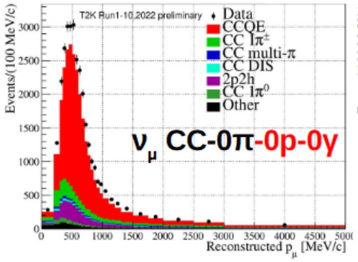
- Improves sample purities
- New (mostly DIS + multi-π) sample with FS π^0

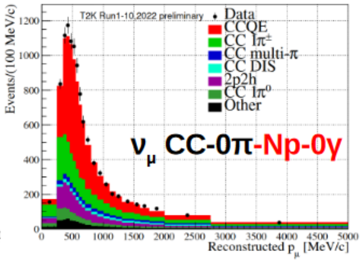


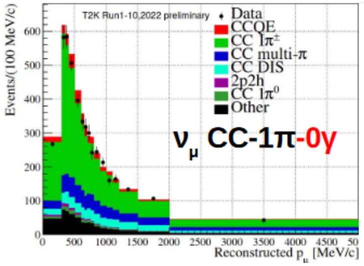
- Subdivide CC0π sample
- Constrain 2p2h + nuclear models

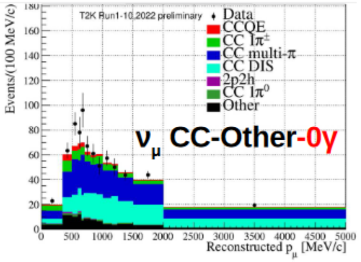


(FGD1 shown here)

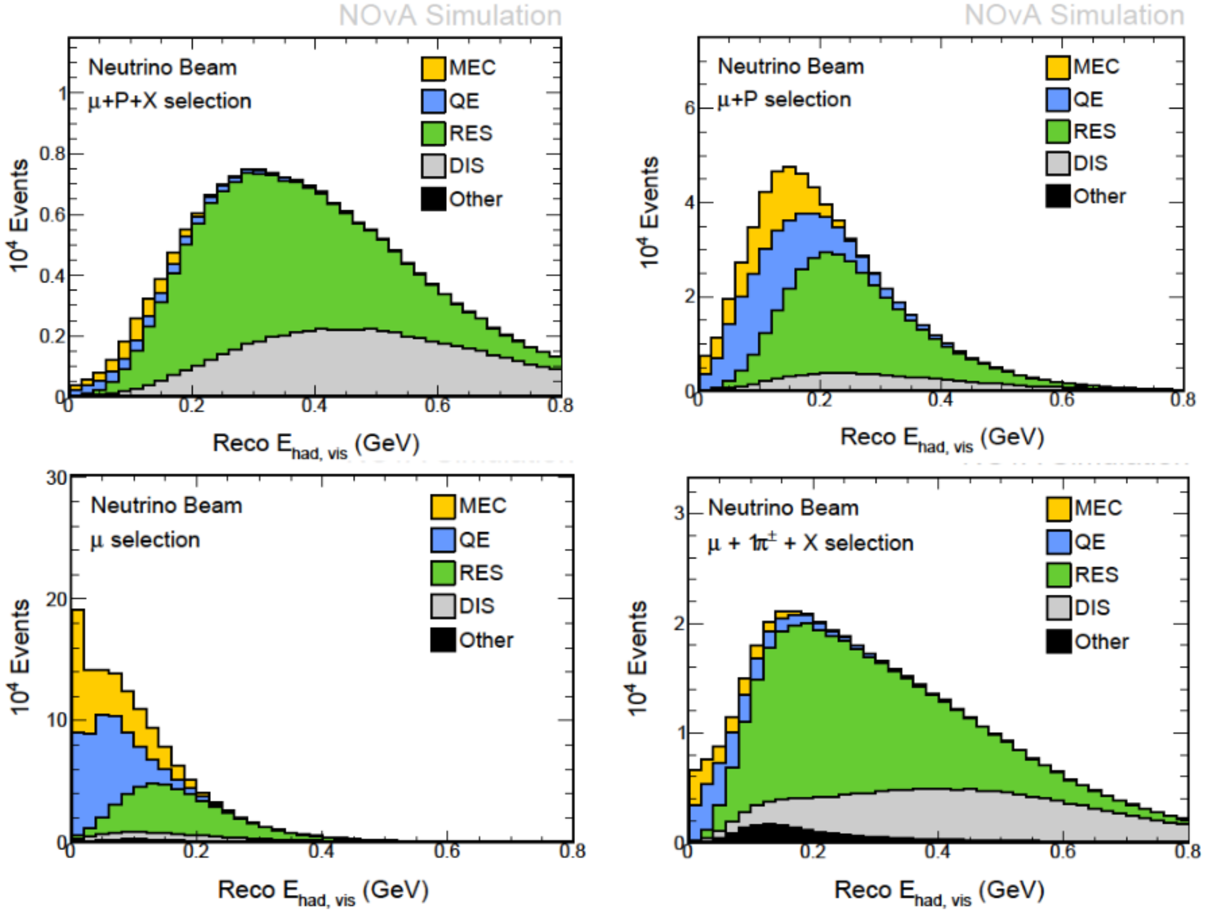








Kirk Bays, Tues PM



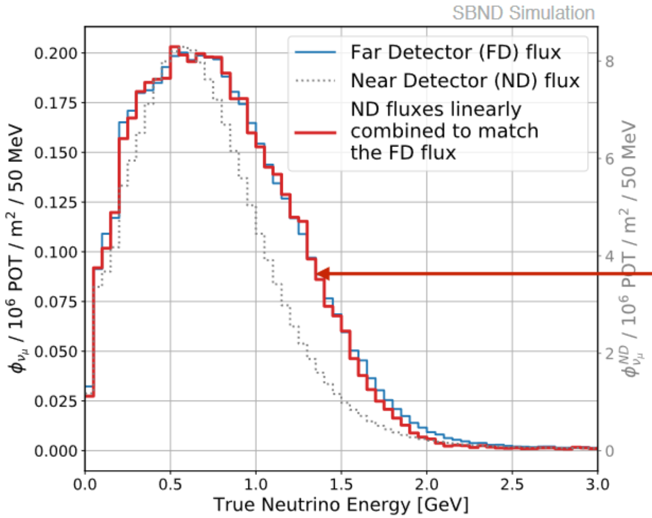
PRISMs everywhere

SBND-PRISM - Sterile Neutrino Oscillations - 2

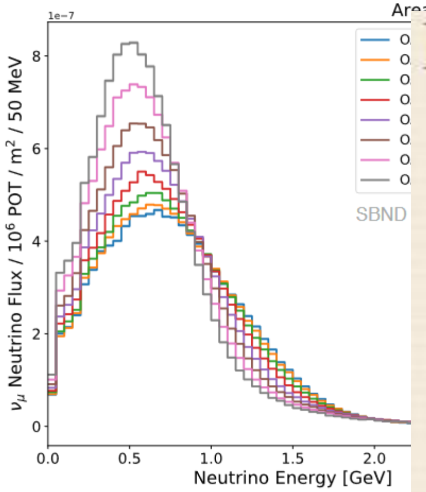
$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

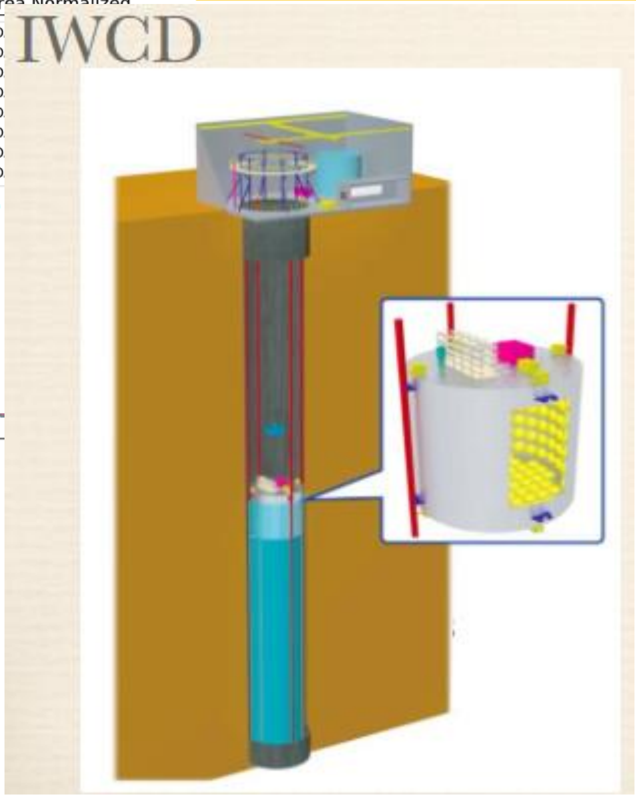
Can we make the two fluxes similar?

Yes!

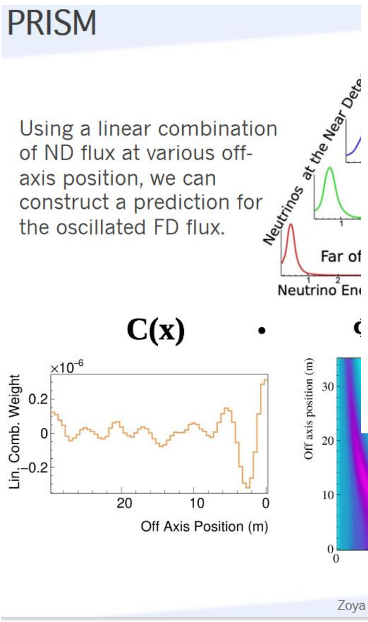


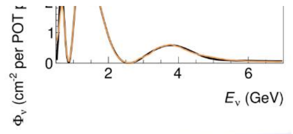
Fit a **linear combination of the ND** fluxes to reproduce the FD flux at the ND





Michael Smy, Mon PM





Marco Del Tutto, Thu AM

Zoya Vallari, Thu AM

~~PRISMs everywhere~~ → Neutrino flux really matters!

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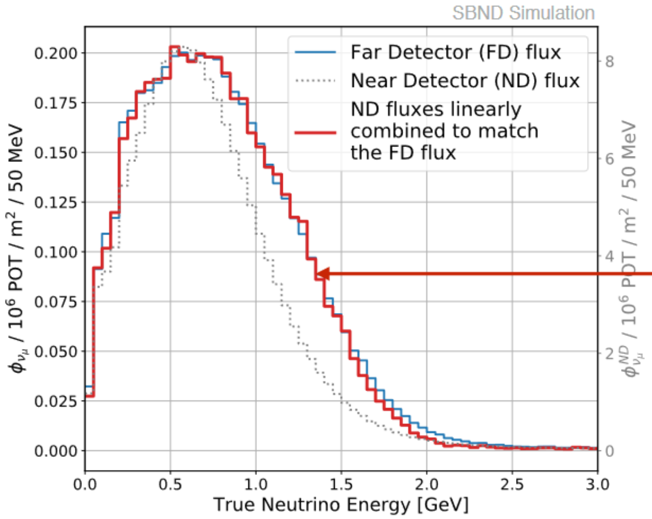
SBND-PRISM - Sterile Neutrino Oscillations - 2

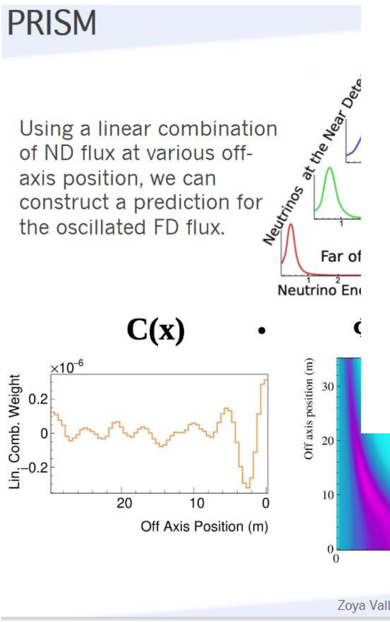
$$\frac{N_{FD}}{N_{ND}} = \frac{\propto \phi_{FD} \otimes \sigma \otimes P_{osc}}{\propto \phi_{ND} \otimes \sigma}$$

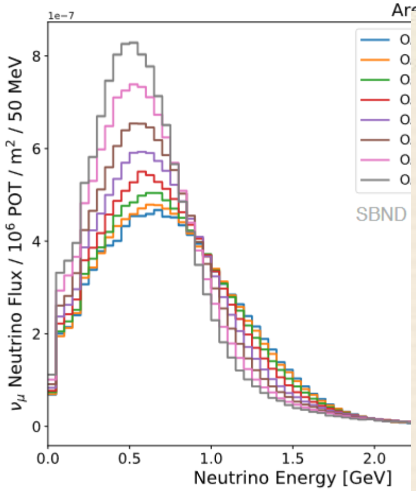
→ Can we make the two fluxes similar?

Yes!

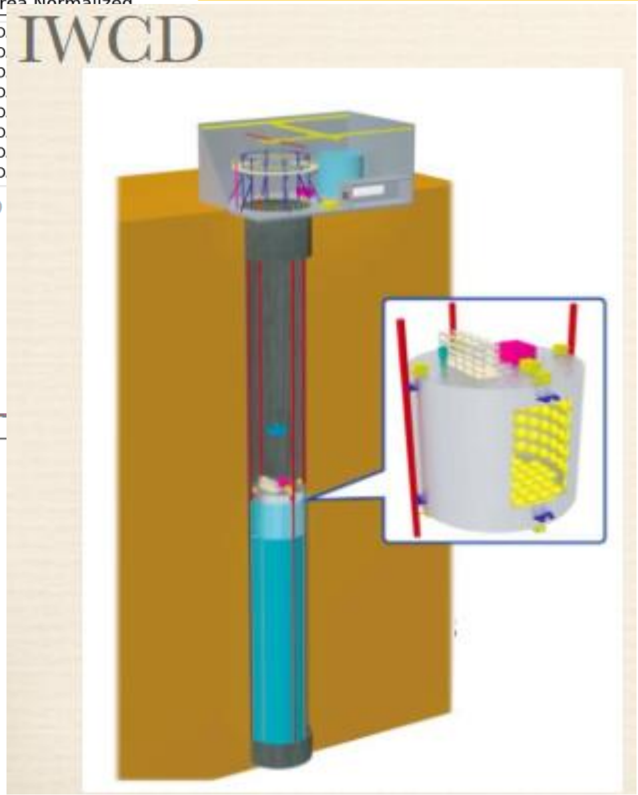


Fit a **linear combination of the ND** fluxes to reproduce the FD flux at the ND





Michael Smy, Mon PM



Marco Del Tutto, Thu AM

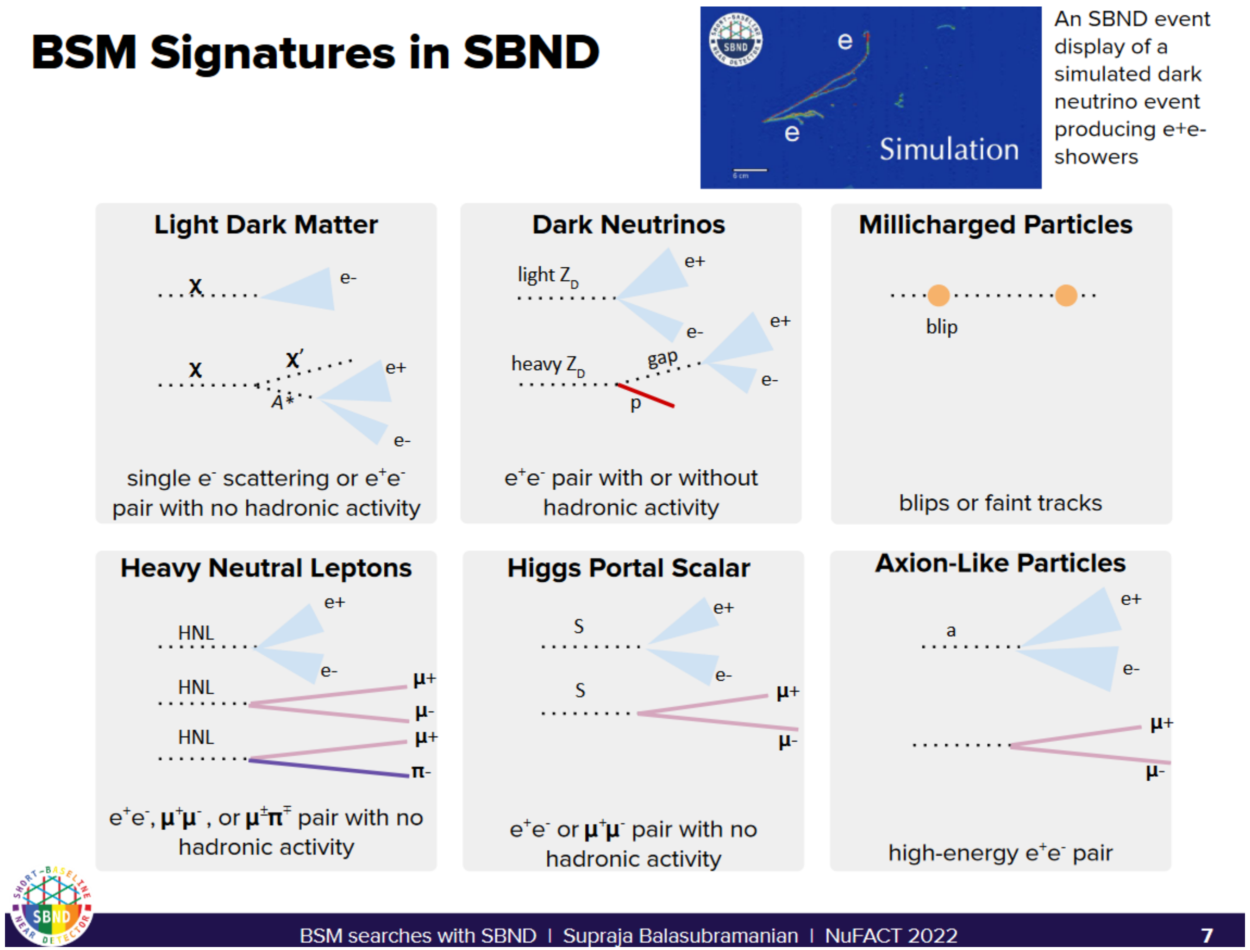
Zoya Vallari, Thu AM

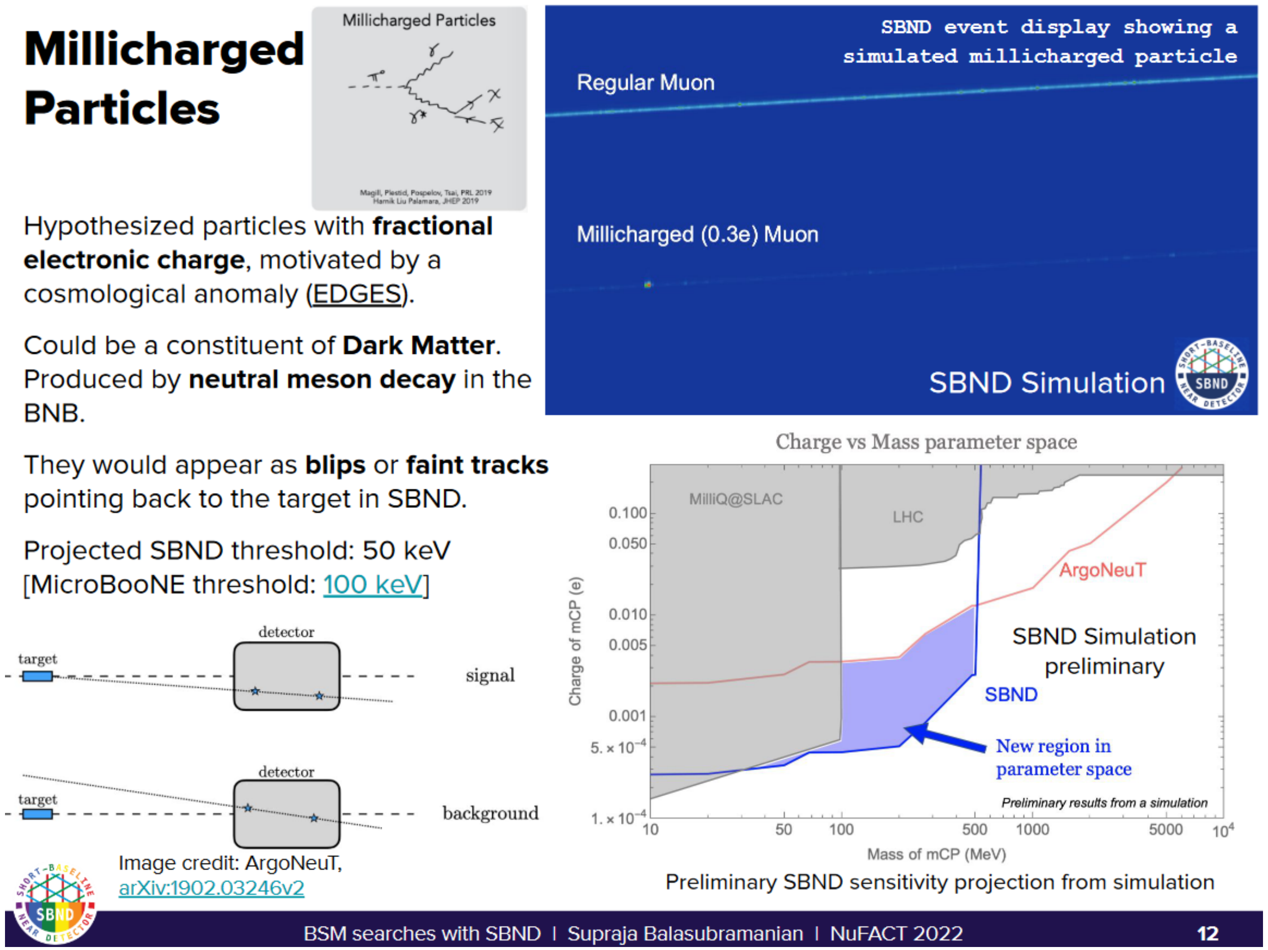
Near detectors takeaway

- 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 @ SBND



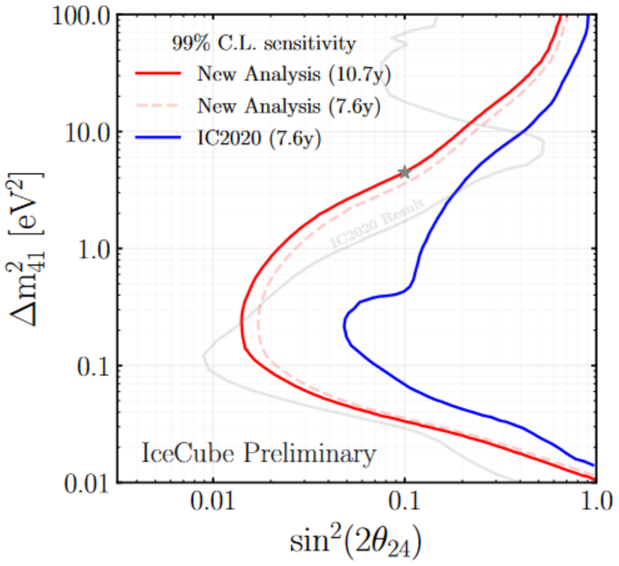


Supraja Balasubramanian, Tue PM

Sterile neutrinos at IceCube and NOvA

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.



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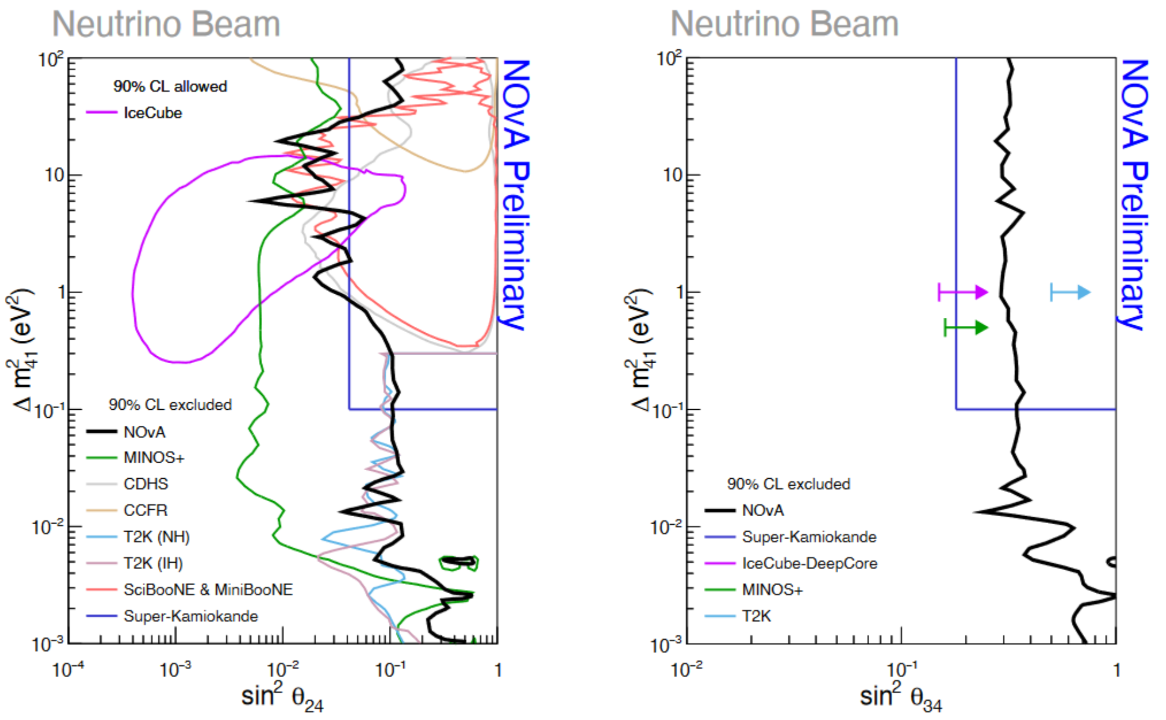
90% CL contours



BSM neutrino oscillations at NOvA – V Hewes – NuFact 2022 14

Alfonso Garcia, Tue PM

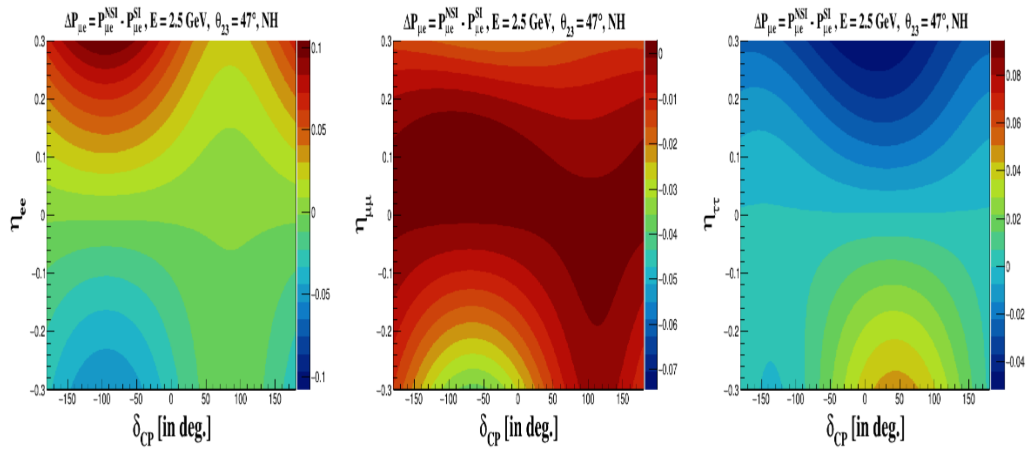
V Hewes, Tue PM

BSM physics effect on PMNS

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

Abinash M., Thu PM

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



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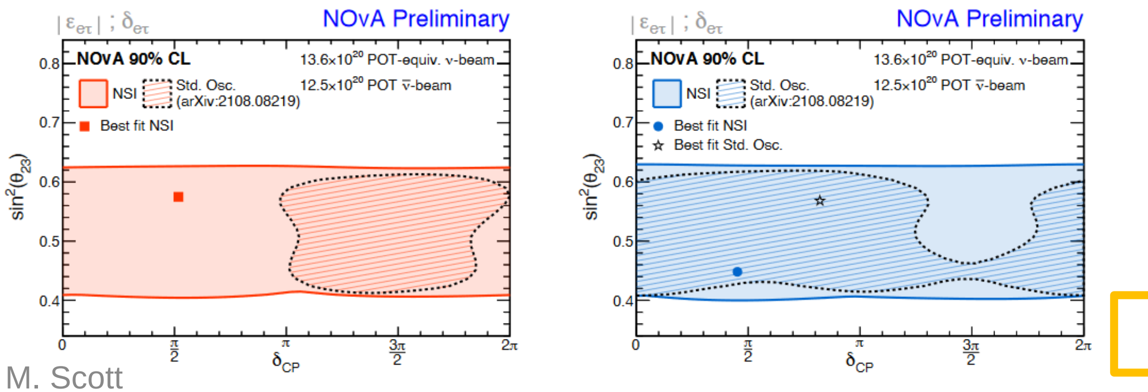
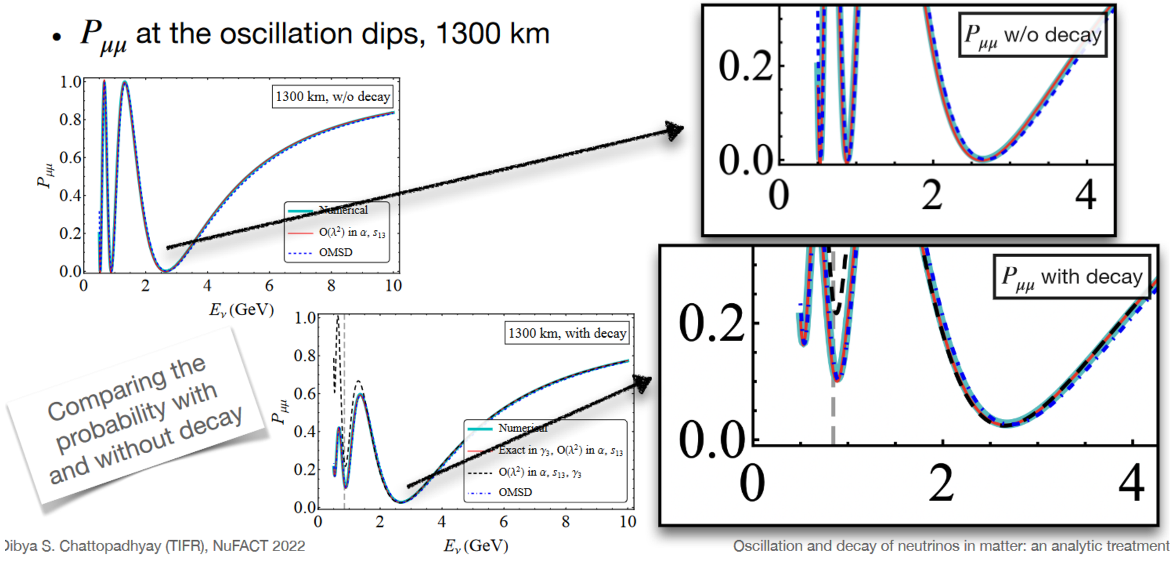
NSI $\epsilon_{e\tau}$ 90% CL limits



Increase of probability due to decay!

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



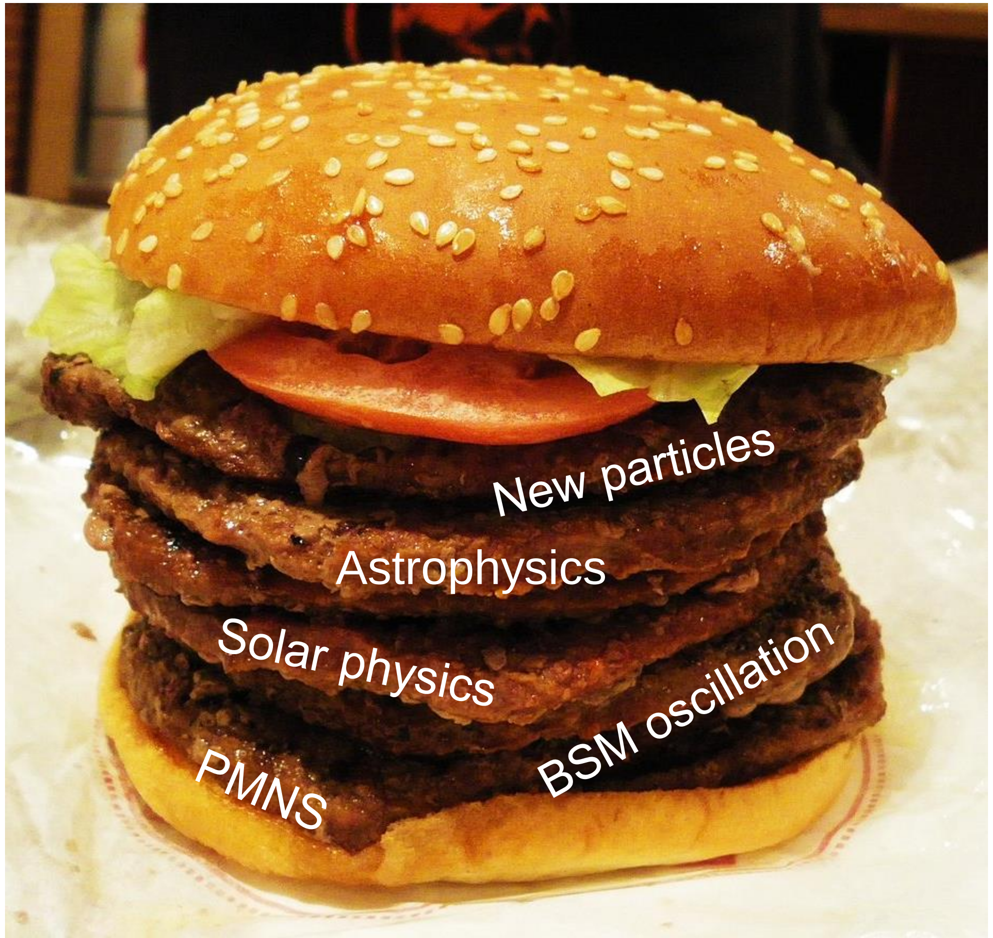
Dibya C., Thu PM

- 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



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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!

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