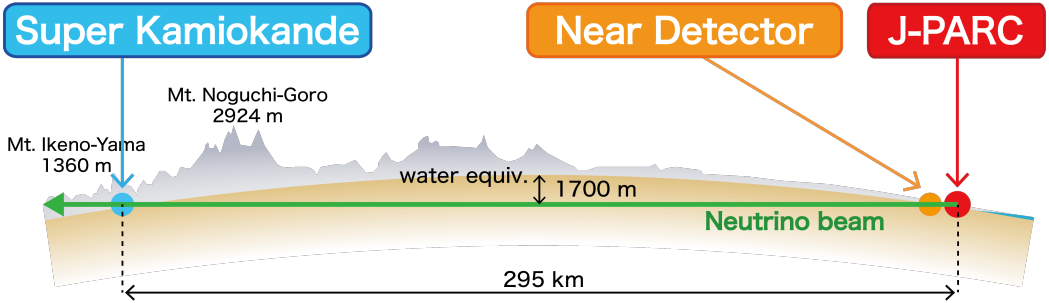
T2K: Current and Future Neutrino Cross Section Measurements

Liam O'Sullivan, for the T2K collaboration
he/him

Lepton Interactions with Nucleons and Nuclei '23, Elba

7th Sep. 2023

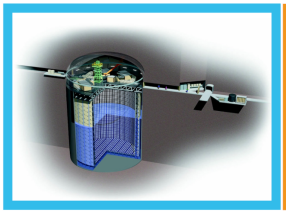
The T2K Experiment

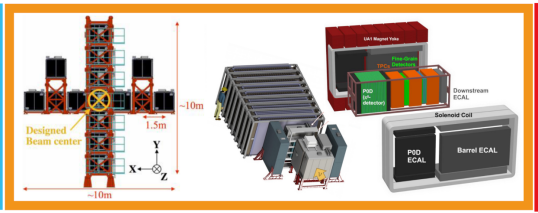


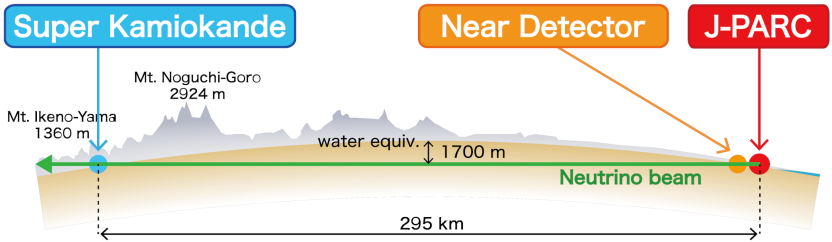
- ν oscillation experiment
- Generate ν_μ beam, measure ν_e component
  - Directly after ν production
  - After 295 km
- Beam 2.5° off-axis

images: t2k-experiment.org

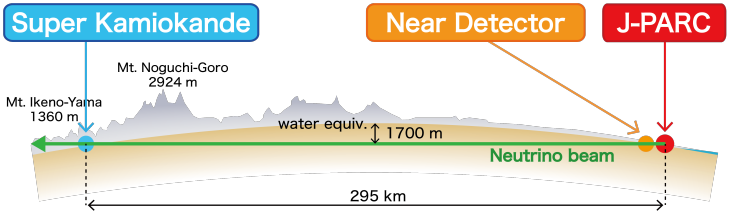
The T2K Experiment

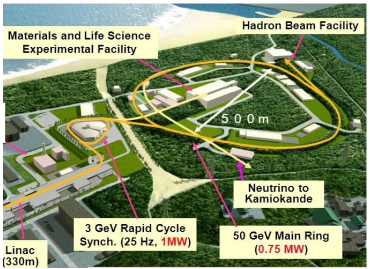


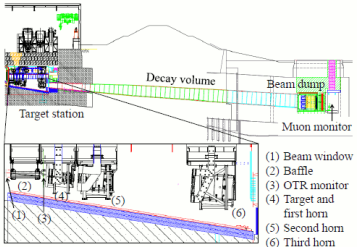


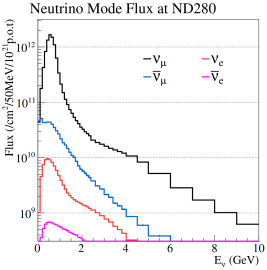


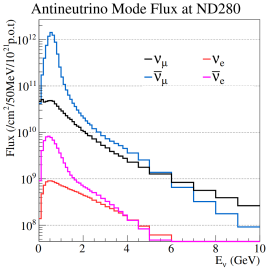
The T2K Experiment











INGRID: On-Axis Detector

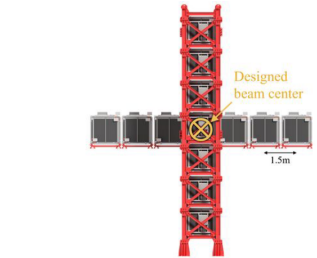
Standard Modules($\times$16)

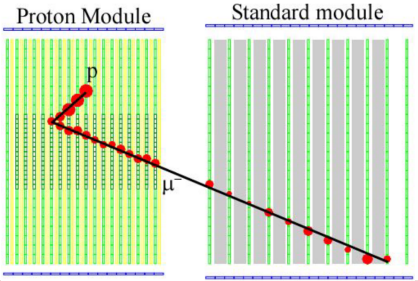
- Alternative iron plates and scintillator bars
- Muon range detector

Proton Module ($\times$1)

- Fully active scintillator
- Lower target mass, better tracking

Monitors beam centre, profile, overall CC rate





The ND280 Detector

Fine Grained Detectors (FGDs)

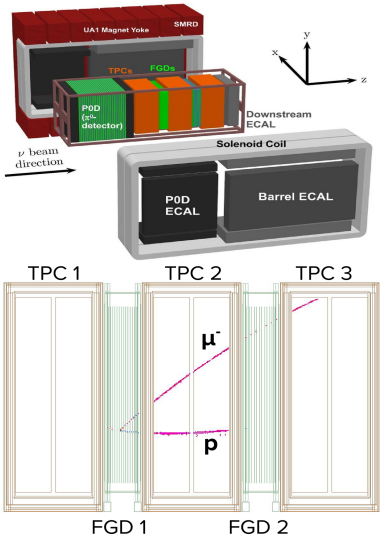
- Active plastic scintillator detector
- Bar direction alternates by layer
- FGD2 contains inactive water layers

Time Projection Chambers (TPCs)

- Low pressure Argon
- Accurate momentum, dE/dx measurement

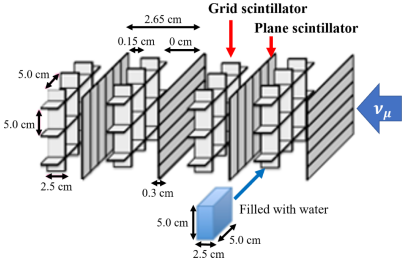
Also

- Enclosed by Elec. Calorimeters
- Magnetised detector
- PØD - Dedicated π^0 detector



The WAGASCI and BabyMIND Detectors

1.5° Off-Axis



WAGASCI:

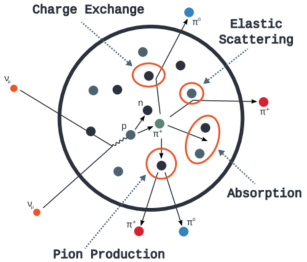
- Active plastic scintillator detector
- Substantial water target ($\sim 80\%$)

BabyMIND:

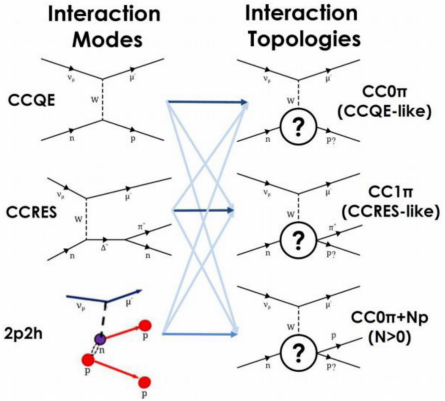
- Magnetised iron and scintillator
- Reconstruct μ charge and range

Measuring Neutrino Interactions

- Define signal by 'topology' (final state)
- Generally split by
  - ν flavour
  - interaction mode ($W^{\pm}/Z^0$)
  - π, proton multiplicity



T. Golan, What is inside MC generators and why it is wrong. NuSTEC 2015



Cross-Section Measurement Strategy

What we measure

- **Select** a **number of events** in a **reconstructed quantity** (e.g. momentum)

What we want

- **True number** of **signal events** in a **true quantity**

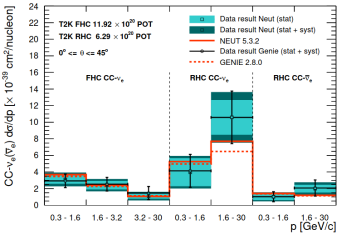
Techniques we use

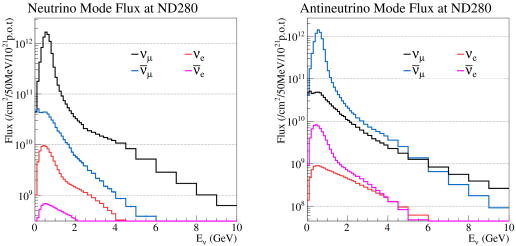
- **Efficiency correction:** account for the events missed by our detector
- **Background estimation:** account for the background rate and distribution
- **Unfolding:** Transform from reconstructed to true quantities

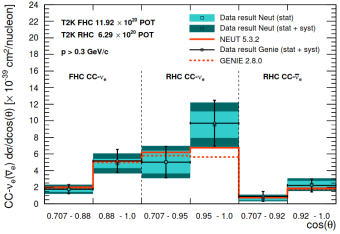
Detailed talk on this analysis method in T2K

ν_e and $\bar{\nu}_e$ CC

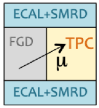
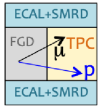
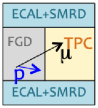
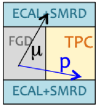
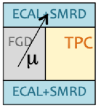
- ν_μ and $\bar{\nu}_\mu$ beams have irreducible ν_e component
- Large uncertainty in oscillation measurements
- Challenging, high-background analysis







ν_μ CC 0π on C and O

	I – μTPC	II – μTPC+pTPC	III – μTPC+pFGD	IV – μFGD+pTPC	V – μFGD
Signal sample					
Description	Single μ candidate tracked in TPC	Both μ and *p* candiates are tracked in the TPC	μ tracked in the TPC and : • 1*p* tracked in the FGD • or multi *p*	μ tracked in FGD/Ecal and: • 1 *p* tracked in the TPC • or 1 *p* tracked in the TPC + multi *p* • or multi *p*	μ_{FGD} only reconstructed in the FGD/ Ecal

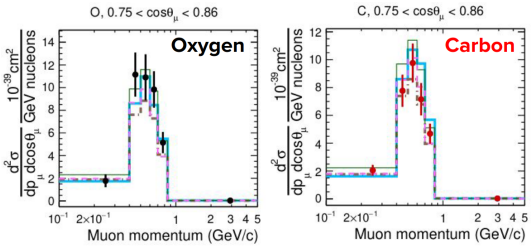
- Expanded acceptance (high θ_μ, low p_μ)
- Selection applied to both FGDs; H_2O component
- Double differential; measure p_μ and $\cos\theta_\mu$

Article in PTEP Vol. (2021) 4

- Update to previous result
  - improved models and techniques
  - $\sim 2\times$ POT with Run 8
  - O/C cross-section ratio

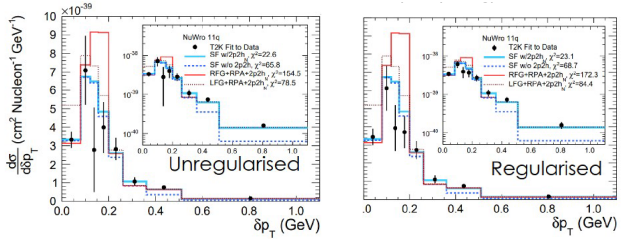
ν_μ CC 0π on C and O

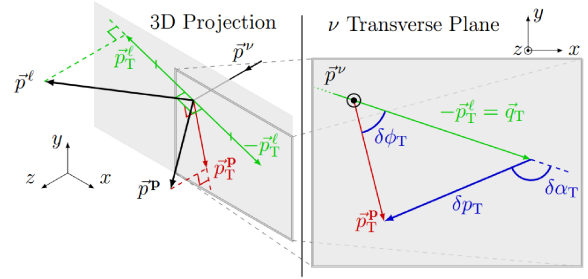
- Double differential (p_μ, $\cos\theta_\mu$) measurement
  - Good granularity in phase-space
- O/C cross-section ratio is useful
  - Flux errors cancel
- Preference for simpler Fermi gas nuclear state models



GENIE v3 SuSa v2 (103.5)
NuWro SF (114.5)
NEUT LFG (44.8)
GiBUU (112.7)

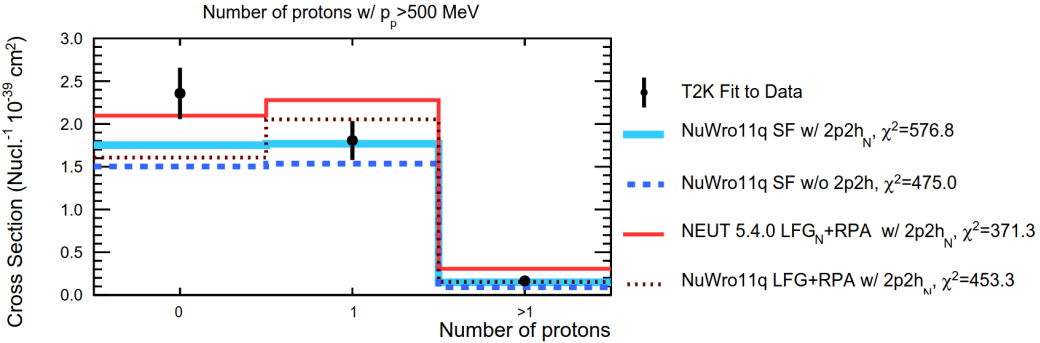
ν_μ CC 0π Transverse Kinematic Imbalance





- Older result
  - Phys. Rev. Lett. (2018) 022504
- Different variables to previous
  - Chosen to challenge theory
- Sensitive to
  - initial nuclear state
  - final-state interactions

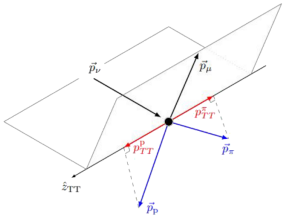
ν_μ CC 0π Transverse Kinematic Imbalance

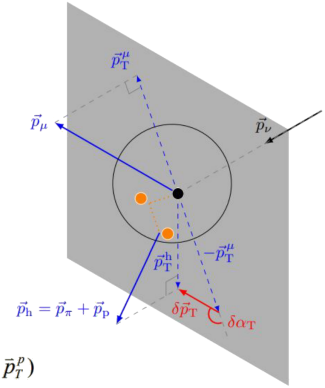


- Inferred number of protons above threshold
- Helps disentangle FSI and 2p2h
- Motivates improvement to proton kinematic prediction in models

ν_μ CC $1\pi^+$ Transverse Kinematic Imbalance

- Signal: $\mu^- + \pi^+ + p$
- Variables measure kinematic imbalances between final state μ, π, and p
- As before, sensitive to
  - initial nuclear state
  - final-state interactions





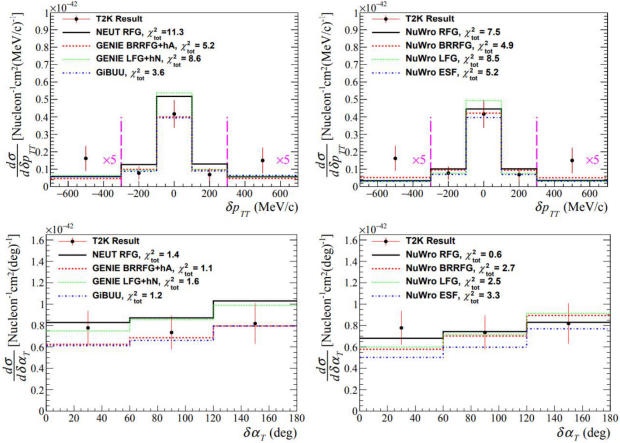
$$\delta\alpha_T = \cos^{-1}\frac{-\vec{p}_T^{\,\mu}\cdot\delta\vec{p}_T}{p_T^{\mu}\delta p_T}$$

$$\delta p_{TT} = p_{TT}^{\pi} + p_{TT}^{\mathrm{p}} = \frac{\vec{p}^{\,\nu}\times\vec{p}_T^{\,\mu}}{\left|\vec{p}^{\,\nu}\times\vec{p}_T^{\,\mu}\right|}\cdot(\vec{p}_T^{\,\pi} + \vec{p}_T^{\,p})$$

Article in PRD

ν_μ CC $1\pi^+$ Transverse Kinematic Imbalance

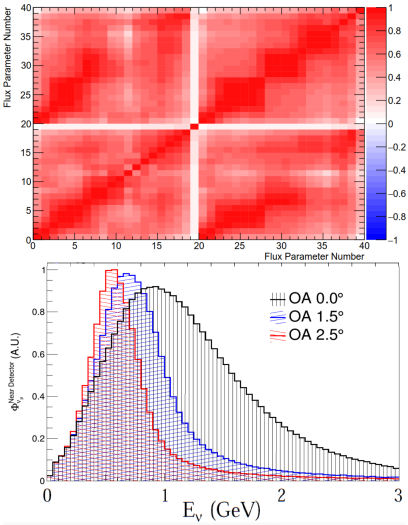
- Simpler Fermi-gas models show tension
- δp_{TT} quite sensitive to FSI
- No model fit everything well
  - Partially by design
  - Models not constructed for this
- Result is statistically limited



ν_μ CC 0π Joint On/Off-Axis

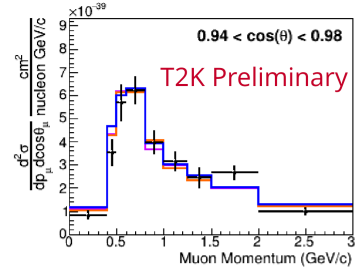
- Simultaneous measurement with two fluxes
  - Fluxes differ significantly
  - Errors correlate strongly
  - Constraints affect both detectors
- Resulting cross-sections correlated
- First such analysis on T2K
- Potential to extend joints analysis to
  - Multiple channels/signals
  - More detectors
  - More correlated parameters

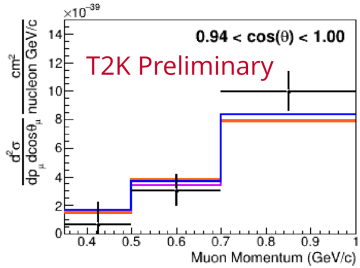
Preprint on arXiv: 2303.14228



ν_μ CC 0π Joint On/Off-Axis

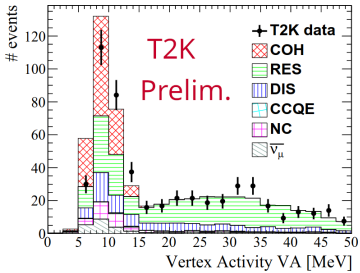
- Can now present two results together
  - Flux errors reduced
  - All bins correlated
  - Data is more powerful
- Not all smooth sailing
  - Conceptually very straightforward
  - Much more work
  - Fit validation much more involved

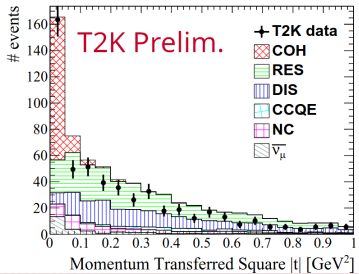




ν_μ and $\bar{\nu}_\mu$ CC Coherent

- Specific channel measurement
  - Scattering off entire nucleus
  - Final state particles: $\mu^\pm$, $\pi^\mp$
  - Nucleus remains in ground state
- Measured for both ν_μ and $\bar{\nu}_\mu$
- 'Vertex Activity' cut
  - No additional hadrionc activity around the vtx.

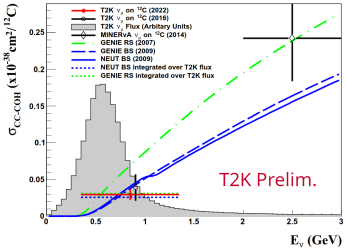


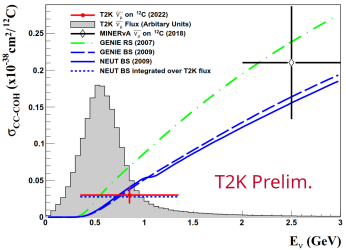


Posted to the arXiv last week! 2308.16606

ν_μ and $\bar{\nu}_\mu$ CC Coherent

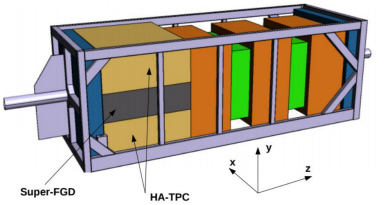
- Specific channel measurement
  - Scattering off entire nucleus
  - Final state particles: $\mu^\pm$, $\pi^\mp$
  - Nucleus remains in ground state
- Analysis has some assumptions baked in
  - Much work to validate sensitivity
  - Many models tested throughout the chain
  - Discussed in detail in paper
- Current data does not exclude models
  - ν_μ and $\bar{\nu}_\mu$ consistent

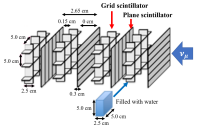




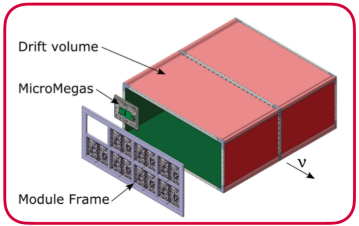
Looking to the Future!

- **WAGASCI/BabyMIND**
  - Intermediate flux ($\sim$ 800 MeV peak)
  - Water target with good 4π reconstruction
  - Muon charge ID and momentum from BabyMIND
  - Selections and analyses are in progress!
- **ND280 Upgrade:**
  - Substantially improved detector
  - Retains much of the original
- **Joint Analyses:**
  - Using T2K data to better constrain T2K data
  - More detectors and neutrinos than ever!

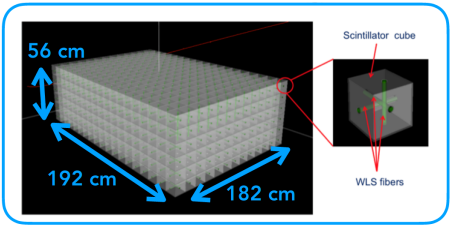




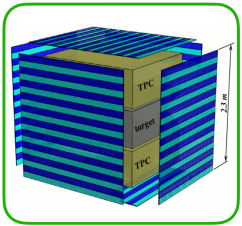
ND280 Upgrade



High-Angle TPC (HATPC)

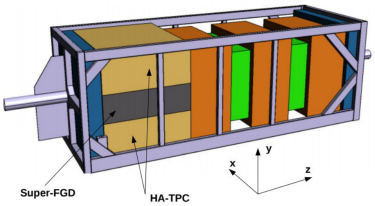


Super Fine-Grained Detector (SuperFGD)



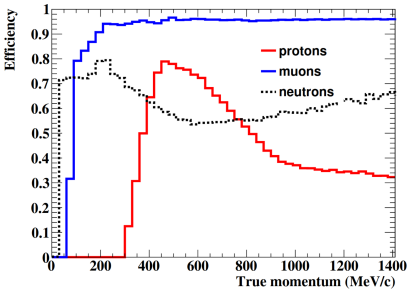
Time-of-Flight (TOF)

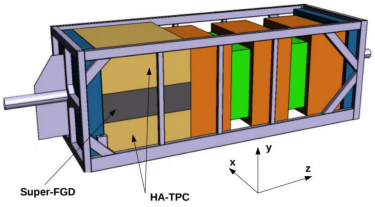
- **Super-FGD:**
  - Fully active scintillator
- **High-Angle TPCs:**
  - High resolution Argon TPCs
- **Time-of-Flight:**
  - Scintillator strips for timing info



ND280 Upgrade

- **Super-FGD:**
  - Greatly improved 3D tracking
  - Much better timing
  - Much lower noise
  - Lower thresholds
  - Neutron mom. resolution $\sim 25\%$
- **High-Angle TPCs:**
  - Adds coverage at higher angles
  - Better constraints for SK
- **Time-of-Flight:**
  - Improves direction and timing
  - Recudes external backgrounds





Conclusion

Many analyses and papers coming soon!

- ND280
  - CC ν_μ and $\bar{\nu}_\mu$ 1π analyses
  - Joint CC ν_μ $0, 1\pi^+$
  - CC ν_μ $1K^+$
  - NC quasi-elastic
- ND280 Upgrade:
  - Almost ready to take data
  - First events this year*
- WAGASCI/BabyMIND:
  - Analyses under very active development

*fingers crossed