A Neutrino Oscillation Global Fit Using GAMBIT

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On behalf of the GAMBIT Collaboration

3rd September 2024

NOW 2024

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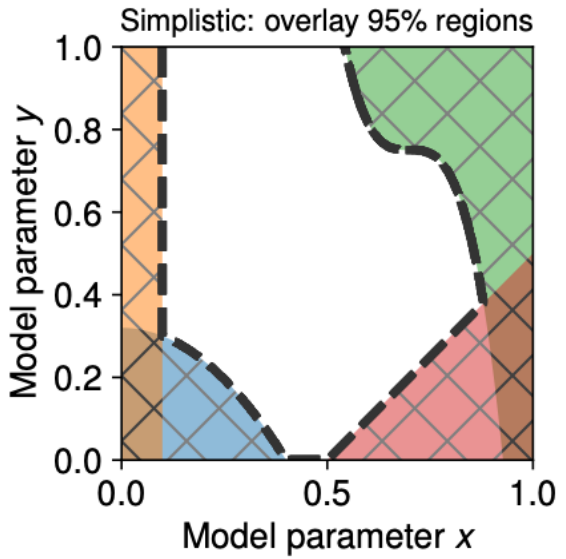
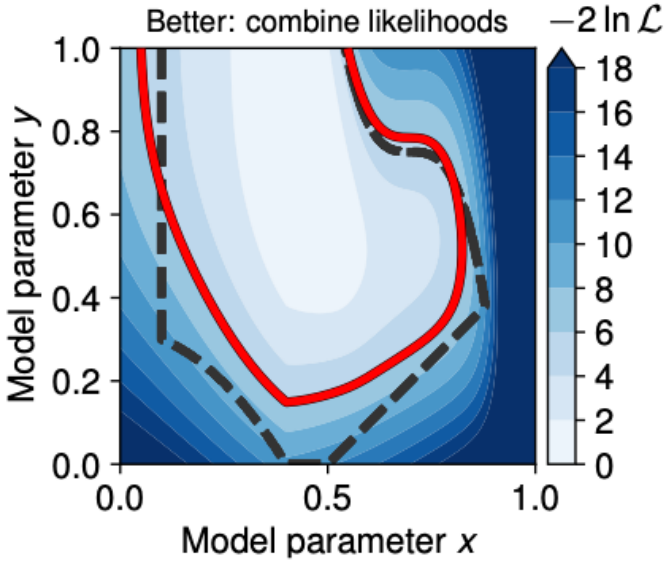
Global Fits

- Utilise data from multiple experiments
- Combine the unique strengths of each experiment
- Return the most accurate confidence/credible regions for model variables
- General approach: combine likelihoods from each experiment
- Past and present global fits (non-exhaustive):
  - NuFIT[1,2]
  - Valencia[3]
  - Bari[4]



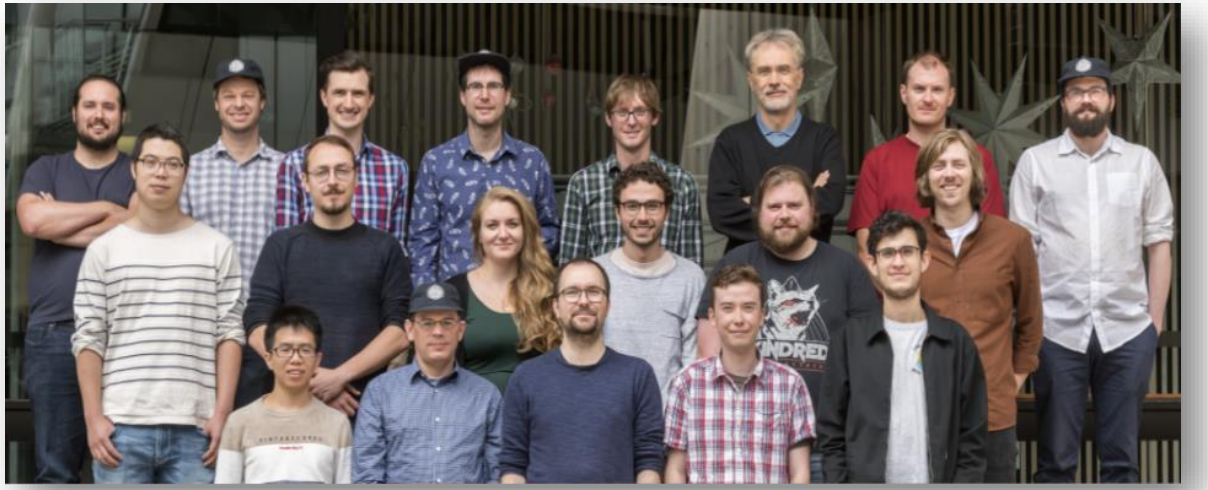


1) JHEP 09 (2020) 178
2) NuFIT 5.3 (2024) www.nu-fit.org
3) JHEP 02 (2021) 071
4) https://doi.org/10.1016/j.ppnp.2005.08.002

GAMBIT: The Global And Modular BSM Inference Tool

gambitbsm.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, NOvA, SHiP, T2K, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE Marsh, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, R Ruiz, A Scaffidi, P Scott, W Shorrock, C Sierra, P Stöcker, W Su, J Van den Abeele, A Vincent, M White, A Woodcock, Y Zhang ++

70+ participants in many experiments and numerous major theory codes

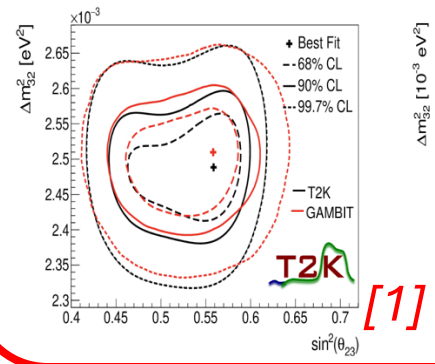
GAMBIT's Approach to Neutrino Oscillations

- Keep things **open source**
- Provide a tool where anyone can utilise neutrino oscillation data from **all major experiments**
- Use **published information** wherever possible
- Use **advanced sampling techniques** for efficient exploration of parameter space
- Publish global fits of the standard three-neutrino oscillation results with **clear procedures**

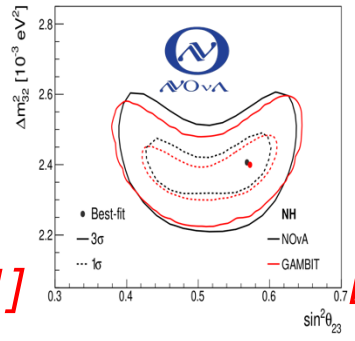
Included Experiments

- Daya Bay
- IceCube
- KamLAND
- MINOS
- NOvA (2020)
- SNO
- T2K (2020)
- More in future

Long-baseline accelerator experiments



[1]



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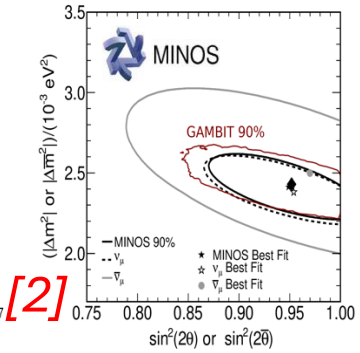

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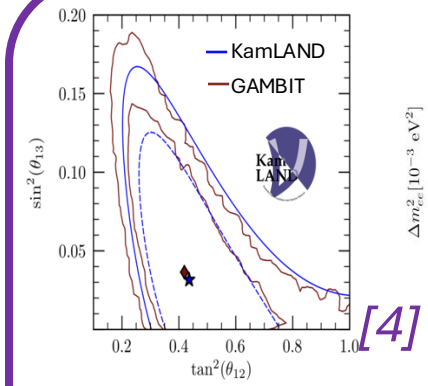

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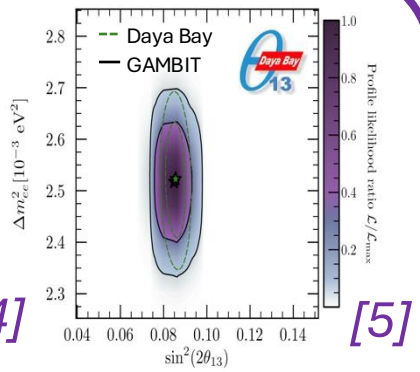
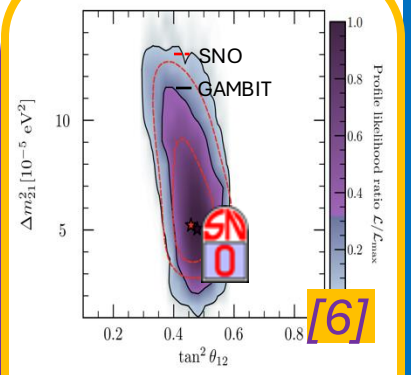


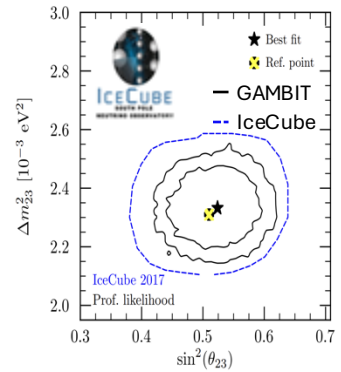
[5]

Reactor Experiments



[6]

Solar Experiments



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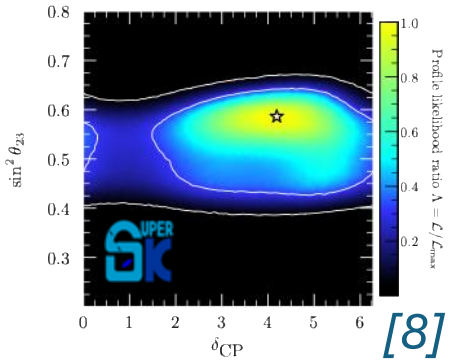


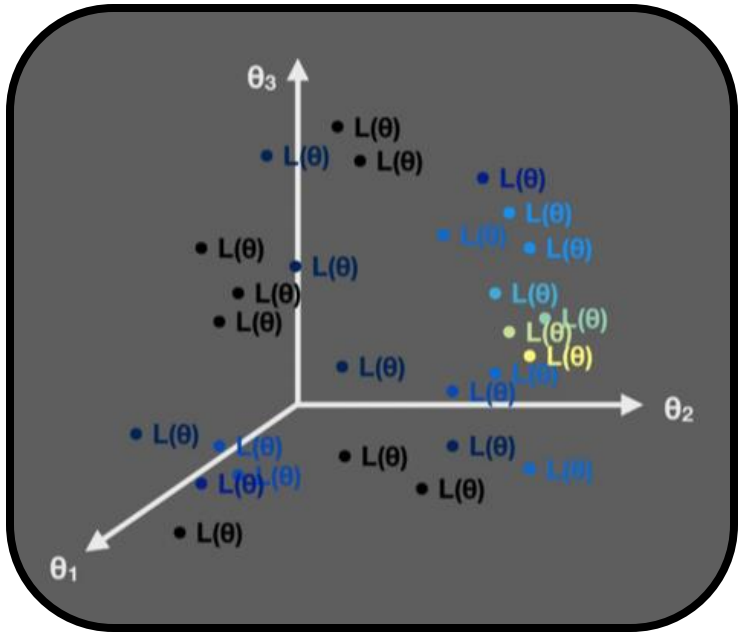
[8]

Atmospheric Experiments

[1] T2K 2020 result. https://doi.org/10.5281/zenodo.3959558
[2] NOvA 2020 result. https://doi.org/10.5281/zenodo.4142045
[3] MINOS 2013 paper. https://doi.org/10.1103/PhysRevLett.110.251801
[4] KamLAND 2011 paper. https://doi.org/10.1103/PhysRevD.83.052002
[5] Daya Bay 2018 paper. https://doi.org/10.1103/PhysRevLett.121.241805
[6] SNO paper. https://arxiv.org/abs/1109.0763
[7] IceCube 2018 paper http://link.aps.org/doi/10.1103/PhysRevLett.120.071801
[8] Super-K paper. https://arxiv.org/abs/1710.09126

Method

- Calculate likelihood (*L*) of each experiment by comparing data to simulation
- Scan through parameter space, calculating *L* for each experiment
- Converge to best fit
- Below is the calculation for the number of detected events for neutrino flavour α in energy bin i



Reconstruction function Neutrino beam flux Efficiency

$$N_i^{\alpha} = N_{\mathrm{bkg},i} + \int_{E_i}^{E_{i+1}} dE_{\mathrm{rec}} \int_0^{\infty} dE_{\nu} R\left(E_{\mathrm{rec}}|E_{\nu}\right) \frac{d\Phi}{dE_{\nu}} \sigma_{\alpha}(E_{\nu}) \epsilon(E_{\nu}) P_{\nu_{\beta}\to\nu_{\alpha}}(E_{\nu})$$

Total cross section

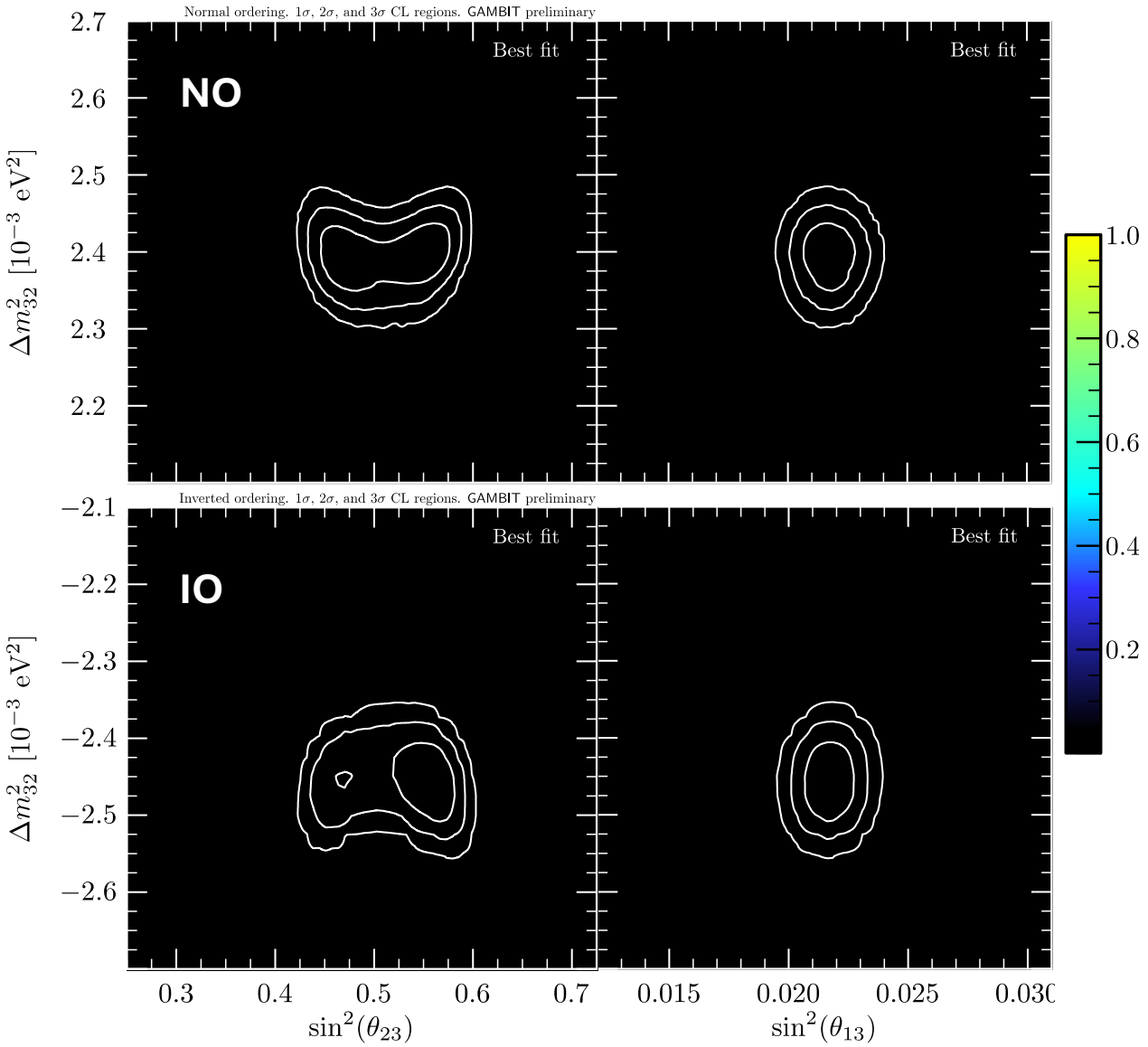
Results

Please note:

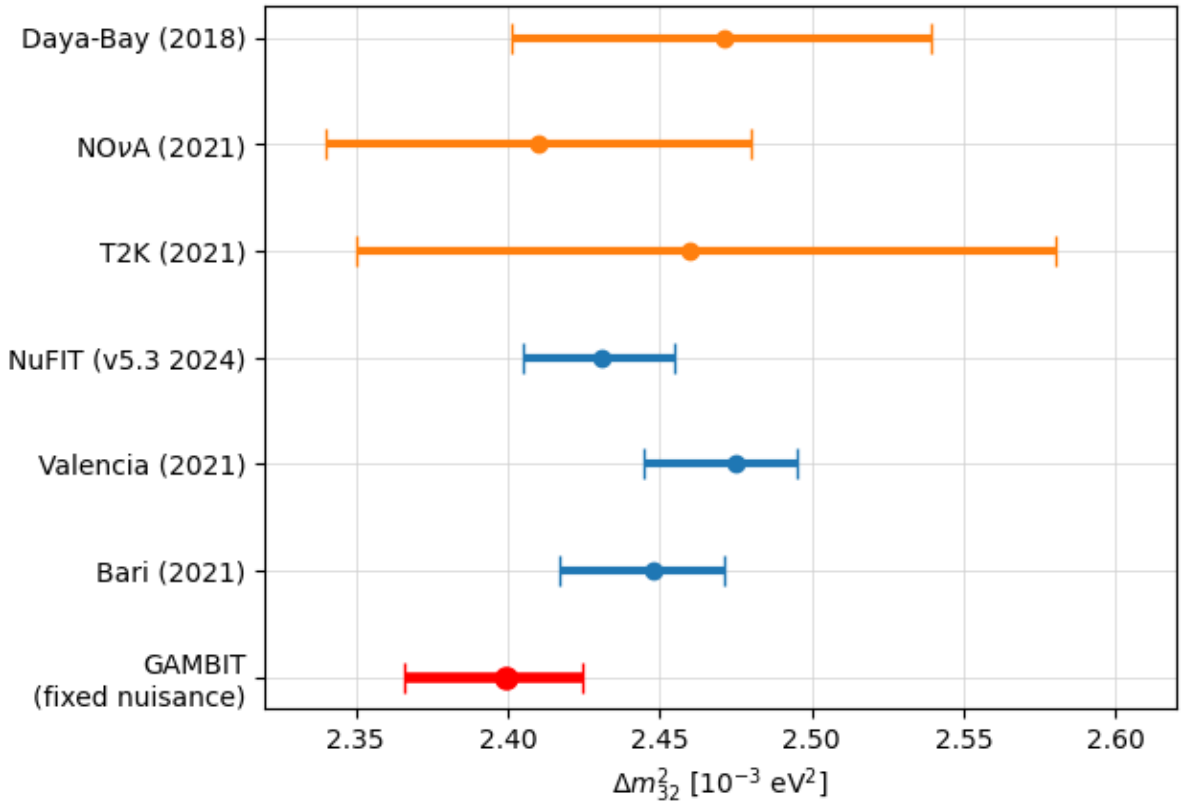
These results are preliminary, with no inclusion of nuisance parameters in the scans.

We plan to publish full results soon.

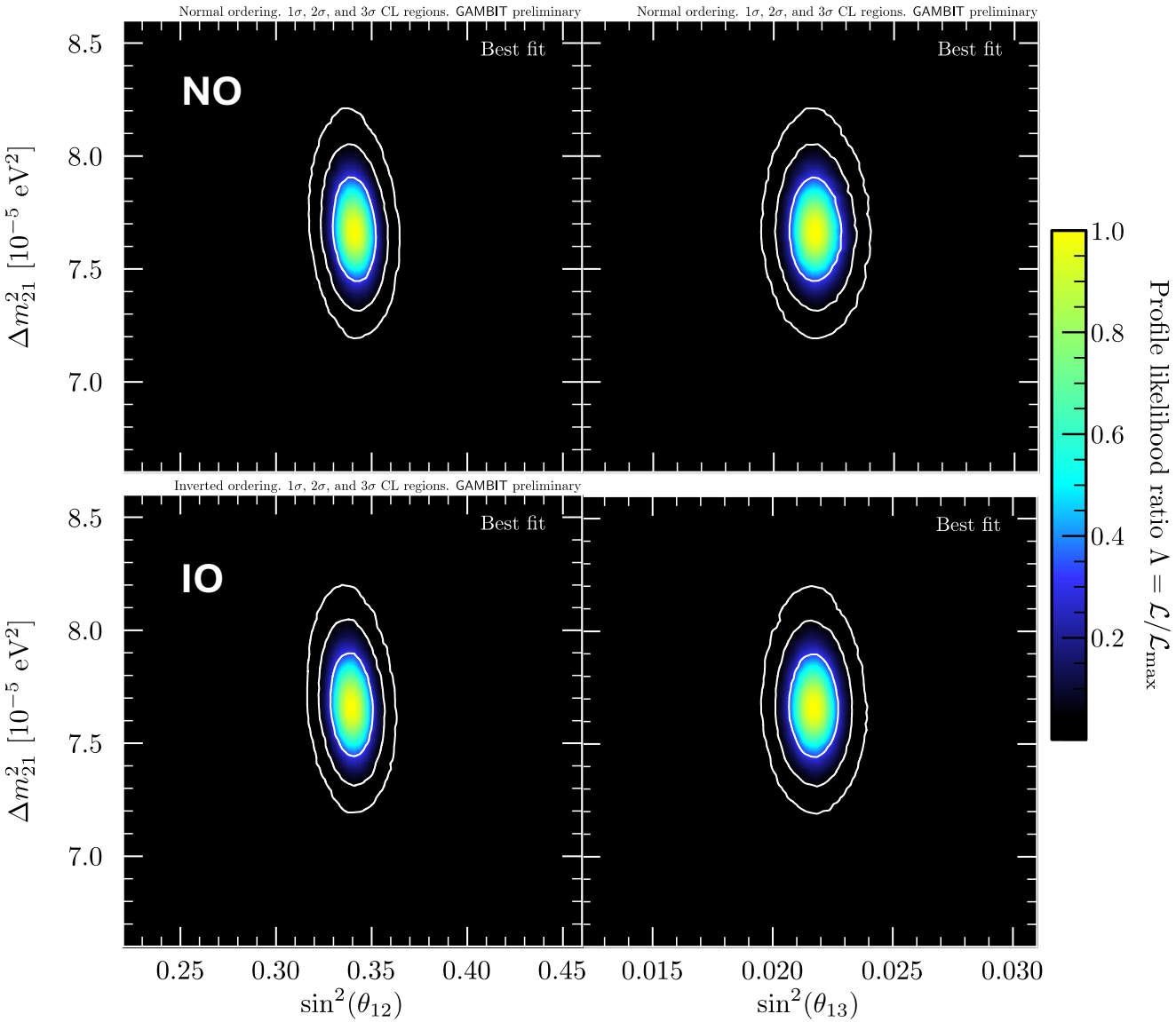
Results (Δm^2_{32})

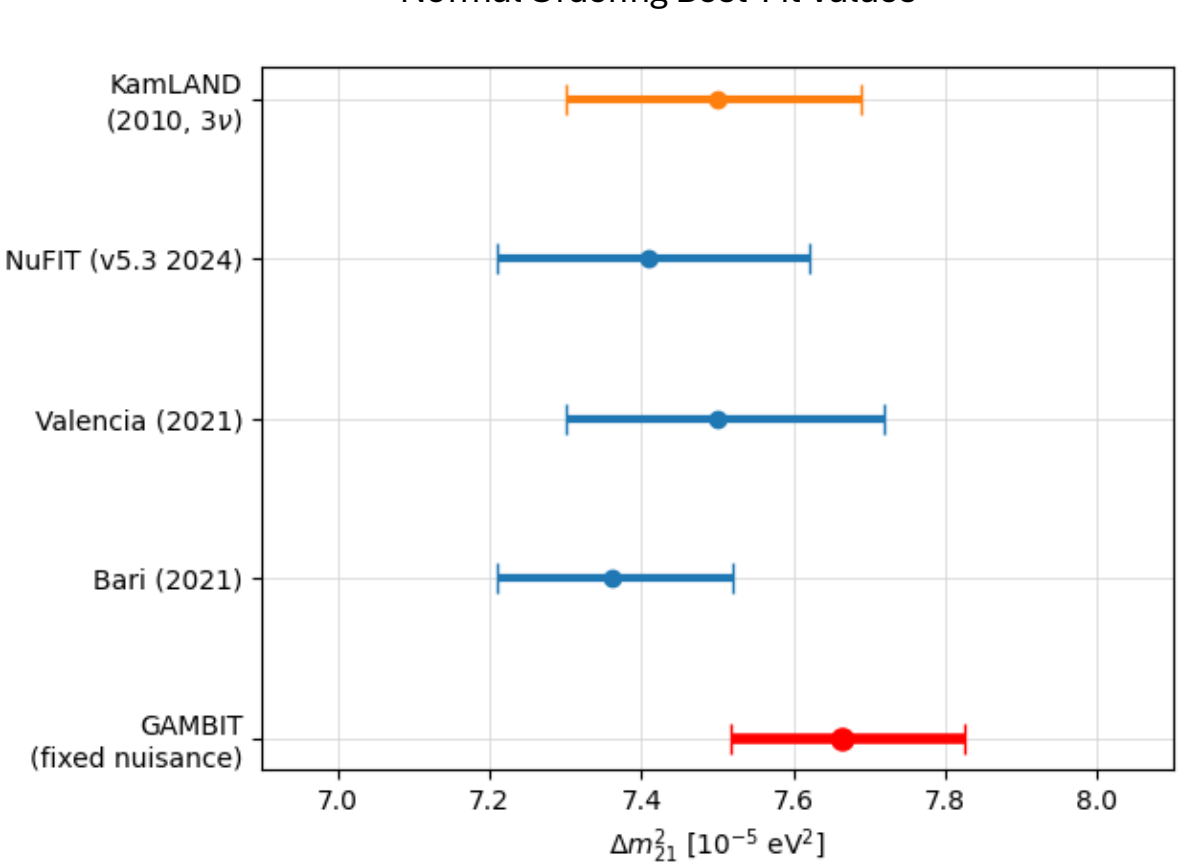


Normal Ordering Best-Fit Values

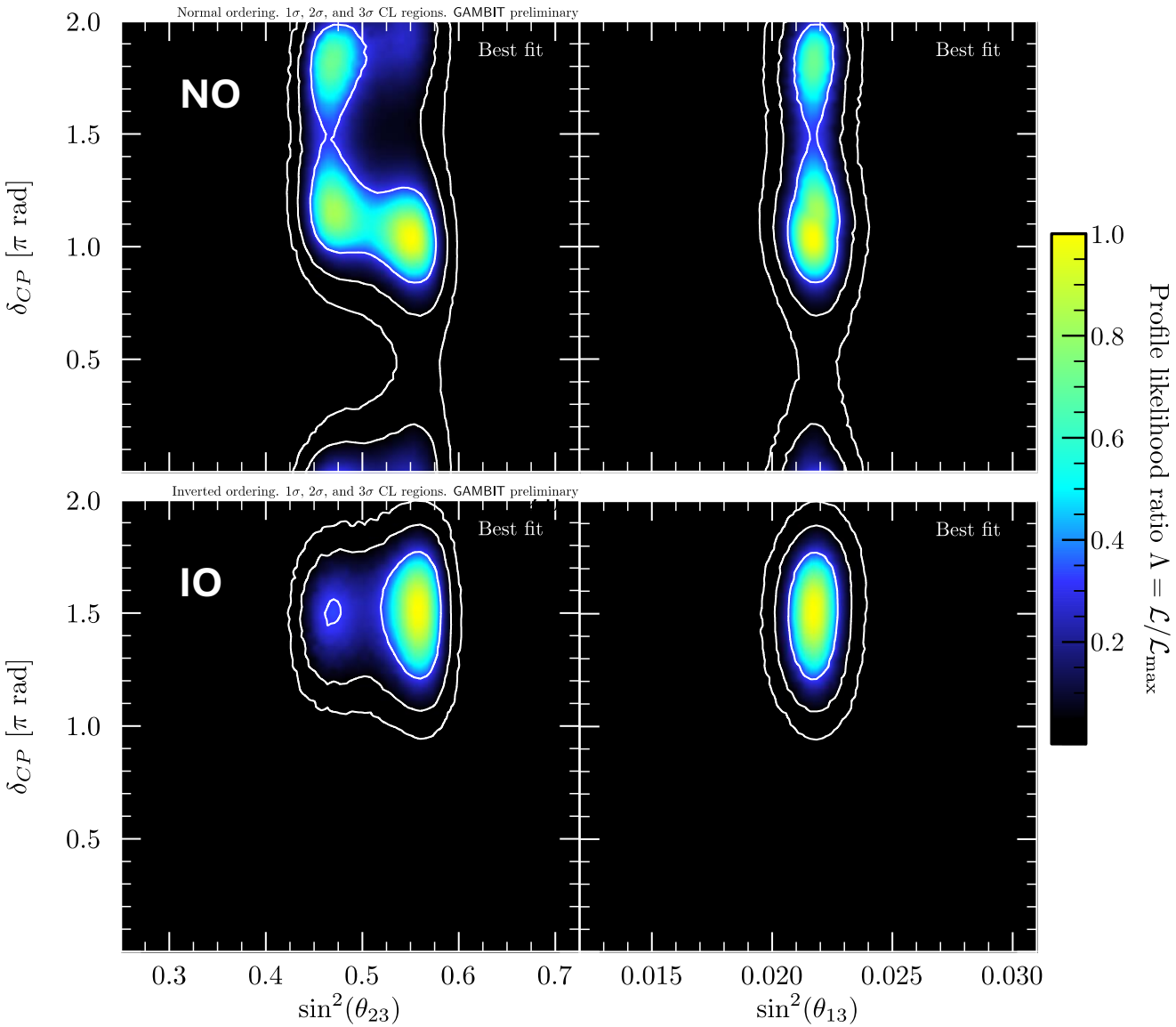


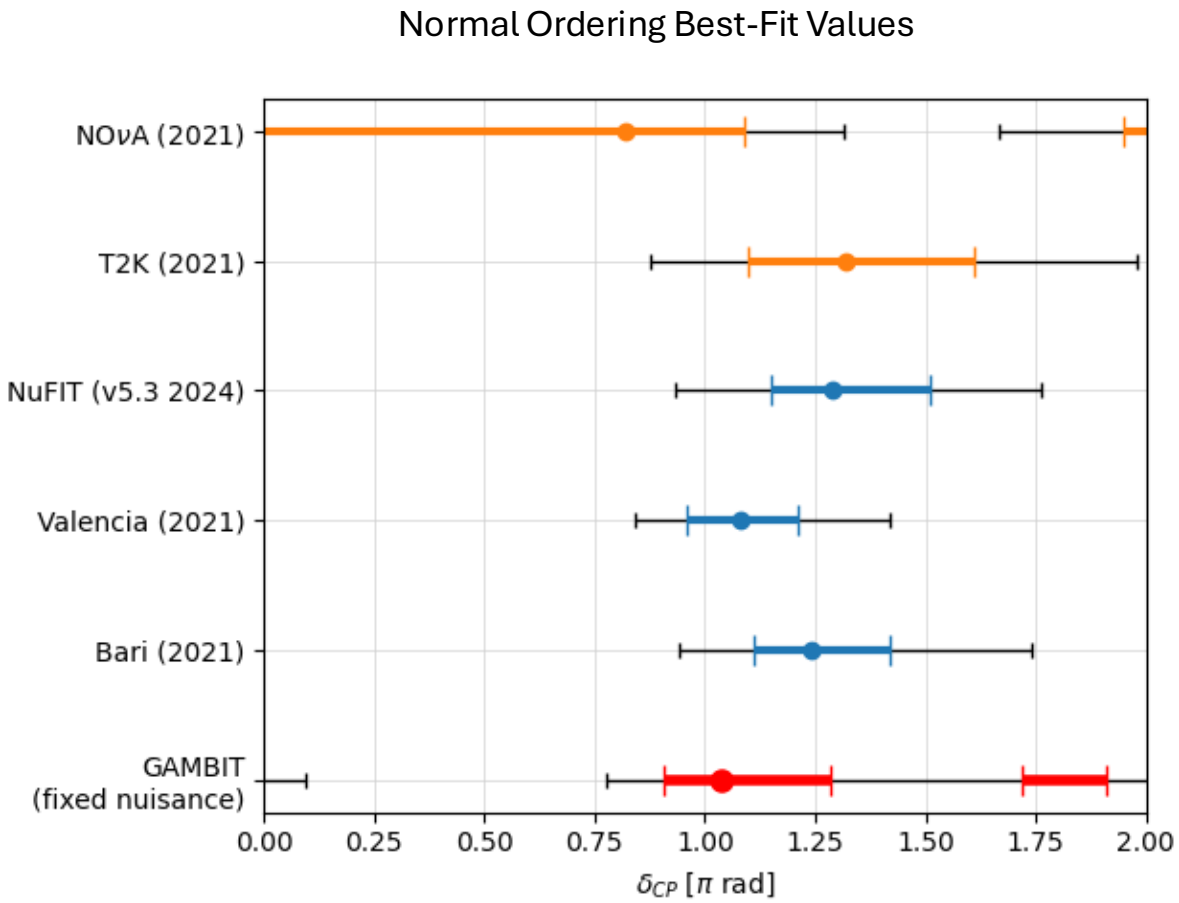
Results (Δm^2_{21})



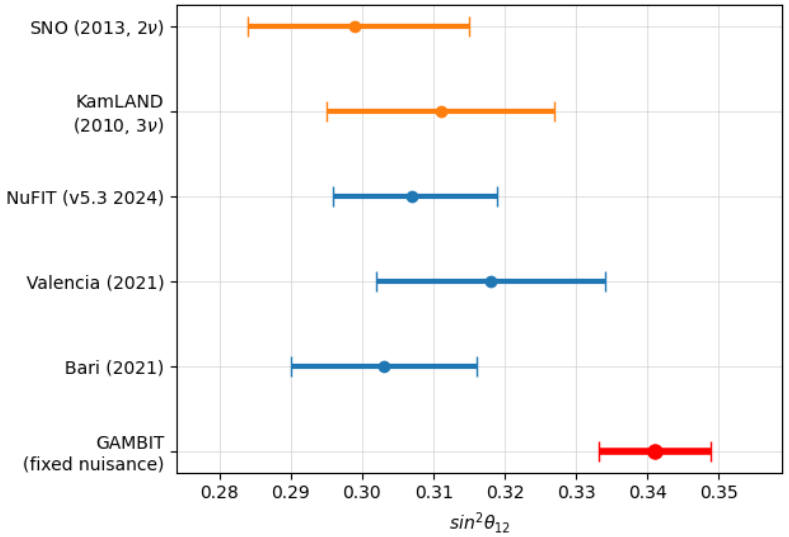


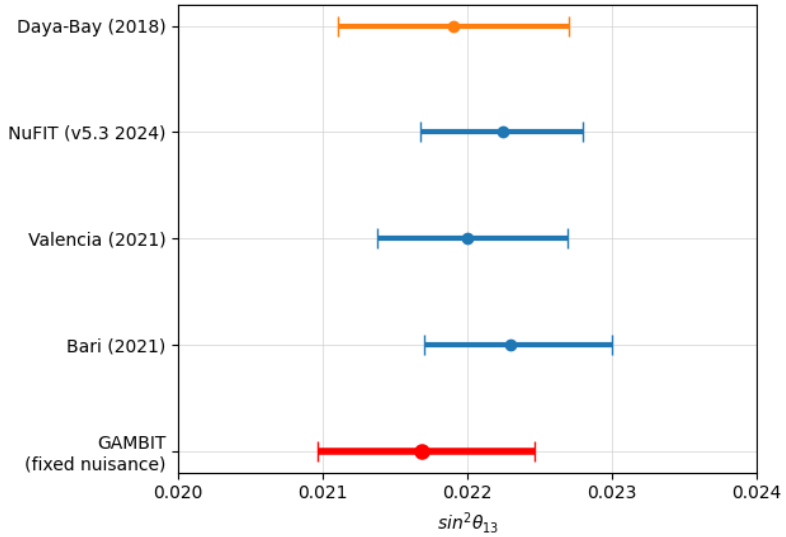
Results (δ_{CP})

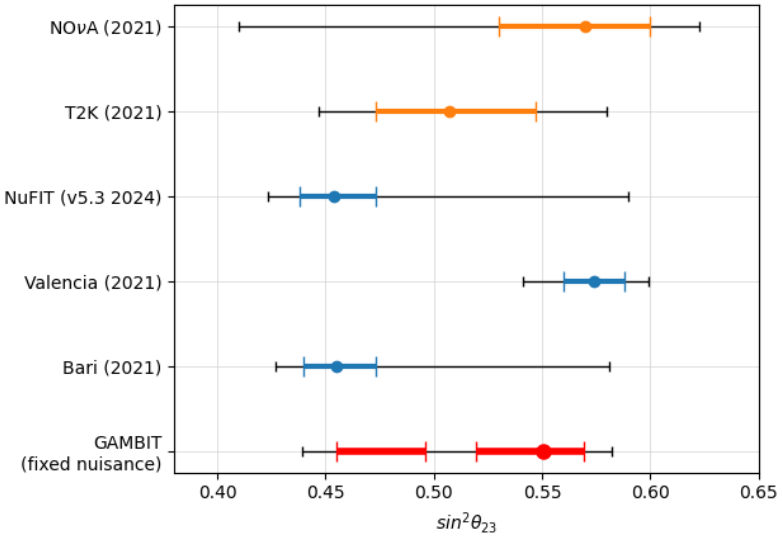




Results (Mixing Angles)







- All best-fit values of parameters agree with previous global fits, except θ_{12}
- We used a new (2016) solar model[1] in our fit, with higher flux. A higher value of θ_{12} is expected
- In our upcoming paper we will show results with both solar models
- This highlights one of GAMBIT's uses, testing new models independent of large collaborations

1) Solar Model B16(AGSS09): arXiv: 1611.09867

Summary

- Preliminary (fixed nuisance) results for GAMBIT neutrino oscillation global fit
- Initial results are consistent with previous global fits where expected
- Full results coming…
- Will provide an open-source tool for testing new models with all available data

	Normal ordering $(\pm 1\sigma)$
θ_{12} $[^\circ]$	35.7 ± 0.5
θ_{13} $[^\circ]$	8.34 ± 0.25
θ_{23} $[^\circ]$	$48.3^{+1.0}_{-1.4}$
$\sin^2\theta_{12}$	0.340 ± 0.009
$\sin^2\theta_{13}$	$0.0211^{+0.0013}_{-0.0012}$
$\sin^2\theta_{23}$	$0.557^{+0.018}_{-0.024}$
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	$7.66^{+0.15}_{-0.14}$
Δm^2_{32} $[10^{-3}\ \mathrm{eV}^2]$	2.41 ± 0.03
δ_{CP} $[^\circ\ /\pi\ \mathrm{rad}]$	$188^{+27}_{-23}\ /\ 1.05^{+0.15}_{-0.13}$

NO results from GAMBIT's fixed nuisance scan

Backups

Diver Scanner

- Open source **differential evolution** parameter sampler
- Population-based self-adaptive λjDE algorithm (rand-to-best/1/bin)
- Mutation -> crossover -> selection