Constraining the reactor antineutrino spectrum in JUNO's oscillation measurement

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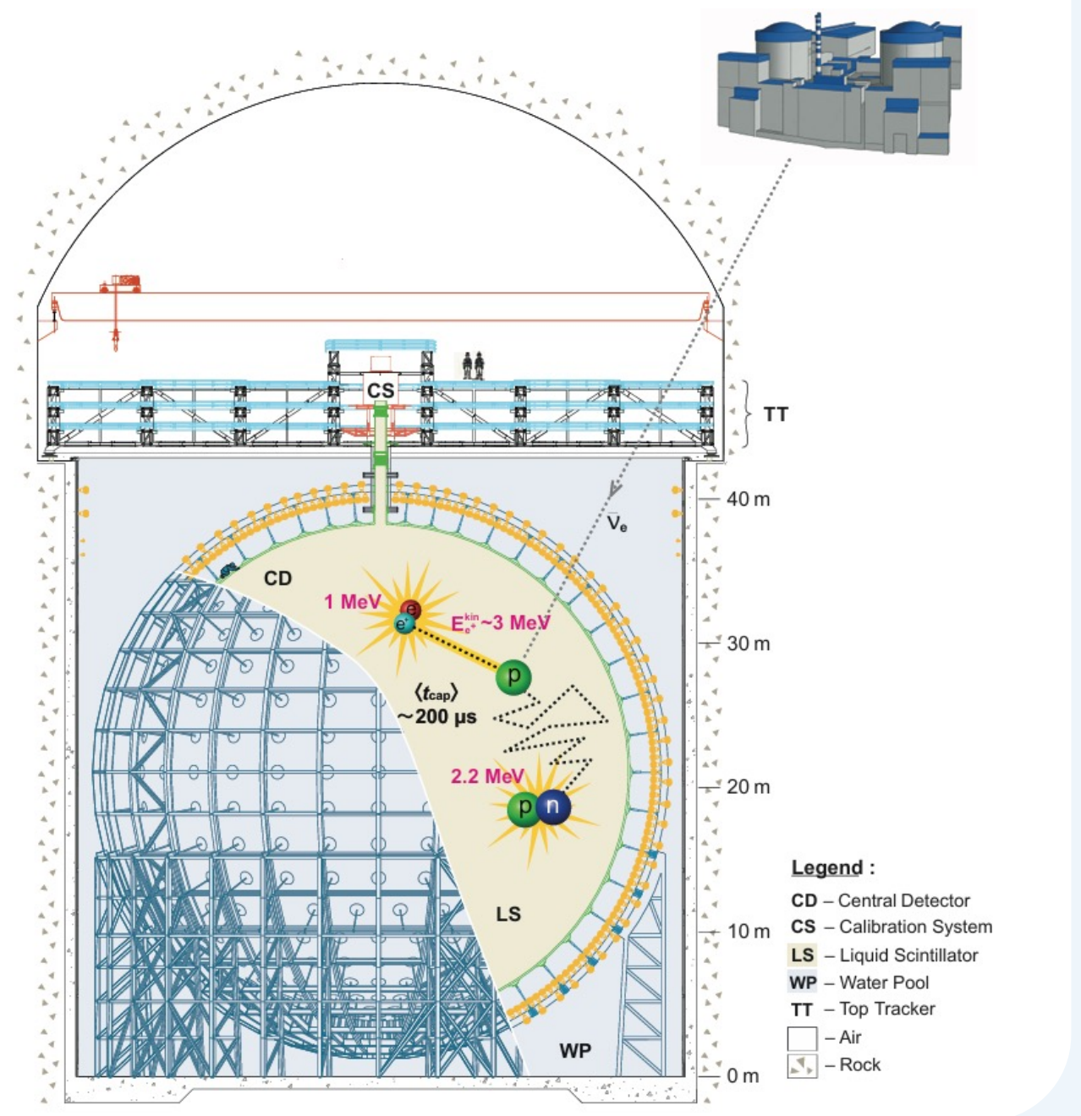
Introduction

JUNO

- 20 kton liquid scintillator detector
- ~52.5 km from Yangjiang and Taishan reactor cores
- ~3.4% @ 1 MeV energy resolution
- **~207 days of exposure**

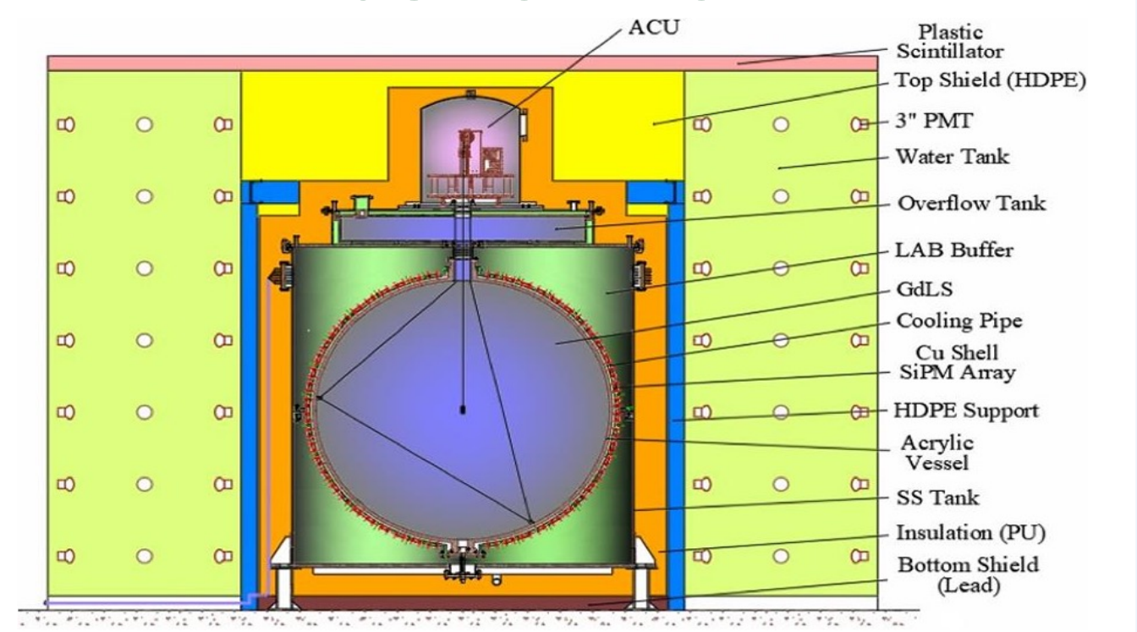


Physics goals

$\sin^2\theta_{12}$	Δm^2_{21}	<1% precision
$\sin^2\theta_{13}$	$\lvert\Delta m^2_{31}\rvert$	

Determine mass ordering

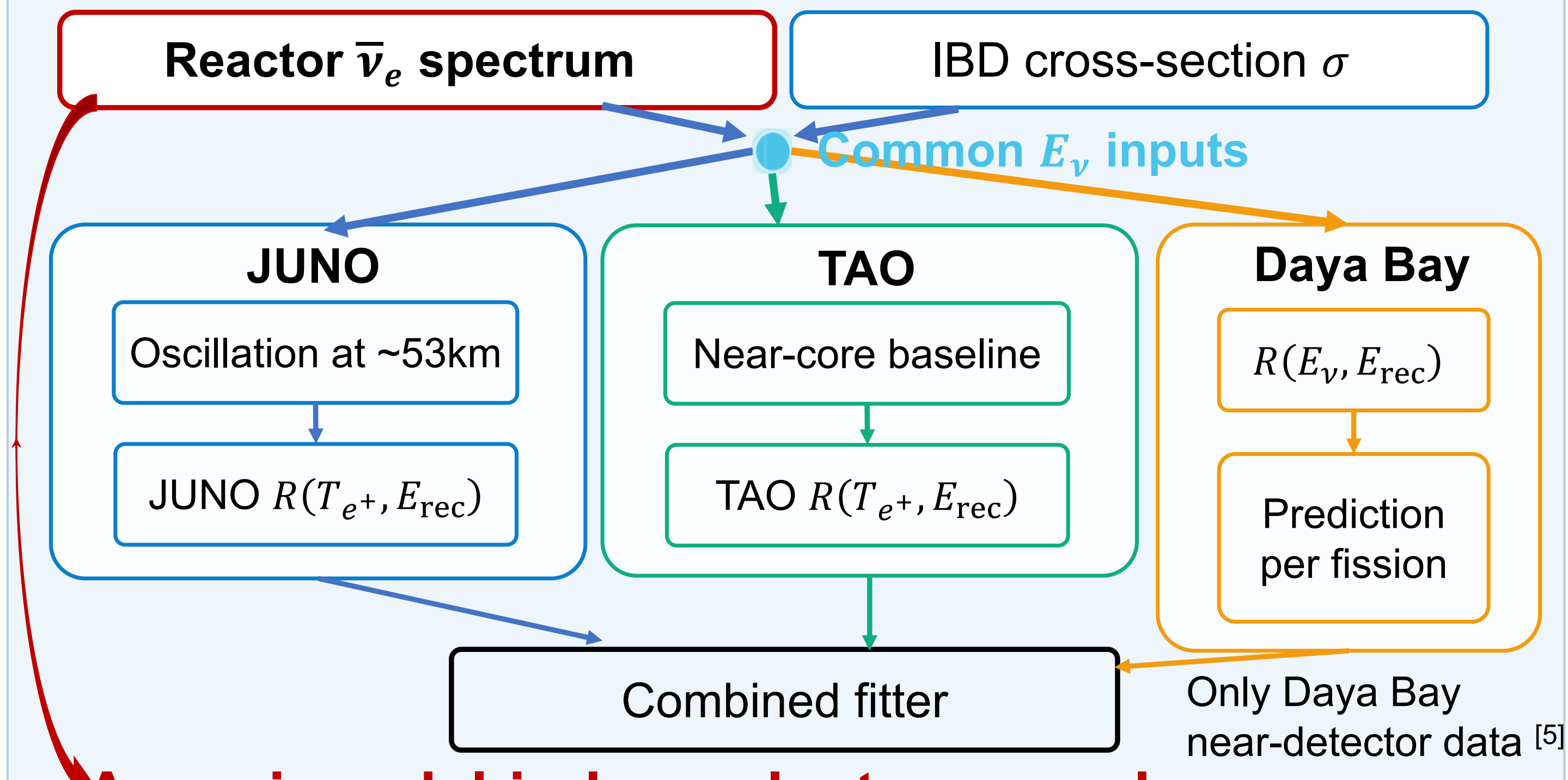
JUNO-TAO



- **44 m** from one Taishan core
- ~ 3% energy resolution @ 1MeV
- **anchors the un-oscillated reactor $\bar{\nu}_e$ spectrum**
- **~31 days reactor-on and ~29 days reactor-off data**

Main idea:
Use TAO and Daya Bay to constrain the reactor $\bar{\nu}_e$ spectrum shape, propagate it into JUNO's oscillation fit, and evaluate the impact on Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$ and NMO determination.

Combine JUNO + TAO + Daya Bay



Reactor $\bar{\nu}_e$ spectrum

IBD cross-section σ

Common E_ν inputs

JUNO
- Oscillation at ~53km
- JUNO $R(T_{e^+}, E_{rec})$

TAO
- Near-core baseline
- TAO $R(T_{e^+}, E_{rec})$

Daya Bay
- $R(E_\nu, E_{rec})$
- Prediction per fission

Combined fitter

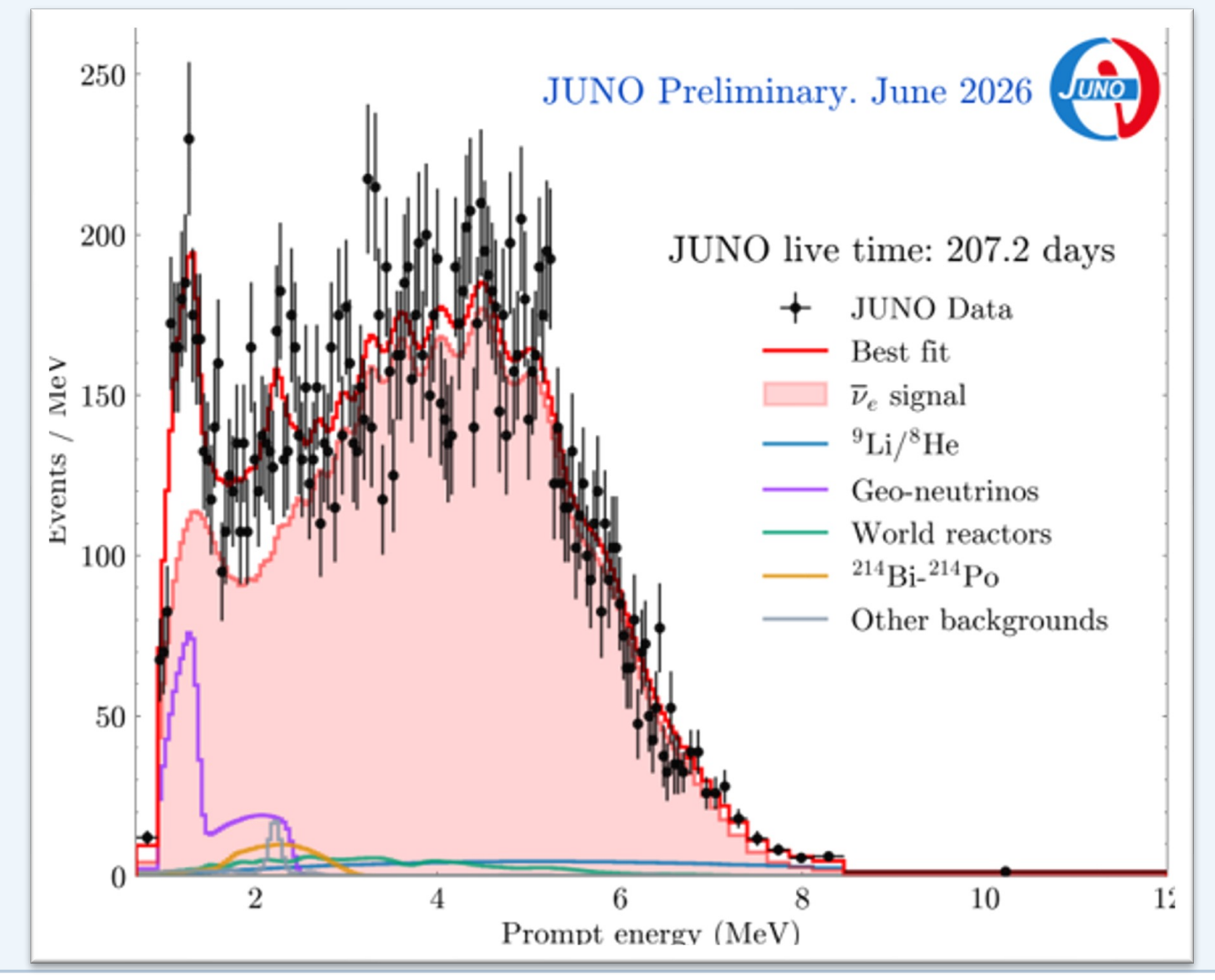
Only Daya Bay near-detector data [5]

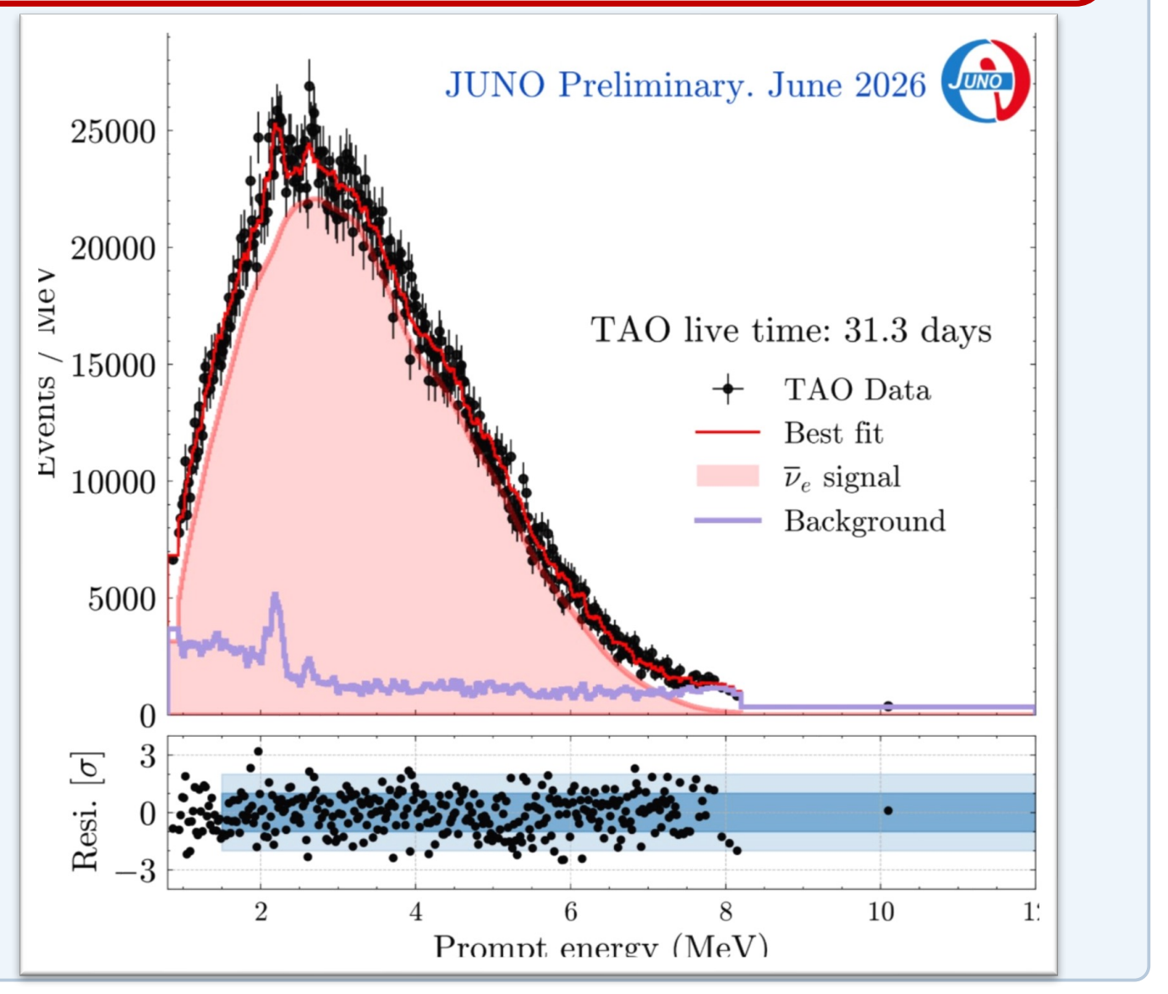
A semi-model-independent approach

Model-independent:

$$S_{\mathrm{MI}}(E_\nu) = S_0(E_\nu) + \sum_{i=1}^{N} \alpha_i B_i(E_\nu)$$

Model-dependent:
- Include corrections for different fission fractions across exps.
- SNF and non-equilibrium contributions for JUNO & TAO





Statistical methods

J → JUNO, T → TAO, D → Daya Bay

$$\chi^2(\boldsymbol{p},\boldsymbol{\eta},\boldsymbol{\alpha}) = \left(N^{\mathrm{J,T,D}}_{\mathrm{obs}} - N^{\mathrm{J,T,D}}_{\mathrm{exp}}\right)^T V^{-1}_{\mathrm{J,T,D}}\left(N^{\mathrm{J,T,D}}_{\mathrm{obs}} - N^{\mathrm{J,T,D}}_{\mathrm{exp}}\right) + \lambda^2_{\mathrm{nuis}}(\boldsymbol{\eta}) + \lambda^2_{\mathrm{flux}}(\boldsymbol{\alpha}) + \chi^2_{\mathrm{osc}}(\sin^2\theta_{13}, \Delta m^2_{31})$$

$\boldsymbol{p}$: oscillation params

χ^2_{osc}: external constraints from Daya Bay[5] or NuFit LBL[2]

$\boldsymbol{\eta}$: describes detector response, backgrounds and overall flux normalization

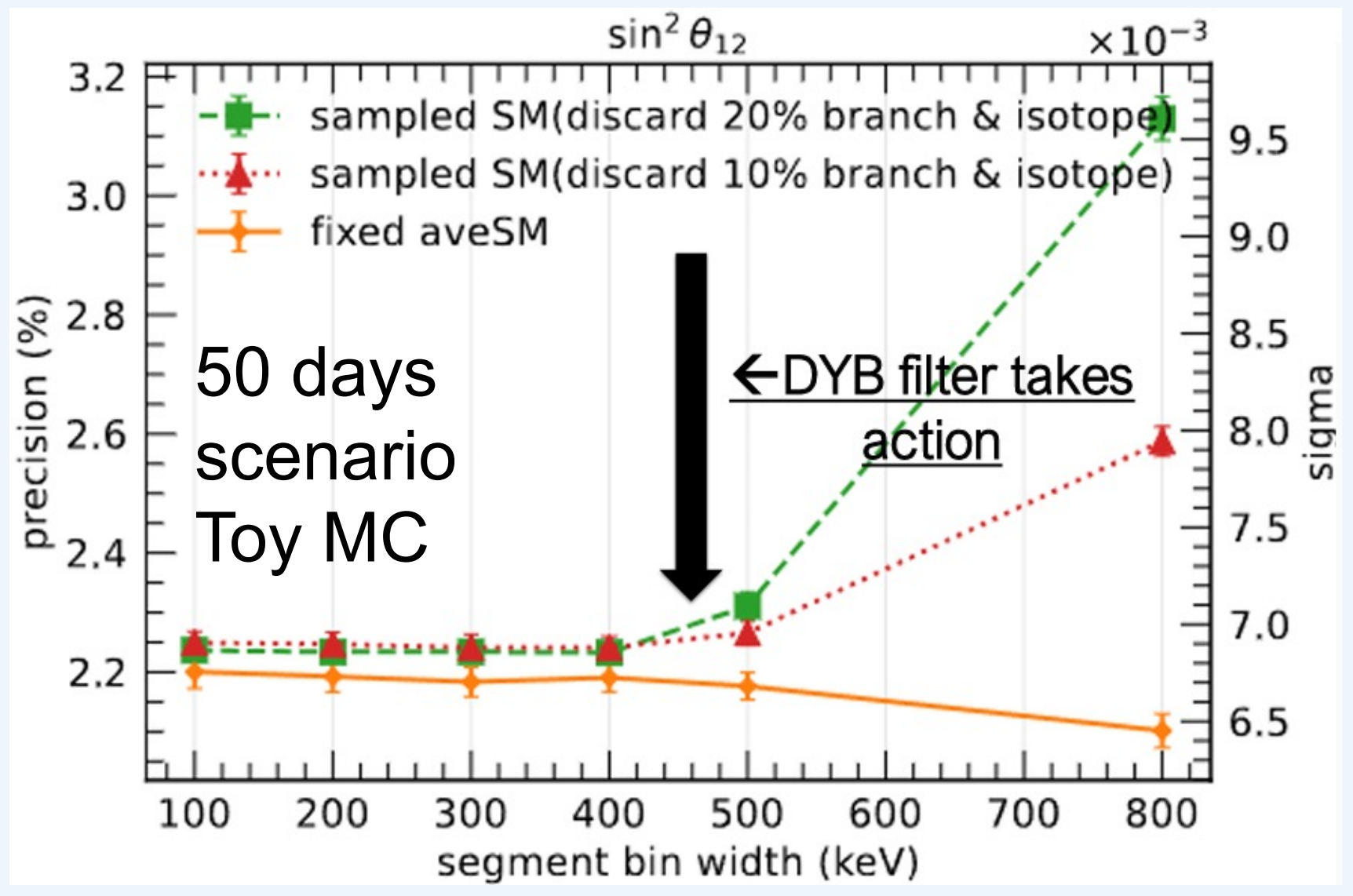
$\boldsymbol{\alpha}$: **free params in reactor $\bar{\nu}_e$ spectrum constrained by Daya Bay and TAO**

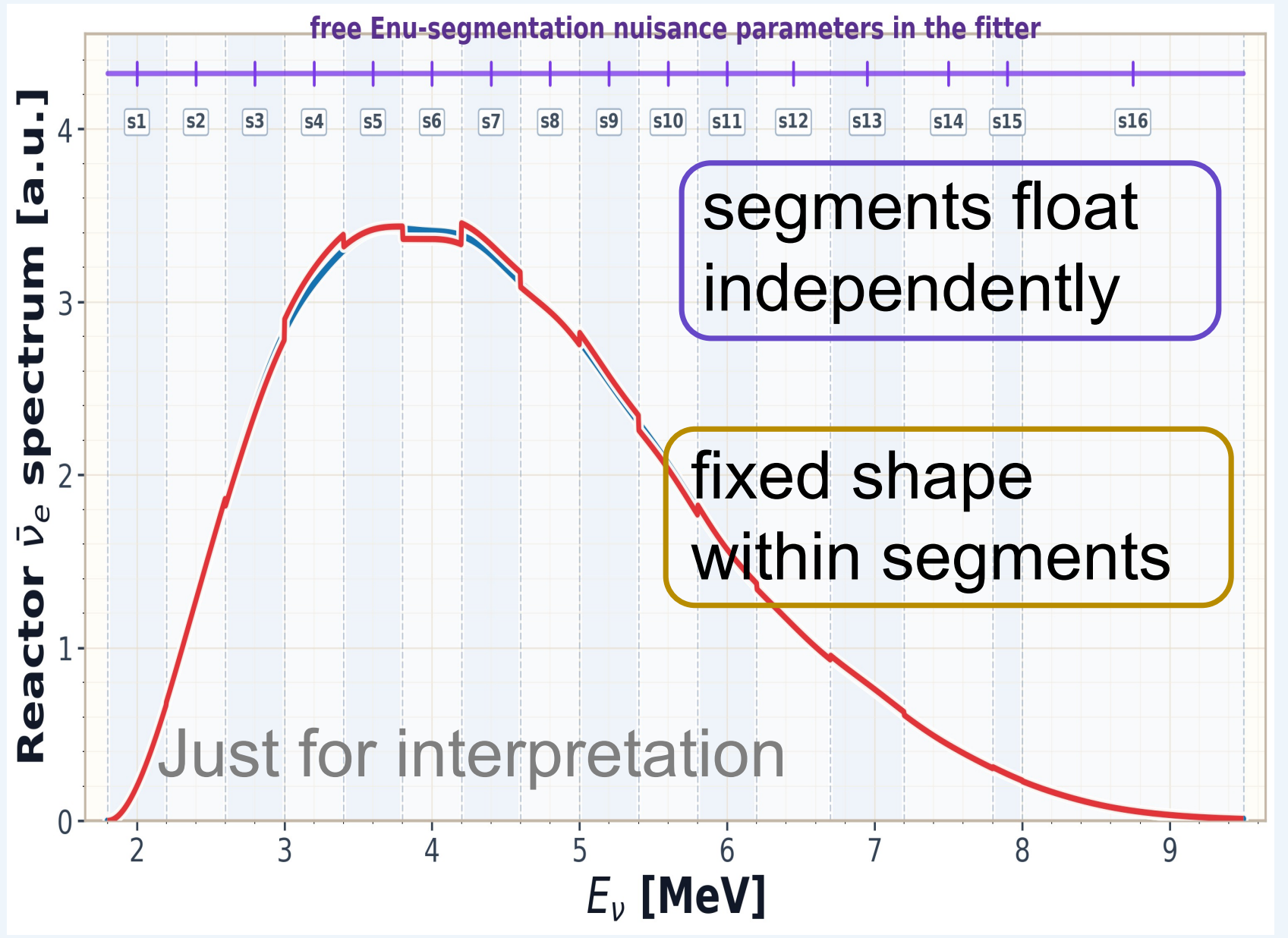
Optimization of reactor-spectrum segmentation

Why to optimize the segmentation?

$$N^{\mathrm{J}}_{\mathrm{obs}}(E_{rec}) = \boxed{[S_{\mathrm{reactor}}(E_\nu)\times P_{ee}(E_\nu)]} \otimes \sigma(E_\nu, T_{e^+}) \otimes R(T_{e^+}, E_{rec})$$

Degeneracy of reactor spectrum shape with osci. distortion or mismatch of spectrum model
→ Bias the oscillation parameters





segments float independently

fixed shape within segments

Just for interpretation

- Current small TAO statistic → not sufficient to constrain the fine structure

Coarse segments: spectrum too fixed → model-dependent sys.↑
Fine segments: more freedom→ DYB statistical unc. / overfit risk↑
Optimized: finest segmentation still constrained by Daya Bay and TAO

N=25
300 keV

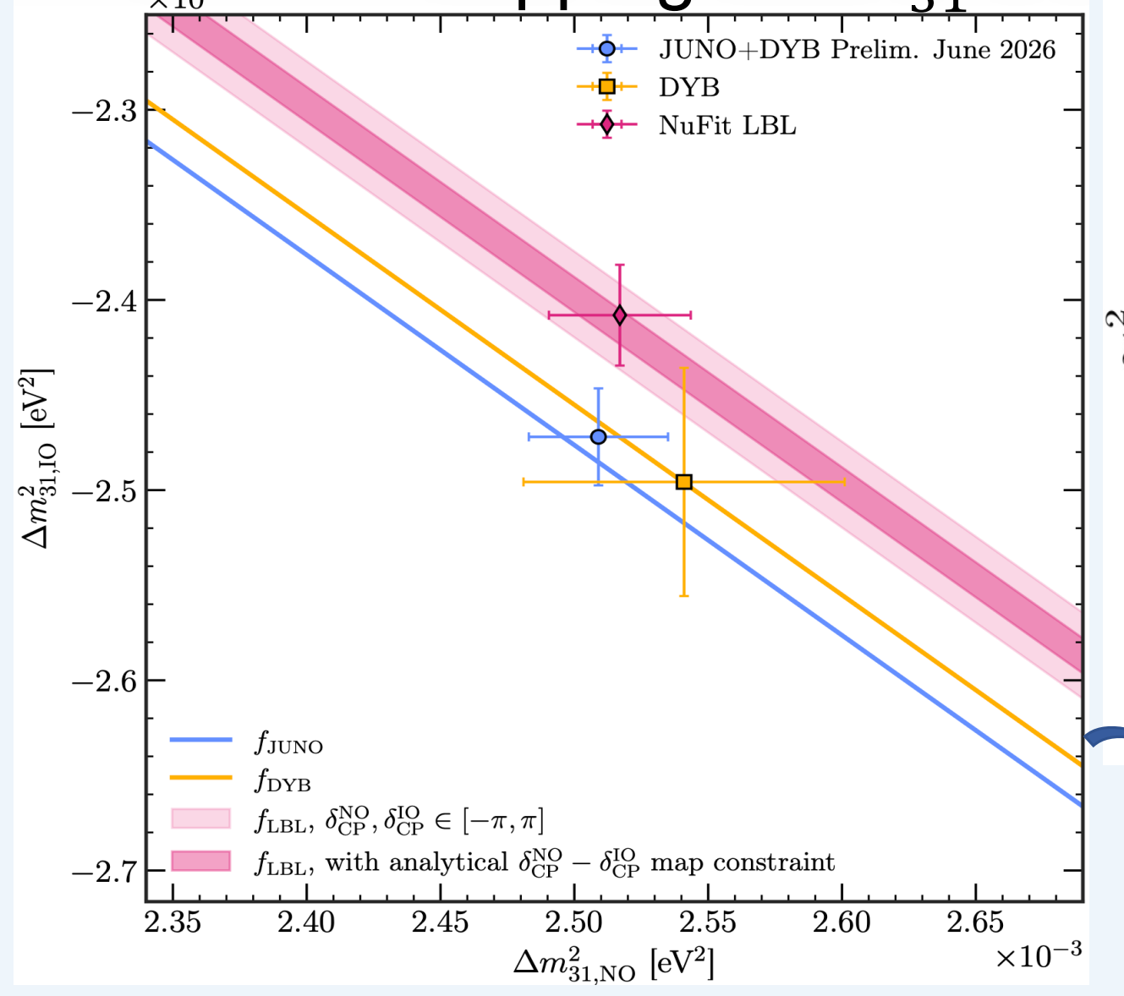
NMO determination with synergy between reactor and long-baseline accelerator (LBL)

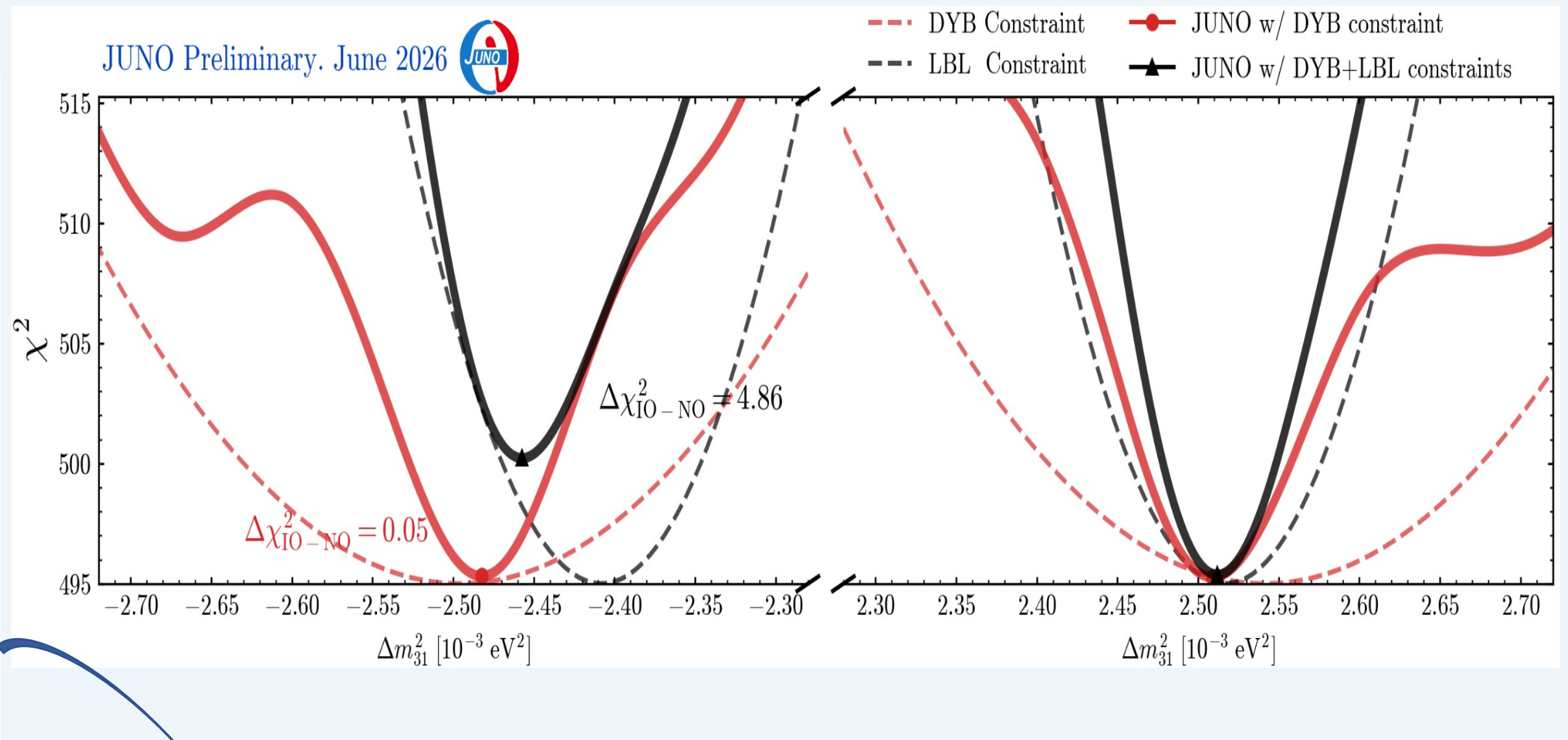
Test statistics: $\Delta\chi^2_{\mathrm{MO}} \equiv \min\chi^2_{\mathrm{marg}}(\mathrm{IO}) - \min\chi^2_{\mathrm{marg}}(\mathrm{NO})$

Phenomenological methodology:

- For a fixed true ordering, the best-fit under the wrong ordering is shifted
- Mismatch IO–NO mapping offset between reactor ($\bar{\nu}_e \to \bar{\nu}_e$) and LBL ($\nu_\mu/\bar{\nu}_\mu \to \nu_\mu/\bar{\nu}_\mu$) **penalizes the wrong ordering.**[3,6,7]
- **The more precisely** Δm^2_{31} is measured by JUNO and LBL, **the stronger** the sensitivity to NMO.

IO-NO mapping of Δm^2_{31}





apply f_{LBL} and f_{DYB}

Build numerical $\Delta\chi^2_{\mathrm{MO}}$ distribution:

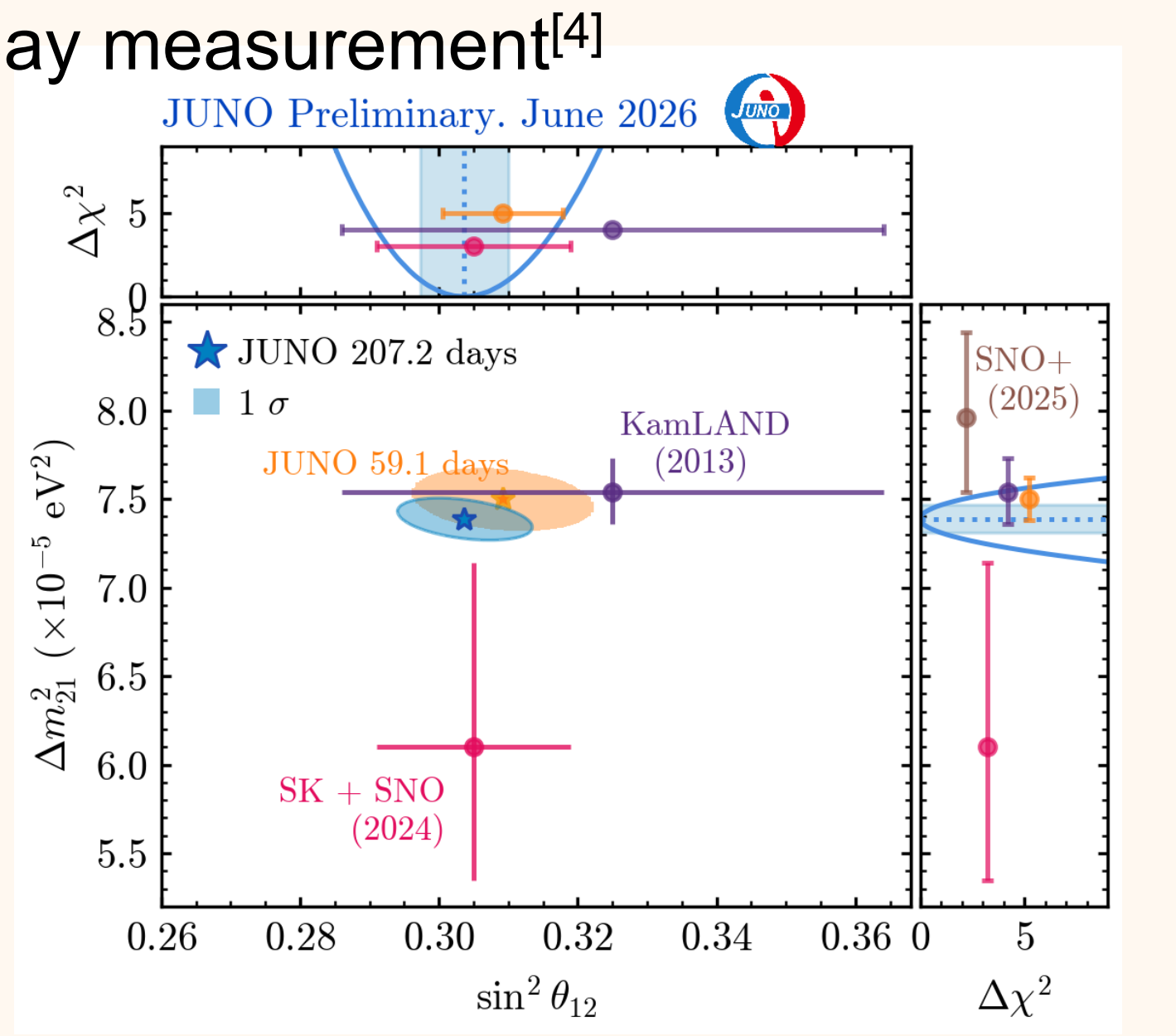
Toy generation ⇨ Simulate pair of Daya Bay/LBL Δm^2_{31} in NO/IO ⇨ NO/IO minimization ⇨ Repeat toys

Latest JUNO oscillation results

$\sin^2\theta_{12}$	Δm^2_{21}
0.304 ± 0.006	7.39 ± 0.08

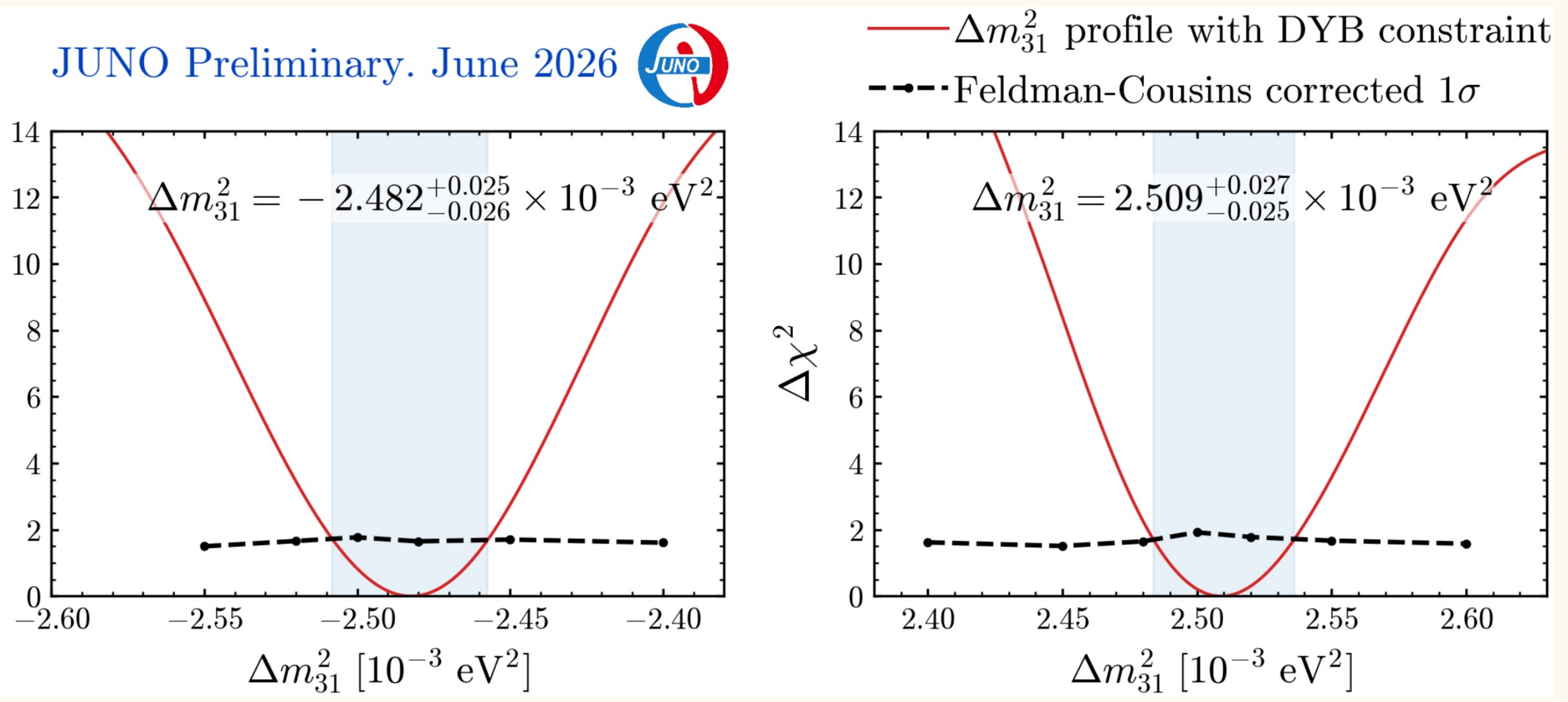
- Consistent result in NO/IO
- Δm^2_{31} constraint has negligible impact
- **World-leading precision**

$\sin^2\theta_{13}$ always constrained by Daya Bay measurement[4]



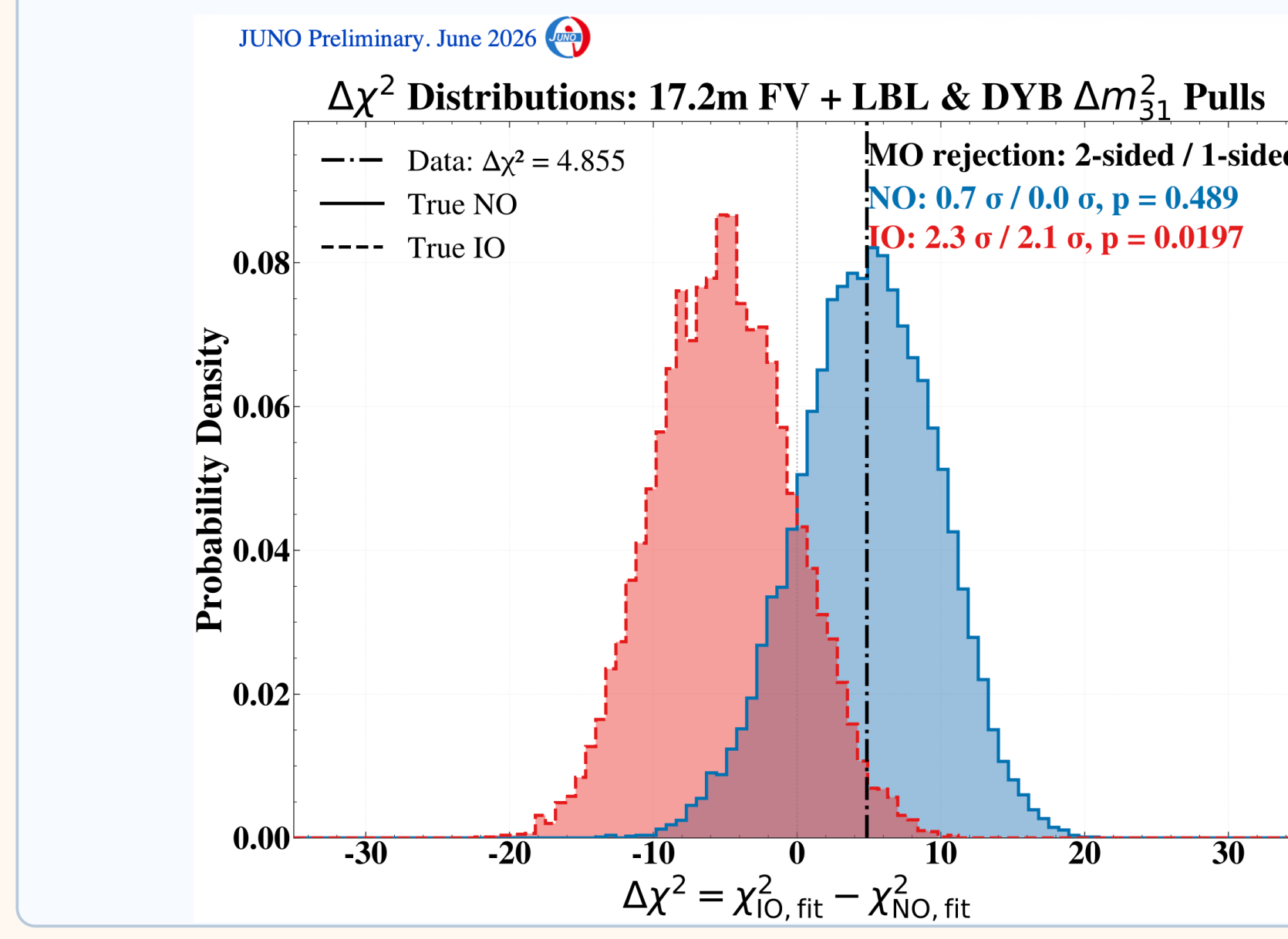
$\Delta m^2_{31,\mathrm{NO}}(10^{-3}\mathrm{eV}^2)$	$\Delta m^2_{31,\mathrm{IO}}(10^{-3}\mathrm{eV}^2)$
$2.509^{+0.027}_{-0.025}$	$-2.482^{+0.025}_{-0.026}$

- 1σ interval is corrected with FC method
- With Daya Bay Δm^2_{31} constraint



Significance of NMO determination

$\Delta\chi^2$ distribution @ best-fit values in the scenario
JUNO + Daya Bay Δm^2_{31} + LBL Δm^2_{31}



Weak preference for normal mass ordering with

CL(IO) = 2.3 σ (2-sided)

- Conservative significance across true values of δ_{CP} from 0 to 2π

Complementary Bayesian results
Bayes factor $2\ln\left(\frac{p(\mathrm{NO})}{p(\mathrm{IO})}\right) = 4.64$
details in Vanessa's poster **#252**

Summary

- Introduce a semi-model-independent approach that combines Daya Bay near-detector data and TAO data with theoretical models to constrain the reactor $\bar{\nu}_e$ spectrum
- The segmentation is optimized to N=25 that allows JUNO+DYB fit to absorb most uncertainties in the absolute reactor spectrum into $\boldsymbol{\alpha}$
- Latest frequentist JUNO results with reactor neutrino are presented.
- Weak preference for normal ordering with 2.3 σ in JUNO + Daya Bay Δm^2_{31} and LBL Δm^2_{31}.

References

[1] JUNO Collaboration, Nature 654, 343-352 (2026).
[2] NuFIT 6.1 (2025), arXiv:2410.05380
[3] JUNO Collaboration, PPNP 123 (2022): 103927.
[4] Daya Bay collaboration, Phys. Rev. Lett. 130, 161802 (2023).
[5] Daya Bay collaboration, Phys. Rev. Lett. 134, 201802 (2025).
[6] Yu-Feng Li, Jun Cao, Yifang Wang, and Liang Zhan, Phys. Rev. D **88**, 013008
[7] Nunokawa, Parke, and Funchal. PRD 72.1 (2005): 013009.