TRI-DIRECT LITTLEST SEESAW WITH PRECISION MEASUREMENTS

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arXiv:1905.12939 submitted to PRD
arXiv:1907.01371 submitted to EPJC

LEPTONIC FLAVOUR SYMMETRY

- It is used to be explain neutrino oscillations at the low energy. [talks by Ma, King, Zhou, Tsumura..etc]

- NOW, it is also used to explain baryogengesis at the high energy and DM in the dark sector. [talks by Ma, King, Chen, and Mondragon..etc]

- Understanding the neutrino oscillation helps us to understand physics at the high energy or in the dark sector with a flavour symmetry model.
—> The measurement of neutrino oscillation parameters is important. *A messenger from the high-energy and dark-sector physics!!*
GOOD NEWS: We are entering in the precision-measurement era (<1% for 1σ precisions), e.g. DUNE, T2HK, JUNO, etc.

THE AIM OF THIS STUDY IS TO KNOW…

- Using tri-direct littlest seesaw as an example,

- 1. Is the precision of oscillation parameters good enough?
- 2. Why do we achieve the precision measurement?
- 3. How do we achieve the precision measurement?
- 4. What is the motivation for precision measurement from the point of view of flavour symmetry?

PRECISION MEASUREMENTS FROM THE PERSPECTIVE OF FLAVOUR SYMMETRY

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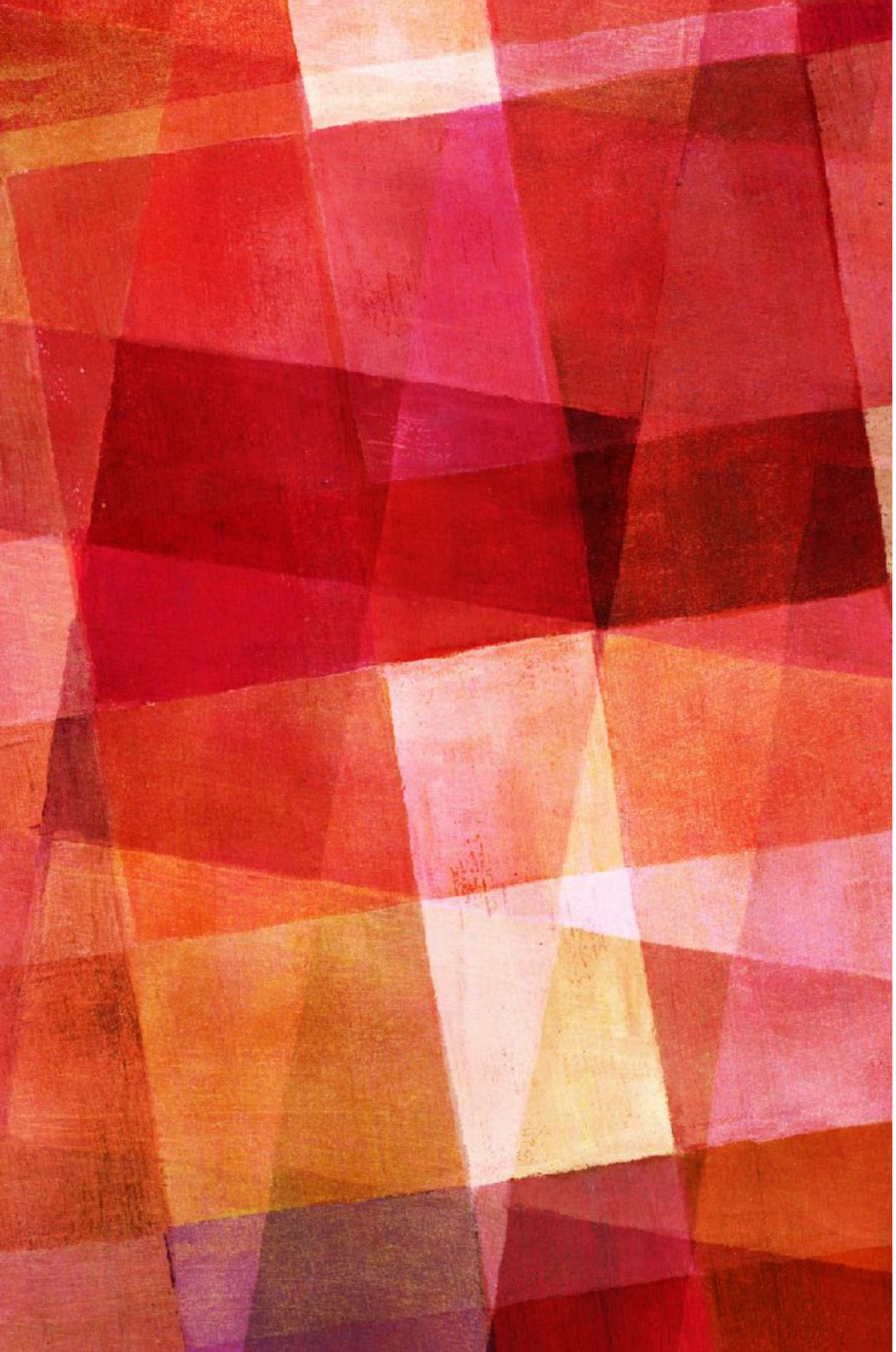


OUTLINE

- A flavour symmetry model in neutrino oscillations: tri-direct littlest seesaw models as example.
- Message 1 & 2
- Message 3 & 4
- Summary of messages and conclusions

OUTLINE

- A flavour symmetry model in neutrino oscillations: tri-direct littlest seesaw models as example.

King's talk this morning.

LITTLEST SEESAW FOR TRI-DIRECT APPROACH (TDLS)

- Proposed by Gui-Jun Ding, Stephen F. King, Cai-Chang Li.

JHEP 12 (2018) 003, arXiv:1807.07538 [hep-ph] .
Phys. Rev. D99 no. 7, (2019) 075035, arXiv:1811.12340 [hep-ph].

- Four parameters in the neutrino mass matrix.

$$m_\nu = m_a \begin{pmatrix} 1 & \omega & \omega^2 \\ \omega & \omega^2 & 1 \\ \omega^2 & 1 & \omega \end{pmatrix} + e^{i\eta} m_s \begin{pmatrix} 1 & x & x \\ x & x^2 & x^2 \\ x & x^2 & x^2 \end{pmatrix}$$

$\omega = e^{i2\pi/3}$

$$r \equiv m_s/m_a$$

Nufit 4.0

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$

JUNO · LBLs · JUNO · LBLs

$\Delta\chi^2$	x	η/π	r	m_a/ meV	$\theta_{12}/^\circ$	$\theta_{13}/^\circ$	$\theta_{23}/^\circ$	$\delta/^\circ$	$\Delta m^2_{21}/10^{-5}\text{eV}^2$	$\Delta m^2_{31}/10^{-3}\text{eV}^2$
~ 6.98	~ -3.65	~ 1.13	~ 0.511	~ 3.71	~ 35.25 !	~ 8.63	~ 46.98 !	~ 278.96 !	~ 7.39	~ 2.525

3σ allowed range: $-5.475 < x < -3.37,\ 0.455 < \eta/\pi < 1.545,$

$$0.204 < r < 0.606,\ 3.343 < m_a/\text{meV} < 4.597.$$

FLAVOUR SYMMETRY & OSCILLATIONS

Model Parameters

$x,\ \eta,\ r,\ m_a$

Predict ↓ ↑ **Constrain**

Oscillation Parameters

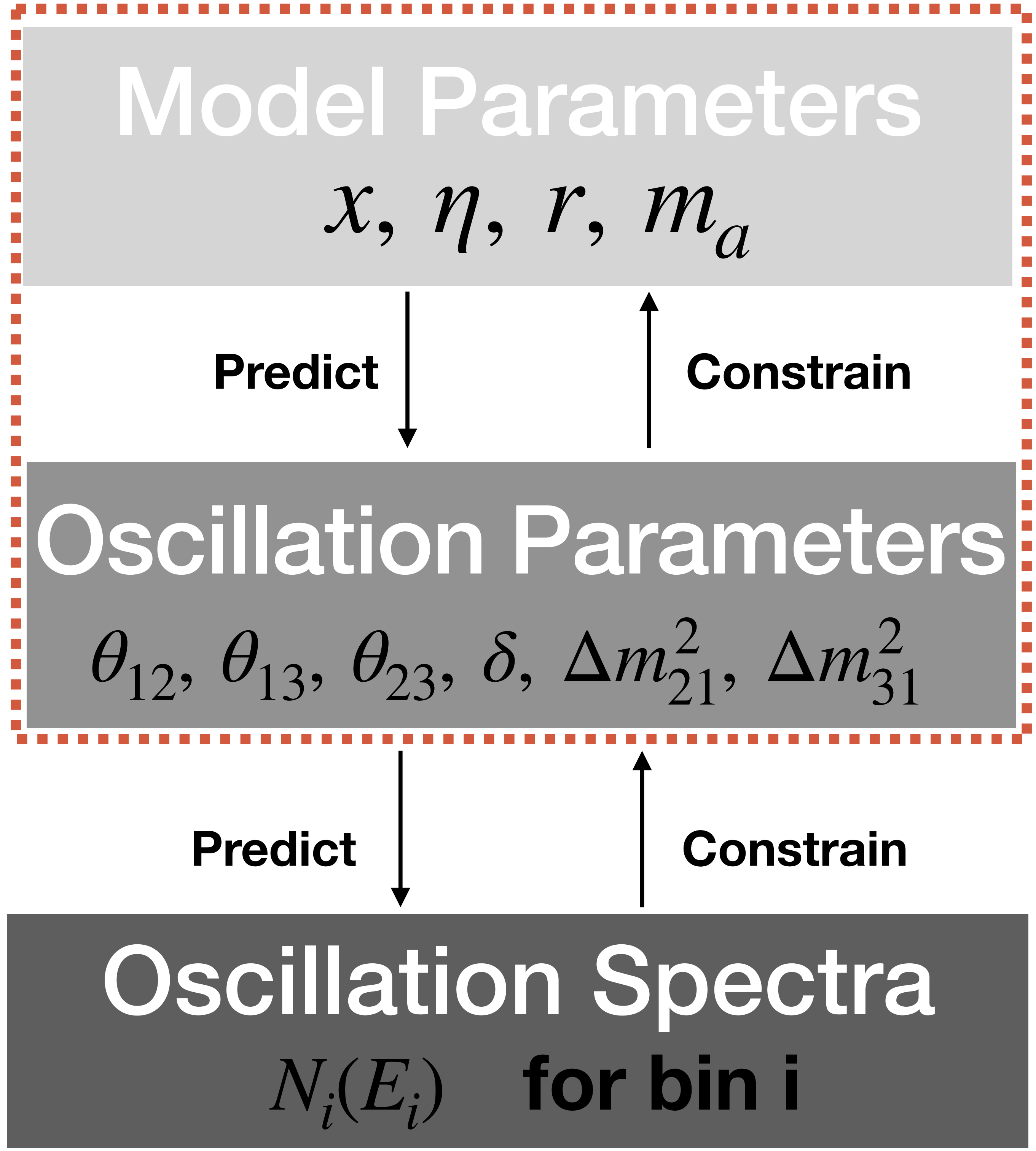
$\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta,\ \Delta m^2_{21},\ \Delta m^2_{31}$

Predict ↓ ↑ **Constrain**

Oscillation Spectra

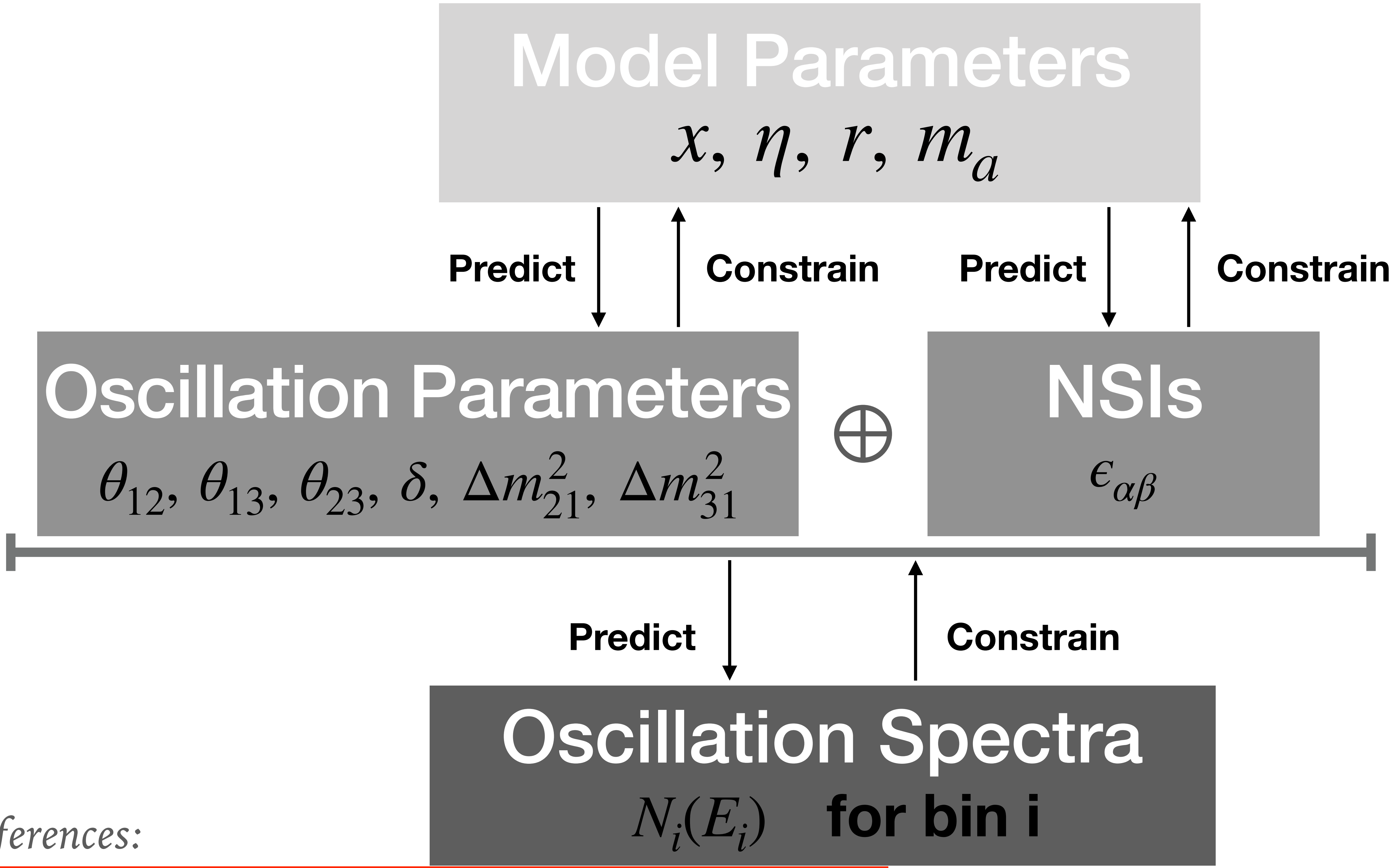
$N_i(E_i)$ **for bin i**

FLAVOUR SYMMETRY & OSCILLATIONS



We use a global-fit result to constrain model parameters.

FLAVOUR SYMMETRY & OSCILLATIONS WITH NONSTANDARD INTERACTIONS (NSIS)

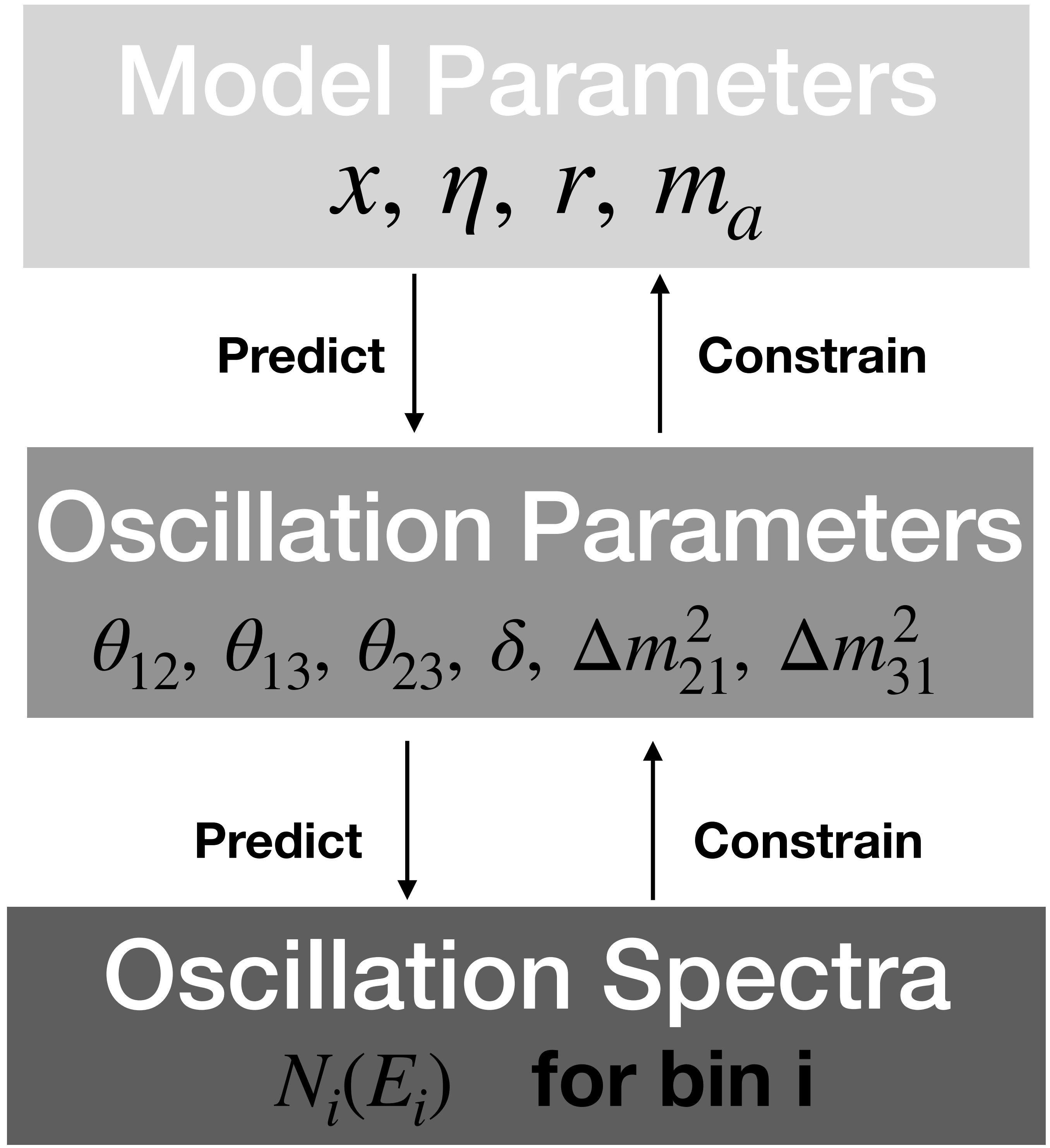


See references:

[1] T. Wang and Y. Zhou, PhysRevD.99.035039, 2019. → *Visit the non-abelian symmetry at NSIs for the first time.*

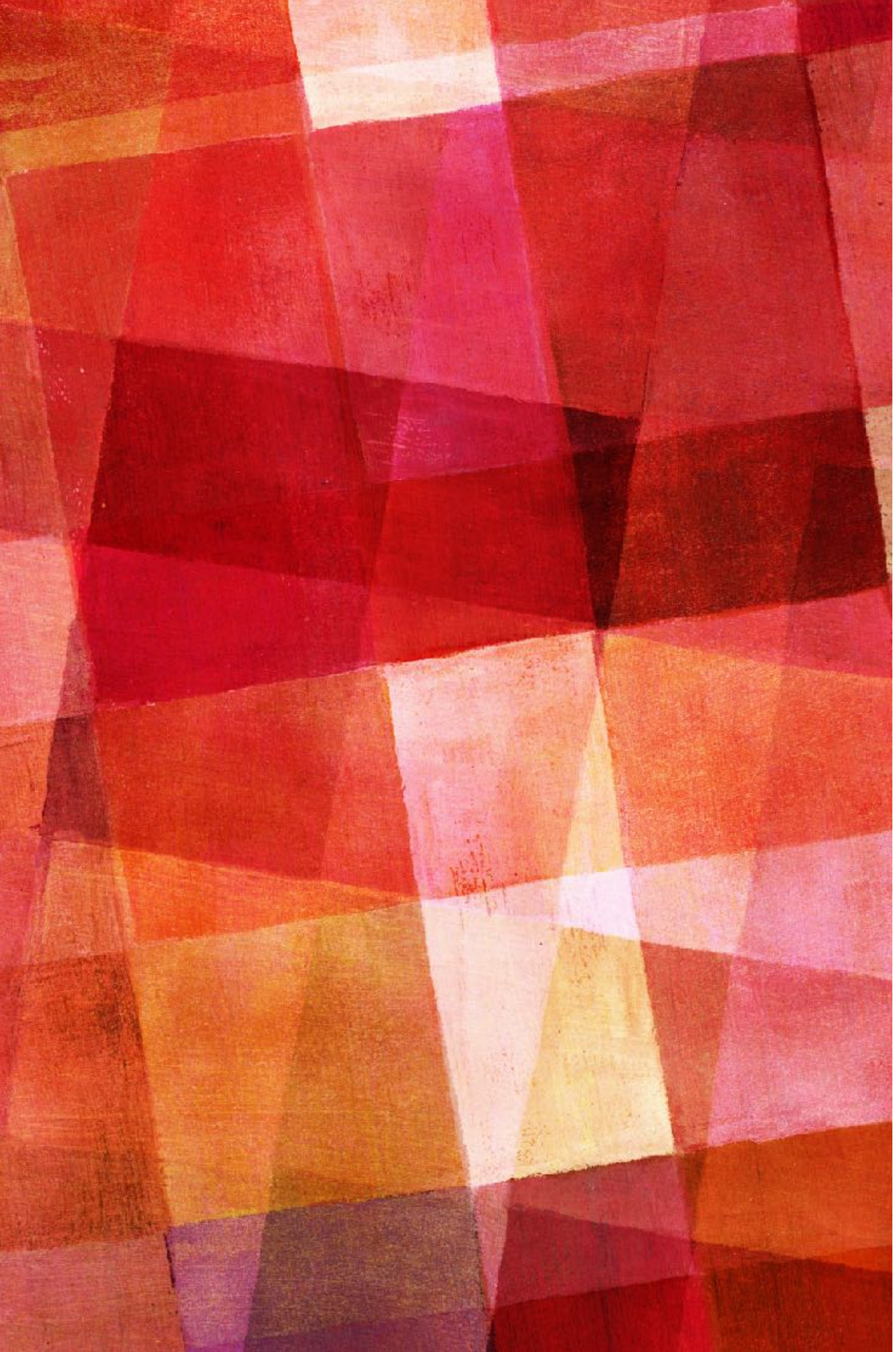
[2] J. Liao, N. Nath, T. Wang and Y. Zhou, coming soon.

IN THIS TALK WE FOCUS ON…



EXPERIMENTS

- ON-GOING (~2025):
  - Full-run NOvA: 36×10^{20} POT
  - Full-run T2K: 7.8×10^{21} POT
- UP-COMING (~2027):
  - 6-year JUNO
- UP-COMING (~2035):
  - 7-year DUNE: 1.47×10^{21} POT
  - 10-year T2HK: 2.5 $years\ \ for\ \ \nu +\ 7.5\ years\ \ for\ \ \bar{\nu}$
    $with\ \ a\ 1.3\ MW\ proton\ beam$
- UNDER-CONSIDERATION (2035~):
  - 10-year MOMENT: $5\ years\ \ for\ \ \nu +\ 5\ years\ \ for\ \ \bar{\nu}$
    $with\ 1.1 \times 10^{24}\ POT$



OUTLINE

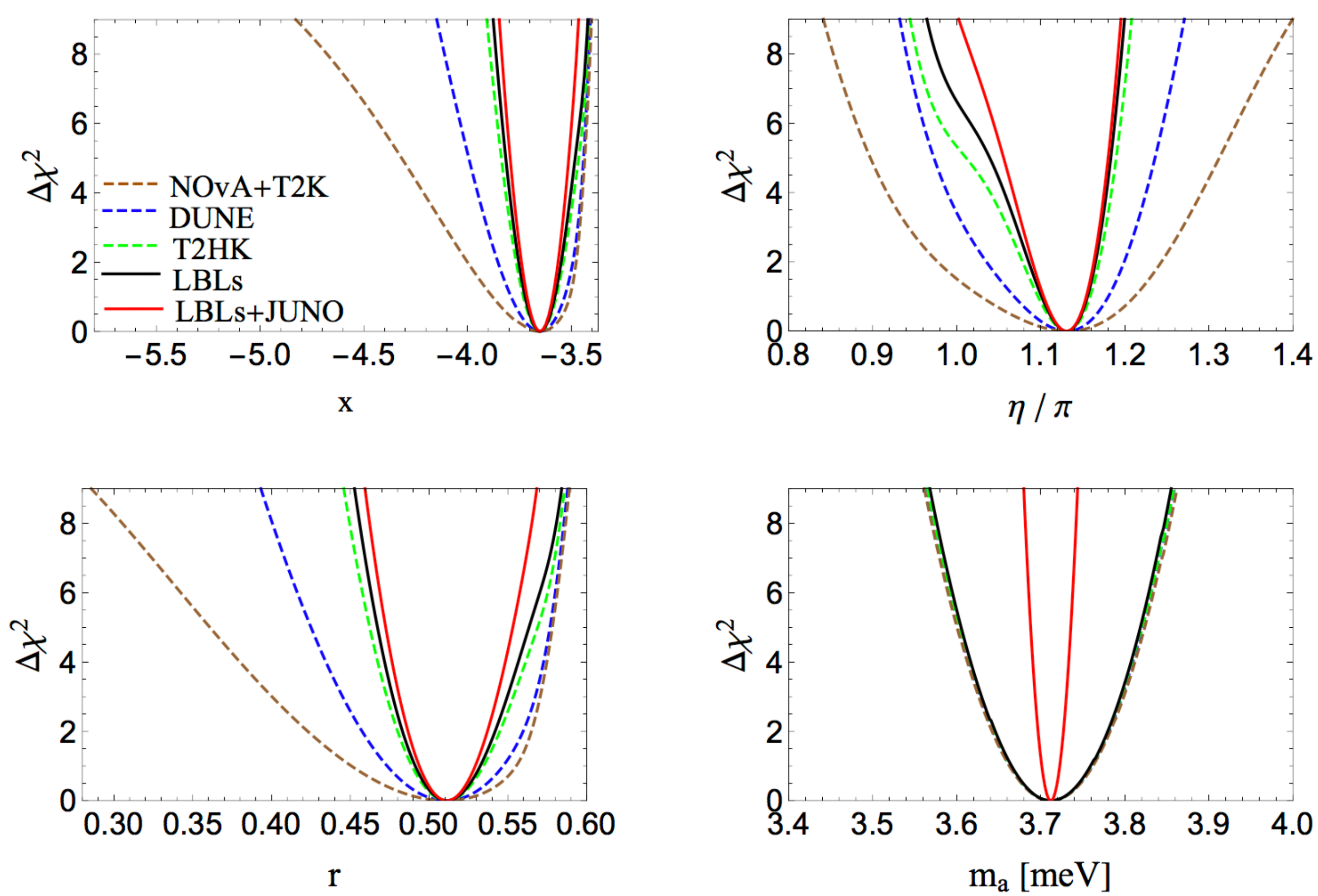
- A flavour symmetry model in neutrino oscillations: tri-direct littlest seesaw models as example.
- Message 1 & 2

LSTD IN THE NEAR FUTURE

- We consider full-run NOvA and T2K, DUNE, T2HK, JUNO, etc.
- Great improvements by combining all exps. is seen.

3σ allowed range with NuFit4.0: $-5.475 < x < -3.37, \; 0.455 < \eta/\pi < 1.545,$

$$0.204 < r < 0.606, \; 3.343 < m_a/\text{meV} < 4.597.$$



MESSAGE 1

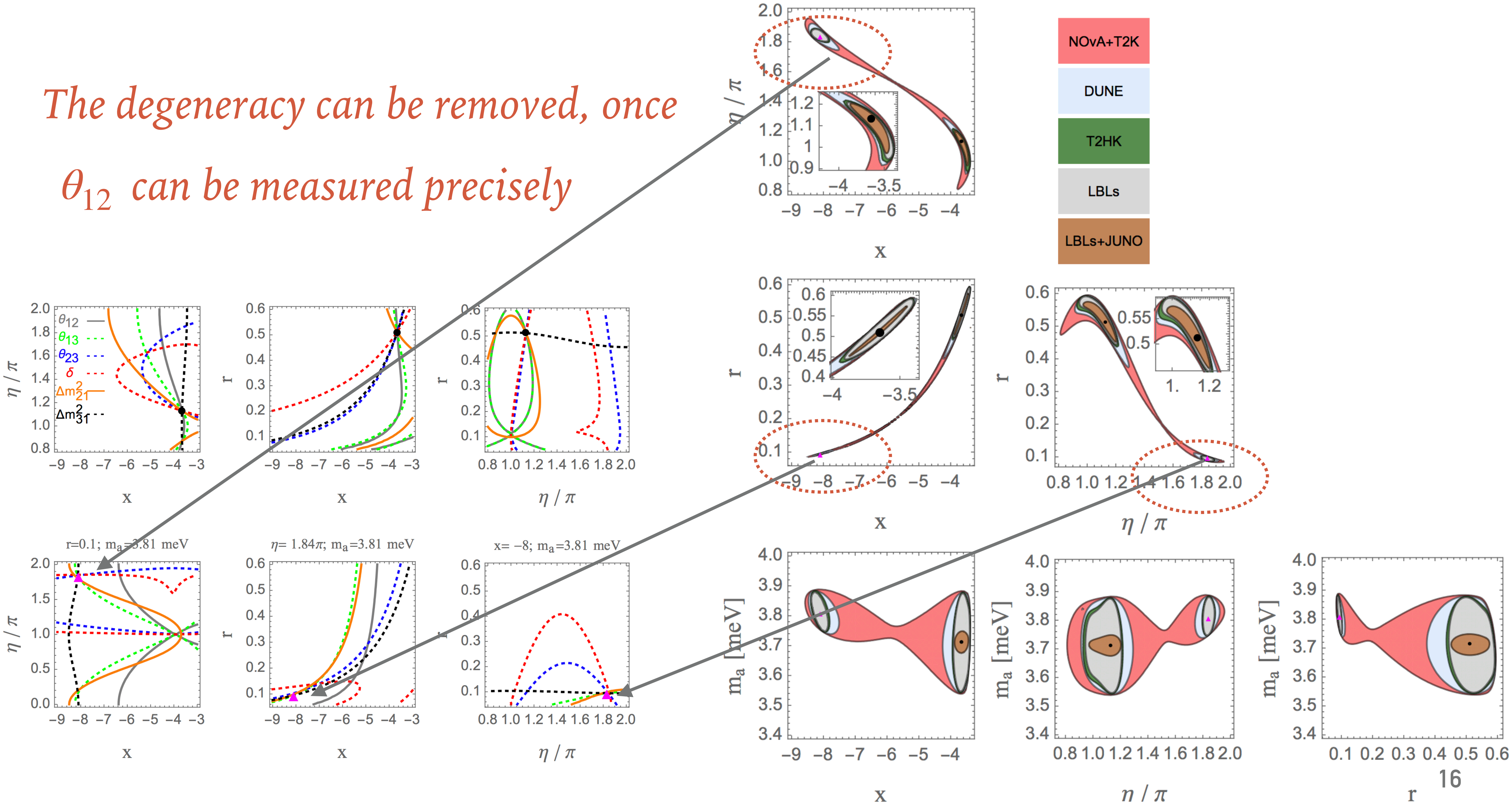
- 1. Understand the model better.

LSTD IN THE NEAR FUTURE

- We consider full-run NOvA and T2K, DUNE, T2HK, JUNO, etc.

The degeneracy can be removed, once

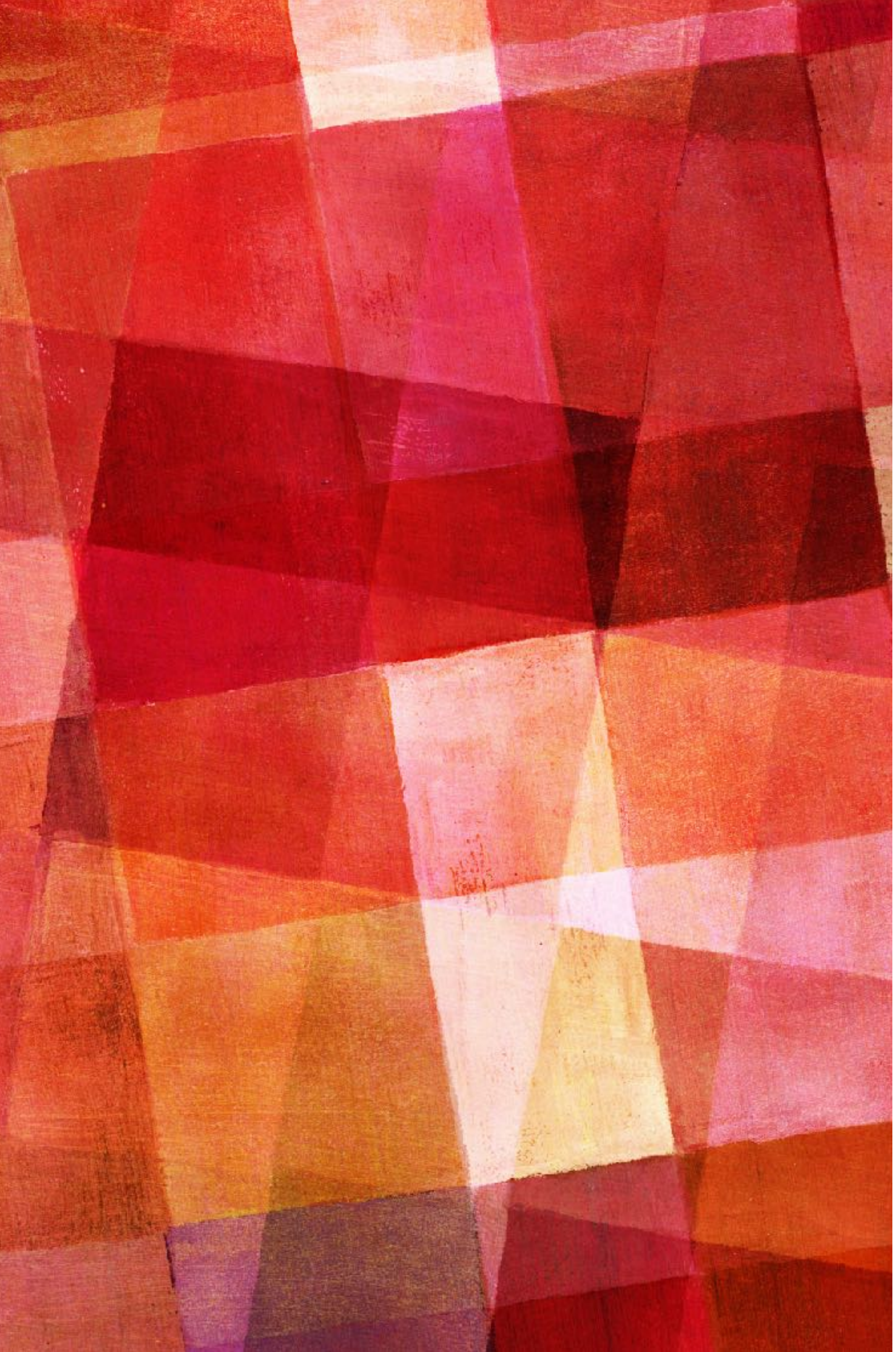
θ_{12} can be measured precisely



MESSAGE 1 & 2

- 1. Understand the model better.

- 2. Resolve the possible degeneracy problem.



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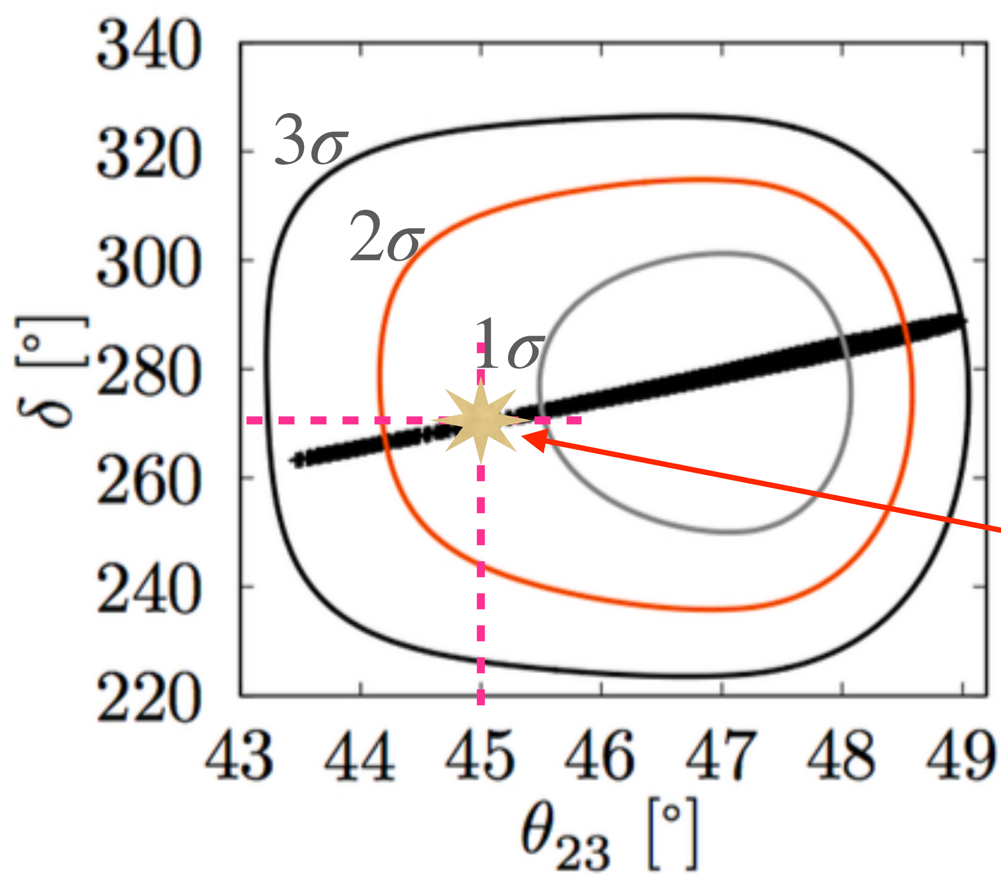
PROJECTION ON OSCILLATION PARAMETERS

- With simulated MOMENT data.
- We see the sum rule predicted by TDLS.



$$\cos\delta = \frac{\cot 2\theta_{23}\,[3x^2 - (4x^2 + x + 1)\cos^2\theta_{13}]}{\sqrt{3}\,|x|\sin\theta_{13}\sqrt{(5x^2+2x+2)\cos^2\theta_{13} - 3x^2}},$$

and

$$\sin\delta = \pm\csc 2\theta_{23}\sqrt{1 + \frac{(x^2+x+1)^2\cot^2\theta_{13}\cos^2 2\theta_{23}}{3x^2\,[3x^2\tan 2\theta_{13} - 2\,(x^2+x+1)]}},$$

with "+" for $x\cos\psi > 0$ and "−" for $x\cos\psi < 0$.

Considering $\theta_{23} \sim 45°$, we have

$$\cos\delta \propto \cot 2\theta_{23} = \frac{\cos 2\theta_{23}}{\sin 2\theta_{23}},$$
$$\sin\delta \propto \pm\csc 2\theta_{23} = \pm\frac{1}{\sin 2\theta_{23}}.$$

Therefore, we have

$$\tan\delta \propto 1/\cos 2\theta_{23}.$$

Cross: the projection of 3σ surface from model-parameter space to oscillation-parameter space.

Contour: without assuming TDLS.

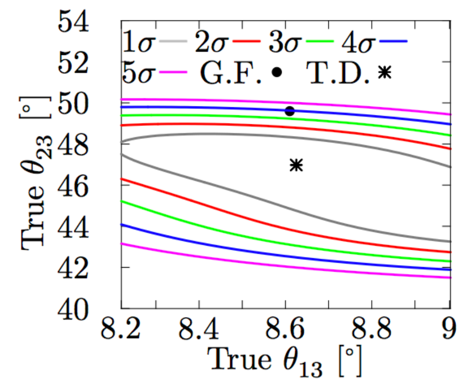
MESSAGE 3

- 3. Discover sum rules.

LSTD VS. THE MOMENT EXPERIMENT (MODEL EXCLUSION)

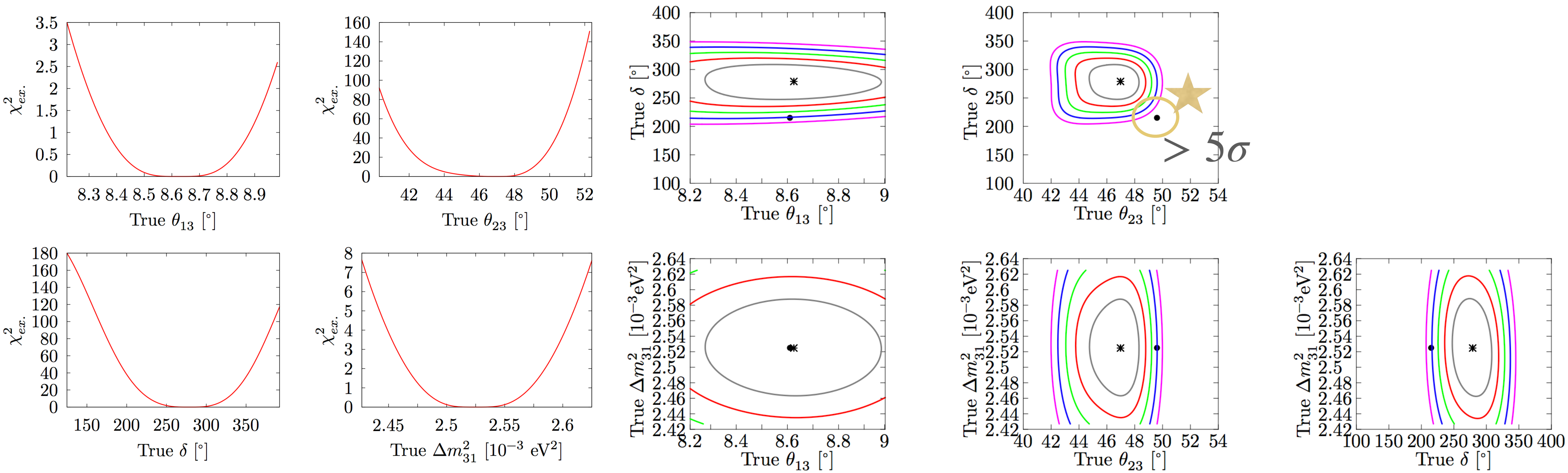
- θ_{23} and δ are the most important two parameters for MOMENT to exclude this model.

- If current best fit is confirmed, the exclusion can be $> 5\sigma$.



The current understanding.

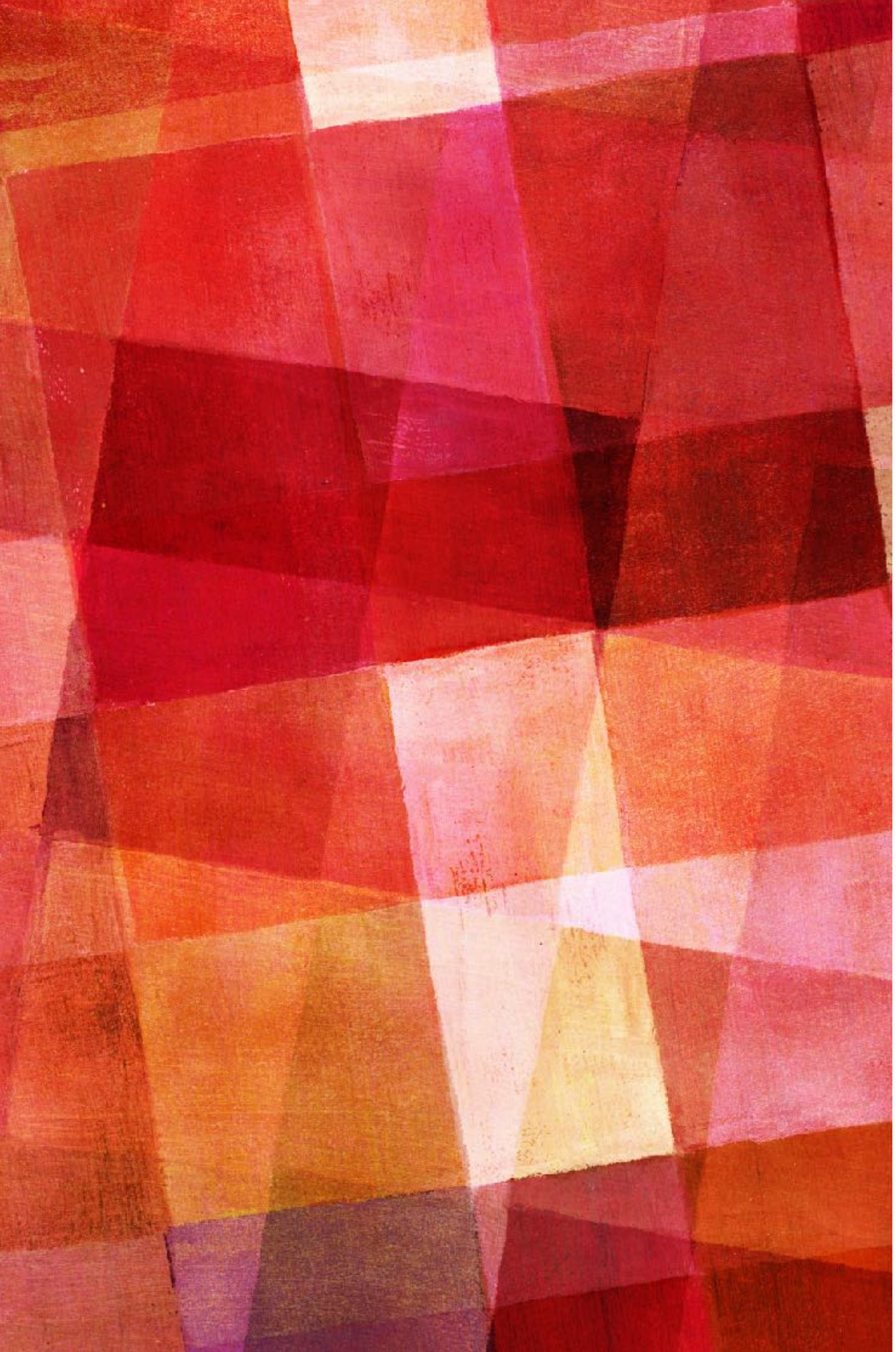
$\Delta\chi^2$	x	η/π	r	$m_a/$ meV
~ 6.98	~ -3.65	~ 1.13	~ 0.511	~ 3.71



MESSAGE 3 & 4

- 3. Discover sum rules.

- 4. Future LBLs well exclude those models that do not fit θ_{23} and δ in the global-fit result, e.g. littlest seesaw (P. Ballet, at. el., JHEP03(2017)110, arXiv: 1612.01999).



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- A flavour symmetry model in neutrino oscillations: tri-direct littlest seesaw models as example.
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SUMMARY: PRECISION MEASUREMENTS CAN…

- Message 1. Understand the model better.
- Message 2. Resolve the possible degeneracy problem.
- Message 3. Discover sum rules.
- Message 4. Future LBLs well exclude those models that do not fit θ_{23} and δ in the global-fit result.

SUMMARY AND CONCLUSION

- Message 1. Understand the model better.
- Message 2. Resolve the possible degeneracy problem.
- Message 3. Discover sum rules.
- Message 4. Future LBLs well exclude those models that do not fit θ_{23} and δ in the global-fit result.

- Conclusion:
  To better understand the flavour symmetry, we need to keep improving the precision of oscillation parameters.

Thank you very much for your attention!!

BACK-UP

MODEL PARAMETERS AND OSCILLATION PARAMETERS

model parameters	$x,\ \eta,\ r,\ m_a$
combinations of model parameters	$y = \frac{5x^2+2x+2}{2(x^2+x+1)}(m_a + e^{i\eta}m_s)$, $z = -\frac{\sqrt{5x^2+2x+2}}{2(x^2+x+1)}\left[(x+2)m_a - x(2x+1)e^{i\eta}m_s\right]$, $w = \frac{1}{2(x^2+x+1)}\left[(x+2)^2 m_a + x^2\left(2x+1\right)^2 e^{i\eta}m_s\right]$, $\sin\psi = \frac{\Im(y^*z+wz^*)}{\lvert y^*z+wz^*\rvert}, \quad \cos\psi = \frac{\Re(y^*z+wz^*)}{\lvert y^*z+wz^*\rvert}$. $\sin 2\theta = \frac{2\lvert y^*z+wz^*\rvert}{\sqrt{(\lvert w\rvert^2-\lvert y\rvert^2)^2+4\lvert y^*z+wz^*\rvert^2}}$, $\cos 2\theta = \frac{\lvert w\rvert^2-\lvert y\rvert^2}{\sqrt{(\lvert w\rvert^2-\lvert y\rvert^2)^2+4\lvert y^*z+wz^*\rvert^2}}$.
oscillation parameters	$\Delta m_{21}^2 = m_2^2 = \frac{1}{2}\left[\lvert y\rvert^2 + \lvert w\rvert^2 + 2\lvert z\rvert^2 - \frac{\lvert w\rvert^2-\lvert y\rvert^2}{\cos\theta}\right]$, $\Delta m_{31}^2 = m_3^2 = \frac{1}{2}\left[\lvert y\rvert^2 + \lvert w\rvert^2 + 2\lvert z\rvert^2 + \frac{\lvert w\rvert^2-\lvert y\rvert^2}{\cos\theta}\right]$, $\sin^2\theta_{12} = 1 - \frac{3x^2}{3x^2+2(x^2+x+1)\cos^2\theta}$, $\sin^2\theta_{13} = \frac{2\left(x^2+x+1\right)\sin^2\theta}{5x^2+2x+2}$, $\sin^2\theta_{23} = \frac{1}{2} + \frac{x\sqrt{3(5x^2+2x+2)}\sin 2\theta\sin\psi}{2[3x^2+2(x^2+x+1)\cos^2\theta]}$, $\cos\delta = \frac{\cot 2\theta_{23}\left[3x^2-\left(4x^2+x+1\right)\cos^2\theta_{13}\right]}{\sqrt{3}\lvert x\rvert\sin\theta_{13}\sqrt{(5x^2+2x+2)\cos^2\theta_{13}-3x^2}}$, $\sin\delta = \pm\csc 2\theta_{23}\sqrt{1 + \frac{(x^2+x+1)^2\cot^2\theta_{13}\cos^2 2\theta_{23}}{3x^2[3x^2\tan^2\theta_{13}-2(x^2+x+1)]}}$.

LSTD VS. THE MOMENT EXPERIMENT (MODEL PARA. CONSTRAIN)

- MOMEN can improve the 3σ uncertainty by at least 50% compared to our current understanding.
- The degeneracy is also seen.