Neutrino Physics in the New Era

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(IHEP, Beijing)

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History of Neutrino Oscillations

60 years (1956-2016)

1930 neutrino hypothesis by Pauli

1934 an effective theory for weak interactions by Fermi

1956 electron antineutrinos $\bar{\nu}_e$ discovered by Cowan and Reines

1957 neutrino-antineutrino transitions proposed by Pontecorvo

1962 the 2nd family of neutrinos $\nu_\mu/\bar{\nu}_\mu$ by Lederman, Schwarz & Steinberger

1962 neutrino flavor conversions proposed by Maki, Nakagawa & Sakata

1968 solar neutrinos ν_e detected by Davis & solar neutrino problem

1998 deficit of atmospheric neutrinos $\nu_\mu/\bar{\nu}_\mu$ in Super-Kamiokande (Kajita)

2000 the 3rd family of neutrinos $\nu_\tau/\bar{\nu}_\tau$ discovered in DONUT

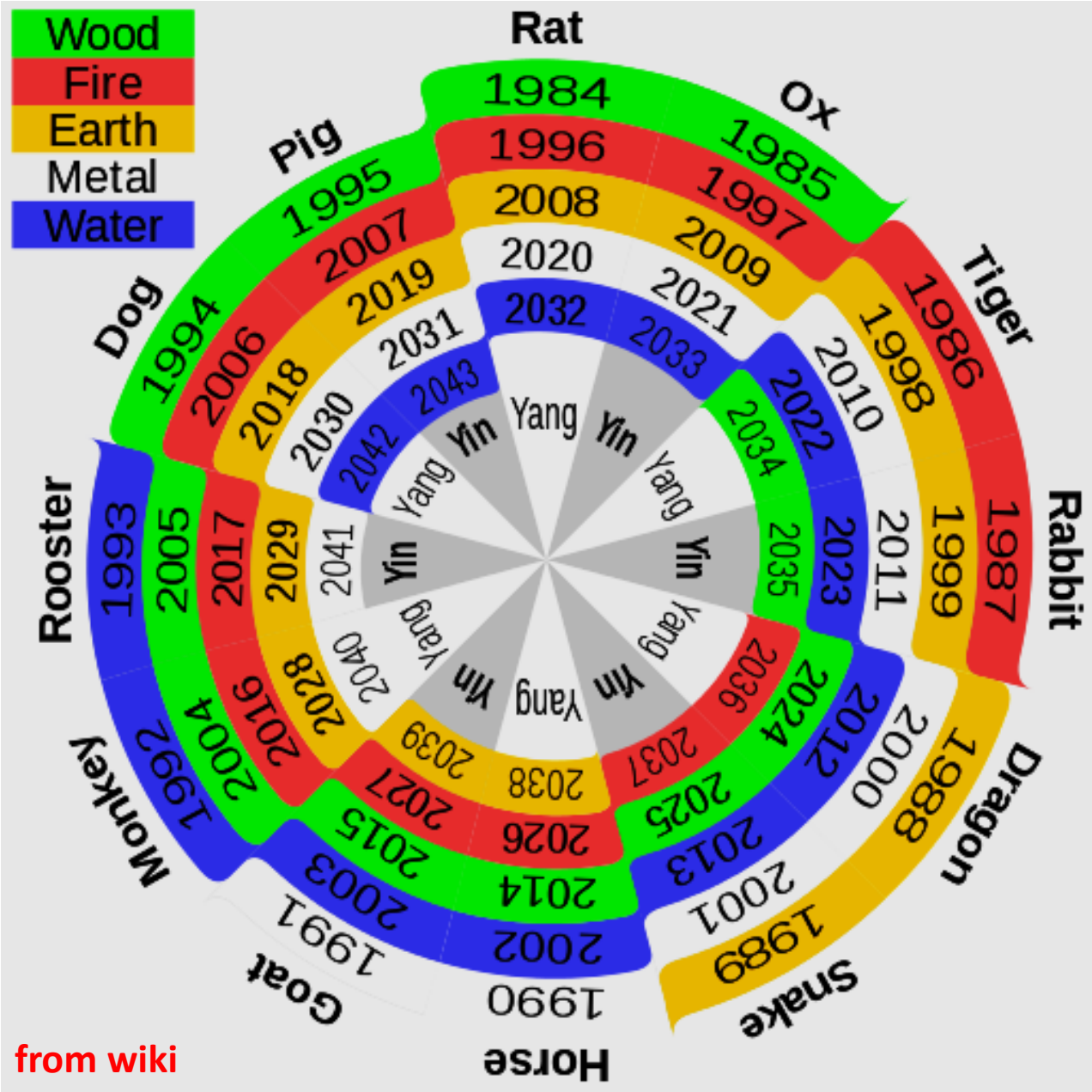
2001 solar ν_e and ν_μ/ν_τ neutrinos found in SNO (McDonald)

2002 KamLAND selects the LMA-MSW solution to solar neutrino problem

2004 K2K & MINOS confirms the disappearance of atmospheric neutrinos

2012 reactor antineutrino disappearance discovered by Daya Bay

The Chinese Sexagenary Cycle



Heavenly Stem 天干	Earthly Branch 地支
甲 Jia	子 Zi
乙 Yi	丑 Chou
丙 Bing	寅 Yin
丁 Ding	卯 Mao
戊 Wu	辰 Chen
己 Ji	巳 Si
庚 Geng	午 Wu
辛 Xin	未 Wei
壬 Ren	申 Shen
癸 Gui	酉 You
	戌 Xu
	亥 Hai

1956 丙申

2016 丙申

a new cycle of 60 years!

What we have learned?

Standard Parametrization of the PMNS Matrix

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$
$|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

Atmospheric,
LBL accelerator

$\theta_{13} \sim 9^\circ$
$\delta \sim ?$

Reactor,
LBL accelerator

$\theta_{12} \sim 34^\circ$
$\Delta m^2_{21} \sim 8 \times 10^{-5}\ \mathrm{eV}^2$

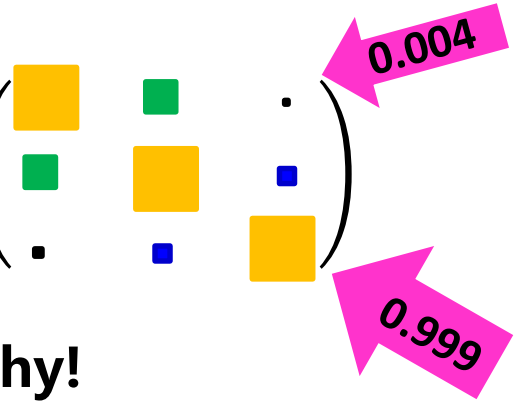
Solar,
KamLAND

0ν2β, LNV?

Quarks vs. Leptons: A big puzzle of fermion flavor mixings

CKM

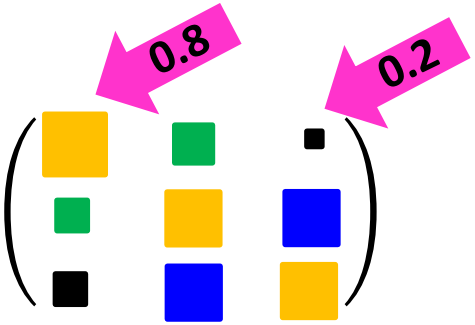
$|U| =$



Hierarchy!

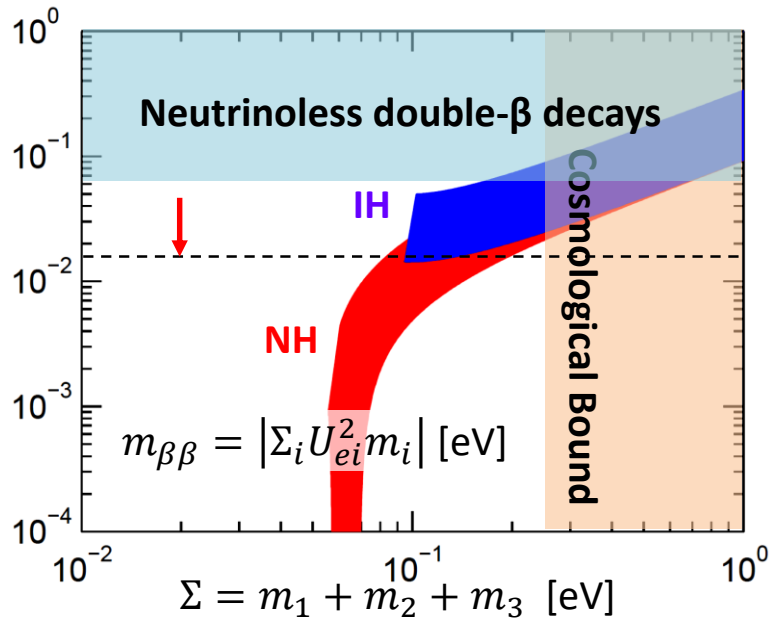
PMNS

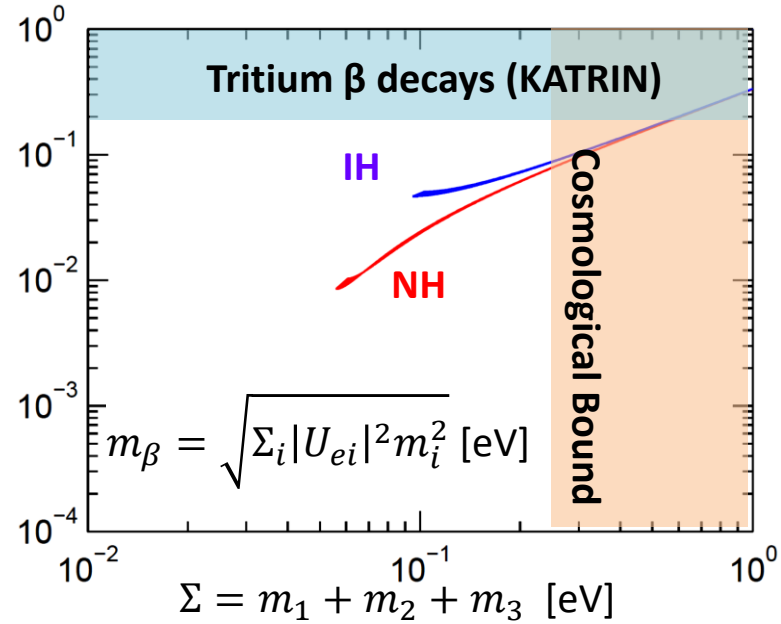
$|V| =$



Approximate μ-τ symmetry?

What we have learned?

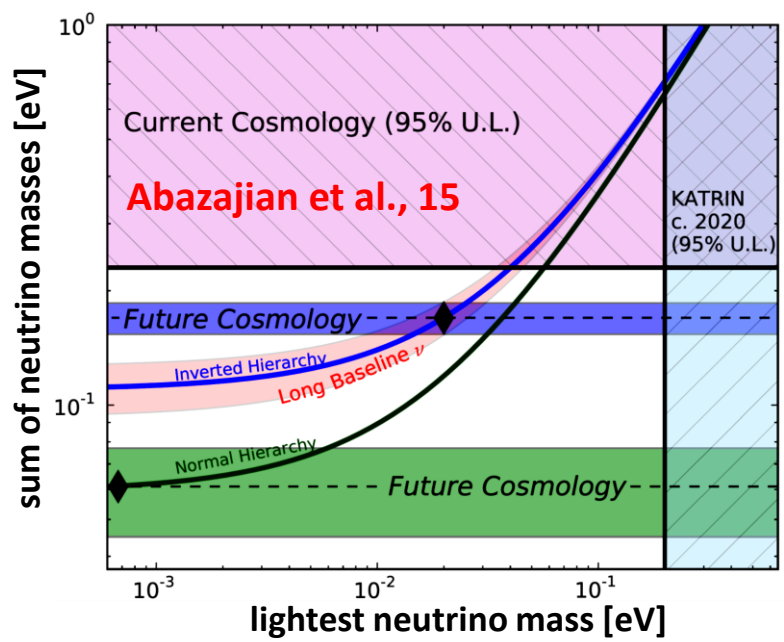




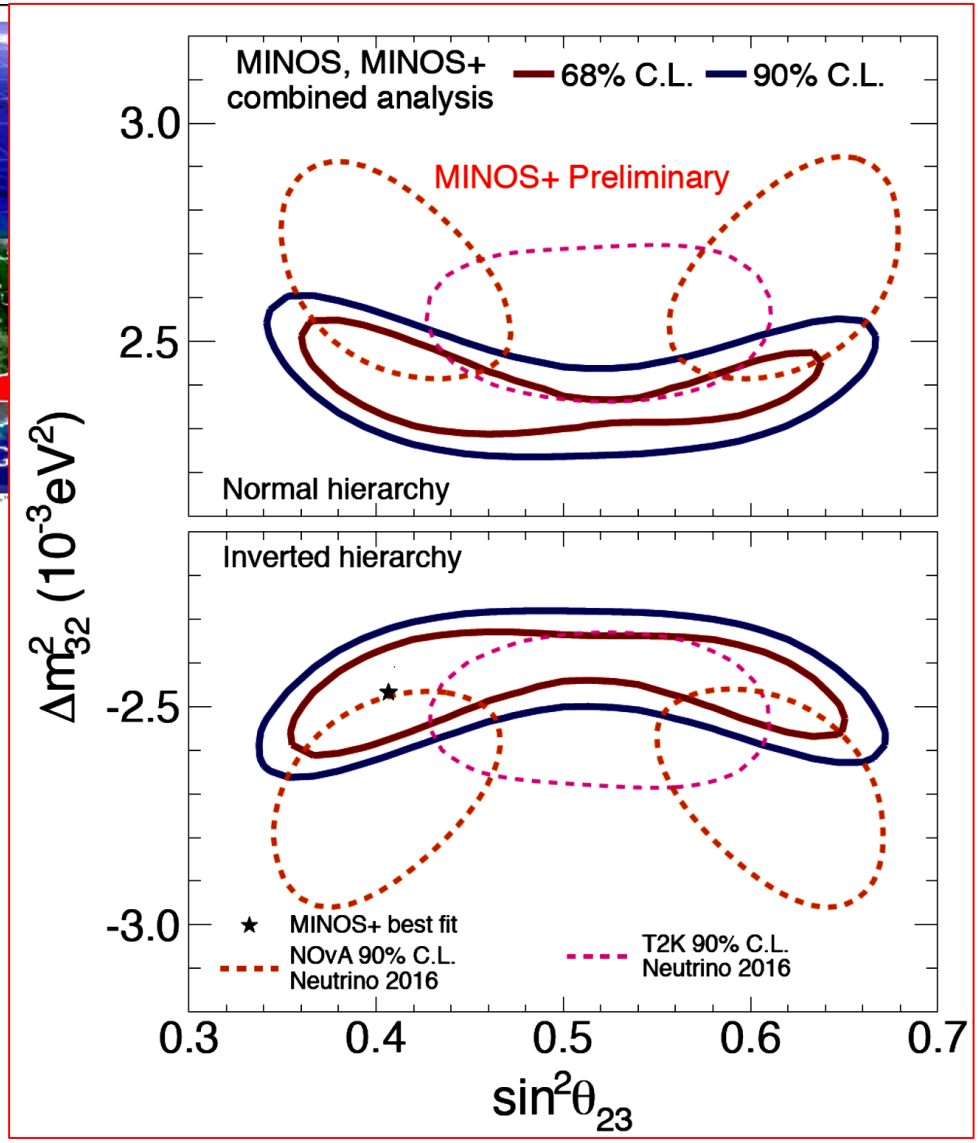
$m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH)

Constraints on absolute neutrino masses

- **Tritium β decays (95% C.L.)**
  $m_\beta < 2.3$ eV (Mainz)
  2.1 eV (Troitzk)
- **Neutrinoless double-β decays (90% C.L.)**
  $m_{\beta\beta} < (0.06 \sim 0.16)$ eV (KamLAND-Zen)
  $(0.19 \sim 0.45)$ eV (EXO-200)
  $(0.22 \sim 0.64)$ eV (GERDA)
- **Cosmological observations (95% probability)**
  $\Sigma < 0.23$ eV (Planck)



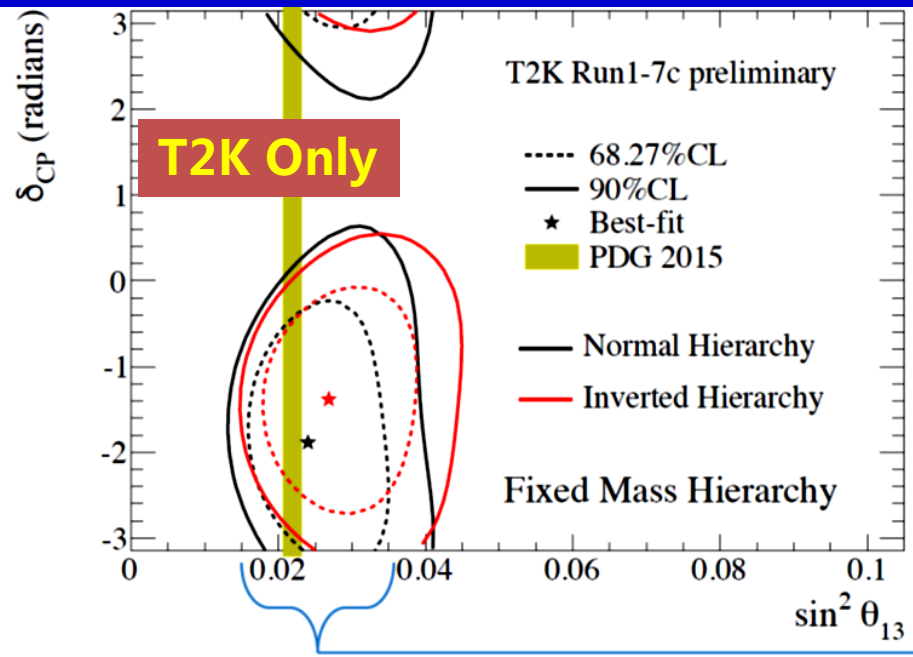
News from Neutrino & ICHEP 2016

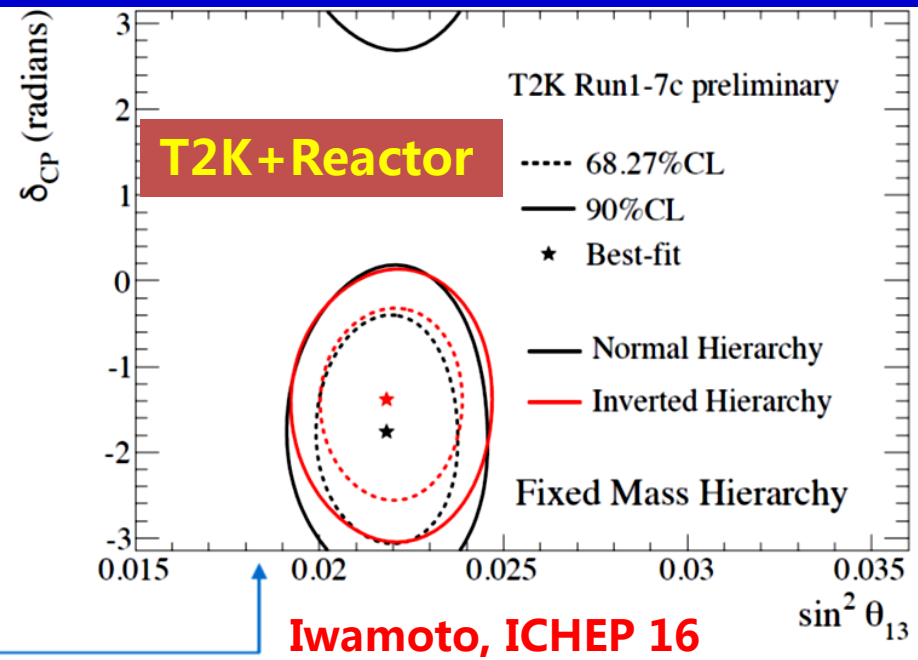


T2K favors a maximal mixing angle $\theta_{23} \sim 45^\circ$, while NOvA & MINOS not

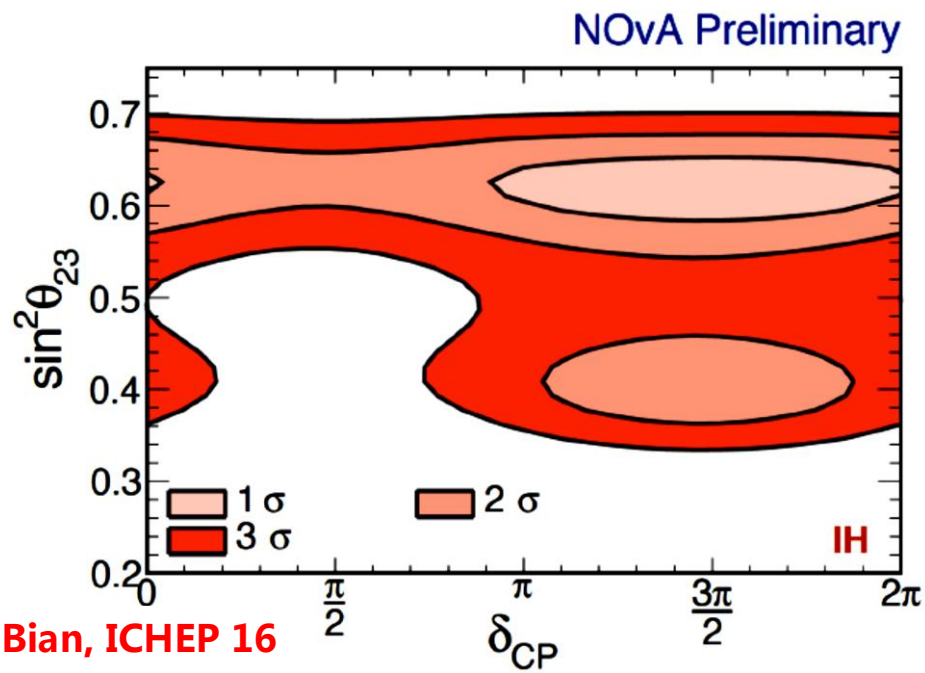
Evans, Neutrino 16; Sanchez, ICHEP 16

News from Neutrino & ICHEP 2016





Iwamoto, ICHEP 16



Bian, ICHEP 16

T2K Results

- T2K-only consistent reactor data
- maximal mixing $\theta_{23} = 45^\circ$ favored
- maximal CP phase $\delta = -90^\circ$ favored

NOvA Results

- maximal mixing $\theta_{23} = 45^\circ$ excluded @ 2.5σ
- NH, $\delta \sim -90^\circ$ and $\theta_{23} \sim 39^\circ$ favored
- IH and $\delta \sim 90^\circ$ for $\theta_{23} < 45^\circ$ excluded @ 3σ

Results from Global-fit Analysis

Gonzalez-Garcia et al., NuFIT 2.1 (2016)

LID	Normal Ordering ($\Delta\chi^2 = 0.55$)		Inverted Ordering (best fit)		Any Ordering
$\sin^2\theta_{12}$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.308^{+0.013}_{-0.012}$	$0.273 \to 0.349$	$0.273 \to 0.349$
$\theta_{12}/^\circ$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$33.72^{+0.79}_{-0.76}$	$31.52 \to 36.18$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.451^{+0.038}_{-0.025}$	$0.387 \to 0.634$	$0.576^{+0.023}_{-0.033}$	$0.393 \to 0.636$	$0.389 \to 0.636$
$\theta_{23}/^\circ$	$42.2^{+2.2}_{-1.4}$	$38.5 \to 52.8$	$49.4^{+1.4}_{-1.9}$	$38.8 \to 52.9$	$38.6 \to 52.9$
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0010}$	$0.0188 \to 0.0249$	$0.0219^{+0.0010}_{-0.0010}$	$0.0189 \to 0.0250$	$0.0189 \to 0.0250$
$\theta_{13}/^\circ$	$8.50^{+0.19}_{-0.20}$	$7.87 \to 9.08$	$8.51^{+0.20}_{-0.20}$	$7.89 \to 9.10$	$7.89 \to 9.10$
$\delta_{CP}/^\circ$	303^{+39}_{-50}	$0 \to 360$	262^{+51}_{-57}	$98 \to 416$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.49^{+0.19}_{-0.17}$	$7.02 \to 8.08$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.477^{+0.042}_{-0.042}$	$+2.351 \to +2.610$	$-2.465^{+0.041}_{-0.043}$	$-2.594 \to -2.339$	$\begin{bmatrix} +2.355 \to +2.606 \\ -2.594 \to -2.339 \end{bmatrix}$
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range

Neutrino Mass Ordering

- Reactor: JUNO, RENO-50
- LBL Acc.: T2K, NOνA, LBNF/DUNE
- Atm: PINGU, ORCA, Hyper-K, INO

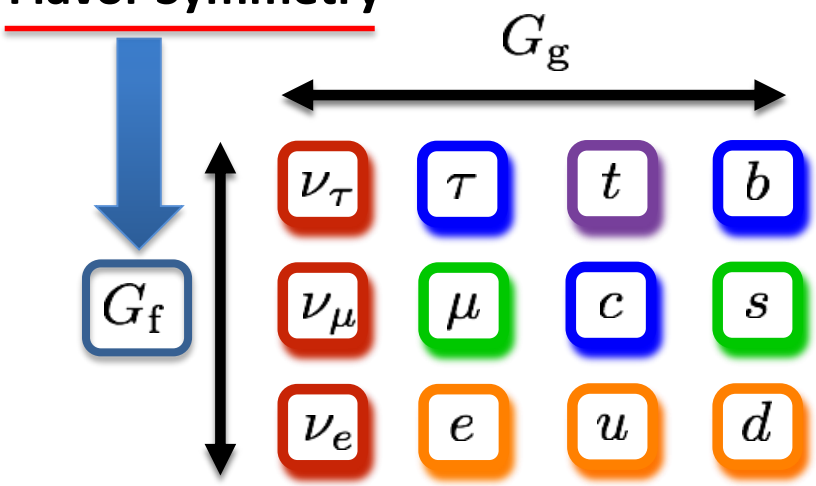
Leptonic CP Violation

- LBL Acc.: LBNF/DUNE
- Super-B: ESSνSB, MOMENT
- NF & Beta-Beams

Absolute Masses: KATRIN, 0ν2β (e.g., ^{136}Xe & ^{76}Ge), cosmology, …

Origin of Flavor Mixing

Flavor Symmetry

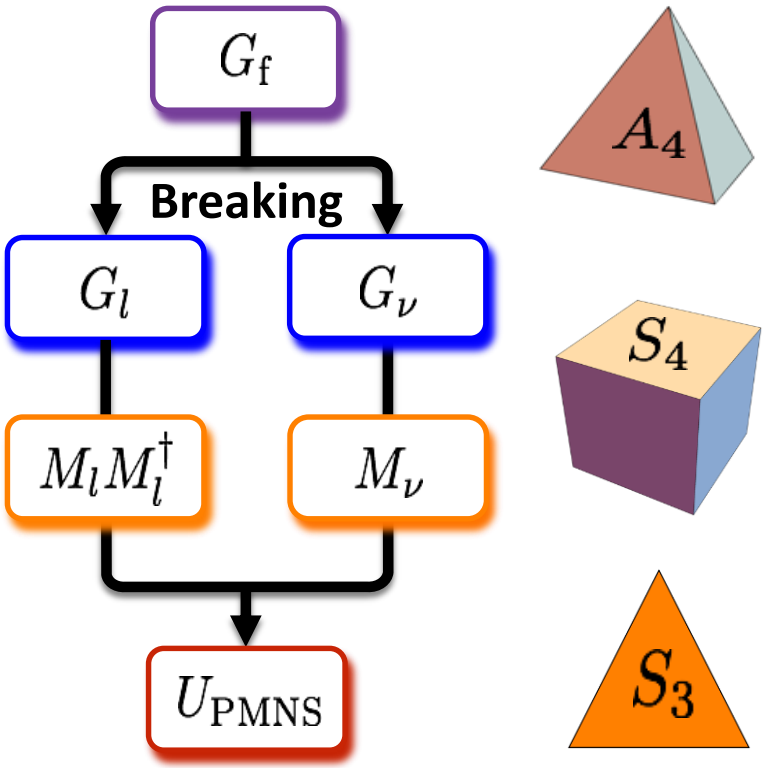


Tri-bimaximal neutrino mixing matrix

Harrison, Pekins, Scott, 02; Xing, 02; He, Zee, 03

$$V_0 = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Paradigm of flavor symmetries



PMNS matrix is (partially) determined by the structure of symmetry groups

See, Ishimori et al., 10; Altarelli, Feruglio, 10; King et al., 14, for recent reviews

Origin of Flavor Mixing

Inspired by the quark-lepton relations in GUT's, and strong quark mass hierarchy

Antusch, Maurer, 11; Mazocca et al., 11; King, 12; Antusch et al., 12, 13

$$\frac{m_u}{m_c} \approx \frac{m_c}{m_t} \approx \lambda^4, \qquad \frac{m_d}{m_s} \approx \frac{m_s}{m_b} \approx \lambda^2$$

$$\theta_{12}^{\mathrm{d}} \approx \theta_{\mathrm{C}}$$

M_{u} ⟷ M_{d}

$$V_{\mathrm{CKM}} = V_{\mathrm{u}}^{\dagger} V_{\mathrm{d}}$$

GUT relations $\left(\frac{m_\tau}{m_b} = c_{33} = 1, \frac{3}{2}\right)$

c_{ij}: **Clebsch factors**

M_{ν} ⟷ M_{l}

$$V_{\mathrm{PMNS}} = V_{l}^{\dagger} V_{\nu}$$

$$\theta_{12}^{l} \approx \frac{c_{12}}{c_{22}} \theta_{12}^{\mathrm{d}} \approx \frac{c_{12}}{c_{22}} \theta_{\mathrm{C}}$$

Tri-bimaximal or Bimaximal mixing for V_ν

$$V_\nu = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \quad \text{with } \theta_{13}^{\nu} = 0$$

Model predictions

(a) Quark-Lepton Complementarity

$$\theta_{13} = \frac{\theta_{12}^{l}}{\sqrt{2}} = \frac{\theta_{\mathrm{C}}}{\sqrt{2}}$$

(b) Sum Rule for mixing parameters

$$\theta_{12} = \theta_{12}^{\nu} + \theta_{13} \cos\delta$$

Part A: Era of Precision Measurements

Example (1)

Two-zero Textures of M_ν

Frampton, Glashow, Marfatia, 02; Xing, 02; Fritzsch, Xing, Zhou, 11

$$A_1 \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix} \qquad A_2 \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

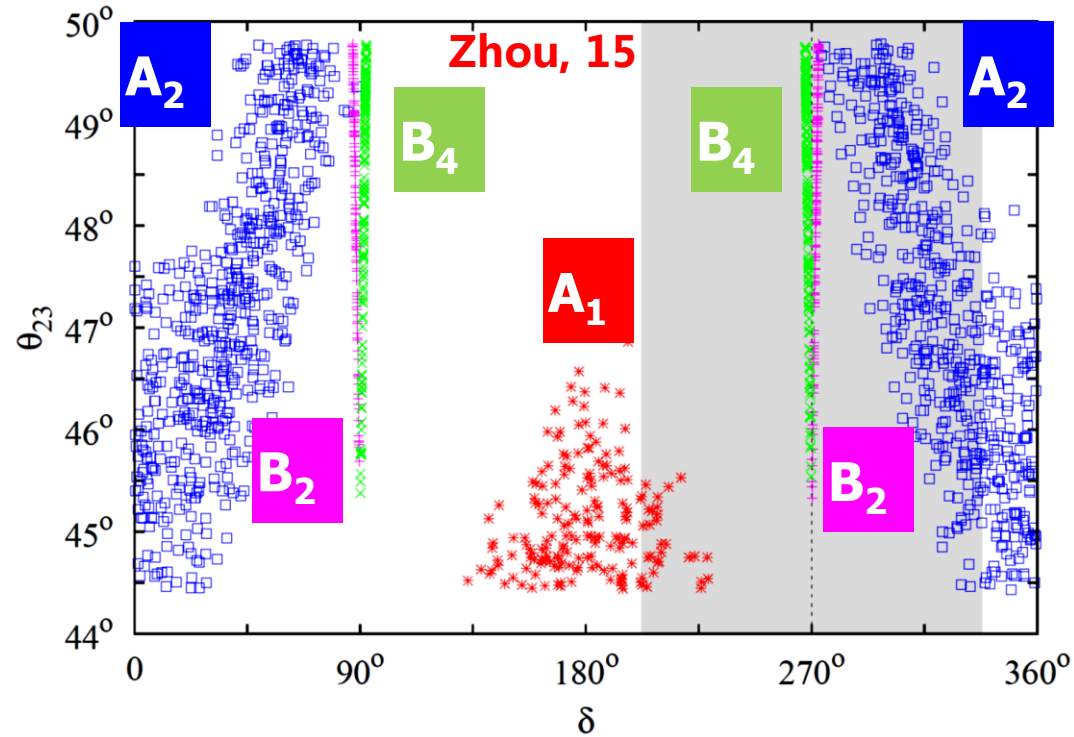
$$B_1 \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \qquad B_2 \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$B_3 \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix} \qquad B_4 \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$$

$$C \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Consistent with nonzero θ_{13} & can be realized by A_4 symmetry

(a) NH; (b) θ_{23}>45°; (c) δ ~ 270°

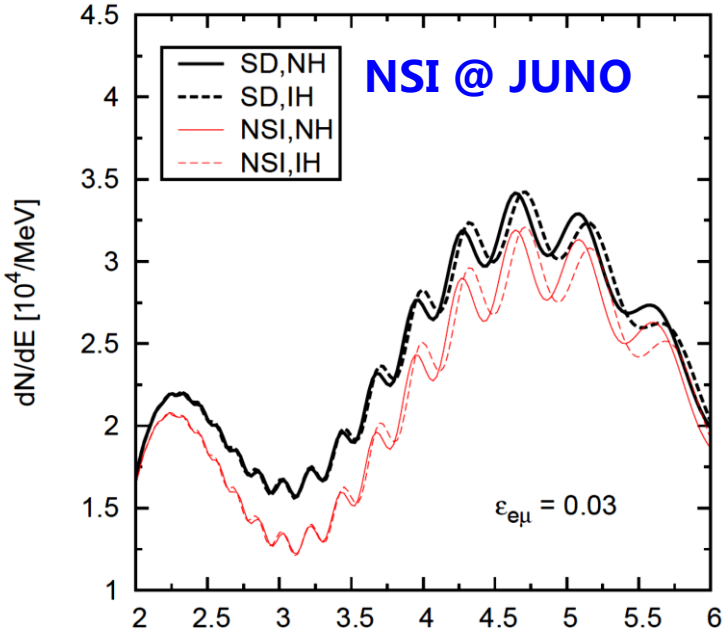


Model building in the type-I+II seesaw model

$l_{\alpha L}$	$E_{\alpha R}$	N_R	Φ_i	φ, ϕ	Δ
1,1',1''	3	1	3	1,1'	1

$$M_\nu = u \begin{pmatrix} 0 & 0 & a_\Delta \\ 0 & b_\Delta & 0 \\ a_\Delta & 0 & 0 \end{pmatrix} - \frac{v^2}{M} \begin{pmatrix} a_\nu^2 & 0 & 0 \\ 0 & 0 & b_\nu c_\nu \\ 0 & b_\nu c_\nu & 0 \end{pmatrix}$$

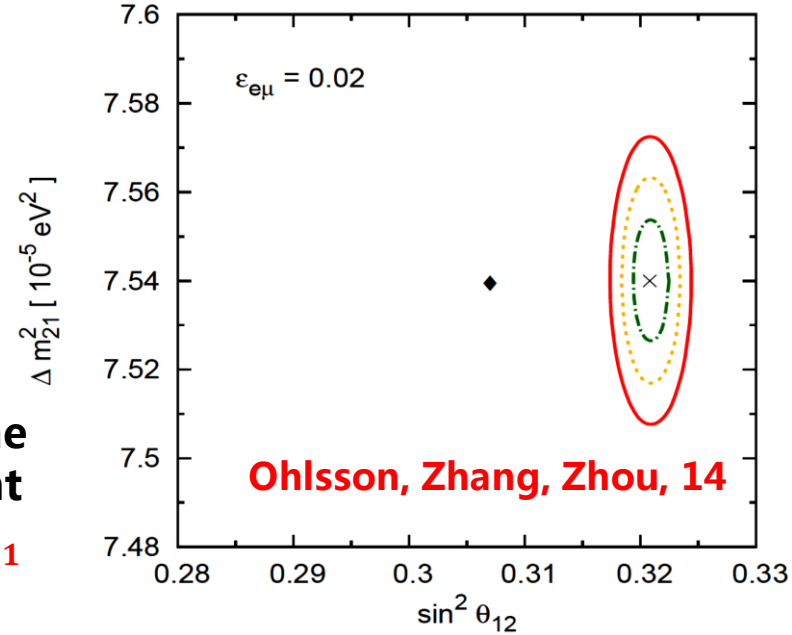
Part A: Era of Precision Measurements

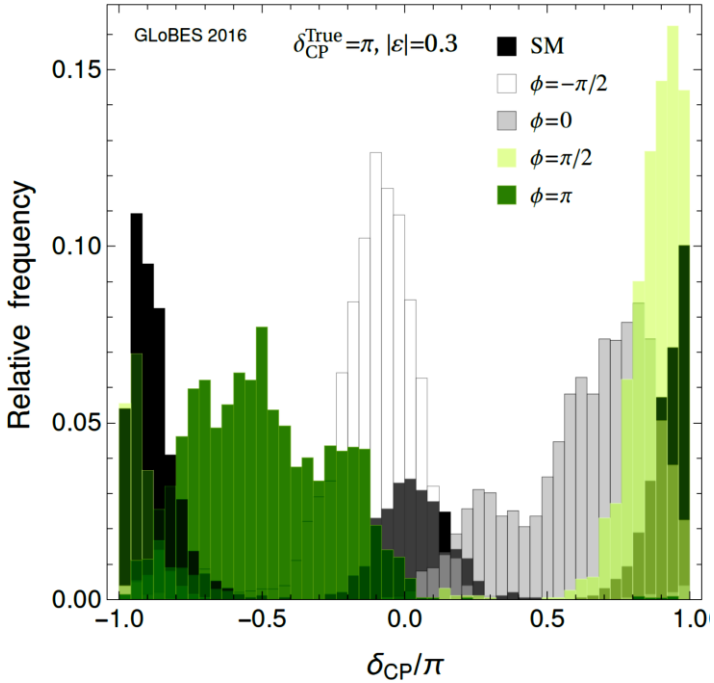


Example (2)

Non-standard Interactions at both sources and detectors for JUNO:

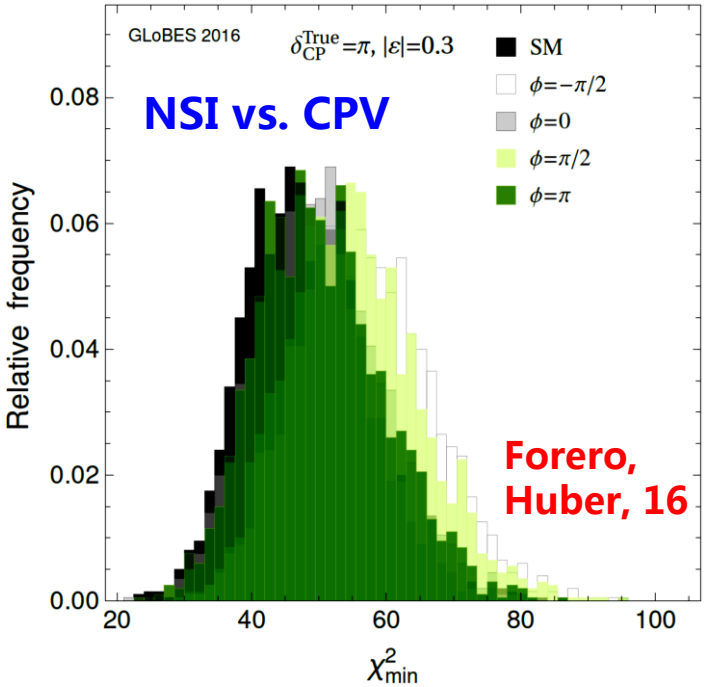
- **Impact on the measurement of θ_{12} & Δm^2_{21}**



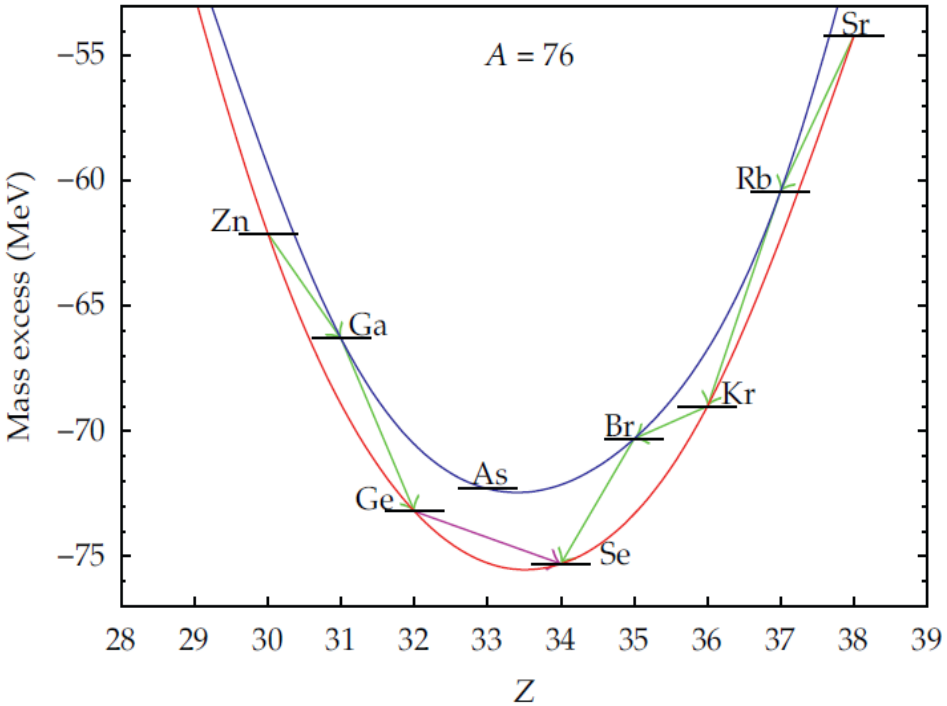


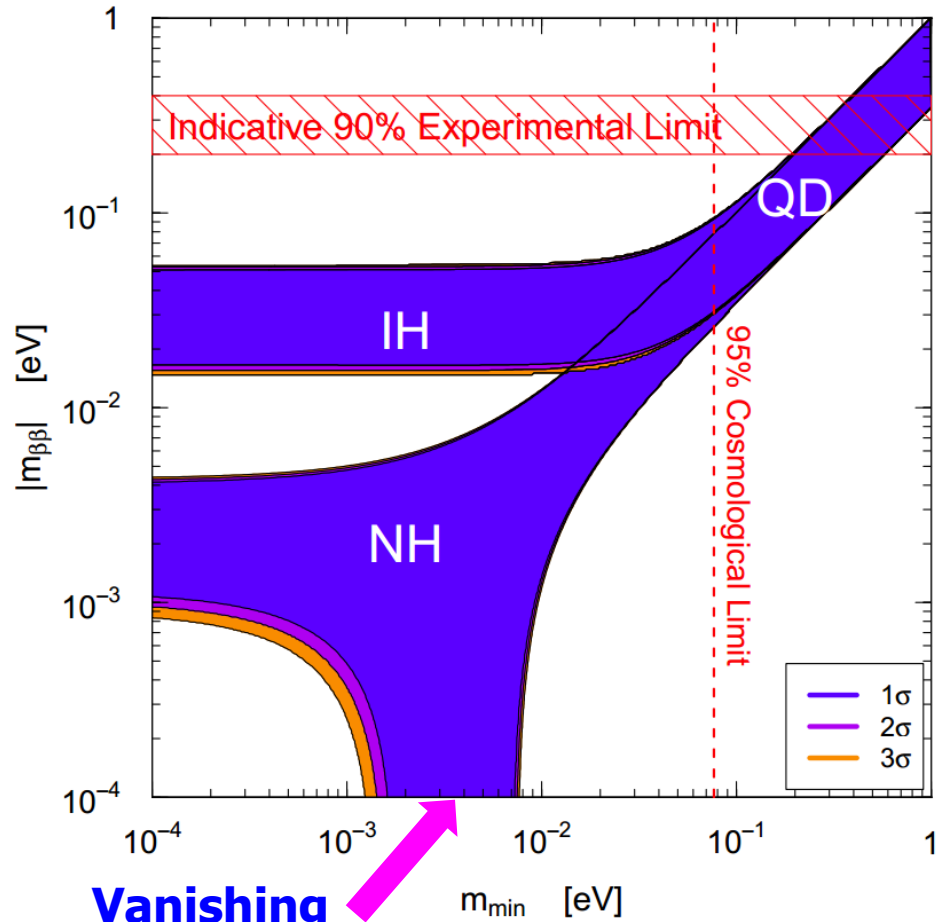
Non-standard Interactions in matter for T2K and NOνA:

- **True value of $\delta = \pi$ (i.e. no CP violation)**
- **NSI-induced fake CPV in neutrino oscillations**

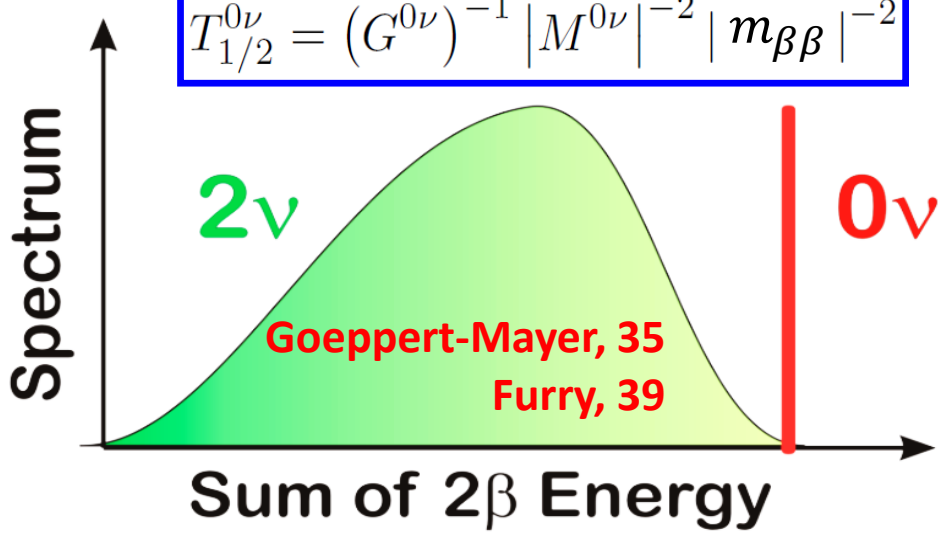


Part B: Majorana vs. Dirac Neutrinos





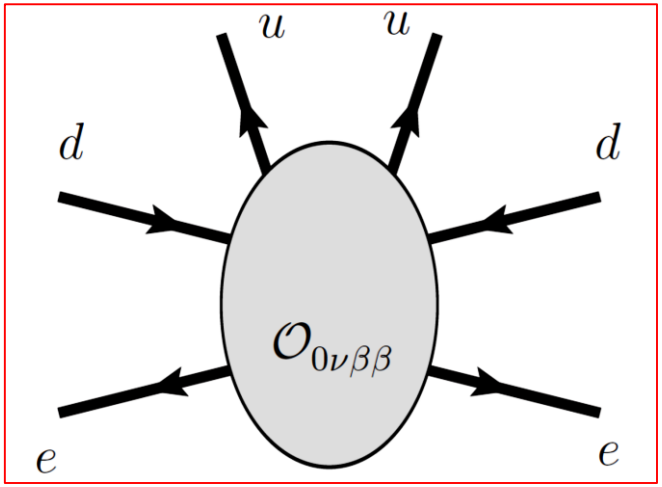
$$T^{0\nu}_{1/2} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|m_{\beta\beta}\right|^{-2}$$

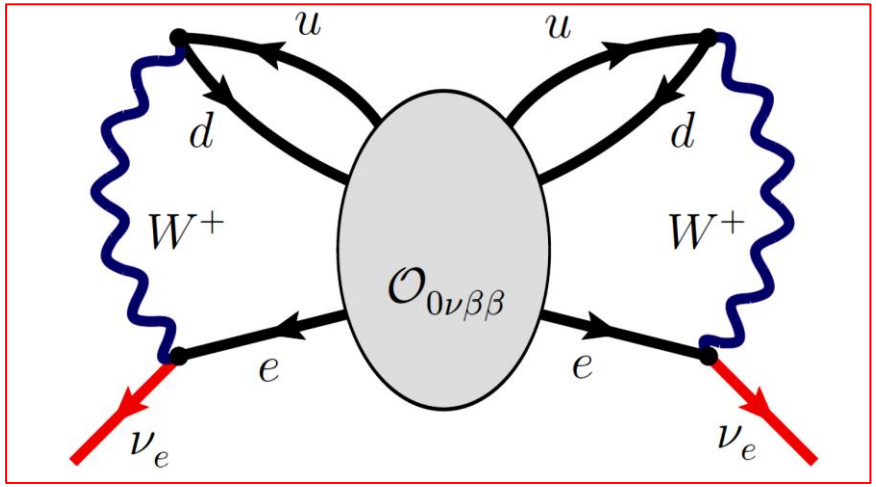


Vanishing 0ν2β mass?

- **Unique feasible way to determine the Majorana nature of neutrinos**
- **Possible to pin down mass ordering**
- **Set constraints on 2 Majorana-type CP-violating phases**

Part B: Majorana vs. Dirac Neutrinos





Schechter-Valle Theorem (82): If the 0ν2β decay happens, there must exist an effective Majorana neutrino mass term.

Quantitatively, the 4-loop Majorana mass from the butterfly diagram is EXTREMELY small:

$$\delta m_\nu = O(10^{-29}\ \mathrm{eV})$$

(Duerr, Lindner, Merle, 11; Liu, Zhang, Zhou, 16)

- **Assume 0ν2β decays are governed by short-distance operators**
- **The Schechter-Valle (Black Box) theorem is qualitatively correct, but the induced Majorana masses are too small to be relevant for neutrino oscillations**
- **Other mechanisms are needed to generate neutrino masses**

Part B: Majorana vs. Dirac Neutrinos

When the temperature $T \sim 1$ MeV, neutrinos became decoupled from the thermal bath, and formed a ν background in the Universe. Today relic neutrinos are nonrelativistic, and their number density is 56 cm^{-3} per flavor, as predicted by the standard model of cosmology.

Temperature today

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945 \text{ K}$$

Mean momentum today

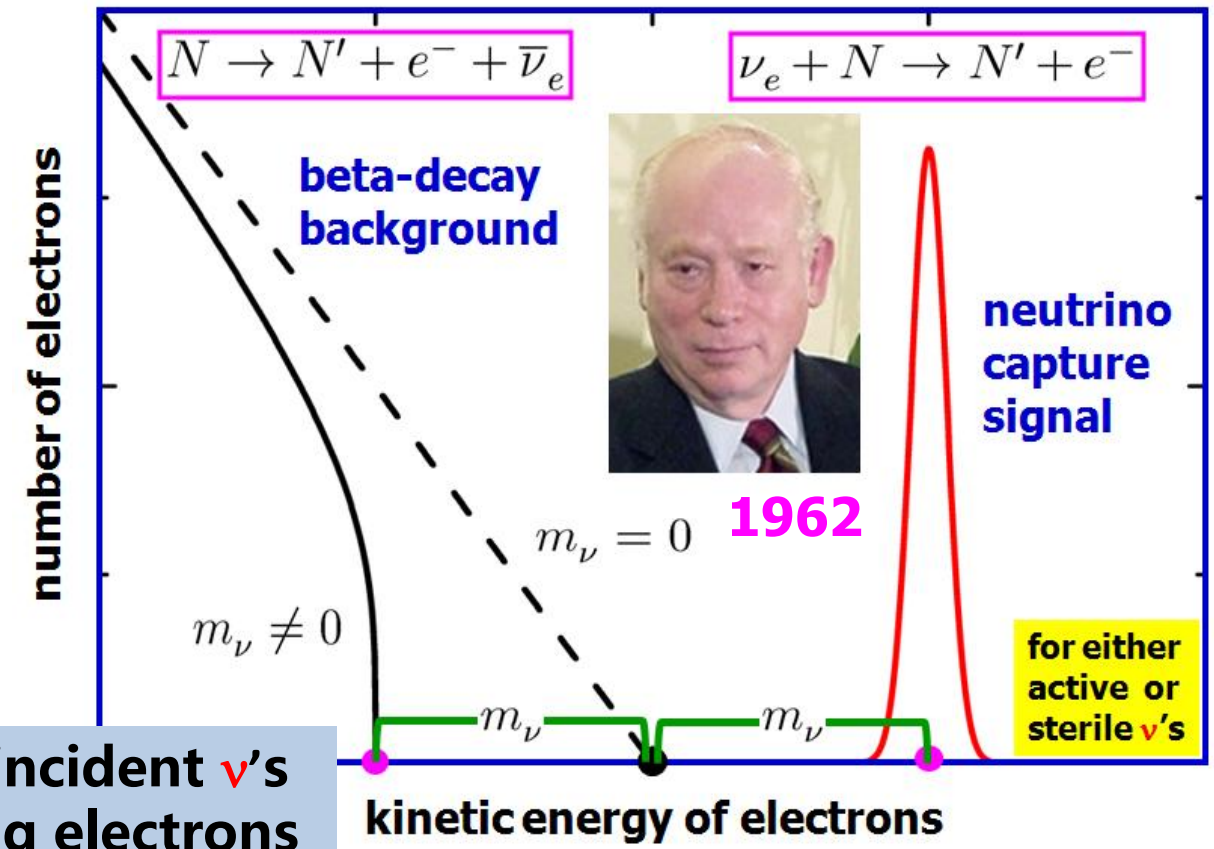
$$\langle p_\nu \rangle \simeq 3.151 T_\nu$$
$$\simeq 5.281 \times 10^{-4} \text{ eV}$$

At least 2 ν's cold today

NON-relativistic ν's!

(Irvine & Humphreys, 83)

Relic neutrino capture on β-decaying nuclei



no energy threshold on incident ν's
mono-energetic outgoing electrons

Capture rate of a polarized neutrino state $\nu_j(s_\nu)$ on a free neutron

$$\sigma_j(s_\nu)v_{\nu_j} = \frac{G_F^2}{2\pi}|V_{ud}|^2|U_{ej}|^2 F(Z,E_e)\frac{m_p}{m_n}E_e p_e A(s_\nu)(f^2+3g^2)$$

Note: Spin-dependent Factor

$$A(s_\nu) \equiv 1 - 2s_\nu v_{\nu_j} = \begin{cases} 1 - v_{\nu_j}, & s_\nu = +1/2 \quad \text{RH Helicity} \\ 1 + v_{\nu_j}, & s_\nu = -1/2 \quad \text{LH Helicity} \end{cases}$$

In the limit $v_{\nu_j} \longrightarrow 1$, the state of $s_\nu = +1/2$ cannot be captured

In the limit $v_{\nu_j} \longrightarrow 0$, both RH and LH helical states do contribute

Total Rate

$$\Gamma_{C\nu B} = \sum_j \left[\sigma_j\left(+\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{hR}) + \sigma_j\left(-\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{hL})\right]N_T$$

Long et al., 14

Part B: Majorana vs. Dirac Neutrinos

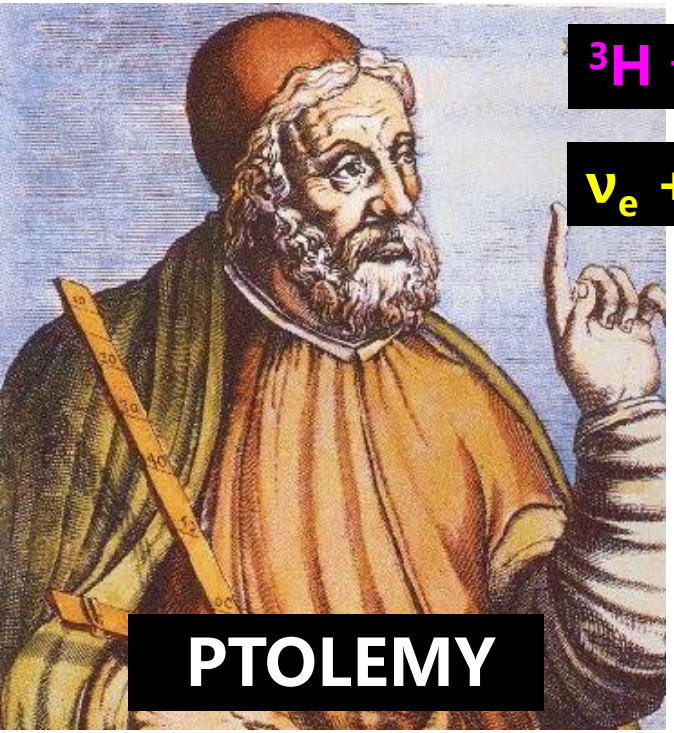
Conservation of Helicity: $[\hat{H}, \hat{h}] = 0$ **for free particles after decoupling**

$$\hat{H} \equiv \gamma^0 m + \gamma^0 \vec{\gamma} \cdot \vec{p} = \begin{pmatrix} m & \vec{\sigma} \cdot \vec{p} \\ \vec{\sigma} \cdot \vec{p} & -m \end{pmatrix} \qquad \hat{h} \equiv \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}|} = \frac{1}{|\vec{p}|} \begin{pmatrix} \vec{\sigma} \cdot \vec{p} & 0 \\ 0 & \vec{\sigma} \cdot \vec{p} \end{pmatrix}$$

In the rest frame of CνB, the background neutrinos are isotropic

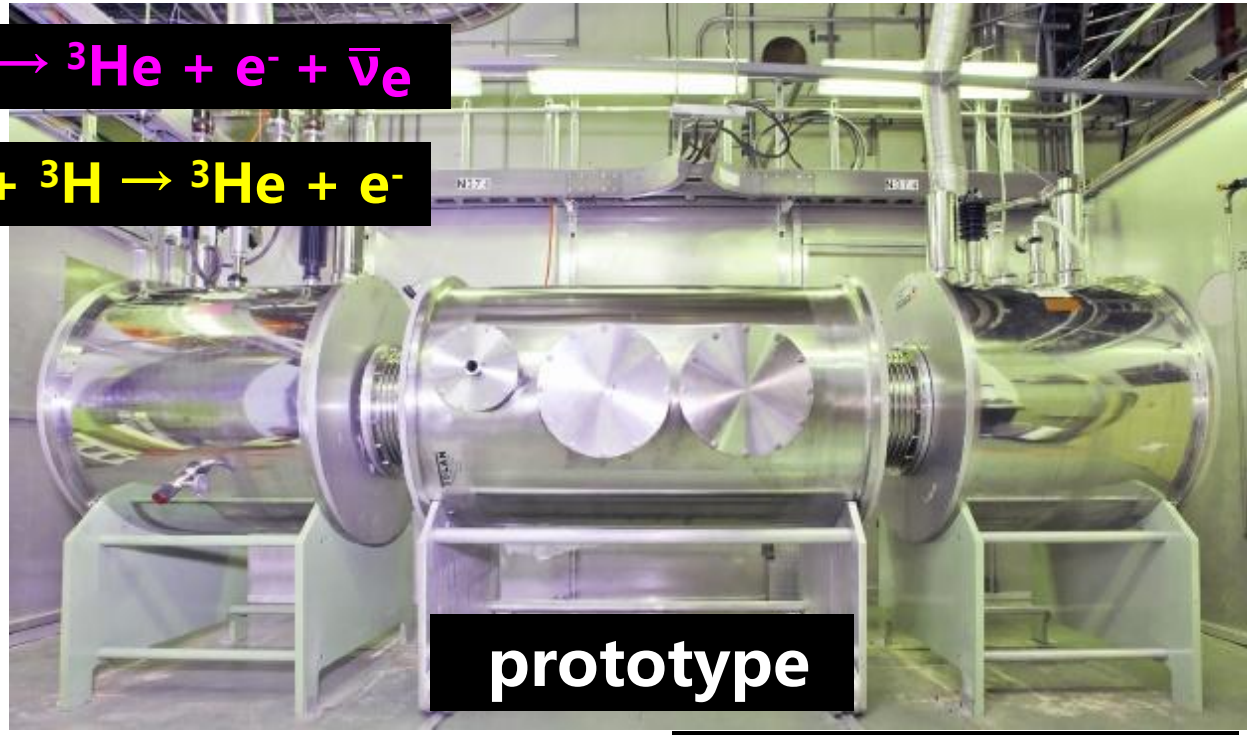
Long et al., 14	Dirac Neutrinos		Majorana Neutrinos
Decoupling	$n(\nu_L) = n(z)$, $n(\bar{\nu}_R) = n(z)$,	$n(\nu_R) \approx 0$ $n(\bar{\nu}_L) \approx 0$	$n(\nu_L) = n(z)$ $n(\nu_R) = n(z)$
Nowadays	$n(\nu_{hL}) = n_0$, $n(\bar{\nu}_{hR}) = n_0$,	$n(\nu_{hR}) \approx 0$ $n(\bar{\nu}_{hL}) \approx 0$	$n(\nu_{hL}) = n_0$ $n(\nu_{hR}) = n_0$
Total Rates	$\Gamma^{D}_{C\nu B} = \bar{\sigma} n_0 N_T$		$\Gamma^{M}_{C\nu B} = 2\bar{\sigma} n_0 N_T$

Part B: Majorana vs. Dirac Neutrinos



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

$\nu_e + {}^3H \rightarrow {}^3He + e^-$



★ first experiment

★ 100 g of tritium

★ graphene target

★ planned energy resolution 0.15 eV

★ CνB capture rate

$$\Gamma^{D}_{C\nu B} \sim 4\ \mathrm{yr}^{-1}$$

$$\Gamma^{M}_{C\nu B} \sim 8\ \mathrm{yr}^{-1}$$

D = Dirac

M = Majorana

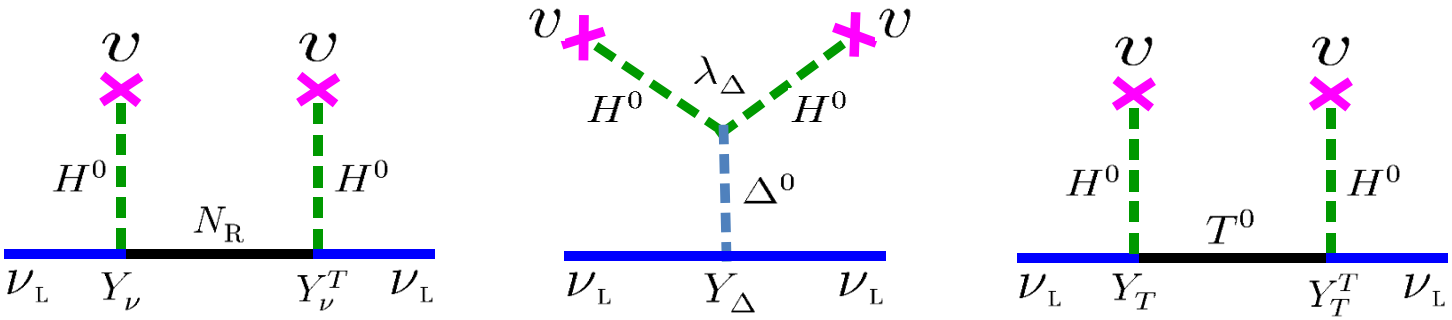
PTOLEMY
Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield
(Betts et al, arXiv:1307.4738)

Origin of Neutrino Masses

Difficulties with Dirac neutrinos

- **Tiny Dirac masses worsen fermion mass hierarchy problem (i.e., $m_i/m_t < 10^{-12}$)**
- **Mandatory lepton number conservation, which is actually accidental in the SM**

Majorana neutrinos: a natural way to understand tiny neutrino masses (seesaw)



$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T \qquad M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} \qquad M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

Type-I: SM + 3 right-handed Majorana ν's (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

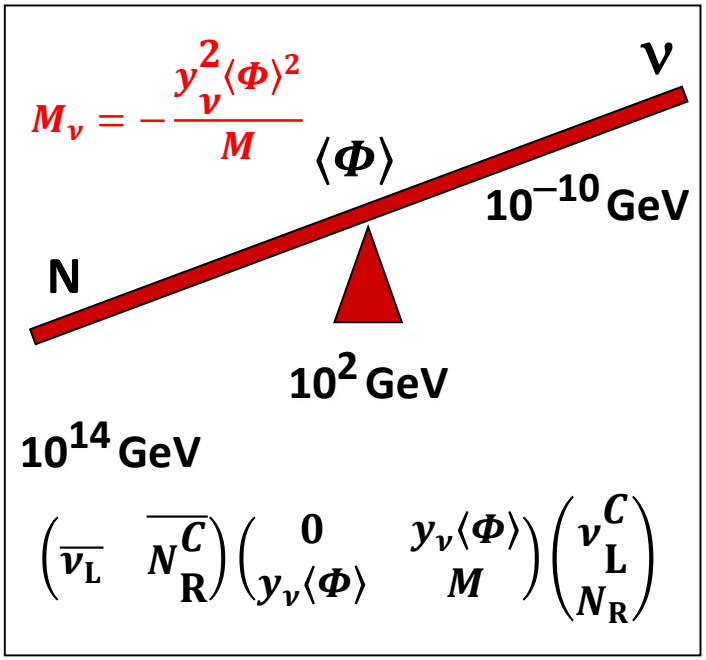
Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

- **Can naturally be embedded into the SO(10) GUT (e.g., type-I + type-II seesaw)**
- **Responsible for both tiny neutrino masses and matter-antimatter asymmetry**

Origin of Neutrino Masses

A natural seesaw scale (e.g., type-I)

- Close to an energy scale of fundamental physics: the GUT scale



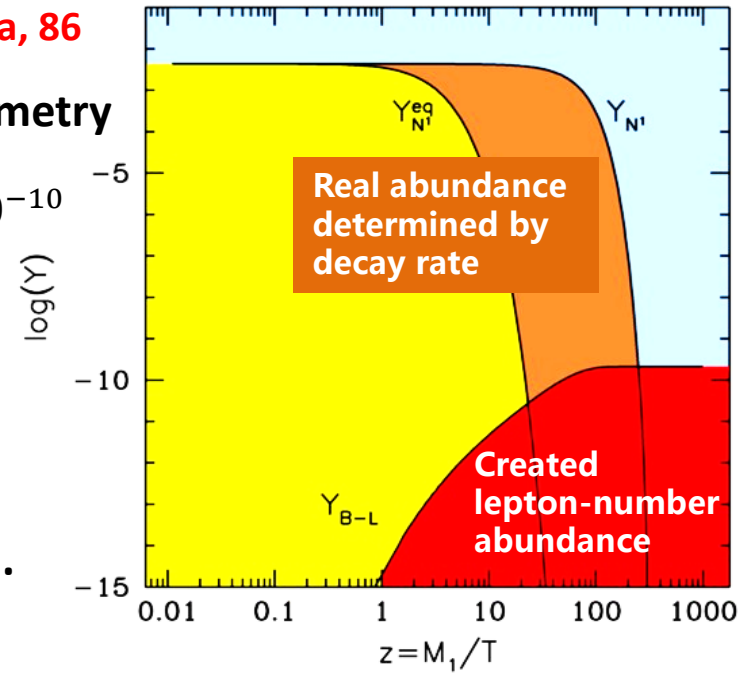
Fukugita, Yanagida, 86

B-number Asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10}$$

Leptogenesis

- CP violation
- B-L violation
- Out-of-equili.
- Sphaleron



Seesaw-induced hierarchy problem

Vissani, 98; Casas et al., 04; Abada et al., 07

$$\delta M_H^2 = \begin{cases} -\frac{y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right) & \text{(Type I)} \\ \frac{3}{16\pi^2}\left[\lambda_3\left(\Lambda^2 + M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right) + 4\lambda_\Delta^2 M_\Delta^2 \ln\frac{M_\Delta^2}{\Lambda^2}\right] & \text{(Type II)} \\ -\frac{3y_i^2}{8\pi^2}\left(\Lambda^2 + M_i^2 \ln\frac{M_i^2}{\Lambda^2}\right) & \text{(Type III)} \end{cases}$$

In type-I seesaw models:

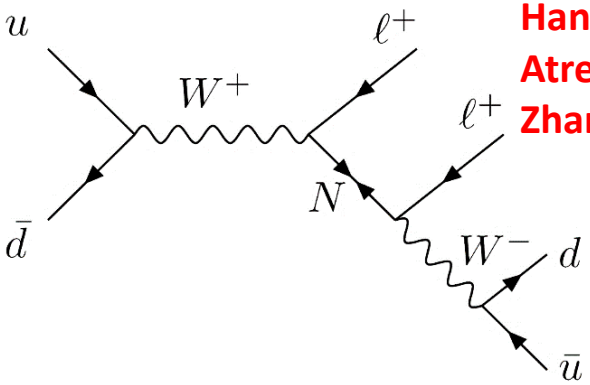
$$M_i \lesssim 10^7 \text{ GeV} \left(\frac{0.2 \text{ eV}}{m_i}\right)^{1/3}$$

for $\delta M_H^2 \sim 0.1 \text{ TeV}^2$

Origin of Neutrino Masses

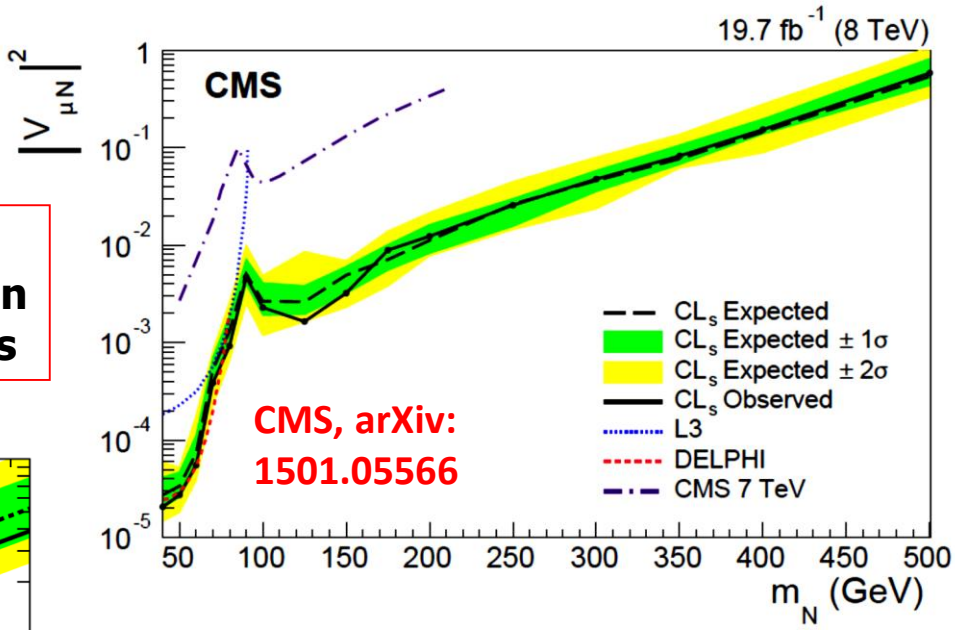
Seesaw models at the EW or TeV scales

- motivated by the naturalness and testability problems of conventional seesaws

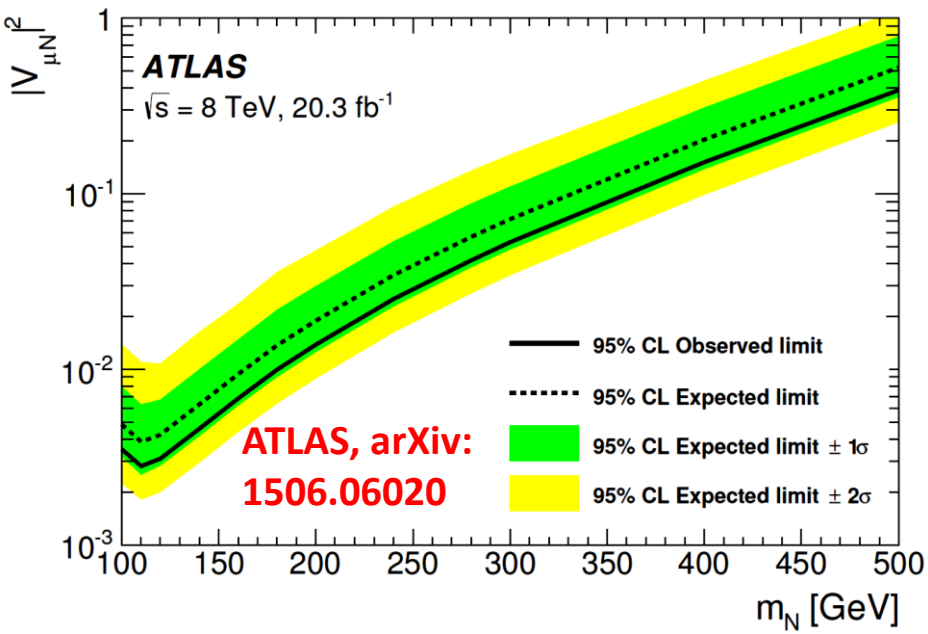


Han, Zhang, 06; Atre, Han, Pascoli, Zhang, 09

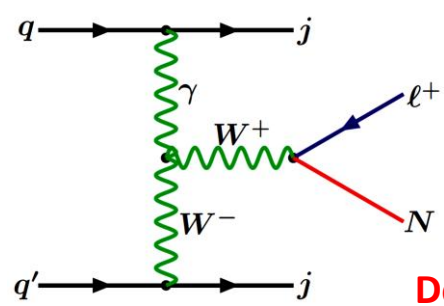
Signals: same-sign dileptons



CMS, arXiv: 1501.05566



ATLAS, arXiv: 1506.06020



For $M_N > 600$ GeV, t-channel γ-mediated production dominates over Drell-Yan process

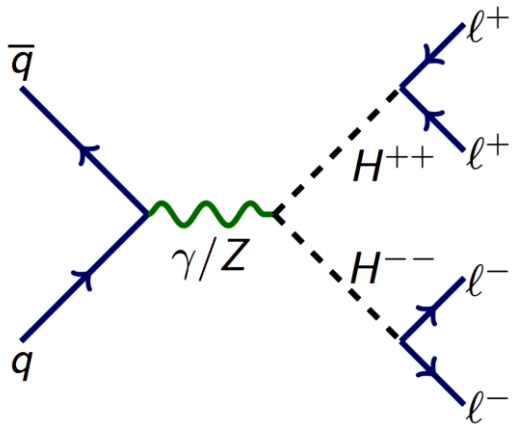
Dev et al., 14; Alva et al., 16

Type-II: 1207.2666 (CMS), 1412.0237 (ATLAS)

Type-III: 1506.01291 (CMS), 1506.01839 (ATLAS)

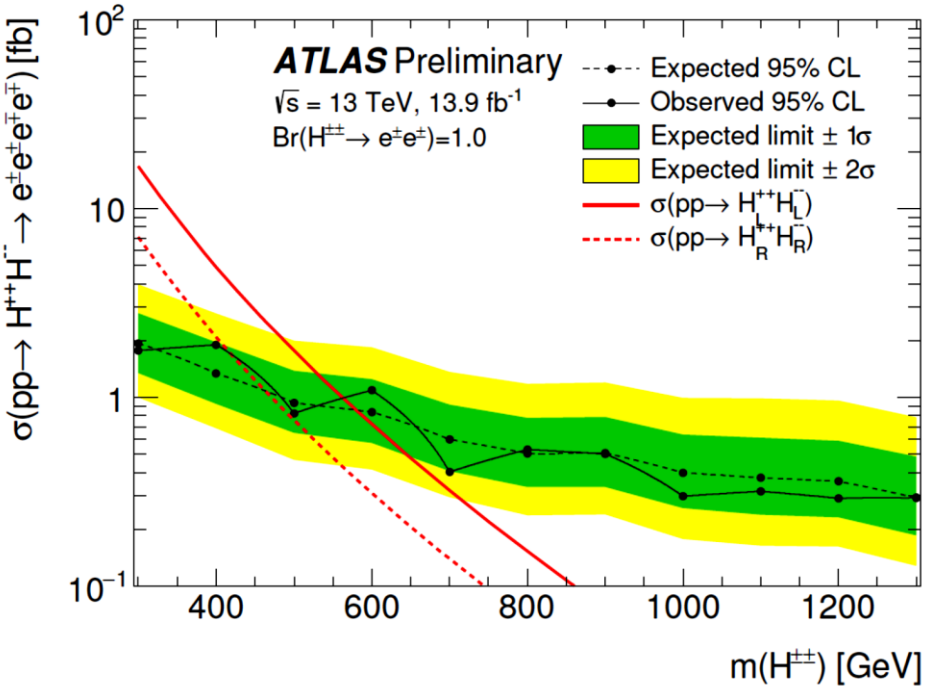
Searches for doubly-charged Higgs bosons

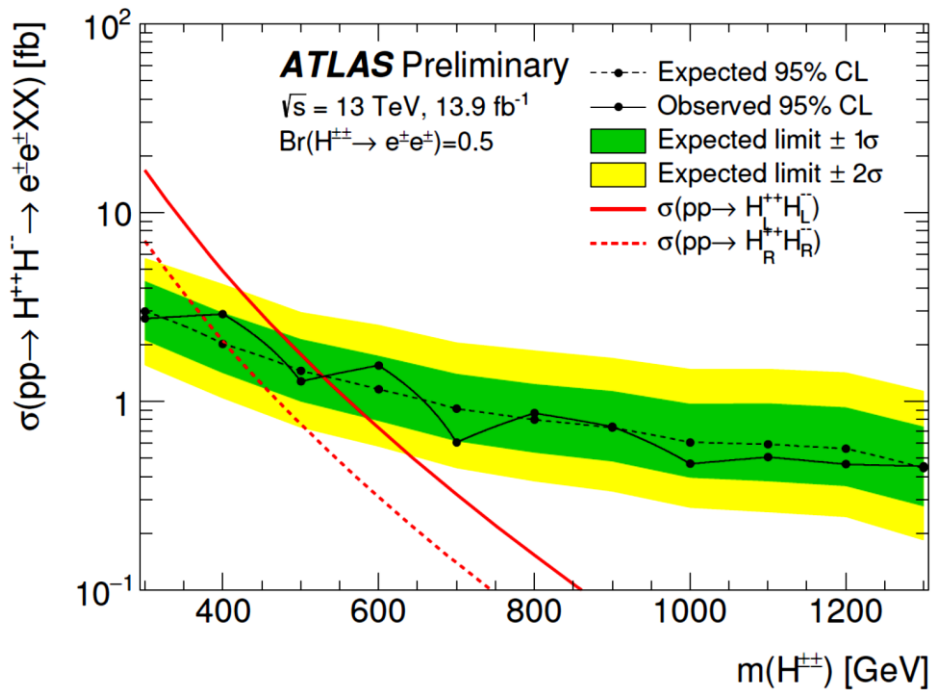
Chun et al., 03; Han et al., 05; Raidal et al., 07; Perez et al., 08; Chao et al., 08; …



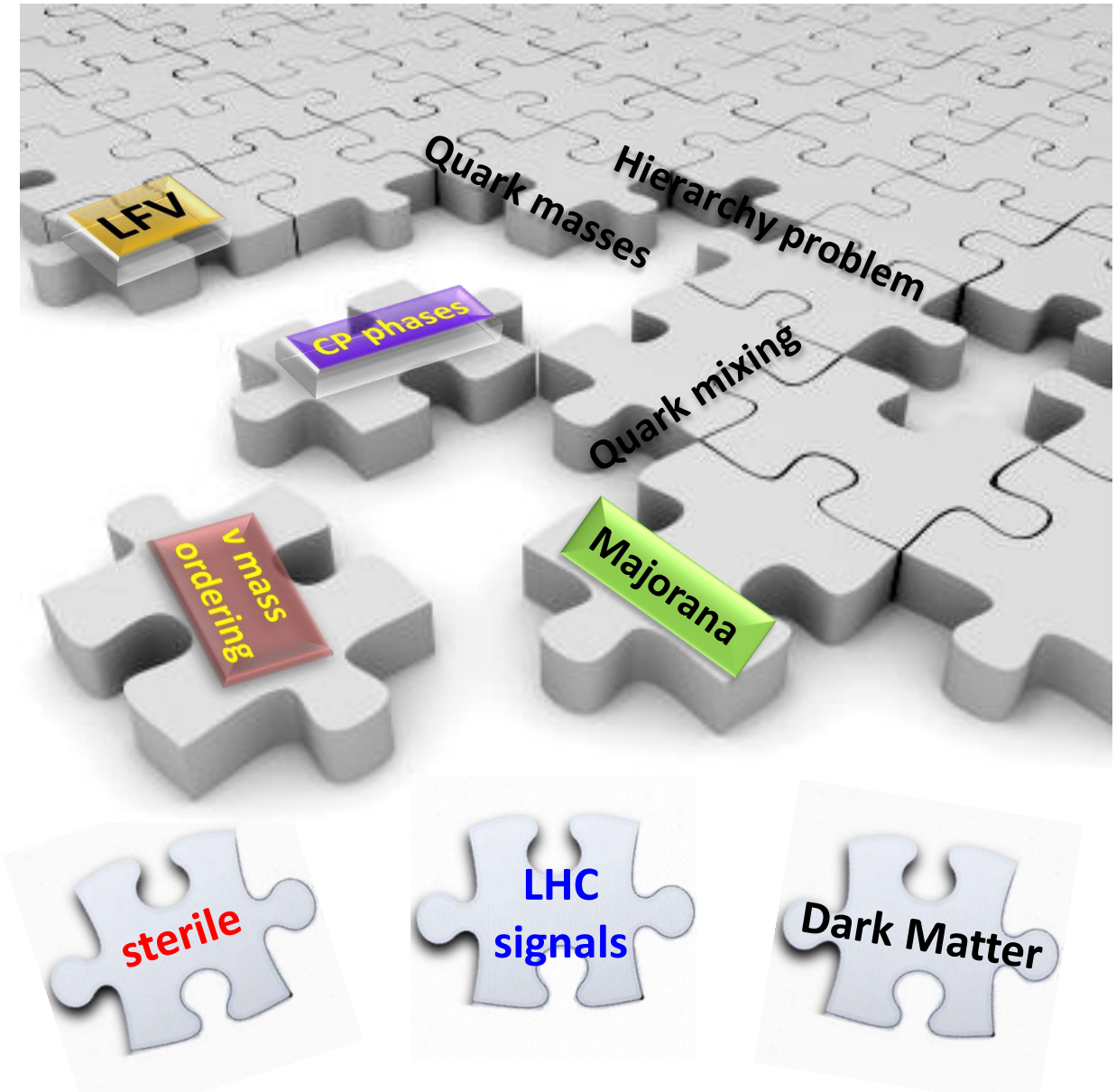
- Depending on the triplet vev, the dominant decay channel is either leptons or W's
- Couplings directly related to neutrino masses and flavor mixing parameters
- Constraints on masses depend on branching ratios of doubly-charged Higgs decays

ATLAS-CONF-2016-051





Summary & Outlook



- Neutrino mass ordering and lepton CP violation will be measured in the oscillation experiments
- Possible to pin down the absolute neutrino mass and the Majorana nature of massive neutrinos
- Huge detectors and new techniques will be used to probe astrophysical neutrinos and CνB
- Future large hadron and lepton colliders will help us explore the origin of neutrino masses

A long way to go, but be optimistic that the future of neutrino physics is bright!