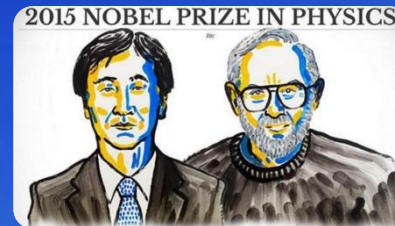
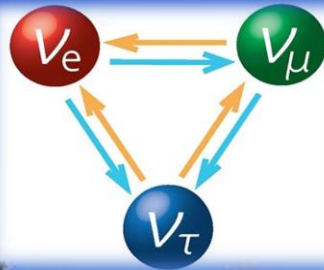
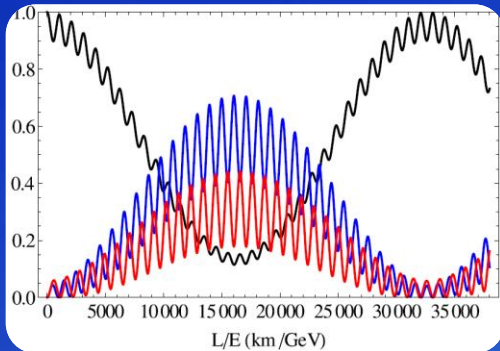


Overview on Neutrino Theory & Phenomenology

Shun Zhou
IHEP, Beijing

The 14th International Workshop on Tau Lepton Physics, Beijing, 2016/9/22



History of Neutrino Oscillations

1

60 years
(1956-2016)

1930 neutrino hypothesis by Pauli

1934 an effective theory for weak interactions by Fermi

1956 electron antineutrino $\bar{\nu}_e$ 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

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 via both CC and NC in SNO

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

2004 K2K & MINOS confirm the disappearance of atmospheric neutrinos

2012 reactor antineutrino disappearance discovered by Daya Bay

Standard Parametrization of the PMNS Matrix

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

$$\theta_{23} \sim 45^\circ$$

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

$$\theta_{12} \sim 34^\circ$$

$0\nu 2\beta$, LNV?

$$|\Delta m_{32}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$$

$$\delta \sim ?$$

$$\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$$

Atmospheric,
LBL accelerator

Reactor,
LBL accelerator

Solar,
KamLAND

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

CKM

©Z.Z. Xing

$$|U| = \begin{pmatrix} \text{yellow} & \text{green} & \text{black} \\ \text{green} & \text{yellow} & \text{blue} \\ \text{black} & \text{blue} & \text{yellow} \end{pmatrix}$$

Strong Hierarchy!

0.004

0.999

PMNS

$$|V| = \begin{pmatrix} \text{yellow} & \text{green} & \text{black} \\ \text{green} & \text{yellow} & \text{blue} \\ \text{black} & \text{blue} & \text{yellow} \end{pmatrix}$$

Approximate μ - τ symmetry?

0.8

0.2

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

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

Neutrino Mass Hierarchy

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

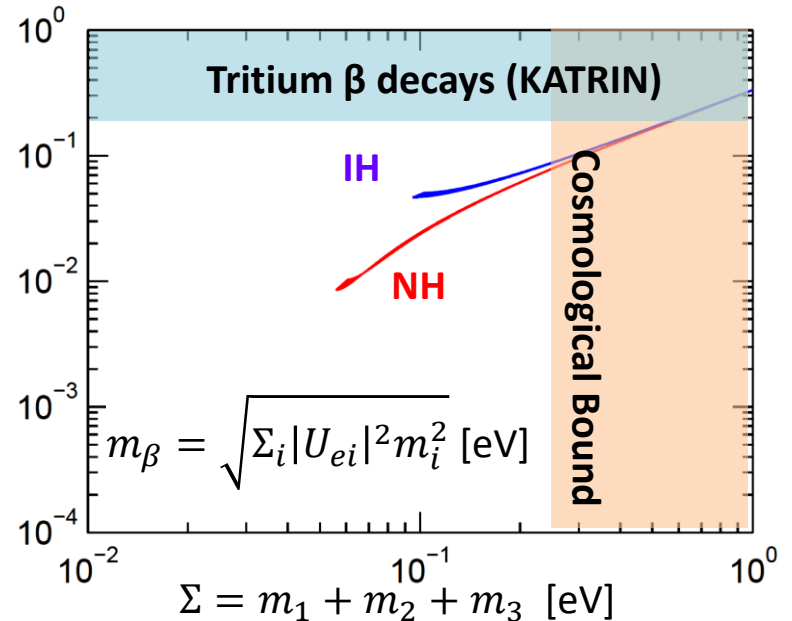
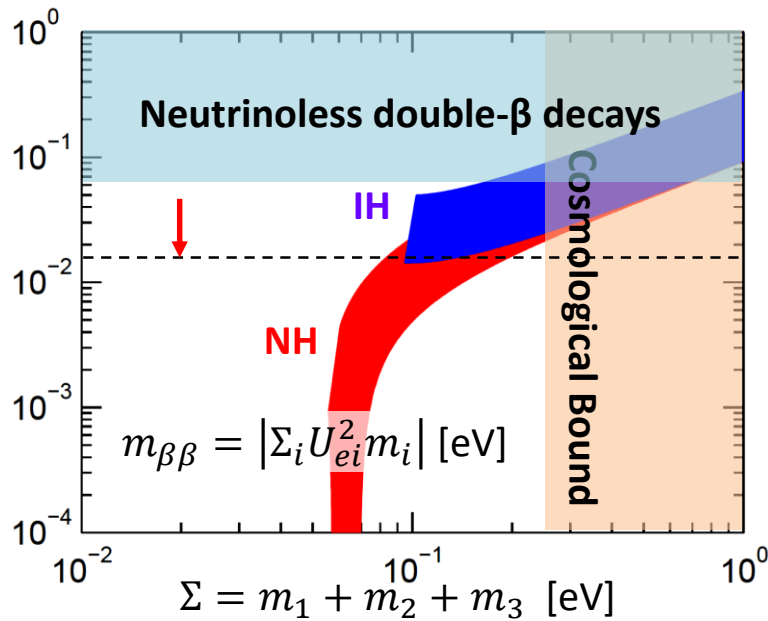
Leptonic CP Violation

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

Absolute Masses: KATRIN, $0\nu 2\beta$ (e.g., ^{136}Xe & ^{76}Ge), cosmology, ...

Non-oscillation Experiments

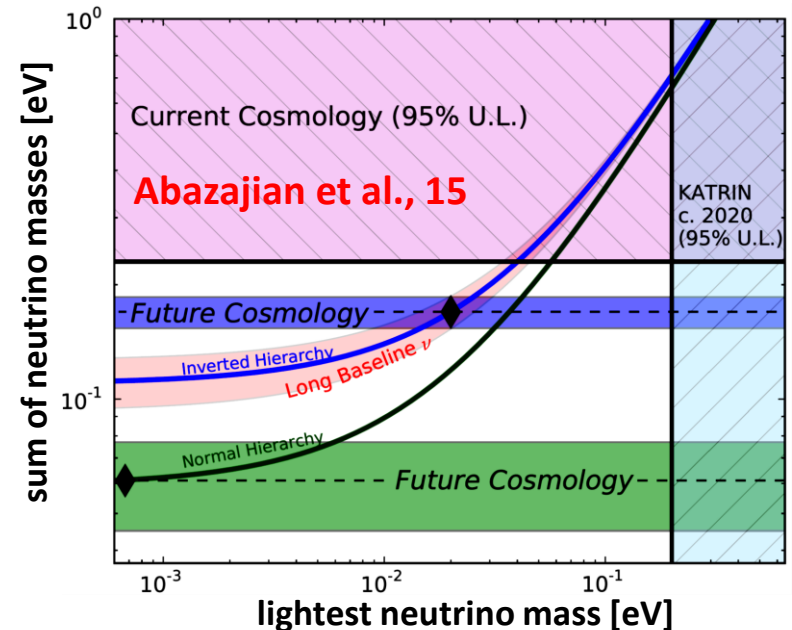
4



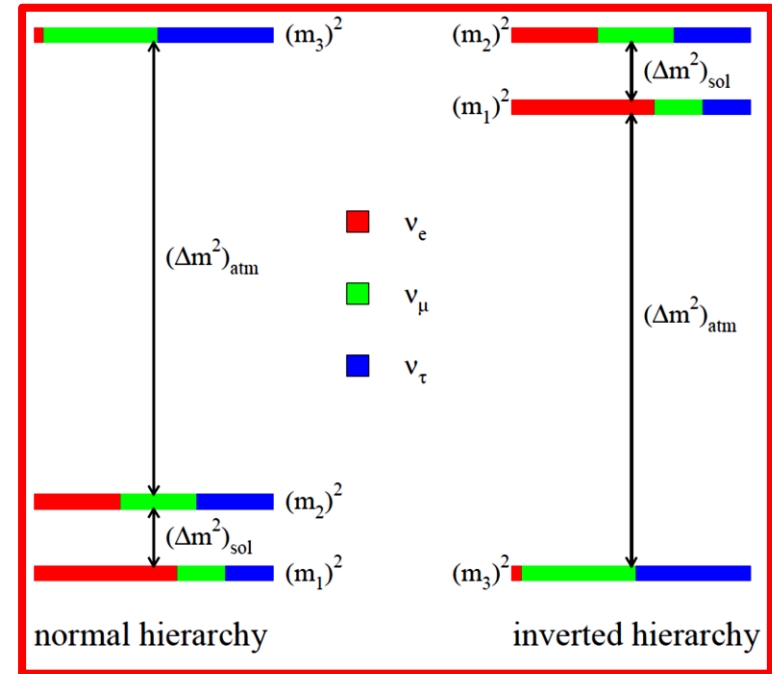
$m_1 < m_2 < m_3$ (NH) or $m_3 < m_1 < m_2$ (IH)

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)



- Normal or Inverted (**sign of Δm_{32}^2 ?**)
- Leptonic CP Violation (**$\delta = ?$**)
- Octant of θ_{23} (**$>$ or $< 45^\circ$?**)
- Absolute Neutrino Masses (**$m_{\text{lightest}} = 0$?**)
- Majorana or Dirac Nature (**$\nu = \nu^c$?**)
- Majorana CP-Violating Phases (**how?**)



- Extra Neutrino Species (**talk by C. Giunti**)
- Exotic Neutrino Interactions
- Other LNV & LFV Processes
- Leptonic Unitarity Violation
- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM, BAU, or NP

Neutrino Oscillation Phenomenology

6

JUNO: 3~4 σ (MH) for 6-year running (from 2020)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 F_{21} - \frac{1}{2} \sin^2 2\theta_{13} (1 - \cos F_* \cos F_{21} + \cos 2\theta_{12} \sin F_* \sin F_{21})$$

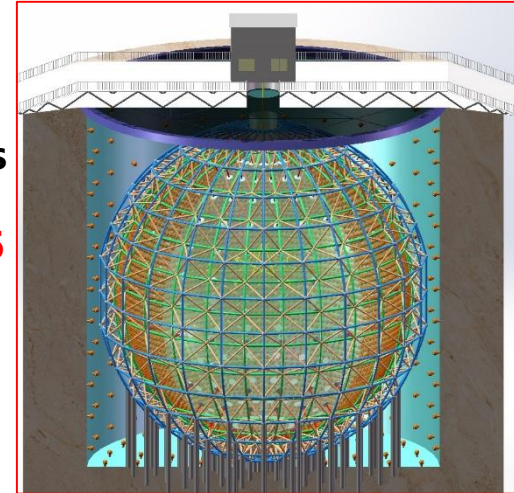
$$F_{ji} = \frac{\Delta m_{ji}^2 L}{4E}$$

Li et al., PRD, 13

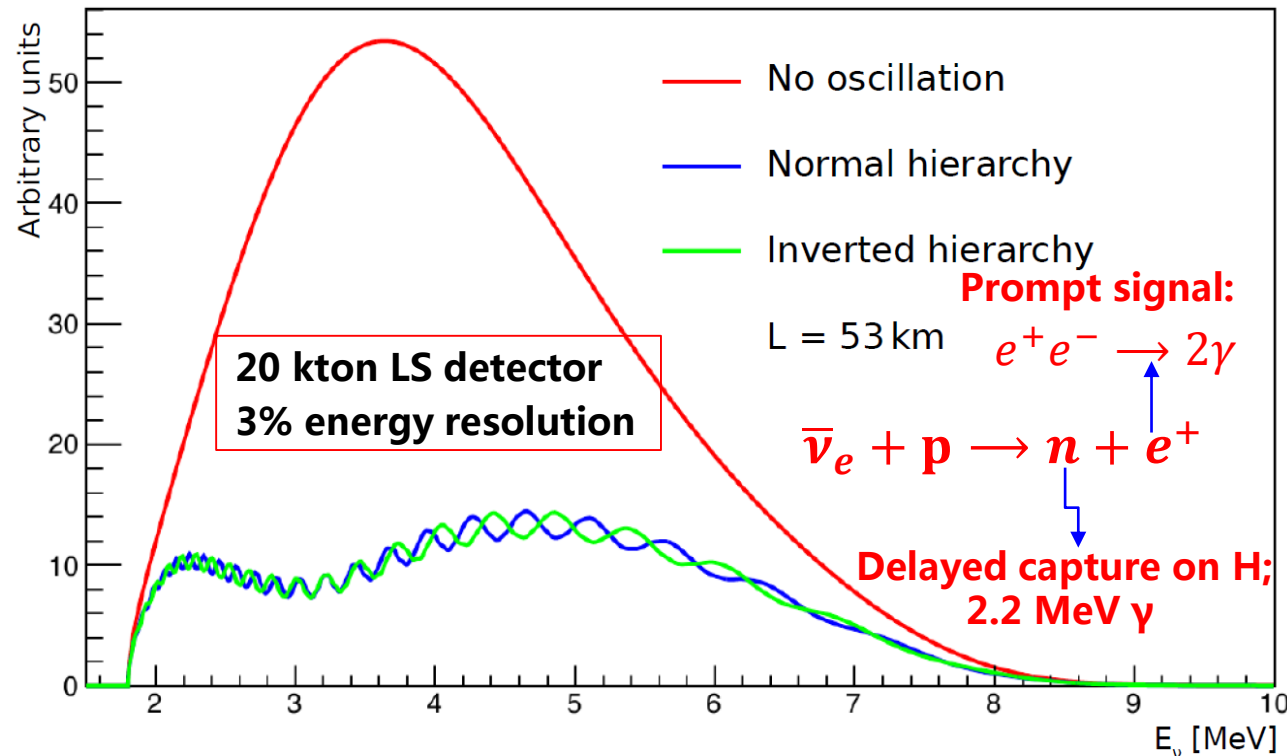
Neutrino Physics with JUNO

An et al., JPG, 16

talks by
C.F. Wong
& H. Lu



$$F_* = F_{31} + F_{32} \quad \text{NH: } F_* > 0 \quad \text{IH: } F_* < 0$$



Parameters	Precision
$\sin^2 2\theta_{12}$	0.54%
Δm_{21}^2	0.24%
$ \Delta m_{ee}^2 $	0.27%

Precision Era (< 1%)

- Test of 3- ν oscillations
- MSW matter effects
- Leptonic unitarity violation, UT
- Constraints on NP (NSI, sterile, CPT, LIV, ...)

Corrections to mixing angles

$$\sin^2 2\tilde{\theta}_{12} \simeq \sin^2 2\theta_{12} \left(1 - 2 \frac{A}{\Delta_{21}} \cos 2\theta_{12} \right)$$

$$\cos^2 2\tilde{\theta}_{12} \simeq \cos^2 2\theta_{12} + \frac{A}{\Delta_{21}} \sin^2 \theta_{12}$$

$$\sin^2 2\tilde{\theta}_{13} \simeq \sin^2 \theta_{13}$$

1%

Earth Matter Effects @JUNO

Li, Wang, Xing, CPC, 16

$$\Delta_{21} \simeq 7.5 \times 10^{-5} \text{ eV}^2$$

$$\Delta_* \simeq \pm 4.8 \times 10^{-3} \text{ eV}^2$$

$$A \simeq 7.9 \times 10^{-7} \text{ eV}^2 \left(\frac{E}{4 \text{ MeV}} \right)$$

Corrections to mass-squared differences

$$\tilde{\Delta}_{21} \simeq \Delta_{21} + A \cos 2\theta_{12}$$

1%

$$\tilde{\Delta}_* \simeq \Delta_* + A$$

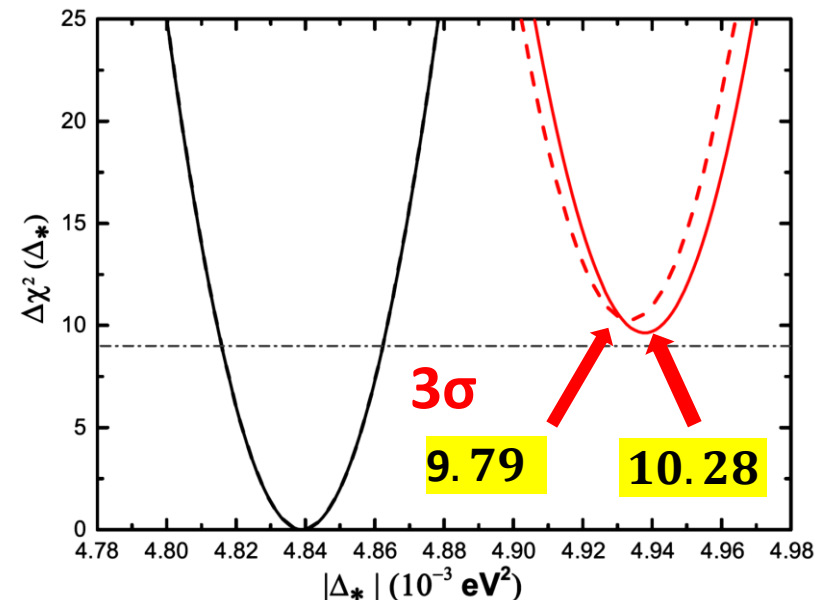
0.02%

$$\tilde{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\tilde{\theta}_{12} \cos^4 \tilde{\theta}_{13} \sin^2 \tilde{F}_{21}$$

$$\Delta_{ji} = m_j^2 - m_i^2 - \frac{1}{2} \sin^2 2\tilde{\theta}_{13} (1 - \cos \tilde{F}_* \cos \tilde{F}_{21})$$

$$\tilde{\Delta}_{ji} = \tilde{m}_j^2 - \tilde{m}_i^2 + \cos 2\tilde{\theta}_{12} \sin \tilde{F}_* \sin \tilde{F}_{21})$$

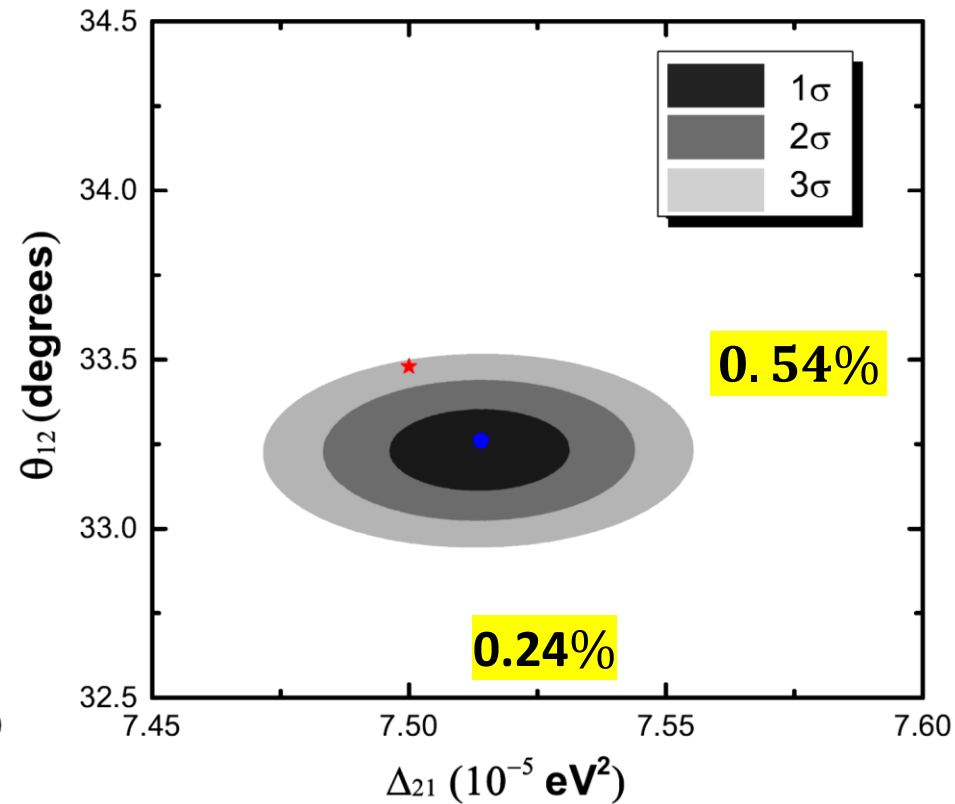
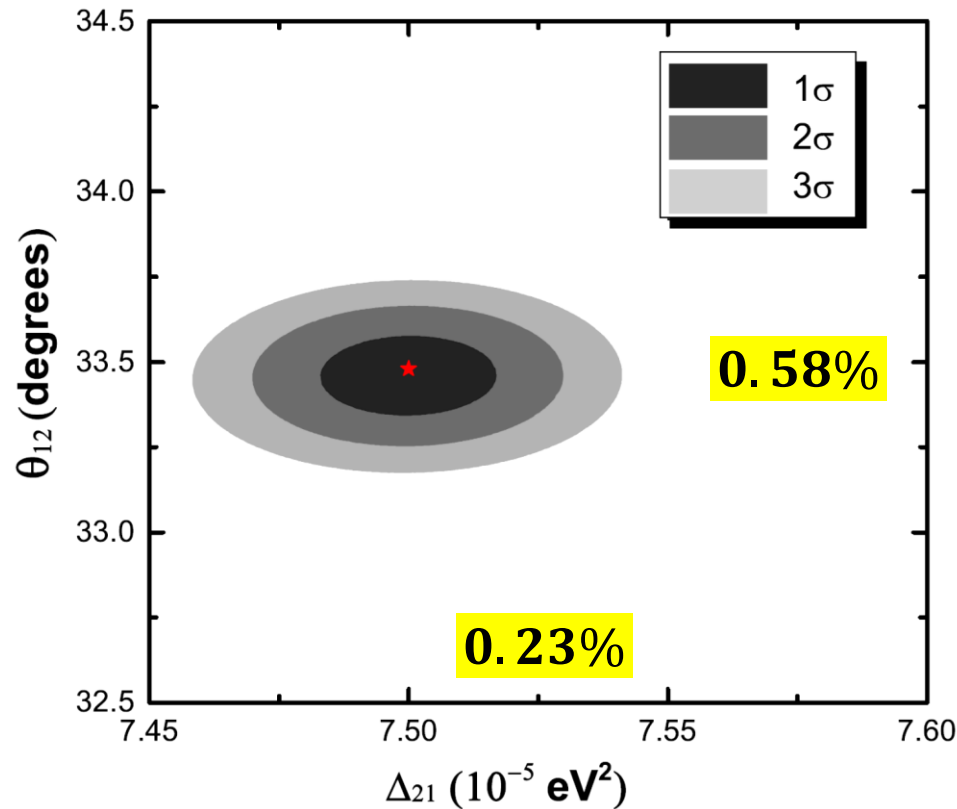
Impact on MH



Impact on precision measurements

Earth Matter Effects @JUNO

Li, Wang, Xing, CPC, 16



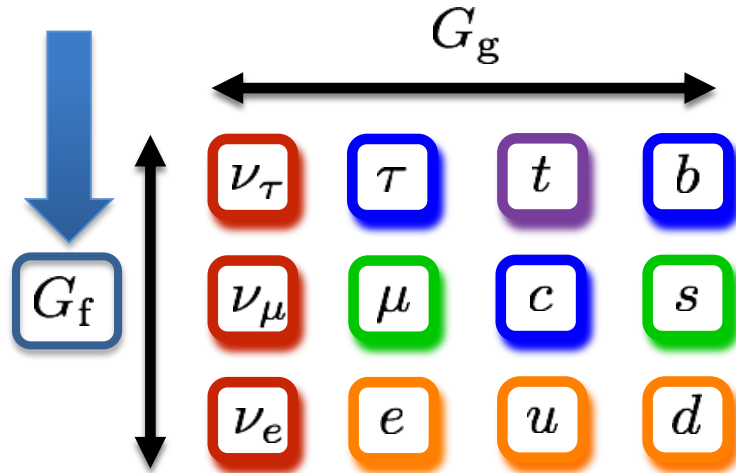
Many phenomenological works for current and future experiments:

JUNO, RENO50/PINGU, ORCA, INO, HK/T2K, NOvA, DUNE/ESSvSB, MOMENT

Analytical formulas, unitary triangles, NP Effects (sterile ν & NSI), sensitivity studies, new ideas for future experiments, ...

Flavor Symmetry

©Y.L. Zhou

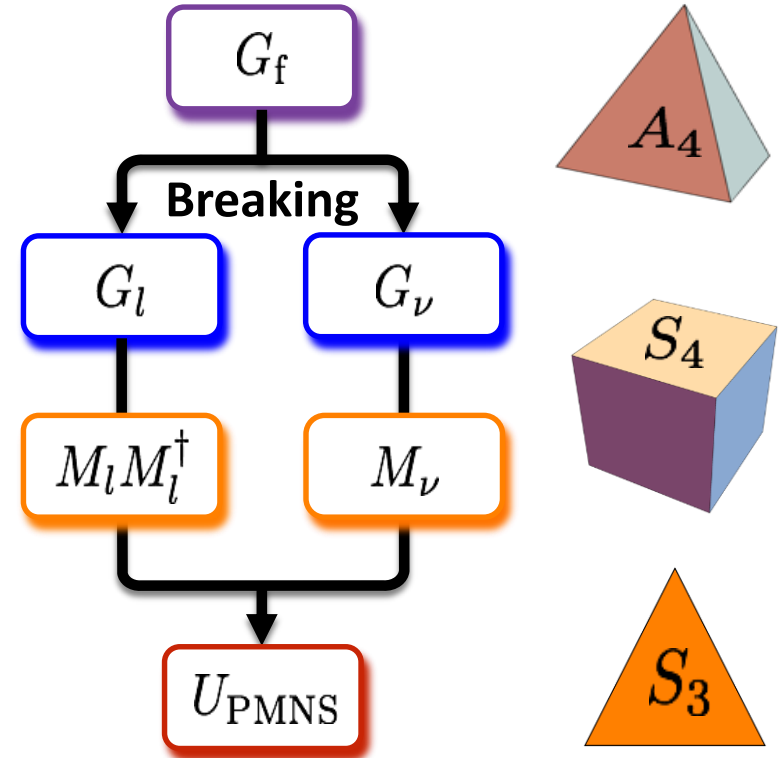


Tri-bimaximal neutrino mixing matrix

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

Allowed ranges of PMNS matrix elements (@ 3σ)

NuFIT 2.1 (2016)

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix} = \begin{pmatrix} 0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\ \mathbf{0.225 \rightarrow 0.517} & \mathbf{0.441 \rightarrow 0.699} & \mathbf{0.614 \rightarrow 0.793} \\ \mathbf{0.246 \rightarrow 0.529} & \mathbf{0.464 \rightarrow 0.713} & \mathbf{0.590 \rightarrow 0.776} \end{pmatrix}$$

In the standard parametrization:

Xing, Zhao, Rept. Prog. Phys. 79 (2016) 076201

μ - τ symmetry $|U_{\mu i}| = |U_{\tau i}|$:

(1) $\theta_{23} = 45^\circ$ & $\theta_{13} = 0$ (excluded)

(2) $\theta_{23} = 45^\circ$ & $\delta = 90^\circ$ or 270° (allowed)

Partial μ - τ symmetry $|U_{\mu 1}| = |U_{\tau 1}|$:

$\theta_{23} \neq 45^\circ$ & $\delta \approx 270^\circ$ (favored by NOvA)

μ - τ reflection symmetry

Harrison, Scott, 02, 04; Grimus, Lavoura, 04

$$M_\nu = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix} \quad \text{Invariant under:} \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \rightarrow \begin{pmatrix} \nu_e^c \\ \nu_\tau^c \\ \nu_\mu^c \end{pmatrix}$$

Predictions: $\theta_{23} = 45^\circ$, $\delta = 90^\circ$ or 270° , but θ_{12} and θ_{13} are left arbitrary

Generalized CP

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \rightarrow X \begin{pmatrix} \nu_e^c \\ \nu_\mu^c \\ \nu_\tau^c \end{pmatrix}$$

X depends on a chosen flavor symmetry

$S_{3'}$, $A_{4'}$
 $S_{4'}$, A_5

T' , $T_{7'}$
 T_{13}

$\Delta(27)$, $\Delta(48)$,
 $\Delta(54)$, $\Delta(96)$, ...

How to **experimentally** verify or rule out one symmetry group?

An incomplete list

- ★ Holthausen et al., JHEP (13)
- ★ Holthausen et al., PLB (13)
- ★ de Medeiros Varzielas et al, JPG (13)
- ★ Antusch et al., PRD (13)
- ★ Ding et al, JHEP (13)
- ★ Ahn et al, PRD (13)
- ★ Nishi, PRD (13)
- ★ Luhn, NPB (13)
- ★ Hagedorn et al., JPA (13)
- ★ Feruglio et al, EPJC (14)
- ★ King, JHEP (14)
- ★ Girardi et al., JHEP (14)
- ★ Chen et al., NPB (14)
- ★ Li, Ding, NPB (14)
- ★ King et al., NJP (14)
- ★ Ding, King, PRD (14)
- ★ King, Neder, PLB (14)
- ★ Ding, Zhou, JHEP (14)
- ★ Zhao, JHEP (14)
- ★ Ding, Zhou, CPC (15)
- ★ G.N. Li, X.G. He, PLB(15)
- ★ H.J. He et al., PLB(15)

- ★ Hagedorn et al, 15
- ★ Everett et al, 15
- ★ Fallbacher, Trautner, 15
- ★ Chen, Li, Ding, 15
- ★ Branco et al., 15
- ★ Feruglio, 15
- ★ Di Lula et al, 15
- ★ Ballett et al, 15
- ★ Mohapatra, Nishi, 15
- ★ Chen, Yao, Ding, 15
- ★ de Medeiros Varzielas , 15
- ★ Shimizu, Tanimoto, 15
- ★ Turner, 15
- ★ S.J. Rong, 16
- ★ Ding et al., 16

Any one **universal** for quarks and leptons?

Two-zero Textures of M_ν

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

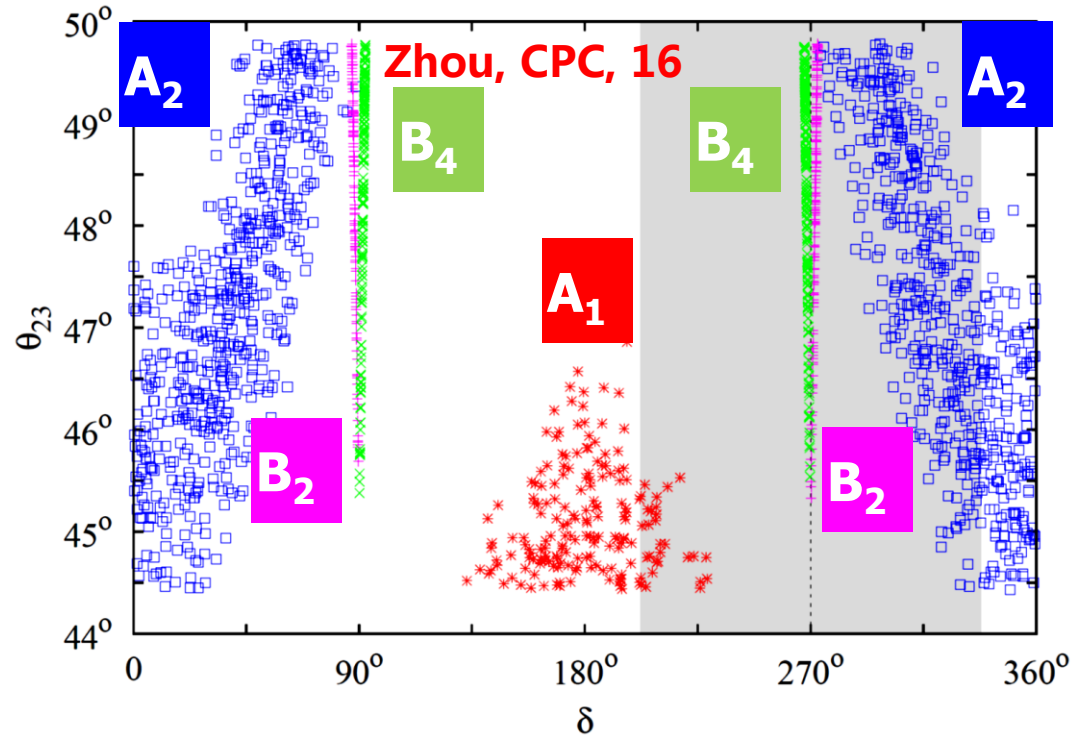
$$\mathbf{A}_1 \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix} \quad \mathbf{A}_2 \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

$$\mathbf{B}_1 \begin{pmatrix} \times & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix} \quad \mathbf{B}_2 \begin{pmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{B}_3 \begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix} \quad \mathbf{B}_4 \begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$$

$$\mathbf{C} \begin{pmatrix} \times & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \quad \text{Consistent with nonzero } \theta_{13} \text{ \& can be realized by } A_4 \text{ symmetry}$$

(a) NH; (b) $\theta_{23} > 45^\circ$; (c) $\delta \sim 270^\circ$



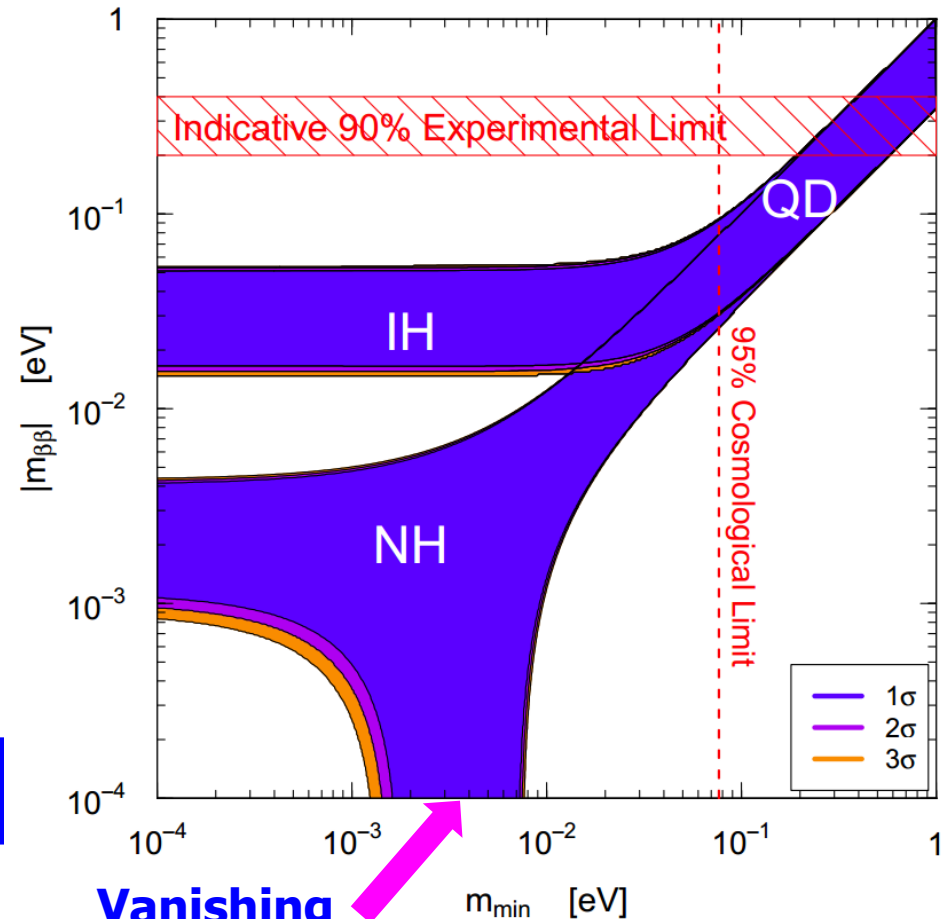
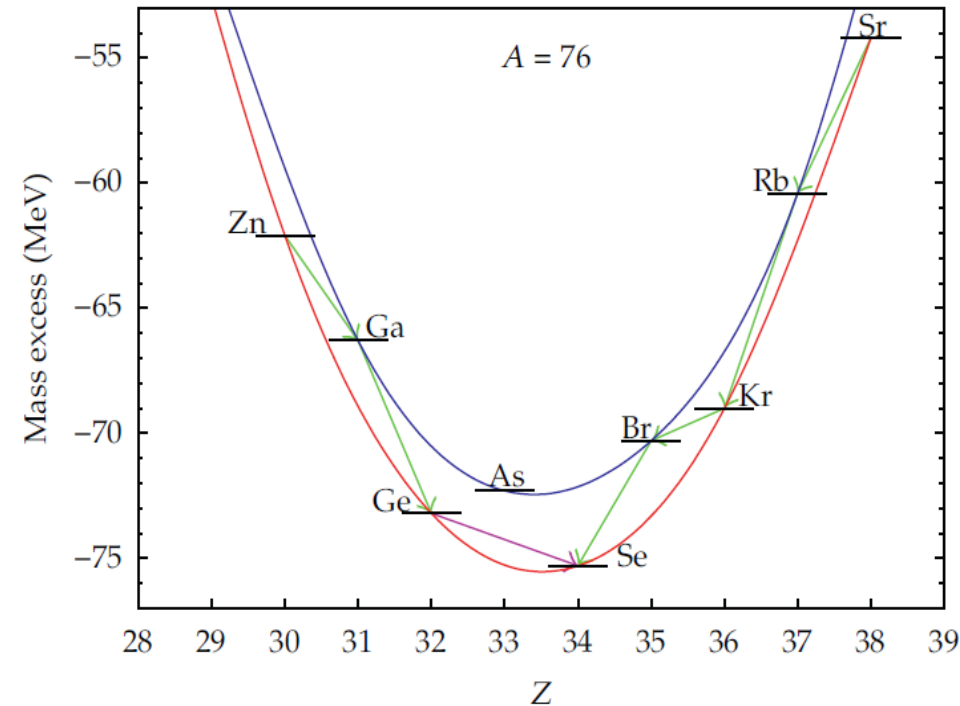
Model building in the type-I+II seesaw model

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

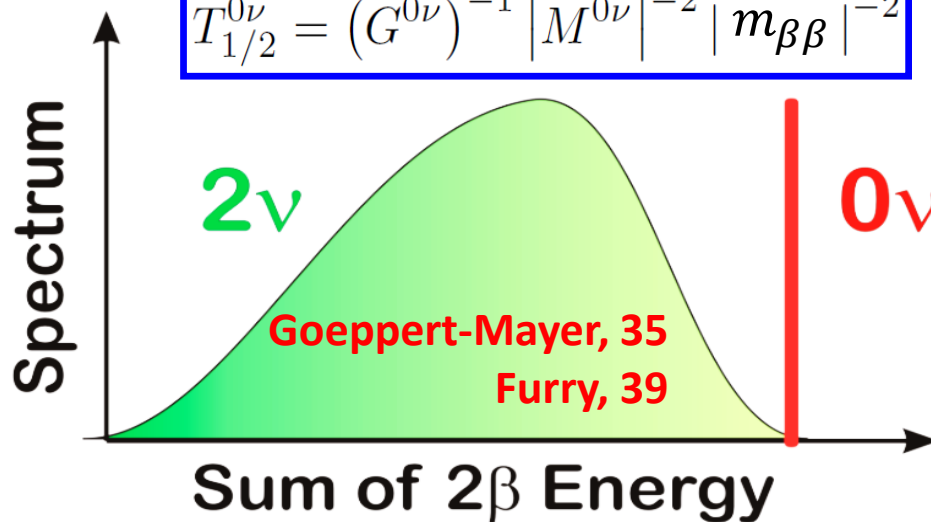
$$M_\nu = u \begin{pmatrix} 0 & 0 & a_\Delta \\ 0 & b_\Delta & 0 \\ a_\Delta & 0 & 0 \end{pmatrix} - \frac{v^2}{M} \begin{pmatrix} a_\nu^2 & 0 & 0 \\ 0 & 0 & b_\nu c_\nu \\ 0 & b_\nu c_\nu & 0 \end{pmatrix}$$

Majorana vs. Dirac

13



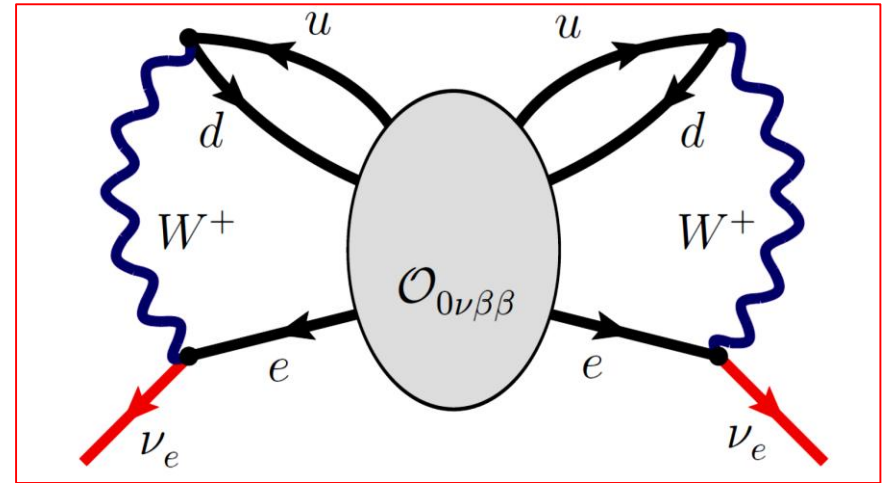
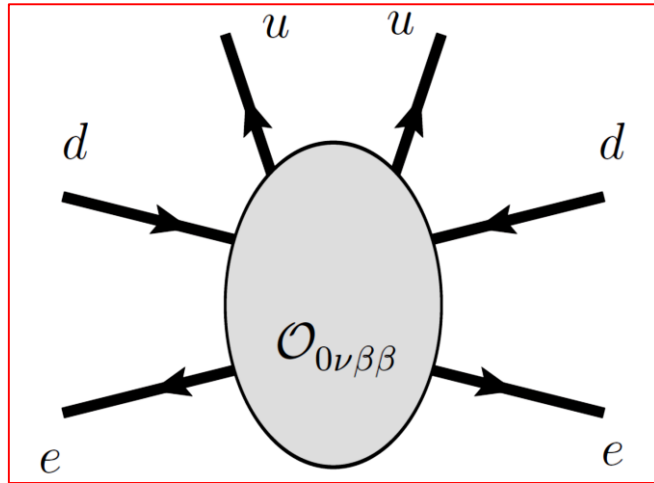
$$T_{1/2}^{0\nu} = (G^{0\nu})^{-1} |M^{0\nu}|^{-2} |m_{\beta\beta}|^{-2}$$



Vanishing $0\nu 2\beta$ mass?

**Bilenky, Giunti, 15
Rodejohann, 11**

- 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



Schechter-Valle Theorem (82): If the $0\nu 2\beta$ decay happens, there must exist an effective Majorana neutrino mass term.

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

$$\delta m_\nu = O(10^{-28} \text{ eV})$$

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

- Assume $0\nu 2\beta$ 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

When the temperature $T \sim 1 \text{ MeV}$, 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

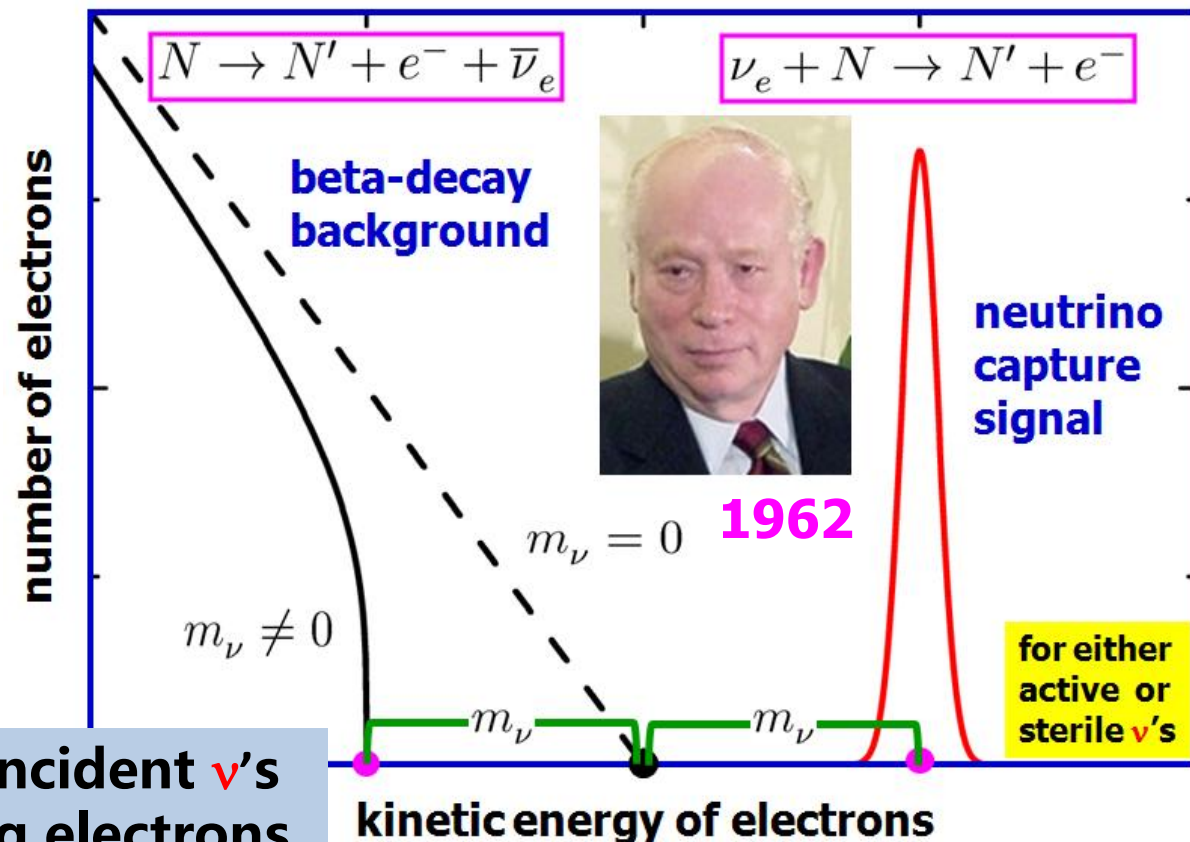
$$\begin{aligned} \langle p_\nu \rangle &\simeq 3.151 T_\nu \\ &\simeq 5.281 \times 10^{-4} \text{ eV} \end{aligned}$$

At least 2 ν 's cold today
NON-relativistic ν 's!

(Irvine & Humphreys, 83)

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

Relic neutrino capture on β -decaying nuclei



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

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



Note: Spin-dependent Factor

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

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

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

Total Rate

$$\Gamma_{\text{CvB}} = \sum_j \left[\sigma_j \left(+\frac{1}{2} \right) \nu_{\nu_j} n_j(\mathbf{v}_{\text{hR}}) + \sigma_j \left(-\frac{1}{2} \right) \nu_{\nu_j} n_j(\mathbf{v}_{\text{hL}}) \right] N_T$$

Long et al., 14

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

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

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

Long et al., 14;
Zhang, Zhou, 16

Dirac Neutrinos

Majorana Neutrinos

Decoupling

$$\begin{aligned} n(\nu_L) &= n(z), & n(\nu_R) &\approx 0 \\ n(\bar{\nu}_R) &= n(z), & n(\bar{\nu}_L) &\approx 0 \end{aligned}$$

$$\begin{aligned} n(\nu_L) &= n(z) \\ n(\nu_R) &= n(z) \end{aligned}$$

Nowadays

$$\begin{aligned} n(\nu_{hL}) &= n_0, & n(\nu_{hR}) &\approx 0 \\ n(\bar{\nu}_{hR}) &= n_0, & n(\bar{\nu}_{hL}) &\approx 0 \end{aligned}$$

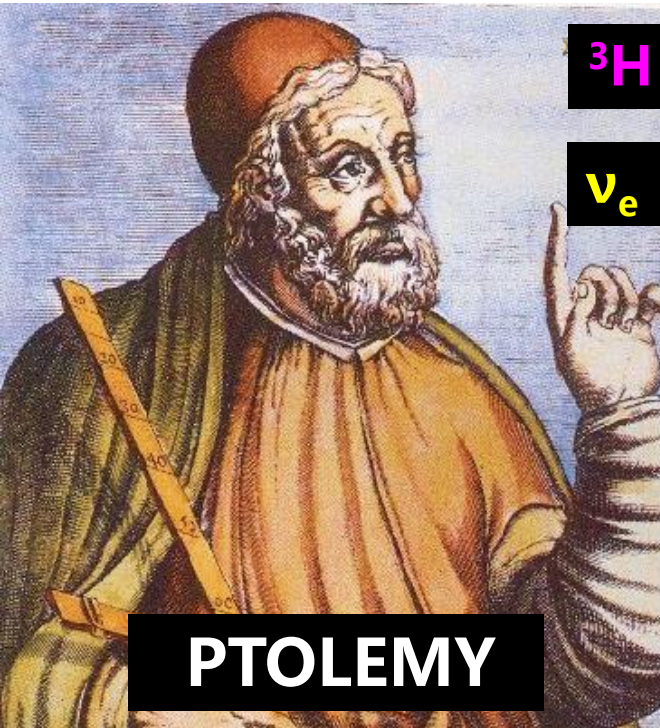
$$\begin{aligned} n(\nu_{hL}) &= n_0 \\ n(\nu_{hR}) &= n_0 \end{aligned}$$

Total Rates

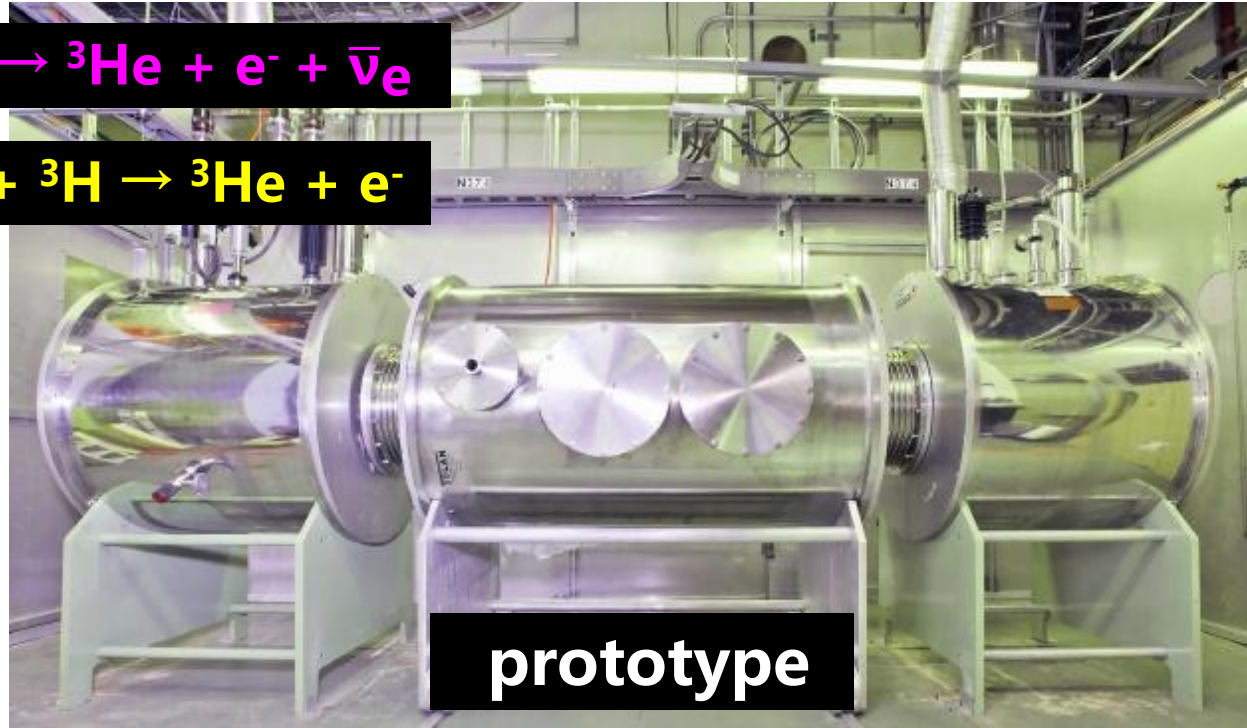
$$\Gamma_{\text{CvB}}^{\text{D}} = \bar{\sigma} n_0 N_{\text{T}}$$

$$\bar{\sigma} \approx 3.8 \times 10^{-45} \text{ cm}^2$$

$$\Gamma_{\text{CvB}}^{\text{M}} = 2\bar{\sigma} n_0 N_{\text{T}}$$



PTOLEMY



prototype

- ★ first experiment
- ★ 100 g of tritium
- ★ graphene target
- ★ planned energy resolution 0.15 eV

★ **C_{νB}** capture rate

$$\Gamma_{\text{C}\nu\text{B}}^{\text{D}} \sim 4 \text{ yr}^{-1}$$

$$\Gamma_{\text{C}\nu\text{B}}^{\text{M}} \sim 8 \text{ yr}^{-1}$$

D = Dirac

M = Majorana

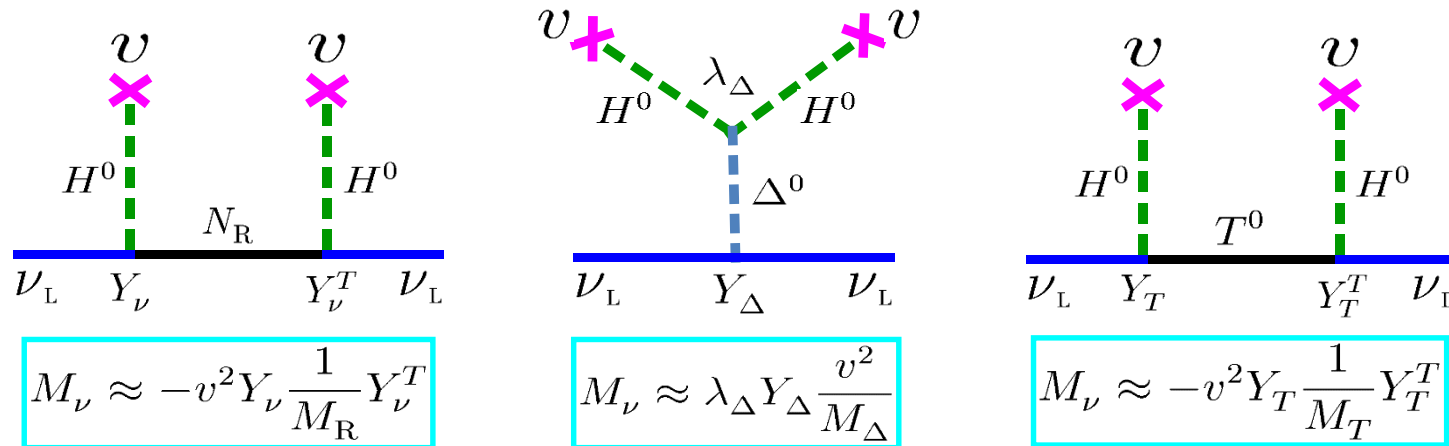
PTOLEMY

Pinceton **T**ritium
Observatory for
Light, **E**arly-
Universe, **M**assive-
Neutrino **Y**ield
(Betts et al,
arXiv:1307.4738)

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)



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

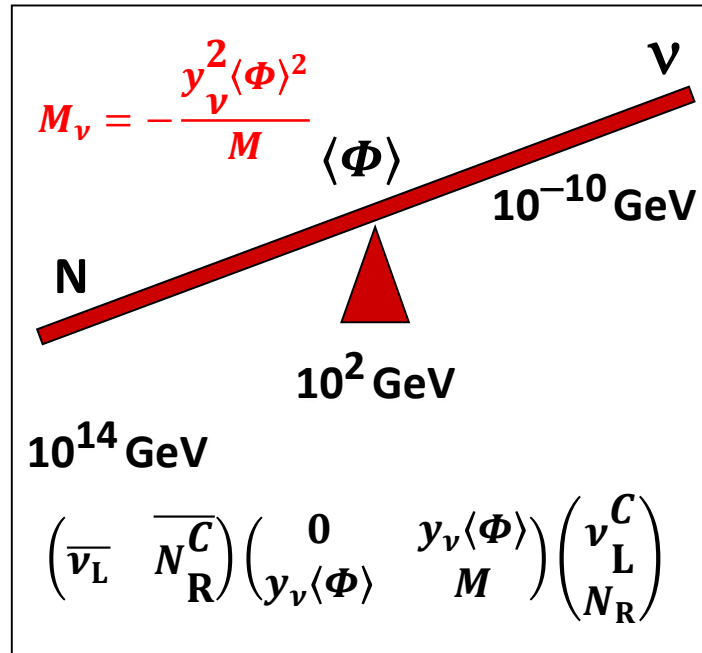
Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

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

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

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



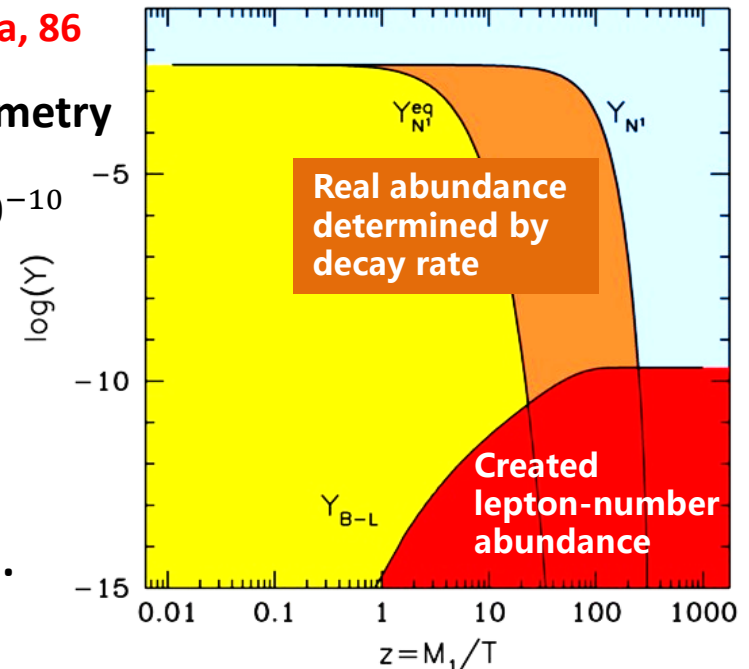
Fukugita, Yanagida, 86

B-number Asymmetry

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

Leptogenesis

- CP violation
- B-L violation
- Out-of-equil.
- 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:

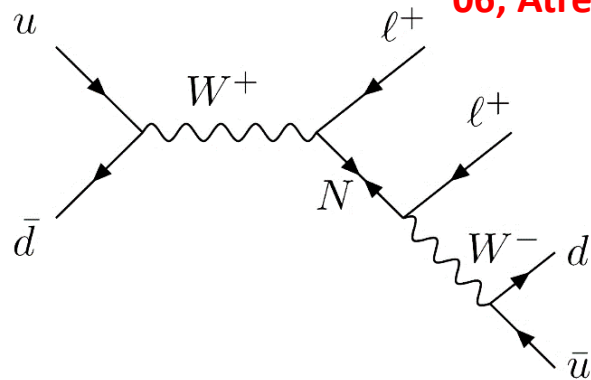
$$M_i \lesssim 10^7 \text{ GeV} \left(\frac{0.2 \text{ eV}}{m_i} \right)^{1/3}$$

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

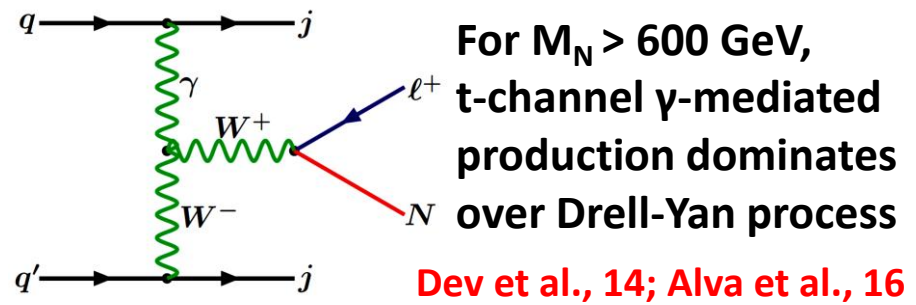
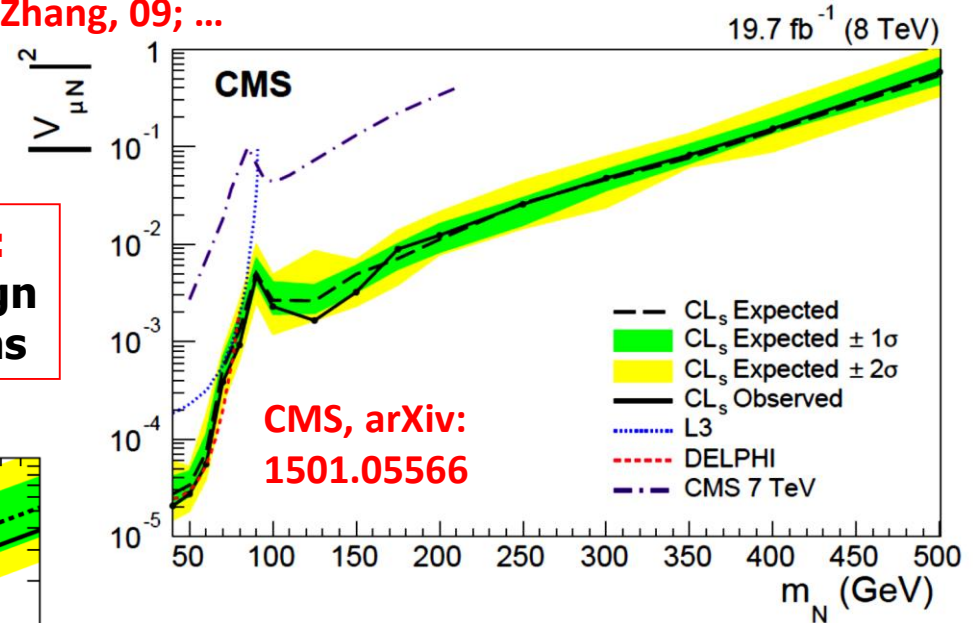
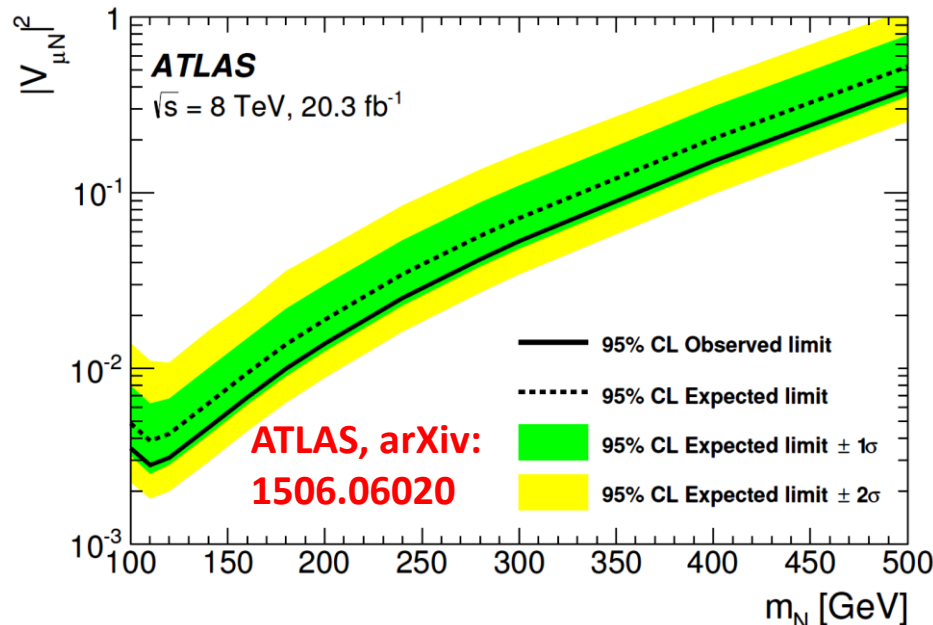
Seesaw models at the EW or TeV scales

- motivated by the naturalness and testability problems of conventional seesaws

Keung, Senjanovic, 83; Pilaftsis, 92; Han, Zhang, 06; Atre, Han, Pascoli, Zhang, 09; ...



**Signals:
same-sign
dileptons**

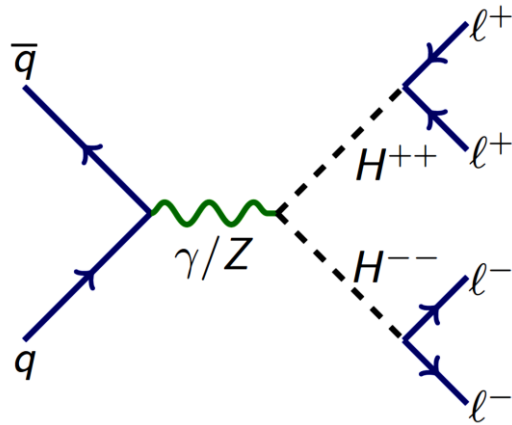


Type-II: 1207.2666 (CMS), 1412.0237 (ATLAS)

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

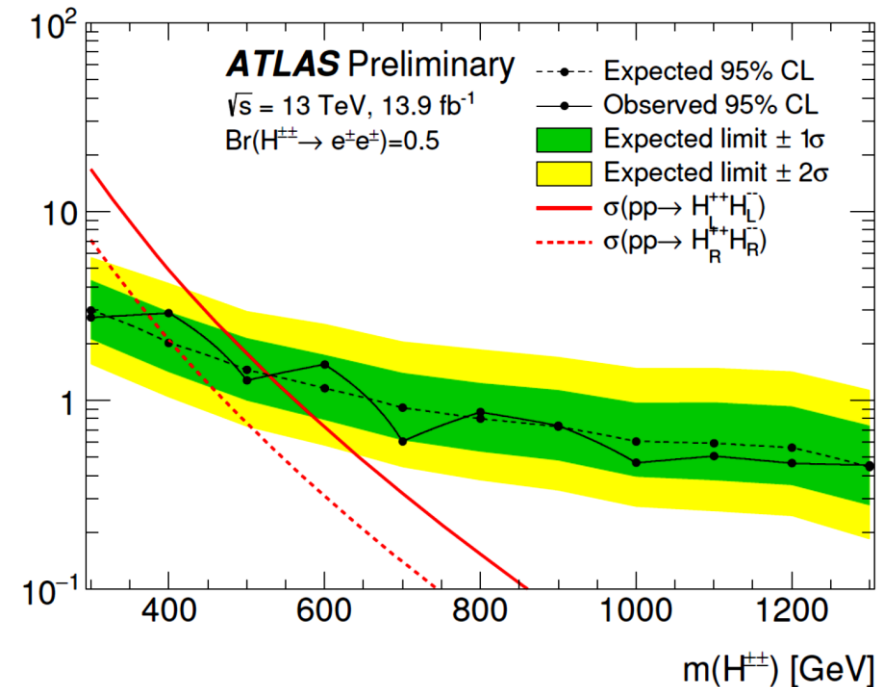
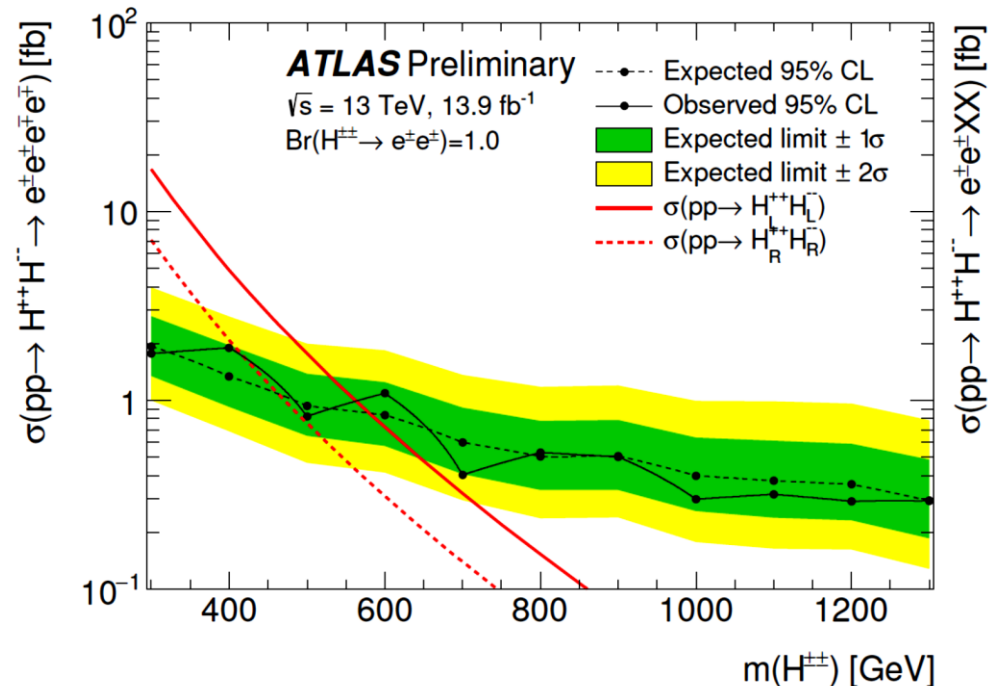
Searches for doubly-charged Higgs bosons

Chun et al., 03; Han et al., 05; Raidal et al., 07;
Perez et al., 08; Chao et al., 08; Z.L. Han, R. Ding,
Y. Liao, 12, 15

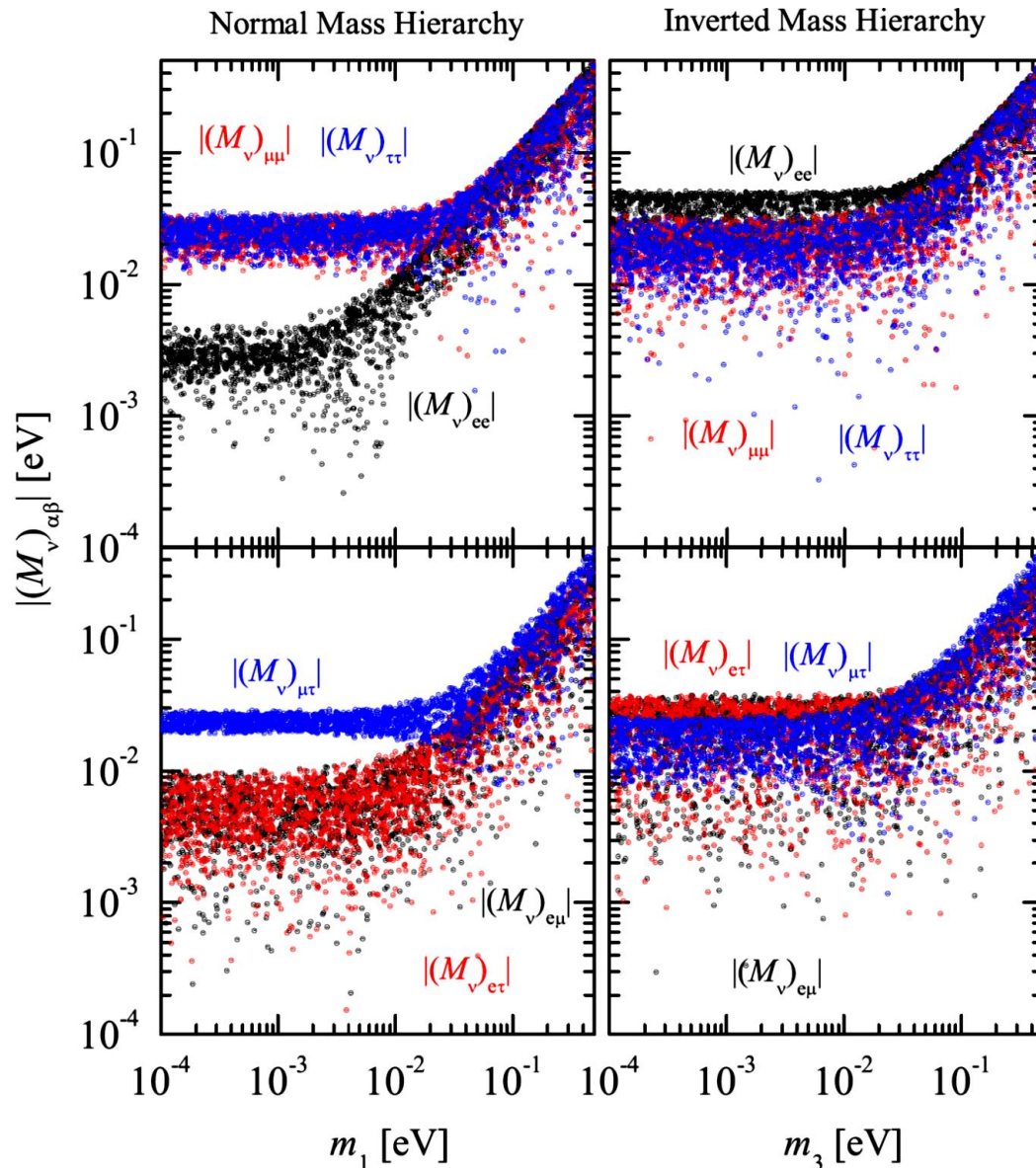


- Depending on the triplet vev, the dominant decay channel is either leptons or W's
- Couplings directly related to neutrino masses and flavor mixing parameters
- Current constraints on masses depend on branching ratios of doubly-charged Higgs decays

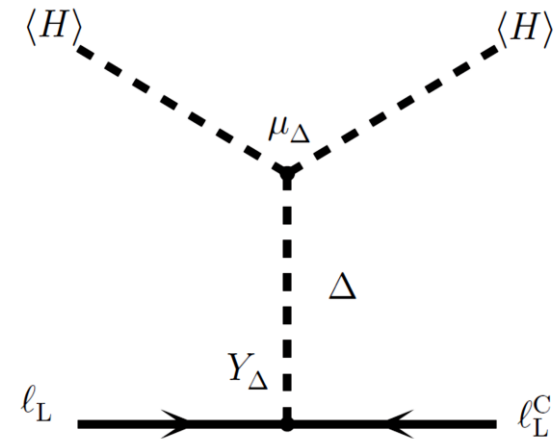
ATLAS-CONF-2016-051



Cornering the type-II seesaw model: Neutrino Oscillation Data



Reconstruction of the Yukawa coupling matrix Y_Δ from data

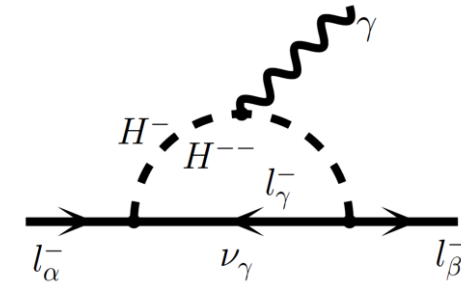


$$M_\nu = Y_\Delta v_\Delta = Y_\Delta \frac{\mu_\Delta v^2}{M_\Delta^2}$$

- Main uncertainties from mass ordering, absolute scale of neutrino masses, and CP-violating phases
- Other model parameters contain v_Δ and M_Δ

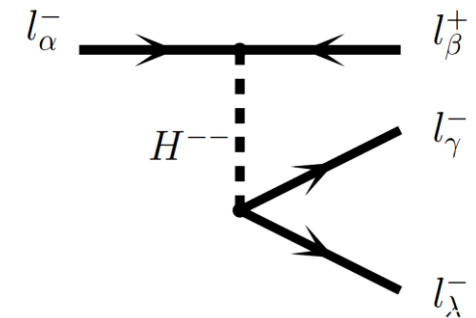
Cornering the type-II seesaw model: LFV Decays of Charged Leptons

Both H^{--} and H^- contribute to radiative decays

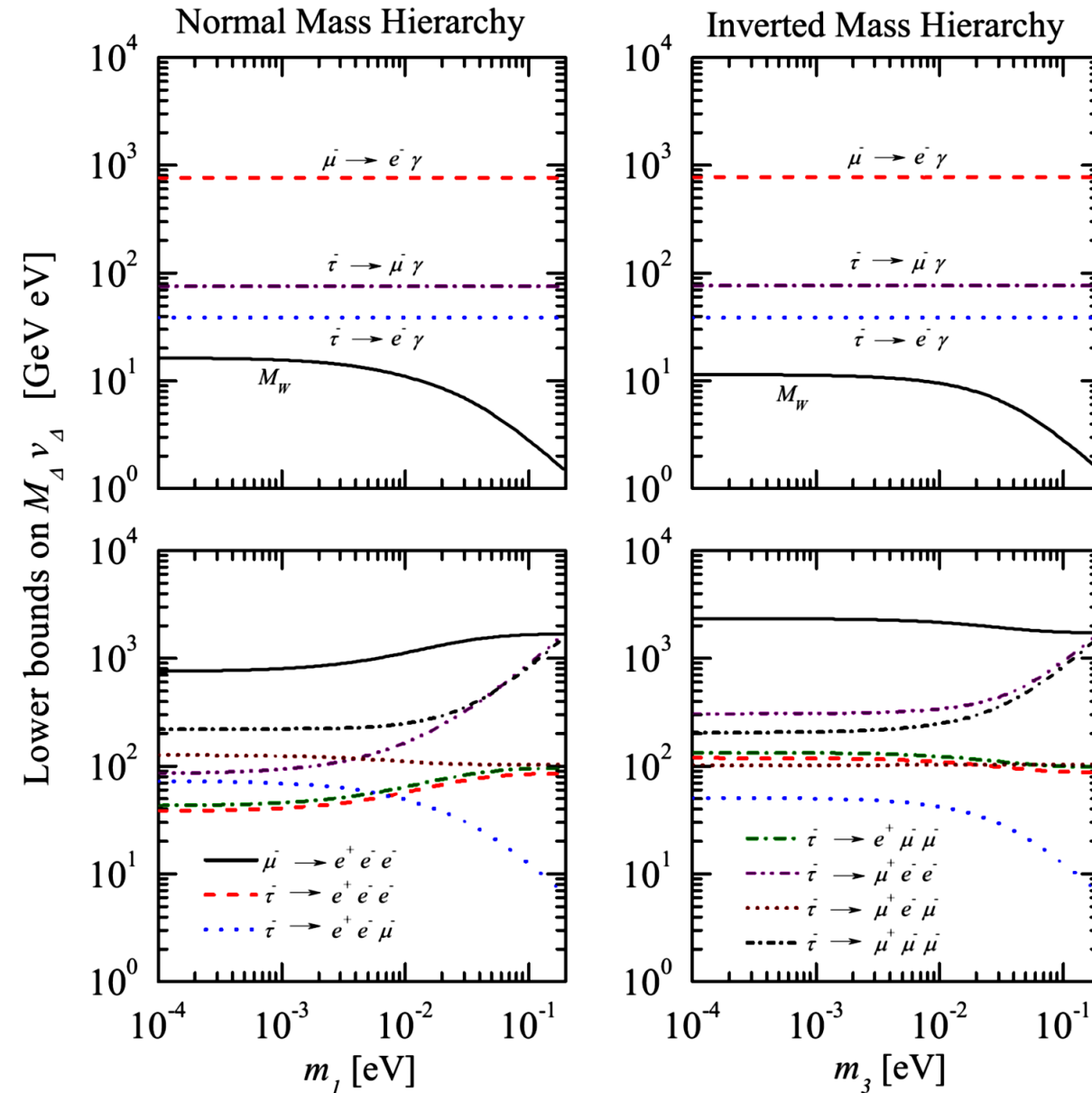


$$\frac{\text{Br}(l_\alpha^- \rightarrow l_\beta^- \gamma)}{\text{Br}(l_\alpha^- \rightarrow l_\beta^- \nu_\alpha \bar{\nu}_\beta)} = \frac{27\alpha | (M_\nu^\dagger M_\nu)_{\alpha\beta} |^2}{256\pi G_F^2 (M_\Delta v_\Delta)^4}$$

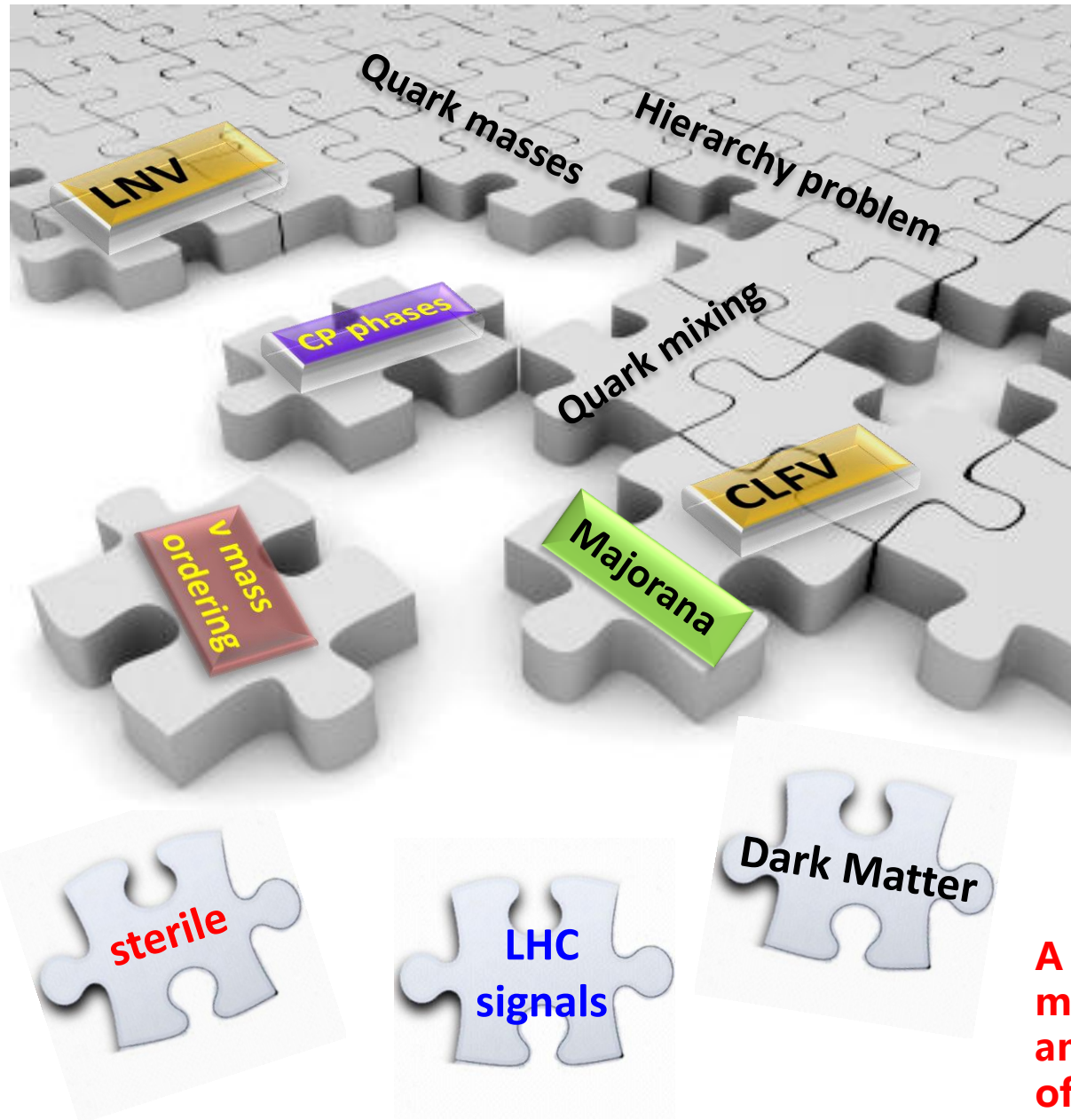
Tree-level effects



$$\frac{\text{Br}(l_\alpha^- \rightarrow l_\beta^+ l_\gamma^- l_\lambda^-)}{\text{Br}(l_\alpha^- \rightarrow l_\beta^- \nu_\alpha \bar{\nu}_\beta)} = \frac{| (M_\nu)_{\alpha\beta} |^2 | (M_\nu)_{\gamma\lambda} |^2}{16G_F^2 (M_\Delta v_\Delta)^4}$$



Summary



- Neutrino mass ordering and leptonic CP violation will be measured in the oscillation experiments
- Possible to pin down the absolute neutrino masses and the Majorana nature of massive neutrinos
- Searches for rare LFV & LNV decays will constrain new physics (NP) models or even give hints for NP
- Future large hadron and lepton colliders will also help us explore the origin of neutrino masses

A complete picture for neutrino masses relies on global efforts and discoveries in all branches of particle physics!