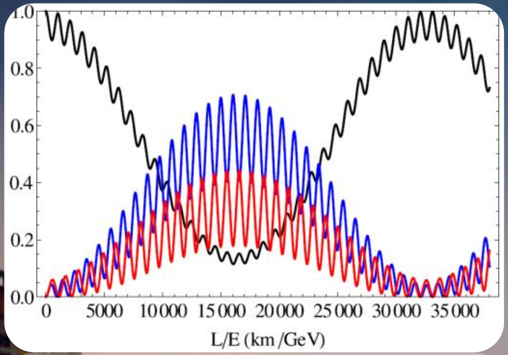
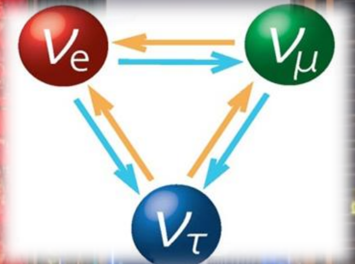
Theoretical Overview on Neutrinos



Shun Zhou
IHEP, Beijing



14th Workshop on HFCPV, SJTU, Shanghai, 2016/11/4

History of Neutrino Oscillations

60 years
(1956-2016)

1930 neutrino hypothesis by Pauli

1934 an effective theory for weak interactions by Fermi

1956 electron antineutrino $\overline{\nu}_e$ discovered by Cowan and Reines

1957 neutrino-antineutrino transitions proposed by Pontecorvo

1962 the 2nd family of neutrinos $\nu_\mu/\overline{\nu}_\mu$ 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 $\nu_\mu/\overline{\nu}_\mu$ in Super-Kamiokande

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

2001 solar ν_e and ν_μ/ν_τneutrinos 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

Lepton Flavor Mixing Matrix (PMNS)

Standard Parametrization of the PMNS Matrix

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

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

$\boldsymbol{|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2}$

Atmospheric,
LBL accelerator

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

$\boldsymbol{\delta \sim ?}$

Reactor,
LBL accelerator

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

$\boldsymbol{\Delta m^2_{21} \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2}$

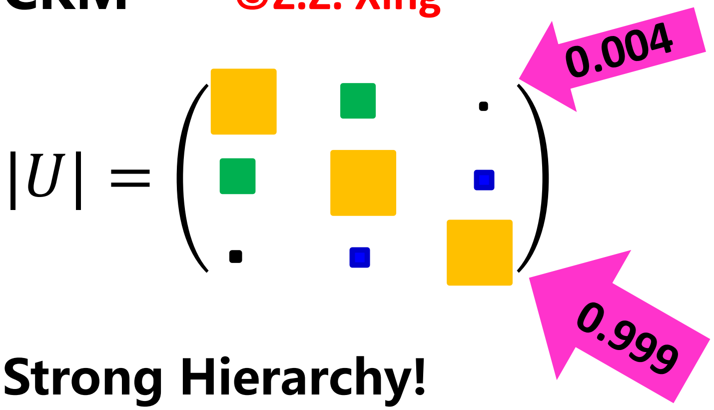
Solar,
KamLAND

0ν2β, LNV?

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

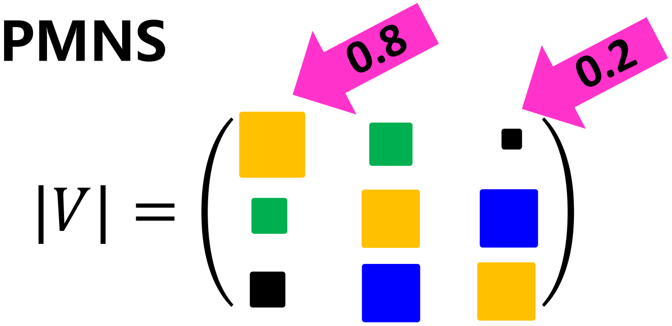
CKM

©Z.Z. Xing



Strong Hierarchy!

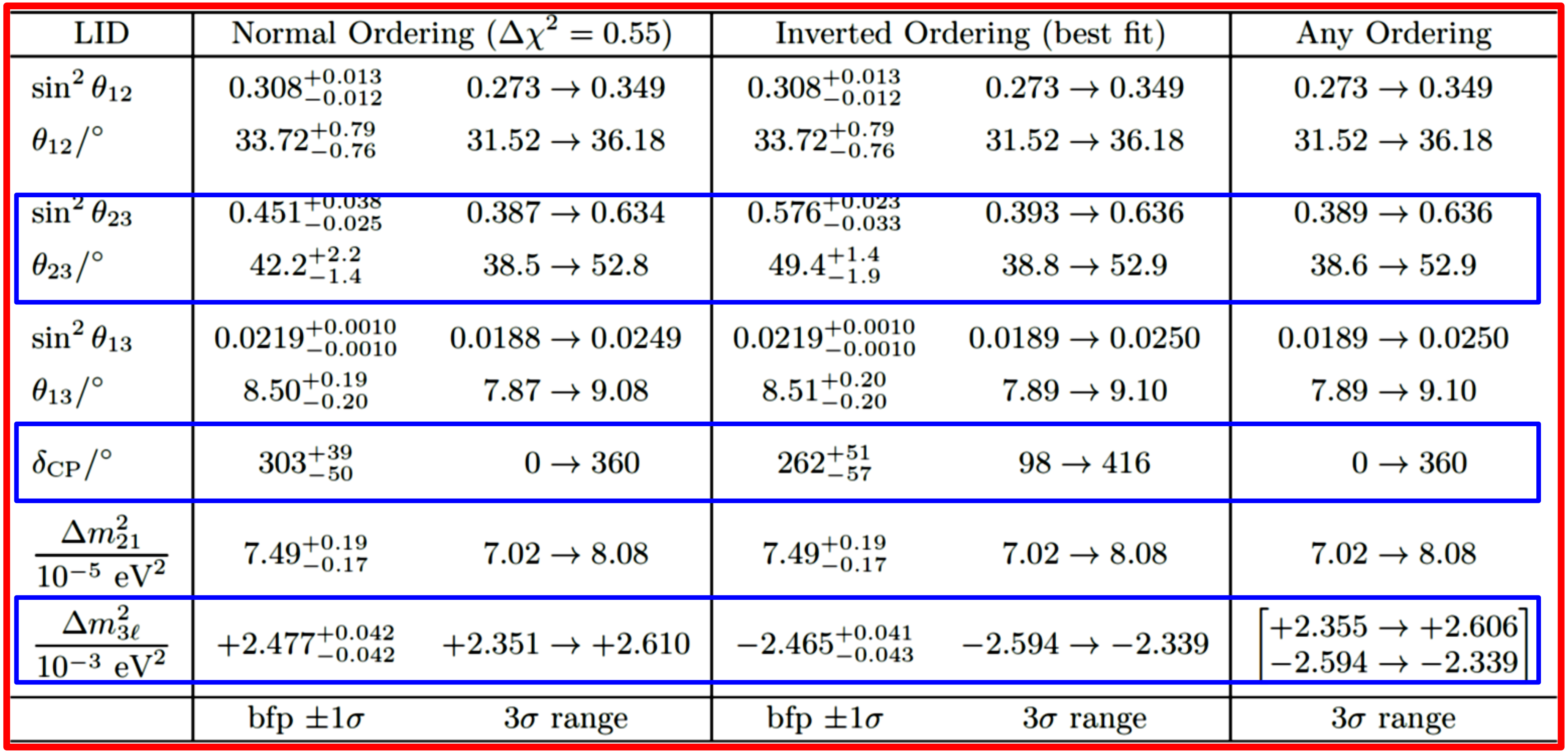
PMNS



Approximate μ-τ symmetry?

Current Status and Outlook

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



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

Neutrino Mass Hierarchy

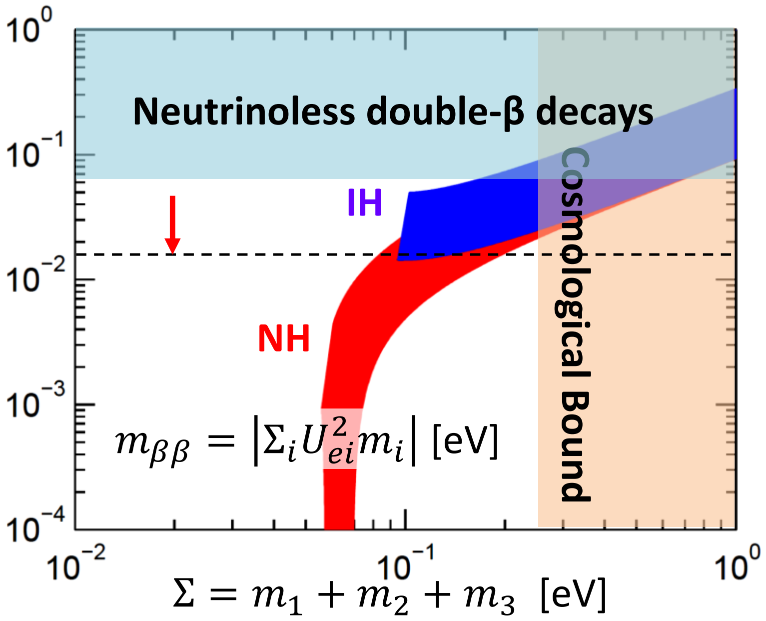
- Reactor: JUNO, RENO-50
- LBL Acc.: T2K, NOνA, LBNF/DUNE
- Atm: PINGU, ORCA, Hyper-K, INO

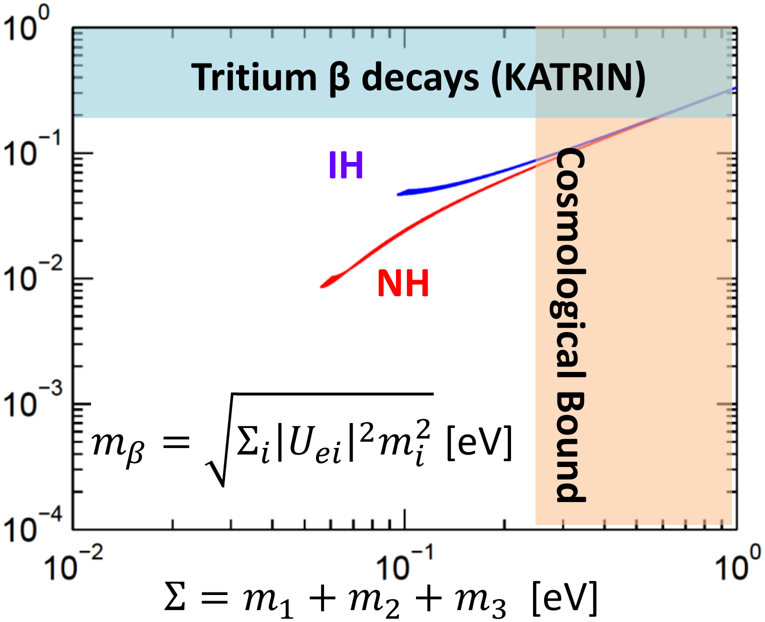
Leptonic CP Violation

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

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

Non-oscillation Experiments





$m_1 < m_2 < m_3$ (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)**

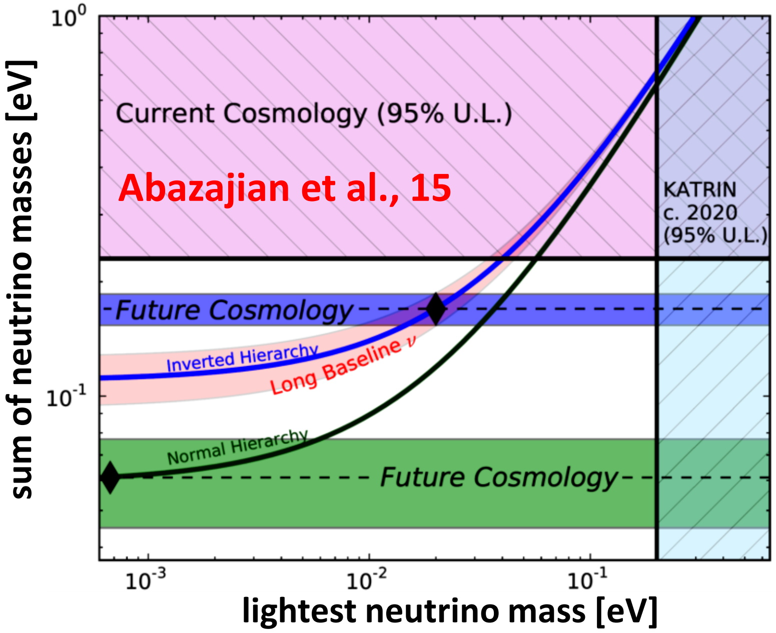
  2.1 eV **(Troitzk)**
- **Neutrinoless double-β decays (90% C.L.)**

  $m_{\beta\beta} < (0.06 \sim 0.16)$ eV **(KamLAND-Zen)**

  $(0.19 \sim 0.45)$ eV **(EXO-200)**

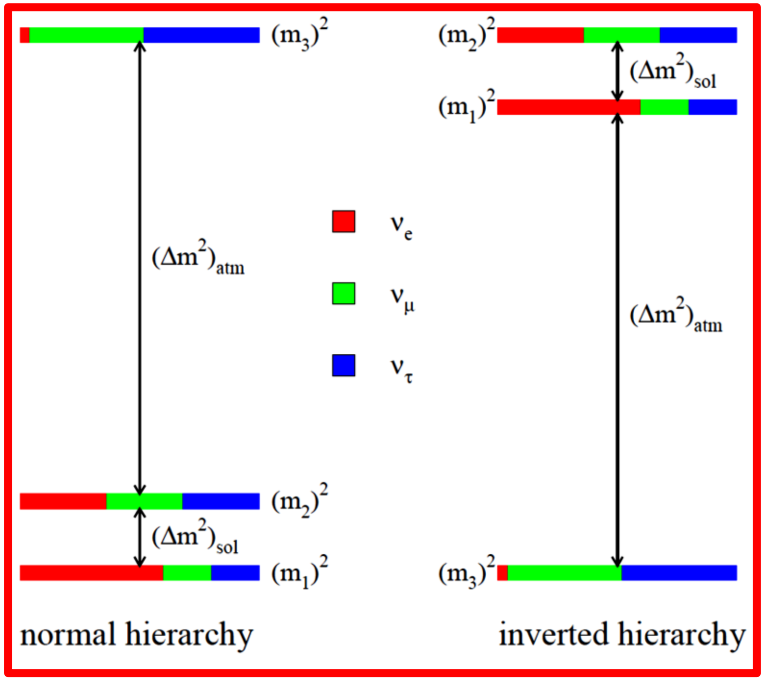
  $(0.22 \sim 0.64)$ eV **(GERDA)**
- **Cosmological observations (95% probability)**

  $\Sigma < 0.23$ eV **(Planck)**



Open Questions in Neutrino Physics

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



- Extra Neutrino Species
- 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

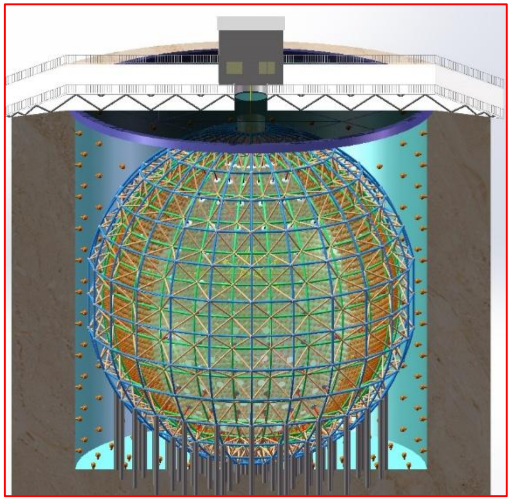
JUNO: 3~4σ (MH) for 6-year running (from 2020)

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

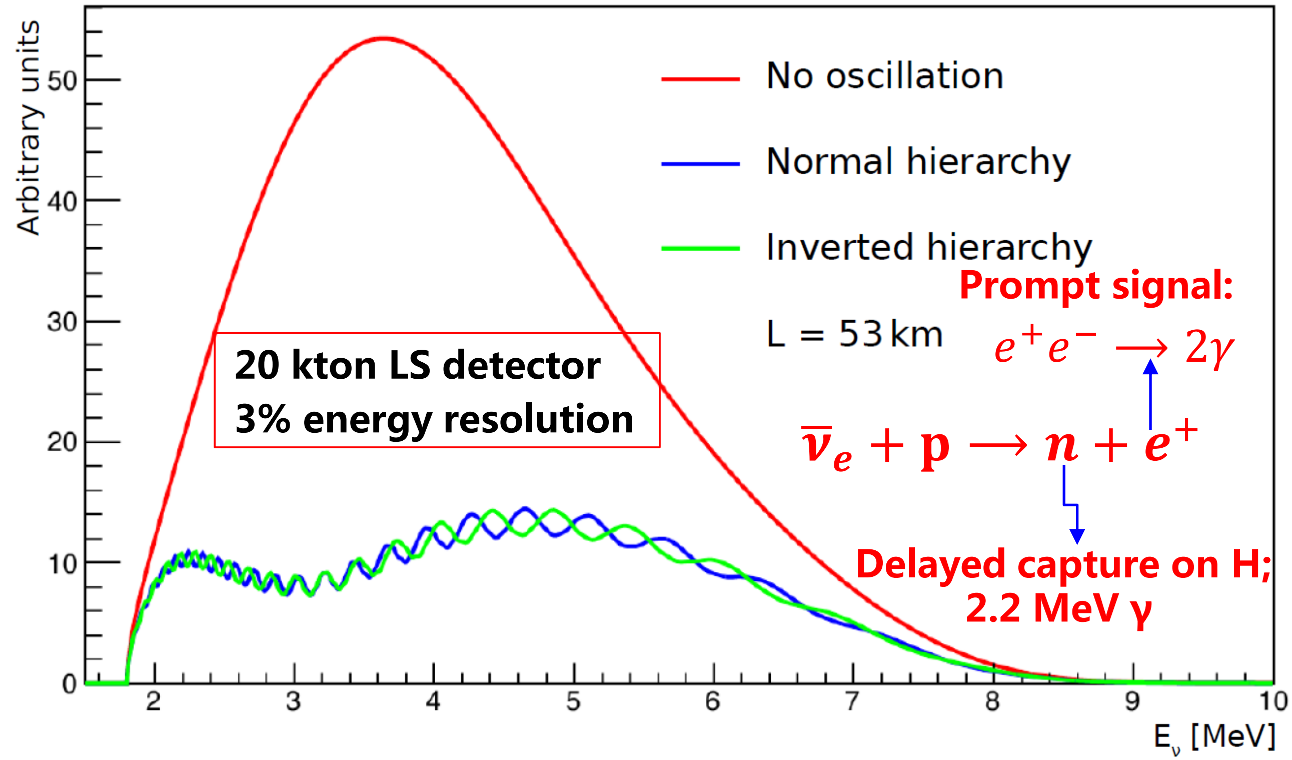
$$F_{ji} = \frac{\Delta m^2_{ji} L}{4E}$$

Li et al., PRD, 13

Neutrino Physics with JUNO
An et al., JPG, 16



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



20 kton LS detector
3% energy resolution

Prompt signal:

$e^+e^- \longrightarrow 2\gamma$

$\bar{\nu}_e + \mathbf{p} \longrightarrow n + e^+$

Delayed capture on H; 2.2 MeV γ

Parameters	Precision
$\sin^2 2\theta_{12}$	0.54%
Δm^2_{21}	0.24%
$\lvert\Delta m^2_{ee}\rvert$	0.27%

Precision Era (< 1%)

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

Neutrino Oscillation Phenomenology

Corrections to mixing angles

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

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

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

1%

Earth Matter Effects @JUNO

Li, Wang, Xing, CPC, 16

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

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

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

Corrections to mass-squared differences

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

1%

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

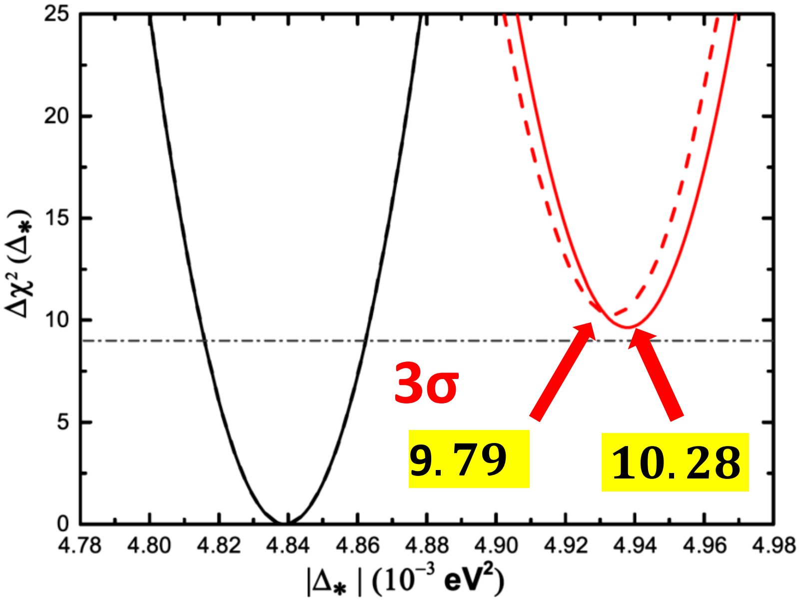
0.02%

$$\widetilde{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\widetilde{\theta}_{12}\cos^4\widetilde{\theta}_{13}\sin^2\widetilde{F}_{21} - \frac{1}{2}\sin^2 2\widetilde{\theta}_{13}(1 - \cos\widetilde{F}_{*}\cos\widetilde{F}_{21} + \cos 2\widetilde{\theta}_{12}\sin\widetilde{F}_{*}\sin\widetilde{F}_{21})$$

$$\Delta_{ji} = m_j^2 - m_i^2$$

$$\widetilde{\Delta}_{ji} = \widetilde{m}_j^2 - \widetilde{m}_i^2$$

Impact on MH



3σ

9.79

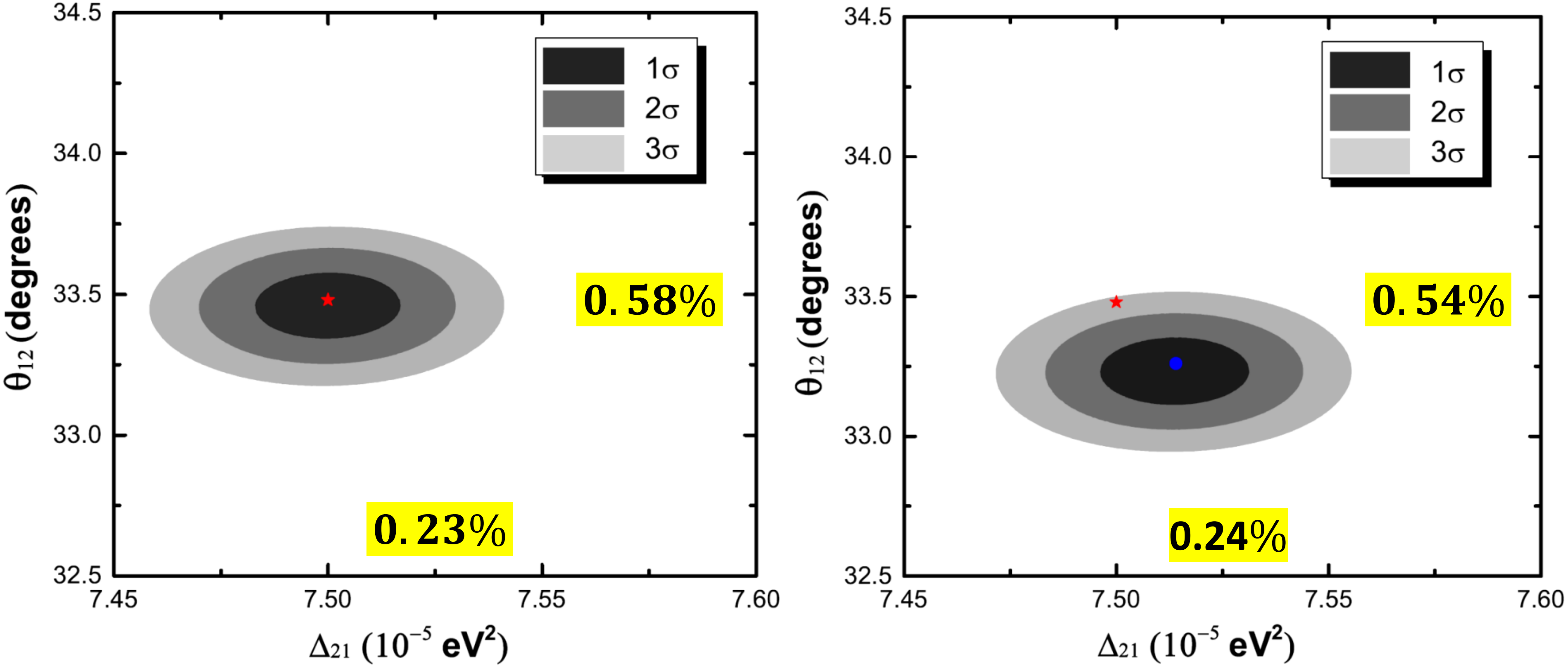
10.28

Neutrino Oscillation Phenomenology

Impact on precision measurements

Earth Matter Effects @JUNO

Li, Wang, Xing, CPC, 16



Many phenomenlogical works for current and future experiments:
JUNO, RENO50/PINGU, ORCA, INO, HK/T2K, NOνA, DUNE/ESSνSB, MOMENT

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

Flavor Symmetries

Flavor Symmetry

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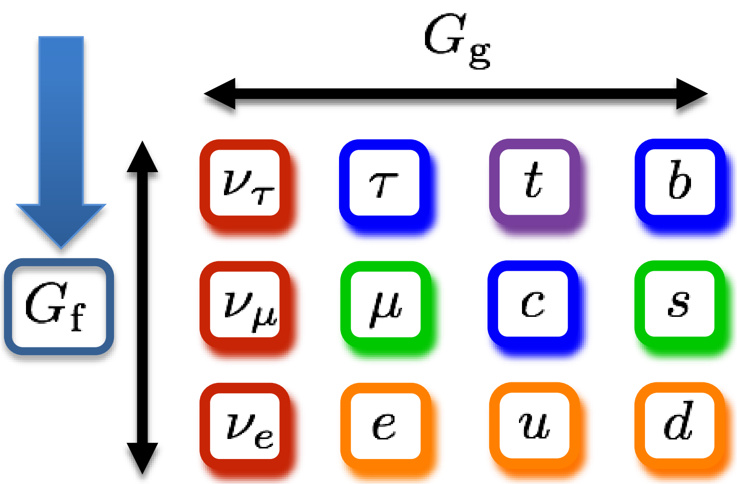
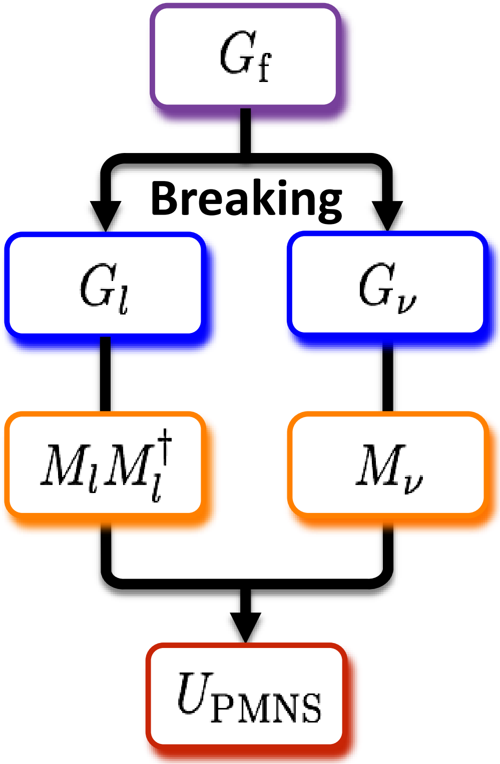


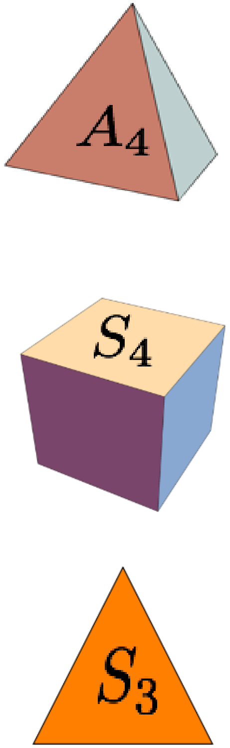
Tri-bimaximal neutrino mixing matrix

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

Flavor Symmetries

Allowed ranges of PMNS matrix elements (@ 3σ)

NuFIT 2.1 (2016)

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{pmatrix} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

In the standard parametrization:

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

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

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

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

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

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

μ-τ reflection symmetry

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

$$M_\nu = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix}$$

Invariant under:

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

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

Flavor Symmetries

Generalized CP

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

X depends on a chosen flavor symmetry

S_3, A_4, S_4, A_5

T′, T_7, T_{13}

Δ(27), Δ(48), Δ(54), Δ(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?

Flavor Symmetries

Two-zero Textures of M_ν

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

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

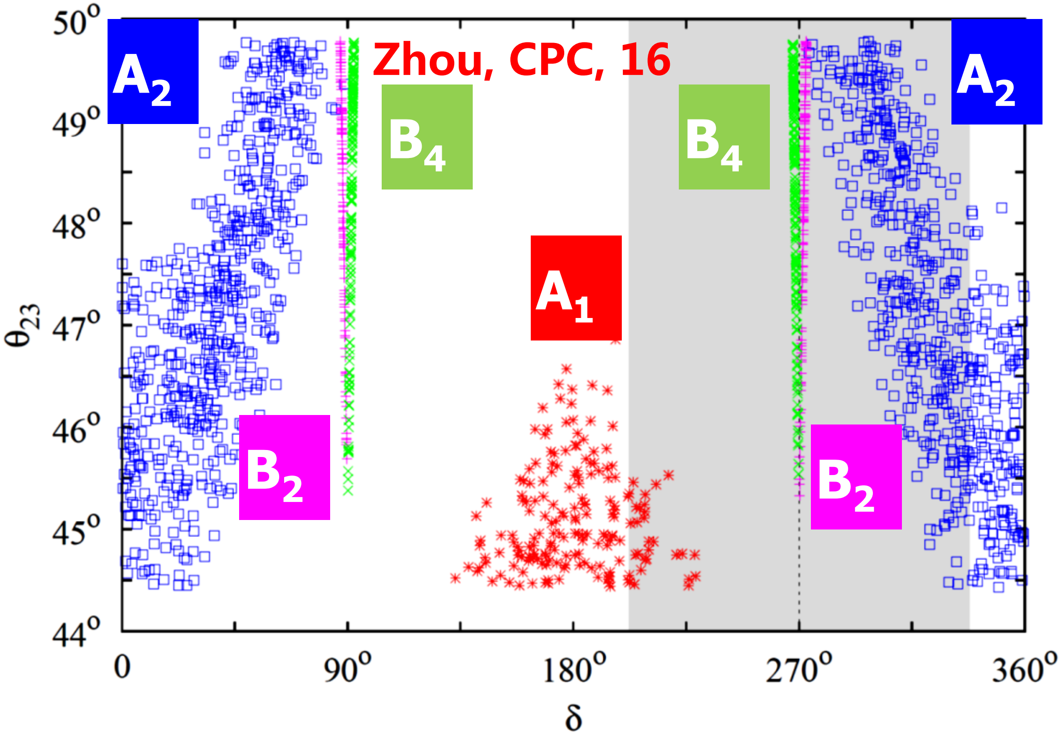
B$_1$ $\begin{pmatrix}\times & \times & 0\\ \times & 0 & \times\\ 0 & \times & \times\end{pmatrix}$ **B$_2$** $\begin{pmatrix}\times & 0 & \times\\ 0 & \times & \times\\ \times & \times & 0\end{pmatrix}$

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

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

Consistent with nonzero θ_{13} & can be realized by A$_4$ symmetry

(a) NH; (b) $\theta_{23}>45^\circ$; (c) δ ~ 270°



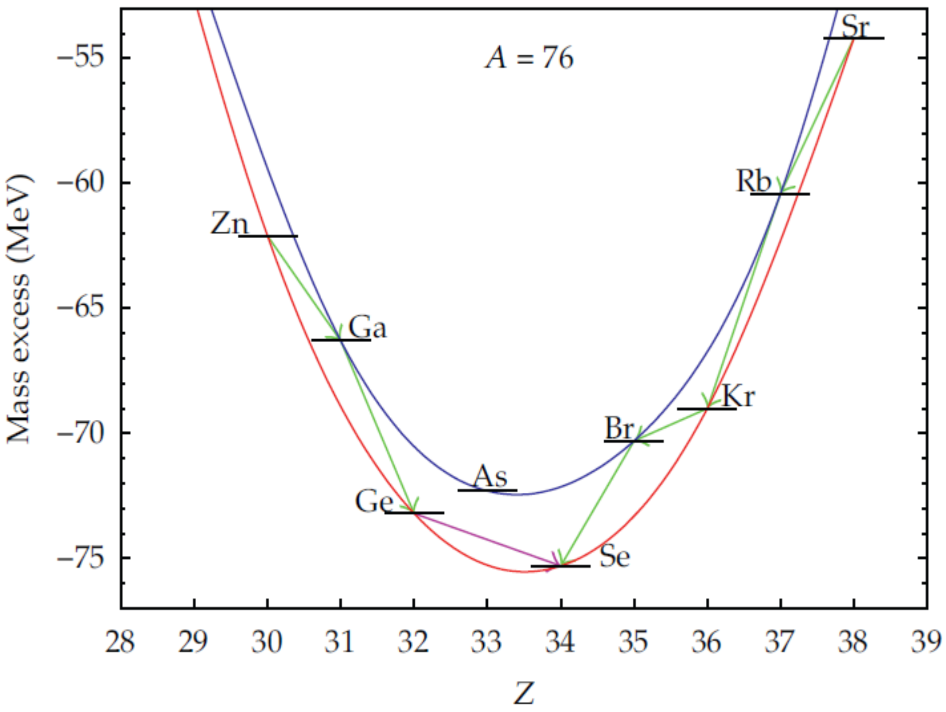
Zhou, CPC, 16

Model building in the type-I+II seesaw model

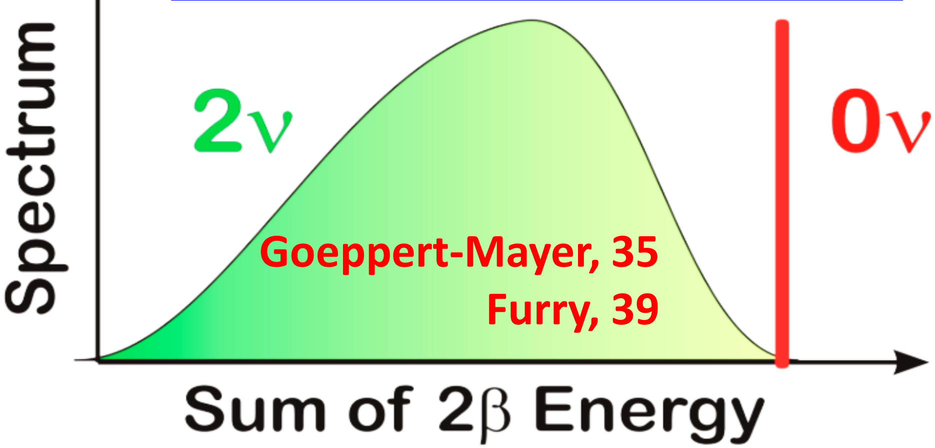
$l_{\alpha \mathrm{L}}$	$E_{\alpha \mathrm{L}}$	N_{R}	Φ_i	φ, ϕ	Δ
1,1’,1’’	3	1	3	1,1’	1

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

Majorana vs. Dirac

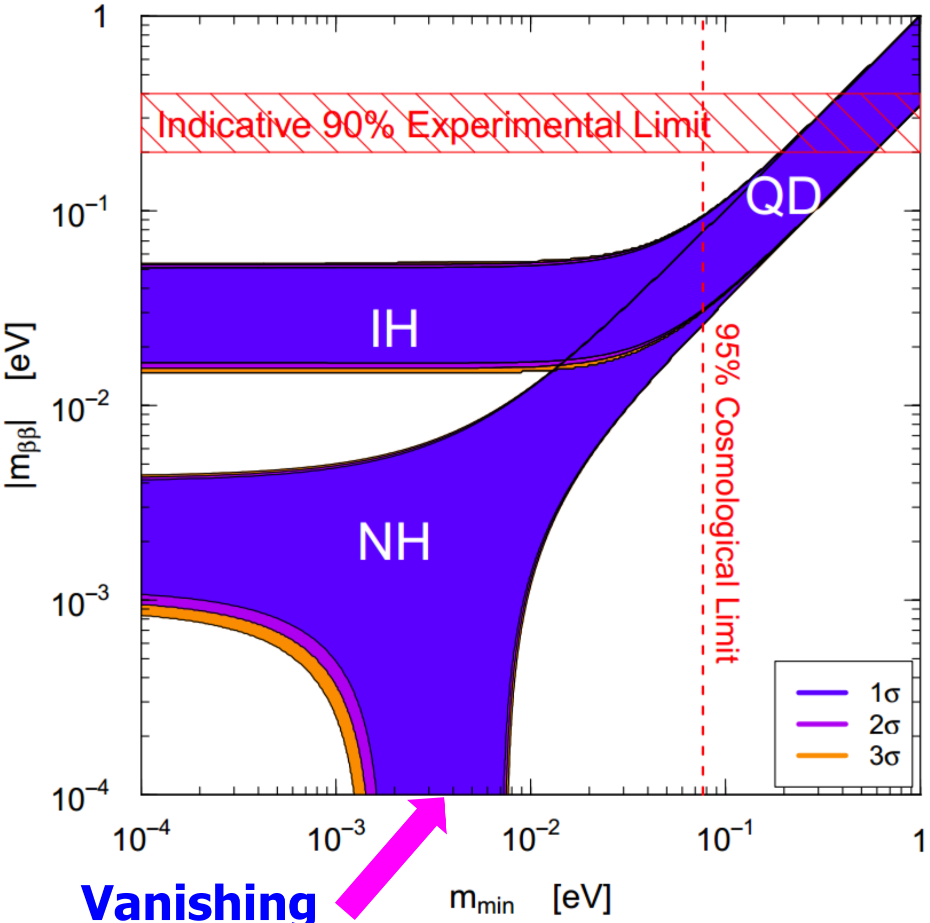


$$T^{0\nu}_{1/2} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|m_{\beta\beta}\right|^{-2}$$



Goeppert-Mayer, 35

Furry, 39



Vanishing

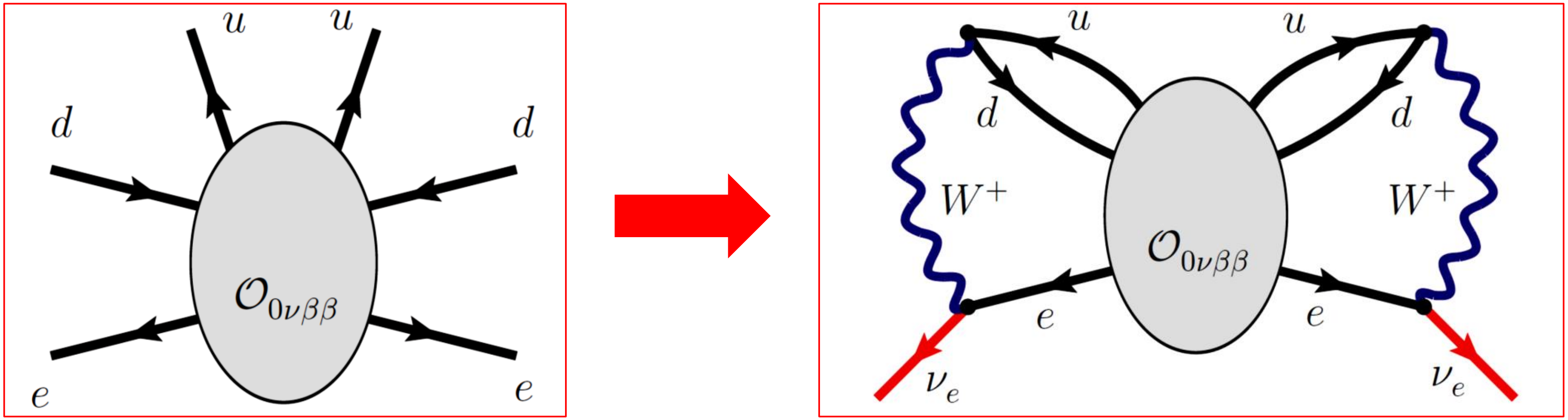
0ν2β mass?

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**

Majorana vs. Dirac



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:

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

(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**

Majorana vs. Dirac

When the temperature *T* ~ 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

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

Mean momentum today

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

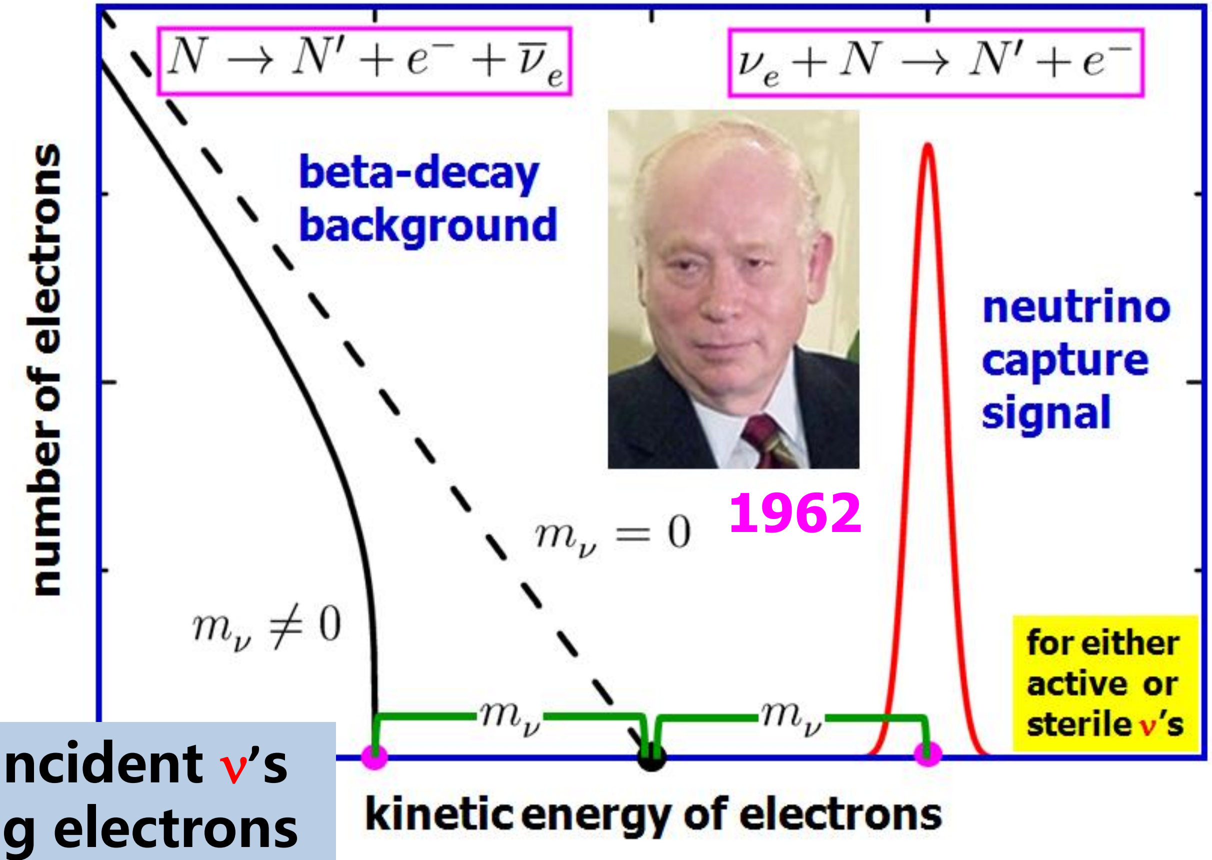
At least 2 ν's cold today

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



Majorana vs. Dirac

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

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

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

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

Long et al., 14

Majorana vs. Dirac

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

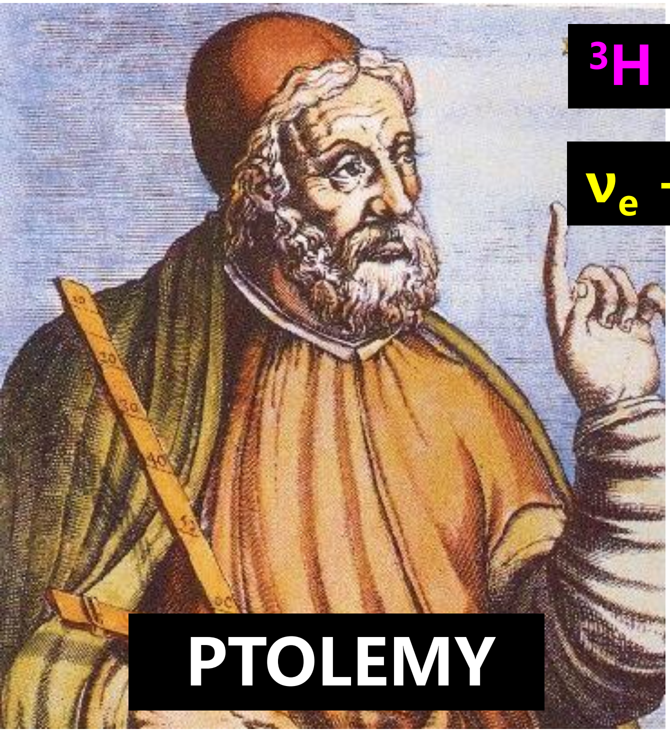
$$\widehat{H}\equiv\gamma^0 m+\gamma^0\vec{\gamma}\cdot\vec{p}=\begin{pmatrix} m & \vec{\sigma}\cdot\vec{p} \\ \vec{\sigma}\cdot\vec{p} & -m \end{pmatrix} \qquad \widehat{h}\equiv\frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}|}=\frac{1}{|\vec{p}|}\begin{pmatrix} \vec{\sigma}\cdot\vec{p} & 0 \\ 0 & \vec{\sigma}\cdot\vec{p}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

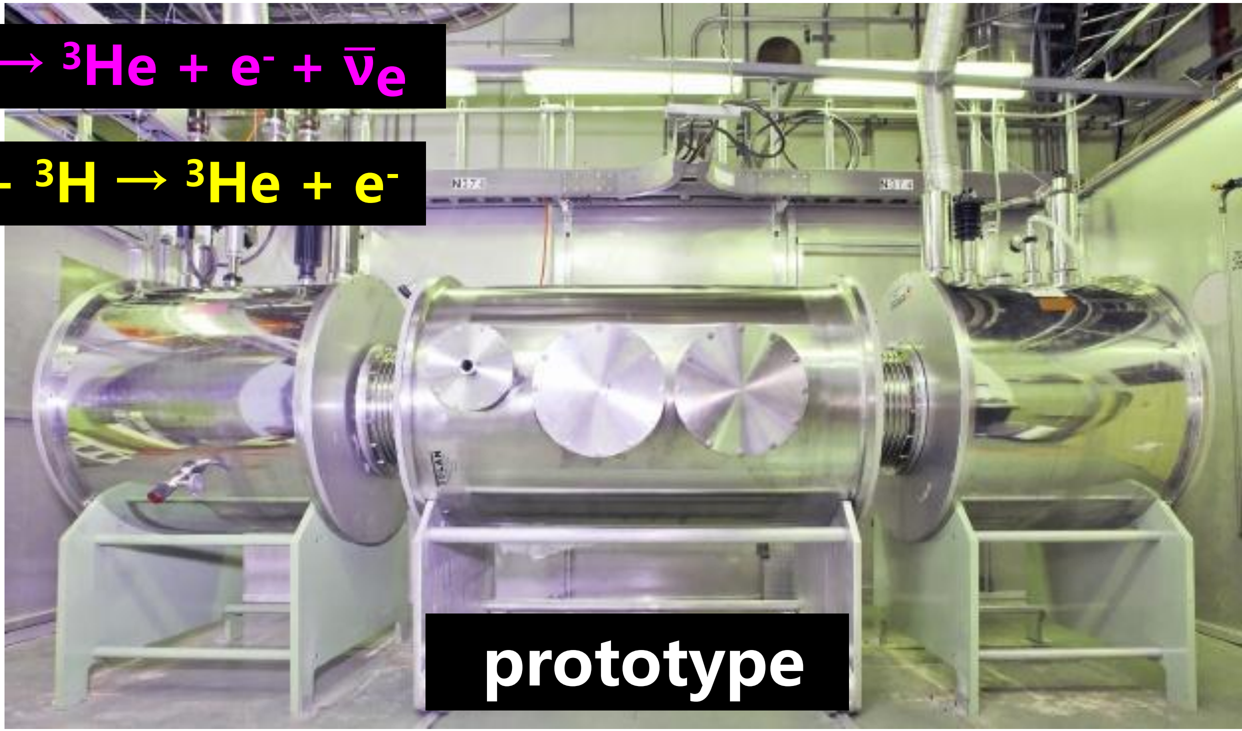
In the rest frame of CνB, the background neutrinos are isotropic

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

	Dirac Neutrinos		Majorana Neutrinos
Decoupling	$n(\nu_{\rm L})=n(z)$, $n(\overline{\nu}_{\rm R})=n(z)$,	$n(\nu_{\rm R})\approx 0$ $n(\overline{\nu}_{\rm L})\approx 0$	$n(\nu_{\rm L})=n(z)$ $n(\nu_{\rm R})=n(z)$
Nowadays	$n(\nu_{\rm hL})=n_0$, $n(\overline{\nu}_{\rm hR})=n_0$,	$n(\nu_{\rm hR})\approx 0$ $n(\overline{\nu}_{\rm hL})\approx 0$	$n(\nu_{\rm hL})=n_0$ $n(\nu_{\rm hR})=n_0$
Total Rates	$\boxed{\Gamma^{\rm D}_{\rm C\nu B}=\overline{\sigma}n_0N_{\rm T}}$	$\overline{\sigma}\approx 3.8\times 10^{-45}\ {\rm cm}^2$	$\boxed{\Gamma^{\rm M}_{\rm C\nu B}=2\overline{\sigma}n_0N_{\rm T}}$

Majorana vs. Dirac





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

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

★ first experiment

★ 100 g of tritium

★ graphene target

★ planned energy resolution 0.15 eV

★ CνB capture rate

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

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

D = Dirac

M = Majorana

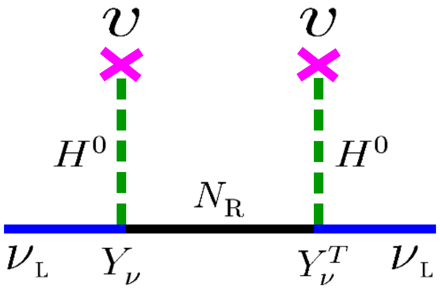
PTOLEMY
Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield (Betts et al, arXiv:1307.4738)

Neutrino Mass Models

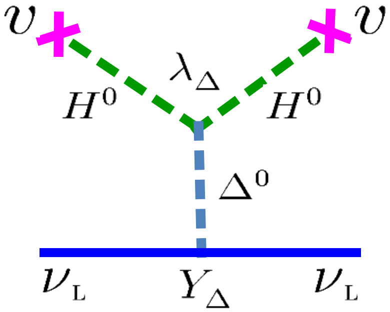
Difficulties with Dirac neutrinos

- 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

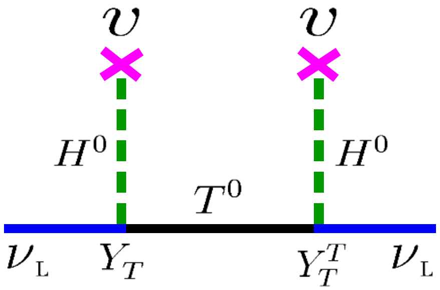
Majorana neutrinos: a natural way to understand tiny neutrino masses (seesaw)



$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$



$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$



$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

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)

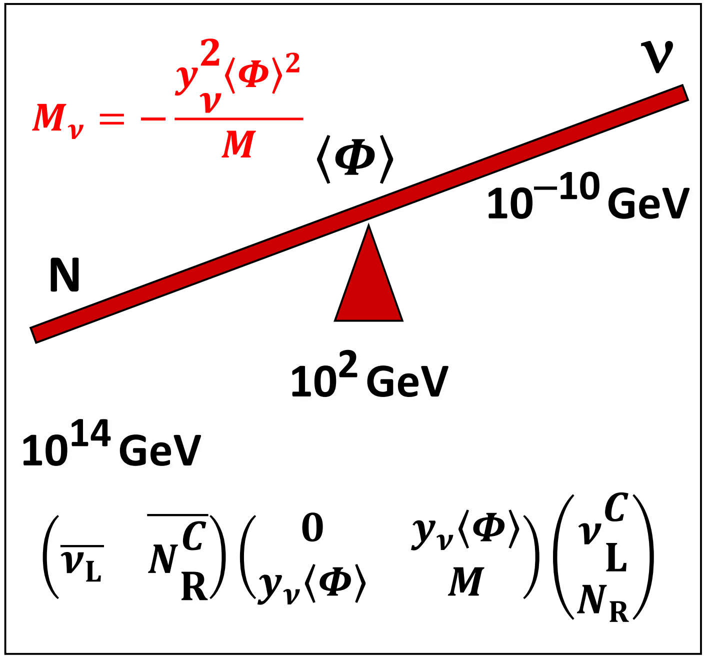
Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

- 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

Neutrino Mass Models

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

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



$$M_\nu = -\frac{y_\nu^2\langle\Phi\rangle^2}{M}$$

$$\begin{pmatrix}\overline{\nu_L} & \overline{N_R^C}\end{pmatrix}\begin{pmatrix}0 & y_\nu\langle\Phi\rangle\\ y_\nu\langle\Phi\rangle & M\end{pmatrix}\begin{pmatrix}\nu_L^C\\ N_R\end{pmatrix}$$

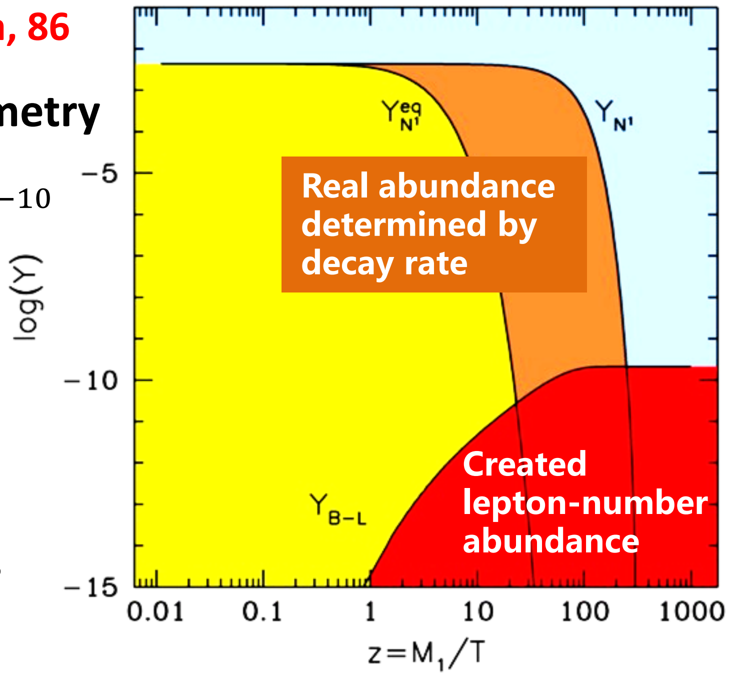
Fukugita, Yanagida, 86

B-number Asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 6\times10^{-10}$$

Leptogenesis

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



Real abundance determined by decay rate

Created lepton-number abundance

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:

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

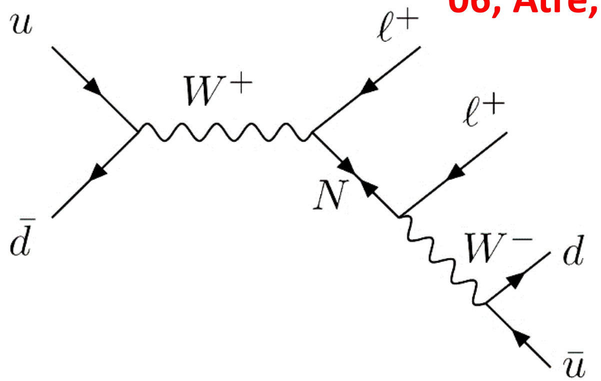
for $\delta M_H^2 \sim 0.1\ \text{TeV}^2$

Neutrino Mass Models

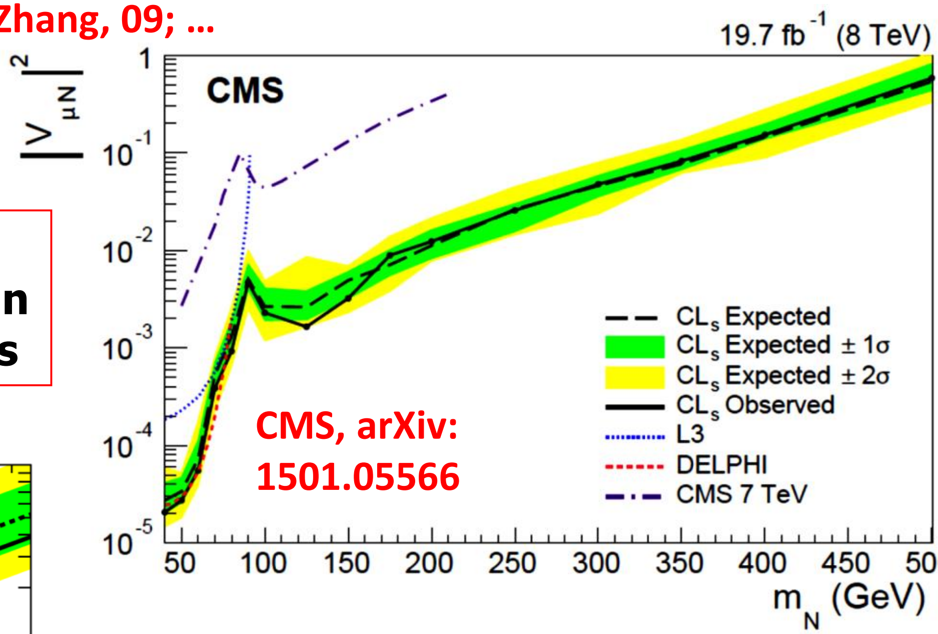
Seesaw models at the EW or TeV scales

- **motivated by the naturalness and testability problems of conventional seesaws**

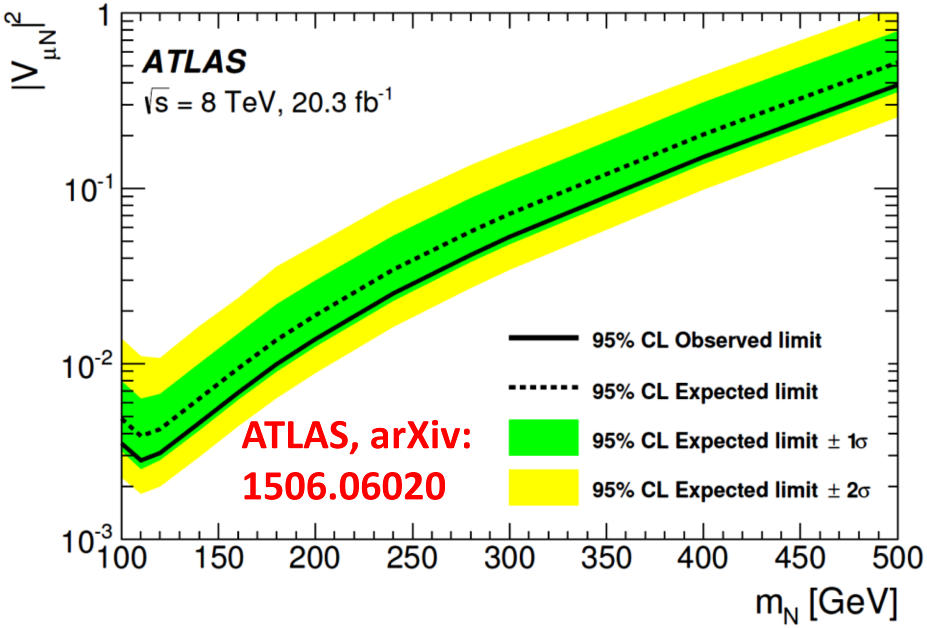
Keung, Senjanovic, 83; Pilaftsis, 92; Han, Zhang, 06; Atre, Han, Pascoli, Zhang, 09; …



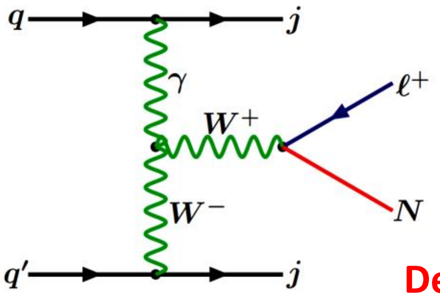
Signals:
same-sign
dileptons



CMS, arXiv: 1501.05566



ATLAS, arXiv: 1506.06020



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

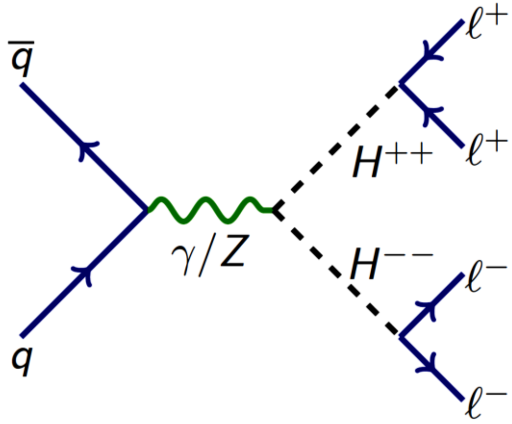
Dev et al., 14; Alva et al., 16

Type-II: 1207.2666 (CMS), 1412.0237 (ATLAS)
Type-III: 1506.01291 (CMS), 1506.01839 (ATLAS)

Neutrino Mass Models

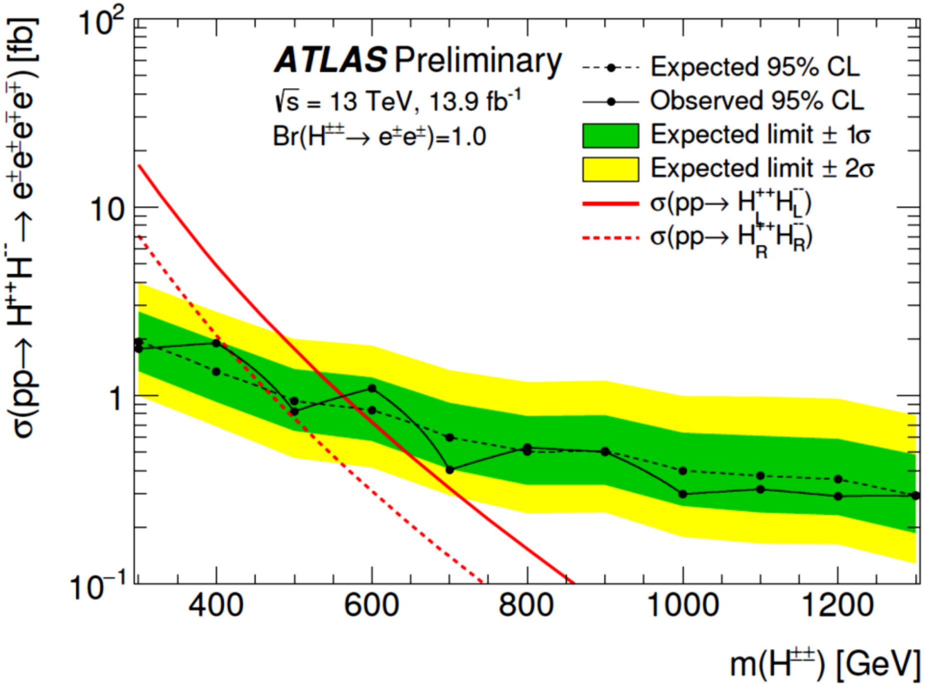
Searches for doubly-charged Higgs bosons

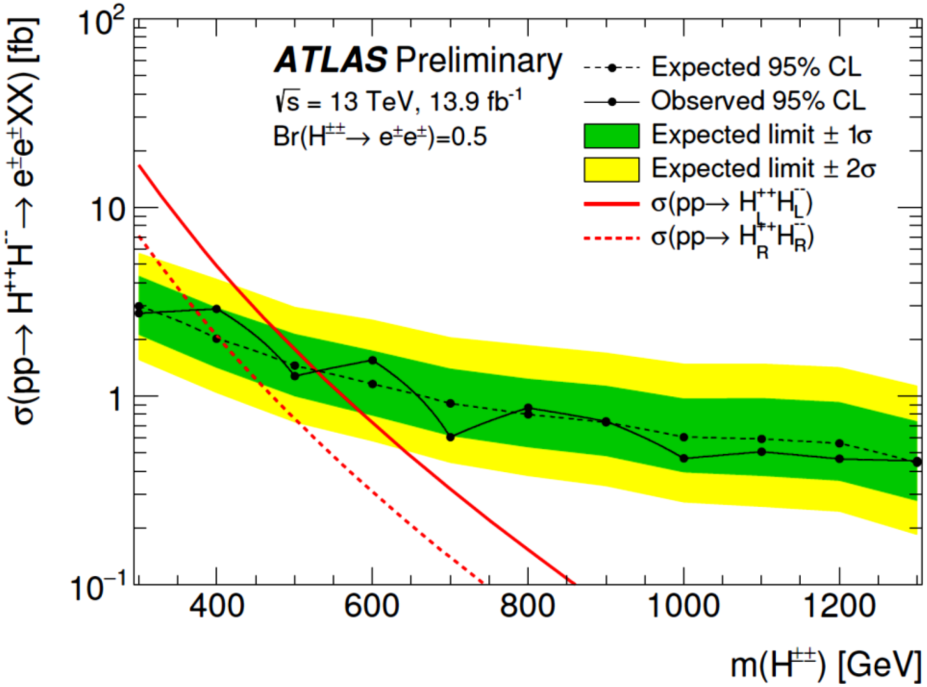
Chun et al., 03; Han et al., 05; Raidal et al., 07; Perez et al., 08; Chao et al., 08; Z.L. Han, R. Ding, Y. Liao, 12, 15



- 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 constants on masses depend on branching ratios of doubly-charged Higgs decays

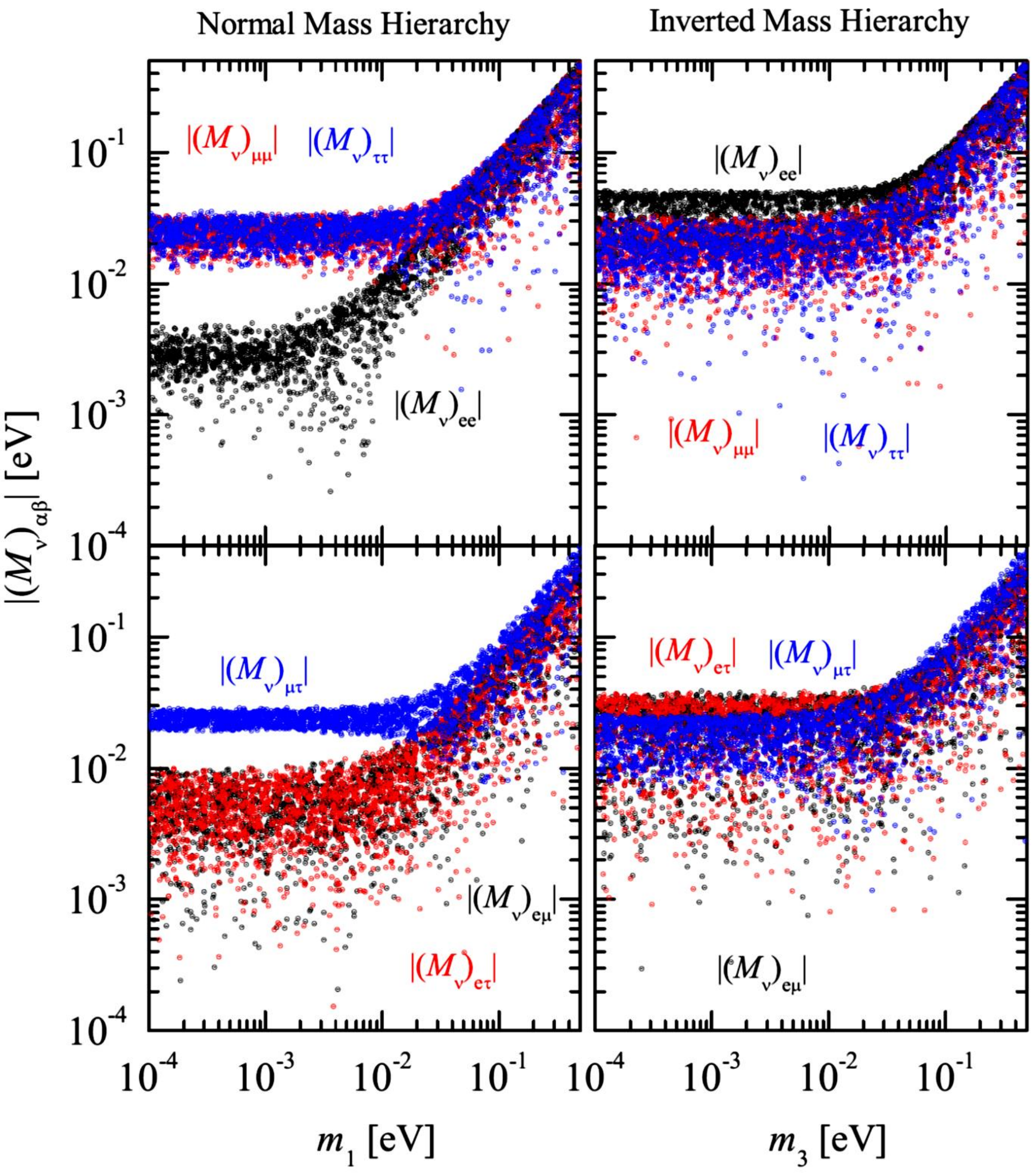
ATLAS-CONF-2016-051



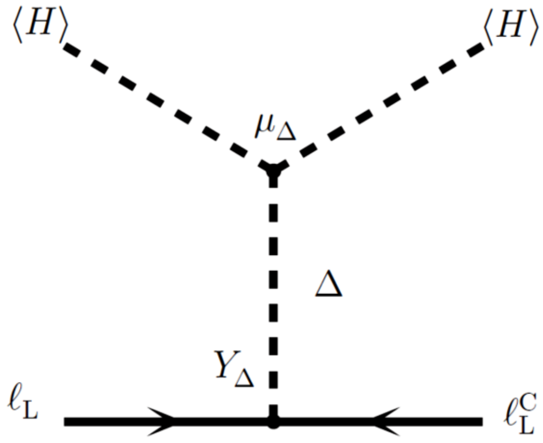


Neutrino Mass Models

Cornering the type-II seesaw model: Neutrino Oscillation Data



Reconstruction of the Yukawa coupling matrix Y_Δ from data

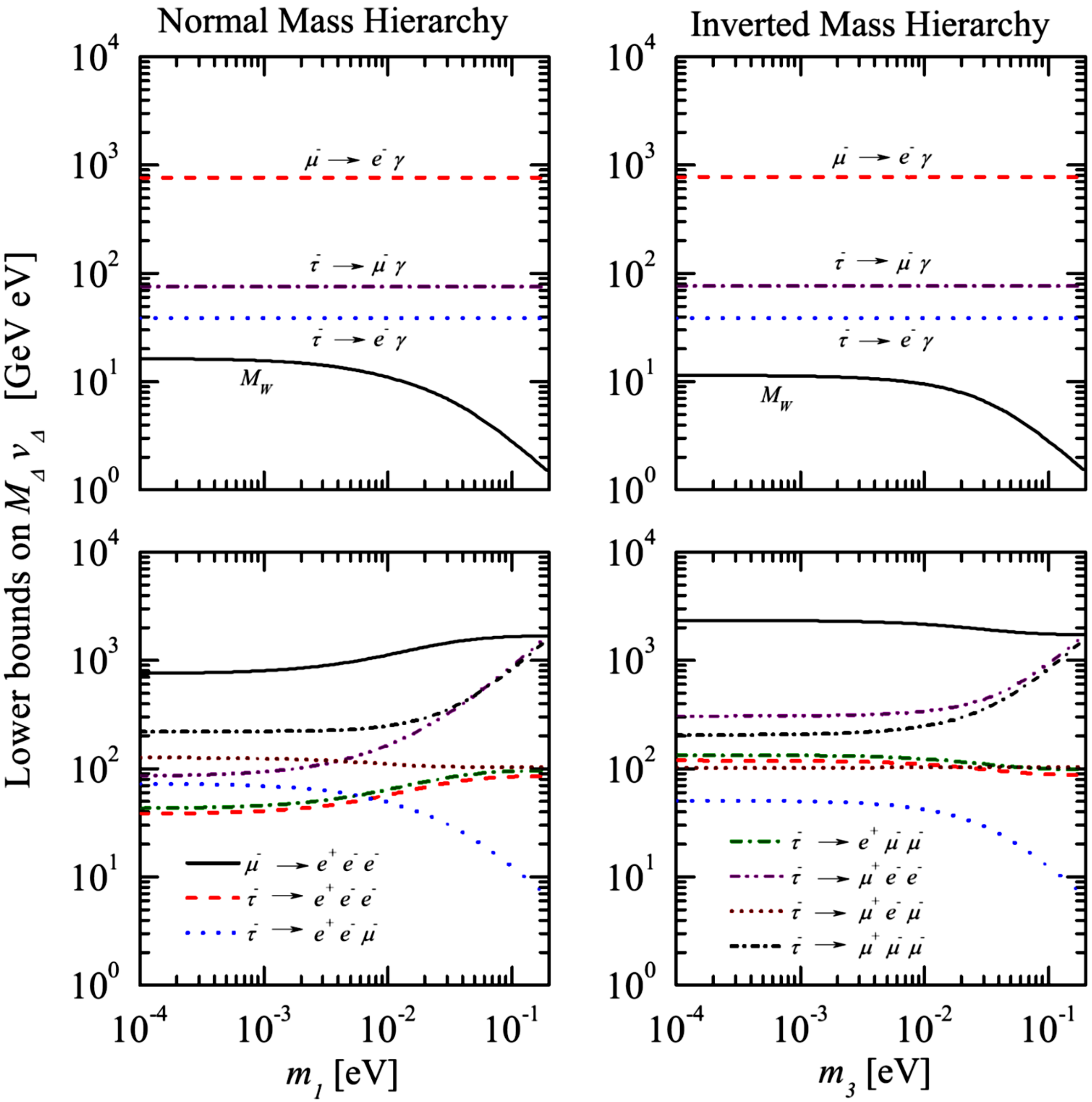


$$\boxed{M_\nu = Y_\Delta v_\Delta = Y_\Delta \frac{\mu_\Delta v^2}{M_\Delta^2}}$$

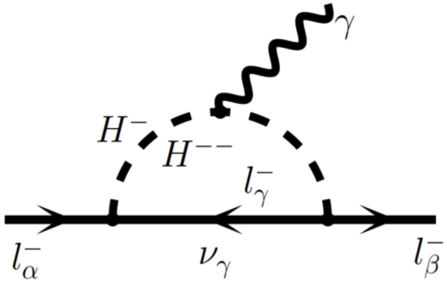
- **Main uncertainties from mass ordering, absolute scale of neutrino masses, and CP-violating phases**
- **Other model parameters contain v_Δ and M_Δ**

Neutrino Mass Models

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

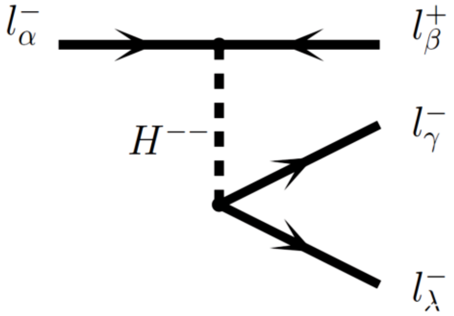


Both H^{--} and H^- contribute to radiative decays



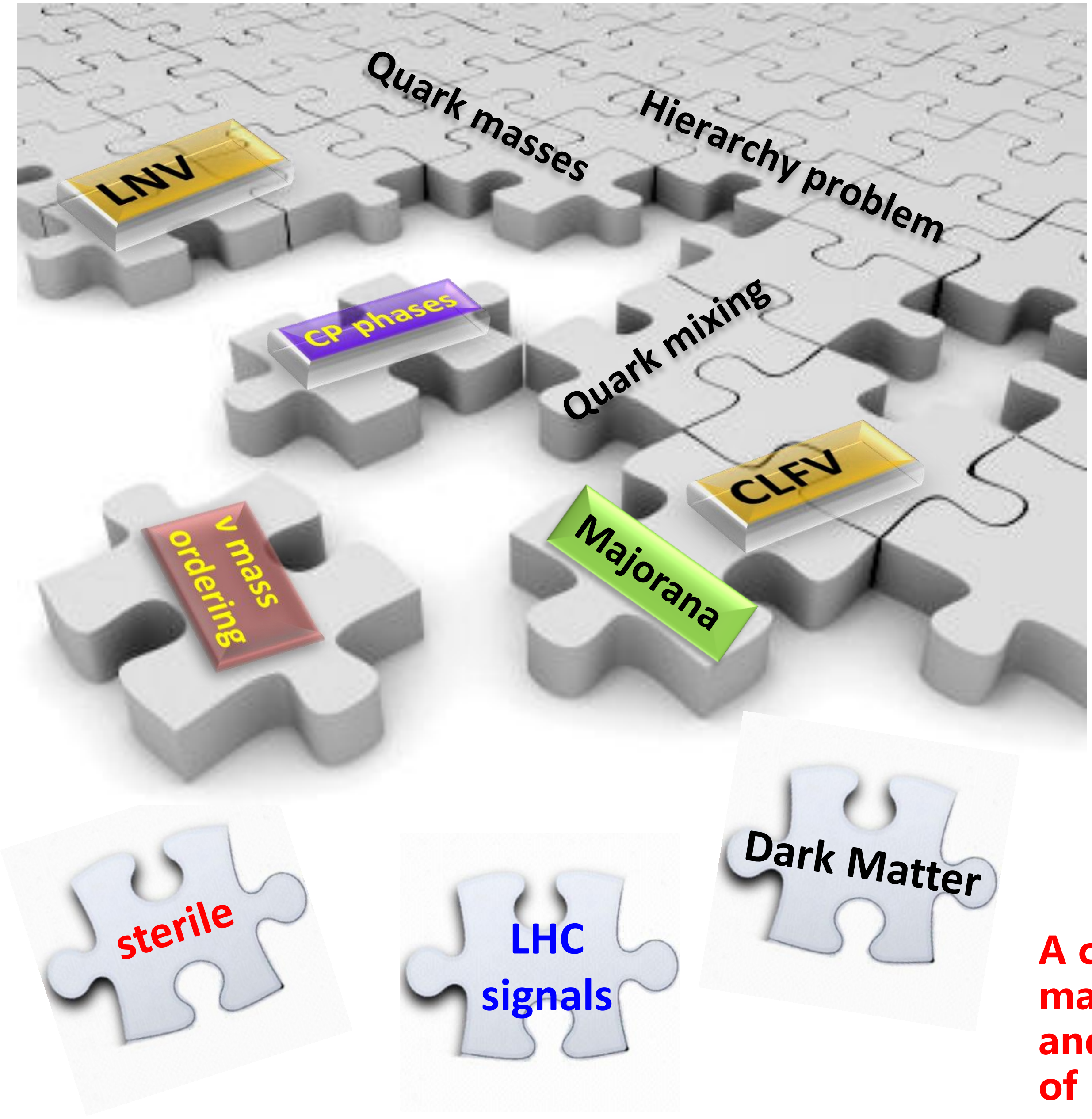
$$\boxed{\frac{\mathrm{Br}(l_\alpha^- \to l_\beta^- \gamma)}{\mathrm{Br}(l_\alpha^- \to l_\beta^- \nu_\alpha \bar{\nu}_\beta)} = \frac{27\alpha |(M_\nu^\dagger M_\nu)_{\alpha\beta}|^2}{256\pi G_\mathrm{F}^2 (M_\Delta v_\Delta)^4}}$$

Tree-level effects



$$\boxed{\frac{\mathrm{Br}(l_\alpha^- \to l_\beta^+ l_\gamma^- l_\lambda^-)}{\mathrm{Br}(l_\alpha^- \to l_\beta^- \nu_\alpha \bar{\nu}_\beta)} = \frac{|(M_\nu)_{\alpha\beta}|^2 |(M_\nu)_{\gamma\lambda}|^2}{16 G_\mathrm{F}^2 (M_\Delta v_\Delta)^4}}$$

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!