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Status of Neutrino Physics

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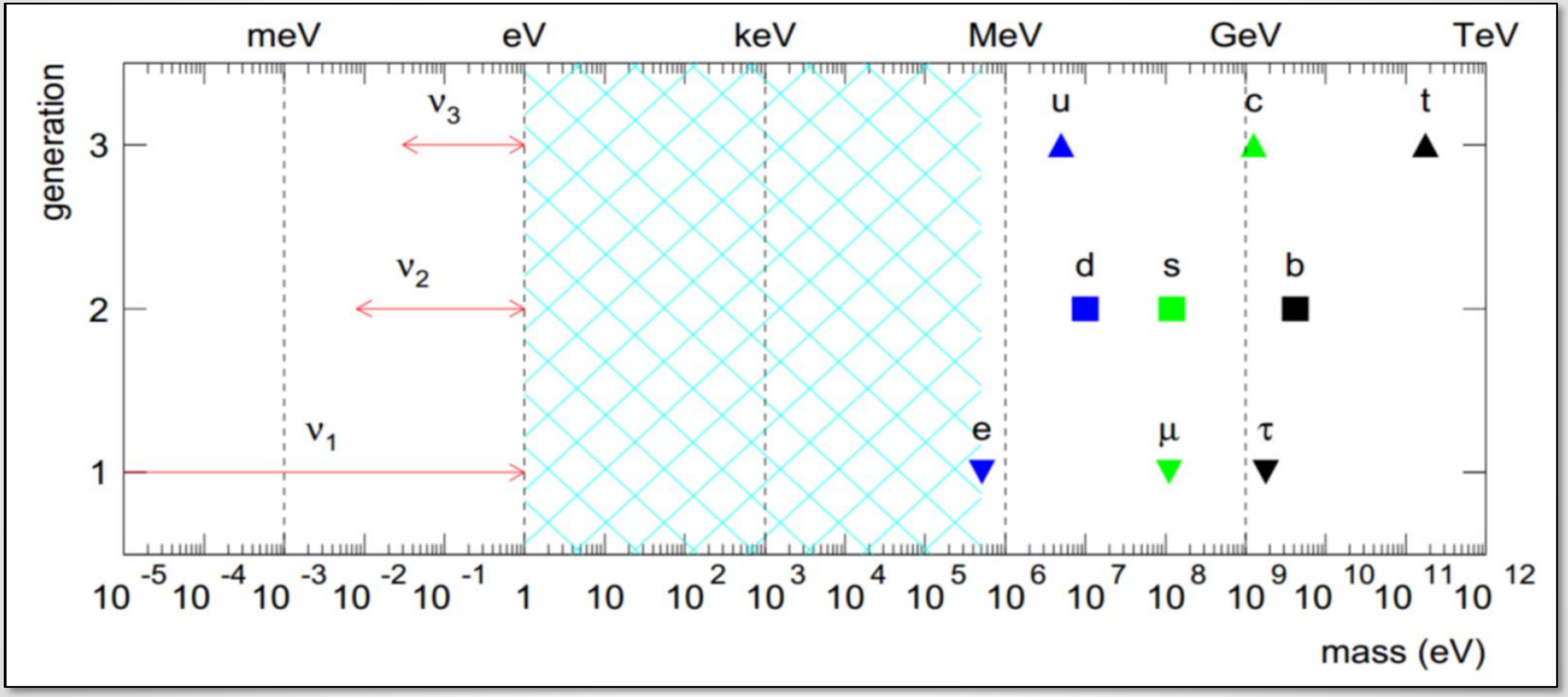
Fermion Masses

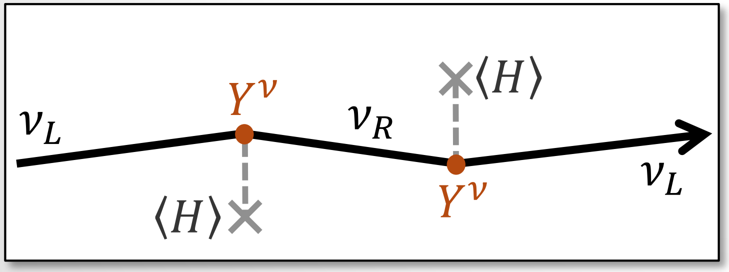


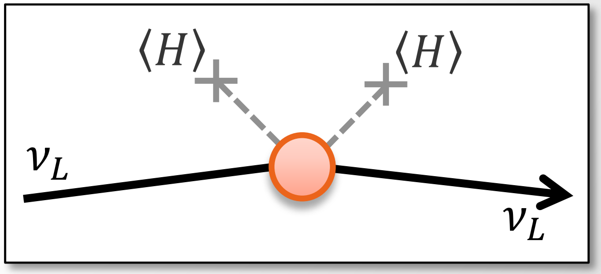
Dirac vs Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with $m_\nu/\Lambda_{EW} \approx 10^{-12}$ couplings to Higgs

Majorana mass, using only a left-handed neutrino → Lepton Number Violation





Neutrino Oscillations

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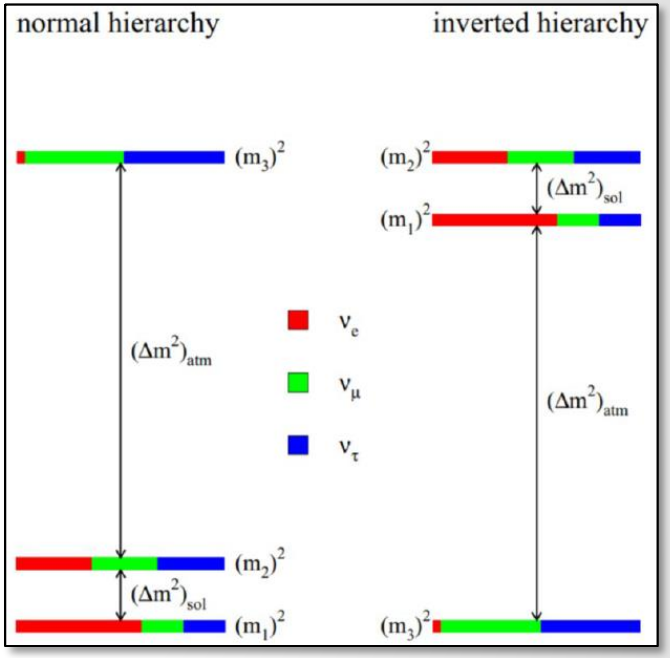
- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation

$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$

$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



- Quantum effect on macroscopic distances
  - Verified in vacuum and matter
- Era of neutrino precision physics
  - Current errors ~ 1–10%
- Experimental unknowns
  - CP Violation? Sign of Δm_{23}? Octant of θ_{23}? Sterile Neutrinos? Non-standard Interactions?

Neutrino Oscillations Experiments

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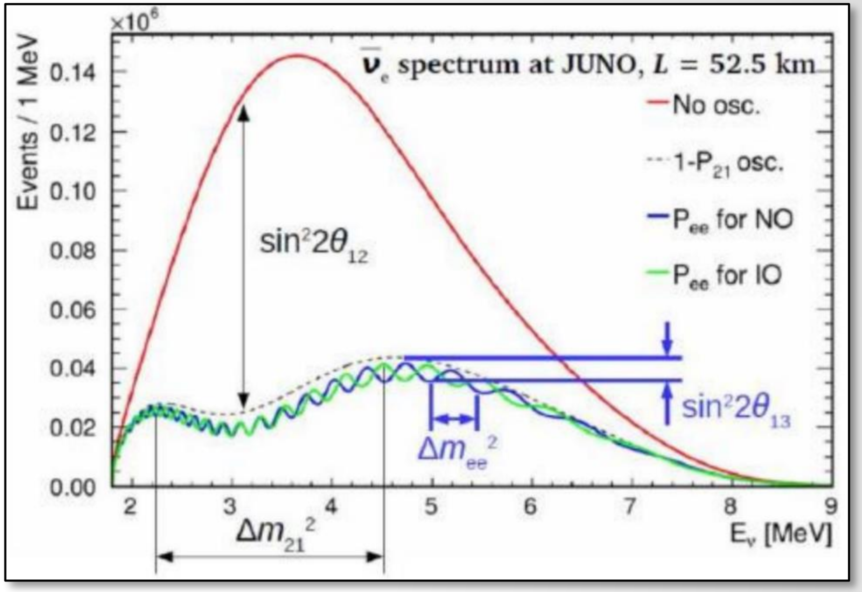
- Solar
  - Radiochemical: Homestake, Gallex, SAGE
    - Only rate of ν_e, no energy
  - Cherenkov radiation: (Super-)Kamiokande, SNO
    - Real-time, energy and direction, all flavours
  - Liquid scintillation: Borexino
    - Low energy threshold
  - Reactor: KamLAND
- Atmospheric ($E_\nu \approx \mathrm{GeV} - \mathrm{TeV}$)
  - Super-Kamiokande
    - Originally background to proton decay
  - Neutrino telescopes: ANTARES, IceCube
    - Originally for high energy neutrinos
- Short-baseline Reactor
  - CHOOZ, Palo Verde, Daya Bay, RENO, Double Chooz, Future: JUNO, RENO-50
    - Measurement of θ_{13}
- Long-baseline Accelerator
  - K2K, MINOS, **T2K, NoνA**, Future: **DUNE**, T2H(H)K

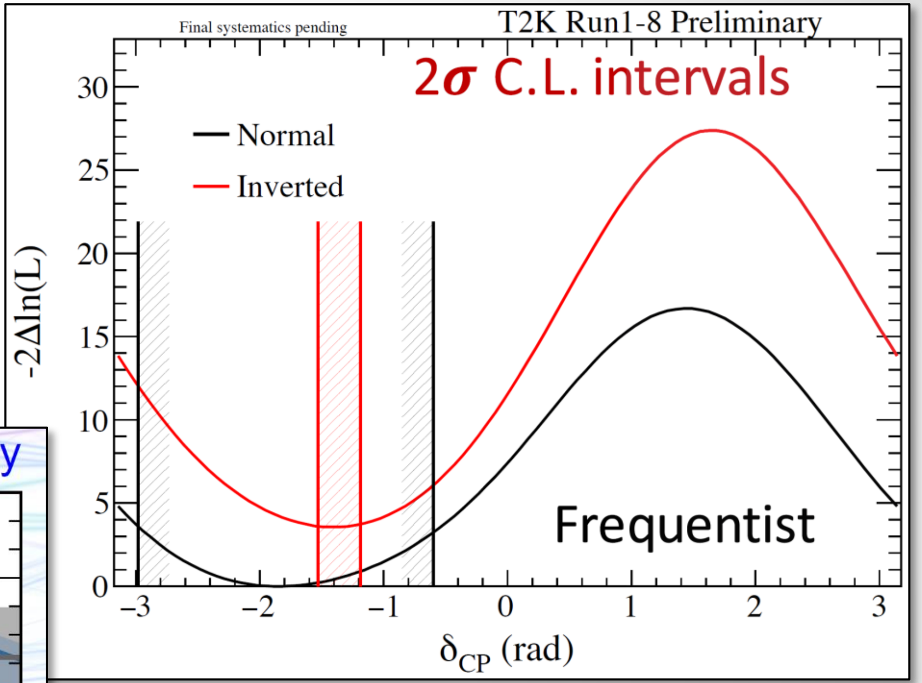


Neutrino Oscillations
CP Violation

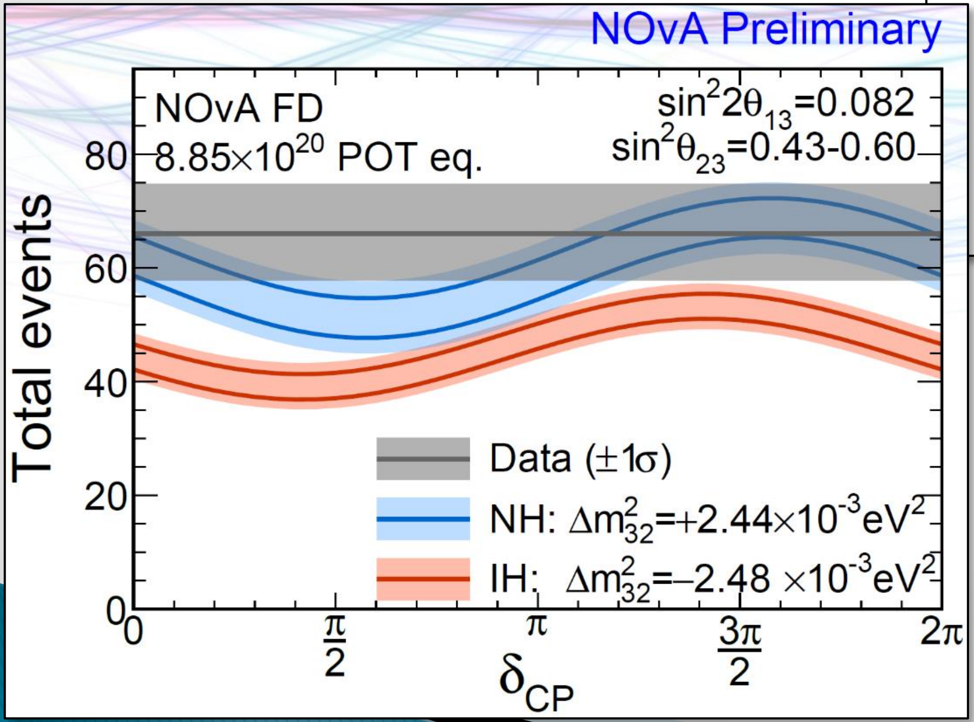
- Hint for maximal CP phase?

$$\delta_{CP} \approx \frac{3}{2}\pi?$$

- Symmetry origin?



Cao, Moriond18



Backhouse, Moriond18

Neutrino Oscillations θ_{23} and Mass Order

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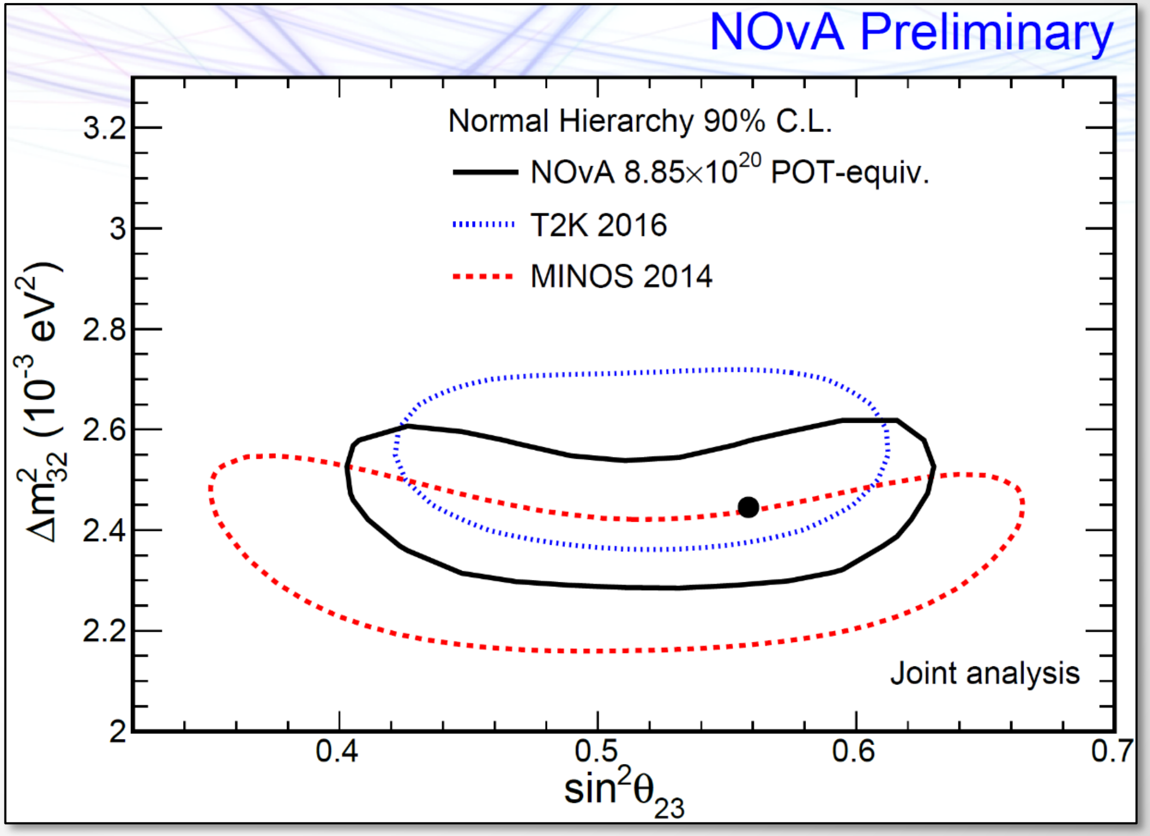
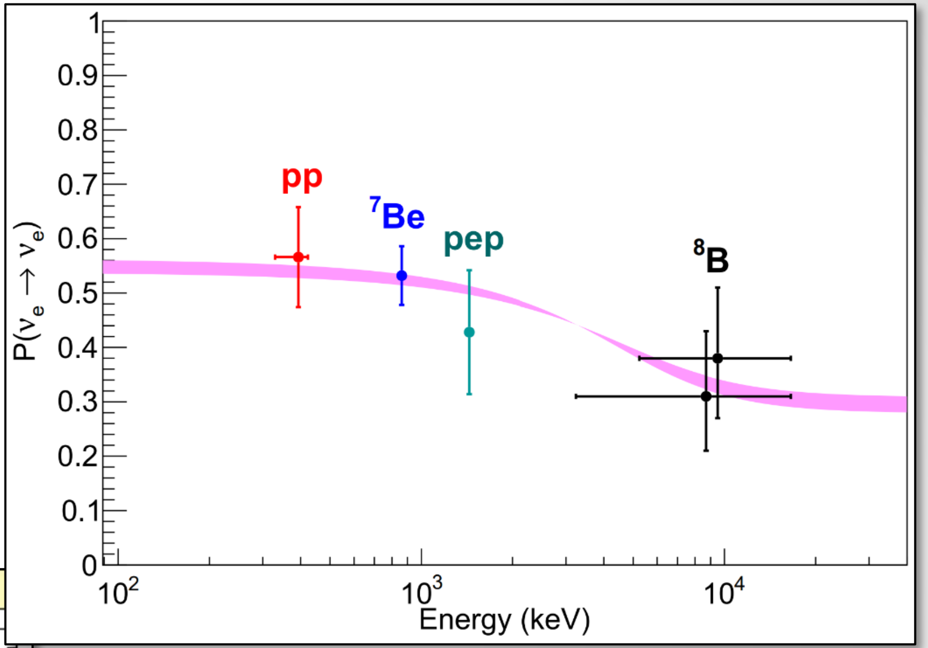
- Atmospheric Mixing Angle
  - Compatible with maximal mixing
  - Symmetry origin?
- Mass Ordering
  - Slightly larger tension for IH between T2K and NoνA

Backhouse, Moriond18

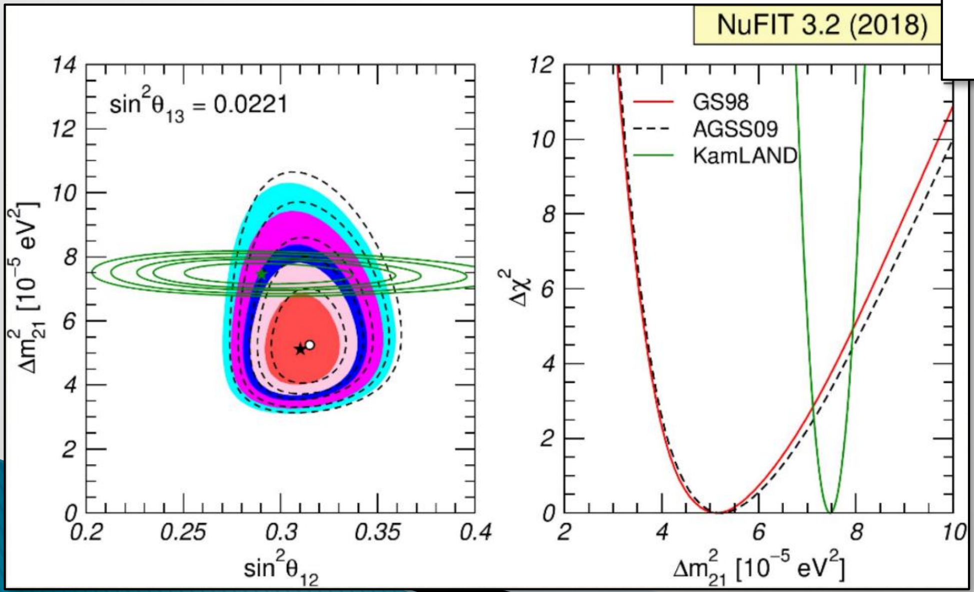


Neutrino Oscillations
Solar Sector

- Solar neutrino mixing
  - Impressive agreement
  - but some tension



Borexino '17



Neutrino Oscillations
Global Fit

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NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

Neutrino Oscillations
Future Prospects

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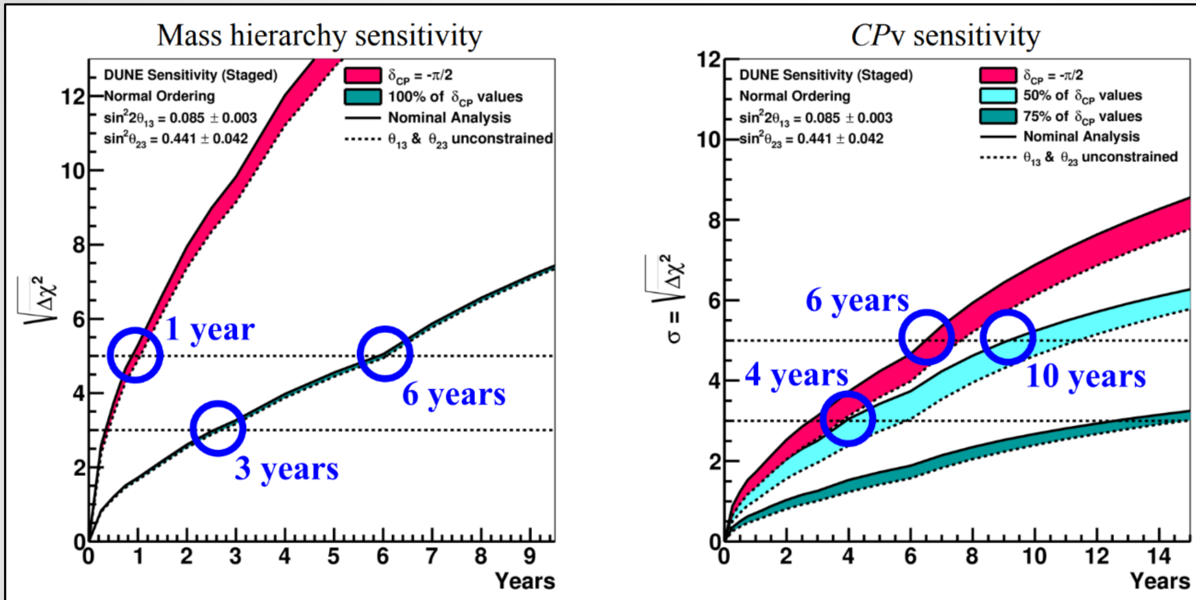
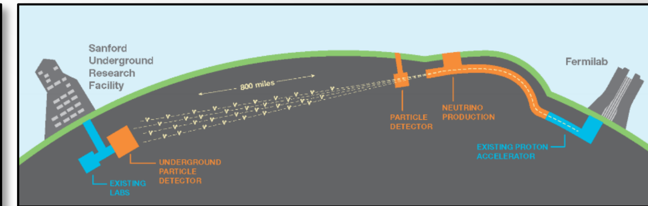
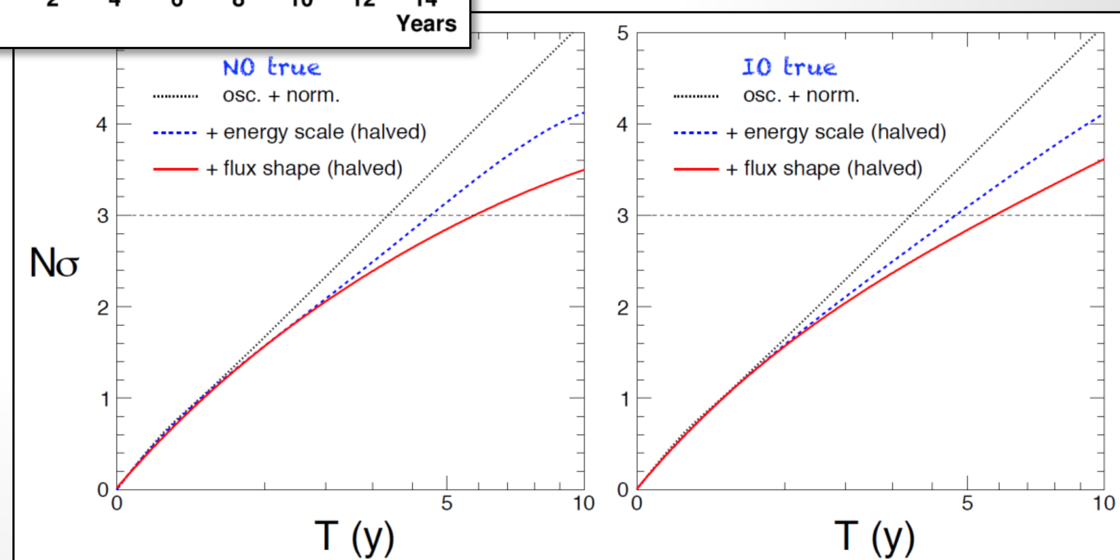




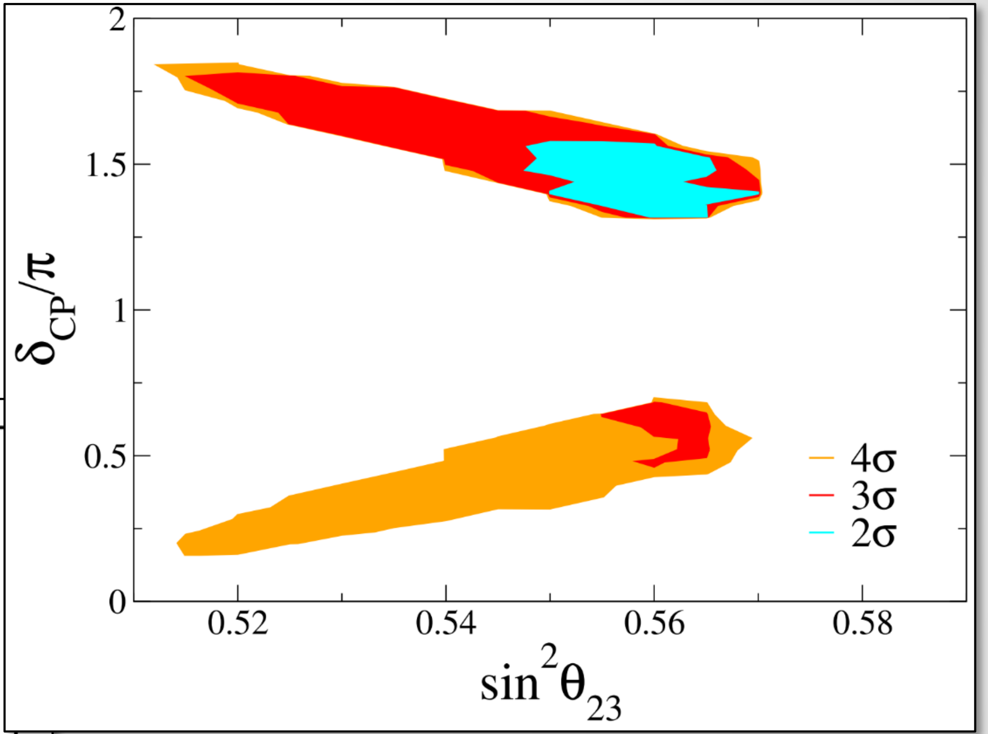
DUNE sensitivity
(Patterson, Moriond18)



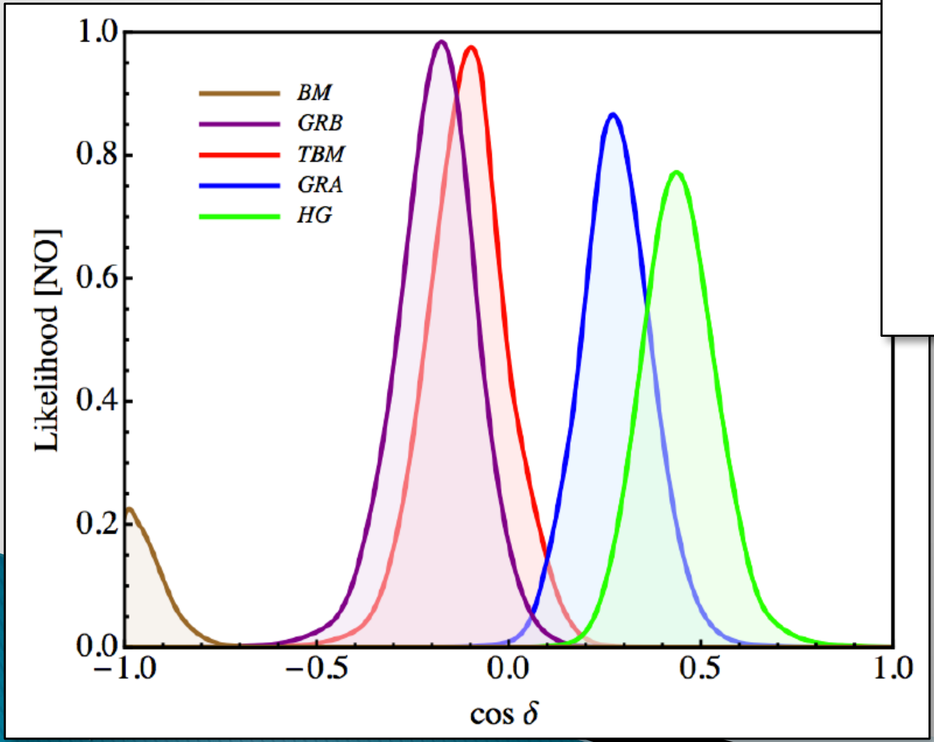
JUNO sensitivity to mass ordering (Marrone et al. '15)

Neutrino Oscillations
Flavour Symmetries

- Hints of large θ_{23} and δ_{CP}
  - interesting for flavour models…
  - of which there are a lot



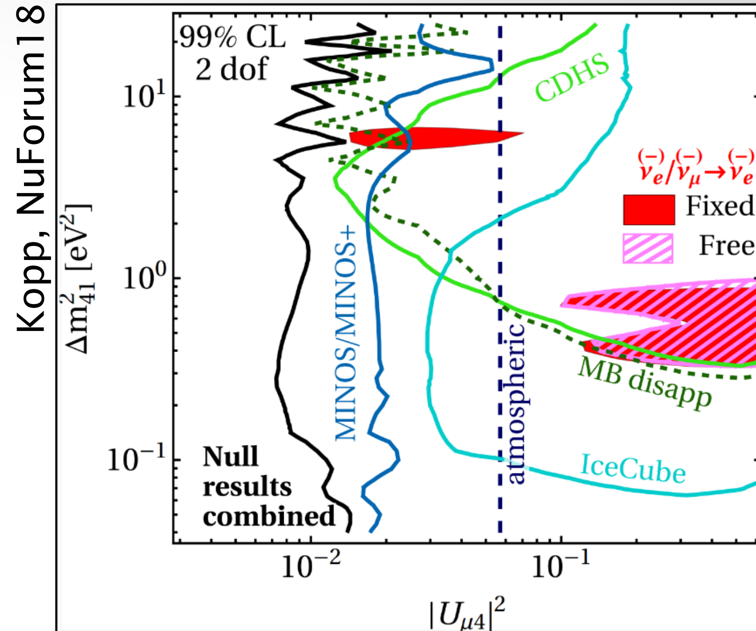
Prediction in example flavour model
(Srivastava et al. '14)

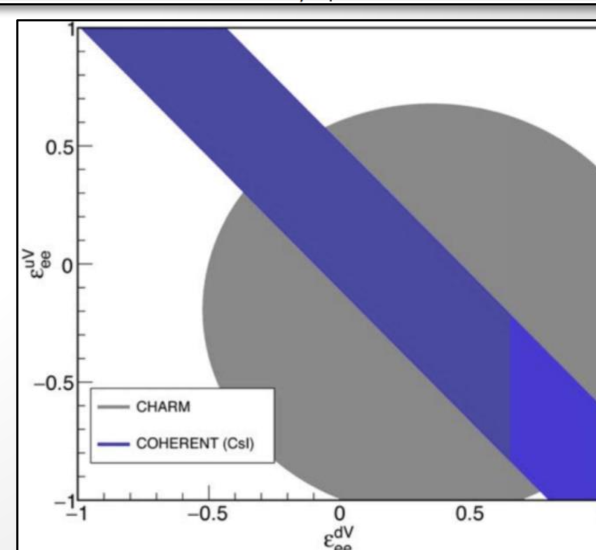


Impact of measurement on flavour models (Girardi '14)

Neutrino Oscillations
New Physics in ν Physics

- Sterile neutrinos
  - Reactor anomaly? / low $\bar{\nu}_e$ flux
- Non-unitarity
  - Generally expected (seesaw), albeit small
- Non-standard interactions
  - Also COHERENT ν-nucleus scattering
  - Can impact standard oscillations but strong bounds from ch. lepton physics (gauge invariance)
- Long-range forces
- Lorentz / CPT violation

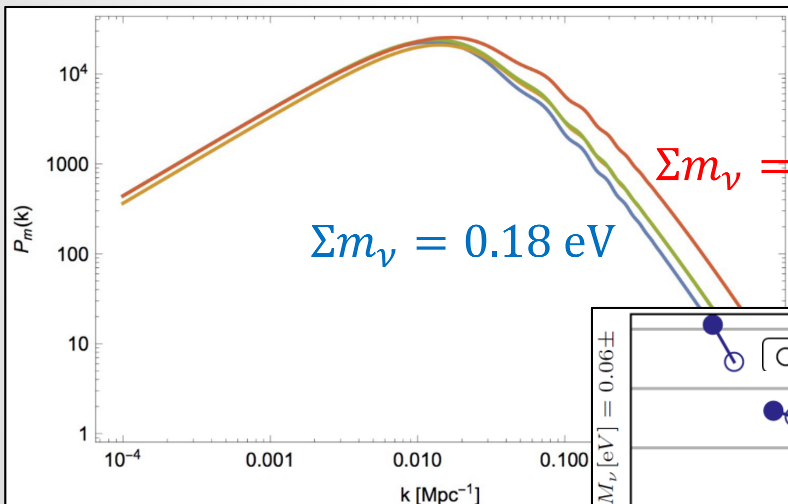




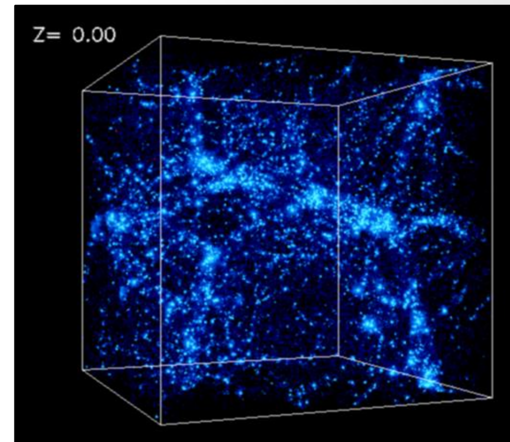
Absolute Neutrino Mass Cosmology

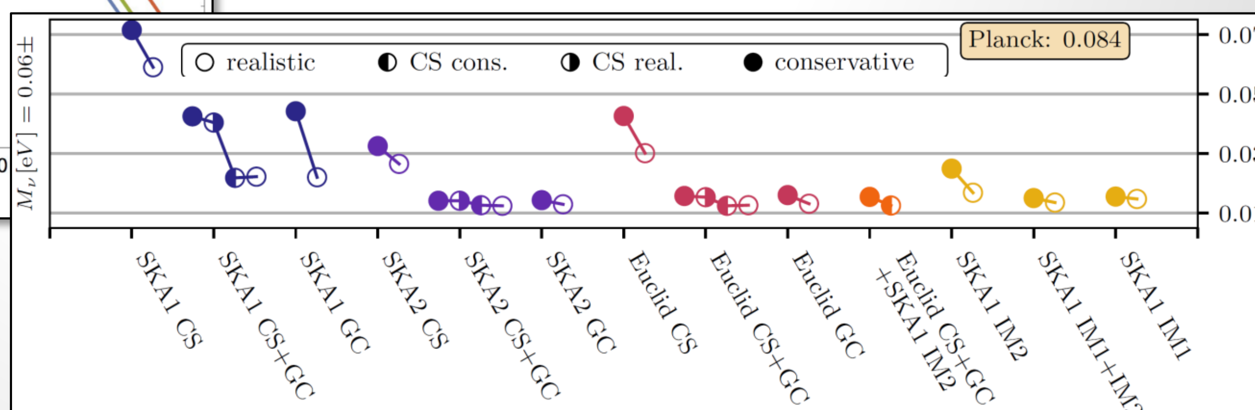
- Impact on large scale structures of the Universe
  - Light sterile neutrinos = extra DOFs of radiation
  - Sensitive to sum of neutrino masses

$$n_{\mathrm{eff}} < 3.4, \quad \sum m_\nu < 0.15 - 0.25\ \mathrm{eV}$$



Gerbino, Lattanzi ‘18





Sprenger et al. ‘18

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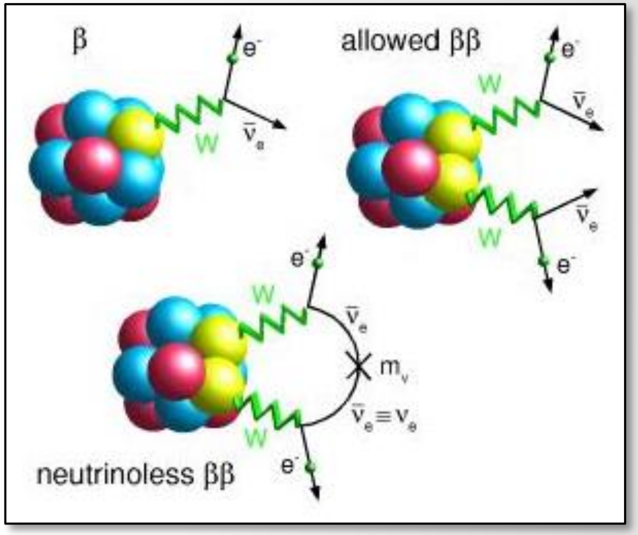
Absolute Neutrino Mass
Beta Decays

- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Tritium decay, KATRIN: $m_\nu \approx 0.2$ eV
  - Probe of exotic interactions (Gonzalez-Alonso et al. 'today)
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos

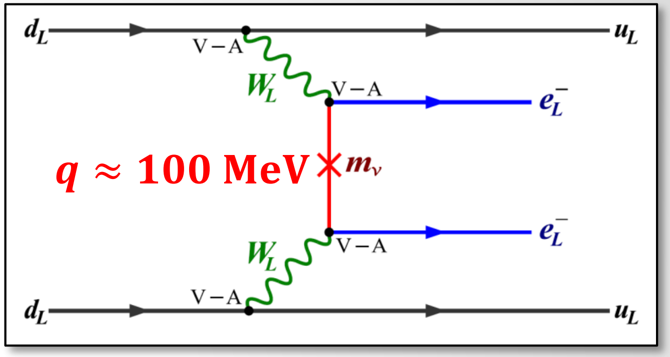


Absolute Neutrino Mass

$0\nu\beta\beta$

- Effective $0\nu\beta\beta$ Mass

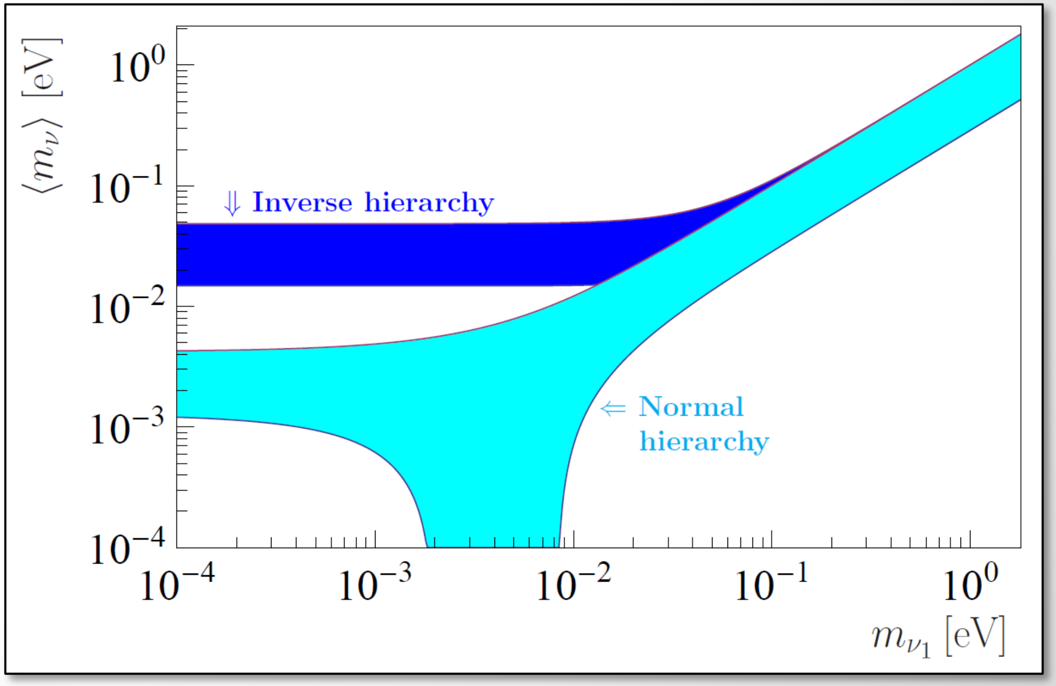
$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$



- Degenerate Regime

$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases



Absolute Neutrino Mass

$0\nu\beta\beta$

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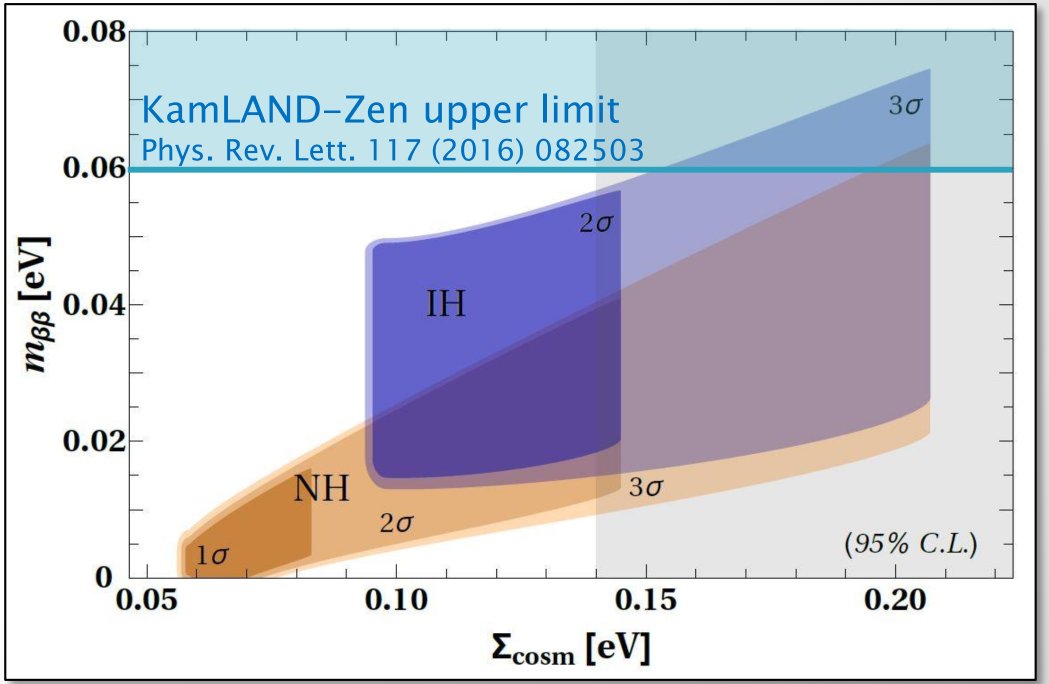

Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

Absolute Neutrino Mass

$0\nu\beta\beta$

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- Effective $0\nu\beta\beta$ Mass

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

- Degenerate Regime

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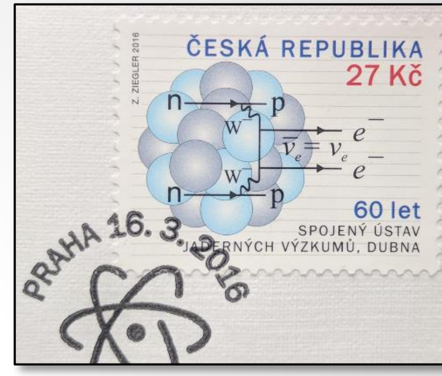

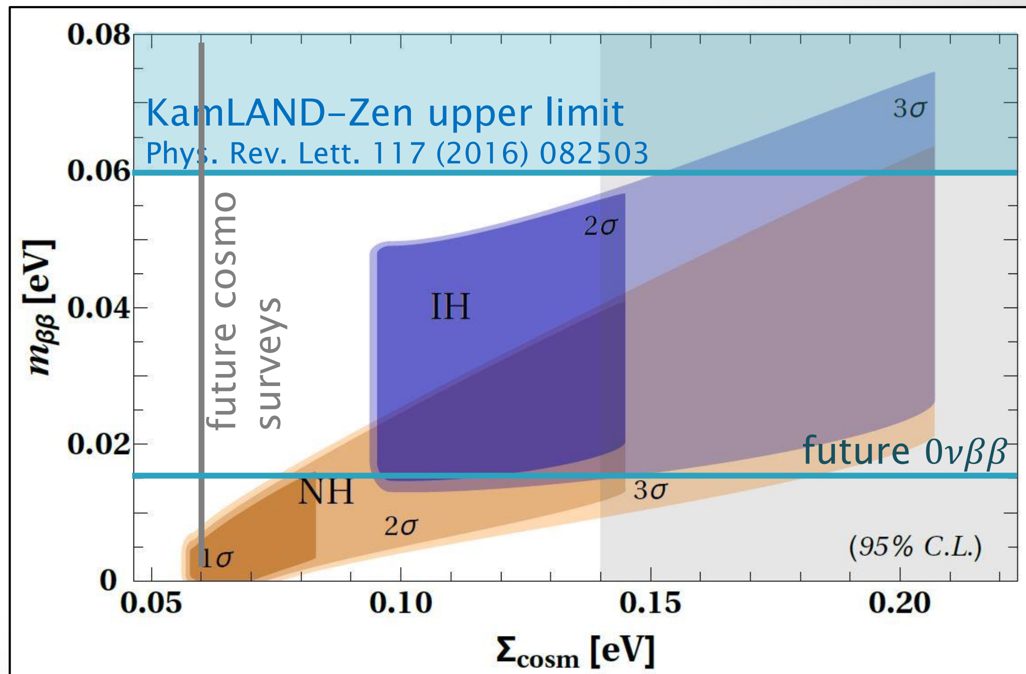

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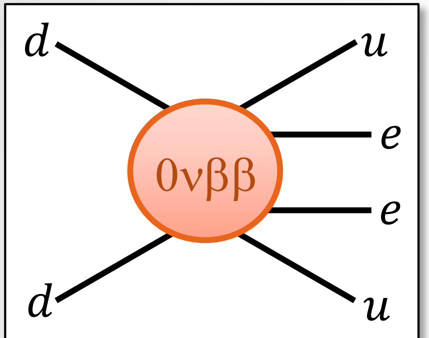
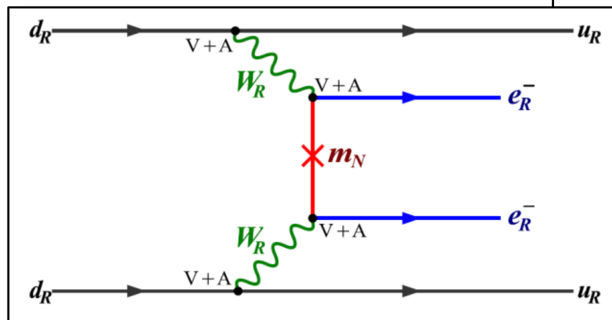
Absolute Neutrino Mass

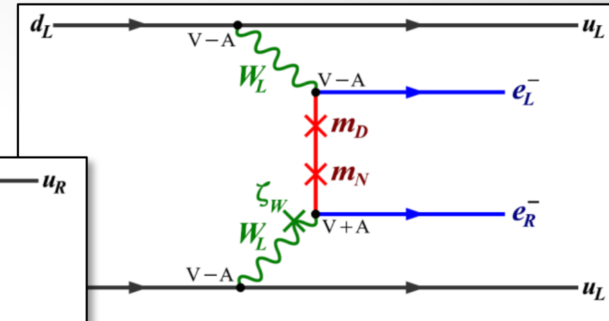
$0\nu\beta\beta$ and New Physics

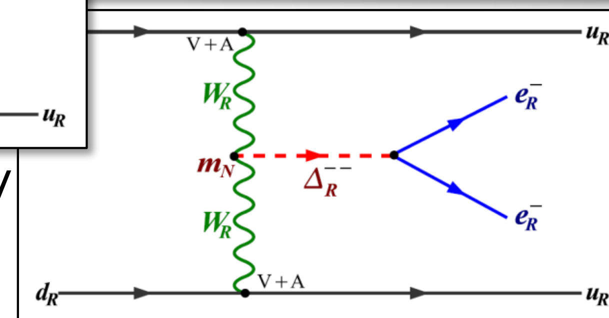
- Plethora of New Physics scenarios



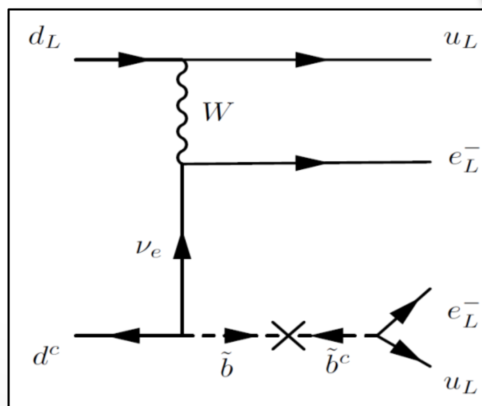
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

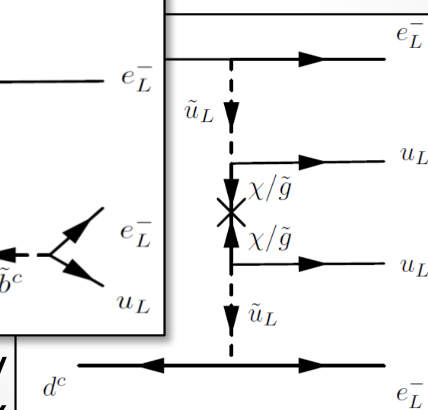






Left-Right Symmetry





R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- …

Absolute Neutrino Mass

$0\nu\beta\beta$ and New Physics

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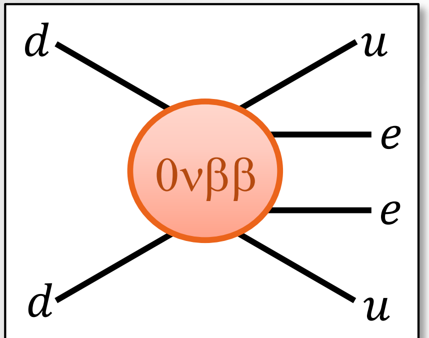
- Examples in Left-Right Symmetry



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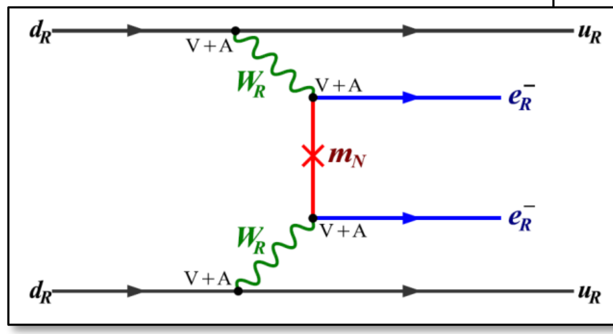
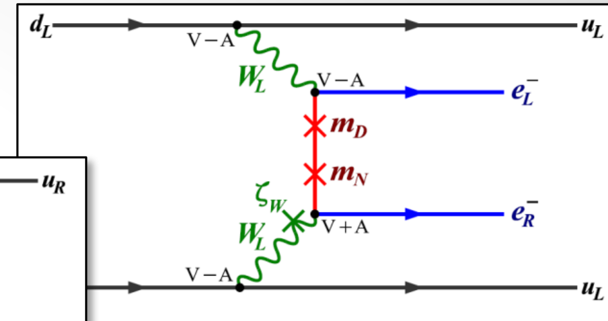


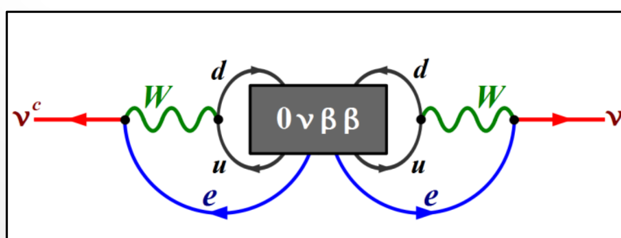


$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan \zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale
- Neutrinos still Majorana



Neutrino Mass Models

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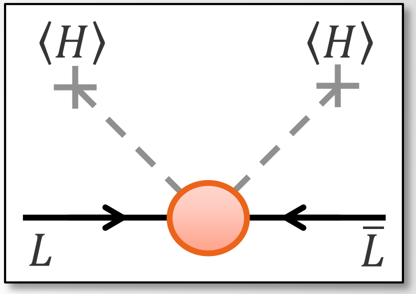
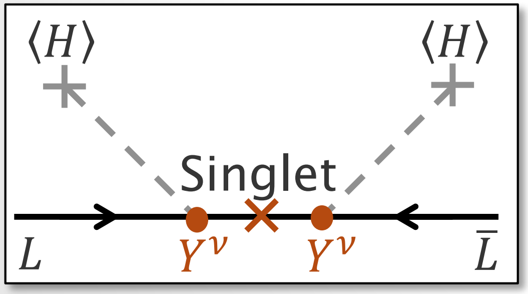
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

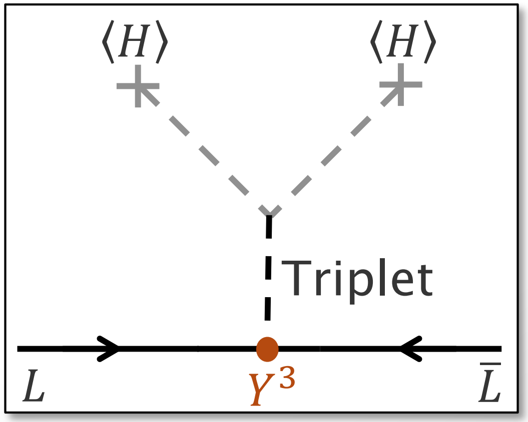


- Seesaw Mechanism

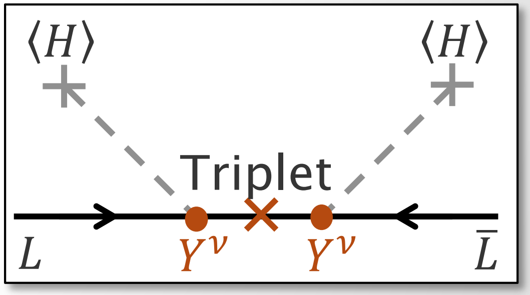
Seesaw I



Seesaw II



Seesaw III

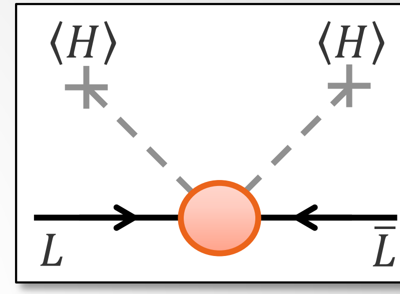


  - GUT scale?
  - Leptogenesis? Naturalness?

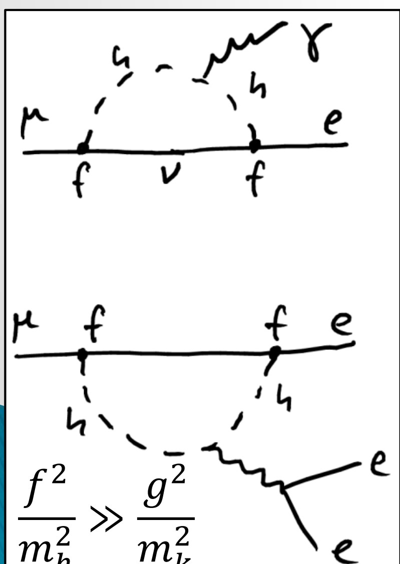
Neutrino Mass Models

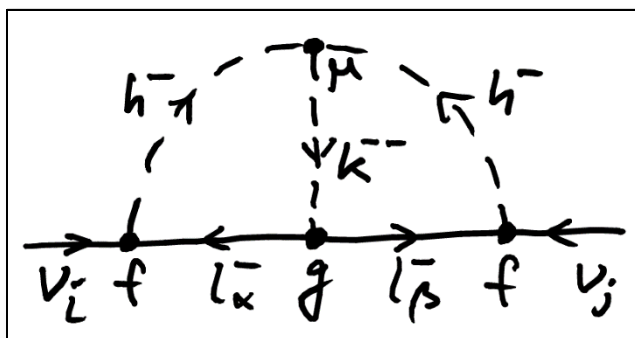
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right) \xrightarrow[\langle H\rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

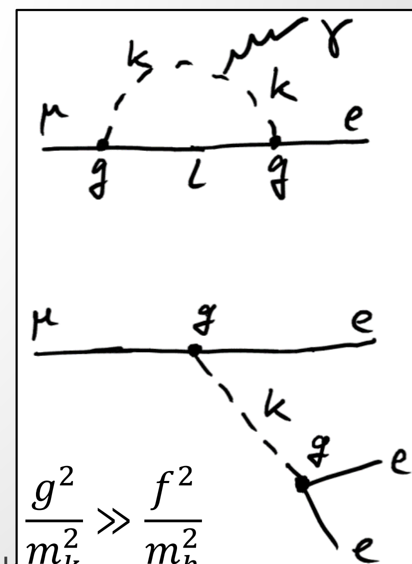


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. Babu-Zee model (Zee ’85, Babu ‘88)





Neutrino masses suppressed at 2-loop



Heavy Sterile Neutrinos

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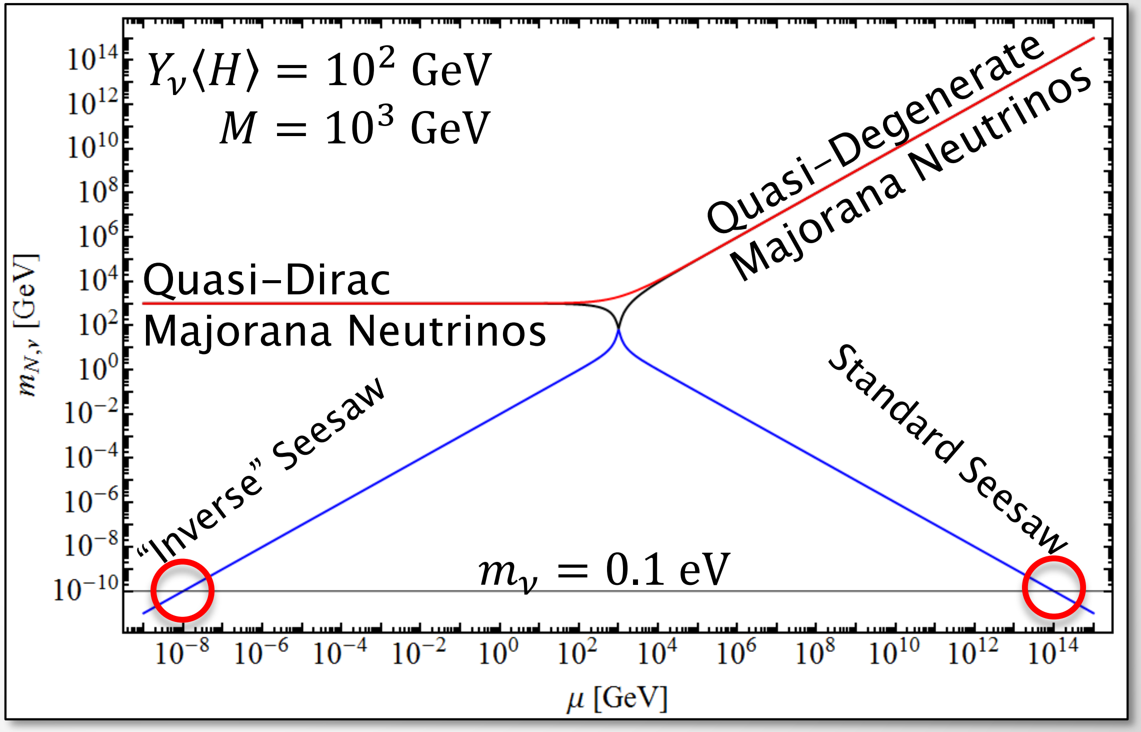
- Correct light neutrino masses for TeV scale heavy neutrinos
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings
    - Charged LFV remains small
  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$V^{LR} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$$

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$



- Potentially large CLFV
- In the limit $\mu \to 0$, no LNV but charged LFV

Heavy Sterile Neutrinos

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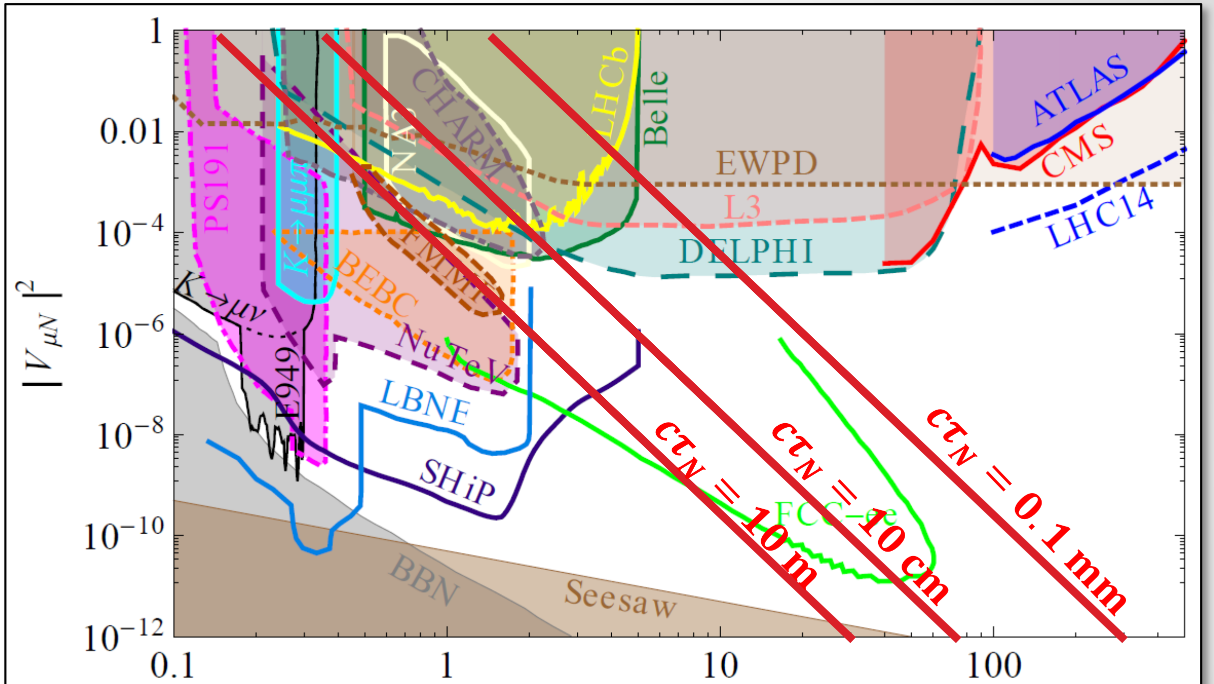
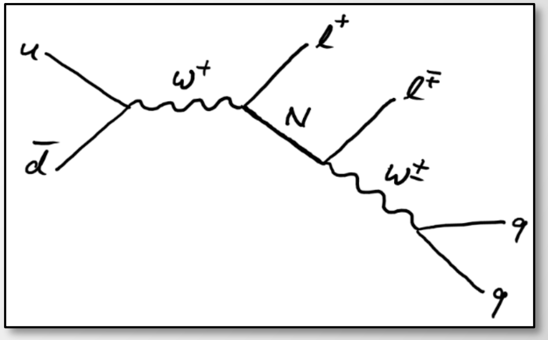
- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
- Peak Searches in Meson Decays
- Beam Dump Experiments
- LNV Meson Decays
- Z Decays
- Electroweak Precision Tests

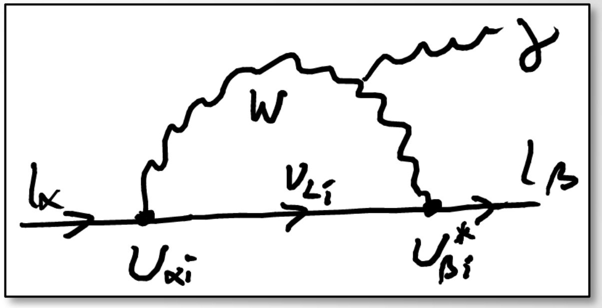


FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019



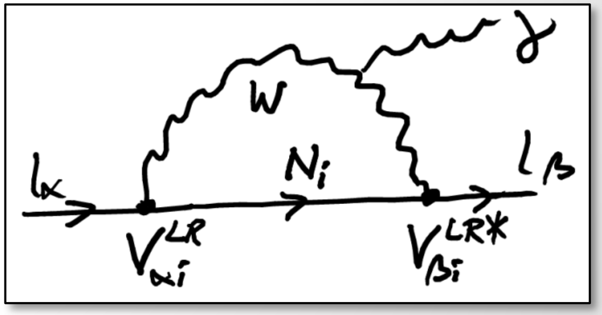
Lepton Flavour Violation

- CLFV in the Seesaw Mechanism
  - Light neutrino exchange
    - Negligible due to small neutrino masses



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W}\right|^2 \approx 10^{-56}$$

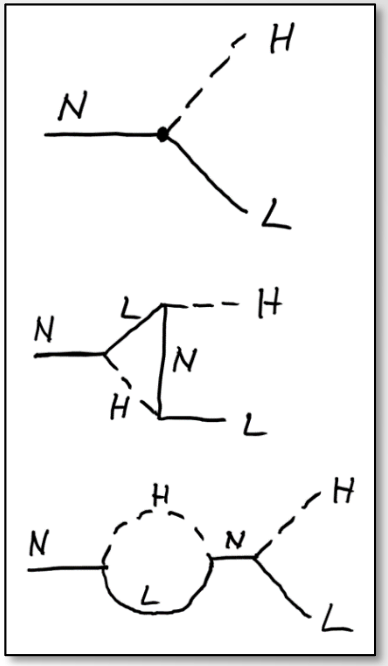
  - Heavy neutrino exchange
    - Sizable for TeV scale heavy neutrinos and large LR mixing $V^{LR} \approx 10^{-2}$



$$Br(\mu \to e\gamma) \approx 4 \times 10^{-3}\left|\sum_i V^{LR*}_{\mu i} V^{LR}_{ei} G\left(\frac{m^2_{N_i}}{m^2_W}\right)\right|^2 \approx 10^{-11}\left(\frac{V^{LR}}{10^{-2}}\right)^4$$

$$\mathcal{U}^\nu = \begin{pmatrix} U & V^{LR} \\ (V^{LR})^\intercal & U^R \end{pmatrix}$$

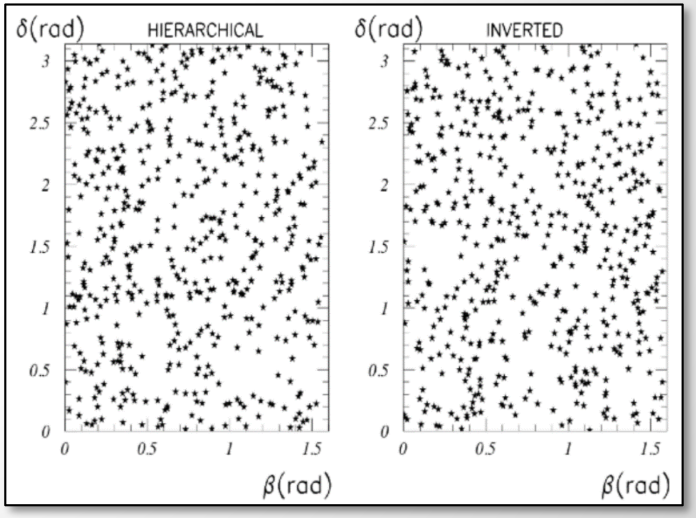
Baryon Asymmetry
CP Violation



- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100$ GeV
    - Observed asymmetry

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

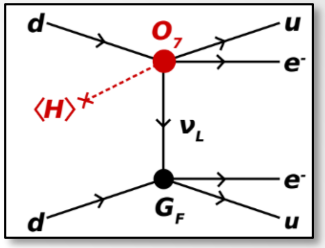
- Observation of δ_{CP} would establish CP violation in lepton sector but connection to baryon asymmetry model-dependent

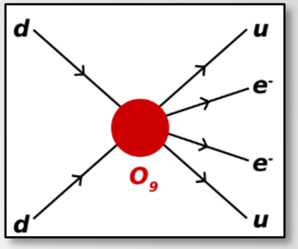


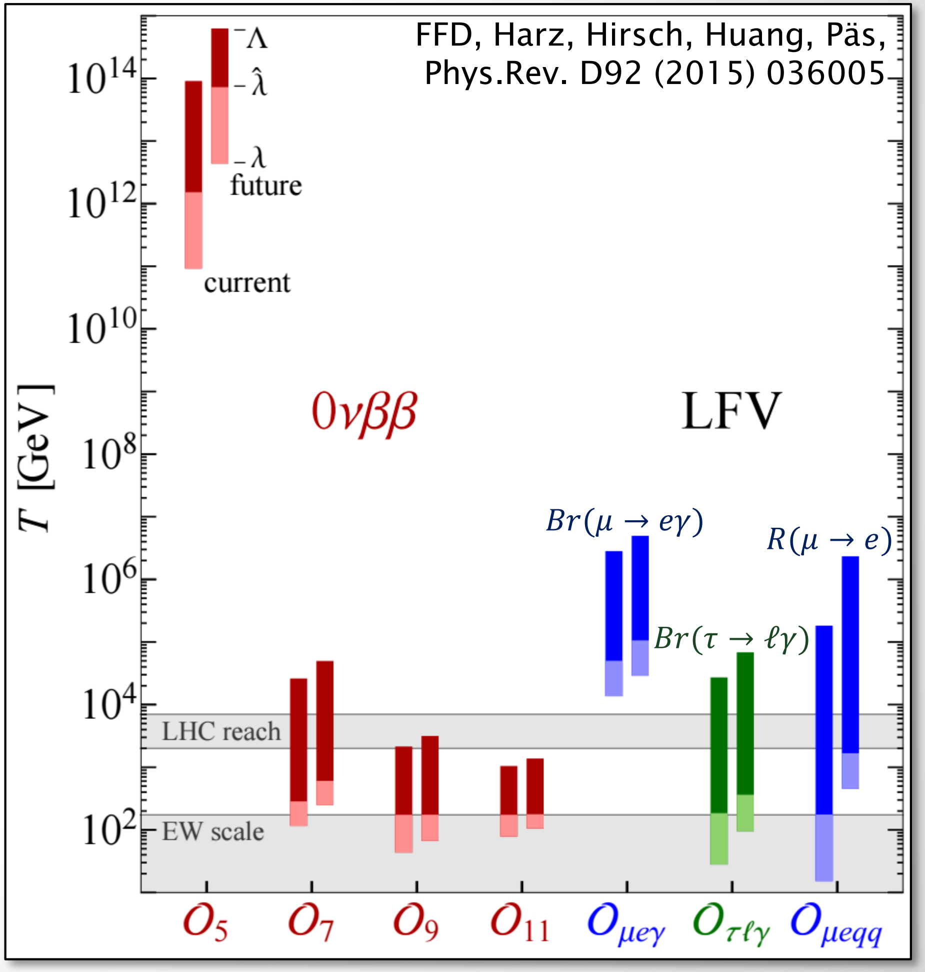
Davidson et al. '07

Baryon Asymmetry
Lepton Number Violation

- What if we observe lepton number violating processes e.g. in $0\nu\beta\beta$?
- Interactions "wash out" lepton (+ baryon with sphalerons) asymmetry
  - gives information at what temperatures operators are in equilibrium
  - corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - can falsify high-scale baryogenesis scenarios







Conclusion

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- Neutrinos much lighter than other fermions
- Lepton Mixing and Possible CP Violation
- Deeper Origin of Neutrino Masses
- ν Physics = New Physics
- Strong Synergy with the rest
  - Charged Lepton Physics
  - Collider Searches
  - Higgs Physics
  - Cosmology