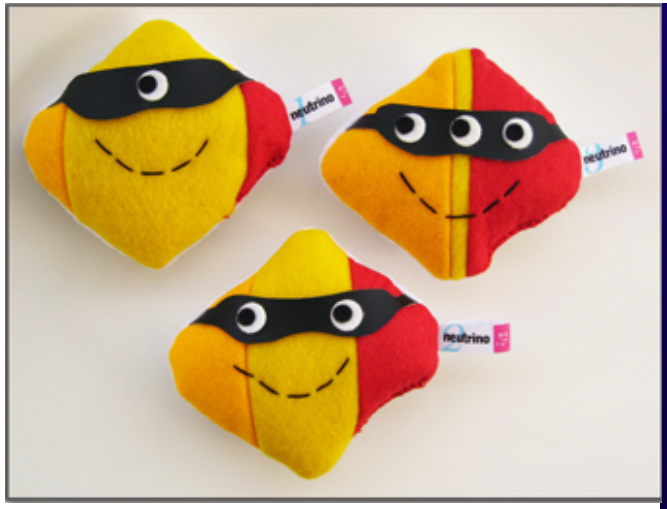
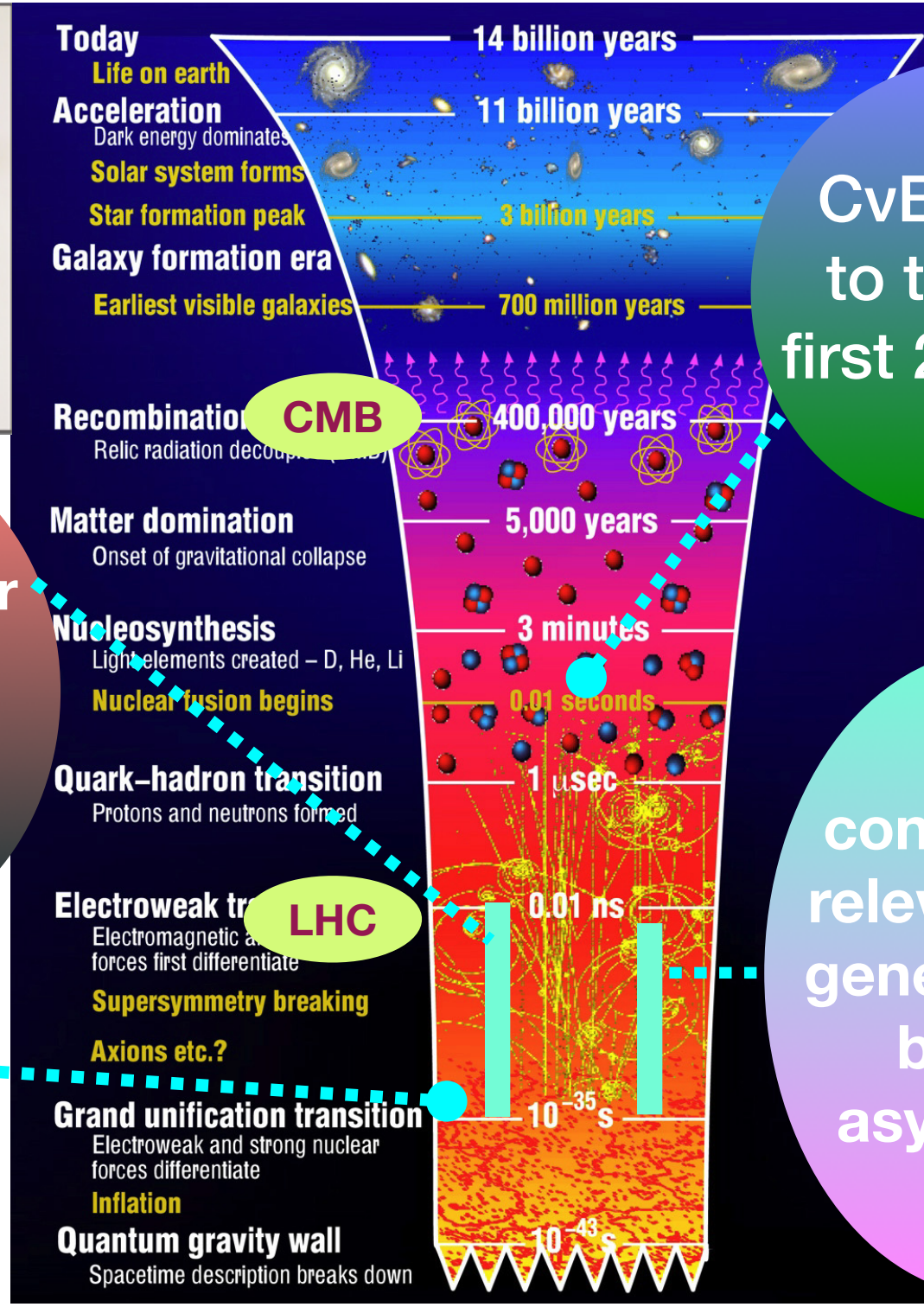
Theoretical Status of Neutrino Physics

Mu-Chun Chen, University of California at Irvine

NuFact 2015, CBPF, Rio de Janeiro, August 10, 2015





CvB - back to the very first 2 second

operator for ν mass generation unknown

conceivable relevance for generation of baryon asymmetry

unique window into GUT scale physics

Where Do We Stand?

- Latest 3 neutrino global analysis (including recent results from reactor experiments and T2K):

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo (2013, updated May 2014)

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49	2.30 – 2.55	2.23 – 2.61
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44	2.25 – 2.50	2.19 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54	1.95 – 2.74	1.76 – 2.95
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59	1.98 – 2.79	1.78 – 2.98
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70	3.93 – 5.52	3.74 – 6.26
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94	4.00 – 6.20	3.80 – 6.41
δ/π (NH)	1.39	1.12 – 1.77	0.00 – 0.16 $\oplus$ 0.86 – 2.00	—
δ/π (IH)	1.31	0.98 – 1.60	0.00 – 0.02 $\oplus$ 0.70 – 2.00	—

➡ evidence of $\theta_{13} \neq 0$

➡ hints of $\theta_{23} \neq \pi/4$

➡ expectation of Dirac CP phase δ

➡ no clear preference for hierarchy

➡ Majorana vs Dirac

Recent T2K result ➪ $\delta \simeq -\pi/2$, consistent with global fit best fit value

Where Do We Stand?

- search for absolute mass scale:
  - end point kinematic of tritium beta decays

$$m_{\nu_e} < 2.2 \text{ eV } (95\% \text{ CL}) \quad \text{Mainz}$$

$$m_{\nu_\mu} < 170 \text{ keV}$$

$$m_{\nu_\tau} < 15.5 \text{ MeV}$$

$$\text{Tritium} \rightarrow He^3 + e^- + \overline{\nu}_e$$

KATRIN: increase sensitivity ~ 0.2 eV

  - neutrinoless double beta decay

$$\text{current bound:} \quad |\langle m \rangle| \equiv \left| \sum_{i=1,2,3} m_i U_{ie}^2 \right|$$

< (0.14-0.38) eV (EXO, 2012)

  - Cosmology $\sum(m_{\nu_i}) < 0.23$ eV

N_{eff} = 3.04 ± 0.2 [Plankck 2015] ⇒ sterile neutrino disfavored

Open Questions - Neutrino Properties

- ☞ Majorana vs Dirac?
- ☞ CP violation in lepton sector?
- ☞ Absolute mass scale of neutrinos?
- ☞ Mass ordering: sign of (Δm_{13}^2)?
- ☞ Precision: $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
- ☞ Sterile neutrino(s)?

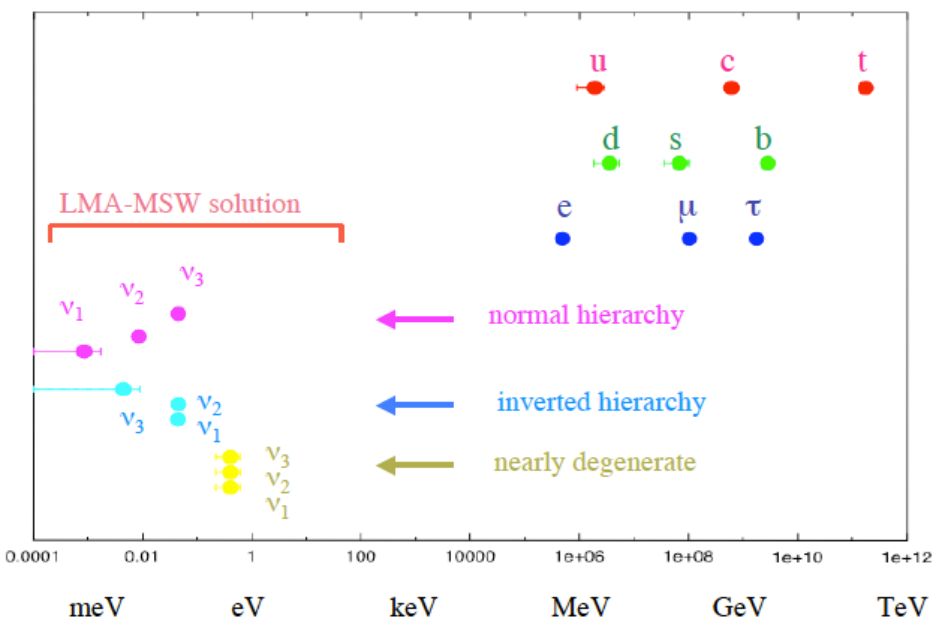
a suite of current and upcoming experiments to address these puzzles

some can only be answered by oscillation experiments

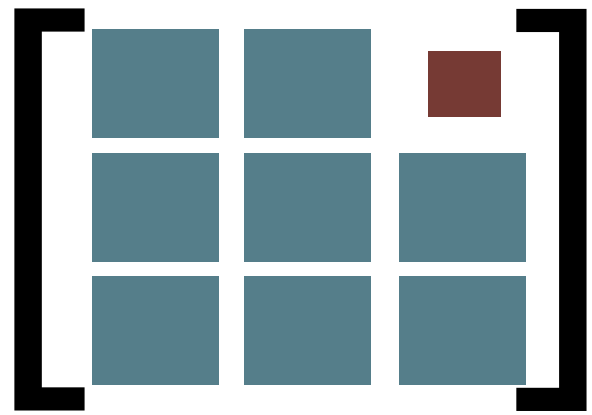
Open Questions - Theoretical

☞ Smallness of neutrino mass:

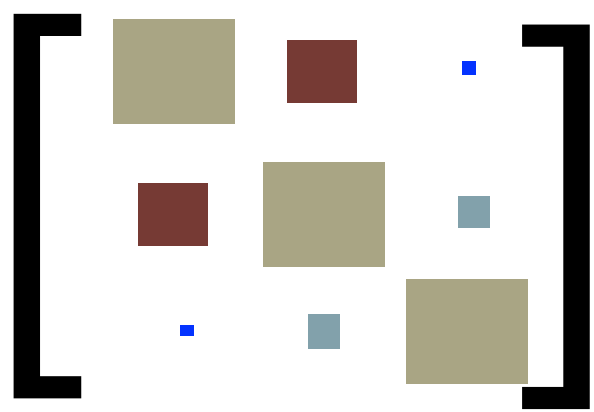
$$m_\nu \ll m_{e,\,u,\,d}$$



☞ Flavor structure:



leptonic mixing



quark mixing

Open Questions - Theoretical

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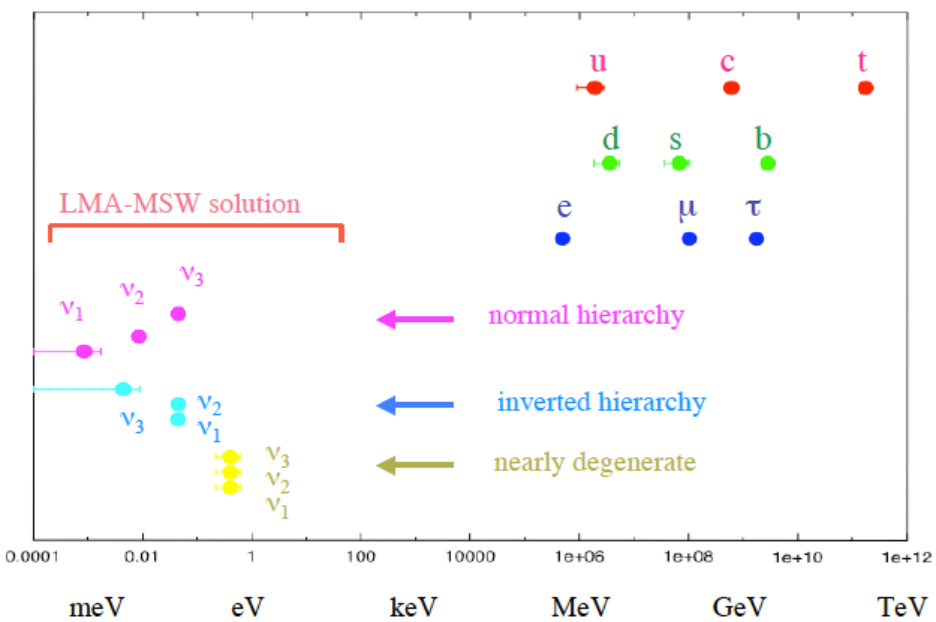
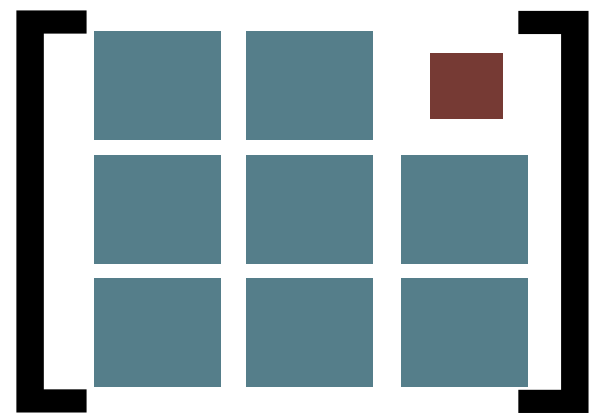
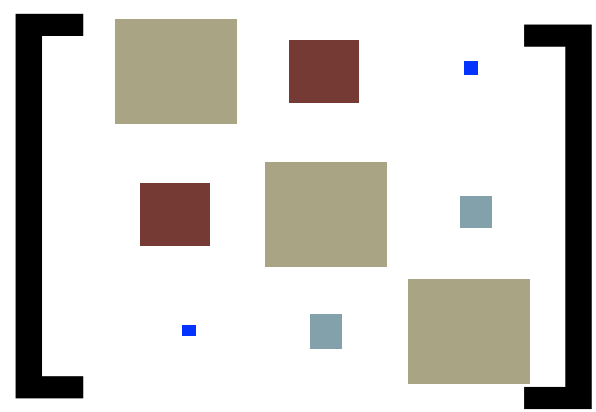


Fermion mass and hierarchy problem ➟ Many free parameters in the Yukawa sector of SM

☞ Flavor structure:



leptonic mixing



quark mixing

Question from NuFact'14

- What can we say about the new Majorana mass scale implied by neutrino masses? What are the current bounds and how much will they improve over the next decade?

Smallness of neutrino masses

What is the operator for neutrino mass generation?

- Majorana vs Dirac
- scale of the operator
- suppression mechanism

Neutrino Mass beyond the SM

- SM: effective low energy theory

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \boxed{\frac{\mathcal{O}_{5D}}{M} + \frac{\mathcal{O}_{6D}}{M^2} + \ldots} \longrightarrow \boxed{\text{new physics effects}}$$

- only one dim-5 operator: most sensitive to high scale physics

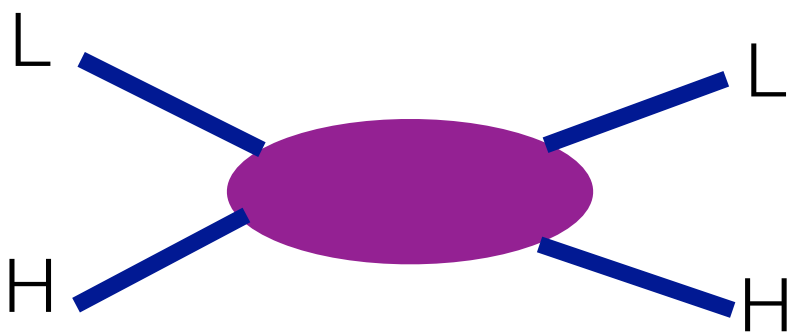
$$\frac{\lambda_{ij}}{M} H H L_i L_j \quad \Rightarrow \quad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

Weinberg, 1979

- $m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.1$ eV with $v \sim 100$ GeV, $\lambda \sim O(1) \Rightarrow M \sim 10^{14}$ GeV
- Lepton number violation ⇨ Majorana fermions

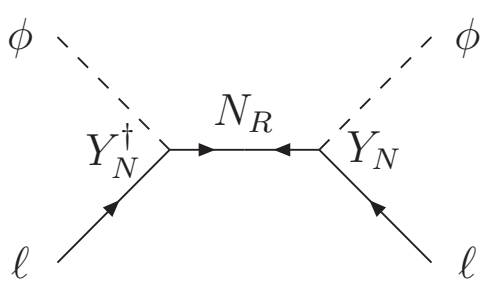
GUT scale

Neutrino Mass beyond the SM



3 possible portals

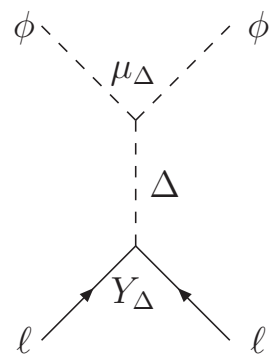
Type-I seesaw



N_R: SU(3)$_c$ x SU(2)$_w$ x U(1)$_Y$ ~(1,1,0)

Minkowski, 1977; Yanagida, 1979; Glashow, 1979;
Gell-mann, Ramond, Slansky,1979;
Mohapatra, Senjanovic, 1979;

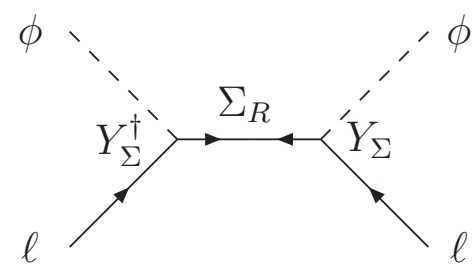
Type-II seesaw



Δ: SU(3)$_c$ x SU(2)$_w$ x U(1)$_Y$ ~(1,3,2)

Lazarides, 1980; Mohapatra, Senjanovic, 1980

Type-III seesaw

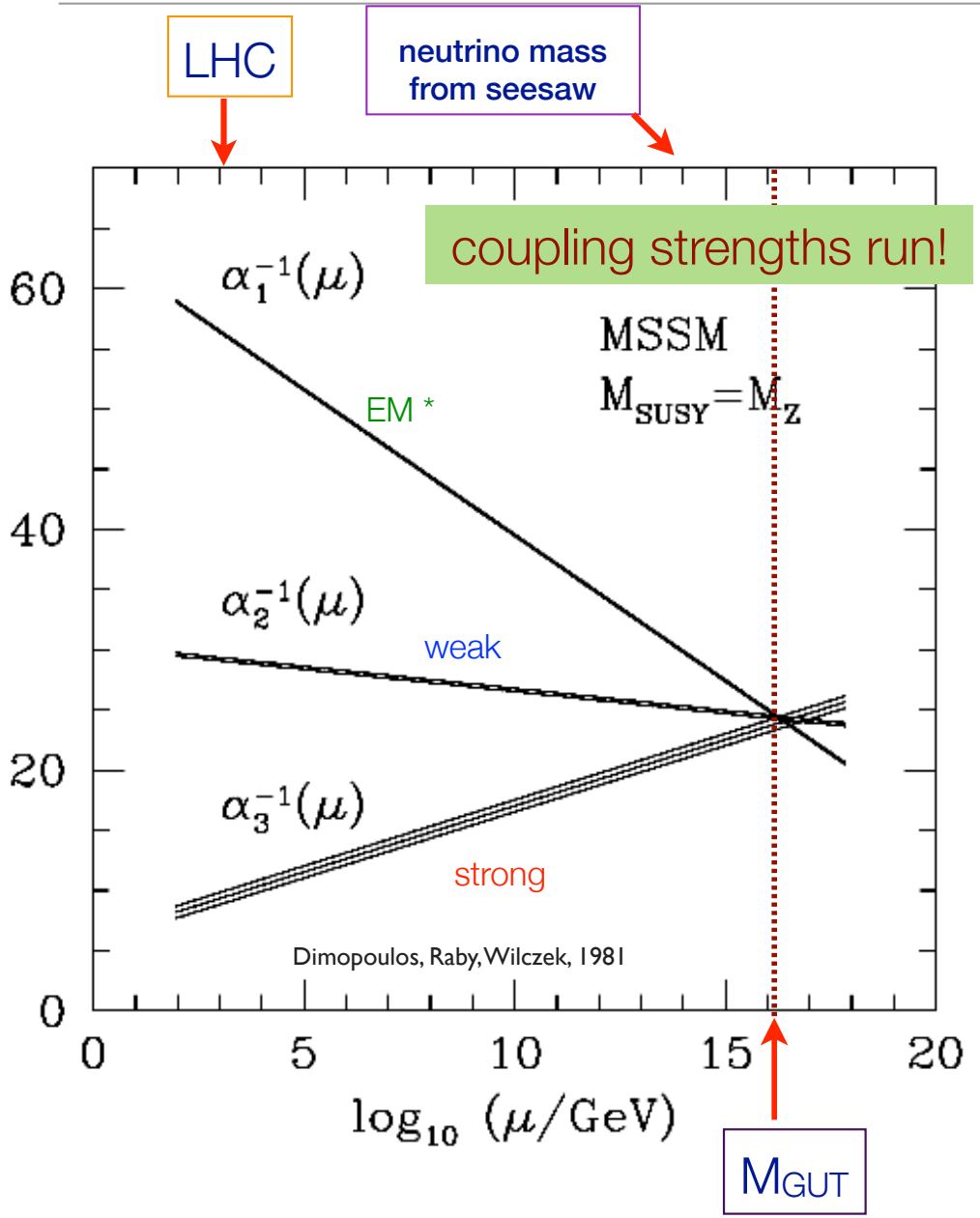


$$\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$$

Σ_R: SU(3)$_c$ x SU(2)$_w$ x U(1)$_Y$ ~(1,3,0)

Foot, Lew, He, Joshi, 1989; Ma, 1998

Grand Unification Naturally Accommodates Seesaw



- origin of the heavy scale ⇒ $U(1)_{B-L}$
- exotic mediators ⇒ predicted in many GUT theories, e.g. SO(10)

$$16 = (3, 2, 1/6) \sim \begin{bmatrix} u & u & u \\ d & d & d \end{bmatrix}$$
$$+ (3^*, 1, -2/3) \sim (u^c \;\; u^c \;\; u^c)$$
$$+ (3^*, 1, 1/3) \sim (d^c \;\; d^c \;\; d^c)$$
$$+ (1, 2, -1/2) \sim \begin{bmatrix} \nu \\ e \end{bmatrix}$$
$$+ (1, 1, 1) \sim e^c$$
$$+ (1, 1, 0) \sim \nu^c$$

Fritzsch, Minkowski, 1975

- exotic mediators in Type II, III: not easy to get in string theories

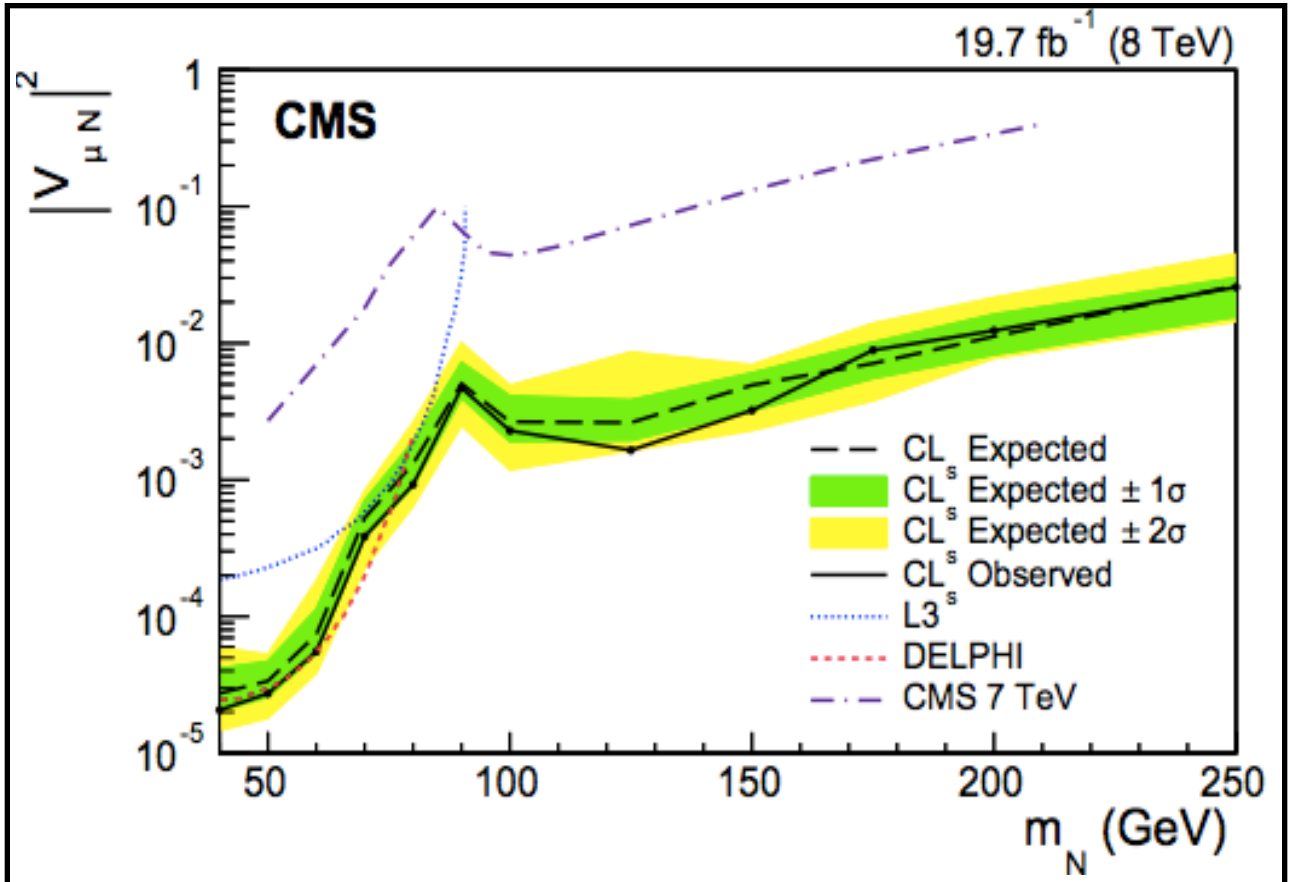
Dienes, March-Russell (1996)

Low Scale Seesaws

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.1$ eV with $v \sim 100$ GeV, $\lambda \sim 10^{-6} \Rightarrow M \sim 10^2$ GeV

- New particles:
  - Type I seesaw: generally decouple from collider experiments
  - Type II seesaw: $\Delta^{++} \to e^+e^+ \,,\, \mu^+\mu^+ \,,\, \tau^+\tau^+$ Franceschino, Hambye, Strumia,2008
  - Type III seesaw: observable displaced vertex
  - inverse seesaw: non-unitarity effects
  - radiative mass generation: model dependent - singly/doubly charged SU(2) singlet, even colored scalars in loops
- New interactions:
  - LR symmetric model: W_R
  - R parity violation: $\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}^0_1 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}^0_1 \to \tau^\pm W^\mp)}$ Mukhopadhyaya, Roy, Vissani, 1998
  - .....

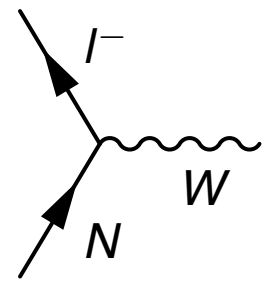
Cautions!!! Is it really the ν_R in Type I seesaw?



Expanded view of the region:
40 GeV < m_N < 250 GeV

PLB748 (2015)144

RH neutrino production thru active-sterile mixing:



$$\propto V = \frac{m_D}{M_R} \sim \frac{10^{-4}\ \text{GeV}}{100\ \text{GeV}} = 10^{-6}$$

RH neutrino relevant for ν mass generation

➪ $|V_{\mu N}|^2 = 10^{-12}$

unless extremely fine-tuned

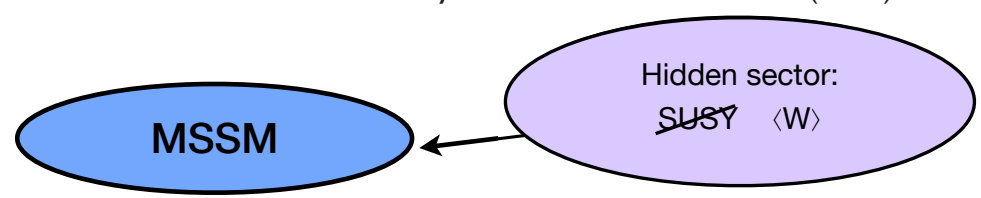
Kersten, Smirnov (2007)

Dirac Neutrinos and SUSY Breaking

- naturally small Dirac neutrino masses can arise
  - Randall-Sundrum model
  - Supersymmetry breaking
- before SUSY breaking: absence of Dirac neutrino masses (as well as Weinberg operator)
- after SUSY breaking: realistic effective Dirac neutrino masses generated

Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner (2001)

$$Y_\nu \sim \frac{m_{3/2}}{M_{\rm P}} \sim \frac{\mu}{M_{\rm P}}$$



- similar to the Giudice-Masiero Mechanism for the mu problem

Giudice, Masiero (1988)

$$\mu \sim \langle \mathscr{W} \rangle / M_{\rm P}^2 \sim m_{3/2}$$

- Need a symmetry reason for the absence of these operators before SUSY breaking

Question from NuFact'14

- What are the new developments and predictions from flavour models on neutrino oscillation parameters? What precision do we need to achieve to probe them? Which parameters (or combinations of them) are more powerful to test them?

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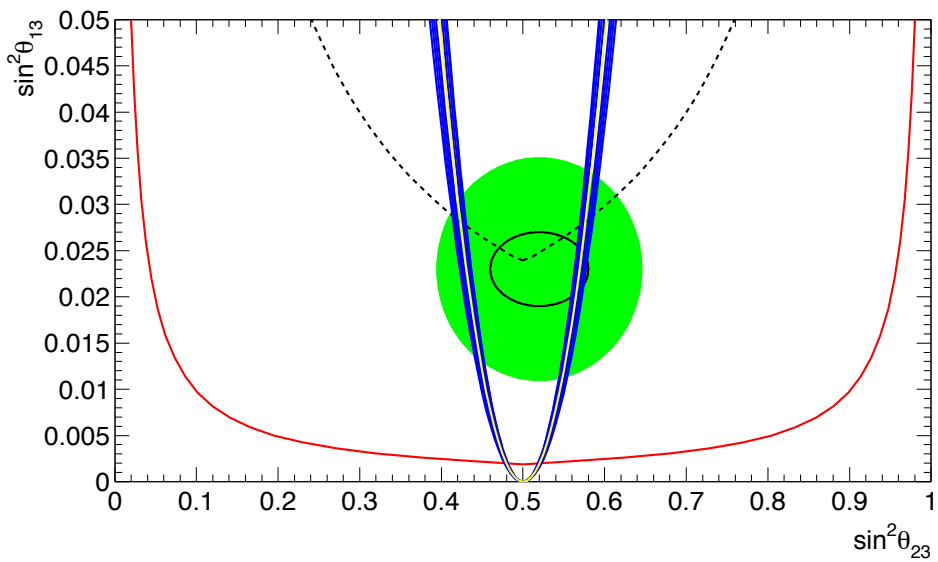
Flavor structure

anarchy vs symmetry

Anarchy

Hall, Murayama, Weiner (2000);
de Gouvea, Murayama (2003)

- there are no parametrically small numbers
- large mixing angle, near mass degeneracy statistically preferred



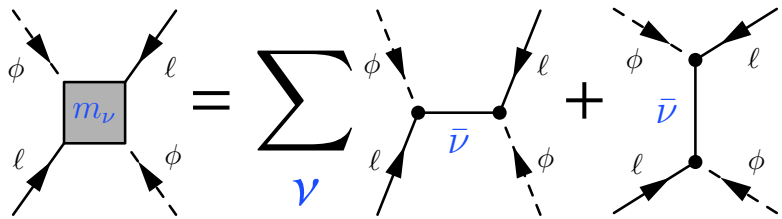
de Gouvea, Murayama (2012)

- UV theory prediction can resemble anarchy
  - warped extra dimensions
  - heterotic string theory

Expectations from Heterotic String Theories

- heterotic string models: O(100) RH neutrinos

Buchmüller, Hamaguchi, Lebedev, Ramos-Sánchez, Ratz (2007)

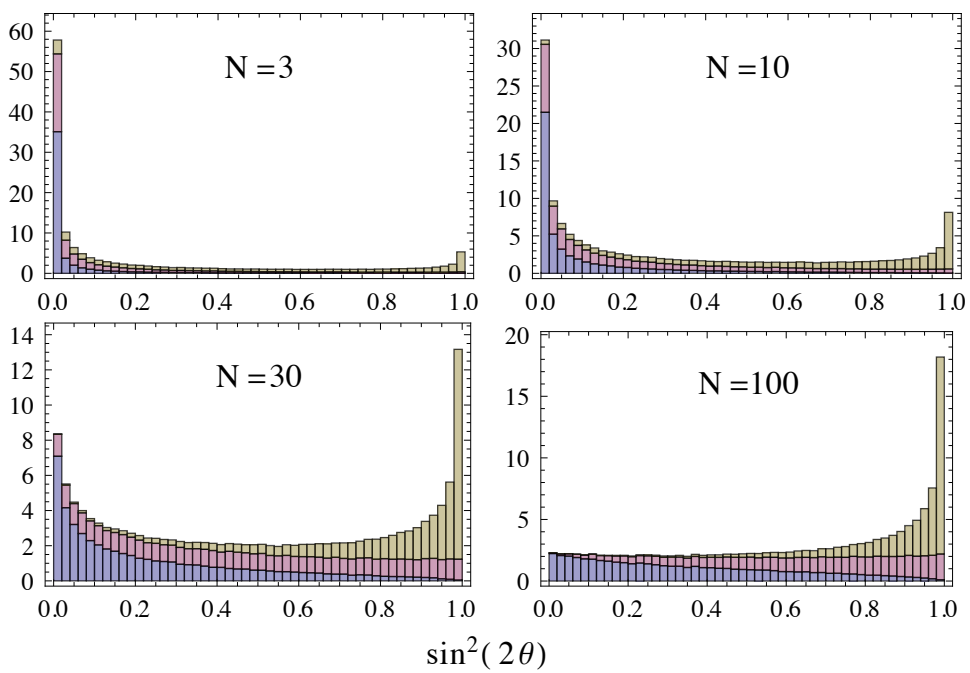


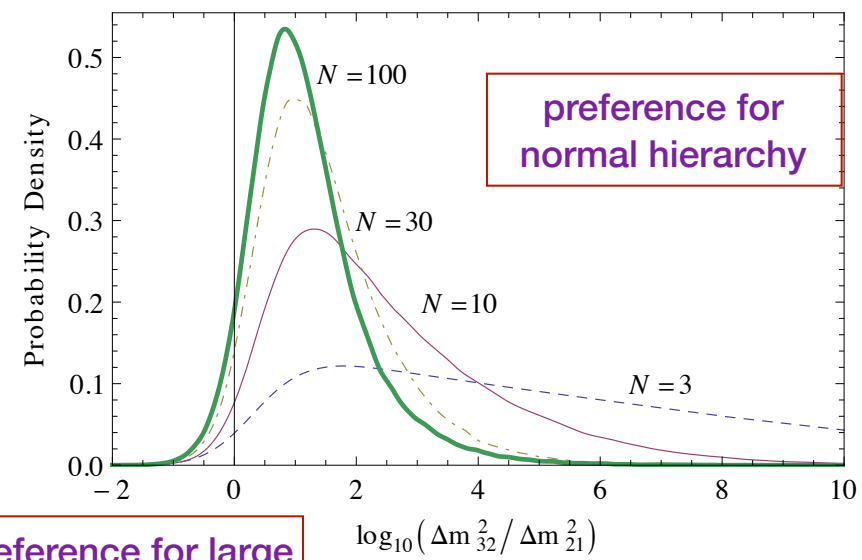
$$m_\nu \sim \frac{v^2}{M_*}$$

$$M_* \sim \frac{M_{\rm GUT}}{10...100}$$

- statistical expectations with large N (= # of RH neutrinos)

Feldstein, Klemm (2012)



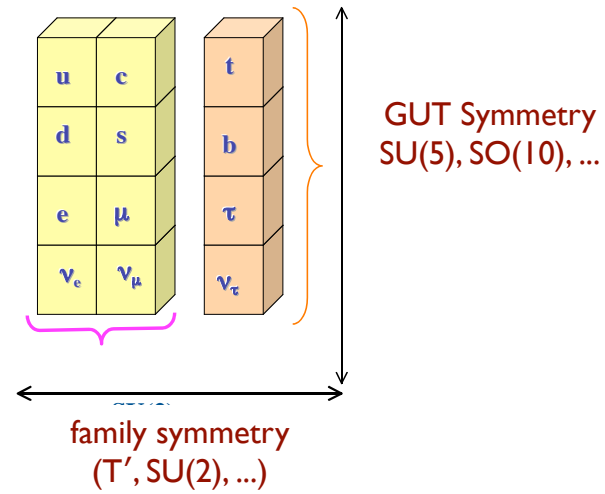


preference for normal hierarchy

preference for large mixing angles

Origin of Flavor Mixing and Mass Hierarchy

- Several models have been constructed based on
  - GUT Symmetry [SU(5), SO(10)] ⊕ Family Symmetry G_F
- Family Symmetries G_F based on continuous groups:
  - U(1)
  - SU(2)
  - SU(3)



- Recently, models based on discrete family symmetry groups have been constructed
  - A_4 (tetrahedron)
  - T′ (double tetrahedron)
  - S_3 (equilateral triangle)
  - S_4 (octahedron, cube)
  - A_5 (icosahedron, dodecahedron)
  - Δ_{27}
  - Q_6

Tri-bimaximal Neutrino Mixing

- Latest Global Fit (3σ)

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo (March 2014)

$$\sin^2\theta_{23} = 0.437\ (0.374 - 0.626) \quad [\theta^{lep}_{23} \sim 41.2°]$$

$$\sin^2\theta_{12} = 0.308\ (0.259 - 0.359) \quad [\theta^{lep}_{12} \sim 33.7°]$$

$$\sin^2\theta_{13} = 0.0234\ (0.0176 - 0.0295) \quad [\theta^{lep}_{13} \sim 8.80°]$$

- Tri-bimaximal Mixing Pattern

Harrison, Perkins, Scott (1999)

$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

$$\sin^2\theta_{\mathrm{atm,\,TBM}} = 1/2 \qquad \sin^2\theta_{\odot,\mathrm{TBM}} = 1/3$$

$$\sin\theta_{13,\mathrm{TBM}} = 0.$$

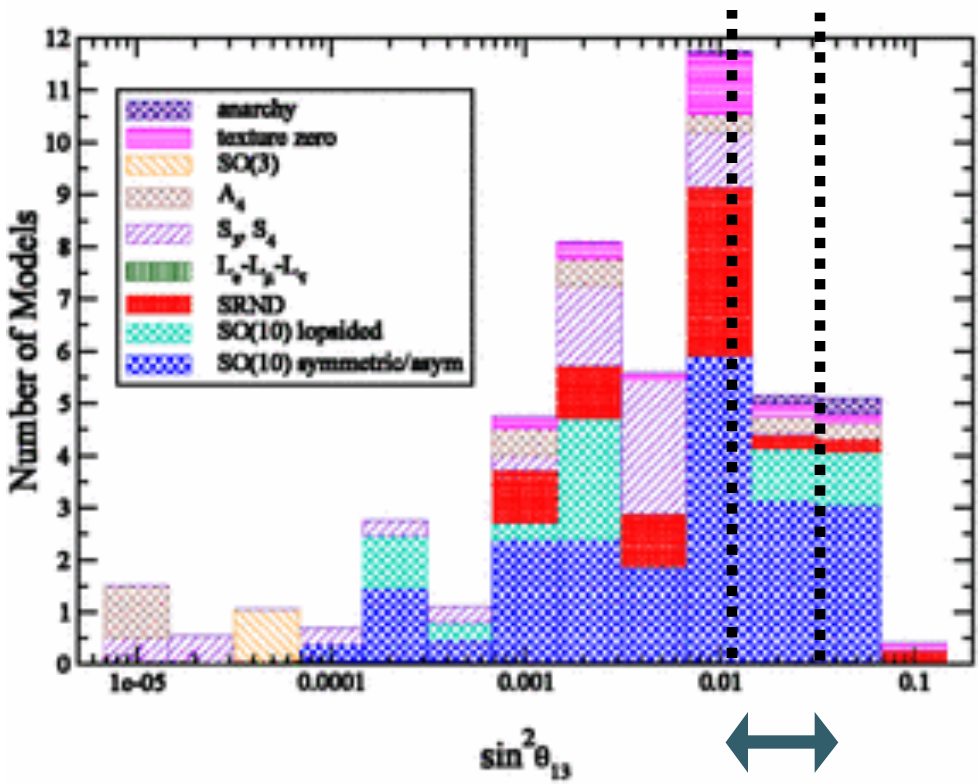
- Leading Order: TBM (from symmetry) + higher order corrections/contributions
- More importantly, corrections to the kinetic terms

Leurer, Nir, Seiberg (1993);
Dudas, Pokorski, Savoy (1995)

M.-C.C, M. Fallbacher, M. Ratz, C. Staudt, (2012)

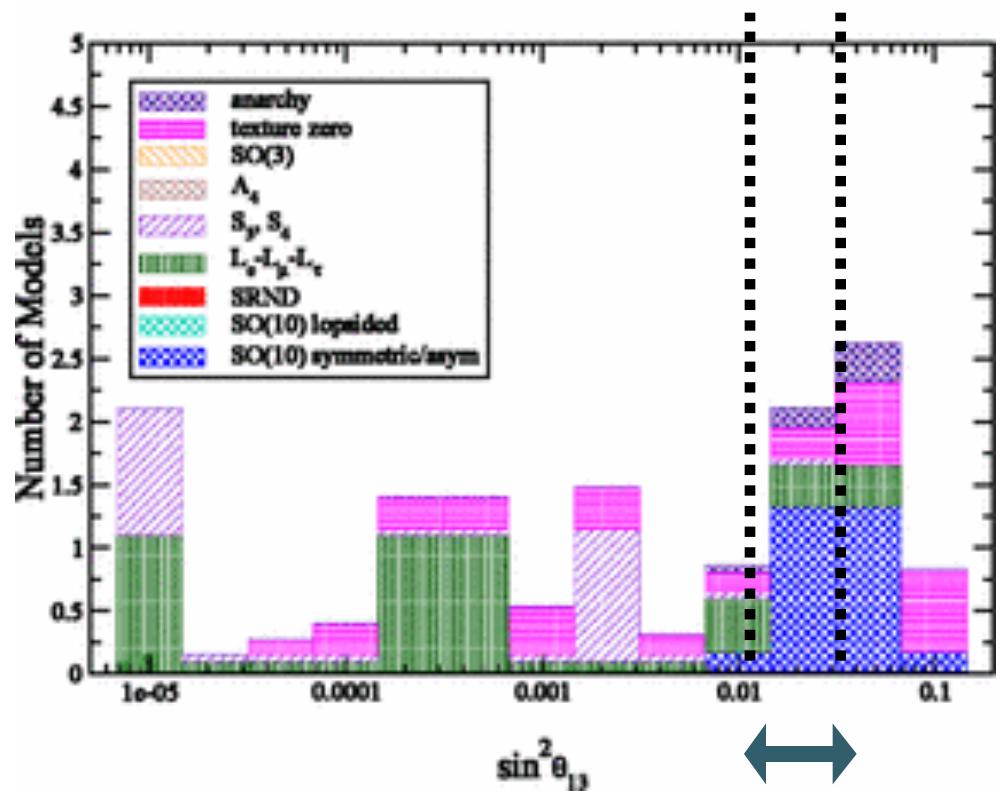
Mixing Parameters and Mass ordering → underlying symmetries

Normal Hierarchy



Daya Bay

Inverted Hierarchy



Daya Bay

C. Albright, M.-C.C. (2006)

Symmetry Relations

Quark Mixing

mixing parameters	best fit	3σ range
θ^q_{23}	2.36°	2.25° - 2.48°
θ^q_{12}	12.88°	12.75° - 13.01°
θ^q_{13}	0.21°	0.17° - 0.25°

Lepton Mixing

mixing parameters	best fit	3σ range
θ^e_{23}	41.2°	35.1° - 52.6°
θ^e_{12}	33.6°	30.6° - 36.8°
θ^e_{13}	8.9°	7.5° -10.2°

- QLC-I $\theta_c + \theta_{sol} \cong 45^o$ Raidal, '04; Smirnov, Minakata, '04

  (BM) $\theta^q_{23} + \theta^e_{23} \cong 45^o$ ☞ **slight inconsistent**

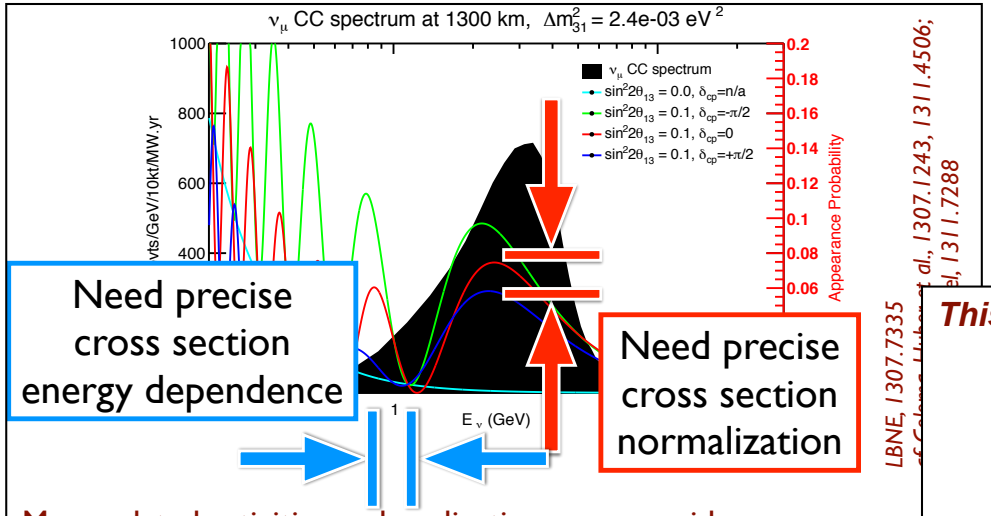
- QLC-II $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_c / 2) * \cos \delta_e$ Ferrandis, Pakvasa; Dutta, Mimura; M.-C.C., Mahanthappa

  (TBM) $\theta^e_{13} \cong \theta_c / 3\sqrt{2}$ ☞ **Too small**

- testing symmetry relations: a *more* robust way to distinguish different classes of models

measuring leptonic mixing parameters to the precision of those in quark sector

Aside: Precision Cross Section



LBNE, 1307.7335
et al., 1307.1243, 1311.4506;
el, 1311.7288

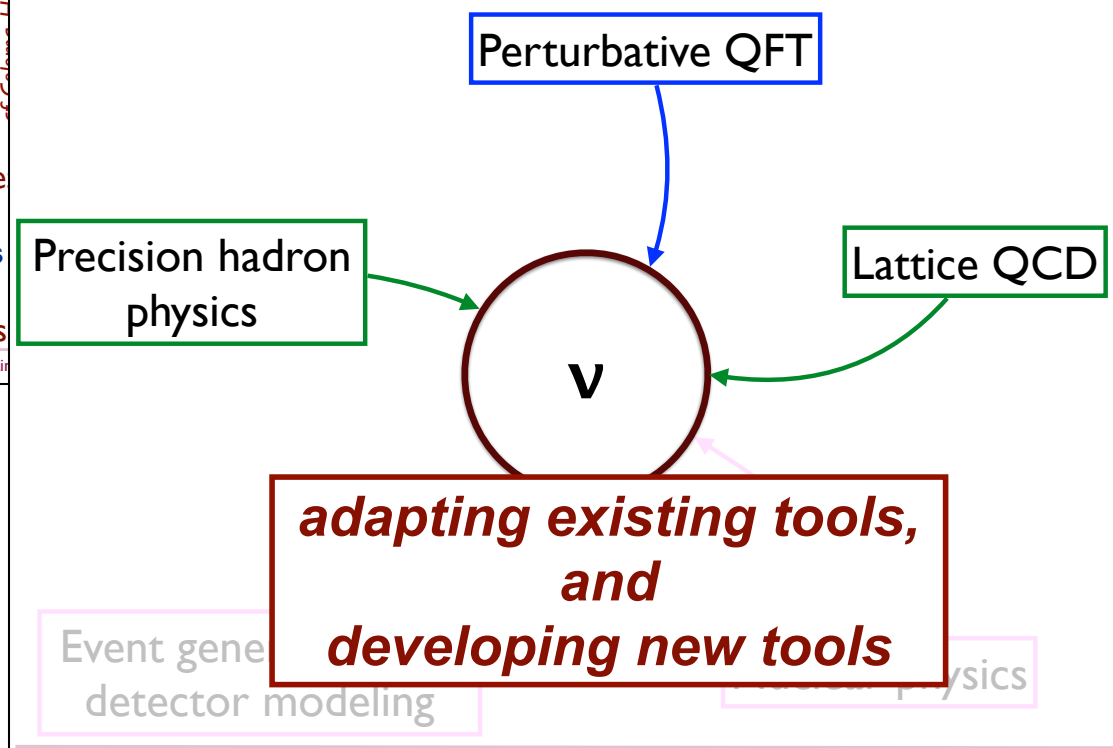
Many related activities and applications, over a wide energy range
- sterile neutrino searches
- reactor, supernova, astrophysical, solar, cosmological ν's
- proton decay, …

Focus here on ~GeV ν cross sections for oscillation experiments

Richard Hill University of Chicago 4 2015 Fermilab Users Meeti

HEP Theory can contribute!

This is a challenging problem. HEP Theory is…



Richard Hill University of Chicago 5 2015 Fermilab Users Meeting

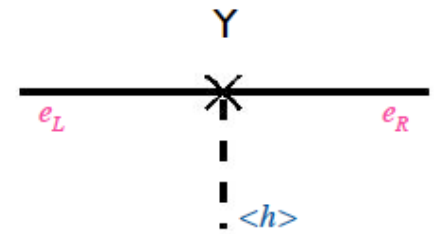
Slides Courtesy of Richard Hill @ 2015 Fermilab Users Meeting

Origin of CP Violation

- CP violation ⇔ complex mass matrices

$$\overline{U}_{R,i}(M_u)_{ij}Q_{L,j} + \overline{Q}_{L,j}(M_u^\dagger)_{ji}U_{R,i} \xrightarrow{\mathcal{CP}} \overline{Q}_{L,j}(M_u)_{ij}U_{R,i} + \overline{U}_{R,i}(M_u)^*_{ij}Q_{L,j}$$

- Conventionally, CPV arises in two ways:
  - Explicit CP violation: complex Yukawa coupling constants Y
  - Spontaneous CP violation: complex scalar VEVs <h>



- **Complex CG coefficients in certain discrete groups ⇒ explicit CP violation**
  - CPV in quark and lepton sectors purely from complex CG coefficients

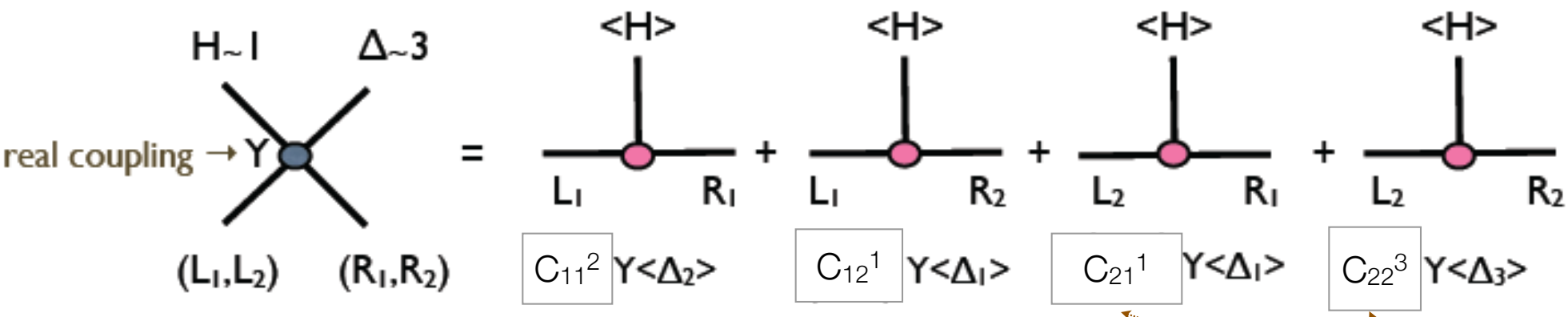
CG coefficients in non-Abelian discrete symmetries
➪ relative strengths and phases in entries of Yukawa matrices
➪ mixing angles and phases (and mass hierarchy)

Group Theoretical Origin of CP Violation

M.-C.C., K.T. Mahanthappa
Phys. Lett. B681, 444 (2009)

Basic idea

Discrete symmetry ***G***



$C_{ij}{}^{k}$: complex CG coefficients of ***G***

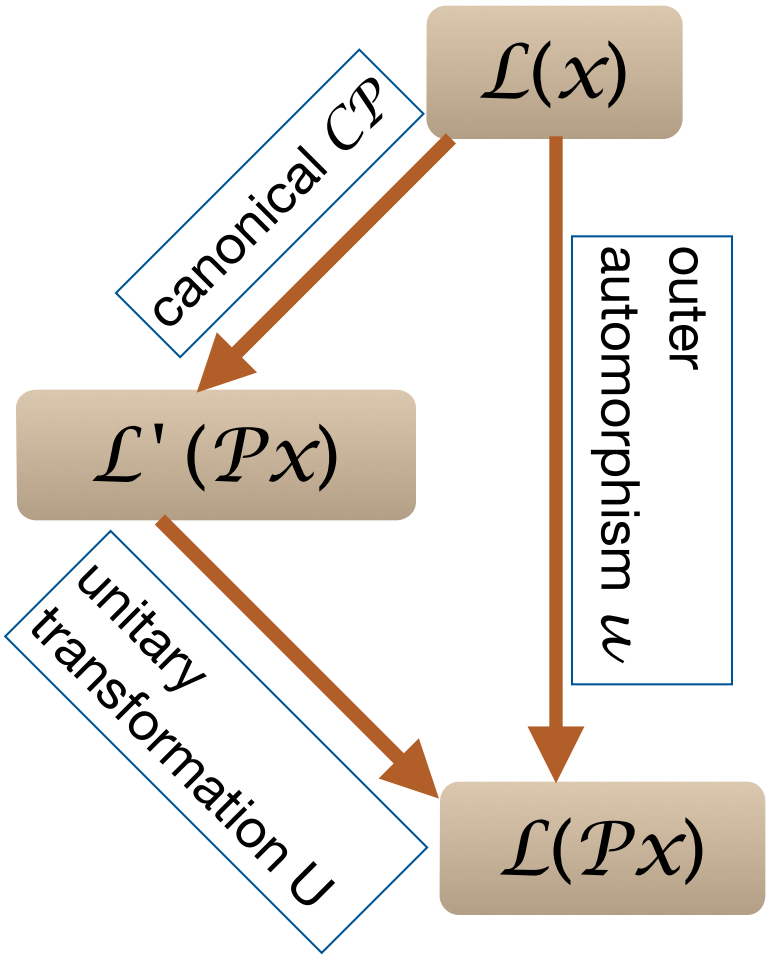
- Scalar potential: if Z_3 symmetric $\Rightarrow$ $\langle\Delta_1\rangle = \langle\Delta_2\rangle = \langle\Delta_3\rangle \equiv \langle\Delta\rangle$ real
- Complex effective mass matrix: **phases determined by group theory**

$$M = \begin{array}{c} (\,L_1 \quad L_2\,) \\ \begin{pmatrix} C_{11}{}^{2} & C_{21}{}^{1} \\ C_{12}{}^{1} & C_{22}{}^{3} \end{pmatrix} \end{array} Y\,\langle\Delta\rangle \begin{pmatrix} R_1 \\ R_2 \end{pmatrix}$$

Group Theoretical Origin of CP Violation

M.-C.C, M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner, NPB (2014)

complex CGs ➪ G and physical CP transformations do not commute



$$\Phi(x) \overset{\widetilde{\mathcal{CP}}}{\longmapsto} U_{\rm CP}\, \Phi^*(\mathcal{P}\ x)$$

$$\rho_{\boldsymbol{r}_i}\big(u(g)\big) = U_{\boldsymbol{r}_i}\, \rho_{\boldsymbol{r}_i}(g)^*\, U^\dagger_{\boldsymbol{r}_i} \quad \forall\, g \in G \text{ and } \forall\, i$$

u has to be a class-inverting, involuntory automorphism of G

➪ non-existence of such automorphism in certain groups

➪ explicit physical CP violation in generic setting

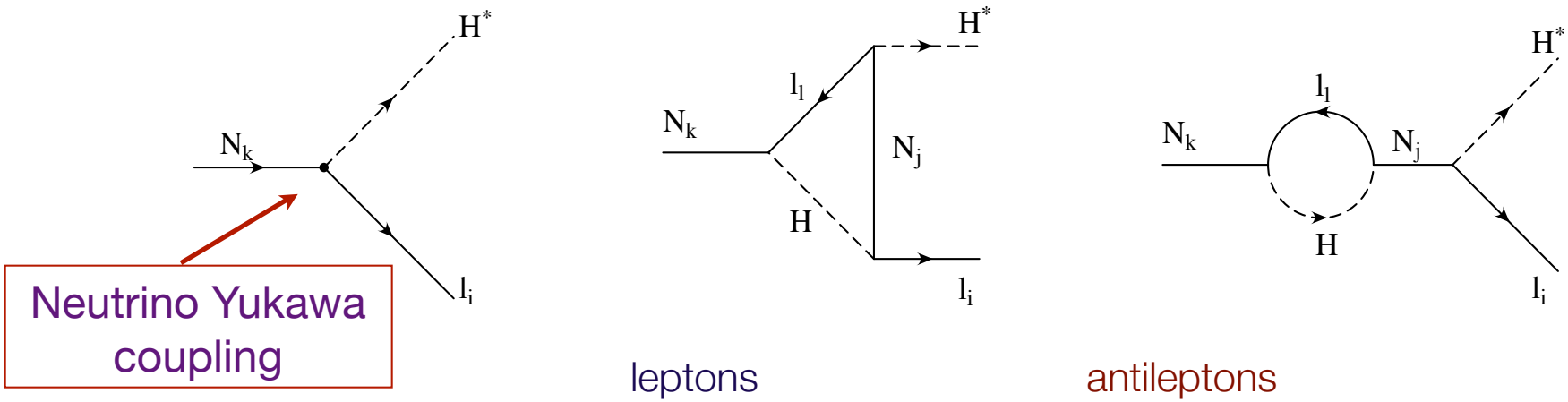
examples: T_7, $\Delta(27)$, …..

Cosmological Connection

Standard Leptogenesis

Fukugita, Yanagida, 1986

- RH heavy neutrino decay:
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry **ΔL**



leptons antileptons

$$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]}$$

Leptonic CP violation ⇒ $\Delta L \propto \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right] \neq 0$

Dirac Leptogenesis

K. Dick, M. Lindner, M. Ratz, D. Wright, 2000;
H. Murayama, A. Pierce, 2002

- Leptogenesis possible even when neutrinos are Dirac particles **(no ΔL = 2 violation)**

- Characteristics of Sphaleron effects:
  - only left-handed fields couple to sphalerons
  - sphalerons change (B+L) but not (B-L)
  - sphaleron effects in equilibrium for T > Tew

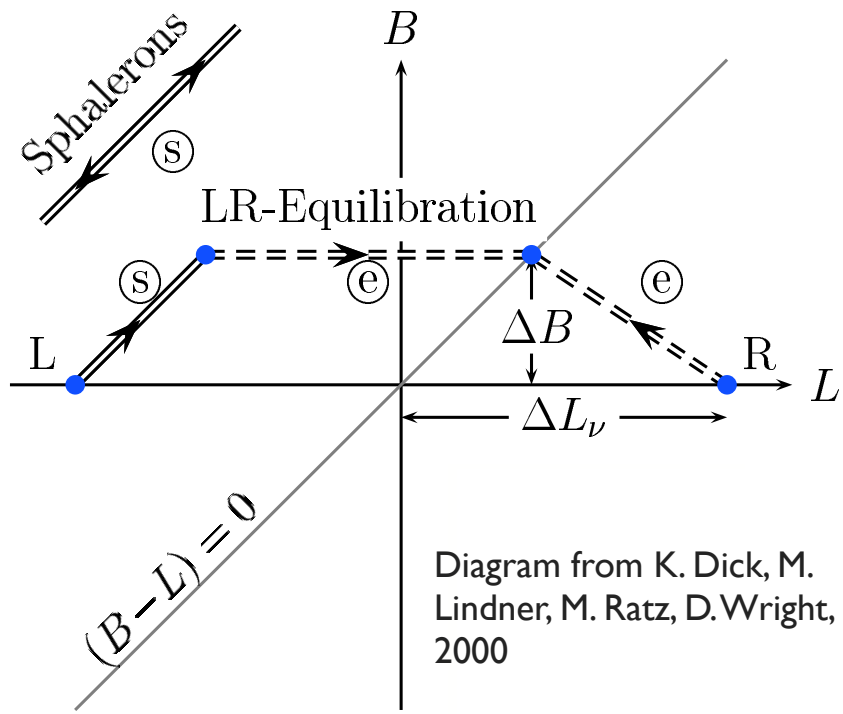


Diagram from K. Dick, M. Lindner, M. Ratz, D. Wright, 2000

late time LR equilibration of neutrinos making Dirac leptogenesis possible with primordial **ΔL = 0**

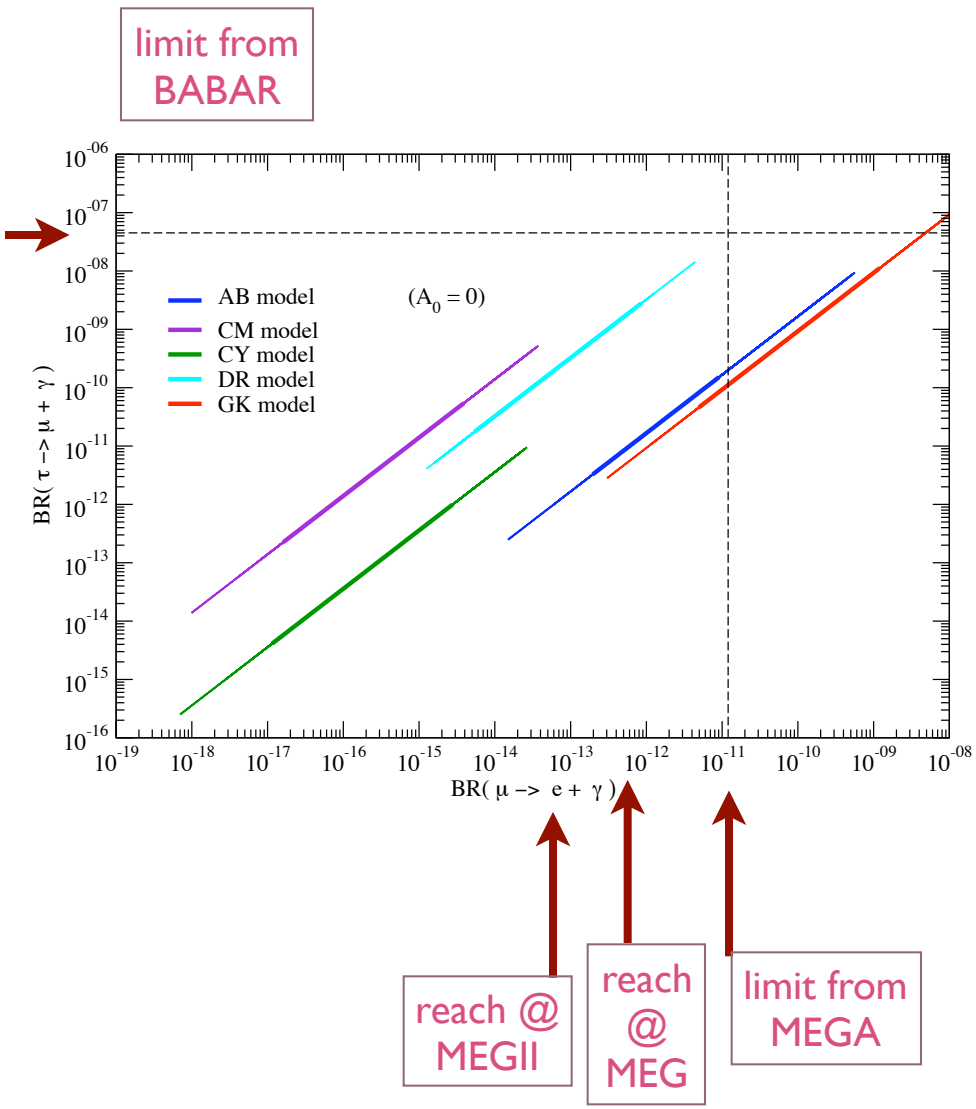
Question from NuFact'14

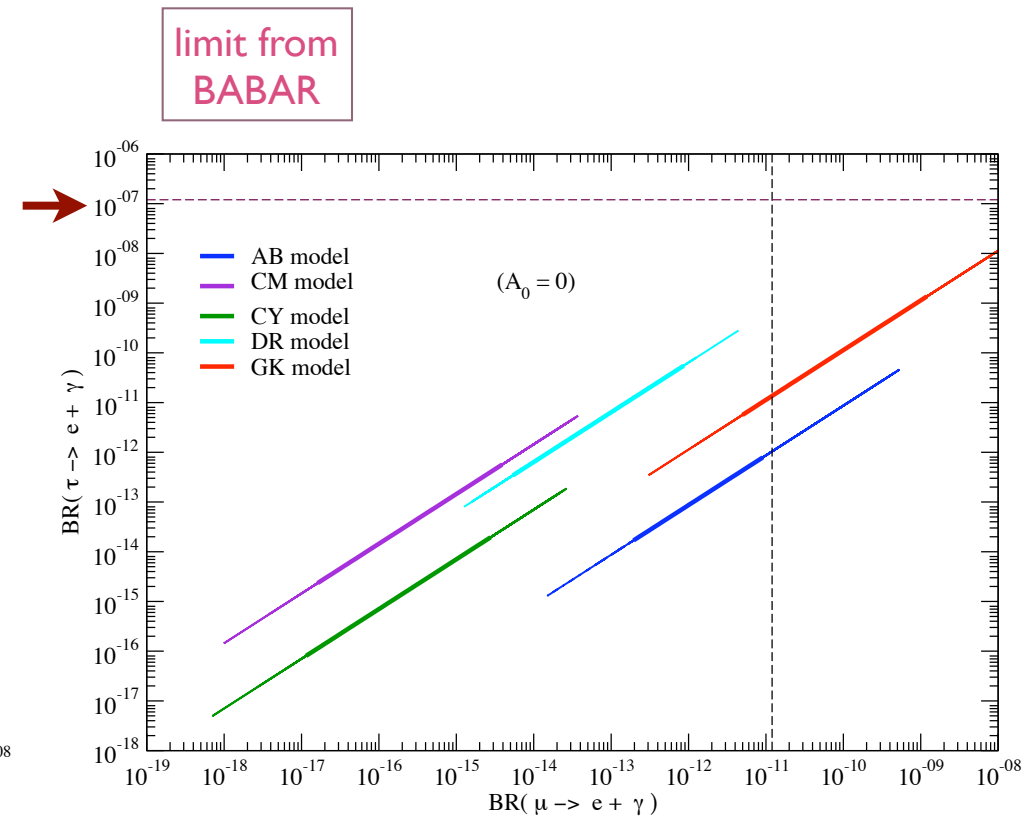
- Explore the synergy between neutrino oscillations and other experiments (absolute mass searches, cosmological constraints, CLFV) to constrain new physics.

Synergy

Correlations among cLFV Processes

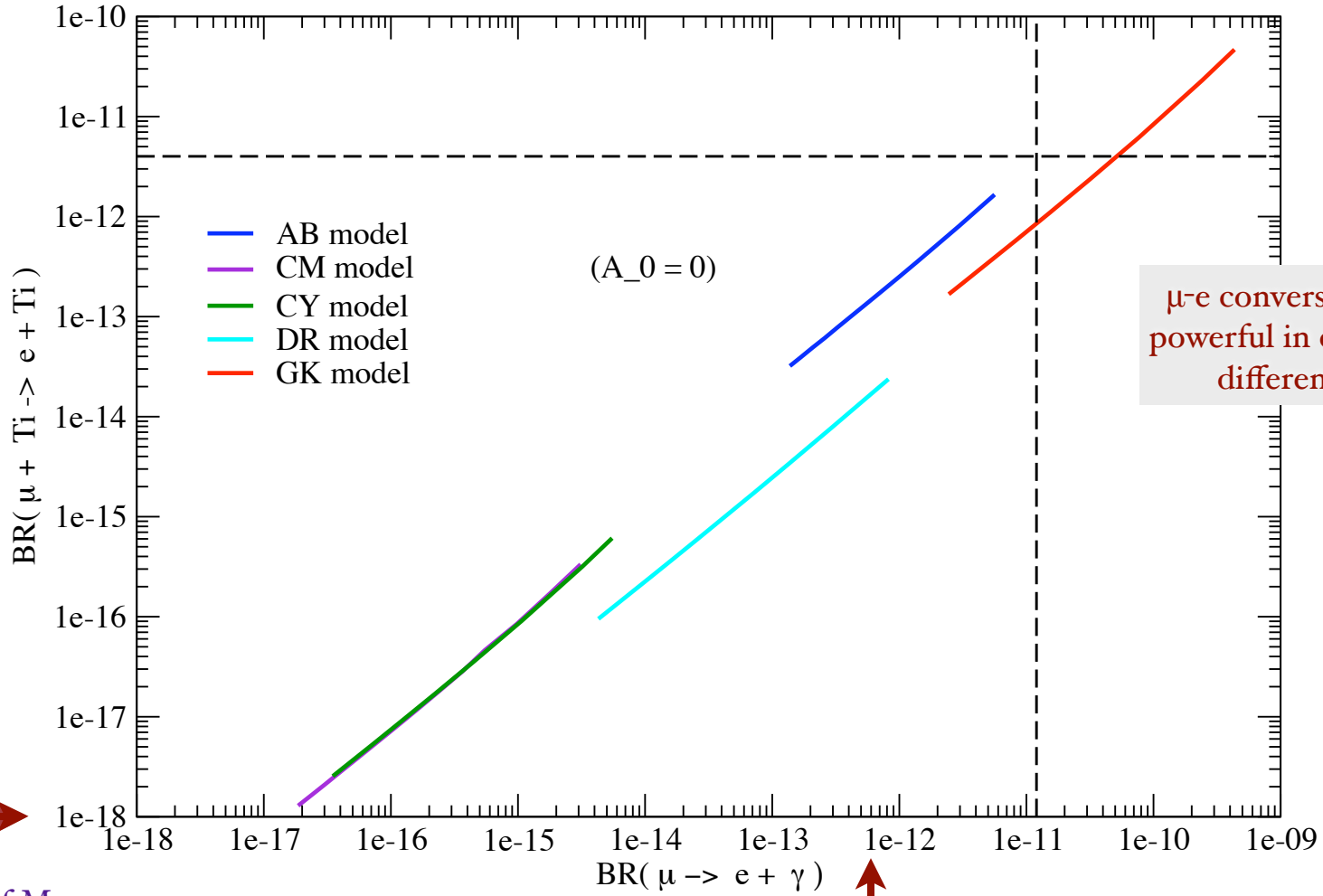
C. Albright & M.-C.C, 2008





Correlations among cLFV Processes

C. Albright & M.-C.C, 2008



μ-e conversion could be powerful in distinguishing different models

sensitivity of Mu2e, COMET

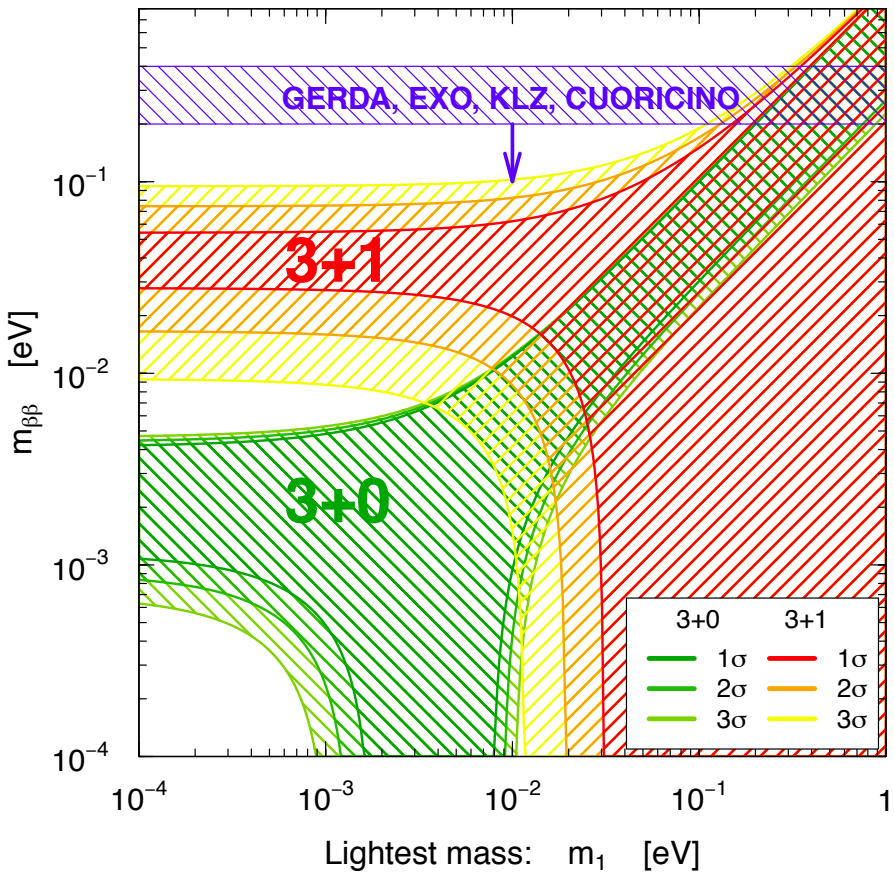
reach at MEGII

reach at MEG

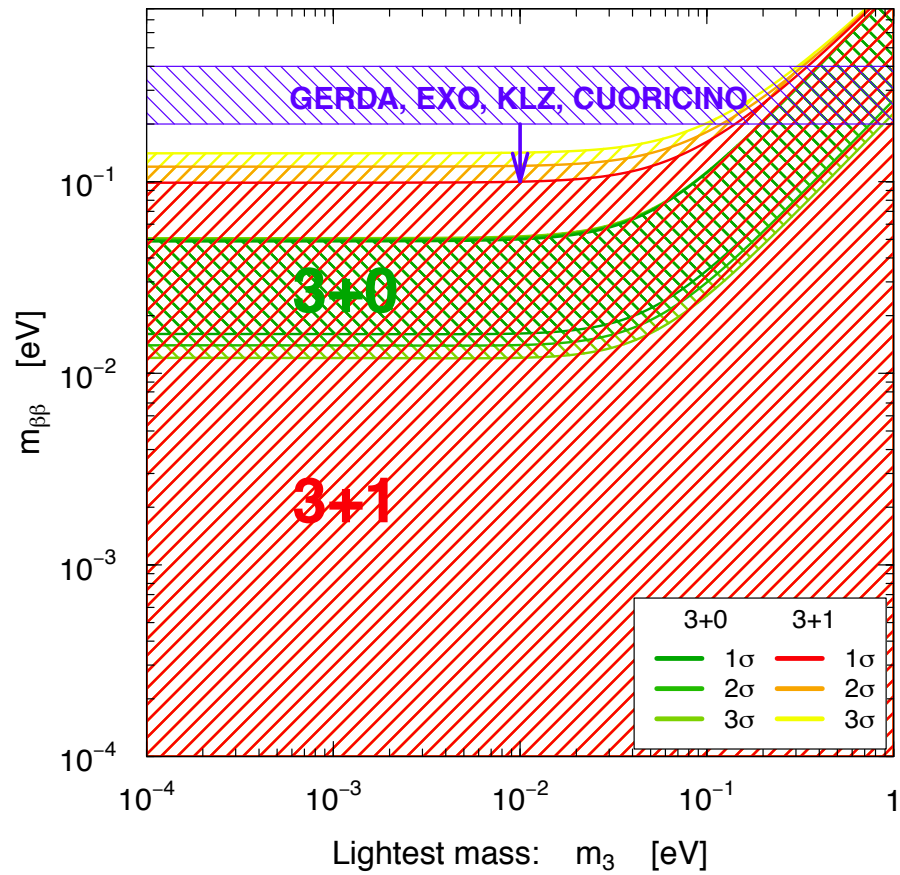
Neutrinoless Double Beta Decay

$$|m_{\beta\beta}| = \left| \sum_{k=1}^{4} U_{ek}^2 \, m_k \right|$$

Normal 3ν Ordering



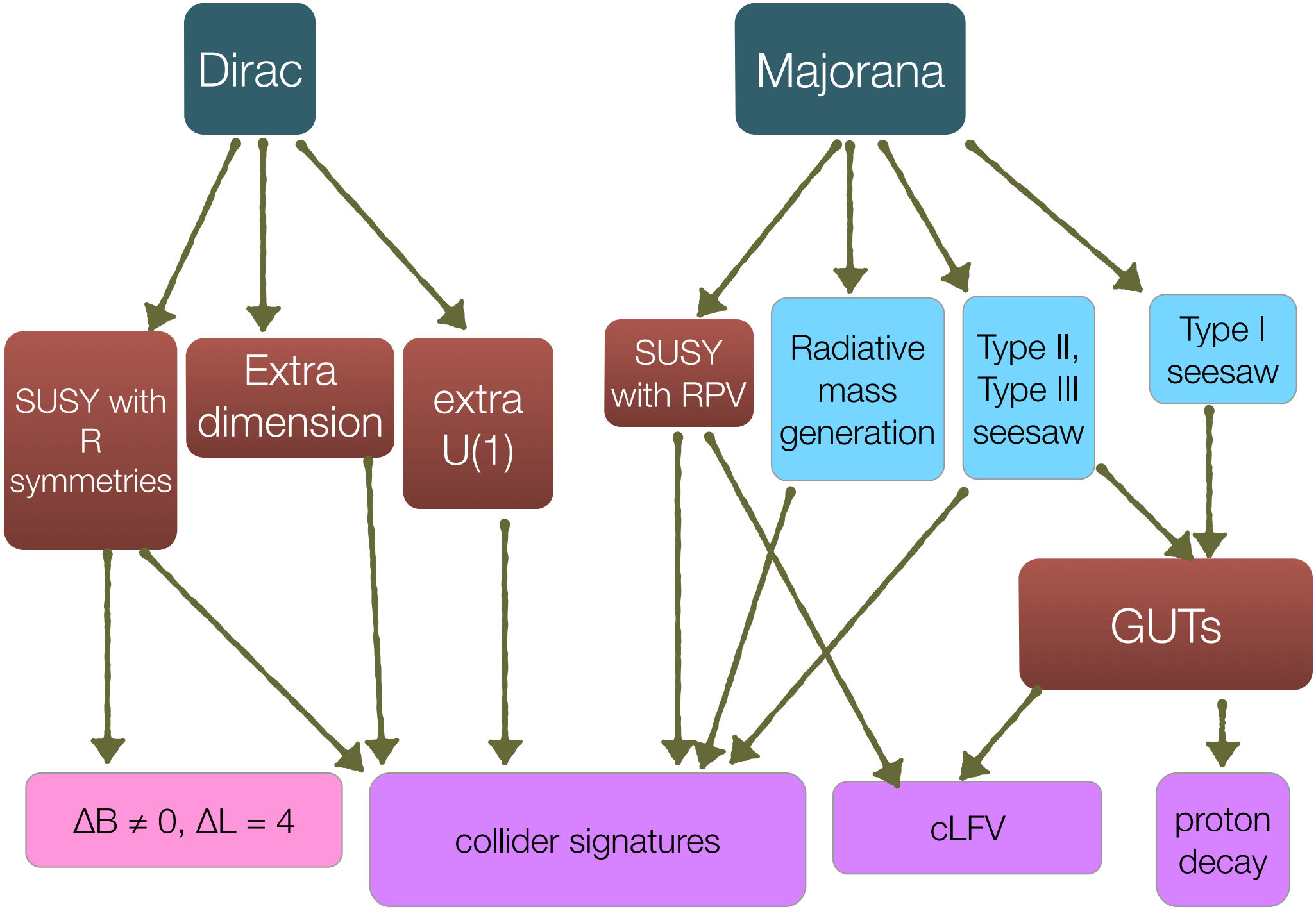
Inverted 3ν Ordering



Giunti, Laveder, Li, Long (2014)

Conclusions

- Fundamental origin of fermion mass hierarchy and flavor mixing still not known
- Neutrino masses: evidence of physics beyond the SM
- Symmetries: can provide an understanding of the pattern of fermion masses and mixing
  - correlations, correlations, correlations:
    - quark & lepton mixing parameters
    - lepton flavor violating charged lepton decays
    - proton (nucleon) decay, neutron-antineutron oscillation


Dirac
Majorana
SUSY with R symmetries
Extra dimension
extra U(1)
SUSY with RPV
Radiative mass generation
Type II, Type III seesaw
Type I seesaw
GUTs
ΔB ≠ 0, ΔL = 4
collider signatures
cLFV
proton decay