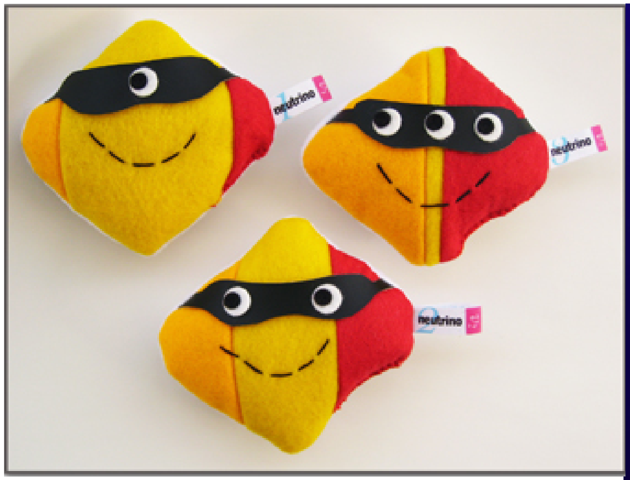
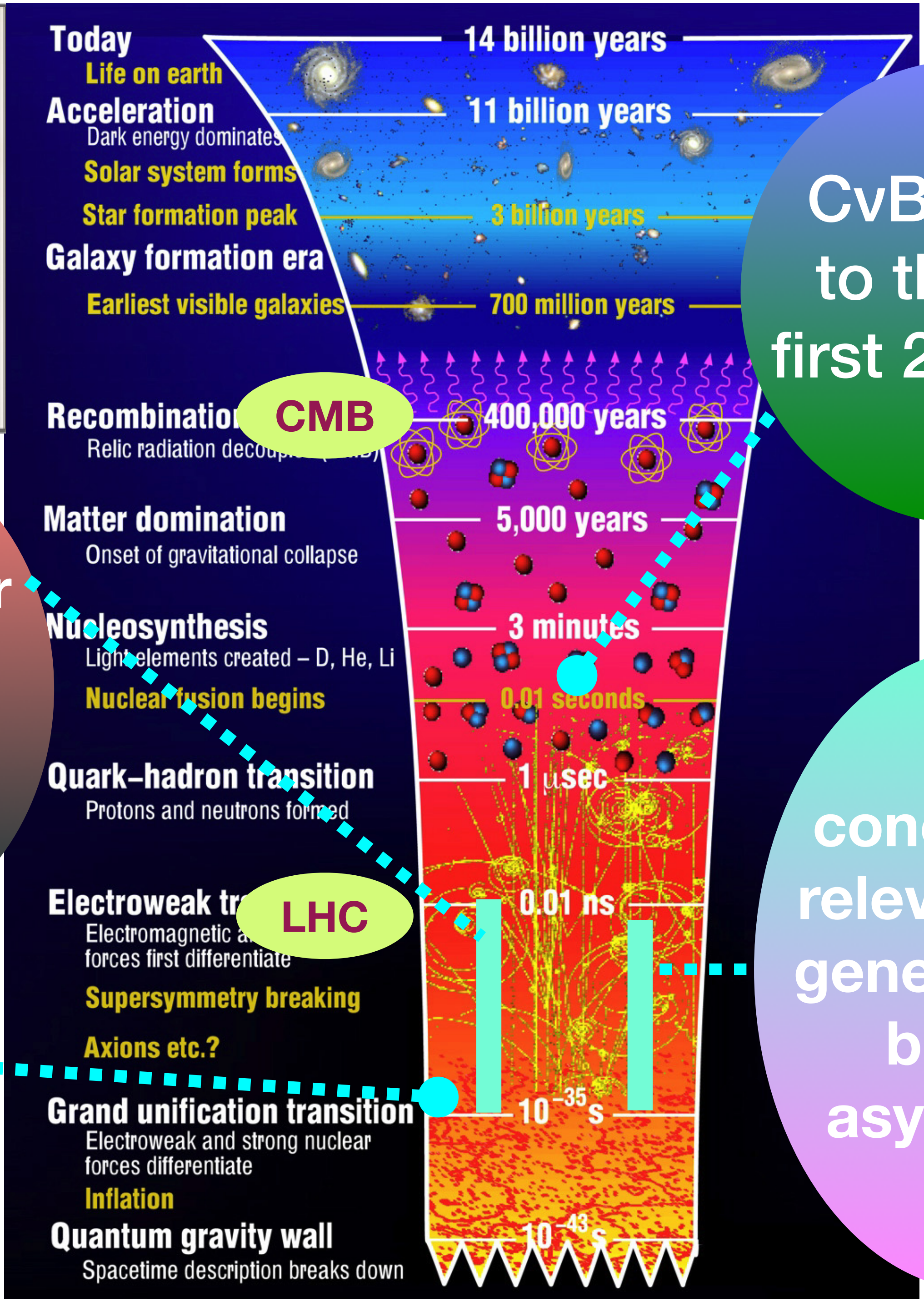
Neutrinos and Physics beyond the Standard Model

Mu-Chun Chen, University of California at Irvine

DPF 2015, University of Michigan, Ann Arbor, August 7, 2015





CνB - 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

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

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

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

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

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 $\sum(m_{\nu_i}) < 0.49 \text{ eV}$

$N_{eff} = 3.04 \pm 0.2$ [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)?

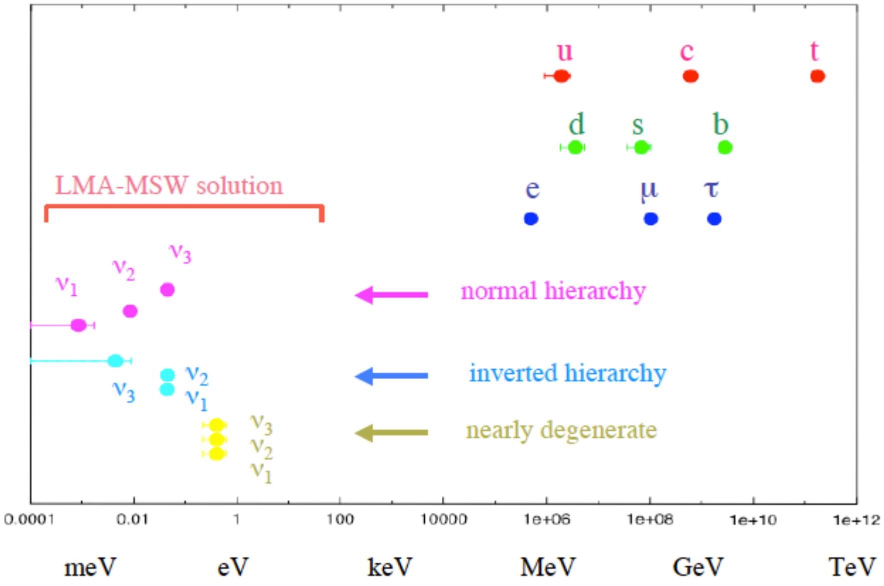
a suite of current and upcoming experiments to address these puzzles

some can only be answered by oscillation experiments

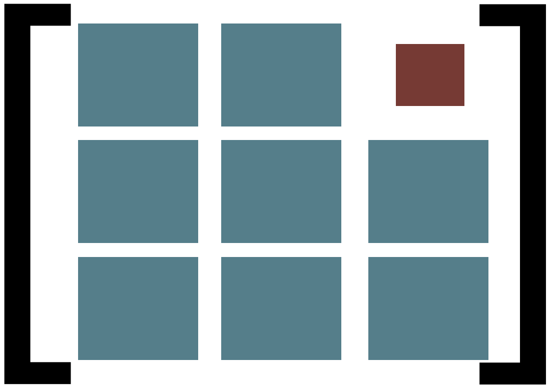
Open Questions - Theoretical

☞ Smallness of neutrino mass:

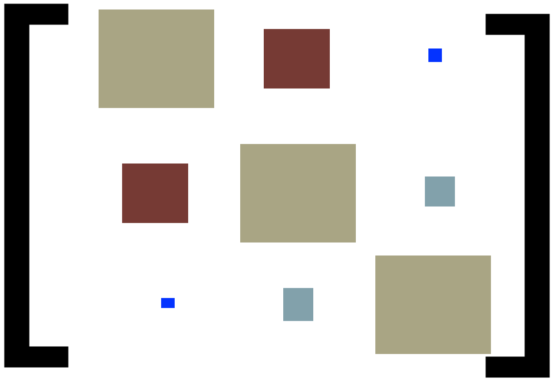
$$m_\nu \ll m_{e,\,u,\,d}$$



☞ Flavor structure:



leptonic mixing

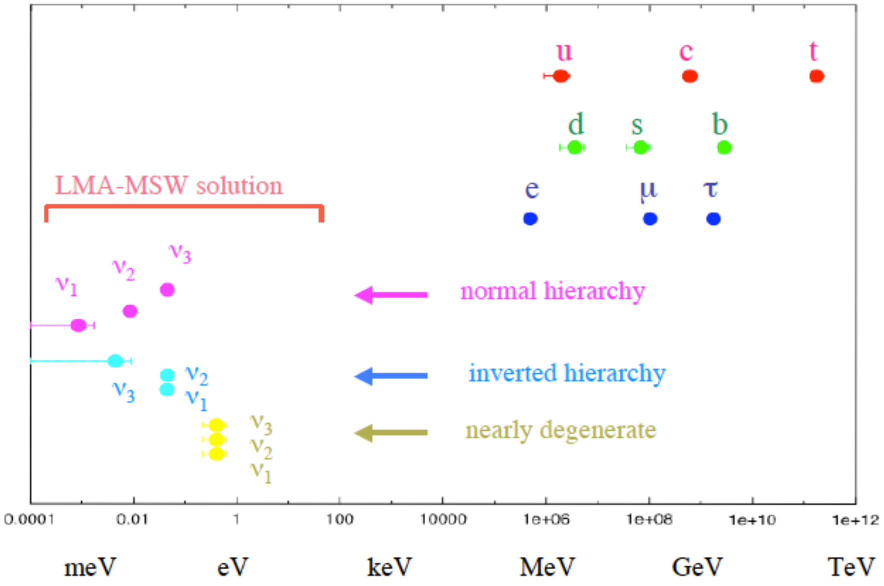


quark mixing

Open Questions - Theoretical

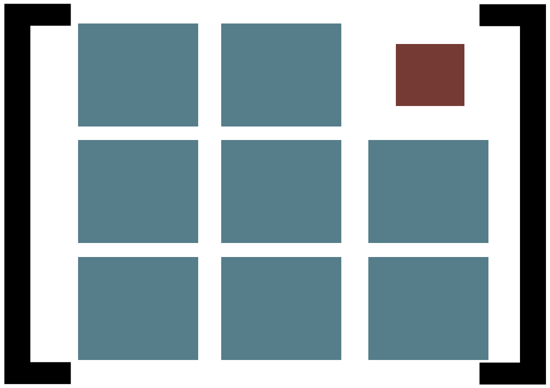
☞ Smallness of neutrino mass:

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

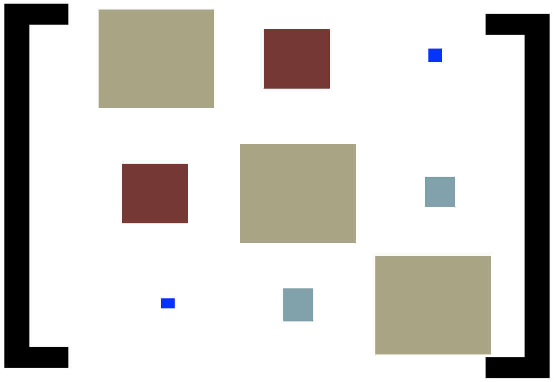


Fermion mass and hierarchy problem ➟ Many free parameters in the Yukawa sector of SM

☞ Flavor structure:



leptonic mixing



quark mixing

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

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

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

Weinberg, 1979

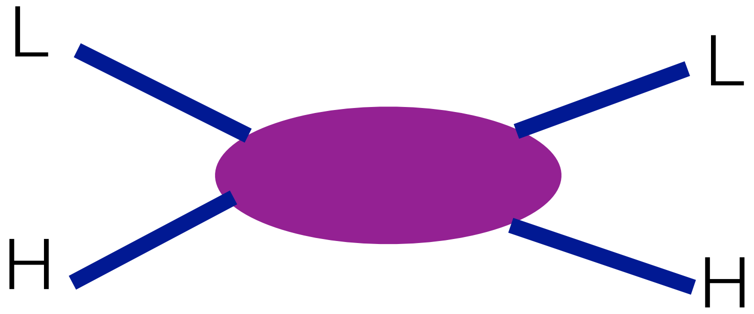
$$\frac{\lambda_{ij}}{M} H H L_i L_j \quad \Rightarrow \quad m_\nu = \lambda_{ij} \frac{v^2}{M}$$

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

↕

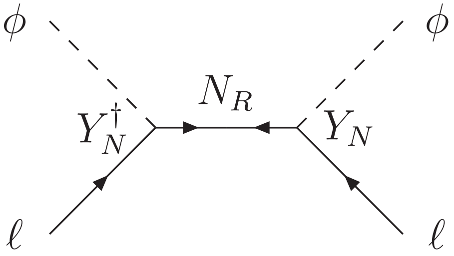
GUT scale

Neutrino Mass beyond the SM



3 possible portals

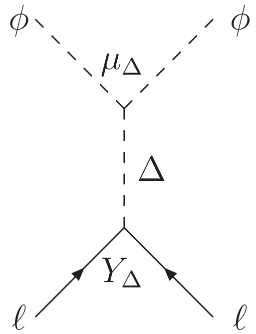
Type-I seesaw



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;

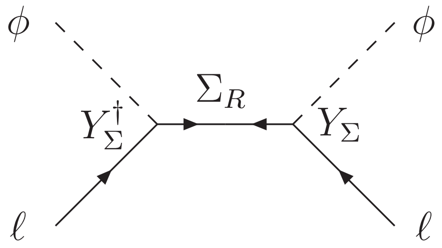
Type-II seesaw



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

Lazarides, 1980; Mohapatra, Senjanovic, 1980

Type-III seesaw

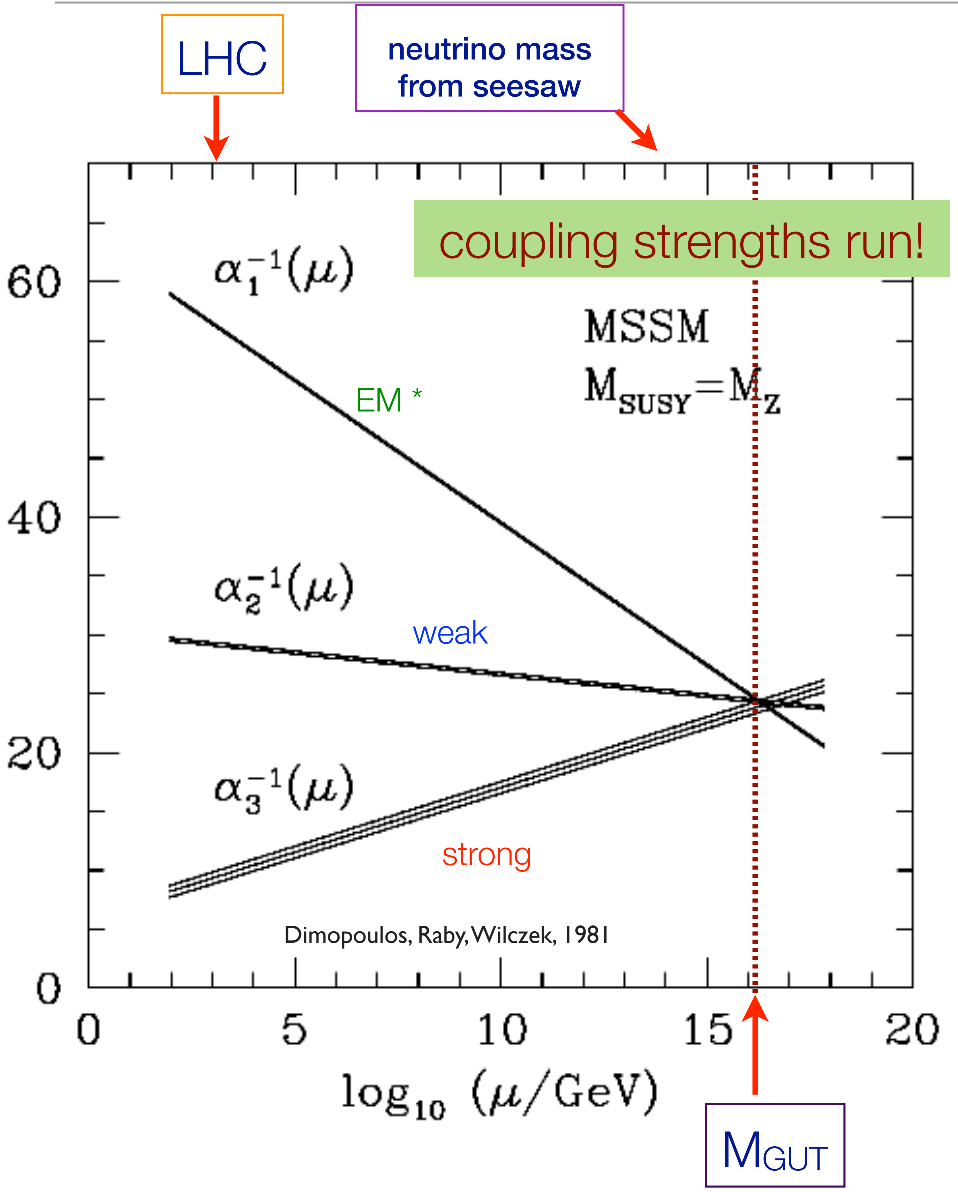


$$\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$$

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



Dimopoulos, Raby, Wilczek, 1981

- 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

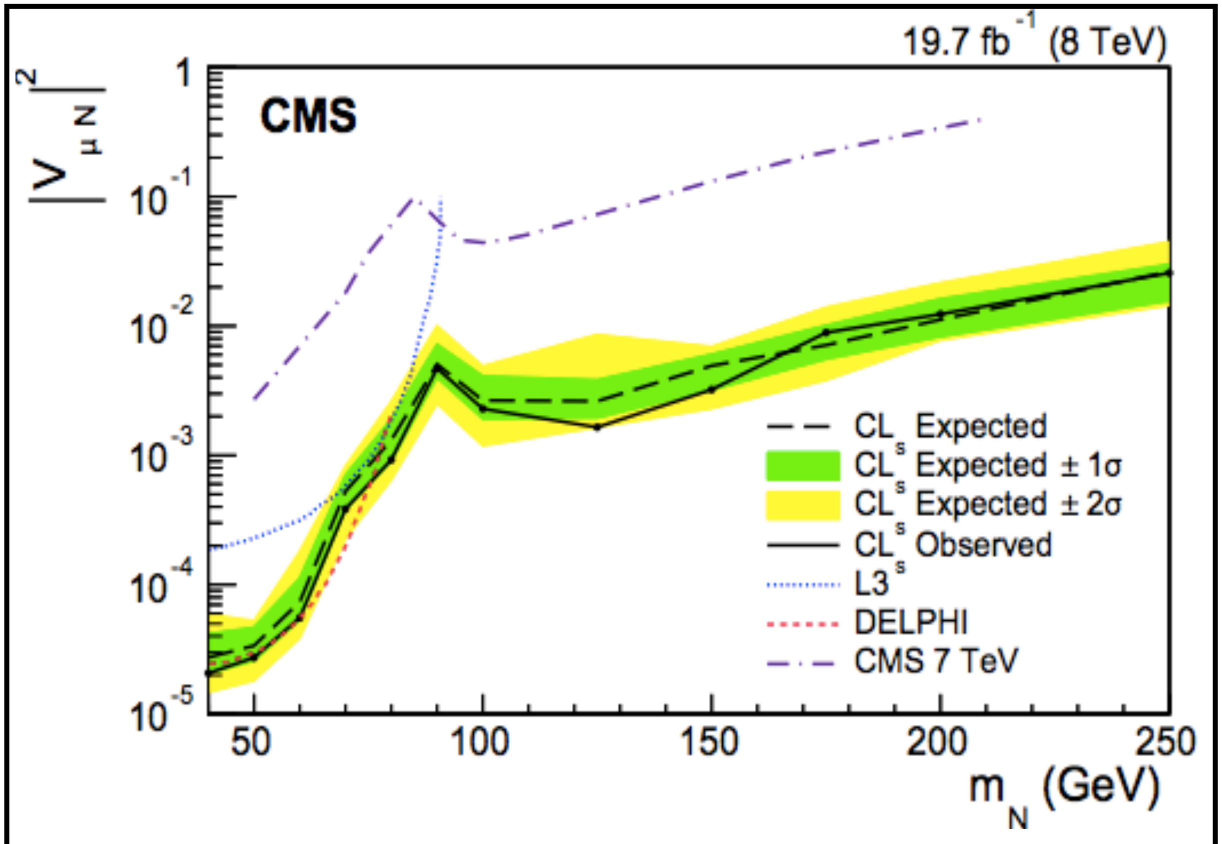
- exotic mediators in Type II, III: not easy to get in string theories

Dienes, March-Russell (1996)

Low Scale Seesaws

- New particles:
  - Type I seesaw: generally decouple from collider experiments
  - Type II seesaw: $\Delta^{++} \to e^+e^+ \,,\ \mu^+\mu^+ \,,\ \tau^+\tau^+$
  - Type III seesaw: observable displaced vertex Franceschino, Hambye, Strumia,2008
  - 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: $\tan^2\theta_{\mathrm{atm}} \simeq \dfrac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$ Mukhopadhyaya, Roy, Vissani, 1998
  - …..

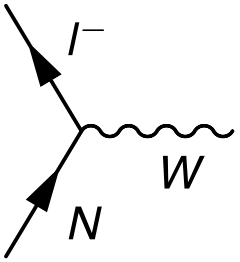
Cautions!!! Is it really the ν_R in Type I seesaw?



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

Talk by E. Tiras

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

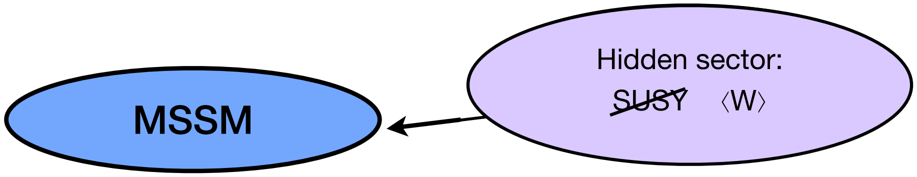
Kersten, Smirnov (2007)

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)

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



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

Giudice, Masiero (1988)

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

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

Dirac Neutrinos and SUSY Breaking

- Simultaneous realization of these two scenarios can arise in MSSM with discrete R symmetries, $\mathbb{Z}_M^R$

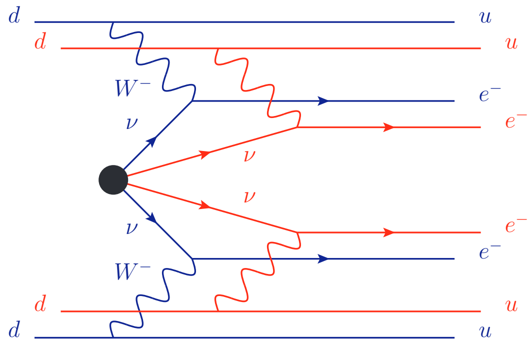
  M.-C. C., M. Ratz, C. Staudt, P. Vaudrevange (2012)

  - **neutrinos are of the Dirac type**, with naturally small masses
  - Δ L = 2 operators forbidden to all orders ⇒ no neutrinoless double beta decay
  - **New signature: lepton number violation ΔL = 4 operators, $(\nu_R)^4$, allowed ⇒ new LNV processes, e.g.**

    M.-C. C., M. Ratz, C. Staudt, P. Vaudrevange (2012)

    - neutrinoless quadruple beta decay

      Heeck, Rodejohann (2013)



- mu term is naturally small, simultaneously
- dangerous proton decay operators forbidden/suppressed
- may simultaneously explain the flavor structure with discrete generation dependent R symmetries (even with non-Abelian!) M.-C.C., M. Ratz, A. Trautner (2013)
- Dynamical generation of RPV operators with size predicted M.-C.C., M. Ratz, V. Takhistov (2014)

Flavor structure

anarchy

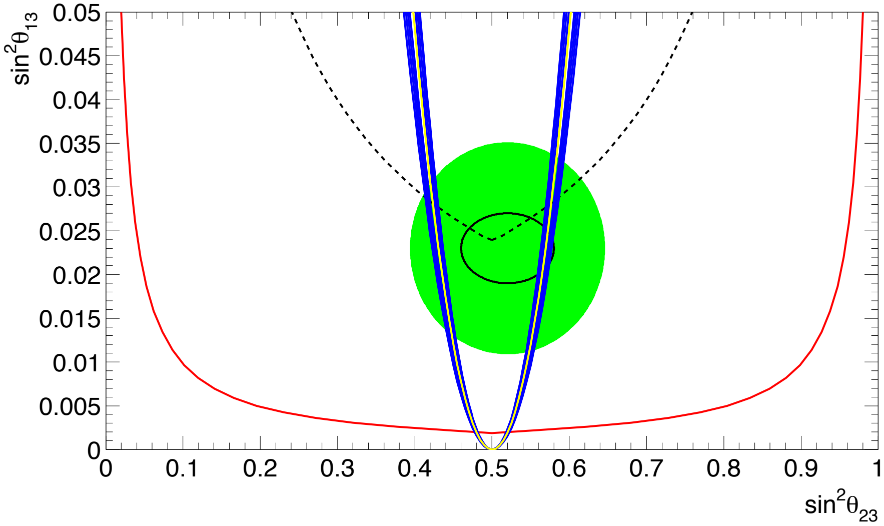
vs

symmetry

Anarchy

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

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



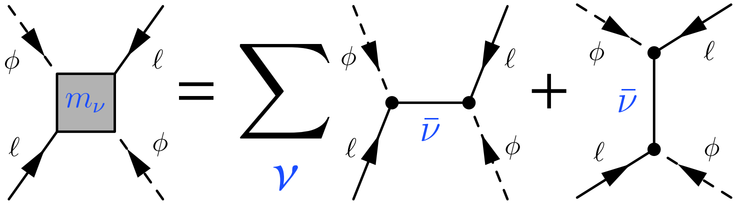
de Gouvea, Murayama (2012)

- 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)

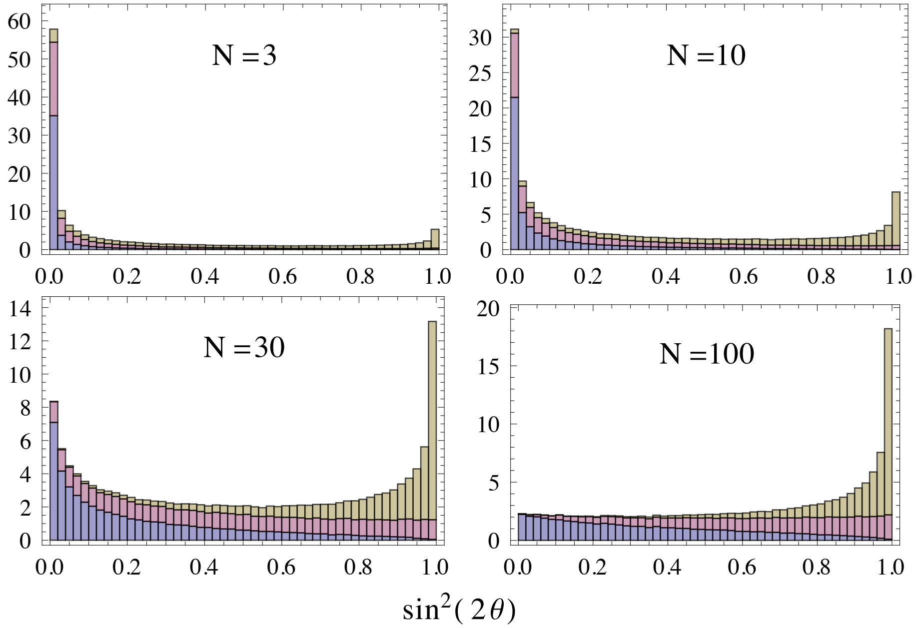


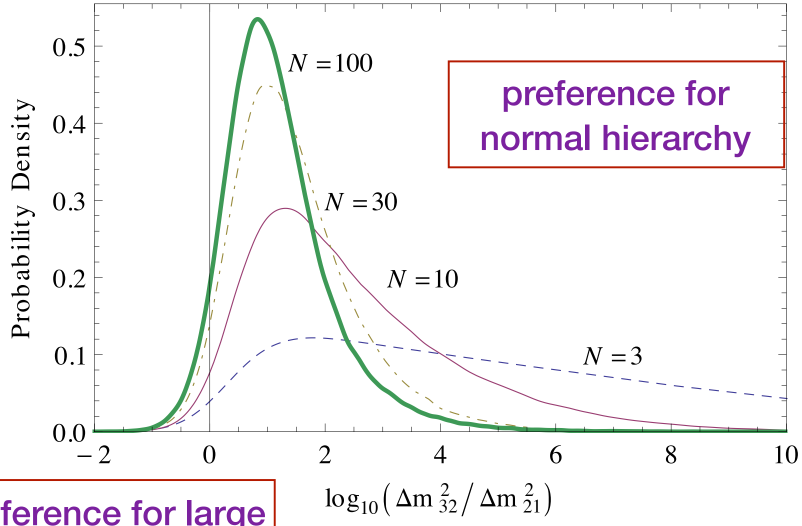
$$m_\nu \sim \frac{v^2}{M_*}$$

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

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

Feldstein, Klemm (2012)



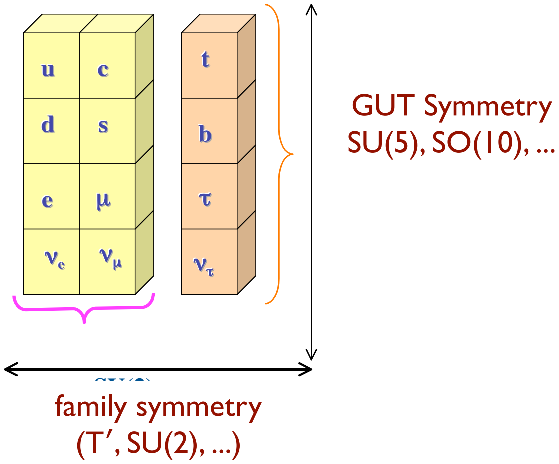


preference for normal hierarchy

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

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

- Latest Global Fit (3σ)

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

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

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

- 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)

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) $\boxed{\theta^q_{23} + \theta^e_{23} \cong 45^o}$ ☜ **slight inconsistent**

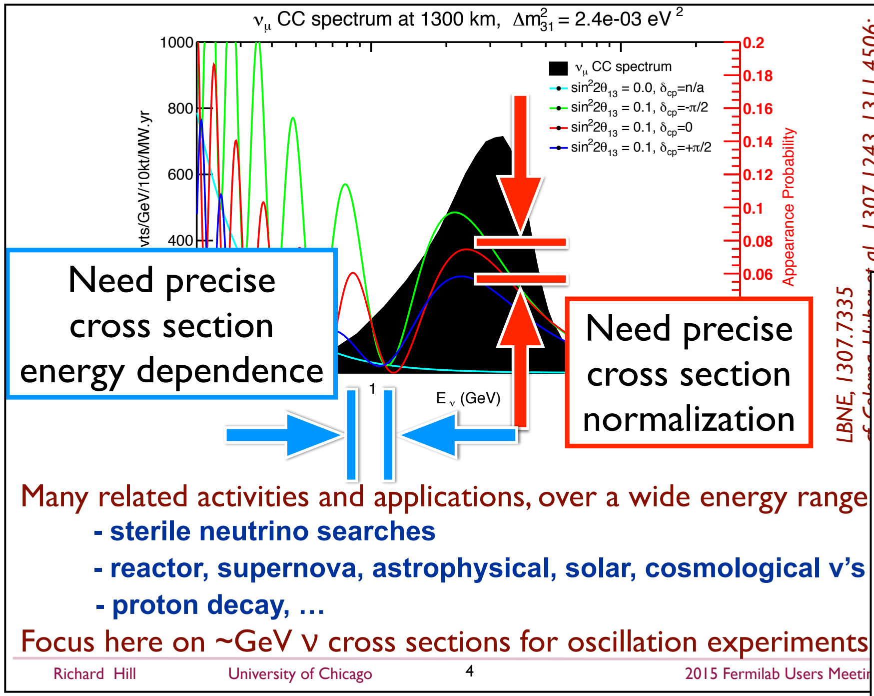
- QLC-II $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_c / 2) * \cos\delta_e$ Ferrandis, Pakvasa; Dutta, Mimura; M.-C.C., Mahanthappa

  (TBM) $\boxed{\theta^e_{13} \cong \theta_c / 3\sqrt{2}}$ ☜ **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



Need precise cross section energy dependence

Need precise cross section normalization

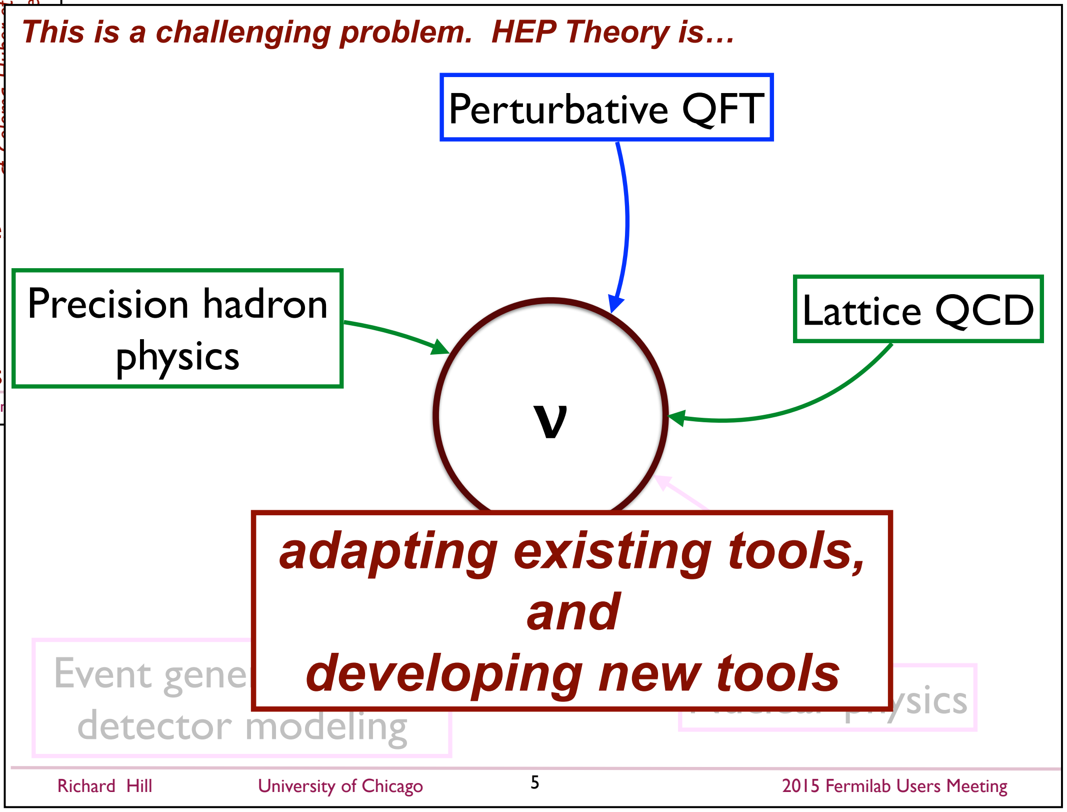
Many related activities and applications, over a wide energy range

- **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 Meetin

HEP Theory can contribute!



This is a challenging problem. HEP Theory is…

Perturbative QFT

Precision hadron physics

Lattice QCD

ν

adapting existing tools, and developing new tools

Event gene detector modeling

ysics

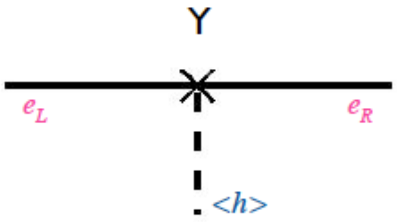
Richard Hill University of Chicago 5 2015 Fermilab Users Meeting

See Talk by Richard Hill

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

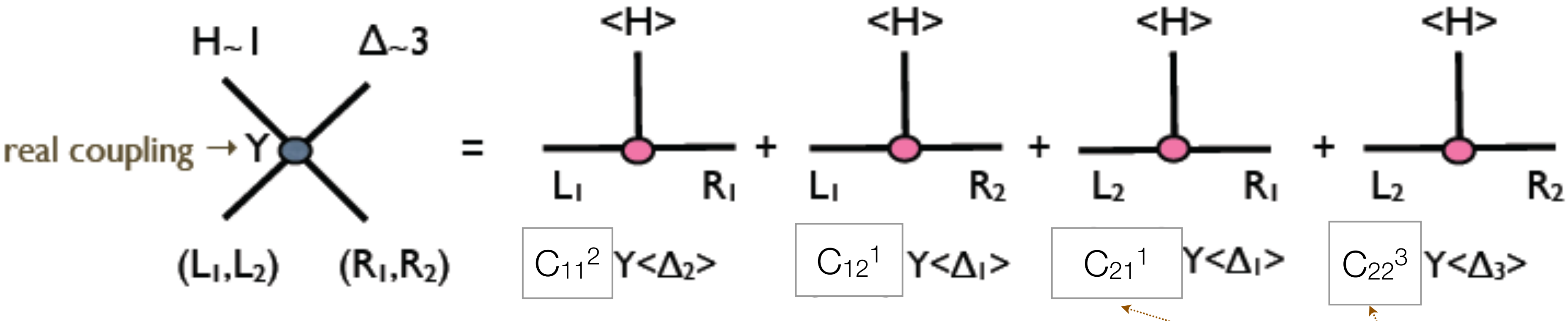
CG coefficients in non-Abelian discrete symmetries
➪ relative strengths and phases in entries of Yukawa matrices
➪ mixing angles and phases (and mass hierarchy)

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 ⇒ $\langle\Delta_1\rangle = \langle\Delta_2\rangle = \langle\Delta_3\rangle \equiv \langle\Delta\rangle$ real
- Complex effective mass matrix: **phases determined by group theory**

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

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

$$\begin{tikzcd}
& \mathcal{L}(x) \arrow[dl, "\text{canonical } \mathcal{CP}"'] \arrow[dd, "\text{outer automorphism } u"] \\
\mathcal{L}'\,(\mathcal{P}x) \arrow[dr, "\text{unitary transformation } U"'] & \\
& \mathcal{L}(\mathcal{P}x)
\end{tikzcd}$$

$$\Phi(x) \xmapsto{\widetilde{\mathcal{CP}}} U_{\mathrm{CP}}\,\Phi^*(\,\mathcal{P}\;x)$$

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

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

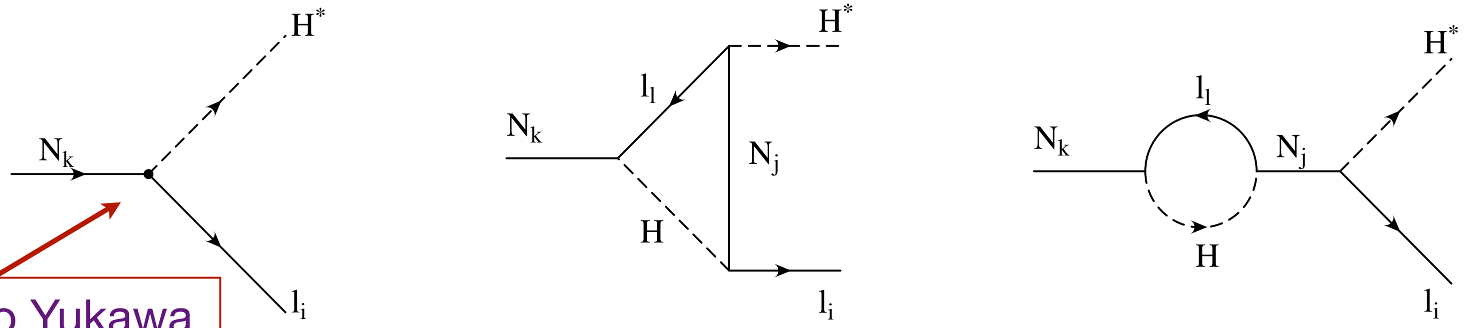
examples: T_7, $\Delta(27)$, …..

Cosmological Connection

Standard Leptogenesis

Fukugita, Yanagida, 1986

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



Neutrino Yukawa coupling

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 ⇒ ΔL ∝ $\left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})\right]$ ≠ 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

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

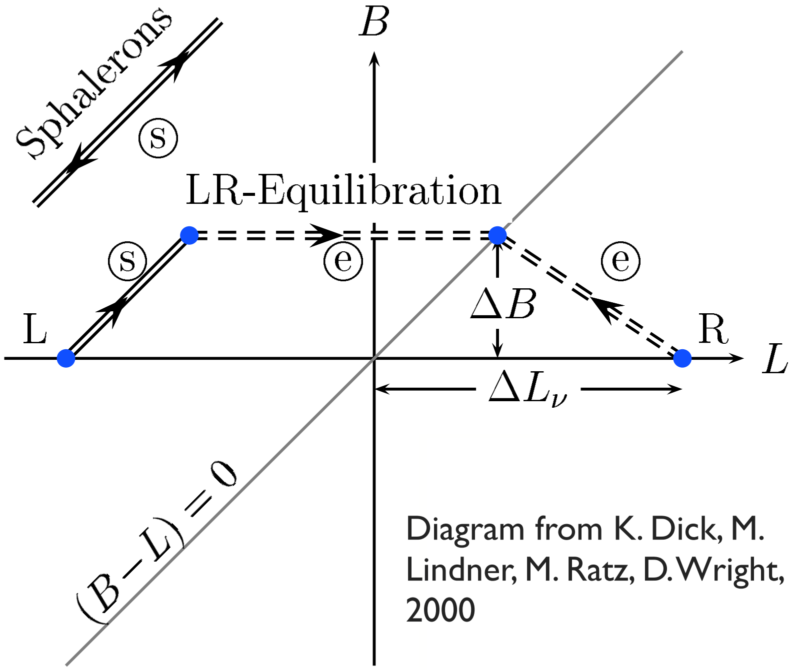


Diagram from K. Dick, M. Lindner, M. Ratz, D. Wright, 2000

Recent progress in Leptogenesis

Toward the Theory of Leptogenesis:

Buchmuller, Fredenhagen, 2000;
Simone, Riotto 2007;
Lindner, Muller 2007

Classical Boltzmann Equations

⬇

Quantum Boltzmann Equations

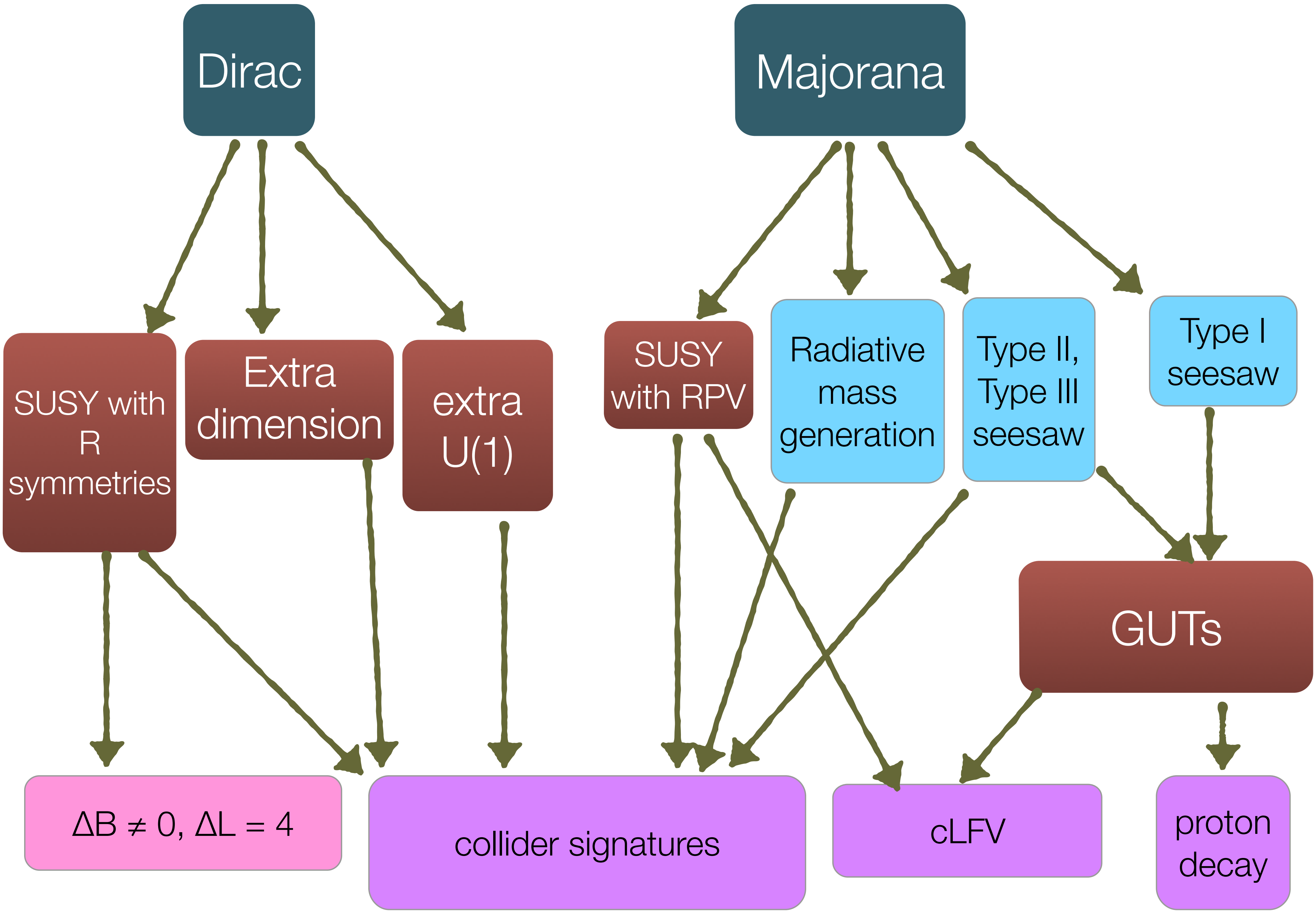
(Closed-time-path formulation for non-equilibrium QFT)

Schwinger, 1961; Mahanthappa, 1962; Bakshi, Mahanthappa, 1963; Keldysh, 1965

Lots of progress, both quantitatively and qualitatively; still too early to see how big the impacts are

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