Origin of the Neutrino Mass and the LHC

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Neutrino Mass beyond the SM

- SM: effective low energy theory with non-renormalizable terms
- new physics effects suppressed by powers of small parameter $\frac{M_W}{M}$
- neutrino masses generated by dim-5 operators

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

λ_{ij} are dimensionless couplings; M is some high scale

- m_ν small: non-renormalizable terms (M is high)

lowest higher dimensional operator that probes new physics

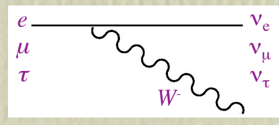
- total lepton number and family lepton numbers broken
  - ➡ lepton mixing and CP violation expected
  - ➡ $\mu \to e \gamma$; $\tau \to \mu \gamma$; $\tau \to e \gamma$ decays ; μ - e conversion
  - ➡ neutrinos are Majorana fermions

Parameters for 3 Light Neutrinos

- three neutrino mixing $\nu_{\ell L} = \sum_{j=1}^{3} U_{\ell j} \nu_{jL} \quad \ell = e,\ \mu,\ \tau$

- mismatch between weak and mass eigenstates

$$\mathcal{L}_{cc} = (\ \overline{\nu}_1, \quad \overline{\nu}_2, \quad \overline{\nu}_3\ ) \gamma^\mu U^\dagger \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} W^+_\mu$$



$$\nu_{1,\,2,\,3} \longrightarrow m_{1,\,2,\,3}$$

- PMNS matrix

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

$$V = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atm}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

  - Dirac CP-violating phase: $\delta = [0, 2\pi]$
  - Majorana CP-violating phases: $\alpha_{21},\ \alpha_{31}$

Compelling Neutrino Oscillation Evidences

Atmospheric Neutrinos:

SuperKamiokande (up-down asymmetry, L/E, θz dependence of μ-like events)

dominant channel: $\nu_\mu \to \nu_\tau$

next: K2K, MINOS, CNGS (OPERA)

Solar Neutrinos:

Homestake, Kamiomande, SAGE, GALLEX/GNO, SK, SNO, BOREXINO, KamLAND

dominant channel: $\nu_e \to \nu_{\mu,\tau}$

next: BOREXINO, KamLAND, ...

LSND:

dominant channel: $\overline{\nu}_\mu \to \overline{\nu}_e$

MiniBOONE -- negative result (2007)

Current Status of Oscillation Parameters

- oscillation probability: $$P(\nu_a \to \nu_b) = \left|\langle \nu_b | \nu,\ t \rangle\right|^2 \simeq \sin^2 2\theta\ \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$
- 3 neutrinos global analysis: [solar+KamLAND+CHOOZ+atmospheric +K2K+Minos]

Maltoni, Schwetz, Tortola, Valle (updated Sep 2007)

$$\sin^2\theta_{23} = 0.5\ (0.38 - 0.64), \quad \sin^2\theta_{13} = 0\ (< 0.028) \quad \sin^2\theta_{12} = 0.30\ (0.25 - 0.34)$$

$$\Delta m^2_{23} = (2.38^{+0.2}_{-0.16}) \times 10^{-3}\ \mathrm{eV}^2, \quad \Delta m^2_{12} = (8.1 \pm 0.6) \times 10^{-5}\ \mathrm{eV}^2$$

- indication of non-zero θ_{13}:

$$\boxed{\sin^2\theta_{13} = 0.016 \pm 0.010\ (1\sigma)}$$

Fogli, Lisi, Marrone, Palazzo, Rotunno, June 2008

- Tri-bimaximal Neutrino Mixing:

$$\sin^2\theta_{\mathrm{atm,\,TBM}} = 1/2 \qquad \sin\theta_{13,\mathrm{TBM}} = 0.$$

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

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

$$\tan^2\theta_{\odot,\mathrm{exp}} = 0.429$$

new KamLAND result: $\tan\theta^2_{\odot,exp} = 0.47^{+0.06}_{-0.05}$

Discovery phase into precision phase for some oscillation parameters

Neutrino Mass Spectrum

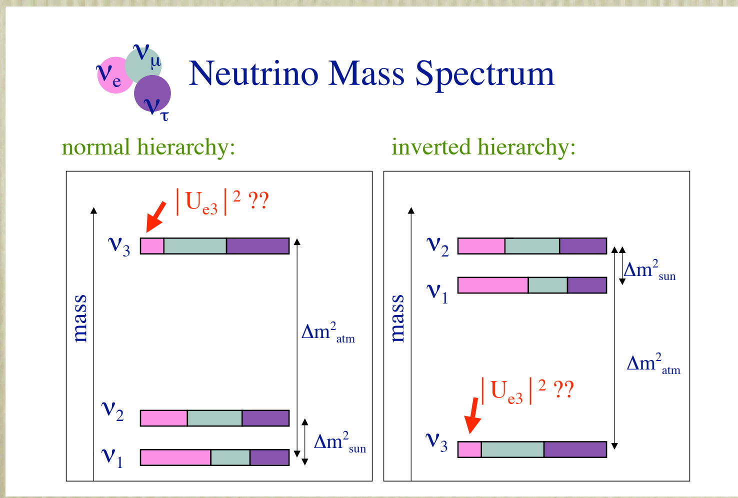
- search for absolute mass scale:
  - end point kinematic of tritium beta decays:

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

Mainz: $m_\nu < 2.2$ eV
KATRIN: increase sensitivity ~ 0.2 eV

  - WMAP + 2dFRGS + Lyα: $\sum(m_{\nu_i}) < (0.7\text{-}1.2)$ eV
  - neutrinoless double beta decay

$$\text{current bound:} \quad |<m>| < (0.19 - 0.68)\ \text{eV} \quad (\text{CUORICINO, Feb 2008})$$



The known unknowns:

- How small is θ_{13}?
- $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?
- Neutrino mass hierarchy (Δm_{13}^2) ?
- CP violation in neutrino oscillations?

Two Theoretical Challenges

- current data post two challenges:
  - why $m_\nu << m_{u,d,l}$
  - why lepton mixing large while quark mixing small

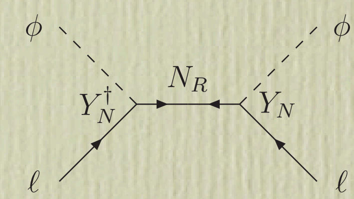
- To answer the first question
  - ✶ Seesaw mechanism: most appealing scenario
  - ✶ can originate from GUT scale physics
  - ✶ can also come from new TeV scale physics

- Seesaw: not sufficient to explain the whole mass matrix with mass hierarchy and two large and one small mixing angles
  - ✶ Flavor Symmetries

Neutrino Mass Generation

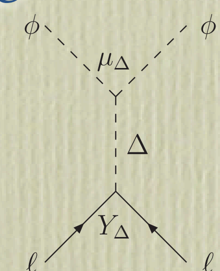
3 ways to generate dim-5 HHLL effective operators

- exchange singlet fermions (1c, 1w, Y=0) [type-I seesaw]



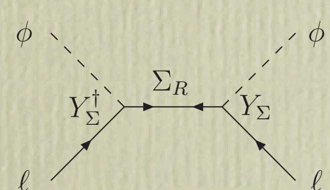
Minkowski, 1977; Yanagida, 1979; Glashow, 1979;
Gell-mann, Ramond, Slansky, 1979;
Mohapatra, Senjanovic, 1979;

- exchange weak triplet scalar (1c, 3w, Y=2) [Type-II seesaw]



Lazarides, 1980; Mohapatra, Senjanovic, 1980

- weak triplet fermions (1c, 3w, Y=0) [type-III seesaw]



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

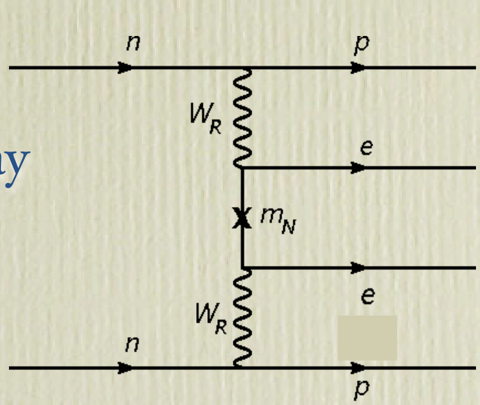
Testing Neutrino Mass Generation Mechanisms

- Naturally small Dirac neutrino masses:
    - extra dimension: through small wave function overlap
    - associated phenomenology in extra dimension
- To test seesaw scenarios for Majorana masses, need to establish
    - Lepton Number Violation $\Delta L = 2$
- Consequences
    - neutrino-less double beta decay:
    - discovery does not imply $m_\nu \neq 0$
    - LR model with low M_R:

      non-zero neutrinoless double beta decay

      even for $y_D,\ m_\nu \to 0$
- Important to have tests @ colliders

Keung, Senjanovic, 1980



GUT Scale Seesaw

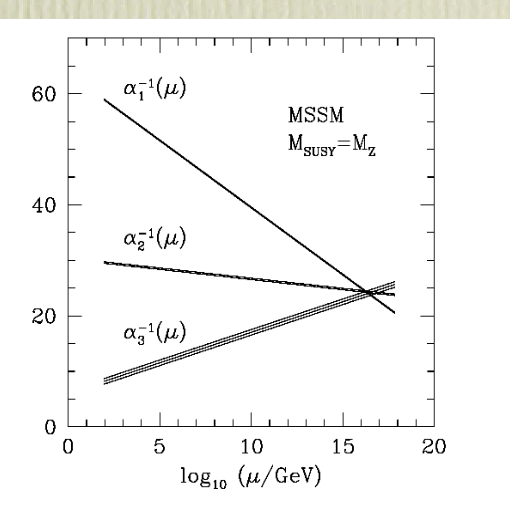
- a natural way to generate small neutrino masses

- Introduce right-handed neutrinos, which are SM gauge singlets
  [predicted in many GUTs, e.g. SO(10)]

- The Lagrangian: $$\mathcal{L}_Y = f_{ij}\overline{e}_{R_i}\ell_{L_j}H^\dagger + h_{ij}\overline{\nu}_{R_i}\ell_{L_j}H - \frac{1}{2}(M_R)_{ij}\overline{\nu}^c_{R_i}\nu_{R_j} + h.c.\ .$$

- integrating out N_R: effective mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad \text{light neutrino mass: } m_\nu \sim \frac{m_D}{M_R} m_D$$



$$m_\nu \sim \sqrt{\Delta m^2_{atm}} \sim 0.05 \text{ eV},\ m_D \sim m_t \sim 172 \text{ GeV}$$

$$\Rightarrow M_R \sim 10^{15}\text{GeV} \quad \sim M_{GUT}$$

seesaw ⇒ Neutrinos are Majorana fermions
⇒ Lepton Number violation

Probing GUT Based Models

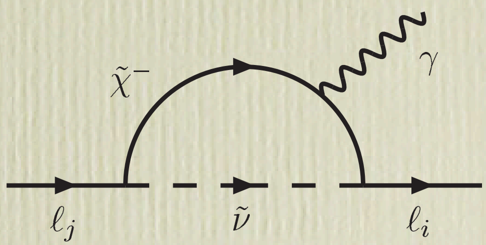
- A direct probe of GUT scale seesaw: LFV charged lepton decays

  ➡ $\mu \to e\,\gamma$; $\tau \to \mu\,\gamma$; $\tau \to e\,\gamma$ decays ; μ - e conversion, etc...

- mSUGRA b.c.'s: slepton mass matrix diagonal at M_{GUT}
- RG induced off-diagonal elements in slepton mass matrices

$$BRji = \frac{\alpha^3}{G_F^2 m_s^8} |(m_{LL}^2)_{ji}|^2 \tan^2\beta,$$

$$(m_{LL}^2)_{ji} = -\frac{1}{8\pi^2} m_0^2 (3 + A_0^2/m_0^2) Y_{jk}^\dagger \log\left(\frac{M_G}{M_k}\right) Y_{ki}.$$



- predictions sensitive to mixing parameters and M_R

Probing GUT Based Models

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

predictions for LFV processes in five viable SUSY SO(10) models:

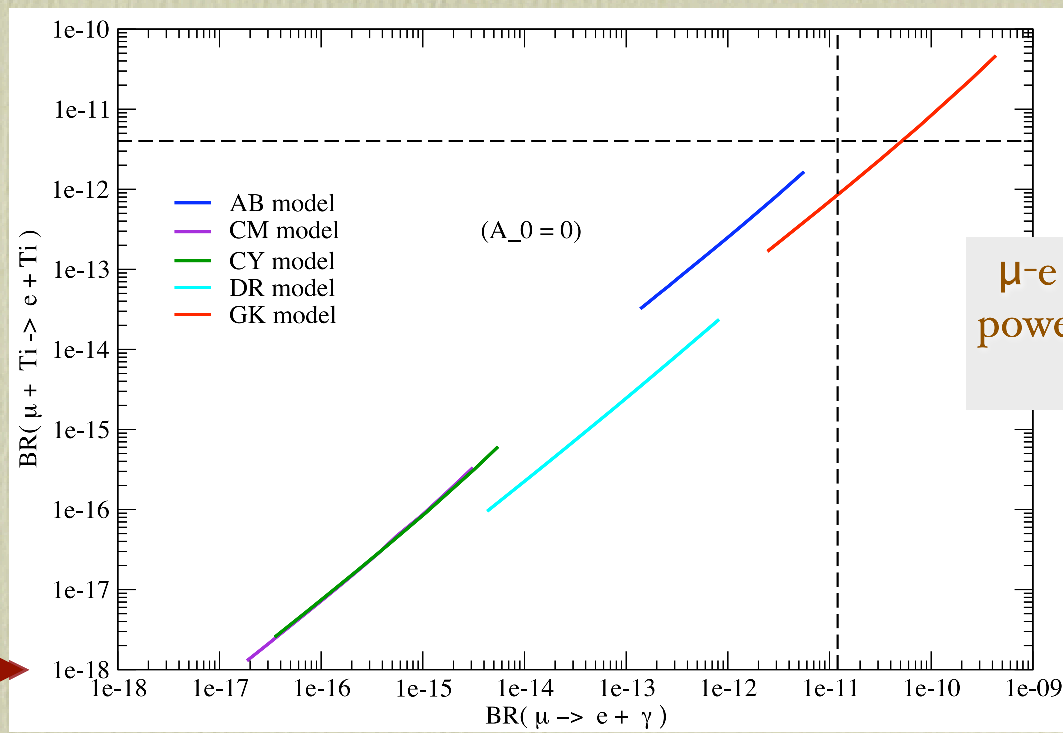
-- assuming MSUGRA boundary conditions
-- including Dark Matter constraints from WMAP

	Models Expt. Limits	$\sin^2\theta_{13}$	M_R's (GeV)	$\tan\beta$	$\lvert A_0/m_0\rvert_{\max}$	BR21($\mu\to e\gamma$) $< 1.2\times10^{-11}$ $\to <10^{-13}$	BR32($\tau\to\mu\gamma$) $< 4.5\times10^{-8}$ $\to <10^{-9}$	BR($\mu+Ti\to e+Ti$) $< 4\times10^{-12}$ $\to <10^{-18}$
Albright & Barr	AB	0.0020 (2.6°)	2.4×10^{14} 4.5×10^{8} 4.5×10^{8}	5	5	$(0.2-9)\times10^{-12}$	$(0.03-1)\times10^{-10}$	$(0.03-2)\times10^{-12}$
M-CC & Mahanthappa	CM	0.013 (6.5°)	7.0×10^{12} 4.5×10^{9} 1.1×10^{7}	10	12	$(0.02-4)\times10^{-15}$	$(0.02-5)\times10^{-11}$	$(0.01-3)\times10^{-16}$
Cai & Yu	CY	0.0029 (3.1°)	2.4×10^{12} 2.4×10^{12} 2.4×10^{12}	10	12	$(0.02-5)\times10^{-15}$	$(0.04-9)\times10^{-13}$	$(0.03-6)\times10^{-16}$
Dermisek & Raby	DR	0.0024 (2.8°)	5.8×10^{13} 9.3×10^{11} 1.1×10^{10}	50	2.5	$(0.05-8)\times10^{-13}$	$(0.02-3)\times10^{-9}$	$(0.01-2)\times10^{-14}$
Grimus & Kuhbock	GK	0.00031 (1.0°)	2.0×10^{15} 4.1×10^{14} 6.7×10^{12}	10	2	$(0.4-80)\times10^{-11}$	$(0.004-1)\times10^{-8}$	$(0.02-5)\times10^{-11}$

prediction sensitive to M_R

LFV Rare Processes

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



μ-e conversion could be powerful in distinguishing different models

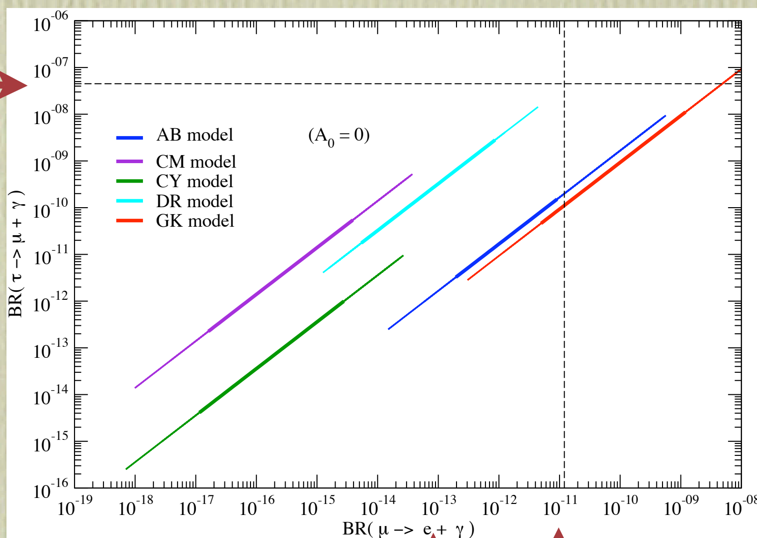
sensitivity of proposed MECO-type exp

reach at MEG

LFV Rare Processes

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

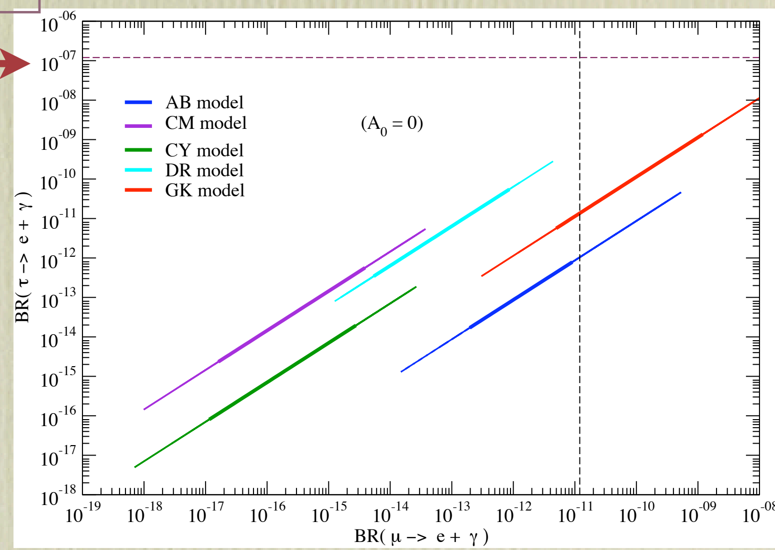
limit from BABAR



reach @ MEG

limit from MEGA

limit from BABAR



LHC: abundant source of tau's

first 3 years low luminosity run ($10 fb^{-1}$)

⇒ improve current limit by an order of magnitude

N.G. Unel, 2005

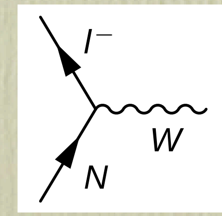
complementary to low energy accelerator based searches

TeV Seesaw without New Interactions

- Assuming no new interaction: small neutrino mass arise with

  $M_R \sim 100 \text{ GeV} \qquad\qquad m_D \sim m_e \sim 10^{-4} \text{ GeV}$

  - not totally unreasonable if small electron Yukawa allowed
  - RH neutrinos may be within reach of LHC/ILC
- only way to test seesaw is by producing RH neutrinos
  - Yukawa ~ O(10^{-6}): irrelevant for colliders
  - RH neutrino production: gauge interaction in the presence of heavy-light mixing; naively,



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

- Observable at colliders: require mixing $V > 0.01$

Han, Zhang, 06; del Aguila, Aguila-Saavedra, Pittau, 06; Bray, Lee, Pilaftsis, 07

TeV Seesaw without New Interactions

- Neutrino mass get contributions from different singlet fermions
- neutrino mass small NOT due to seesaw, but cancellation among these contributions

Buchmuller, Wyler '90; Pilaftsis, '92

- universality of weak interaction & Z-width: $V < 0.1$
- cancellation at 10^{-8} level to get 0.1 eV neutrino mass

$$m_\nu^{(i)} \sim |V_{\alpha i}|^2 M_i = 10^7 \text{ eV} \left(\frac{|V_{\alpha i}|}{0.01}\right)^2 \left(\frac{M_i}{100 \text{ GeV}}\right)$$

- with 3 singlets: light neutrino masses vanish if and only if
  - Dirac mass matrix has rank 1

$$m_\mathrm{D} = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix}$$

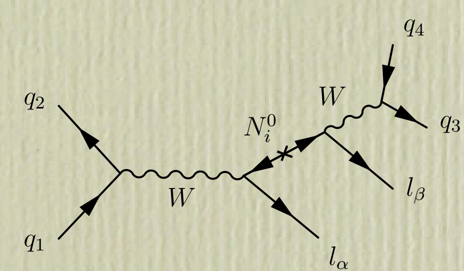
Buchmuller, Greub '91; Ingelman, Rathsman, '93; Heusch, Minkowski, '94; Kersten, Smirnov, '07

  - three contributions add up to zero $\frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$
- Yukawa couplings arbitrary ⇒ allowing large heavy-light mixing

TeV Seesaw without New Interactions

Kersten & Yu Smirnov, 2007

- symmetry justification for such cancellation:
  - L-conservation; discrete subgroups of $U(1)_L$
  - A4
- neutrino masses arise as small perturbations to the cancellation structure
- Collider signatures
  - Lepton Number Violating processes:



$$q\bar{q} \rightarrow l_\alpha^- l_\beta^- + \text{jets}$$

- leading order: $m_\nu=0$ by symmetry (L-conservation) $\Rightarrow \sigma = 0$
- small L-violating effects $\Rightarrow$ small neutrino mass
- unobservable unless fine-tuned

Neutrino mass generation & collider physics decouple

Type-II Seesaw at Colliders

- SU(2) triplet Higgs contribute to neutrino mass $y\Delta LL$

$$M_\nu = \sqrt{2}\, Y_\nu\, v_\Delta, \qquad v_\Delta = \mu\, v_0^2/\sqrt{2}\, M_\Delta^2.$$

μ : custodial symmetry breaking coupling in scalar potential $H\Delta H^\dagger$

need $Y_\nu \mu \sim 10^{-12}$ $\longrightarrow$ $Y_\nu = 1,\ \mu \sim 10^{-12}$ or $Y_\nu \sim \mu \sim 10^{-6}$

- Higgs spectrum after SSB: 7 massive physical higgs bosons

$$H_1,\ H_2,\ A,\ H^\pm, \text{ and } H^{\pm\pm}$$

- Generic predictions: doubly charged Higgs
  - only couple to leptons, not quarks
  - unique signatures: different from SUSY scalar spectrum

$$\Delta^{++} \to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-$$

Type-II Seesaw at Colliders

- current limits on doubly charged Higgs:
  - CDF, D0: > 136 GeV
  - HERA: > 141 GeV
  - muonium-anti-muonium oscillation (PSI):

$$\mathcal{A}_{\mu^+ e^- \to \mu^- e^+} \leq 3G_F \times 10^{-3} \simeq \frac{\sqrt{2} f_{ee} f_{\mu\mu}}{8M_\Delta^2}$$

$$\text{for } f_{ee} \simeq f_{\mu\mu} \simeq 0.1, \; \Rightarrow M_{\Delta^{++}} > 250 \text{ GeV}$$

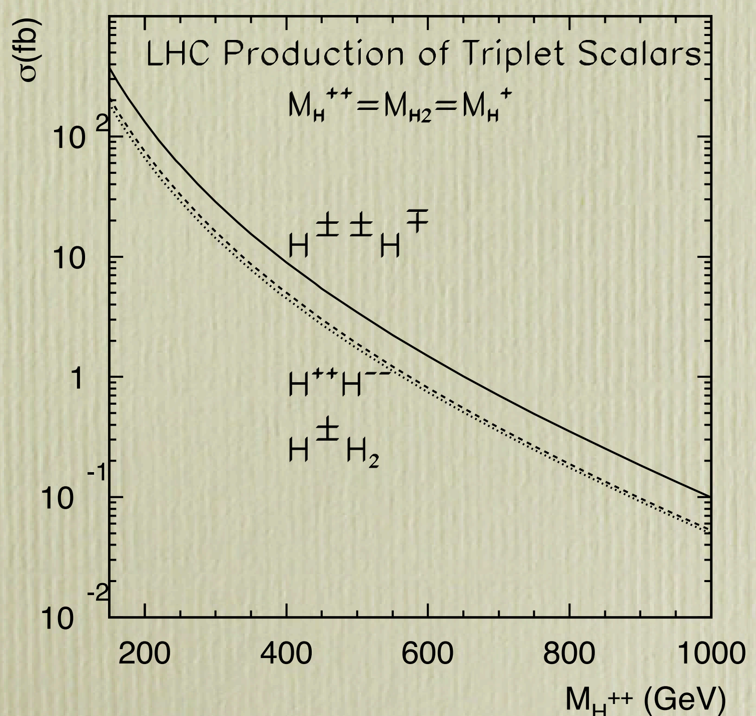
Type-II Seesaw at Collider

Han, Mukhopadhyaya, Si, Wang, ‘07;
Akeroyd, Aoki, Sugiyama, ‘08;
Perez, Han, Huang, Li, Wang, ‘08; ...

- doubly charged Higgs at the LHC:
  - produced through Drell-Yan

$$q\bar{q} \to \gamma^*, Z^* \to H^{++}H^{--}, \qquad q\bar{q}' \to W^* \to H^{\pm\pm}H^{\mp}.$$

Perez, Han, Huang, Li, Wang, ‘08; ...



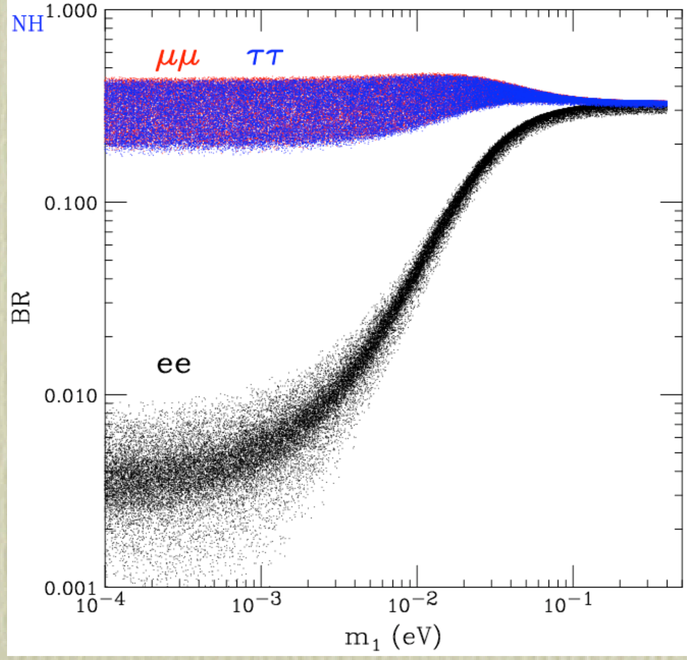
For a mass ~ (200-1000) GeV:
cross-section: 100-0.1 fb

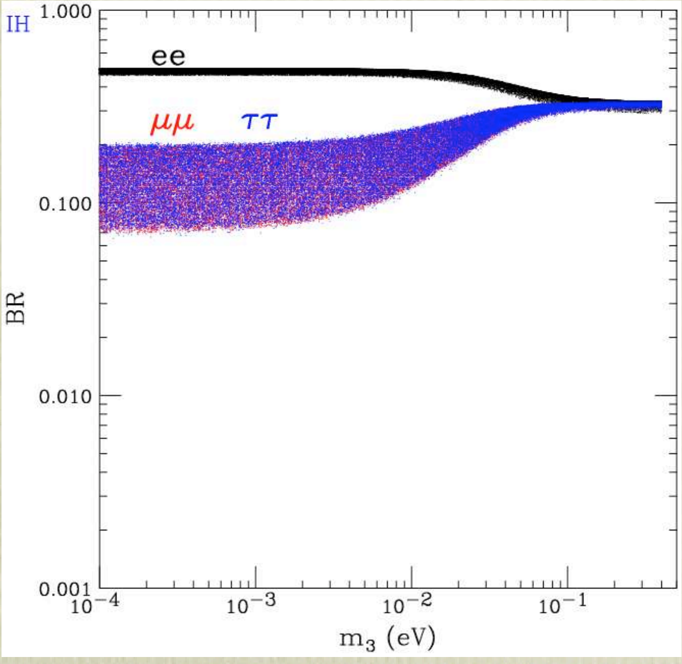
potentially observable rate with high luminosity of 300 fb^{-1} for M_Δ ~ 600 GeV

Type-II Seesaw at Colliders

- distinguishing NH vs IH mass spectra

Perez, Han, Huang, Li, Wang, '08





Spectrum	Relations
NH	$\mathrm{Br}(\tau^+\tau^+)$, $\mathrm{Br}(\mu^+\mu^+) \gg \mathrm{Br}(e^+e^+)$
$\Delta m^2_{31} > 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+)$, $\mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(\tau^+\bar{\nu})$, $\mathrm{Br}(\mu^+\bar{\nu}) \gg \mathrm{Br}(e^+\bar{\nu})$
IH	$\mathrm{Br}(e^+e^+) > \mathrm{Br}(\mu^+\mu^+)$, $\mathrm{Br}(\tau^+\tau^+)$
$\Delta m^2_{31} < 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+)$, $\mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(e^+\bar{\nu}) > \mathrm{Br}(\mu^+\bar{\nu})$, $\mathrm{Br}(\tau^+\bar{\nu})$
QD	$\mathrm{Br}(e^+e^+) \approx \mathrm{Br}(\mu^+\mu^+) \approx \mathrm{Br}(\tau^+\tau^+)$
	$\mathrm{Br}(\mu^+\tau^+) \approx \mathrm{Br}(e^+\tau^+) \approx \mathrm{Br}(e^+\mu^+)$ (suppressed)
	$\mathrm{Br}(e^+\bar{\nu}) \approx \mathrm{Br}(\mu^+\bar{\nu}) \approx \mathrm{Br}(\tau^+\bar{\nu})$

TeV Seesaw with New Interactions

- new gauge interactions RH neutrinos participate:
- seesaw mechanism may be tested even for small heavy-light mixing
- an example is the left-right $SU(2)_L$ x $SU(2)_R$ symmetric model
- particle content

Pati, Salam, 74; Mohapatra, Pati, 75; Mohapatra, Senjanovic, 75

  - fermions:

$$Q_{i,L} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,L} \sim (1/2, 0, 1/3), \qquad Q_{i,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{i,R} \sim (0, 1/2, 1/3)$$

$$L_{i,L} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,L} \sim (1/2, 0, -1), \qquad L_{i,R} = \begin{pmatrix} e \\ \nu \end{pmatrix}_{i,R} \sim (0, 1/2, -1)$$

  - scalars:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (1/2,\ 1/2,\ 0) \qquad \Delta_L = \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix} \sim (1,\ 0,\ 2) \qquad \Delta_R = \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix} \sim (0,\ 1,\ 2)$$

- upon LR symmetry breaking: neutrino masses generated
- type-I + type-II contribution

$$m_\nu = f v_L - \frac{y^2 v^2}{f v_R}$$

Left-Right Model

- Left-right Model attractive:
  - Parity restoration

    Pati, Salam, 74; Mohapatra, Pati, 75; Mohapatra, Senjanovic, 75
  - solution to the strong CP problem
  - if CP broken spontaneously through complex VEV, connection between leptogenesis and low energy leptonic CPV processes (neutrino oscillation, neutrinoless double decay, ...) possible

    M-CC & Mahanthappa, 05

Left-Right Model

- TeV scale LR model:
  - neutrino mass
    - preferred SUSY vacuum: preserved R-parity, break P

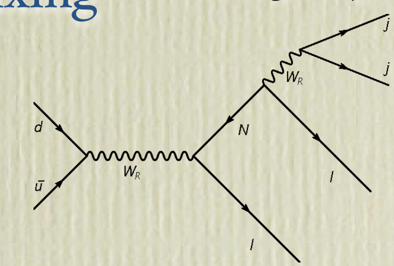
      $$v_R \neq 0,\ v_L = 0$$

    - small neutrino mass with TeV W_R and Yukawa y ~ 10^{-6}
  - W_R & Z' at LHC
  - production independent of light-heavy mixing
  - signal:

    $$pp \to \mu^+\mu^+ jj + X$$

  - very small background
  - current limit from D0 & CDF: M_{W_R} > 780 GeV
  - LHC can easily probe W_R up to (3-4) TeV and ν_R in (100-1000) GeV range

Keung, Senjanovic, '83



Azuleos et al 06; del Aguila et al 07, Han et al 07; Chao, Luo, Xing, Zhou, '08; ...

Left-Right Model

Mohapatra, Okada, Yu, 07
Setzer, Spinner, Mohapatra, 08

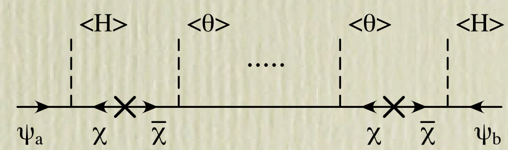
- High Scale SUSY Left-right Model
  - $M_R \sim 10^{11} - 10^{12}$ GeV
  - if SUSY broken by Anomaly Mediation
    - TeV scale triplet Higgs to avoid electric charge non-conservation

TeV Scale Seesaw with $U(1)_{NA}$

M.-C.C, A. de Gouvea, B. Dobrescu, 2006

- gauge symmetry SM x non-anomalous $U(1)_\nu$ + N ν_R
- SM particles & ν_R : all charged under U(1)
- U(1) forbids dim-4, dim-5 operators
- To get $m_\nu \neq 0$: $\cancel{U(1)}_\nu$ $\langle\phi\rangle$: SM singlet breaks $U(1)_\nu$

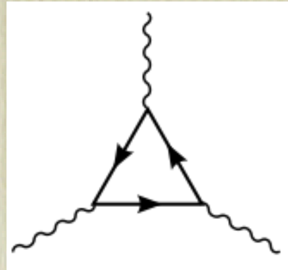
$$\frac{HH\ell\ell}{M}\left(\frac{\langle\phi\rangle}{\Lambda}\right)^p \quad , \quad p \quad \text{large} \qquad \langle\phi\rangle < \Lambda, \qquad \frac{\langle\phi\rangle}{\Lambda} \sim 10^{-1}$$



- non-anomalous $U(1)_\nu$ $\boxed{\Lambda \sim \text{TeV!}}$
  - anomaly cancellation conditions ⇒ constraints on U(1) charges
  - generation dependent charges ⇒ U(1) flavor symmetry

    ⇒ mixing pattern & mass hierarchy (FN)
  - TeV cutoff possible with 3 RH neutrinos
  - light sterile neutrinos: DM candidate
  - TeV scale Z': probing flavor sector at colliders

Non-anomalous v.s. Anomalous U(1)



- anomaly cancellations: relating charges of different fermions
  - $[U(1)]^3$ condition generally difficult to solve
- most models utilized anomalous U(1):
  - mixed anomaly: cancelled by Green-Schwarz mechanism
  - $[U(1)]^3$ anomaly: cancelled by exotic fields besides RH neutrinos
  - U(1) broken at fundamental string scale

constraints not as stringent

  - earlier claim that U(1) has to be anomalous to be compatible with SU(5) while giving rise to realistic fermion mass and mixing patterns L.E. Ibanez, G.G. Ross 1994
- non-anomalous U(1) can be compatible with SUSY SU(5) while giving rise to realistic fermion mass and mixing patterns
  - no exotics other than 3 RH neutrinos M.-C.C, D.R.T. Jones, A. Rajaraman, H.B. Yu, 2008
  - U(1) also forbids Higgs-mediated proton decay

TeV Scale Seesaw

M.-C.C, A. de Gouvea, B. Dobrescu, 2006

- "Leptocratic model" with 3 ν_R: N_1, N_2, N_3
  - ❖ "Orwellian Leptocratic" model:
    - all $U(1)_{NA}$ charges for SM fermions are generation independent: no charged lepton flavor violating FCNC mediated by Z' at tree level
    - $Q(N_2) = Q(N_3) \neq Q(N_1)$
    - bi-large mixing through anarchy
    - three active neutrinos: can either be Dirac or Majorana fermions
    - three light sterile neutrinos: two heavy ones (1keV ~ 1MeV) & one ultra light (10^{-9} eV)
    - active-sterile neutrino mixing: $< 10^{-3}$
  - ❖ "2+1 leptocratic": allowed lepton doublets to have generation dependent $U(1)_{NA}$ charges
    - bi-large mixing from $U(1)_{NA}$

TeV Scale Seesaw

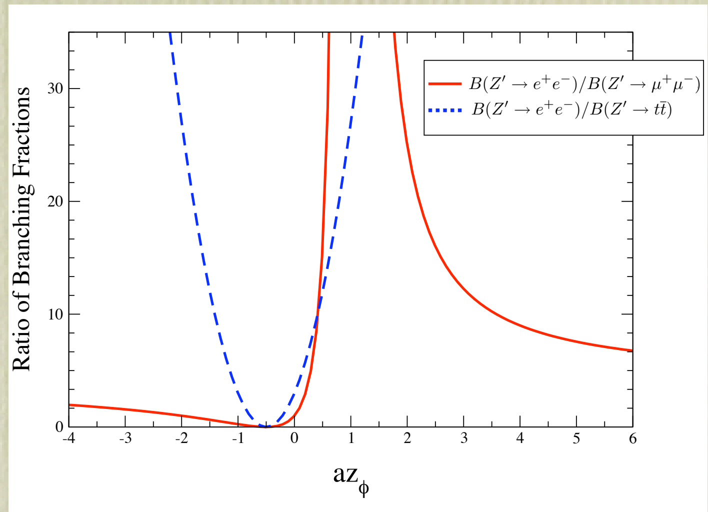
M.-C.C, A. de Gouvea, B. Dobrescu, 2006

- probing the flavor sector at the colliders
- (2+1) leptocratic models

$$\frac{B\left(Z' \to e^+e^-\right)}{B\left(Z' \to \mu^+\mu^-\right)} = \left(\frac{1+2az_\phi}{1-az_\phi}\right)^2$$

$$\frac{B\left(Z' \to e^+e^-\right)}{B\left(Z' \to t\bar{t}\right)} = 3\left(1+2az_\phi\right)^2$$

$$z_\phi = -\frac{3(a+b)}{a^2+ab+b^2}$$



- invisible decays of Z': distinguish different U(1)
  - $U(1)_{B-L}$: B(Z' ⟶ invisible) = 3/8
  - Orwellian Z': B(Z' ⟶ invisible) = 6/7

Conclusion

- conventional GUT scale seesaw:
  - can be tested through LFV searches
  - LHC useful for tau decays
- TeV scale seesaw without new interactions
  - type-I seesaw:
    - cancellation required
    - LNV processes - small perturbation that generate small neutrino mass ⇒ decouple from collider physics
  - type-II seesaw:
    - TeV doubly charged Higgs⇔small couplings (unnatural?)
    - unique signature: $\Delta^{++} \to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-$
    - doubly charged Higgs produced through gauge interaction (independent of light-heavy mixing)
    - 300 fb^{-1} for $M_\Delta \sim 600$ GeV

Conclusion

- TeV Scale Seesaw with new interactions
  - SUSY Left-right model:
    - TeV scale $W_R \Leftrightarrow$ small Yukawa
    - tested via searches for W_R
    - production independent of light-heavy mixing
    - LHC: W_R up to (3-4) TeV , ν_R in (100-1000) GeV range
  - $U(1)_{NA}$ model:
    - TeV cutoff naturally arise
    - anomaly cancellations: constraints on charges, predict flavor structure
    - TeV scale seesaw possible for 3 RH neutrinos
    - measuring Z' decay: can probe the flavor sector at colliders