Neutrino Masses from TeV Scale New Physics

-- Tests of Neutrino Masses at the LHC

Mu-Chun Chen, University of California at Irvine

GGI What’s Nu?, June 26, 2012

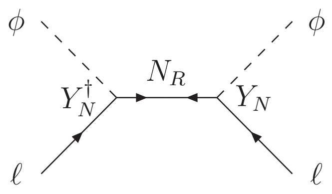
Theoretical Challenges

(i) Absolute mass scale: Why $m_\nu << m_{u,d,e}$?

- seesaw mechanism: most appealing scenario ⇒ Majorana
- UV completions of Weinberg operators HHLL
  - Type-I seesaw: exchange of singlet fermions

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

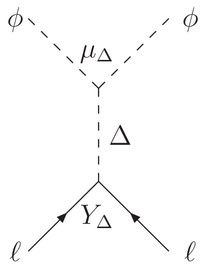
N_R: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,1,0)$



  - Type-II seesaw: exchange of weak triplet scalar

Lazarides, 1980; Mohapatra, Senjanovic, 1980

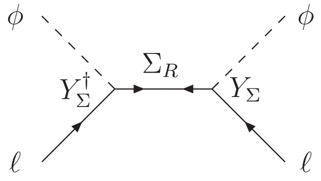
Δ: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,3,2)$



  - Type-III seesaw: exchange of weak triplet fermion

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

Σ_R: $SU(3)_c \times SU(2)_w \times U(1)_Y \sim (1,3,0)$



Theoretical Challenges

For a recent review on TeV scale seesaw:
M.-C. C., J.R. Huang, arXiv:1105.3188

(i) Absolute mass scale: Why $m_\nu << m_{u,d,e}$?

- seesaw mechanism: most appealing scenario ⇒ Majorana
  - can originate from GUT scale Physics:
    - indirect probe through LFV processes at colliders
  - seesaw scale can also be at TeV (if yukawa ~ 10^{-6} allowed)
    - type II, III, inverse seesaw, ...
- TeV scale new physics ⇒ Dirac or Majorana
  - extra dimension: through small wave function overlap
    - associated phenomenology in extra dimension [Talk by Renata Zukanovich-Funchal]
  - extra U(1)' gauge symmetry
    - associated Z' phenomenology
  - Discrete R-Symmetries
    - simultaneous solution to mu problem and small Dirac mass

Theoretical Challenges

(ii) Flavor Structure: Why neutrino mixing large while quark mixing small?

- seesaw doesn't explain entire mass matrix w/ 2 large, 1 small mixing angles
- family symmetry: there's a structure, expansion parameter (~~symmetry~~ effect)
  - mixing result from dynamics of underlying symmetry
  - if symmetry breaking at TeV ⇒ signatures at colliders
  - with SUSY: superpartners charged under family symmetry, can probe (indirectly) flavor sector even for high symmetry breaking scale

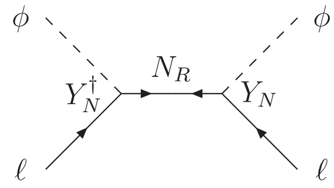
Type-I Seesaw at Colliders

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

- assuming no new interaction: small neutrino mass from

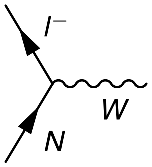
$$M_R \sim 100\ \text{GeV} \qquad m_D \sim m_e \sim 10^{-4}\ \text{GeV}$$

  - same level of “un-naturalness” if small electron Yukawa allowed
  - RH neutrino may be within reach of LHC



N_R: $SU(3)_C \times SU(2)_W \times U(1)_Y \sim (1,1,0)$

- Only way to test seesaw is by producing RH neutrinos
  - Yukawa ~ $O(10^{-6})$: irrelevant for colliders
  - RH neutrino production: gauge interaction through heavy-light mixing



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

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

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

Type-I Seesaw at Colliders

- 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

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

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

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

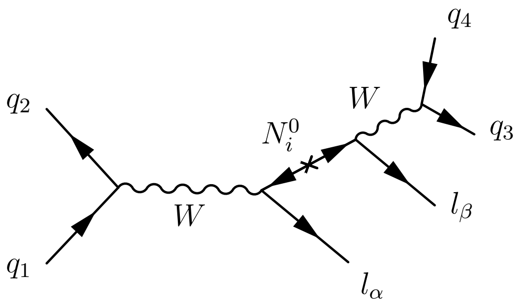
Type-I Seesaw at Colliders

- symmetry justification for such cancellation:

Kersten, Smirnov, 2007

  - L-conservation; discrete subgroups of $U(1)_L$
  - A4, S3
- neutrino masses arise as small perturbations to the cancellation structure
- Collider signatures
  - Lepton Number Violating processes:

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



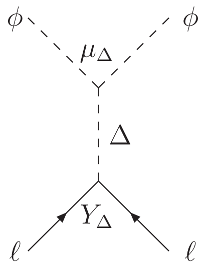
  - leading order: m_ν=0 by symmetry (L-conservation)
  - small L-violating effects ⇒ small neutrino mass
  - unobservable unless fine-tuned

Neutrino mass generation & collider physics decouple

Type-II Seesaw at Colliders

Lazarides, 1980; Mohapatra, Senjanovic, 1980

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



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

$$\text{need } Y_\nu \mu \sim 10^{-12} \qquad v_\Delta = \mu\, v_0^2/\sqrt{2}\, M_\Delta^2,$$

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

$$M_\nu = \sqrt{2}\, Y_\nu\, v_\Delta, \quad \longrightarrow \quad Y_\nu = 1,\ \mu \sim 10^{-12} \text{ or } Y_\nu \sim \mu \sim 10^{-6}$$

- 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

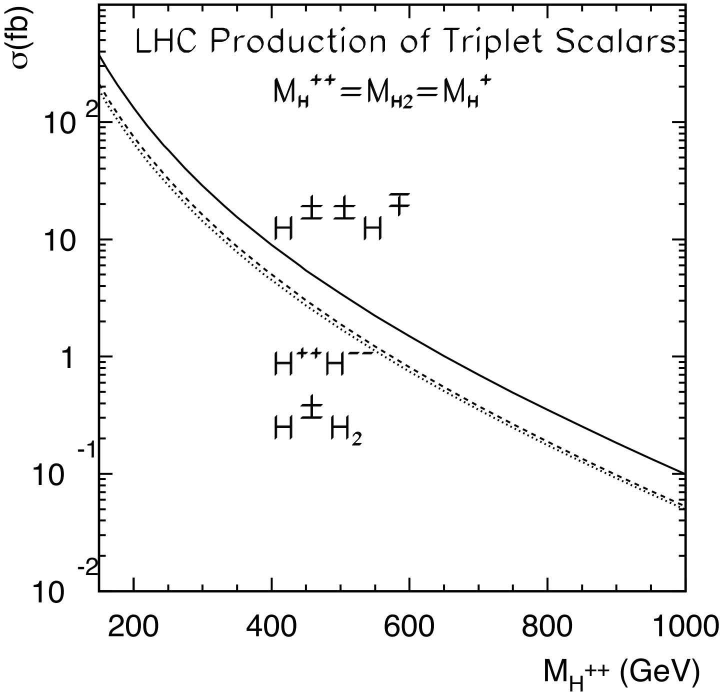
$$\Delta^{++} \rightarrow e^+e^+,\ \mu^+\mu^+,\ \tau^+\tau^+$$

Type-II Seesaw at Colliders

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

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

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



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

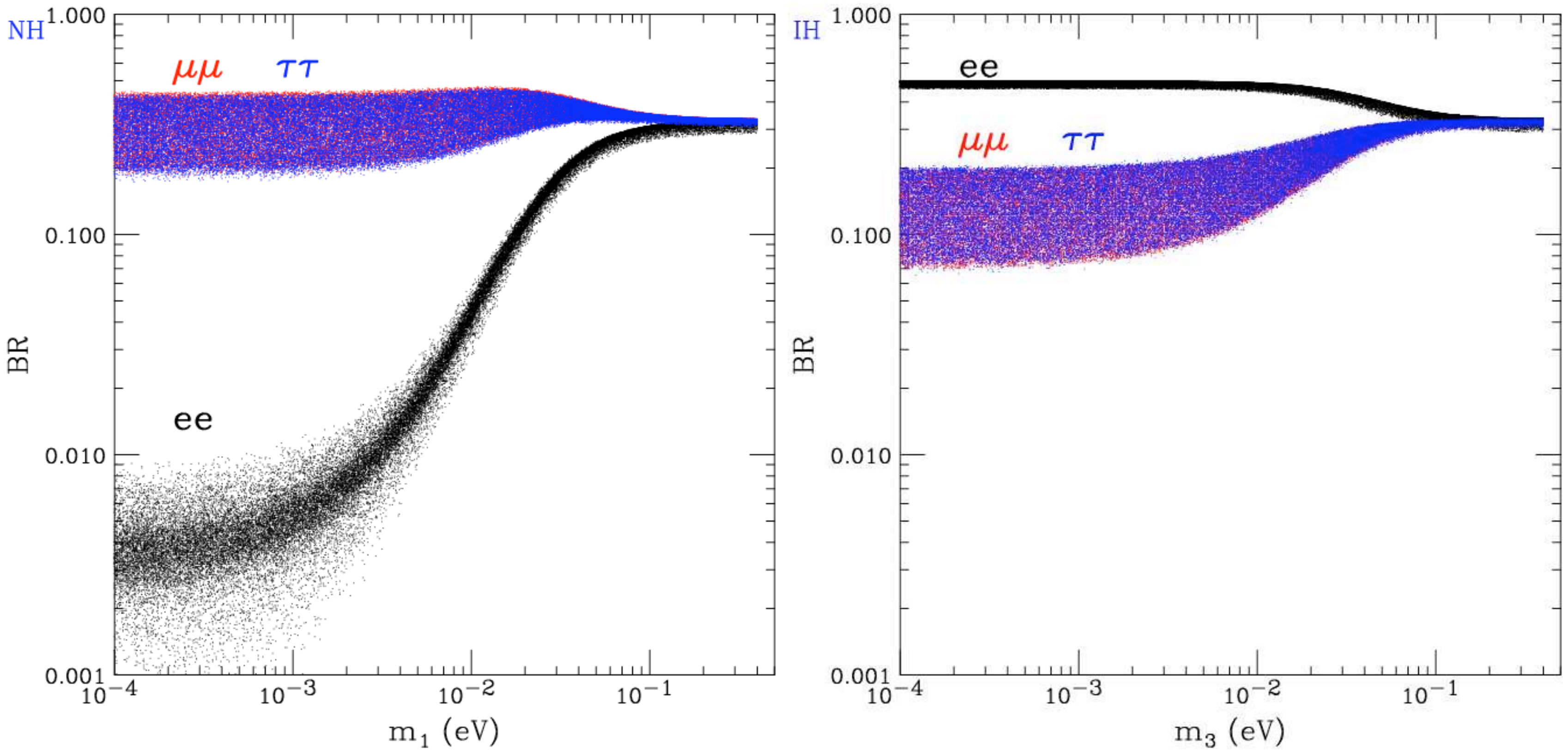
For a mass ~ (200-1000) GeV:
cross-section: 100-0.1 fb

potentially observable rate with high luminosity of 300 fb^{-1} for $M_\Delta \sim 600$ GeV

Type-II Seesaw at Colliders

- distinguishing NH vs IH mass spectra

Perez, Han, Huang, Li, Wang, ‘08



Type-II Seesaw at Colliders

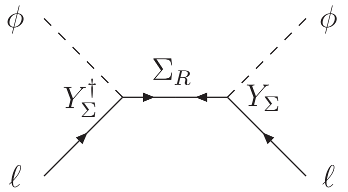
Perez, Han, Huang, Li, Wang, '08

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

Type-III Seesaw at Colliders

- Type-III seesaw: exchange of weak triplet fermion with Y = 0

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



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

Σ_R: $SU(3)_C \times SU(2)_W \times U(1)_Y \sim (1,3,0)$

- small neutrino mass with TeV Σ_R and Yukawa y ~ 10^{-6}

- triplet fermion produced through gauge (weak) interaction

Franceschino, Hambye, Strumia,2008

$$pp \to \Sigma^0\Sigma^+ \to \overline{\nu} W^+ W^\pm \ell^\mp \to 4\ \text{jets} + \not{E}_T + \ell$$

- TeV scale triplet decay : observable displaced vertex

$$\tau \leq 1\ \text{mm} \times \left(\frac{0.05\ \text{eV}}{\sum_i m_i}\right)\left(\frac{100\ \text{GeV}}{\Lambda}\right)^2$$

- neutral component Σ^0 can be dark matter candidate

E. J. Chun, 2009

Inverse Seesaw

- additional singlets S: in $(\nu_L,\ \nu_R,\ S)$ basis

Mohapatra,1986; Mohapatra, Valle, 1986;
Gonzalez-Garcia, Valle, 1989

$$M_\nu = \begin{pmatrix} 0 & M_{\rm D} & 0 \\ M_{\rm D}^T & 0 & M_{\rm NS} \\ 0 & M_{\rm NS} & M_{\rm S} \end{pmatrix}$$

- effective mass

$$M_{\rm eff} \simeq (M_{\rm D} M_{\rm NS}^{-1}) M_{\rm S} (M_{\rm D} M_{\rm NS}^{-1})^T$$

with

$$M_{\rm NS} \sim \mathcal{O}(1\ \text{TeV}),\ M_{\rm D} \sim \mathcal{O}(100\ \text{GeV}) \qquad M_{\rm S} \sim \mathcal{O}(0.1\ \text{keV})$$

- correlation between

Hirsch, Kernreiter, Romao, del Moral, 2010

$$\frac{\text{BR}(\tilde{\chi}_1^\pm \to \tilde{N}_{1+2} + \mu^\pm)}{\text{BR}(\tilde{\chi}_1^\pm \to \tilde{N}_{1+2} + \tau^\pm)} \propto \frac{\text{BR}(\mu \to e + \gamma)}{\text{BR}(\tau \to e + \gamma)}$$

- non-unitarity effects
- enhanced LFV (both SUSY and non-SUSY cases)

Radiative Seesaw

- Zee-Babu Model: neutrino mass at 2 loop

  Zee 1986; Babu, 1989
  - singlet charged SU(2) singlet scalar + doubly charged SU(2) singlet scalar

- neutrino mass at higher loops

  Krauss, Nasri, Trodden, 2003; E. Ma, 2006;
  Aoki, Kanemura, Seto, 2009
  - can be achieved with Z_2 symmetry
  - TeV scale RH neutrinos

- loop particles can also have color charges

  Perez, Han, Spinner, Trenkel, 2011
  - enhanced production cross section

- different models involve different (TeV scale) particles in loops
  - collider phenomenology very model-dependent

TeV Seesaw with New Interactions - LR Symmetry

- 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

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

  - particle content
    - 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

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

TeV Scale Left-Right Model

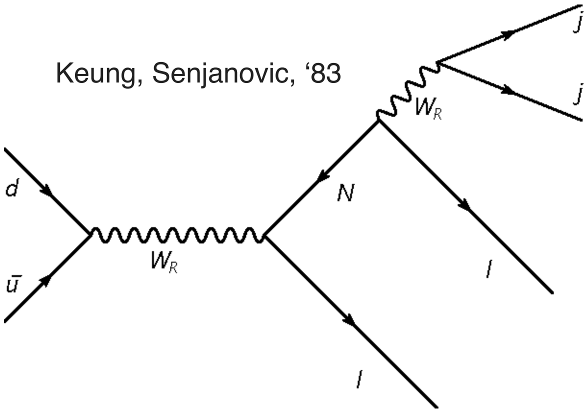
- TeV scale LR model:
  - neutrino mass
    - preferred SUSY vacuum: preserved R-parity, break P

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

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

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

    - 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 v_R in (100-1000) GeV range



Keung, Senjanovic, '83

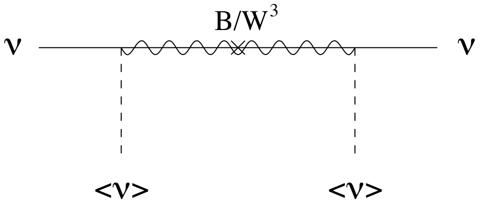
Azuleos et al 06; del Aguila et al 07, Han et al 07; Chao, Luo, Xing, Zhou, '08; ...

TeV Scale Seesaw Model: R-Parity Violation

- MSSM with bi-linear R-Parity Violation Kaplan, Nelson, 1999

$$\mathcal{W}_R = \epsilon_i \hat{L}_i \hat{H}_u$$

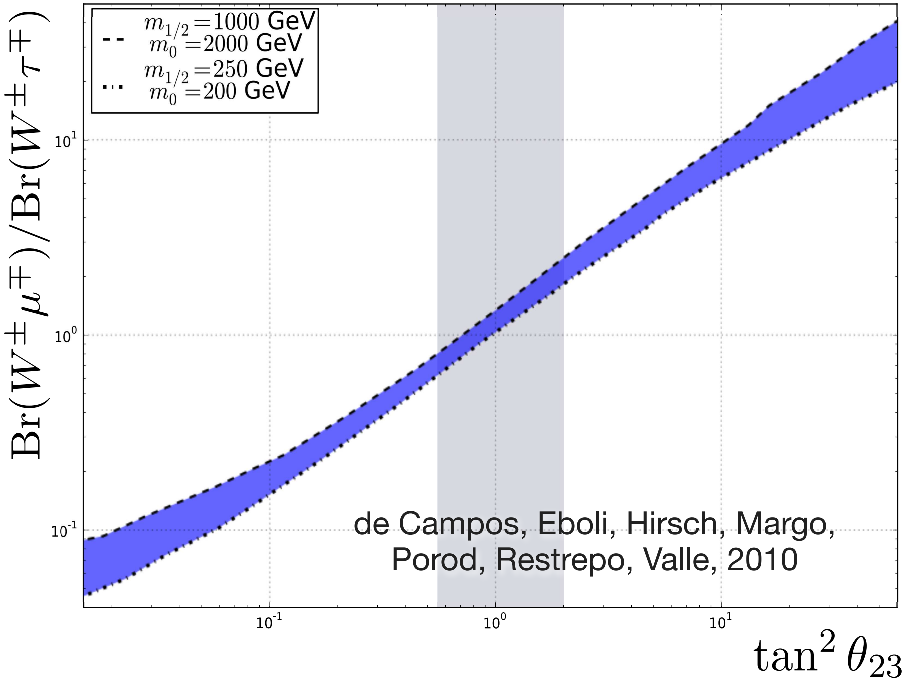
- mass generation for $\Delta m_{\rm atm}^2$:



- mixing angle ↔ neutralino decay:

Mukhopadhyaya, Roy, Vissani, 1998

$$\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$$



de Campos, Eboli, Hirsch, Margo, Porod, Restrepo, Valle, 2010

Mechanisms Naturally Suppress Neutrino Masses with TeV Scale New Physics

Two examples:

- TeV scale U(1)’ Family Symmetry for quarks and leptons
  - associated Z’ collider phenomenology
- Discrete R-Symmetry in SUSY
  - simultaneous solution to mu problem, proton decay problem, naturally suppressed Dirac neutrino mass

TeV Scale Seesaw and Non-anomalous U(1)

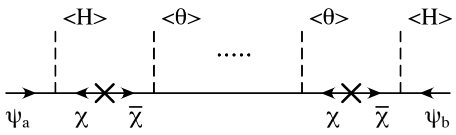
M.-C. C., de Gouvea, Dobrescu (2006)

- SM x $U(1)_{NA}$ + 3 ν_R: charged under $U(1)_{NA}$ symmetry, broken by $<\phi>$
- $U(1)_{NA}$ forbids usual dim-4 Dirac operator and dim-5 Majorana operator

$$m_{LL} \sim \frac{HHLL}{M} \rightarrow M \sim 10^{14}\ GeV$$

- neutrino masses generated by very high dimensional operators

$$m_{LL} \sim \left(\frac{\langle\phi\rangle}{M}\right)^p \frac{HHLL}{M} \rightarrow M \sim\ TeV, \quad \text{for large } p \qquad \frac{\langle\phi\rangle}{M} \sim \text{not too small} \quad \sim 0.1$$



$\Lambda \sim$ TeV!

low seesaw scale achieved
with all couplings ~ O(1)

- anomaly cancellation: relate generation-dependent fermion charges

⇒ predict mass hierarchy and mixing

  - TeV cutoff possible with 3 RH neutrinos
  - neutrino can either be Dirac or Majorana particles
  - light sterile neutrinos: DM candidate
  - TeV scale Z′: probing flavor sector at LHC

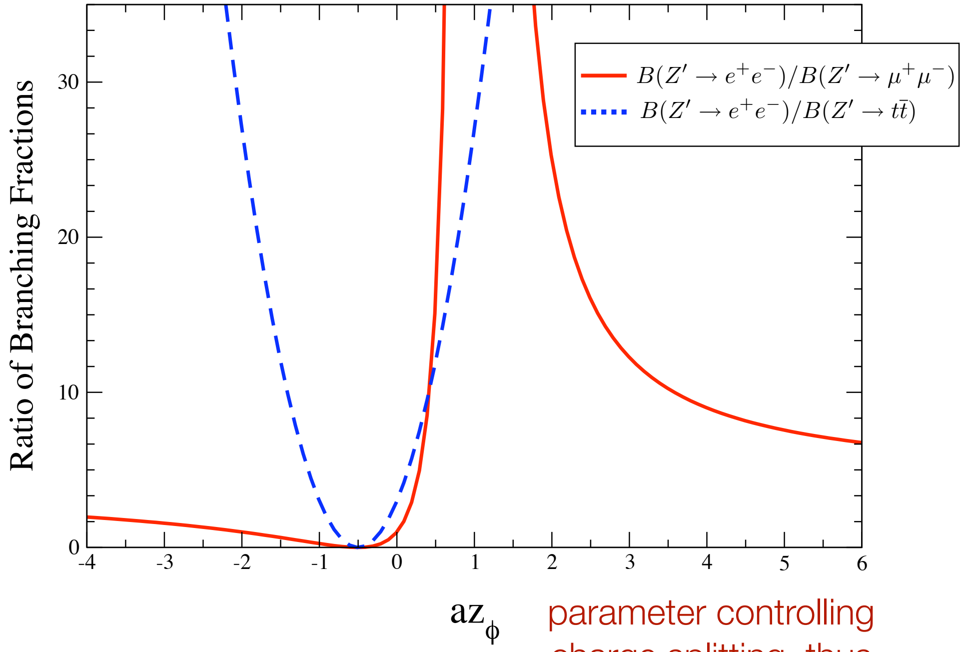
TeV Scale Seesaw and Non-anomalous U(1)

- probing flavor sector at colliders
- (2+1) Leptocratic models
  - generation dependent charges for lepton doublets
  - bi-large mixing

M.-C. C., de Gouvea, Dobrescu (2006)

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

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



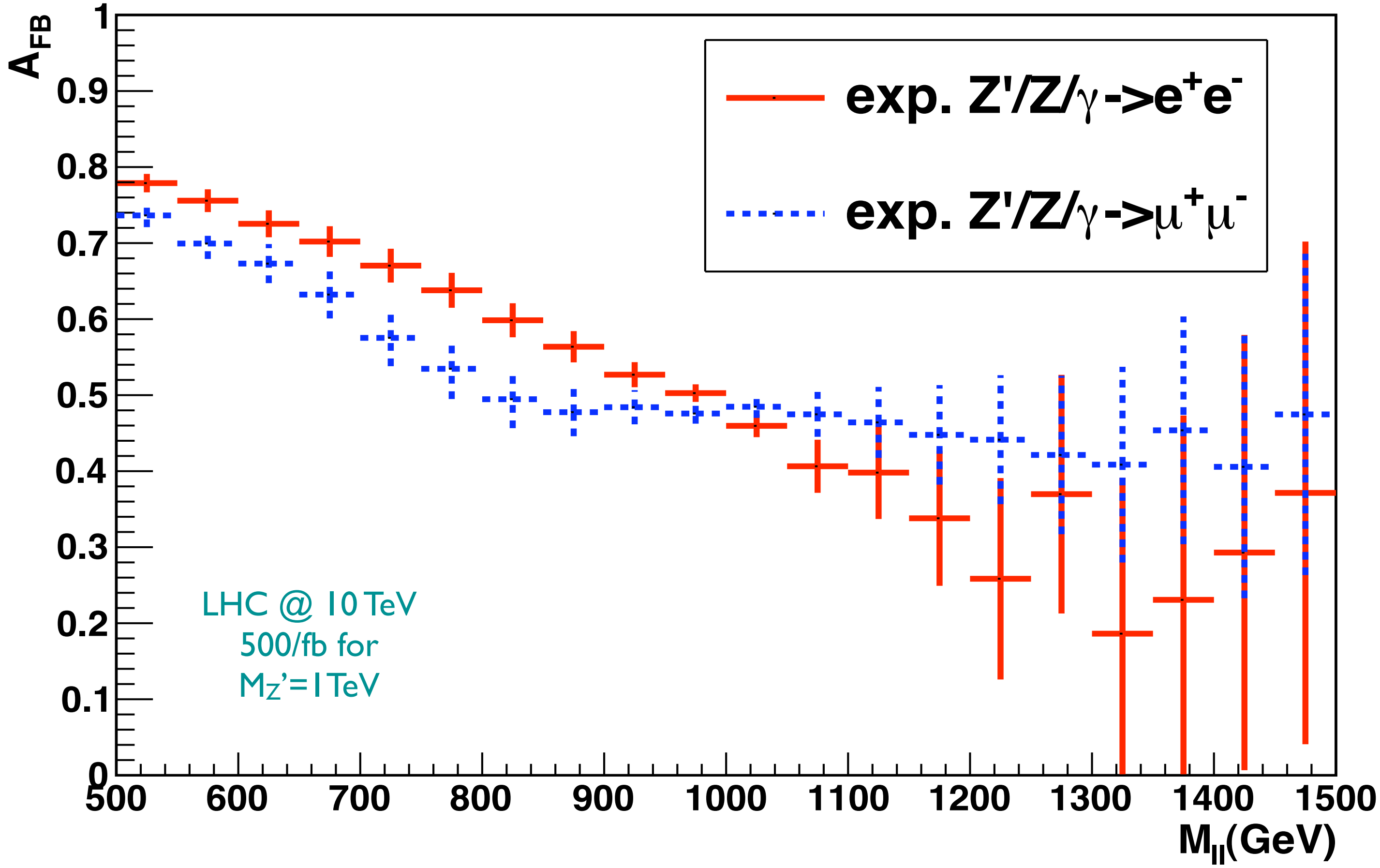
parameter controlling charge splitting, thus mixing parameters

- invisible decays of Z': distinguish different U(1) models
  - $U(1)_{B-L}$: Br(Z' → invisible) = 3/8
  - Orwellian Z' (universal lepton doublet charges): Br(Z' → invisible) = 6/7

TeV Scale Seesaw and Non-anomalous U(1)

- Establishing “flavorful” nature of Z’: 5 sigma distinction of e and mu channels

M.-C. C., J.-R. Huang (2009)



Prediction for Sparticle Spectrum

- U(1)' family (for quarks and leptons) also dictates sparticle mass spectrum (once SUSY breaking mechanism is specified)
- U(1)' family suppresses mu term
- predict testable (RG invariant) mass sum rules in Anomaly Mediated SUSY Breaking (AMSB) among sparticles at colliders

M.-C. C., J.-R. Huang (2010)

$$\bar{m}^2_{Q_i} + \bar{m}^2_{u^c_i} + \bar{m}^2_{H_u} = (m^2_{Q_i} + m^2_{u^c_i} + m^2_{H_u})_{AMSB} \ (i = 1,2,3)$$

$$\bar{m}^2_{Q_i} + \bar{m}^2_{d^c_i} + \bar{m}^2_{H_d} = (m^2_{Q_i} + m^2_{d^c_i} + m^2_{H_d})_{AMSB} \ (i = 1,2,3)$$

$$\bar{m}^2_{L_i} + \bar{m}^2_{e^c_i} + \bar{m}^2_{H_d} = (m^2_{L_i} + m^2_{e^c_i} + m^2_{H_d})_{AMSB} \ (i = 1,2,3)$$

functions of gauge couplings, Yukawa couplings and gravitino mass ($m_{3/2}$)

Flavor Physics at the Collider

Naturally Light Dirac Neutrinos from ~~SUSY~~

- MSSM: many attractive features (solving gauge hierarchy problem, gauge unification)
  - Dirac neutrino mass from Kähler potential   Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner (2001)

$$K \supset k_{LH_u\bar{\nu}} \frac{X^\dagger}{M_{\mathrm{P}}^2} L\, H_u\, \bar{\nu} + \mathrm{h.c.} \quad \Longleftrightarrow \quad Y_\nu \sim \frac{m_{3/2}}{M_{\mathrm{P}}} \sim \frac{\mu}{M_{\mathrm{P}}}$$

<X>: SUSY breaking VEV

  - However, it has several problems
    - mu problem: μ << M_{pl}
      - Giudice-Masiero mechanism   Giudice, Masiero (1988)
        - absence of mu term in superpotential
        - effective mu term (non-perturbatively) from Kähler potential

$$K \supset k_{H_uH_d} \frac{X^\dagger}{M_{\mathrm{P}}} H_u\, H_d + \mathrm{h.c.} \quad \Longleftrightarrow \quad \mathscr{W}_{\mathrm{eff}} \sim \frac{F_X}{M_{\mathrm{P}}} H_u\, H_d =: \mu_{\mathrm{eff}}\, H_u\, H_d$$

      - proton decay through dim-4, dim-5 operators
        - dim-4 operators: forbidden by imposing R-parity
        - dim-5 operators: severe experimental constraints on the models
  - no symmetry reason for the absence of holomorphic mu term/Dirac neutrino mass

Simultaneous solution based on symmetries to all problems?

Dirac Neutrino Mass and the μ Term

- Requiring Symmetries
  - to forbid mu term
  - be anomaly-free
  - be consistent with SU(5)

H.M. Lee, S. Raby M. Ratz, G.G. Ross, R. Schieren, K. Schmidt-Hoberg, P.K. Vaudrevange, (2011);

→ **R Symmetries**

- continuous R symmetries not available

A.H. Chamseddine, H.K. Dreiner (1996)

→ **Discrete R Symmetries**

- Search Abelian discrete R symmetries, $\mathbb{Z}_M^R$, that satisfy
  - Majorana neutrino case for q_θ = integer:
    - anomaly freedom (allowing Green-Schwarz)
    - mu term forbidden perturbatively
    - consistent with SU(5)
    - usual Yukawa allowed
    - Weinberg operators allowed

H.M. Lee, S. Raby M. Ratz, G.G. Ross, R. Schieren, K. Schmidt-Hoberg, P.K. Vaudrevange, (2011);

M.-C. C., Michael Ratz, Christian Staudt, Patrick Vaudrevange, arXiv:1206.5375

→

- five viable symmetries found;
- one unique solution consistent with SO(10) ➜ Z4 R-symmetry

Dirac Neutrino Mass and the μ Term

M.-C. C., Michael Ratz, Christian Staudt, Patrick Vaudrevange, arXiv:1206.5375

- Search Abelian discrete R symmetries, $\mathbb{Z}_M^R$, that satisfy
  - Dirac neutrino case for q_θ = integer:
    - anomaly freedom (a la Green-Schwarz)
    - forbidding mu term perturbatively
    - consistent with SU(5)
    - allowing usual Yukawa
    - Weinberg operators forbidden perturbatively

classes of models found

  - an example: $\mathbb{Z}_\mathbf{8}^R$ symmetry
    - at non-perturbative level $\mathscr{W}_\text{eff} \sim m_{3/2}\, H_u\, H_d + \frac{m_{3/2}}{M_\text{P}}\, L\, H_u\, \bar{\nu} + \frac{m_{3/2}}{M_\text{P}^2}\, Q\, Q\, Q\, L$
    - Δ L = 2 operators forbidden ⇒ no neutrinoless double beta decay
    - ΔL = 4 operators allowed ⇒ new LNV processes

Discrete R Symmetries

M.-C. C., Michael Ratz, Christian Staudt,
Patrick Vaudrevange, arXiv:1206.5375

- For all solutions:
  - absence of perturbative mu term ⇒ constraints on R charges of Hu, Hd
    - ➜ non-perturbative mu term ~ TeV automatically arise

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

  - absence of perturbative Weinberg operator ⇒ constraints on R charges of leptons
    - ➜ non-perturbative, realistic Dirac neutrino mass automatically arise

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

  - solutions automatically forbid dim-4 proton decay
  - solutions automatically suppress dim-5 proton decay (allowed only at non-perturbatively level through Kähler potential)
  - predictions for B and L violating operators to all orders with Hilbert basis method

R. Kappl, M. Ratz, C. Staudt (2011)

anomaly-free, SU(5) compatible symmetries simultaneously solve mu problem, suppress Dirac neutrino masses, and forbid proton decay problems!!

Conclusion

- Seesaw based Mechanisms: to have observable effects at colliders
  - TeV cutoff scale, assuming small Yukawa (~10^{-6})
  - no new gauge interactions:
    - mediators charged under SM gauge group (type-II, III, radiative seesaw)
  - new interactions: left-right symmetric model
  - common operators for superpartner decays and neutrino mass generations (RPV, inverse seesaw)
    - correlation between mixing parameters and decay branching fractions
- More Naturally: inverse seesaw or higher dimensional operators or Extra Dim
  - SO(10): adjoint fermions + inverse seesaw
  - inverse seesaw
  - adjoint SU(5)
  - higher dimensional effective operators (from, e.g. extra U(1))
  - TeV Scale Extra Dimension

Conclusion

M.-C. C., Michael Ratz, Christian Staudt,
Patrick Vaudrevange, arXiv:1206.5375

- anomaly-free, SU(5) consistent Discrete R-Symmetries:
  - very predictive framework (prediction to ALL order with Hilbert basis method)
  - common origin of a suppressed mu term and Dirac neutrino mass

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

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

  - automatically forbid dim-4 proton decay operators
  - automatically suppress dim-5 proton decay operators to high power
  - new L number violation operators