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TeV Seesaw at Colliders

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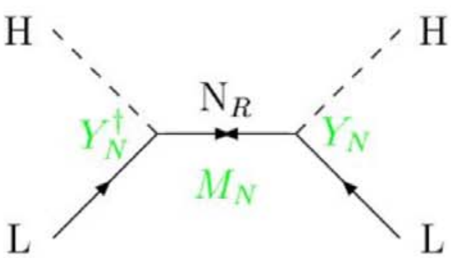
Neutrino Mass Models

- RHN (and Z') (Type I)
- Higgs Triplet Model (Type II)
- Fermion Triplet Model (Type III)
- MSSM with R-parity/L violation
- Radiative models: Zee-Babu
- …

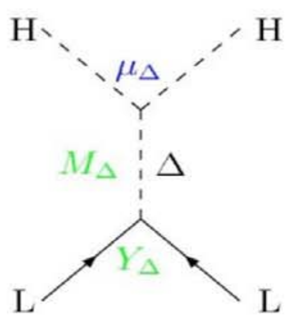
Three seesaws at TeV

Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

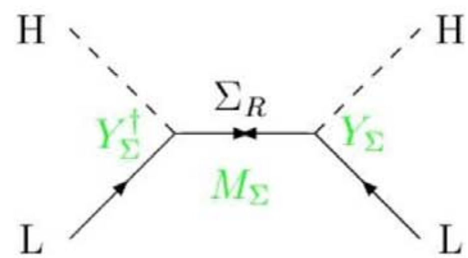
Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Y(Δ) =1

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Y(Σ) =0

c) T.Hambye

Type I with U(1)'

$$W = yLH_2N + hNNS$$

ν–N mixing: $\delta = y\frac{\langle H_2\rangle}{M}$ $\qquad m_\nu = y^2\frac{\langle H_2\rangle^2}{M}$

- RHN mass after U(1)' breaking at TeV scale: M=h <S>.
- RHN production: pp → Z'→ NN.
- LNV & LFV: same-sign dileptons, NN→ $l^+l^+W^-W^-$.
- Small Yukawa $y < 10^{-7}$ → Displaced vertices.
- In case of SUSY, sRHN can be a thermal dark matter.

Z' models from E6

Langacker , 0801.1345

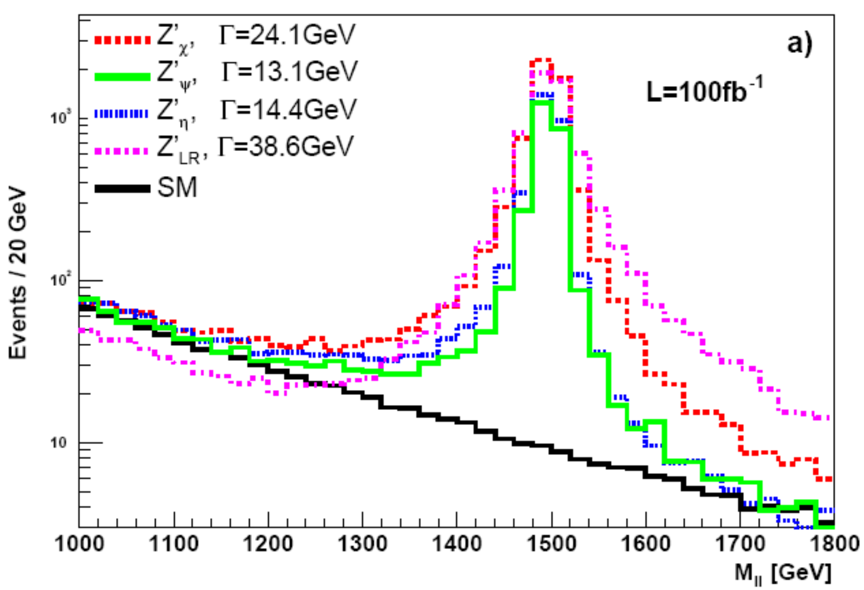
$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q_\eta$	$2Q_I$	$2\sqrt{10}Q_N$	$2\sqrt{15}Q_S$
16	$10\ (u, d, u^c, e^+)$	-1	1	-2	0	1	$-1/2$
	$5^*\ (d^c, \nu, e^-)$	3	1	1	-1	2	4
	ν^c	-5	1	-5	1	0	-5
10	$5\ (D, H_u)$	2	-2	4	0	-2	1
	$5^*\ (D^c, H_d)$	-2	-2	1	1	-3	$-7/2$
1	$1\ S$	0	4	-5	-1	5	$5/2$

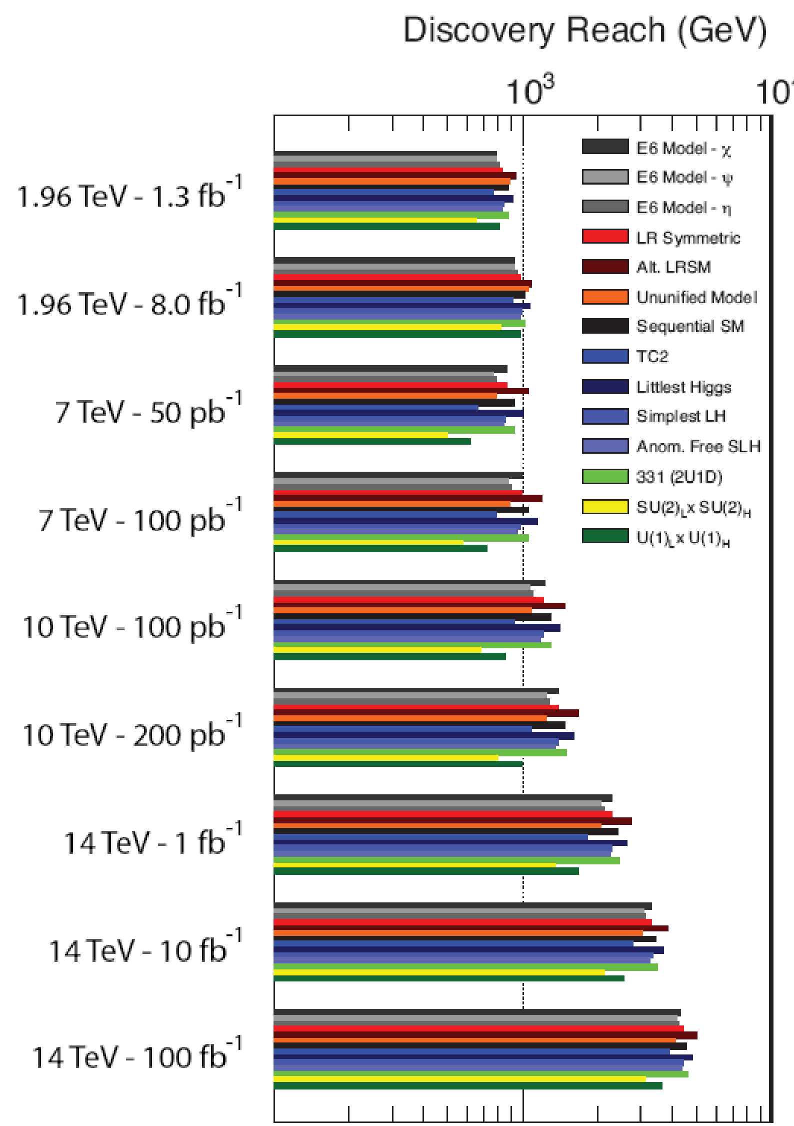
EWPT and Tevatron limit

Z'	$M_{Z'}$ [GeV]				$\sin\theta_{ZZ'}$			$\chi^2_{\min}$
	electroweak	CDF	DØ	LEP 2	$\sin\theta_{ZZ'}$	$\sin\theta_{ZZ'}^{\min}$	$\sin\theta_{ZZ'}^{\max}$	
Z_χ	1,141	892	800	673	-0.0004	-0.0016	0.0006	47.3
Z_ψ	147	878	763	481	-0.0005	-0.0018	0.0009	46.5
Z_η	427	982	810	434	-0.0015	-0.0047	0.0021	47.7
Z_I	1,204	789	692		0.0003	-0.0005	0.0012	47.4
Z_S	1,257	821	719		-0.0003	-0.0013	0.0005	47.3
Z_N	623	861	744		-0.0004	-0.0015	0.0007	47.4
Z_R	442				-0.0003	-0.0015	0.0009	46.1
Z_{LR}	998	630		804	-0.0004	-0.0013	0.0006	47.3
$Z_{\not L}$	(803)	(740)			-0.0015	-0.0094	0.0081	47.7
Z_{SM}	1,403	1,030	950	1,787	-0.0008	-0.0026	0.0006	47.2
Z_{string}	1,362				0.0002	-0.0005	0.0009	47.7
SM	∞				0			48.5

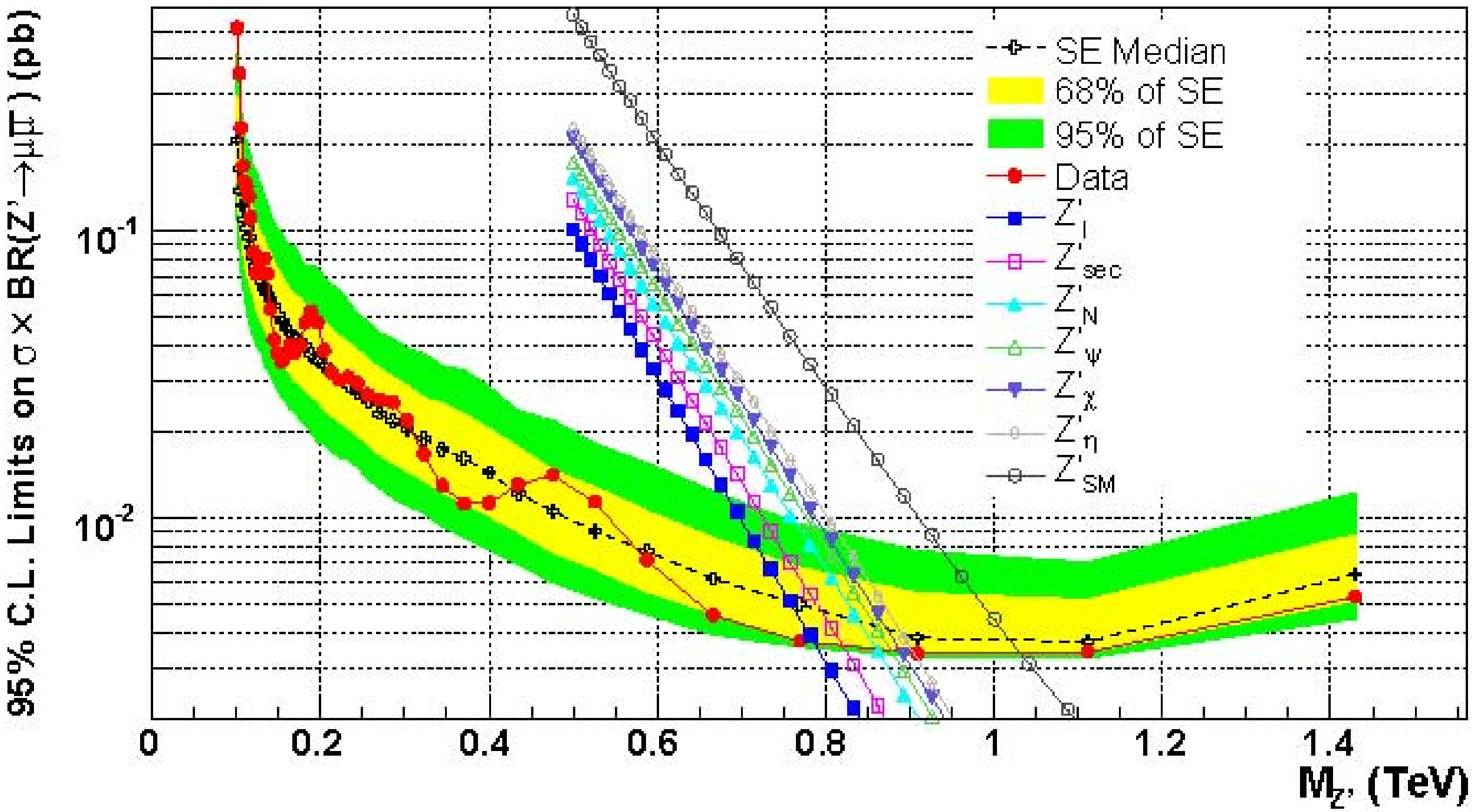
LHC discovery

Dilepton invariant mass spectrum



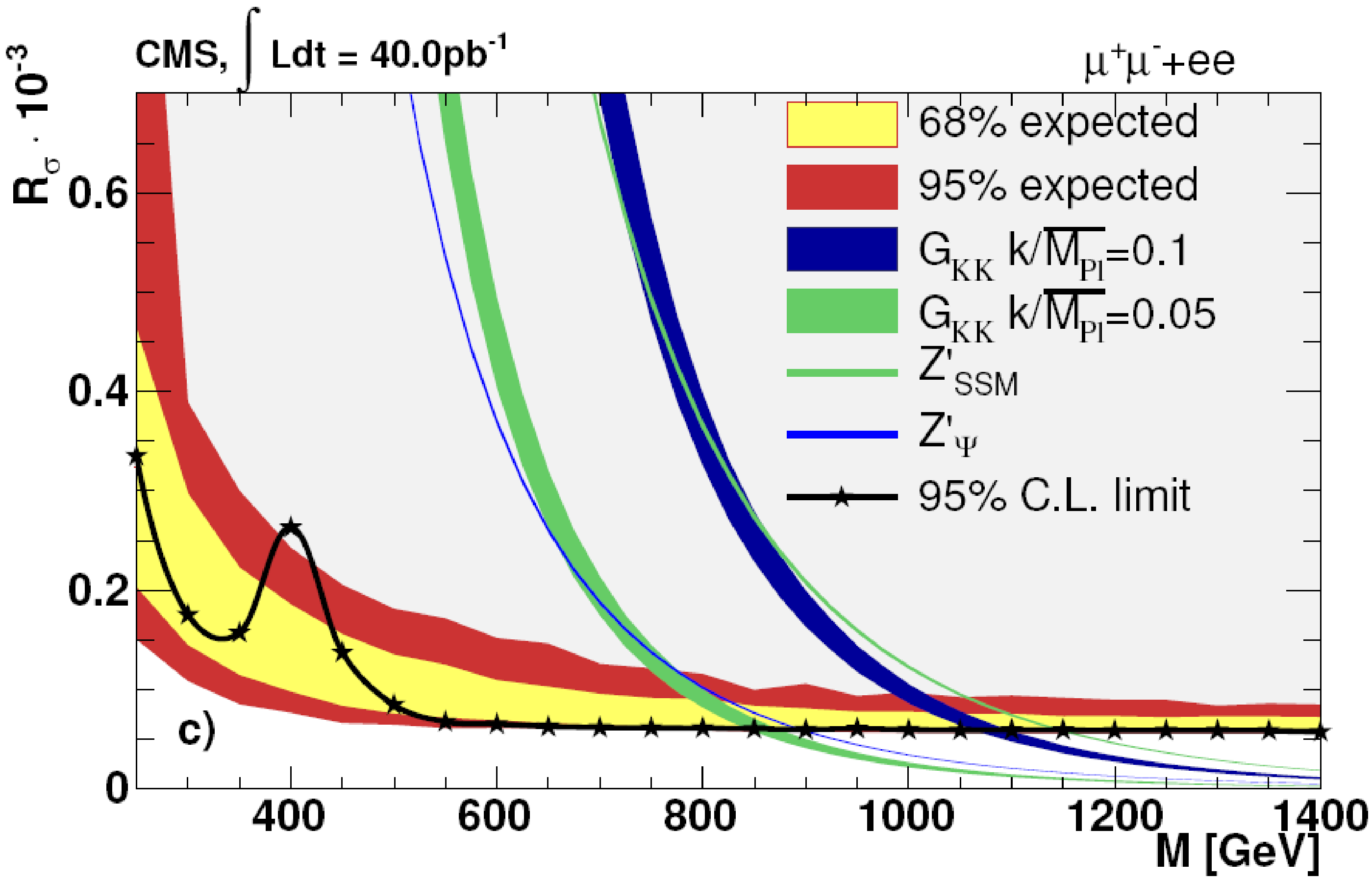


CDF di-muon limit



CMS limit

CMS-EXO-10-013

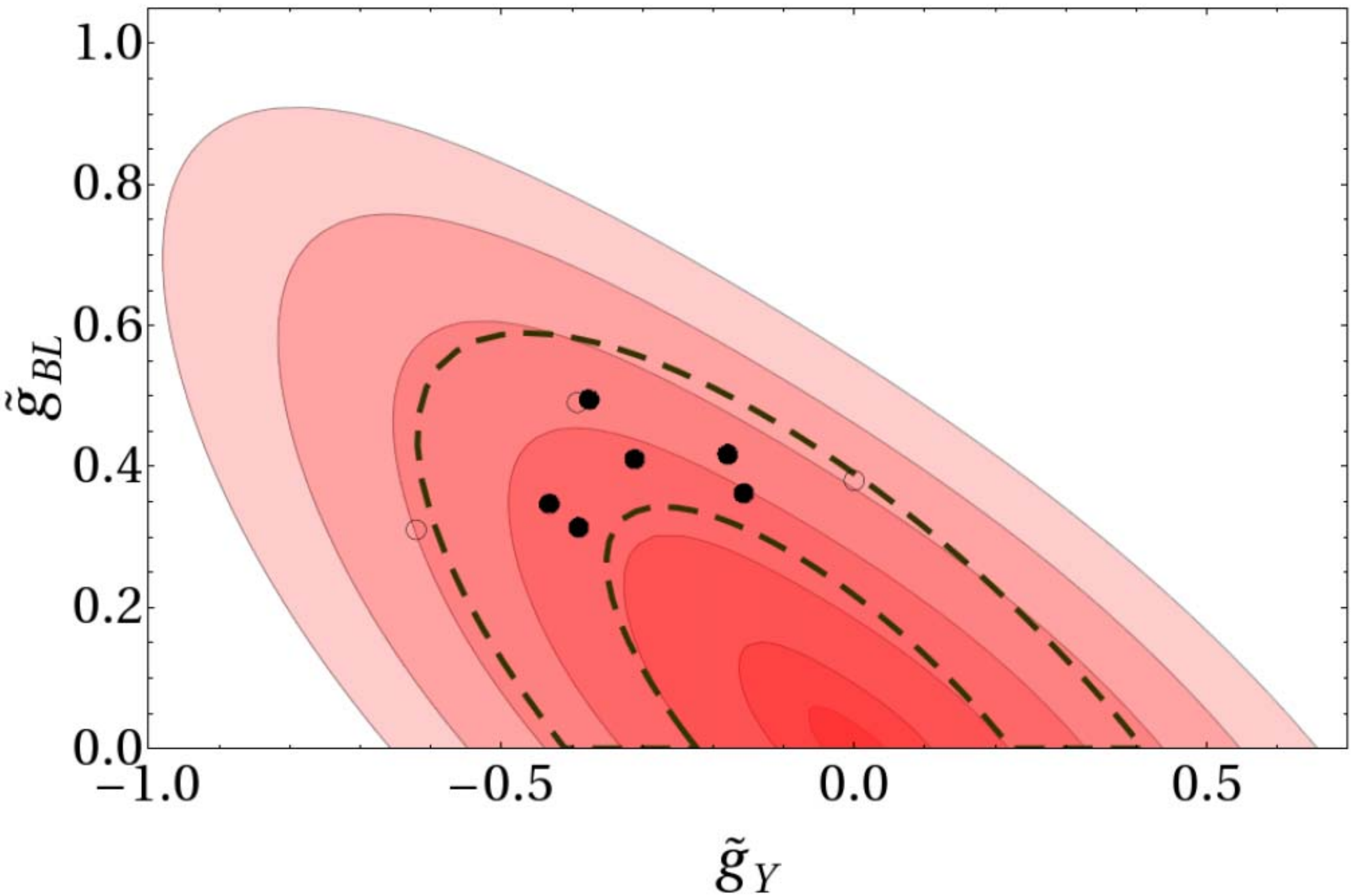


B−L models

Salvioni, Villadoro & Zwirner, 0909.1320

	(u,d)	u^c	d^c	(ν,e)	ν^c	e^c
T_{3L}	$(+\frac{1}{2},-\frac{1}{2})$	0	0	$(+\frac{1}{2},-\frac{1}{2})$	0	0
Y	$+\frac{1}{6}$	$-\frac{2}{3}$	$+\frac{1}{3}$	$-\frac{1}{2}$	0	$+1$
$B-L$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	$+1$	$+1$
$Q_{Z'}$	$\frac{1}{6}\widetilde{g}_Y+\frac{1}{3}\widetilde{g}_{BL}$	$-\frac{2}{3}\widetilde{g}_Y-\frac{1}{3}\widetilde{g}_{BL}$	$\frac{1}{3}\widetilde{g}_Y-\frac{1}{3}\widetilde{g}_{BL}$	$-\frac{1}{2}\widetilde{g}_Y-\widetilde{g}_{BL}$	$\widetilde{g}_{BL}$	$\widetilde{g}_Y+\widetilde{g}_{BL}$

EWPT



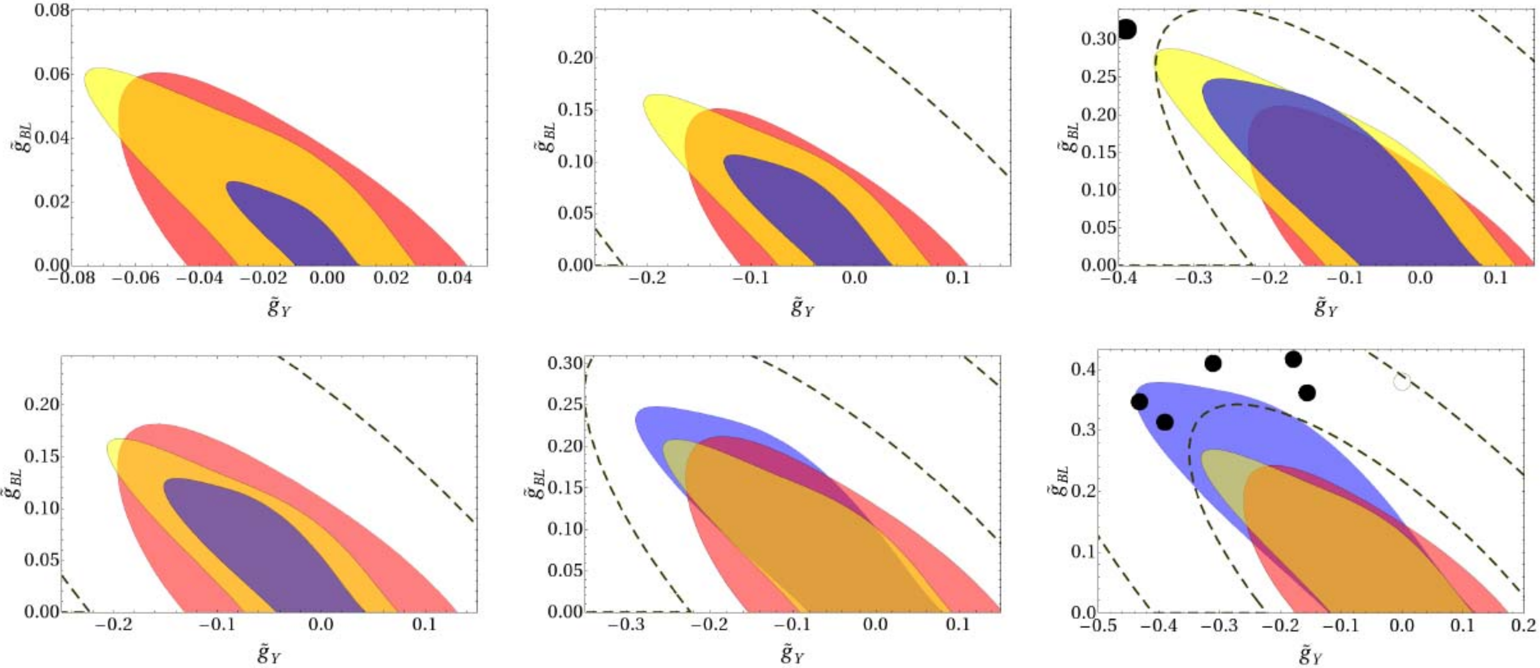
M(Z')/GeV
= 3000,
2500,
2000,
1500,
1000,
500,
200

7 TeV LHC discovery

200GeV 500GeV 700GeV

50/pb

100/pb



600GeV 700GeV 800GeV

EWPT (inside red); Tevatron (inside blue); LHC discovery (outside yellow)

Light $\tilde{Z}_{B-L}$ and $\tilde{N}$ DM

PB, JCP, EJC, work to appear

- RH sneutrino thermal freeze-out density determined by t-channel B-L gaugino exchange.
- RH neutrino decay process is important.

$$\tilde{N}\tilde{N} \to NN$$

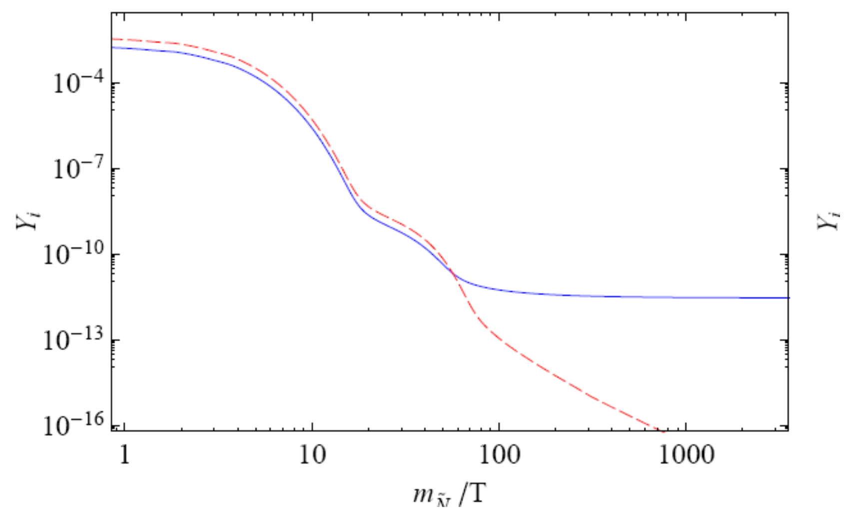
Light $\tilde{Z}_{B-L}$ exchange

$$NN \to f\bar{f}$$

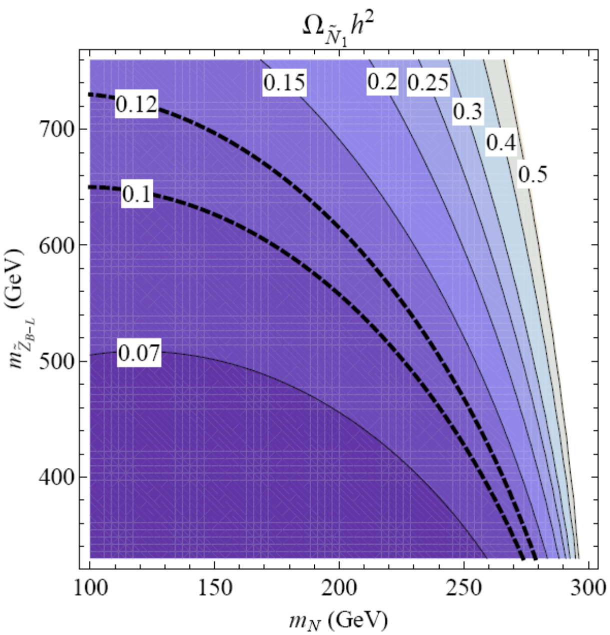
Heavy Z_{B-L} exchange

$$N \to \nu h,\ l^{\pm}W^{\mp},\ \nu Z$$

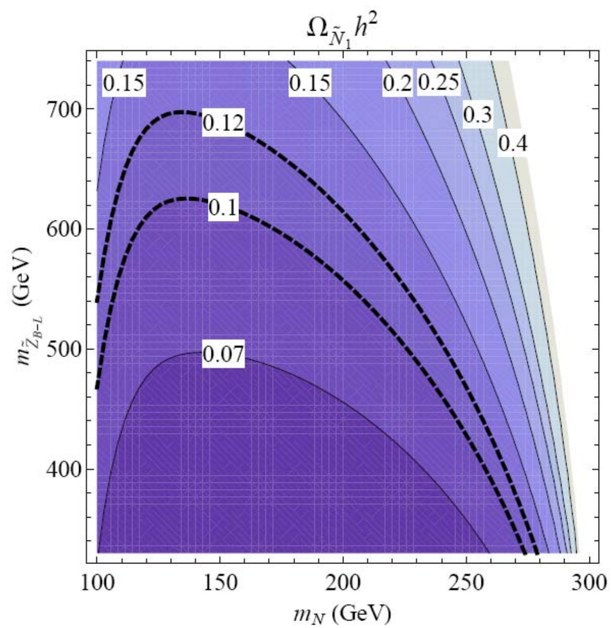
Yukawa interaction



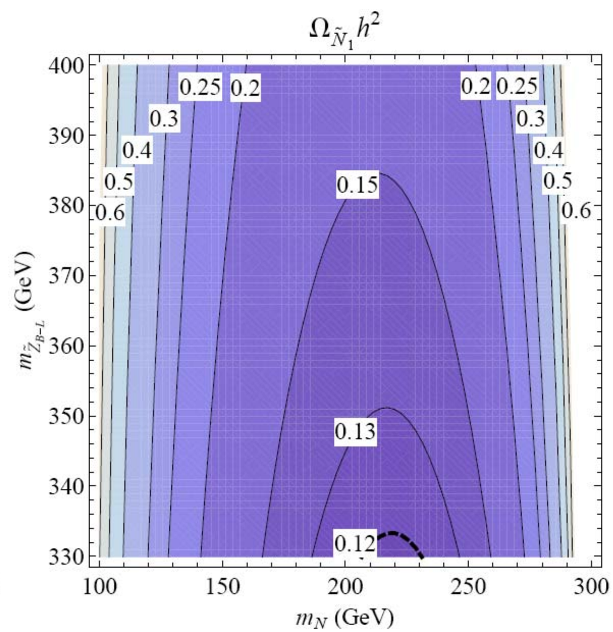
Relic abundance of Ñ DM



m_ν = 0.1 eV



m_ν = 10^{-3} eV



m_ν = 10^{-5} eV

Sneutrino mass = 300 GeV

Displaced Higgs from cascade

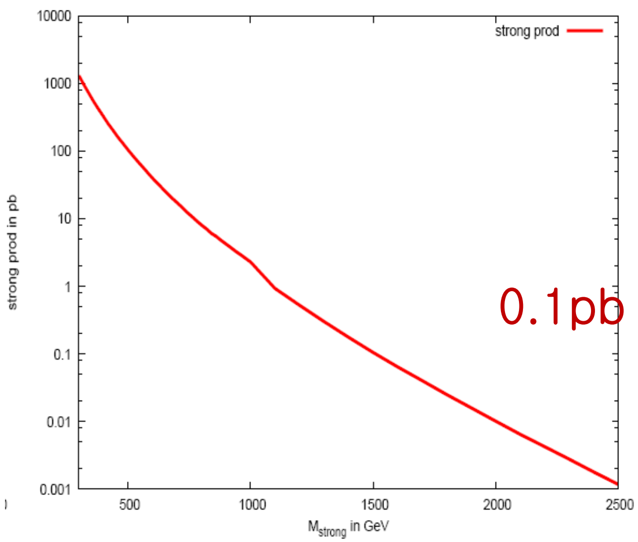
$$\tilde{q} \rightarrow q\tilde{Z}_{B-L}$$

$$\hookrightarrow N\tilde{N}$$

$$\hookrightarrow \nu h, l^{\pm}W^{\mp}, \nu Z$$

$$\hookrightarrow b\bar{b}$$

Dijet, same-sign dilepton, MET
Dijet, displaced b-jet(s), MET



0.1pb for m_{squark}=1.5 TeV

τ=0.2cm
for $m_\nu=10^{-3}$eV and m_N=200GeV

Type II seesaw

EJC, Jung, Park, hep-ph/0304069

$\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$ with $Y = 1$; $L_i = (\nu_i, l_i)_L$ and $\Phi = (\phi^0, \phi^-)$

$$\mathcal{L}_\Delta = f_{ij} L_i L_j \Delta + \mu \Phi \Phi \Delta + h.c.$$

$$v_\Delta = \mu \frac{v_\Phi^2}{M_\Delta^2} \quad \Longrightarrow \quad M^\nu_{ij} = f_{ij} v_\Delta \quad \Longleftarrow \quad f_{ij} \frac{\mu}{v_\Phi} \sim 10^{-12}$$

- Same flavor structure for M^ν and f
- Neutrino mass patterns distinguishable by lepton flavor violating processes
- Production and decay of the doubly charged Higgs boson at colliders:

$\Longrightarrow$ Direct test of the model

5 Physical fields

$$(\phi^0, \phi^-)$$
$$(\Delta^{++}, \Delta^+, \Delta^0)$$
$$\Delta^{++},\ H^+,\ H^0,\ A^0 \text{ and } h^0$$

Triplet VEV: $v_\Delta = \mu v_\Phi^2 / 2M_{\Delta^0}^2 \qquad \xi \equiv v_\Delta / v_\Phi$

$$a = 2 + 4(4\lambda_1 - \lambda_4 - \lambda_5) m_W^2 / g^2 (m_{H^0}^2 - m_{h^0}^2)$$

Physical basis
in the limit of ξ<<1:

$$\phi_R^0 = h^0 - a\xi\, H^0 ,$$
$$\Delta_R^0 = H^0 + a\xi\, h^0$$

$$\phi_I^0 = G^0 - 2\xi A^0 , \qquad \phi^+ = G^+ + \sqrt{2}\xi H^+$$
$$\Delta_I^0 = A^0 + 2\xi G^0 , \qquad \Delta^+ = H^+ - \sqrt{2}\xi G^+$$

Mass spectrum

$$M^2_{\Delta^{\pm\pm}} = M^2 + 2\frac{\lambda_4 - \lambda_5}{g^2} M_W^2$$

$$M^2_{H^\pm} = M^2_{\Delta^{\pm\pm}} + 2\frac{\lambda_5}{g^2} M_W^2$$

$$M^2_{H^0,A^0} = M^2_{H^\pm} + 2\frac{\lambda_5}{g^2} M_W^2 .$$

Mass relations: $M^2_{H^0} = M^2_{A^0}$

$$M^2_{H^+} - M^2_{\Delta^{++}} = M^2_{H^0} - M^2_{H^+} = 2\frac{\lambda_5}{g^2} M_W^2$$

Note: $\lambda_5 > 0$, $M_{\Delta^{\pm\pm}} < M_{H^\pm} < M_{H^0,A^0}$

$$\Delta^{++} \xrightarrow{f,\ \xi} l^+ l^+, W^+ W^+ \qquad \Delta^{++} \overset{g}{\not\longrightarrow} H^+ W^{+*}$$

Doubly charge Higgs Decay

$$\mathcal{L} = \frac{1}{\sqrt{2}}\left[f_{ij}\,\bar{l^c}_i P_L l_j + g\xi M_W\, W^- W^-\right]\Delta^{++} + h.c.$$

$$\Gamma(\Delta^{--} \to l_i l_j) \;=\; S\frac{f_{ij}^2}{16\pi} M_{\Delta^{\pm\pm}}$$

$$\Gamma(\Delta^{--} \to WW) \;=\; \frac{\alpha_2 \xi^2}{32}\frac{M_{\Delta^{\pm\pm}}^3}{M_W^2}(1 - 4r_W + 12 r_W^2)(1 - 4r_W)^{1/2}$$

$$S = 2\,(1) \text{ for } i \neq j\;(i = j) \qquad r_W = M_W^2/M_{\Delta^{\pm\pm}}^2$$

Maximal decay length

$$M^\nu_{ij} = f_{ij}\xi v_\Phi \quad \Rightarrow \quad \sum_{ij} f^2_{ij} \propto \mathrm{Tr}(M^2_\nu)$$

$$\Gamma_{\Delta^{\pm\pm}} = M_{\Delta^{\pm\pm}} \left(\frac{1}{16\pi} \frac{\bar{m}^2}{\xi^2 v^2_\Phi} + \frac{\alpha_2}{32} \frac{\xi^2}{r_W} (1 - 4r_W + 12 r^2_W)(1-4r_W)^{1/2} \right)$$

$$\Gamma_{\Delta^{\pm\pm}}\big|_{min} = \frac{1}{8\pi} \frac{M_{\Delta^{\pm\pm}} \bar{m}^2}{\hat{\xi}^2 v^2_\Phi}$$

$$\hat{\xi}^2 \equiv (2\sqrt{2}/g) r_W^{1/2} (\bar{m}/v_\Phi)(1 - 4r_W + 12 r^2_W)^{-1/2}(1-4r_W)^{-1/4}$$

$\bar{m} = 0.05$ eV

$M_{\Delta^{\pm\pm}} = 200$ GeV

$\Gamma_{\pm\pm}\big|_{min} \approx 6 \times 10^{-13}$ GeV

$\hat{\xi} \approx 6 \times 10^{-7}$

$\tau\big|_{max} \approx 0.03$ cm

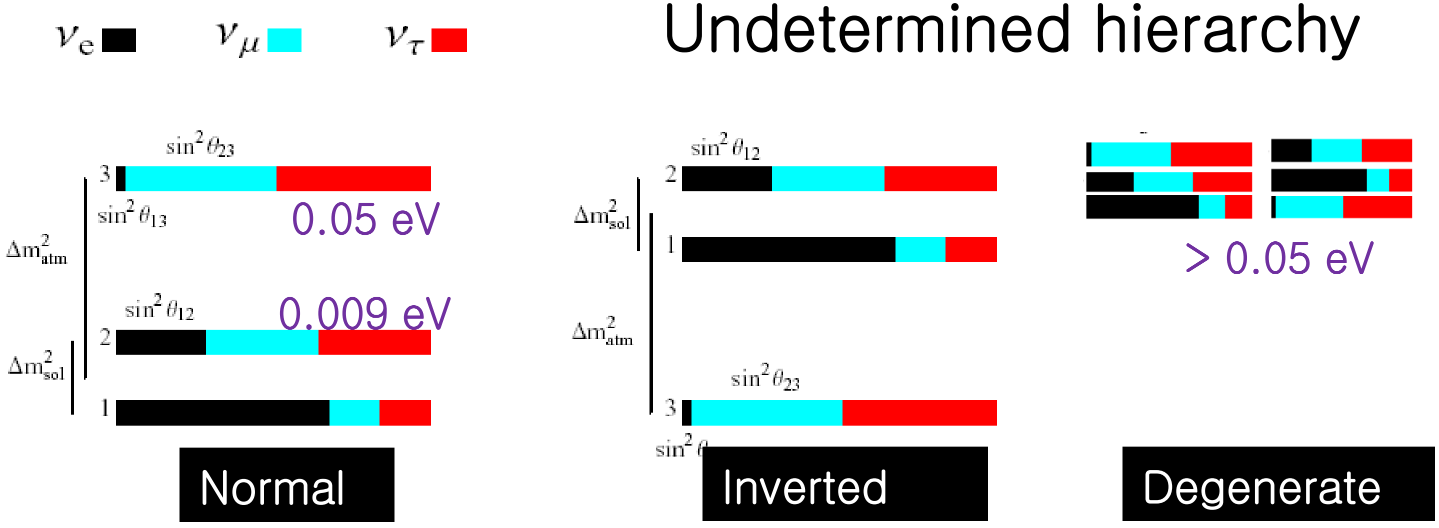
Neutrino mass matrix

$$|\Delta m^2_{31}| = 2.4 \times 10^{-3} \mathrm{eV}^2 \qquad \sin\theta^2_{23} = 0.5$$

$$\Delta m^2_{21} = 7.7 \times 10^{-5} \mathrm{eV}^2 \qquad \sin\theta^2_{12} = 0.3$$

$$\sin\theta^2_{13} < 0.04$$

Undetermined hierarchy



CP even Hierarchies

- HI : $m_1 < m_2 < m_3$
- IN1 : $m_1 \simeq m_2 \gg m_3$
- IN2 : $m_1 = -m_2 \gg m_3$
- DG1 : $m_1 \simeq m_2 \simeq m_3$
- DG2 : $m_1 \simeq m_2 \simeq -m_3$
- DG3 : $m_1 \simeq -m_2 \simeq m_3$
- DG4 : $m_1 \simeq -m_2 \simeq -m_3$

Branching ratios and neutrino mass matrix

$$B(ee) : B(\mu\mu) : B(\tau\tau) : B(e\mu) : B(e\tau) : B(\mu\tau)$$

- (HI) $2r\sin^4\theta_3 : \frac{1}{2} : \frac{1}{2} : \frac{1}{2}r\sin^2 2\theta_3 : \frac{1}{2}r\sin^2 2\theta_3 : 1$
- (IN1) $1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{16}r^2\sin^2 2\theta_3 : \frac{1}{16}r^2\sin^2 2\theta_3 : \frac{1}{2}$
- (IN2) $\cot^2 2\theta_3 : \frac{1}{4}\cot^2 2\theta_3 : \frac{1}{4}\cot^2 2\theta_3 : 1 : 1 : \frac{1}{2}\cot^2 2\theta_3$
- (DG1) $1 : 1 : 1 : \frac{1}{16}R^2r^2\sin^2 2\theta_3 : \frac{1}{16}R^2r^2\sin^2 2\theta_3 : \frac{1}{8}R^2$
- (DG2) $\frac{1}{2} : \frac{1}{32}R^2 : \frac{1}{32}R^2 : \frac{1}{8}r^2\sin^2 2\theta_3 : \frac{1}{8}r^2\sin^2 2\theta_3 : 1$
- (DG3) $\cot^2 2\theta_3 : \frac{1}{4}\tan^2\theta_3 : \frac{1}{4}\tan^2\theta_3 : 1 : 1 : \frac{1}{2}\cot^2\theta_3$
- (DG4) $\cot^2 2\theta_3 : \frac{1}{4}\cot^2\theta_3 : \frac{1}{4}\cot^2\theta_3 : 1 : 1 : \frac{1}{2}\tan^2\theta_3$

$r \equiv \Delta m^2_{atm}/\Delta m^2_{sol}$

~ 0.03

$R \equiv \Delta m^2_{atm}/m^2_1$

$\sim (0.1, 1)$

Characteristic BRs

- (HI) $B(\mu\mu) : B(\tau\tau) : B(\mu\tau) = \frac{1}{2} : \frac{1}{2} : 1$
- (IN1) $B(ee) : B(\mu\mu) : B(\tau\tau) : B(\mu\tau) = 1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{2}$
- (IN2) $B(e\mu) : B(e\tau) = 1 : 1$
- (DG1) $B(ee) : B(\mu\mu) : B(\tau\tau) = 1 : 1 : 1$
- (DG2) $B(ee) : B(\tau\tau) = 1 : 1$
- (DG3) $B(e\mu) : B(e\tau) : B(\mu\tau) = 1 : 1 : \frac{1}{2}\cot^2\theta_3$
- (DG4) $B(\mu\mu) : B(\tau\tau) : B(e\mu) : B(e\tau) = \frac{1}{4}\cot^2\theta_3 : \frac{1}{4}\cot^2\theta_3 : 1 : 1$

Early LHC study

LHC with $L = 1000/\mathrm{fb}$

$$N = (10^5 - 10^3) \text{ for } M_{\Delta^{\pm\pm}} = (100 - 450) \text{ GeV}$$

$$N = 10 \text{ for } M_{\Delta^{\pm\pm}} = 1000 \text{ GeV}$$

J.F. Gunion, C. Loomis and K.T. Pitts, hep-ph/9610237; B. Dion *et. al.*, Phys. Rev. **D59** (1999) 075006; A. Datta and A. Raychaudhuri, Phys. Rev. **D62** (2000) 055002.

Recent LHC studies

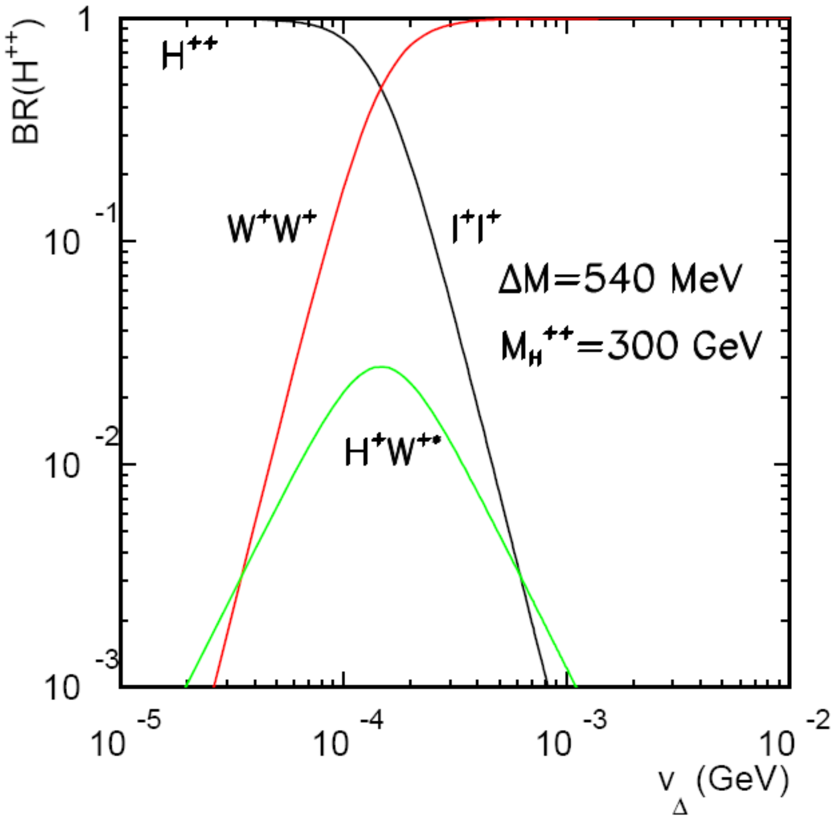
Akeroyd, Aoki, hep-ph/0506176

Garayoa, Schwetz, 0712.1453
Kadastik, Raidal, Rebane, 0712.3912
Akeroyd, Aoki, Sugiyama, 0712.4019

Han, Mukhopadhyaya, Si, Wang, 0706.0441
Perez, Han, Huang, Li, Wang, 0805.3536

Assuming no tree spliting

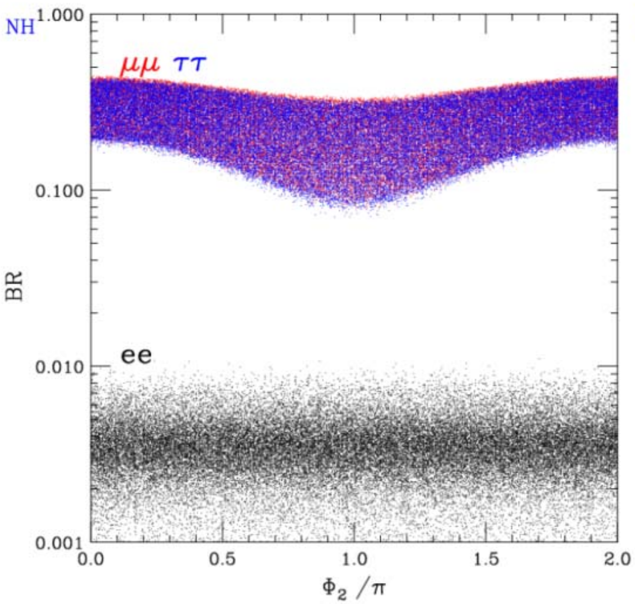
Radiative mass splitting: $\Delta M \equiv M_{H^{++}} - M_{H^{+}} \approx 540 \text{ MeV.}$

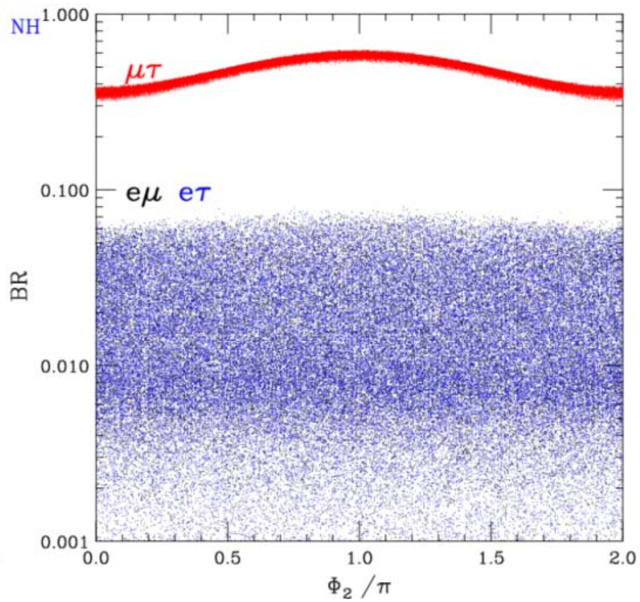


Note) Tree splitting

$$\Delta M \approx -\frac{\lambda_5}{g^2}\frac{M_W^2}{M_\Delta} \text{ (tree)}$$

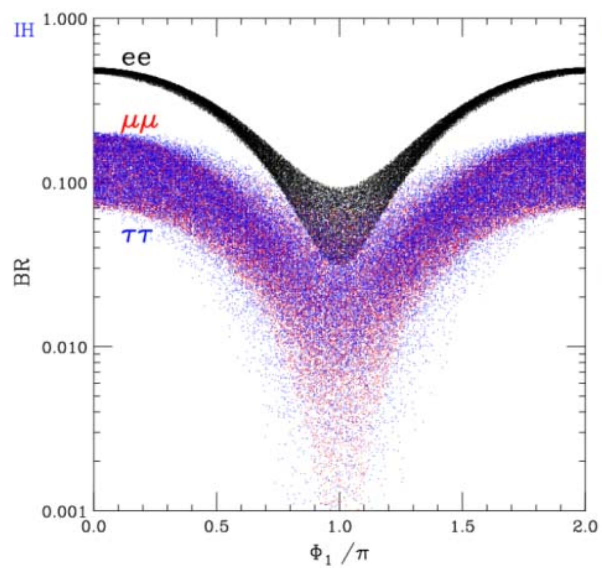
CP phase effect I

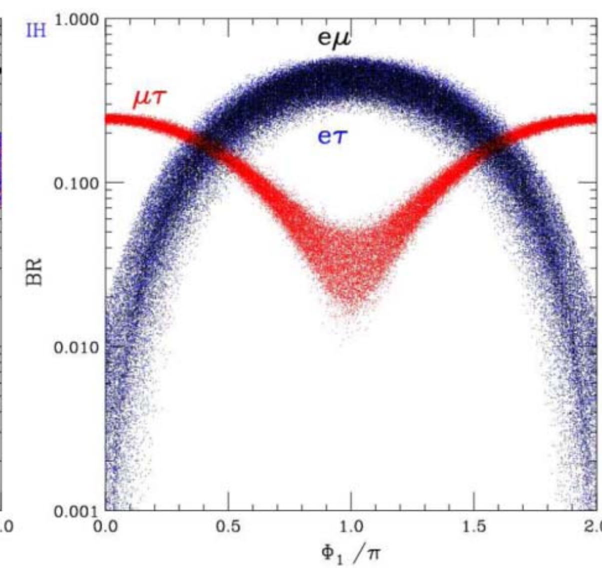




$\phi_1 = 0 \sim 2\pi$

$\phi_2 = 0 \sim 2\pi$





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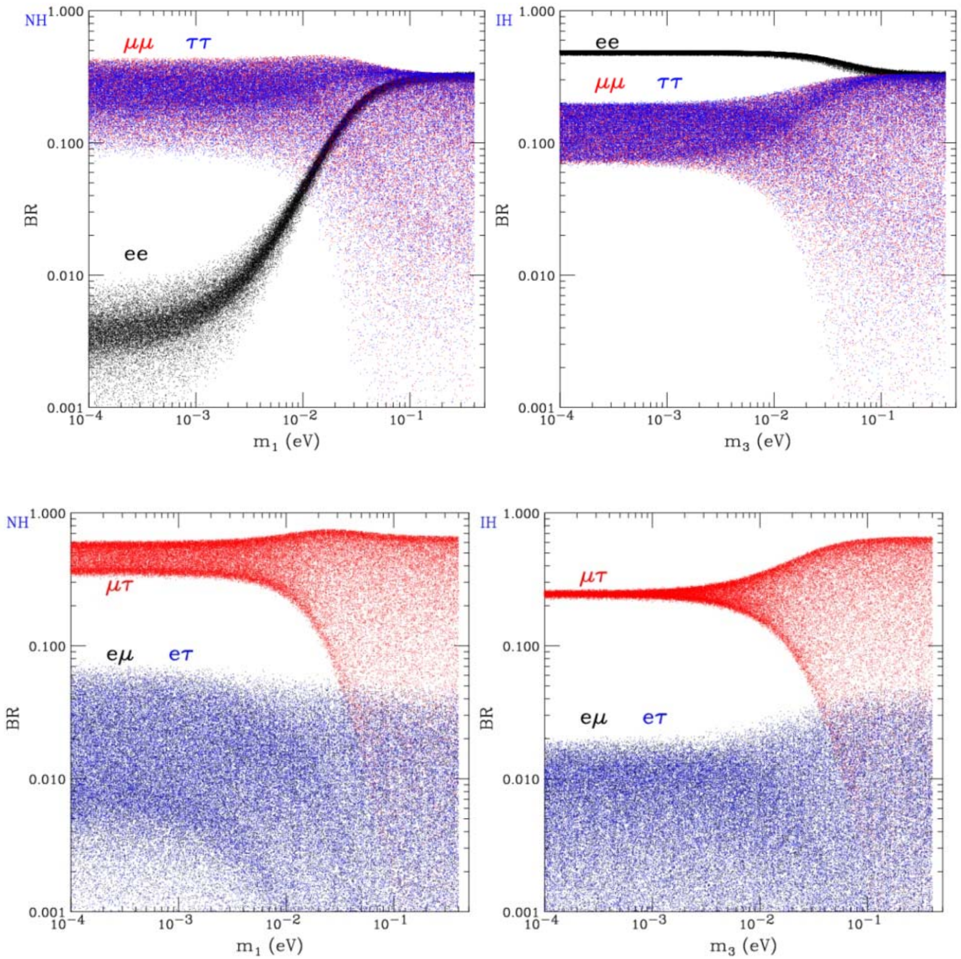
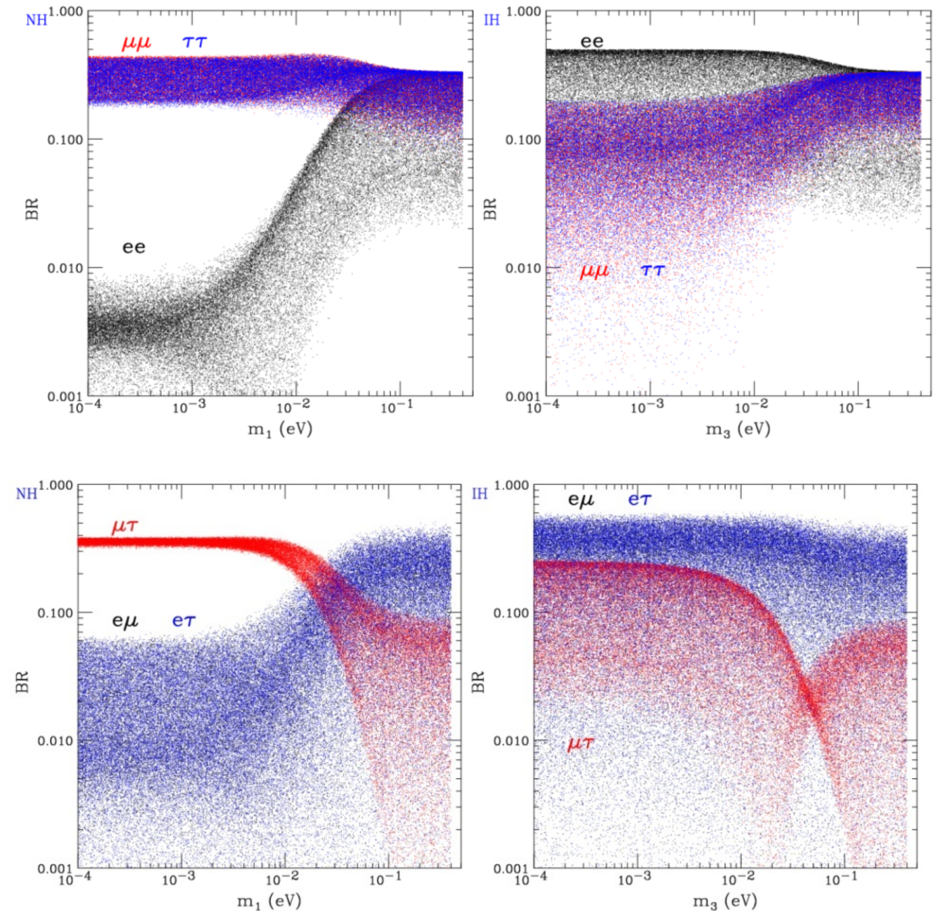
CP phase effect II

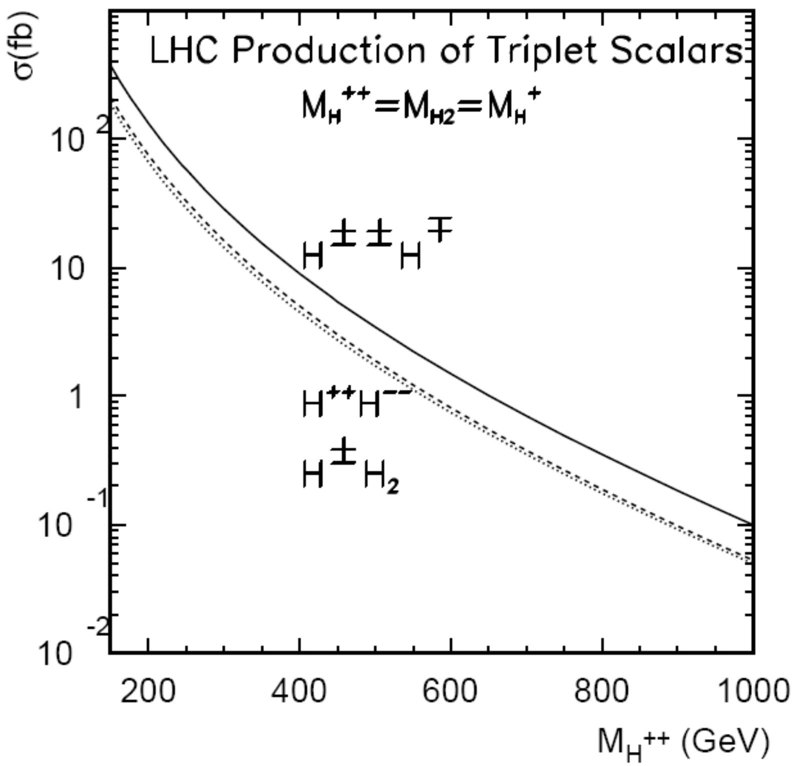
ϕ_1=0, ϕ_2=0~2π



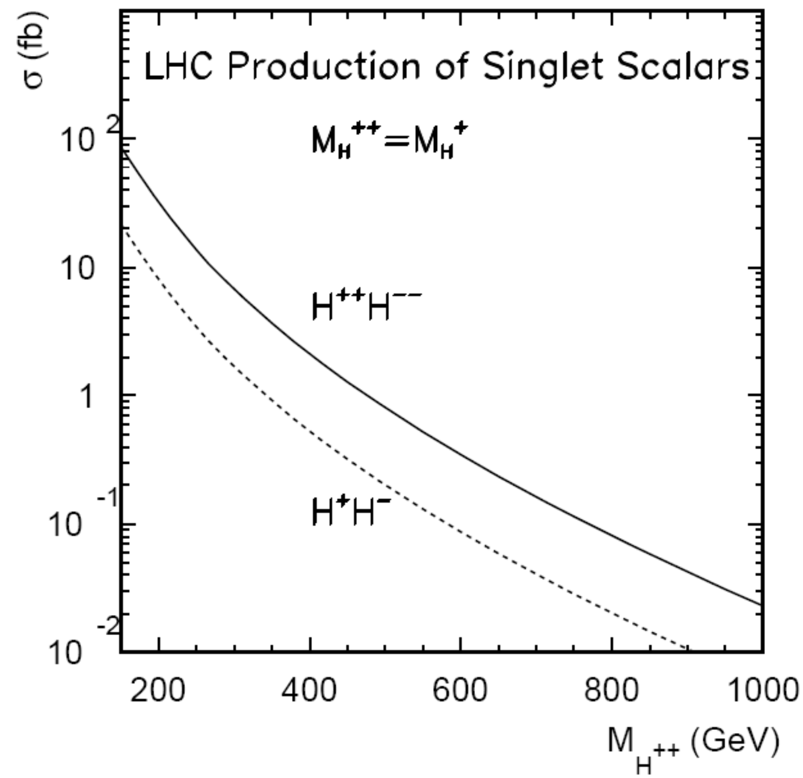
ϕ_2=0, ϕ_1=0~2π



LHC H^{++} production



Higgs Triplet model



Zee-Babu model

Type III seesaw

Franceschini et.al. 0805.1613

hyperchargeless triplet(s) of fermions: $\Sigma^+, \Sigma^0, \Sigma^-$

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L} = \mathcal{L}_{SM} + Tr[\overline{\Sigma} i \not{D} \Sigma] - \frac{1}{2} Tr[\overline{\Sigma} M_\Sigma \Sigma^c + \overline{\Sigma^c} M_\Sigma^* \Sigma] - \tilde{\phi}^\dagger \overline{\Sigma} \sqrt{2} Y_\Sigma L + h.c.$$

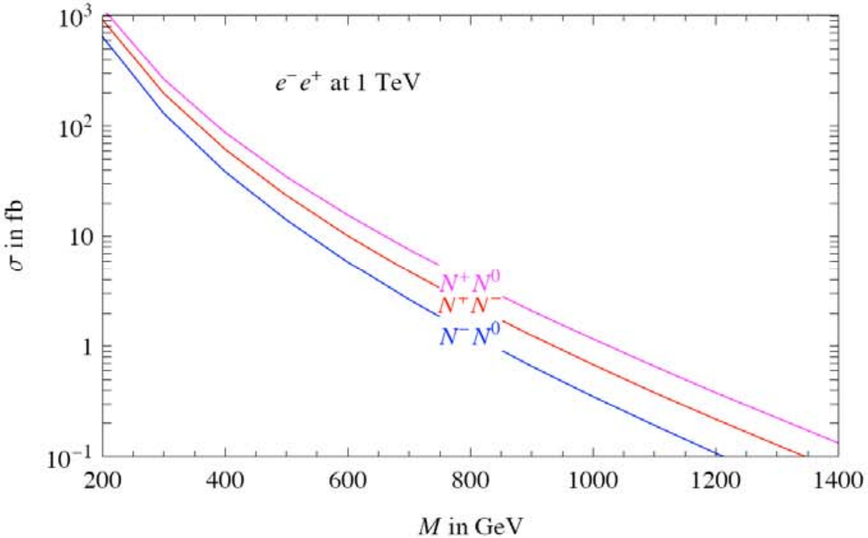
Majorana mass term

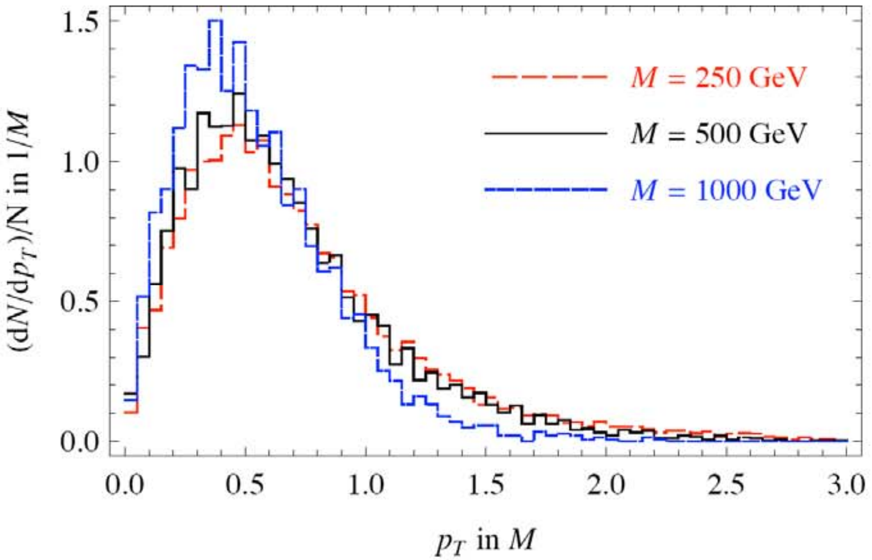
kinetic term: interactions with W and Z bosons

Yukawa interactions

Production at LHC

$$q\bar{q} \to Z \to \Sigma^+\Sigma^-$$
$$q\bar{q} \to W^\pm \to \Sigma^\pm\Sigma^0$$





⇒ for $M_\Sigma = 250\,\text{GeV}$: **3000 triplet pairs for** $\mathcal{L} = 3\,\text{fb}^{-1}$
$M_\Sigma = 1\,\text{TeV}$: **10 triplet pairs for** $\mathcal{L} = 3\,\text{fb}^{-1}$

⇒ up to $M_\Sigma \sim 1.5\,\text{TeV}$

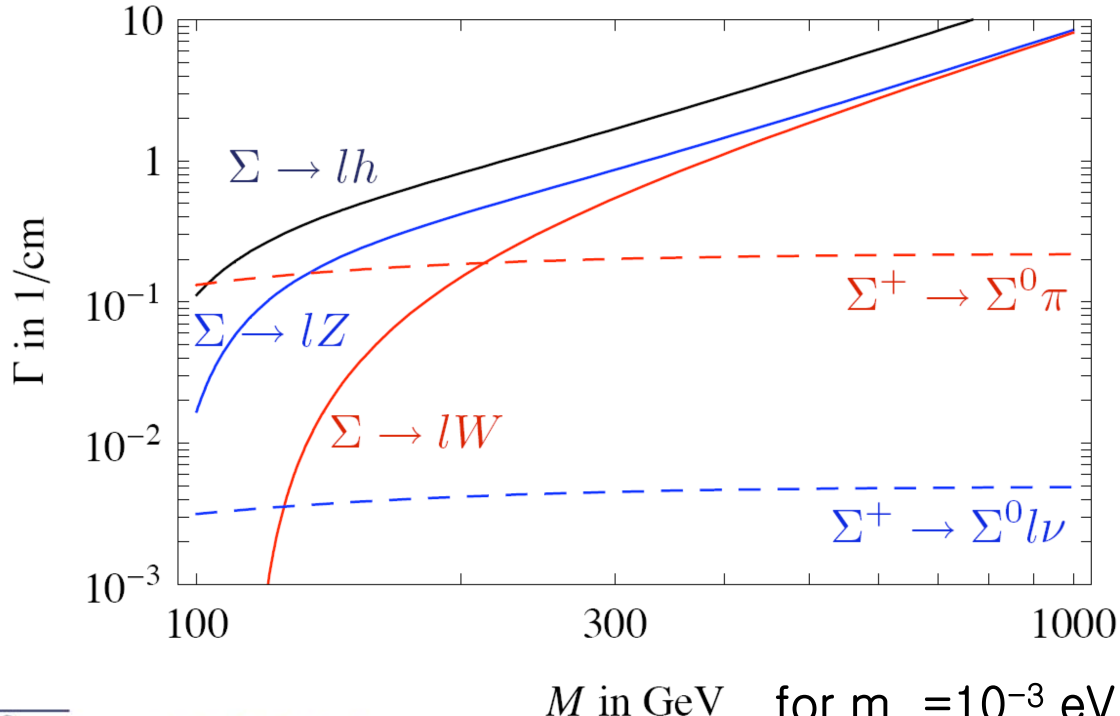
⇒ to determine M_Σ, establish it is a fermion produced via gauge interaction

Decay of triplets

Franceschini, TH, Strumia '08

$$\Sigma^0 \to \nu h$$
$$\Sigma^0 \to Z\nu$$
$$\Sigma^0 \to W^- l^+$$

$$\Sigma^+ \to l^+ h$$
$$\Sigma^+ \to Z l^+$$
$$\Sigma^+ \to W^+ \nu$$



for $m_\nu = 10^{-3}$ eV

$$\tau_\Sigma = \frac{8\pi v^2}{\tilde{m} M_\Sigma^2} = 0.3\,\mathrm{mm} \cdot \frac{\sqrt{\delta m^2_{atm}}}{\tilde{m}} \cdot \left(\frac{100\,\mathrm{GeV}}{M_\Sigma}\right)^2$$

$\widetilde{\Sigma}^0$ DM

EJC, 0909.3408

- Thermal relic abundance suppressed by strong gauge interactions. Requires non-standard cosmology.
- m_{DM}>520 GeV, otherwise, annihilation to WW produces too much cosmic antiproton.
- $\Sigma^+ \rightarrow \Sigma^0 \pi^+$ with τ=5.5cm-6.3m depending on the mass splitting (tree+loop) → slowly-moving and highly-ionizing tracks disappearing inside a detector.
- Cascade Higgs from Bino decay: larger than 0.5fb for squark/gluino mass below 1 TeV → look for Higgs to bb at displaced vertices.

$$\tilde{B} \rightarrow \nu\tilde{\Sigma}^0,\ l^\pm\tilde{\Sigma}^\mp$$
$$h\nu\tilde{\Sigma}^0,\ hl^\pm\tilde{\Sigma}^\mp$$

PB, EJC, 1007.2281

Conclusion

- Seesaw is a favorable mechanism to explain tiny neutrino masses.
- Supersymmetric TeV seesaw models have interesting DM connection.
- The model can be tested at LHC by observing LNV, LFV and/or exotic signatures associated with seesaw DM.