Probing the See Saw Mechanism at Future Hadron Colliders

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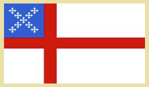
U Mass Amherst



Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

My pronouns: he/him/his

1812.01630: J.C. Helo, H. Li, N. Neill, MJRM, J.C. Vasquez
1810.09450: Y. Du, A. Dunbrack, MJRM, J.-H. Yu
1806.08499: B. Dev, MJRM, Y. Zhang

IAS Future Collider Workshop
January 2019

Goals For This Talk

- *Illustrate how studies of the tri-lepton channel at the HL/HE-LHC & a 100 TeV pp collider may help distinguish between mLRSM and non-minimal LRSM/minimal types I or II see saw mechanisms*
- *Illustrate reach of a 100 TeV collider for discovery and characterization of type II see saw scalar sector*
- *Encourage future work*

Outline

I. Context

II. Type I+II See Saw & LRSM

III. Tri-lepton Channel at pp Colliders

IV. Probing the Scalar Potential

V. Outlook

I. Context

Neutrino Mass Low-Energy EFT

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \; + \; {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \; + \; {\rm h.c.}$$

Majorana

Neutrino Mass Low-Energy EFT

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

What is the mass scale Λ associated with m_ν generation ?

Neutrino Mass Low-Energy EFT

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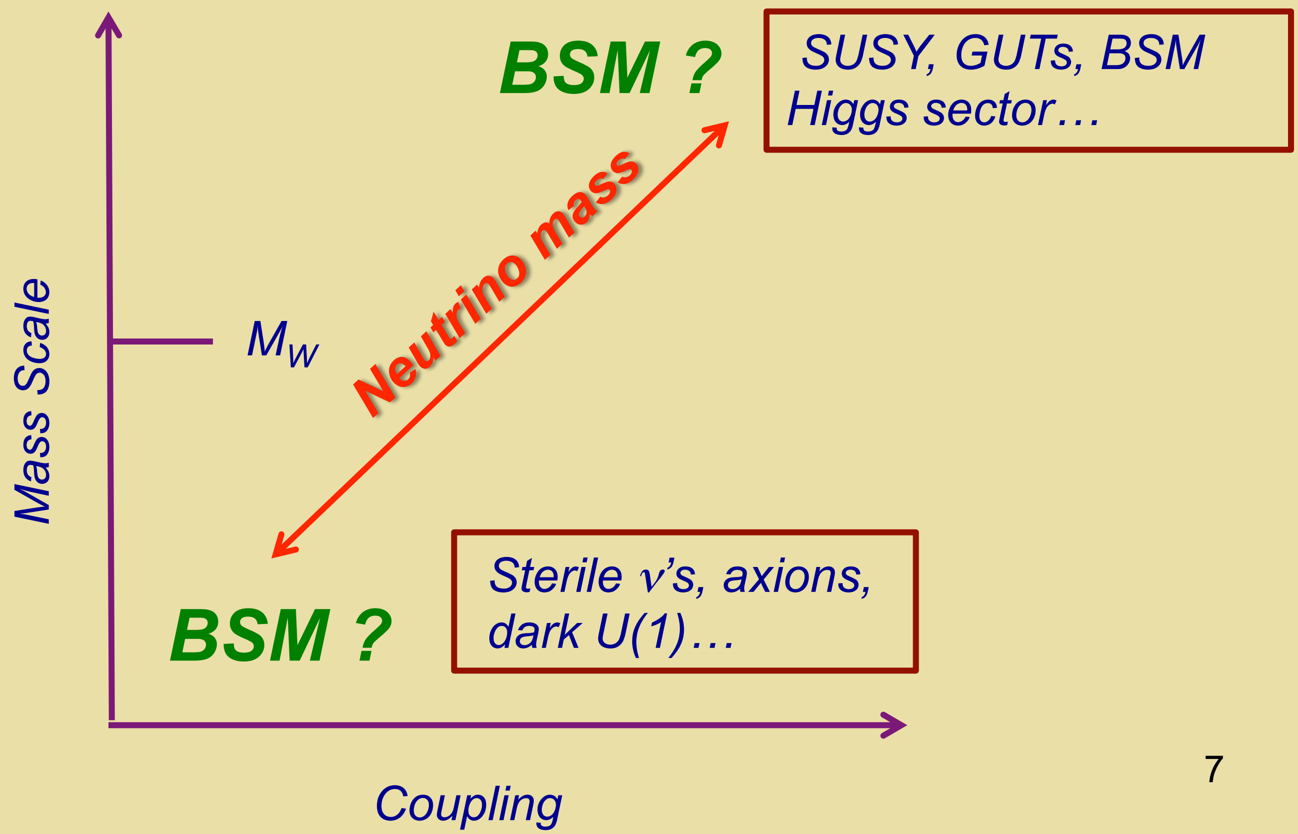


Neutrino Mass Low-Energy EFT

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

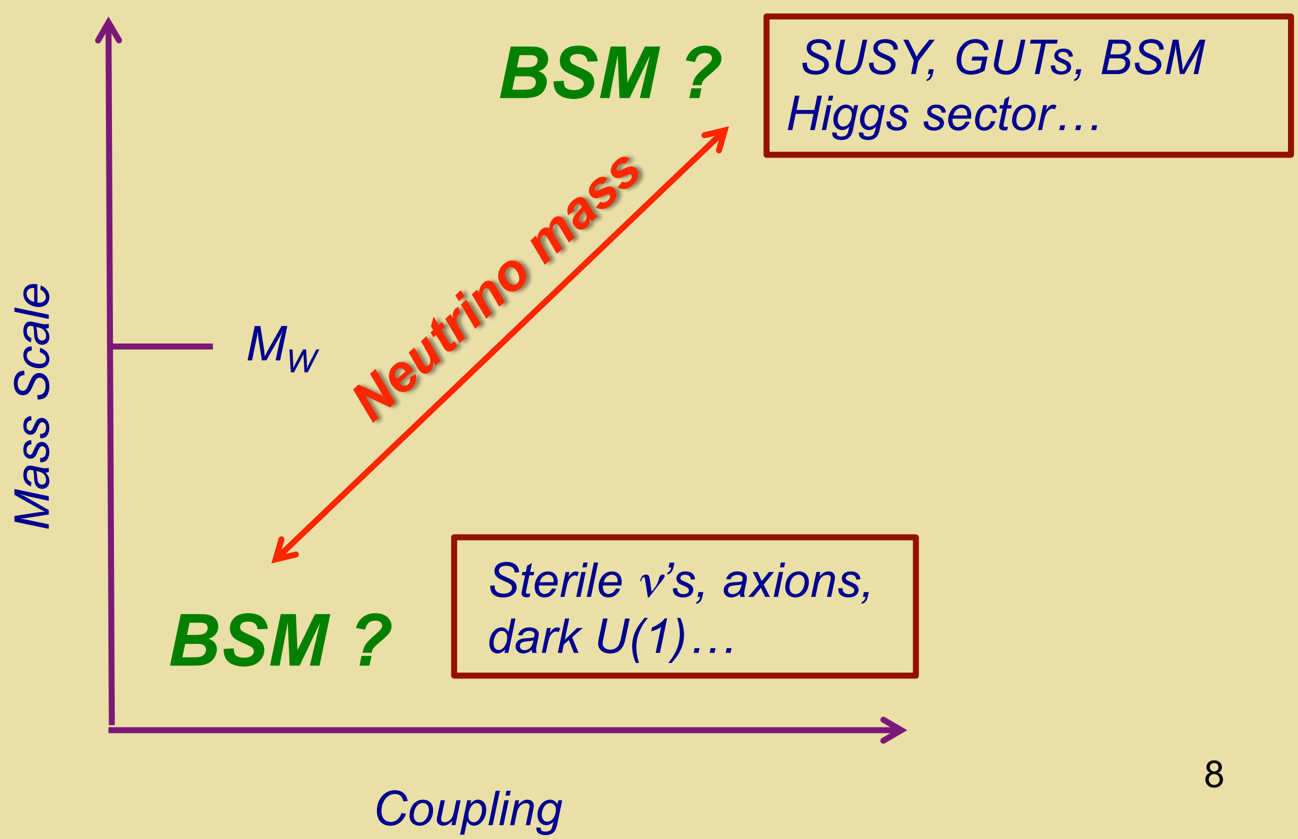
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

What is the mass scale Λ associated with m_ν generation ?

What are the corresponding dynamics ?



Neutrino Mass Models

- Type I see-saw — “νSM”, “νMSSM”, LRSM,
- Type II see-saw — LRSM
- Type III see-saw — GUTs
- Inverse see-saw — LRSM
- Radiative — MSSM

+ combinations & many other examples

Type I See-Saw

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

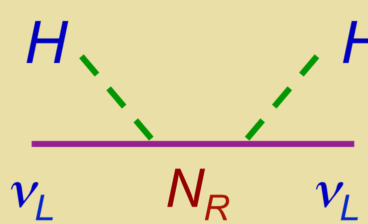
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana

Low-energy eff theory

$\Lambda = m_N$



Type I: N_R *SU(2)*$_L$ *singlet*
Type III: N_R *SU(2)*$_L$ *triplet*

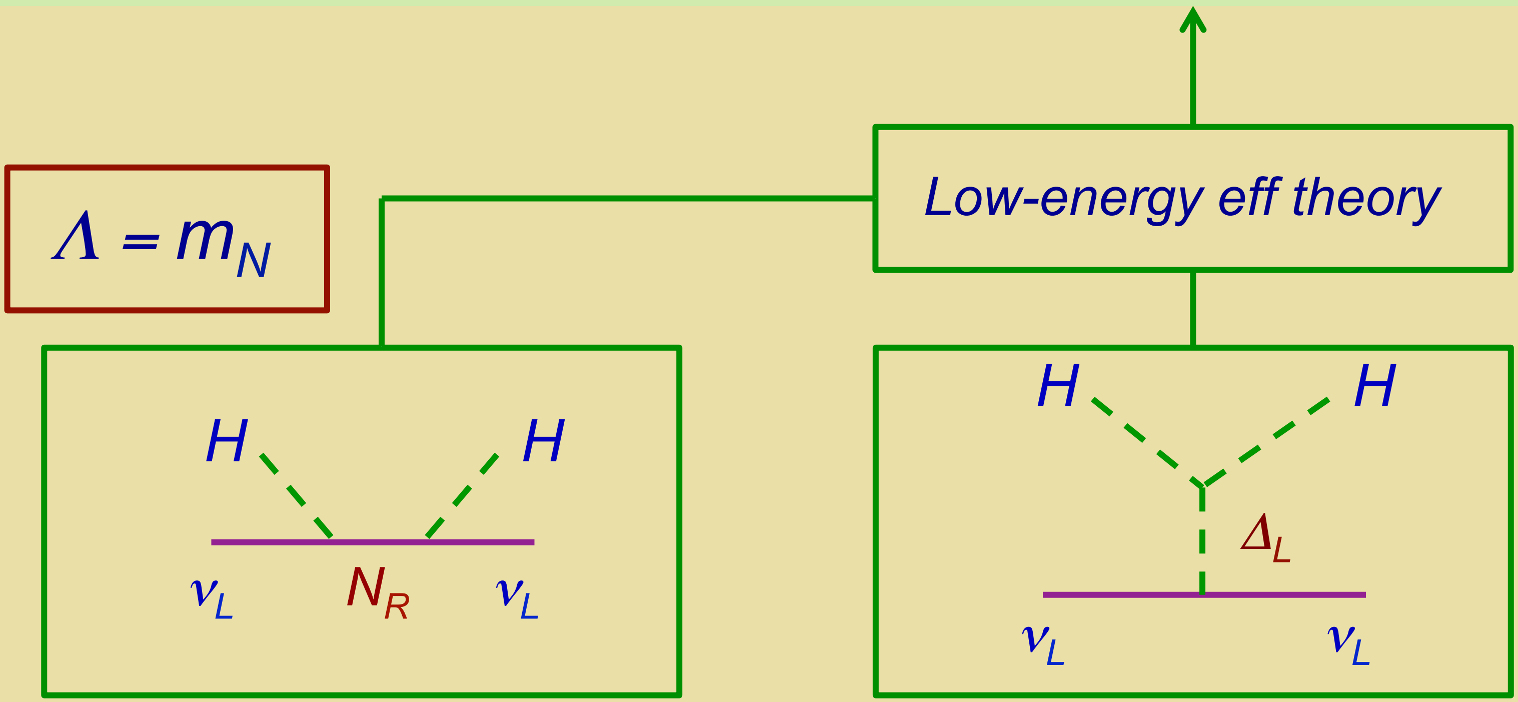
Type I See-Saw

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana



Type I: N_R $SU(2)_L$ *singlet*

Type III: N_R $SU(2)_L$ *triplet*

Type II: Δ_L $SU(2)_L$ *triplet*

Type II See-Saw

$$\mathcal{L}_{\text{mass}} = y \bar{L} \tilde{H} \nu_R \; + \; \text{h.c.}$$

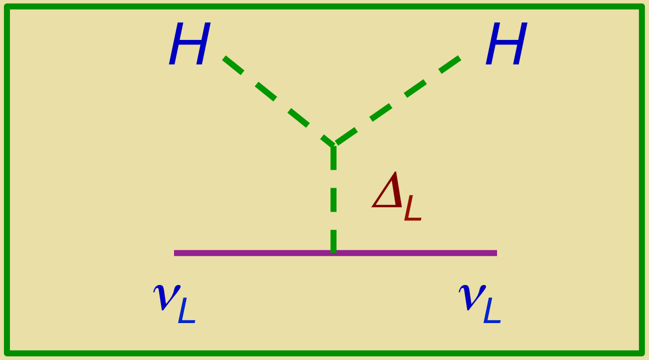
Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda} \bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Introduce "Complex Triplet": Δ_L ~ (1, 3, 2)

$$\Delta_L = \begin{pmatrix} \Delta^+ \sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+ \sqrt{2} \end{pmatrix}$$



$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + \text{h.c.}$$

$$\frac{y}{\Lambda} \sim g h \left(\frac{\mu}{m_\Delta} \right) \frac{1}{m_\Delta}$$

See Saw Scenarios

Model Class	*Minimal*	*LRSM*	ΔV
Type I	✔	✔	✖
Type II	✔	✔	✔
Type III	✔	✖	✖
Inverse	✔	✔	✖

See Saw Scenarios

Model Class	Minimal	LRSM	ΔV
Type I	✔	✔	✖
Type II	✔	✔	✔
Type III	✔	✖	✖
Inverse	✔	✔	✖

This Talk: How can we probe with LHC & future pp colliders

Comments

- *Many other earlier works on see saw collider pheno (e.g. Keung & Senjanovic ‘83, Perez et al ‘08, Nemevsek et al ‘12, Han et al ‘13, Izaguirre & Shuve ’15,…) Apologies to others not cited here !*

- *Following assumes see saw scale at the 10’s of TeV or below*

II. Types I + II See Saw & LRSM

See Saw Scenarios

Model Class	Minimal	LRSM	ΔV
Type I	✔	✔	✖
Type II	✔	✔	✔
Type III	✔	✖	✖
Inverse	✔	✔	✖

How to distinguish minimal LRSM from non-minimal LRSM or other minimal scenarios

Minimal Left-Right Symmetric Model

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \mathrm{h.c.}$$ **+ *Yukawa***

$$\mathcal{L}_{\mathrm{mass}} = \left(\bar{\nu}_L \;\; \bar{N}_R^C \right) \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} + m_L \bar{\nu}_L^C \nu_L$$

Minimal Left-Right Symmetric Model

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$ **+ *Yukawa***

Type I see-saw *Type II see-saw*

$$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix} + m_L \bar{\nu}_L^C \nu_L$$

$$m_N \sim g h_R \left\langle \Delta_R^0 \right\rangle$$

$$m_L \sim g h_L \left\langle \Delta_L^0 \right\rangle$$

Non-Minimal Left-Right Symmetric Model

LRSM inverse see saw:

Add gauge singlet neutral leptons
w/ Majorana mass μ

$$\mathcal{M} = \begin{pmatrix} 0 & M_D^T & 0 \\ M_D & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}$$

$$M_\nu \simeq M_D^T \frac{1}{M_N^T} \mu \frac{1}{M_N} M_D$$

Heavy-Light Neutrino Mixing

Mass matrix diagonalization

$$\begin{pmatrix} \nu' \\ N'^c \end{pmatrix} = \begin{pmatrix} 1 & \Theta \\ -\Theta^T & 1 \end{pmatrix} \begin{pmatrix} \nu \\ N^c \end{pmatrix}$$

$$\boxed{\Theta \simeq M_D^* M_N^{-1}}$$

Heavy-Light Neutrino Mixing

Mass matrix diagonalization

$$\begin{pmatrix} \nu' \\ N'^c \end{pmatrix} = \begin{pmatrix} 1 & \Theta \\ -\Theta^T & 1 \end{pmatrix} \begin{pmatrix} \nu \\ N^c \end{pmatrix}$$

$$\Theta \simeq M_D^* M_N^{-1}$$

Colliders:

Probe Θ for M_N at or below O(few) TeV

Models:

- *Minimal LRSM: predict Θ*
- *Minimal type I or non-minimal LRSM: Θ arbitrary*

Heavy-Light Neutrino Mixing

Minimal Model

$$M_D = V_L^* \hat{M}_N \sqrt{\frac{v_L}{v_R} - \frac{\hat{M}_\nu}{\hat{M}_N}} V_L^\dagger$$

Non-Minimal Model

$$V_R^\dagger M_D = \hat{M}_N U_R^\dagger \frac{1}{\sqrt{\hat{\mu}}} \mathcal{R} \sqrt{m_\nu} V_L^\dagger$$

Heavy-Light Neutrino Mixing

Minimal Model

$$M_D = V_L^* \hat{M}_N \sqrt{\frac{v_L}{v_R} - \frac{\hat{M}_\nu}{\hat{M}_N}} V_L^\dagger$$

Low-energy ν pheno

Collider studies

Non-Minimal Model

Collider studies

Low-energy ν pheno

$$V_R^\dagger M_D = \hat{M}_N U_R^\dagger \frac{1}{\sqrt{\hat{\mu}}} \mathcal{R} \sqrt{m_\nu} V_L^\dagger$$

Heavy-Light Neutrino Mixing

Minimal Model

$$M_D = V_L^* \hat{M}_N \sqrt{\frac{v_L}{v_R} - \frac{\hat{M}_\nu}{\hat{M}_N}} V_L^\dagger$$

Low-energy ν pheno

Collider studies

Non-Minimal Model

Arbitrary (Casas-Ibarra)

Collider studies

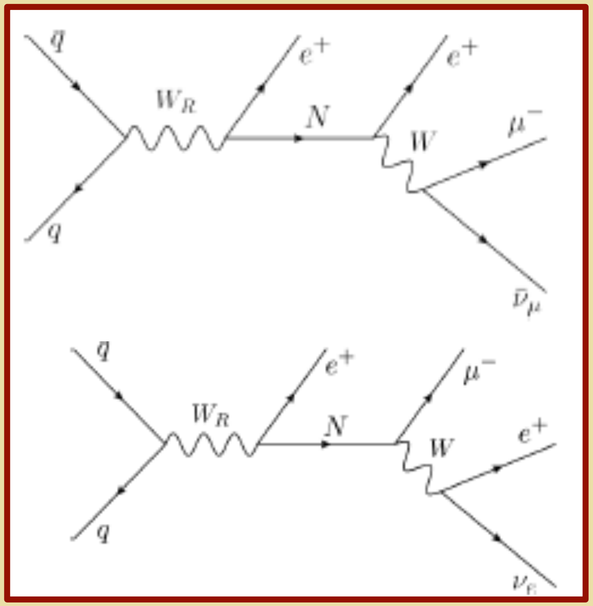
Low-energy ν pheno

$$V_R^\dagger M_D = \hat{M}_N U_R^\dagger \frac{1}{\sqrt{\hat{\mu}}} \mathcal{R} \sqrt{m_\nu} V_L^\dagger$$

III. Tri-Lepton Channel at pp Colliders

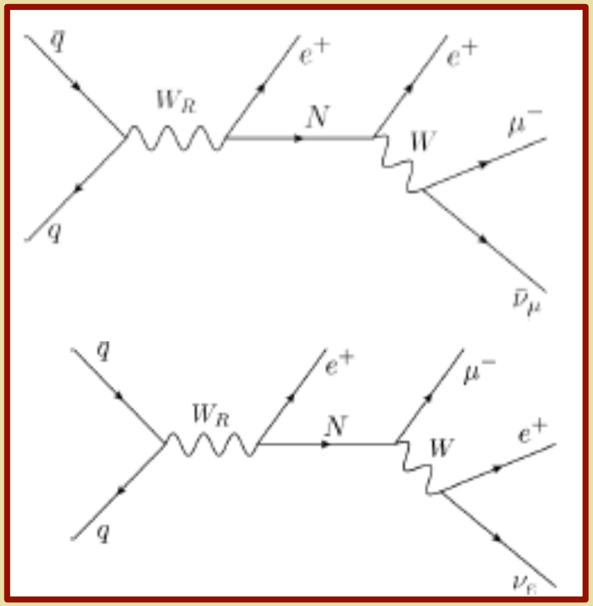
1812.01630: J.C. Helo, H. Li, N. Neill, MJRM, J.C. Vasquez

Tri-Lepton Channel



- *Relatively clean*
- *Previous work min type I*
- *Study prompt decay region*
- *Analysis: back up slides*

Tri-Lepton Channel

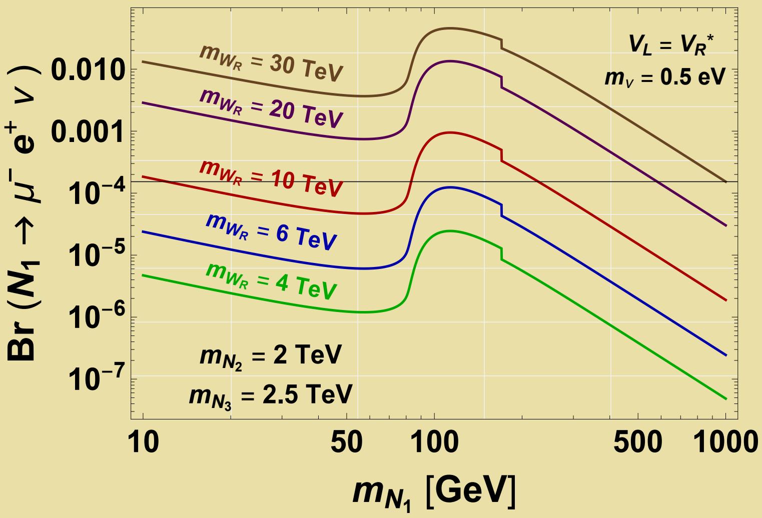


$$\Gamma\left(N \to l^{\pm} l'^{\mp} \nu\right) = \left(|(\Theta_L)_{lN}|^2 + |(\Theta_L)_{l'N}|^2\right)$$

$$\times \quad \frac{G_F^2}{96\pi^4 m_N} \int_0^{m_N^2} dx \frac{\pi(m_N^2 - x)(m_N^4 + x m_N^2 - 2x^2)}{m_N^2(1 - \frac{x}{M_W^2})^2}$$

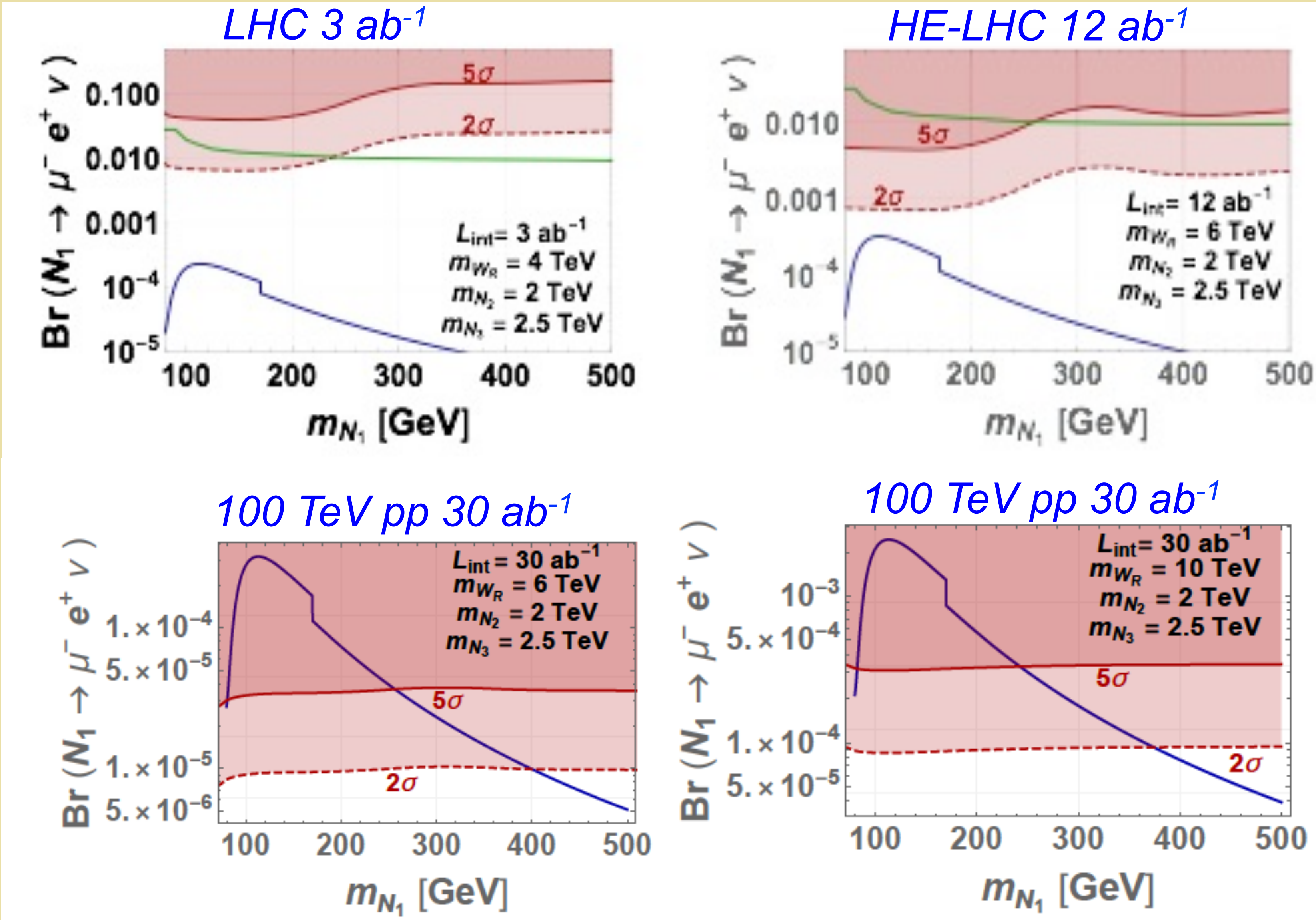
- *Relatively clean*
- *Previous work min type I*
- *Study prompt decay region*
- *Analysis: back up slides*

mLRSM N_1 BR

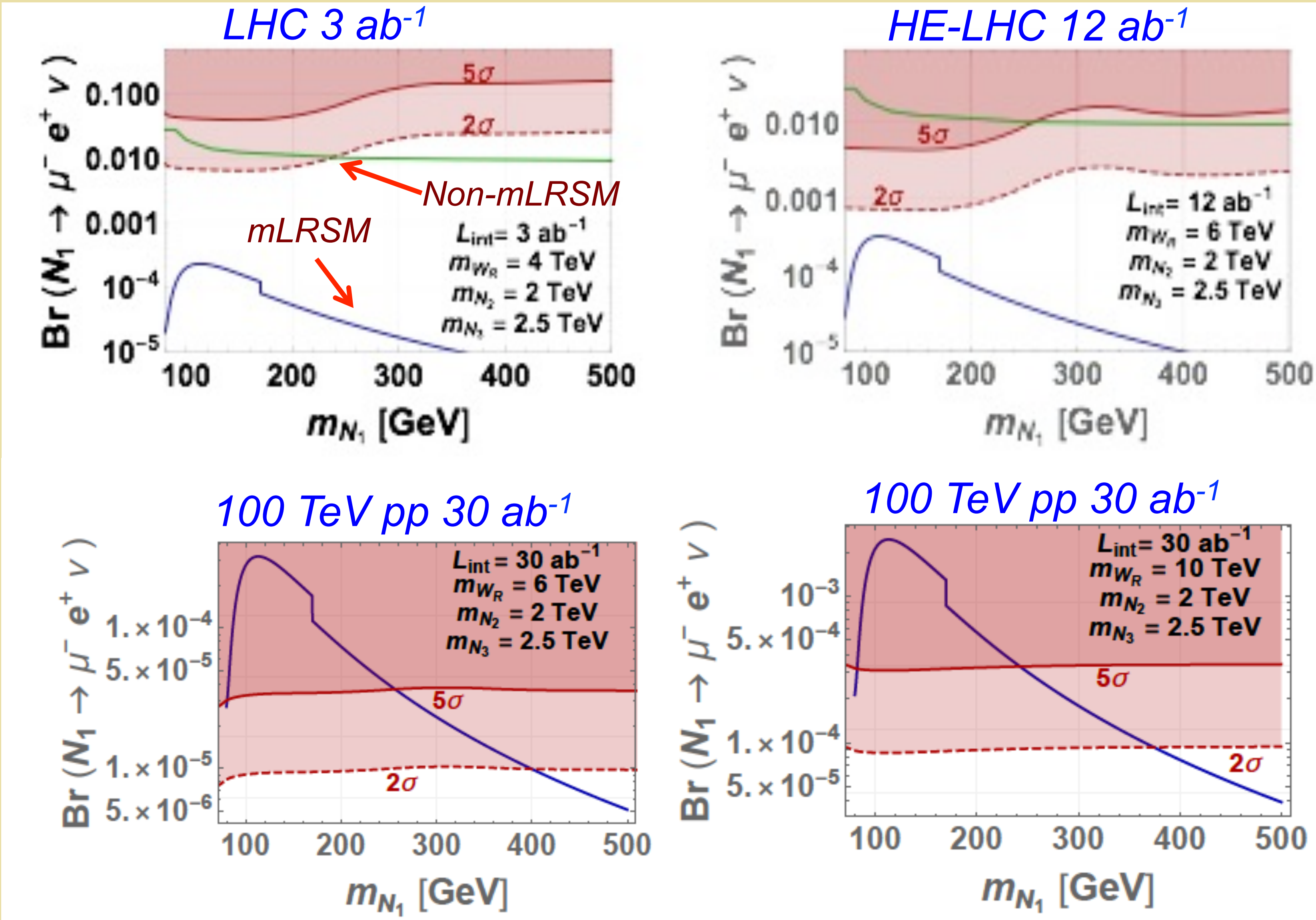


Dominant: $N_1 \to W_R^* l \to jj\, l$

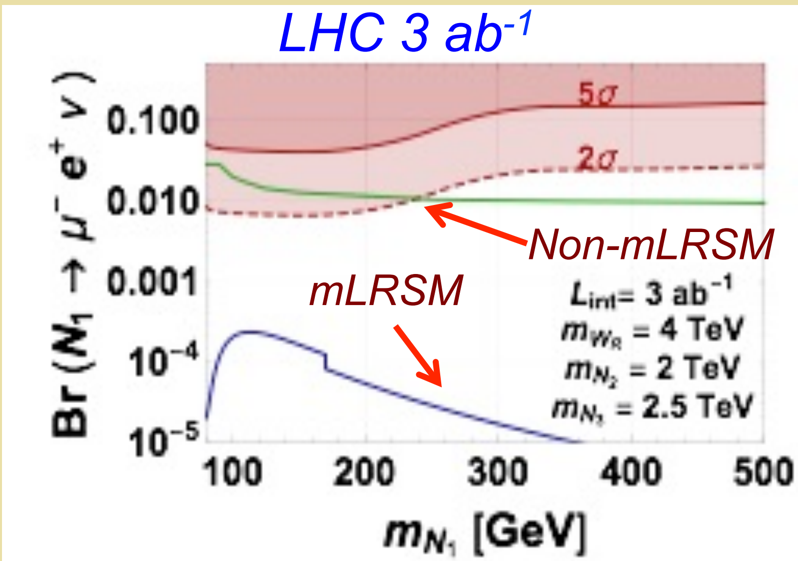
Sensitivities

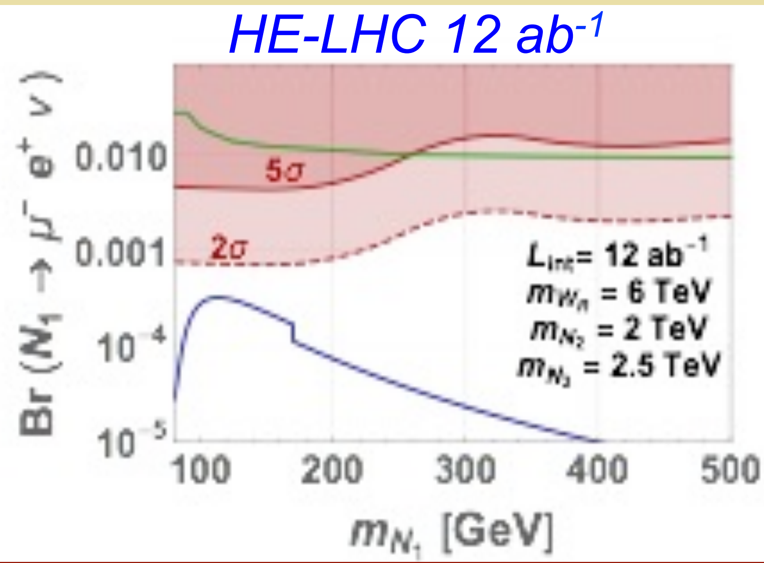


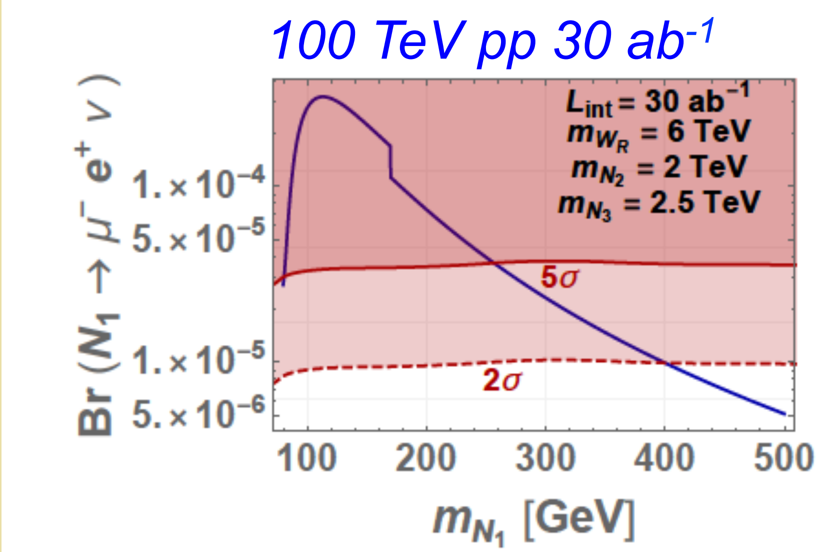
Sensitivities



Sensitivities



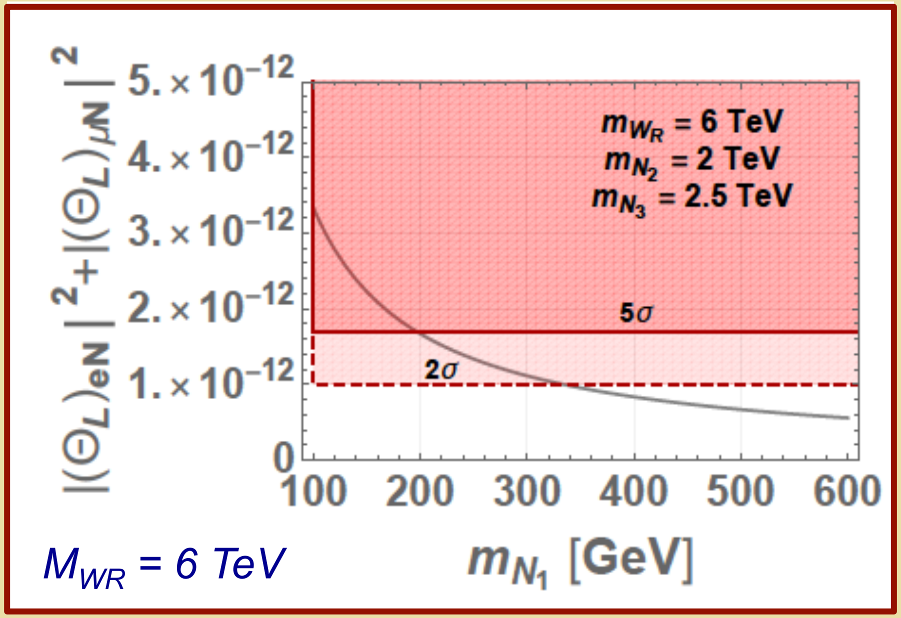


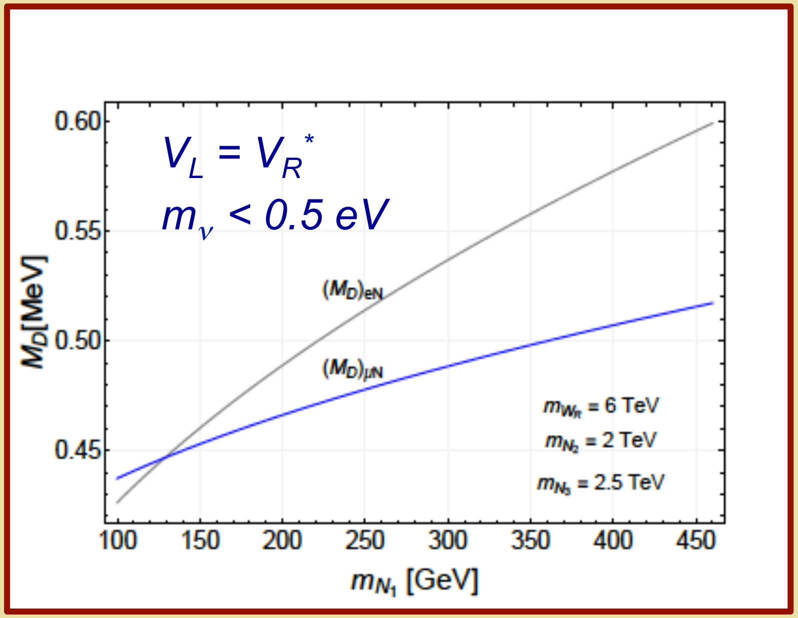


- *Observation of the tri-lepton channel at the HL/HE-LHC → non-minimal model or minimal type I*
- *Observing the tri-lepton channel in the mLRSM → 100 TeV pp collider needed*

Interpreting a Signal

100 TeV pp





Probing O(MeV) Dirac masses

IV. Probing the Scalar Potential

1810.09450: Y. Du, A. Dunbrack, MJRM, J.-H. Yu

- *If tri-lepton signal seen at HL/HE-LHC how distinguish between minimal type I, minimal type II, or non-minimal LRSM ?*

- *If tri-lepton signal first seen at 100 TeV pp collider, how confirm it is in context of LR symmetry*

See Saw Scenarios

Model Class	Minimal	LRSM	ΔV
Type I	✔	✔	✖
Type II	✔	✔	✔
Type III	✔	✖	✖
Inverse	✔	✔	✖

- *Follow on to Perez et al '08*
- *No assumption of LR symmetry*

Minimal Type II Potential

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

Minimal Type II Potential

$$V(\Phi, \Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^\mathrm{T}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2$$
$$+ \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

- ***How to discover Δ scalars ?***
- ***How to determine potential parameters ?***

Minimal Type II Potential

$$V(\Phi,\Delta) = -m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu\Phi^{\mathrm{T}}\mathrm{i}\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}[\Delta^\dagger\Delta\Delta^\dagger\Delta] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

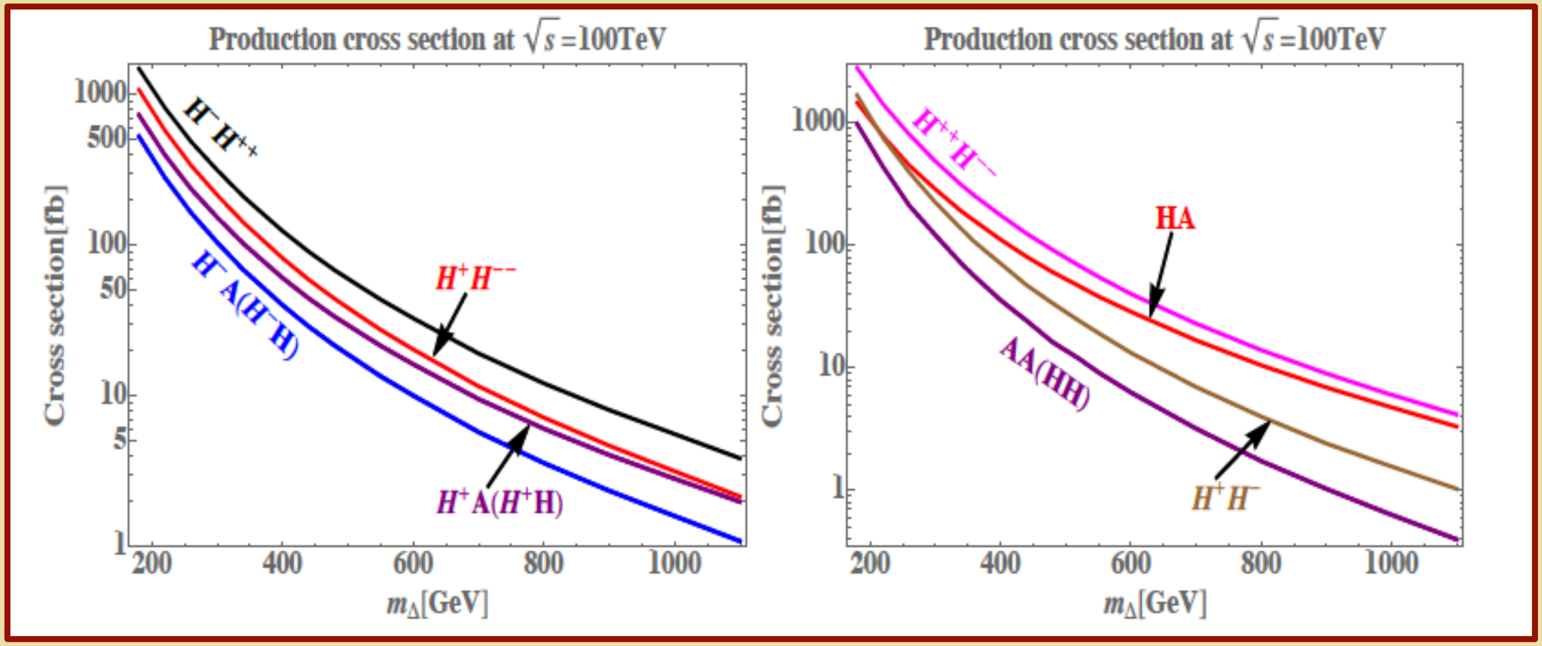
- ***How to discover Δ scalars ?***
- ***How to determine potential parameters ?***

Parameter	*Significance*	*Probe*
μ	*Type II m_ν*	*Neutrino mass*
λ_5	*Δ mass spectrum*	*Δ mass splittings*
λ_4	*Higgs portal*	*H^+ decays*
$\lambda_{2,3}$	*Δ self interaction*	*Challenging*

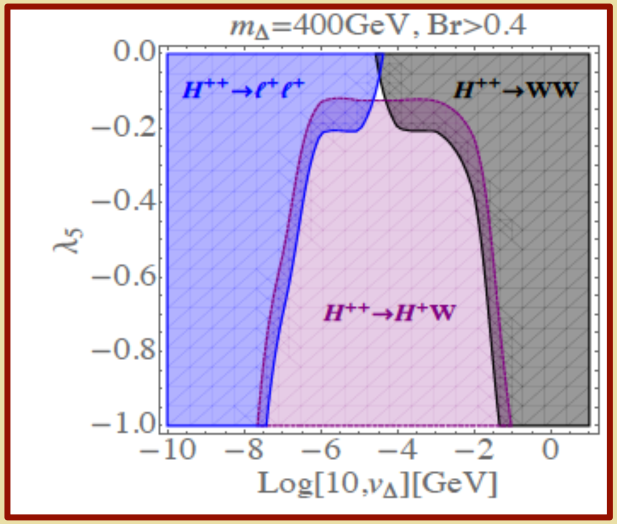
Discovery

Production	*Decay mode + final state*	*Regime*
$H^{++}H^{--}$	$l^+l^+l^-l^-$	Small v_Δ
$H^{++}H^{++}$	$W^+W^+W^-W^- \rightarrow l^+l^+l^-l^- + MET$	Large v_Δ
$H^{++}H^-$	$l^+l^+hW^- \rightarrow l^+l^+ bb\ l^- + MET$	Intermediate v_Δ
$H^{++}H^-$	$W^+W^+hW^- \rightarrow l^+l^+ bb\ l^- + MET$	Intermediate v_Δ

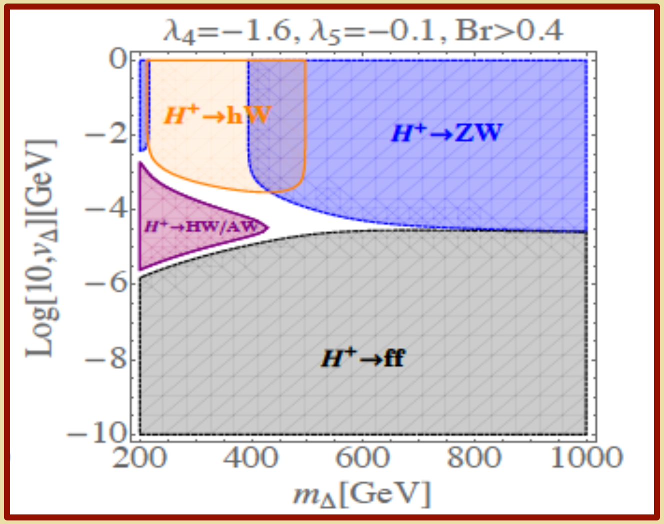
Discovery



Production cross section at $\sqrt{s}$=100TeV
Cross section[fb]
m_Δ[GeV]
$H^- H^{++}$
$H^+ H^{--}$
$H^- A(H^- H)$
$H^+ A(H^+ H)$
Production cross section at $\sqrt{s}$=100TeV
Cross section[fb]
m_Δ[GeV]
$H^{++} H^{--}$
HA
AA(HH)
$H^+ H^-$

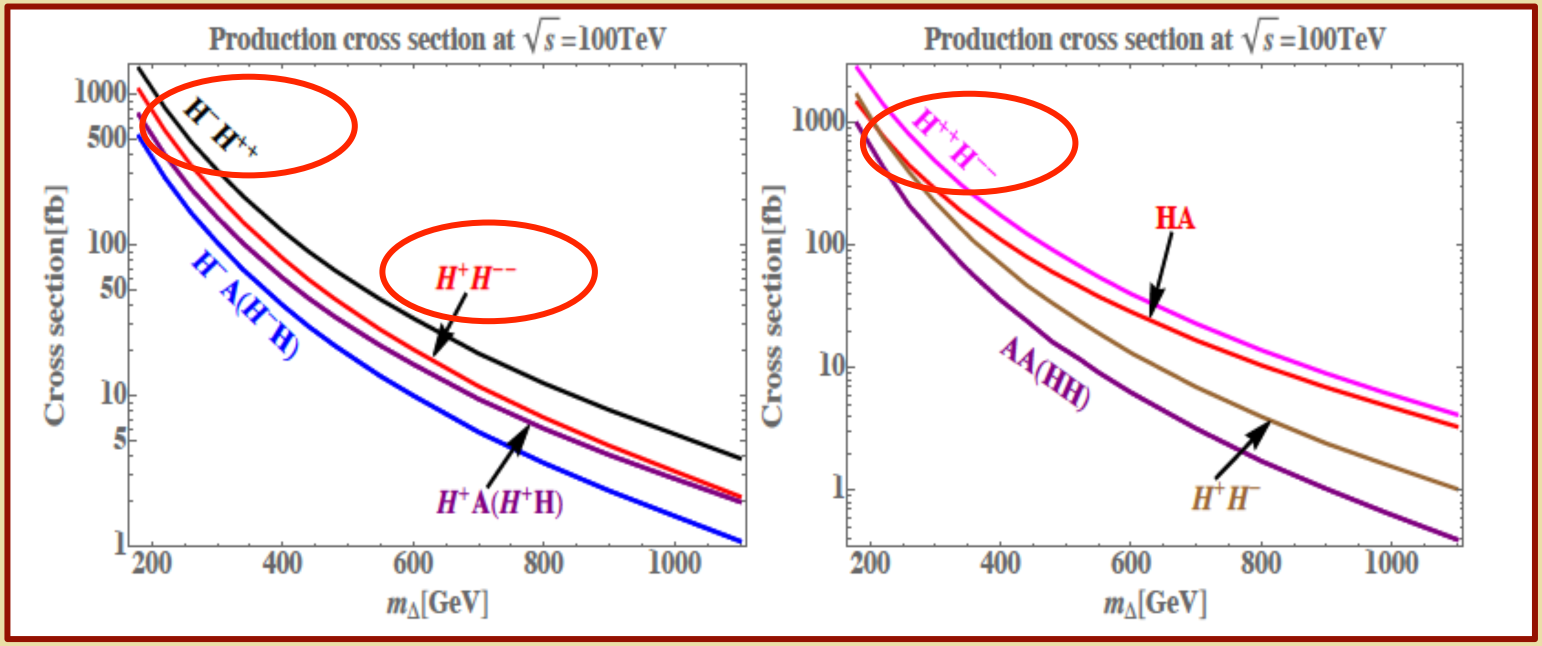


m_Δ=400GeV, Br>0.4
λ_5
Log[10,v_Δ][GeV]
$H^{++} \to \ell^+ \ell^+$
$H^{++} \to WW$
$H^{++} \to H^+ W$

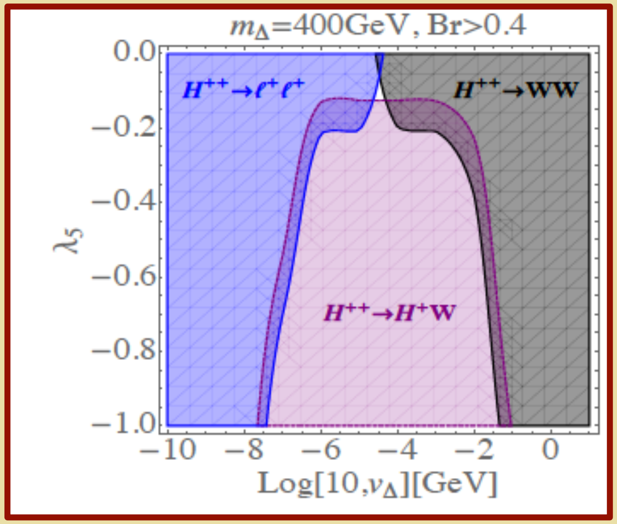


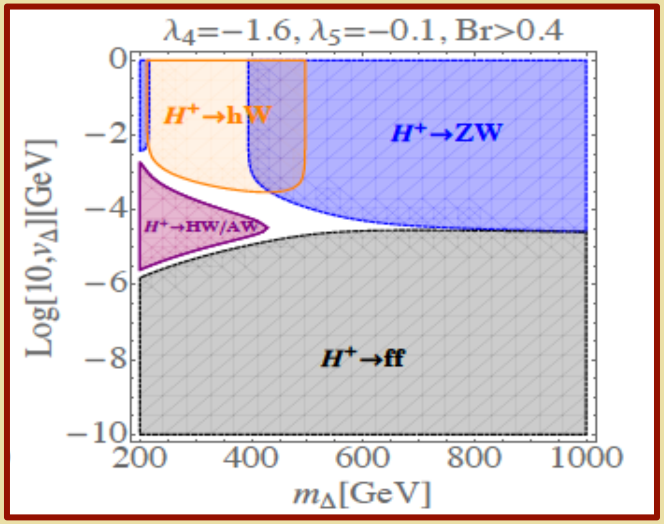
λ_4=−1.6, λ_5=−0.1, Br>0.4
Log[10,v_Δ][GeV]
m_Δ[GeV]
$H^+ \to hW$
$H^+ \to ZW$
$H^+ \to HW/AW$
$H^+ \to ff$

Discovery

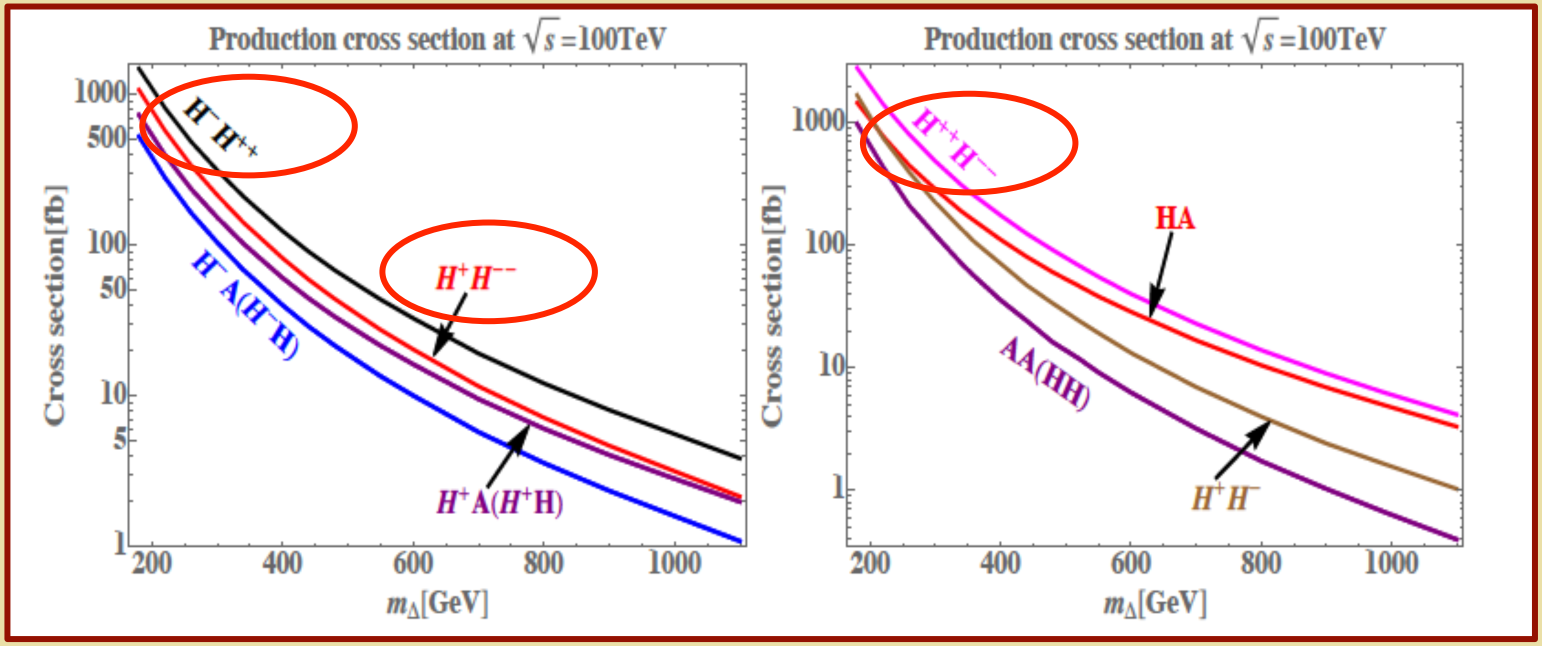


This study





Discovery



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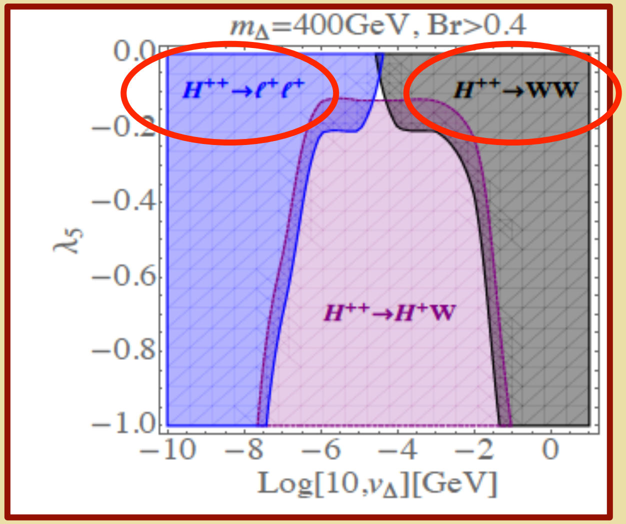
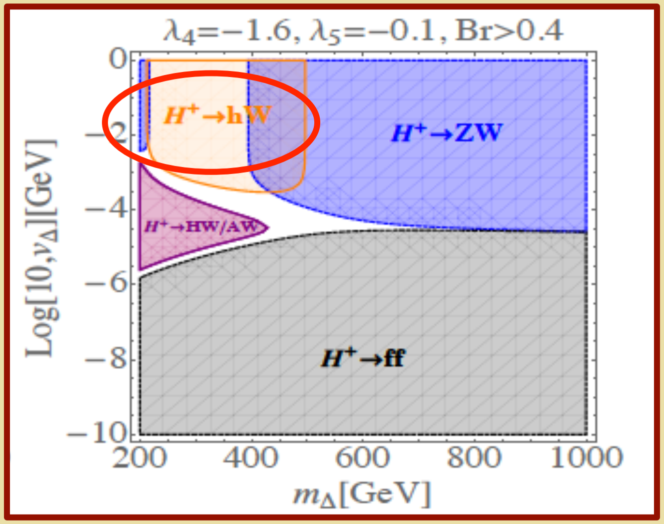
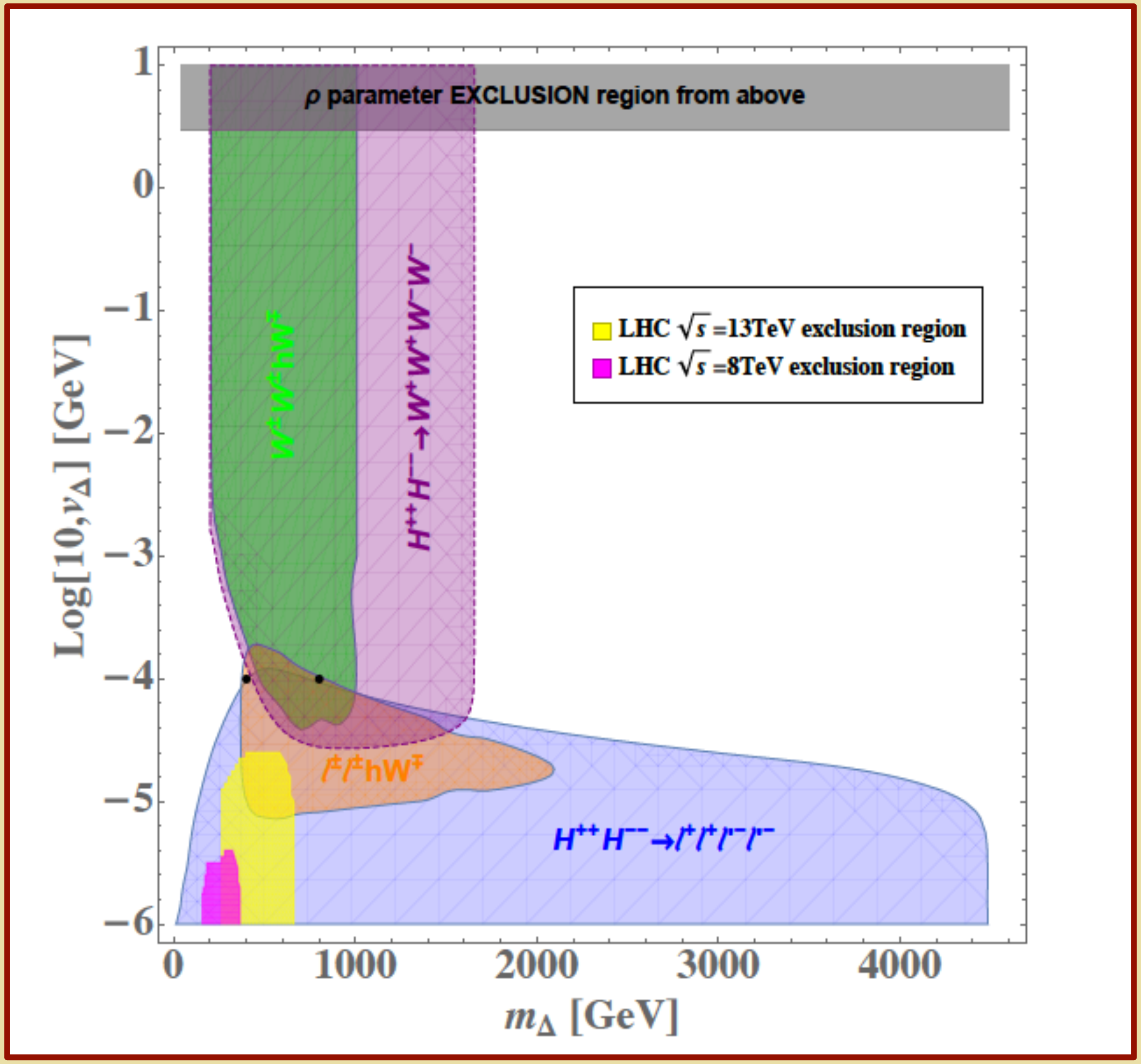




This study

Discovery



ρ parameter EXCLUSION region from above
LHC √s =13TeV exclusion region
LHC √s =8TeV exclusion region
W±W±hW∓
H++H−−→W+W+W−W−
l±l±hW∓
H++H−−→l+l+l−l−
Log[10,vΔ] [GeV]
mΔ [GeV]
1
0
−1
−2
−3
−4
−5
−6
0
1000
2000
3000
4000

Probing the Scalar Potential: λ_5

$$m^2_{H^{++}} - m^2_{H^+} \simeq -\frac{\lambda_5}{4} v^2_H$$

Probing the Scalar Potential

$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + v_\Phi + i\chi) \end{bmatrix} \qquad \Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$$

$$\begin{pmatrix} \varphi \\ \delta \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$$\tan 2\alpha \approx \frac{v_\Delta}{v_\Phi} \cdot \frac{2v_\Phi^2\lambda_{45} - 4m_\Delta^2}{2\lambda_1 v_\Phi^2 - m_\Delta^2} \approx \frac{v_\Delta}{v_\Phi} \cdot \frac{2v_\Phi^2\lambda_{45} - 4m_\Delta^2}{m_h^2 - m_\Delta^2}$$

Probing the Scalar Potential

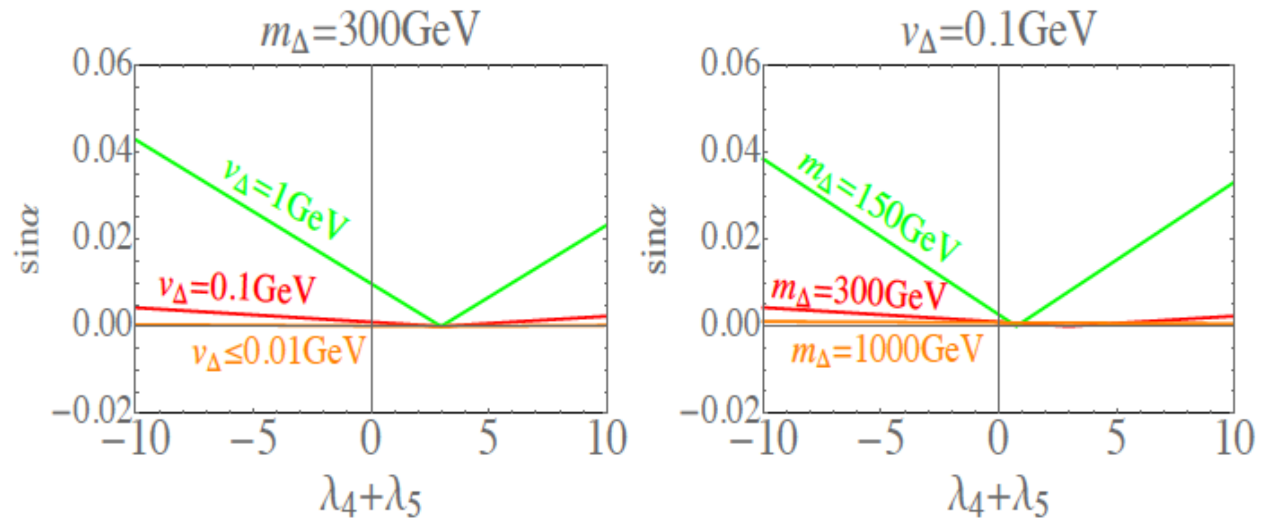
$$\Phi = \begin{bmatrix} \varphi^+ \\ \frac{1}{\sqrt{2}}(\varphi + v_\Phi + i\chi) \end{bmatrix} \qquad \Delta = \begin{bmatrix} \frac{\Delta^+}{\sqrt{2}} & H^{++} \\ \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) & -\frac{\Delta^+}{\sqrt{2}} \end{bmatrix}$$

$$\begin{pmatrix} \varphi \\ \delta \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

Triplet mass scale

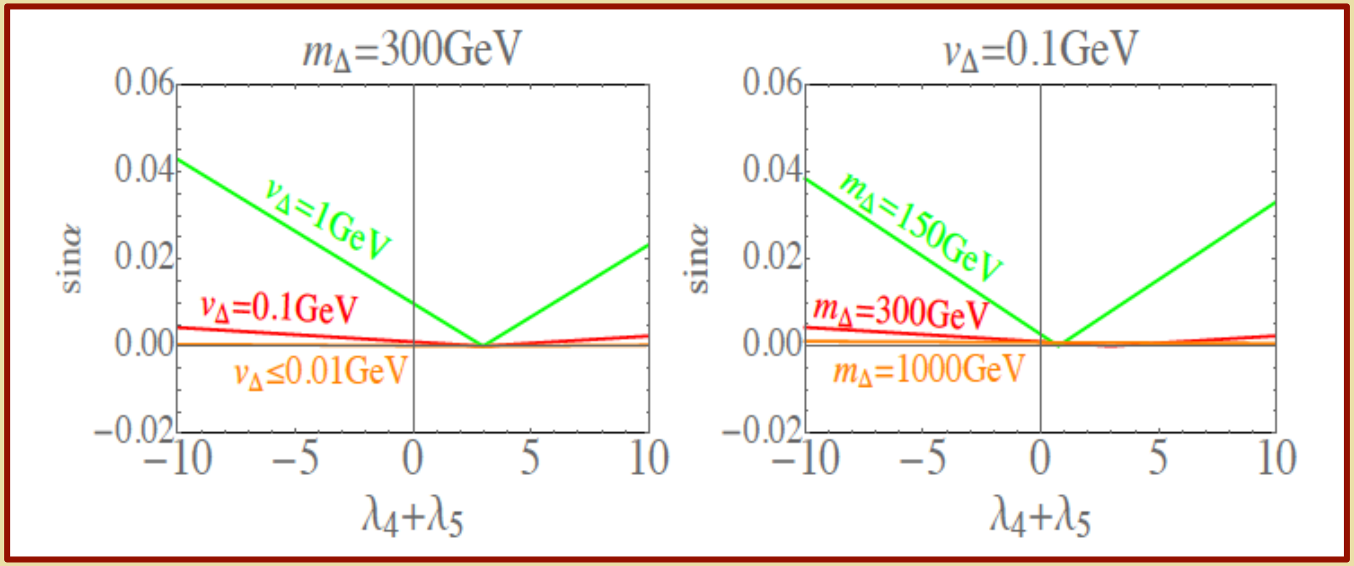
$$\tan 2\alpha \approx \frac{v_\Delta}{v_\Phi} \cdot \frac{2v_\Phi^2\lambda_{45} - 4m_\Delta^2}{2\lambda_1 v_\Phi^2 - m_\Delta^2} \approx \frac{v_\Delta}{v_\Phi} \cdot \frac{2v_\Phi^2\lambda_{45} - 4m_\Delta^2}{m_h^2 - m_\Delta^2}$$

Probing the Scalar Potential



Vertex	Coupling
hAZ	$-\frac{g}{2\cos\theta_W}(\cos\alpha\sin\beta_0 - 2\sin\alpha\cos\beta_0)$
HZZ	$\frac{2iem_Z}{\sin 2\theta_W}(2\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
HW^+W^-	$igm_Z\cos\theta_W(\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
hH^-W^+	$\frac{ig}{2}(\sin\beta_\pm\cos\alpha - \sqrt{2}\cos\beta_\pm\sin\alpha)$

Probing the Scalar Potential



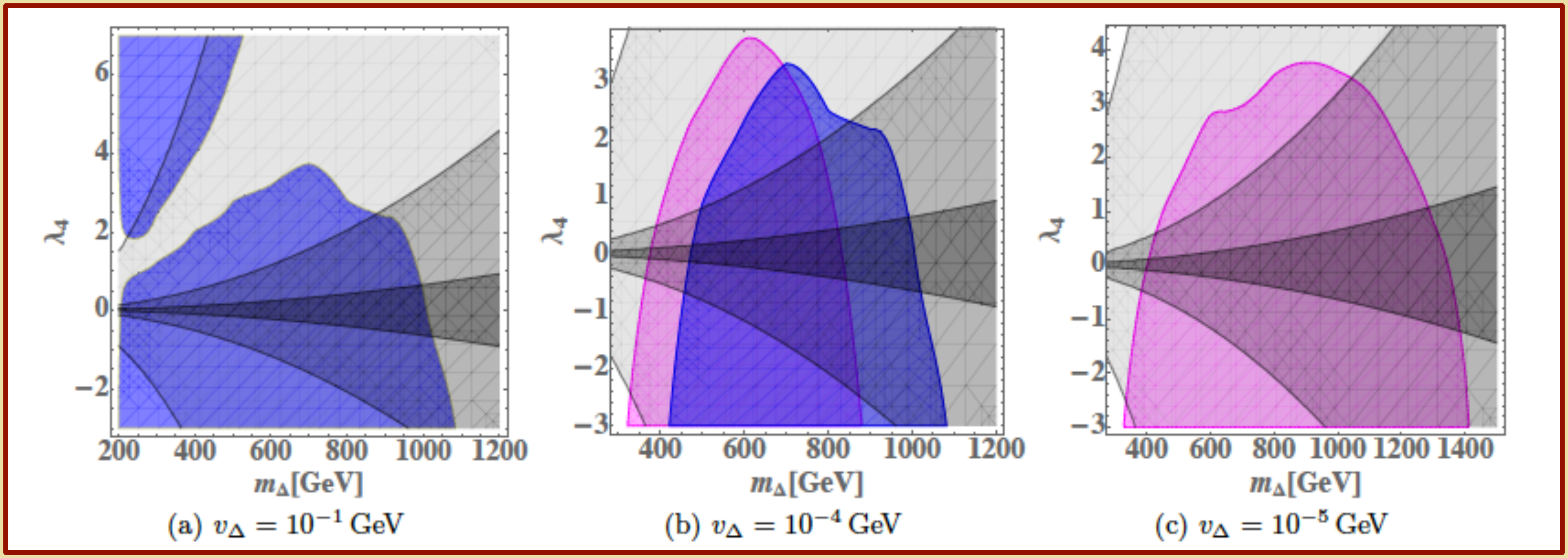
Vertex	Coupling
hAZ	$-\frac{g}{2\cos\theta_W}(\cos\alpha\sin\beta_0 - 2\sin\alpha\cos\beta_0)$
HZZ	$\frac{2iem_Z}{\sin 2\theta_W}(2\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
HW^+W^-	$igm_Z\cos\theta_W(\sin\beta_0\cos\alpha - \cos\beta_0\sin\alpha)$
hH^-W^+	$\frac{ig}{2}(\sin\beta_\pm\cos\alpha - \sqrt{2}\cos\beta_\pm\sin\alpha)$

Probing the Scalar Potential

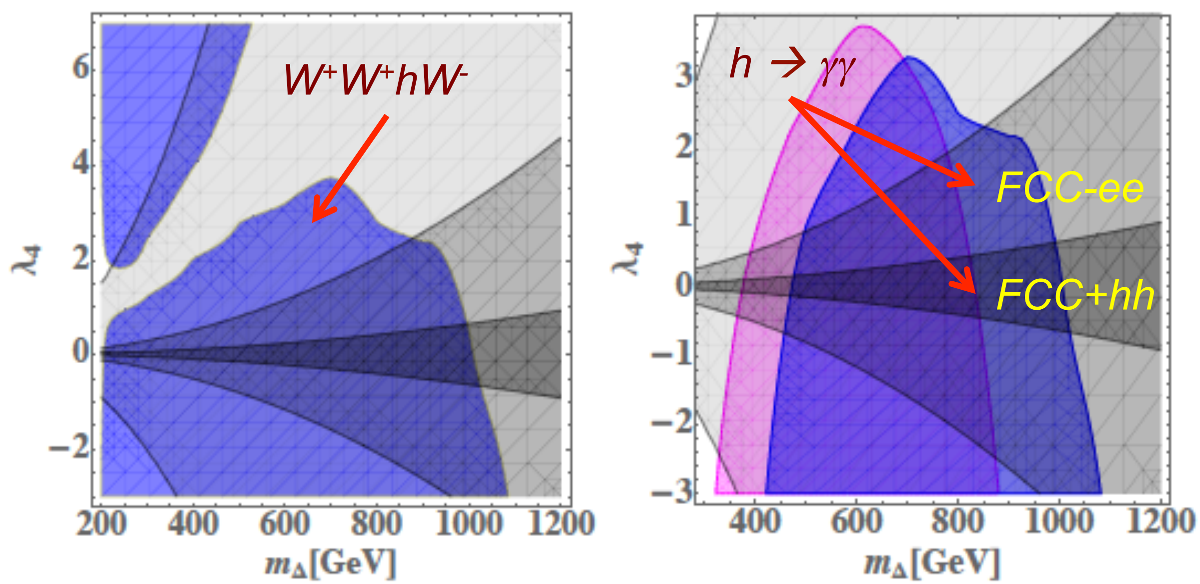
Production	Decay mode + final state	Regime
$H^{++}H^{-}$	$l^+l^+hW^- \rightarrow l^+l^+\, bb\, l^- + MET$	Intermediate v_Δ
$H^{++}H^{-}$	$W^+W^+hW^- \rightarrow l^+l^+\, bb\, l^- + MET$	Intermediate v_Δ

Vertex	Coupling
hAZ	$-\frac{g}{2\cos\theta_W}(\cos\alpha\sin\beta_0 \;-\; 2\sin\alpha\cos\beta_0)$
HZZ	$\frac{2iem_Z}{\sin 2\theta_W}(2\sin\beta_0\cos\alpha \;-\; \cos\beta_0\sin\alpha)$
HW^+W^-	$igm_Z\cos\theta_W(\sin\beta_0\cos\alpha \;-\; \cos\beta_0\sin\alpha)$
hH^-W^+	$\frac{ig}{2}(\sin\beta_\pm\cos\alpha \;-\; \sqrt{2}\cos\beta_\pm\sin\alpha)$

Probing the Scalar Potential



Probing the Scalar Potential



(a) $v_\Delta = 10^{-1}$ GeV (b) $v_\Delta = 10^{-4}$ GeV (c) $v_\Delta = 10^{-5}$ GeV

V. Outlook

- *Uncovering the origin of m_ν is a key open problem in particle physics and one for which a variety of experimental probes are needed*
- *For m_ν dynamics at the TeV scale or below, hadron colliders could provide unique tests of the see saw mechanism*
- *The tri-lepton channel can be used to probe the heavy-light neutrino mixing angle, and a comparison of HL/HE-LHC and 100 TeV pp collider searches could distinguish the minimal LRSM scenario from other see saw mechanisms*
- *A 100 TeV pp collider could significantly extend the discovery reach for scalars associated with the type II scenario and probe a variety of scalar sector couplings*
- *There exist many opportunities for additional studies → others are encouraged to get involved!*

Back Up Slides

Heavy-Light Neutrino Mixing

Minimal Model

$$\Theta = \sqrt{\epsilon - M_N^{-1} M_\nu} = M_D^* M_N^{-1} \qquad \Theta_L = \Theta V_R^*, \quad \Theta_R = \Theta V_L^*.$$

$$M_D = V_L^* \hat{M}_N \sqrt{\frac{v_L}{v_R} - \frac{\hat{M}_\nu}{\hat{M}_N}} V_L^\dagger$$

Non-Minimal Model

$$\Theta_L = \frac{1}{\sqrt{2}} M_D^\dagger V_R \hat{M}_N^{-1} \qquad V_R^\dagger M_D = \hat{M}_N U_R^\dagger \frac{1}{\sqrt{\hat{\mu}}} \mathcal{R} \sqrt{m_\nu} V_L^\dagger$$

Analysis: Backgrounds

ttZ, ttW, tt (j), WZ (j), 3W, Z/γ (j)

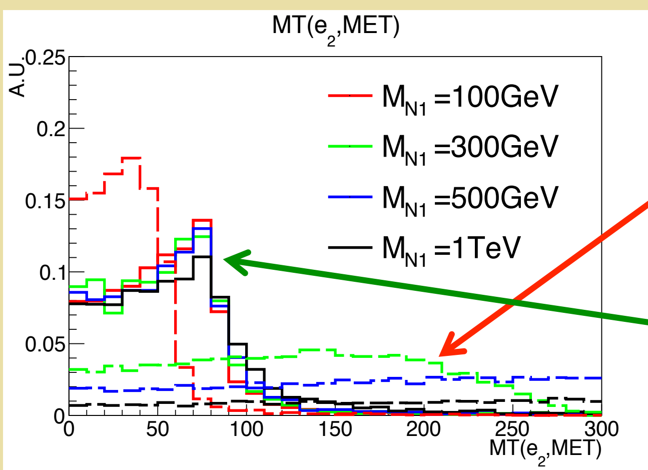
Cuts

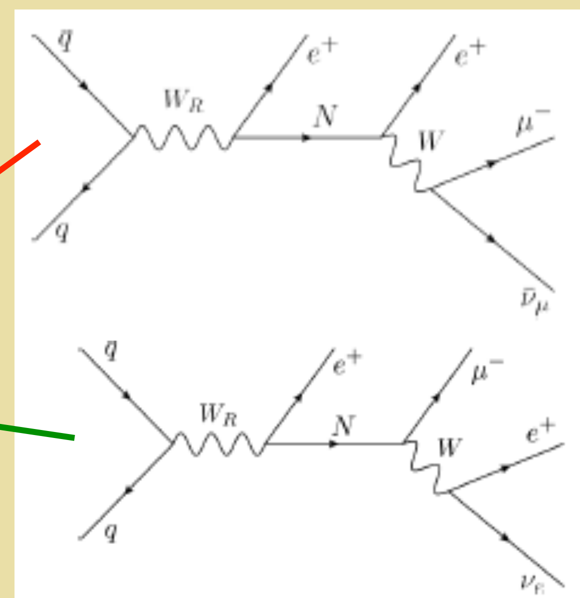
Cut description	
$e^+e^+\mu^-$, no b jets and no additional leptons	signal selection
$p^{lead}_{T,e^+} > 200$ GeV, $p^{sub}_{T,e^+} > 100$ GeV, $p^{lead}_{T,\mu^-} > 100$ GeV	reduce all backgrounds
$\not{E}_T > 100$ GeV	reduce mostly $t\bar{t}(j)$ and $Z/\gamma(j)$
$\lvert m_{inv}(e^+e^+) - 91.2\rvert) > 10$ GeV	reduce mostly $WZ(j)$
$m_T(e^+_{sub}\not{E}_T) < 150$ GeV	select channel shown in Fig. 1 (right)
$m_T(e^+e^+\mu^-\not{E}_T) > M_{W_R}/2$	reduce all backgrounds

Analysis: Cuts

100 TeV pp

Cut description	
$e^+e^+\mu^-$, no b jets and no additional leptons	signal selection
$p_{T,e^+}^{lead} > 200$ GeV, $p_{T,e^+}^{sub} > 100$ GeV, $p_{T,\mu^-}^{lead} > 100$ GeV	reduce all backgrounds
$\not{E}_T > 100$ GeV	reduce mostly $t\bar{t}(j)$ and $Z/\gamma(j)$
$\|m_{inv}(e^+e^+) - 91.2\|) > 10$ GeV	reduce mostly $WZ(j)$
$m_T(e^+_{sub}\not{E}_T) < 150$ GeV	select channel shown in Fig. 1 (right)
$m_T(e^+e^+\mu^-\not{E}_T) > M_{W_R}/2$	reduce all backgrounds

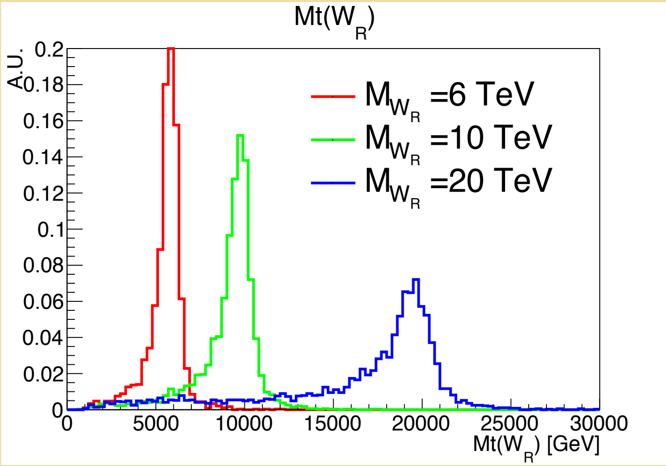




Analysis: Cuts

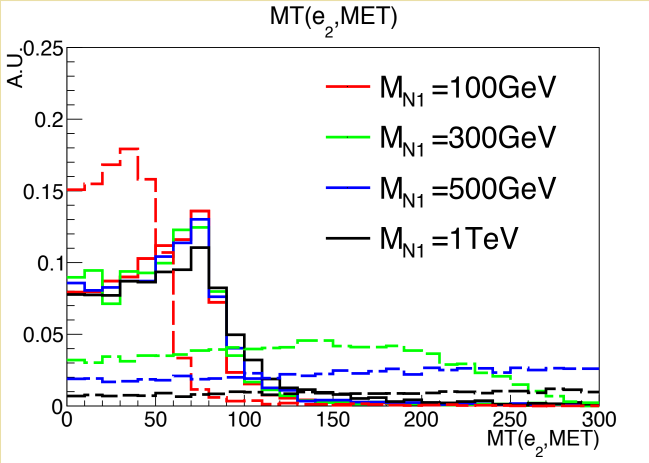
100 TeV pp

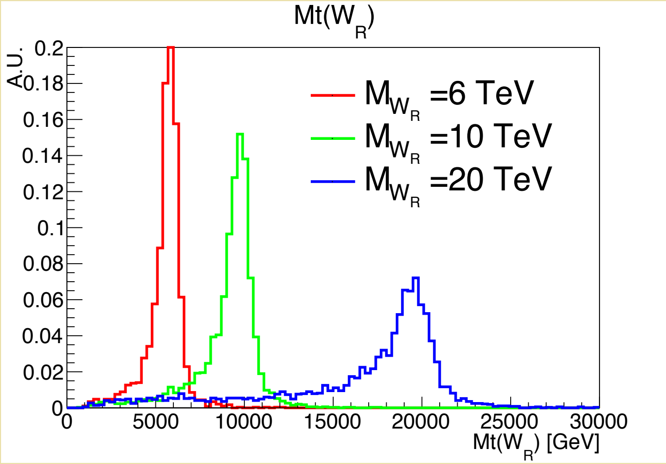
Cut description	
$e^+e^+\mu^-$, no b jets and no additional leptons	signal selection
$p^{lead}_{T,e^+} > 200$ GeV, $p^{sub}_{T,e^+} > 100$ GeV, $p^{lead}_{T,\mu^-} > 100$ GeV	reduce all backgrounds
$\not{E}_T > 100$ GeV	reduce mostly $t\bar{t}(j)$ and $Z/\gamma(j)$
$\|m_{inv}(e^+e^+) - 91.2\|) > 10$ GeV	reduce mostly $WZ(j)$
$m_T(e^+_{sub}\not{E}_T) < 150$ GeV	select channel shown in Fig. 1 (right)
$m_T(e^+e^+\mu^-\not{E}_T) > M_{W_R}/2$	reduce all backgrounds



Analysis: Cuts

	Backgrounds						Signal	
$\sqrt{s}$ =13TeV	$t\bar{t}Z$	$t\bar{t}W$	$t\bar{t}(j)$	$WZ(j)$	$3W$	$Z/\gamma(j)$	m_N(100 GeV)	m_N(500 GeV)
$e^+e^+\mu^-$ (b-veto)	11.8	74.9	23058	24.8	6.71	901	1293	371
P_T cuts	0.325	3.75	216	0.215	2.33	5.31	825	253
$\not{E}_T$ GeV	0.158	1.85	117	0.0761	1.06	0.0911	646	188
$m_{inv}(e^+\ e^+)$	0.155	1.82	113	0.0761	1.05	0	646	188
$m_T(e^+_{sub}\ \not{E}_T)$	0.0582	0.743	48.4	0.0277	0.491	0	622	176
$m_T(e^+e^+\mu^-\not{E}_T)$	0	7.82×10^{-3}	0	0	0.0169	0	597	158





Analysis: Efficiencies

$$r \equiv \frac{Br(N_1 \to e^+(W^- \to \mu^- \bar{\nu_\mu}))}{Br(N_1 \to \mu^-(W^+ \to e^+ \nu_e))}$$