Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Carleton
University

Neutrino masses from A Hybrid Type I + III Inverse Seesaw Mechanism in $U(1)_{R-L}$-symmetric MSSM

Based on *JHEP* 11 (2023) 085

Cem Murat Ayber
(pronounced as "💎")

WNPPC 2025

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Carleton
University

One SUSY to Rule the All:

From Neutrino Masses to the Beyond

Based on *JHEP* 11 (2023) 085

Cem Murat Ayber
(pronounced as "💎")

WNPPC 2025

Neutrinos Have Mass

Discovery of neutrino oscillations ⟶ Massive neutrinos

$$U_{PMNS} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\textbf{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\textbf{Reactor}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\textbf{Solar}}$$

$c_{ij} \equiv \cos\theta_{ij}\,,\ s_{ij} \equiv \sin\theta_{ij}$

$$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2} = 7.49^{+0.19}_{-0.19}$$

$$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2} = 2.534^{+0.025}_{-0.023}$$

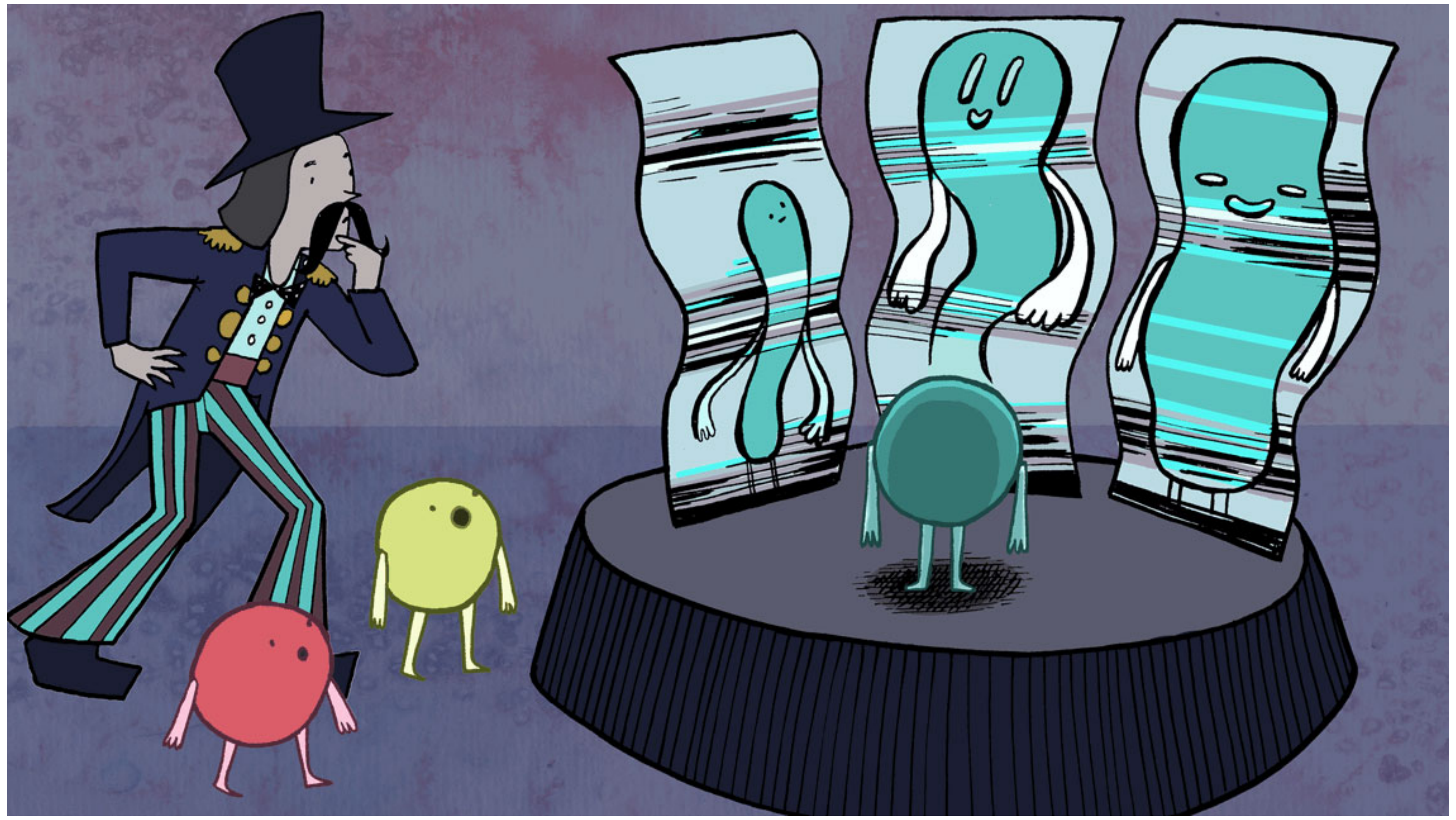
$$\sin^2\theta_{12} = 0.307^{+0.012}_{-0.011}$$

$$\sin^2\theta_{23} = 0.561^{+0.012}_{-0.015}$$

$$\sin^2\theta_{13} = 0.02195^{+0.00054}_{-0.00058}$$

$$\delta_{\mathrm{CP}}/^{\mathrm{o}} = 117^{+19}_{-20}$$

Esteban et al., JHEP **2024**, 216 (2025)178 www.nu-fit.org



Symmetry Magazine/Sandbox Studio, Chicago

$U(1)_{R'}$ symmetric SUSY

⟶ Gauginos are **pseudo-Dirac fermions** in *approximate* $R' = R - L$ global symmetry

Frugiuele, C., Grégoire, T., Kumar, P. *et al. JHEP* 2013, 156

SUSY is broken in a hidden sector

Dirac Mass: Supersoft SUSY breaking

$M_{\tilde{B}}, M_{\tilde{W}}$ P. J. Fox, A. E. Nelson and N. Weiner, JHEP 08 (2002) 035

small Majorana Mass: Anomaly mediation $m_{3/2} \ll M_{\tilde{B},\tilde{W}}$

$$m_{\tilde{B}}, m_{\tilde{W}}, m_S, m_T \sim \mathcal{O}(m_{3/2})$$

Gravitino mass

we call them $\psi^T_{\tilde{B}} = \left(\tilde{B}\ S^\dagger\right)^T$: “biνo” $\psi^T_{\tilde{W}} = \left(\tilde{W}\ T^\dagger\right)^T$: “wiνo”

Superfields	$SU(2)_L$	$U(1)_{R'}$
L_i	2	0
E^c_i	1	2
$H_{u,d}$	2	0
$R_{u,d}$	2	2
$W^\alpha_{\tilde{B}}$	1	1
Φ_S	1	0
$W^\alpha_{\tilde{W}}$	3	1
Φ_T	3	0

⟶ SM leptons are charged under $U(1)_{R'}$

Allows the mixing between gauginos and SM leptons!

Neutrino masses

→ $$\frac{1}{\Lambda_M^2}\int d^2\theta \left(f^i_{\tilde{B}} W'_\alpha W^\alpha_{\tilde{B}} H_u L_i + f^i_{\tilde{W}} W'_\alpha W^\alpha_{\tilde{W}} H_u L_i\right) \Longrightarrow f^{\,i}_{\tilde{B}} \frac{M_{\tilde{B}}}{\Lambda_M} \underline{\tilde{B}\, h_u} \ell_i + f^{\,i}_{\tilde{W}} \frac{M_{\tilde{W}}}{\Lambda_M} \underline{\tilde{W}\, h_u} \ell_i$$

They act as *RH* neutrinos

→ $$\frac{1}{\Lambda_M}\int d^2\theta d^2\bar{\theta}\phi^\dagger \left(d^i_S \Phi_S H_u L_i + d^i_T \Phi_T H_u L_i\right) \Longrightarrow \frac{m_{3/2}}{\Lambda_M}\left(d^{\,i}_S \underline{S\, h_u} \ell_i + d^{\,i}_T \underline{T\, h_u} \ell_i\right)$$

$f^i_{\tilde{B},\tilde{W}}$, $d^i_{S,T}$: Dimensionless coefficients, $i = e, \mu, \tau$

Highly suppressed because $m_{3/2} \ll M_{\tilde{B},\tilde{W}}$

If bino, wino, and higgsinos mix, the coefficients $f^i_{\tilde{B},\tilde{W}}$ are rescaled by a mixing angle.

This will not affect the neutrino mixing structure.

Neutrino masses

This is a Hybrid Type I+III inverse seesaw scenario!

$$\mathscr{L} \supset \underbrace{\begin{array}{l} \dfrac{f^i_{\tilde{B}} M_{\tilde{B}}}{\Lambda_M} \overline{\ell} h_u \tilde{B} + M_{\tilde{B}} S \tilde{B} \\ + \dfrac{f^i_{\tilde{W}} M_{\tilde{W}}}{\Lambda_M} \overline{\ell} h_u \tilde{W} + M_{\tilde{W}} T \tilde{W} \end{array}}_{U(1)_{R-L}\text{-conserving}} + \underbrace{\begin{array}{l} \dfrac{d^i_{\tilde{B}} m_{3/2}}{\Lambda_M} \overline{\ell} h_u S^\dagger + m_{\tilde{B}} \tilde{B} \tilde{B} + m_S S S \\ \dfrac{d^i_{\tilde{W}} m_{3/2}}{\Lambda_M} \overline{\ell} h_u T^\dagger + m_{\tilde{W}} \tilde{W} \tilde{W} + m_T T T \end{array}}_{U(1)_{R-L}\text{-violating}}$$

Type-I ISS texture

+

Type-III ISS texture

Neutrino masses

Neutrino mass matrix in the $(\nu_i, \tilde{B}, \tilde{W}, S, T)$ basis after EWSB

$$M_\nu = \begin{pmatrix} \mathbf{0}_{3\times3} & \mathbf{Y}_{\tilde{B}} v & \mathbf{Y}_{\tilde{W}} v & \mathbf{G}_S v & \mathbf{G}_T v \\ \mathbf{Y}^T_{\tilde{B}} v & m_{\tilde{B}} & 0 & M_{\tilde{B}} & 0 \\ \mathbf{Y}^T_{\tilde{W}} v & 0 & m_{\tilde{W}} & 0 & M_{\tilde{W}} \\ \mathbf{G}^T_S v & M_{\tilde{B}} & 0 & m_S & 0 \\ \mathbf{G}^T_T v & 0 & M_{\tilde{W}} & 0 & m_T \end{pmatrix}$$

In its most general form, the mass matrix generates **three massive** light neutrinos with the correct mass splittings.

$$\mathbf{Y}^T_{\tilde{B},\tilde{W}} = \frac{M_{\tilde{B},\tilde{W}}}{\Lambda_M} \left(f^e_{\tilde{B},\tilde{W}}\, f^\mu_{\tilde{B},\tilde{W}}\, f^\tau_{\tilde{B},\tilde{W}}\right) \qquad \mathbf{G}^T_{S,T} = \frac{m_{3/2}}{\Lambda_M} \left(d^e_{S,T}\, d^\mu_{S,T}\, d^\tau_{S,T}\right)$$

Analytically unsolvable due to the large number of free parameters

$$m_{\tilde{B},\tilde{W}} \propto m_{3/2},\ m_S,\ m_T,\ M_{\tilde{B}},\ M_{\tilde{W}},\ \Lambda_M,\ f^i_{\tilde{B}},\ f^i_{\tilde{W}},\ d^i_S,\ d^i_T$$

Neutrino masses: A Simplified Scenario

Non-zero Majorana masses, $m_{S,T} \neq 0$, and vanishing couplings of Dirac partners, $G_{S,T} \sim 0$

The light-neutrino mass eigensystem in the normal ordering:

$$m_1 = 0\,, \quad m_{2,3} = \frac{v^2(m_S + m_T)}{\sqrt{2}\Lambda_M^2}\sqrt{1 - 2\beta_{\text{NO}} \pm \sqrt{1 - 4\beta_{\text{NO}}}}$$

$m_{2,3} \propto m_T + m_S$

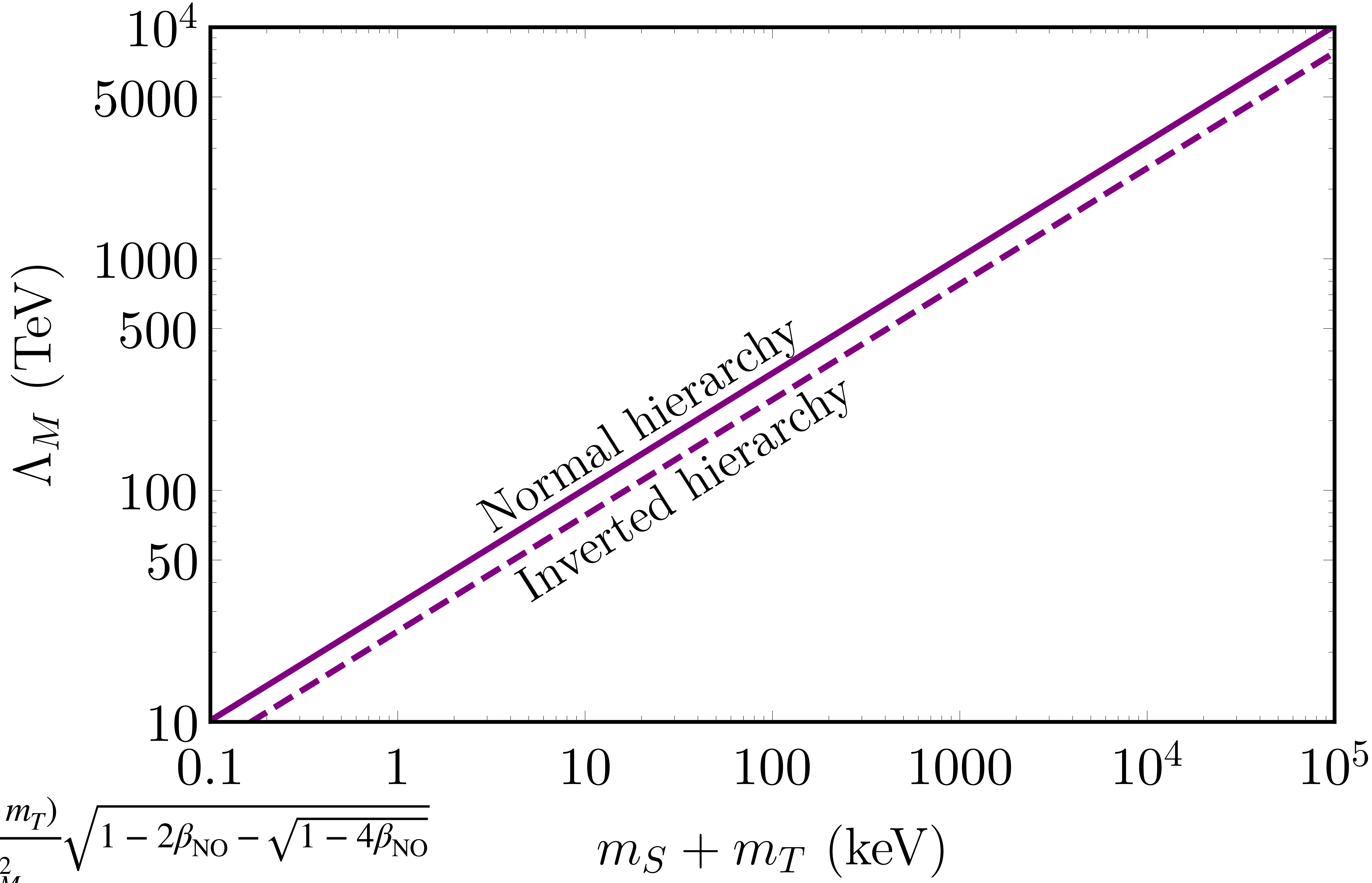
where β_{NO} is set by the mass-squared splitting ratios,

$$\beta_{\text{NO}} = -2r(r+1) + \sqrt{r(r+1)}(2r+1) \simeq 0.13 \text{ with } r = \frac{|\Delta m^2_{\text{sol}}|}{|\Delta m^2_{\text{atm}}|} \simeq 0.03$$

$$u^i_{\tilde{B}} = \left(\frac{a_2}{b_2} - \frac{a_3}{b_3}\right)^{-1}\left[\frac{1}{b_2 N_2}U_{i2} - \frac{1}{b_3 N_3}U_{i3}\right] \qquad u^i_{\tilde{W}} = \left(\frac{b_2}{a_2} - \frac{b_3}{a_3}\right)^{-1}\left[\frac{1}{a_2 N_2}U_{i2} - \frac{1}{a_3 N_3}U_{i3}\right]$$

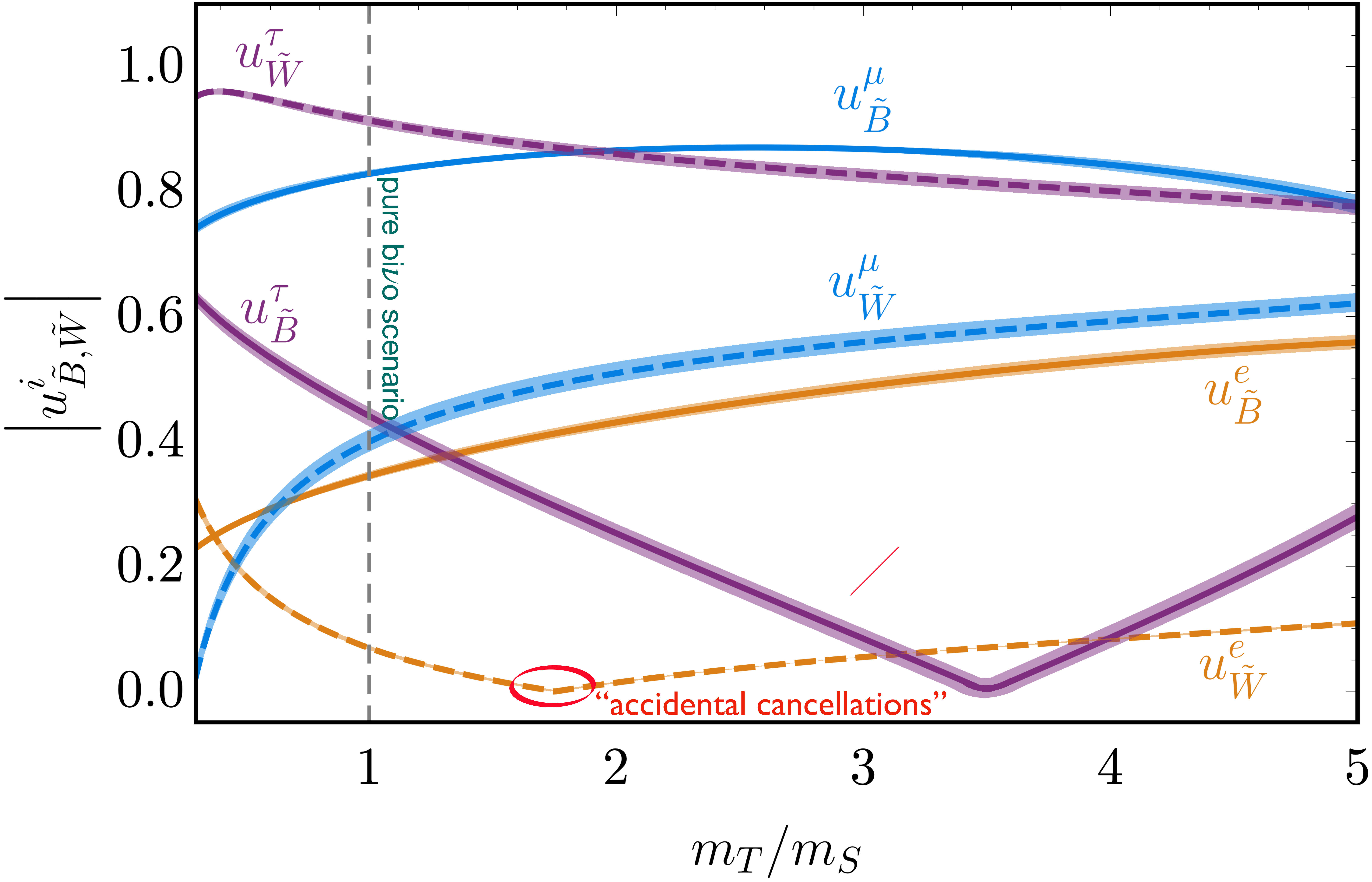
$u^i_{\tilde{B},\tilde{W}} \propto \frac{m_T}{m_S}$

$\Lambda_M - m_S + m_T$



$$\sqrt{\Delta m^2_{\text{sol}}} = \frac{v^2(m_S + m_T)}{\sqrt{2}\Lambda_M^2}\sqrt{1 - 2\beta_{\text{NO}} - \sqrt{1 - 4\beta_{\text{NO}}}}$$

Neutrino Mixing Structure



$\sin^2\theta_{12} = 0.303^{+0.012}_{-0.012}$

$\sin^2\theta_{23} = 0.451^{+0.019}_{-0.016}$

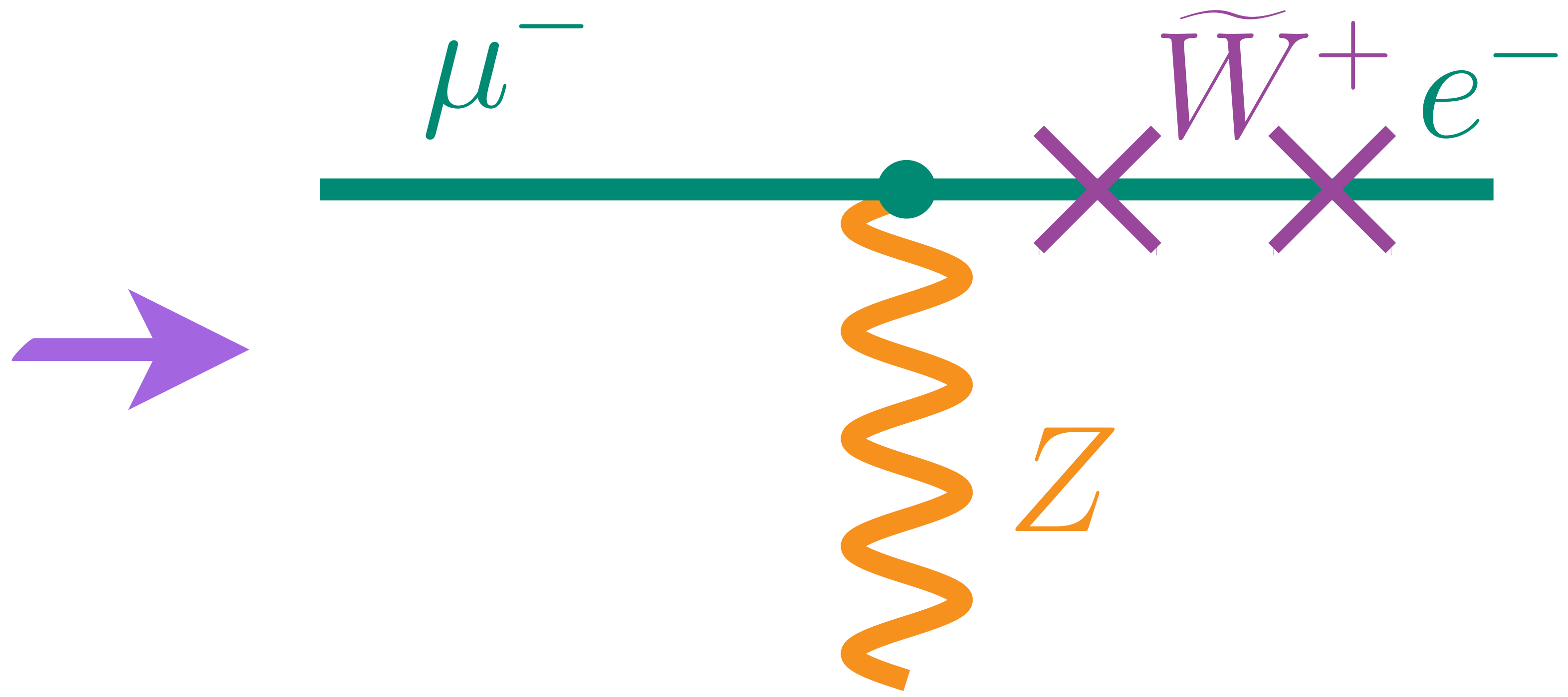
$\sin^2\theta_{13} = 0.02225^{+0.00056}_{-0.00059}$

Low Energy Constraints

The biνo-wiνo-light neutrino mixing can result in observable lepton-flavor-violating (LFV) effects, which can be constrained by (non-)observations.

$U(1)_{R-L}$-conserving wino term, $vY^{i}_{\tilde{W}}\widetilde{W}^{+}\ell^{-}_{i}$, **mixes charginos and charged leptons**

$$\widetilde{W}^{+c} - \ell^{-} \text{ mixing} \propto \mathcal{O}\left(\frac{vY_{\tilde{W}}}{M_{\tilde{W}}}\right)$$

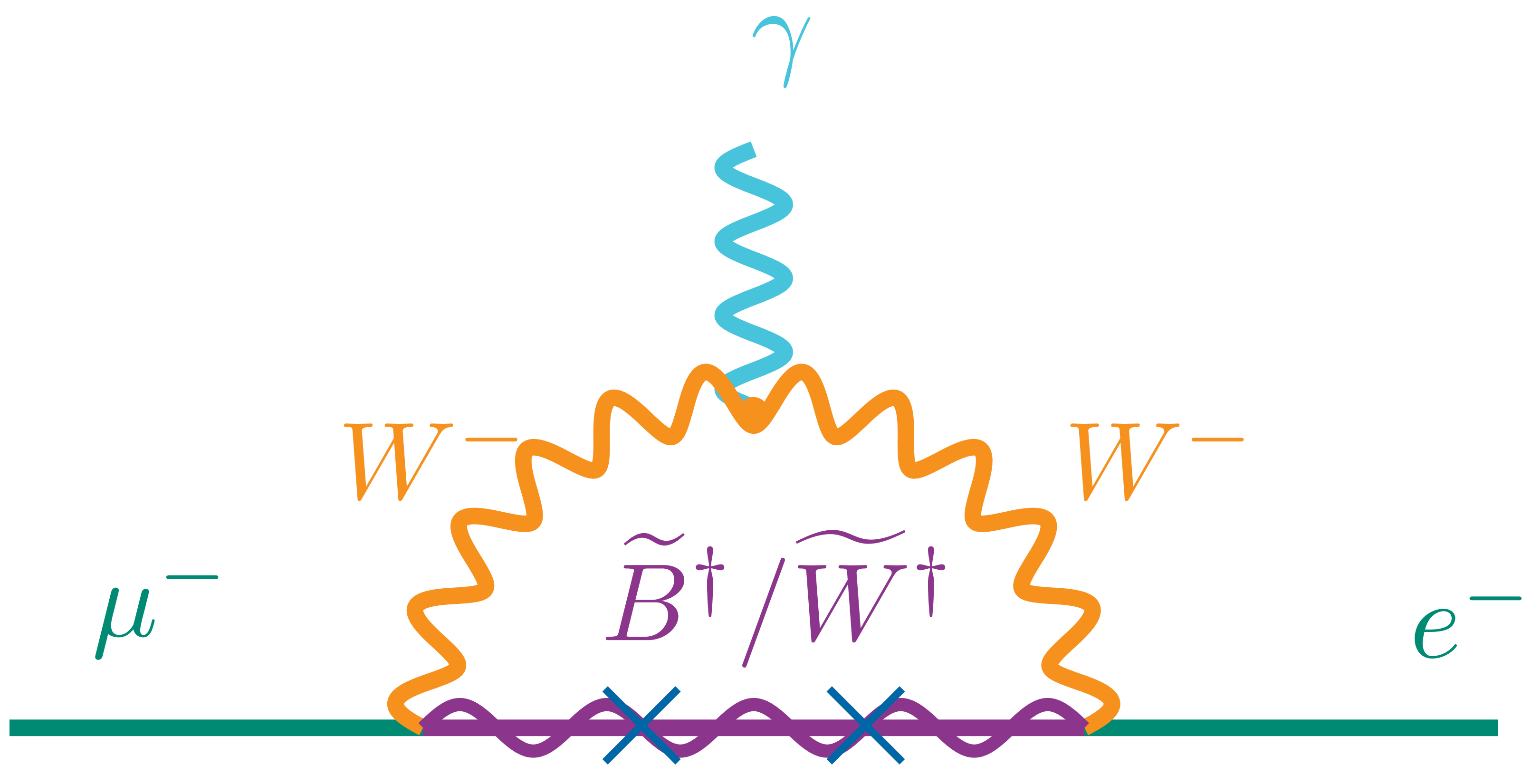


$$\propto \frac{v^2}{2}\left(Y^{\dagger}_{\tilde{W}}\frac{1}{M^{\dagger}_{\tilde{W}}M_{\tilde{W}}}Y_{\tilde{W}}\right)_{e\mu}$$

Flavor-changing neutral currents at tree level!

LFV processes

$\mu \to e\,\gamma$

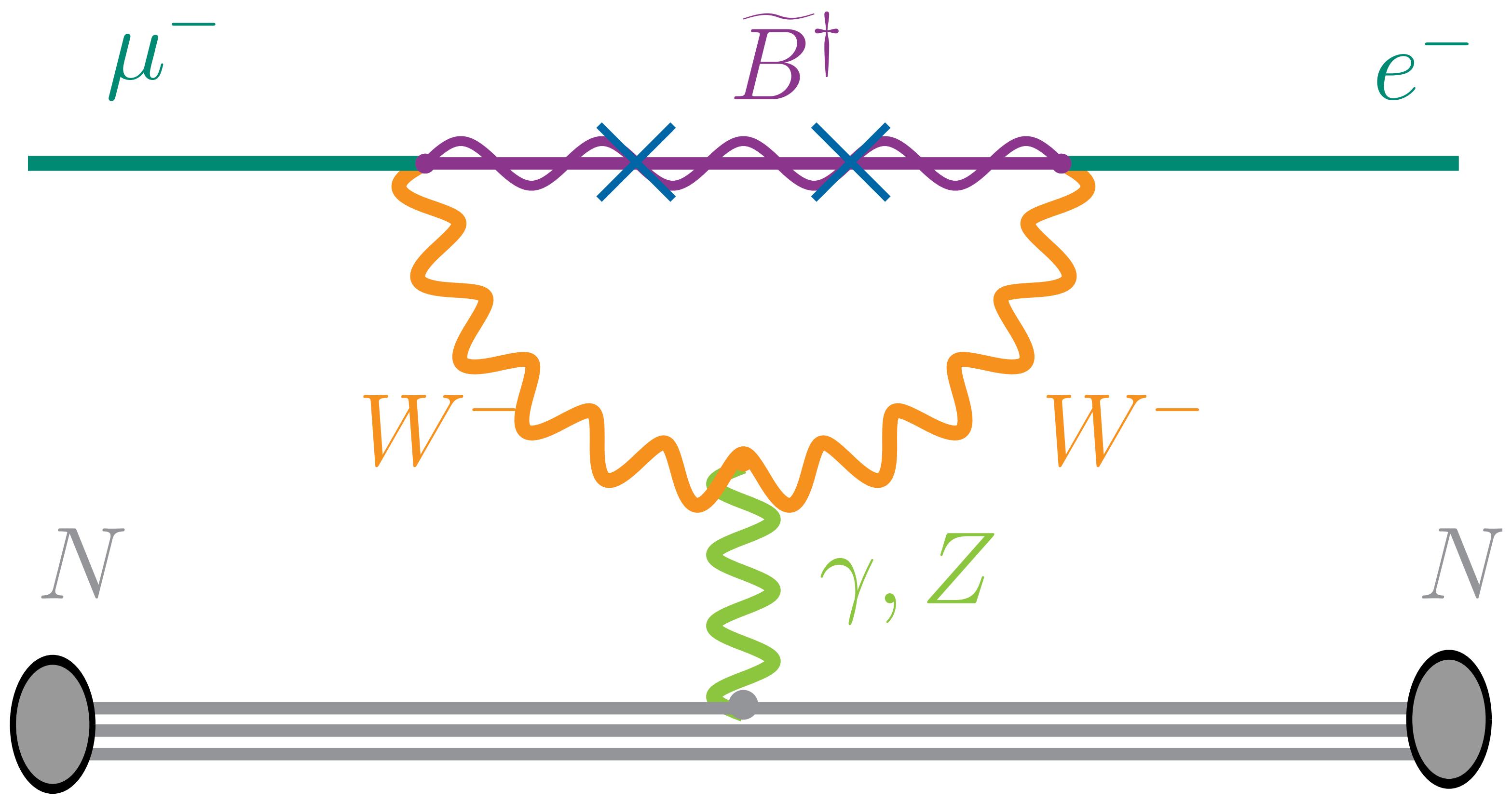


type-I: one loop

type-III: one loop

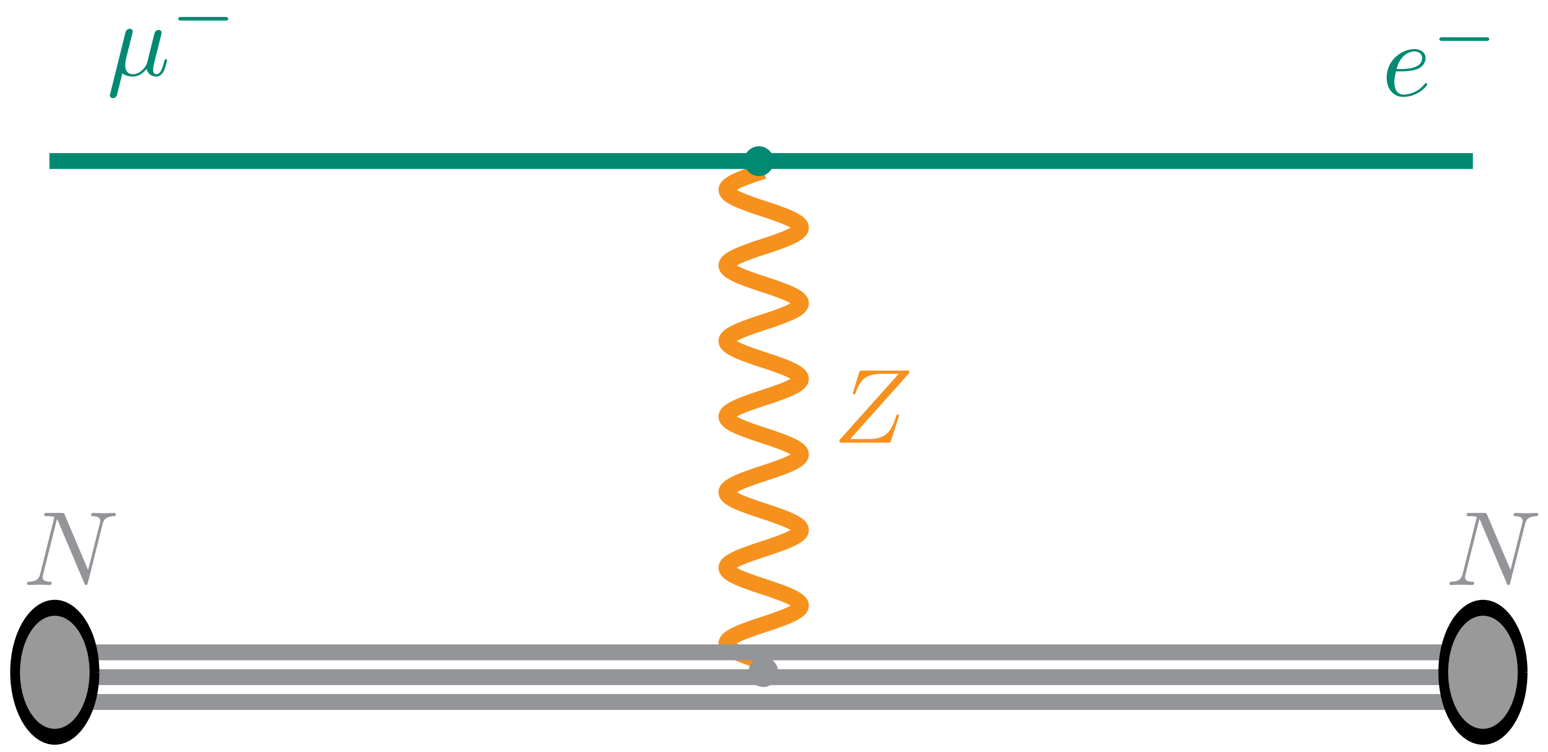
Loop suppressed

$\mu - e$ conversion in nuclei

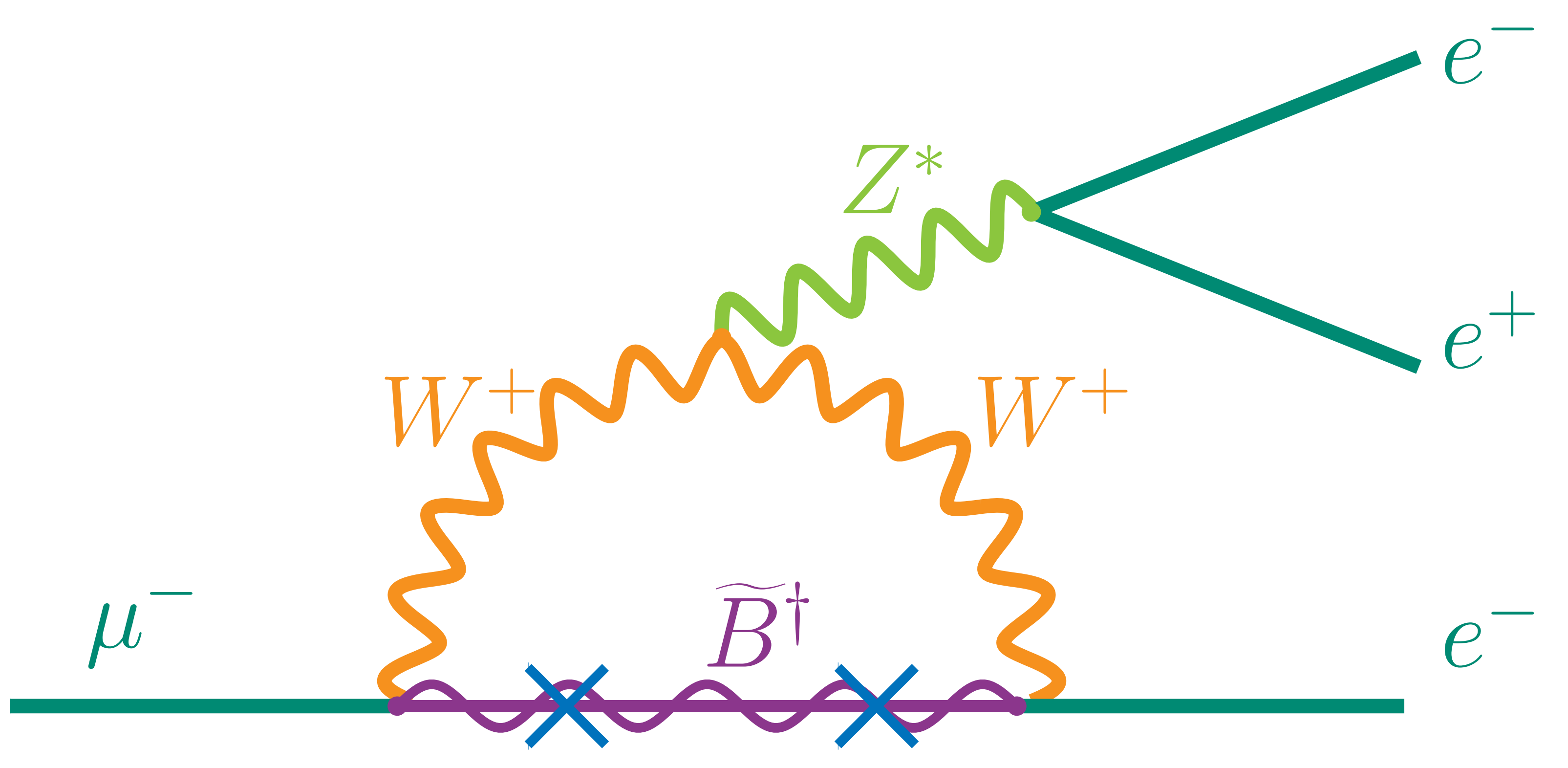


type-I: one loop

type-III: tree level

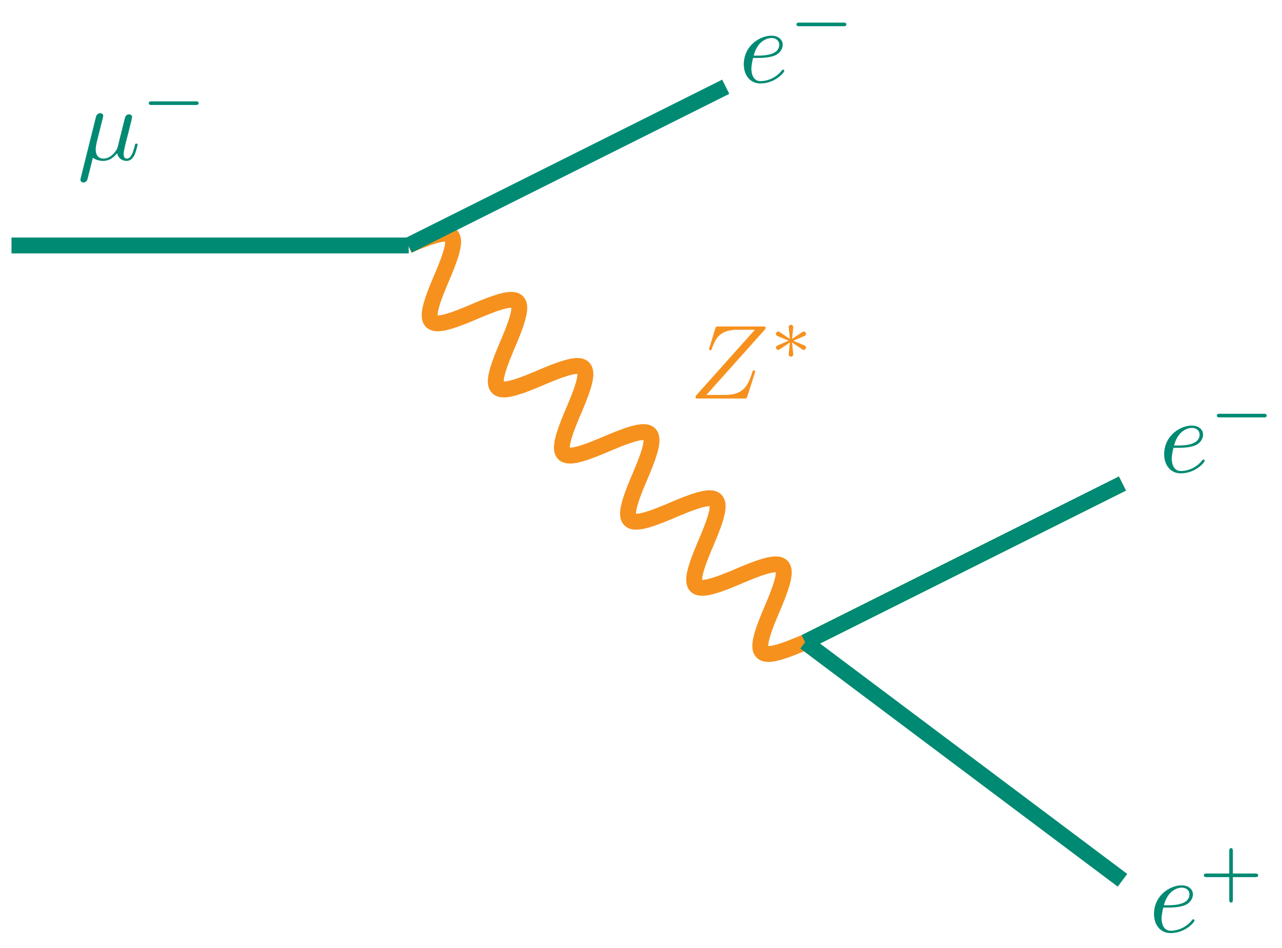


$\mu \to e\,e\,e$



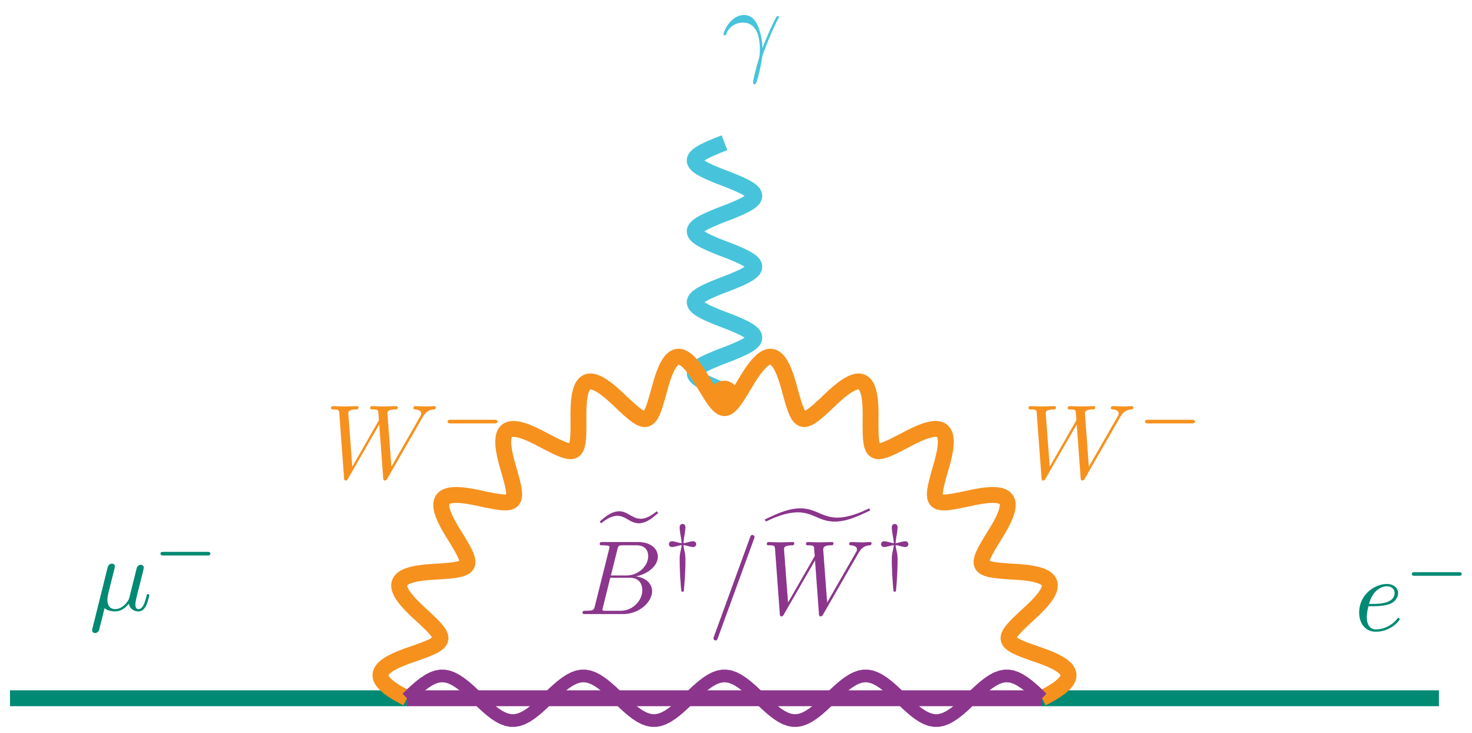
type-I: one loop

type-III: tree level

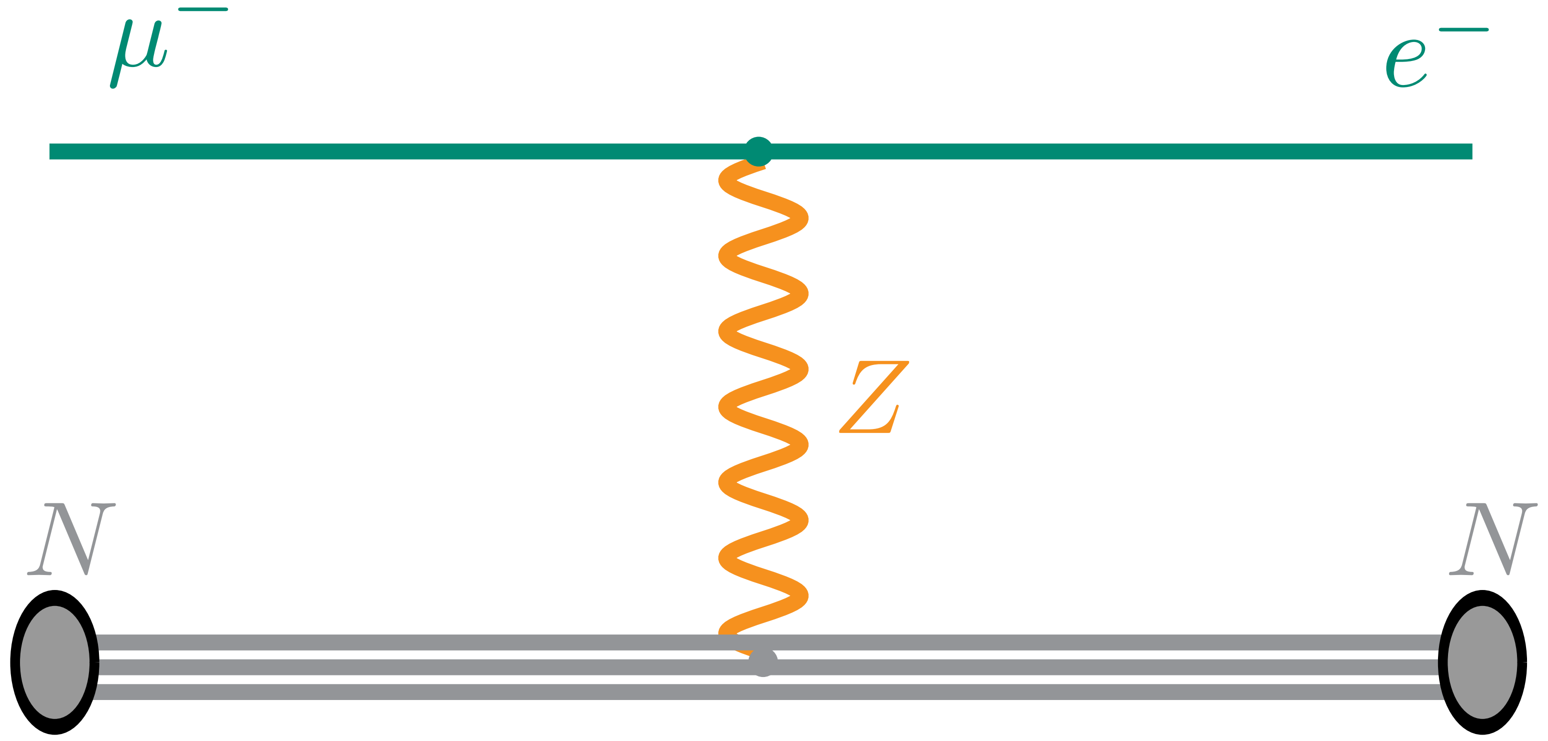


LFV processes

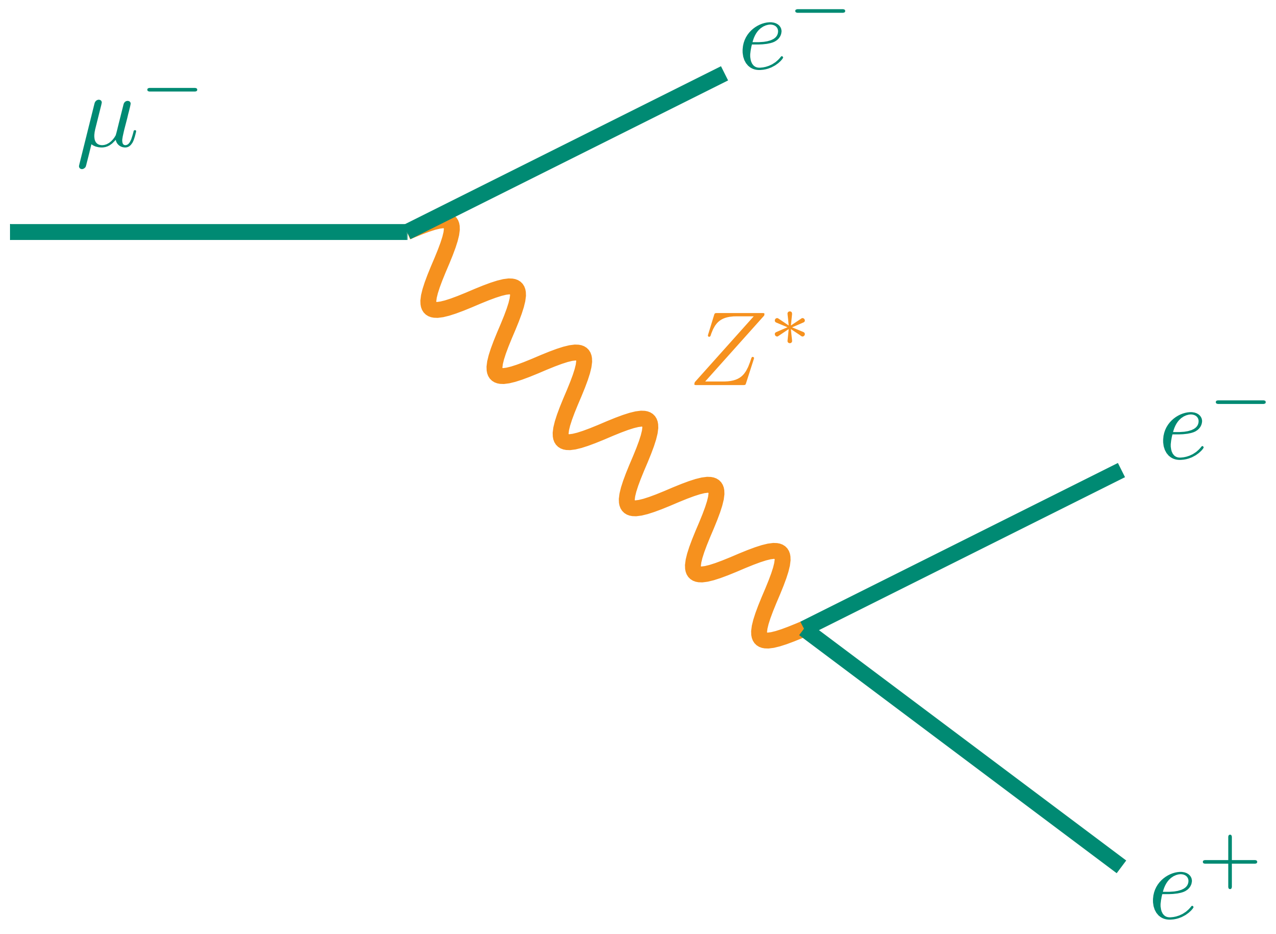
$\mu \rightarrow e\,\gamma$



$\mu - e$ conversion in nuclei



$\mu \rightarrow e\,e\,e$



All depend on the same combination: $\underbrace{\epsilon^{d=6} = v^2 \left| \mathbf{Y}^T \frac{1}{\mathbf{\Lambda}^T \mathbf{\Lambda}} \mathbf{Y} \right|}$

$$\mathbf{Y} = (\underbrace{\mathbf{Y}_{\tilde{B}}\,,\mathbf{Y}_{\tilde{W}}}) \quad \mathbf{\Lambda} = \begin{pmatrix} M_{\tilde{B}} & 0 \\ 0 & M_{\tilde{W}} \end{pmatrix}$$

$$\mathbf{Y}_{\tilde{B},\tilde{W}} \propto \frac{M_{\tilde{B},\tilde{W}}}{\Lambda_M}$$

Independent of Dirac biνo and wiνo masses: $\left(\epsilon^{d=6}\right)_{e\mu} = \frac{v^2}{\Lambda_M^2} \left| u^e_{\tilde{B}} u^\mu_{\tilde{B}} + u^e_{\tilde{W}} u^\mu_{\tilde{W}} \right|$

By far the strongest constraints are on the $e - \mu$ element

Constraints on the Messenger Scale

$$\Lambda_M \gtrsim \left(500 - 1000\right)\ \text{TeV}$$

$$m_S + m_T \sim \mathcal{O}(100\ \text{keV} - 10\ \text{MeV})$$

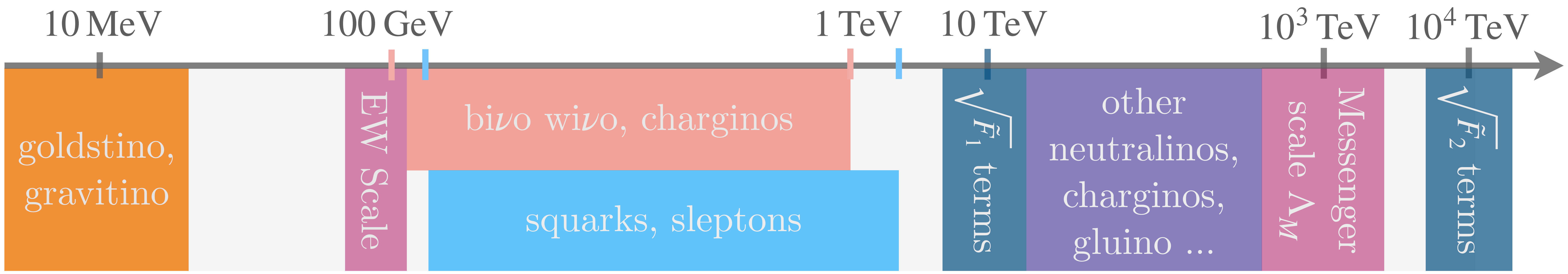
Outcomes of our Model

→ **Rich LHC phenomenology**

→ **Out-of-equilibrium decay of bino in the early Universe could explain the Baryon Asymmetry of the Universe (BAU)**

→ **Uneaten Goldstino and the gravitino could be a DM candidate**

LHC Phenomenology

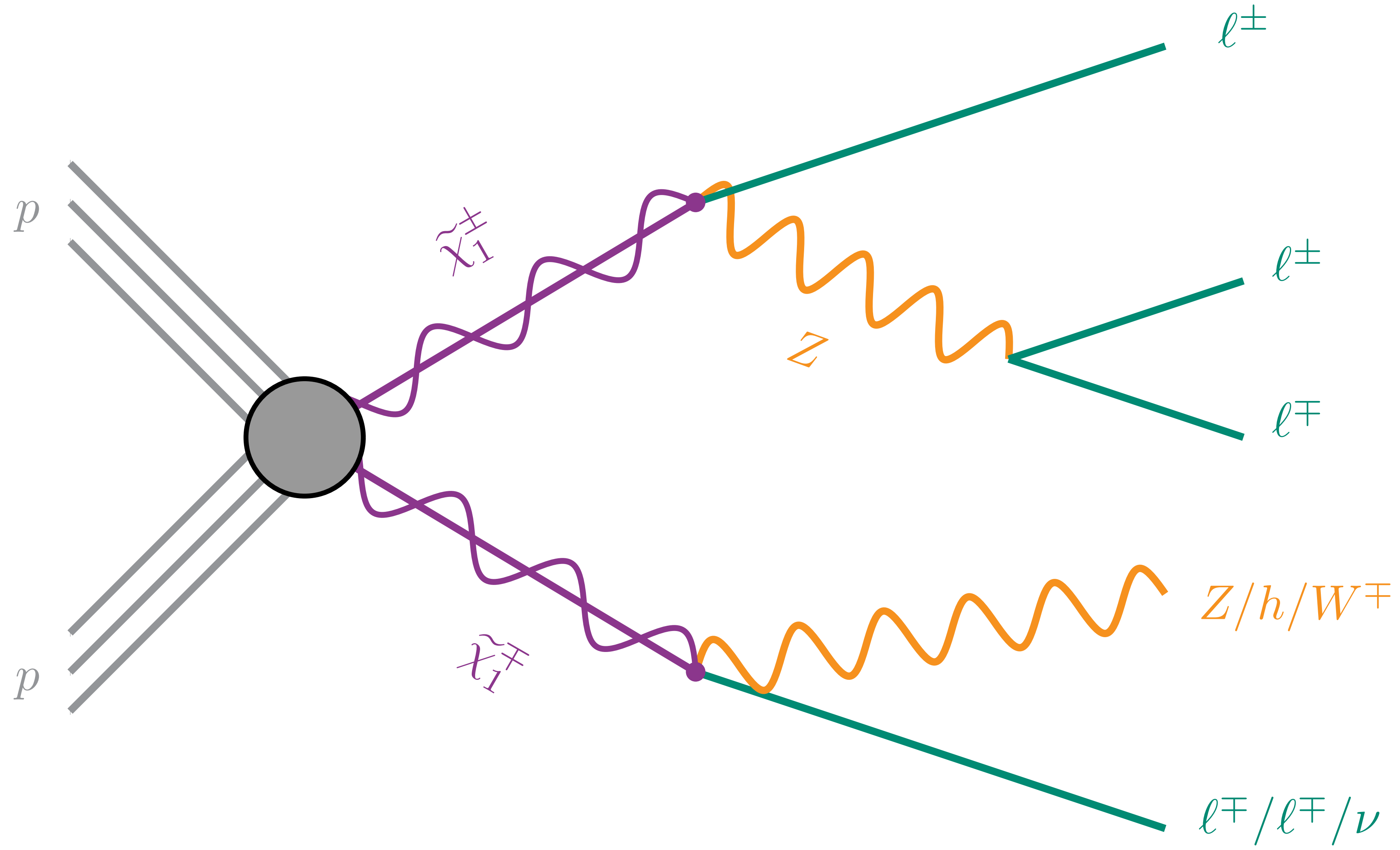


These scales are motivated by the resulting phenomenology of J. Gehrlein, **S. Ipek** and P.J. Fox, JHEP 03 (2019) 073

Search for trilepton resonances from chargino and neutralino pair production

A decay channel would be $\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm} Z(\rightarrow \ell^{\pm}\ell^{\mp})$

ATLAS collaboration, Phys. Rev. D 103 (2021) 112003

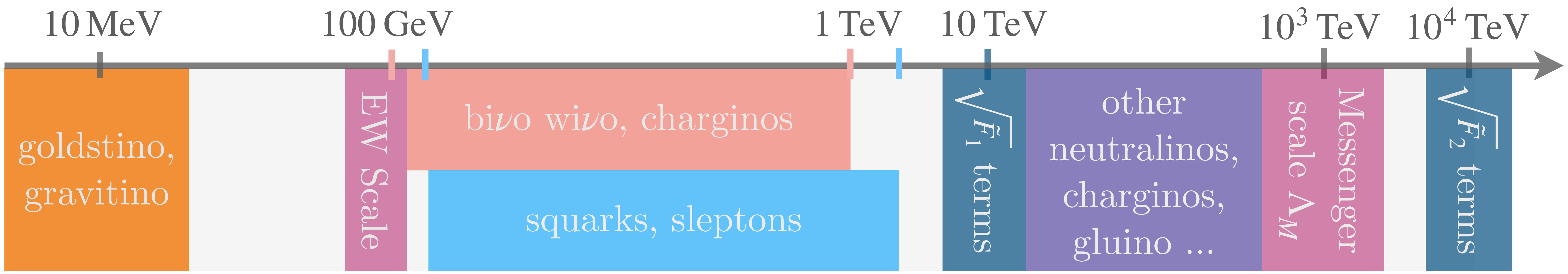


$100\ \text{GeV} < M_{\tilde{W}/\chi_1^{\pm}} < 1.1\ \text{TeV}$ **Excluded**

Depends on their branching fraction to different lepton flavors $\Bigg\}$ free parameter for the analysis

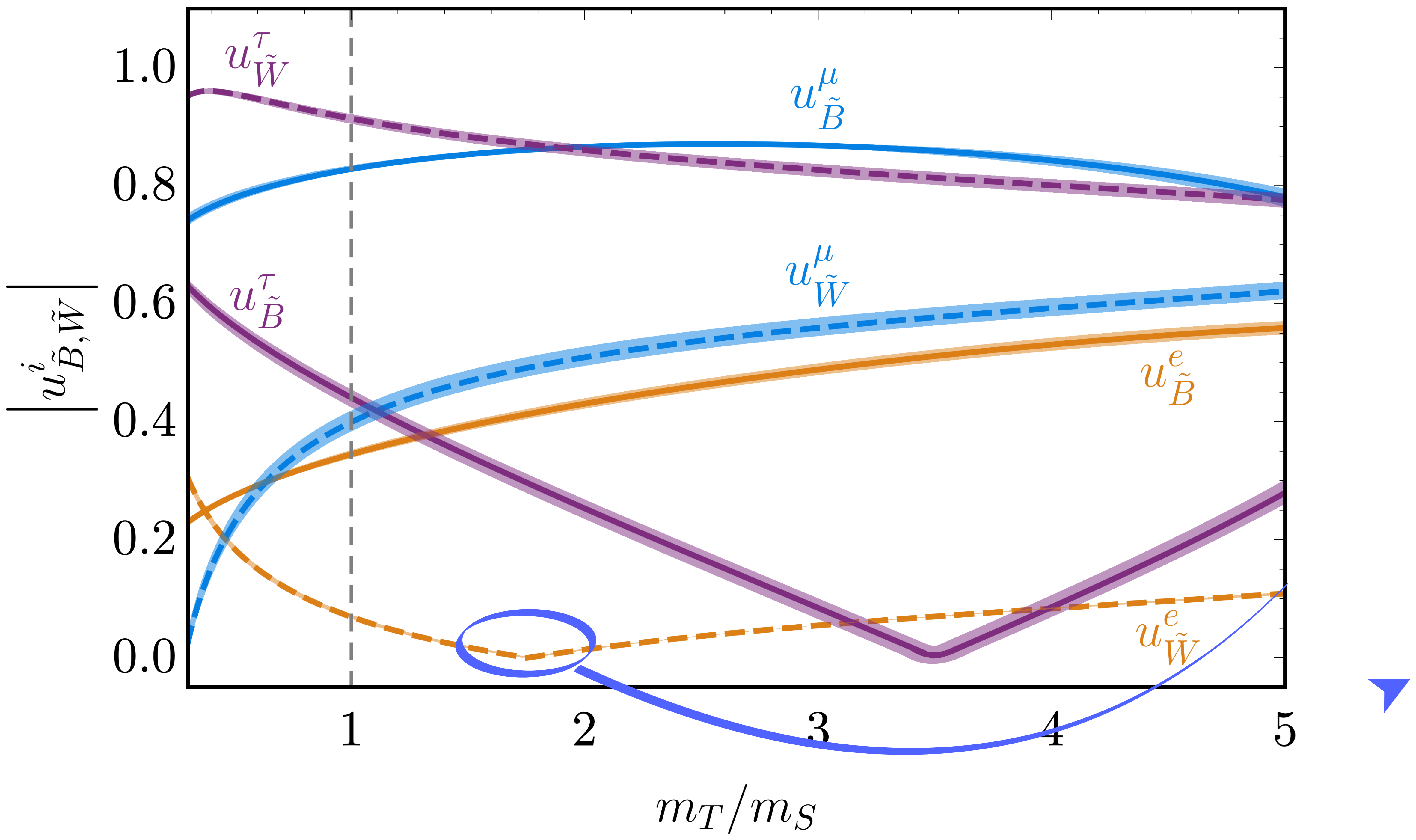
e and μ final states are the most constraining

LHC Phenomenology



These scales are motivated by the resulting phenomenology of J. Gehrlein, **S. Ipek** and P.J. Fox, JHEP 03 (2019) 073

Search for trilepton resonances from chargino and neutralino pair production



Directly applies to our model!

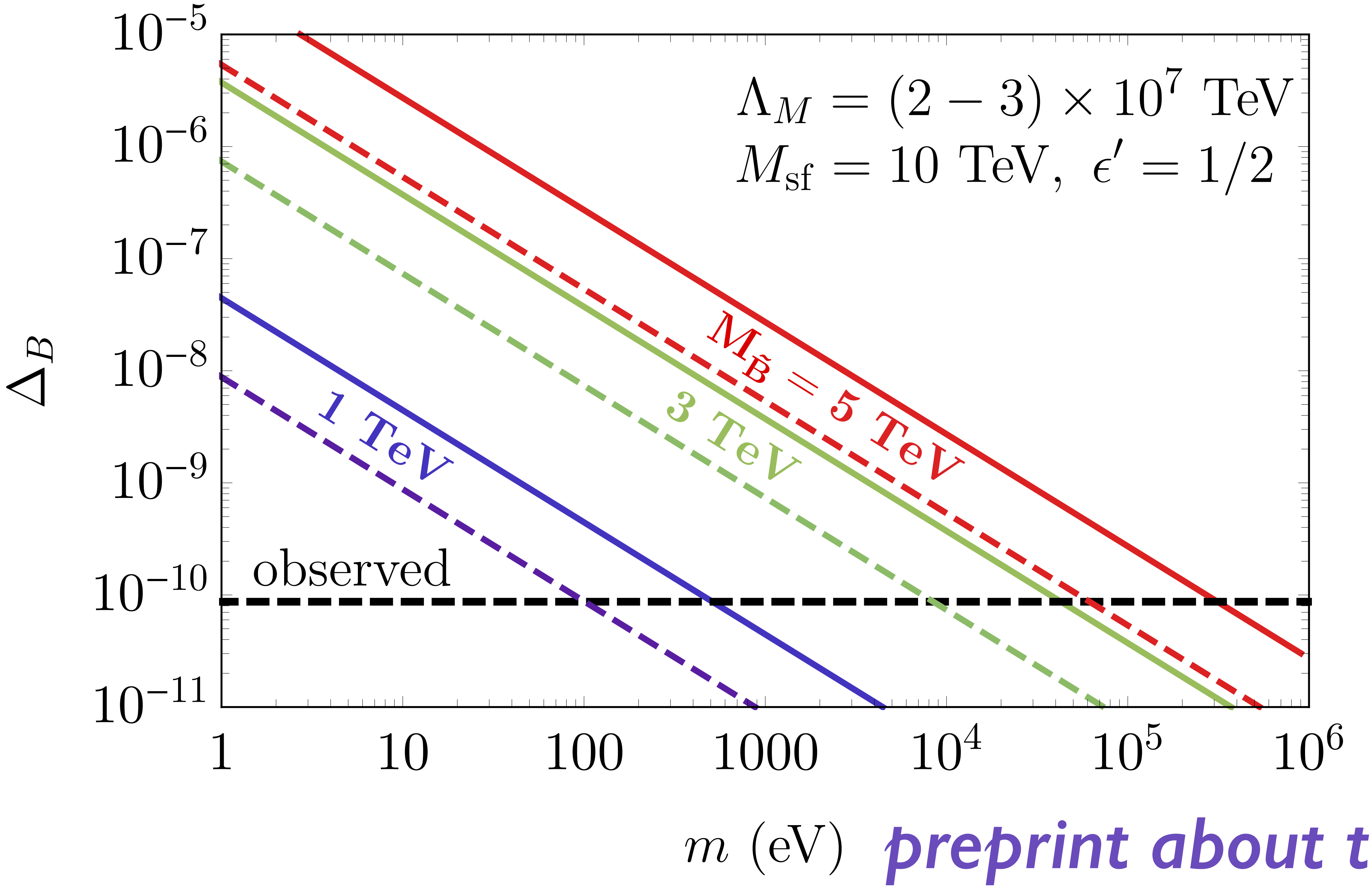
Branching fractions to different lepton families (e, μ, τ) are determined by the observed neutrino mixing structure.

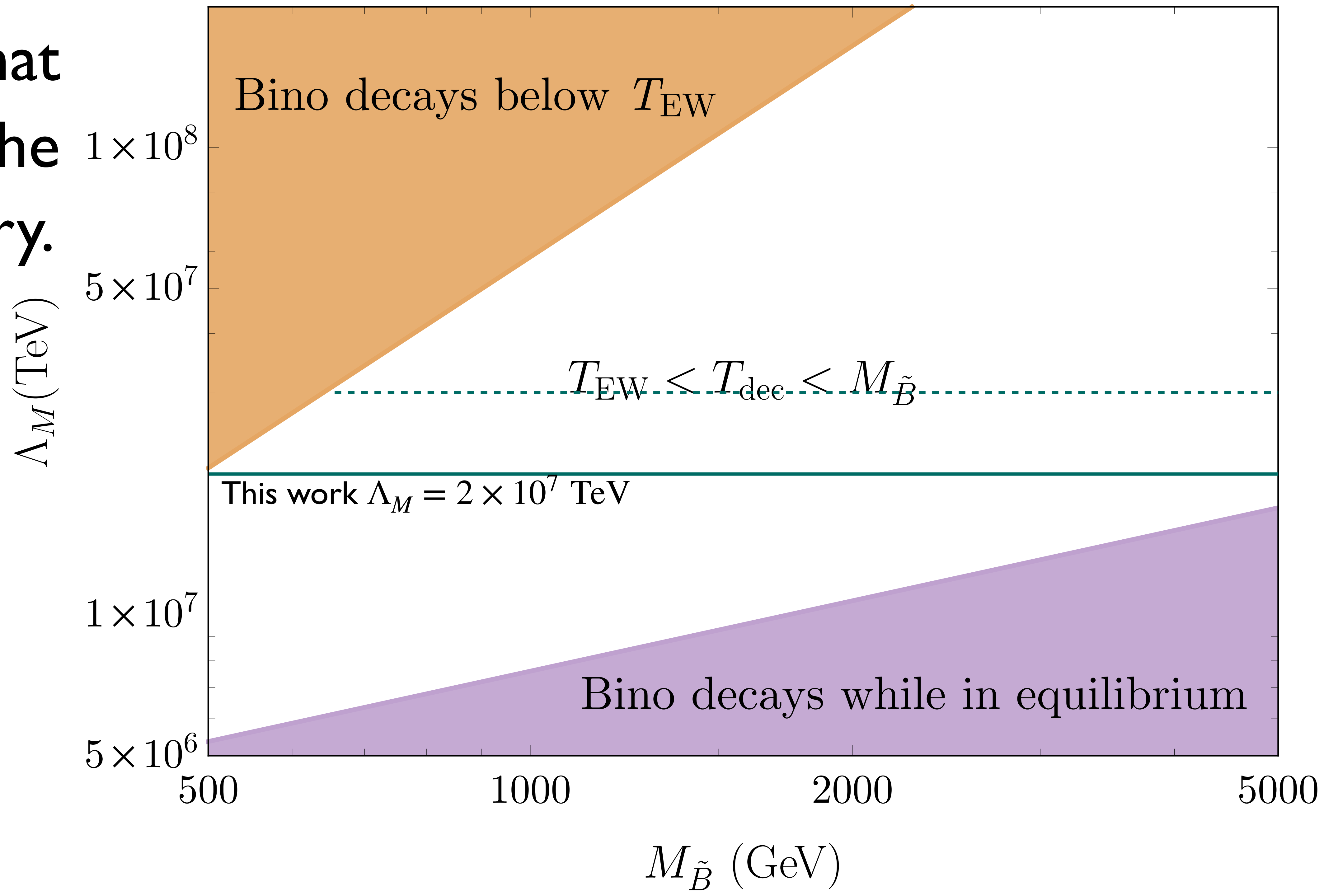
Alleviates the constraints from this search

Leptogenesis via Bino-Anti-Bino Oscillations

- For successful leptogenesis, we assume bino heavier than 130 GeV and messenger scales $\Lambda_M \gtrsim \mathcal{O}(10^7 \text{ TeV})$

- We consider a hierarchy where $m_S \ll m_T$ and $G_S \ll G_T$ such that the wino participates in the neutrino mass generation whilst the bino decays out-of-equilibrium, generating the baryon asymmetry.





To have enough CP violation (encoded in ϵ')
we require $m_{\tilde{B}} + m_S \ll M_{\tilde{B}}$ and $G_S/Y_{\tilde{B}} \sim \mathcal{O}(10^{-5}-1)$

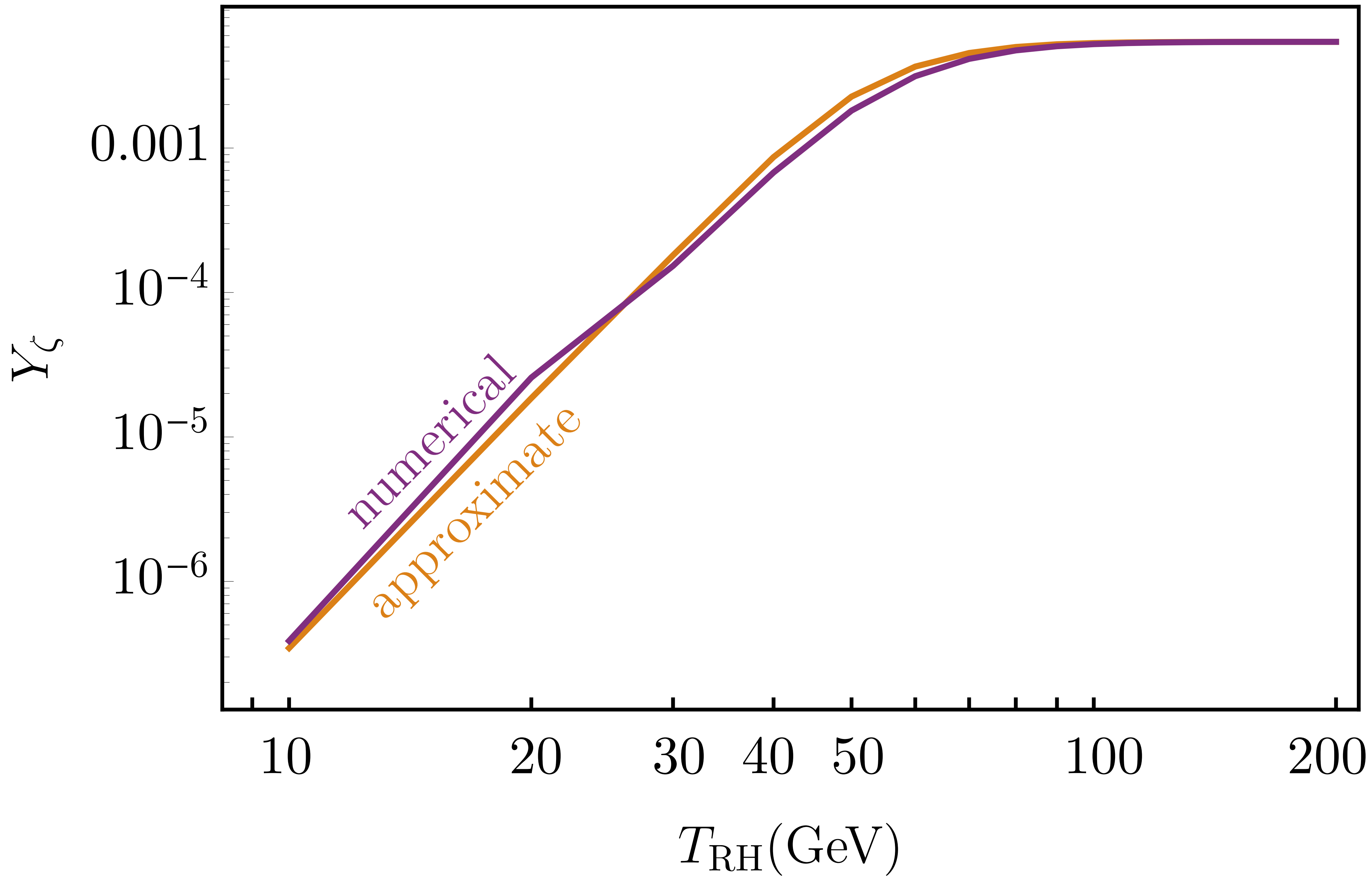
preprint about to be published

Gravitino/Goldstino DM with low $T_{\rm RH}$

For the parameter region we are interested, $m_{3/2} \sim \mathcal{O}(1\,\mathrm{keV} - 10\,\mathrm{MeV})$, goldstino will overpopulate the universe, if the reheating temperature is sufficiently high, e.g. $T_{\rm RH} \sim \mathcal{O}(\mathrm{TeV})$

A. Monteux and C. S. Shin,Phys. Rev. **D92**, 035002 (2015)

$$m_{\zeta/\eta},\, T_{\rm RH} \ll \tilde{m} \sim \mathcal{O}(\mathrm{TeV}) \lesssim \mathrm{T_{MAX}}$$



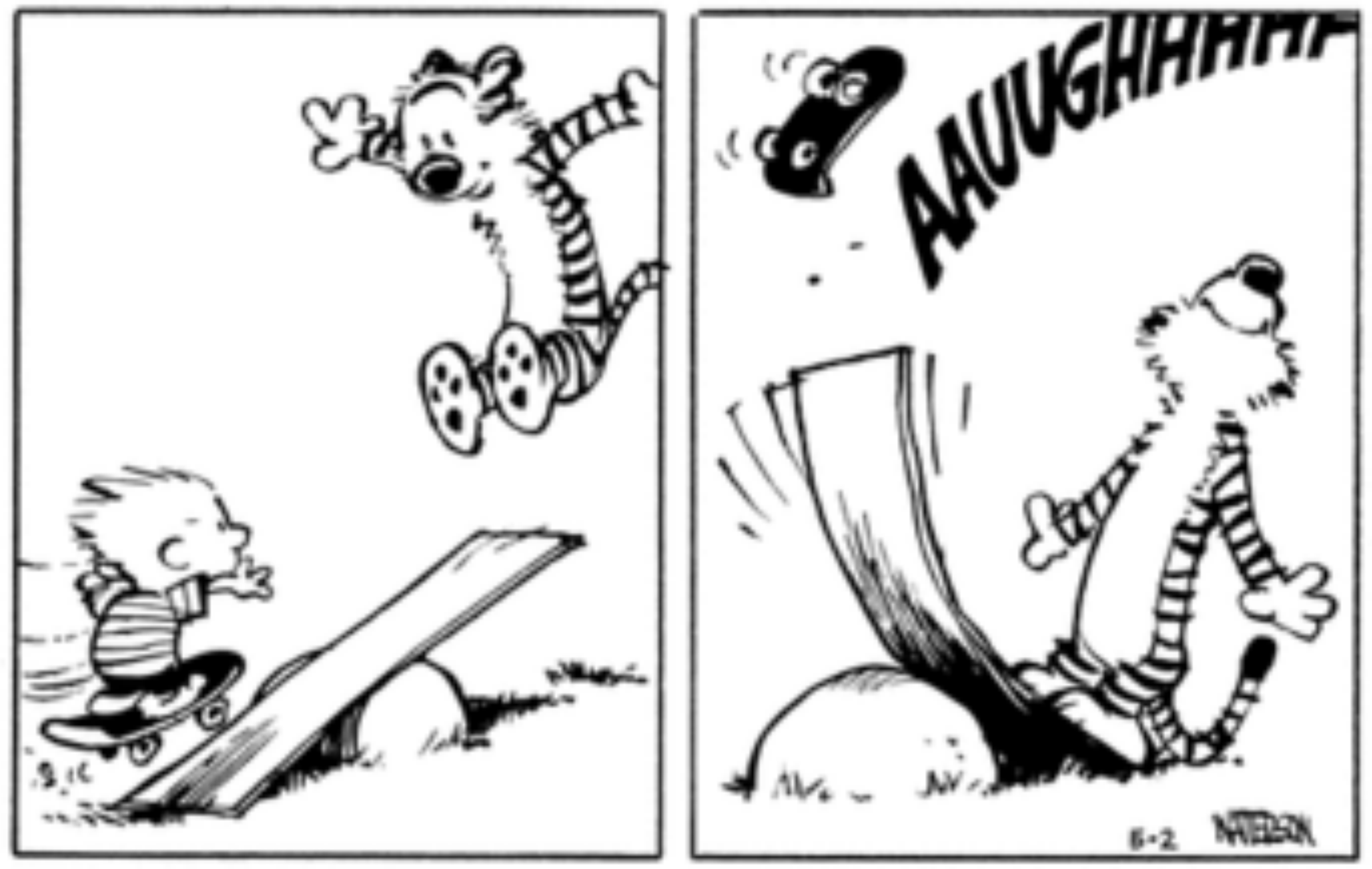
In Progress

Takeaways from our Model

- The neutrino-bino/wino mixing follows a hybrid type I+III ISS pattern and can generate non-zero masses for all three neutrinos in its most general form.
- The hierarchy between the gravitino mass and the messenger scale can explain the smallness of the neutrino masses.
- Branching fractions to different lepton families (e, μ, τ) are determined by the observed neutrino mixing structure.
- Offers a rich LHC phenomenology → Next step: A comprehensive LHC analysis
- Out-of-equilibrium decay of bino in the early universe can explain the BAU via a leptogenesis scenario → About to be published
- Light gravitino/goldstino with low reheating temperature could accommodate the observed dark matter abundance → In progress

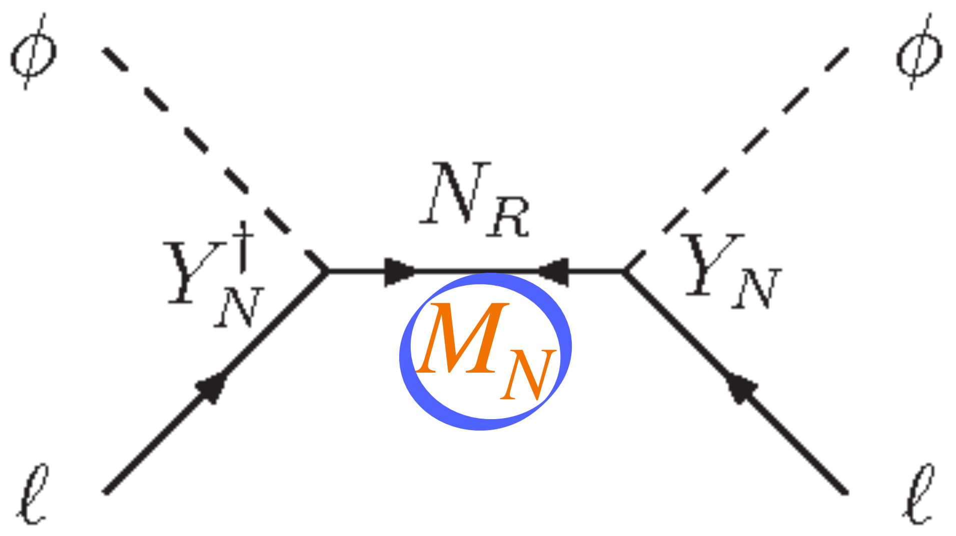
Backup Slides

Basics: Seesaw Mechanism



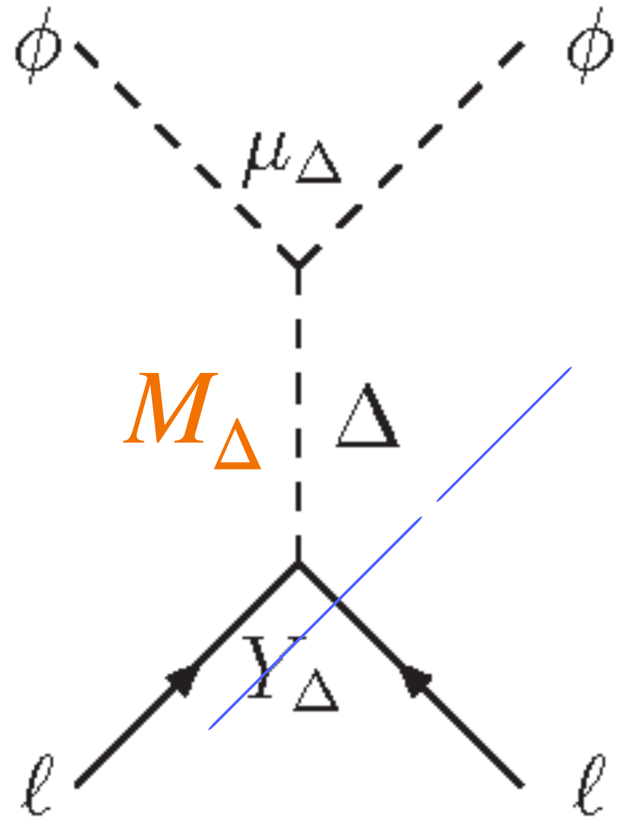
Type-I

SM singlet fermion



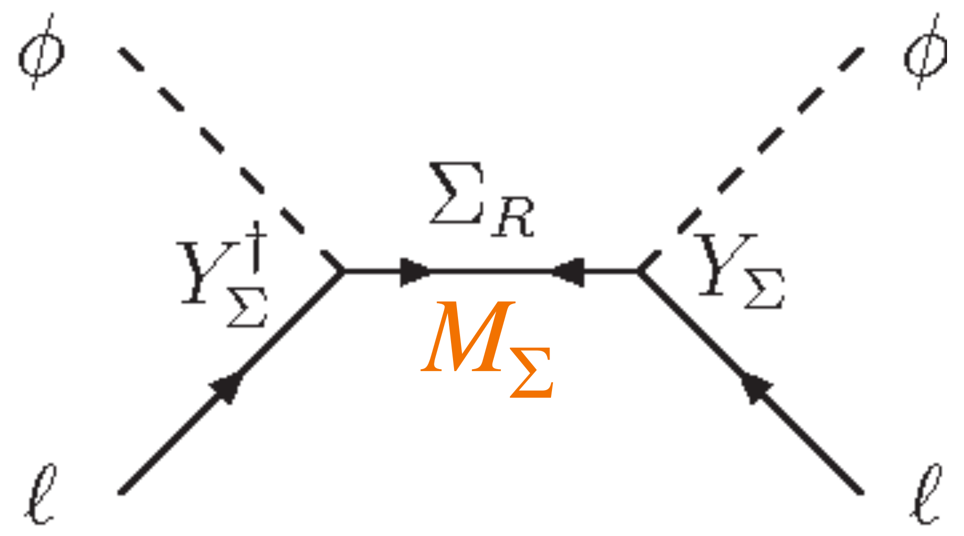
Type-II

SM triplet scalar



Type-III

SM triplet fermion



Abada, A. et al. JHEP (2007) 061-061

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

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

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

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

Neutrino masses are inversely proportional to the Majorana masses

Lepton number is violated

S.F. King, Nucl. Phys. B 908 (2016) 456

Y. Cai, T. Han, T. Li and R. Ruiz, Frontiers in Phys. 6 (2018)

Basics: Inverse Seesaw Mechanism

D. Wyler and L. Wolfenstein,, Nucl. Phys. B 218 (1983) 205

R.N. Mohapatra, Phys. Rev. Lett. 56 (1986) 561

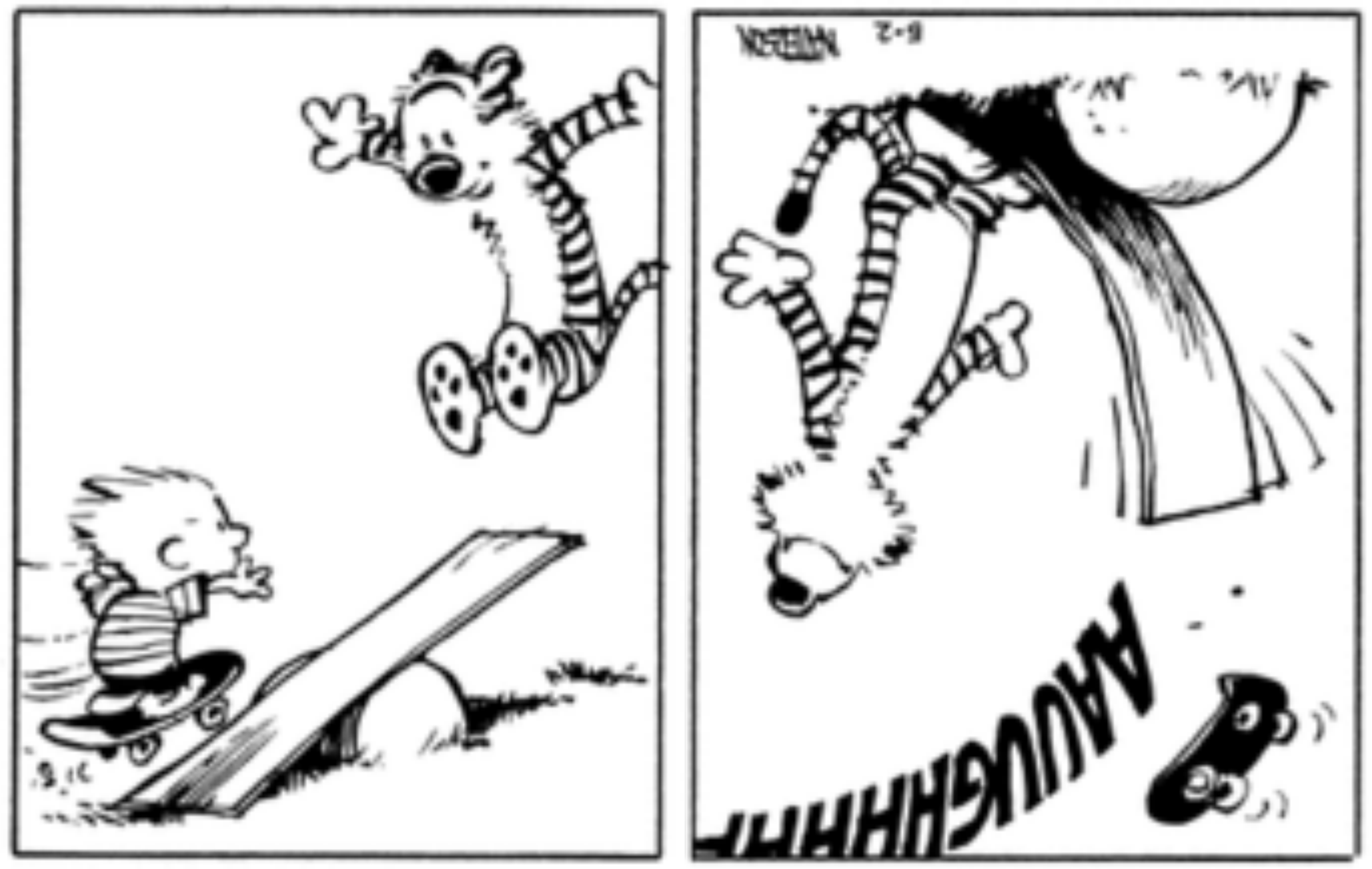
R.N. Mohapatra and J.W.F. Valle, Phys. Rev. D34 (1986) 1642

Type-I

2 SM singlets $N,\ N' \longrightarrow L(N) = +1,\ L(N') = -1$

$$\mathscr{L}_{type-I\ ISS} \supset \overline{N} Y_N^T \tilde{\phi}^\dagger \ell_L + M_D \overline{N} N'^c \longrightarrow$$ **L-conserving**

$$+\overline{N}' Y_N'^T \tilde{\phi}^\dagger \ell_L + \mu \overline{N} N^c + \mu' \overline{N}' N'^c \longrightarrow$$ **L-violating**



pseudo-Dirac fermions $\Bigg\{$

- Dirac mass $M_D = \begin{pmatrix} 0 & \Lambda^T \\ \Lambda & 0 \end{pmatrix}$
- Majorana masses $\mu,\ \mu'$

Type-III ISS is identical to type-I

Instead of 2 SM singlets, we have 2 $SU(2)$-triplet fermions

Basics: Type-I and Type-III ISS

Type III models offer a richer phenomenology

- Have gauge interactions: $\overline{\Sigma}^{-}\Sigma^{-}Z,\ \overline{\Sigma}^{+}\Sigma^{+}Z,\ \overline{\Sigma}^{0}\Sigma^{+}W^{-},\ \overline{\Sigma}^{0}\Sigma^{-}W^{+} + \text{ h.c.}$
- Charged leptons mix with new states: $\Sigma^{+^{c}} - l^{-}$

production at colliders and rare decays

Type-I Type-III ISS

$$M_\nu = \begin{pmatrix} 0 & Y_N^T v & {Y_N}'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{pmatrix} \longrightarrow m_\nu \sim \left({Y_N}'^T \frac{1}{\Lambda^T} Y_N + Y_N^T \frac{1}{\Lambda} Y_N' \right) v^2 + \mathcal{O}\underbrace{\left(Y_N^T \frac{1}{\Lambda} \mu \frac{1}{\Lambda^T} Y_N v^2 \right)}_{\text{Minimal Lepton Flavor Violation!}}$$

Neutrino masses are proportional to the Majorana masses

Supersoft SUSY Breaking

SUSY is broken in a hidden sector

P. J. Fox, A. E. Nelson and N. Weiner, JHEP 08 (2002) 035

SUSY breaking is communicated to the visible sector at a **messenger scale** Λ_M.

Dirac gaugino masses are generated via D-term spurions.

$$\int d^2\theta \sqrt{2}\, c_{\tilde{B}} \frac{W'_\alpha}{\Lambda_M} W^\alpha W_{\tilde{B}} \Phi_S \Rightarrow \frac{\sqrt{2}\, c_{\tilde{B}} D}{\Lambda_M} \tilde{B} S \equiv M_{\tilde{B}} \tilde{B} S$$

$D = \langle W'_\alpha \rangle$: SUSY–breaking vev of a D–term spurion field

$$\int d^2\theta \sqrt{2}\, c_{\tilde{W}} \frac{W'_\alpha}{\Lambda_M} W^\alpha W_{\tilde{W}} \Phi_T \Rightarrow \frac{\sqrt{2}\, c_{\tilde{W}} D}{\Lambda_M} \tilde{W} T \equiv M_{\tilde{W}} \tilde{W} T$$

$$\psi^T_{\tilde{B}} = \left(\tilde{B}\ S^\dagger\right)^T$$

$$\psi^T_{\tilde{W}} = \left(\tilde{W}\ T^\dagger\right)^T$$

Dirac gauginos

$U(1)_{R-L}$-breaking AMSB

As with all global symmetries, $U(1)_{R-L}$ must be broken due to gravity.

Anomaly mediation → **Majorana gaugino masses** (but small)

$$m_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} \boxed{m_{3/2}}$$ **Gravitino mass**

L. Randall and R. Sundrum, Nucl. Phys. B557 (1999) 79
G.F. Giudice, et.al., JHEP 12 (1998) 027
T. Gherghetta, et al., Nucl. Phys. B 559 (1999) 27

Dirac partners can also acquire Majorana masses: $m_S, m_T \sim \mathcal{O}(m_{3/2})$

$U(1)_{R-L}$ is approximately conserved when $\Lambda_M \ll M_{\rm Pl}$ ➤ $m_{\tilde{B}}, m_{\tilde{W}}, m_S, m_T \propto m_{3/2} \ll M_{\tilde{B}}, M_{\tilde{W}}$

$U(1)_{R-L}$ is (approximately) broken:

$$\psi^T_{\tilde{B}} = \left(\tilde{B}\ S^\dagger\right)^T$$

$$\psi^T_{\tilde{W}} = \left(\tilde{W}\ T^\dagger\right)^T$$

→ **pseudo-Dirac gauginos**

"biνo"

"wiνo"

Electroweak sector

After EWSB, S and T participate in both neutralino and chargino mixing due to the presence of $U(1)_R$ symmetry.

The relevant part of the superpotential:

G.D. Kribs, A. Martin and T.S. Roy, JHEP 01 (2009) 023

$$\mathscr{W} = \mu_u H_u R_u + \mu_d H_d R_d + \Phi_S \left(\lambda^u_{\tilde{B}} H_u R_u + \lambda^d_{\tilde{B}} H_d R_d \right) + \Phi_T \left(\lambda^u_{\tilde{W}} H_u R_u + \lambda^d_{\tilde{W}} H_d R_d \right)$$

In the large $\tan\beta \equiv v_u / v_d$ limit, ($v_d \to 0$), the mixing matrices in neutral and charged sectors:

$$\mathbb{M}_N \simeq \begin{pmatrix} M_{\tilde{B}} & 0 & g_Y v/2 & 0 \\ 0 & M_{\tilde{W}} & -g_2 v/\sqrt{2} & 0 \\ \lambda^u_{\tilde{B}} v/2 & -\lambda^u_{\tilde{W}} v/2 & \mu_u & 0 \\ 0 & 0 & 0 & \mu_d \end{pmatrix}$$

$$\mathbb{M}_C \simeq \begin{pmatrix} M_{\tilde{W}} & -g_2 v/\sqrt{2} & 0 \\ 0 & \mu_u & 0 \\ 0 & 0 & \mu_d \end{pmatrix}$$

In the basis $(\tilde{B}, \tilde{W}^0, \tilde{R}^0_u, \tilde{R}^0_d) \times (S, T^0, \tilde{h}^0_u, \tilde{h}^0_d)$

In the basis $(\tilde{W}^+, \tilde{R}^+_u, \tilde{R}^+_d) \times (\Phi^-_T, \tilde{h}^-_u, \tilde{h}^-_d)$

We further assume $\lambda^u_{\tilde{B},\tilde{W}} = 0$ such that bino, wino and Higgsinos do not mix

Neutrino masses: A Simplified Scenario

Non-zero Majorana masses, $m_{S,T} \neq 0$, and vanishing couplings of Dirac partners, $G_{S,T} \sim 0$

$$c^{d=5} = -\frac{1}{\Lambda_M^2}\left(m_S\, \mathbf{u}_{\tilde{B}}\mathbf{u}_{\tilde{B}}^T + m_T\, \mathbf{u}_{\tilde{W}}\mathbf{u}_{\tilde{W}}^T\right) \equiv -\frac{1}{\Lambda_M^2}\mathcal{O}$$

$$\mathbf{Y}^T_{\tilde{B},\tilde{W}} \equiv y_{\tilde{B},\tilde{W}}\, \mathbf{u}^T_{\tilde{B},\tilde{W}}, \quad \mathbf{G}^T_{S,T} \equiv g_{S,T}\, \mathbf{v}^T_{S,T}, \quad y_{\tilde{B},\tilde{W}} = \frac{M_{\tilde{B},\tilde{W}}}{\Lambda_M}, \quad g_{S,T} = \frac{m_{3/2}}{\Lambda_M}, \quad \mathbf{u}_{\tilde{B}} \cdot \mathbf{u}_{\tilde{B}} = \mathbf{u}_{\tilde{W}} \cdot \mathbf{u}_{\tilde{W}} = 1, \quad \mathbf{u}^\dagger_{\tilde{B}}\mathbf{u}_{\tilde{W}} = \mathbf{u}^\dagger_{\tilde{W}}\mathbf{u}_{\tilde{B}} \equiv \lambda_{\text{NO}}$$

The light-neutrino mass eigenvalues in the normal ordering are

$$m_1 = 0\,, \quad m_{2,3} = \frac{v^2(m_S + m_T)}{\sqrt{2}\Lambda_M^2}\sqrt{1 - 2\beta_{\text{NO}} \pm \sqrt{1 - 4\beta_{\text{NO}}}}$$

$m_{2,3} \propto m_T + m_S$

where β_{NO} is set by the mass-squared splitting ratios,

$$\beta_{\text{NO}} = -2r(r+1) + \sqrt{r(r+1)}(2r+1) \simeq 0.13 \text{ with } r = \frac{|\Delta m^2_{\text{sol}}|}{|\Delta m^2_{\text{atm}}|} \simeq 0.03$$

Neutrino Mass Eigensystem

The entries in the PMNS matrix fix the mass eigenstates to accommodate the correct mixing structure

$$U_{\text{PMNS}} = \begin{pmatrix} U_{i1} & U_{i2} & U_{i3} \end{pmatrix} = \begin{pmatrix} \hat{\mathbf{e}}_1 & \hat{\mathbf{e}}_2 & \hat{\mathbf{e}}_3 \end{pmatrix}, \quad i = e, \mu, \tau$$

Assuming $\hat{\mathbf{e}}_{2,3} = N_{2,3}(a_{2,3}\mathbf{u}_{\tilde{B}} + b_{2,3}\mathbf{u}_{\tilde{W}})$,

$$u^i_{\tilde{B}} = \left(\frac{a_2}{b_2} - \frac{a_3}{b_3}\right)^{-1}\left[\frac{1}{b_2N_2}U_{i2} - \frac{1}{b_3N_3}U_{i3}\right] \qquad u^i_{\tilde{W}} = \left(\frac{b_2}{a_2} - \frac{b_3}{a_3}\right)^{-1}\left[\frac{1}{a_2N_2}U_{i2} - \frac{1}{a_3N_3}U_{i3}\right]$$

$$u^i_{\tilde{B},\tilde{W}} \propto \frac{m_T}{m_S}$$

$$\lambda_{\text{NO}} = \sqrt{1 + \beta_{\text{NO}}\frac{(m_S + m_T)^2}{m_S m_T}}, \quad \begin{aligned} a_{2,3} &= -2m_S\lambda_{\text{NO}}, \\ b_{2,3} &= (m_S - m_T) \mp \sqrt{(m_S - m_T)^2 + 4m_S m_T \lambda_{\text{NO}}^2}, \end{aligned} \quad N_{2,3} = \frac{1}{\sqrt{a_{2,3}^2 + b_{2,3}^2 + 2a_{2,3}b_{2,3}\lambda_{\text{NO}}}}$$

Comparison to the Pure Biνo Case

* P. Coloma and **S. Ipek**, Phys. Rev. Lett. 117 (2016) 111803

When $m_S = m_T$, this scenario is equivalent to the pure biνo case*

$$u^i_{\tilde{B}} = \frac{1}{\sqrt{2}}\left[\sqrt{1+\lambda_{NO}}U_{i3} + \sqrt{1-\lambda_{NO}}U_{i2}\right]$$

$$u^i_{\tilde{W}} \Rightarrow v^i_S = \frac{1}{\sqrt{2}}\left[\sqrt{1+\lambda_{NO}}U_{i3} - \sqrt{1-\lambda_{NO}}U_{i2}\right]$$

Using the central values of the PMNS mixing parameters:

$$\mathbf{u}_{\tilde{B}} = \begin{pmatrix} 0.35 \\ 0.85 \\ 0.39 \end{pmatrix} \text{ and } \mathbf{v}_S = \begin{pmatrix} -0.06 \\ 0.44 \\ 0.89 \end{pmatrix}$$

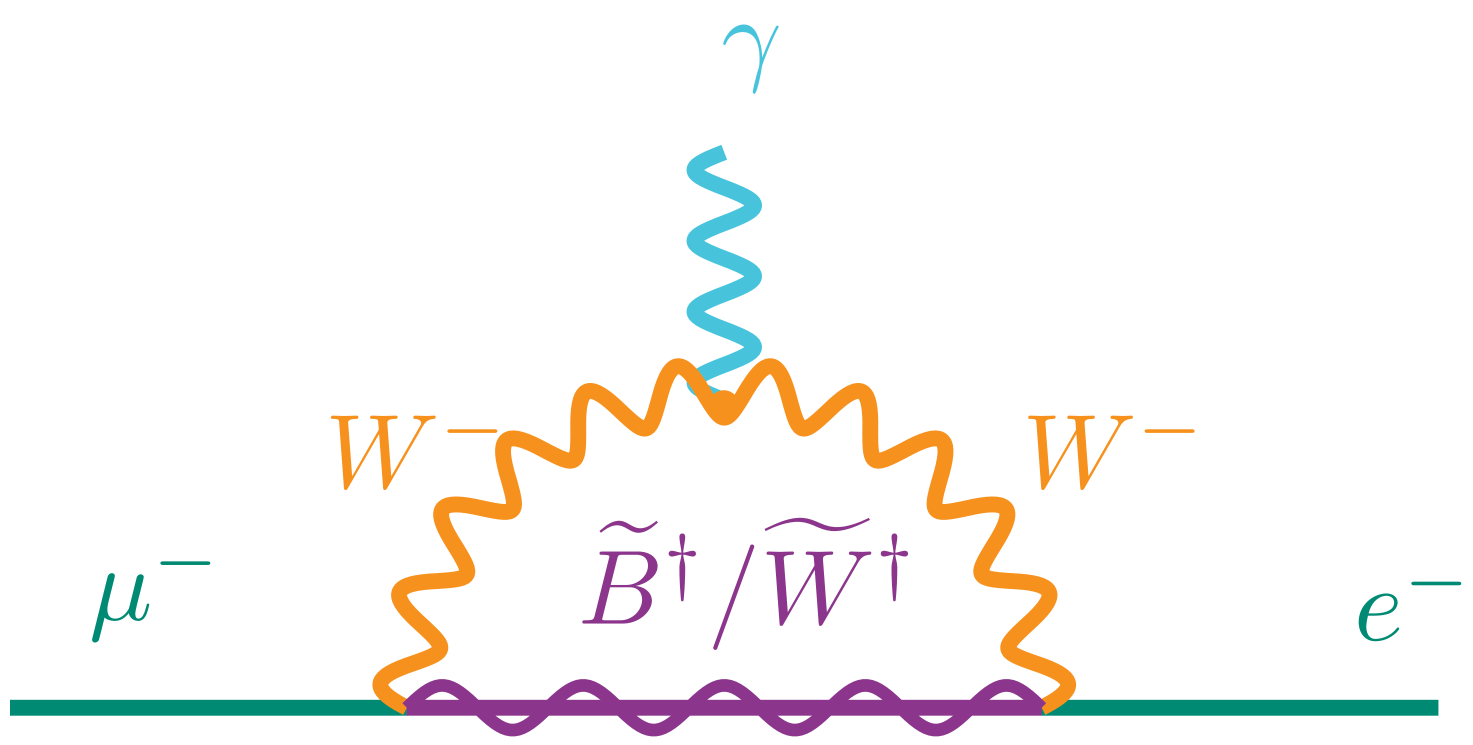
intrinsic dependence to the gravitino mass

hybrid biνo/wiνo case $$m_{2,3} = \frac{(m_S + m_T)v^2}{\sqrt{2}\Lambda_M^2}\sqrt{1 - 2\beta \pm \sqrt{1-4\beta}} \text{ with } \beta \simeq 0.13$$

pure biνo case* $$m_{2,3} = \frac{m_{3/2}v^2}{\Lambda_M^2}\left(1 \pm \rho\right) \text{ with } \rho \simeq 0.7$$

Experimental Bounds

$\mu \to e\,\gamma$



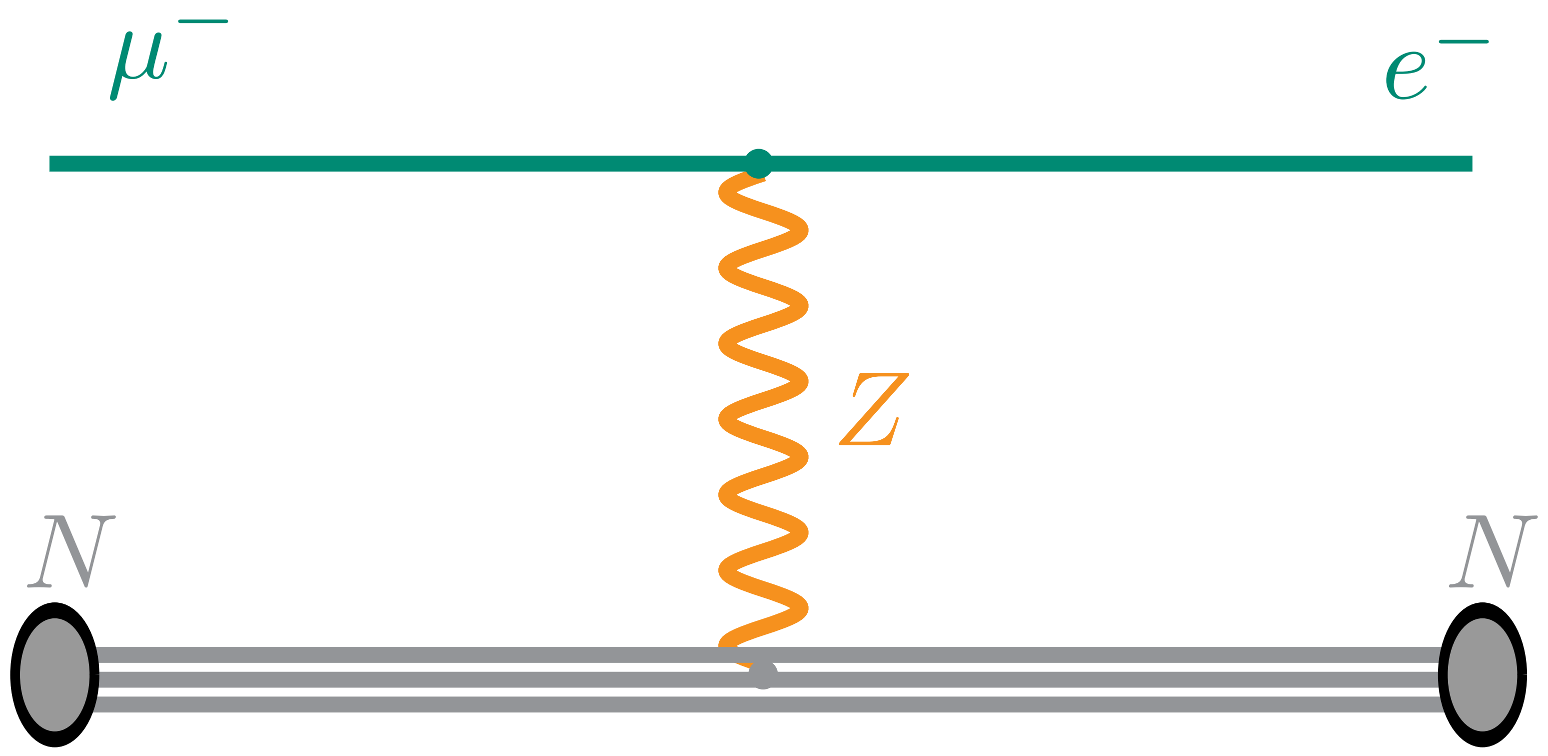
$$\mathrm{Br}(\mu \to e\gamma)\Big|_{\text{now}} < 4.2 \times 10^{-13}$$

MEG Collaboration, Eur. Phys. J. C 76 (2016) 8, 434

$$\mathrm{Br}(\mu \to e\gamma)\Big|_{\text{future}} \lesssim 10^{-14}$$

MEG II Collaboration, PoS NuFact2021 (2022) 120

$\mu - e$ conversion in nuclei



$$\mathrm{R}_{\mu e}\Big|_{\text{now}} < 7 \times 10^{-13}$$

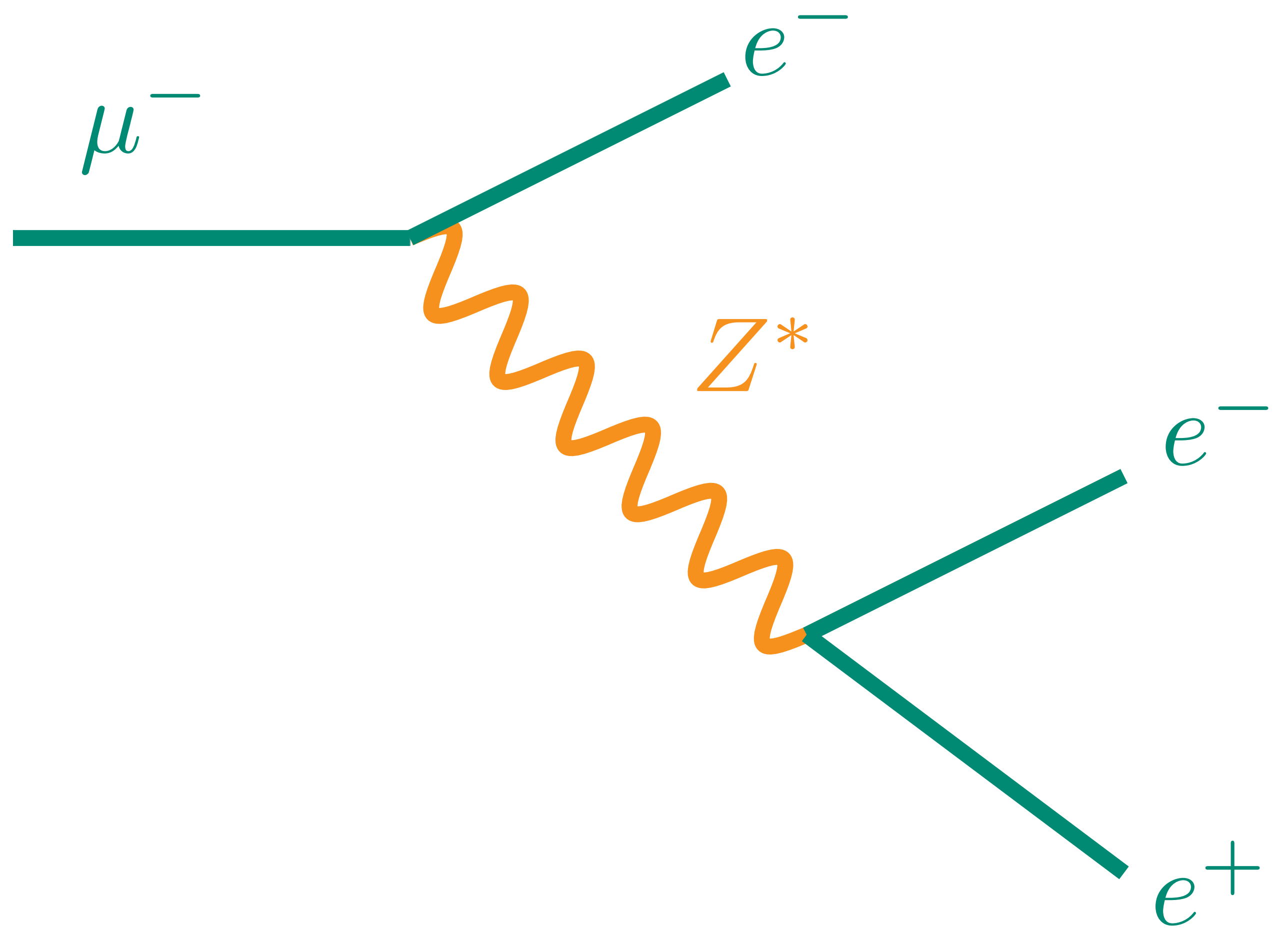
SINDRUM II Collaboration, Eur. Phys. J. C 47 (2006) 337

$$\mathrm{R}_{\mu e}\Big|_{\text{future}} < 6.2 \times 10^{-16}$$

Mu2e Collaboration. Universe 2023, 9, 54

strongest constraint

$\mu \to e\,e\,e$



$$\mathrm{Br}(\mu \to eee) < 1.0 \times 10^{-12}$$

SINDRUM collaboration, Nucl. Phys. B 299 (1988) 1

Combined Constraints

A. Abada, C. Biggio, F. Bonnet, M.B. Gavela and T. Hambye, Phys. Rev. D 78 (2008) 033007
A. Abada, C. Biggio, F. Bonnet, M.B. Gavela and T. Hambye, JHEP 12 (2007) 061

Type-I

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta} \lesssim \begin{pmatrix} 10^{-2} & \boxed{7.0 \cdot 10^{-5}} & 1.6 \cdot 10^{-2} \\ \boxed{7.0 \cdot 10^{-5}} & 10^{-2} & 1.0 \cdot 10^{-2} \\ 1.6 \cdot 10^{-2} & 1.0 \cdot 10^{-2} & 10^{-2} \end{pmatrix}$$

Stronger than type-I due to tree level FCNC

Type-III

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3 \cdot 10^{-3} & \boxed{< 1.1 \cdot 10^{-6}} & < 1.2 \cdot 10^{-3} \\ \boxed{< 1.1 \cdot 10^{-6}} & 4 \cdot 10^{-3} & < 1.2 \cdot 10^{-3} \\ < 1.2 \cdot 10^{-3} & < 1.2 \cdot 10^{-3} & 4 \cdot 10^{-3} \end{pmatrix}$$

$\alpha, \beta = e, \mu, \tau$

By far the strongest constraints are on the $e - \mu$ element

$$\left(\epsilon^{d=6}\right)_{e\mu} = \frac{v^2}{\Lambda_M^2}\left| u^e_{\tilde{B}} u^\mu_{\tilde{B}} + u^e_{\tilde{W}} u^\mu_{\tilde{W}} \right|$$

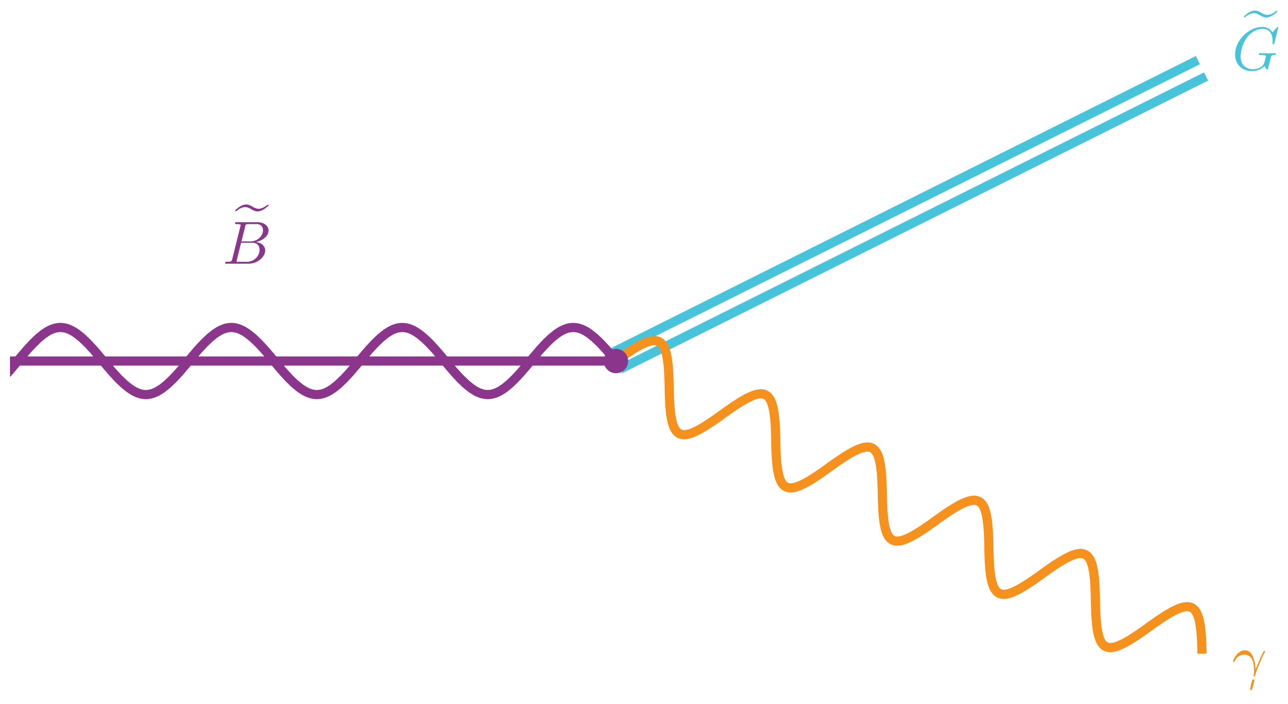
MEG Collaboration, Eur. Phys. J. C 76 (2016) 8, 434
MEG II Collaboration, PoS NuFact2021 (2022) 120
SINDRUM II Collaboration, Eur. Phys. J. C 47 (2006) 337
Mu2e Collaboration. Universe 2023, 9, 54
SINDRUM collaboration, Nucl. Phys. B 299 (1988) 1

Bino Decays

If kinematically allowed

$m_{3/2} \sim 10 \text{ MeV} \quad M_{\tilde{B}} \sim 500 \text{ GeV} \quad \Lambda_M \sim 500 \text{ TeV}$

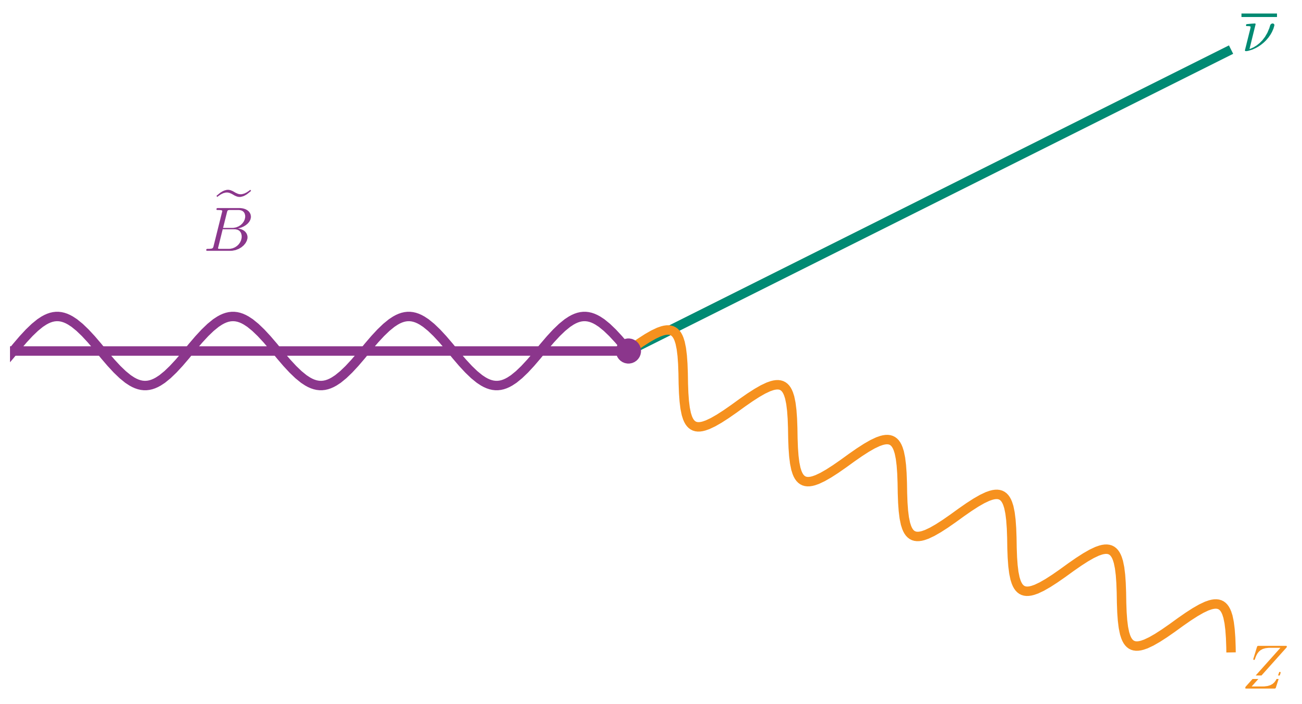
$\tilde{B} \to \tilde{G}\,\gamma$



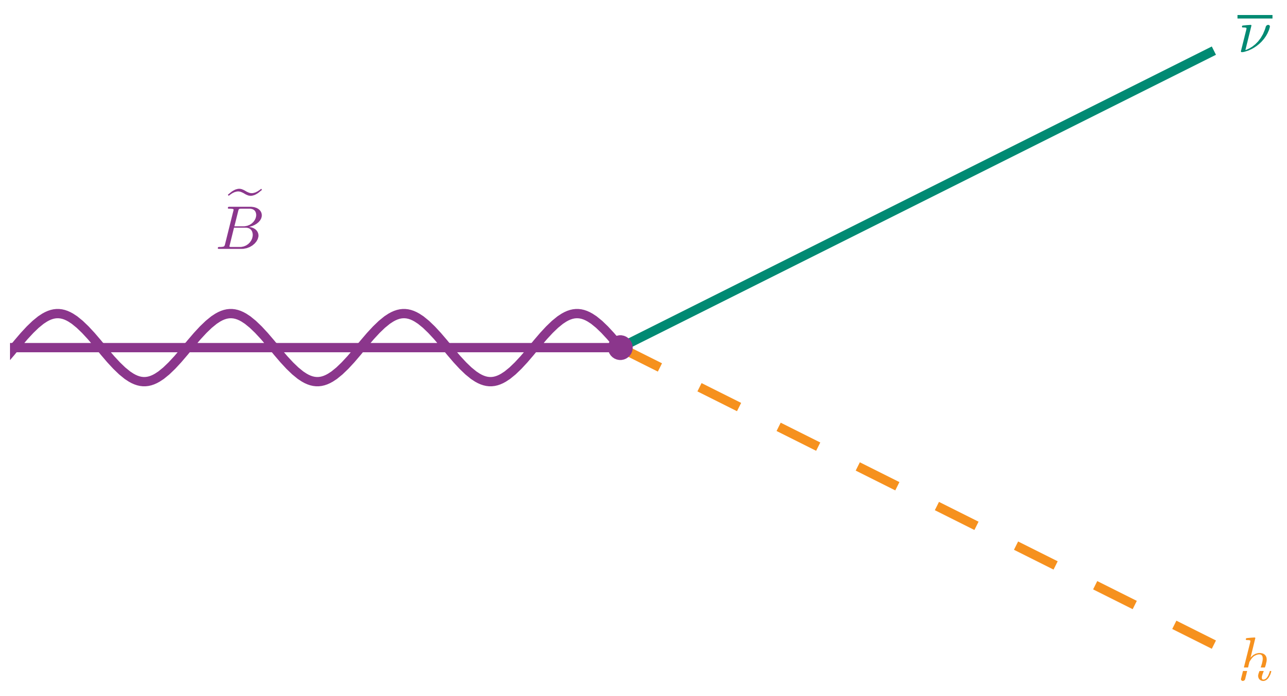
Suppressed by the Planck mass

$$\Gamma\left(\tilde{B} \to \tilde{G}\gamma\right) \sim \frac{M_{\tilde{B}}^5}{\boxed{M_{\rm Pl}^2} m_{3/2}^2} \sim 10^{-12} \text{ eV}$$

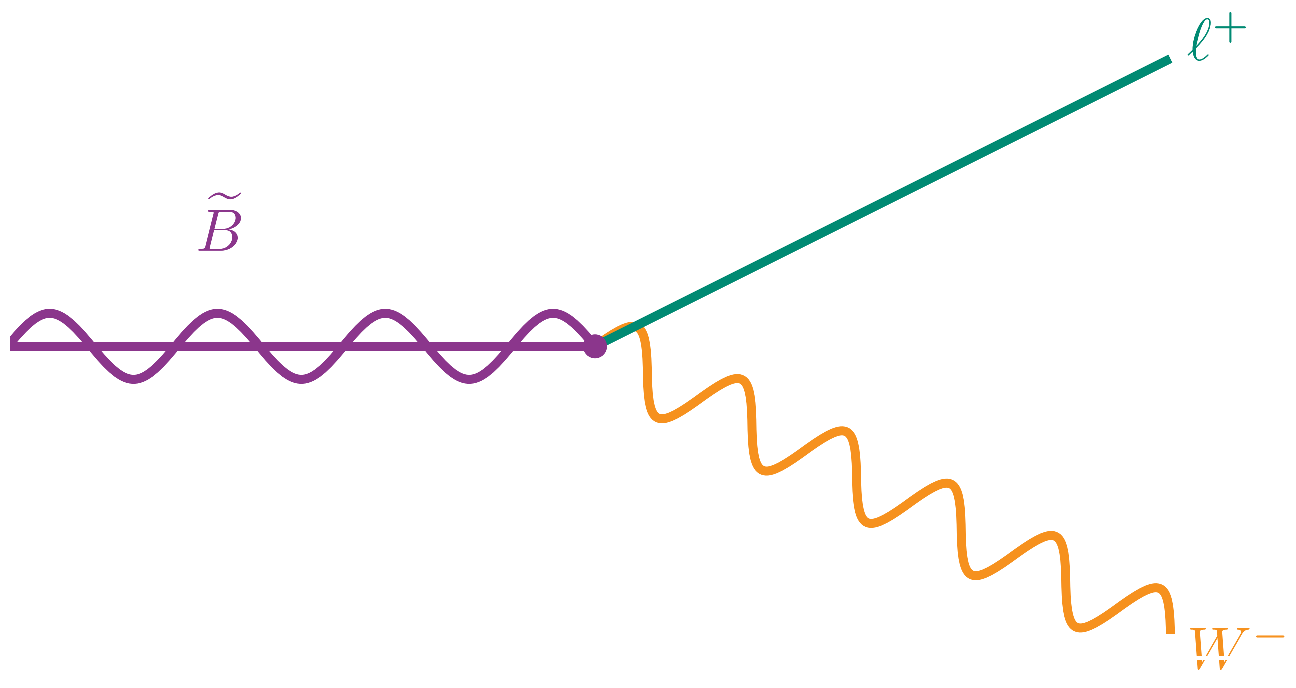
$\tilde{B} \to Z\bar{\nu}$



$\tilde{B} \to h\,\bar{\nu}$



$\tilde{B} \to W^-\ell^+$



Total decay width

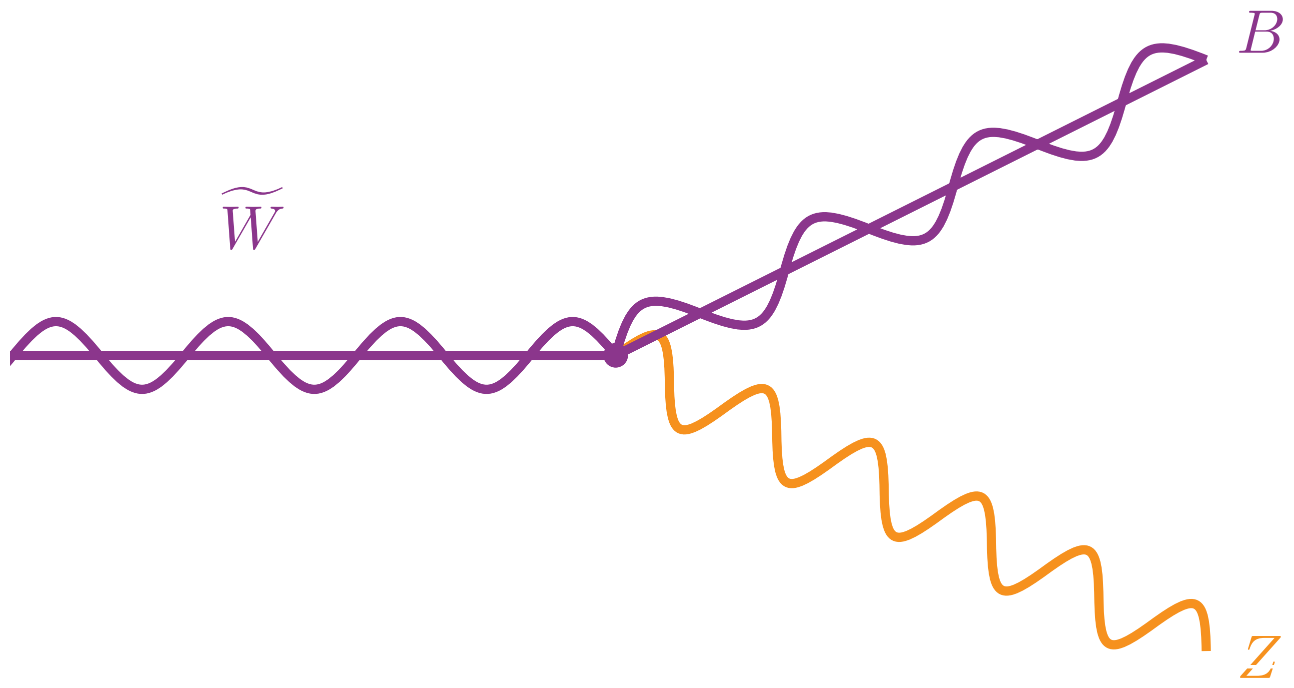
$$\Gamma_{\tilde{B},\,\rm tot} = \sum_i Y_i^2 M_{\tilde{B}} \sim \frac{M_{\tilde{B}}}{\Lambda_M^2} \sim 0.5 \text{ MeV}$$

decays promptly at the LHC

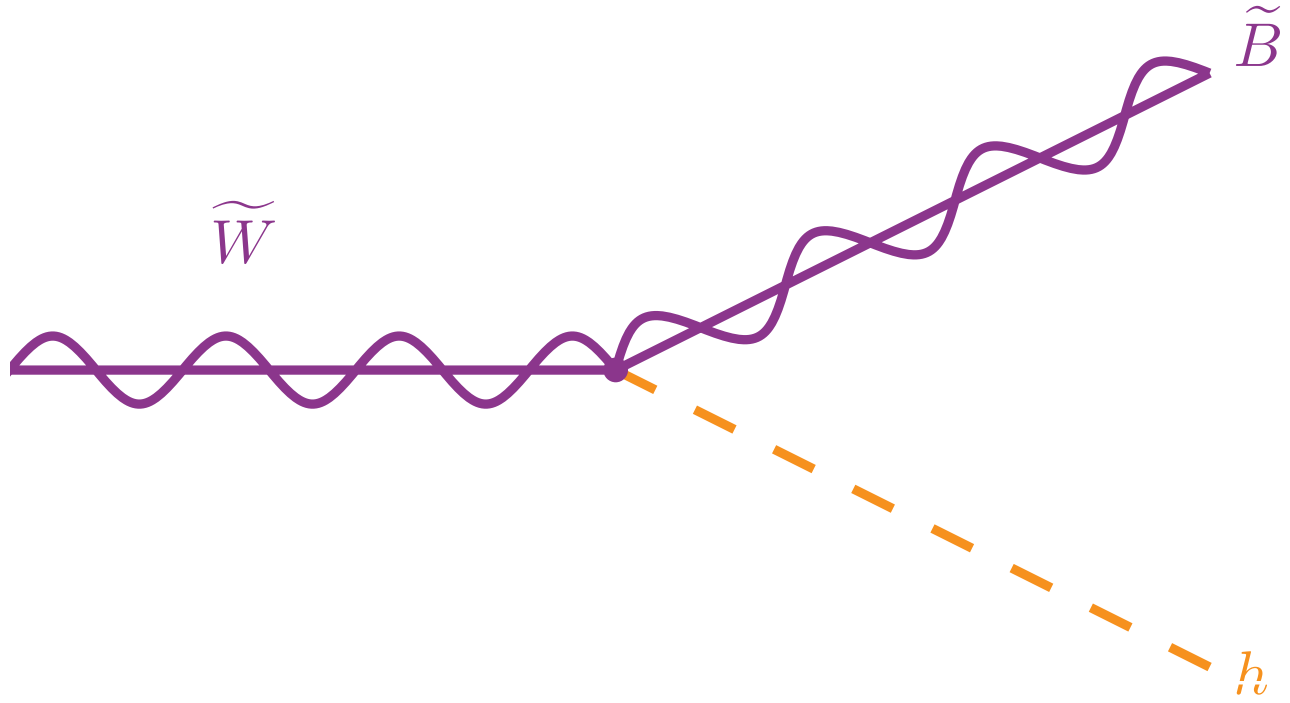
Wino Decays

If kinematically allowed

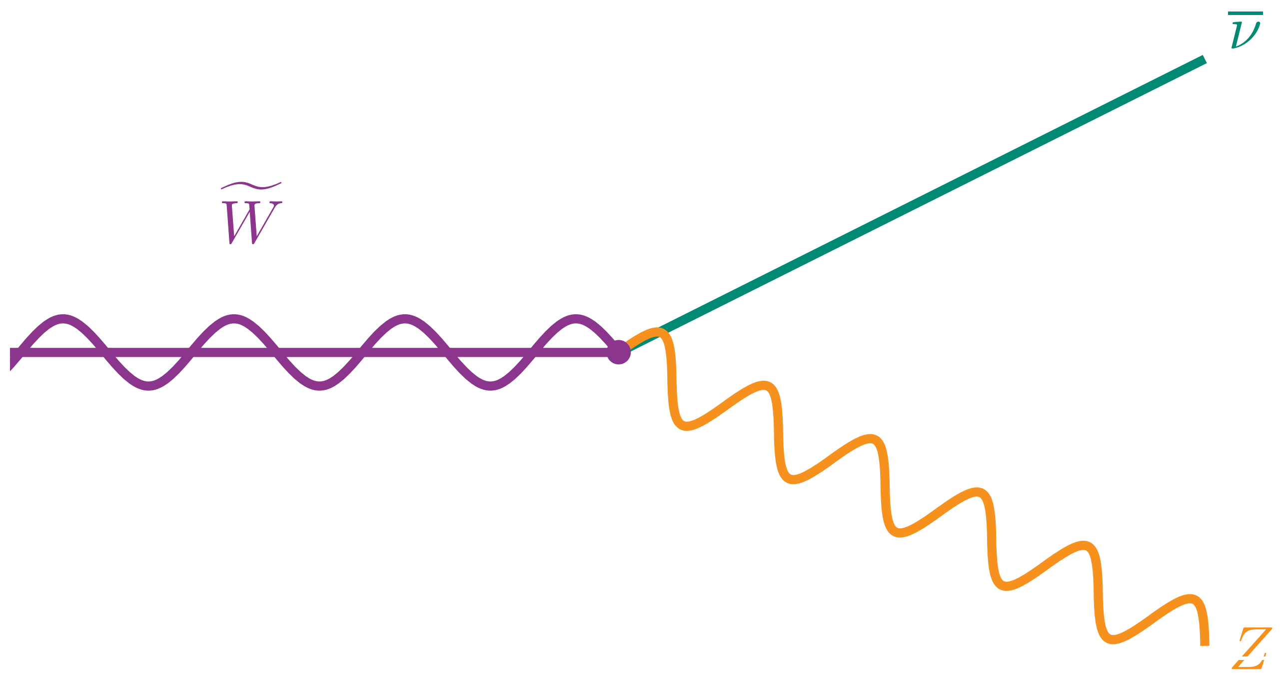
$\tilde{W} \to Z\tilde{B}$



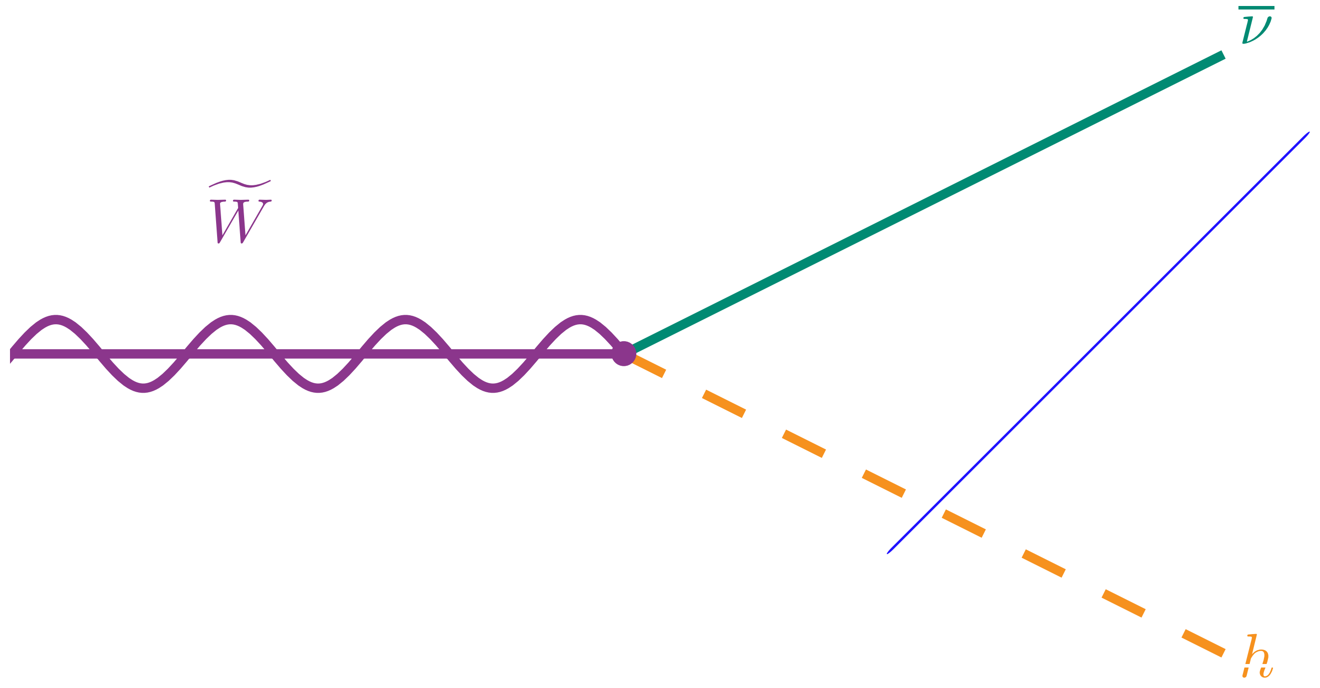
$\tilde{W} \to h\tilde{B}$



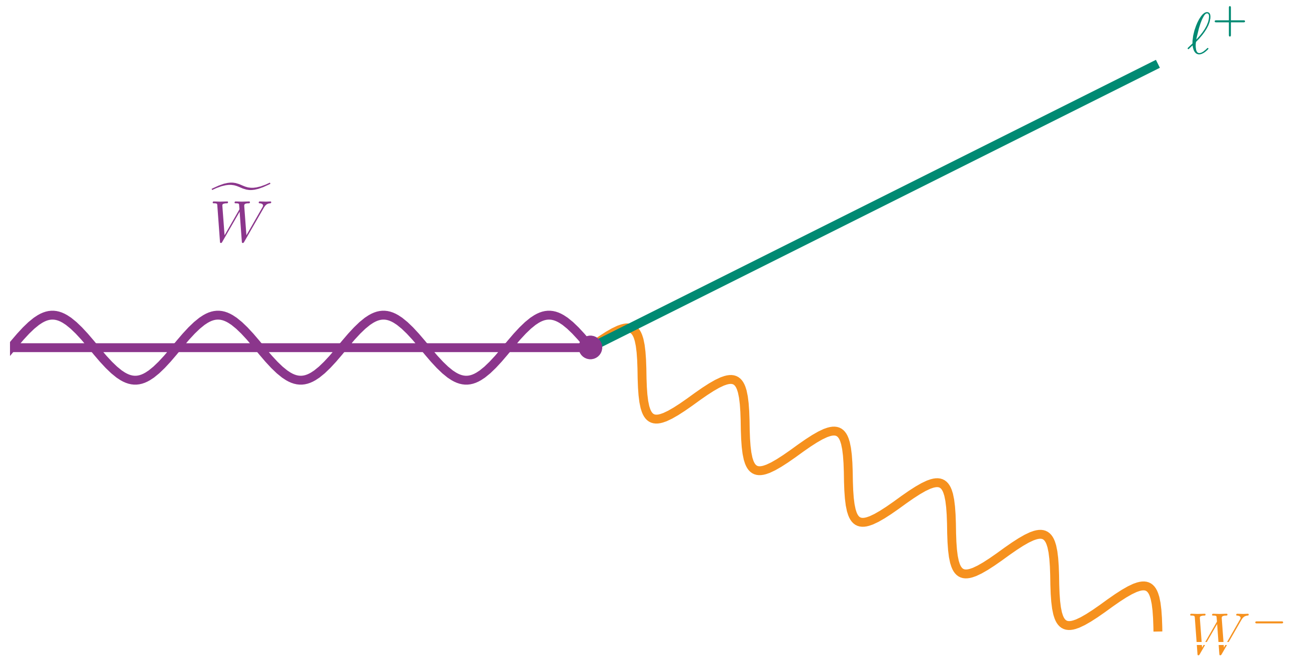
$\tilde{W} \to Z\bar{\nu}$



$\tilde{W} \to h\bar{\nu}$



$\tilde{W} \to W^{-}\ell^{+}$



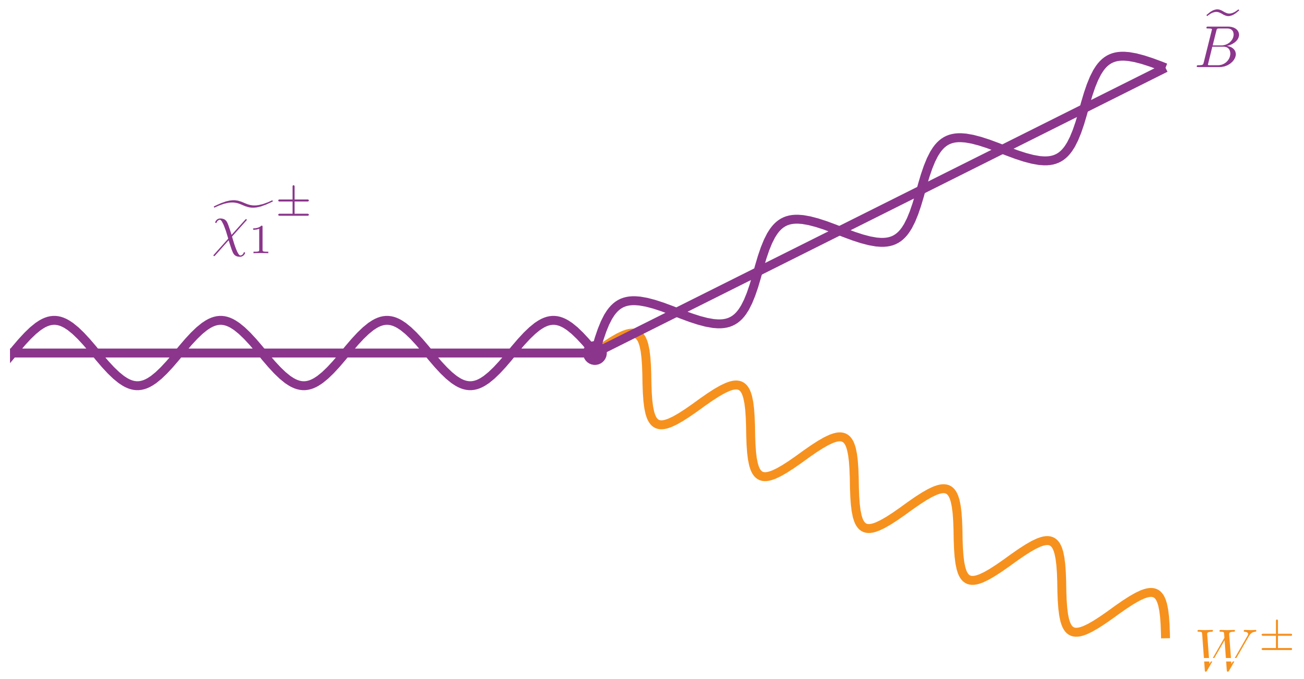
These channels are suppressed by the mixing angle:

$$\theta^2 \sim \left(\frac{y_{\tilde{W}} v}{M_{\tilde{W}}}\right) \sim \frac{v^2}{\Lambda_M^2} \sim 10^{-7}$$

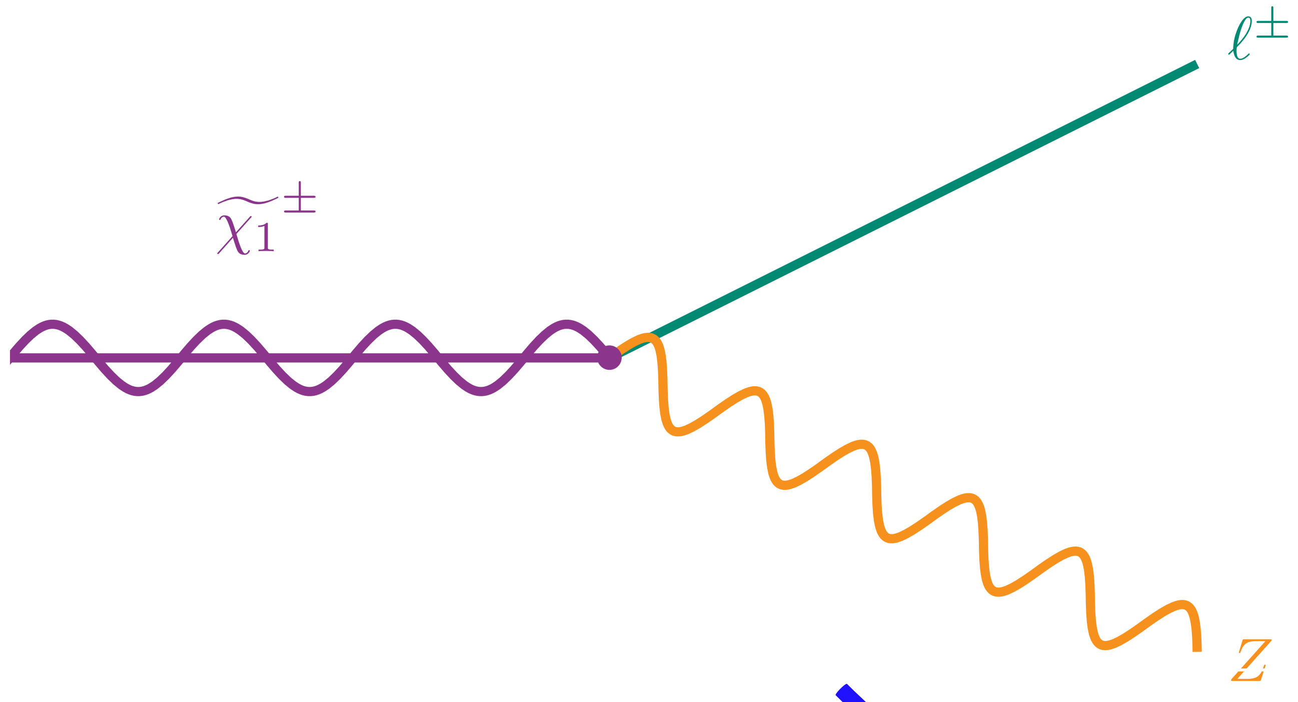
Chargino Decays

If kinematically allowed

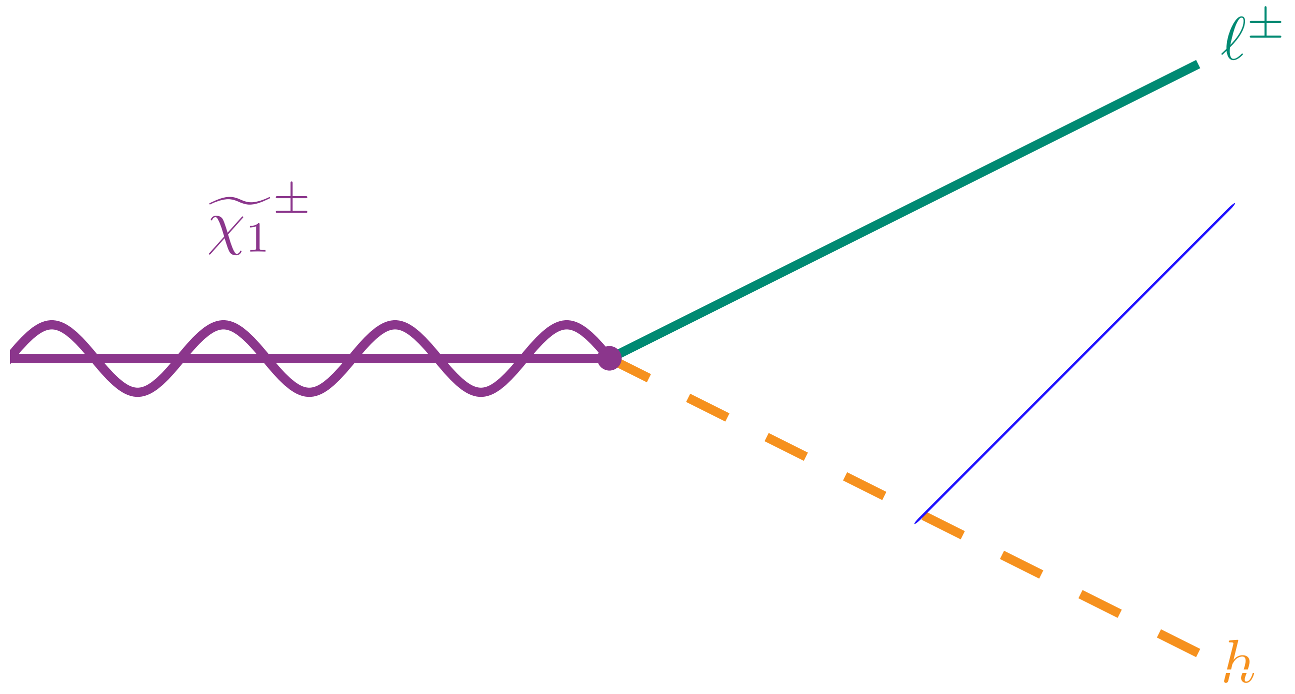
$\tilde{\chi}_1^\pm \to W^\pm \tilde{B}$



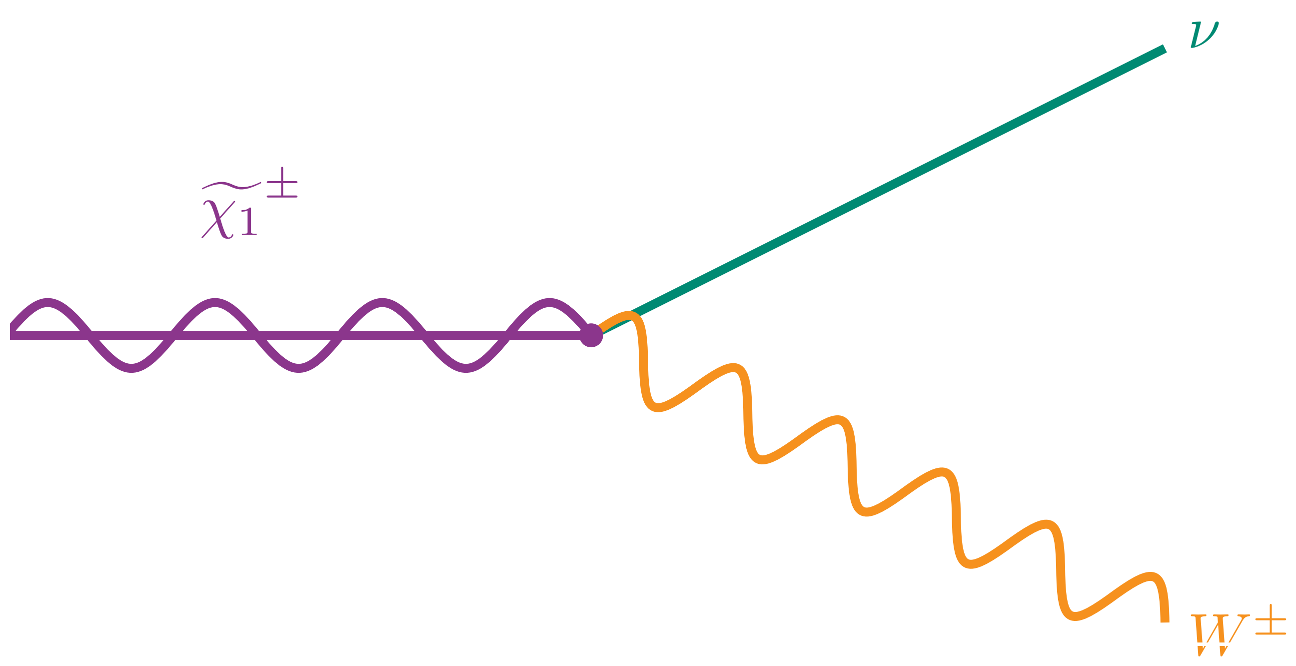
$\tilde{\chi}_1^\pm \to Z \ell^\pm$



$\tilde{\chi}_1^\pm \to h \ell^\pm$



$\tilde{\chi}_1^\pm \to W^\pm \nu$



These channels are suppressed by the mixing angle: $\theta^2 \sim \left(\frac{y_{\tilde{W}} v}{M_{\tilde{W}}}\right) \sim \frac{v^2}{\Lambda_M^2} \sim 10^{-7}$