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 "💎")

ICHEP 2024

Neutrinos Have Mass

Discovery of neutrino oscillations ⟶ Massive neutrinos

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

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

$$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2} = 7.41^{+0.21}_{-0.20}$$

$$\frac{\Delta m^2_{31}}{10^{-3}\,\mathrm{eV}^2} = 2.511^{+0.028}_{-0.027}$$

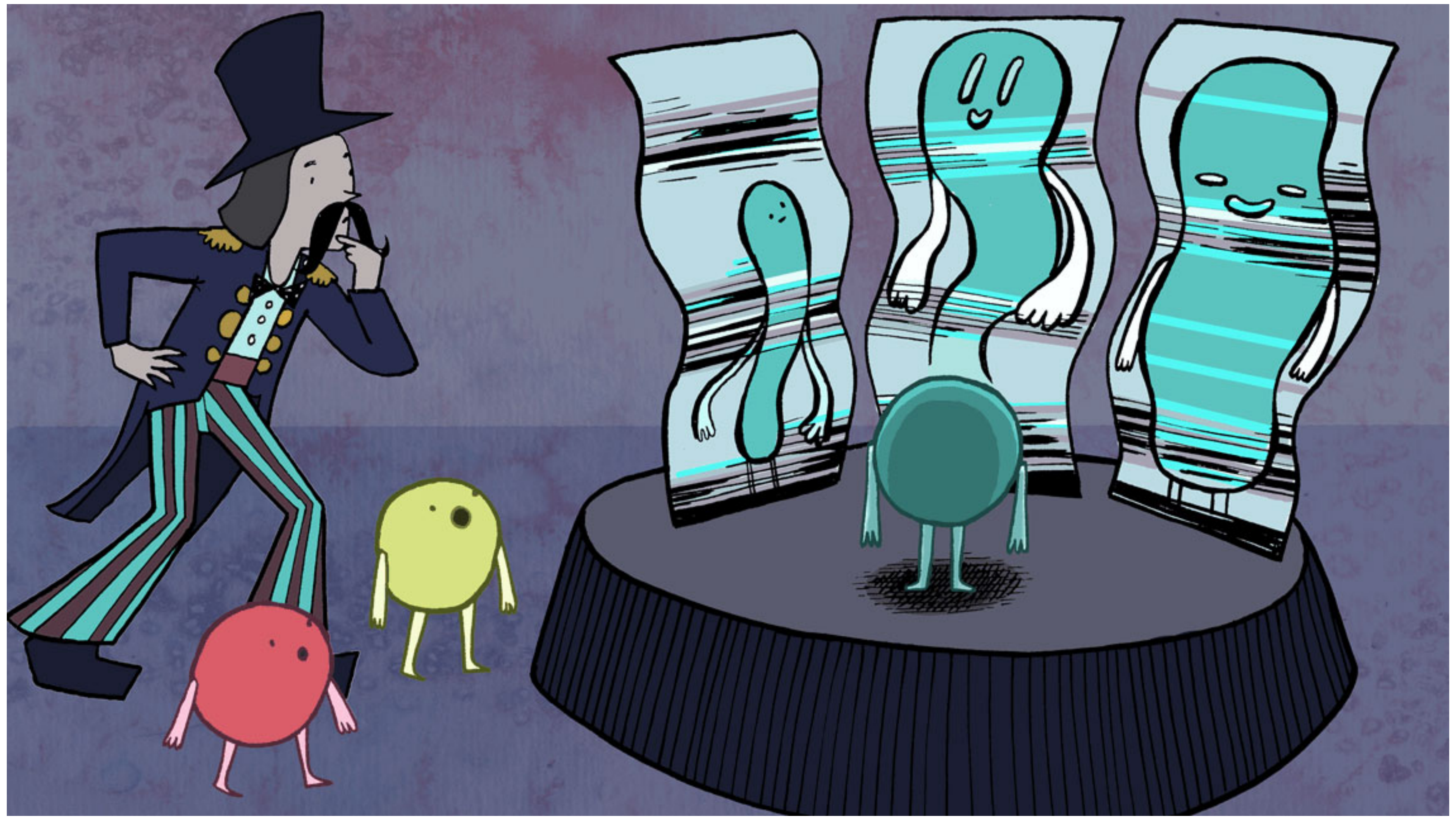
$$\sin^2\theta_{12} = 0.307^{+0.012}_{-0.011}$$

$$\sin^2\theta_{23} = 0.454^{+0.019}_{-0.016}$$

$$\sin^2\theta_{13} = 0.02224^{+0.00056}_{-0.00057}$$

$$\delta_{CP}/^{\circ} = 232^{+39}_{-25}$$

I. Esteban et al., JHEP(2020) 178 www.nu-fit.org



Symmetry Magazine/Sandbox Studio, Chicago

$U(1)_R$-symmetric SUSY

L. J. Hall and L. Randall, Nucl. Phys. B352, 289 (1991)
G. D. Kribs, E. Poppitz, and N. Weiner, Phys. Rev. D78, 055010 (2008)

SM particles are *neutral* under $U(1)_R$

Superpartners have $+1$ R-charges

→ Majorana gaugino masses are **forbidden**

$M_\lambda \bar{\lambda} \lambda^c$ R-charges: $1 + 1 \neq 0$

Introduce three adjoint fields with $R = -1$ charges:

- A hypercharge singlet: ***Singlino*** S
- An $SU(2)$ triplet: ***Tripletino*** T
- An $SU(3)_c$ octet: ***Octino*** $\mathcal{O}$

→ Higgsino mass terms are **forbidden**

Introduce two *inert* doublets: R_u , R_d, $\langle R_{u,d} \rangle = 0$

Superfields	$SU(2)_L$	$U(1)_R$
L_i	2	1
E_i^c	1	1
$H_{u,d}$	2	0
$R_{u,d}$	2	2
$W^\alpha_{\tilde{B}}$	1	1
$\Phi_S = \phi_S + \theta D$	1	0
$W^\alpha_{\tilde{W}}$	3	1
$\Phi_T = \phi_T + \theta D$	3	0
$W'_\alpha = \theta D$	1	1

2 $SU(2)$ singlet fermions ($W^\alpha_{\tilde{B}}$, Φ_S)

2 $SU(2)$ triplet fermions ($W^\alpha_{\tilde{W}}$, Φ_T)

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**

$U(1)_{R-L}$-symmetric SUSY

Lets extend the R-symmetry by including lepton number L Frugiuele, C., Grégoire, T., Kumar, P. *et al.* *JHEP* 2013, 156

$U(1)_R \rightarrow U(1)_{R-L}$

SM leptons are charged under $U(1)_{R-L}$

Superfields	$SU(2)_L$	$U(1)_R$	$U(1)_{R-L}$
L_i	2	1	0
E_i^c	1	1	2
$H_{u,d}$	2	0	0
$R_{u,d}$	2	2	2
$W_{\tilde{B}}^{\alpha}$	1	1	1
$\Phi_S = \phi_S + \theta D$	1	0	0
$W_{\tilde{W}}^{\alpha}$	3	1	1
$\Phi_T = \phi_T + \theta D$	3	0	0
$W'_{\alpha} = \theta D$	1	1	1

Allows the mixing between electroweakinos and SM leptons!

- ✦ Neutralinos and neutrinos — Neutrino masses
- ✦ Charginos and charged leptons — LFV at tree level

$U(1)_{R-L}$ symmetry can provide a natural mechanism for neutrino mass generation.

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

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

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

$$m_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{3/2}$$

Gravitino mass ($m_{3/2}$)

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:

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

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

→ **pseudo-Dirac gauginos** "biνo" "wiνo"

Neutrino masses

$U(1)_{R-L}$-conserving, dimension-6 operators:

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

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

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

Explicitly violate $U(1)_R$ and $U(1)_L$

Bino and wino act as *RH* neutrinos

$$\mathbf{Y}^T_{\tilde{B},\tilde{W}} = \begin{pmatrix} Y^e_{\tilde{B},\tilde{W}} & Y^\mu_{\tilde{B},\tilde{W}} & Y^\tau_{\tilde{B},\tilde{W}} \end{pmatrix} = \frac{M_{\tilde{B},\tilde{W}}}{\Lambda_M} \begin{pmatrix} f^e_{\tilde{B},\tilde{W}} & f^\mu_{\tilde{B},\tilde{W}} & f^\tau_{\tilde{B},\tilde{W}} \end{pmatrix}$$

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

$U(1)_{R-L}$-violating, dimension-5 operators:

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

$$\frac{1}{\Lambda_M}\int d^2\theta d^2\bar{\theta}\phi^\dagger\left(d_S^i\Phi_S H_u L_i + d_T^i\Phi_T H_u L_i\right) \Longrightarrow \frac{m_{3/2}}{\Lambda_M}\left(\underbrace{d_S^{\,i} S\, h_u \ell_i} + \underbrace{d_T^{\,i} T\, h_u \ell_i}\right)$$

$d^i_{S,T}$: Dimensionless coefficients, $i = e, \mu, \tau$ $\qquad$ $\phi = 1 + \theta^2 m_{3/2}$: The conformal compensator

S and T are the other *RH* neutrinos

$$\mathbf{G}^T_{S,T} = \begin{pmatrix} G^e_{S,T} & G^\mu_{S,T} & G^\tau_{S,T}\end{pmatrix} = \frac{m_{3/2}}{\Lambda_M}\begin{pmatrix} d^e_{S,T} & d^\mu_{S,T} & d^\tau_{S,T}\end{pmatrix}$$

Highly suppressed compared to the $U(1)_{R-L}$−conserving terms because $m_{3/2} \ll M_{\tilde{B},\tilde{W}}$

Neutrino masses

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

$$\mathscr{L} \supset \frac{f^i_{\tilde{B}} M_{\tilde{B}}}{\Lambda_M} \bar{\ell} h_u \tilde{B} + M_{\tilde{B}} S \tilde{B} + \frac{d^i_{\tilde{B}} m_{3/2}}{\Lambda_M} \bar{\ell} h_u S^\dagger + m_{\tilde{B}} \tilde{B}\tilde{B} + m_S SS$$

$$+ \frac{f^i_{\tilde{W}} M_{\tilde{W}}}{\Lambda_M} \bar{\ell} h_u \tilde{W} + M_{\tilde{W}} T \tilde{W} + \frac{d^i_{\tilde{W}} m_{3/2}}{\Lambda_M} \bar{\ell} h_u T^\dagger + m_{\tilde{W}} \tilde{W}\tilde{W} + m_T TT$$

Type-I ISS texture

+

Type-III ISS texture

$U(1)_{R-L}$**-conserving** (the $\frac{f^i M}{\Lambda_M}\bar{\ell} h_u \tilde{W} + M T\tilde{W}$ terms)

$U(1)_{R-L}$**-violating** (the $\frac{d^i m_{3/2}}{\Lambda_M}\bar{\ell} h_u T^\dagger + m \tilde{W}\tilde{W} + m_T TT$ terms)

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, $G_{S,T} \sim 0$

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

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

The light-neutrino mass eigenvalues in the normal ordering are

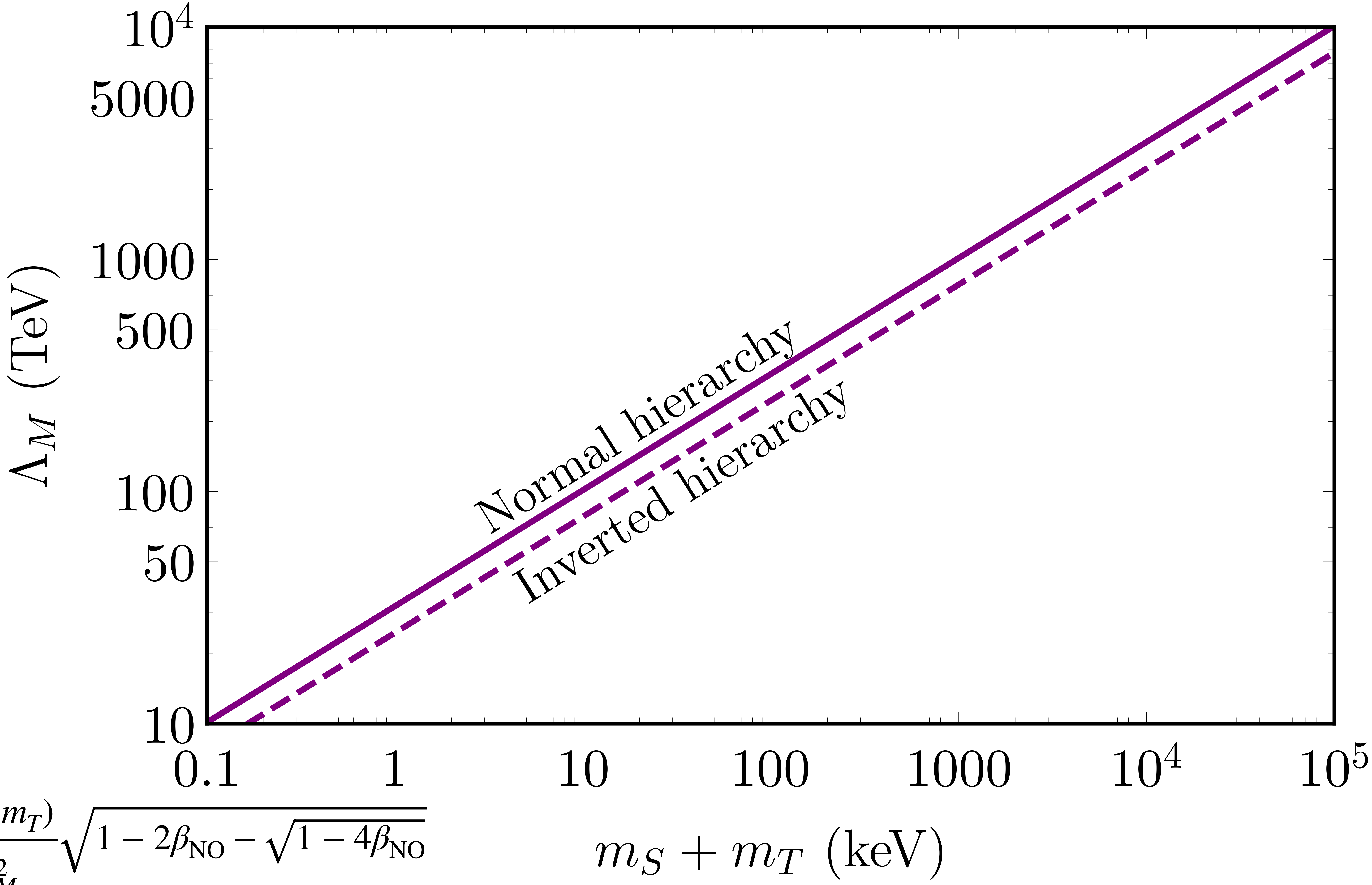
$$m_1 = 0\,, \quad m_{2,3} = \frac{v^2(m_S + m_T)}{\sqrt{2}\Lambda_M^2}\sqrt{1 - 2\beta_{\rm NO} \pm \sqrt{1 - 4\beta_{\rm NO}}}$$

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

where $\beta_{\rm NO}$ is set by the mass-squared splitting ratios,

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

$\Lambda_M - m_S + m_T$



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

Neutrino Mass Eigensystem

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

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

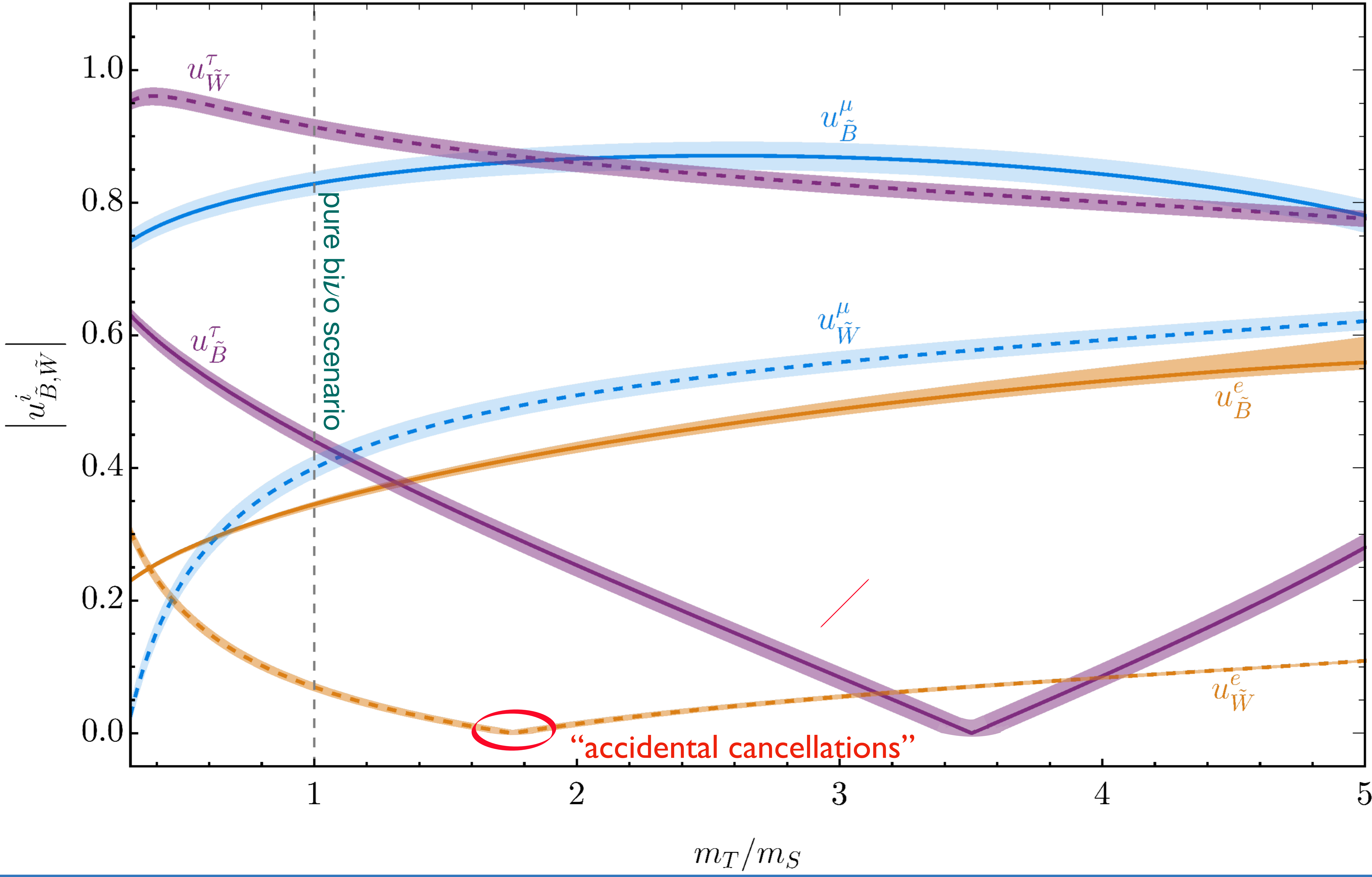
Assuming $\hat{\mathbf{e}}_{2,3} = N_{2,3}(a_{2,3}\mathbf{u}_{\tilde{B}} + b_{2,3}\mathbf{u}_{\tilde{W}})$,

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

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

$$\lambda_{\text{NO}} = \sqrt{1 + \beta_{\text{NO}}\frac{(m_S+m_T)^2}{m_Sm_T}}, \quad a_{2,3} = -2m_S\lambda_{\text{NO}}, \quad b_{2,3} = (m_S - m_T) \mp \sqrt{(m_S-m_T)^2 + 4m_Sm_T\lambda^2_{\text{NO}}}, \quad N_{2,3} = \frac{1}{\sqrt{a^2_{2,3} + b^2_{2,3} + 2a_{2,3}b_{2,3}\lambda_{\text{NO}}}}$$

Neutrino Mixing Structure



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

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

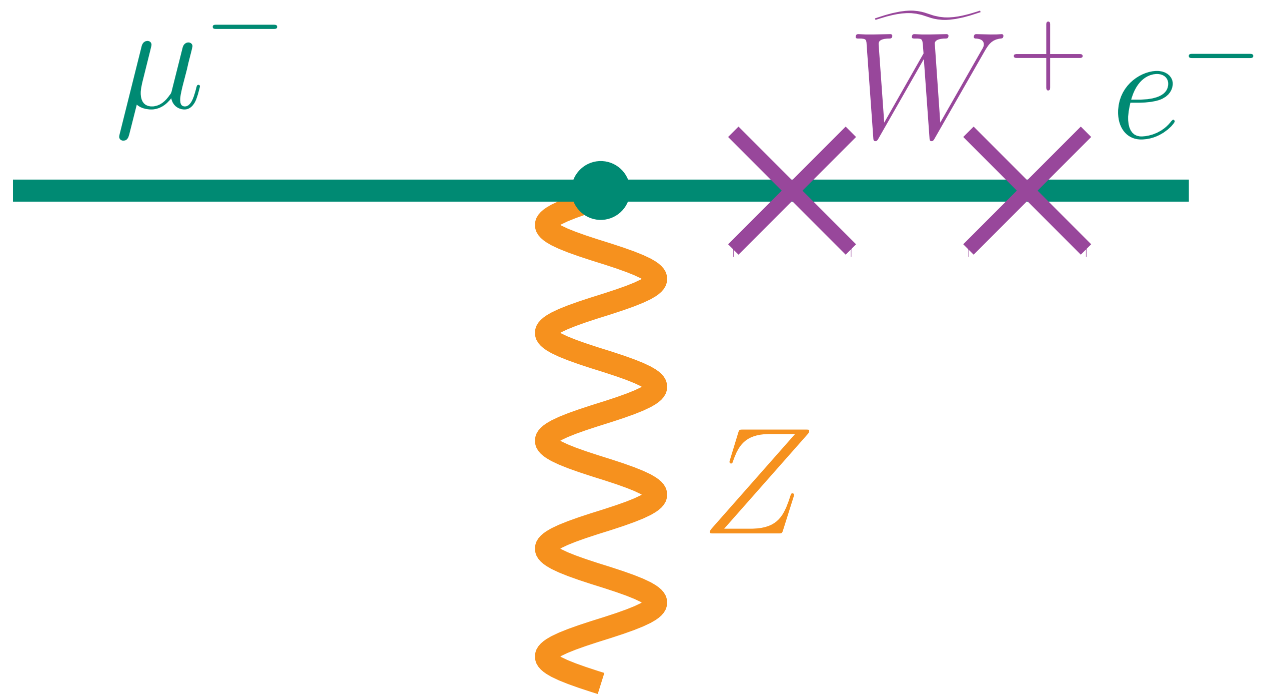
$\sin^2\theta_{13} = 0.02225^{+0.00056}_{-0.00059}$

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**

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

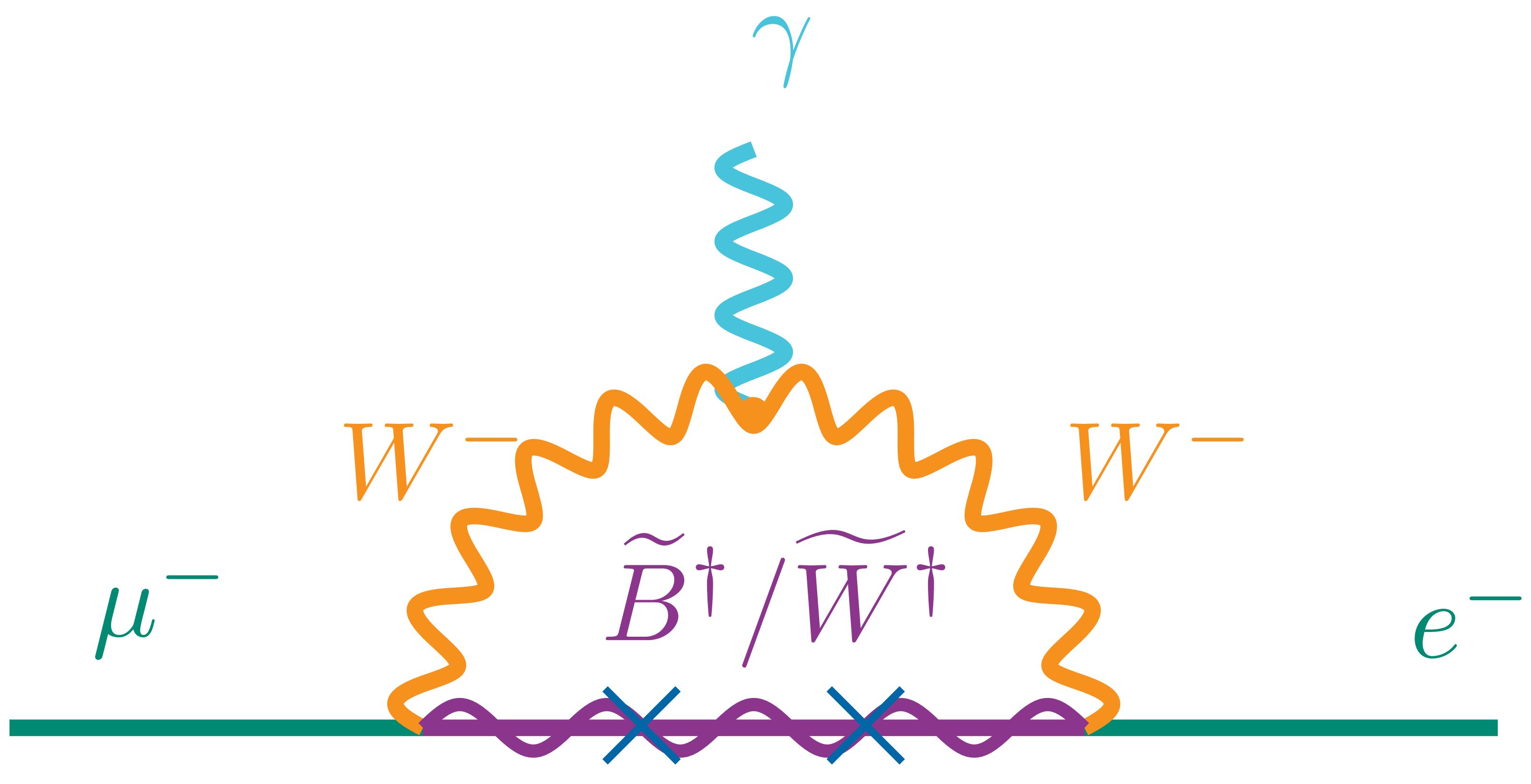


$$\propto \frac{v^2}{2}\left(Y^\dagger_{\tilde{W}}\frac{1}{M^\dagger_{\tilde{W}}M_{\tilde{W}}}Y_{\tilde{W}}\right)_{e\mu}$$

Flavor-changing neutral currents at tree level!

LFV processes

$\mu \to e\gamma$

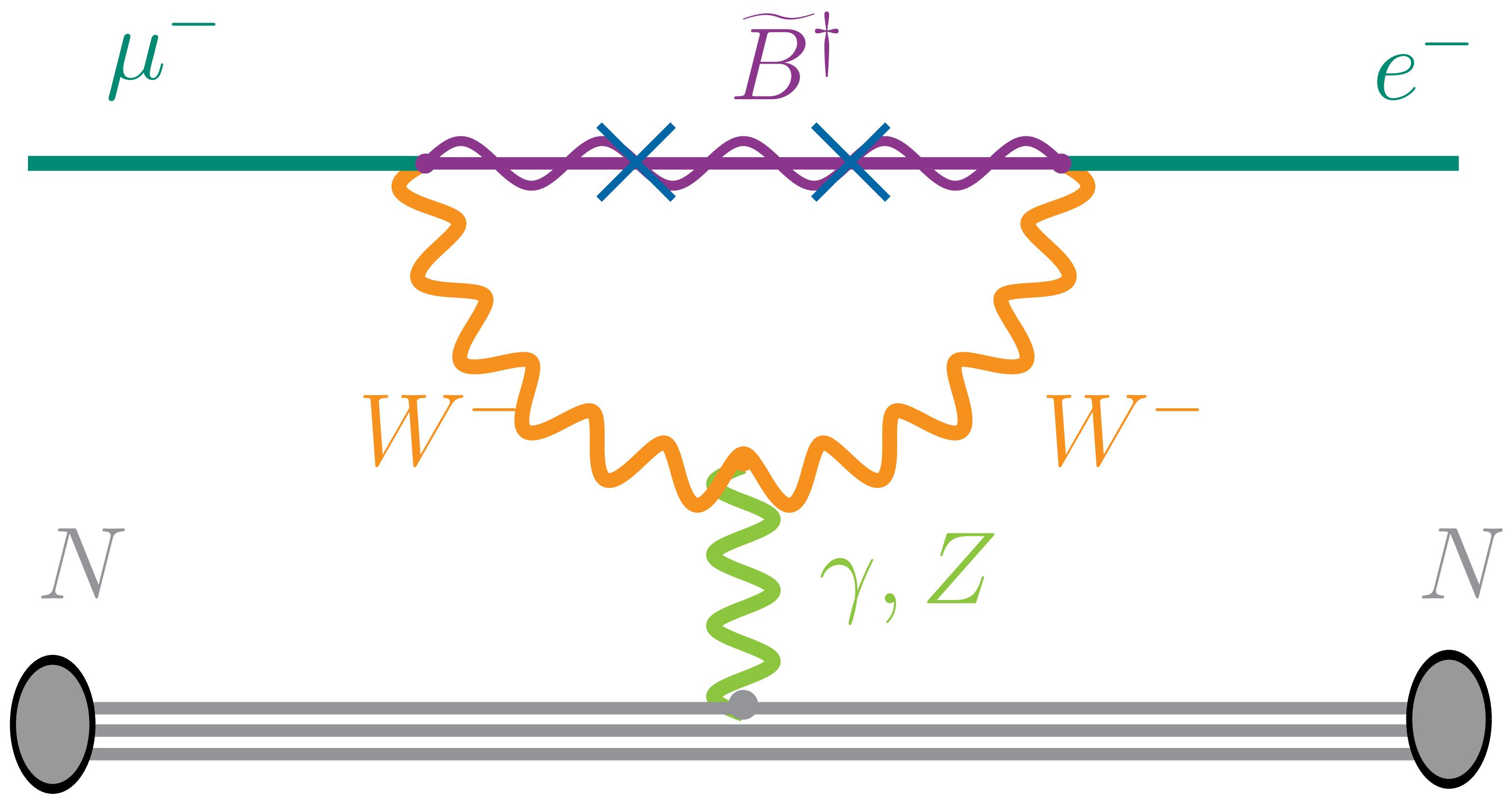


type-I: one loop

type-III: one loop

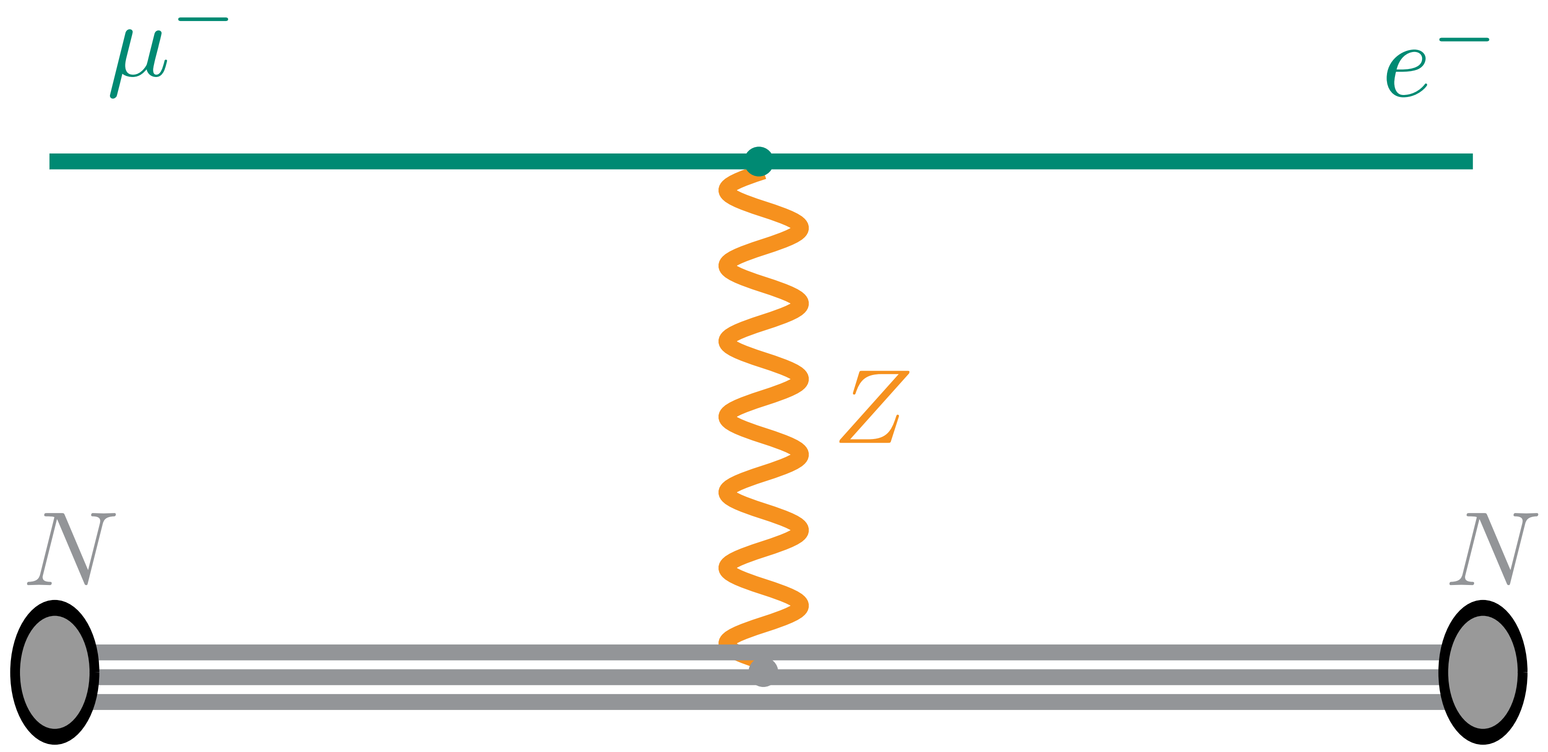
Loop suppressed

$\mu - e$ conversion in nuclei

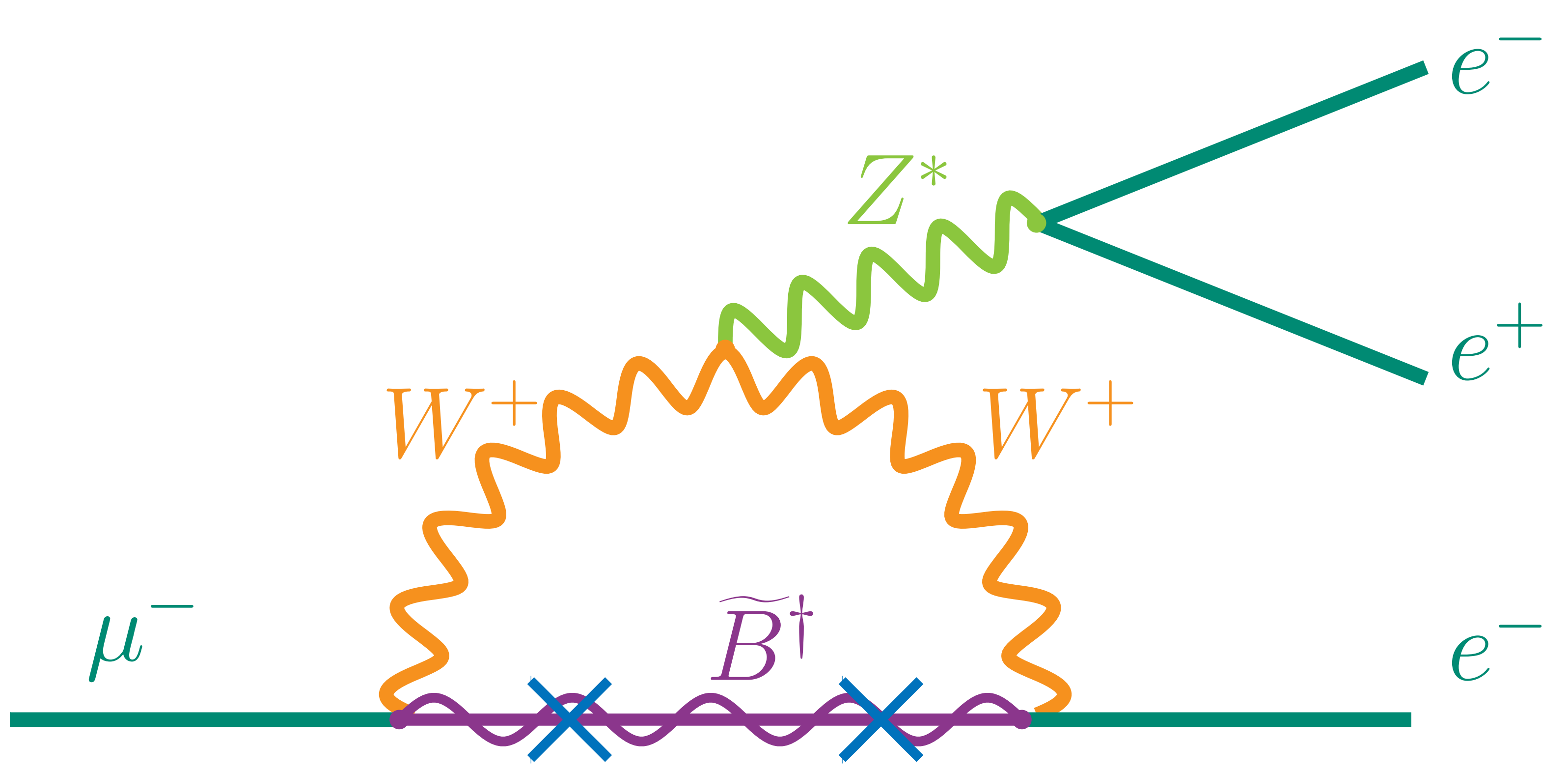


type-I: one loop

type-III: tree level

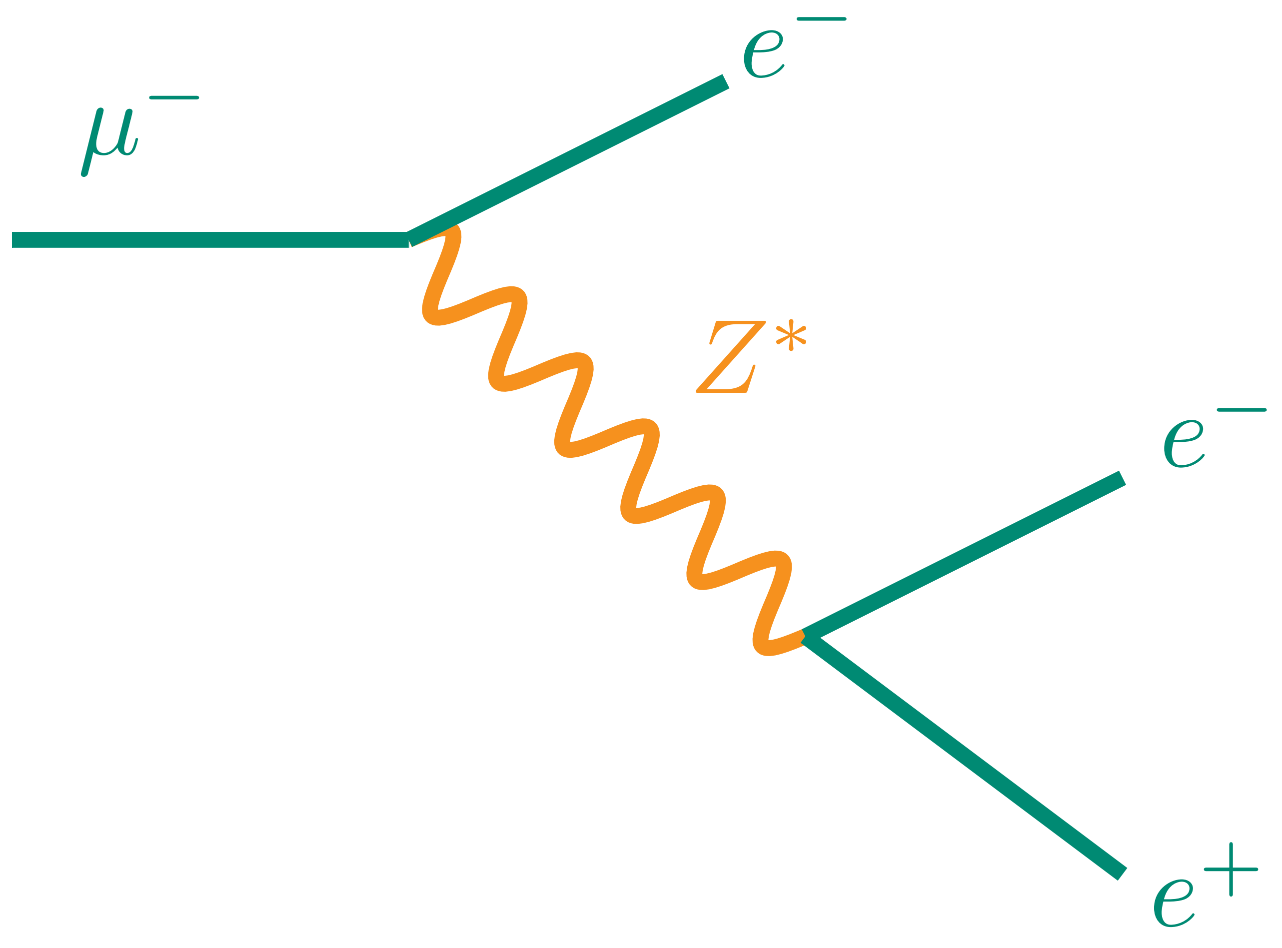


$\mu \to e\,e\,e$



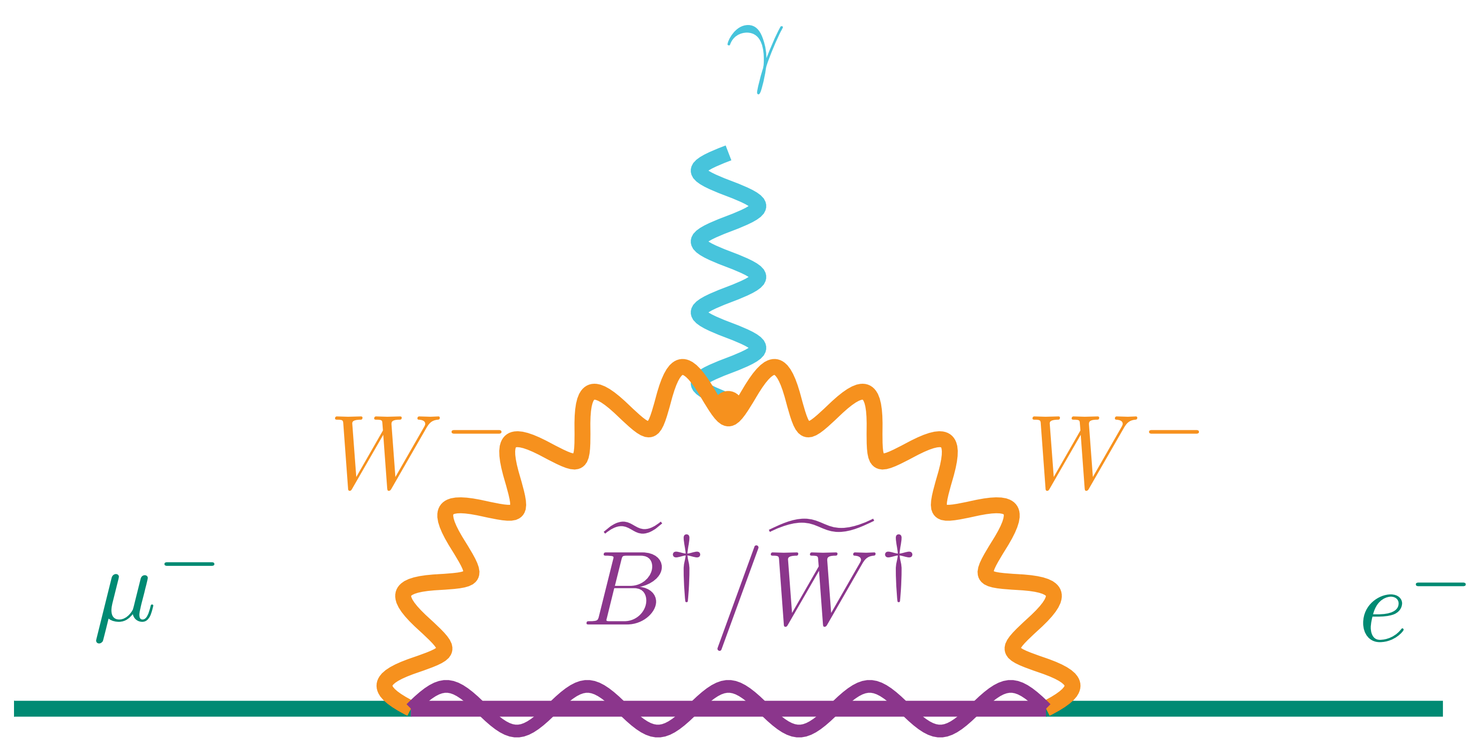
type-I: one loop

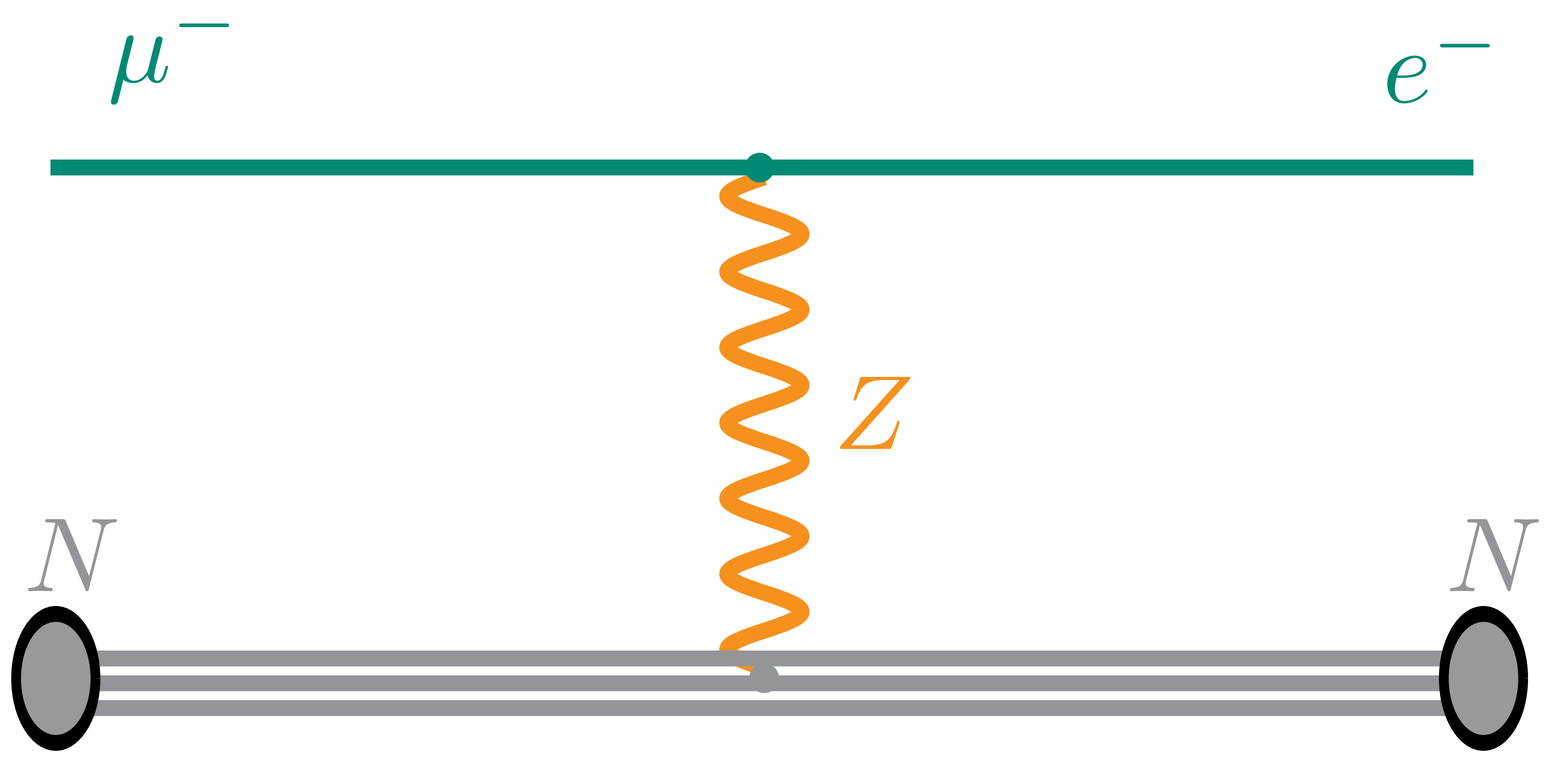
type-III: tree level

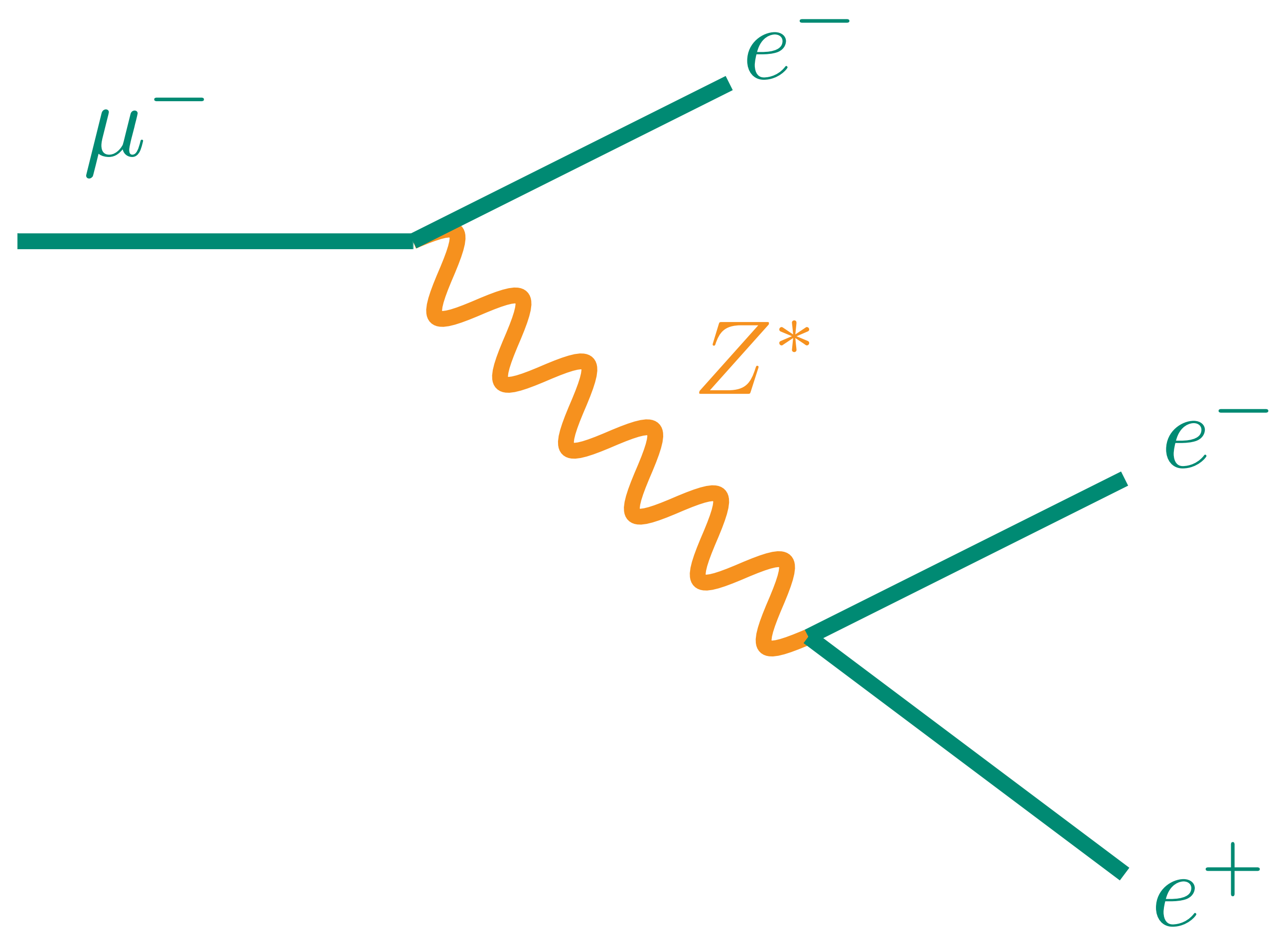


LFV processes

$\mu \to e\,\gamma$ | $\mu - e$ conversion in nuclei | $\mu \to e\,e\,e$







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

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

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

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

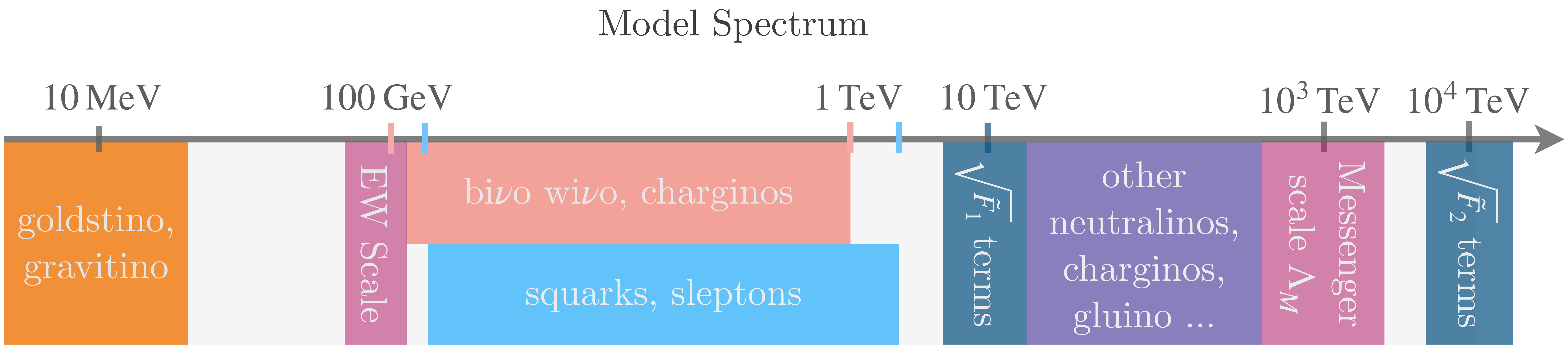
By far the strongest constraints are on the $e - \mu$ element

Constraints on the Messenger Scale

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

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

Outcomes of our Model



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

Two of the lightest neutralinos are purely biνo- and wiνo-like (degenerate with charginos)

Two SUSY breaking sectors: two *goldstini* Cheung, C., Nomura, Y. and Thaler, J. JHEP **2010**, 73 (2010)

- **Lightest supersymmetric particle (LSP) is the gravitino:** $m_{3/2} \sim \mathcal{O}(10 \text{ MeV})$
- **Uneaten Goldstino with a mass** $2m_{3/2}$ **can be a DM candidate when** $T_{\text{RH}} \sim \mathcal{O}(\text{GeV})$

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

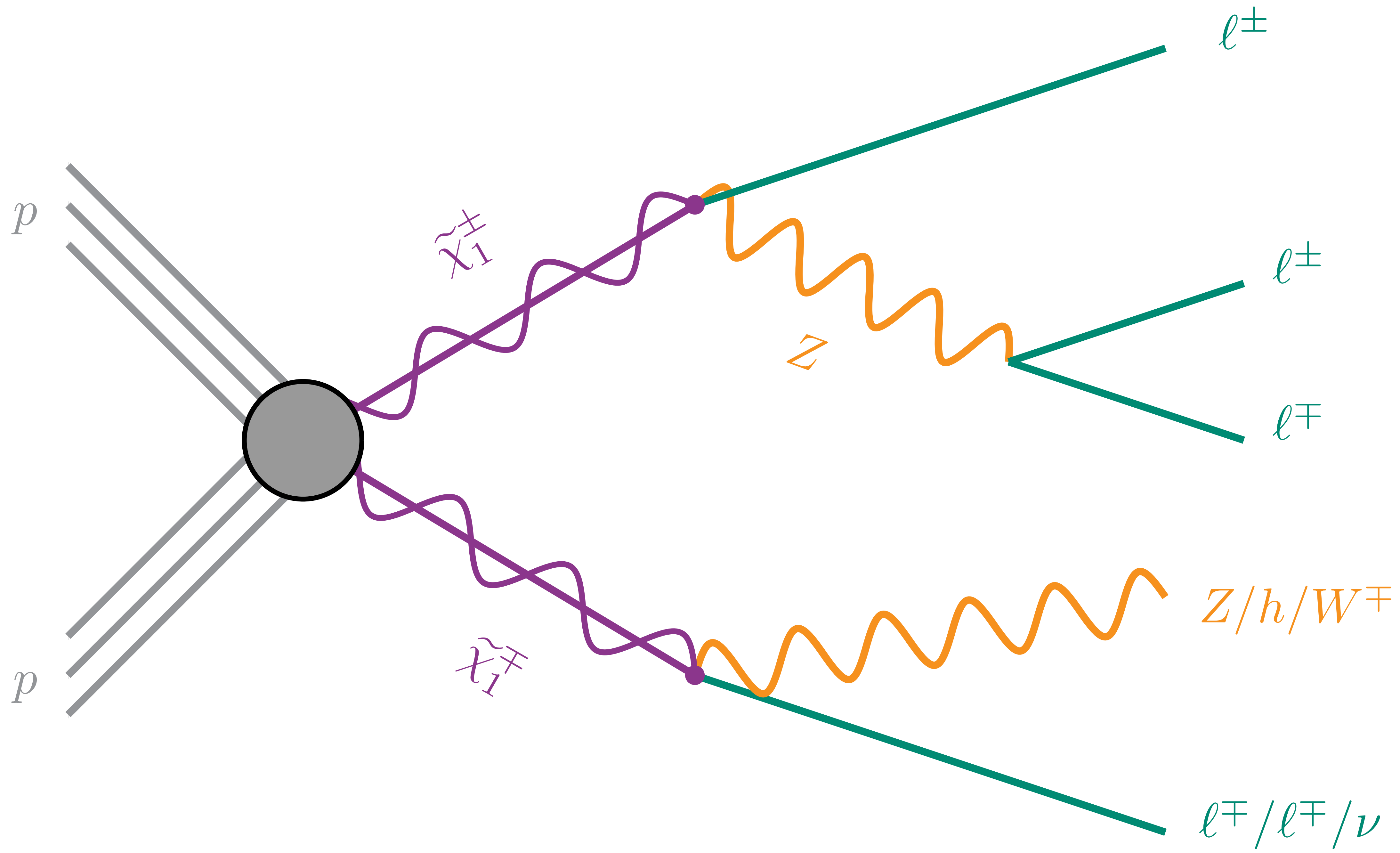
Wiνo as the Lightest Neutralino

Wiνo Phenomenology

Search for trilepton resonances from chargino and neutralino pair production

Directly applies to our model

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



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

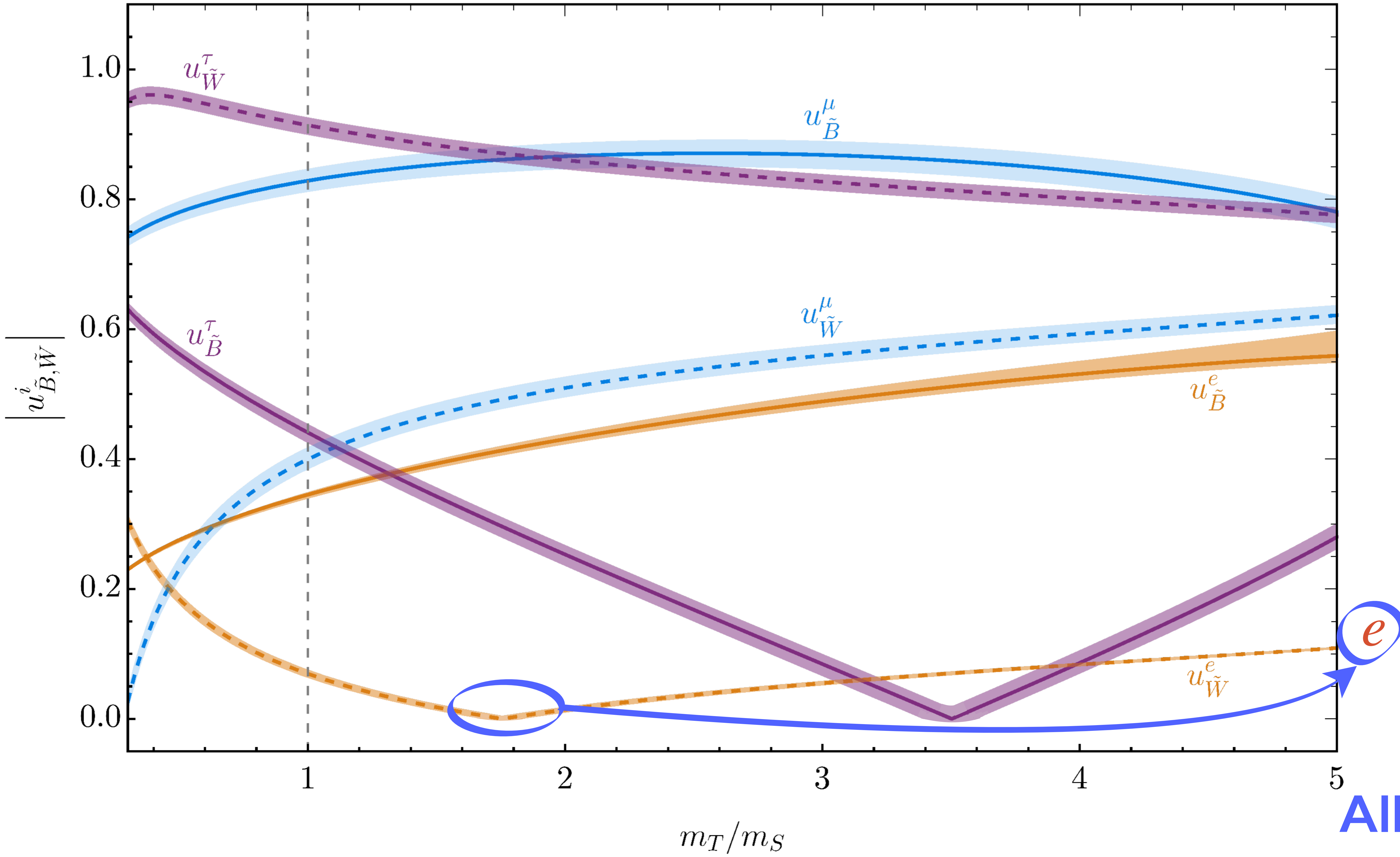
Depends on their branching fraction to different lepton flavors } free parameter for the analysis

e and μ final states are the most constraining

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

Wiνo as the Lightest Neutralino

Wiνo Phenomenology



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

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

e and μ final states are the most constraining

Alleviates the constraints from this search

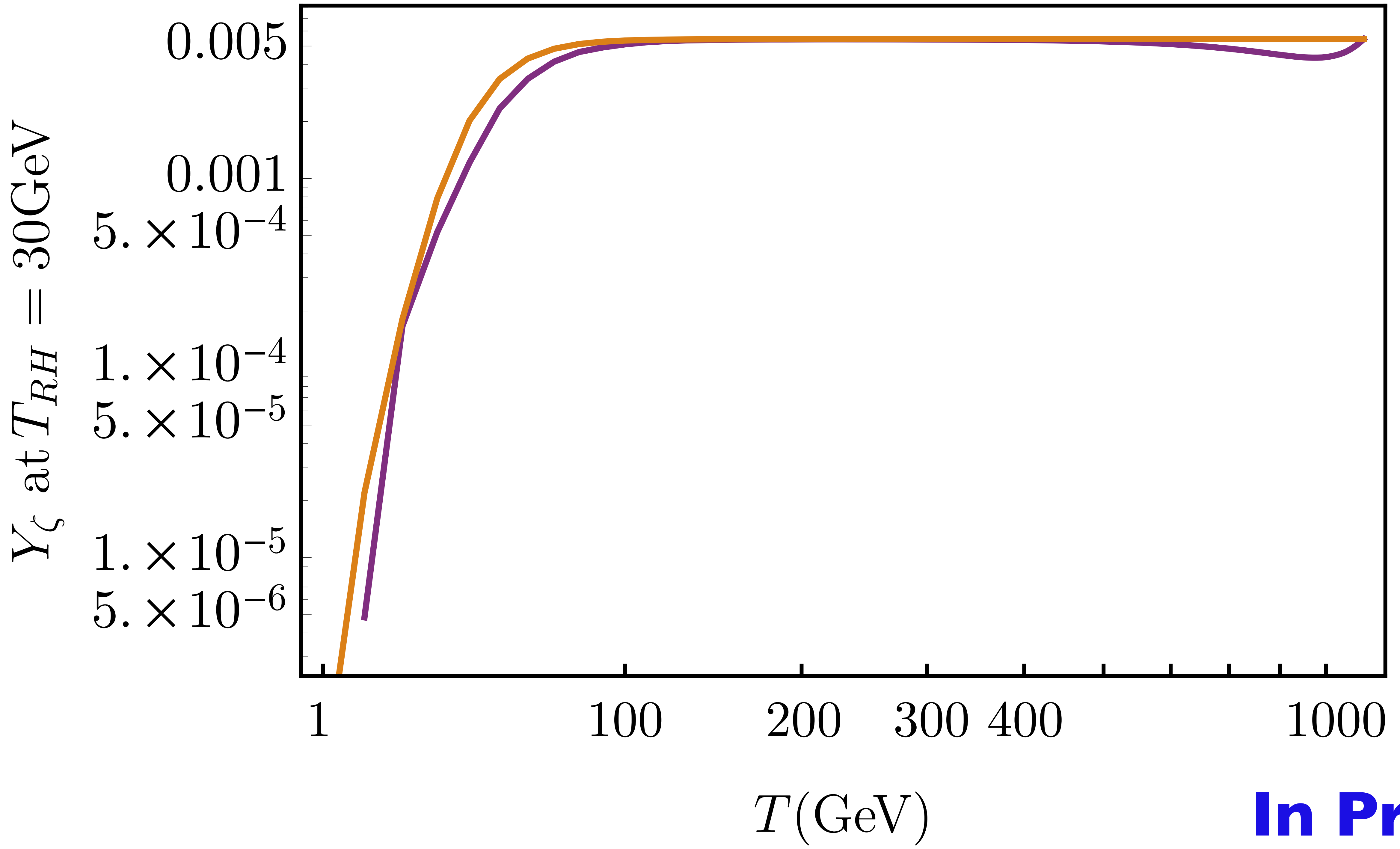
ATLAS collaboration, Phys. Rev. D 103 (2021) 112003

Gravitino/Goldstino DM with low T_{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. $T_{\mathrm{RH}} \sim \mathcal{O}(\mathrm{TeV})$

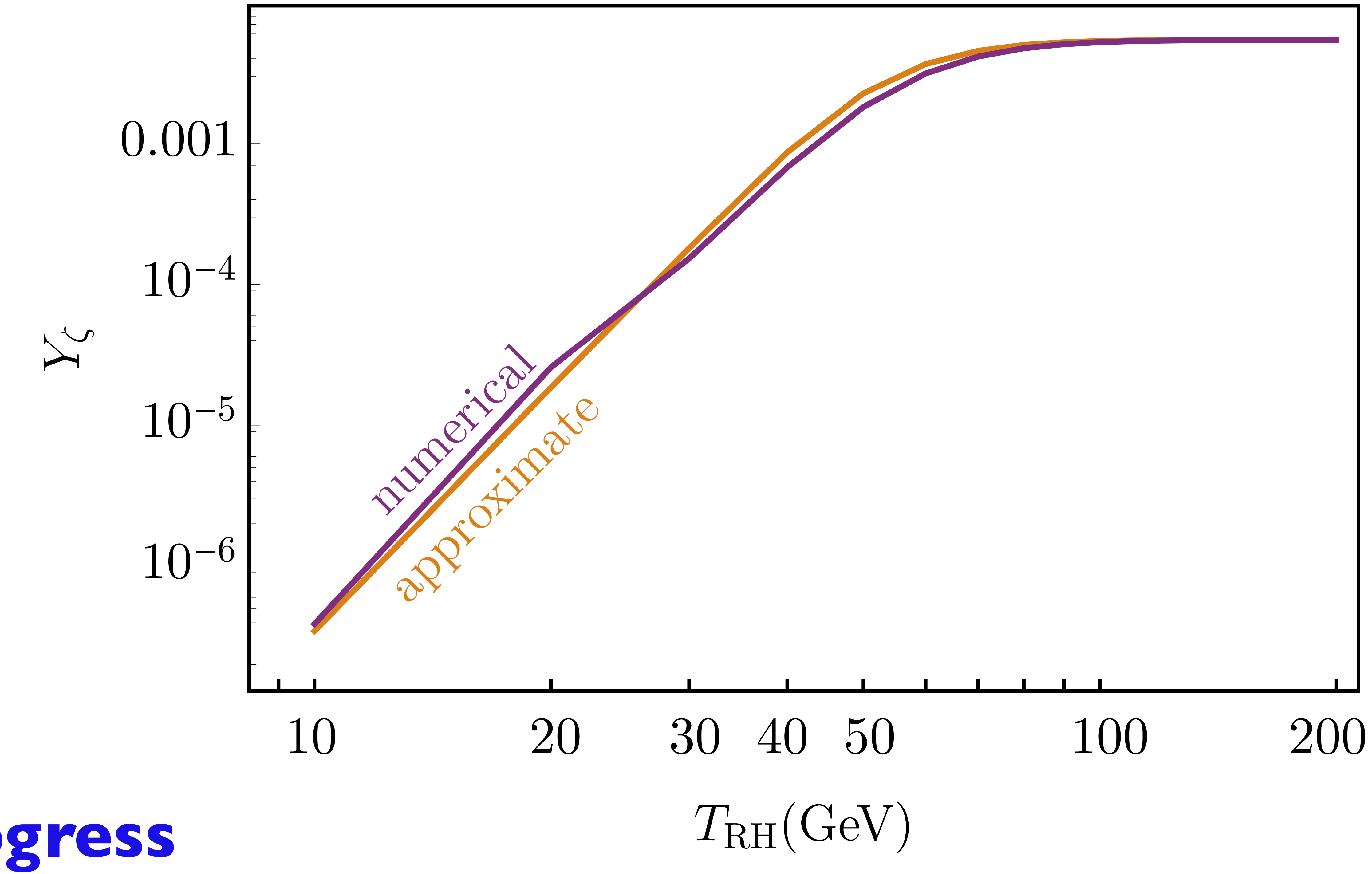
$$m_{\zeta/\eta},\ T_{\mathrm{RH}} \ll \tilde{m} \sim \mathcal{O}(\mathrm{TeV}) \lesssim \mathrm{T_{MAX}}$$

Goldstino Yield



In Progress

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

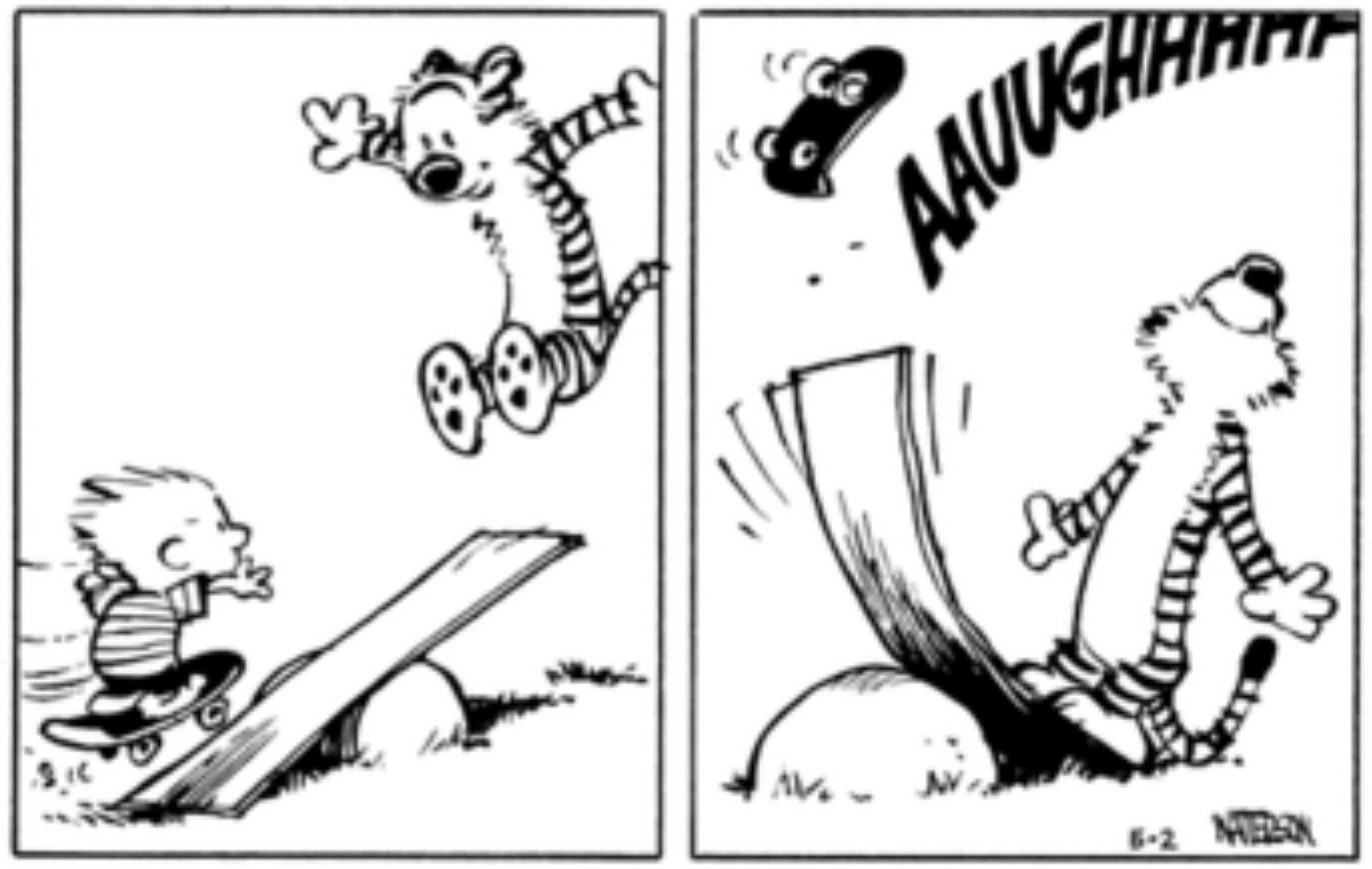


Takeaways from our Model

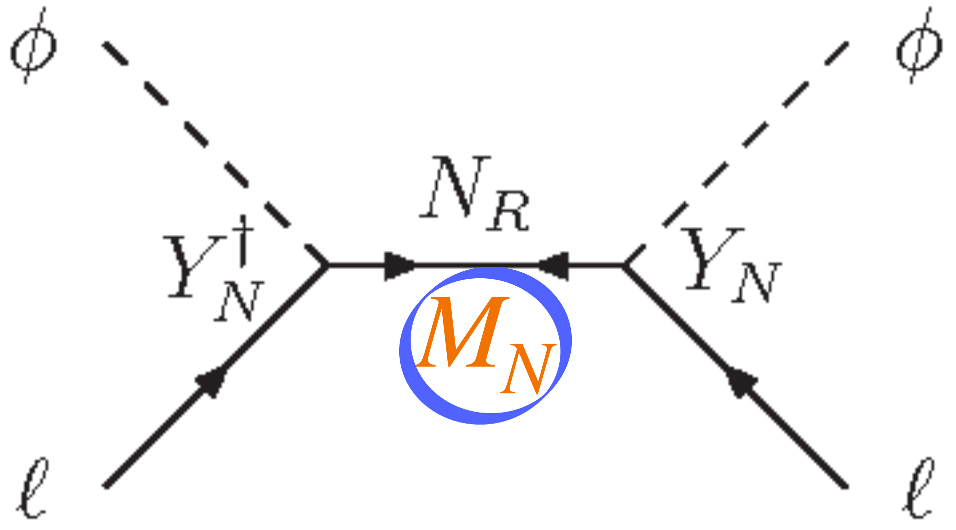
- The neutrino-bino/wino mixing follows a hybrid type I+III ISS pattern and can generate non-zero masses for all three neutrinos in its most general form.
- The hierarchy between the gravitino mass and the messenger scale can explain the smallness of the neutrino masses.
- Branching fractions to different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

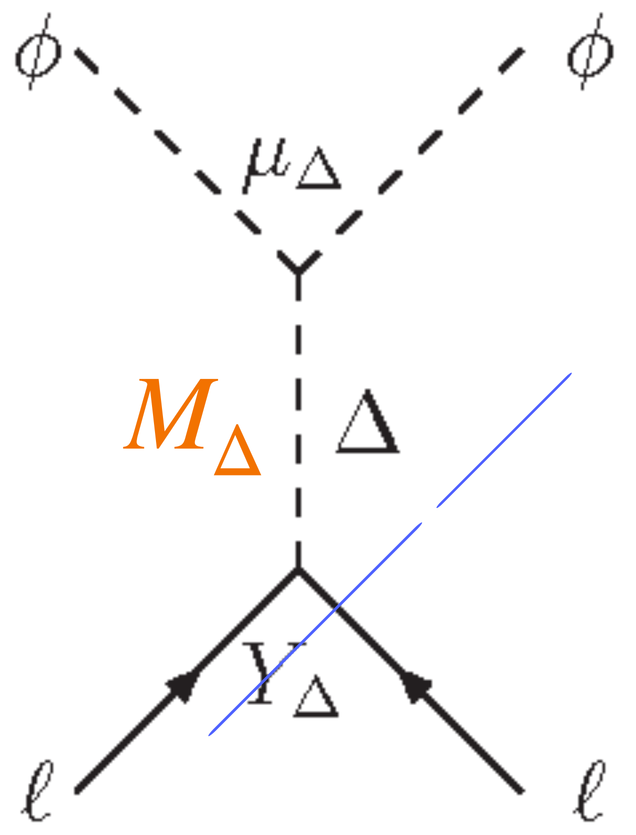
Backup Slides

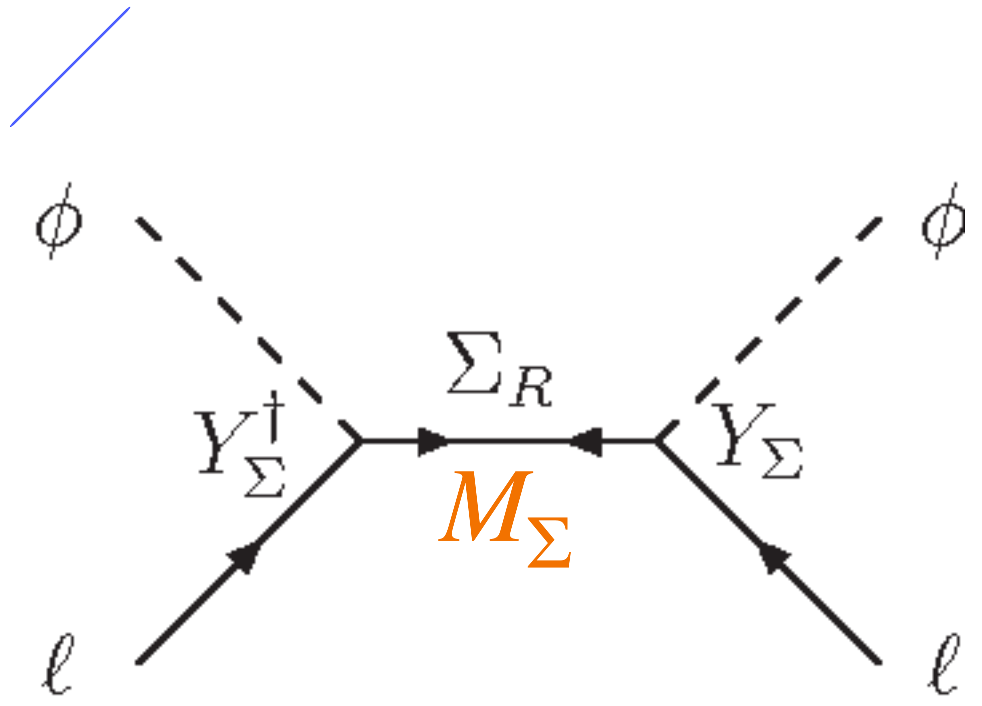
Basics: Seesaw Mechanism



Type-I	Type-II	Type-III
SM singlet fermion	SM triplet scalar	SM triplet fermion







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

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

$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2 \qquad m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta} v^2 \qquad m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

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

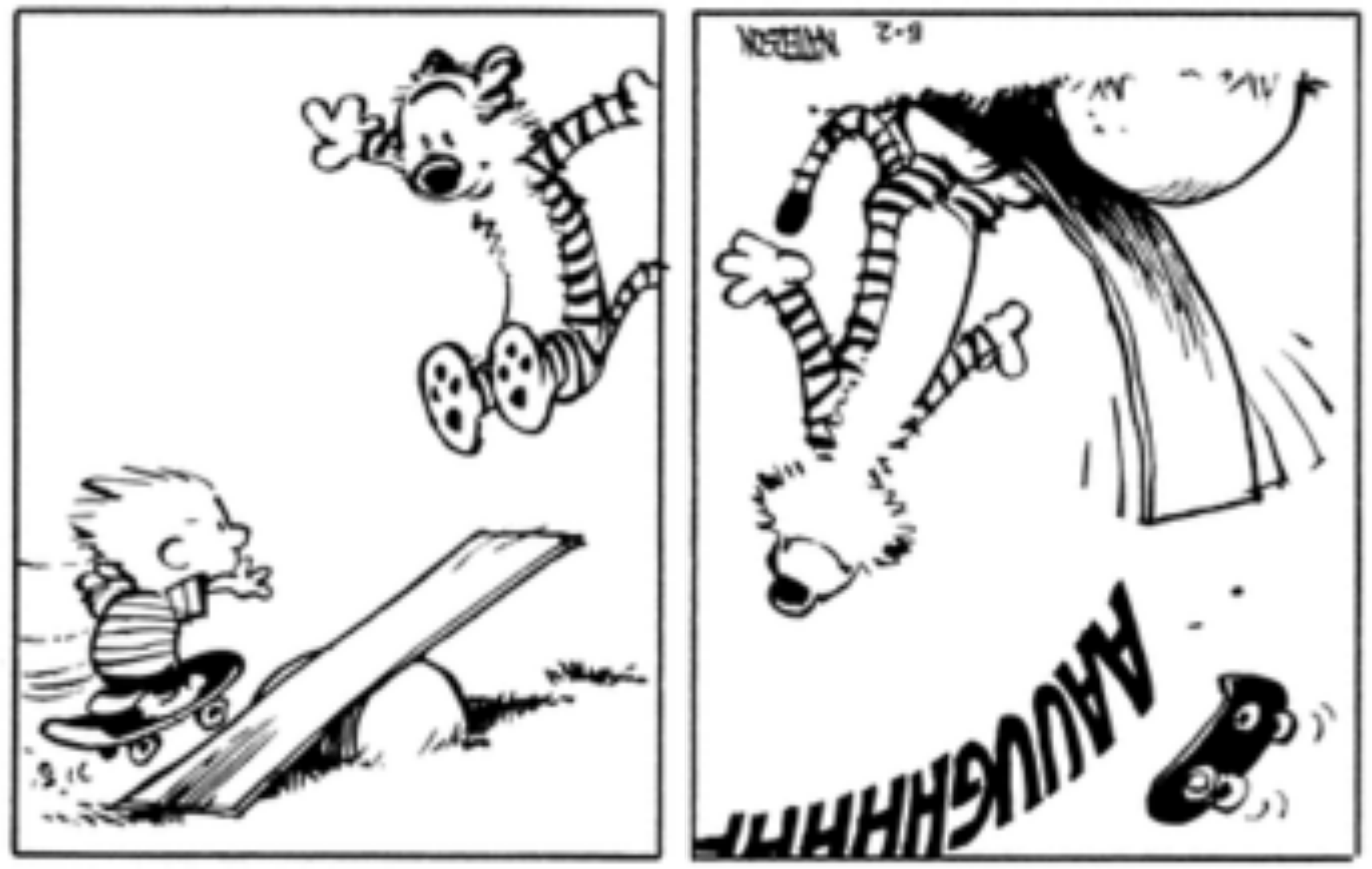
R.N. Mohapatra and J.W.F. Valle, Phys. Rev. D34 (1986) 1642

Type-I

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

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

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



pseudo-Dirac fermions
- 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

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

Minimal Lepton Flavor Violation!

Neutrino masses are proportional to the Majorana masses

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:

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

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

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

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

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

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:

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

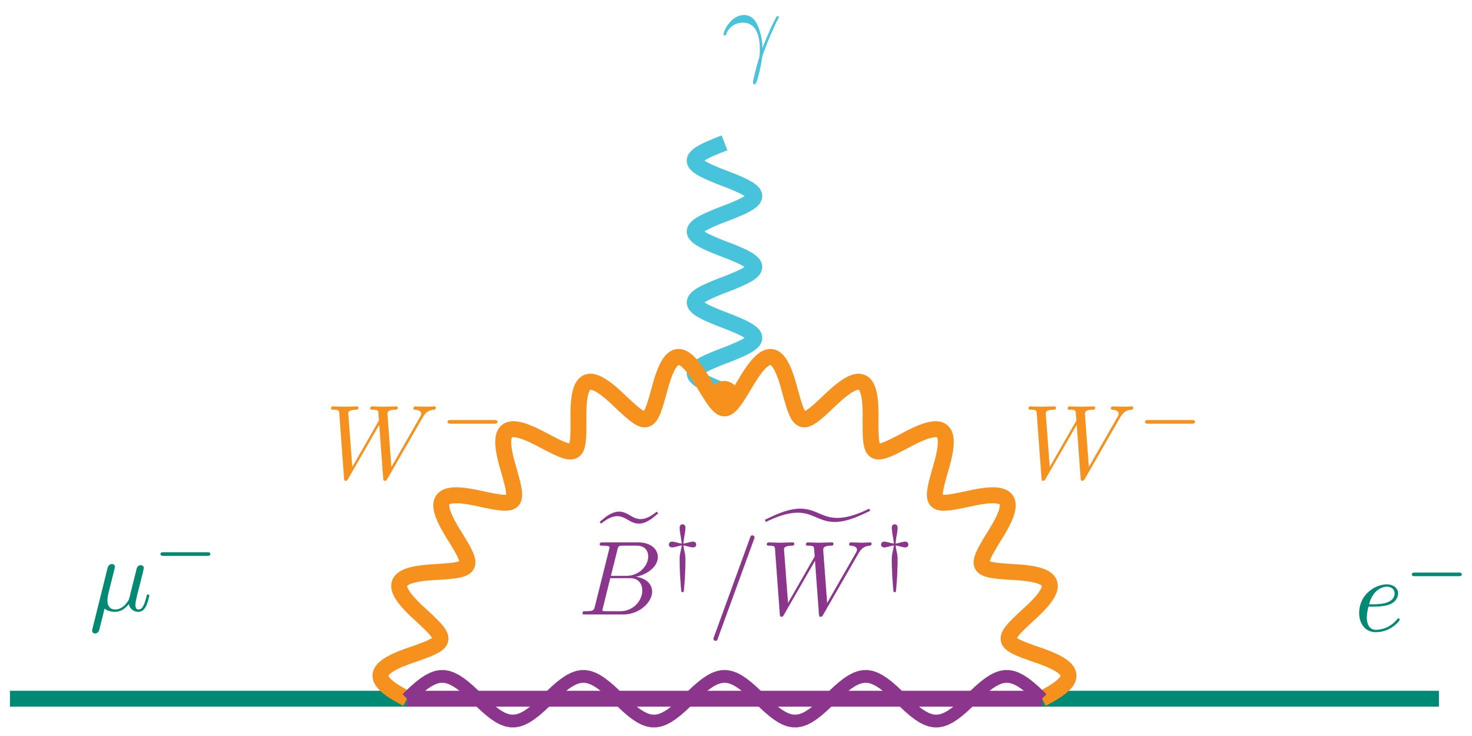
intrinsic dependence to the gravitino mass

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

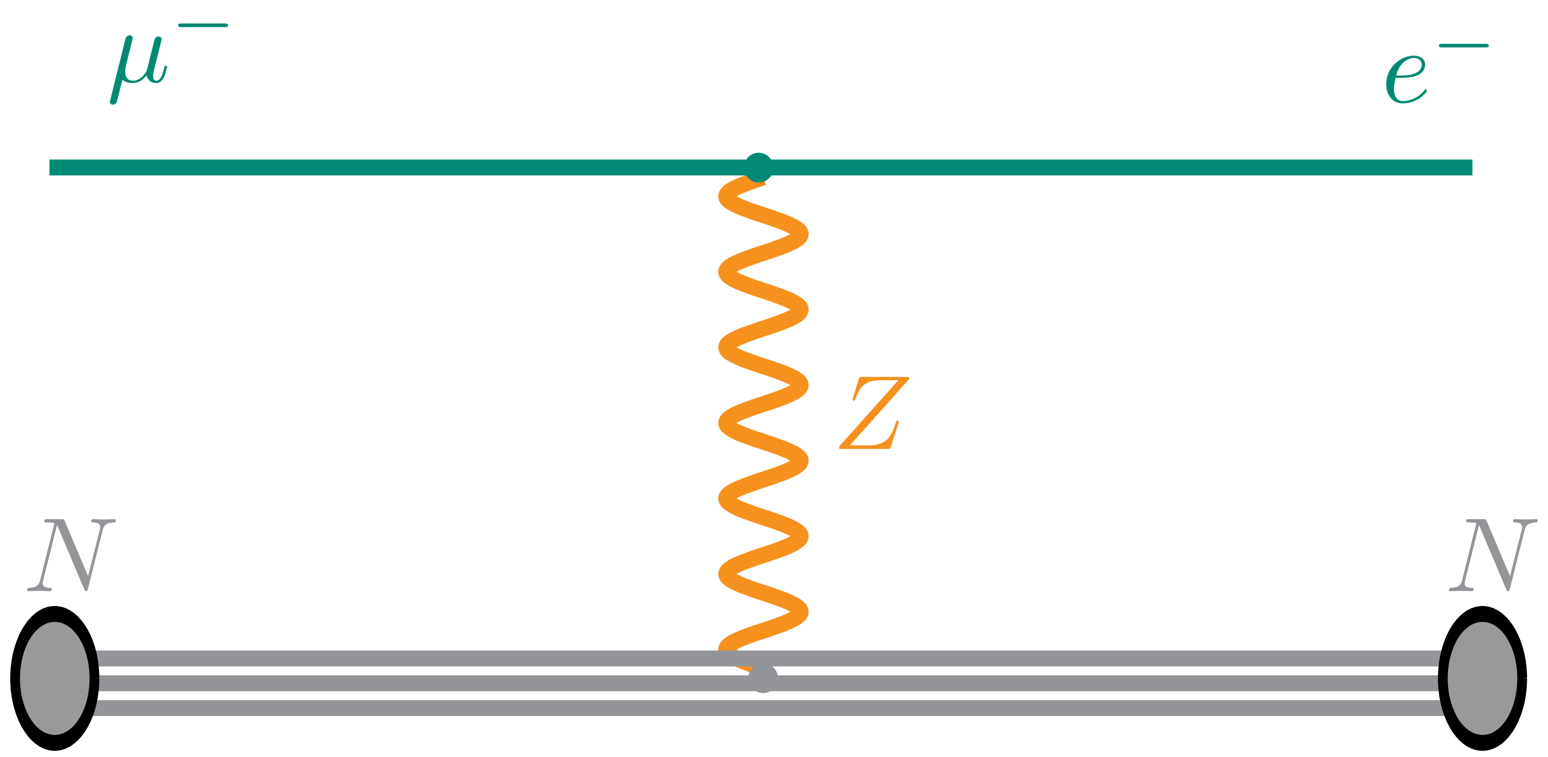
pure biνo case* $$m_{2,3} = \frac{m_{3/2}v^2}{\Lambda_M^2}\left(1 \pm \rho\right) \text{ with } \rho \simeq 0.7$$

Experimental Bounds

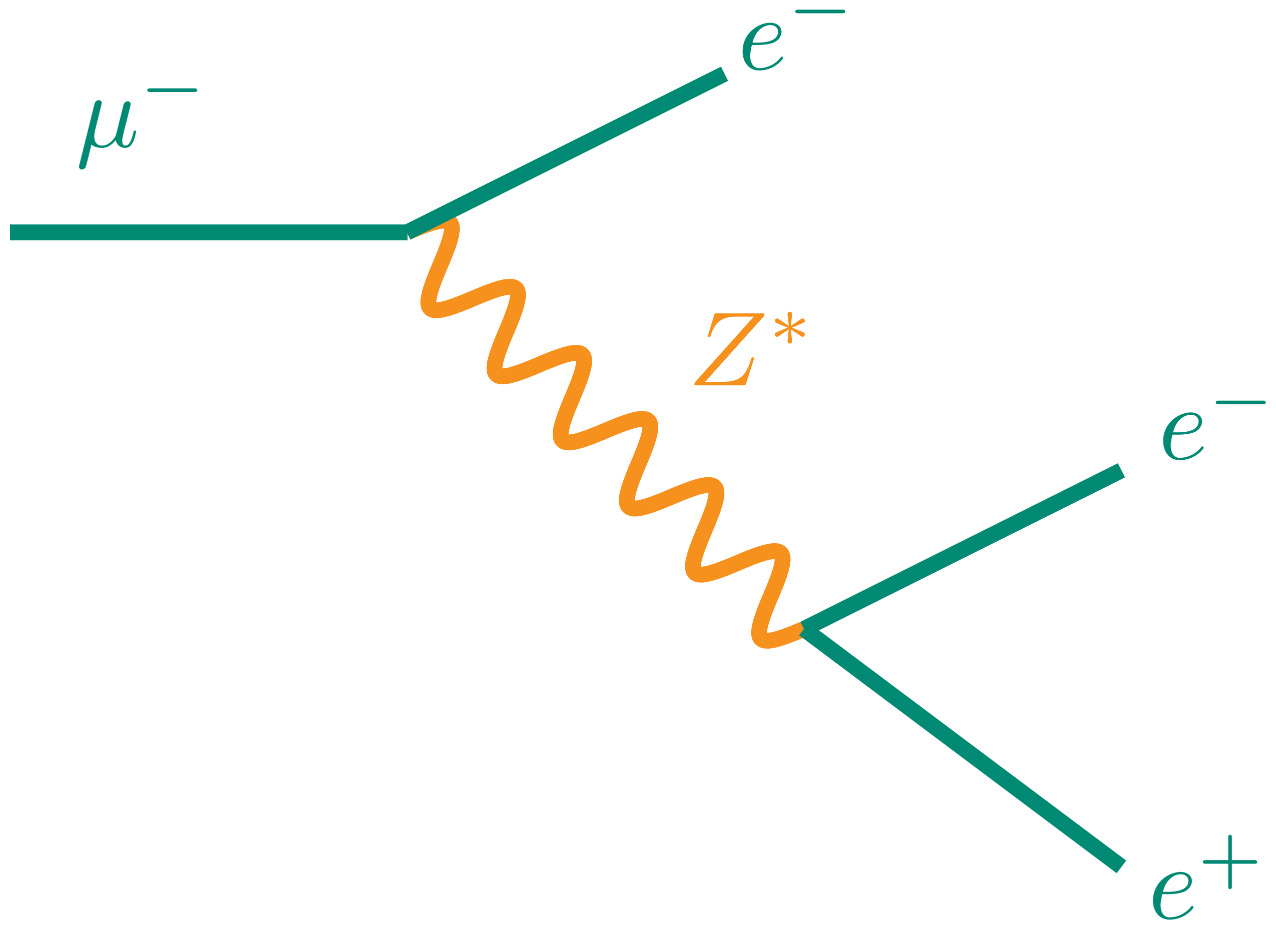
$\mu \to e\,\gamma$



$\mu - e$ conversion in nuclei



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



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

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

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

MEG II Collaboration, PoS NuFact2021 (2022) 120

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

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

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

Mu2e Collaboration. Universe 2023, 9, 54

strongest constraint

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

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

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

Stronger than type-I due to tree level FCNC

Type-III

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

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

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

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

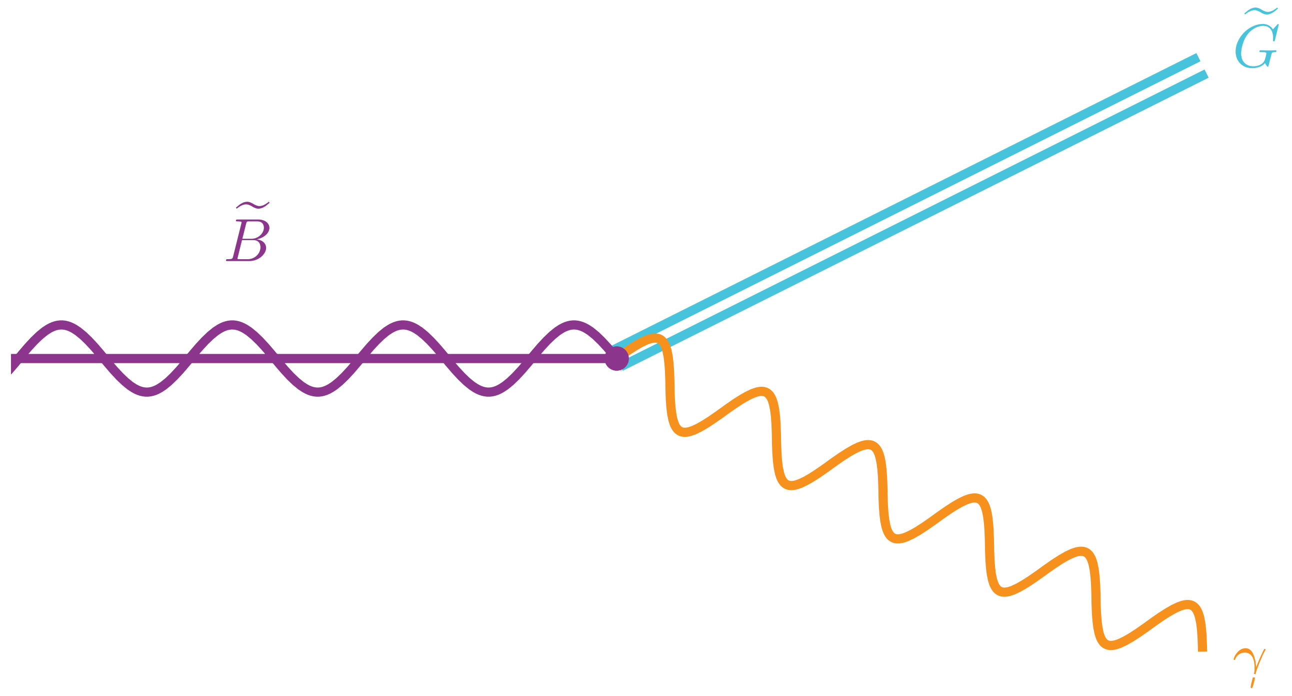
MEG Collaboration, Eur. Phys. J. C 76 (2016) 8, 434
MEG II Collaboration, PoS NuFact2021 (2022) 120
SINDRUM II Collaboration, Eur. Phys. J. C 47 (2006) 337
Mu2e Collaboration. Universe 2023, 9, 54
SINDRUM collaboration, Nucl. Phys. B 299 (1988) 1

Bino Decays

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

If kinematically allowed

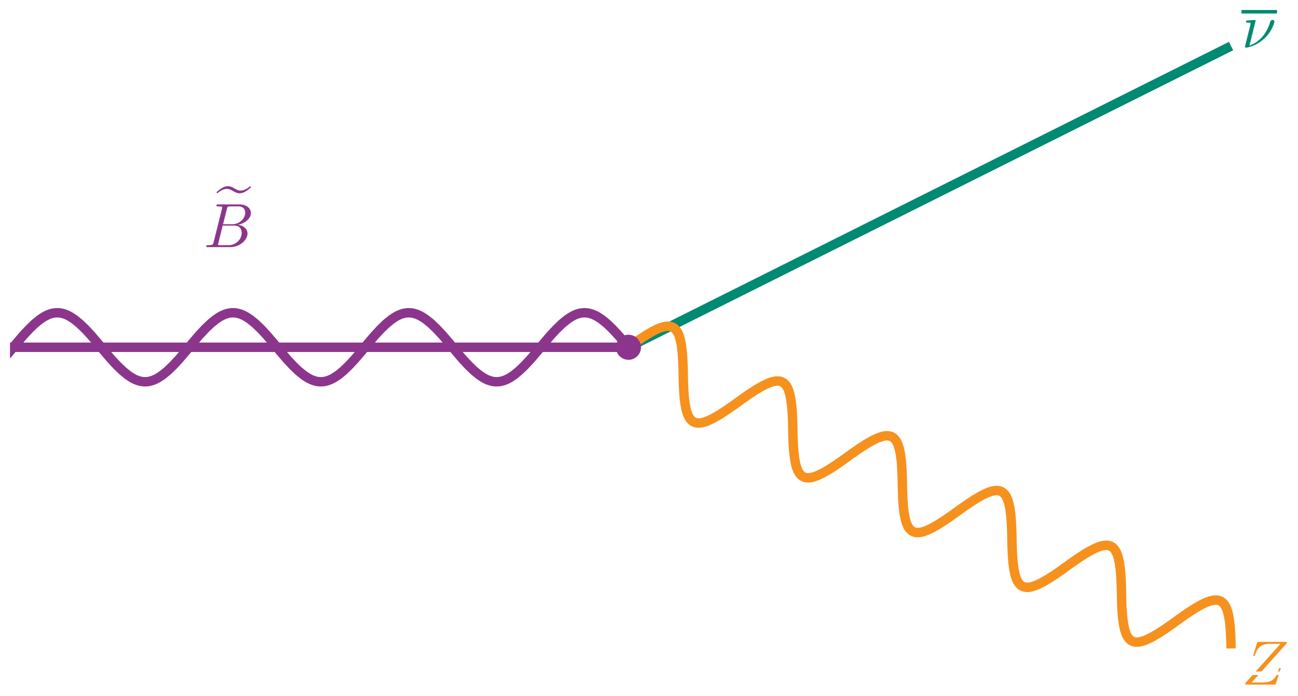
$\tilde{B} \to \tilde{G}\gamma$



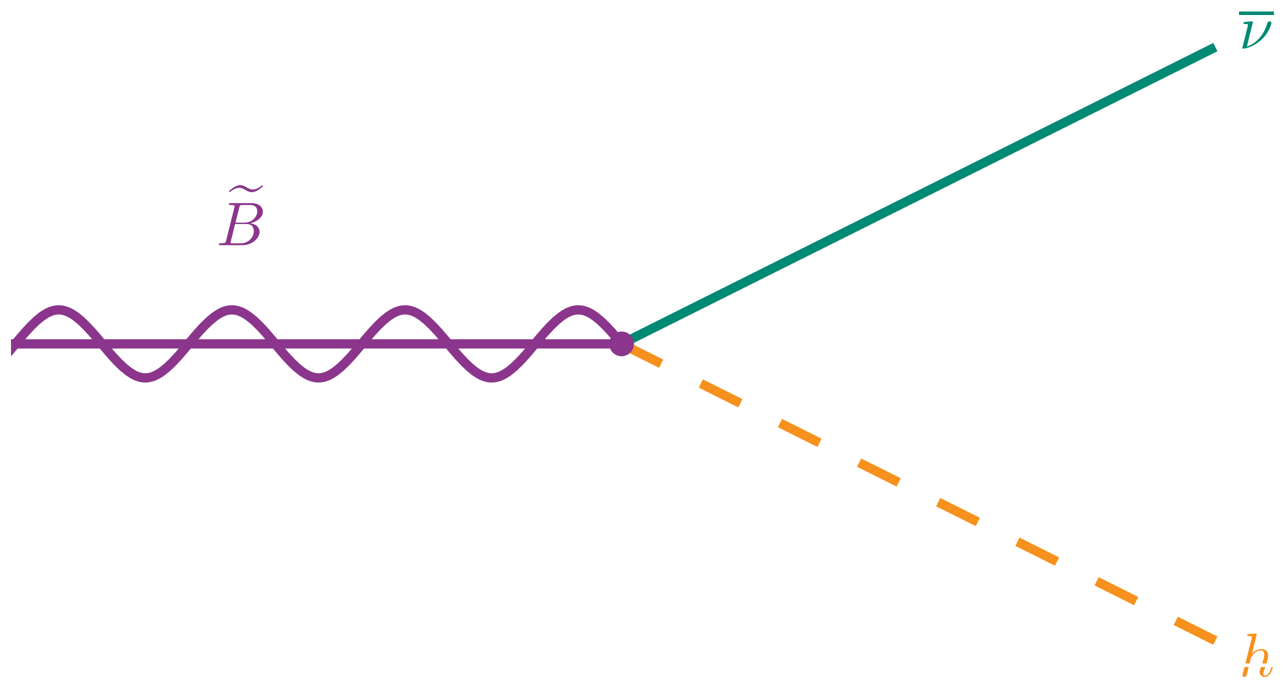
Suppressed by the Planck mass

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

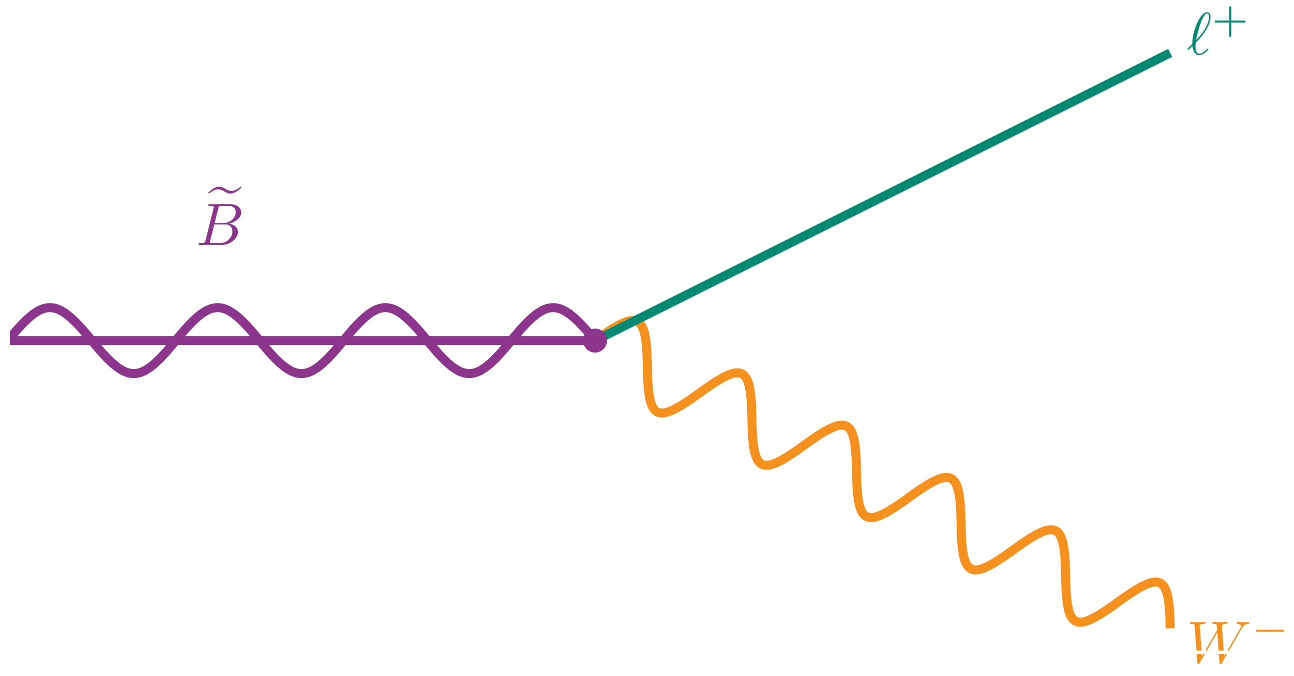
$\tilde{B} \to Z\bar{\nu}$



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



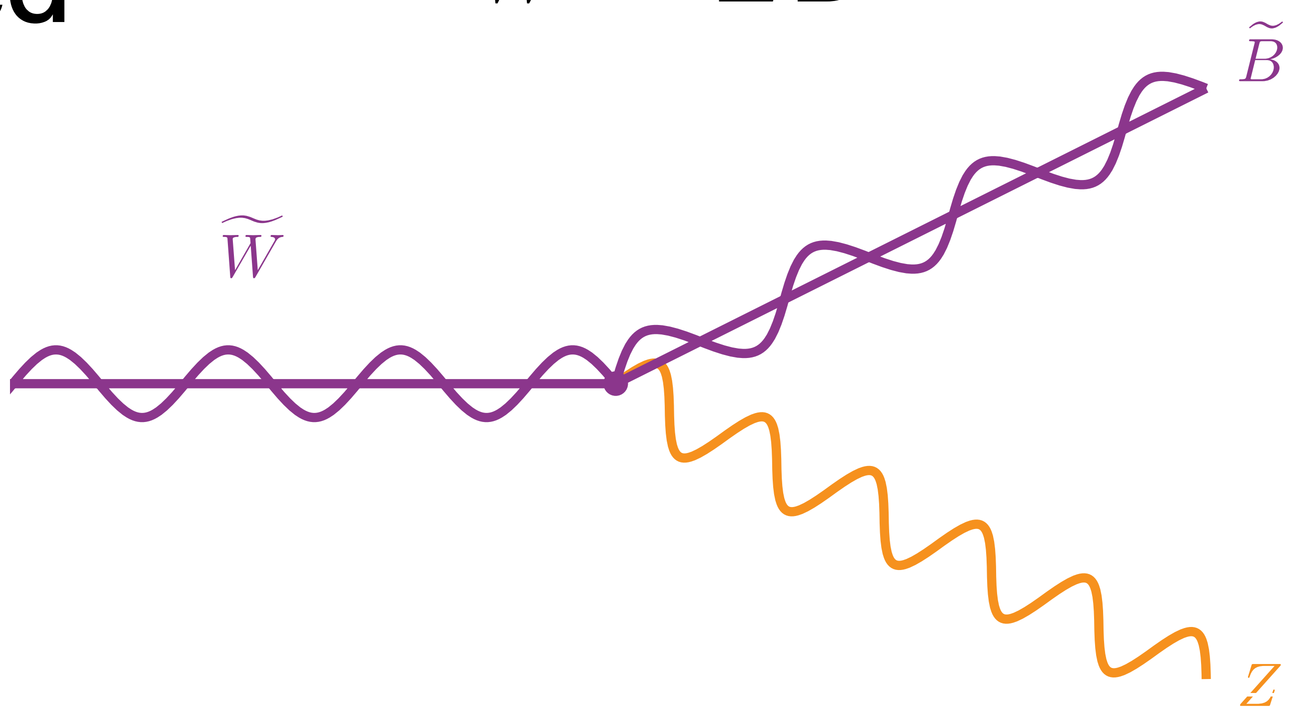
$\tilde{B} \to W^-\ell^+$



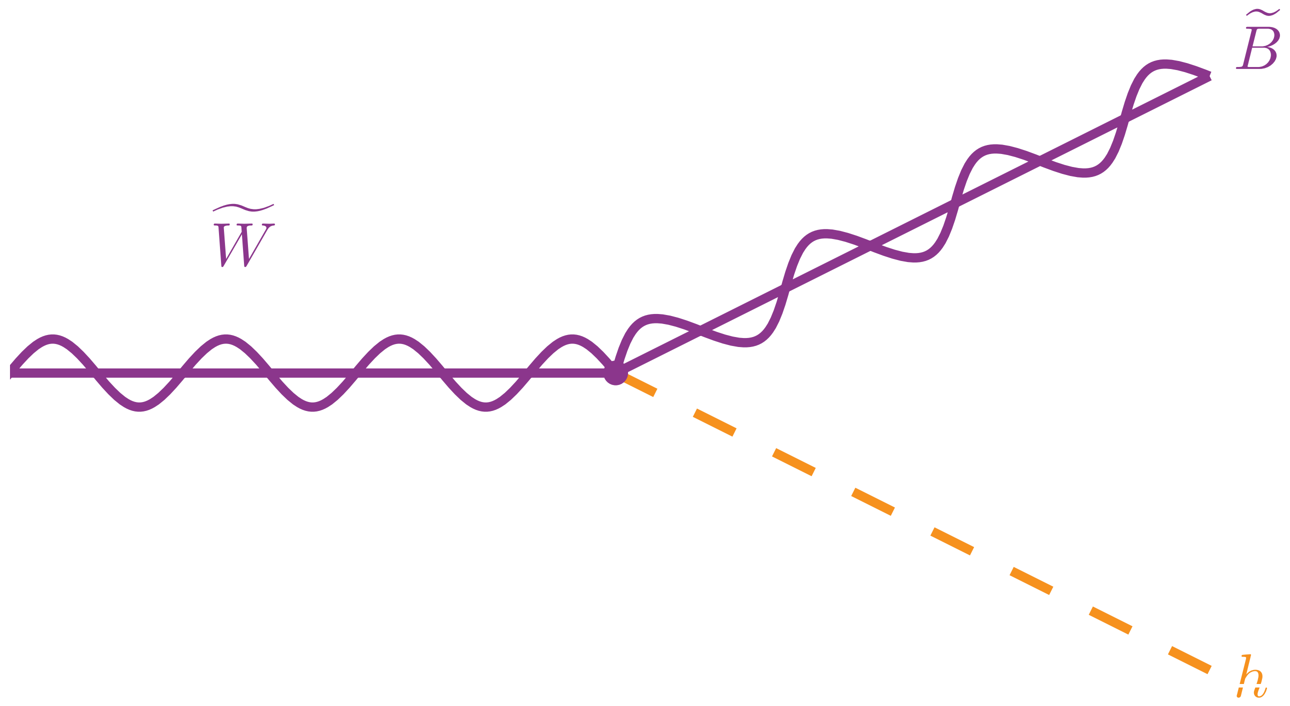
Total decay width $\quad \Gamma_{\tilde{B},\text{tot}} = \sum_i Y_i^2 M_{\tilde{B}} \sim \frac{M_{\tilde{B}}}{\Lambda_M^2} \sim 0.5\ \text{MeV}$ $\quad$ **decays promptly at the LHC**

If kinematically allowed

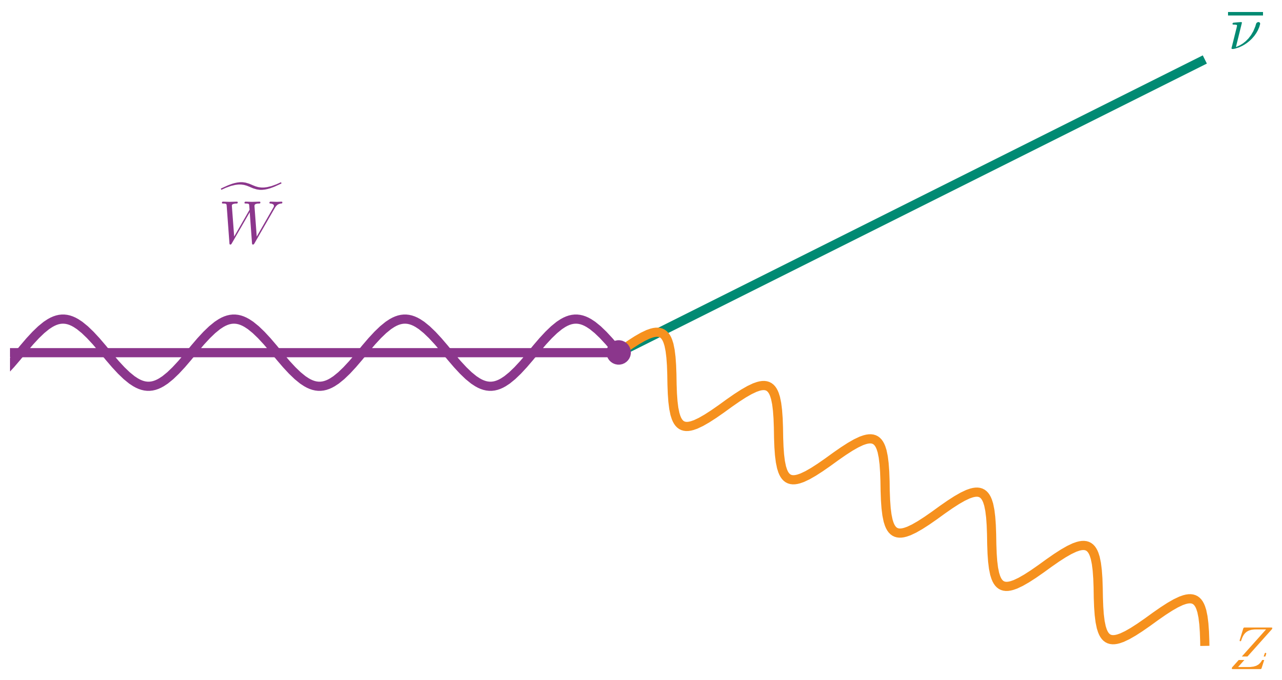
$\tilde{W} \to Z\tilde{B}$



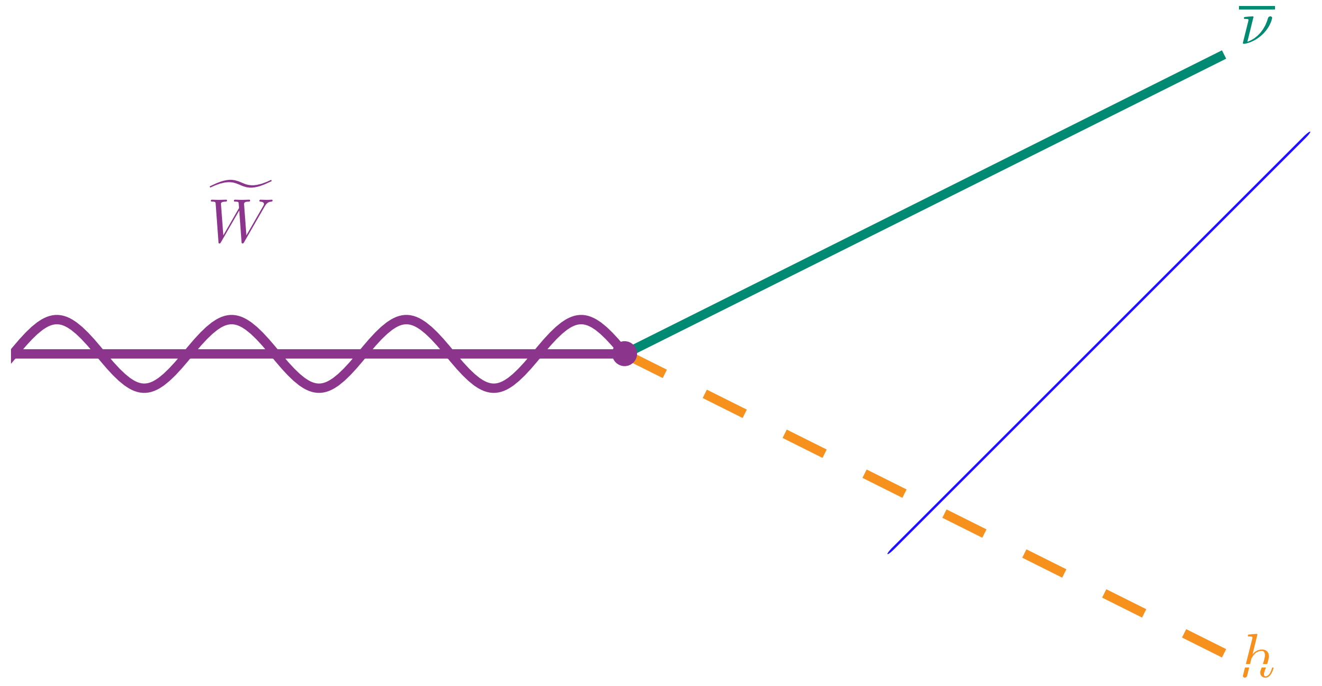
$\tilde{W} \to h\tilde{B}$



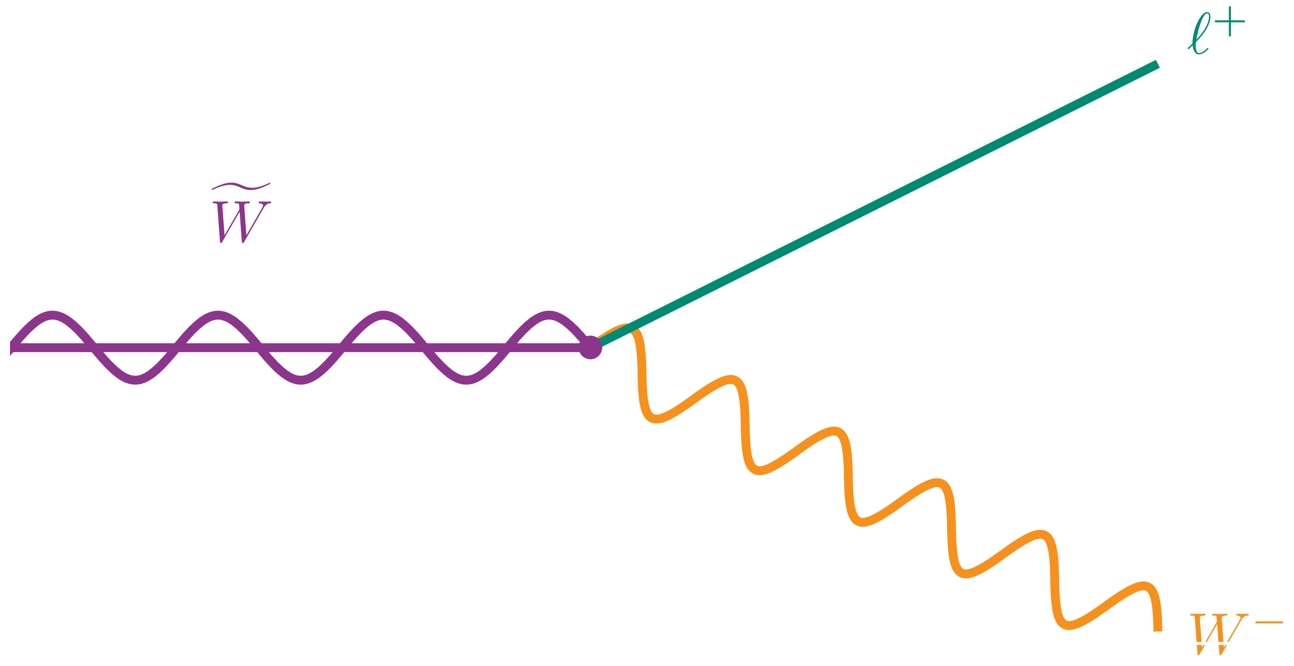
$\tilde{W} \to Z\bar{\nu}$



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



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

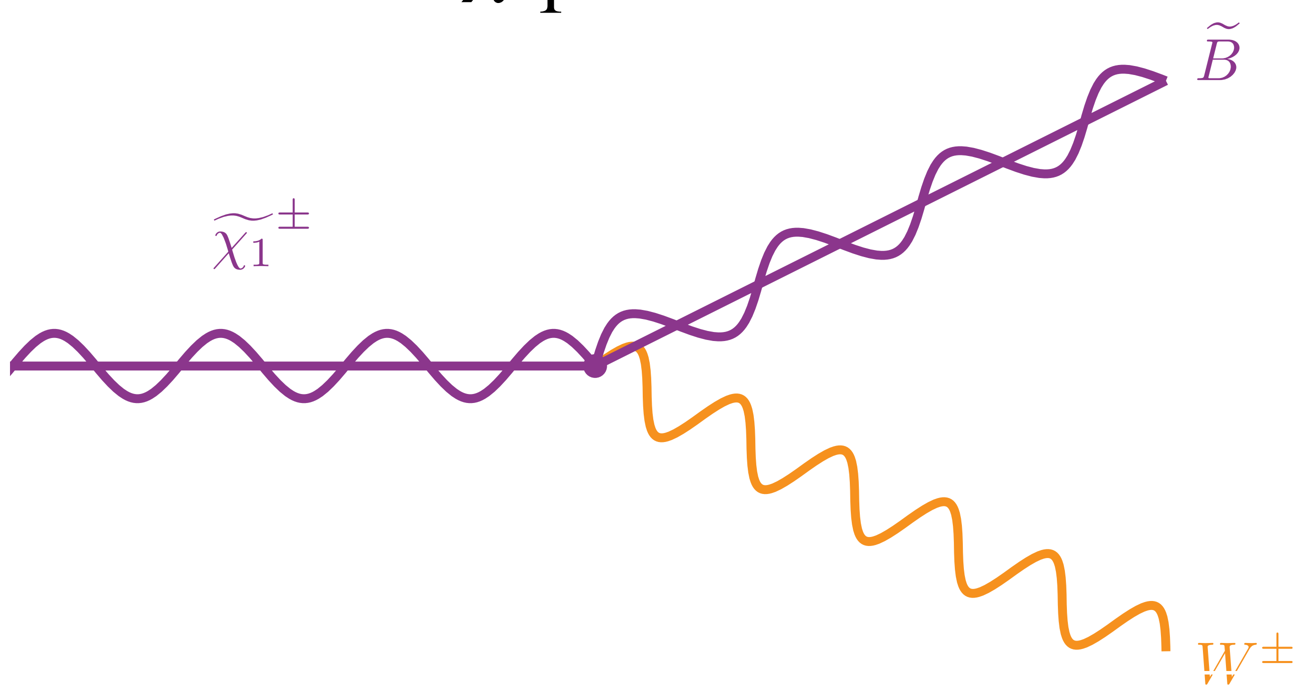


These channels are suppressed by the mixing angle: $\theta^2 \sim \left(\frac{y_{\tilde{W}} v}{M_{\tilde{W}}}\right) \sim \frac{v^2}{\Lambda_M^2} \sim 10^{-7}$

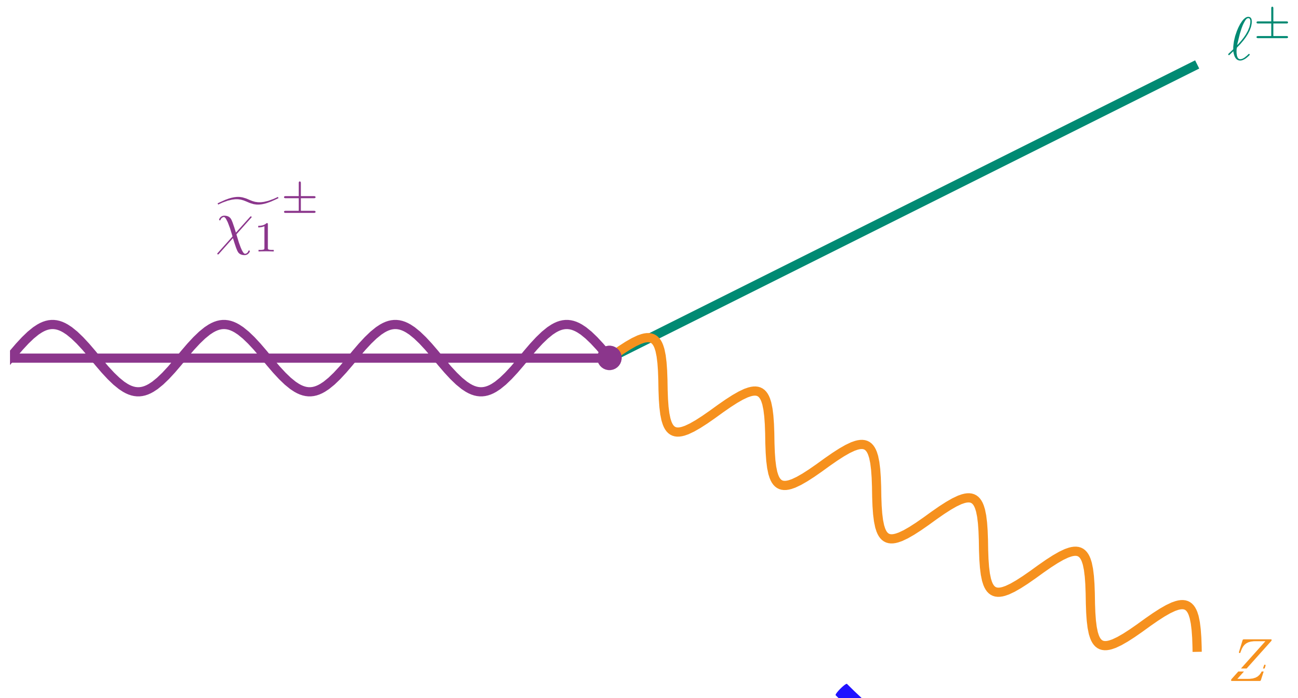
Chargino Decays

If kinematically allowed

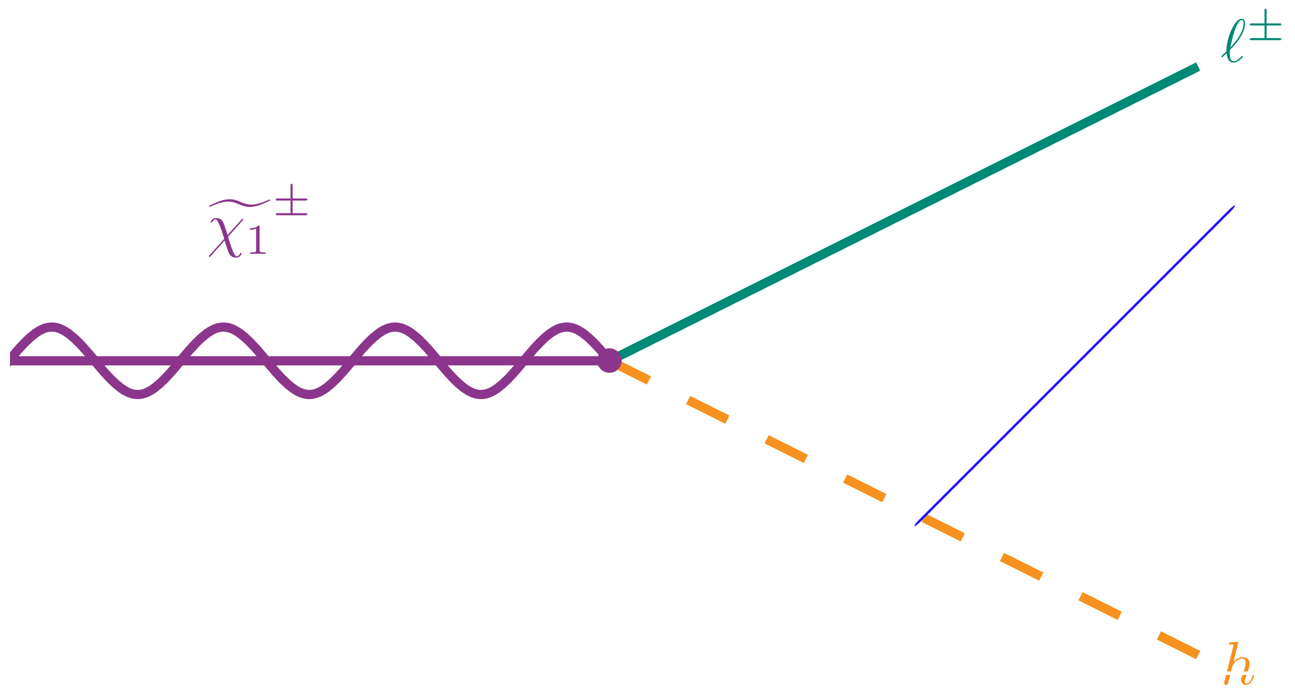
$\widetilde{\chi}_1^{\pm} \to W^{\pm}\tilde{B}$



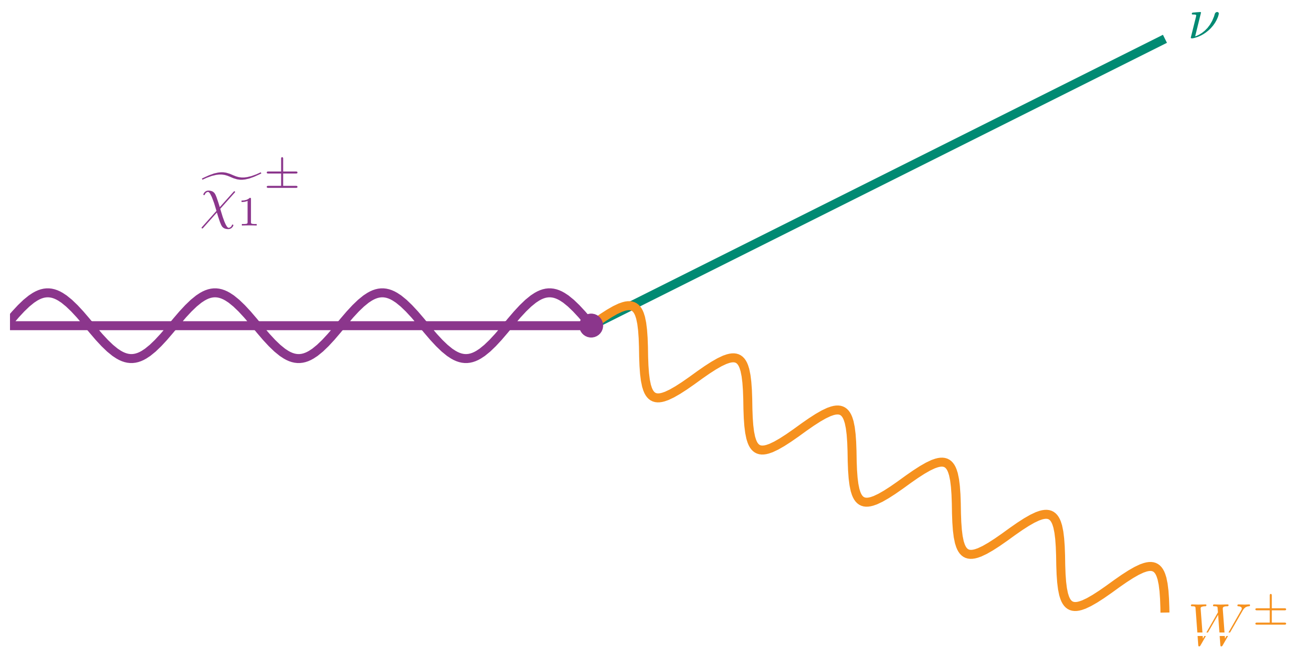
$\widetilde{\chi}_1^{\pm} \to Z\ell^{\pm}$



$\widetilde{\chi}_1^{\pm} \to h\,\ell^{\pm}$



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



These channels are suppressed by the mixing angle:

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