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

Based on *JHEP* 11 (2023) 085

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pronounced as “”

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Istituto Nazionale di Fisica Nucleare



The Galileo Galilei Institute for Theoretical Physics

Neutrinos Have Mass

Discovery of neutrino oscillations \longrightarrow Massive neutrinos

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

$$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2} = 7.41^{+0.21}_{-0.20}$$

$$\frac{\Delta m_{31}^2}{10^{-3} \text{ eV}^2} = 2.511^{+0.028}_{-0.027}$$

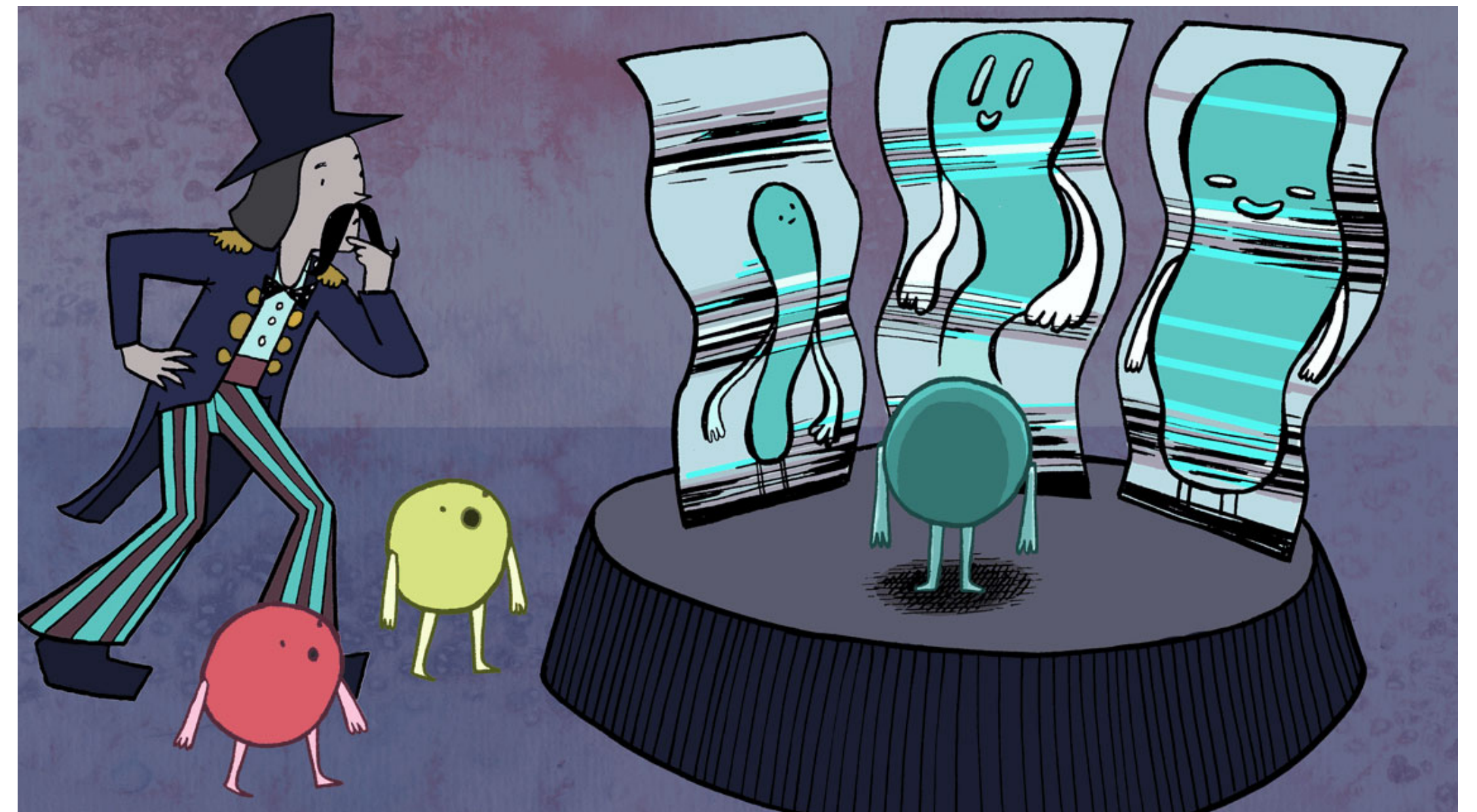
$$\sin^2 \theta_{12} = 0.307^{+0.012}_{-0.011}$$

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

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

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

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

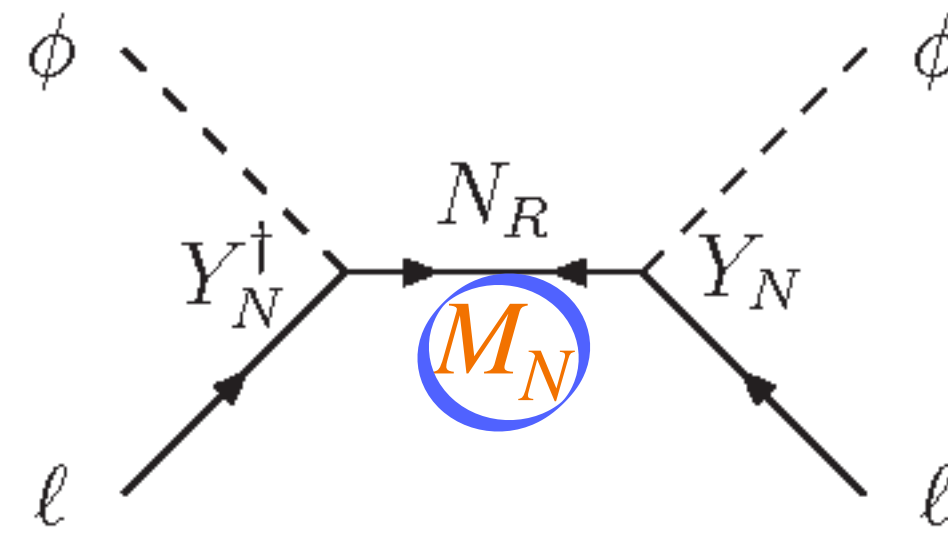


Symmetry Magazine/Sandbox Studio, Chicago

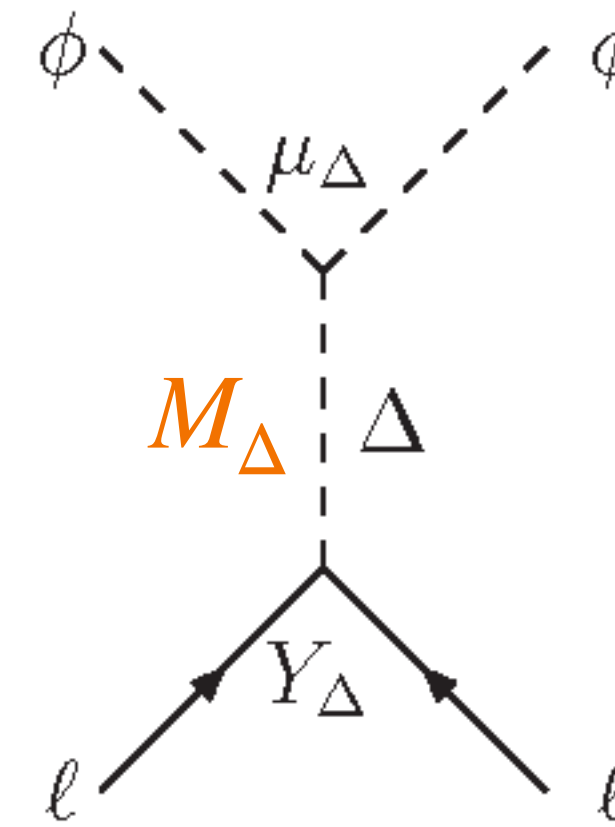
Seesaw Mechanism



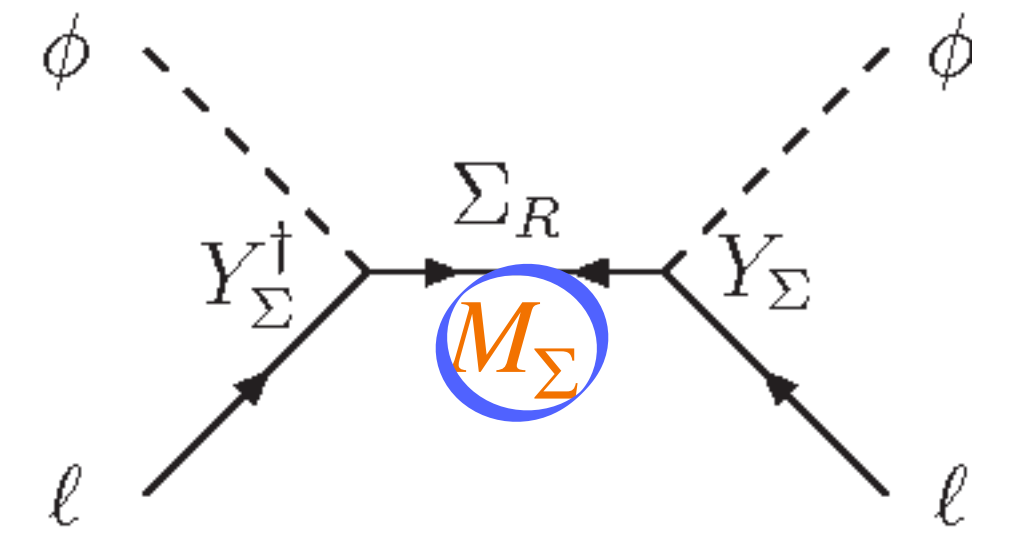
Type-I
SM singlet fermion



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)

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

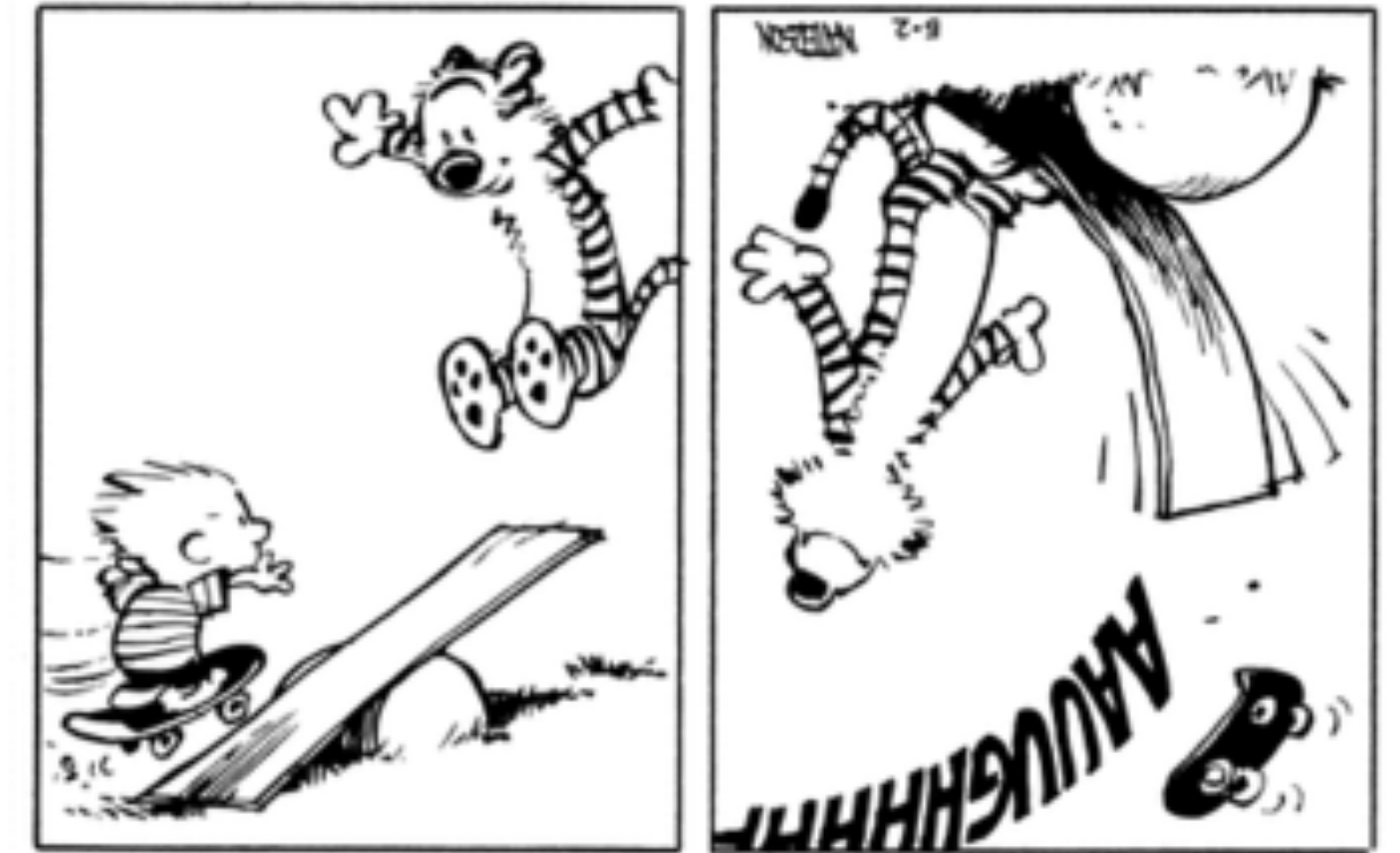
Type-I

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

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

$$+ \bar{N}' Y_{N'}'^T \tilde{\phi}^\dagger \ell_L + \mu \bar{N} N^c + \mu' \bar{N}' N'^c \longrightarrow \text{L-violating}$$

pseudo-Dirac fermions $\left\{ \begin{array}{l} \text{Dirac mass } M_D = \begin{pmatrix} 0 & \Lambda^T \\ \Lambda & 0 \end{pmatrix} \\ \text{Majorana masses } \mu, \mu' \end{array} \right.$



Type-III ISS is identical to type-I

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

Type-I and Type-III ISS

Type III models offer a richer phenomenology

- ▶ Have gauge interactions: $\bar{\Sigma}^-\Sigma^-Z, \bar{\Sigma}^+\Sigma^+Z, \bar{\Sigma}^0\Sigma^+W^-, \bar{\Sigma}^0\Sigma^-W^+ + \text{h.c.}$
 - ▶ Charged leptons mix with new states: $\Sigma^{+c} - l^-$
- production at colliders and rare decays

Type-I Type-III ISS

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

Neutrino masses are proportional to the Majorana masses

$U(1)_R$ -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**

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

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}

2 $SU(2)$ singlet
fermions

2 $SU(2)$ triplet
fermions

→ 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
$W_{\tilde{B}}^\alpha$	1	1
$\Phi_S = \phi_S + \theta D$	1	0
$W_{\tilde{W}}^\alpha$	3	1
$\Phi_T = \phi_T + \theta D$	3	0
$W'_\alpha = \theta D$	1	1

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.

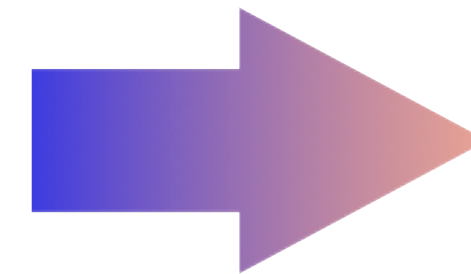
$$\int d^2\theta \sqrt{2} c_{\tilde{B}} \frac{W'_\alpha}{\Lambda_M} W^\alpha W_{\tilde{B}} \Phi_S \Rightarrow \frac{\sqrt{2} c_{\tilde{B}} D}{\Lambda_M} \tilde{B} S \equiv M_{\tilde{B}} \tilde{B} S$$

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

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

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

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



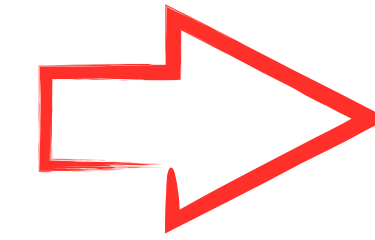
**Dirac
gauginos**

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



Allows the mixing between electroweakinos and SM leptons!

✦ **Neutralinos and neutrinos**

Neutrino masses

✦ **Charginos and charged leptons**

LFV at tree level

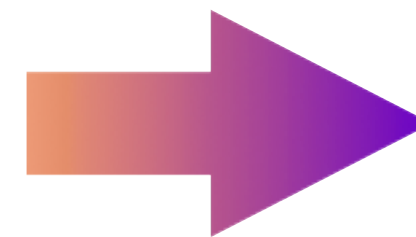
Superfields	$SU(2)_L$	$U(1)_R$	$U(1)_{R-L}$
L_i	2	1	0
E_i^c	1	1	2
$H_{u,d}$	2	0	0
$R_{u,d}$	2	2	2
$W_{\tilde{B}}^\alpha$	1	1	1
$\Phi_S = \phi_S + \theta D$	1	0	0
$W_{\tilde{W}}^\alpha$	3	1	1
$\Phi_T = \phi_T + \theta D$	3	0	0
$W'_\alpha = \theta D$	1	1	1

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

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

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

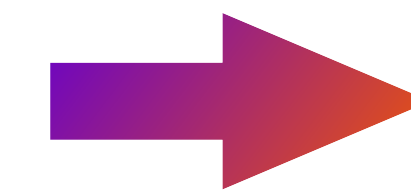
Dirac partners can also acquire **Majorana masses**: $m_S, m_T \sim \mathcal{O}(m_{3/2})$

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

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

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

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



**pseudo-Dirac
gauginos**

“bivO”
“wivO”

Neutrino masses

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

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

$$\frac{1}{\Lambda_M^2} \int d^2\theta \left(f_{\tilde{B}}^i W'_\alpha W_{\tilde{B}}^\alpha H_u L_i + f_{\tilde{W}}^i W'_\alpha W_{\tilde{W}}^\alpha H_u L_i \right) \Rightarrow \underbrace{f_{\tilde{B}}^i \frac{M_{\tilde{B}}}{\Lambda_M} \tilde{B} h_u \ell_i}_{\text{Explicitly violate } U(1)_R \text{ and } U(1)_L} + \underbrace{f_{\tilde{W}}^i \frac{M_{\tilde{W}}}{\Lambda_M} \tilde{W} h_u \ell_i}_{\text{Explicitly violate } U(1)_R \text{ and } U(1)_L},$$

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

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

Bino and wino act as RH neutrinos

$$\mathbf{Y}_{\tilde{B}, \tilde{W}}^T = \begin{pmatrix} Y_{\tilde{B}, \tilde{W}}^e & Y_{\tilde{B}, \tilde{W}}^\mu & Y_{\tilde{B}, \tilde{W}}^\tau \end{pmatrix} = \frac{M_{\tilde{B}, \tilde{W}}}{\Lambda_M} \begin{pmatrix} f_{\tilde{B}, \tilde{W}}^e & f_{\tilde{B}, \tilde{W}}^\mu & f_{\tilde{B}, \tilde{W}}^\tau \end{pmatrix}$$

If bino, wino, and higgsinos mix, the coefficients $f_{\tilde{B}, \tilde{W}}^i$ 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

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

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

S and T are the other RH neutrinos

$$\mathbf{G}_{S,T}^T = \begin{pmatrix} G_{S,T}^e & G_{S,T}^\mu & G_{S,T}^\tau \end{pmatrix} = \frac{m_{3/2}}{\Lambda_M} \begin{pmatrix} d_{S,T}^e & d_{S,T}^\mu & d_{S,T}^\tau \end{pmatrix}$$

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!

$$\begin{aligned}
 \mathcal{L} \supset & \underbrace{\frac{f_{\tilde{B}}^i M_{\tilde{B}}}{\Lambda_M} \bar{\ell} h_u \tilde{B} + M_{\tilde{B}} S \tilde{B}}_{U(1)_{R-L}\text{-conserving}} + \underbrace{\frac{d_{\tilde{B}}^i m_{3/2}}{\Lambda_M} \bar{\ell} h_u S^\dagger + m_{\tilde{B}} \tilde{B} \tilde{B} + m_S S S}_{U(1)_{R-L}\text{-violating}} \\
 & + \underbrace{\frac{f_{\tilde{W}}^i M_{\tilde{W}}}{\Lambda_M} \bar{\ell} h_u \tilde{W} + M_{\tilde{W}} T \tilde{W}}_{U(1)_{R-L}\text{-conserving}} + \underbrace{\frac{d_{\tilde{W}}^i m_{3/2}}{\Lambda_M} \bar{\ell} h_u T^\dagger + m_{\tilde{W}} \tilde{W} \tilde{W} + m_T T T}_{U(1)_{R-L}\text{-violating}}
 \end{aligned}$$

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

$$M_\nu = \begin{pmatrix} \mathbf{0}_{3 \times 3} & \mathbf{Y}_{\tilde{B}\nu} & \mathbf{Y}_{\tilde{W}\nu} & \mathbf{G}_S \nu & \mathbf{G}_T \nu \\ \mathbf{Y}_{\tilde{B}\nu}^T & m_{\tilde{B}} & 0 & M_{\tilde{B}} & 0 \\ \mathbf{Y}_{\tilde{W}\nu}^T & 0 & m_{\tilde{W}} & 0 & M_{\tilde{W}} \\ \mathbf{G}_S^T \nu & M_{\tilde{B}} & 0 & m_S & 0 \\ \mathbf{G}_T^T \nu & 0 & M_{\tilde{W}} & 0 & m_T \end{pmatrix}$$

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


$$\mathbf{Y}_{\tilde{B}, \tilde{W}}^T = \frac{M_{\tilde{B}, \tilde{W}}}{\Lambda_M} (f_{\tilde{B}, \tilde{W}}^e f_{\tilde{B}, \tilde{W}}^\mu f_{\tilde{B}, \tilde{W}}^\tau) \quad \mathbf{G}_{S, T}^T = \frac{m_{3/2}}{\Lambda_M} (d_{S, T}^e d_{S, T}^\mu d_{S, T}^\tau)$$

Analytically unsolvable due to the large number of **free parameters**

$$m_{\tilde{B}, \tilde{W}} \propto m_{3/2}, m_S, m_T, M_{\tilde{B}}, M_{\tilde{W}}, \Lambda_M, f_{\tilde{B}}^i, f_{\tilde{W}}^i, d_S^i, d_T^i$$

Neutrino masses: A Simplified Scenario

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

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


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

The light-neutrino mass eigenvalues in the normal ordering are

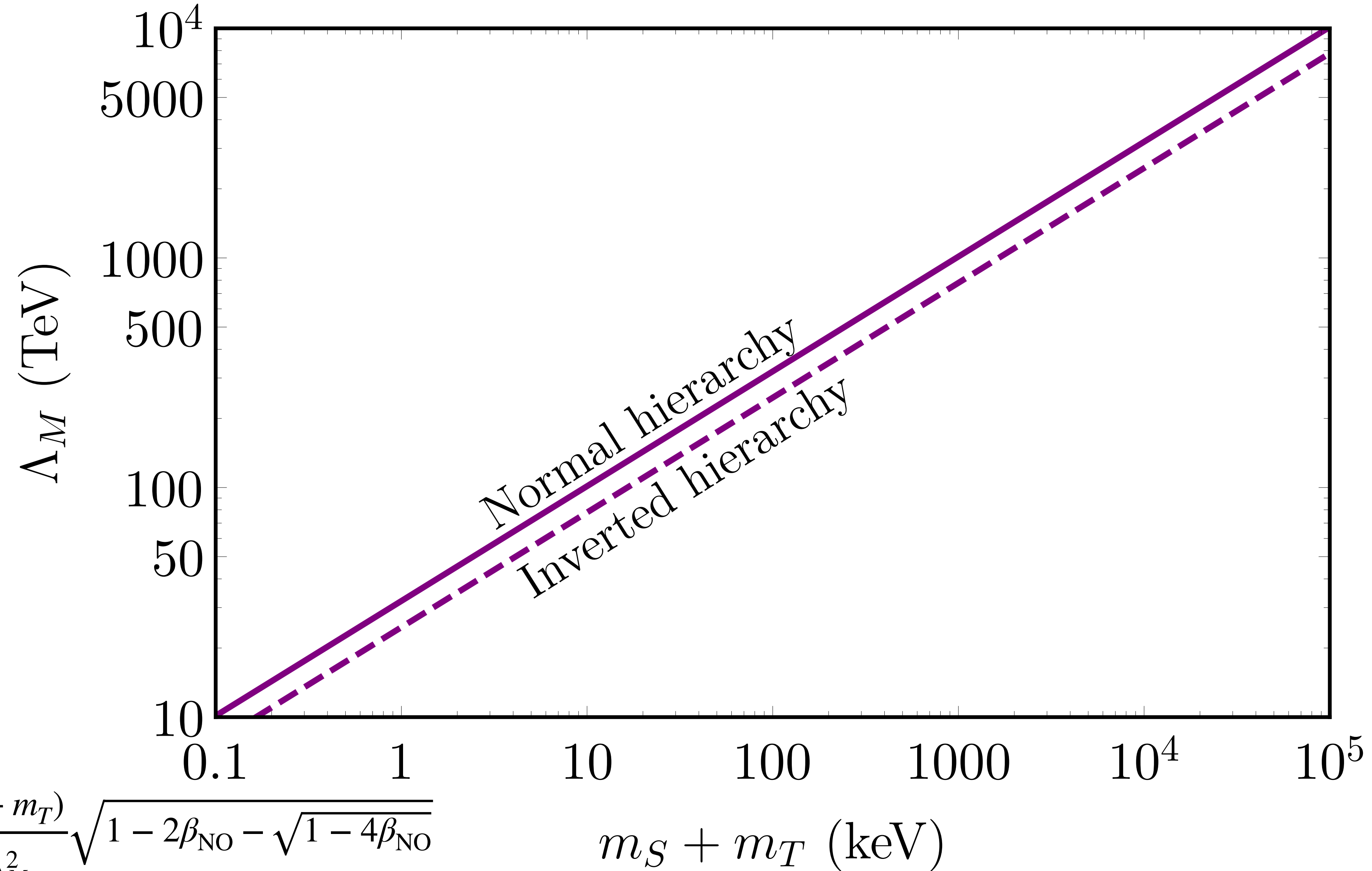
$$m_1 = 0, \quad m_{2,3} = \frac{v^2(m_S + m_T)}{\sqrt{2}\Lambda_M^2} \sqrt{1 - 2\beta_{\text{NO}} \pm \sqrt{1 - 4\beta_{\text{NO}}}}$$

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

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

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

$$\Lambda_M - m_S + m_T$$



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

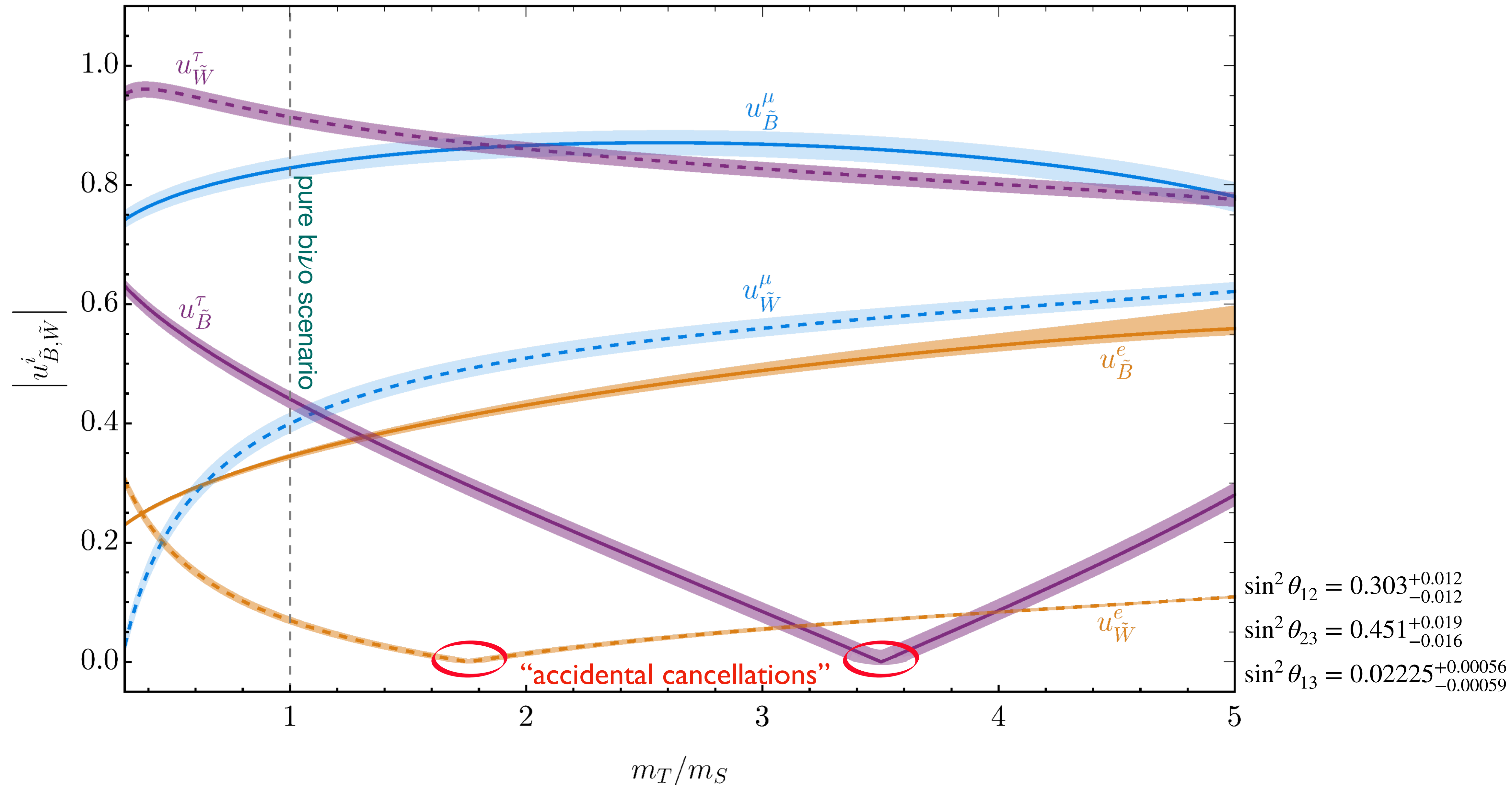
$$u_{\tilde{B}}^i = \left(\frac{a_2}{b_2} - \frac{a_3}{b_3} \right)^{-1} \left[\frac{1}{b_2 N_2} U_{i2} - \frac{1}{b_3 N_3} U_{i3} \right] \quad u_{\tilde{W}}^i = \left(\frac{b_2}{a_2} - \frac{b_3}{a_3} \right)^{-1} \left[\frac{1}{a_2 N_2} U_{i2} - \frac{1}{a_3 N_3} U_{i3} \right]$$

$$u_{\tilde{B}, \tilde{W}}^i \propto \frac{m_T}{m_S}$$

$$\lambda_{\text{NO}} = \sqrt{1 + \beta_{\text{NO}} \frac{(m_S + m_T)^2}{m_S m_T}}, \quad a_{2,3} = -2m_S \lambda_{\text{NO}},$$

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

Neutrino Mixing Structure



Low Energy Constraints

The **bino-wino-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, $\nu Y_{\tilde{W}}^i \tilde{W}^+ \ell_i^-$, **mixes charginos and charged leptons**

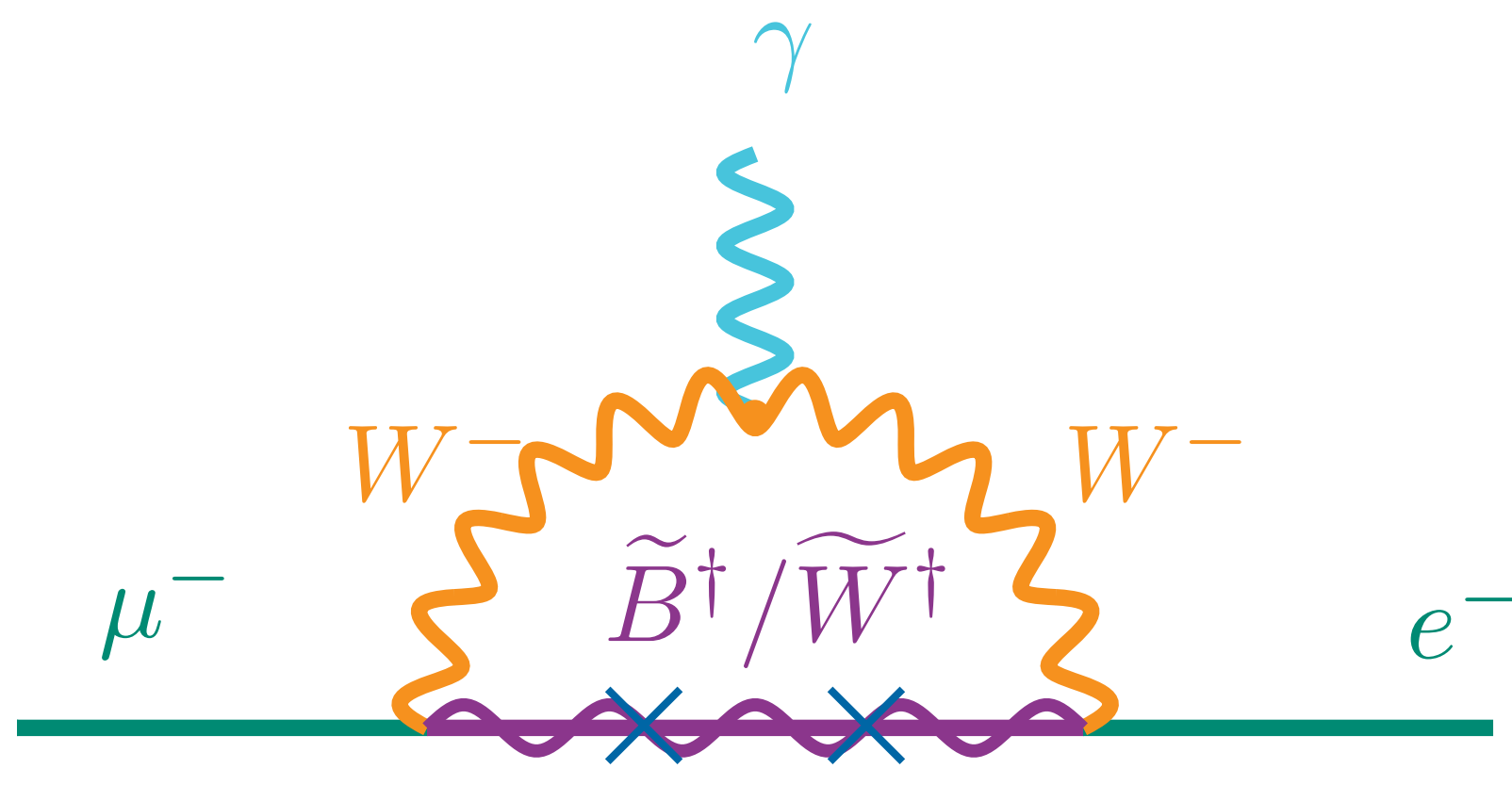
$$\tilde{W}^{+c} - \ell^- \text{ mixing} \propto \mathcal{O} \left(\frac{\nu Y_{\tilde{W}}}{M_{\tilde{W}}} \right) \rightarrow \begin{array}{c} \mu^- \\ \text{---} \bullet \text{---} \tilde{W}^+ e^- \\ \quad \quad \quad \times \quad \times \\ \quad \quad \quad \text{Z} \end{array} \propto \frac{\nu^2}{2} \left(Y_{\tilde{W}}^\dagger \frac{1}{M_{\tilde{W}}^\dagger M_{\tilde{W}}} Y_{\tilde{W}} \right)_{e\mu}$$

The diagram illustrates a flavor-changing neutral current process. A horizontal green line represents a lepton, starting as a muon (μ^-) on the left and ending as an electron (e^-) on the right. A vertical orange wavy line labeled 'Z' connects this line to a vertex. At this vertex, there is a purple 'X' and a purple line labeled \tilde{W}^+ that connects to another vertex. This second vertex also has a purple 'X' and is connected to the electron line. A purple arrow points from the mixing term on the left towards the diagram.

Flavor-changing neutral and charged currents at tree level!

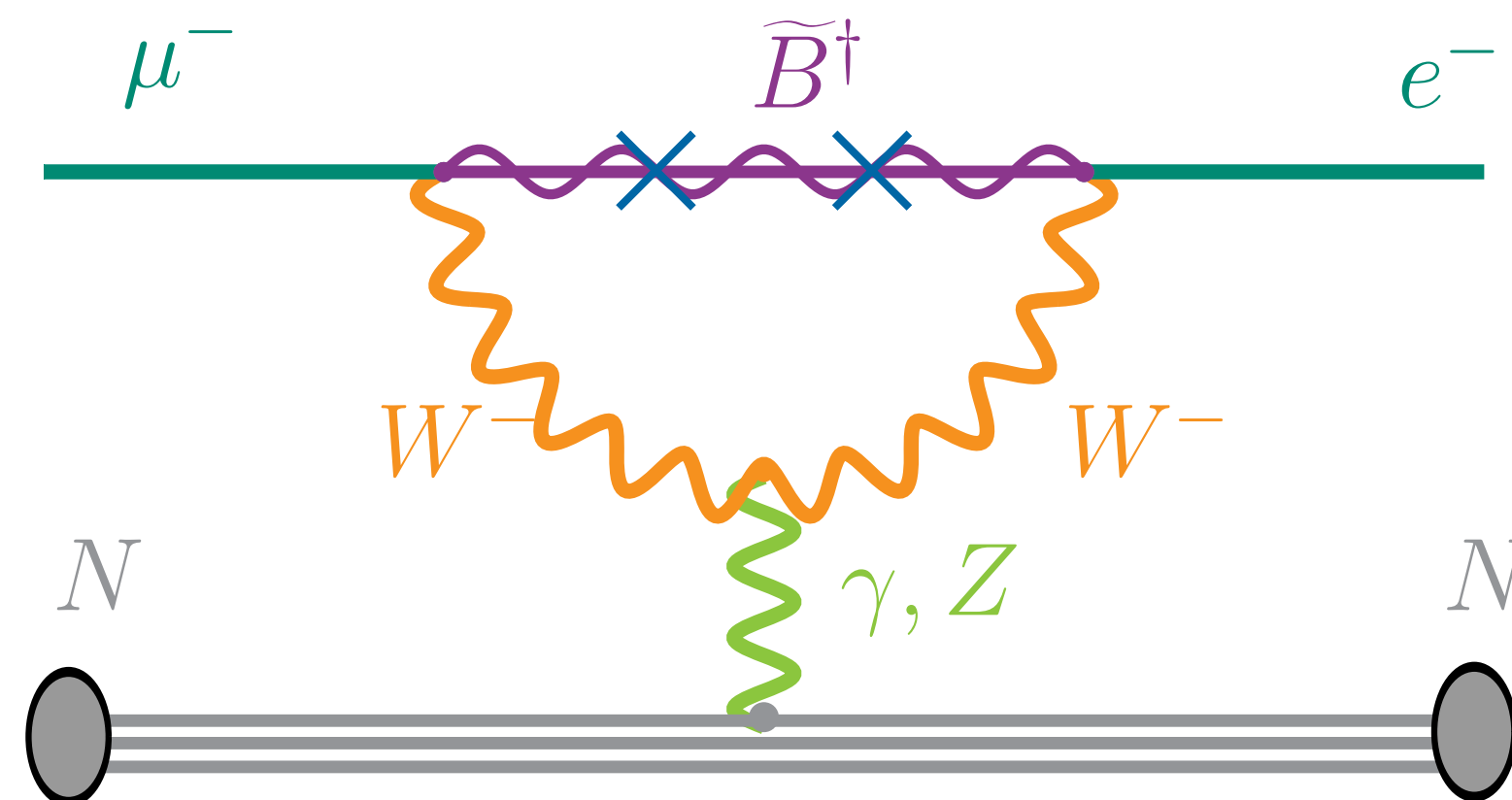
LFV processes

$$\mu \rightarrow e \gamma$$



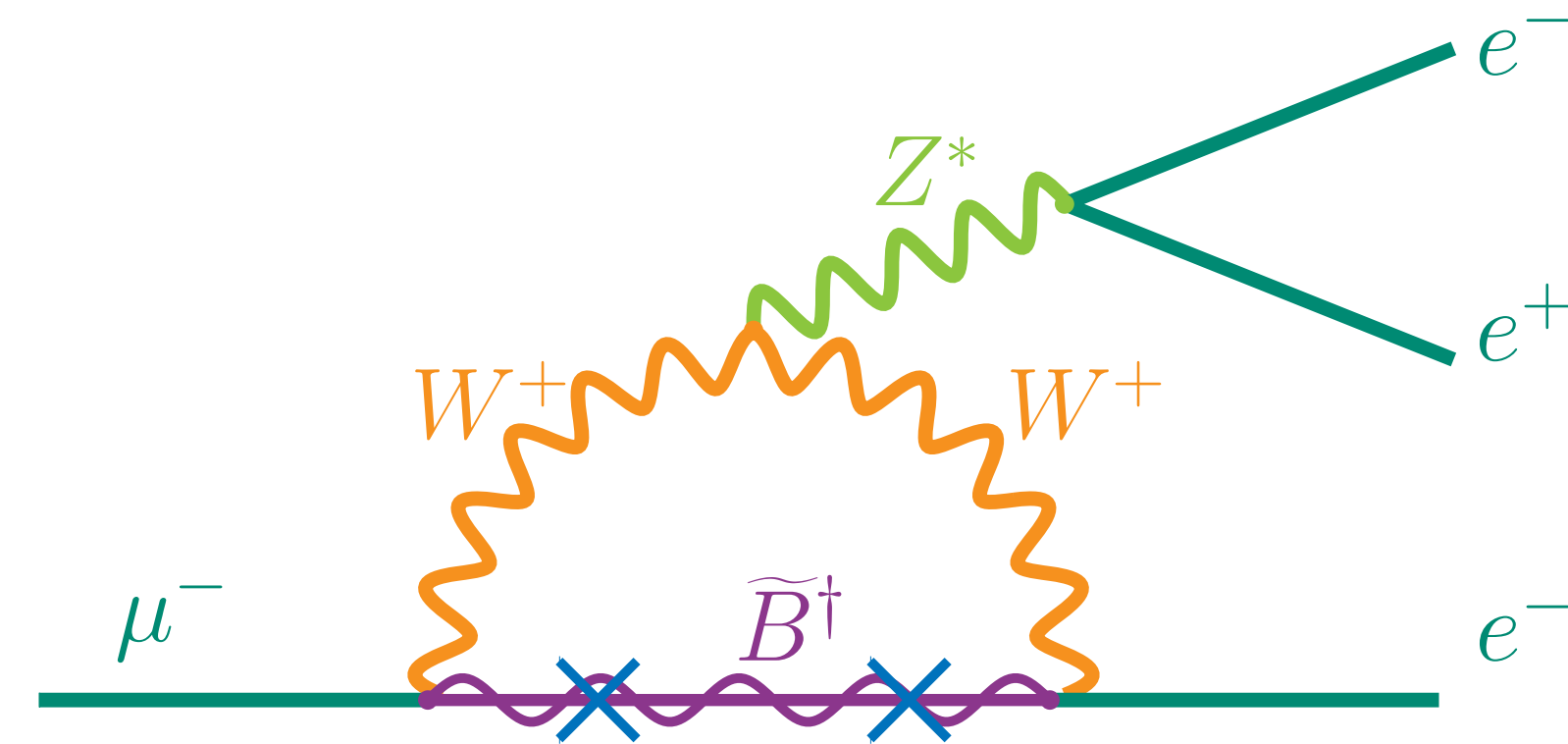
type-I: one loop
type-III: one loop

$$\mu - e \text{ conversion in nuclei}$$

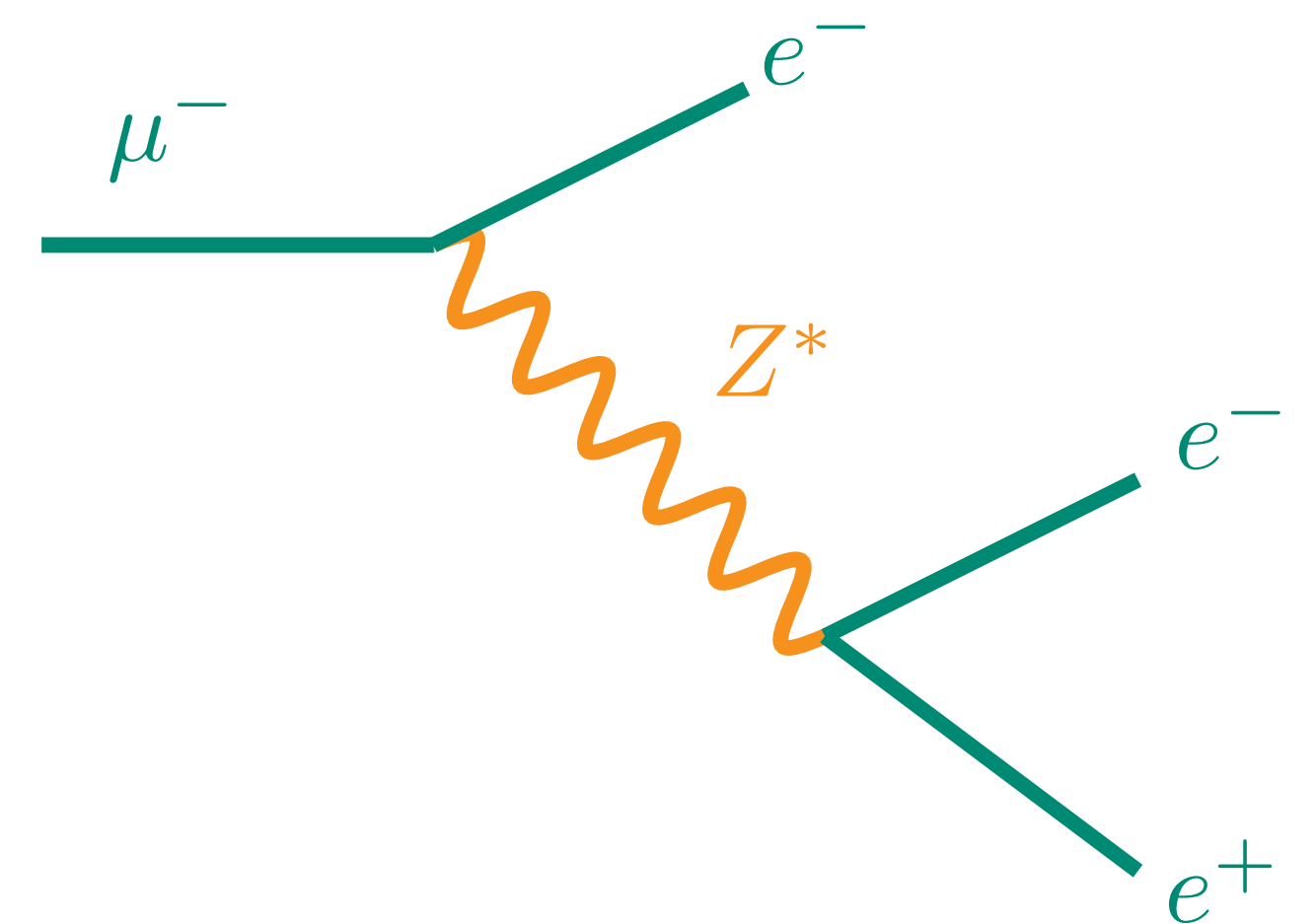
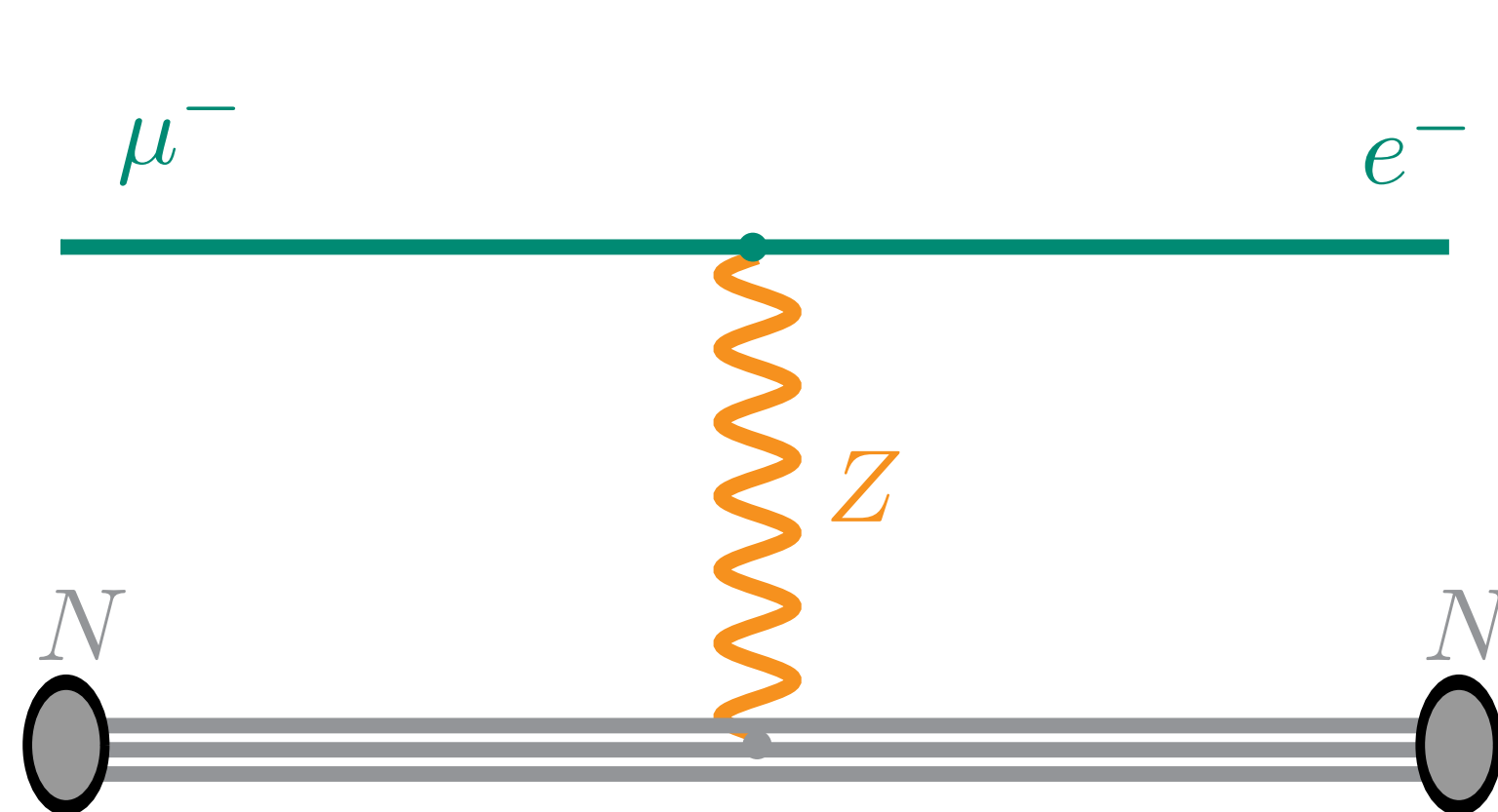


type-I: one loop
type-III: tree level

$$\mu \rightarrow e e e$$

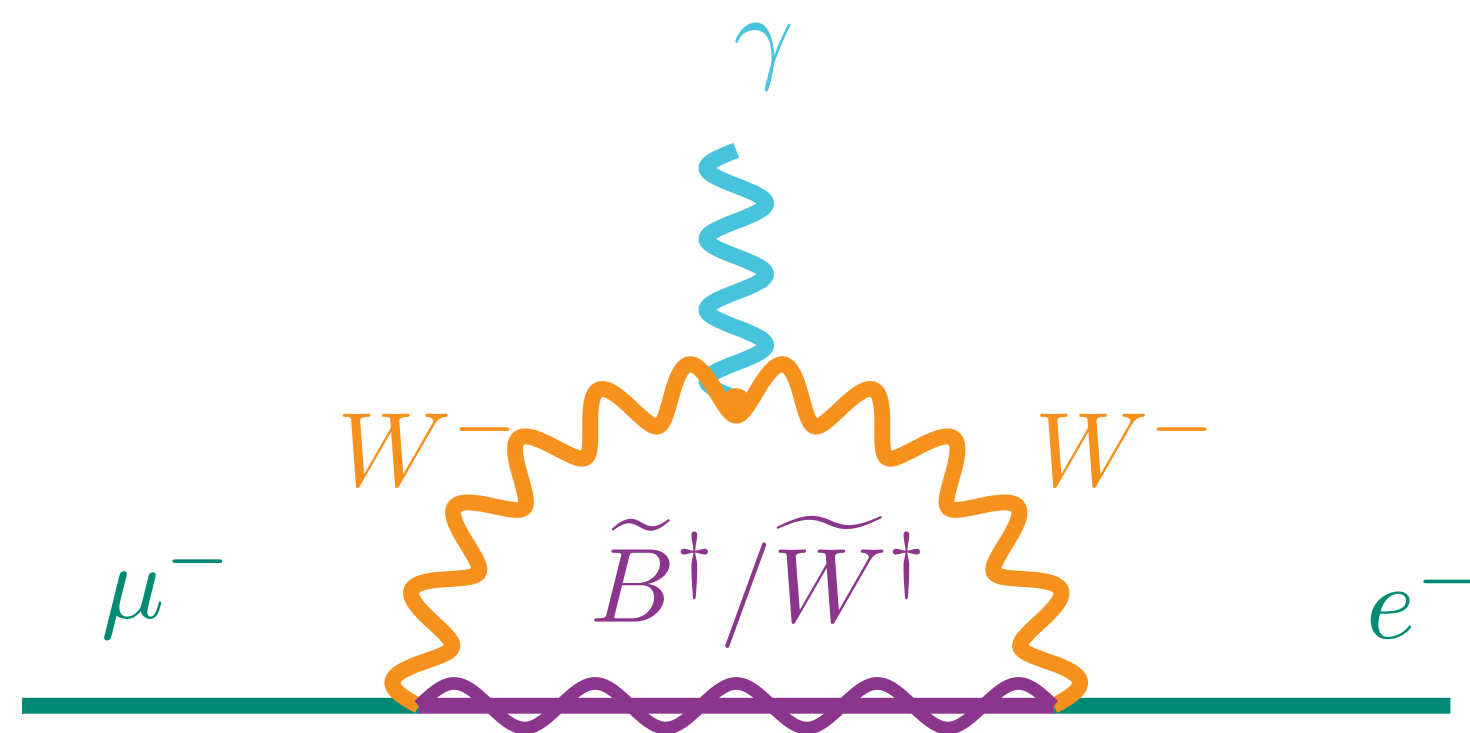


type-I: one loop
type-III: tree level

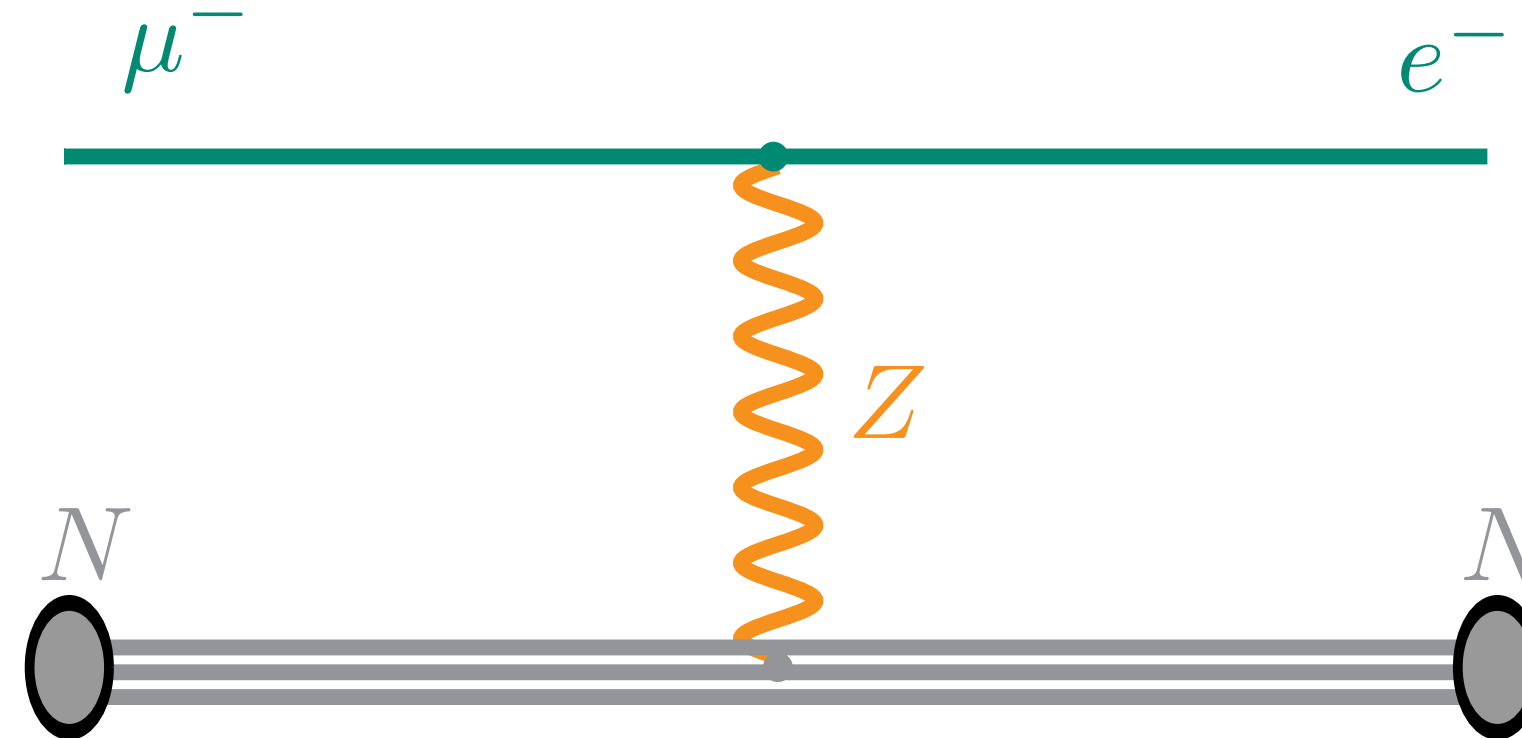


LFV processes

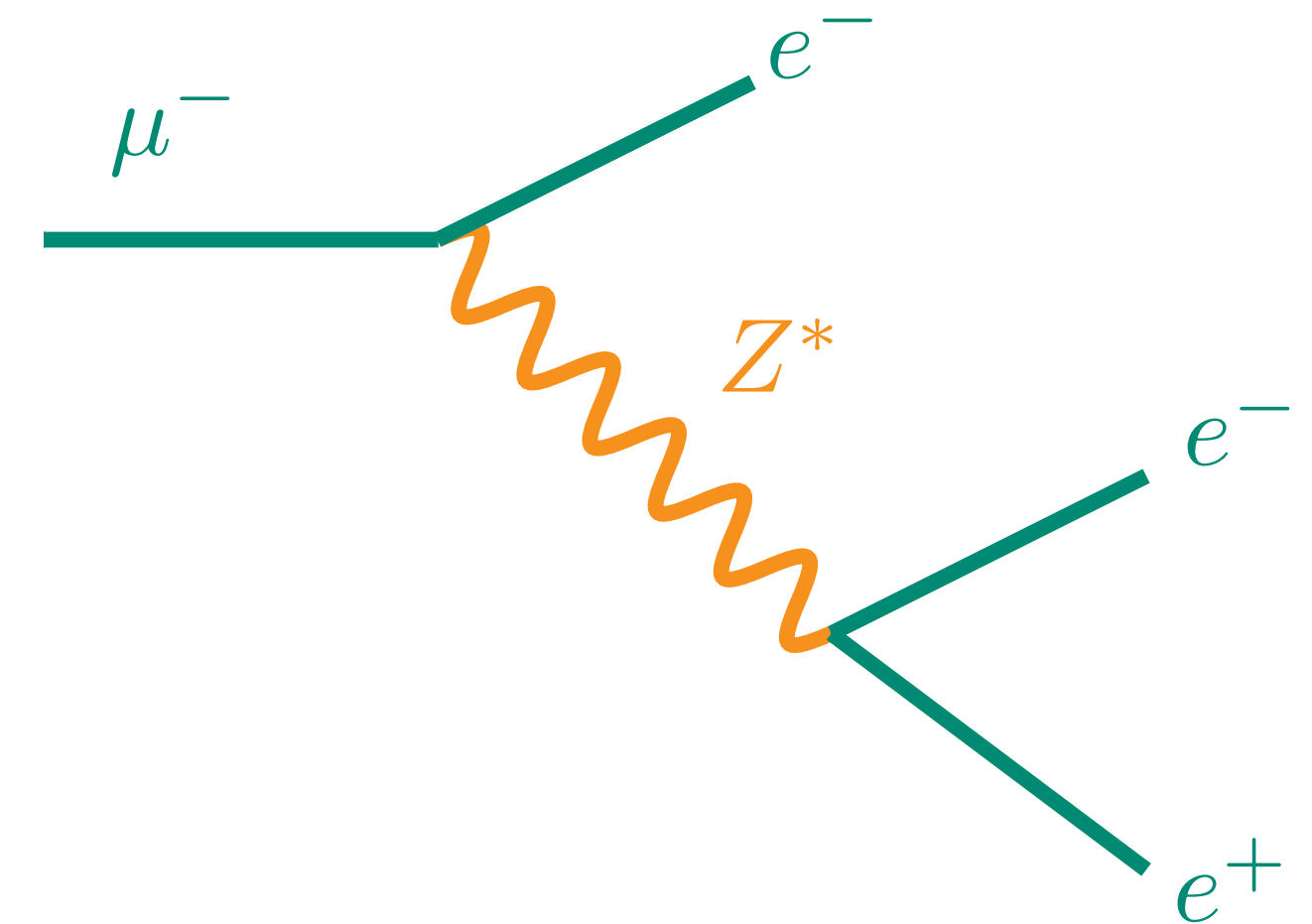
$$\mu \rightarrow e \gamma$$



$$\mu - e \text{ conversion in nuclei}$$



$$\mu \rightarrow e e e$$



All depend on the same combination:

$$\epsilon^{d=6} = v^2 \left| \mathbf{Y}^T \frac{1}{\Lambda^T \Lambda} \mathbf{Y} \right|$$

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

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

Independent of Dirac ν_0 and $w\nu_0$ masses:

$$\epsilon^{d=6} \propto \frac{v^2}{\Lambda_M^2}$$

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

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

Type-III

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

Stronger than type-I
due to tree level FCNC

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

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

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

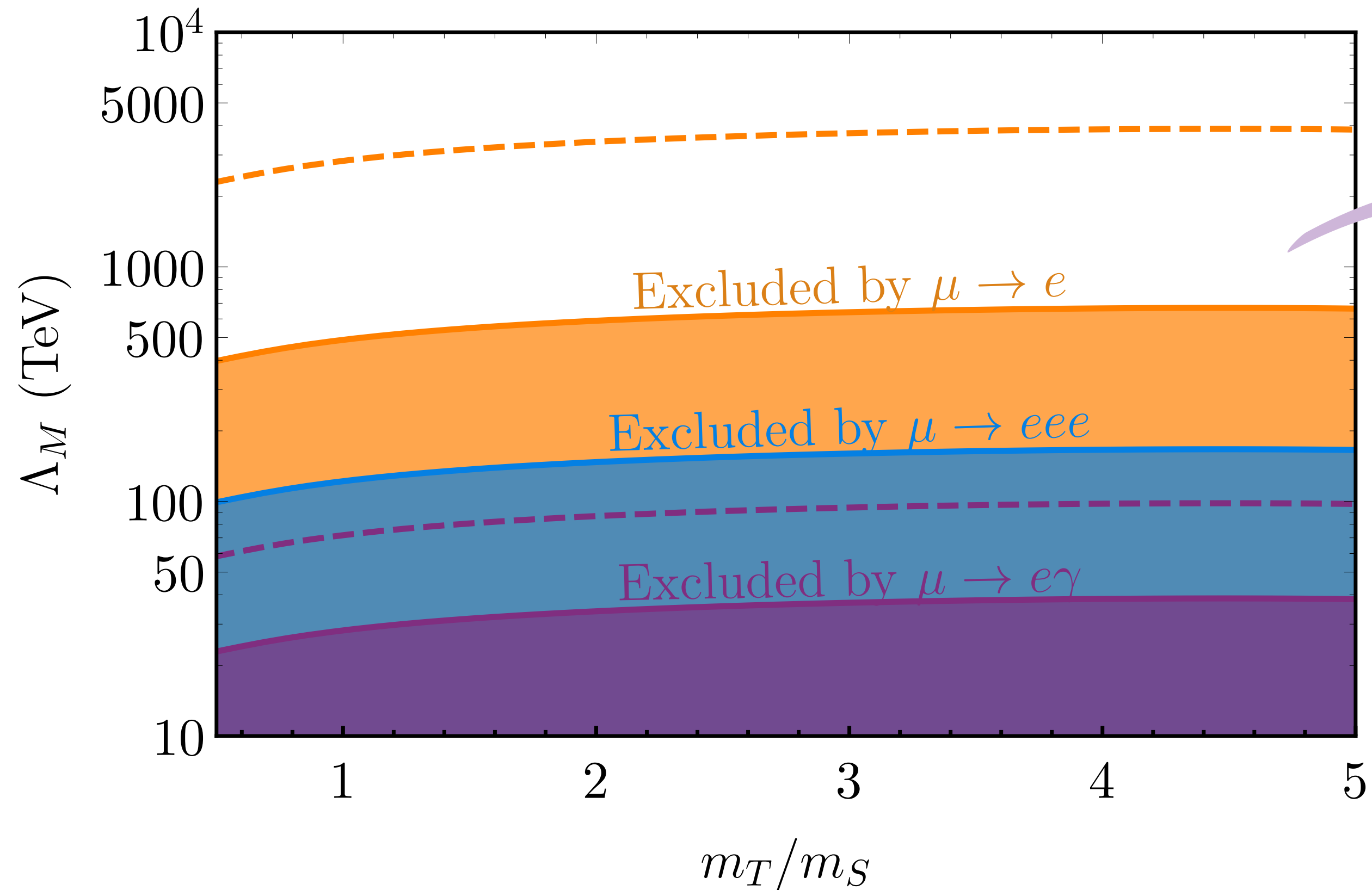
MEG II Collaboration, PoS NuFact2021 (2022) 120

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

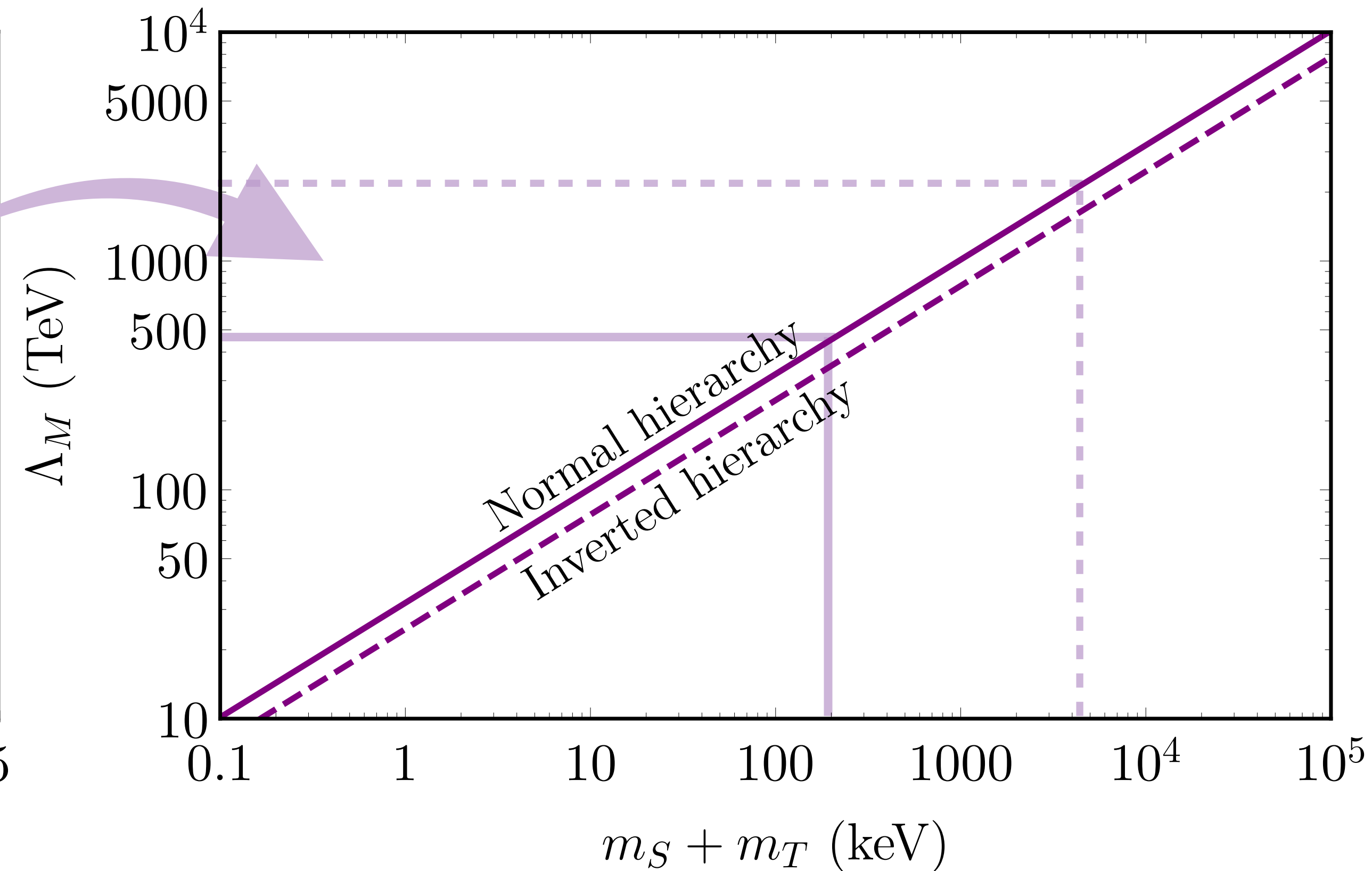
Mu2e Collaboration, Universe 2023, 9, 54

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

Constraints on the Messenger Scale

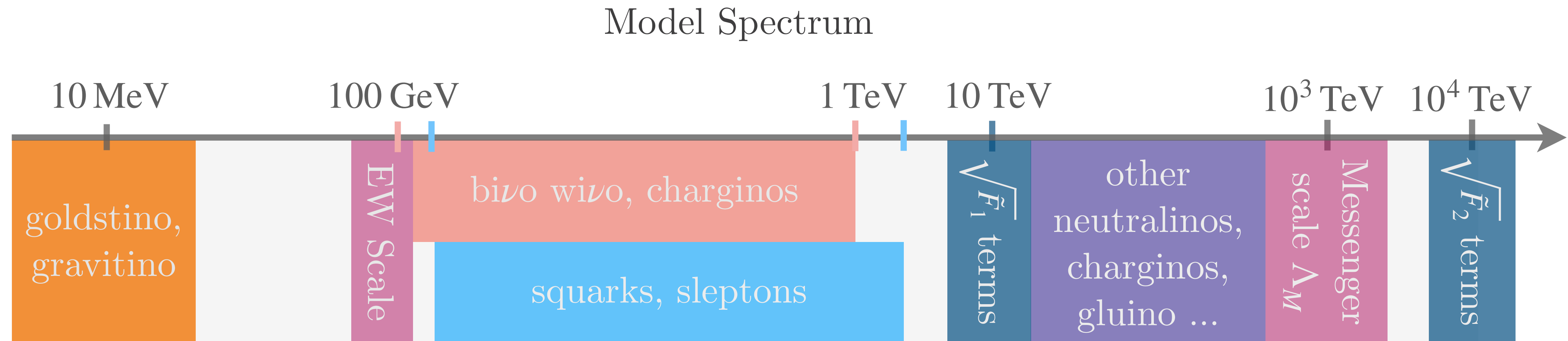


$$\Lambda_M \gtrsim (500 - 1000) \text{ TeV}$$



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

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: $m_{3/2} \sim \mathcal{O}(10 \text{ MeV})$

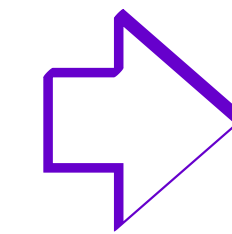
→ **Uneaten Goldstino** with a mass $2m_{3/2}$ can be a **DM candidate** when $T_{\text{RH}} \sim \mathcal{O}(\text{GeV})$

[A. Monteux and C. S. Shin, Phys. Rev. D92, 035002 \(2015\)](#)

Wino as the Lightest Neutralino

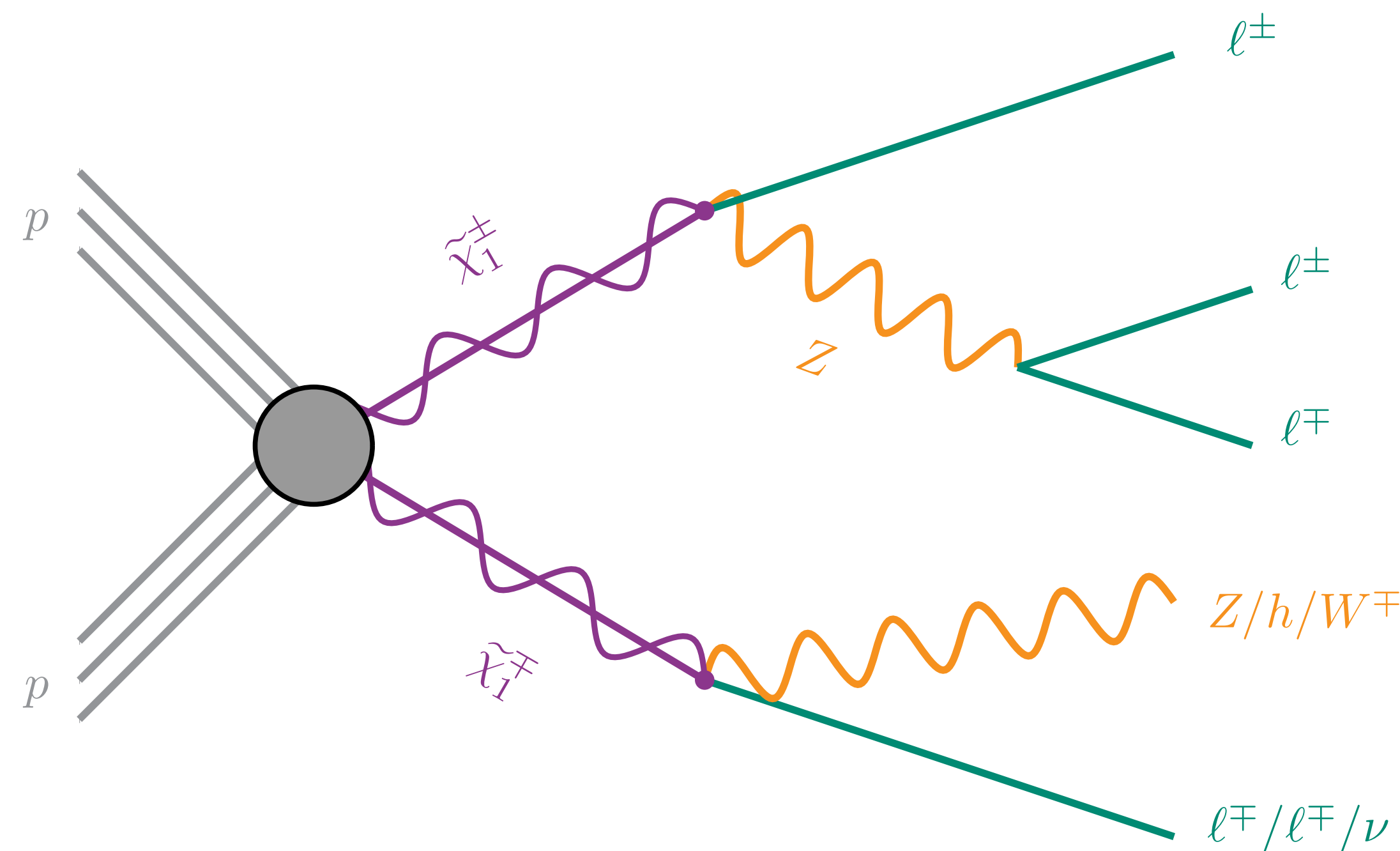
Wino Phenomenology

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

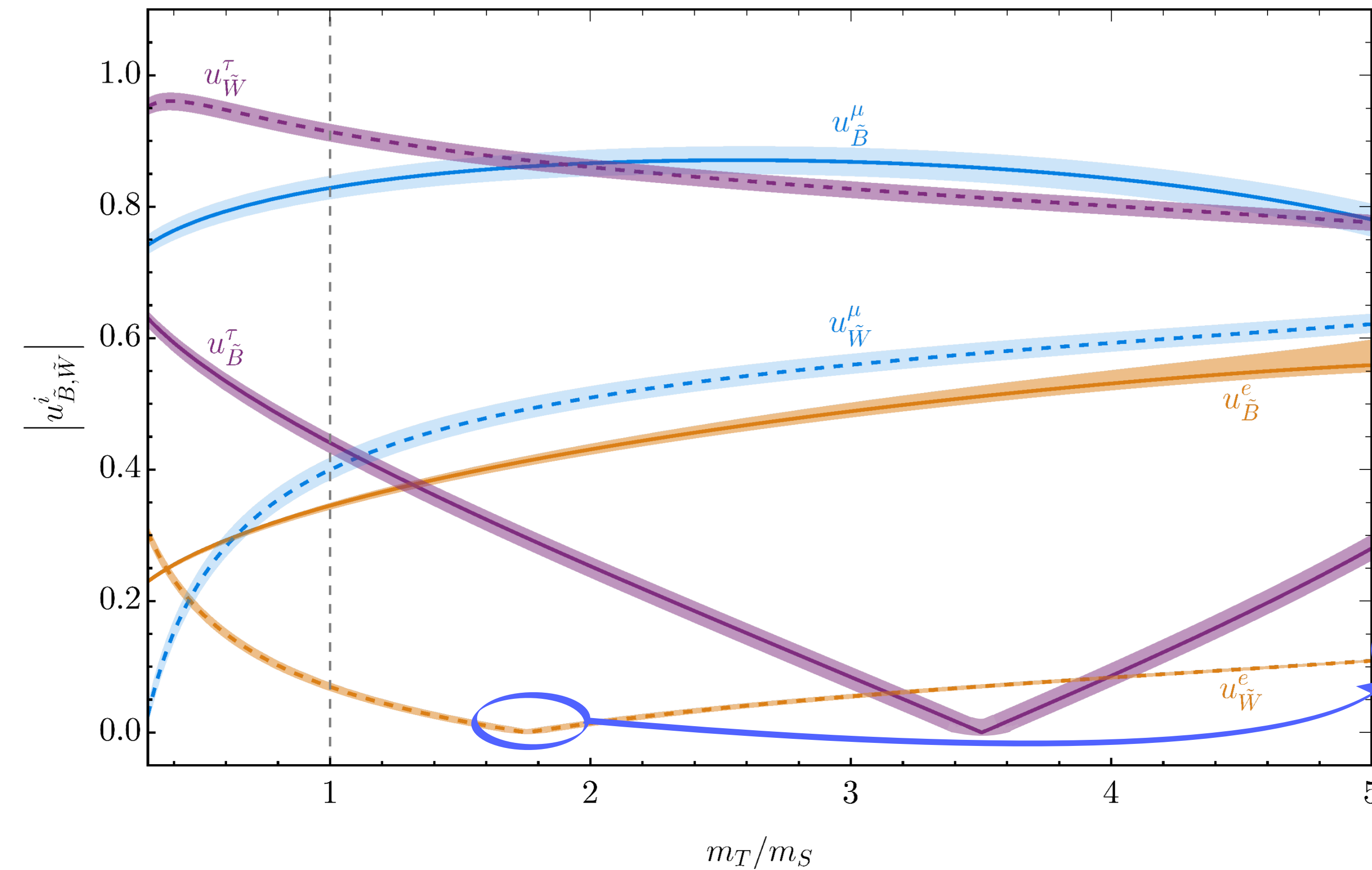
} free parameter
for the analysis

e and μ final states are the most constraining

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

Wino as the Lightest Neutralino

Wino Phenomenology



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

Depends on their
branching fraction to
different lepton flavors

free parameter
for the analysis

e and μ final states are the most constraining

Alleviates the constraints
from this search

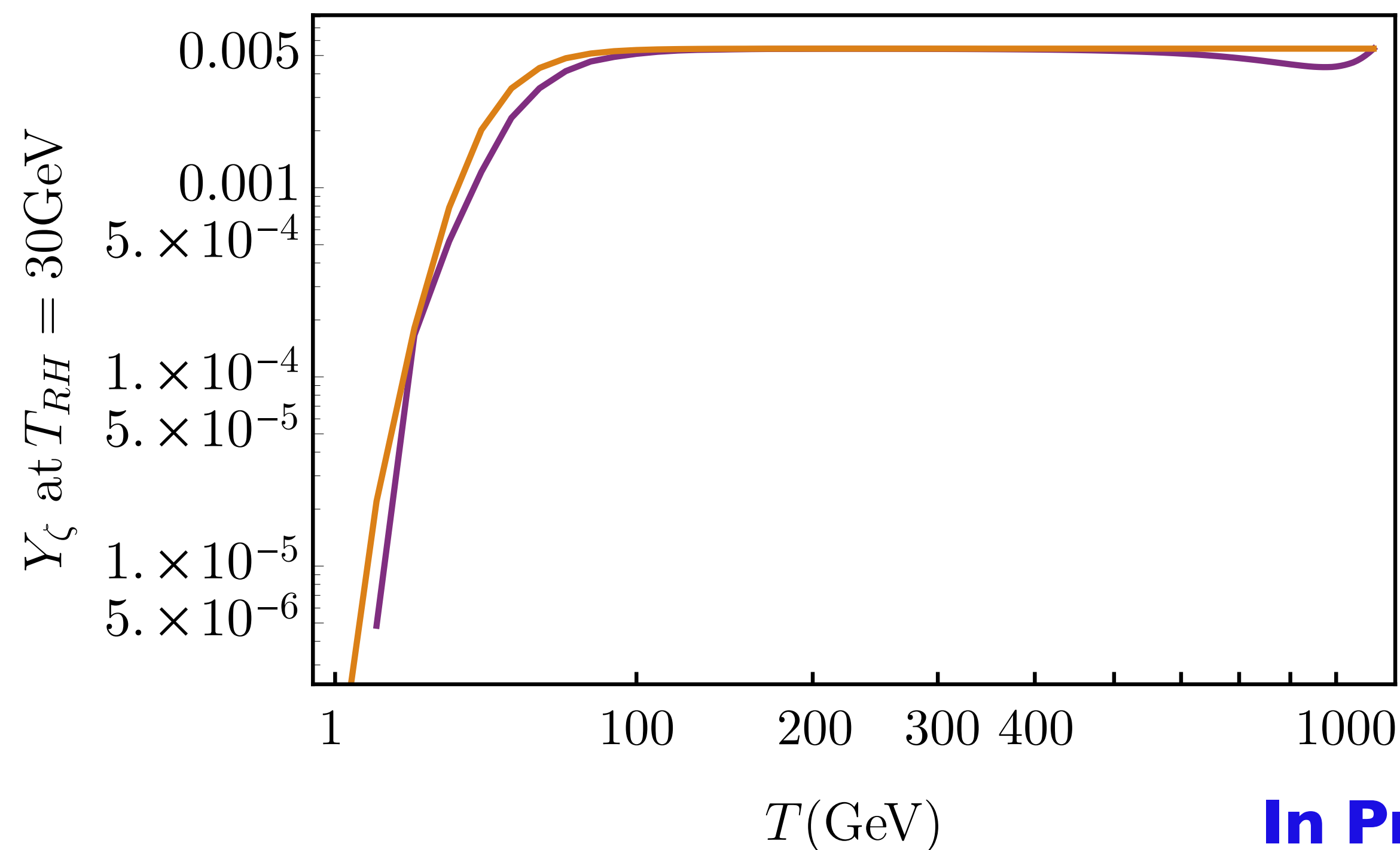
ATLAS collaboration, Phys.
Rev. D 103 (2021) 112003

Gravitino/Goldstino DM with low T_{RH}

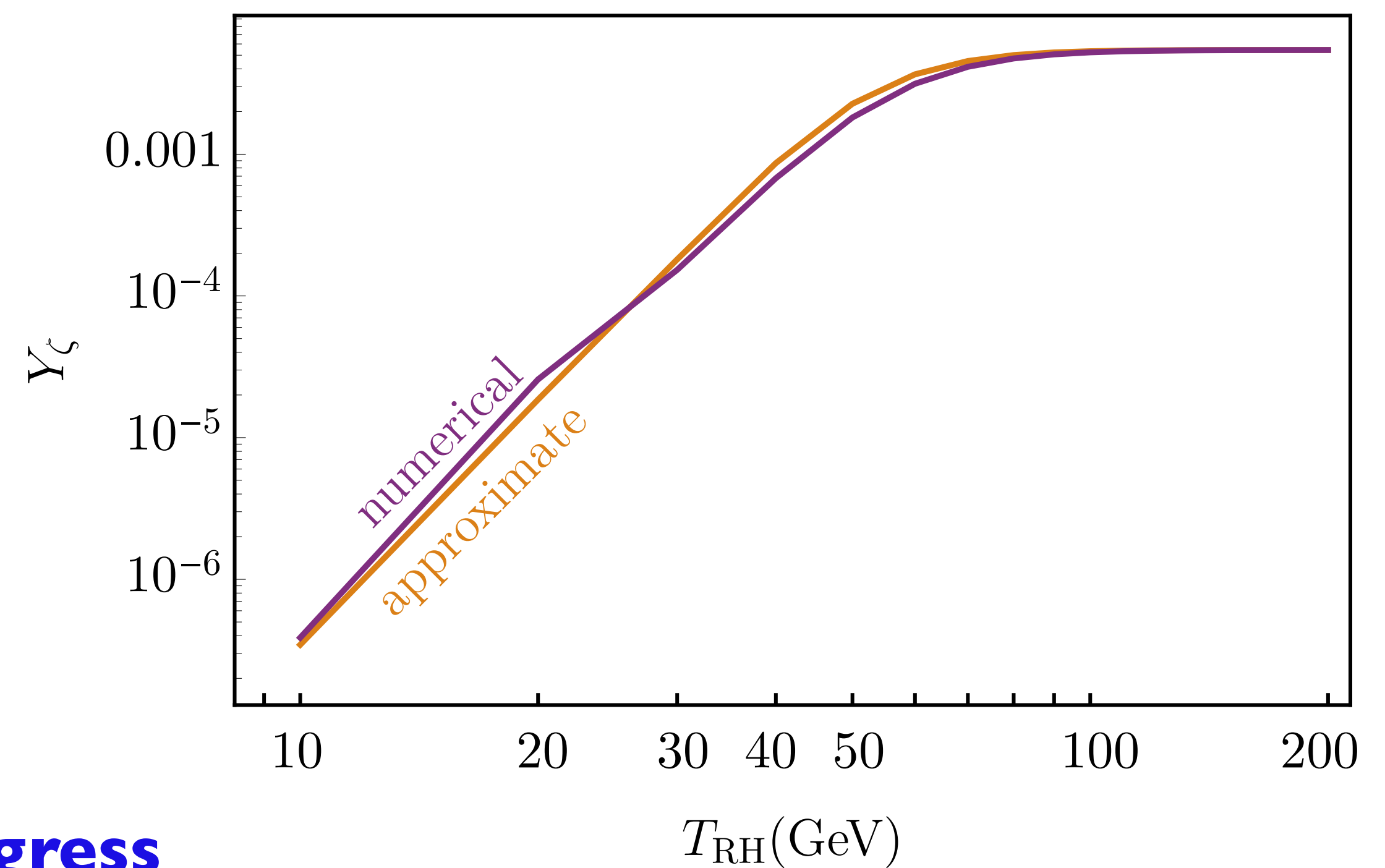
For the parameter region we interest, $m_{3/2} \sim \mathcal{O}(1 \text{ keV} - 10 \text{ MeV})$, goldstino will overpopulated the universe, if the reheating temperature is sufficiently high, e.g. $T_{RH} \sim \mathcal{O}(\text{TeV})$

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

Goldstino Yield



A. Monteux and C. S. Shin, Phys. Rev. D **92**, 035002 (2015)



In Progress