Neutrino Masses: First Signal From SUSY!

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Simplicity II
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Pilar Coloma, SI, arXiv:1606.06372

Sneak Peek

- The Standard Model is great!
- But…
  - Cannot explain the neutrino masses
  - Cannot explain dark matter
  - Cannot explain the matter—antimatter asymmetry

Will focus on a SIMPLE
solution for neutrino masses!

Neutrinos are massive

PDG review, www.nu-fit.org, …

We know this because they mix!

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric reactor solar

$s_{ij} \equiv \sin\theta_{ij}$

Mass differences

$$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

Mixing angles

$$\theta_{23} \sim 45^\circ$$

$$\theta_{13} \sim 9^\circ$$

$$\theta_{12} \sim 33^\circ$$

Absolute masses and the mass hierarchy are not known

Mass differences

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$$|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

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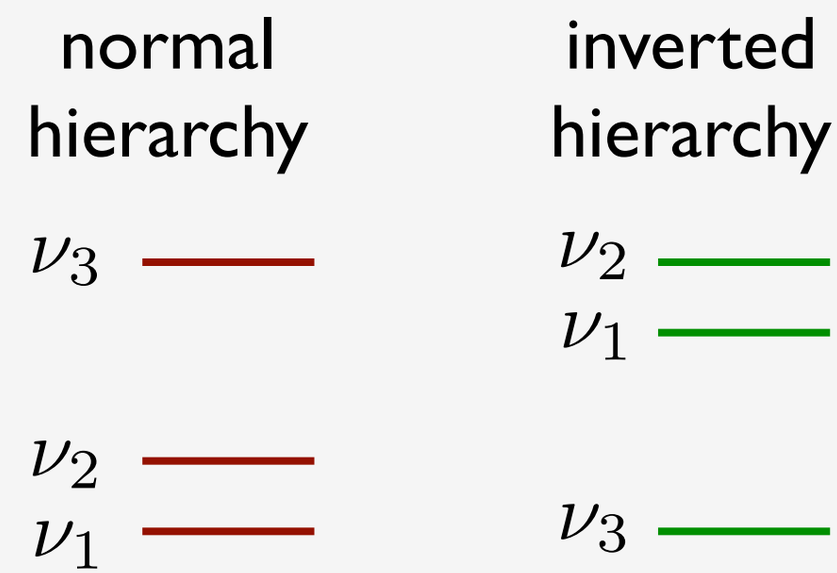


Is there a massless neutrino?

Origin of the masses is not known

Massless in the SM — no right-handed neutrinos

SM singlet fermions

Let's add some!

1- Dirac mass	2- Majorana mass
$y_\nu \bar{\ell}\, \tilde{\phi}\, \nu_R \to m_\nu \overline{\nu_L} \nu_R$	$y_\nu \bar{\ell}\, \tilde{\phi}\, \nu_R + \frac{1}{2} M_R \nu_R^c \nu_R$
$y_\nu \sim 10^{-12}$	$m_\nu \sim y_\nu^{\mathrm{T}} M_R^{-1} y_\nu\, v^2$
	$M_R \sim \mathcal{O}(10^{14}\ \mathrm{GeV})$
Conserved lepton number	Seesaw mechanism

Origin of the masses is not known

3- Dirac + Majorana mass

Add 2 SM singlets: $N, \; N'$

$L = 1 \quad L = -1$

$$\psi = \begin{pmatrix} N \\ N'^{\dagger} \end{pmatrix}$$: pseudo-Dirac fermion

Let's say lepton number is (approximately) conserved

$$Y_N \, \bar{\ell} \, \tilde{\phi} \, N + \epsilon Y_{N'} \, \bar{\ell} \, \tilde{\phi} \, N' + M_D \, \bar{N} N'^c + \mu \, \bar{N} N^c + \mu' \, \bar{N}' N'^c$$

lepton number violation

Inverse Seesaw Mechanism

Origin of the masses is not known

3- Dirac + Majorana mass

Neutrino mass matrix:

$$\mathbb{M} = \begin{pmatrix} \mathbf{0}_{3\times 3} & Y_N\, v & \epsilon Y_{N'}\, v \\ Y_N^{\mathrm{T}}\, v & \mu & M_D \\ \epsilon Y_{N'}^{\mathrm{T}}\, v & M_D & \mu' \end{pmatrix}$$

in the basis:

$$(\nu_i,\ N,\ N')$$

Light neutrino masses:

$$m_\nu \sim \frac{\epsilon Y_N^{\mathrm{T}} Y_{N'}\, v^2}{M_D} + \mathcal{O}\left(\frac{Y_N^{\mathrm{T}} \mu Y_N\, v^2}{M_D^2}\right)$$

For $Y_N \sim Y_{N'} \sim 1,$
$M_D \sim \mathrm{TeV}$

need: $\epsilon \sim 10^{-12}$

Why so small?

What we need

(Usually) SM singlet fermions as right-handed neutrinos

High mass scale

and/or

<u>Small</u> lepton-number violating parameters

SUSY has (a) SM singlet fermion!

Bino is a SM singlet fermion!

Why isn't the MSSM bino a *RH neutrino*?

3 main reasons:

- Cannot write supersymmetric terms
- One bino is not enough for at least 2 massive neutrinos
- Lepton number must be violated

Neutrino masses in RPV SUSY

Need R-parity violation to have lepton number violation

Can use bilinear RPV: $\mu_i H_u L_i$

H_u : up-type Higgs superfield

L_i : lepton doublet superfield

Higgsino - neutrino mixing → 1 neutrino gets a mass

Other neutrinos get mass at loop level

Might need a combination of bilinear and trilinear RPV or extra RH neutrinos

Need to explain why RPV?

Hall, Randall, *Nuc.Phys.B-352.2 1991*
Kribs, Poppitz, Weiner, arXiv: *0712.2039*
Frugiuele, Gregoire, arXiv:1107.4634

SI, McKeen, Nelson, arXiv: *1407.8193*
SI, John March-Russell, *arXiv:1604.00009*
Pilar Coloma, SI, arXiv:1606.06372

My favorite model for everything!

$U(1)_R$ -symmetric SUSY

Dirac gauginos are awesome
Solves SUSY CP
and flavor problem, …

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

SM particles are not charged under $U(1)_R$

Sfermions have +1 R-charge

Add lepton number

Superfields	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$U(1)_R$	$U(1)_{R-L}$
L_i	1	2	-1/2	1	0
E_i^c	1	1	1	1	2
H_u	1	2	1/2	0	0
$W_{\tilde{B}}^{\alpha}$	1	1	0	1	1
$\Phi_S = \phi_S + \theta\, S$	1	1	0	0	0
$W'_\alpha = \theta\, D$	1	1	0	1	1

Bino has +1 R-charge

Singlino (S) has -1 R-charge

2 SM singlet fermions!

Dirac bino mass

No Majorana gaugino masses due to the *R*-charges

Dirac masses come from the spurion D-term

$$\int d^2\theta\, c\frac{W'_\alpha}{\Lambda_M}W^\alpha_{\tilde{B}}\Phi_S \to \boxed{\frac{cD}{\Lambda_M}}\tilde{B}S$$

Λ_M : messenger scale

Dirac bino mass: M_D

$$\tilde{B} \equiv (1,1,0)_{+1}$$
$$S \equiv (1,1,0)_{-1}$$

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

$U(1)_{R\text{-}L}$ must be broken

…because (anomaly mediation)

(Small) Majorana mass for the bino

$$m_{\tilde{B}} = \frac{\beta(g_Y)}{g_Y} m_{3/2}$$

$m_{3/2}$: gravitino mass

Can also have a singlino Majorana mass

$$m_{\tilde{B}} \sim m_S \ll M_D$$

$U(1)_{R\text{-}L}$ is only slightly broken

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

: pseudo-Dirac bino

No bilinear or trilinear RPV operators

$\mu_i H_u L_i$ is not allowed due to charge assignments

$\lambda_{ijk}\, L_i\, L_j\, E_k^c$ allowed but we ignore to make a point

Then how do we generate the neutrino masses?

Bino as a RH neutrino

Not UV-complete

Consider the dim-6 operator:

$$\frac{f_i}{\Lambda_M^2}\int d^2\theta\, W'_\alpha W^\alpha_{\tilde{B}} H_u L_i$$

$U(1)_{R\text{-}L}$ conserving

Relevant neutrino mass operator:

$$\rightarrow \quad \frac{f_i' M_D}{\Lambda_M}\ell_i\, h_u\, \tilde{B}$$

$$M_D \sim \frac{D}{\Lambda_M}$$

Bino acts as a RH neutrino!

Singlino as a RH neutrino

Not UV-complete

How about the other singlet - the singlino?

Consider the dim-5 operator:

$$\frac{d_i}{\Lambda_M}\int d^2\theta d^2\bar{\theta}\,\phi^\dagger\,\Phi_S H_u L_i \longrightarrow \frac{m_{3/2}}{\Lambda_M} d_i \int d^2\theta\,\Phi_S H_u L_i$$

$$\phi = 1 + \theta^2 m_{3/2}$$

conformal compensator

$U(1)_{R\text{-}L}$ violating

Relevant neutrino mass operator $\longrightarrow$ $\frac{d_i m_{3/2}}{\Lambda_M}\ell_i\, h_u S$

Singlino is the other RH neutrino!

All the mass terms

$$-\mathcal{L} \supset \frac{f_i M_D}{\Lambda_M} \ell_i \, h_u \tilde{B} + \frac{d_i m_{3/2}}{\Lambda_M} \ell_i \, h_u S$$
$$+ M_D \tilde{B} S + m_{\tilde{B}} \tilde{B} \tilde{B} + m_S S S$$

$U(1)_{R\text{-}L}$ violating

$\propto m_{3/2}$

This is an Inverse SeeSaw scenario!

SIMPLICITY IS BLISS!

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$: We call this "biνo" (pronounced exactly like 'bino')

(like 'too' and 'two')

Biνo gives an Inverse SeeSaw structure

assume there is no bino-higgsino/weakino mixing

After EW symmetry breaking:

$$\mathbb{M} = \begin{pmatrix} \mathbf{0}_{3\times 3} & \mathbf{Y}v & \mathbf{G}\,v \\ \mathbf{Y}^{\mathrm{T}}v & m_{\tilde{B}} & M_D \\ \mathbf{G}^{\mathrm{T}}v & M_D & m_S \end{pmatrix}$$

in the basis

$$(\nu_i,\ \tilde{B},\ S)$$

Parameter scales:

$$\mathbf{Y} = \begin{pmatrix} Y_e \\ Y_\mu \\ Y_\tau \end{pmatrix} \equiv f_i \frac{M_D}{\Lambda_M} \qquad \mathbf{G} = \begin{pmatrix} G_e \\ G_\mu \\ G_\tau \end{pmatrix} \equiv d_i \frac{m_{3/2}}{\Lambda_M}$$

$$f_i,\ d_i \sim \mathcal{O}(1)$$

$$G_i \ll Y_i$$

and

$$m_{\tilde{B}},\ m_S \ll M_D$$

since $m_{3/2} \ll M_D$

keV TeV

Neutrino masses

Neutrino mixing matrix gives:

$$\mathbf{Y} \simeq \frac{M_D}{\Lambda_M} \begin{pmatrix} 0.35 \\ 0.85 \\ 0.39 \end{pmatrix}, \quad \mathbf{G} \simeq \frac{m_{3/2}}{\Lambda_M} \begin{pmatrix} 0.06 \\ 0.44 \\ 0.89 \end{pmatrix} \qquad + \mathcal{O}\left(\frac{m_S}{\Lambda_M}\right)$$

<u>1 massless</u>, 2 massive neutrinos:

$$m_2 = \frac{m_{3/2}\, v^2}{\Lambda_M^2}(1-\rho)$$

$$m_3 = \frac{m_{3/2}\, v^2}{\Lambda_M^2}(1+\rho)$$

No dependence on M_D

$M_D \gg v$ is assumed for practical reasons

$\rho \simeq 0.7$ from mass splittings

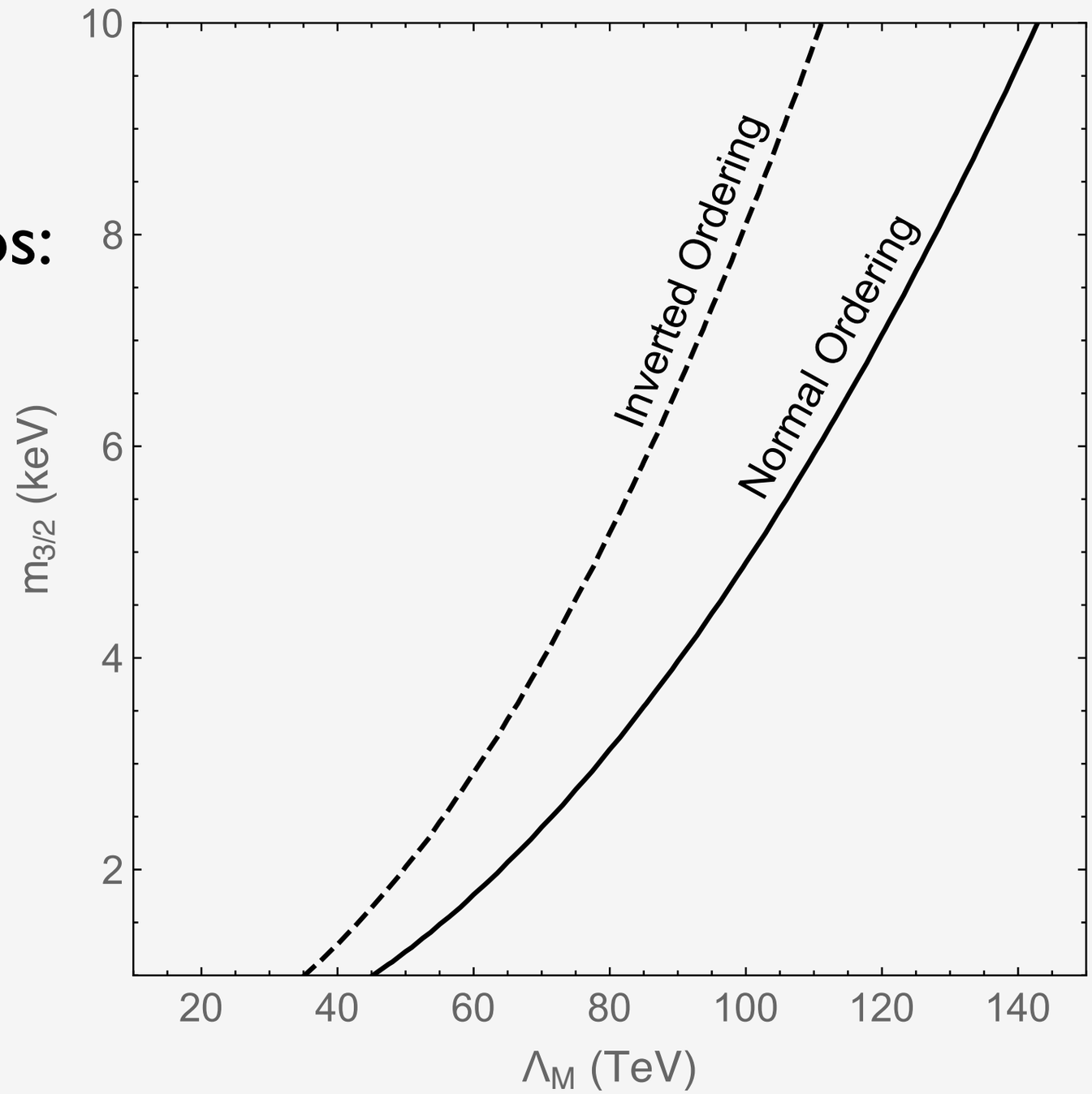
Neutrino masses

<u>1 massless</u>, 2 massive neutrinos:

$$m_2 = \frac{m_{3/2}\, v^2}{\Lambda_M^2}(1-\rho)$$

$$m_3 = \frac{m_{3/2}\, v^2}{\Lambda_M^2}(1+\rho)$$

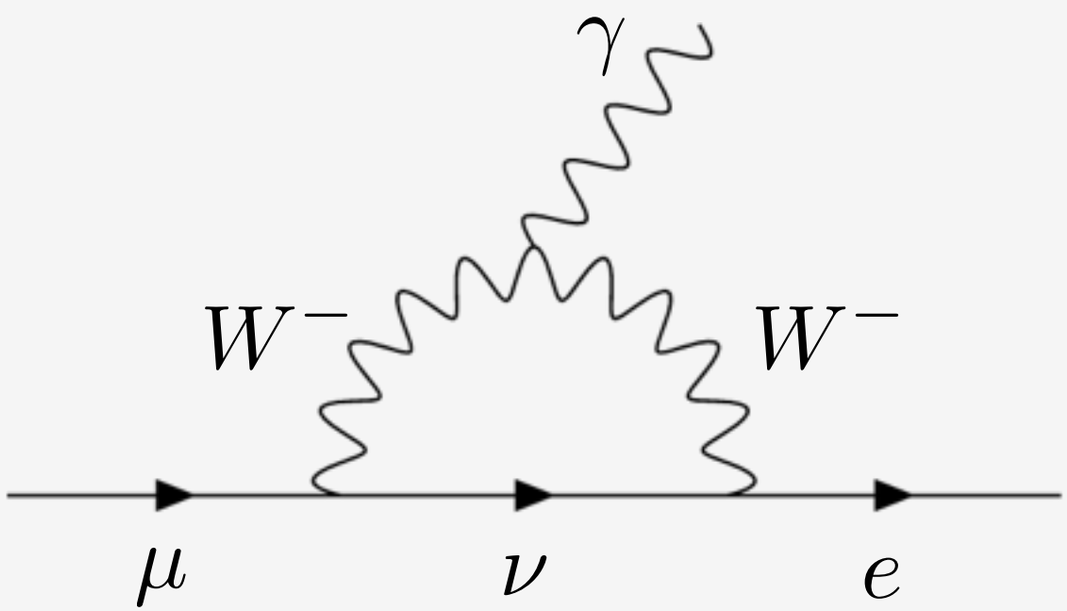
$\rho \simeq 0.7$ from mass splittings



Charged lepton flavor violation

We extend the lepton mixing sector → expect lepton flavor violation

- Lepton flavor violating charged lepton decays



most constraining

$$\boxed{\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}}$$

$$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

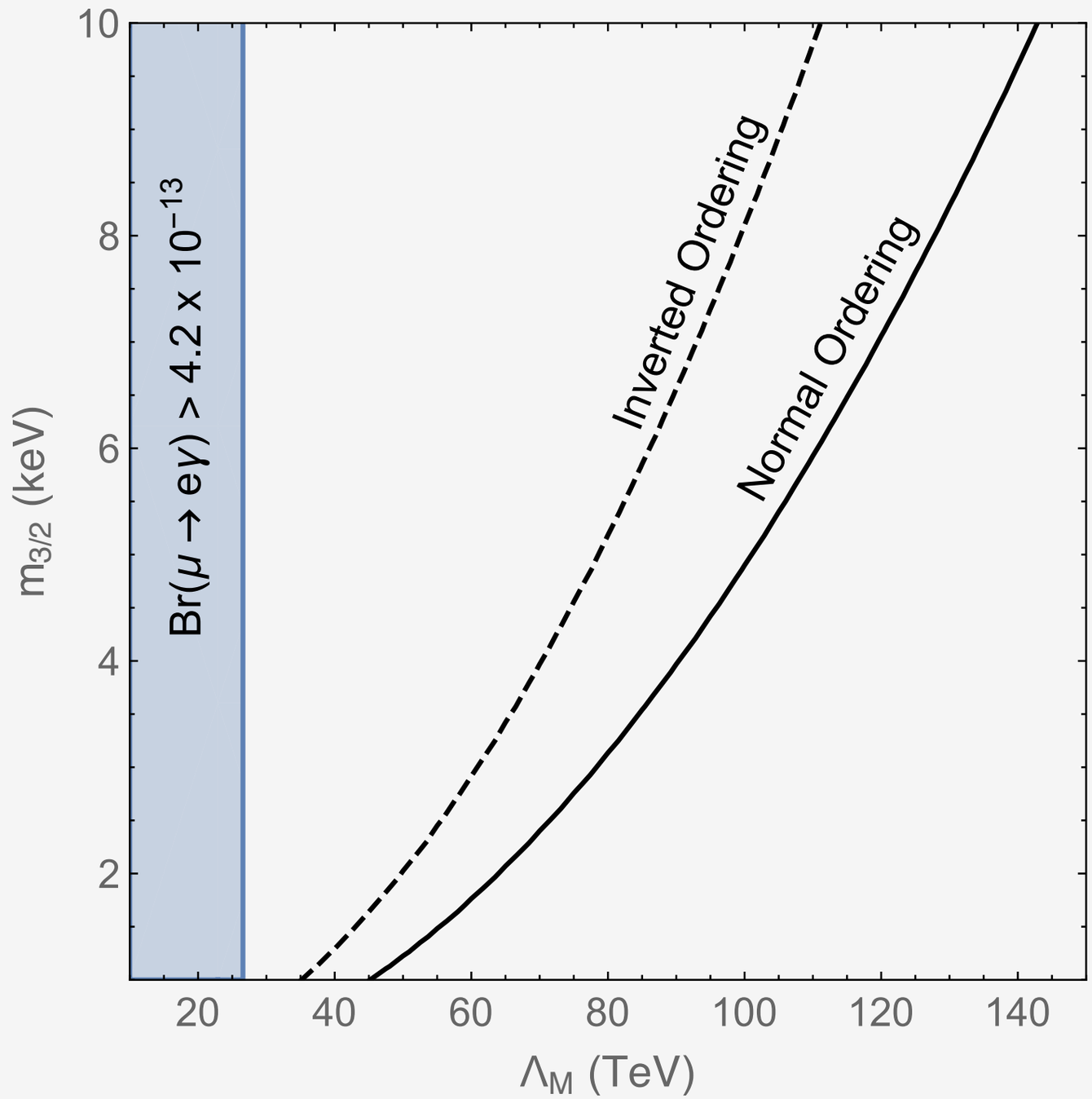
→ $$\frac{v^2}{2M_D^2} Y_e Y_\mu^* < 2.4 \times 10^{-5}$$

Charged lepton flavor violation

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

$$\frac{v^2}{2M_D^2} Y_e Y_\mu^* < 2.4 \times 10^{-5}$$

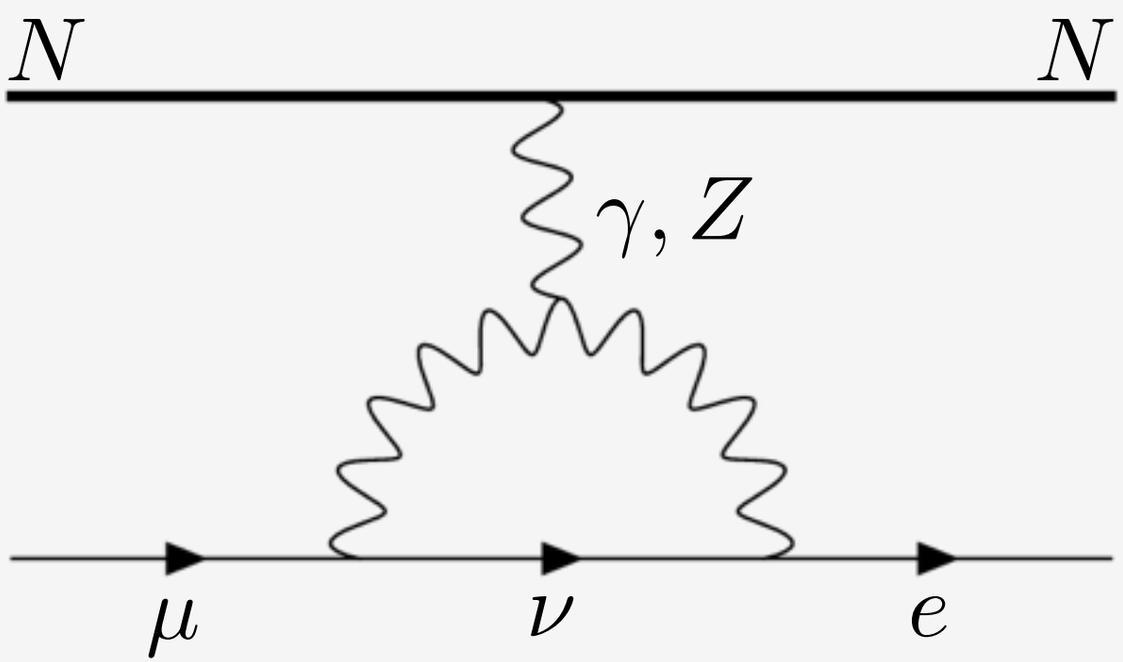
$$\Lambda_M \gtrsim 30 \text{ TeV}$$



Charged lepton flavor violation

We extend the lepton mixing sector → expect lepton flavor violation

- Lepton conversion in nuclei



Constraints are not yet competitive

BUT more experiments are coming!

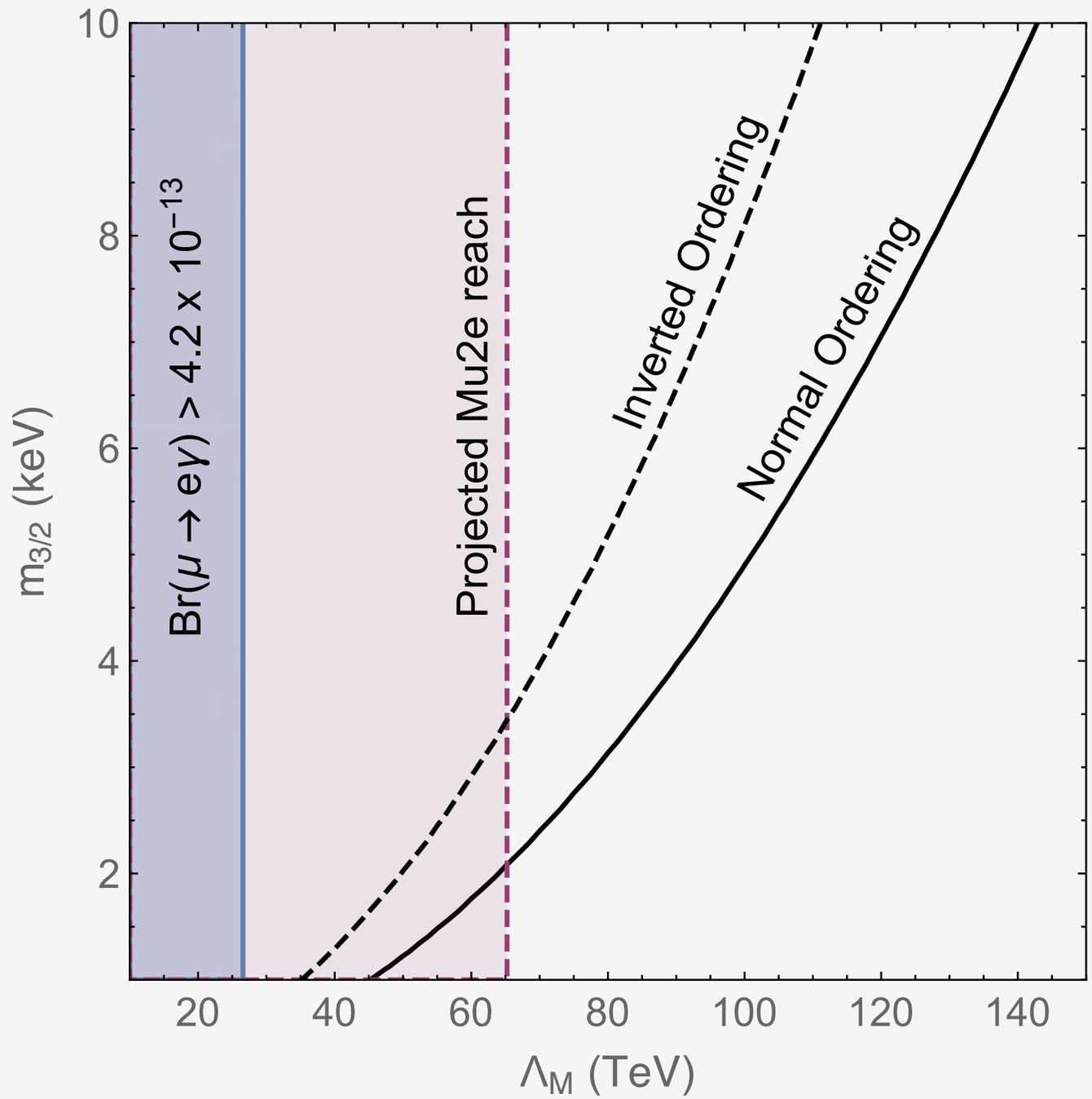
Mu2e, COMET, PRISM…

Parameter space

Neutrino masses
+
Lepton flavor
violation constraints

$$m_{3/2} \sim \mathcal{O}(\text{keV})$$

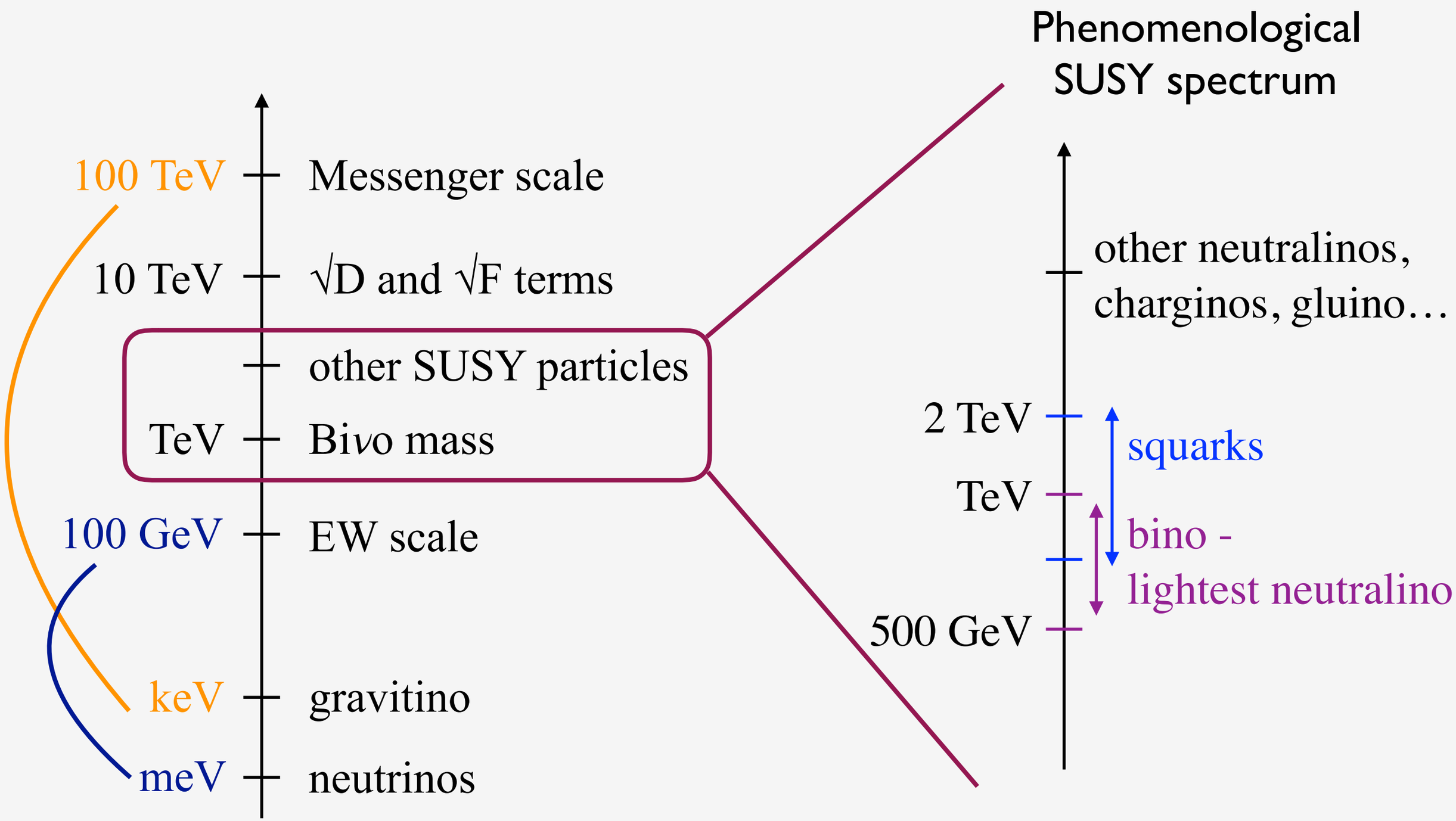
$$\Lambda_M \sim \mathcal{O}(100\ \text{TeV})$$



No constraints from neutrinoless double-beta decay

LHC Phenomenology of $B i\nu o$

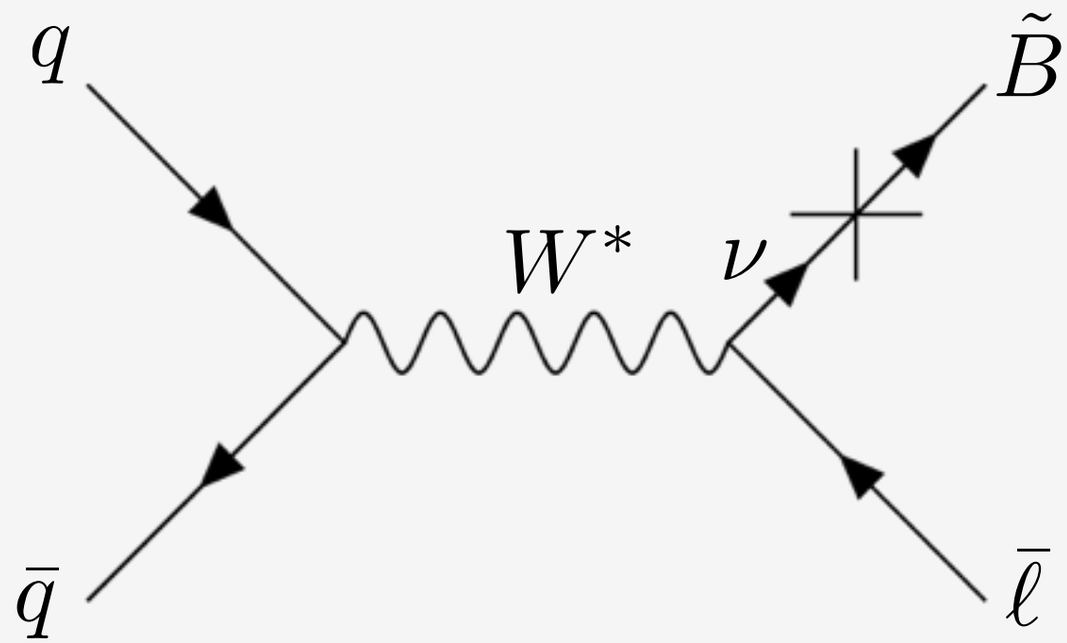
Hypothetical Spectrum



LHC pheno: production

$M_D = 1 \text{ TeV}$

RH neutrinos are usually produced via mixing with the SM neutrinos



Pay a mixing price on top of EW interactions: $\theta^2 \sim 10^{-5}$

Too small for observation

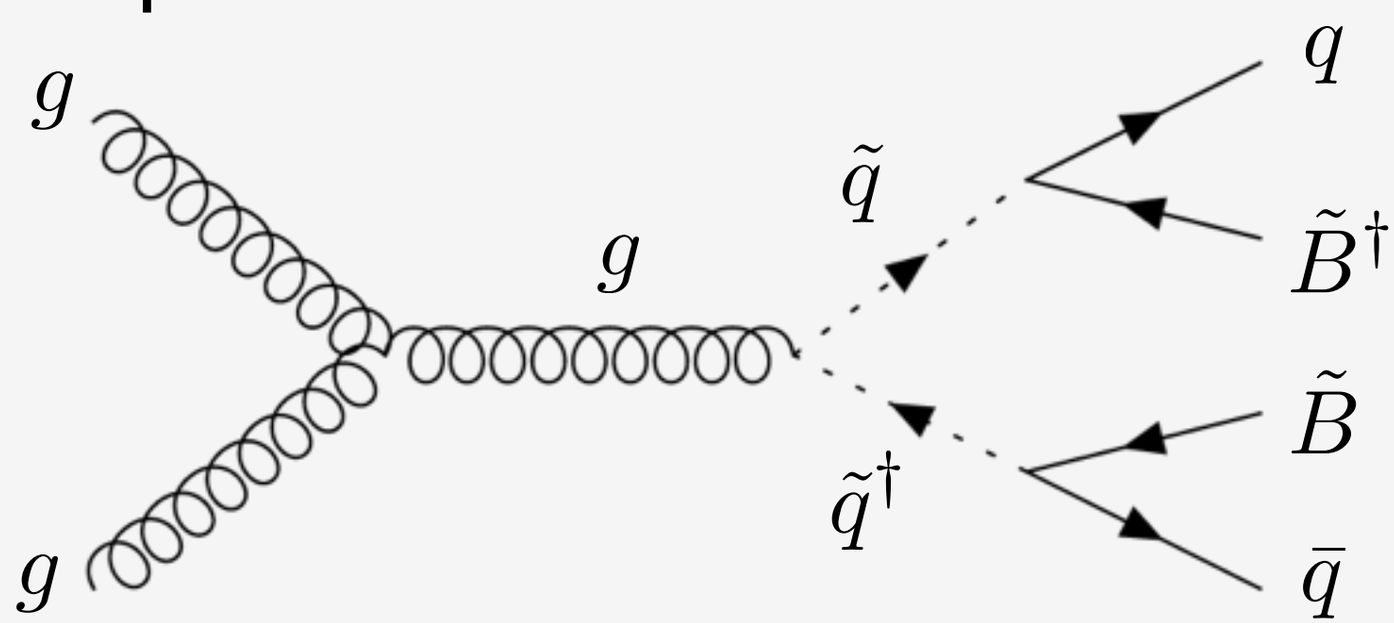
LHC pheno: production

$M_D = 1\ \mathrm{TeV}$

bino NLSP
degenerate squarks
lightest neutralino is a pure bino

There are better ways to produce a bino!

For example, this is a very good way:



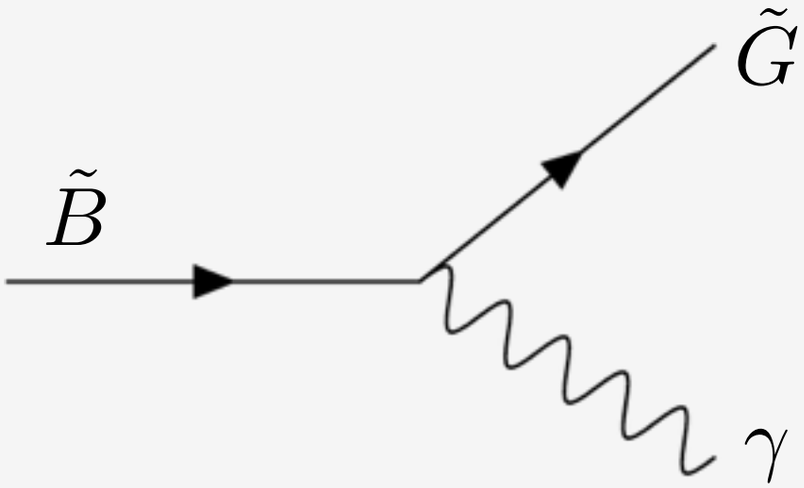
assuming $\mathcal{B}(\tilde{q} \to \tilde{B}q) \sim 1$ and $m_{\tilde{q}} = 1.5\ \mathrm{TeV}$

cross-section is ~3 fb @ 14 TeV

LHC pheno: decays

$M_D = 1 \text{ TeV}$

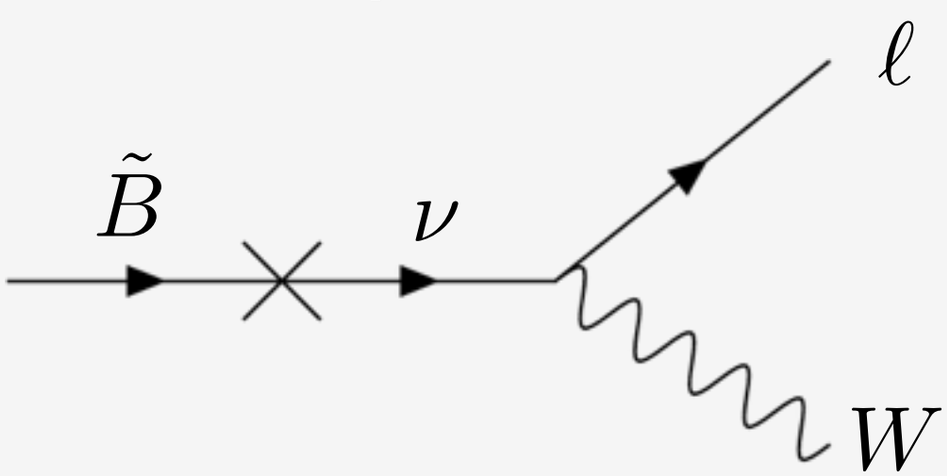
1) Decays to a gravitino and a photon



very small

$$\Gamma(\tilde{B} \to \tilde{G}\gamma) \sim \frac{M_D^5}{M_{Pl}^2 m_{3/2}^2} \sim 10^{-8} \text{ eV}$$

2-4) Decays to $W\ell,\ Z\nu,\ h\nu$



etc

total width:

$$\Gamma_{tot} \sim \frac{M_D^3}{\Lambda_M^2} \sim \mathcal{O}(500 \text{ MeV})$$

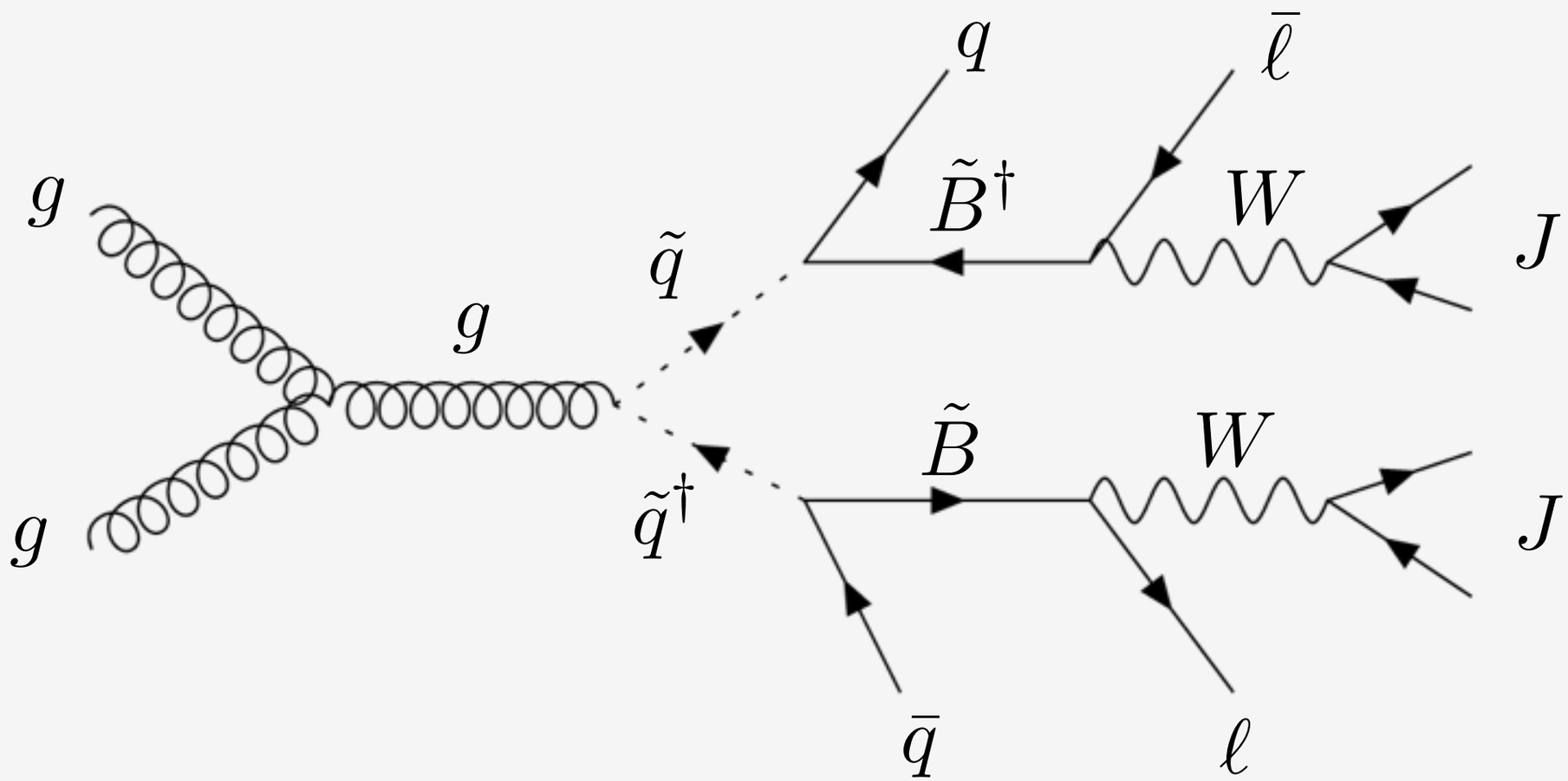
LHC pheno: signals

$M_D = 1\ \mathrm{TeV}$

Bino decays promptly, no displaced vertices

A combination of jets, leptons and missing energy is expected

e.g.



cross section is ~ 0.16 fb @ 14 TeV

LHC pheno: signals

$M_D = 1 \text{ TeV}$

Signals with more leptons and/or missing energy can be at a comparable rate, but probably harder to study

Leptoquark searches can be relevant:

$\sigma(\mu\mu jj) \lesssim 0.4 \text{ fb}$ for $m_{LQ} = 1 \text{ TeV}$

ATLAS, arXiv:1508.04735

In our benchmark scenario $\sigma(pp \to 2j \ \mu\mu \ 2J) \sim 0.04 \text{ fb}$

not yet constraining!

Lepton number violating signatures $\propto$ Majorana masses

small!

Summary

- Neutrinos need mass
- We (generally) need SM singlet fermions to do that
- The pseudo-Dirac bino of $U(1)_{R\text{-}L}$ symmetric SUSY is perfect for the job!
- Can be done with a keV gravitino and O(100 TeV) messenger scale
- Interesting LHC phenomenology — *Work in progress*
- UV completion? — Ideas are welcome!