Neutrino Masses and the LHC

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Carleton University

SI, D. Tuckler, *arXiv:* 2305.00017
C. M. Ayber, **SI**, *arXiv:* 2308.09686
J. Gehrlein, **SI**, *arXiv: 2103.01251*
P. Fox, J. Gehrlein, **SI**, *arXiv: 1901.09284*
P. Coloma, **SI**, *arXiv: 1606.06372*

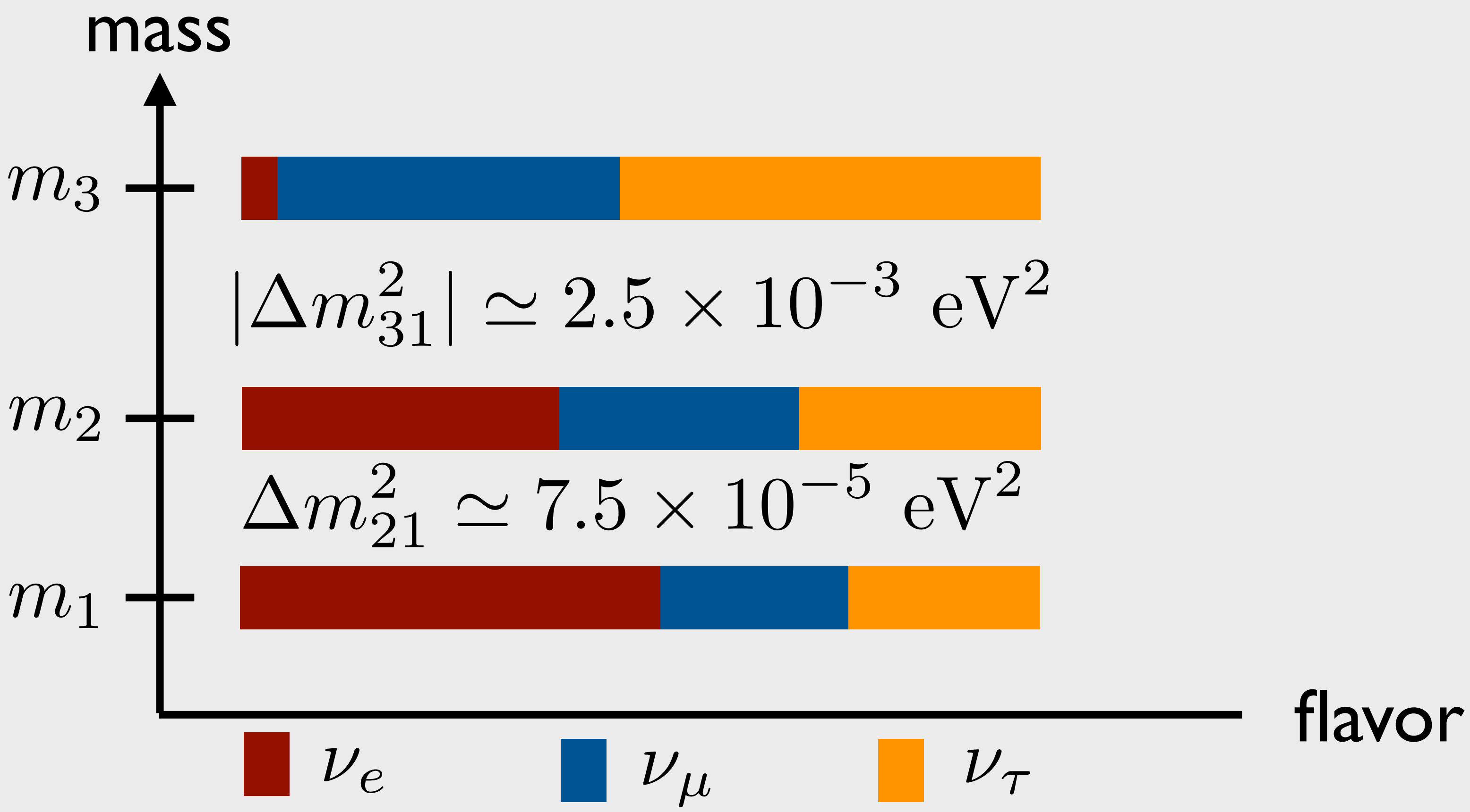
Carleton
UNIVERSITY
Canada's Capital University

Different neutrino flavors mix via the PMNS matrix

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

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

atmospheric reactor solar



PDG review, www.nu-fit.org, …

Mixing angles

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

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

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

δ = ???

recently measured?

What we need…

(Usually) SM singlet fermions as right-handed neutrinos

Don't couple to anything

High mass scale

Not produced at colliders

and/or

Small lepton-number violation

Small cross sections

Pseudo-Dirac bino could act like a right-handed neutrino!

P. Coloma, **SI**, *PRL 117 (2016) no.11, 111803, arXiv: 1606.06372*

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

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

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

Sfermions: +1 R-charge

Bino: +1 R-charge

Singlino (S): -1 R-charge

↓

2 SM singlet fermions!

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: $M_{\tilde{B}}$

$U(1)_R$ must be broken

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

Interesting higher dimensional operators

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

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

We can get an Inverse SeeSaw scenario!

Dirac mass

$$\mathscr{L} \supset \boxed{\frac{f_i M_{\tilde{B}}}{\Lambda_M} \bar{\ell} h_u \tilde{B} + M_{\tilde{B}} \tilde{B} S}$$

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

$$\boxed{+\frac{d_i m_{3/2}}{\Lambda_M} \bar{\ell} h_u S + m_{\tilde{B}} \tilde{B}\tilde{B} + m_S S S}$$

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

Majorana masses

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

:We call this “biνo” (pronounced exactly like ‘bino’)

(like ‘too’ and ‘two’)

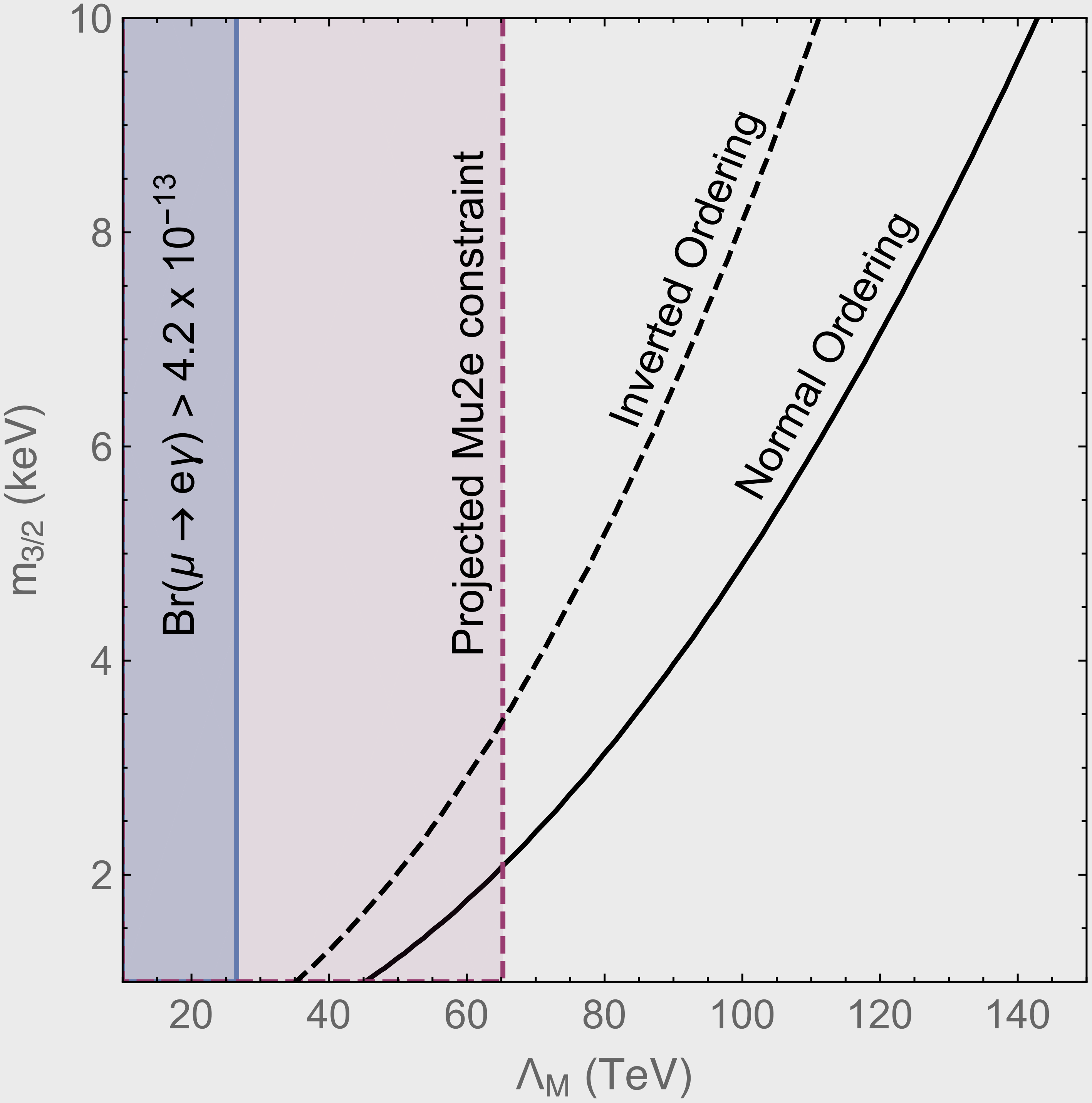
Light neutrino masses

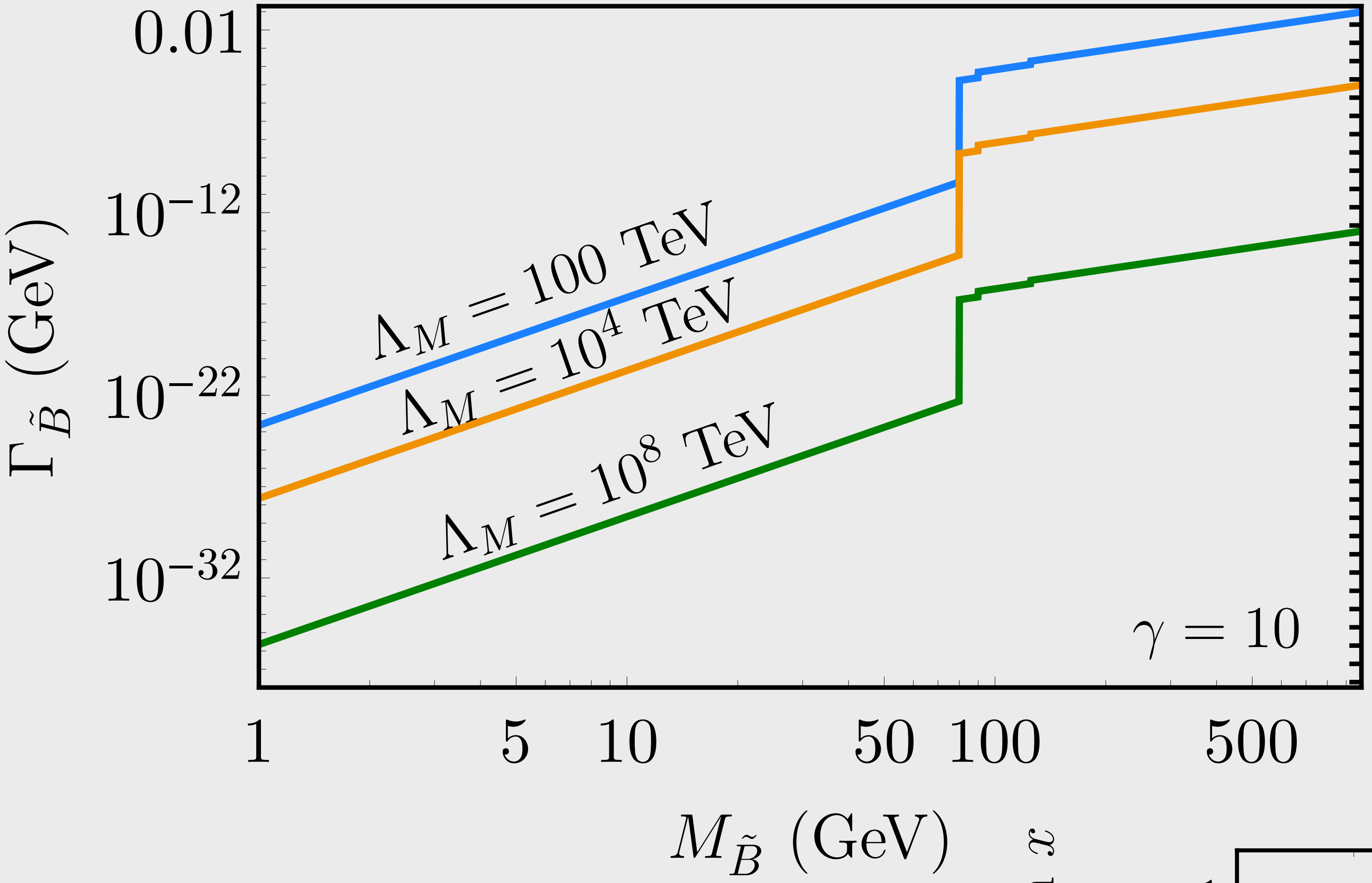
$$m_1 = 0$$

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

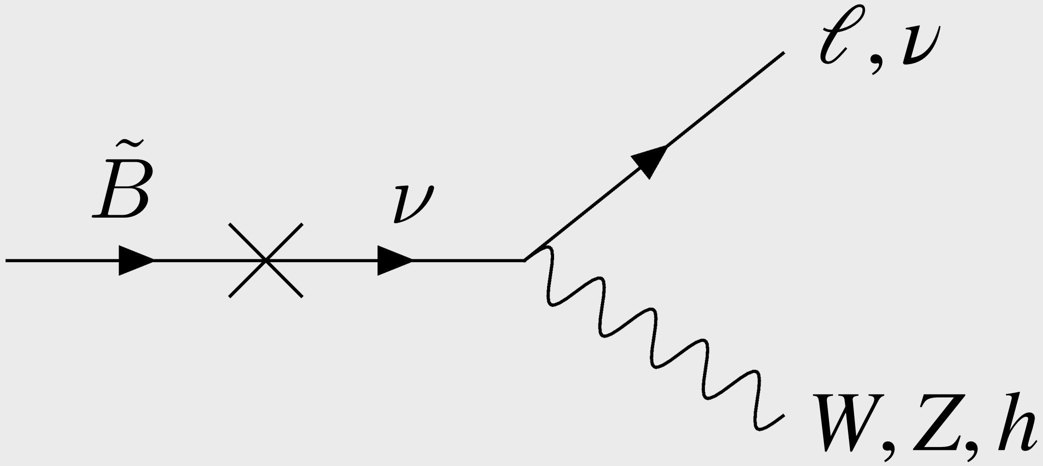
$$m_3 = \frac{m_{3/2} v^2}{\Lambda_M^2}(1+\rho)$$

$\rho \simeq 0.7$ from mass splittings





Decays to $W\ell, Z\nu, h\nu$



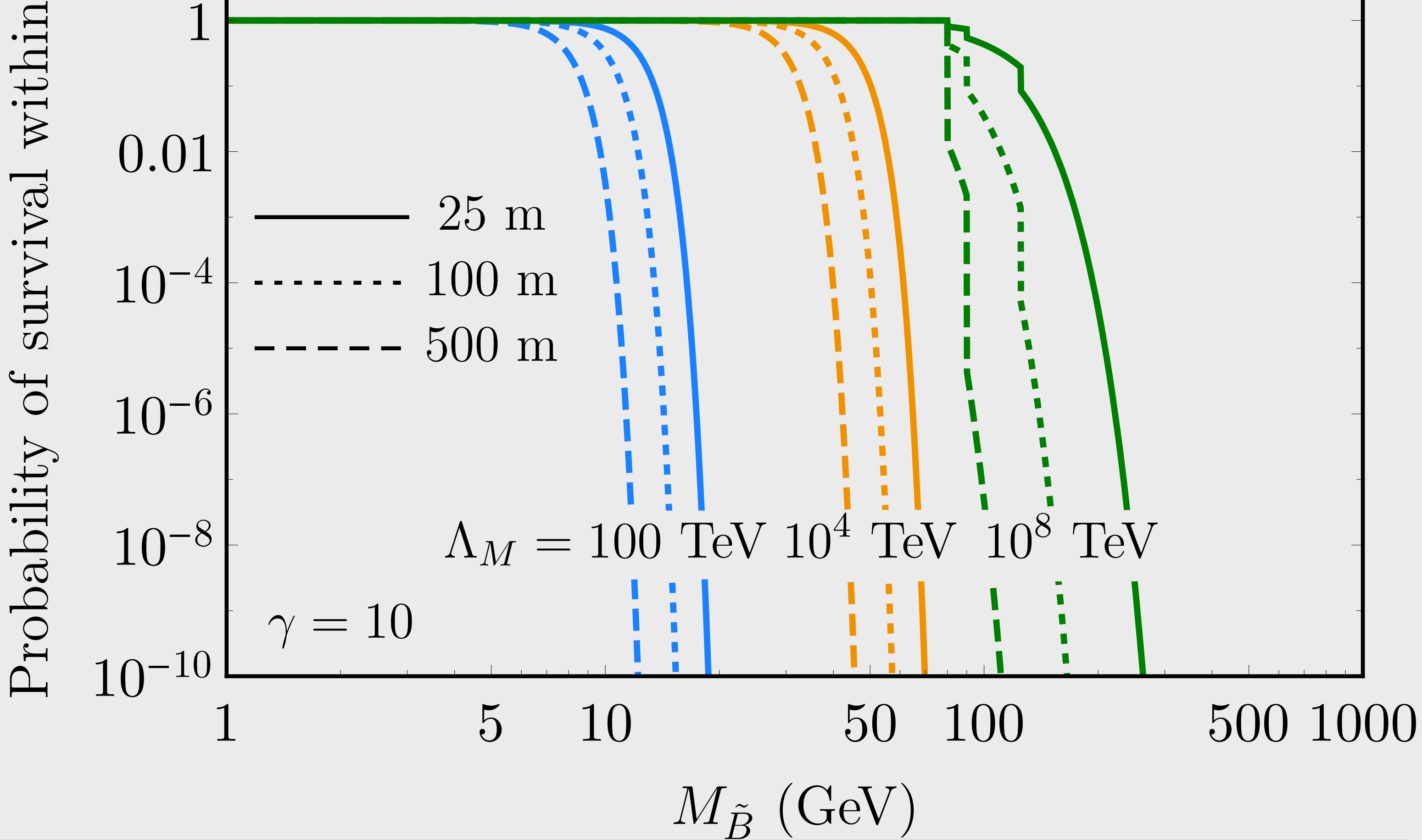
2 mass regions

$M_{\tilde{B}} < M_W$

$$\Gamma_{\tilde{B}} \simeq \frac{G_F^2 M_{\tilde{B}}^7}{192\pi^3 \Lambda_M^2}$$

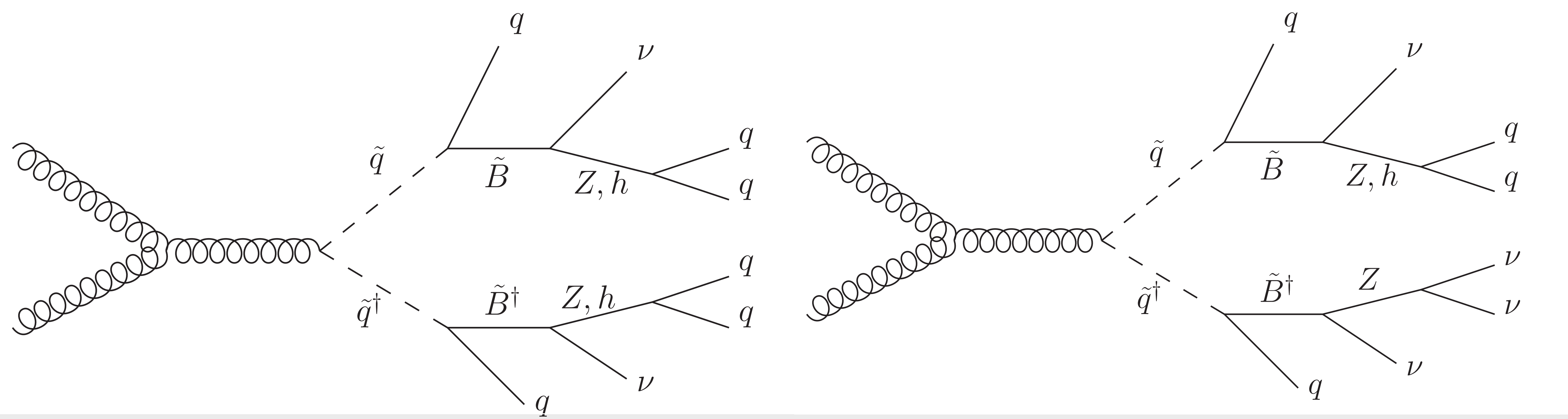
$M_{\tilde{B}} > M_h$

$$\Gamma_{\tilde{B}} \simeq \frac{M_{\tilde{B}}^3}{\Lambda_M^2}$$



Prompt bino signals at the LHC

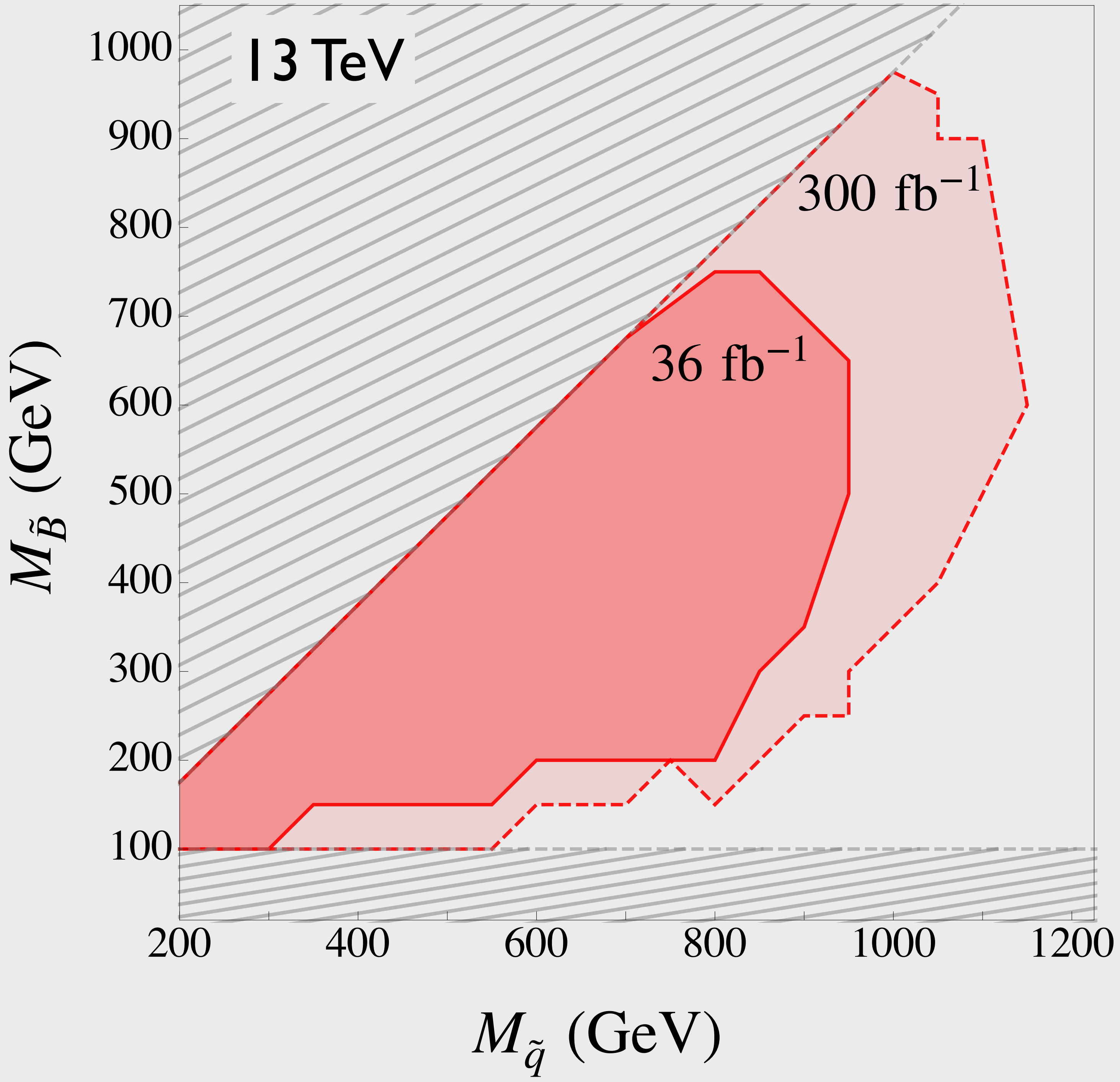
Largest branching fractions into jets+MET



~20% ~5%

Most constraining search: ATLAS-CONF-2017-022

P. Fox, J. Gehrlein, **SI**, arXiv:1901.09284



we recast
ATLAS-CONF-2017-022

24 signal regions:

2-6 jets

m$_{\text{eff}}$ based

$E_{\text{miss}} > 250$ GeV

$p_T > 50$ GeV

region of interest

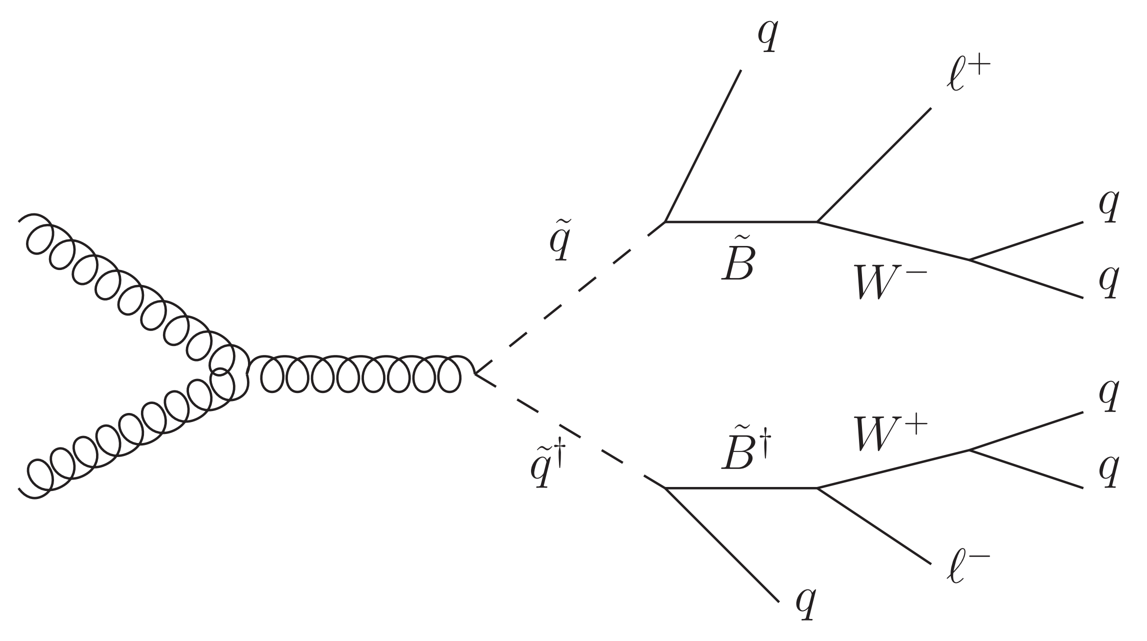
$M_{\tilde{B}} - M_{\tilde{q}} < 25$ GeV

$M_{\tilde{B}} > 100$ GeV

Smoking gun signal

Lepton couplings are determined by the neutrino sector

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



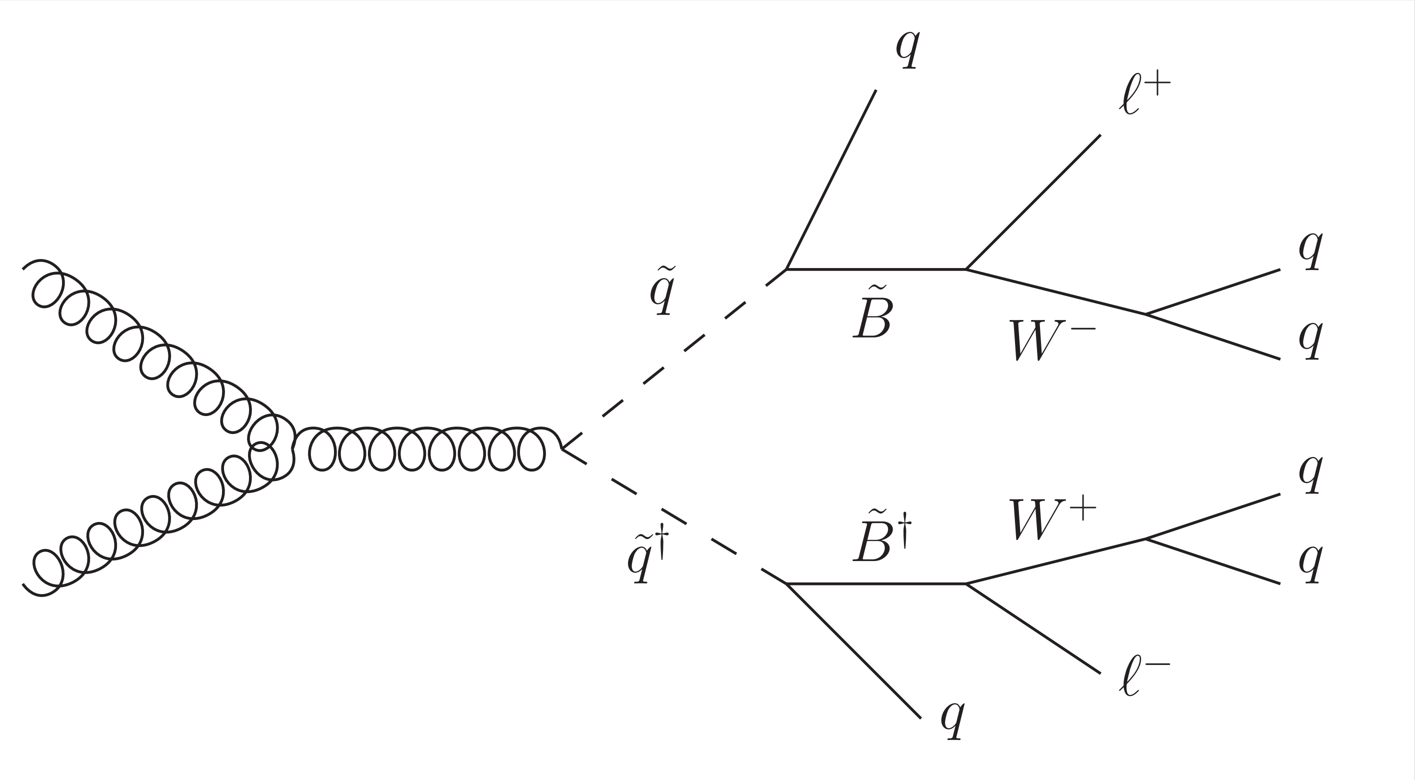
Neutrino oscillation data sets:

$$\mathbf{Y} \simeq \frac{M_{\tilde{B}}}{\Lambda_M} \begin{pmatrix} 0.35 \\ 0.85 \\ 0.39 \end{pmatrix}, \quad \mathbf{G} \simeq \frac{m_{3/2}}{\Lambda_M} \begin{pmatrix} 0.06 \\ 0.44 \\ 0.89 \end{pmatrix}$$

Smoking gun signal

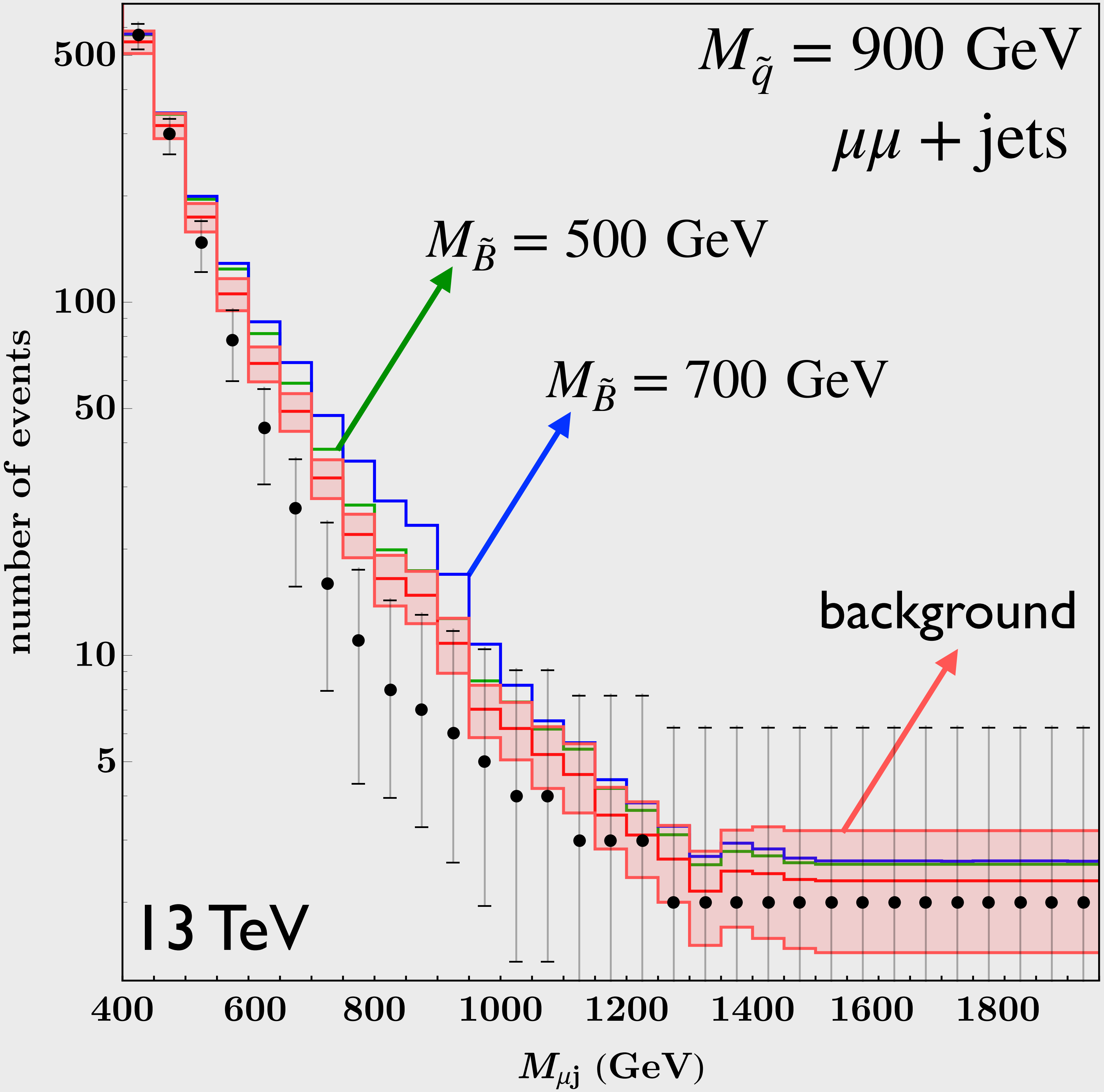
If "leptoquark" signal observed…

electron : muon : tau ratios are fully determined



1st and 2nd generation leptoquark searches will see the relative rates:

$ee : \mu\mu = 1 : 16$ and $e\nu : \mu\nu = 1 : 2$

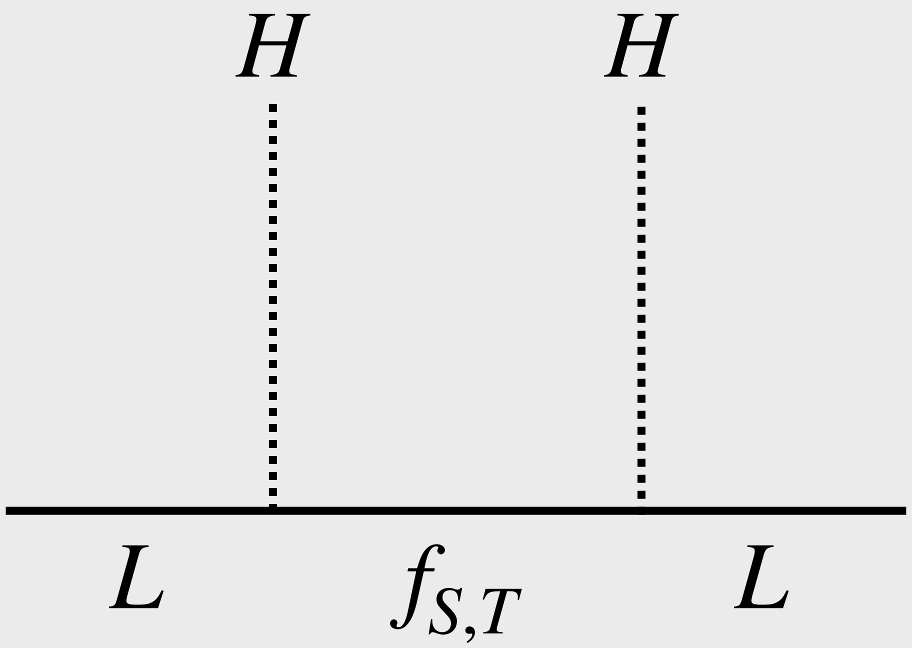


based on
2nd generation
leptoquark searches
CMS-EXO-2017-003

S/B too small

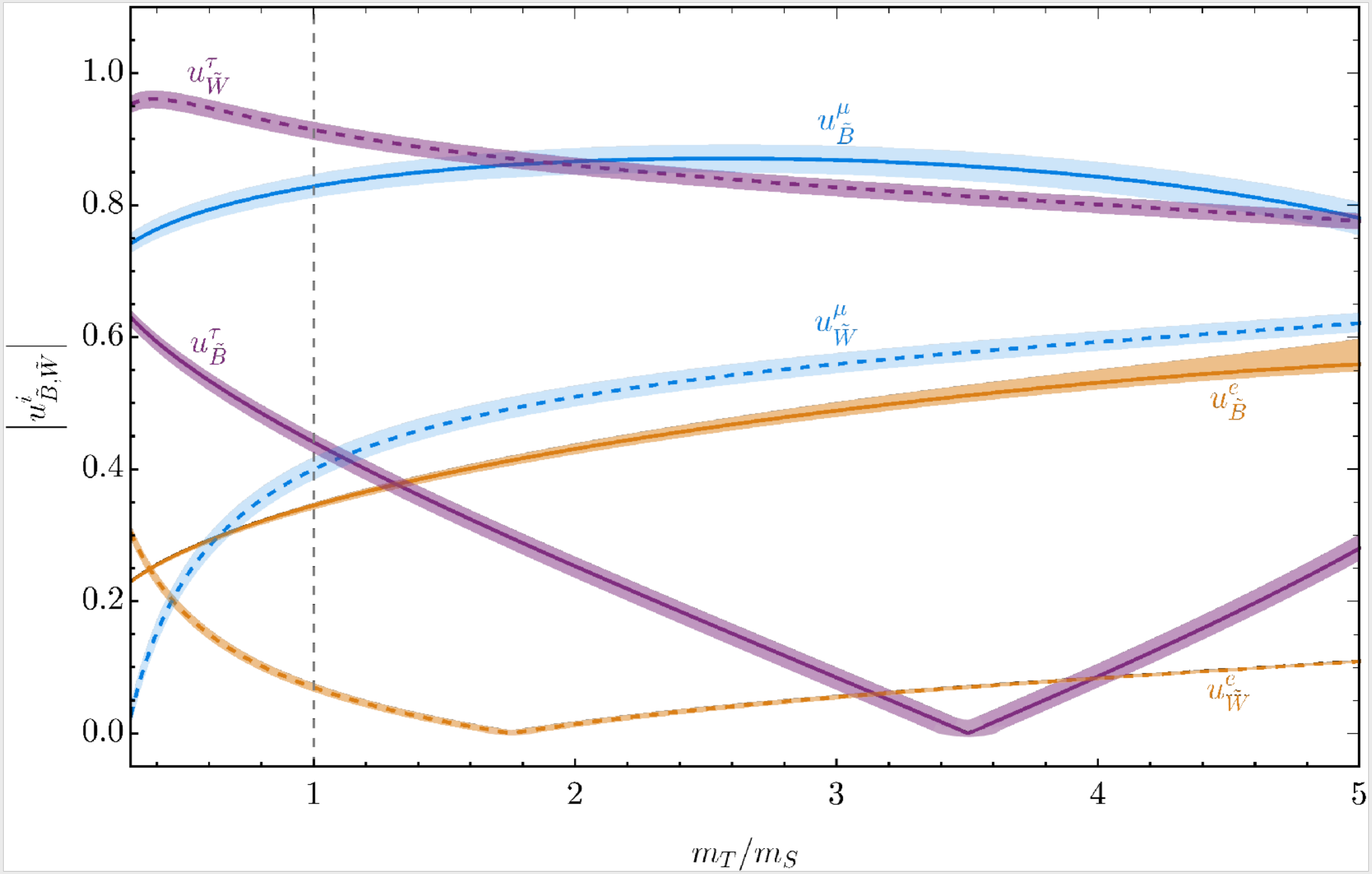
Not quite better
than jets+MET, but…

How about the wino?

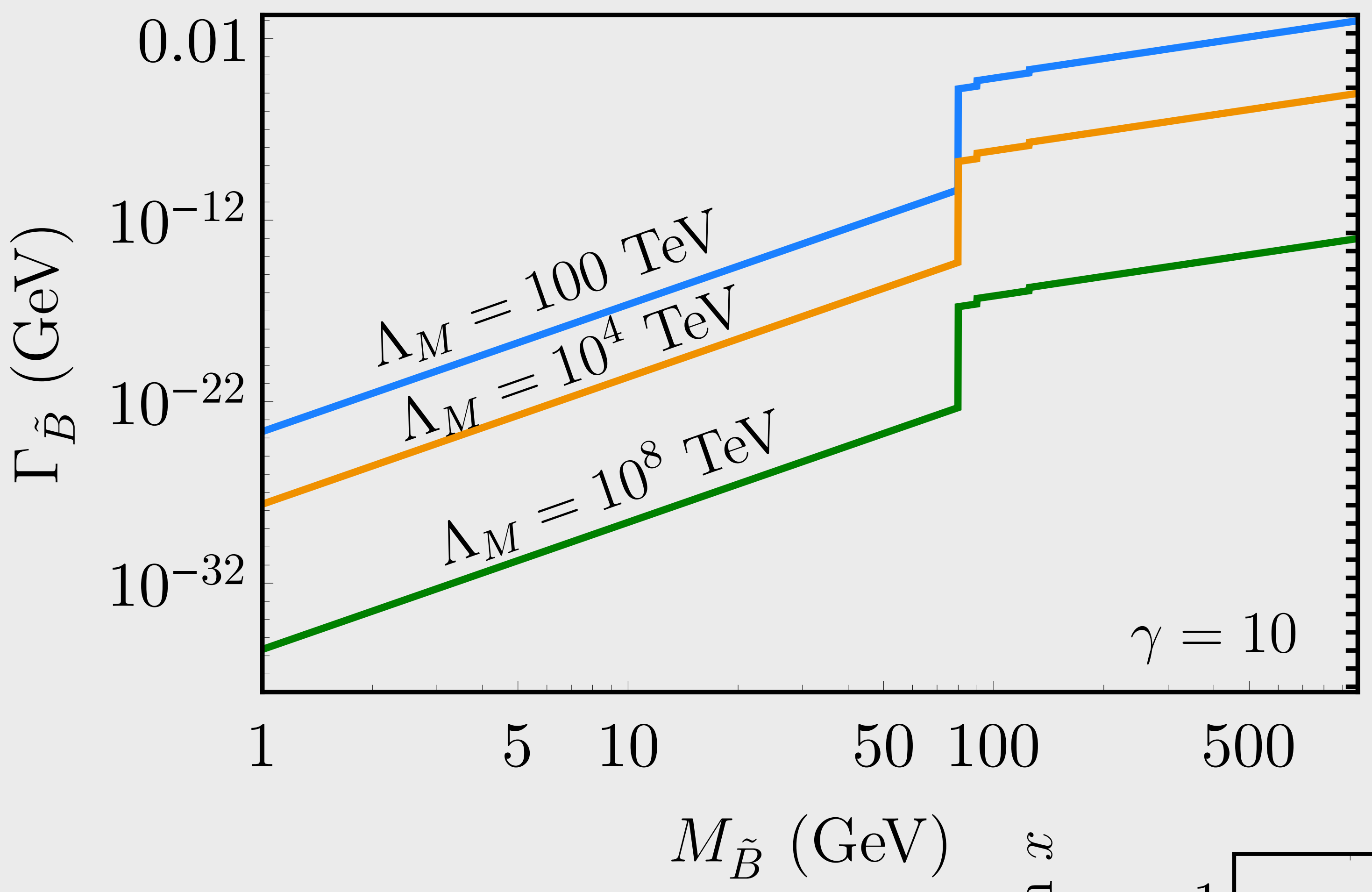


Type III seesaw: EW triplet fermions

Can the wino be involved in neutrino mass generation?



C. M. Ayber, **SI**, *arXiv:* 2308.09686



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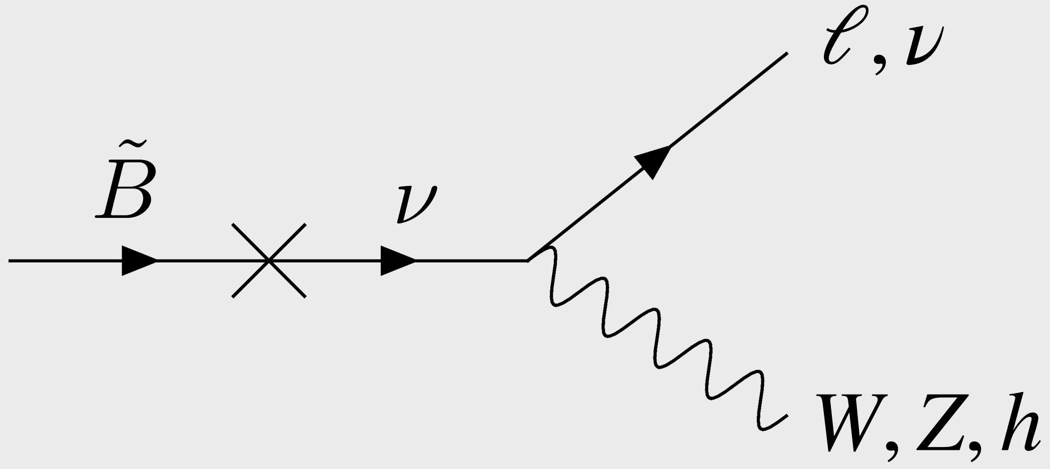

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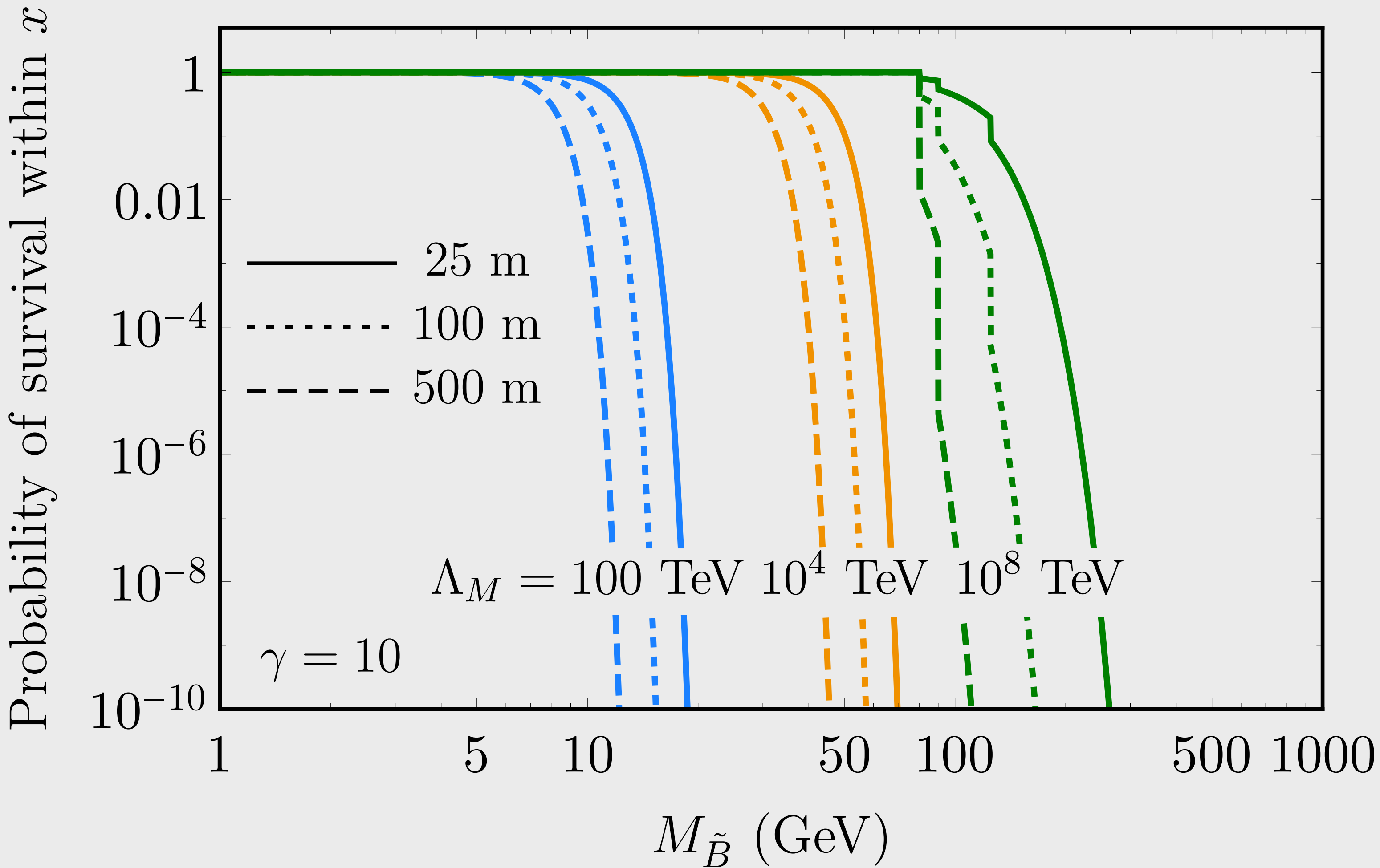
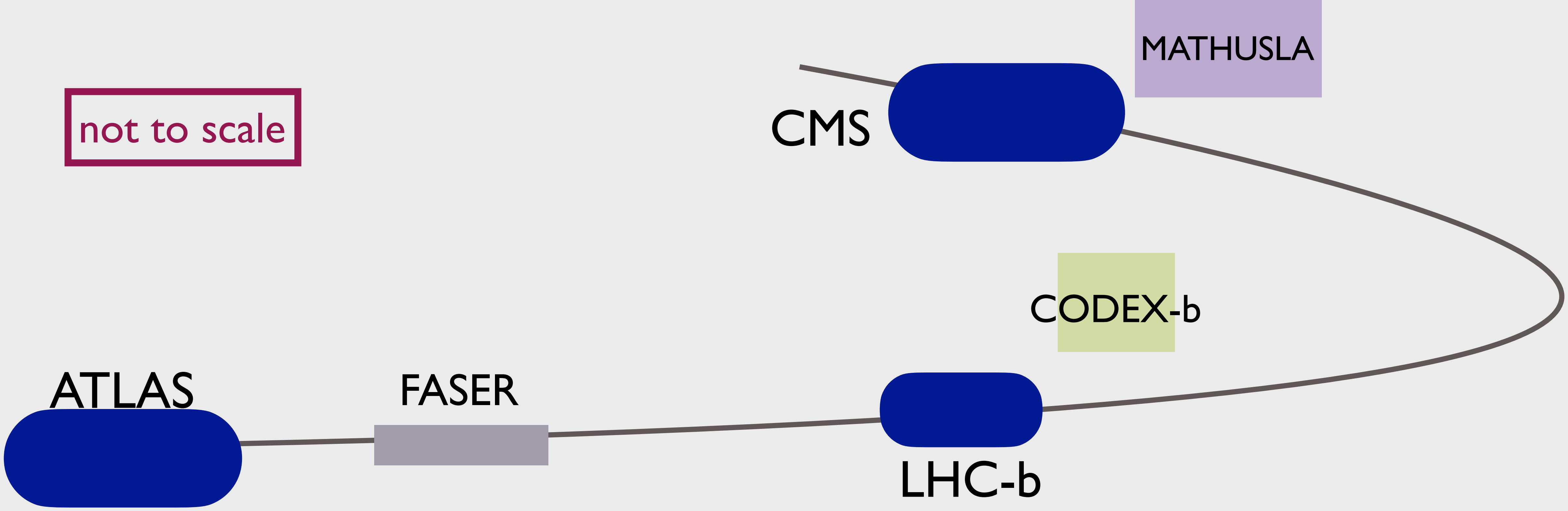


not to scale


CMS

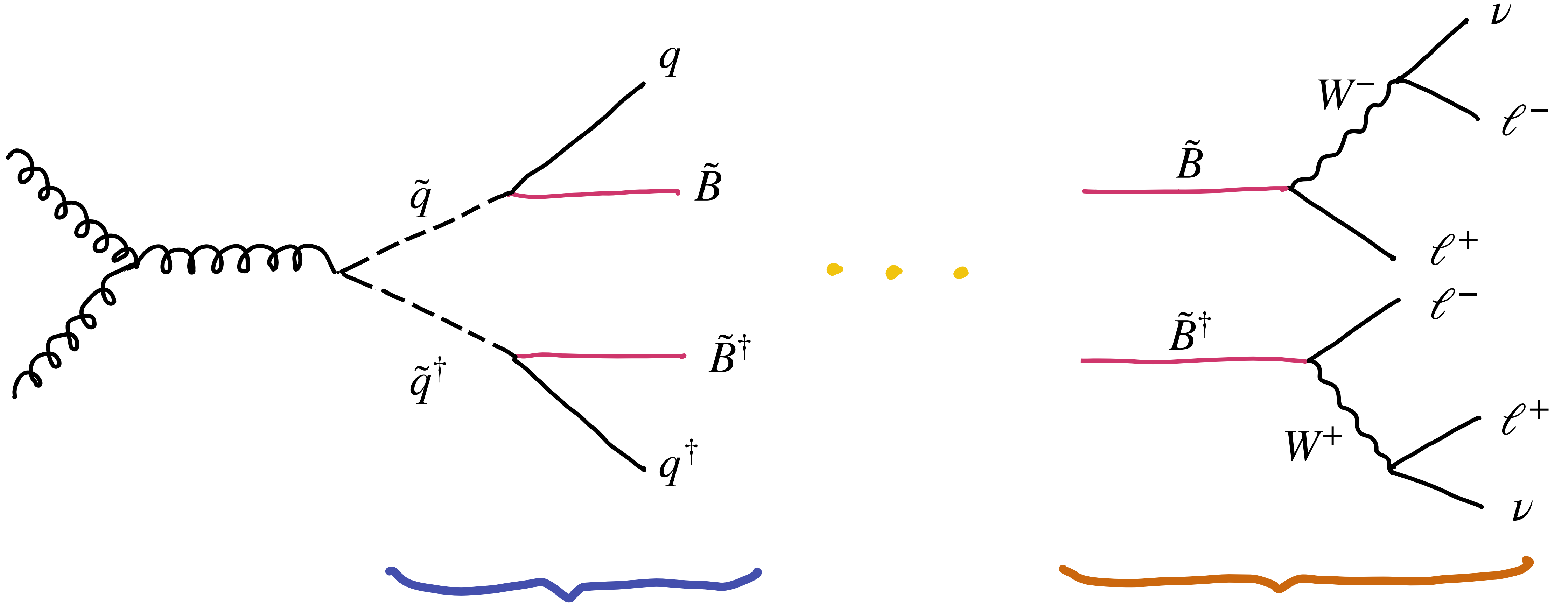
MATHUSLA

CODEX-b

ATLAS

FASER

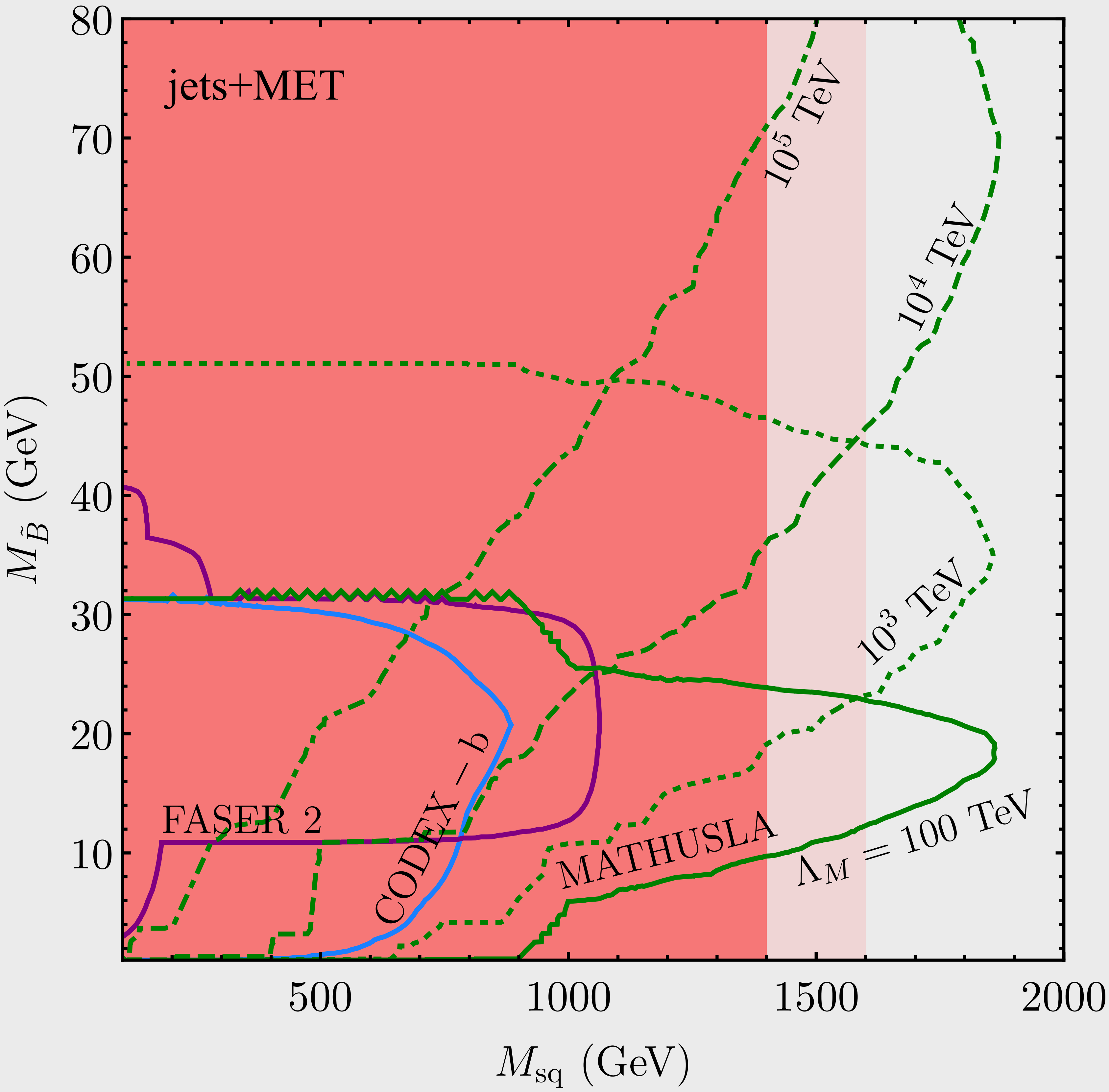
LHC-b



jets+MET final state
at ATLAS and CMS

decay to charged leptons at
MATHUSLA, CODEX-b or FASER

Light biνo region

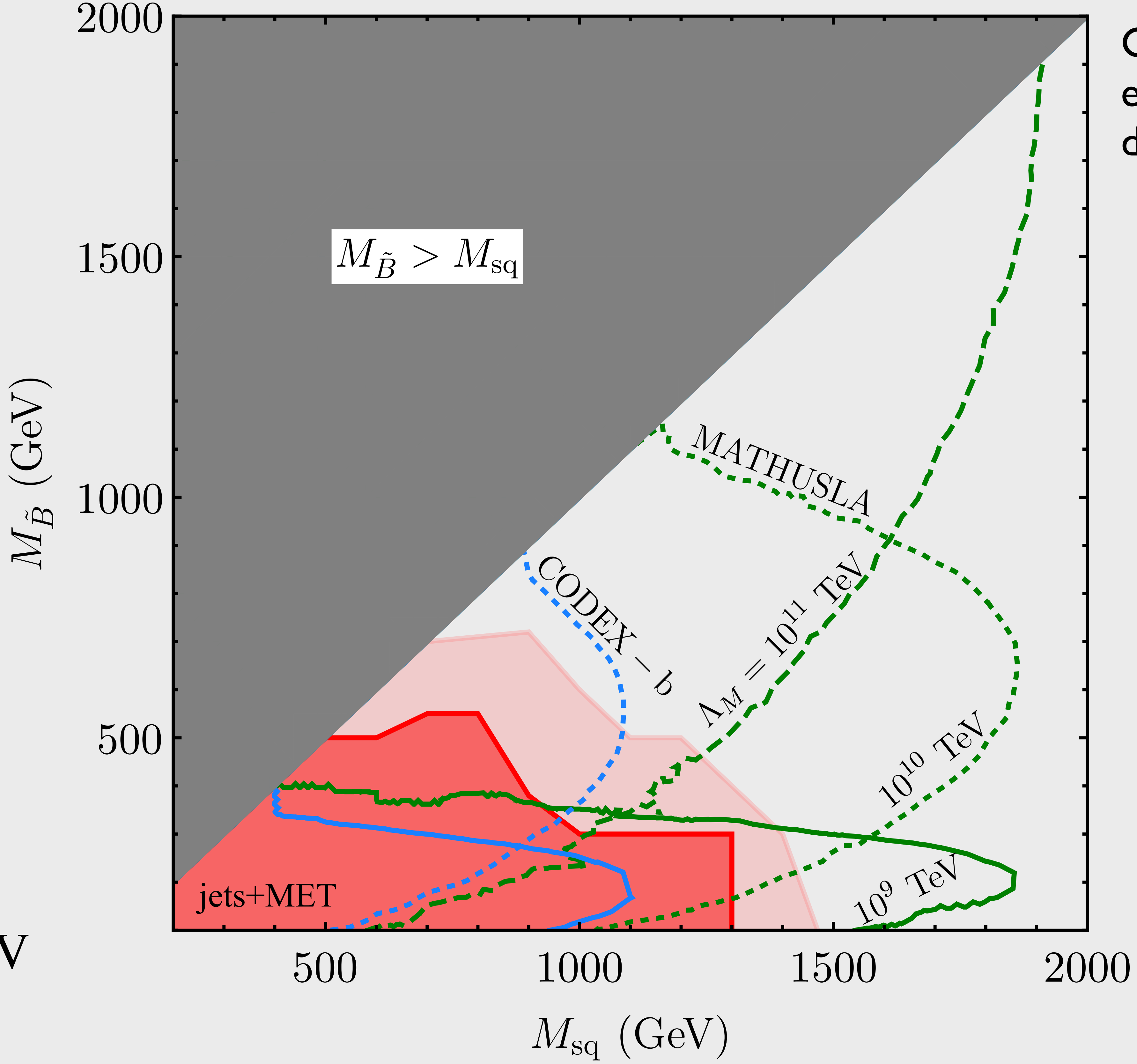


Contours of 5 events at LLP detectors

$$\sqrt{s} = 13 \text{ TeV}$$

$$\mathscr{L} = 3 \text{ ab}^{-1}$$

Heavy biνo region



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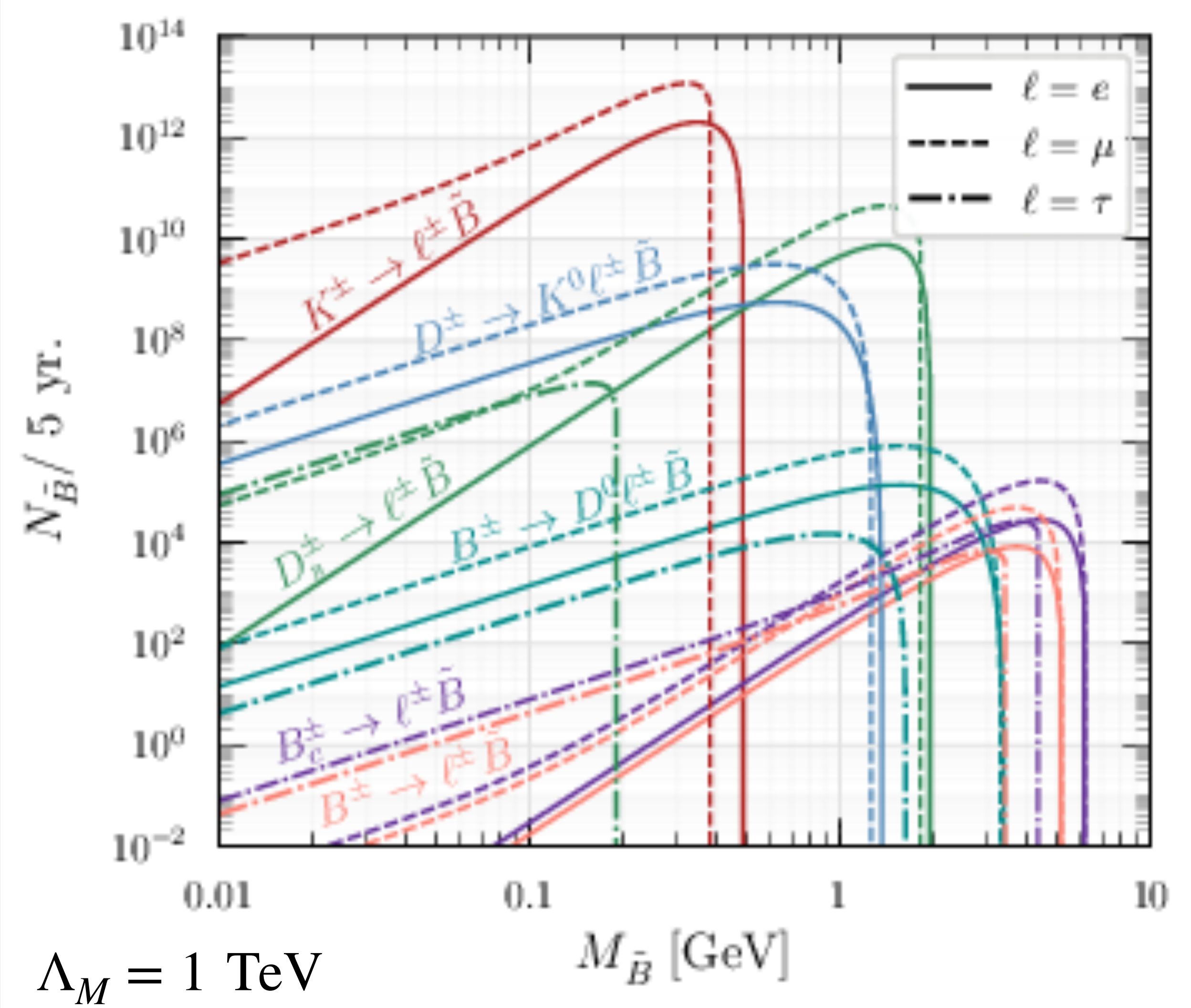
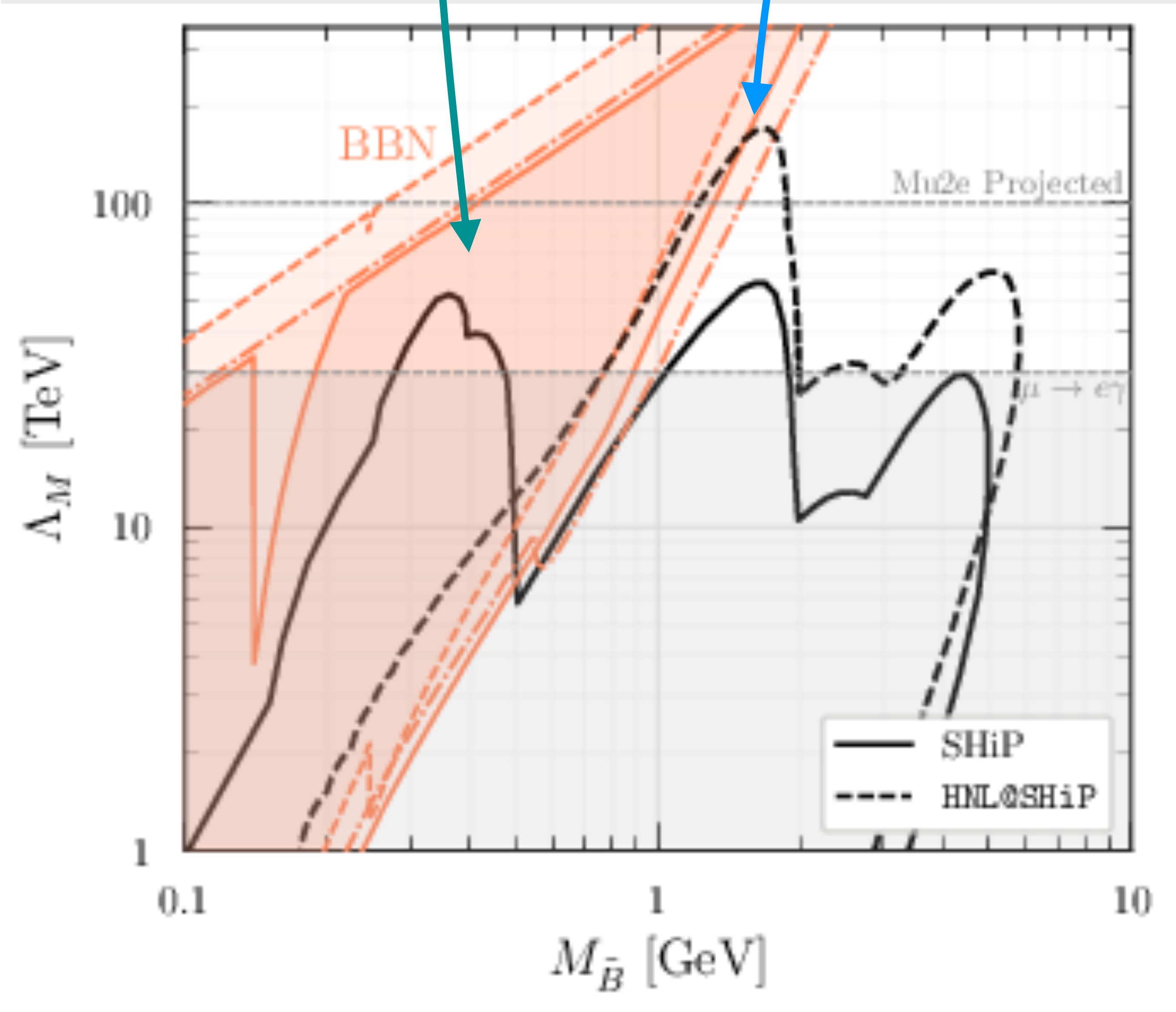
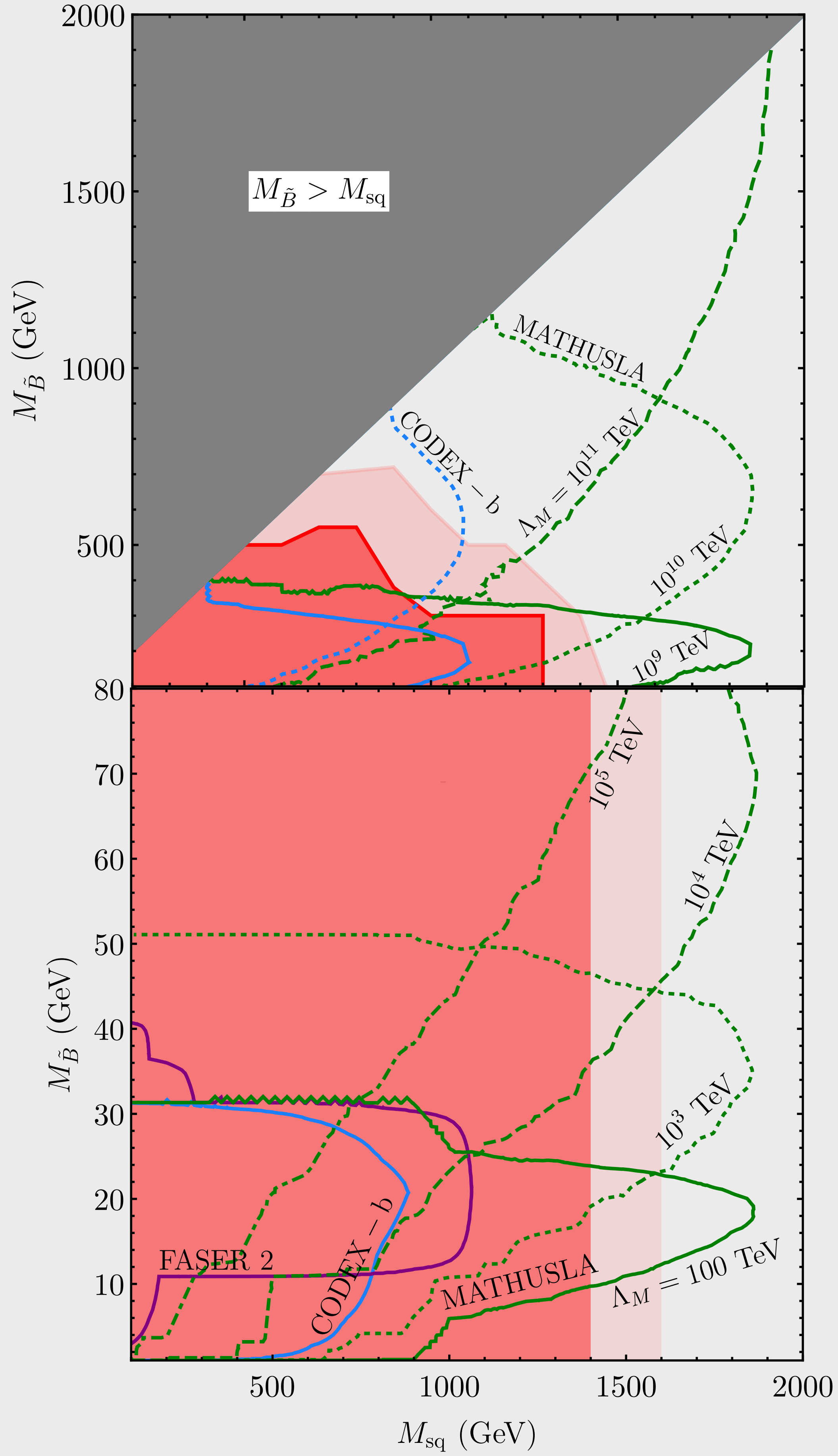


kaon production included

all channels included



SI, D. Tuckler, *arXiv:* 2305.00017

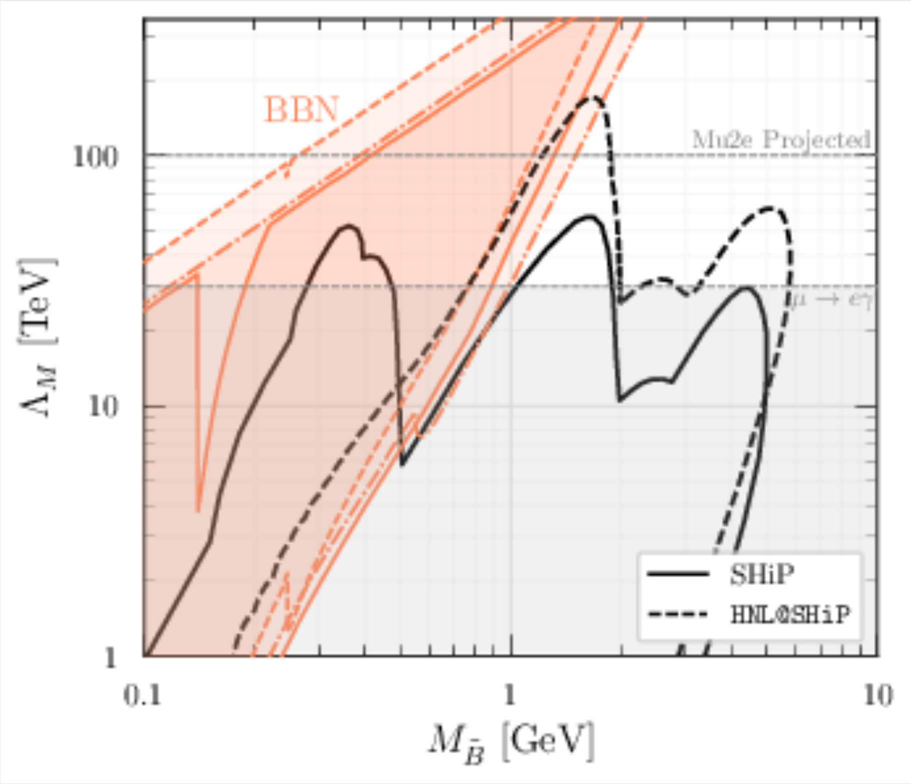


jets+MET searches can put a loose lower bound on Λ_M

LLP detectors probing: $M_{\tilde{B}}$, M_{sq}, Λ_M

neutrino masses set $m_{3/2}$

How about LLP searches at ATLAS and CMS?



More

Origin of the masses is not known

Pseudo-Dirac masses — Inverse Seesaw Mechanism

a mixture of L-violating and conserving terms

add 2 Standard Model singlets: $N, \;\; N'$

$L = 1 \qquad L = \text{-}1$

$$\mathscr{L} \supset \boxed{y_N \, \bar{\ell} \tilde{\phi} N + M_D \, \bar{N} N'^c}$$ L-conserving

$$\boxed{+ y'_N \, \bar{\ell} \tilde{\phi} N' + \mu \, \bar{N} N^c + \mu' \, \bar{N}' N'^c}$$ L-violating

Origin of the masses is not known

Pseudo-Dirac masses — Inverse Seesaw Mechanism

Light neutrino masses are *proportional* to the Majorana mass:

$$m_\nu \sim \frac{y_N\, y'_N\, v^2}{M_D} + O\left(\frac{y_N^2\, \mu\, v^2}{M_D^2}\right)$$

$O(1)$ L-conservation: $y_N \sim 1,\ M_D \sim \mathrm{TeV}$

very small L-violation: $y'_N \sim 10^{-12},\ \mu \sim \mathrm{keV}$

Where does the hierarchy come from?

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: $M_{\tilde{B}}$

$U(1)_{R\text{-}L}$ symmetry → $\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$:Dirac bino

After EW symmetry breaking:

assume there is no bino-higgsino/weakino mixing

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

in the basis $(\nu_i,\ \tilde{B},\ S)$

Neutrino oscillation data

$$\mathbf{Y} \simeq \frac{M_{\tilde{B}}}{\Lambda_M}\begin{pmatrix} 0.35 \\ 0.85 \\ 0.39 \end{pmatrix}, \quad \mathbf{G} \simeq \frac{m_{3/2}}{\Lambda_M}\begin{pmatrix} 0.06 \\ 0.44 \\ 0.89 \end{pmatrix}$$

Λ_M : messenger scale, $m_{3/2}$: gravitino mass

$$m_1 = 0$$

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

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

Proportional to the gravitino mass

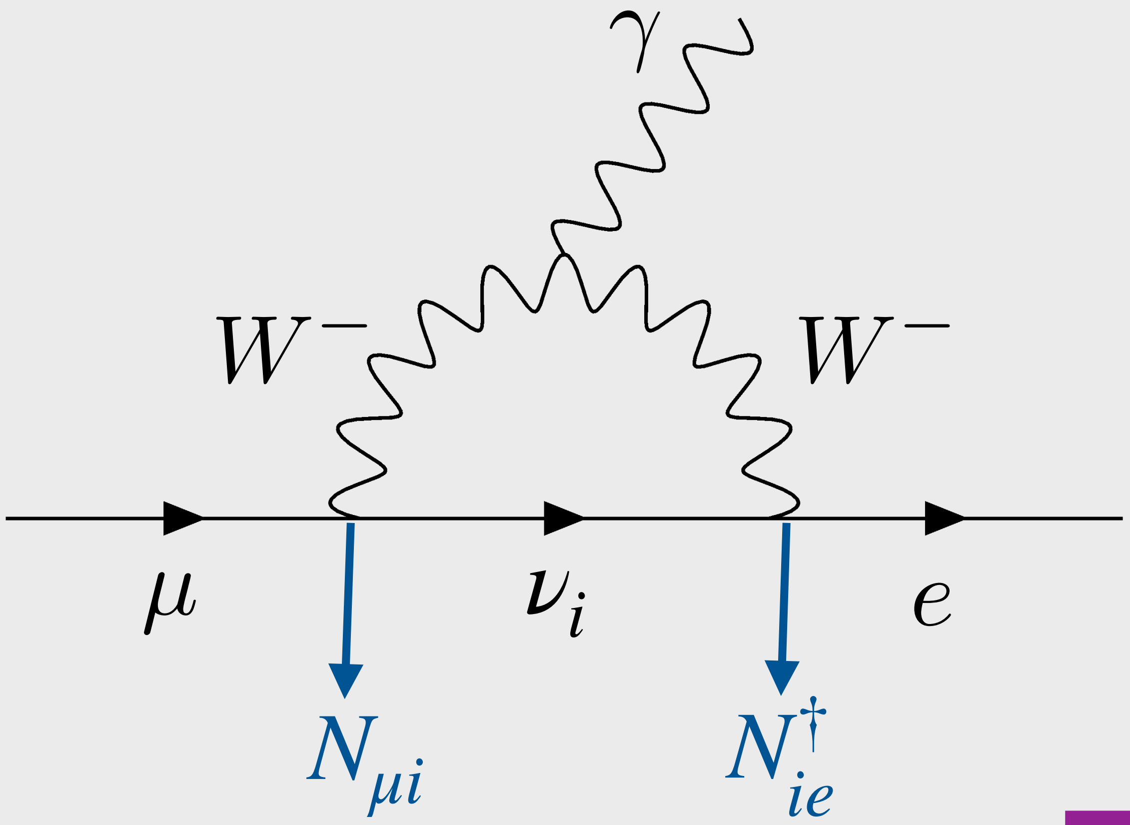
$\rho \simeq 0.7$ from mass splittings

Low Energy Constraints

Charged lepton flavor violation

Extend the lepton mixing sector → Expect lepton flavor violation

- Lepton flavor violating charged lepton decays



mixing matrix elements

MEG, arxiv: 1605.05081

most constraining

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

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

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

→

$$\boxed{\frac{v^2}{2\,M_{\tilde{B}}^2} Y_e Y_\mu^* < 2.4 \times 10^{-5}}$$

Charged lepton flavor violation

P. Coloma, **SI**, arXiv:1606.06372

MEG, arxiv: 1605.05081

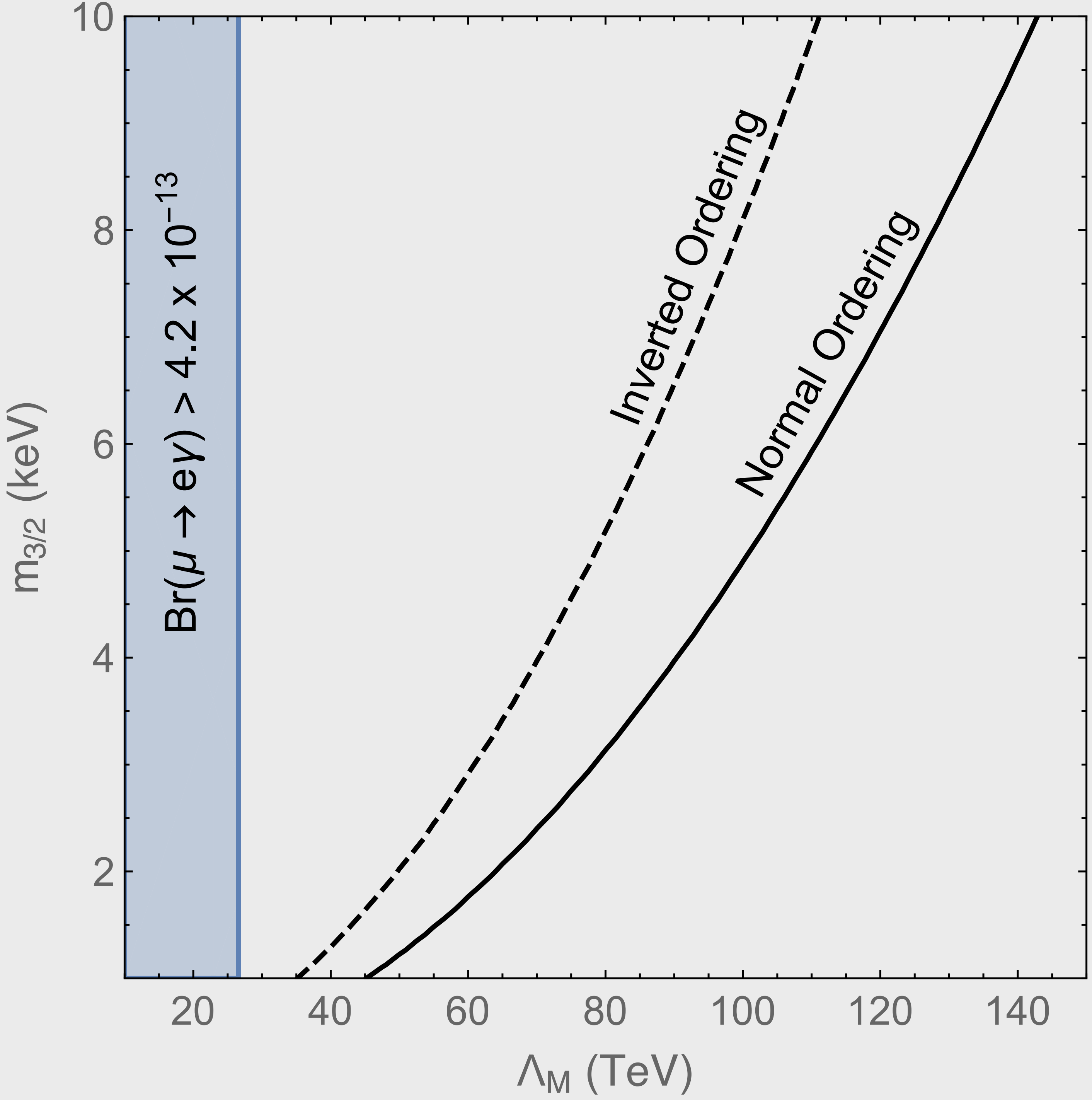
$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

⬇

$$\frac{v^2}{2\,M_{\tilde{B}}^2} Y_e Y_\mu^* < 2.4 \times 10^{-5}$$

⬇

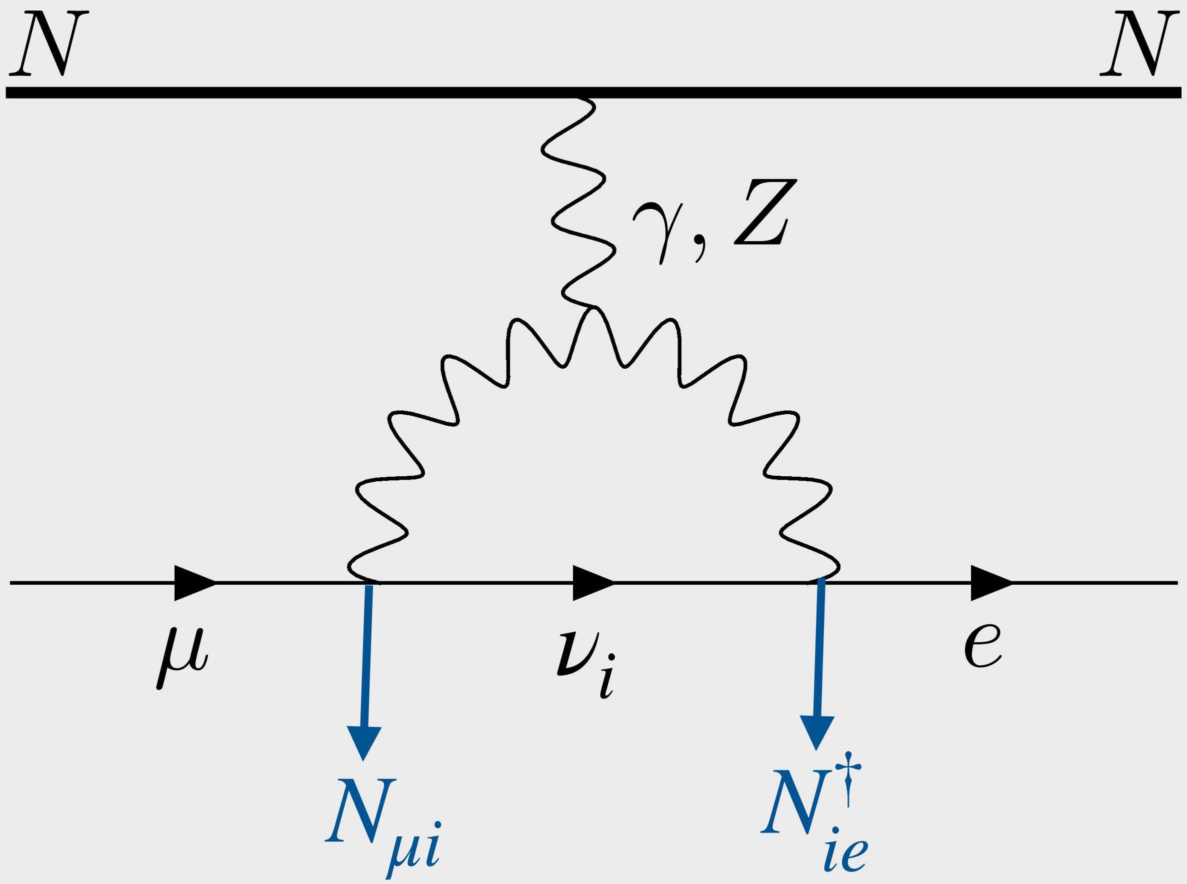
$$\Lambda_M \gtrsim 30 \text{ TeV}$$



Charged lepton flavor violation

Extend the lepton mixing sector → Expect lepton flavor violation

- Lepton conversion in nuclei



mixing matrix elements

Constraints are not yet competitive

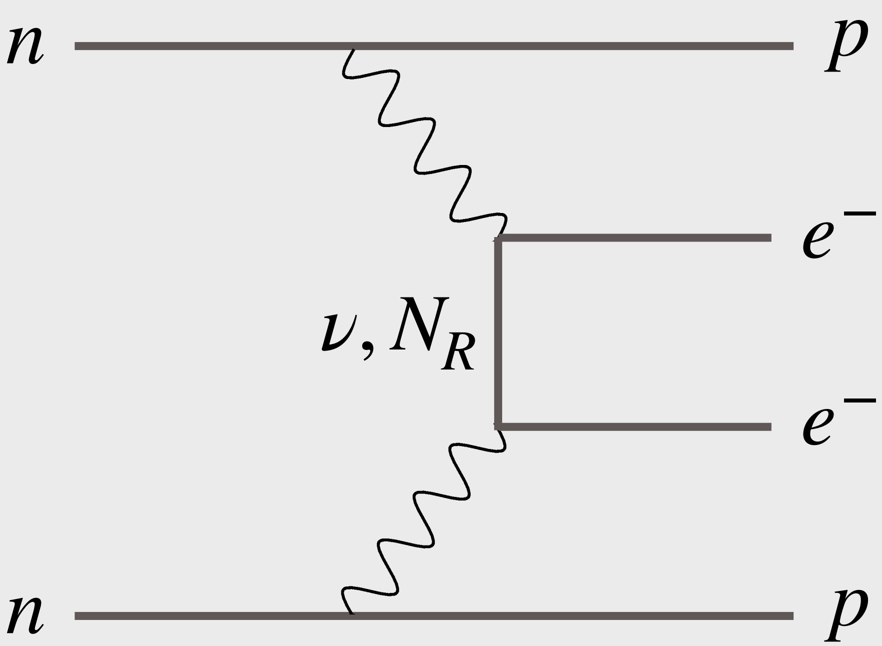
BUT more experiments are coming!

Mu2e, COMET, PRISM…

at Fermilab (~2020)

Mu2e, arxiv: 1501.05241

Neutrinoless double-beta decay



Effective $0\nu\beta\beta$ decay neutrino mass

$$m_{\beta\beta} = \sum_i m_i U_{ei}^2$$

current constraint: $m_{\beta\beta} < 60 \text{ meV}$

KamLAND-Zen, arxiv: 1605.02889

Biνo contributions:

$$m_{\beta\beta}^{\text{heavy}} \simeq f(A) \frac{\Lambda_A^2 v^2}{2M_{\tilde{B}}^4} \left([2m_B + m_S] Y_e^2 - 2M_{\tilde{B}} Y_e G_e \right)$$

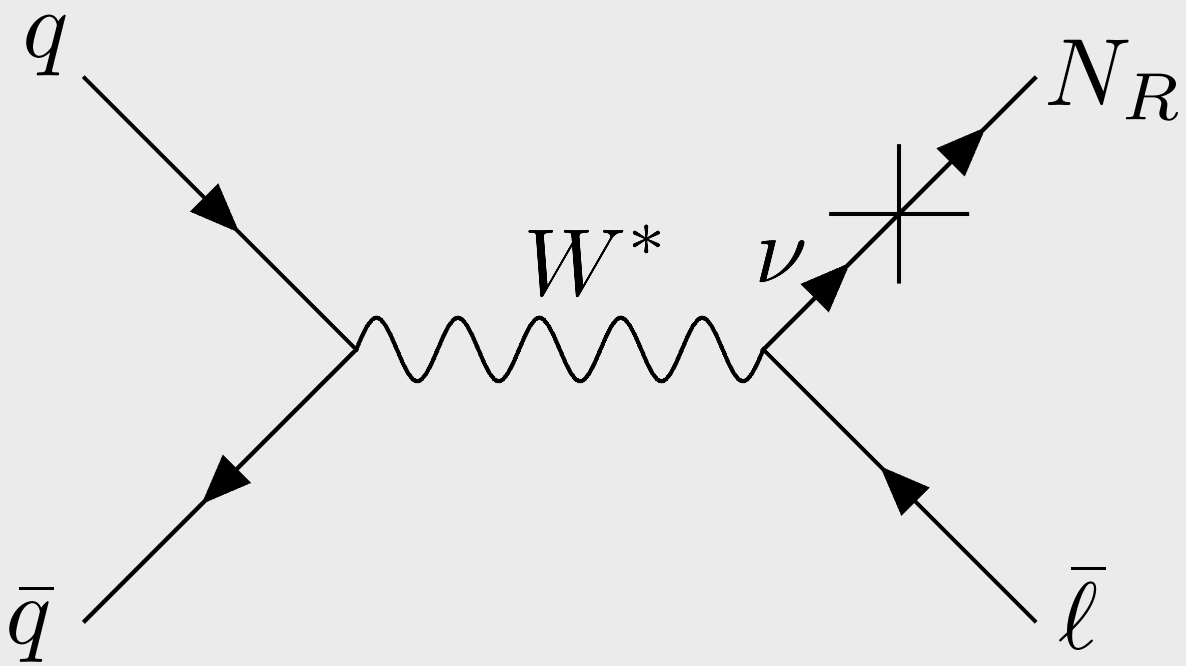
$$\Lambda_A \sim 0.9 \text{ GeV}, \quad f(A) \sim 0.1$$

$$m_{\beta\beta}^{1-\text{loop}} \sim \mathcal{O}\left(\frac{v^2}{(4\pi)^2 \Lambda_M^2} m_{3/2} \right)$$

No constraints from neutrinoless double-beta decay

Neutrino masses and LHC

RH neutrinos are produced via mixing with the SM neutrinos

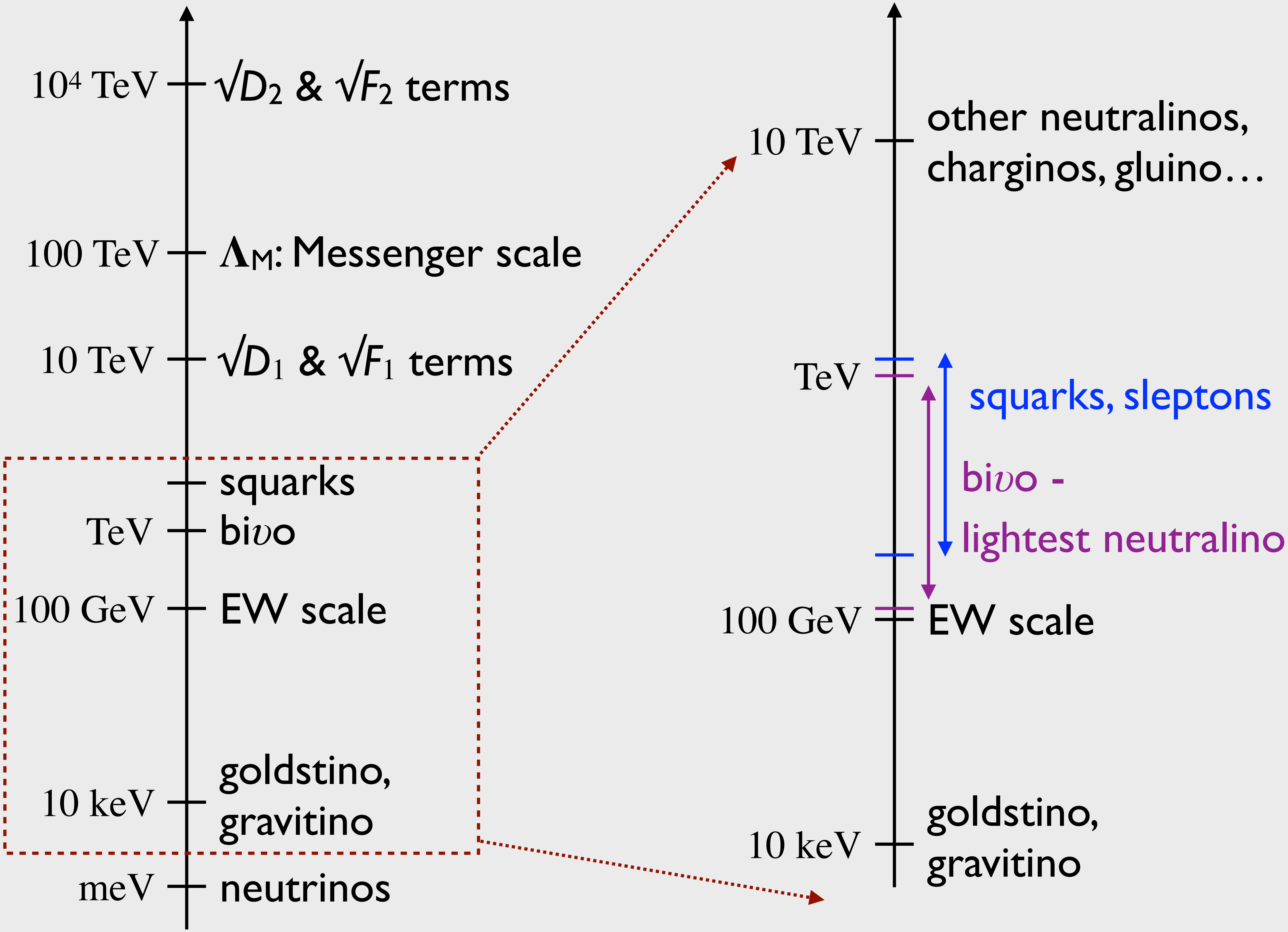


Even with ~TeV right-handed neutrino masses:

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

Hopeless? Not for biυo!

Particle Spectrum



10^4 TeV — $\sqrt{D_2}$ & $\sqrt{F_2}$ terms

100 TeV — Λ_M: Messenger scale

10 TeV — $\sqrt{D_1}$ & $\sqrt{F_1}$ terms

squarks

TeV — biυo

100 GeV — EW scale

10 keV — goldstino, gravitino

meV — neutrinos

10 TeV — other neutralinos, charginos, gluino…

TeV

squarks, sleptons

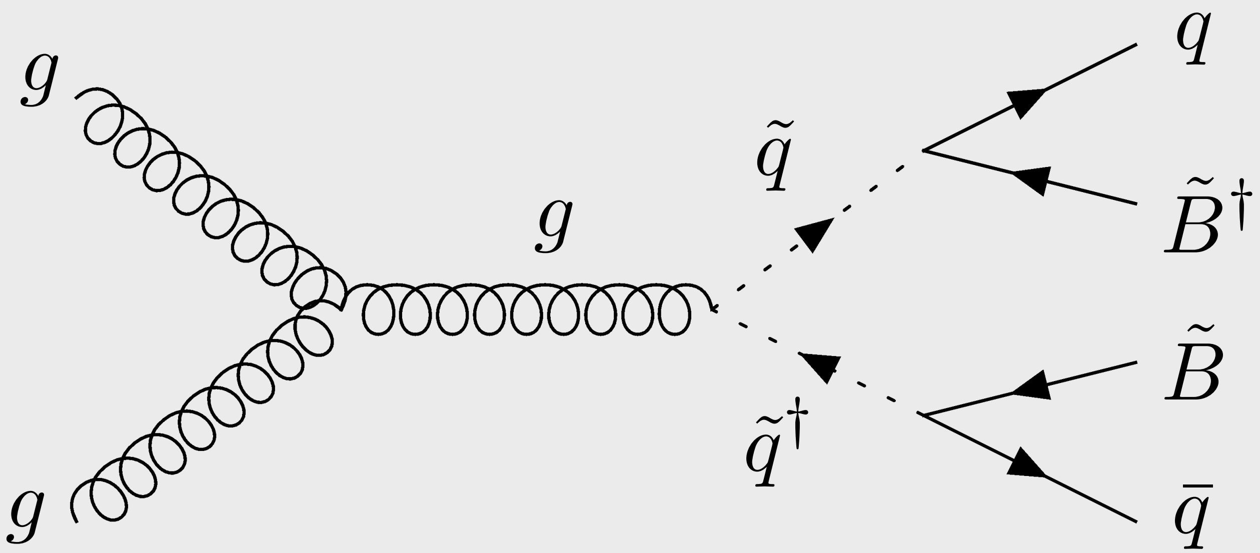
biυo - lightest neutralino

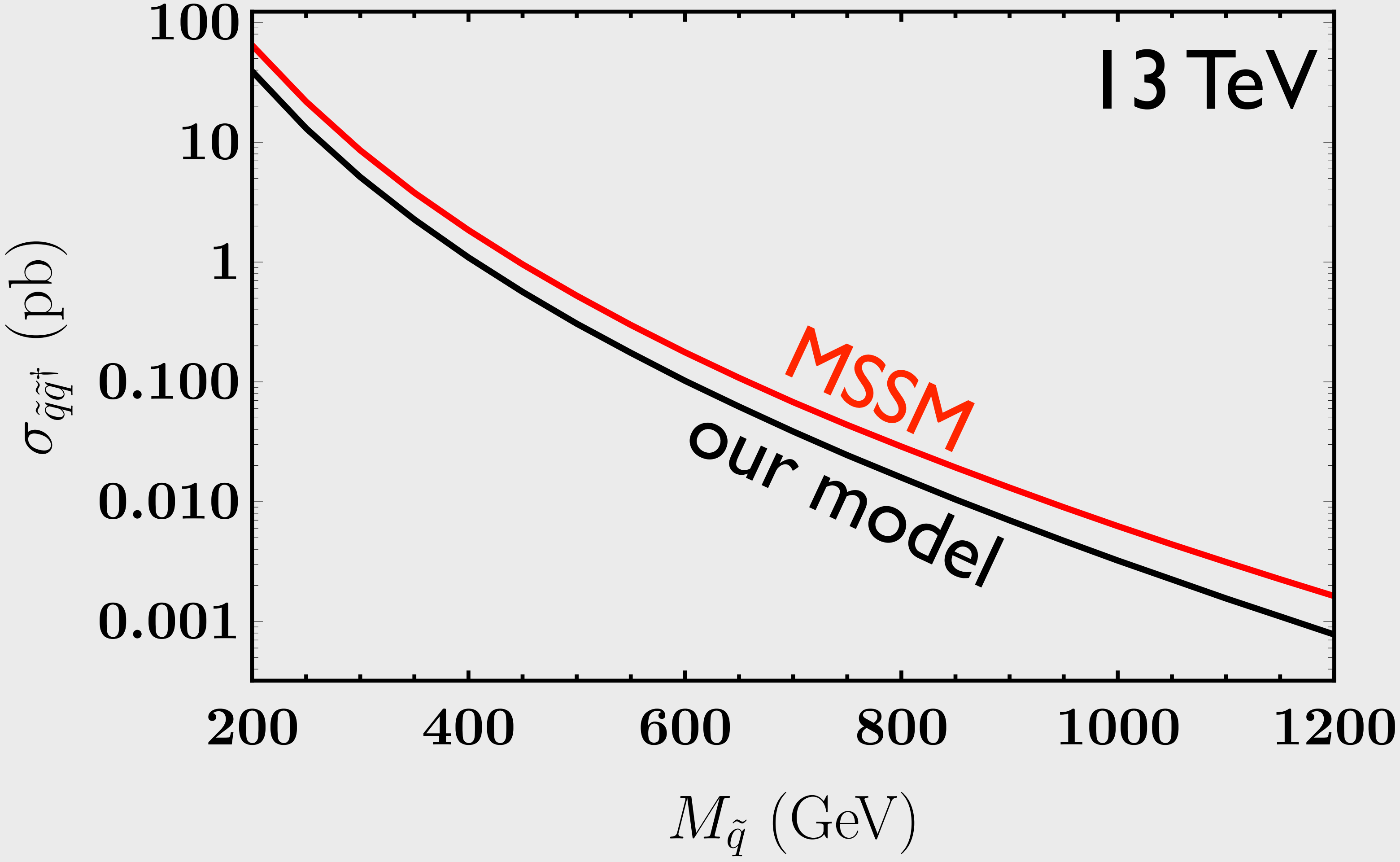
100 GeV — EW scale

10 keV — goldstino, gravitino

Biνo production

Biνo is produced via squark decays:





gluinos decoupled

squark x-section is reduced due to $U(1)_R$ symmetry

Prompt biνo decays

$$M_{\tilde{B}} \gtrsim 80 \text{ GeV}$$

$$\Lambda_M = 100 \text{ TeV}$$

Paddy Fox, Julia Gehrlein, **SI**, *JHEP*, 1903 (2019), 073