A Model of Neutrino Masses and the LHC

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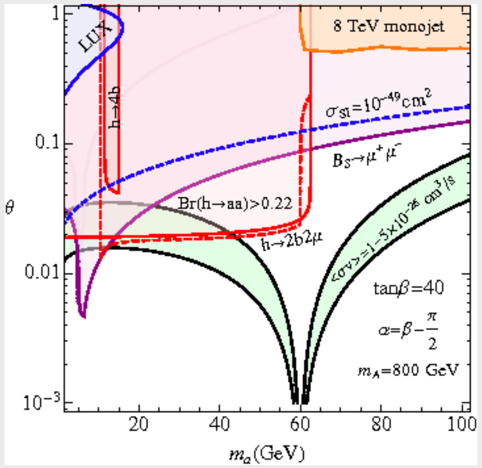
What is wrong with the SM?

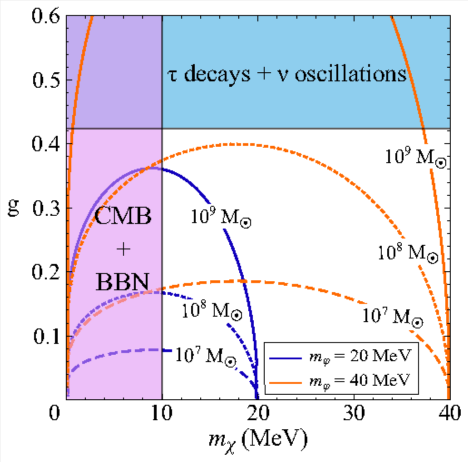
What is dark matter???

SI, D. McKeen, A. Nelson, PRD 90 (2014), no.5

SI, B. Bertoni, D. McKeen, A. Nelson, JHEP 1504 (2015) 170

D. Berger, **SI**, T. Tait, M. Waterbury, *in progress*





Why is there more matter than antimatter in the Universe???

SI, J. March-Russell, PRD 93 (2016), no.12

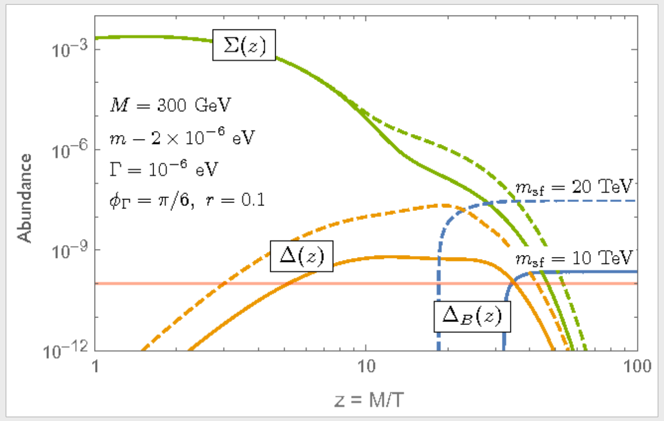
SI, A. D. Plascencia, J. Turner, JHEP 1812 (2018) 111

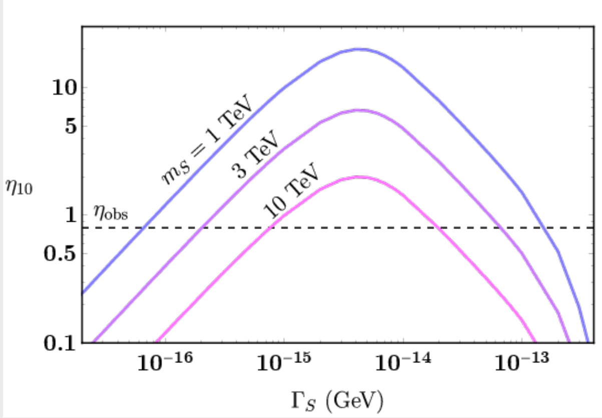
SI, T. Tait, PRL 122 (2019), 112001

M. Chen, **SI**, M. Ratz, PRD 100 (2019) no.3

S. Ellis, **SI**, G. White, JHEP 1908 (2019) 002

D. Croon, J. Howard, **SI**, T. Tait, *arXiv:1911.01432*

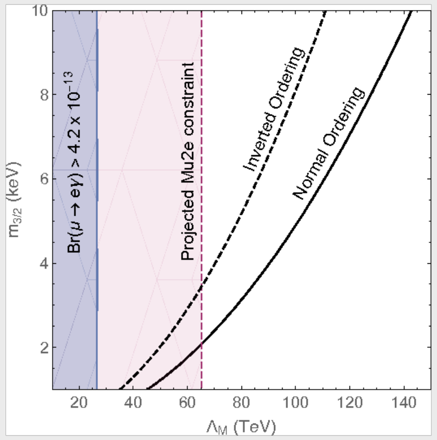


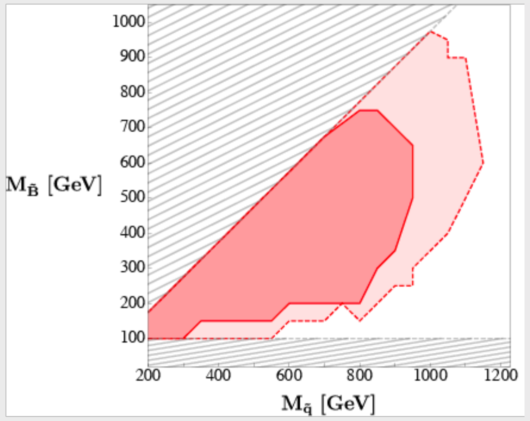


Why are neutrinos massive???

P. Coloma, **SI**, PRL 117 (2016), no.11

J. Gehrlein, **SI**, P. Fox, *JHEP*, 1903 (2019), 073
+ work in progress





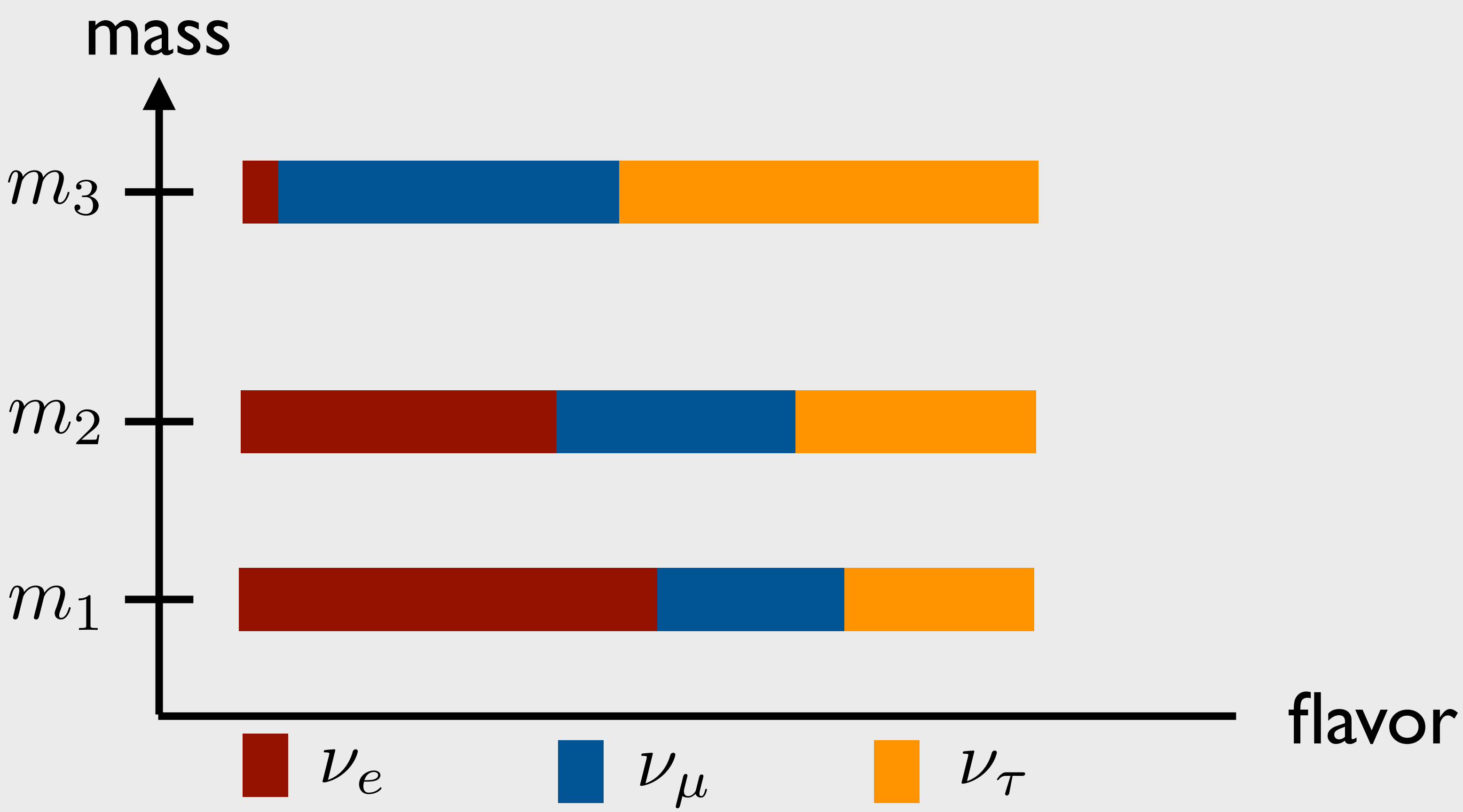
Neutrinos have mass

PDG review, www.nu-fit.org, …

Mass eigenstates are different than flavor eigenstates

↕

Neutrinos are massive particles

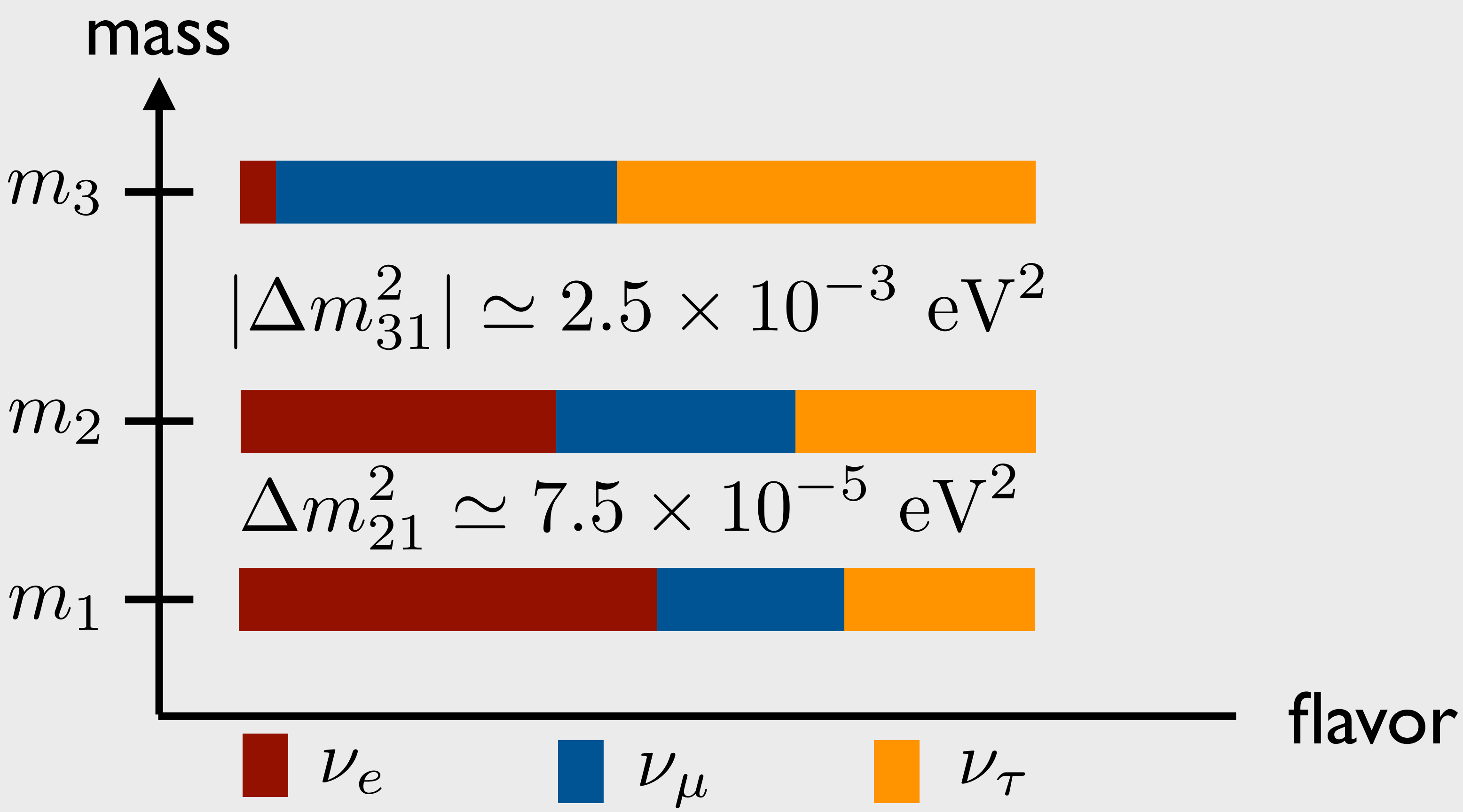


Neutrinos have mass

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



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

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

Mixing angles

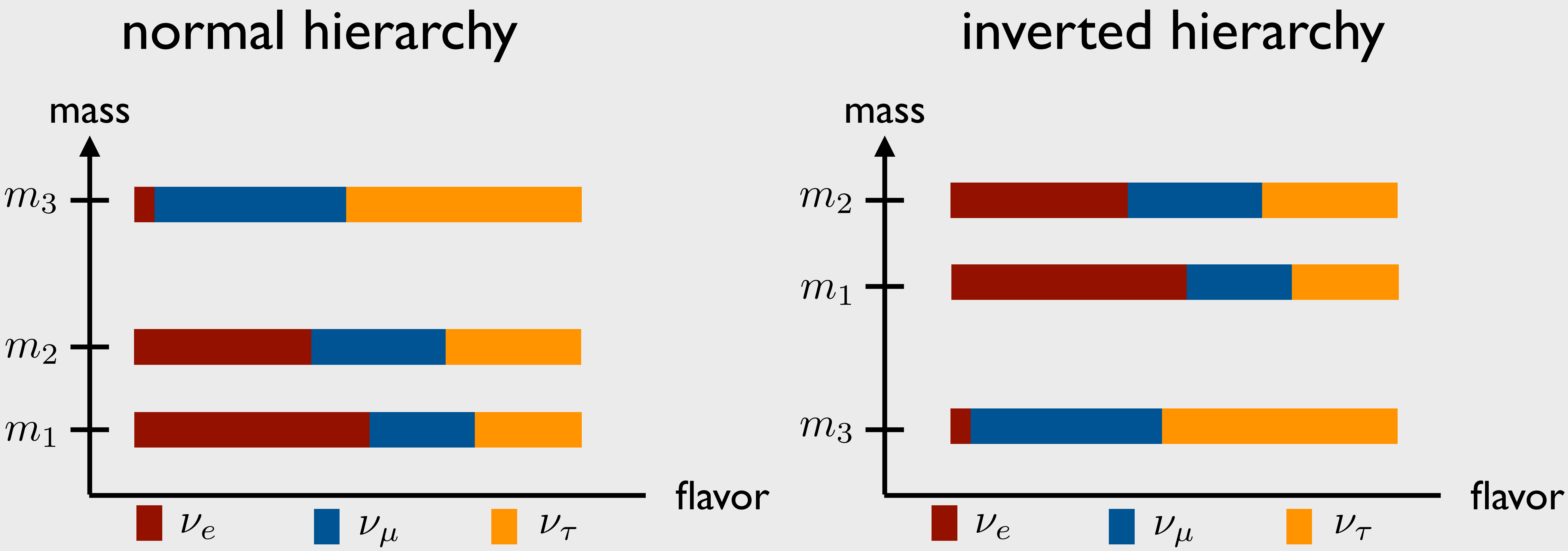
$\theta_{23} \sim 45^\circ$

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

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

Mass hierarchy is not known

We only know the mass differences of neutrinos, not the absolute masses!

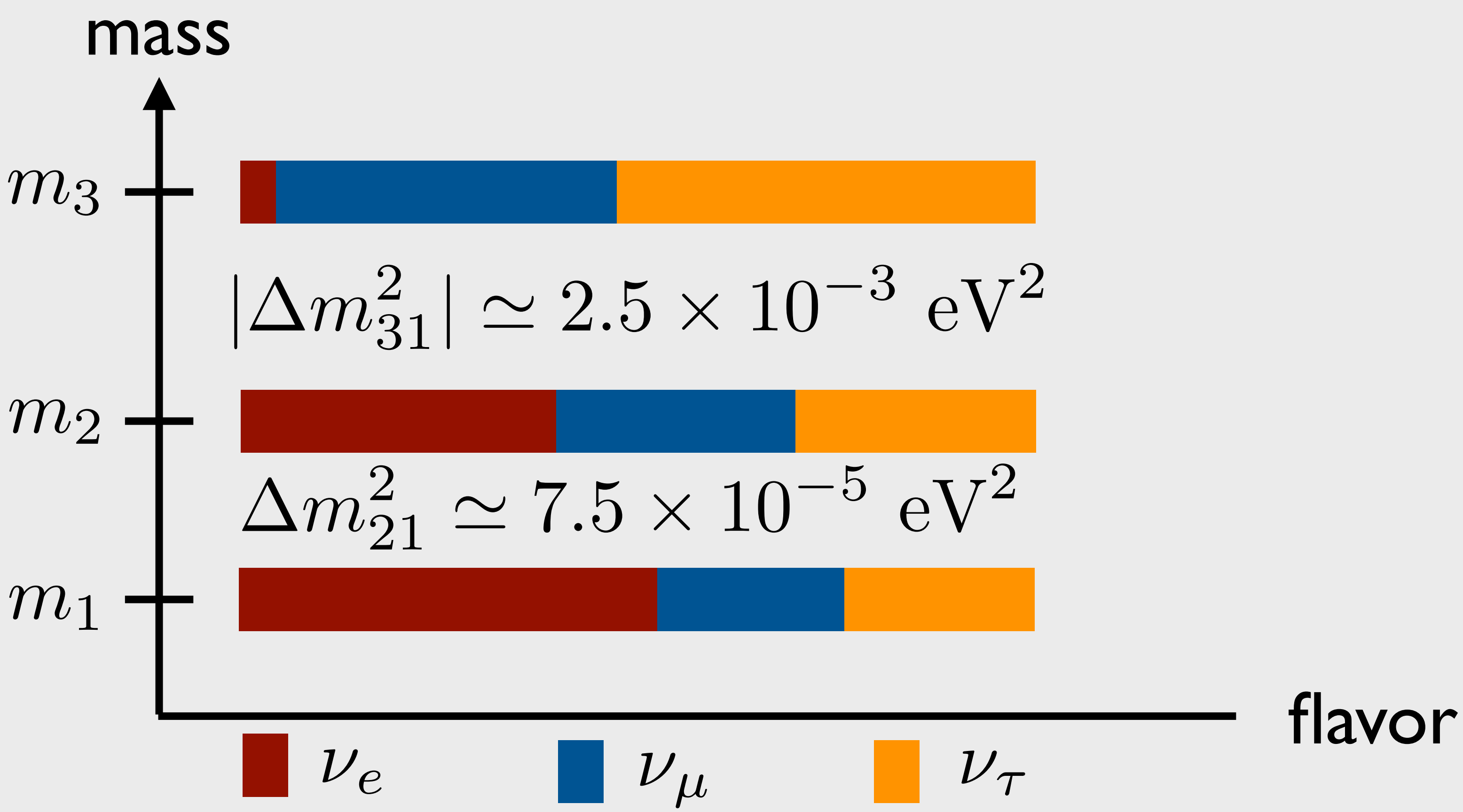


CP Violation is not known

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



Mixing angles

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

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

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

δ = ???

Origin of the masses is not known

Right-handed neutrinos haven’t been observed

Neutrinos are massless in the SM

Neutrinos are massive in Nature

Origin of the masses is not known

1- “SM” masses

Neutrinos might be like other SM fermions

$$y_\nu \bar{\ell}\,\tilde{\phi}\,\nu_R \to m_\nu \overline{\nu_L}\nu_R \qquad \Longleftrightarrow \qquad y_\nu \sim 10^{-12}$$

Fermion masses are technically natural…

BUT

‘We’ don’t like very small numbers

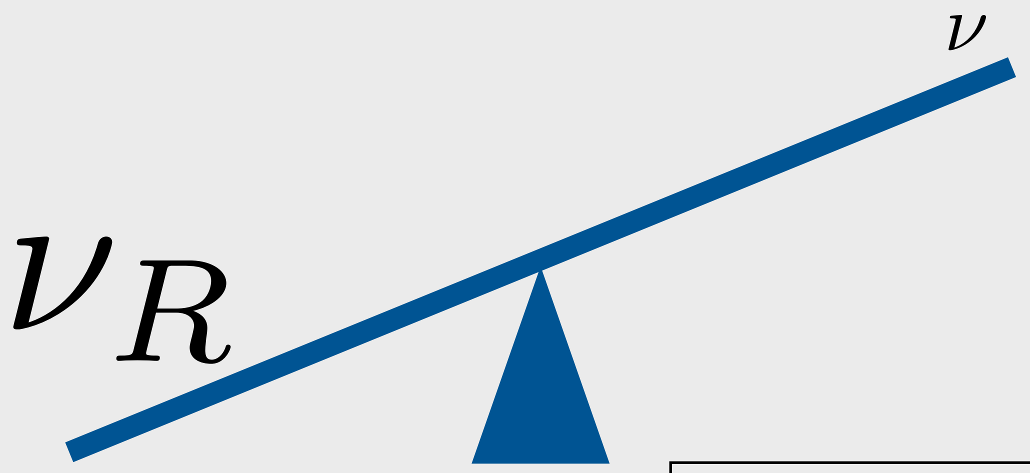
Origin of the masses is not known

2- Majorana masses — Seesaw mechanism

$$y_\nu \bar{\ell}\, \tilde{\phi}\, \nu_R + \frac{1}{2} M_R \nu_R^c \nu_R \longrightarrow m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

$$y_\nu \sim \mathcal{O}(1)$$

$$M_R \sim \mathcal{O}(10^{14}\ \mathrm{GeV})$$



Majorana particles are their own antiparticles

Lepton number is violated

Particle numbers are accidental symmetries of the SM…

Origin of the masses is not known

3- Pseudo-Dirac masses — Inverse Seesaw Mechanism

a mixture of L-violating and conserving terms

add 2 Standard Model singlets:

$$\begin{tikzcd} & N, \arrow[dl] & N' \arrow[dr] & \\ L = 1 & & & L = \text{-}1 \end{tikzcd}$$

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

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

3- 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: $y_N \sim 1,\, M_D \sim \text{TeV}$

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

Where does the hierarchy come from?

What we need

(Usually) SM singlet fermions as right-handed neutrinos

High mass scale

and/or

Small lepton-number violation

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

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

SI, D. McKeen, A. Nelson, PRD 90 (2014), no.5
SI, J. March-Russell, PRD 93 (2016), no.12

Model building with $U(1)_R$ -symmetric SUSY

P. Coloma, **SI**, PRL 117 (2016), no.11
J. Gehrlein, **SI**, P. Fox, *JHEP*, 1903 (2019), 073

$U(1)_R$ - symmetric SUSY

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

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

Sfermions: +1 R-charge

Bino: +1 R-charge

Singlino (S): -1 R-charge

↓

2 SM singlet fermions!

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

Let's add lepton number!

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

Spurion D-term

SUSY is broken in a hidden sector

Dirac bino mass

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

Dirac masses come from the spurion D-term

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

Λ_M : messenger scale

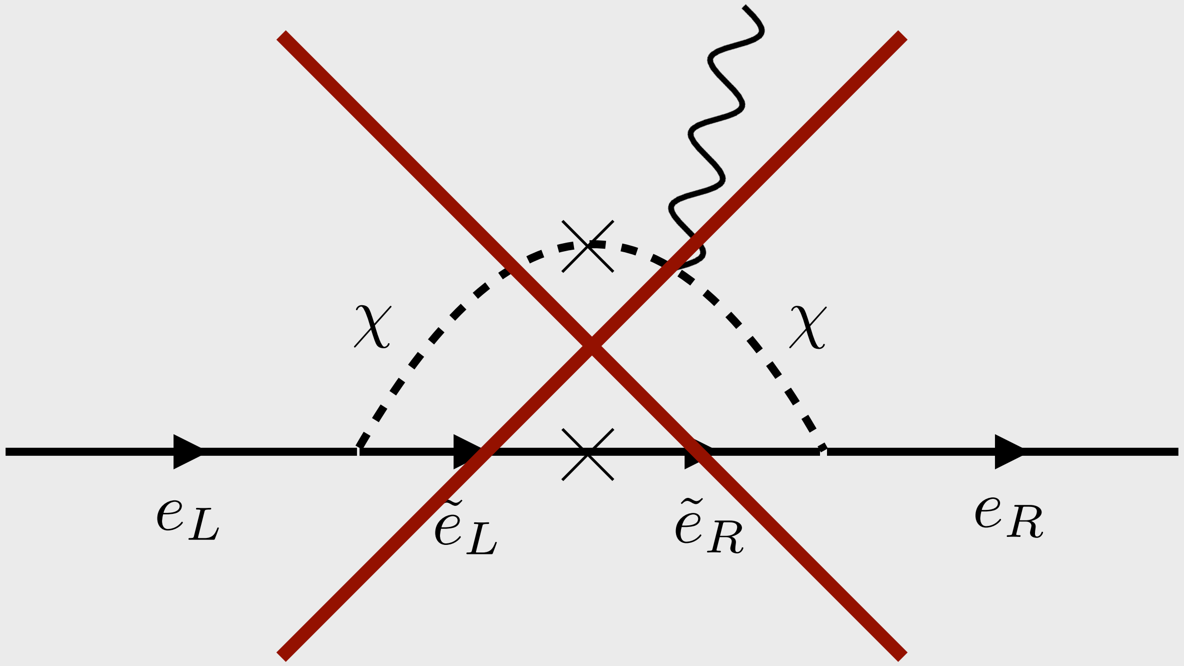
Dirac bino mass: $M_{\tilde{B}}$

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

Why is it great?

Because: Dirac gauginos!

Solves SUSY CP problem: Electron EDM not allowed at 1-loop



Solves SUSY flavor problem

Less tuning for heavier stops

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

Can also have a singlino Majorana mass $m_{\tilde{B}} \sim m_S \ll M_{\tilde{B}}$

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

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

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

Bino as a RH neutrino

Consider the dim-6 operator:

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

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

Relevant neutrino mass operator:

$$\rightarrow \quad \frac{f'_i M_{\tilde{B}}}{\Lambda_M} \ell_i h_u \tilde{B}$$

$$M_{\tilde{B}} \sim \frac{D}{\Lambda_M}$$

Bino acts as a RH neutrino!

Singlino as a RH neutrino

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!

Pseudo-Dirac masses

This is an Inverse SeeSaw scenario!

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

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

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

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

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

:We call this “biνo”

(pronounced exactly like ‘bino’)

(like ‘too’ and ‘two’)

Bivo gives an Inverse SeeSaw structure

assume there is no bino-higgsino/weakino mixing

After EW symmetry breaking:

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

in the basis

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

Neutrino oscillation data sets:

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

Neutrino masses

normal hierarchy

$$m_1 = 0$$ → 1 neutrino is massless

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

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

→ Proportional to the gravitino mass

$\rho \simeq 0.7$ from mass splittings

No dependence on $M_{\tilde{B}}$

$M_{\tilde{B}} \gg v$ is assumed for practical reasons

Parameter space

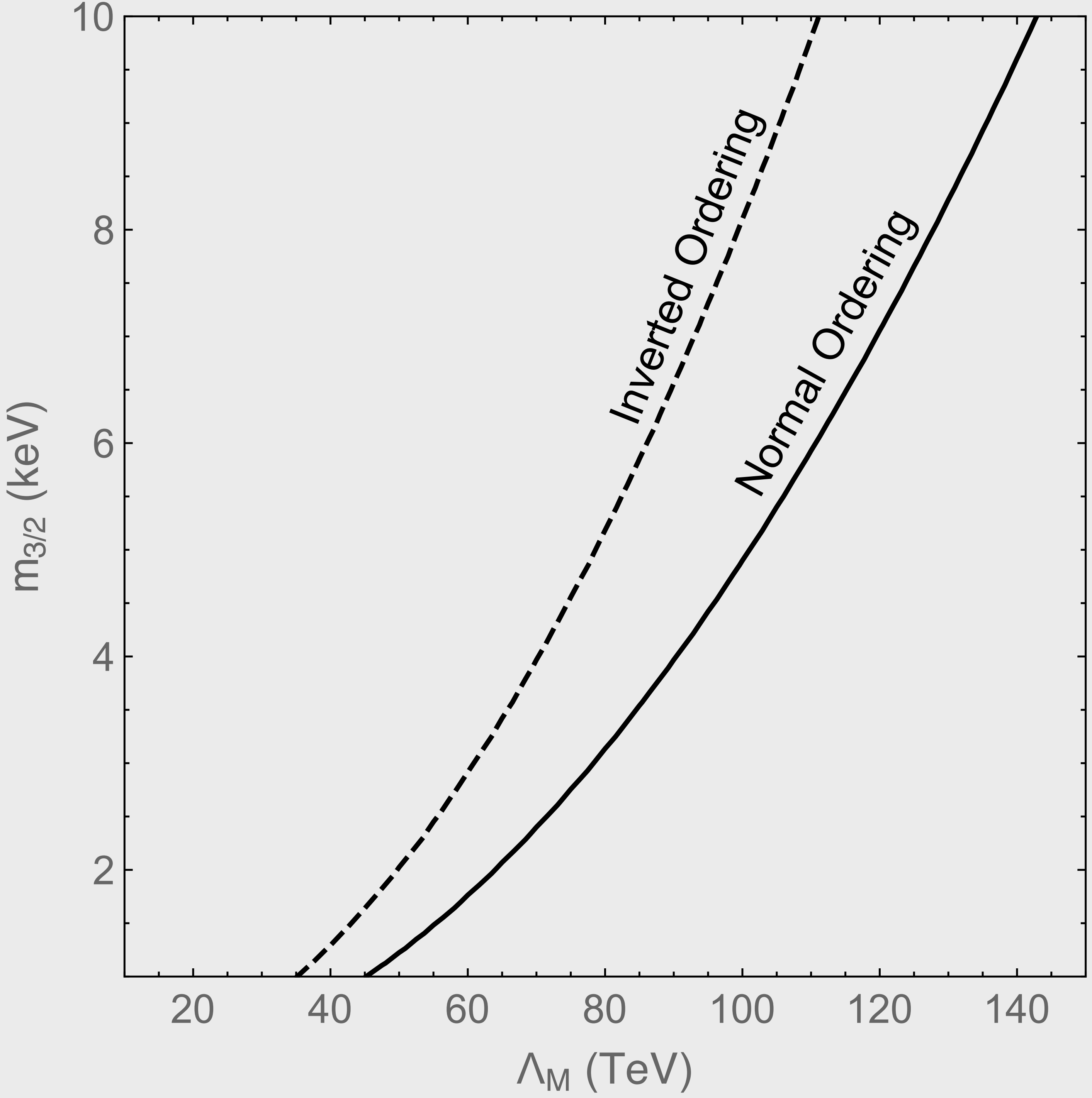
Neutrino masses:

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

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

$\rho \simeq 0.7$ from mass splittings

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

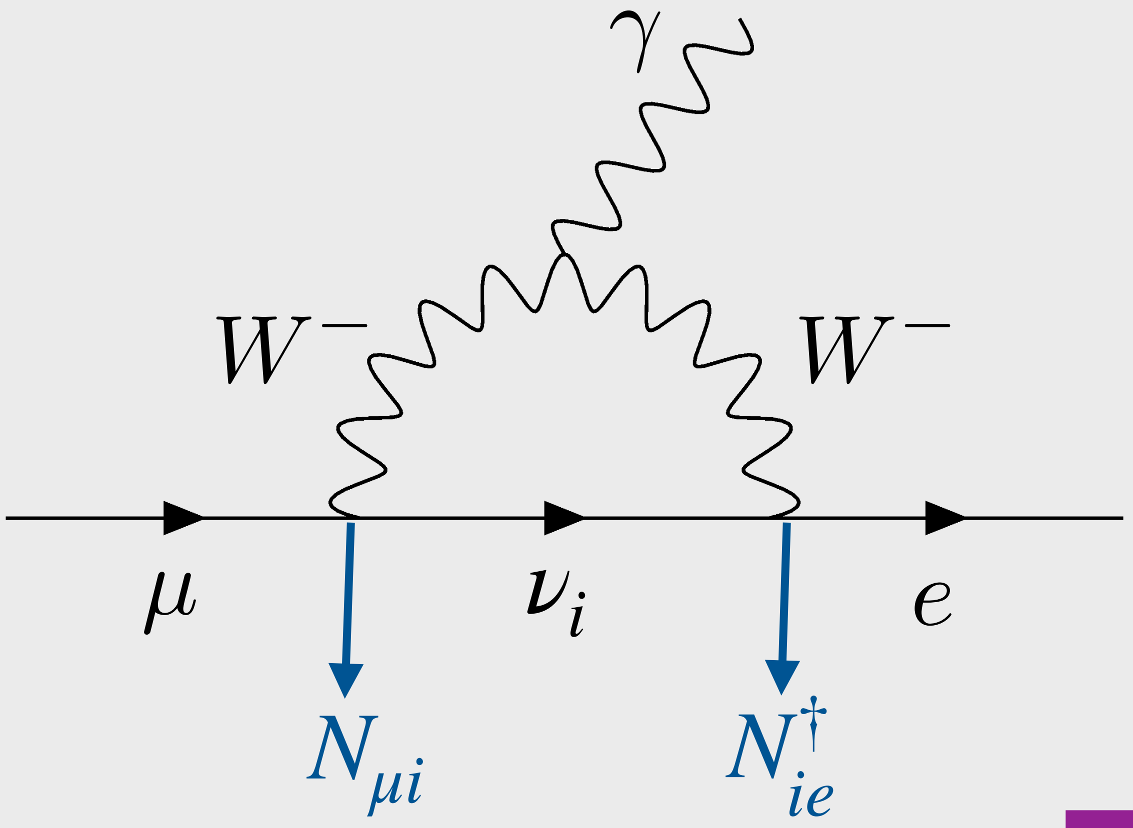


Low Energy Constraints

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

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

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

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

→

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

Charged lepton flavor violation

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

MEG, arxiv: 1605.05081

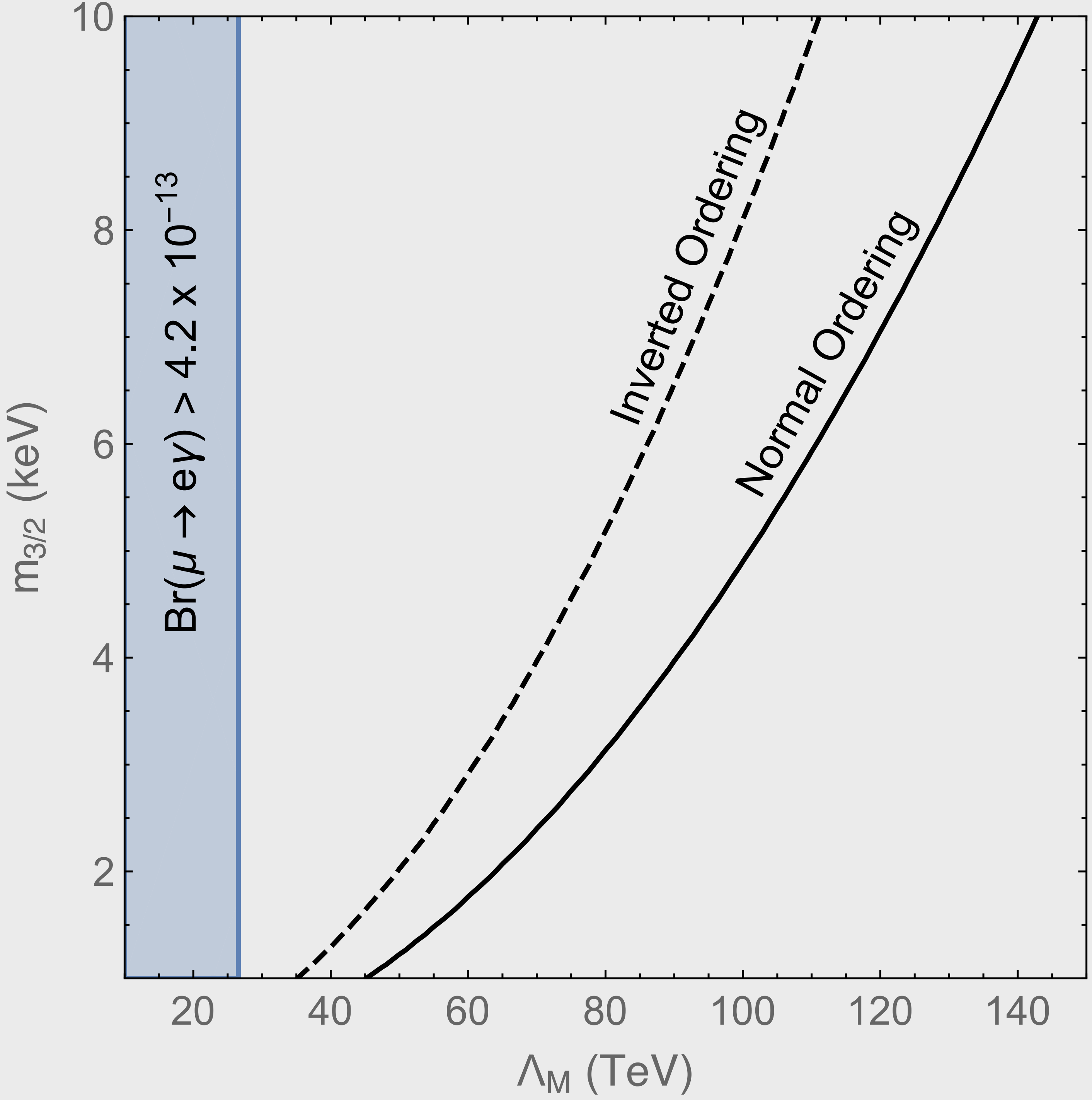
$$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

$$\Downarrow$$

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

$$\Downarrow$$

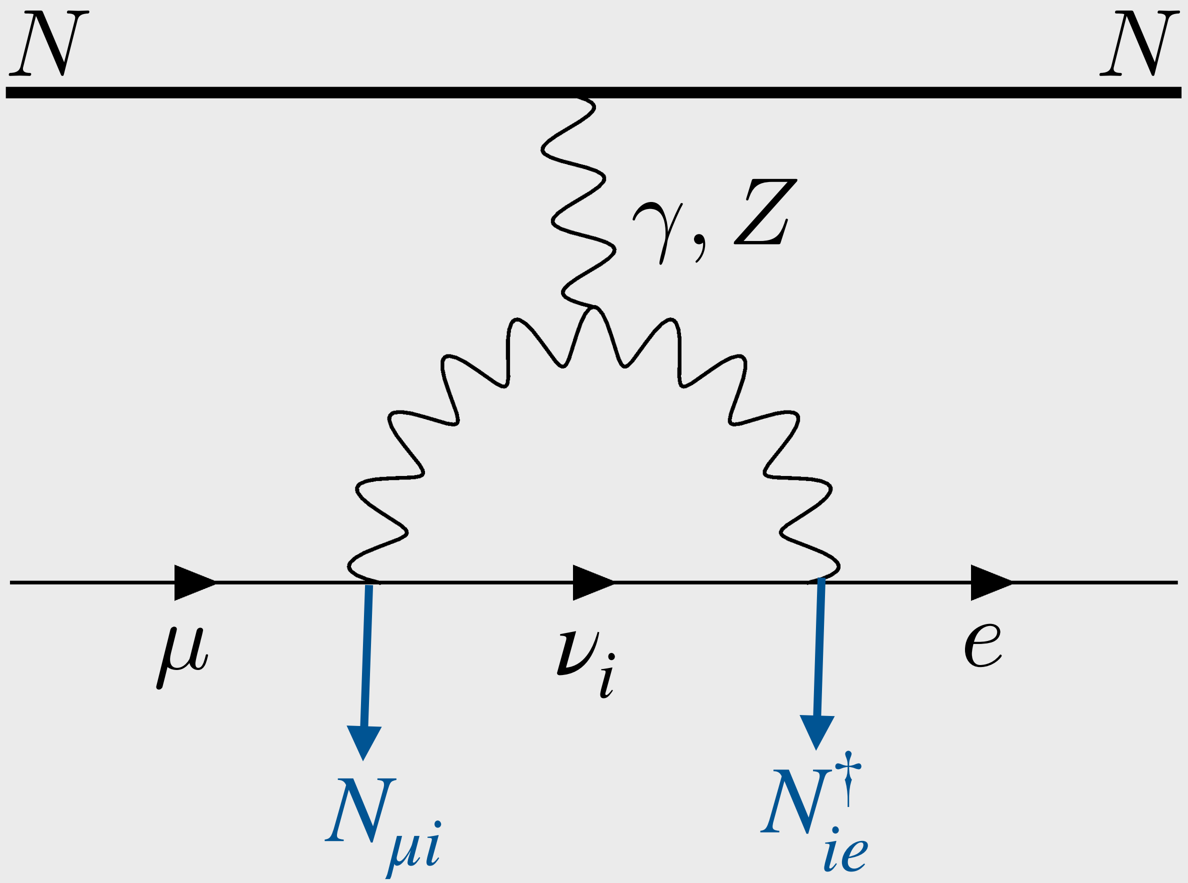
$$\Lambda_M \gtrsim 30\ \mathrm{TeV}$$



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…

Mu2e, arxiv: 1501.05241

at Fermilab (~2020)

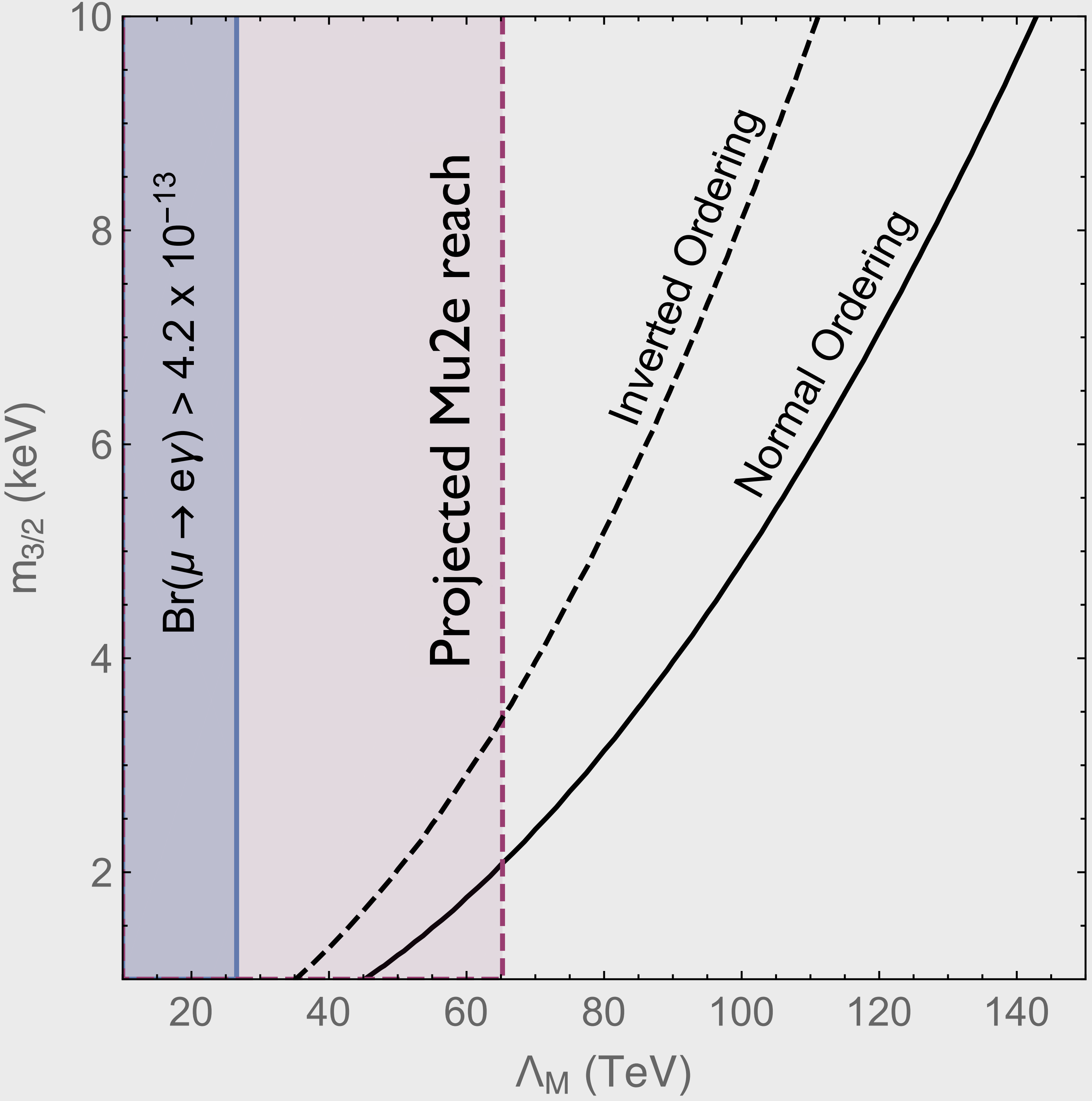
Parameter space

Neutrino masses
+
Lepton flavor violation constraints

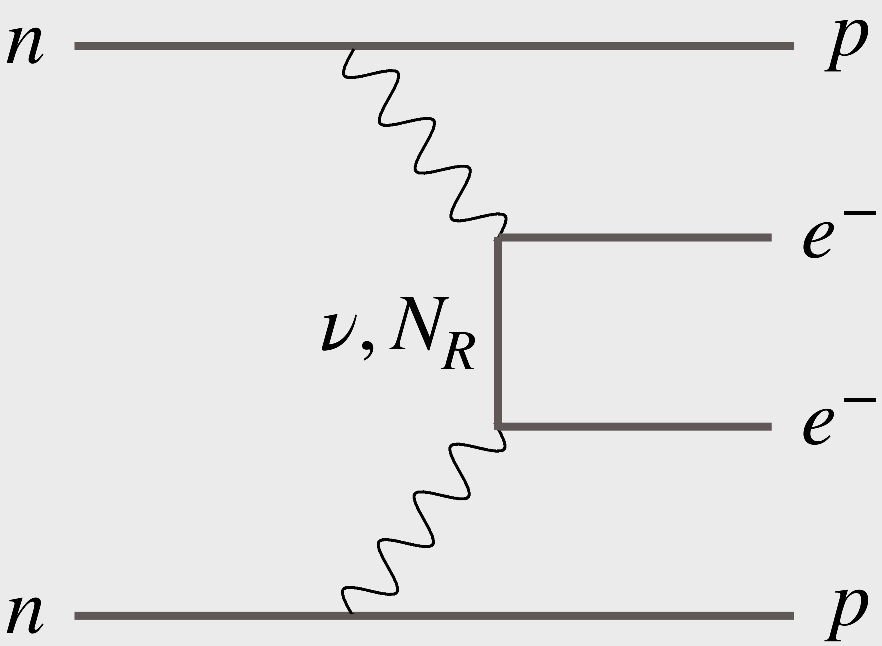
$$m_{3/2} \sim \mathcal{O}(\mathrm{keV})$$

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

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



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:

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

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

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

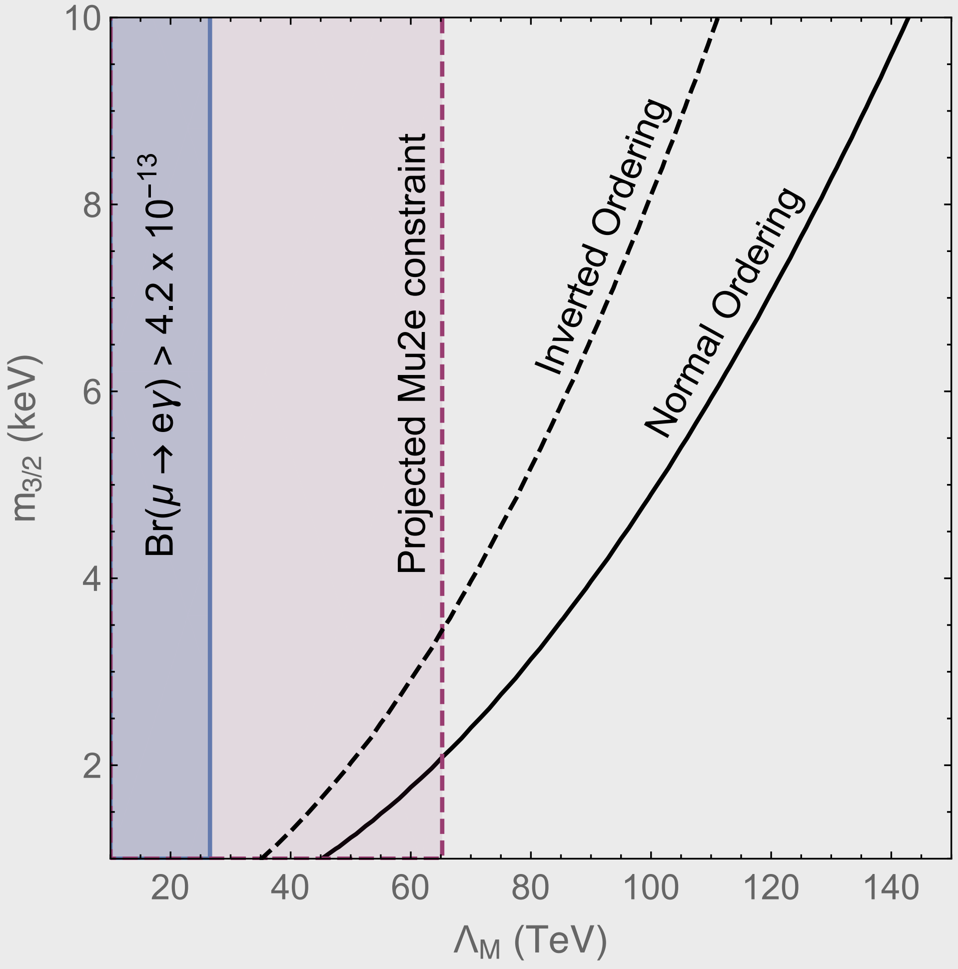
No constraints from neutrinoless double-beta decay

Low energy experiments probe:

$m_{3/2}, \Lambda_M$

How about the biνo mass?

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

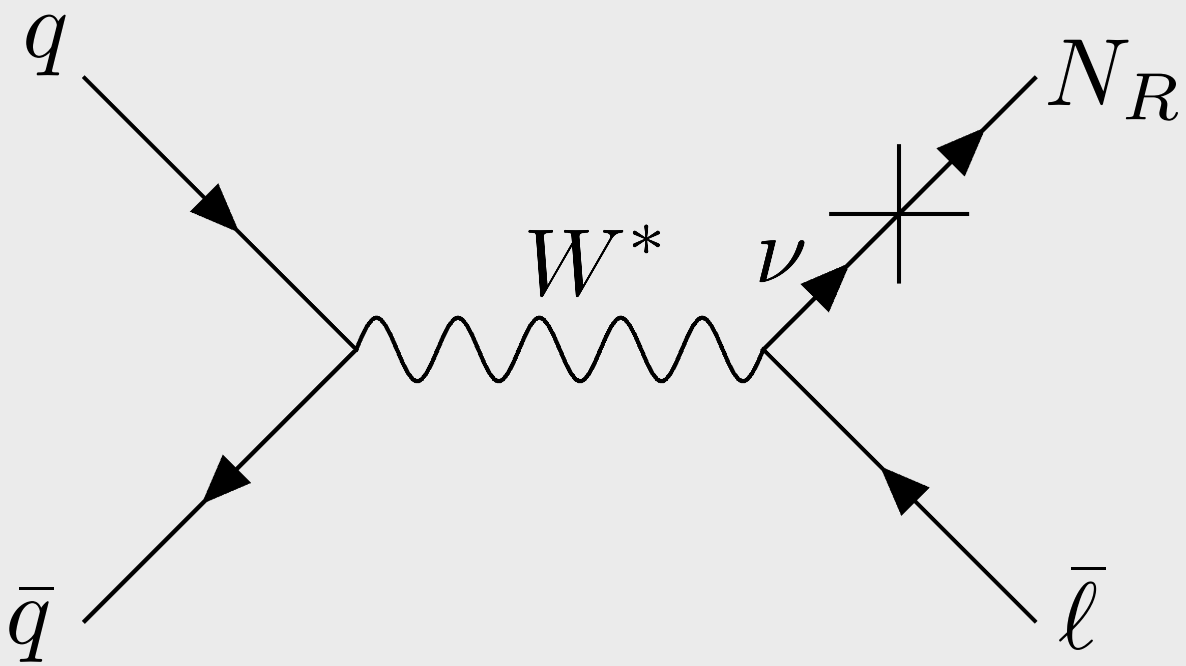


LHC Phenomenology

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

Neutrino masses and LHC

RH neutrinos are produced via mixing with the SM neutrinos

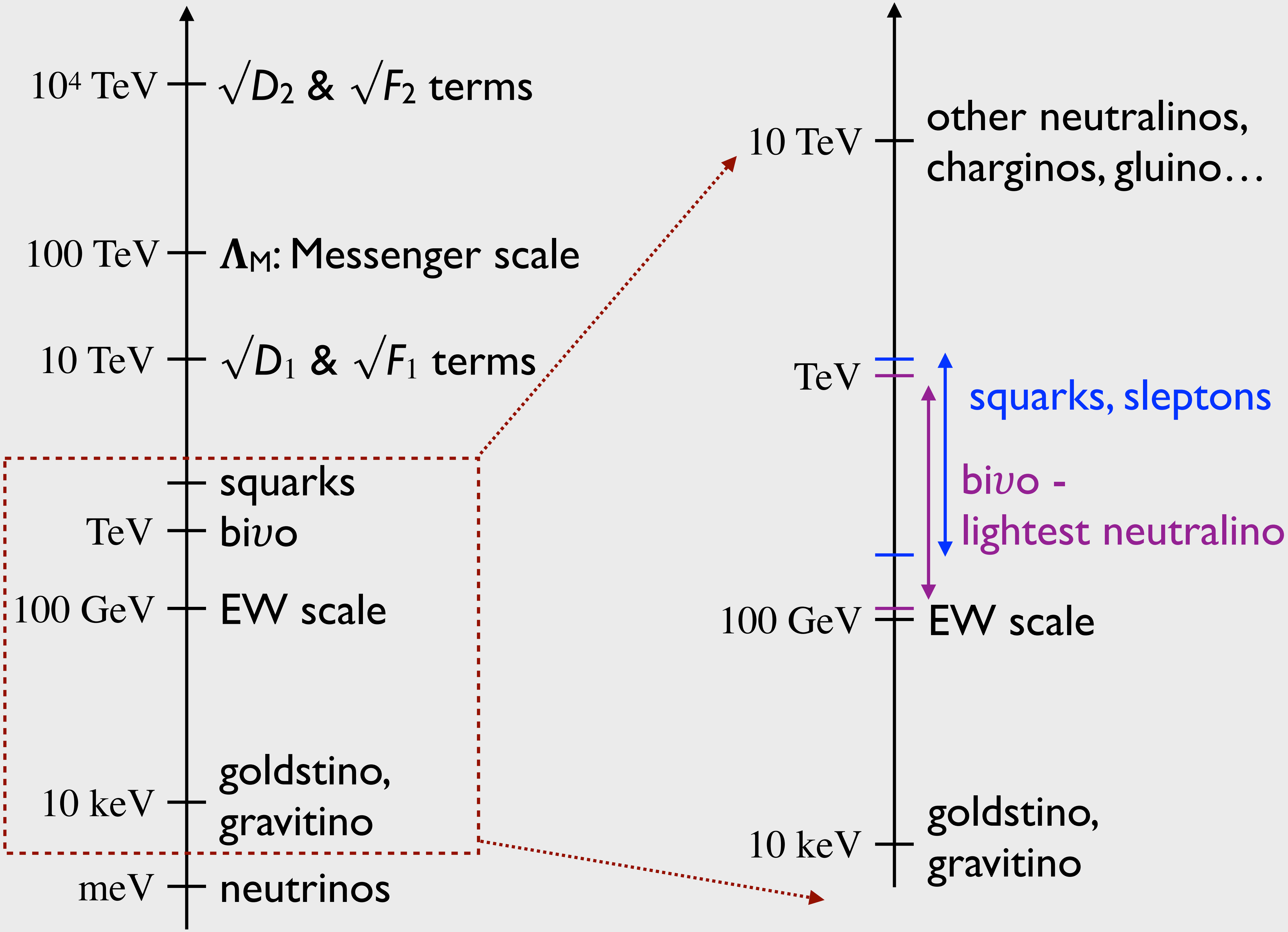


Even with ~TeV right-handed neutrino masses:

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 — bi$v$o

100 GeV — EW scale

10 keV — goldstino, gravitino

meV — neutrinos

10 TeV — other neutralinos, charginos, gluino…

TeV

squarks, sleptons

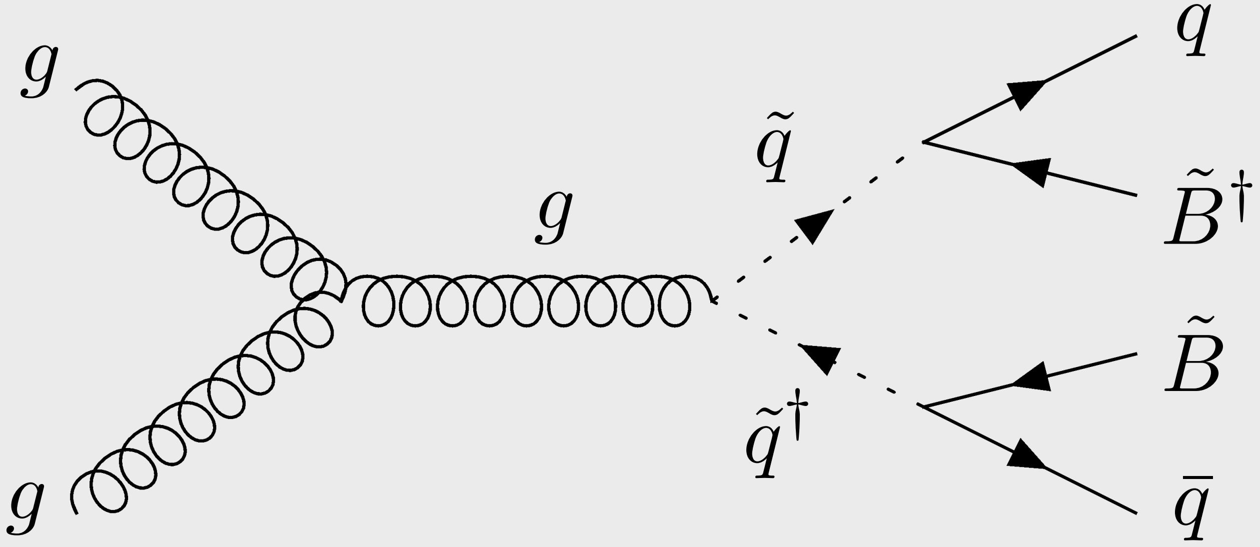
bi$v$o - lightest neutralino

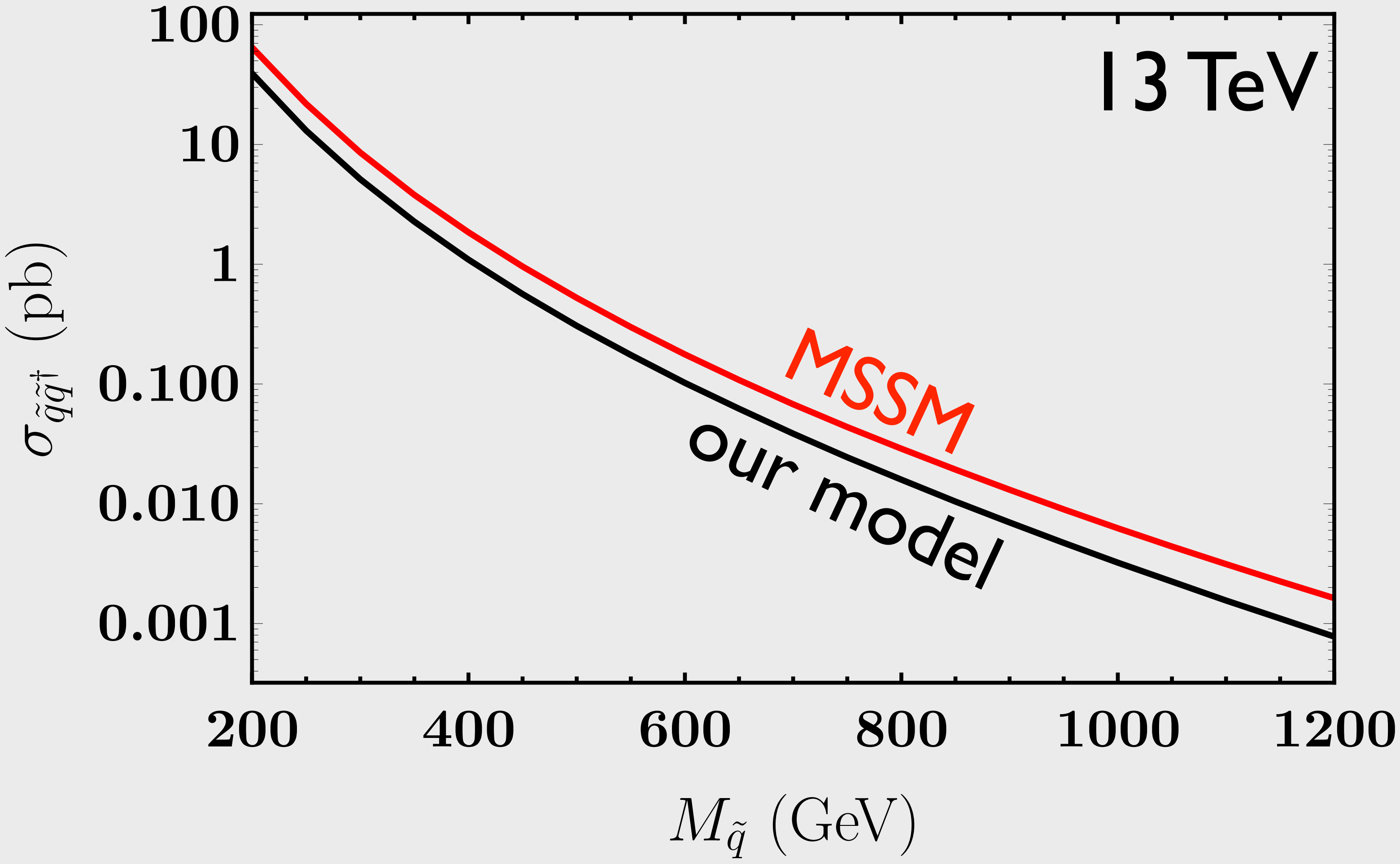
100 GeV — EW scale

10 keV — goldstino, gravitino

Bivo production

Bivo is produced via squark decays:



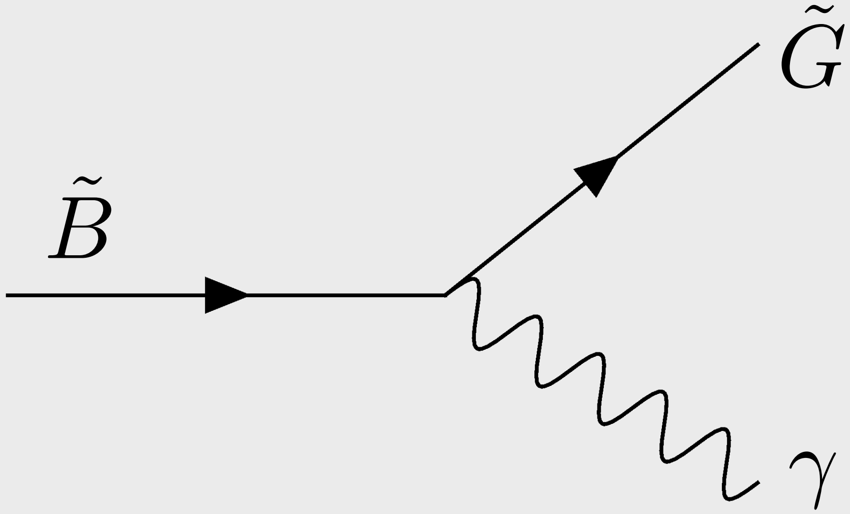


gluinos decoupled

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

Biνo decays

1) Decays to a gravitino and a photon

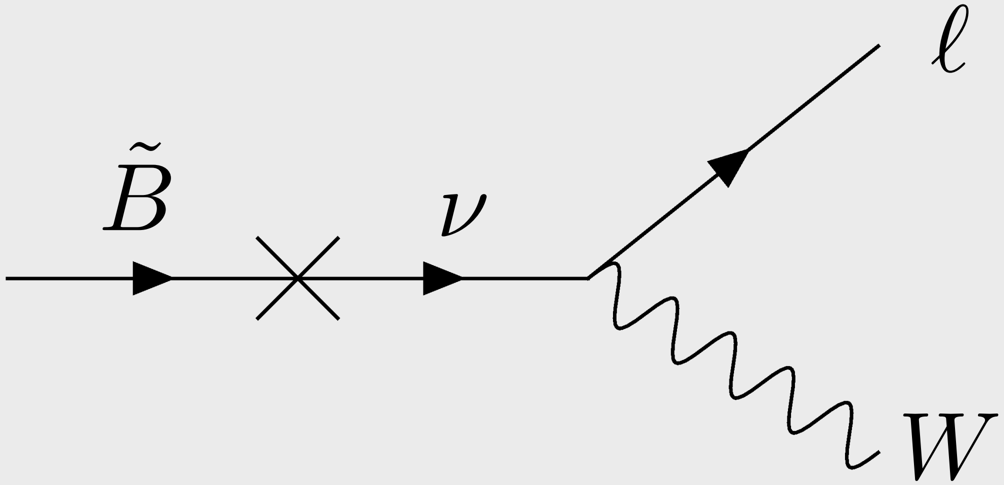


very small

$$\Gamma(\tilde{B} \to \tilde{G}\gamma) \sim \frac{M_{\tilde{B}}^5}{M_{\rm Pl}^2\, m_{3/2}^2} \sim 10^{-6}\ {\rm eV}$$

$M_{\tilde{B}} \sim 500\ {\rm GeV}$

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



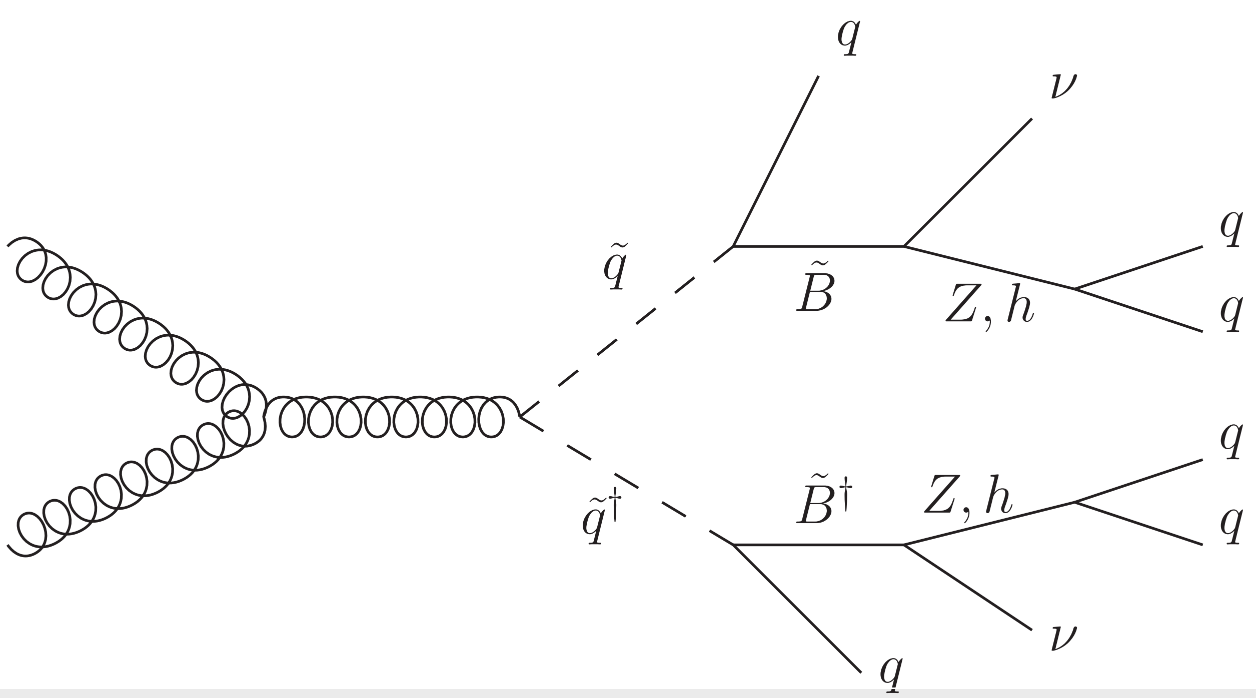
etc

total width:

$$\Gamma_{\rm tot} \sim \frac{M_{\tilde{B}}^3}{\Lambda_M^2} \sim 10\ {\rm MeV}$$

Biνo signals: jets + MET

Largest branching fractions into jets+MET



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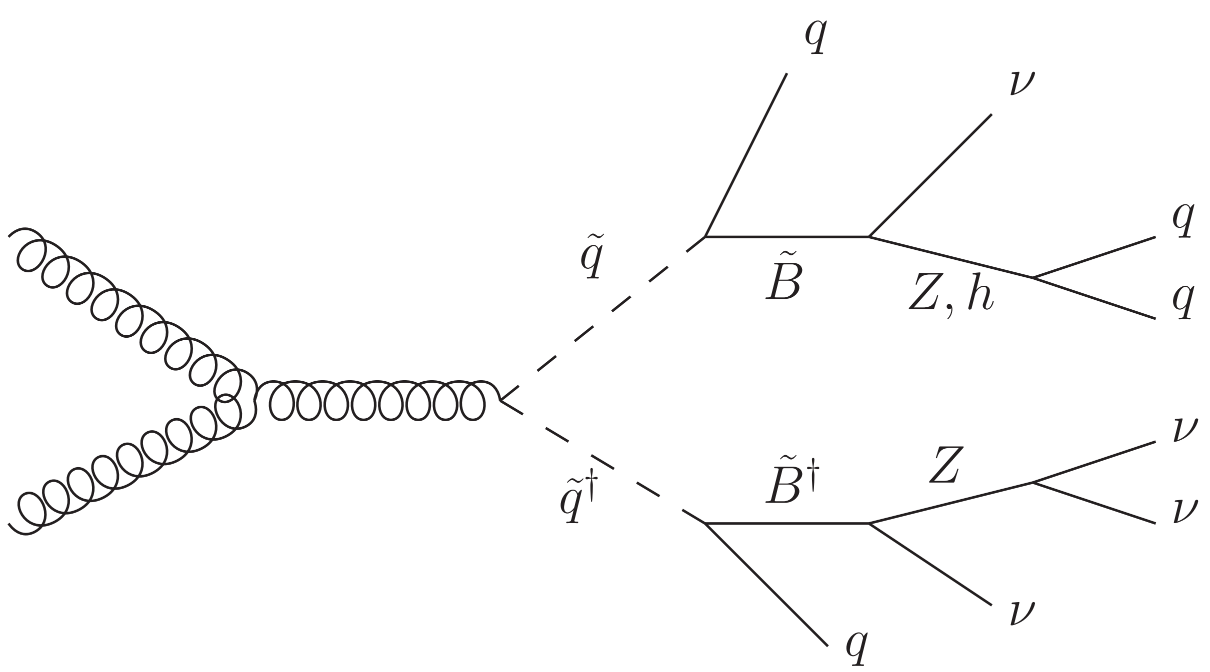

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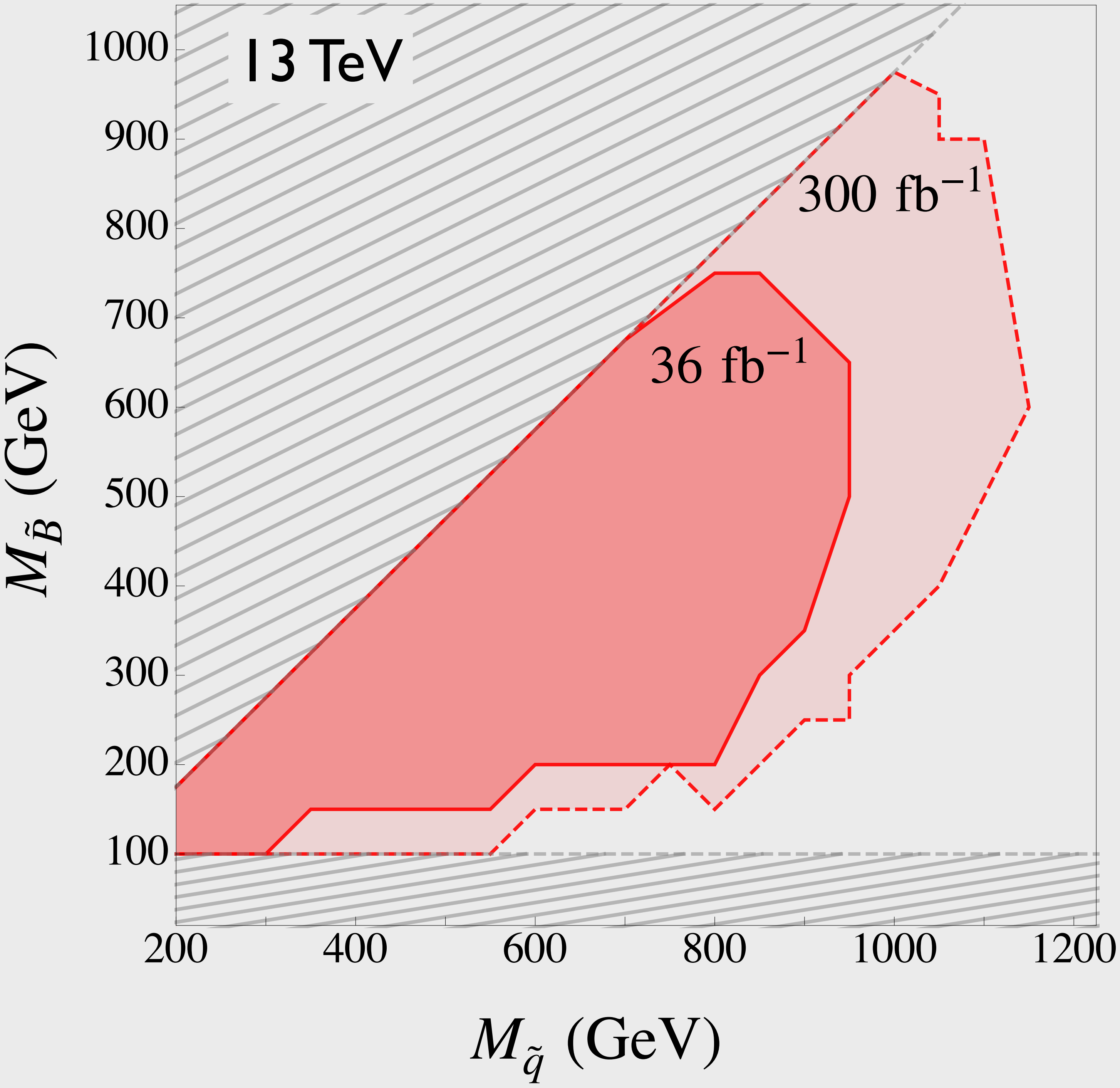
Most constraining search: ATLAS-CONF-2017-022

Biνo limits: jets + MET

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



we recast
ATLAS-CONF-2017-022

24 signal regions:

2-6 jets

m_{eff} based

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

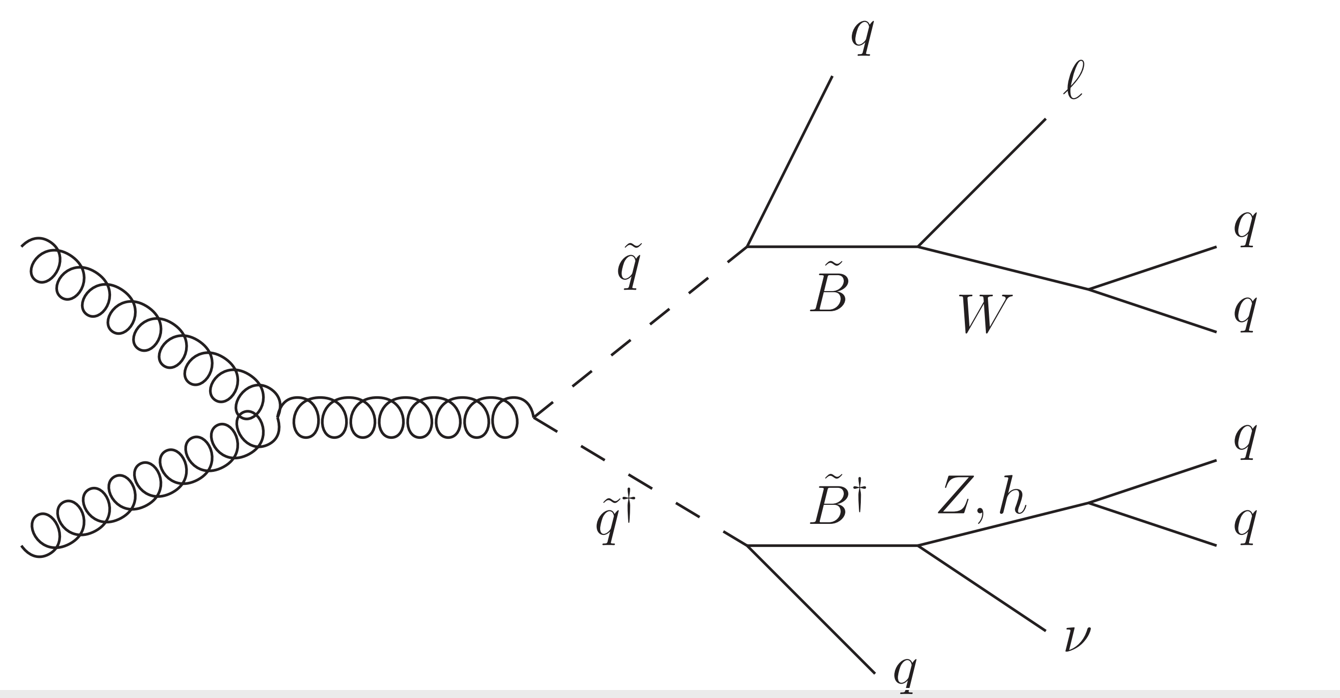
$p_T > 50$ GeV

region of interest

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

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

Biνo signals: jets + leptons



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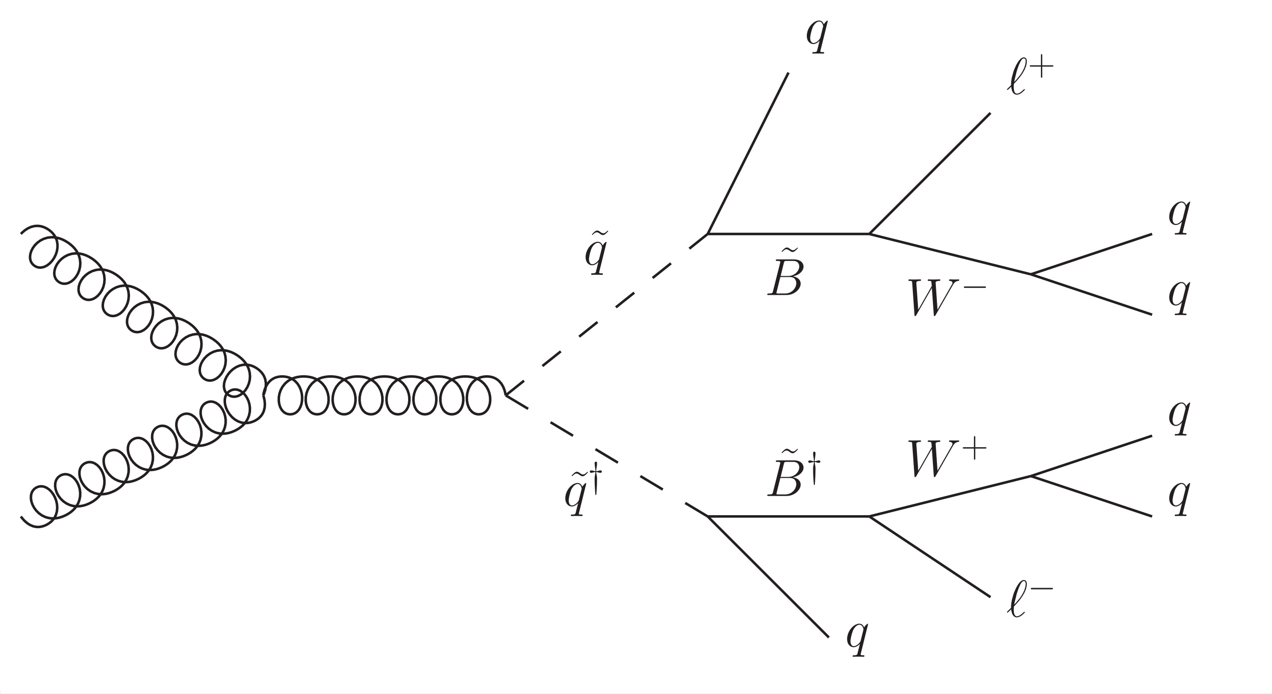

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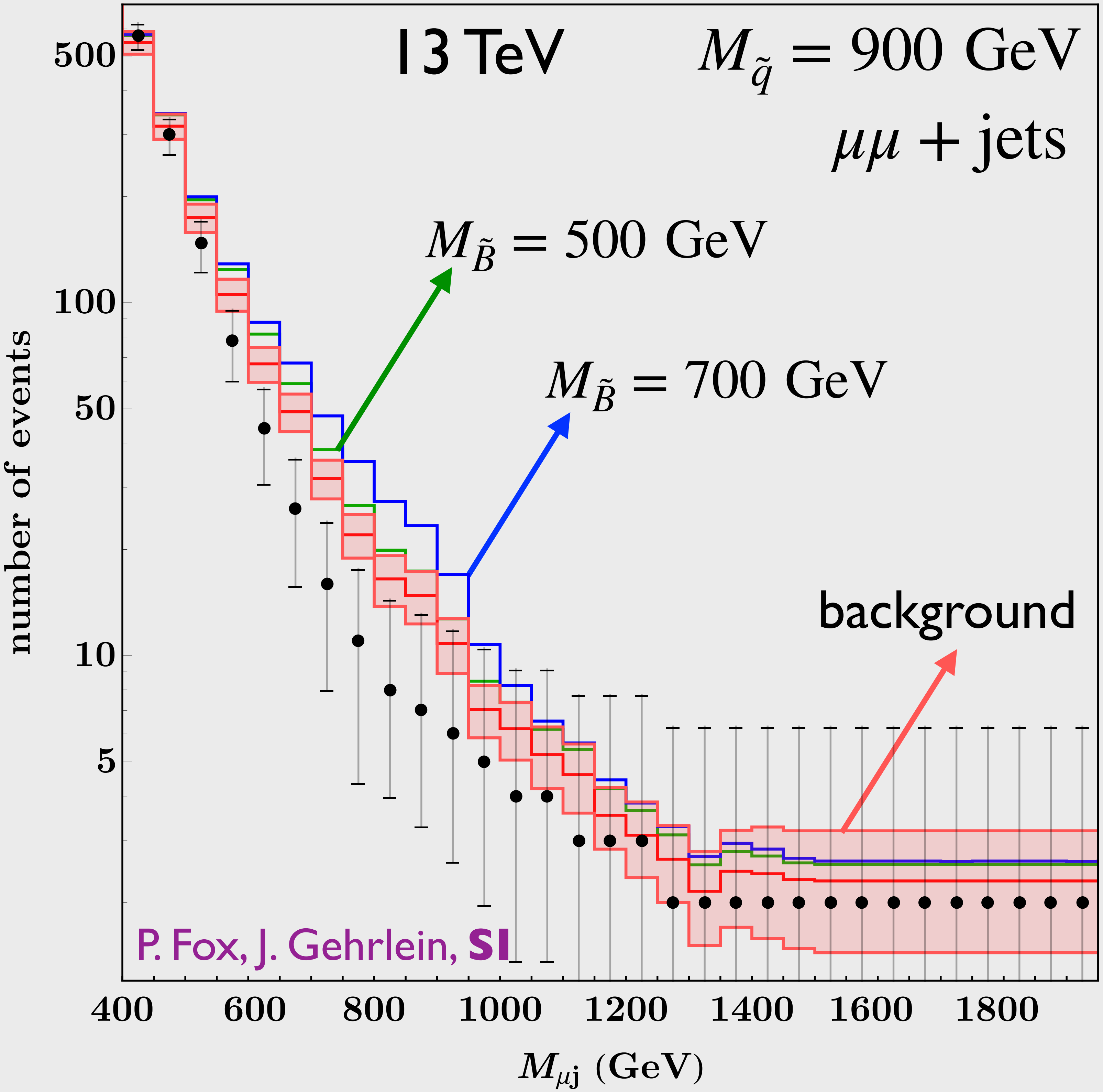
Combining
largest p_T lepton + jet → leptoquark searches:
CMS-EXO-2017-003

No limits from jets + leptons



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

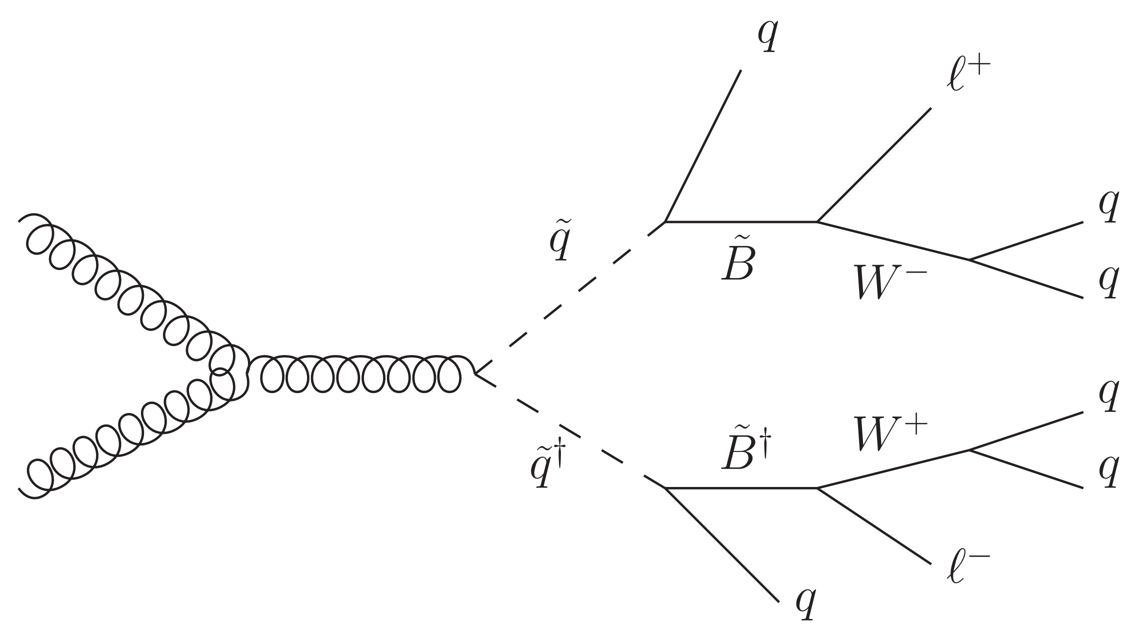
S/B too small

Not quite better than jets+MET, but…

Smoking gun signal

Lepton couplings are determined by the neutrino sector

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

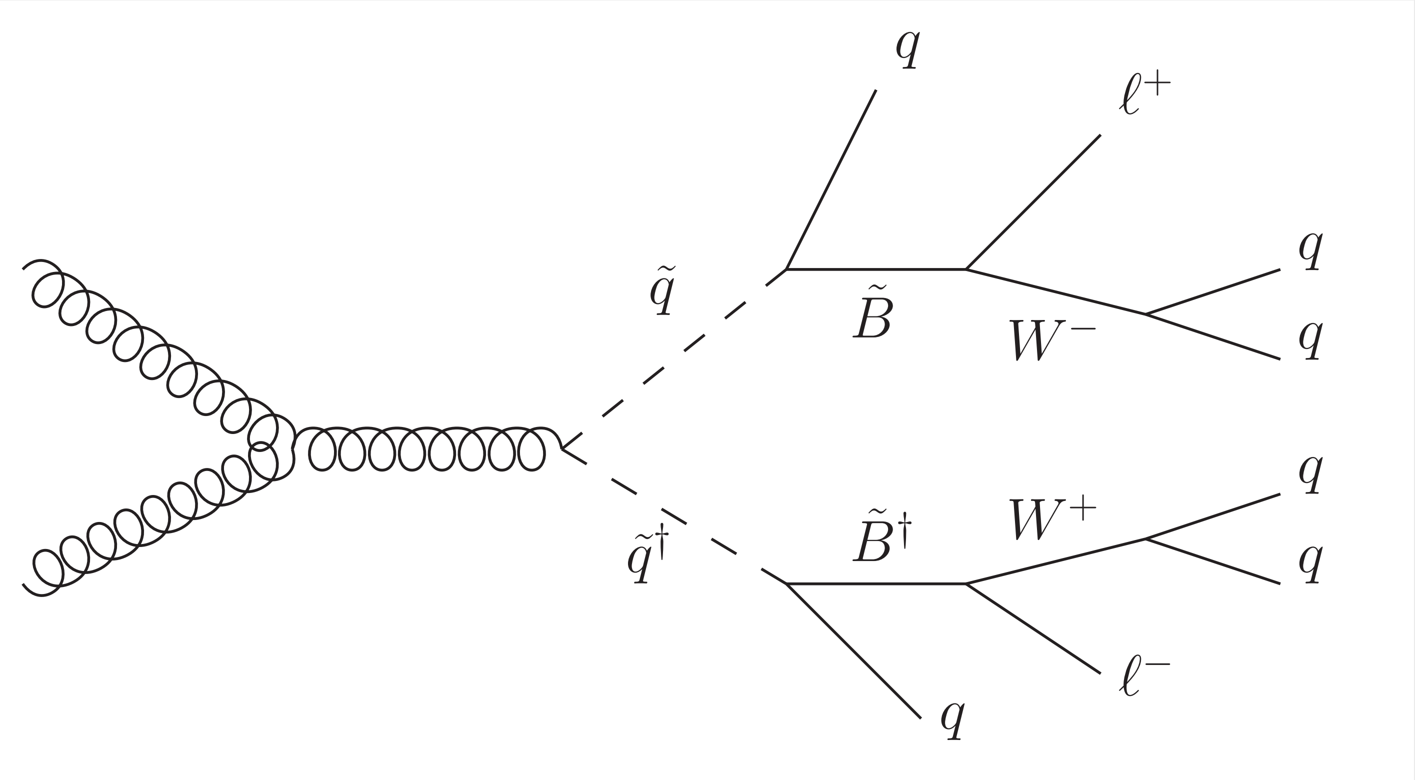


Neutrino oscillation data sets:

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

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 $e\nu : \mu\nu = 1 : 2$

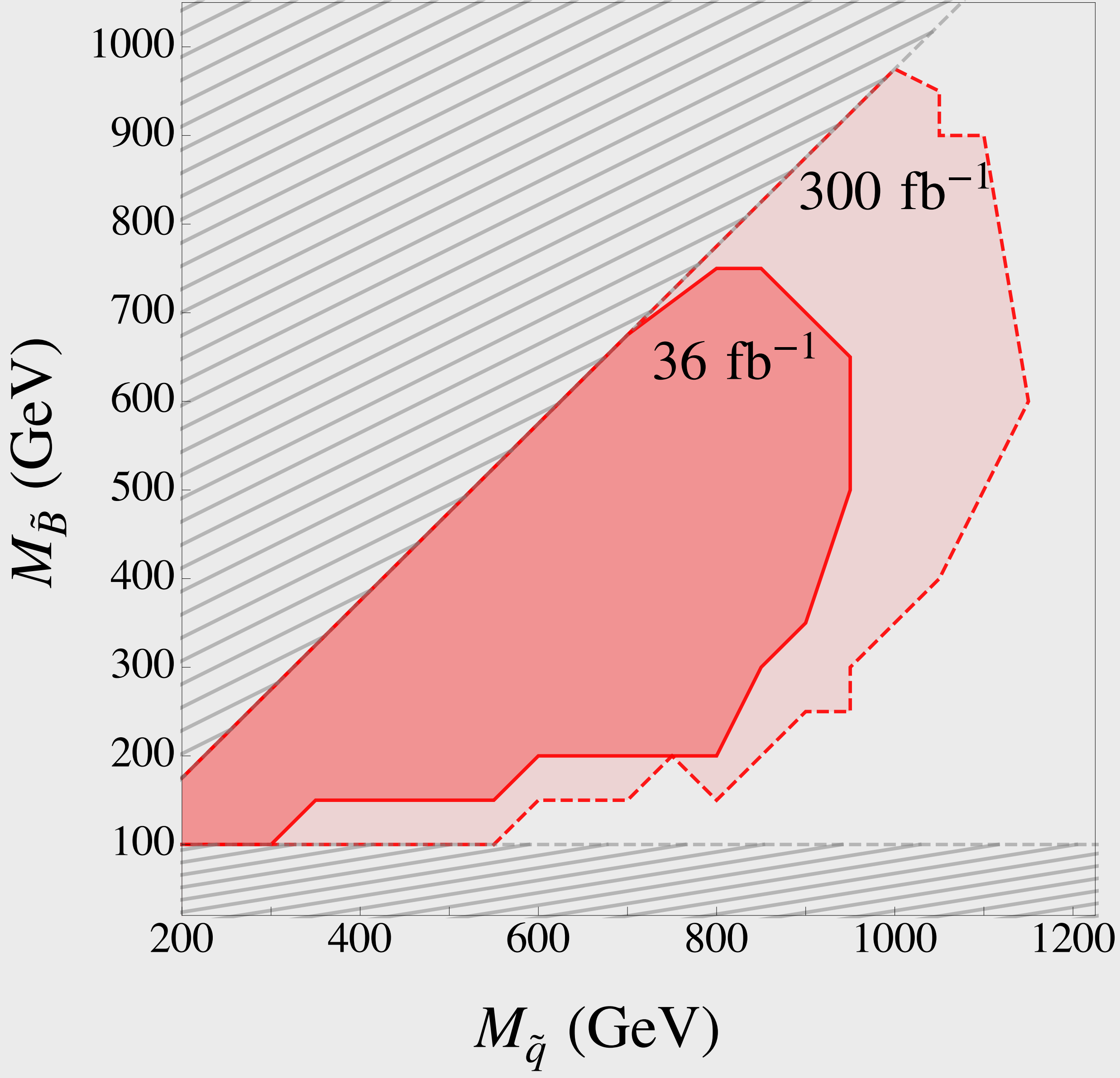
What's next for biνo?

Looking more carefully at leptoquark searches

Are there different cuts for better constraints for biνo?

Light biνo region?

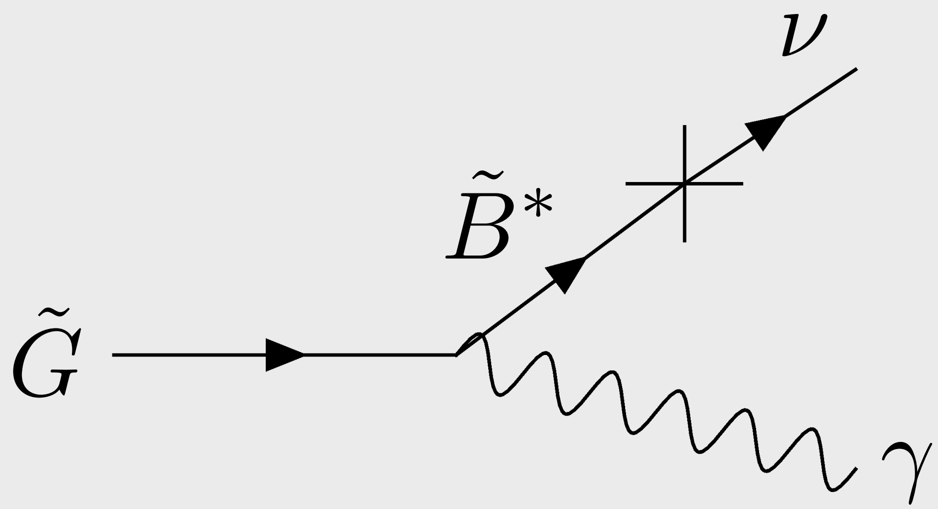
P. Fox, J. Gehrlein, **SI**, arXiv:1901.09284



Gravitino dark matter?

keV gravitino is a viable DM candidate

it can decay via

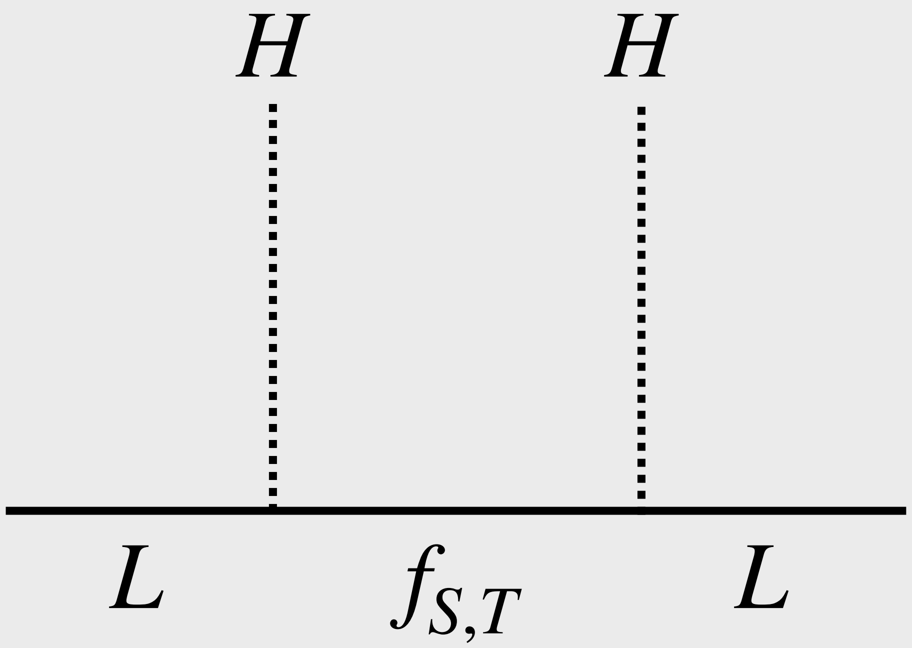


but the lifetime is long enough:

$$\Gamma^{-1}(\tilde{G} \to \nu\gamma) \simeq M_{\rm pl}^2/(\theta^2 m_{3/2}^3) \simeq 10^{39} \text{ s}$$

$\theta \sim \dfrac{v}{\Lambda_M} \sim 10^{-3}$: neutrino-bivo mixing angle

How about the wino?



Type III seesaw: EW triplet fermions

Can the wino be involved in neutrino mass generation?

Outlook

Many *opportunities* to understand the Universe better:
nature of DM, matter—antimatter asymmetry, neutrinos…

↕

Model building + phenomenology

↕

Wide range of experiments:
particle colliders, DM experiments, neutrino experiments…