FLASY 2022 | 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

June 27 - July 1, 2022
IST Congress Centre, Instituto Superior Técnico
Lisbon, Portugal

Organised by Centro de Física Teórica de Partículas (CFTP)

Neutrino phenomenology in the presence of light gauge bosons

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Dirección General de Asuntos del Personal Académico

CONACYT

Based on:

L. Flores, N. Nath, EP, JHEP (2020)
L. Flores, et. al. SBC collaboration PRD (2021)
LMG de la Vega, L. Flores, N. Nath, EP JHEP (2021)
Pita, Flores, EP, Vazquez-Jauregui PRD (2022)
L. M. G. de la Vega and R. Ferro, EP (In progress)

Outline

Light vector bosons

Dark matter

Constraints from CEvNS

Conclusions

Motivations

Erler and Rojas JHEP 2015

Gauge extensions of the SM

$E_6 \to SO(10) \times U(1)$

$SO(10) \to SU(5) \times U(1)$

Impact on low and high energy experiments

Z´ production

Z´effects at low energies

Different couplings

$J_\mu Z'_\mu$

$\delta m^2 Z_\mu Z'_\mu$

$\epsilon B^{\mu\nu} F'_{\mu\nu}$

Seabra´s talk

Light Vector Boson from $U(1)'$

$$\mathscr{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + i g' Z'_{\mu} (Q_f \bar{f} \gamma^{\mu} f)$$

SSB

$$\langle \phi_i \rangle = \frac{v_i}{\sqrt{2}}$$

$$m_{Z'}^2 = \sum_i g' Q_i^2 v_i^2$$

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Small

Low scale

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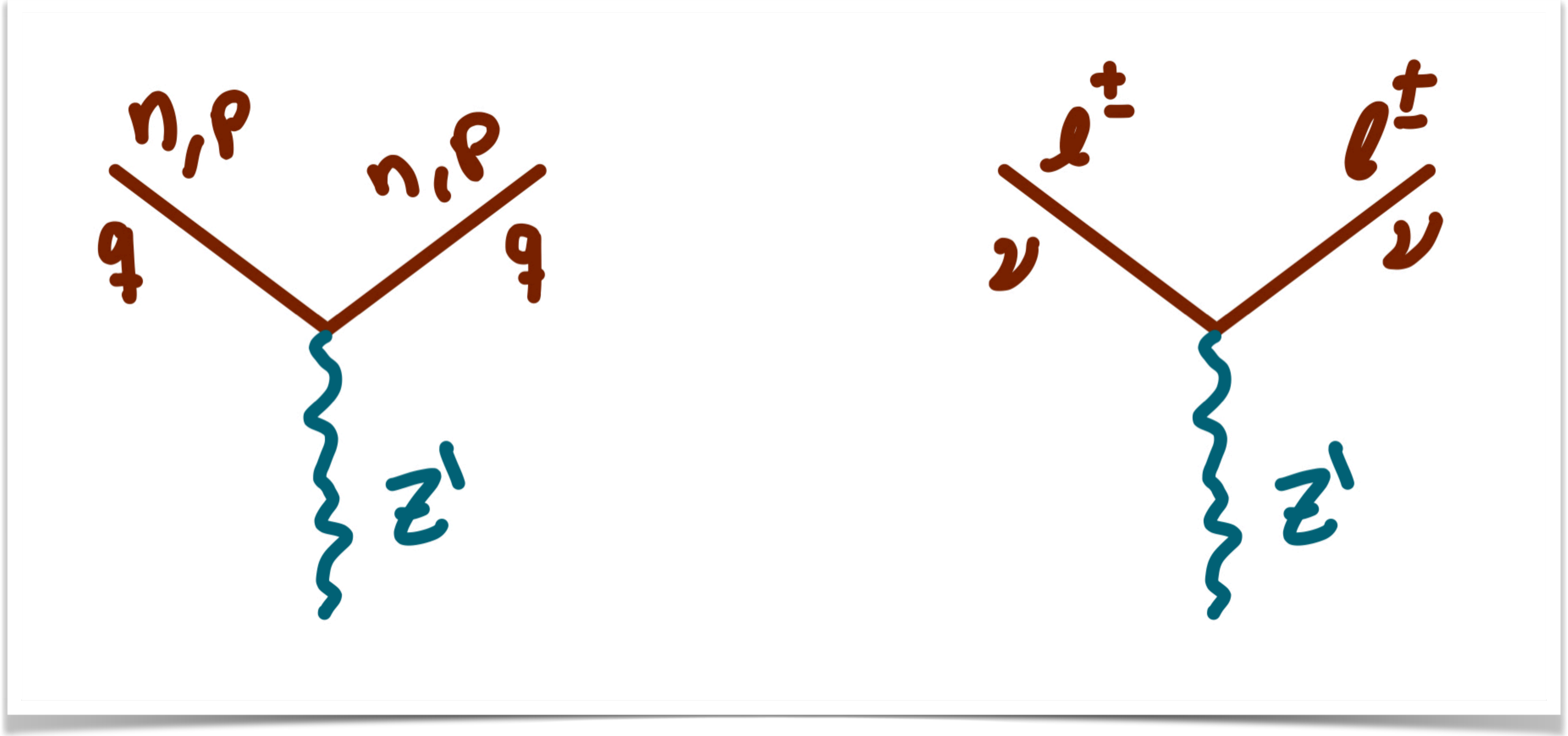
If $Q_f \neq 0$ for quarks



If $Q_f \neq 0$ for leptons

Dark Matter and neutrino nature $U(1)'$

Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

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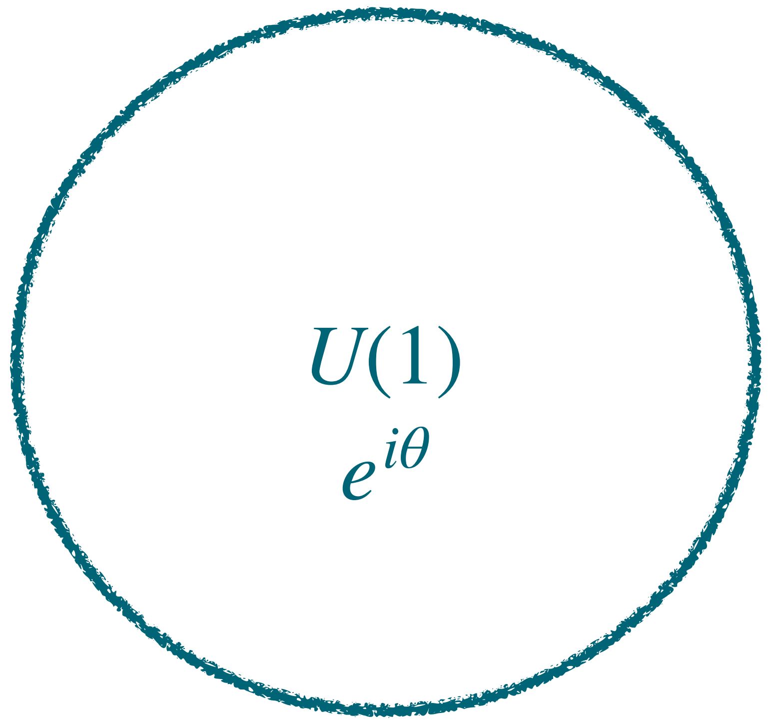


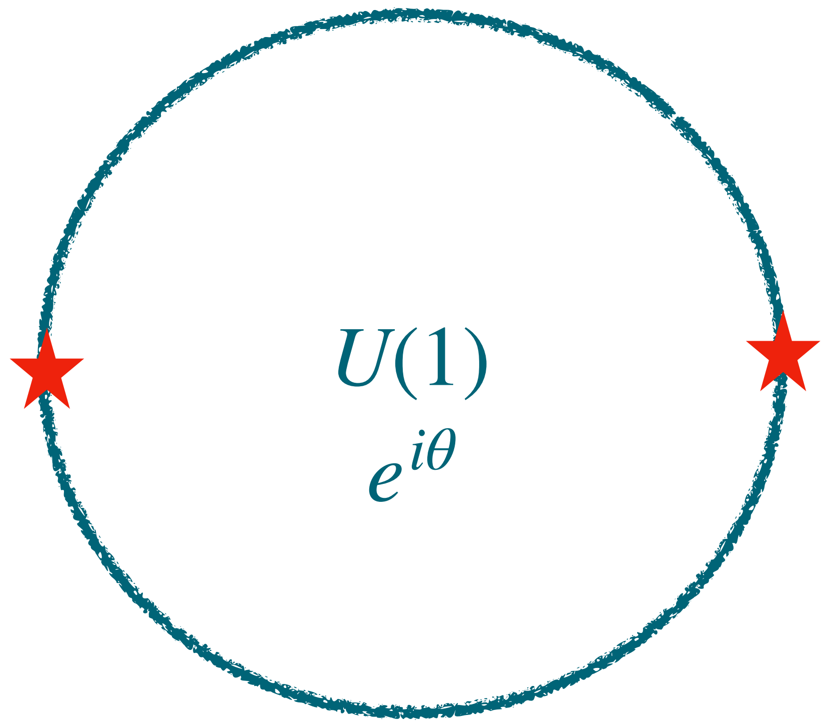
$U(1)$

$e^{i\theta}$

Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

Dark Matter and neutrino nature $U(1)'$

Z_2 ± 1

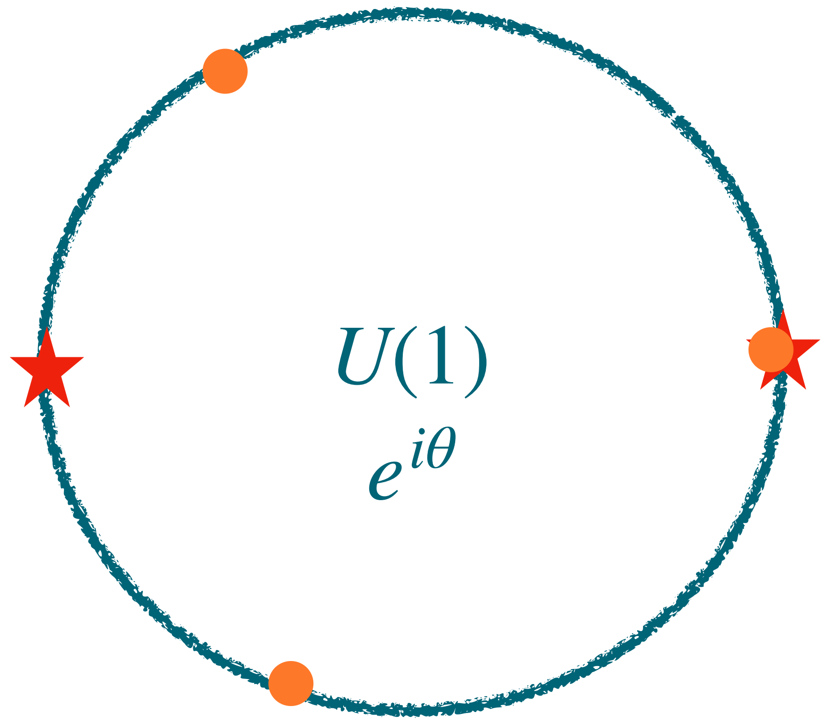


Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

Dark Matter and neutrino nature $U(1)'$

Z_2 ± 1

Z_3 ω^n $\omega = e^{i2/3\pi}$

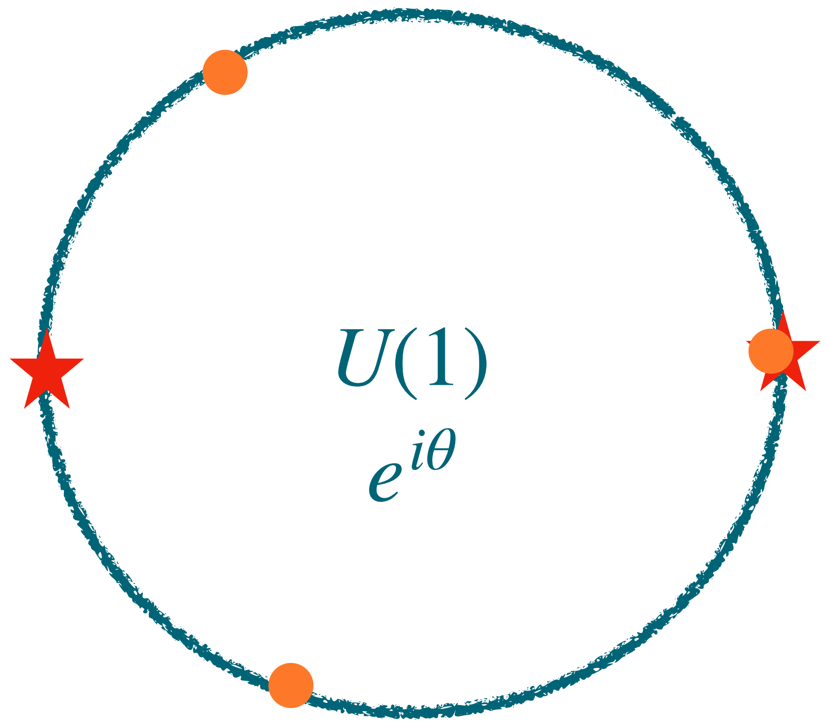


Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

Dark Matter and neutrino nature $U(1)'$

$Z_2 \quad \pm 1$

$Z_3 \quad \omega^n \qquad \omega = e^{i2/3\pi}$



Krauss and Wilczek (1988)

Toy example

$$\phi \to e^{im\theta}\phi \qquad \chi \to e^{-in\theta}\chi$$

$$m < n \qquad V \supset \phi^y \chi$$

SSB $\langle \chi \rangle \neq 0$

$$V \supset \phi^y$$

$$U(1)' \to Z_N \qquad N = \frac{n}{m}$$

Can be used for DM stability

$U(1)'$ global or local

Bonilla, Centelles-Chulia, Cepedello, EP, Srivastava (2018)

Up to now only COHERENT SNS detected

De Romeri and Marfatia talks on Friday
Hati on Thursday

$$p \longrightarrow Hg$$

$$\pi^- \quad (99.9\,\%\ captured\ by\ Hg)$$

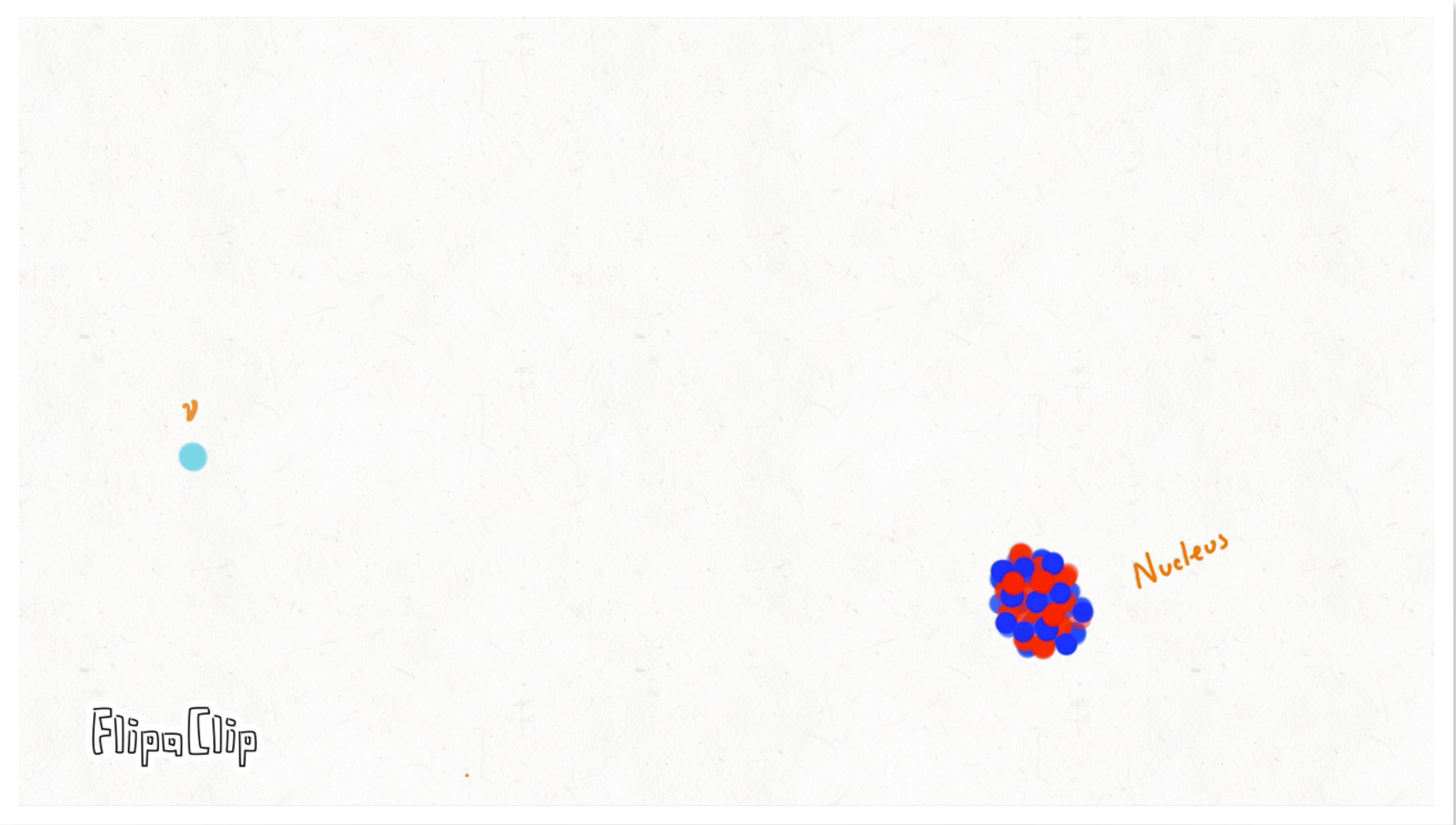
$$\pi^+ \rightarrow \mu^+ + \nu_\mu (29.9\ MeV)$$

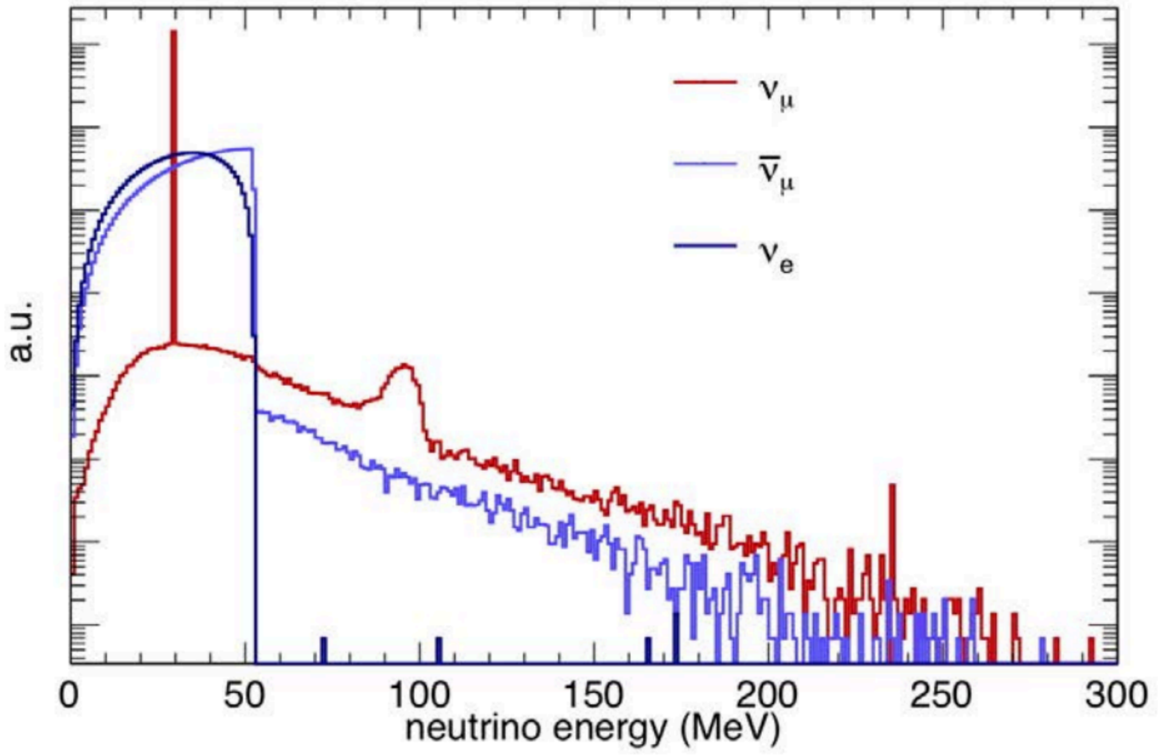
$$e^+ + \bar{\nu}_\mu + \nu_e$$

14.6 Kg **CsI** 134 events (~300 day)

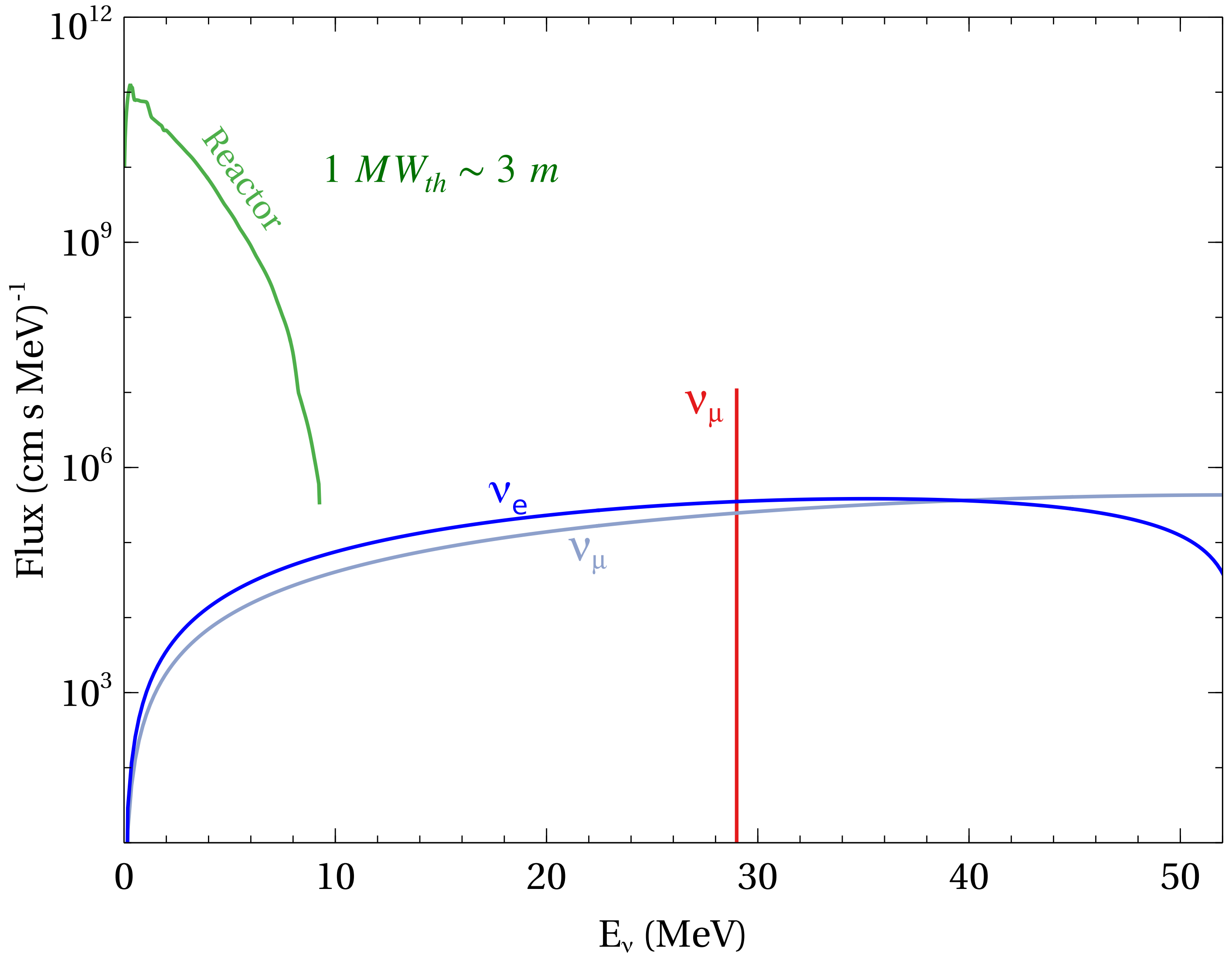
24 Kg **Ar** 159 events (~ 240 days)

Ar will continue …





$$T_{max} = 2\frac{E_\nu^2}{M}$$



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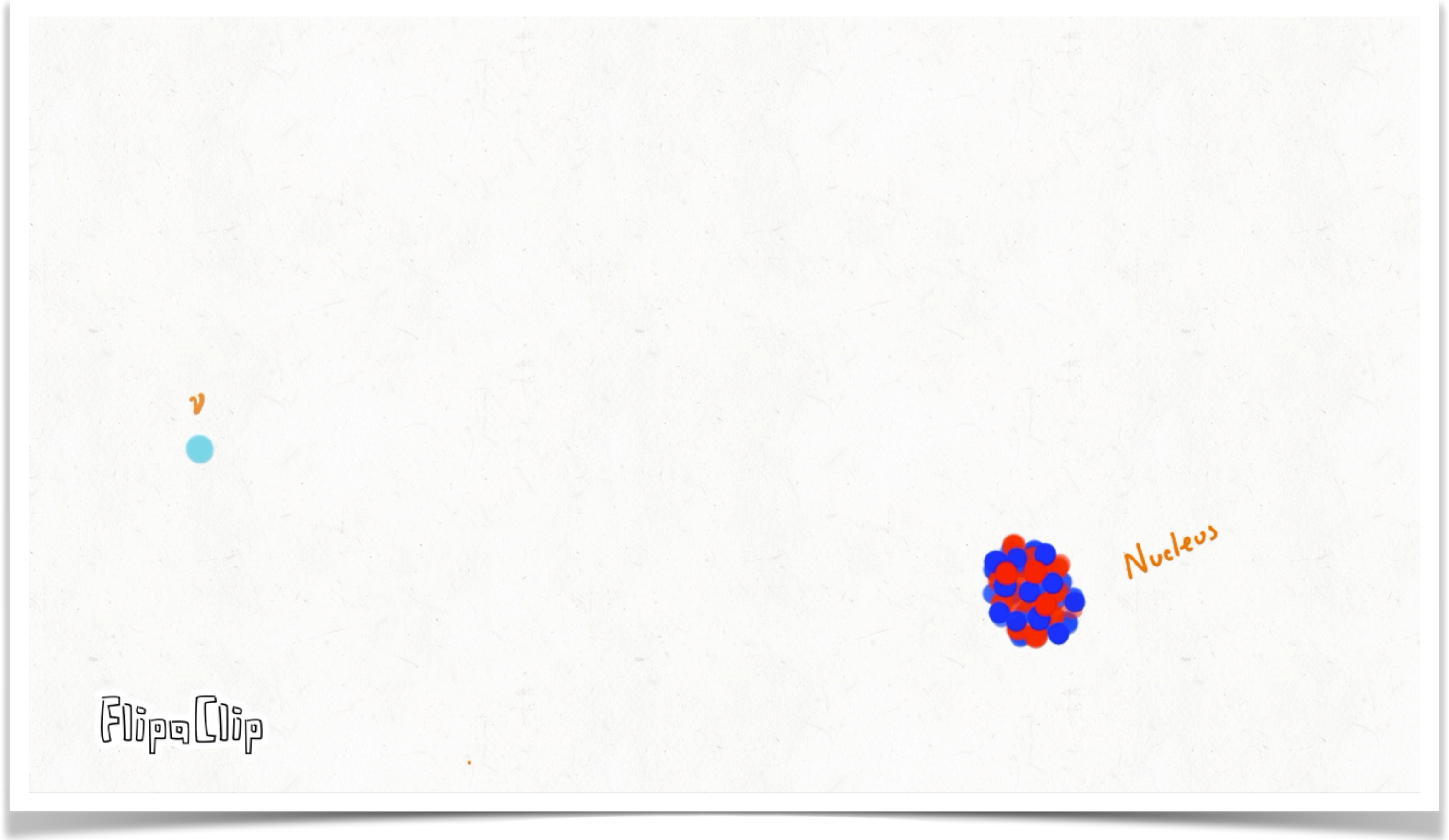

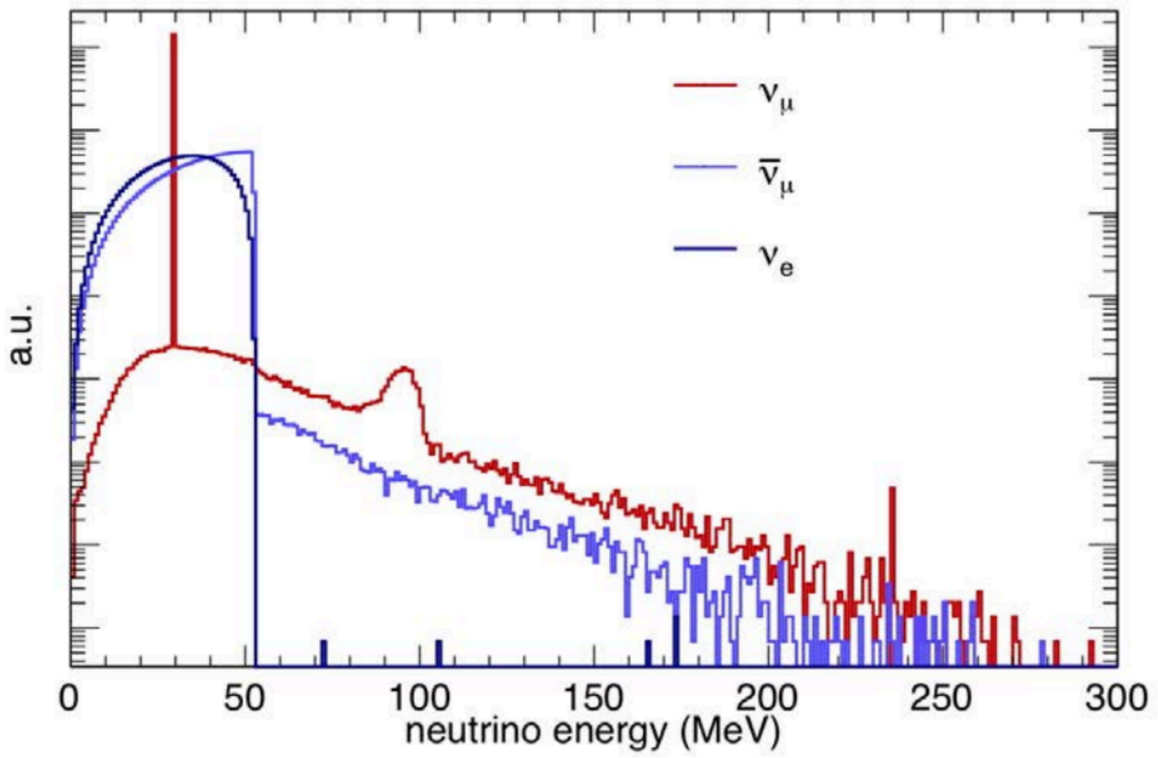

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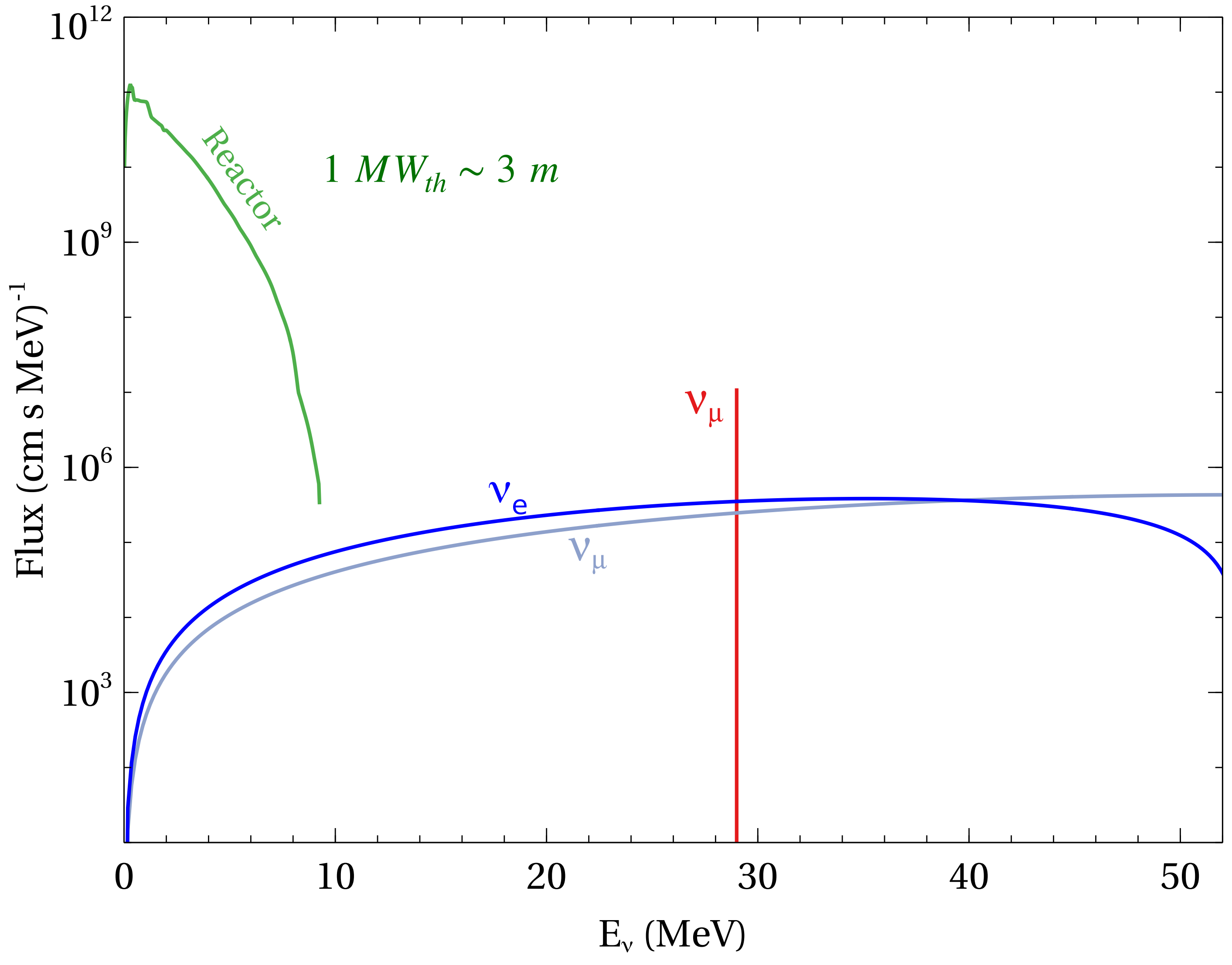

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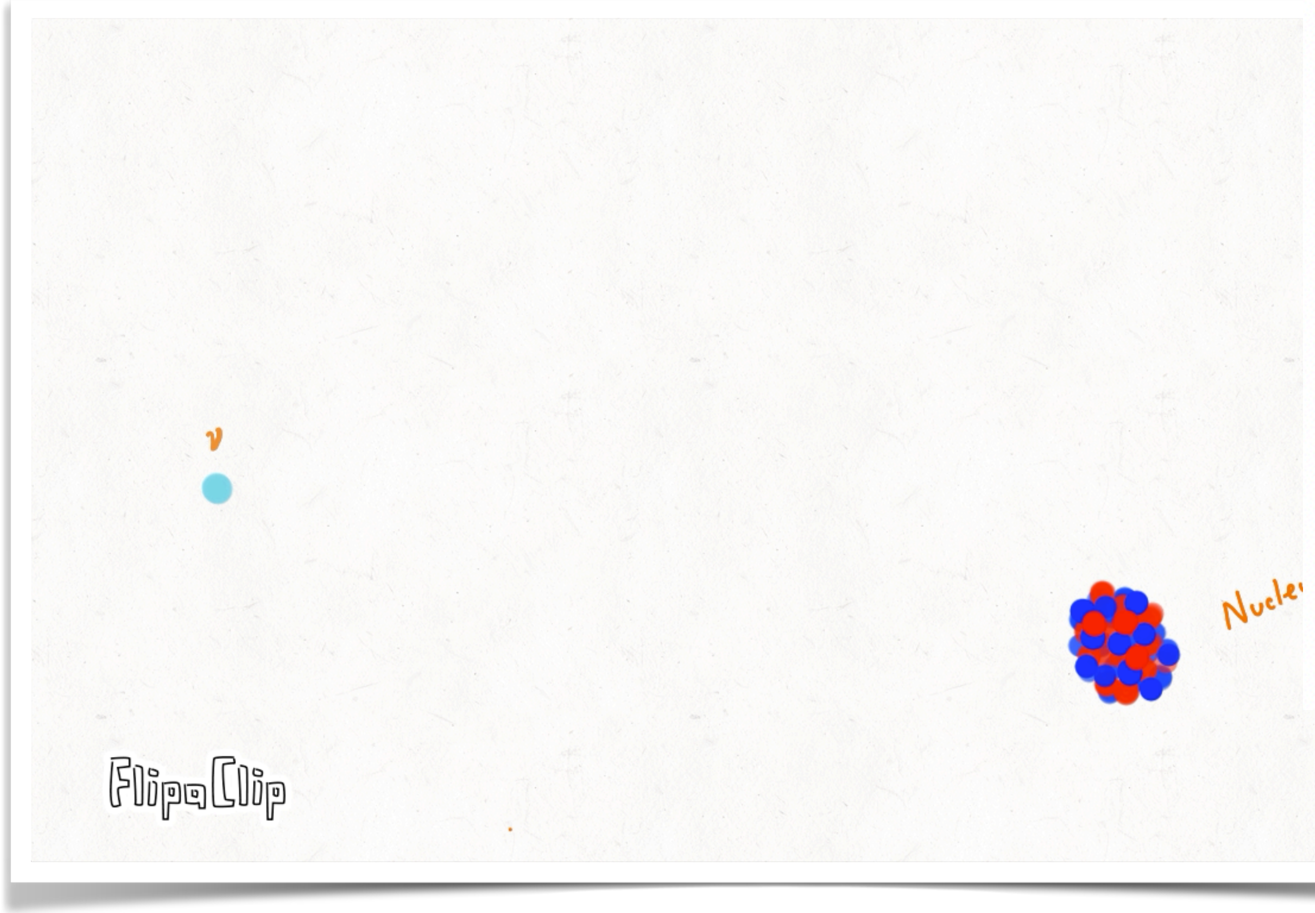
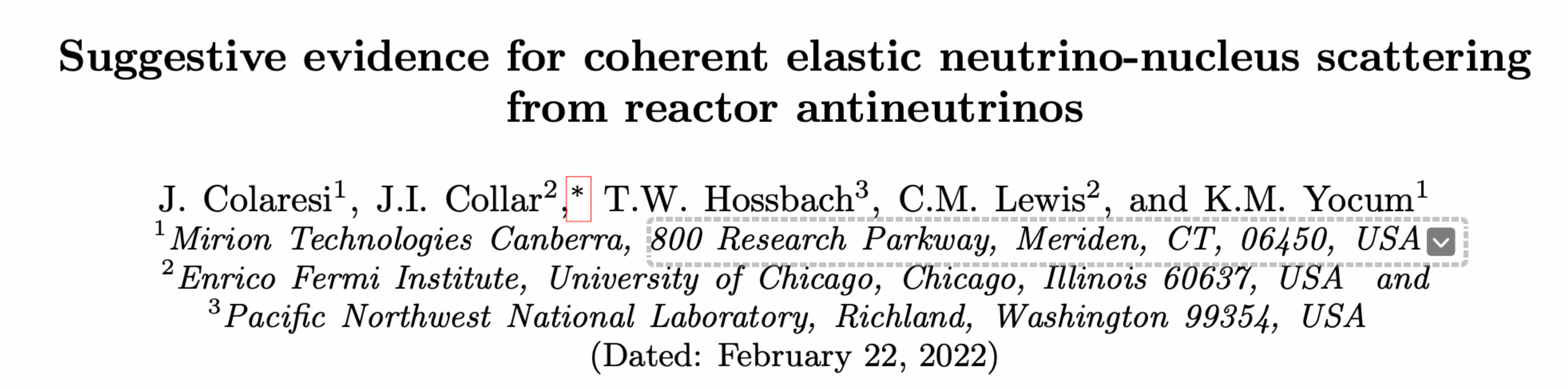
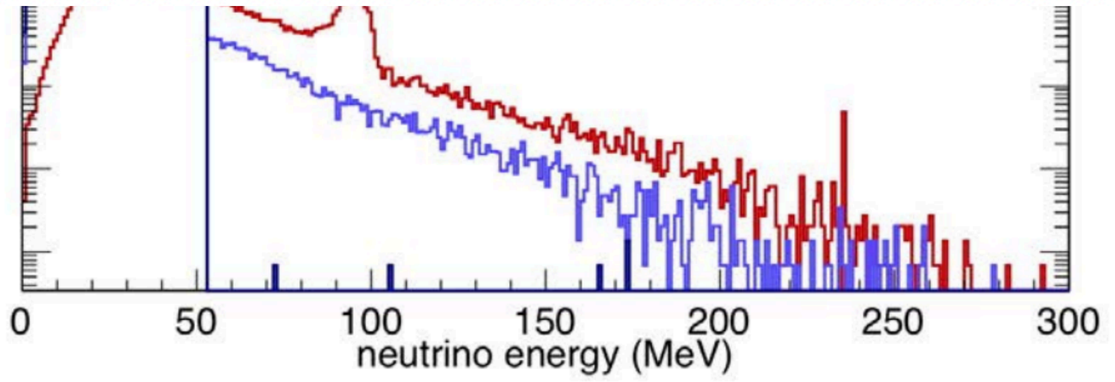


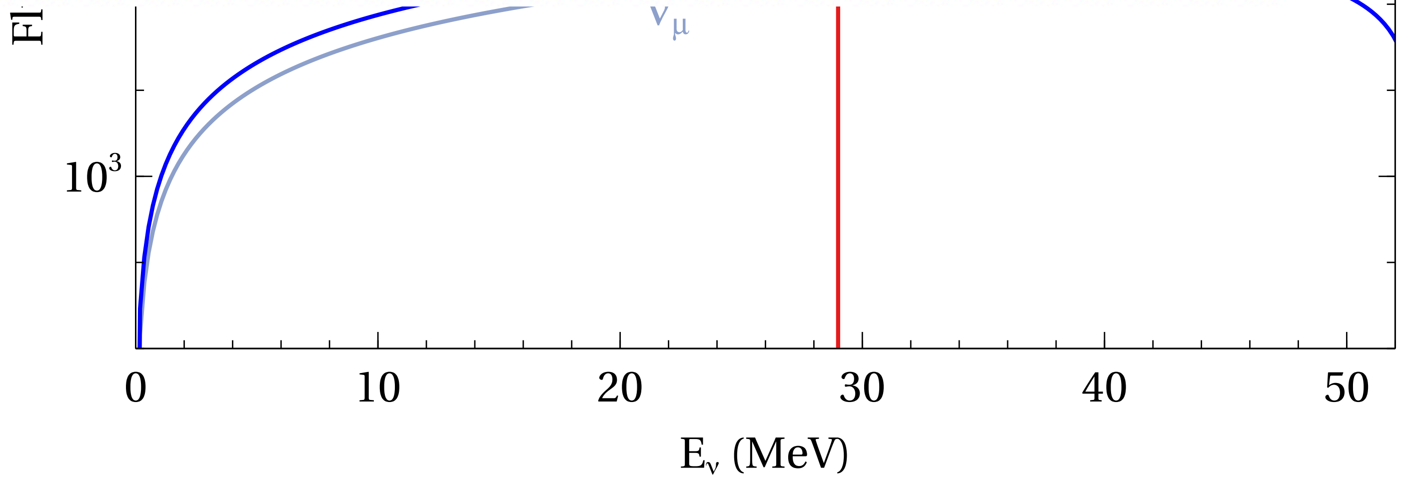


Suggestive evidence for coherent elastic neutrino-nucleus scattering from reactor antineutrinos

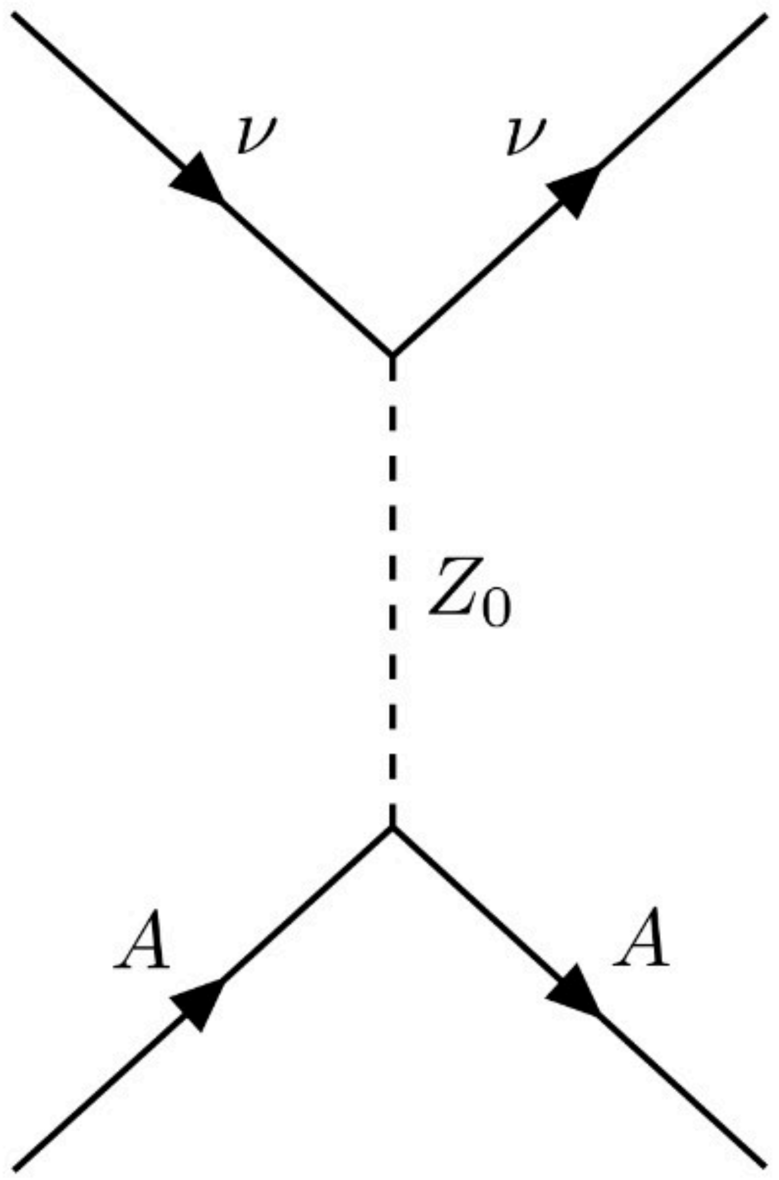
J. Colaresi[1], J.I. Collar[2],* T.W. Hossbach[3], C.M. Lewis[2], and K.M. Yocum[1]
[1] *Mirion Technologies Canberra, 800 Research Parkway, Meriden, CT, 06450, USA*
[2] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA* and
[3] *Pacific Northwest National Laboratory, Richland, Washington 99354, USA*

(Dated: February 22, 2022)





CEvNS cross section



$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right)$$

Weak charge

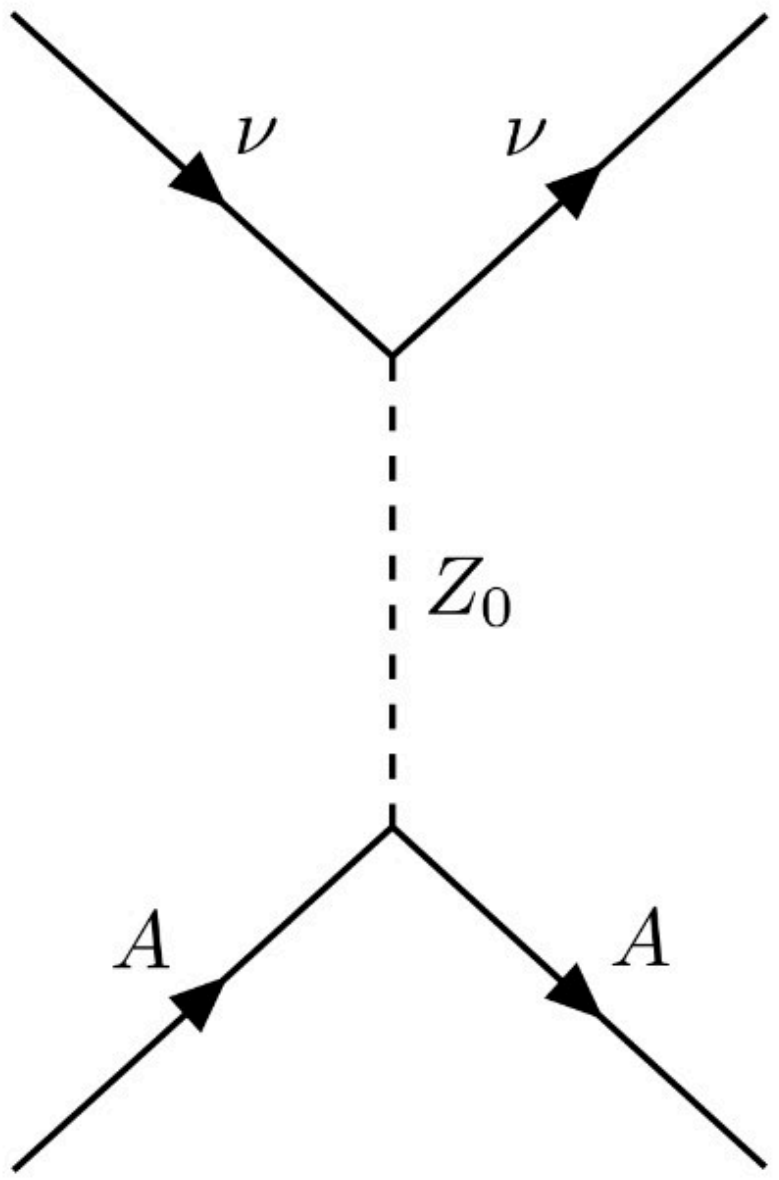
$$Q_w^2 = \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2)\right]^2$$

$$Q_{w\,\alpha}^2 = \left[Z(g_p^V + \boxed{2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{dV})} F_Z(q^2) + N(g_n^V + \boxed{\epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{dV})} F_N(q^2)\right]^2$$

NSI

J. Barranco, O. G. Miranda, and T. I. Rashba JHEP, 12:021, 2005.
A. Drukier and Leo Stodolsky Phys. Rev., D30:2295, 1984

CEvNS cross section



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Weak charge

$$Q_w^2 = \left[Z g_p^V F_Z(q^2) + \boxed{N} g_n^V F_N(q^2)\right]^2$$

$$\frac{d\sigma}{dT} \propto N^2$$

$$Q^2_{w\,\alpha} = \left[Z(g_p^V + \boxed{2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha}})F_Z(q^2) + N(g_n^V + \boxed{\epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha}})F_N(q^2)\right]^2$$

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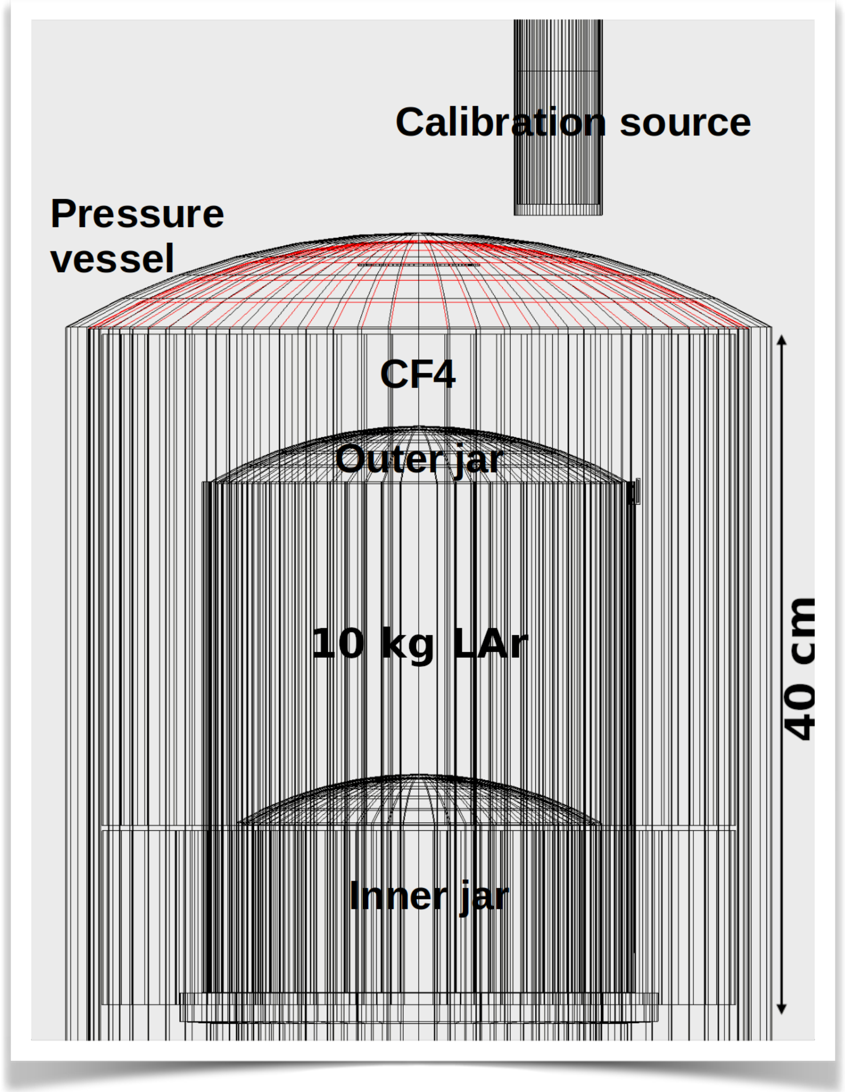
SBC collaboration

L. Flores, et. al. SBC collaboration PRD (2021)



100 eV threshold

Currently under construction

10 kg at 3 m a 1-MW_{th} reactor

100 kg at 30 m from a 2000-MW_{th} power reactor

E. Alfonso-Pita

10 kg liguid Argon bubble chamber similar to PICO detector

T~90-130 ^oK
P~2 atm

A TRIGA Mark III research ININ

~8 neutrino events/day

~2,900 neutrino events in 1 year

~320 background events cosmogenic

~140 background events Neutrons from reactor

Laguna Verde

~1570 neutrino events/day

~570 K neutrino events in 1 year

~68 K background events cosmogenic

Light Vector Boson from $U(1)'$

L. Flores, et. al. SBC collaboration (2021)

$$\mathscr{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + i g' Z'_{\mu}(Q_f \bar{f}\gamma^{\mu} f)$$

SSB

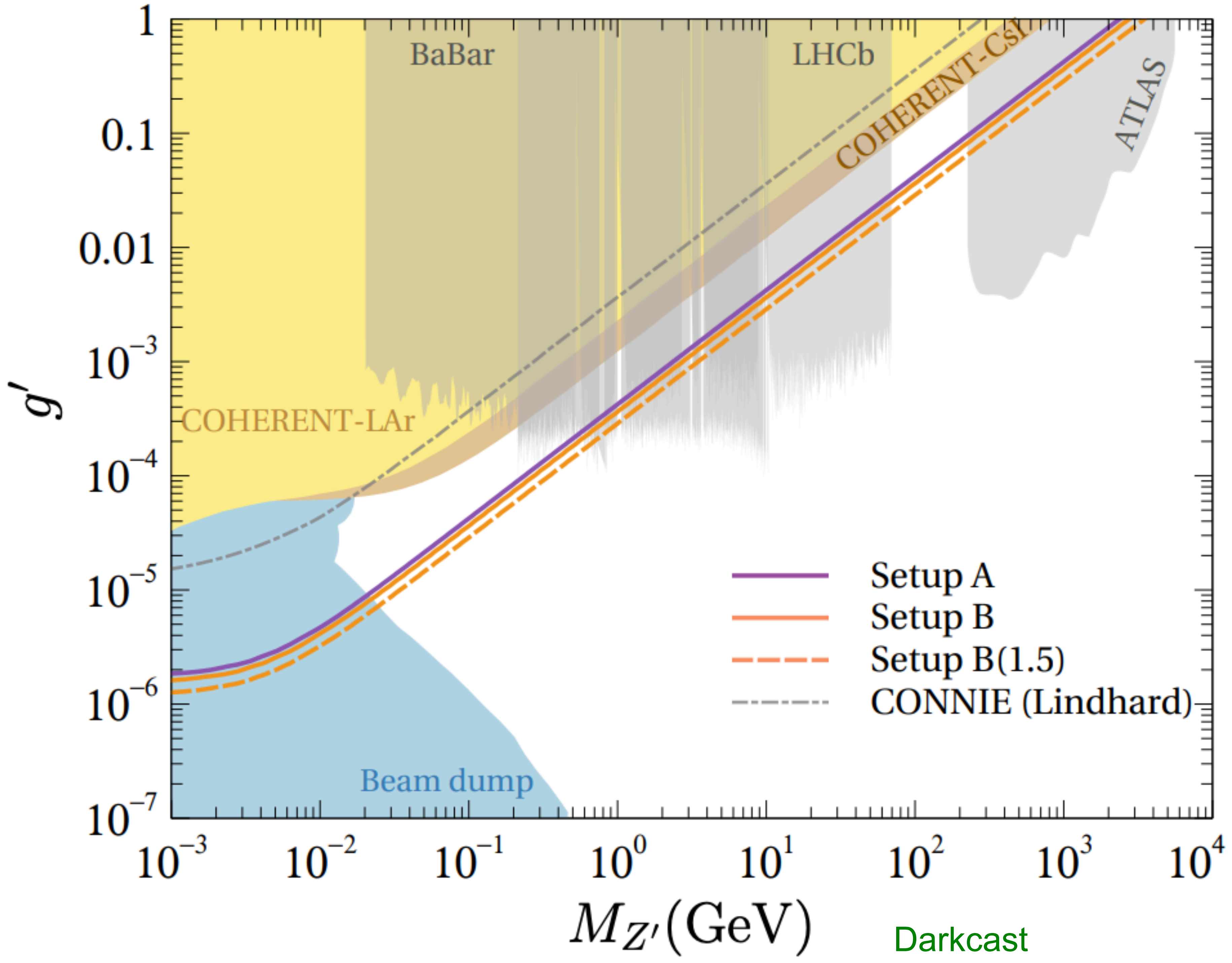
$$\langle\phi_i\rangle = \frac{v_i}{\sqrt{2}}$$

$$m_{Z'}^2 = \sum_i g' Q_i^2 v_i^2$$

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

NSI

$$\mathcal{L}_{\rm eff} = -\frac{g'^2 Q_l Q_q}{q^2+M_{Z'}^2}\left[\sum_\alpha \bar{\nu}_\alpha\gamma^\mu P_L\nu_\alpha\right]\left[\sum_q \bar{q}\gamma_\mu q\right]$$



Darkcast
Ilten, Soreq, Williams and Xue, JHEP (2018)

L. Flores, et. al. SBC collaboration (2021)

Weak mixing angle $\sin^2 \theta_W$

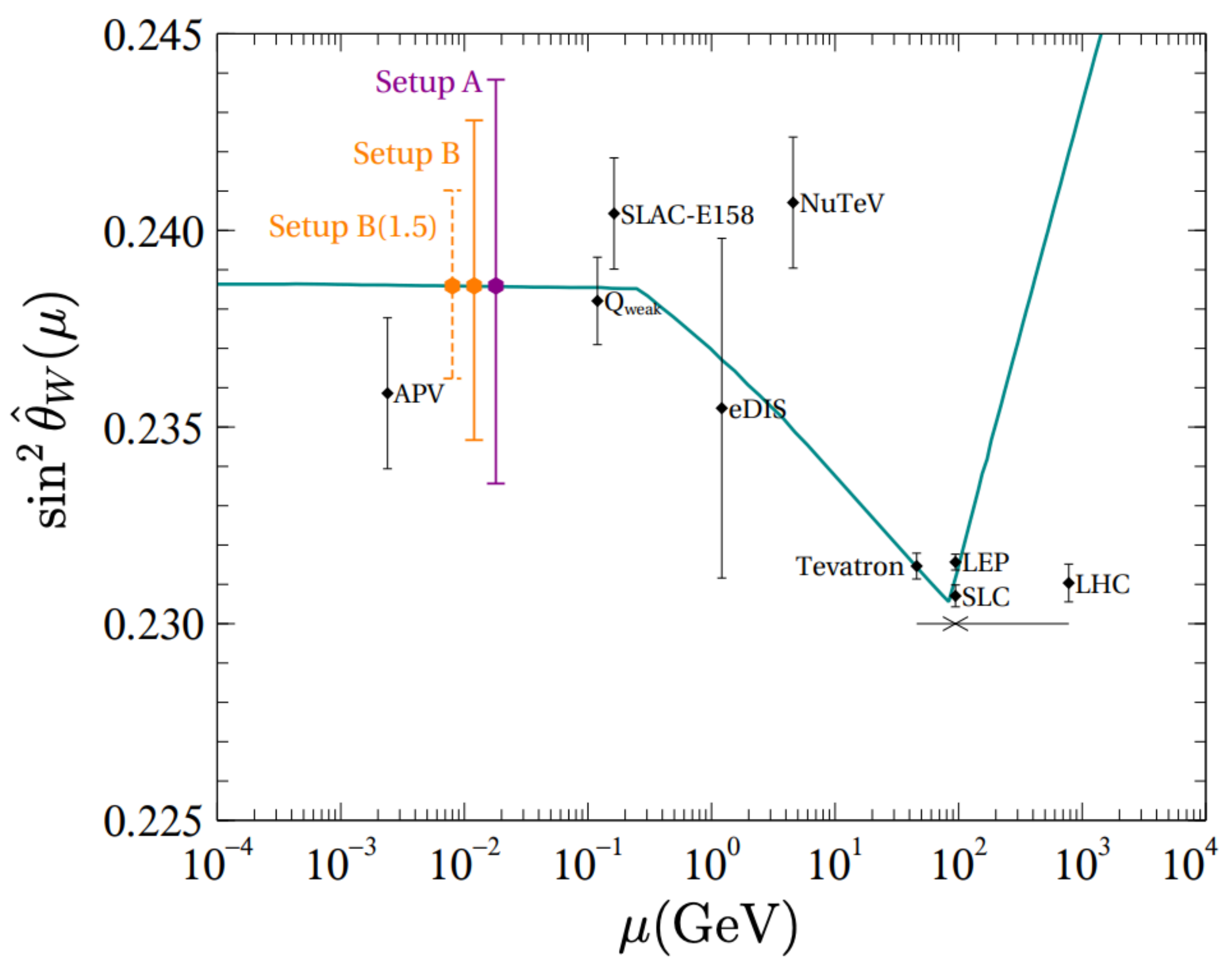
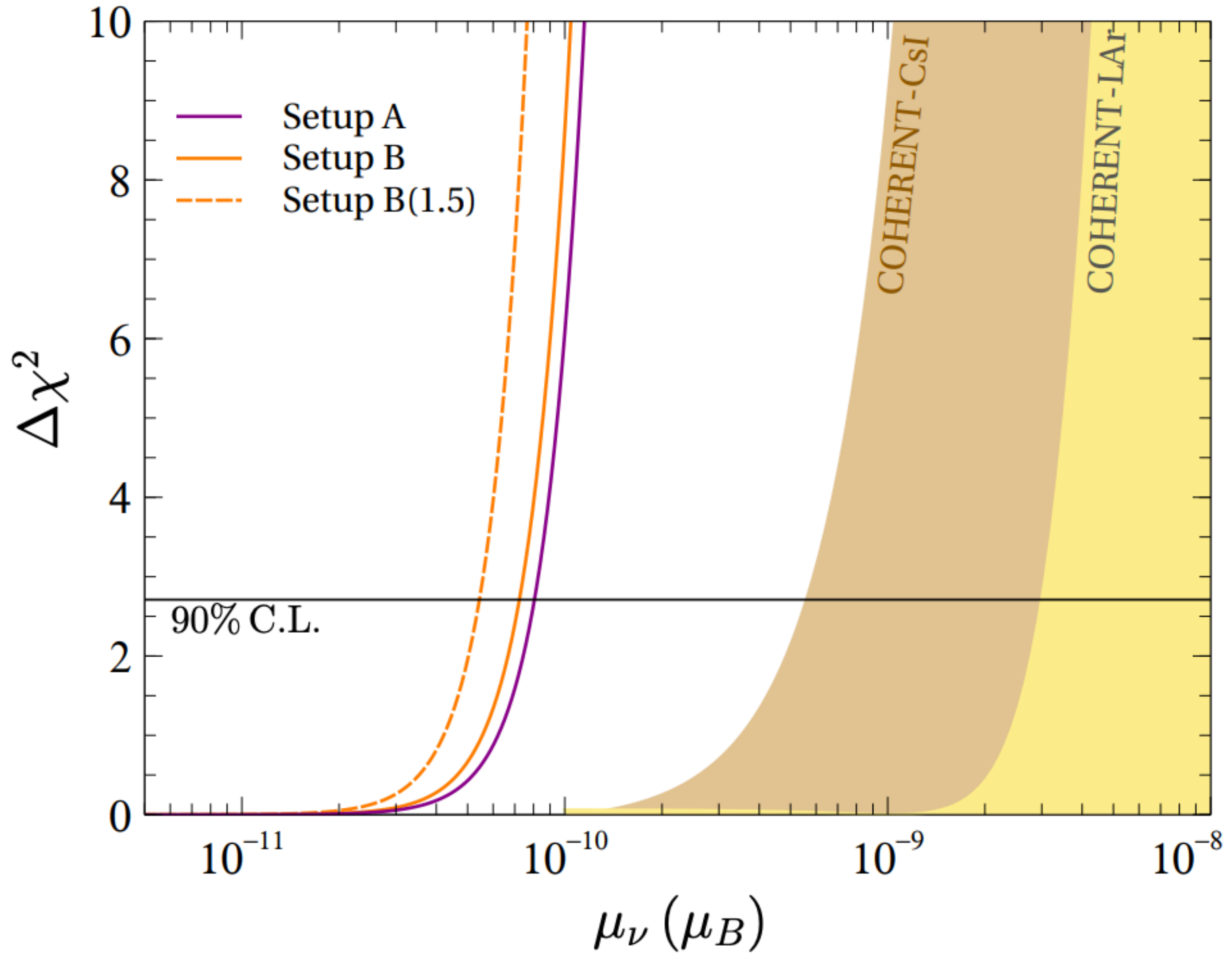


FIG. 1: RGE running of the weak mixing angle in the $\overline{\text{MS}}$ renormalization scheme [39, 40], as a function of the energy scale μ. The expected measurements and 1σ uncertainties for setups A, B and B(1.5) are shown in solid purple, solid orange, and dashed orange, respectively. Measurements from other experiments are also presented. Figure adapted from [39].

Neutrino magnetic moment

$$\frac{d\sigma}{dT} = \pi \frac{\alpha_{\text{EM}}^2 Z^2 \mu_\nu^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu} + \frac{T}{4E_\nu^2} \right) F^2(q^2)$$



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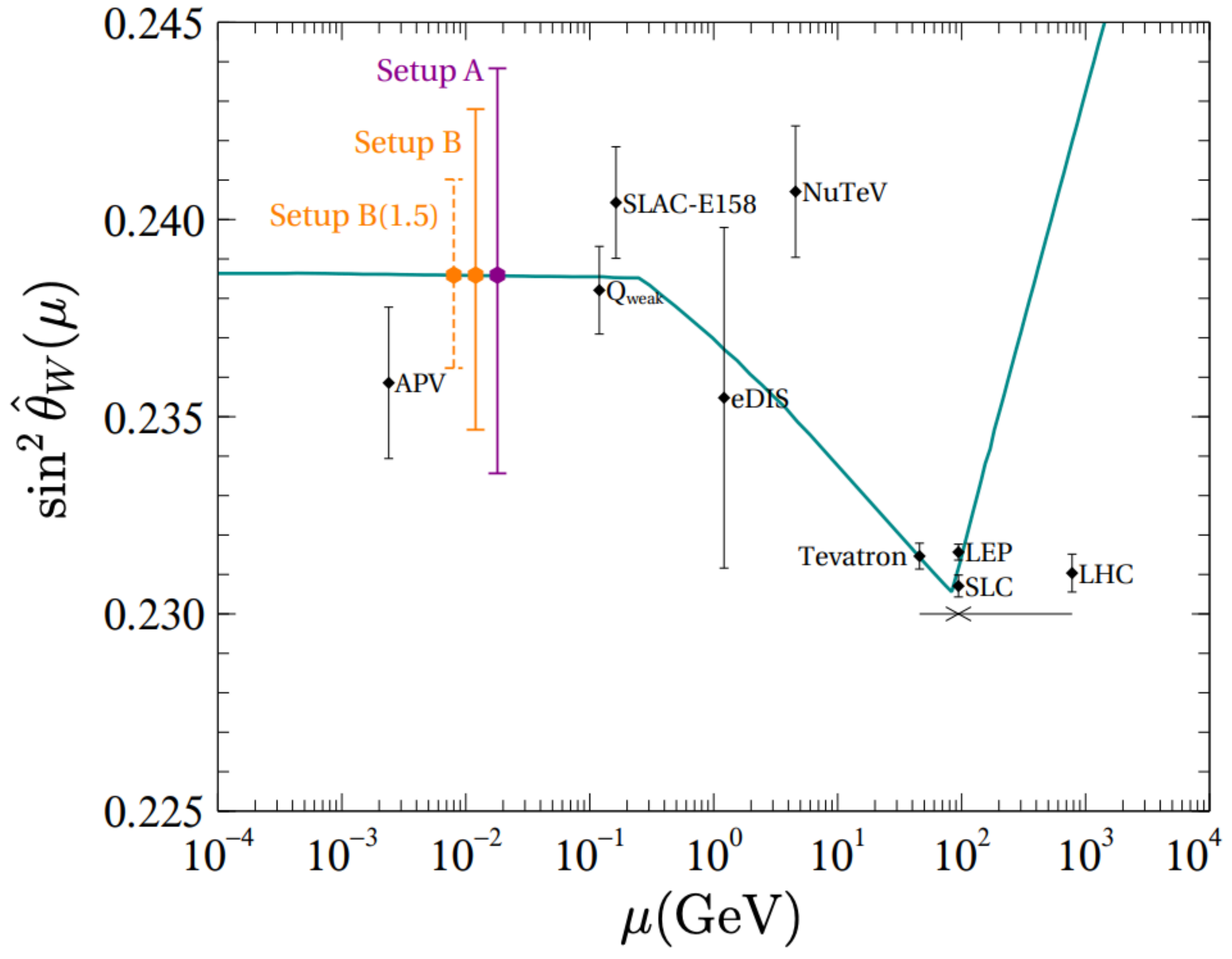
L. Flores, et. al. SBC collaboration (2021)



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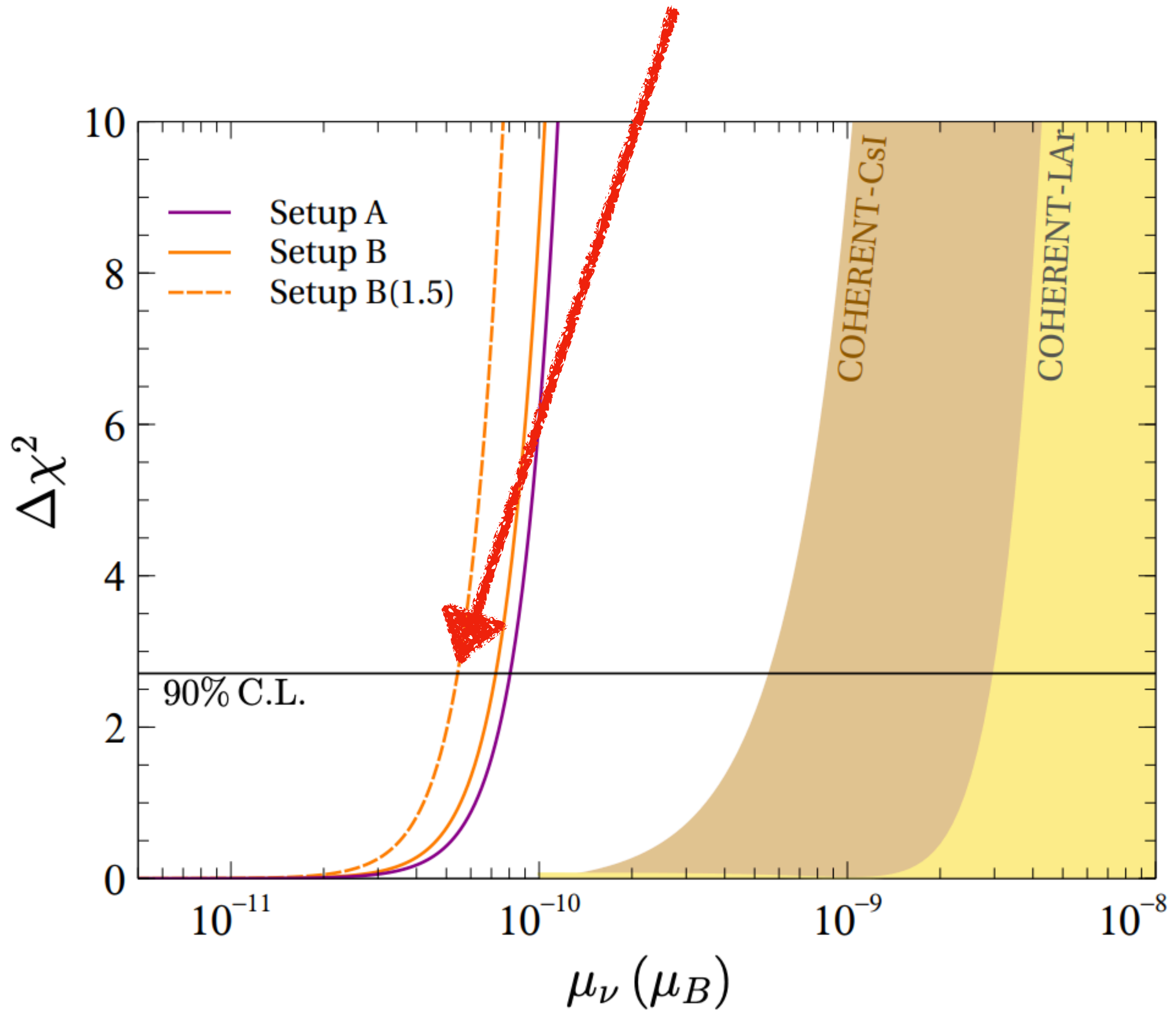
$5.4\times10^{-11}\ \mu_B\quad(90\,\%\,C.L.)$



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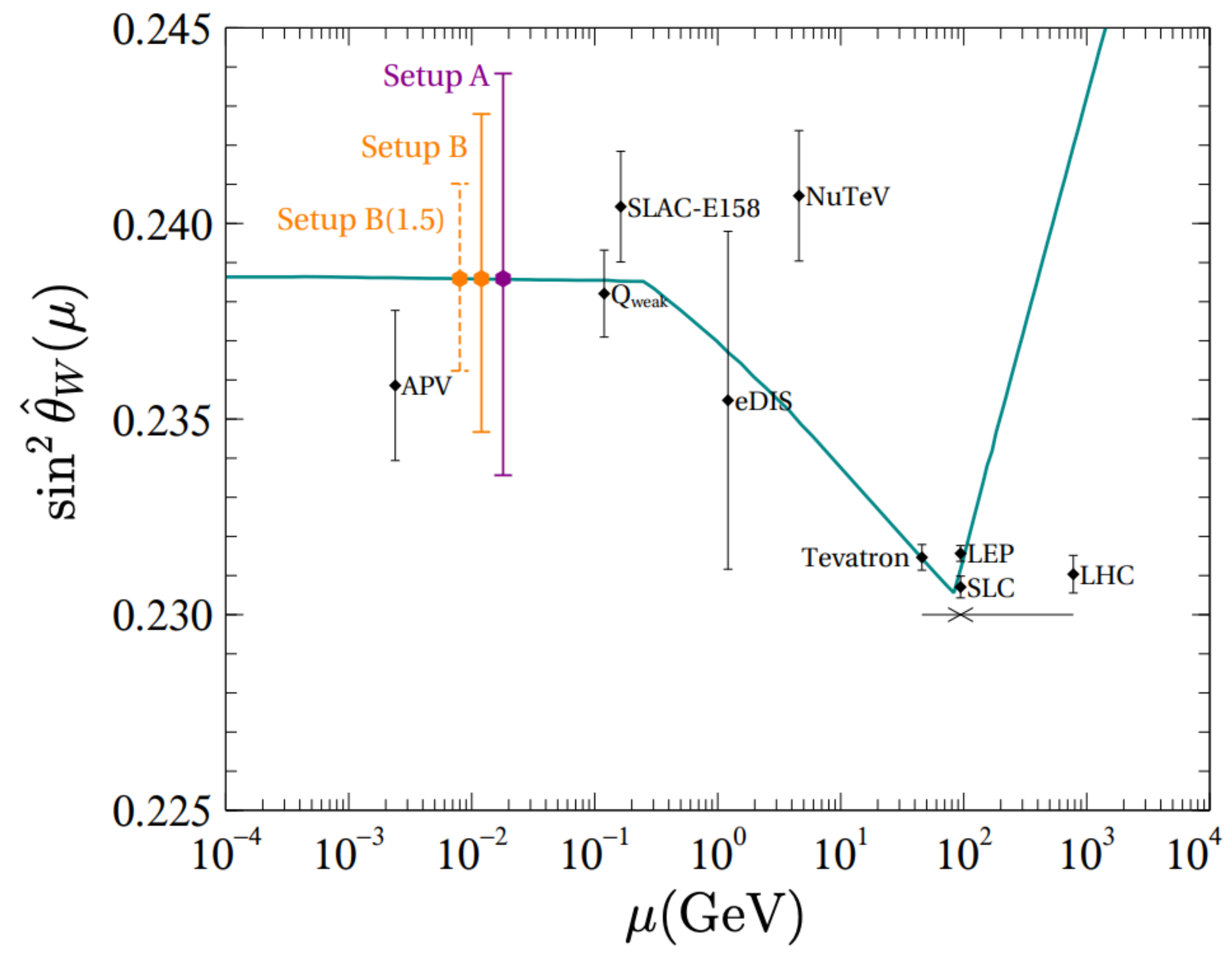

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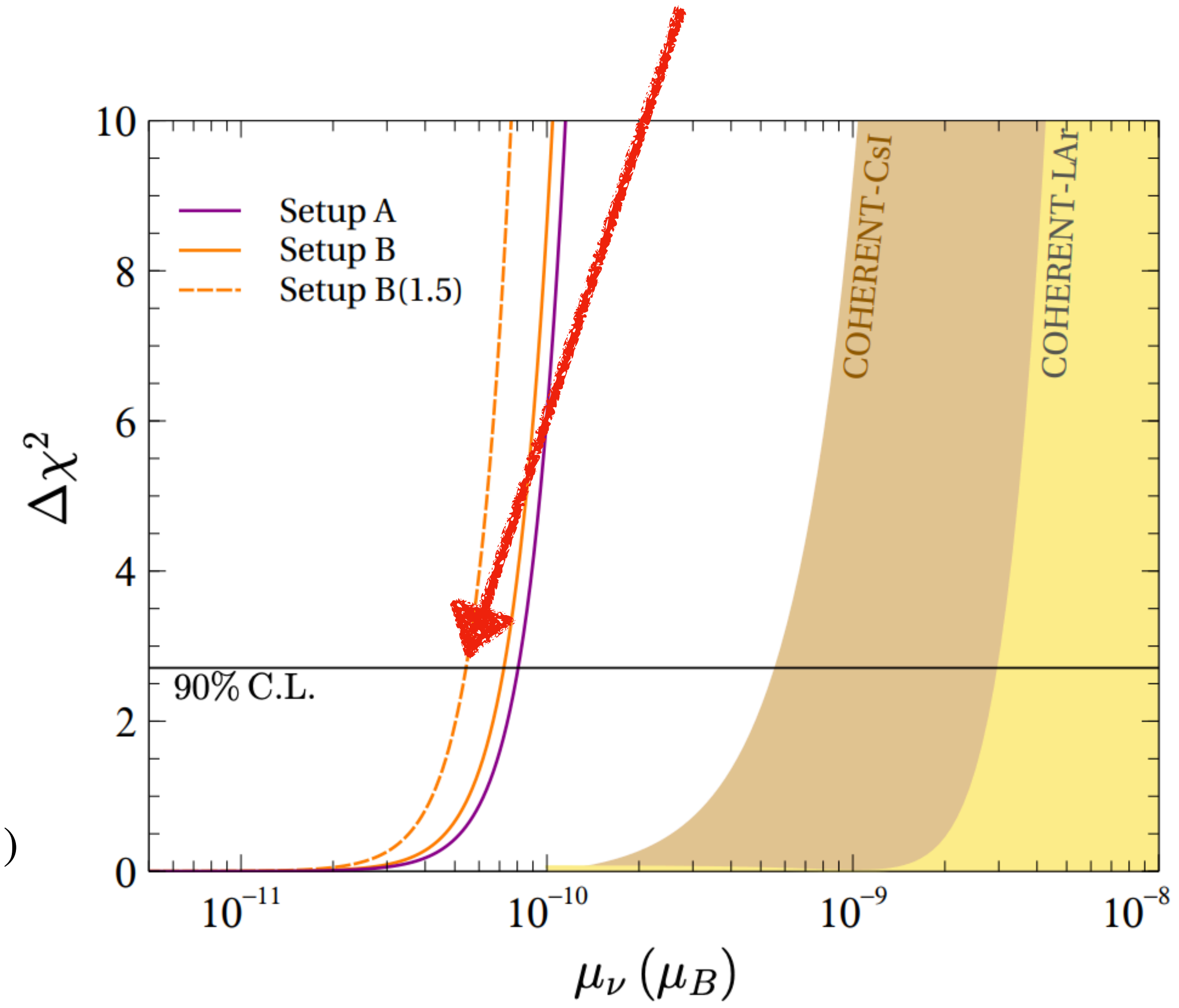
GEMMA $2.9 \times 10^{-11}\ \mu_B\ \ (90\,\%\,C.L.)$

Borexino $2.8 \times 10^{-11}\ \mu_B\ \ (90\,\%\,C.L.)$

$5.4 \times 10^{-11}\ \mu_B\ \ (90\,\%\,C.L.)$



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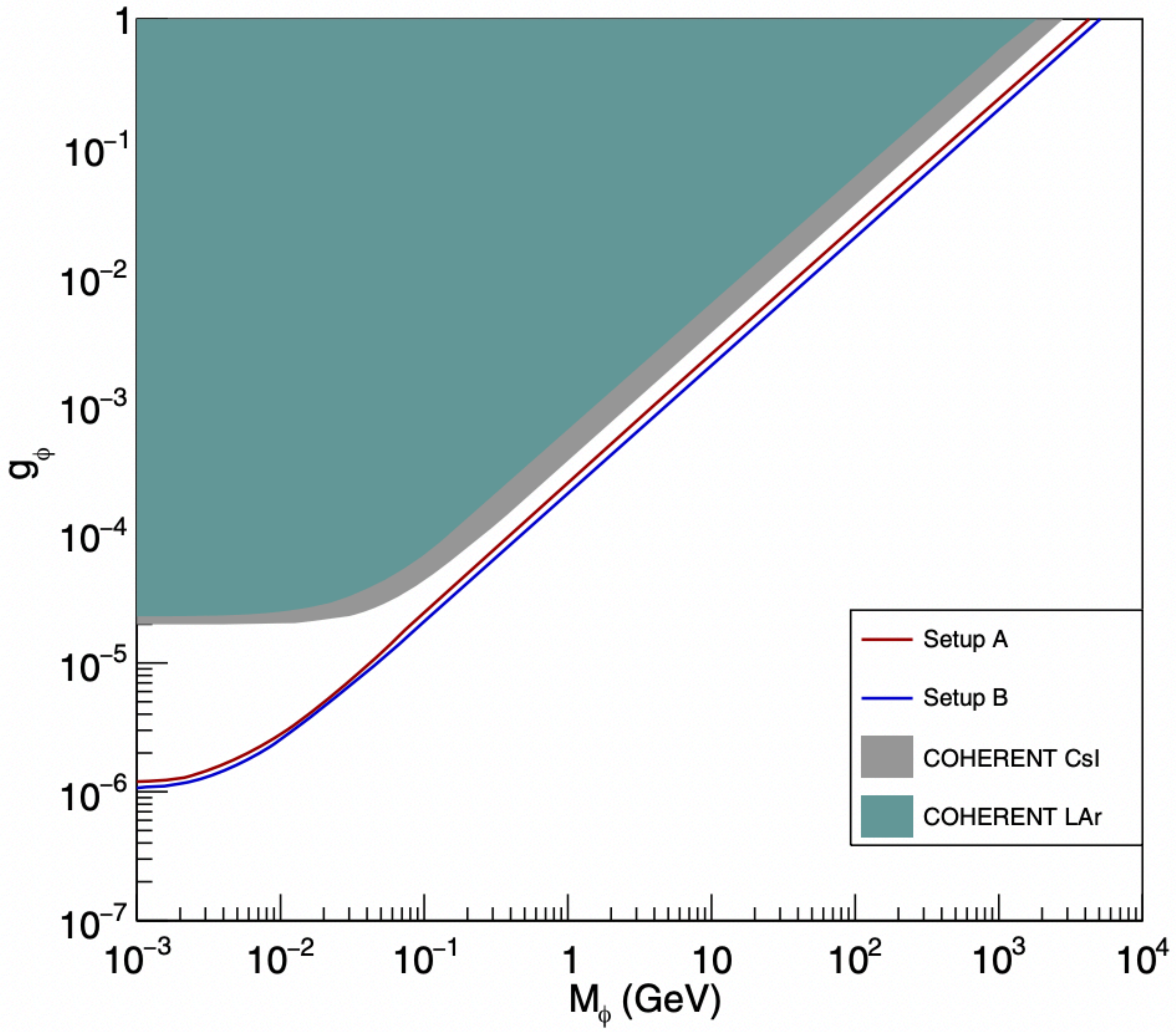

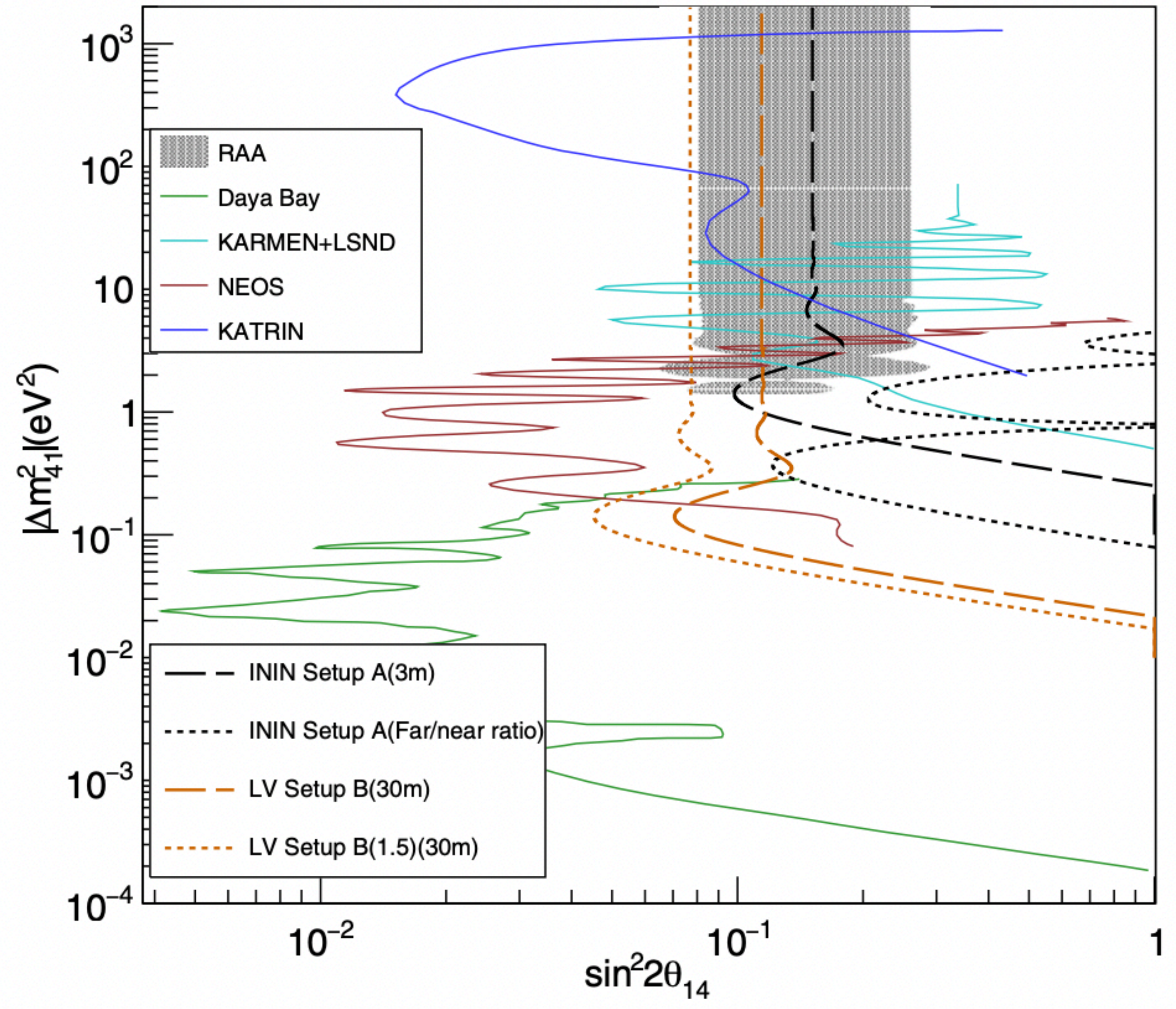

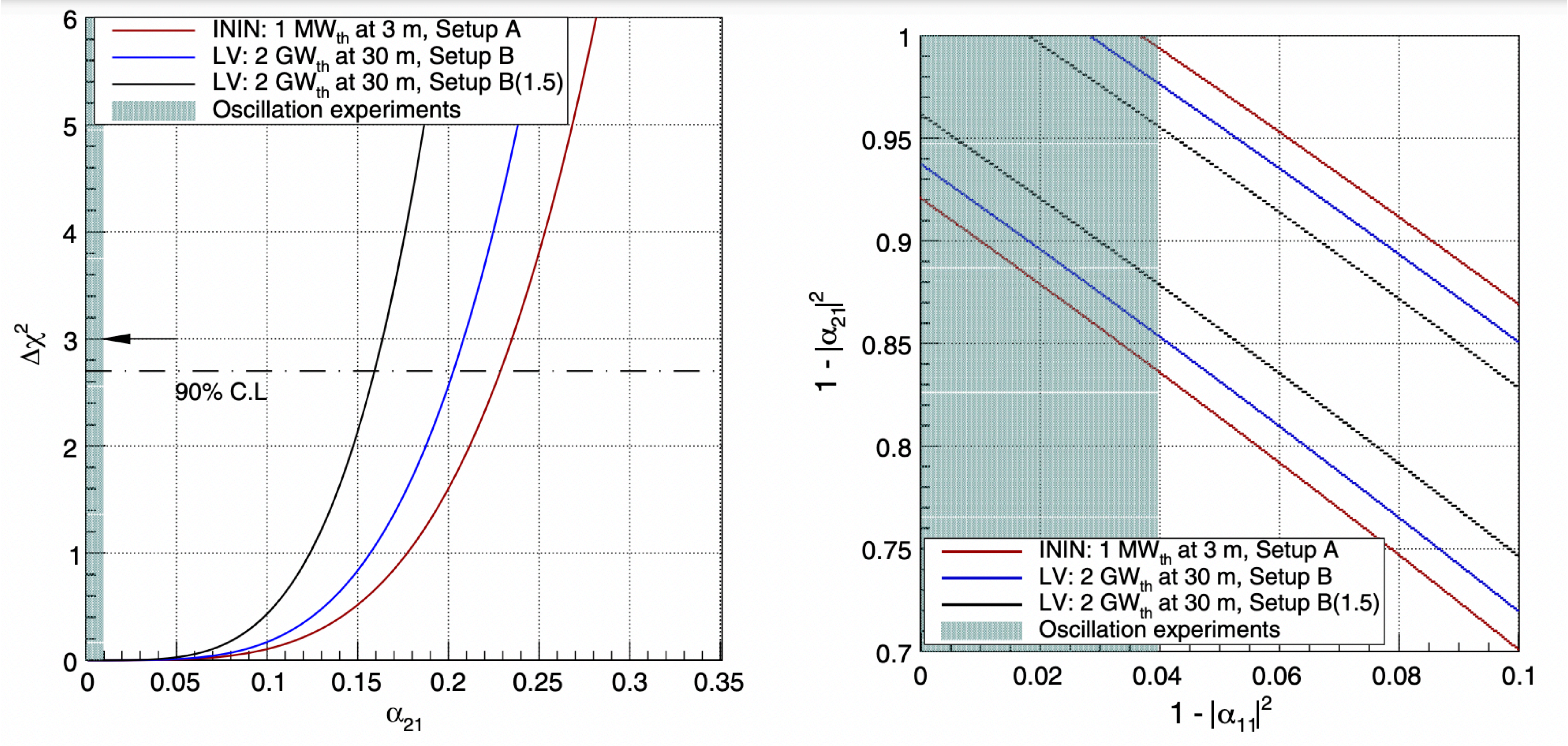

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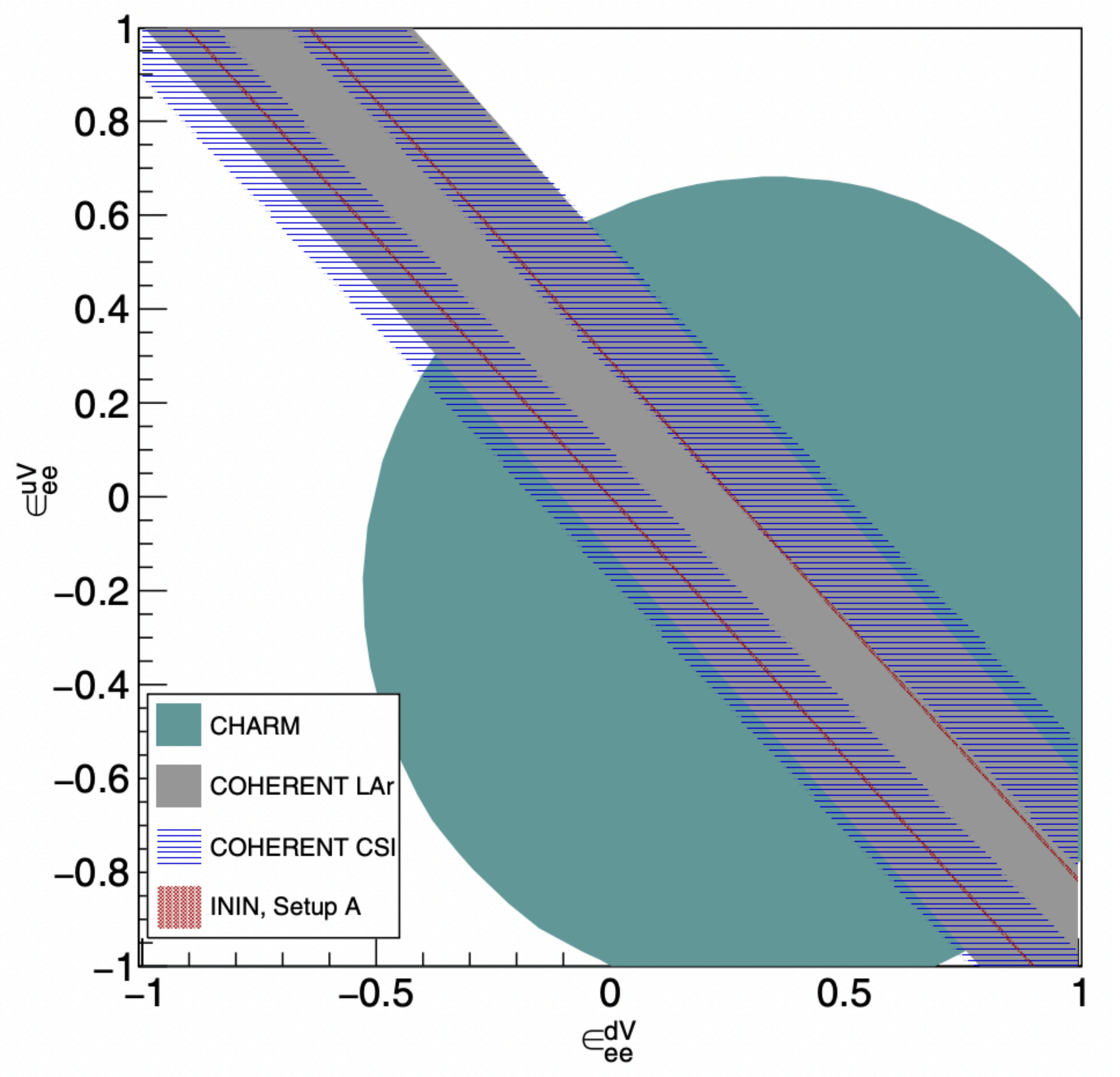


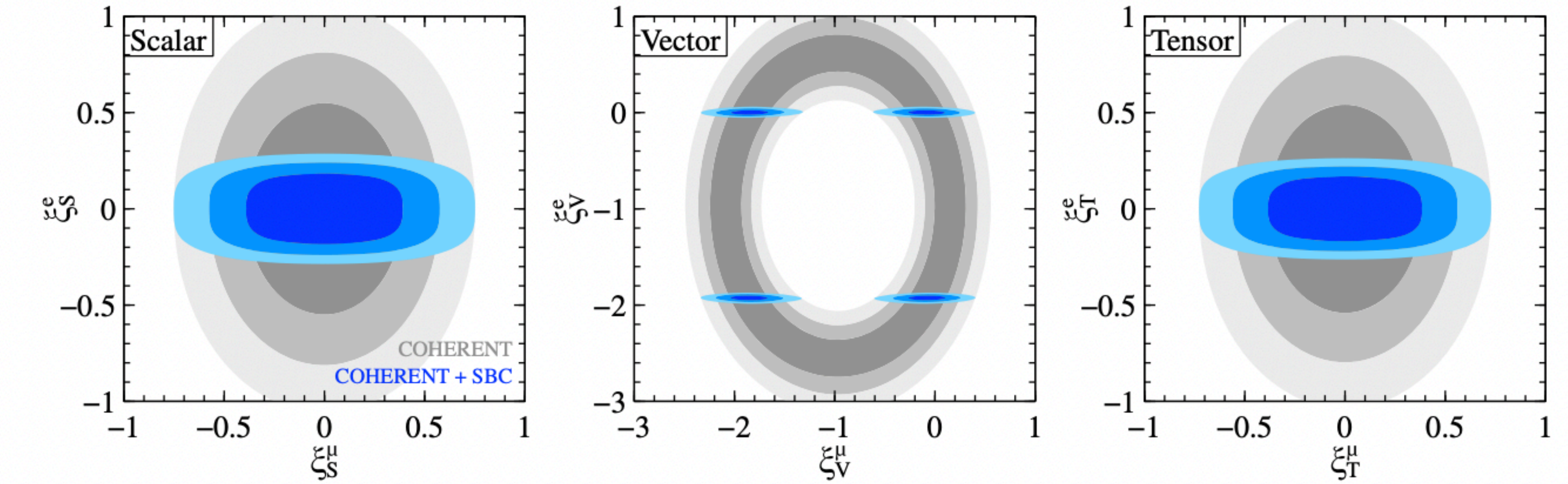
$$N = N^{UV} U_{3\times 3}$$

$$N^{\mathrm{UV}} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

GNI from CEvNS

Flores, Nath and EP PRD (2022)

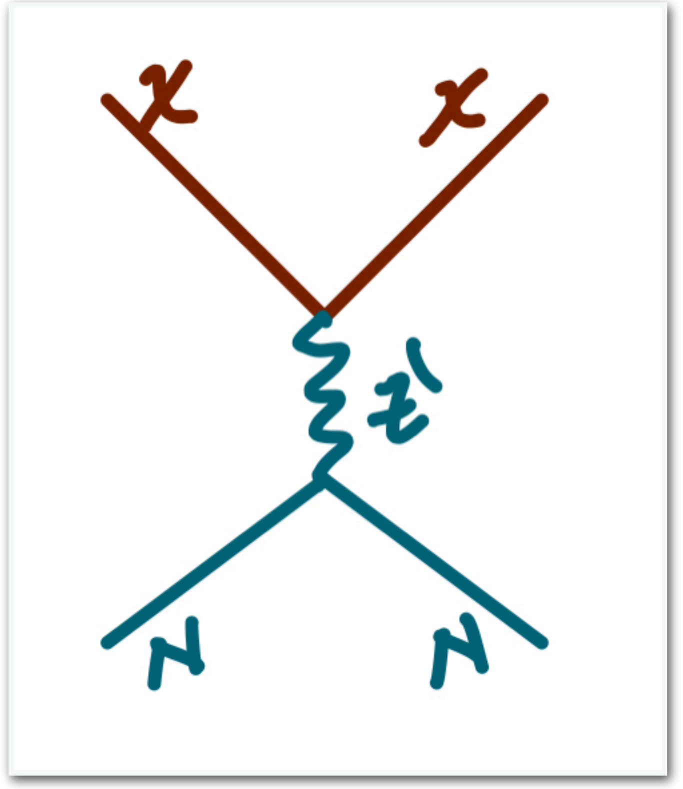
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \bar{\nu}\Gamma^a \nu [\bar{q}\Gamma^a (C_a^{(q)} + \bar{D}_a^{(q)} i\gamma^5) q],$$

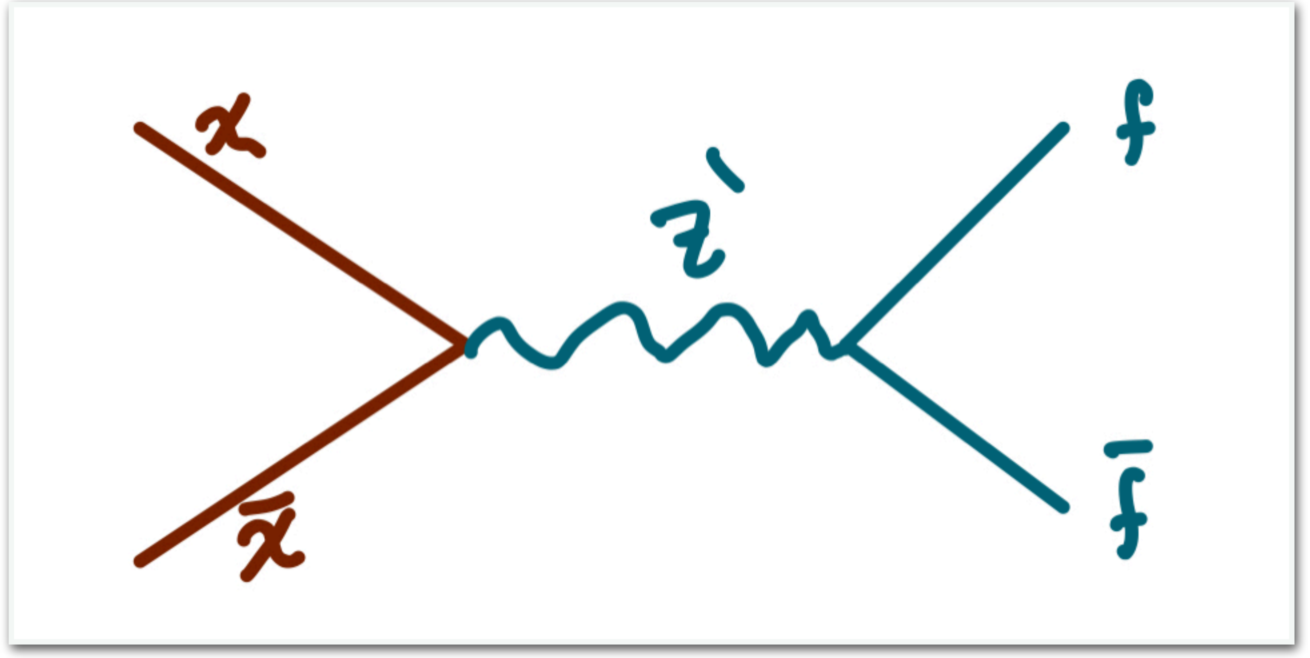


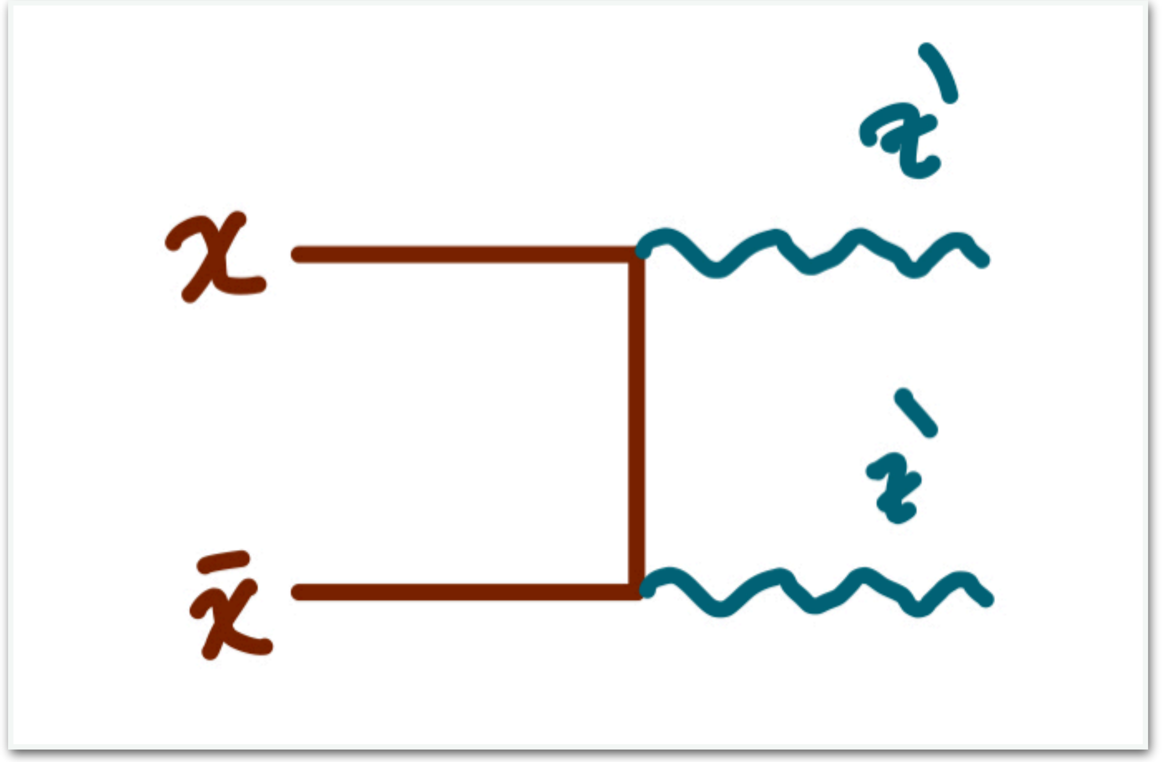
Dark Matter from $U(1)_{B-L}$

Extend the SM with a Dirac fermion χ with $Q_\chi = 1/3$

$$\mathscr{L} \supset M_D \bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + ig' Q_\chi Z'_\mu)\chi$$







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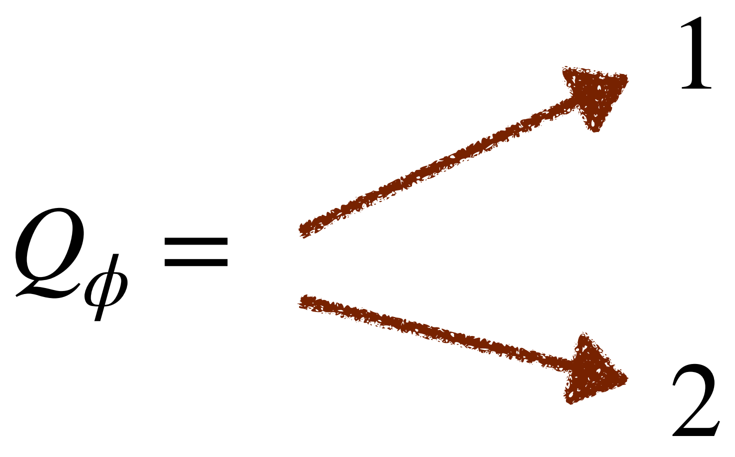
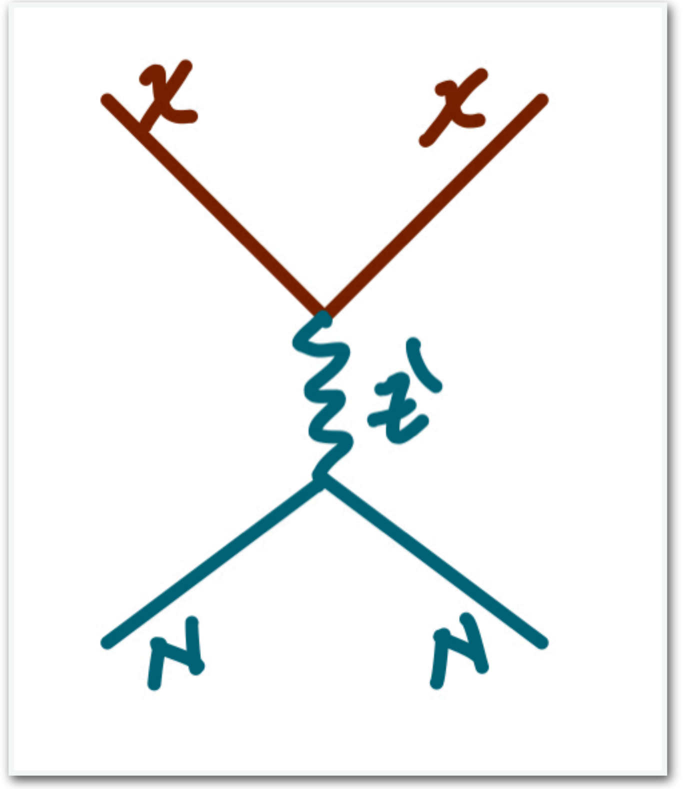
Will need a scalar field ϕ for SSB

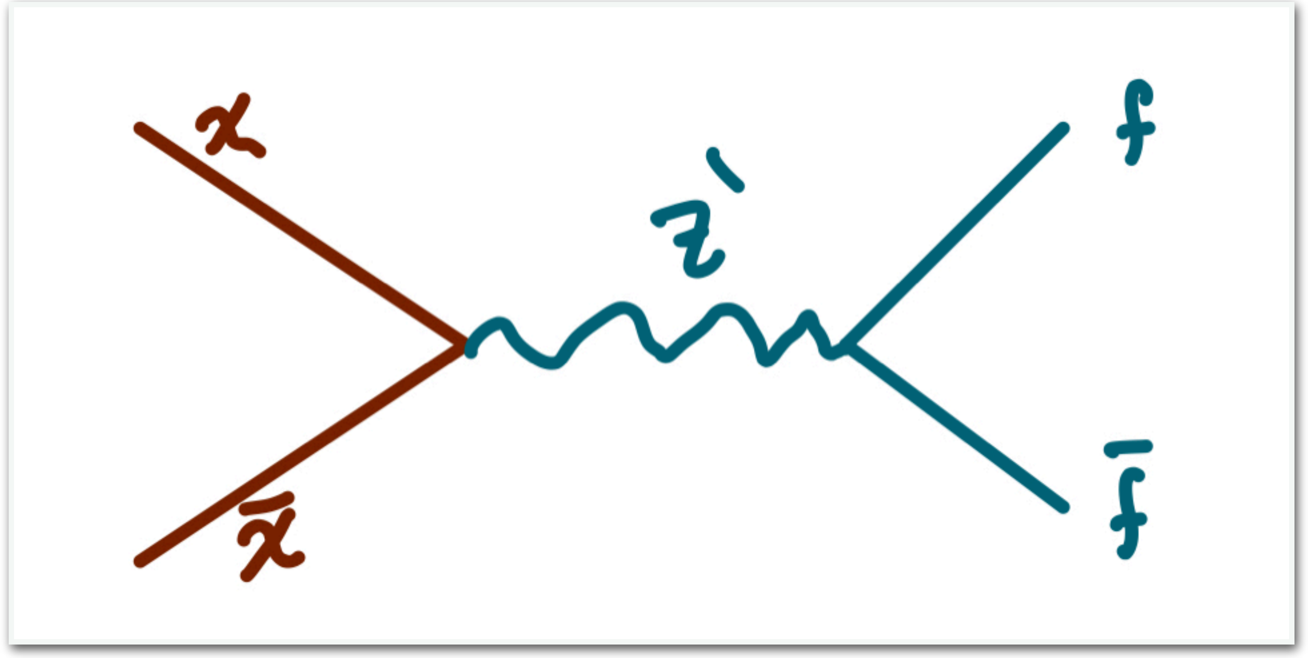


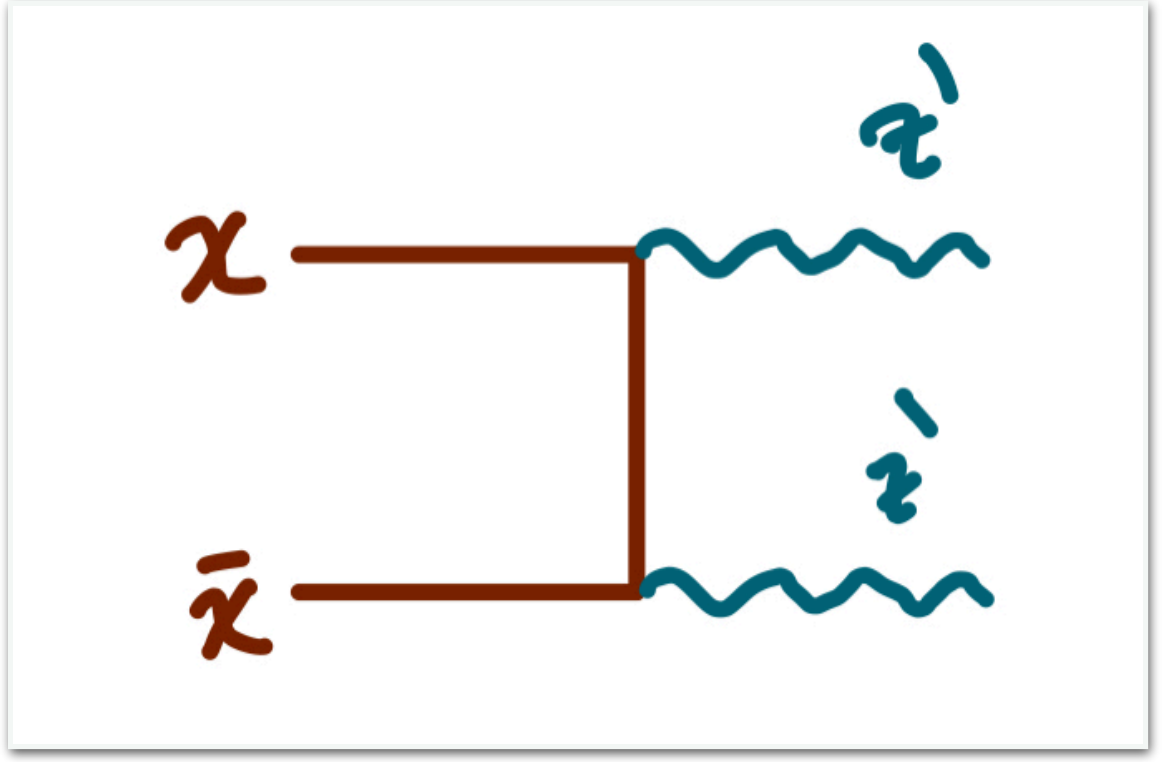
$Q_\phi =$

1 — Dirac neutrinos

2 — Majorana neutrinos $\phi \bar{N}^c N$







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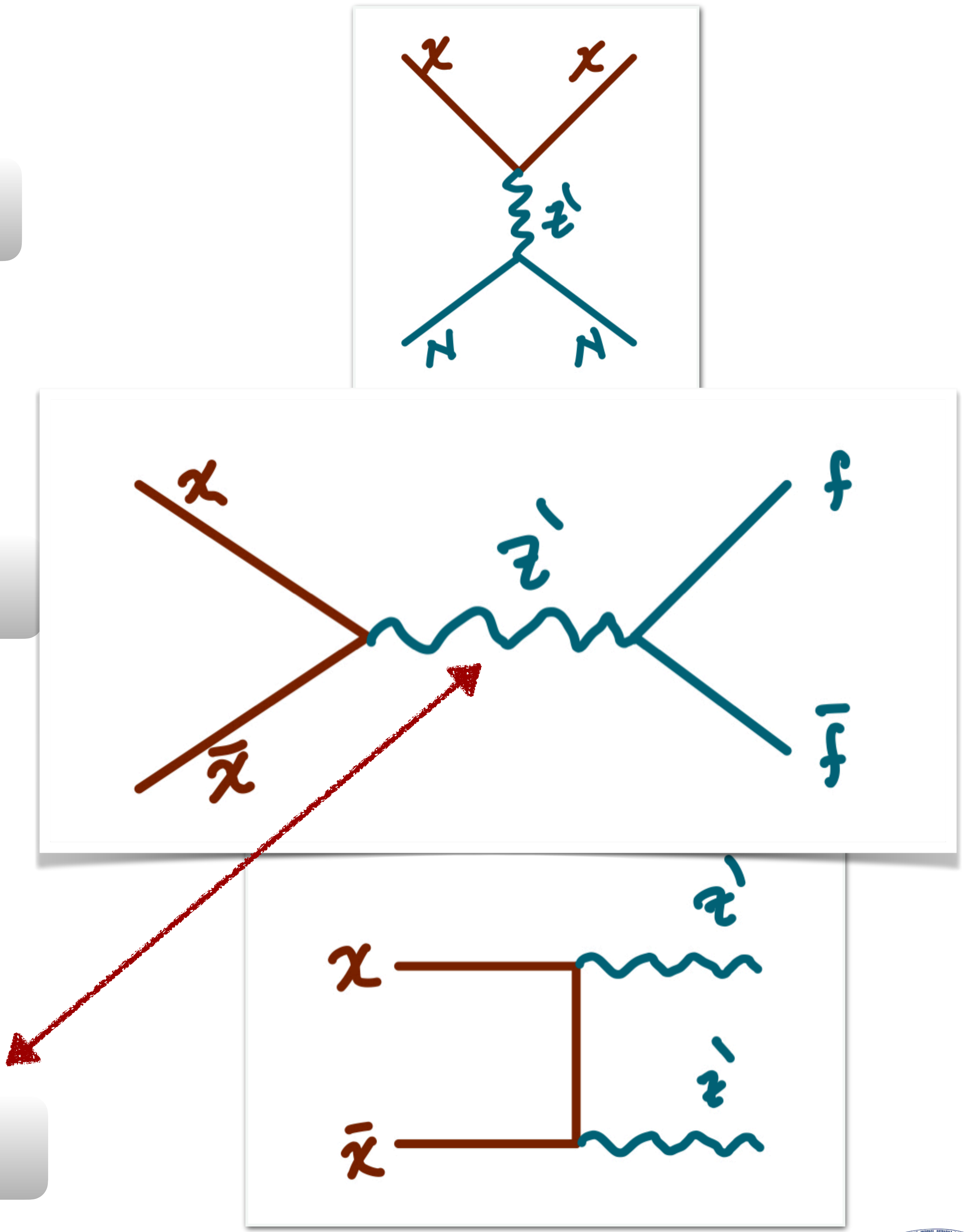
$Q_\phi =$

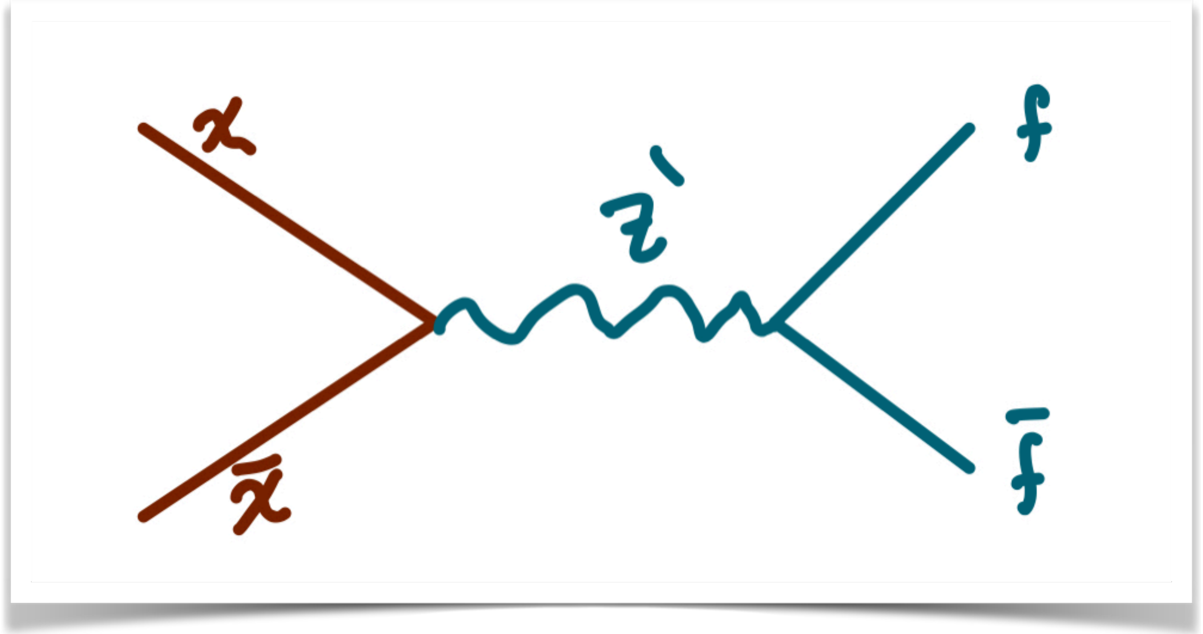
1 Dirac neutrinos

2 Majorana neutrinos $\phi \bar{N}^c N$

Resonant annihilation $M_\chi \simeq M_{z'}/2$



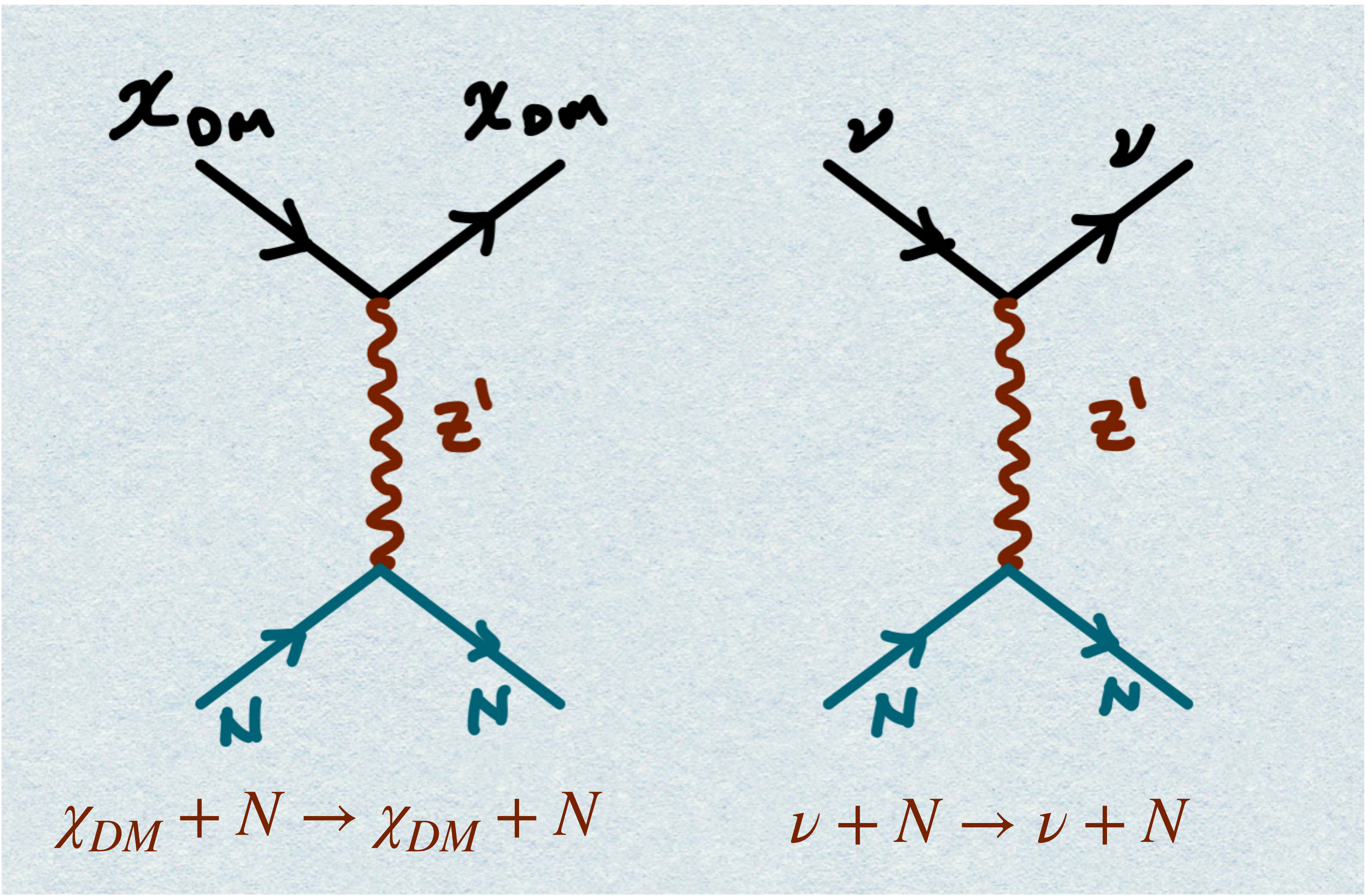
DM abundance



Resonant annihilation
$M_\chi \simeq M_{z'}/2$

DM Detection

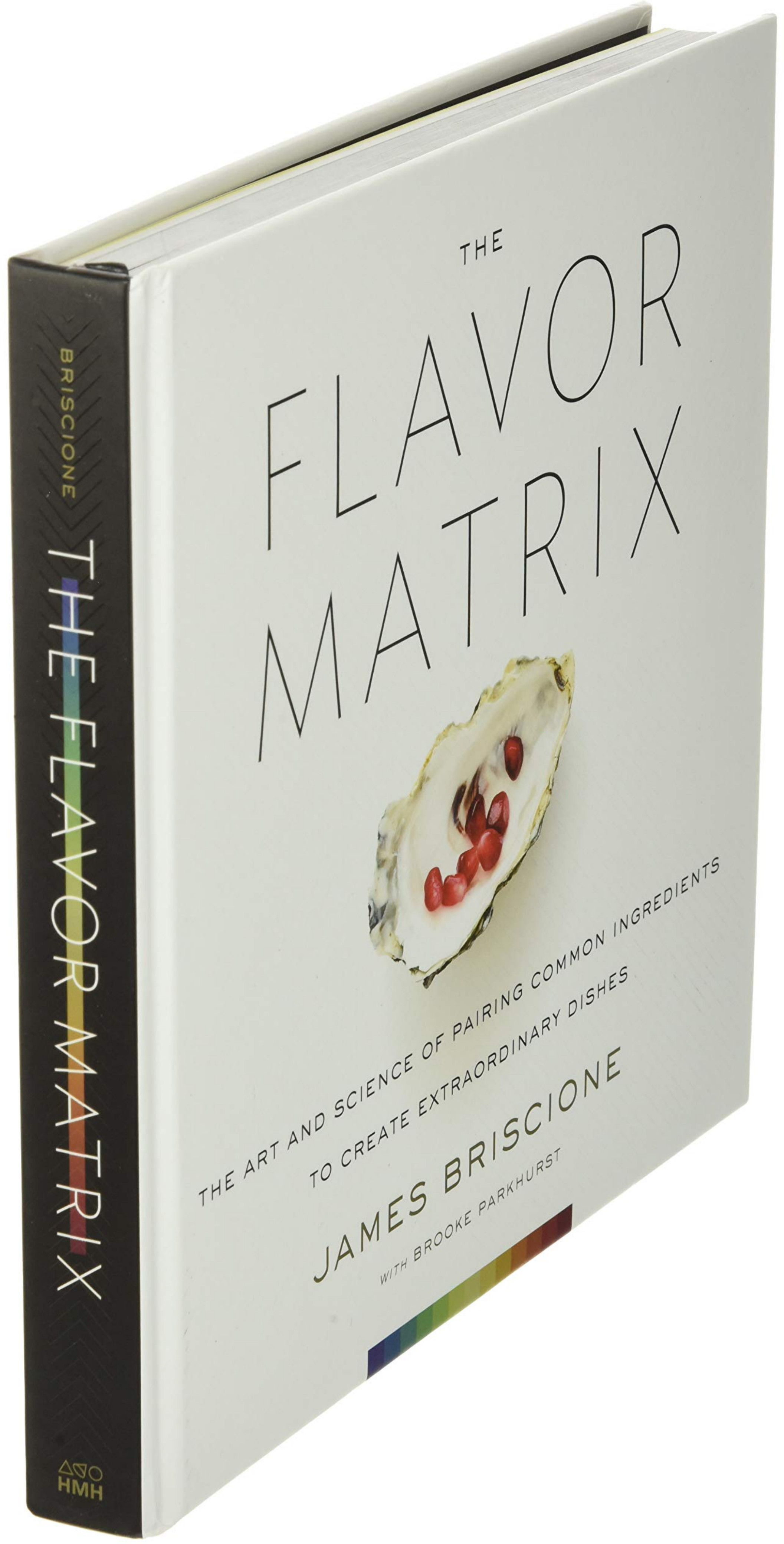
CEνNS



$\chi_{DM} + N \to \chi_{DM} + N$ $\nu + N \to \nu + N$

LMG de la Vega, L. Flores, N. Nath JHEP (2021)

Lepton flavored $U(1)' = U(1)_{B-2L_\alpha-L_\beta}$



L. Flores, N. Nath, EP, JHEP (2020)

Gauge $U(1)_{B-2L_\alpha-L_\beta}$

- Anomaly free
- 3 RH neutrinos
- 2 U(1) breaking scalar fields

$$\frac{1}{2}M_{Z'}^2 = g'^2\,\frac{1}{2}(\underset{\underset{\langle\phi_1\rangle}{\uparrow}}{v_1^2} + 4\underset{\underset{\langle\phi_2\rangle}{\uparrow}}{v_2^2})$$

	ϕ_1	ϕ_2
$U(1)$	1	2

- Neutrino phenomenology

Lepton flavored $U(1)' = U(1)_{B-2L_\alpha-L_\beta}$

L. Flores, N. Nath, EP, JHEP (2020)

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	ϕ_1	ϕ_2
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Neutrino phenomenology

$$-\mathcal{L}_{Majorana} = \frac{1}{2}M_1\overline{N_1^c}N_1 + \frac{1}{2}y_1^N\overline{N_1^c}N_2\phi_1 + \frac{1}{2}y_2^N\overline{N_1^c}N_3\phi_2 + \frac{1}{2}y_3^N\overline{N_2^c}N_2\phi_2$$

6 possible choices for α and β

$\alpha=\mu$ and $\beta=\tau$

$$M_N = \begin{pmatrix} M_1 & y_1^N\langle\phi_1\rangle & y_2^N\langle\phi_2\rangle \\ y_1^N\langle\phi_1\rangle & y_3^N\langle\phi_2\rangle & 0 \\ y_2^N\langle\phi_2\rangle & 0 & 0 \end{pmatrix}$$

Charged leptons diagonal

Lepton flavored $U(1)' = U(1)_{B-2L_\alpha-L_\beta}$

Frampton, Glashow, Marfatia, PLB (2002)

L. Flores, N. Nath, EP, JHEP (2020)

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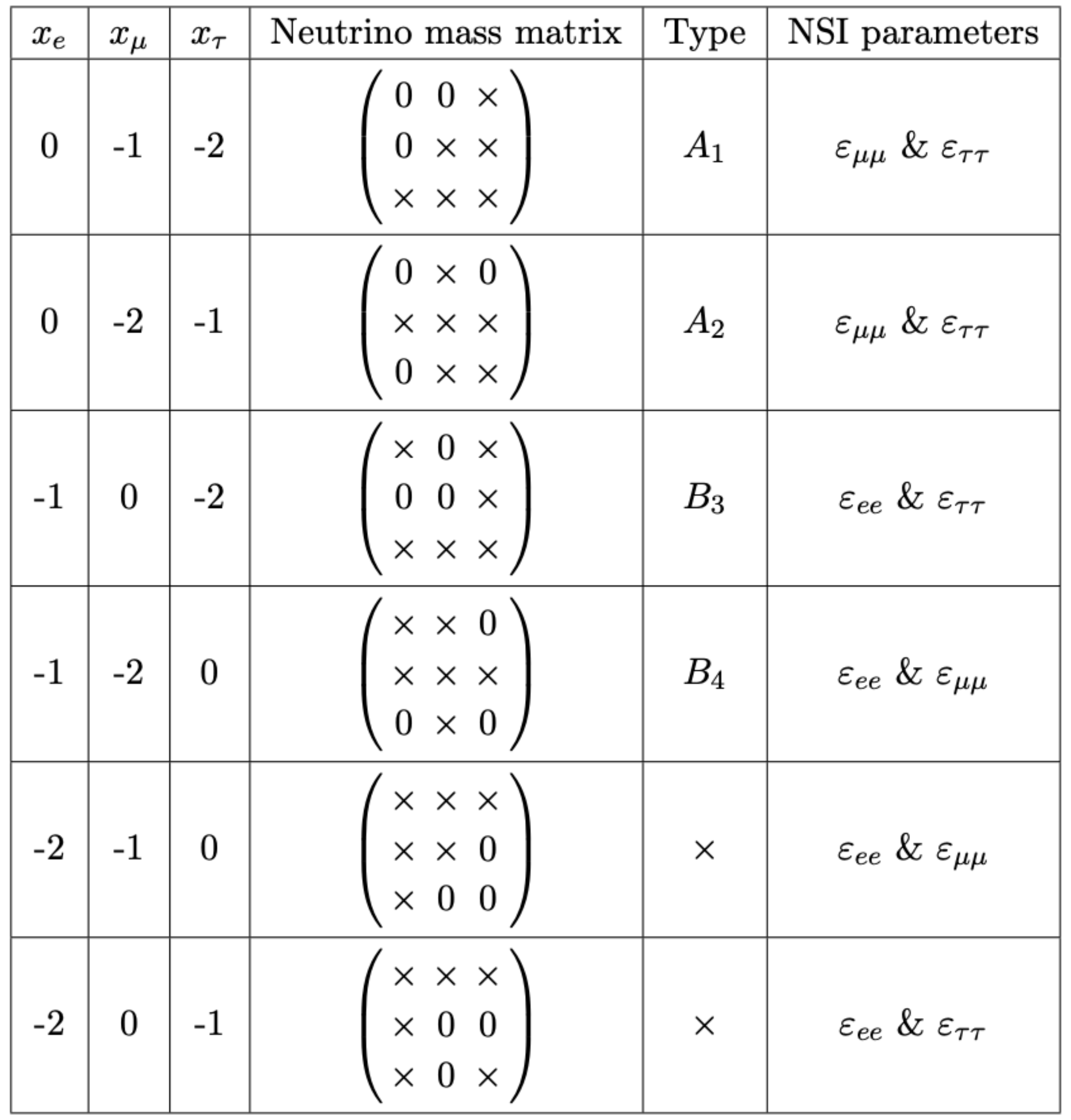

x_e	x_μ	x_τ	Neutrino mass matrix	Type	NSI parameters
0	-1	-2	$\begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$	A_1	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
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-1	0	-2	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	B_3	ε_{ee} & $\varepsilon_{\tau\tau}$
-1	-2	0	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	B_4	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	×	ε_{ee} & $\varepsilon_{\mu\mu}$
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L. Flores, N. Nath, EP, JHEP (2020)

Gauge $U(1)_{B-2L_\alpha-L_\beta}$

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3 RH neutrinos

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$$\begin{array}{ccc} & \phi_1 & \phi_2 \\ U(1) & 1 & 2 \end{array}$$

Neutrino phenomenology

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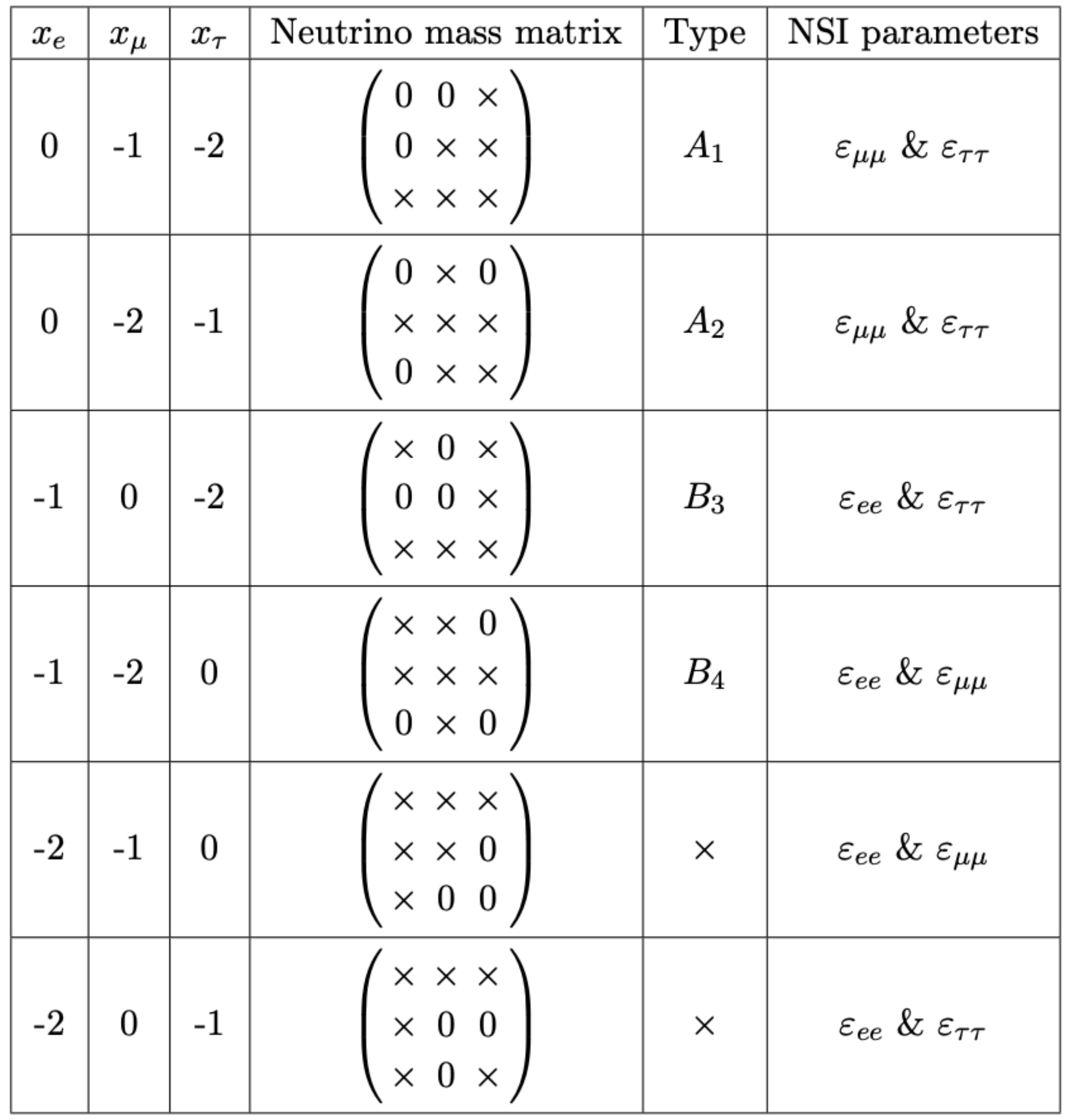
Charged leptons diagonal

Frampton, Glashow, Marfatia, PLB (2002)



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-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	×	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	×	ε_{ee} & $\varepsilon_{\tau\tau}$

Good pheno

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Frampton, Glashow, Marfatia, PLB (2002)

L. Flores, N. Nath, EP, JHEP (2020)

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-1	0	-2	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	B_3	ε_{ee} & $\varepsilon_{\tau\tau}$
-1	-2	0	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	B_4	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	×	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	×	ε_{ee} & $\varepsilon_{\tau\tau}$

Better agreement

Good pheno

Lepton flavored $U(1)' = U(1)_{B-2L_\alpha-L_\beta}$

L. Flores, N. Nath, EP, JHEP (2020)

Frampton, Glashow, Marfatia, PLB (2002)

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$\alpha=\mu$ and $\beta=\tau$

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Charged leptons diagona

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-1	0	-2	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	B_3	ε_{ee} & $\varepsilon_{\tau\tau}$
-1	-2	0	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	B_4	ε_{ee} & $\varepsilon_{\mu\mu}$
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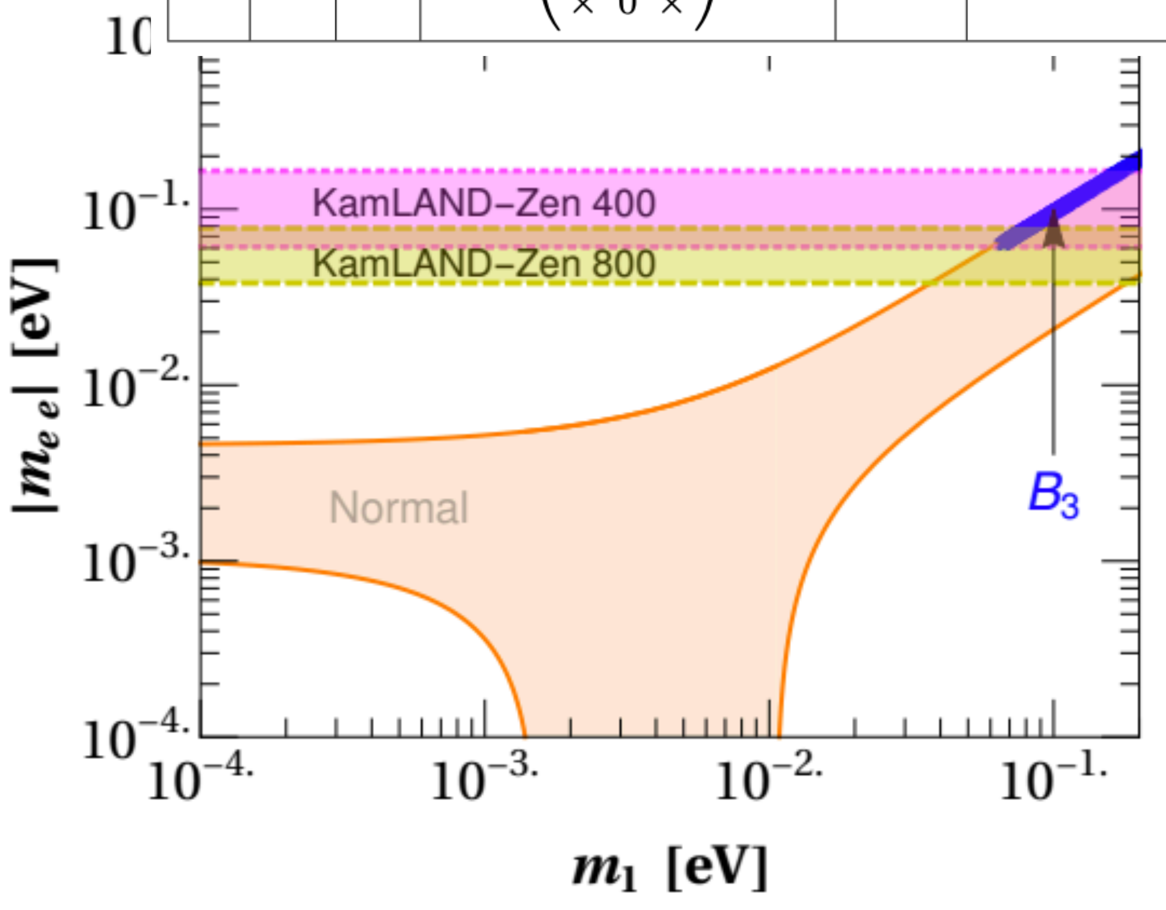
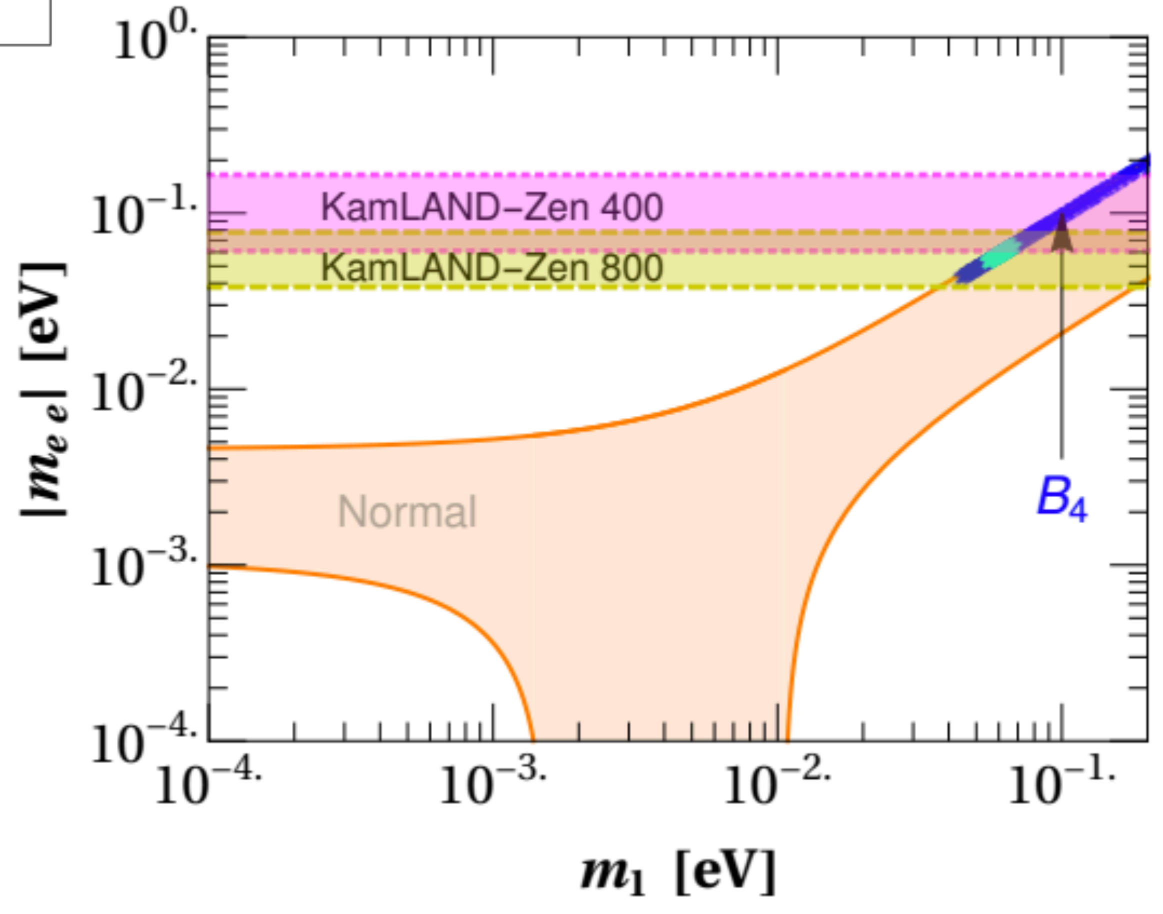
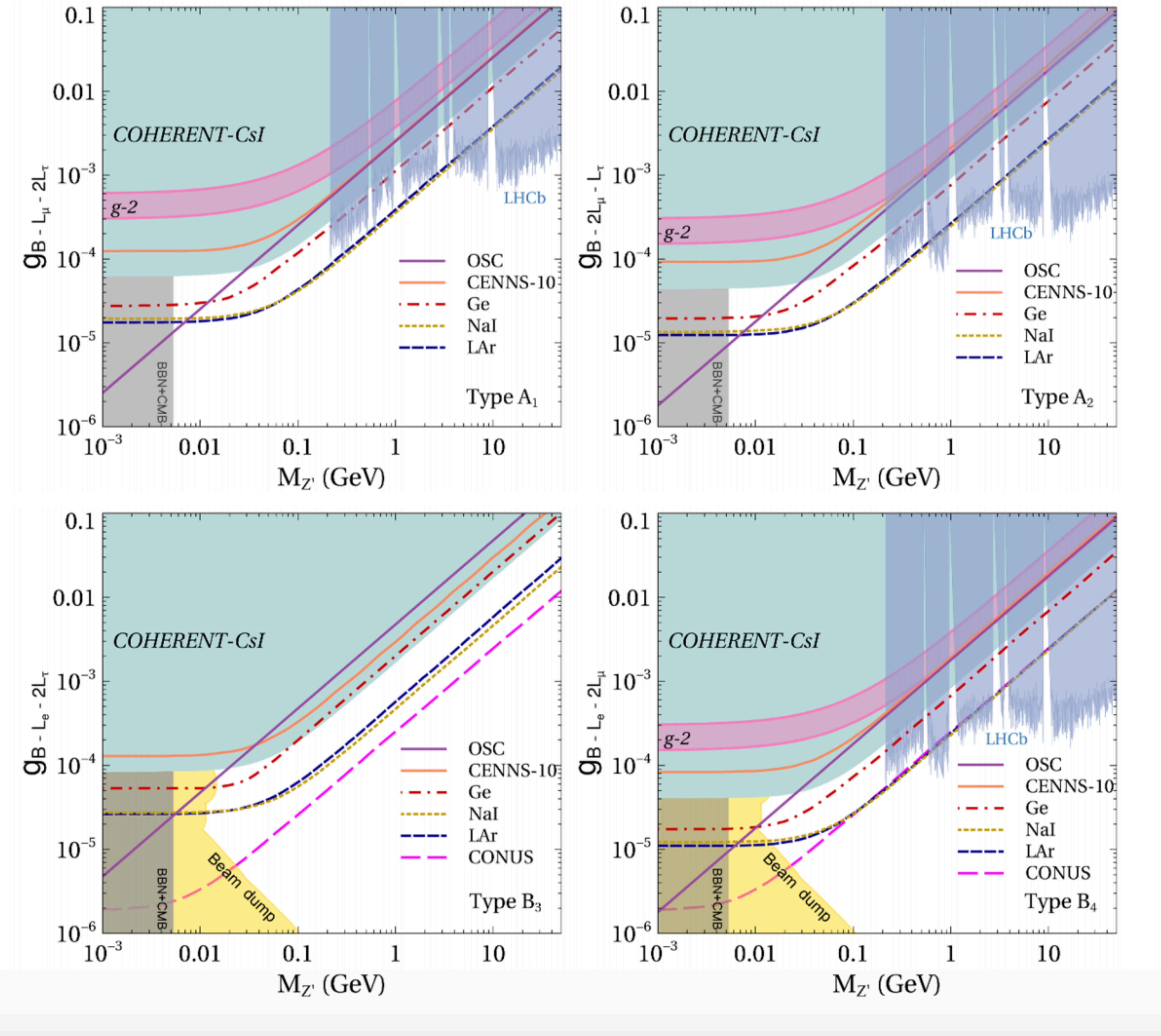
Better agreement

Good pheno







$$\frac{1}{2}M_{Z'}^2 = g'^2 \ \frac{1}{2}(v_1^2 + 4v_2^2)$$

$$M_{Z'} = 0.1\,\mathrm{GeV}$$

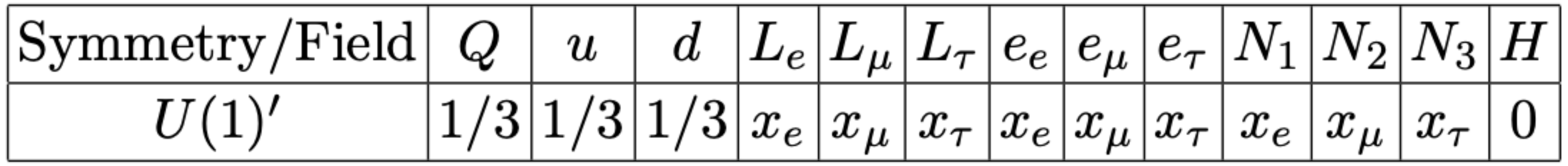
$$g' = 2.8\times 10^{-5}$$

$$v_1 \approx 3\,\mathrm{TeV} \quad v_2 \approx 1\,\mathrm{TeV}$$

L. Flores, N. Nath, EP, JHEP (2020)

Darkcast
Ilten, Soreq, Williams and Xue, JHEP (2018)

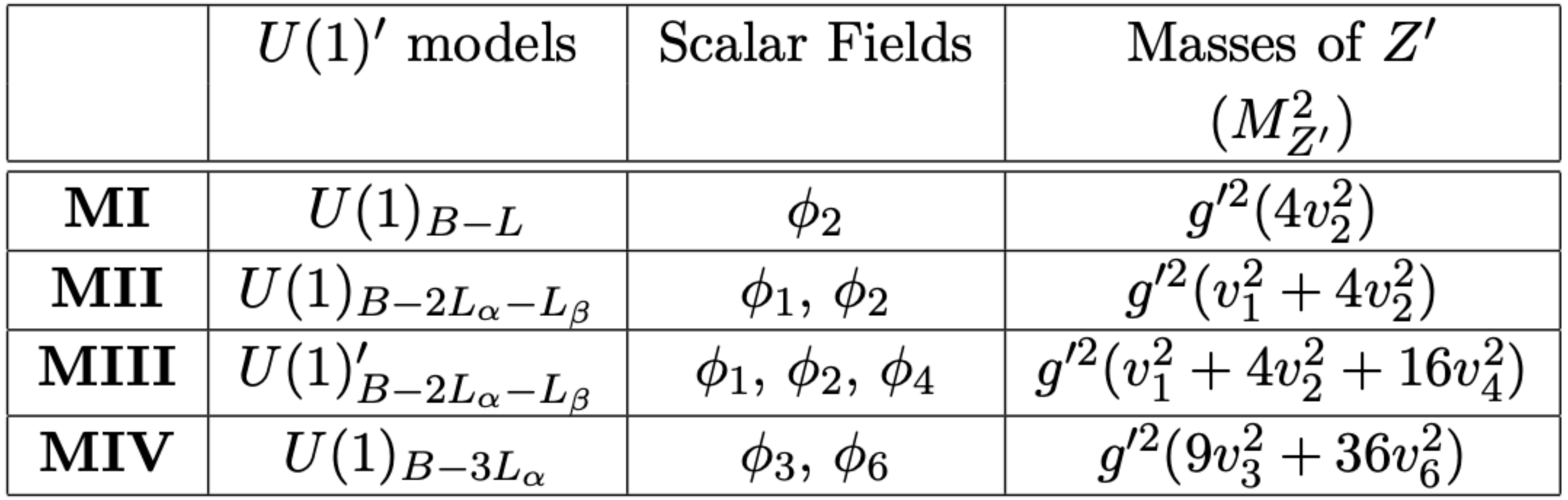
LMG de la Vega, L. Flores, N. Nath JHEP (2021)



Symmetry/Field	Q	u	d	L_e	L_μ	L_τ	e_e	e_μ	e_τ	N_1	N_2	N_3	H
$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

Singlet scalar fields ϕ_i having charges i under U(1)$'$

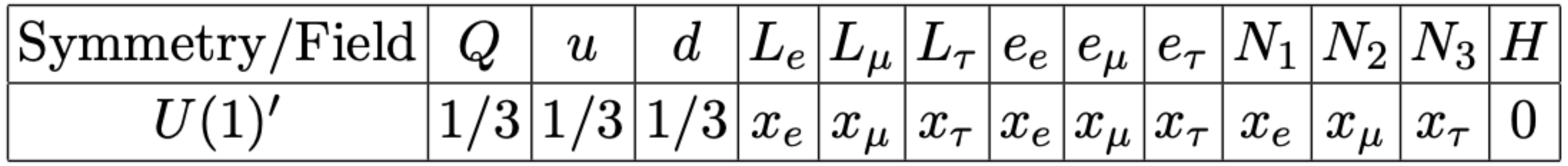
Good ν pheno



	$U(1)'$ models	Scalar Fields	Masses of Z' ($M^2_{Z'}$)
MI	$U(1)_{B-L}$	ϕ_2	$g'^2(4v_2^2)$
MII	$U(1)_{B-2L_\alpha-L_\beta}$	ϕ_1, ϕ_2	$g'^2(v_1^2+4v_2^2)$
MIII	$U(1)'_{B-2L_\alpha-L_\beta}$	ϕ_1, ϕ_2, ϕ_4	$g'^2(v_1^2+4v_2^2+16v_4^2)$
MIV	$U(1)_{B-3L_\alpha}$	ϕ_3, ϕ_6	$g'^2(9v_3^2+36v_6^2)$

Singlet scalar fields ϕ_i having charges i under U(1)$'$

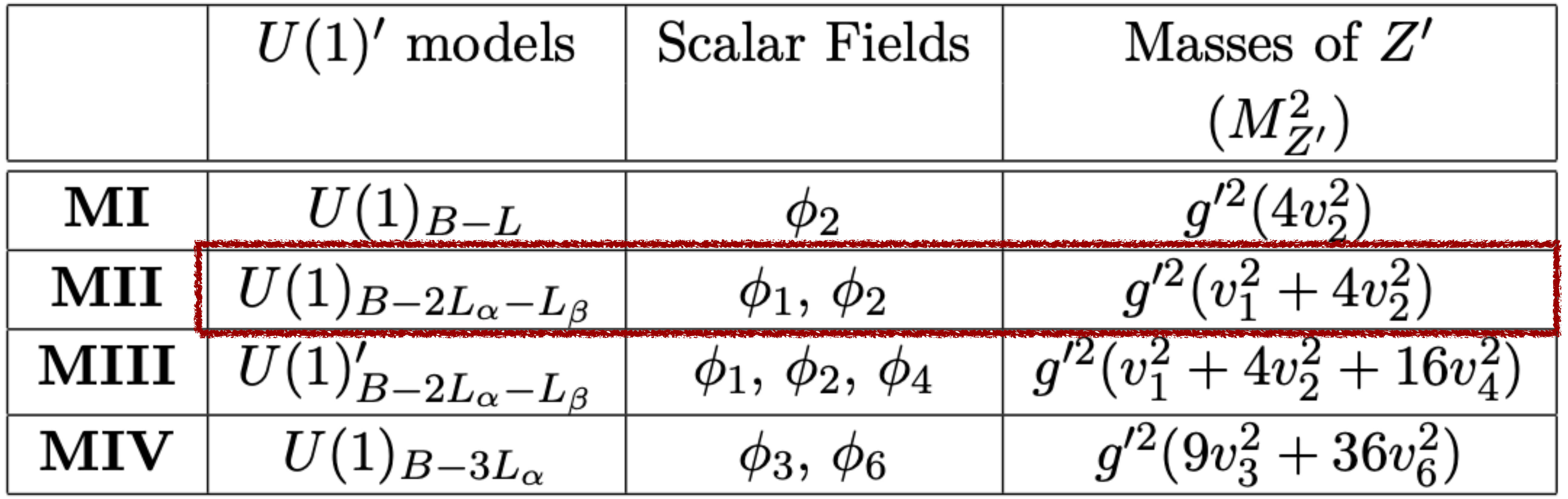
LMG de la Vega, L. Flores, N. Nath JHEP (2021)



Symmetry/Field	Q	u	d	L_e	L_μ	L_τ	e_e	e_μ	e_τ	N_1	N_2	N_3	H
$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

Singlet scalar fields ϕ_i having charges i under $\mathrm{U}(1)'$

Good ν pheno



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L. Flores, N. Nath, EP, JHEP (2020)

4 different cases, two-zero textures, good pheno and predictions

LMG de la Vega, L. Flores, N. Nath JHEP (2021)

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$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

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L. Flores, N. Nath, EP, JHEP (2020)

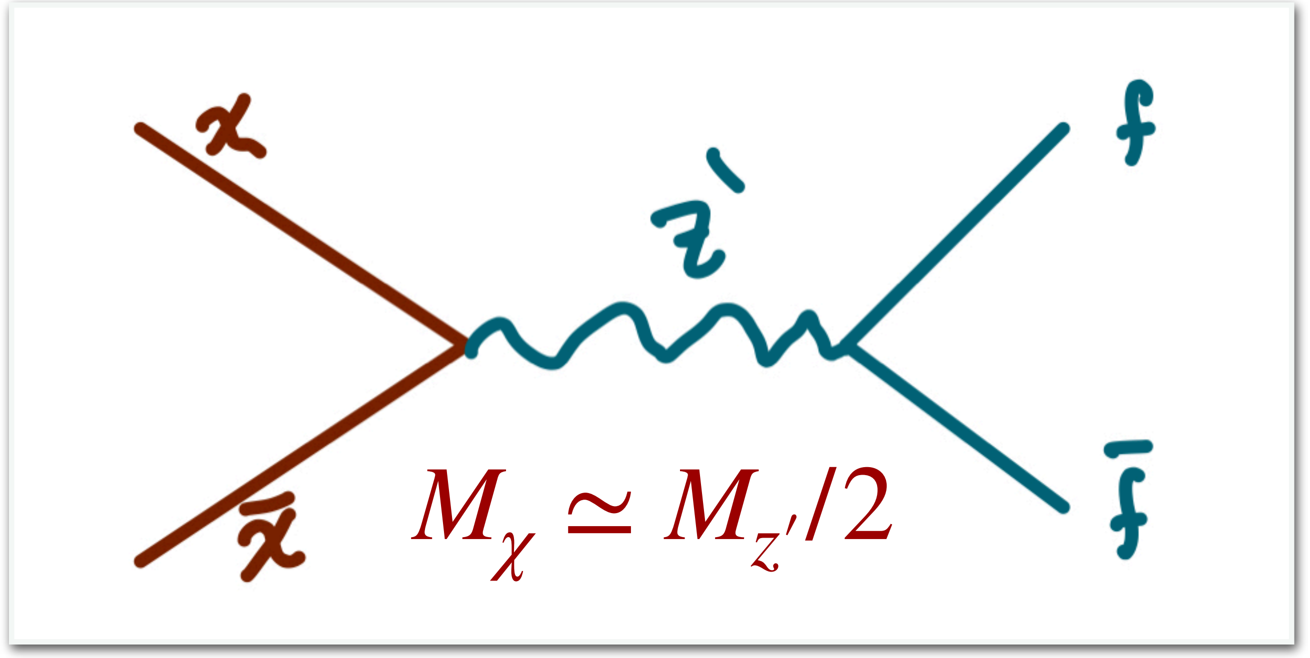
4 different cases, two-zero textures, good pheno and predictions

2 different cases, one-zero textures, good pheno and prediction

CEvNS and DM searches complementarity

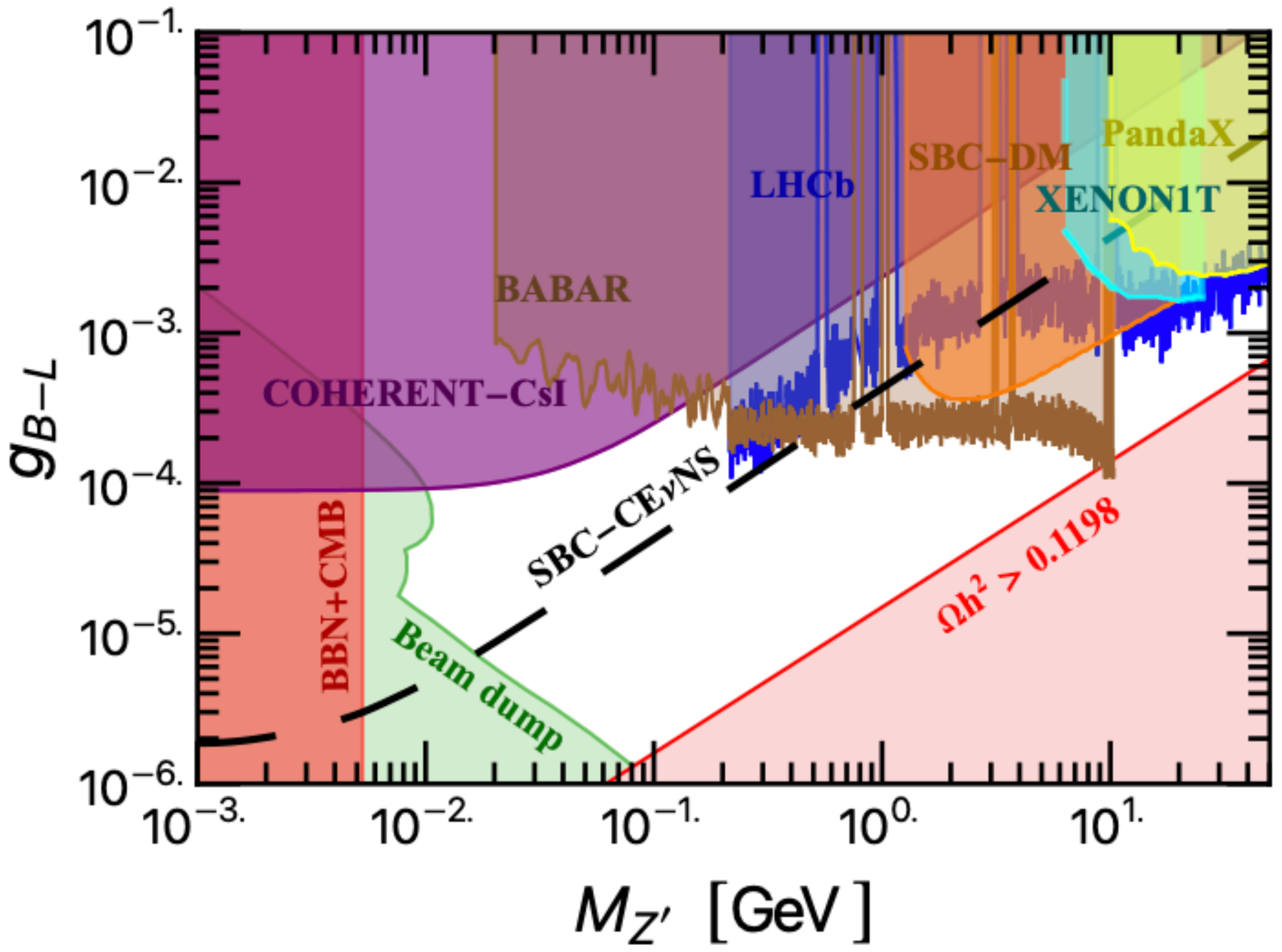
LMG de la Vega, L. Flores, N. Nath, EP JHEP (2021)

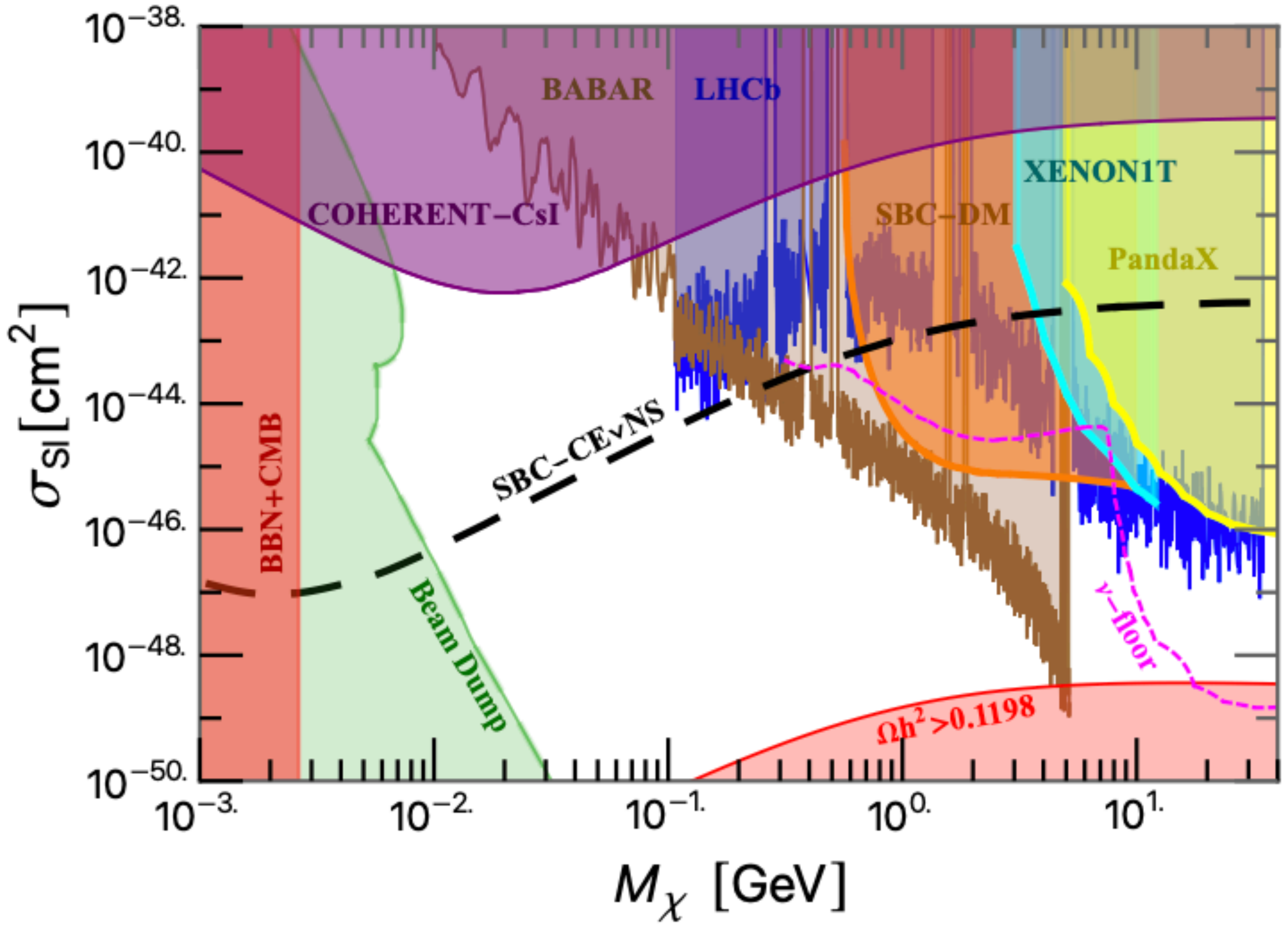
$U(1)_{B-L}$



$M_\chi \simeq M_{z'}/2$

$Q_\chi = 1/3$





CEvNS and DM searches complementarity

LMG de la Vega, L. Flores, N. Nath, EP JHEP (2021)

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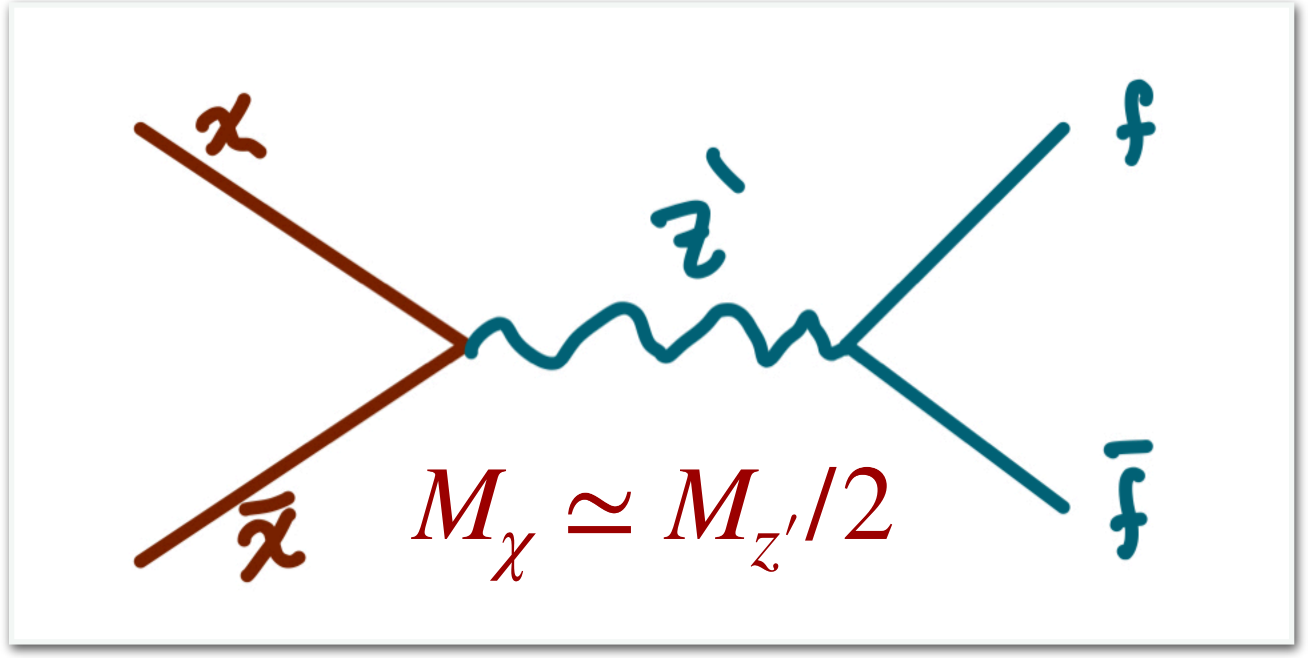

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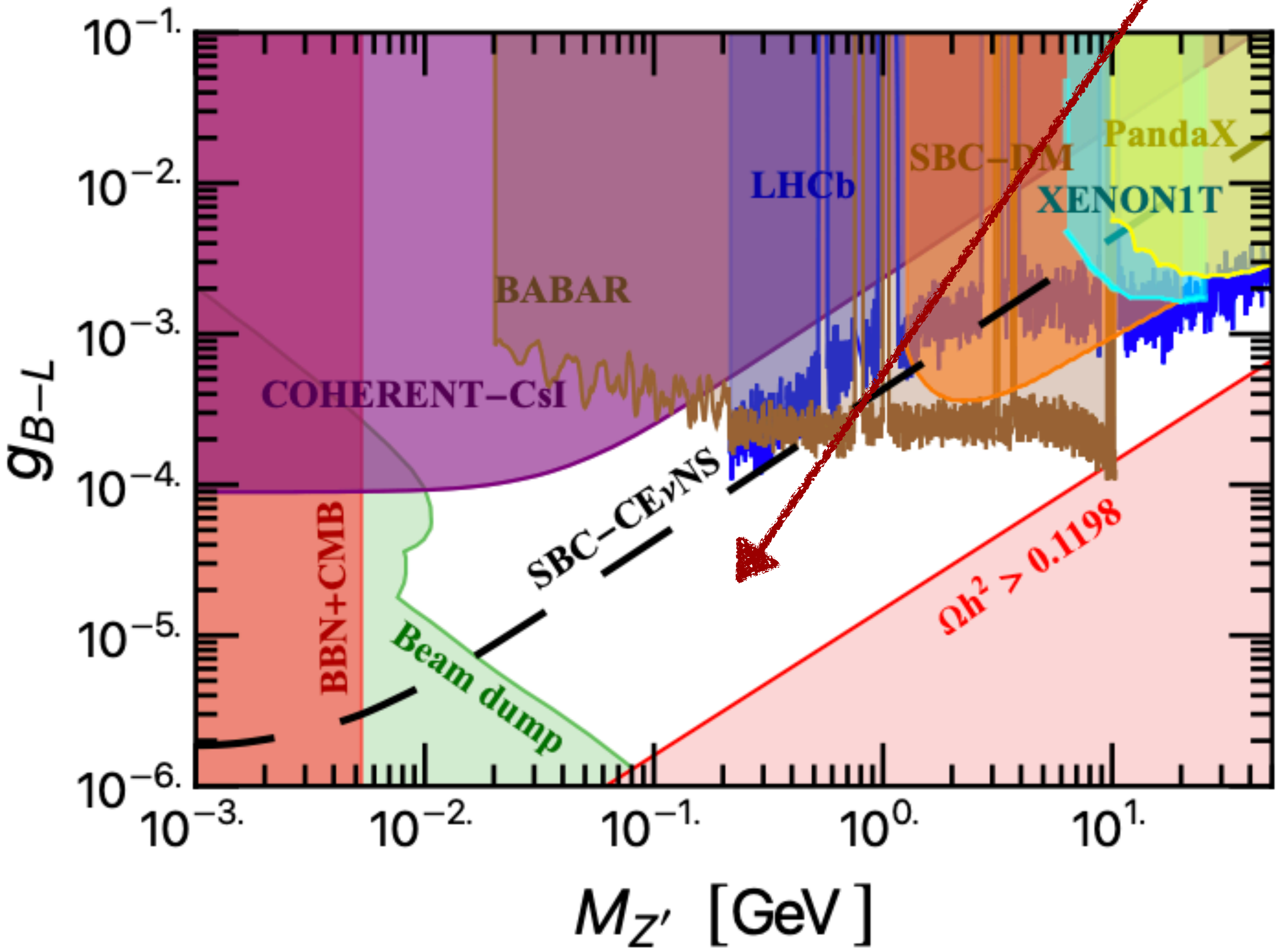
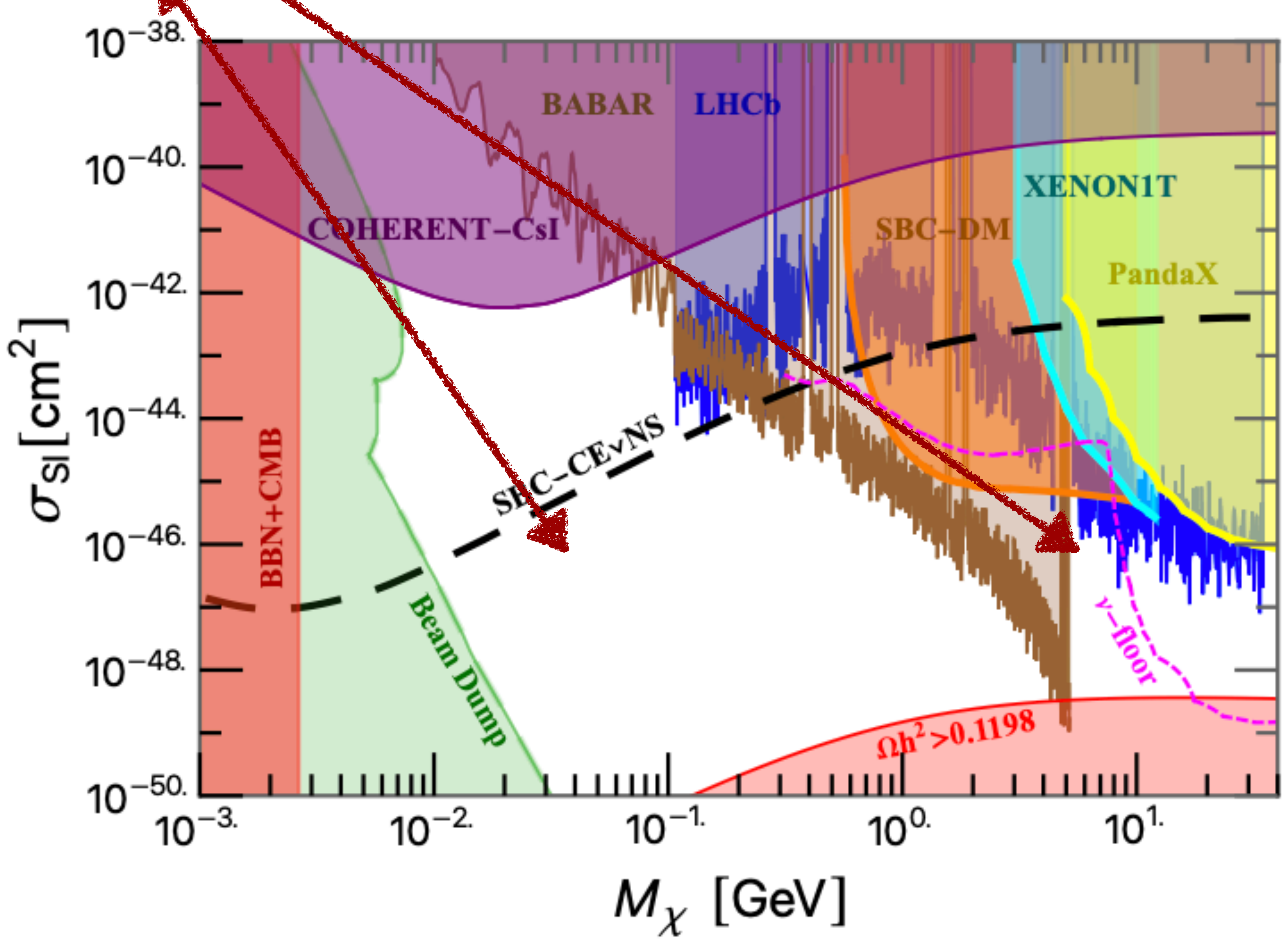
Allowed Region

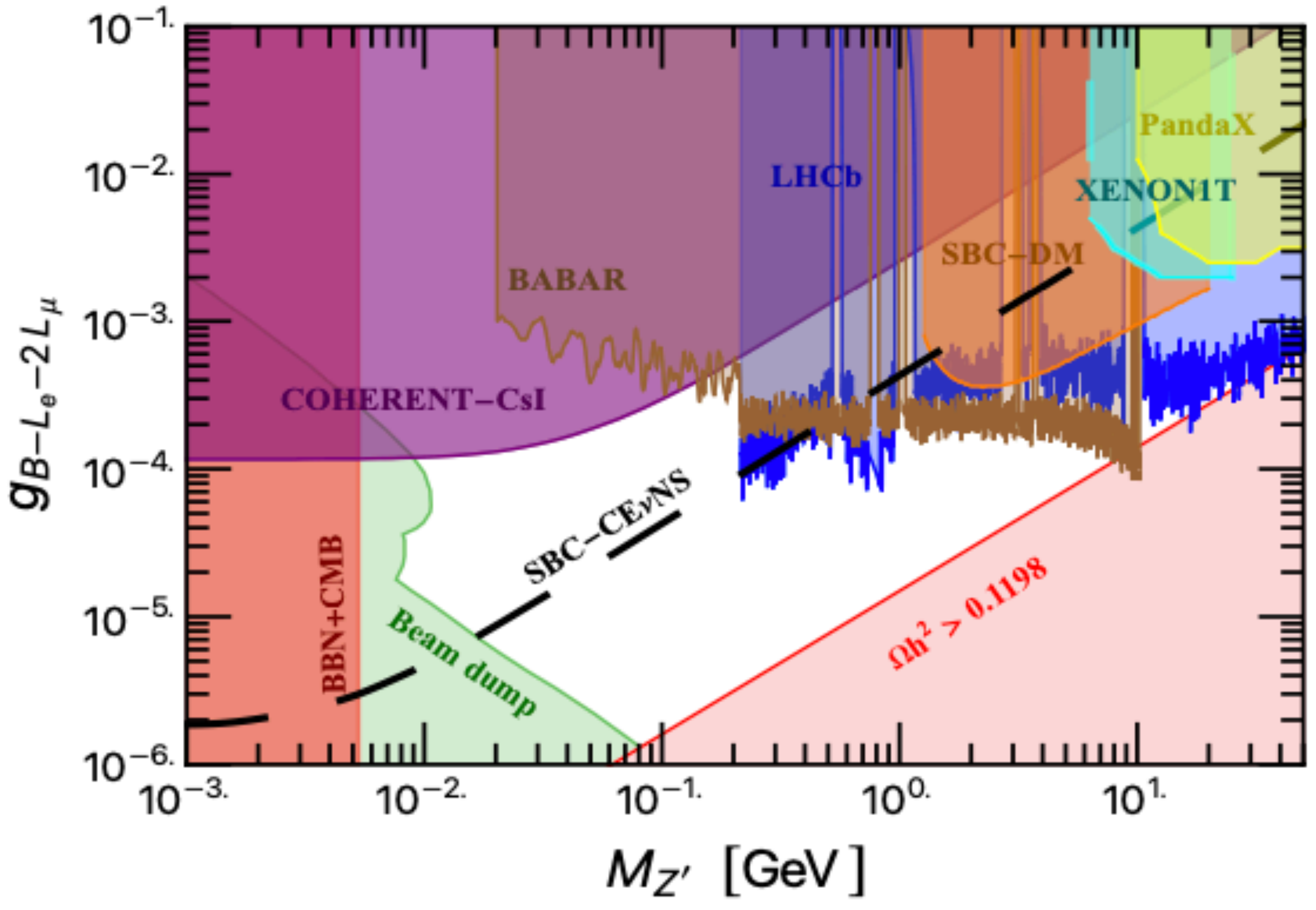


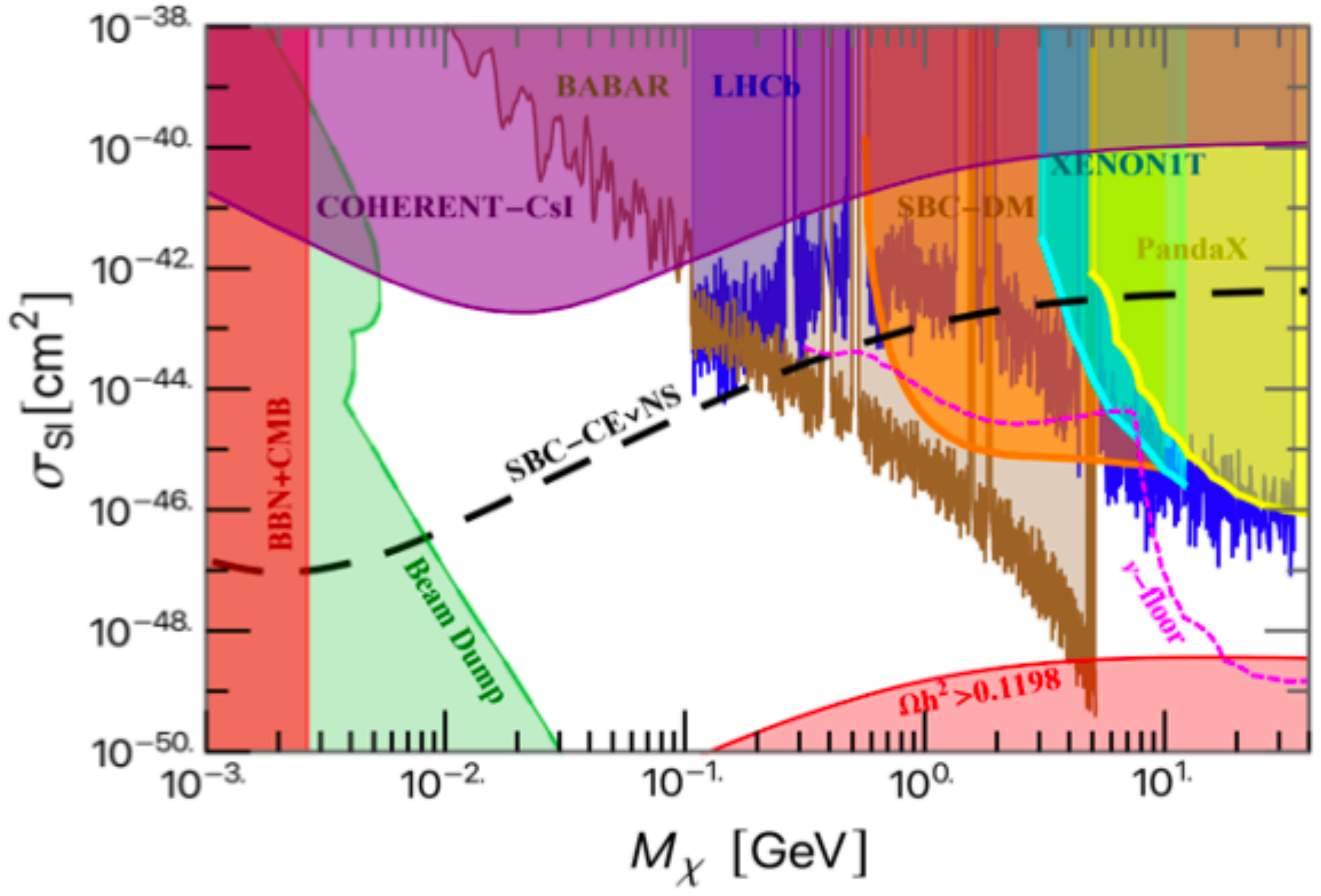


$U(1)_{B-2L_\alpha-L_\beta}$

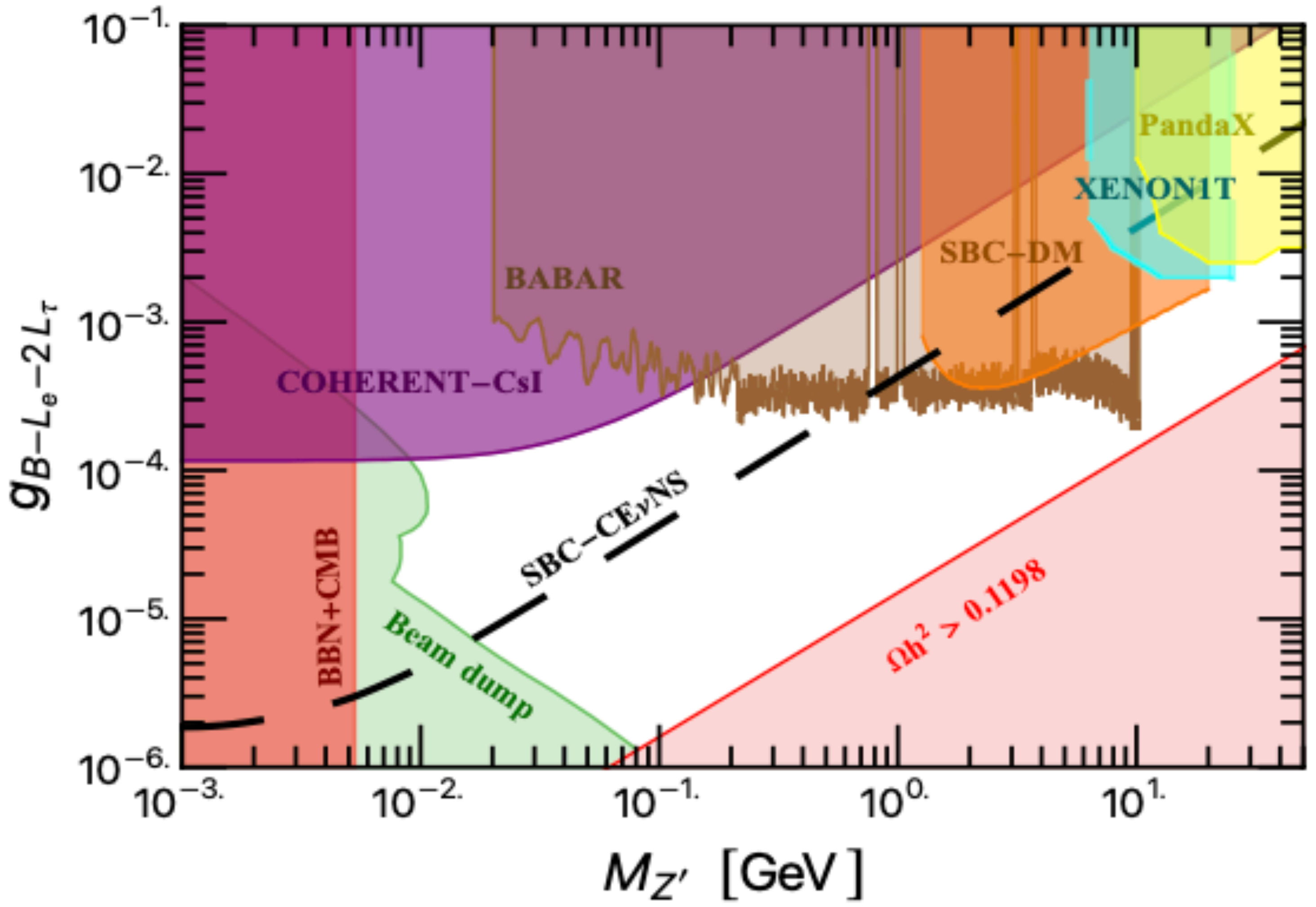
L. Flores, N. Nath, EP, JHEP (2020)

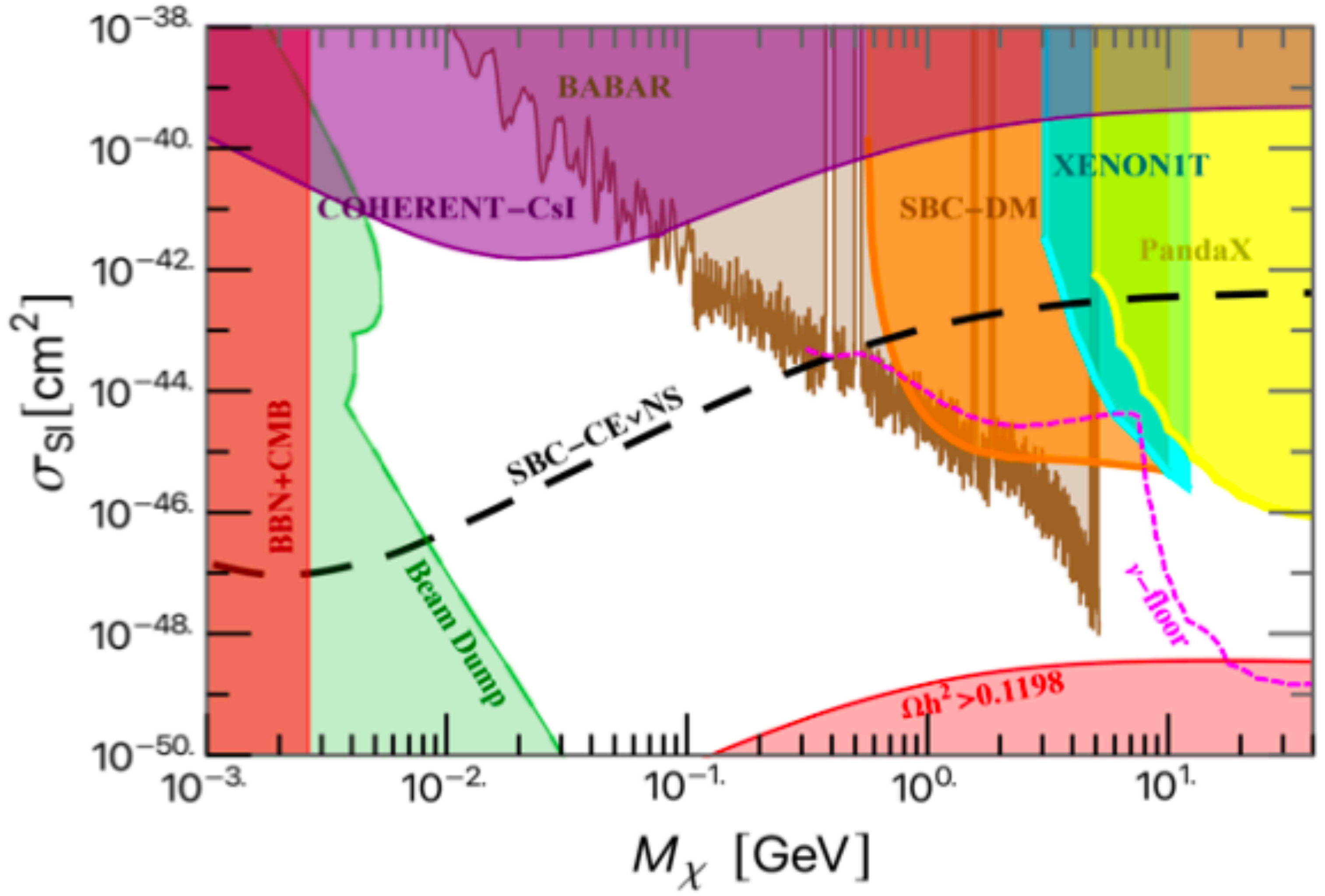
LMG de la Vega, L. Flores, N. Nath JHEP (2021)





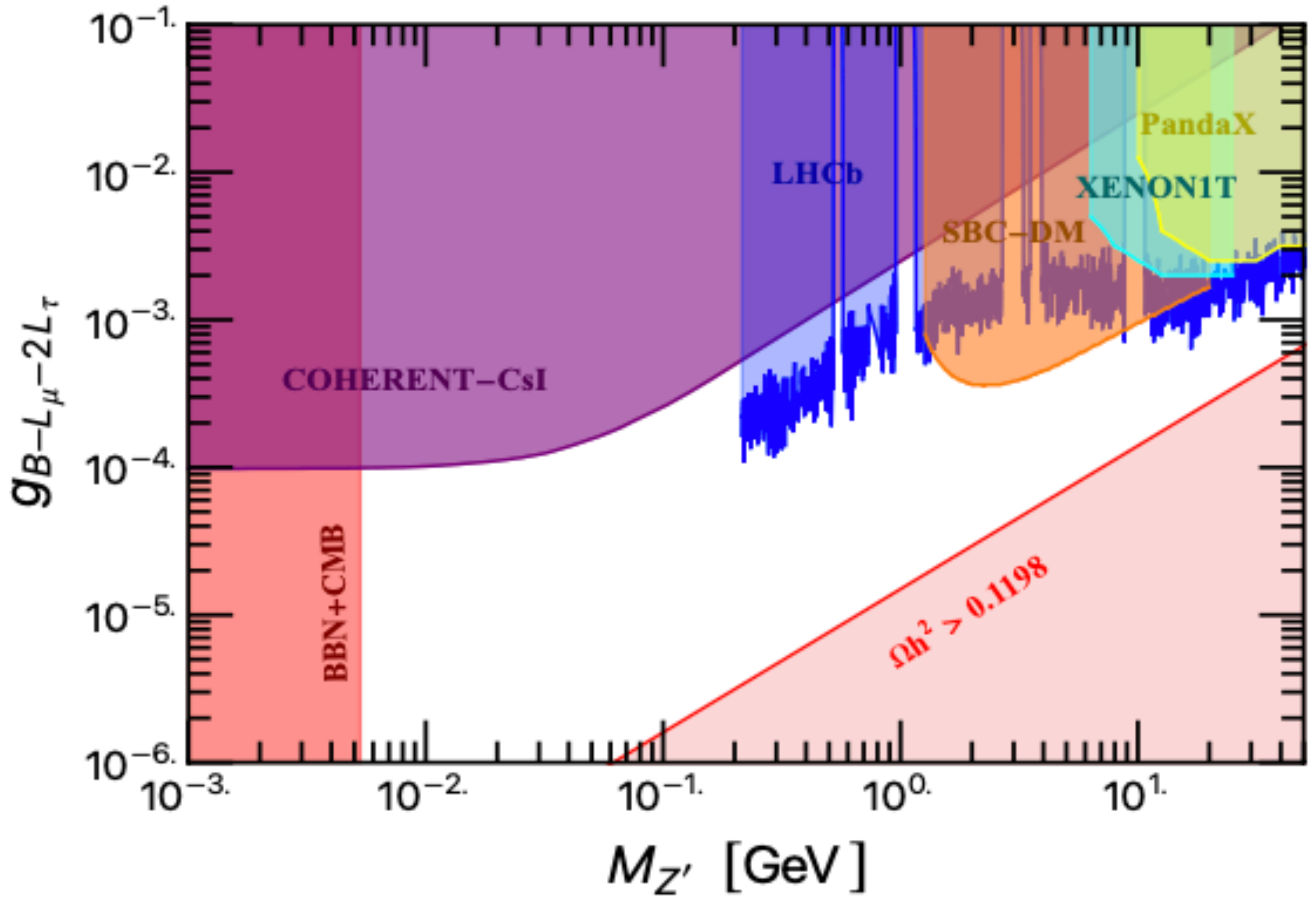
B_4

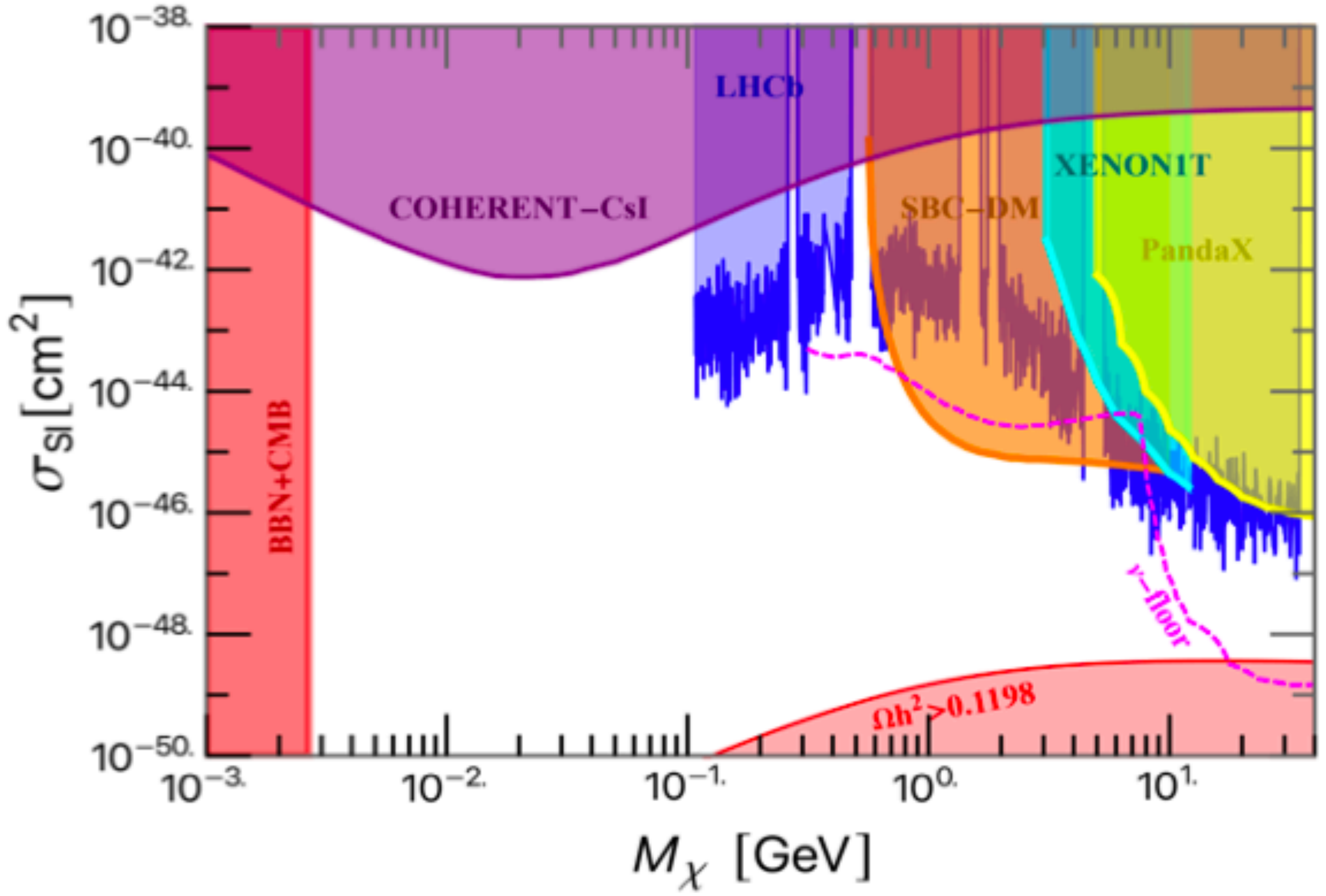




B_3

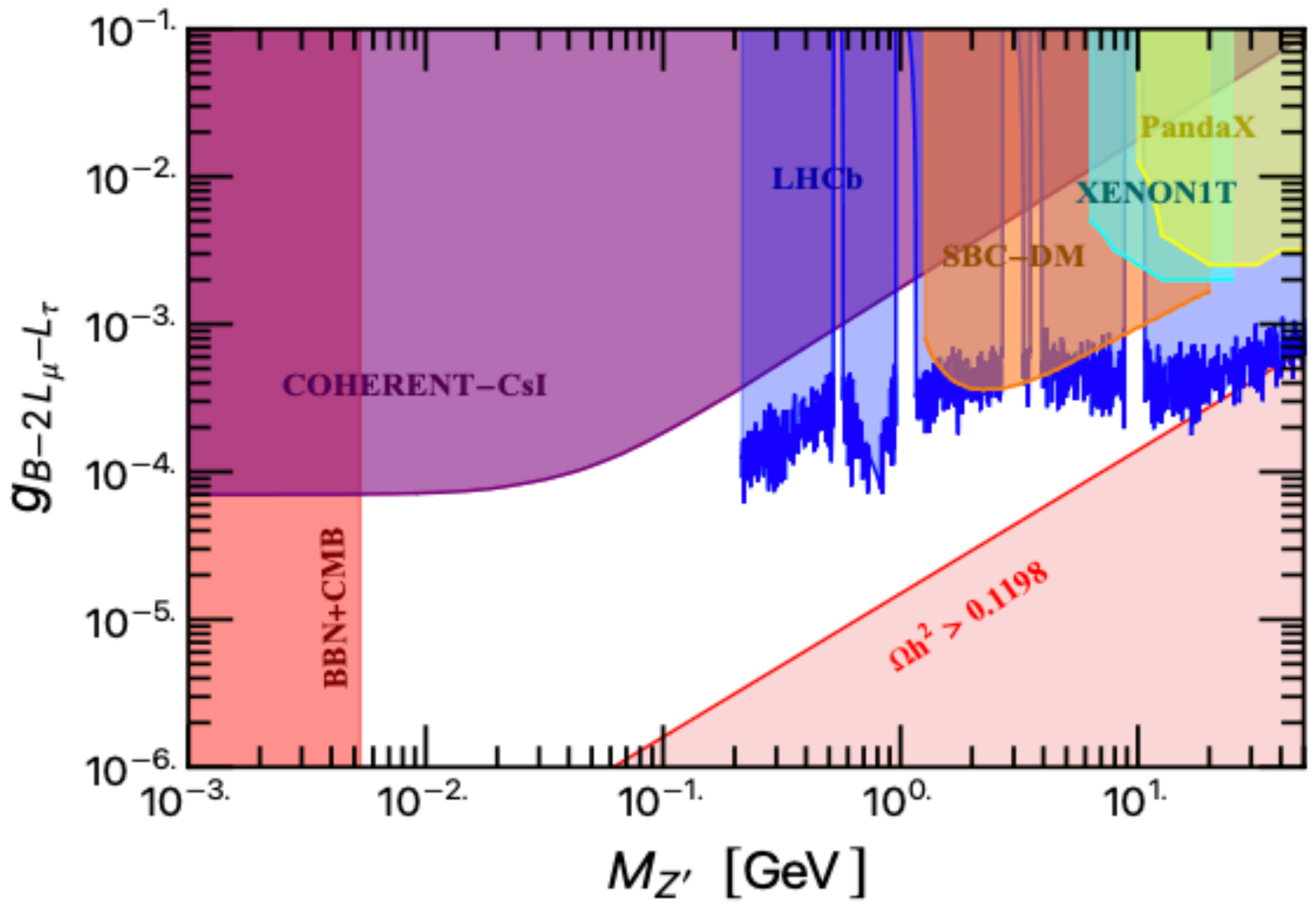
LMG de la Vega, L. Flores, N. Nath JHEP (2021)

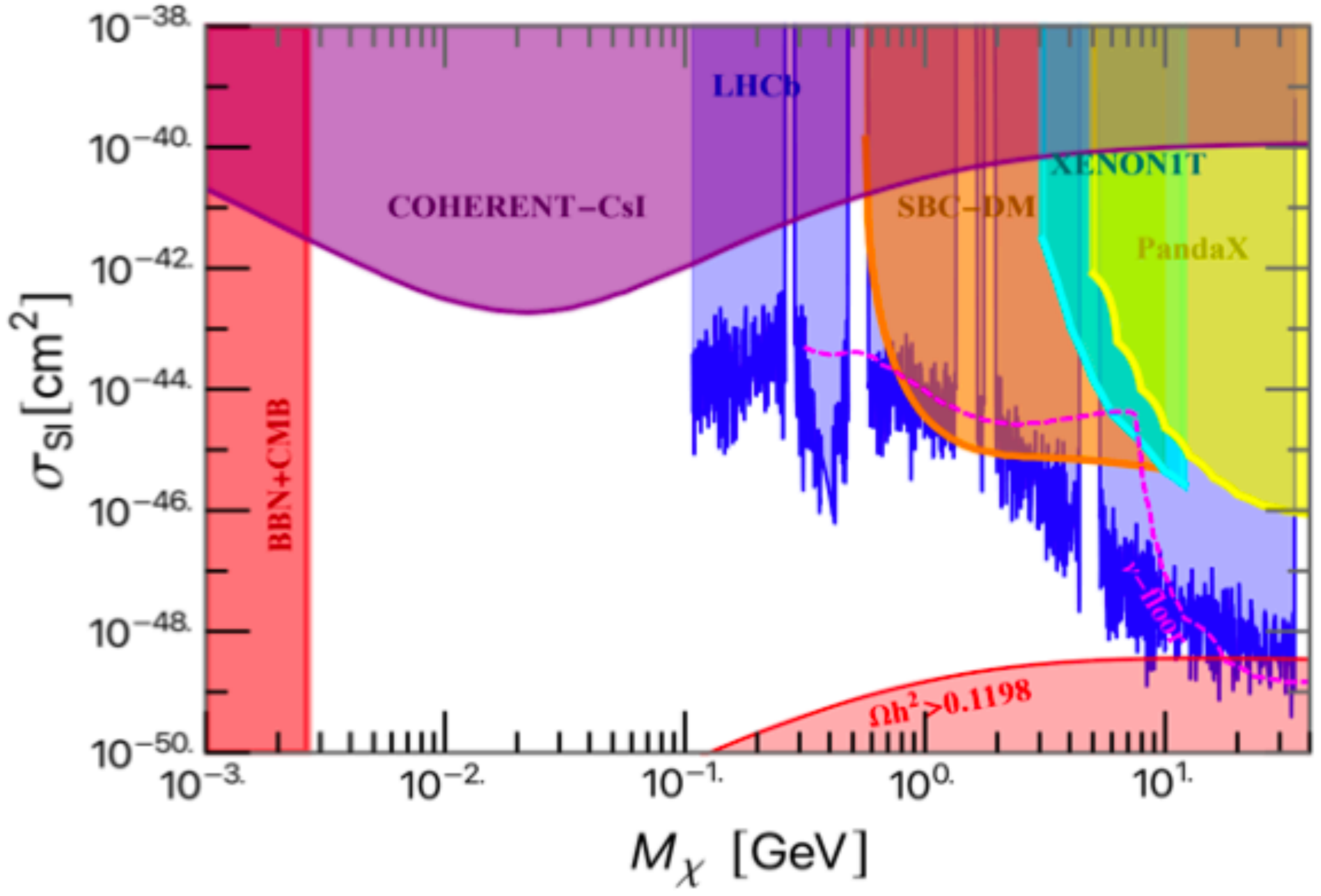




A_1

$m_{ee} = 0$





A_2

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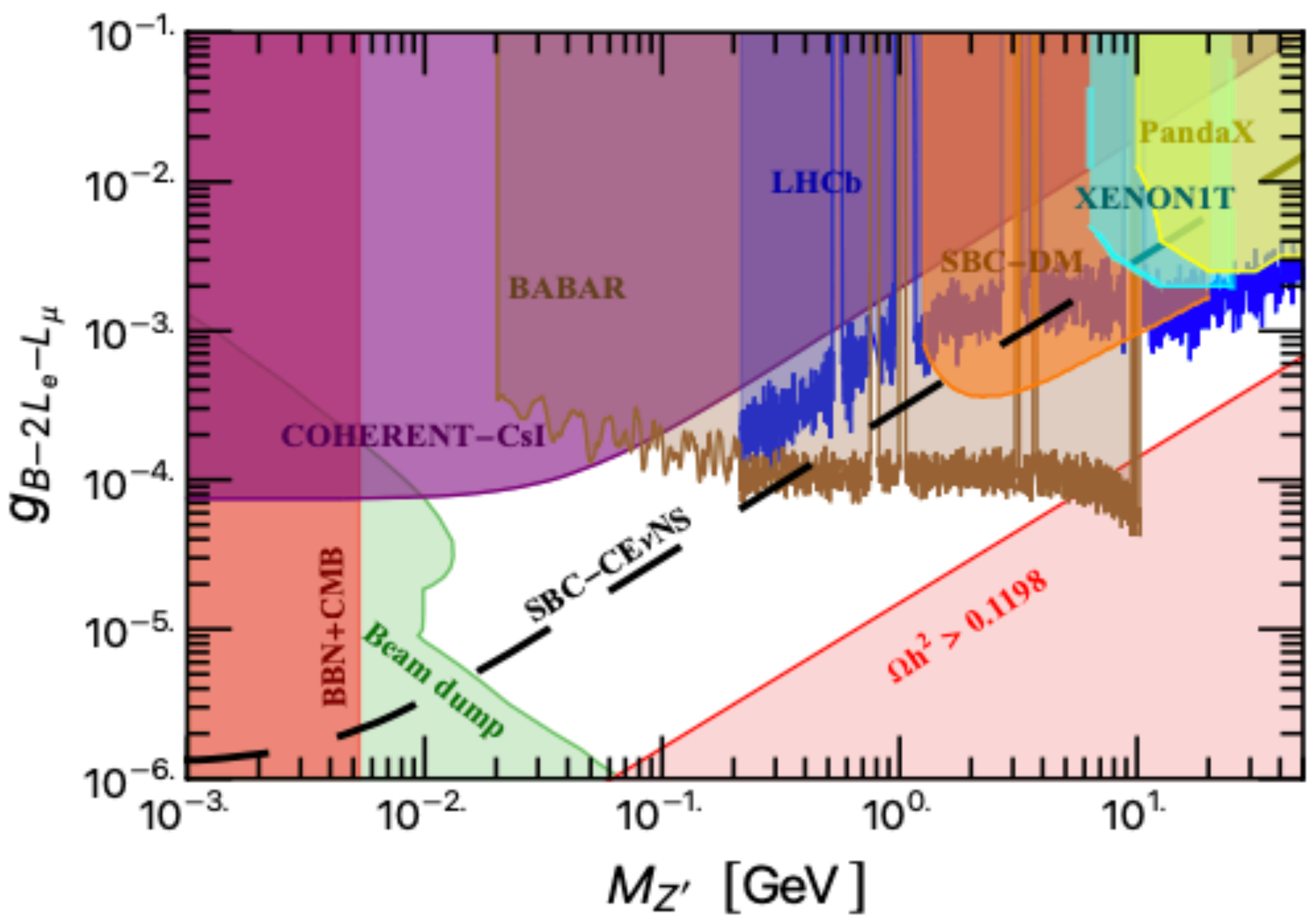
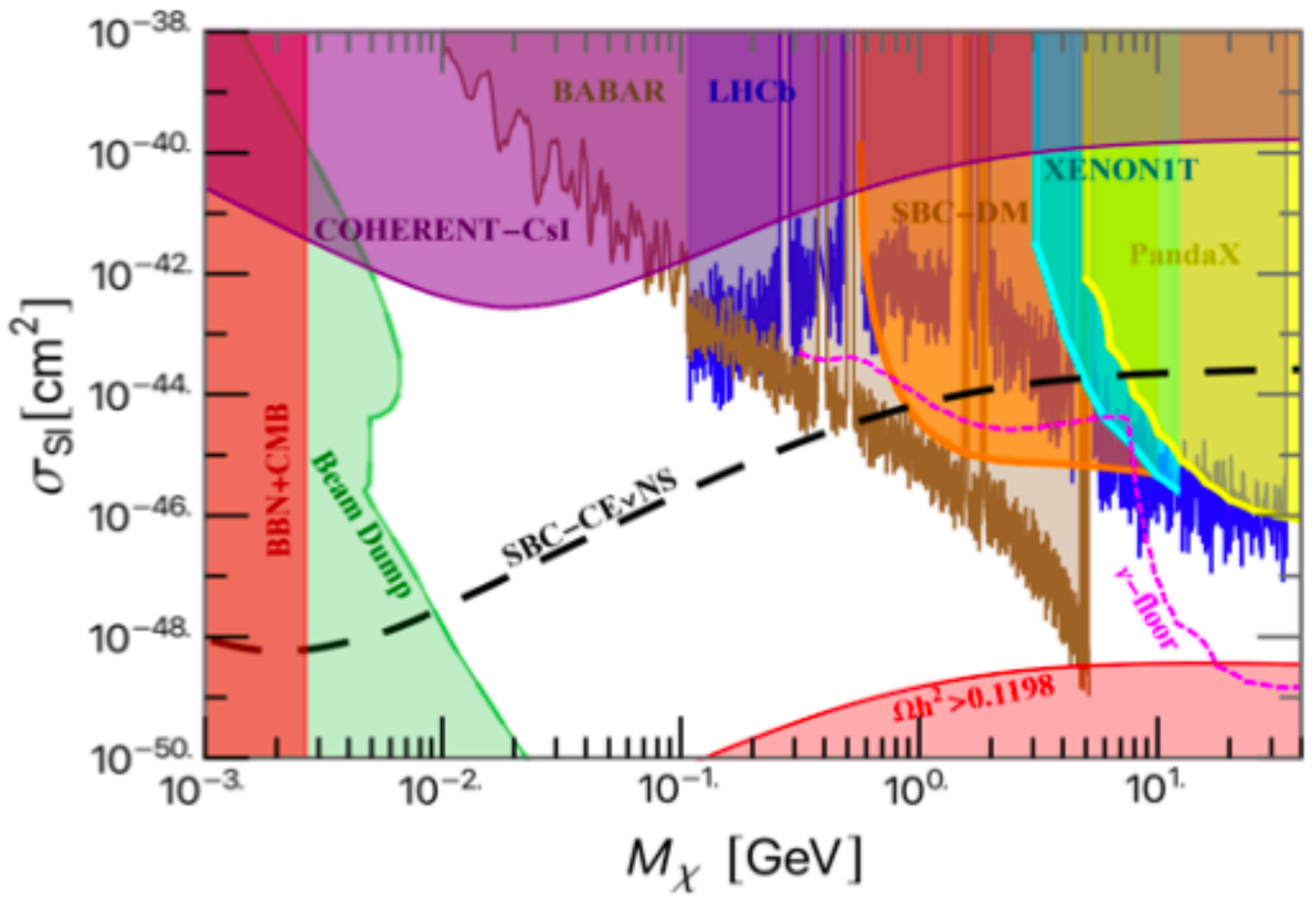
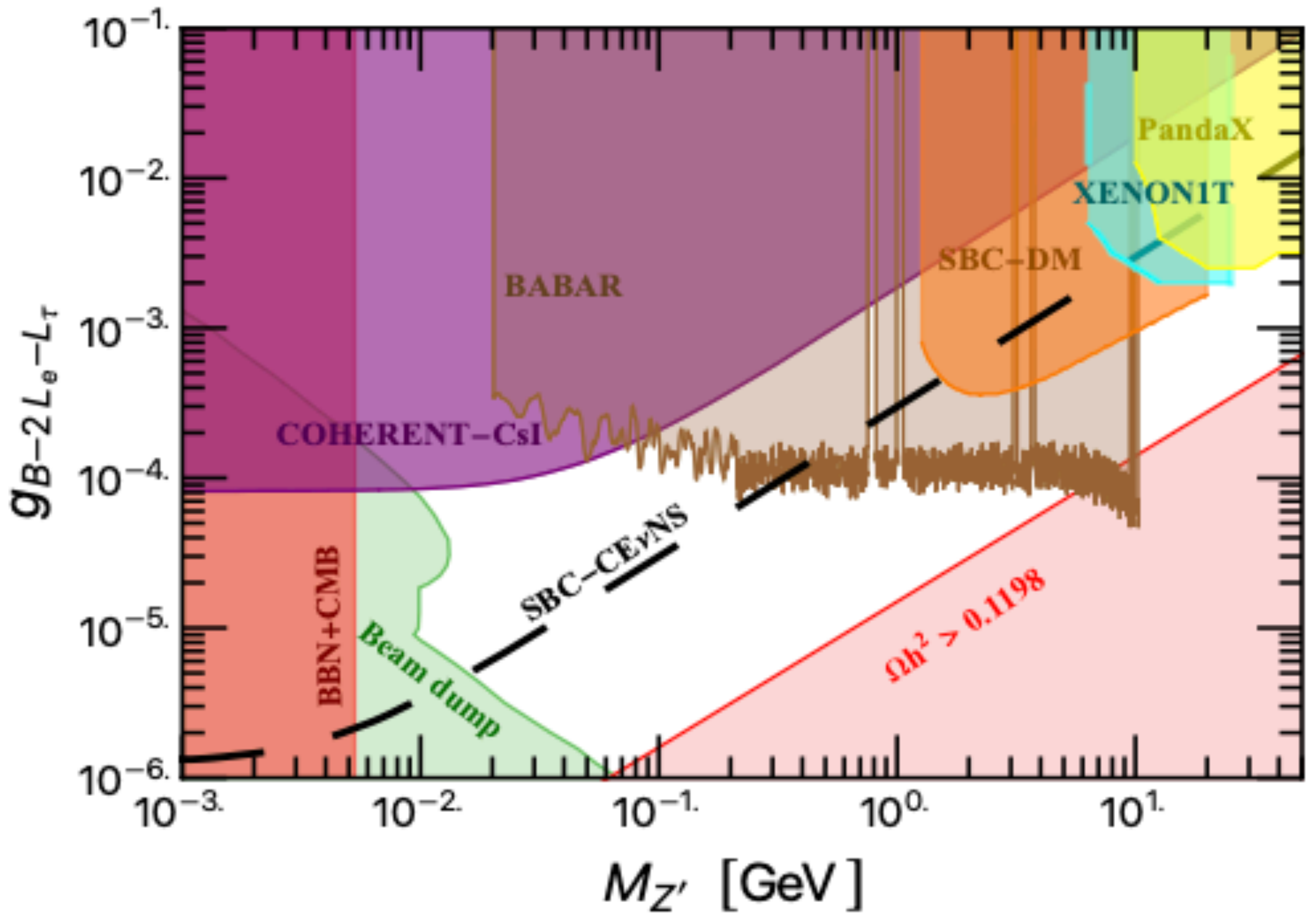
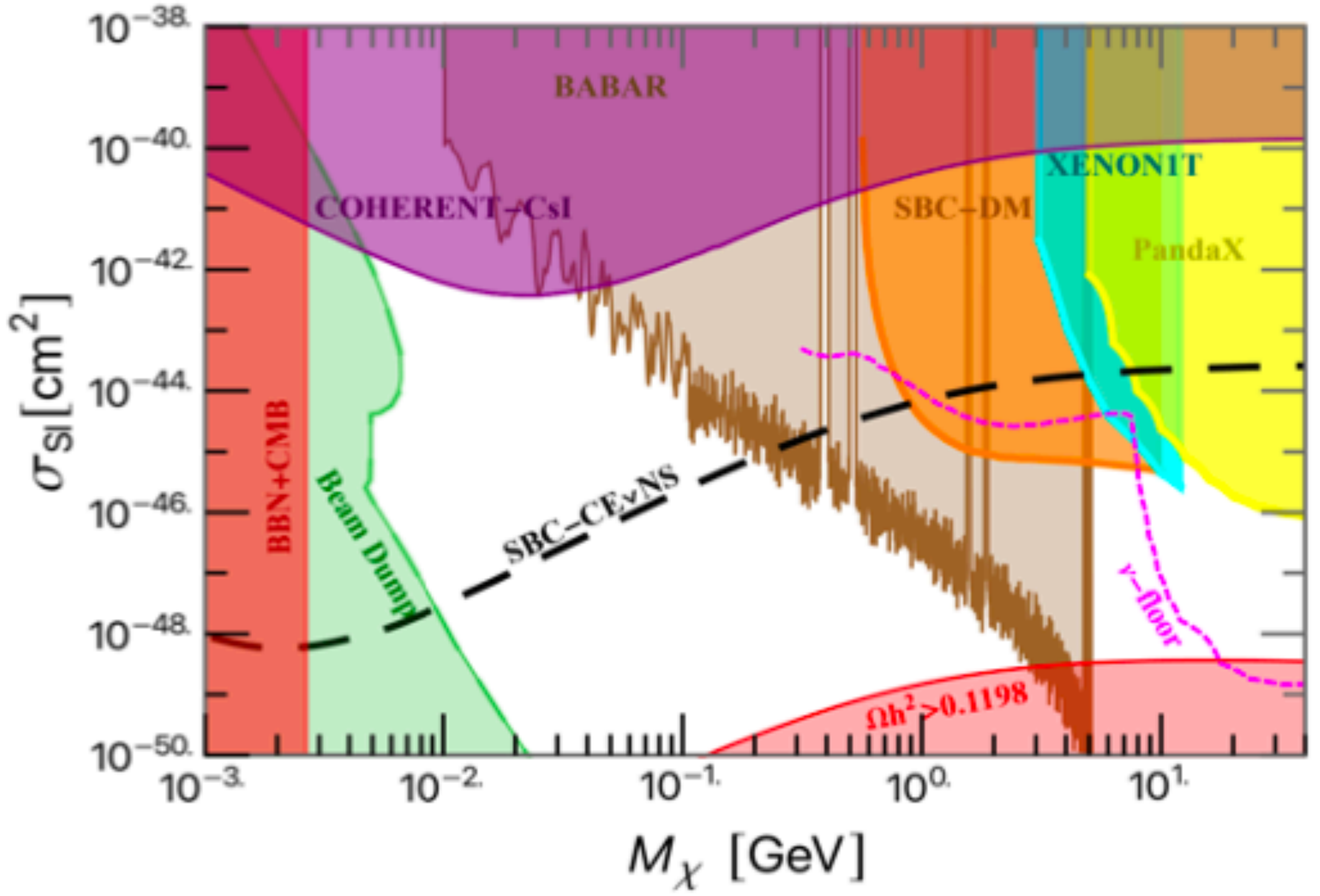


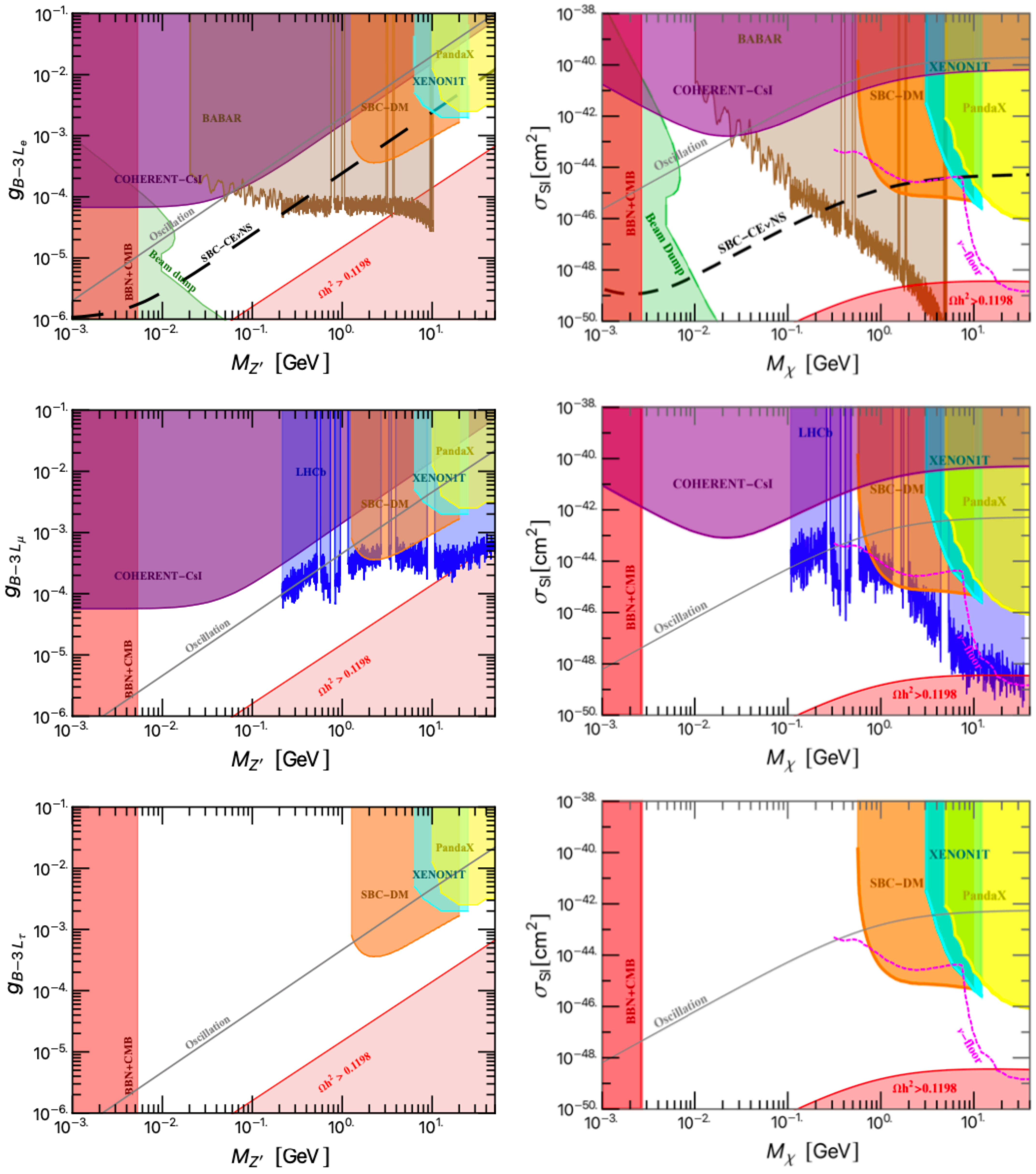


$$m_{12}m_{33} = m_{13}m_{23}$$





$$m_{12}m_{23} = m_{13}m_{22}$$



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Oscillation for $U(1)_{B-3L_\alpha}$

P. Coloma, M. C. Gonzalez-Garcia, and M. Maltoni
JHEP. (2021)

Conclusions

- Light vector bosons can have a strong impact in low energy experiments
- CEvNS are competitive for light vector bosons with direct couplings to SM Fermions
- Complementarity between DM direct searches, collider and CEvNS experiments.

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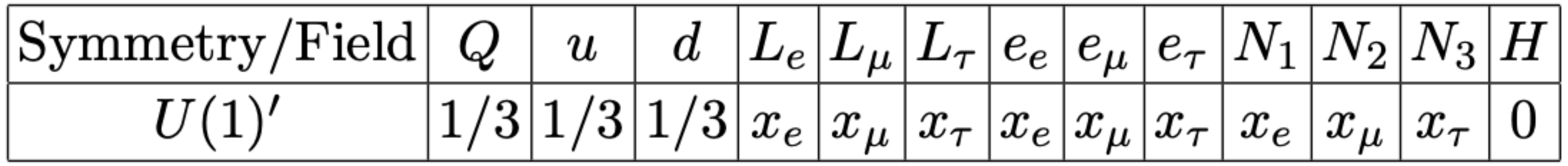
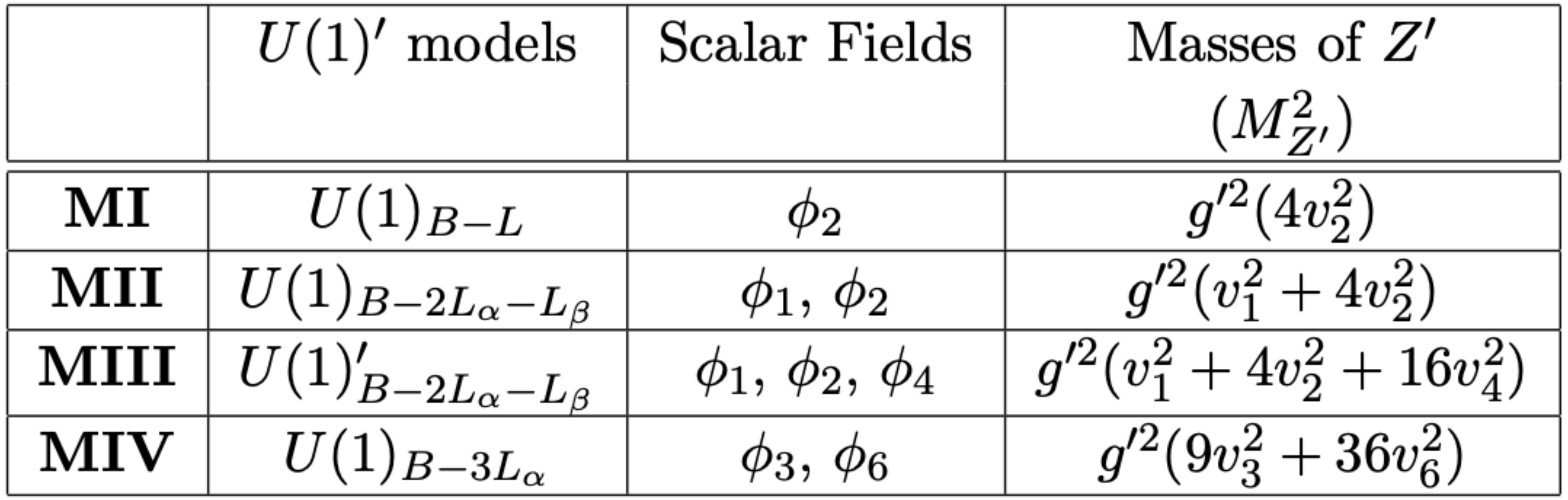


Symmetry/Field	Q	u	d	L_e	L_μ	L_τ	e_e	e_μ	e_τ	N_1	N_2	N_3	H
$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

Singlet scalar fields ϕ_i having charges i under $\mathrm{U}(1)'$

Good ν pheno



	$U(1)'$ models	Scalar Fields	Masses of Z' ($M_{Z'}^2$)
MI	$U(1)_{B-L}$	ϕ_2	$g'^2(4v_2^2)$
MII	$U(1)_{B-2L_\alpha-L_\beta}$	$\phi_1,\ \phi_2$	$g'^2(v_1^2+4v_2^2)$
MIII	$U(1)'_{B-2L_\alpha-L_\beta}$	$\phi_1,\ \phi_2,\ \phi_4$	$g'^2(v_1^2+4v_2^2+16v_4^2)$
MIV	$U(1)_{B-3L_\alpha}$	$\phi_3,\ \phi_6$	$g'^2(9v_3^2+36v_6^2)$

Singlet scalar fields ϕ_i having charges i under $\mathrm{U}(1)'$

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Symmetry/Field	Q	u	d	L_e	L_μ	L_τ	e_e	e_μ	e_τ	N_1	N_2	N_3	H
$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

Singlet scalar fields ϕ_i having charges i under U(1)$'$

Good ν pheno

↕

L. Flores, N. Nath, EP, JHEP (2020)

4 different cases, two-zero textures, good pheno and predictions

	$U(1)'$ models	Scalar Fields	Masses of Z' ($M^2_{Z'}$)
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MII	$U(1)_{B-2L_\alpha-L_\beta}$	$\phi_1,\ \phi_2$	$g'^2(v_1^2+4v_2^2)$
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Singlet scalar fields ϕ_i having charges i under U(1)$'$

LMG de la Vega, L. Flores, N. Nath JHEP (2021)

Symmetry/Field	Q	u	d	L_e	L_μ	L_τ	e_e	e_μ	e_τ	N_1	N_2	N_3	H
$U(1)'$	$1/3$	$1/3$	$1/3$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0

Singlet scalar fields ϕ_i having charges i under $\mathrm{U}(1)'$

Good ν pheno

↕

	$U(1)'$ models	Scalar Fields	Masses of Z' $(M^2_{Z'})$
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Singlet scalar fields ϕ_i having charges i under $\mathrm{U}(1)'$

L. Flores, N. Nath, EP, JHEP (2020)

4 different cases, two-zero textures, good pheno and predictions

2 different cases, one-zero textures, good pheno and prediction

Extend the SM with a Dirac fermion χ
with $Q_\chi = 1/3$

$$\mathscr{L} \supset M_D\bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + ig'Q_\chi Z'_\mu)\chi$$

Only trough gauge boson
Z'

LMG de la Vega, L. Flores, N. Nath JHEP (2021)

Extend the SM with a Majorana fermion χ
with $Q_\chi = 1/2$

$$\mathscr{L} \supset M_D\bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + ig'Q_\chi Z'_\mu)\chi + \lambda\phi_1\bar{\chi}^c\chi$$

Annihilation ans co-annihilation
ϕ_1

See for instance Bonilla et al. New Journal of Physics (2020)