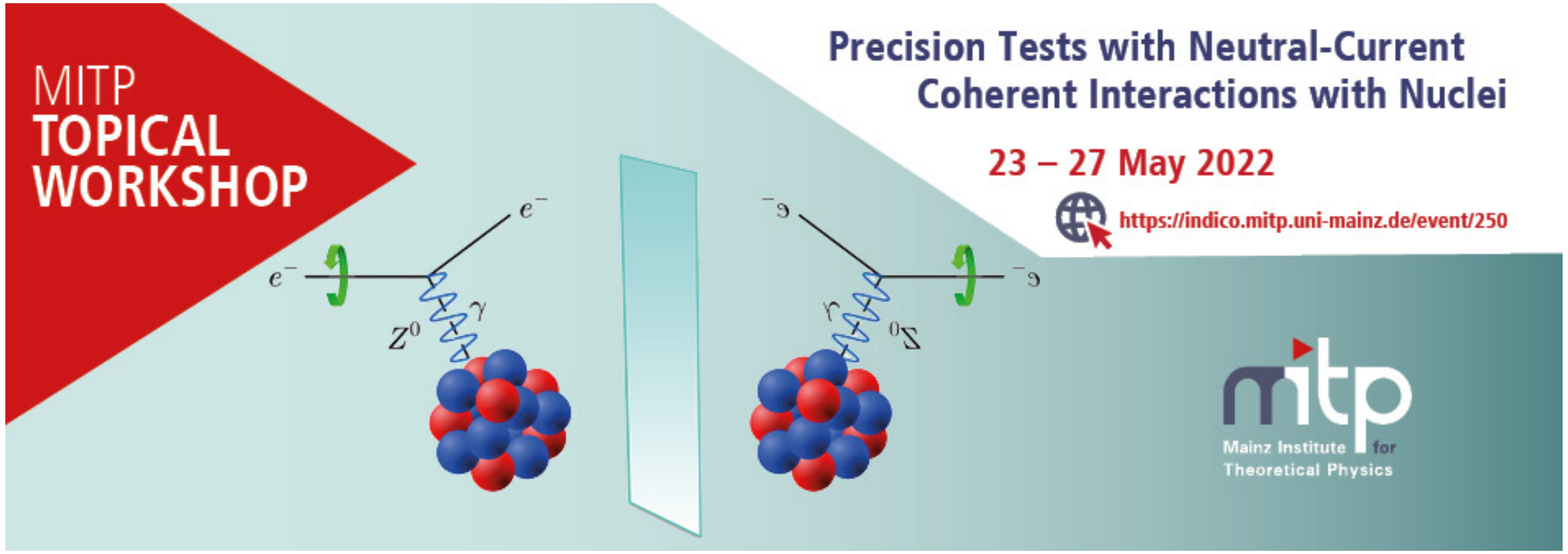

Eduardo Peinado

Departamento de Física Teórica
Instituto de Física UNAM

Constraining light vector bosons with CEvNS and PVES

Dirección General de Asuntos
del Personal Académico

CONACYT

Outline

Light vector bosons

Dark matter

Constraints from CEvNS

Constraints from PV

Conclusions

Motivations

Gauge extensions of the SM

Erler and Rojas JHEP 2015

$E_6 \to SO(10) \times U(1)$ $\quad SO(10) \to SU(5) \times U(1)$

Impact on low and high energy experiments

Z´production

Z´effects at low energies

Different couplings

$\epsilon B^{\mu\nu} F_{\mu\nu}$ $\quad \delta m^2 Z_\mu Z'_\mu$

$J_\mu Z'_\mu$

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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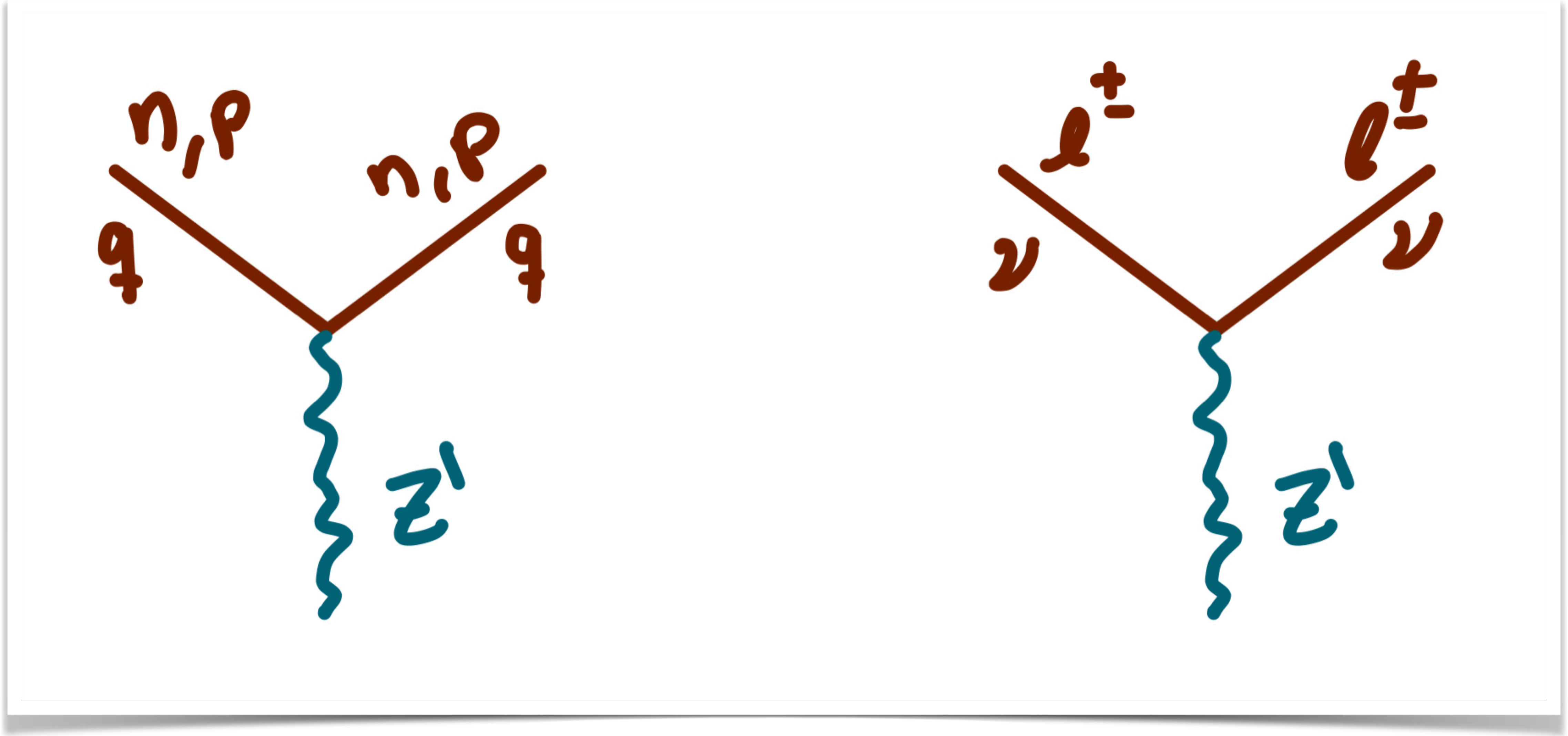
If $Q_f \neq 0$ for quarks



If $Q_f \neq 0$ for leptons

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

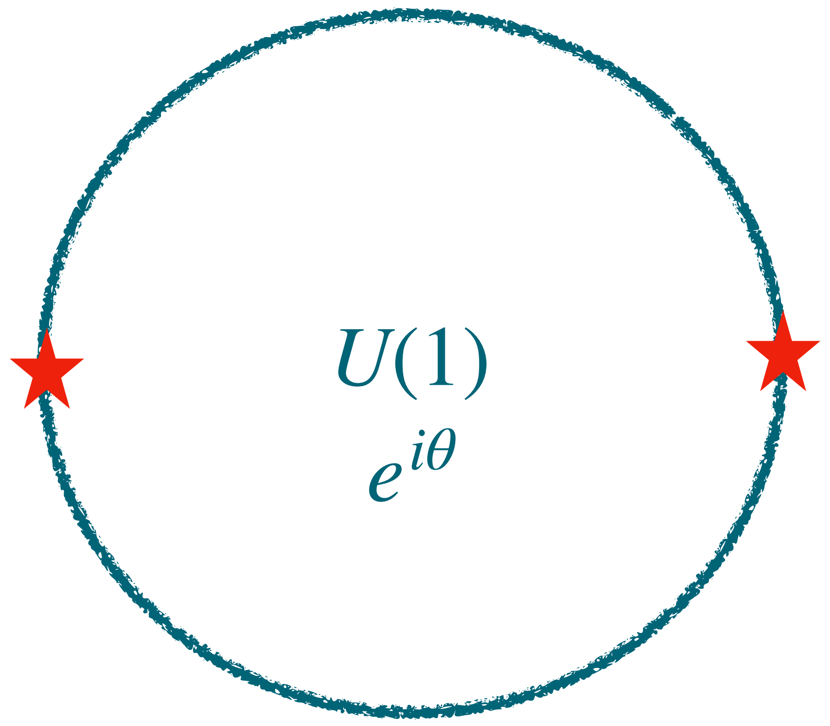
Dark Matter and neutrino nature $U(1)'$

$U(1)$

$e^{i\theta}$

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

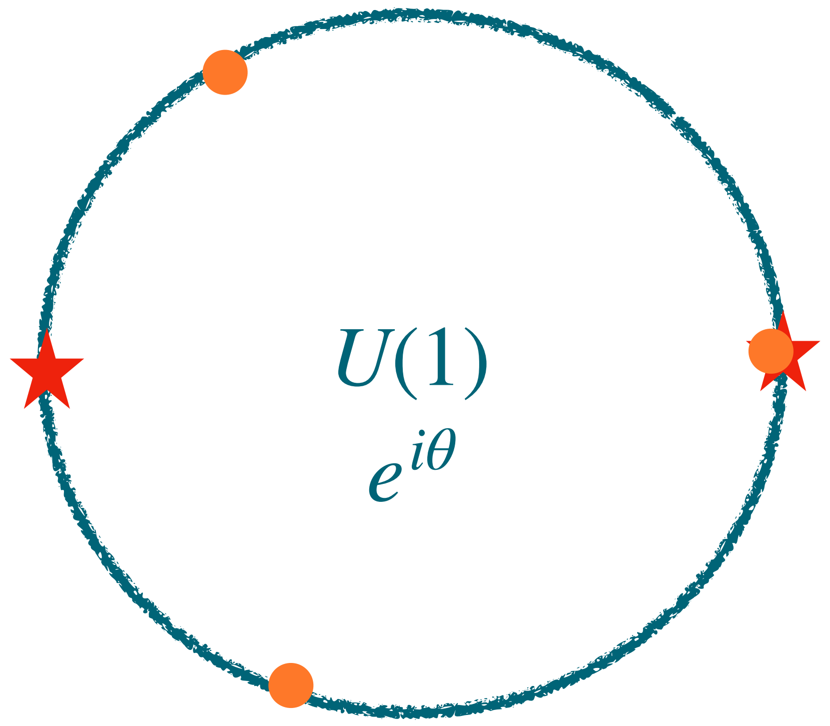
Z_2 ± 1



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

Z_2 ± 1

Z_3 ω^n $\omega = e^{i2/3\pi}$



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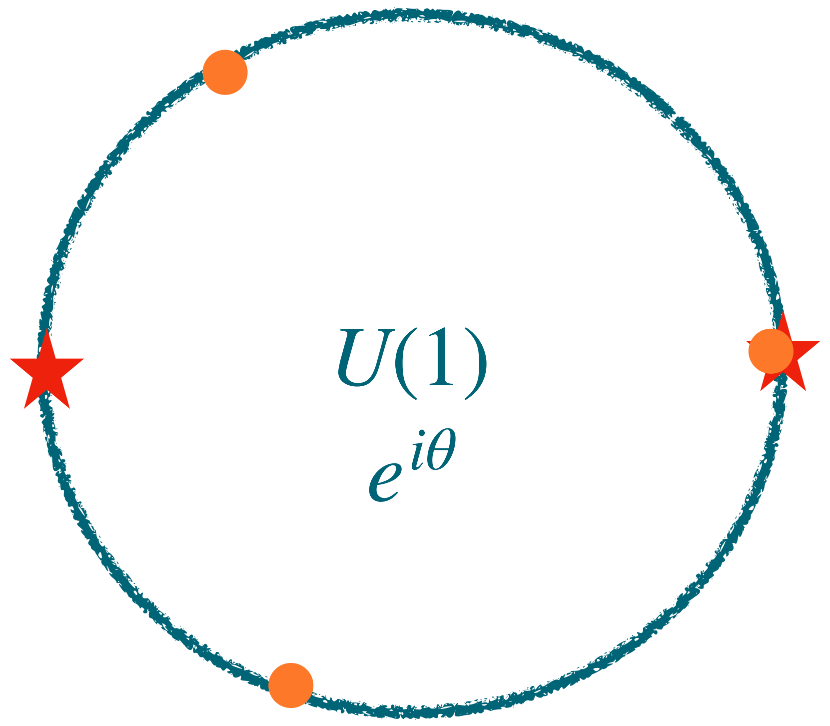


Can be used for DM stability

$U(1)'$ global or local

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 $\langle \chi \rangle \neq 0$ $\quad V \supset \phi^y$

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

Up to now only COHERENT SNS detected

Kate Scholberg on Thursday

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

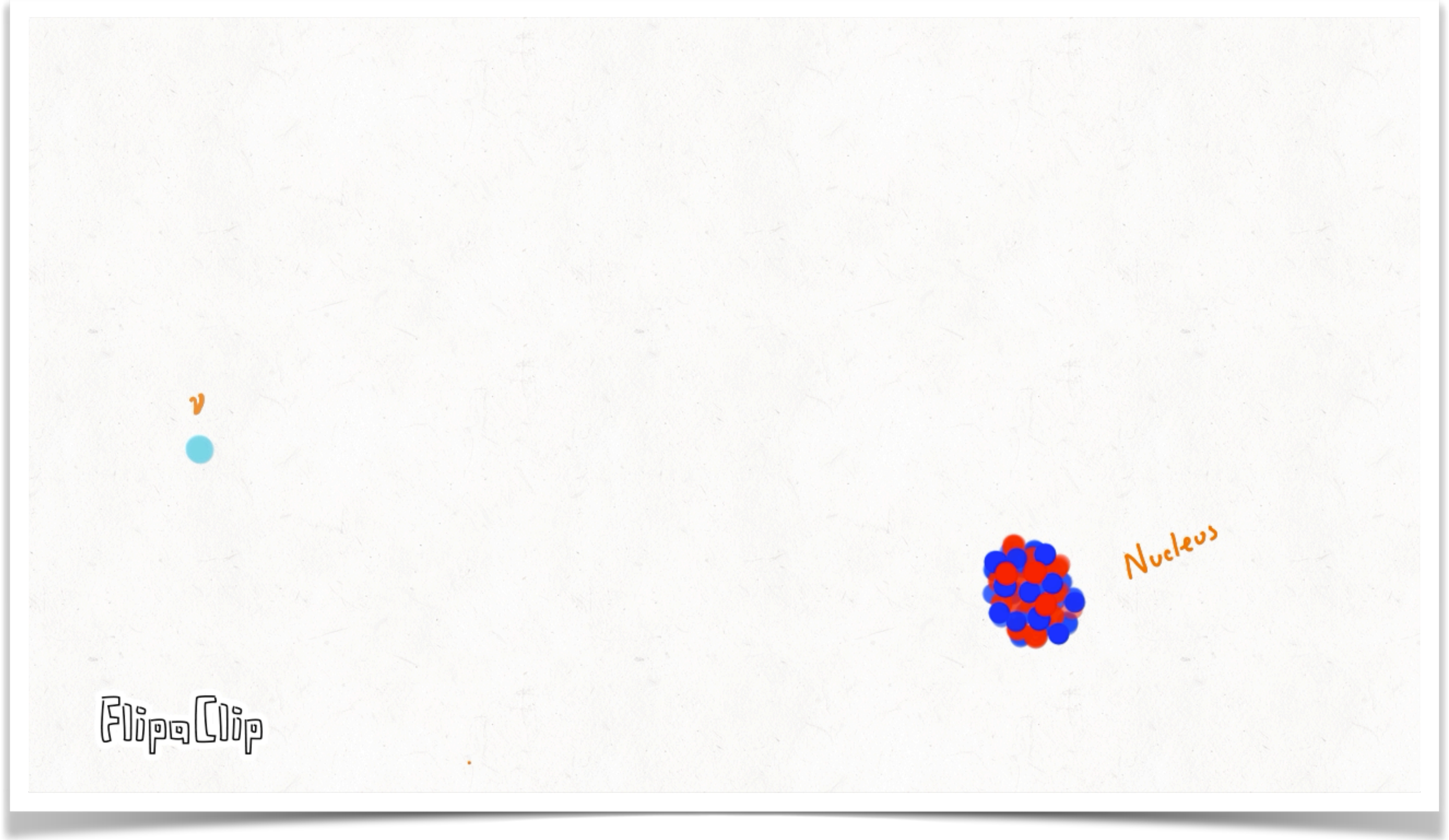
24 Kg **Ar** 159 events (~ 240 days)

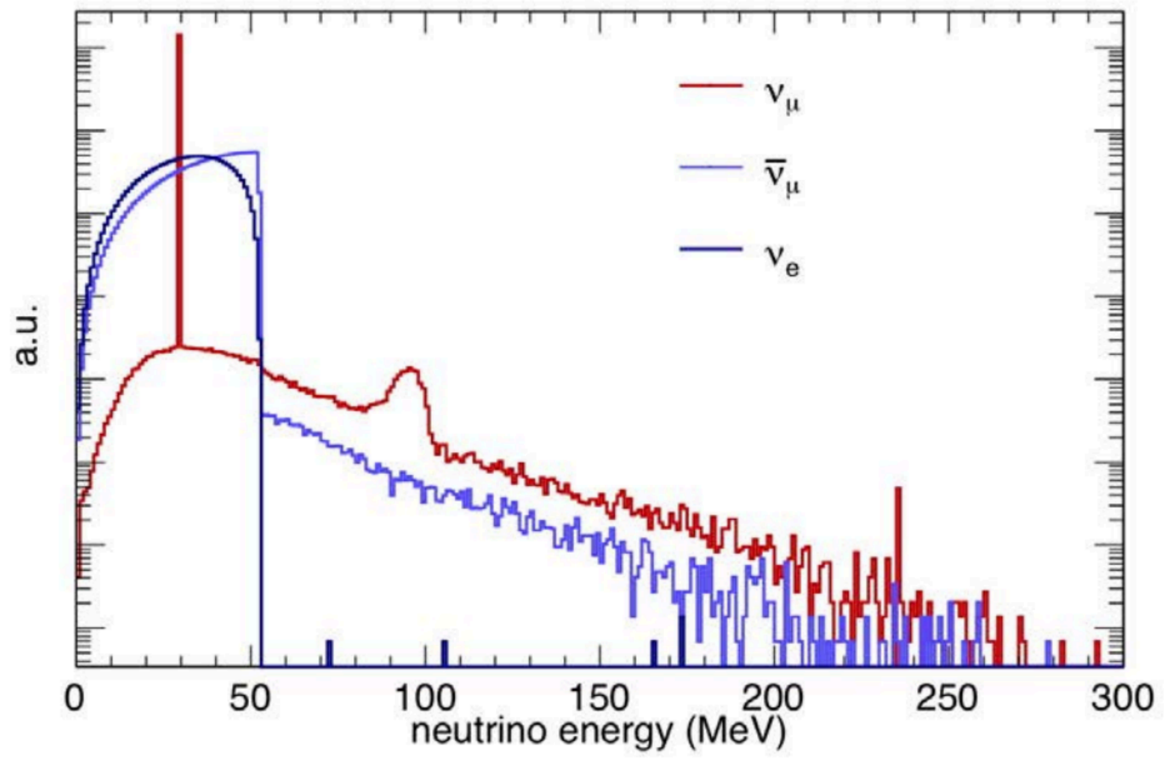
Ar will continue …

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

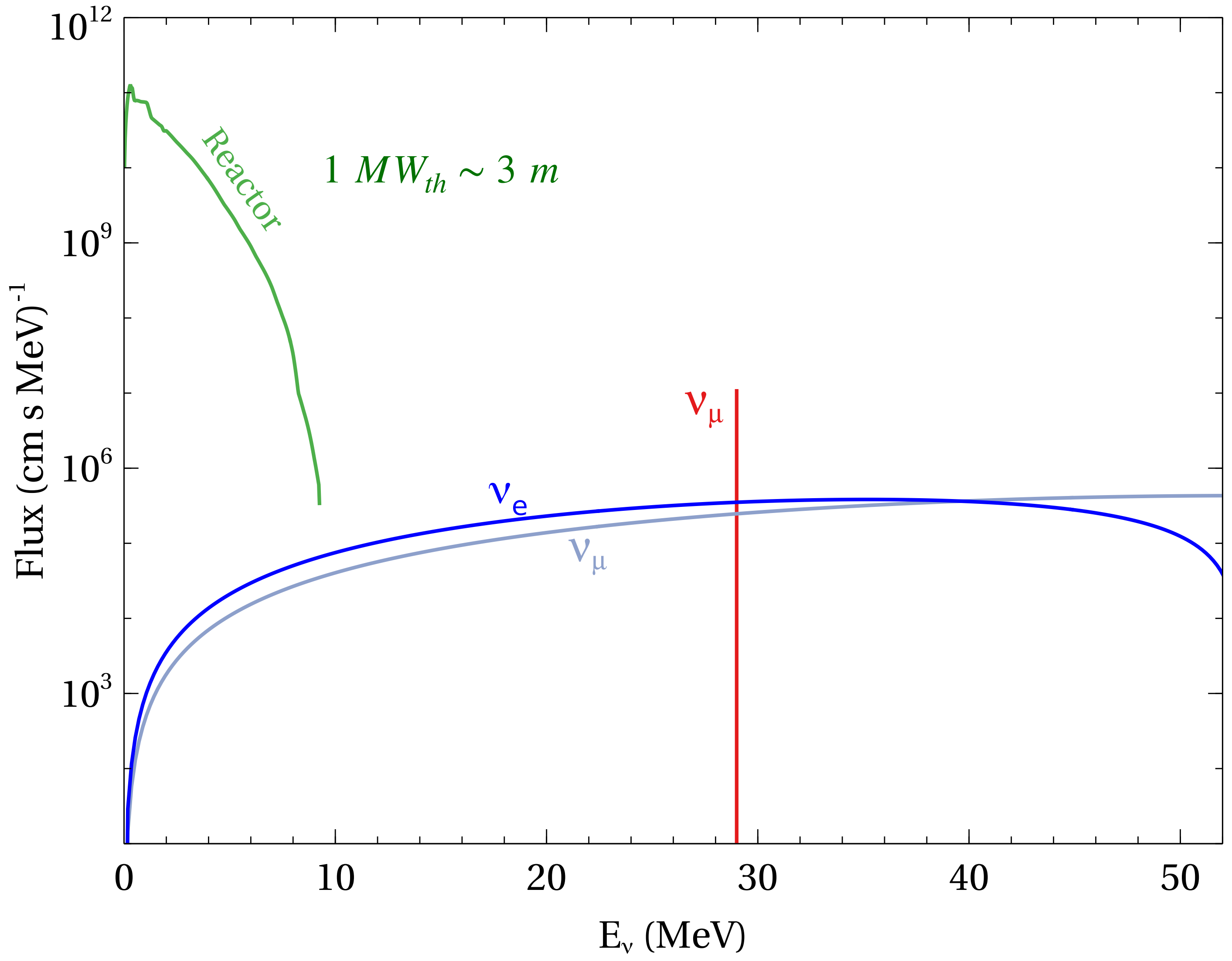
$$Hg \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu (29.9\ MeV)$$

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





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



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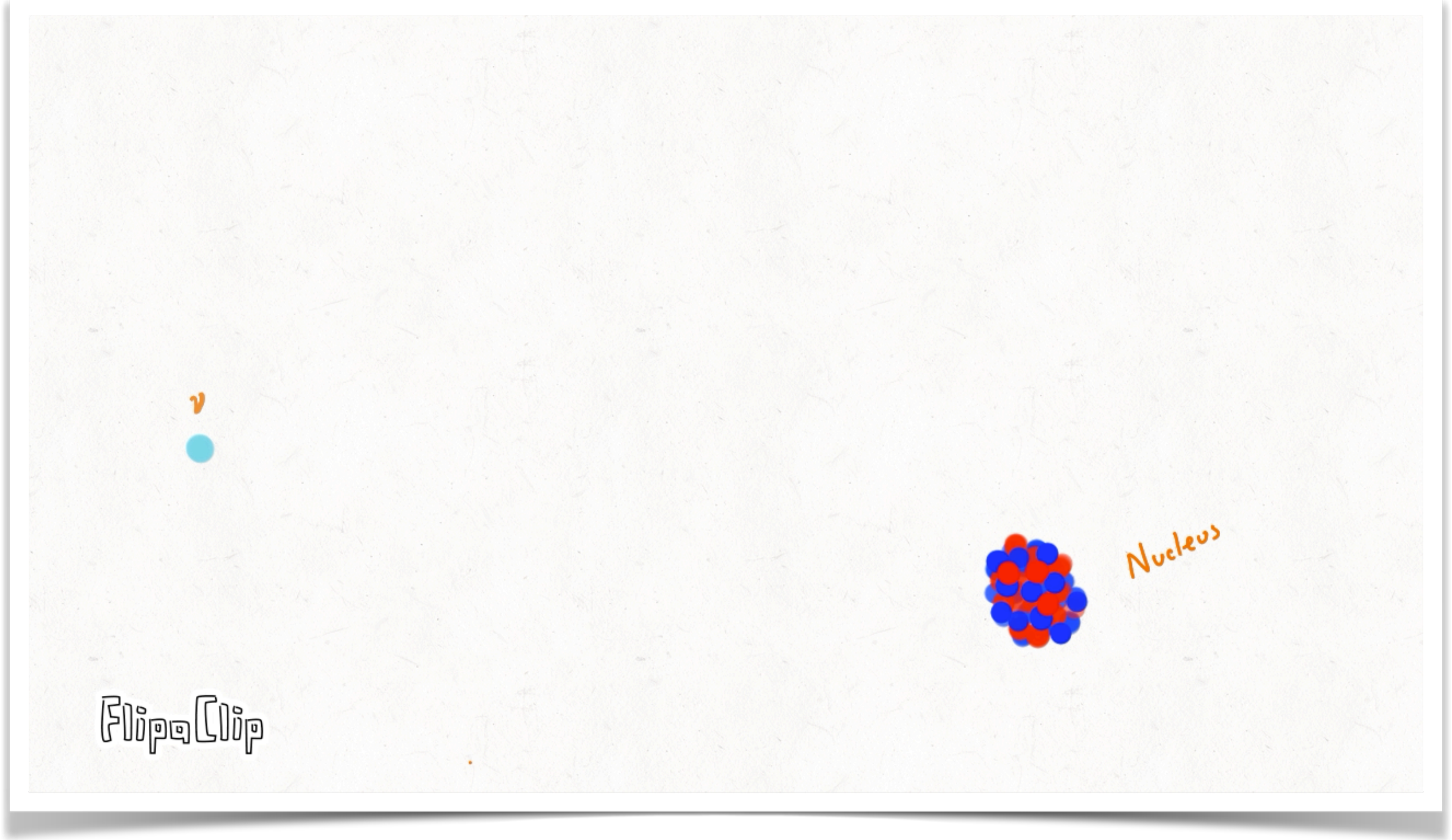

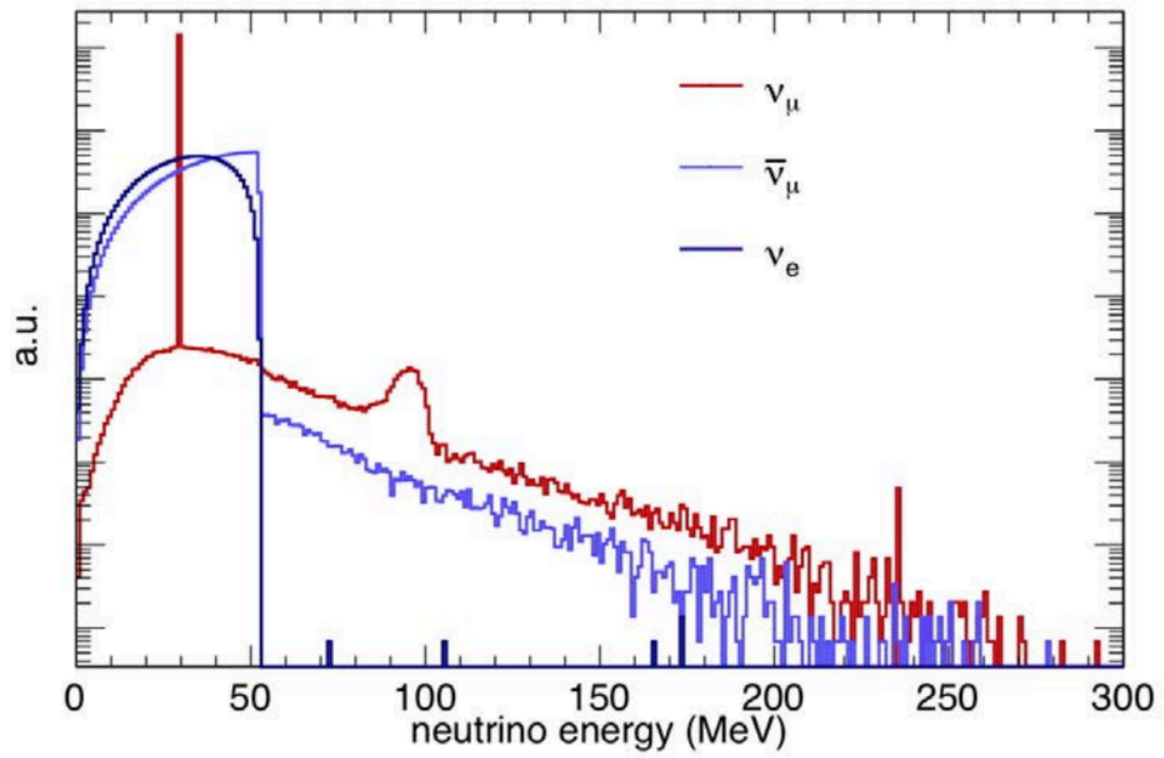

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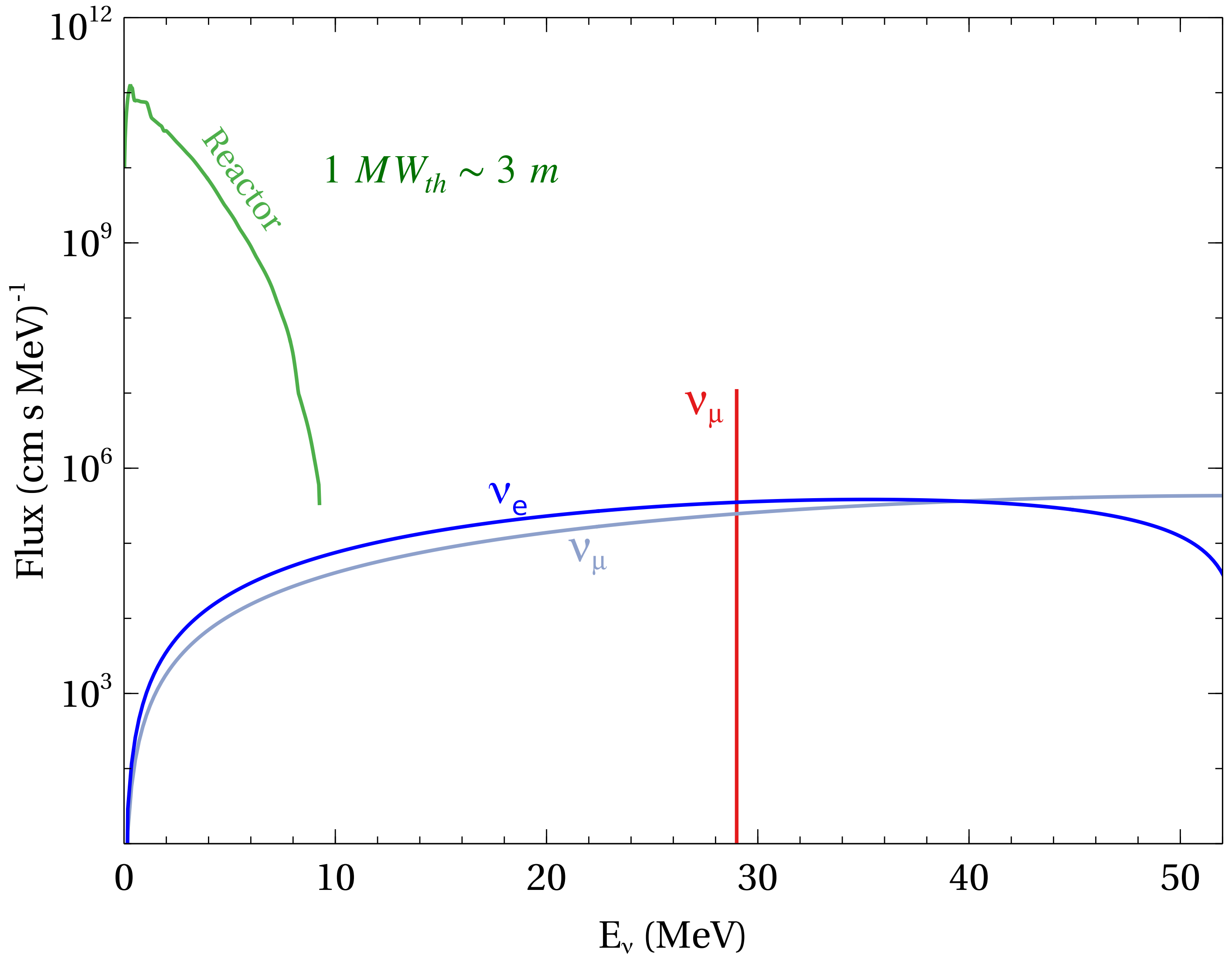
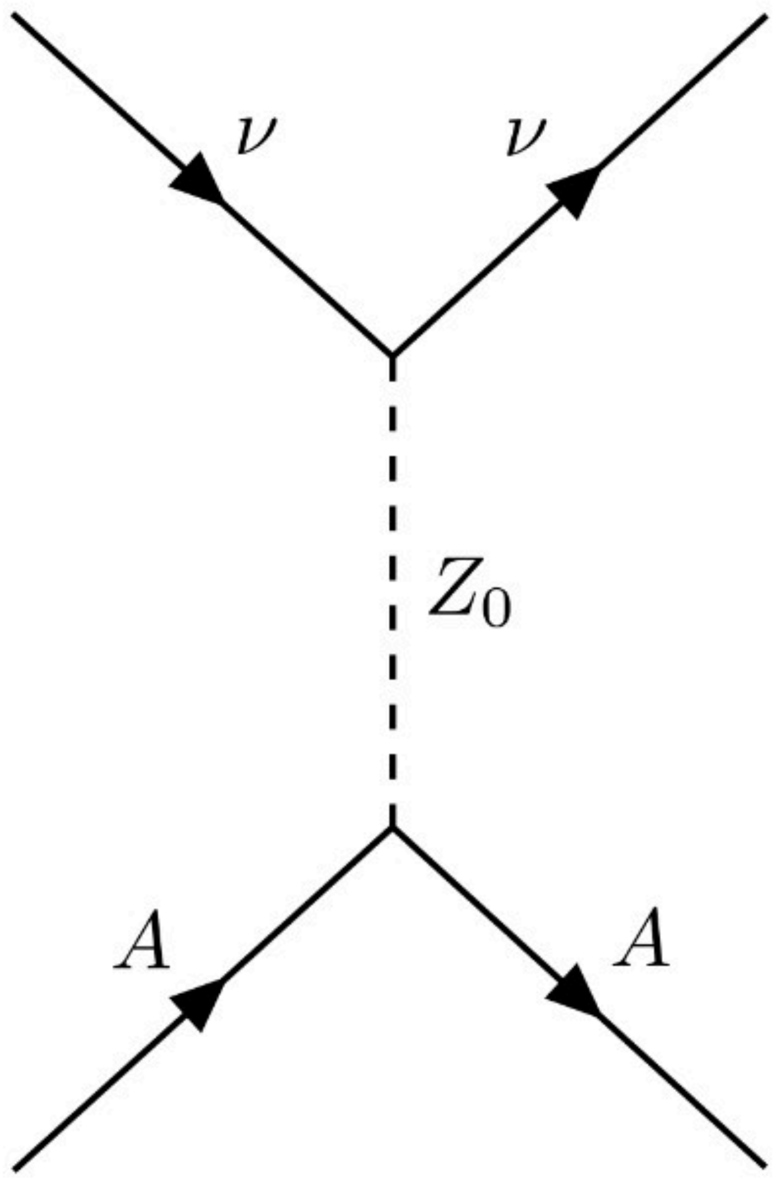


CEvNS cross section



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

Weak charge

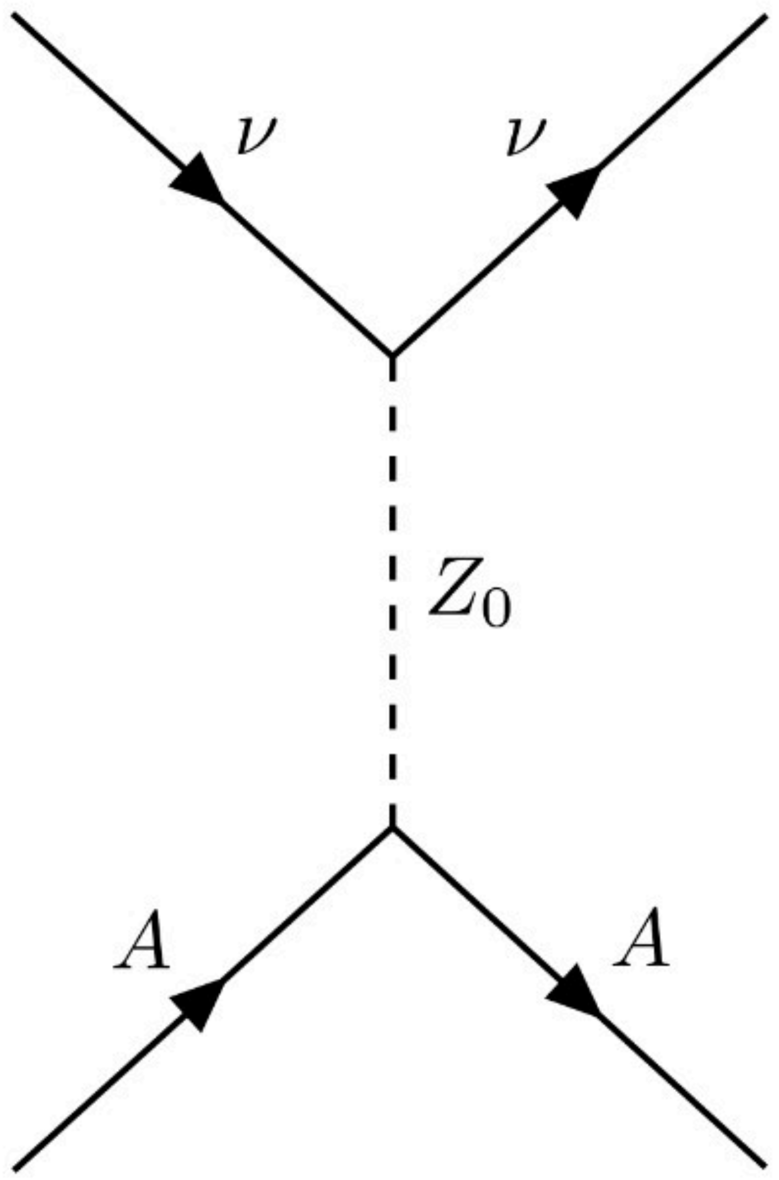
$$Q_w^2 = \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2)\right]^2$$

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

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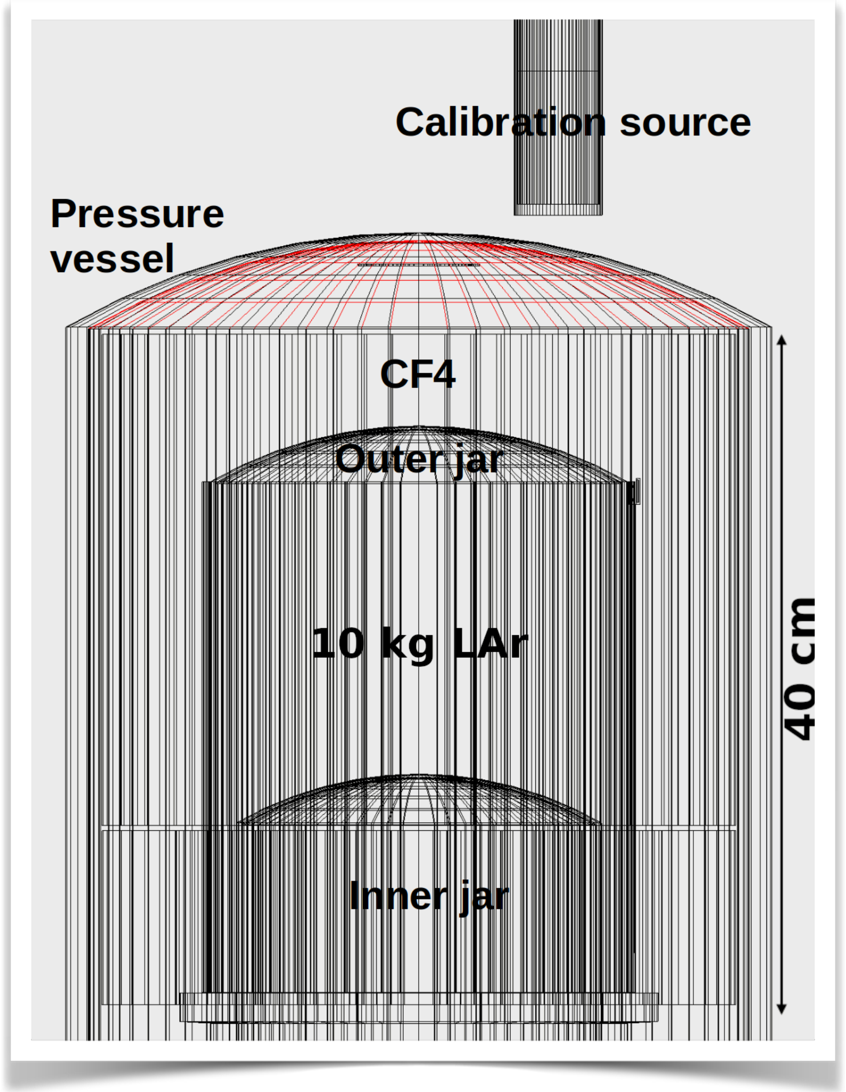
$$\frac{d\sigma}{dT} \propto N^2$$

NSI

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

SBC collaboration

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



E. Alfonso-Pita

10 kg liguid Argon bubble chamber similar to PICO detector

T~90-130 ^oK
P~2 atm

100 eV threshold

More details on Friday
E. Vazquez-Jauregui and L. Flores talks

Currently under construction

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

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

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

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

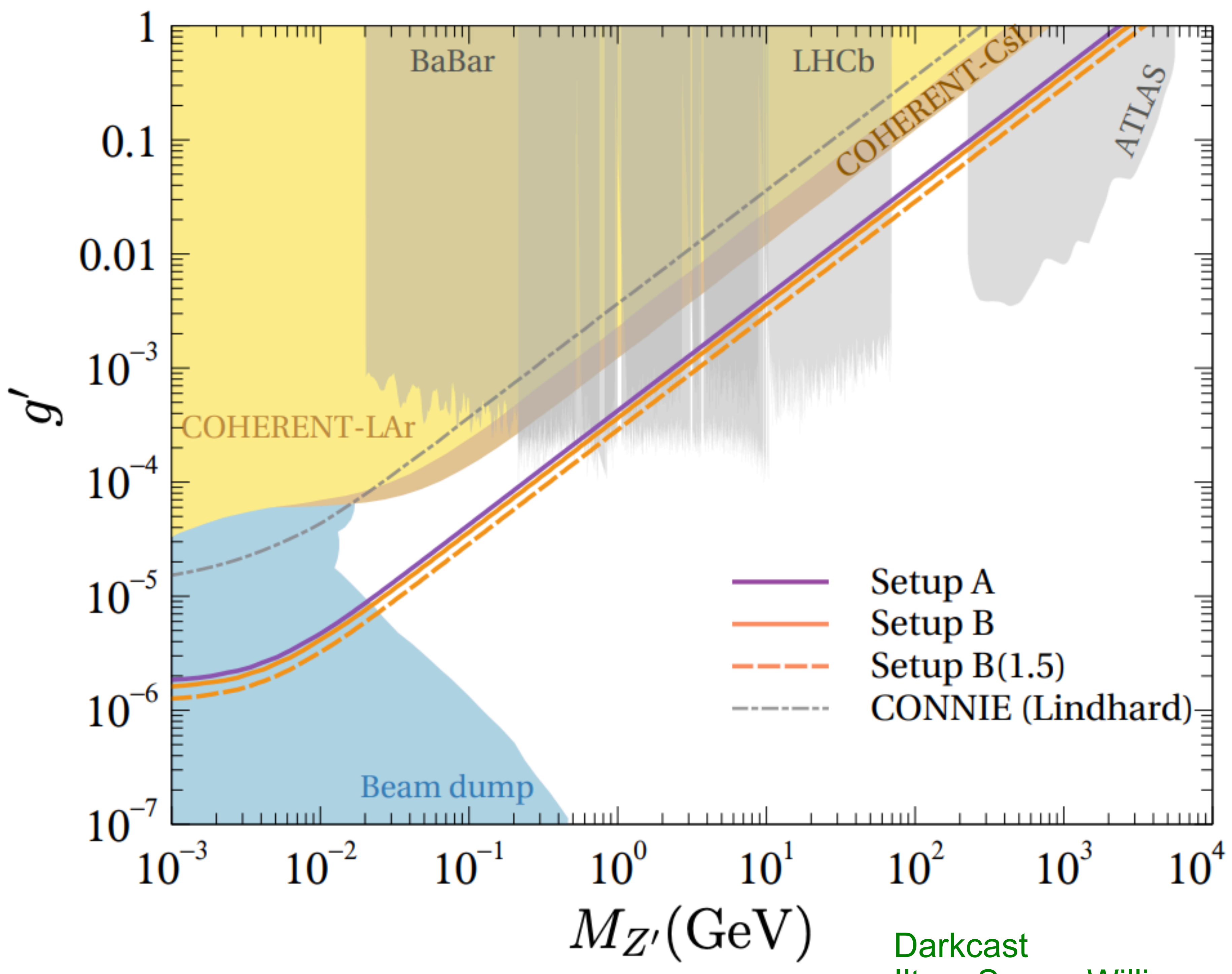
SSB

$$\langle \phi_i \rangle = \frac{v_i}{\sqrt{2}} \qquad m_{Z'}^2 = \sum_i g' Q_i^2 v_i^2$$

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

NSI

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

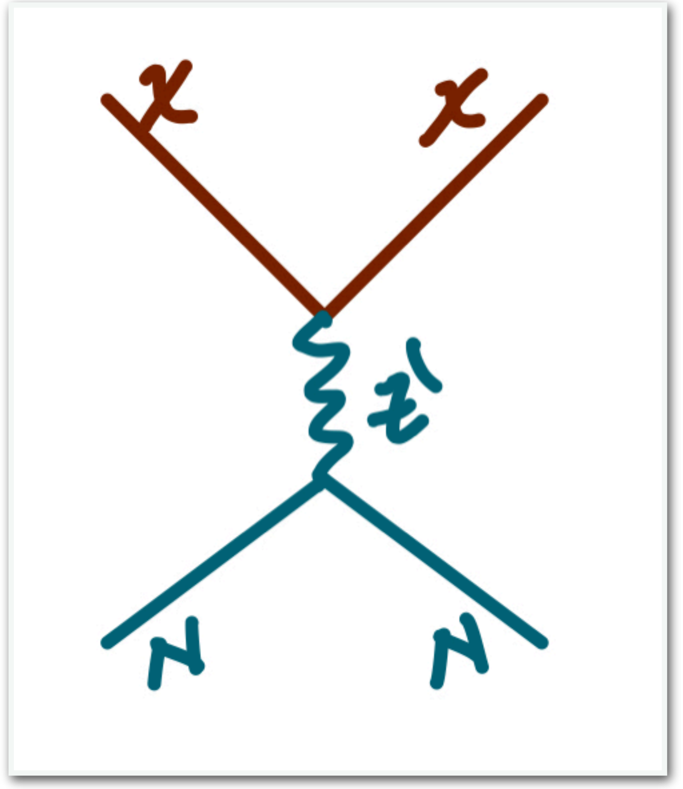


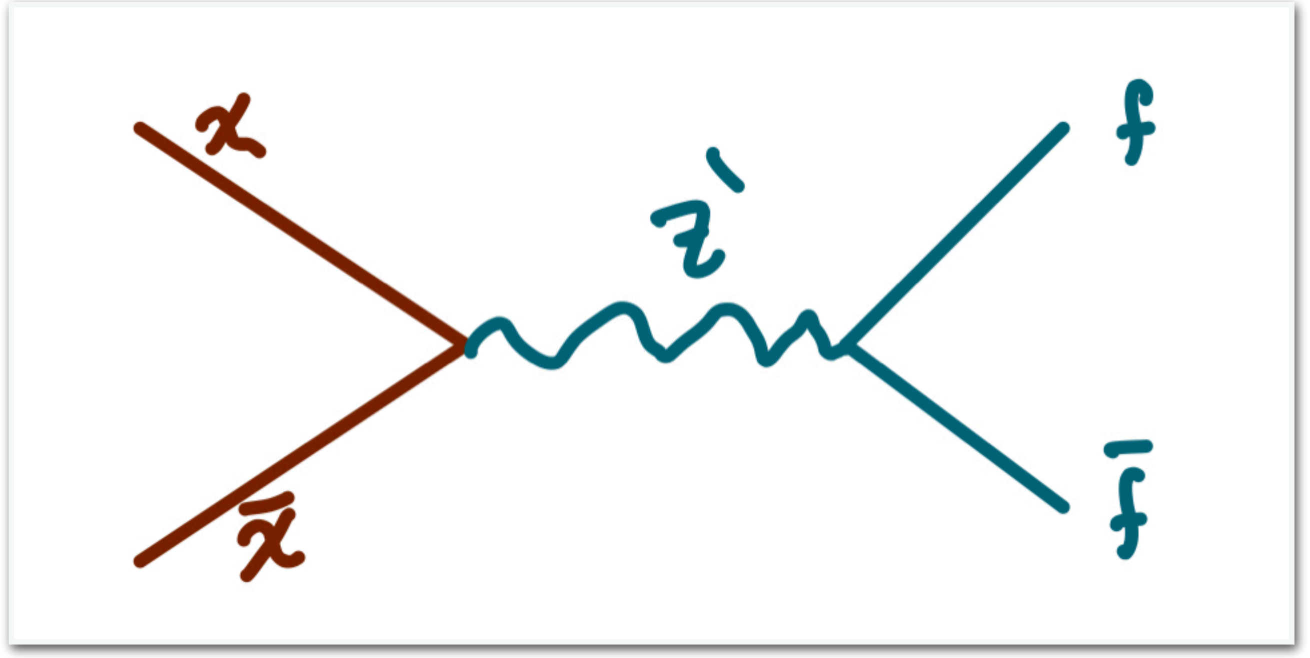
Darkcast
Ilten, Soreq, Williams and Xue, JHEP (2018)

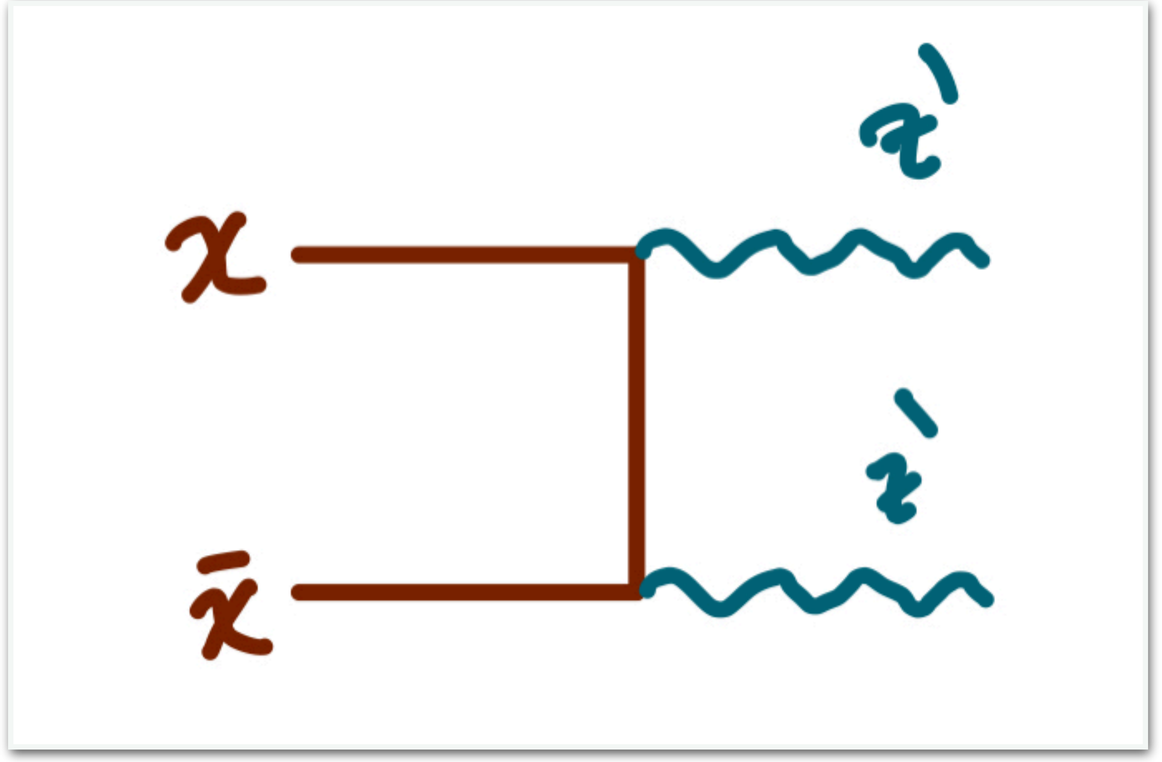
Dark Matter from $U(1)_{B-L}$

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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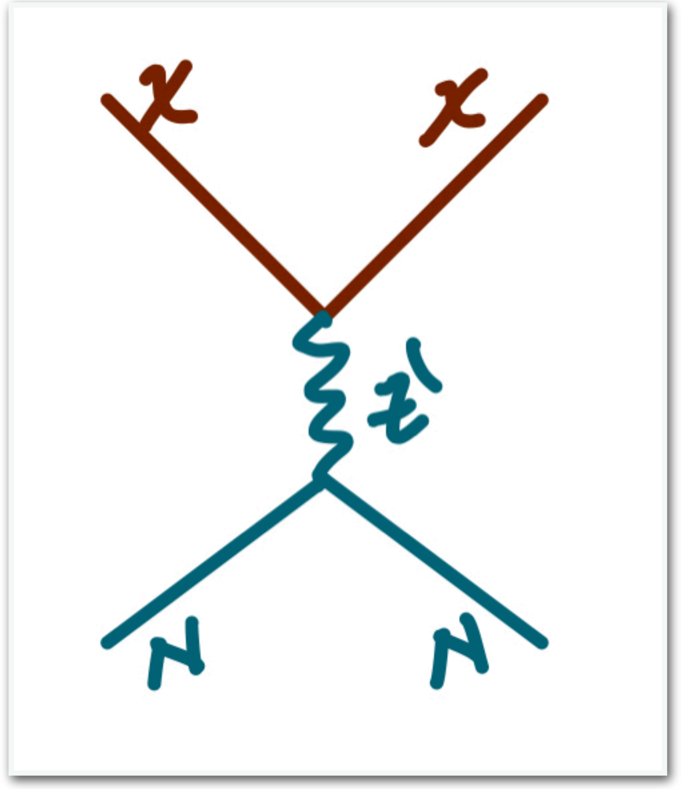

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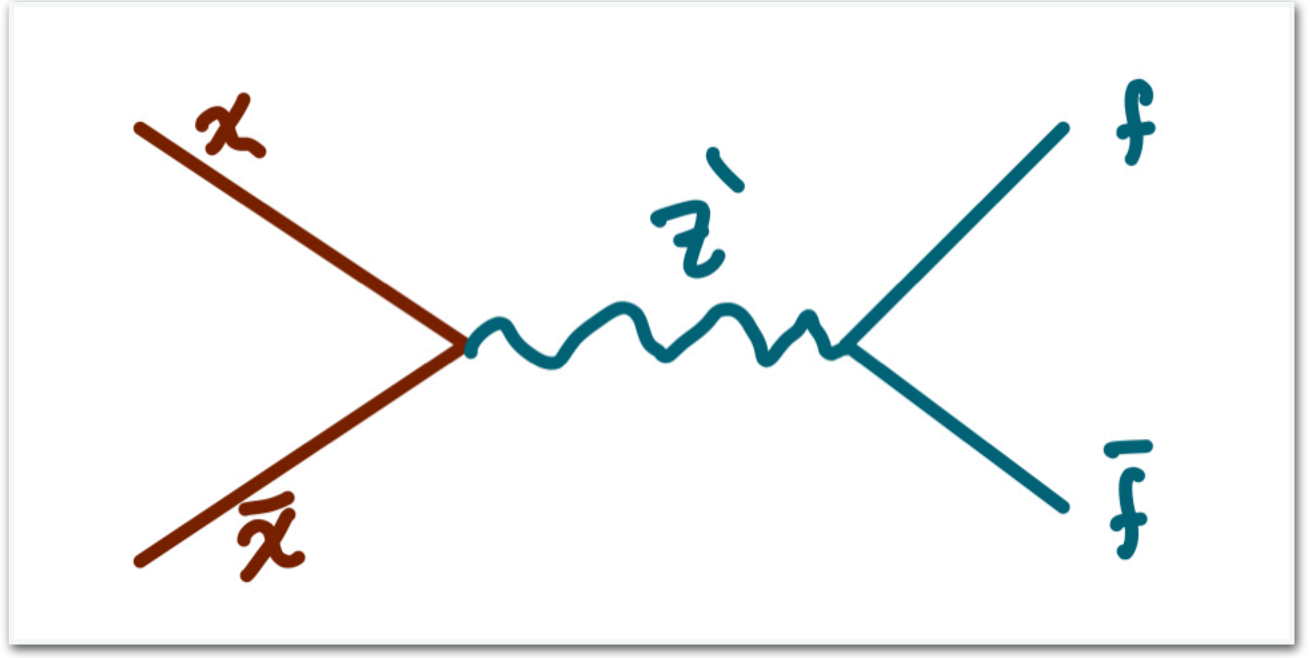
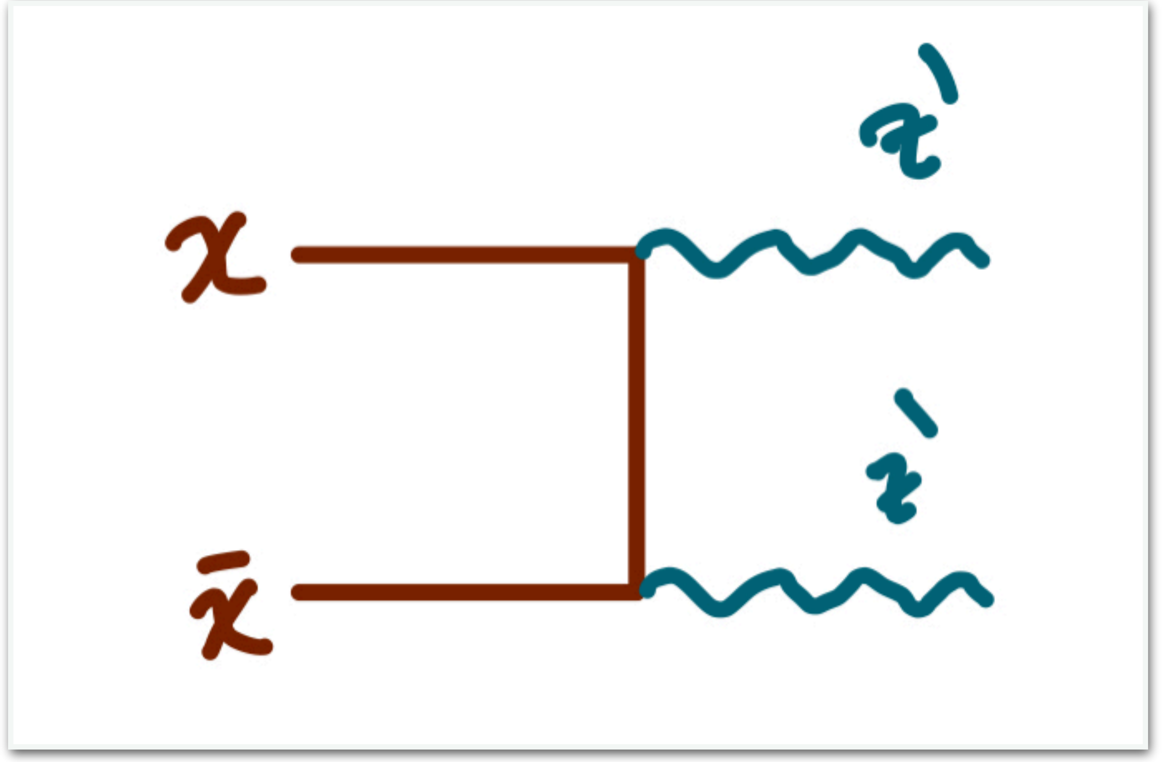


Will need a scalar field ϕ for SSB

$$Q_\phi = \begin{cases} 1 \\ 2 \end{cases}$$

Dirac neutrinos

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



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

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

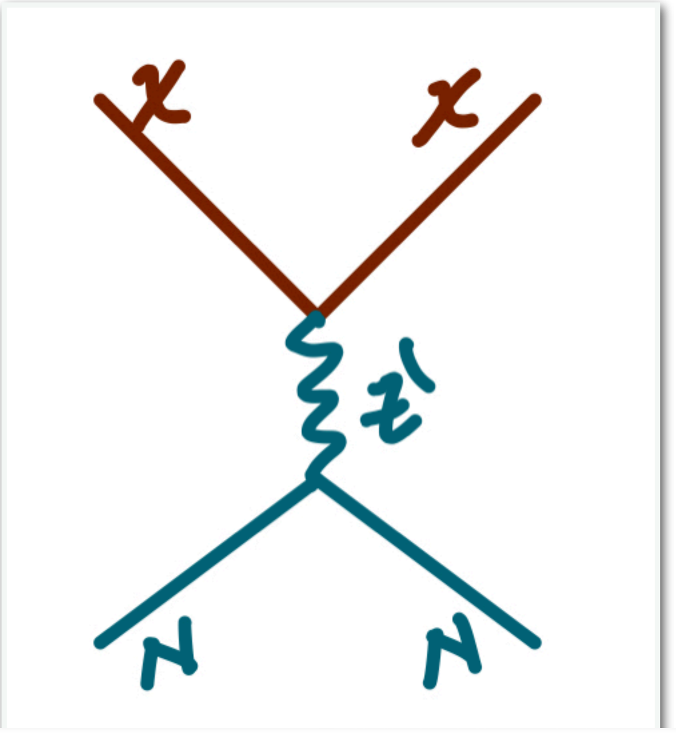
$$\mathscr{L} \supset M_D \bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + i g' Q_\chi Z'_\mu)\chi$$

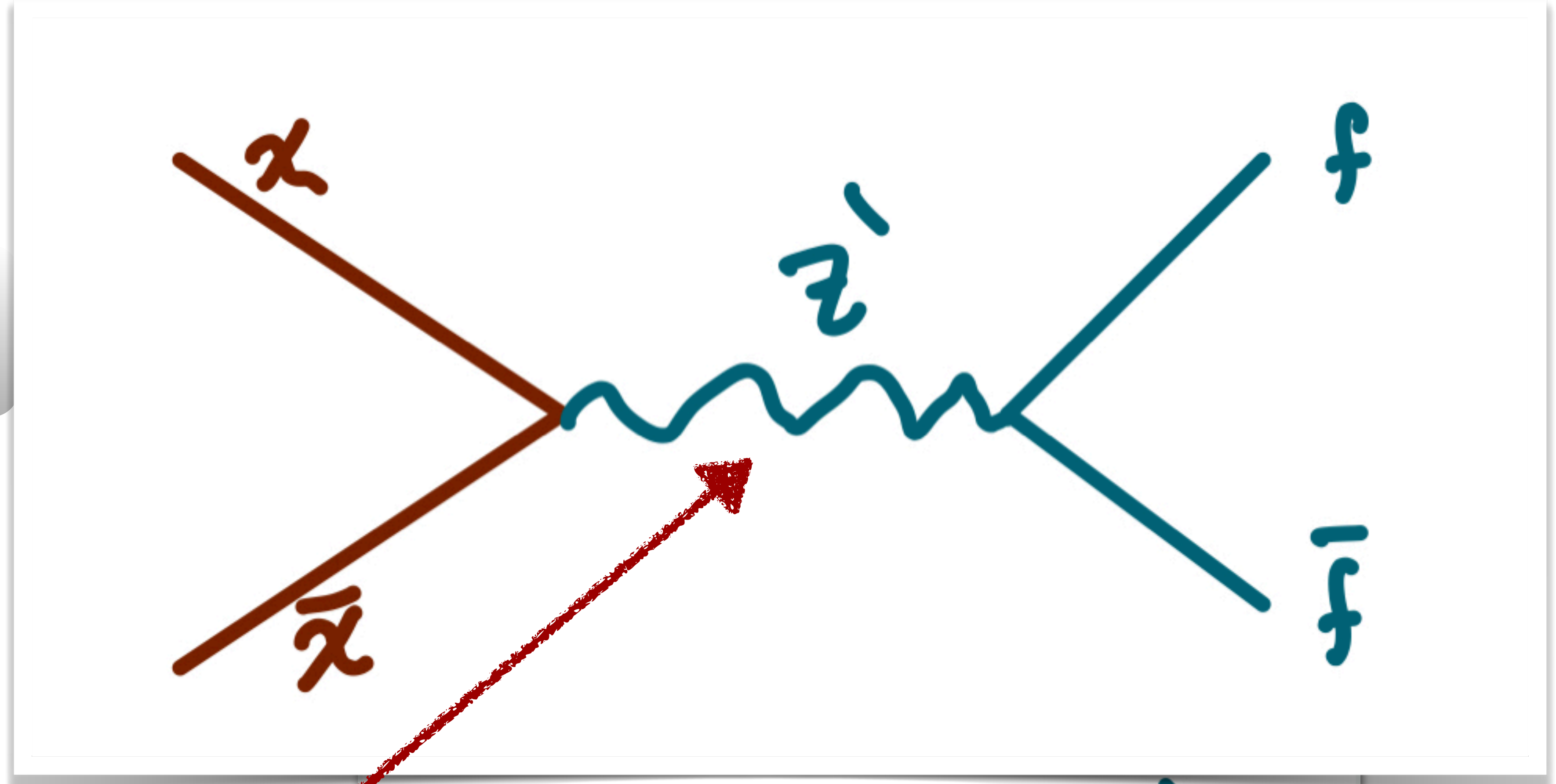
Will need a scalar field ϕ for SSB

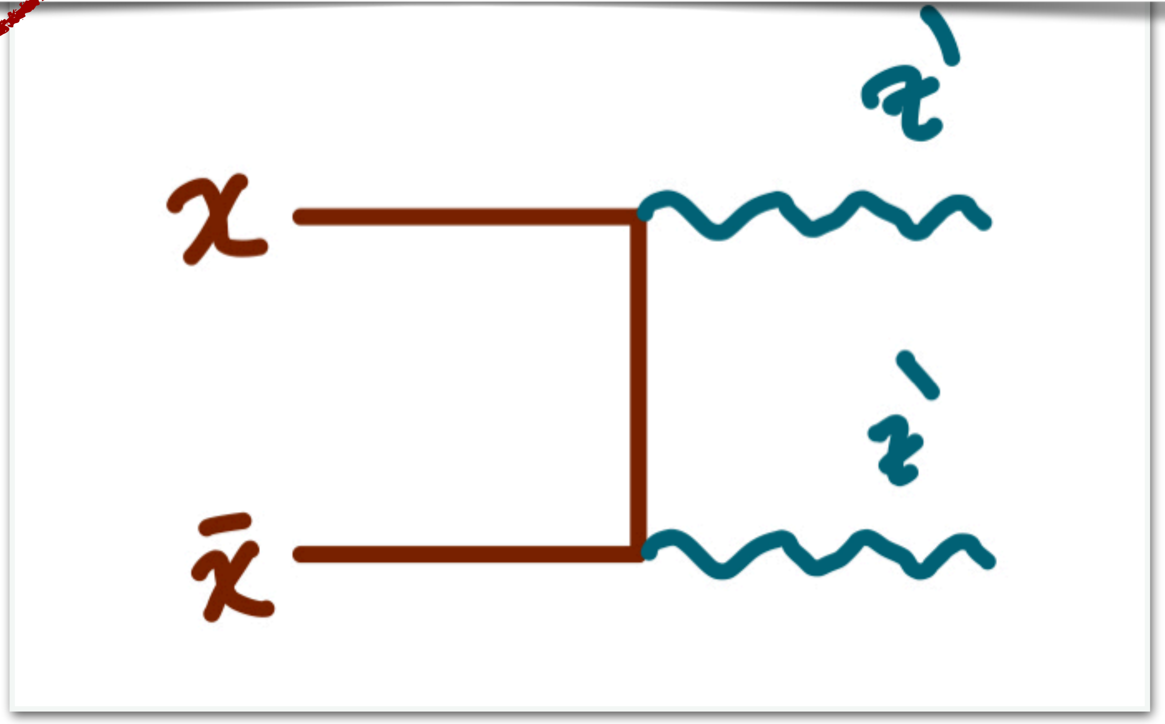
$Q_\phi =$ 1 → Dirac neutrinos

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

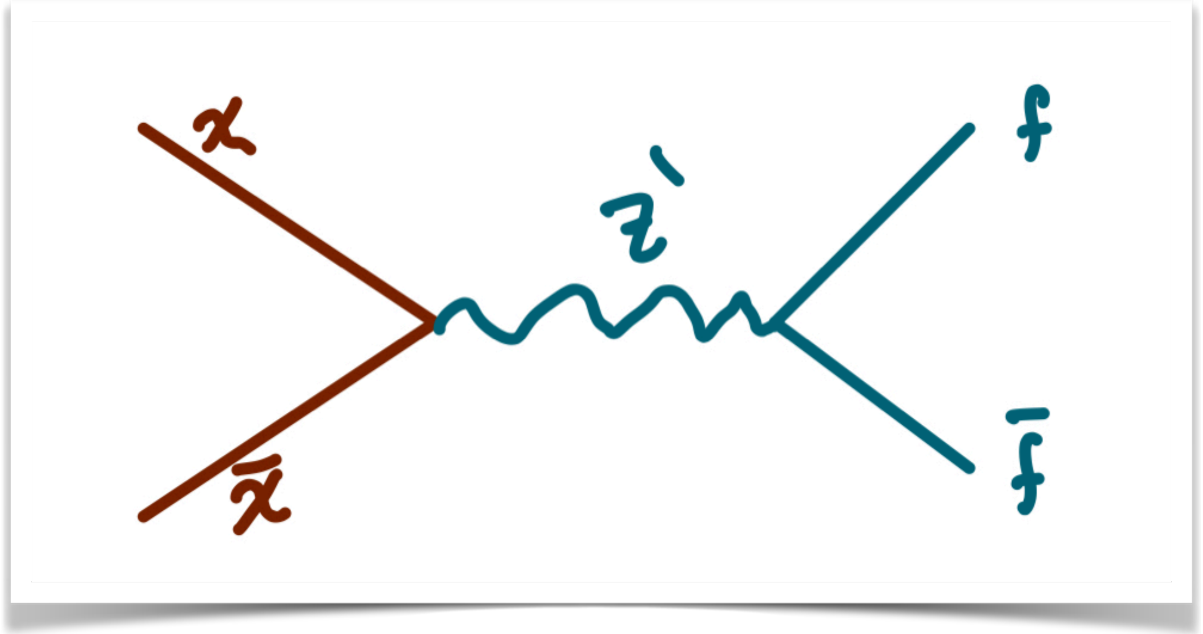
Resonant annihilation $M_\chi \simeq M_{z'}/2$







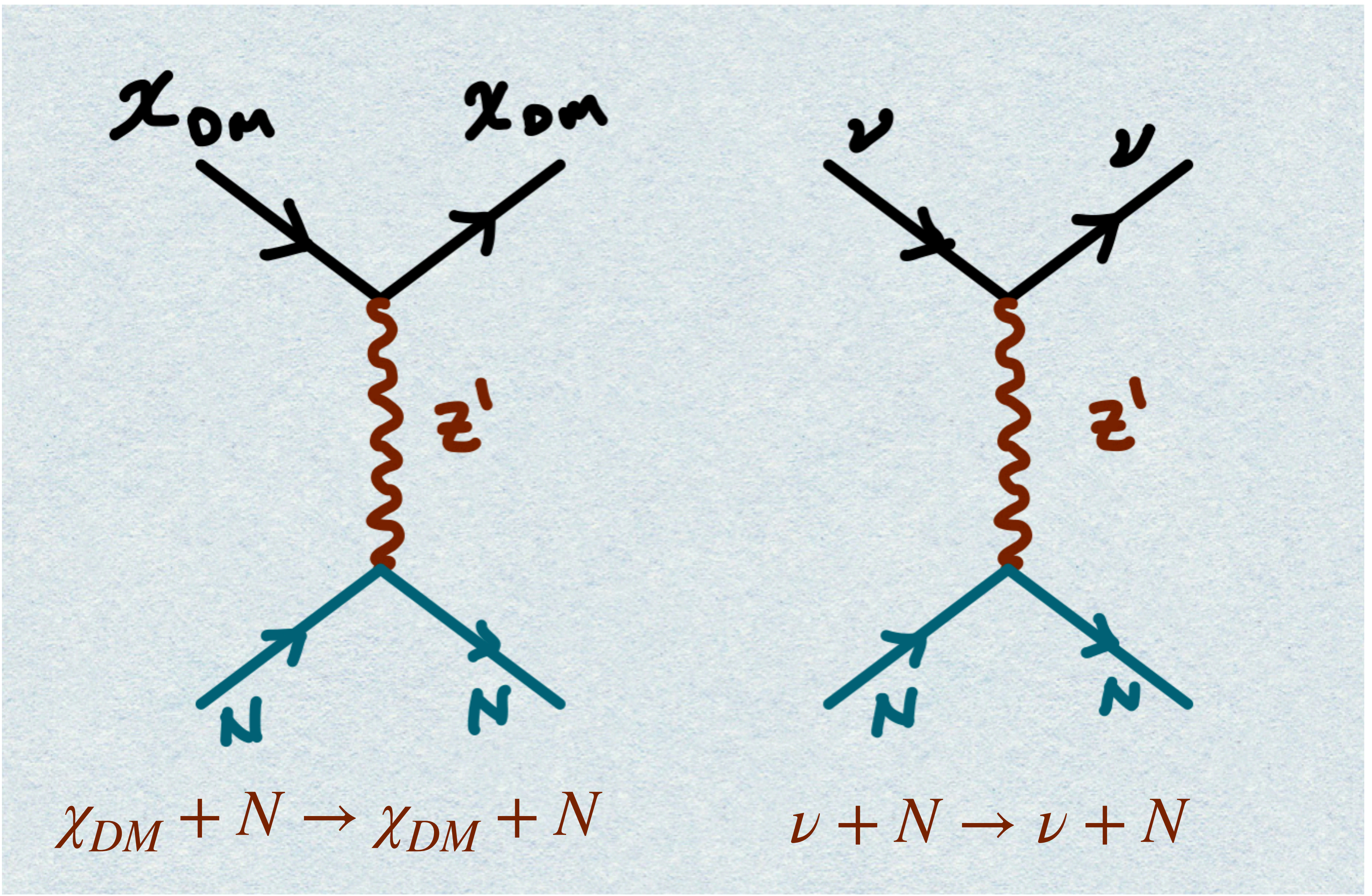
DM abundance



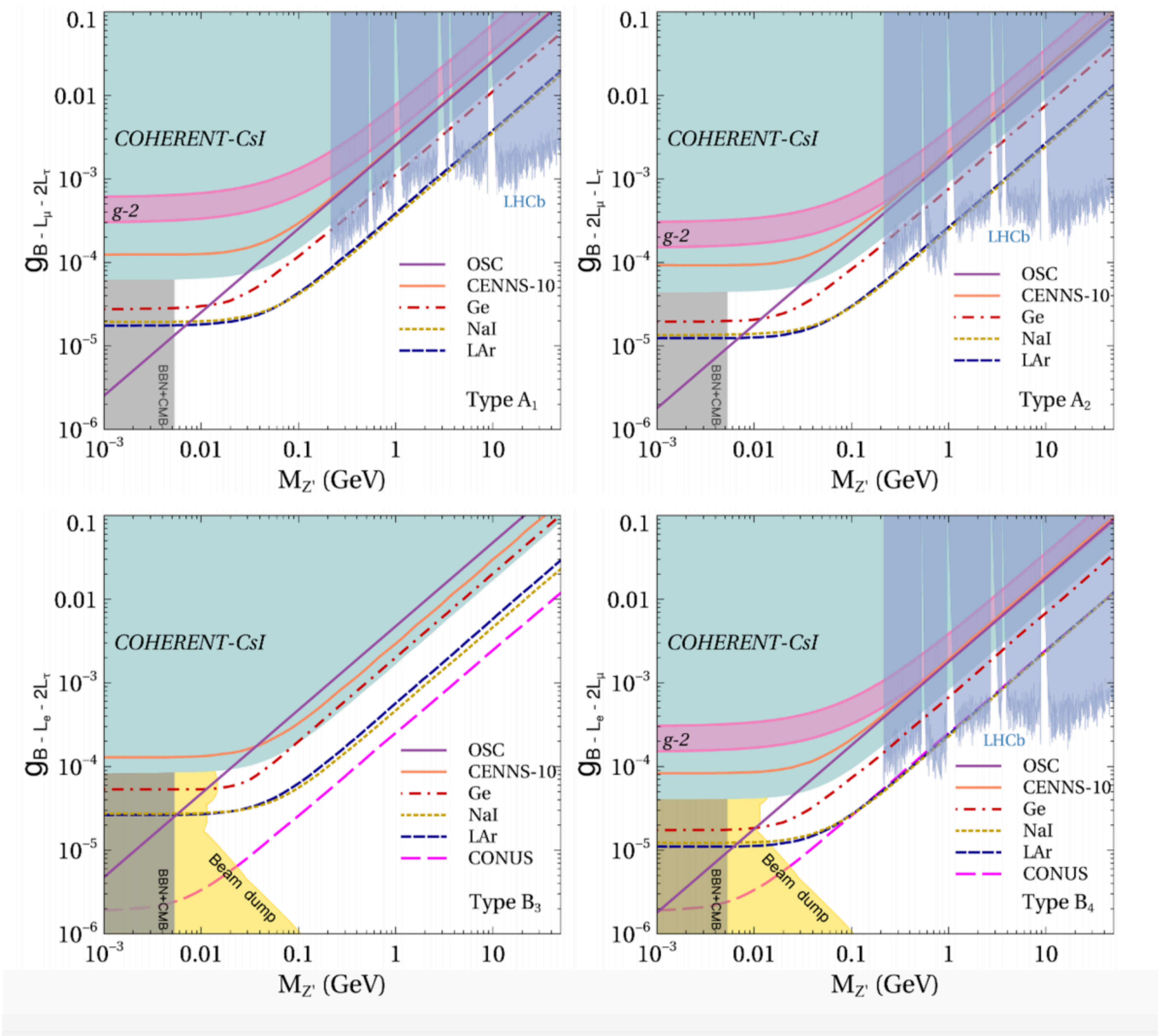
Resonant annihilation
$M_\chi \simeq M_{z'}/2$

DM Detection

CEνNS



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



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

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

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

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

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

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

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

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

$\langle\phi_1\rangle$ $\langle\phi_2\rangle$

	ϕ_1	ϕ_2
$U(1)$	1	2

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)

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	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
0	-2	-1	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	A_2	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
-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	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\tau\tau}$

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

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

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-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	$\times$	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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Charged leptons diagonal

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	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
0	-2	-1	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	A_2	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
-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	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	$\times$	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)

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

Anomaly free

3 RH neutrinos

2 U(1) breaking scalar fields

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

$\langle\phi_1\rangle$ $\langle\phi_2\rangle$

	ϕ_1	ϕ_2
$U(1)$	1	2

Neutrino phenomenology

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

6 possible choices for α and β

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

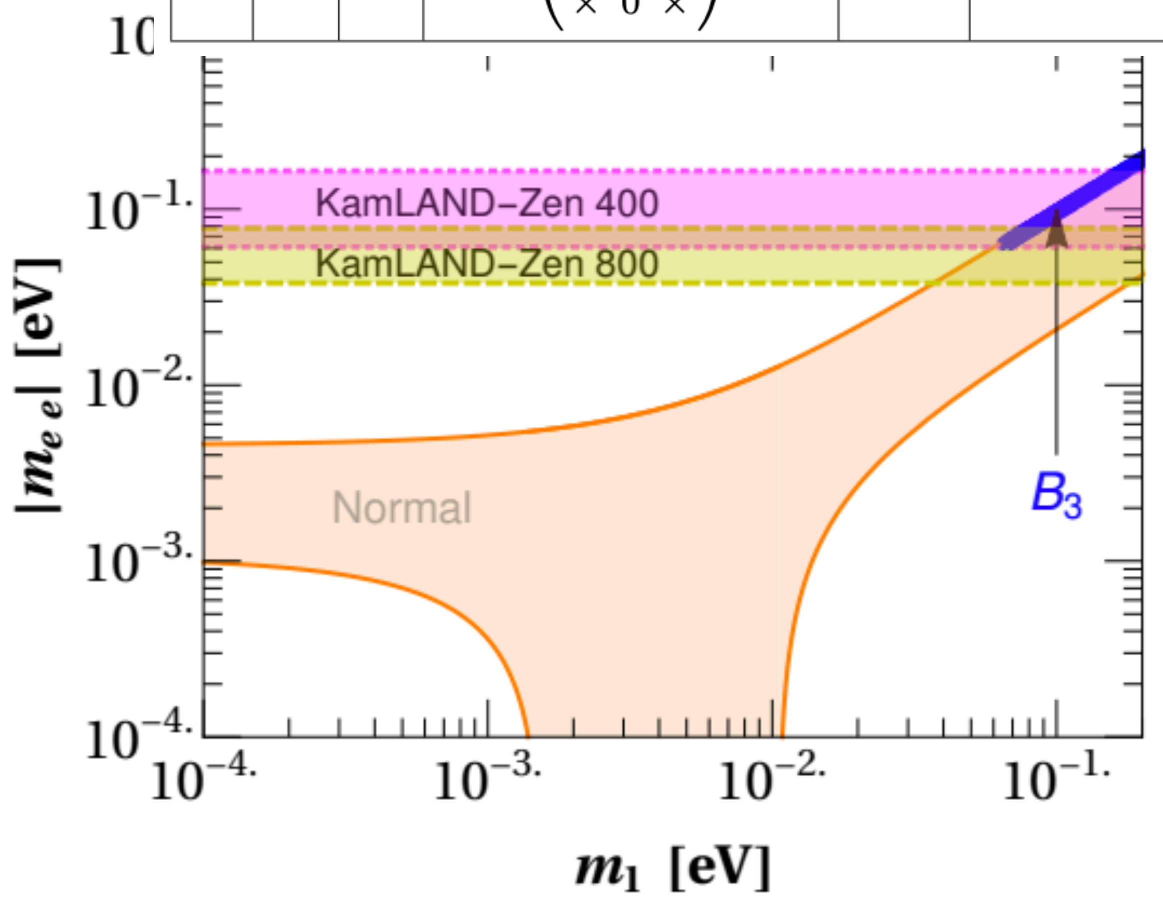
$$M_N = \begin{pmatrix} M_1 & y_1^N\langle\phi_1\rangle & y_2^N\langle\phi_2\rangle \\ y_1^N\langle\phi_1\rangle & y_3^N\langle\phi_2\rangle & 0 \\ y_2^N\langle\phi_2\rangle & 0 & 0 \end{pmatrix}$$

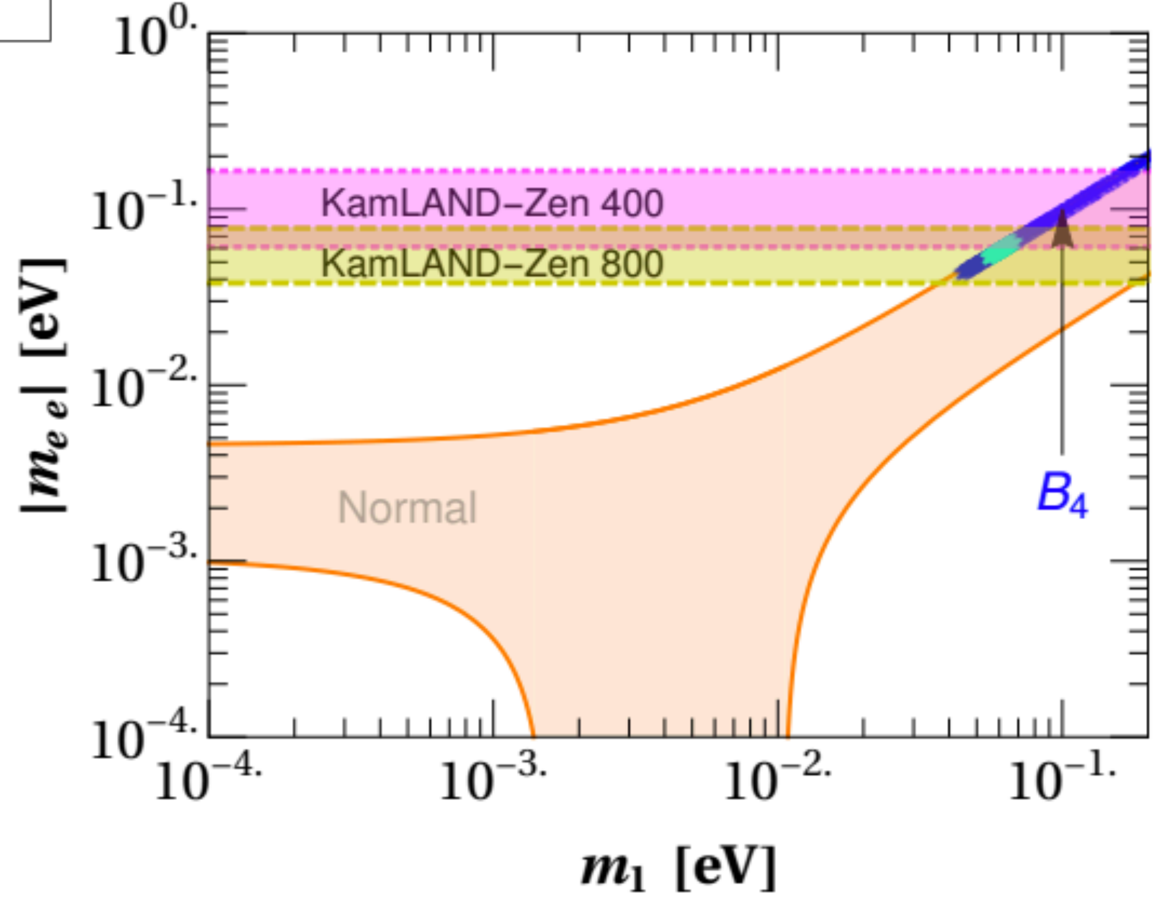
Charged leptons diagona

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	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
0	-2	-1	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	A_2	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
-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	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	0	-1	$\begin{pmatrix} \times & \times & \times \\ \times & 0 & 0 \\ \times & 0 & \times \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\tau\tau}$

Better agreement

Good pheno

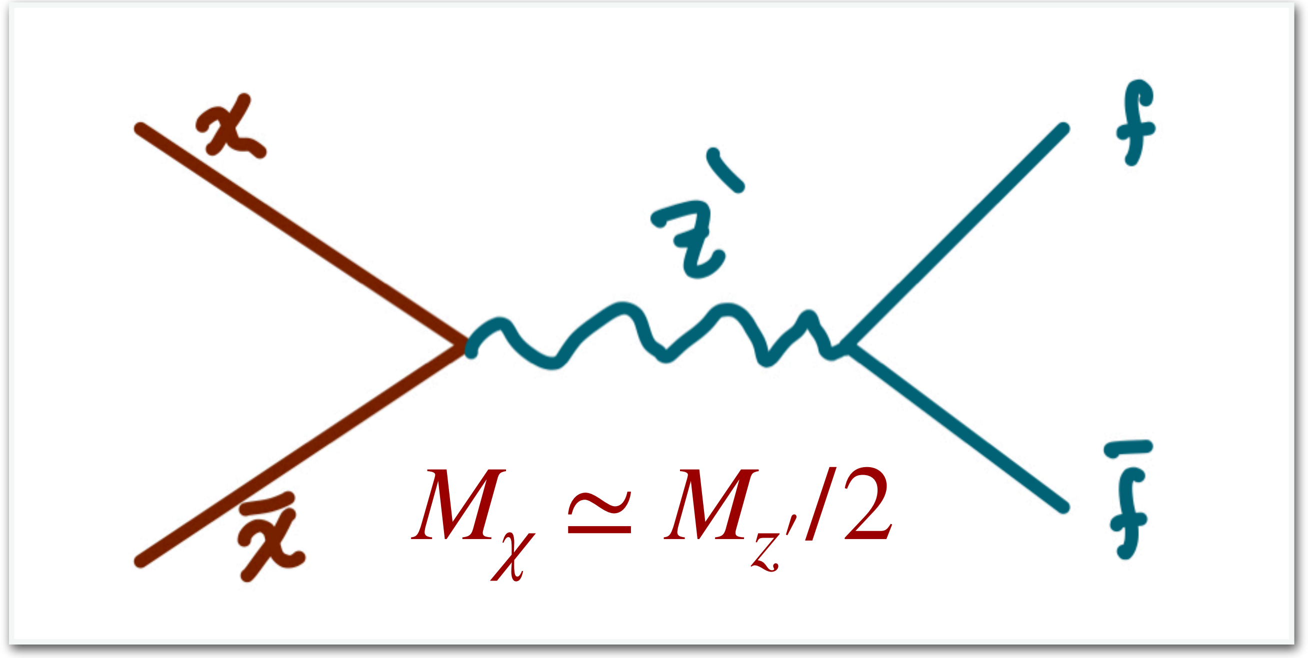




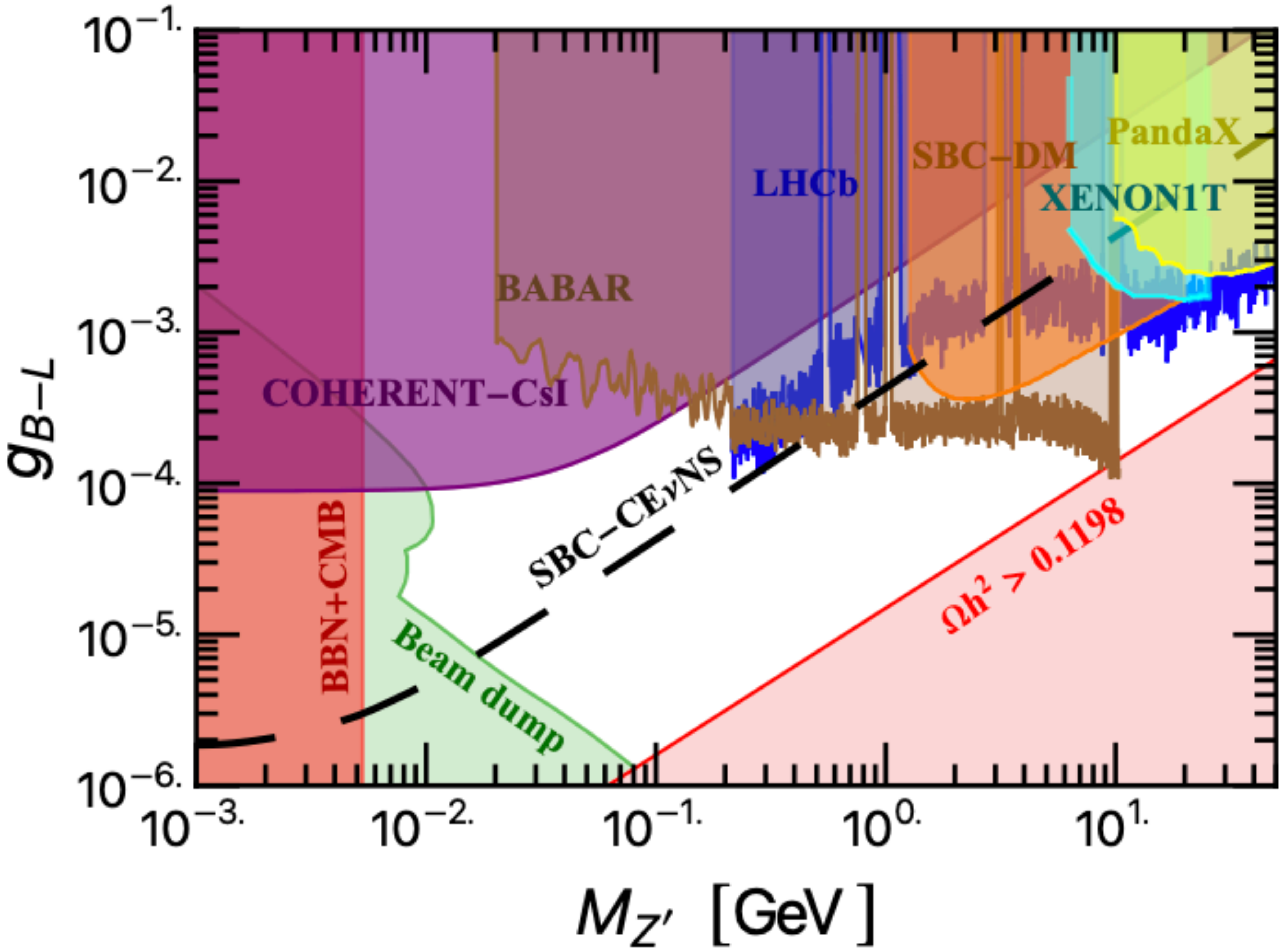
CEvNS and DM searches complementarity

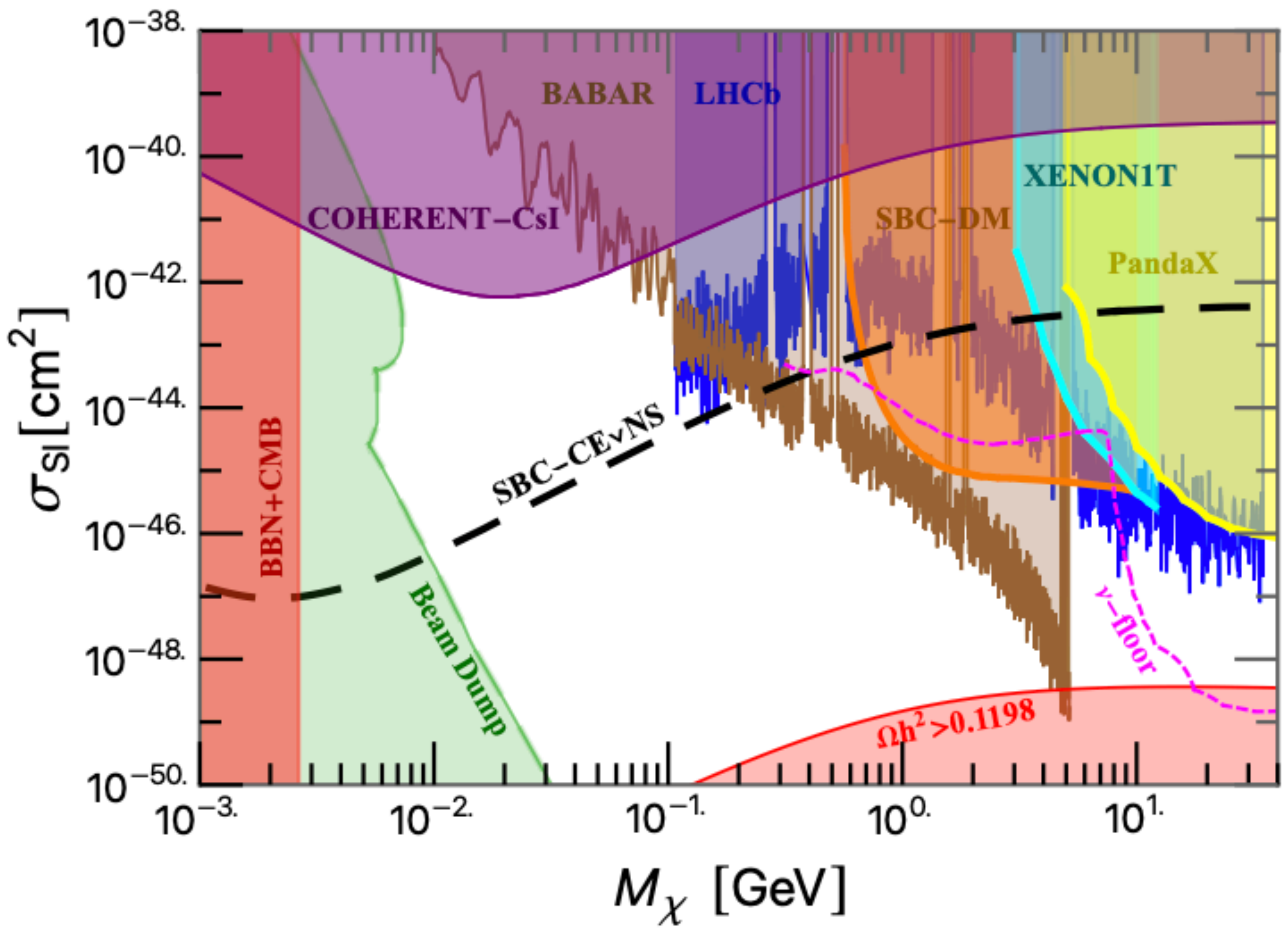
LMG de la Vega, L. Flores, N. Nath JHEP (2021)

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



$Q_\chi = 1/3$





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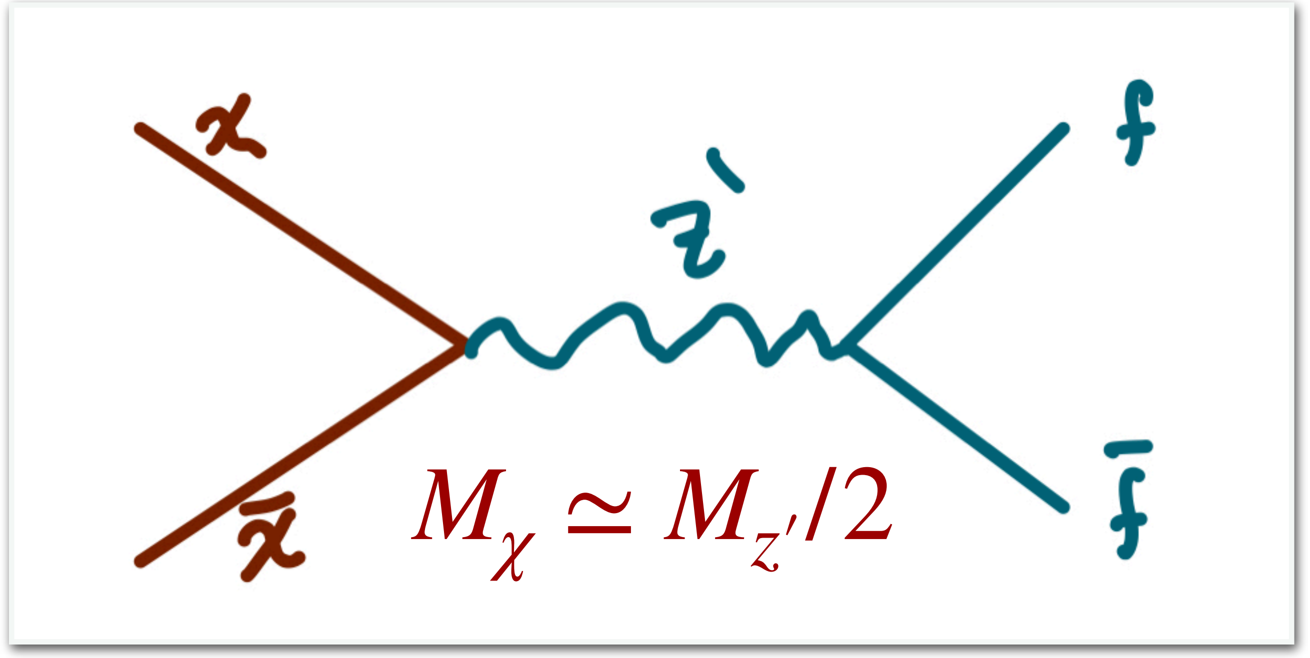
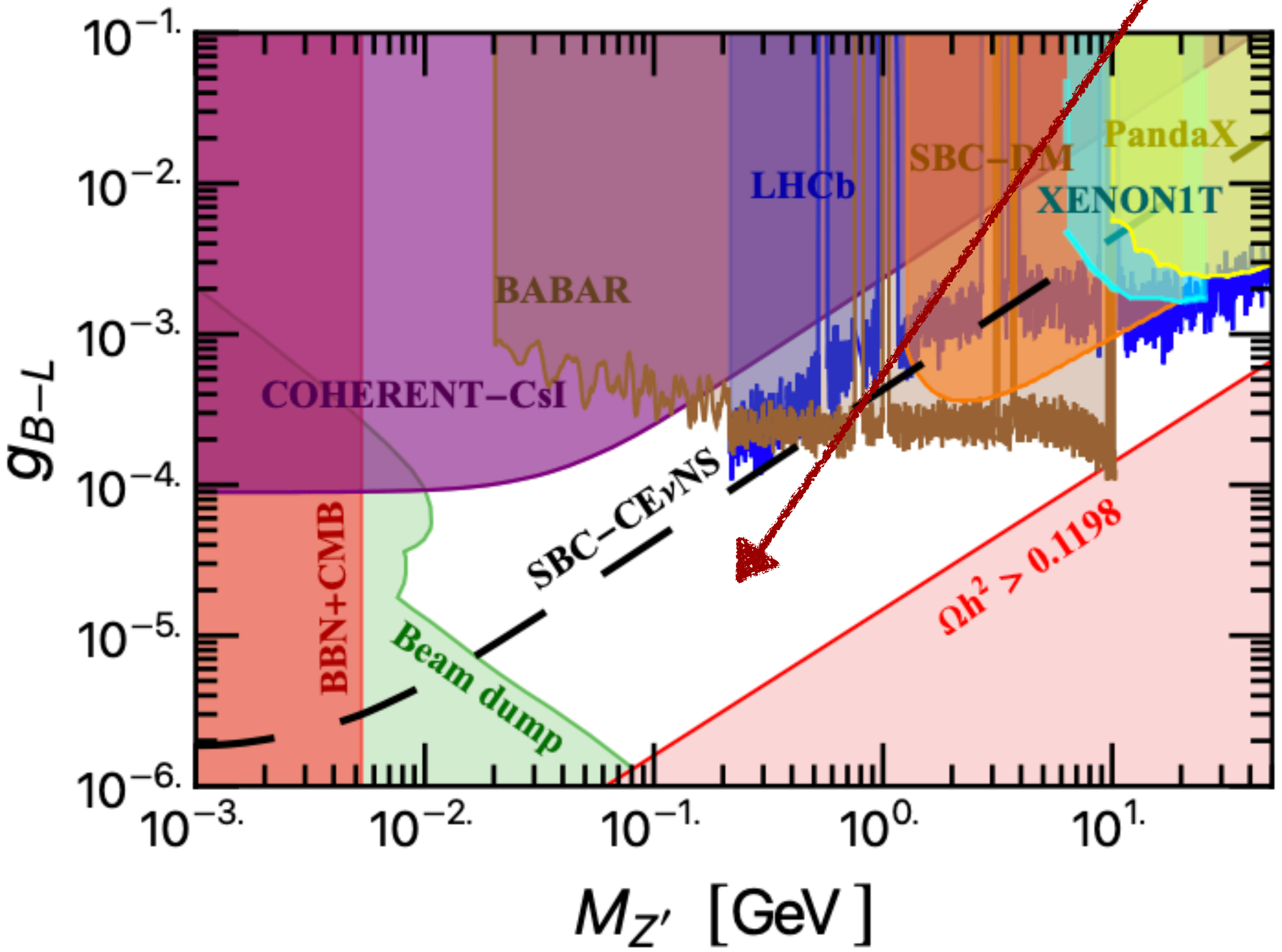
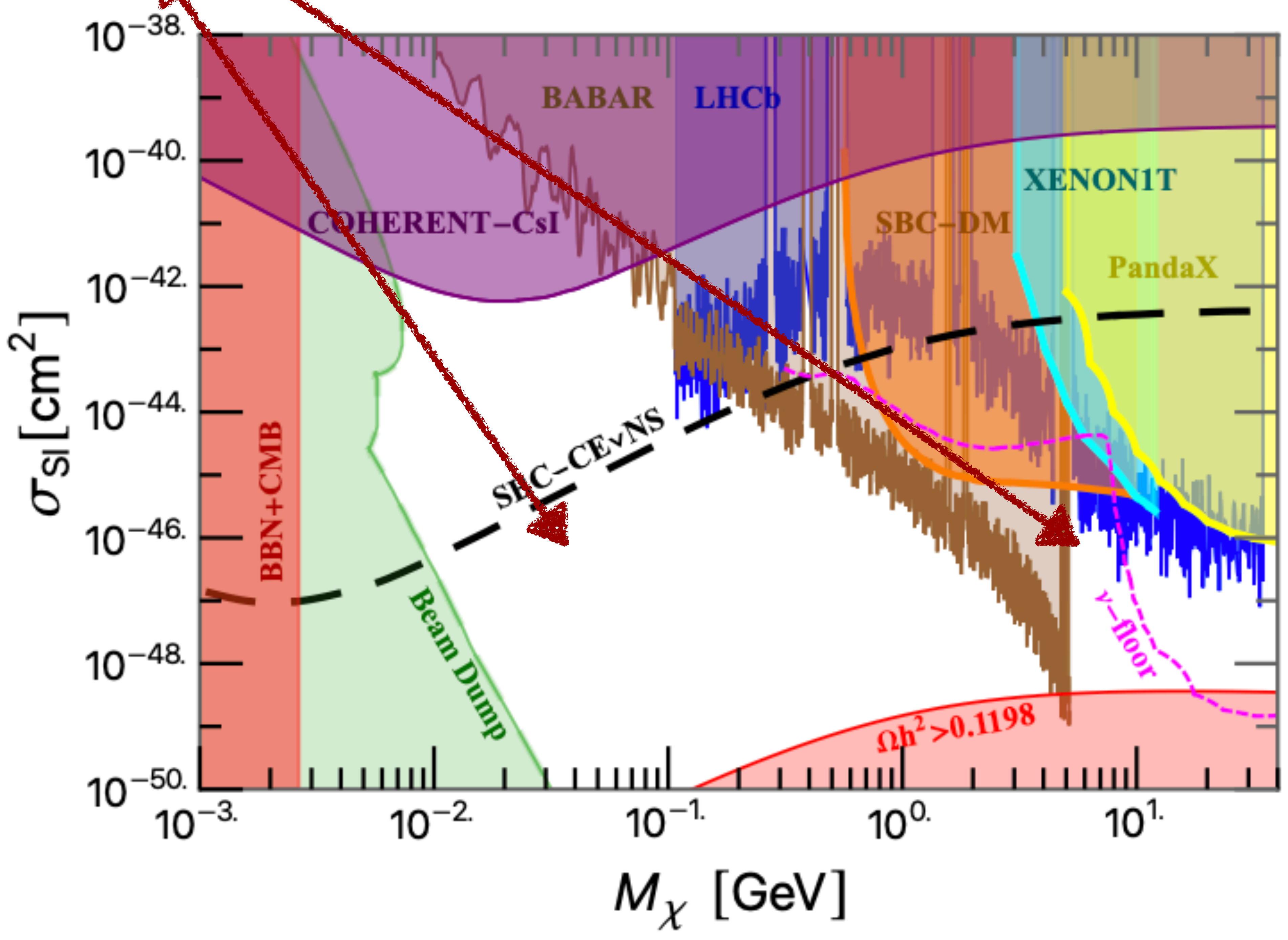


Allowed Region





Light Vector Boson $U(1)'$
No coupling with fermions

Davoudiasl, Lee and Marciano, PRD (2014)
Lindner et. al. JHEP (2018)

$$\mathscr{L}_{\mathbf{Z-Z'}} = -\frac{1}{4}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \frac{1}{4}\mathbf{F}'_{\mu\nu}\mathbf{F}'^{\mu\nu} - \frac{\varepsilon}{2}\mathbf{F}_{\mu\nu}\mathbf{F}'^{\mu\nu} + \delta\mathbf{m}^2\mathbf{B}_\mu\mathbf{B}'^\mu$$

$$(W_3, B, B') \to (A, Z, Z')$$

$\sin\theta_w$ **and** $\tan\alpha \approx \tan\theta + \dfrac{\varepsilon M_Z^2 s_W}{M_{Z'}^2 - M_Z^2}$

$$\mathscr{L}_{ffZ/Z'} = Z^\mu J_\mu^Z + Z'^\mu J_\mu^{Z'}$$

$$J_\mu^Z = c_\alpha J_\mu^{NC} - s_\alpha J_\mu^X$$

$$J_\mu^{Z'} = s_\alpha J_\mu^{NC} + c_\alpha J_\mu^X$$

$$J_\mu^{NC} = \sum_f g\bar{f}\gamma_\mu(c_W Q_{em}^f - \frac{Q_Y^f}{2c_W})f$$

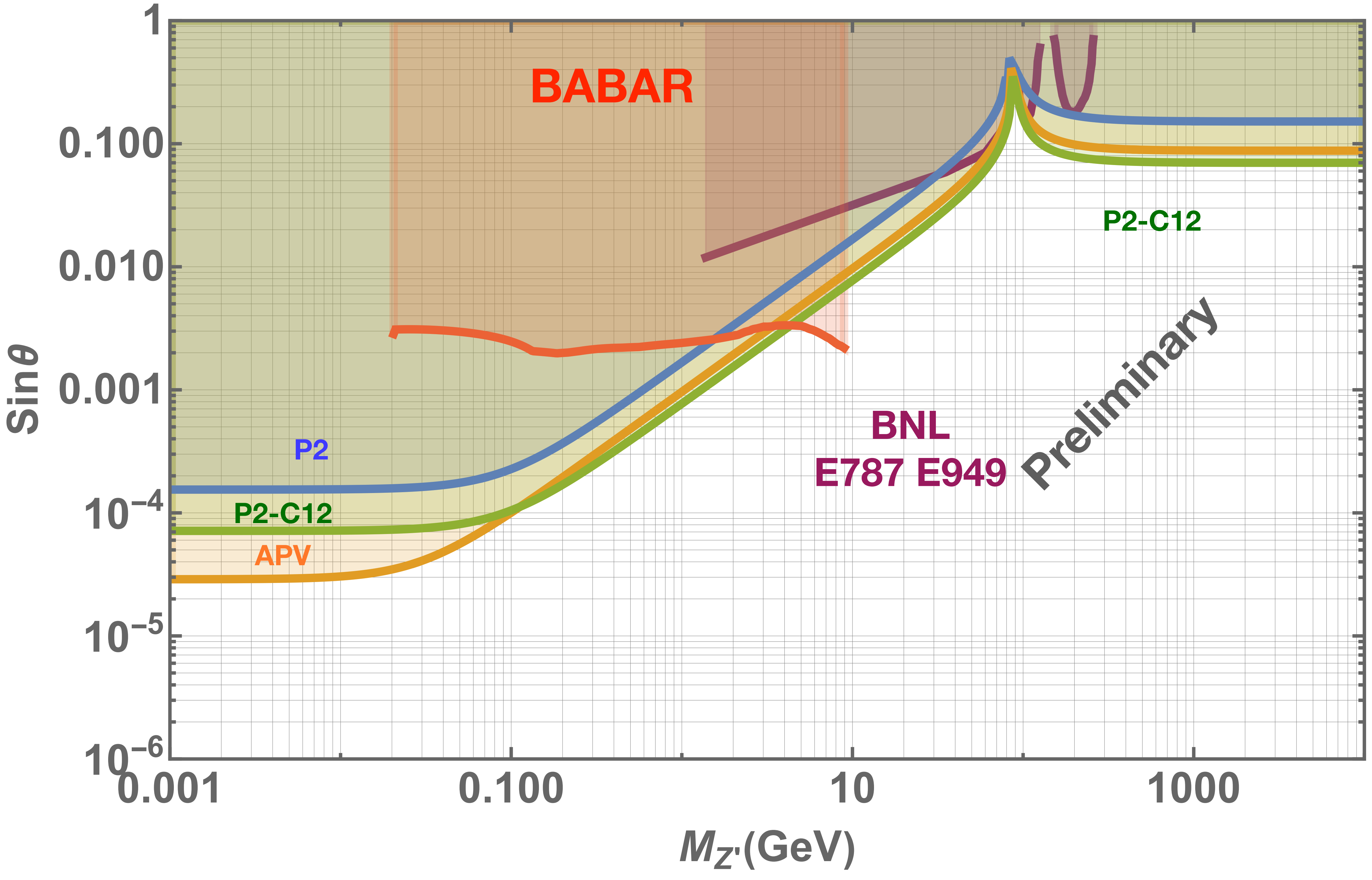
$$J_\mu^X = \sum_f \bar{f}\gamma_\mu \frac{g_X Q_X^f c_W - g\varepsilon Q_Y^f s_W}{2\sqrt{1-\varepsilon^2}c_W} f$$

Light Vector Boson $U(1)'$ PV

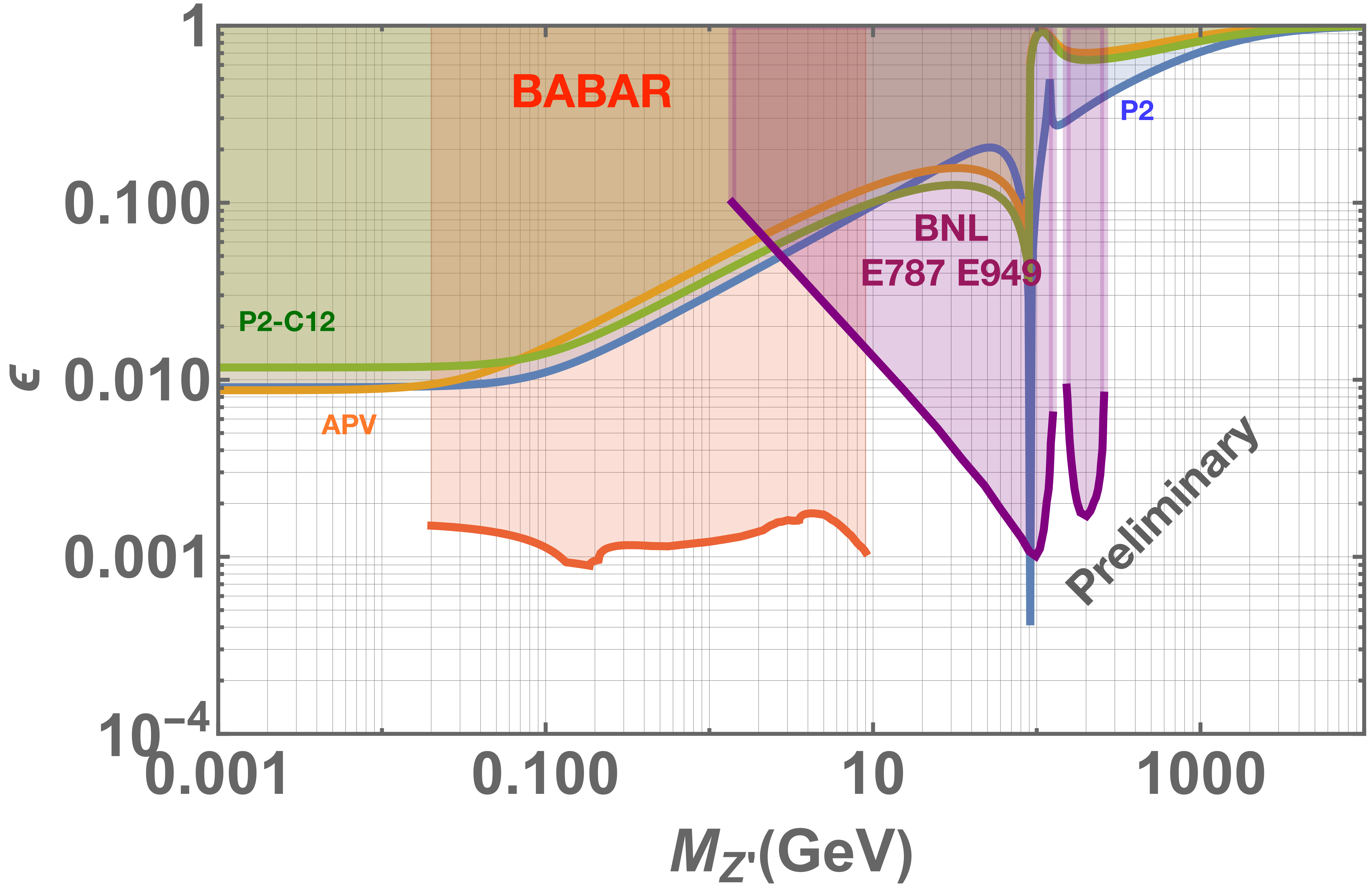
Preliminary results
L. M. G. de la Vega and R. Ferro

$$A^{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}$$

$\epsilon = 0$

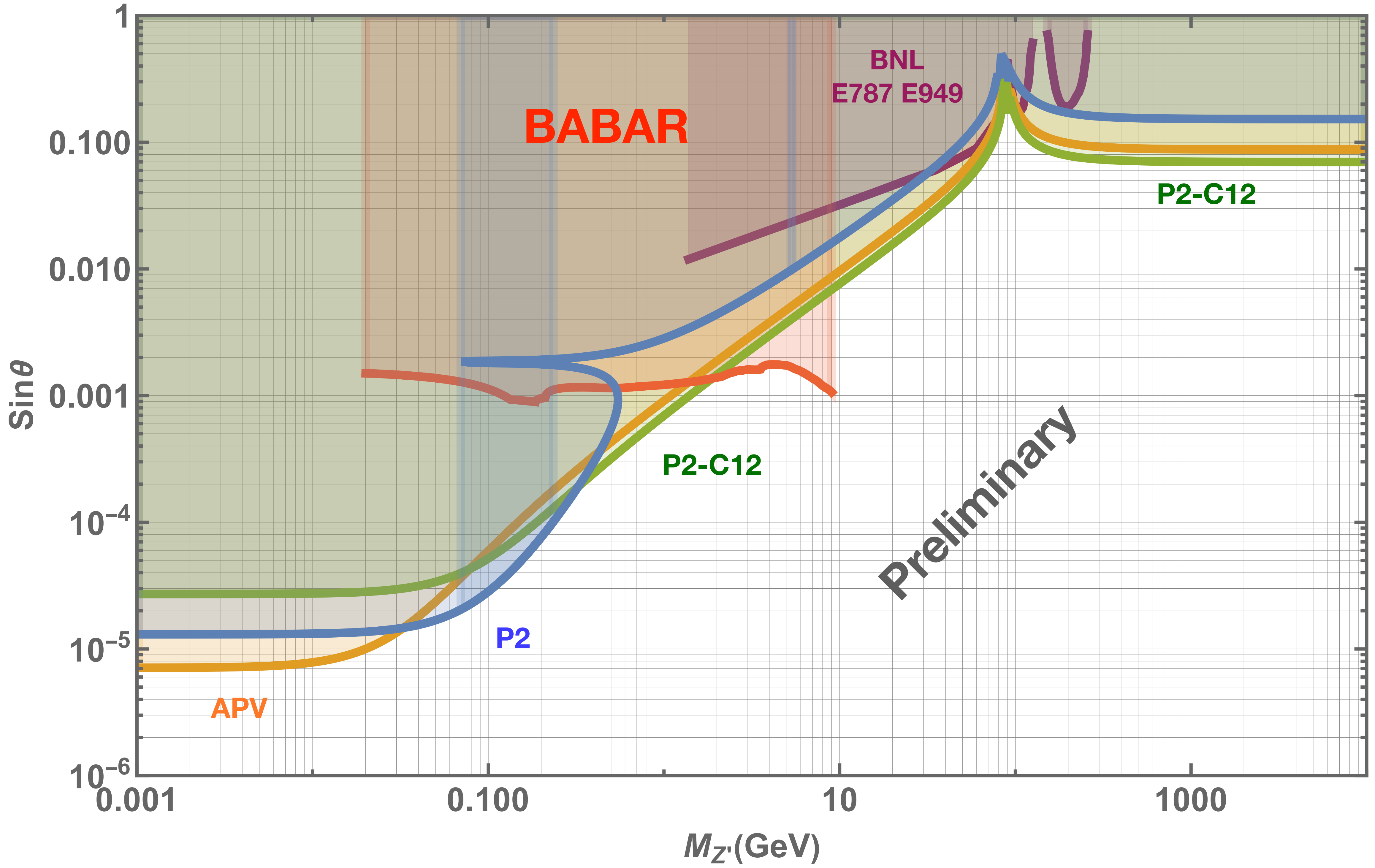


$\theta = 0$

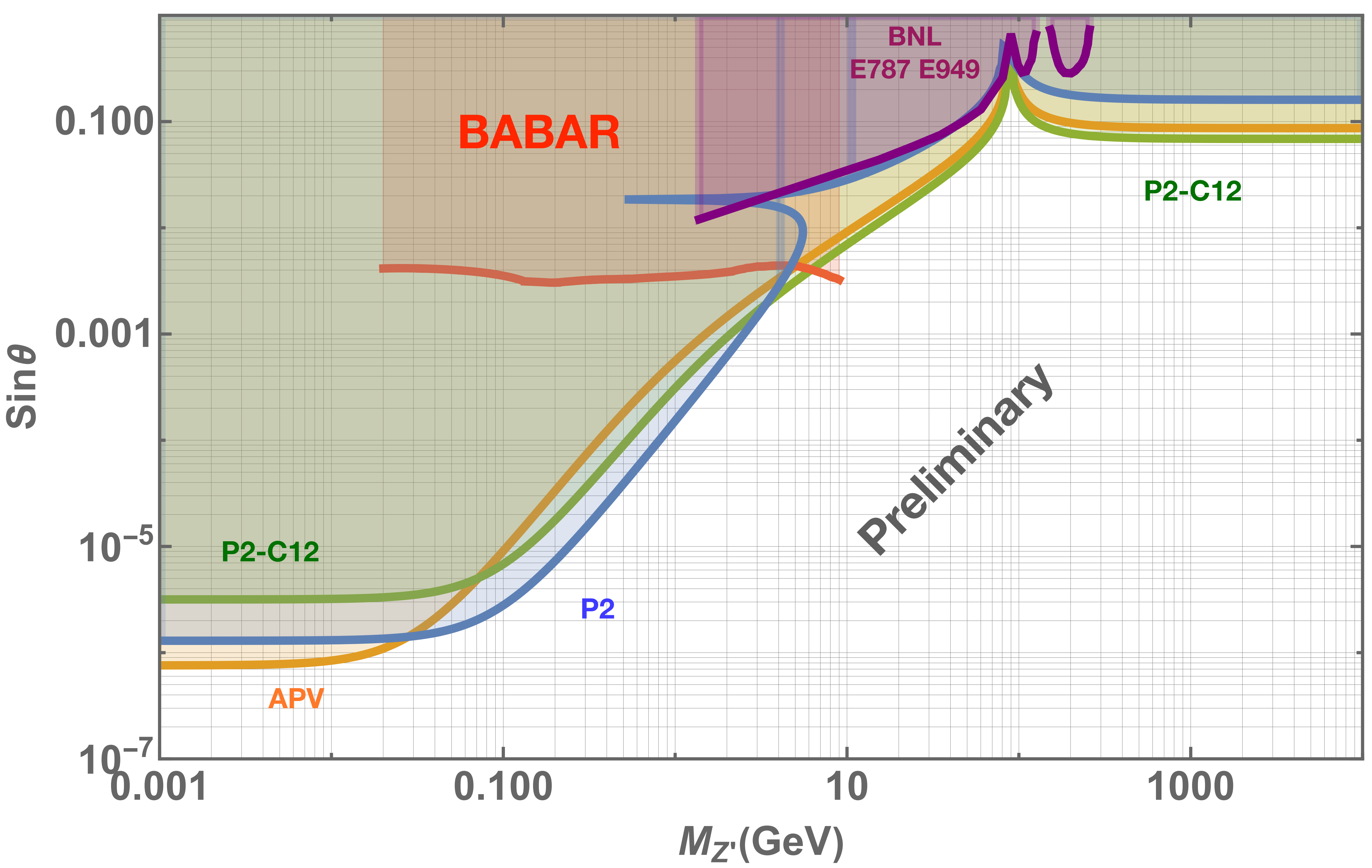


Preliminary results
L. M. G. de la Vega and R. Ferro

$\epsilon = 10^{-4}$

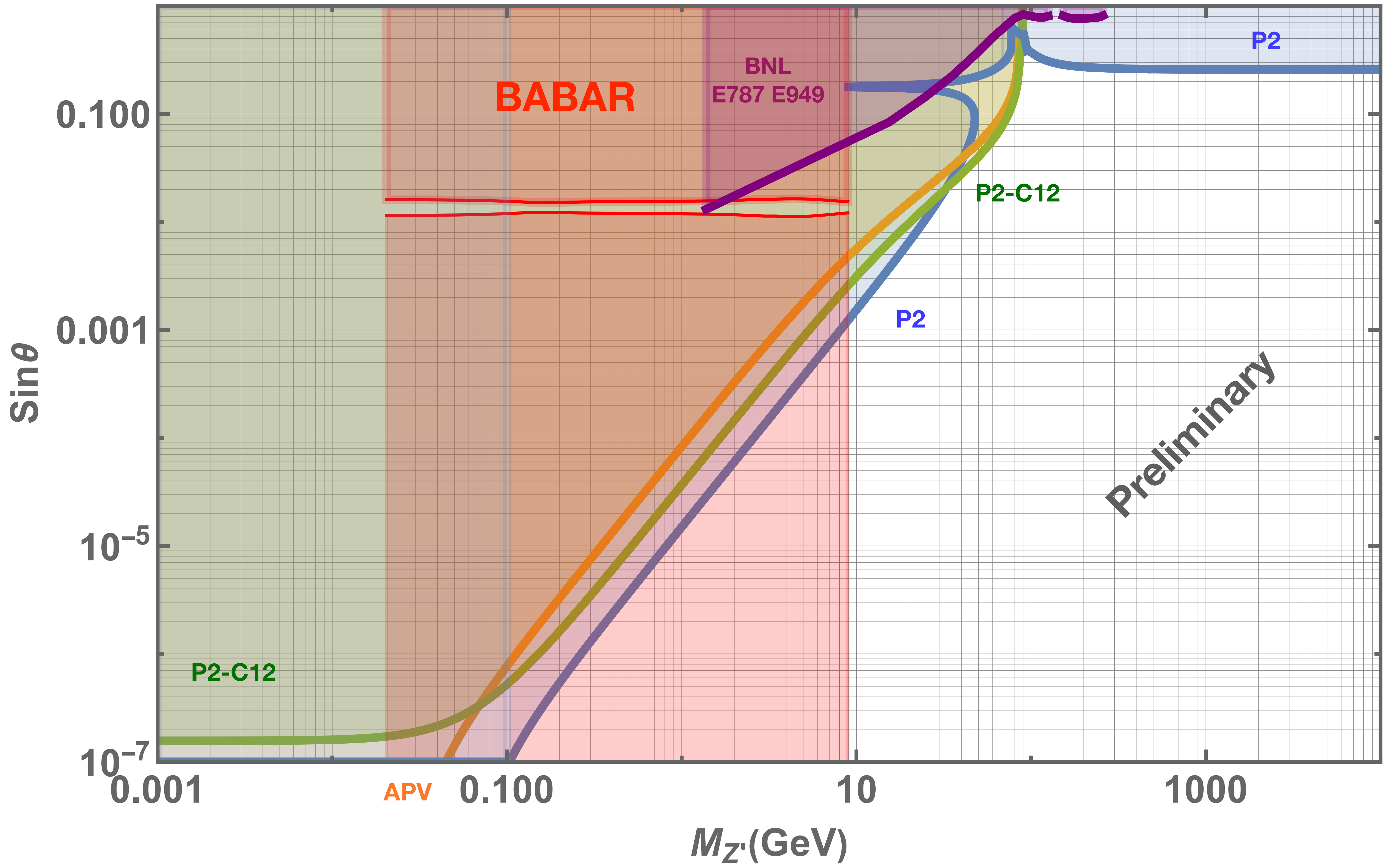


$\epsilon = 10^{-3}$



Preliminary results
L. M. G. de la Vega and R. Ferro

$$\epsilon = 10^{-2}$$



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.
- PV experiments are sensitive for kinetic and mass mixing and depending on the couplings, even better constraints than BABAR

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' ($M^2_{Z'}$)
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 $\mathrm{U}(1)'$

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

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

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

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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 $\mathrm{U}(1)'$

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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)