New Neutrino Interactions at COHERENT

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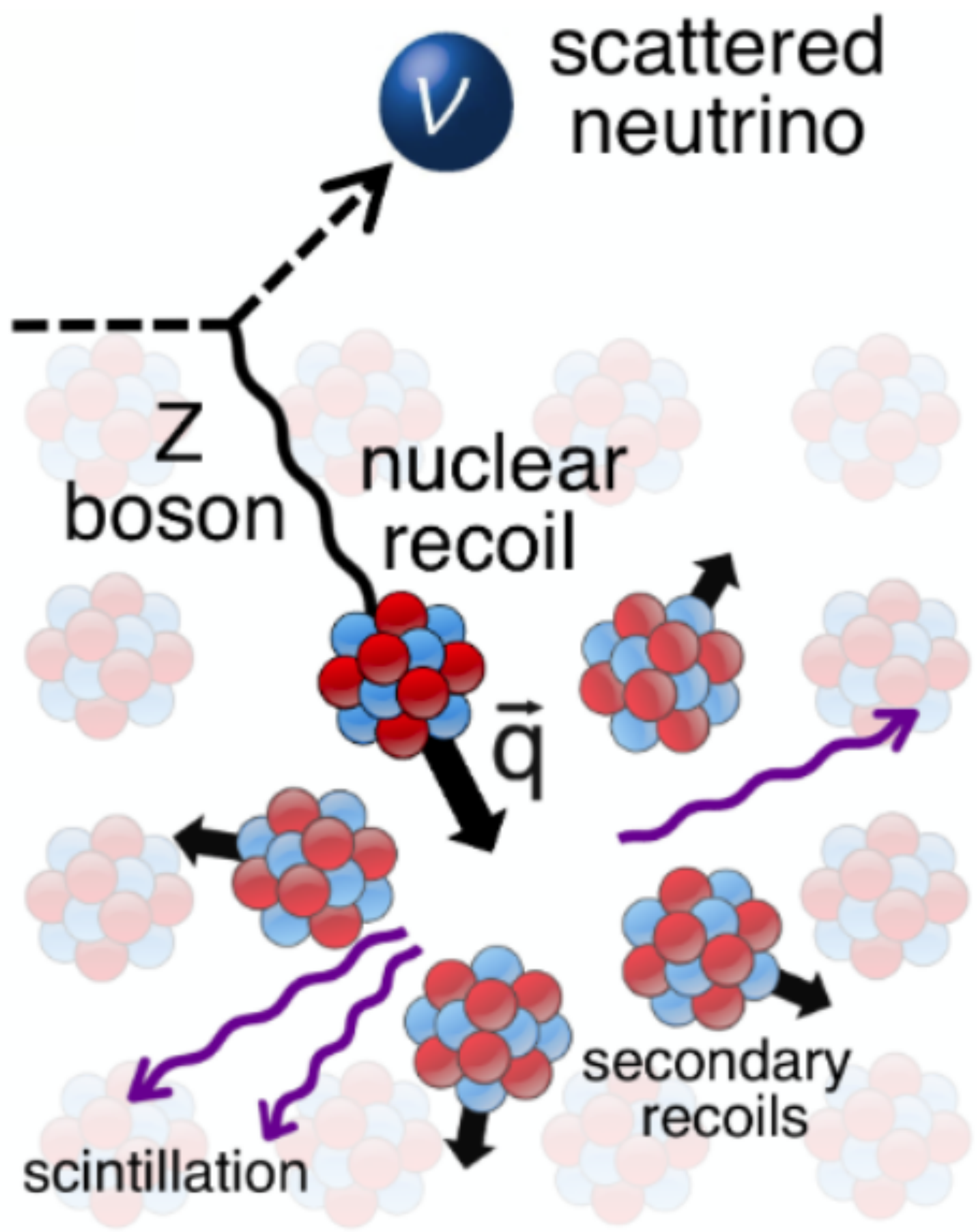
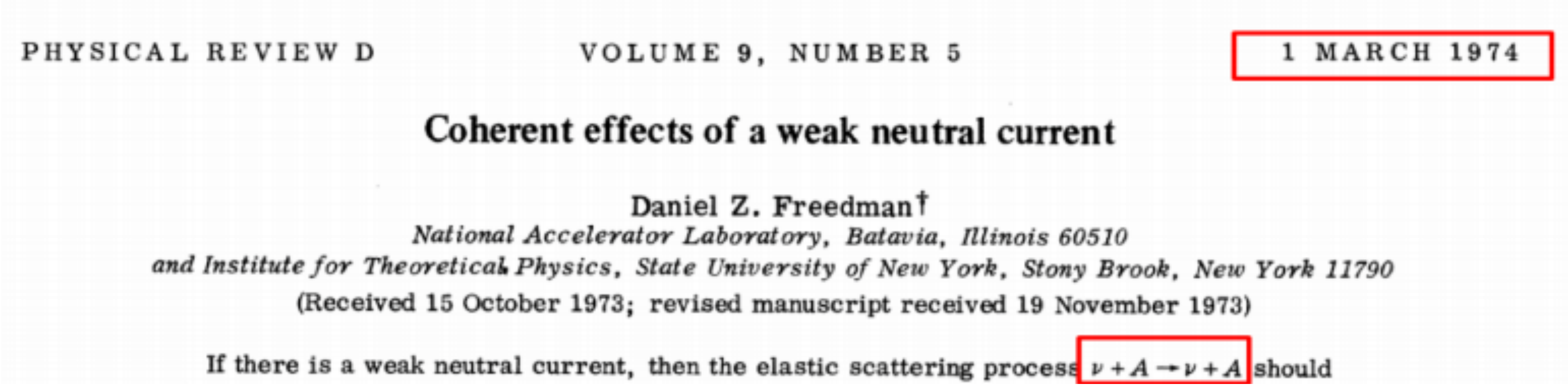
Based on: *JHEP* (2020), arXiv: 2002.12342, L. Flores, **NN**, E. Peinado,
JHEP (2021), arXiv: 2107.04037, de la Vega, L. Flores, **NN**, E. Peinado,
arXiv: 2112.0XXXX, L. Flores, **NN**, E. Peinado

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering




PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should

$$E_\nu \lesssim 50\,\mathrm{MeV}$$

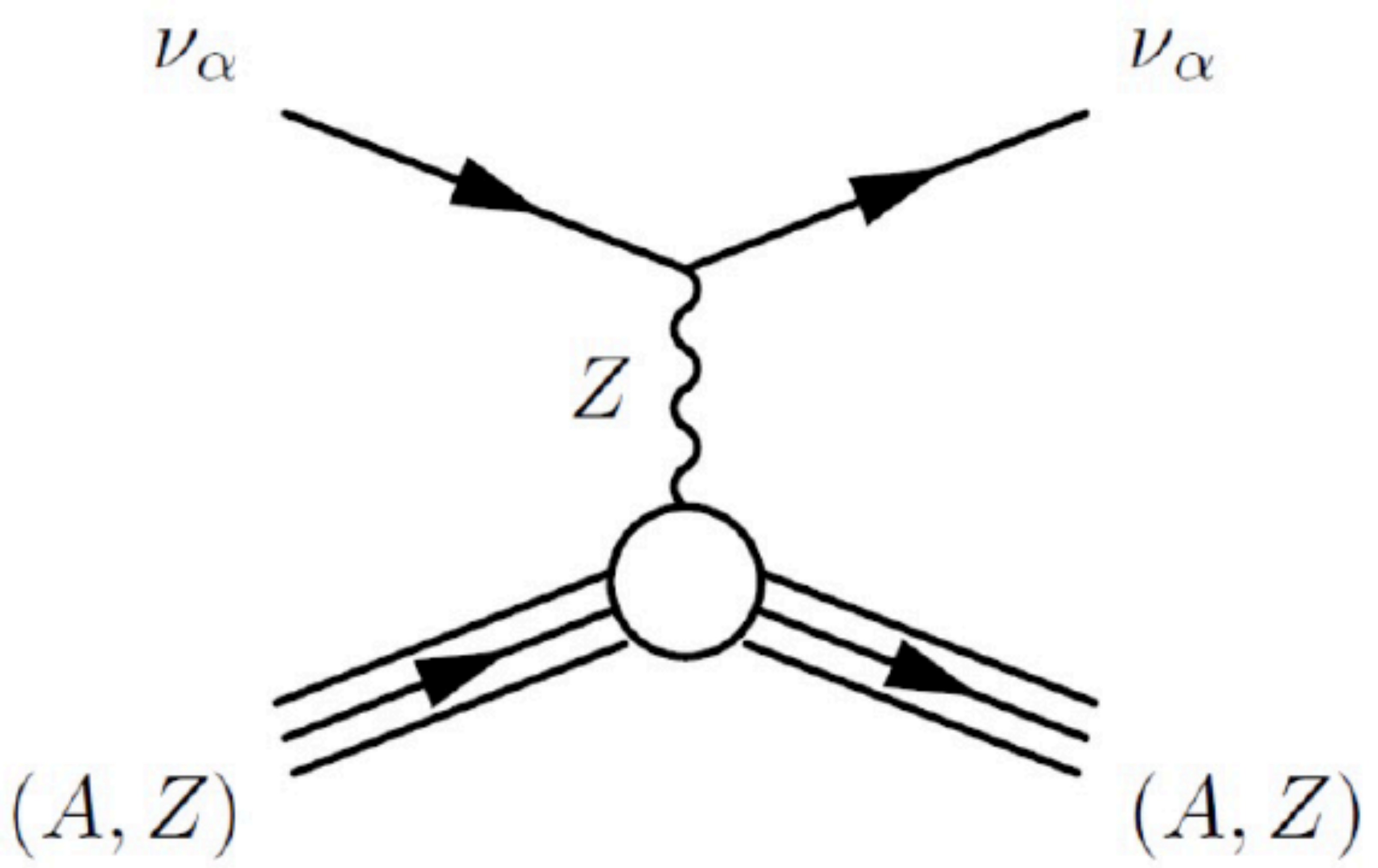
$$q\,.\,R \ll 1$$

3-momentum transfer

Nuclear radius

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 Nuclear Charge:

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

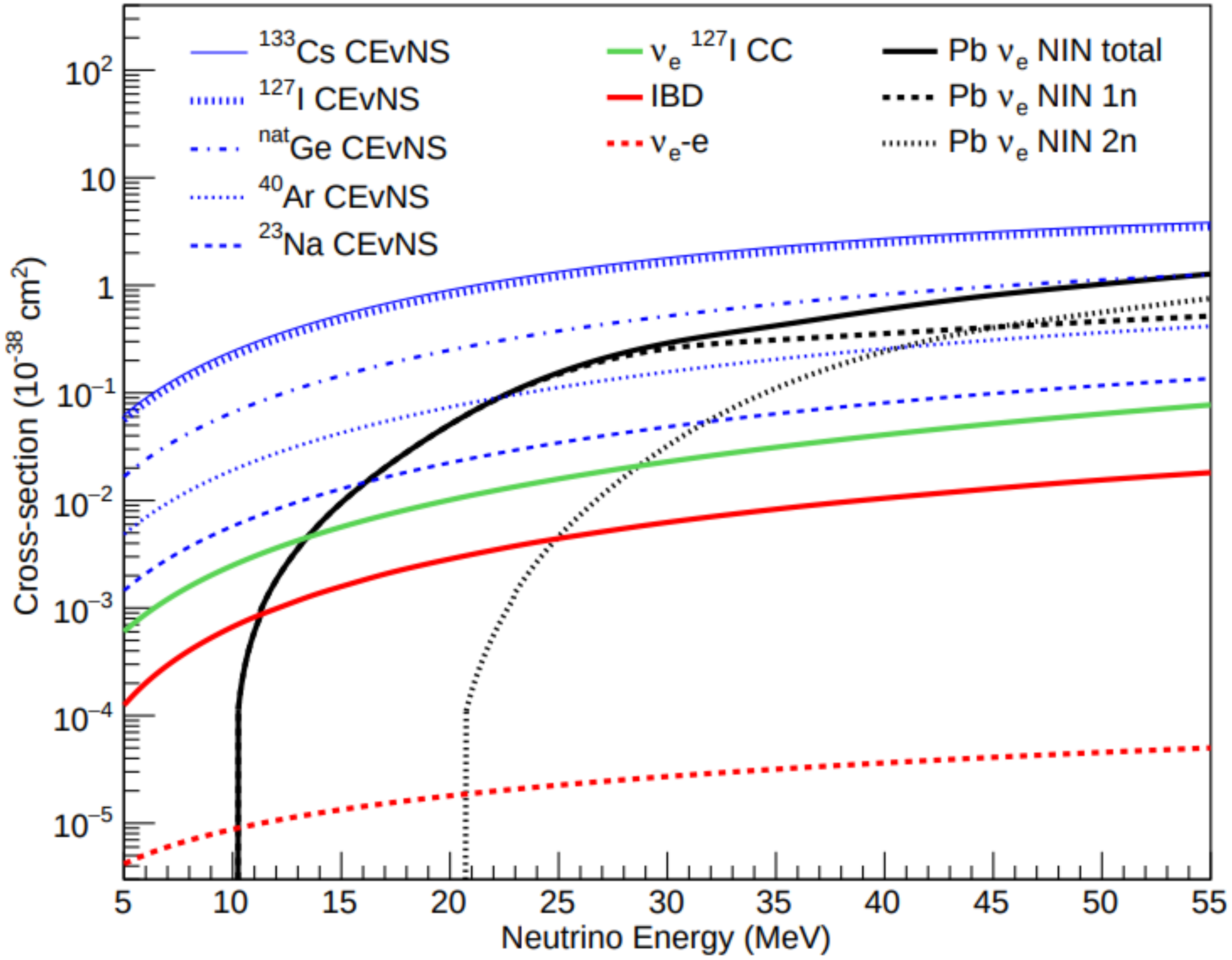
$$g_p^V = 1/2 - 2\sin^2\theta_W, \; g_n^V = -1/2$$

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

Cont…

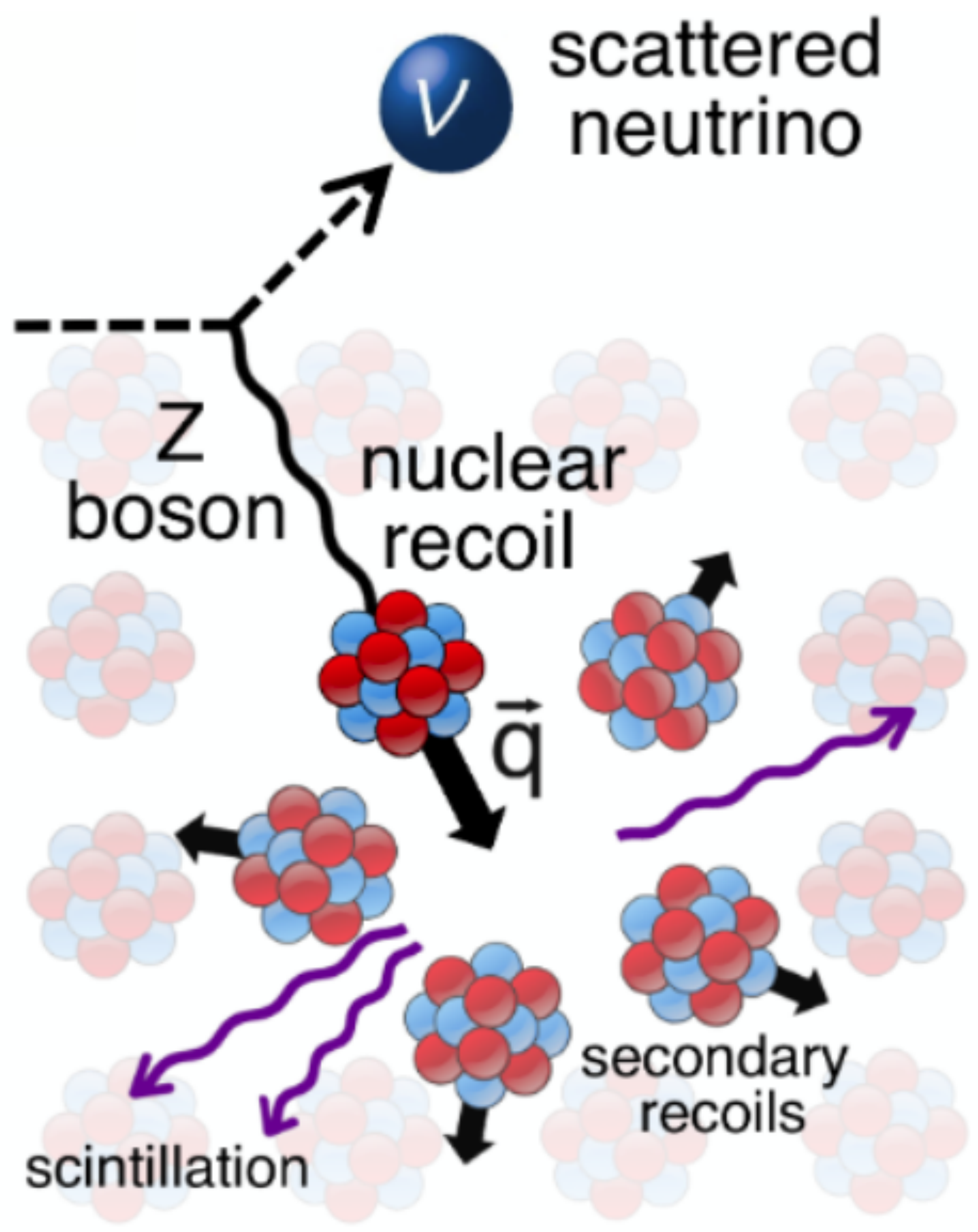
$$\sigma \propto N^2$$

Higher cross-section



COHERENT Collaboration, Science 357,1123 (2017)

Cont…



Main challenge to observe nuclear recoils with a very small kinetic energy of a few keV

$$T_{\max}(E_\nu) = \frac{2E_\nu^2}{M + 2E_\nu} \, .$$

For $E_\nu \sim 50MeV, T_{max}(E_\nu) \approx 40keV$

For CEνNS:

- a low nuclear-recoil-energy threshold detector,
- a low-background environment,
- an intense neutrino flux.

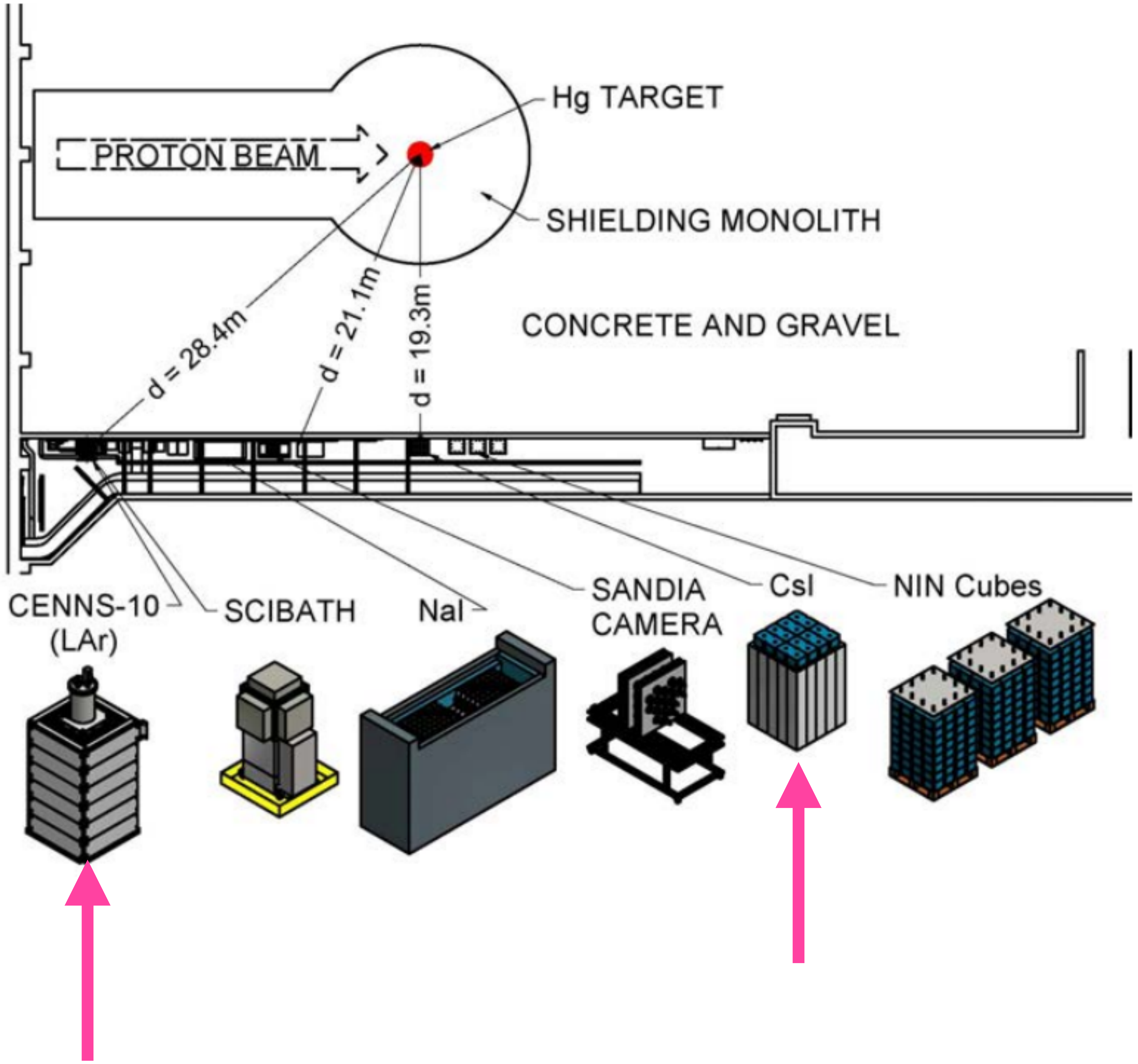
Two types of neutrino sources

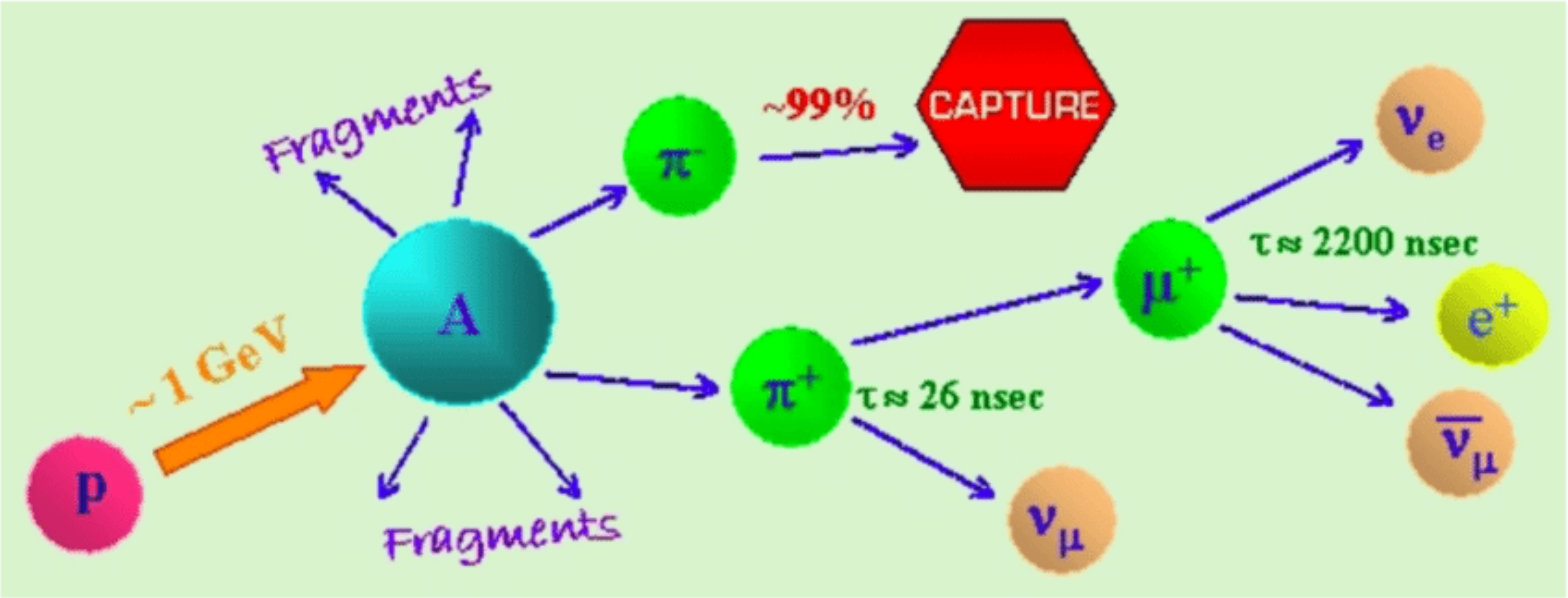
At Spallation Neutron Source,
$\pi^+ \rightarrow \mu^+ \nu_\mu$

At nuclear reactors,
$n \rightarrow p e \overline{\nu_e}$

COHERENT Collaboration:

Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL)





Results:

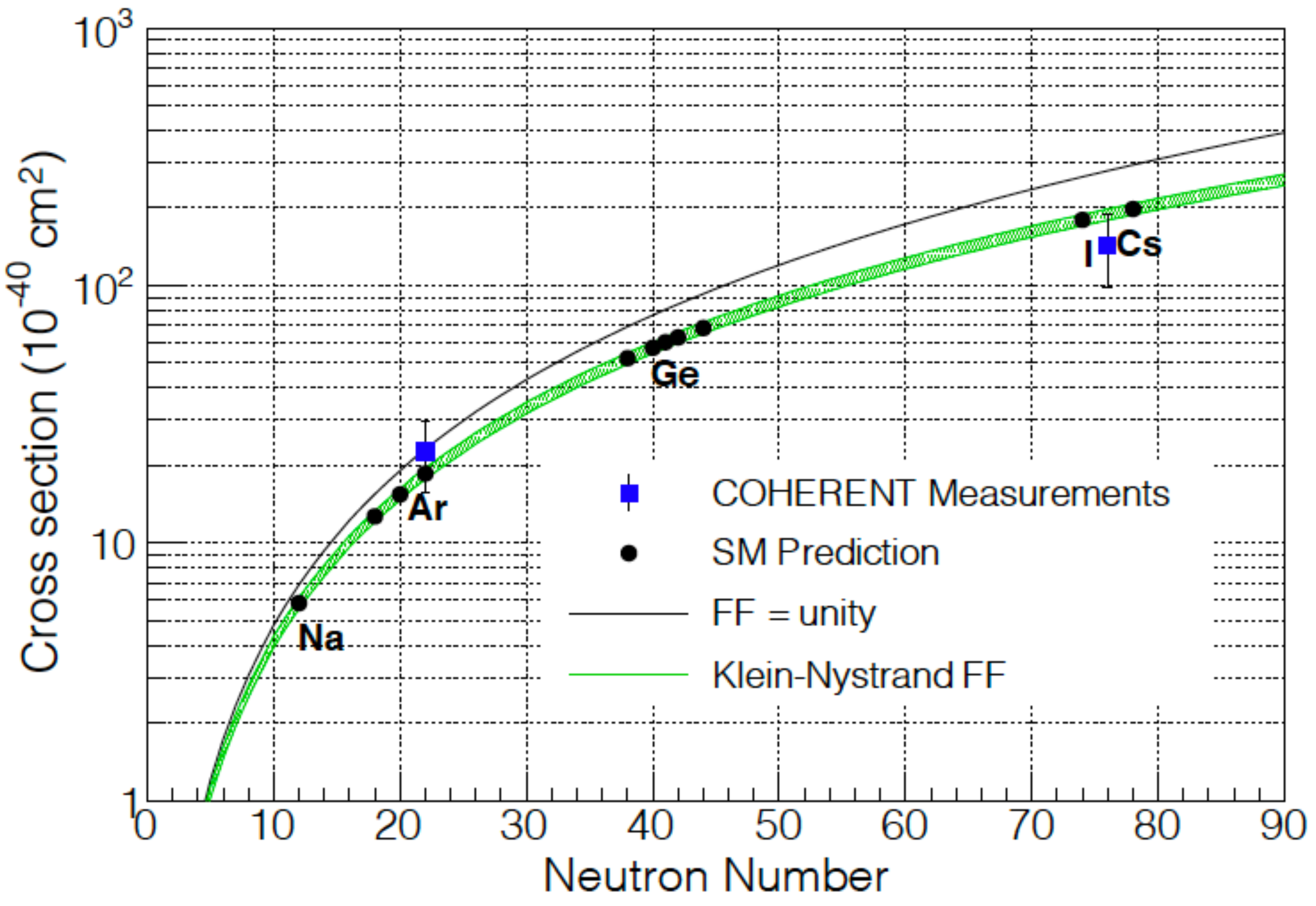
- 134 $\pm$ 22 events at 6.7 σ CL (CsI)
- 306 $\pm$ 20 events at 11.6 σ CL (CsI)
- 159 $\pm$ 43 and 121 $\pm$ 36 events at 3 σ CL (LAr)

COHERENT Collaboration, Science 357,1123 (2017),
arXiv: 2110.07730 [hep-ph] , arXiv: 2006.12659 [nucl-ex]

Cont…

$$\sigma \propto N^2$$

Observed cross-section consistent with N^2 dependence

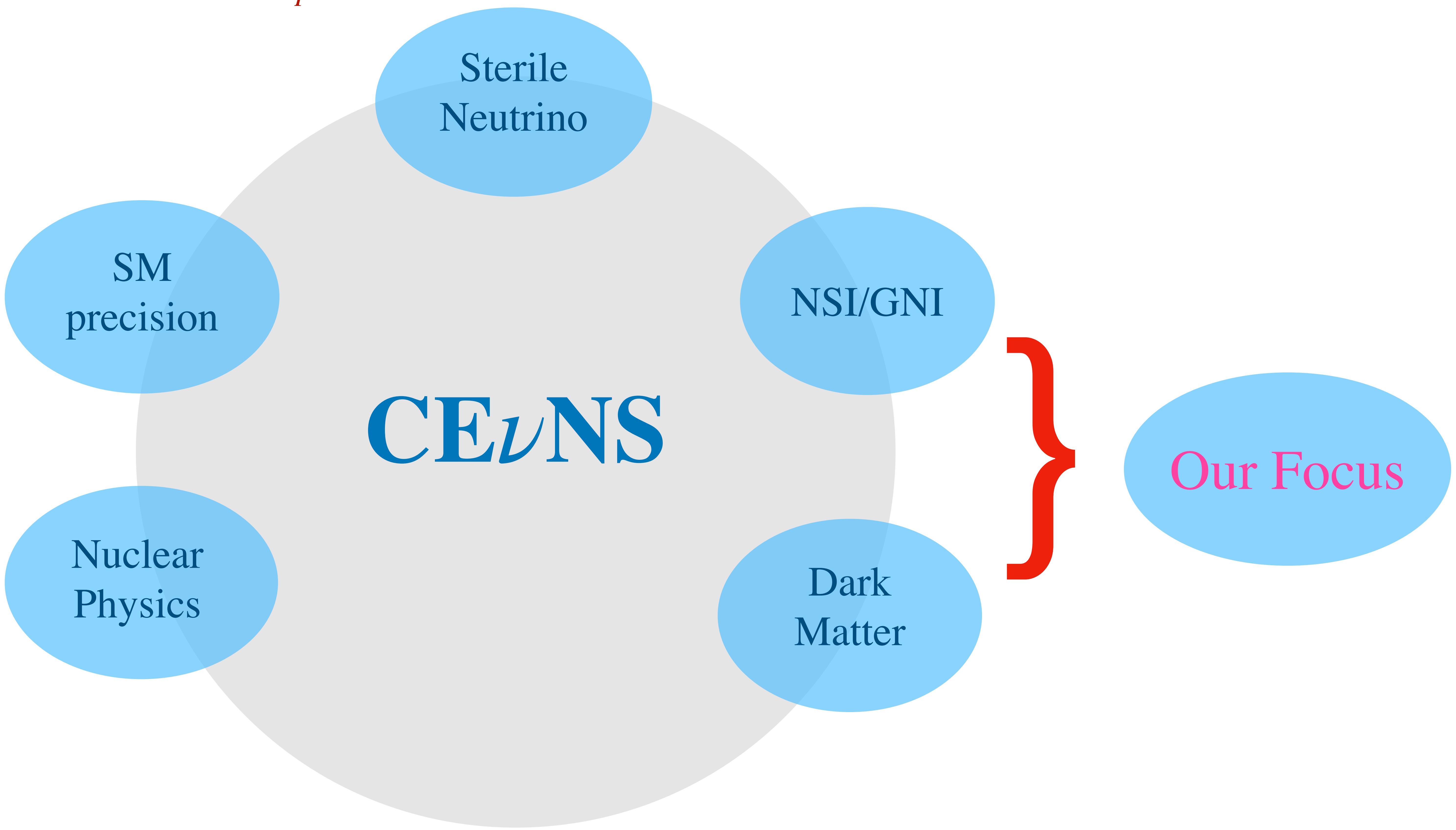


COHERENT Collaboration, arXiv: 2006.12659 [nucl-ex]

Importance: The SM differential cross-section:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2) \right]^2 \left(2 - \frac{M_N T}{E_\nu^2} \right) + \ldots$$

$$g_p^V = 1/2 - 2\sin^2\theta_W,\ g_n^V = -1/2$$



Non-standard interactions

- The effective Lagrangian: $\mathscr{L}^{eff} = \mathscr{L}_{SM} + \frac{1}{\Lambda}\delta\mathscr{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathscr{L}^{d=6} + \dots$
- The effective dimension-6 term: $\supset (\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f}\gamma_\rho P_C f')2\sqrt{2}G_F \epsilon^{fC}_{\alpha\beta} + h.c.$

[Wolfenstein, '78, Valle '87]

Ohlsson, RPP, 76 (2013) 044201

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

NSI @ CEνNS:

The SM differential cross-section: $$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right)$$

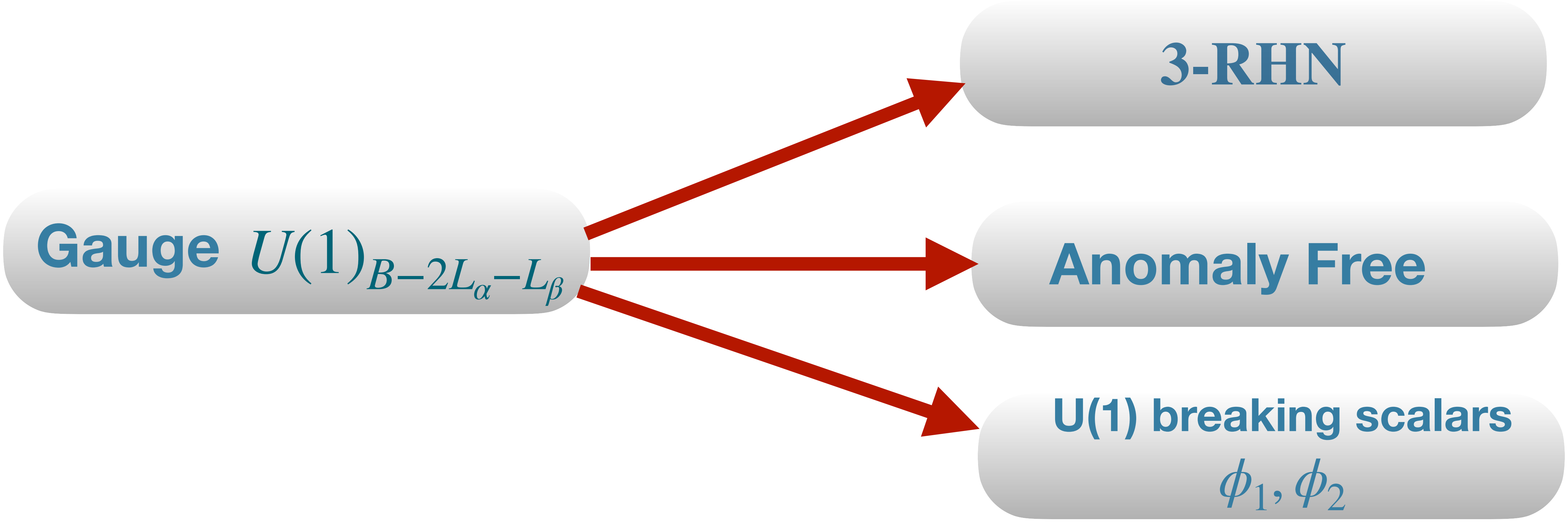
In SM: $$Q_w^2 = \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2)\right]^2$$

NSI

In presence of NSI:
$$Q^2_{W,\alpha\alpha} = \left[Z(g_p^V + 2\varepsilon^u_{\alpha\alpha} + \varepsilon^d_{\alpha\alpha}) + N(g_n^V + 2\varepsilon^d_{\alpha\alpha} + \varepsilon^u_{\alpha\alpha})\right]^2,$$
$$Q^2_{W,\alpha\beta} = \sum_{\beta\neq\alpha} \left| Z(2\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta}) + N(2\varepsilon^d_{\alpha\beta} + \varepsilon^u_{\alpha\beta})\right|^2.$$

# of events: $$N_i = \int_{E_r^i}^{E_r^{i+1}} A(E_r) \sum_\alpha N_a \int_{E_\nu^{\min}}^{E_\nu^{\max}} \phi_\alpha(E_\nu) \frac{d\sigma}{dE_r} dE_\nu dE_r$$

NSI in $U(1)'$ Models:



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

leads to

$$\varepsilon_{\alpha\alpha}^{qV} = \frac{g'^2 x_\alpha x_q}{\sqrt{2} G_F (Q^2 + M_{Z'}^2)} .$$

Flores, NN, Peinado, JHEP 06 (2020) 045

Cont…

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} & $\varepsilon_{\mu\mu}$

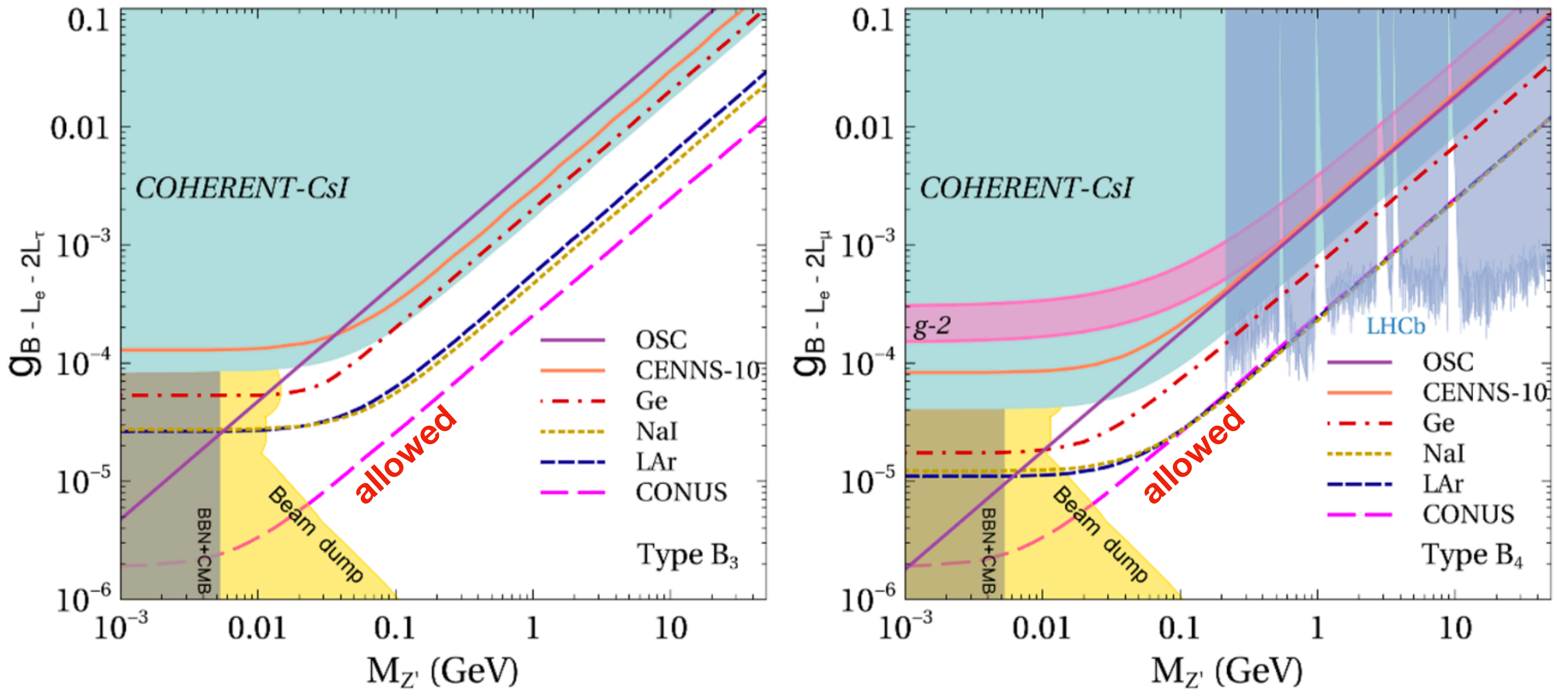
Consistent with neutrino phenomenology

Flores, NN, Peinado, JHEP 06 (2020) 045

Cont…

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

$M_{Z'} = 0.1\,\mathrm{GeV}$ $\quad g' = 2.8 \times 10^{-5}$ $\quad v_1 \approx 3\,\mathrm{TeV}$ $\quad v_2 \approx 1\,\mathrm{TeV}$



Flores, NN, Peinado, JHEP 06 (2020) 045

CEvNS and DM searches in $U(1)'$ models

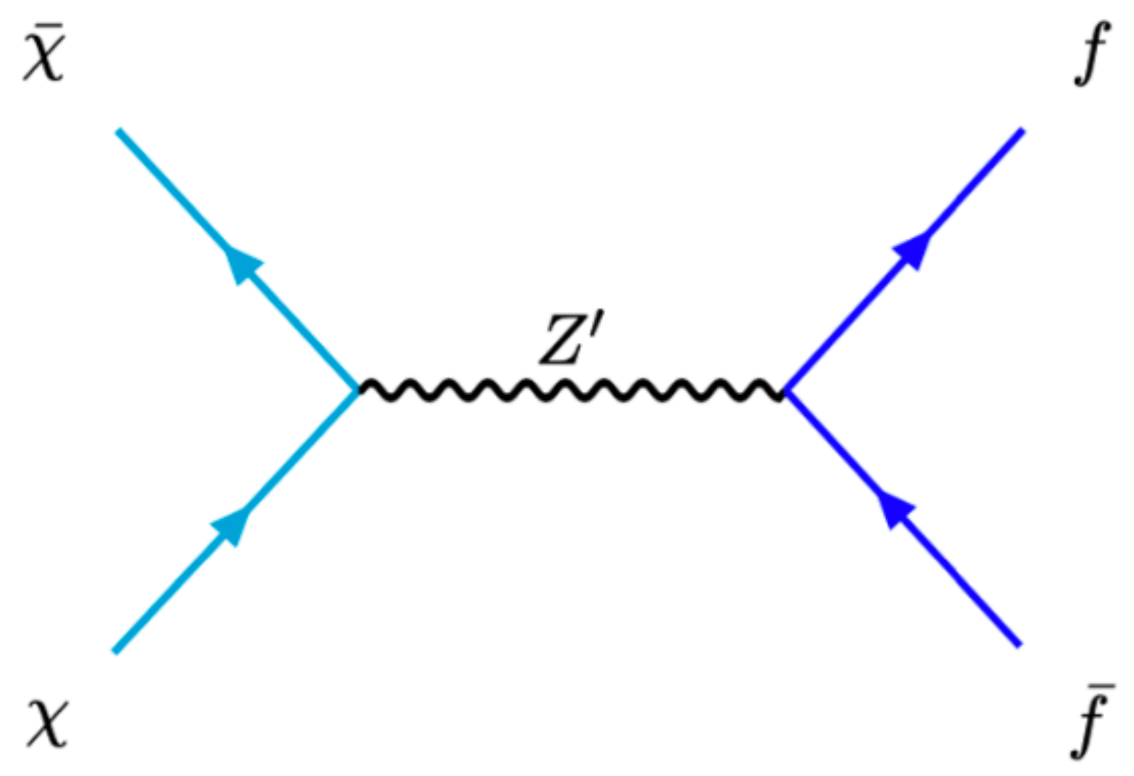
Extend the SM with a Dirac fermion χ with $Q_\chi = 1/3$

de la Vega, Flores, NN, Peinado, JHEP 09 (2021) 146

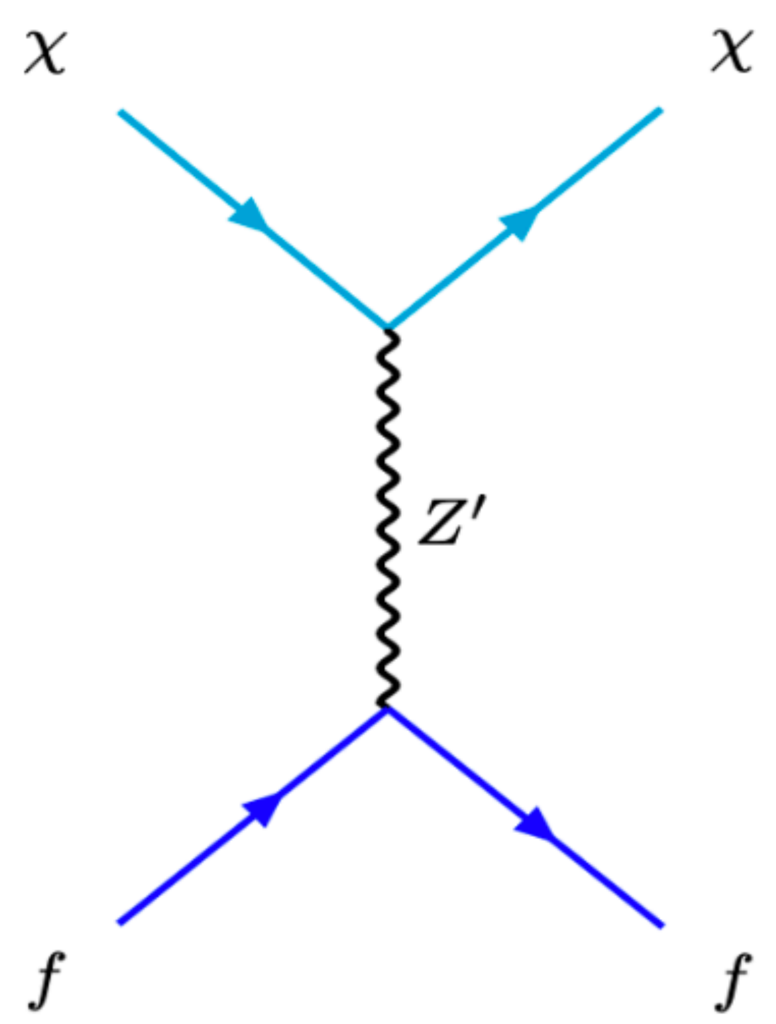
Z_3 symmetry stabilises χ

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

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



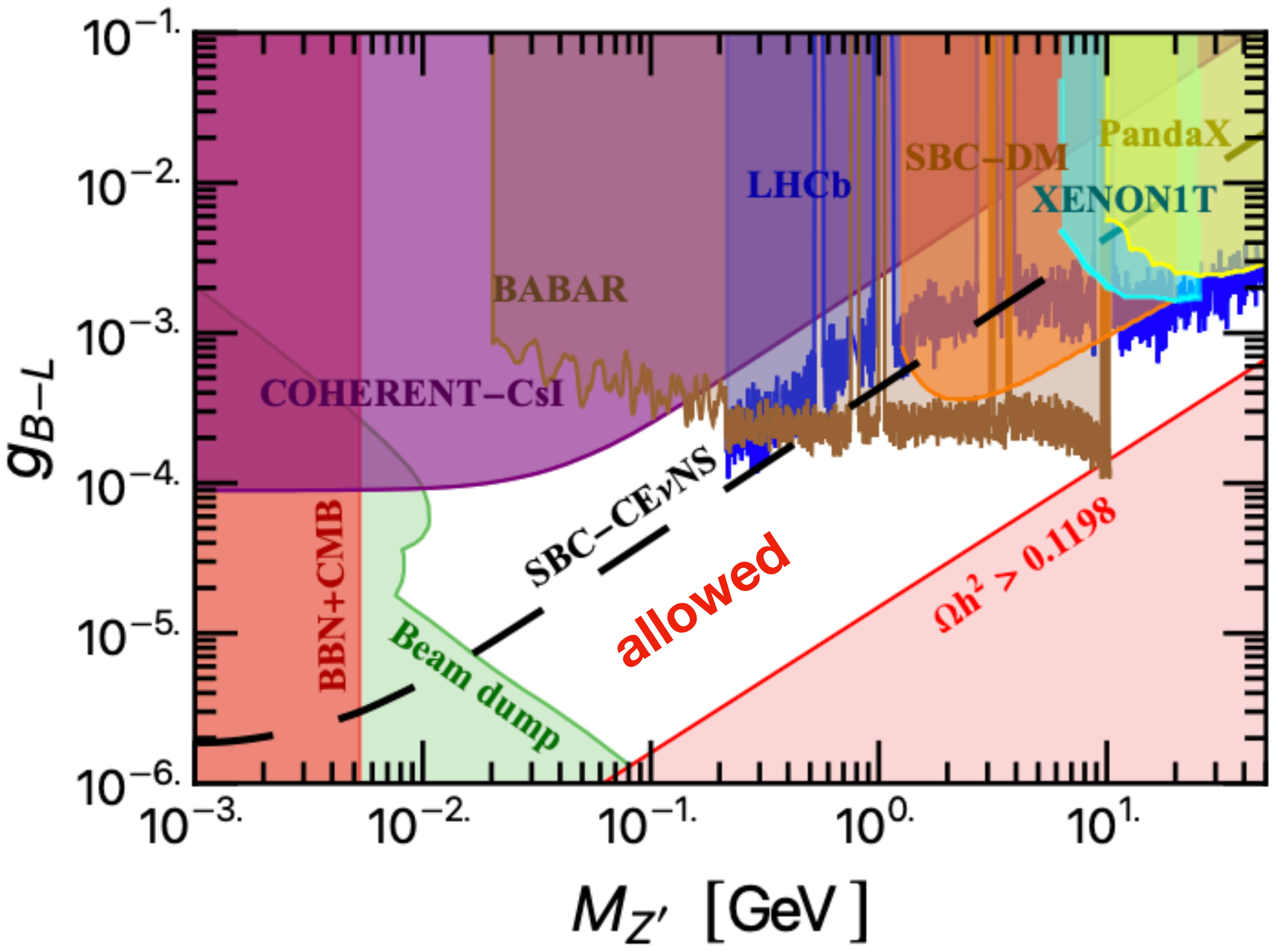
DM annihilation
freeze-out

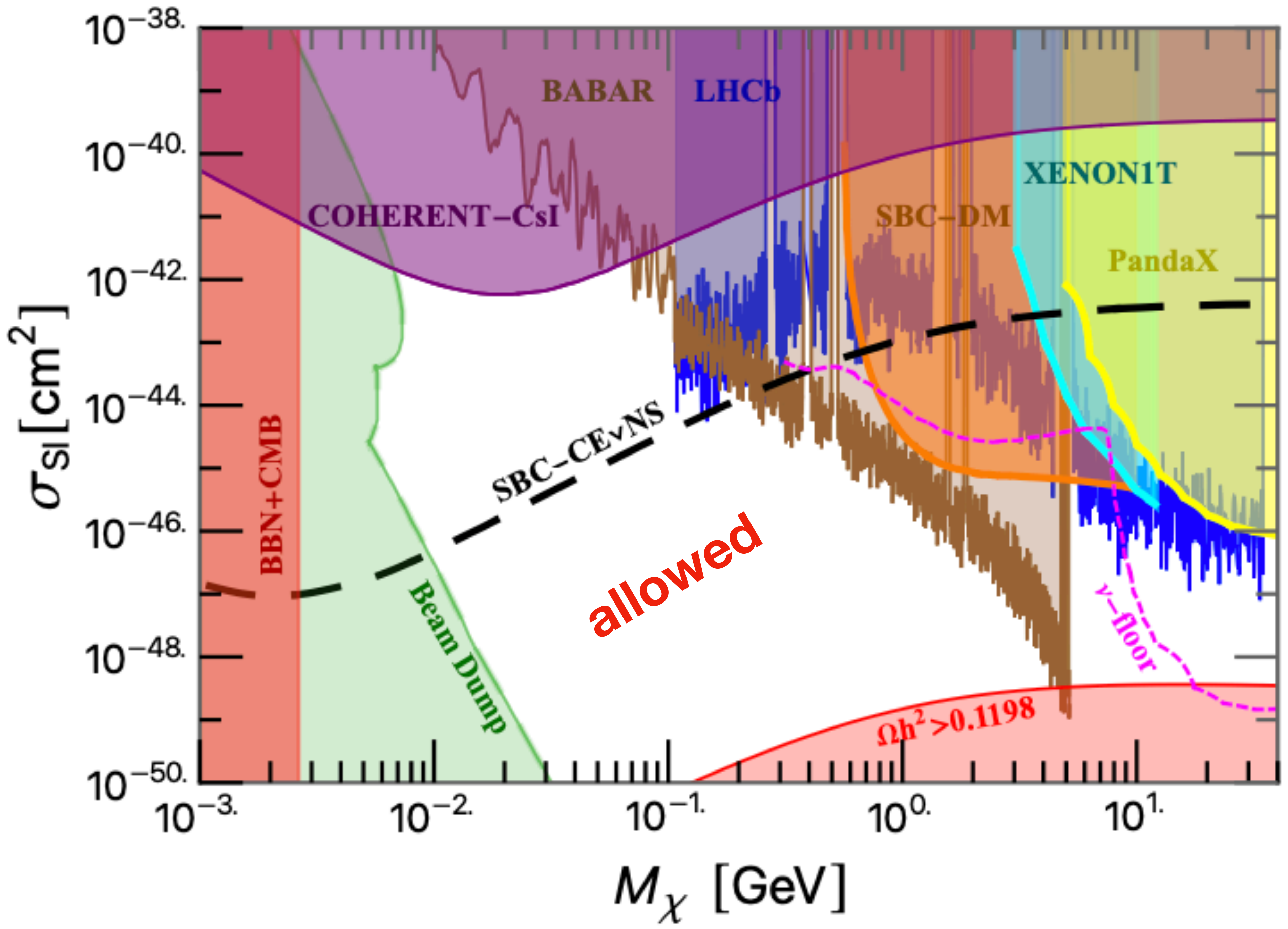


DM
Direct-detection

Cont…

The dark matter-nucleus SI cross-section per nucleon: $\sigma_{\rm SI} \approx \frac{\mu_{\chi n}^2}{\pi}\frac{g'^4}{9M_{Z'}^4}$.





SBC: Scintillating Bubble Chamber, a reactor-based CEνNS experiment

de la Vega, Flores, NN, Peinado, JHEP 09 (2021) 146

Generalized Neutrino Interactions (GNI):

$$\mathscr{L}_{\rm NSI} \supset 2\sqrt{2}G_F\epsilon^{fC}_{\alpha\beta}\ (\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_C f')$$

Bergmann, Grossman, Nardi, PRD 60, 093008 (1999)

j	$\widetilde{\varepsilon}^j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ε_L	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
2	$\widetilde{\varepsilon}_L$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
3	ε_R	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
4	$\widetilde{\varepsilon}_R$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
5	ε_S	$(1-\gamma^5)$	1
6	$\widetilde{\varepsilon}_S$	$(1+\gamma^5)$	1
7	$-\varepsilon_P$	$(1-\gamma^5)$	γ^5
8	$-\widetilde{\varepsilon}_P$	$(1+\gamma^5)$	γ^5
9	ε_T	$\sigma_{\mu\nu}(1-\gamma^5)$	$\sigma^{\mu\nu}(1-\gamma^5)$
10	$\widetilde{\varepsilon}_T$	$\sigma_{\mu\nu}(1+\gamma^5)$	$\sigma^{\mu\nu}(1+\gamma^5)$

Another parametrization:

$$\mathscr{L}_{\rm GNI} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \bar{\nu}\,\Gamma^a\nu \left[\bar{q}\Gamma^a(C_a^{(q)} + \overline{D}_a^{(q)} i\gamma^5)q\right]; \Gamma^a = \{I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}; \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

Generalized Neutrino Interactions (GNI):

$$\mathscr{L}_{\mathrm{GNI}} \supset \frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \tilde{\varepsilon}^{\,q,\,j}_{\alpha\beta\gamma\delta}(\overline{\nu}_\alpha \mathcal{O}_j \nu_\beta)\ (\overline{q}_\gamma \mathcal{O}'_j q_\delta)$$

Bergmann, Grossman, Nardi, PRD 60, 093008 (1999)

j	$\tilde{\varepsilon}^j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ε_L	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
2	$\tilde{\varepsilon}_L$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
3	ε_R	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
4	$\tilde{\varepsilon}_R$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
5	ε_S	$(1-\gamma^5)$	1
6	$\tilde{\varepsilon}_S$	$(1+\gamma^5)$	1
7	$-\varepsilon_P$	$(1-\gamma^5)$	γ^5
8	$-\tilde{\varepsilon}_P$	$(1+\gamma^5)$	γ^5
9	ε_T	$\sigma_{\mu\nu}(1-\gamma^5)$	$\sigma^{\mu\nu}(1-\gamma^5)$
10	$\tilde{\varepsilon}_T$	$\sigma_{\mu\nu}(1+\gamma^5)$	$\sigma^{\mu\nu}(1+\gamma^5)$

NSI (rows 1–4)

Another parametrization:

$$\mathscr{L}_{\mathrm{GNI}} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\,\Gamma^a \nu \left[\overline{q}\Gamma^a(C_a^{(q)} + \overline{D}_a^{(q)} i\gamma^5)q\right]; \Gamma^a = \{I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}; \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

GNI @ CEνNS:

- Differential cross-section:

$$\left(\frac{d\sigma}{dE_r}\right)^f = \frac{G_F^2}{4\pi} M_N N^2 F^2(Q^2) \times \left[\xi_S^{f\,2} \frac{E_r}{E_r^{\max}} + (\xi_V^f + A_{\rm SM})^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) \pm \right.$$

$$\left. 2\xi_V^f \xi_A^f \frac{E_r}{E_\nu} + \xi_A^{f\,2} \left(1 + \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^{f\,2} \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right) \mp R \frac{E_r}{E_\nu} + \mathcal{O}\left(\frac{E_r^2}{E_\nu^2}\right) \right]$$

Lindner, Werner Rodejohann, Xu, JHEP 03 (2017) 097
Aristizabal Sierra, De Romeri, Rojas, PRD 98 (2018) 075018

where $A_{\rm SM} = 1 - (1 - 4\sin^2\theta_w)Z/N,$ **and**

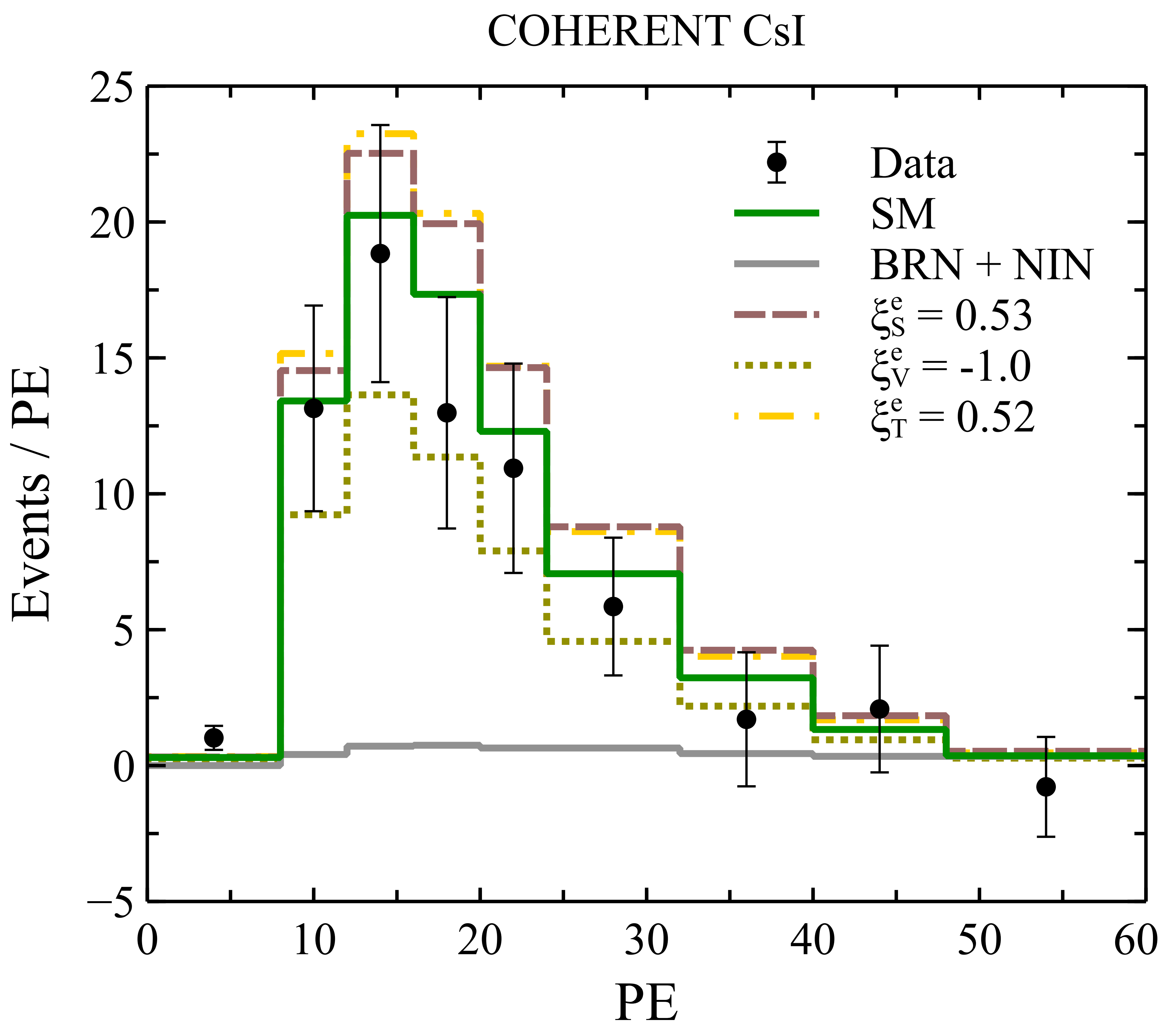
$$\xi_S^{f\,2} = \frac{1}{N^2}(C_S^2 + D_P^2), \quad \xi_V^f = \frac{1}{N}(C_V + D_A),$$
$$\xi_A^f = \frac{1}{N}(C_A + D_V), \quad \xi_T^{f\,2} = \frac{8}{N^2}(C_T^2 + D_T^2),$$
$$R = \frac{2}{N^2}(C_S C_T - C_P C_T + D_S D_T - D_P D_T).$$

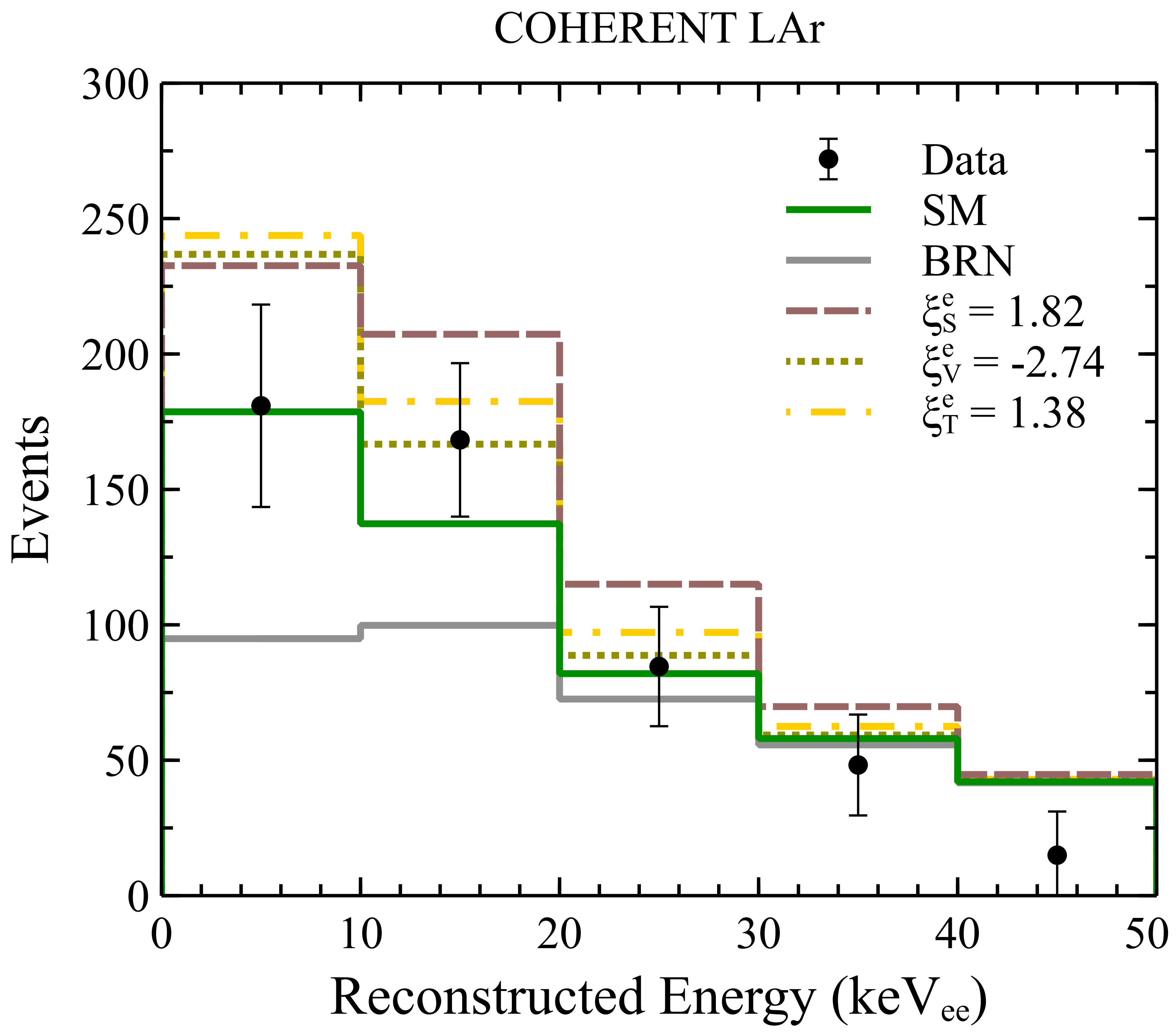
- # of events:

$$N_i = \int_{E_r^i}^{E_r^{i+1}} A(E_r) \sum_\alpha N_a \int_{E_\nu^{\min}}^{E_\nu^{\max}} \phi_\alpha(E_\nu) \frac{d\sigma}{dE_r} dE_\nu dE_r$$

where $\alpha = \nu_\mu, \overline{\nu_\mu}, \nu_e$

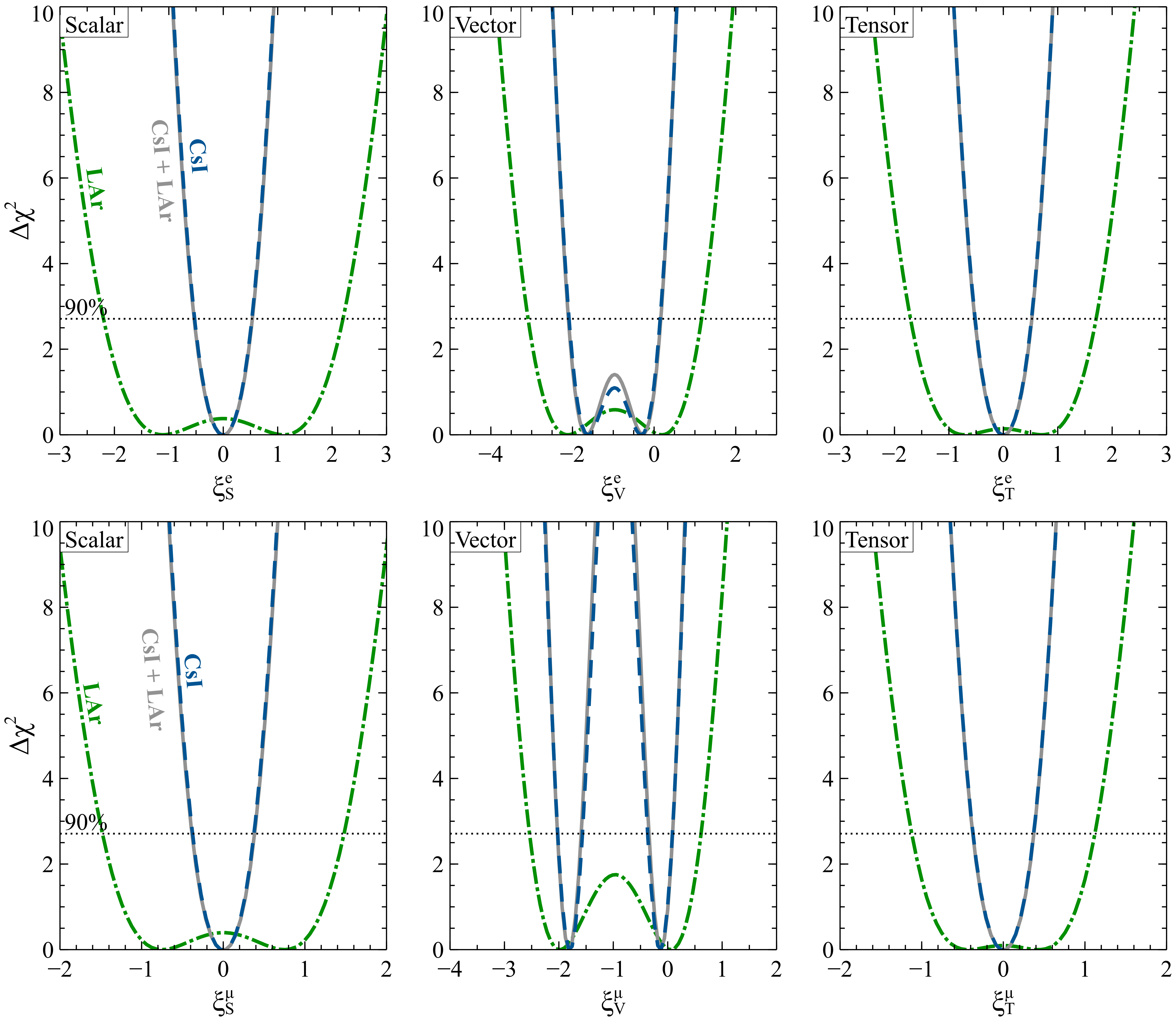
- **# of events:**





Flores, NN, Peinado, (in preparation)

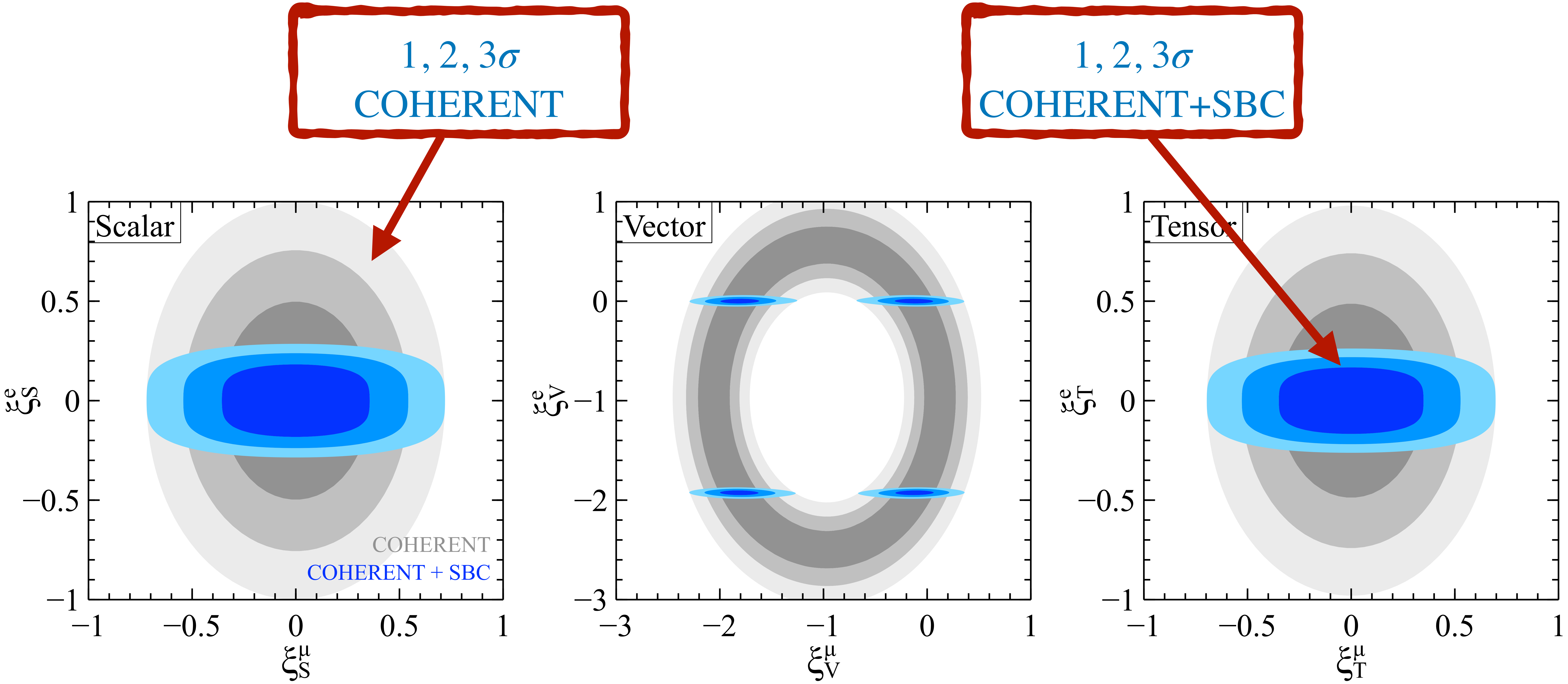
One-parameter analysis:



$$\frac{d\sigma}{dE_r} \propto \xi_S^2 \frac{E_r}{E_r^{\max}} + (\xi_V + A_{\mathrm{SM}})^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\max}} - \frac{E_r}{E_\nu}\right)$$

- **ξ_e's are less constrained than ξ_μ's given the lower ν_e flux at the SNS**
- **Limits from CsI measurement are better than the LAr**

Two-parameter analysis:



Note: combined analysis of COHERENT+SBC significantly constrained different ξ_e's

Final Comments:

- NSI coming from $U(1)'$ models have been studied for the COHERENT data

- Complementarity between dark-matter direct searches and CEνNS experiments has been explored

- Combined analysis using COHERENT and reactor data has been performed to constrain GNI parameters