LUIS J. FLORES

NATIONAL TECHNOLOGICAL INSTITUTE OF MEXICO

JEREZ CAMPUS

MITP TOPICAL WORKSHOP

Precision Tests with Neutral-Current Coherent Interactions with Nuclei

PHYSICS REACH OF FUTURE REACTOR ANTINEUTRINOS CEVNS EXPERIMENTS

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PHYSICS REACH OF FUTURE REACTOR ANTINEUTRINOS CEVNS EXPERIMENTS

Outline

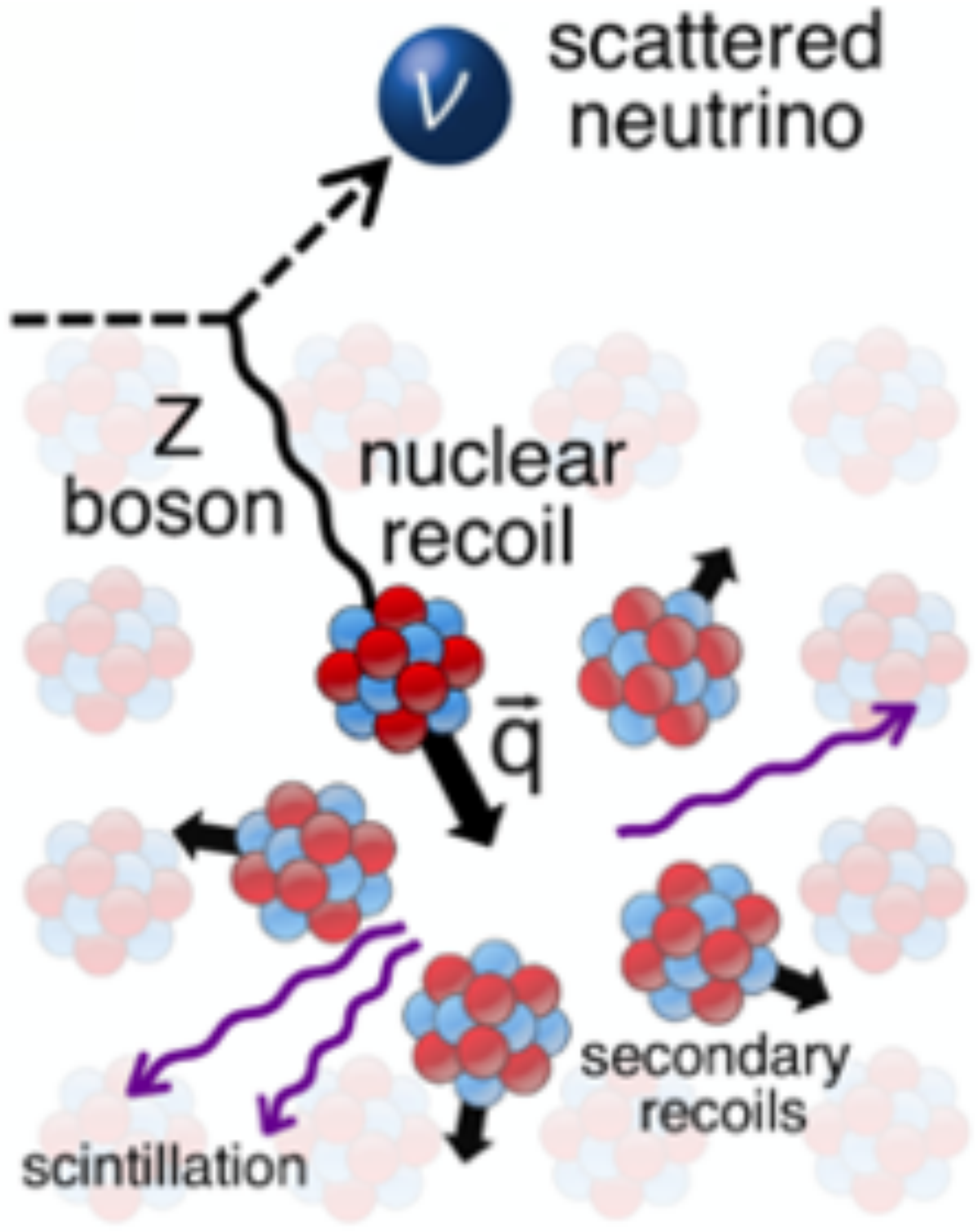
- CEvNS in the SM
  - Stopped-pion beam
  - Nuclear reactor
- Current measurements
- Future measurements (SBC)
- Final comments

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CEVNS)

$$E_\nu \leq 50 \text{ MeV}$$

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

Maximum NR energy: $T_{\max} = \frac{2E_\nu^2}{M_N}$

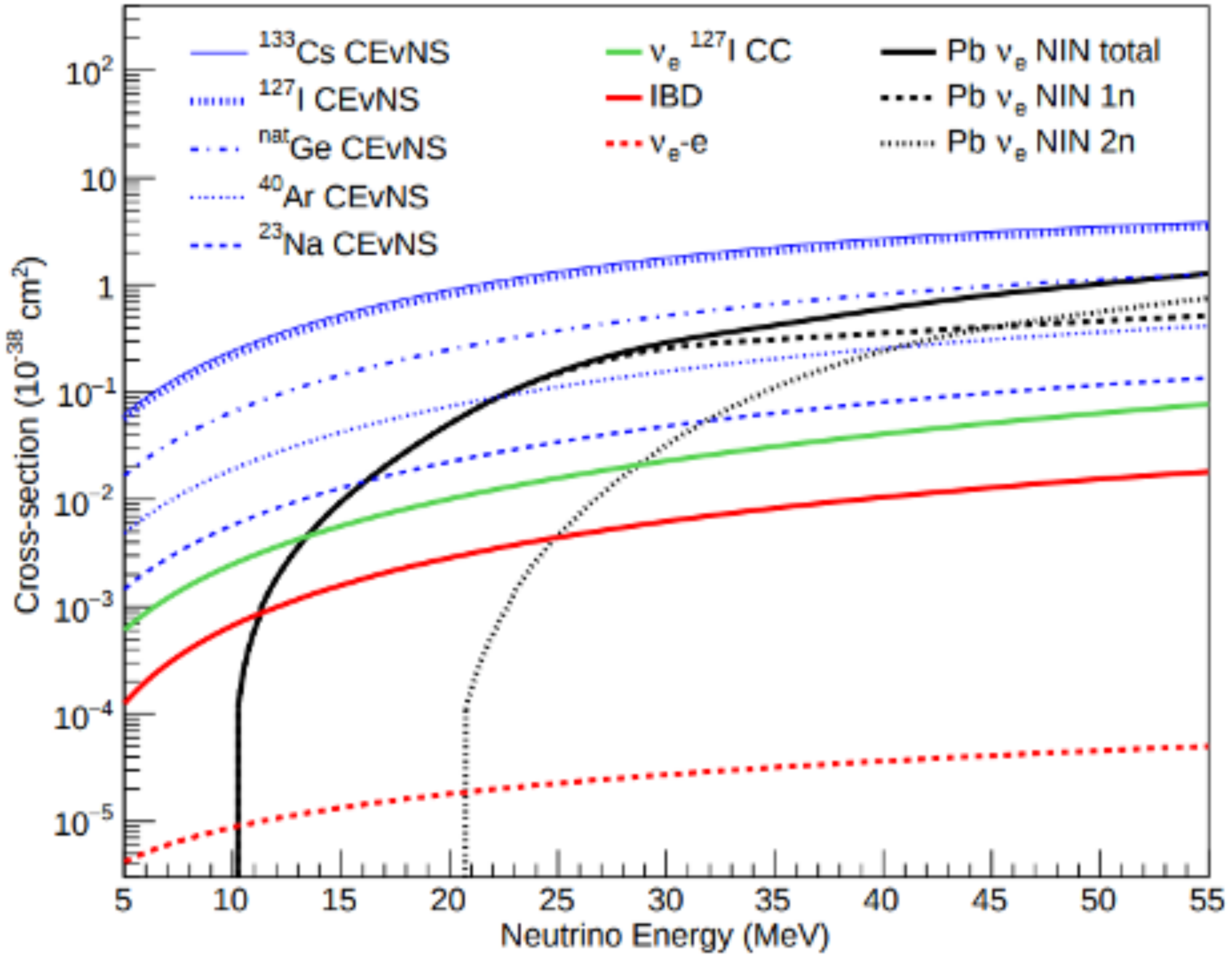


$$Q_w^2 = \left[Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2)\right]^2$$

Weak charge

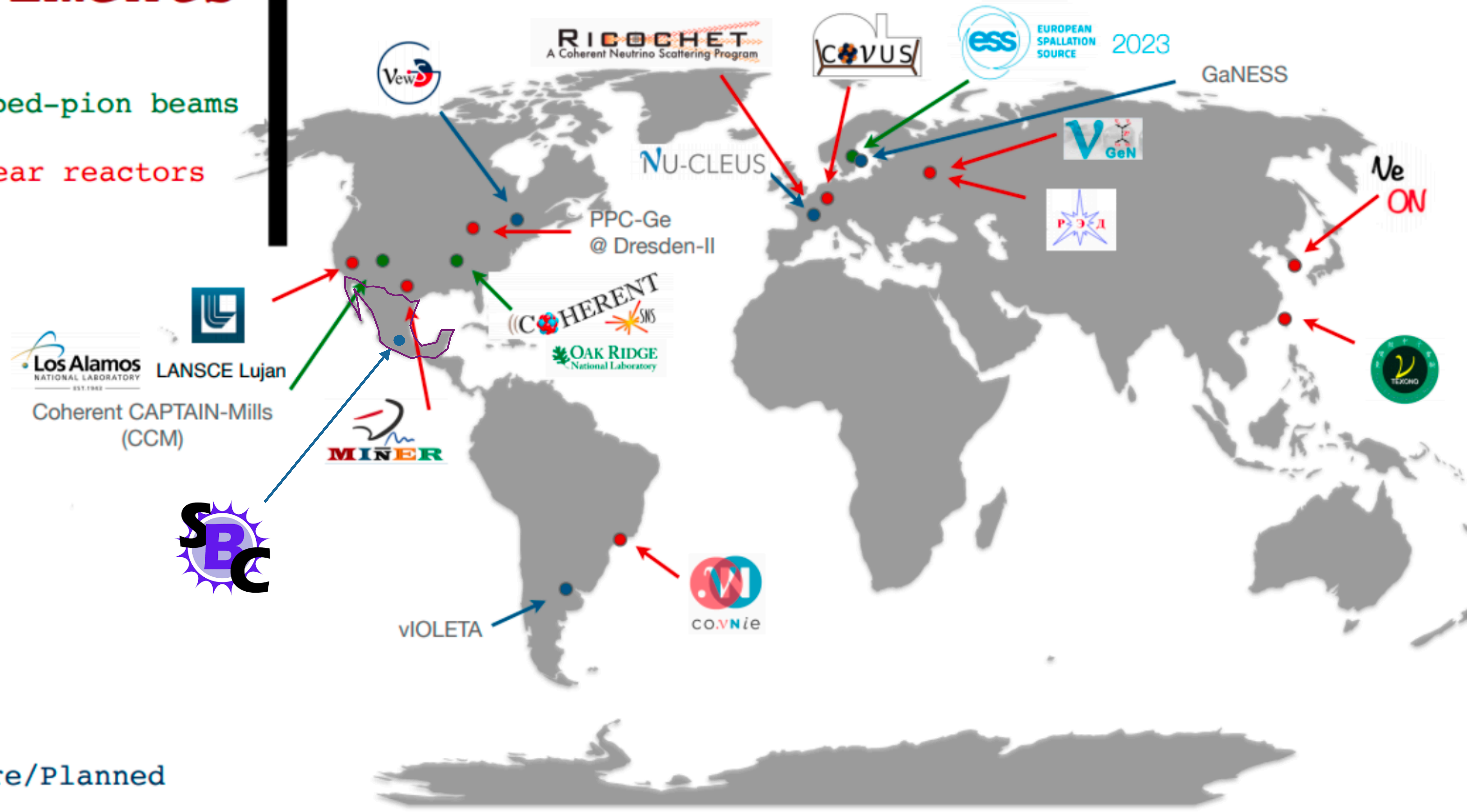
$$g_p^V = \frac{1}{2} - 2\sin\theta_W^2$$

$$g_n^V = -\frac{1}{2}$$



Experiments

- Stopped-pion beams
- Nuclear reactors



- Future/Planned

Adapted fromM. Green talk at Aspen 2019 Winter Conference

NEUTRINO SOURCES FOR CEVNS

Typical sources:

Stopped-pion beams

$$\pi^+ \to \mu^+ + \nu_\mu$$

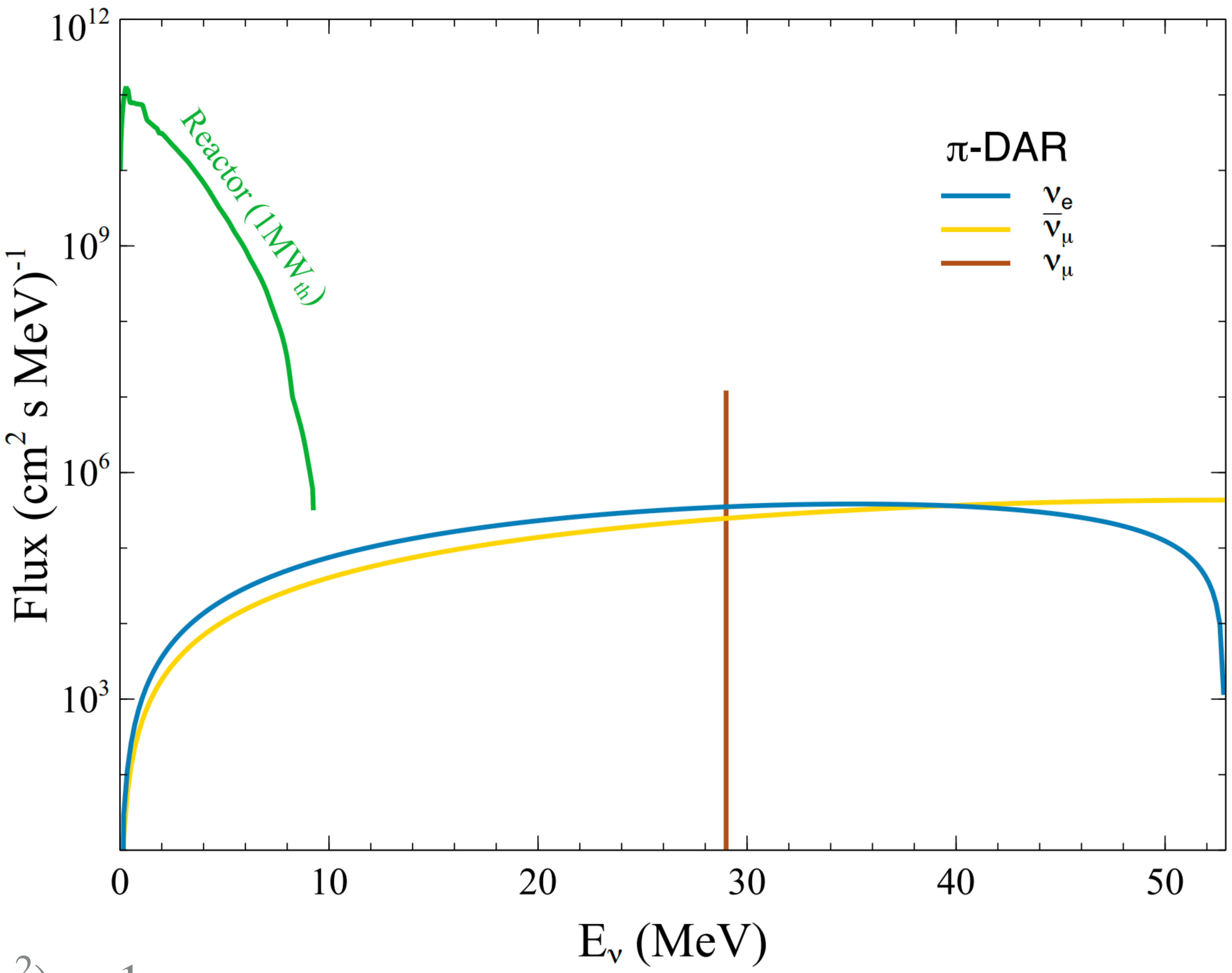
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

- Pulsed beam
- Three channels
- Higher recoils

Nuclear Reactors

$$\bar{\nu}_e$$

- Intense flux
- One channel
- Fully coherent $F(q^2) \approx 1$



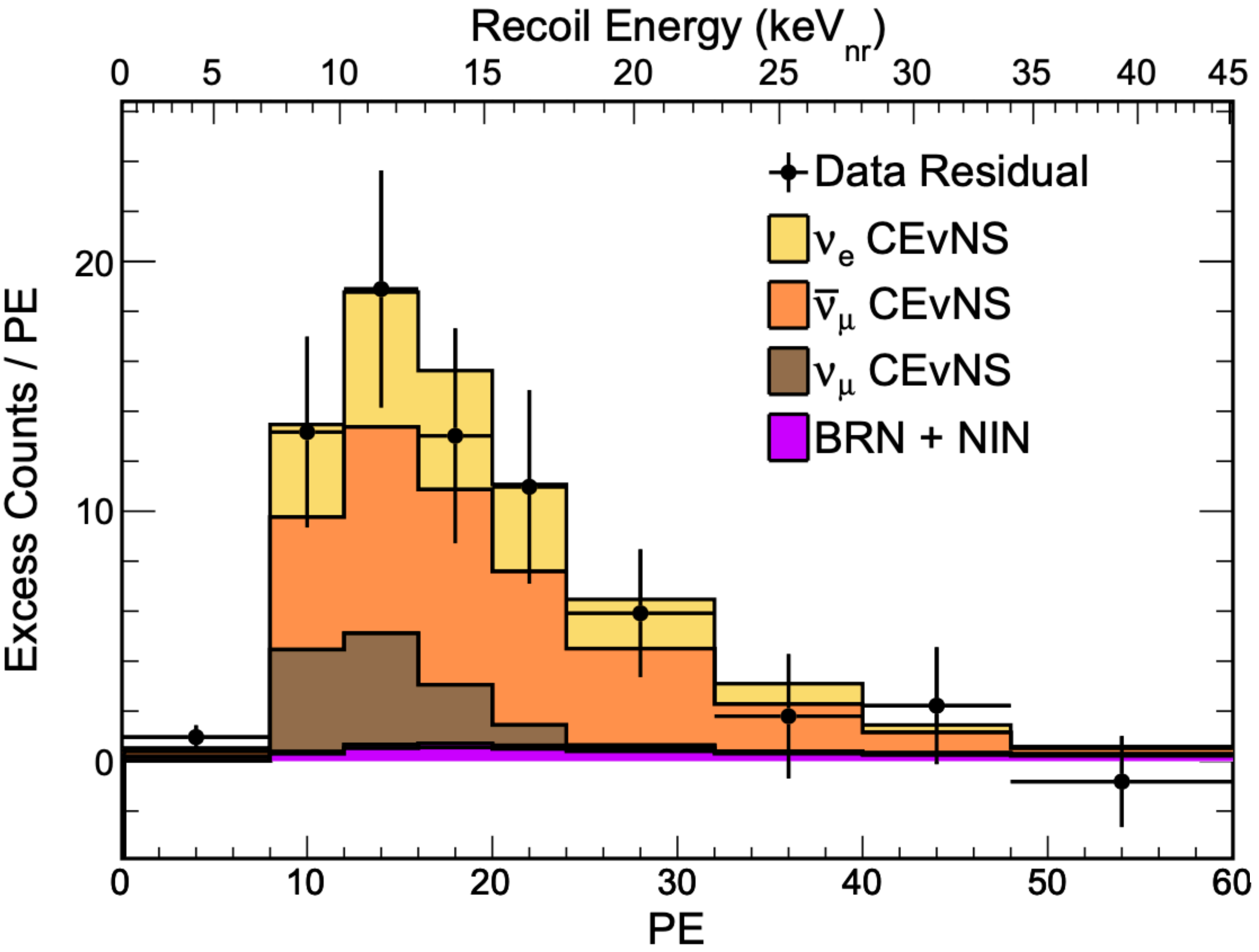
REACTOR EXPERIMENTS ON THE RUN

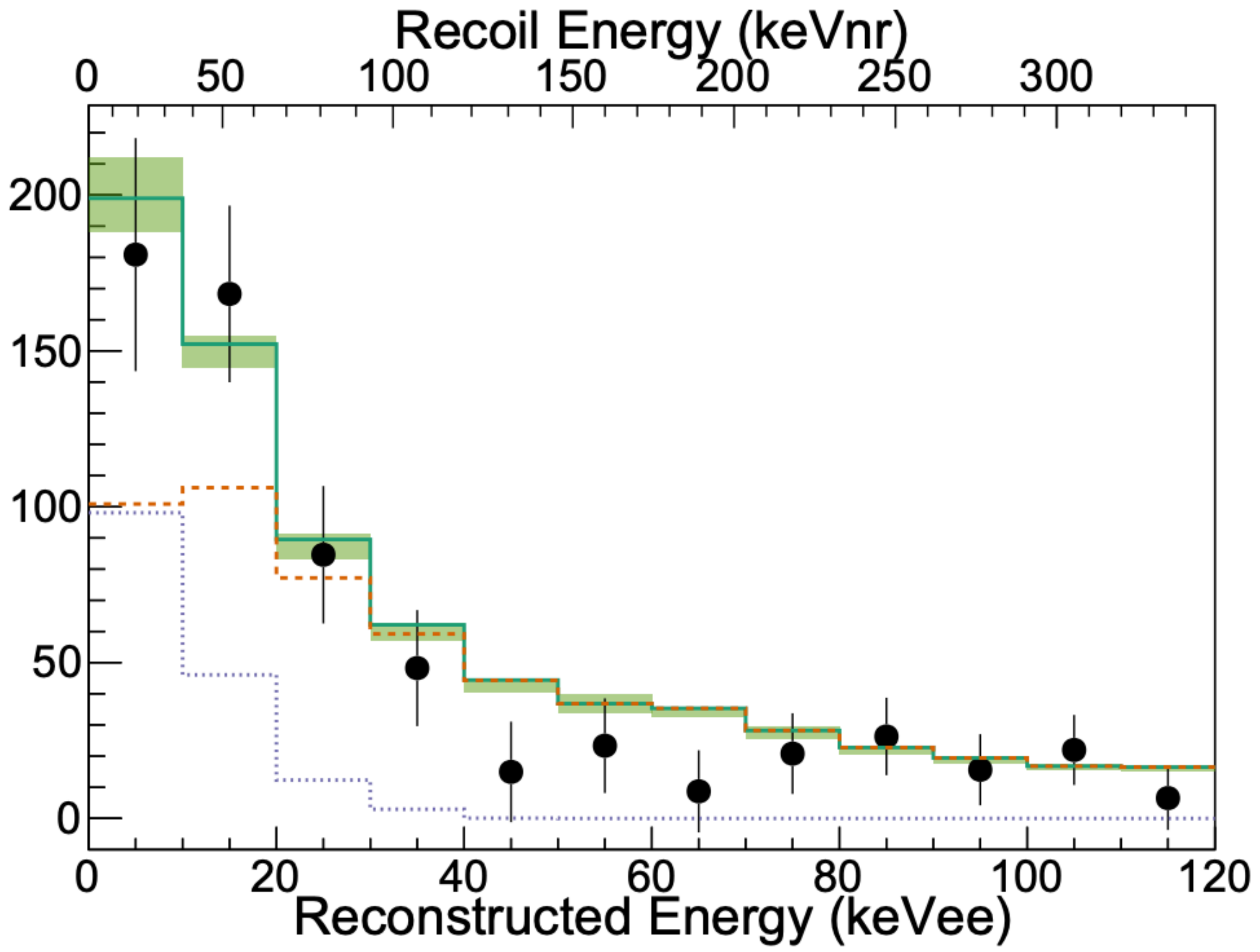
Experiment	Nuclear Reactor	Power [GW]
TEXONO [41]	Kuo-Sheng Nuclear Power Station	2.9
CONUS [37]	Brokdorf	3.9
νGeN [72]	Kalinin Nuclear Power Plant	~ 1
MINER [36]	TRIGA 1	10^{-3}
νCLEUS [38]	FRM2	4
Ricochet [39]	Chooz Nuclear Power Plant	8.54
RED-100 [40]	Kalinin Nuclear Power Plant	~ 1
SBC [73]	ININ (or Laguna Verde)	10^{-3} (2)
CONNIE [74]	Angra 2	3.8
vIOLETA [75]	Atucha II	2
SoLid [76]	BR2	$(0.4, 1) \times 10^{-1}$
NEON [77]	Hanbit Nuclear Power Plant	2.8

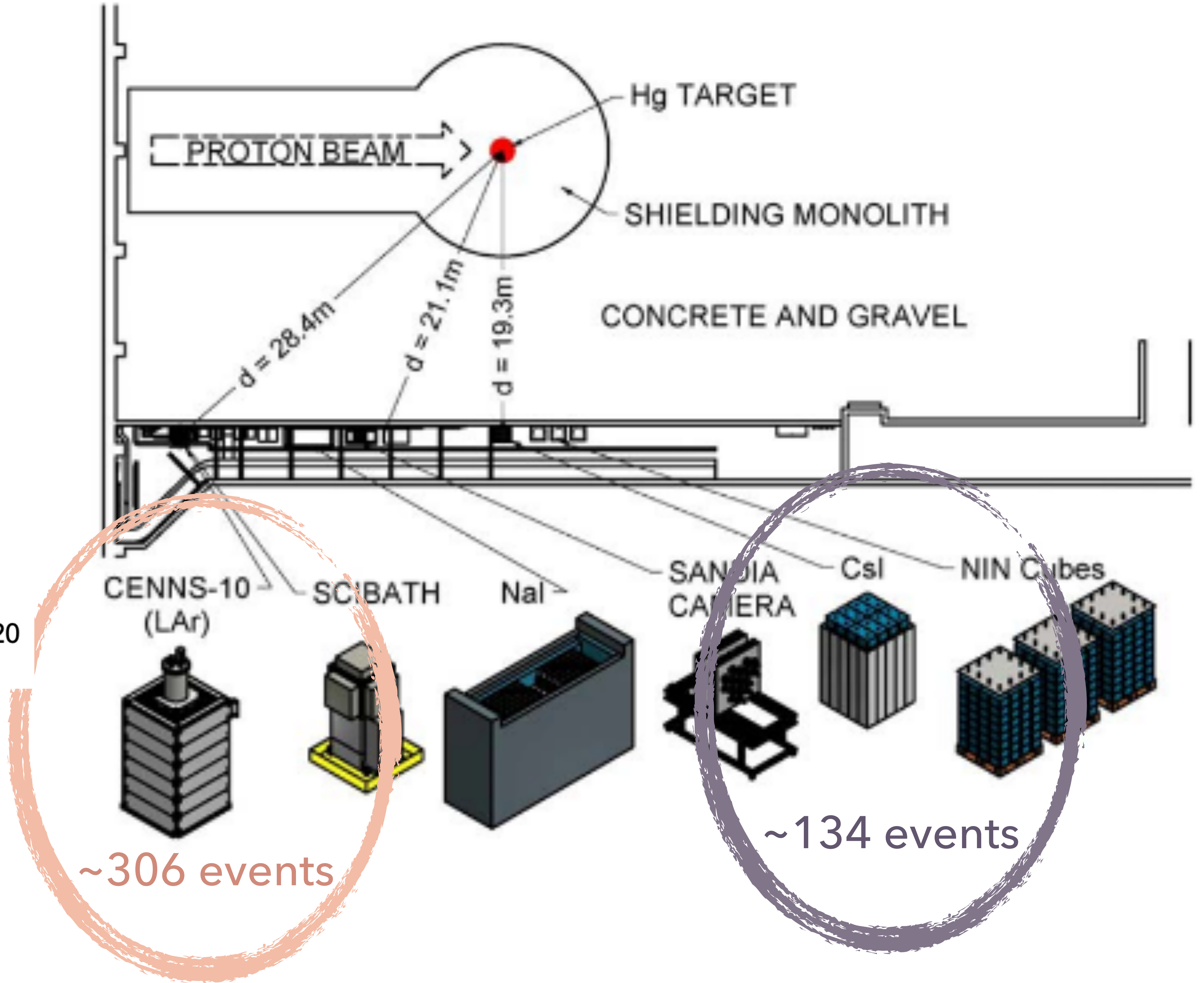
Detector	Experiment	Material	m_{det}[kg]	L [m]
Semiconductor detectors (ionization)	TEXONO [40]	Ge	1.06	28
	CONUS [36]	Ge	1	17.1
	νGeN [70]	Ge	1.6-5	10-12
Low temperature bolometers	MINER [35]	Ge, Si	4	1-2.5
	νCLEUS [37]	$CaWO_4$, Al_2O_3	10^{-2}	15-100
	Ricochet [38]	Ge, Zn	10	355/469
Liquid noble-gas detectors (TPC)	RED-100 [39]	Xe	100	19
	SBC [71]	LAr, Xe	10	3/30
CCD	CONNIE [72]	Si	~ 0.05	30
	vIOLETA [73]	Si	1	12
Scintillators	SoLid [74]	^{6}LiF : ZnS(Ag)	1600	~ 7.6
	NEON [75]	NaI[Tl]	3.3-10	24

Taken from D. Aristizabal-Sierra, V. De Romeri, LJF, D.K. Papoulias, JHEP 03 (2021) 294

MEASUREMENTS FROM STOPPED-PION SOURCE:





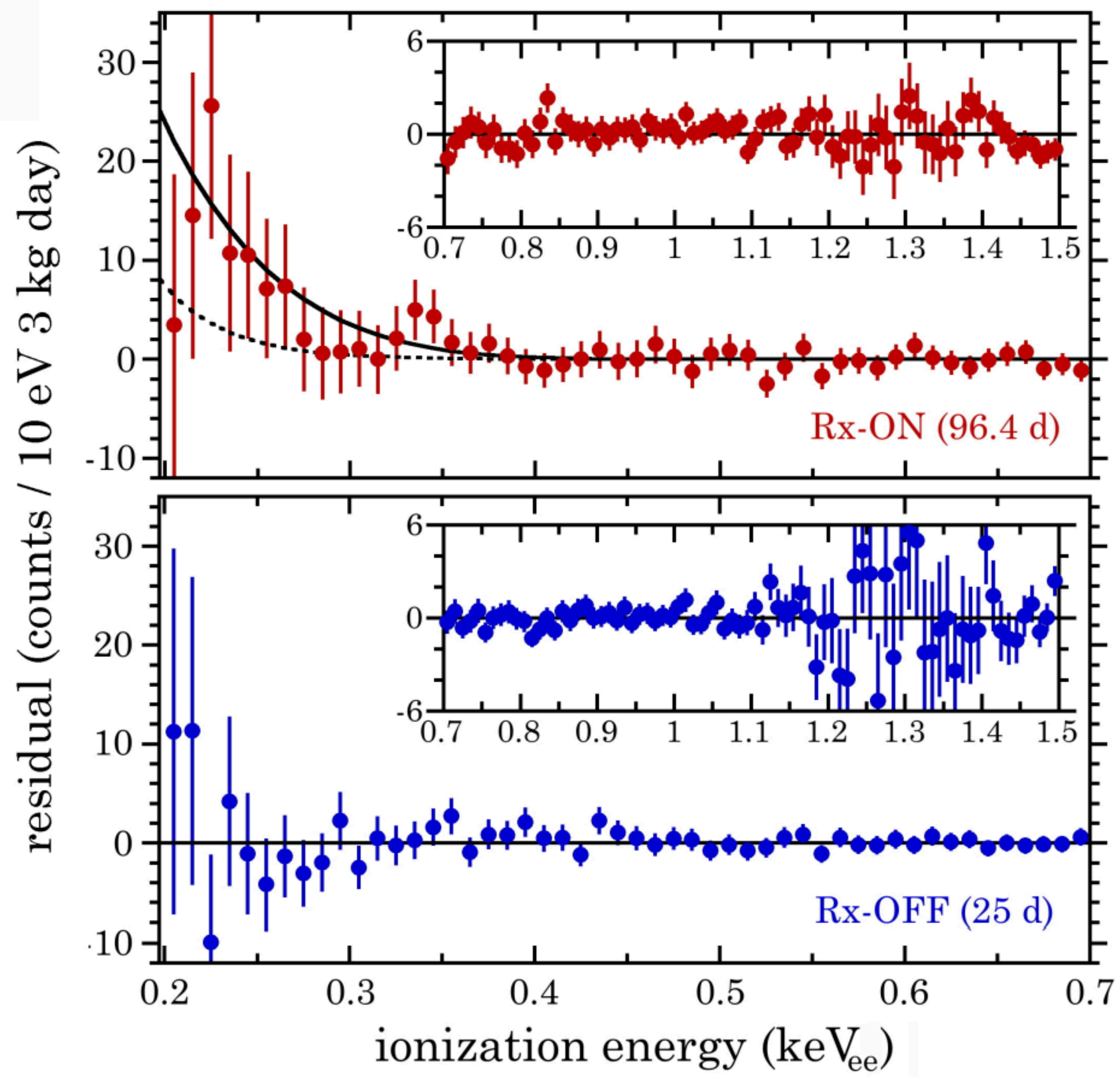


COHERENT Collaboration, Science 357,1123 (2017) & Phys.Rev.Lett. 126 (2021) 1, 012002

COHERENT Collaboration, arXiv:2110.07730

COHERENT Collaboration, Phys.Rev.Lett. 126 (2021) 1, 012002

EVIDENCE FROM NUCLEAR REACTOR: NCC-1701 DETECTOR @ DRESDEN II



The detector

- PPC Ge
- 2.924 kg
- Threshold: 0.2 keVee

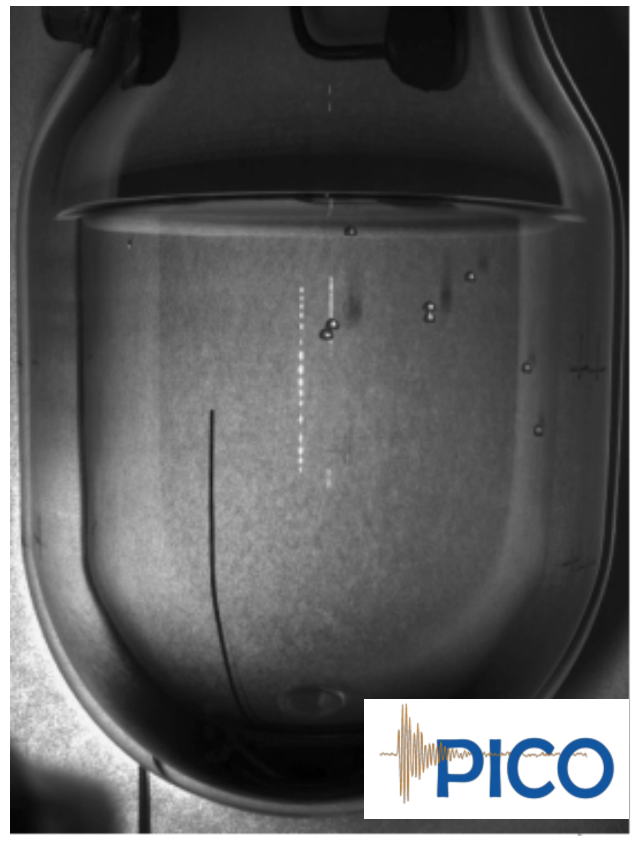
The reactor

- 2.96 GWth
- 10.39 m

NOVEL DETECTOR FROM THE SBC

Combines features of scintillation detectors and bubble chambers

- Insensitive to electron recoils
- Sub-keV thresholds (~100 eV)
- Single bubble created from nuclear recoils
- Energy resolution for backgrounds above ~5 keV



*LJF, E. Peinado, E. Alfonso-Pita, E. Vázquez-Jáuregui, SBC Collaboration (https://journals.aps.org/prd/pdf/10.1103/PhysRevD.103.L091301)

Proposed reactor locations

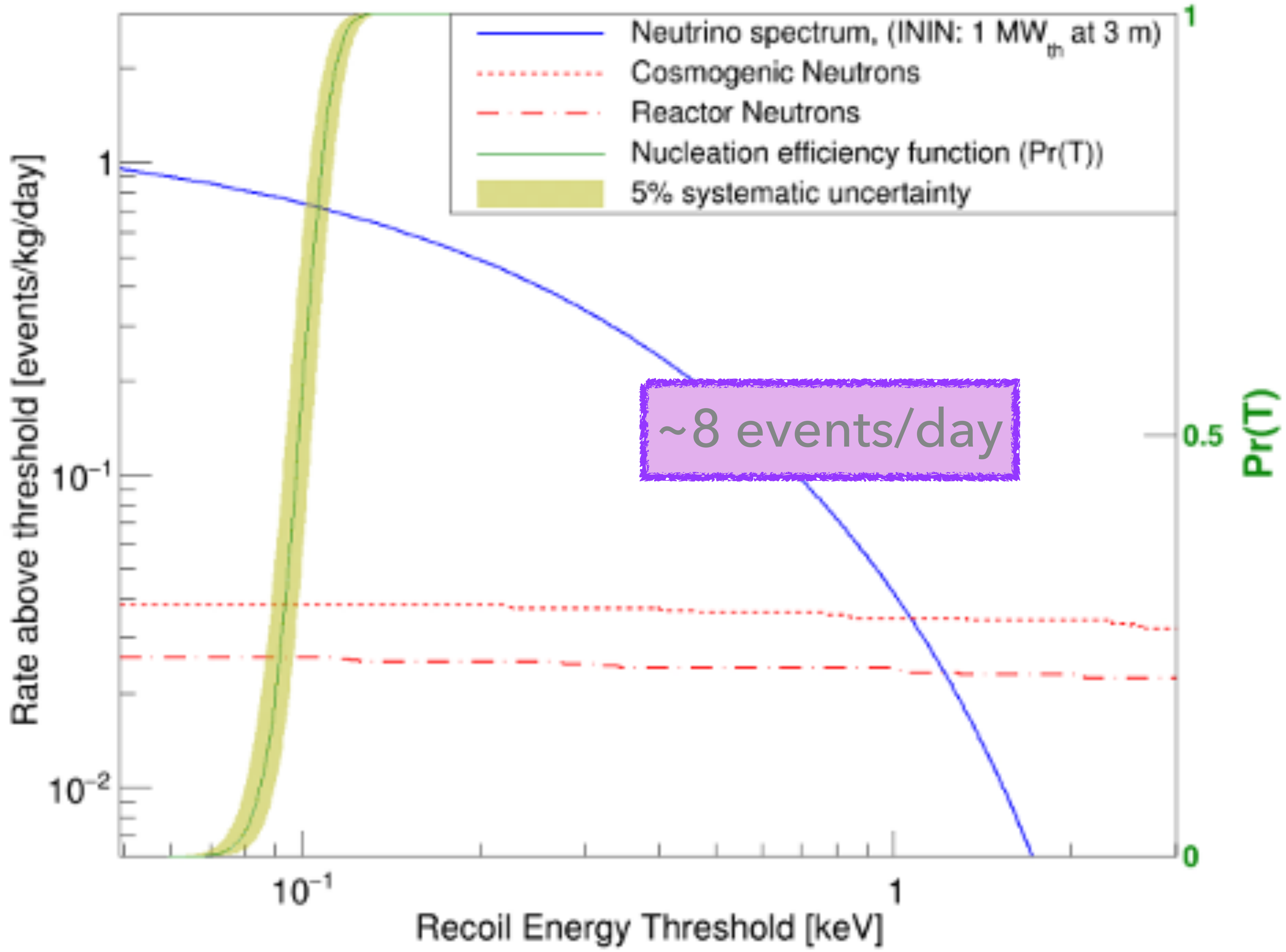
ININ
INSTITUTO NACIONAL DE INVESTIGACIONES NUCLEARES

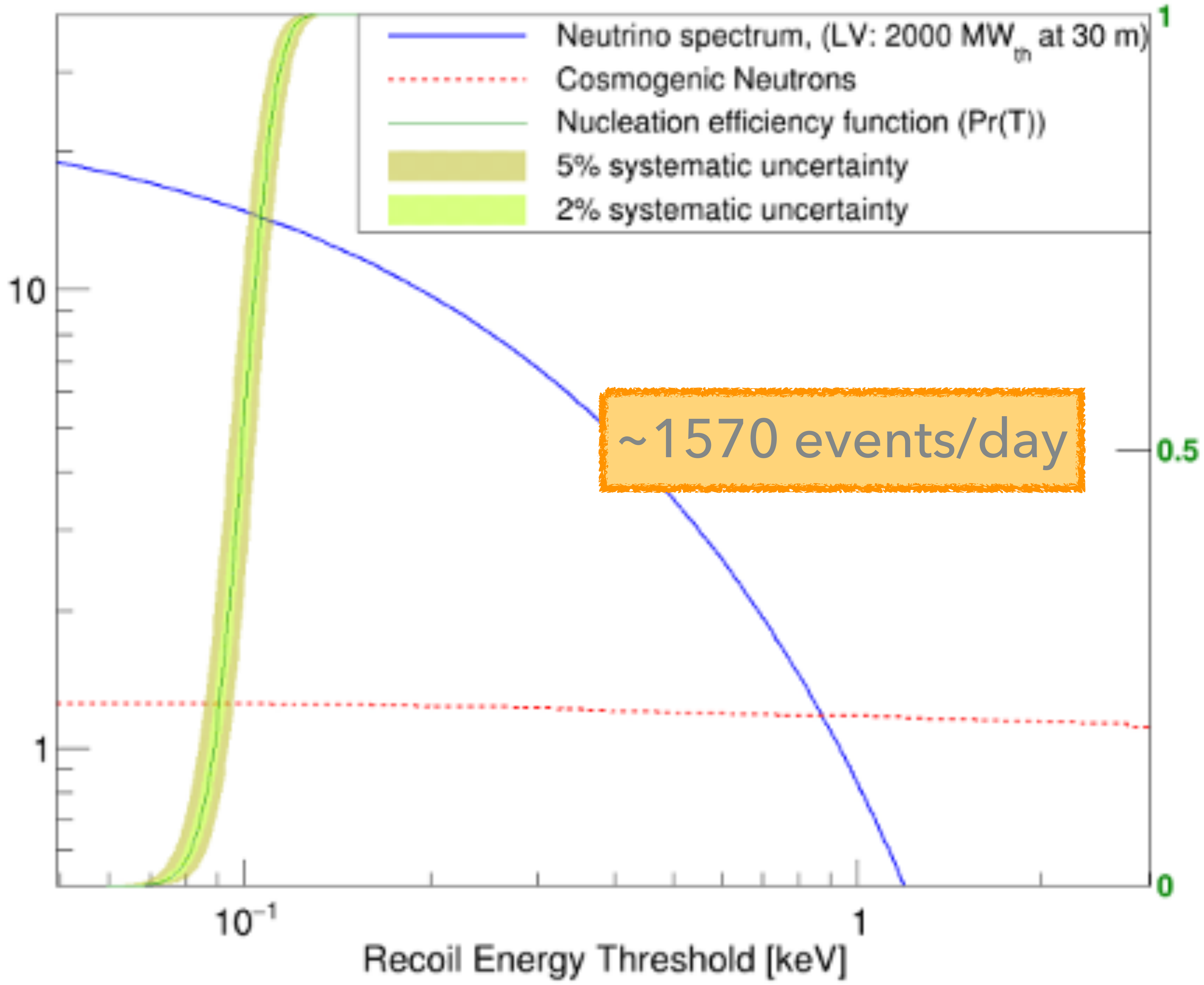
Power	1 MWth
Baseline	3 - 10 m
Target mass	10 kg

Laguna Verde Nuclear Power Plant

Power	2 GWth
Baseline	30 m
Target mass	100 kg

EXPECTED EVENT RATE





STATISTICAL ANALYSIS

$$\chi^2 = \min_{\alpha,\beta,\gamma}\left[\left(\frac{N_{\text{meas}} - (1+\alpha)N_{\text{th}}(X,\gamma) - (1+\beta)B_{\text{reac}}}{\sigma_{\text{stat}}}\right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2\right], \qquad \sigma_{\text{stat}} = \sqrt{N_{\text{meas}} + (1+R)B_{\text{cosm}}}$$

STATISTICAL ANALYSIS

Fitted variable

Nuisance parameters

$$\chi^2 = \min_{\alpha,\beta,\gamma}\left[\left(\frac{N_{\rm meas} - (1+\alpha)N_{\rm th}(X,\gamma) - (1+\beta)B_{\rm reac}}{\sigma_{\rm stat}}\right)^2 + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \left(\frac{\gamma}{\sigma_\gamma}\right)^2\right],$$

$$\sigma_{\rm stat} = \sqrt{N_{\rm meas} + (1+R)B_{\rm cosm}}$$

R = reactor ON/OFF time

α : flux

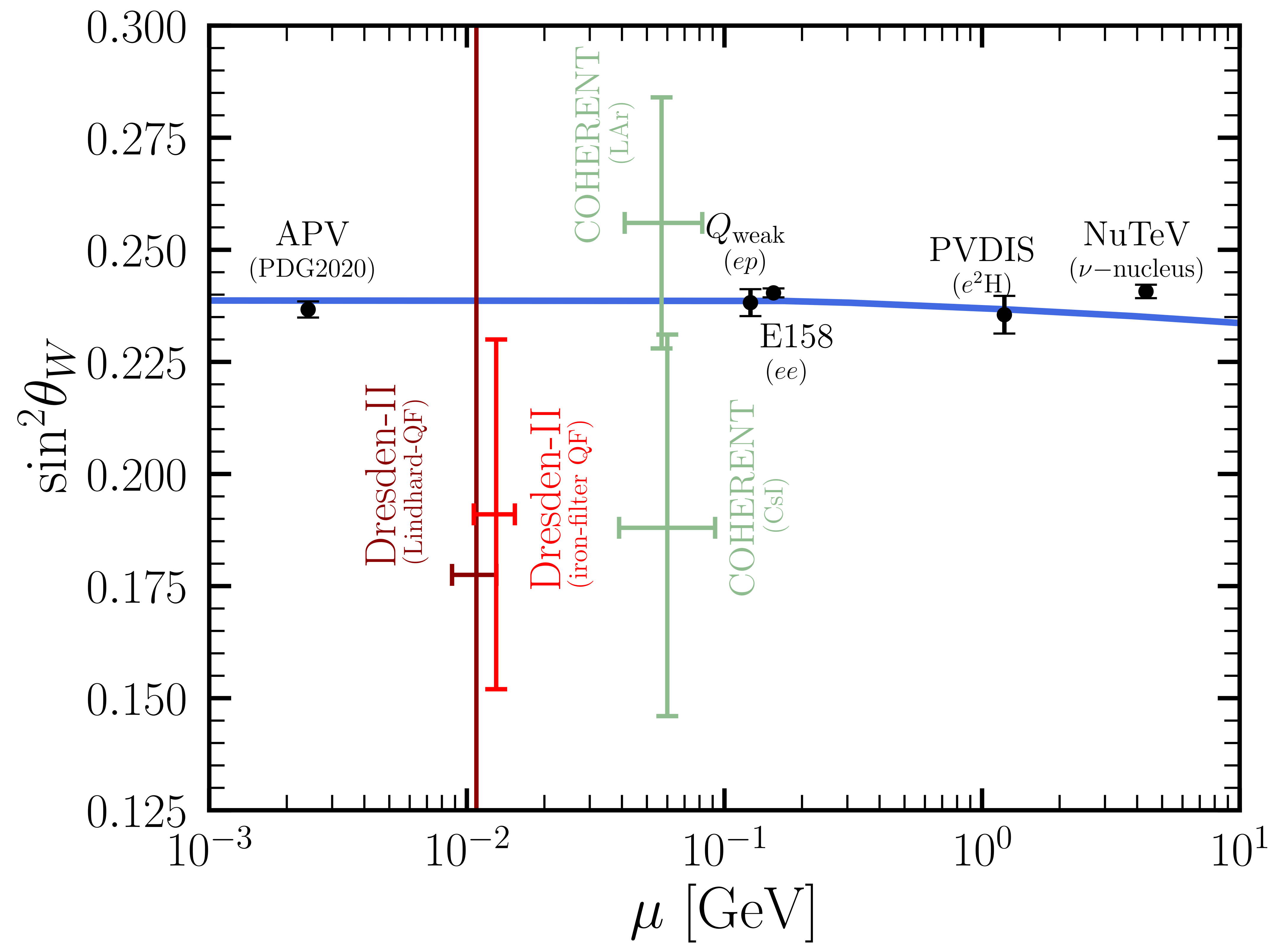
β : background

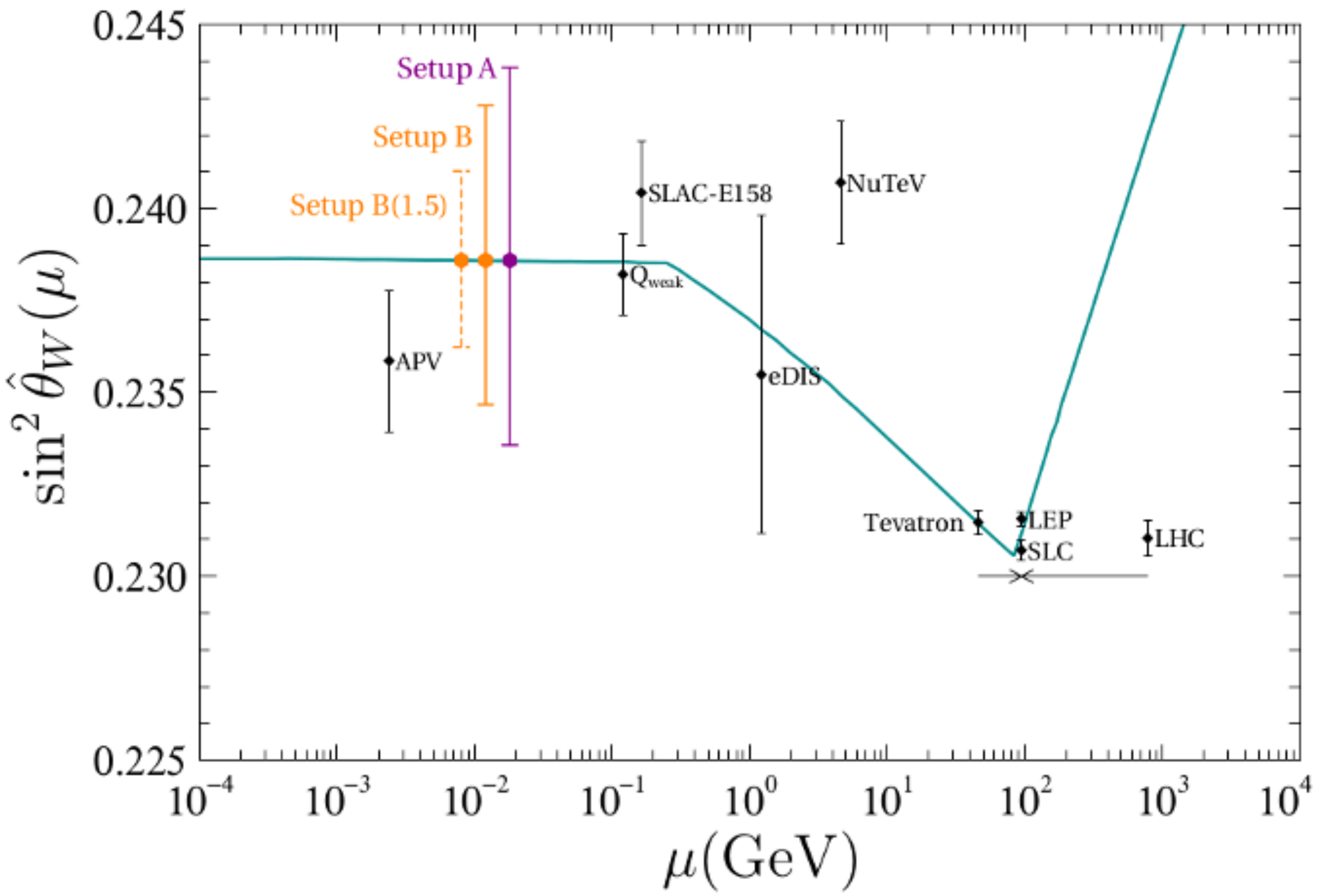
γ : threshold

	Setup	LAr mass (kg)	Power (MW_{th})	Distance (m)	CEνNS events per day	Anti-ν flux uncertainty (%)	Threshold uncertainty (%)	Backgrounds (events/day)						
								Reactor			Cosmogenic		Total	
								Neutrons	(γ,n)	Thomson	Neutrons	(μ,n)		
ININ →	A	10	1	3	8.1	2.4	5	0.003	0.22	0.0002	0.38	0.47	1.07	$R = 3$
Laguna Verde →	B	100	2000	30	1565.2	2.4	5	0	0	0	125	55	180	} $R = 12$
Laguna Verde (best-case scenario) →	B(1.5)	100	2000	30	1565.2	1.5	2	0	0	0	125	55	180	

PHENO FROM CEVNS: WEAK MIXING ANGLE

$$Q_w = Z(1/2 - 2\sin^2\theta_W) + N(-1/2)$$





Private communication with Aristizabal, De Romeri, Papoulias, 2203.02414

LJF, E. Peinado, E. Alfonso-Pita, E. Vázquez-Jáuregui, SBC Collaboration(2021)

PHENO FROM CEVNS: NSI

Barranco,Miranda, Moura, Valle, PRD 73 (2006)

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f=u,d} \sum_{\alpha,\beta=e,\mu,\tau} \epsilon^{fP}_{\alpha\beta}[\bar{\nu}_\alpha \gamma_\rho L \nu_\beta][\bar{f}\gamma^\rho P f]$$

Flavor conserving: $\epsilon_{\alpha\alpha}$

Flavor changing: $\epsilon_{\alpha\beta}$

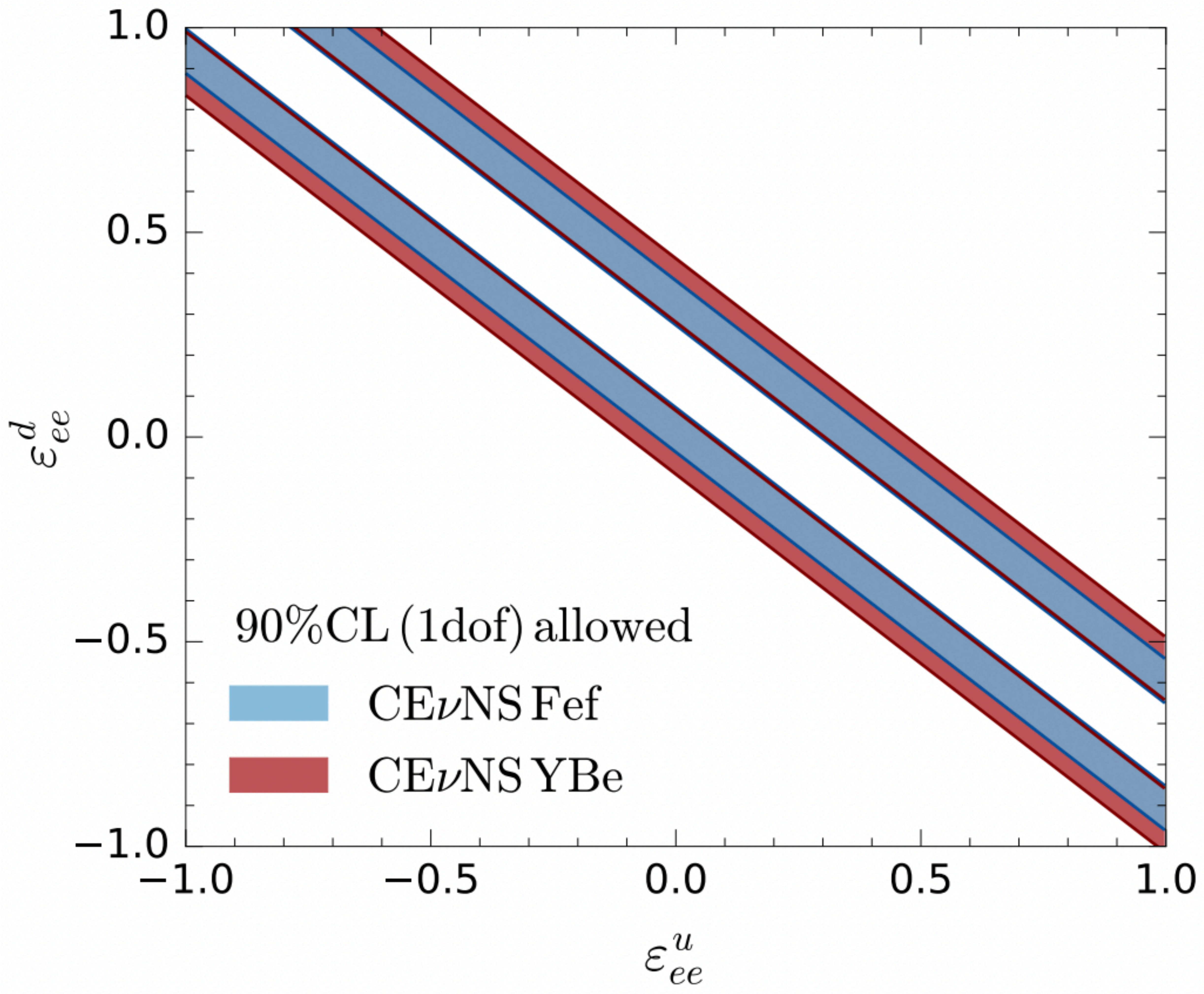
Vector: $\epsilon^{fV}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$

Axial-vector: $\epsilon^{fA}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} - \epsilon^{fR}_{\alpha\beta}$

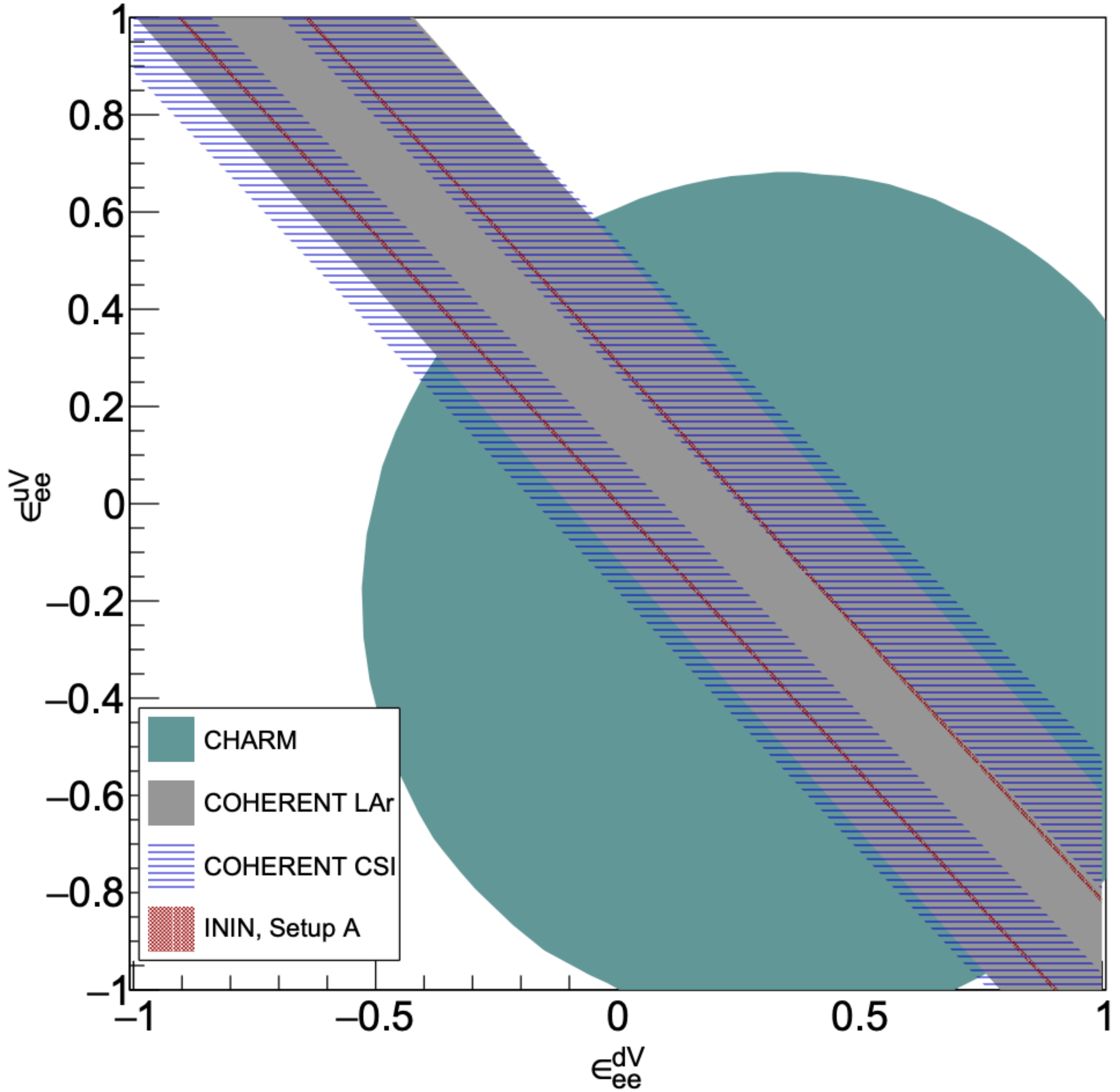
NSI in CEvNS

$$Q^2_{w\,\alpha} = \left[Z(g^V_p + 2\epsilon^{uV}_{\alpha\alpha} + \epsilon^{dV}_{\alpha\alpha})F_Z(q^2) + N(g^V_n + \epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha})F_N(q^2)\right]^2$$

PHENO FROM CEVNS: NSI



P. Coloma et al, *JHEP* 05 (2022) 037



E. Alfonso-Pita, LJF, E. Peinado, E. Vázquez-Jáuregui, 2203.05982

PHENO FROM CEVNS: GNI

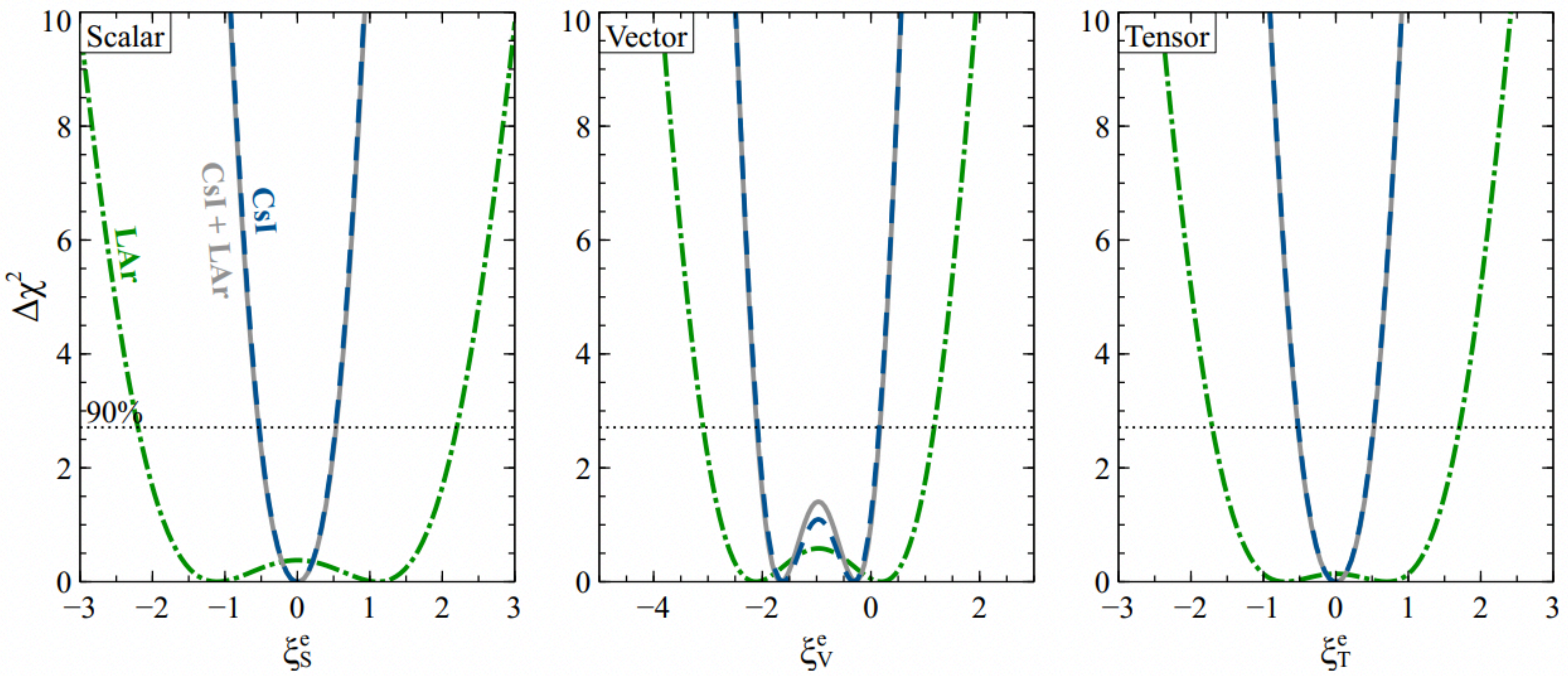
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a \nu \left[\overline{q}\Gamma^a (C_a^{(q)} + \overline{D}_a^{(q)} i\gamma^5) q\right] \qquad \Gamma^a = \{I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$

For CEvNS

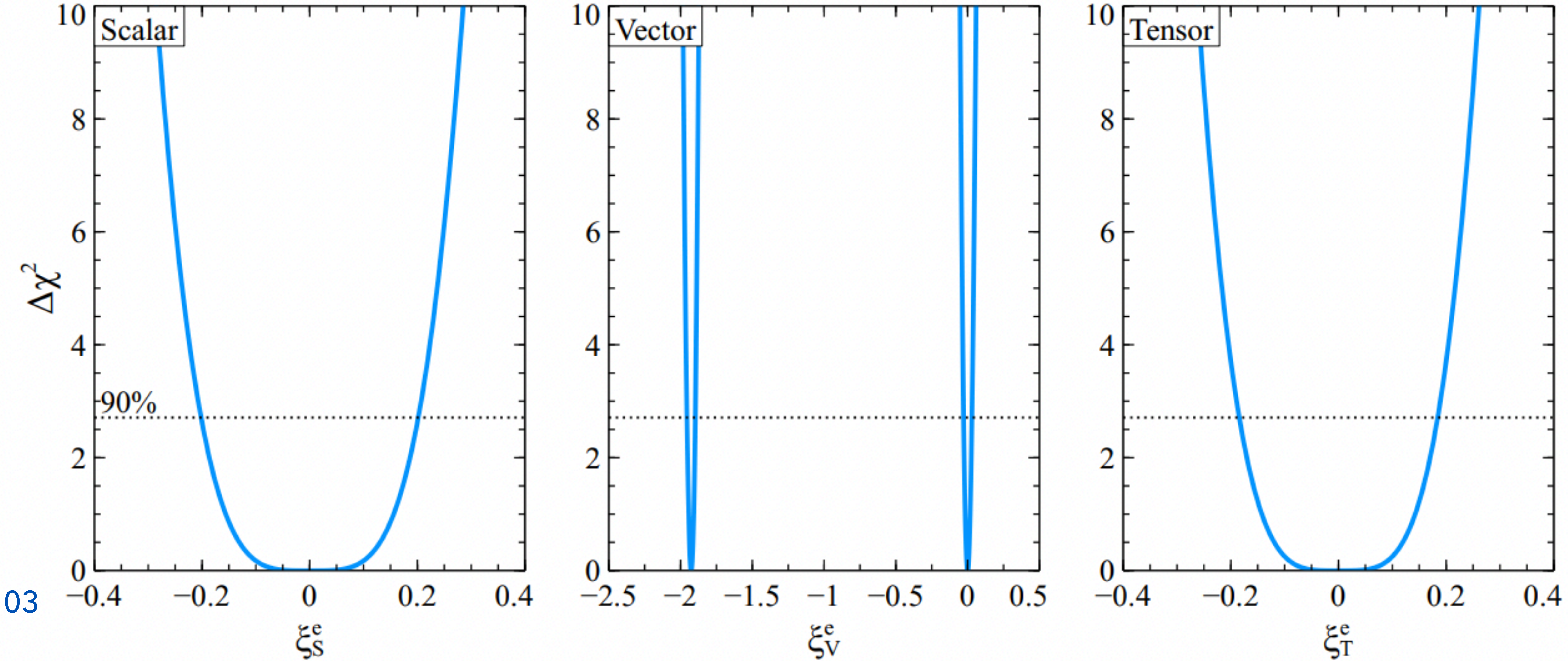
$$\left(\frac{d\sigma}{dE_r}\right)^f = \frac{G_F^2}{4\pi} M_N N^2 F^2(Q^2) \times \left[\xi_S^{f\,2} \frac{E_r}{E_r^{\max}} + (\xi_V^f + A_{\rm SM})^2 \left(1 - \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right) \pm 2\xi_V^f \xi_A^f \frac{E_r}{E_\nu} + \xi_A^{f\,2}\left(1 + \frac{E_r}{E_r^{\max}} - \frac{E_r}{E_\nu}\right)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

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

PHENO FROM CEVNS: GNI



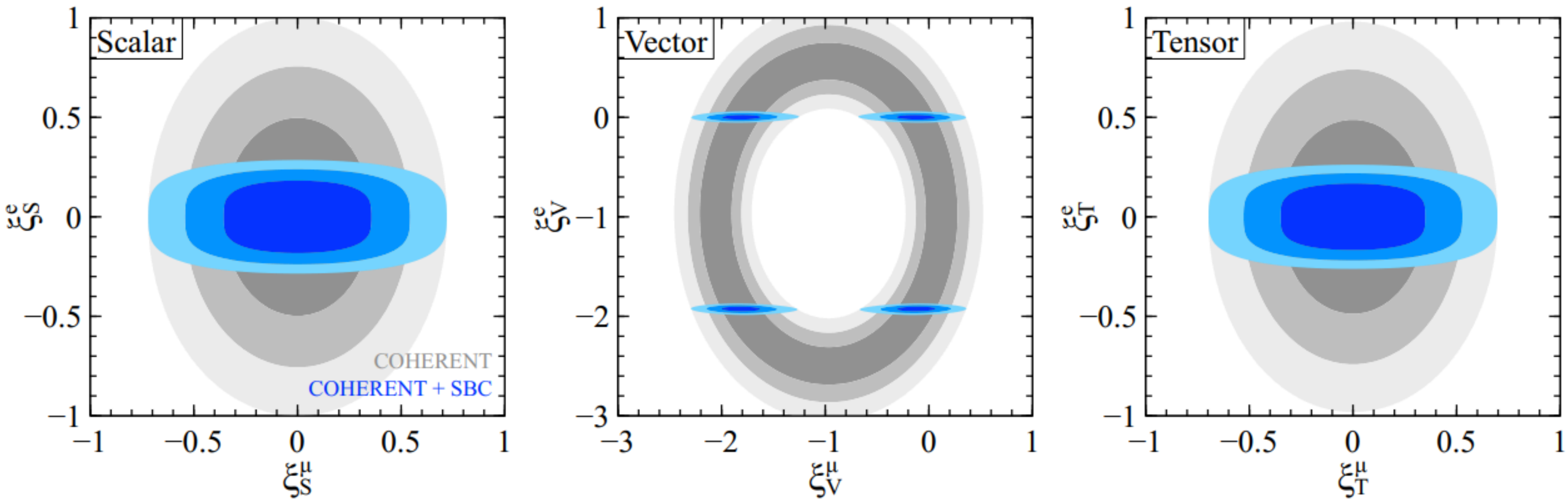
Projection



LJF, N. Nath, E. Peinado, *Phys.Rev.D* 105 (2022) 5, 5 2112.05103

PHENO FROM CEVNS: GNI

Combined 2 dof análisis

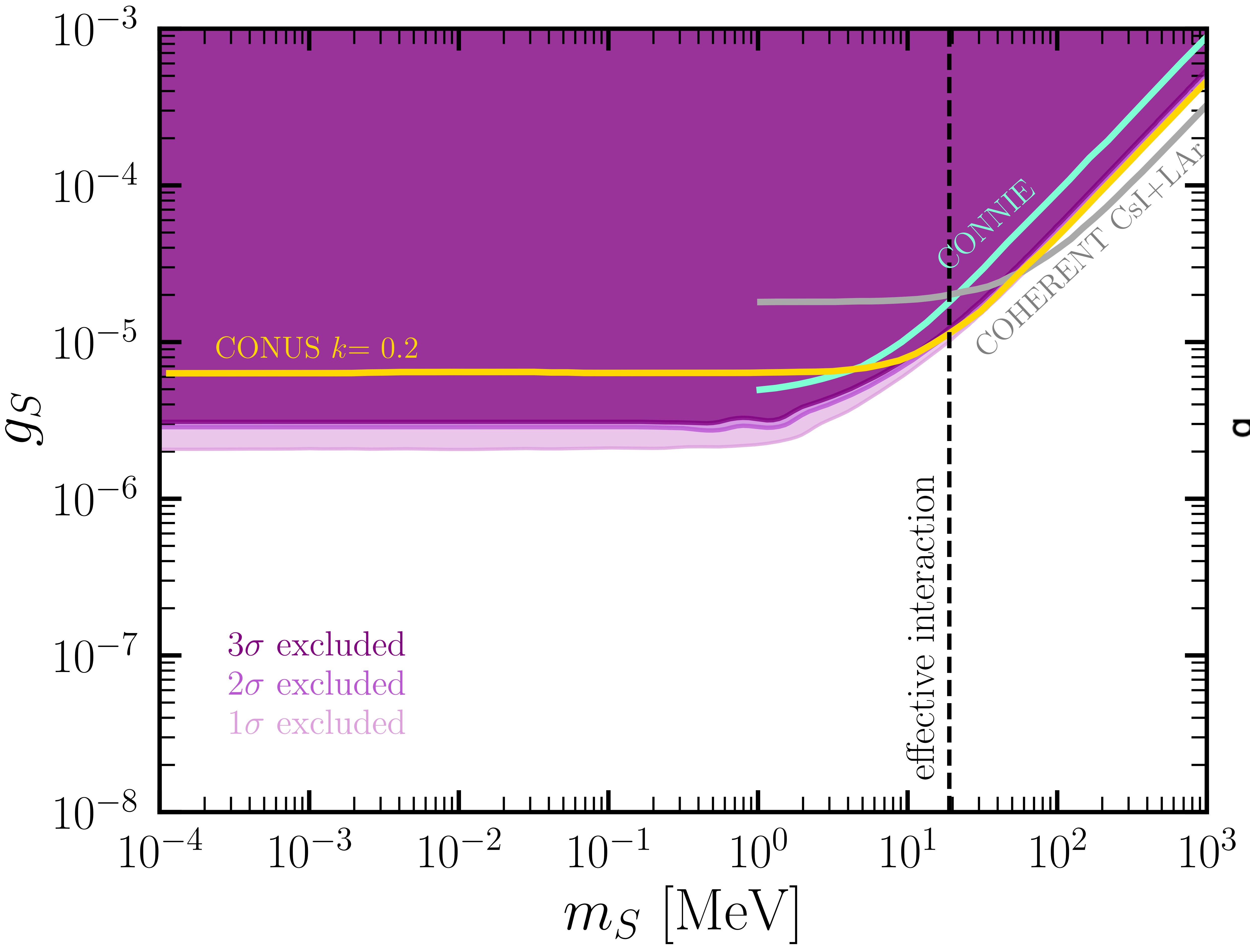


*Time resolution not considered

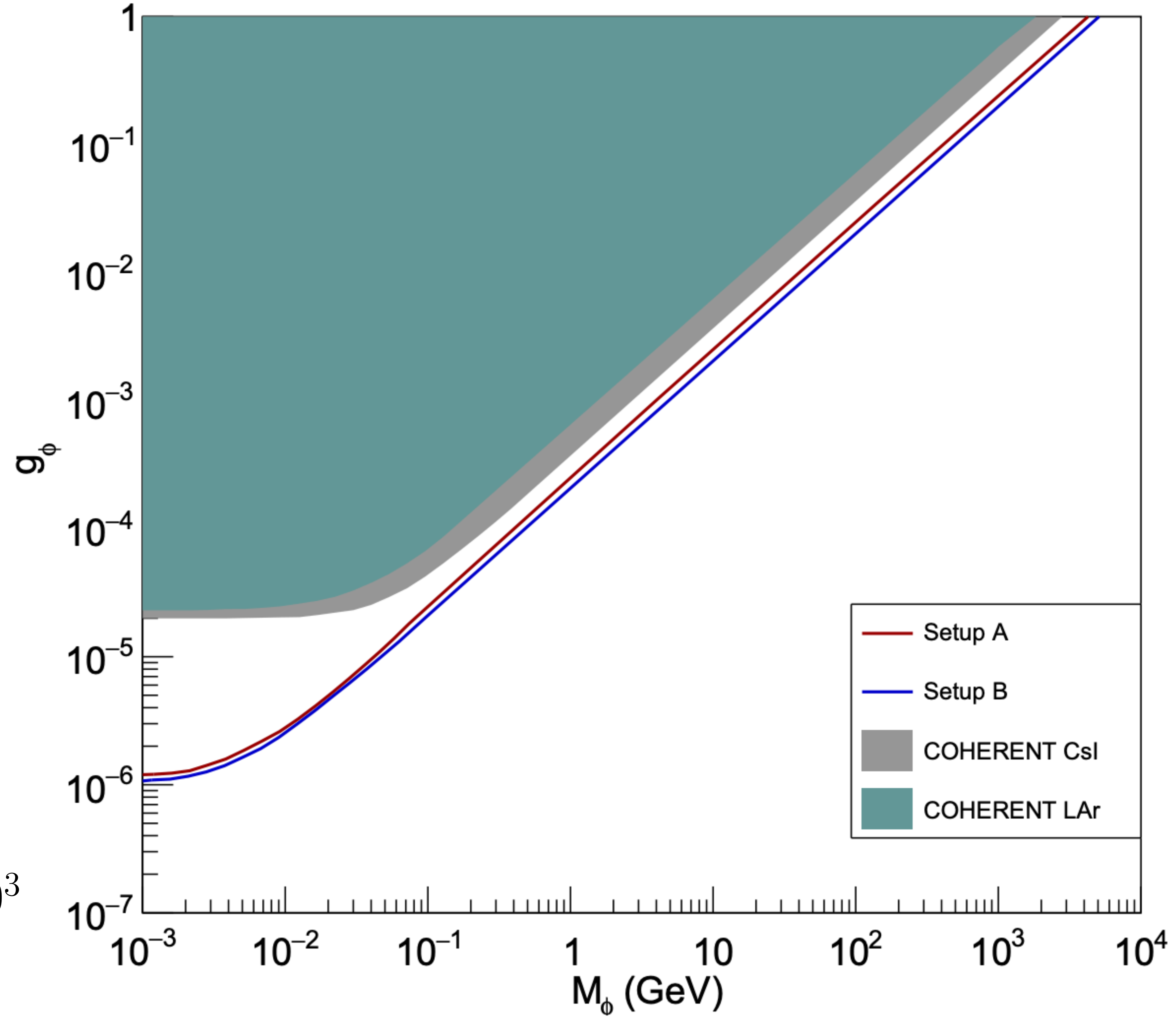
LJF, N. Nath, E. Peinado, *Phys.Rev.D* 105 (2022) 5, 5 2112.05103

PHENO FROM CEVNS: LIGHT SCALAR MEDIATORS

$$\frac{d\sigma}{dT} = \frac{M_N^2}{4\pi} \frac{g_\phi^4 Q_\phi^2 T}{E_\nu^2 (2M_N T + M_\phi^2)^2}$$



Private communication with D. Aristizabal, V. De Romeri, D. Papoulias, 2203.02414



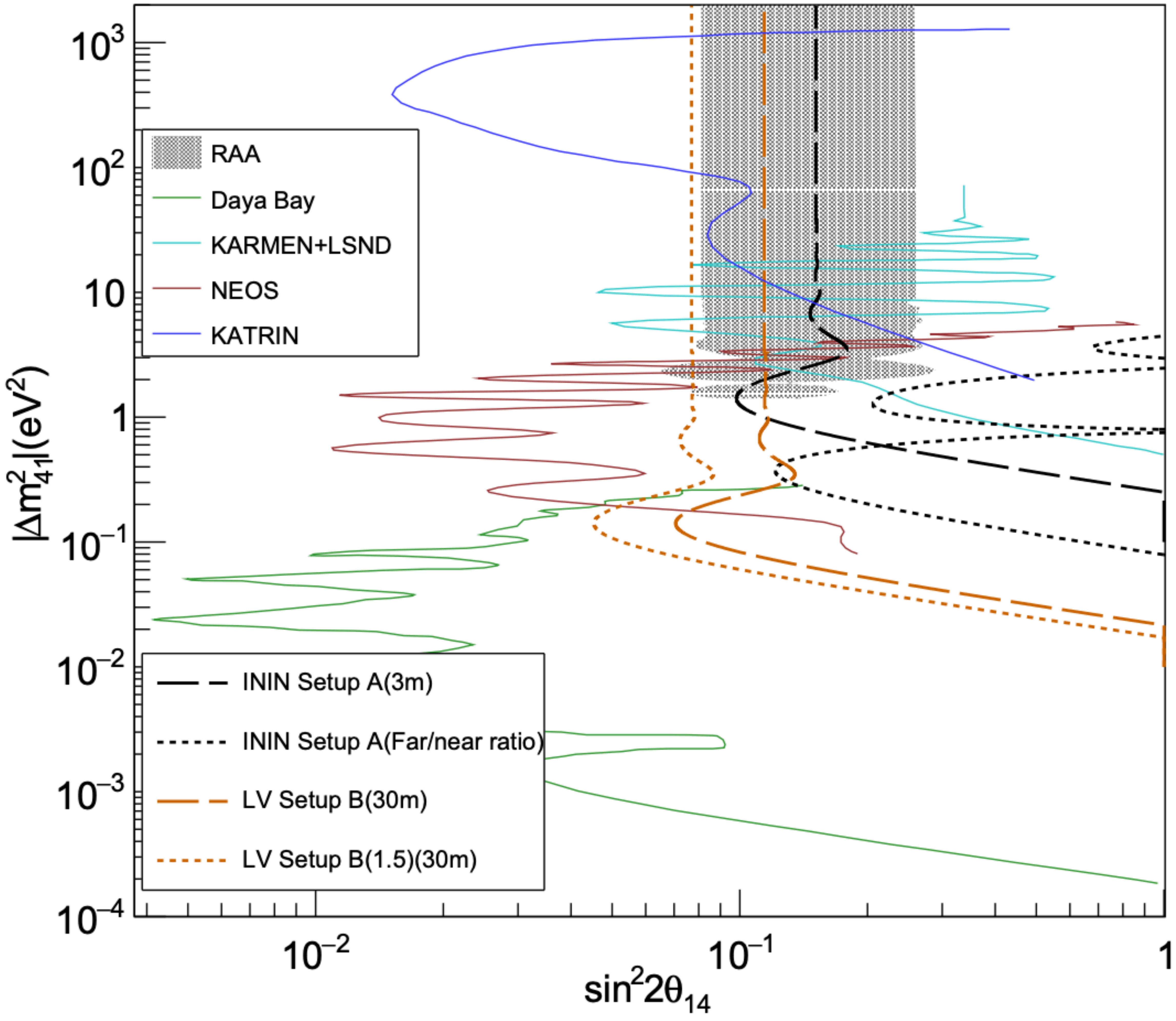
E. Alfonso-Pita, LJF, E. Peinado, E. Vázquez-Jáuregui, 2203.05982

PHENO FROM CEVNS: STERILE NEUTRINOS

For light sterile neutrinos in a 3+1 scheme

$$P_{ee}(E_\nu) \simeq 1 - \sin^2 2\theta_{14} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

$$P_{\mu\mu}(E_\nu) \simeq 1 - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m^2_{42} L}{4E_\nu}\right)$$



E. Alfonso-Pita, LJF, E. Peinado, E. Vázquez-Jáuregui, 2203.05982

PHENO FROM CEVNS: UNITARITY VIOLATION

Mixing matrix

$$N = N^{UV} \cdot U^{PMNS}$$

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

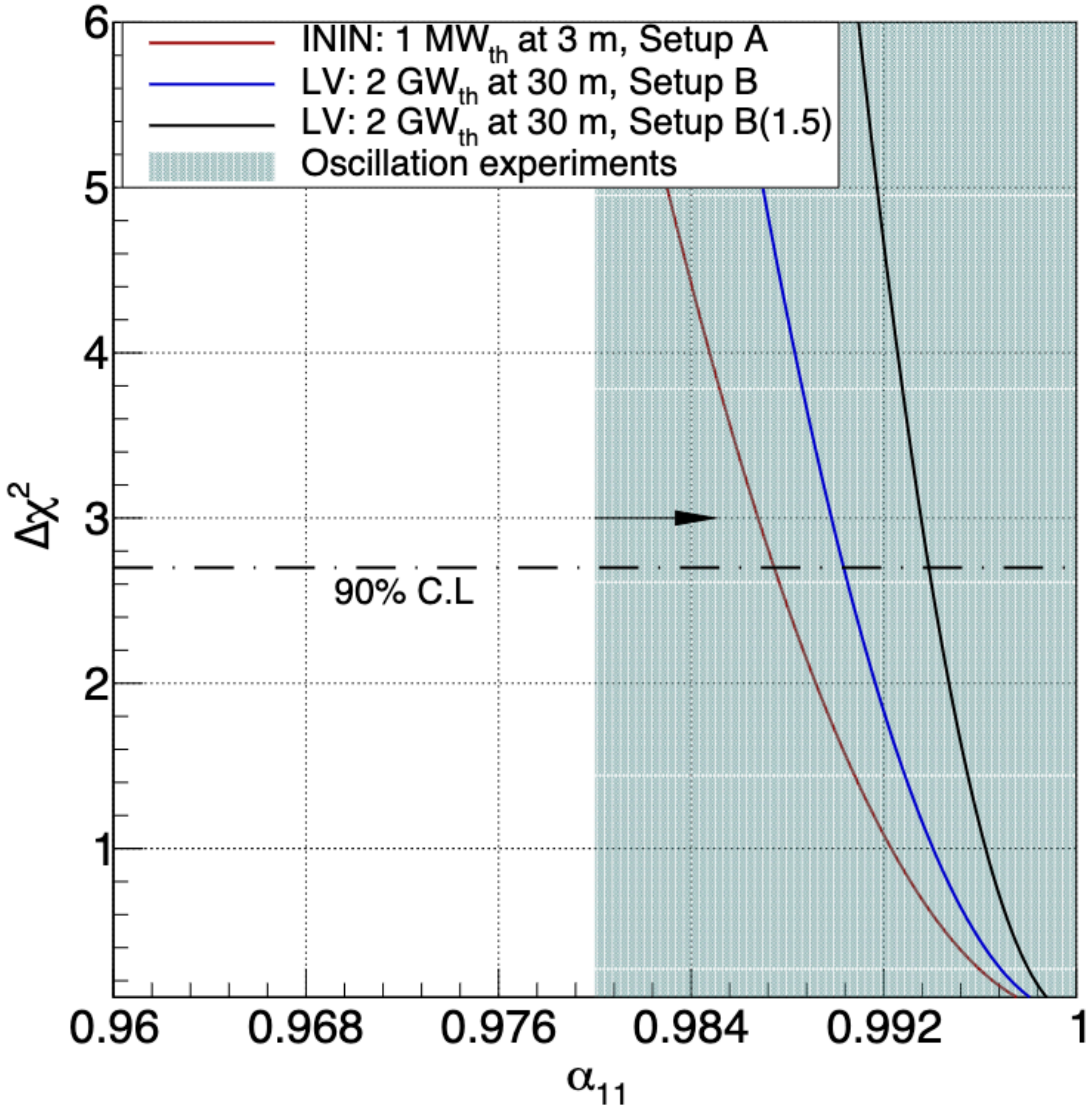
Oscillation probabilities (zero distance)

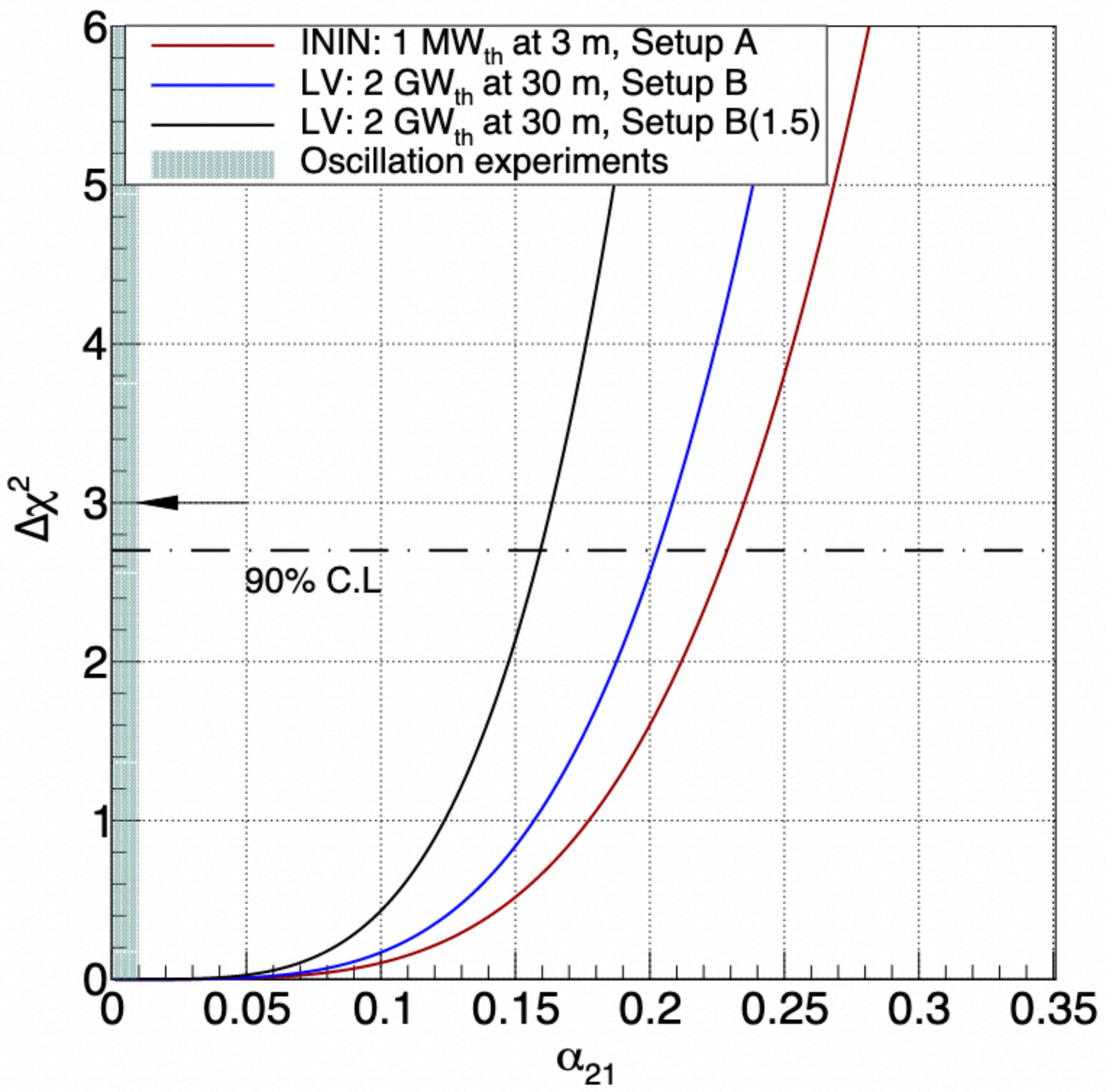
$$P_{ee} = \alpha_{11}^4,$$

$$P_{e\mu} = \alpha_{11}^2 |\alpha_{21}|^2,$$

$$P_{e\tau} = \alpha_{11}^2 |\alpha_{31}|^2.$$

Escrihuela, Forero, Miranda, Tortola, Valle, Phys.Rev.D 92 (2015)





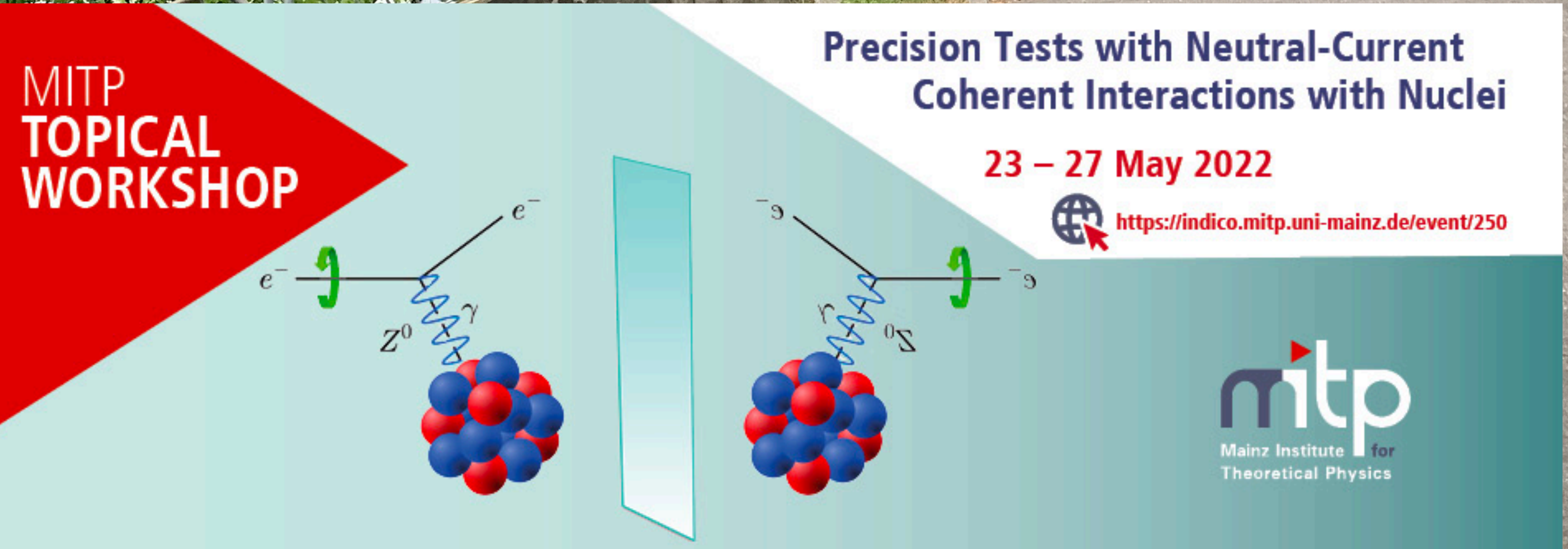
E. Alfonso-Pita, LJF, E. Peinado, E. Vázquez-Jáuregui, 2203.05982

FINAL REMARKS

Reactor facilities offer a great chance of measuring CEvNS

LAr Scintillating Bubble Chambers:

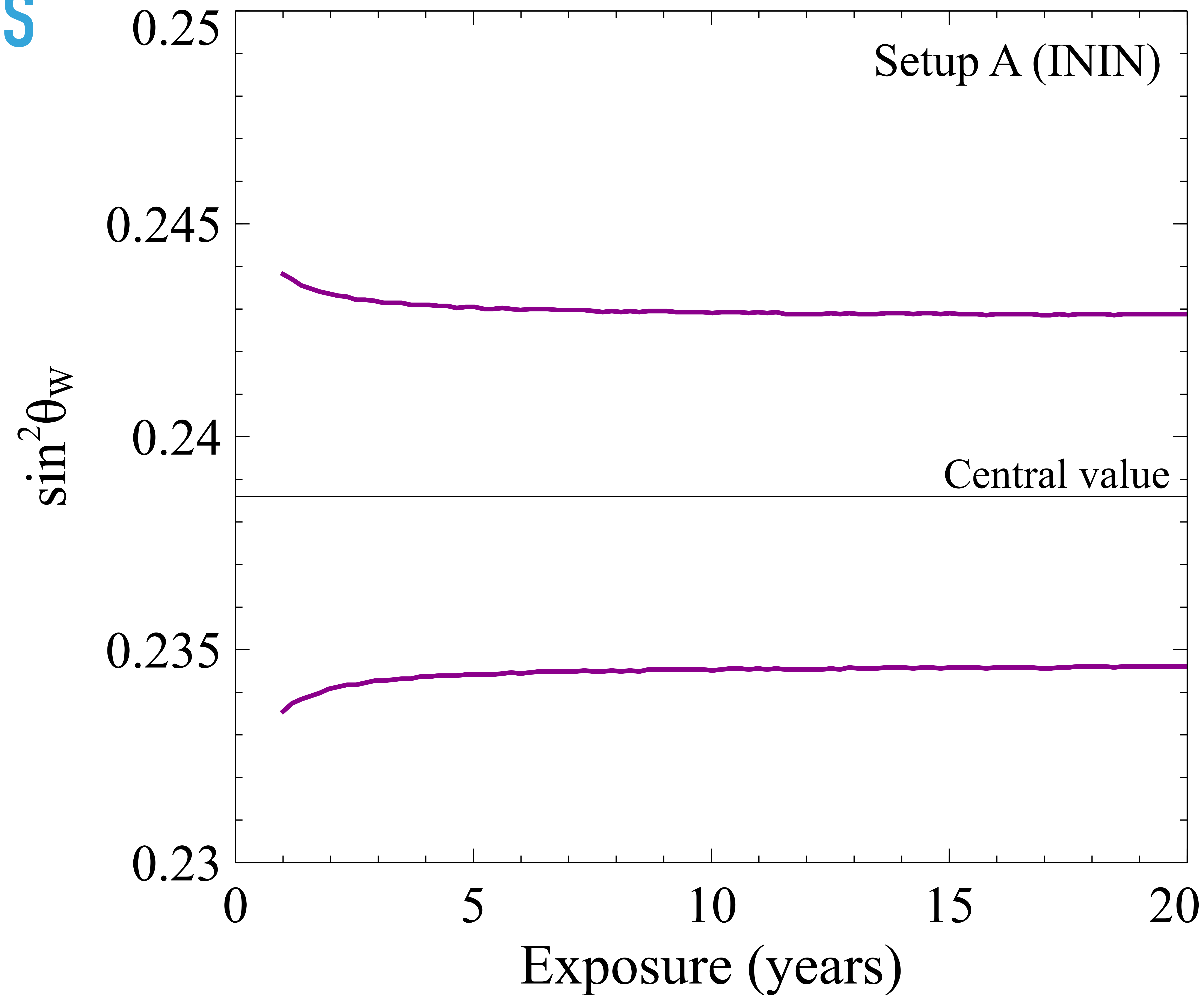
- Realistic chance of detecting CEvNS given their *great background control* and *low threshold*
- Precise measurement of the weak mixing angle
- Competitive limits to new physics signals, compared with other CEvNS experiments

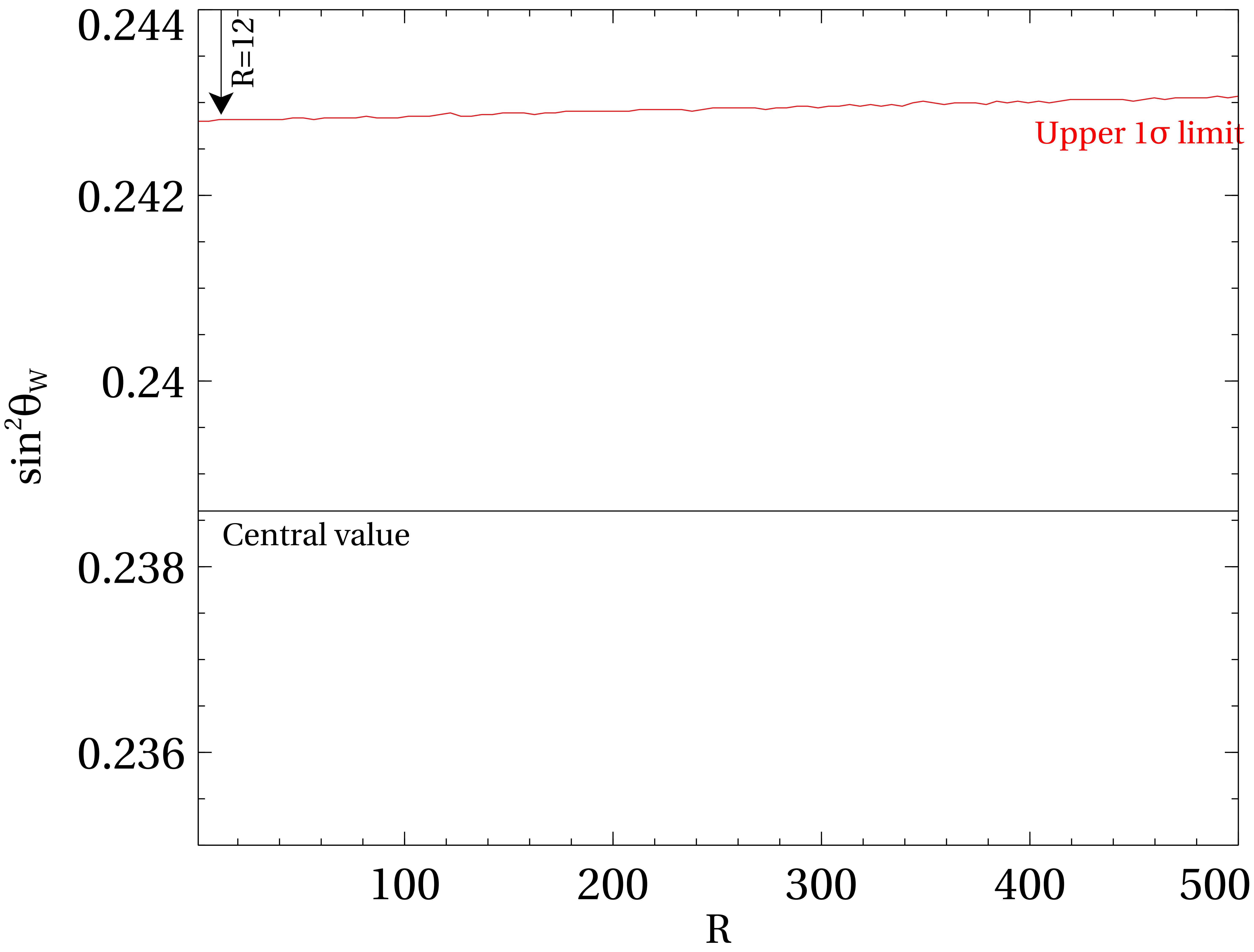


THANK YOU FOR YOUR ATTENTION

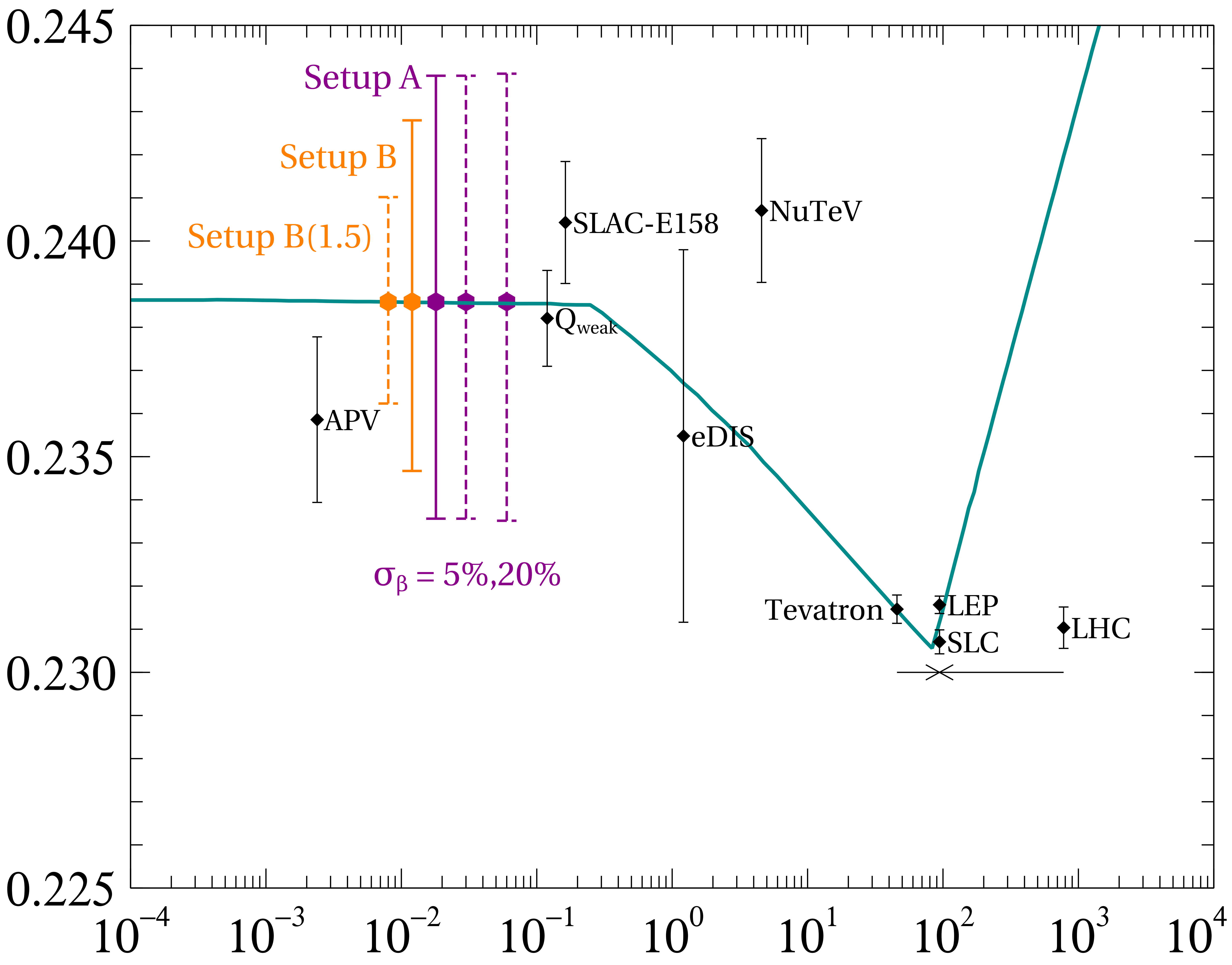
BACKUP SLIDES

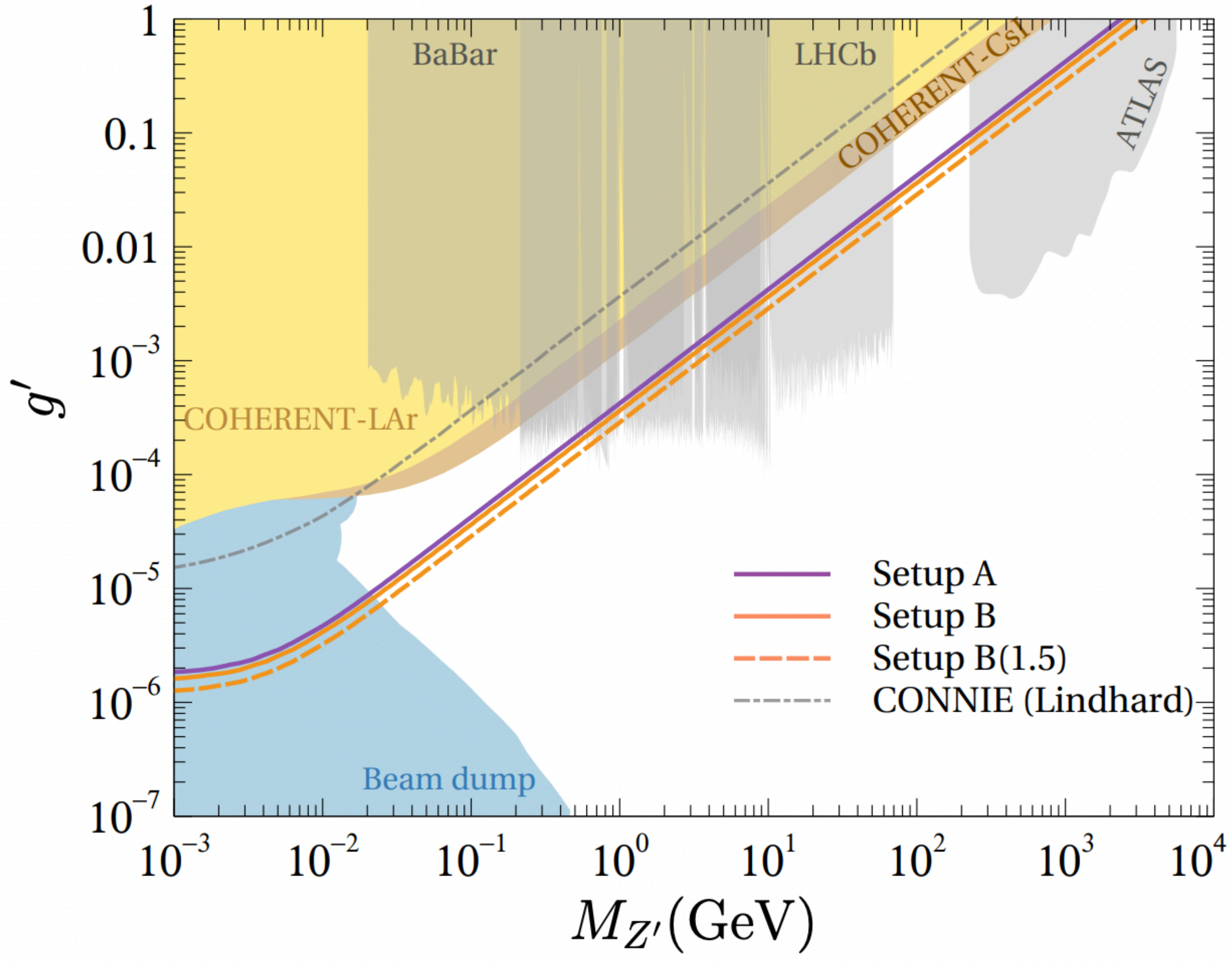
CONSTRAINED BY SYSTEMATICS

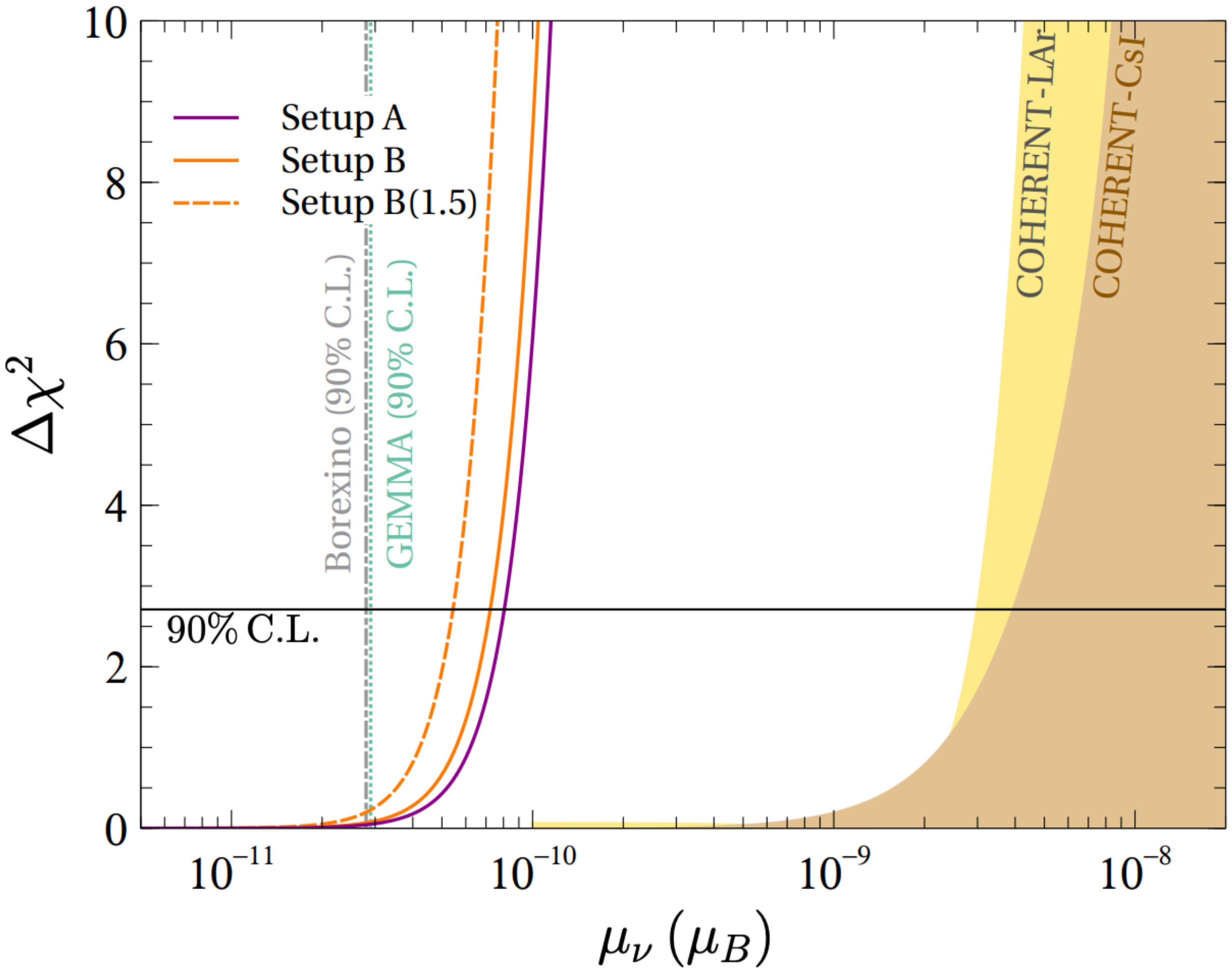



0.244
0.242
0.24
0.238
0.236
$\sin^2\theta_W$
R=12
Upper 1σ limit
Central value
100
200
300
400
500
R

LV or Setup B


0.245
0.240
0.235
0.230
0.225
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Setup A
Setup B
Setup B(1.5)
σ_β = 5%,20%
SLAC-E158
NuTeV
Q_{weak}
APV
eDIS
Tevatron
LEP
SLC
LHC

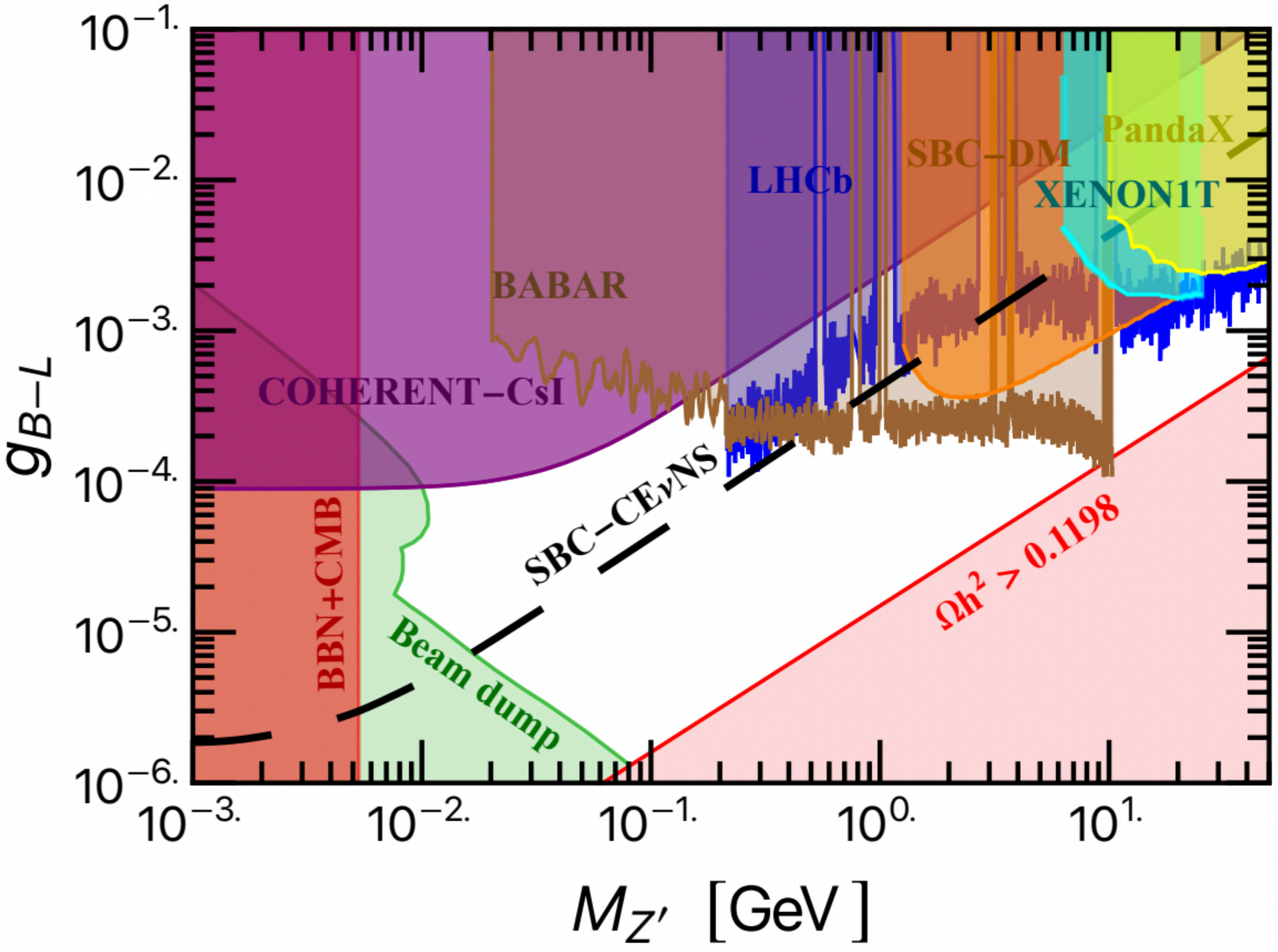

BaBar
LHCb
COHERENT-CsI
ATLAS
COHERENT-LAr
Beam dump
Setup A
Setup B
Setup B(1.5)
CONNIE (Lindhard)
g′
$M_{Z'}$(GeV)

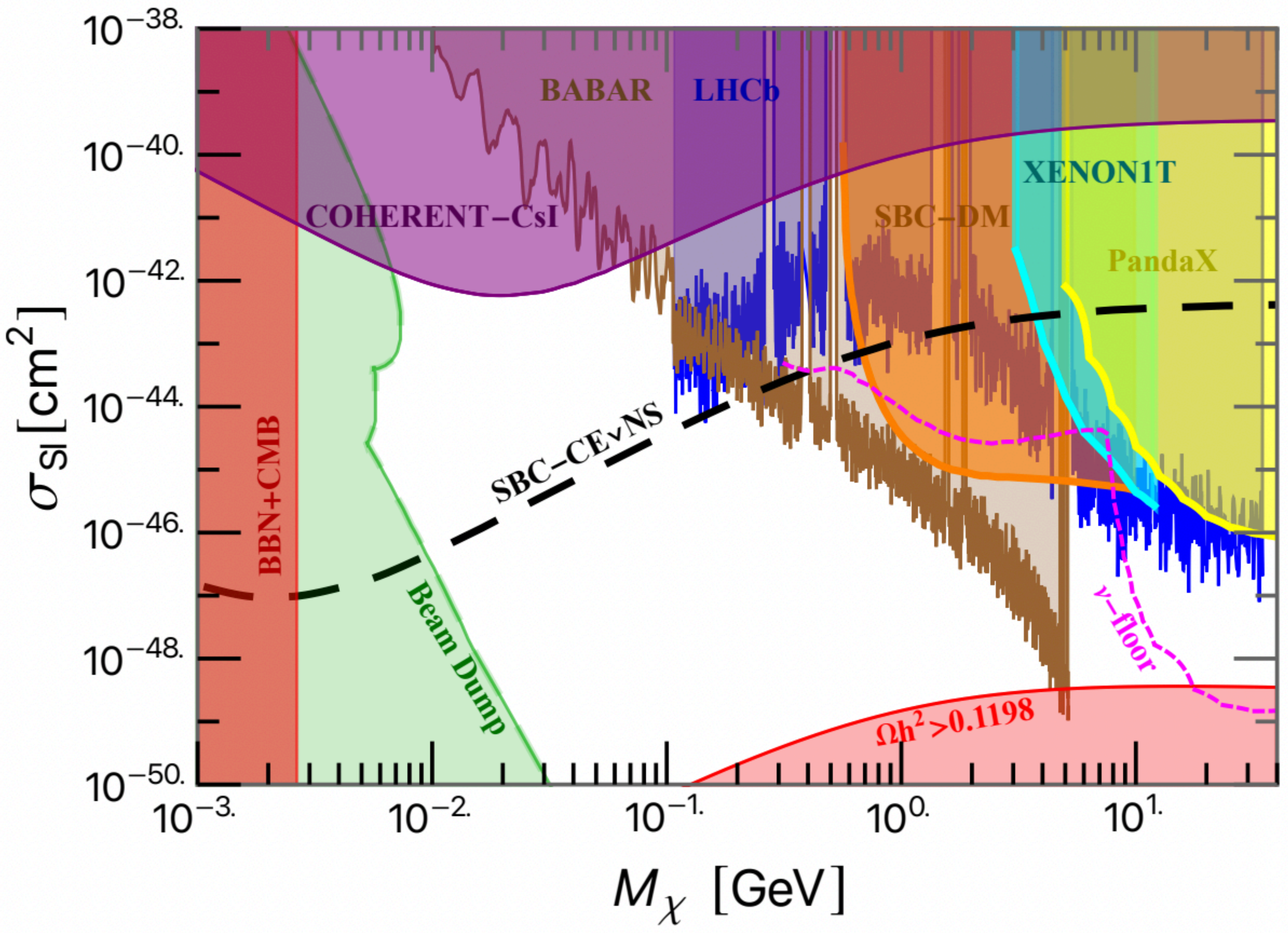

Setup A
Setup B
Setup B(1.5)
Borexino (90% C.L.)
GEMMA (90% C.L.)
COHERENT-LAr
COHERENT-CsI
90% C.L.
$\Delta\chi^2$
μ_ν (μ_B)

PHENO FROM CEVNS: LIGHT VECTOR MEDIATORS AND DARK MATTER

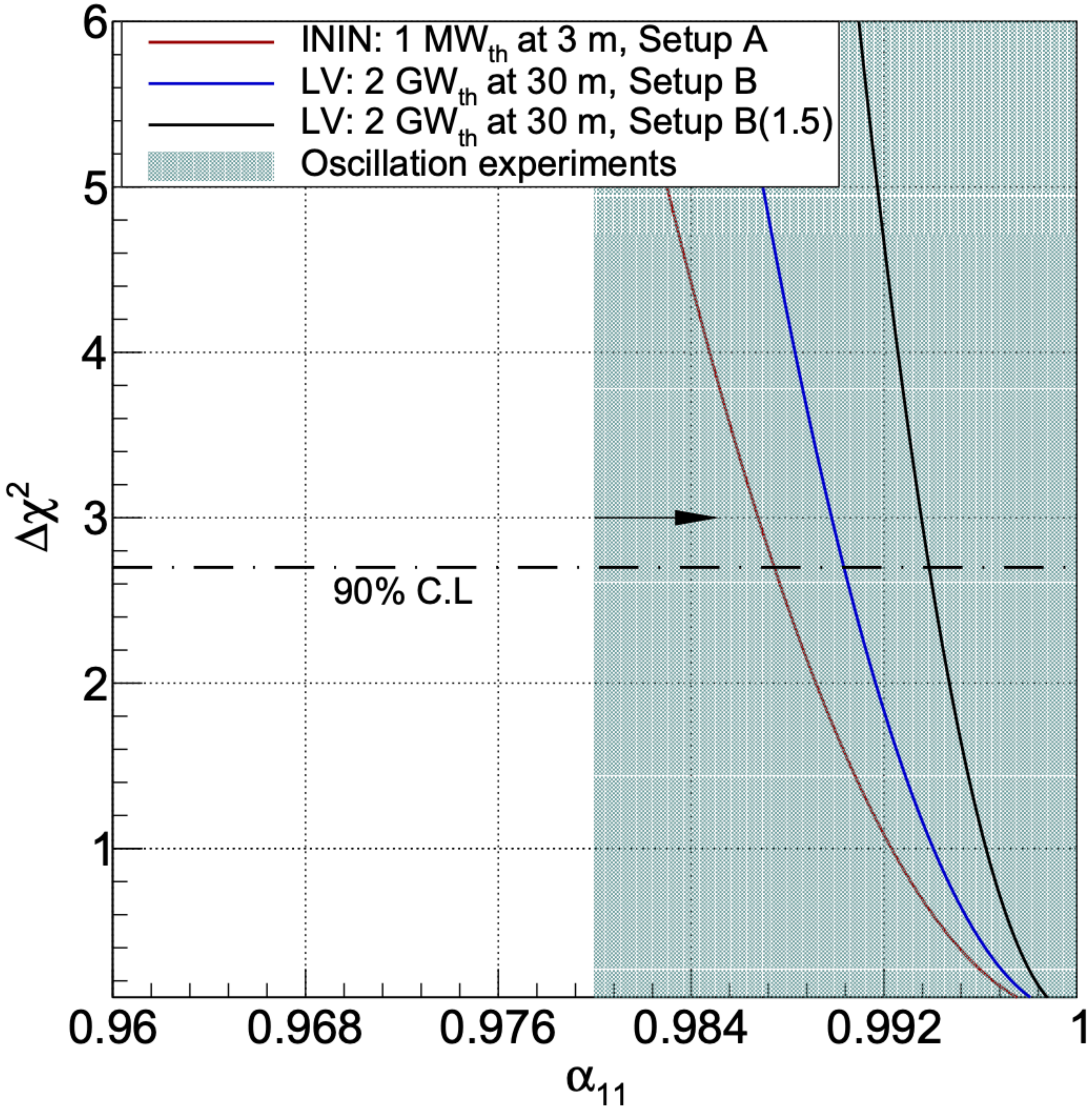
Z' as a dark matter χ mediator

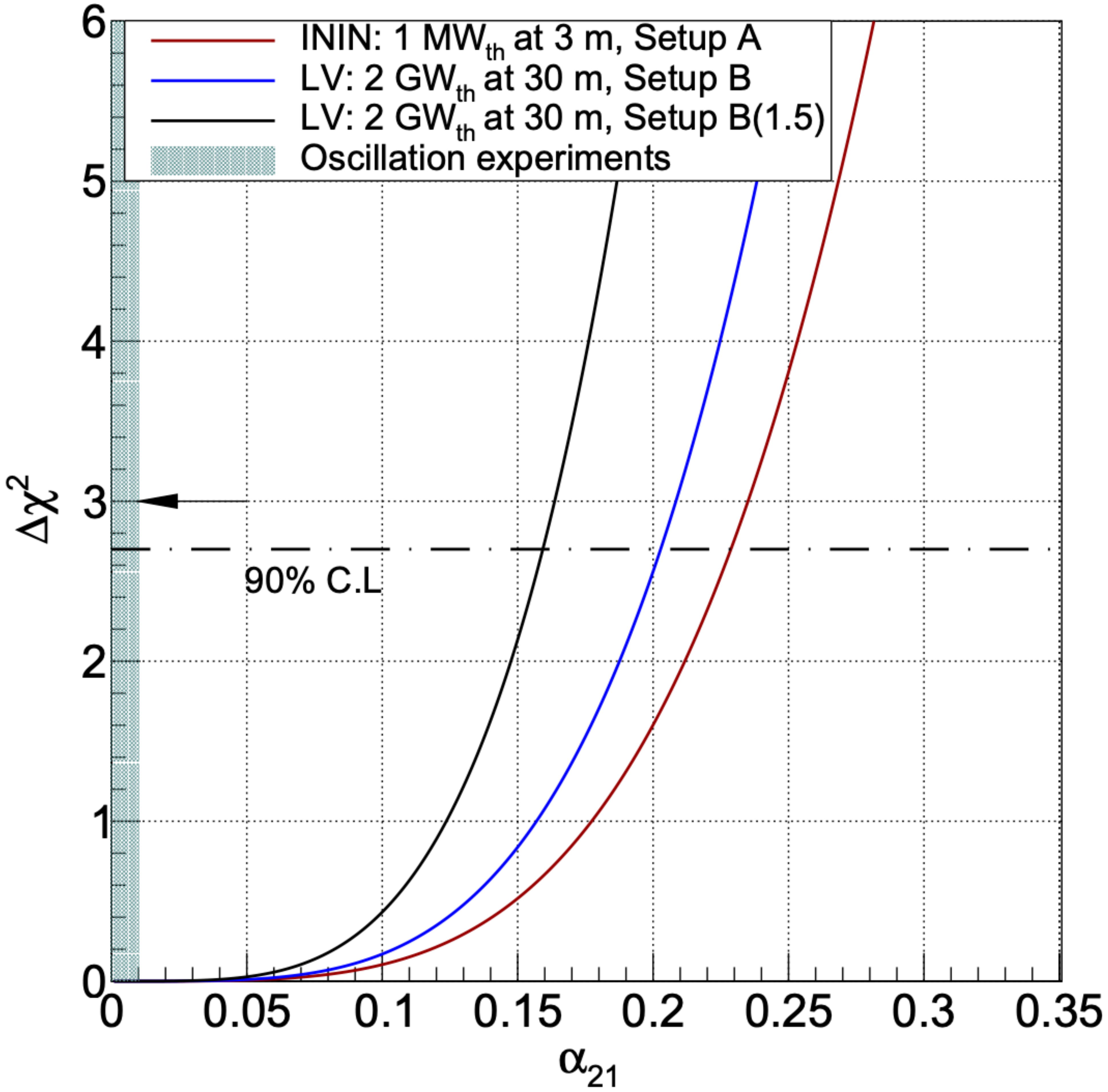
Resonance condition: $2M_\chi \sim M_{Z'}$





León M . G. De la Vega, LJF, N. Nath, E. Peinado, *JHEP* 09 (2021) 146


ININ: 1 MW$_{th}$ at 3 m, Setup A
LV: 2 GW$_{th}$ at 30 m, Setup B
LV: 2 GW$_{th}$ at 30 m, Setup B(1.5)
Oscillation experiments
90% C.L
$\Delta\chi^2$
α_{11}
0.96
0.968
0.976
0.984
0.992
1
1
2
3
4
5
6


ININ: 1 MW$_{th}$ at 3 m, Setup A
LV: 2 GW$_{th}$ at 30 m, Setup B
LV: 2 GW$_{th}$ at 30 m, Setup B(1.5)
Oscillation experiments
90% C.L
$\Delta\chi^2$
α_{21}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
1
2
3
4
5
6

	This work		Previous works	
	CsI	LAr	CsI [54]	CsI [12]
ξ_S^e	[-0.53, 0.53]	[-2.19, 2.19]	[-1.22, 1.22]	[-0.62, 0.62]
ξ_S^μ	[-0.37, 0.37]	[-1.48, 1.48]	[-0.77, 0.77]	
ξ_V^e	[-2.06, 0.15]	[-3.08, 1.16]	–	[-2.102, -1.554] & [-0.324, 0.224]
ξ_V^μ	[-2.02, -1.56] & [-0.37, 0.09]	[-2.53, 0.61]	–	
ξ_T^e	[-0.52, 0.52]	[-1.71, 1.71]	[-1.26, 1.26]	[-0.591, 0.591]
ξ_T^μ	[-0.37, 0.37]	[-1.11, 1.11]	[-0.85, 0.85]	

TABLE I. Allowed regions of the scalar, vector, and tensor GNI at 90% C. L. from the COHERENT-CsI and LAr detector analyses. The first two columns correspond to the results of this work, while the other columns to the limits obtained in [54] and [12]. The limits from the last column where obtained assuming $\xi_X^e = \xi_X^\mu$.

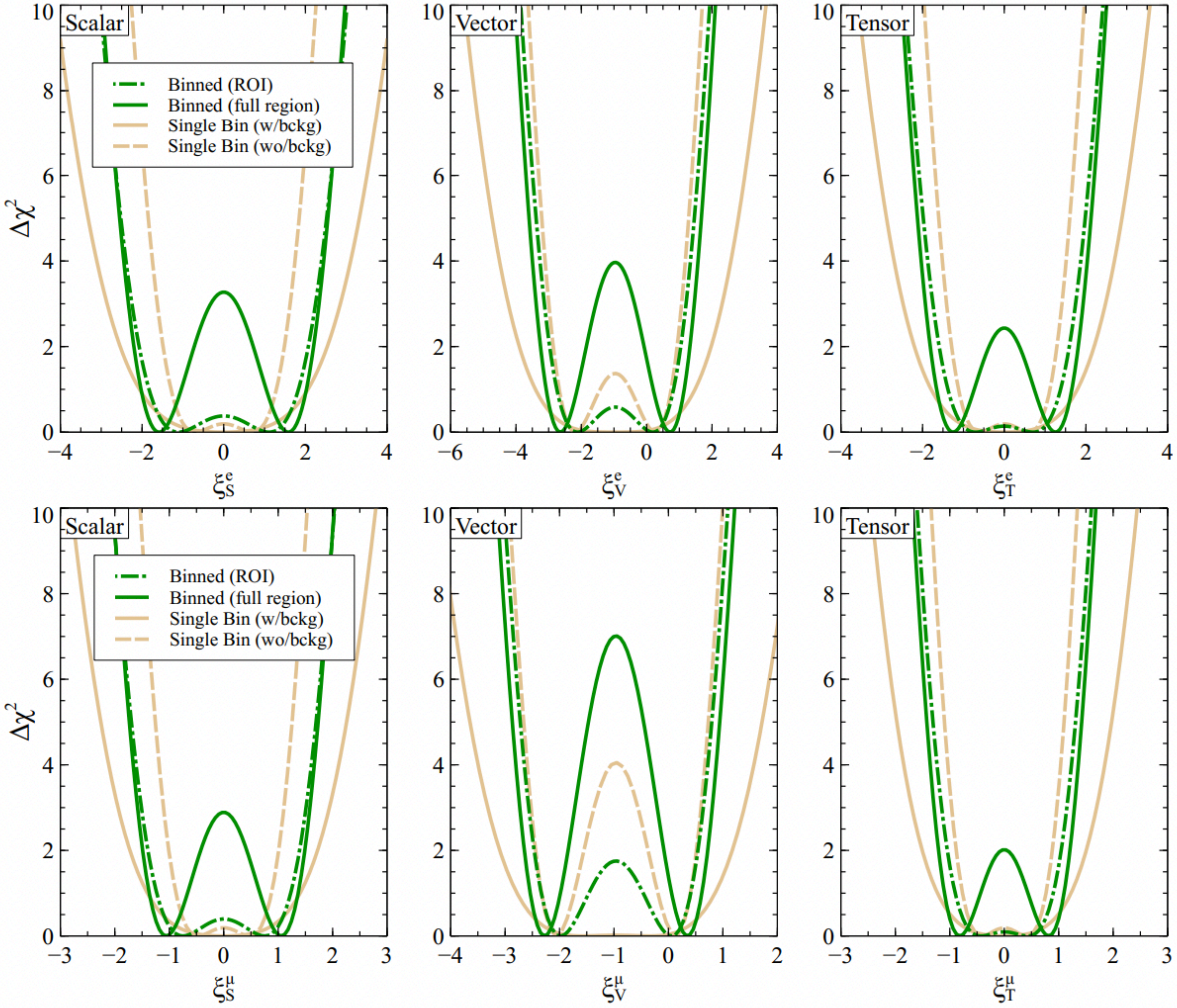


FIG. 6. $\Delta\chi^2$ for different GNI parameters, where top (bottom) row corresponds to electron (muon) flavor.