Impact of nuclear matrix element calculations on neutrinoless double beta decay searches

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Based on the work with Prof. Thomas Schwetz and Federica Popma, 2303.10562

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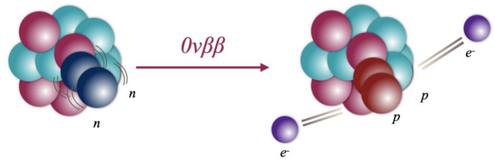
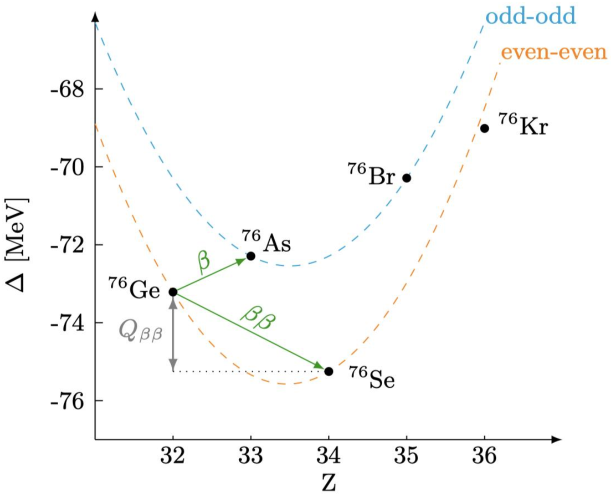
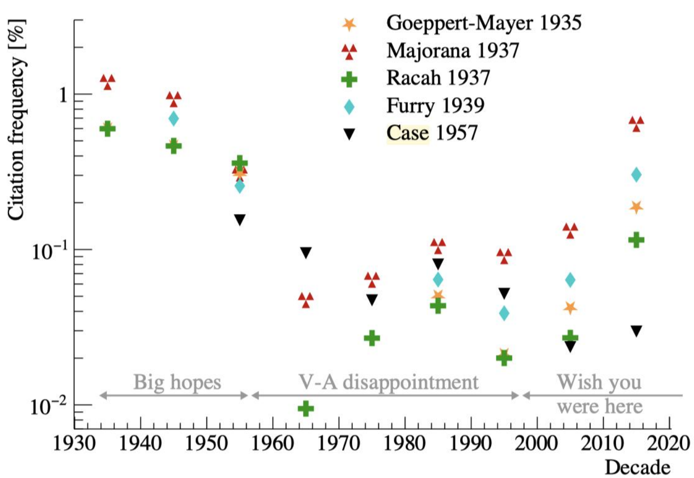
Brief background







Agostini et al. 2202.01787

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}_e$$

Mayer, 1935; first detected in 1987 by Moe

$$\nu_i^c = \nu_i$$

Majorana, 1937

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$

Furry, 1939

Experiments:
background, exposure, energy resolution
Theoretical difficulties:

- **The production mechanism**
- **Calculation of nuclear matrix elements (NME)**

Formula (light neutrino exchange mechanism)

$$(T_{1/2}^{-1})_\alpha = \widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i}) = \frac{\Gamma_\alpha(m_{\beta\beta}, M_{\alpha i})}{\ln 2} = G_\alpha \left|M_{\alpha i}\right|^2 m_{\beta\beta}^2$$

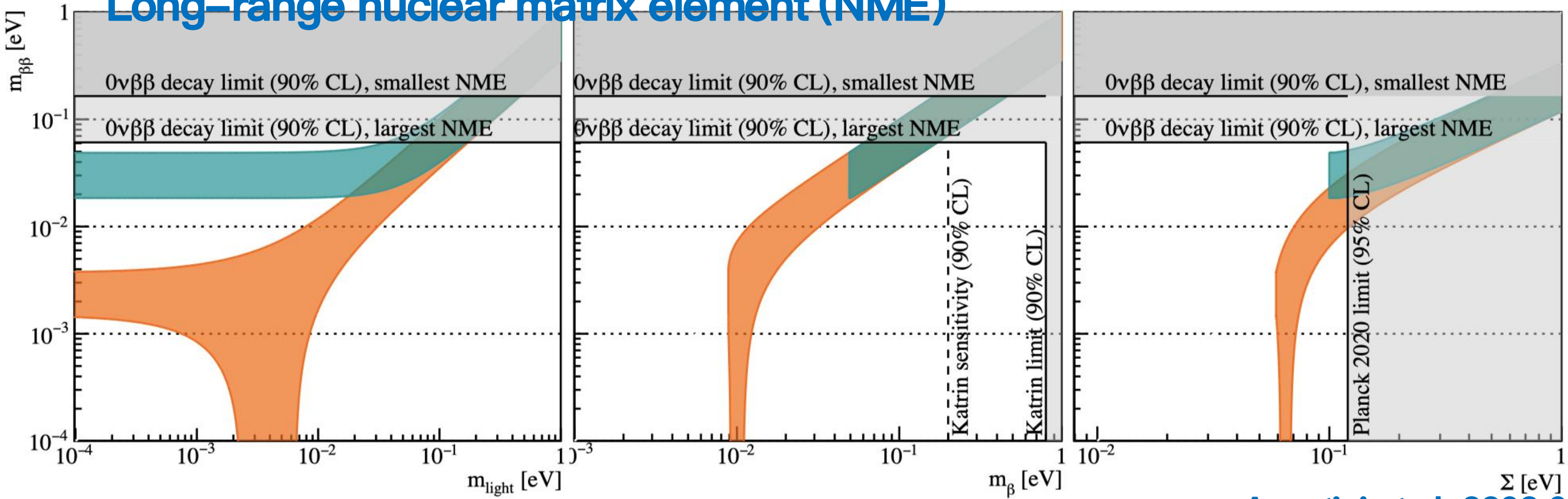
$$m_{\beta\beta} = \left|\sum_j U_{ej}^2 m_j\right|$$

$$M_{\alpha i} = M_{\alpha i}^{\text{long}} + M_{\alpha i}^{\text{short}} = M_{\alpha i}^{\text{long}}(1 + n_{\alpha i}) \qquad n_{\alpha i} = \frac{M_{\alpha i}^{\text{short}}}{M_{\alpha i}^{\text{long}}}$$

$$g_A^{\text{eff}} = q\, g_A^{\text{free}} \qquad g_A^{\text{free}} = 1.27$$

Quenching effect: correct the NME by q^2 and the decay rate by q^4

Long-range nuclear matrix element (NME)



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Motivations:

- Interpreting the constraints/sensitivities on $m_{\beta\beta}$ of current/future 0νββ experiments
- Checking the possibilities of discriminating NME models in future 0νββ experiments

Long-range NME

Nuclear Model	Index	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
NSM	N1	2.89	2.73	-	2.76	2.28
	N2	3.07	2.90	-	2.96	2.45
	N3	3.37	3.19	-	1.79	1.63
	N4	3.57	3.39	-	1.93	1.76
	N5	2.66	2.72	2.24	3.16	2.39
QRPA	Q1	5.09	-	-	1.37	1.55
	Q2	5.26	3.73	3.90	4.00	2.91
	Q3	4.85	4.61	5.87	4.67	2.72
	Q4	3.12	2.86	-	2.90	1.11
	Q5	3.40	3.13	-	3.22	1.18
	Q6	-	-	-	4.05	3.38
EDF	E1	4.60	4.22	5.08	5.13	4.20
	E2	5.55	4.67	6.59	6.41	4.77
	E3	6.04	5.30	6.48	4.89	4.24
IBM	I1	5.14	4.19	3.84	3.96	3.25
	I2	6.34	5.21	5.08	4.15	3.40

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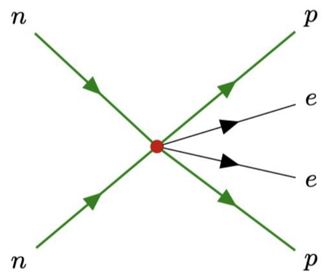
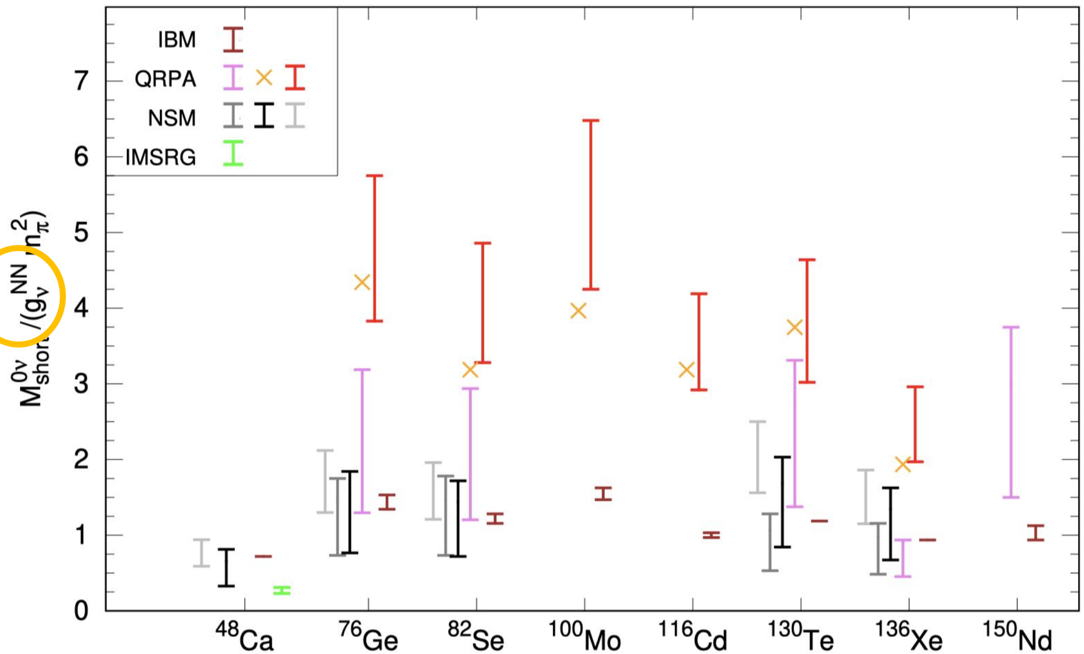
Short-range NME

Cirigliano et al , Phys.Rev.Lett. 120 (2018) 20, 202001



Isotope	NSM %	QRPA %
^{76}Ge	15–42	32–73
^{82}Se	15–41	30–70
^{100}Mo	-	49–108
^{130}Te	17–47	34–77
^{136}Xe	17–47	30–70

Phys. Lett. B 823 (2021) 136720



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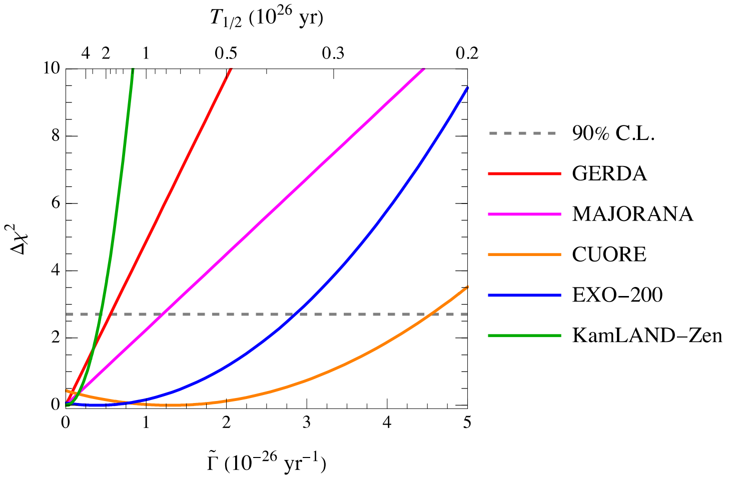
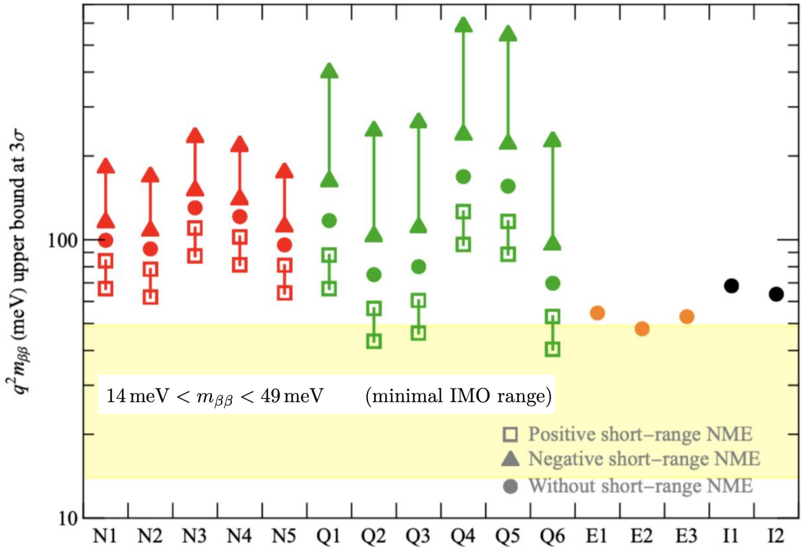
Current constraints:

$$\Delta\chi^2_r(\widetilde{\Gamma}_\alpha) = a_r\,(\widetilde{\Gamma}_\alpha)^2 + b_r\,\widetilde{\Gamma}_\alpha + c_r$$





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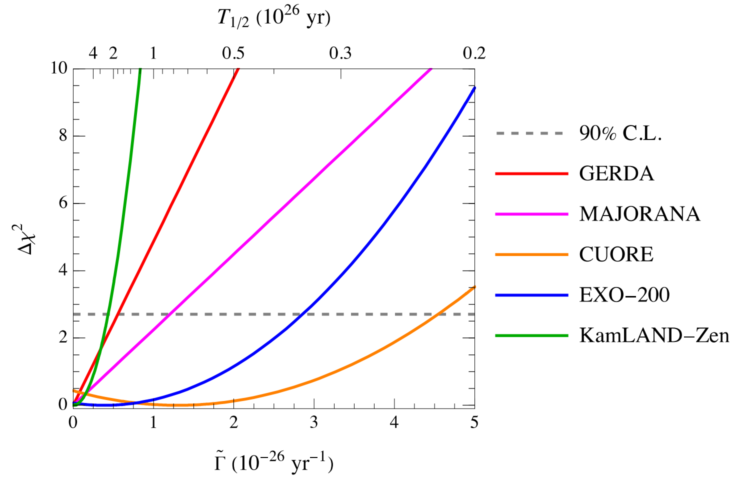
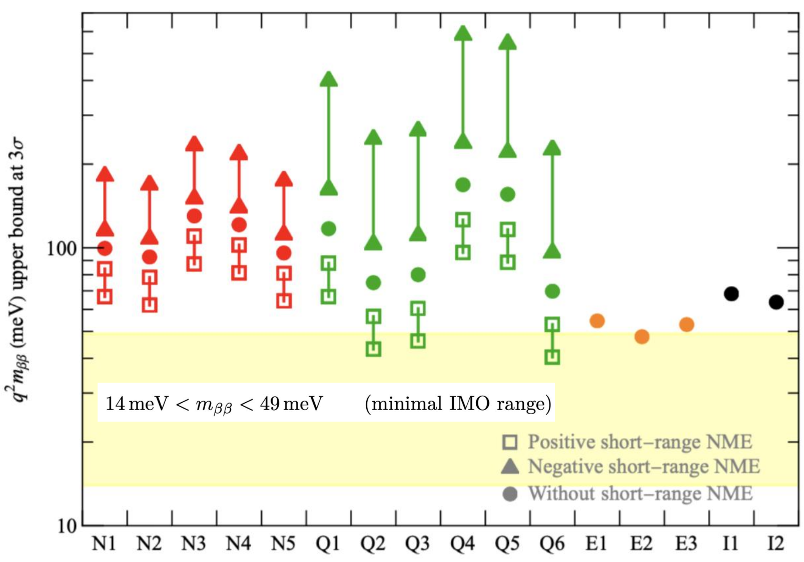




Setups of future experiments:

Experiment	Isotope	ε [mol·yr]	b [events/(mol·y)]	PSF [$\mathrm{yr}^{-1}\ \mathrm{eV}^{-2}$]
LEGEND-1000	^{76}Ge	8736	$4.9\cdot10^{-6}$	$2.36\cdot10^{-26}$
SuperNEMO	^{82}Se	185	$5.4\cdot10^{-3}$	$10.19\cdot10^{-26}$
CUPID	^{100}Mo	1717	$2.3\cdot10^{-4}$	$15.91\cdot10^{-26}$
SNO+II	^{130}Te	8521	$5.7\cdot10^{-3}$	$14.2\cdot10^{-26}$
nEXO	^{136}Xe	13700	$4.0\cdot10^{-5}$	$14.56\cdot10^{-26}$

$$N_{\mathrm{LEGEND-1000}} = \left\{0.97\times\left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2\left(\frac{M^{\mathrm{long}}_{\mathrm{Ge}}}{2.66}\right)^2 + 0.04\right\}\times\frac{T}{1\ \mathrm{yr}}$$

$$N_{\mathrm{SuperNEMO}} = \left\{0.09\times\left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2\left(\frac{M^{\mathrm{long}}_{\mathrm{Se}}}{2.72}\right)^2 + 1.0\right\}\times\frac{T}{1\ \mathrm{yr}}$$

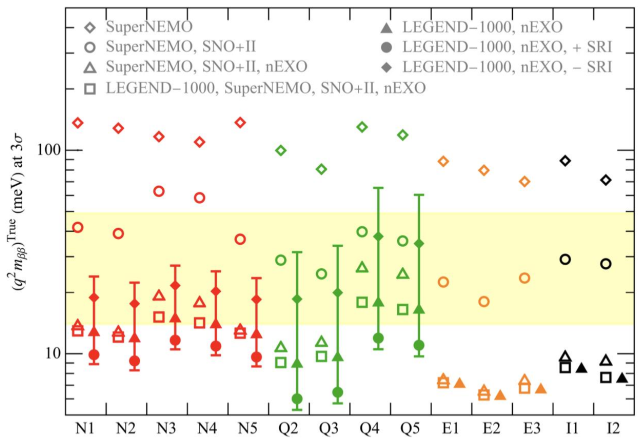
$$N_{\mathrm{nEXO}} = \left\{1.64\times\left[\frac{(q^2 m_{\beta\beta})^{\mathrm{True}}}{40\ \mathrm{meV}}\right]^2\left(\frac{M^{\mathrm{long}}_{\mathrm{Xe}}}{1.11}\right)^2 + 0.5\right\}\times\frac{T}{1\ \mathrm{yr}}$$

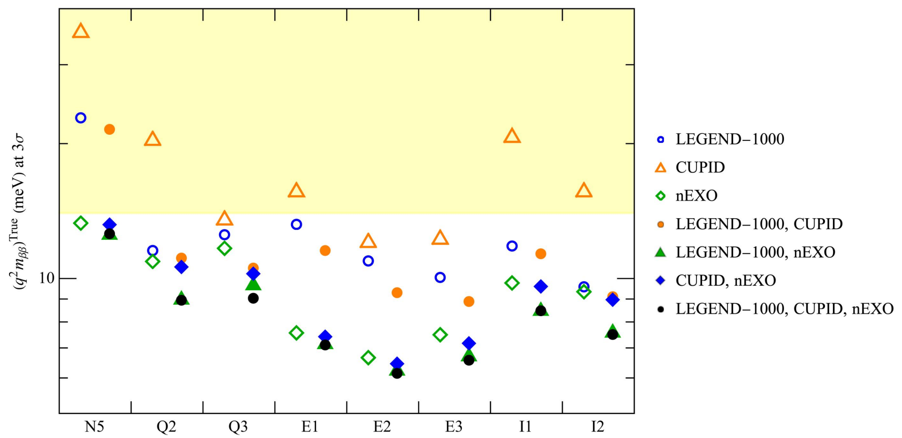
$$N_{\alpha i} = S_{\alpha i} + B_\alpha \qquad B_\alpha = b_\alpha\cdot\varepsilon_\alpha\cdot\left(\frac{T}{1\ \mathrm{yr}}\right)$$

$$S_{\alpha i}(m_{\beta\beta}, M_{\alpha i}) = \ln 2\cdot N_A\cdot\varepsilon_\alpha\cdot\left(\frac{T}{1\ \mathrm{yr}}\right)\cdot\widetilde{\Gamma}_\alpha(m_{\beta\beta}, M_{\alpha i})$$

$$\Delta\chi^2_{ij}(m_{\beta\beta}, M_{\alpha j}\,;\, m^{\mathrm{True}}_{\beta\beta}, M^{\mathrm{True}}_{\alpha i}) = 2\sum_\alpha\left(N_{\alpha j} - N^{\mathrm{True}}_{\alpha i} + N^{\mathrm{True}}_{\alpha i}\ln\frac{N^{\mathrm{True}}_{\alpha i}}{N_{\alpha j}}\right)$$

Sensitivities to $(q^2 m_{\beta\beta})^{True}$ at 3σ:





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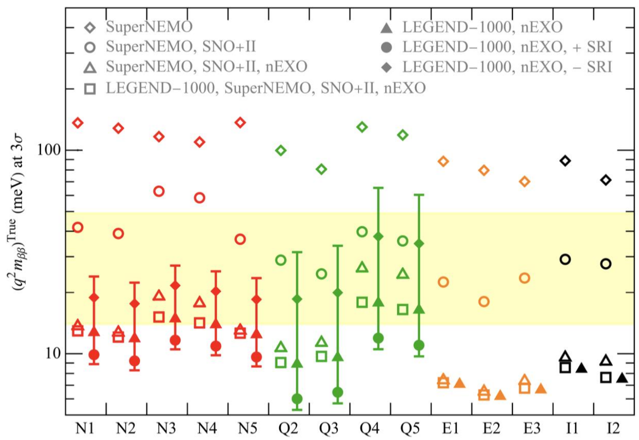
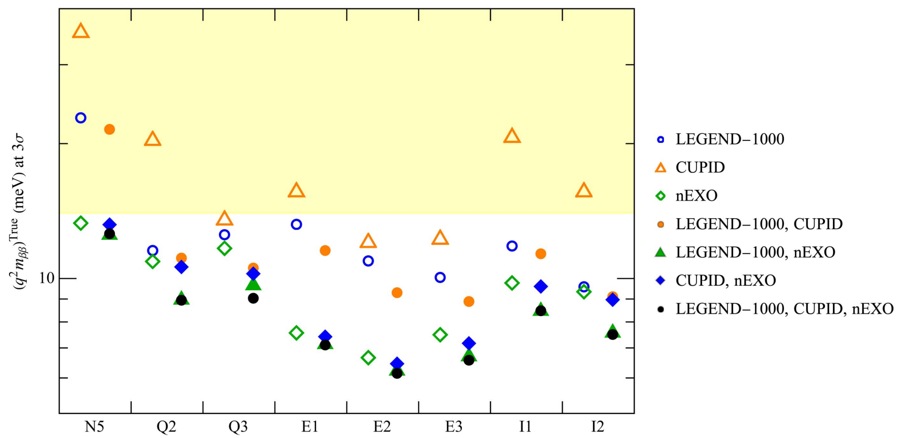
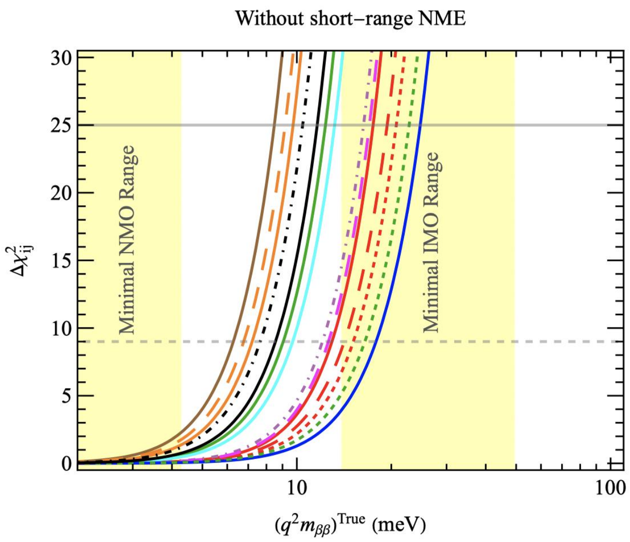
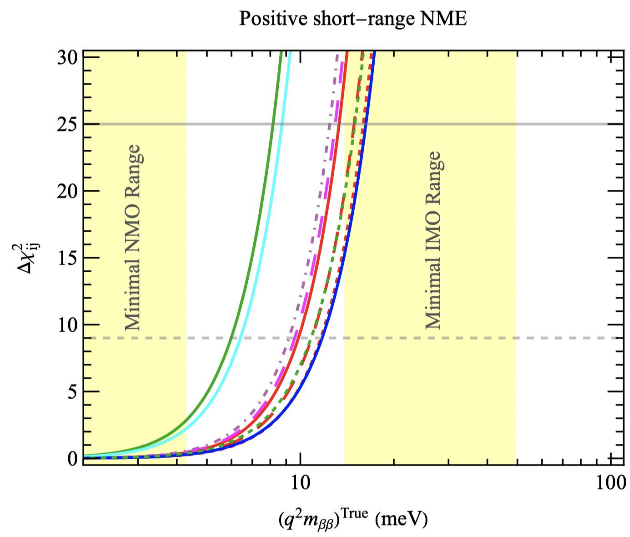




The significance of observing one positive signal:



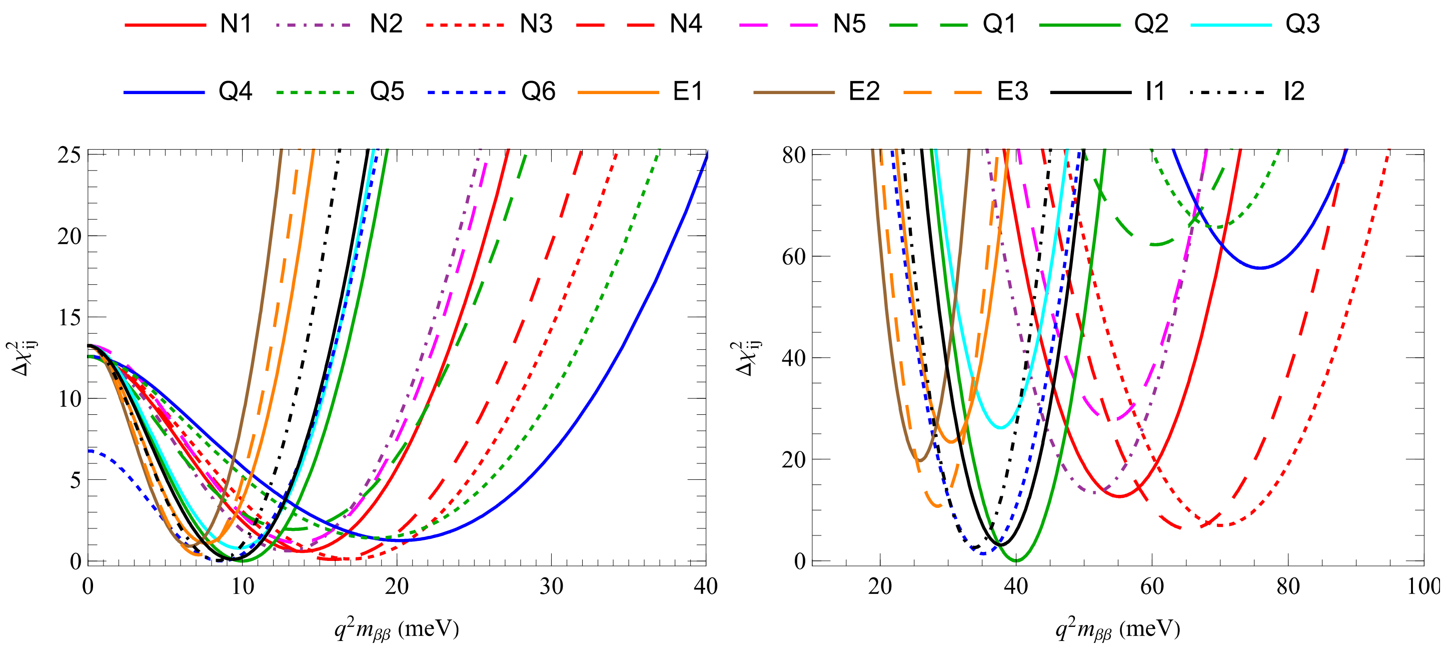


$m_{\beta\beta}=0$, $T=10$ yr

N1 N2 N3 N4 N5 Q2 Q3 Q4 Q5 E1 E2 E3 I1 I2

$(\Delta\chi^2_{ij})$ as function of $q^2 m_{\beta\beta}$

i=Q2



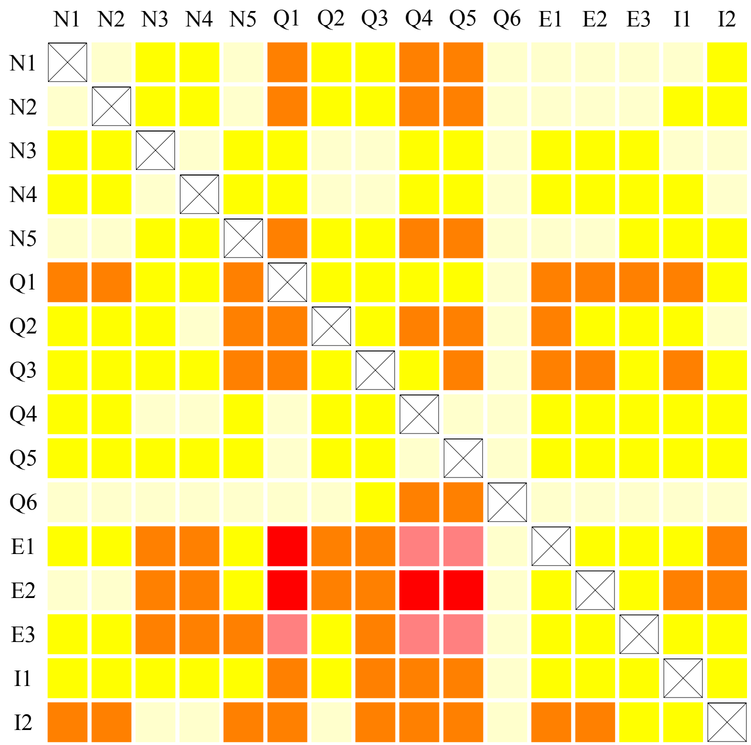
$(q^2 m_{\beta\beta})^{True}=10$ meV

$(q^2 m_{\beta\beta})^{True}=40$ meV

Discrimination without short-range NME

$$(\Delta\chi^2_{ij})_{\min} = \min_{m_{\beta\beta}} \Delta\chi^2_{ij}(m_{\beta\beta}, M_{\alpha j}\,;\,(q^2 m_{\beta\beta})^{\rm True}, M^{\rm True}_{\alpha i})$$

$(q^2 m_{\beta\beta})^{True}$=10 meV



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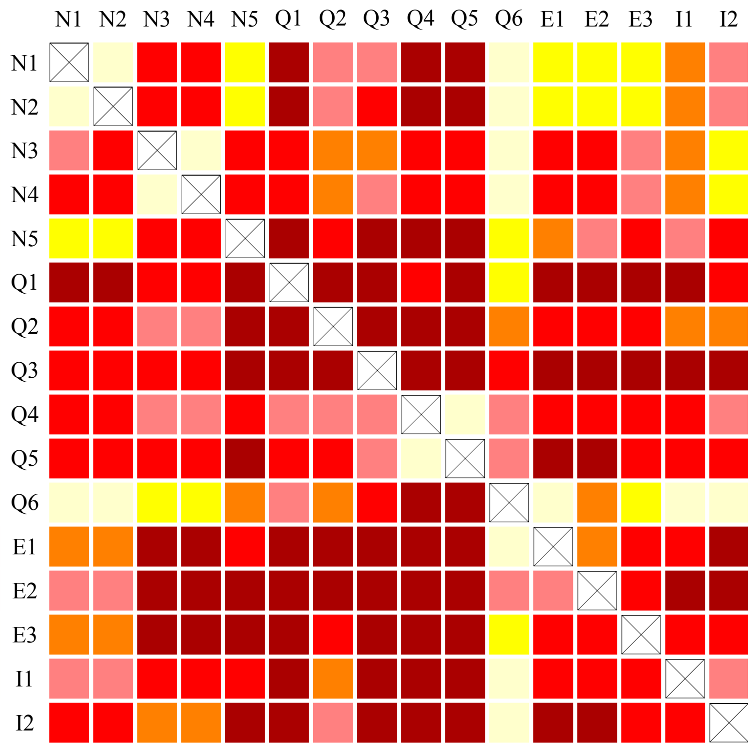
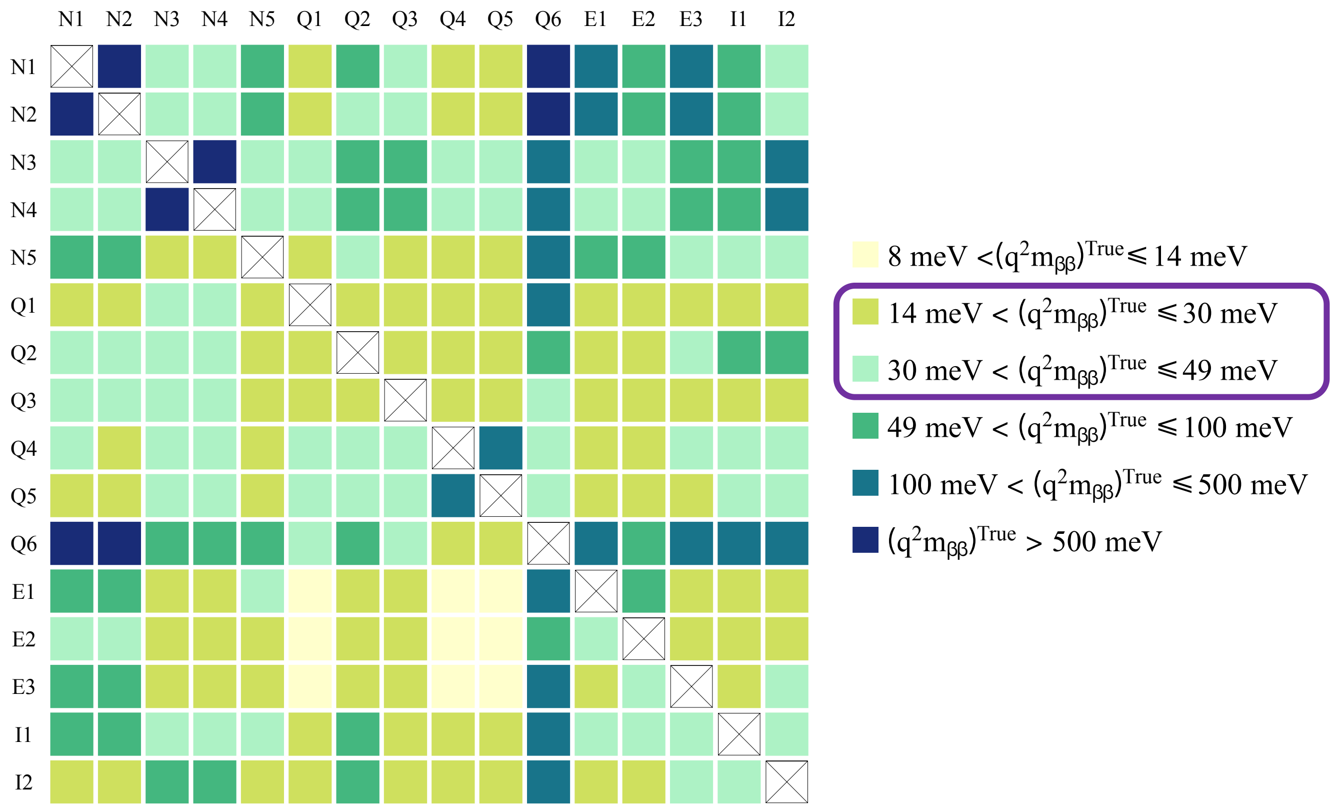
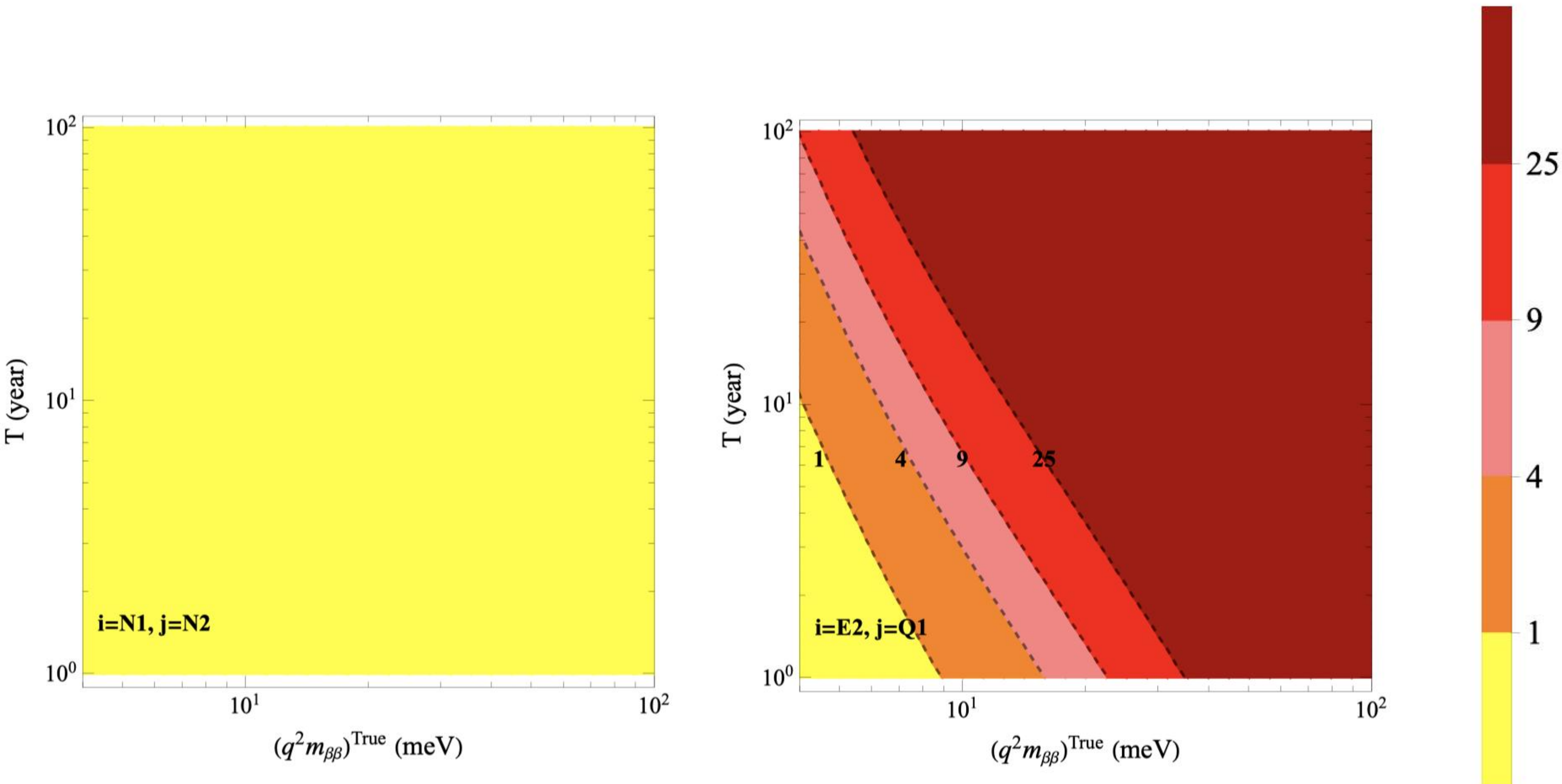


$(\Delta\chi^2_{ij})_{\min} \leqslant 0.1$ $0.1 < (\Delta\chi^2_{ij})_{\min} \leqslant 1$ $1 < (\Delta\chi^2_{ij})_{\min} \leqslant 4$ $4 < (\Delta\chi^2_{ij})_{\min} \leqslant 9$ $9 < (\Delta\chi^2_{ij})_{\min} \leqslant 25$ $(\Delta\chi^2_{ij})_{\min} > 25$

$m_{\beta\beta}^{True}$ corresponding to discrimination at 3σ (without short-range NME)



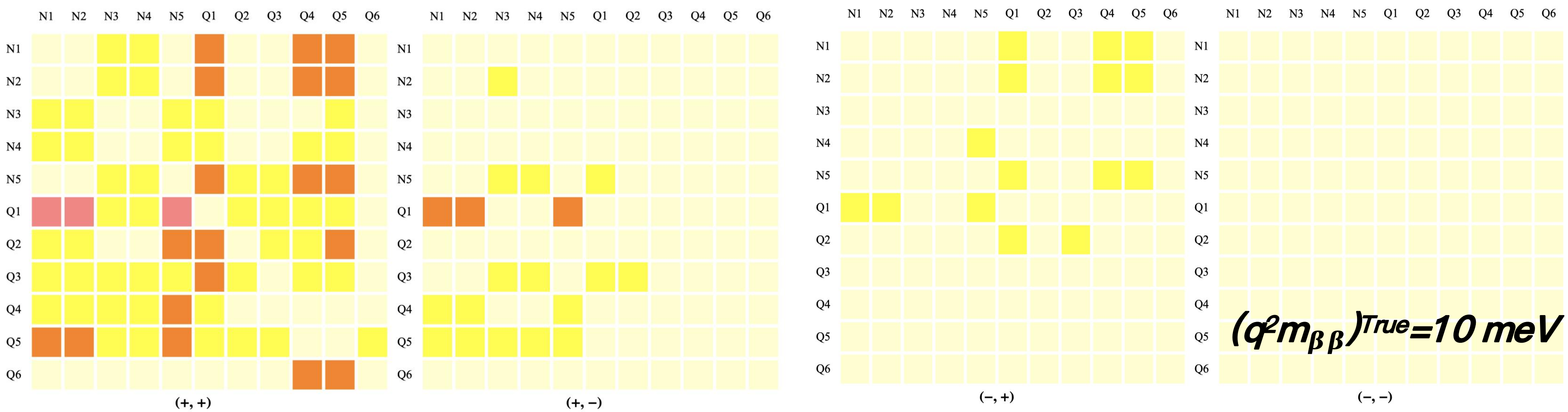
The contours of $(\Delta\chi^2_{ij})_{min}$ as function of the exposure time T and $(q^2 m_{\beta\beta})^{True}$

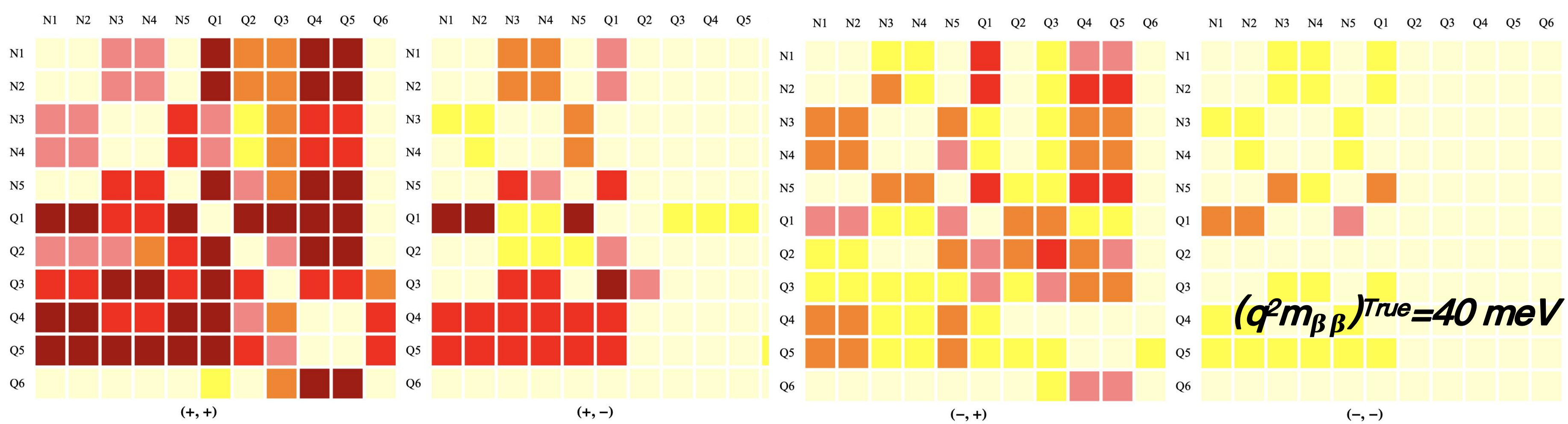


without short-range NME

Discrimination with short-range NME, T=10 yr

$(\Delta\chi^2_{ij})_{min} \leq 0.1$ $0.1 < (\Delta\chi^2_{ij})_{min} \leq 1$ $1 < (\Delta\chi^2_{ij})_{min} \leq 4$ $4 < (\Delta\chi^2_{ij})_{min} \leq 9$ $9 < (\Delta\chi^2_{ij})_{min} \leq 25$ $(\Delta\chi^2_{ij})_{min} > 25$





Conclusions and outlook

- NME uncertainties due to the SRI may lead to the bound on $q^2 m_{\beta\beta}$ varying by a factor of order 10
- Promising discrimination of different NMEs if $(q^2 m_{\beta\beta})^{\text{True}} > 40$ meV, positive SRI and 10 year exposure

- From 0νββ to $m_{\beta\beta}$: improving the calculations of NME
- From 0νββ to discriminating NME models: more input of $m_{\beta\beta}$

Which way is faster?
(the first?)

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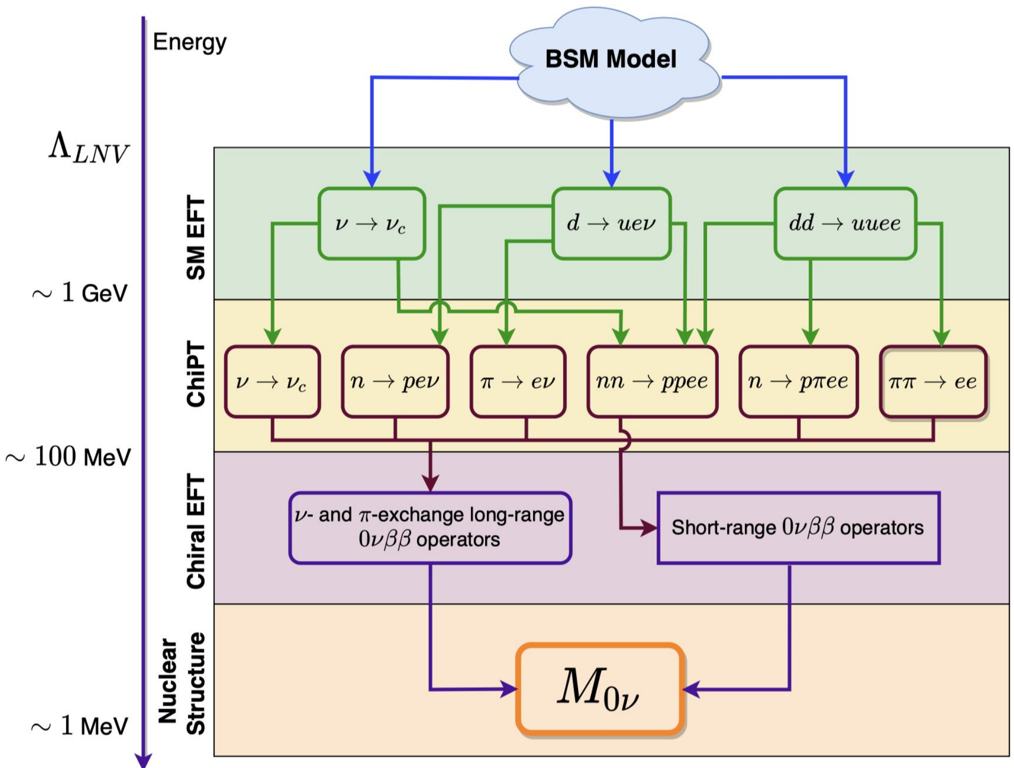
Thanks for your attention!

Backups

From EFT to Nuclear Matrix Element (NME)



Cirigliano et al., J.Phys.G 49 (2022) 12, 120502

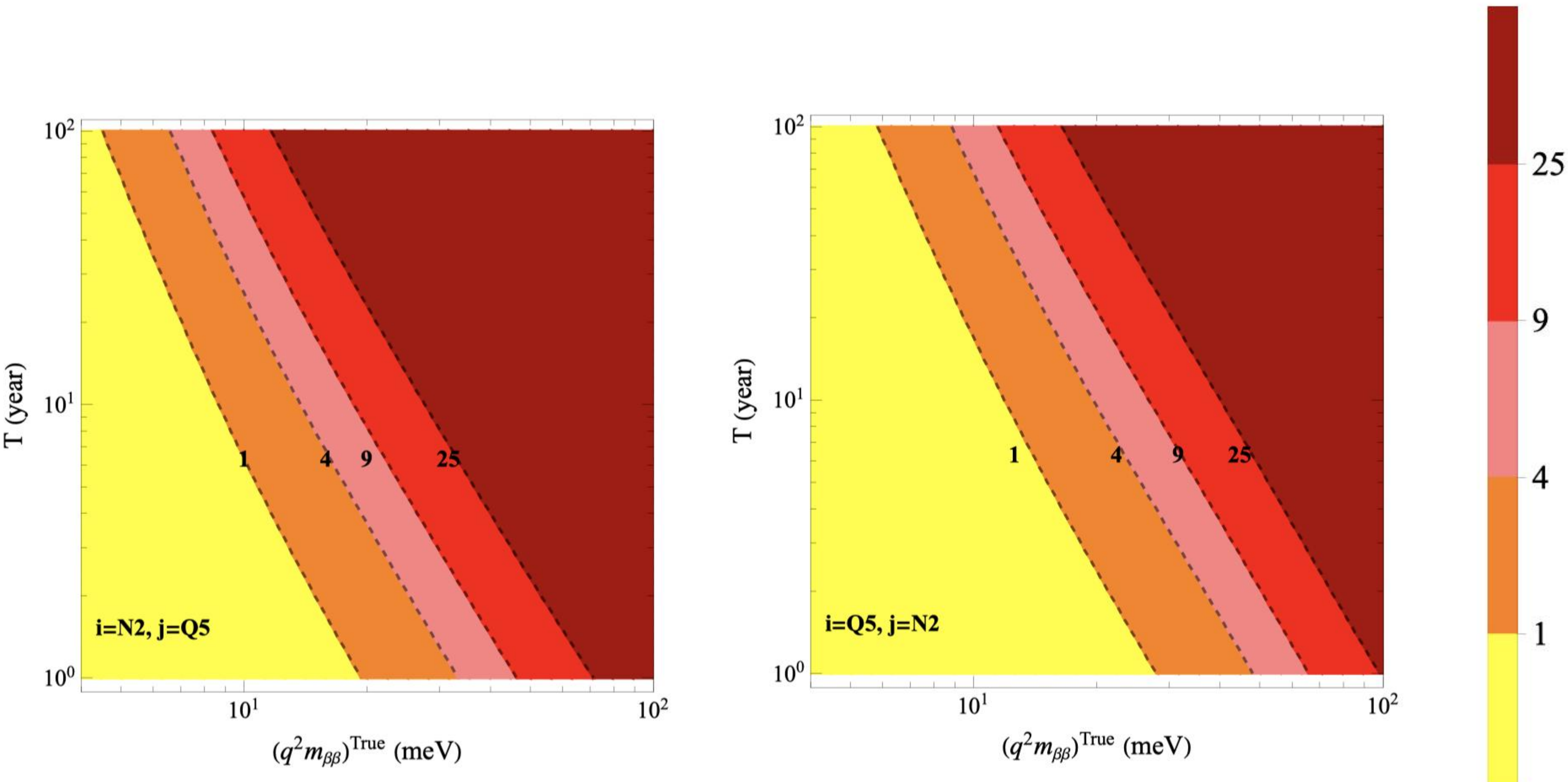
Naive Dimensional Analysis(NDA) problem

D. B. Kaplan, M. J. Savage, and M. B. Wise, Nucl. Phys. **B478**, 629 (1996).
S. R. Beane, P. F. Bedaque, M. J. Savage, and U. van Kolck, Nucl. Phys. **A700**, 377 (2002).
A. Nogga, R. G. E. Timmermans, and U. van Kolck, Phys. Rev. C **72**, 054006 (2005).
B. Long and C.-J. Yang, Phys. Rev. C **86**, 024001 (2012).
M. Pavón Valderrama and D. R. Phillips, Phys. Rev. Lett. **114**, 082502 (2015).

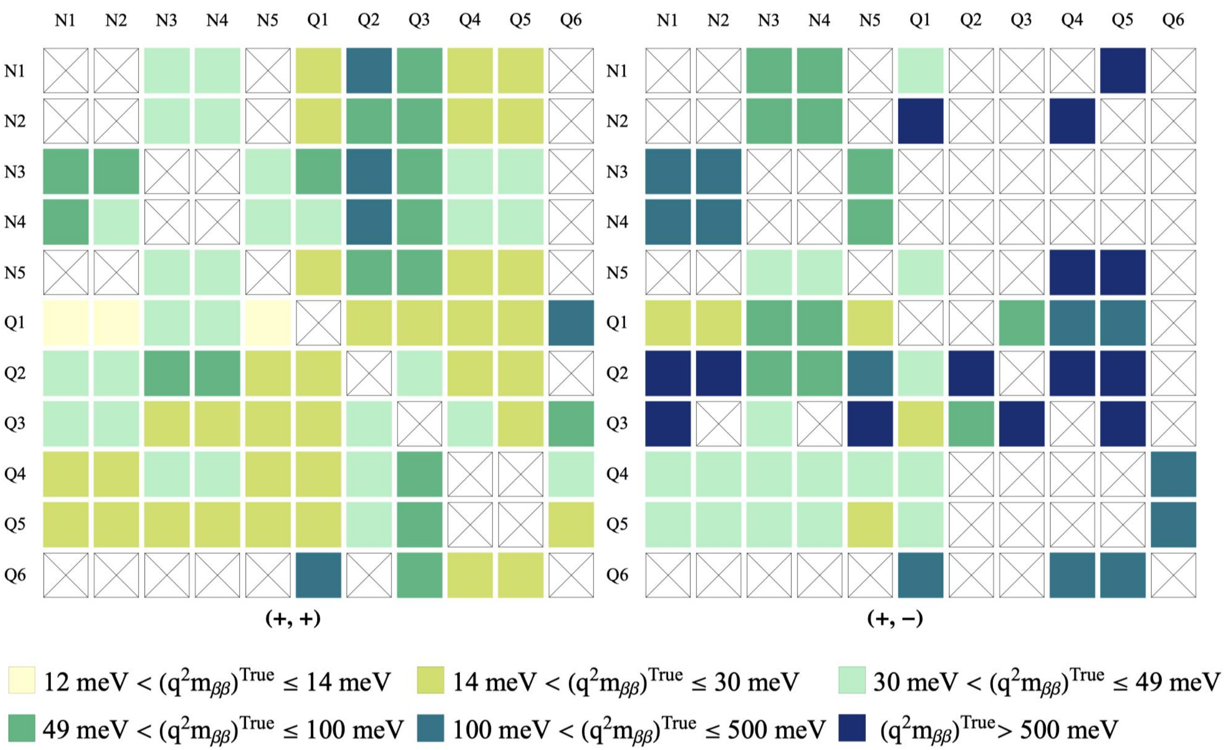
and $F_\pi = 92.2$ MeV is the pion decay constant. However, it is known that Weinberg's power counting leads to inconsistent results in nucleon-nucleon scattering [34–37] and nuclear processes mediated by external currents [38], due to a conflict between naive dimensional analysis and nonperturbative renormalization. We therefore investigate the scaling of g_ν^{NN} by studying the amplitude $\mathcal{A}(nn \to ppee) \equiv \mathcal{A}_{\Delta L=2}$ with strong interactions $H_{\rm strong}$ included nonperturbatively.

Cirigliano et al , Phys.Rev.Lett. 120 (2018) 20, 202001

The contours of $(\Delta\chi^2_{ij})_{min}$ as function of the exposure time T and $(q^2 m_{\beta\beta})^{True}$



$m_{\beta\beta}^{True}$ corresponding to discrimination at 3σ (with SRI)



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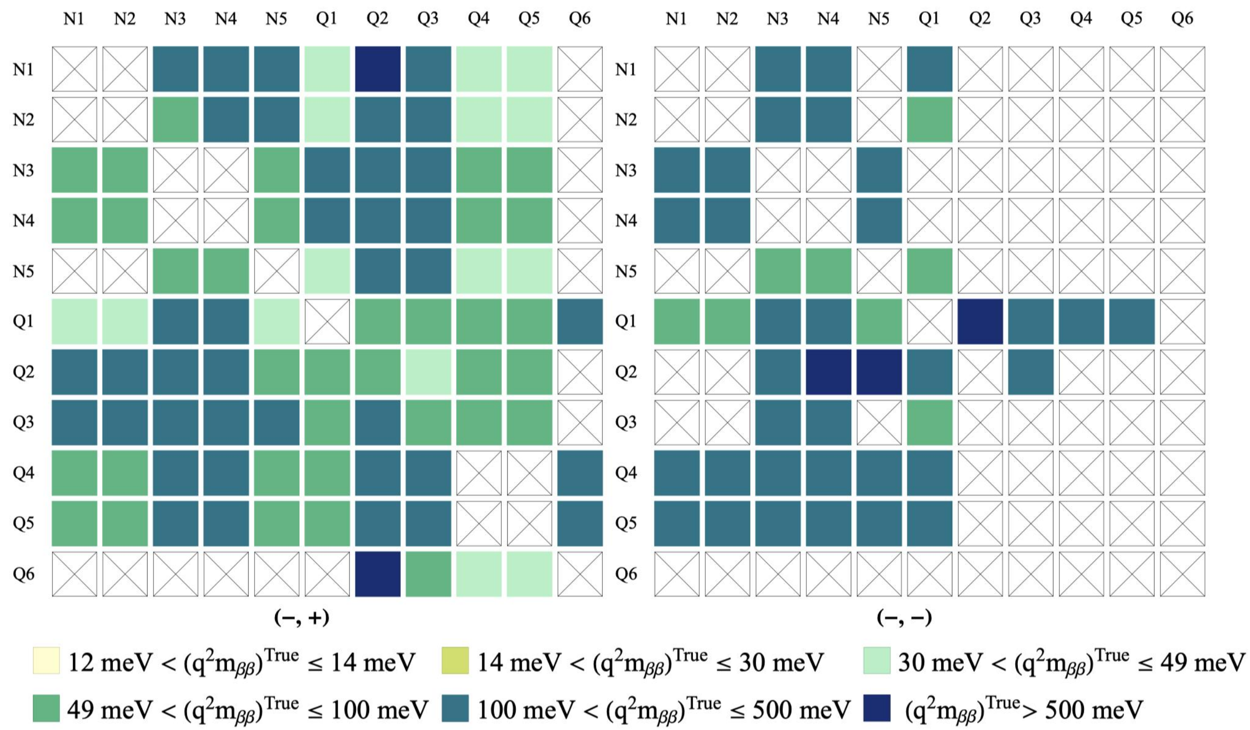
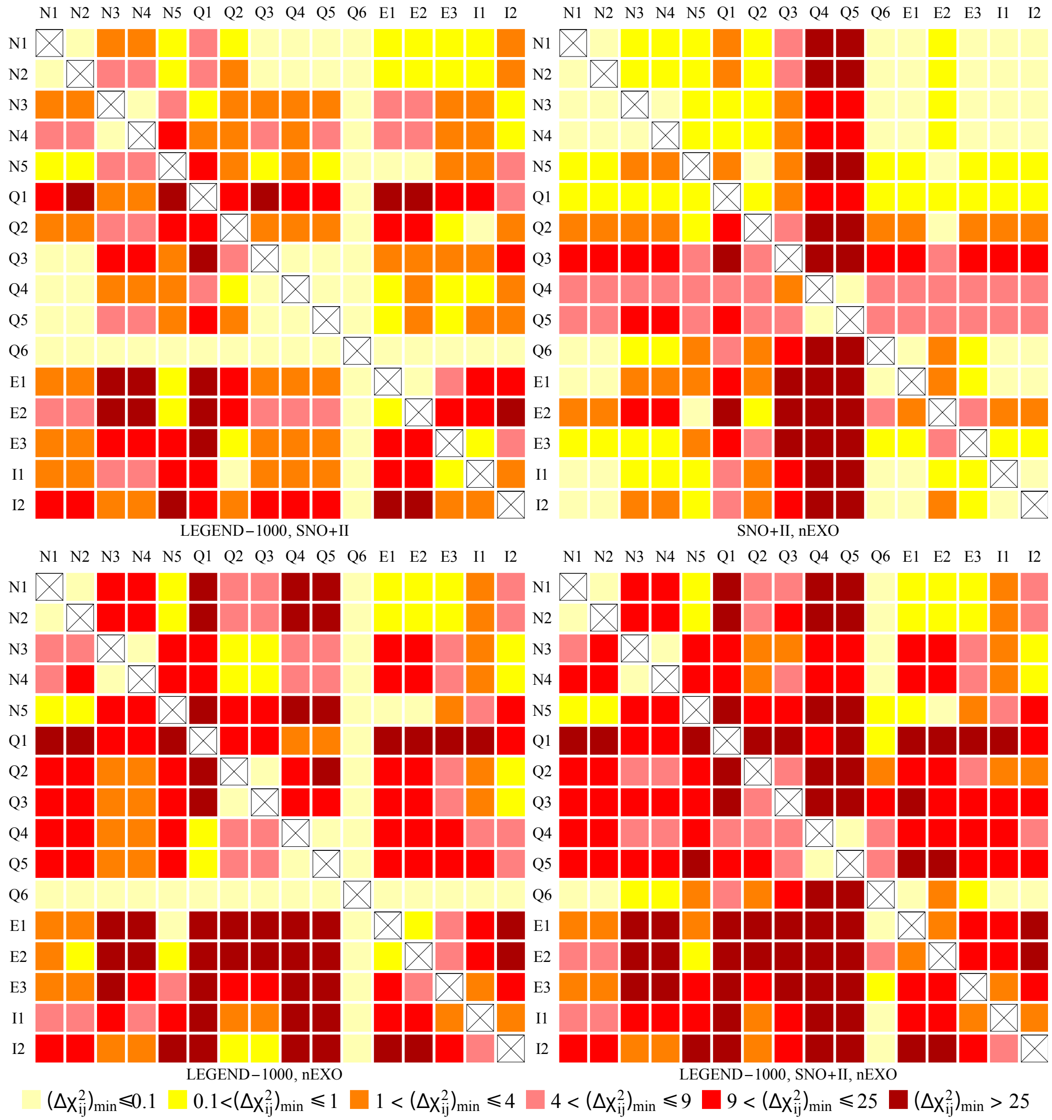
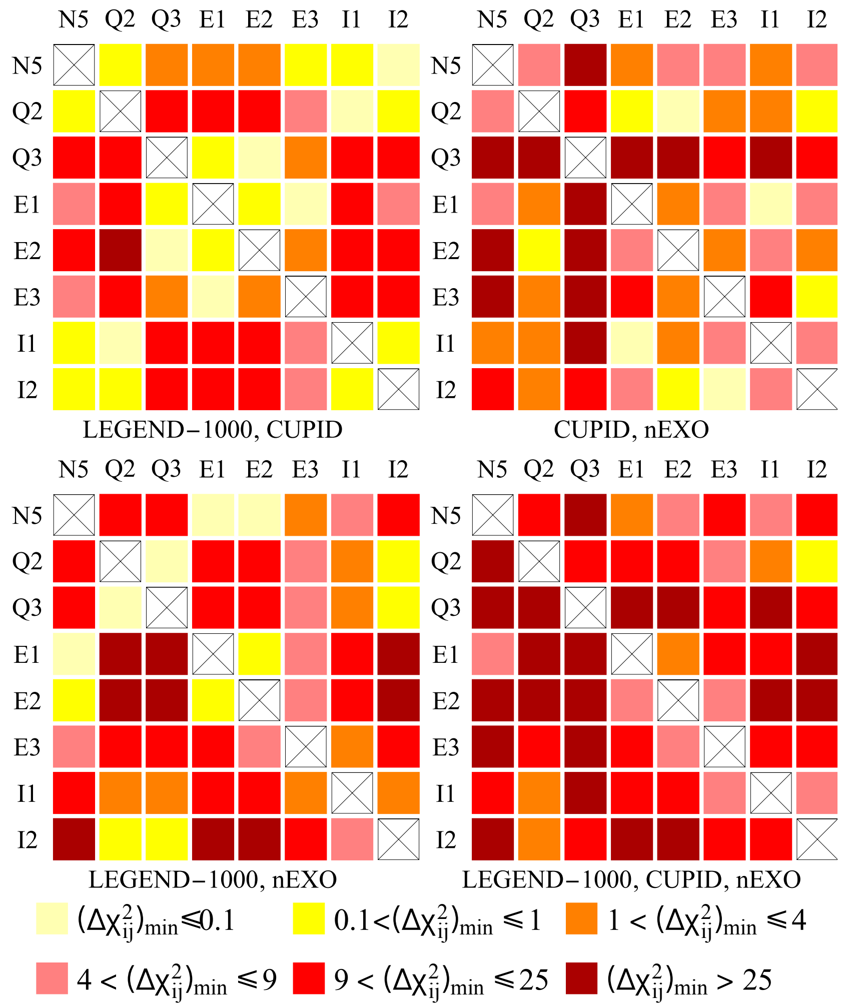




nEXO and LEGEND−1000 dominate

$m_{\beta\beta}^{True} = 40$ meV



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