Future DUNE constraints on EFT

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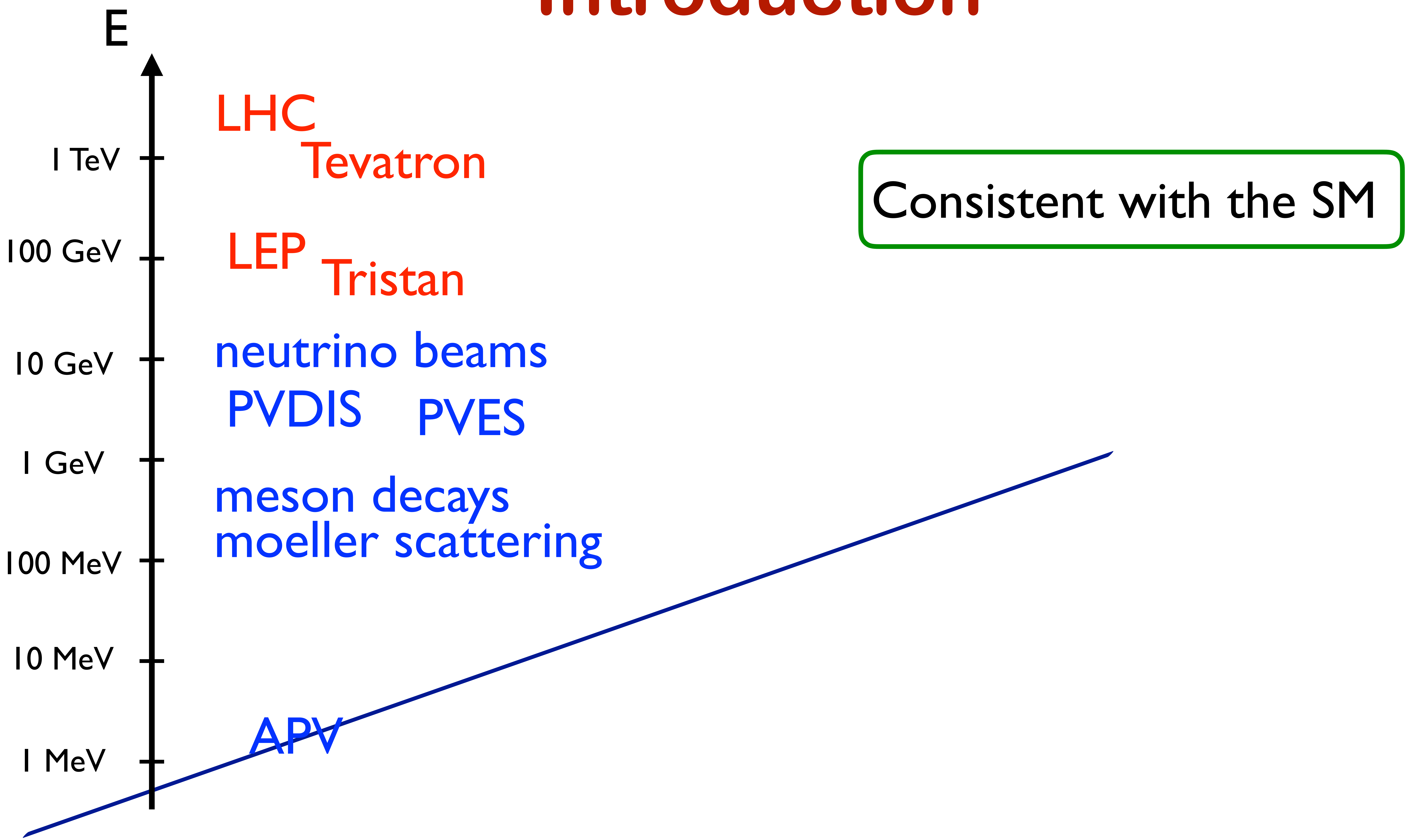
FAPESP

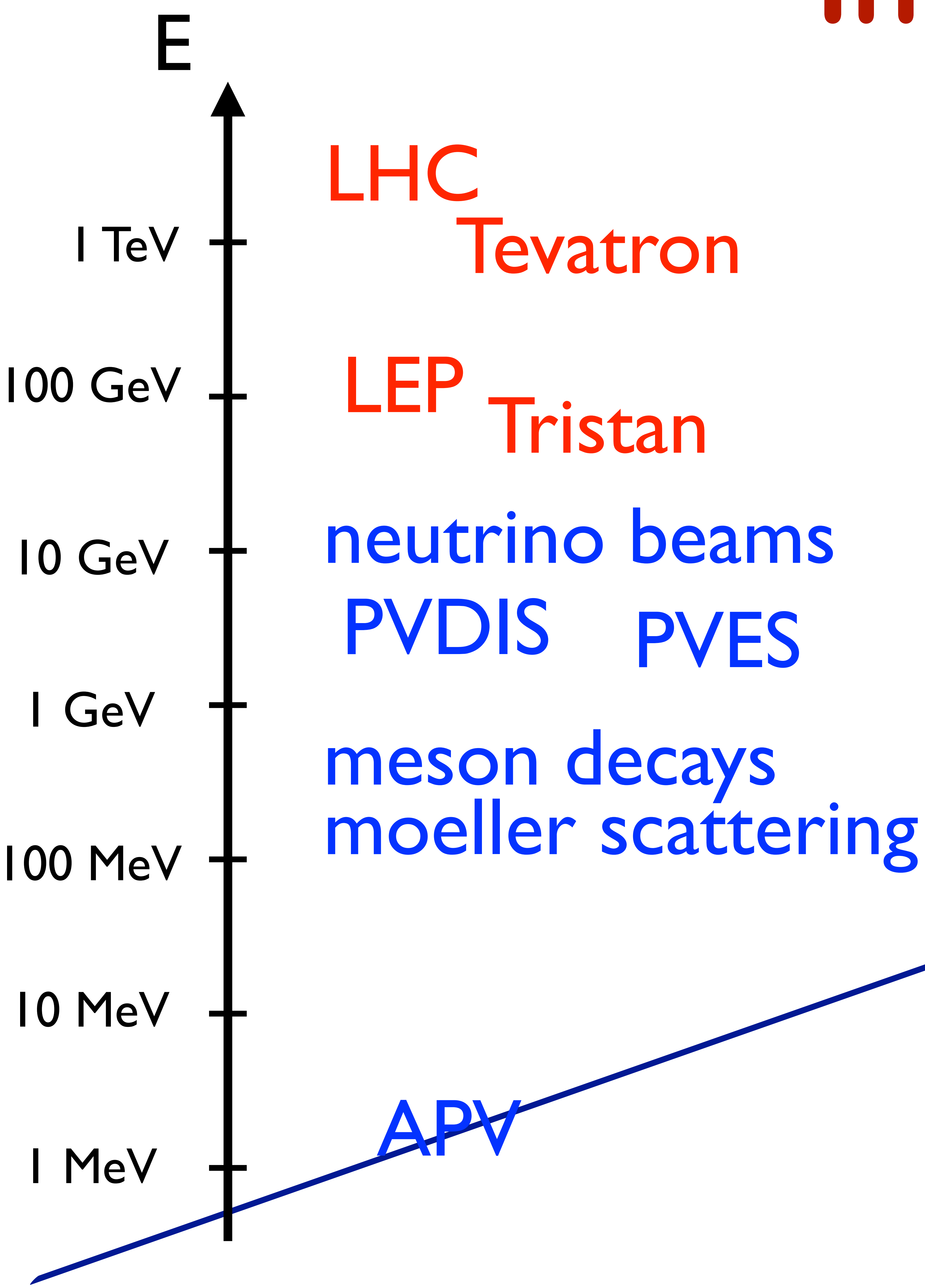
based on: A. Falkowski, GGdC, Z. Tabrizi,
JHEP04(2018)101, arXiv:1802.08296

Planck 2018, Bonn

Introduction



Introduction



Consistent with the SM

New Physics?

Neutrino masses, dark matter, inflation, baryon asymmetry

+

Strong CP problem, flavour hierarchy, gauge coupling unification, naturalness

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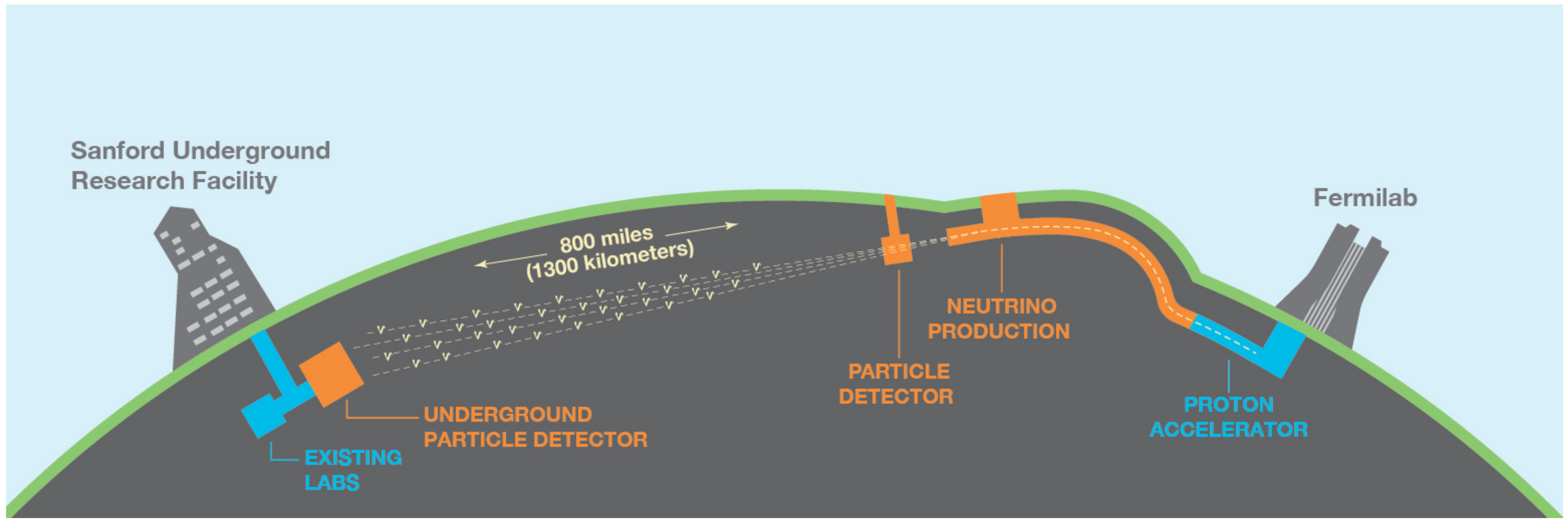
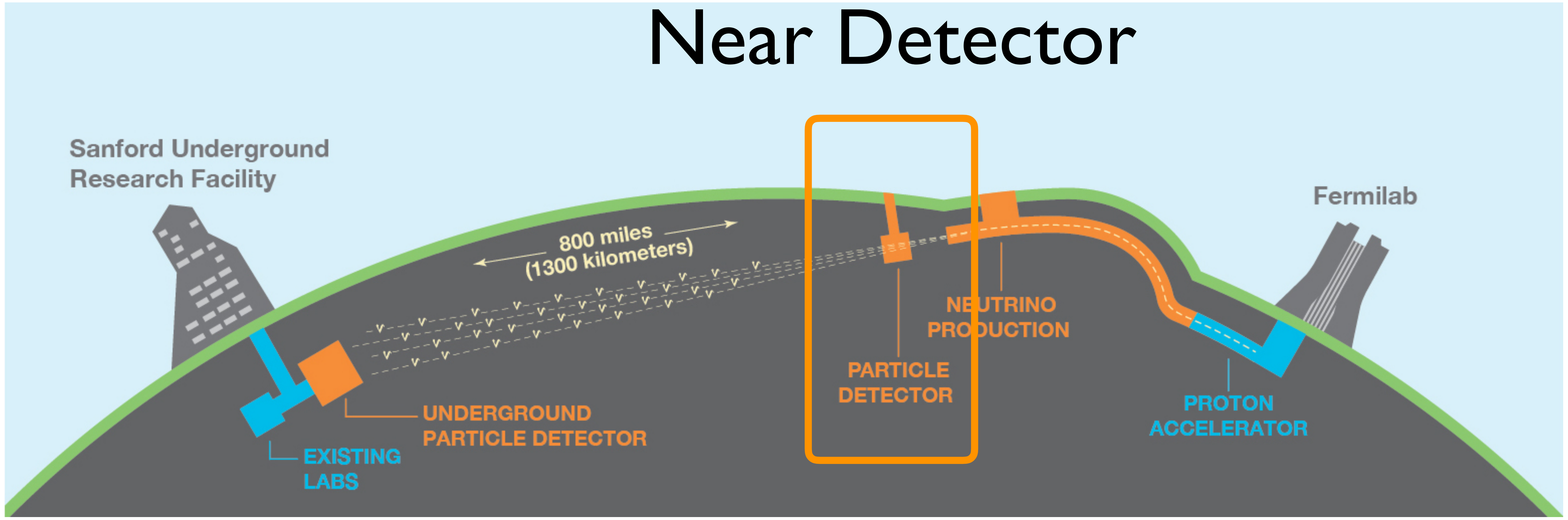
Introduction



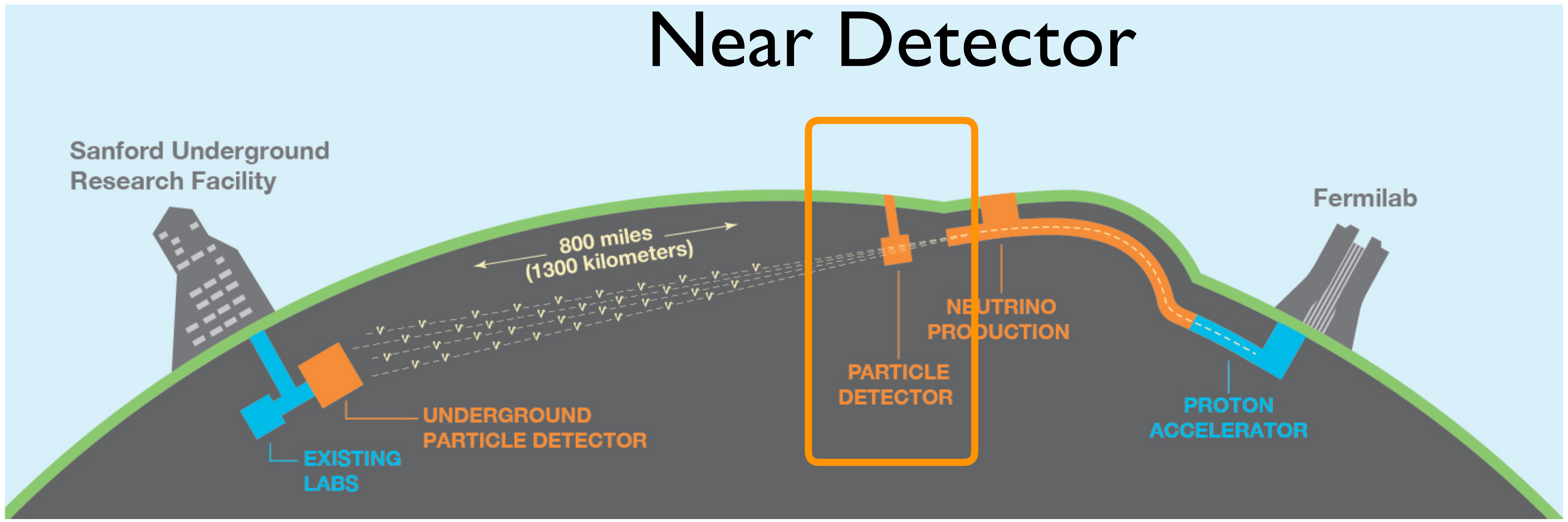
Main goals:
measure the parameters governing neutrino oscillations (CP violating phase in the PMNS matrix and neutrino mass ordering), searches for proton decay and for neutrino from core-collapse supernovas

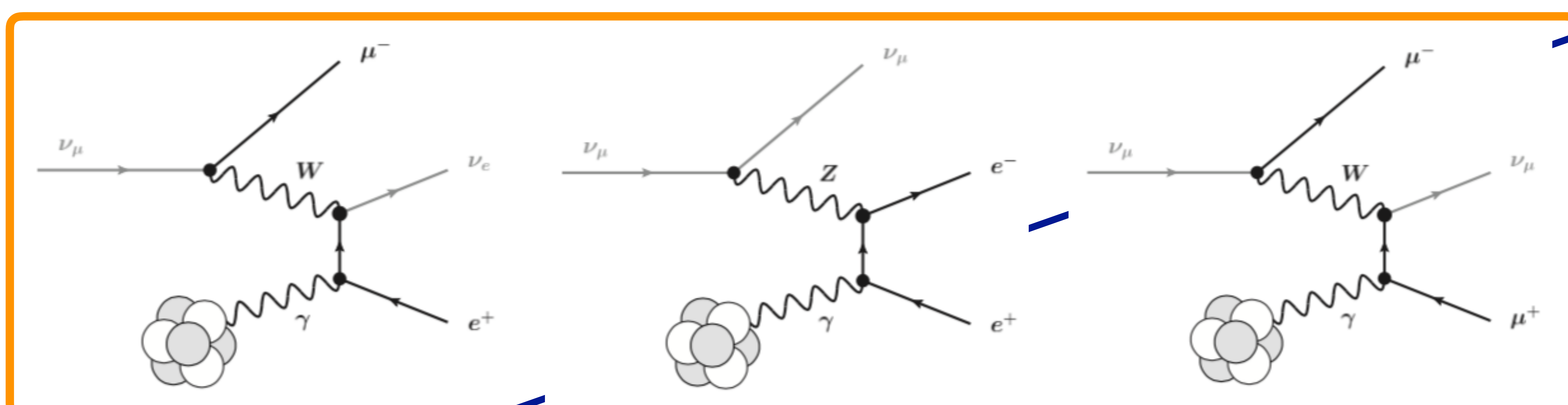
Introduction

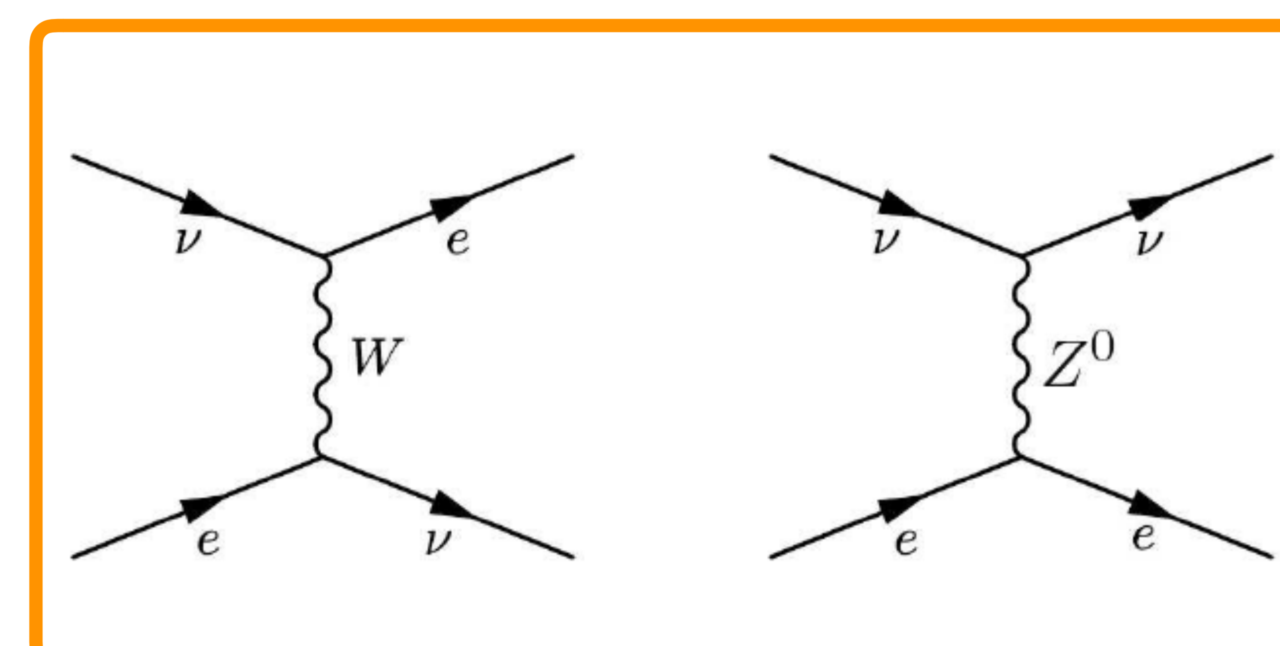


1) Constrain systematic uncertainties in neutrino flux and neutrino scattering cross section;
2) neutrino - nucleus/electron scattering measurement and BSM searches;

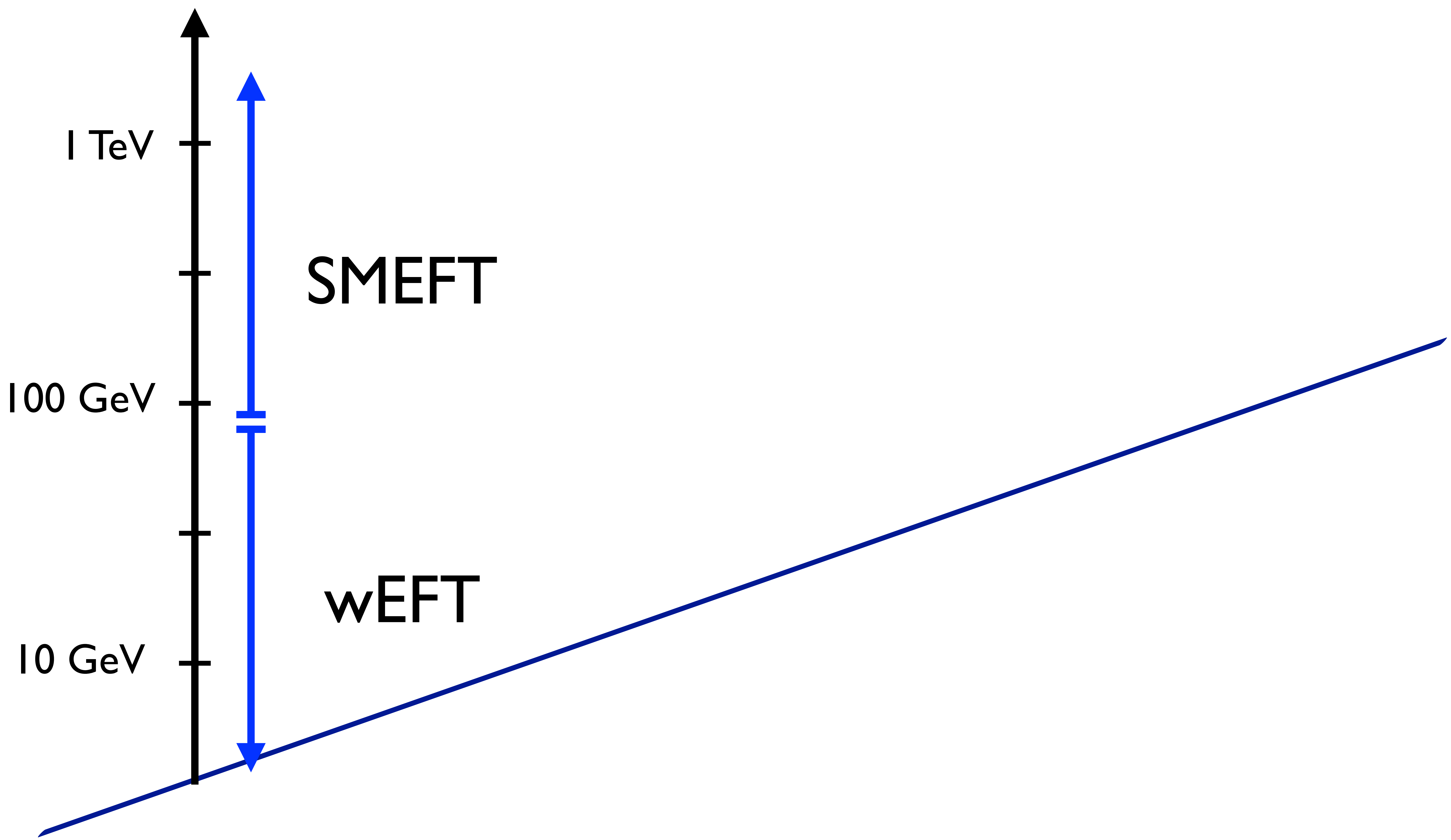
Introduction





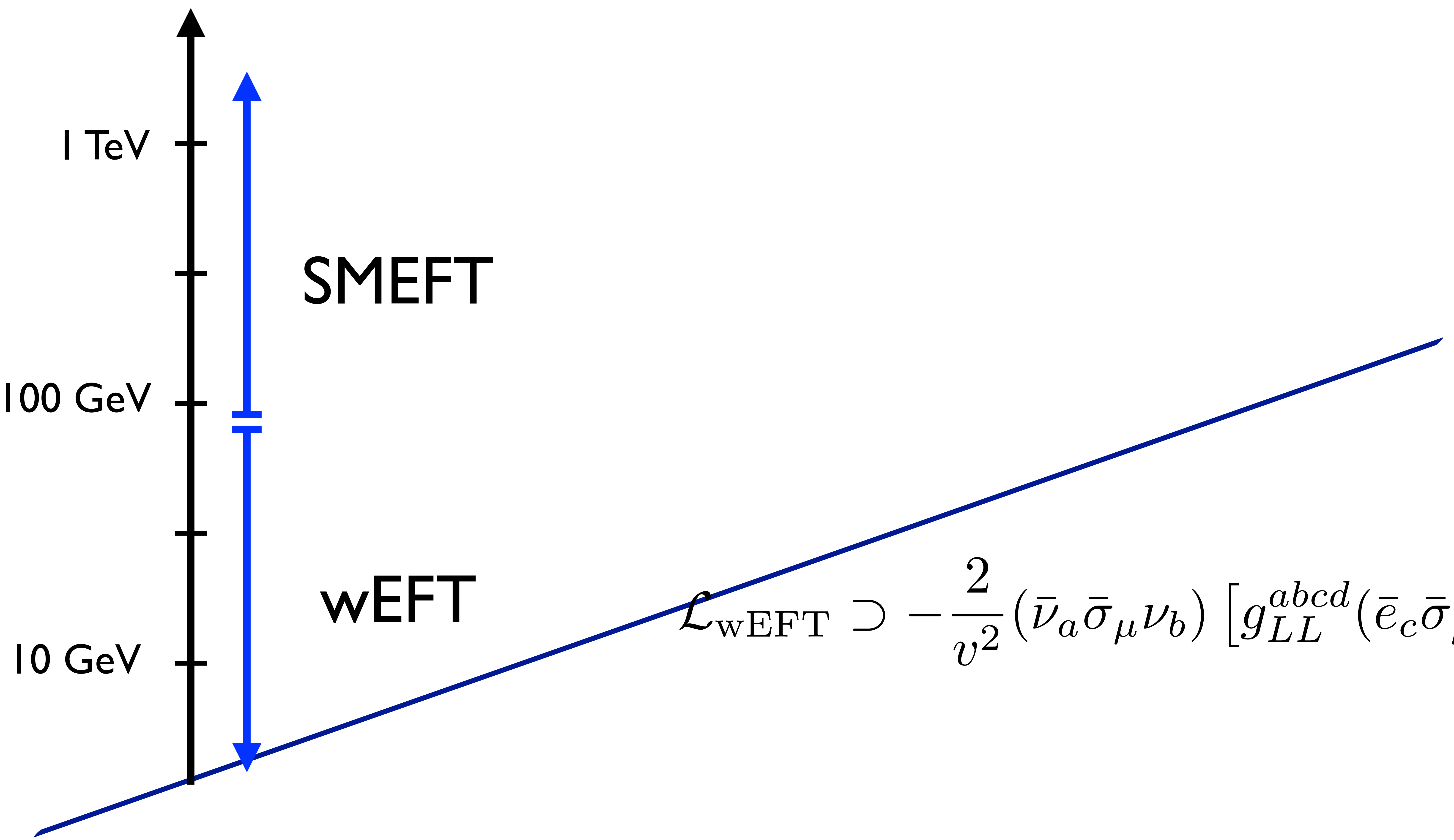


Formalism



Formalism

Neutrino interactions with charged leptons



$$\mathcal{L}_{\rm wEFT} \supset -\frac{2}{v^2}(\bar\nu_a \bar\sigma_\mu \nu_b)\left[g_{LL}^{abcd}(\bar e_c \bar\sigma_\mu e_d) + g_{LR}^{abcd}(e_c^c \sigma_\mu \bar e_d^c)\right]$$

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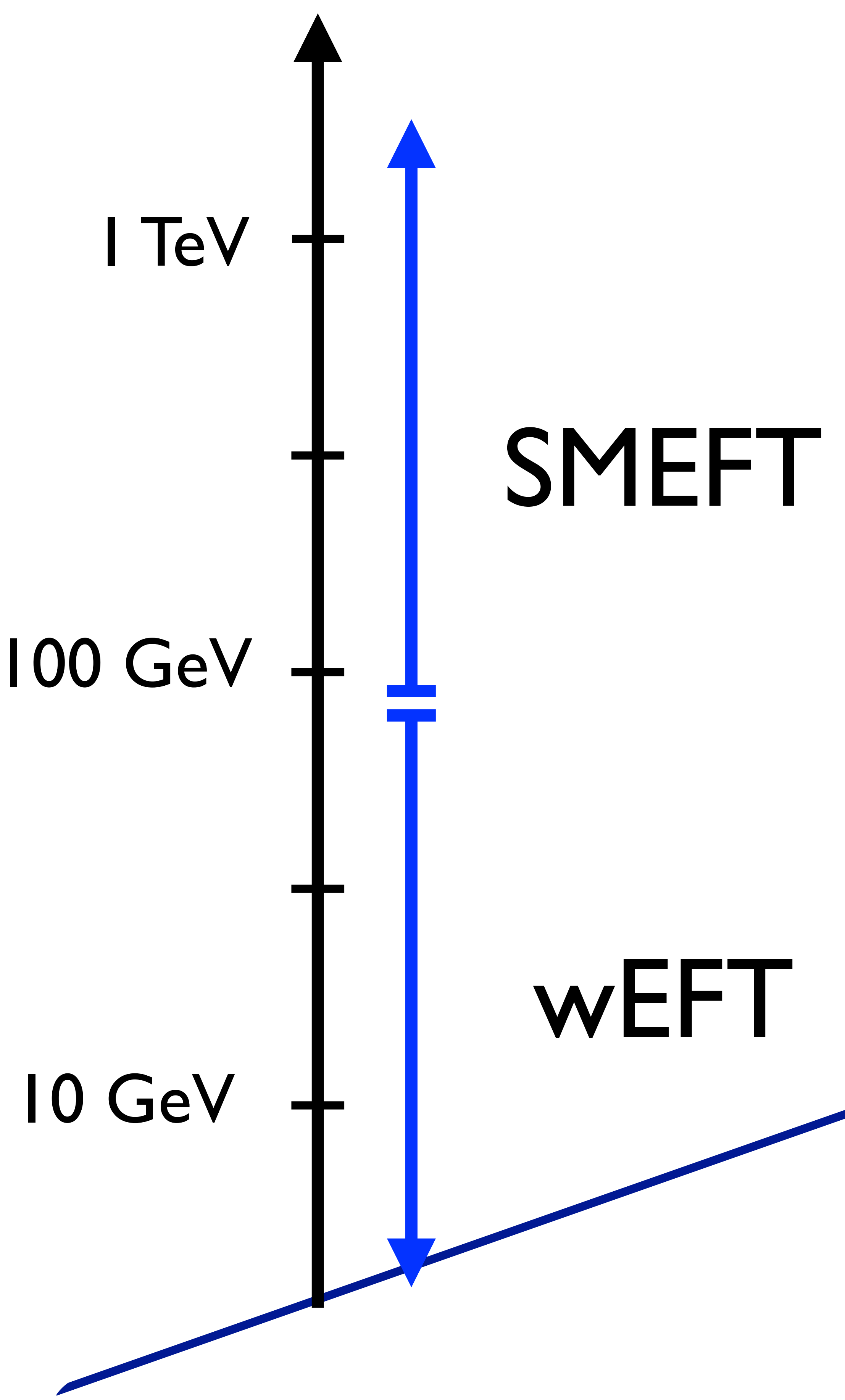
Formalism

Neutrino interactions with charged leptons

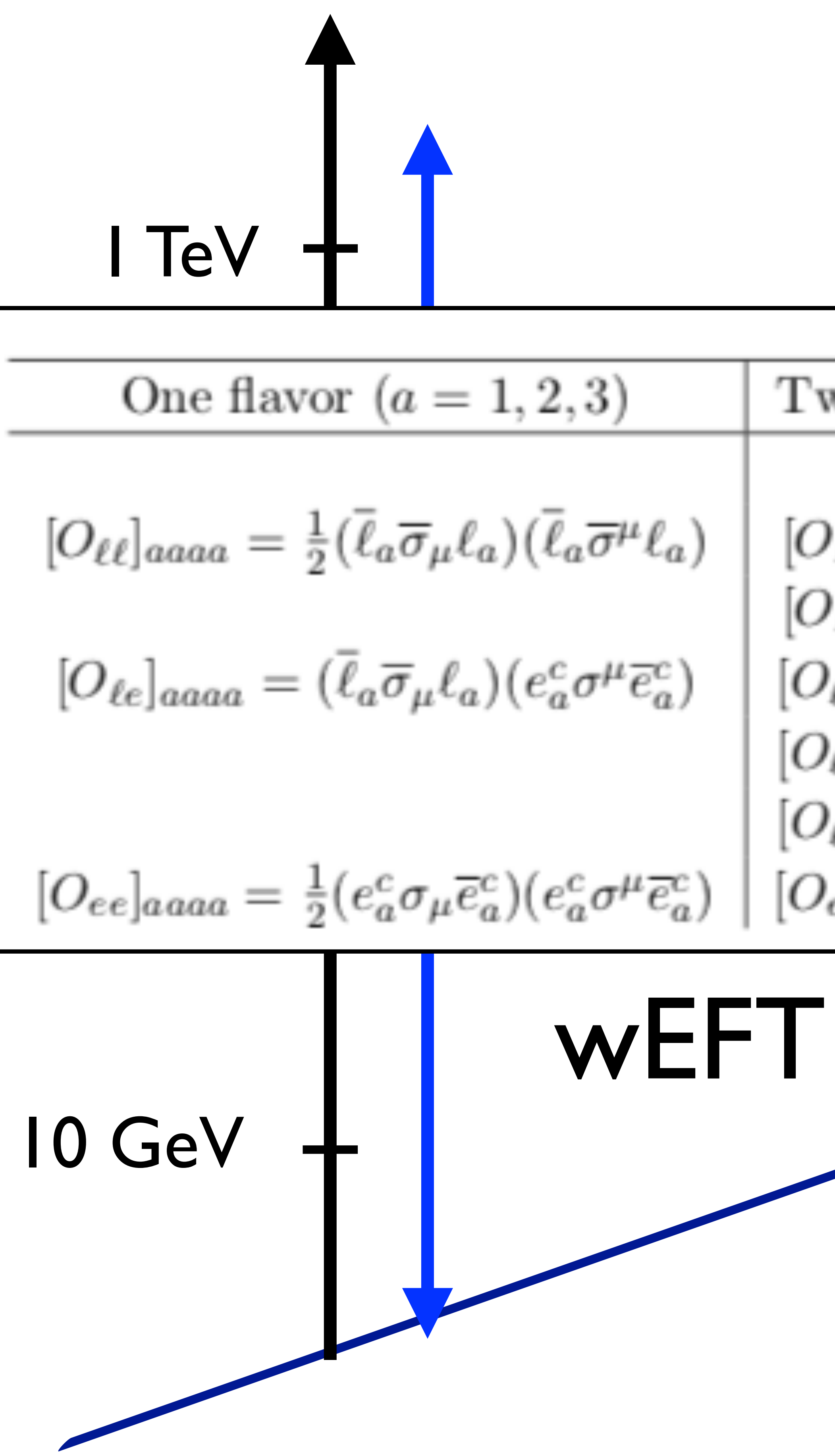


$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT} \quad \supset \quad & \frac{g_L}{\sqrt{2}}\left[W^{\mu+}\bar{\nu}_a\bar{\sigma}_\mu(1+\delta g_L^{We_a})e_a + \text{h.c.}\right] \\
+ \quad & \sqrt{g_L^2+g_Y^2}\,Z^\mu e_a^c\sigma_\mu\left(-s_\theta^2 Q_f + \delta g_R^{Ze_a}\right)\bar{e}_a^c \\
+ \quad & \sqrt{g_L^2+g_Y^2}\,Z^\mu \sum_{f=e,\nu}\bar{f}_a\bar{\sigma}_\mu\left(T_3^f - s_\theta^2 Q_f + \delta g_L^{Zf_a}\right)f_a
\end{aligned}
$$

$$
\mathcal{L}_{\rm wEFT} \supset -\frac{2}{v^2}(\bar{\nu}_a\bar{\sigma}_\mu\nu_b)\left[g_{LL}^{abcd}(\bar{e}_c\bar{\sigma}_\mu e_d) + g_{LR}^{abcd}(e_c^c\sigma_\mu\bar{e}_d^c)\right]
$$

Formalism

Neutrino interactions with charged leptons



One flavor $(a=1,2,3)$	Two flavors $(a<b=1,2,3)$
$[O_{\ell\ell}]_{aaaa} = \frac{1}{2}(\bar\ell_a\bar\sigma_\mu\ell_a)(\bar\ell_a\bar\sigma^\mu\ell_a)$	$[O_{\ell\ell}]_{aabb} = (\bar\ell_a\bar\sigma_\mu\ell_a)(\bar\ell_b\bar\sigma^\mu\ell_b)$
	$[O_{\ell\ell}]_{abba} = (\bar\ell_a\bar\sigma_\mu\ell_b)(\bar\ell_b\bar\sigma^\mu\ell_a)$
$[O_{\ell e}]_{aaaa} = (\bar\ell_a\bar\sigma_\mu\ell_a)(e^c_a\sigma^\mu\bar e^c_a)$	$[O_{\ell e}]_{aabb} = (\bar\ell_a\bar\sigma_\mu\ell_a)(e^c_b\sigma^\mu\bar e^c_b)$
	$[O_{\ell e}]_{bbaa} = (\bar\ell_b\bar\sigma_\mu\ell_b)(e^c_a\sigma^\mu\bar e^c_a)$
	$[O_{\ell e}]_{abba} = (\bar\ell_a\bar\sigma_\mu\ell_b)(e^c_b\sigma^\mu\bar e^c_a)$
$[O_{ee}]_{aaaa} = \frac{1}{2}(e^c_a\sigma_\mu\bar e^c_a)(e^c_a\sigma^\mu\bar e^c_a)$	$[O_{ee}]_{aabb} = (e^c_a\sigma_\mu\bar e^c_a)(e^c_b\sigma^\mu\bar e^c_b)$

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{g_L}{\sqrt{2}}\left[W^{\mu+}\bar\nu_a\bar\sigma_\mu(1+\delta g_L^{We_a})e_a + \mathrm{h.c.}\right]$$
$$+\sqrt{g_L^2+g_Y^2}\,Z^\mu e^c_a\sigma_\mu\left(-s_\theta^2 Q_f+\delta g_R^{Ze_a}\right)\bar e^c_a$$
$$+\sqrt{g_L^2+g_Y^2}\,Z^\mu\sum_{f=e,\nu}\bar f_a\bar\sigma_\mu\left(T_3^f-s_\theta^2 Q_f+\delta g_L^{Zf_a}\right)f_a$$

$$\mathcal{L}_{\mathrm{wEFT}} \supset -\frac{2}{v^2}(\bar\nu_a\bar\sigma_\mu\nu_b)\left[g_{LL}^{abcd}(\bar e_c\bar\sigma_\mu e_d)+g_{LR}^{abcd}(e^c_c\sigma_\mu\bar e^c_d)\right]$$

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Formalism

Neutrino interactions with charged leptons

$$\delta g_L^{Z\nu_a} = \delta g_L^{We_a} + \delta g_L^{Ze_a}$$

SM

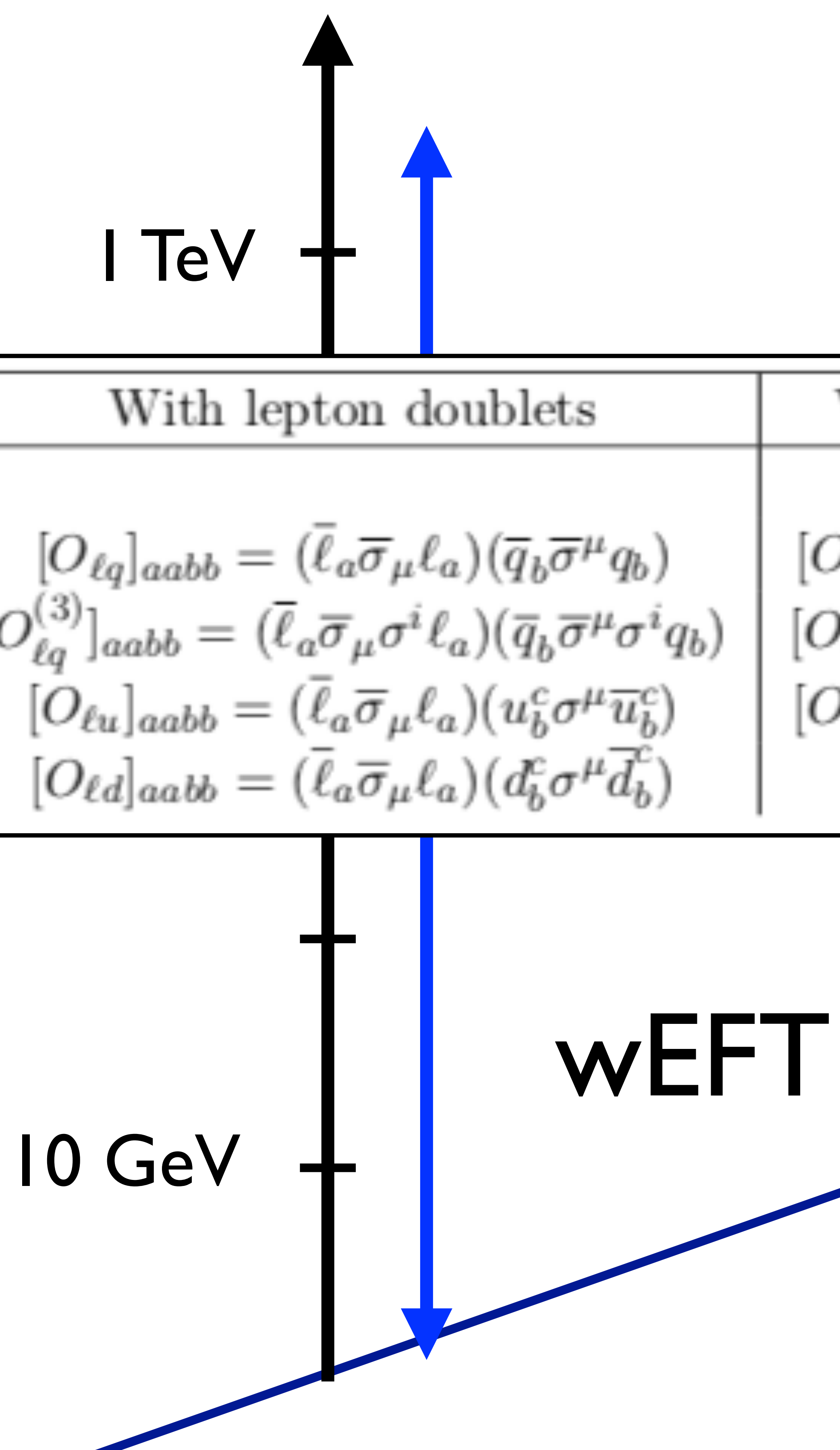
Shifted Z couplings

$$g_{LL}^{1111} = \frac{1}{2} + s_\theta^2 - \frac{1}{2}[c_{\ell\ell}]_{1111} + \frac{1}{2}[c_{\ell\ell}]_{1221} - \delta g_L^{W\mu} + 2s_\theta^2\left(\delta g_L^{We} + \delta g_L^{Ze}\right)$$

$$g_{LR}^{1111} = s_\theta^2 - \frac{1}{2}[c_{\ell e}]_{1111} + \delta g_R^{Ze} + 2s_\theta^2\left(\delta g_L^{We} + \delta g_L^{Ze}\right)$$

Tree-level matching of
4-fermion operators

Formalism



With lepton doublets	Without lepton doublets
$[O_{\ell q}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(\bar{q}_b \bar{\sigma}^\mu q_b)$	$[O_{eq}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(\bar{q}_b \bar{\sigma}^\mu q_b)$
$[O^{(3)}_{\ell q}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \sigma^i \ell_a)(\bar{q}_b \bar{\sigma}^\mu \sigma^i q_b)$	$[O_{eu}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(u^c_b \sigma^\mu \bar{u}^c_b)$
$[O_{\ell u}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(u^c_b \sigma^\mu \bar{u}^c_b)$	$[O_{ed}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(d^c_b \sigma^\mu \bar{d}^c_b)$
$[O_{\ell d}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(d^c_b \sigma^\mu \bar{d}^c_b)$	

Neutrino interactions with quarks

$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT} \quad \supset \quad & \sqrt{g_L^2 + g_Y^2}\, Z^\mu \sum_{q=u,d} \Big[\bar{q}\bar{\sigma}_\mu \left((T_3^q - s_\theta^2 Q_q) + \delta g_L^{Zq} \right) q \\
+ \quad & q^c \sigma_\mu \left(- s_\theta^2 Q_q + \delta g_R^{Zq} \right) \bar{q}^c \Big] \\
+ \quad & \left[W^{\mu +} \bar{u} \bar{\sigma}_\mu \left(V_{ud} + \delta g_L^{W q_1} \right) d + \text{h.c.} \right]
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\rm wEFT} \quad \supset \quad & - \frac{2 \hat{V}_{ud}}{v^2} (1 + \bar{\epsilon}_L^{d e_a}) (\bar{e}_a \bar{\sigma}_\mu \nu_a)(\bar{u}\, \bar{\sigma}^\mu d) \\
- \quad & \frac{2}{v^2} (\bar{\nu}_a \bar{\sigma}_\mu \nu_a) \sum_{q=u,d} \left[g_{LL}^{\nu_a q}\, \bar{q}\, \bar{\sigma}^\mu q + g_{LR}^{\nu_a q} (q^c \sigma^\mu \bar{q}^c) \right]
\end{aligned}
$$

Neutrino scattering in DUNE

3 years neutrino mode +
3 years antineutrino mode

Efficiency: 85% for ν_μ ($\bar{\nu}_\mu$), 80% for ν_e ($\bar{\nu}_e$)

neutrino flux

$$N_{\text{events}} = \boxed{\text{time}} \times \boxed{N_{\text{T}}} \times \boxed{\epsilon} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu} \boxed{\sigma(E_\nu)}$$

N_T for 1.1x10^{21} proton on target (POT) in (anti-)neutrino mode with a 120 GeV proton beam with 1.2 MW of power for a Near Detector of 100 tonnes Argon mass

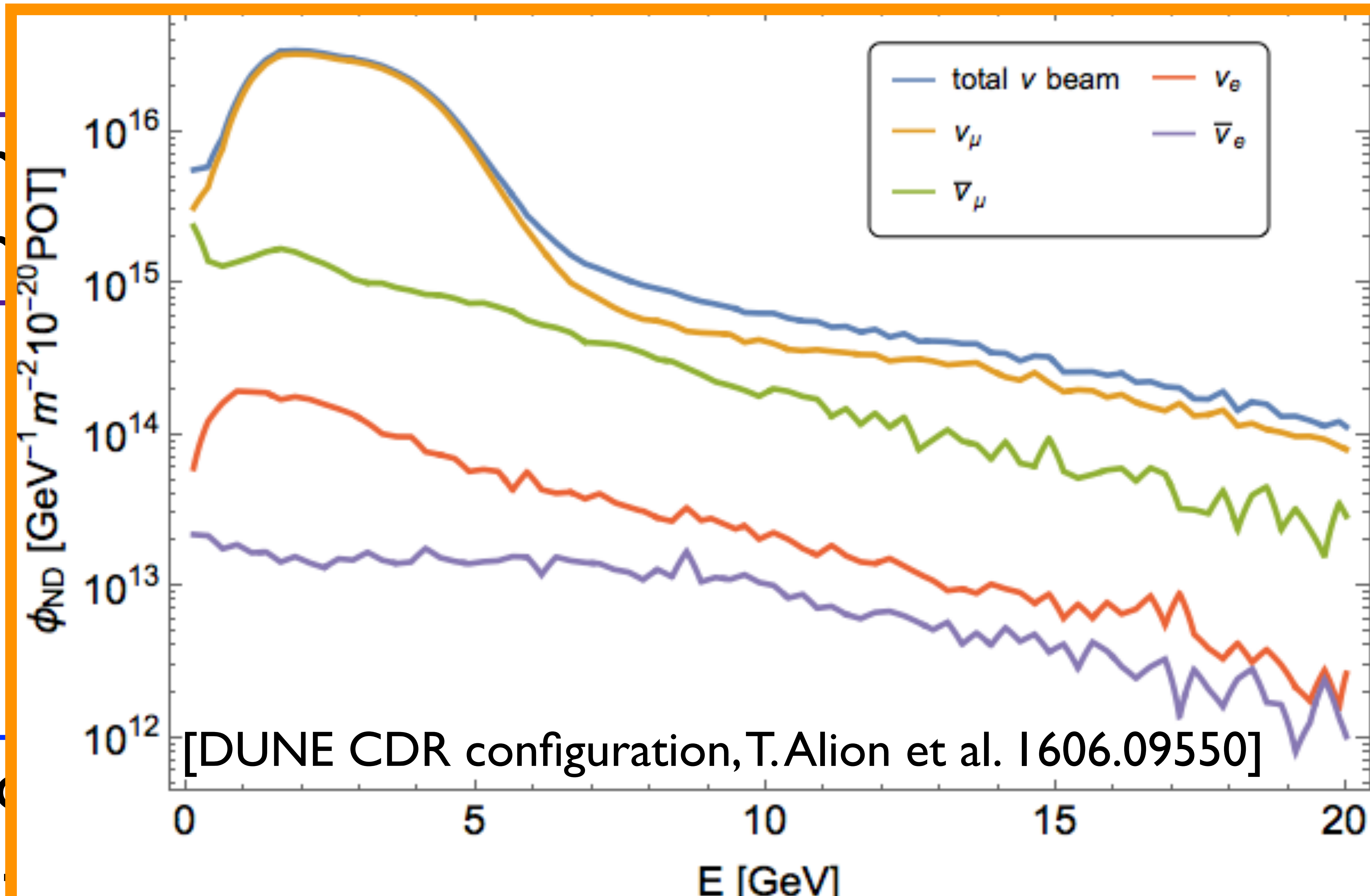
Cross section of the process

Neutrino scattering in DUNE

3 year
3 year

ν_μ
$\nu_e)$

neutrino flux

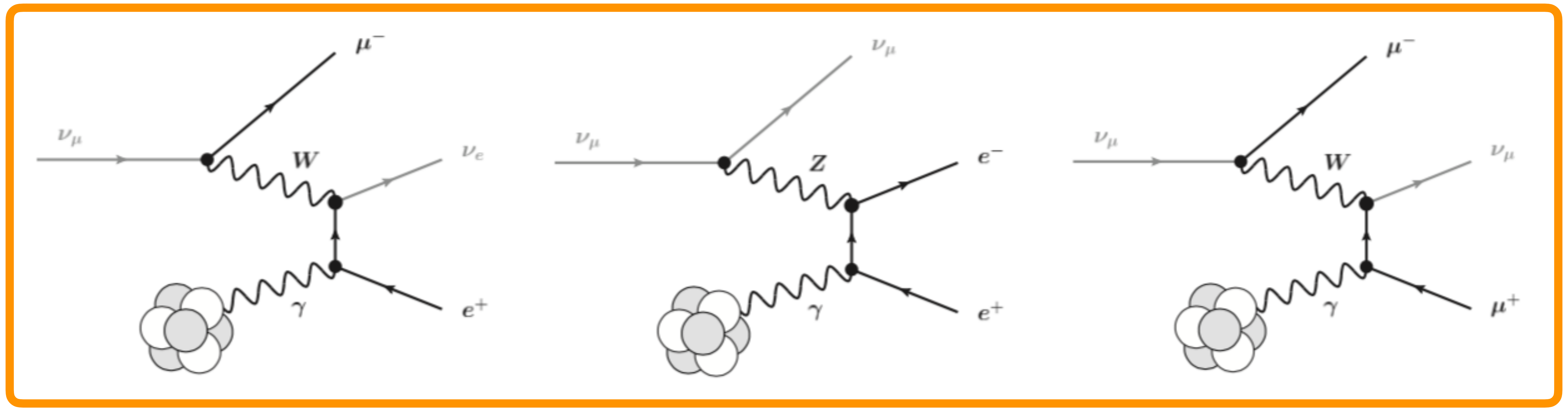


$$dE_\nu \boxed{\frac{d\phi(E_\nu)}{dE_\nu}} \boxed{\sigma(E_\nu)}$$

N_T fo
(anti-
proton beam with 1.2 MW of power for a Near Detector of 100 tonnes Argon mass

Cross section of the process

Neutrino trident production



[Phys.Lett. B245, 271(1990)]

$$\sigma_{\mathrm{CHARMII}}/\sigma_{\mathrm{SM}} = 1.58 \pm 0.57$$

[Phys.Rev.Lett. 66, 3117(1991)]

$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28$$

ν beam		$\overline{\nu}$ beam	
$\nu_\mu \to \nu_\mu \mu^- \mu^+$	357	$\overline{\nu}_\mu \to \overline{\nu}_\mu \mu^- \mu^+$	305
$\nu_e \to \nu_e \mu^- \mu^+$	1.27	$\overline{\nu}_e \to \overline{\nu}_e \mu^- \mu^+$	1.03

$$\frac{\sigma(\nu_b\gamma^* \to \nu_a \ell_c^- \ell_d^+)}{\sigma_{\mathrm{SM}}(\nu_b\gamma^* \to \nu_a \ell_c^- \ell_d^+)} = \frac{\sigma(\bar\nu_a\gamma^* \to \nu_b \ell_c^- \ell_d^+)}{\sigma_{\mathrm{SM}}(\bar\nu_a\gamma^* \to \nu_b \ell_c^- \ell_d^+)} \approx 1+2\frac{g^{abcd}_{LL,\mathrm{SM}}\delta g^{abcd}_{LL} + g^{abcd}_{LR,\mathrm{SM}}\delta g^{abcd}_{LR}}{(g^{abcd}_{LL,\mathrm{SM}})^2 + (g^{abcd}_{LR,\mathrm{SM}})^2}$$

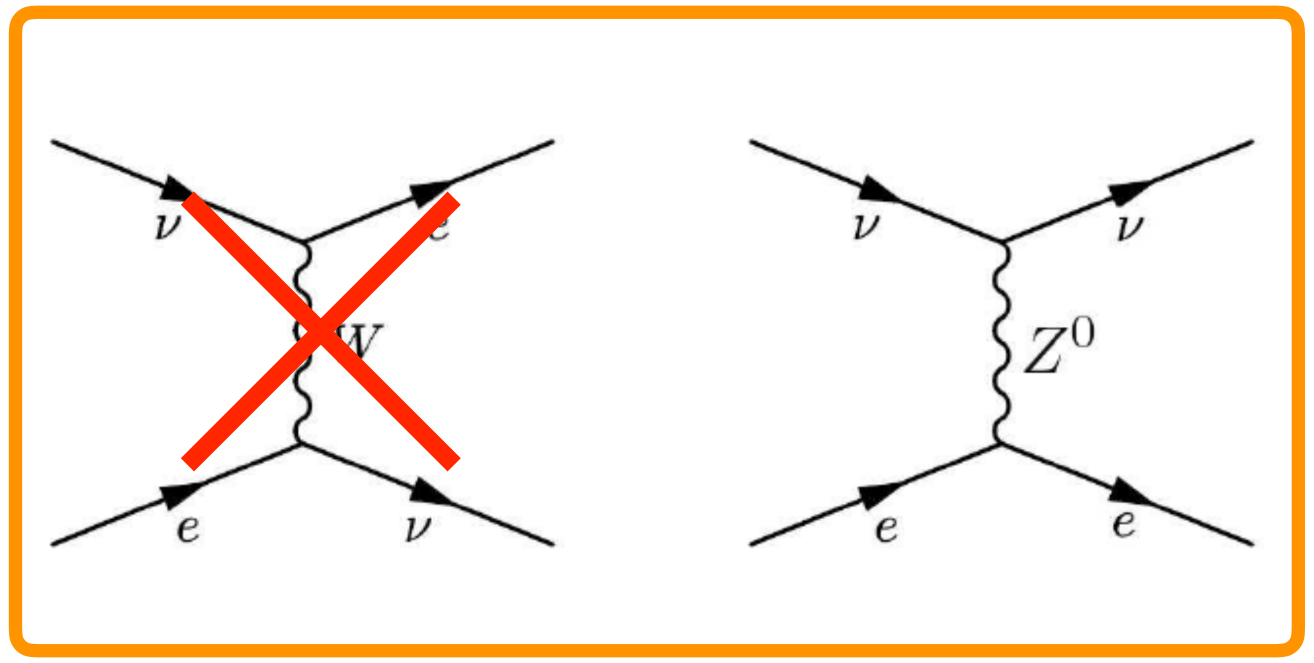
Neutrino trident production

ν beam		$\bar{\nu}$ beam	
$\nu_\mu \to \nu_\mu \mu^- \mu^+$	357	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^- \mu^+$	305
$\nu_e \to \nu_e \mu^- \mu^+$	1.27	$\bar{\nu}_e \to \bar{\nu}_e \mu^- \mu^+$	1.03

$$R_\mu \equiv \frac{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+) + \sigma(\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^- \mu^+)}{\sigma(\nu_\mu \to \nu_\mu \mu^- \mu^+)_{\rm SM} + \sigma(\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^- \mu^+)_{\rm SM}} = 1 \pm 0.039$$

$$\boxed{-0.039 < 2\frac{g^{2222}_{LL,\rm SM}\delta g^{2222}_{LL} + g^{2222}_{LR,\rm SM}\delta g^{2222}_{LR}}{(g^{2222}_{LL,\rm SM})^2 + (g^{2222}_{LR,\rm SM})^2} < 0.039}$$

Neutrino scattering off electrons

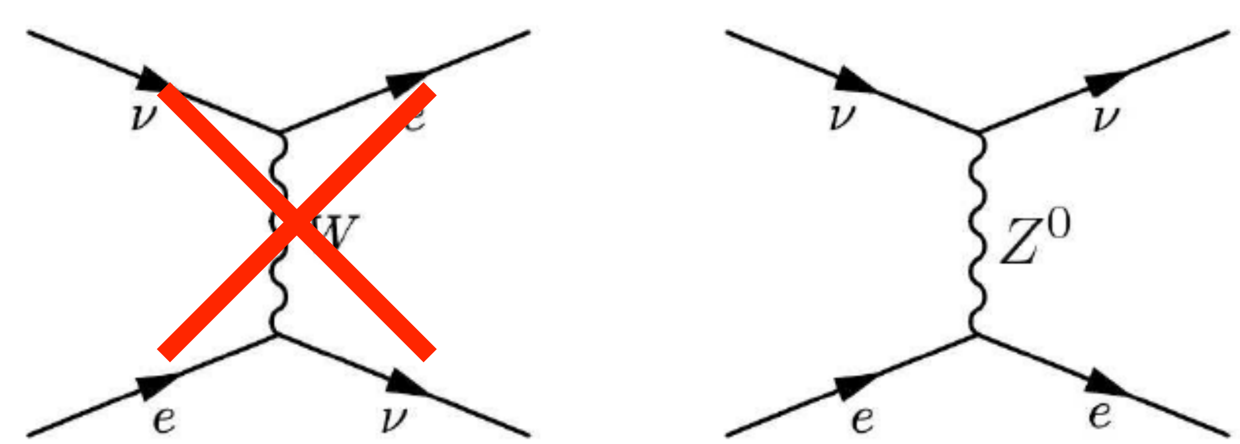


	$N_{\rm tot}^{\nu-e}$	$r_{\nu_\mu}^{\nu-e}$	$r_{\overline{\nu}_\mu}^{\nu-e}$	$r_{\nu_e}^{\nu-e}$	$r_{\overline{\nu}_e}^{\nu-e}$
ν-mode	1.69×10^6	0.898	0.059	0.040	0.003
$\overline{\nu}$-mode	1.29×10^6	0.103	0.867	0.013	0.017

$$\underset{\nu_\mu e^- \to \nu_e \mu^-}{E_{\rm th}^{CC}} = \frac{m_\mu^2}{2m_e} = 10.9 \text{ GeV}$$

$$\begin{aligned}
\sigma_{\nu_\mu e} &= \frac{s}{2\pi v^4}\left[(g_{LL}^{2211})^2 + \frac{1}{3}(g_{LR}^{2211})^2\right] \approx \frac{m_e E_\nu}{\pi v^4}\left[(g_{LL}^{2211})^2 + \frac{1}{3}(g_{LR}^{2211})^2\right] \\
\sigma_{\bar{\nu}_\mu e} &= \frac{s}{2\pi v^4}\left[(g_{LR}^{2211})^2 + \frac{1}{3}(g_{LL}^{2211})^2\right] \approx \frac{m_e E_\nu}{\pi v^4}\left[(g_{LR}^{2211})^2 + \frac{1}{3}(g_{LL}^{2211})^2\right]
\end{aligned}$$

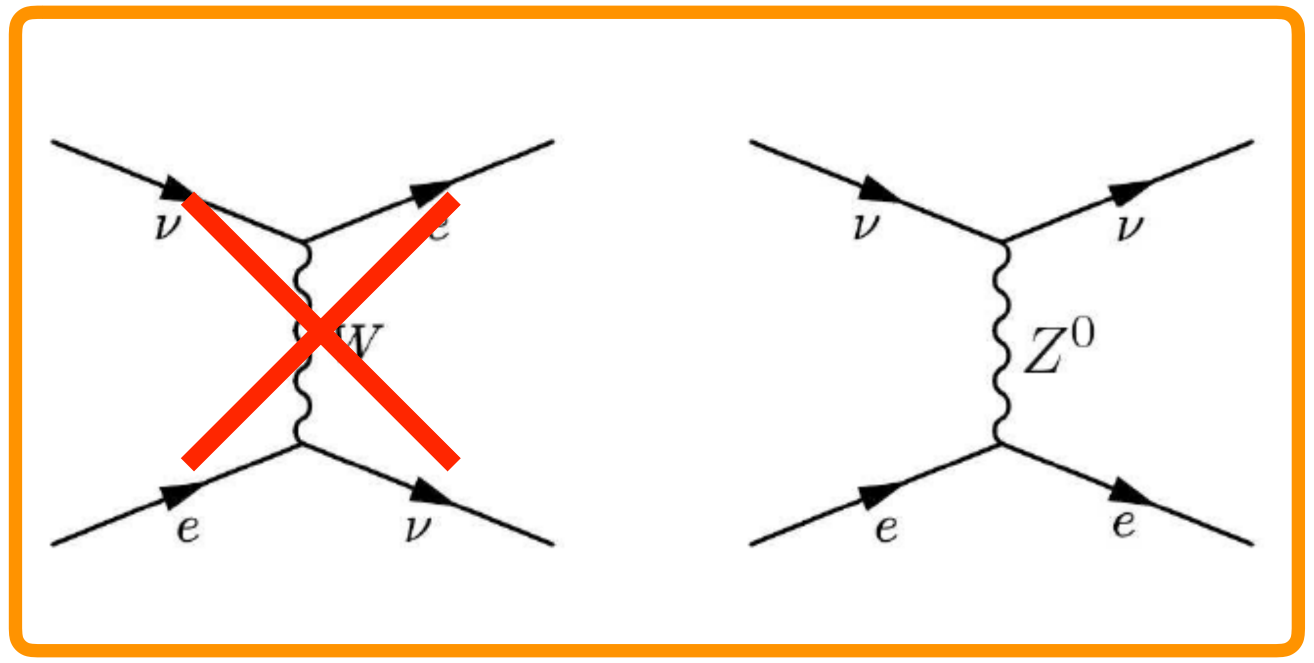
Neutrino scattering off electrons



	$N_{\rm tot}^{\nu-e}$	$r_{\nu_\mu}^{\nu-e}$	$r_{\overline{\nu}_\mu}^{\nu-e}$	$r_{\nu_e}^{\nu-e}$	$r_{\overline{\nu}_e}^{\nu-e}$
ν-mode	1.69×10^6	0.898	0.059	0.040	0.003
$\overline{\nu}$-mode	1.29×10^6	0.103	0.867	0.013	0.017

$$R^i_{\nu e} \equiv \frac{x_i \sigma_{\nu_\mu e} + \bar{x}_i \sigma_{\bar{\nu}_\mu e}}{x_i \sigma^{\rm SM}_{\nu_\mu e} + \bar{x}_i \sigma^{\rm SM}_{\bar{\nu}_\mu e}} \longrightarrow \begin{cases} x_\nu = 0.9 \\ \bar{x}_i = 1 - x_i \end{cases}$$

Neutrino scattering off electrons



	$N_{\rm tot}^{\nu-e}$	$r_{\nu_\mu}^{\nu-e}$	$r_{\overline{\nu}_\mu}^{\nu-e}$	$r_{\nu_e}^{\nu-e}$	$r_{\overline{\nu}_e}^{\nu-e}$
ν-mode	1.69×10^6	0.898	0.059	0.040	0.003
$\overline{\nu}$-mode	1.29×10^6	0.103	0.867	0.013	0.017

$$\delta R^i_{\nu e} = 2\frac{(1+2x_i)\,\delta g_{LL}^{2211} g_{LL,\rm SM}^{2211} + (3-2x_i)\,\delta g_{LR}^{2211} g_{LR,\rm SM}^{2211}}{(1+2x_i)\,(g_{LL,\rm SM}^{2211})^2 + (3-2x_i)\,(g_{LR,\rm SM}^{2211})^2}$$

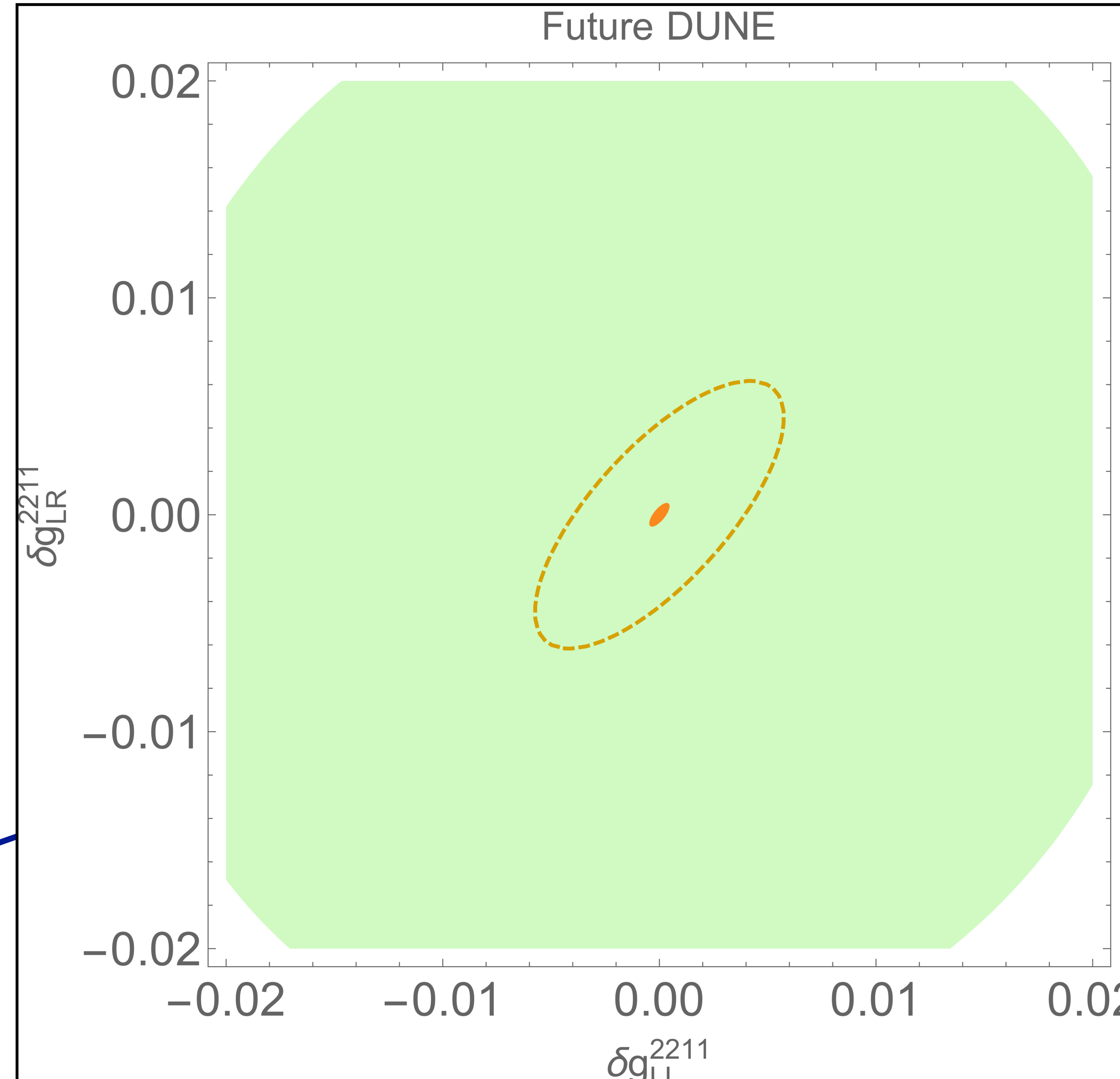
$$\boxed{-8.0 \times 10^{-4} < \delta R^{\nu}_{\nu e} < 8.0 \times 10^{-4} \qquad -9.1 \times 10^{-4} < \delta R^{\bar\nu}_{\nu e} < 9.1 \times 10^{-4}}$$

Neutrino scattering off electrons

CHARM +
CHARM II +
BNL-E734

stat. dominated

1% syst. Error



Neutrino scattering off nuclei

$$R_{\nu_a N} \equiv \frac{x\sigma_{\nu_a N\to\nu_a N} + \bar{x}\sigma_{\bar{\nu}_a N\to\bar{\nu}_a N}}{x\sigma_{\nu_a N\to e_a^- N} + \bar{x}\sigma_{\bar{\nu}_a N\to e_a^+ N}} = (g_L^{\nu_a})^2 + r^{-1}(g_R^{\nu_a})^2$$

$$r = \frac{x\sigma_{\nu_a N\to e_a^- N} + \bar{x}\sigma_{\bar{\nu}_a N\to e_a^+ N}}{x\sigma_{\nu_a N\to e_a^- N} + \bar{x}\sigma_{\bar{\nu}_a N\to e_a^+ N}}$$

generalised Llewellyn-Smith formula

	N_{tot}^{CC}	$r_{\nu_\mu}^{CC}$	$r_{\bar{\nu}_\mu}^{CC}$	$r_{\nu_e}^{CC}$	$r_{\bar{\nu}_e}^{CC}$
ν-mode	4.25×10^8	0.964	0.028	0.007	0.001
$\bar{\nu}$-mode	1.74×10^8	0.201	0.790	0.004	0.005

	N_{tot}^{NC}	$r_{\nu_\mu}^{NC}$	$r_{\bar{\nu}_\mu}^{NC}$	$r_{\nu_e}^{NC}$	$r_{\bar{\nu}_e}^{NC}$
ν-mode	1.48×10^8	0.956	0.037	0.006	0.001
$\bar{\nu}$-mode	7.58×10^7	0.157	0.835	0.003	0.005

only dependence on the nuclear structure

$$r_\nu \sim 2.5$$
$$r_{\bar{\nu}} \sim 0.4$$

but

1) the ^{40}Ar target nuclei are not isoscalar and the LS formula has to be corrected
2) neglected admixture of electron neutrinos

Cannot neglect systematics!

Neutrino scattering off nuclei

$$R^i_{\nu_\mu N} = R^i_{\nu_\mu N,\mathrm{SM}}(1 + \delta R^i_{\nu_\mu N})$$

$$-9.6 \times 10^{-5} < \delta R^{\nu}_{\nu_\mu N} < 9.6 \times 10^{-5}$$
$$-1.4 \times 10^{-4} < \delta R^{\bar{\nu}}_{\nu_\mu N} < 1.4 \times 10^{-4}$$

Neutrino scattering off nuclei

$$R^i_{\nu_\mu N} = R^i_{\nu_\mu N,\mathrm{SM}}(1 + \delta R^i_{\nu_\mu N})$$

$$-9.6 \times 10^{-5} < \delta R^{\nu}_{\nu_\mu N} < 9.6 \times 10^{-5}$$
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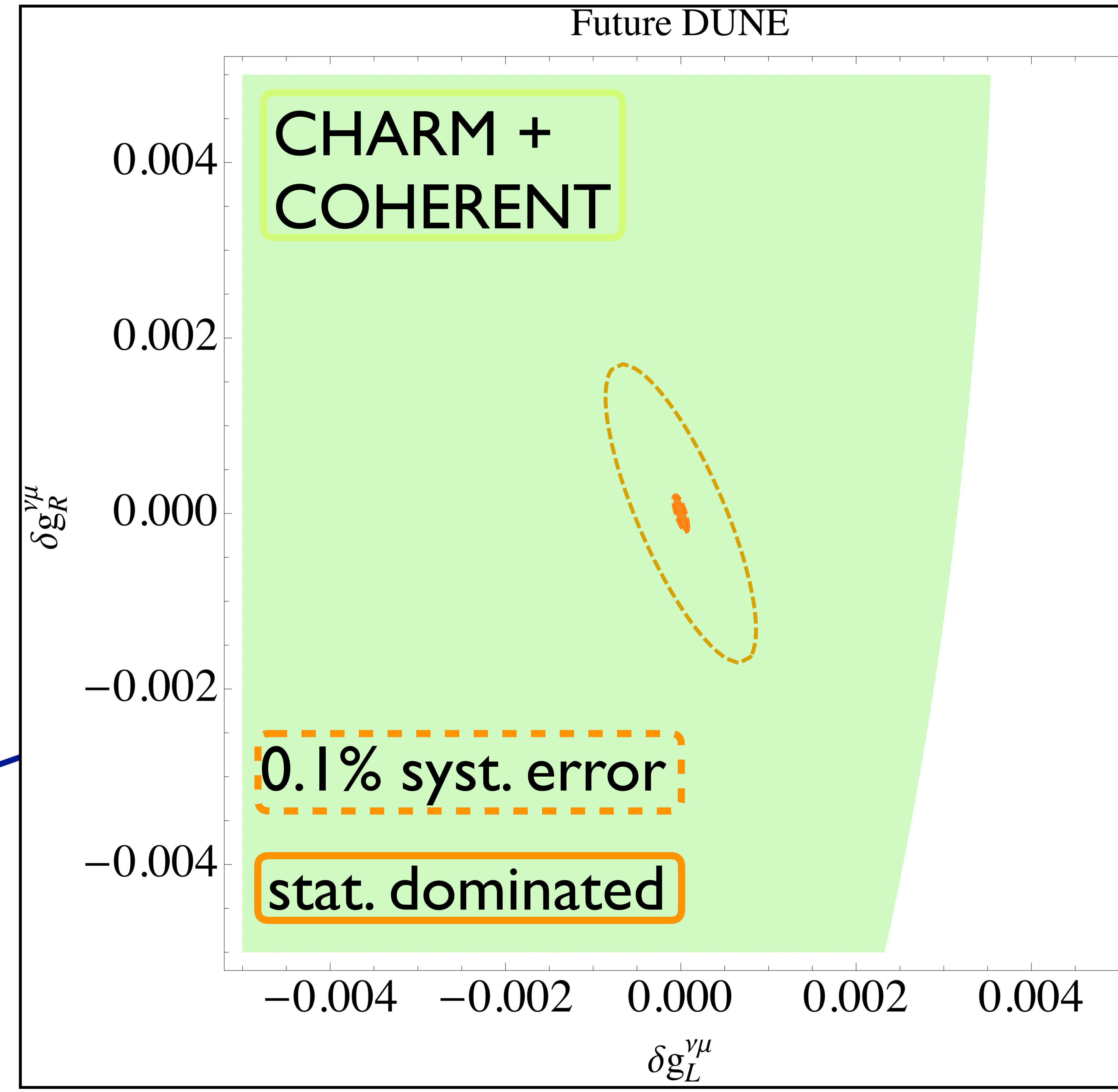

Results

[Falkowski et al., 1706.03783]

Coefficient	Δ(current)	Δ (no sys.)	Δ (0.1% sys.)	Δ (1% sys.)
δg_L^{We}	3.5	0.37	2.5	3.4
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
δg_L^{Zu}	1.9	0.34	1.4	1.5
δg_R^{Zu}	9.5	0.57	2.0	2.3
δg_L^{Zd}	1.9	0.28	1.4	1.6
δg_R^{Zd}	9.7	1.1	3.0	3.1
$\delta g_R^{Wq_1}$	1.9	0.36	1.7	1.9
$[c_{\ell\ell}]_{1122}$	28	2.6	2.6	21
$[c_{\ell e}]_{2211}$	45	3.1	3.1	27
$[c_{\ell\ell}]_{2222}$	2100	310	310	310
$[c_{\ell e}]_{2222}$	6300	970	970	970
$[c_{\ell q}^{(3)}]_{1111}$	1.9	0.36	1.7	1.9
$[c_{\ell q}^{(3)}]_{2211}$	12	1.8	10	12
$[c_{\ell q}]_{2211}$	210	3.0	30	180
$[c_{\ell u}]_{2211}$	190	1.2	9.5	85
$[c_{\ell d}]_{2211}$	370	2.4	19	170

$\times 10^{-4}$

One SMEFT parameter at a time

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Results

[Falkowski et al., 1706.03783]

Coefficient	Δ(current)	Δ (no sys.)	Δ (0.1% sys.)	Δ (1% sys.)
δg_L^{We}	3.5	0.37	2.5	3.4
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
δg_L^{Zu}	1.9	0.34	1.4	1.5
δg_R^{Zu}	9.5	0.57	2.0	2.3
δg_L^{Zd}	1.9	0.28	1.4	1.6
δg_R^{Zd}	9.7	1.1	3.0	3.1
$\delta g_R^{Wq_1}$	1.9	0.36	1.7	1.9
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$[c_{\ell u}]_{2211}$	190	1.2	9.5	85
$[c_{\ell d}]_{2211}$	370	2.4	19	170

$\times 10^{-4}$

One SMEFT parameter at a time

Planck 2018

Results

[Falkowski et al., 1706.03783]

Coefficient	Δ(current)	Δ (no sys.)	Δ (0.1% sys.)	Δ (1% sys.)
δg_L^{We}	3.5	0.37	2.5	3.4
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
δg_L^{Zu}	1.9	0.34	1.4	1.5
δg_R^{Zu}	9.5	0.57	2.0	2.3
δg_L^{Zd}	1.9	0.28	1.4	1.6
δg_R^{Zd}	9.7	1.1	3.0	3.1
$\delta g_R^{Wq_1}$	1.9	0.36	1.7	1.9
$[c_{\ell\ell}]_{1122}$	28	2.6	2.6	21
$[c_{\ell e}]_{2211}$	45	3.1	3.1	27
$[c_{\ell\ell}]_{2222}$	2100	310	310	310
$[c_{\ell e}]_{2222}$	6300	970	970	970
$[c_{\ell q}^{(3)}]_{1111}$	1.9	0.36	1.7	1.9
$[c_{\ell q}^{(3)}]_{2211}$	12	1.8	10	12
$[c_{\ell q}]_{2211}$	210	3.0	30	180
$[c_{\ell u}]_{2211}$	190	1.2	9.5	85
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One SMEFT parameter at a time

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Conclusions

We investigated the precision reach in the determination of the SMEFT Wilson coefficients relevant for the DUNE experiment.

We studied observables related to trident production, neutrino scattering off electrons and neutrino scattering off nuclei at the DUNE Near Detector.

The results show the importance of precision measurements in DUNE and the importance of the effort to reduce the experimental and theoretical source of systematic errors.

Backup

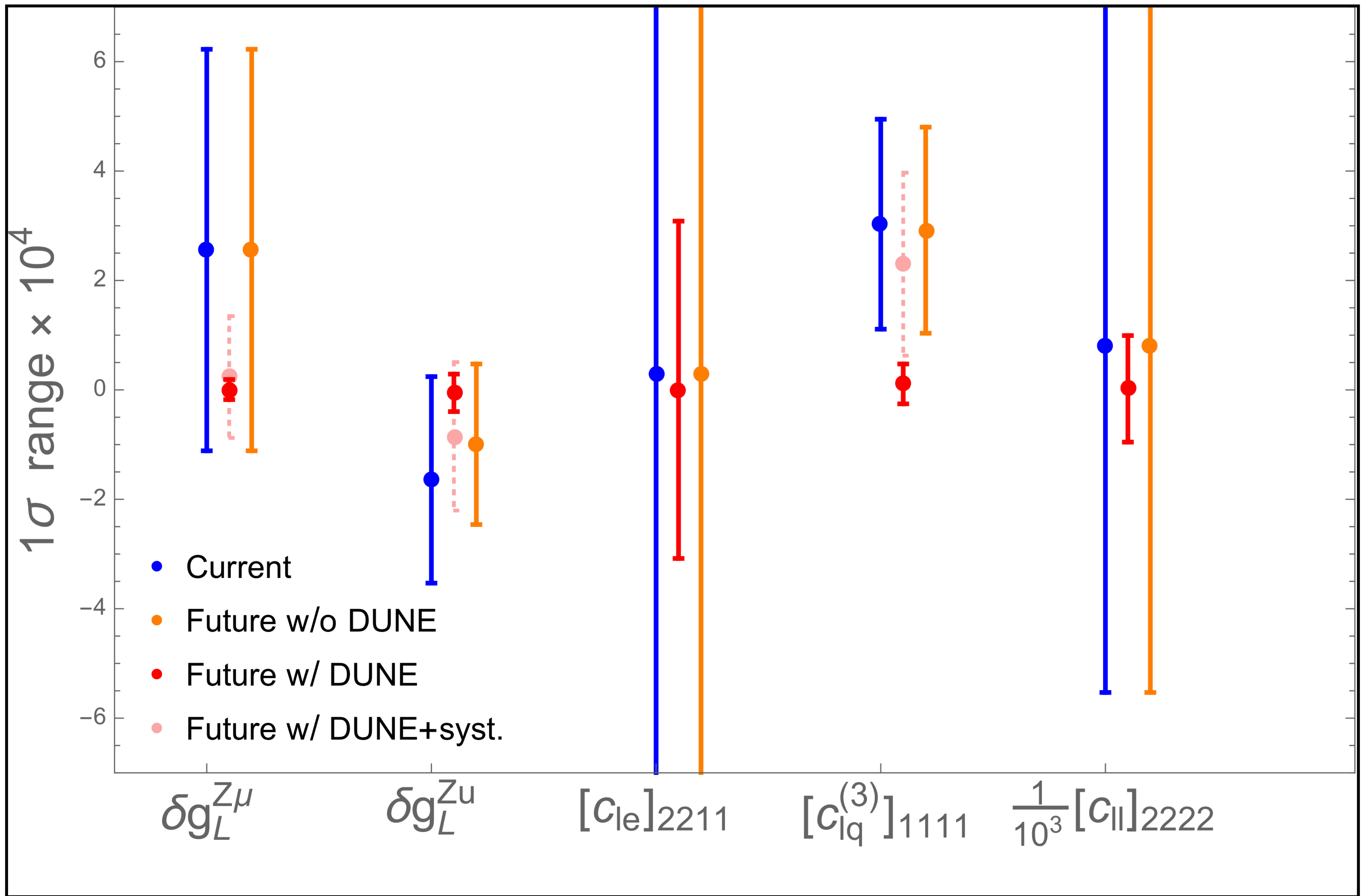
Systematic uncertainties

statistical uncertainty

$$\chi^2 = \sum_{\nu \& \bar{\nu}} \delta R^2 \left(\frac{1}{\boxed{\sigma^2_{\delta R}}} + \frac{1}{\boxed{\sigma^2_{\rm sys}}} \right)$$

systematic uncertainty

Result



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