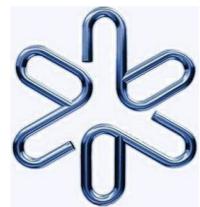


# FUTURE DUNE CONSTRAINTS ON EFT

**Giovanni Grilli di Cortona**



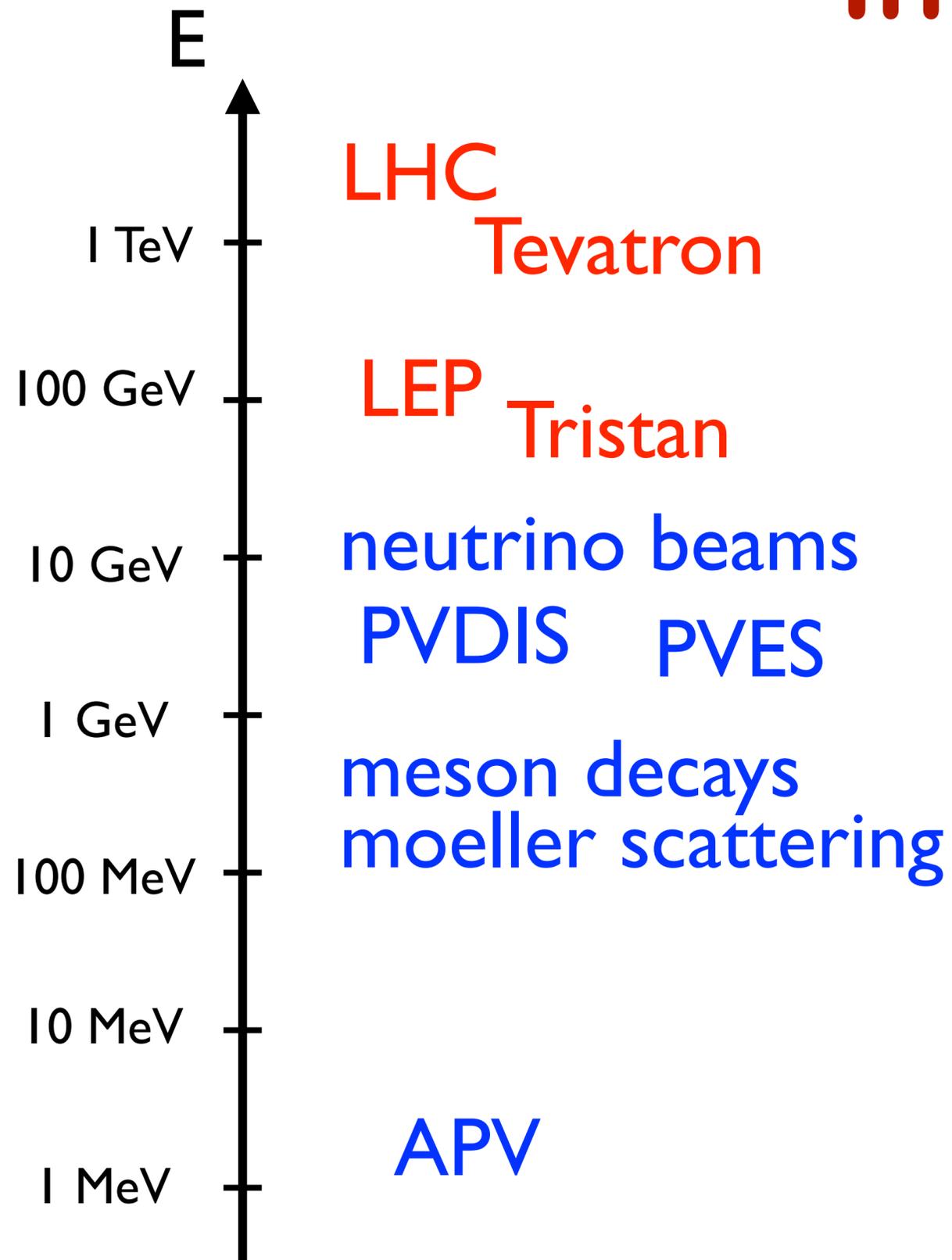
Instituto de Física  
Universidade de São Paulo



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

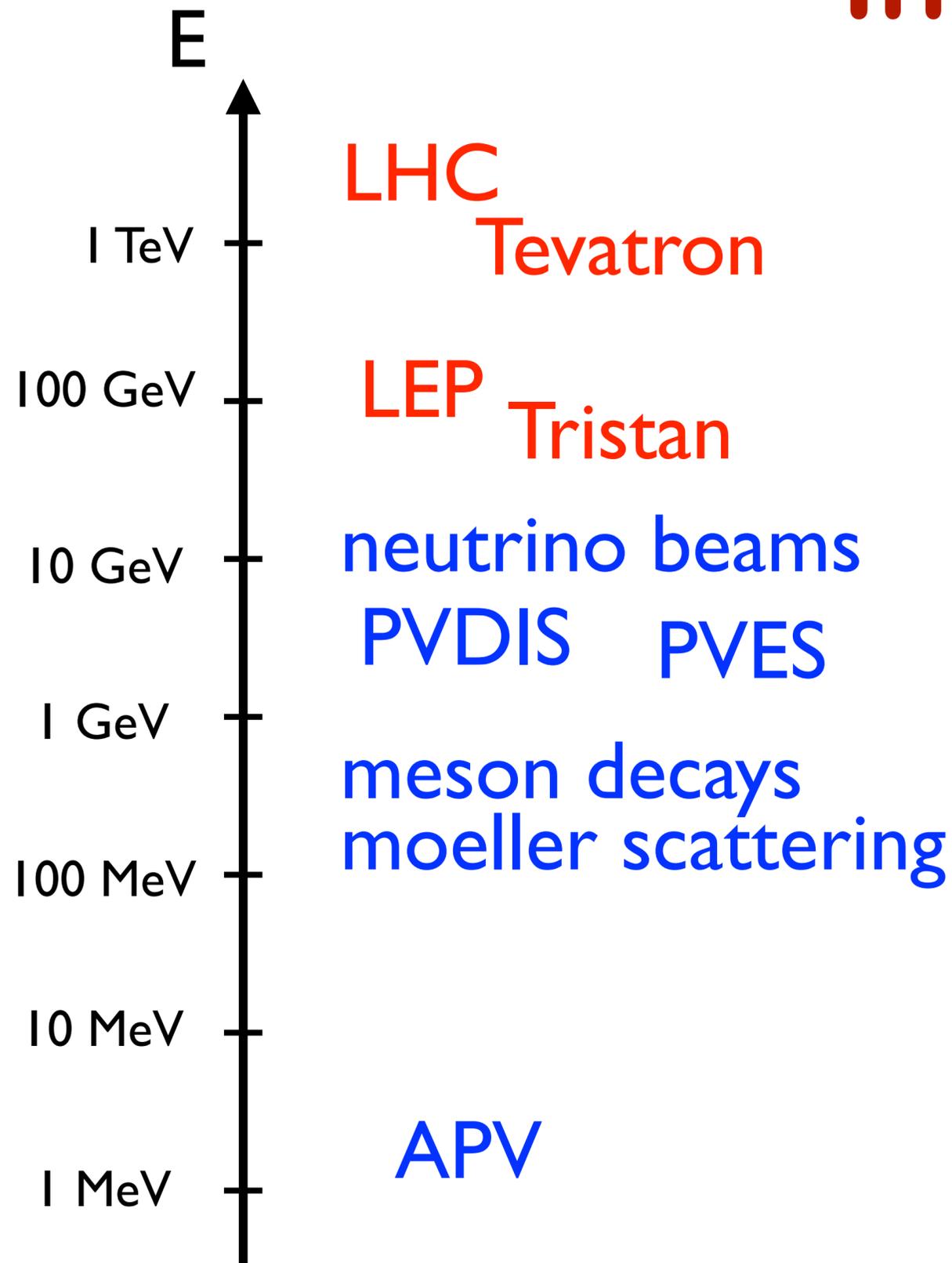
SUSY 2018, Barcelona

# Introduction



Consistent with the SM

# Introduction



Consistent with the SM

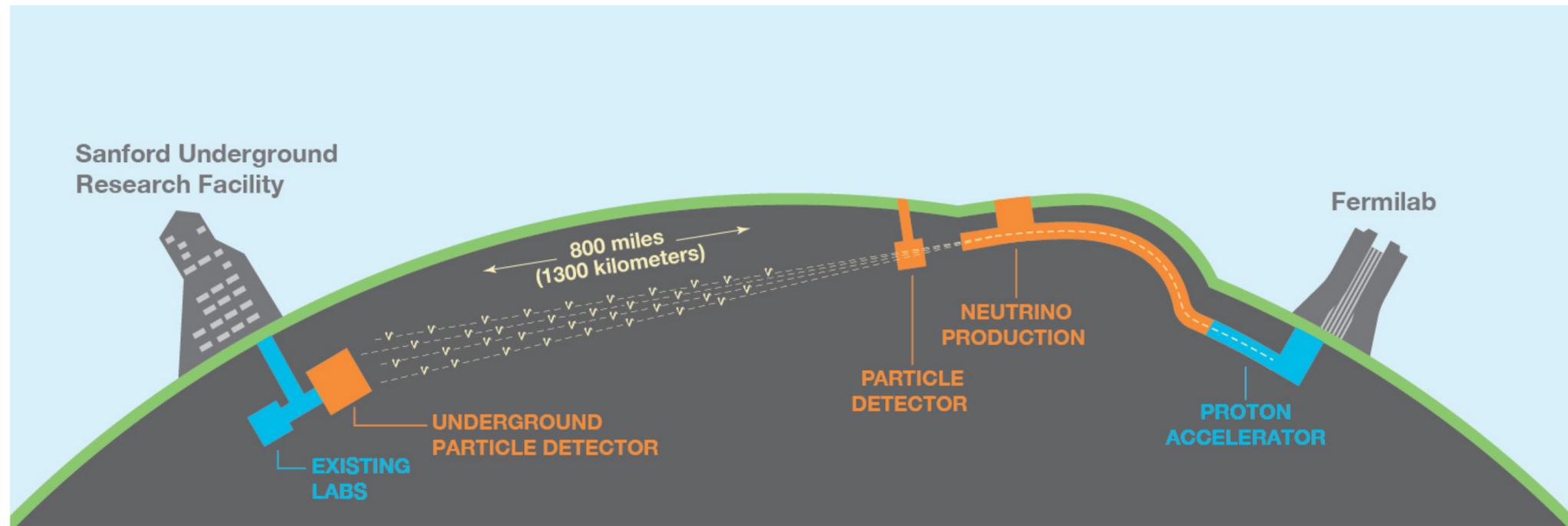
New Physics?

Neutrino masses, dark matter,  
inflation, baryon asymmetry

+

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

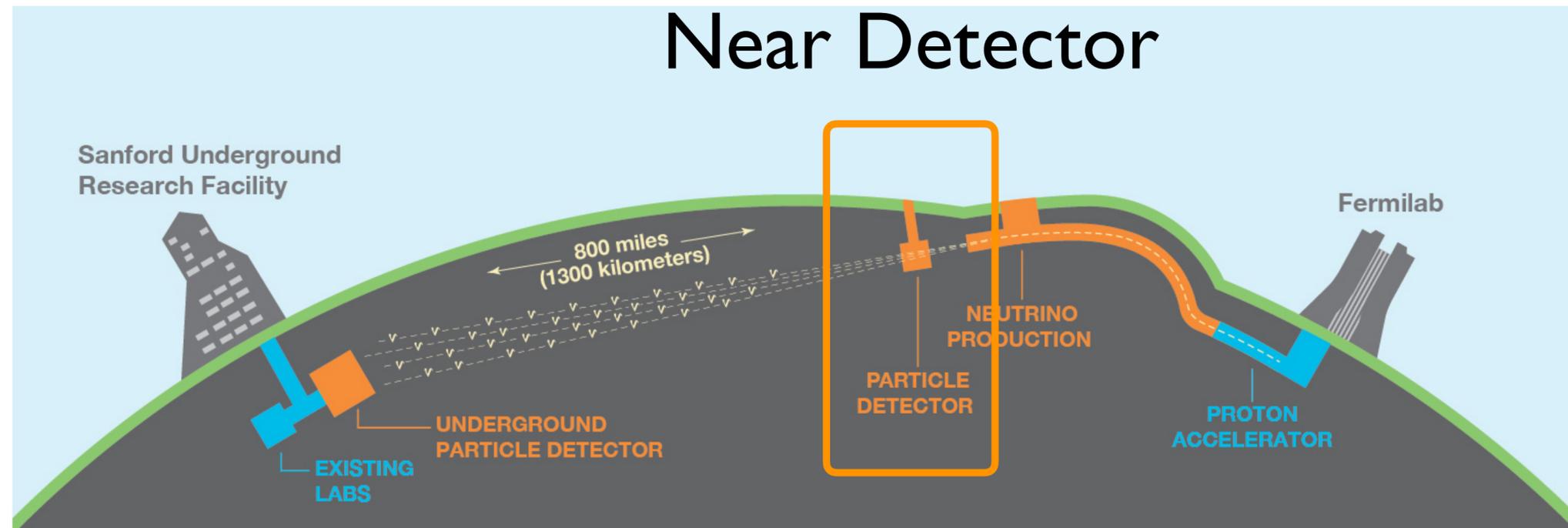
# Introduction



Main goals:

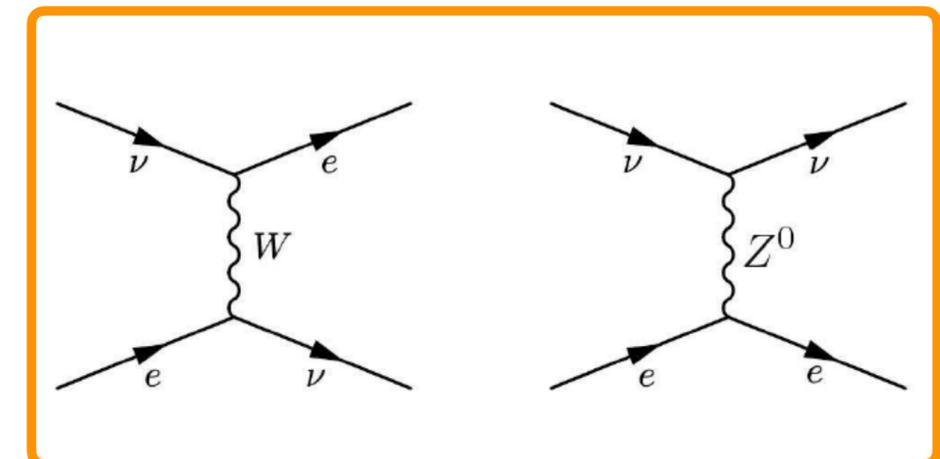
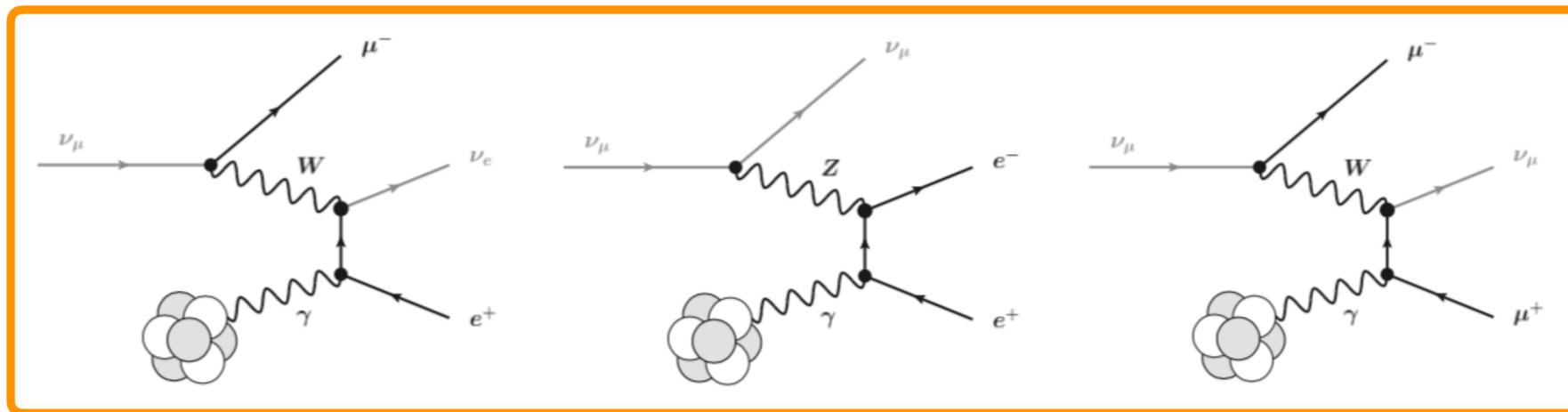
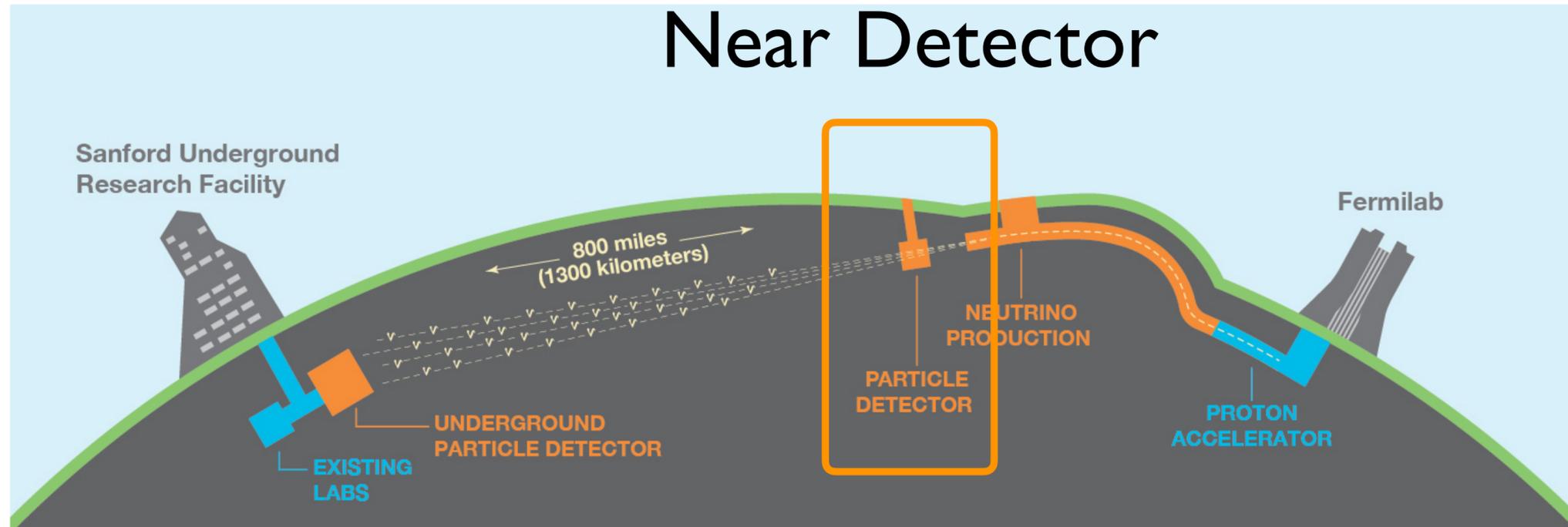
measure the parameters governing neutrino oscillations (CP violating phase in the PMNS matrix and neutrino mass ordering), searches for proton decay and for neutrino from core-collapse supernovas

# Introduction

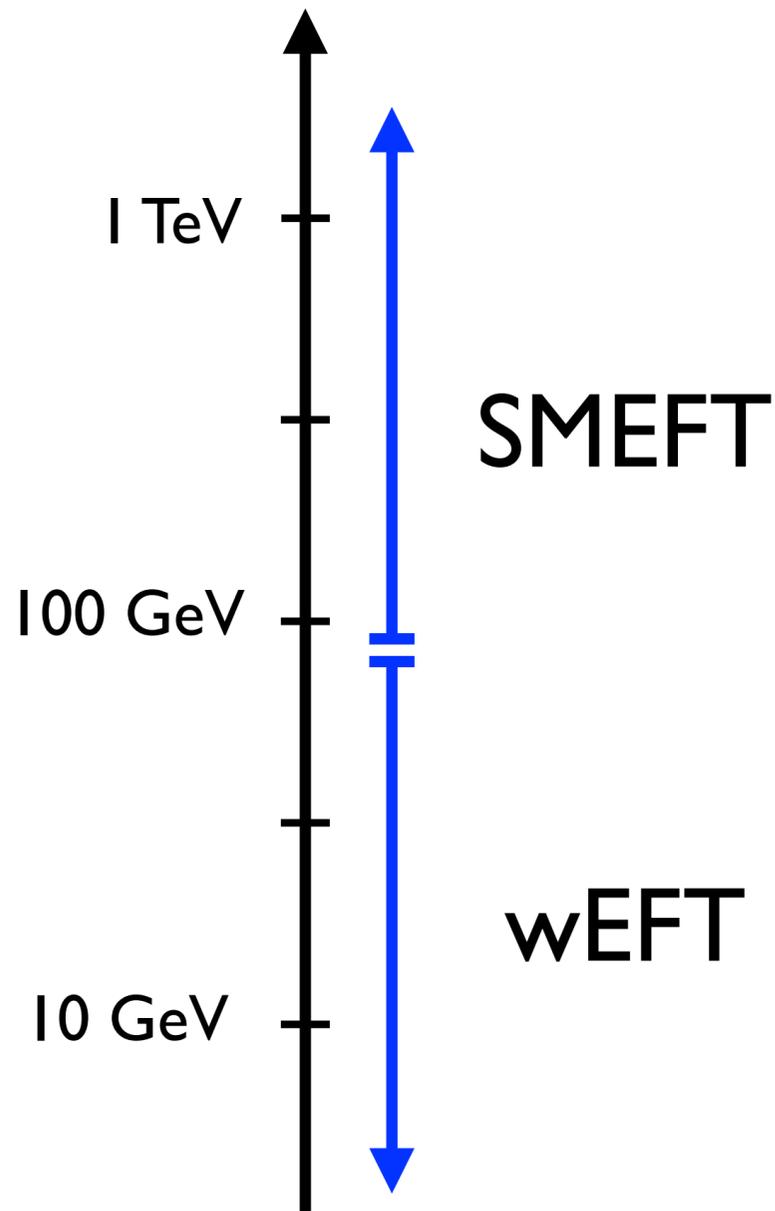


- 1) Constrain systematic uncertainties in neutrino flux and neutrino scattering cross section;
- 2) neutrino - nucleus/electron scattering measurement and BSM searches;

# Introduction

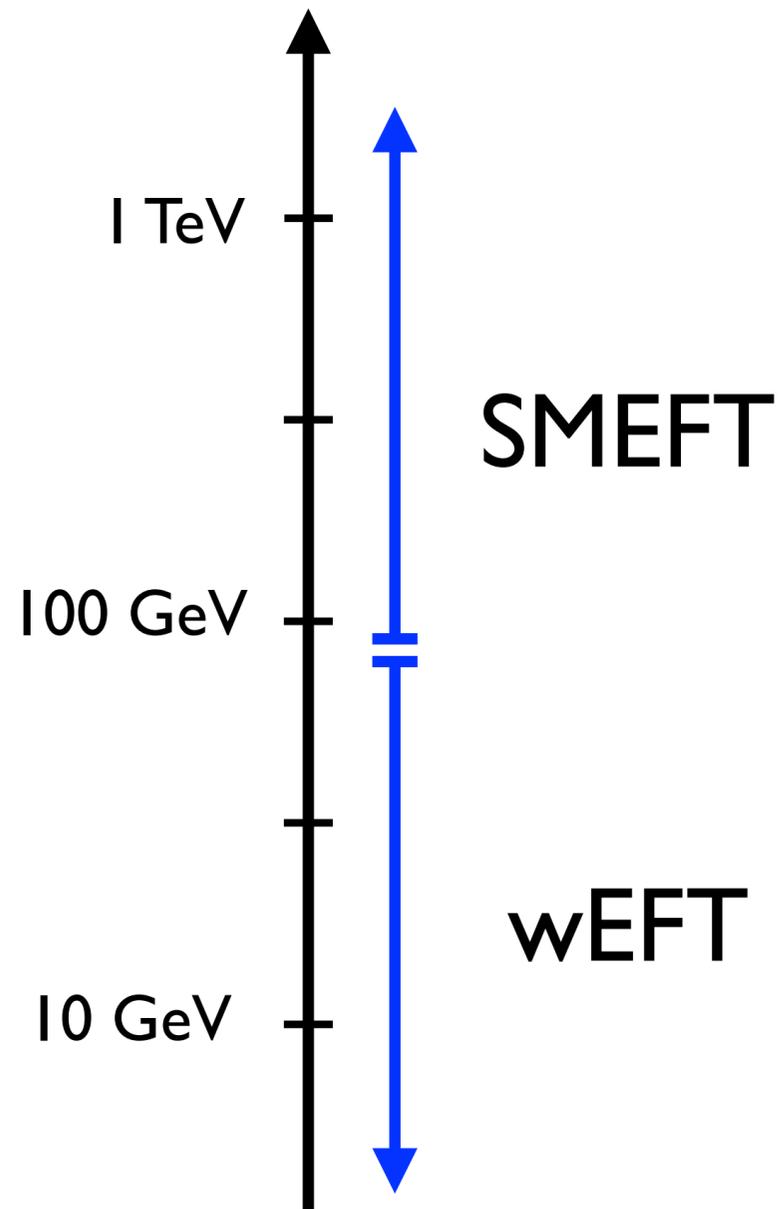


# Formalism



# Formalism

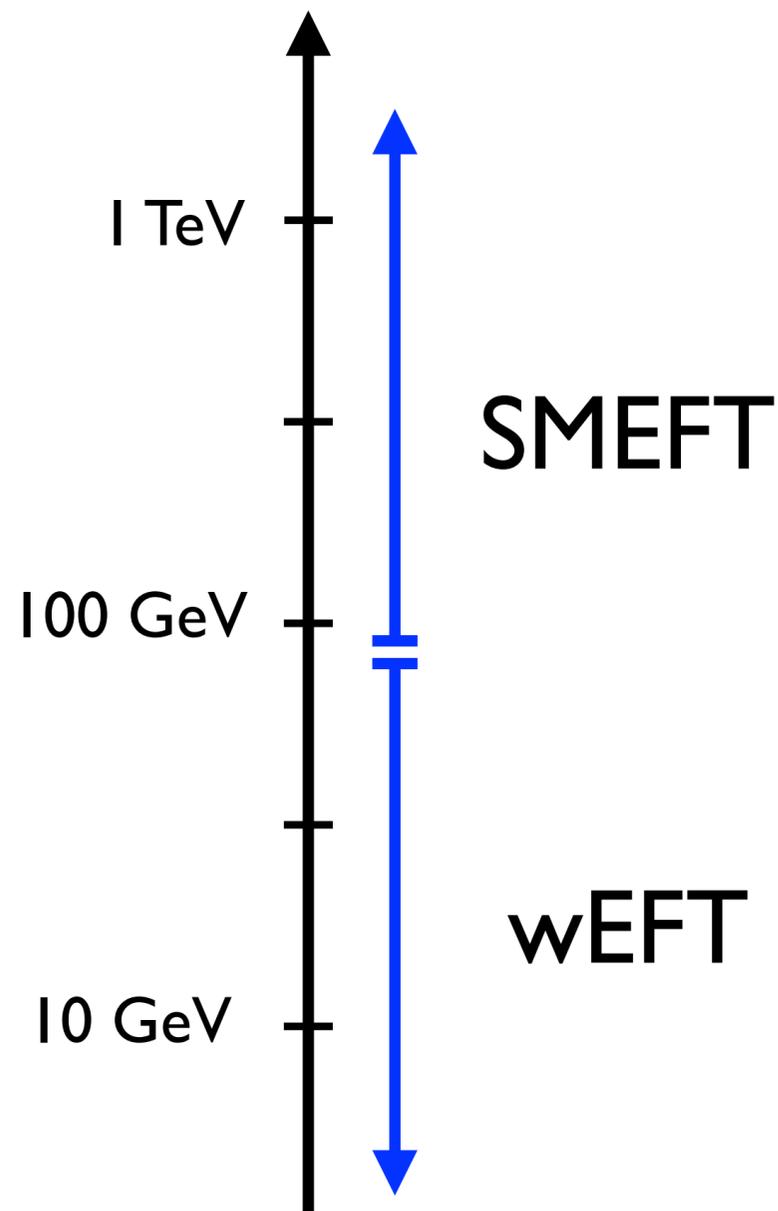
## Neutrino interactions with charged leptons



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

# Formalism

## Neutrino interactions with charged leptons



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

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

# Formalism

## Neutrino interactions with charged leptons

1 TeV

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{g_L}{\sqrt{2}} \left[ W^{\mu+} \bar{\nu}_a \bar{\sigma}_\mu (1 + \delta g_L^{W e_a}) e_a + \text{h.c.} \right]$$

$$+ \sqrt{g_L^2 + g_Y^2} Z^\mu e_a^c \sigma_\mu \left( -s_\theta^2 Q_f + \delta g_R^{Z e_a} \right) \bar{e}_a^c$$

$$+ \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=e,\nu} \bar{f}_a \bar{\sigma}_\mu \left( T_3^f - s_\theta^2 Q_f + \delta g_L^{Z f_a} \right) f_a$$

One flavor ( $a = 1, 2, 3$ )	Two flavors ( $a < b = 1, 2, 3$ )
$[O_{\ell\ell}]_{aaaa} = \frac{1}{2} (\bar{l}_a \bar{\sigma}_\mu l_a) (\bar{l}_a \bar{\sigma}^\mu l_a)$	$[O_{\ell\ell}]_{aabb} = (\bar{l}_a \bar{\sigma}_\mu l_a) (\bar{l}_b \bar{\sigma}^\mu l_b)$
$[O_{\ell e}]_{aaaa} = (\bar{l}_a \bar{\sigma}_\mu l_a) (e_a^c \sigma^\mu \bar{e}_a^c)$	$[O_{\ell e}]_{abba} = (\bar{l}_a \bar{\sigma}_\mu l_b) (\bar{l}_b \bar{\sigma}^\mu l_a)$
$[O_{ee}]_{aaaa} = \frac{1}{2} (e_a^c \sigma_\mu \bar{e}_a^c) (e_a^c \sigma^\mu \bar{e}_a^c)$	$[O_{\ell e}]_{aabb} = (\bar{l}_a \bar{\sigma}_\mu l_a) (e_b^c \sigma^\mu \bar{e}_b^c)$
	$[O_{\ell e}]_{bbaa} = (\bar{l}_b \bar{\sigma}_\mu l_b) (e_a^c \sigma^\mu \bar{e}_a^c)$
	$[O_{\ell e}]_{abba} = (\bar{l}_a \bar{\sigma}_\mu l_b) (e_b^c \sigma^\mu \bar{e}_a^c)$
	$[O_{ee}]_{aabb} = (e_a^c \sigma_\mu \bar{e}_a^c) (e_b^c \sigma^\mu \bar{e}_b^c)$

10 GeV

**wEFT**

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

# Formalism

## Neutrino interactions with charged leptons

$$\delta g_L^{Z\nu_a} = \delta g_L^{W e_a} + \delta g_L^{Z e_a}$$

SM

Shifted Z couplings

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

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

Tree-level matching of  
4-fermion operators

# Formalism

## Neutrino interactions with quarks

1 TeV

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

10 GeV

**wEFT**

$$\begin{aligned}
 \mathcal{L}_{\text{SMEFT}} \supset & \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{q=u,d} [\bar{q} \bar{\sigma}_\mu \left( (T_3^q - s_\theta^2 Q_q) + \delta g_L^{Zq} \right) q \\
 & + q^c \sigma_\mu \left( -s_\theta^2 Q_q + \delta g_R^{Zq} \right) \bar{q}^c] \\
 & + \left[ W^{\mu+} \bar{u} \bar{\sigma}_\mu \left( V_{ud} + \delta g_L^{Wq1} \right) d + \text{h.c.} \right] \\
 \mathcal{L}_{\text{wEFT}} \supset & -\frac{2\tilde{V}_{ud}}{v^2} (1 + \bar{\epsilon}_L^{de a}) (\bar{e}_a \bar{\sigma}_\mu \nu_a) (\bar{u} \bar{\sigma}^\mu d) \\
 & - \frac{2}{v^2} (\bar{\nu}_a \bar{\sigma}_\mu \nu_a) \sum_{q=u,d} [g_{LL}^{\nu_a q} \bar{q} \bar{\sigma}^\mu q + g_{LR}^{\nu_a q} (q^c \sigma^\mu \bar{q}^c)]
 \end{aligned}$$

# Neutrino scattering in DUNE

3 years neutrino mode +  
3 years antineutrino mode

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

neutrino  
flux

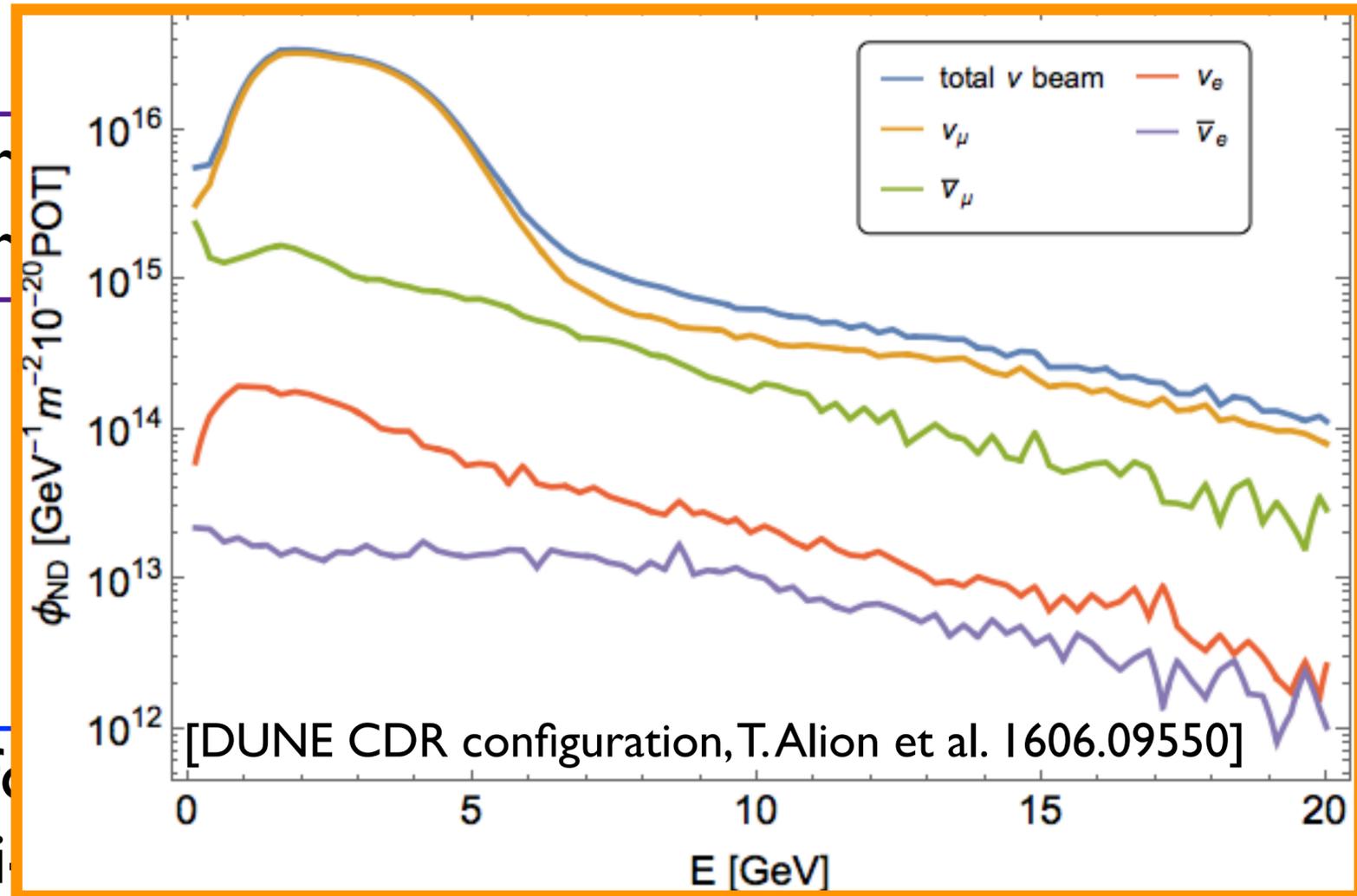
$$N_{\text{events}} = \text{time} \times N_T \times \epsilon \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu} \sigma(E_\nu)$$

$N_T$  for  $1.1 \times 10^{21}$  proton on target (POT) in  
(anti-)neutrino mode with a 120 GeV  
proton beam with 1.2 MW of power;  
Near Detector of 100 tonnes Argon mass

Cross section of  
the process

# Neutrino scattering in DUNE

3 year  
3 year



$\nu_\mu$   
 $\bar{\nu}_e$

neutrino  
flux

$dE_\nu$

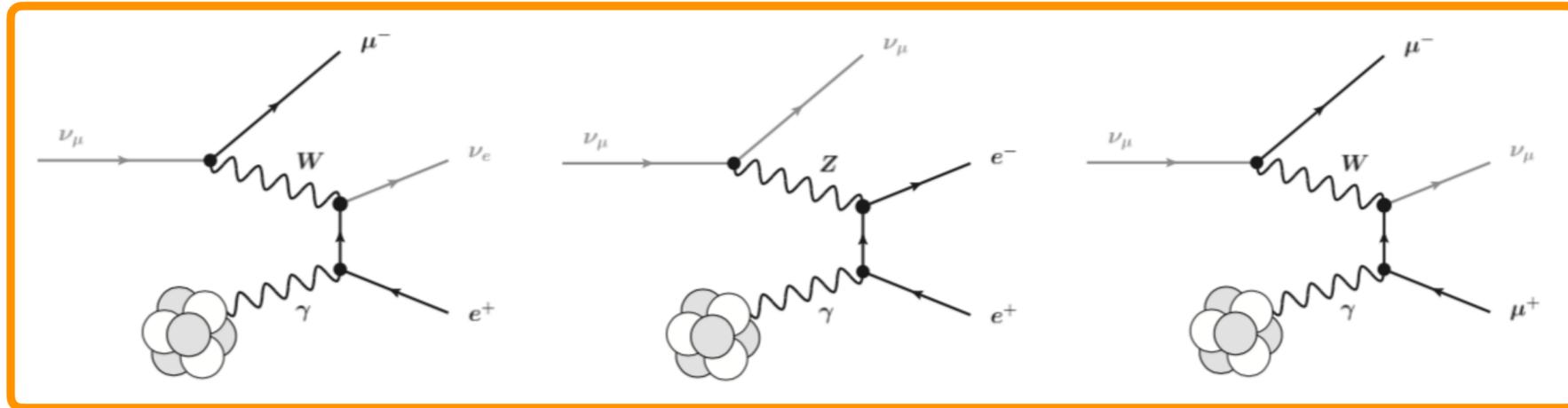
$$\frac{d\phi(E_\nu)}{dE_\nu}$$

$$\sigma(E_\nu)$$

$N_T$  for  
(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)]

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

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

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

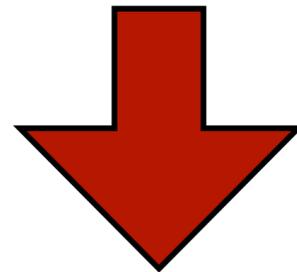
$\nu$ beam		$\bar{\nu}$ beam	
$\nu_{\mu} \rightarrow \nu_{\mu} \mu^{-} \mu^{+}$	357	$\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu} \mu^{-} \mu^{+}$	305
$\nu_e \rightarrow \nu_e \mu^{-} \mu^{+}$	1.27	$\bar{\nu}_e \rightarrow \bar{\nu}_e \mu^{-} \mu^{+}$	1.03

$$\frac{\sigma(\nu_b \gamma^* \rightarrow \nu_a l_c^- l_d^+)}{\sigma_{\text{SM}}(\nu_b \gamma^* \rightarrow \nu_a l_c^- l_d^+)} = \frac{\sigma(\bar{\nu}_a \gamma^* \rightarrow \nu_b l_c^- l_d^+)}{\sigma_{\text{SM}}(\bar{\nu}_a \gamma^* \rightarrow \nu_b l_c^- l_d^+)} \approx 1 + 2 \frac{g_{LL,\text{SM}}^{abcd} \delta g_{LL}^{abcd} + g_{LR,\text{SM}}^{abcd} \delta g_{LR}^{abcd}}{(g_{LL,\text{SM}}^{abcd})^2 + (g_{LR,\text{SM}}^{abcd})^2}$$

# Neutrino trident production

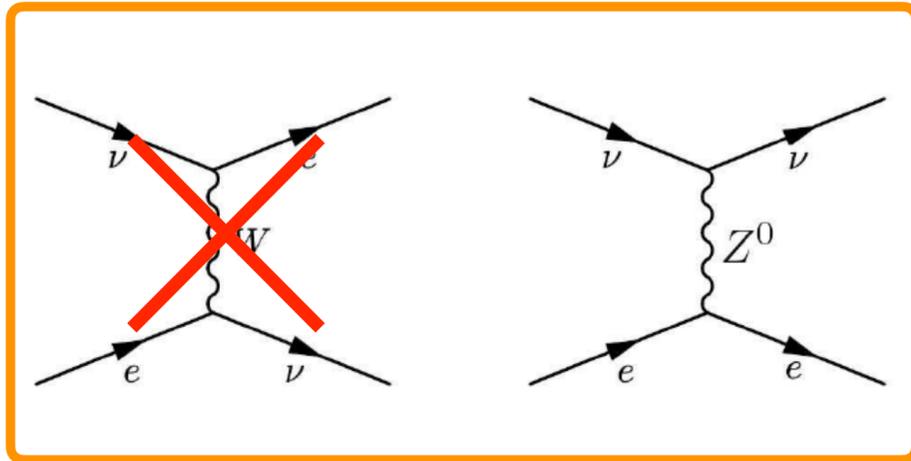
$\nu$ beam		$\bar{\nu}$ beam	
$\nu_\mu \rightarrow \nu_\mu \mu^- \mu^+$	357	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \mu^- \mu^+$	305
$\nu_e \rightarrow \nu_e \mu^- \mu^+$	1.27	$\bar{\nu}_e \rightarrow \bar{\nu}_e \mu^- \mu^+$	1.03

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



$$-0.039 < 2 \frac{g_{LL,\text{SM}}^{2222} \delta g_{LL}^{2222} + g_{LR,\text{SM}}^{2222} \delta g_{LR}^{2222}}{(g_{LL,\text{SM}}^{2222})^2 + (g_{LR,\text{SM}}^{2222})^2} < 0.039$$

# Neutrino scattering off electrons



	$N_{\text{tot}}^{\nu-e}$	$r_{\nu\mu}^{\nu-e}$	$r_{\bar{\nu}\mu}^{\nu-e}$	$r_{\nu e}^{\nu-e}$	$r_{\bar{\nu}e}^{\nu-e}$
$\nu$ -mode	$1.69 \times 10^6$	0.898	0.059	0.040	0.003
$\bar{\nu}$ -mode	$1.29 \times 10^6$	0.103	0.867	0.013	0.017

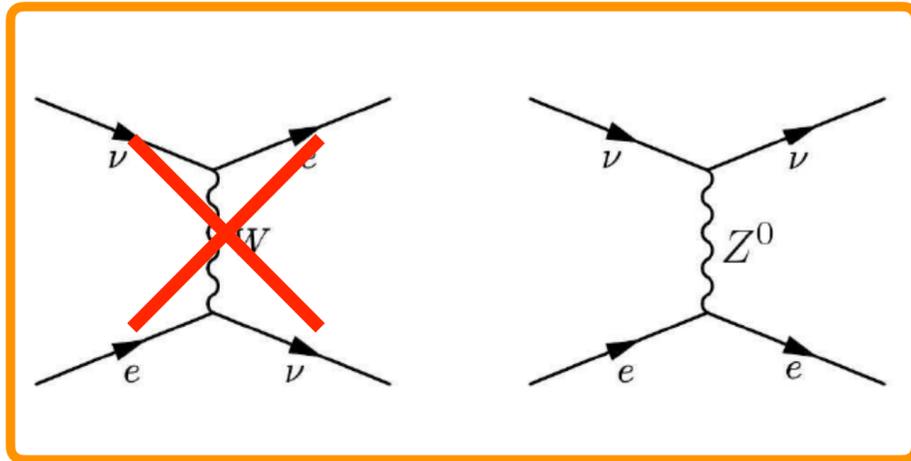
$$E_{\text{th}}^{\text{CC}} = \frac{m_{\mu}^2}{2m_e} = 10.9 \text{ GeV}$$

$\nu_{\mu} e^{-} \rightarrow \nu_e \mu^{-}$

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

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

# Neutrino scattering off electrons



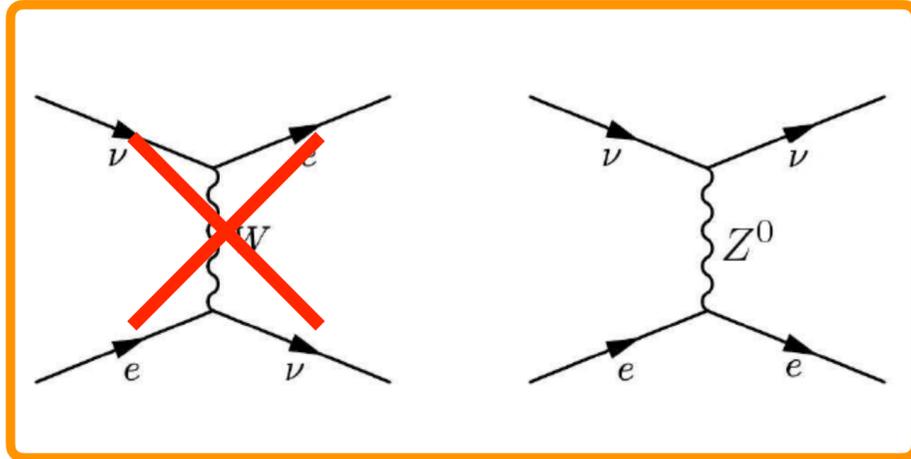
	$N_{\text{tot}}^{\nu-e}$	$r_{\nu\mu}^{\nu-e}$	$r_{\bar{\nu}\mu}^{\nu-e}$	$r_{\nu e}^{\nu-e}$	$r_{\bar{\nu}e}^{\nu-e}$
$\nu$ -mode	$1.69 \times 10^6$	0.898	0.059	0.040	0.003
$\bar{\nu}$ -mode	$1.29 \times 10^6$	0.103	0.867	0.013	0.017

$$R_{\nu e}^i \equiv \frac{x_i \sigma_{\nu\mu e} + \bar{x}_i \sigma_{\bar{\nu}\mu e}}{x_i \sigma_{\nu\mu e}^{\text{SM}} + \bar{x}_i \sigma_{\bar{\nu}\mu e}^{\text{SM}}}$$



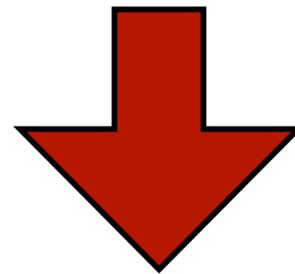
$$\begin{cases} x_\nu & = & 0.9 \\ x_{\bar{\nu}} & = & 0.1 \\ \bar{x}_i & = & 1 - x_i \end{cases}$$

# Neutrino scattering off electrons



	$N_{\text{tot}}^{\nu-e}$	$r_{\nu\mu}^{\nu-e}$	$r_{\bar{\nu}\mu}^{\nu-e}$	$r_{\nu e}^{\nu-e}$	$r_{\bar{\nu}e}^{\nu-e}$
$\nu$ -mode	$1.69 \times 10^6$	0.898	0.059	0.040	0.003
$\bar{\nu}$ -mode	$1.29 \times 10^6$	0.103	0.867	0.013	0.017

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



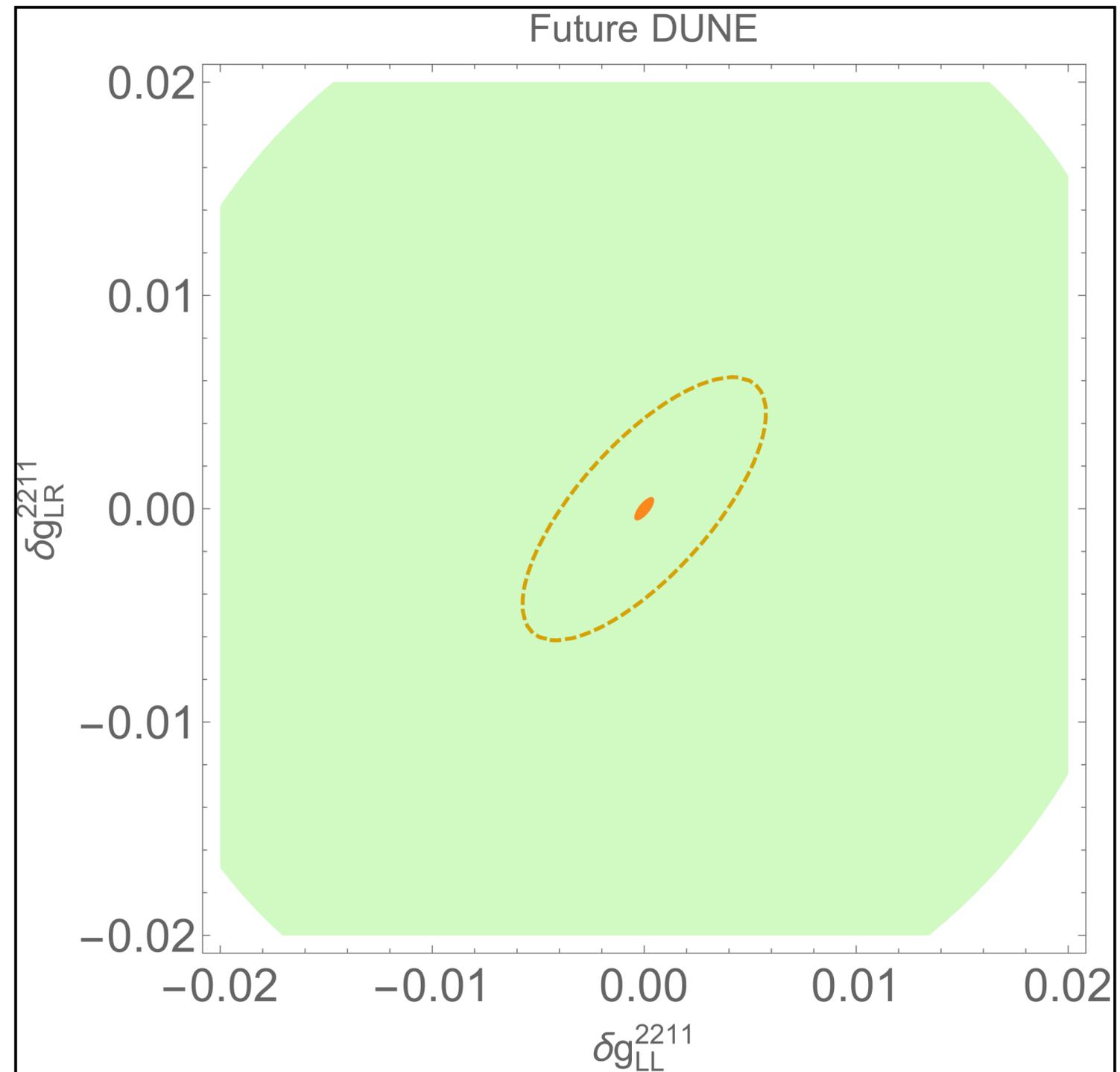
$$-8.0 \times 10^{-4} < \delta R_{\nu e}^\nu < 8.0 \times 10^{-4} \quad -9.1 \times 10^{-4} < \delta R_{\nu e}^{\bar{\nu}} < 9.1 \times 10^{-4}$$

# Neutrino scattering off electrons

CHARM +  
CHARM II +  
BNL-E734

stat. dominated

1% syst. Error



# Neutrino scattering off nuclei

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

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

generalised  
Llewellyn-Smith  
formula

	$N_{\text{tot}}^{CC}$	$r_{\nu_\mu}^{CC}$	$r_{\bar{\nu}_\mu}^{CC}$	$r_{\nu_e}^{CC}$	$r_{\bar{\nu}_e}^{CC}$
$\nu$ -mode	$4.25 \times 10^8$	0.964	0.028	0.007	0.001
$\bar{\nu}$ -mode	$1.74 \times 10^8$	0.201	0.790	0.004	0.005
	$N_{\text{tot}}^{NC}$	$r_{\nu_\mu}^{NC}$	$r_{\bar{\nu}_\mu}^{NC}$	$r_{\nu_e}^{NC}$	$r_{\bar{\nu}_e}^{NC}$
$\nu$ -mode	$1.48 \times 10^8$	0.956	0.037	0.006	0.001
$\bar{\nu}$ -mode	$7.58 \times 10^7$	0.157	0.835	0.003	0.005

only dependence on  
the nuclear structure

$$r_\nu \sim 2.5$$

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

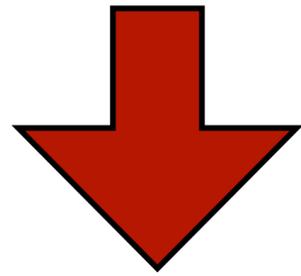
but

- 1) the  $^{40}\text{Ar}$  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

$$R_{\nu_{\mu}N}^i = R_{\nu_{\mu}N,SM}^i (1 + \delta R_{\nu_{\mu}N}^i)$$

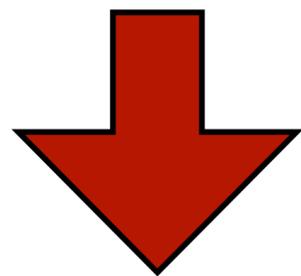


$$-9.6 \times 10^{-5} < \delta R_{\nu_{\mu}N}^{\nu} < 9.6 \times 10^{-5}$$

$$-1.4 \times 10^{-4} < \delta R_{\nu_{\mu}N}^{\bar{\nu}} < 1.4 \times 10^{-4}$$

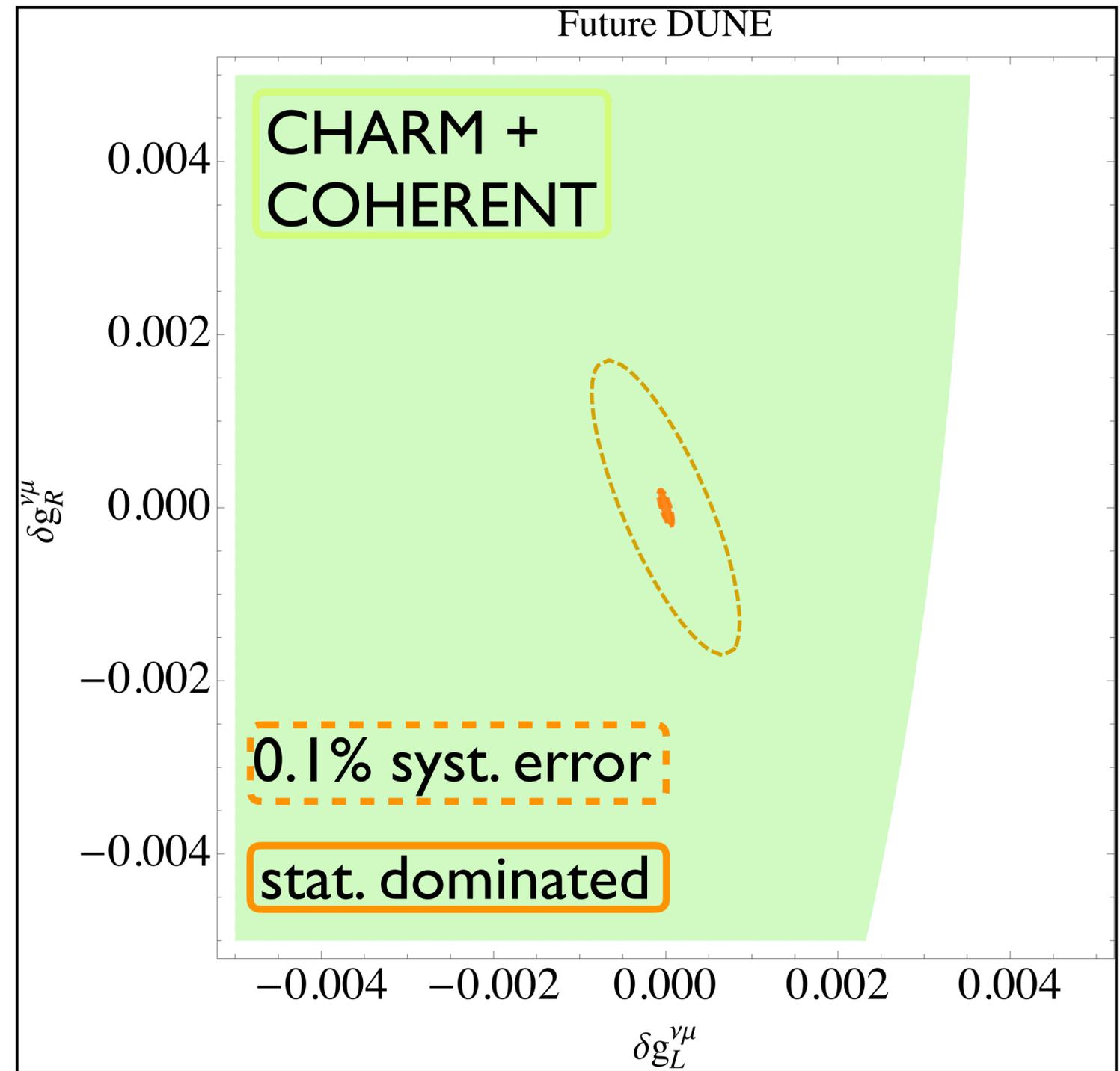
# Neutrino scattering off nuclei

$$R_{\nu_{\mu}N}^i = R_{\nu_{\mu}N,SM}^i (1 + \delta R_{\nu_{\mu}N}^i)$$



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

$$-1.4 \times 10^{-4} < \delta R_{\nu_{\mu}N}^{\bar{\nu}} < 1.4 \times 10^{-4}$$



# Results

[Falkowski et al.,  
1706.03783]

[Falkowski, GGdC, Tabrizi, 1802.08296]

Coefficient	$\Delta$ (current)	$\Delta$ (no sys.)	$\Delta$ (0.1% sys.)	$\Delta$ (1% sys.)
$\delta g_L^{We}$	3.5	0.37	2.5	3.4
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
$\delta g_L^{Zu}$	1.9	0.34	1.4	1.5
$\delta g_R^{Zu}$	9.5	0.57	2.0	2.3
$\delta g_L^{Zd}$	1.9	0.28	1.4	1.6
$\delta g_R^{Zd}$	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

One SMEFT  
parameter at  
a time

$\times 10^{-4}$

# Results

[Falkowski et al.,  
1706.03783]

[Falkowski, GGdC, Tabrizi, 1802.08296]

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$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
$\delta g_L^{Zu}$	1.9	0.34	1.4	1.5
$\delta g_R^{Zu}$	9.5	0.57	2.0	2.3
$\delta g_L^{Zd}$	1.9	0.28	1.4	1.6
$\delta g_R^{Zd}$	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

One SMEFT  
parameter at  
a time

$\times 10^{-4}$

# Results

[Falkowski et al.,  
1706.03783]

[Falkowski, GGdC, Tabrizi, 1802.08296]

Coefficient	$\Delta$ (current)	$\Delta$ (no sys.)	$\Delta$ (0.1% sys.)	$\Delta$ (1% sys.)
$\delta g_L^{We}$	3.5	0.37	2.5	3.4
$\delta g_L^{Z\mu}$	3.7	0.18	1.1	3.5
$\delta g_L^{Zu}$	1.9	0.34	1.4	1.5
$\delta g_R^{Zu}$	9.5	0.57	2.0	2.3
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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

$$\chi^2 = \sum_{\nu \& \bar{\nu}} \delta R^2 \left( \frac{1}{\sigma_{\delta R}^2} + \frac{1}{\sigma_{\text{sys}}^2} \right)$$

statistical uncertainty

systematic uncertainty

# Neutrino scattering off nuclei

$$\delta R_{\nu_\mu N}^i \simeq 2 \frac{g_{L,SM}^\nu \delta g_L^{\nu\mu} + r_i^{-1} g_{R,SM}^\nu \delta g_R^{\nu\mu}}{(g_{L,SM}^\nu)^2 + r_i^{-1} (g_{R,SM}^\nu)^2}$$

$$g_{X,SM}^\nu \delta g_X^{\nu\mu} = \sum_{q=u,d} g_{LX,SM}^{\nu\mu q} \delta g_{LX}^{\nu\mu q} - (g_{X,SM}^\nu)^2 \epsilon_L^{\nu\mu d}$$

# Result

