

Neutrino Deep Inelastic Scattering at Accelerators, Colliders and Telescopes

Keping Xie

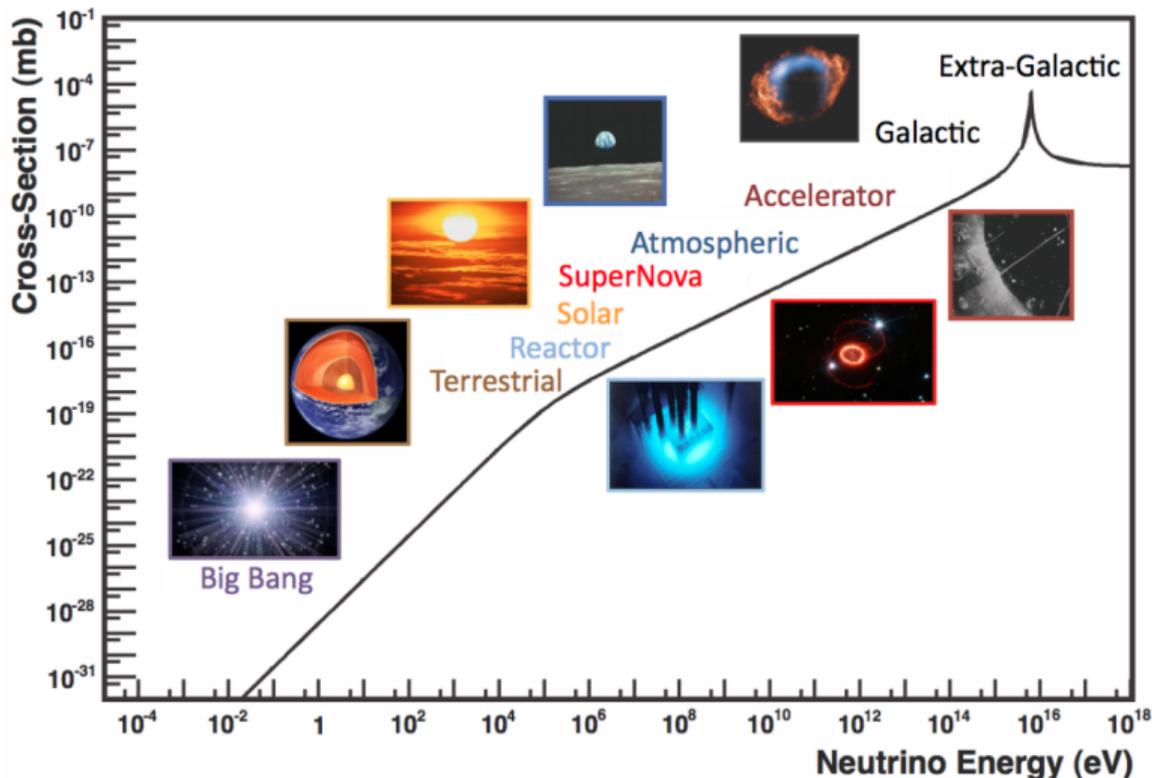
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Good ν 's: Neutrino Physics at a Muon Collider
University of Pittsburgh
October 27, 2025

Based on work in [2303.13607](#) (w/ CT collaboration), [2510.13948](#) (w/ Bai, Zhou)
and Snowmass studies [2109.10905](#), [2203.05090](#)
Also see Juan Rojo's talk

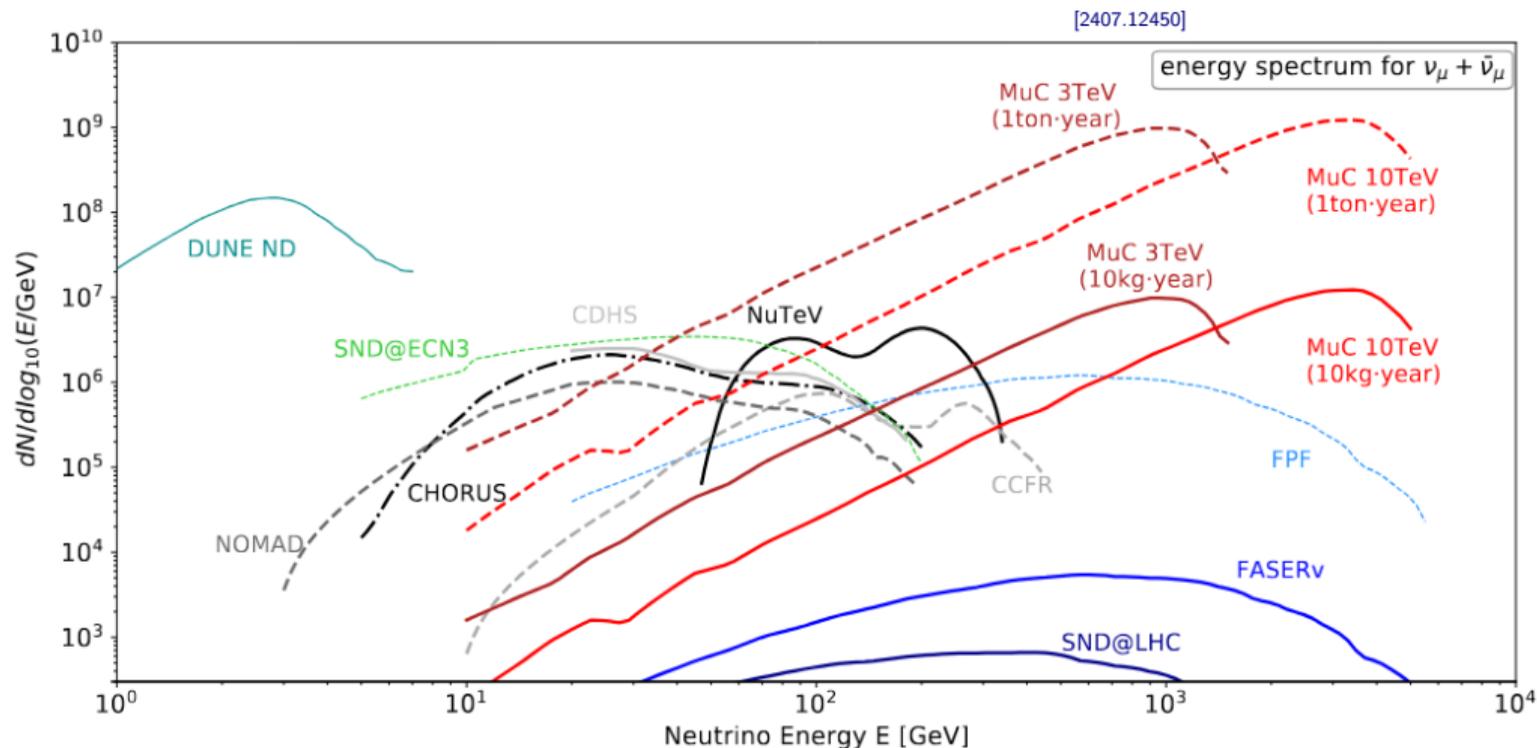
Neutrino Sources

[Formaggio, Zeller, Rev. Mod. Phys. 84 (2012)]



- (Ultra-)High-Energy neutrinos, mainly from Galactic (astrophysical/cosmic) source.
- Collider and accelerator neutrinos can reach intermediate energies ($\gtrsim 10$ GeV)

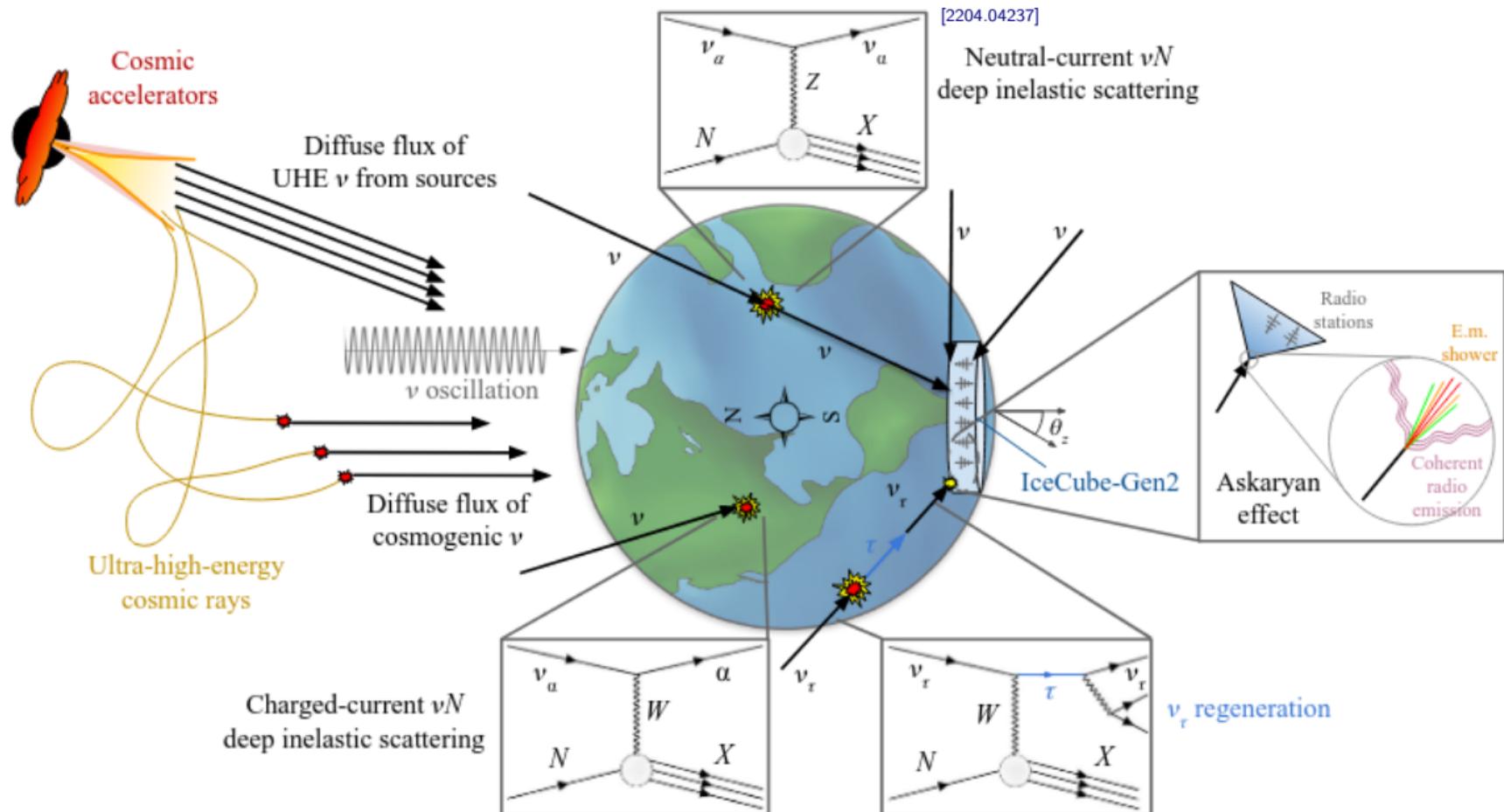
Accelerator and Collider Neutrinos



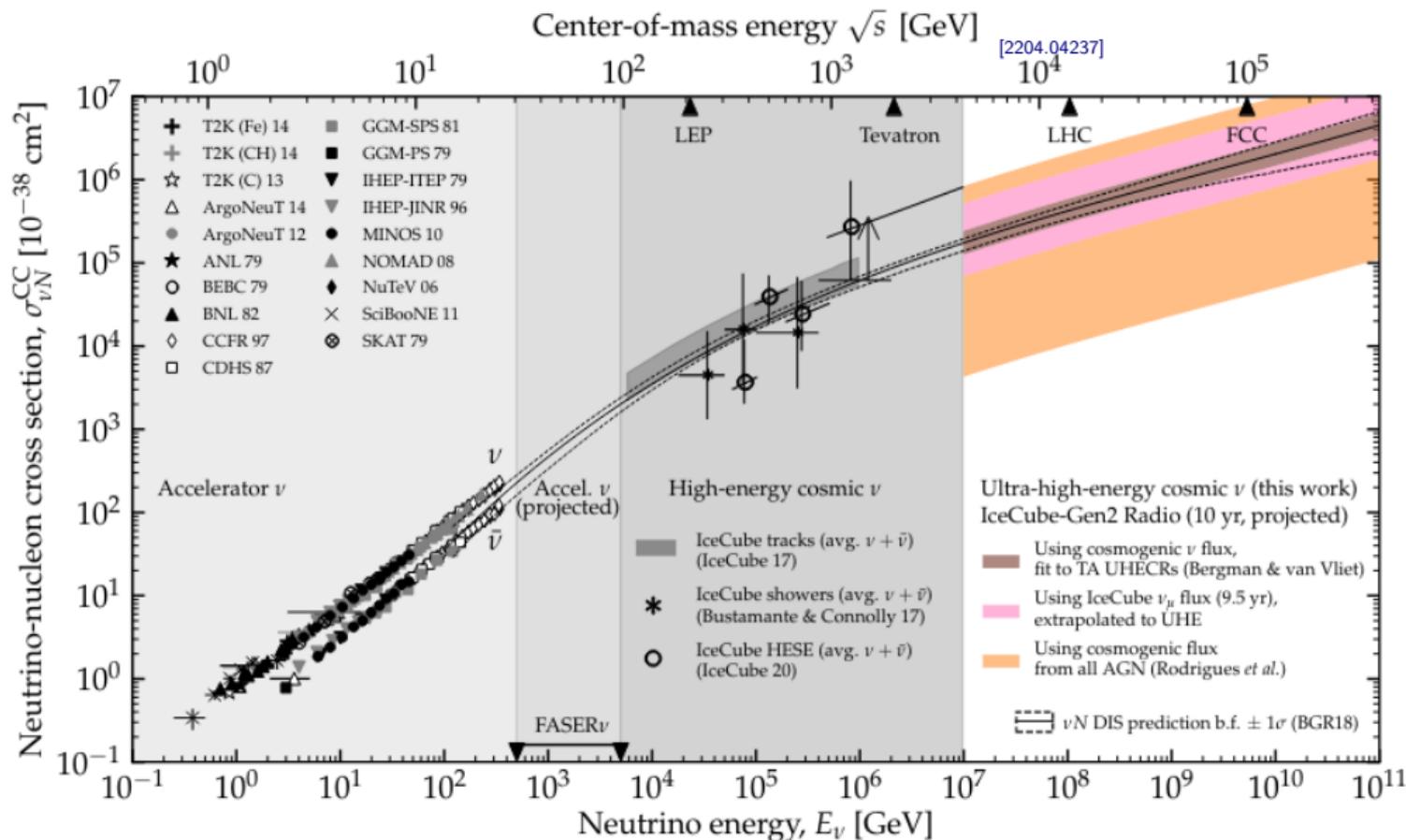
- NuTeV, CCFR, NOMAD (past) → FASER, SND@LHC, FPF (ongoing) → MuC (future)

Astrophysical and cosmic neutrinos

See talks of Parrish, Kamp, and Prohira

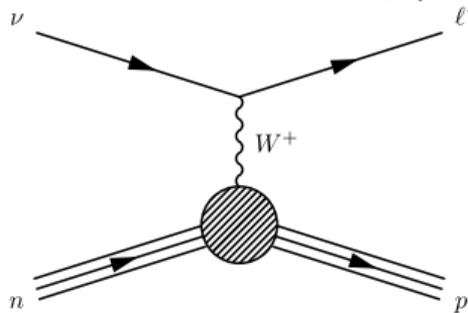


From Accelerators to Telescopes

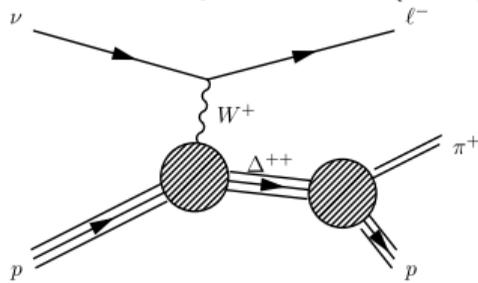


Neutrino-nucleon Interactions (charged-current)

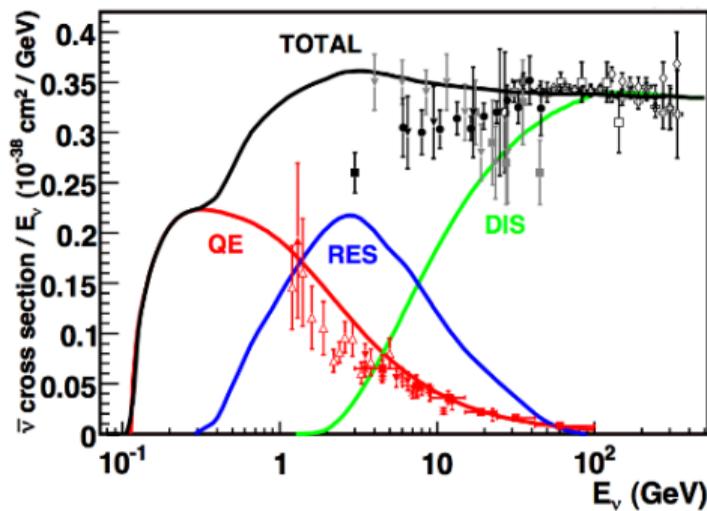
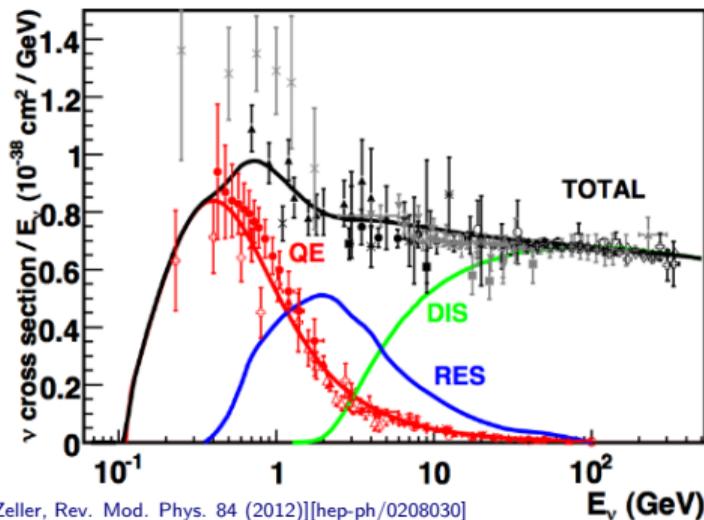
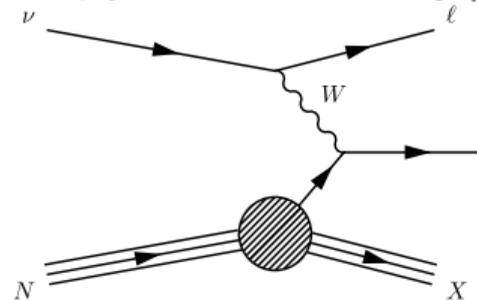
Quasi-elastic scattering (QE)



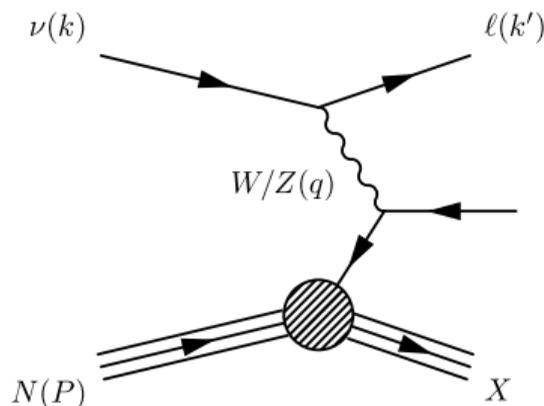
Resonance production (RES)



Deeply inelastic scattering (DIS)



The neutrino-nucleon DIS cross section



Kinematic variables

$$Q^2 = -q^2 = -m_\ell^2 + 2E_\nu(E' - k' \cos \theta)$$

$$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M(E_\nu - E')}, \quad y = \frac{P \cdot q}{P \cdot k} = \frac{E_\nu - E'}{E_\nu} = \frac{Q^2}{2xME_\nu},$$

Inclusive cross section

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 ME_\nu}{\pi \left(1 + Q^2/M_{W,Z}^2\right)^2} \left[\begin{aligned} & \frac{y^2}{2} 2xF_1(x, Q^2) + \left(1 - y - \frac{Mxy}{2E}\right) F_2(x, Q^2) \\ & \pm y \left(1 - \frac{y}{2}\right) xF_3(x, Q^2) \end{aligned} \right]$$

Kinematic Phase space

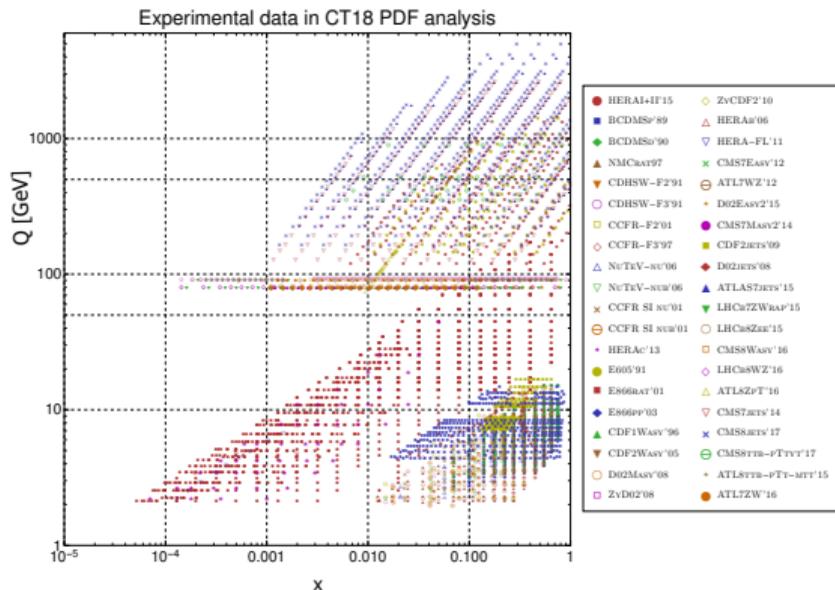
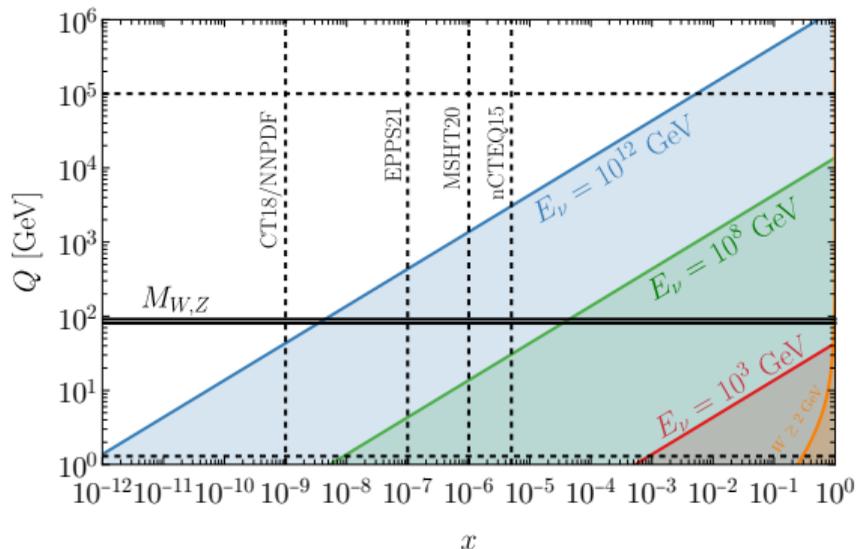
The DIS inclusive cross section

$$\sigma = \int_{Q_{\min}^2}^{2ME_{\nu}} dQ^2 N(Q^2) \int_{Q^2/(2ME_{\nu})}^1 \frac{dx}{x} \mathcal{F}[F_{i=1,2,3}](x, Q^2).$$

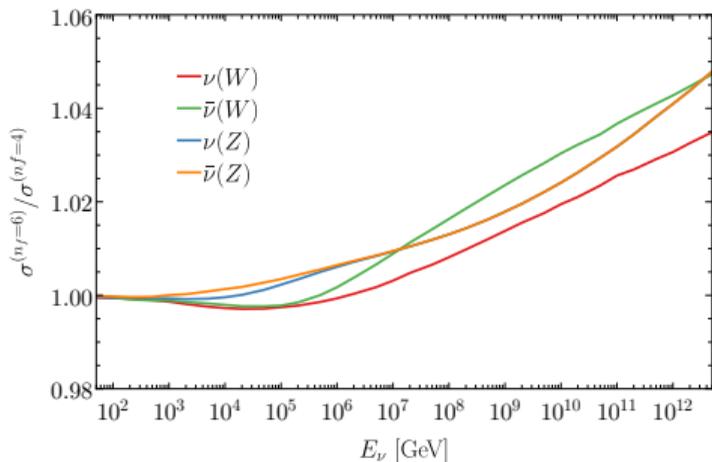
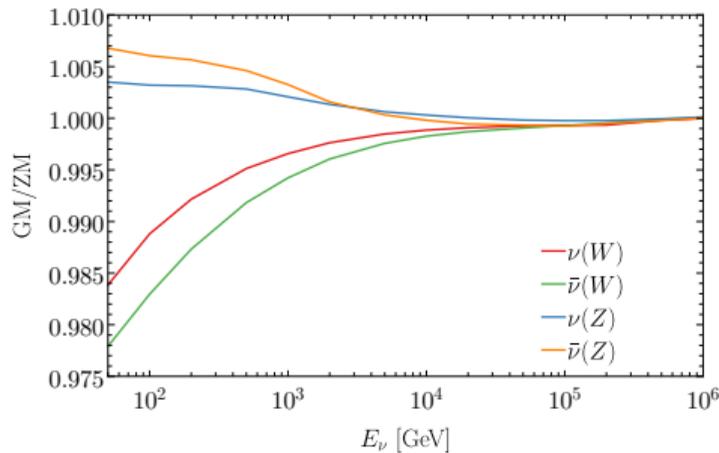
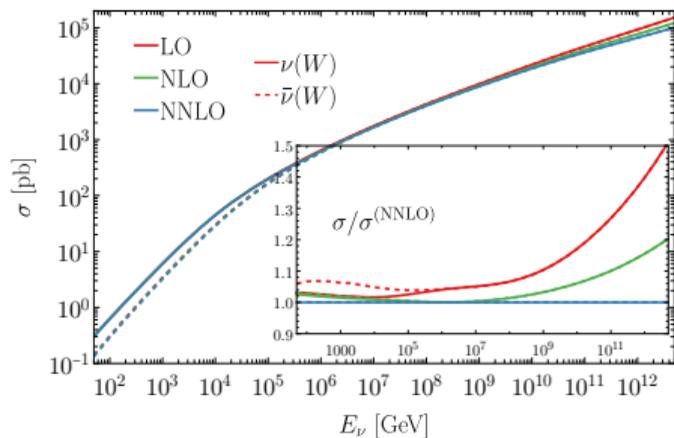
Integration limits

$$Q^2 \in [Q_{\min}^2, 2ME_{\nu}], \quad x \in [Q^2/(2ME_{\nu}), 1].$$

DIS lower bound $Q_{\min} \sim 1 \text{ GeV}$ in MINERvA [\[1601.06313\]](#).



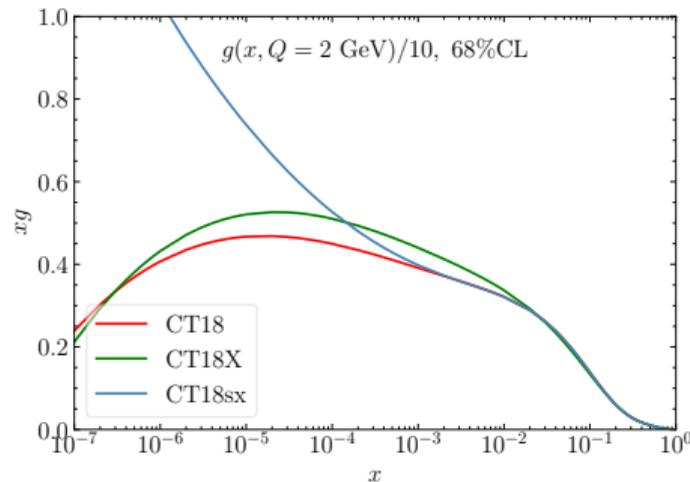
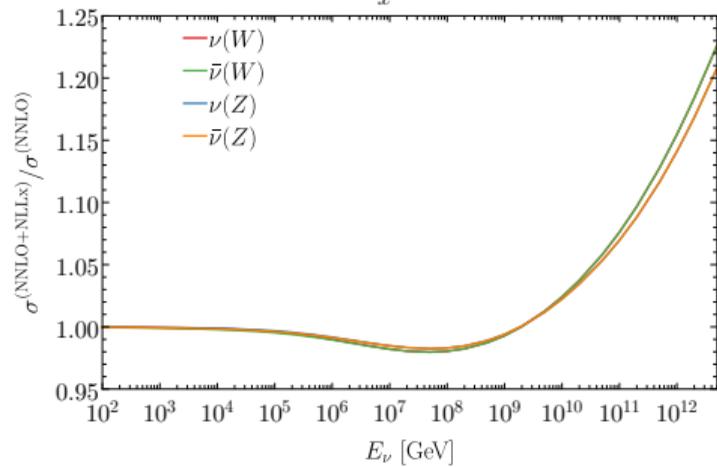
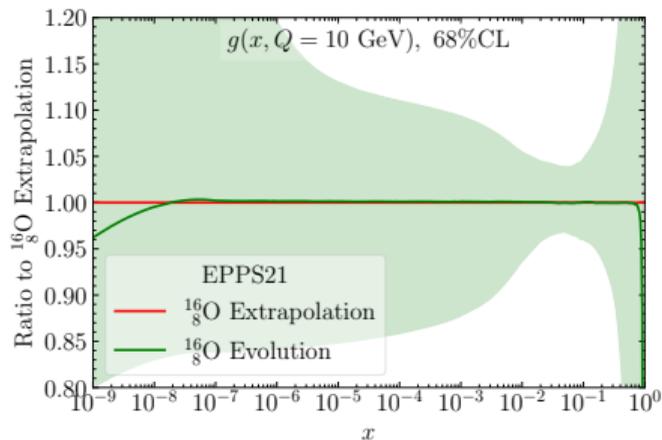
High orders, heavy quarks and flavors



[CT18LO:2205.00137],[CT18(N)NLO:1912.10053]

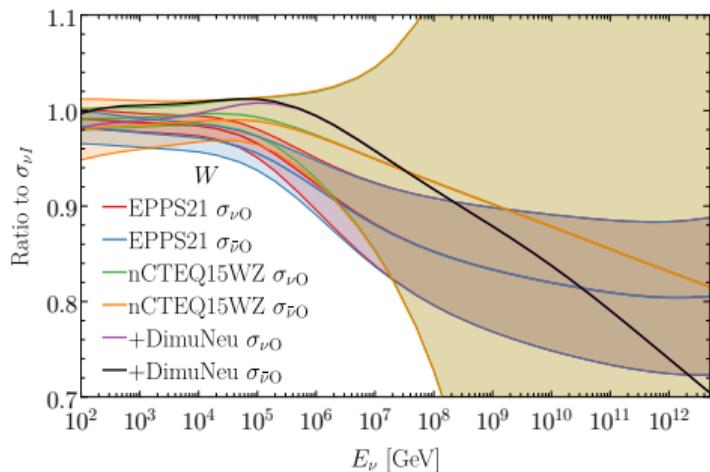
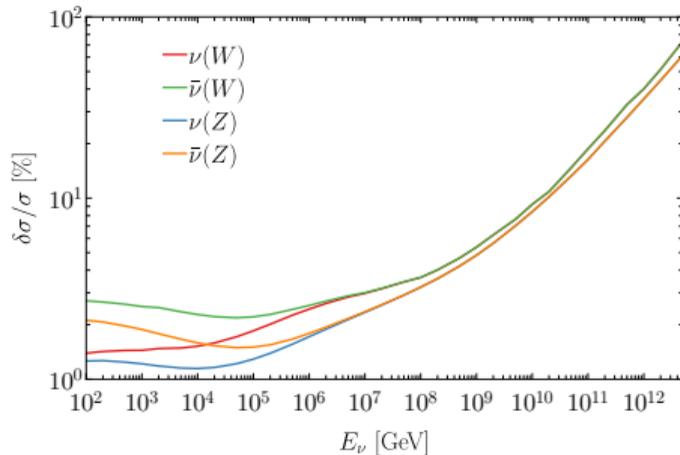
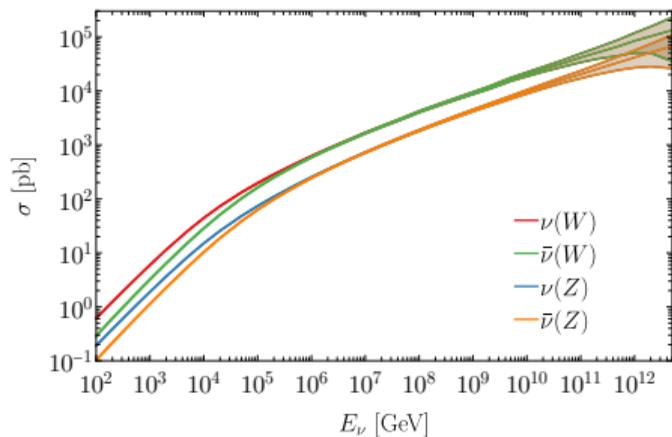
- QCD orders up to LO/NLO/NNLO and partial N3LO
- The complete heavy-quark effect up to NNLO [2107.00460]
- Bottom and even top quark PDFs will become relevant at UHE.

PDFs at small x



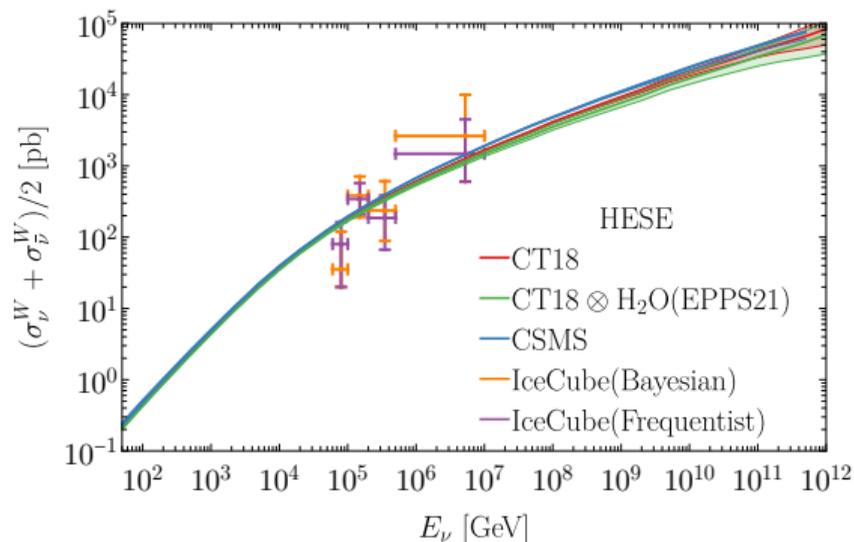
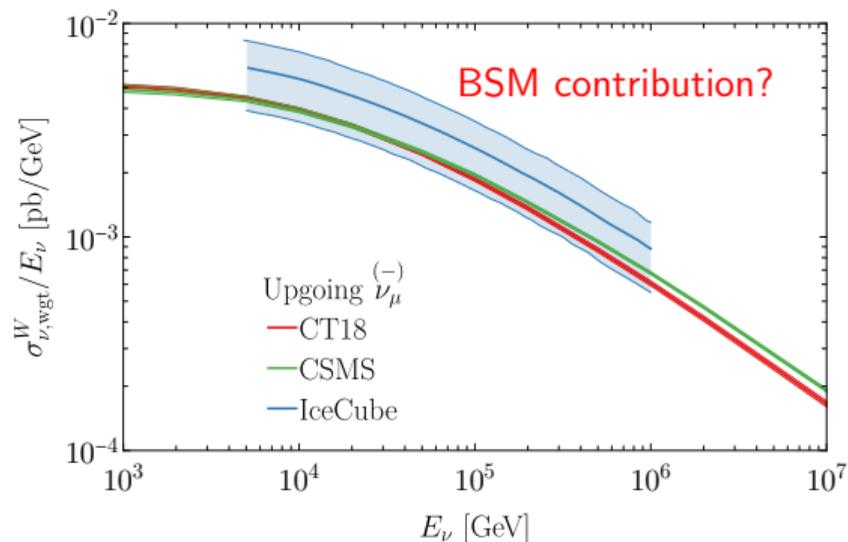
- Fitted data is only viable down to $x \sim 10^{-5}$
- We take the extrapolation (and evolution)
- At extremely small x , the BFKL resummation of $\log(x)$ (CT18sx [2108.06596]) and saturation (CT18X [1912.10053]) effects.
- The resummation gives up to about 20% enhancement at UHE

Nucleon and nuclear cross sections



- The based line take an iso-scalar nucleon PDF
- The PDF uncertainty varies from a percent level up to a few tens percent at UHE
- Nuclear effect, quantified with nuclear PDFs, decreases cross sections but only up to 20% level, with additional uncertainties

IceCube measurements

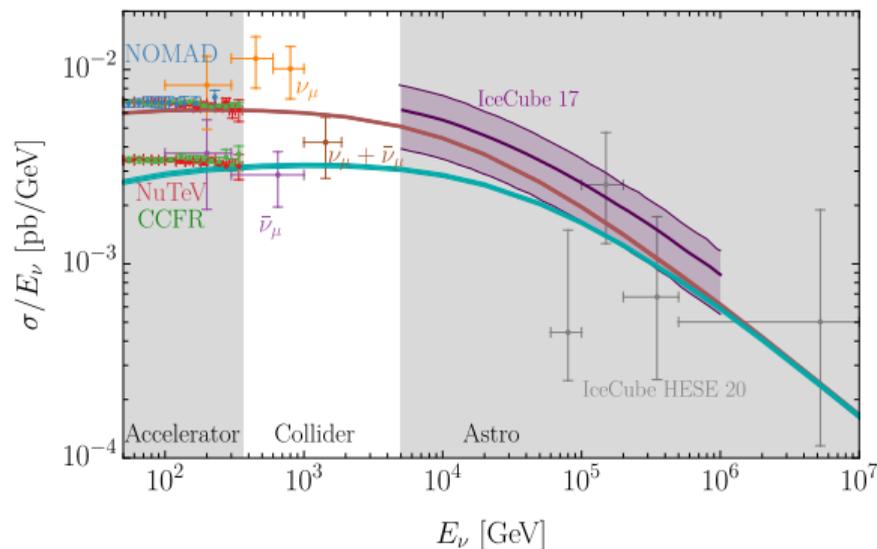
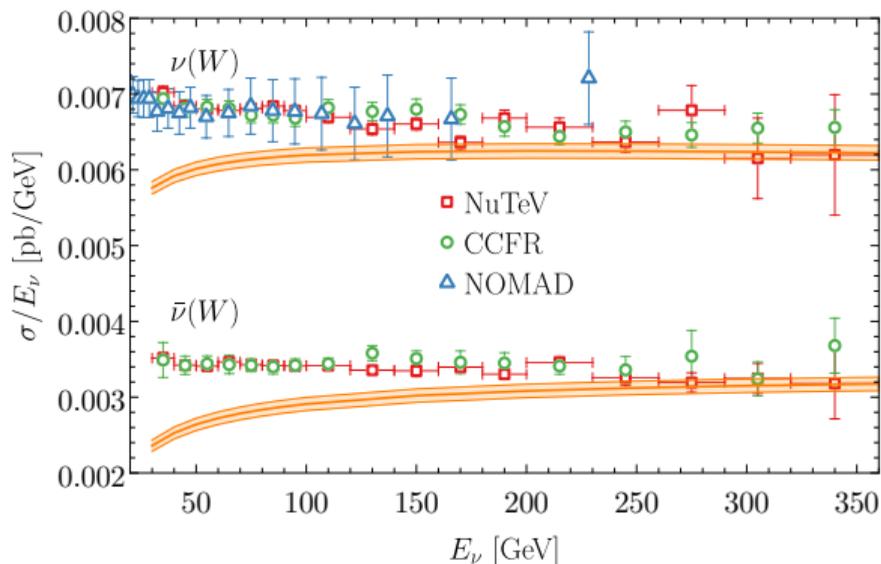


- The absorption cross section [IceCube, Nature 17'] is weighted with neutrino flux.

$$\sigma_{\nu, \text{wgt}} = \frac{\Phi_\nu \sigma_\nu + \Phi_{\bar{\nu}} \sigma_{\bar{\nu}}}{\Phi_\nu + \Phi_{\bar{\nu}}}$$

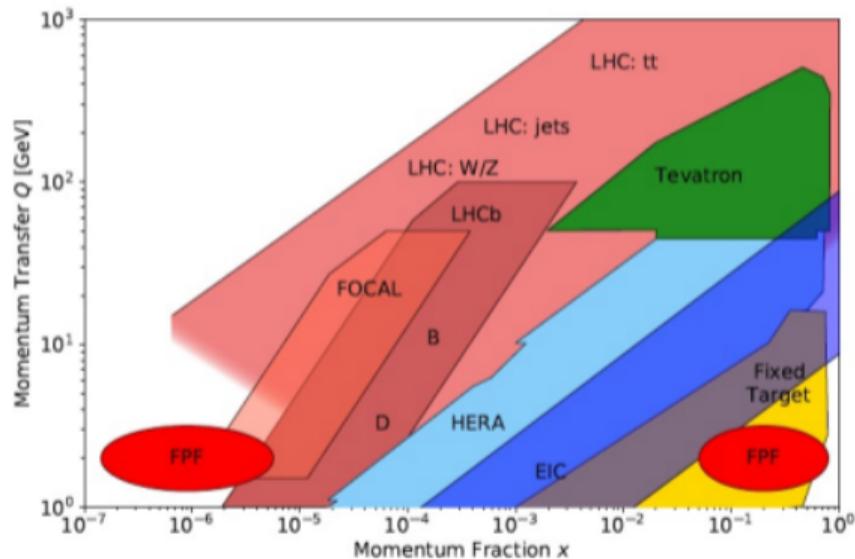
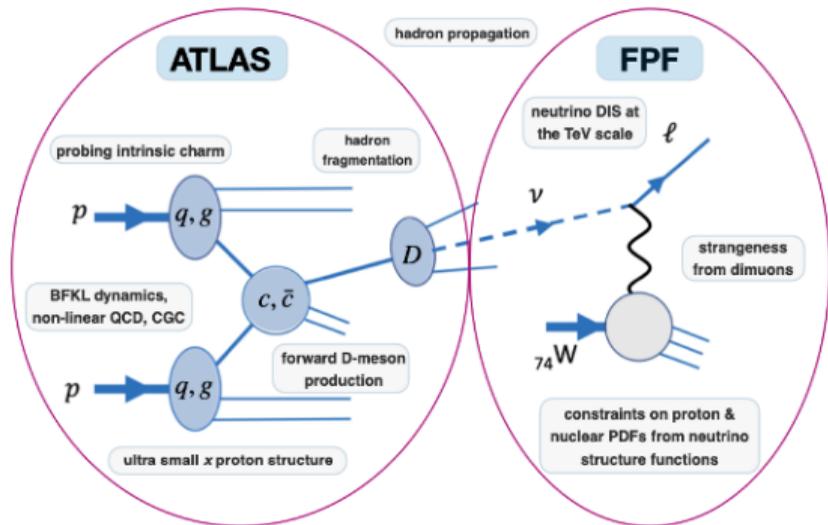
- The High Energy Starting Event (HESE) cross section is averaged [IceCube, PRD20'].

Bridge accelerator and telescope: collider



- At low E_ν , the missing Quasi-Elastic (QE) scattering and Resonance (RES) production become important, which can be parameterized with the Bodek-Yang model.
- The energy gap can be potentially filled by the FASER (FPF) [2412.03186].
- Muon colliders can get more events

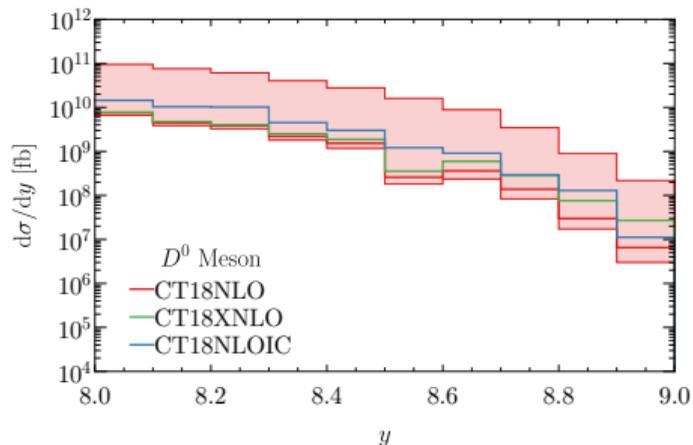
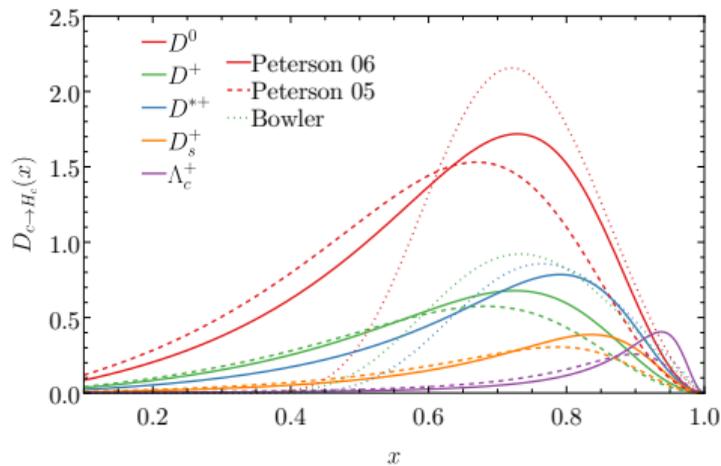
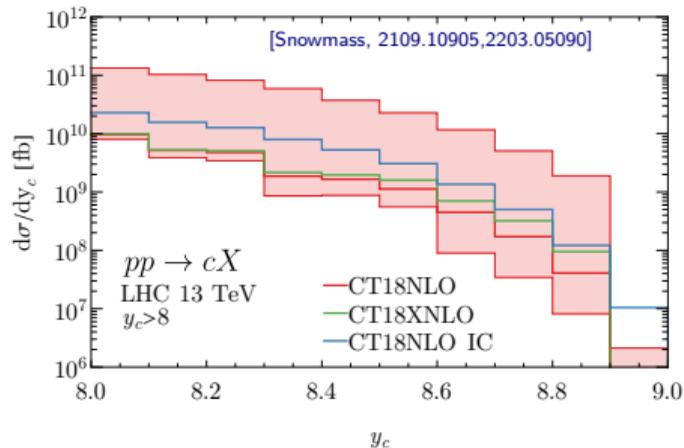
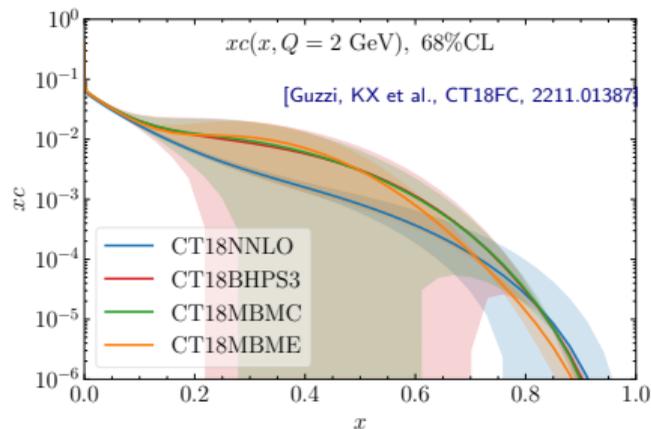
FASER and Forward Physics Facility



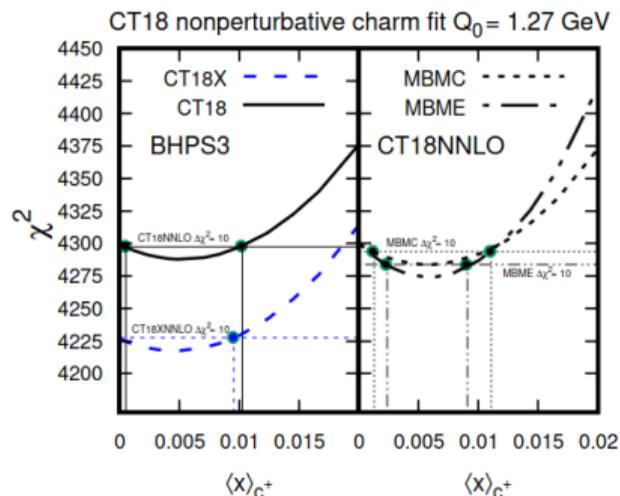
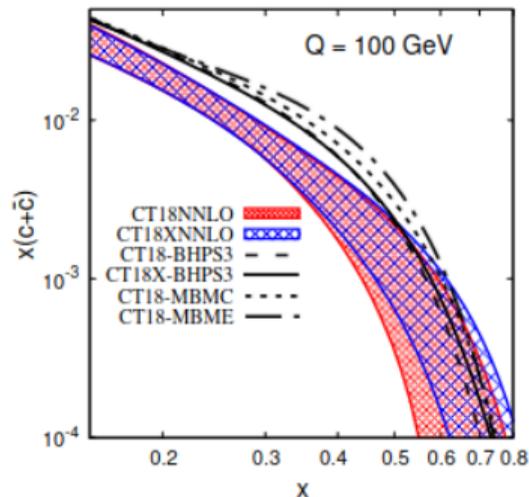
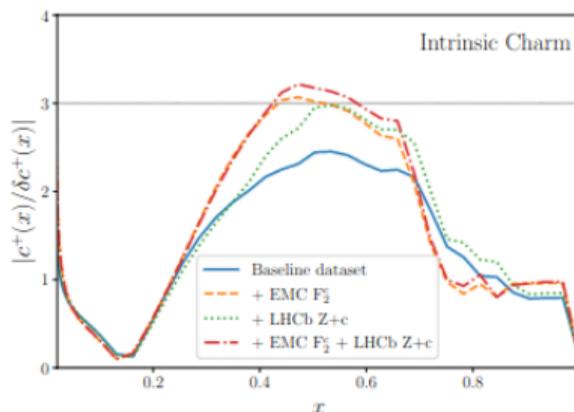
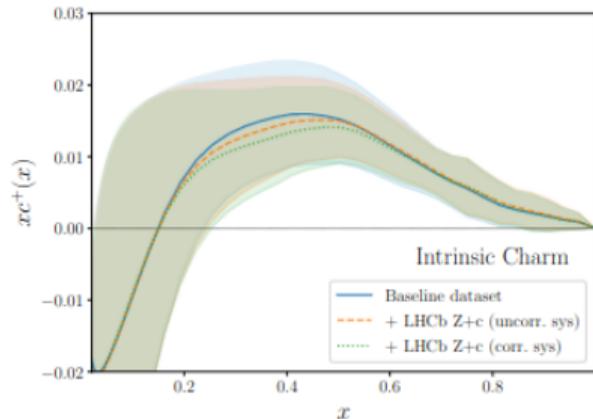
The neutrino measurement in the ongoing FASER and future FPF probe both large and small Bjoken x .

[Snowmass 2203.05090]

The charm production at the FPF



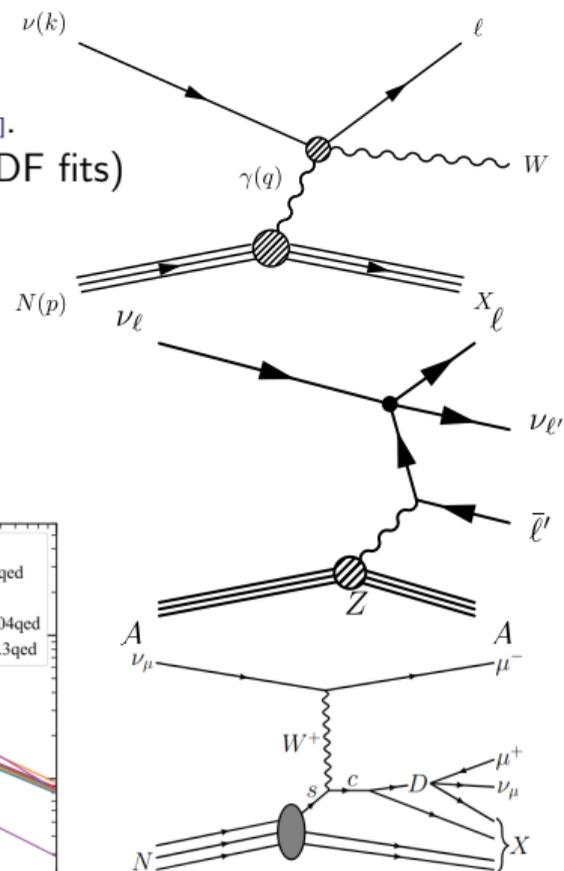
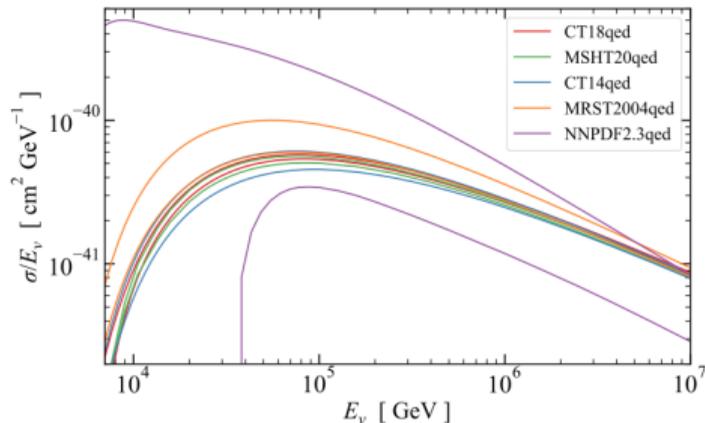
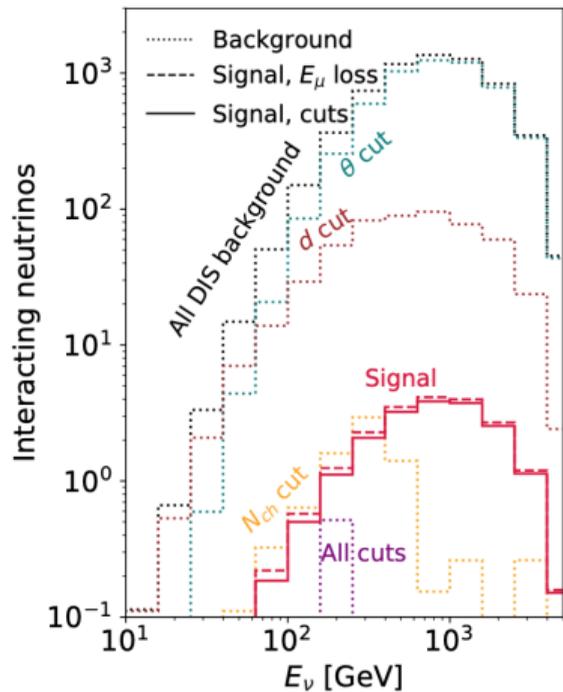
Intrinsic Charm PDF



- NNPDF found a 3σ discovery of intrinsic charm PDF [[Nature, 2208.08372](#)]
- We re-do a more comprehensive IC analysis carefully, and found 1σ significance [[Guzzi, Hobbs, KX et al., CT18FC, 2211.01387](#)]
- Quantification of error bands [[Nadolsky, KX et al., 2205.10444](#)]
- FPF and Muon Colliders have a great potential (ongoing)
- Also see Juan Rojo's talk

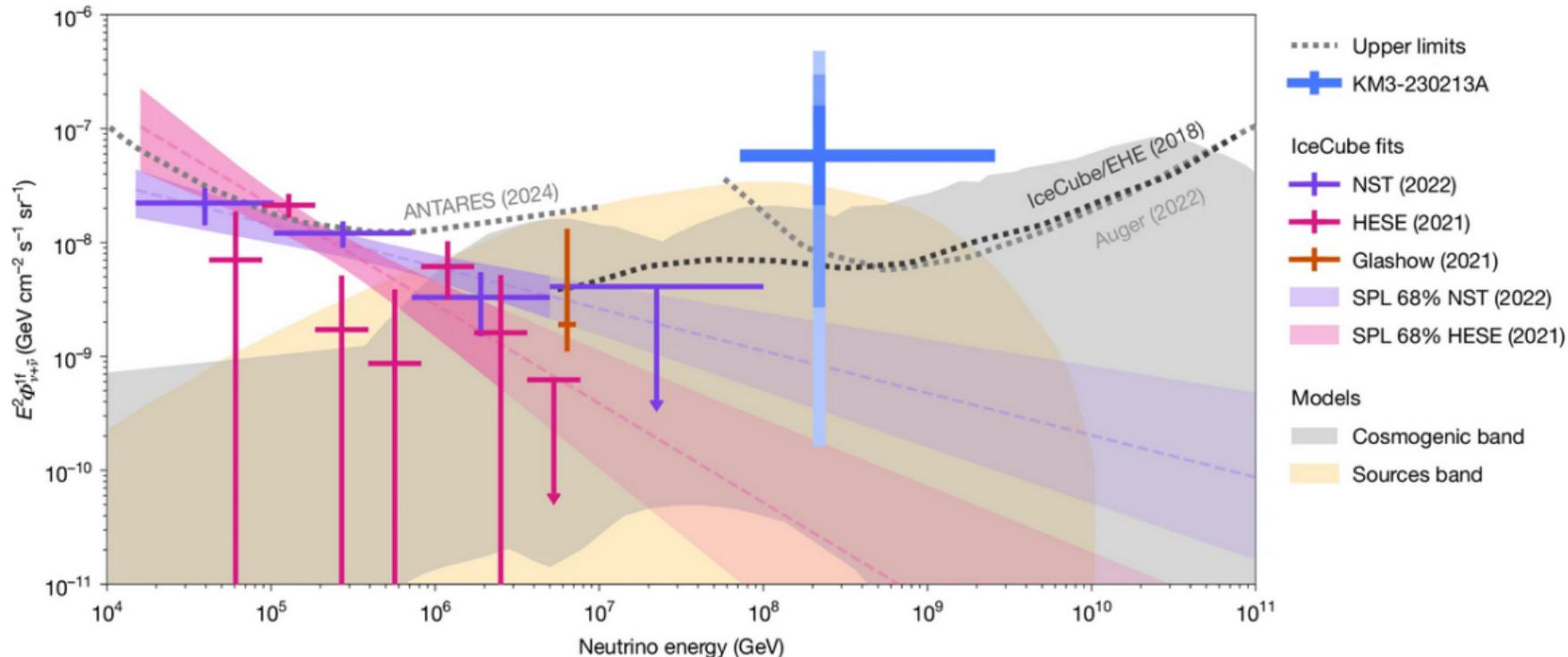
W boson, trident and di-muon production

- W -boson production [KX, Zhou, JHEP'24].
- 5σ discovery for neutrino trident at FASERv2 (FPF) [Trojanowski, KX+, PRD'24].
- Dimuon events have been measured at NuTeV/CCFR (included in PDF fits)
- Can be measured at FPF and MuC as well



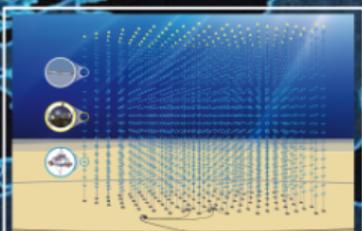
Astrophysical and Cosmic Neutrinos

[KM3Net, Nature 2025]



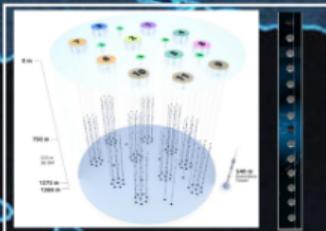
- Above $\sim 5\text{PeV}$ IceCube observed **3** events
- KM3NeT detected **1** outlier event around 120 PeV
- With cross section, it basically determines the neutrino flux

Future Global Neutrino Telescopes



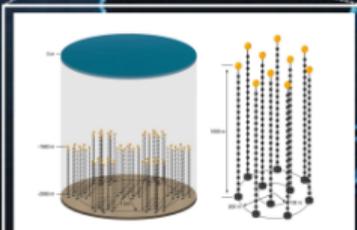
KM3NeT (Mediterranean Sea)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 1 km³
Number of strings: ~ 230



Baikal-GVD (Lake Baikal)

Medium: Deep-lake water
Depth: ~ 1.4 km
Volume: ~ 1 km³
Number of strings: ~ 140



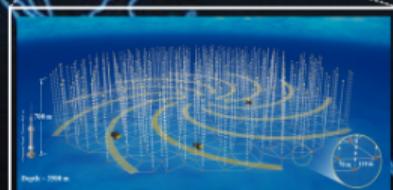
P-ONE (East Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 2.6 km
Volume: ~ 1 km³
Number of strings: ~ 70



IceCube Gen-2 (South Pole)

Medium: Glacial ice
Depth: ~ 2.5 km
Volume: ~ 8 km³
Number of strings: ~ 210

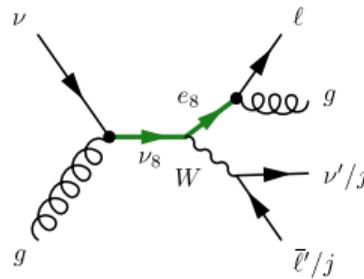
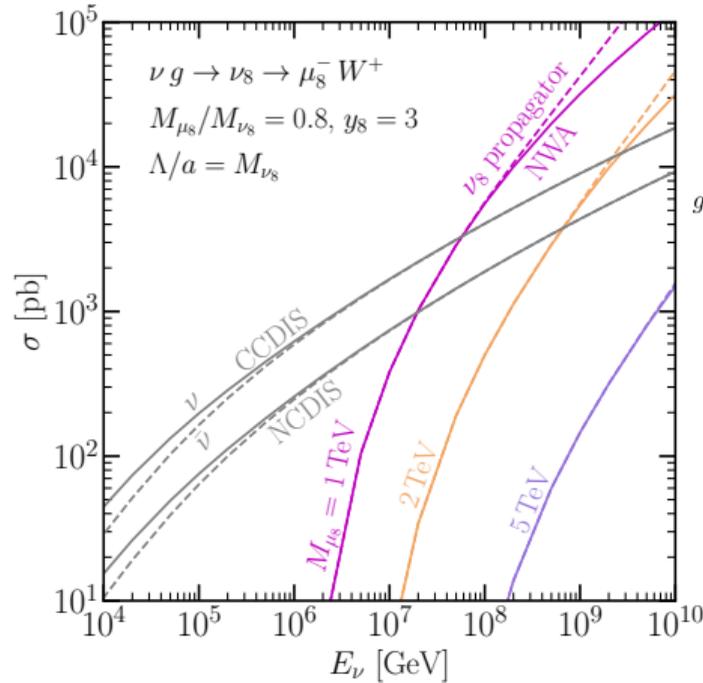
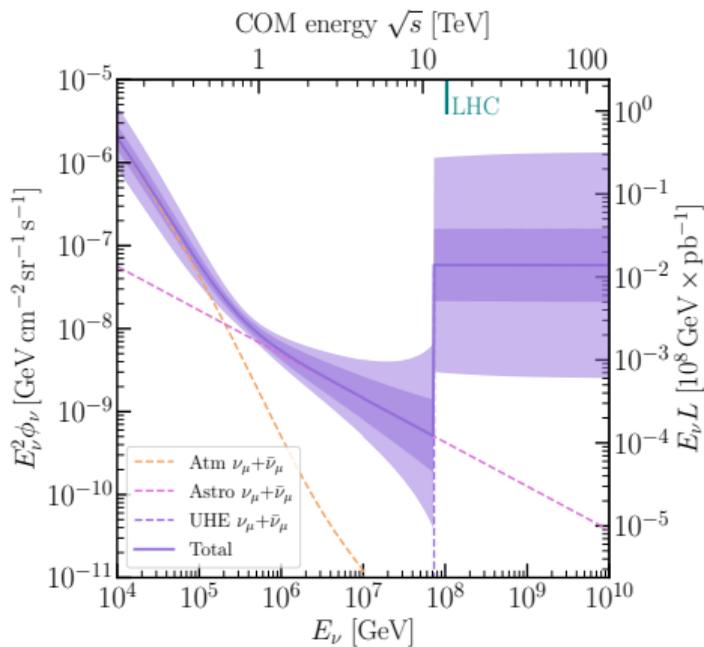


TRIDENT (West Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 8 km³
Number of strings: ~ 1000

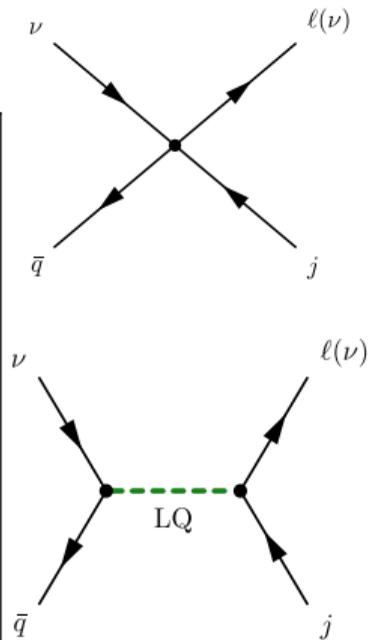
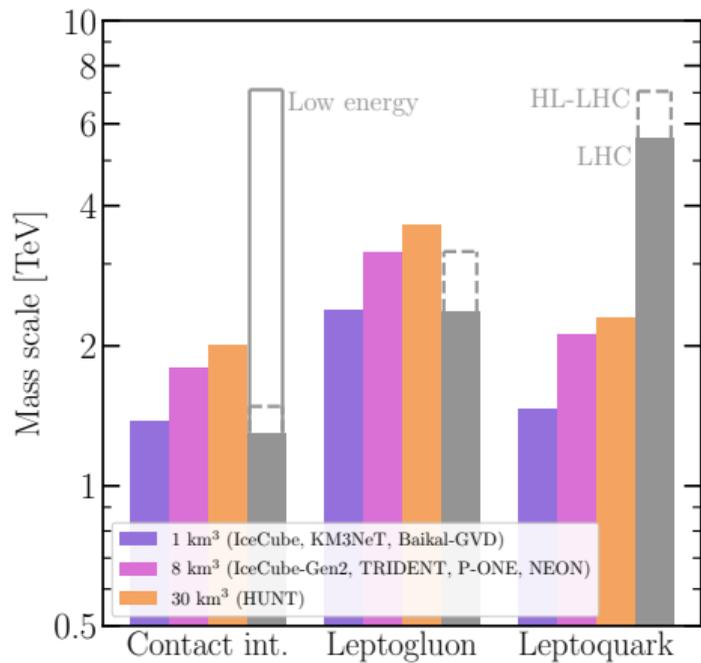
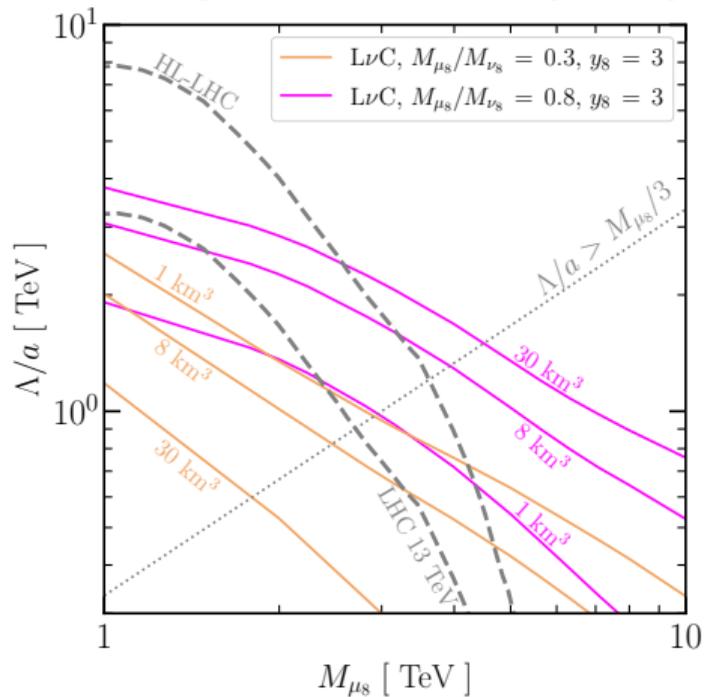
(HUNT, NEON)

Large Neutrino “Collider” (LvC) [2510.13948]



- Neutrino flux with the combination of IceCube and KM3NeT measurement, up to 10^{10} GeV
- The collision energy can reach the current LHC, and even 100 TeV FCC/SppC
- New physics models can be tested at LvC, e.g., neutrino-gluon (ν_8).

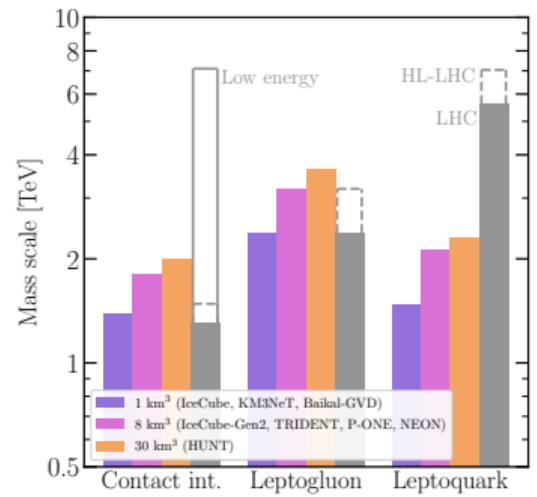
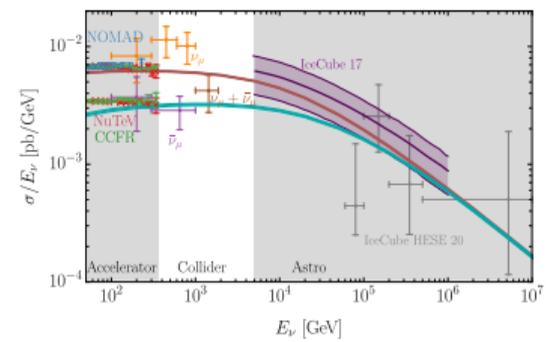
In comparison with (HL-)LHC



- We have explored the physics potential with SMEFT, LG, LQs [\[2510.13948\]](#)
- Some cases can be comparable, even beyond the (HL-)LHC

Conclusion

- **QCD corrections** to the neutrino DIS have reached up to NNLO and partial N3LO, including heavy-quark mass, flavor numbers, small- x , nuclear corrections have been explored in details
- The **energy gap** between accelerator and astrophysical neutrinos can be filled by colliders (FPF and Muon Colliders)
- The FPF neutrino measurements can constrain large- x and small- x PDFs, which is crucial for UHE neutrinos
- W boson, trident, di-muon production can be measured as well.
- Neutrino telescopes as **large neutrino colliders (LvCs)** can probe many new physics potential, including SMEFT operators, leptoquarks, and leptogluons, which can probe comparable and even beyond for new physics as (HL-)LHC.



The Earth absorption

- At high E_ν , astrophysical neutrinos dominate.
- Single-power-law astro. flux

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},$$

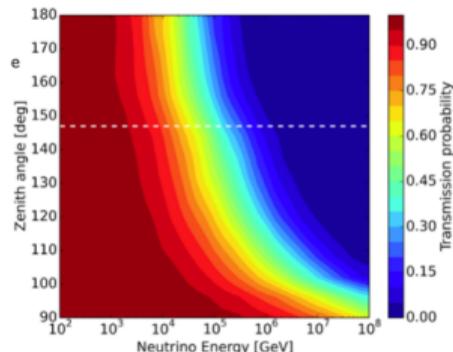
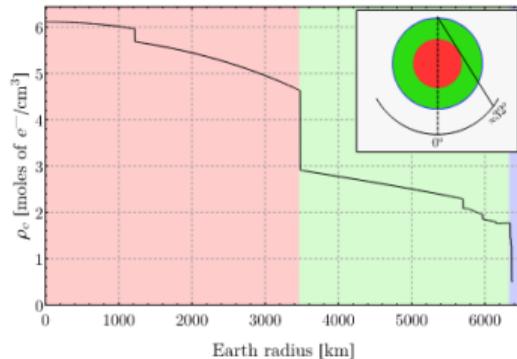
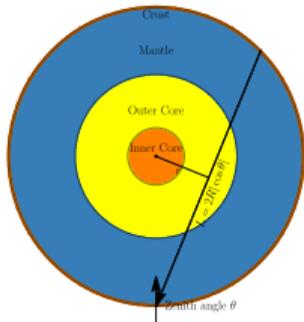
- The upward-going events (from northern sky)

$$\frac{dN_{\text{evt}}}{dE_\nu} = \sigma_\nu^W \frac{d\Phi_{6\nu}}{dE_\nu} \mathcal{P}_{\text{trans}}$$

- The transmission probability

$$\mathcal{P}_{\text{trans}} \sim \exp\{-L(\theta)/\lambda(E_\nu)\} = \exp\{-L(\theta)\kappa\sigma(E_\nu)\}$$

- Earth model: isotopic abundance and density

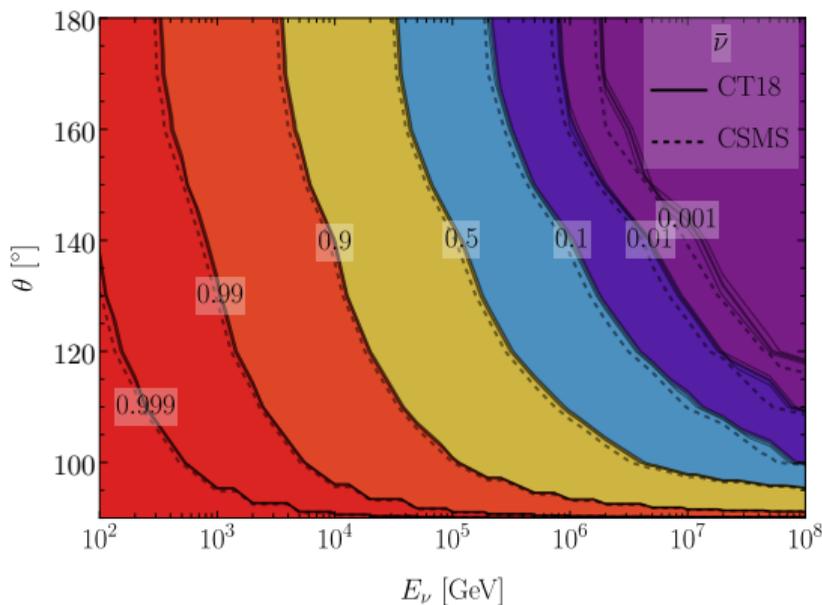
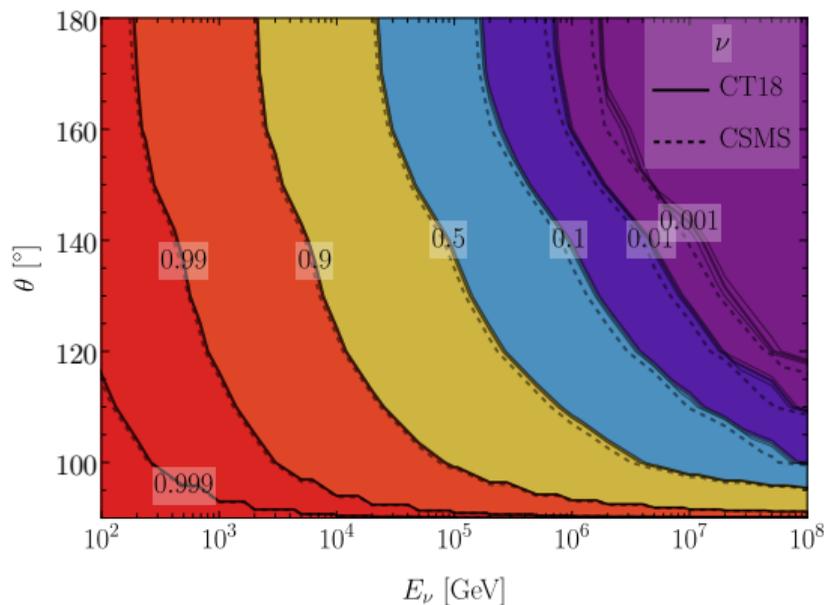


The transmission probability

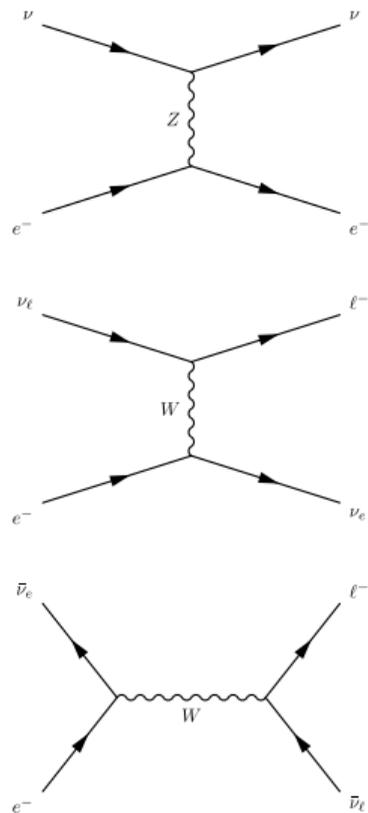
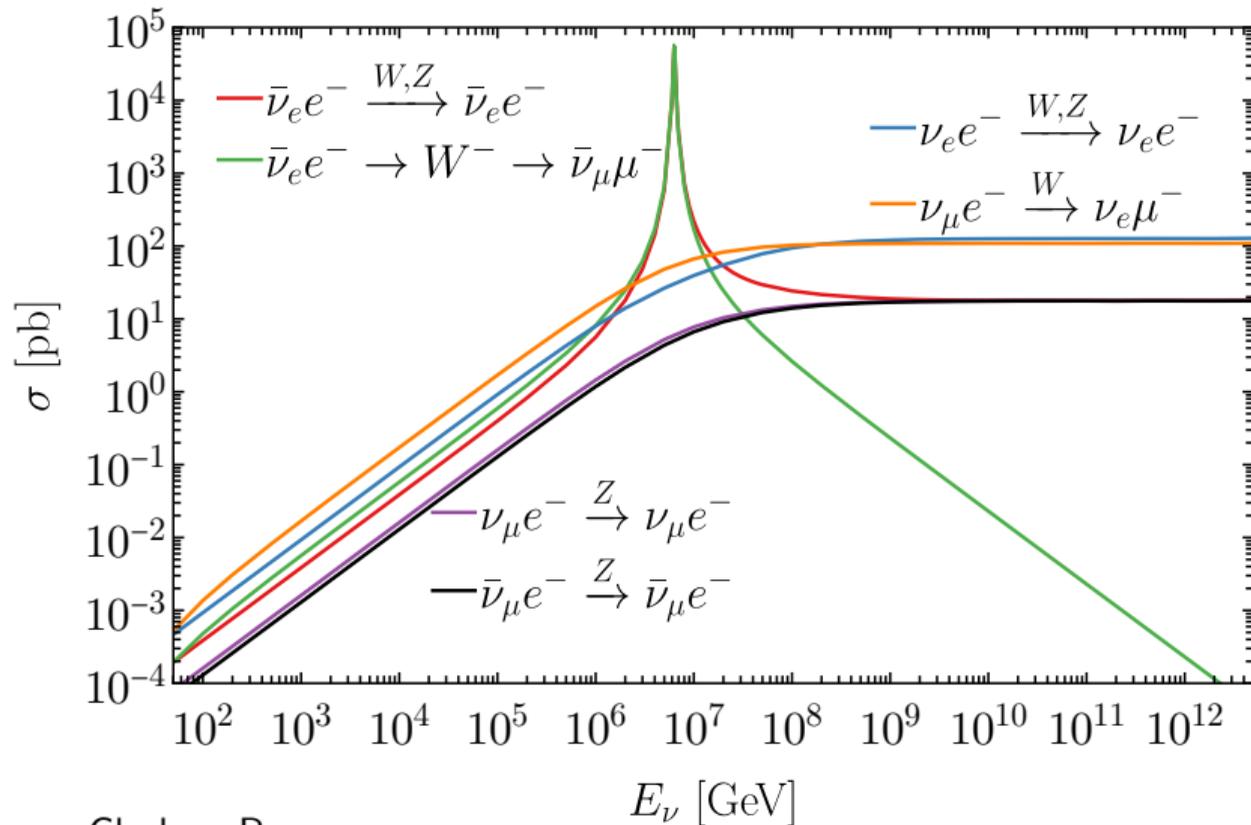
- We take a spherical earth model, with the density from Preliminary Reference Earth Model (PREM) [Dziewonski&Anderson, 1981].
- The transmission probability

$$\mathcal{P}_{\text{trans}}(E_\nu, \theta) = \Pi_{\Delta z} P_{\alpha\alpha}(E_\nu, \Delta z) \exp\{-\Delta z/\lambda(r, E_\nu)\}$$

where the oscillation probability is $P_{\alpha\alpha} \approx 1$ when $E_\nu \gtrsim 1$ TeV, and the mean-free path $\lambda = 1/n_N(r)\sigma_\nu(E_\nu)$.



Neutrino-electron scattering



- Glashow Resonance [IceCube, Nature 21']

Other cross-section calculations

- Gandhi-Quigg-Reno-Sarcevic [[hep-ph/9807264](#)]: CTEQ4M, LO
- Connolly-Thorne-Waters [[1102.0691](#)]: MSTW08, LO
- Cooper-Sarkar-Mertsch-Sarkar [[1106.3723](#)]: HERAPDF1.5, NLO (IceCube)
- Argüelles-Halzen-Wille-Kroll-Reno [[1504.06639](#)]: Color dipole model
- Bertone-Gauld-Rojo [[1808.02034,2004.04756](#)]: NNPDF3.1sx, NNLO (NLO in Genie)
- NNSFv [[2302.08527](#)]: Bodek-Yang model, NNPDF4.0, NNLO
- Jeong-Reno [[2307.09241](#)]: Shallow inelastic scattering

Events and statistics

- Starting events:

$$\frac{dN^{\text{st}}}{dE_\mu}(E_\mu) = T V \rho N_A \int_{E_\mu}^{\infty} dE_\nu \frac{d\sigma}{dE_\mu}(E_\mu, E_\nu) 2\pi \int_{-1}^1 d\cos\theta_z \frac{d\phi_\nu}{dE_\nu}(E_\nu, \cos\theta_z) e^{-\tau(E_\nu, \cos\theta_z)}.$$

- Through-going events

$$\frac{dN^{\text{thr}}}{dE_\mu}(E_\mu) = T \frac{N_A V^{2/3}}{\alpha + \beta E_\mu} \int_{E_\mu}^{\infty} dE_\nu \int_{E_\mu}^{E_\nu} dE'_\mu \frac{d\sigma}{dE'_\mu}(E'_\mu, E_\nu) 2\pi \int_{-1}^0 d\cos\theta_z \frac{d\phi_\nu}{dE_\nu}(E_\nu, \cos\theta_z) e^{-\tau(E_\nu, \cos\theta_z)}$$

- Muon energy average

$$\frac{d\sigma}{dE'_\mu}(E'_\mu, E_\nu) \simeq \sigma(E_\nu) \delta(E'_\mu - \langle E'_\mu \rangle(E_\nu)),$$

- Likelihood

$$\mathcal{L}(\{n_{i,j}\} | s, b, \theta^s, \theta^b) = \prod_{i,j} \text{Poisson}(n_{i,j} | s_{i,j}^{\text{eff}} + b_{i,j}^{\text{eff}}) \times \mathcal{N}(\theta_{i,j}^s | 0, \log_{10} \delta_{i,j}^s) \times \mathcal{N}(\theta_{i,j}^b | 0, \log_{10} \delta_{i,j}^b).$$

and 95% confidence level

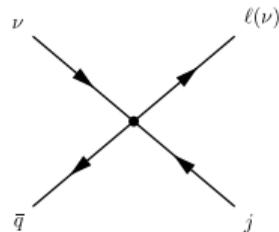
$$q_0 = -2 \log \left(\frac{\mathcal{L}(n_{i,j} = s_{i,j} + b_{i,j} | s_{i,j} = 0, \hat{\theta}_{i,j}^b)}{\mathcal{L}(n_{i,j} = s_{i,j} + b_{i,j} | s_{i,j}, \hat{\theta}_{i,j}^s, \hat{\theta}_{i,j}^b)} \right) \sim 1.960^2.$$

SMEFT operators

- Relevant for CC-like events

$$O_{\ell q}^{(3)} = (\bar{\ell} \bar{\sigma}_\mu \sigma^i \ell) (\bar{q} \bar{\sigma}^\mu \sigma^i q), \quad O_{ledq} = (\bar{\ell} \bar{e}^c) (d^c q),$$

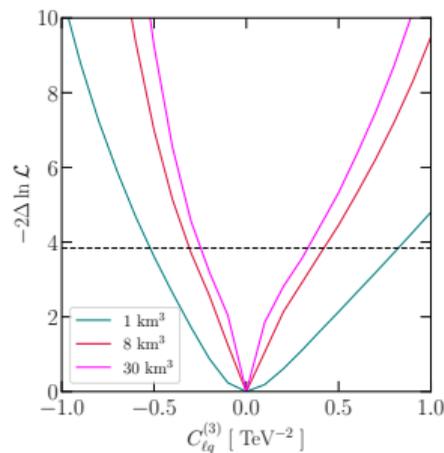
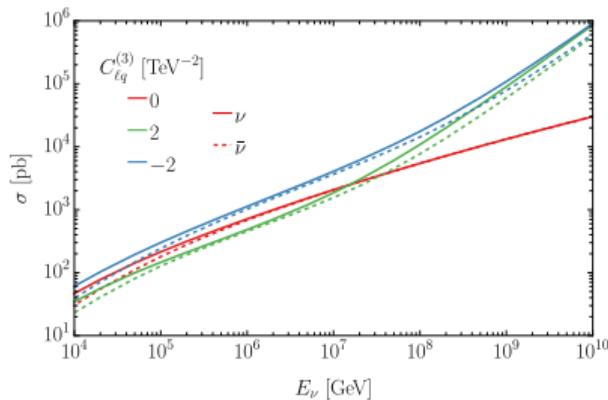
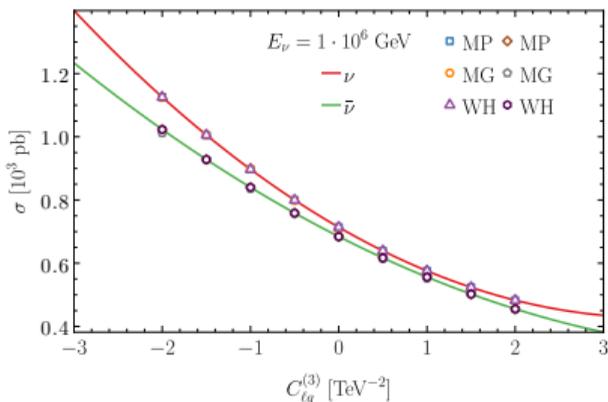
$$O_{\ell equ}^{(3)} = (\bar{\ell} \bar{\sigma}_{\mu\nu} \bar{e}^c) \varepsilon (\bar{q} \bar{\sigma}^{\mu\nu} \bar{u}^c), \quad O_{lequ}^{(1)} = (\bar{\ell} \bar{e}^c) \varepsilon (\bar{q} \bar{u}),$$



- Cross section dependence

$$|\mathcal{M}_{\nu d \rightarrow \ell^- u}|^2 = \left(\frac{g_W^2}{2(\hat{t} - M_W^2)} + 2C_{\ell q}^{(3)} \right)^2 \hat{s}^2 + \left[\left(\frac{1}{2} C_{lequ}^{(1)} + 2C_{lequ}^{(3)} (1 + 2\hat{s}/\hat{t}) \right)^2 + \frac{1}{4} C_{ledq}^2 \right] \hat{t}^2.$$

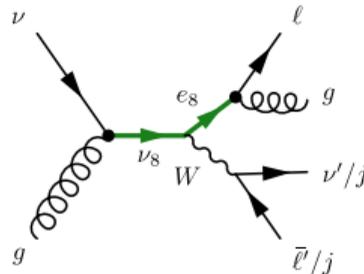
- We restrict ourselves within $\hat{\sigma} \sim \frac{|C_{\ell q}^{(3)}|}{2\pi} \hat{s} \leq \frac{4\pi}{\hat{s}}$



A vector-like LG model

- Vector-like leptogluon and neutrinogluon

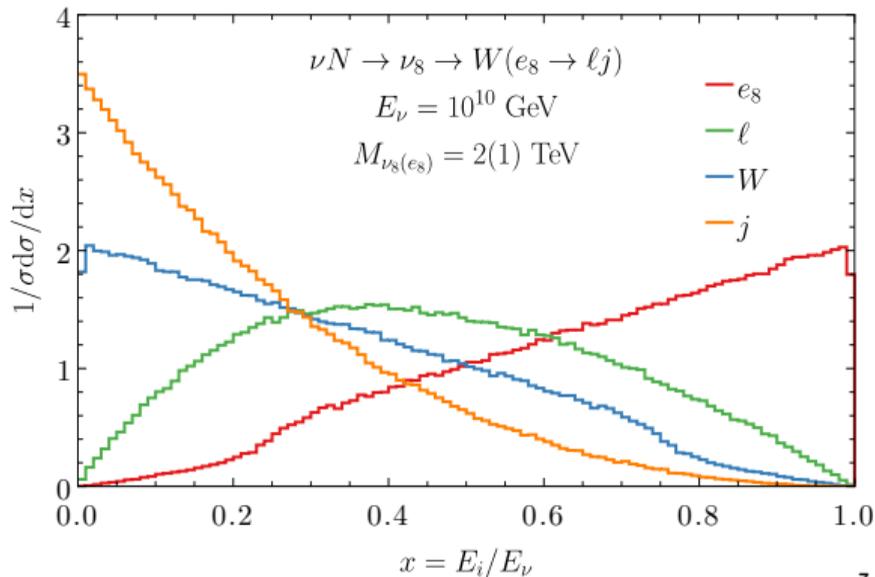
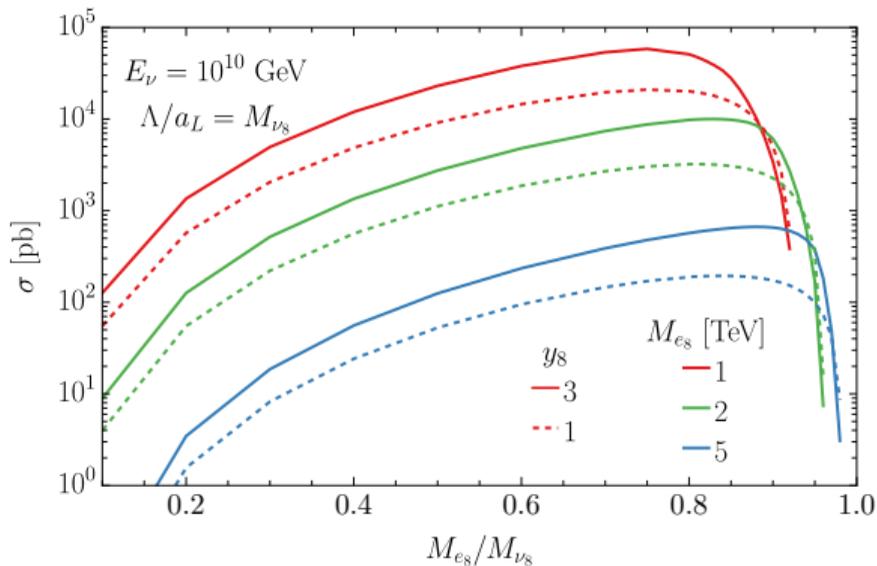
$$(8, 2)_{-1/2} : L_8 = \begin{pmatrix} \nu_8 \\ \lambda_8 \end{pmatrix}, \text{ and } (8, 1)_{-1} : E_8,$$



- Interactions

$$-\mathcal{L} \supset M_{L_8} \bar{L}_{8L} L_{8R} + M_{E_8} \bar{E}_{8L} E_{8R} + y_8 \bar{L}_{8L} \Phi E_{8R} + \text{h.c.},$$

- Production and muon energy distribution



Vector and Scalar Leptoquarks

Spin	$SU(2)_W$	Y	Notation	Interactions
0	1	1/3	$S_1^{1/3}$	$S_1^{1/3} (y_1^{LL} \bar{q}_L^c \ell_L + y_1^{RR} \bar{u}_R^c e_R)$
0	2	7/6	$R_2 = (R_2^{5/3}, R_2^{2/3})$	$R_2 (y_2^{LR} \bar{q}_L^c e_R + y_2^{RL} \bar{u}_R \ell_L)$
0	3	1/3	$S_3 = \begin{pmatrix} S_3^{1/3} & S_3^{4/3} \\ S_3^{-2/3} & -S_3^{1/3} \end{pmatrix}$	$y_3^{LL} \bar{q}_L^c S_3 \ell_L$
1	1	2/3	$V_1^{2/3}$	$V_{1\mu}^{2/3} (g_1^{LL} \bar{q}_L \gamma^\mu \ell_L + g_1^{RR} \bar{d}_R \gamma^\mu e_R)$
1	2	5/6	$V_2 = (V_2^{4/3}, V_2^{1/3})$	$V_{2\mu} (g_2^{LR} \bar{q}_L^c \gamma^\mu e_R + g_2^{RL} \bar{d}_R^c \gamma^\mu \ell_L)$
1	3	2/3	$V_3 = \begin{pmatrix} V_3^{2/3} & V_3^{5/3} \\ V_3^{-1/3} & -V_3^{2/3} \end{pmatrix}$	$g_3^{LL} \bar{q}_L V_{3\mu} \gamma^\mu \ell_L$

