Probing ν_R-philic Z' at the DUNE near detector

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Based on **G.C.**, Bhupal Dev (WUSTL) and Xun-Jie Xu (IHEP-CAS) [arXiv: 2204.11876]

PASCOS 2022: 27th International Symposium on Particles, Strings and Cosmology

Max Planck Institute for Nuclear Physics
July 25, 2022

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- ν_R's are motivated BSM candidates - ν masses, dark matter and matter-antimatter asymmetry (η_B)

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- Here, couplings to neutrinos are generically larger than its loop-induced couplings to electrons.
- We'll explore how this feature is useful for probing this scenario at DUNE.

How dark is this Dark Photon ?

- We consider Z' coupled to ν_R with relevant lagrangian,

$$\mathcal{L} \supset g' Z'_\mu \nu_R \gamma^\mu \nu_R + m_D \bar{\nu}_L \nu_R + \frac{M_R}{2} \nu_R \nu_R + \cdots$$

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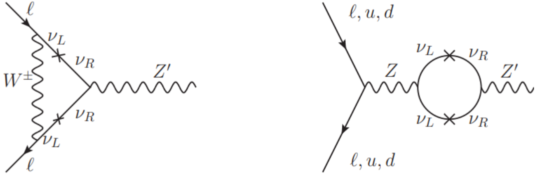
- In absence of kinetic mixing with SM, this Z' can interact with SM particles through these loop-level diagrams,

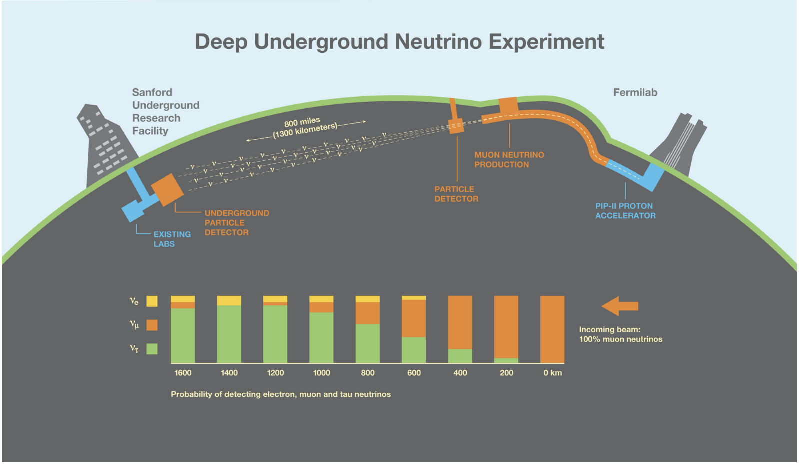


$$g_f^{(W)} = \frac{\sqrt{2} G_F m_D^2}{8\pi^2} g', \quad g_f^{(Z)} = \frac{\sqrt{2} G_F m_D^2}{8\pi^2} g' Q_f^{(Z)}.$$

where $Q_f^{(Z)} \equiv I_3 - Q_{\rm em} s_W^2$.

DUNE

- DUNE is a long-baseline neutrino experiment, with a high intensity neutrino beam originating at Fermilab with a massive far detector (1300 km away) in South Dakota.



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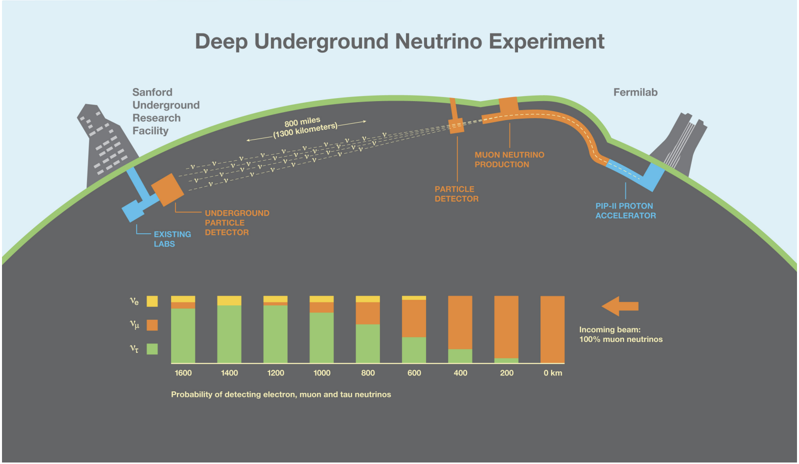

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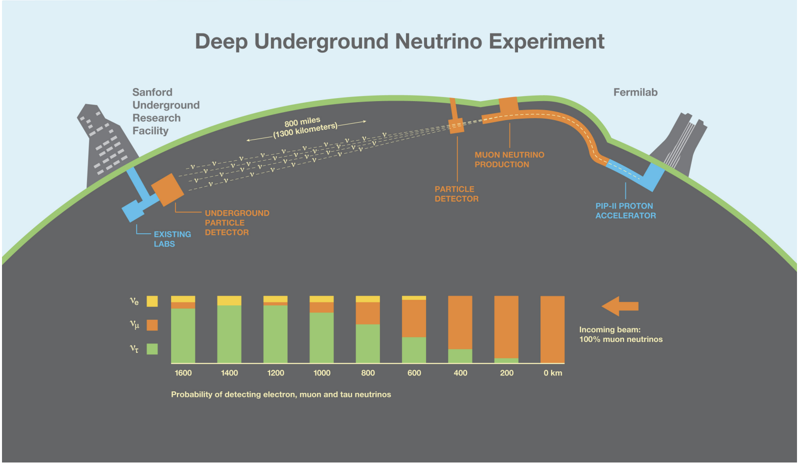

- The far detector consists of 4 massive liquid argon detectors each about 10 kilotons.
- Uses liquid argon time projection chamber (LArTPC) technology, which provide excellent particle identification and energy measurements.

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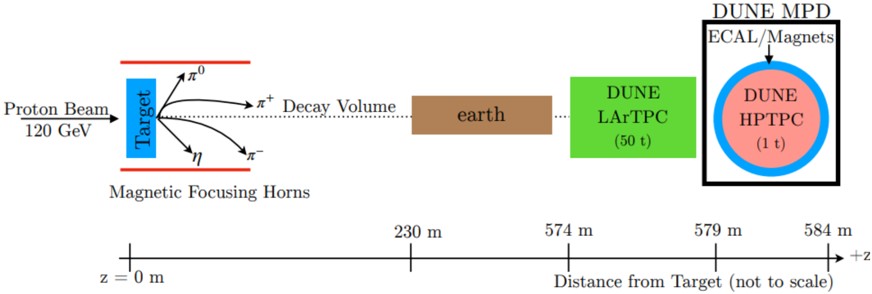

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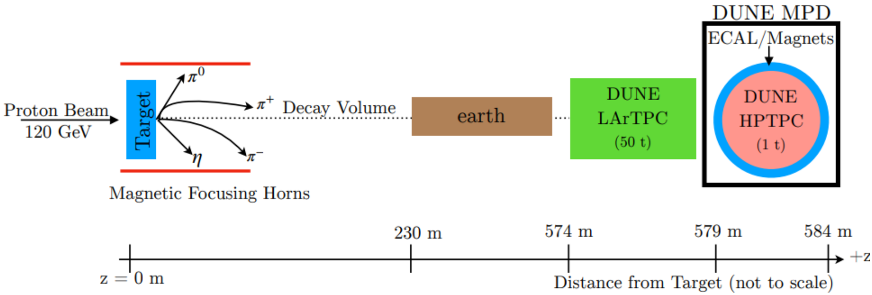

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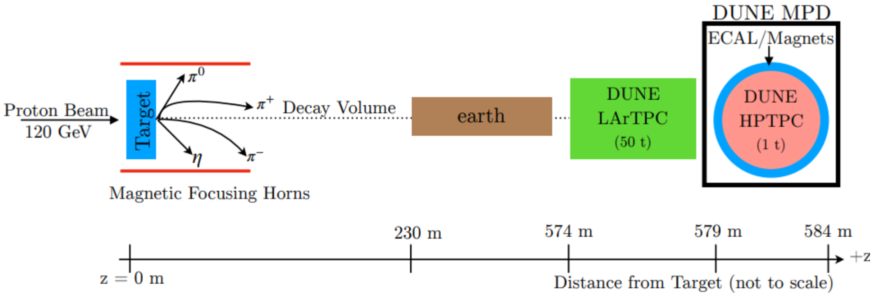

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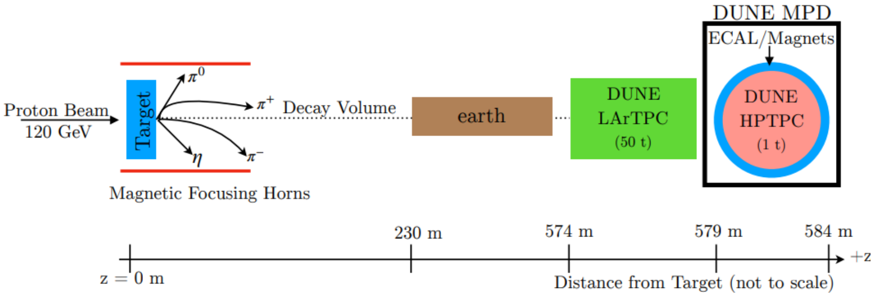

- The ND consists of
  - a LArTPC called ArgonCube
  - a high-pressure gaseous argon TPC (HPgTPC) surrounded by an electromagnetic calorimeter (ECAL) in a 0.5 T magnetic field

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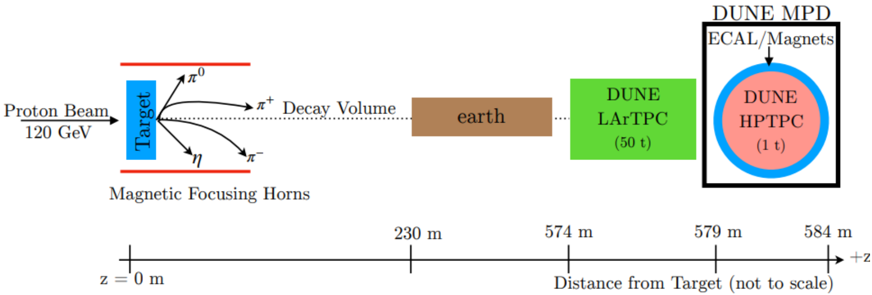
- We assume data collection of 5 years each in ν ("forward horn current") and $\bar{\nu}$ ("reverse horn current") modes.
- DUNE produces a large flux of charged mesons (mostly $\pi^{\pm}$ and $K^{\pm}$) that decay leptonically, leading to a large flux of SM neutrinos.



$\nu - e$ scattering

- The effective couplings of Z' to normal matter and neutrinos:

$$\mathcal{L} = \overline{\psi}\left[g_{eL}\gamma^{\mu}P_L + g_R\gamma^{\mu}P_R\right]Z'_{\mu}\psi + \overline{\psi_{\nu}}\left[g_{\nu}\gamma^{\mu}P_L\right]Z'_{\mu}\psi_{\nu}\,,$$

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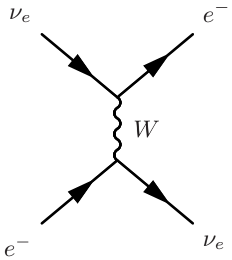
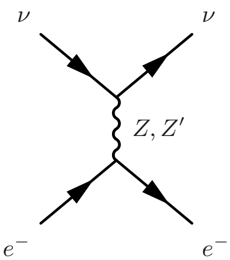
- For later use, we define

$$g \equiv \sqrt{g_L^2 + g_R^2}\,,$$

and

$$r \equiv \frac{g_{\nu}}{g_e},\ \ (g_L,\ g_R) = (\cos\beta,\ \sin\beta)g_e\,.$$





- Differential cross section for elastic neutrino-electron scattering including both the SM and the new physics contributions:

$$\frac{d\sigma}{dT} = \frac{2m_e G_F^2}{\pi}\left[c_L^2 + c_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - c_L c_R \frac{m_e T}{E_\nu^2}\right],$$

where

$$c_L = c_L^{(\mathrm{SM})} + \frac{g_{eL} g_\nu}{2\sqrt{2}G_F\left(2m_e T_e + m_{Z'}^2\right)}, \quad c_L^{(\mathrm{SM})} = -\frac{1}{2} + s_W^2 + \delta_{\alpha e},$$
$$c_R = c_R^{(\mathrm{SM})} + \frac{g_{eR} g_\nu}{2\sqrt{2}G_F\left(2m_e T_e + m_{Z'}^2\right)}, \quad c_R^{(\mathrm{SM})} = s_W^2 .$$

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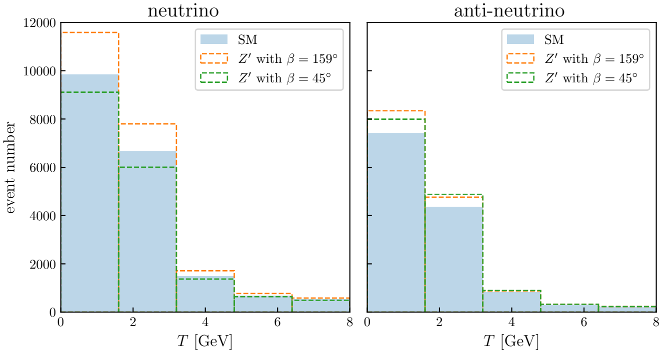
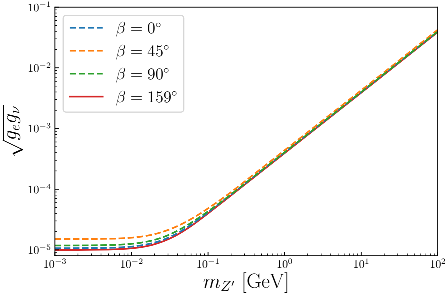
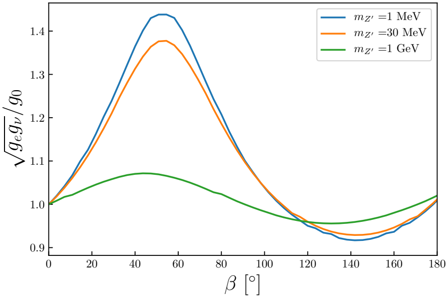
- The event rate of elastic neutrino-electron scattering at the detector is computed by:

$$\frac{dN}{dT} = N_e \lambda_{\mathrm{POT}} \int \Phi(E_\nu)\frac{d\sigma(T,\ E_\nu)}{dT}\Theta(T_{\max} - T)dE_\nu\,,$$

- assuming $m_{Z'} = 100$ MeV and $\sqrt{g_e g_\nu} = 10^{-4}$

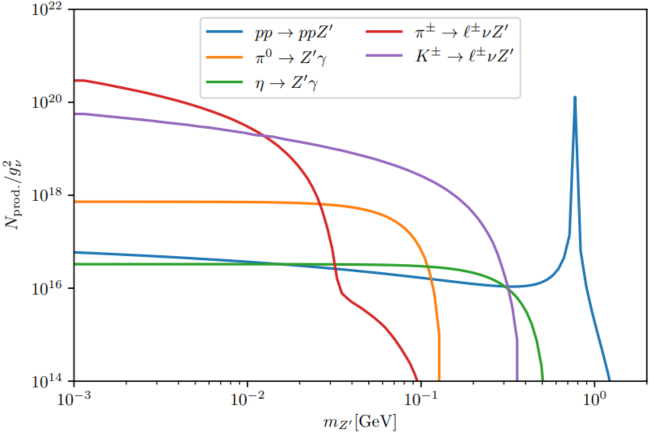



$\beta = 0°$
$\beta = 45°$
$\beta = 90°$
$\beta = 159°$
$\sqrt{g_e g_\nu}$
$m_{Z'}$ [GeV]


$m_{Z'}$ =1 MeV
$m_{Z'}$ =30 MeV
$m_{Z'}$ =1 GeV
$\sqrt{g_e g_\nu}/g_0$
β [°]

DUNE as beam dump

- At the neutrino production site of DUNE, Z' can be produced from the proton beam striking the target. Due to its weak loop-level couplings to SM fermions, the produced Z' boson can be long-lived.
- assuming $r = 100$,



- The number of events are calculated as

$$N_{\text{det.}} = \int dp_{Z'} \frac{dN_{\text{prod.}}(p_{Z'})}{dp_{Z'}} P_{\text{decay}}(p_{Z'}) \, \text{BR}_{Z' \to \text{vis.}} \, ,$$

$$P_{\text{decay}} = e^{-L_1/L_{Z'}} \left(1 - e^{-L_2/L_{Z'}}\right)$$

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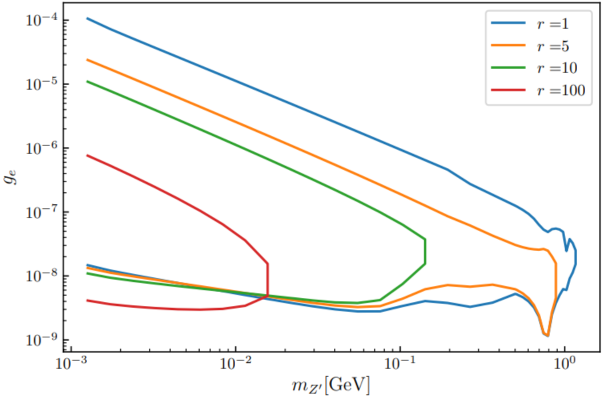
- The visible decay width is

$$\text{BR}_{Z' \to \text{vis.}} \equiv 1 - \frac{\Gamma_{Z' \to \nu\overline{\nu}}}{\Gamma_{Z'}} \, .$$

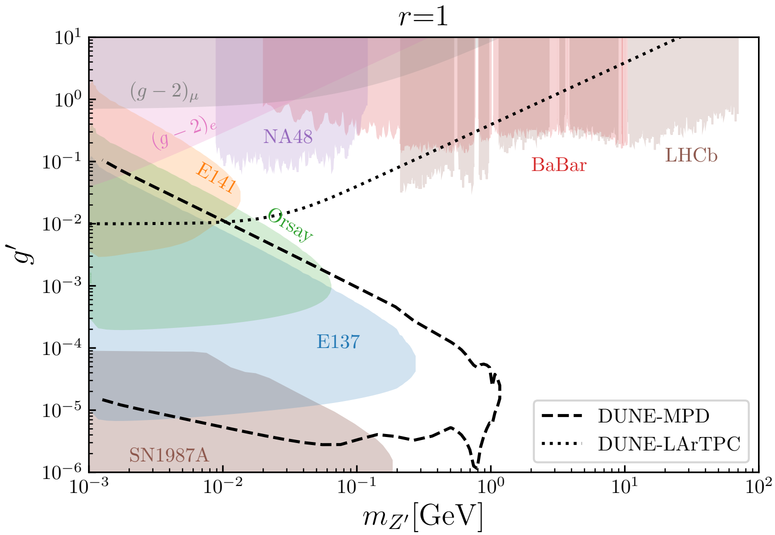
when $g_\nu \gg g_e$ and g_q, we have $\text{BR}_{Z' \to \text{vis.}} \ll 1$

DUNE as beam dump

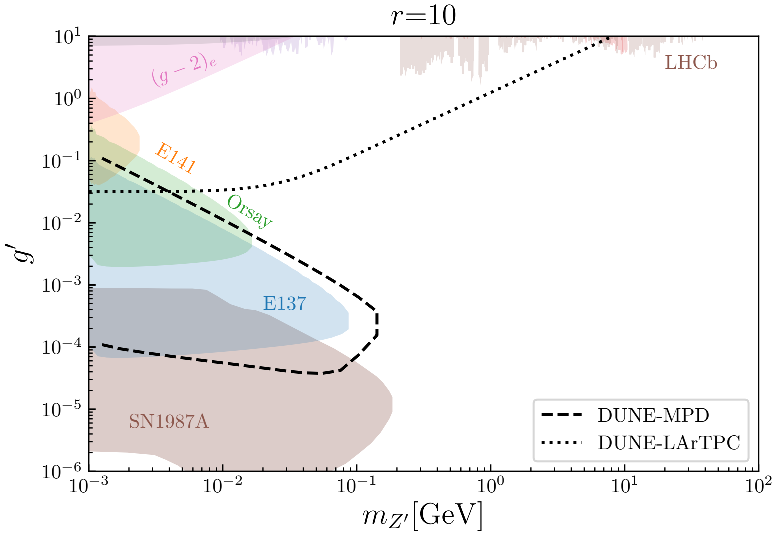
- The sensitivity reach of DUNE MPD to the ν_R-philic Z' with loop-induced couplings. The results depend on the ratio r



- For $r = 1$, DUNE-MPD exhibits a significant advantage over other beam dump experiments in the mass range $0.1\mathrm{GeV} \lesssim m_{Z'} \lesssim 1\mathrm{GeV}$.

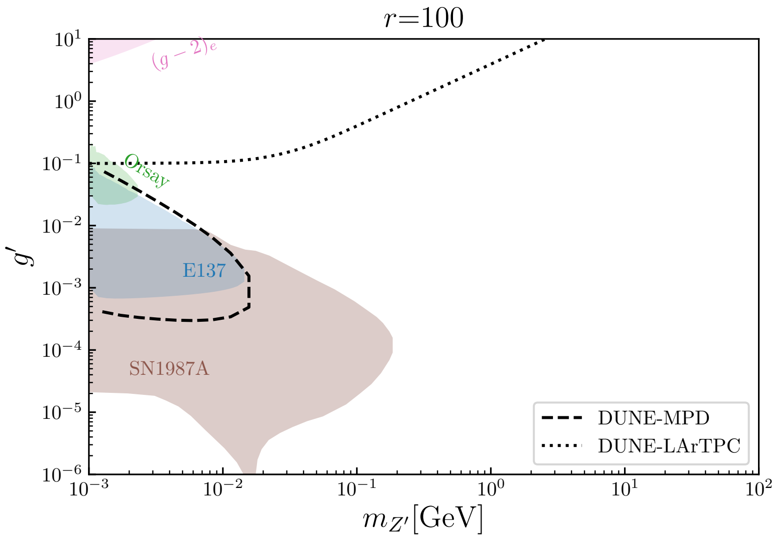


Combined Results



Combined Results

- For larger r such as $r = 10$ or 100, DUNE-LArTPC will be able to generate the leading constraints, exceeding collider bounds from BaBar, LHCb, etc.



Conclusion

- Hidden $U(1)$ symmetries in ν_R sector give rise to dark gauge boson : ν_R-philic Z'.
- Loop-suppressed couplings to SM and larger couplings to ν, neutrino experiments are the most suited to probe this scenario.
- We consider two complementary near DUNE detectors LArTPC and DUNE-MPD (HPgTPC); could be sensitive to Z' signals via elastic ν-e scattering and via Z' decay.
- Larger ν couplings lead to higher elastic ν-e scattering rates in DUNE-LArTPC but make Z' decay less visible in DUNE-MPD due to the enhanced invisible decay width.
- Excellent prospect of DUNE probing new physics hidden in the sector of ν_R.

Thank you!

Additional Slide

- The ArgonCube shares same aspects of form and functionality with the FD, reduces sensitivity to nuclear effects and detector-driven systematic uncertainties in extracting the oscillation signal at the FD.
- Muons with momentum higher than 0.7 GeV/c will not be contained in the LArTPC volume. Since muon momentum is critical to determining the incoming neutrino's energy, a magnetic spectrometer is needed downstream of the LArTPC to measure the momentum and charge of the muons i.e. MPD.
- Both ArgonCube and MPD can move off-axis relative to the beam, providing access to different neutrino energy spectra.