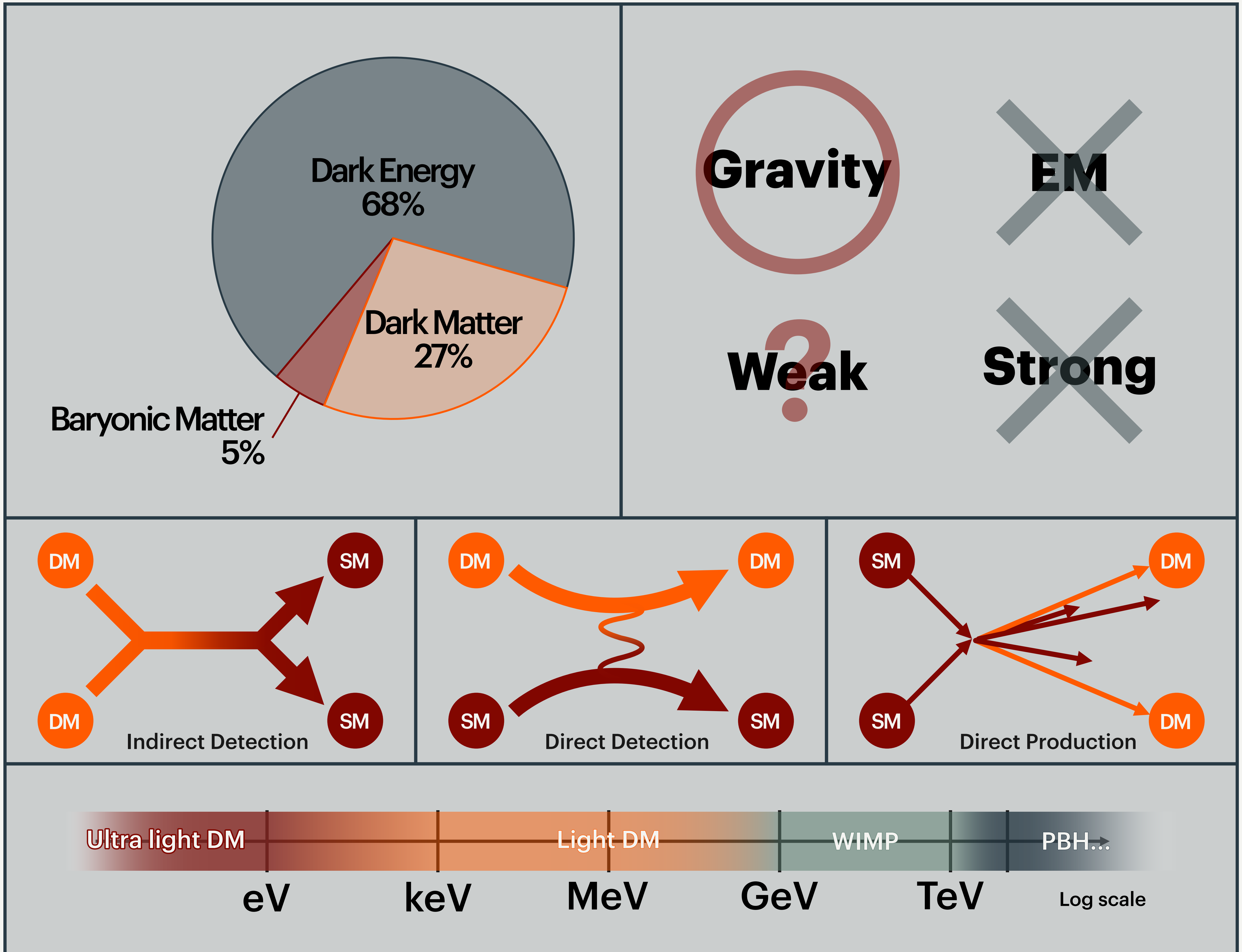
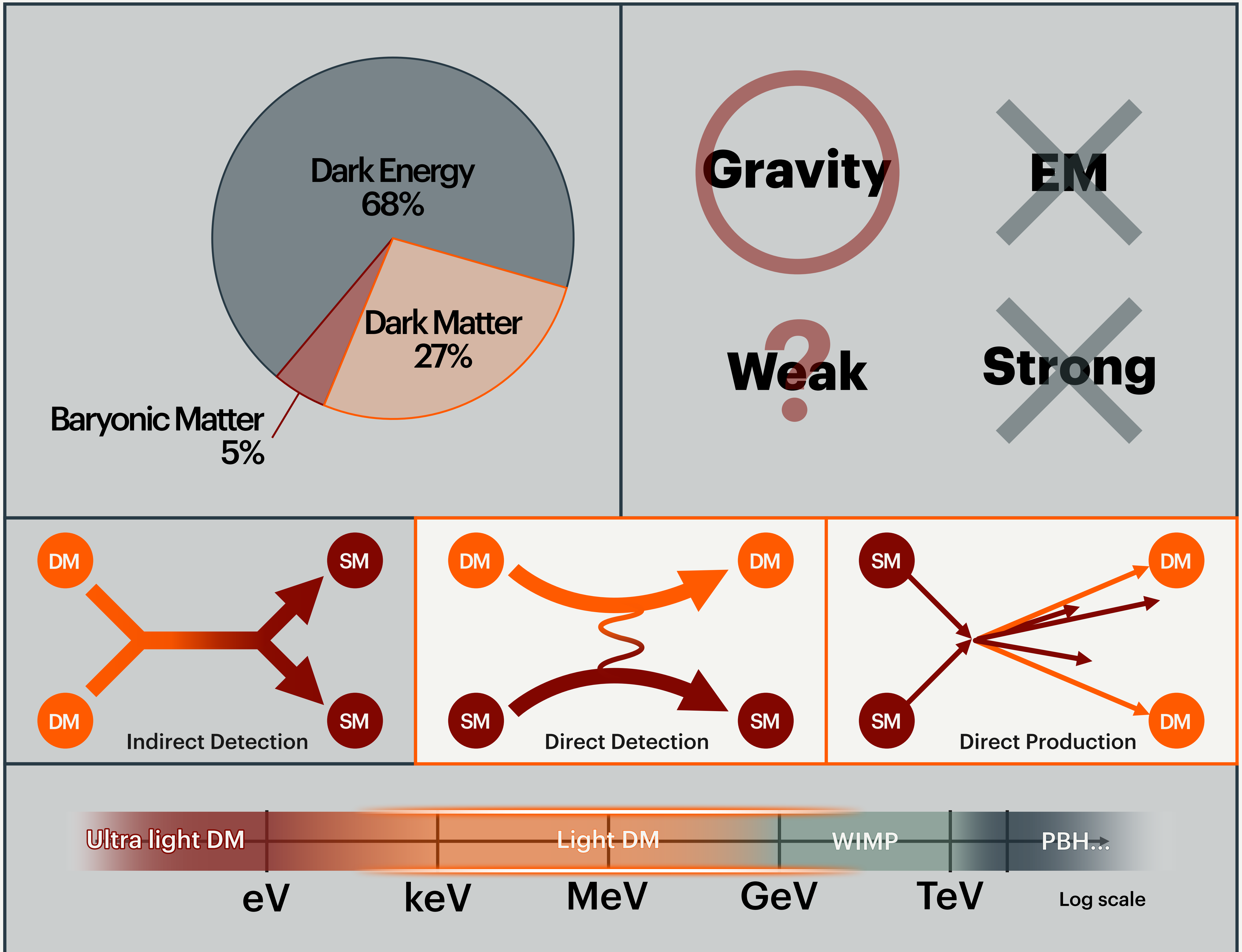
Light Dark Matter Sensitivity at the J-PARC Intermediate Water Cherenkov Detector

Seong-ha Kim
(Chungnam National University)
with Koun Choi & Jong-Chul Park

Dark matter


Dark Energy
68%
Dark Matter
27%
Baryonic Matter
5%
Gravity
EM
Weak
Strong
DM
DM
SM
SM
Indirect Detection
DM
DM
SM
SM
Direct Detection
SM
SM
DM
DM
Direct Production
Ultra light DM
Light DM
WIMP
PBH...
eV
keV
MeV
GeV
TeV
Log scale

Dark matter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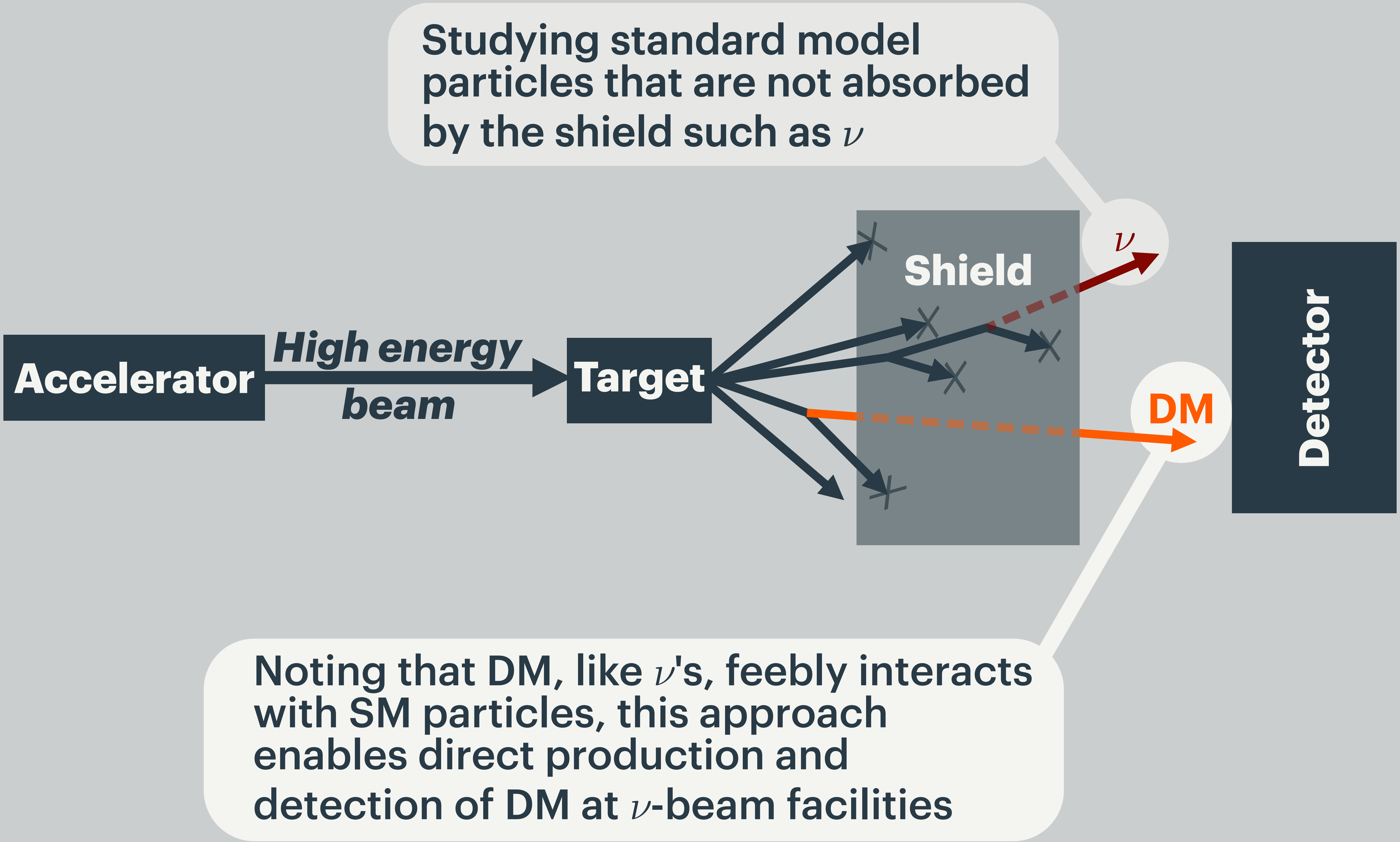
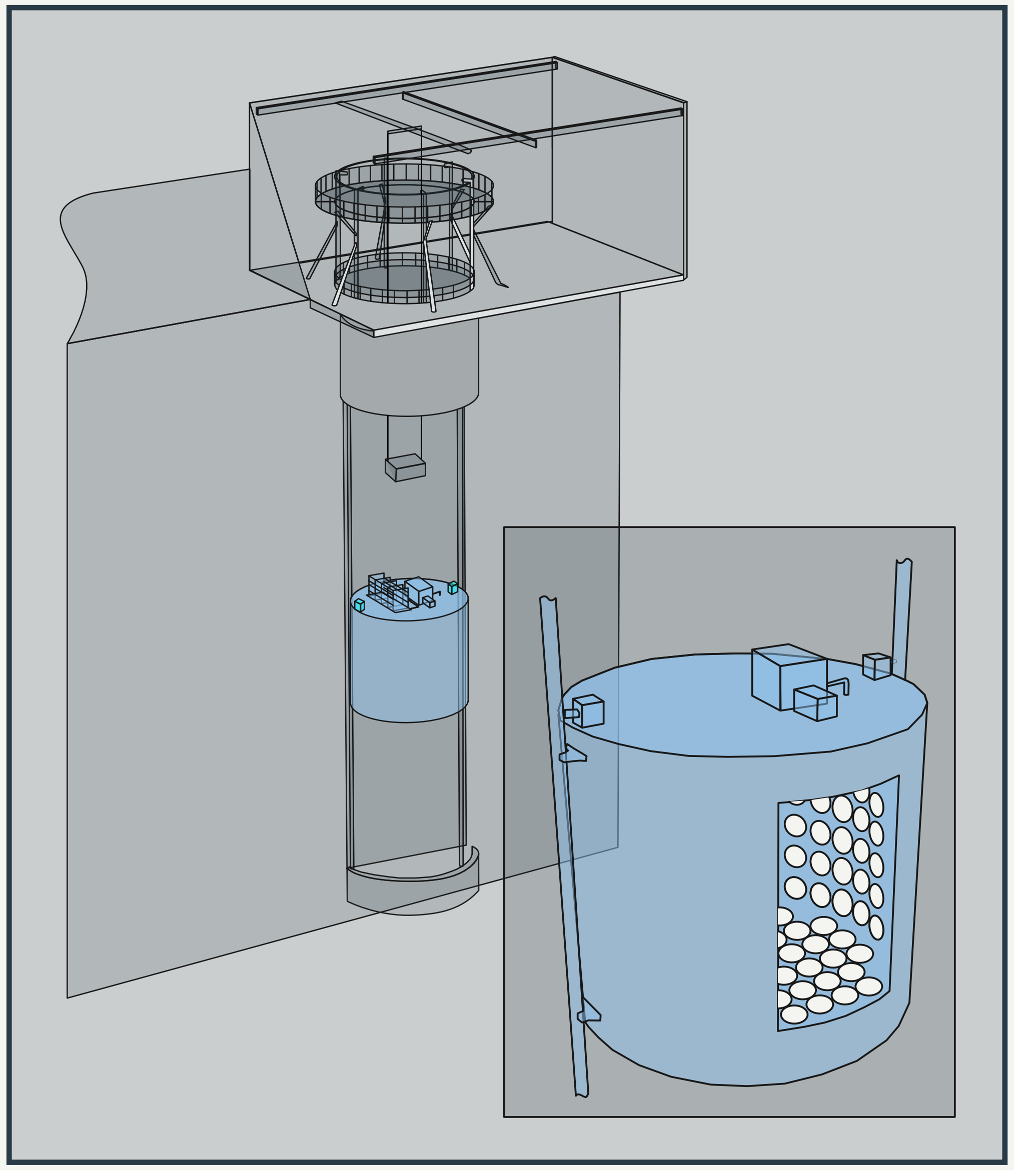
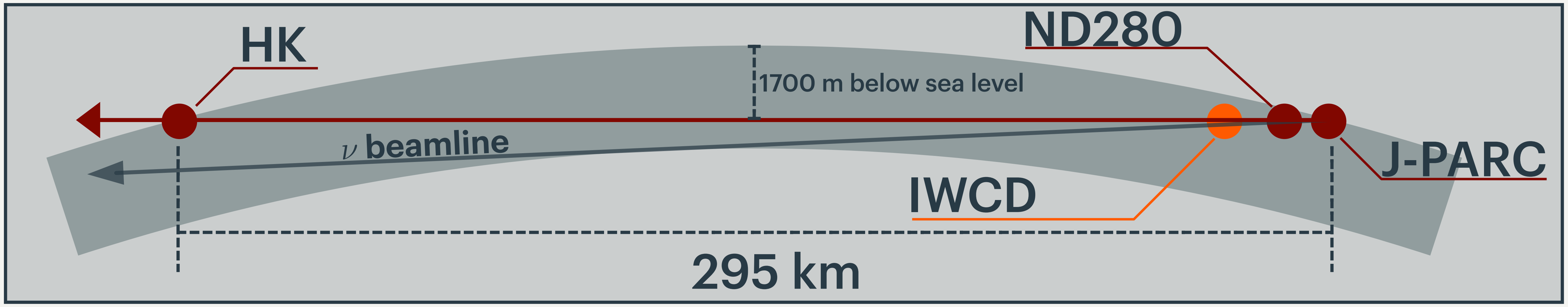
Neutrino beam experiment for DM search

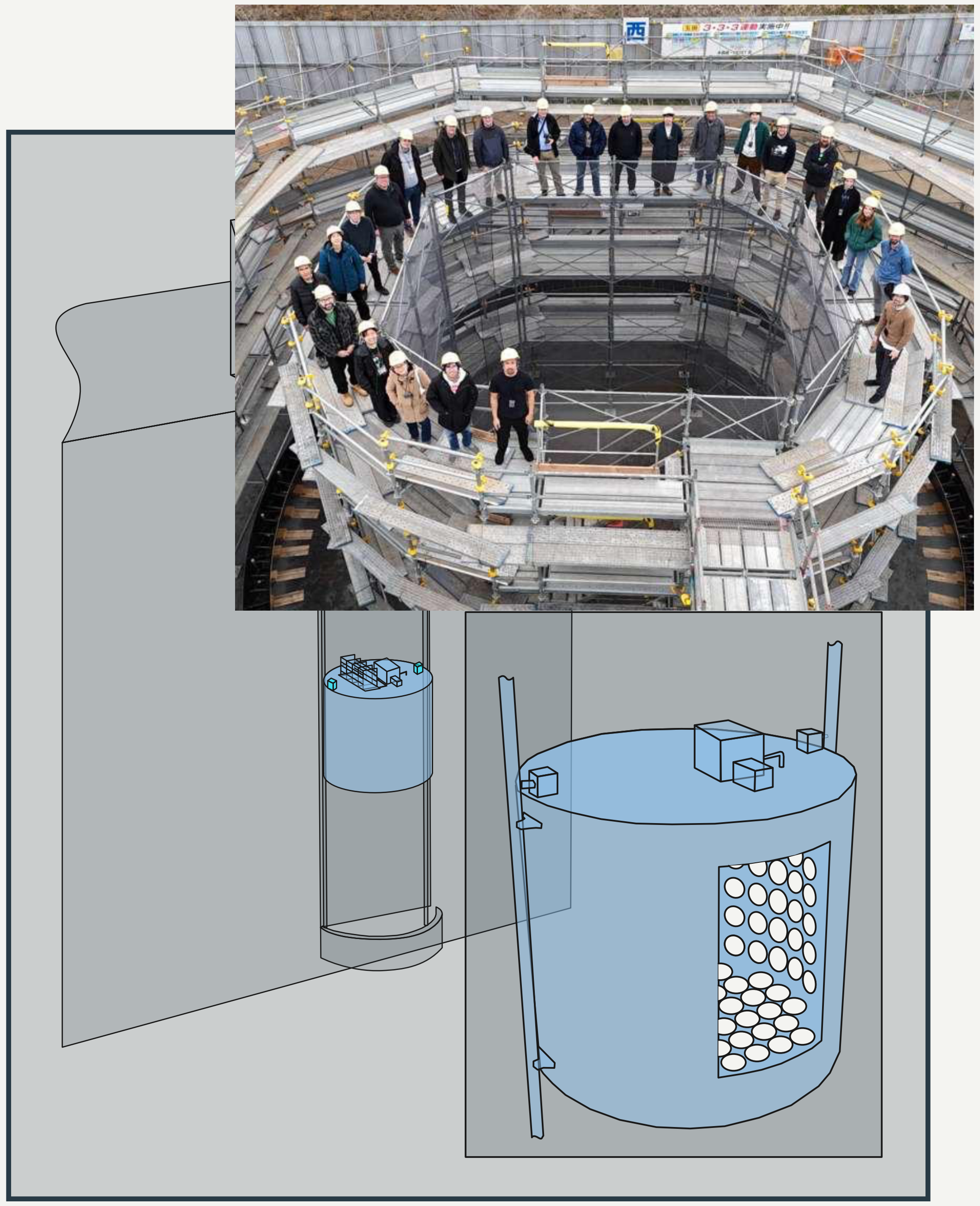




- 0.8 kt pure water Cherenkov detector
- 750 m downstream the beam
- Operation planned as a near detector of T2HK at 2028
- nuPRISM Feature



IWCD-PRISM : Overview



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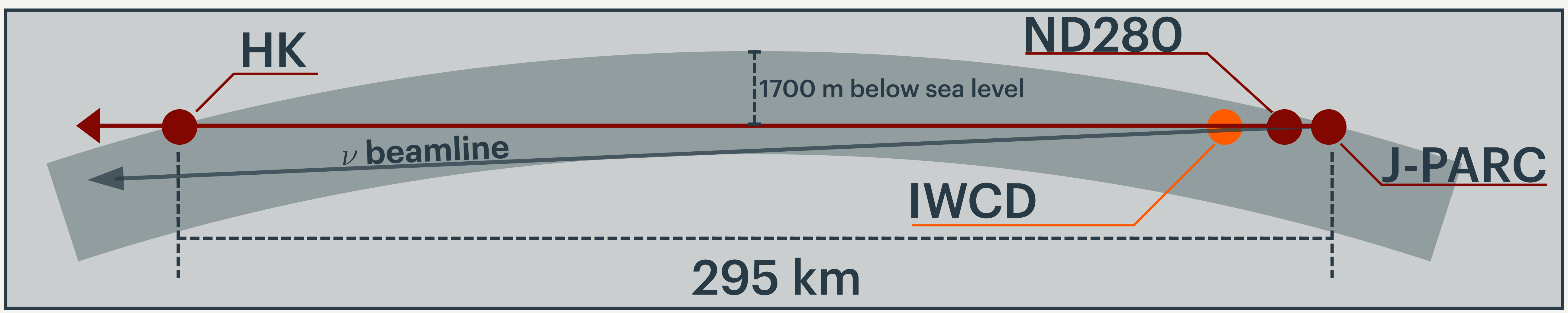
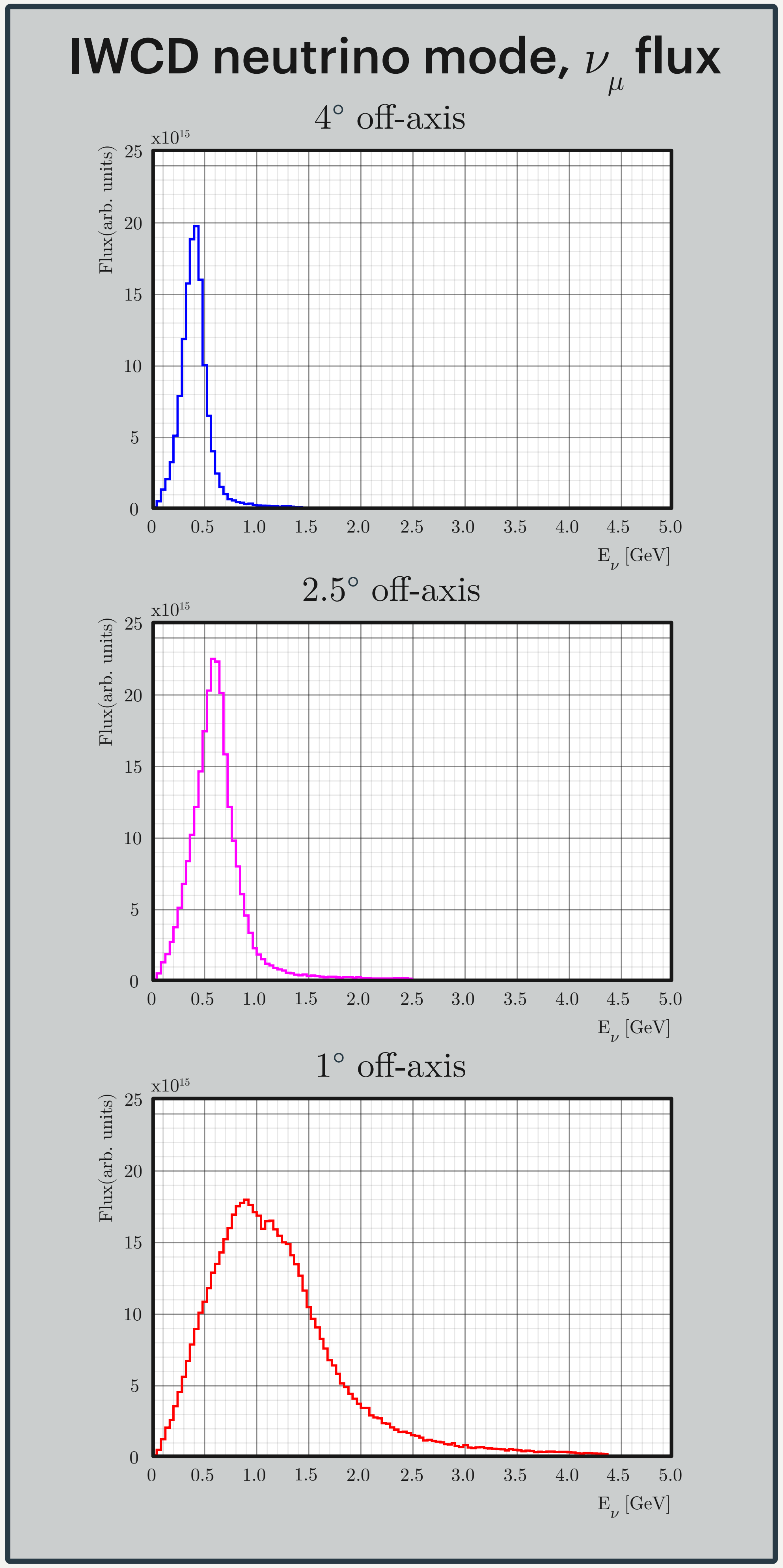
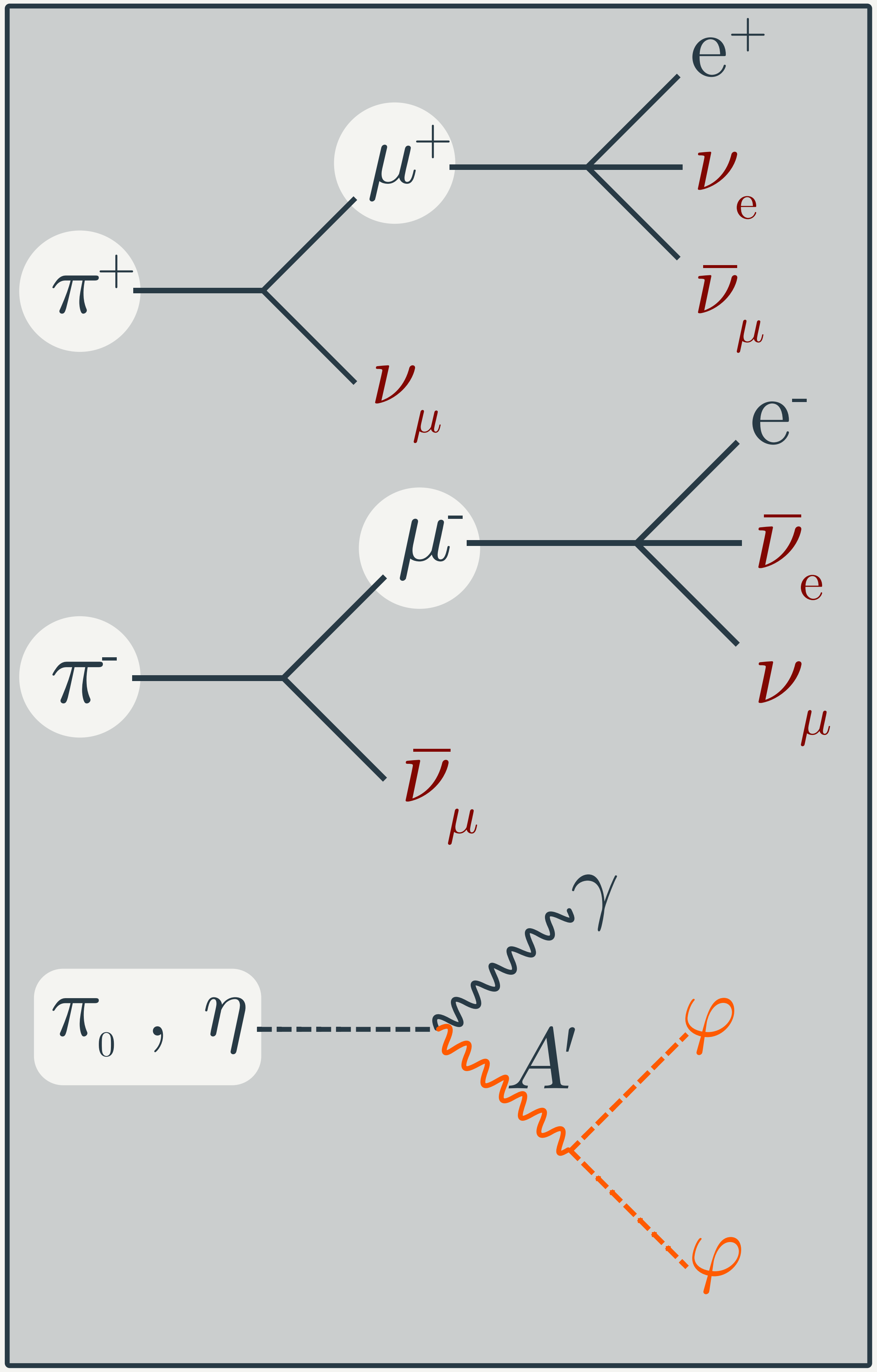


IWCD-PRISM : nuPRISM feature



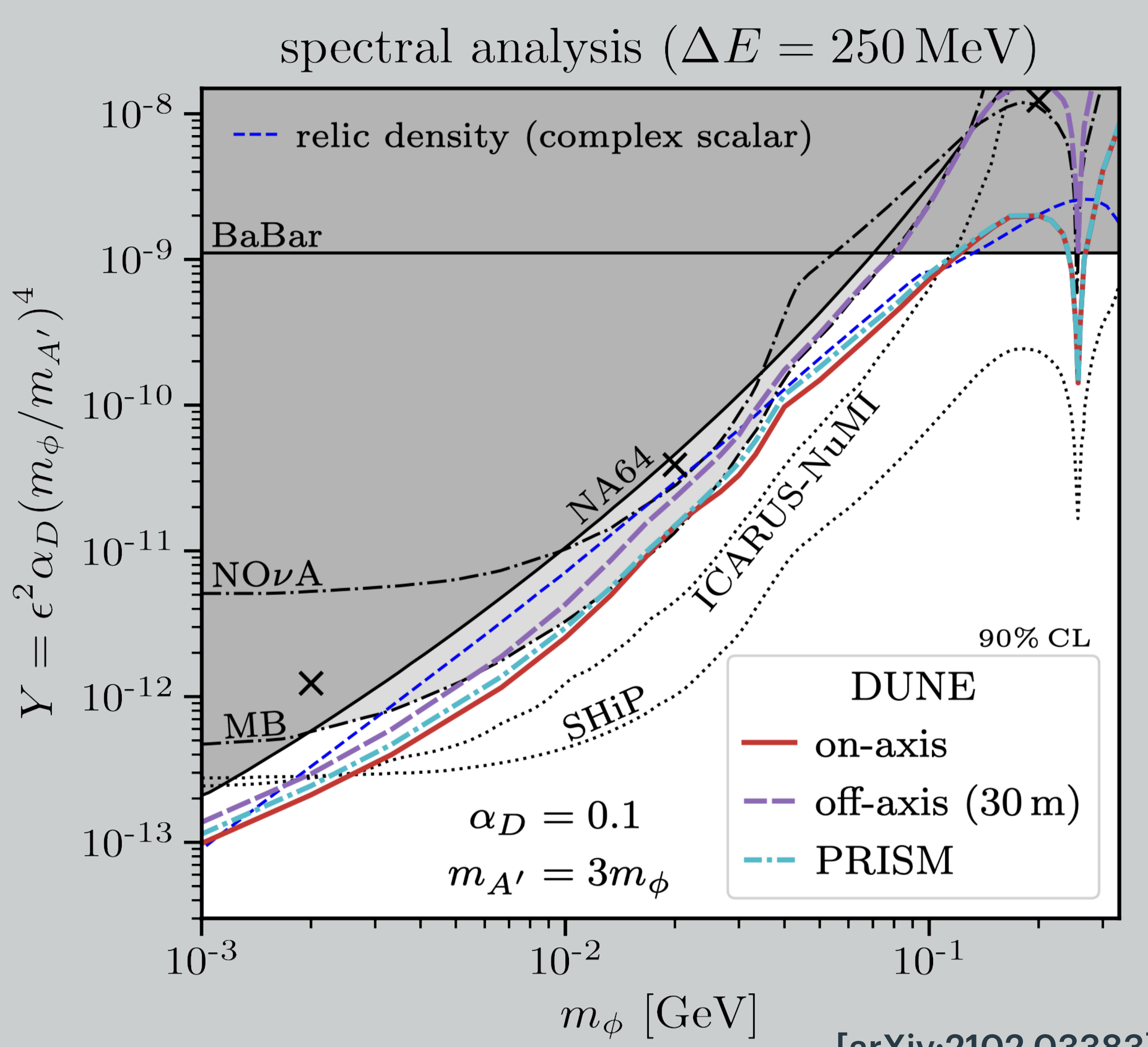
- Vertically movable feature : 1°~ 4° off axis from beamline
- Reduces systematic uncertainties associated with neutrino interaction modeling [arXiv:1412.3086]
- PRISM provides multiple neutrino energy spectra by sampling different off-axis angles



- At J-PARC, a set of magnetic horns located around of the target is used to focus the charged particles, which produce the aligned ν beam
- Dark photon produced from neutral mesons are unaffected by the horns and thus have a wide, less focused distribution

Motivation & Previous study

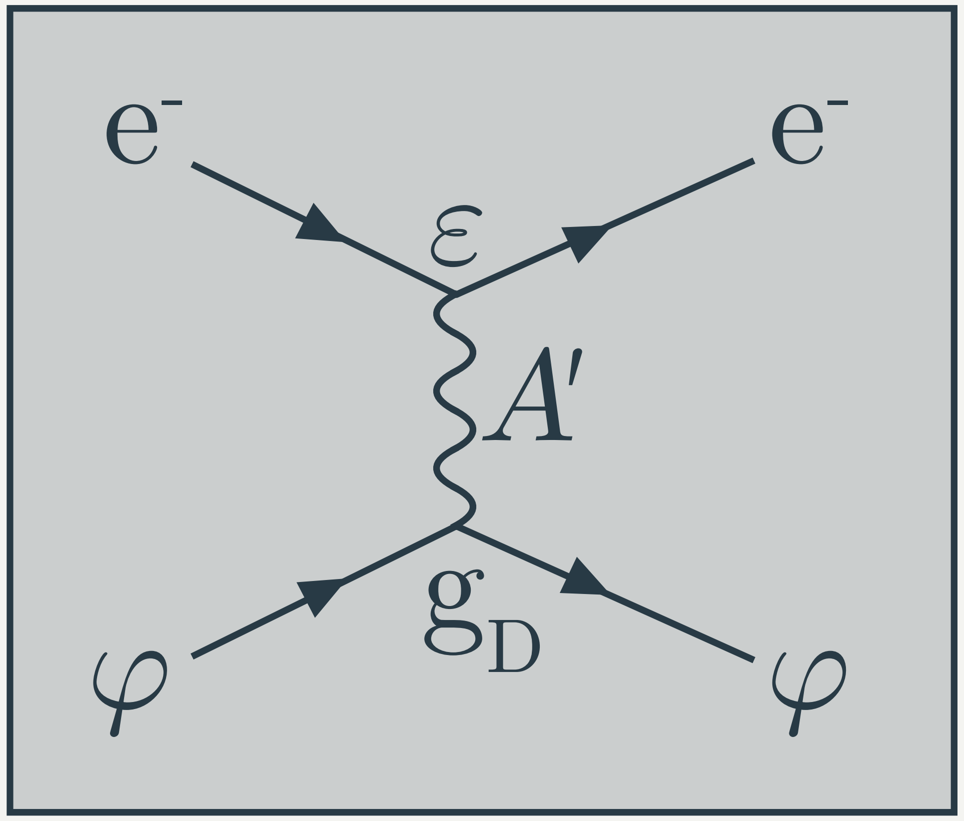
- Motivated by the nuPRISM idea, DUNE also planned DUNE-PRISM. → LDM search studies using DUNE-PRISM
- From DUNE-PRISM studies, we adapted the off-axis spectral-analysis framework to IWCD.



[arXiv:2102.03383]

Signal simulation : BdNMC[arXiv:1609.01770] + α

- m_{DM} : 3 ~ 266.6 MeV
- offset : 1°, 2.5°, 4°
- 10^8 trial
- 7×10^{20} POT/year
- Scalar DM + dark photon model*
- proton beam energy : 30 GeV
- Considered $\pi,\ \eta$ channel (FTF-BERT model) and proton bremsstrahlung production[arXiv:1311.3870], [arXiv:1411.4007]

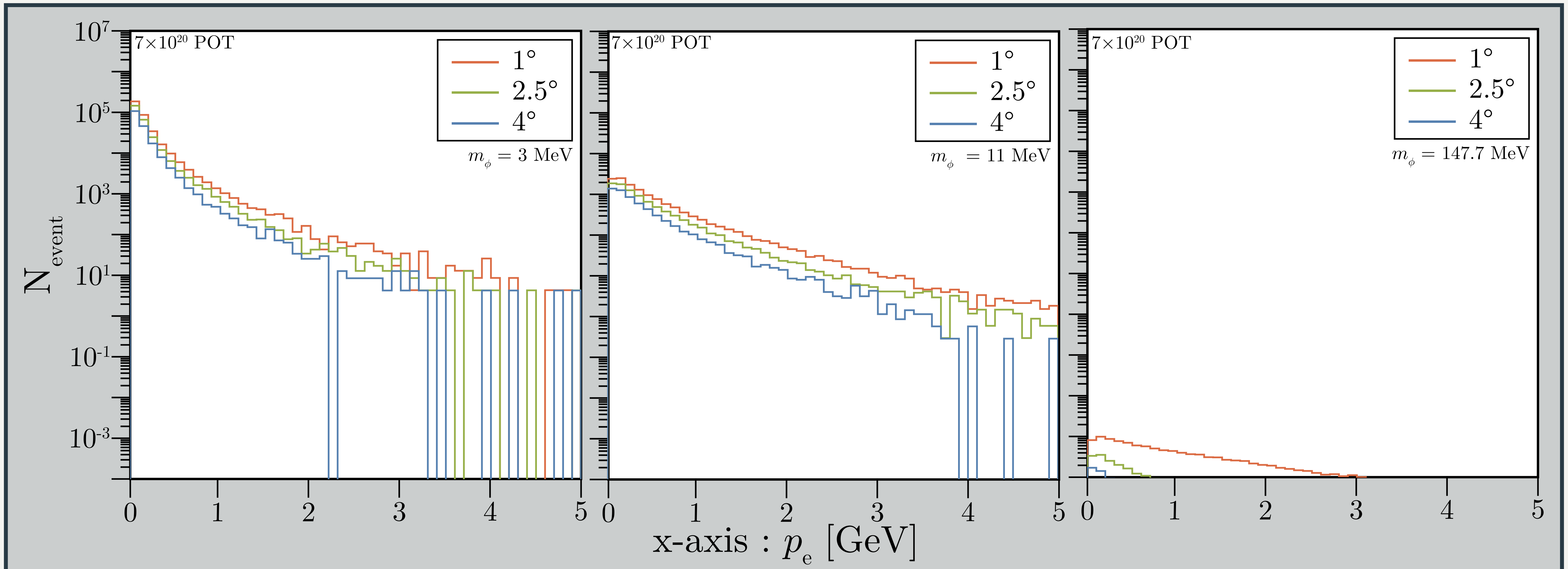


* Lagrangian

$$\mathscr{L} \supset -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{M_{A'}^2}{2}A'_{\mu}A'^{\mu} + |D_\mu\phi|^2 - M_\phi^2|\phi|^2$$

$$\alpha_D = \frac{g_D^{\ 2}}{4\pi} = 0.1,\ m_{A'} = 3m_\varphi$$

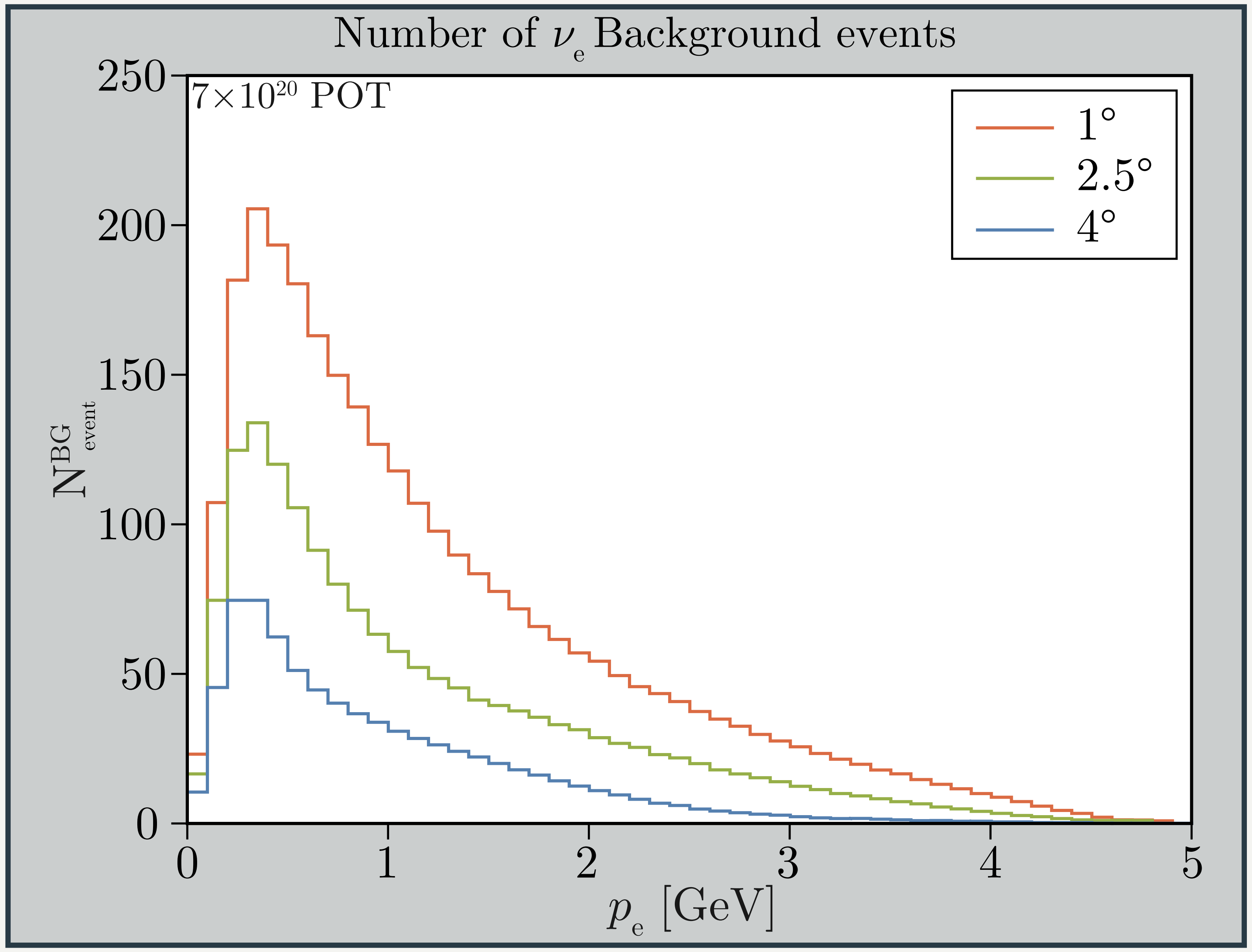
Signal simulation : BdNMC[arXiv:1609.01770] + α



Signal

meson prod. **bremsstrahlung prod.**

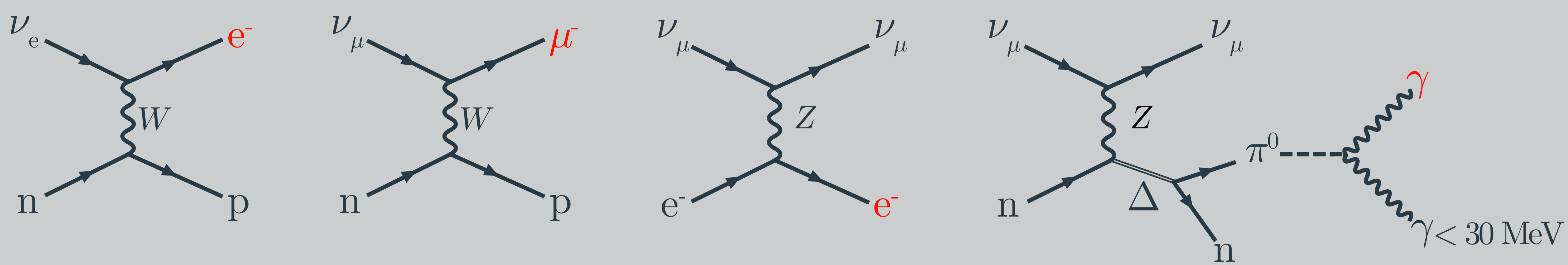
Background simulation : GENIE [arXiv:0905.2517]



- Inject the ν flux calculated by the T2HK coll. [theses.hal.science/tel-03935726
- Generated 10^8 events and normalized to target POT
- Flux Dominance: ν_μ ~ 100 × ν_e. ν_μ background contribution non-negligible

Background simulation : GENIE[arXiv:0905.2517]

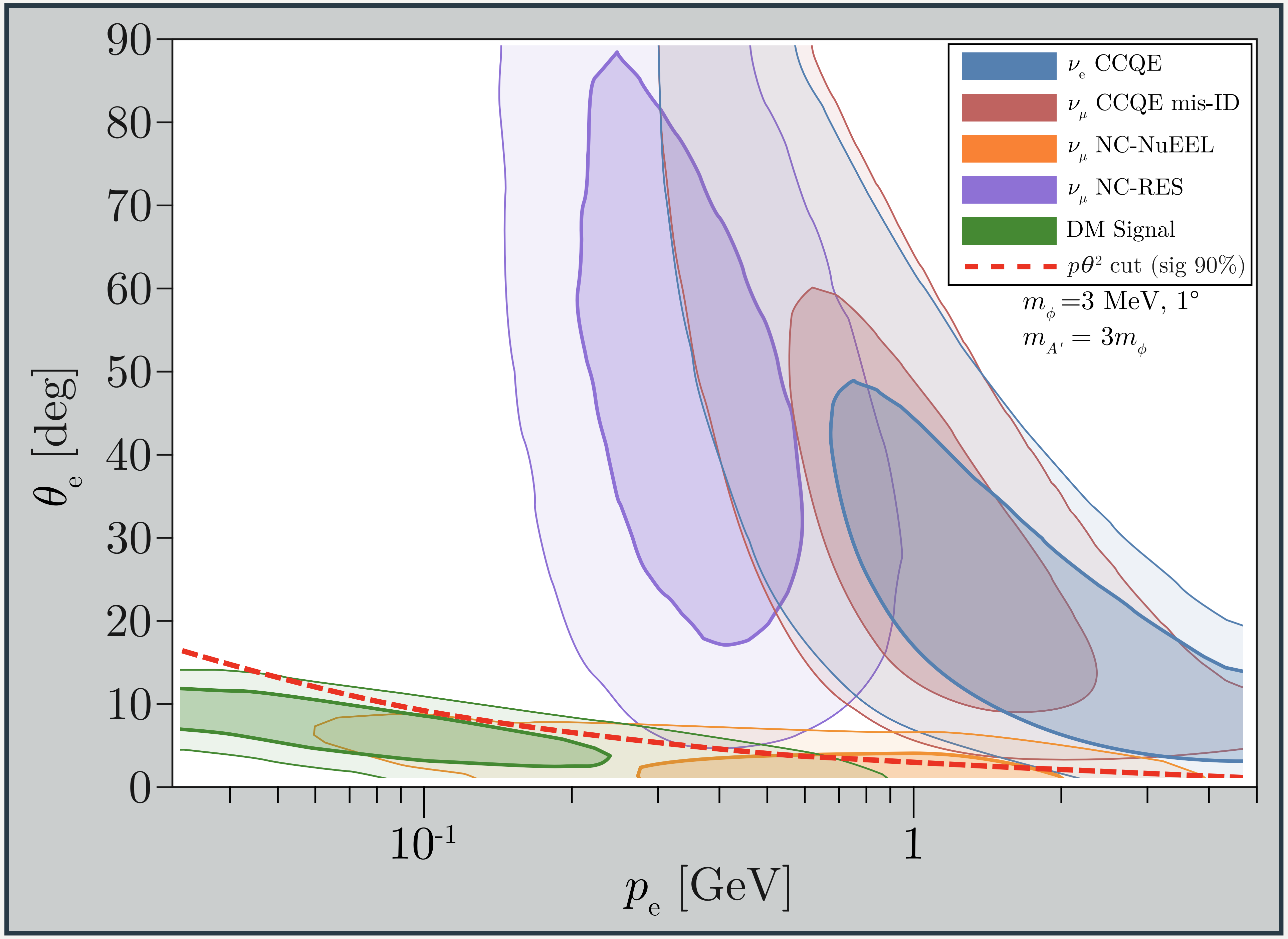
Background



ν_e CCQE ν_μ CCQE mis-id ν_μ NuEEL ν_μ NC-RES

- Consider four main background channels

Background cut : $p\theta^2$ cut



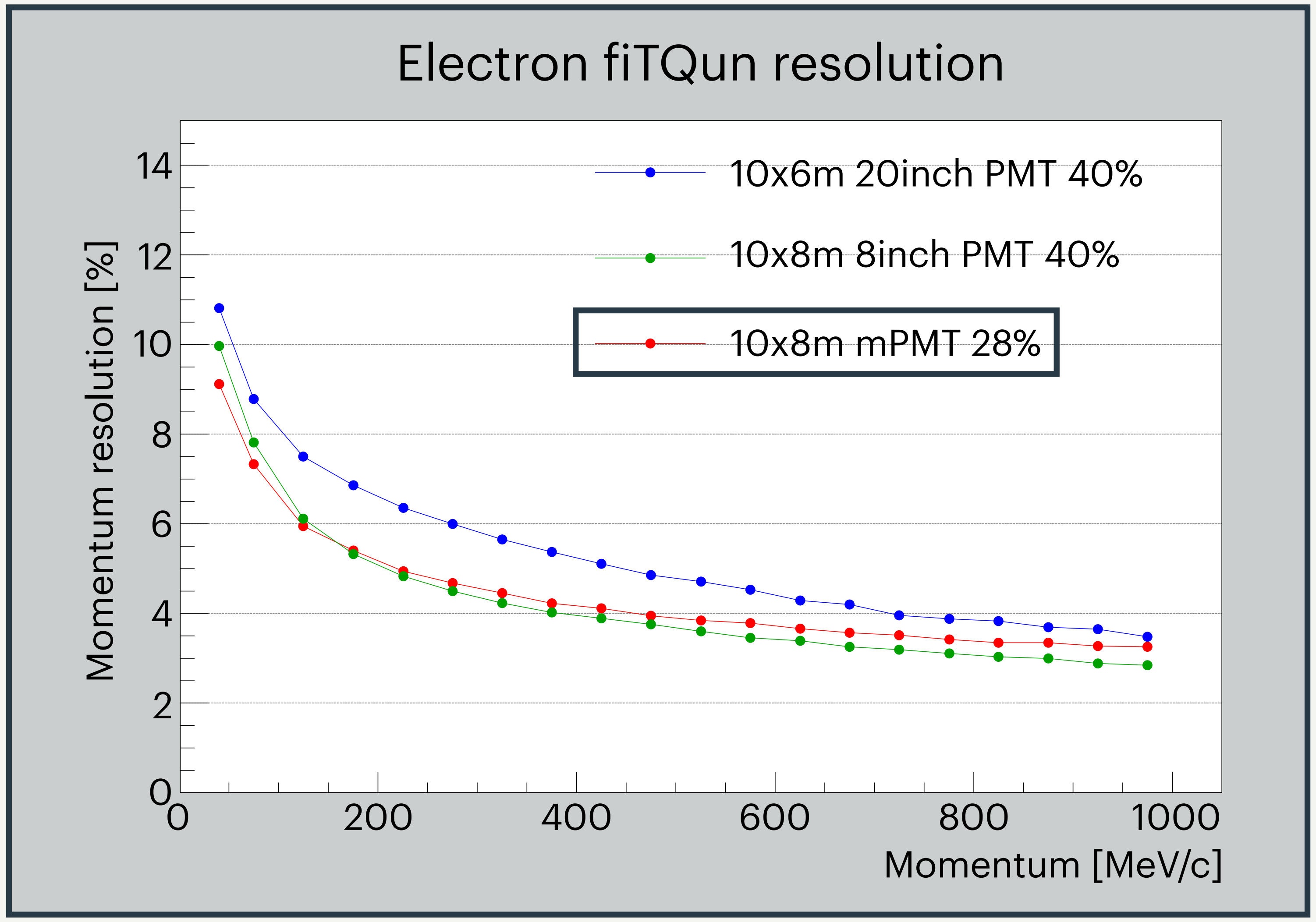
- $p\theta^2$ variable is useful to remove large portion of background from the signal.

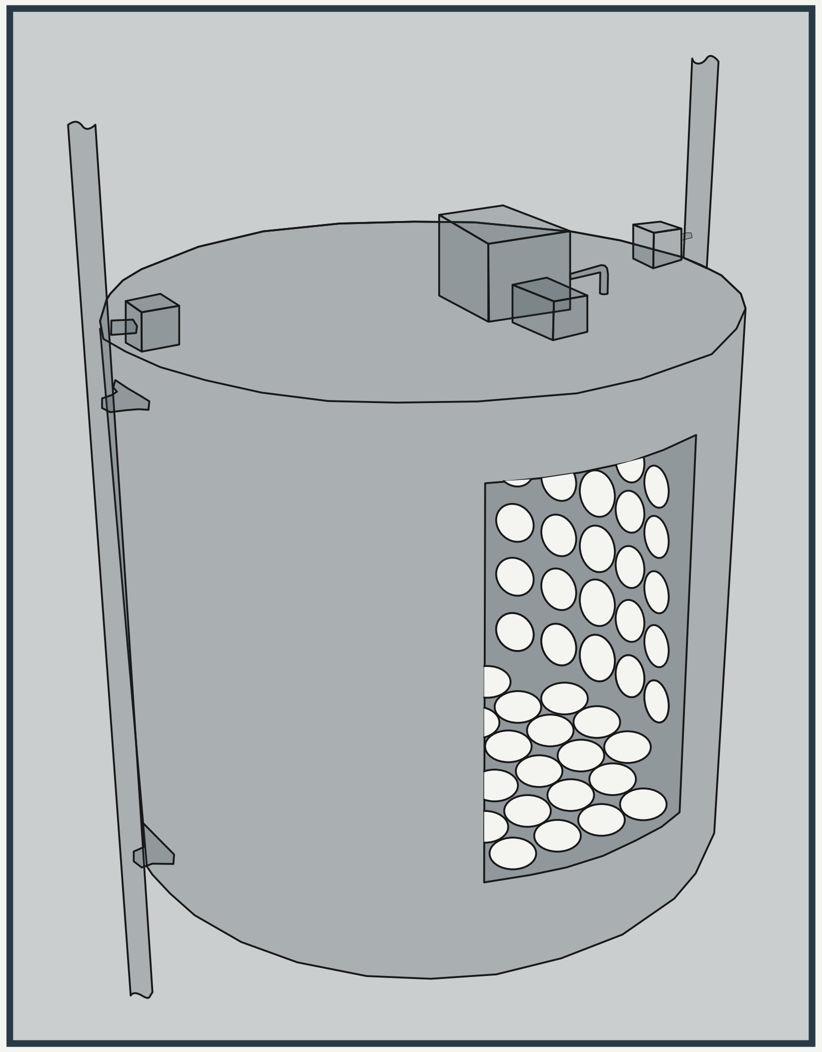
Log-likelihood fitting

$$\mathcal{L}_{ij} = -\left(\left(\frac{\epsilon}{\epsilon_0}\right) N_{ij}^{\phi} + N_{ij}^{\nu}\right) + N_{ij}^{\nu} \ln\left(\left(\frac{\epsilon}{\epsilon_0}\right) N_{ij}^{\phi} + N_{ij}^{\nu}\right) - \ln\left(N_{ij}^{\nu}!\right)$$

- 2-dimensional likelihood (location : 3 bins, E : 50 bins)
- Assumed Poisson distribution
- Fitted expected background (Asimov data set) with signal + background for 7×10^{20} POT
- Momentum smearing via resolution & position-dependent systematic uncertainties are evaluated to test robustness.

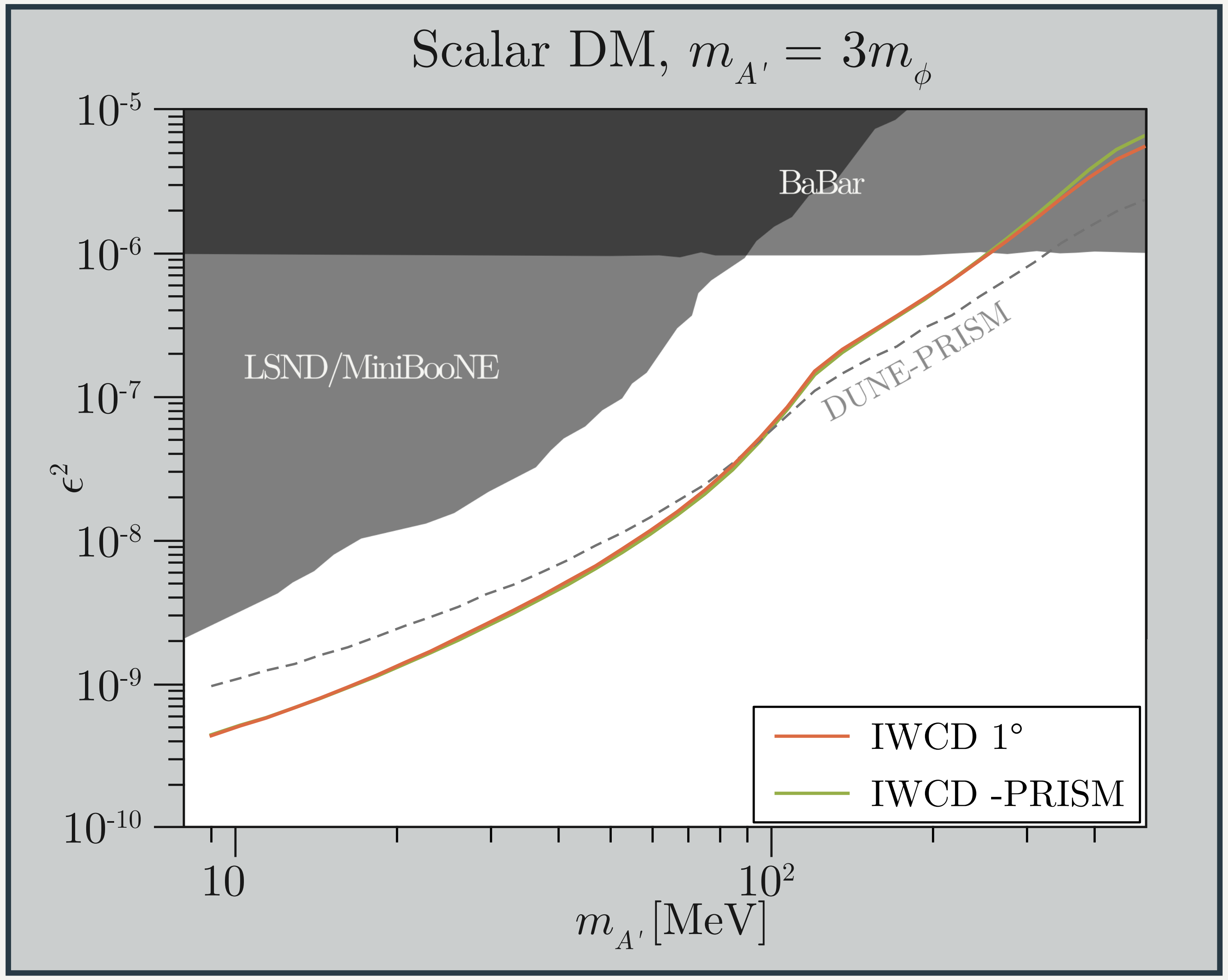
Log-likelihood fitting : Realization





- **Smearing: Apply fiTQun momentum resolution tuned to the IWCD's mPMT layout to obtain reconstruction-level spectra**
- **Likelihood: Calculation log-likelihood with 20% position dependent systemat uncertainties and 10 % overall normalization uncertainties**
- **Imposing 1 m fiducial cut from walls**

Log-likelihood fitting : Search prospects



- At higher mass region, DUNE is better due to higher proton beam energy.
- IWCD(7×10^{20} POT) shows better sensitivity than DUNE (1.1×10^{21} POT) in the lower energy (π^0 dominant).

Summary

- We evaluated the sensitivity of IWCD to scalar light dark matter in the dark-photon model
- In the present spectral profile-likelihood analysis, the 1° off-axis sample gives nearly the same or slightly better sensitivity than the three-position PRISM combination, because its larger statistics dominate
- The $p\theta^2$ cut is useful for reducing background from the signal
- IWCD reaches $\epsilon^2 \sim O(10^{-9})$ in the low-mass region and provides sensitivity complementary to DUNE-PRISM: IWCD provides stronger sensitivity in the low-mass region, while DUNE-PRISM has an advantage at higher masses