Background from neutrino interactions in dark matter searches at DUNE ND

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To appear soon on arXiv: 210X.XXXX

UNIVERSIDAD SERGIO ARBOLEDA

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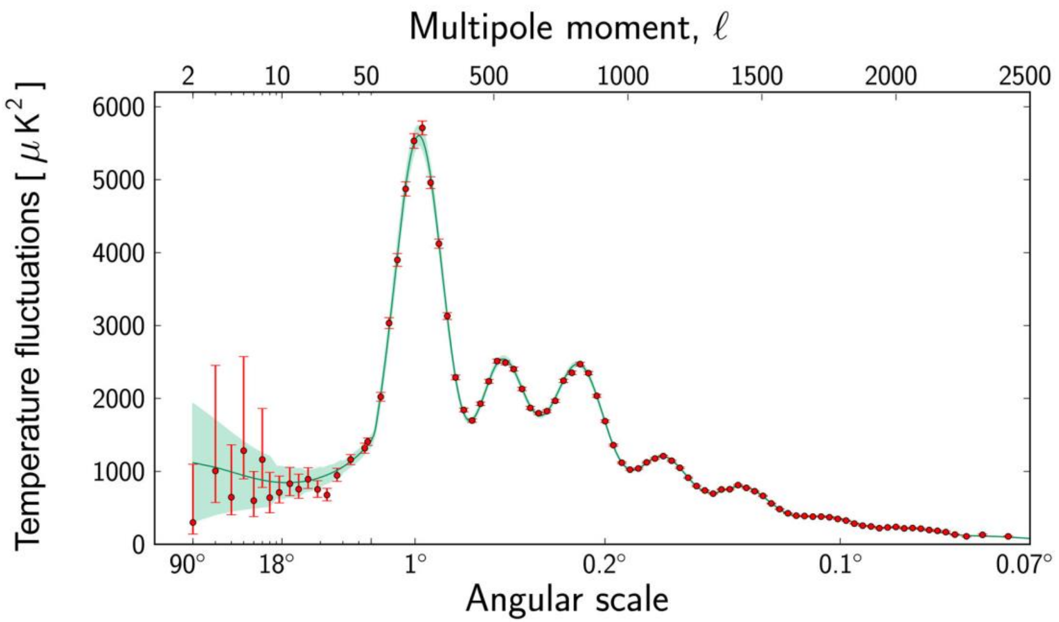
Astroparticle Theory

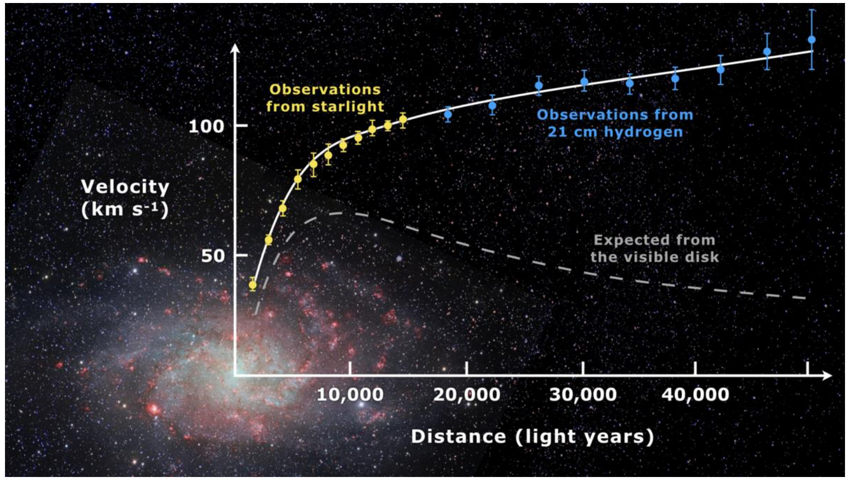
UNIVERSIDAD EIA
Ser, Saber y Servir

Outline

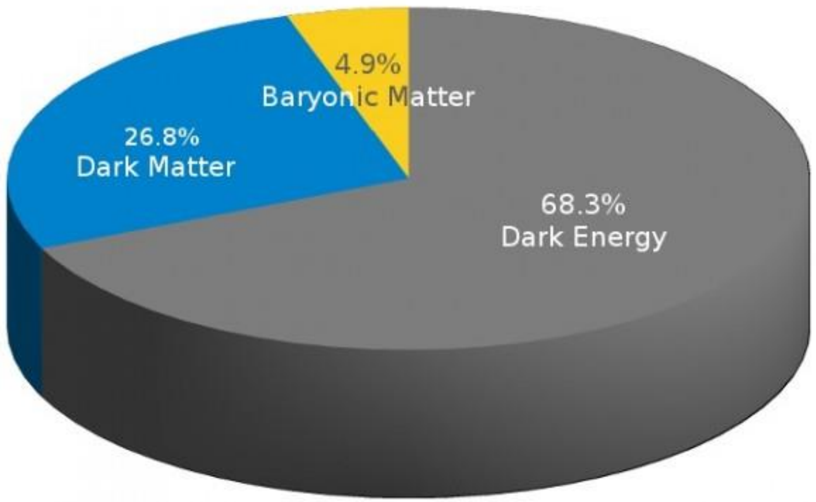
- **Motivation to two component light DM**
- **DUNE as a new physics experiment**
- **Neutrino background**
- **DUNE-Sensitivity**

Observational evidence for DM





CMB anisotropies, X-rays, gravitational lensing on clusters, Large Scale Structures, Galaxies (velocity curves)



$$\Omega h^2 = 0.1200 \pm 0.0012$$

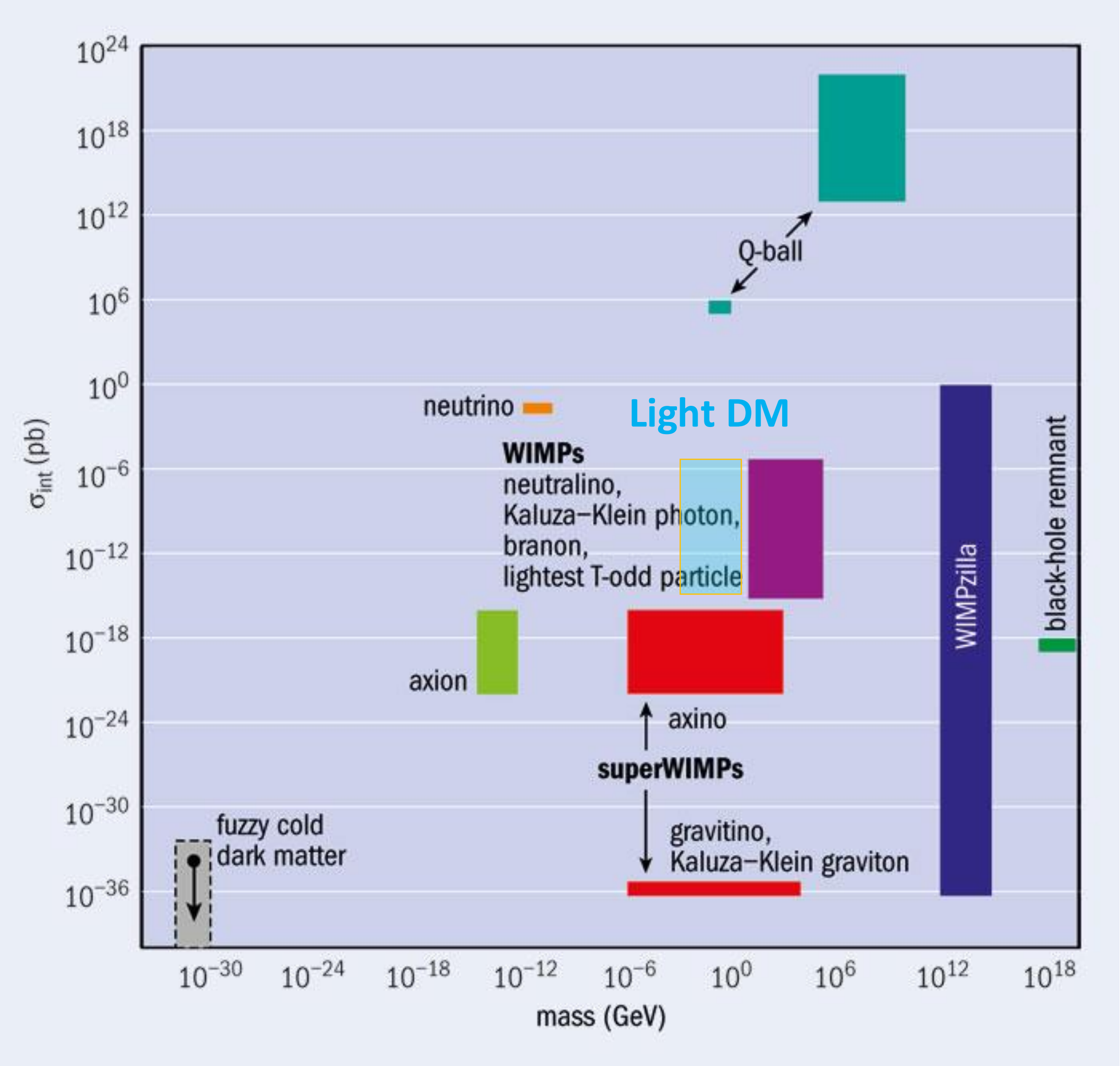
@Planck collab. 2018

Light DM motivation

- **WIMP Dark matter candidates could be below the usual mass scales (sub-GeV), but a new annihilation channel is needed.**

- **Light dark matter freeze out give the correct relic density when new mediators are considered. How do they interact with SM fields?**

- **Many models focus on one DM candidate, but there could be several, just as the baryonic matter has a structure composed for several particles.**

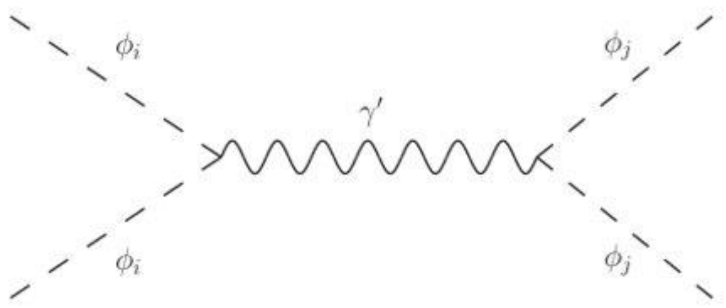


@Park, E.-K (2007)

Two component light DM model

Multicomponent DM model with lighter WIMP particles (SubGeV)

Light WIMP	Spin	Symmetries
ϕ_1	0	$U(1)_D \times Z_2$
ϕ_2	0	$U(1)_D \times Z_2'$



$$\mathcal{L}_G = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

@Pospelov et al (2008-2009)

Free parameters:
ϵ , α_D, $m_{\gamma'}$, m_{ϕ_1}, and m_{ϕ_2}

- $U(1)_D$ symmetry is broken, thus there is a massive gauge boson, the dark photon γ'
- There is a kinetic mixing between the photon and the dark photon.

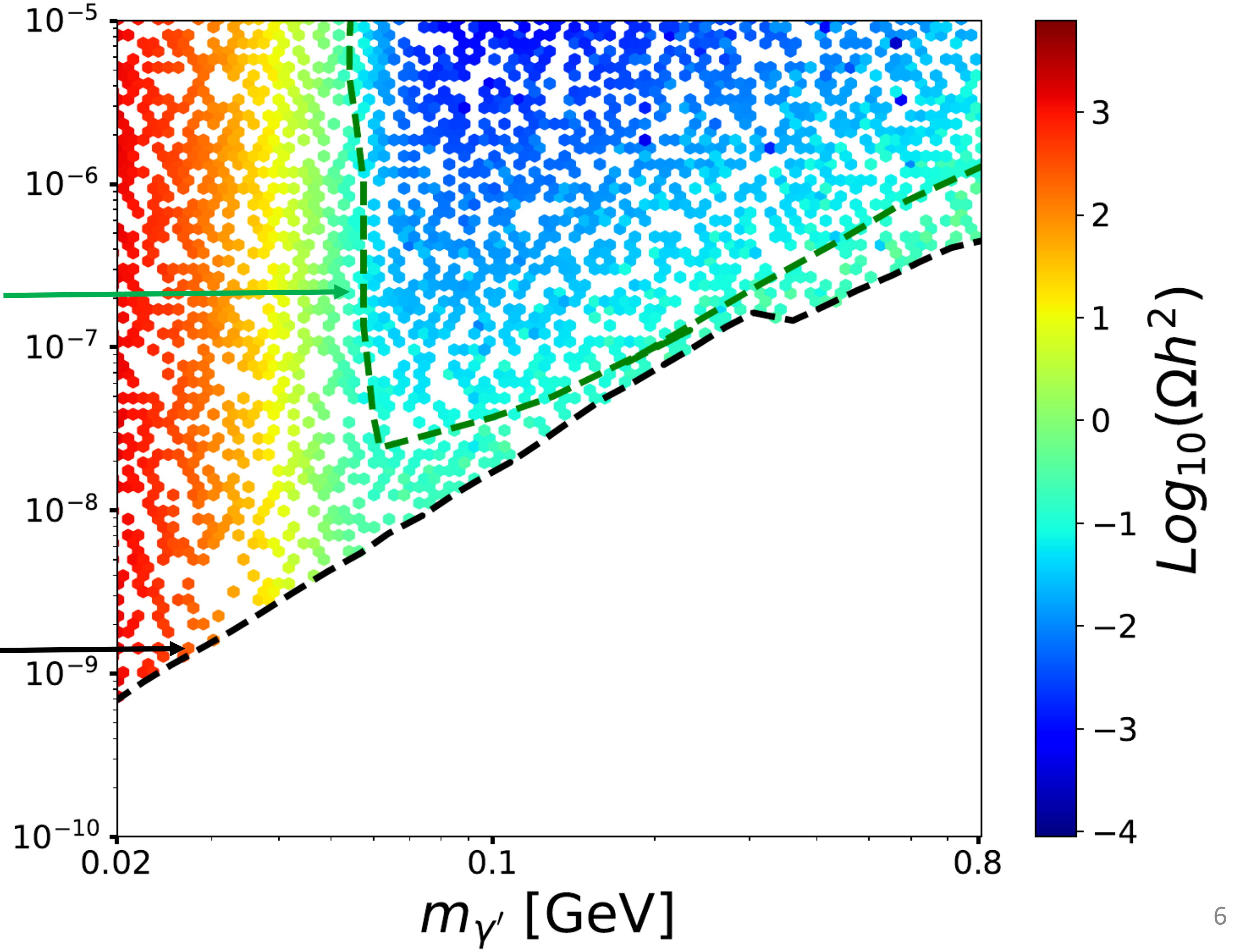
Relic density for the two component DM model

Choose:
α_D=0.1, $m_{\gamma'}$=3m_{ϕ_1}, $m_{\phi_2} > m_{\phi_1}$

RD multicomponent model

RD one scalar DM

@Valentina De Romeri et al (2019)

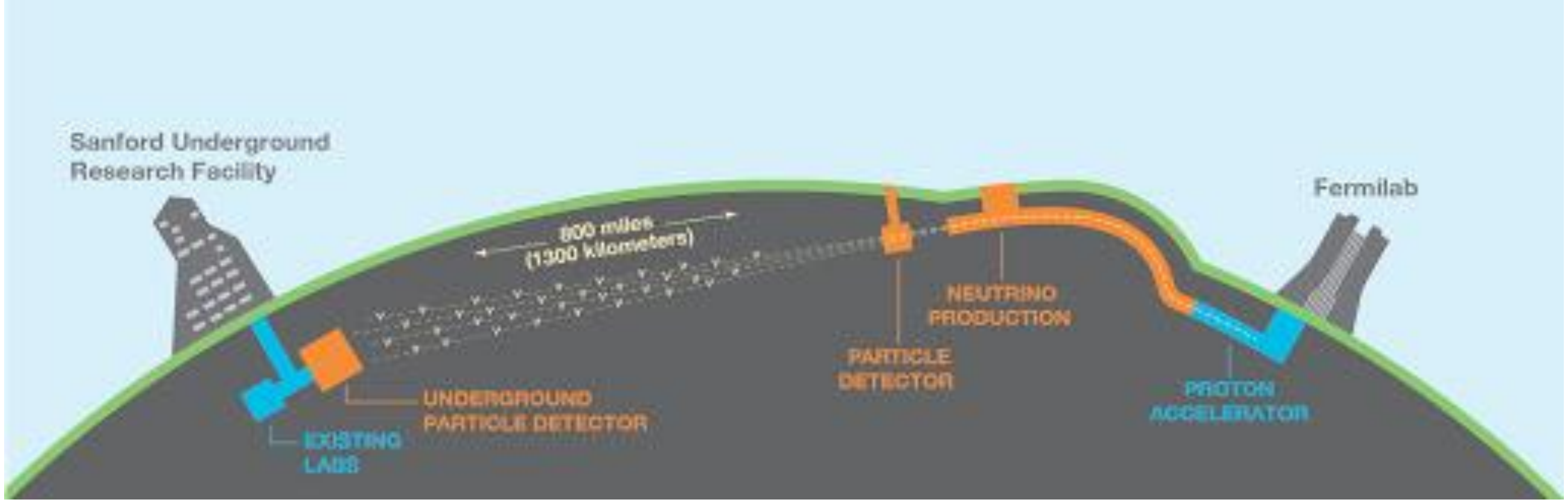


Dark sector production at DUNE

Light DM signal at neutrino factories: DUNE

- The Deep Underground Neutrino Experiment (DUNE) will have a high intensity neutrino beam with two state of the art neutrino detectors (mainly composed by Liquid Argon)

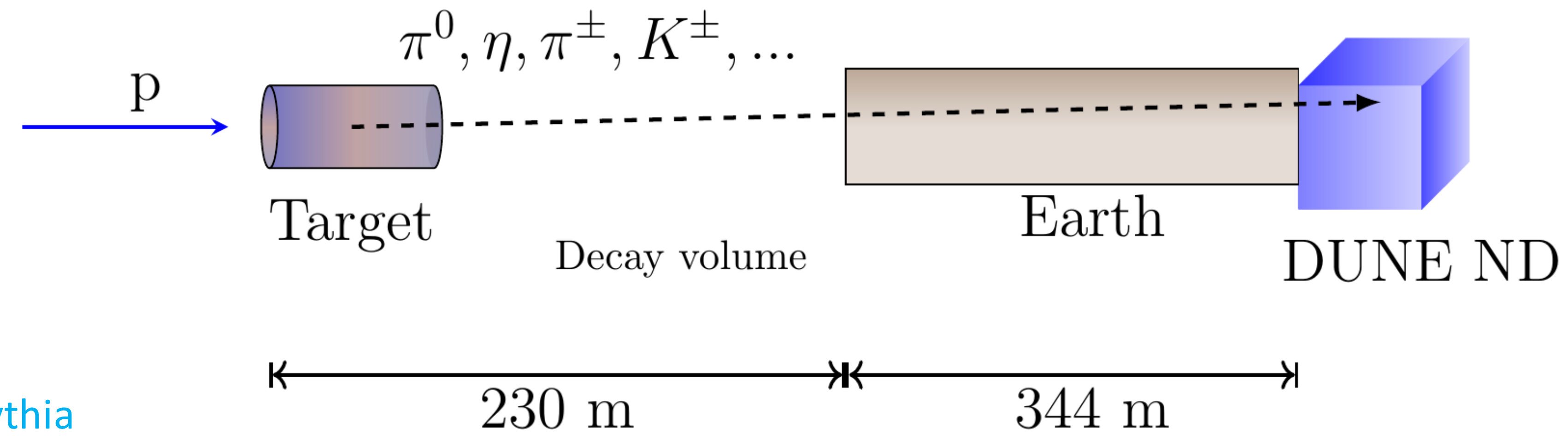
(Talk by Alexander de Sousa)



- Other direct detection experiments and LHC have limited sensitivity to sub-GeV DM
- DUNE and other neutrino experiments could probe light dark matter-nucleon (electron) interactions

Dark sector production at DUNE

- Protons at 120 GeV collide against a fixed-target made of carbon, producing a bunch of particles

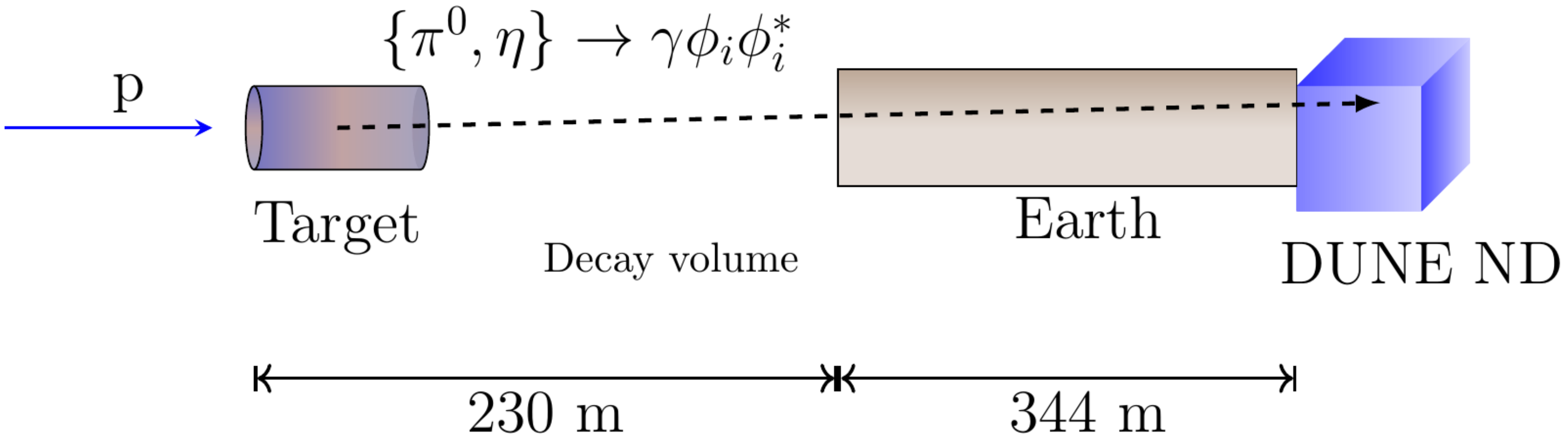


simulated with pythia

- High intensity proton beam 1.1 X 10 ^ 21 POT/year

Dark sector production at DUNE

- Dark photon decay into lighter DM particles



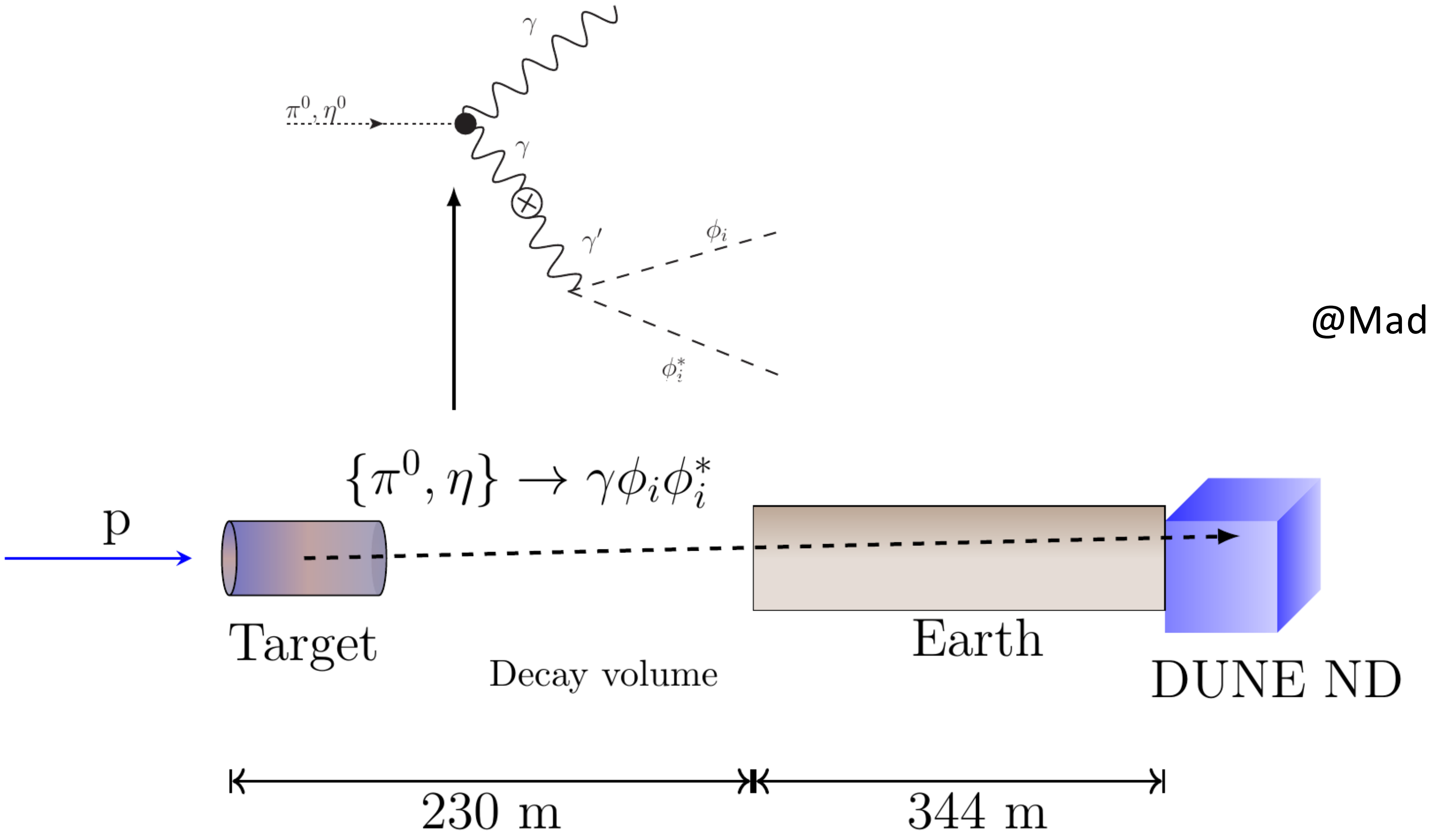
- On-shell production for DM

@De Romeri et al (2019)

$$\mathrm{Br}(\mathbf{m} \to \gamma\phi_i\phi_i^*) \simeq \mathrm{Br}(\mathbf{m} \to \gamma\gamma) \times 2\varepsilon^2 \left(1 - \frac{m_{\gamma'}^2}{m_{\mathbf{m}}^2}\right)^3 \mathrm{Br}(\gamma' \to \phi\phi^*)$$

Dark sector production at DUNE

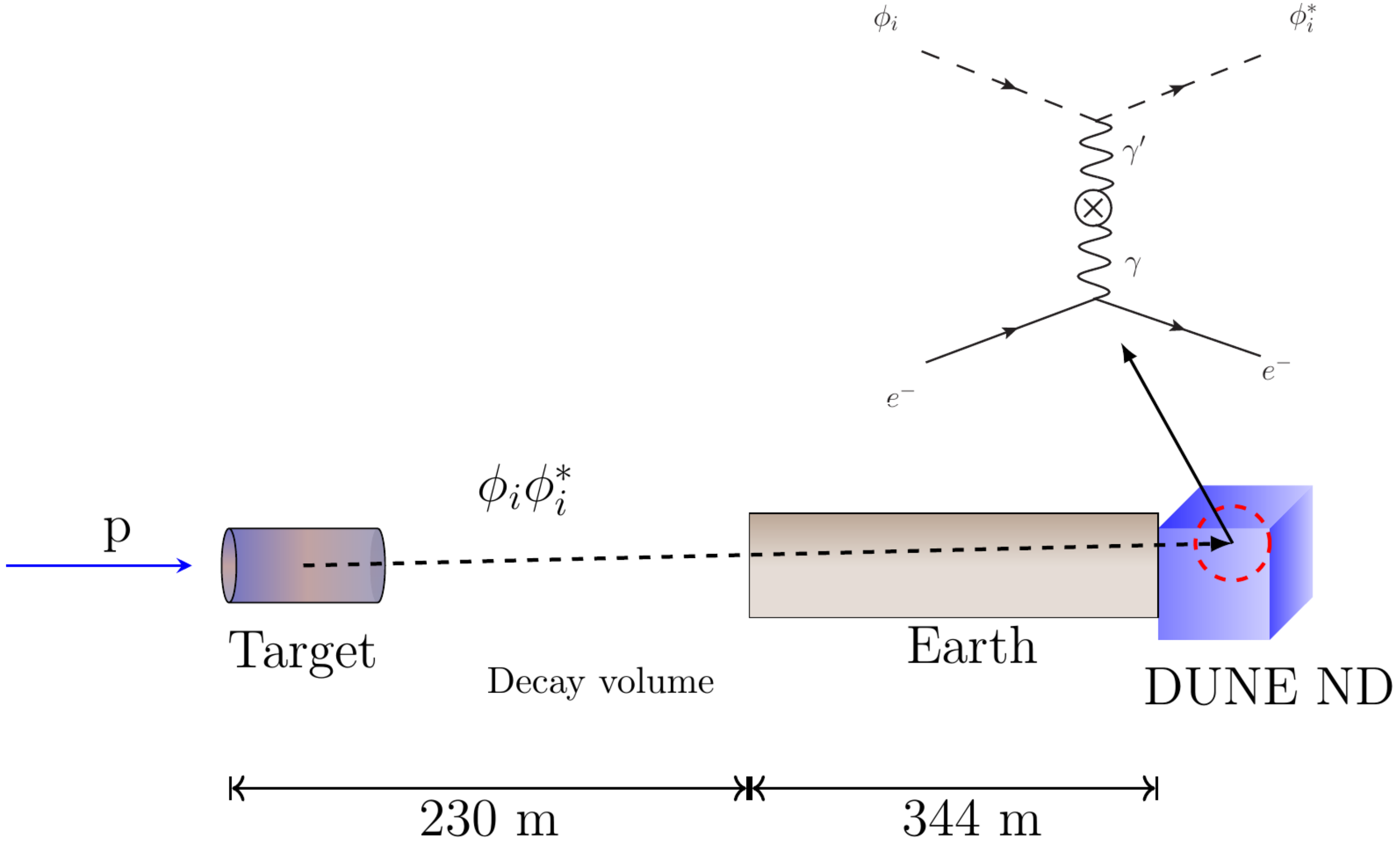
- The process of DM particles on-shell production is mediated by mixing dark photon-photon



@MadDump

Dark sector production at DUNE

- The DM candidates travel up to ND and interact with the electrons of the liquid argon via DM-e scattering

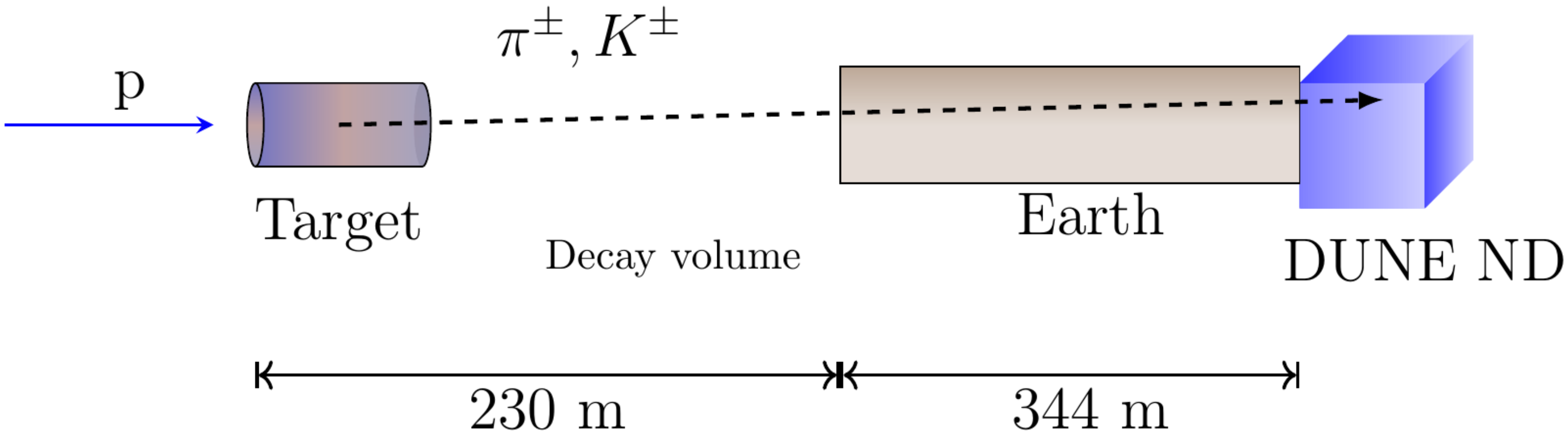


- Neutrino interactions will produce a huge background to search this DM-e scattering! @Maddump

Neutrino beam and background for DM searches

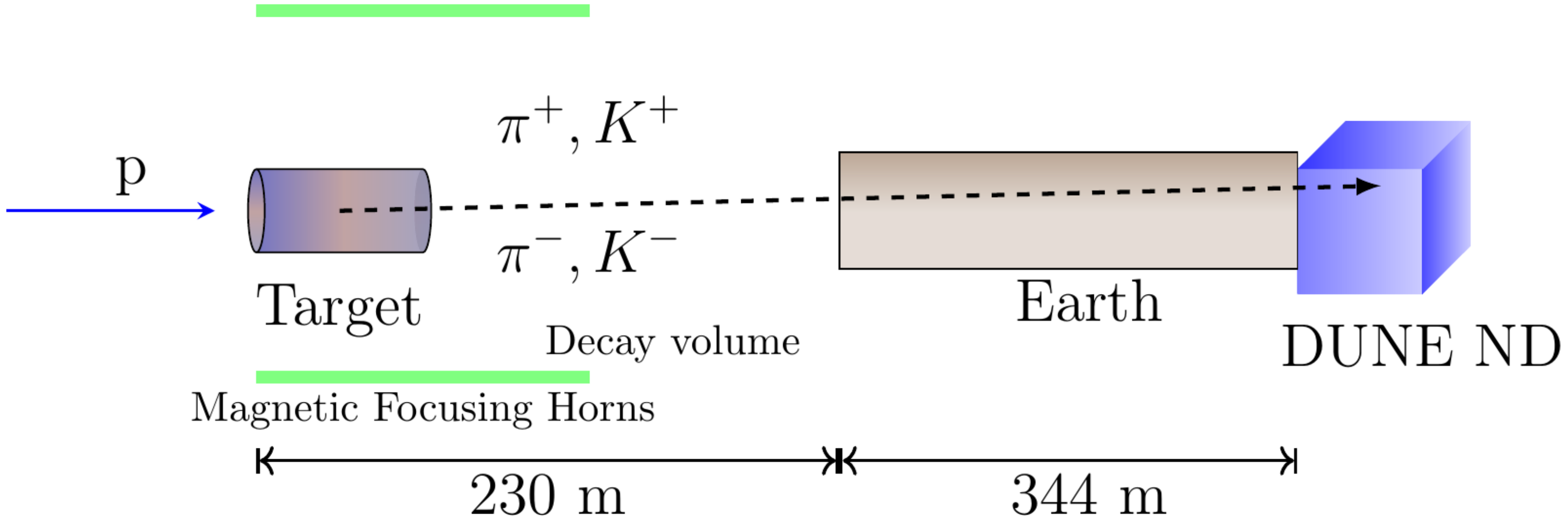
Neutrino beam and background for DM searches

- Neutrinos produced from decays of charged mesons propagating through decay volume



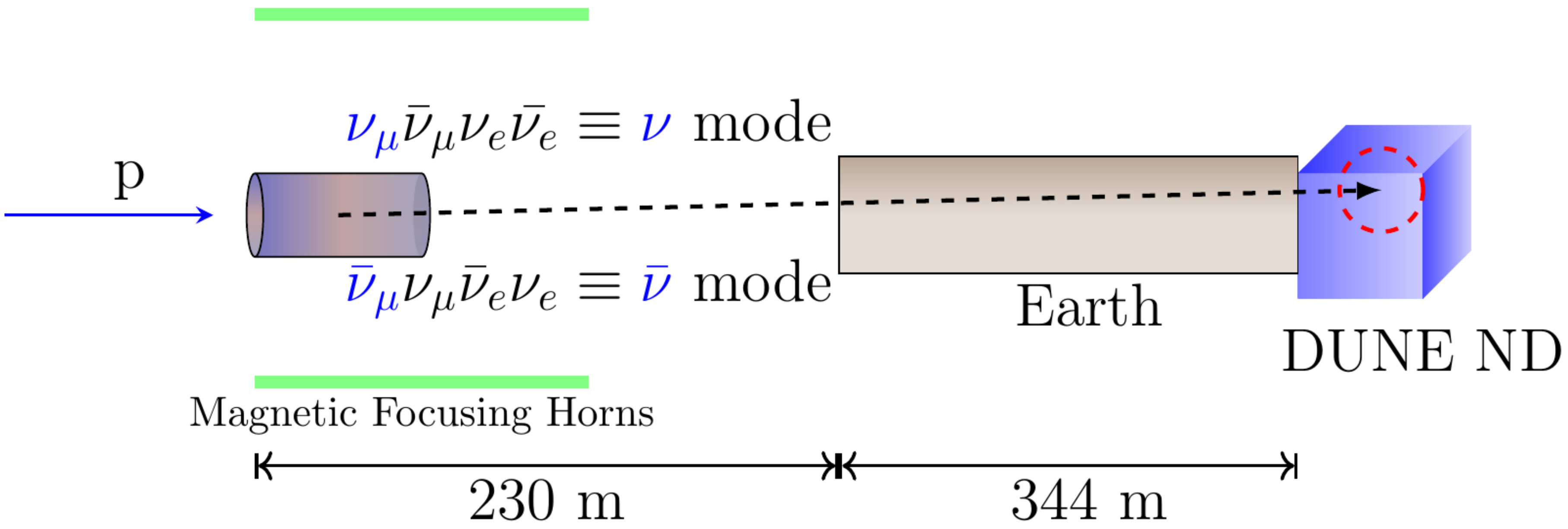
Neutrino beam

- Magnetic focusing horns allow to select what charged meson enters in the decay volume



Neutrino beam

- Charged mesons decay into neutrinos (antineutrinos) and antimuons (muons)

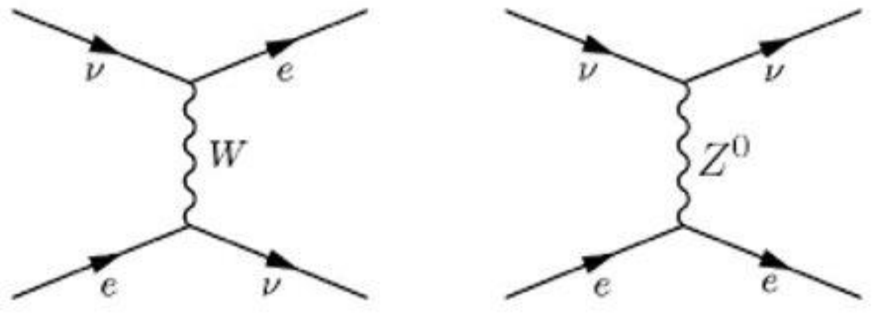


•Non-neutrinos are removed from the beam before they reach the detector to reduce background.
•Final fluxes considering magnetic horns and propagation effects on matter of neutrino events

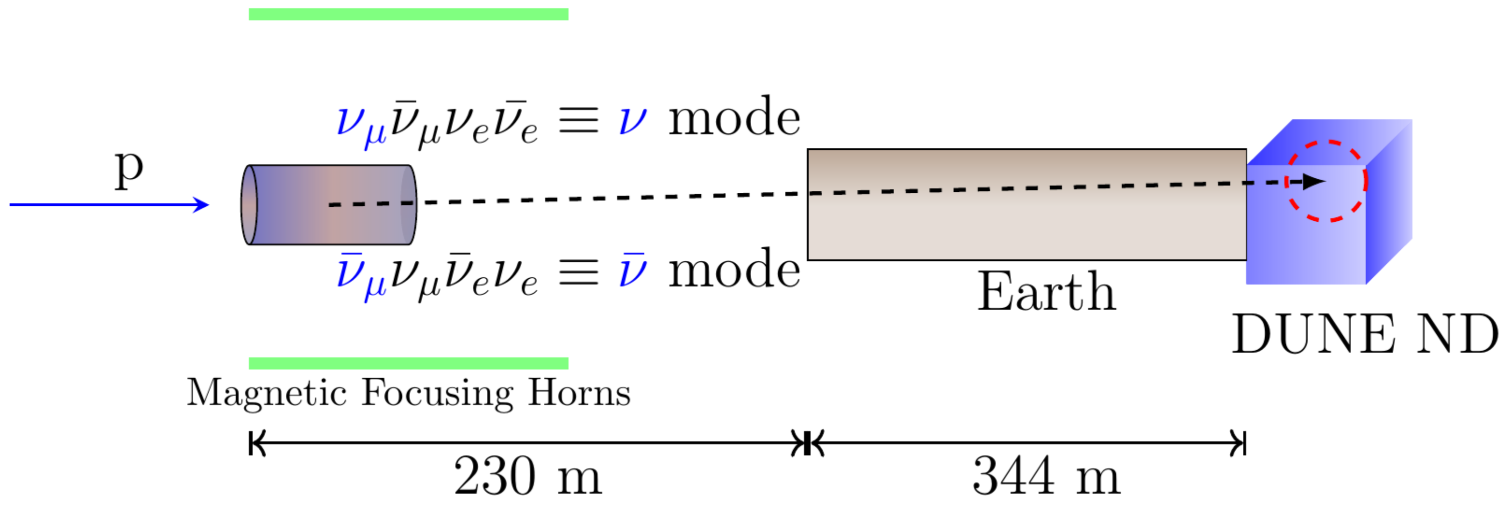
@Fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

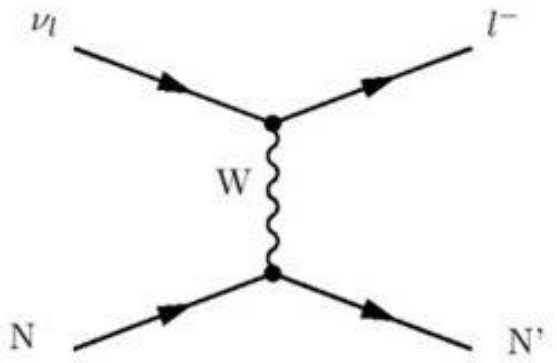
Neutrino beam

- Neutrinos interact with the detector, e.g., via neutrino electron scattering and CCQE



@Simulated with NuWro

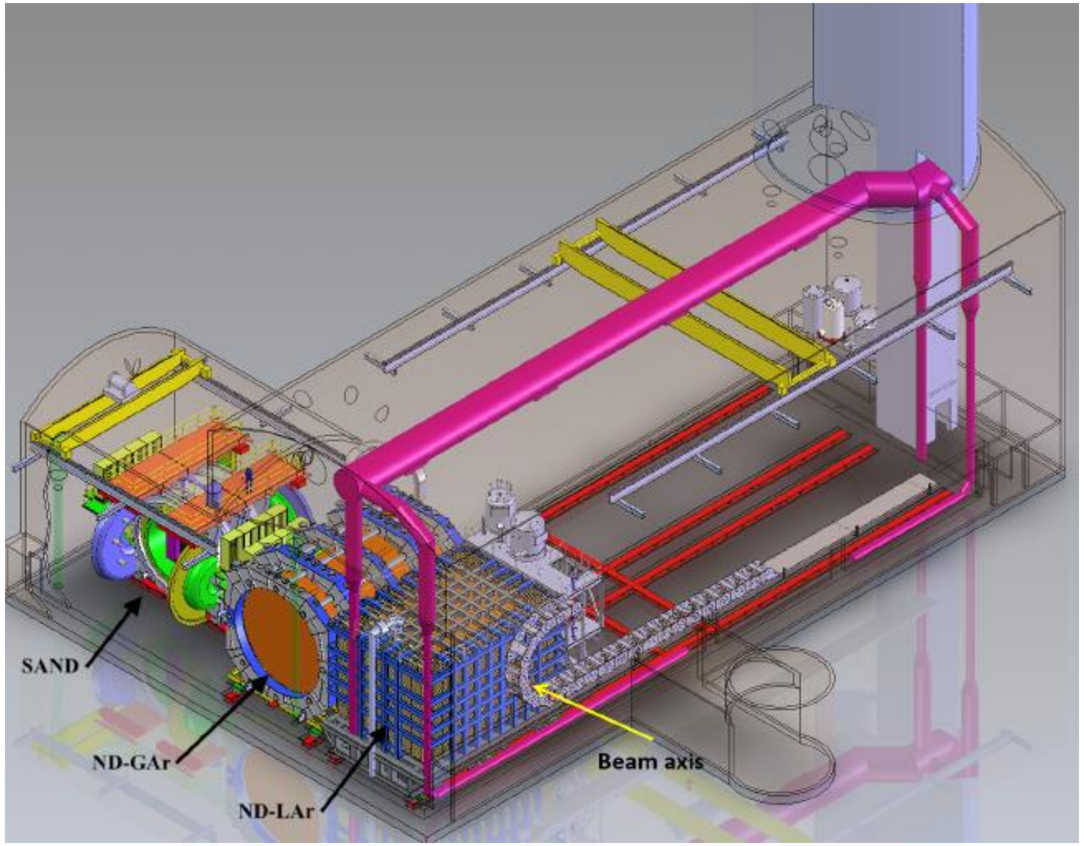


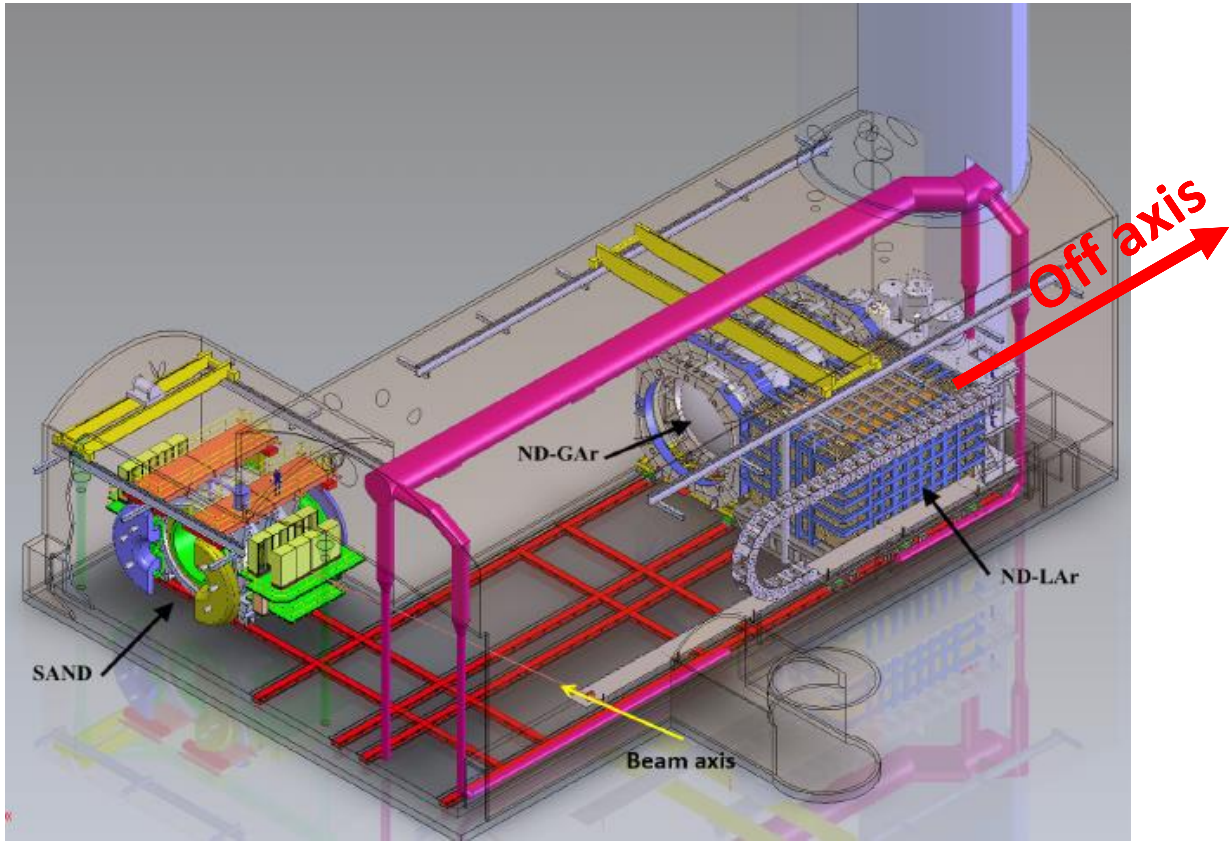


- Electrons in the final state will have distributions and signatures that look like those produced by DM-e

Reference design for ND

@ DUNE ND CDR 2021



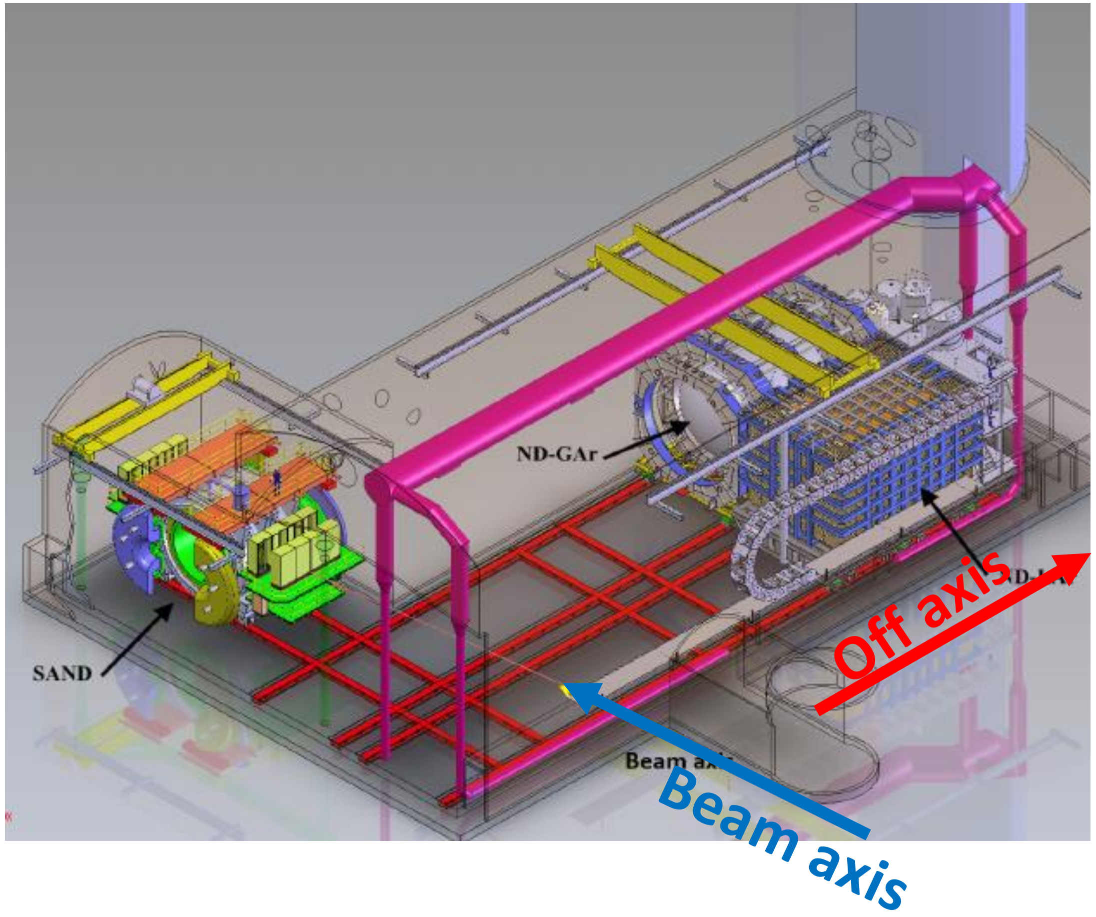


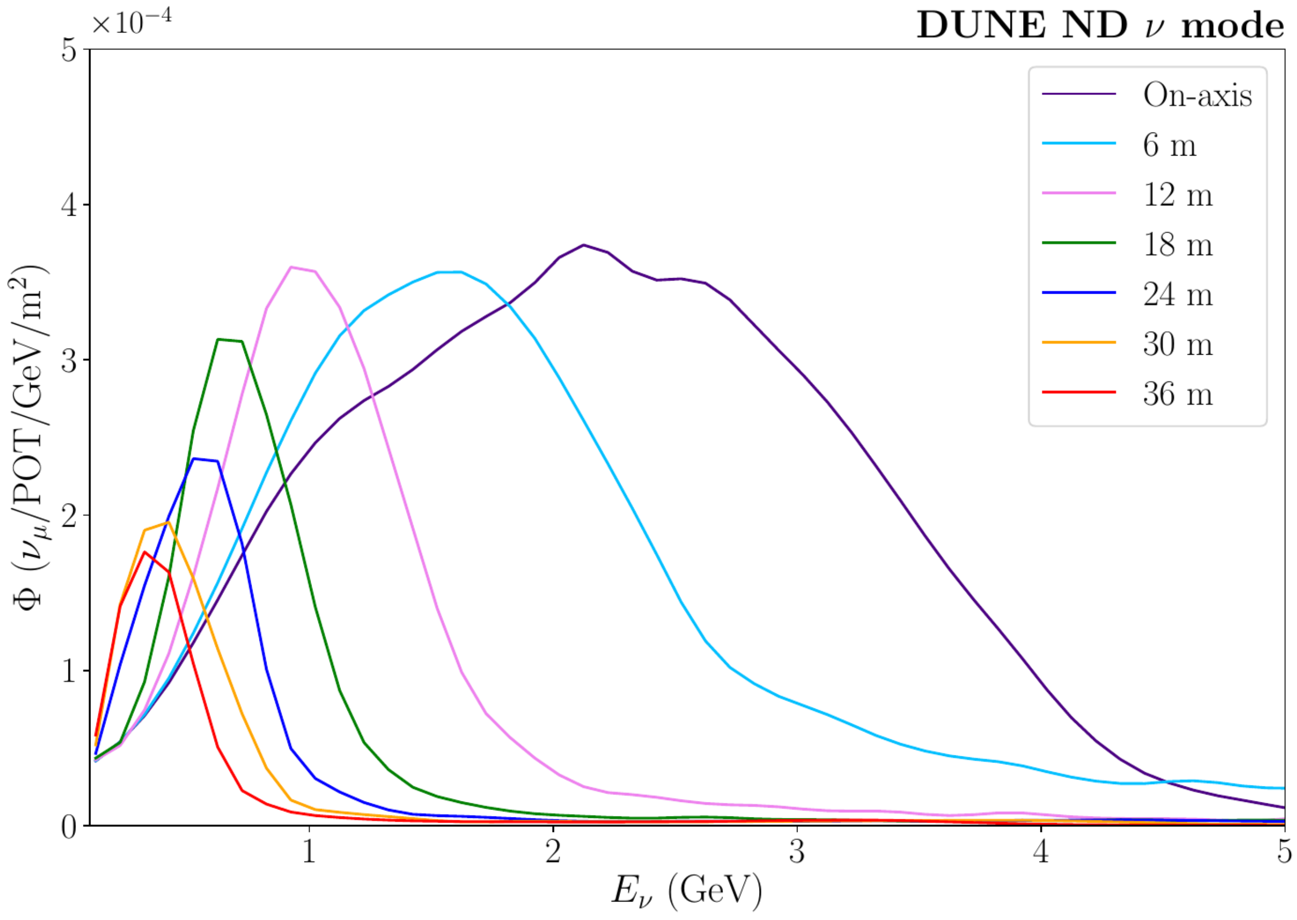
ND-LAr: Off axis Movement (up to 30-36 m). High statistics detector (50 tons). PRISM concept

ND-GAr (MPD): Low-threshold magnetised detector for spectrometry and powerful cross-section constraint

SAND: System for on Axis Neutrino Detection. Beam stability, Flux measurements, nuclear effects

PRISM (Precision Reaction Independent Spectrum Measurement) concept





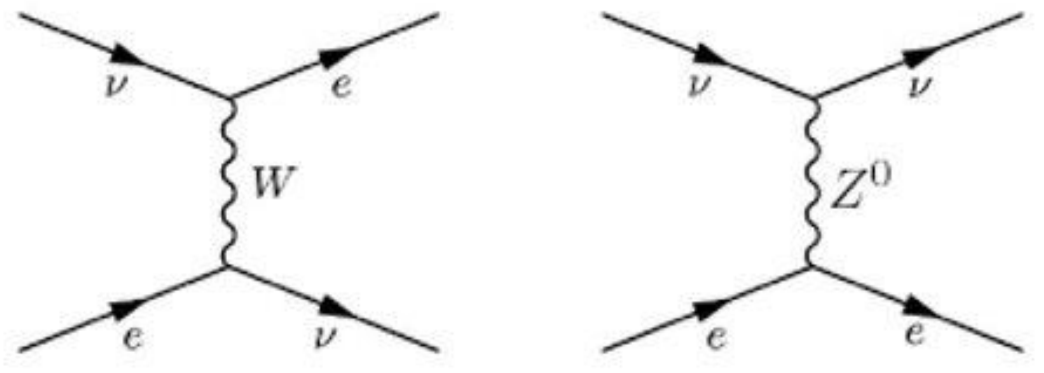
- Neutrino flux is reduced when DUNE-ND moves along different off-axis positions

Fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

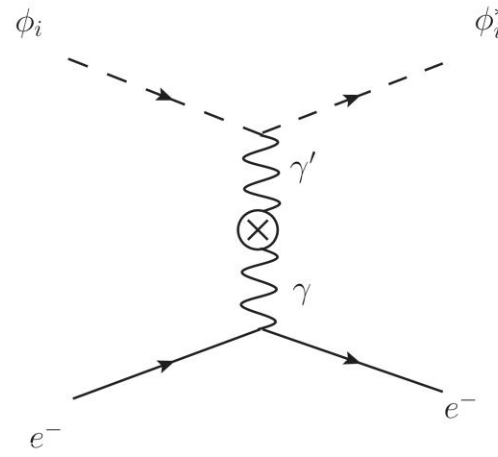
Background distributions: Neutrino interactions at DUNE ND

Neutrino interactions as background

- Neutrino interactions will produce events that seem like DM signature



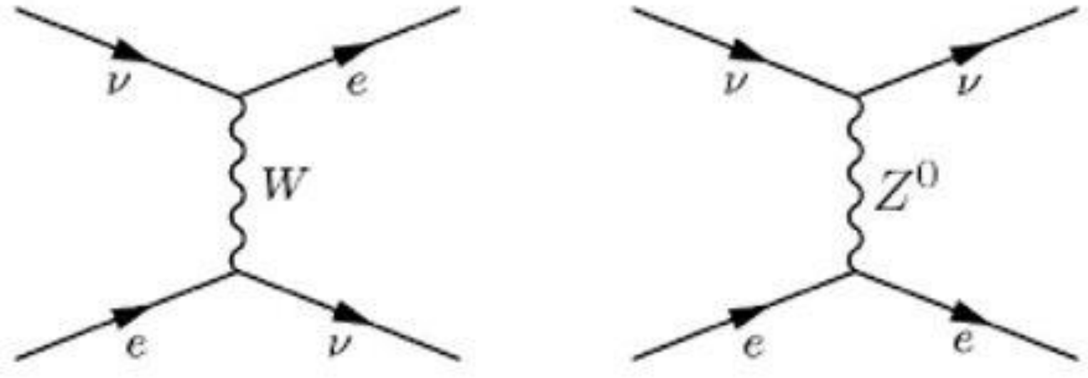
Neutrino Electron scattering

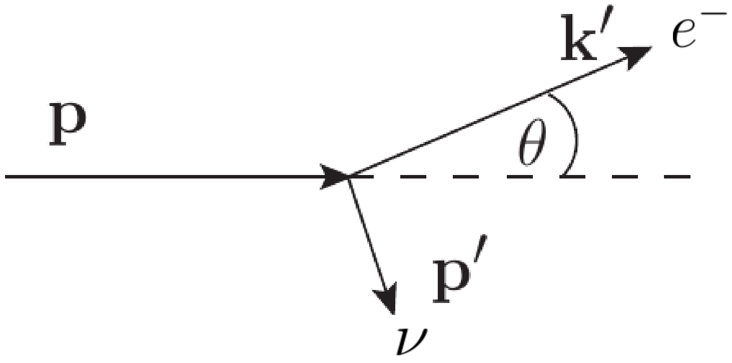


DM electron scattering

- Neutrino scattering on atomic shells electrons is a purely EW process.
- All flavors interact with different cross-sections

Neutrino-electron scattering





Laboratory Frame

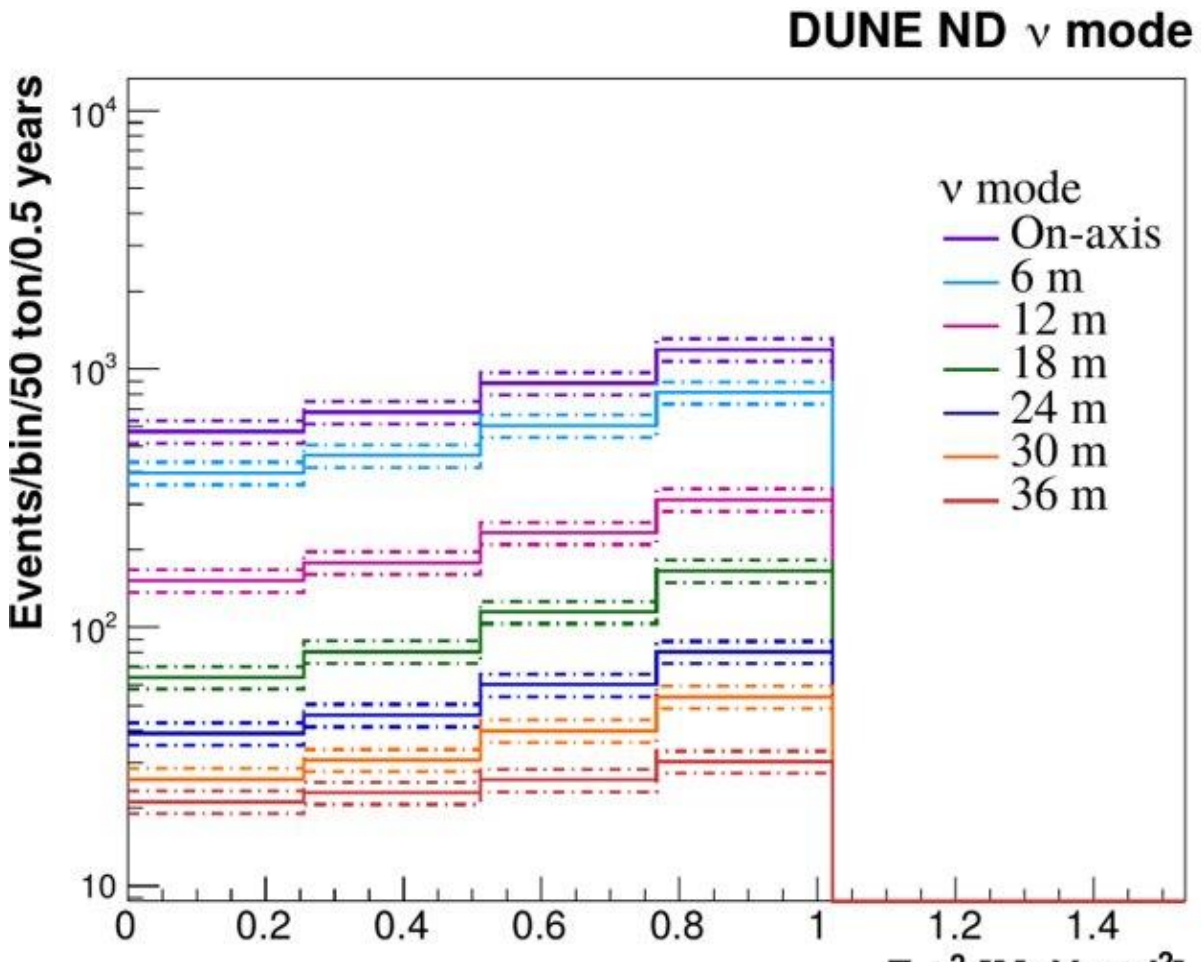
- Variables for events distribution analyses

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta_e)}{2m_e}}$$

- Yields a natural cut for electron energy and angle events distributions

$$E_e\theta_e^2 \leq 2m_e$$

Neutrino electron scattering (neutrino mode)



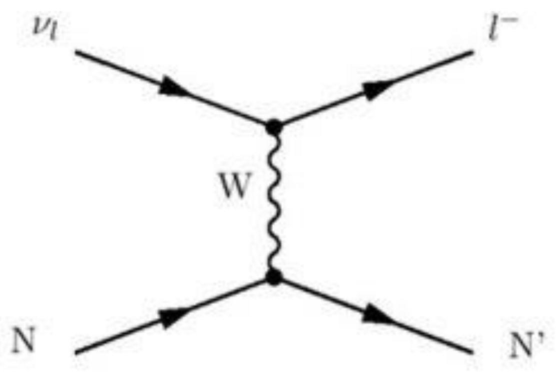
$E_e\theta_e^2 \leq 2m_e$

@NuWro

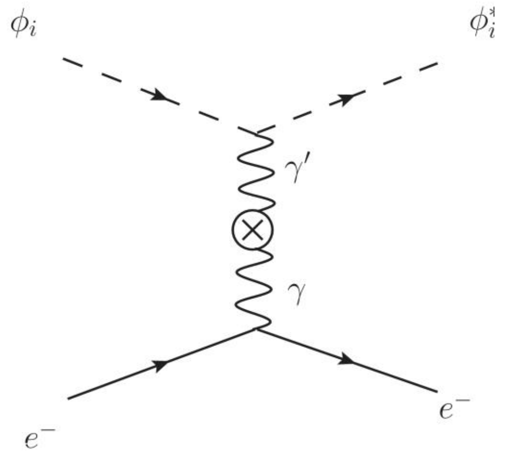
- Prism concept allows the background reduction when the ND is moved in different off axis positions!

Neutrino interactions as Background

- Electrons can also appear via ve charged-current quasi-elastic (CCQE) scattering



CCQE



DM electron scattering

- The final hadronic system is not identified. Only we count the electrons in the final state.
- Other BKG for DM signal, but it is reducible when information over electrons in the final state is included

Signal vs Background signatures

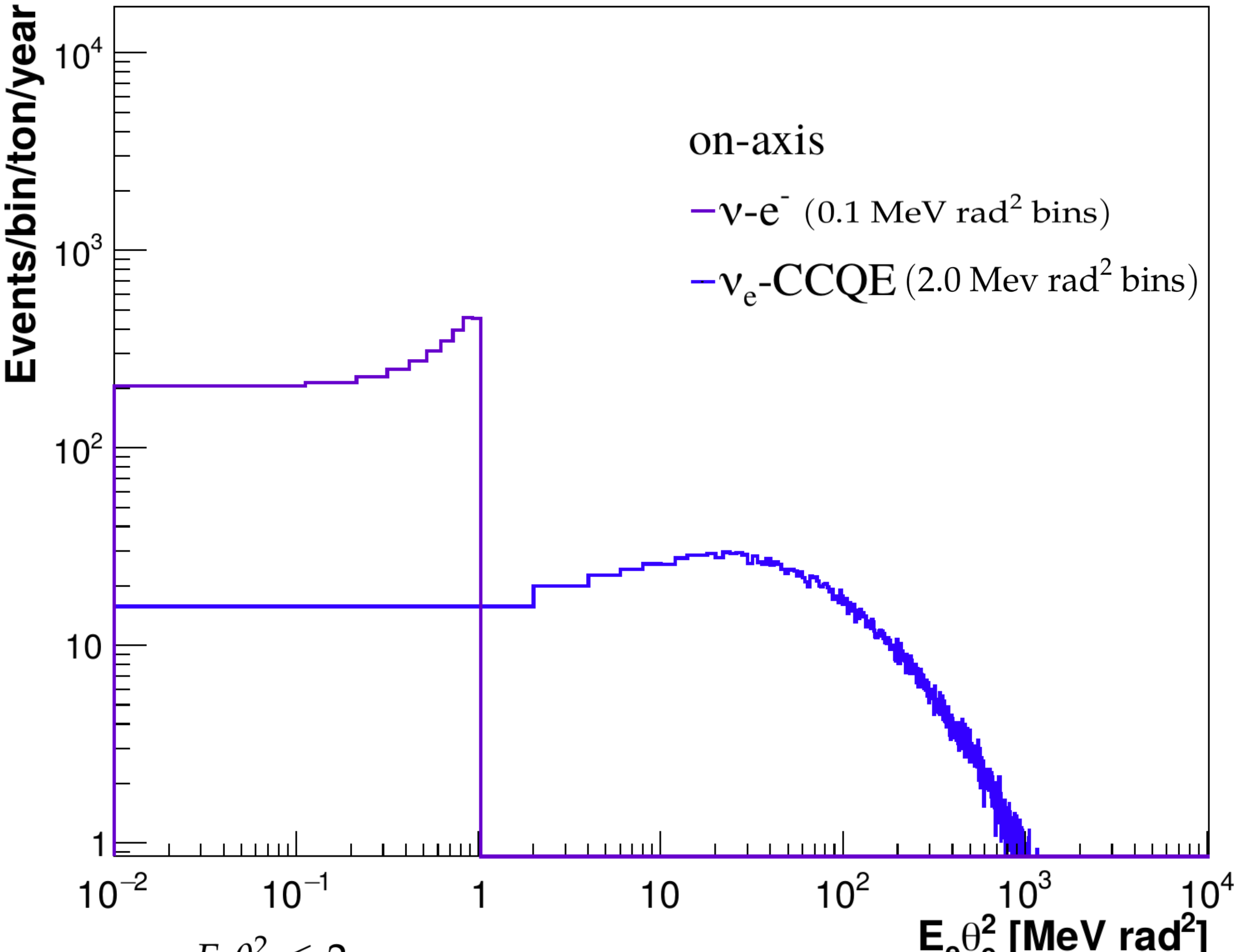
- Neutrino-electron scattering is the most significant background for regimes with natural cut

$$E_e\theta_e^2 \leq 2m_e$$

- Existence hadronic states lead electrons scatter in larger angles in $\nu_e - \text{CCQE}$

- In the events number, we did a cross check with DUNE ND-CDR (Genie) to validate the NuWro outputs; obtaining discrepancies < 10%

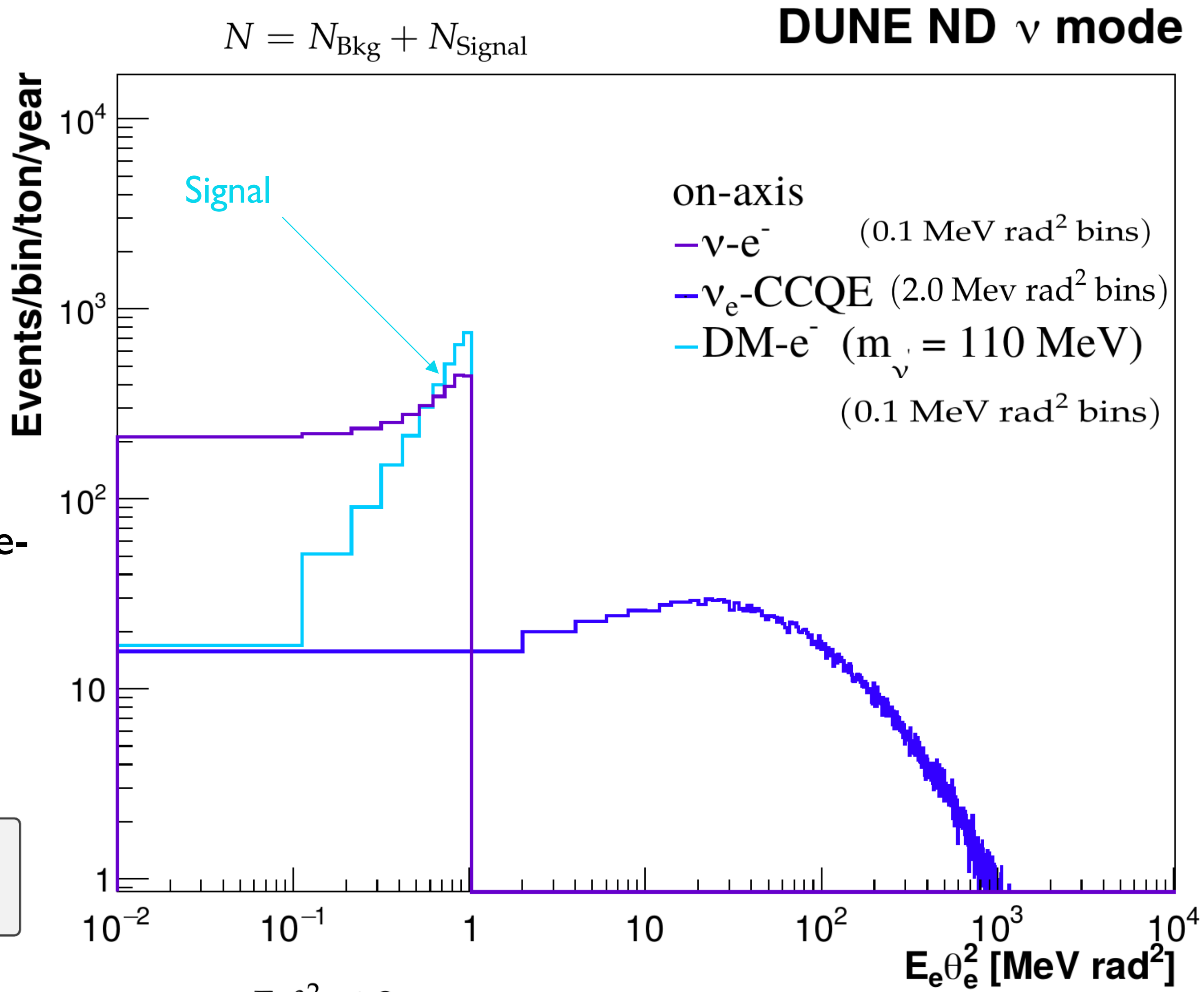
$$N_{\text{Bkg}} = N_{\nu-e} + N_{\nu_e-\text{CCQE}}$$



$$E_e\theta_e^2 \leq 2m_e$$

Signal vs Background signatures

$N = N_{\text{Bkg}} + N_{\text{Signal}}$



$E_e\theta_e^2 \leq 2m_e$

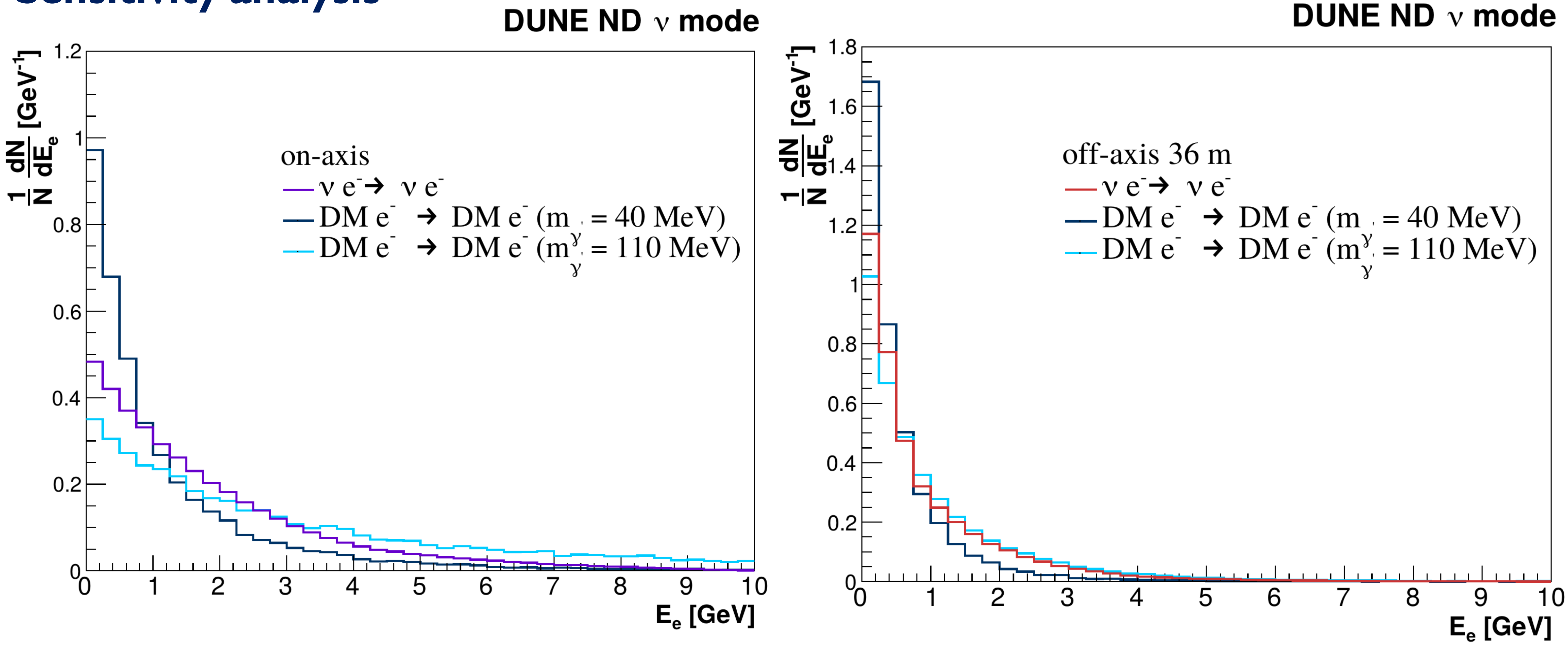
- Signal and neutrino electron scattering differ from ve-CCQE
- It is possible to cut more 99.0% events of ve-CCQE (without the hadronic identification)

Benchmark point $\epsilon^2 = 1.5 \times 10^{-8}$

$m_{\gamma'} = 110\,\text{MeV}, m_{\phi_1} = m_{\gamma'}/3, m_{\phi_2} = 1\,\text{GeV}$

Sensitivity analysis

Sensitivity analysis



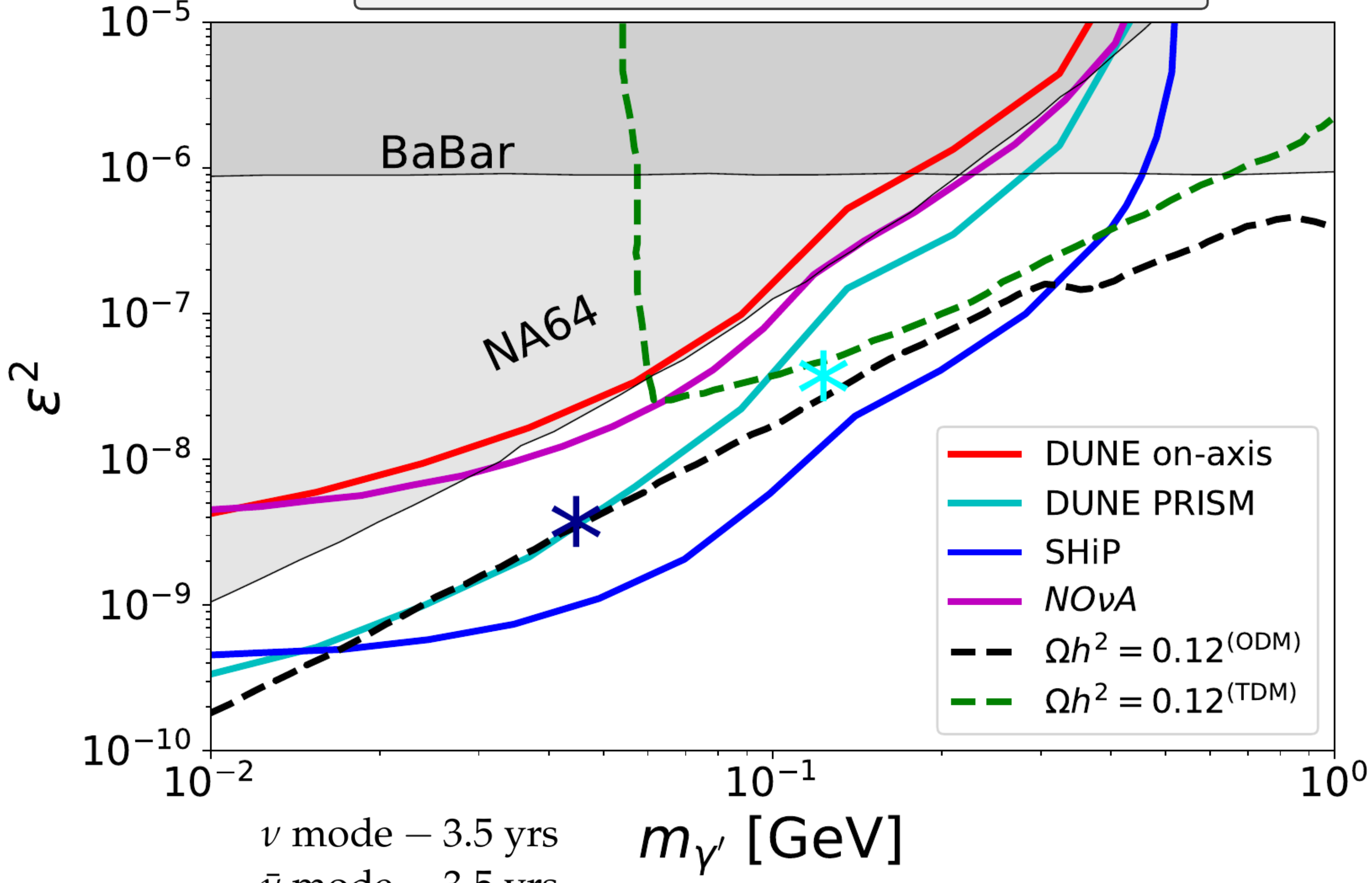
- Sensitivity can be improved by including information about the final-state electron kinematics.

- Statistical analyses of sensitivity used a Poisson likelihood for signal- background ratio in a linear combination of different off axis positions.

@D.Romeri et al, 2019 and M. Breitbach et al 2021.

Sensitivity analysis

$$m_{\phi_1} = m_{\gamma'}/3, m_{\phi_2} = 1\ \mathrm{GeV}, \alpha_D = 0.1$$

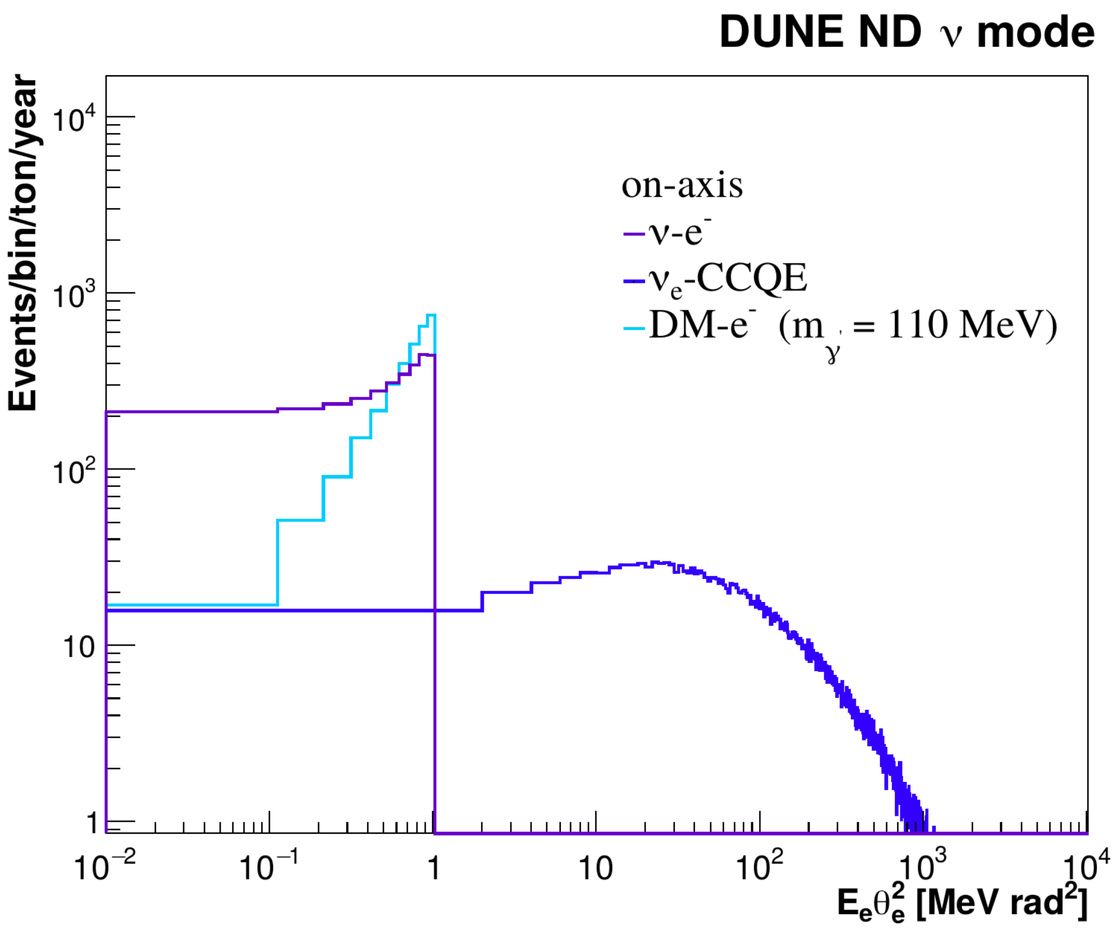


ν mode – 3.5 yrs

$\bar{\nu}$ mode – 3.5 yrs

Summary

- The correct relic density region for multicomponent models can be explored using neutrino detectors (as the study case of DUNE-ND)
- Neutrino-electron scattering is critical for the sensitivity analyses.
- CCQE is subdominant when angle and energy cuts for the electron in the final state are considered in the distributions.
- DUNE PRISM configuration improve the sensitivity of DUNE on-axis by roughly one order of magnitude in the kinetic mixing squared.
- Improvements: Distributions using the detector response

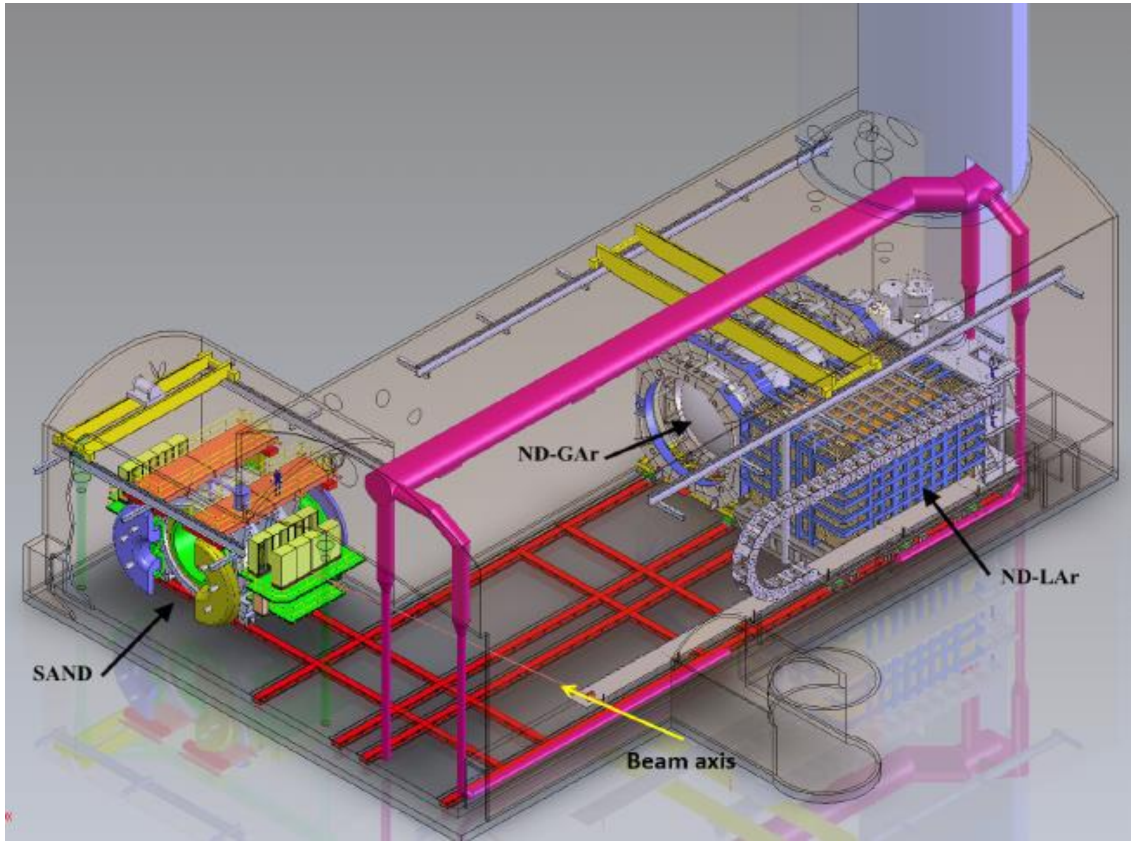


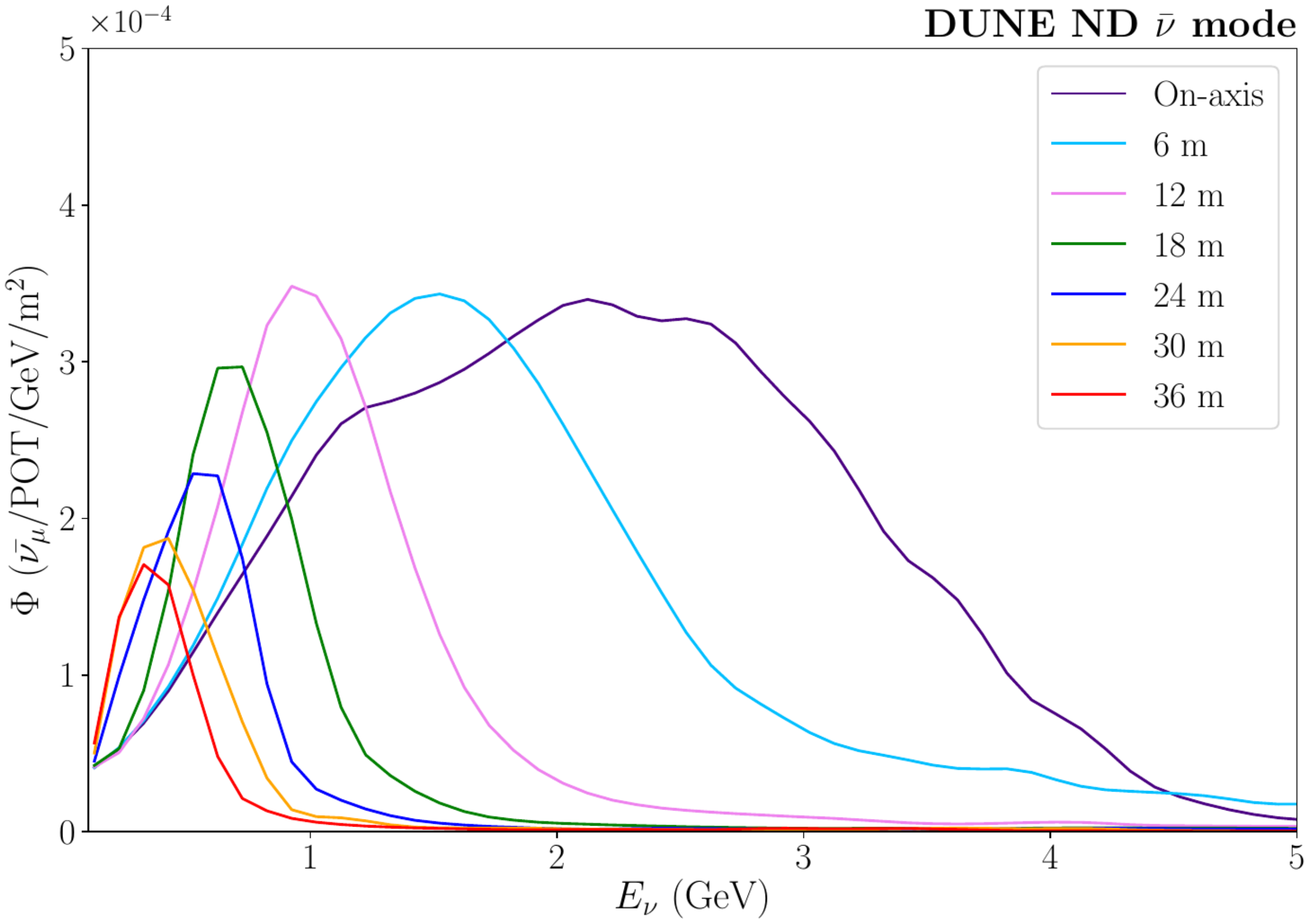
Thanks! Gracias NuCo!

To appear soon on arXiv! Stay tuned

Complementary slides

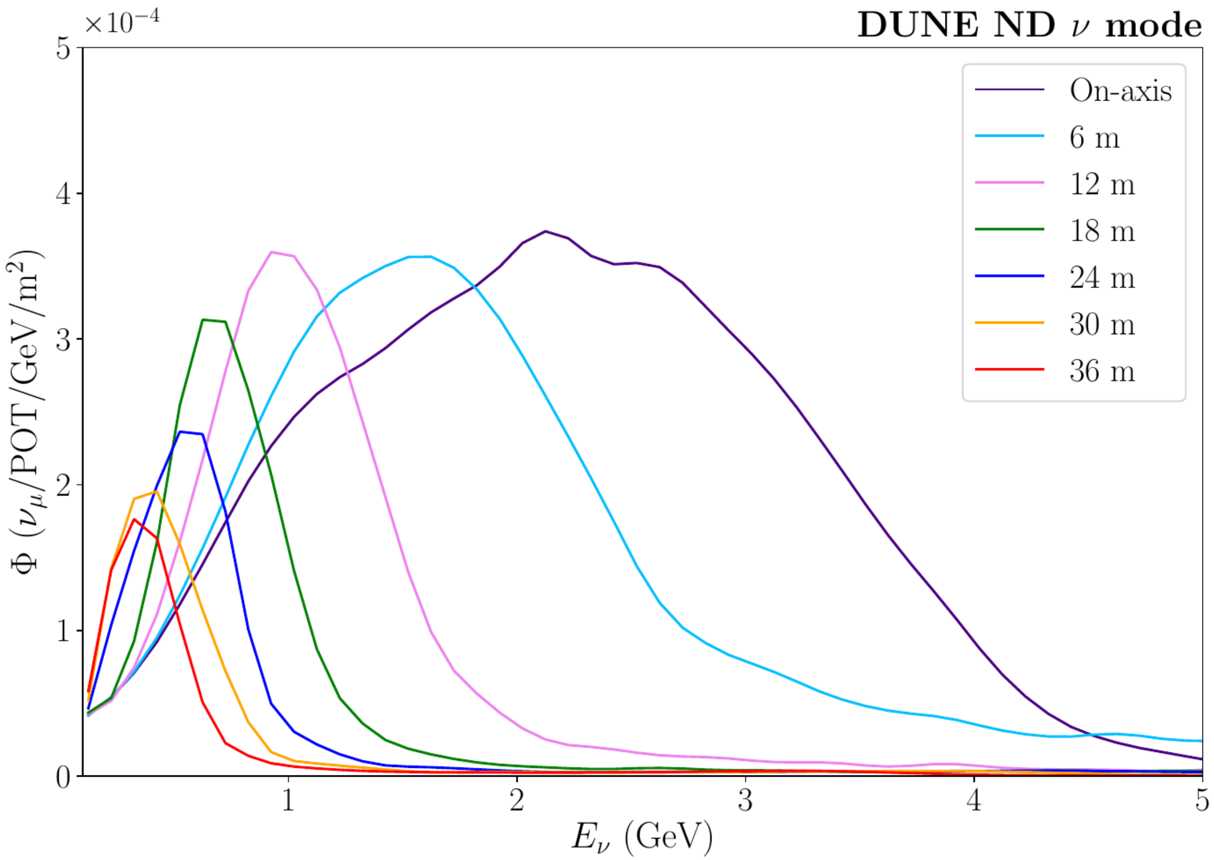
PRISM (antineutrino mode)

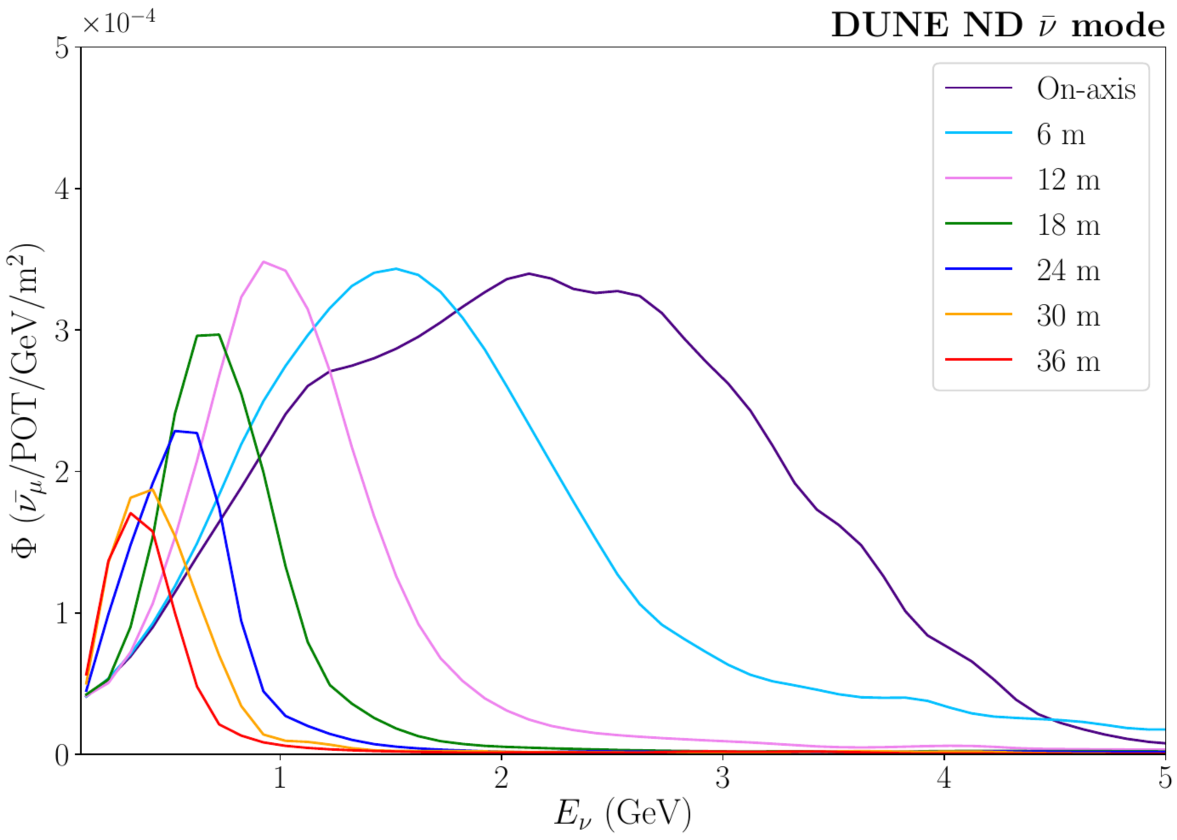




Fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

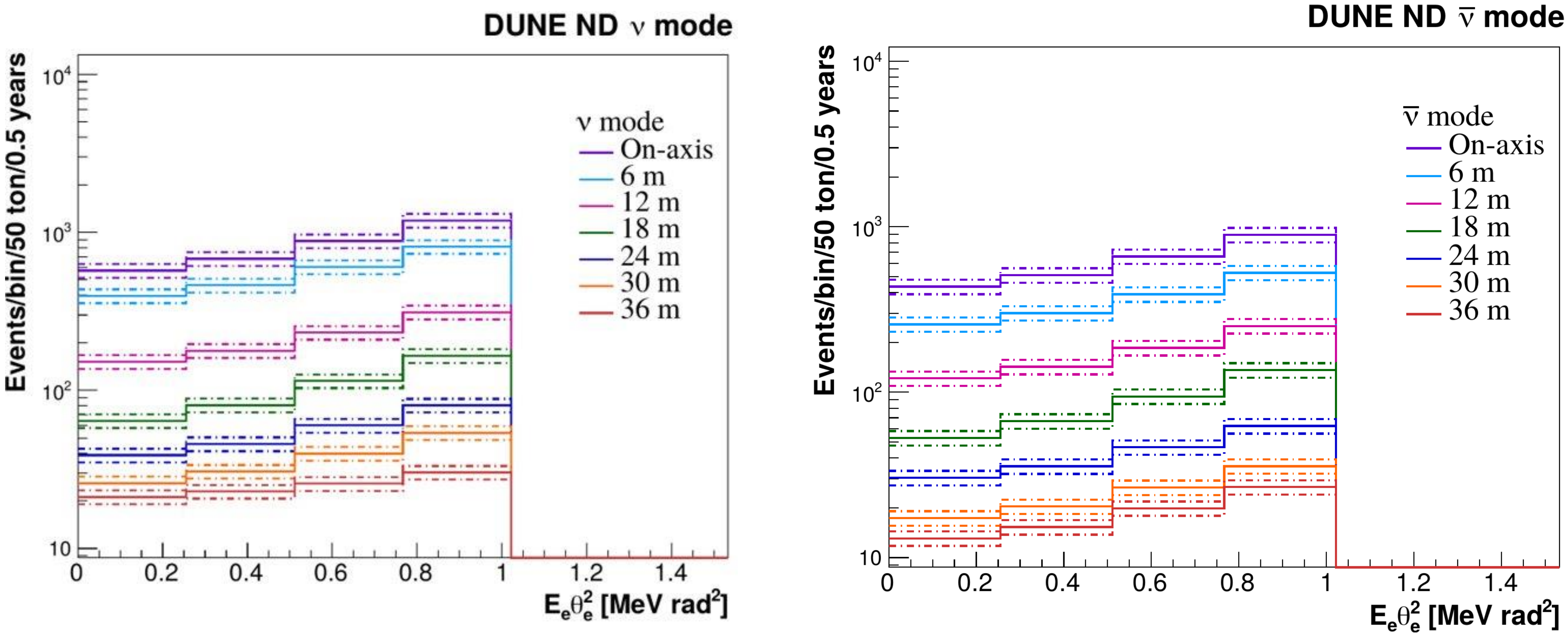
PRISM



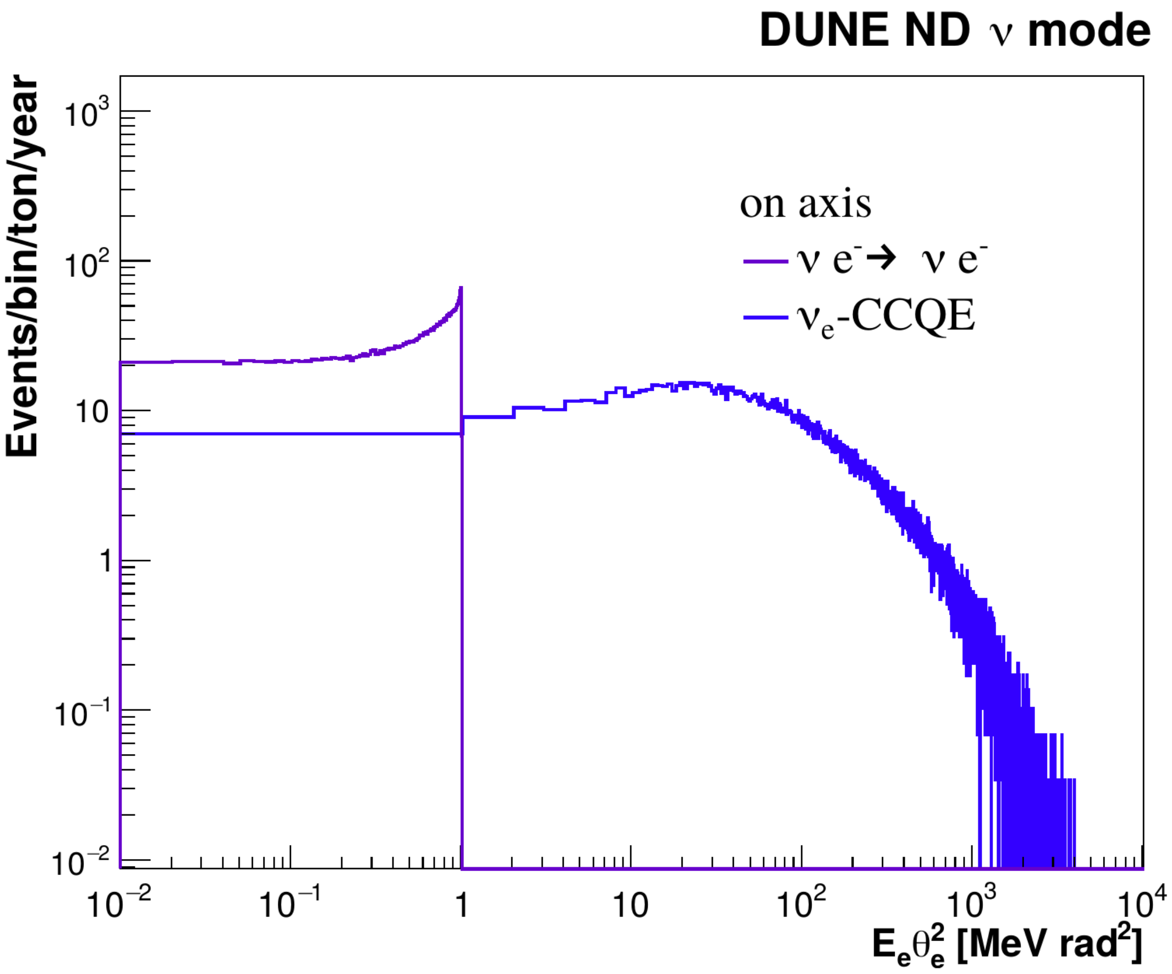


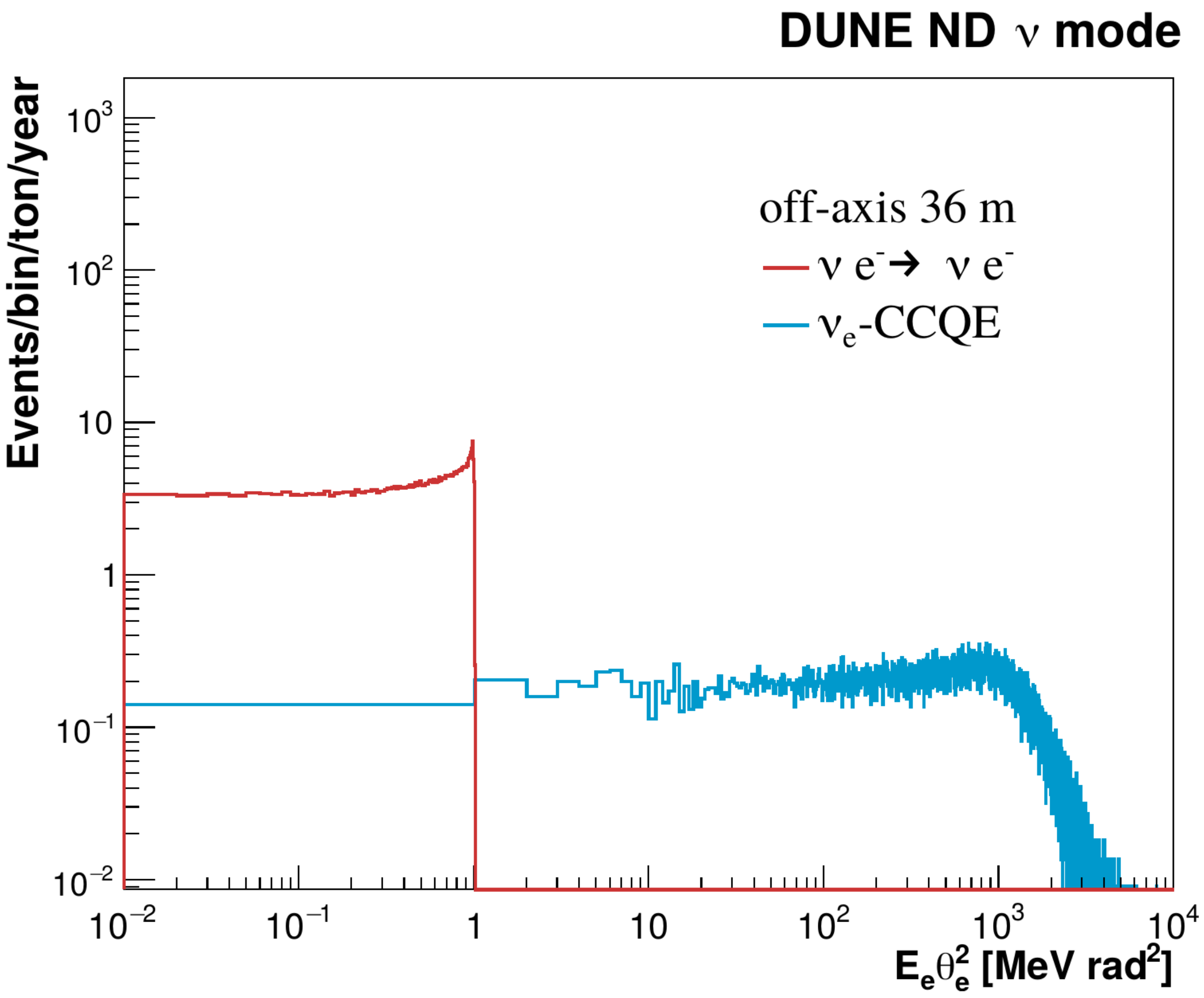
@Fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

Neutrino-electron scattering (both modes)



Neutrino-electron scattering and ve-CCQE





Events for backgrounds

DUNE ND (ν and $\bar{\nu}$ modes)							
Channel	**On axis**	**6 m**	**12 m**	**18 m**	**24 m**	**30 m**	**36 m**
$\nu_\mu e \to \nu_\mu e$	115 12	78 10	27 5	13 3	7 2	4 1	3 1
$\nu_e e \to \nu_e e$	9 3	6 2	4 2	2 1	1 0	1 0	1 0
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	8 82	6 45	3 20	2 9	1 5	1 3	1 2
$\bar{\nu}_e e \to \bar{\nu}_e e$	1 3	1 2	1 1	0 1	0 0	0 0	0 0
Total $\nu e \to \nu e$	133 100	91 59	35 28	17 14	9 7	6 4	5 3
Total ν_e**-CCQE**	3003 676	2355 595	1572 476	1067 357	750 272	550 219	412 178
ν_e-CCQE*	14 3	10 3	6 2	3 1	2 1	1 0	0 0

- Expected number of ν −e and νe -CCQE events (per ton per year) in DUNE ND for on-axis and six off-axis position. Events numbers in ν ($\bar{\nu}$) mode are in top (bottom) row.

Statistical test

- Sensitivity can be improved if the final-state electron kinematics for the signal and background distributions is considered in the statistical analyses.

- The binned test statistics:

$$\mathcal{L}_{ij}(\mu) = \frac{(w_{ij})^{d_{ij}} e^{-(w_{ij})}}{d_{ij}!} \quad \text{with} \quad w_{ij} = A f_i (\mu N^{\phi}_{ij} + N^{\nu}_{ij})$$

$$q = -2\Delta L = \sum_{i=1}^{n_{\rm pos}} \left[\sum_{j=1}^{n_{\rm bins}} -2\log\left(\frac{\mathcal{L}_{ij}(\mu=1)}{\mathcal{L}_{ij}(\mu=0)}\right) + \frac{(f_i-1)^2}{\sigma^2_{f_i}} \right] + \frac{(A-1)^2}{\sigma^2_A}$$

$$q > 4.61 \qquad 90\% \text{ CL}$$

- Unbinned analysis:

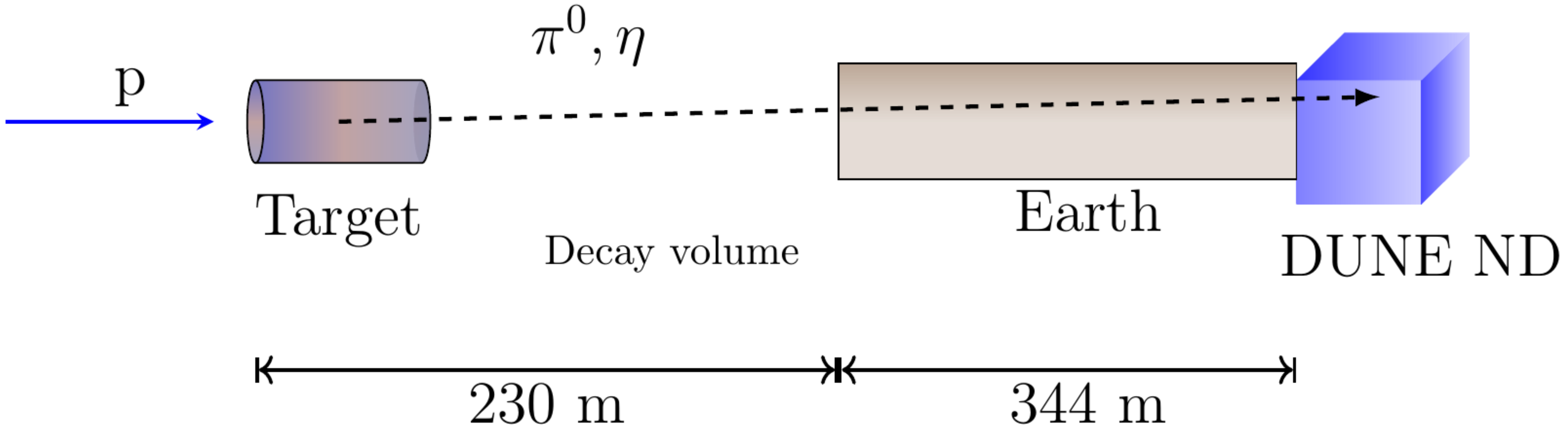
$$Z = \frac{N^{\phi}}{\sqrt{N^{\nu} + \sum_{i\in(\nu_e,\nu_\mu,\overline{\nu}_e,\overline{\nu}_\mu)} (k_i N^{\nu}_i)^2}}$$

$$Z \geq 1.64 \quad 90\% \text{ CL}$$

@D.Romeri et al, 2019 and M. Breitbach et al 2021.

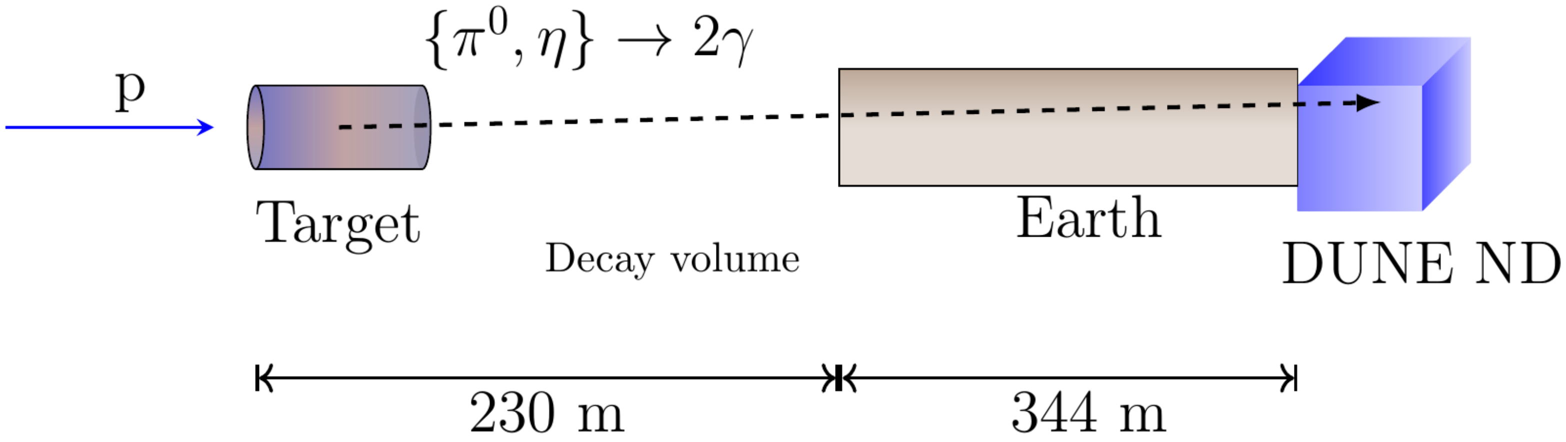
Dark sector production at DUNE

- For DM production, we consider first neutral pions



Dark sector production at DUNE

- Neutral pions decay mainly in two photons

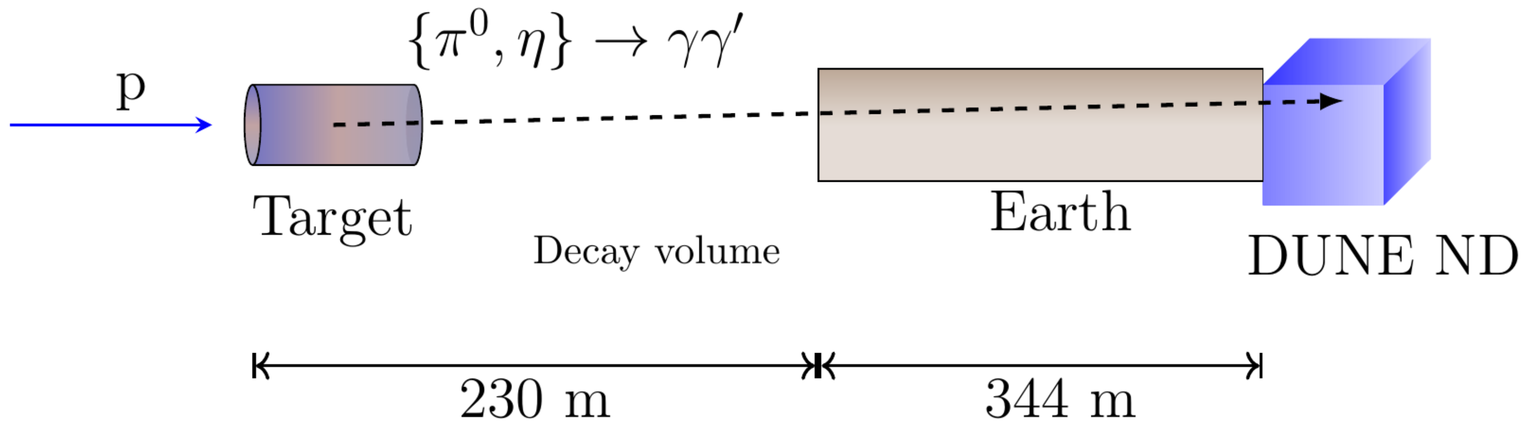


meson **m**	meson/POT	Br(**m** $\rightarrow \gamma\gamma$)
π^0	4.1	99.82 %
η	0.5	39.41 %

@Pythia

Dark sector production at DUNE

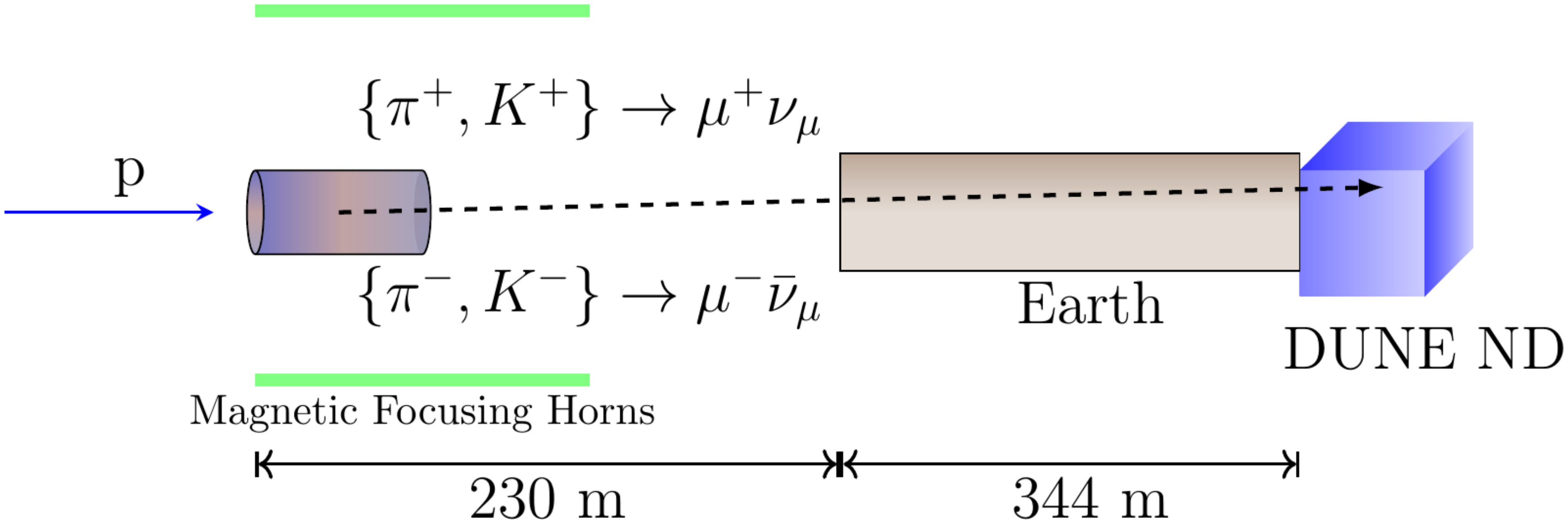
- LDM could be produced thanks to the mixing between γ' and γ



- Simulations for Dark photons production and the subsequent decay into DM @Maddump

Neutrino beam

- Charged mesons decay into neutrinos (antineutrinos) and antimuons (muons)



meson **m**	meson/POT	Br($\mathbf{m}^+ \rightarrow \mu^+\nu_\mu$)	Br($\mathbf{m}^+ \rightarrow e^+\nu_e$)
$\pi^+(\pi^-)$	4.3(4.0)	99.98 %	1.2×10^{-4} %
$K^+(K^-)$	0.39(0.27)	63.56 %	1.58×10^{-5} %

@Pythia

Neutrino beam

- Antimuons (muons) decay via beta decay.