

Light Dark Matter at MINERvA

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Neutrino Joint Theory-Experiment Working Group

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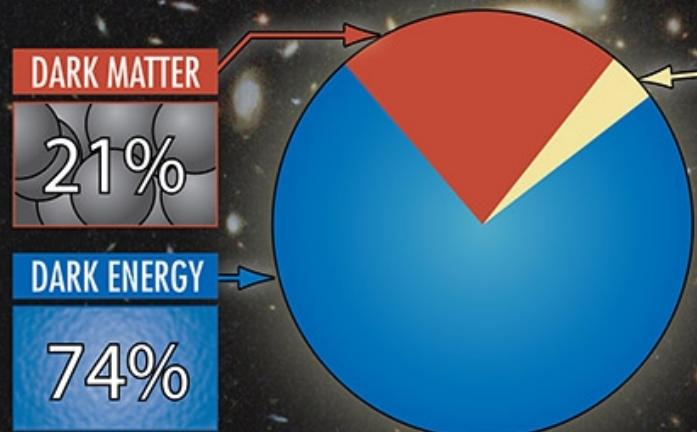
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Outline

1. Light dark matter
2. Neutrino and dark matter
 - Flux
 - Differential cross-section
3. Dark matter signal events
4. Analysis of toy χ^2
5. Summary and perspectives

Dark matter

What The Universe Is Made Of



A background image showing a complex web of filaments and galaxies, representing the large-scale structure of the universe.

Couplings

- Mass
- Spin
- Gravity
- Weak interaction?
- Higgs?
- Quarks/Gluons?
- Leptons?

Wanted:
FIMP

Fuzzy Inert Massive Particles

Wanted:
SIMP

Strongly Interacting Massive Particles

Wanted:
Fuzzy dark matter

Scalar Field Dark Matter
Mass: extremely light (in the 10^{-22} eV range)

Wanted:
WIMP

Weakly Interacting Massive Particles

SUB-GeV or light dark matter

Light dark matter (LDM) model

Standard Model (SM) symmetry

$$SM : SU(3)_{\text{Color}} \times SU(2)_{\text{Left}} \times U(1)_{\text{Hypercharge}}$$

From observations **DM** should be described by a quantum field **uncharged under $U(1)_{\text{EM}}$** electromagnetic or **$SU(3)_C$** of color (and if it is, it must be very small)

LDM model is an extension of the SM that introduces a **new dark $U(1)$ gauge group:**

$$U(1)_H \times U(1)_D$$

LDM is the simplest dark sector scenario. The LDM **χ** interacts with standard model particles through a dark photon **A'** that is **kinetically mixed** with the ordinary **photon**.

The LDM is described by the effective Lagrangian:

$$\mathcal{L}_{DM} = \mathcal{L}_{A'} + \mathcal{L}_{\chi}$$

A' is the **gauge boson** of $U(1)_D$. **χ** serves as a **DM candidate** and is charged under $U(1)_D$ (charge equal to one and neutral with respect to the SM gauge group).

Light dark matter (LDM) model

$m_\chi, m_{A'}, \alpha_D, \epsilon$

LDM is written in terms of **four parameters**:

- The **dark matter mass** m_χ
- The **dark photon mass** $m_{A'}$
- The dark gauge coupling g_D or the dark fine structure constant α_D

$$\alpha_D = \frac{g_D^2}{4\pi}$$

- The dark photon-photon **kinetic mixing** ϵ or in terms of the variable Y :

$$Y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4 ,$$

$$U(1)_H \times U(1)_D$$

$$\mathcal{L}_{A'} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{L}_\chi = i g_D A'^\mu J_\mu^\chi + \partial_\mu \chi^\dagger \partial^\mu \chi - m_\chi^2 \chi^\dagger \chi$$

$$J_\mu^\chi = (\partial_\mu \chi^\dagger) \chi - \chi^\dagger \partial^\mu \chi$$

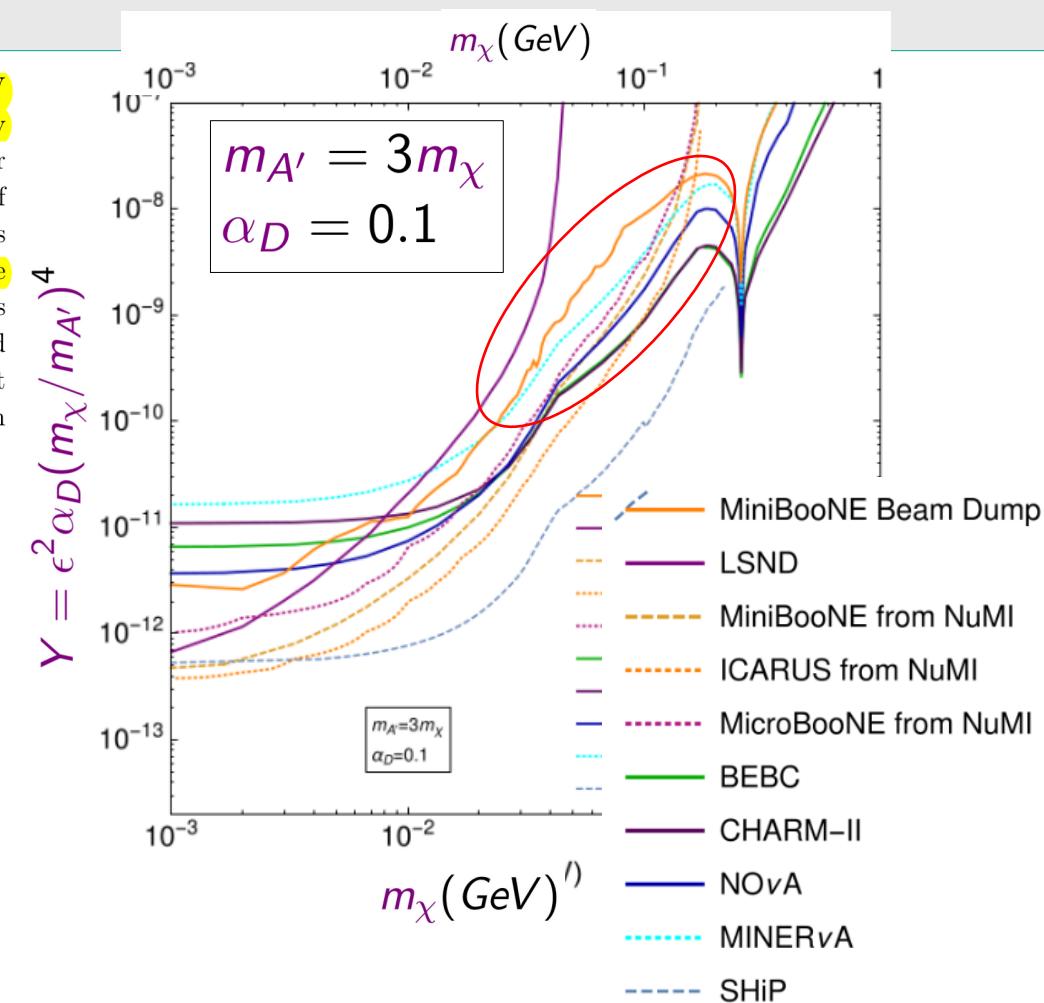
State of the art

Experiment	α_D	ϵ	$m_{A'}$	m_χ	Observations
BABAR	0.1	$<10^{-3}$	$<8\text{GeV}$	$>60\text{MeV}$	Excluded region
	0.1	-	-	$>100\text{MeV}$	With χ Termal relic
NA64	0.1	-	$<150\text{MeV}$	-	Via missing energy analisis
CRESST- II and III	Large values	-	-	$>500 \text{ MeV}$	χ relic abundance corresponds to the observed DM abundance
	<0.1	-	-	MeV-GeV	
	<0.5	-	-	$>10\text{MeV}$	
Planck	-	-	-	$>6.9 \text{ MeV}$	Minimal DP model χ is a complex scalar
MiniBooNE	0.5, 0.1	$<10^{-3}$	$7m_\chi, 3m_\chi$	sub-GeV	Special run for DM search

Sensitivity to LDM at neutrino facilities

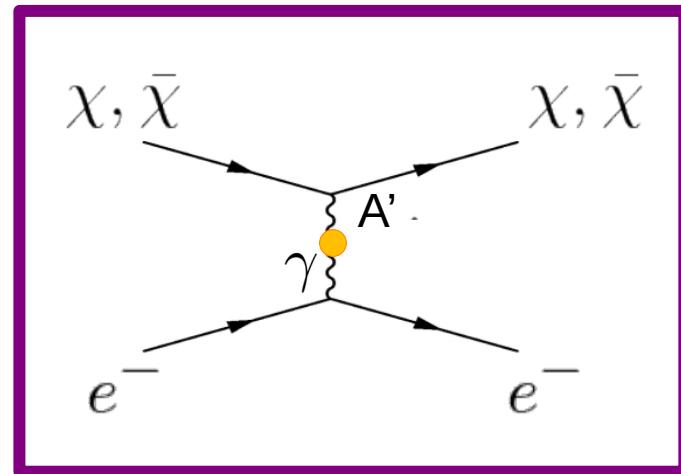
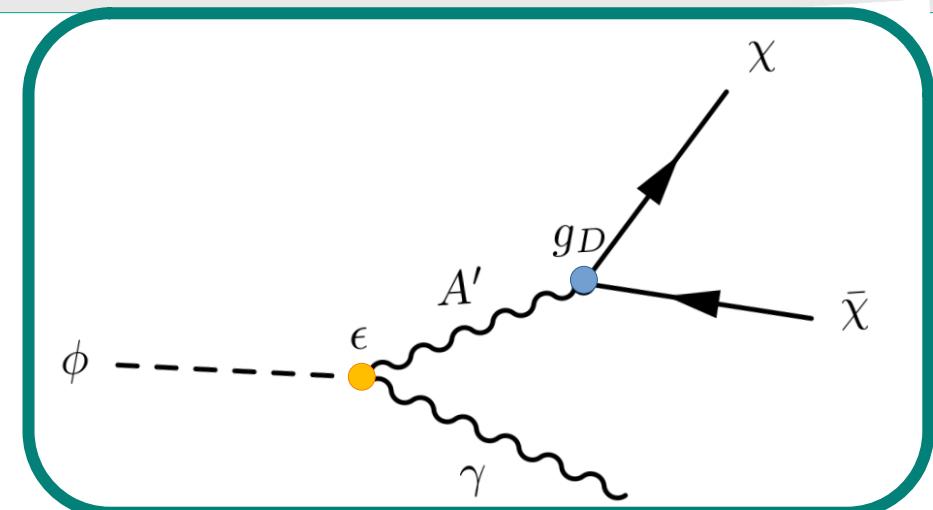
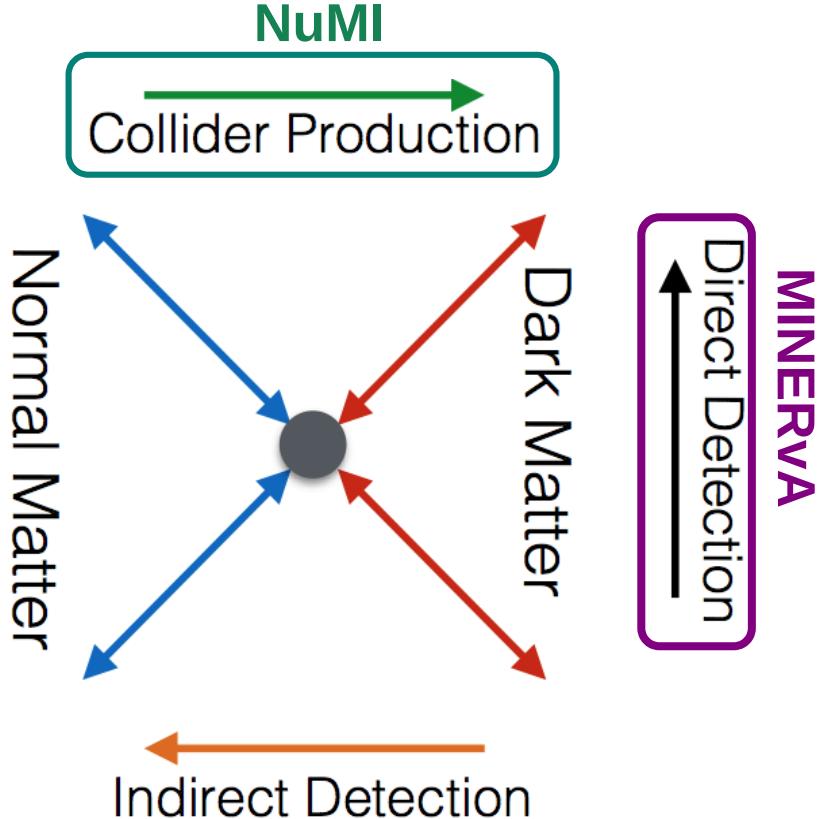
ABSTRACT: We survey the sensitivity of past and present neutrino experiments to MeV-GeV scale vector portal dark matter and find that these experiments possess novel sensitivity that has not yet fully explored. Taking $\alpha_D = 0.1$ and a dark photon to dark matter mass ratio of three, the combined recast of previous analyses of BEBC and a projection of NO ν A's sensitivity are found to rule out the scalar thermal target for dark matter masses between 10 MeV to 100 MeV with existing data, while CHARM-II and MINER ν A place somewhat weaker limits. These limits can be dramatically improved by off-axis searches using the NuMI beamline and the MicroBooNE, MiniBooNE or ICARUS detectors, and can even begin to probe the Majorana thermal target. We conclude that past and present neutrino facilities can search for light dark matter concurrently with their neutrino program and reach a competitive sensitivity to proposed future experiments.

Hunt for sub-GeV dark matter at neutrino facilities: A survey of past and present experiments. Buonocore, L. and Frugiuele, C. and deNiverville, P. PRD 102, 035006 (2020).



2. Neutrino and dark matter

Direct detection of accelerator produced DM in proton beamline



Hadron and meson production at NuMI energies (Pythia8)

$$p + p \rightarrow \pi^\pm, K^\pm, \pi^0, \eta, \dots$$

1) **p+p** collision, one proton belongs to the **120 GeV** beam and the other one is at rest as a fix target (**0 GeV**).

2) Pythia8 classify the processes in the physics scenario. In this part we evaluate **hard** and **soft QCD**.

3) **HardQCD** gives better agreement with the production^{1,2,3}

Prod. per p+p

π^+	4.28
π^-	3.57
K^+	0.41
K^-	0.28
π^0	4.01
η	0.53

1-<http://hal.in2p3.fr/in2p3-00021835>

2 - arXiv 1809.06388

3 - arXiv 1912.09346)

Dark matter flux

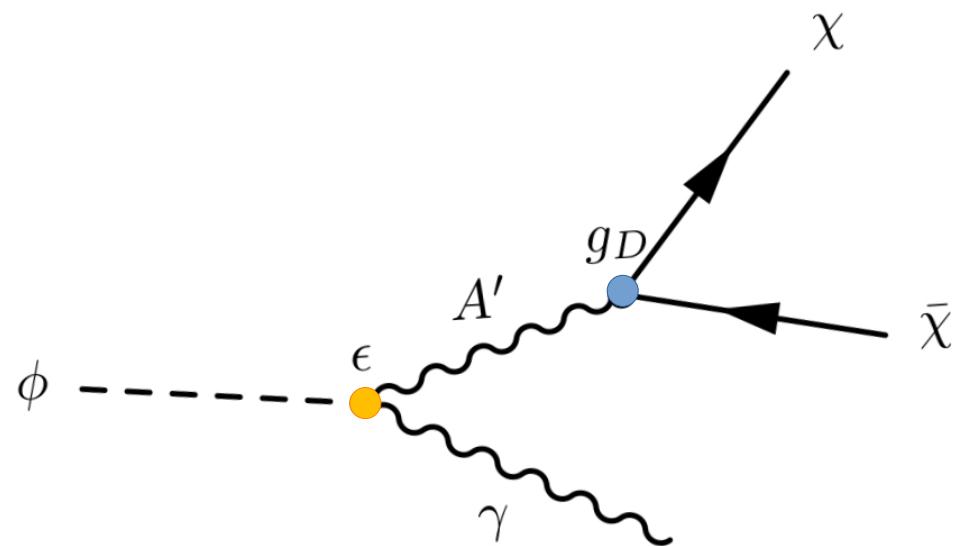
$$p + p \rightarrow \pi^\pm, K^\pm, \boxed{\pi^0, \eta, \dots}$$

$$(1) \phi = \{\pi^0, \eta\} \rightarrow \gamma A'$$

$$(2) A' \rightarrow \chi \bar{\chi}$$

$$\boxed{\pi^0, \eta \rightarrow \gamma \chi \bar{\chi}}$$

$$\mathcal{L}_{A'} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \boxed{\frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu}}$$
$$\mathcal{L}_\chi = i g_D A'^\mu J_\mu^\chi + \partial_\mu \chi^\dagger \partial^\mu \chi - m_\chi^2 \chi^\dagger \chi$$



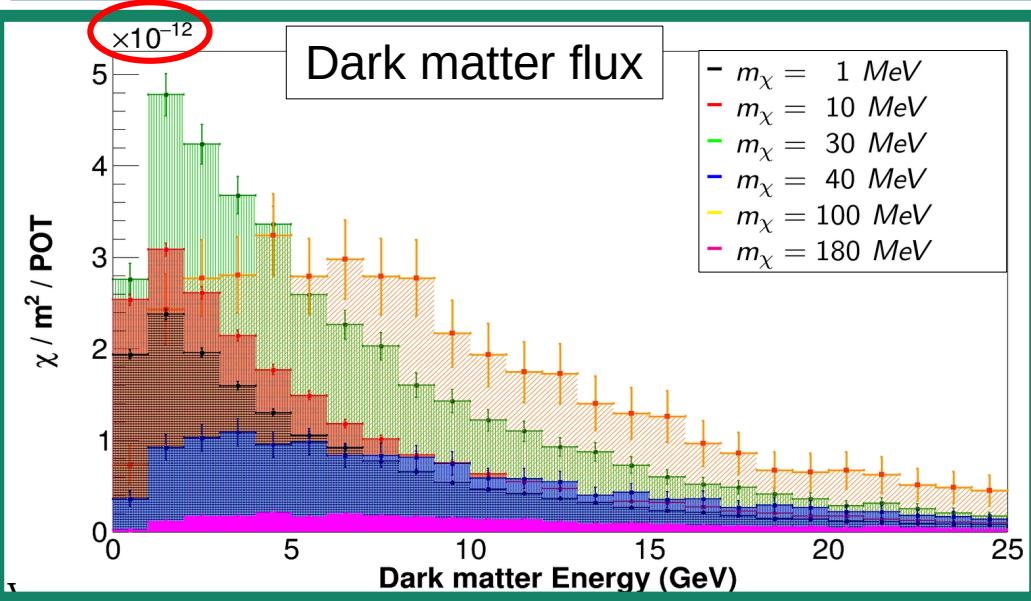
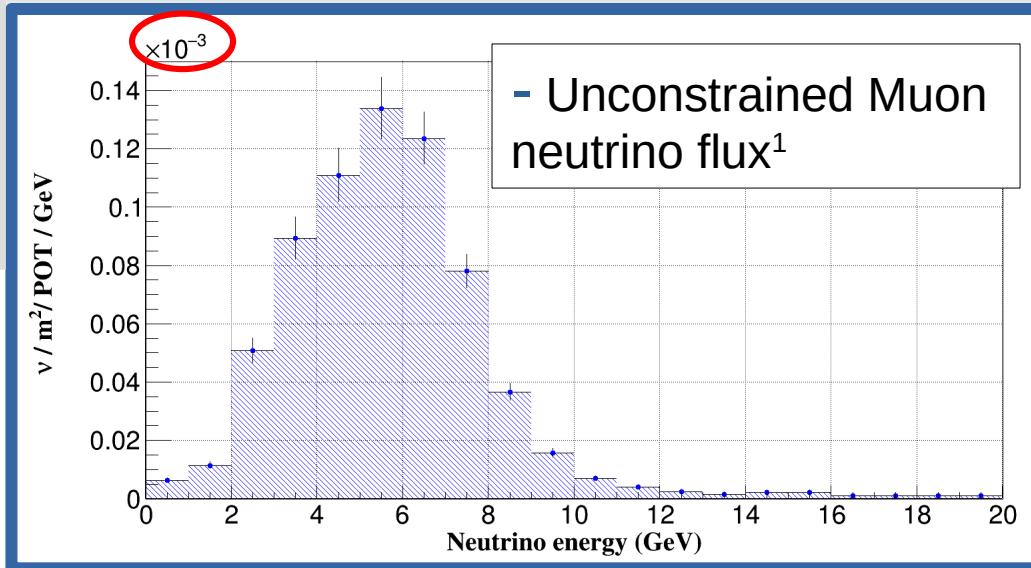
Production of neutrino and dark matter fluxes (Pythia8)

$$p + p \rightarrow \pi^{\pm}, K^{\pm}, \pi^0, \eta, \dots$$

$$\pi^{\pm}, K^{\pm}, \mu^{\pm} \rightarrow \nu_{\mu}, \bar{\nu}_{\mu}, \nu_e, \bar{\nu}_e$$

$$\pi^0, \eta \rightarrow \gamma \chi \bar{\chi}$$

[1] Constraint of the MINERvA medium energy neutrino flux using neutrino-electron elastic scattering. MINERvA collaboration, PRD.100.092001, (2019)



Event selection

- Data POT: 1.16×10^{21}
- MC p+p: 10^8

Note. The 10^8 MC does not yield a DM energy distribution. For that reason, we artificially increase the decay rates of π^0 and η .

$$Br(\pi^0 \rightarrow \gamma A') \in [10^{-9} - 10^{-8}]$$

$$Br(\eta \rightarrow \gamma A') \in [10^{-10} - 10^{-7}]$$

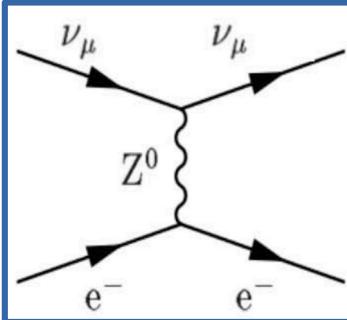
Weights

$$Br(\phi \rightarrow \gamma A') \approx 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\phi^2}\right)^3 Br(\phi \rightarrow \gamma\gamma)$$

- $Br(\pi^0 \rightarrow \gamma A') \rightarrow 0.012$
- $Br(\eta \rightarrow \gamma A') \rightarrow 0.005$
- Solid angle area of 83.6m^2 that corresponds to 5mrad ($\theta_x < 5\text{mrad}$) and a distance of 1031.7m (where MINERvA is located after the first focusing horn)
- MC p+p

Differential cross-sections

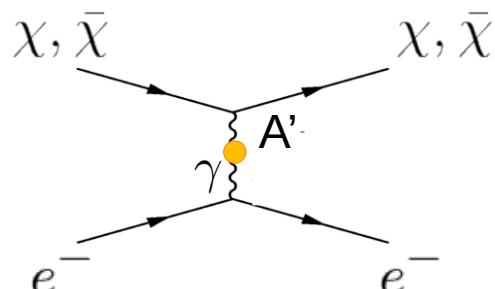
$$\pi^\pm, K^\pm, \mu^\pm \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$



$$\frac{d\sigma_{nc}(\nu_l e \rightarrow \nu_l e)}{dT_e} = \frac{2G_F^2 m_e}{\pi} \left[g_1^2 + g_2^2 (1 - \frac{T_e}{E_\nu})^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2} \right],$$

$$T_e^{max} = \frac{2E_\nu^2}{2E_\nu + m_e}$$

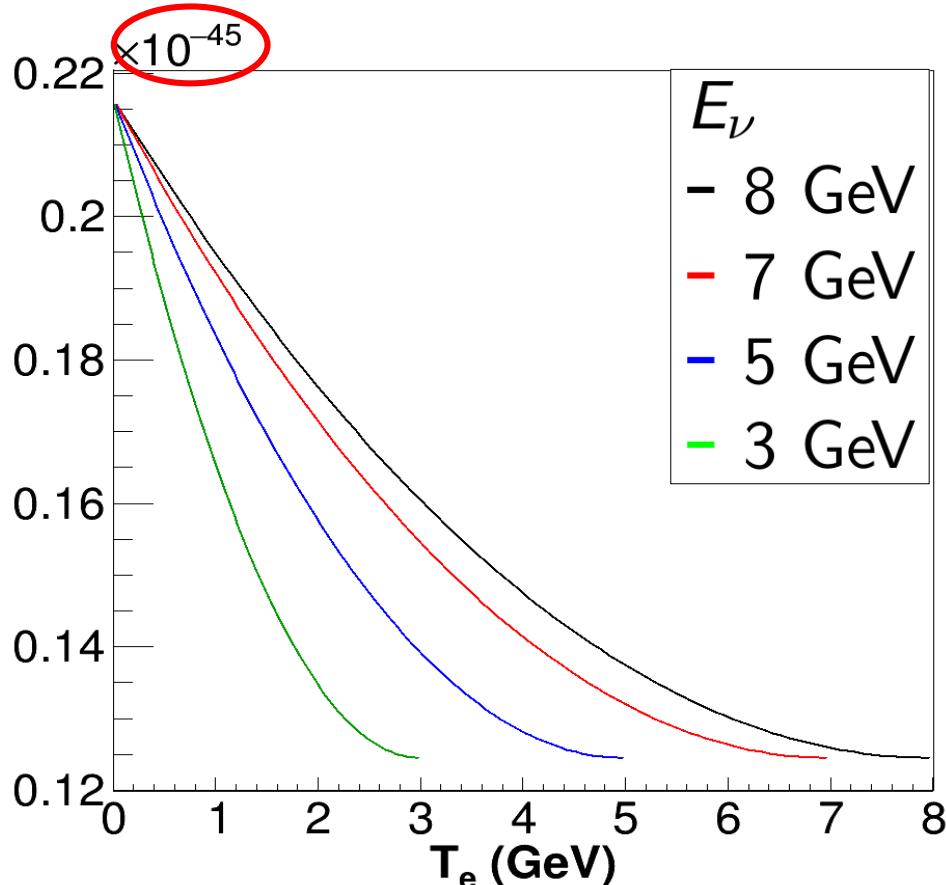
$$\pi^0, \eta \rightarrow \gamma \chi \bar{\chi}$$



$$\frac{d\sigma(\chi e \rightarrow \chi e)}{dT_e} = \frac{\epsilon^2 \alpha_D}{\alpha} \times \frac{4\pi \alpha^2 [2m_e(E_\chi^2 - E_\chi T_e) - \cancel{m_\chi^2} T_e]}{E_\chi^2 (\cancel{m_{A'}^2} + 2m_e T_e)^2}$$

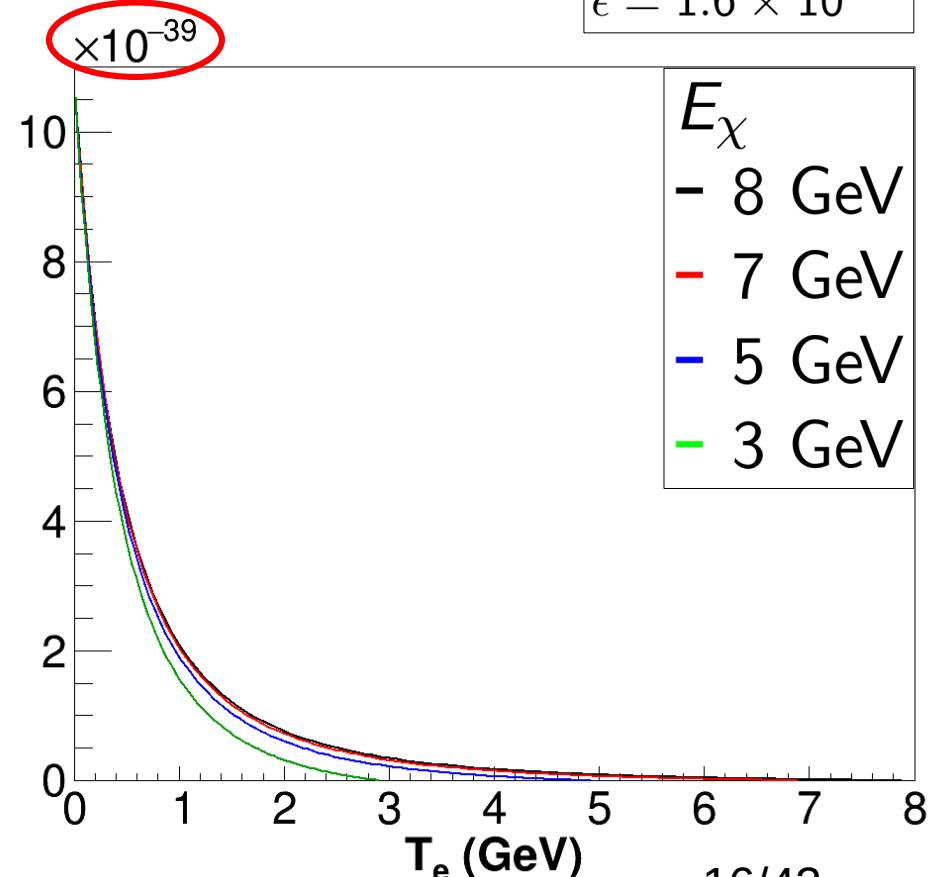
$$T_e^{max} = \frac{2E_\chi^2}{2E_\chi + \frac{m_\chi^2}{m_e}}$$

$$\frac{d\sigma(\nu_\mu e)}{dT_e}(m^2 \text{GeV}^{-1})$$



$$\frac{d\sigma(\chi e)}{dT_e}(m^2 \text{GeV}^{-1})$$

$m_\chi = 10 \text{ MeV}$
 $m_{A'} = 30 \text{ MeV}$
 $\alpha_D = 0.1$
 $\epsilon = 1.6 \times 10^{-4}$



3. Dark matter signal events

Dark matter signal events

$$\text{events} = \text{acceptance} \times \text{No. target electrons} \times \text{POT} \times \int_{0.8 \text{ GeV}}^{T_e^{\max}} \phi_\chi [1/m^2 / \text{POT}_{MC}] \frac{d\sigma(\chi e)}{dE_e} [m^2 \text{ GeV}^{-1}] dE_e$$

acceptance = 1

No. target electrons = $(1.99 \pm 0.03) \times 10^{30}$

POT = 1.16×10^{21}

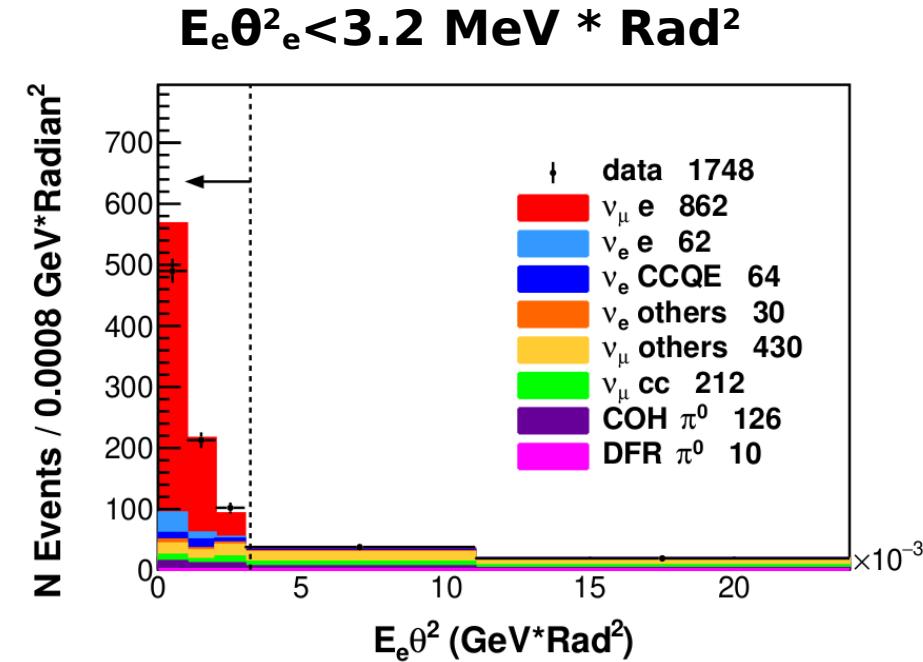
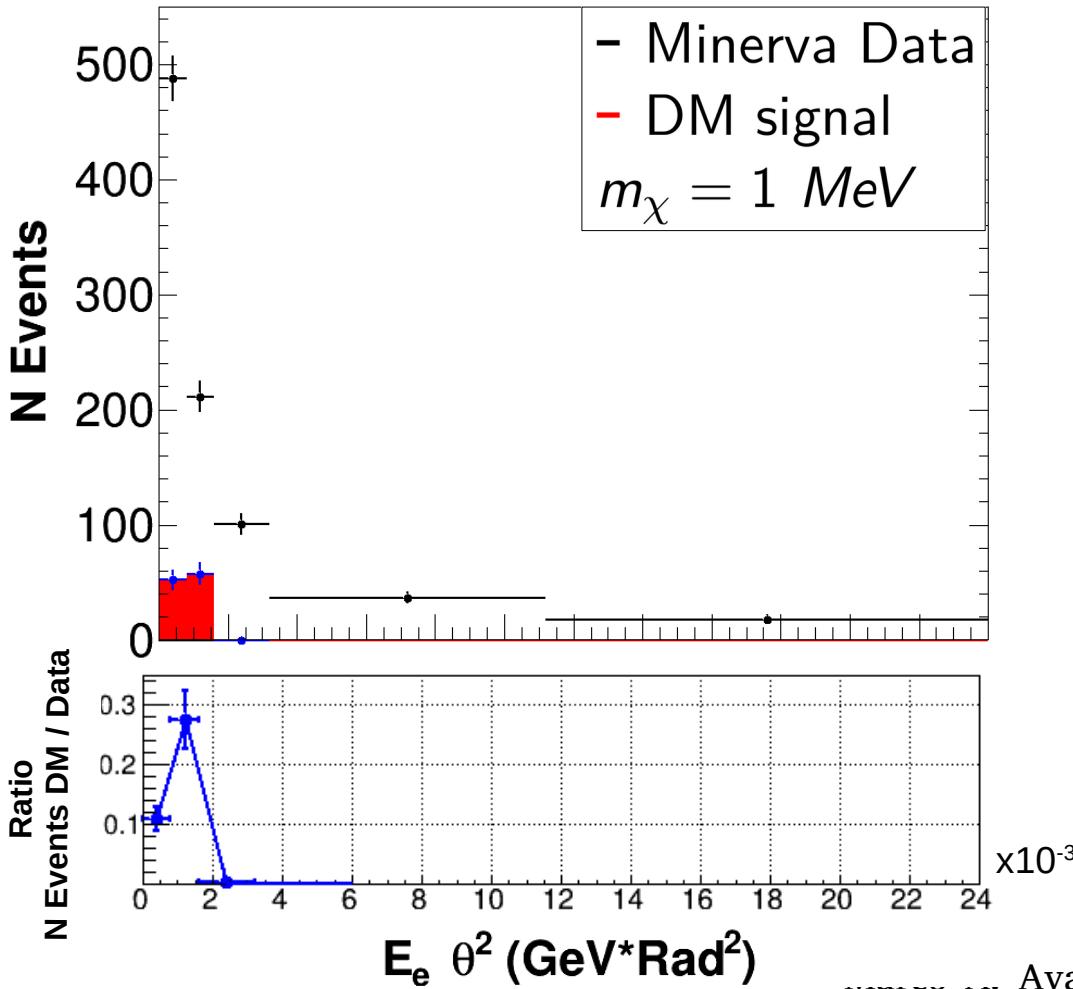
$m_\chi = 1 \text{ MeV}$, $Y = 2 \times 10^{-11}$
Events = 111

Analysis Cuts¹

Electron recoil energy cut:
 $E_e > 0.8 \text{ GeV}$

Electron energy times the square of the electron angle with respect to the beam:
 $E_e \theta_e^2 < 3.2 \text{ MeV} * \text{Rad}^2$

The electron energy times the square of the electron angle with respect to the beam



4. Analysis of toy χ^2

χ^2 analysis

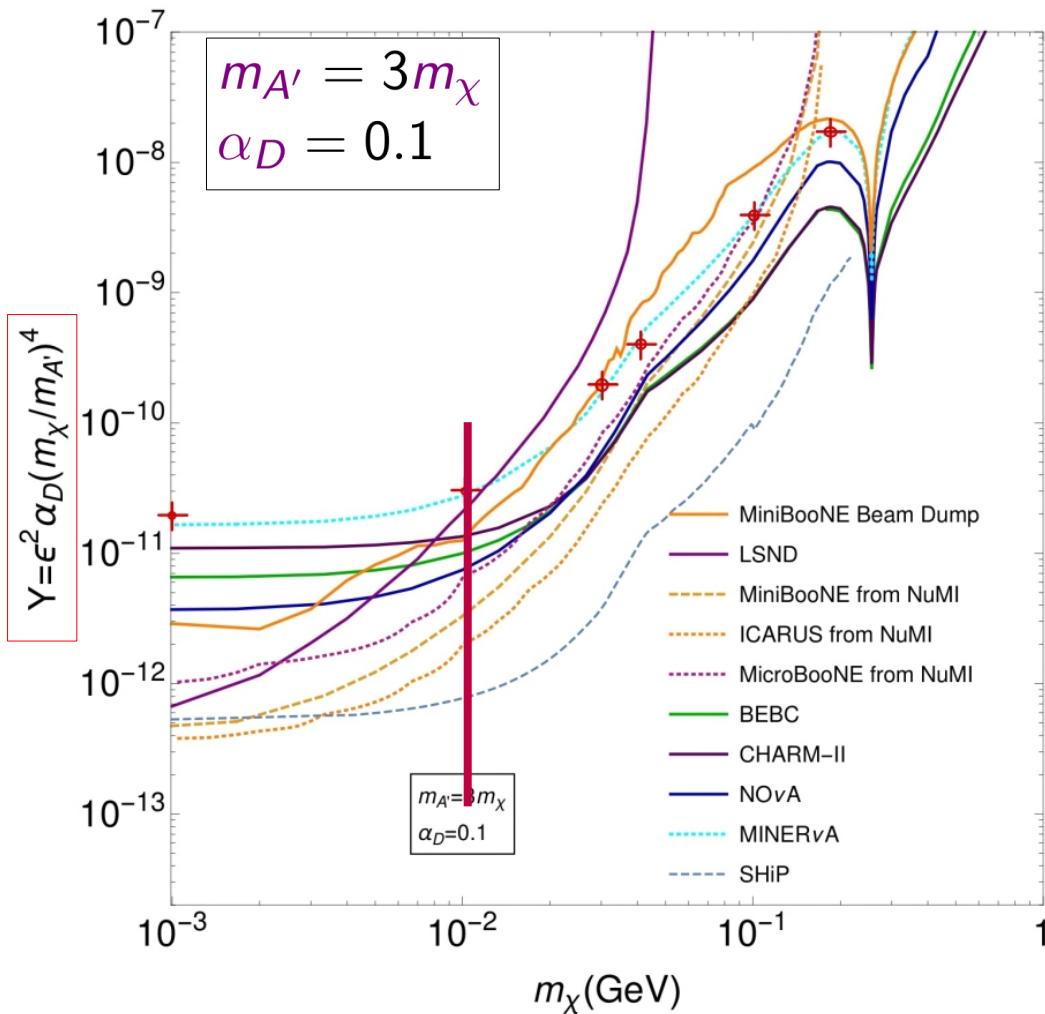
The following part correspond to a simple analysis of χ^2 to estimate the sensitivity of MINERvA, where correlation between bins is not considered. For the analysis, we set a **normalization to 100 events** for data and MC. The **MC prediction** corresponds to the sum of **1) $\nu_\mu + e$, 2)background($!(\nu_\mu+e)$) and 3) DM signal.**

χ^2 is given by:

$$\chi^2 = \sum_{i_{bin}} \left(\frac{M_i^{true} - M_i^{data}}{\sigma_i} \right)^2$$

where M^{true} and M^{Data} correspond to the value of the i-th bin for MC and data, respectively, σ_i is the error associated with the data of the i-th bin.

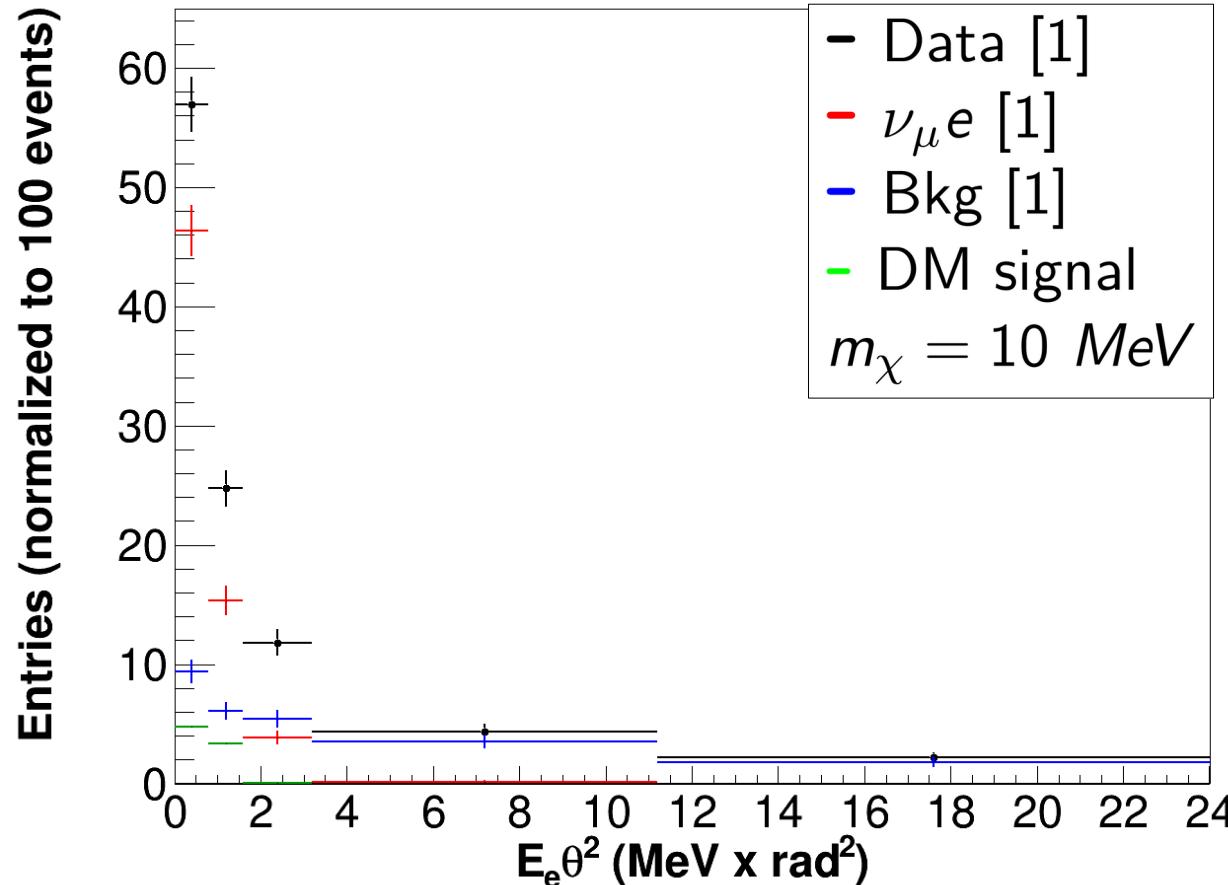
Values scanned in the space parameter



For a DM mass of 10MeV, the Y values explored were:

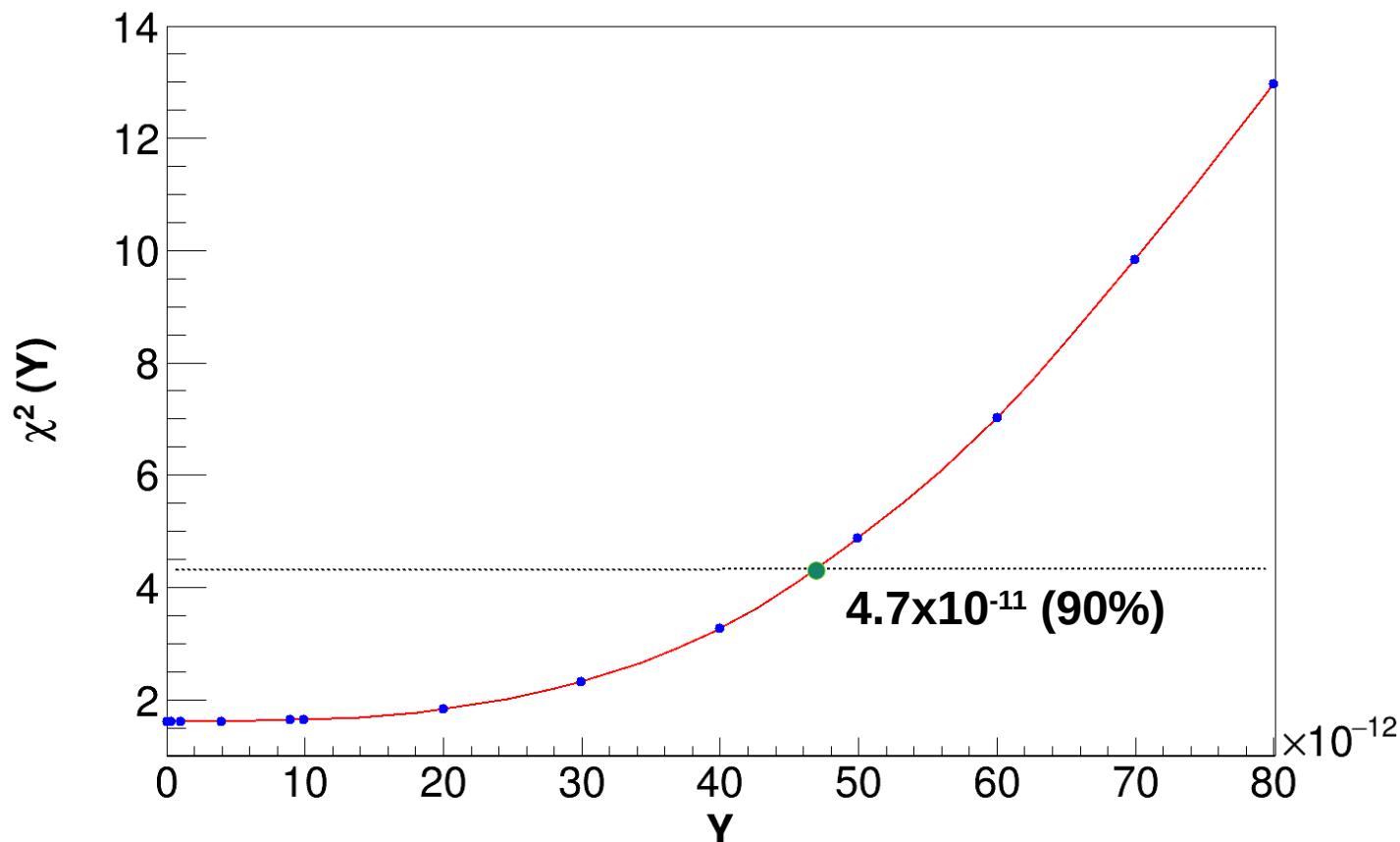
Y
1E-13
4E-13
1E-12
4E-12
9E-12
1E-11
2E-11
3E-11
4E-11
5E-11
6E-11
7E-11
8E-11
1E-10

Example of $E_e \theta^2$ distribution for $Y=3 \times 10^{-11}$

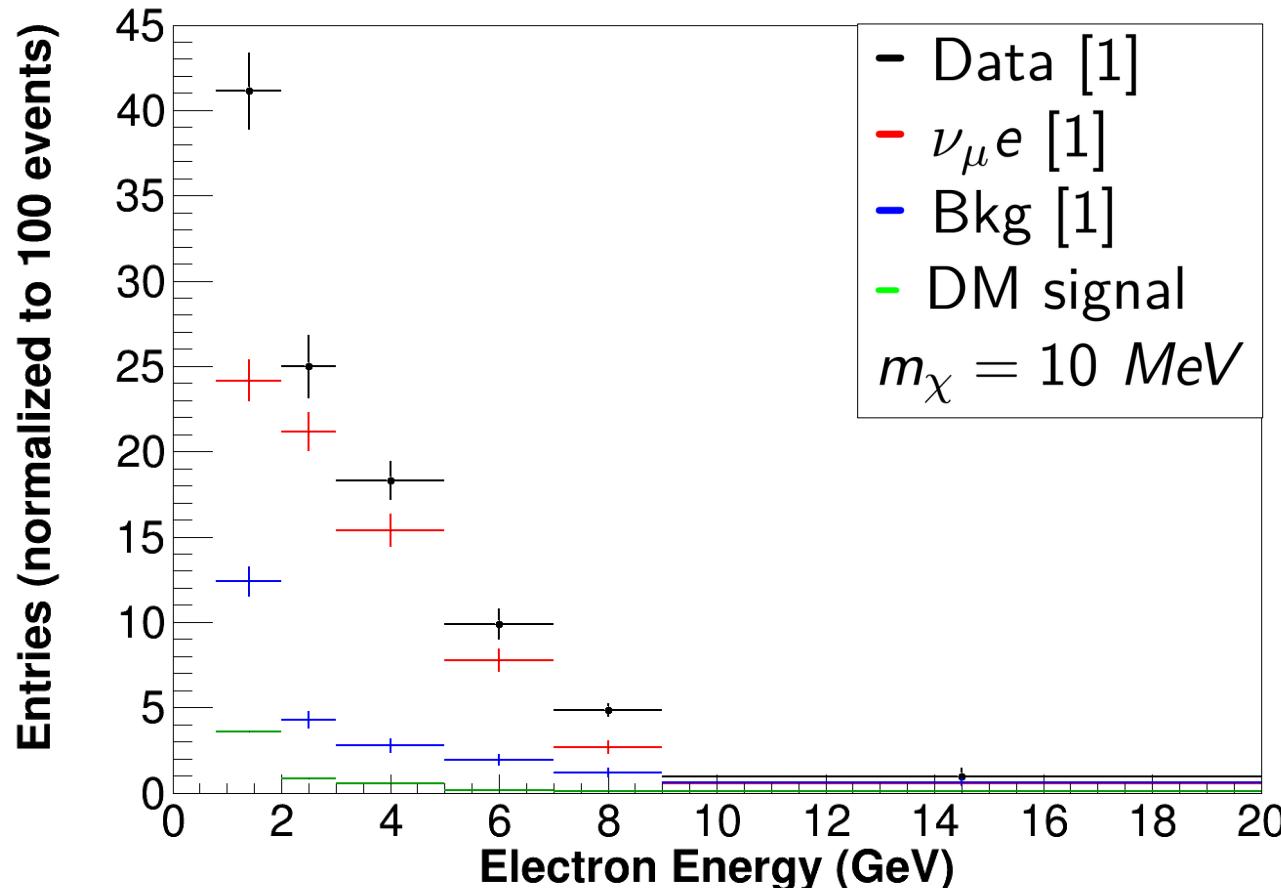


χ^2 distribution for $E\theta^2$

$$\chi^2 = \sum_{i_{bin}} \left(\frac{M_i^{true} - M_i^{data}}{\sigma_i} \right)^2$$

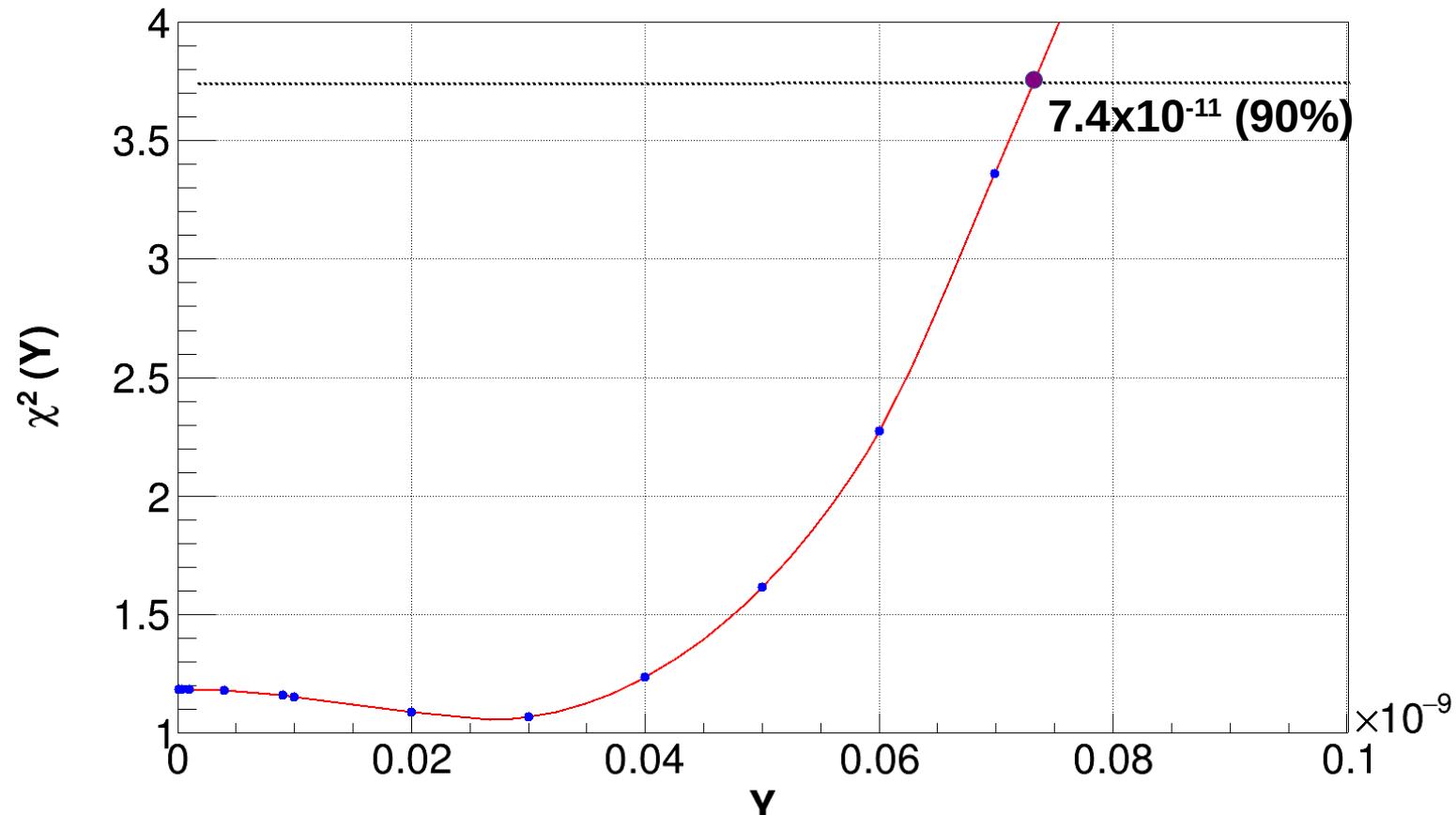


Example of the **electron recoil energy** distribution for $\Upsilon = 3 \times 10^{-11}$

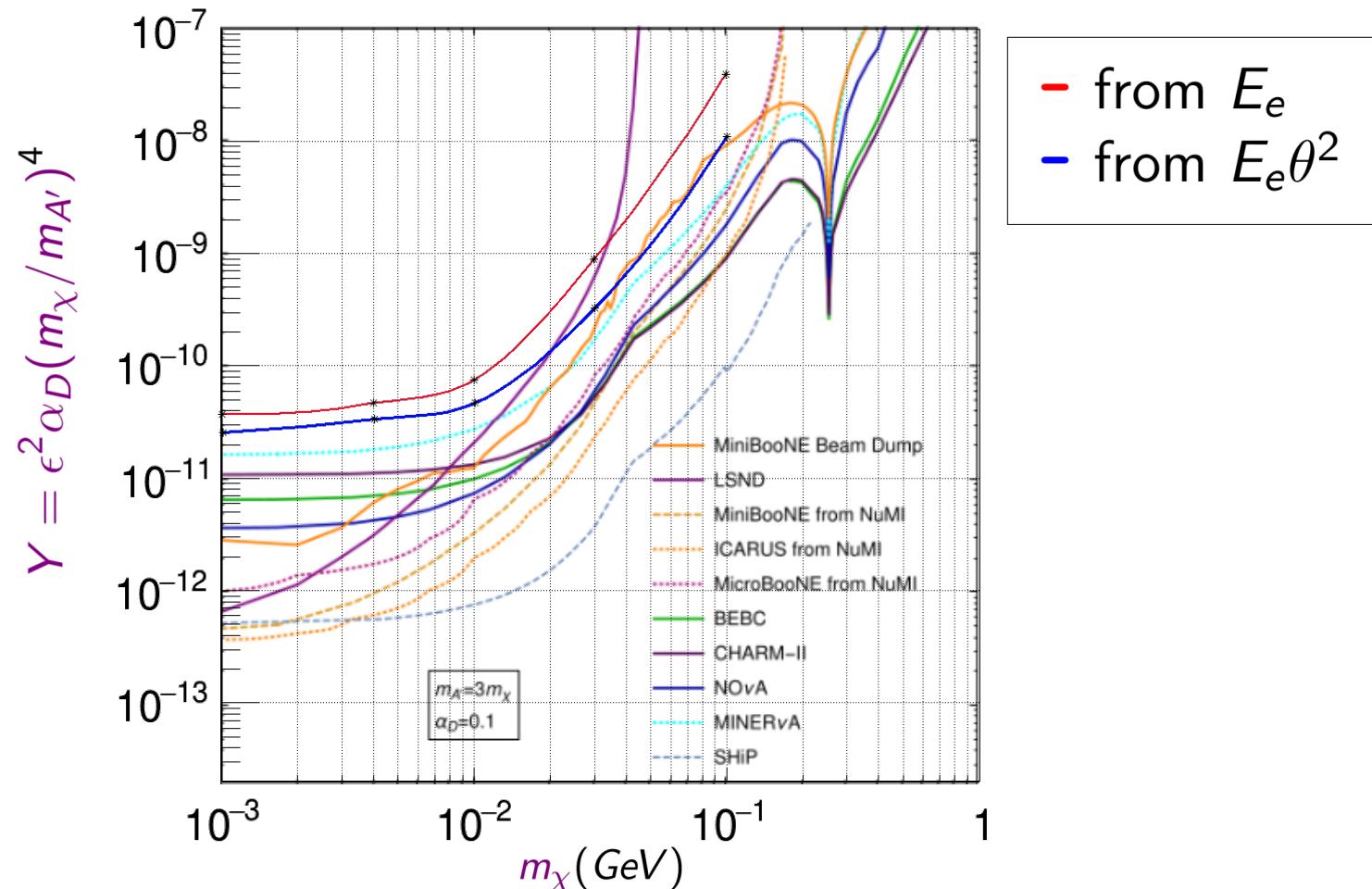


χ^2 distribution for E_e

$$\chi^2 = \sum_{i\text{bin}} \left(\frac{M_i^{true} - M_i^{data}}{\sigma_i} \right)^2$$



Values scanned in the space parameter



Summary

- The implementation of this toy χ^2 that uses the shape distribution of MINERvA signal can constrain the accepted region of the Light Dark Matter parameters. This first estimate is in accordance with what is reported by deNiverville et al.

Status and next steps to implement LDM in GENIE v3

- For the exploration and training, I got the $\nu_\mu + e$ and $\nu_e + e$ scattering n-tuples in **CH** and the reproduce the $E\theta^2$ and E_e distributions [1] (similar for the boosted dark matter). For me, the most immediate way to implement the light dark matter model is through the **weight** of the **differential cross-section of $\nu_\mu + e$ scattering** to approach it to the **differential cross-section of DM + e scattering** and use the **DM flux** obtained with Pythia8 (as input).

Backup

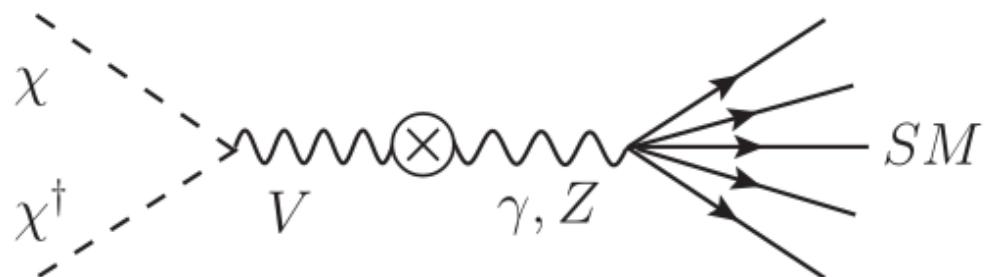
$$\langle\sigma\nu\rangle_{ann} = \langle\sigma\nu\rangle_{ann}(\epsilon, \alpha_D, m_\chi, m_{A'})$$

P. deNiverville,
PRD 84, 075020 (2011)

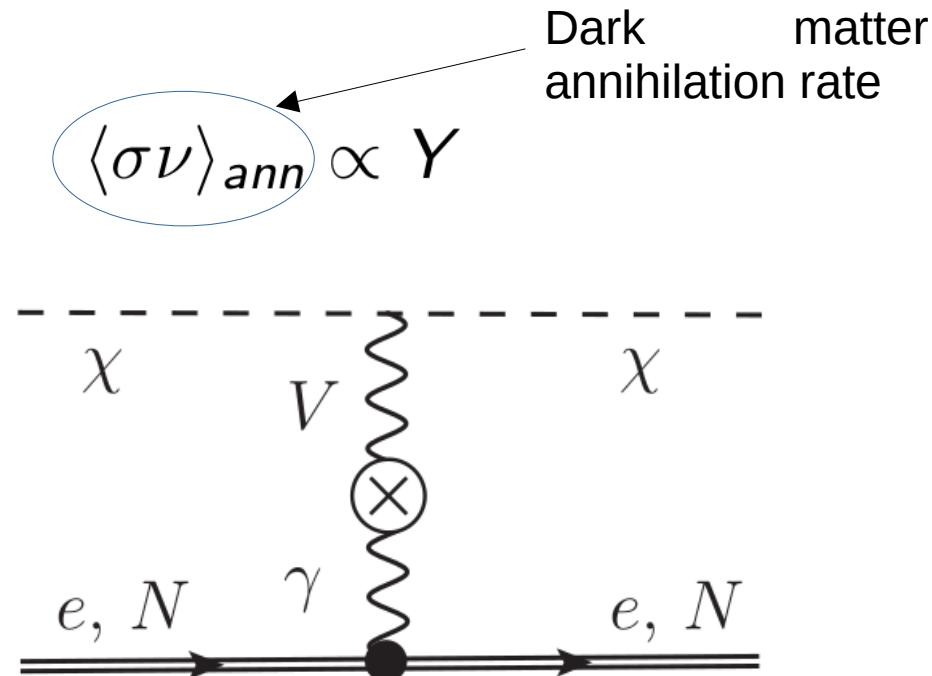
$$\langle\sigma\nu\rangle_{ann} \simeq 3 \times 10^{-27} \text{ cm}^2 \times \left(\frac{\epsilon^2 \alpha_D}{\alpha} \langle\nu^2\rangle \right) \times \left(\frac{\text{MeV}}{m_\chi} \right)^2 \times \sqrt{1 - \frac{m_e^2}{m_\chi^2}} \left(\frac{4m_\chi^2}{4m_\chi^2 - m_{A'}^2} \right)^2$$

With $\nu \sim 0.3$ at freeze-out, this mass scale imposes the following restriction on the model parameters:

$$\frac{Y}{m_\chi^2} \propto 4 \times 10^{-8}$$



Tree-level annihilation of scalar dark matter in the $U(1)_D$



Scattering of scalar dark matter in the $U(1)_D$

Dark matter flux

Pythia8

- (1) $p + p \rightarrow \pi^0, \eta, \dots$
- (2) $\phi = \{\pi^0, \eta\} \rightarrow \gamma + V$
- (3) $V \rightarrow 2\chi$

$$Br_{\phi \rightarrow \gamma V} \approx 2\epsilon^2 \left(1 - \frac{m_V^2}{m_\phi^2}\right)^3 Br_{\phi \rightarrow \gamma\gamma}$$

$$m(\pi^0) = 135 \text{ MeV}$$

$$m(\eta) = 538 \text{ MeV}$$

$Br_{\pi^0 \rightarrow \gamma V}$

$Br_{\eta \rightarrow \gamma V}$

$$m_V = 3m_\chi$$
$$\alpha_D = 0.1$$

$$\epsilon$$

m_V (MeV)	m_χ (MeV)
3	1
30	10
90	30
120	40
300	100
540	180

Event selection

- Data POT: 1.16×10^{21}
- MC p+p: 10^8

Analysis Cuts

- Electron energy cut

$$E_e > 0.8 \text{ GeV}$$

- Electron energy times the square of the electron angle with respect to the beam

$$E_e \theta_e^2 < 3.2 \text{ MeV} * \text{Rad}^2$$

Weights

$$Br(\phi \rightarrow \gamma A') \approx 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\phi^2}\right)^3 Br(\phi \rightarrow \gamma\gamma)$$

- $Br(\pi^0 \rightarrow \gamma A') \in [10^{-9} - 10^{-8}]$

- $Br(\eta \rightarrow \gamma A') \in [10^{-10} - 10^{-7}]$

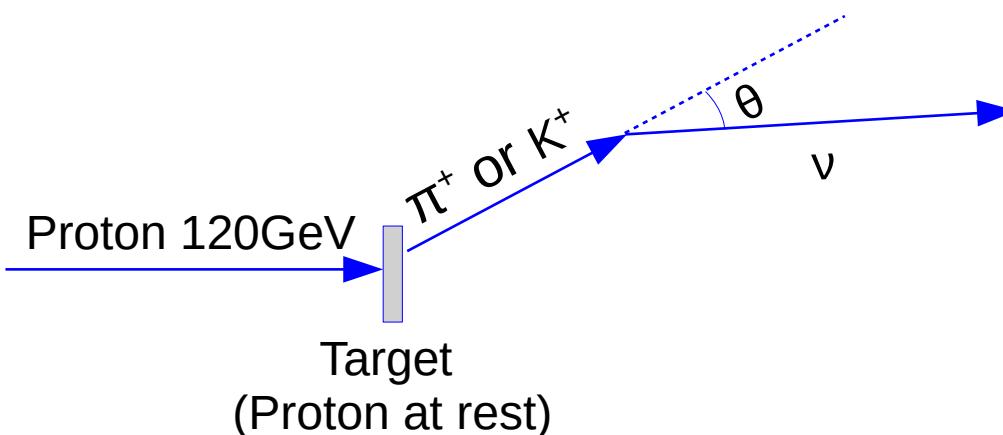
- Solid angle area of 83.6 m^2 that corresponds to 5 mrad ($\chi < 5 \text{ mrad}$) and a distance of 1031.7 m (where MINERvA is located after the first focusing horn)
- MC p+p

Neutrino flux

$$p + p \rightarrow \boxed{\pi^\pm, K^\pm}, \pi^0, \eta, \dots$$

$$\pi^\pm, K^\pm, \mu^\pm \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

Daughter particles focusing
(charged π or kaon and also the muons from its decay)



$$\theta = \cos^{-1} \left(\frac{\vec{p} \cdot \vec{p}_\nu}{|\vec{p}| |\vec{p}_\nu|} \right)$$

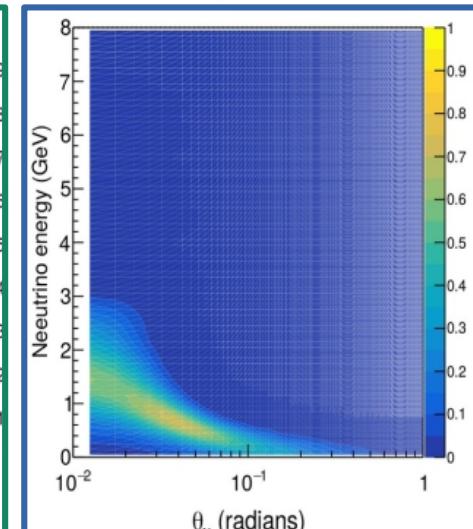
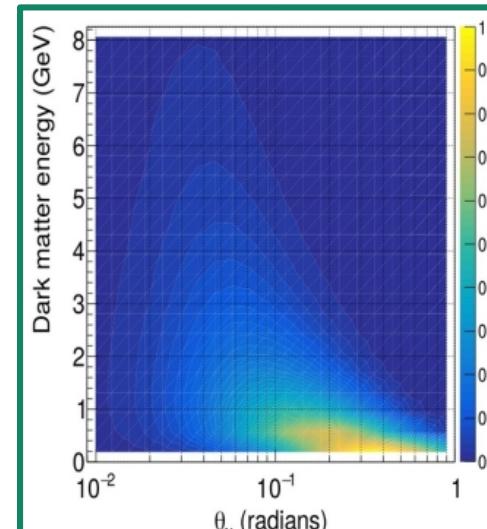
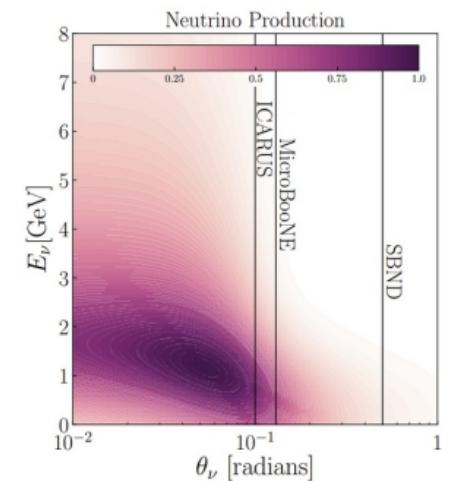
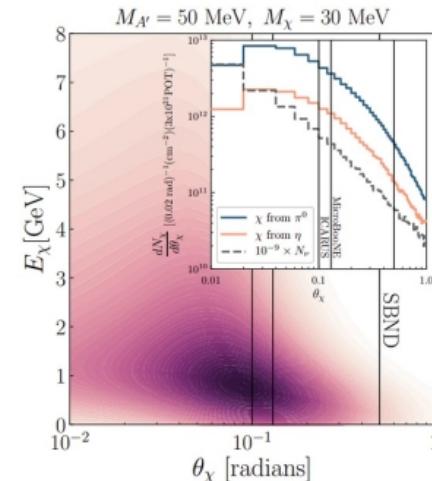
Validation - off-axis region

$p + p \rightarrow \pi^\pm, K^\pm, \boxed{\pi^0, \eta, \dots}$

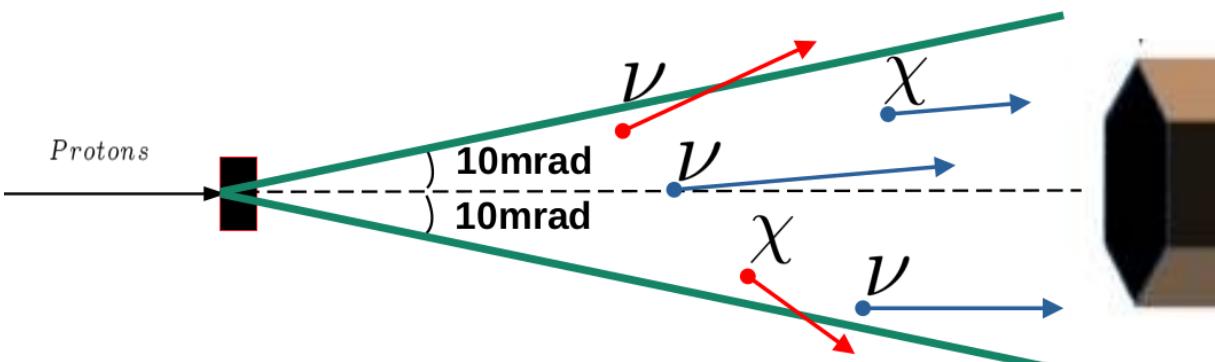
$\pi^\pm, K^\pm, \mu^\pm \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

$\boxed{\pi^0, \eta} \rightarrow \gamma \chi \bar{\chi}$

Dark tridents at off-axis LAr neutrino detectors



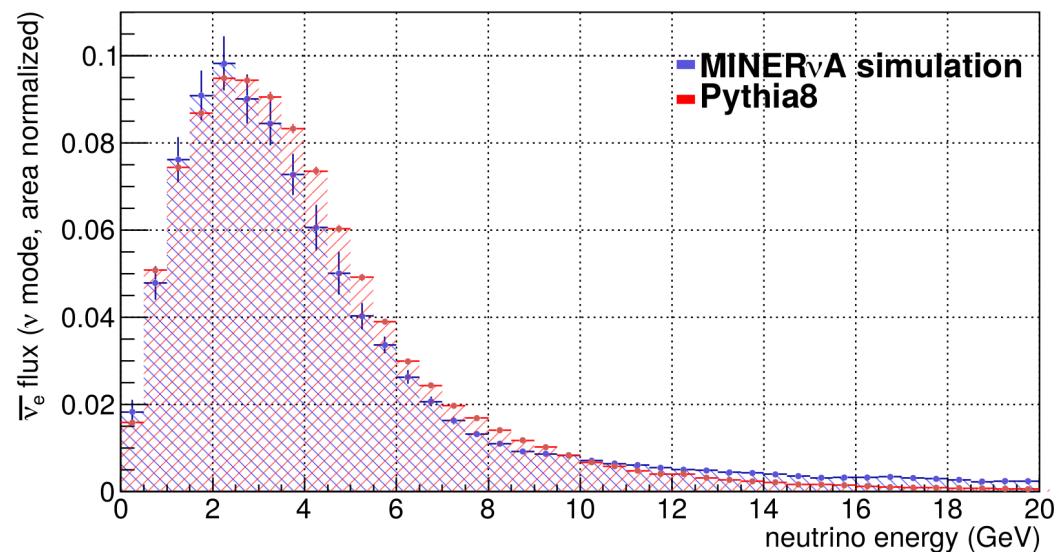
Validation - on-axis region



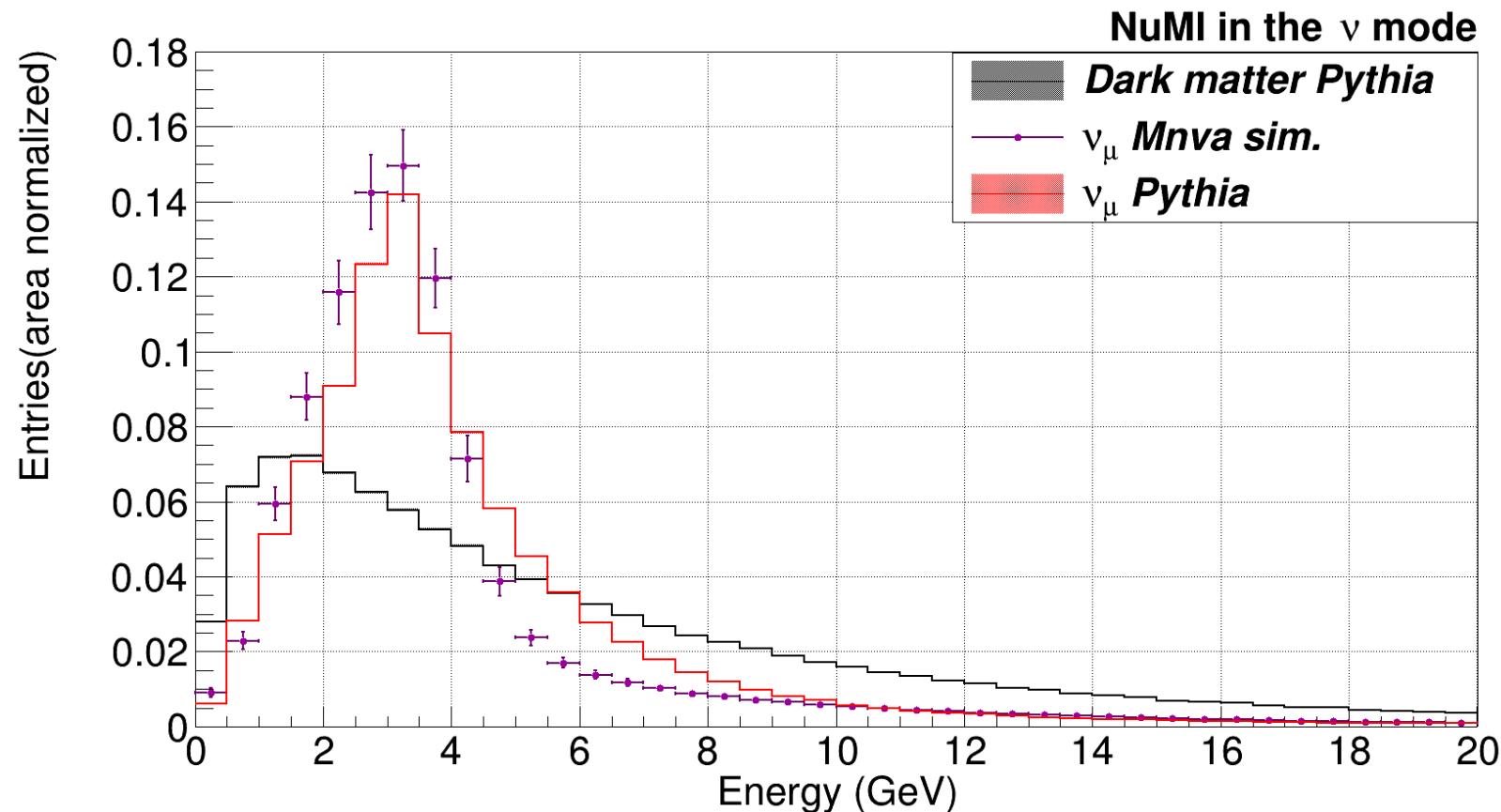
MINERvA TDR

NOvA is Off-axis in the region of 12-14mrad

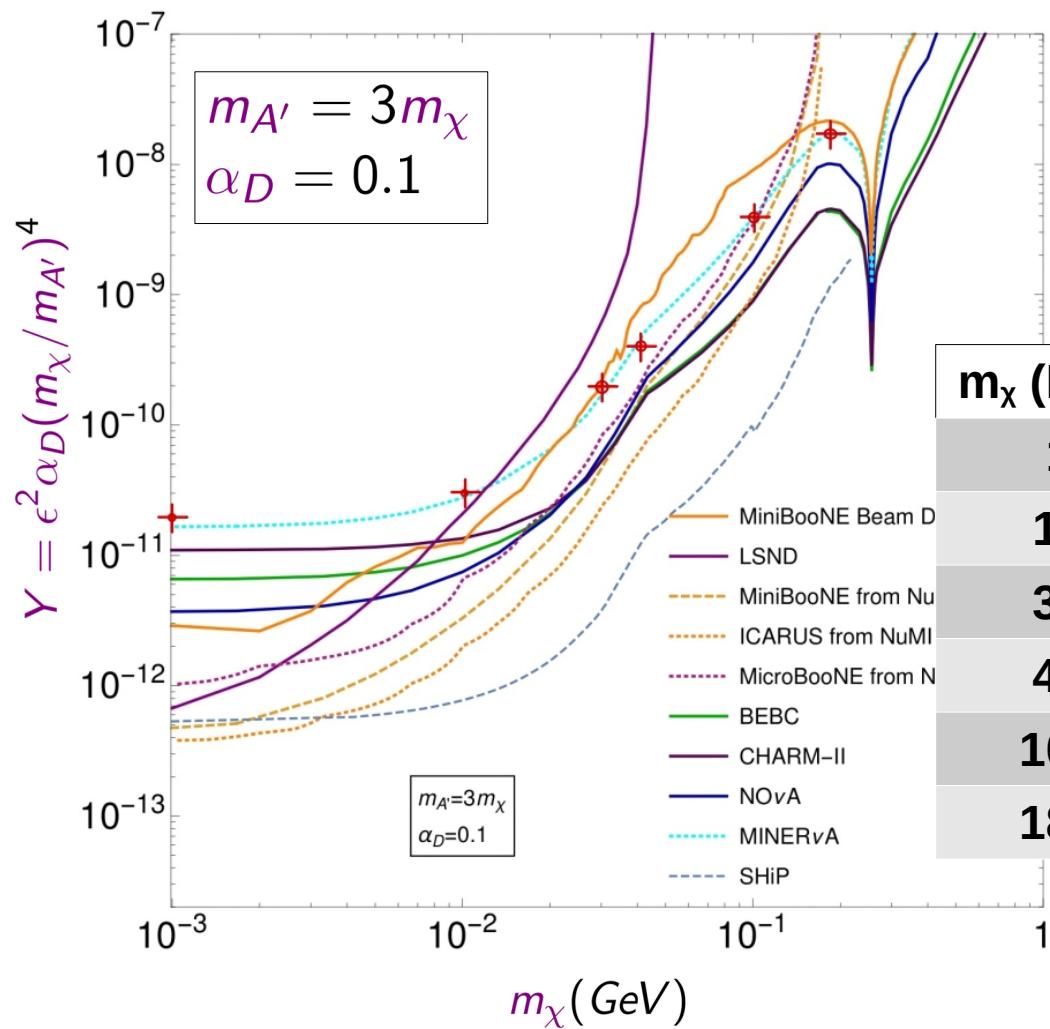
- **On-axis:** $\theta < 10\text{mrad}$ (0.57°)
- **Off-axis:** $\theta > 10\text{mrad}$



ν and DM fluxes in MINERvA (LE)



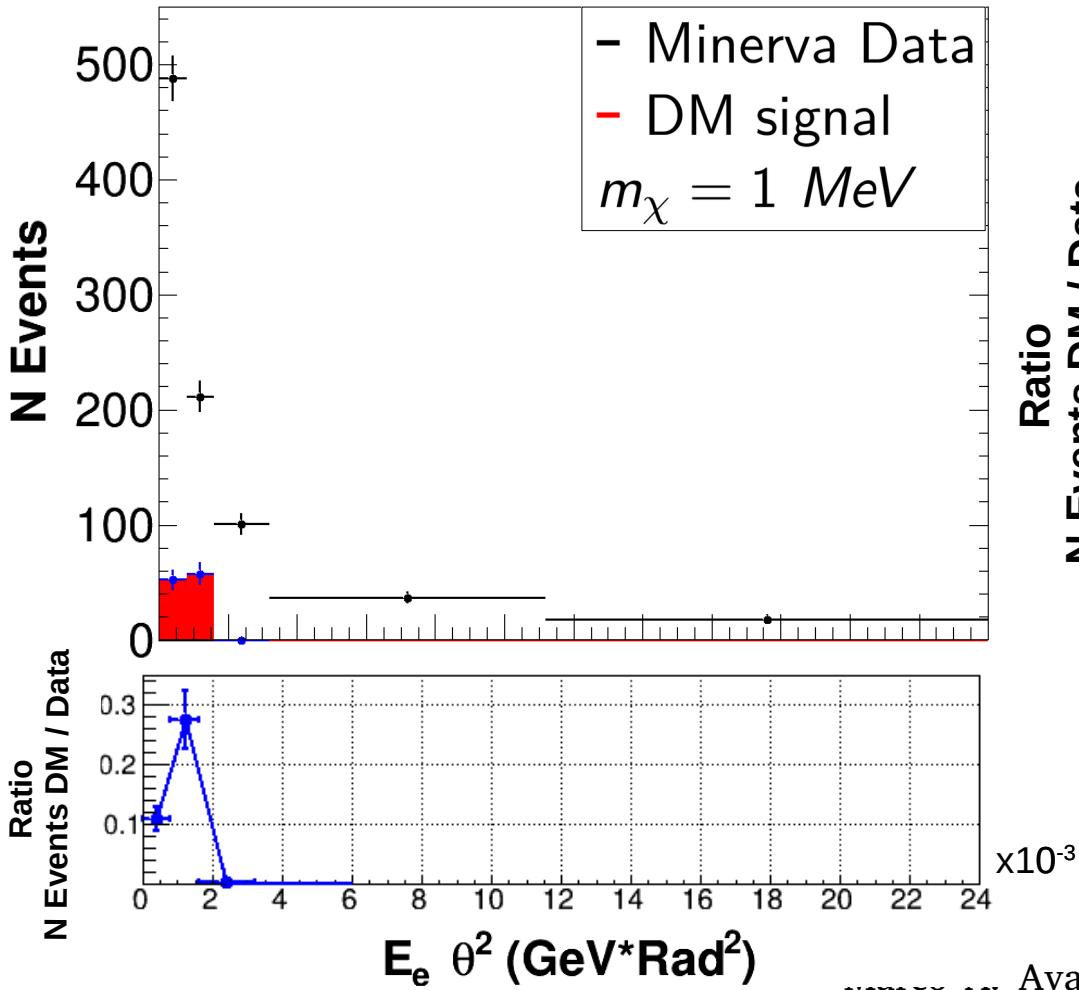
The parameter space



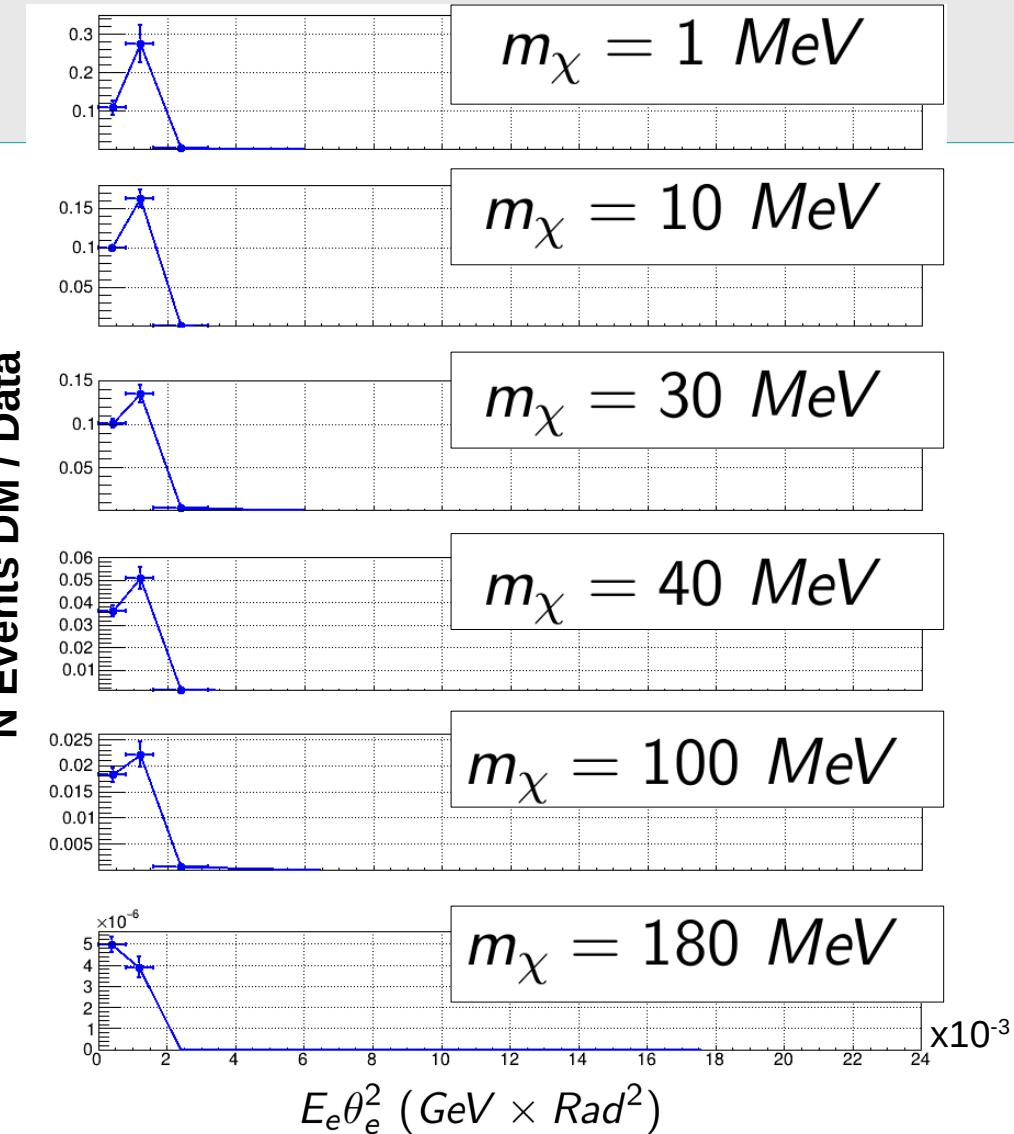
$$Br(\phi \rightarrow \gamma A') \approx 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\phi^2}\right)^3 Br(\phi \rightarrow \gamma\gamma)$$

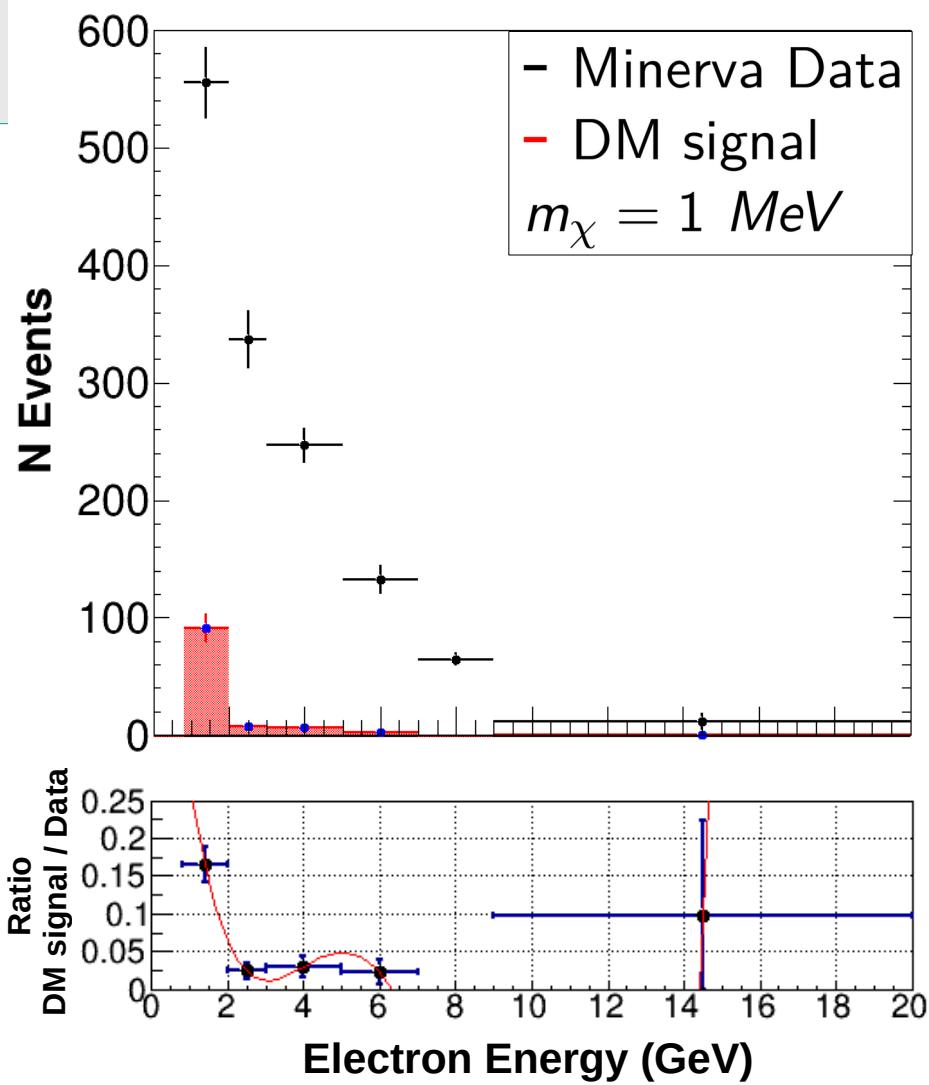
$m_\chi \text{ (MeV)}$	Y	$\epsilon = \sqrt[9]{\frac{Y}{\alpha_D}}$	$Br(\pi^0 \rightarrow \gamma V)$	$Br(\eta \rightarrow \gamma V)$
1	2×10^{-11}	1.3×10^{-4}	3.2×10^{-8}	1.3×10^{-8}
10	3×10^{-11}	1.6×10^{-4}	4.2×10^{-8}	1.9×10^{-8}
30	2×10^{-10}	4.0×10^{-4}	5.6×10^{-8}	1.2×10^{-7}
40	4×10^{-10}	5.7×10^{-4}	6.0×10^{-9}	2.2×10^{-7}
100	3×10^{-9}	1.6×10^{-3}	-	6.5×10^{-7}
180	2×10^{-8}	4.0×10^{-3}	-	3.1×10^{-10}

The electron energy times the square of the electron angle with respect to the beam

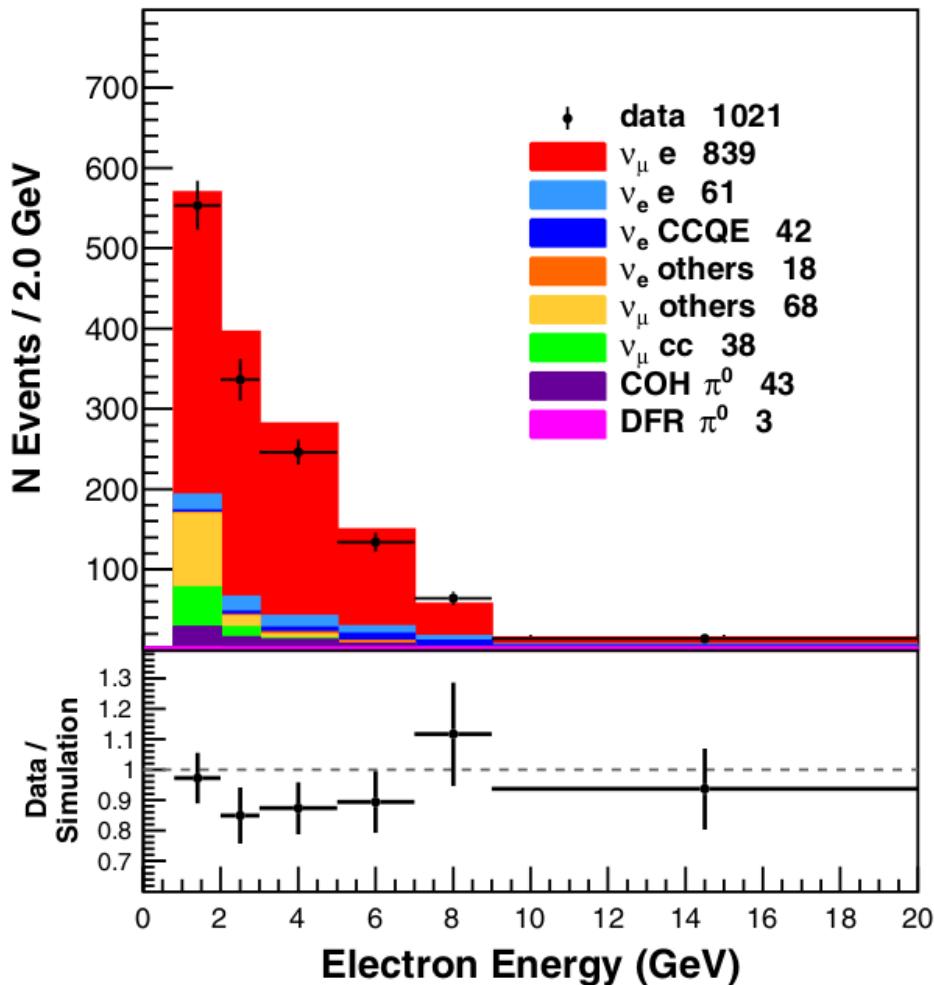


Ayala-Torres





Ratio DM signal/background Events
after the cut $E\theta^2 < 0.0032 \text{ GeV} \times \text{rad}^2$



Ratio DM signal/background Events after the cut $E\theta^2 > 0.0032 \text{ GeV} \times \text{rad}^2$

