Boosted Dark Matter Search with ICARUS at Gran Sasso

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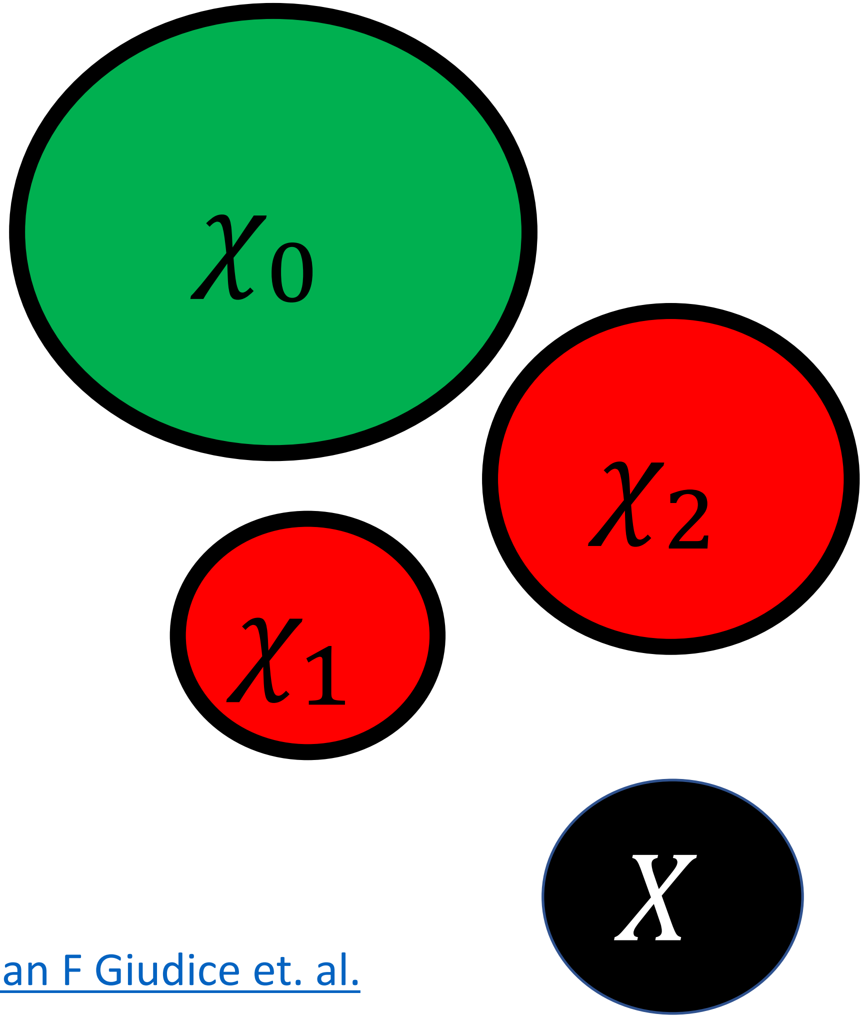
Example of DM Multi-Component Search: Adding a New U(1)′ Gauge Symmetry

- This new U(1)′ (in our study) will have a new gauge boson **X (dark photon),** and a dark sector containing 3 particles
- χ_0 represents the abundant dark matter
- χ_1 represents the DM particle that can come from χ_0 self-annihilation in the galactic center, the galactic DM halo, etc.
  - $m_1 \ll m_0;\ \gamma_1 = m_0/m_1$
- χ_2 represents an excited state of χ_1, which can decay



Gian F Giudice et. al.

The Free Parameters

- Adding BDM to the Lagrangian of the Standard Model, we have the terms:

Gian F Giudice et. al.

$$L_{density} \sim L_{SM} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 B_\mu - \frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 B_\mu + \frac{1}{2}m_X^2 B_\mu B^\mu$$

Non-Flavor Changing → g_{11}: Can be highly suppressed ~ 0

Kinetic Mixing Term → ϵ

Flavor Changing → g_{12}: Suppressing $g_{11} \rightarrow g_{12} \sim 1$

Dark Photon Mass Term → m_X

Parameters of Interest

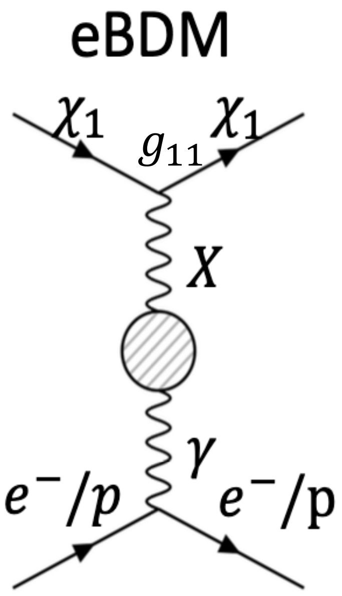
Parameter Space Variables (ϵ, m_X)

And

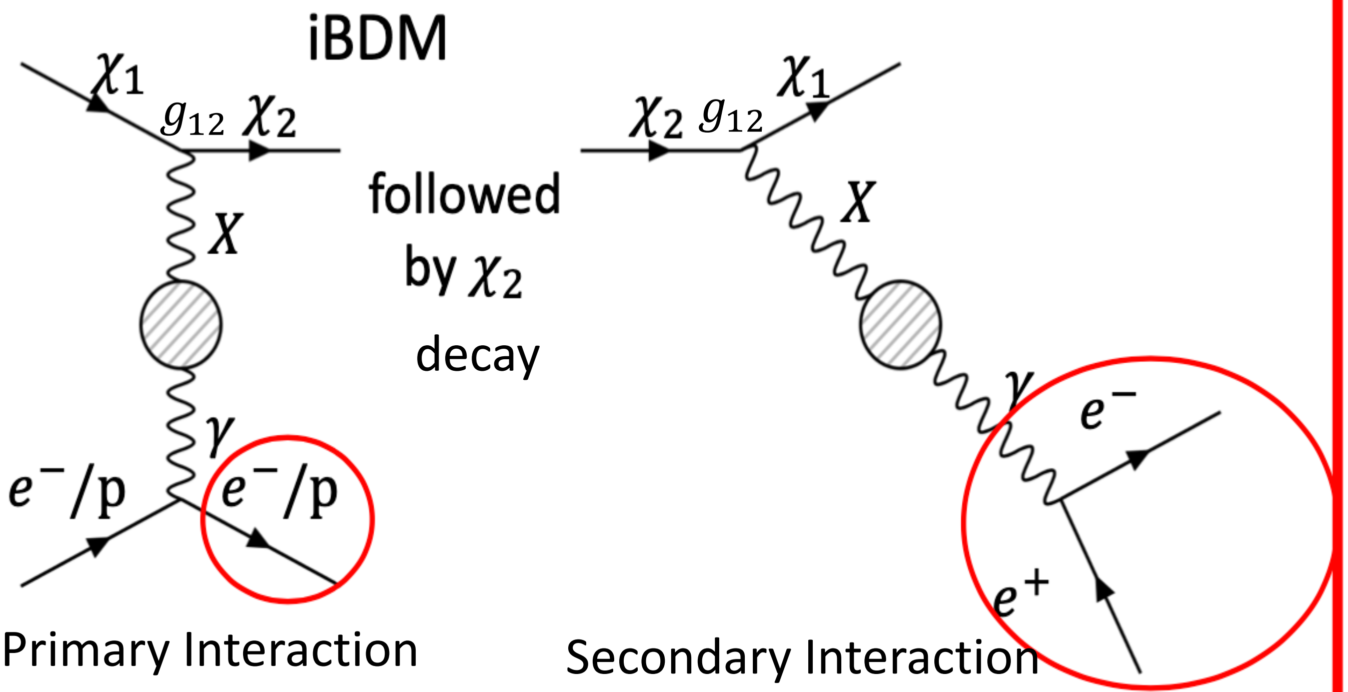
Constrained by DM Relic abundance estimates → m_0

m_1 m_2 ← Correlated to χ_1 boost factor, where boost is set for detector sensitive interaction energies

Elastic (eBDM) and Inelastic (iBDM) Boosted Dark Matter Interactions



One event in the detector



Primary Interaction

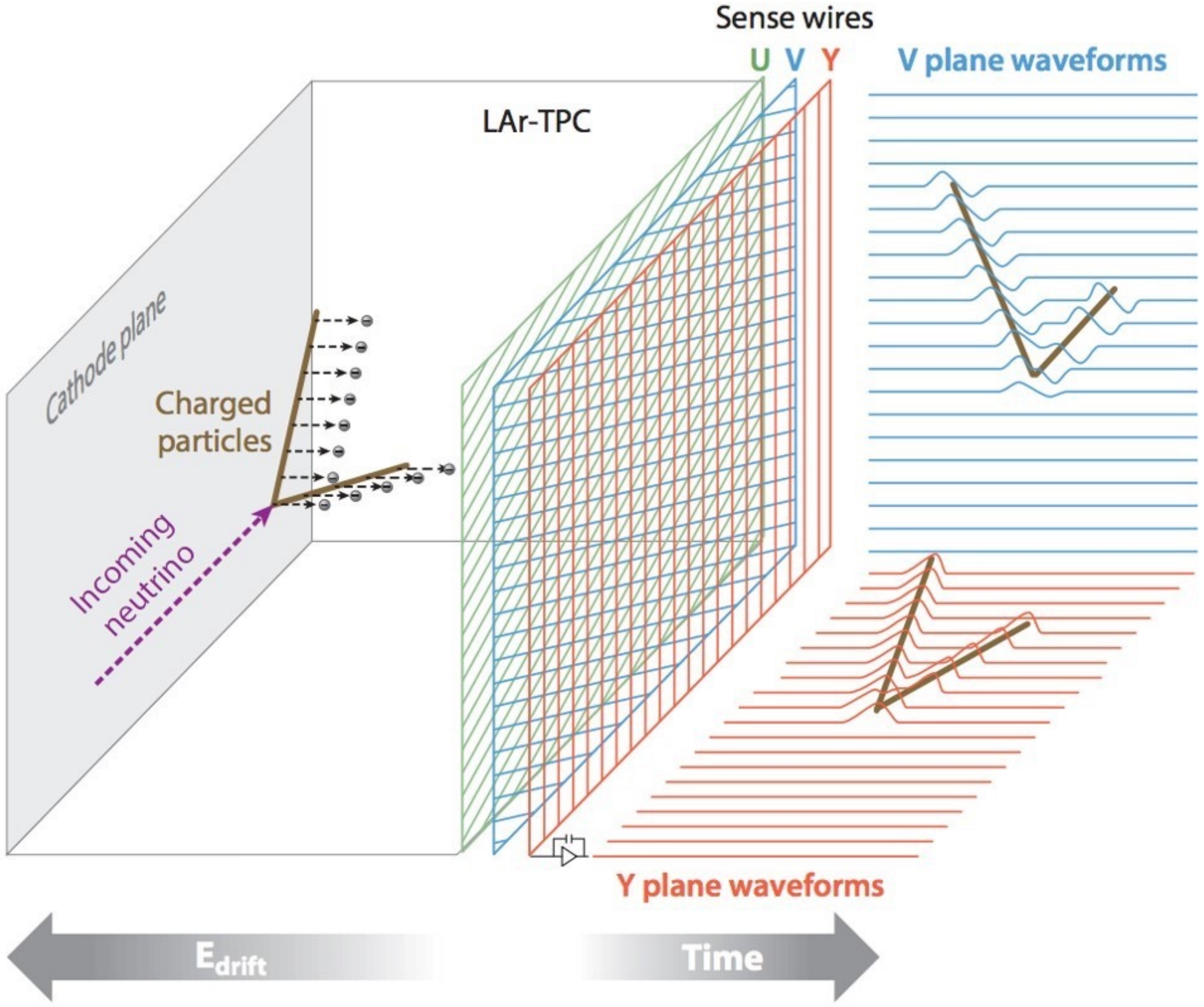
Secondary Interaction

Experimental signature of interest

$e^- + e^- e^+$

Liquid Argon Time Projection Chambers (LArTPCs)

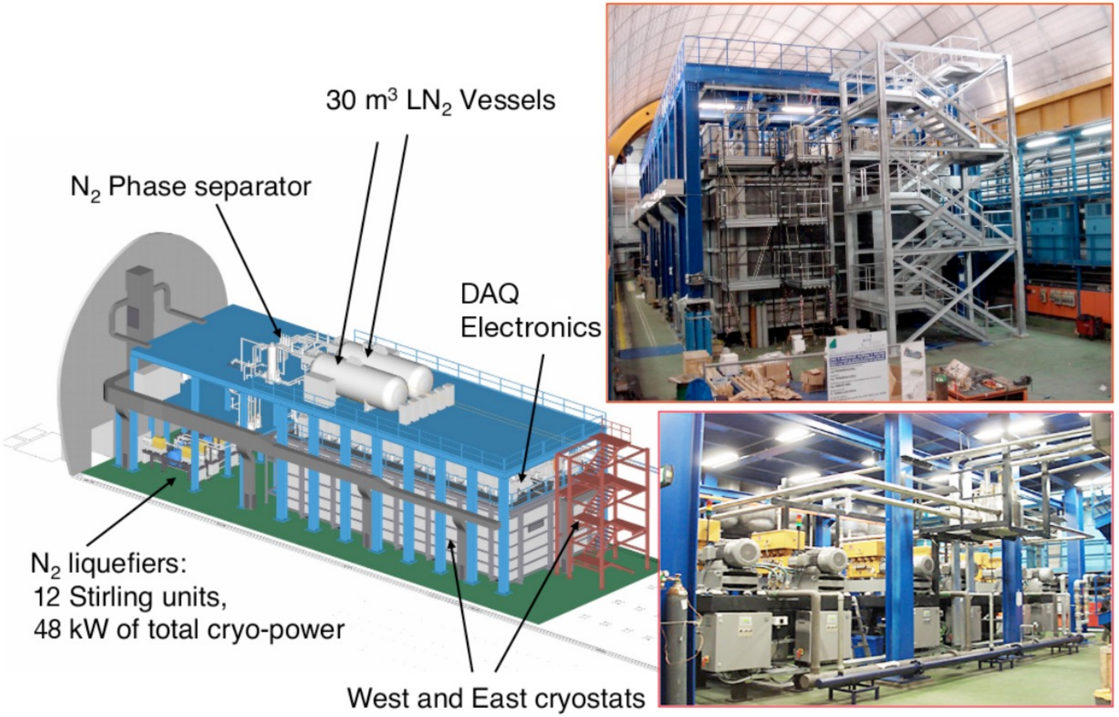
- Technology proposed by Carlo Rubbia in 1977 [Rubbia 1977]
- Detectors range up to ktons!
  - Having dense and adequate detector medium for interactions is important for DM studies
- The novel charge collection system allows for excellent event energy and spatial reconstruction, both important when studying beyond Standard Model interactions
- LArTPCs are used in neutrino experiments, which complements greatly our search for iBDM considering the signal!



ICARUS-T600 Detector at Gran Sasso

- 0.43 kton year exposure:
  - **3 years total Gran Sasso data, 1 year worth of relevant data for analysis (filtered data)**
- Fiducial Volume (FV): at least 5 cm from the active LAr volume
- Event Trigger System
  - Photomultiplier Tubes -> scintillation light detection
- **Event Energy Deposition minimum threshold is 200 MeV**
- The large liquid argon volume gives ICARUS the edge on potential DM interactions
- **Most importantly, ICARUS at Gran Sasso is underground!**
  - **Cosmic backgrounds are highly suppressed**

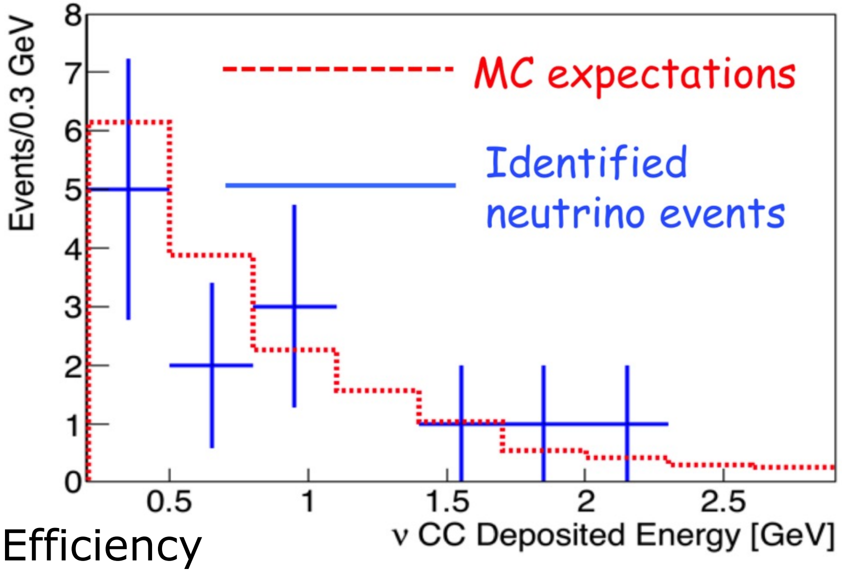
C Rubbia *et al* 2011 *JINST* **6** P07011

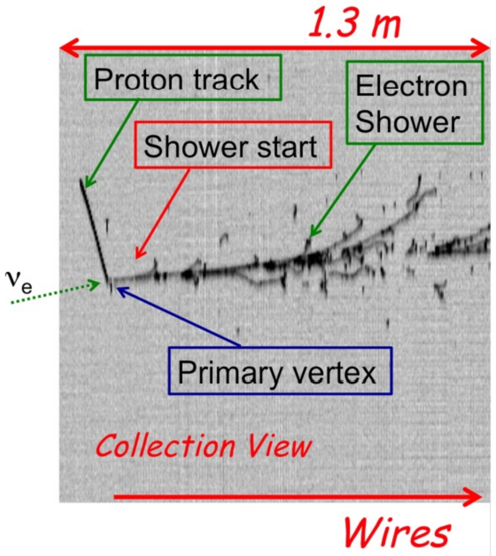


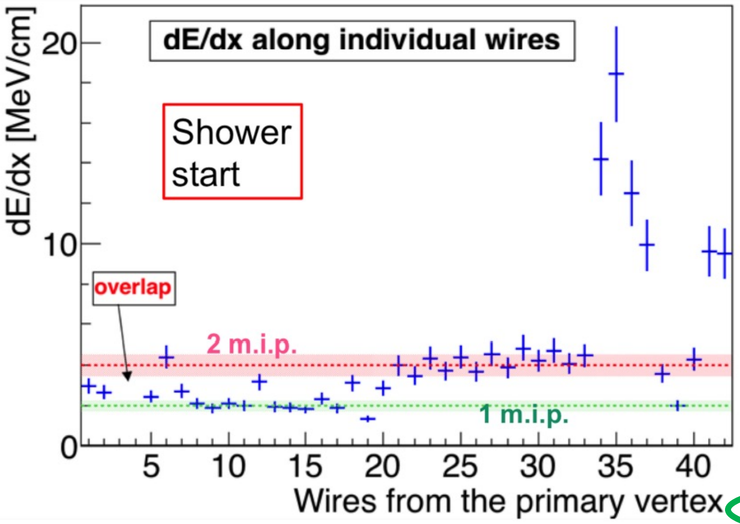
Baseline Study: Atmospheric Neutrinos

[Farnese 2019]

Stages of the Analysis	Expected ν_μ CC	Expected ν_e CC
Events per kton y	96.2	78.2
Events in the studied exposure	41.4	33.7
Events in the fiducial volume (91.4%)	37.8	30.8
Events with deposited energy >200 MeV	24.9	24.2
Filter efficiency	25.7 %	81.4%
Events selected including the filter efficiency	6.4	19.7
Trigger efficiency	86.7%	84.7%
Events selected including the trigger efficiency	5.5	16.7
Events selected including the scanning efficiency (80%)	4.4	13.3
Observed events	6	8



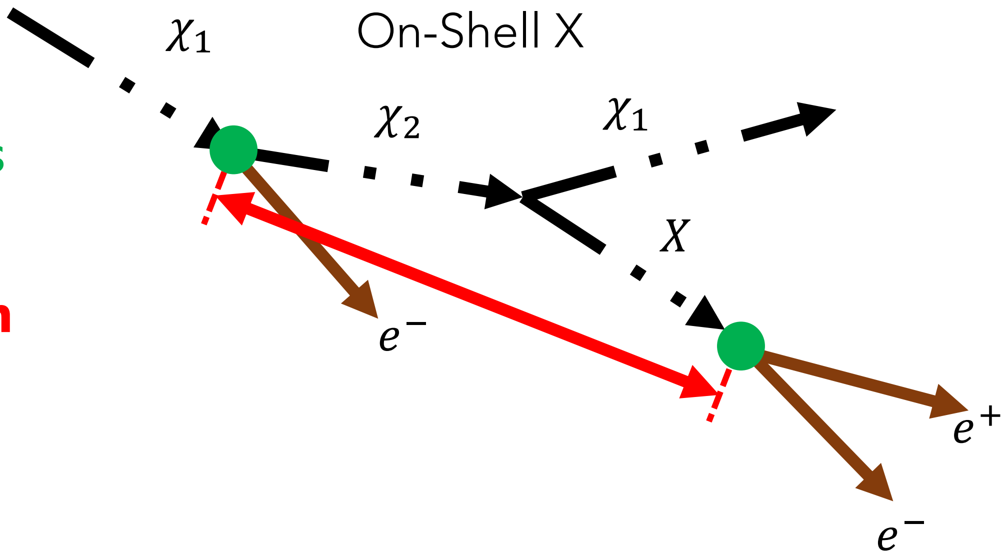




- Filter Efficiency
  - **Electron Shower recognition** -> charge signals in collection TPC wires
- Trigger Efficiency
  - **ICARUS PMT light trigger** -> function of energy
- Selection Efficiency
  - **Visual identification of events**
- **If iBDM exists, It can be in filtered sample!**

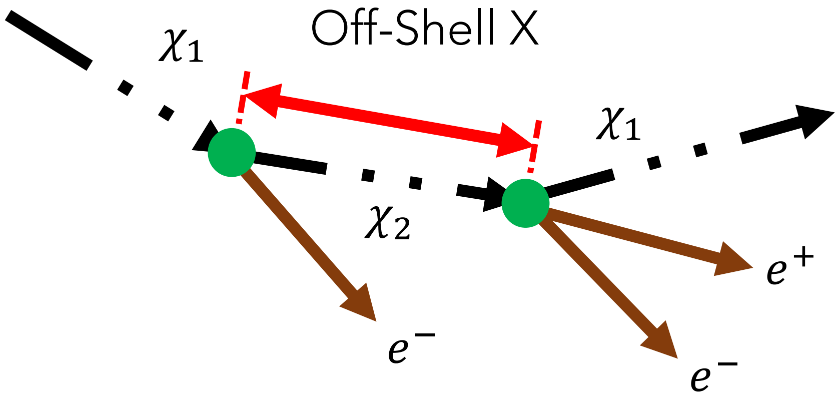
Event Topology and Kinematic Selection Criteria

1. Primary and Secondary in **FV**
   - This eliminates the neutral current neutrino backgrounds



2. Distance of **Secondary Interaction from Primary > 3cm**
   - dE/dx of recoil electron needs to be identified, and this happens early in the electron shower

3. **Total Visible Event Energy** $(\mathbf{E}(\mathbf{e}^-_{\mathbf{recoil}}) + \mathbf{E}(\mathbf{e}^+\mathbf{e}^-)) > \mathbf{200MeV}$ to ensure a good trigger efficiency and event energy resolution
   - Gives an idea on how many events will be triggered on



Calculating Expected Events $N_{expected}$

- To calculate the expected event $N_{expected}$, we use the formula

$$N_{expected} = N_T t_{data} F_{\chi_1} A_{global} A_{kinematic} \sigma_{\chi_1 e^- \rightarrow \chi_2 e^-}$$

  - A_{global} = Detector acceptance/global efficiency

$$A_{global} = (a_{FV})(Trigger_{eff})(Filter_{eff})$$

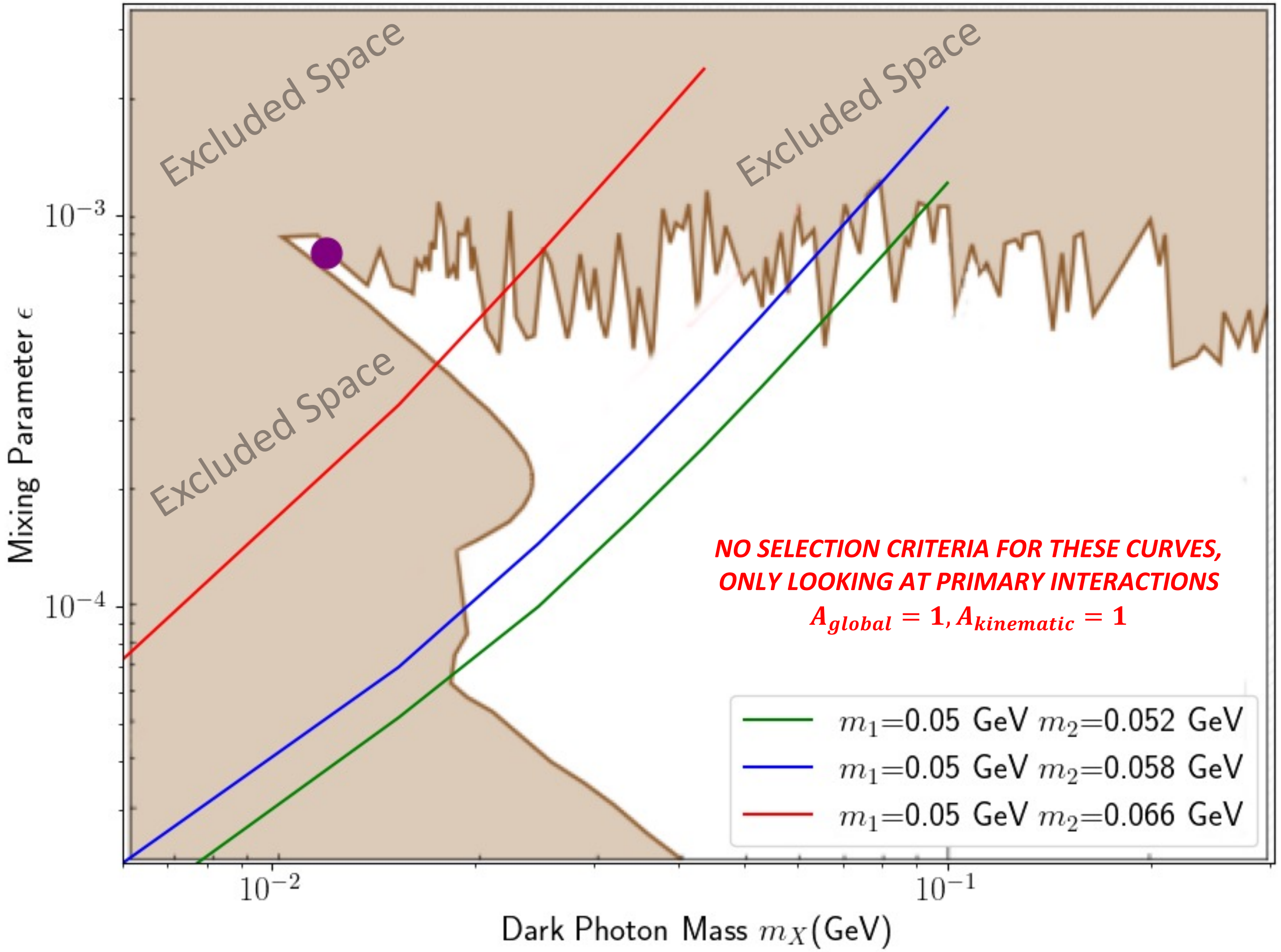
$$a_{FV} = \text{fraction of Active volume belonging to fiducial volume} \sim 0.9$$

  - $A_{kinematic}$ = fraction of events satisfying selection criteria
  - F_{χ_1} = Flux of χ_1 coming from the center of the galaxy
  - N_T = number of target particles in detector (in our case, the argon electrons)
  - t_{data} = detector exposure time (1 year)
- **A_{global}=1 is assumed throughout the presentation**
- **$A_{kinematic}$ achieved by using the iBDM Generator MC and applying the selection criteria**
- **Zero Background assumption**

Sensitivity Curve With Only The Primary Interactions ($\chi_1 e^- \rightarrow \chi_2 e^-$)

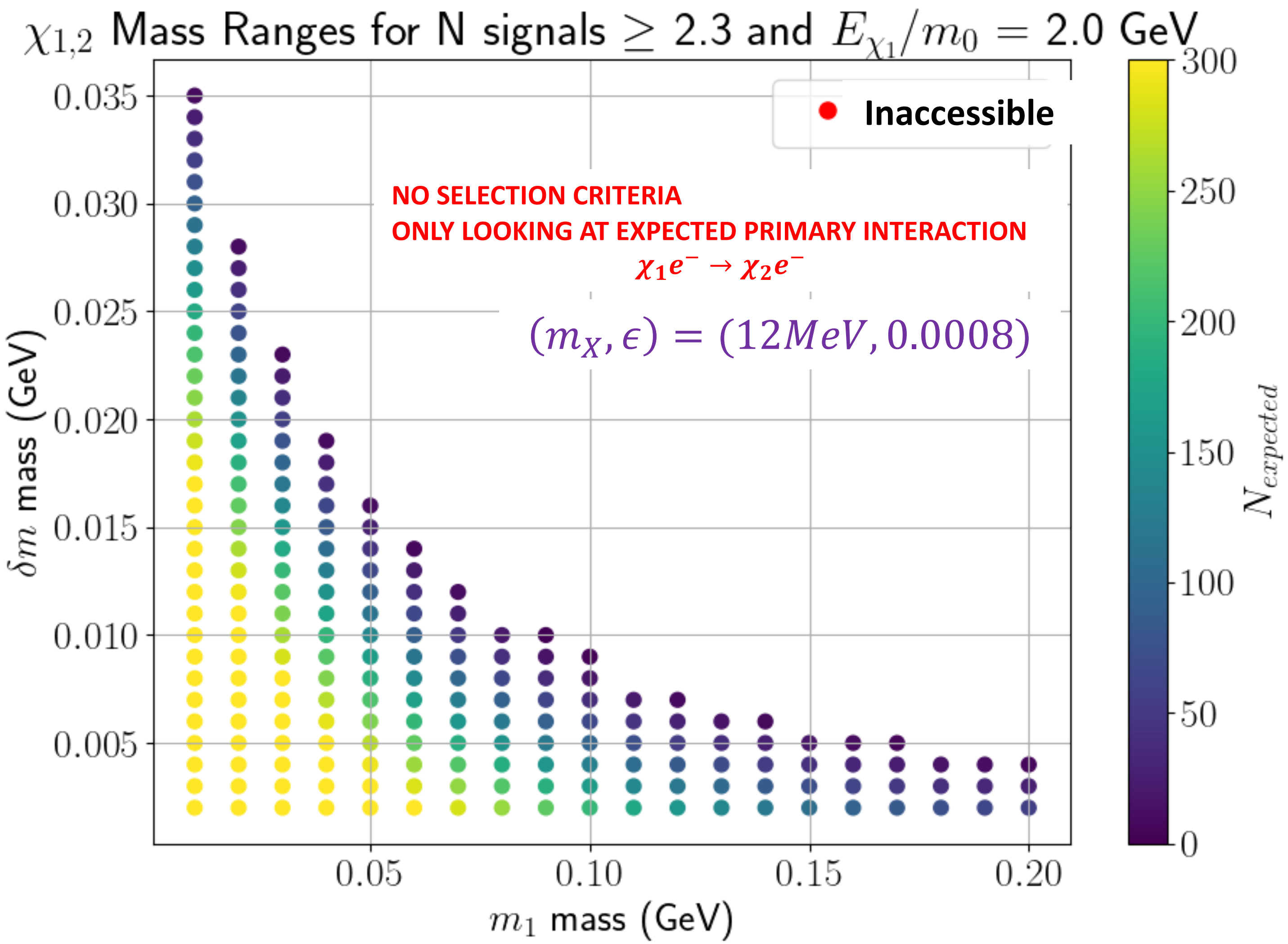
- Example 90%CL curves show ICARUS, in terms of primary interactions interactions, has enough events for select example parameters

- $N_{expected}$ at the **purple point** $(m_X, \epsilon) = (12MeV, 8e-4)$ will be the reference to our study (edge of available parameter space)



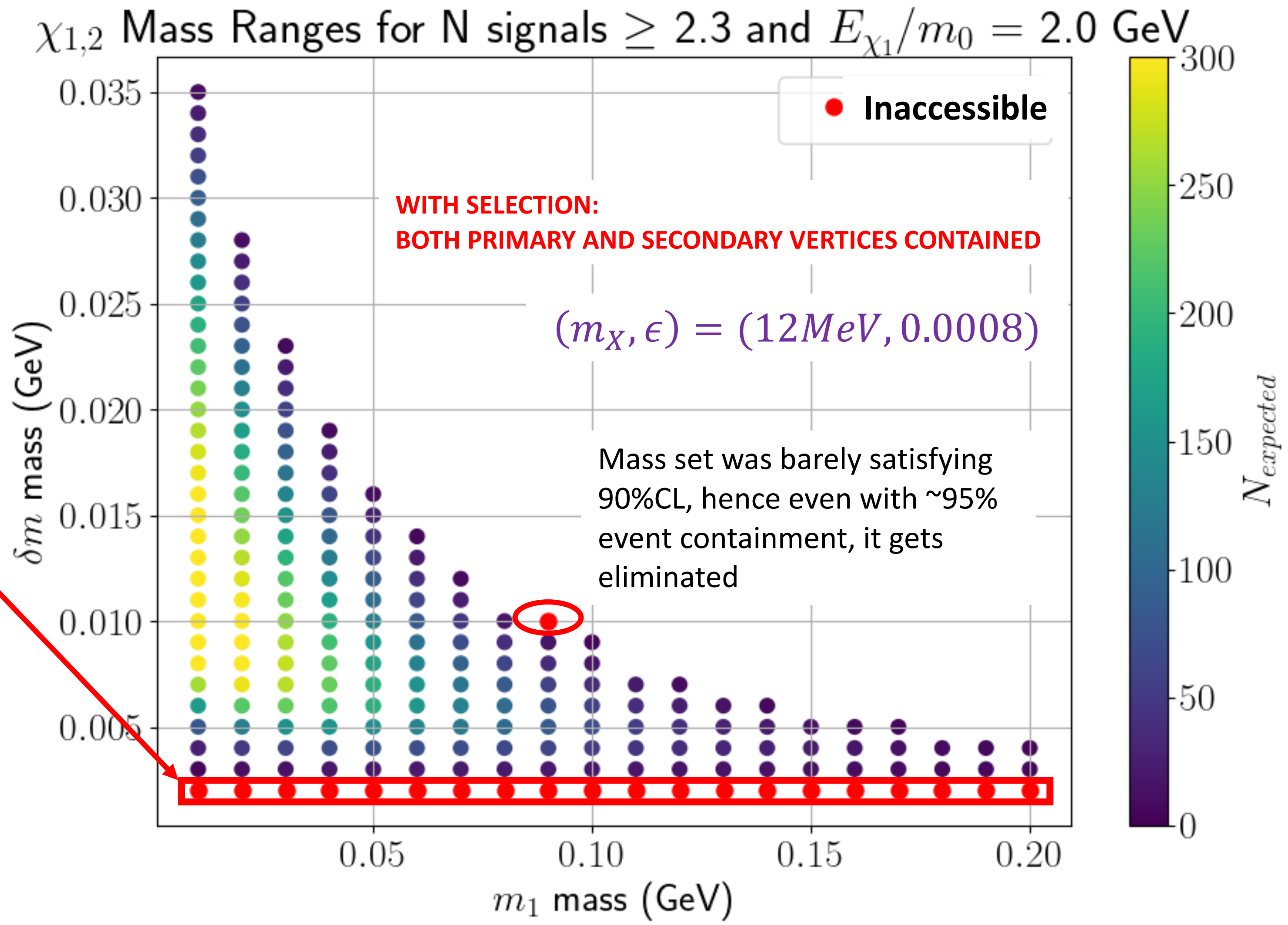
$N_{expected}$ Baseline: $N_{\chi_1 e^- \rightarrow \chi_2 e^-}$

- Here $\delta m = m_2 - m_1$
- All $N_{expected}$ are in reference to $(m_X, \epsilon) = (12MeV, 0.0008)$
- Since no selection criteria is implemented, we are only counting the number of expected primary interactions under our fiducial volume assumption, 1 year exposure
- Smaller δm allows for more primary interactions for a given mass pair



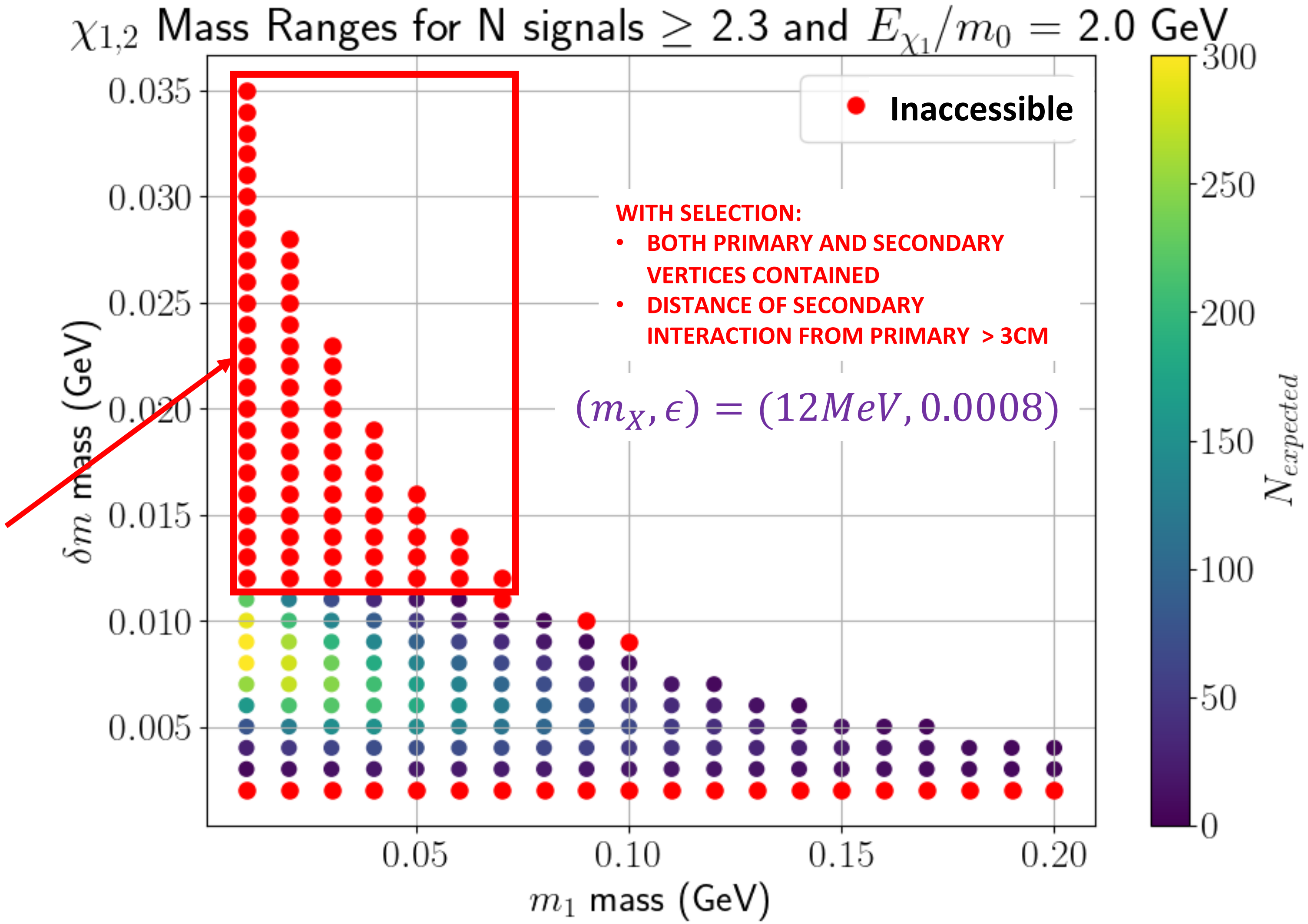
$N_{expected}$ With Primary and Secondary Vertex Within FV

- Small mass difference allows χ_2 to have a longer lifetime
- Adding primary and secondary vertex containment makes small δm inaccessible to ICARUS at Gran Sasso



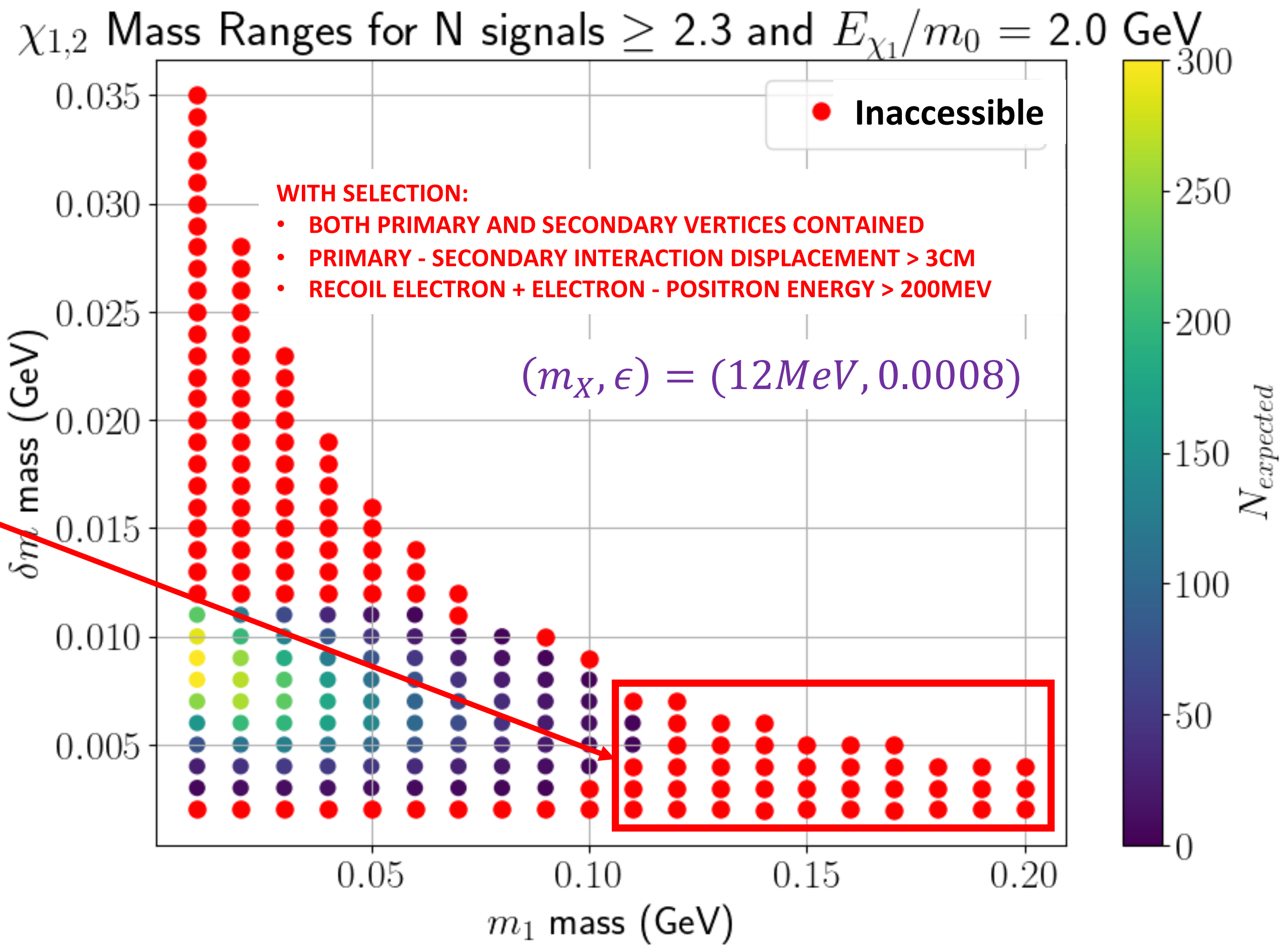
$N_{expected}$ With Vertices in FV + Vertex Distance Requirement

- Since the dark photon mass is 12 MeV, when $\delta m > m_X$, on-shell dark photons are possible. This scenario allows for very prompt χ_2 decay
- Imposing minimum vertex separation distance for dE/dx measurement makes on-shell dark photons scenarios inaccessible with E_1= 2 GeV



$N_{expected}$ With Previous Selection Criteria + 200 MeV Energy Threshold

- In this region, (m_1, m_2) pairs have high mass
- More energy is therefore put into the mass of the particles rather than the kinetic energy of visible particles (recoil electron and electron-positron pair)



The Future Looks Bright

With optimal $(E_1(m_0), m_1, m_2)$ parameter sets, perform detector simulation for points in non-excluded (m_X, ϵ)

1. Generate Signal Monte Carlo Event
2. Convert from HEPEVT format to art root format
3. Perform GEANT4 simulation within ICARUScode
4. Convert GEANT4 file for compatibility with ICARUS at Gran Sasso analysis software
5. Perform event reconstruction
6. Obtain trigger and filter efficiencies

With Trigger and Filter efficiencies, the full $\mathrm{N}_{\mathrm{expected}}$ can be calculated. This portion of the analysis takes time since a full detector simulation is required, depending on the statistics for the parameter set.

Summary

- ✓ The ICARUS T-600 detector underground at Gran Sasso data can make a real impact to BDM searches!
- ✓ A strategy for selecting optimal iBDM parameter sets established
  - ✓ Well motivated iBDM parameter sets that can be explored by ICARUS at Gran Sasso presented here
- ✓ Full Detector simulation infrastructure for signal generation in place
- ✓ Data meant for study has been filtered, visual scanning done for the atm neutrino study!
  - ✓ Filtered data and methodology can be implemented for iBDM study
  - ✓ Visual scanning of monte carlo sample and ~10% of the real data started with initial training

Thank You For Listening!