# Light Dark Matter searches with the NOvA Near Detector

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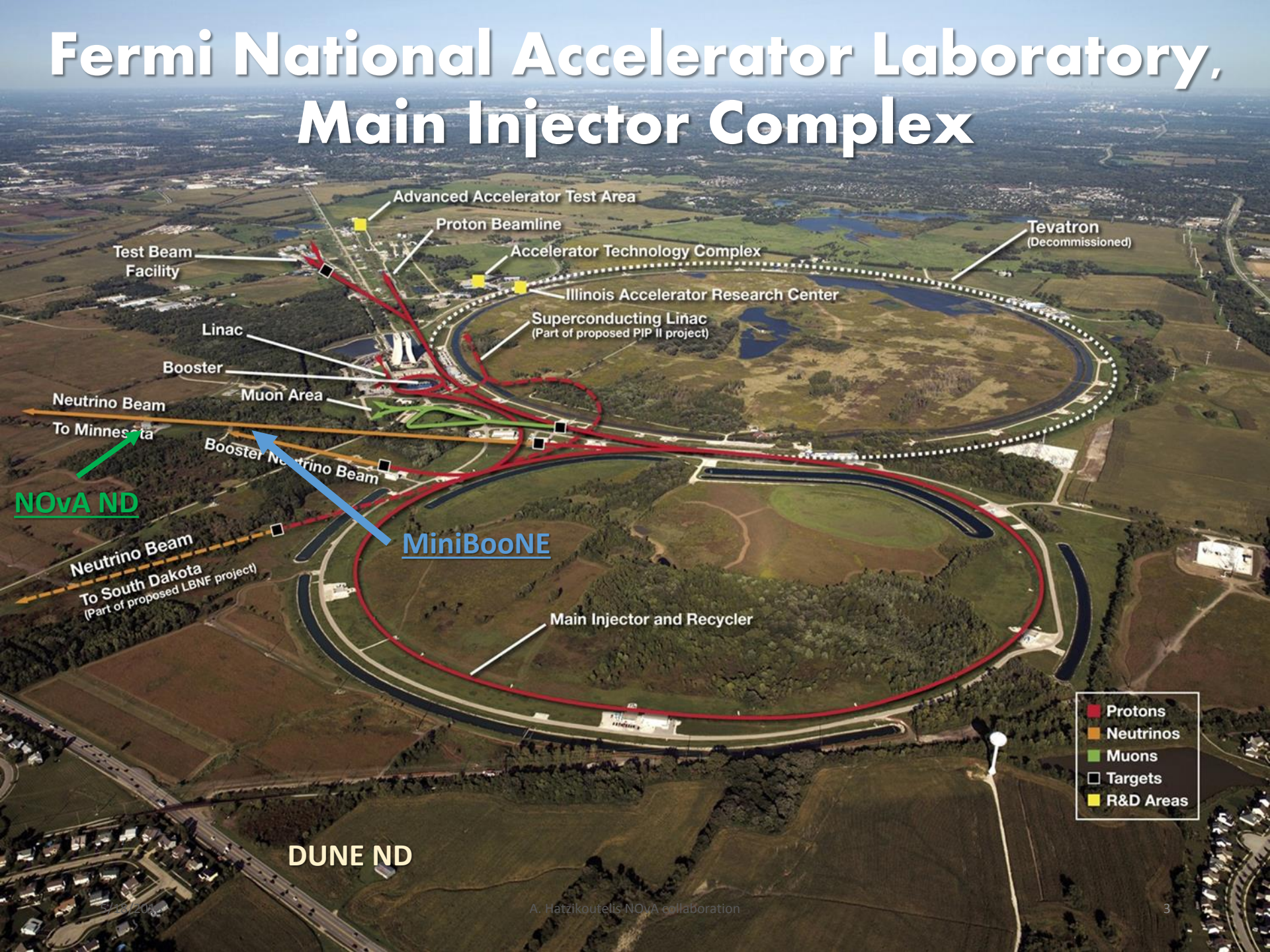
# Outline

- The NuMI and the NOvA Near Detector complexes.
- The benefits of using the NuMI/NOvA for rare event searches.
- Re-interpreting NuMI/NOvA as a beam-dump experiment.
- Example for Light Dark matter in the NOvA Near Detector.

# Fermi National Accelerator Laboratory, Main Injector Complex

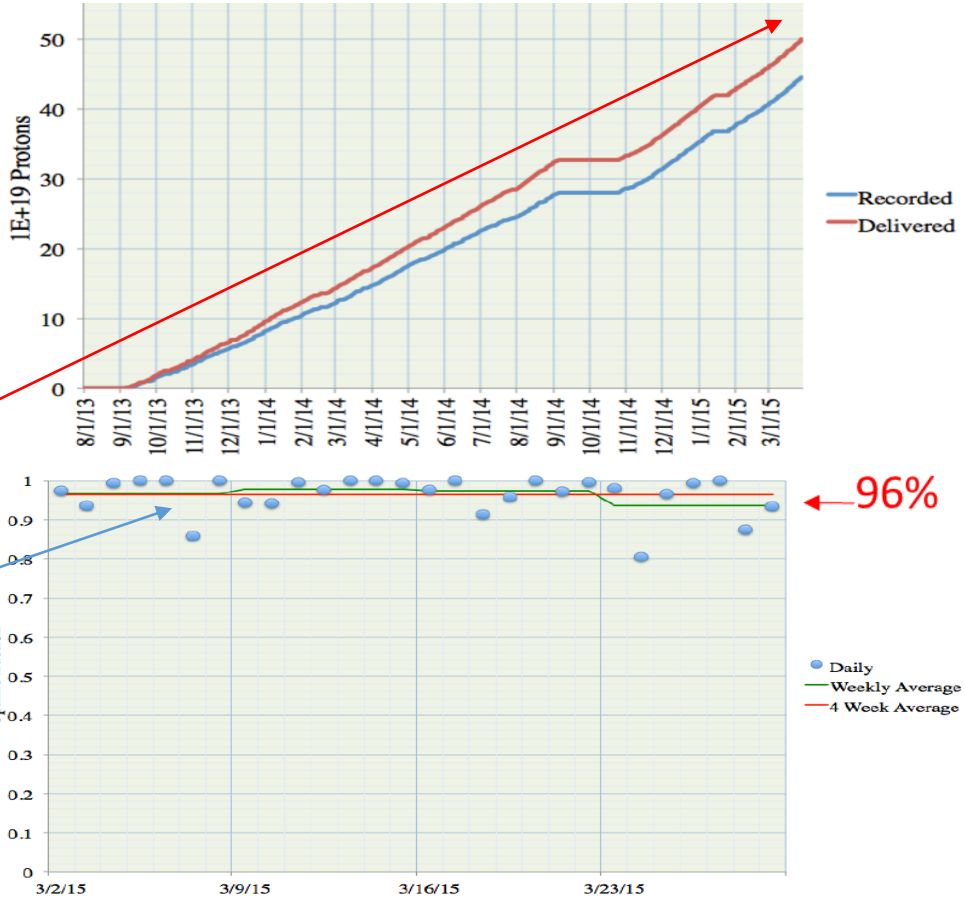


# Advantages of the NuMI/NOvA

- Design
  - Aimed for energy and direction reconstruction of protons, neutrons, muons, electrons, and photons.
- Precedent
  - There have been observed significant unexplained electron/photon-like excesses in both neutrino and anti-neutrino mode.
    - "LSND anomaly",
    - "MiniBooNE anomaly".
- Investment & Effort for high protons-on-target (POT)
  - 6 bunches= $10^{12}$POT/sec =350 kW
  - Slip Stacking Cycles technique
    - As of March 2015: 420 kW
    - Projected for 11/2015: 575 kW
    - Projected for 2/2016: 700 kW
  - Event readout (timing ~nsec)
  - Detector robustness ( average 91% uptime)
- Geometry
  - Sensitive to heavier (> MeV), subluminal particles.

POT from NuMI target recorded by the NOvA Detectors.

Record intensity of **450 kW** and projected 700kW.



# The NOvA Near Detector

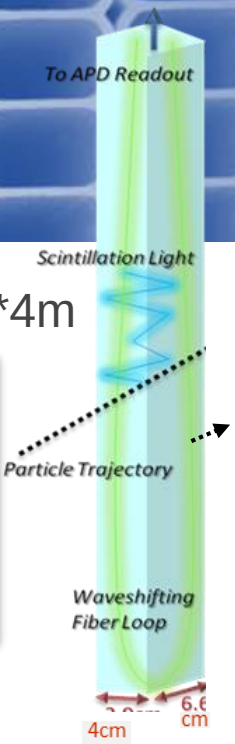
## Detector Cell

- Extruded PVC walls.
- Filled with liquid scintillator
- Instrumented with wavelength-shifting fiber
- Read out by avalanche photodiode (APD).

## Readout & Digitization

- 32 pixel APD reads out fibers from 32 cells.
- Custom electronics provides amplifier/shaper.
- Each pixel/cell continuously digitized.
- Detection threshold set at ~ ½ MIP.

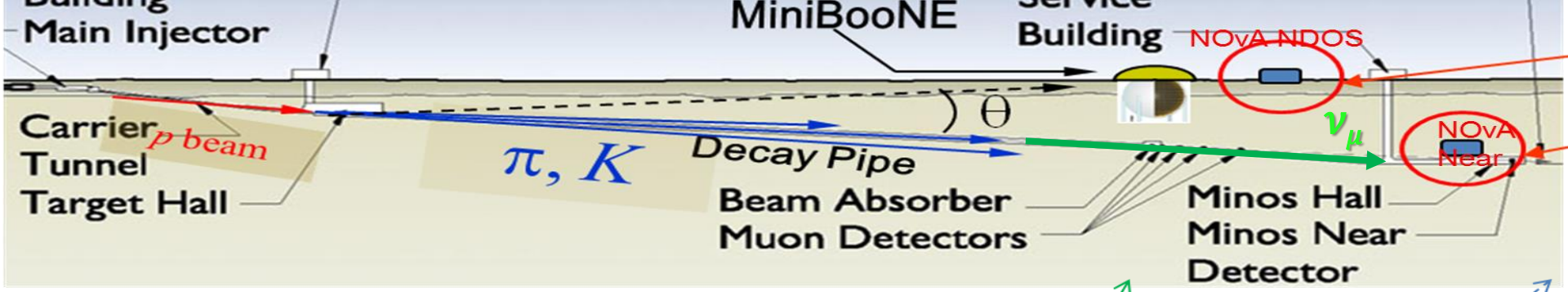
Near Det. 4cm*6cm*4m




beam

Muon Catcher:
Steel layers, downstream,
Muon and EM-shower
ranging.

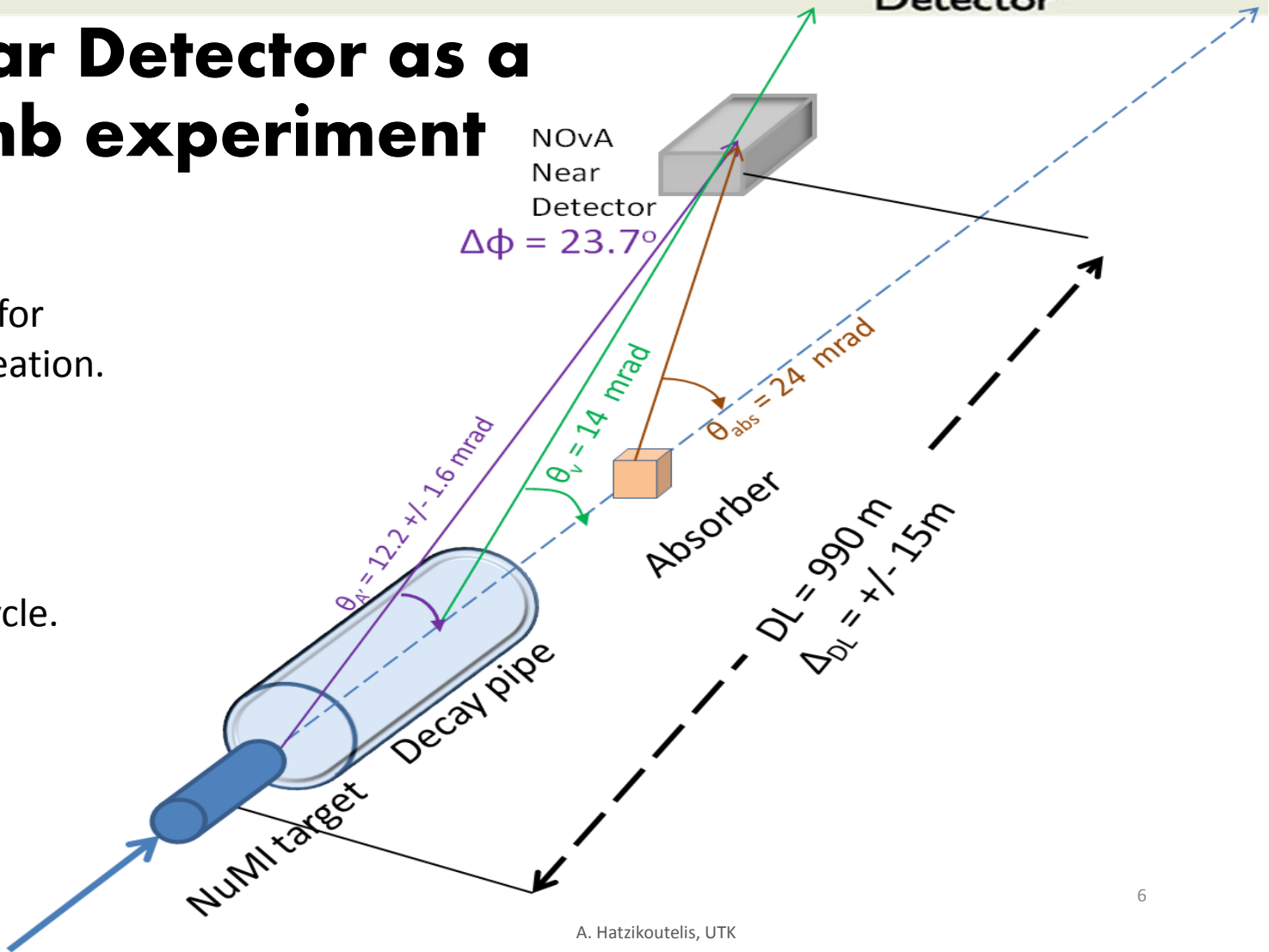
NOvA ND:
300 ton,
operational
since summer
of 2014.




# NOvA Near Detector as a Beam-dumb experiment

Different decay path for different points of creation.

Protons $E_p$ = 120 GeV
$10^{12}$ bunch/1.3 sec cycle.

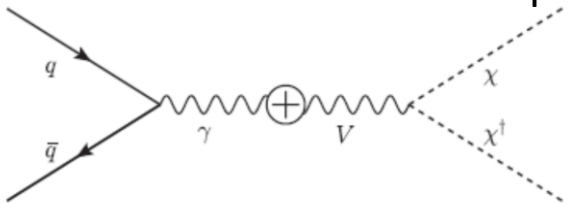


# New Physics at NuMI/NOvA.

## PORTALS

| | |
|---|---|
| Dark photons | $-\frac{\kappa}{2}B_{\mu\nu}V^{\mu\nu}$ |
| Dark scalars | $(AS+\lambda S^2)H^\dagger H$ |
| Sterile neutrinos | $y_N LHN$ |
| Pseudoscalars | $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$ |

Direct production favored at the 120 GeV.
(example: scalar DM via the vector portal).

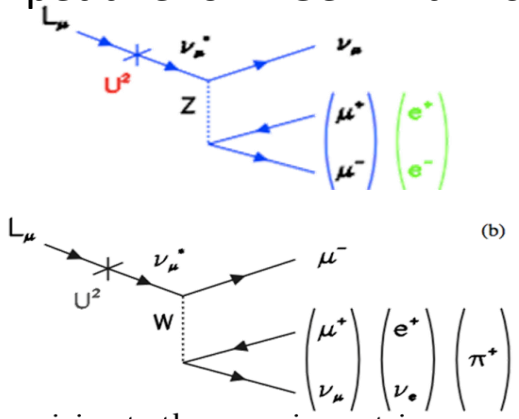



Mass range for mediators 1-15 GeV.
Mass range for DM 100 MeV – 7 GeV.

Indirect production (through meson decay) is favored at the MiniBooNE energies.

## Heavy Neutral Leptons (HNL).

- Simplest extension to SM.
  - Heavy Neutrinos (HN).
- Production at NuMI
  - 2-body leptonic decay of $D^+$ ,$D_s^+$
  - Suppressed due to weight of target.
  - High neutrino background.
  - Competitive for ~ GeV with 10μs lifetimes.




$|U|^2$ is the mixing to the muonic neutrino.

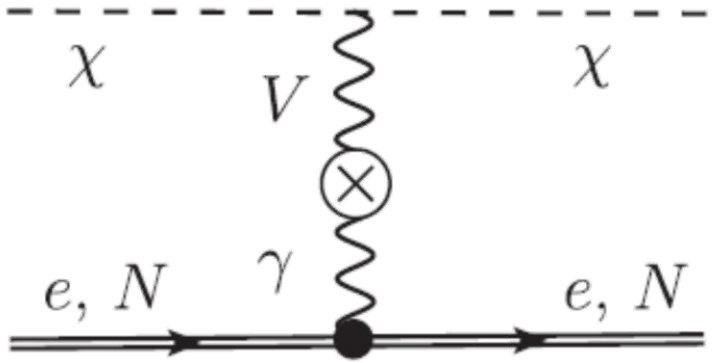
MSM: T.Asaka, M.Shaposhnikov
PL B620 (2005) 17

# New Physics program at NOvA.

## Model independent search for New Physics signatures.

**Example of a model dependent signature.**

Dark matter scalar scattering on a nucleus or an atomic electron.
PRD 84(075020)2011




**General New Physics signatures**

- Elastic scattering on electrons or nucleons.
  - From ALPs, Light-DM.
- Particle decay-in-flight into di-leptons within the detector.
  - From Axions, ALPs, other Hidden Sector particles, etc.
- Single photons, di-muons.
  - From HNL decays.

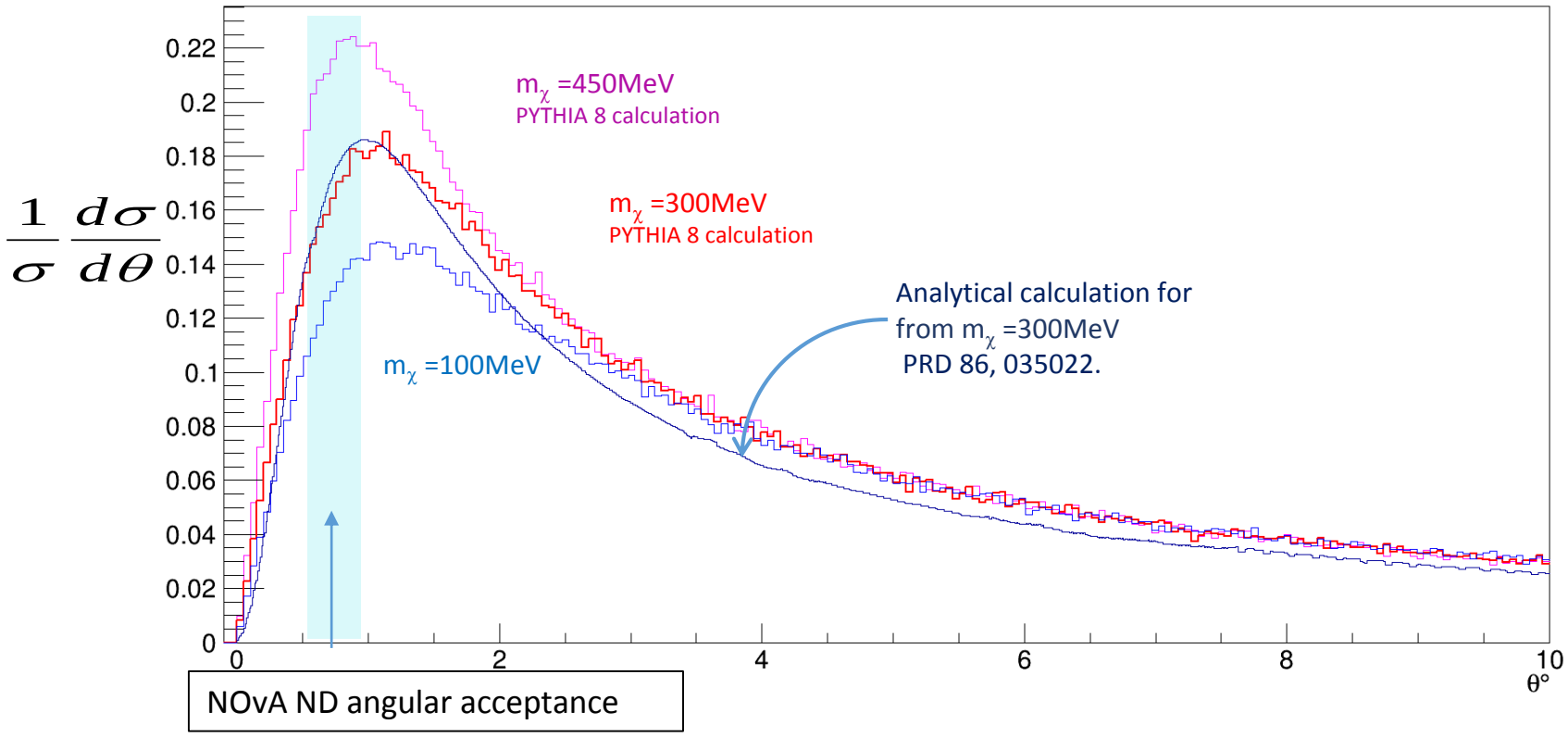
For references see preprints from FNAL: FERMILAB-CONF-13-544-E, and FERMILAB-CONF-14-376-PPD

# Dark Matter production at NuMI.

**Example of angular distribution of light dark matter from the NuMI target region.**

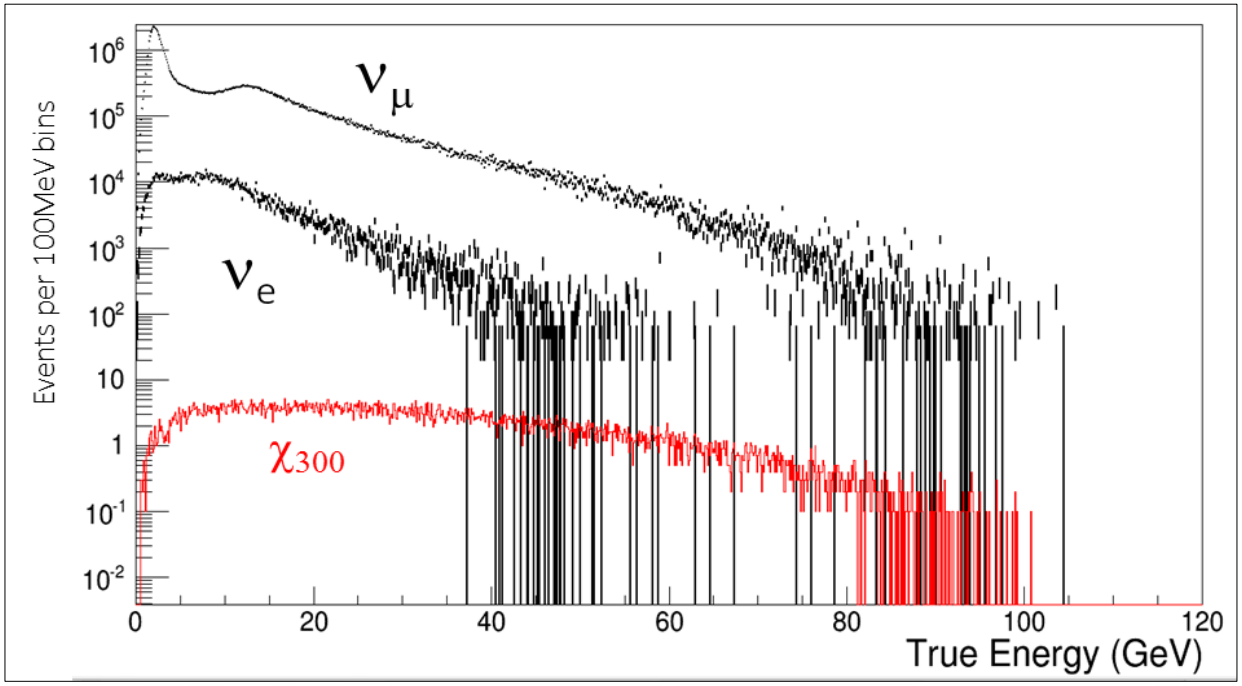
Vector Portal. → Vector mediator 1 GeV. →Decay in a Dark Matter pair ($\chi$,$\chi^+$).

$$p + p \rightarrow V_\chi \rightarrow \chi + \bar{\chi}$$



# Dark matter flux in the NOvA-ND

Simulated of the expected ND neutrino spectrum components normalized to 1 year data equivalent, or 6E20 POT.

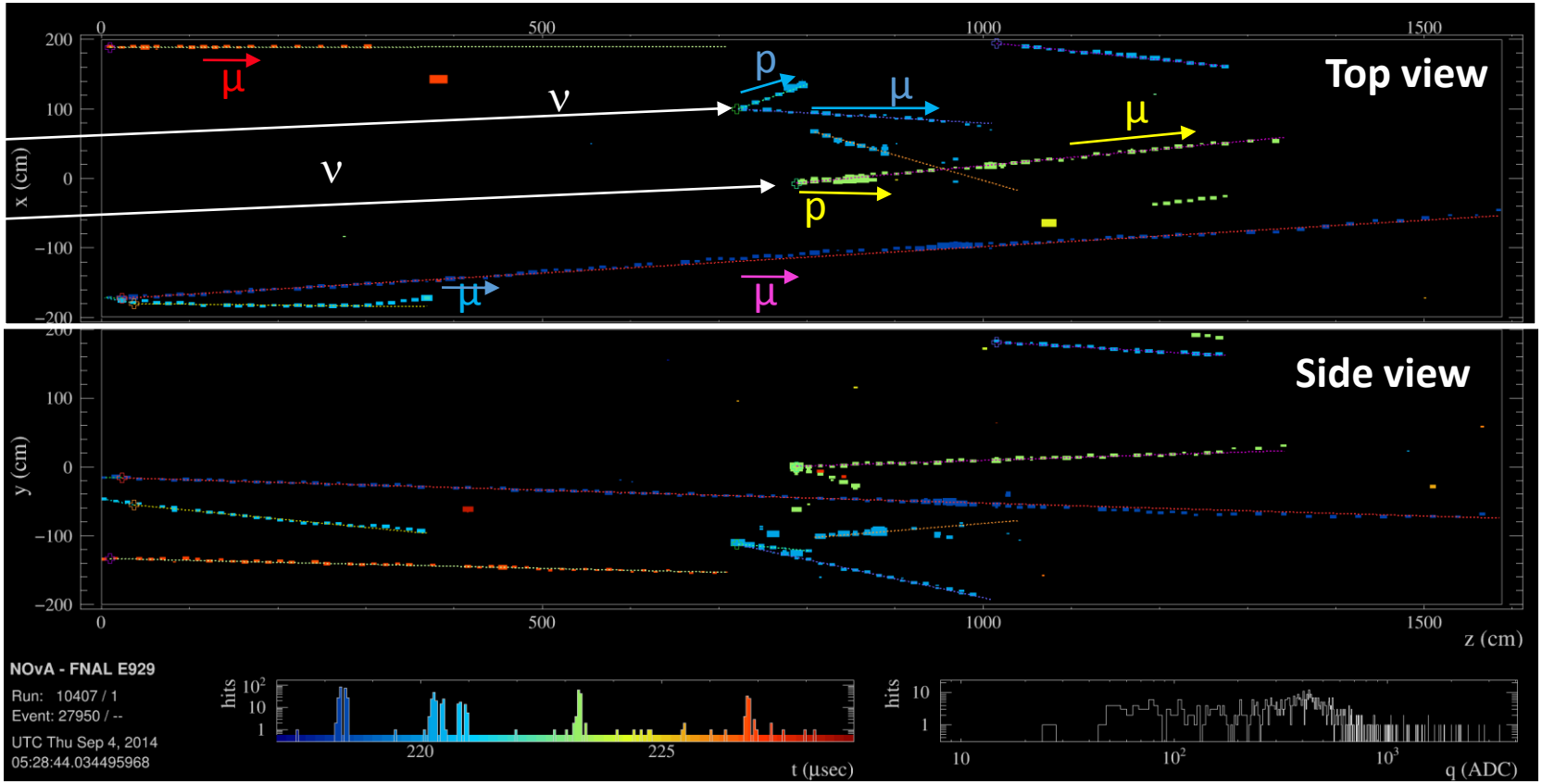



- Total ND spectrum will have several components.
  - The $\nu_\mu$ and $\nu_e$ here are taken without any cuts.
- The DM spectrum $\chi_{300}$ represents a mass of 300MeV from a 1GeV vector mediator.

Expected DM flux in a year.
The 1000 events spectrum correspond to a $10^{-30}$ cm$^2$ production cross-section for the mediator.
(from cosmological constraints in PRD 86, 035022).

# NOvA Near Detector running

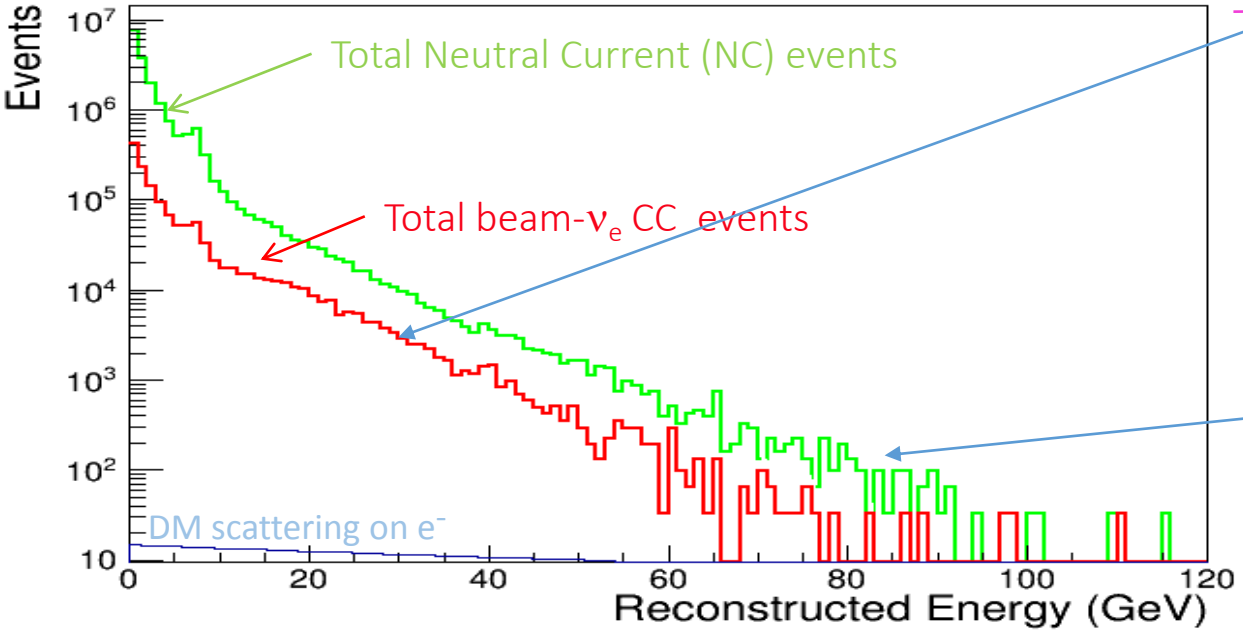
Average hit rate: 1- 5 events per sec in the beam trigger.



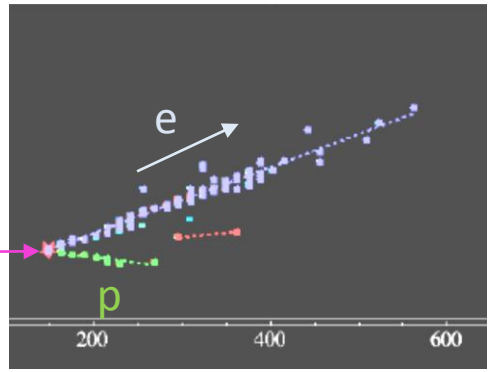
# Event signatures in NOvA ND

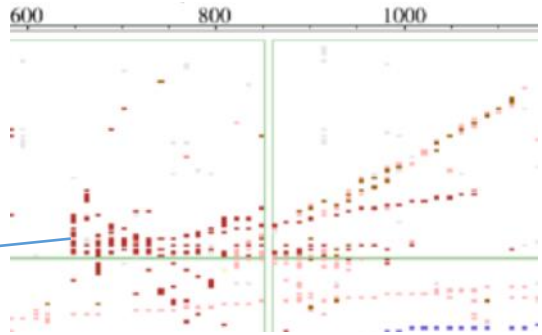
Background to the $\chi$+e→$\chi$+e channel : NC, beam-$\nu_e$ CC

NOvA simulation of neutrino signals in ND by category.
Normalized to 1year running of 6E20 POT.




$\nu_e$

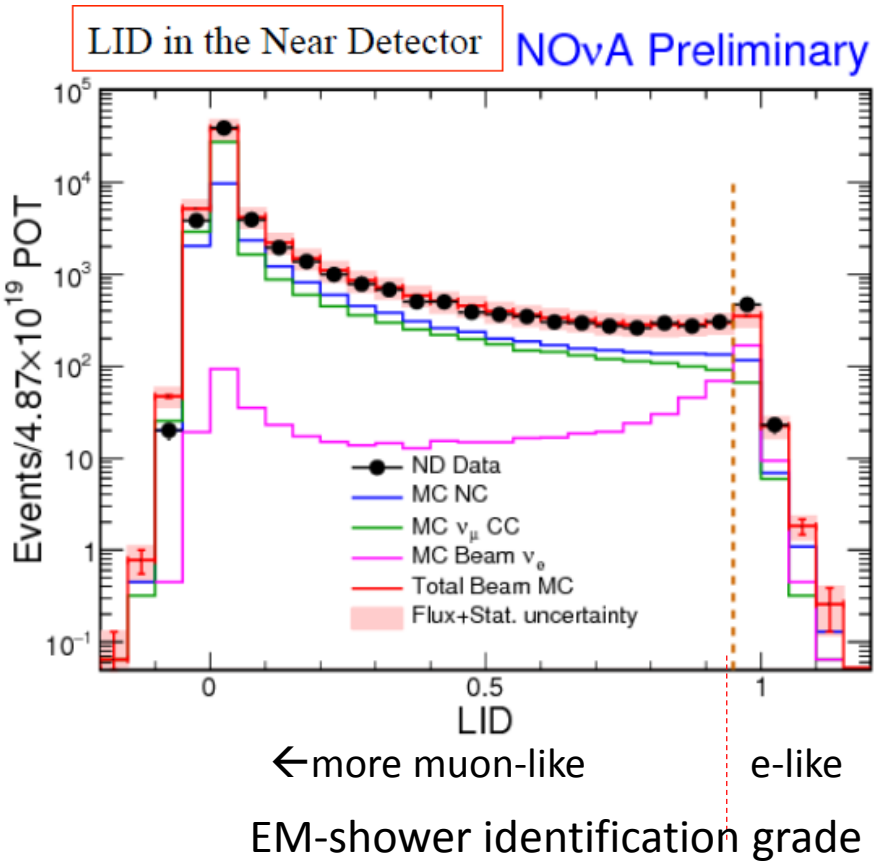



Expected rate of $\chi$+e→$\chi$+e channel (DM scattering on electrons in NOvA ND) rate within 1 year of NOvA data runs : 1- 10 events per GeV bin for scattering cross-section >1000pbarns. Substantial background (NC and miss-identified beam-$\nu_e$ CC events) reduction needed.

# Analysis: Particle Identification

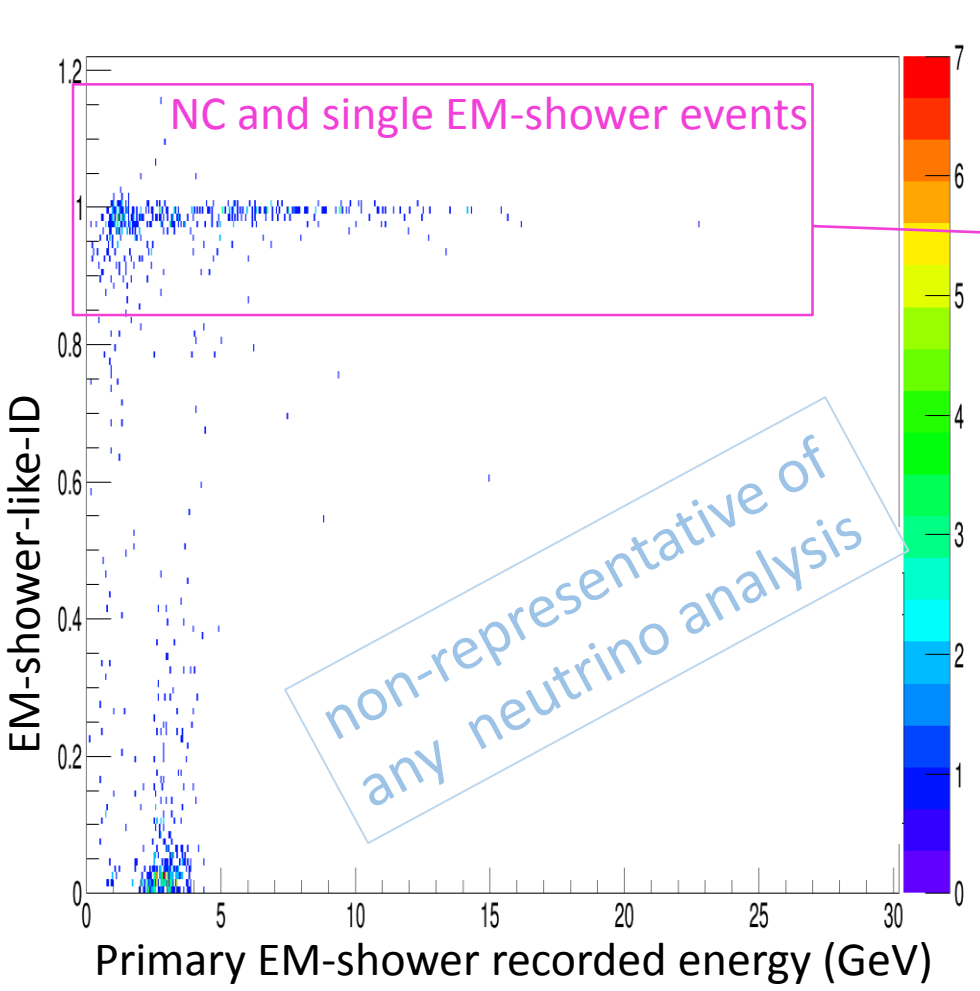
- Two methods:
- "LID" (right) is a neural net evaluation of the shower longitudinal and transverse profile
- "LEM" (not shown) matches the event topologies to large libraries of signal and background events.
- Both achieve acceptable levels of rejection 40M:1 and 21M:1 against cosmic-rays recorded using the Far Detector.
- Evaluation of performance on beam neutrinos awaits full analysis of near detector data.

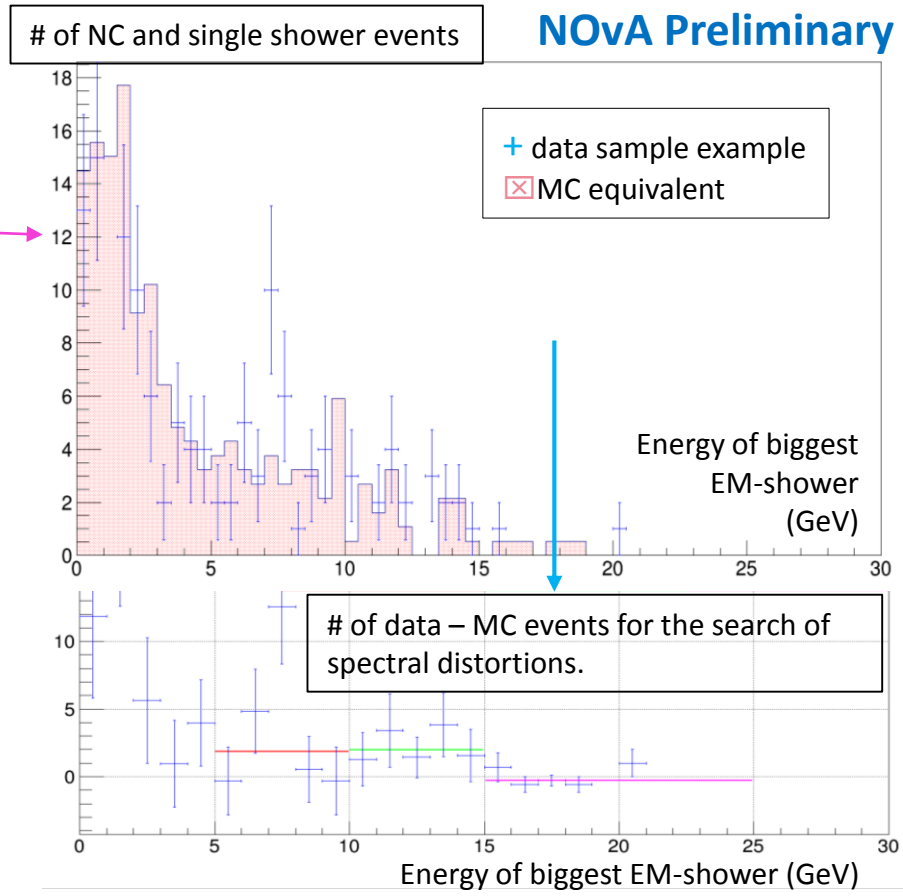


# Data Analysis strategy

**Seeking spectral distortions between the data and the simulations (no DM channels).**

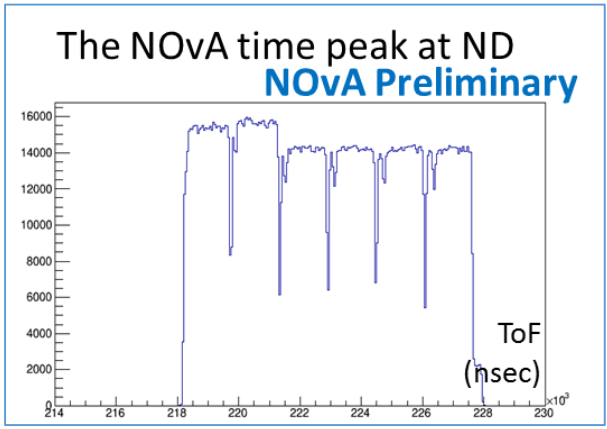
Analysis example: Applying preselection cuts to the data to suppress the neutrino interaction events



# Future of the Light-DM analysis.

- Extensive studies for:
  - The efficiency of reconstruction.
  - The efficiency of particle ID.
  - The selection-cut purity for DM-induced EM-showers.
    - LDM generator and NOvA–MC packages for simulating various signatures (models).
  - The invention of DM-specific selections.
    - Deep understanding of the reconstruction resolutions.
      - e.g. directional, or Time-of-Flight.
- Expand the analysis to channels with complicated background:
  - DM scattering on nuclei at all energies.
    - Understanding DIS and energy transport in nuclear matter.
  - DM from decays producing combinations of mesons.



# Other proton-beam-dump experiments

Comparing results and models

**MiniBooNE**

- Upcoming first results from off-target runs.
- Compare the lower mass (<3 GeV), indirectly production, mediator models.
- Compare light-DM scattering on electrons and nuclei rates.

**DUNE (**the ND program**)**

- Planned for 2021 with similar energy range as NOvA.
- Can potentially probe smaller cross-sections.
- Design requirements for the ND are based on NOvA experience.
  - Evaluation of systematics even before construction.

**SHiP**

- Planned for 2014 with a wider scope in HNL.
- Neutrino background can be evaluated at NOvA ND.
- Reconstruction and particle-ID codes and ideas can be tested with NOvA data while the offline software are maturing.
- Model rates can be constrained from the NOvA measurments.

# Conclusions and Outlook

NOvA has entered the realm of active light-DM experiments.

It can be interpreted as a proton-accelerator, beam-dump search.

NOvA's advantages are:

- The High Intensity NuMI beam.
- The 300 ton, low-Z, tracking Near Detector.

The data analysis of the 1$^{st}$ year data is underway.

- We study our sensitivity capabilities and
- Prepare a comprehensive light-DM NOvA-based simulation.

Experience with NOvA-ND DM search, will affect future experiments including DUNE and SHIP early in their design cycle.

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# Extra material