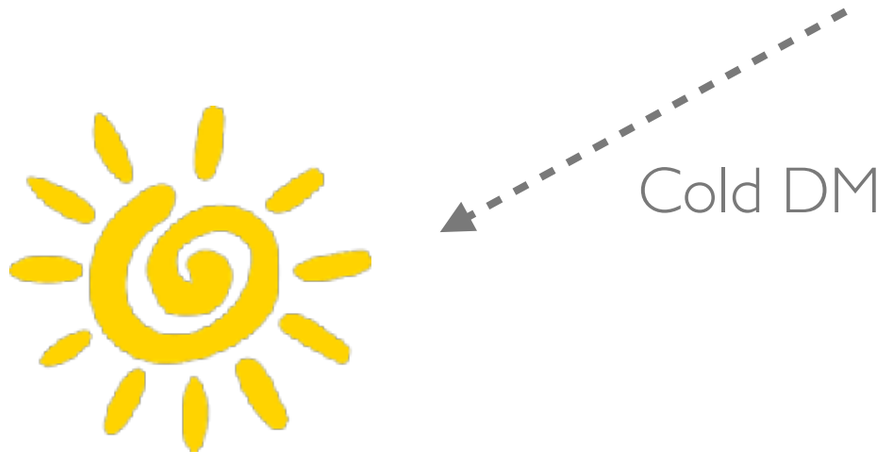
Search for Boosted Dark Matter in DUNE

Yun-Tse Tsai (SLAC)

NuTheories Workshop

November 6th 2018

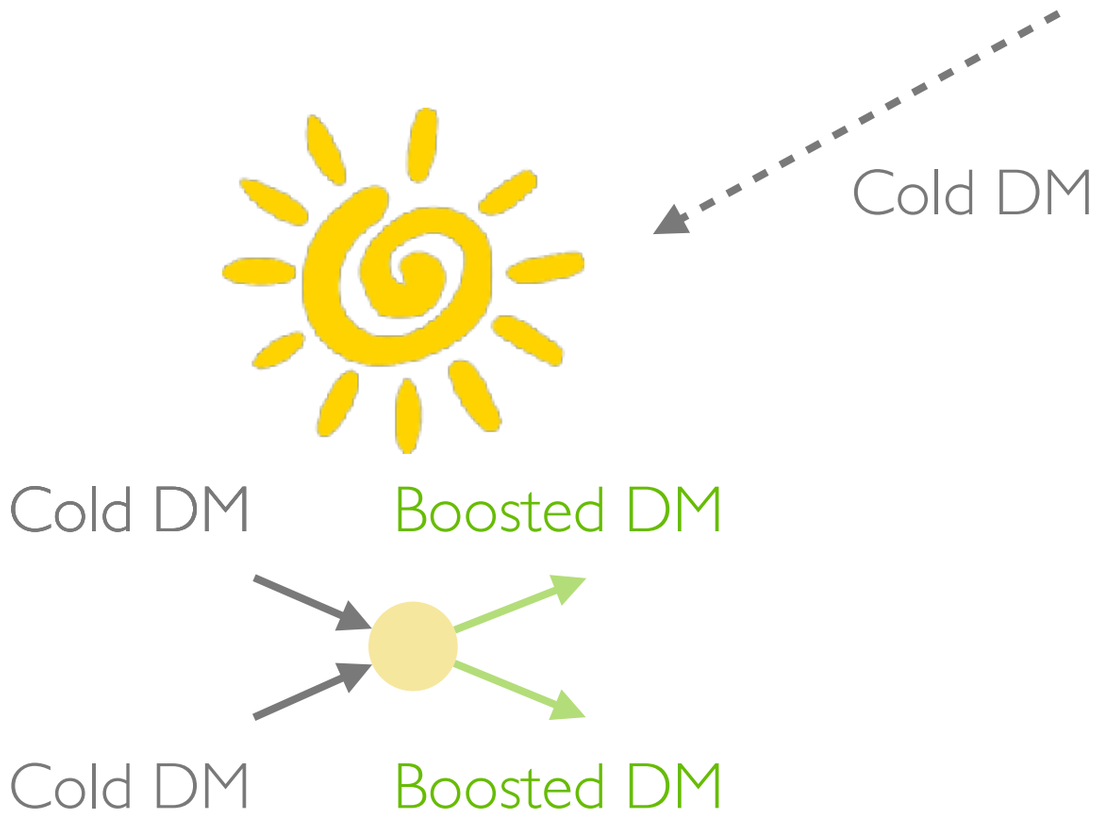
Boosted Dark Matter



1. Cold dark matter captured by dark matter concentrated region, such as the Sun or Galaxy Center

Refs: J. Berger's Talk, JCAP 1502 (2015) 005

Boosted Dark Matter



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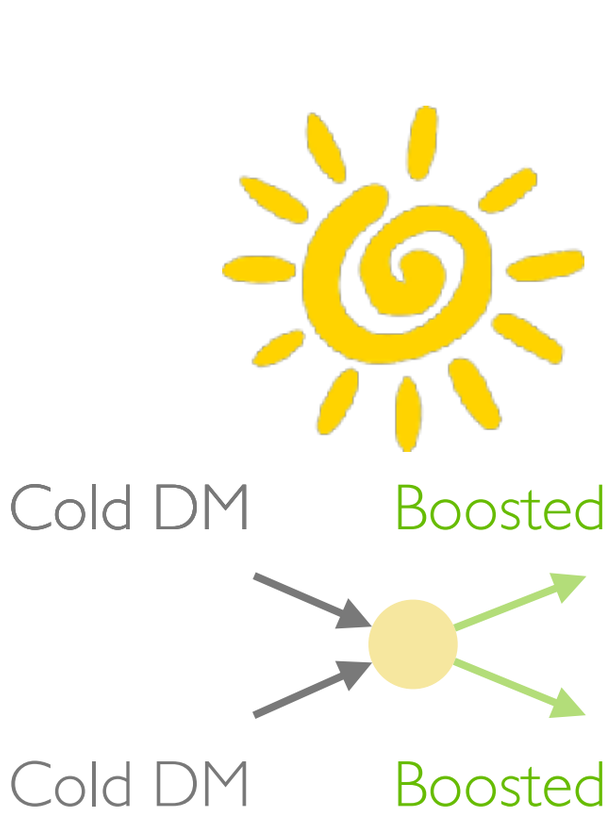

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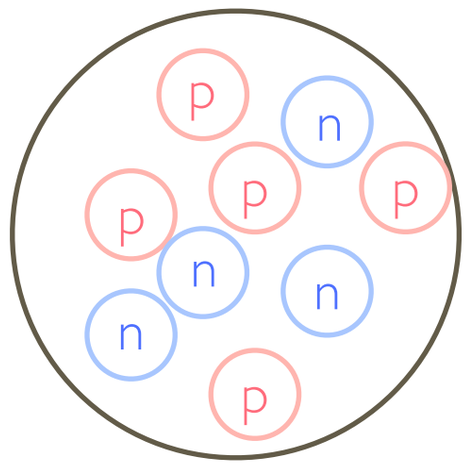
3. Boosted dark matter interact with electrons or nucleons in detectors



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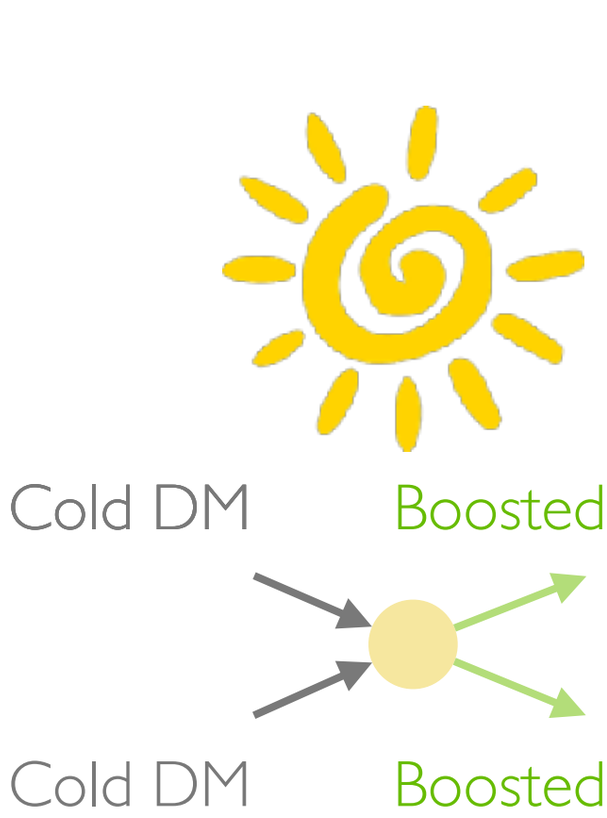

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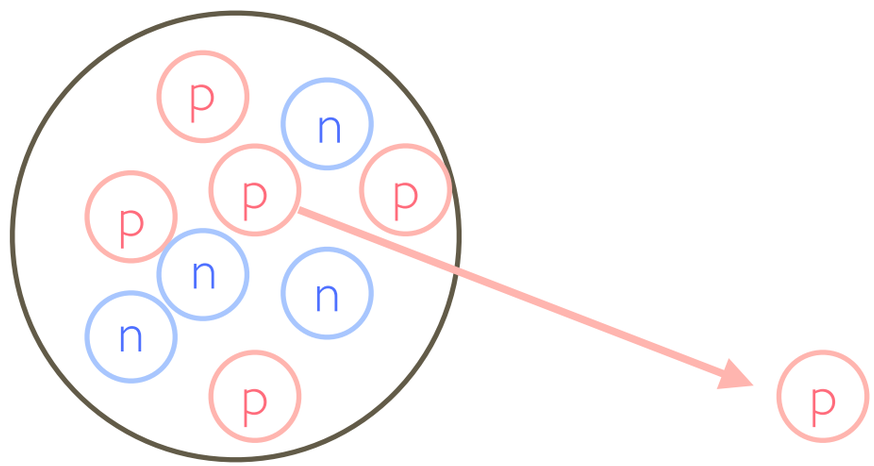
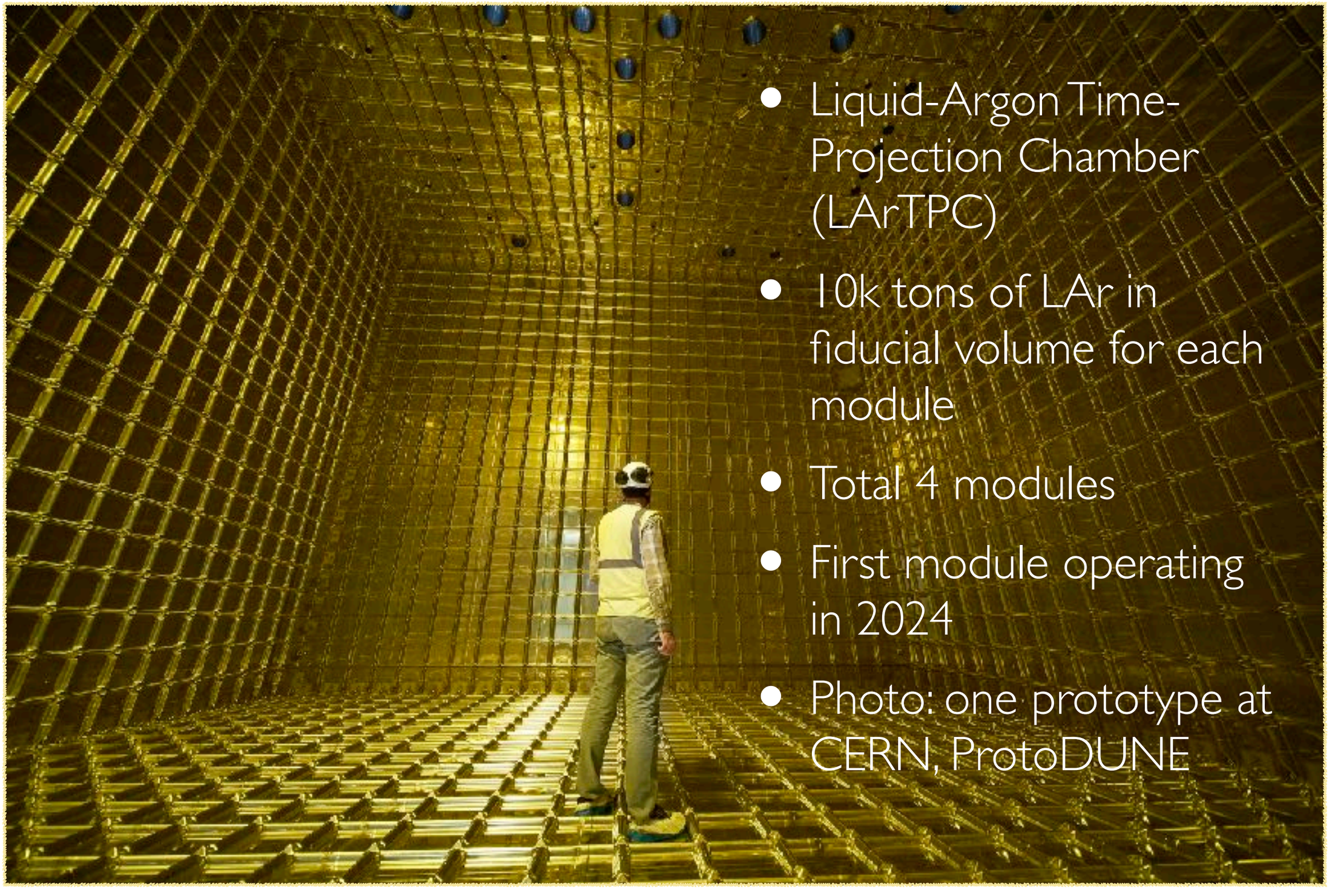


4. Look for scattered electrons or recoil protons

Refs: J. Berger's Talk, JCAP 1502 (2015) 005

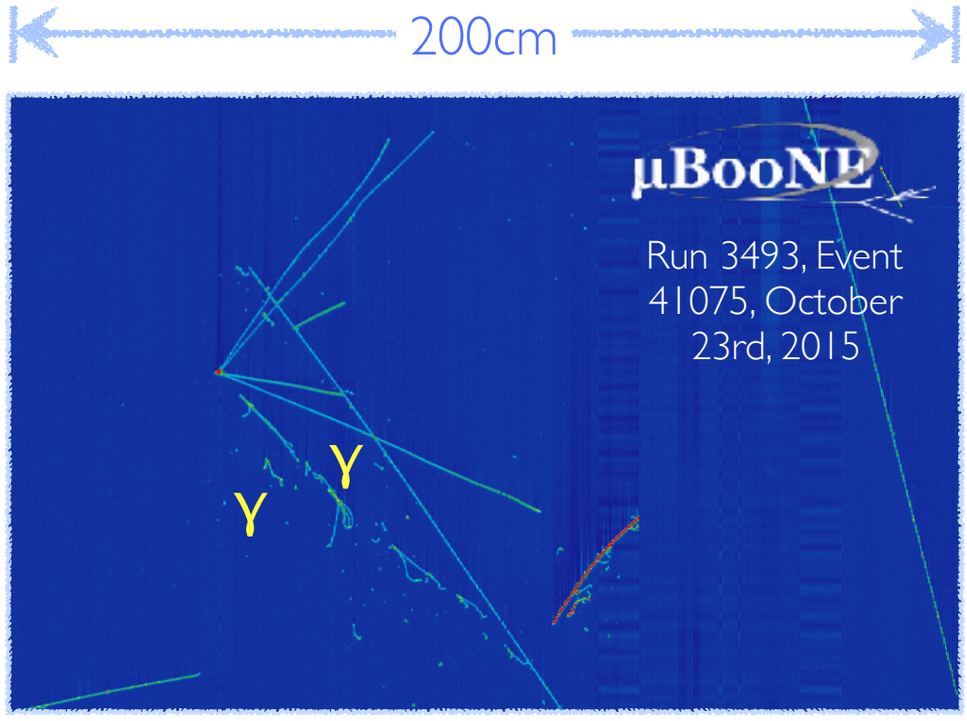
Detector: DUNE

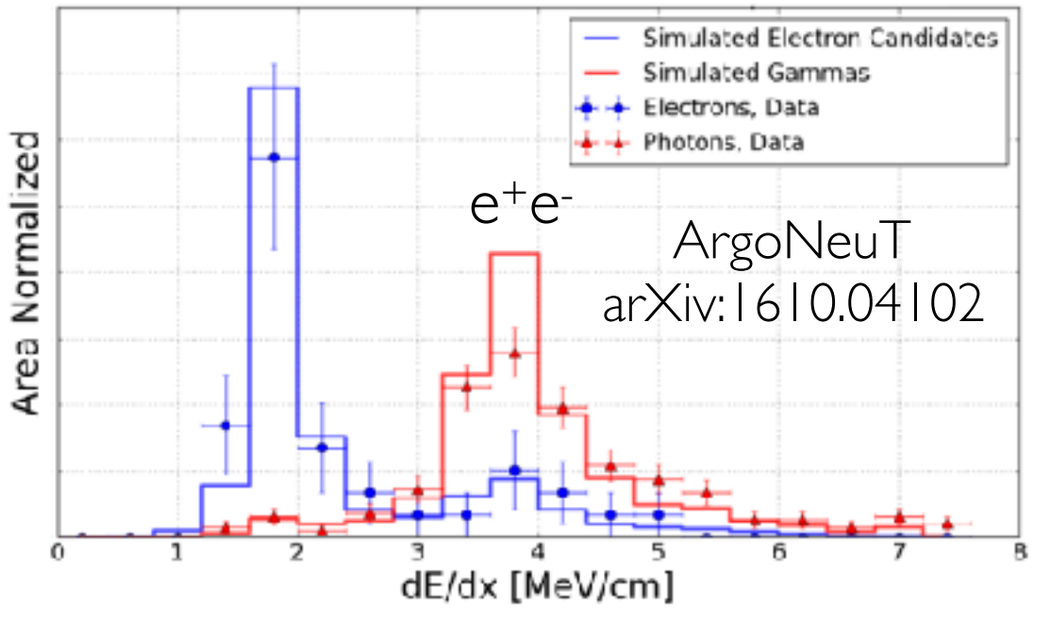


- Liquid-Argon Time-Projection Chamber (LArTPC)
- 10k tons of LAr in fiducial volume for each module
- Total 4 modules
- First module operating in 2024
- Photo: one prototype at CERN, ProtoDUNE

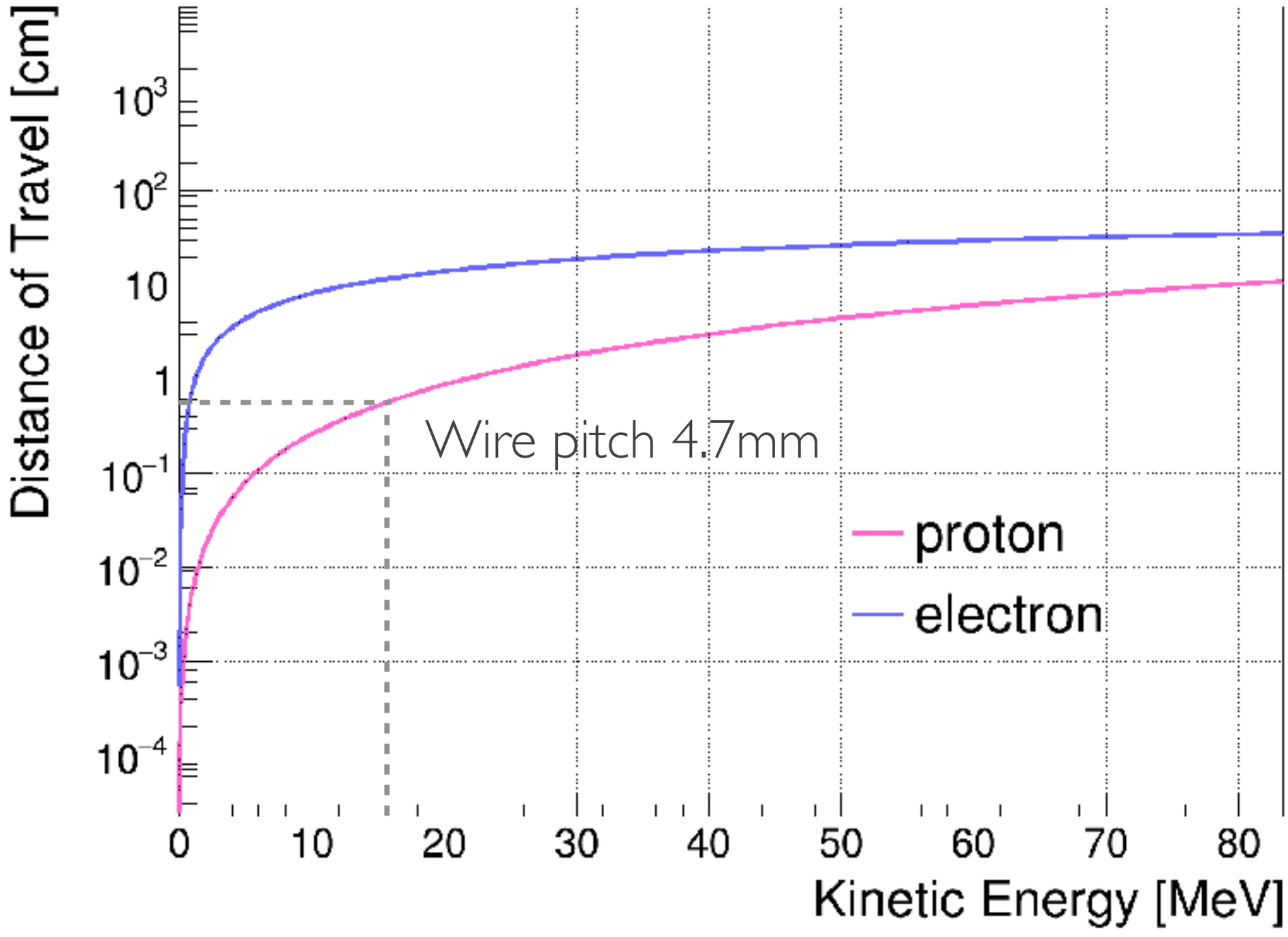
LArTPC

- LAr: large interaction rate
- Scalability: Ar inexpensive
- High spatial resolution
  - able to characterize complicated events
- Calorimetry measurement
  - e/γ separation
- Low detection threshold
- Sensitive to supernova ν_e





Low Energy Threshold

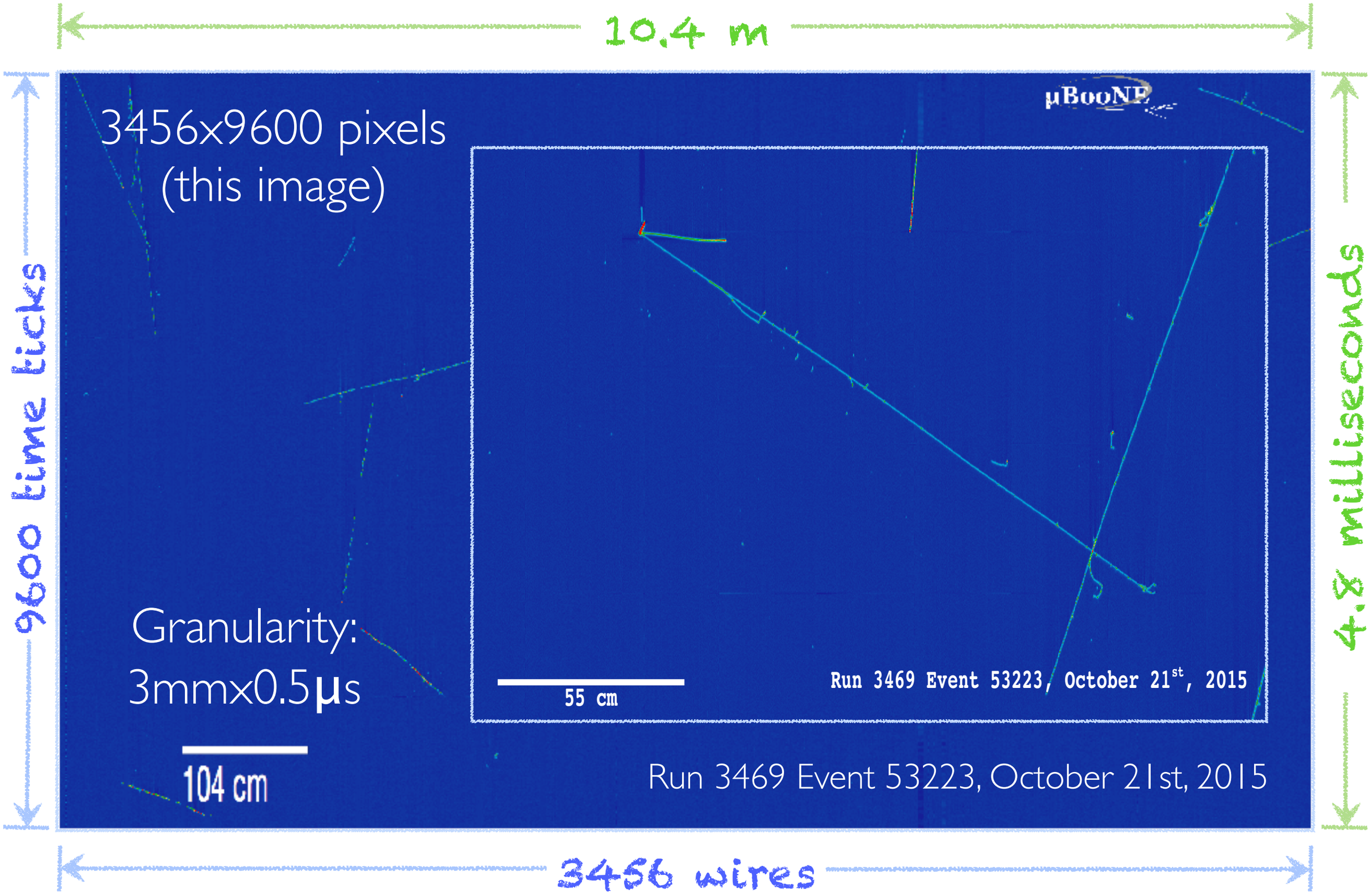


10.4 m

9600 time ticks

4.8 milliseconds

3456 wires


10.4 m
9600 time ticks
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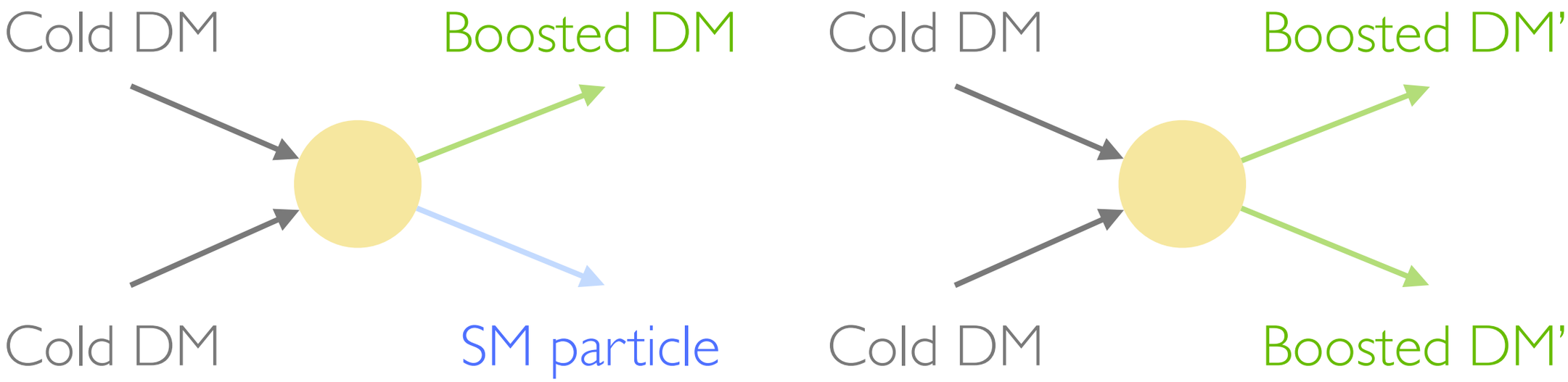
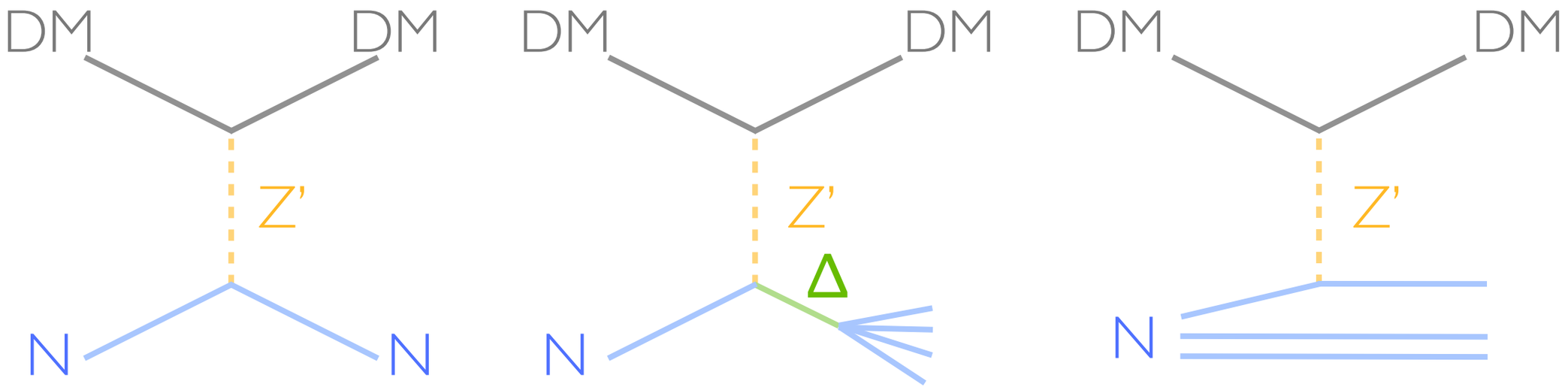
3456x9600 pixels
(this image)
μBooNE
Granularity:
3mmx0.5μs
104 cm
55 cm
Run 3469 Event 53223, October 21st, 2015
Run 3469 Event 53223, October 21st, 2015
3456 wires

Production



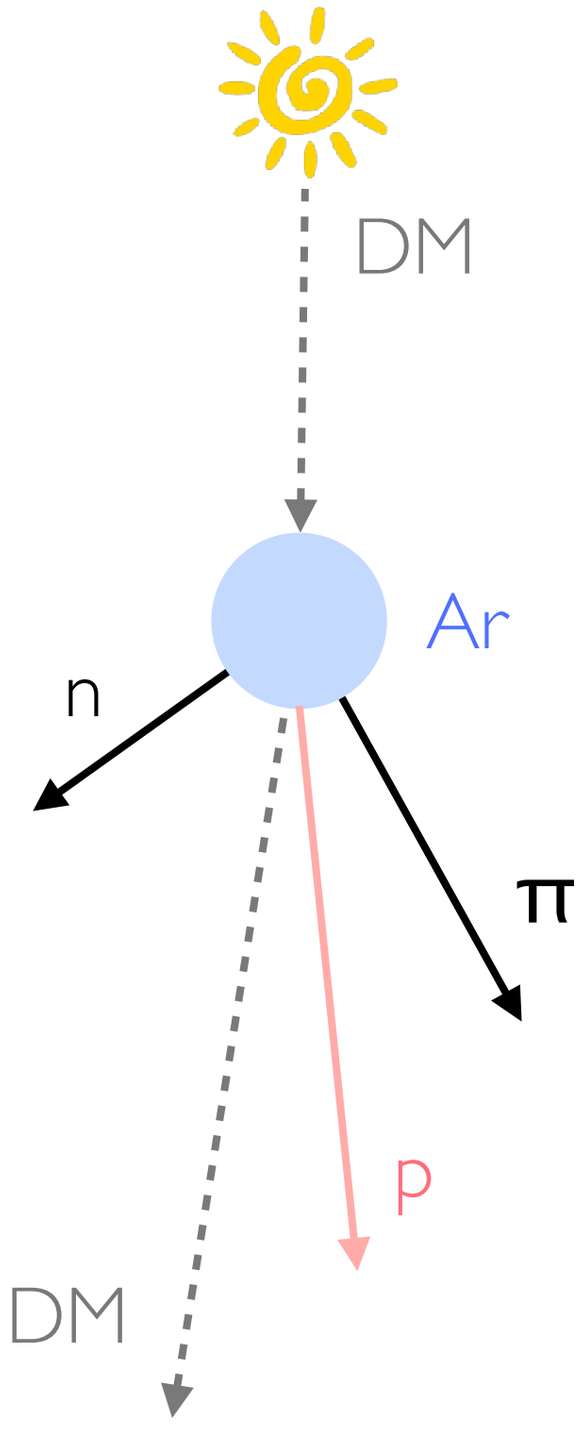
- Focus on boosted DM produced via annihilation in the Sun
- Benchmark classification: mono-energetic boosted DM flux (JCAP 1502 (2015) 005)
  - Energy depends on masses of dark matter

Detection



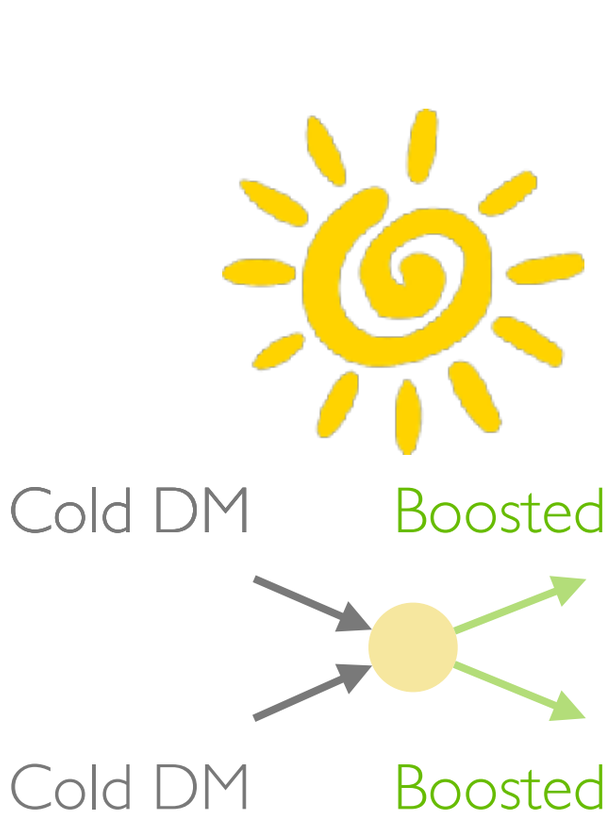
- DM-SM particle interactions mediated by Z' vector boson (neutral current-like)
- Focus on baryophilic channels: better sensitivity in DUNE; complementary to other searches
- Only spin dependent couplings at tree level
- Focus on elastic scattering and deep inelastic scattering at this stage (resonant scattering to come)

Boosted DM Signal



- Mono-energetic boosted DM flux coming from the Sun direction, with information about relative DUNE location
- DM-Ar interaction events provided by J. Berger
- GENIE simulates the final state interactions
  - GENIE default FSI model: HAIntranuke model
- Probe the (DM-Z', Z'-SM) coupling constants ($g_{Z'}$)

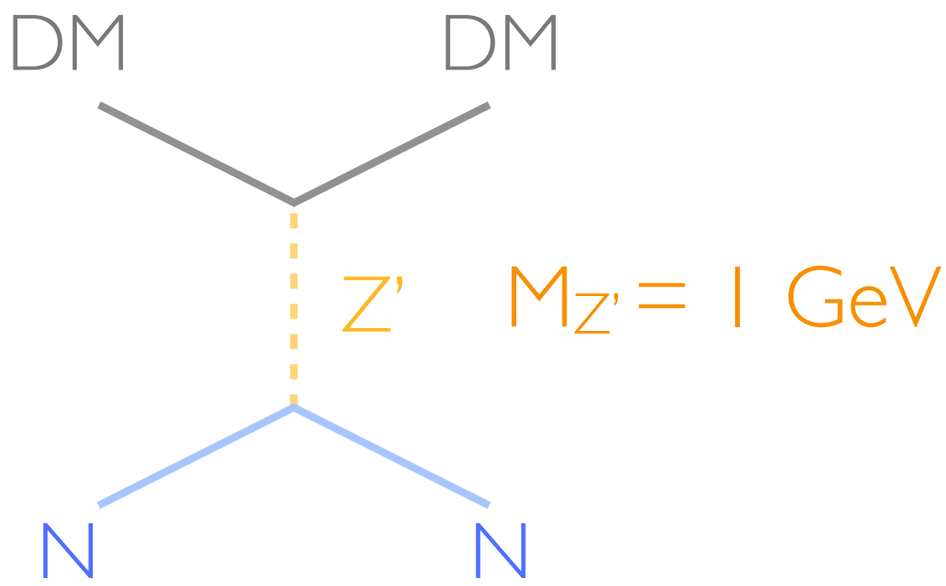
Parameter Space



Four boosted DM mass (M_{DM}): 5, 10, 20, 40 GeV

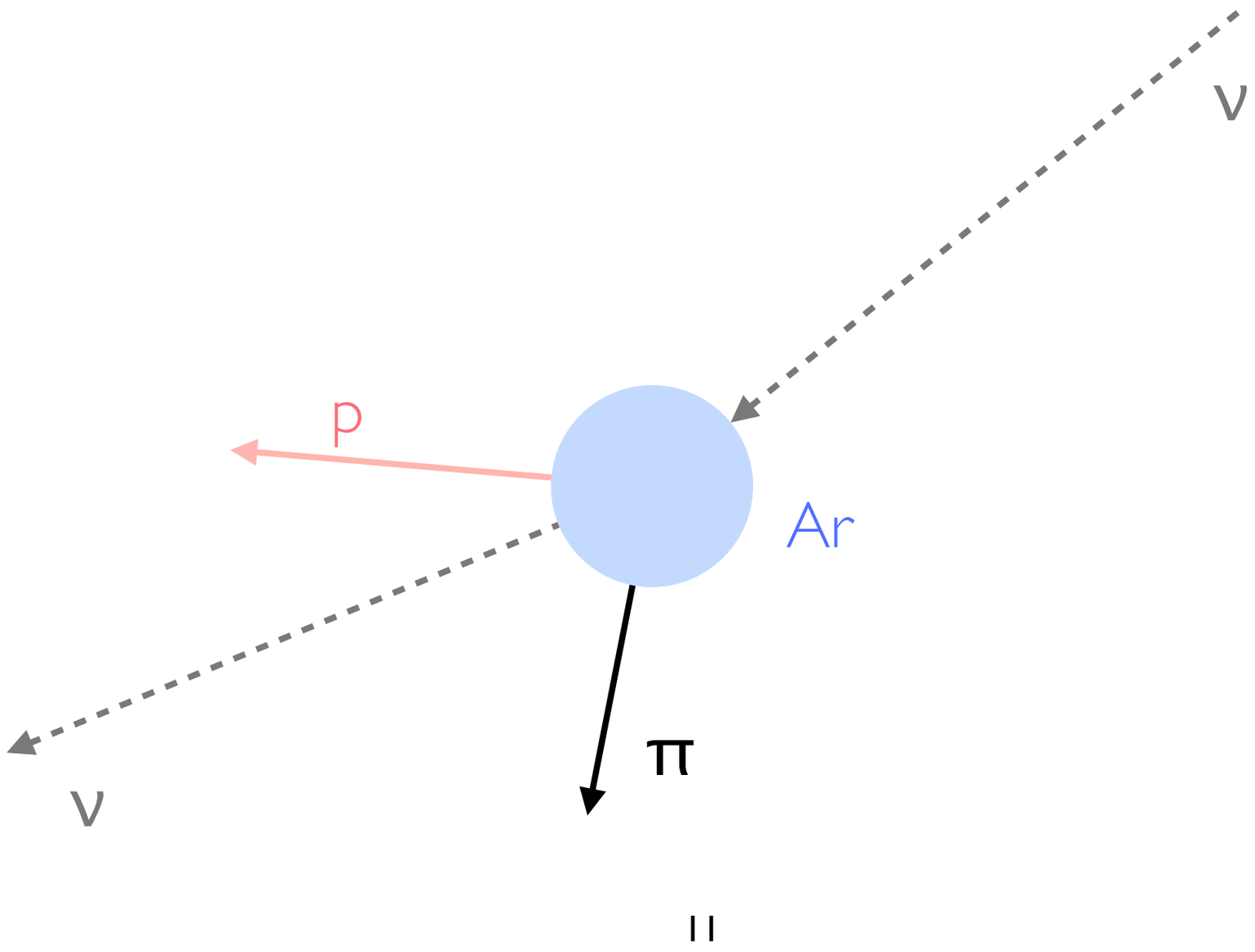
Three boosted factors (γ): 1.25, 2, 10

$$\gamma = \frac{M_{\text{cold DM}}}{M_{\text{boosted DM}}}$$



Main Background

Main background events:
neutral-current (NC)
atmospheric neutrinos



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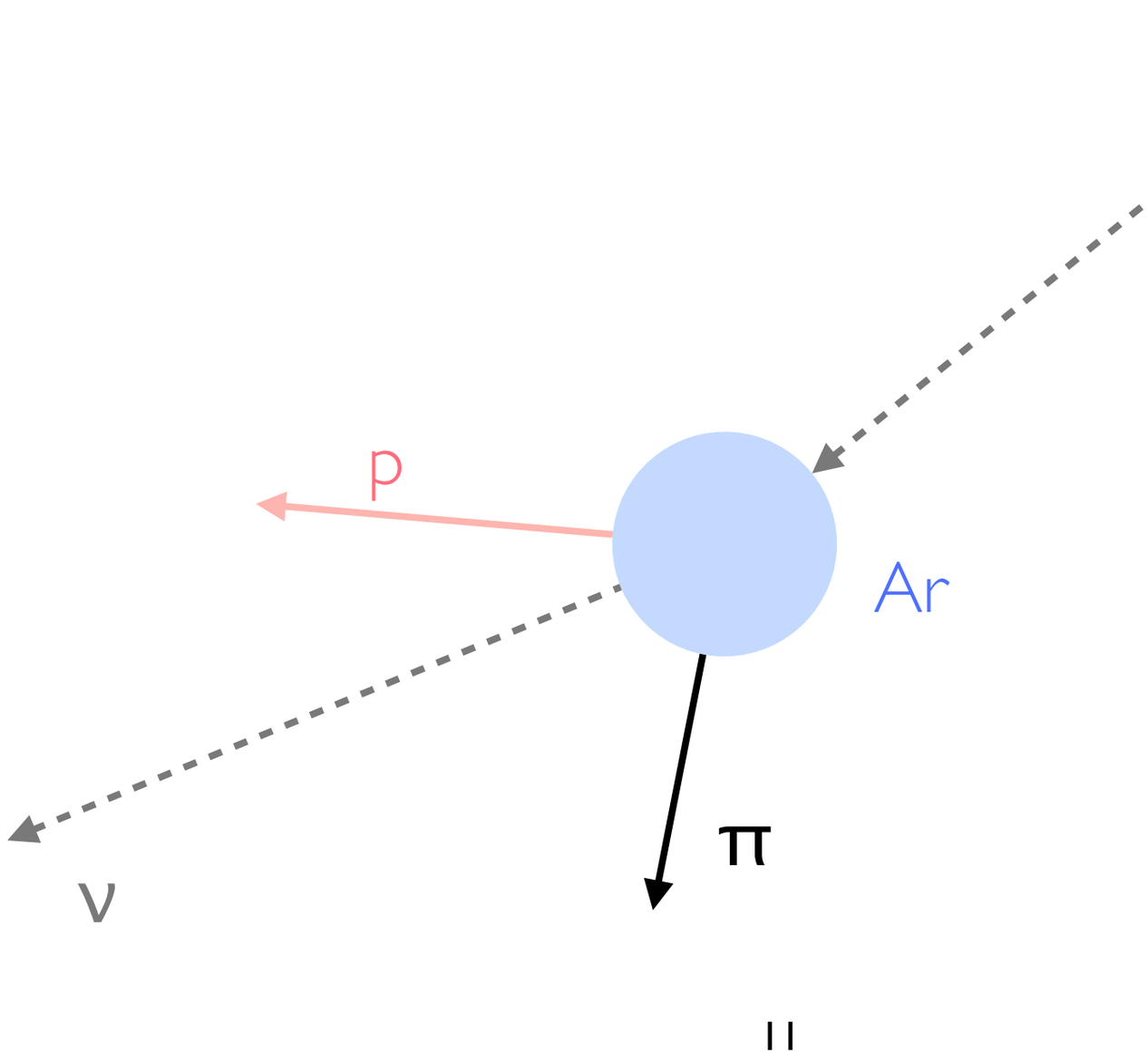
Bartol maximum
flux: ν_e, ν_μ, $\overline{\nu}_e$, $\overline{\nu}_\mu$



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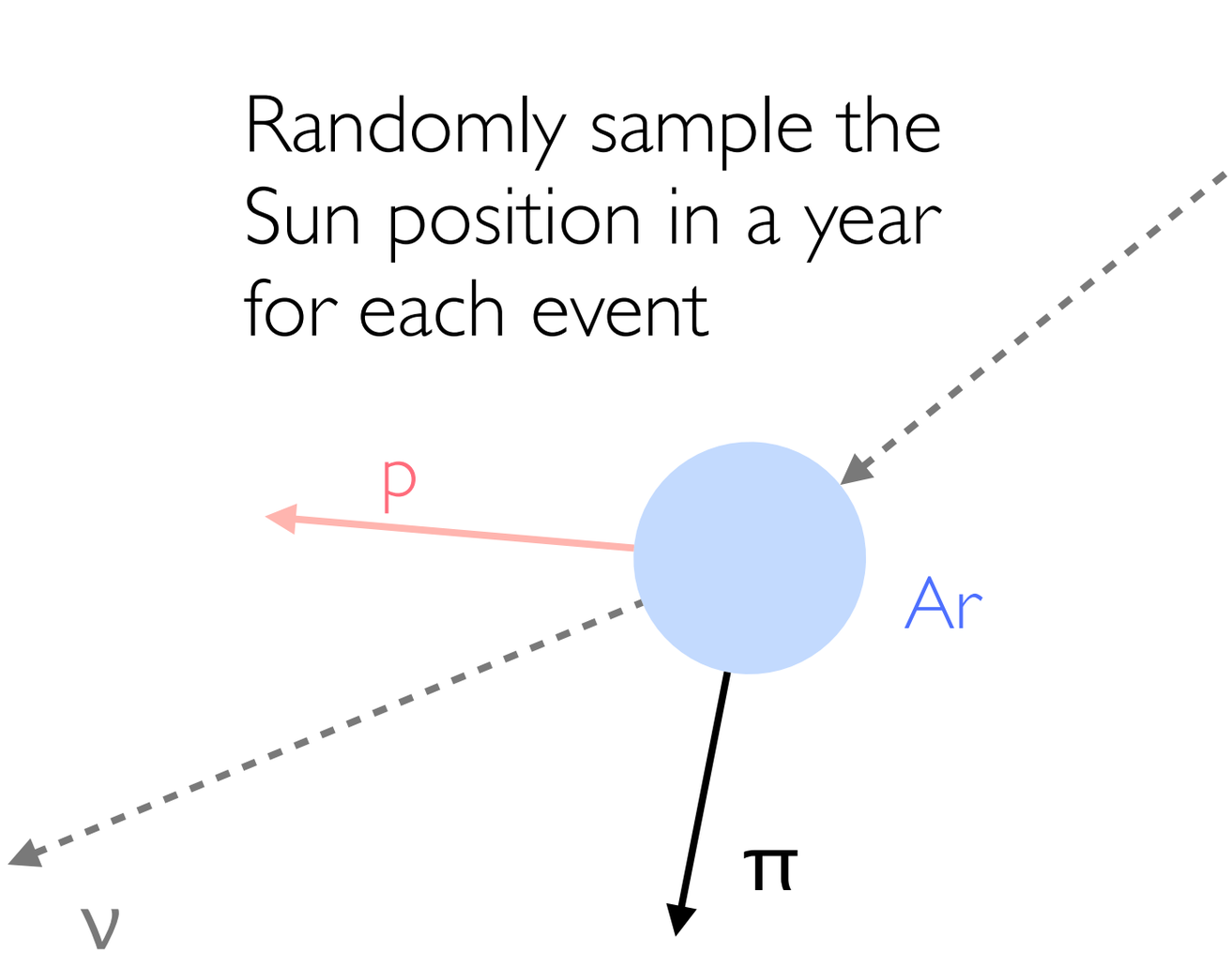
Randomly sample the
Sun position in a year
for each event



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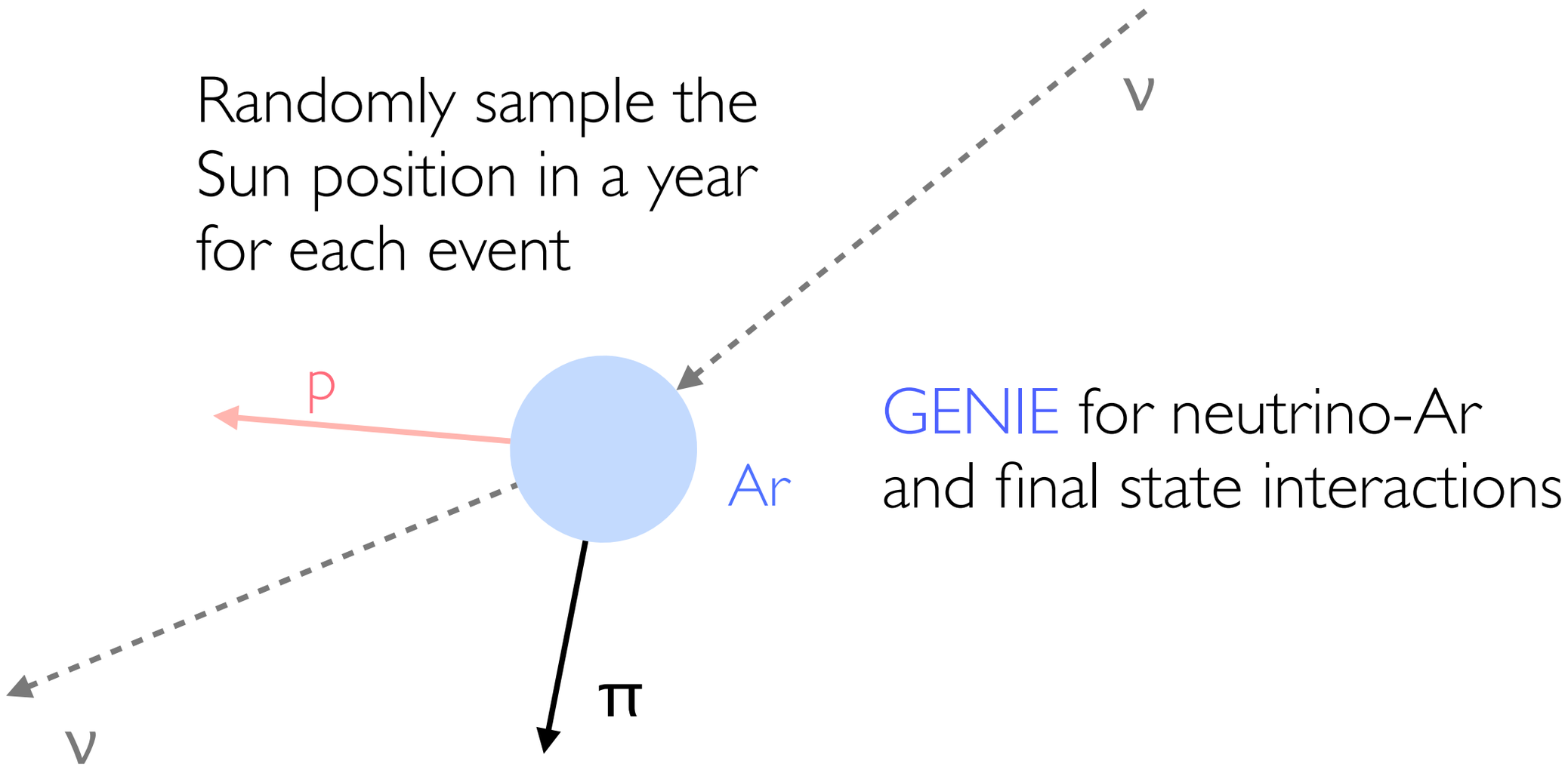

GENIE for neutrino-Ar
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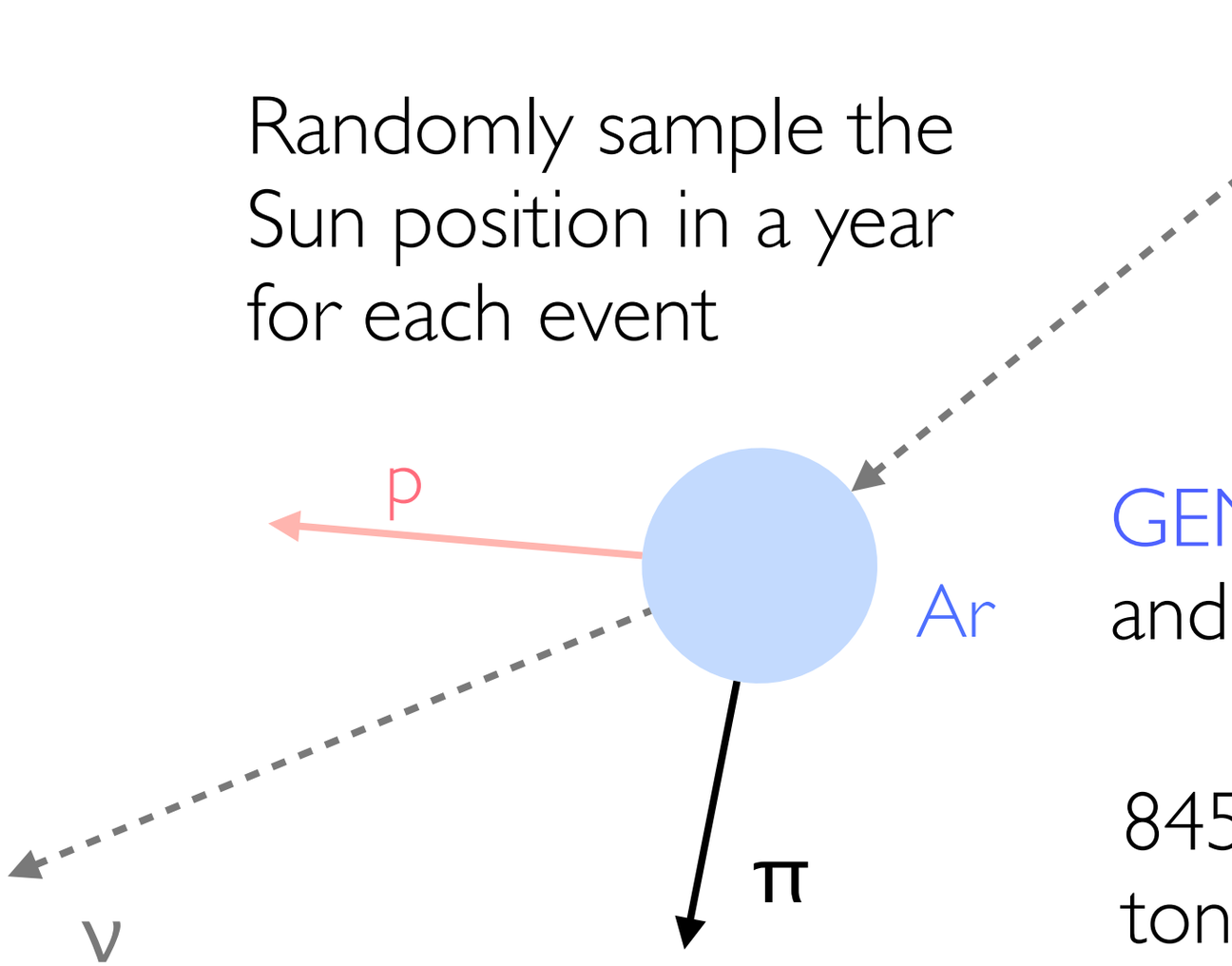
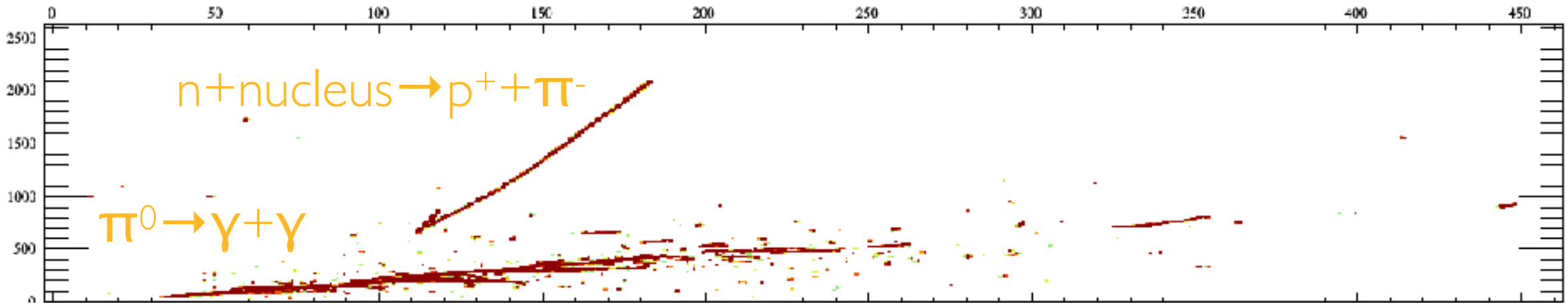


GENIE for neutrino-Ar
and final state interactions

845 NC events in 10k
ton LAr per year

Detector Response

M_{DM} = 40 GeV, E_{DM} = 400 GeV DM+Ar→DM+π^0+π^0+n+X



- GEANT4 detector material (LAr) simulation
- Consider quasi-stable final state particles:
  $p^{\pm}$, n, $\pi^{\pm}$, $\mu^{\pm}$, $e^{\pm}$, γ

Detector Response

- Detector effects
  - Angular resolution
  - Energy resolution
  - Detection threshold (in kinetic energy)
  - Detector acceptance
  - Reconstruction efficiency
  - Particle identification efficiency
- Study different scenarios
  - DUNE CDR, MicroBooNE, and other scenarios
  - Include neutrons or not

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Today's results

Detector Response Today

- DUNE Conceptual Design Report (2016) scenario
- Other detector effects in progress

	Angular resolution	Energy/Momentum resolution	KE Threshold [MeV]
p	5°	p<400 MeV/c: 10% p>400 MeV/c: 5%⊕30%/√E [GeV]	50
n	5°	40%/√E [GeV]	50
π	1°	**μ**-like contained: track length **π**-like contained: 5% Shower or exiting: 30%	100
e/**γ**	1°	2%⊕15%√E [GeV]	30
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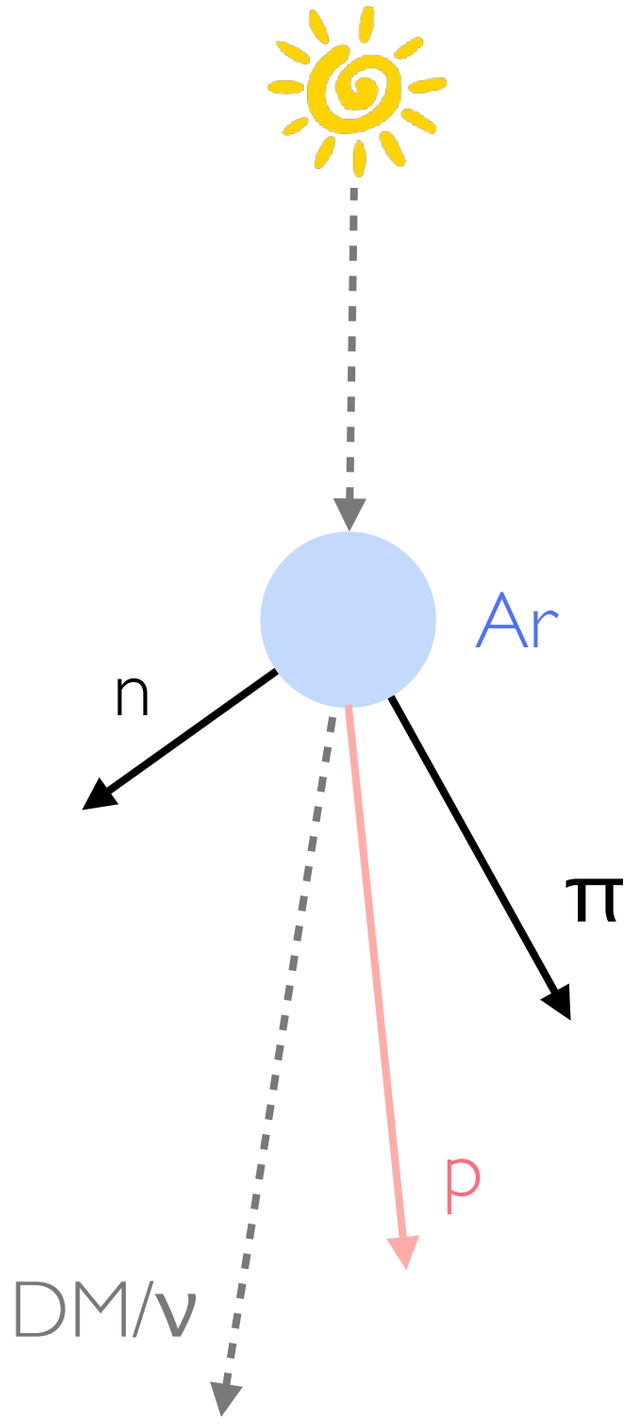
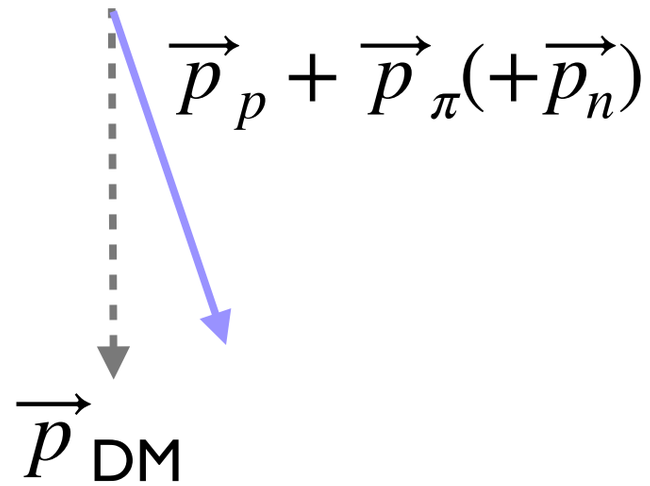
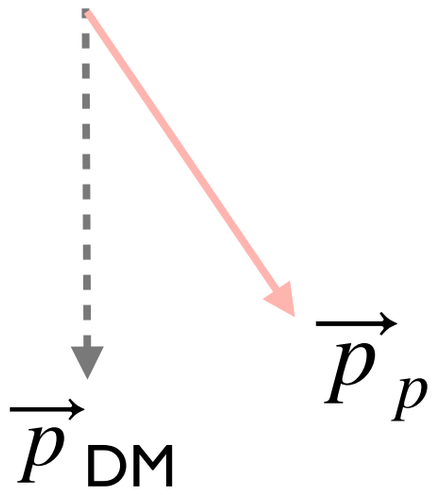


1. Angle between the Sun direction and the total momentum of all the visible particles in the final state



2. Angle between the Sun direction and the leading particle in the final state



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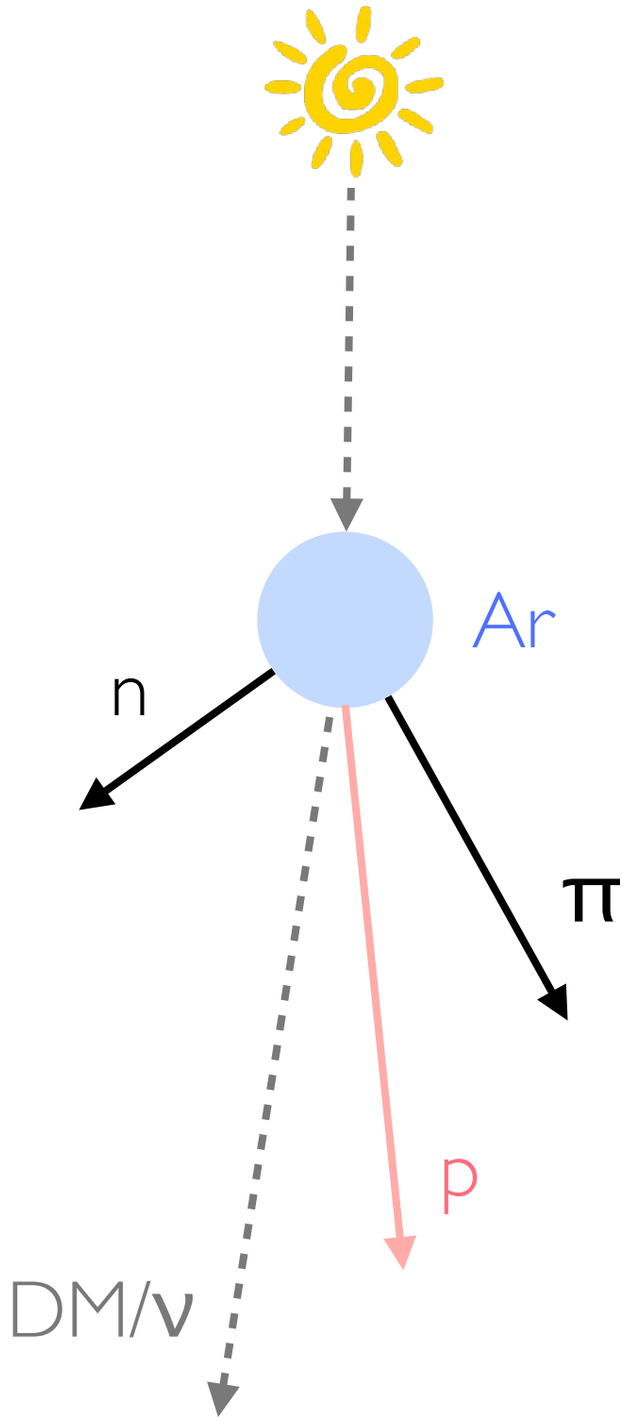

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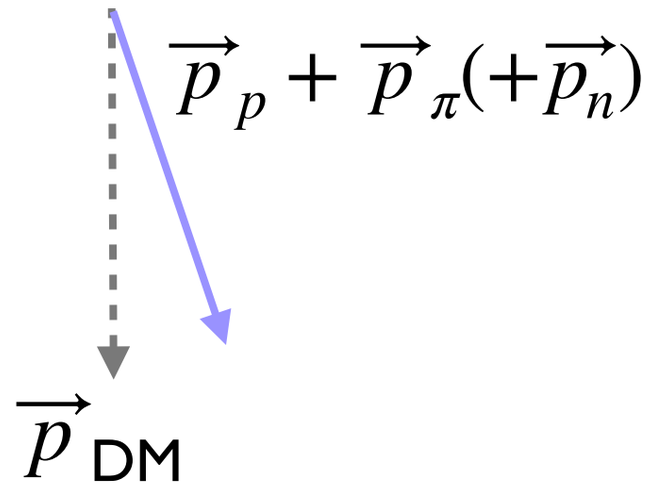

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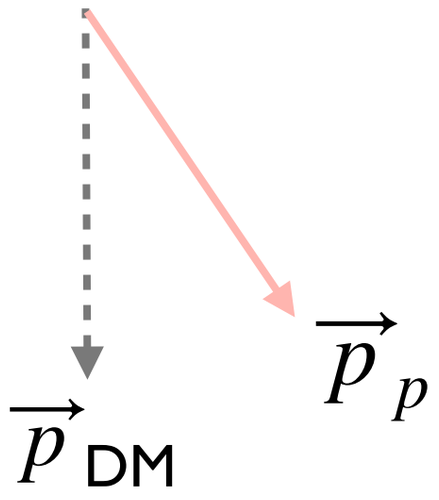
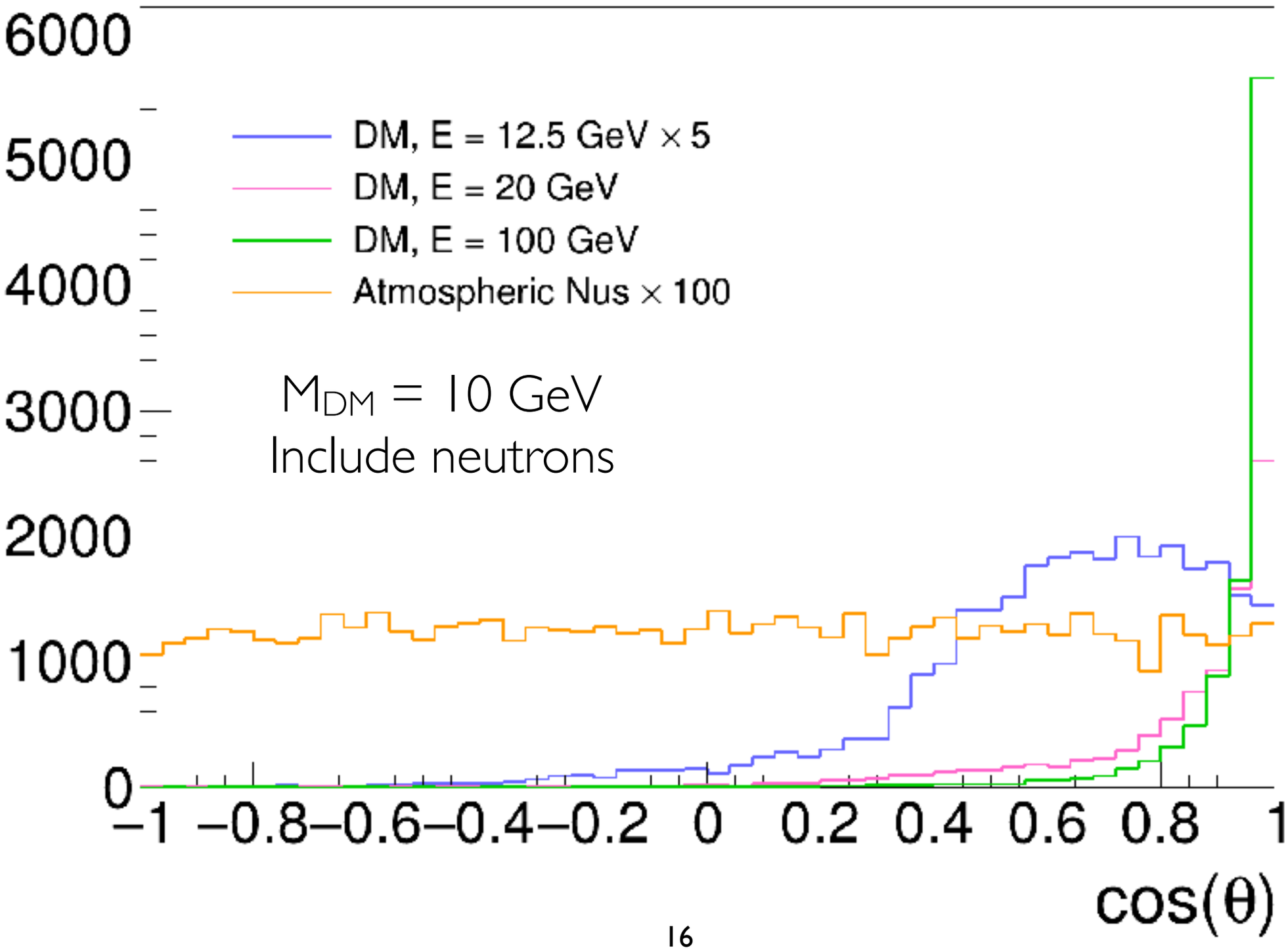


Total Momentum



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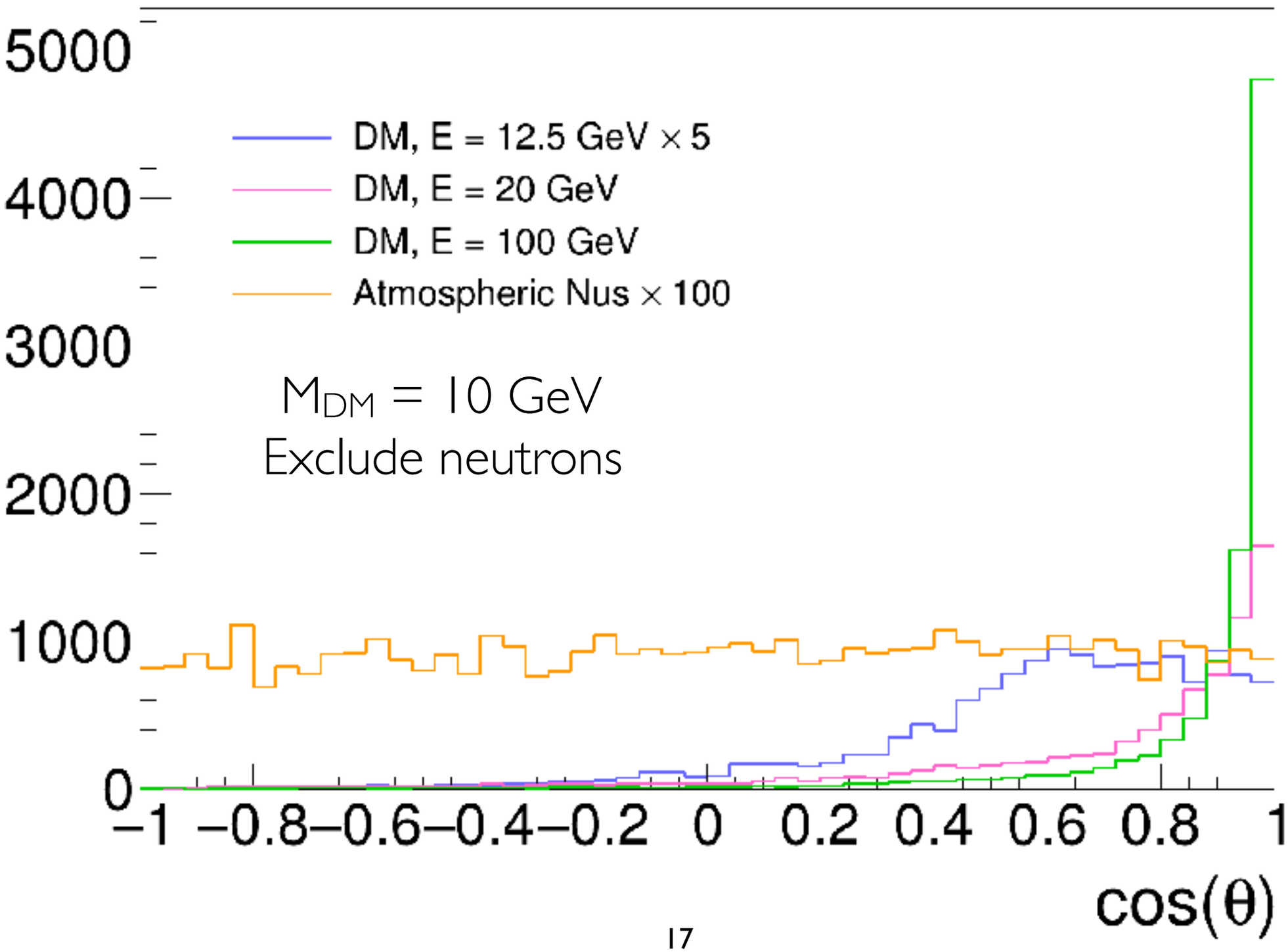
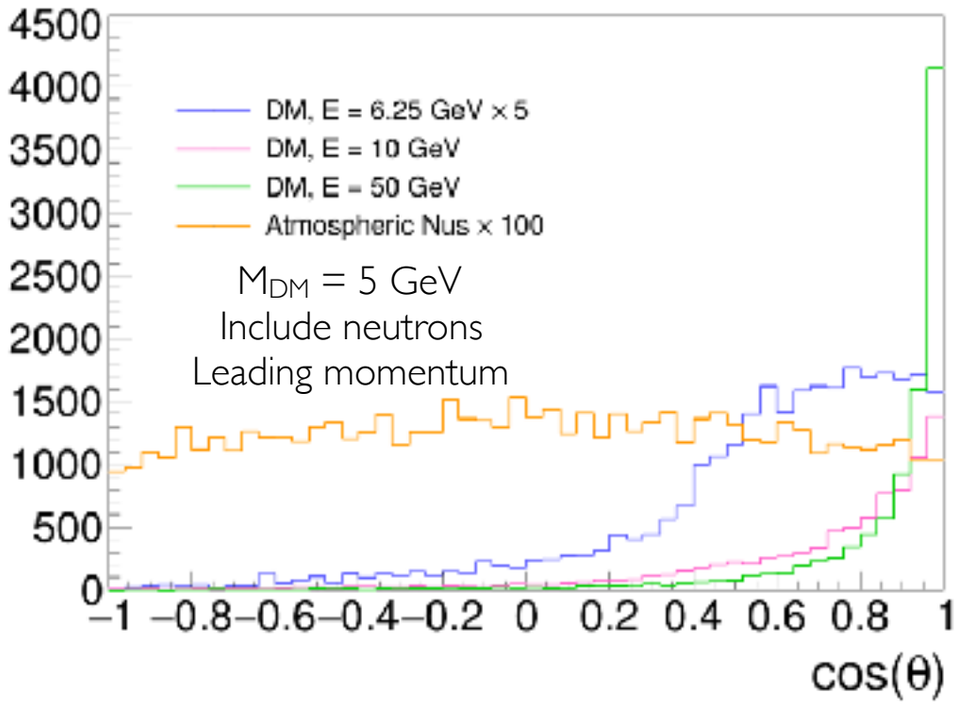
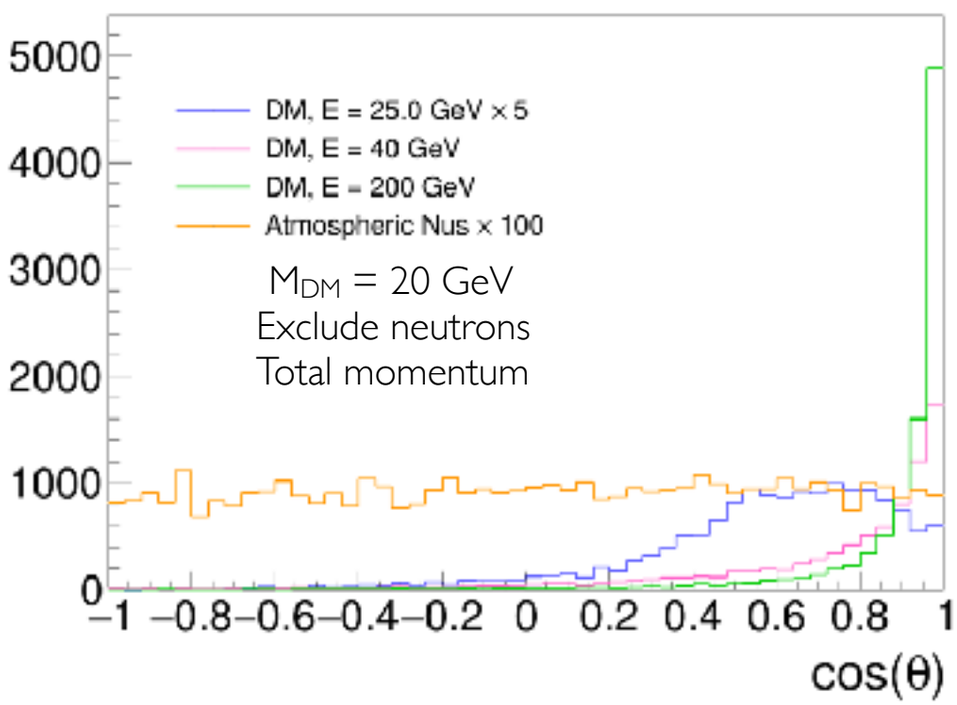
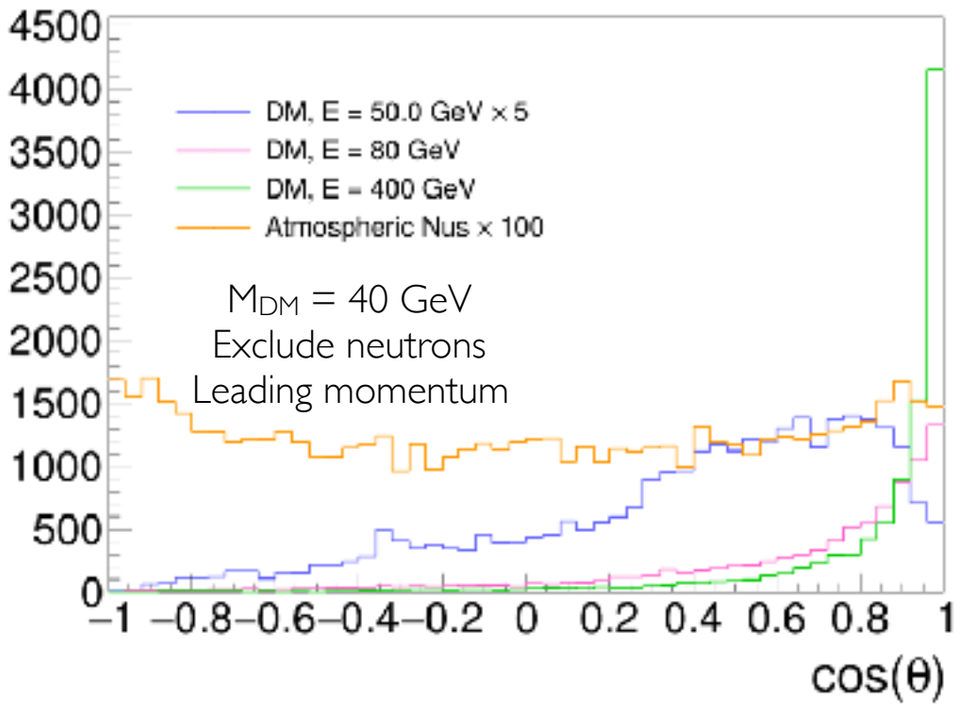
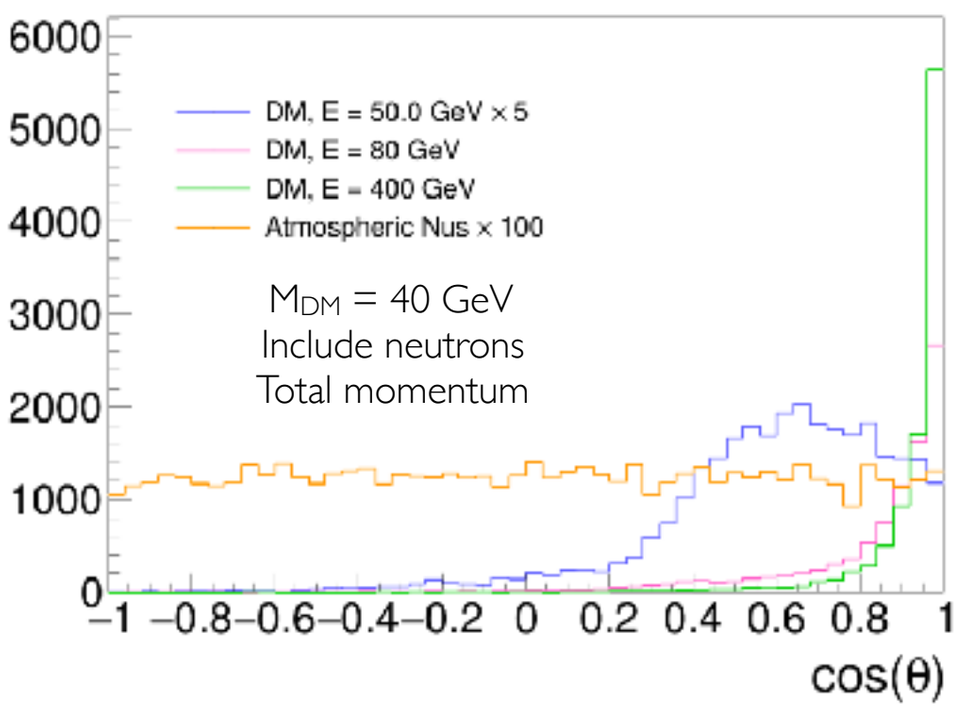


Angular Distribution

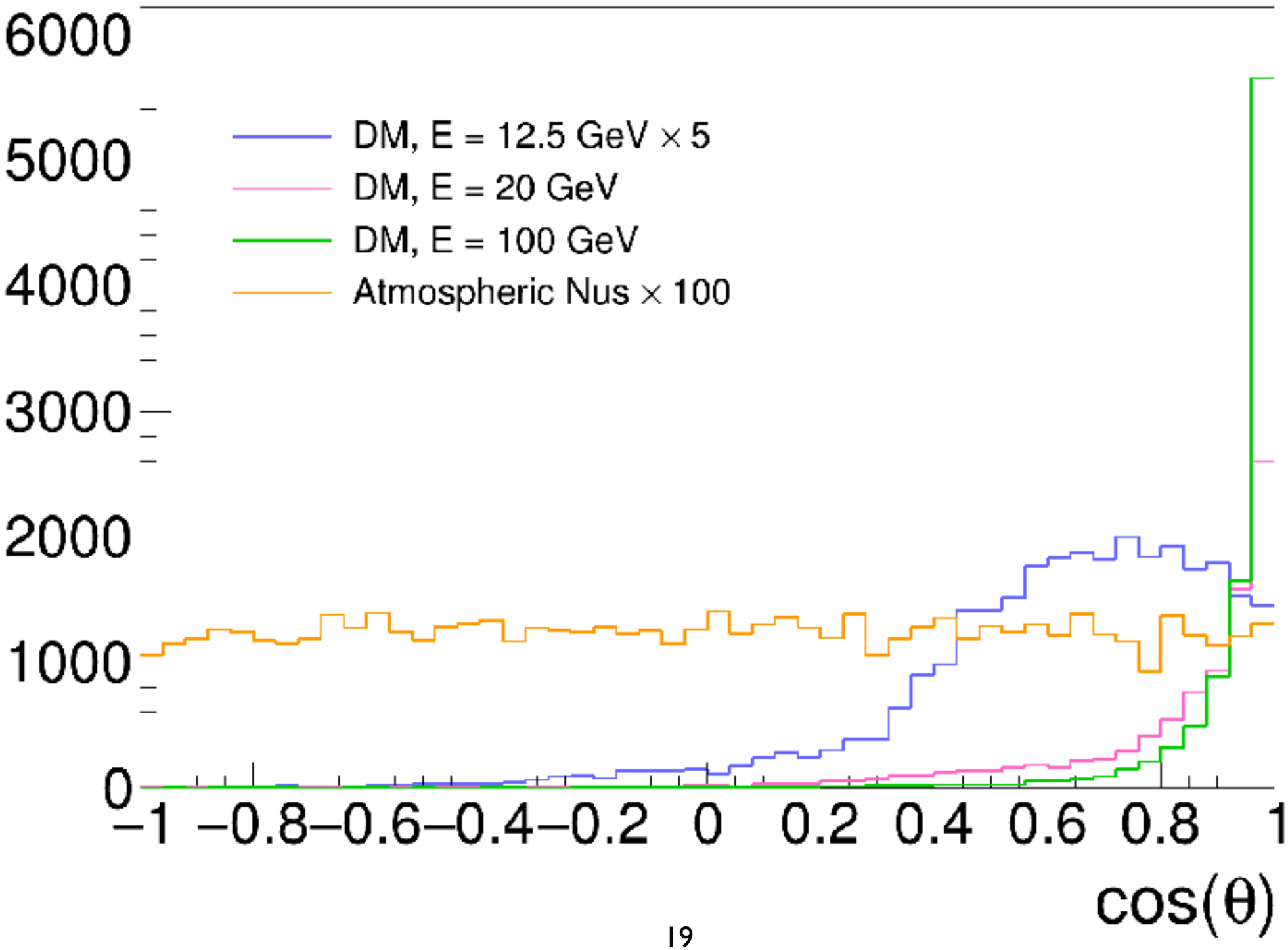








Preliminary Selection



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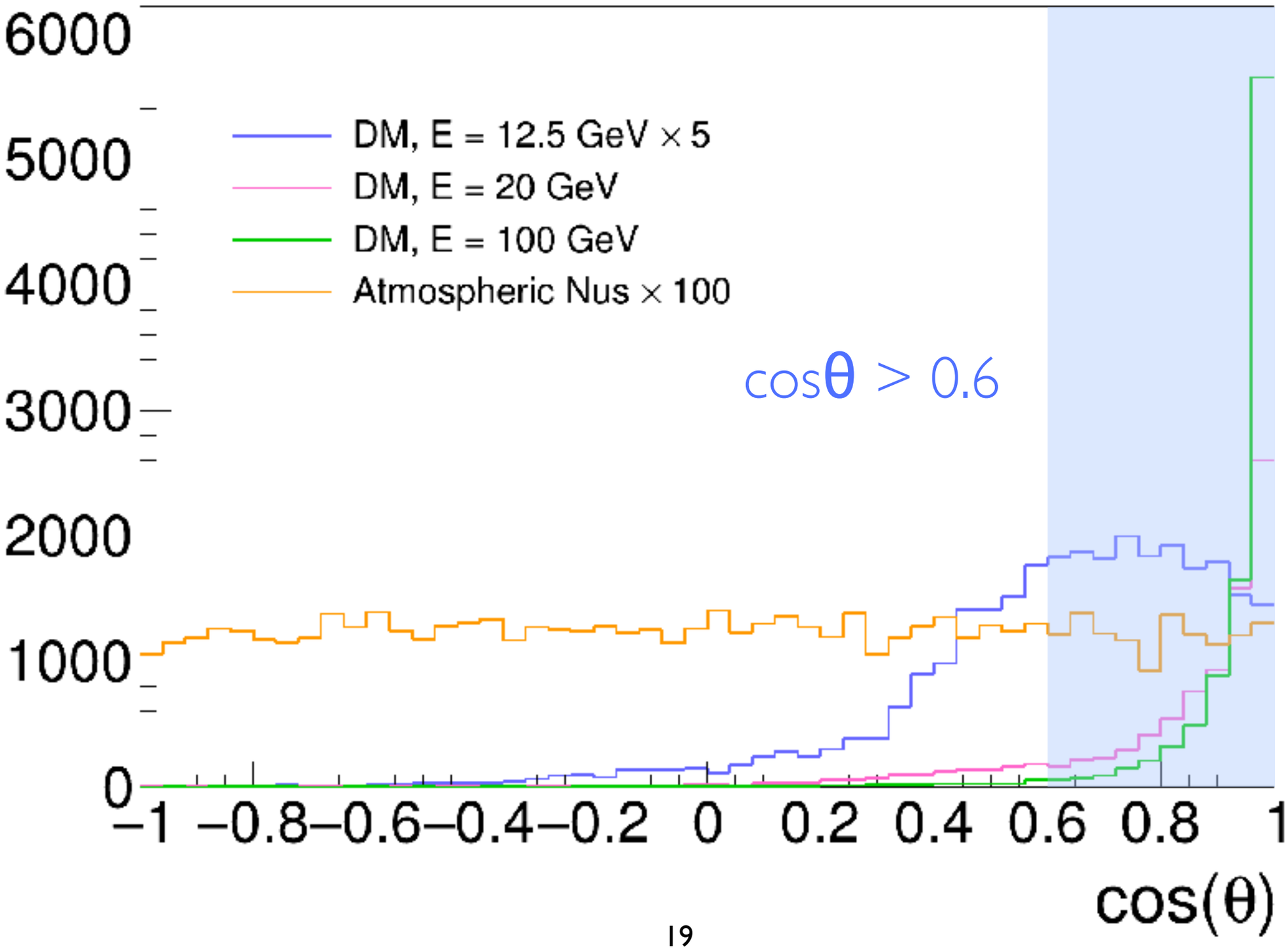

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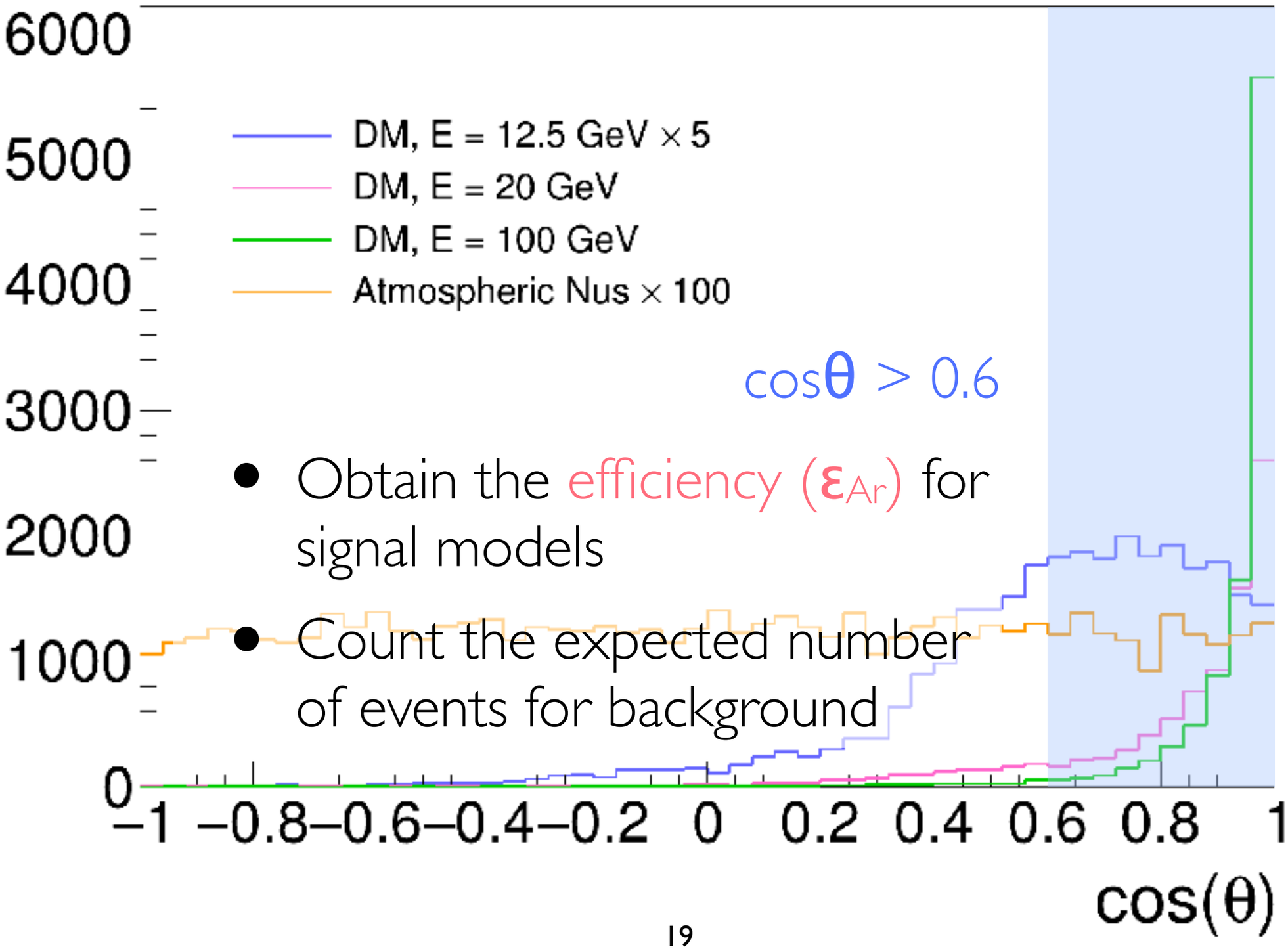


- Obtain the efficiency (ε_{Ar}) for signal models
- Count the expected number of events for background

Event Rate

- Signal event rate (per second):

$$\Phi(g_{Z'}=1) \times \sigma_{\text{DM-SM}}(g_{Z'}=1) \times g_{Z'}^{8} \times \epsilon_{\text{Ar}} \times N_p$$

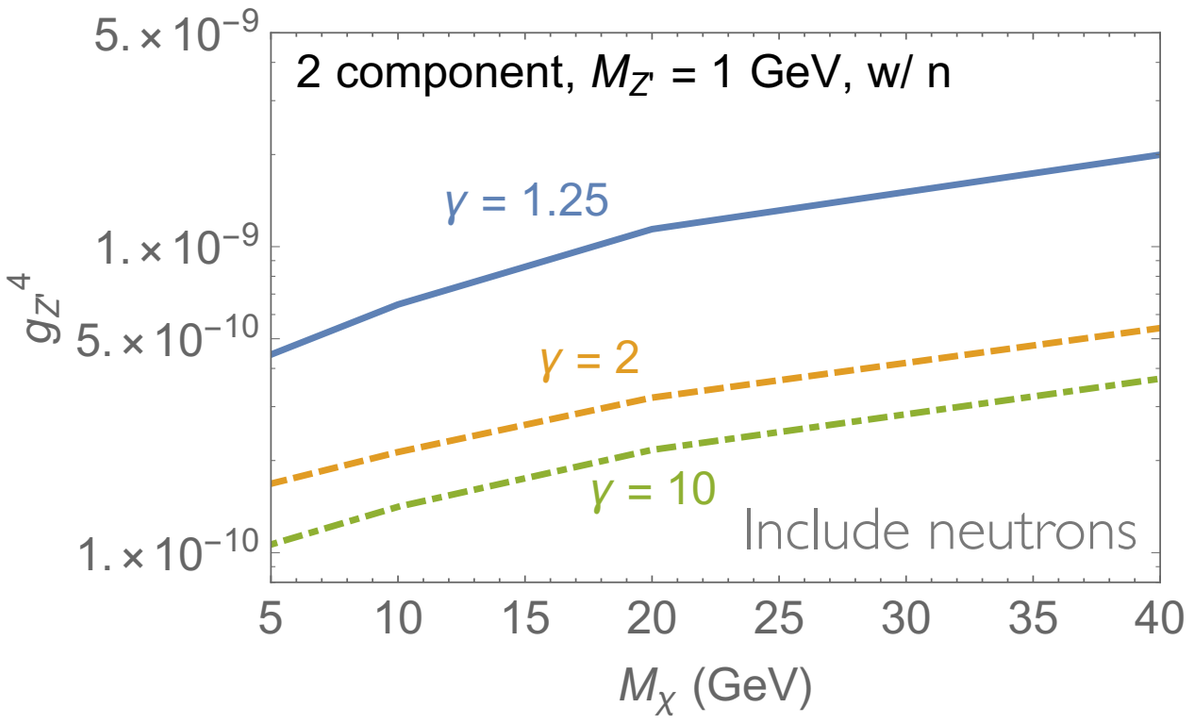
  - $N_p = 2.7\text{x}10^{33}$ for 10k tons of LAr
- Expected numbers of background events per year
  - Scenario if reconstructing neutrons: 104.0±2.7
  - Scenario if *not* reconstructing neutrons: 79.4±2.4

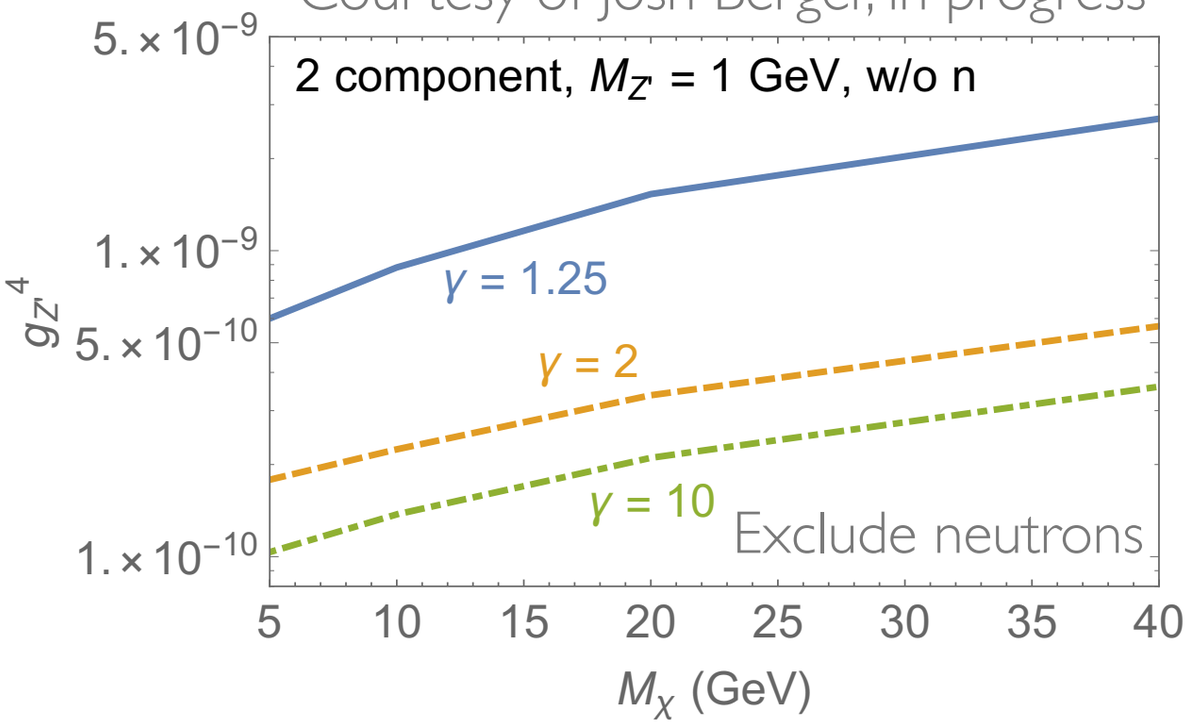
Efficiency and Cross Section

M_{DM} (GeV)	γ	ϵ_{Ar} (w/ n)	ϵ_{Ar} (w/o n)	$\sigma_{\mathrm{DM-Ar}}/g_{Z'}^4$ (cm^2)
5	1.25	0.3621	0.1745	3.12217×10^{-28}
10	1.25	0.3557	0.1689	2.79196×10^{-28}
20	1.25	0.3401	0.1664	2.28276×10^{-28}
40	1.25	0.332	0.1601	2.25314×10^{-28}
5	2	0.732	0.5718	1.07767×10^{-27}
10	2	0.7745	0.6163	1.18175×10^{-27}
20	2	0.7885	0.6306	1.24278×10^{-27}
40	2	0.7974	0.642	1.27414×10^{-27}
5	10	0.9494	0.8825	2.07506×10^{-27}
10	10	0.9569	0.8892	2.17985×10^{-27}
20	10	0.9607	0.8979	2.23837×10^{-27}
40	10	0.9636	0.9013	2.25703×10^{-27}

Sensitivity

Courtesy of Josh Berger, in progress





- Large statistic estimate for the expected significance

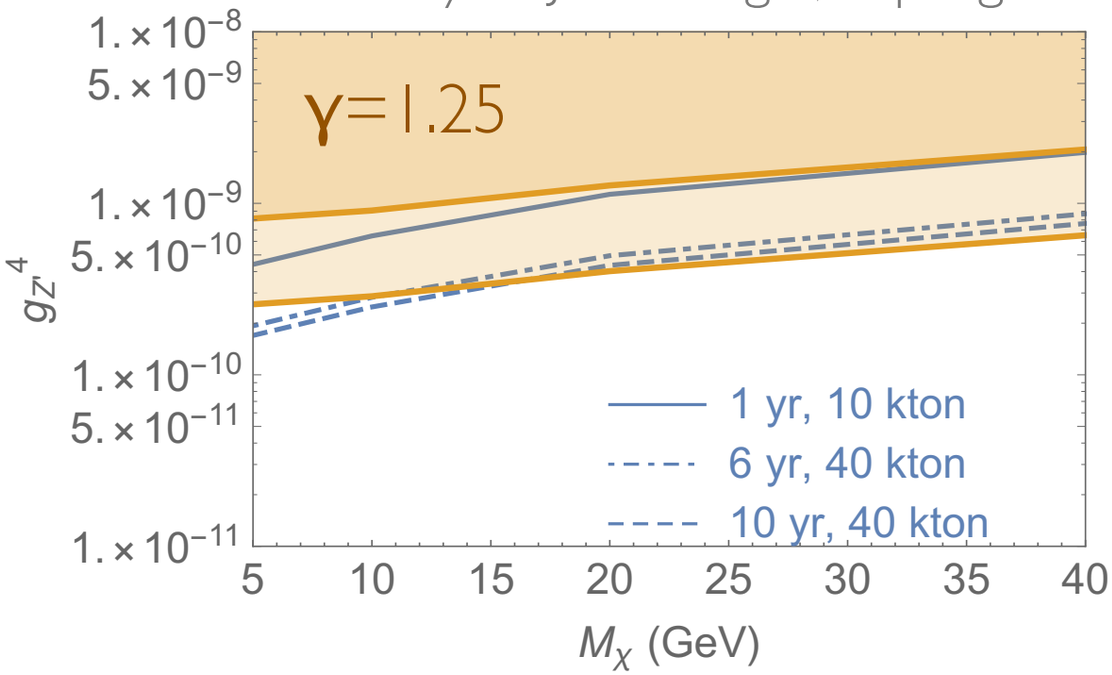
$$Z \approx \sqrt{2\left[(s+b)\log\left(1+\frac{s}{b}\right)-s\right]}$$

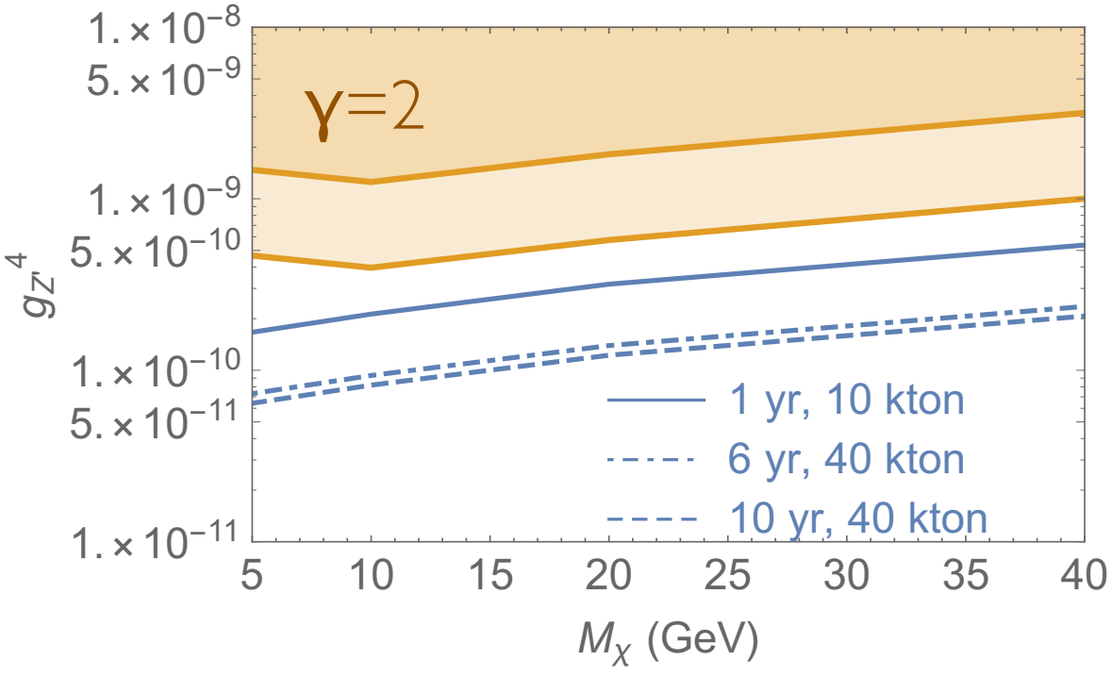
- Project 5SD discovery reach with 10k ton x1 year

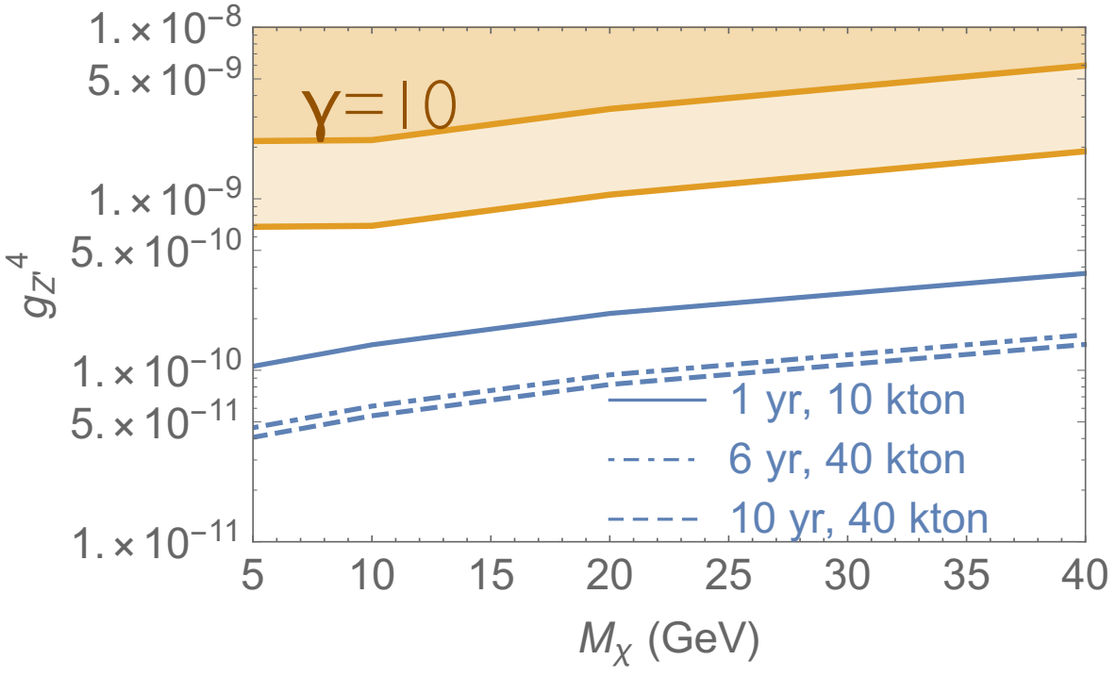
Sensitivity Comparison

- Super-Kamiokande with 6 years and 22.5k ton fiducial volume
- No oriented efficiency measurement from Super-K; not fair comparison

Courtesy of Josh Berger, in progress



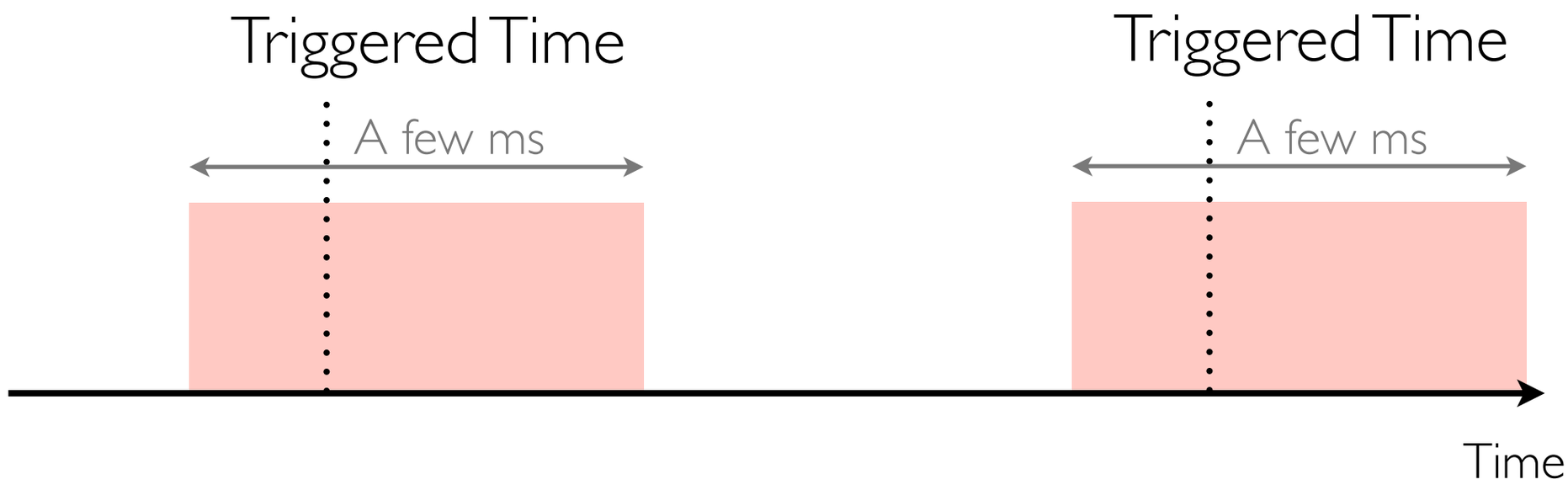




Experimental Remarks

Collect Data in DUNE

Record neutrino events induced by accelerator beam:
Know when neutrinos arrive in advance
Record the relevant chunk of data



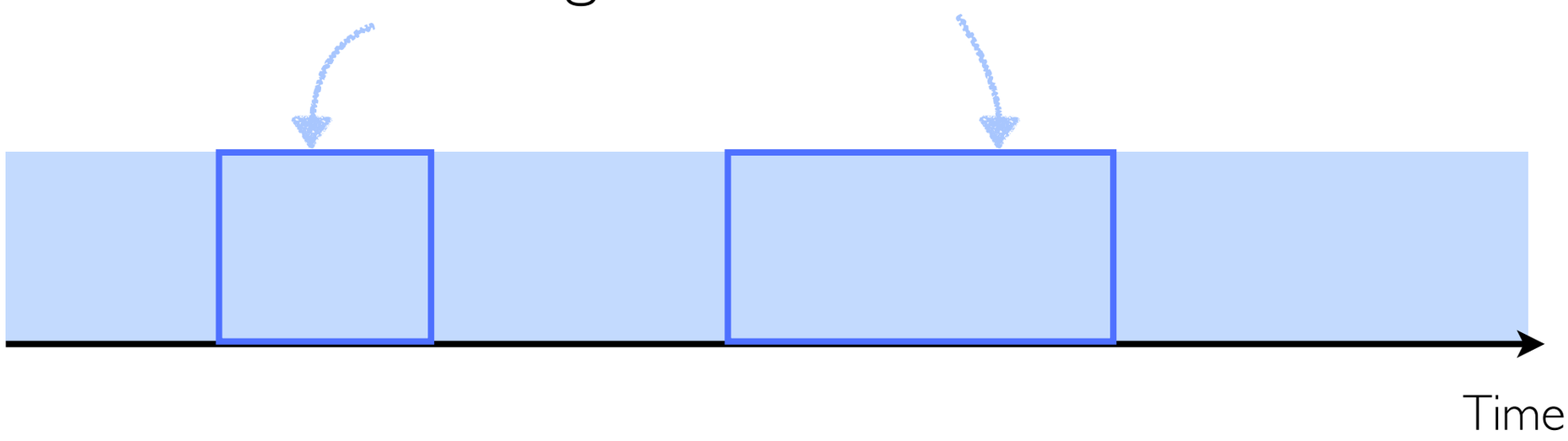
Collect Data in DUNE

Record physics events not induced by accelerator beam:
Do not know when interesting events occur in advance
Continuously read out data

Collect Data in DUNE

Record physics events not induced by accelerator beam:
Do not know when interesting events occur in advance
Continuously read out data

Find interesting events in real time and record them



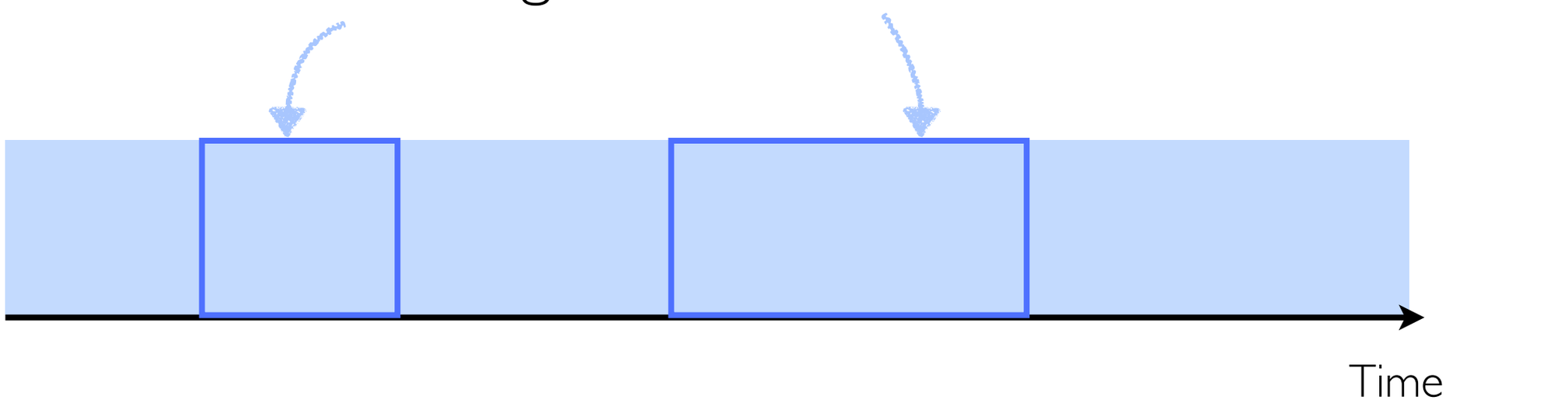
Collect Data in DUNE

High spatial resolution in LArTPC results in a huge volume of data

Main challenge on data acquisition

Drive the DUNE data acquisition design

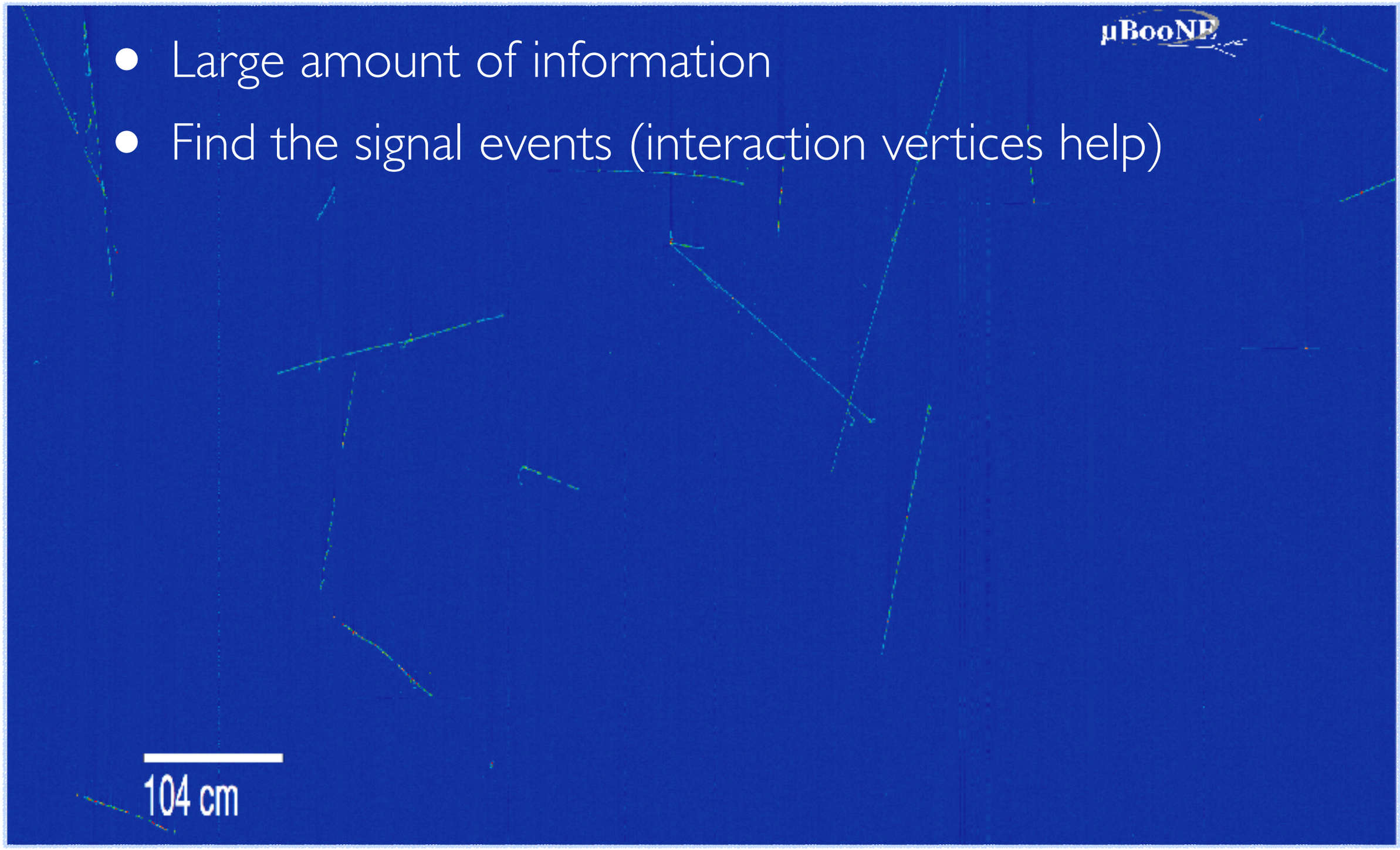
Find interesting events in real time and record them



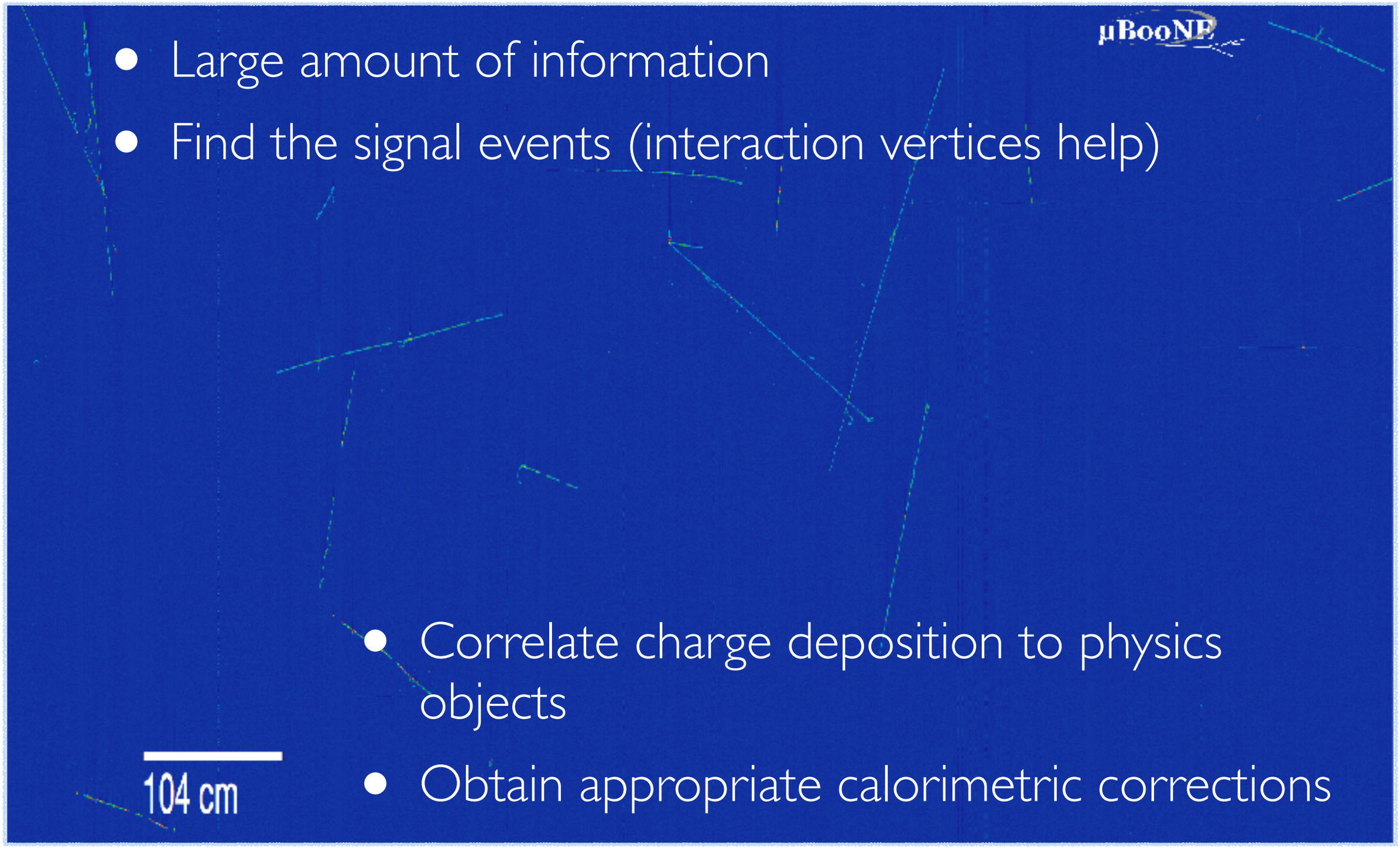
Reconstruction Challenges

Reconstruction Challenges

- Large amount of information
- Find the signal events (interaction vertices help)

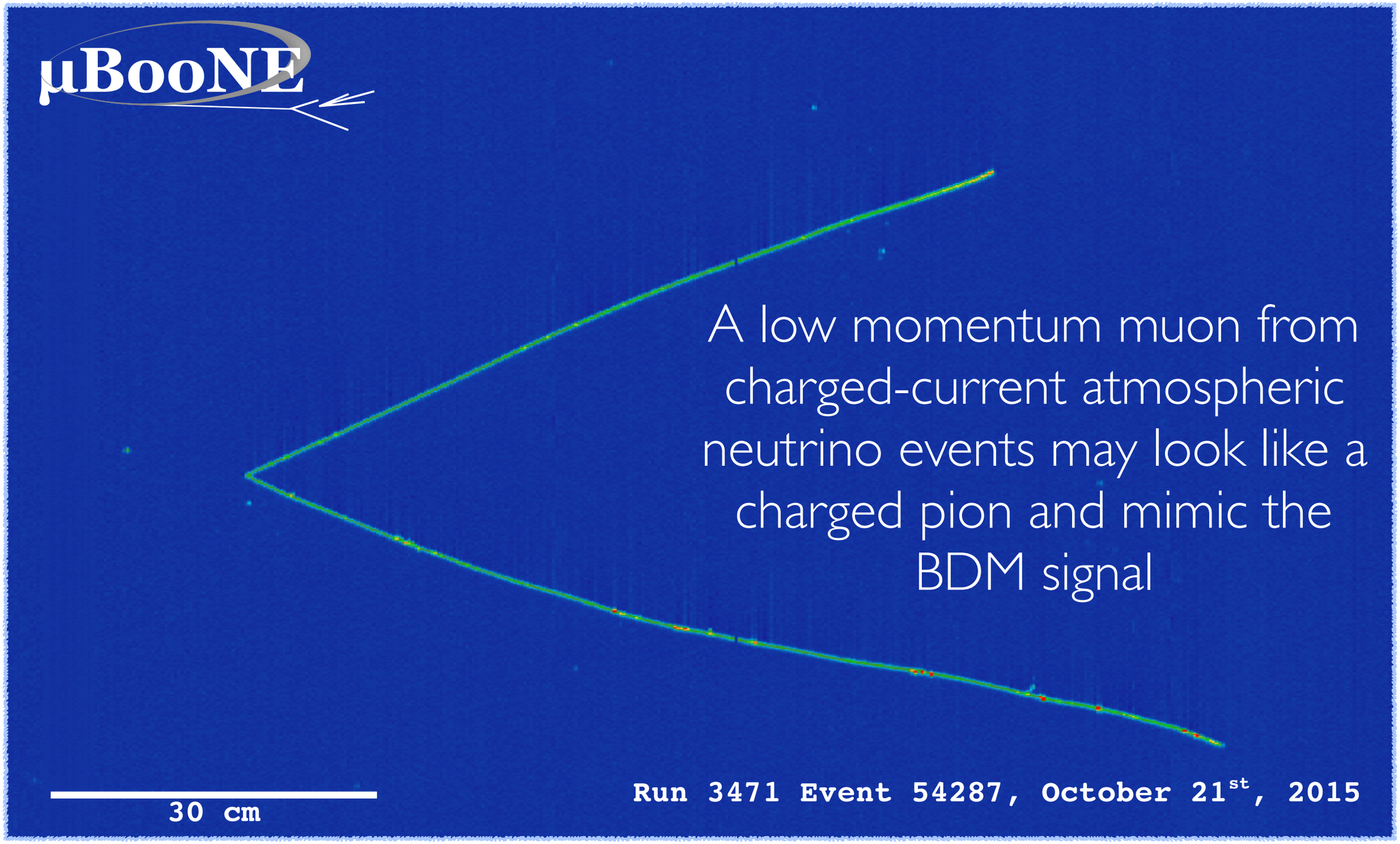


Reconstruction Challenges



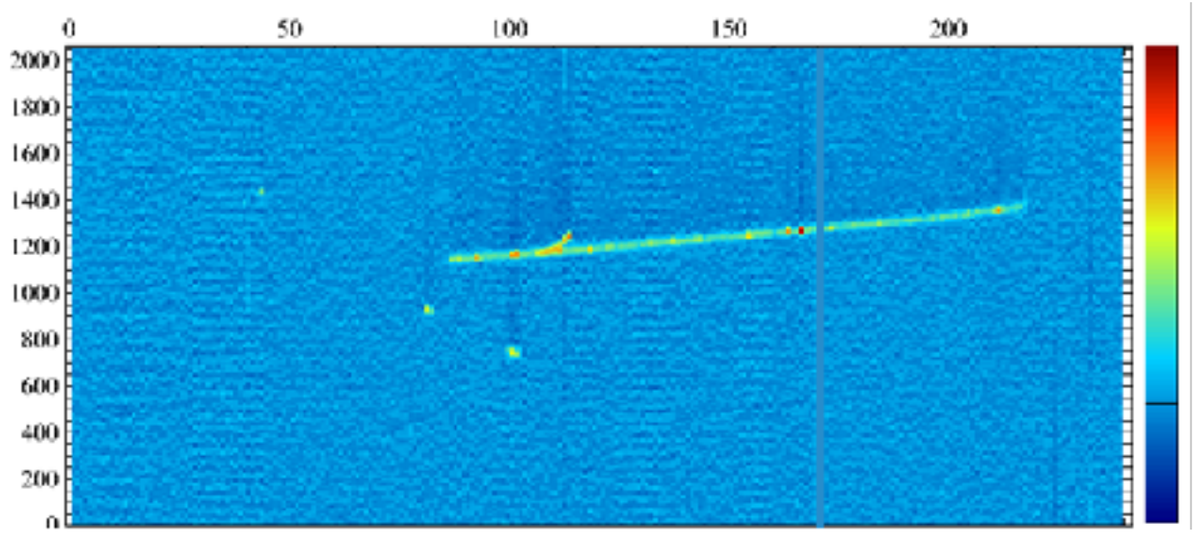
- Large amount of information
- Find the signal events (interaction vertices help)
- Correlate charge deposition to physics objects
- Obtain appropriate calorimetric corrections

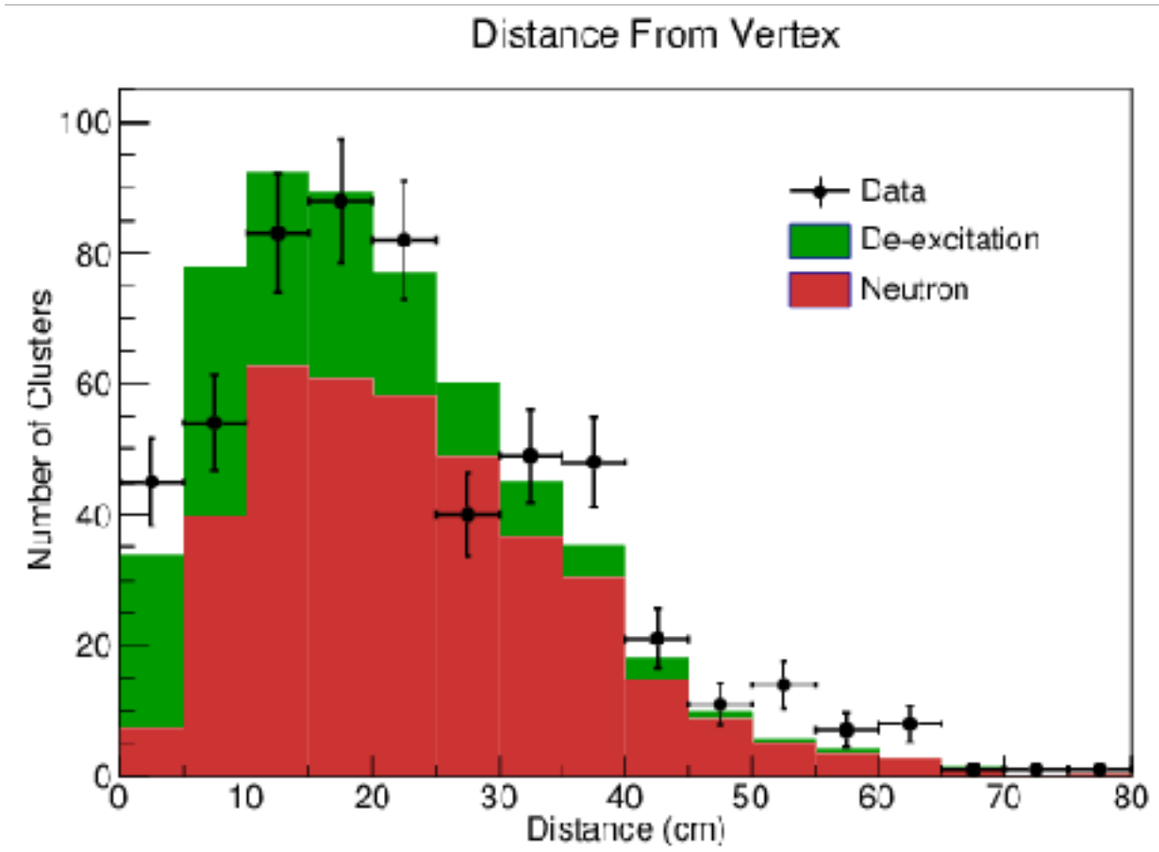
Possible Background Source



Neutron Detection

- ArgoNeuT measured energy depositions from photons produced by
  - De-excitation of the interacted nucleus
  - Inelastic scattering of primary neutrons
- Open a window of studies of new physics scenarios
- Not able to separate the two sources yet
- arXiv: 1810.06502



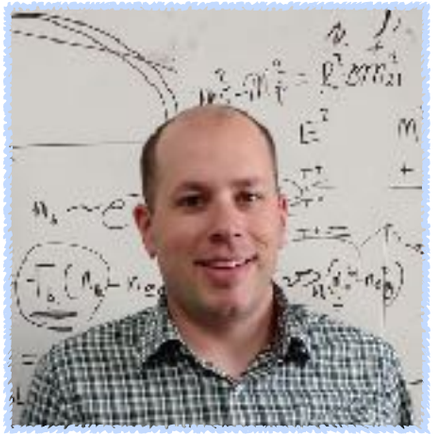


Summary

- Search for boosted dark matter in massive neutrino detectors, such as DUNE,
  - Provides an alternative way for dark matter search
    - Broadens the physics program in neutrino experiments
- First relatively realistic study in massive LArTPCs
- Improvement of the analysis and comparison to dark matter direct detection results in progress
  - Stay tuned!

The Boosted Team

Theorists



Josh Berger

Yanou Cui

Lina Necib

Yue Zhao

Experimentalists

Yun-Tse Tsai

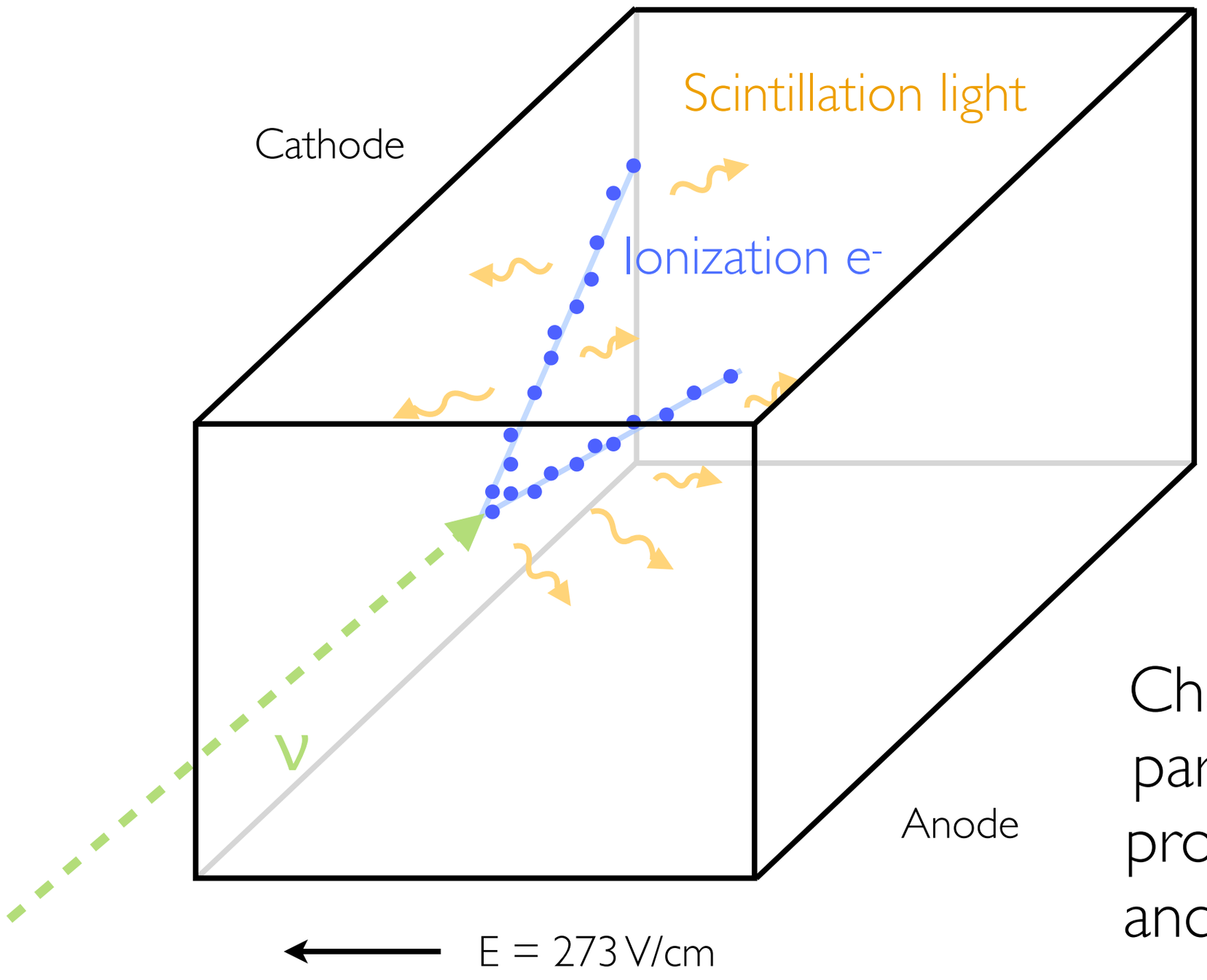
Gianluca Petrillo

Dane Stocks

Mark Convery
Matt Graham
Jonathan Assadi

Backup

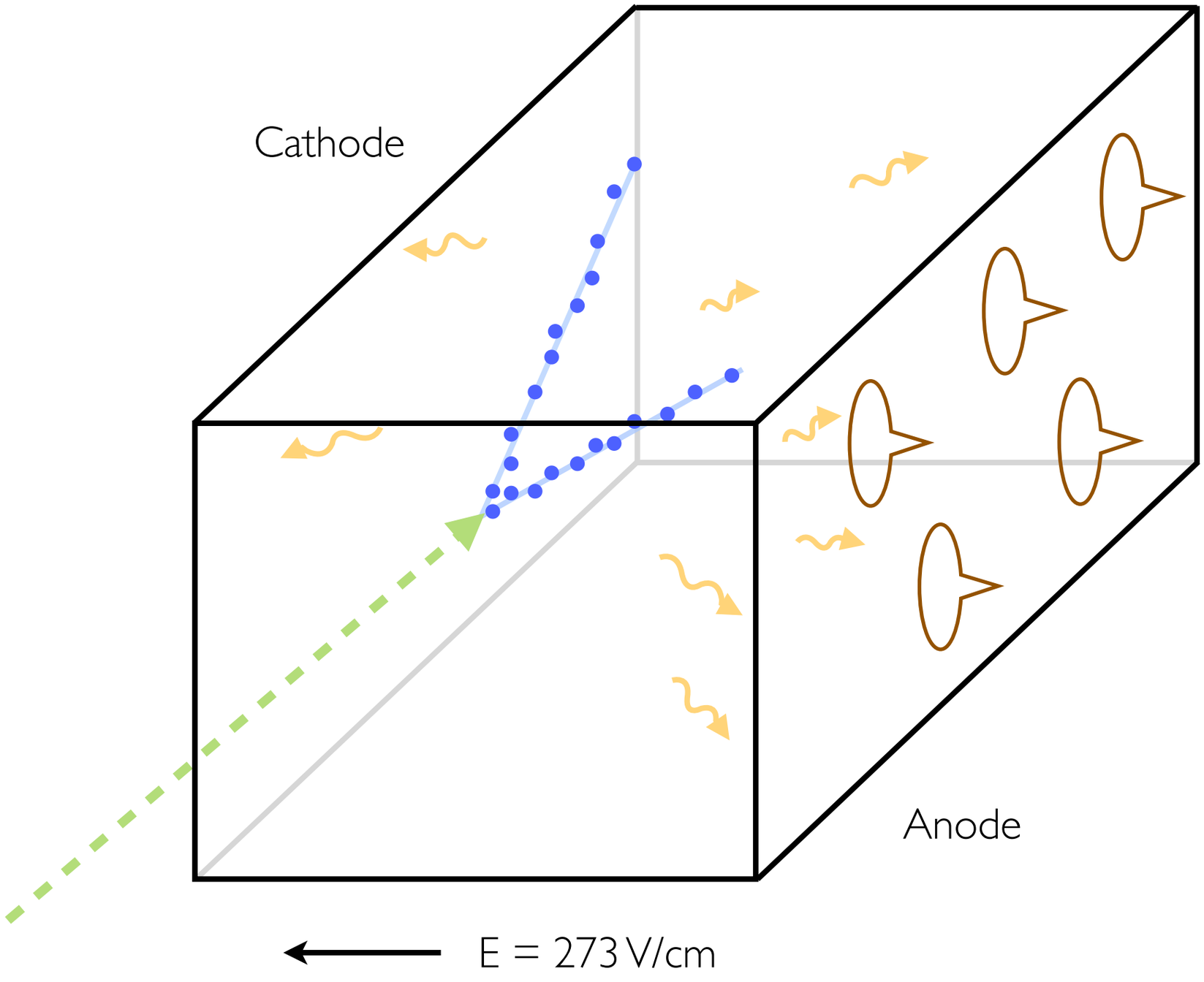
How A LArTPC Works



Incoming neutrino interacting with LAr

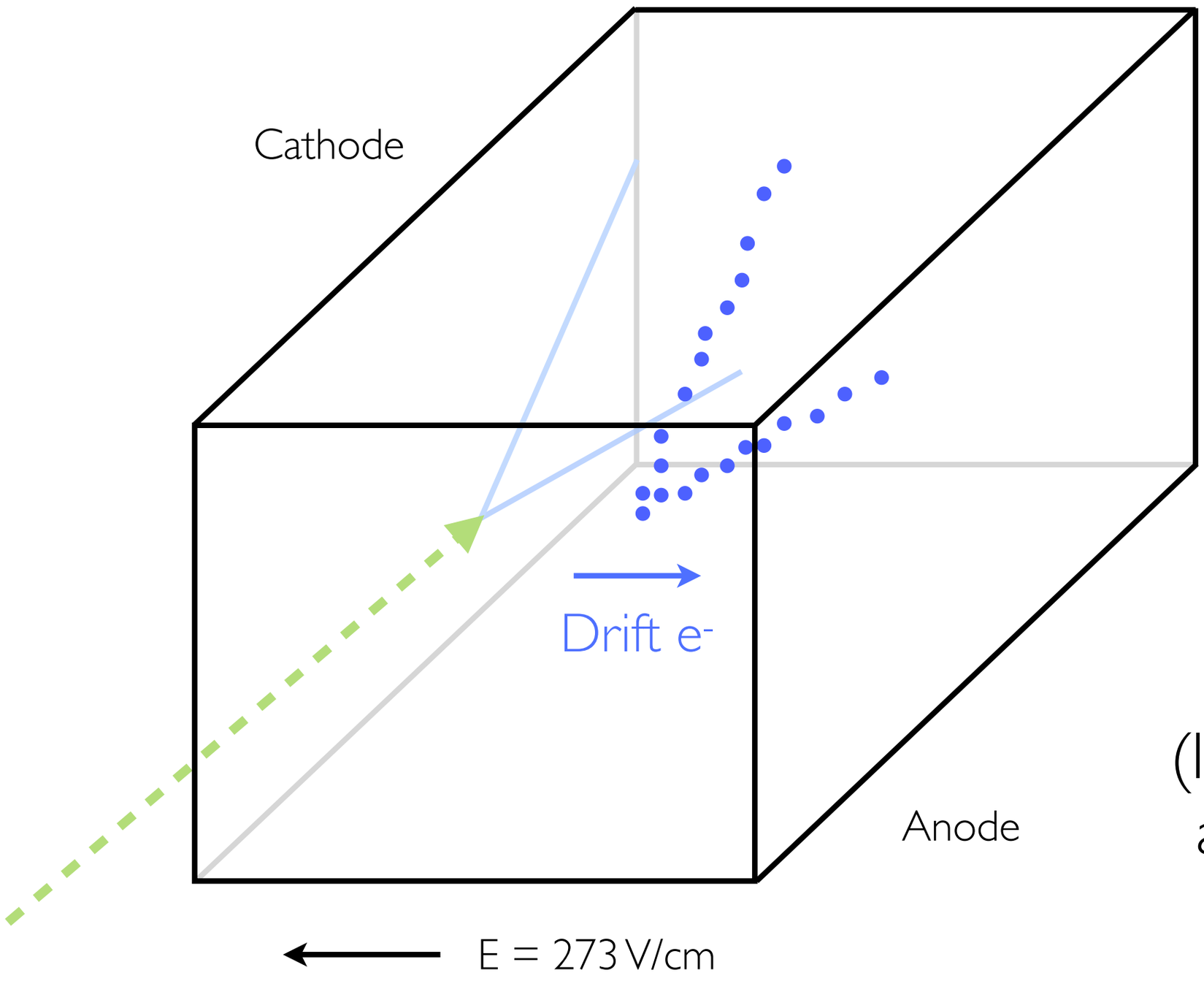
Charged secondary particles ionize LAr, producing electrons and scintillation light

How A LArTPC Works



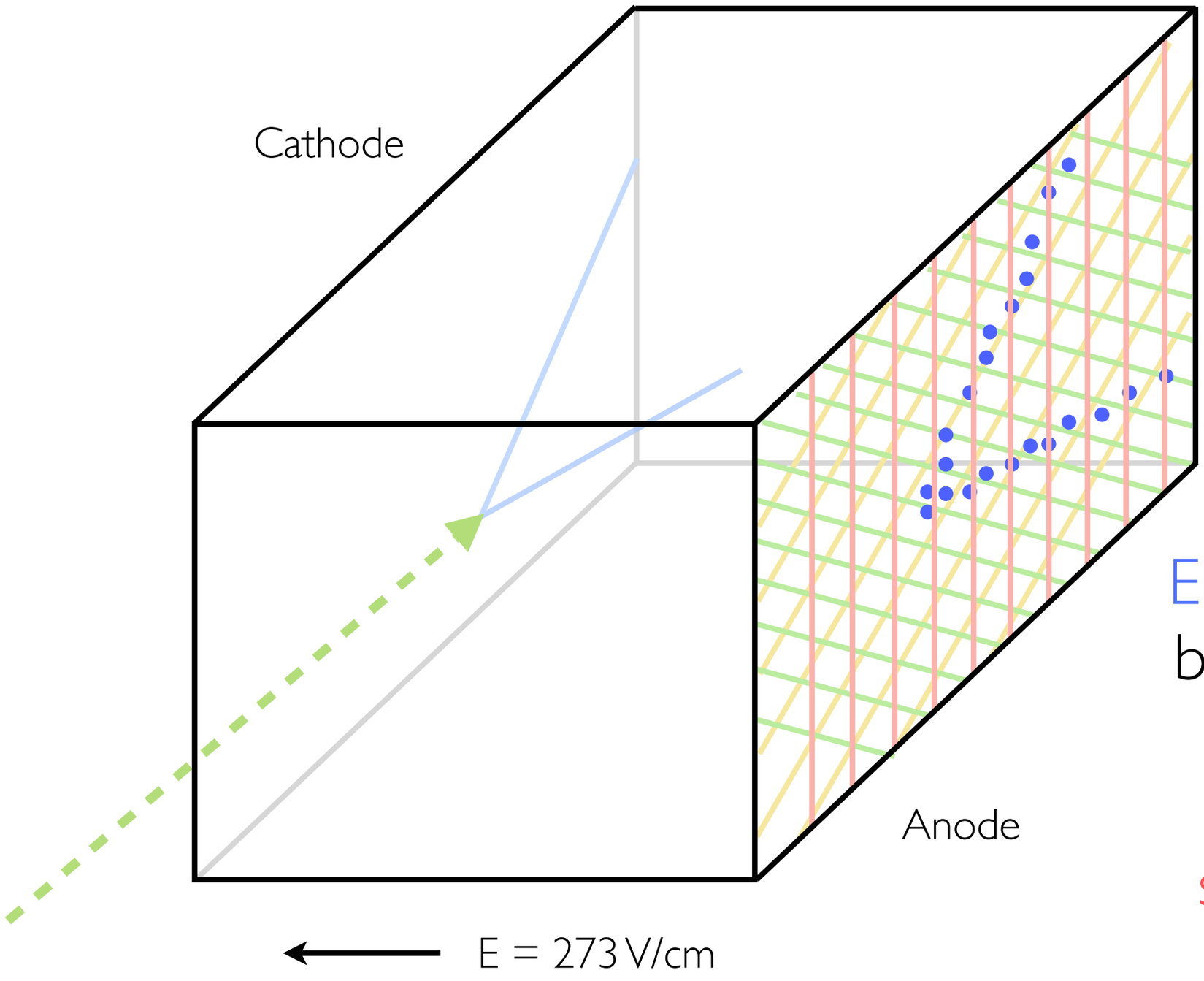
Light collected by PMT, determining event time t_0

How A LArTPC Works



Electrons drift towards anode (longest drift time at MicroBooNE: 2.3ms)

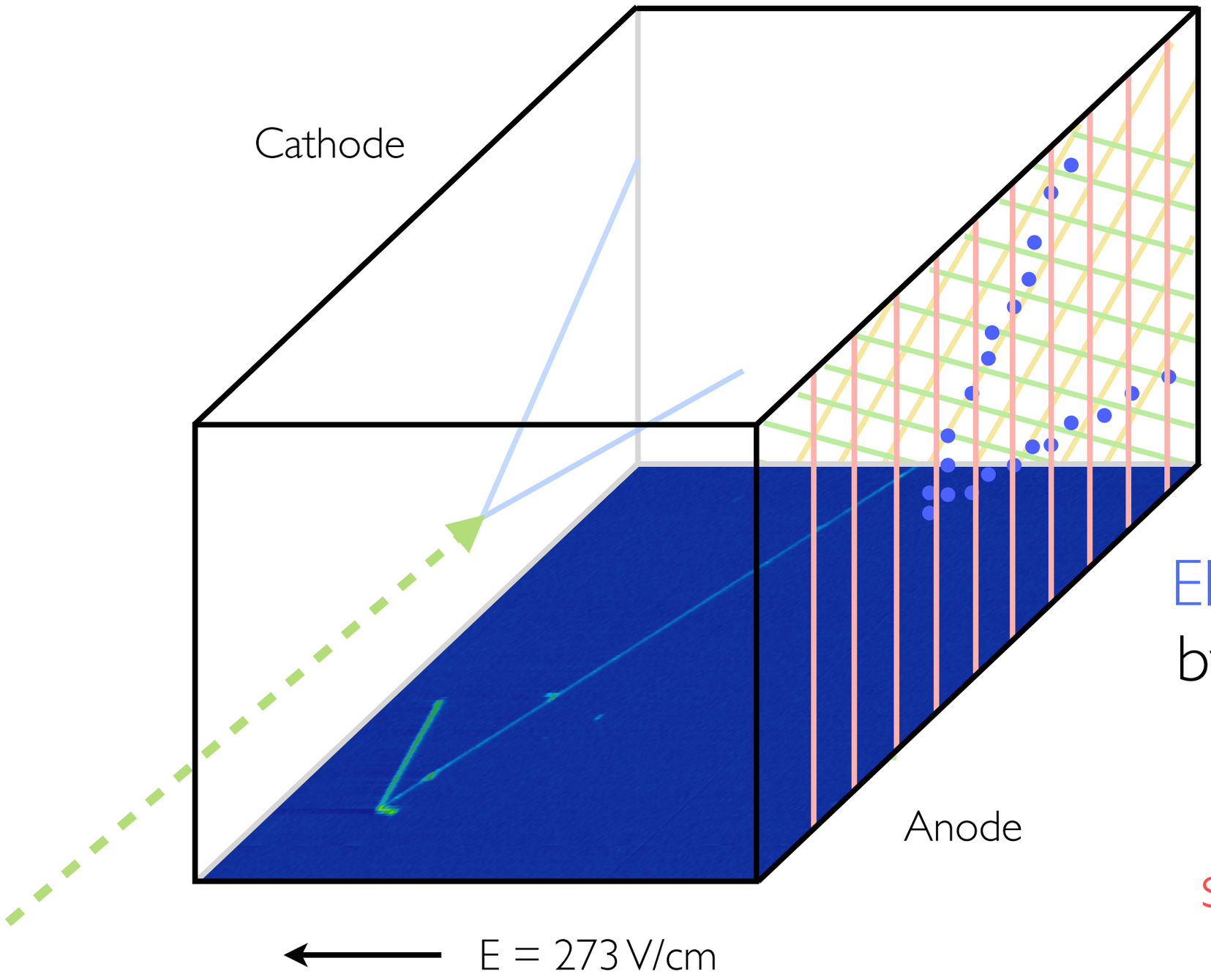
How A LArTPC Works



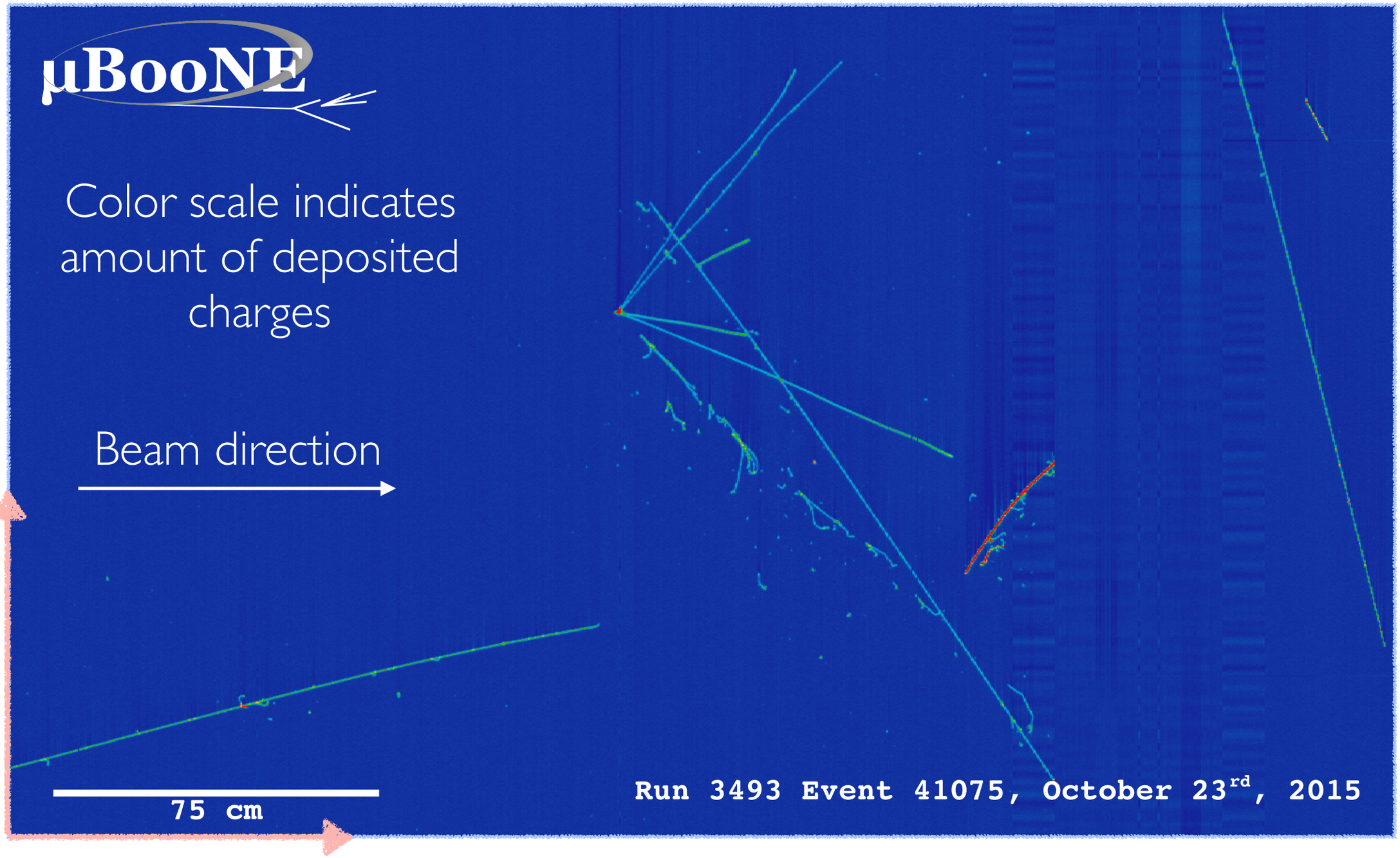
2 induction planes
1 collection plane

Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

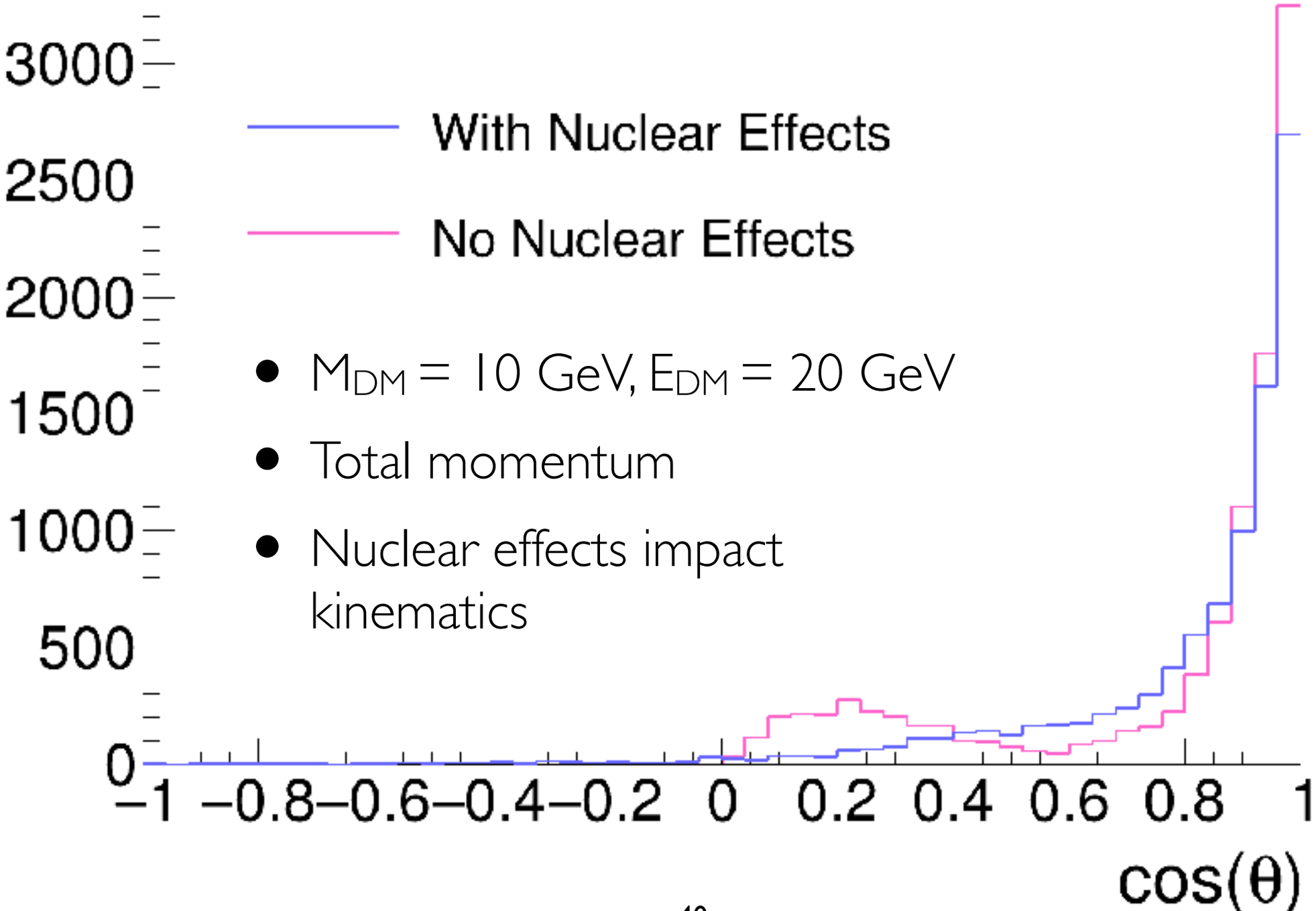
How A LArTPC Works



Electrons detected by the wire planes at anode, providing the spatial, kinematic information.


μBooNE
Color scale indicates amount of deposited charges
Beam direction
75 cm
Run 3493 Event 41075, October 23rd, 2015
Time (-drift direction)
Wire

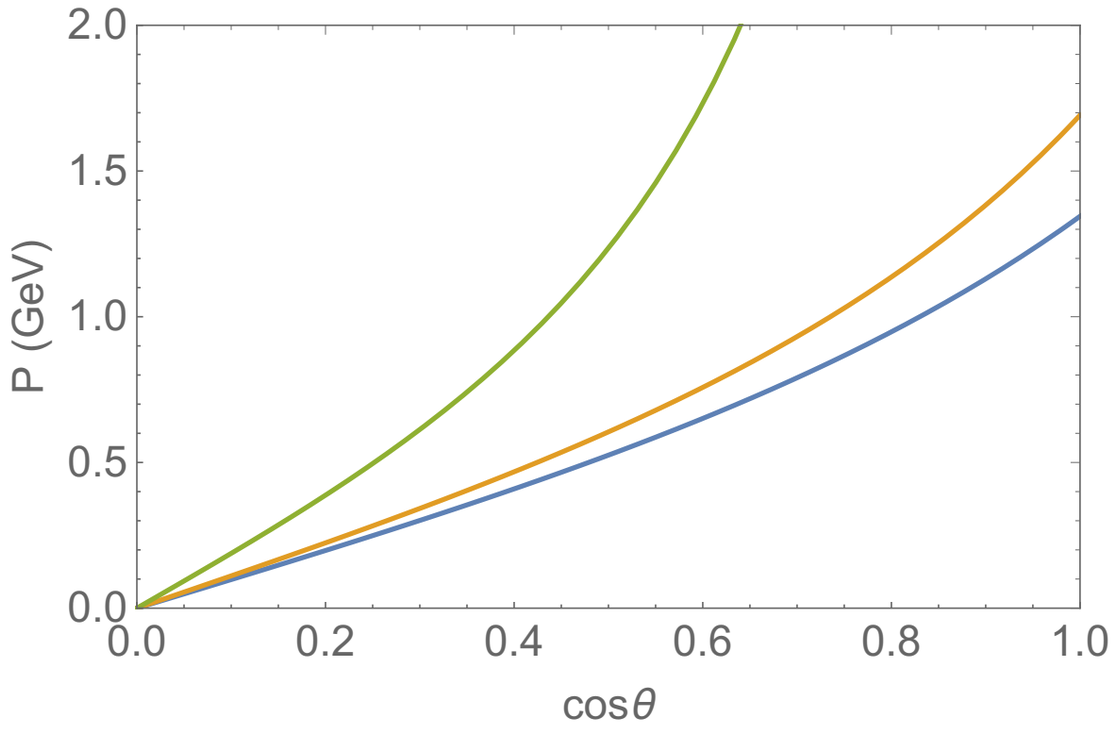
Nuclear Effects in Argon

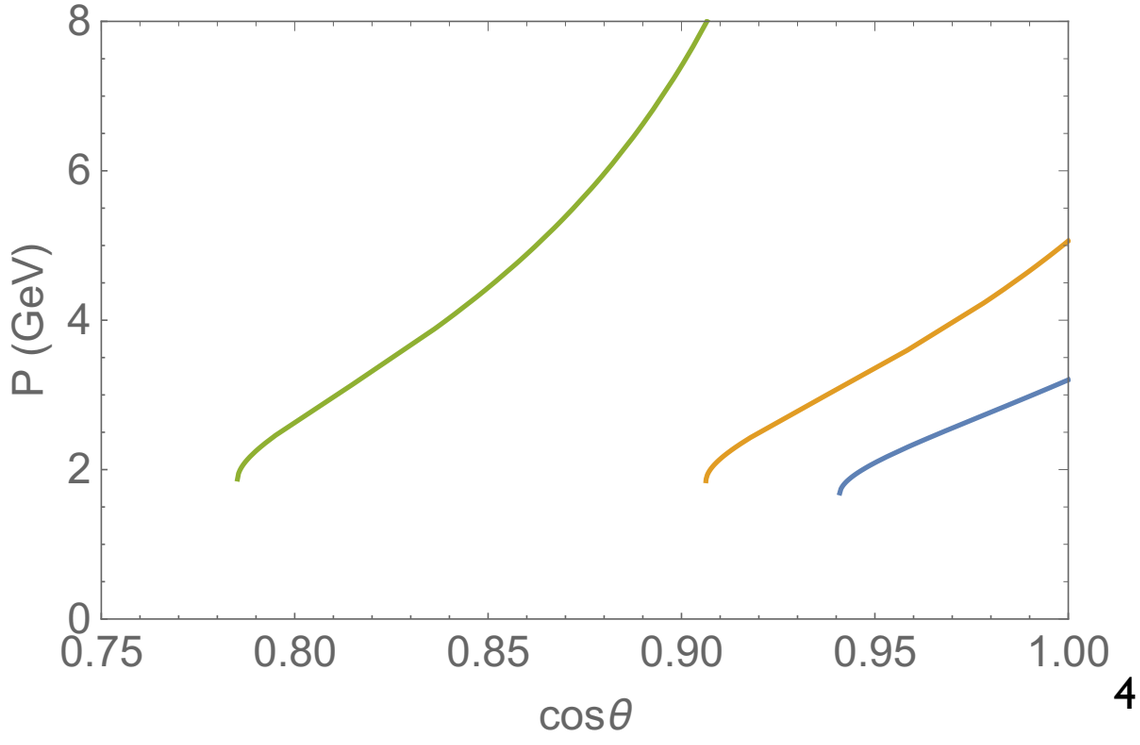


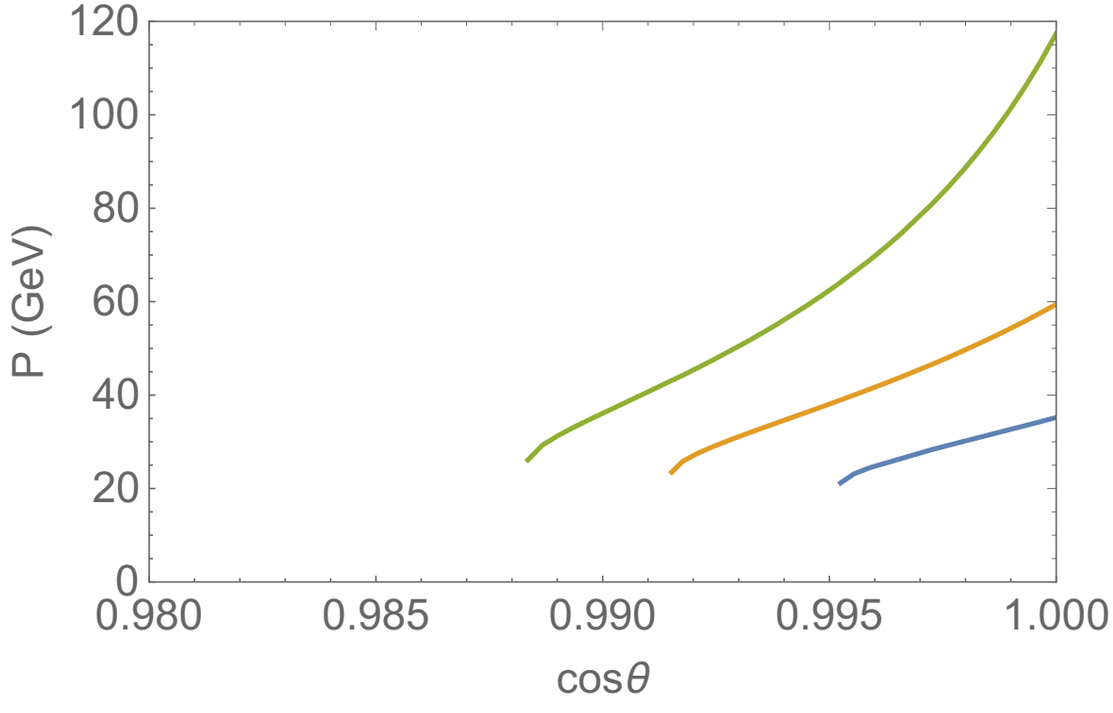
- M_{DM} = 10 GeV, E_{DM} = 20 GeV
- Total momentum
- Nuclear effects impact kinematics

BDM Signal Kinematics

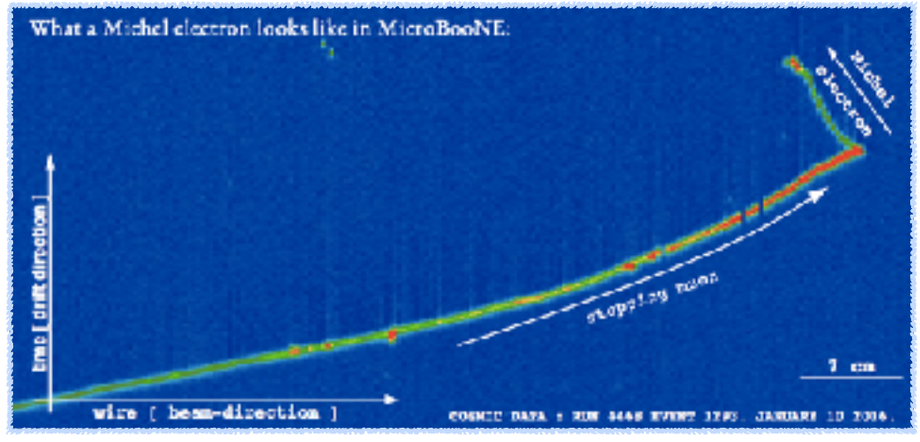
- Investigating the correlation between kinematic variables in BDM signal events

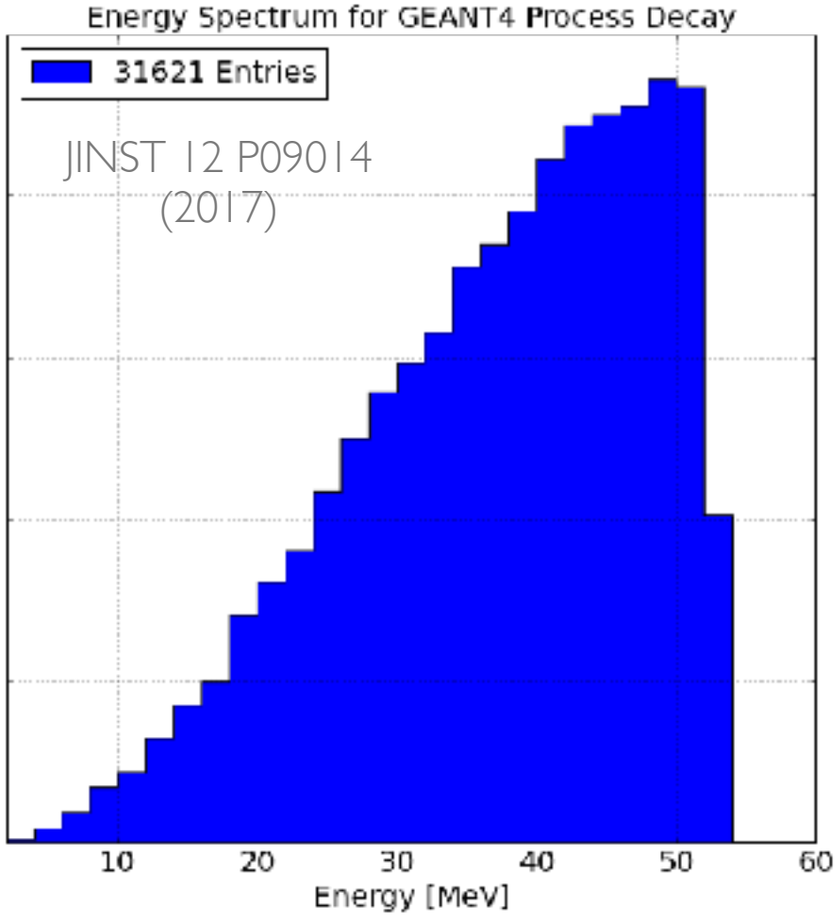


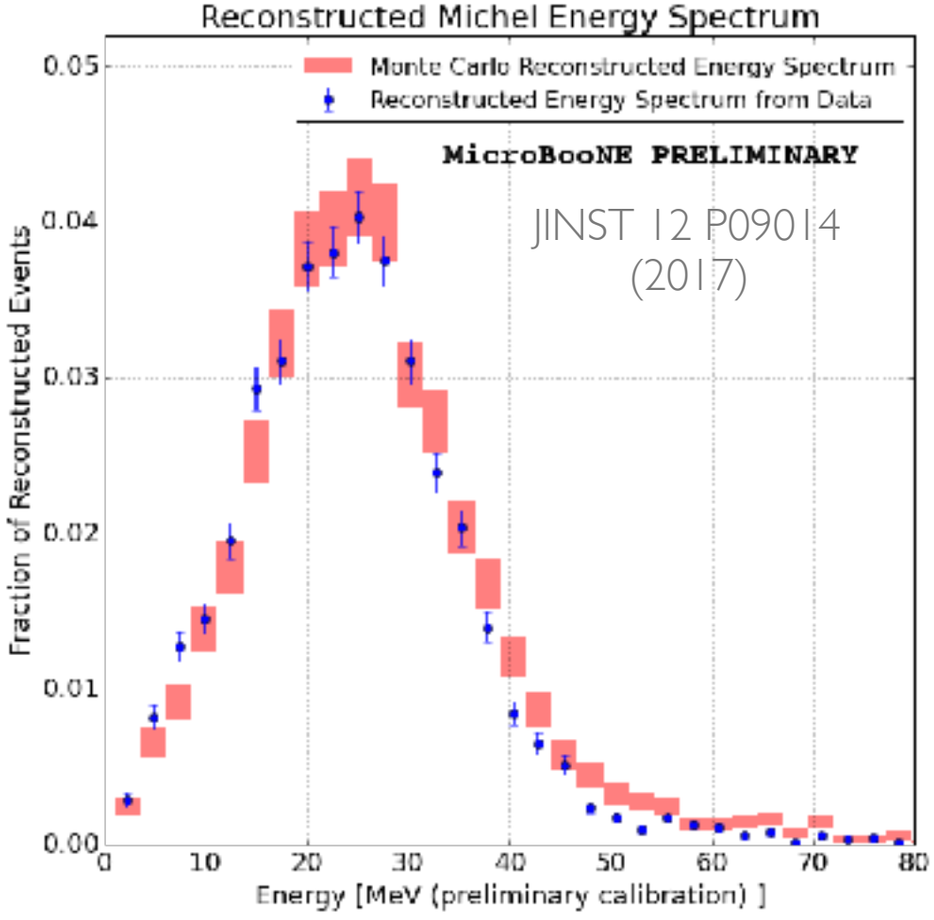




Michel Electron







Possible Background Source