MEASUREMENTS OF PION AND MUON NUCLEAR CAPTURE AT REST ON ARGON IN THE LARIAT EXPERIMENT

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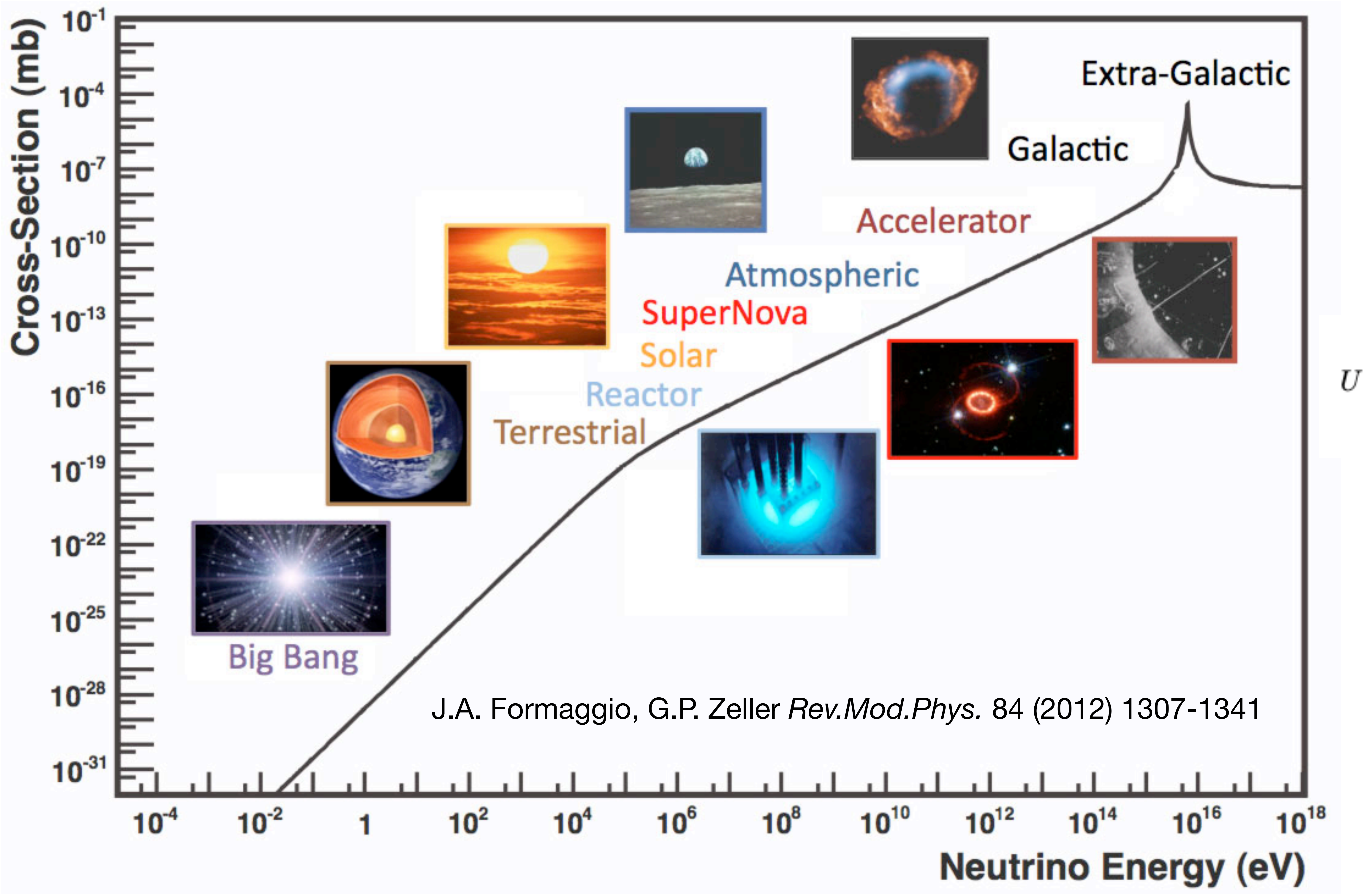
on behalf of the LArIAT collaboration

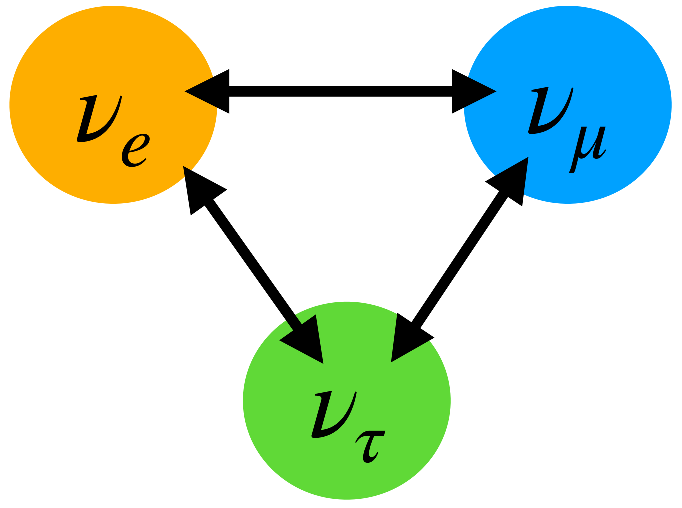
Fermilab Joint Experimental and Theoretical Physics Seminar

October 25 2024

Neutrinos



J.A. Formaggio, G.P. Zeller *Rev.Mod.Phys.* 84 (2012) 1307-1341

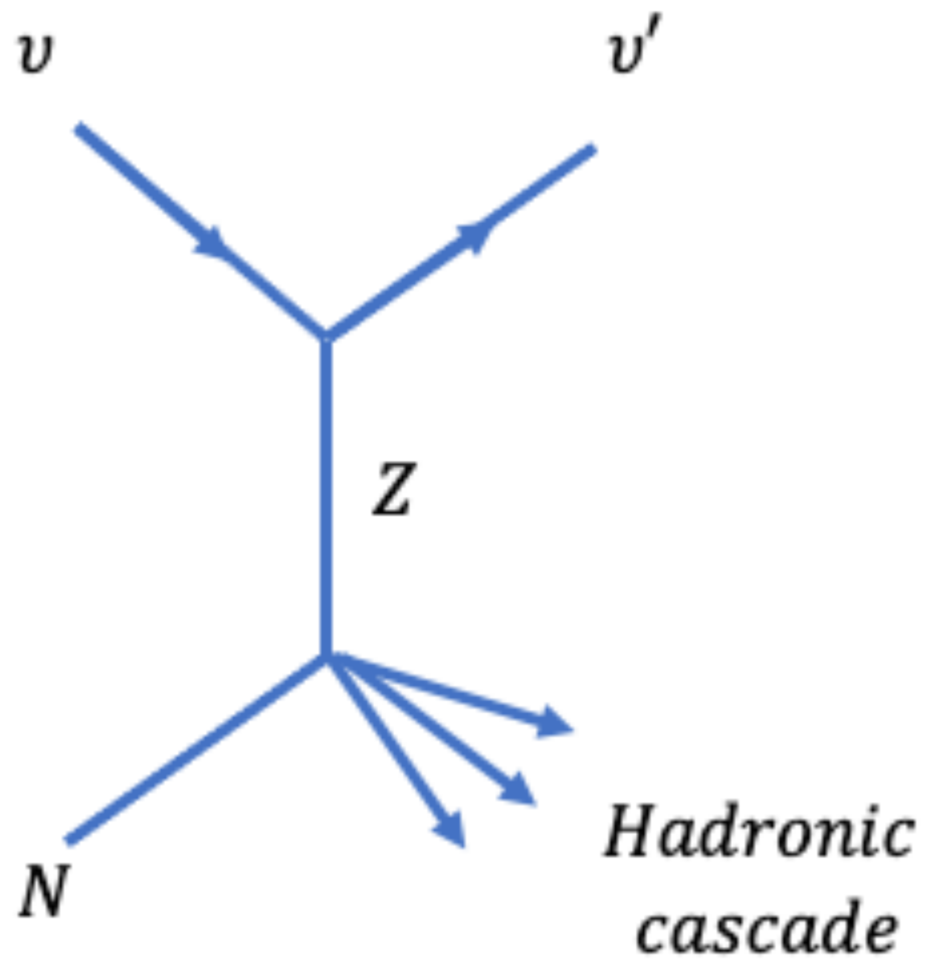


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

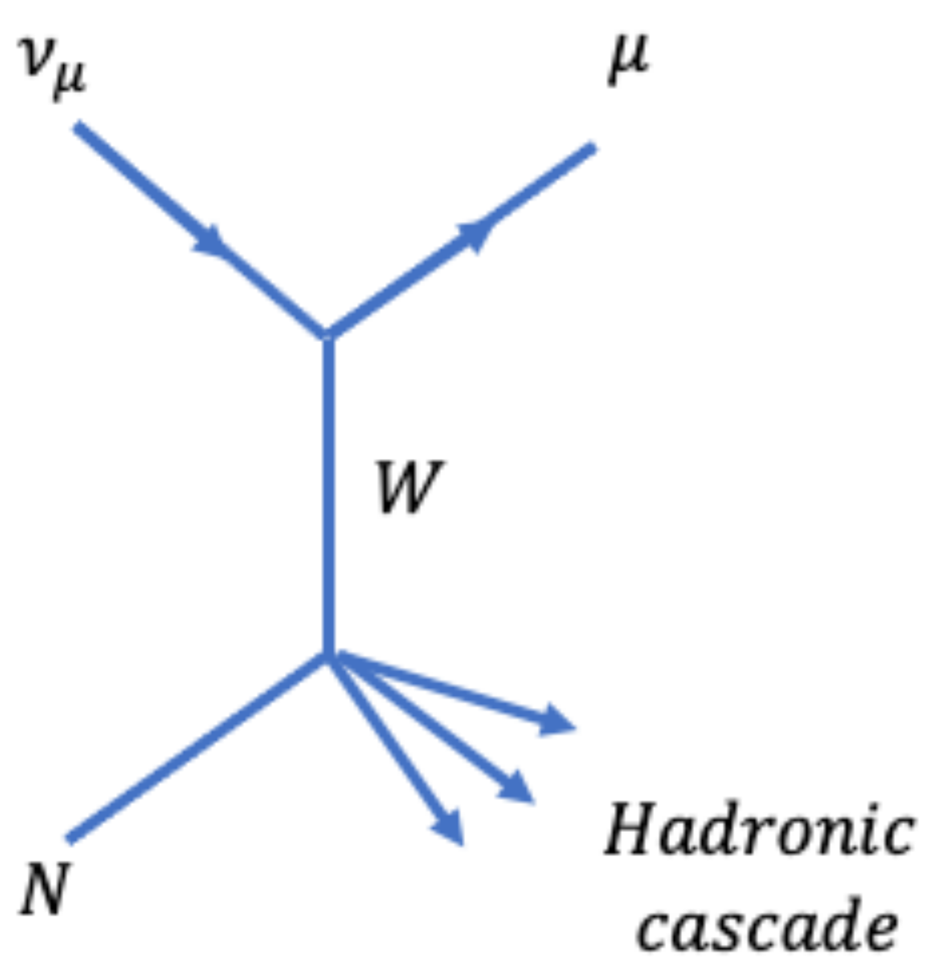
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}]$$

NC and CC interactions



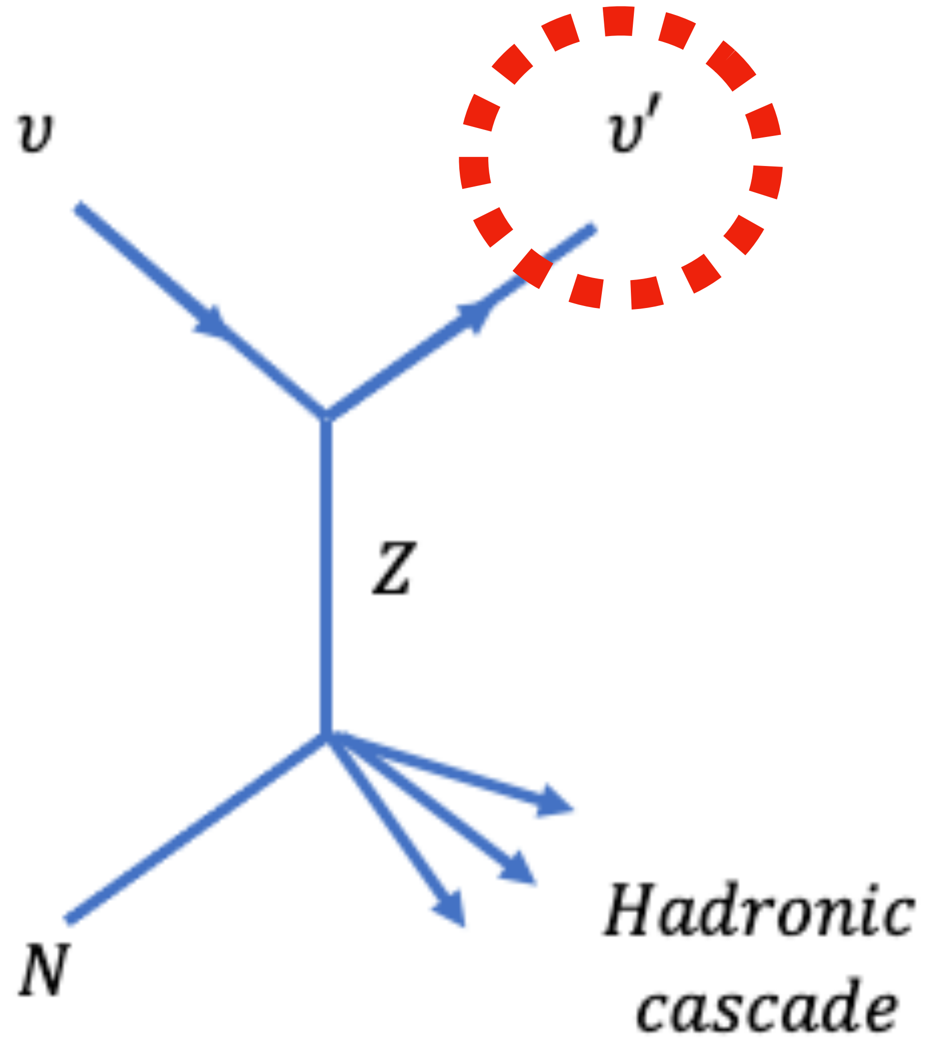
NC



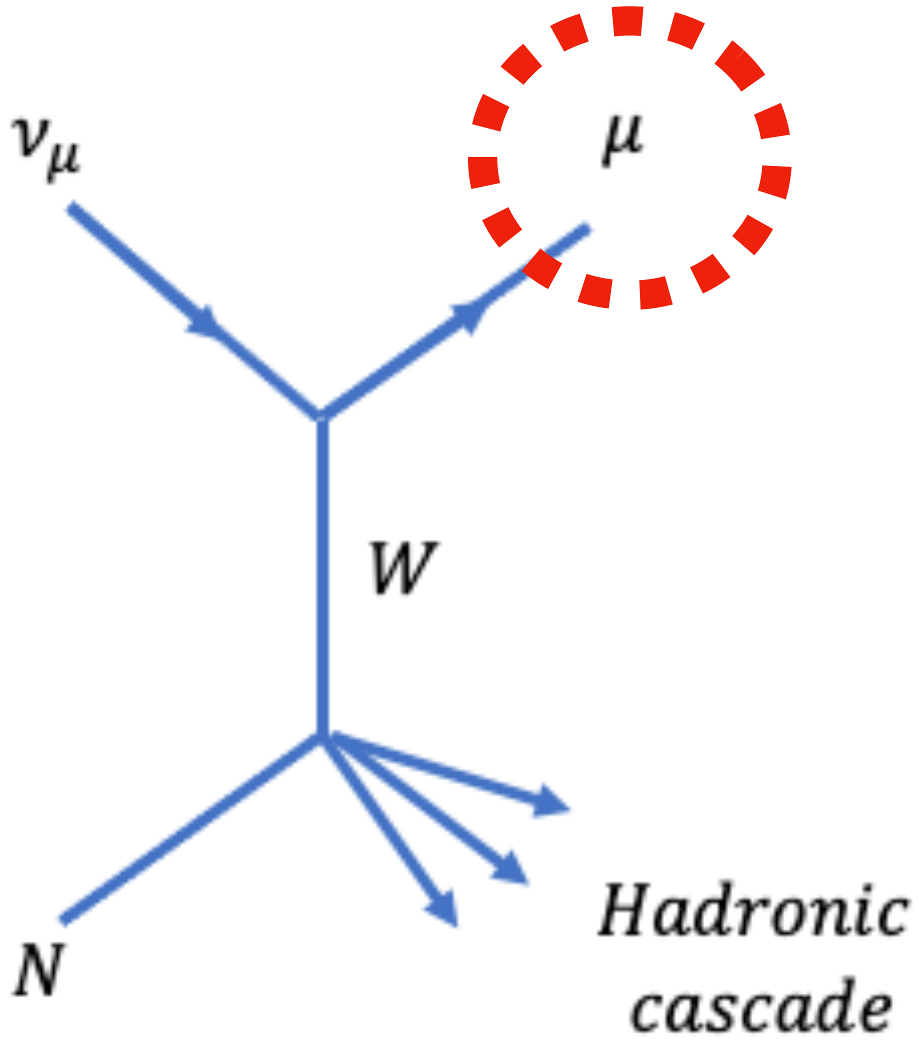
CC

Neutrinos interacts through weak force only (nuclear decay), Neutral current and Charged current.

NC and CC interactions



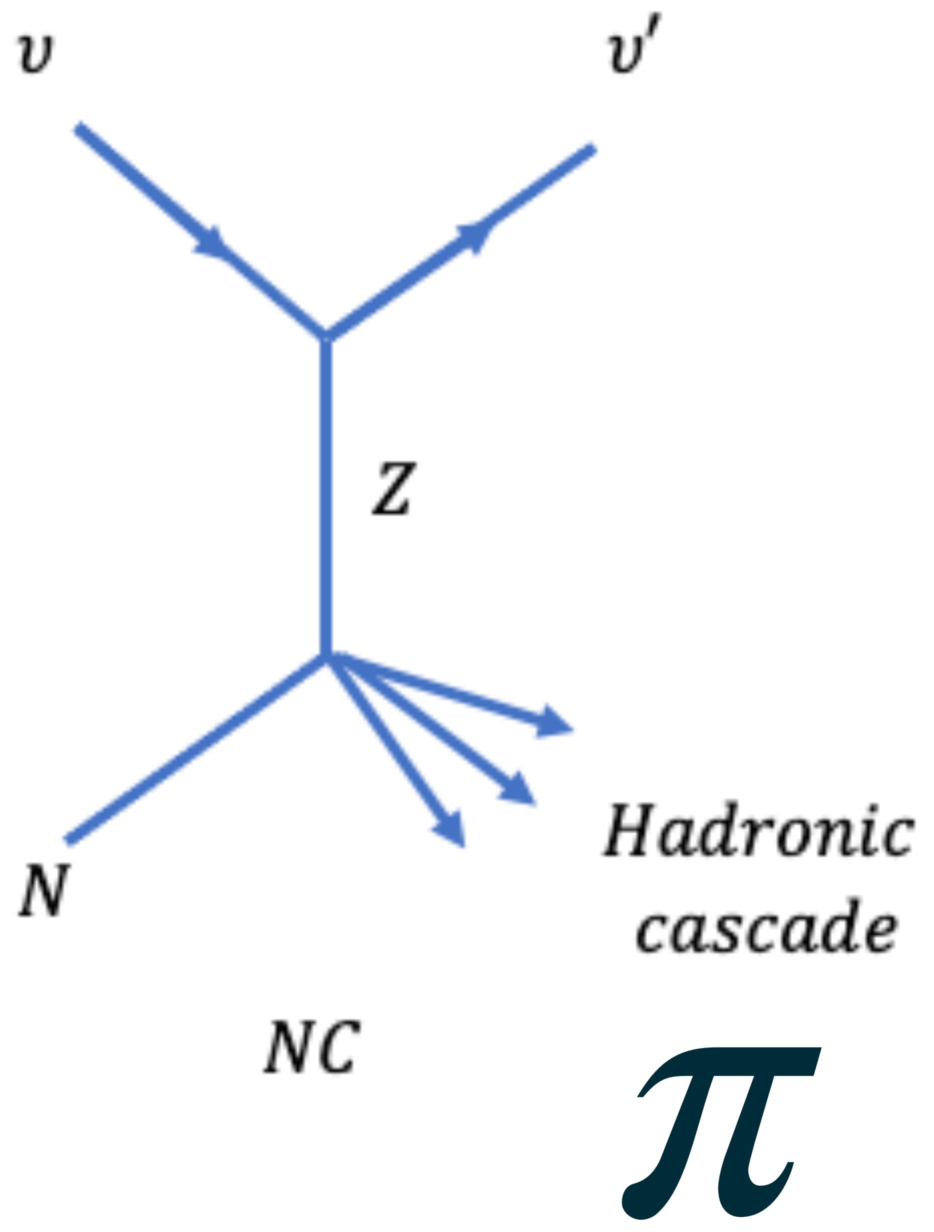
NC

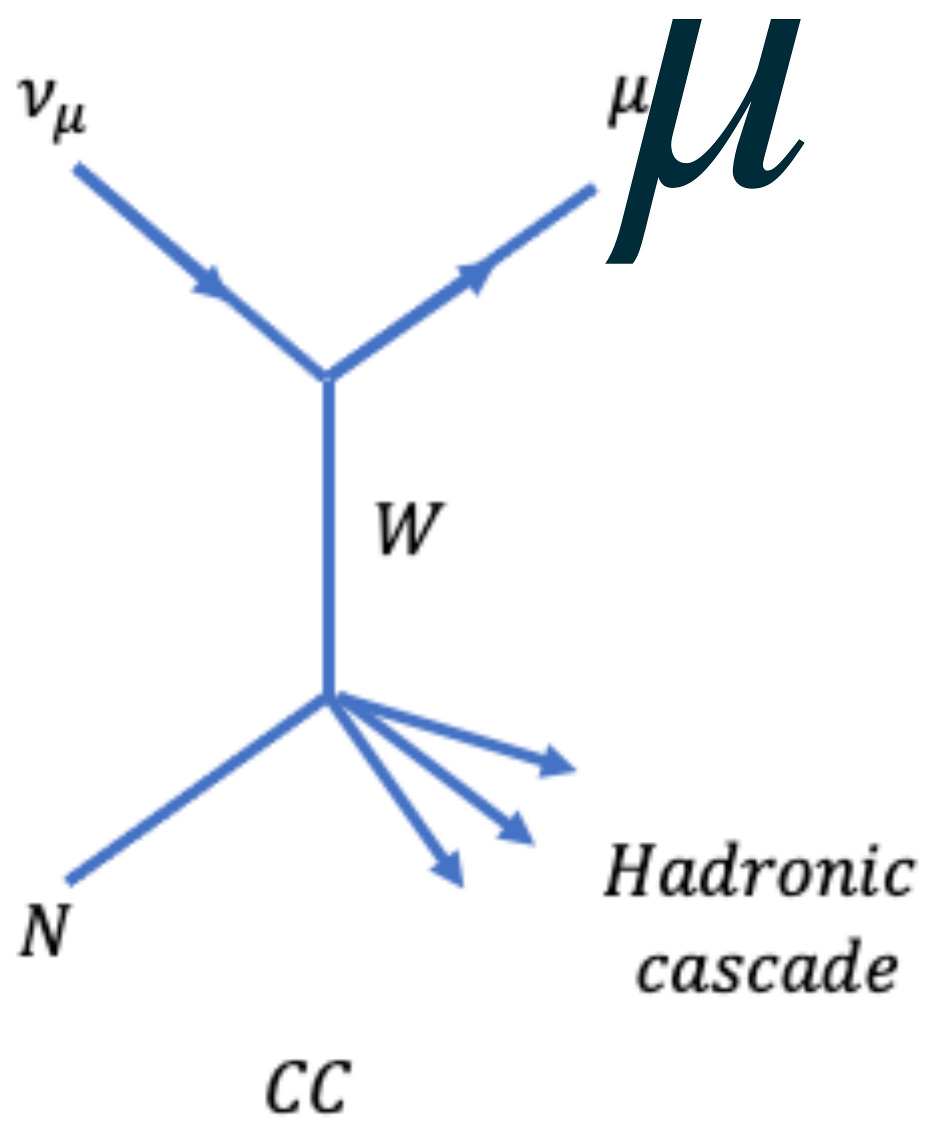


CC

The key to neutrino detection lies in the final state lepton. If we measure it, we will know the flavor of the incoming neutrino ν_e, ν_μ and the physics process behind this event, NC or CC.

Muon and pion identification importance





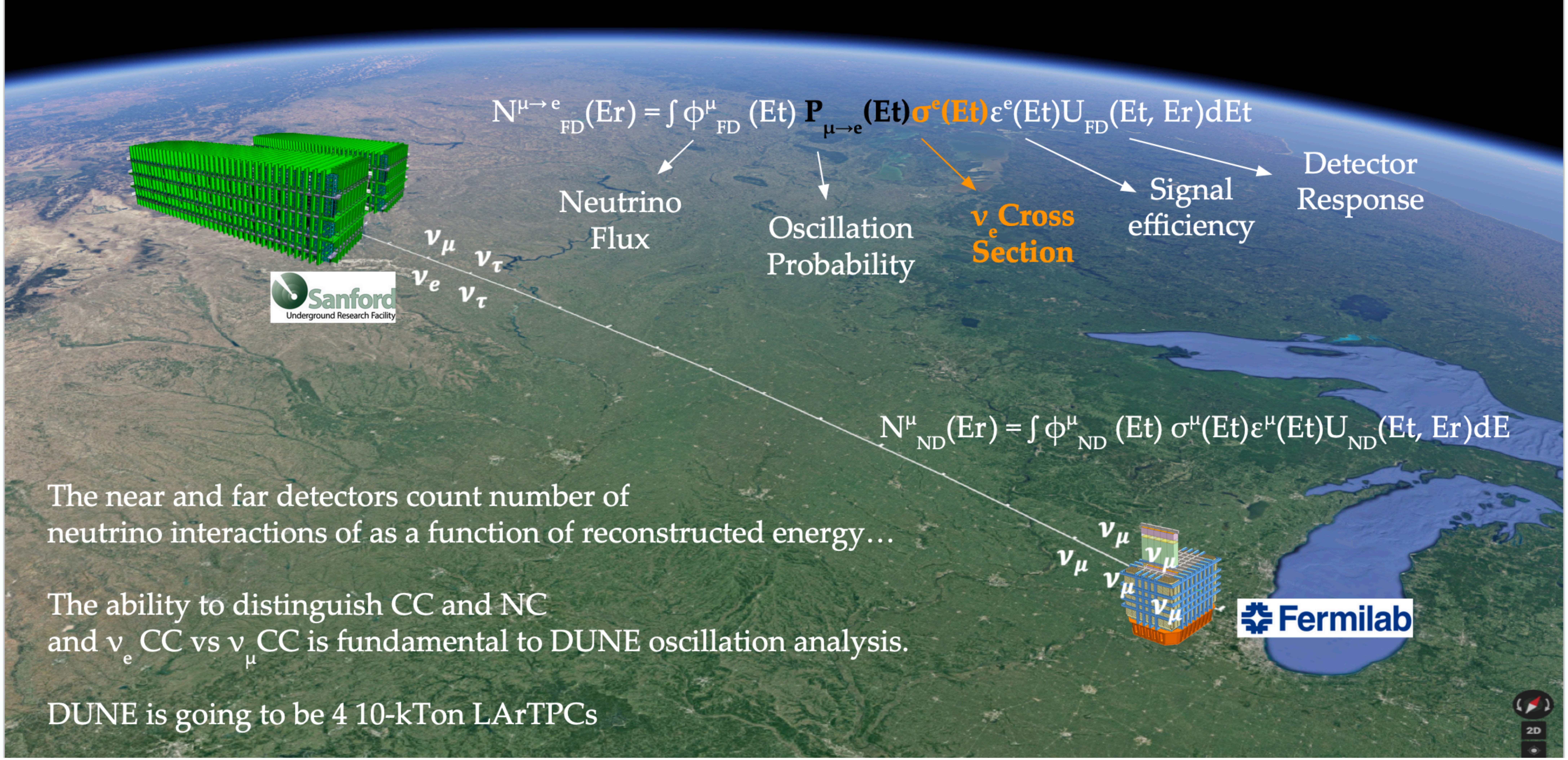
Neutral Current

Charged current

Identifying pions and muons is a valuable facet of differentiating CC and NC.

DUNE ν-oscillation search 101

***STEP 1**: Making a ν_μ beam*
***STEP 2**: Checking oscillation into ν_e*



$$N^{\mu\to e}_{FD}(\text{Er}) = \int \phi^{\mu}_{FD}(\text{Et})\, \mathbf{P}_{\mu\to e}\mathbf{(Et)}\sigma^{e}(\text{Et})\varepsilon^{e}(\text{Et})U_{FD}(\text{Et}, \text{Er})d\text{Et}$$

Neutrino Flux

Oscillation Probability

ν_e Cross Section

Signal efficiency

Detector Response

$$N^{\mu}_{ND}(\text{Er}) = \int \phi^{\mu}_{ND}(\text{Et})\, \sigma^{\mu}(\text{Et})\varepsilon^{\mu}(\text{Et})U_{ND}(\text{Et}, \text{Er})d\text{E}$$

The near and far detectors count number of neutrino interactions of as a function of reconstructed energy…

The ability to distinguish CC and NC and ν_e CC vs ν_μ CC is fundamental to DUNE oscillation analysis.

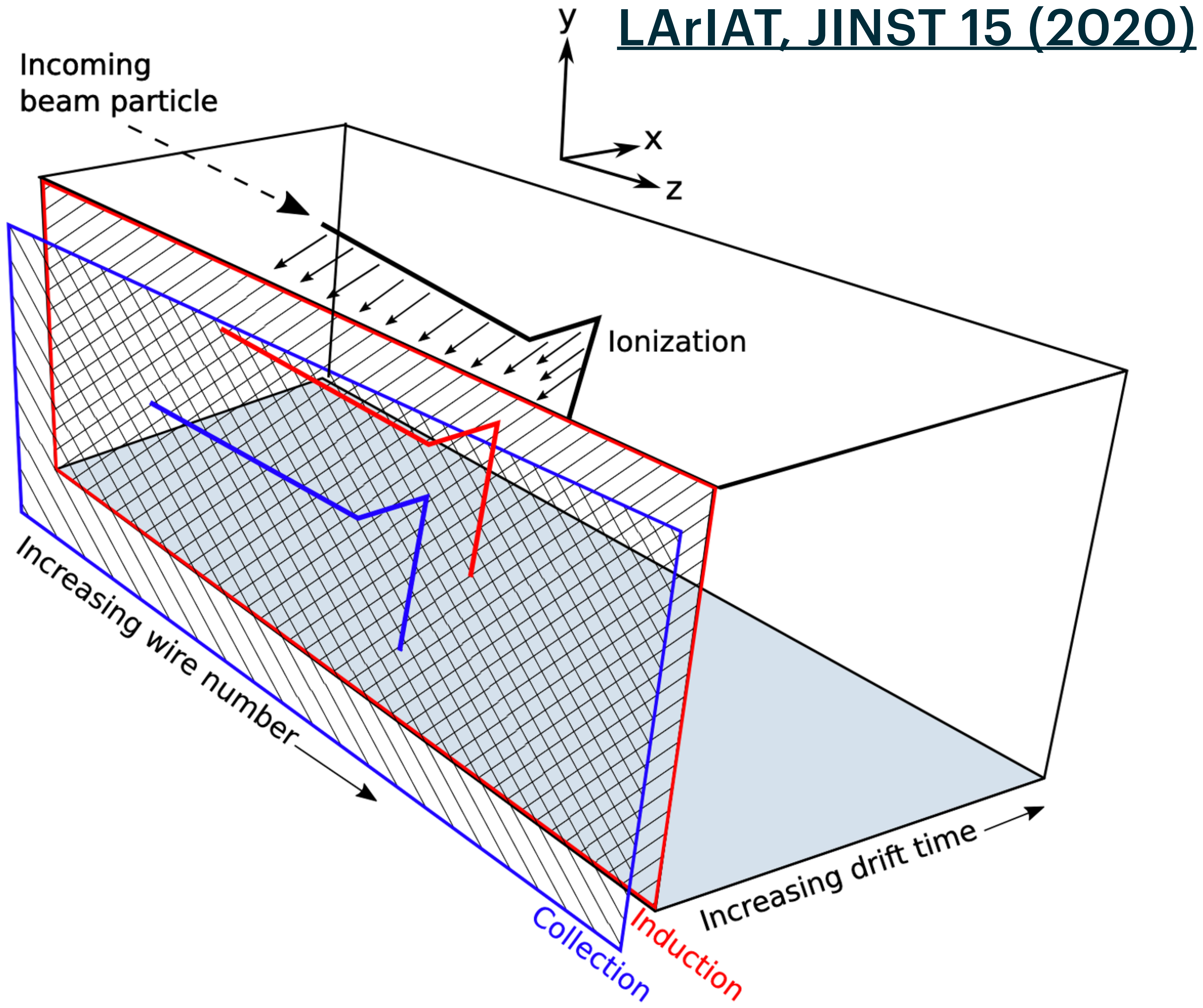
DUNE is going to be 4 10-kTon LArTPCs

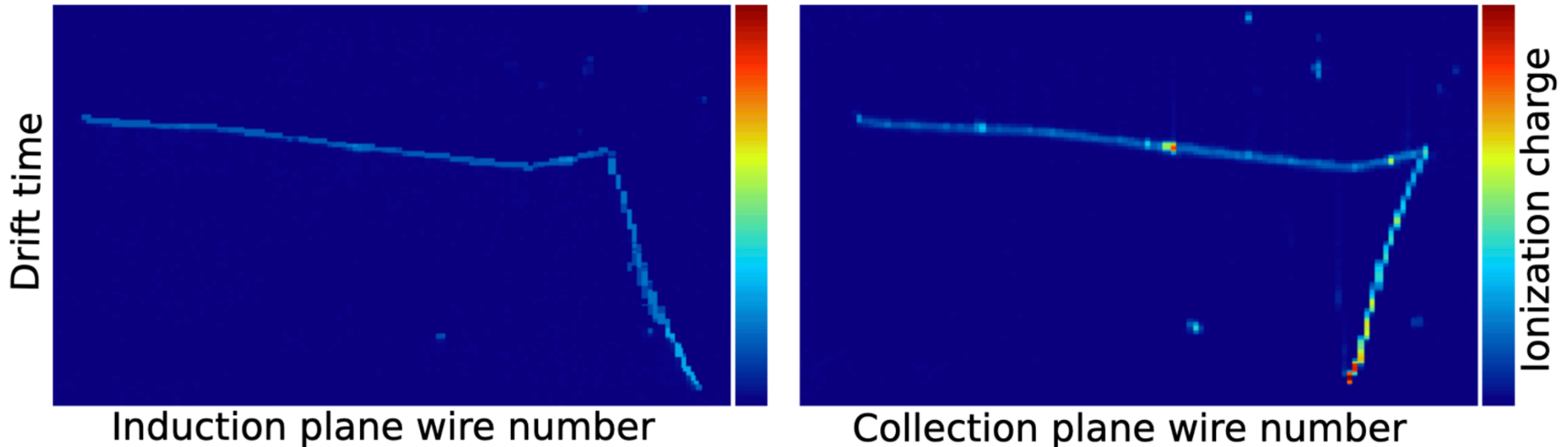
What is a LArTPC?

LArTPCs are charged particle detectors

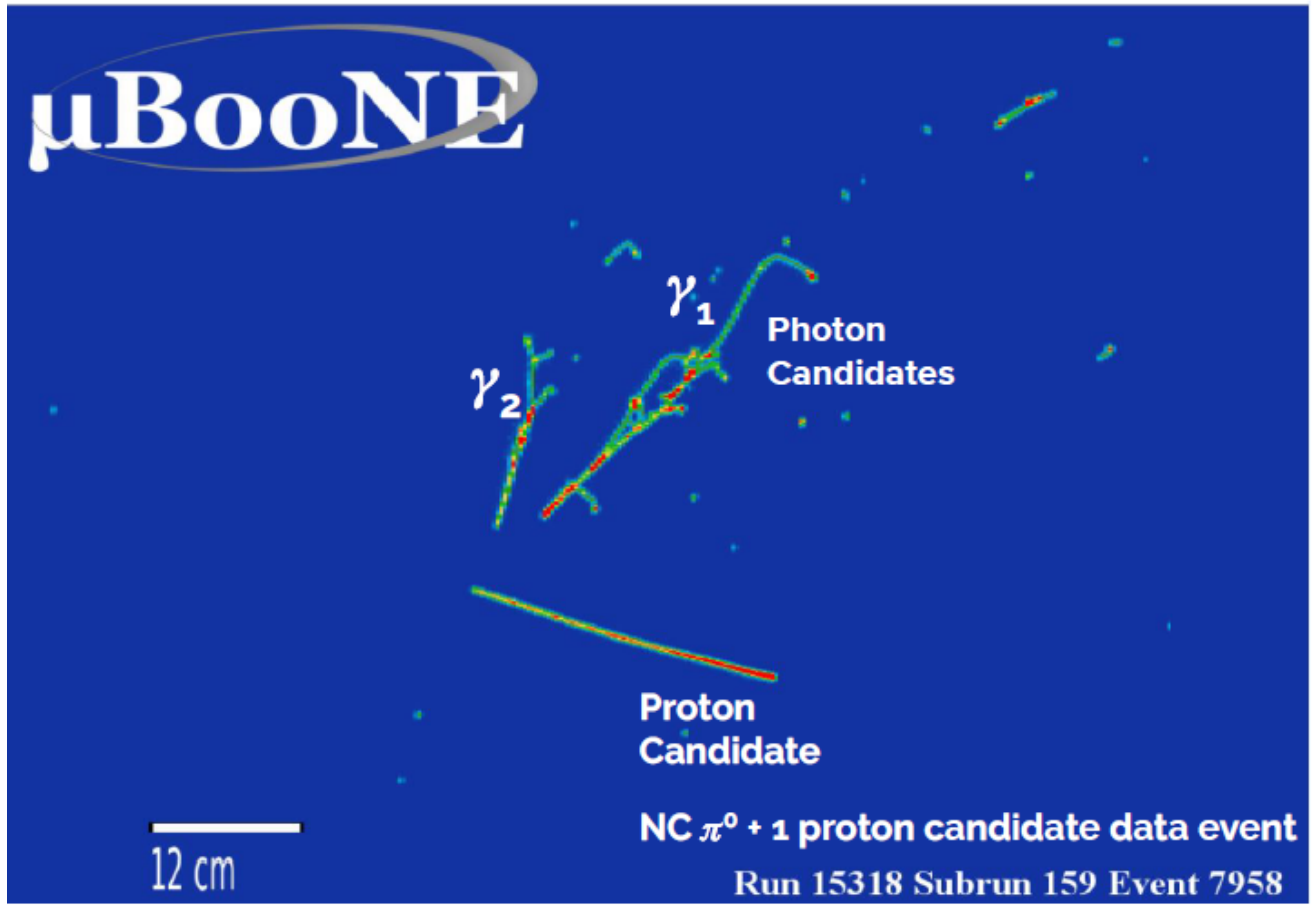
- When a charged particle passes through LAr, ionization is created
- Ionized electrons are drifted under an electric field, forming signals on multiple wire planes
- 3D event reconstruction is performed using these signals + their drift time

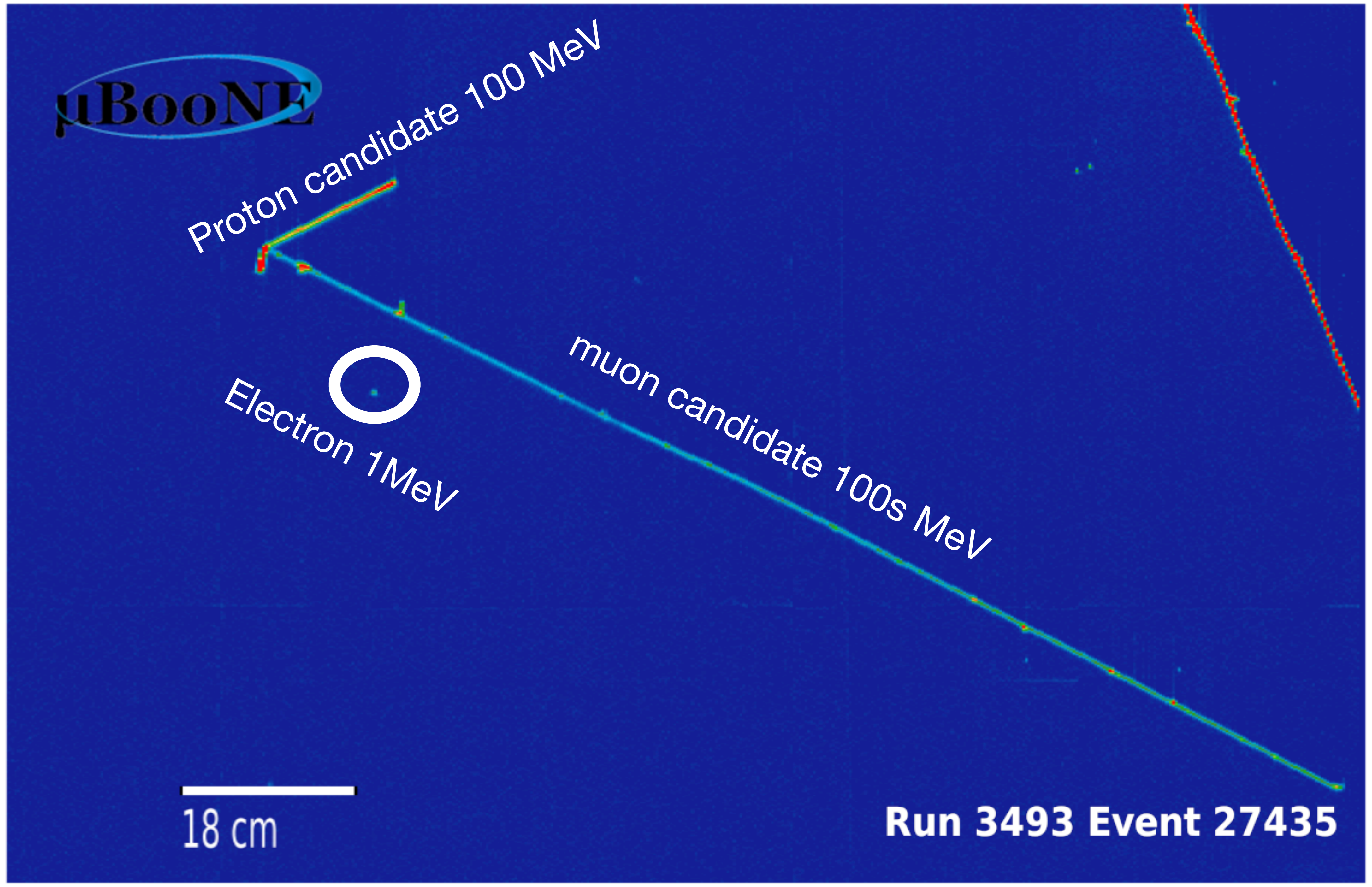
LArIAT, JINST 15 (2020)

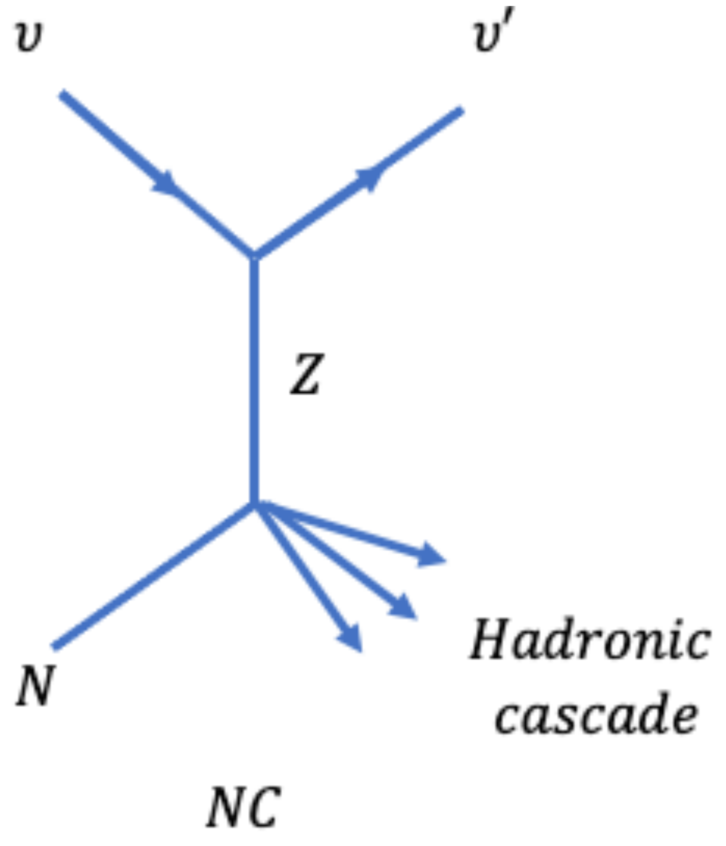


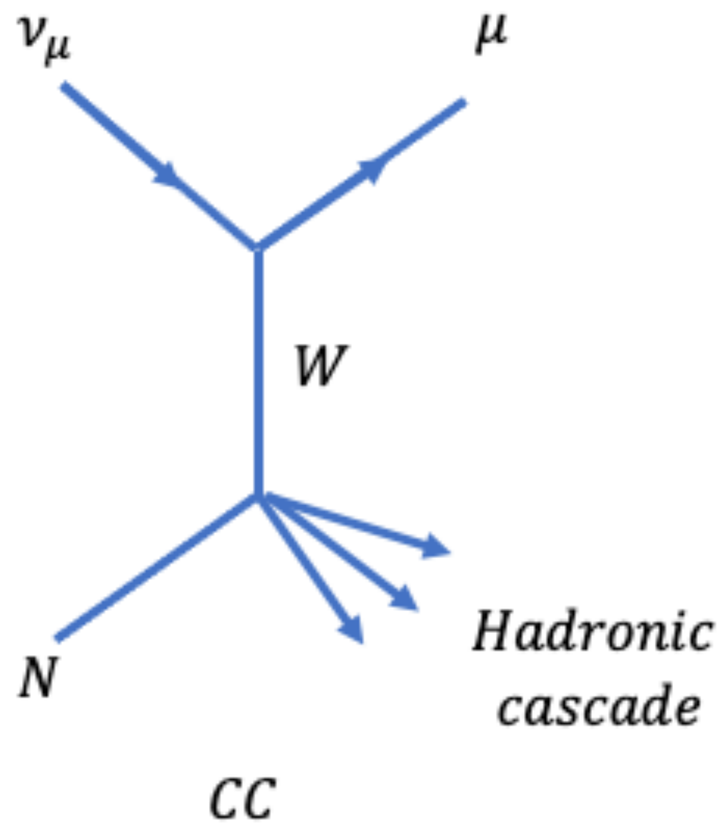


LArTPC, a mm precision digital camera

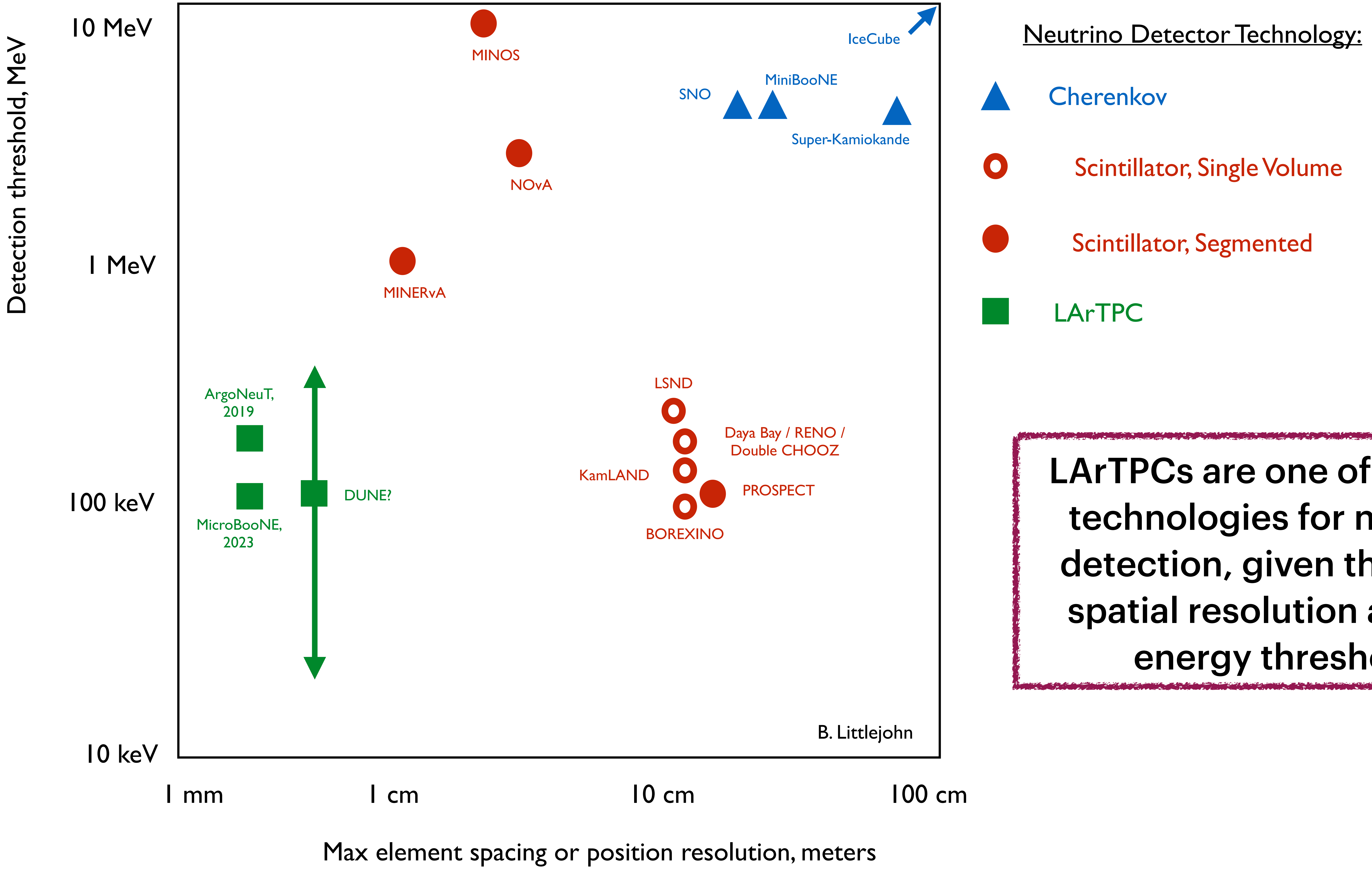








Why a LArTPC?



LArTPCs are one of the best technologies for neutrino detection, given their high spatial resolution and low energy threshold.

dEdx vs Residual Range

J. High Energ. Phys. **2021**, 153 (2021)

To do particle identification (PID), profiles of energy deposited along the track are used.

dEdx vs Residual Range

this is not viable for pi/mu separation given their small mass difference!

J. High Energ. Phys. **2021**, 153 (2021)

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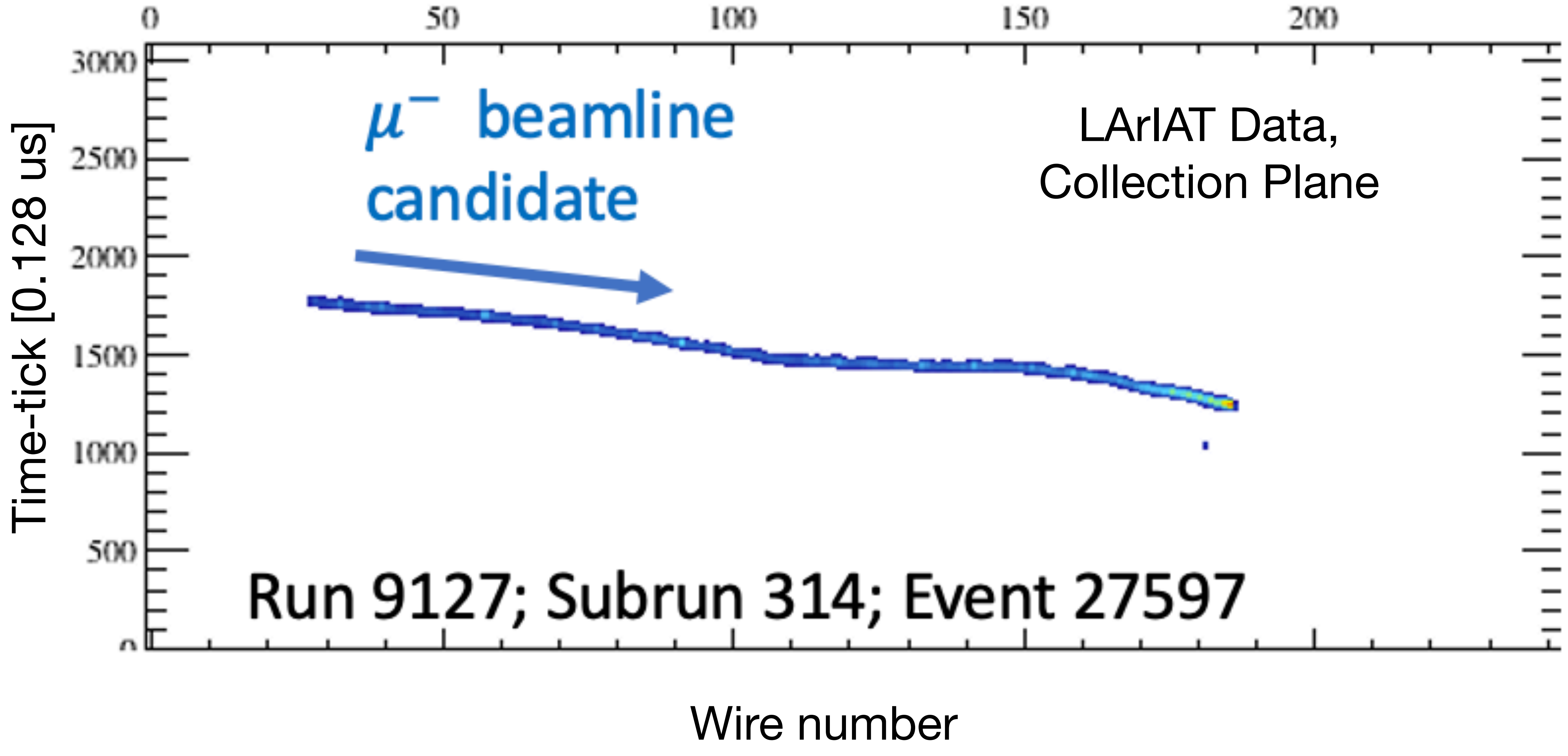
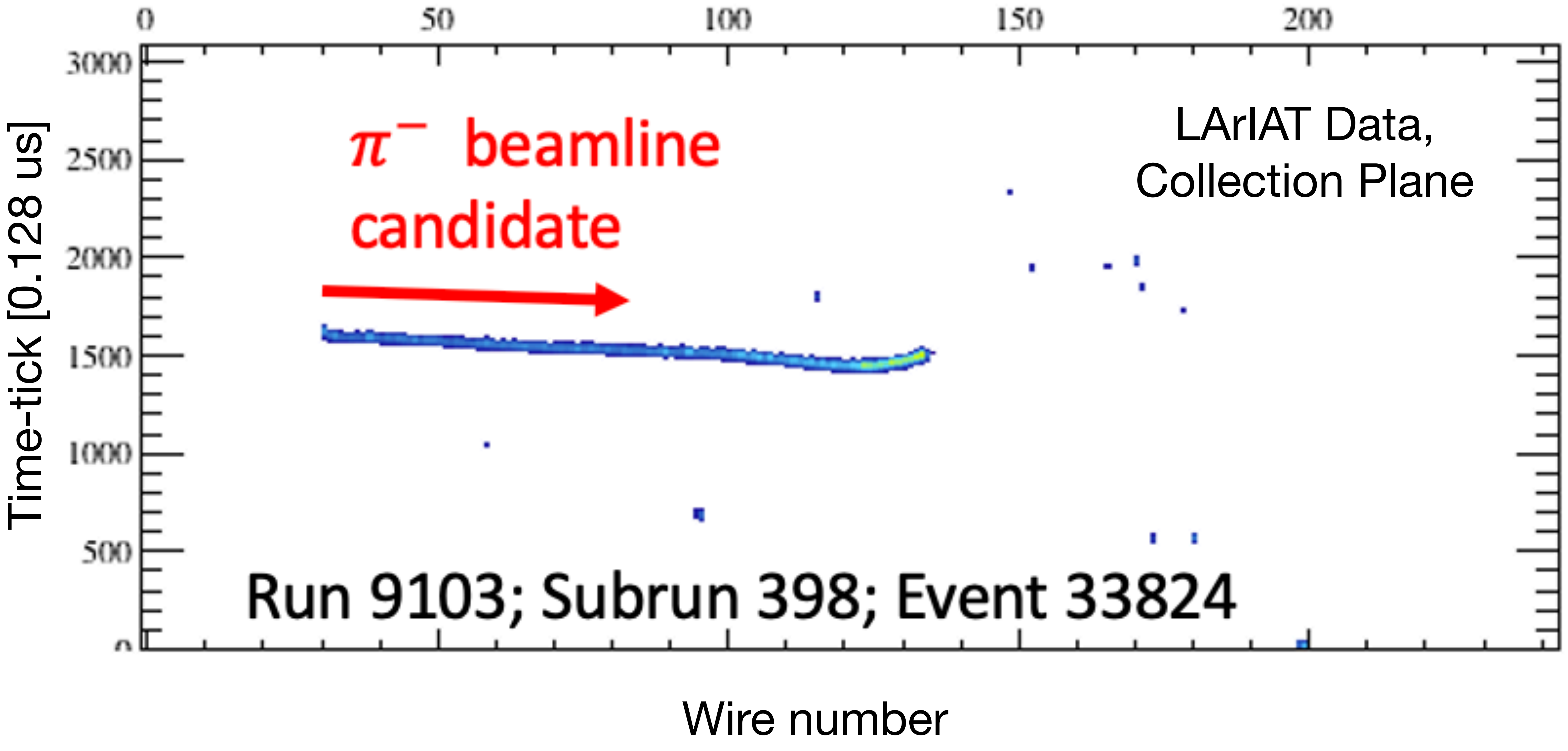
Muons and pions in LArTPCs



μ^- beamline candidate

LArIAT Data,
Collection Plane

Run 9127; Subrun 314; Event 27597



π^- beamline candidate

LArIAT Data,
Collection Plane

Run 9103; Subrun 398; Event 33824

Muons and pions in LArTPCs

we need to find another method for PID...

Muon and Pion Captured At Rest (CAR)

$$\mu^- + p \rightarrow n + \nu_\mu$$

$$\pi^- + p \rightarrow n$$

Muon capture at rest process

Pion capture at rest process

- Pions and muons captured at rest transfer different amounts of energy to nucleus

Muon and Pion Captured At Rest (CAR)

$$\mu^- + p \rightarrow n + \nu_\mu$$

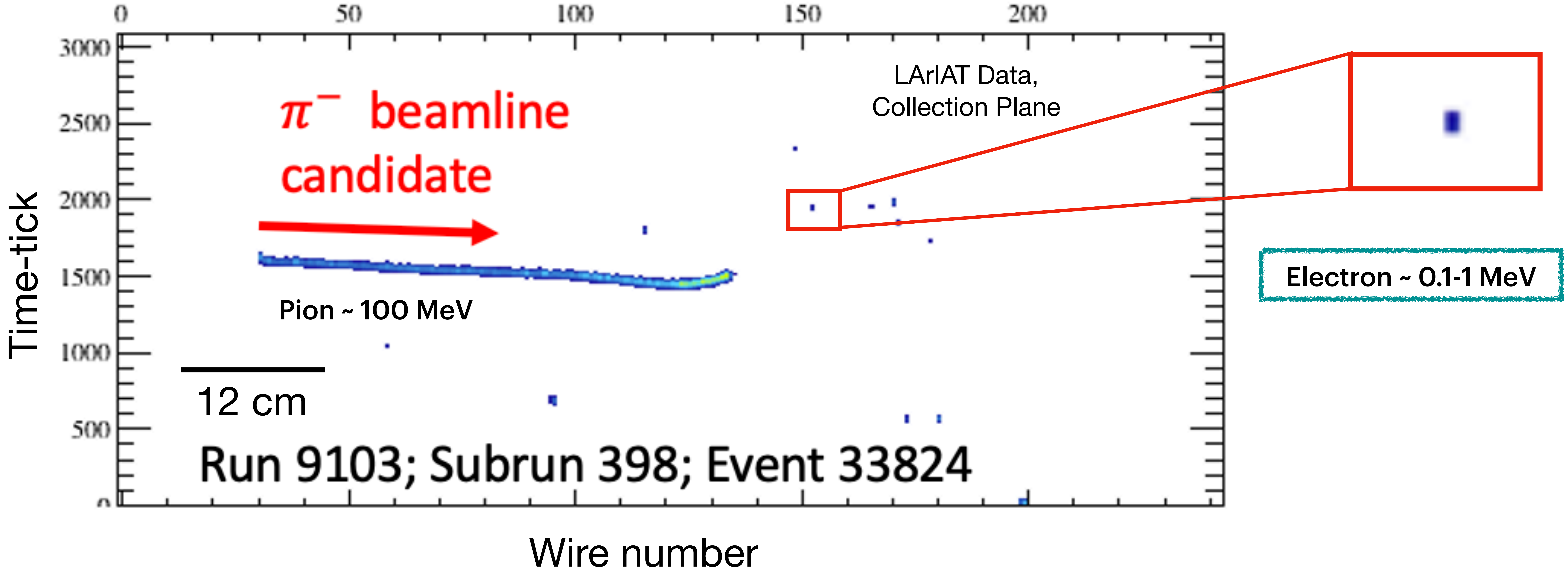
Muon capture at rest process

$$\pi^- + p \rightarrow n$$

Pion capture at rest process

Pions transfer all energy to nucleus; muons transfer some energy to neutrinos
Total energy released by nuclear de-excitation will be higher for pions

Energy scales



π^- beamline candidate

LArIAT Data,
Collection Plane

Pion ~ 100 MeV

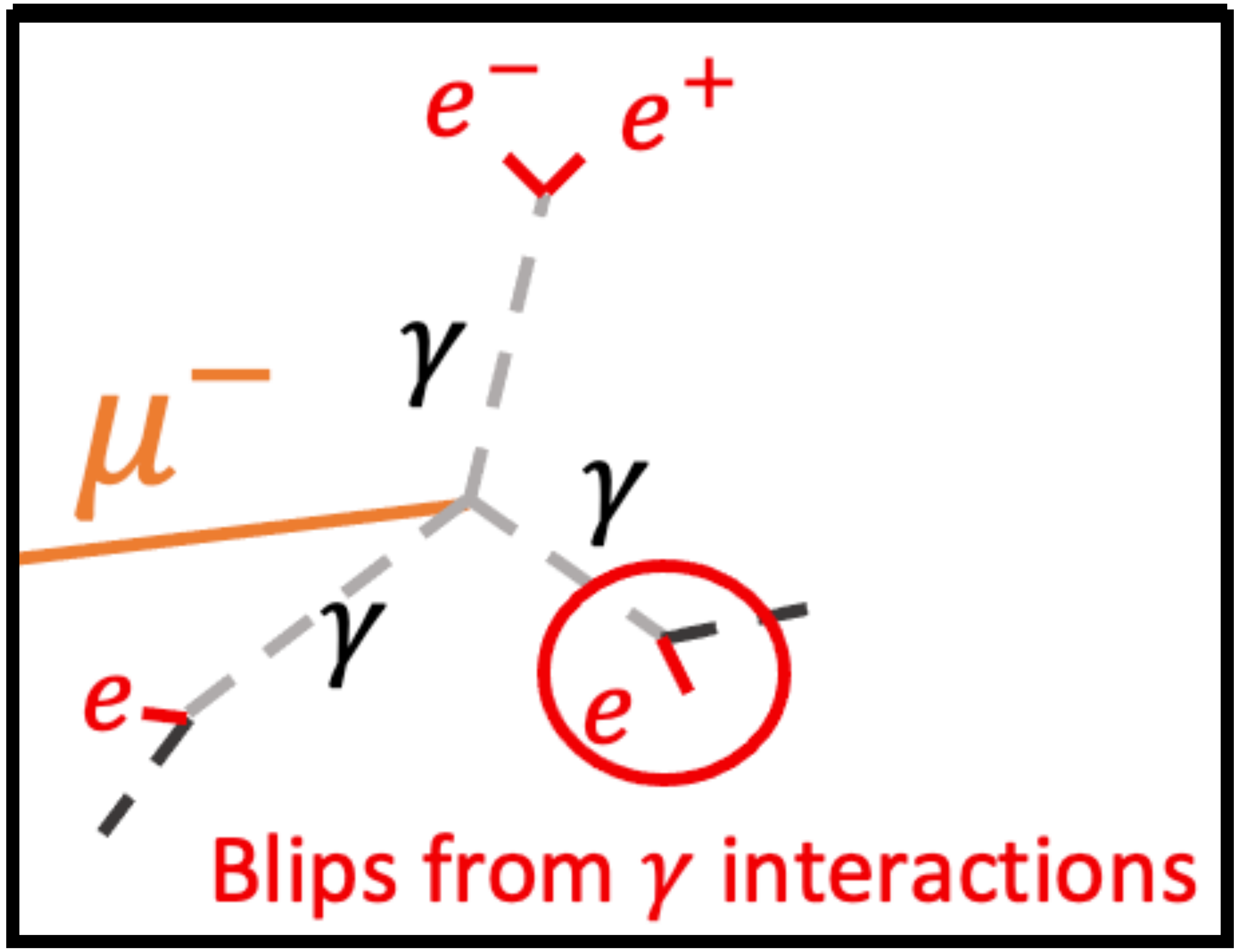
Electron ~ 0.1-1 MeV

12 cm

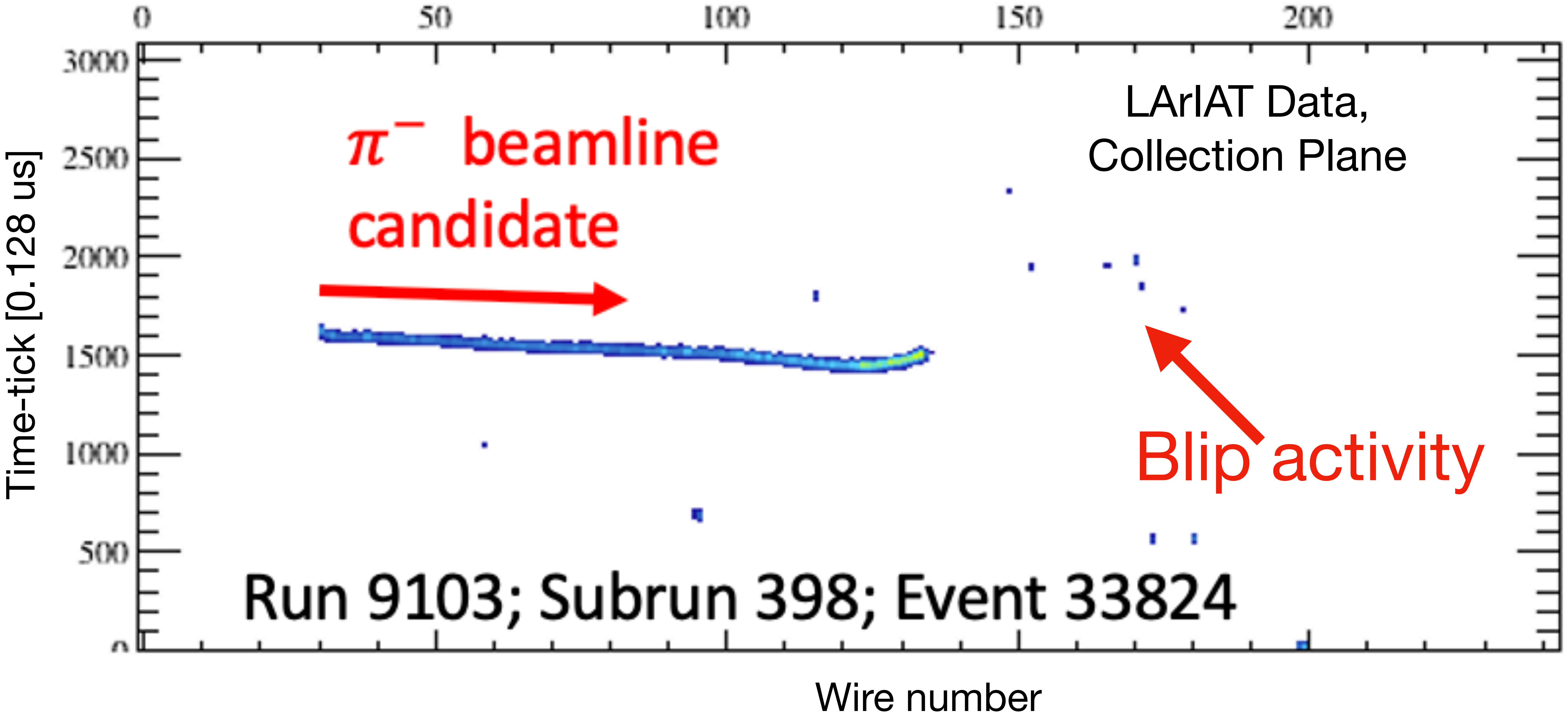
Run 9103; Subrun 398; Event 33824

What is a Blip?

Blips are small, isolated energy deposits sensed only by a limited number of wires per plane (~1-3).

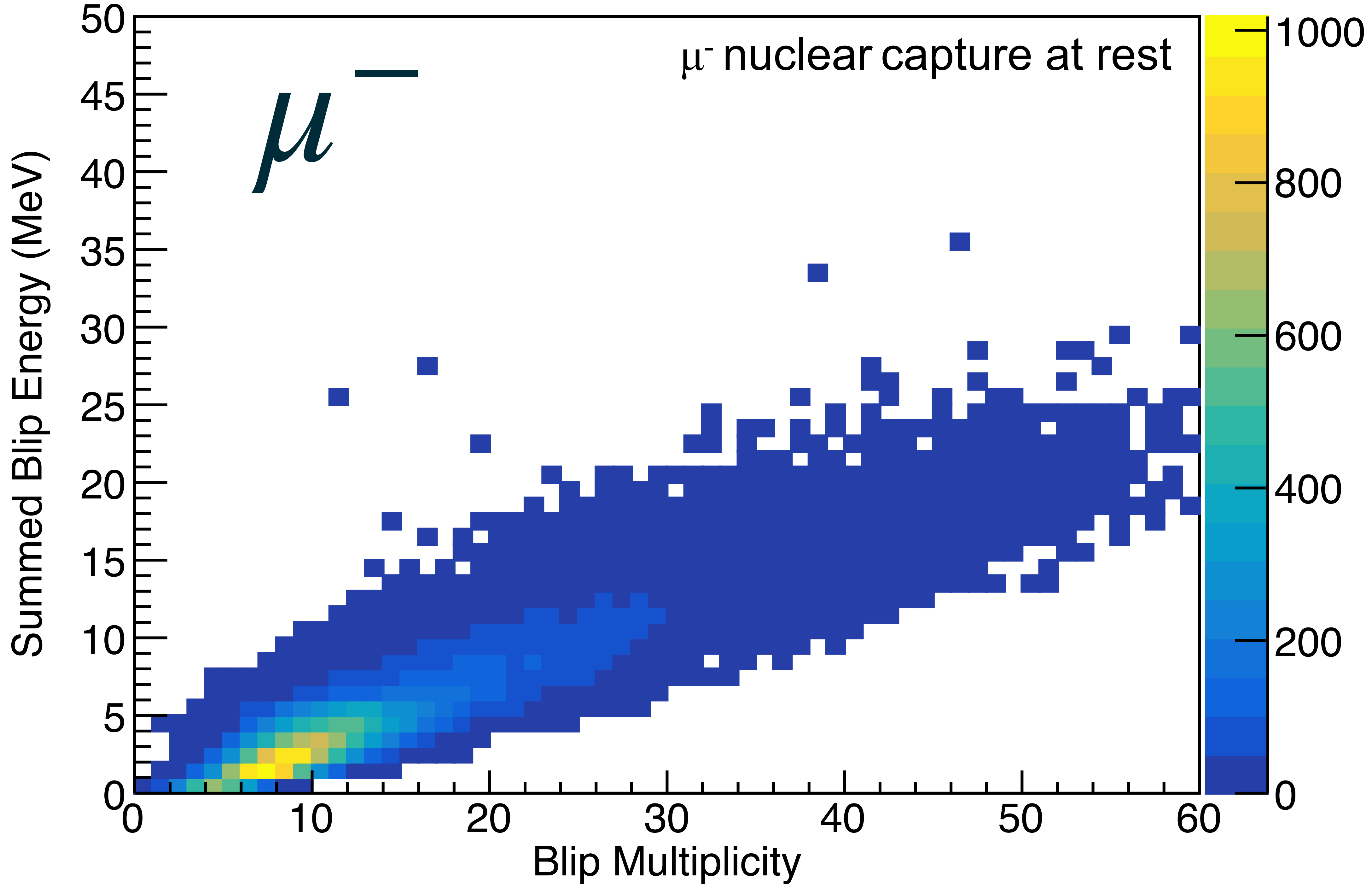


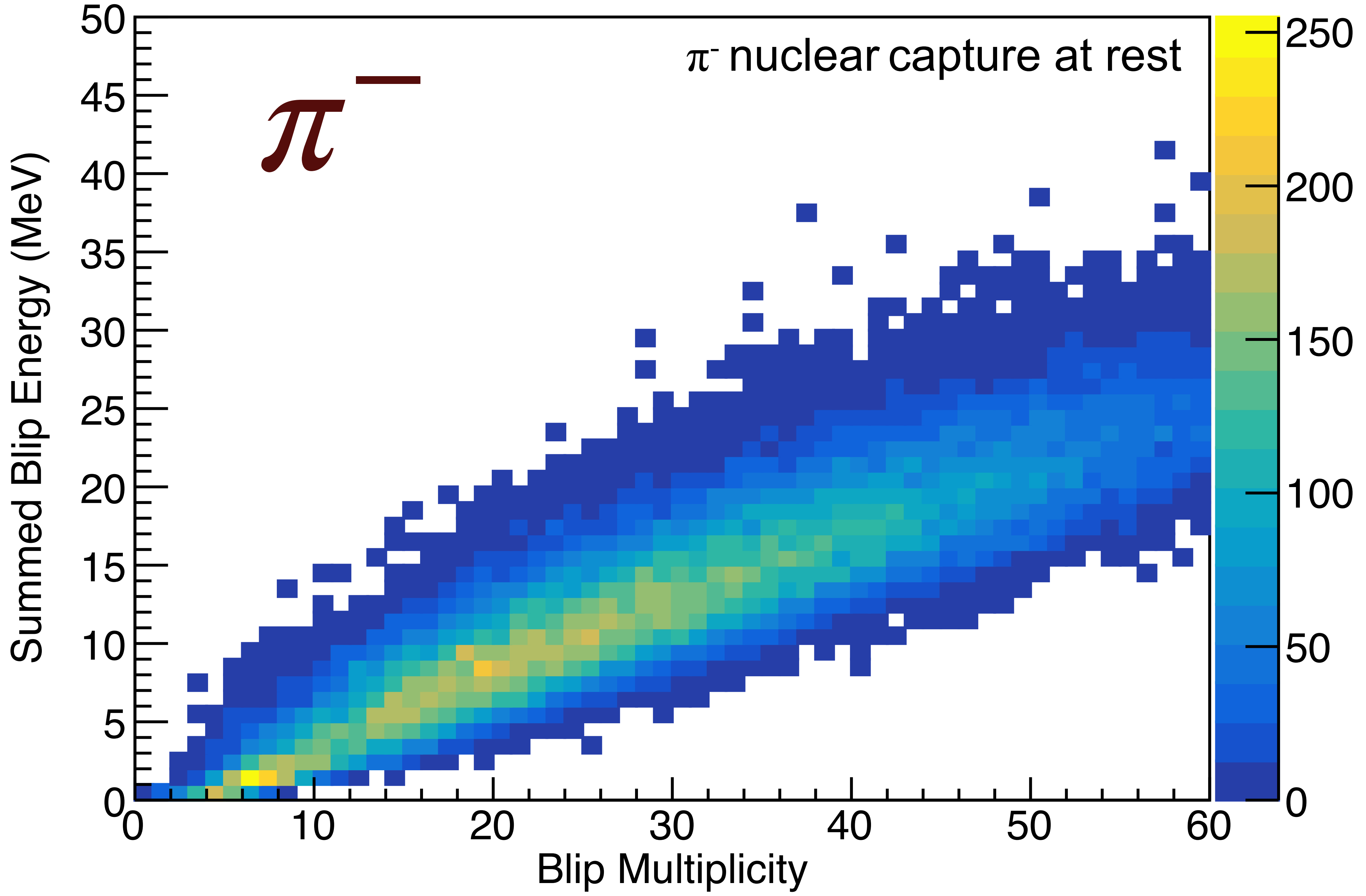
Blips from γ interactions



Energy range:
Pion ~ 100 MeV
Electron ~ 1 MeV

Muon and Pion Blips

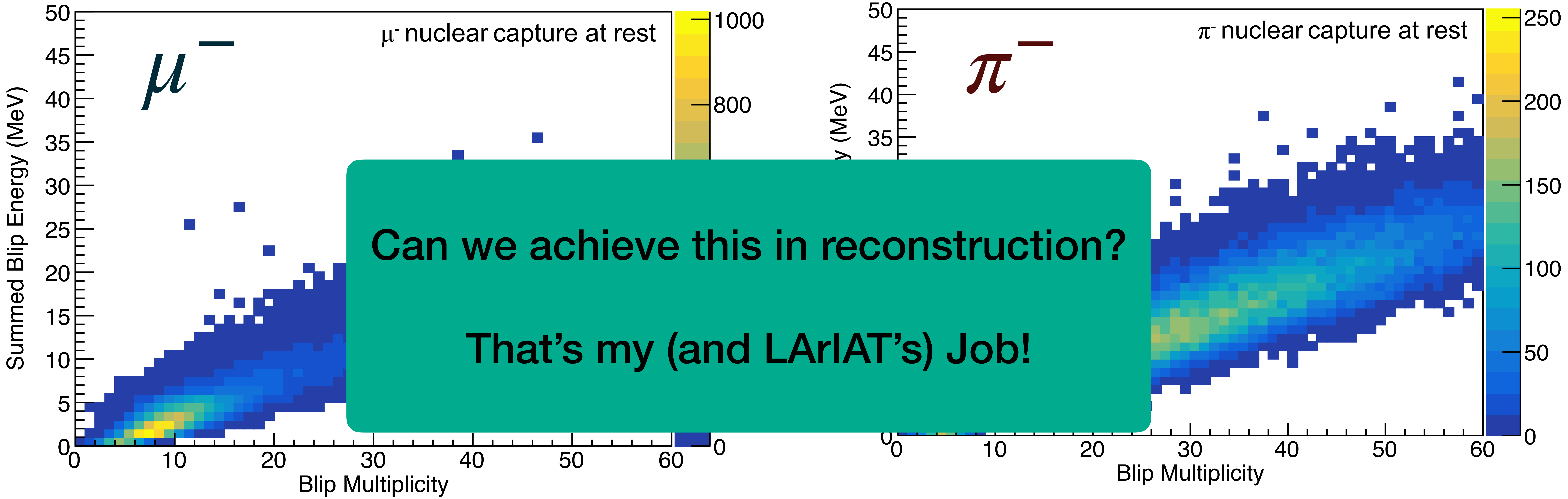




Images from W. Castiglioni et al, PRD 102 (2020)

For this generic LAr simulation, on average we have a higher blip multiplicity and summed blip energy for π^-

Muon and Pion Blips



Can we achieve this in reconstruction?

That’s my (and LArIAT’s) Job!

Images from W. Castiglioni et al, PRD 102 (2020)

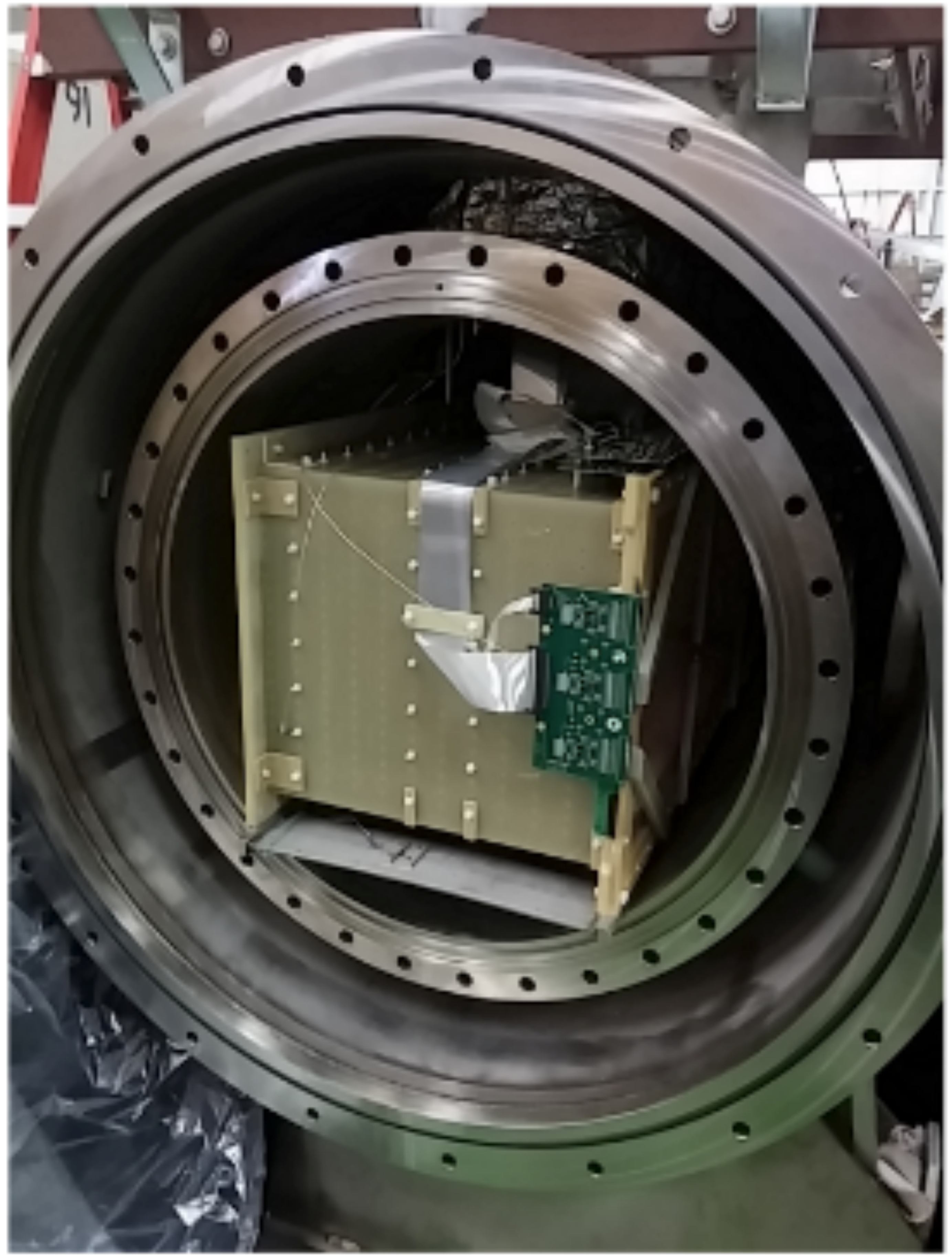
For this generic LAr simulation, on average we have a higher blip multiplicity and summed blip energy for π^-

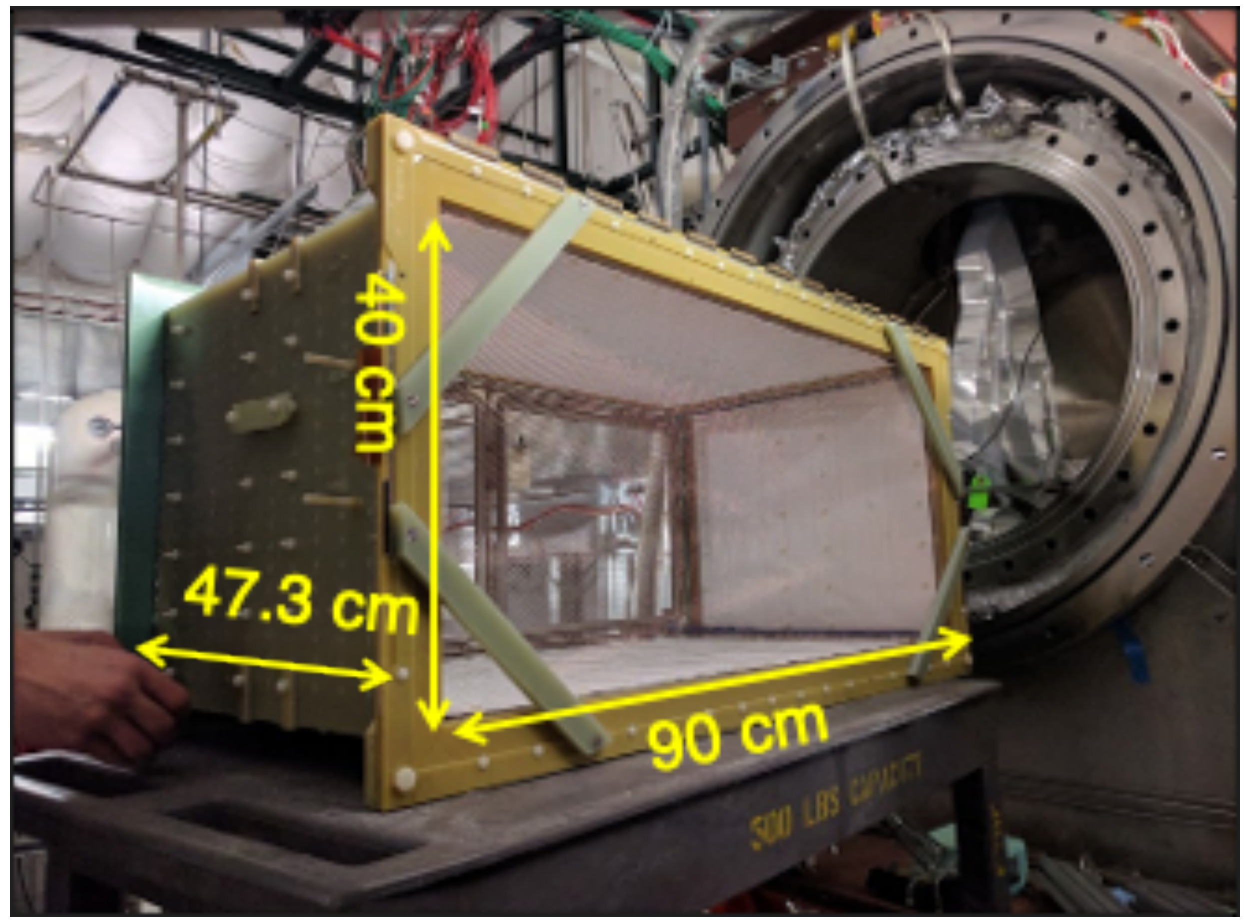
Liquid Argon In A Testbeam

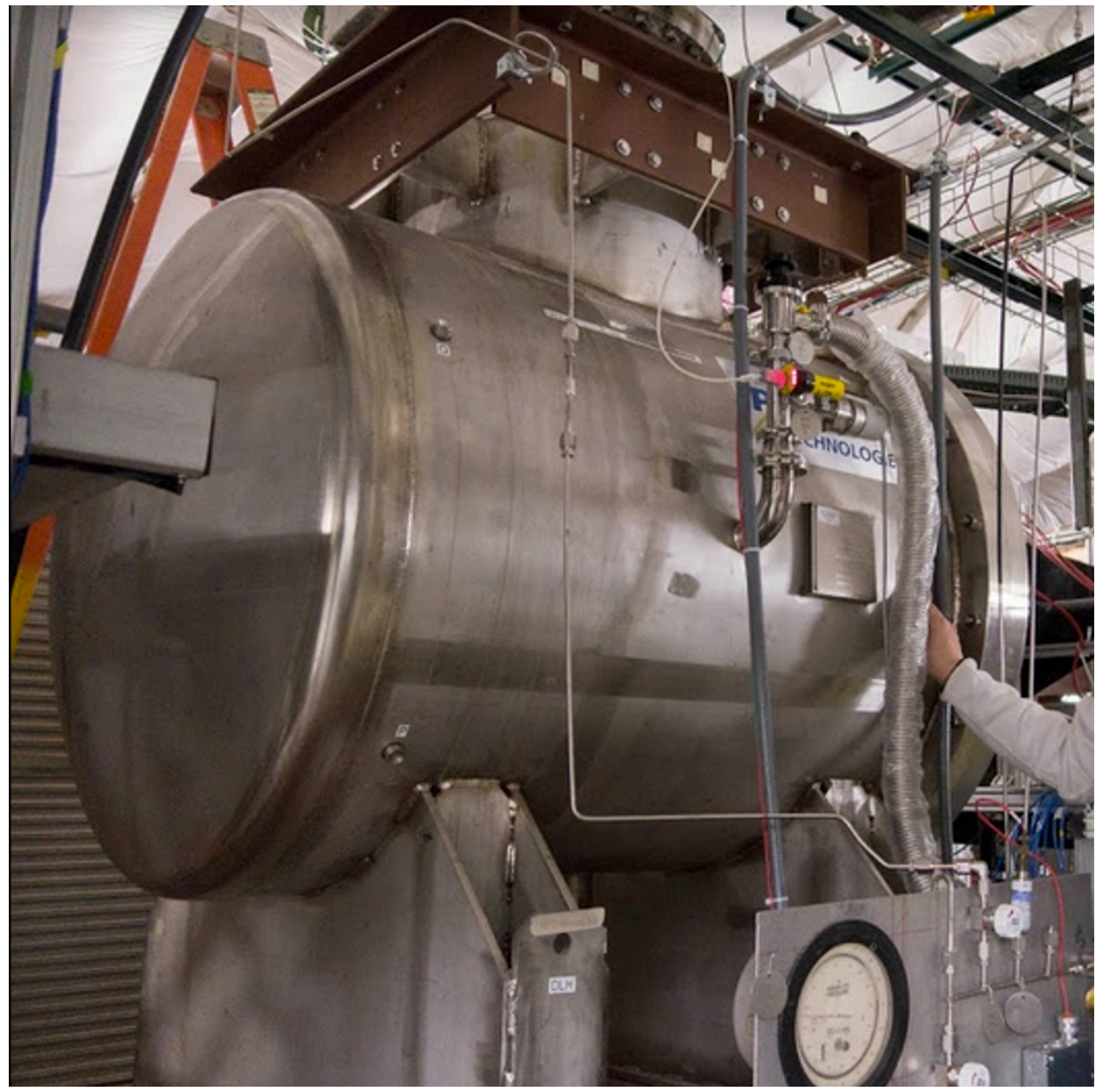
LArIAT is focused on the study of charged particles that can emerge from neutrino-argon interactions

- LArIAT characterizes the response of LArTPCs to particles in the energy range relevant to next-generation neutrino experiments.
- Most particle identification (PID) in LArTPCs uses calorimetry.
- LArIAT data can be used to explore new analysis techniques for improving PID!

- 90 cm x 47 cm x 40 cm TPC volume
- 2 instrumented readout planes, each with 240 parallel wires (induction and collection, at +/-60 deg from horizontal, respectively)



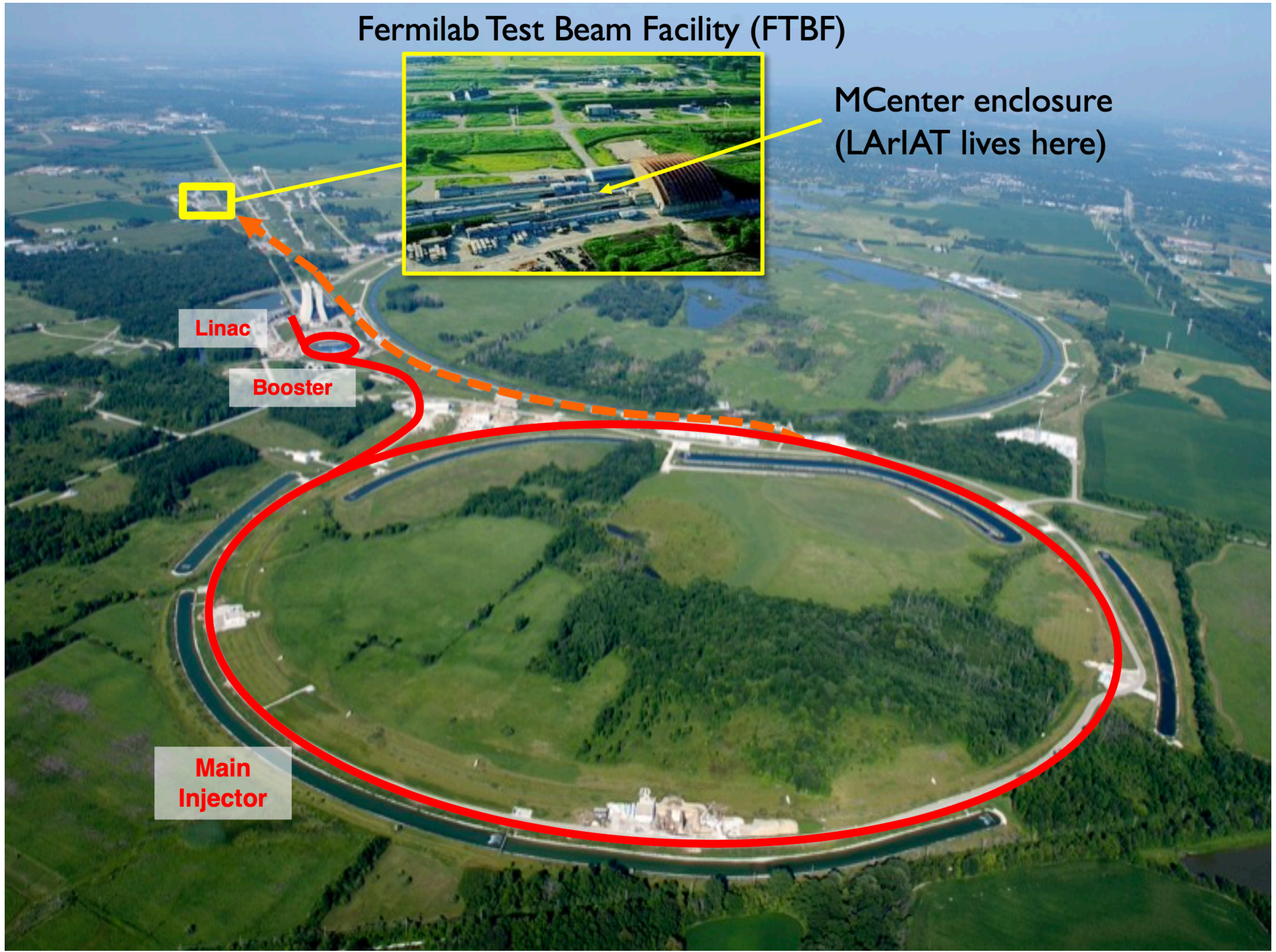




LArIAT cryostat with TPC, image from LArIAT, JINST 15 (2020).

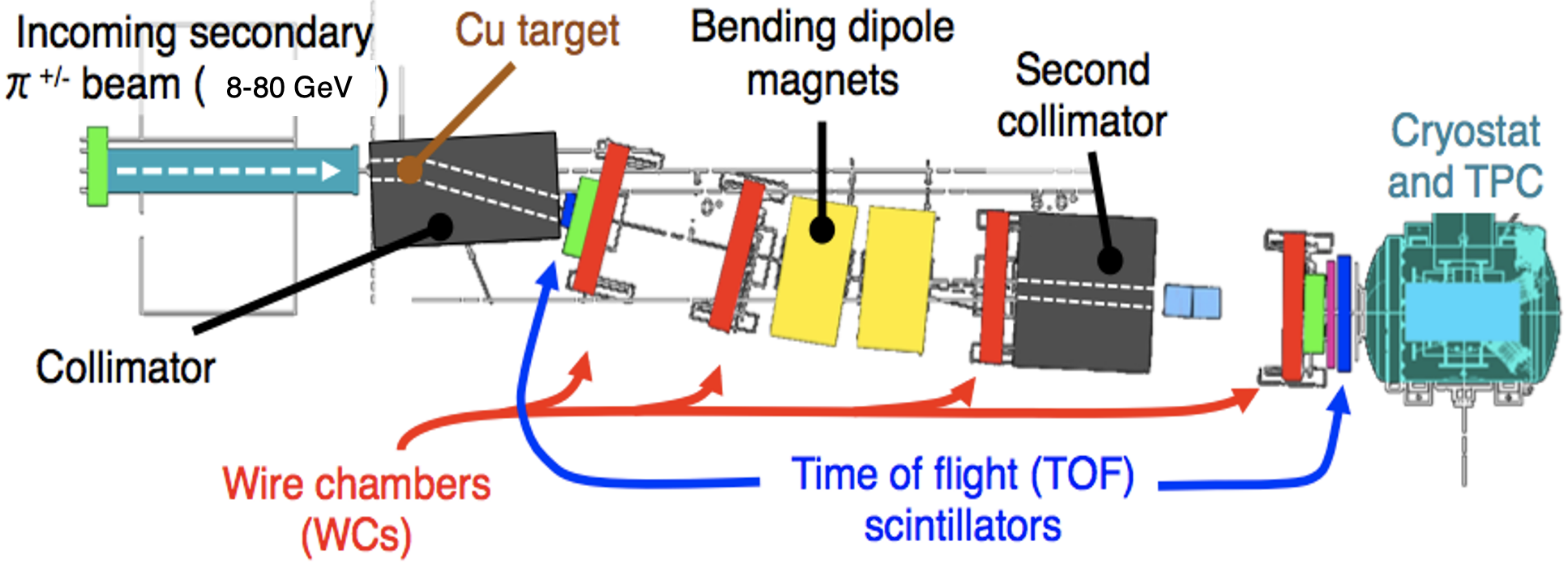
LArIAT in the Test Beam Facility

LArIAT was taking data at the TestBeam Facility from 2015 to 2017



LArIAT Tertiary Beamline at FTBF MCenter Enclosure

Beamline



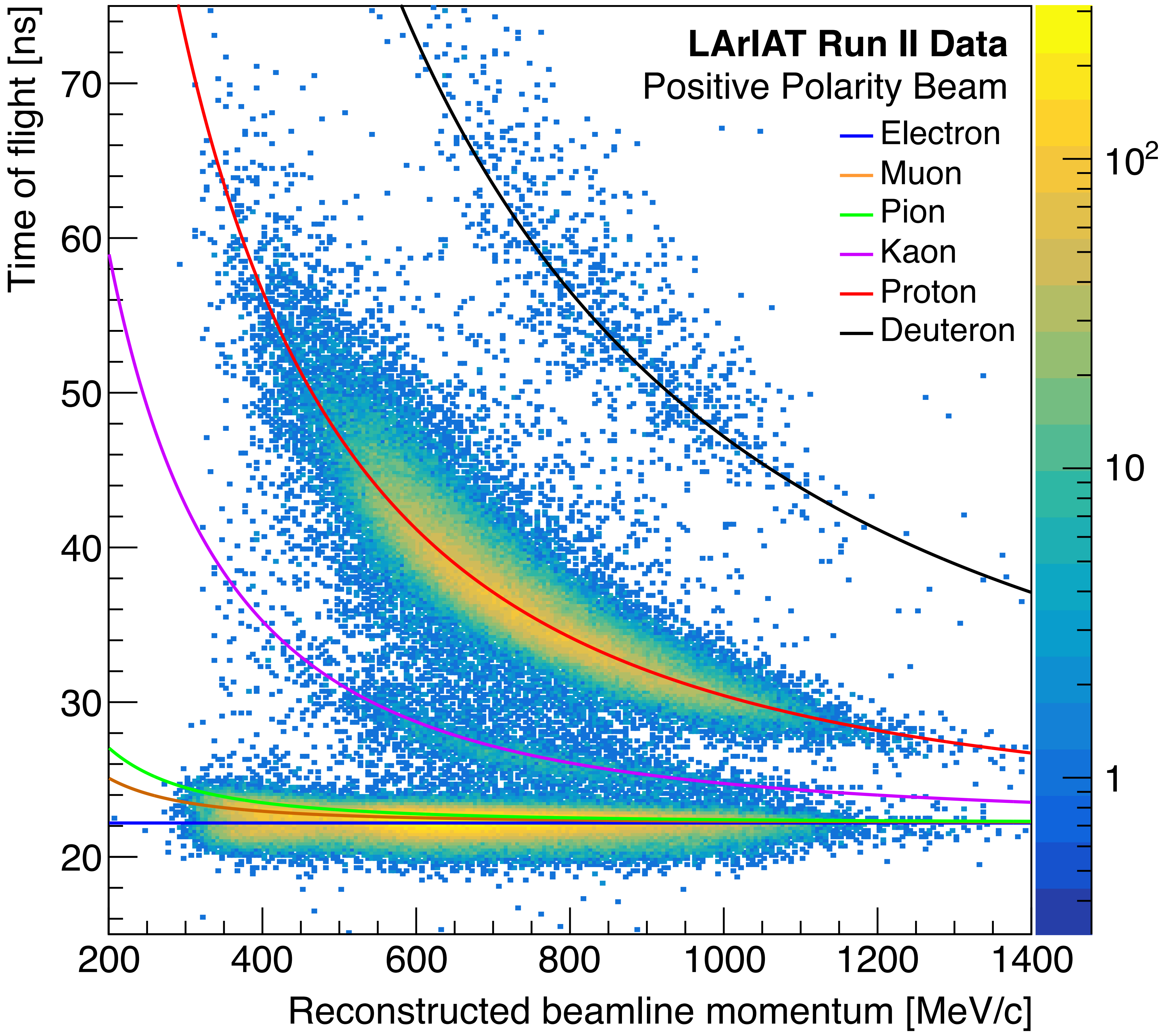
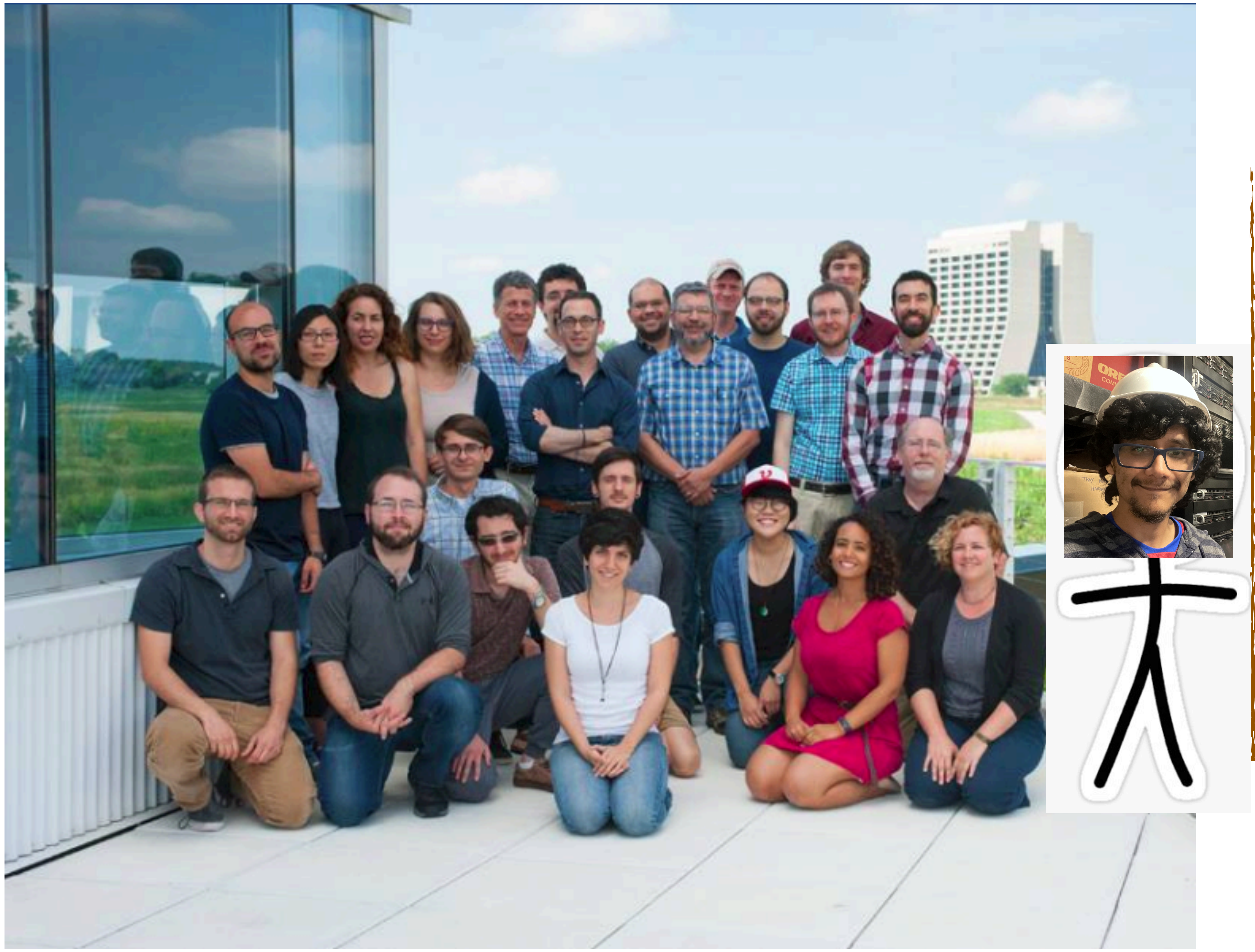


Image from LArIAT, JINST 15 (2020).

LArIAT, a small detector with a big heart



LArIAT is a small collaboration (~25 scientists) with several PHYSICS MEASUREMENTS

- Calorimetry for low-energy electrons using charge and light in liquid argon, Phys. Rev. D 101, 012010 (2020).
- Measurement of the $\pi^- - Ar$ total hadronic cross section at the LArIAT experiment, Phys Rev. D 106, 052009 (2022).
- Measurements of pion and muon nuclear capture at rest on argon in the LArIAT experiment, arxiv2408.05133 (2024).
- First observation of antiproton annihilation at rest on argon in the LArIAT Experiment, arxiv2409.13596 (2024).

Muon and Pion capture at rest on argon measurement

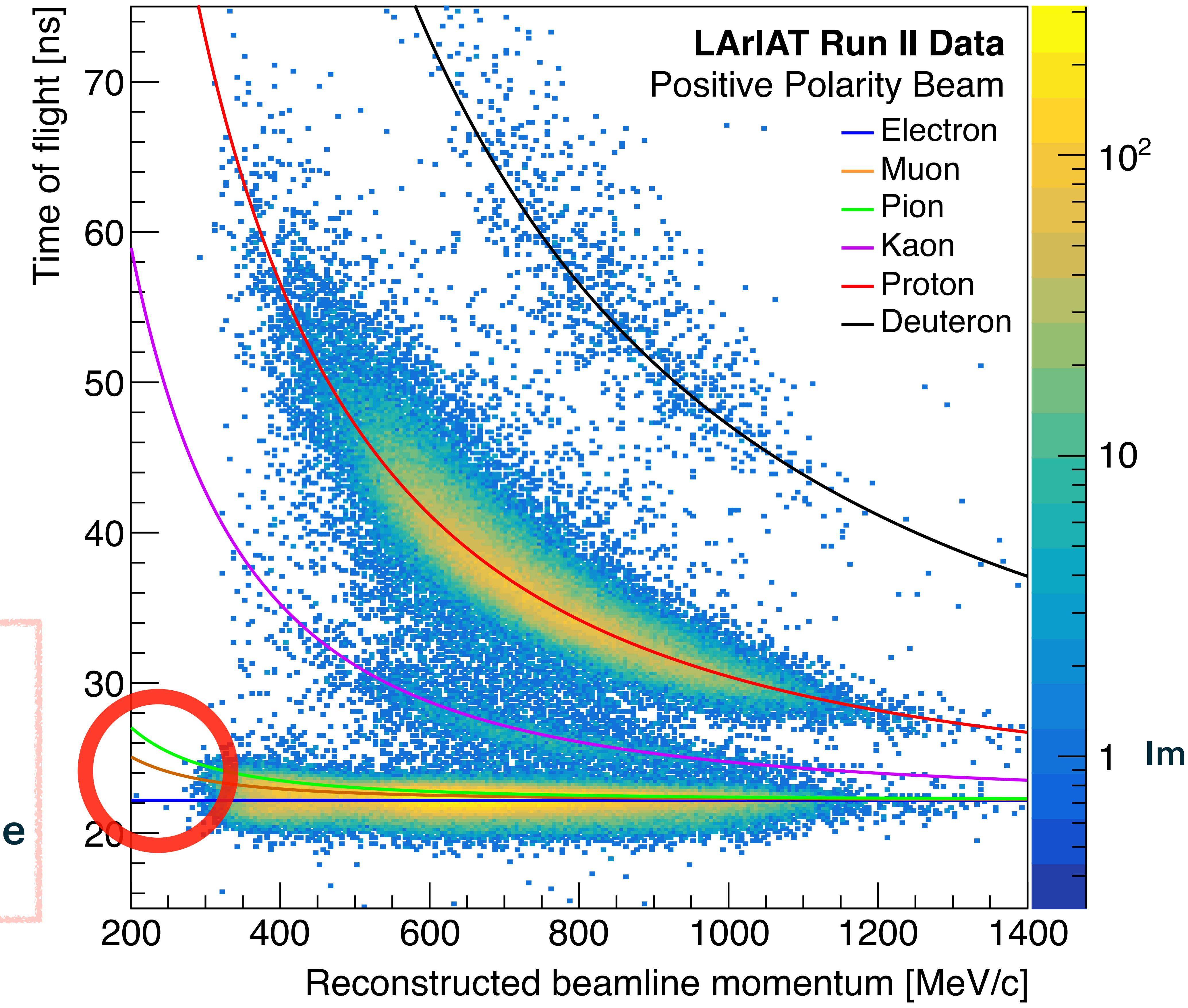
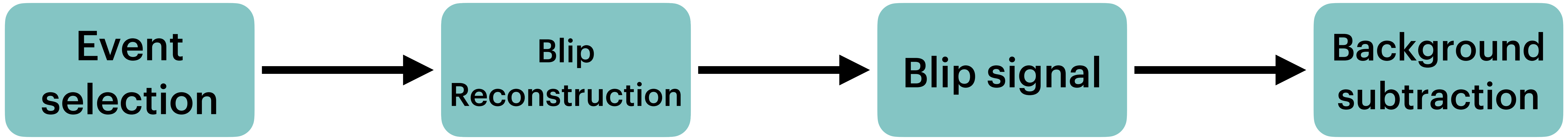


Image from LArIAT, JINST 15 (2020)

LArIAT is ideal for this measurement because data collected are low enough energy for capture at rest

Studying blip activity for different particles will demonstrate if it is possible to do PID and sign determination for pions/muons

Workflow analysis



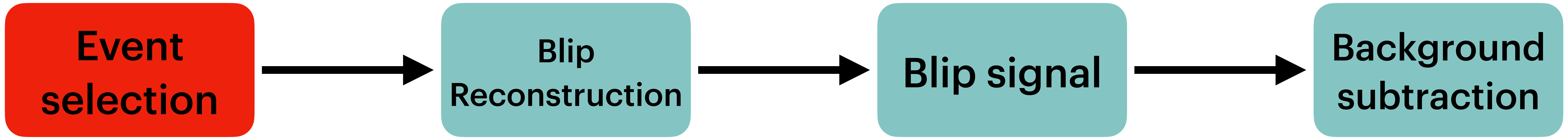
Event selection

Blip Reconstruction

Blip signal

Background subtraction

Workflow analysis

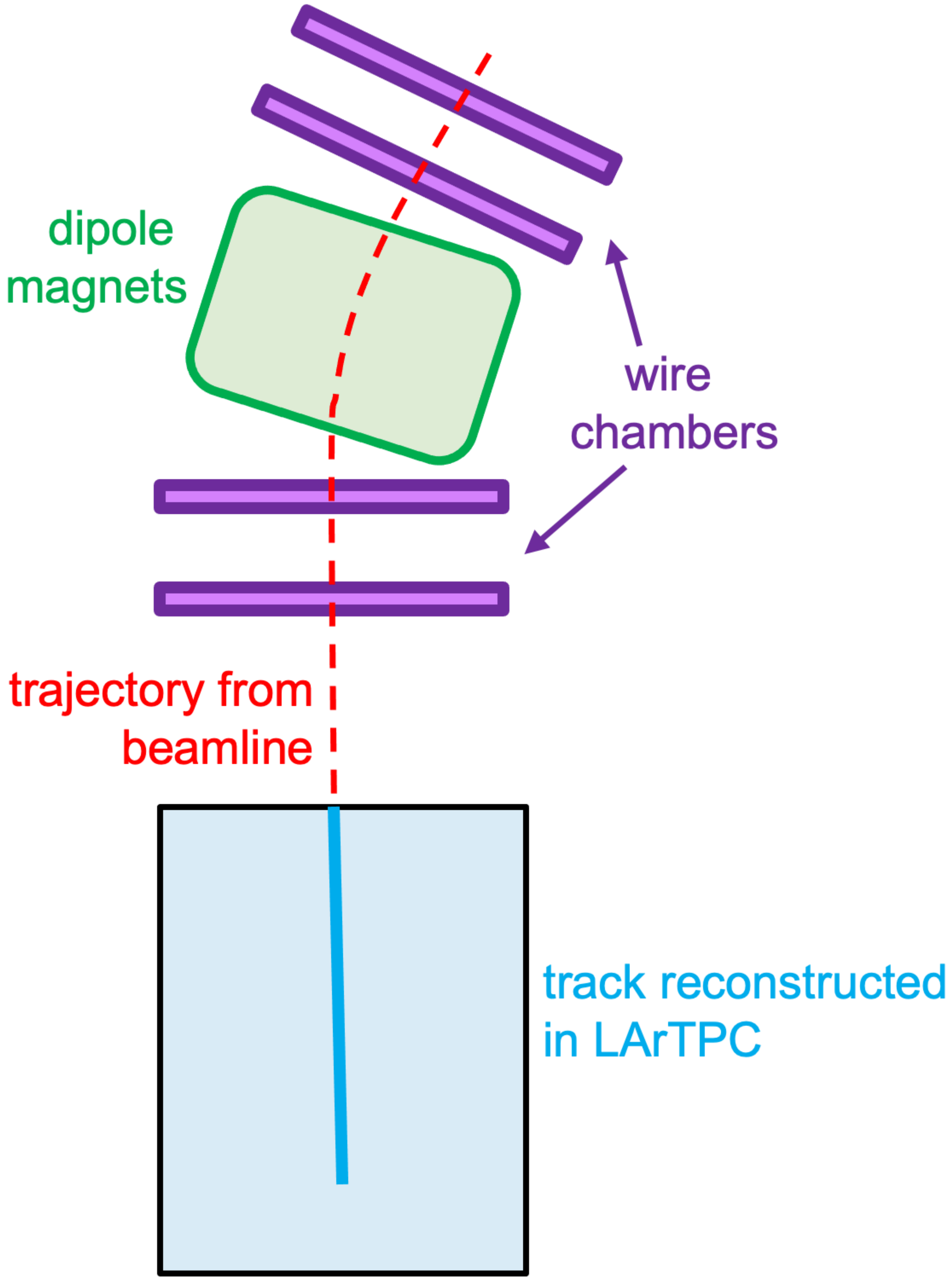


Event selection → Blip Reconstruction → Blip signal → Background subtraction

Cuts for track classification

We need a pure sample of muCAR or piCAR to analyze blips.

- A projection from the beamline wire chambers (WCs) to the front face of the TPC.
- Remove events with WC track momentum > 415 MeV.
- Require reconstructed track > 35 cm that enters front-face of TPC and ends at least 2 cm before the end of the active volume.
- Require a Bragg peak by looking for energy deposition density (*dE/dx*) > 3 MeV/cm in final 2 cm of track.
- Remove events with more than 4 tracks (pile-up) or events with these pile-up tracks close to the main track < 8 cm.



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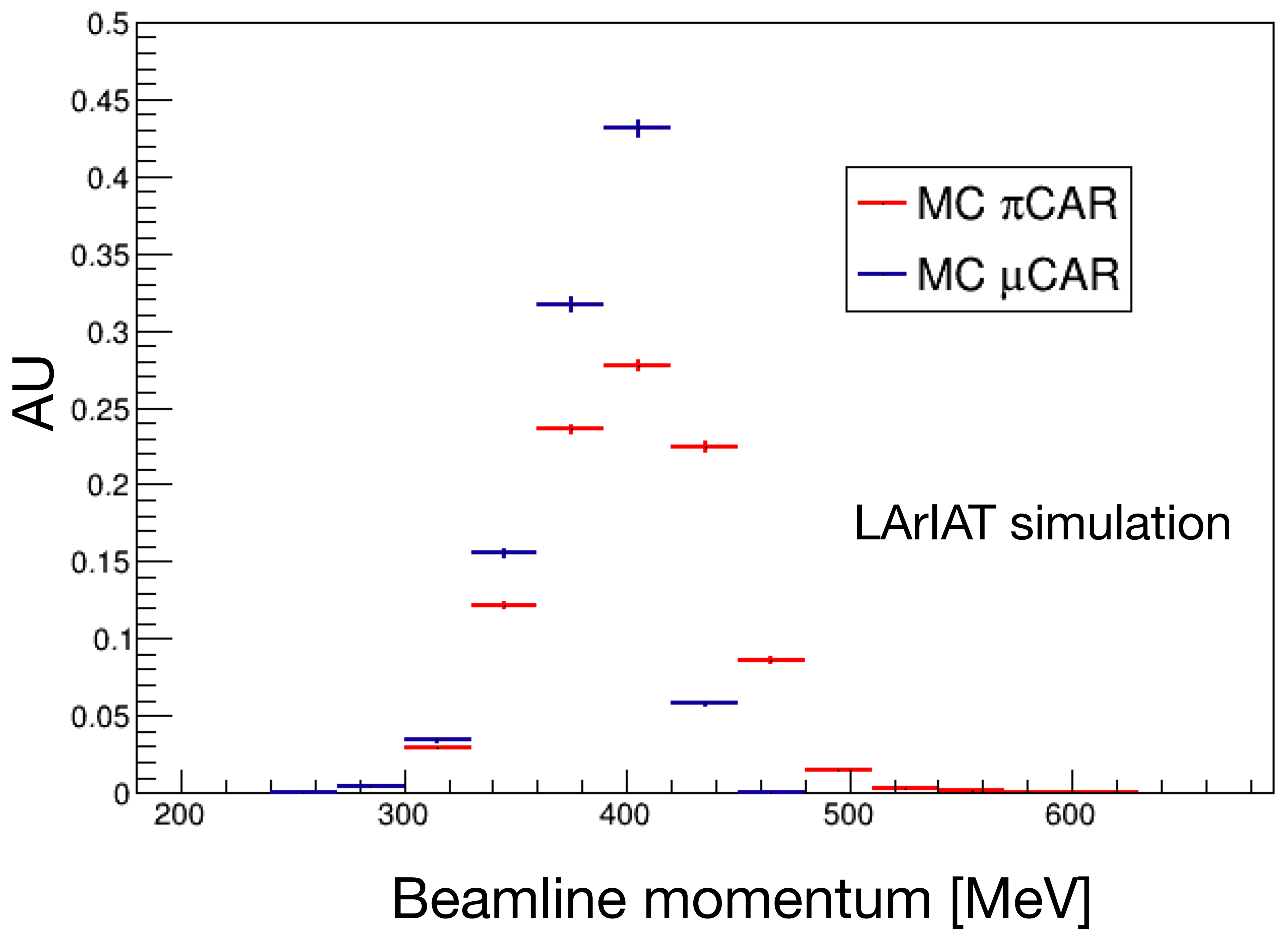

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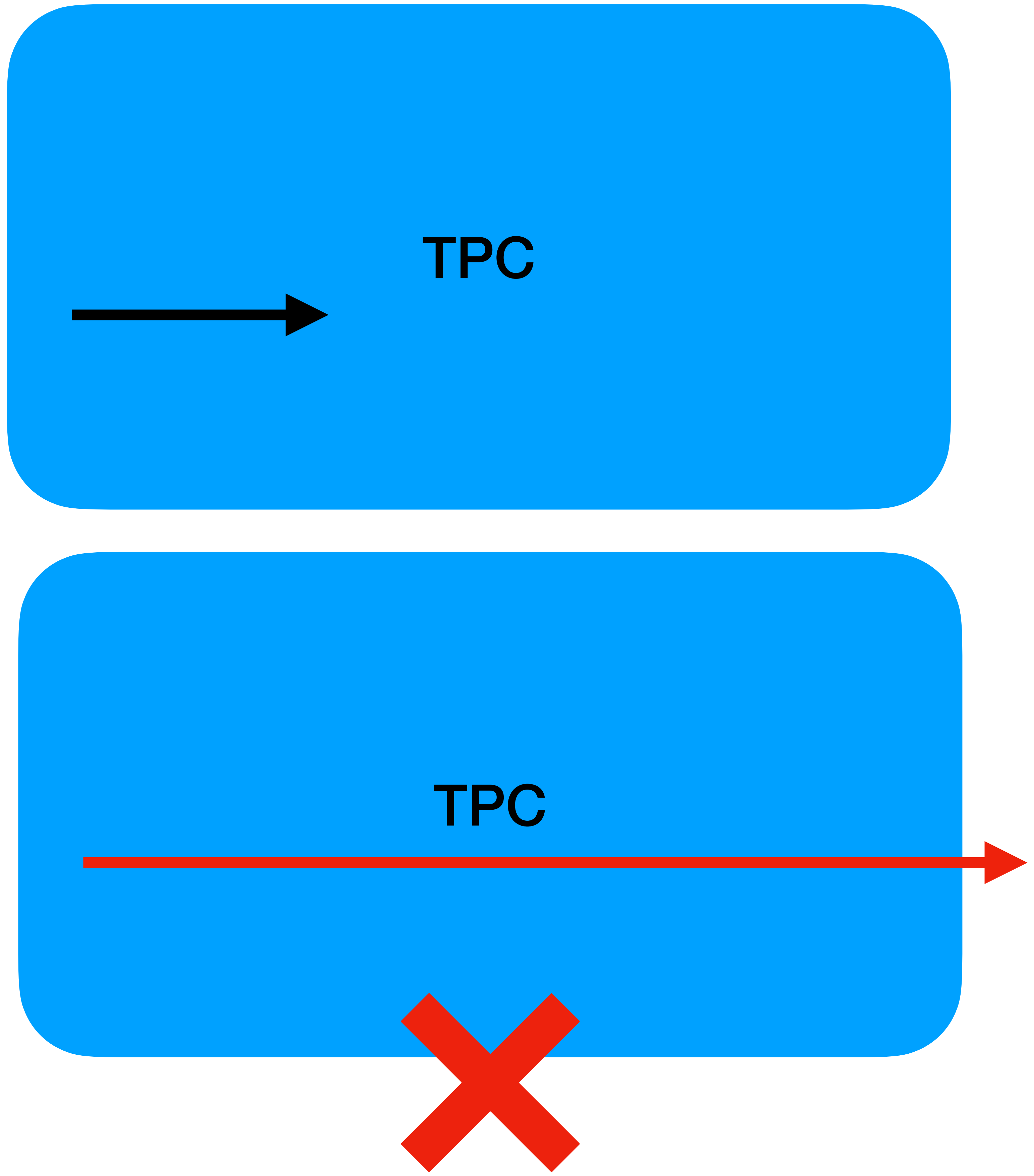

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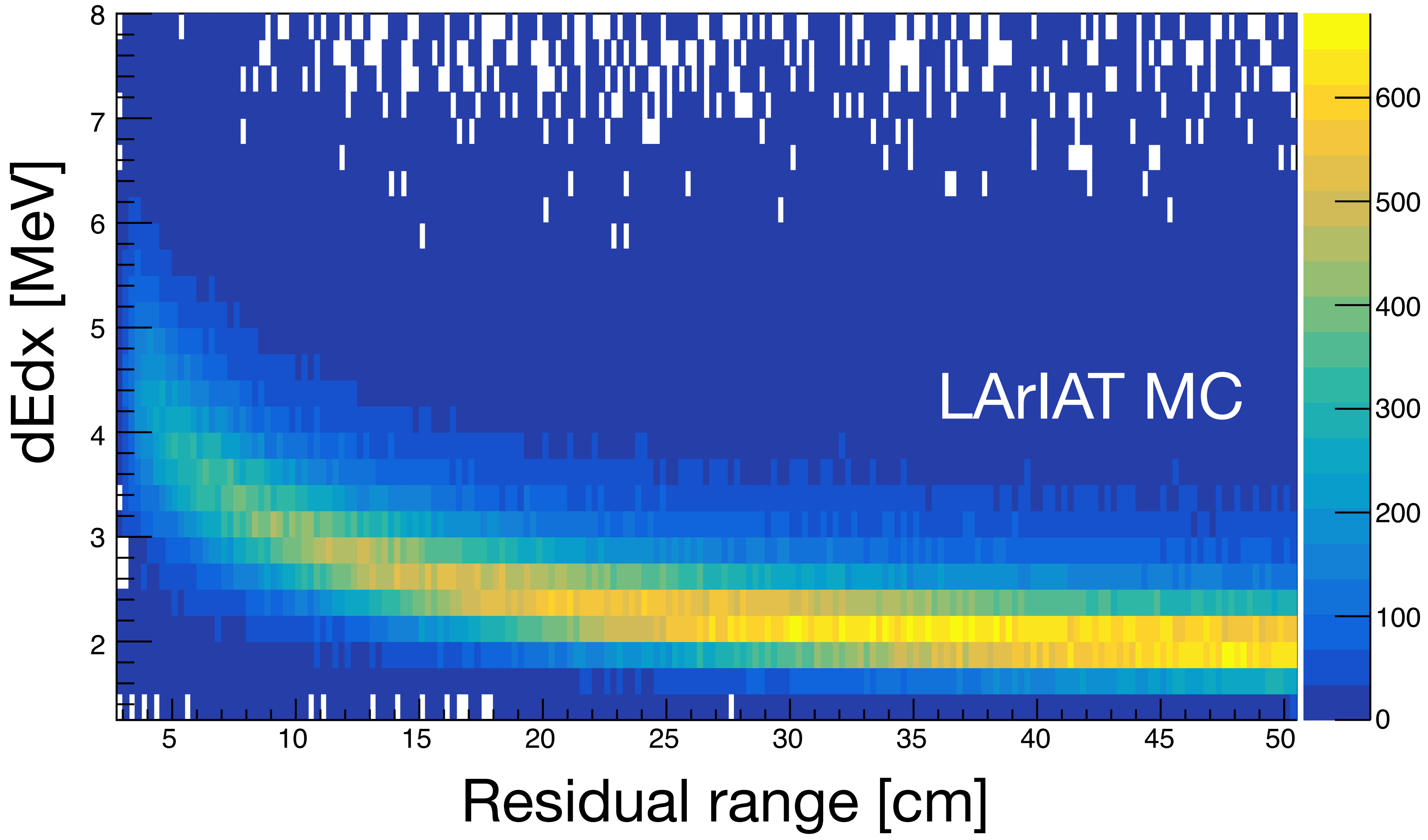

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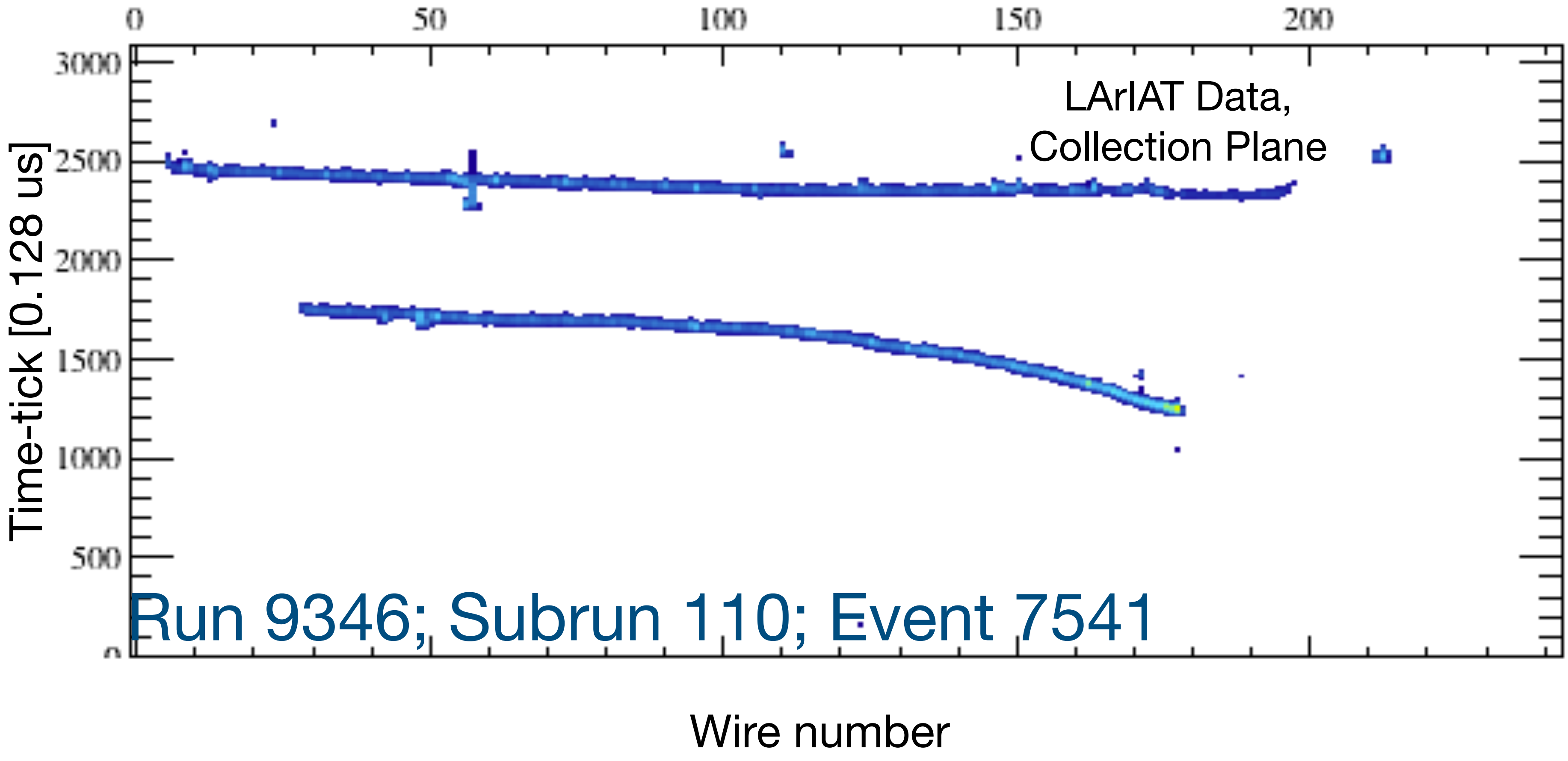
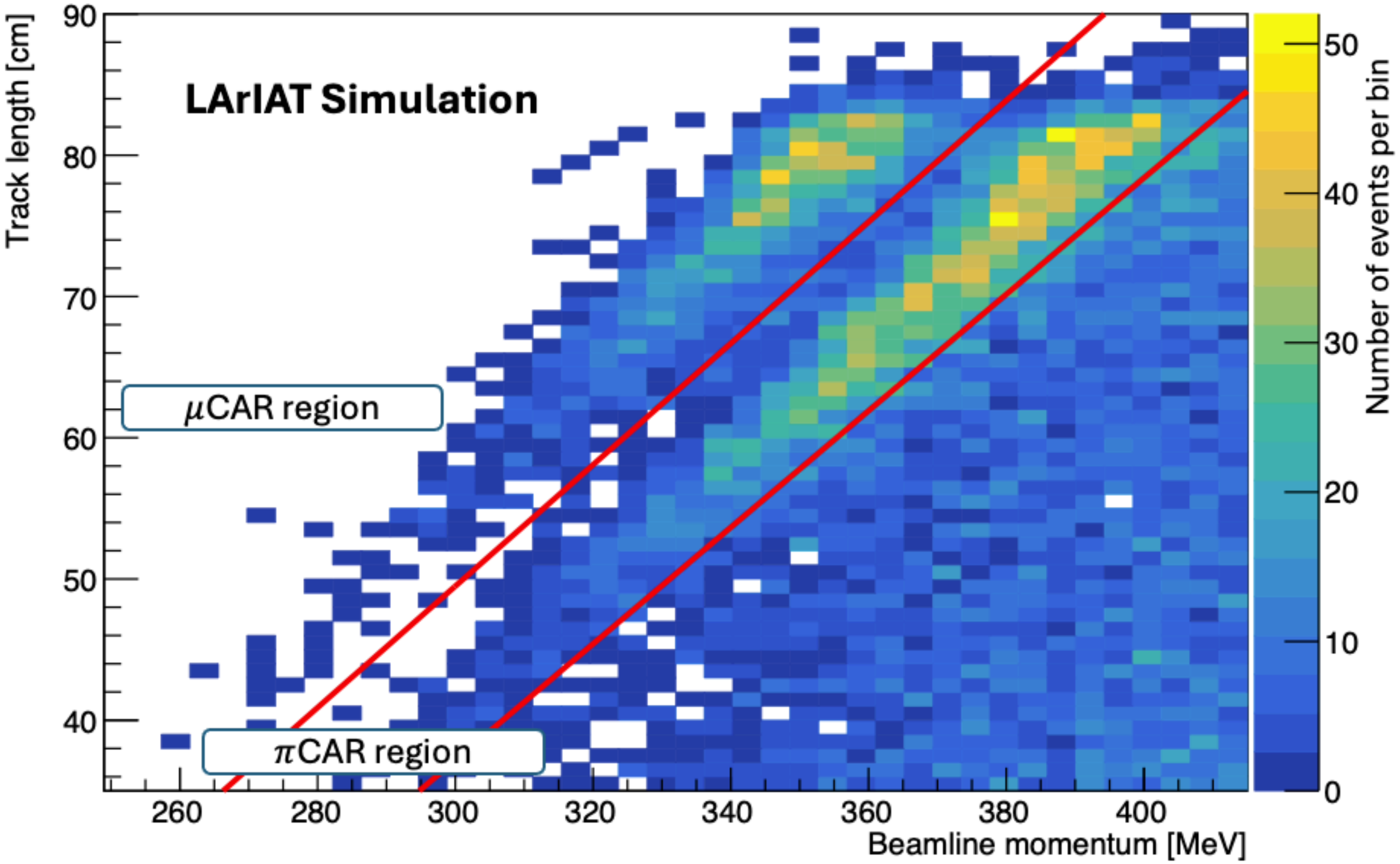


Muon and Pion CAR selection



LArIAT SIMULATION

Purity = signal events / Total events

Using beam momentum and track stopping point inside of the TPC we separate stopping muons from stopping pions.

With a MC sample of 500k events in the -60A configuration, my final selection is made with

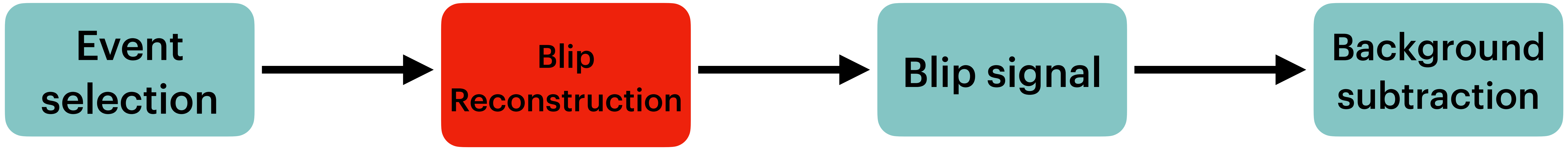
2132 muon CAR events (79% purity)
3931 pion CAR events (76% purity)

Data has 87 muon CAR and 209 pion CAR candidates.

$l > 0.43p - 79.5$ for muon CAR

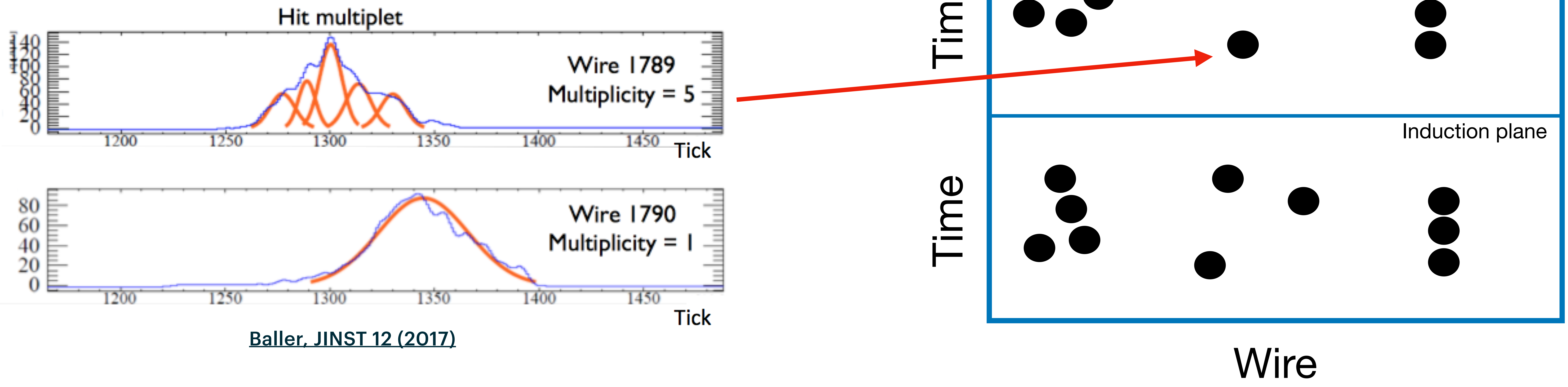
$0.43p - 79.5 > l > 0.41p - 86.5$ for pion CAR

Workflow analysis



Event selection → Blip Reconstruction → Blip signal → Background subtraction

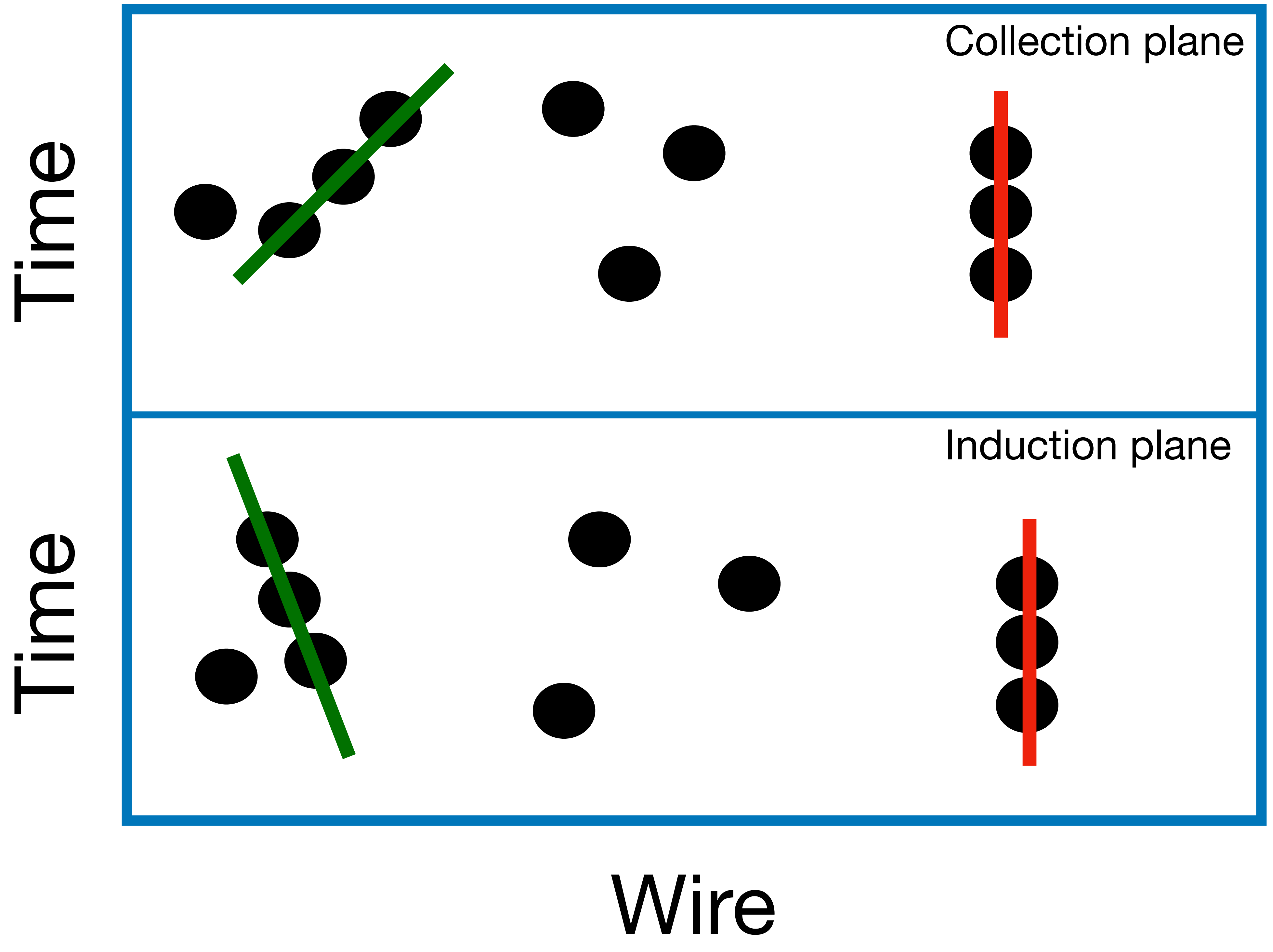
Blip Reconstruction



Baller, JINST 12 (2017)

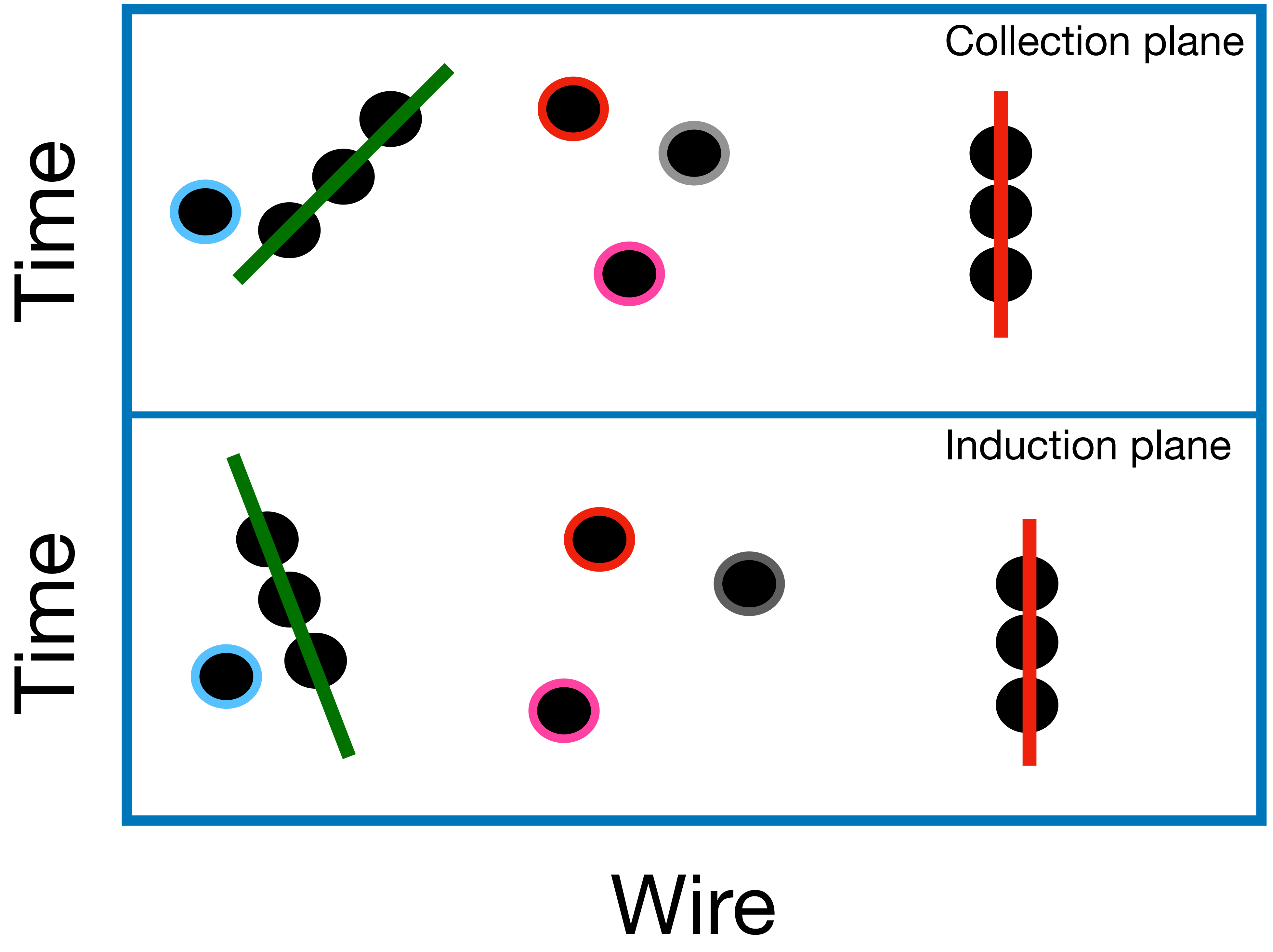
Blip Reconstruction

1. Hits not associated with any track > 5cm are taken.



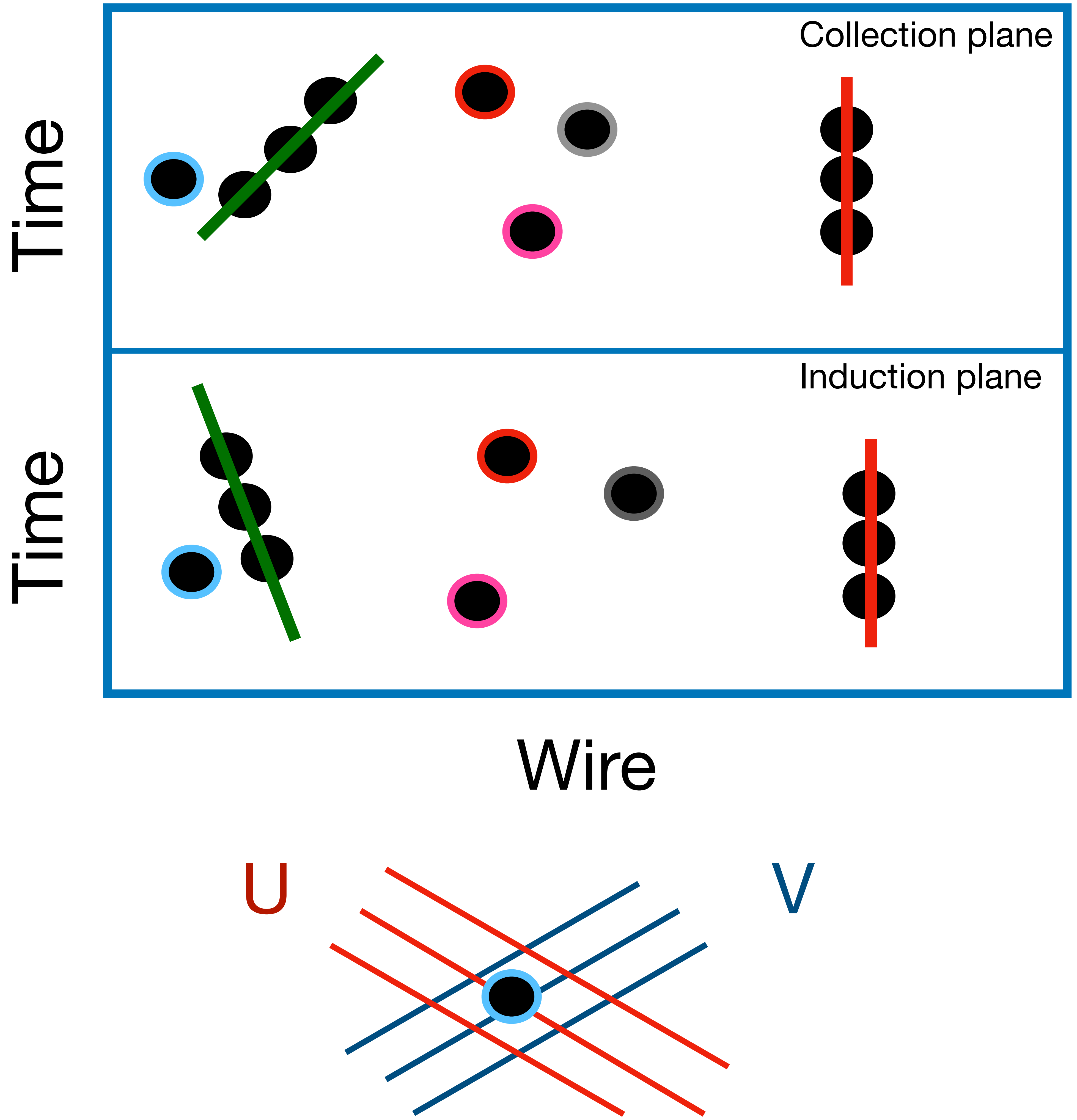
Blip Reconstruction

1. Hits not associated with any track > 5cm are taken.
2. Clusters in each plane are made using time and wire match.



Blip Reconstruction

1. Hits not associated with any track > 5cm are taken.
2. Clusters in each plane are made using time and wire match.
3. Clusters of one plane are matched with the ones in the other plane, using time, space, and energy requirements.



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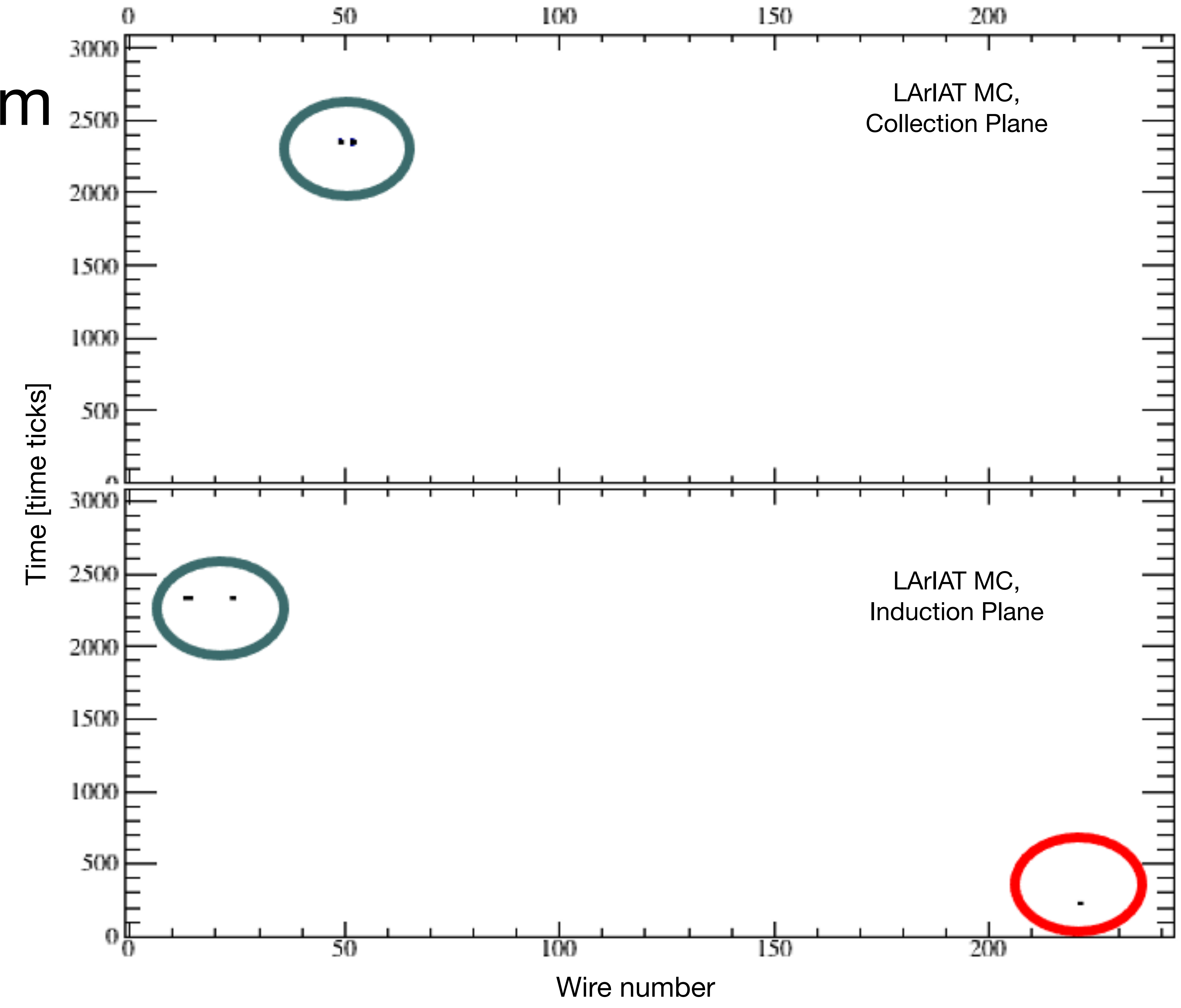
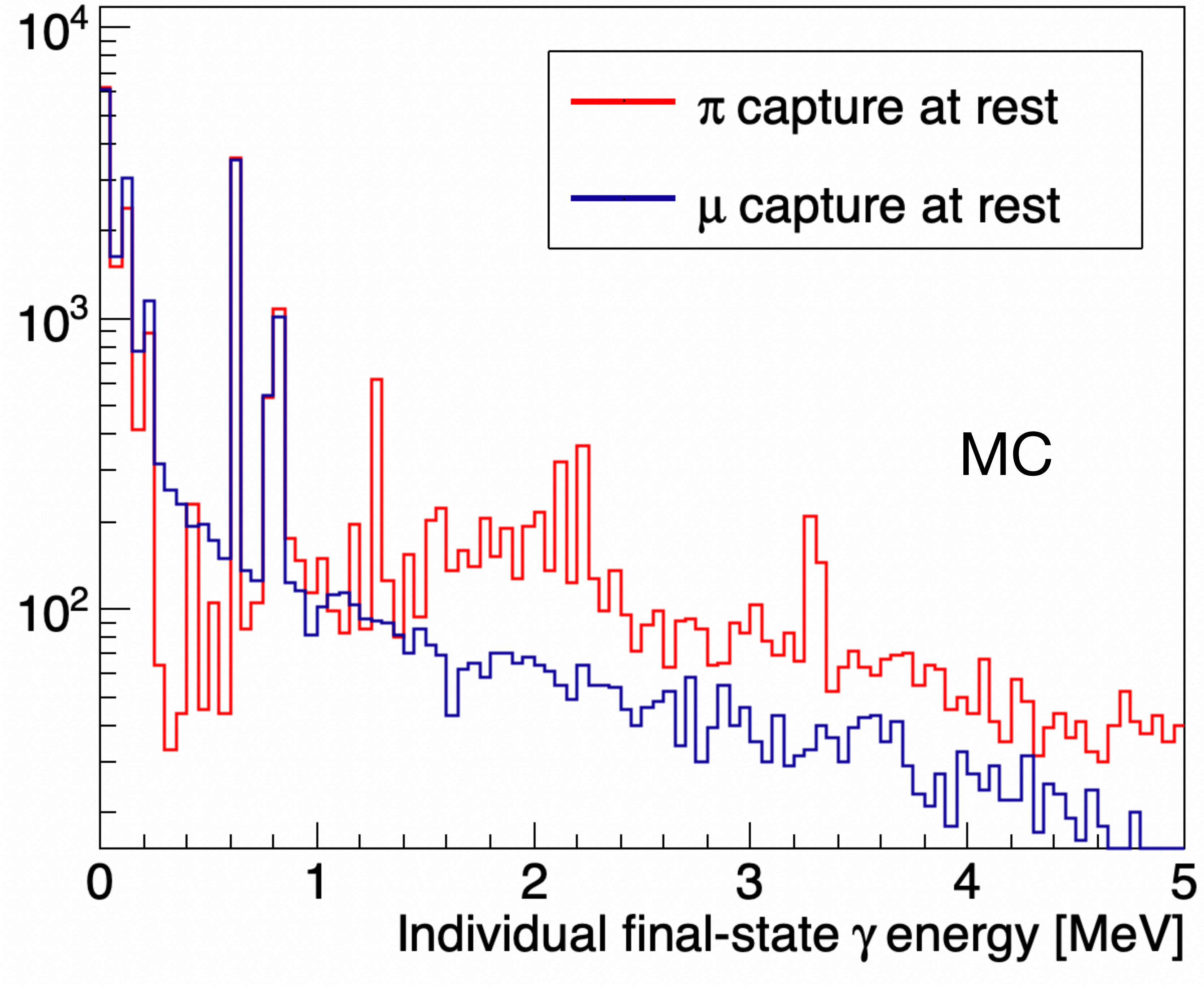


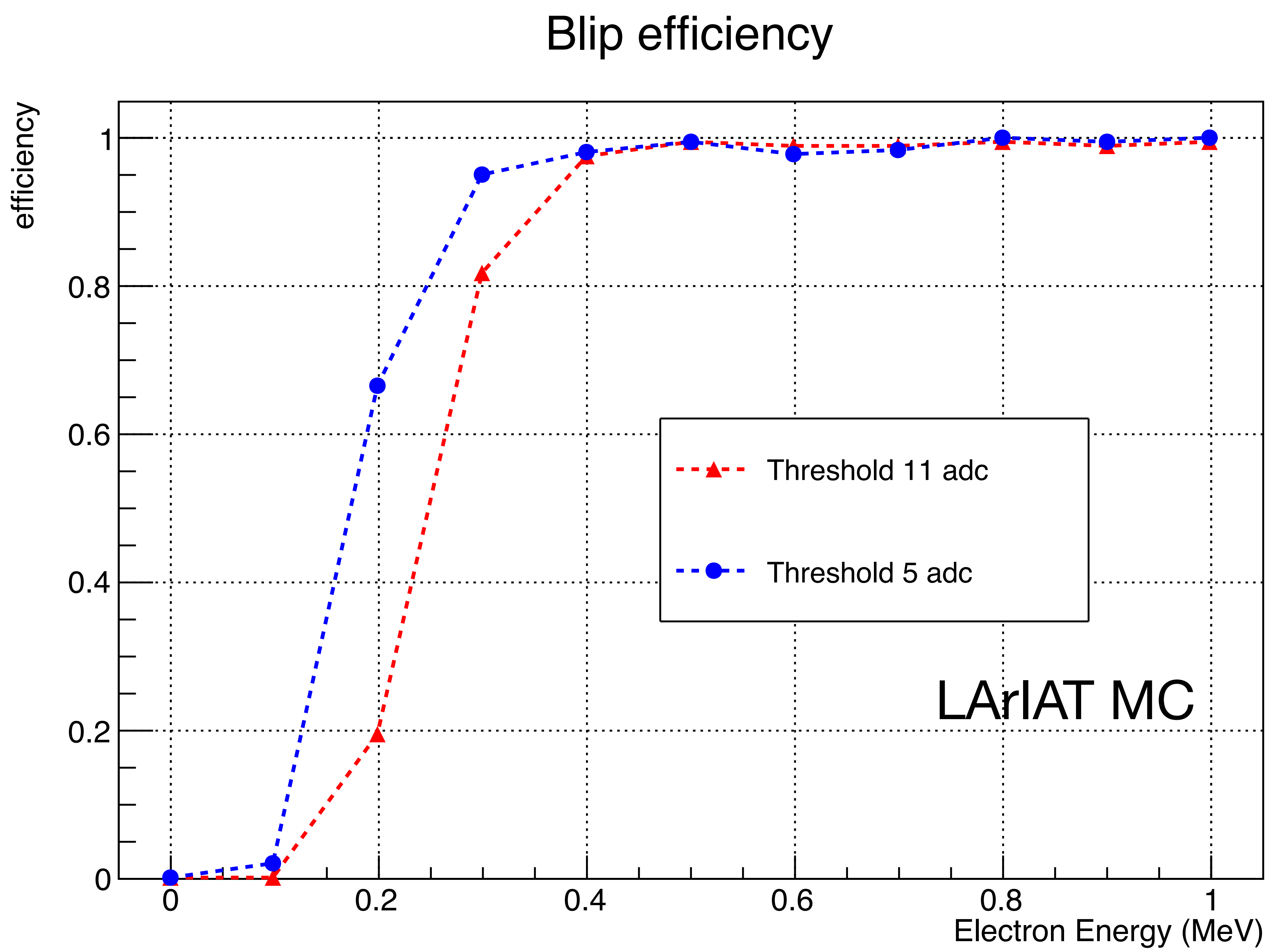
LArIAT SIMULATION

Blip Reconstruction efficiency

Studying the blip efficiency using single electrons in the TPC we optimized the Gaussian-based hit-finding threshold to achieve >50% detection efficiency for electrons of 200 KeV.

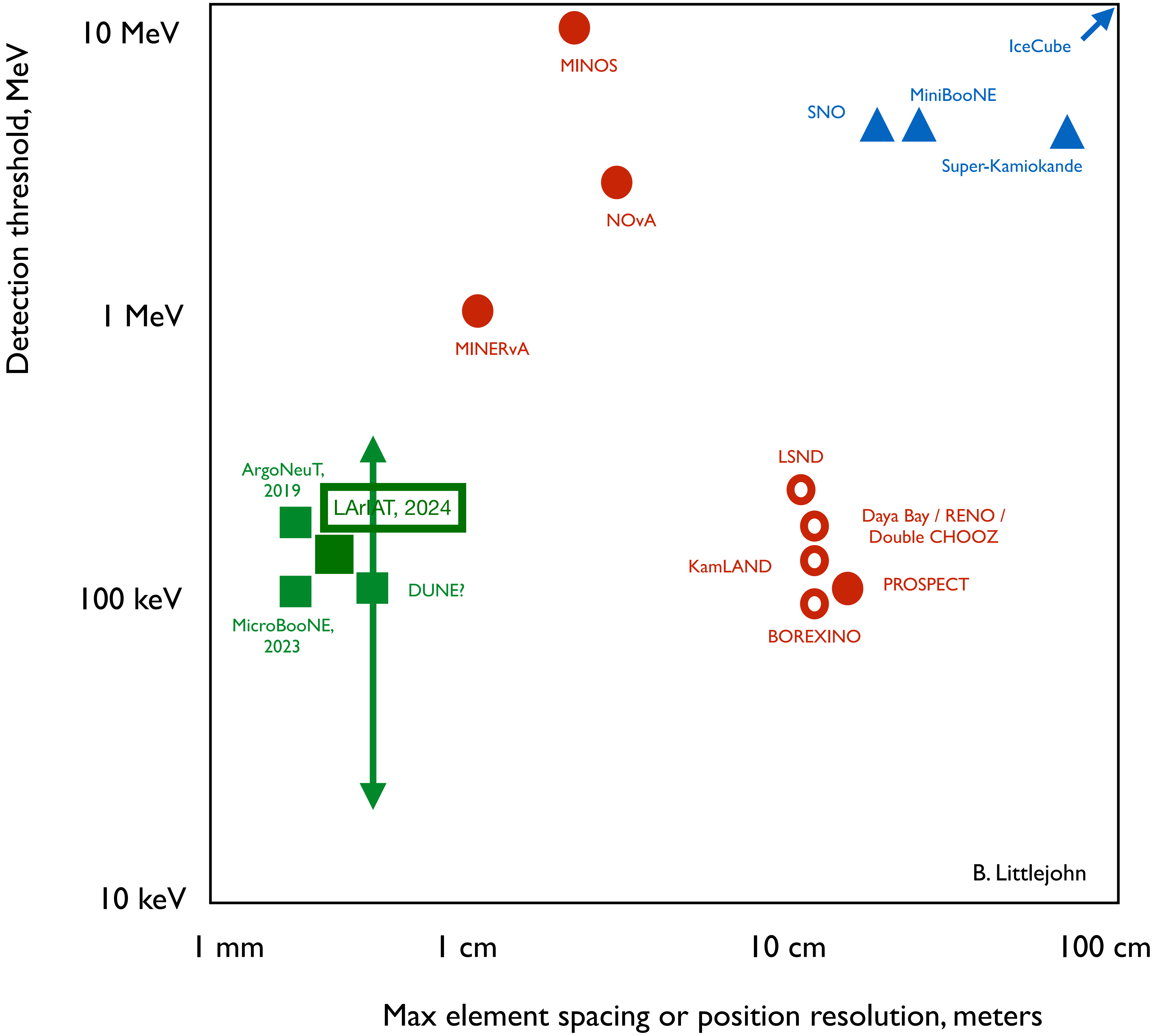


Efficiency = Blips detected / Blips created



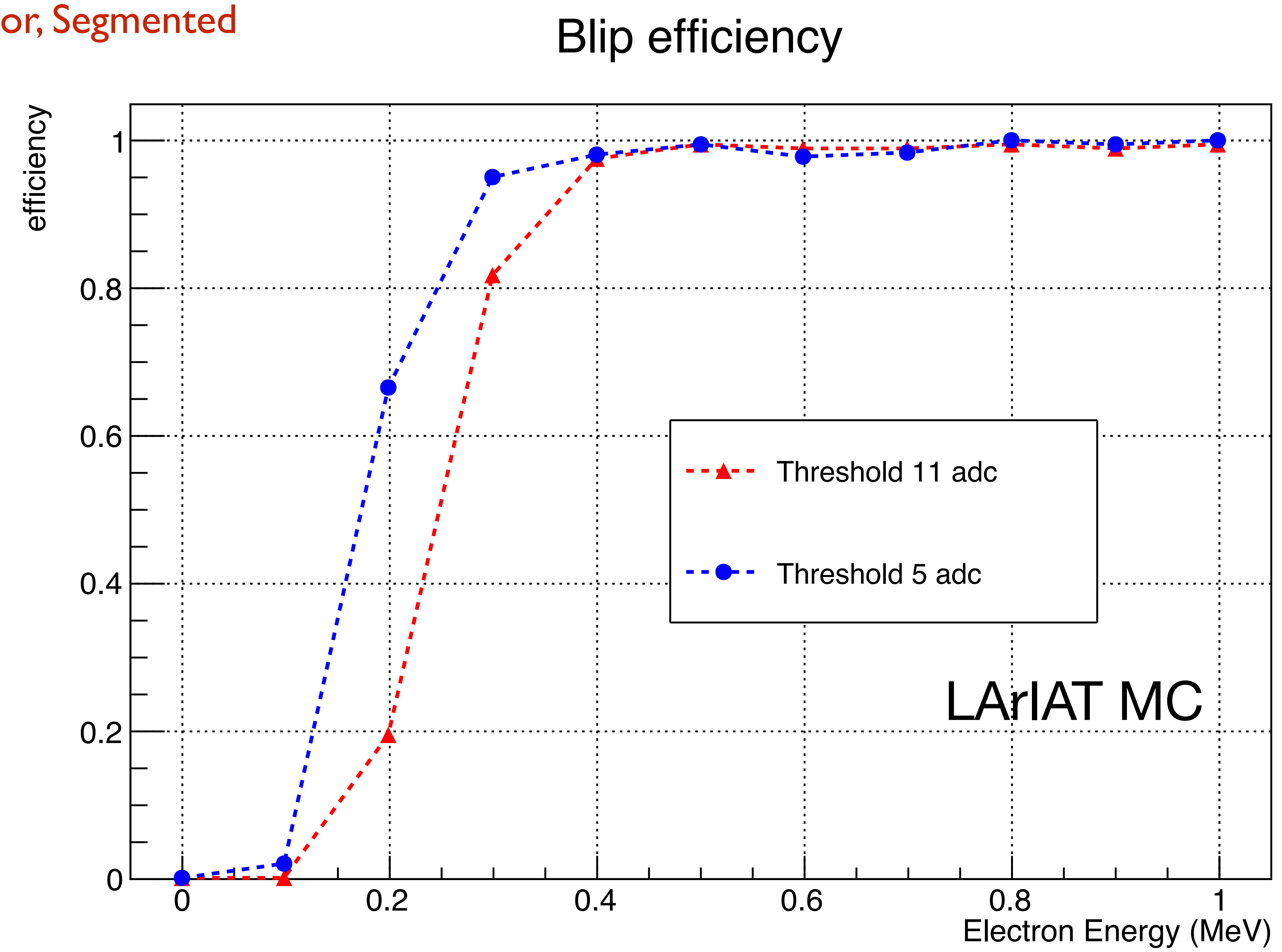
LArIAT SIMULATION,
Blip efficiency with default thresholds (11 ADC) and low thresholds (5 ADC)

Blip Reconstruction efficiency



<u>Neutrino Detector Technology:</u>

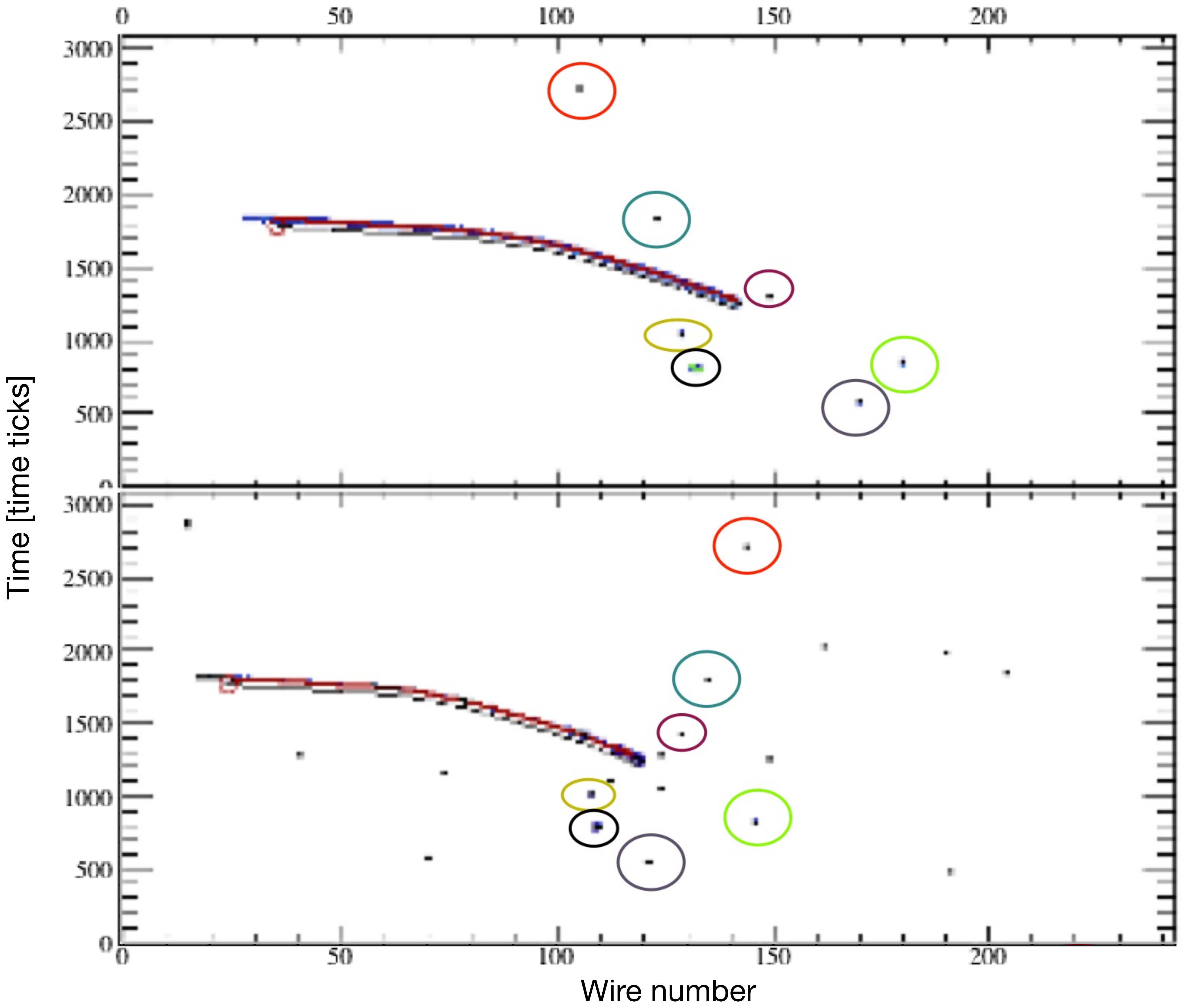
- ▲ Cherenkov
- ○ Scintillator, Single Volume
- ● Scintillator, Segmented
- ■ LArTPC



Blip efficiency with default thresholds (11 ADC) and low thresholds (5 ADC)

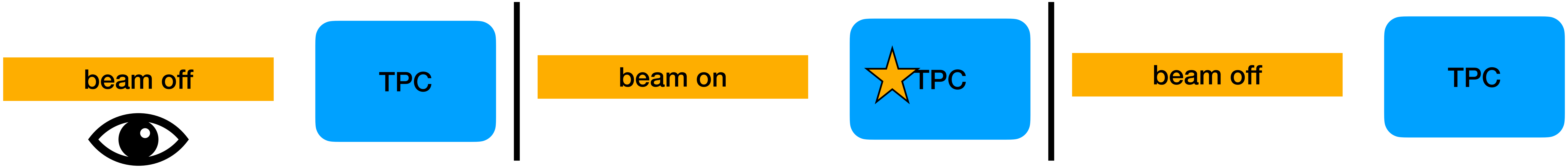
Blip Reconstruction (example)

Example of an event with 7 blips matched (these blips match with truth information too)



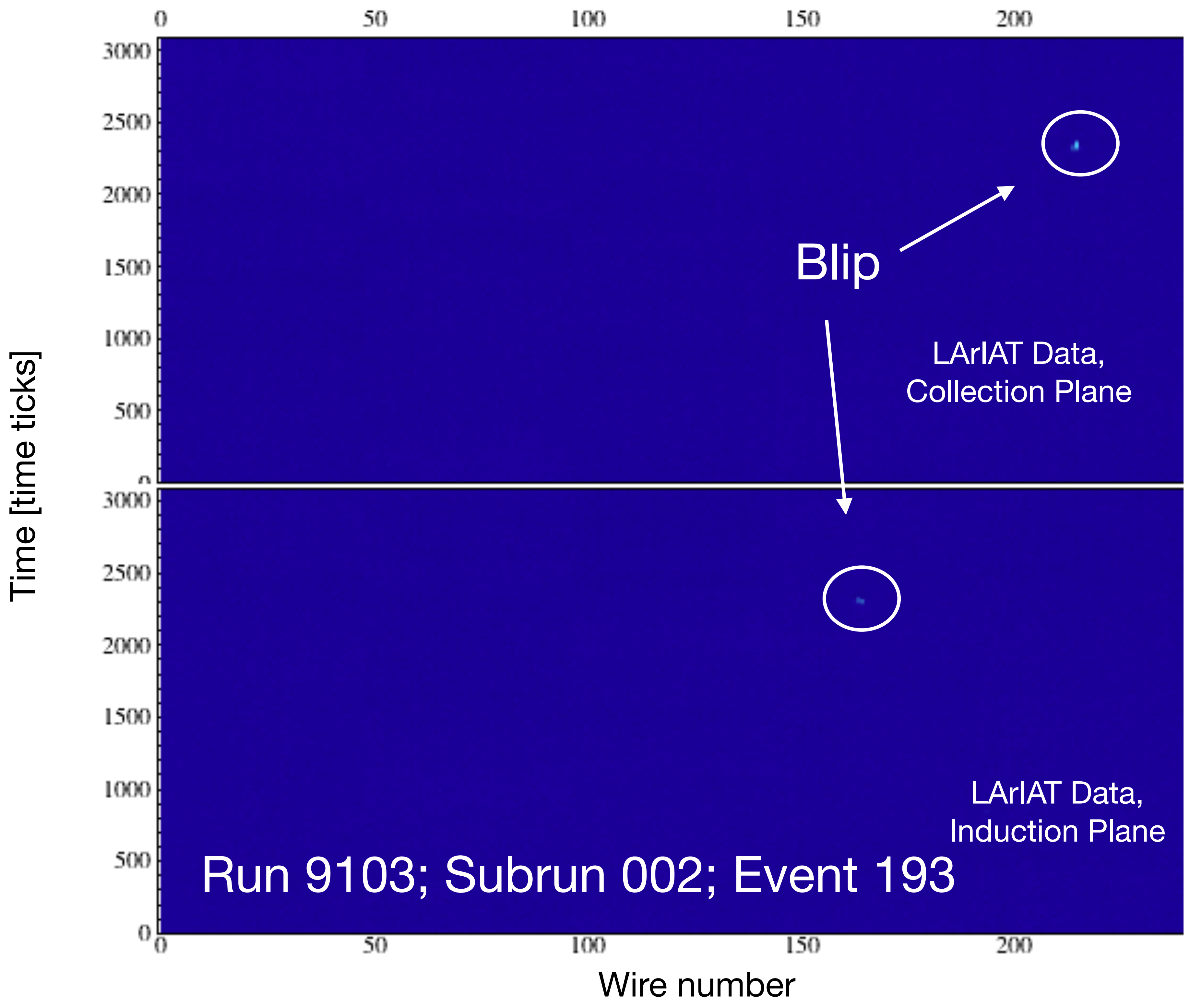
LArIAT SIMULATION,
Activity in an event with 7 matched blips

Blip Reconstruction in a pedestal sample

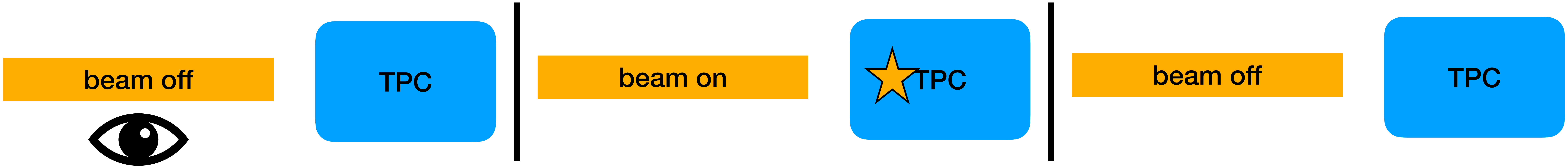


- Pedestal events are collected before each trigger formed by the overlap of the test beam spill

- We’d expect these blips to be formed from wire noise or radiogenic backgrounds



Blip Reconstruction in a pedestal sample


beam off

TPC

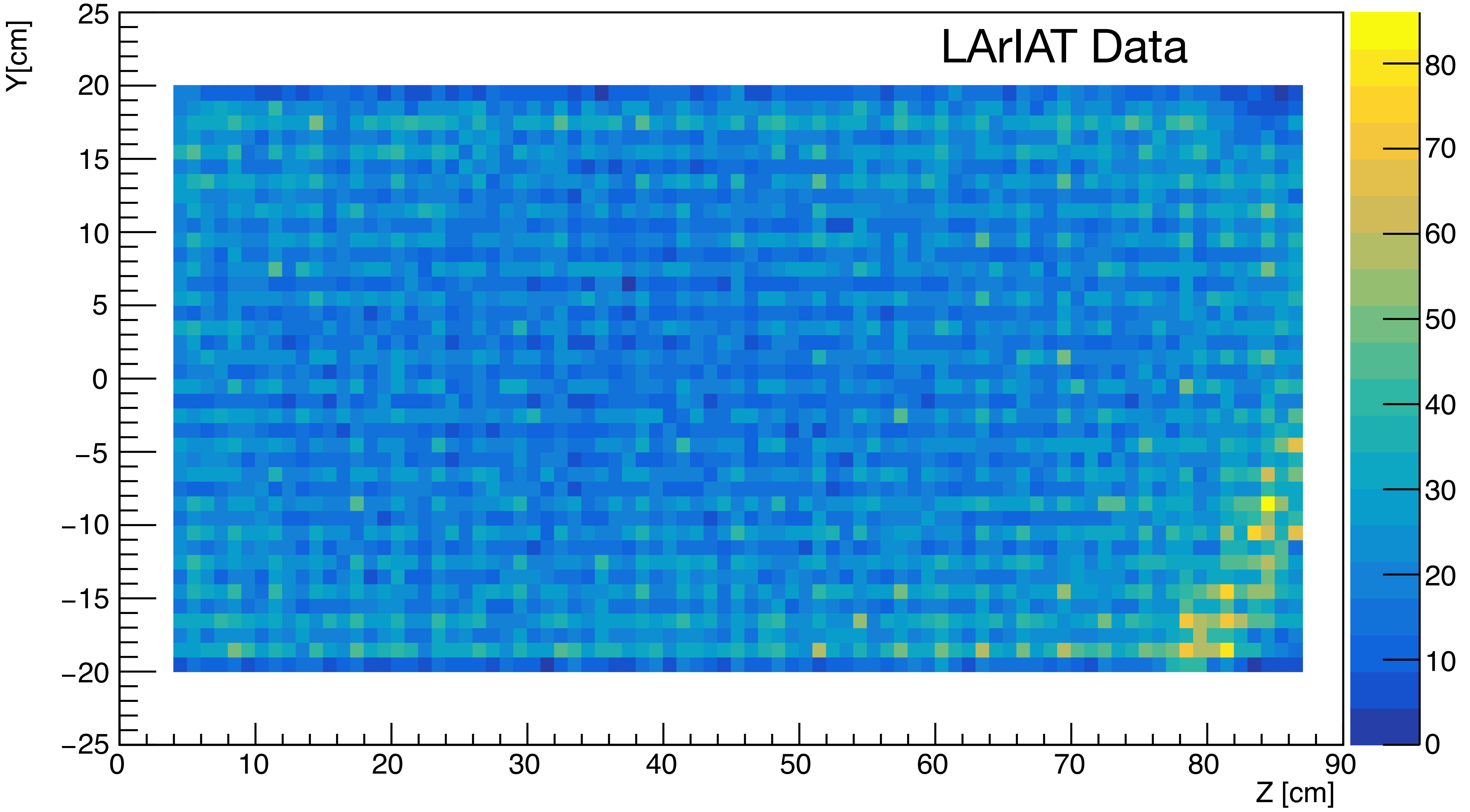
beam on

TPC

beam off

TPC

- Pedestal events are collected before each trigger formed by the overlap of the test beam spill
- We'd expect these blips to be formed from wire noise or radiogenic backgrounds
- Blip multiplicity of 0.36 ± 0.001 per event
- The blip count in pedestal events provides a data-driven tool to constrain environmental backgrounds

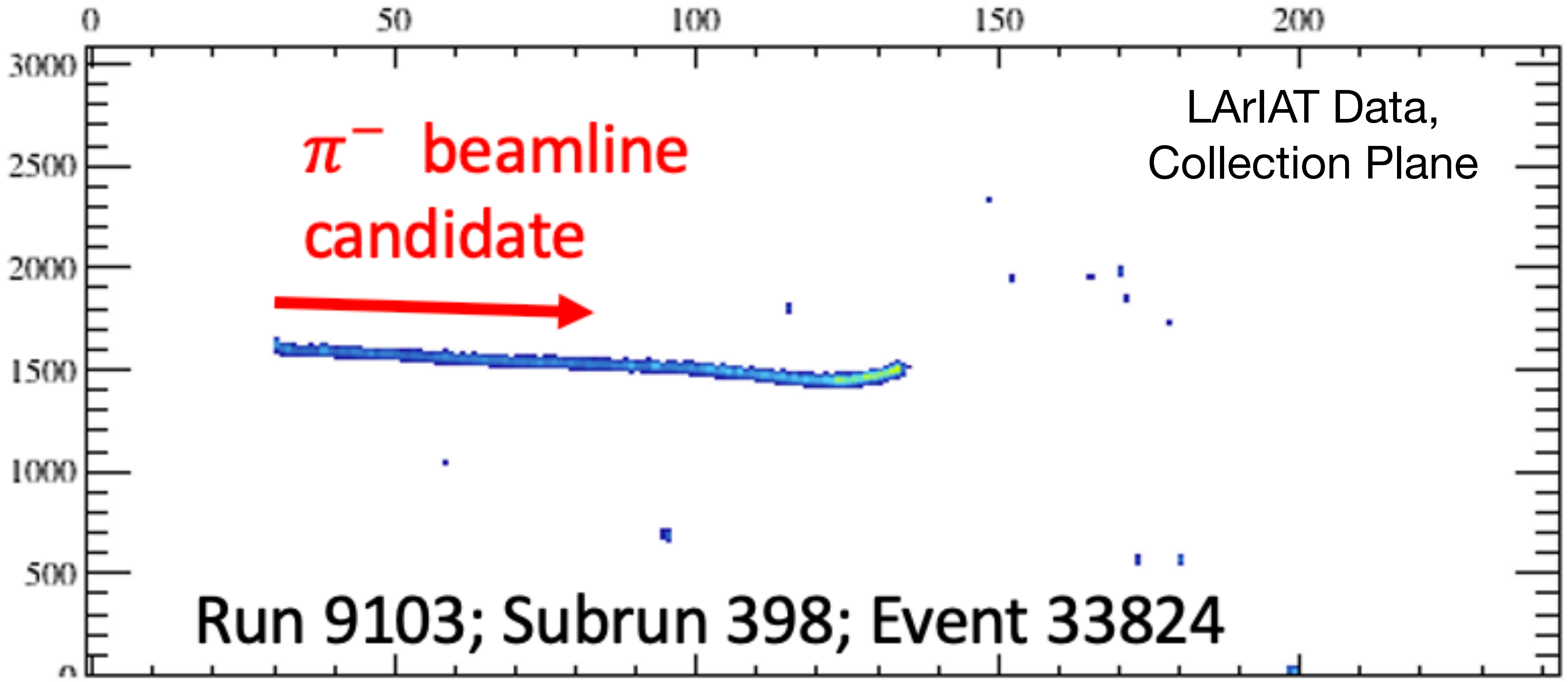


LArIAT Data

Workflow analysis

Event selection → Blip Reconstruction → **Blip signal** → Background subtraction

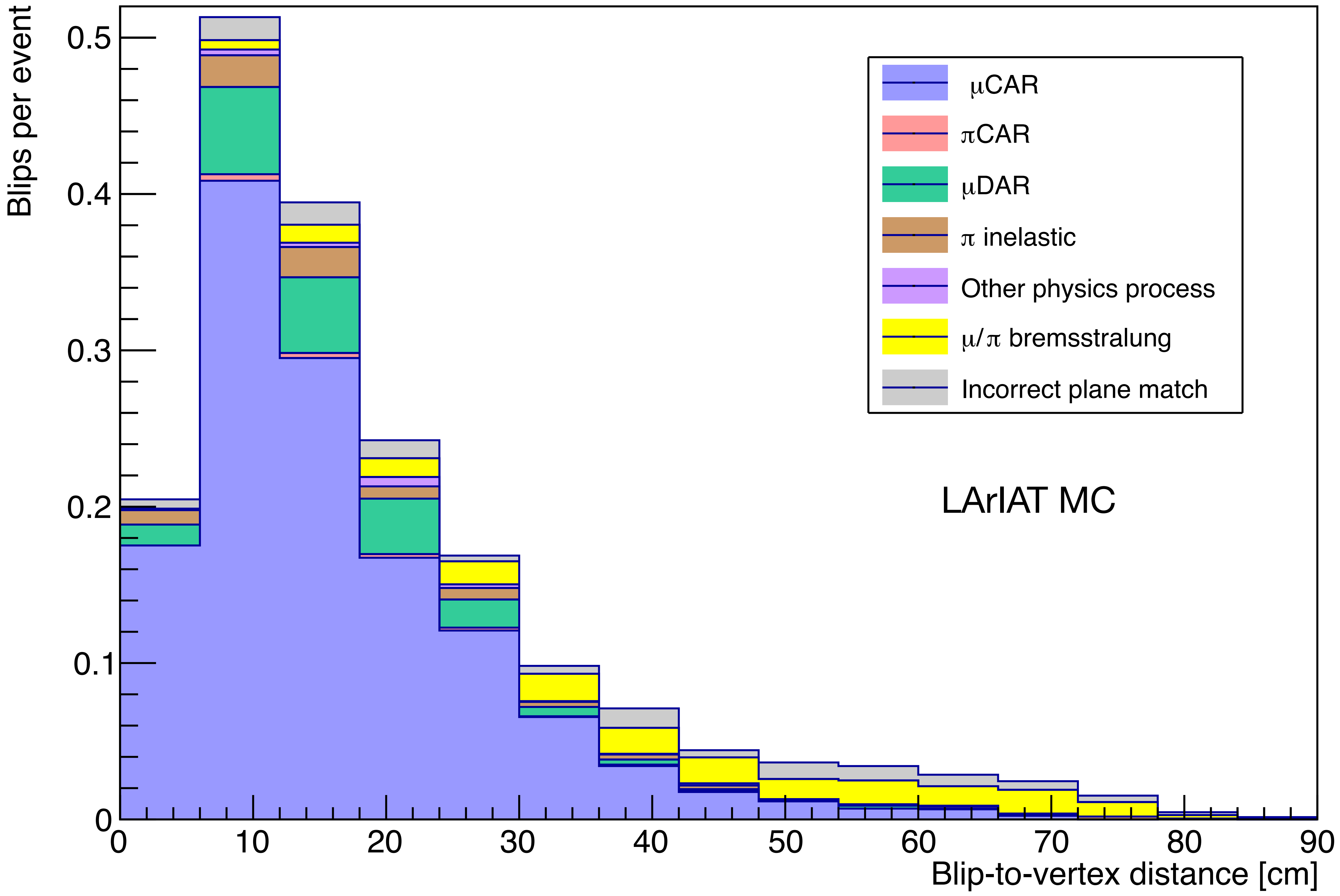
Blip metrics



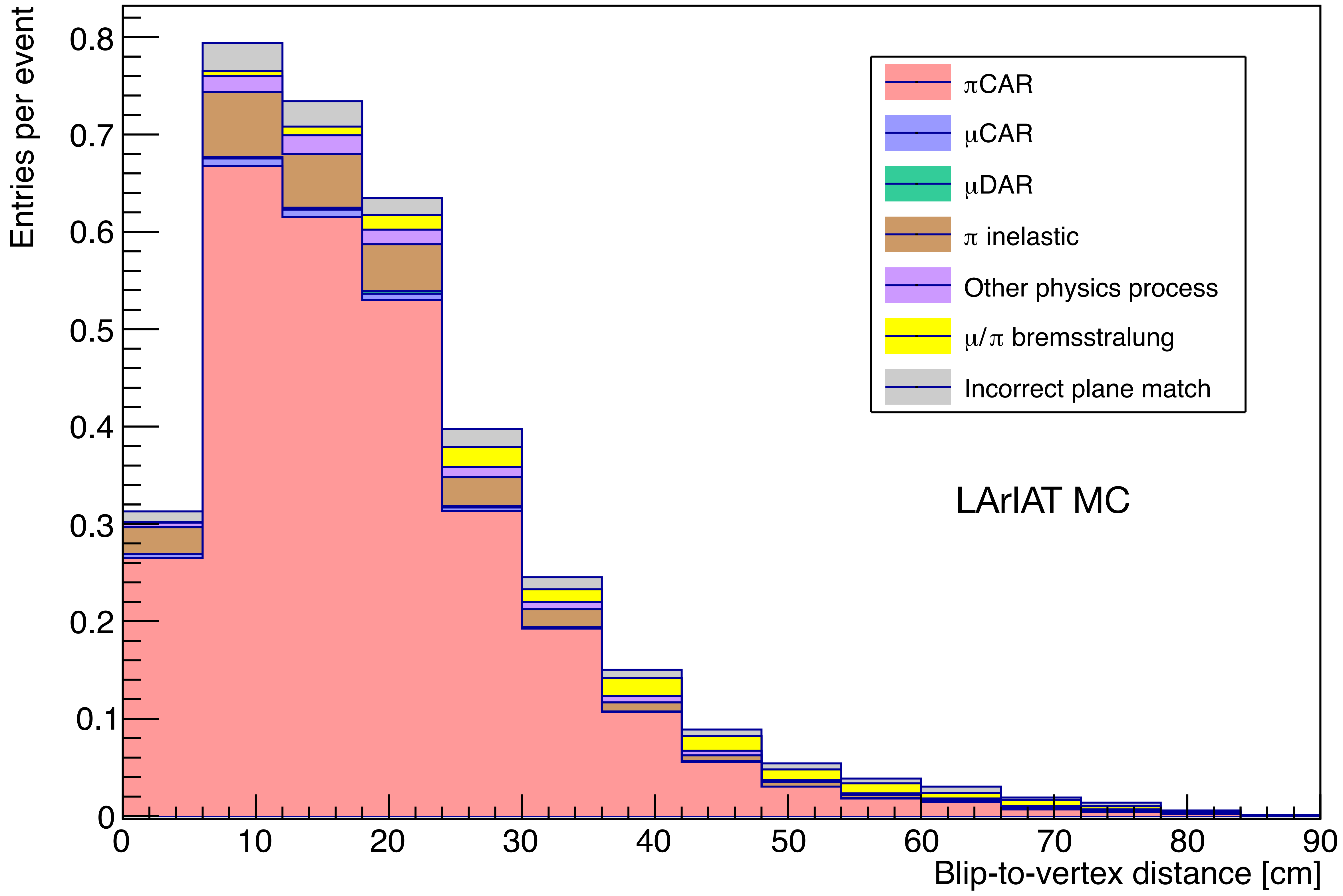
- Blip multiplicity
- Blip energy
- Blip distance to vertex
- Blip Z

Blip Signal (MC)

muCAR selection cuts

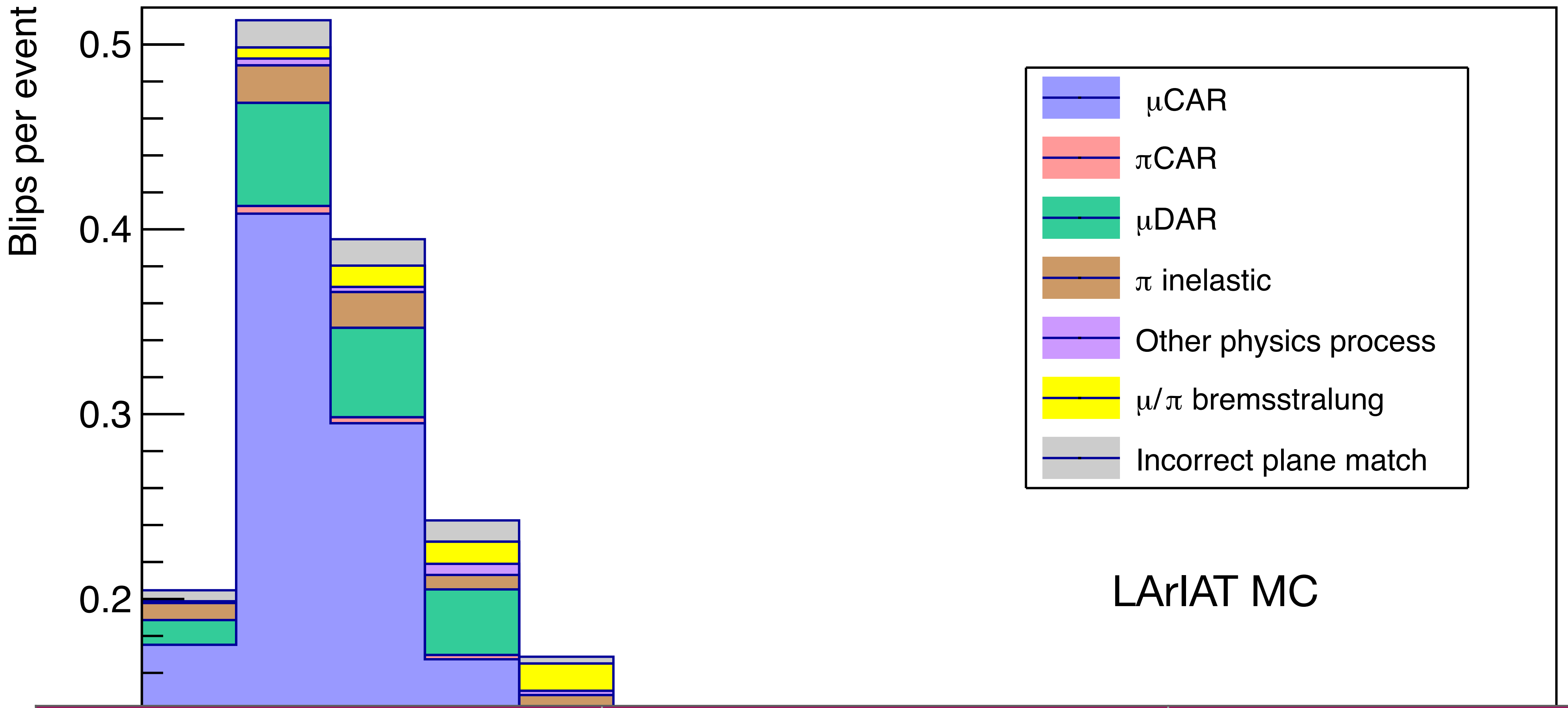


piCAR selection cuts

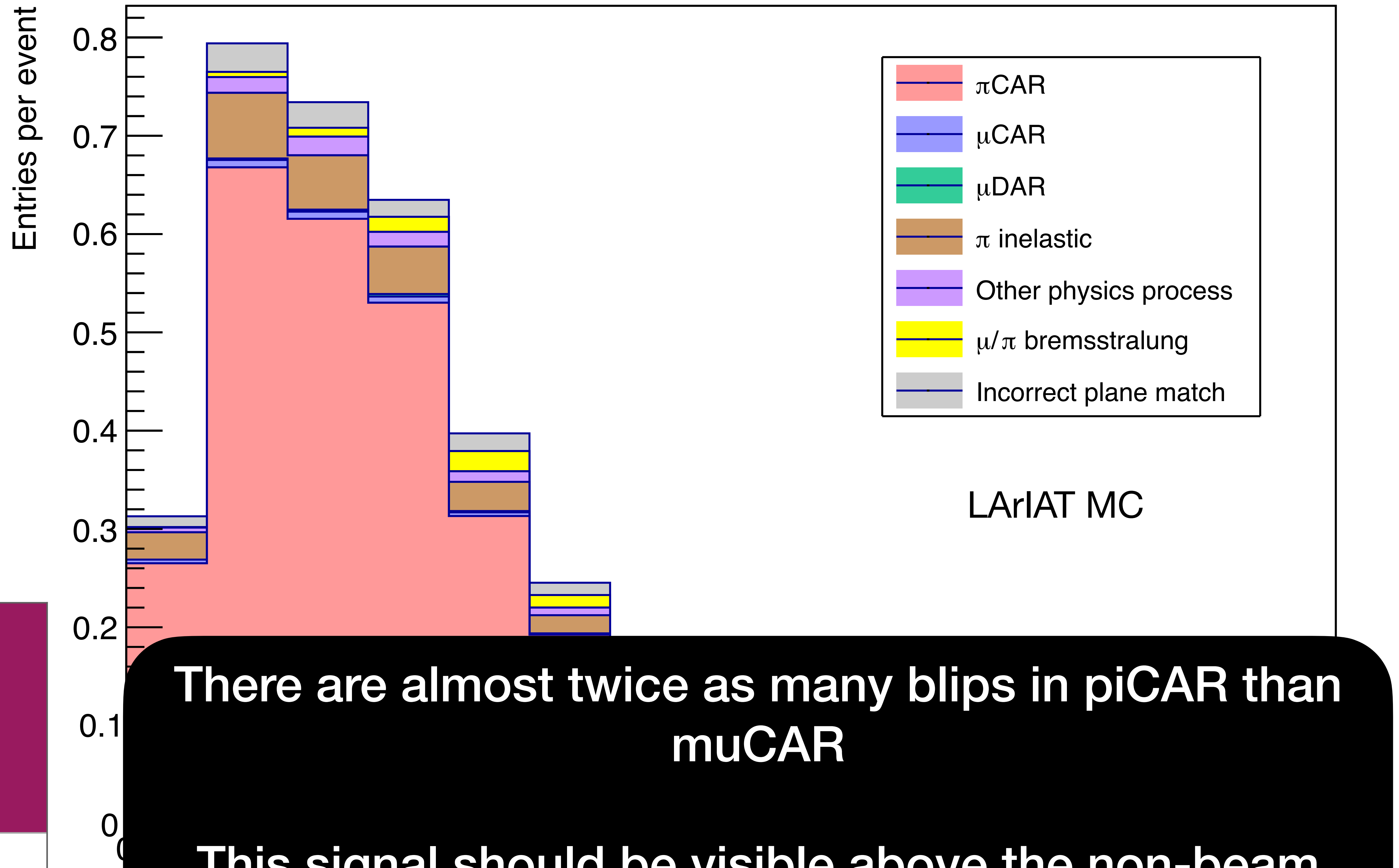


Blip Signal (MC)

muCAR selection cuts



piCAR selection cuts



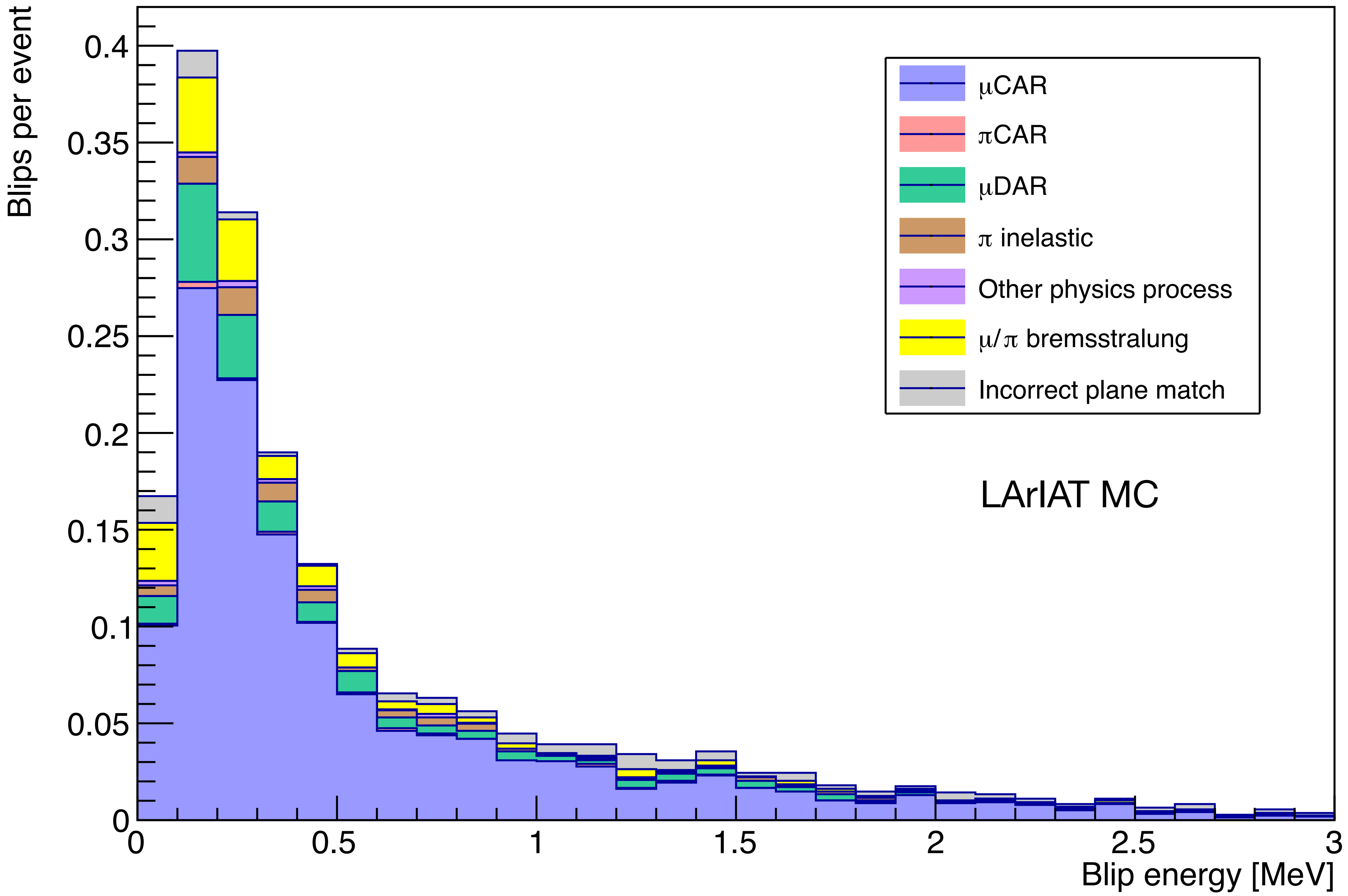
	MuCAR	PiCAR
Blip multiplicity	1.88 ± 0.04	3.52 ± 0.04

There are almost twice as many blips in piCAR than muCAR

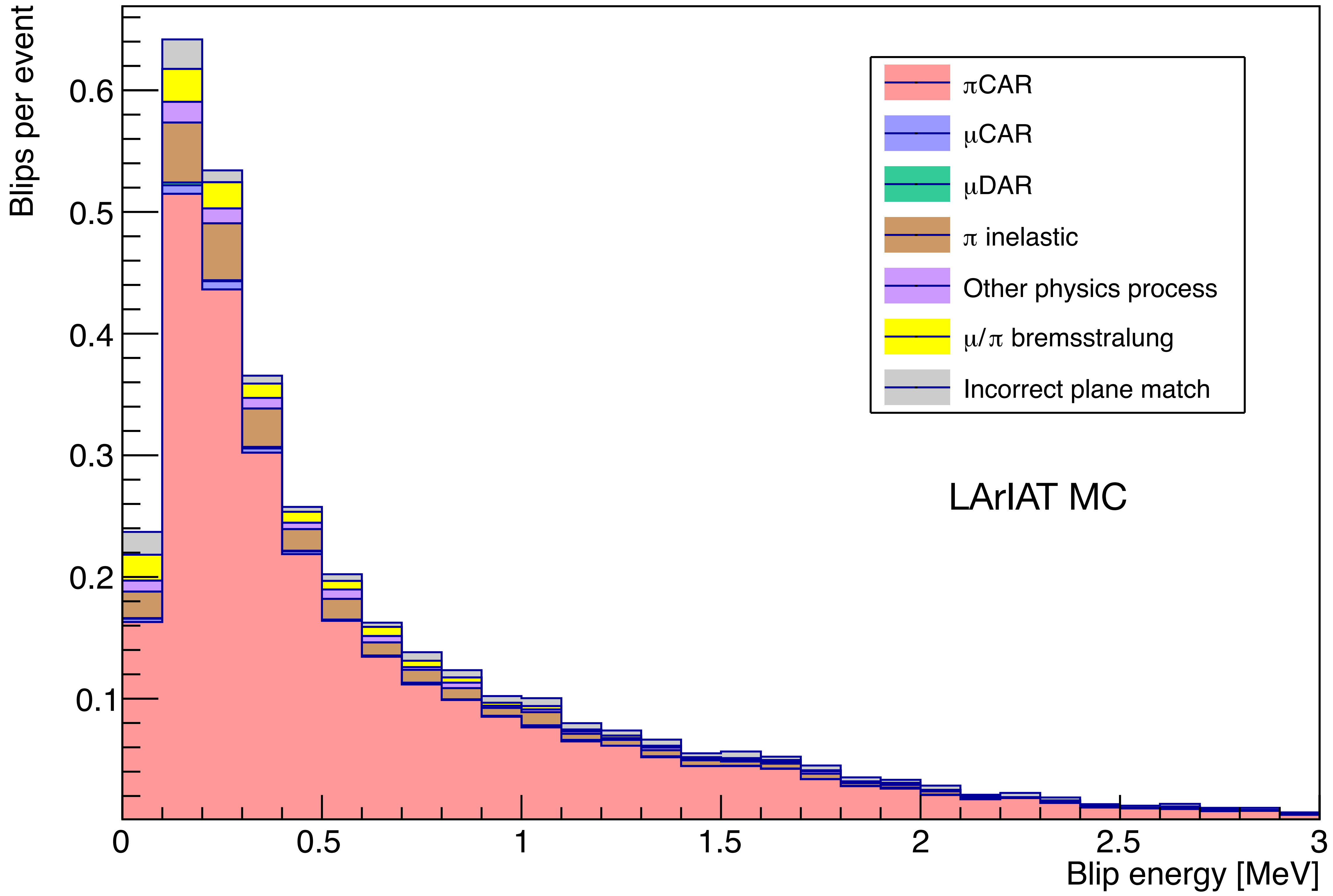
This signal should be visible above the non-beam noise and radiogenic backgrounds of the pedestal sample

Blip Signal (MC)

muCAR selection cuts



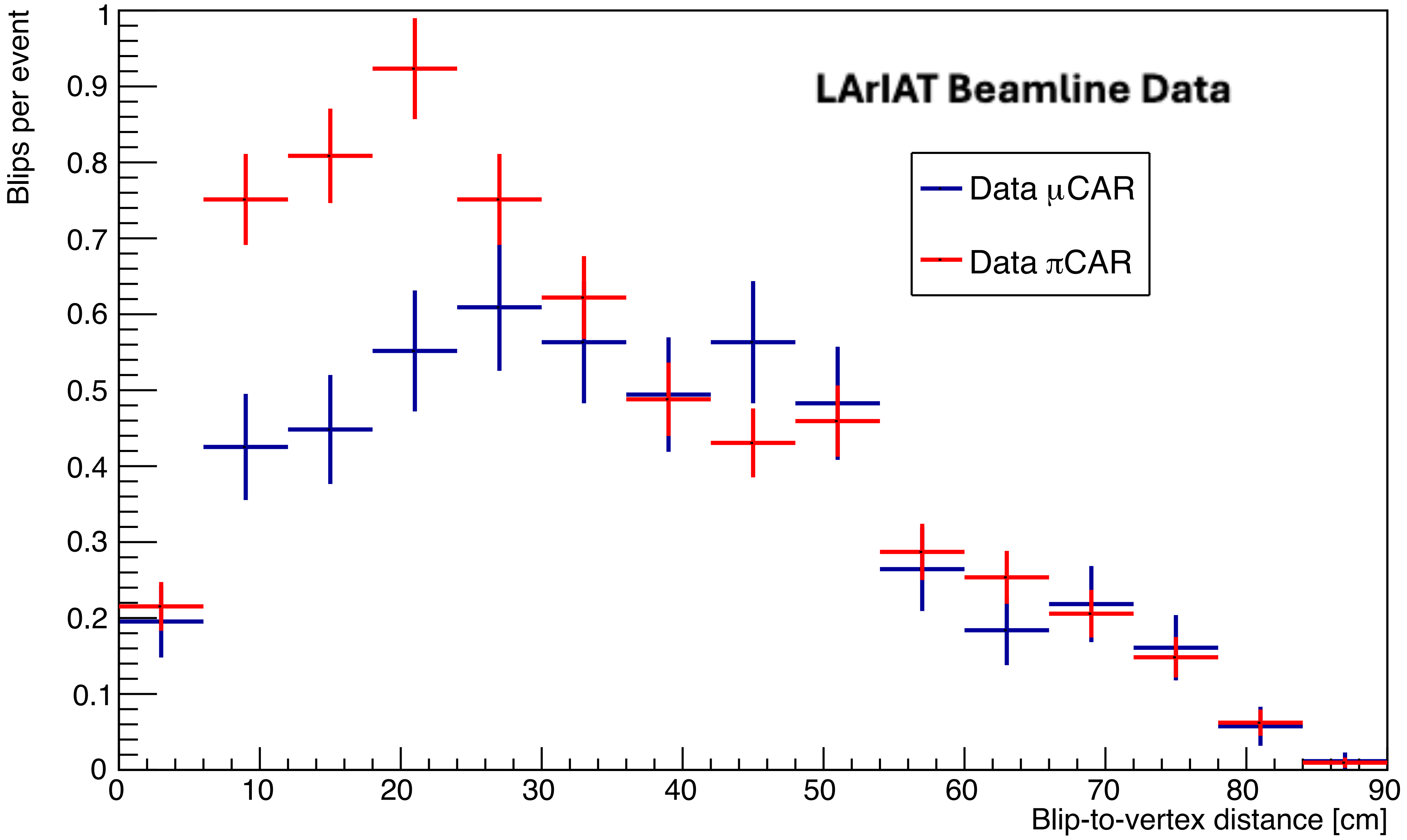
piCAR selection cuts



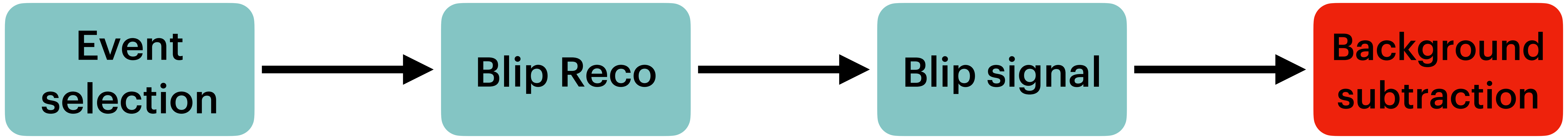
Blip Signal (Data)

	MuCAR	PiCAR
Blip multiplicity	5.21 ± 0.37	6.30 ± 0.26

On average, we see 2 more blips per event in data compared to MC



Workflow analysis



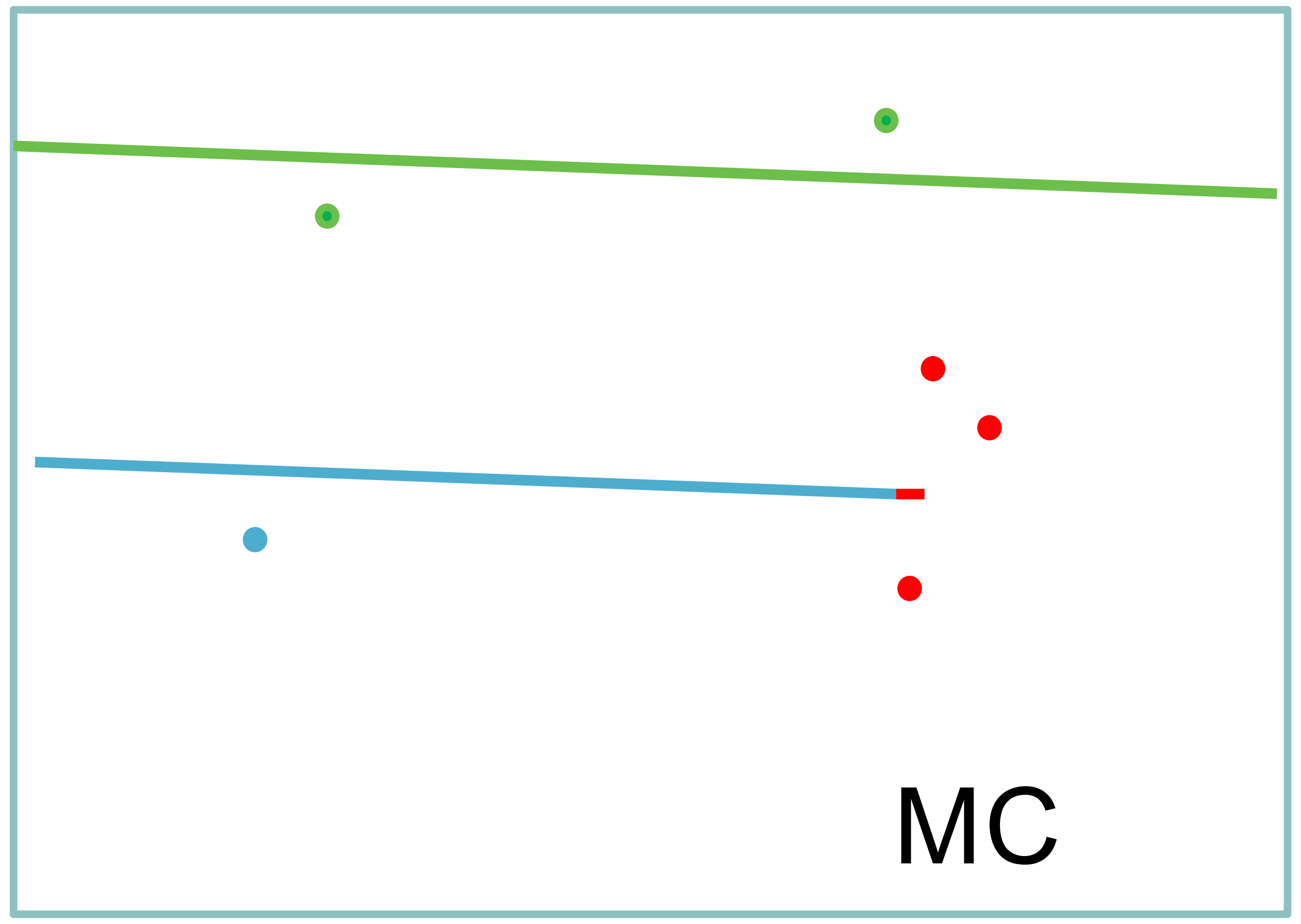
Event selection

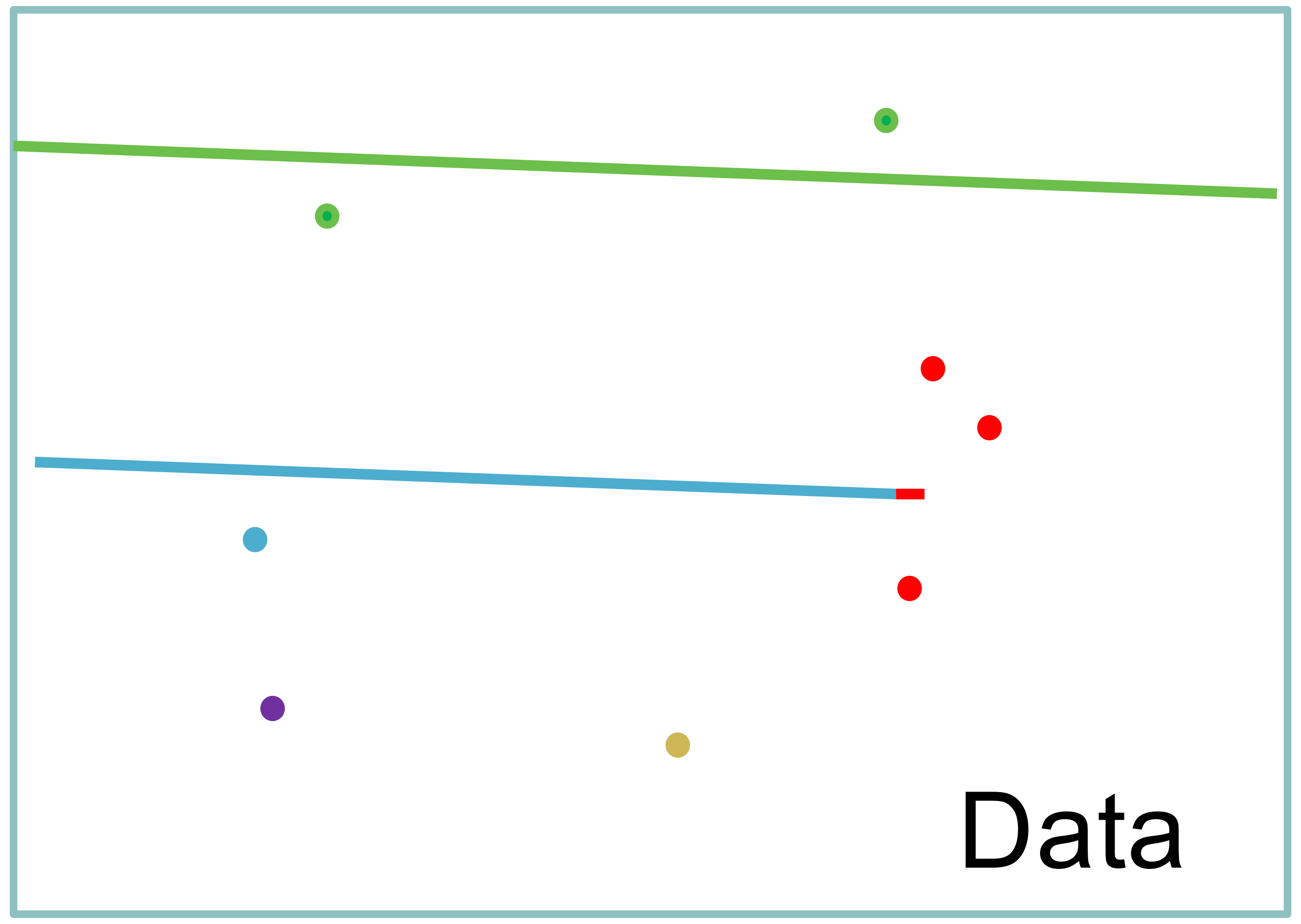
Blip Reco

Blip signal

Background subtraction

Blips in LArIAT, Data and MC background





MC is missing some sources of backgrounds we see in data

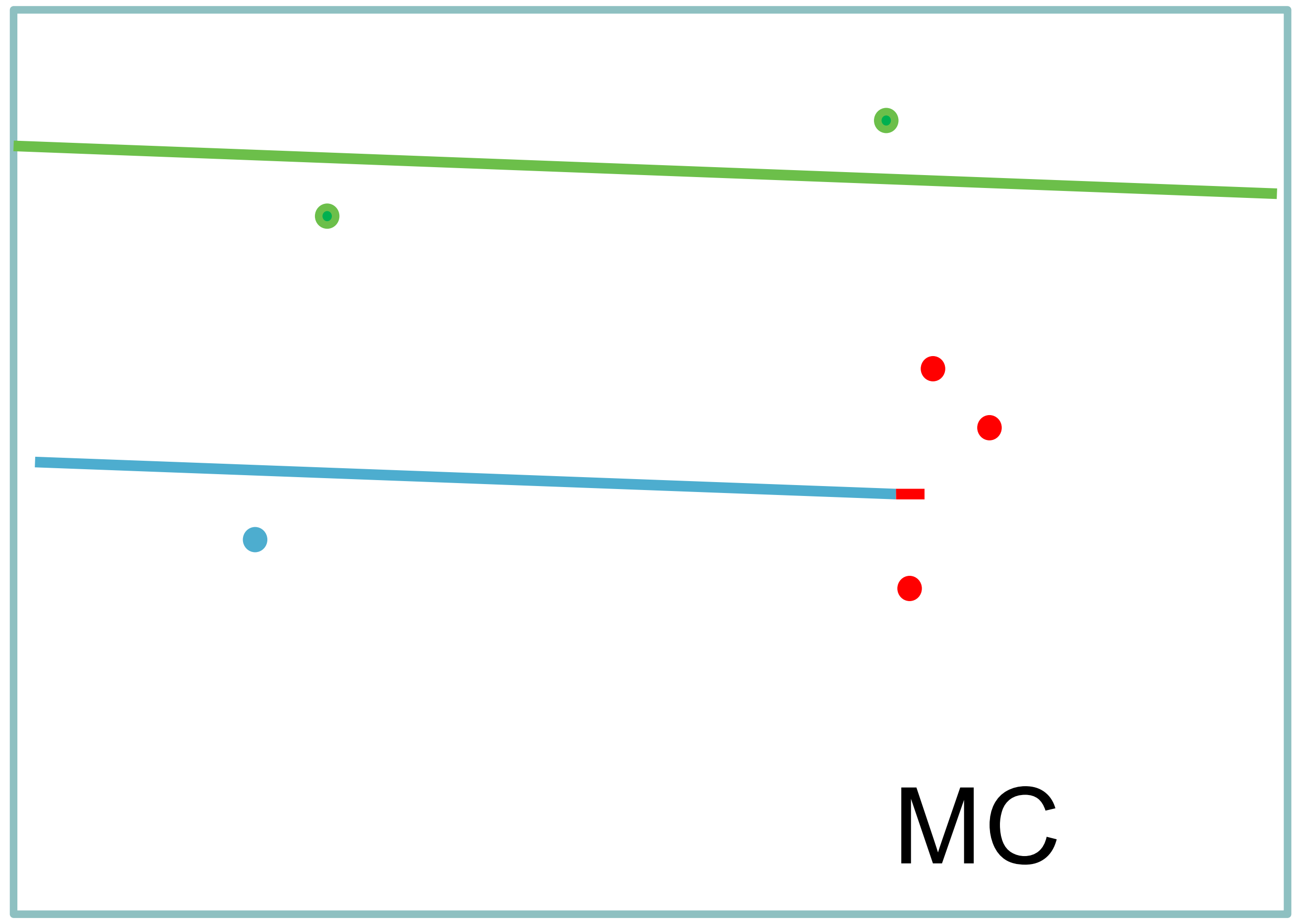
MC Blip

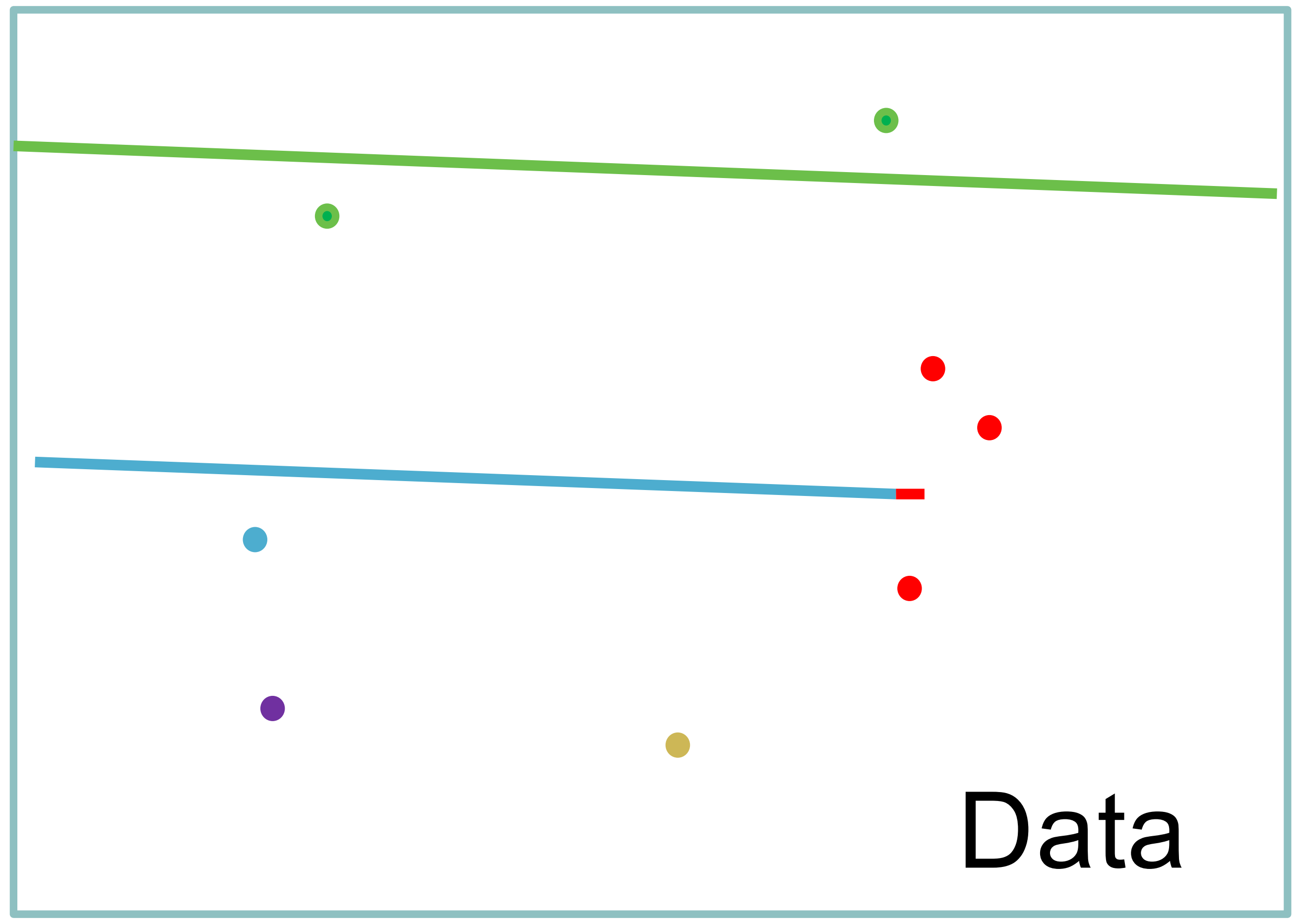
- Blips produced by mu/pi car
- Blips produced by main track but not related to car process
- Blips produced by pileup muons

Data Blip

- Blips produced by mu/pi car
- Blips produced by main track but not related to car process
- Blips produced by pileup muons
- Blips produced by beam-induced neutrons from surrounding materials
- Blips produced by nuclear activity (pedestal, Ar39)

Blips in LArIAT, Data and MC background





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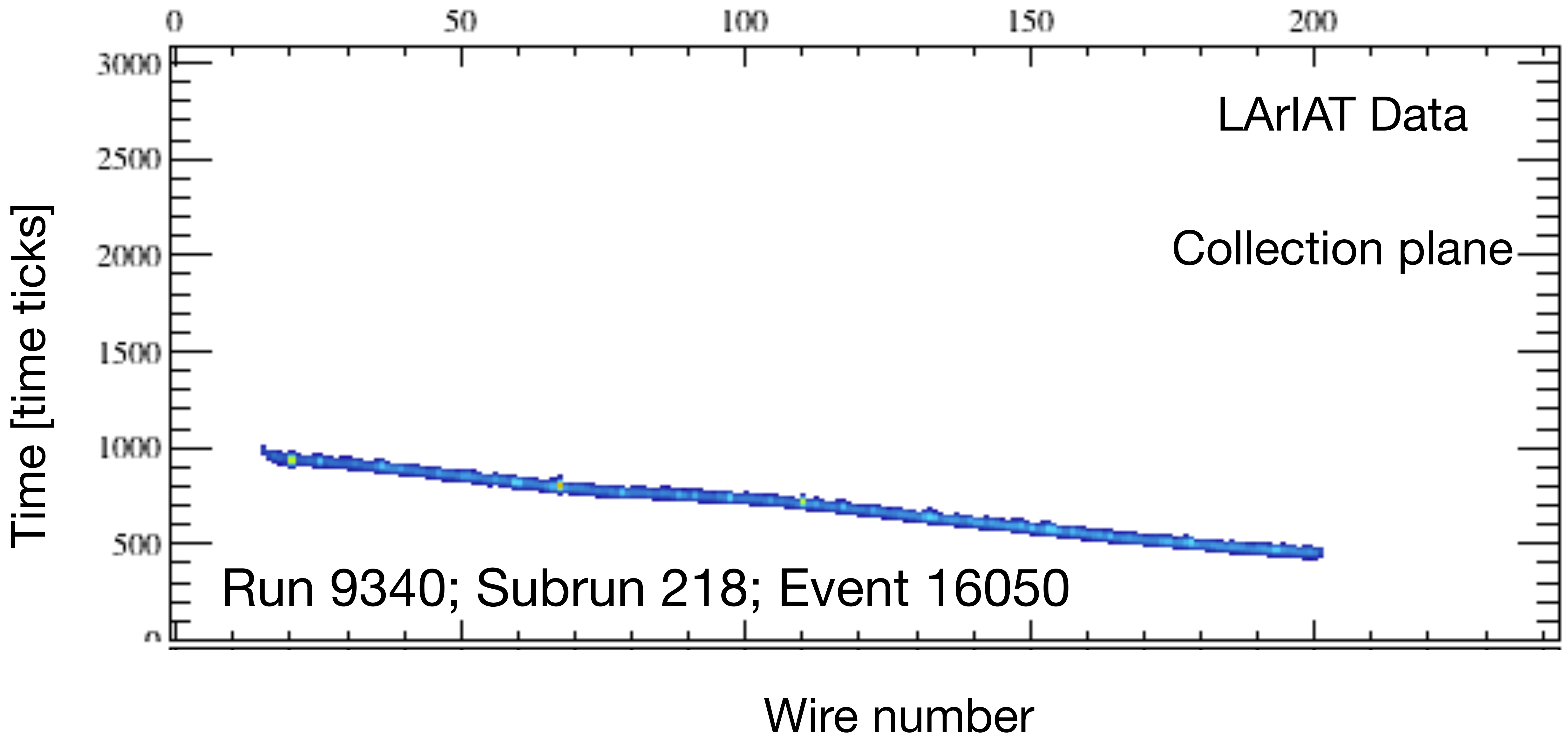
- Blips produced by nuclear activity (pedestal, Ar39)

Blips produced when the beam is on

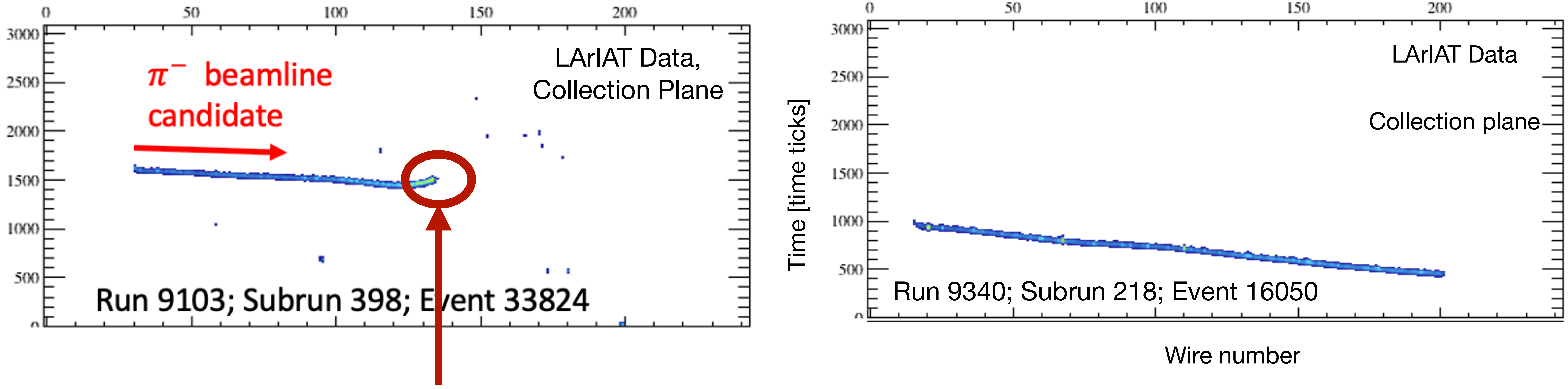
Throughgoing sample

We use a DATA sample to model all the background blips and perform a data-driven background subtraction.

Throughgoing sample, a sample with particles that goes through all the TPC and contains all the background blips in MC and Data.

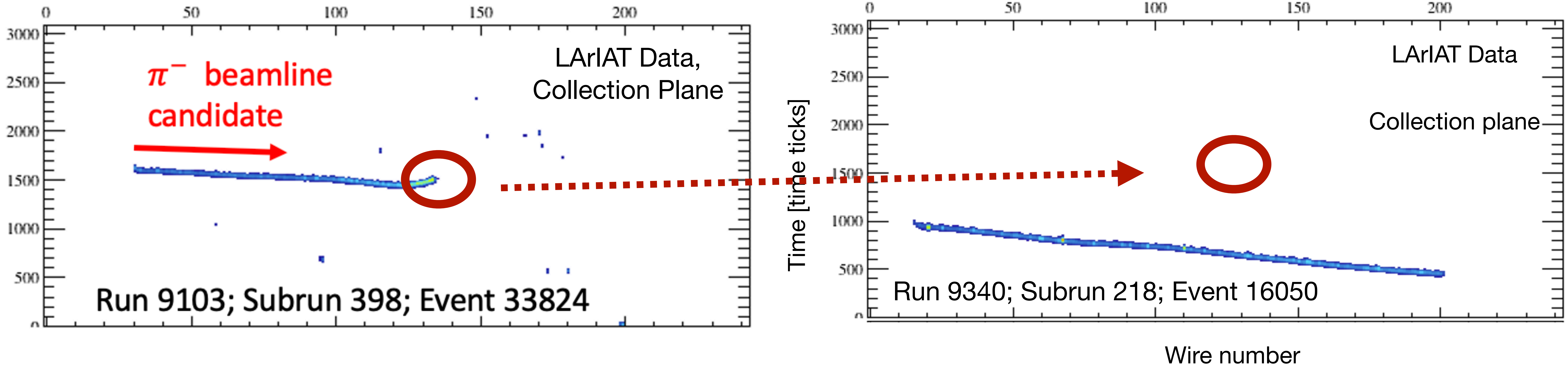


Throughgoing sample (blip to vertex distance)



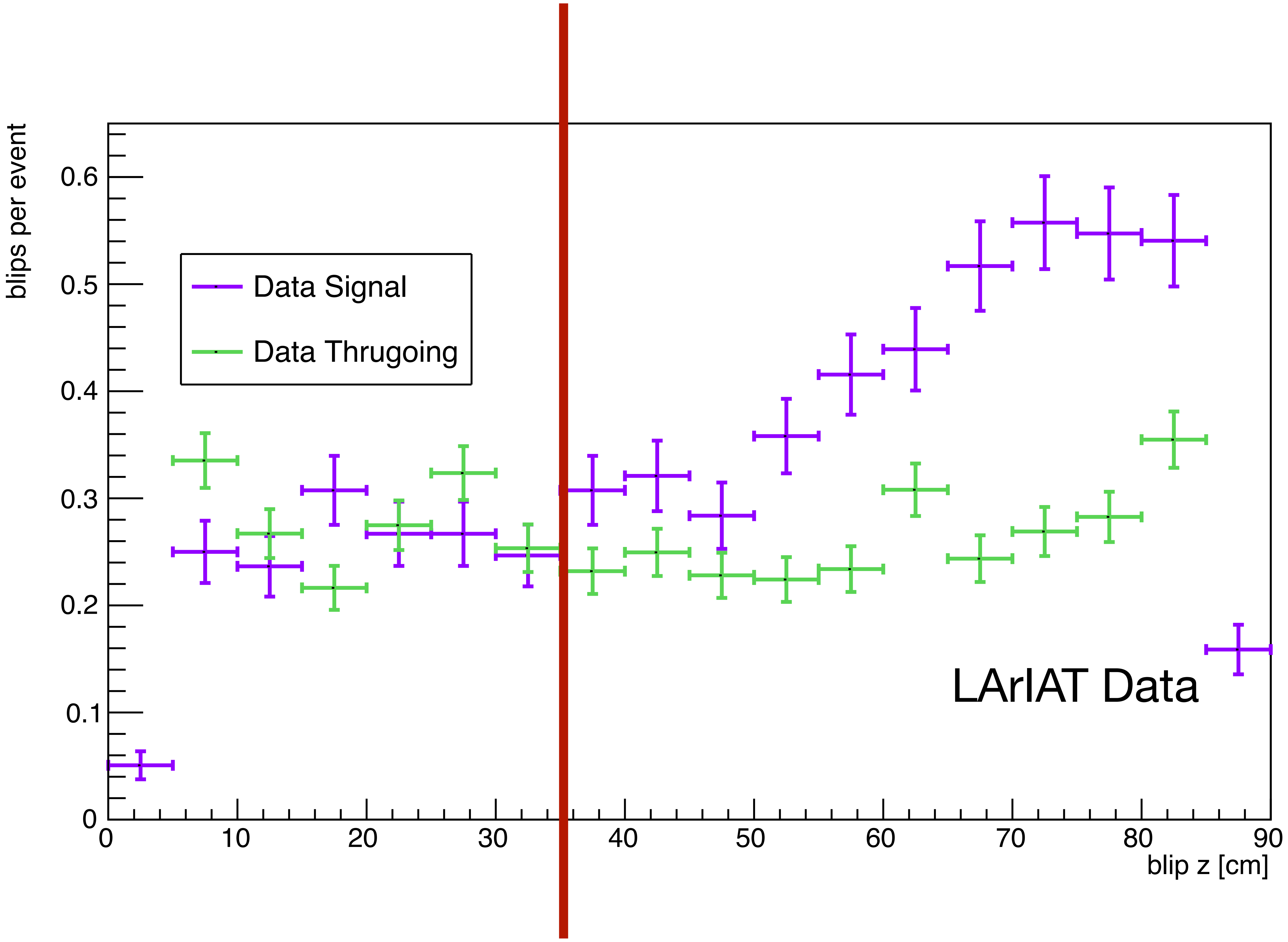
We took the vertex from our CAR samples

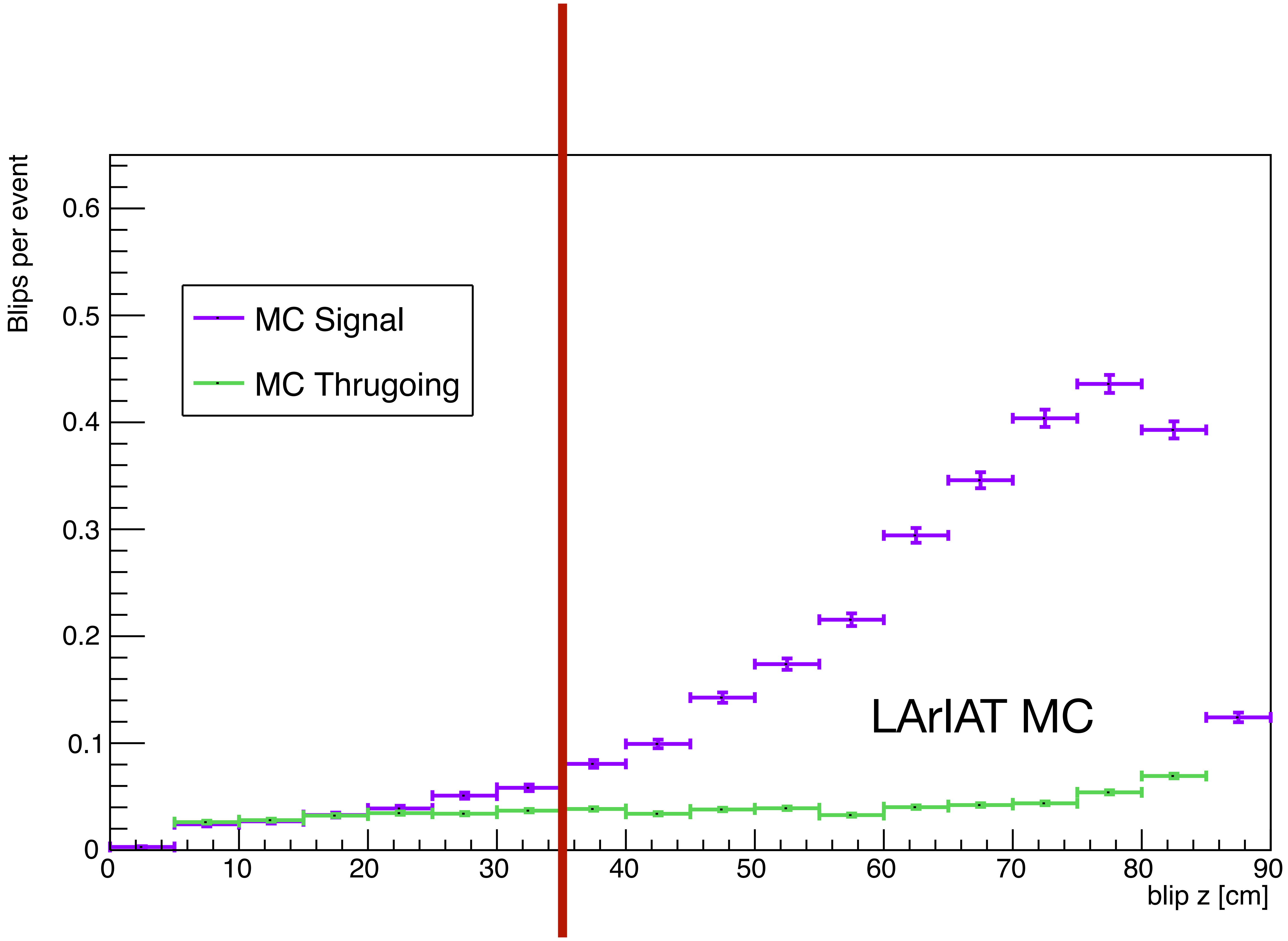
Throughgoing sample (blip to vertex distance)



We use the vertex taken from data in our throughgoing sample

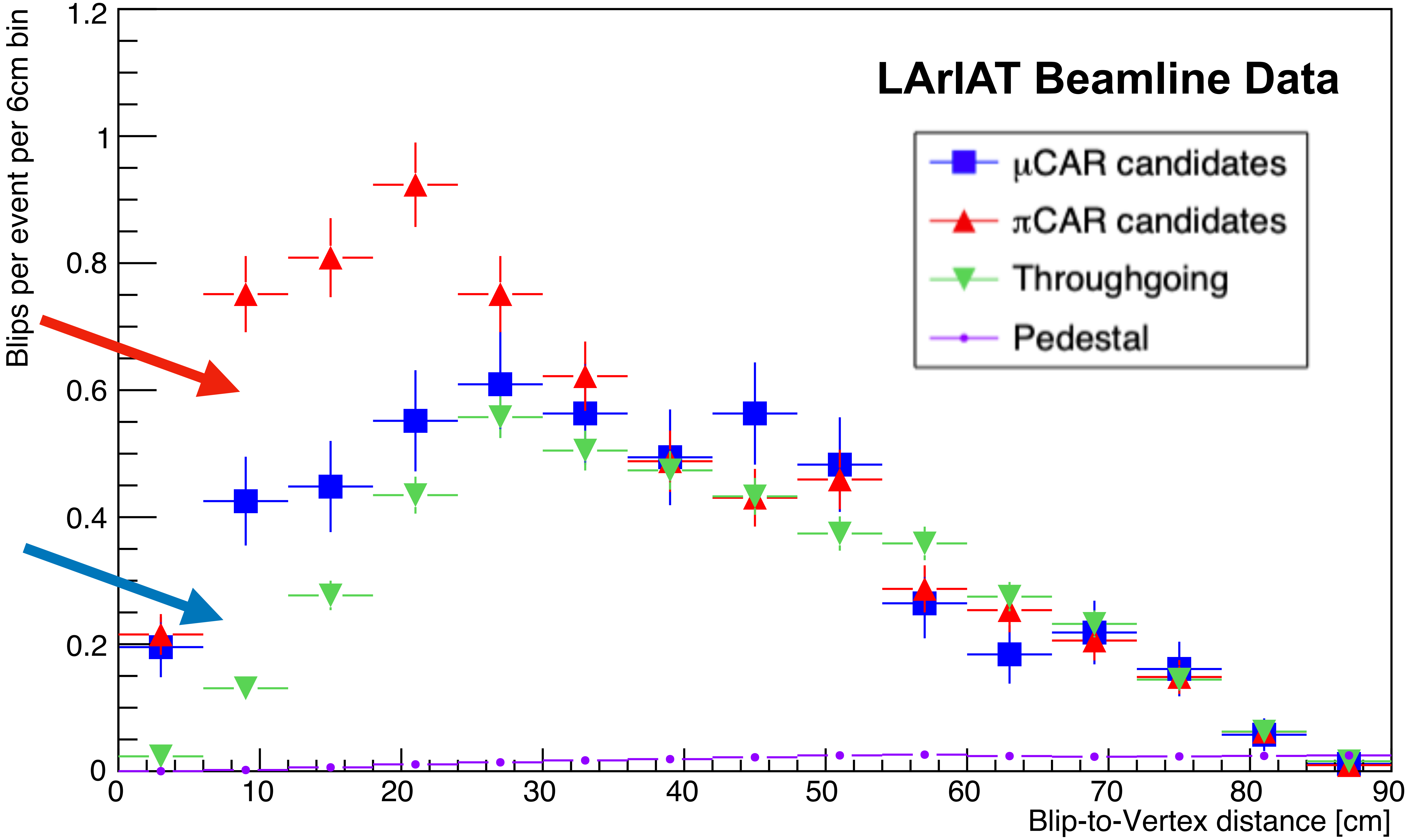
Blip Z





Throughgoing sample is uniform across the TPC as we expected.

Data PiCAR and MuCAR difference



3.6σ between piCAR and muCAR

4.2σ between muCAR and throughgoing

We have provided the first observation of the products of stopped pion and muon nuclear capture on argon, and have shown that capture products of the two particle types are clearly distinguishable from one another in neutrino LArTPC data.

Difference on blip activity for Muon CAR, Pion CAR and throughgoing for real data.

Systematics

We are considering 5 different systematic uncertainties:

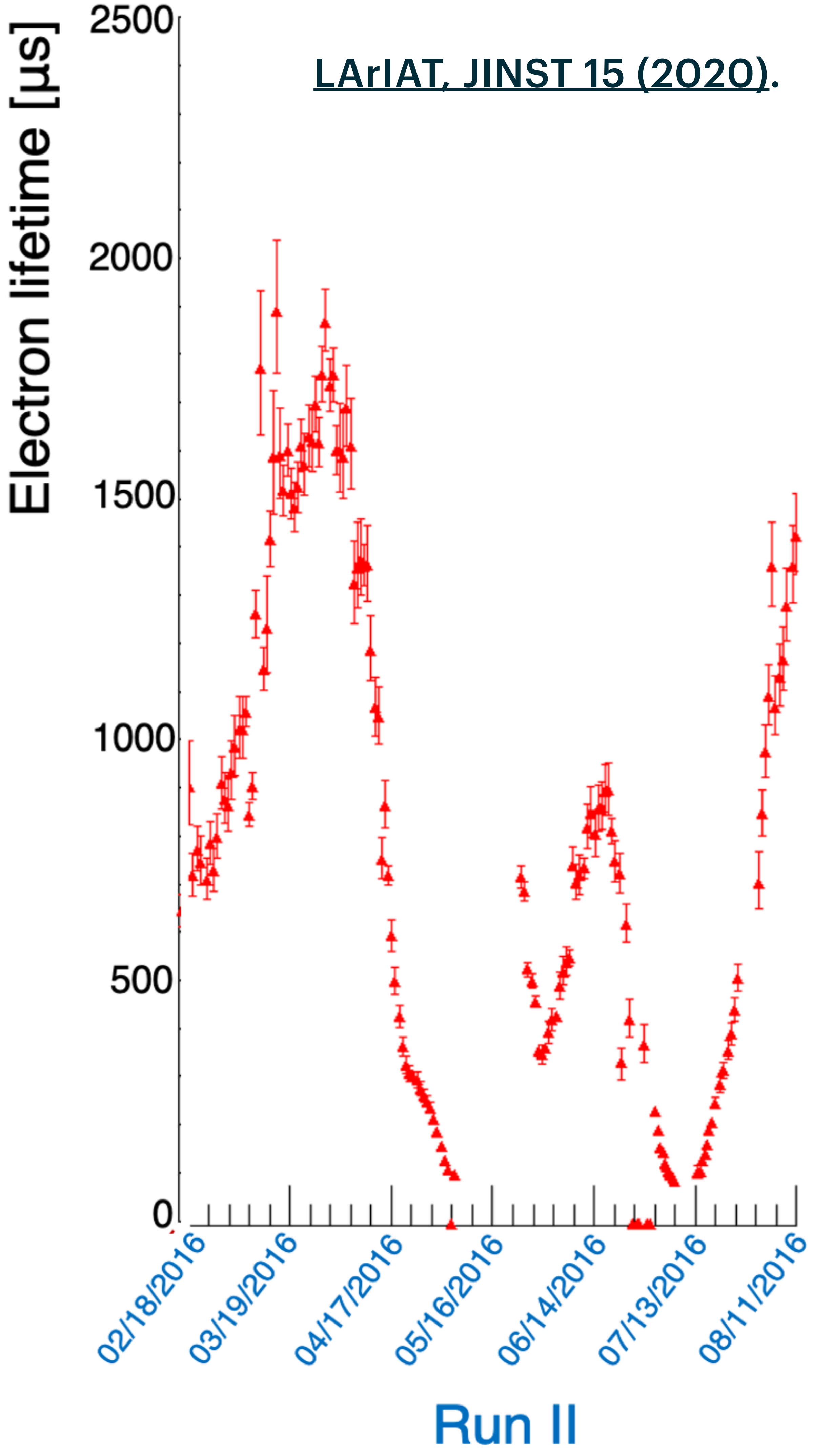
- Electron lifetime.
- Detector thresholds.
- Energy loss.
- Energy scale.
- Background subtraction.

Systematics

We are considering 5 different systematic uncertainties:

- Electron lifetime (1.3%).
- Detector thresholds.
- Energy loss.
- Energy scale.
- Background subtraction.

LArIAT did not employ a LAr re-circulation system; a subset of runs exhibited poor LAr purity.
12 different lifetimes were simulated to measure change in detected blip activity on signal.

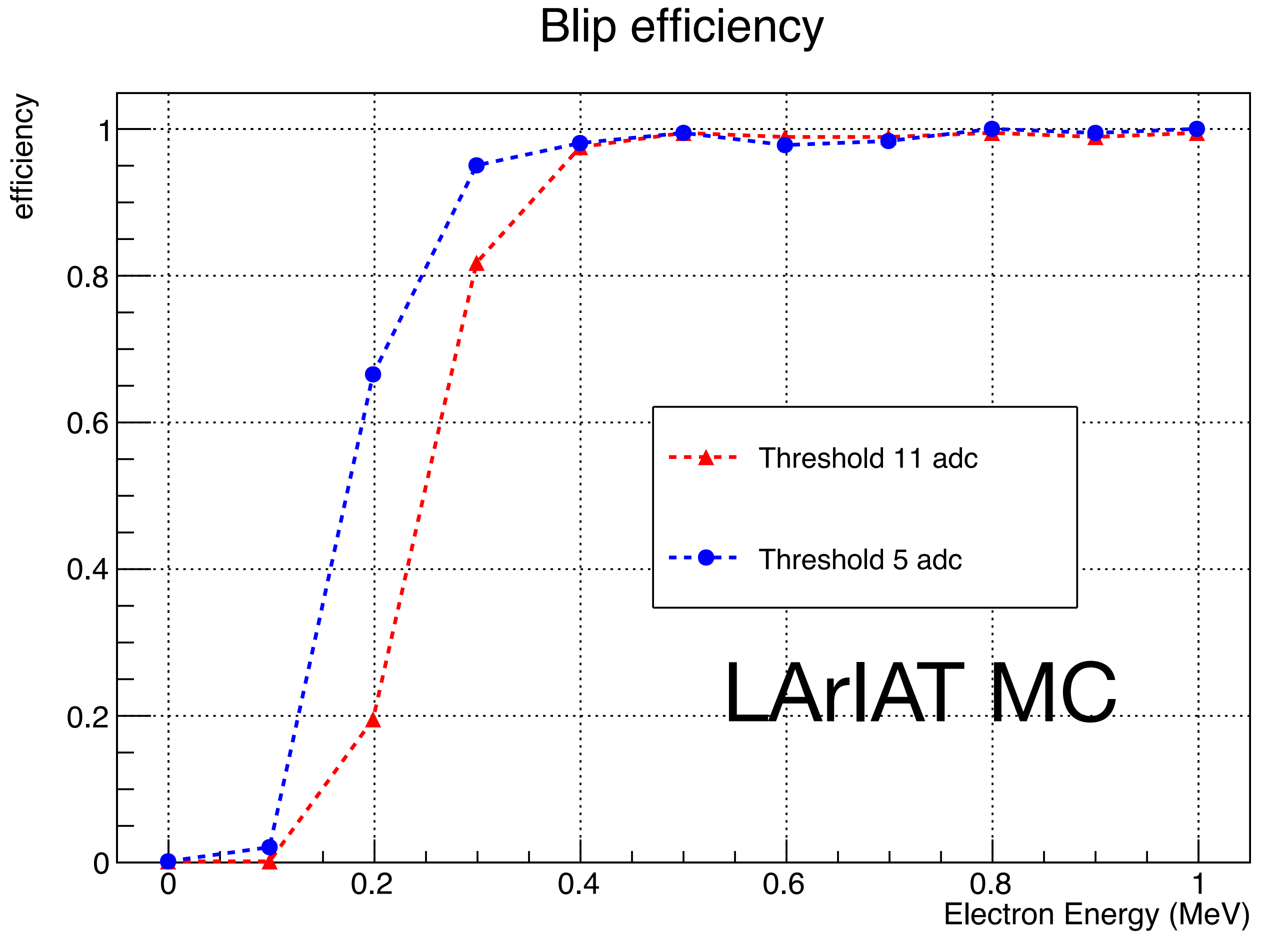


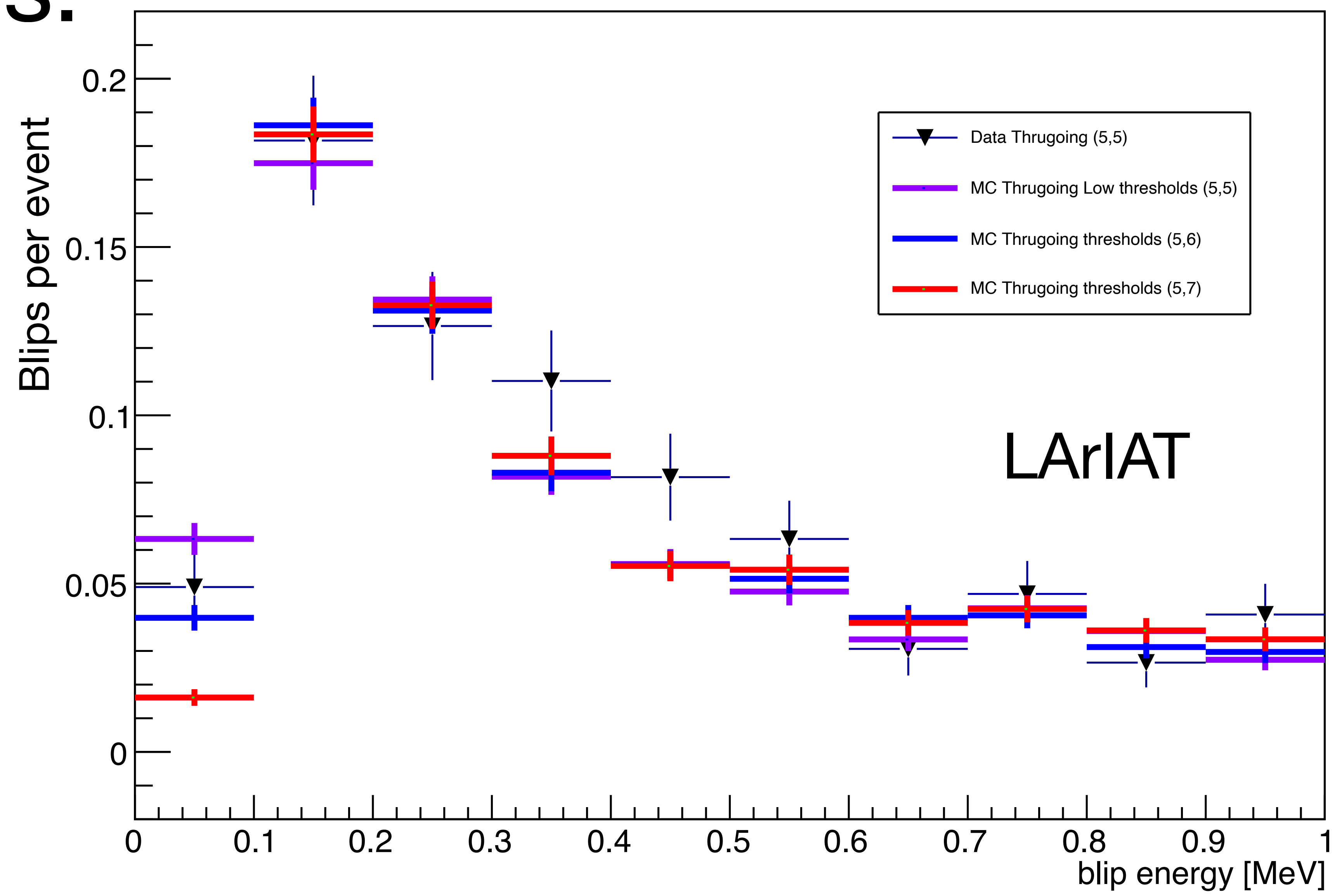
LArIAT, JINST 15 (2020).

Systematics

We are considering 5 different systematic uncertainties:

- Electron lifetime.
- Detector thresholds (2.4%).
- Energy loss.
- Energy scale.
- Background subtraction.





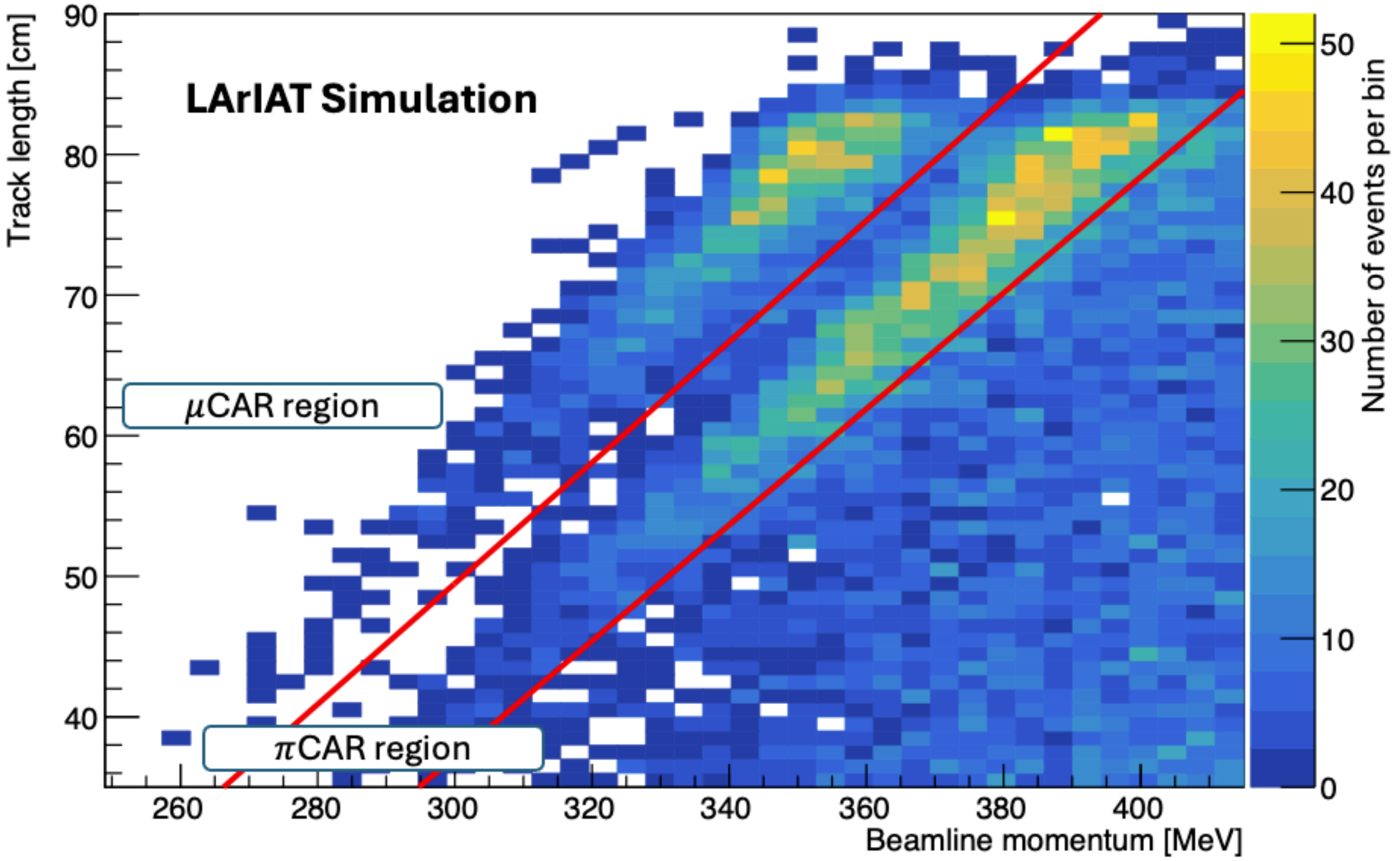
MC simulations with different threshold configurations to find the one with a better data/MC agreement.

Systematics

We are considering 5 different systematic uncertainties:

- Electron lifetime.
- Detector thresholds.
- Energy loss (3.3% for muCAR and 1.3% for piCAR).
- Energy scale.
- Background subtraction.

Uncertainty in the track length due to energy losses. How does this impact our selection?

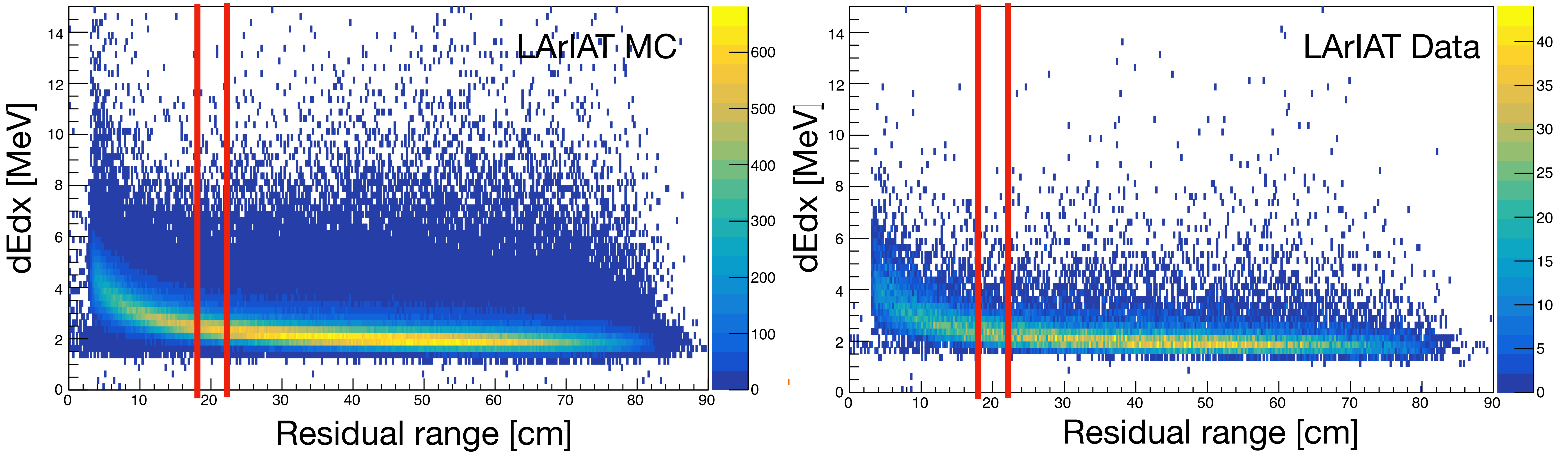


Systematics

We are considering 5 different systematic uncertainties:

- Electron lifetime.
- Detector thresholds.
- Energy loss.
- Energy scale (1.3%).
- Background subtracti

Differences in the minimum ionization point for data and MC at different Z positions.

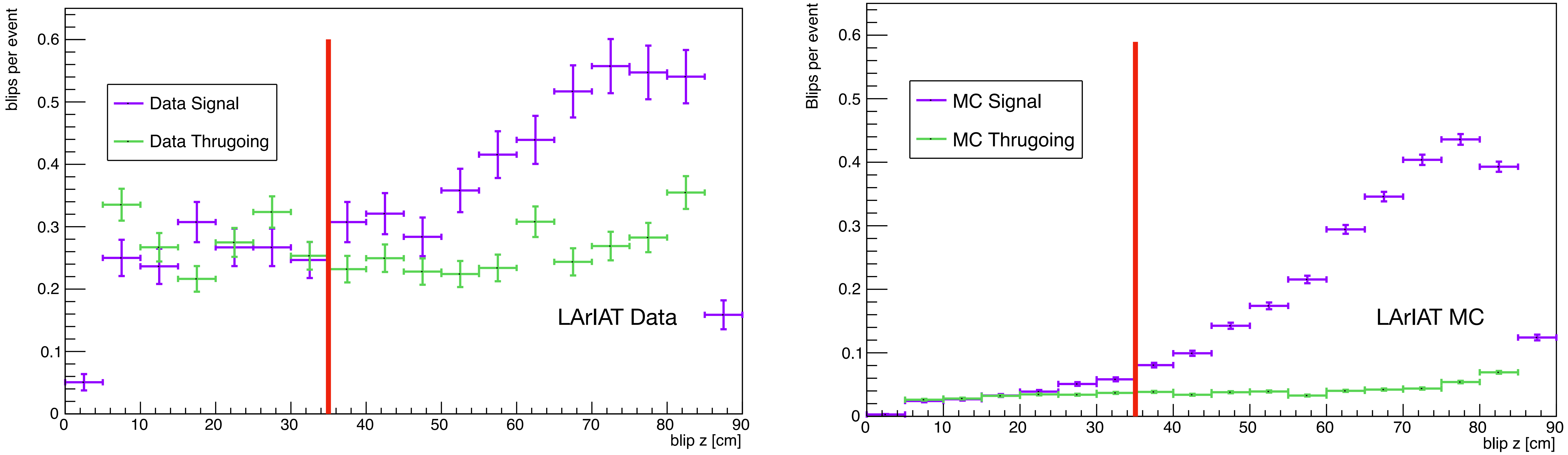


Systematics

We are considering 5 different systematic uncertainties:

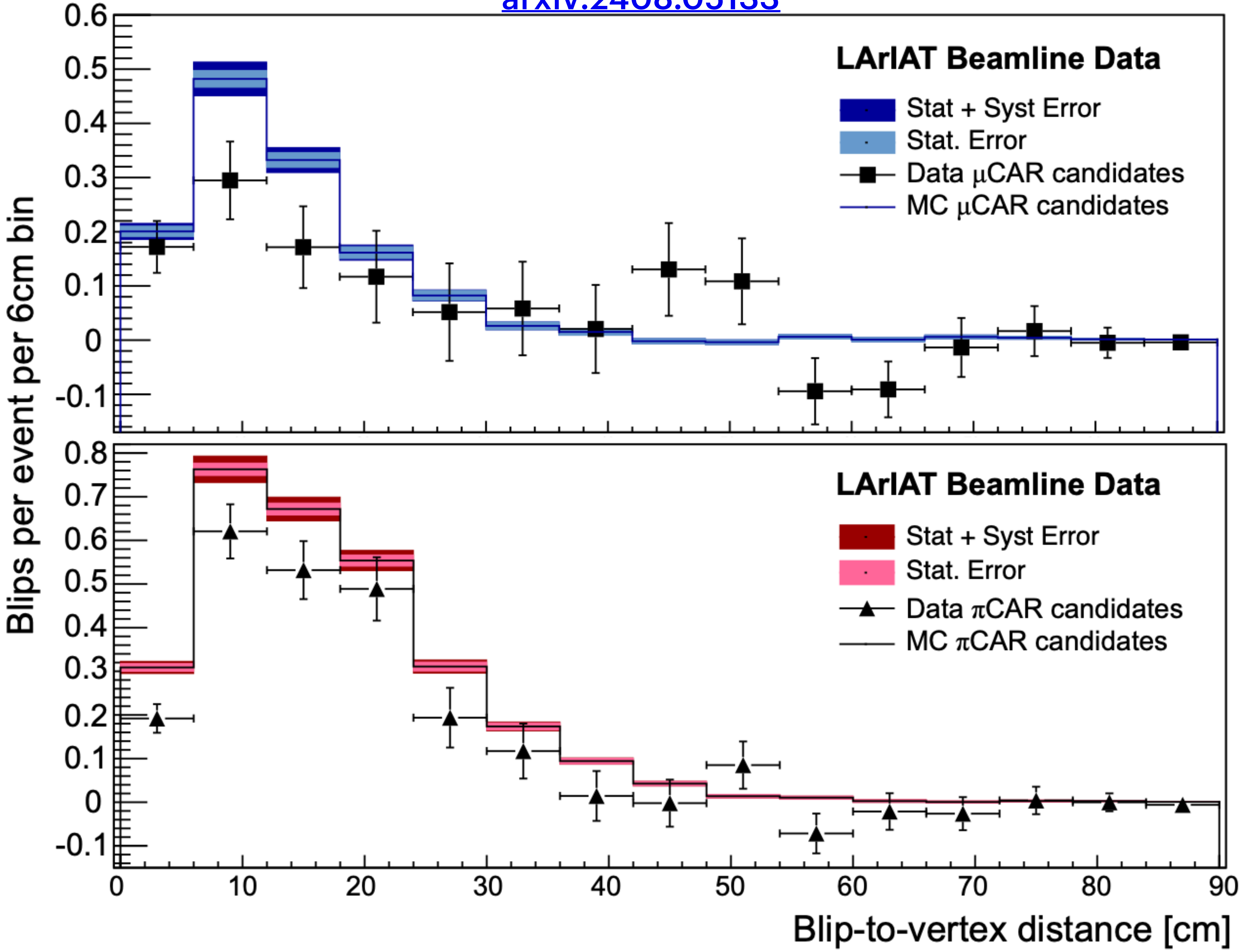
Fractional difference between signal and thrugoing.

- Electron lifetime.
- Detector thresholds.
- Energy loss.
- Energy scale.
- Background subtraction (3.5% for muCAR and 1.3% for piCAR).



Blip activity after background subtraction

arxiv:2408.05133



Blip activity after background subtraction

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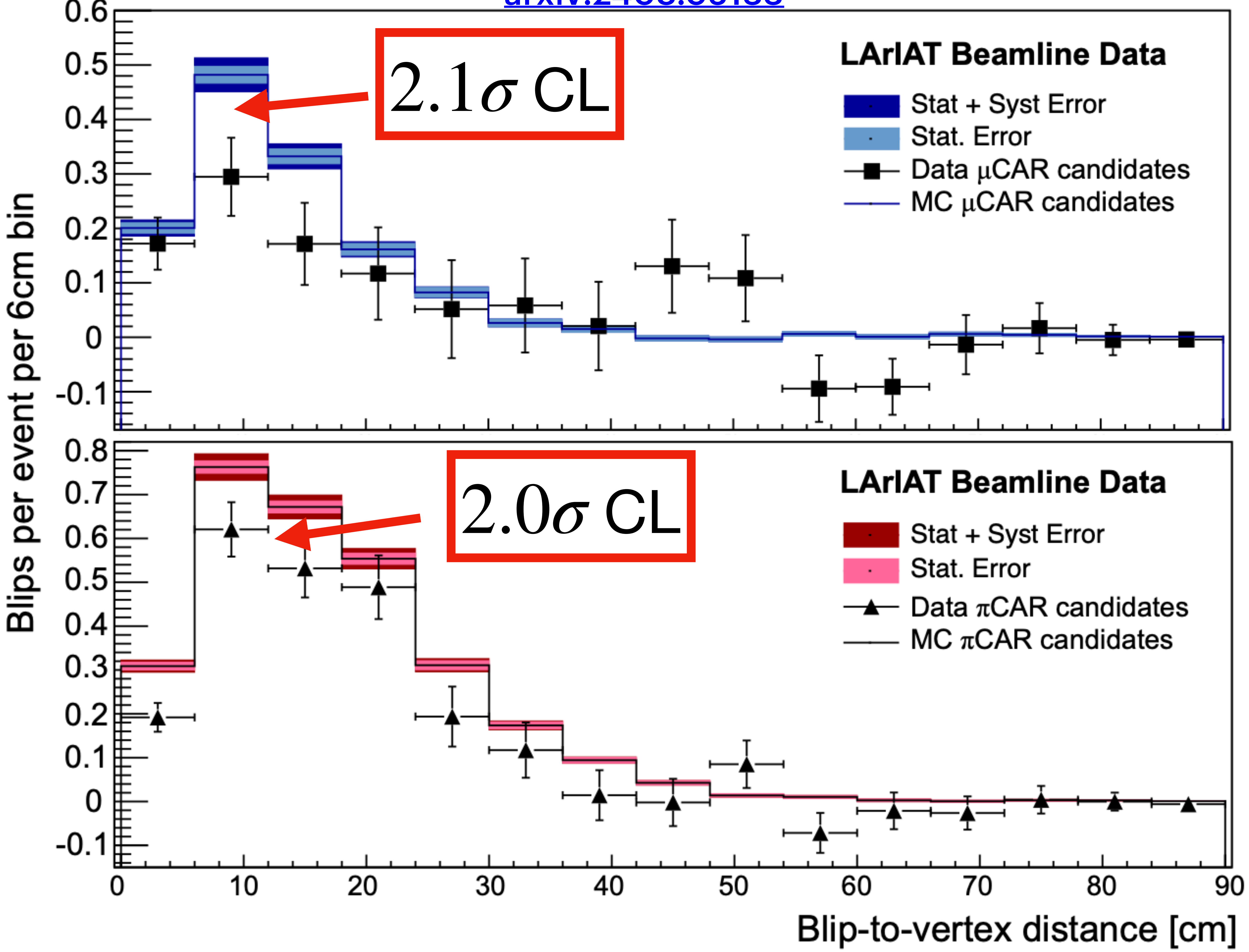


Blip multiplicity for MC and Data with big difference, 0.48 ± 0.20 for muon CAR and 0.48 ± 0.18 for pion CAR.

Systematics

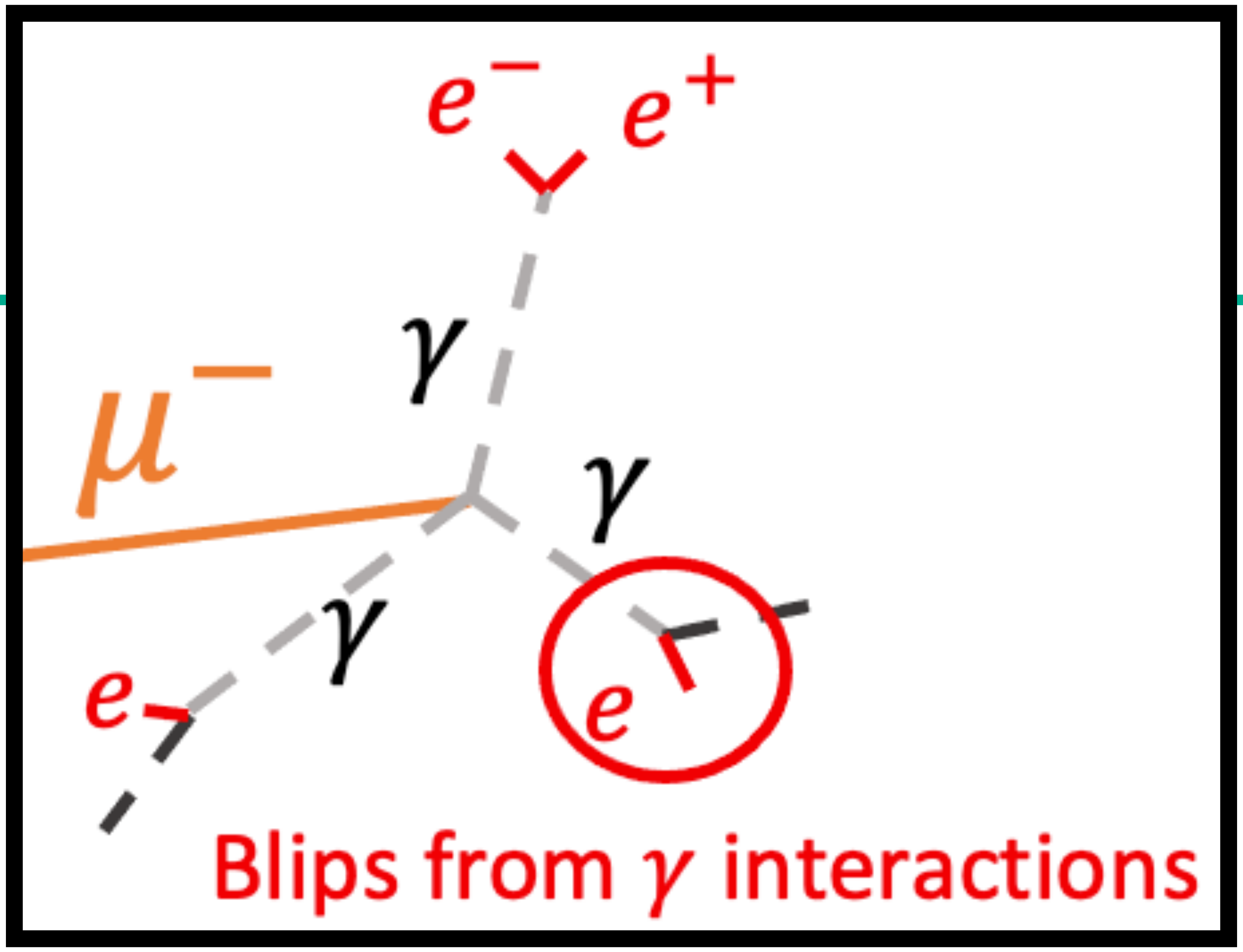
We could separate Signal (S) to Background (B) to Correlated (C) uncertainties.

- Electron lifetime (1.3%).
- Detector thresholds (2.4%).
- Energy loss (3.3% for muon CAR and 1.3% for pion CAR).
- Energy Scale (1.3%).
- Background Subtraction (3.5% for muon CAR and 1.3% for pion CAR).

$$\chi^2 = \sum_i \left(\frac{((S_i^{MC}(1+\eta_S) - T_i^{MC})(1+\eta_C) - (S_i^D - T_i^D(1+\eta_B)))^2}{\sigma_{stat}^2} \right) + \frac{\eta_B^2}{\sigma_B^2} + \frac{\eta_S^2}{\sigma_S^2} + \frac{\eta_C^2}{\sigma_C^2} \,.$$

MC/Data mismatch

- We see disagreement between data and MC not explained by the systematic uncertainties shown earlier.
- Incomplete modeling of Geant4 capture/de-excitation could be to blame.
    - G4’s final state predictions are based on nuclear models tuned from data on other target nuclei.



MC reweight

- We see disagreement between data and MC not explained by the systematic uncertainties shown earlier.
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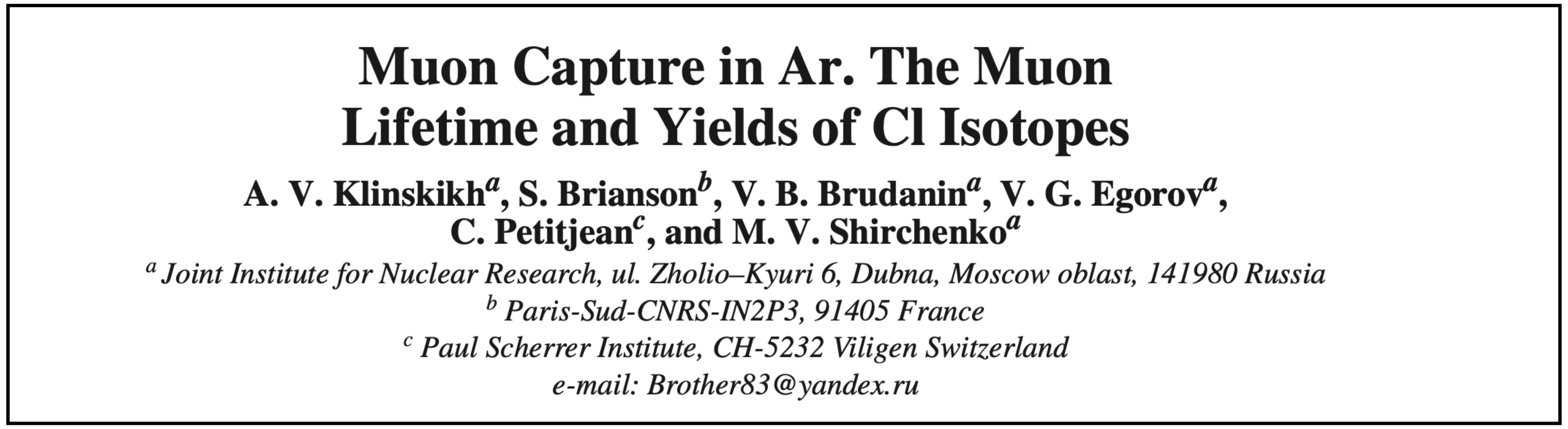
  - G4's final state predictions are based on nuclear models tuned from data on other target nuclei.
- Muon CAR final-states were measured in 2008, with gamma rays accompanying muon nuclear captures using Ge detectors.
- Unfortunately, no similar data for pion CAR final-states

Final state nuclei	LArIAT/G4 MC	Data from 2008 paper
Cl40	29%	7%
Cl39	9%	49%
Cl38	6%	17%
Muon decay	15%	25%
A<38	36%	0%



Muon Capture in Ar. The Muon Lifetime and Yields of Cl Isotopes

A. V. Klinskikh[a], S. Brianson[b], V. B. Brudanin[a], V. G. Egorov[a], C. Petitjean[c], and M. V. Shirchenko[a]

[a] *Joint Institute for Nuclear Research, ul. Zholio–Kyuri 6, Dubna, Moscow oblast, 141980 Russia*
[b] *Paris-Sud-CNRS-IN2P3, 91405 France*
[c] *Paul Scherrer Institute, CH-5232 Viligen Switzerland*
e-mail: Brother83@yandex.ru

Bull. Russ. Acad. Sci. Phys. 72, 735–736 (2008)

MC reweight

- We see disagreement between data and MC not explained by the systematic uncertainties shown earlier.
- Incomplete modeling of Geant4 capture/de-excitation could be to blame.
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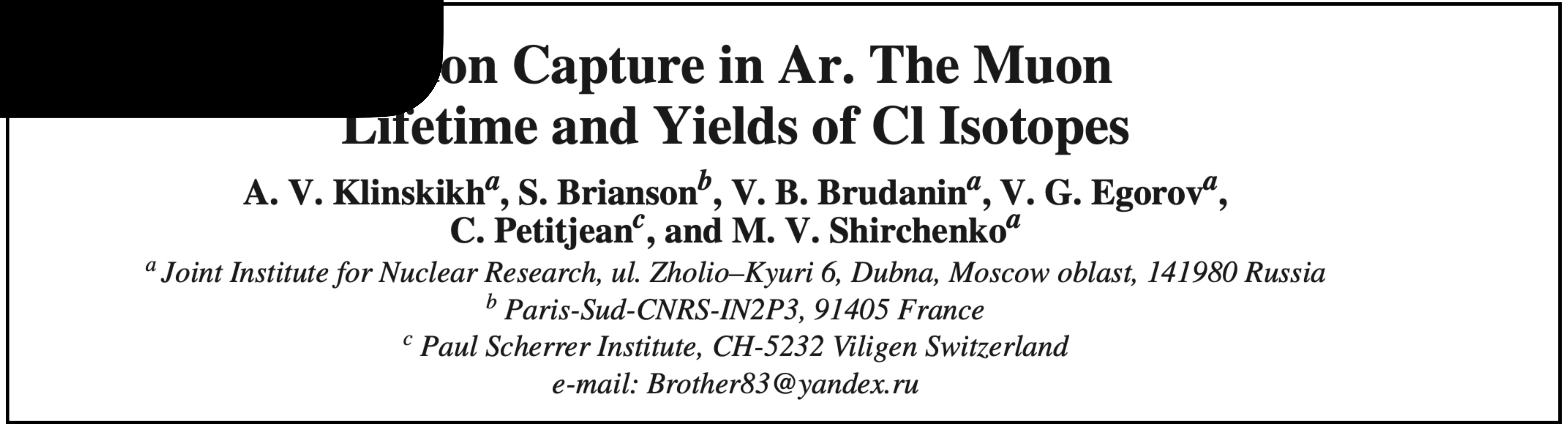
- Unfortunately, no similar data for pion CAR fi

This is a significant change. What if we weight our MC events to better reflect this data?

Final state nuclei	LArIAT/G4 MC	Dat
Cl40	29%	7%
Cl39	9%	49%
Cl38	6%	17%
Muon decay	15%	25%
A<38	36%	0%



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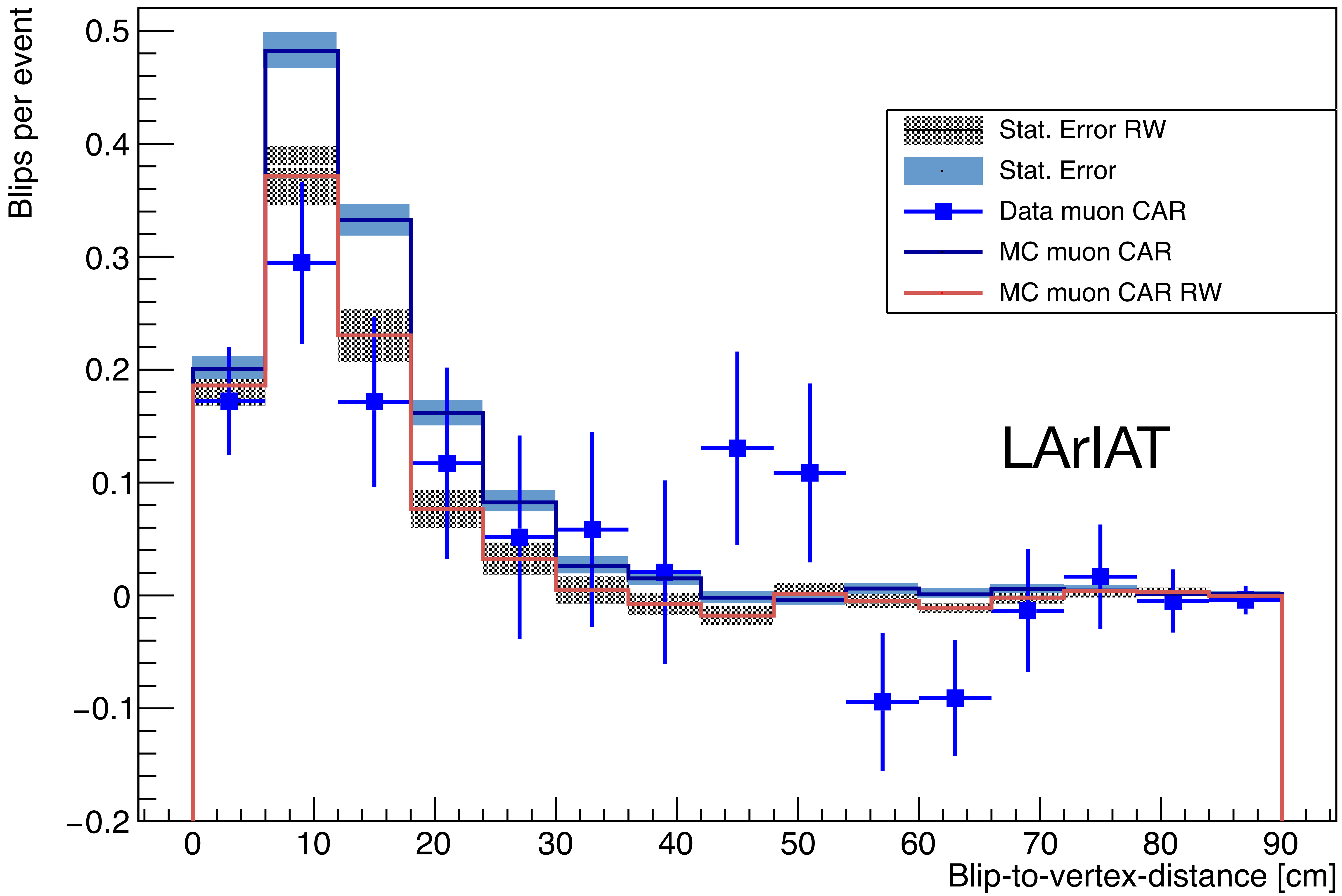
[c] Paul Scherrer Institute, CH-5232 Viligen Switzerland
e-mail: Brother83@yandex.ru

Bull. Russ. Acad. Sci. Phys. 72, 735–736 (2008)

MC reweight



Data and MC show better agreement after re-weighting the MC final-states.

For default MC simulation $\chi^2/ndf = 22.07/12$

For reweight MC simulation $\chi^2/ndf = 11.94/12$

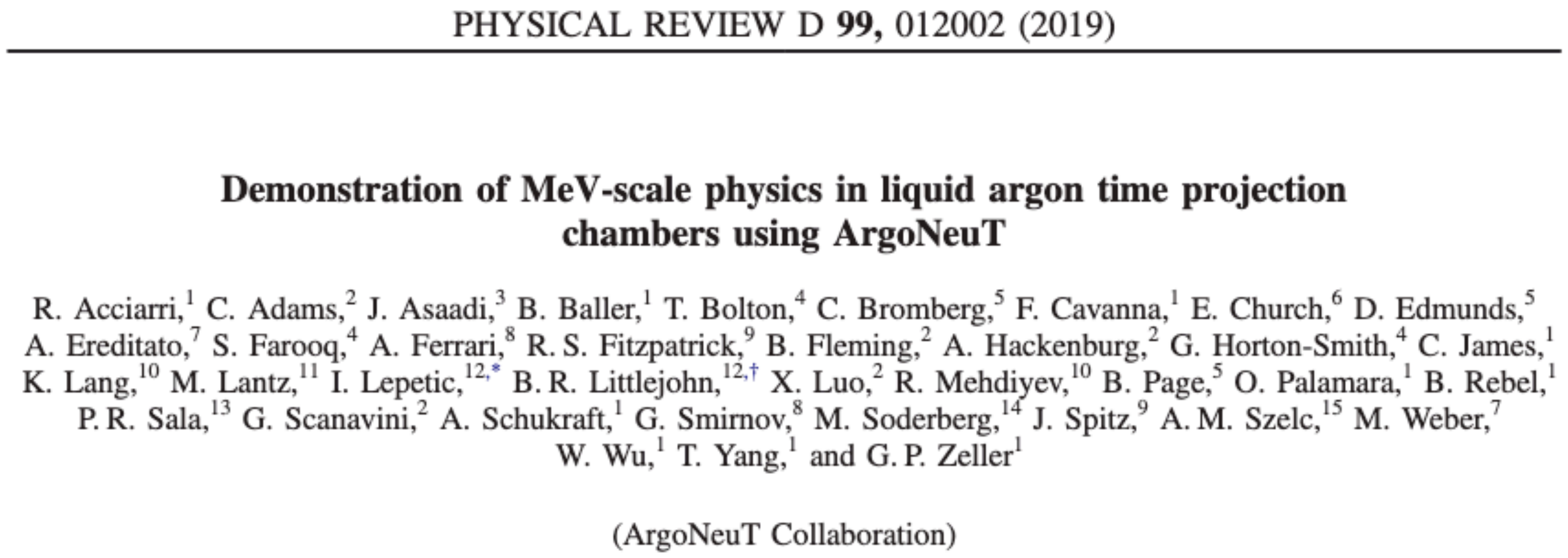
MC simulations for MeV-scale nuclear de-excitation and capture need improvement

MeV-scale Physics in DUNE

An experiment to understand neutrino oscillations, BSM physics and astrophysical neutrinos.

Could blips help DUNE?

MeV-scale LArTPC Physics: Beam neutrinos



PHYSICAL REVIEW D **99,** 012002 (2019)

Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT

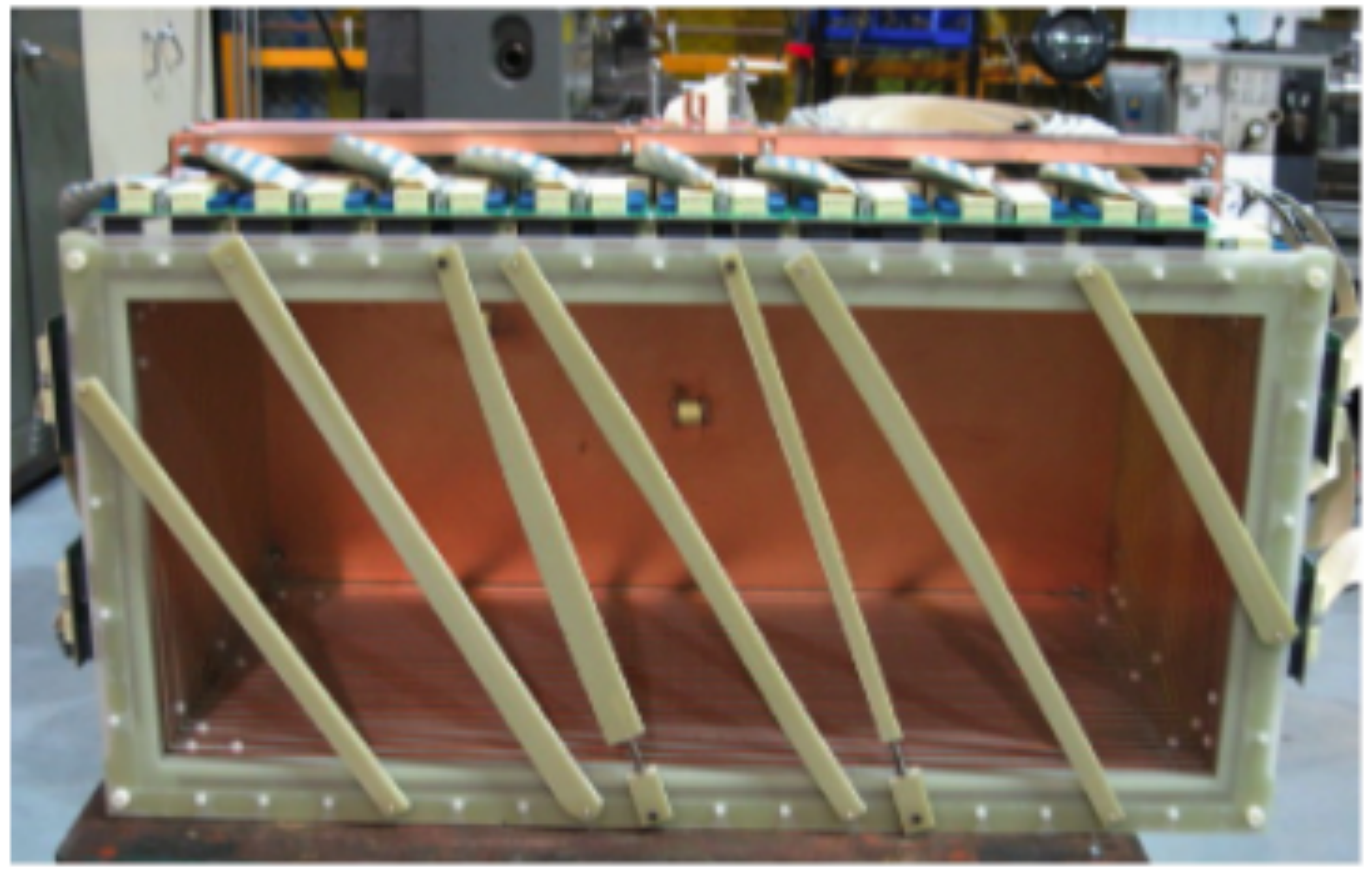
R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] E. Church,[6] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] A. Ferrari,[8] R. S. Fitzpatrick,[9] B. Fleming,[2] A. Hackenburg,[2] G. Horton-Smith,[4] C. James,[1] K. Lang,[10] M. Lantz,[11] I. Lepetic,[12,*] B. R. Littlejohn,[12,†] X. Luo,[2] R. Mehdiyev,[10] B. Page,[5] O. Palamara,[1] B. Rebel,[1] P. R. Sala,[13] G. Scanavini,[2] A. Schukraft,[1] G. Smirnov,[8] M. Soderberg,[14] J. Spitz,[9] A. M. Szelc,[15] M. Weber,[7] W. Wu,[1] T. Yang,[1] and G. P. Zeller[1]

(ArgoNeuT Collaboration)

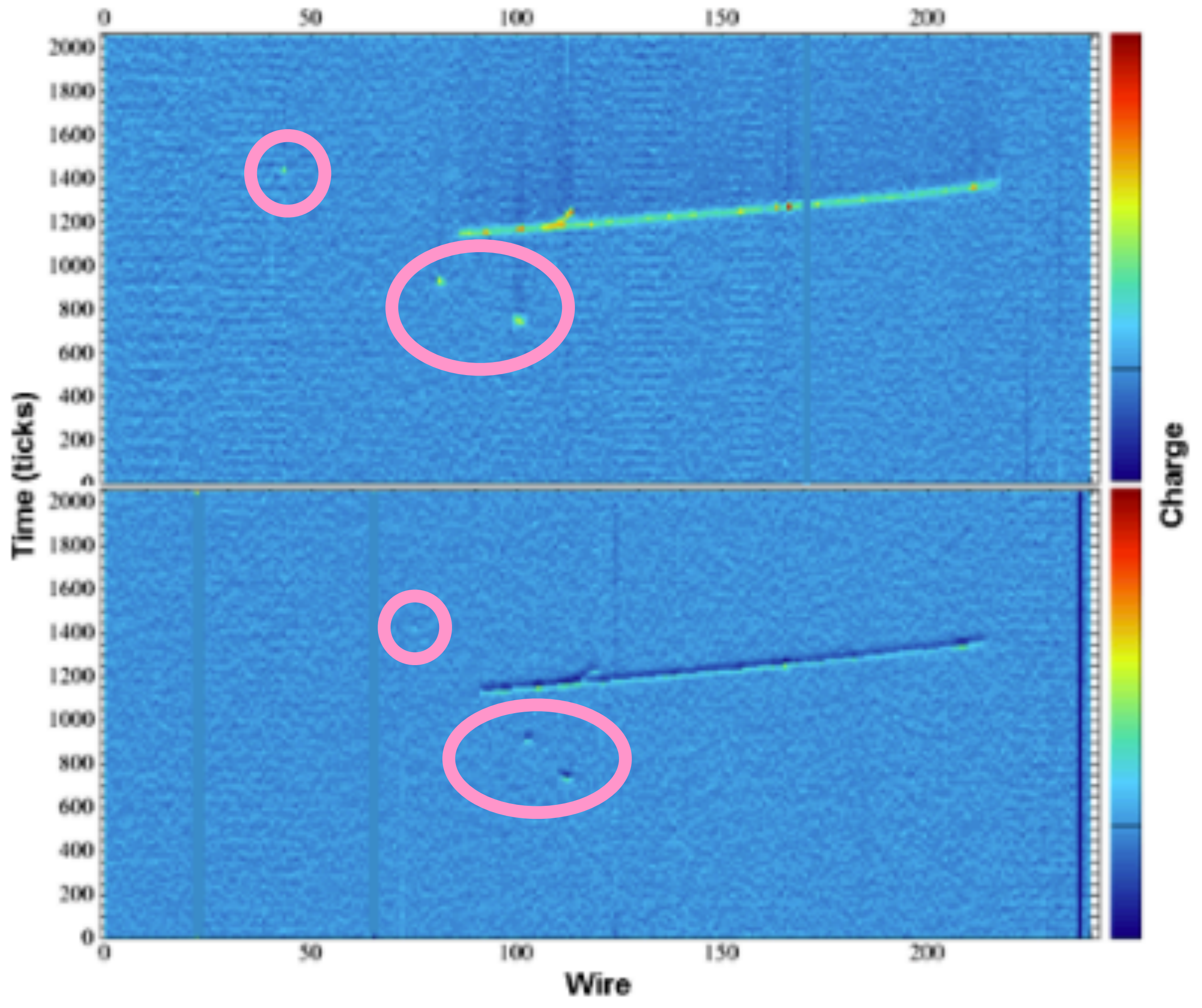
ArgoNeuT

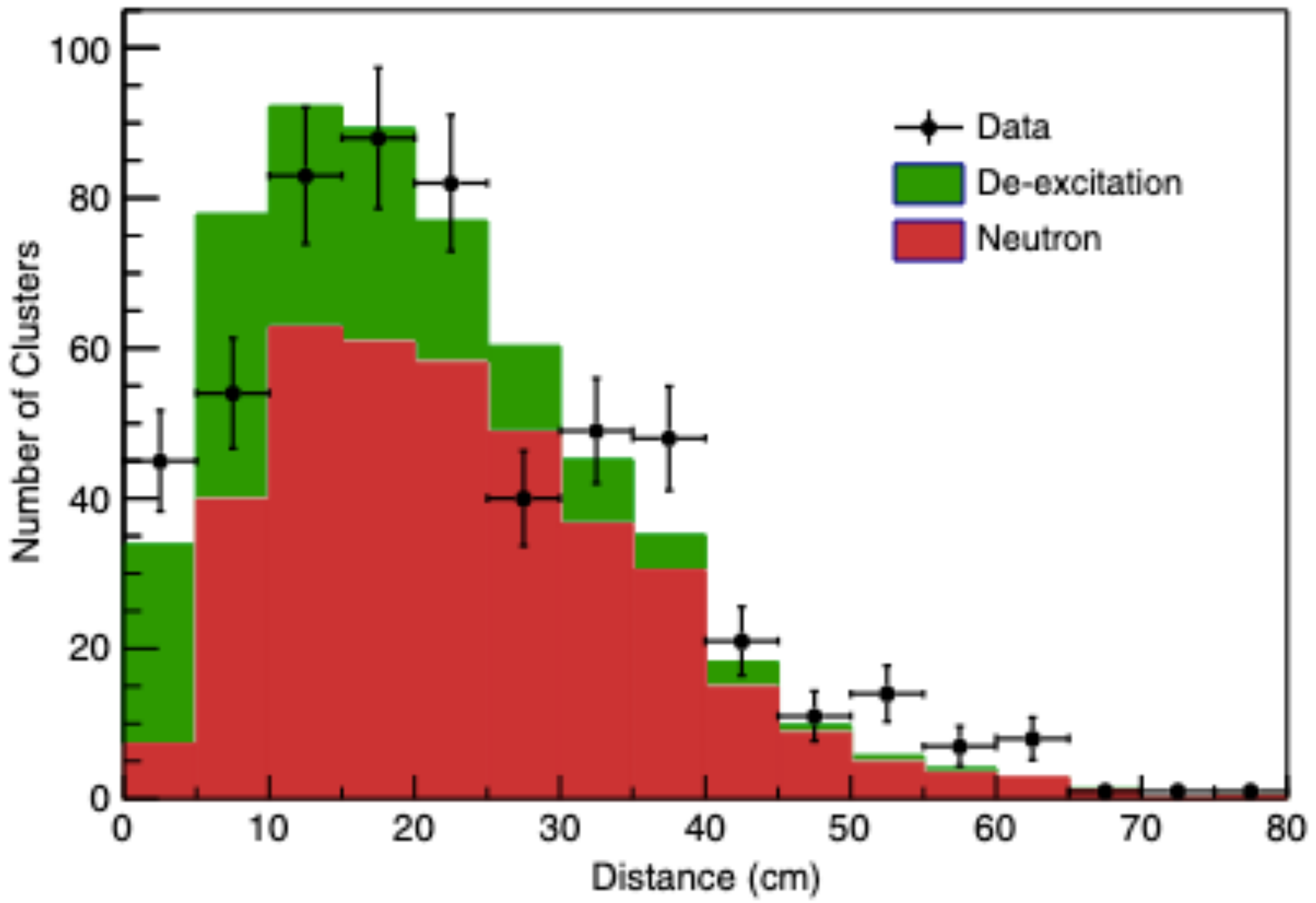
First LArTPC in a neutrino beam in the US (Fermilab).

First measurement of final-state neutrons from neutrino-argon nuclear interactions.



ArgoNeuT TPC





ILLINOIS INSTITUTE
OF TECHNOLOGY

LArIAT

MeV-scale LArTPC Physics: Beam neutrinos

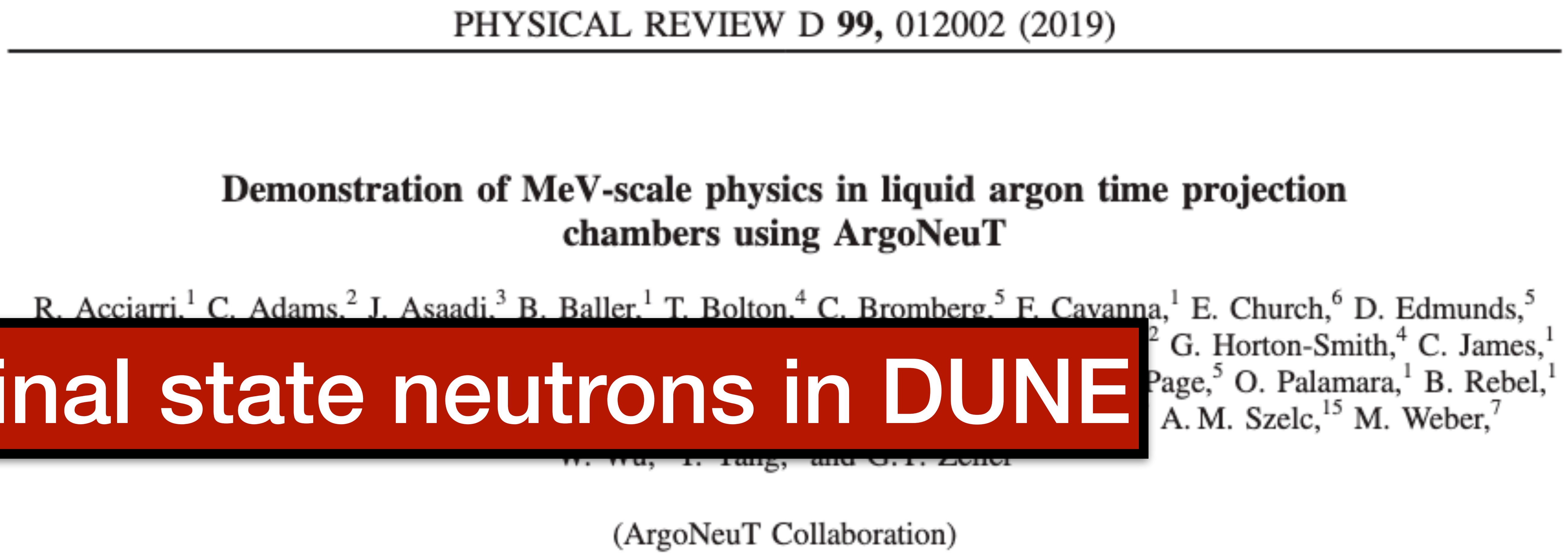
ArgoNeuT

First LArTPC in a neutrino beam in the US (Fermilab).

First measuren

neutrino-argon nuclear interactions.

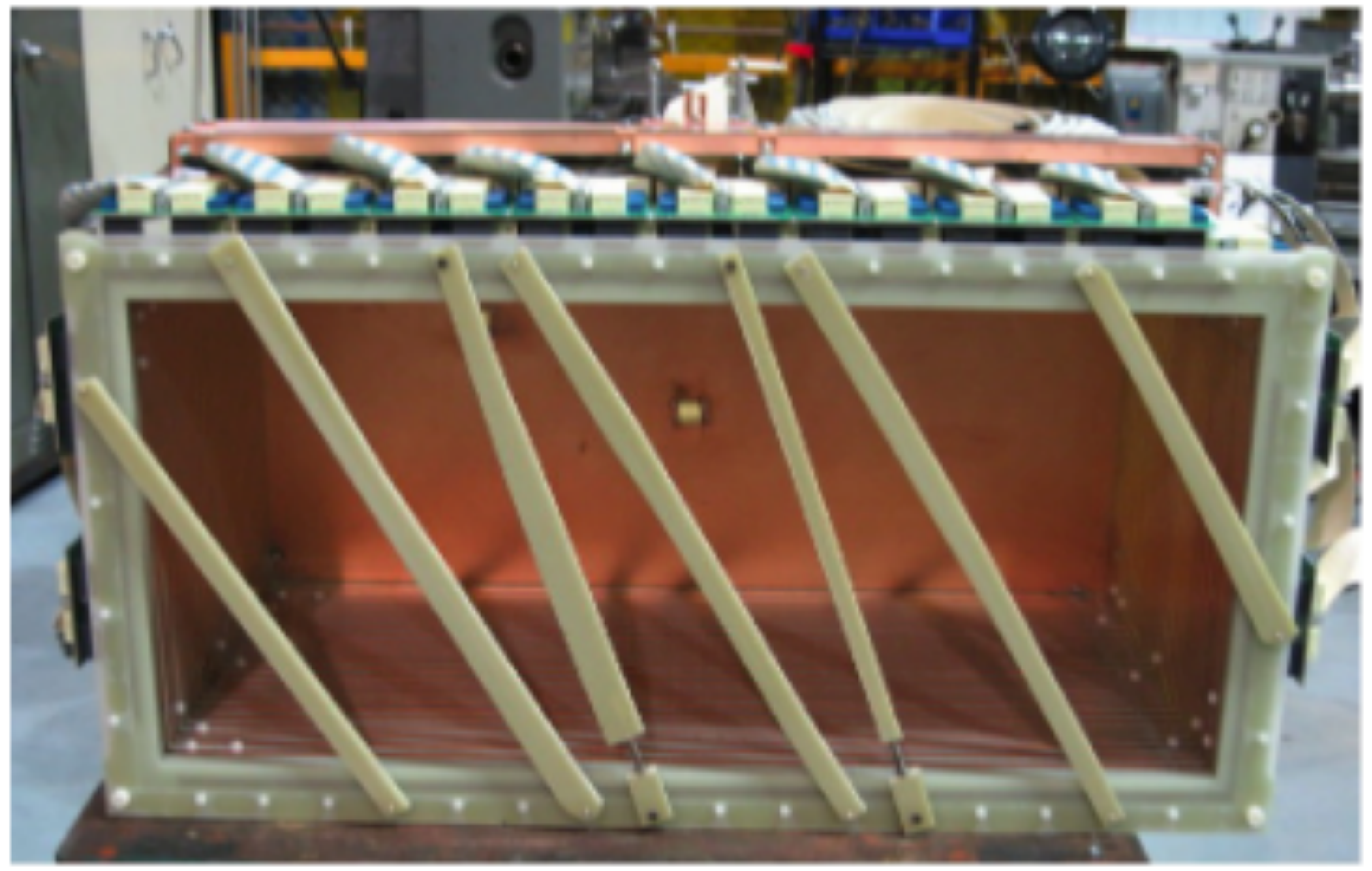
Blips will help us see final state neutrons in DUNE

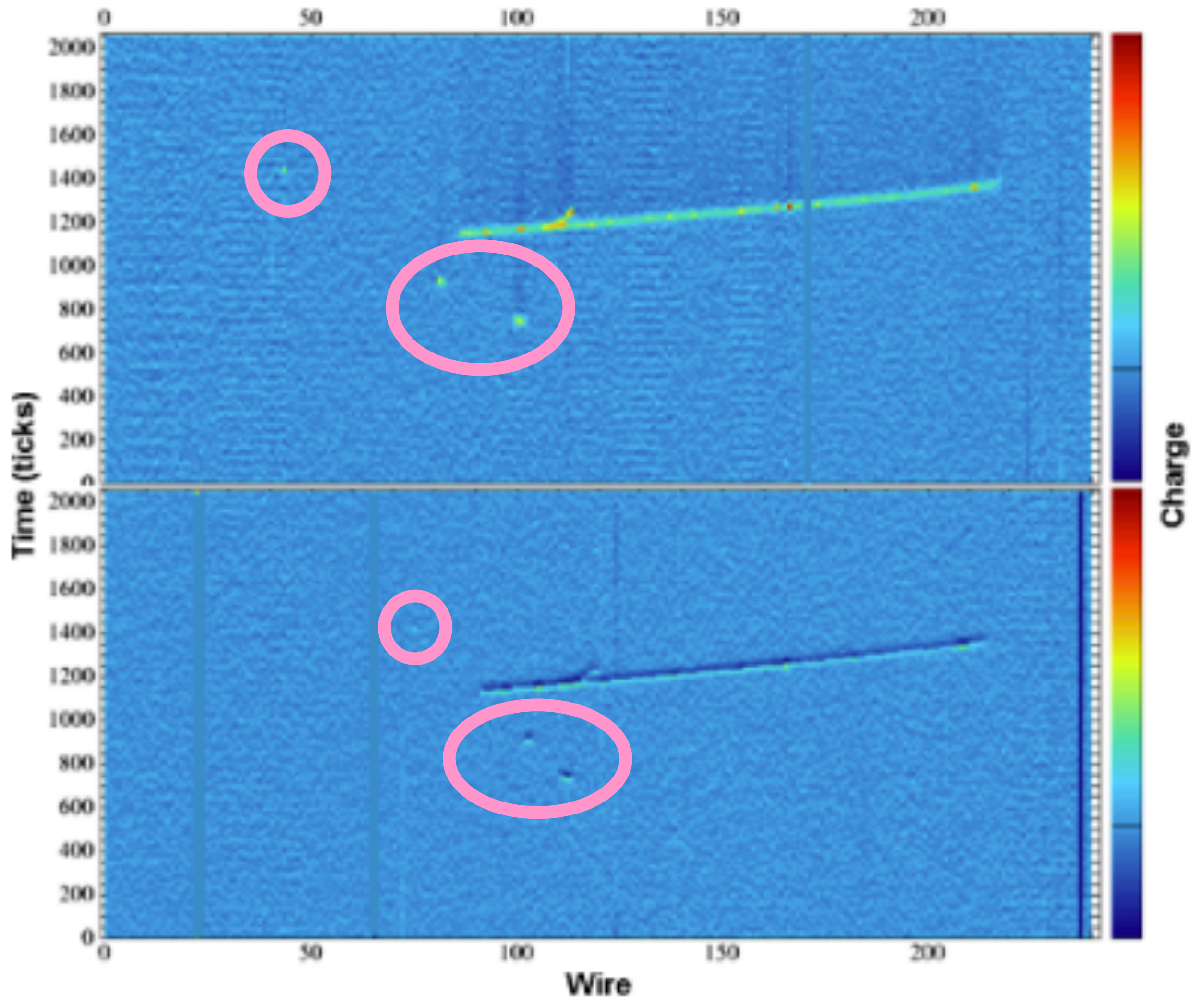

PHYSICAL REVIEW D **99,** 012002 (2019)

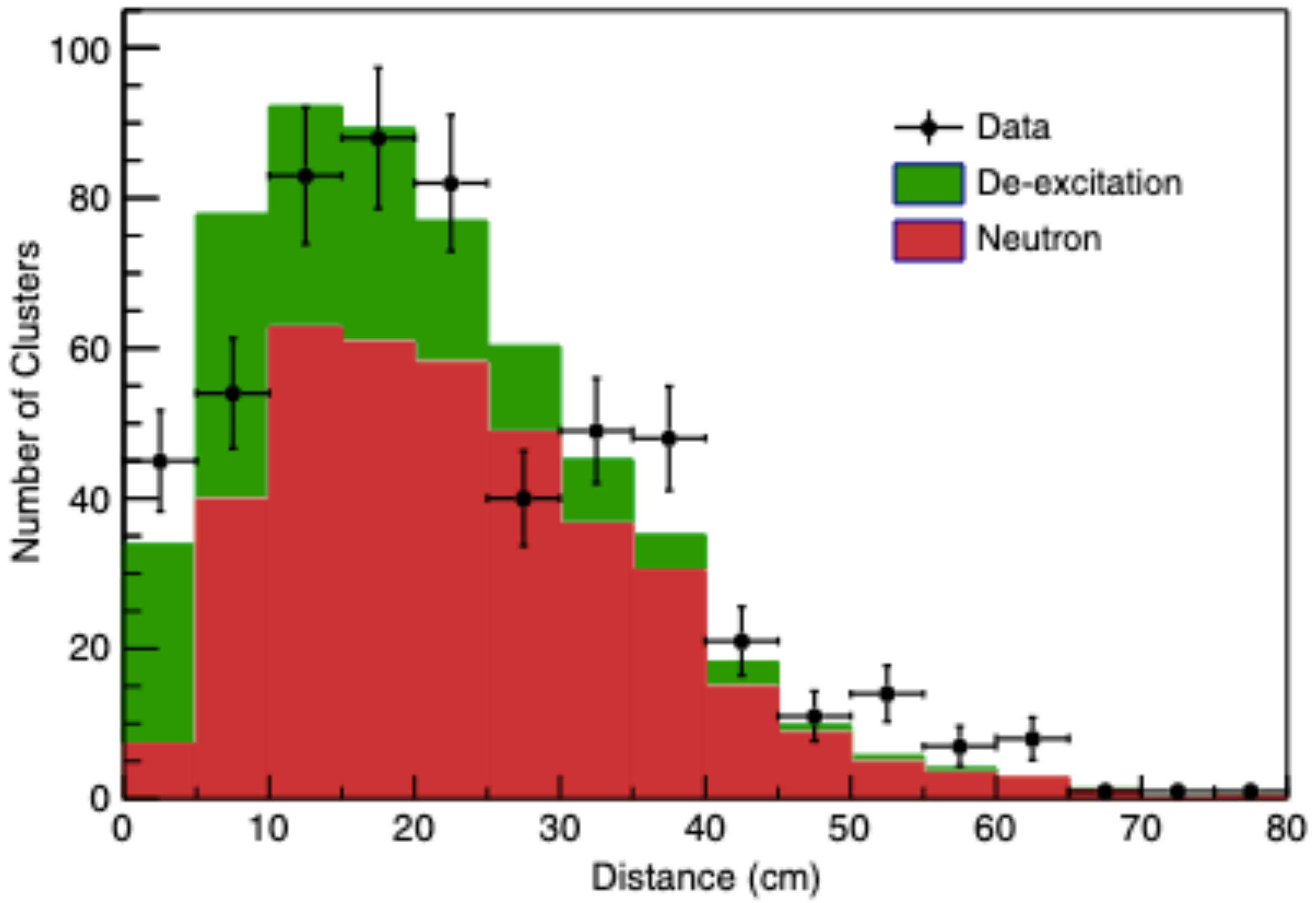
Demonstration of MeV-scale physics in liquid argon time projection chambers using ArgoNeuT

R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] E. Church,[6] D. Edmunds,[5]
[2] G. Horton-Smith,[4] C. James,[1]
Page,[5] O. Palamara,[1] B. Rebel,[1]
A. M. Szelc,[15] M. Weber,[7]
W. Wu, T. Yang, and G. P. Zeller

(ArgoNeuT Collaboration)


ArgoNeuT TPC





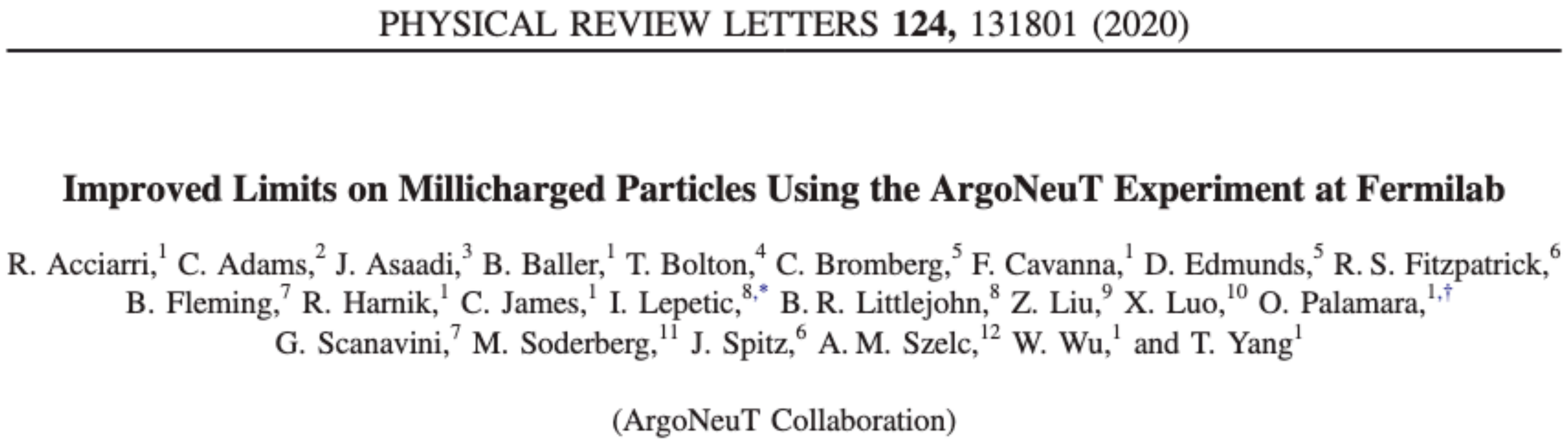
MeV-scale LArTPC Physics: Beam neutrinos

ArgoNeuT

First LArTPC in a neutrino beam in the US (Fermilab).

First measurement of final-state neutrons from neutrino-argon nuclear interactions.

Improved limits in millicharged particles $(10^{-3}e - 10^{-1}e)$

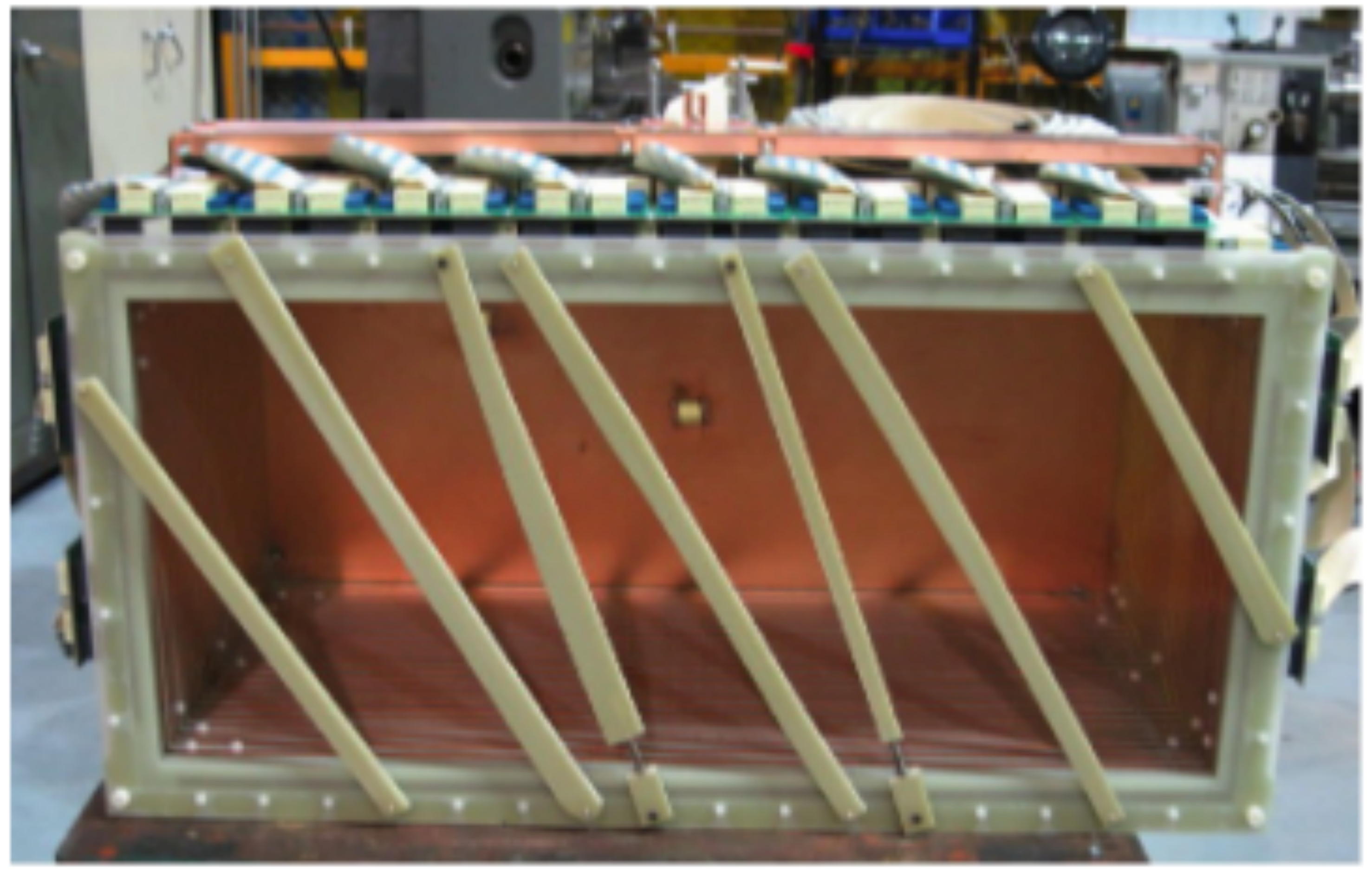


PHYSICAL REVIEW LETTERS **124,** 131801 (2020)

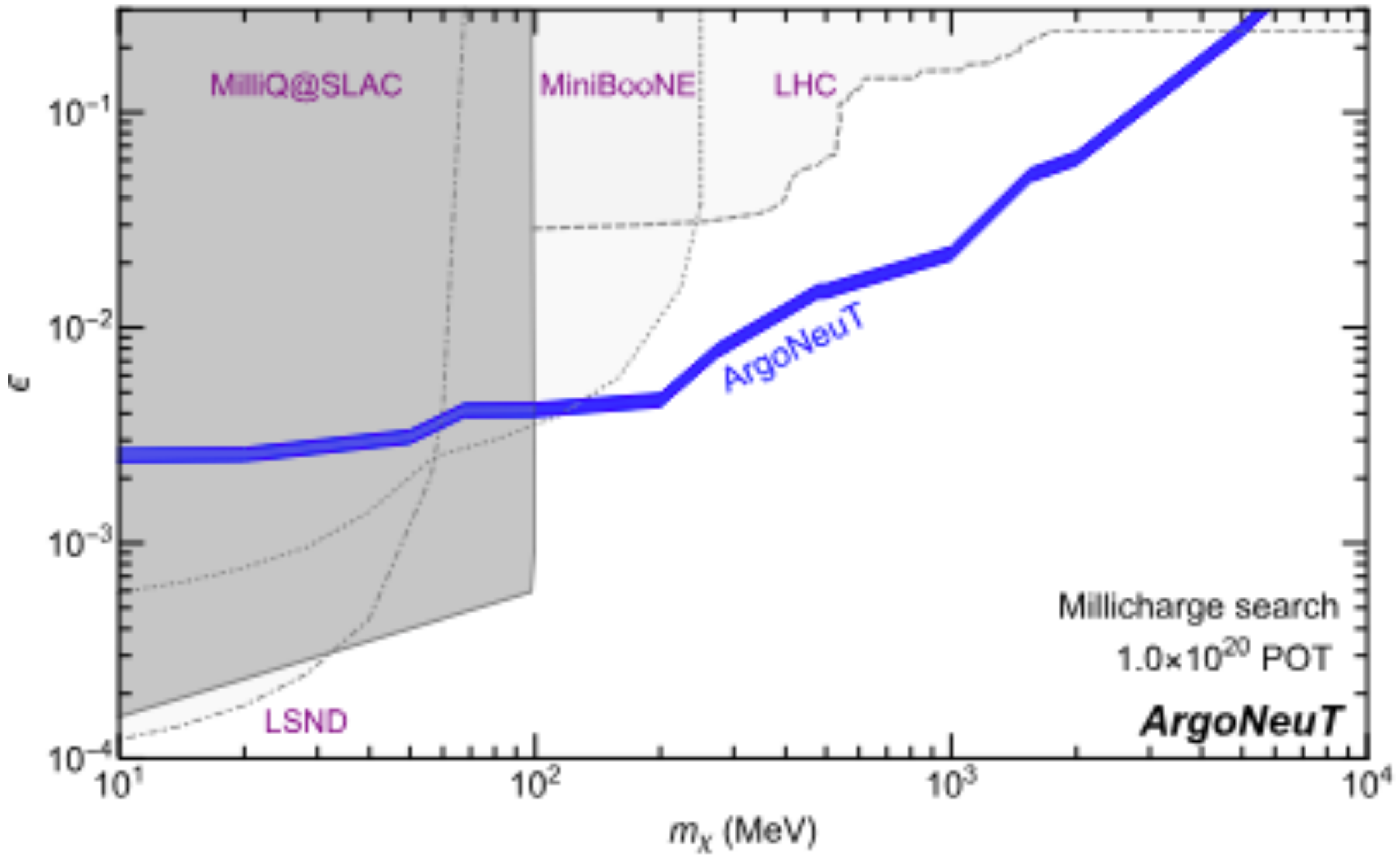
Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab

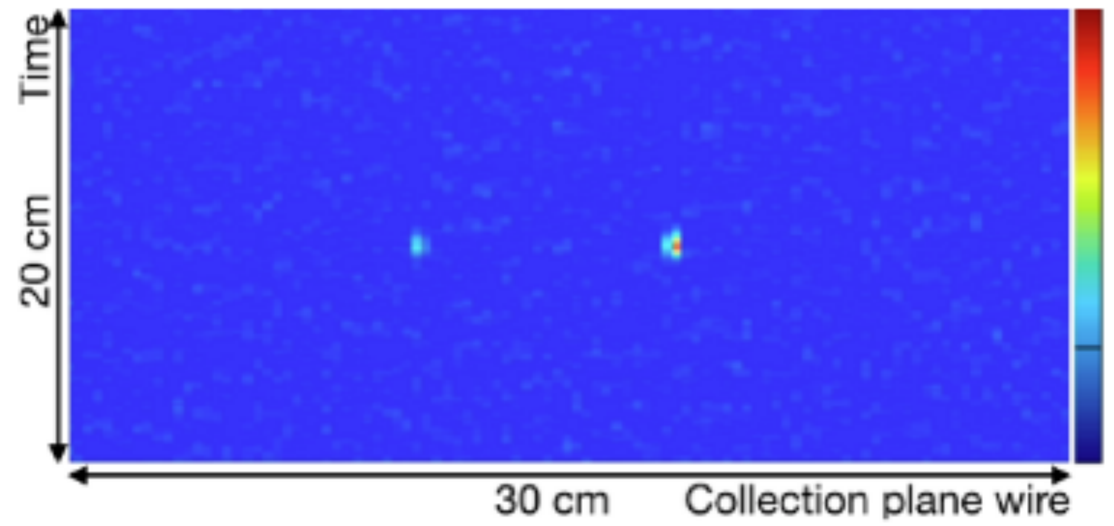
R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] D. Edmunds,[5] R. S. Fitzpatrick,[6] B. Fleming,[7] R. Harnik,[1] C. James,[1] I. Lepetic,[8,*] B. R. Littlejohn,[8] Z. Liu,[9] X. Luo,[10] O. Palamara,[1,†] G. Scanavini,[7] M. Soderberg,[11] J. Spitz,[6] A. M. Szelc,[12] W. Wu,[1] and T. Yang[1]

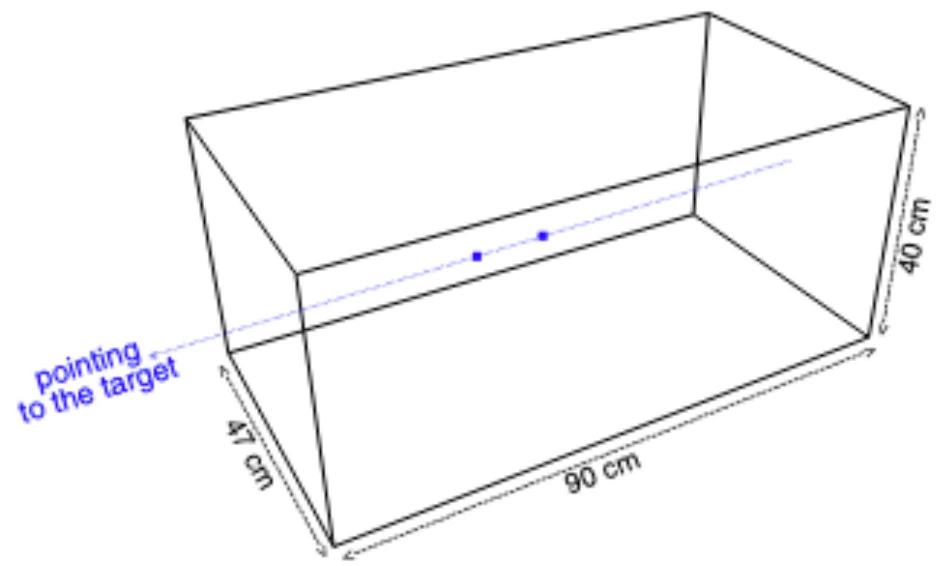
(ArgoNeuT Collaboration)



ArgoNeuT TPC

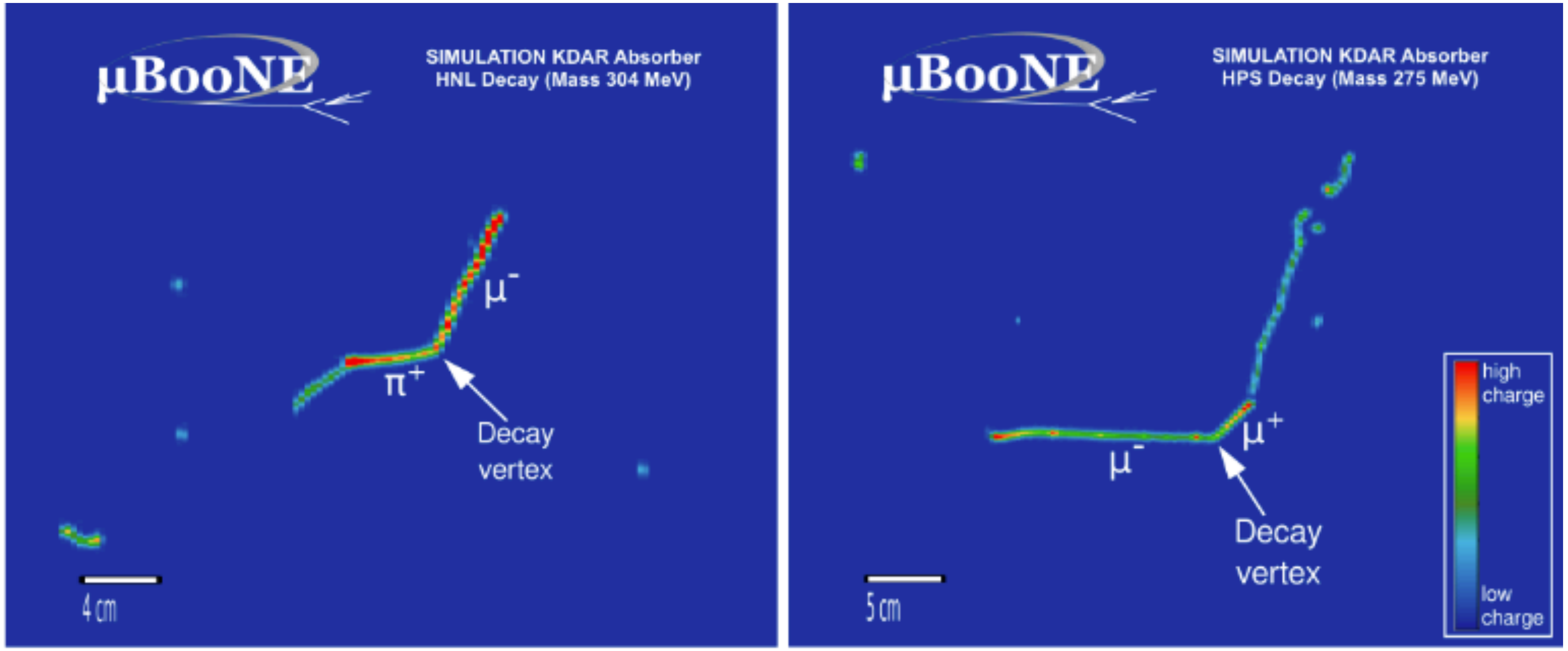






MeV-scale LArTPC Physics: More BSM

Microboone, PRD.106.092006

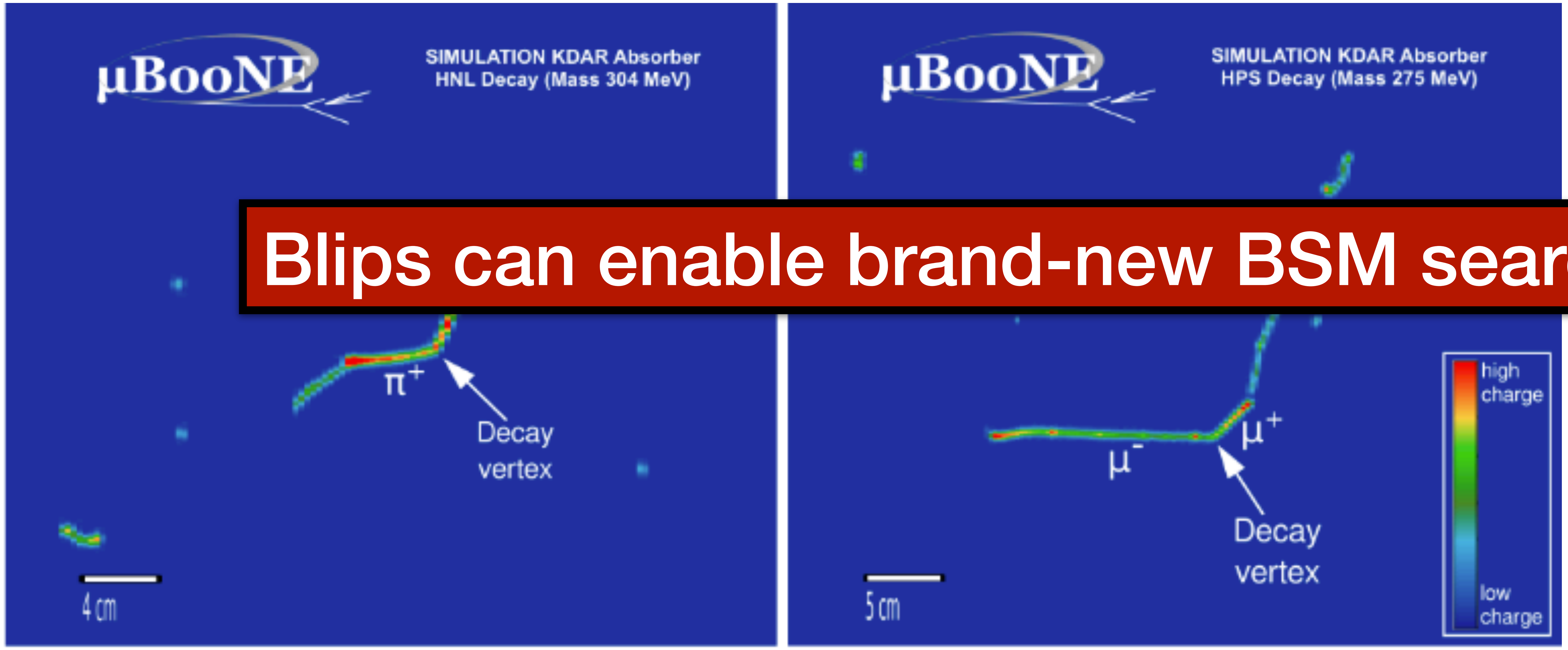


MicroBooNE has looked for this track-like BSM signature of dimuon track pairs; you may ask — how are blips relevant here?

A big background is CCnumu1pi — blips can help to reduce this background

MeV-scale LArTPC Physics: More BSM

Microboone, PRD.106.092006



Blips can enable brand-new BSM searches in LArTPCs!!

MicroBooNE has looked for this track-like BSM signature of dimuon track pairs; you nt here?

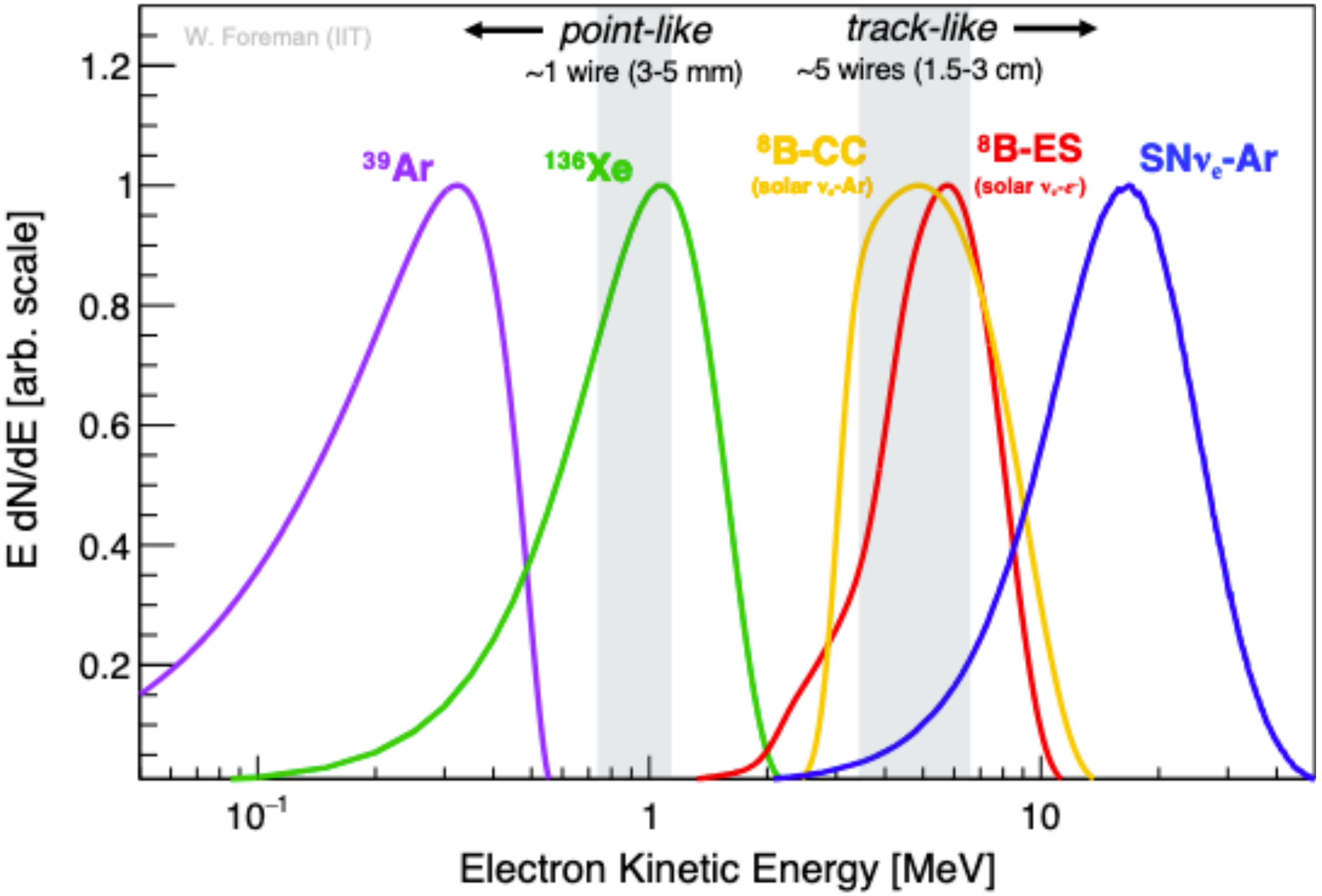
A big background is CCnumu1pi — blips can help to reduce this background

MeV-scale LArTPC Physics: Astrophysical neutrinos

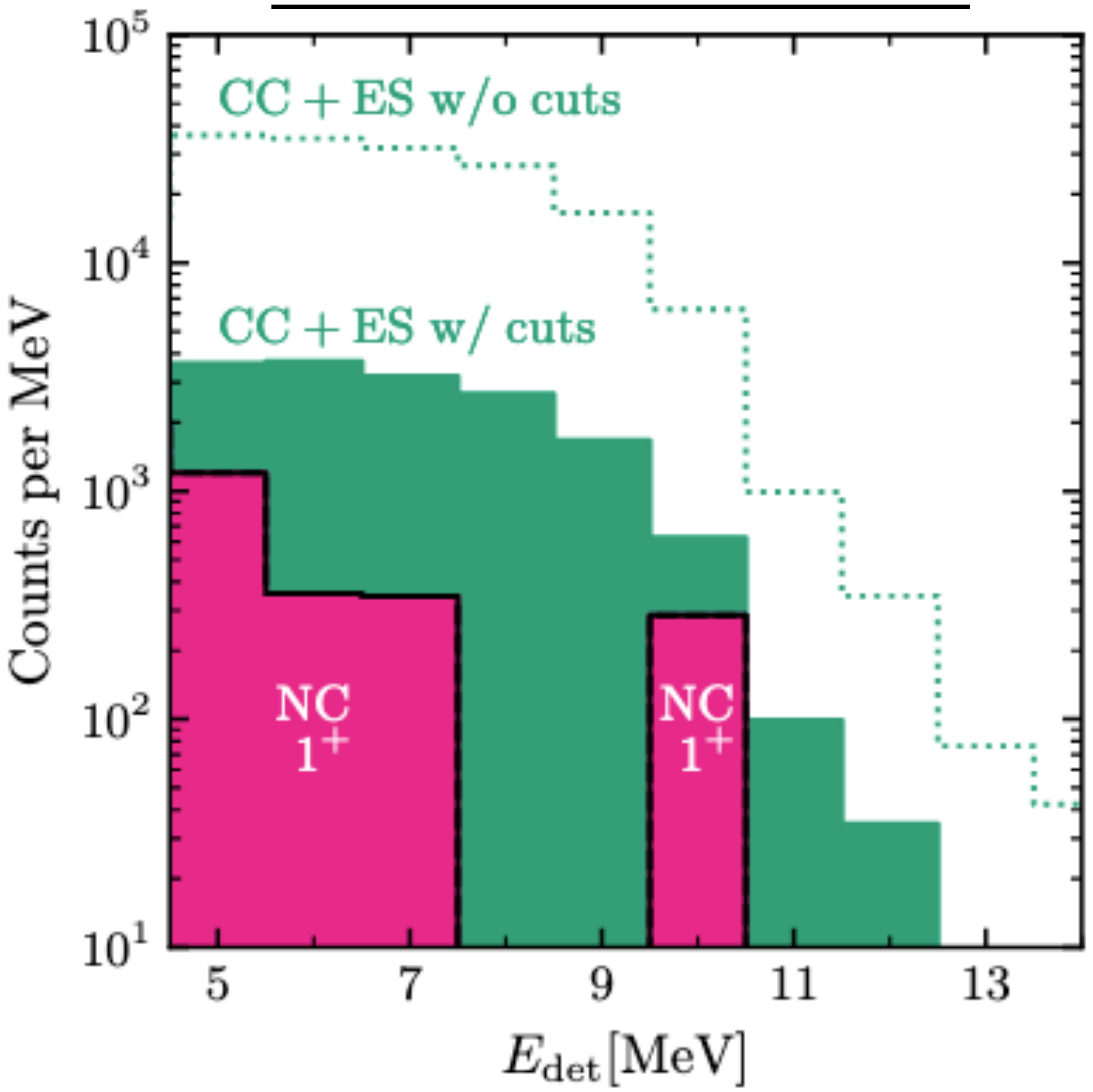
Dune has the potential to make a precise measurement of solar neutrinos via NC and CC.

Expected spectra for a DUNE exposure of 100-kton-year.

arxiv 2203.00740



arxiv 2410.00330



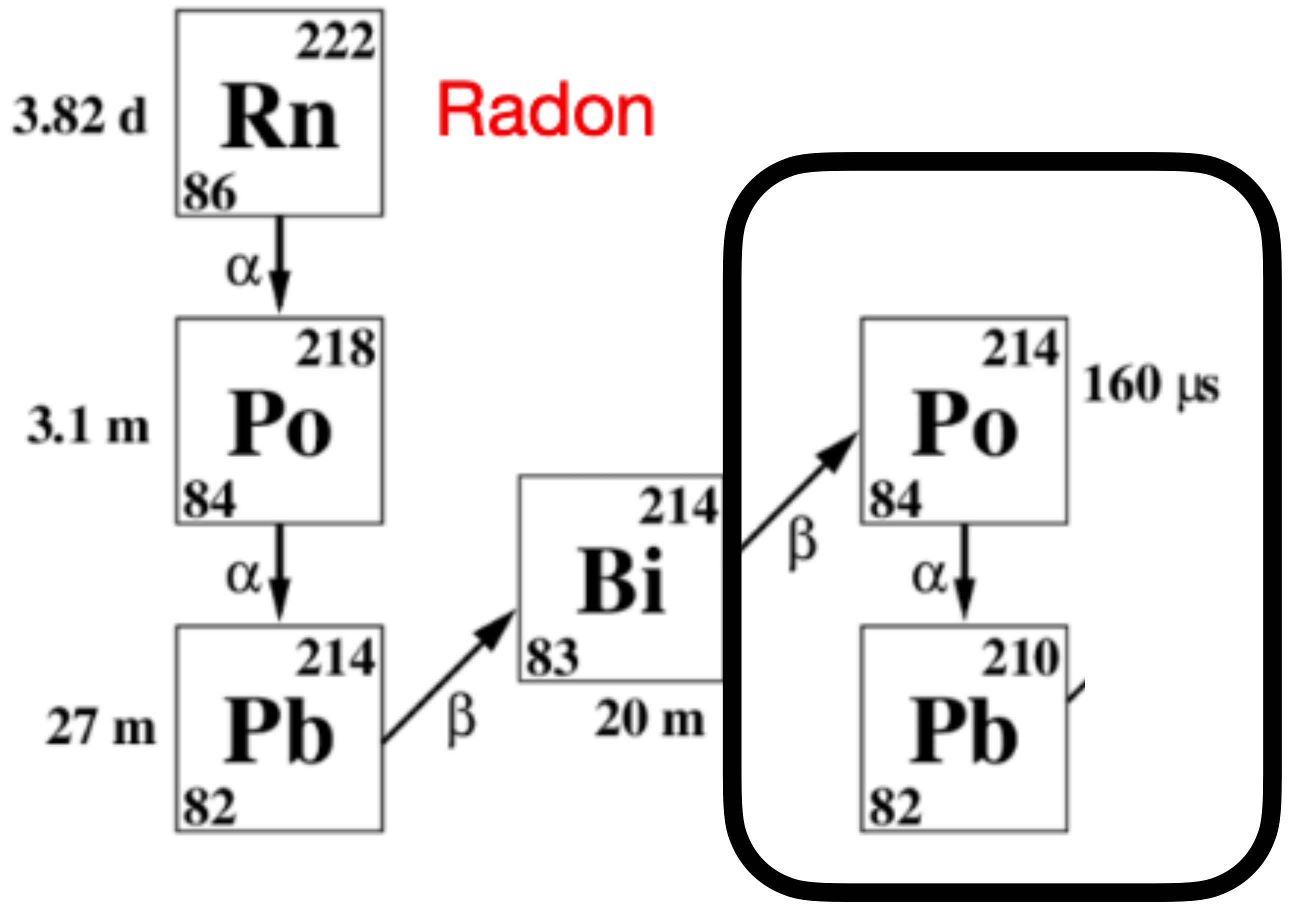
Blips are essential for astrophysical neutrino detection and classification in LArTPCs!

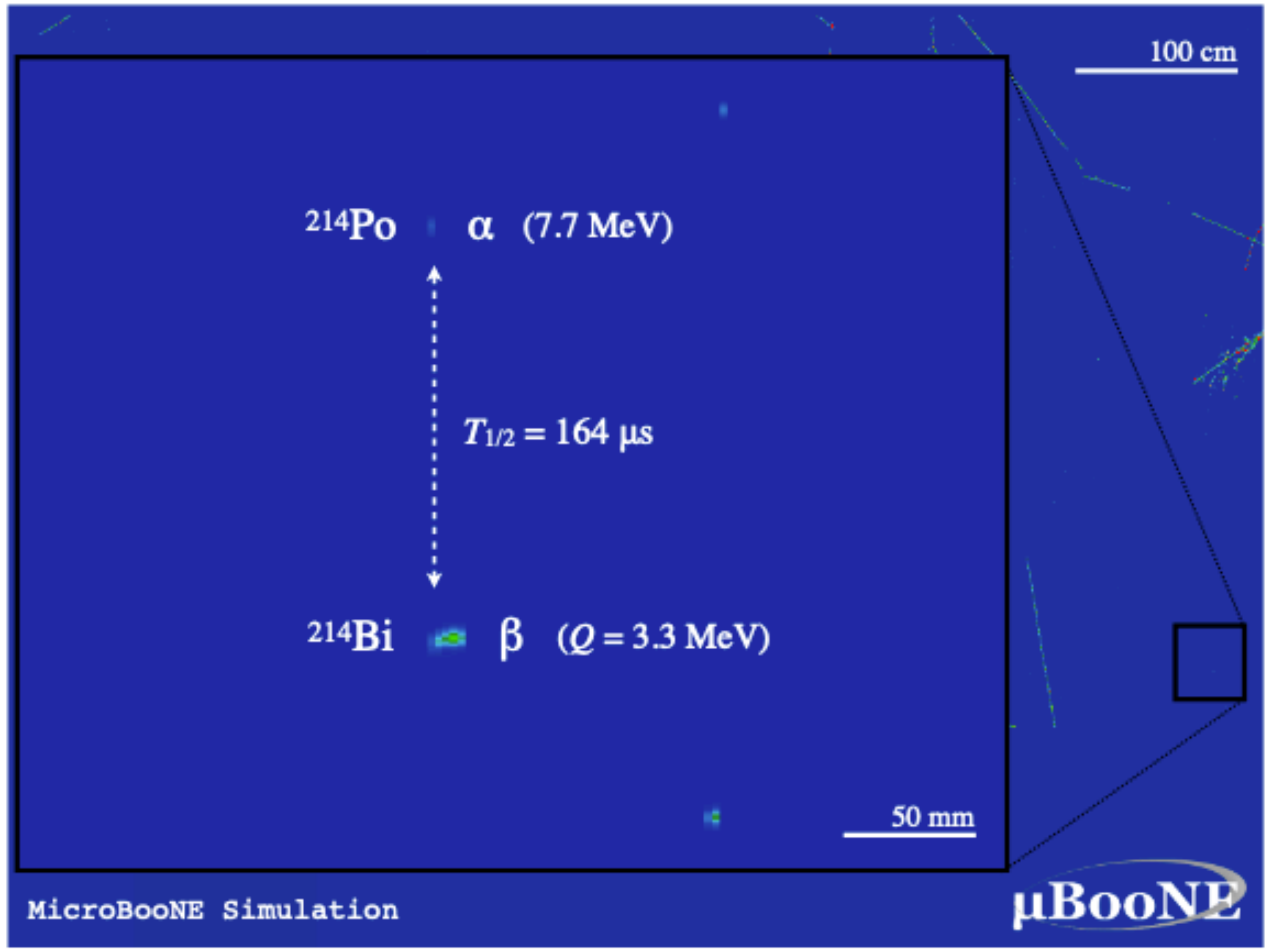
MeV-scale LArTPC Physics: Astrophysical neutrinos

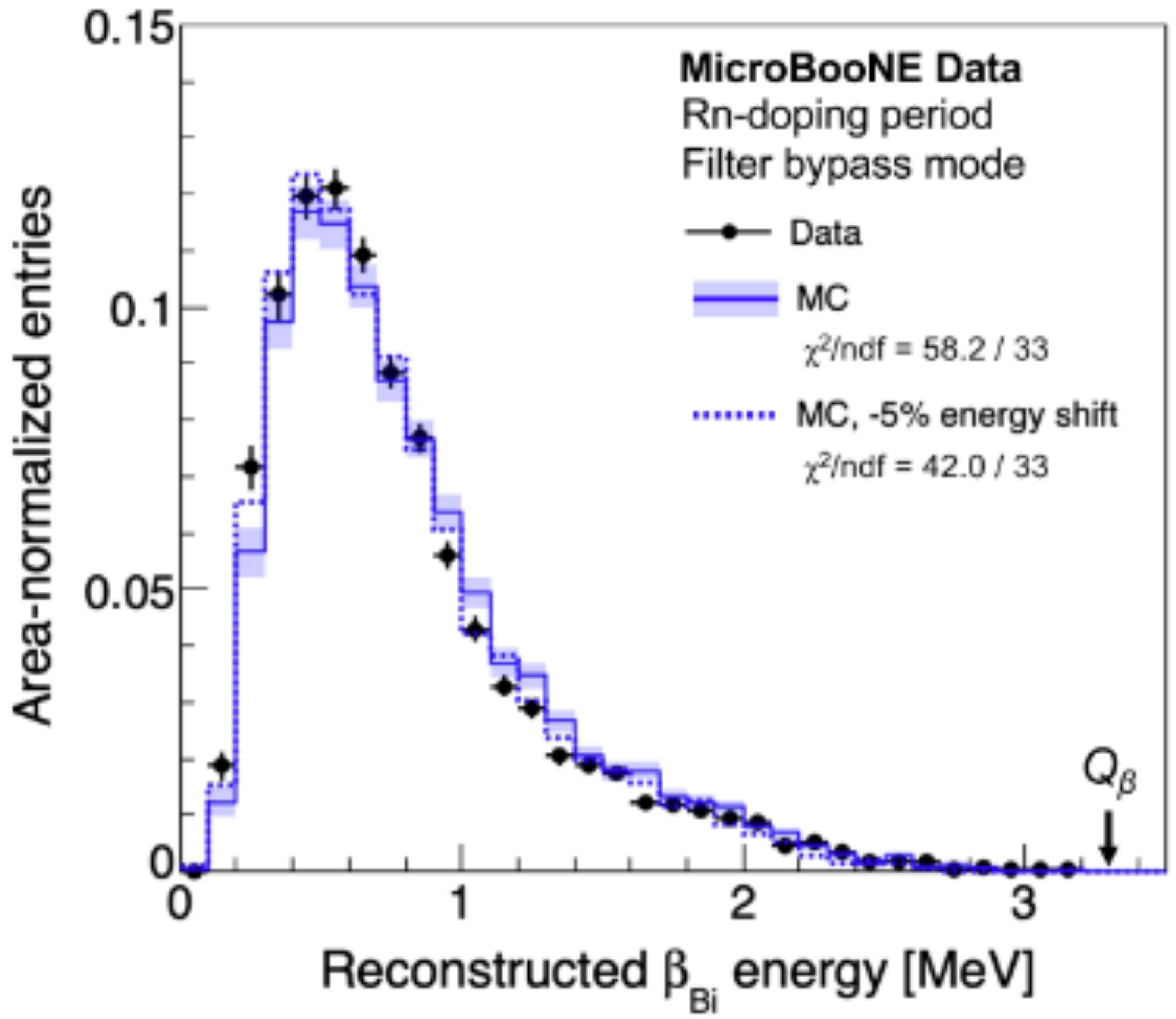
MicroBooNE is already studying backgrounds for future astrophysical neutrino measurements: radon daughters!

PHYSICAL REVIEW D **109**, 052007 (2024)

Measurement of ambient radon progeny decay rates and energy spectra in liquid argon using the MicroBooNE detector

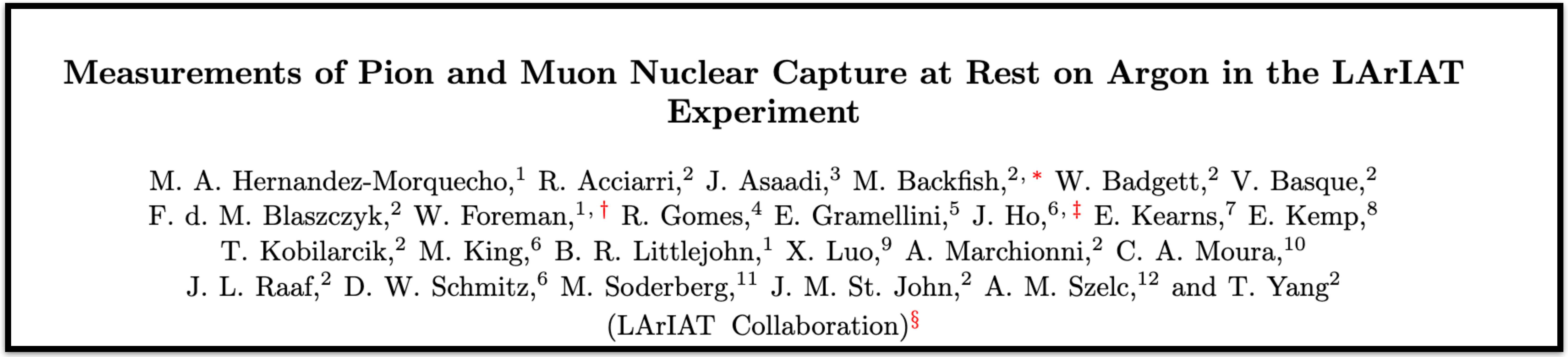






Summary

- LArIAT has shown that low-energy electrons can be detected and quantified using LArTPCs.
- Developed a brand new technique for pion/muon particle identification.
- First-ever measurement of final-state products of stopped pion/muon nuclear capture in a LArTPC.
- Data/MC differences suggest that Geant4 modeling of low-energy nuclear processes is inaccurate.
- Paper draft under review by PRL (arXiv posting: arxiv:2408.05133)



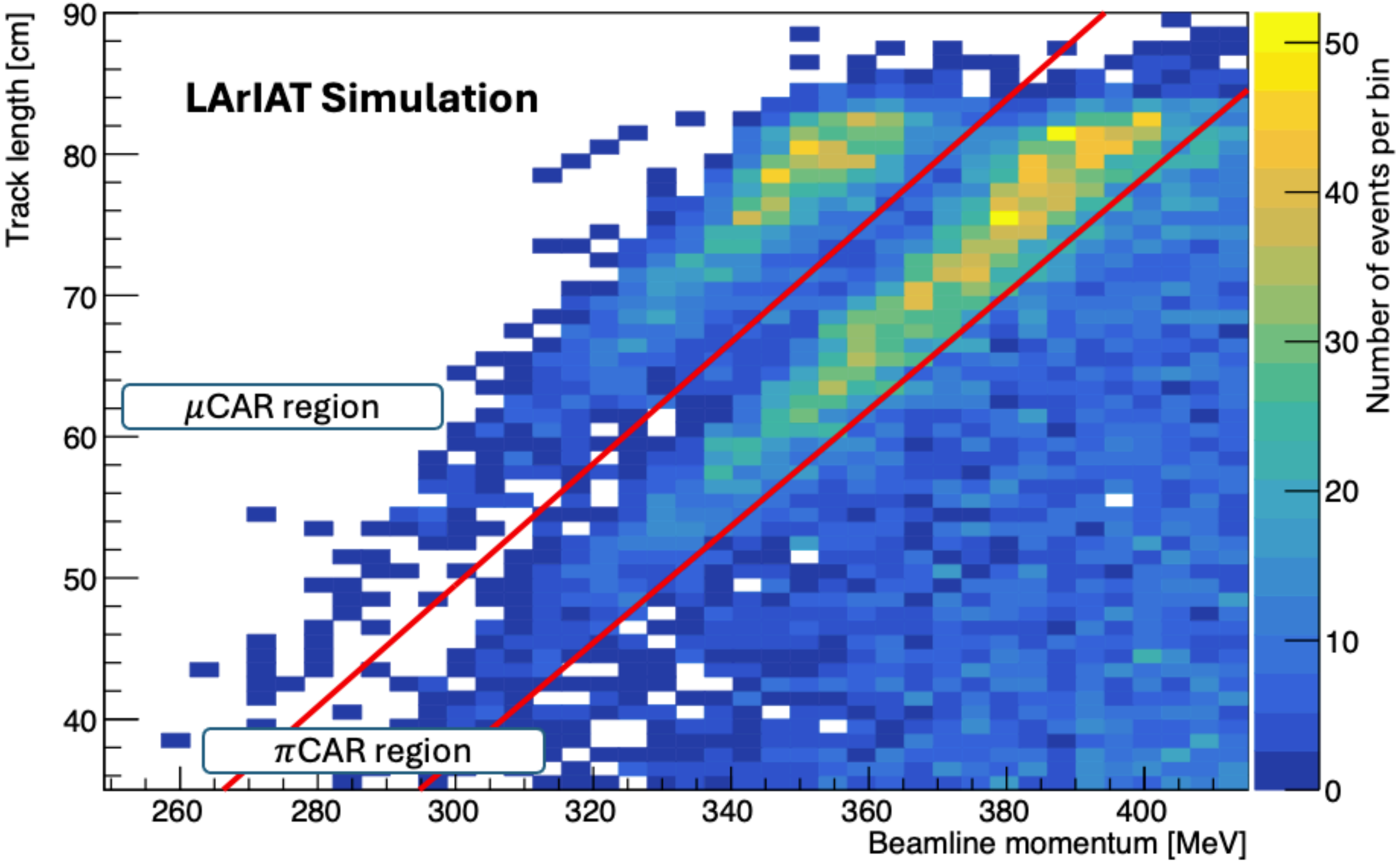
Measurements of Pion and Muon Nuclear Capture at Rest on Argon in the LArIAT Experiment

M. A. Hernandez-Morquecho,[1] R. Acciarri,[2] J. Asaadi,[3] M. Backfish,[2,*] W. Badgett,[2] V. Basque,[2]
F. d. M. Blaszczyk,[2] W. Foreman,[1,†] R. Gomes,[4] E. Gramellini,[5] J. Ho,[6,‡] E. Kearns,[7] E. Kemp,[8]
T. Kobilarcik,[2] M. King,[6] B. R. Littlejohn,[1] X. Luo,[9] A. Marchionni,[2] C. A. Moura,[10]
J. L. Raaf,[2] D. W. Schmitz,[6] M. Soderberg,[11] J. M. St. John,[2] A. M. Szelc,[12] and T. Yang[2]
(LArIAT Collaboration)[§]

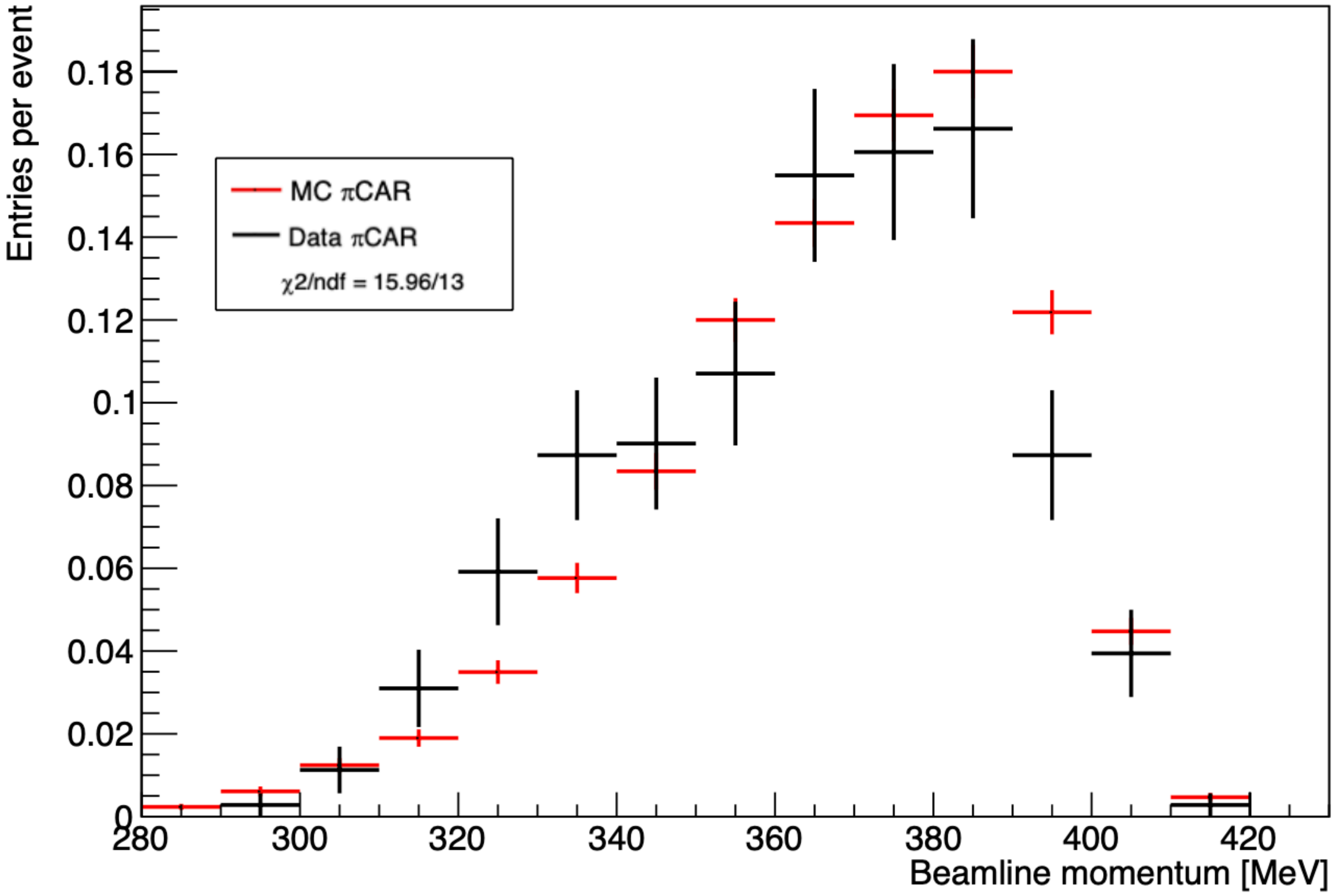
Thanks

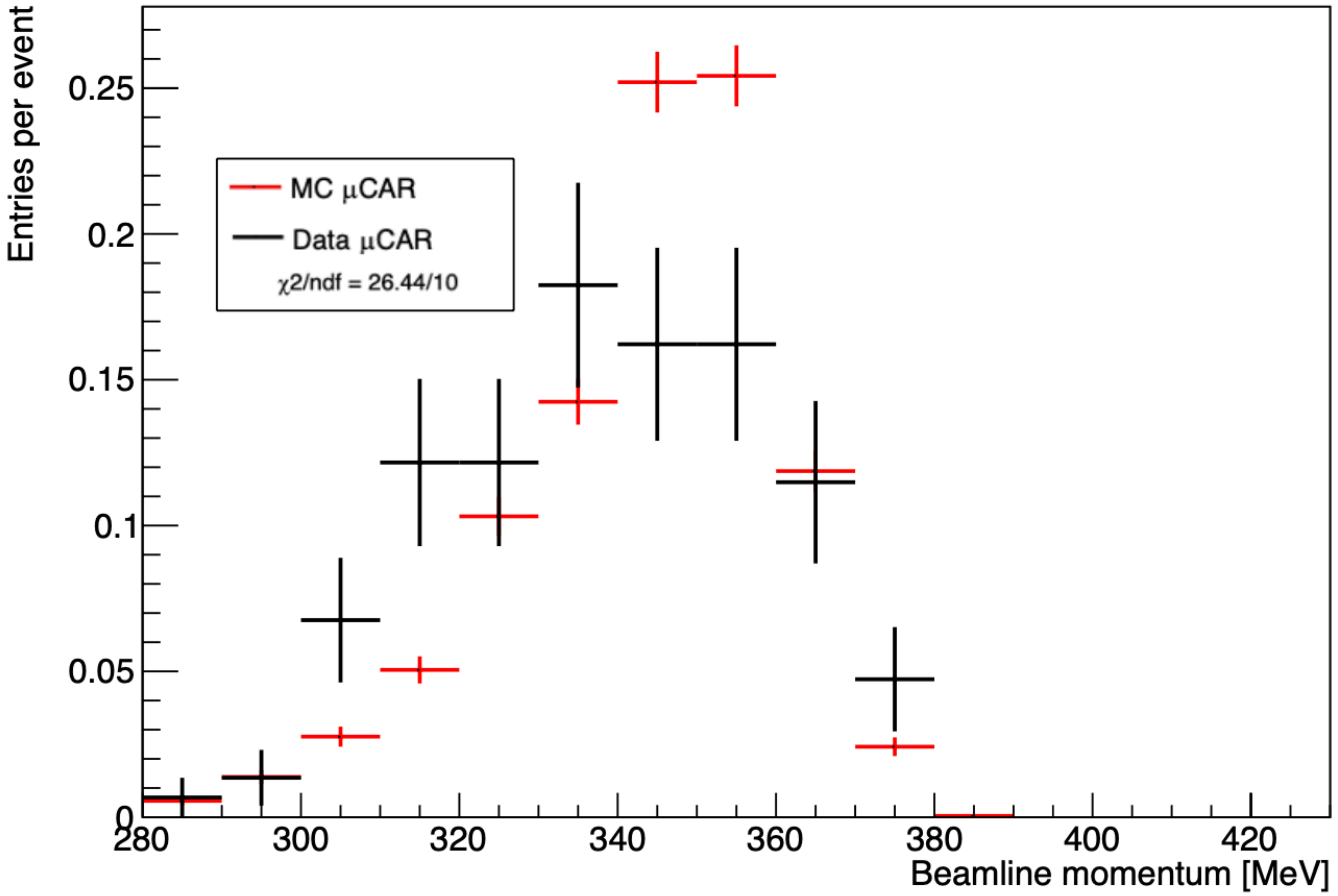
Backup

Muon and Pion CAR selection



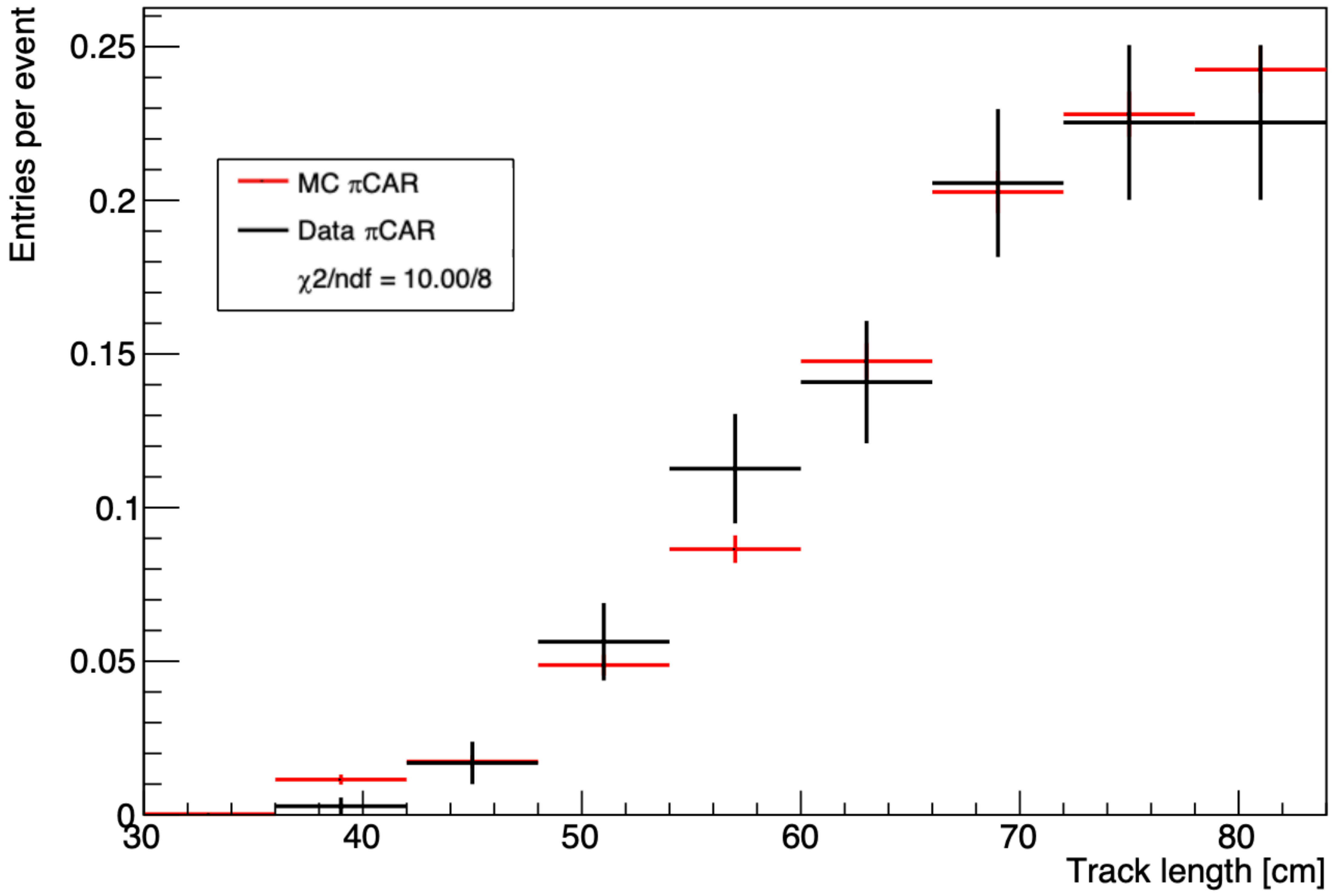
Data-MC comparisson

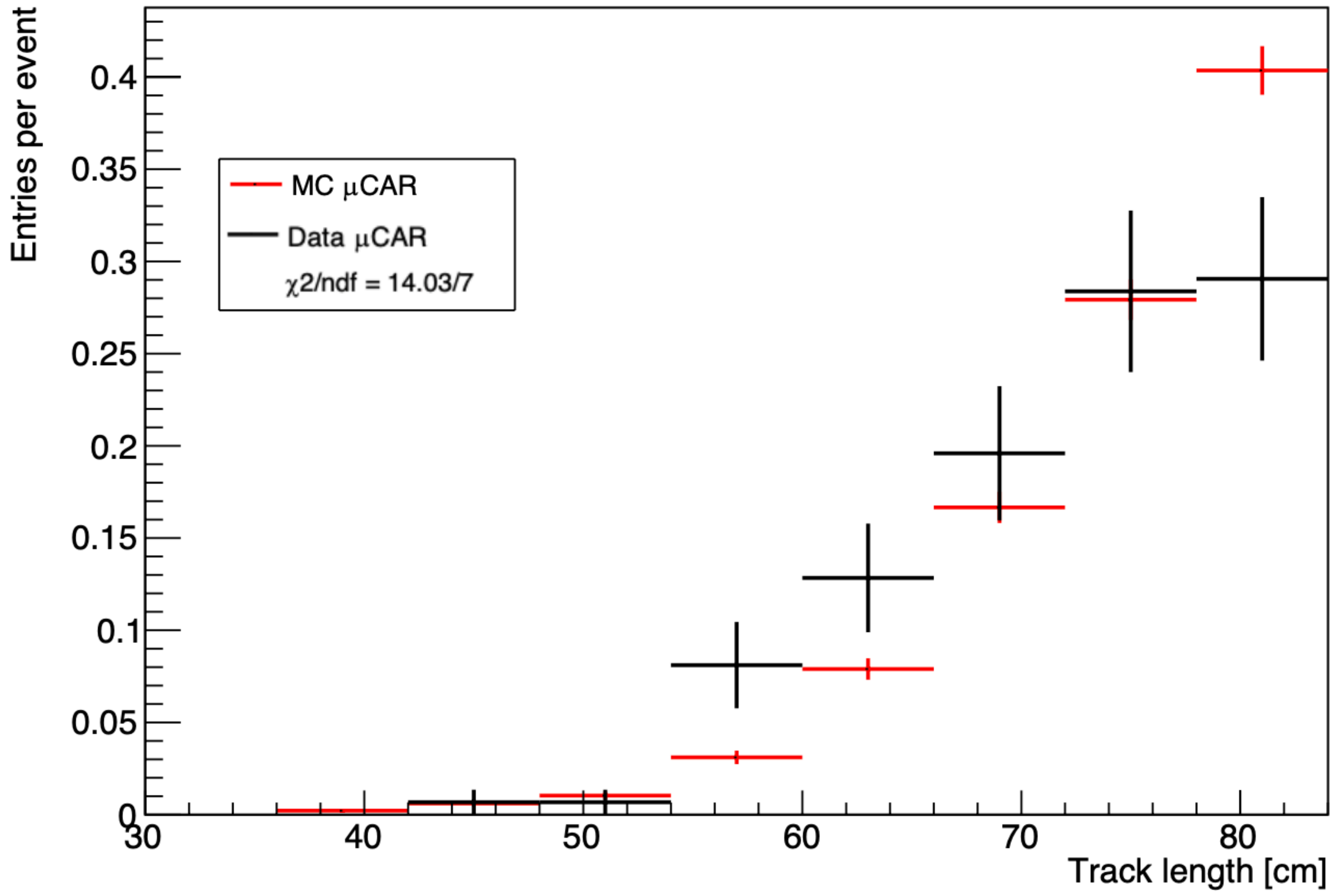




Beam momentum (pion on the left and muon on the right).

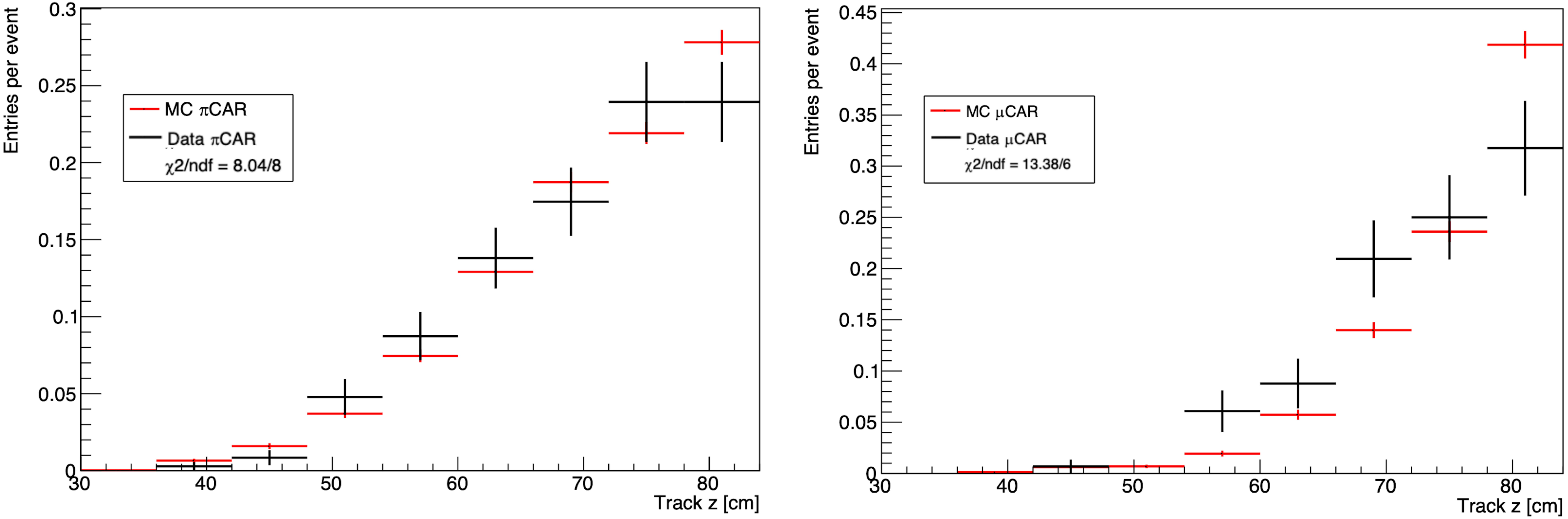
Data-MC comparisson





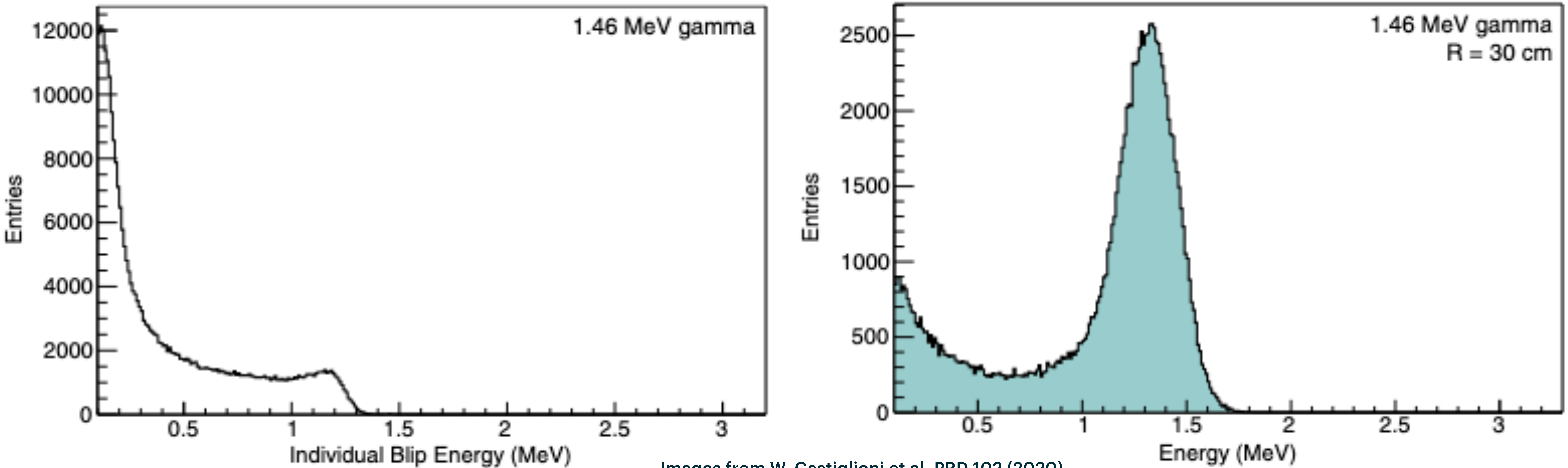
Track length (pion on the left and muon on the right).

Data-MC comparisson



Track Z (pion on the left and muon on the right).

Muon and Pion Captured At Rest (CAR)



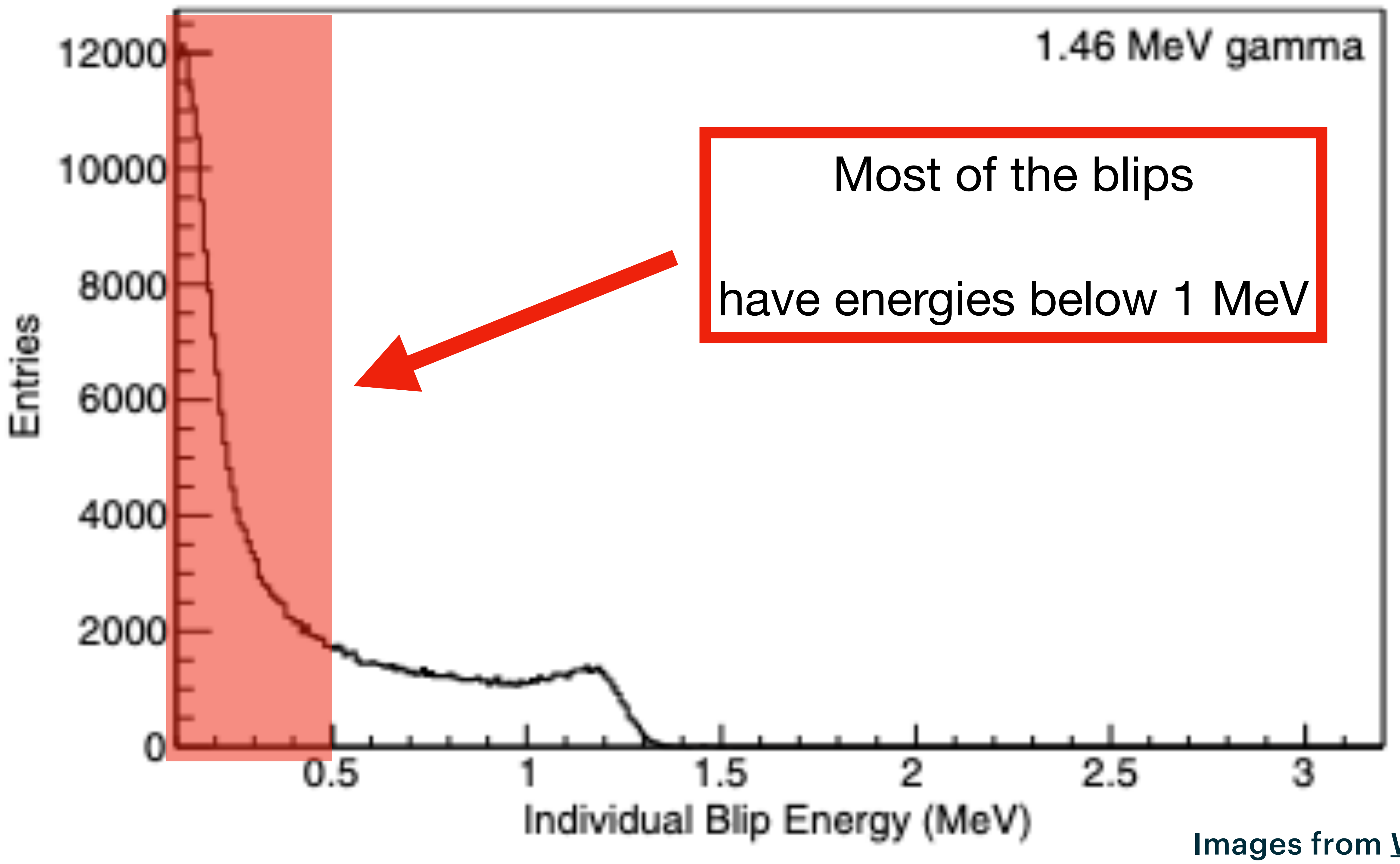
Images from W. Castiglioni et al, PRD 102 (2020)

For this generic LAr simulation, individual blip energy is on the left, and total blip energy is on the right. Gammas from neutron scattering on argon around 1.46 MeV.

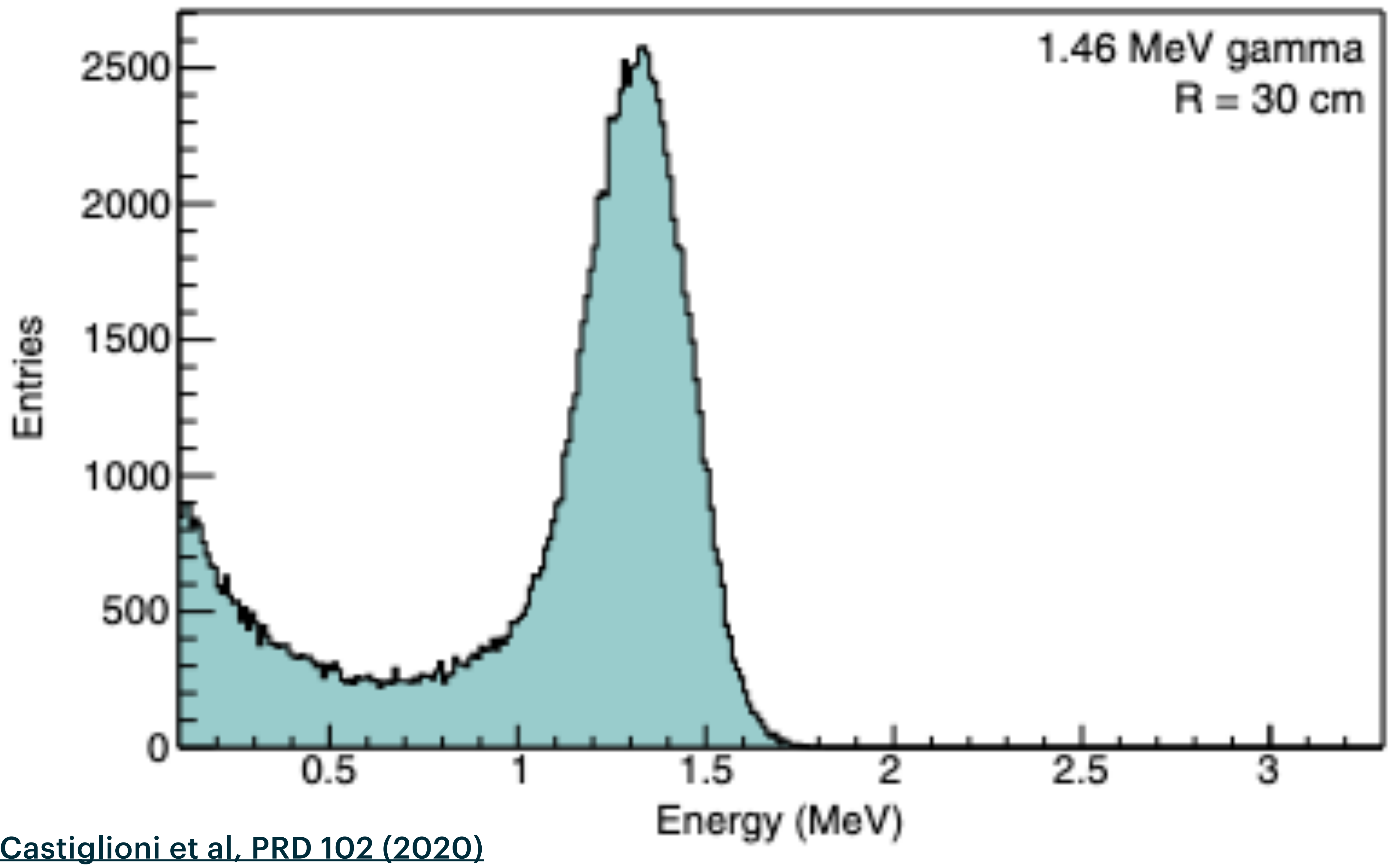
ILLINOIS INSTITUTE OF TECHNOLOGY

LArIAT

Muon and Pion Captured At Rest (CAR)



Most of the blips have energies below 1 MeV



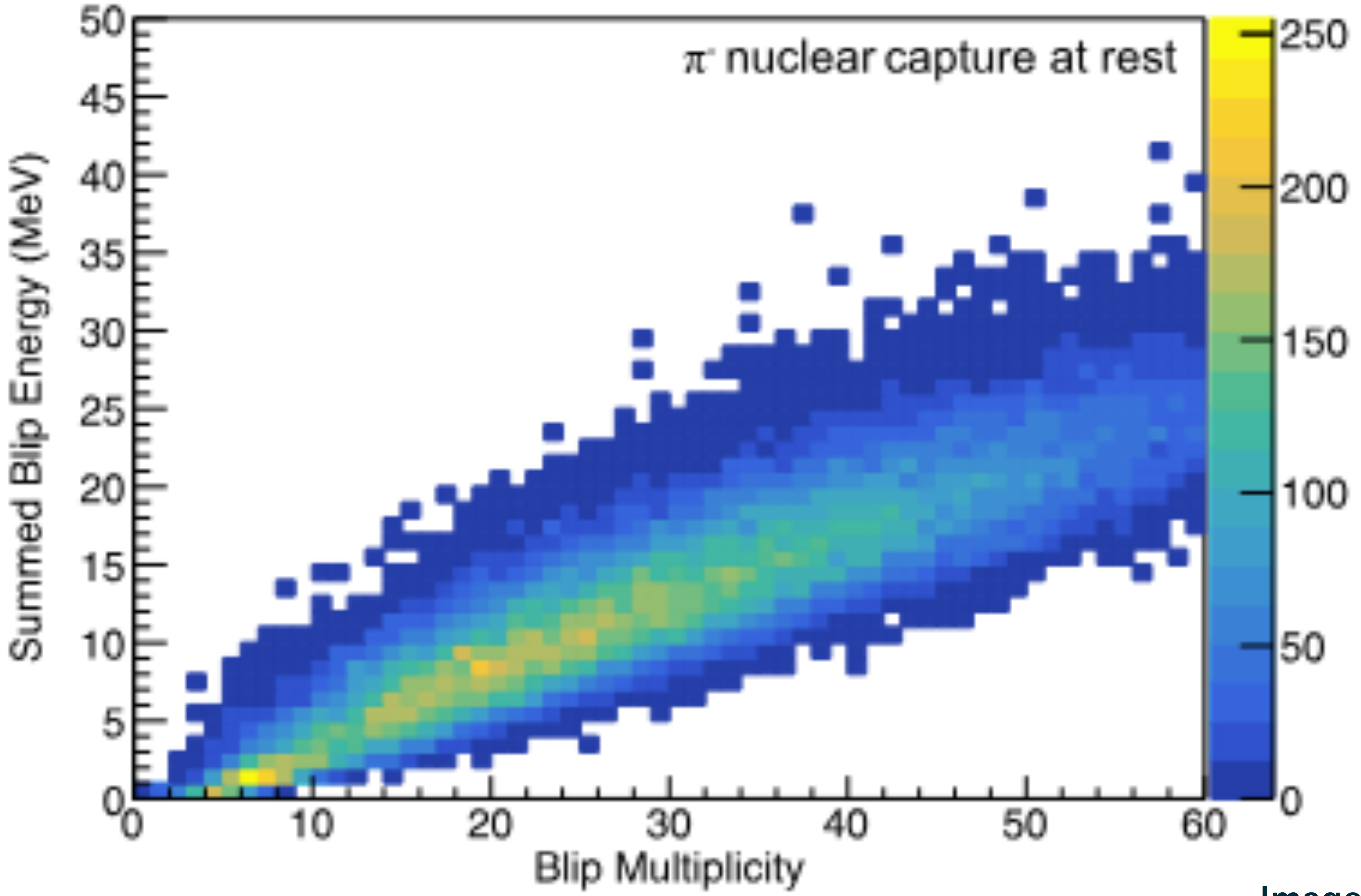
Images from W. Castiglioni et al, PRD 102 (2020)

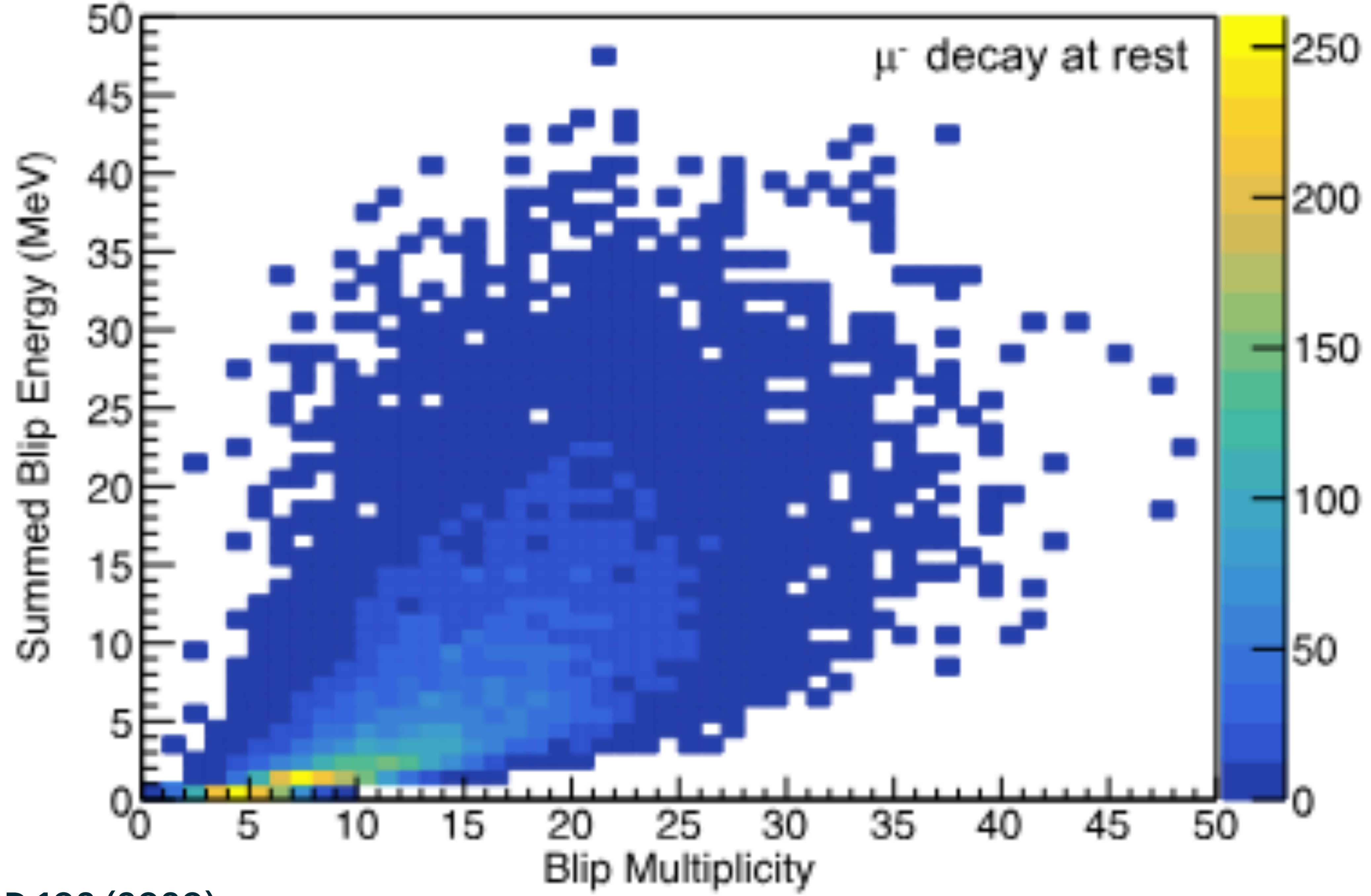
For this generic LAr simulation, individual blip energy is on the left, and total blip energy is on the right. Gammas from neutron scattering on argon around 1.46 MeV.

Blips used for charge identification

μ^+ and π^+ can not be captured at rest.

For positive charge polarity, π^+ will decay in a low energetic μ^+ that will subsequently decay to a Michel electron. A μ^- decay at rest will show a similar blip activity for positive charge particles.





Images from W. Castiglioni et al, PRD 102 (2020)

Particle and charge identification using low-energy activity.

Energy reconstruction

To make energy reconstruction from charge,

$E = (Q \times R^{-1}) \times W_{ion}$

Where

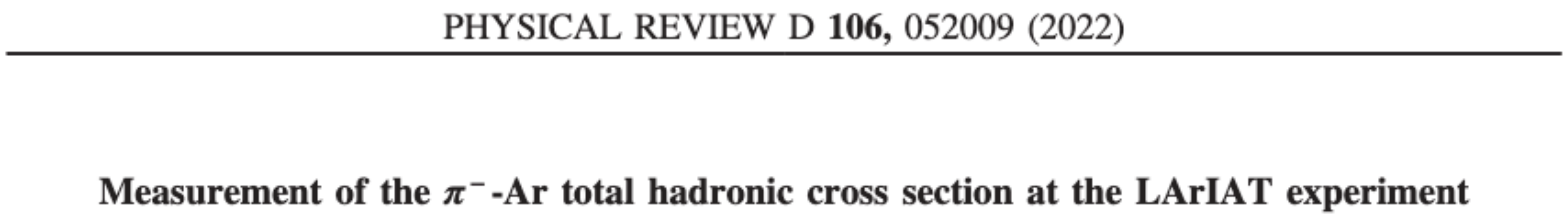
$Q = C^{cal}_{e^-} \times \sum_{i}^{N} [q_i^{ADC} \times e^{t_i/\tau_e}]$ the Q containing N reconstructed wire hits, and q_i^{ADC} is the integrated charge of each individual hit in ADC counts and $C^{cal}_{e^-}$ is the ADC to electron calibration constant.

$R = N_e/N_i$ is the average recombination factor.

W_{ion} is the ionization work function.

Phys. Rev. D 101, 012010

LArIAT cool results



PHYSICAL REVIEW D **106,** 052009 (2022)

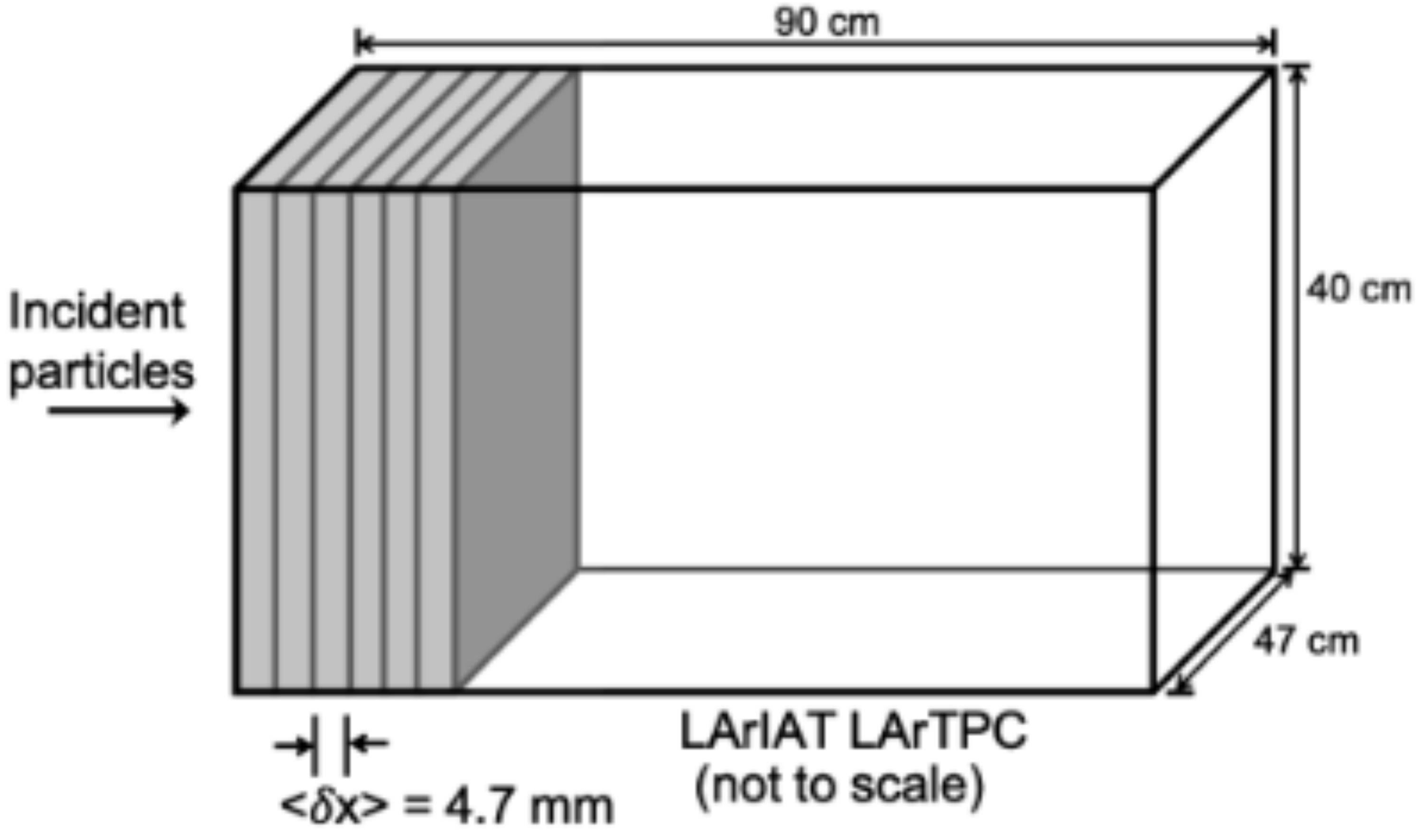
Measurement of the π^--Ar total hadronic cross section at the LArIAT experiment

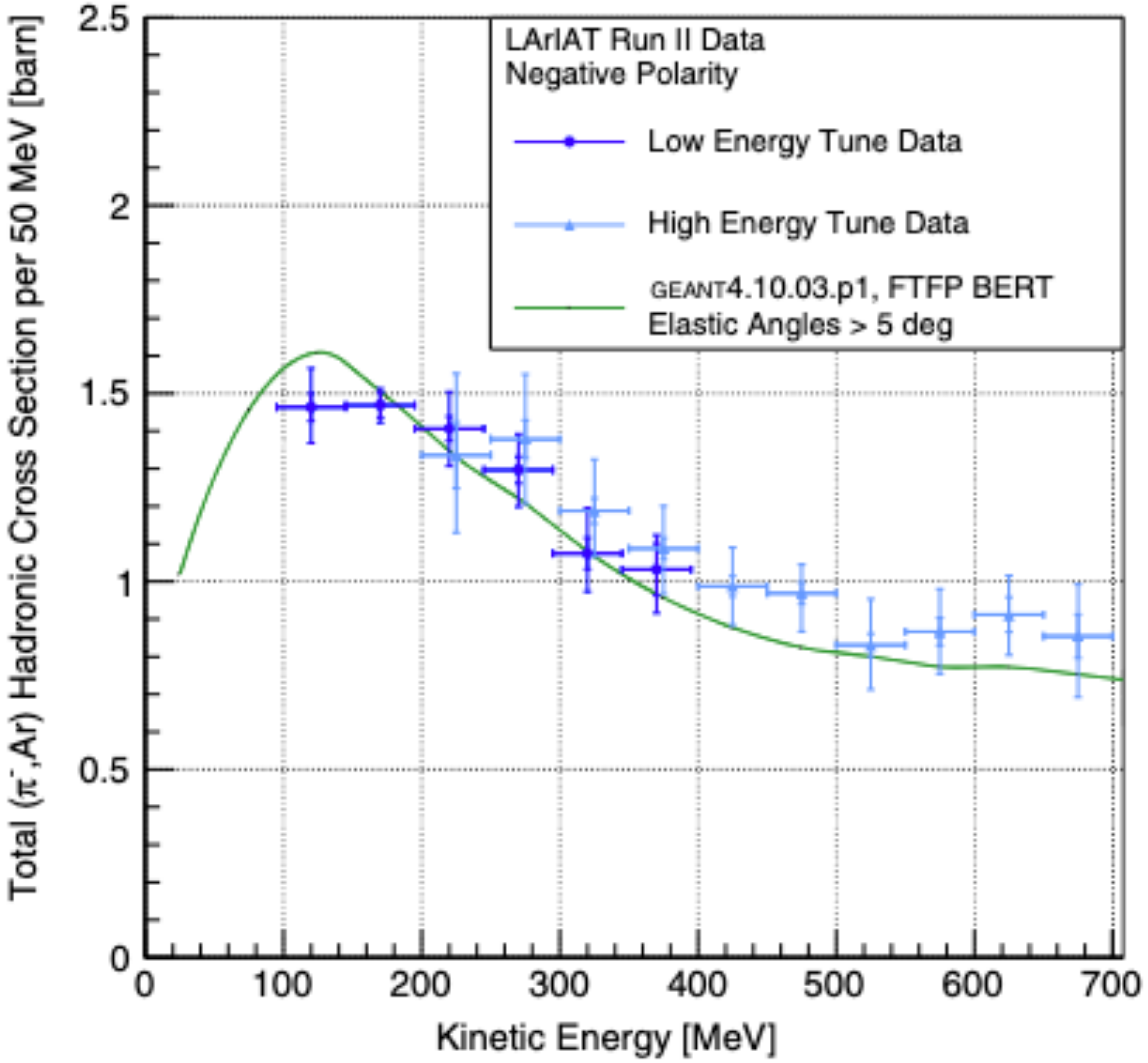
First measurement of the negative pion total hadronic cross section on argon

Thin slice method

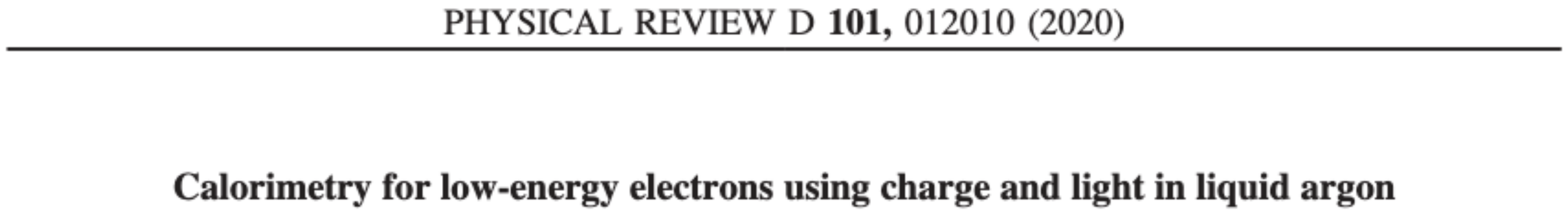
Inelastic scattering
Charge exchange
Absorption
Pion production

Phys Rev. D 106, 052009
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.106.052009





LArIAT cool results


PHYSICAL REVIEW D **101,** 012010 (2020)

Calorimetry for low-energy electrons using charge and light in liquid argon

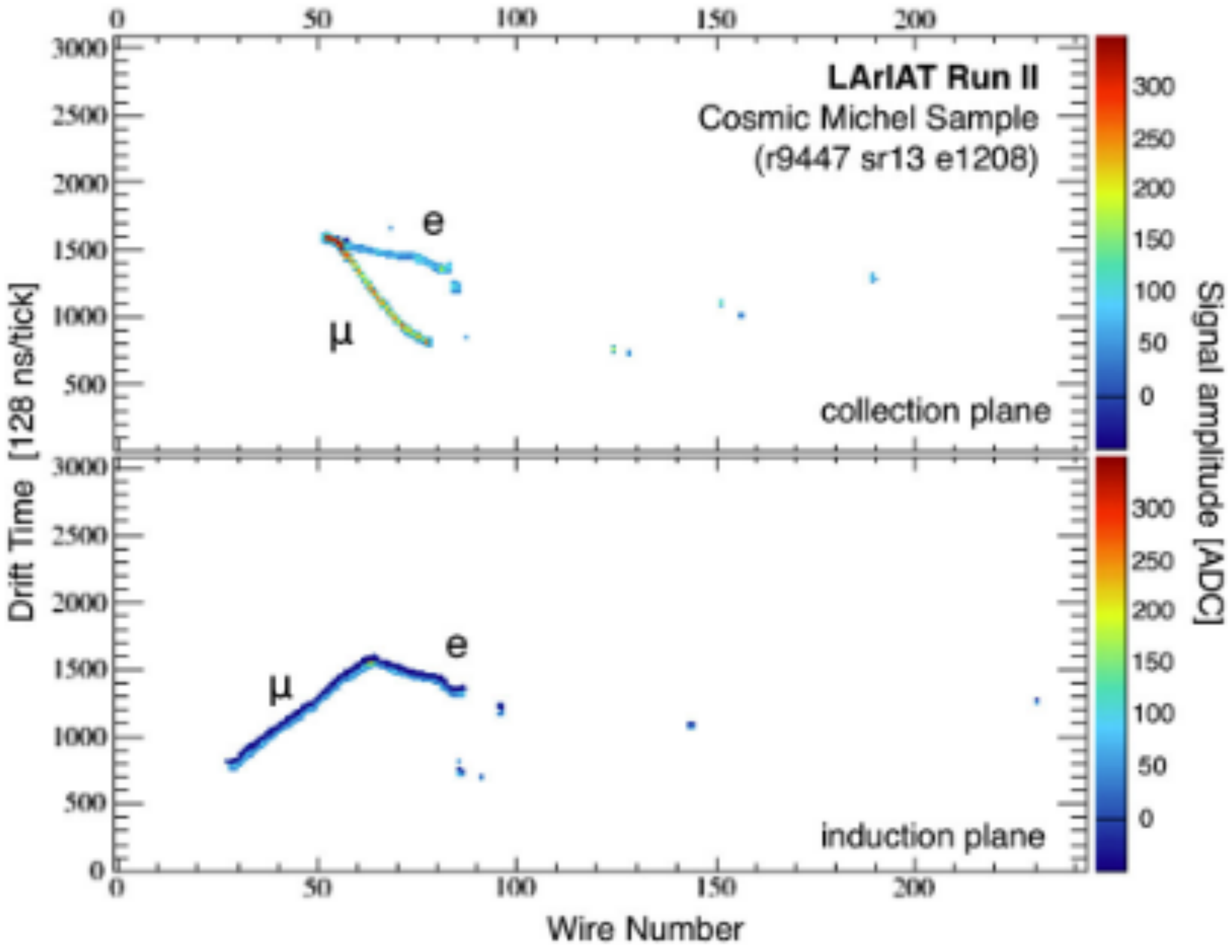
Michel electron measurements using charge and light

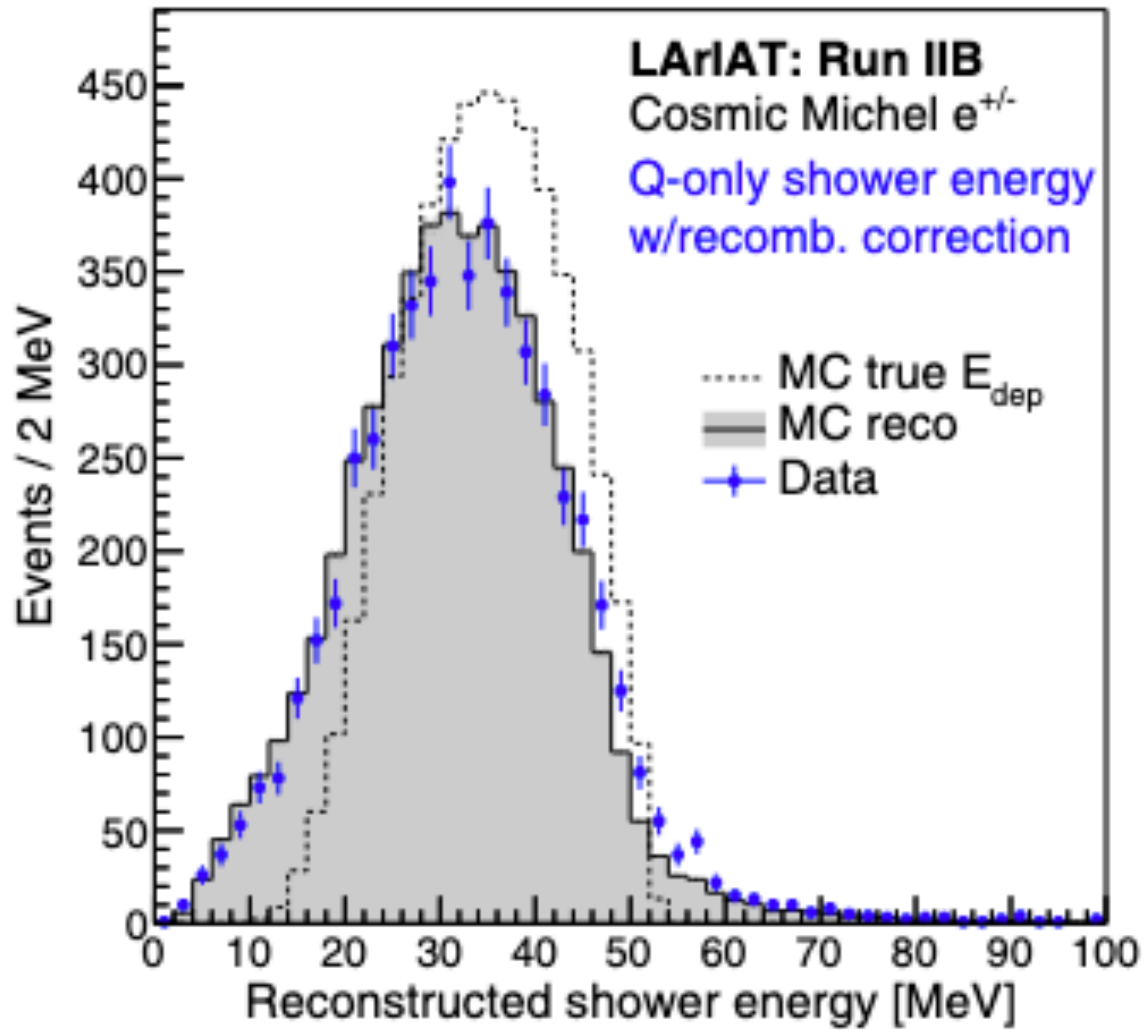
Scintillation light is used to trigger the readout of cosmic muons that stop and decay to Michel electrons.

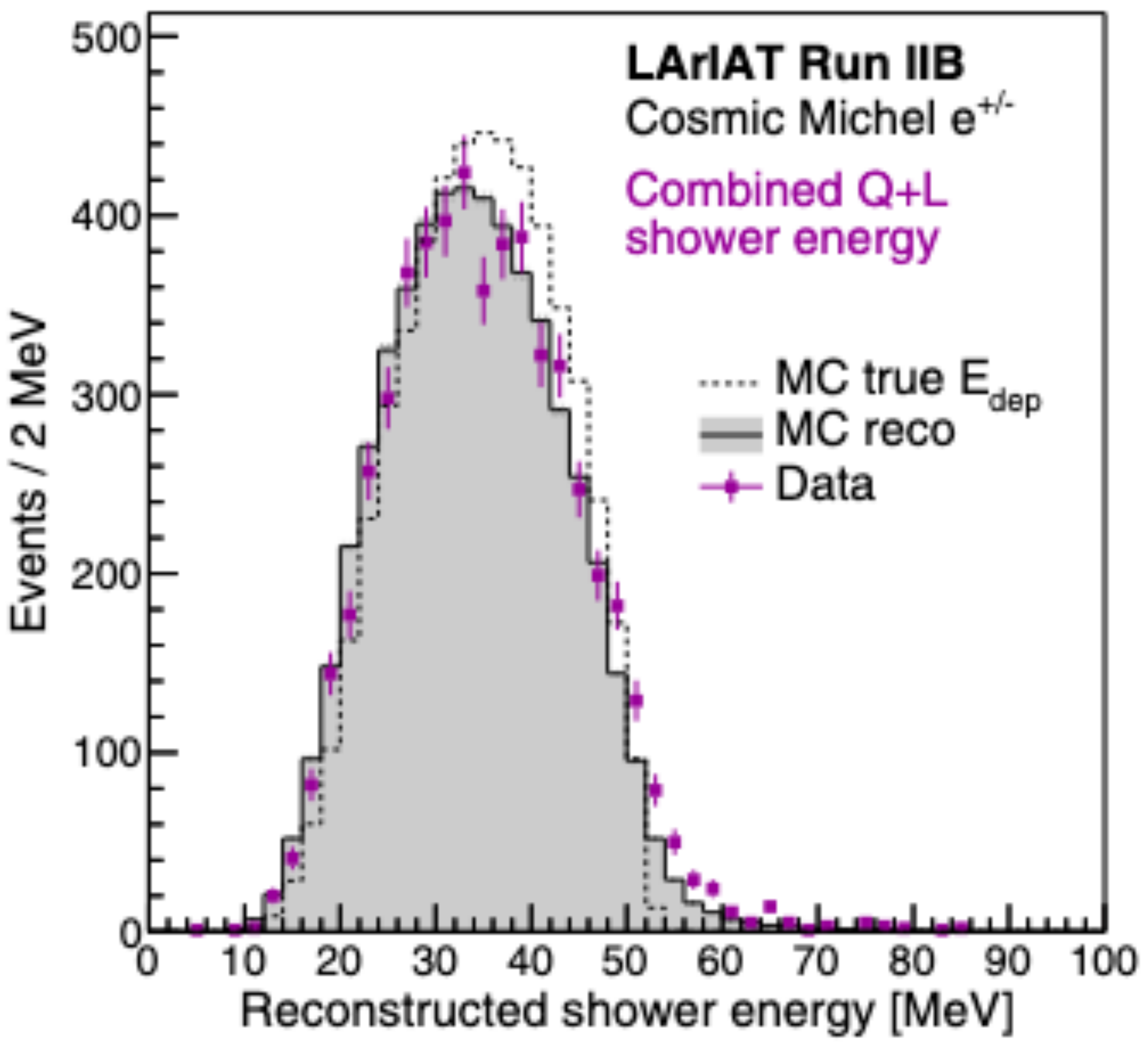
Precise calorimetry reconstruction of 5-50MeV electrons in LArTPCs.

Energy range similar to supernovae neutrinos.

Phys. Rev. D 101, 012010
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.012010

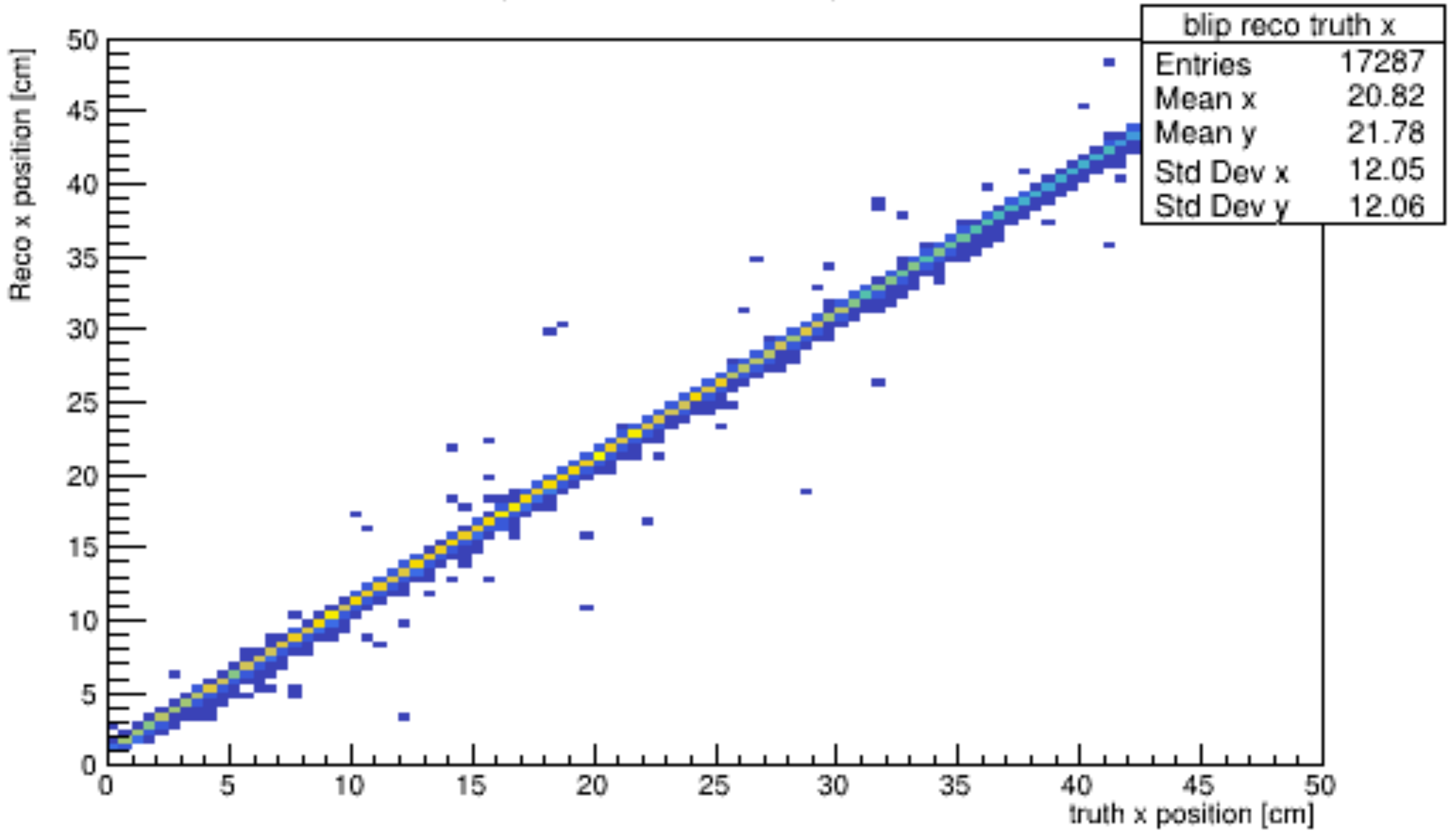




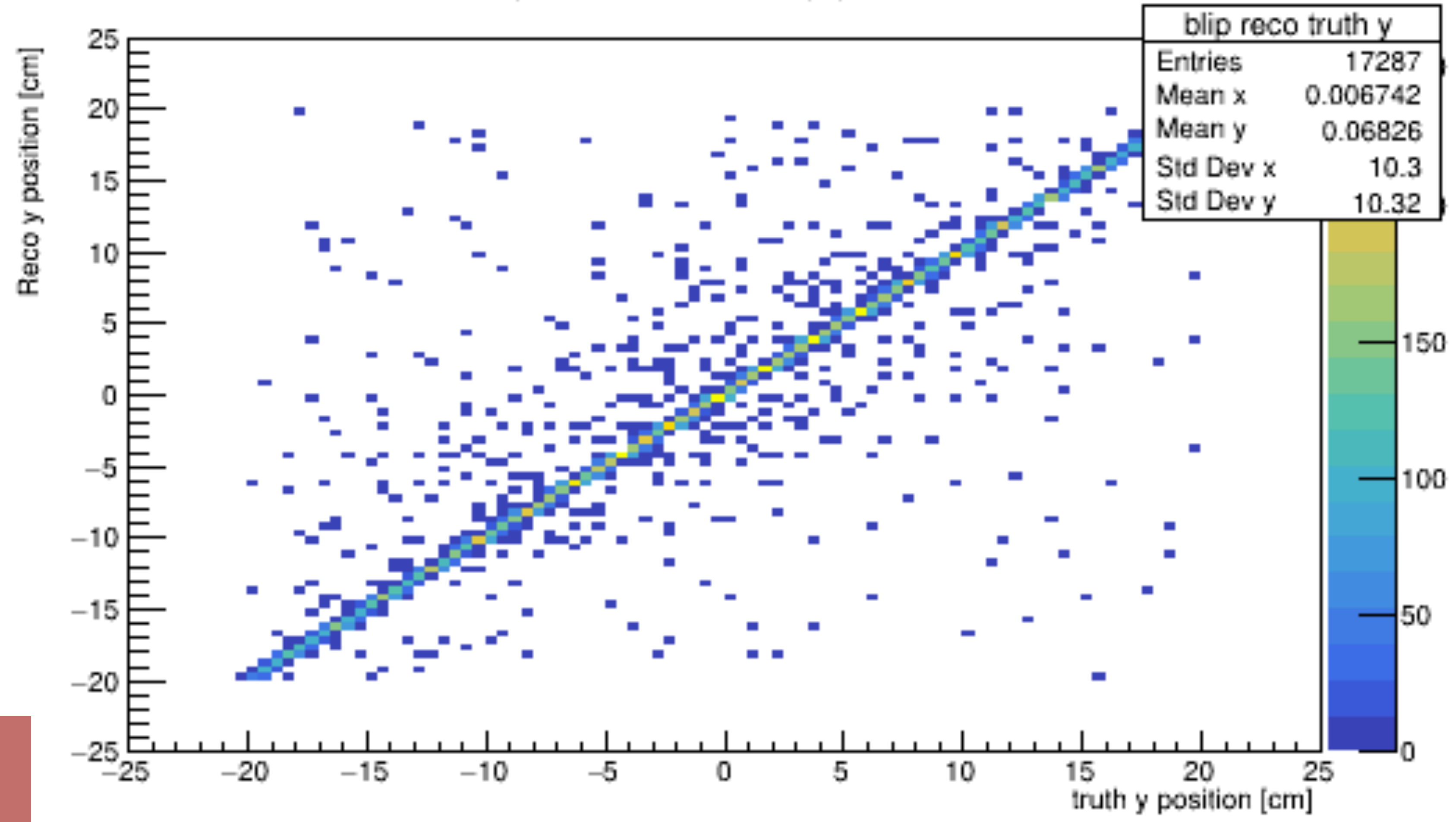


Blip performance

Blip Reco vs truth x position

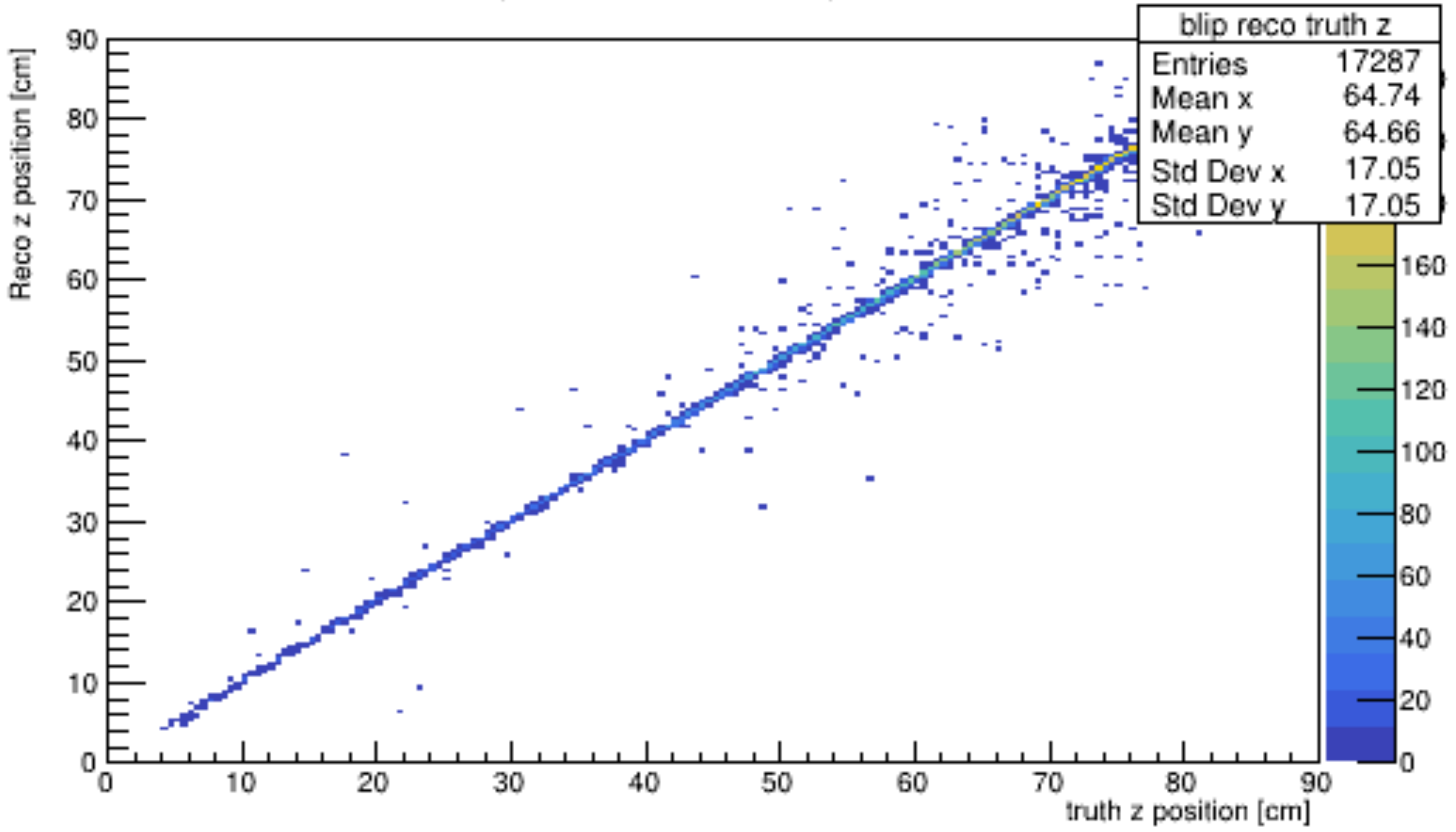


Blip Reco vs truth y position

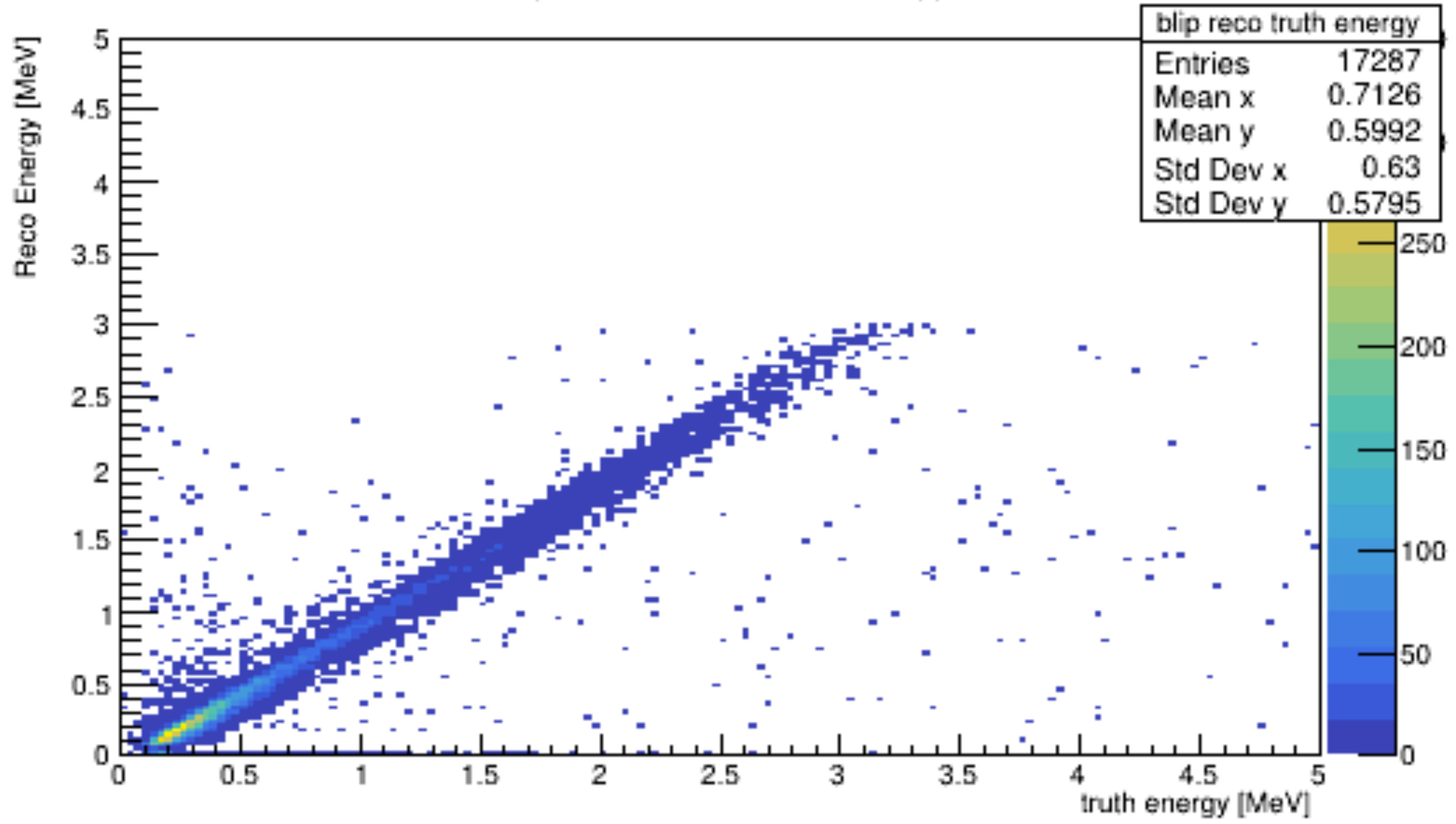


Plots from Pion CAR MC sample.

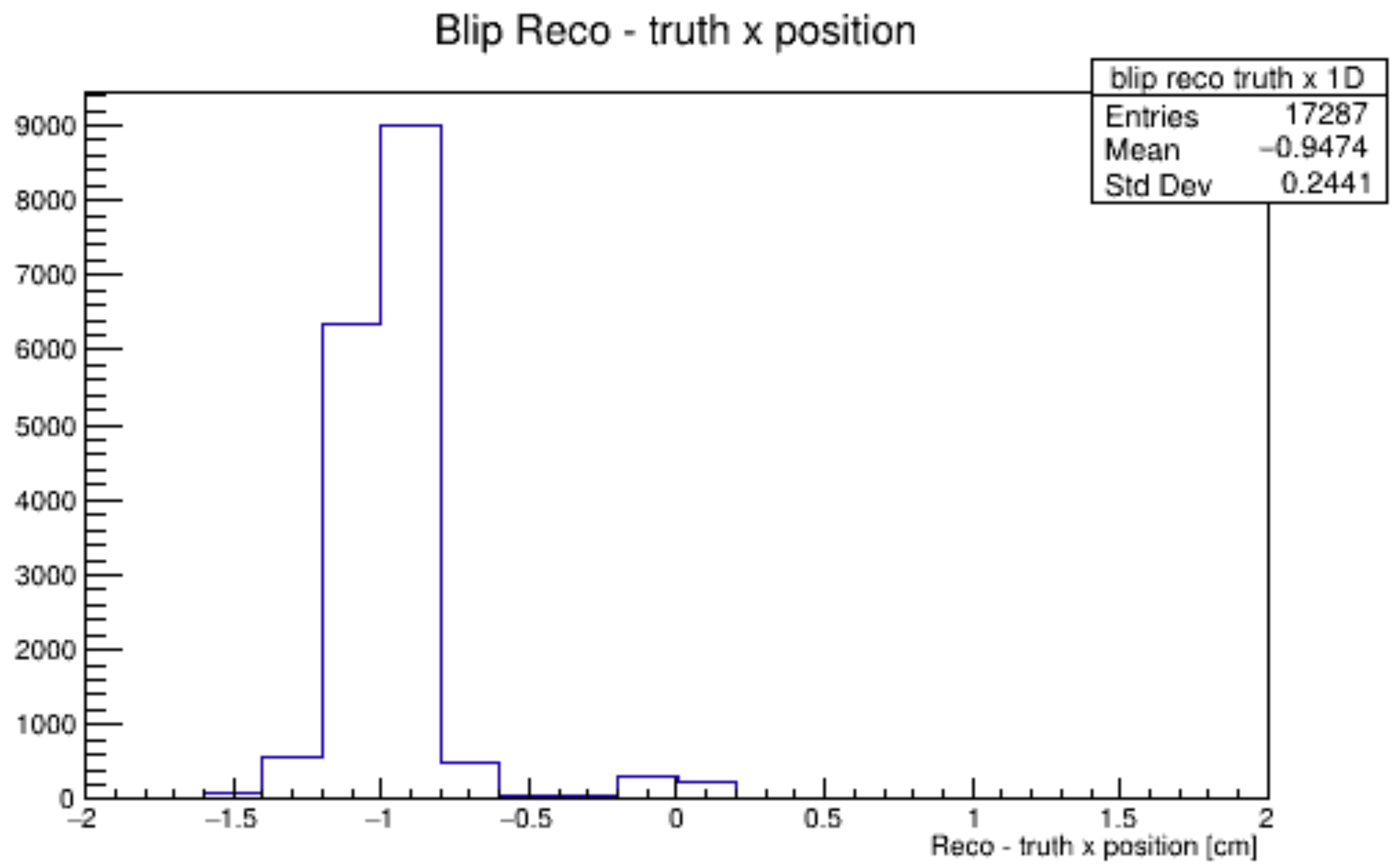
Blip Reco vs truth z position

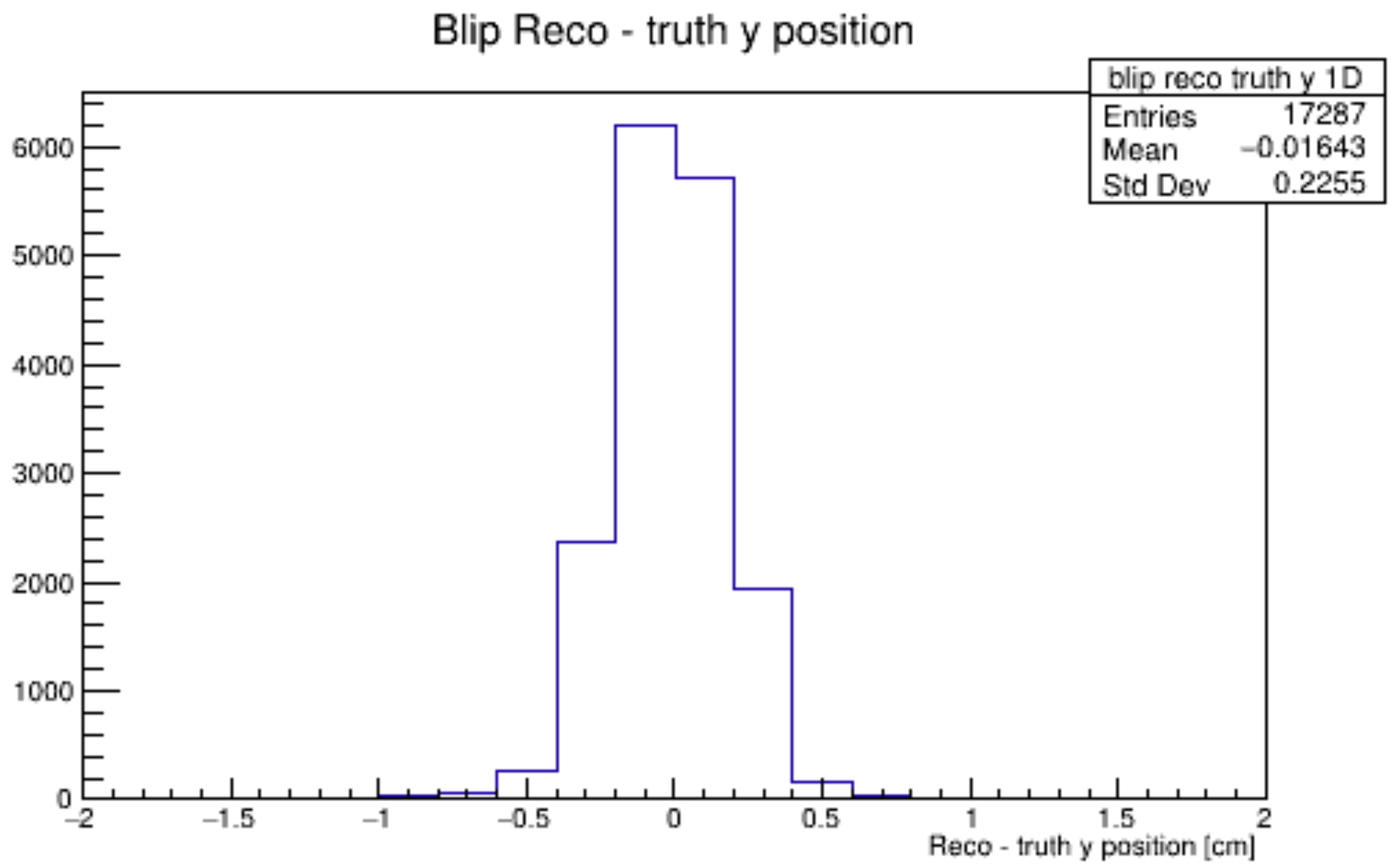


Blip Reco vs truth energy

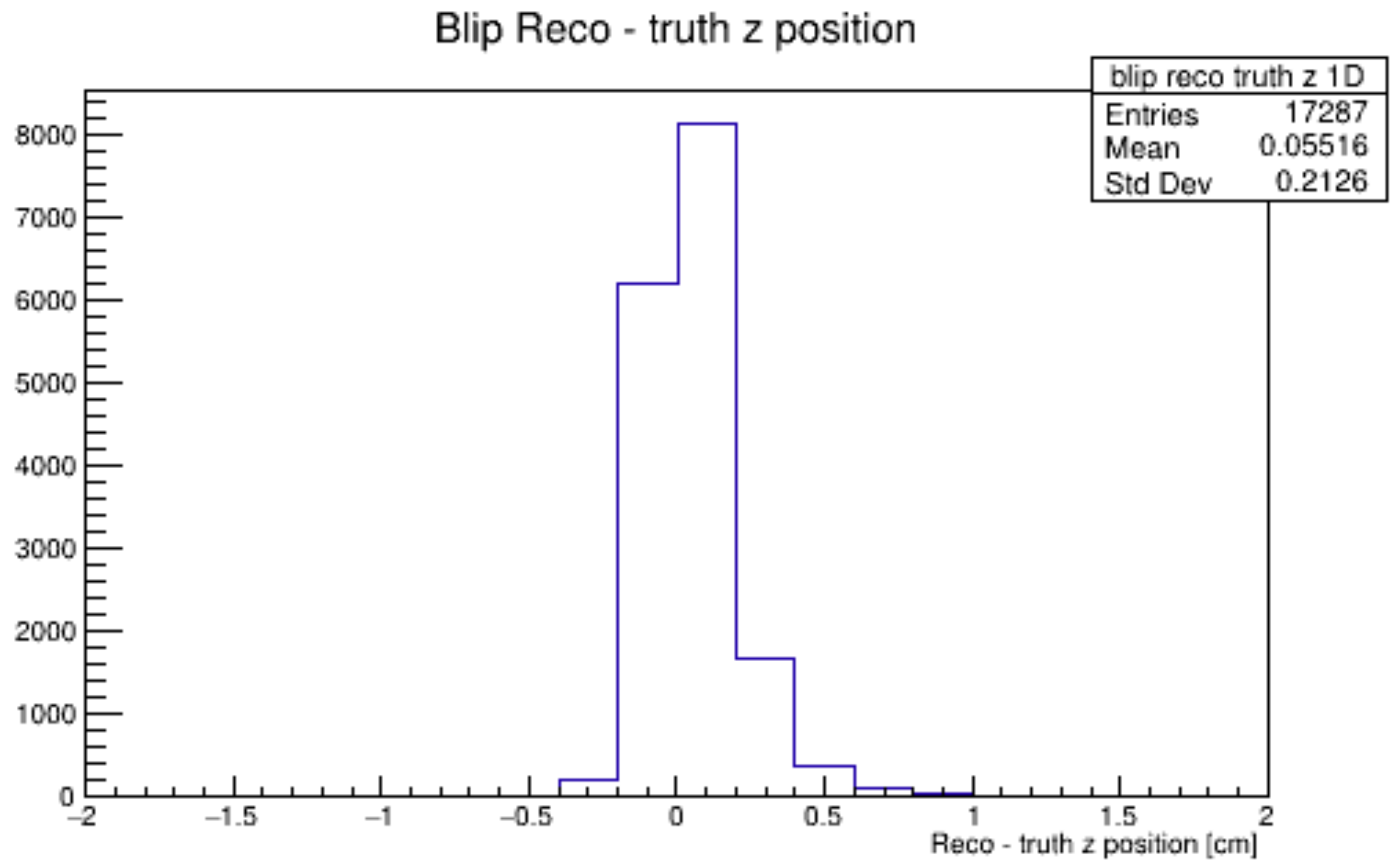


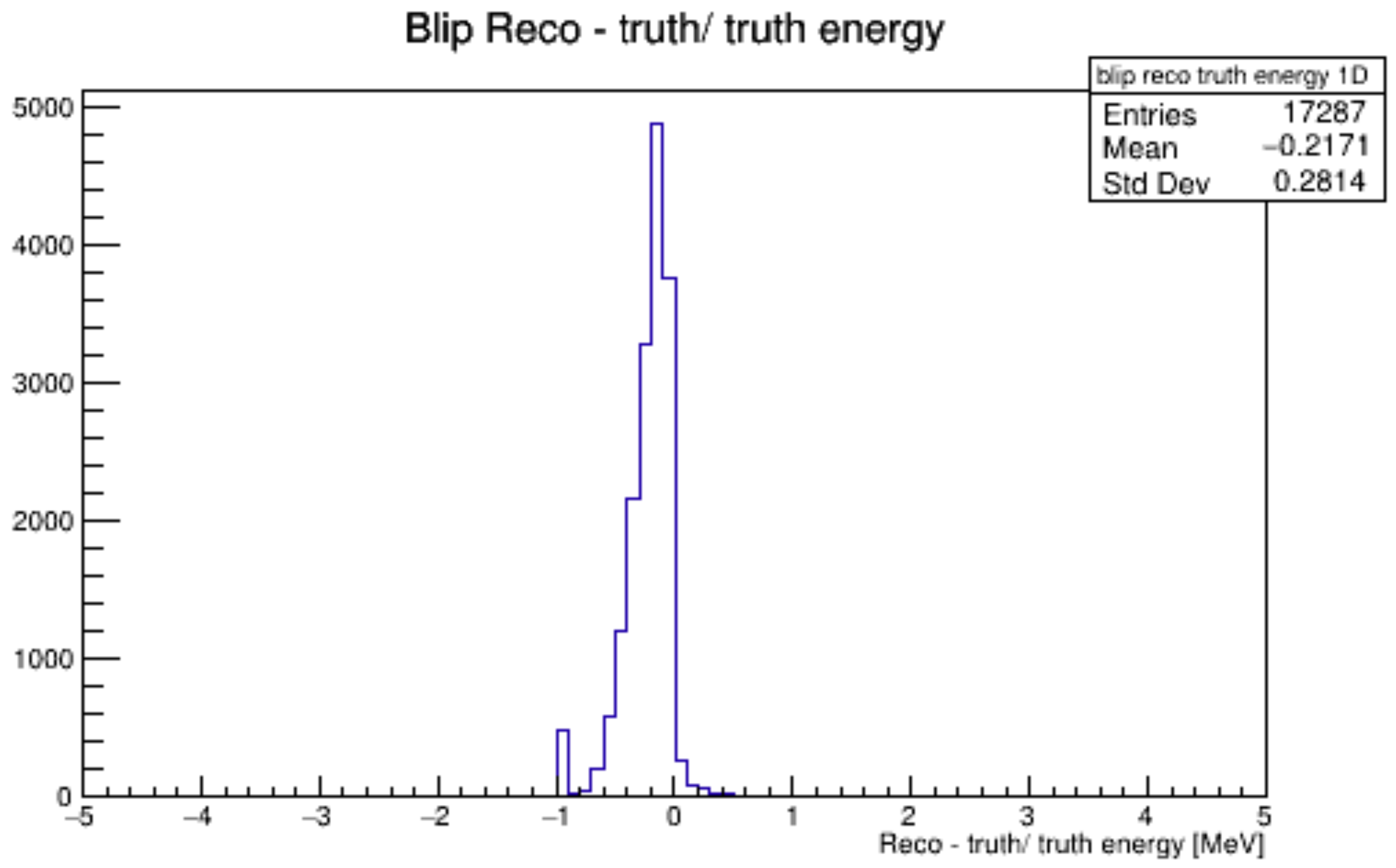
Blip performance


Blip Reco - truth x position


Blip Reco - truth y position

Plots from Pion CAR MC sample.


Blip Reco - truth z position


Blip Reco - truth/ truth energy