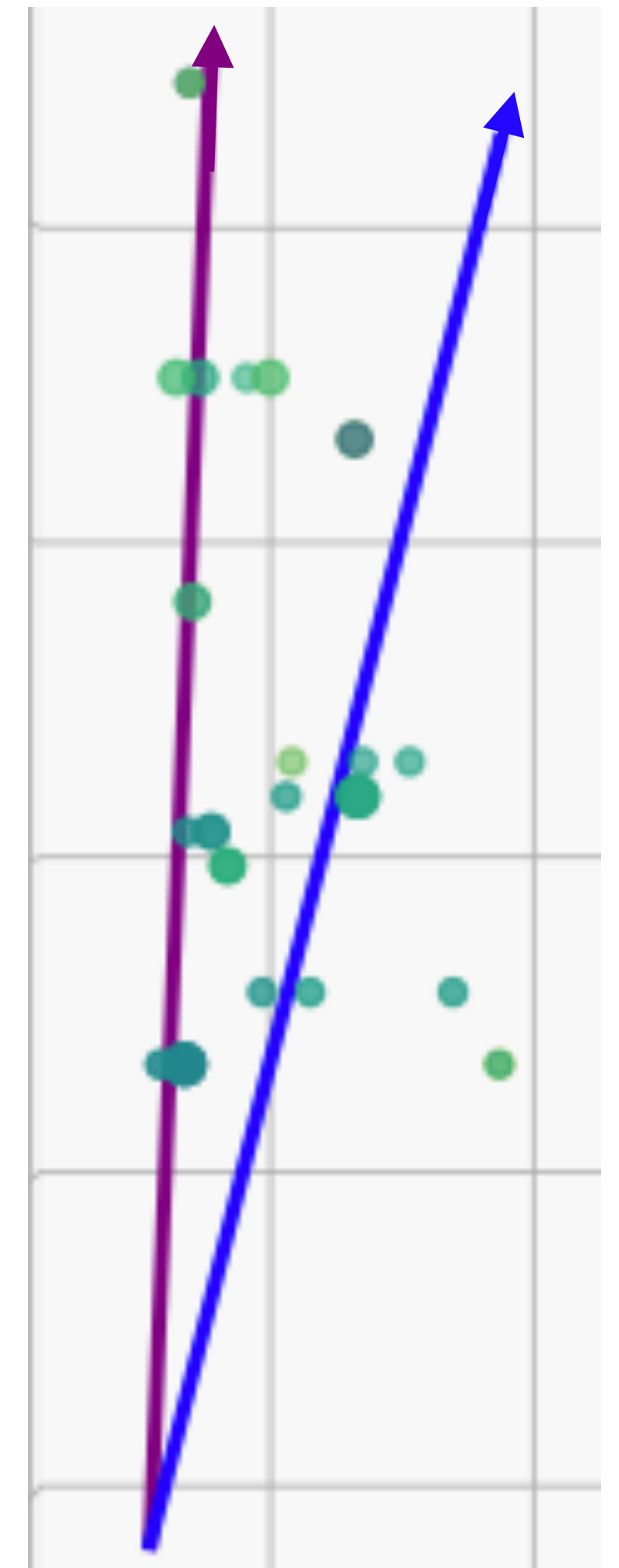# A Brief Overview of Dimuon Searches with IceCube

TeVPA 2025 @ Valencia, ES
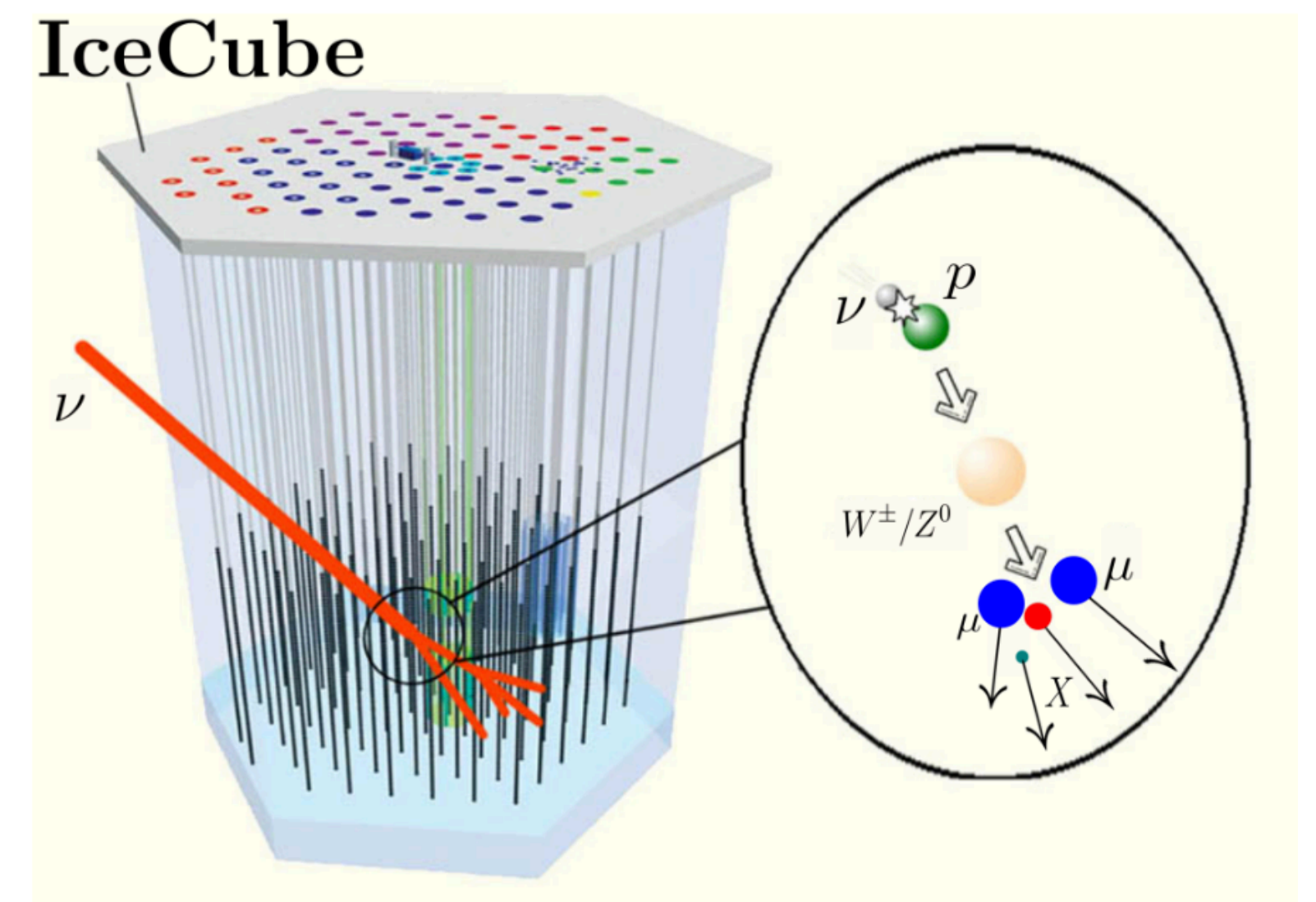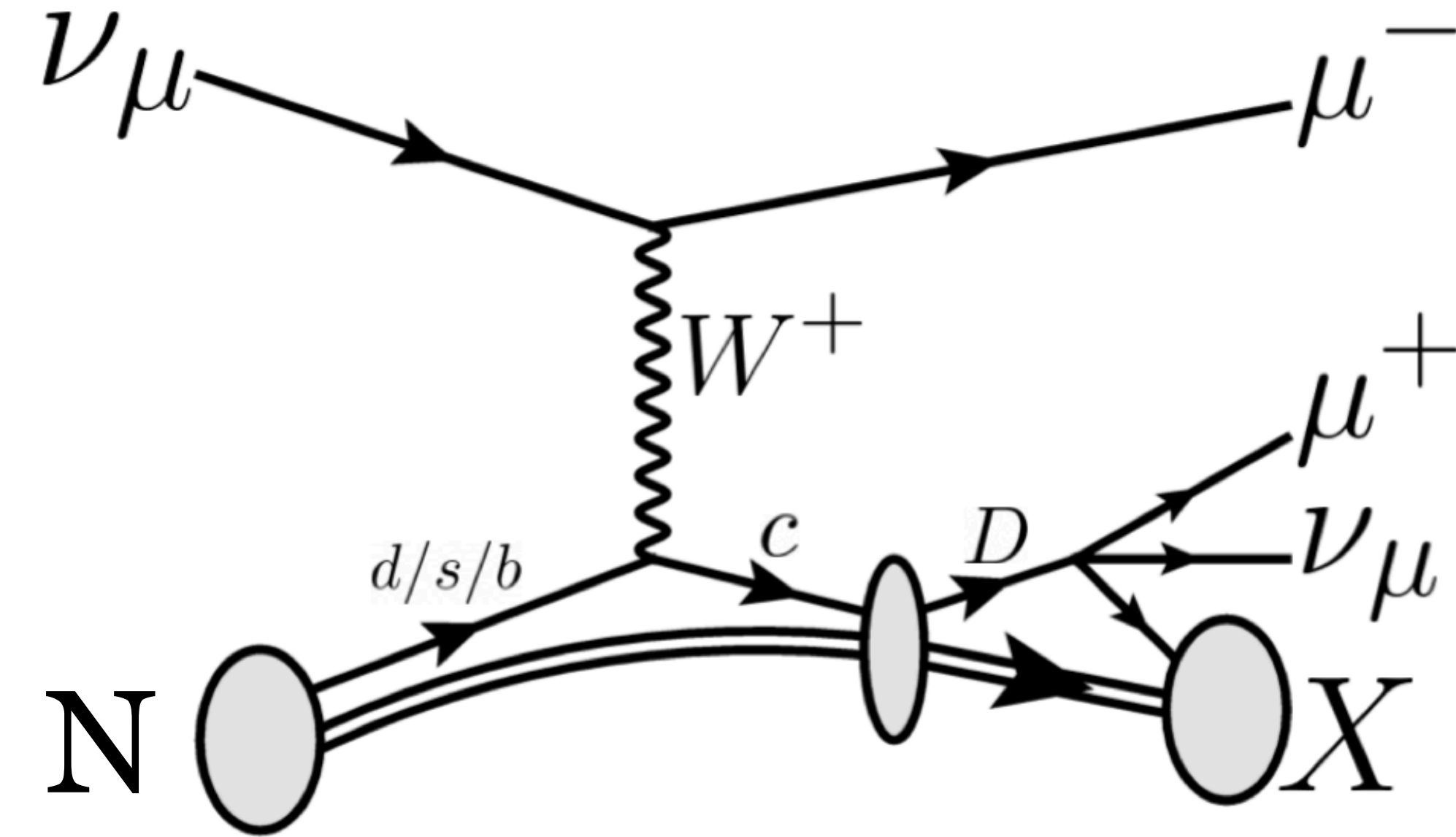## November 6th, 2025

Pavel Zhelnin; pzhelnin@g.harvard.edu

Plan for the talk

- **Overview/motivation**

- Results from most recent IceCube dimuon analysis (MEOWS-2023)

- Current IceCube dimuon analysis using MEOWS-2026
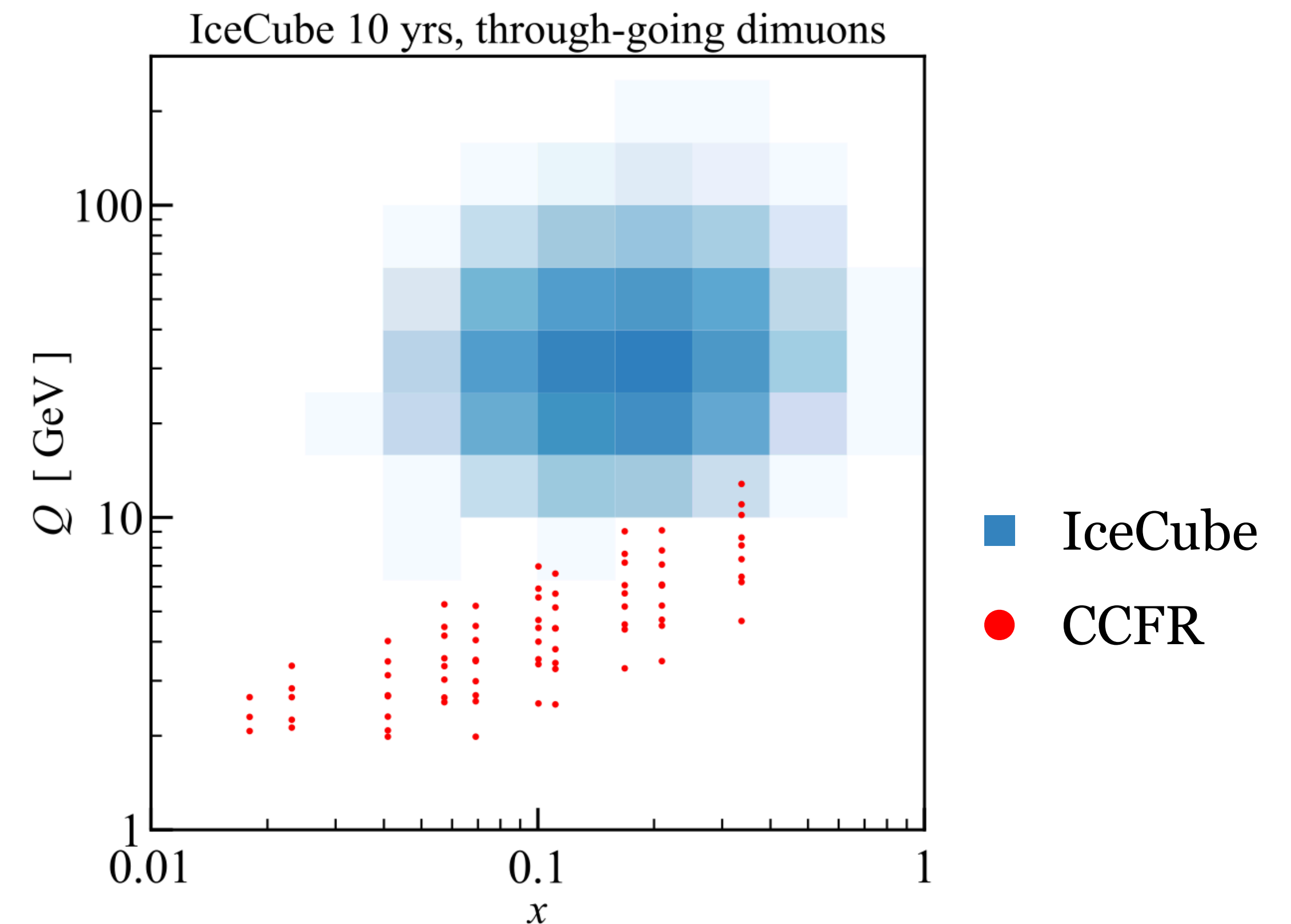
- Conclusion

What are dimuons?

- Dimuon events: **2 muons** produced in final state of neutrino interaction

- **The main source:** charm-induced dimuon production

- Dimuons provided first process to probe strange-quark physics (clean signature)

- They were studied at 'low' energies at CCFR, NuTeV, NOMAD etc.

Modified from image made by Yicong Sui, Washington University
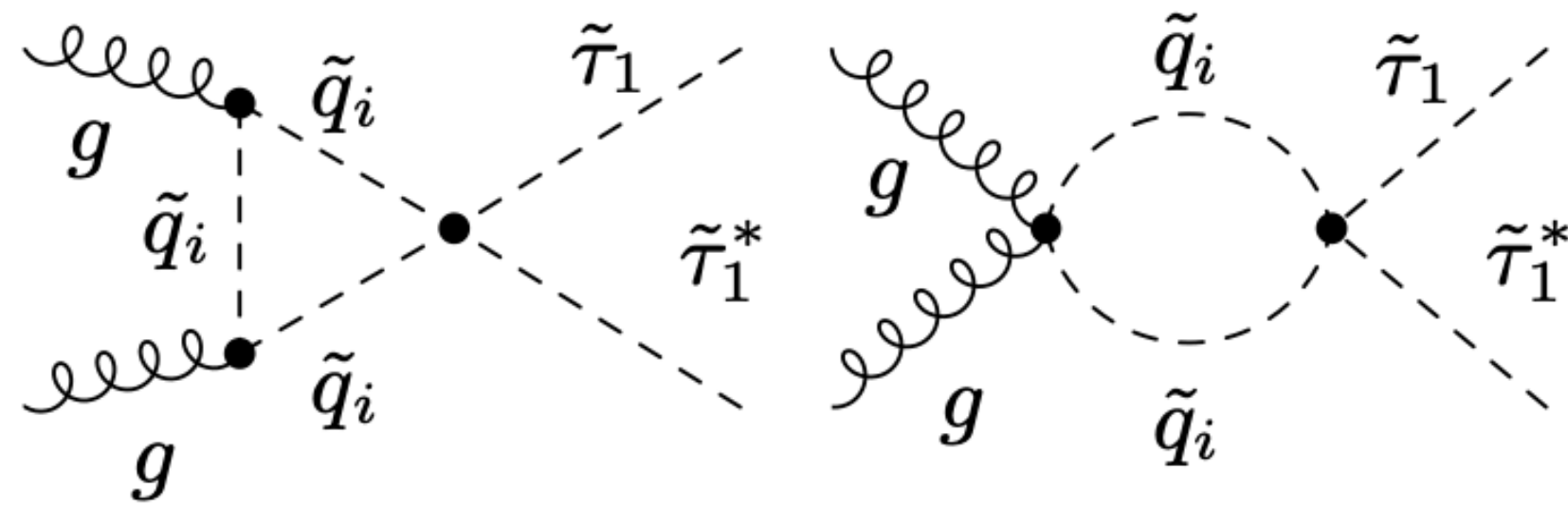
Motivation (SM)

- IceCube can probe a unique part (higher Q^2) of the kinematic phase space of the strange quark pdf

- This is because of the **high neutrino energies (> 1 TeV)** unavailable to other previous neutrino experiments

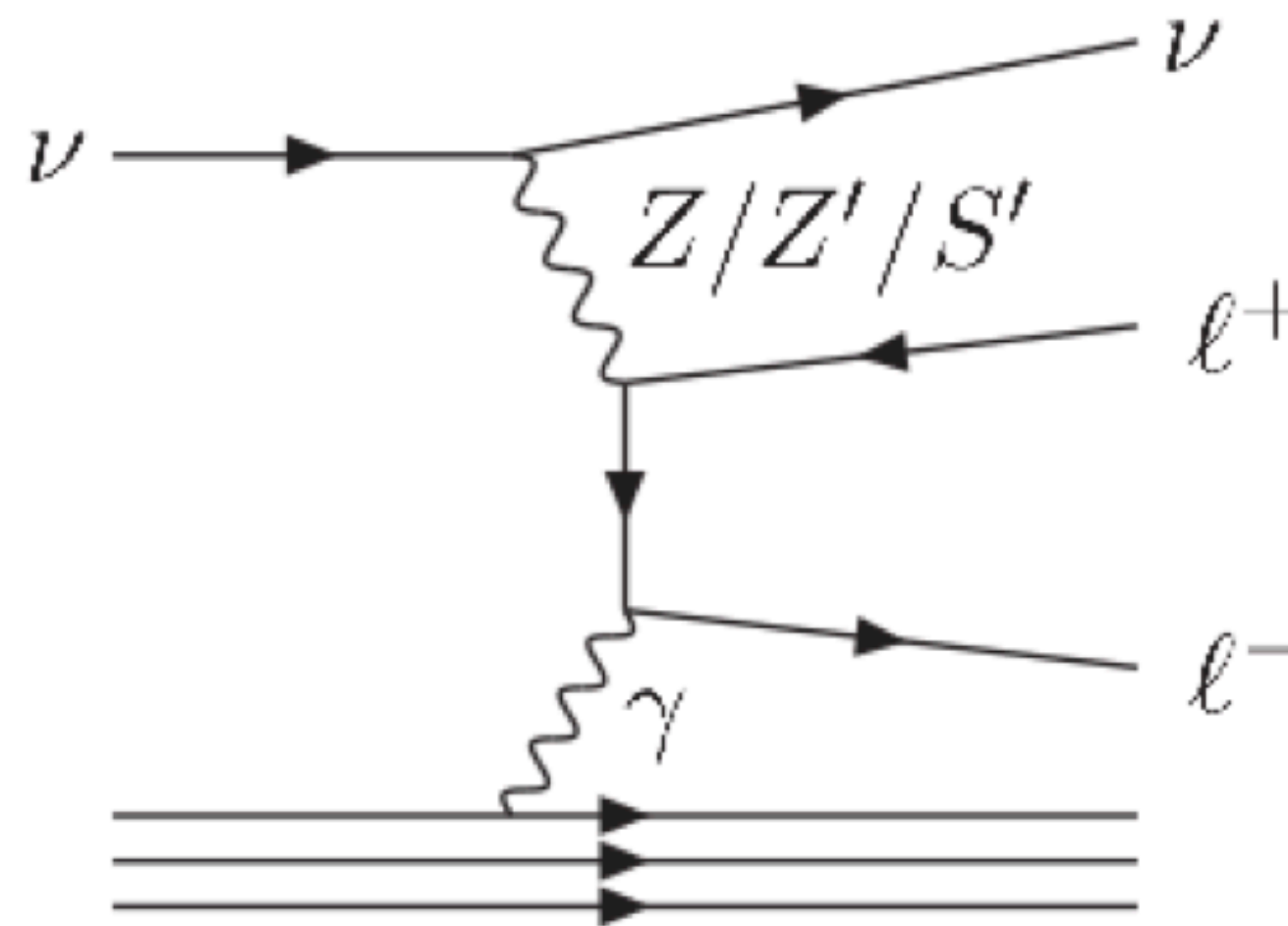- Also can probe CKM matrix elements (quark mixing), and D physics

IceCube 10 yrs, through-going dimuons

IceCube

CCFR

Zhou and Beacom , arXiv:2110.02974

Motivation (BSM)

- Many BSM models can produce dimuon signatures, look for excess in dimuon population
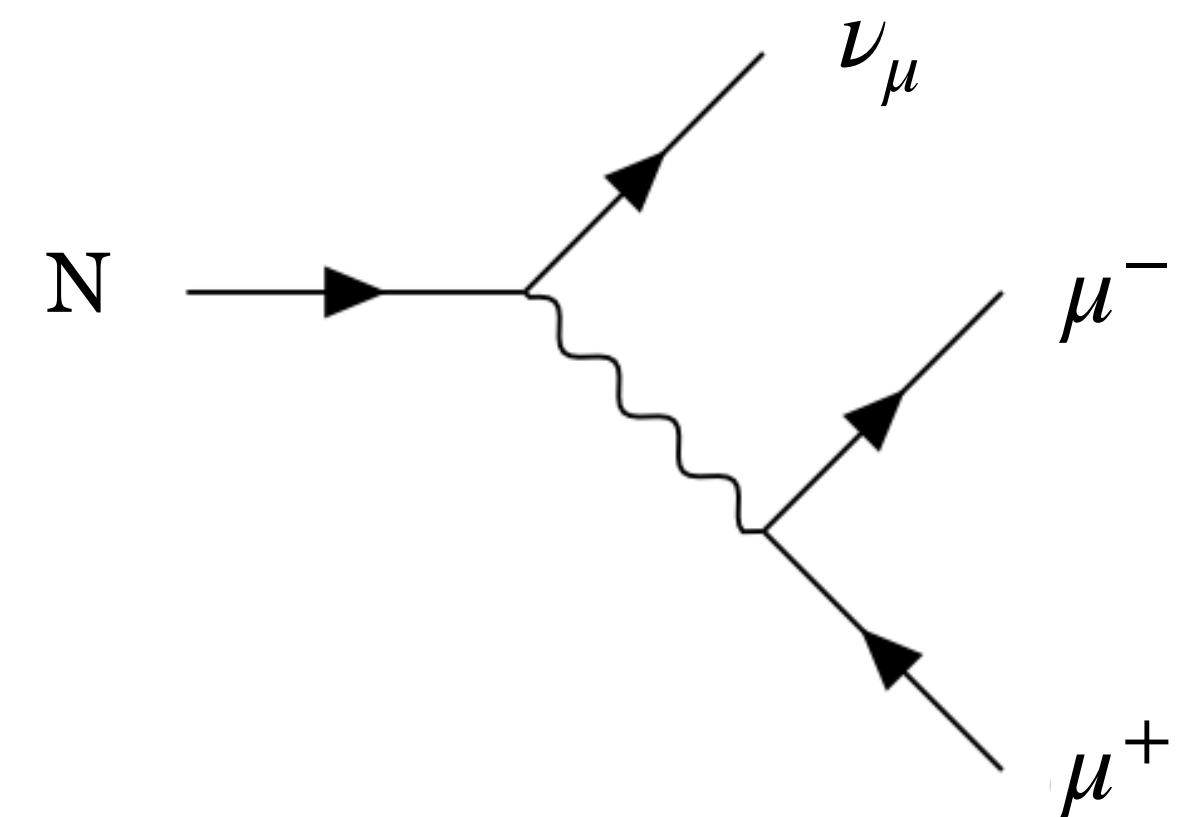
SUSY stau searches

Z' searches

HNL decays

Adapted from: Lindert et al., arXiv:1204.2379

Adapted from: Altmannshofer et al., arXiv:1406.2332v2

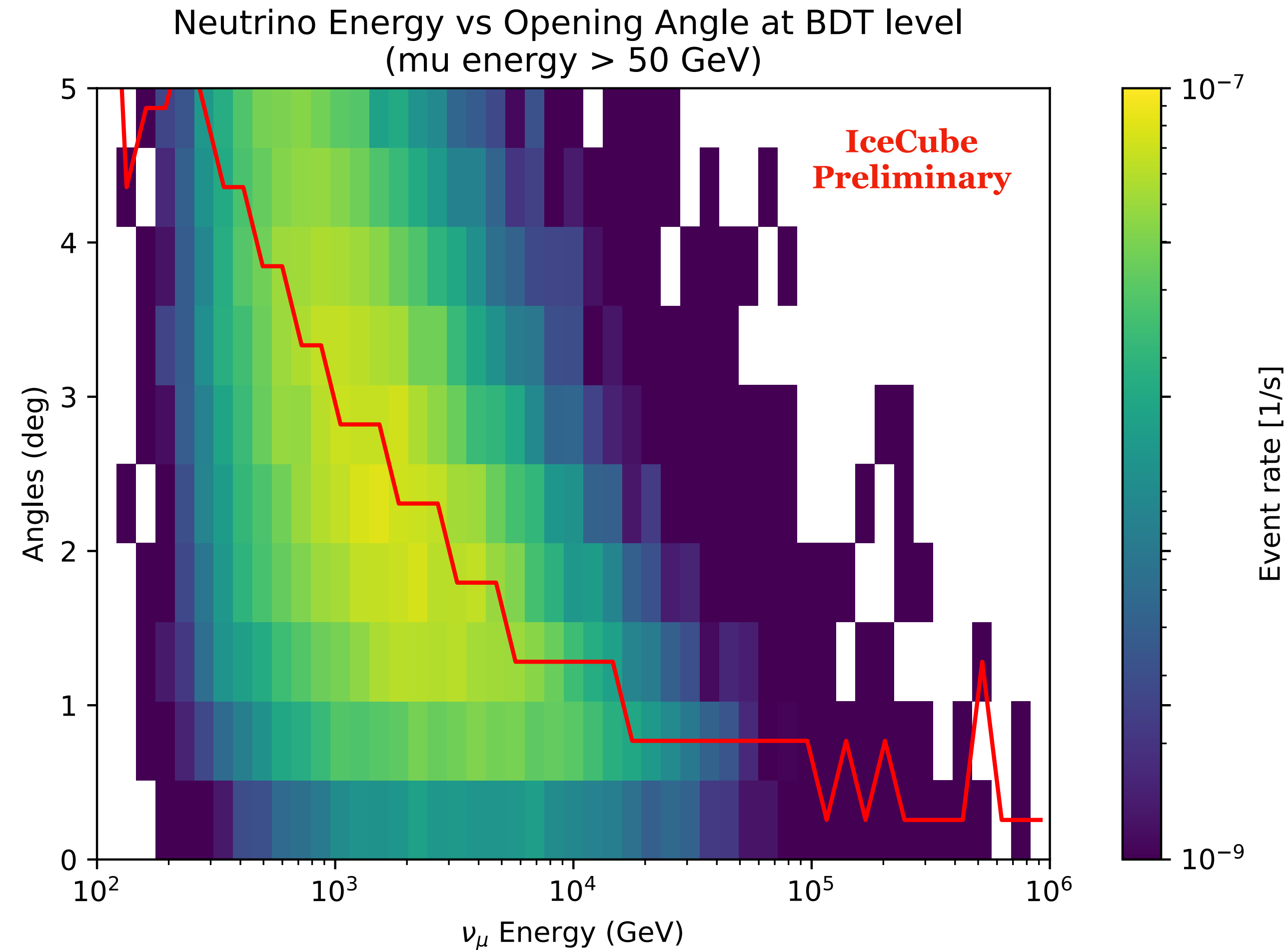Adapted from: Ema et al., arXiv:2306.07315

Plan for the talk

- Overview/motivation

- **Results from most recent IceCube dimuon analysis (MEOWS-2023)**

- Current Icecube dimuon analysis using MEOWS-2026

- Conclusion

Crux of the Analysis

- Separating dimuon signal from single muon background

  - The ratio $\dfrac{\sigma_{\mu\mu}}{\sigma_\mu}$ is $\sim \dfrac{1}{100}$; so a rare search

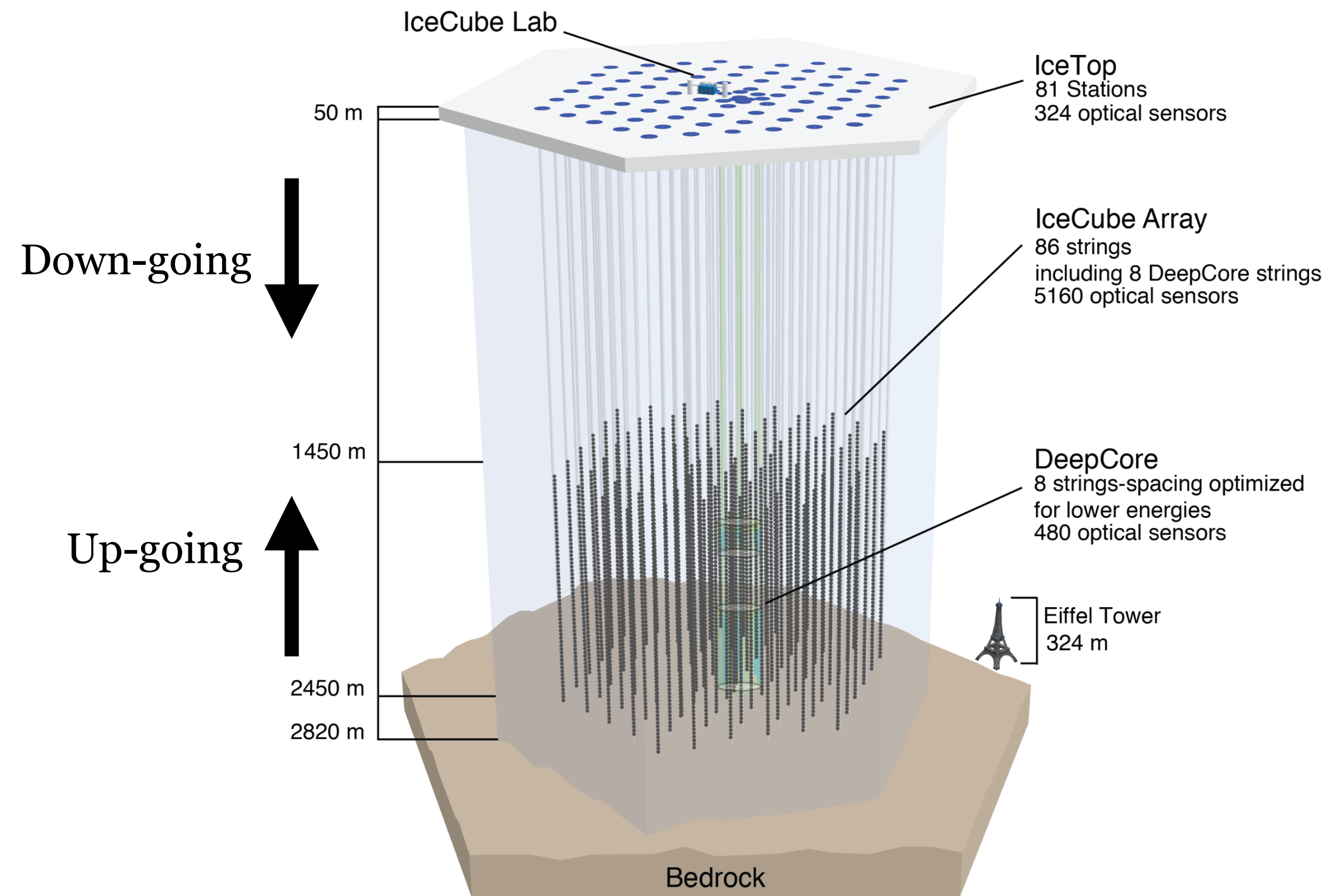 - Opening angle is small relative to spatial resolution ($\sim 1° - 5°$ between 'visible' muons)

Neutrino Energy vs Opening Angle at BDT level
(mu energy > 50 GeV)

IceCube Preliminary

Angles (deg)

ν_μ Energy (GeV)

Event rate [1/s]

Which looks

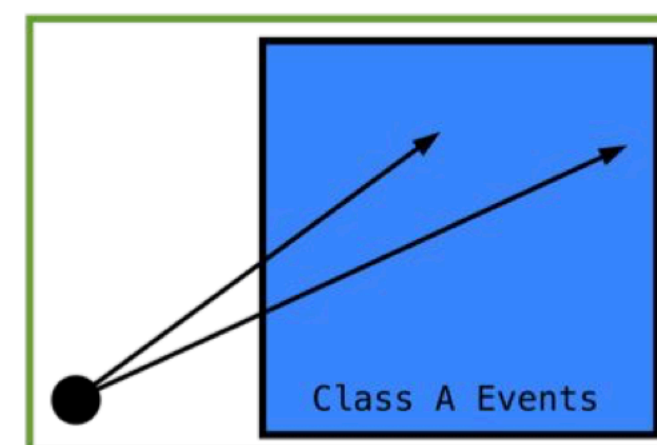$\mu\mu$

μ

IceCube Data Sample for Both Analyses

- Using the **MEOWS** sample

- A pure up-going sample of 'tracks', purity of **99.9%** ν_μ

- MEOWS-2023 has ~380k tracks at final level (after 'platinum' cuts)

- MEOWS-2026 will have ~20% more data

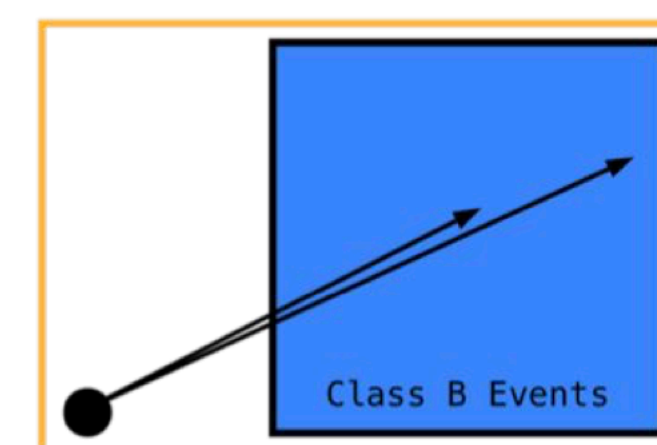https://icecube.wisc.edu/gallery/diagrams/

MEOWS-2023 Dimuon Analysis

- **Recent IC dimuon analysis:** used Graph Neural Networks (publication under preparation)

- Split dimuon MC set into two class regions, A ("golden") and B ("silver")
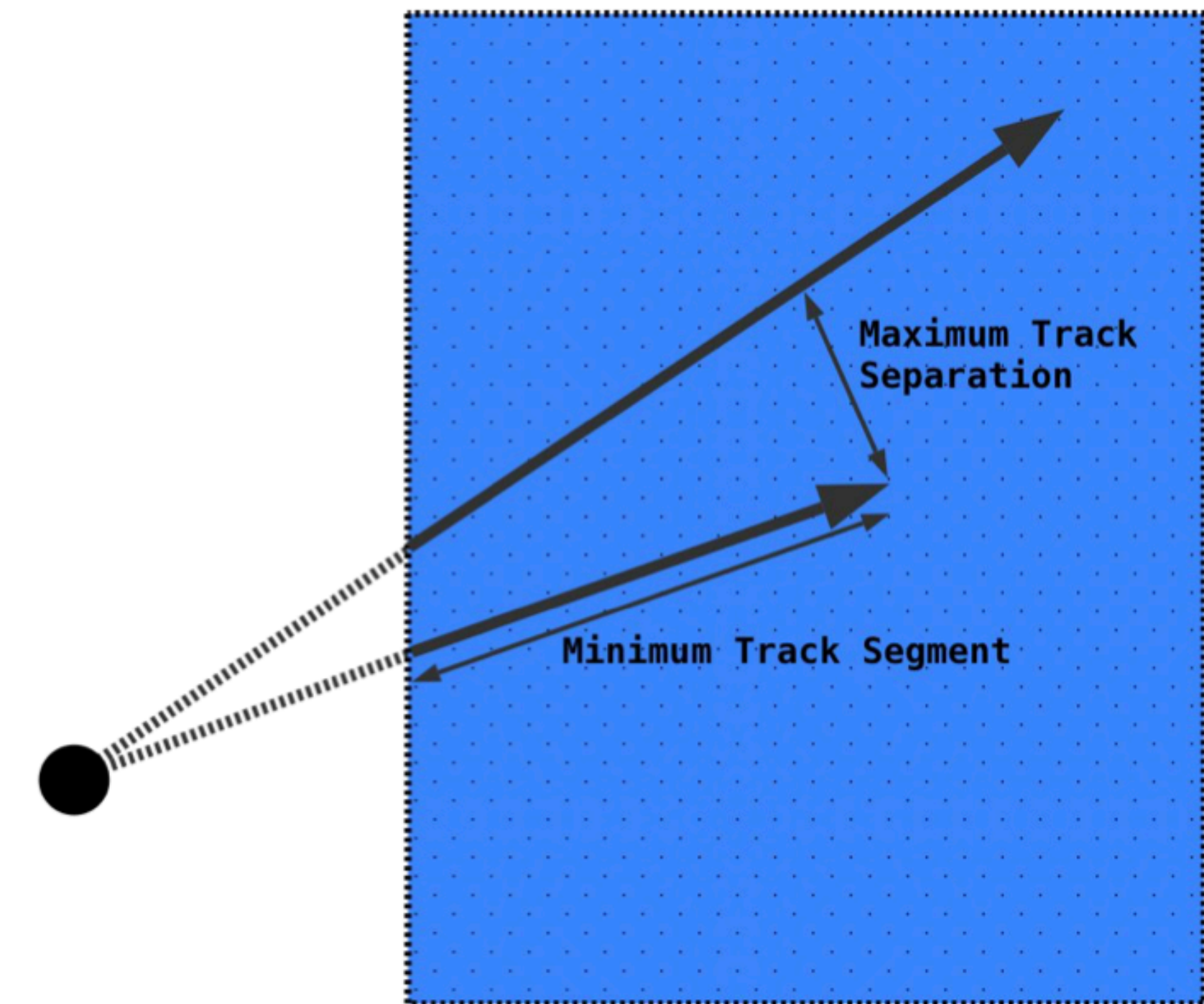
- Trained two GNNs; one on A and another on A+B

Class A	Minimum track segment > 200 m Maximum tracks separation > 25 m
Class B	Minimum track segment > 200 m

Class A   Class B

MEOWS-2023 GNN Scores

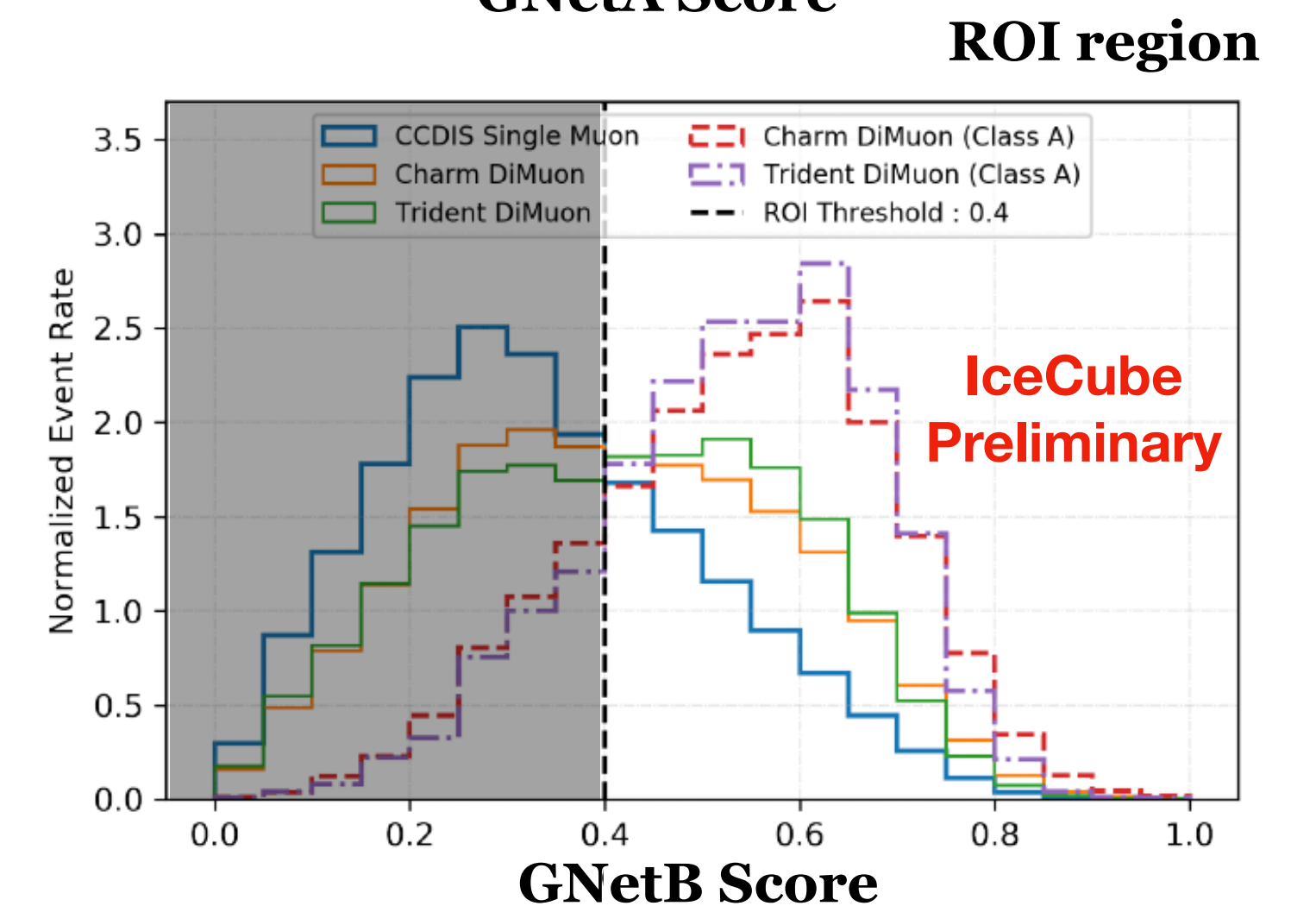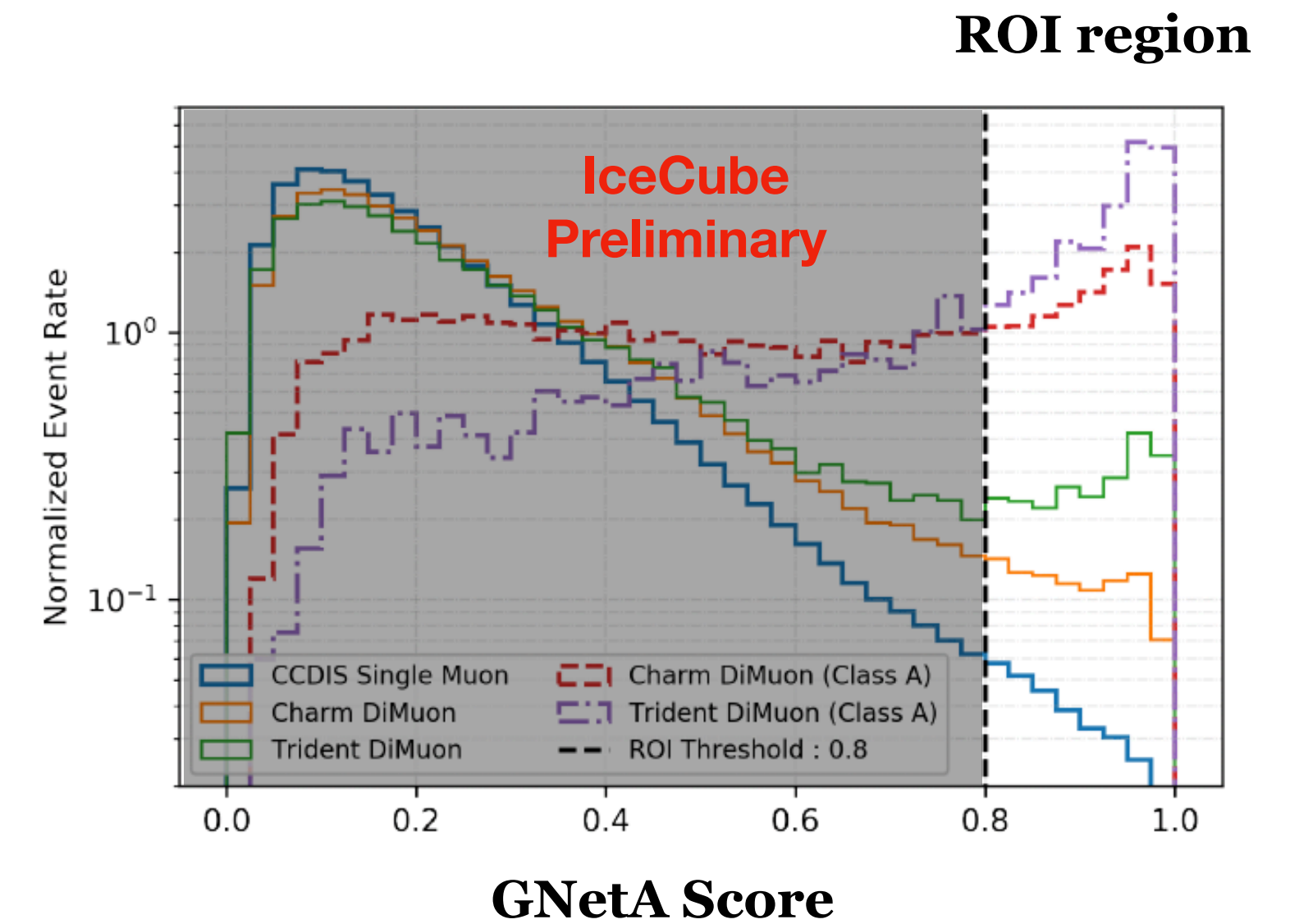**Output scores of GNN models**

- Analysis cuts:

  - based on GNN scores (called Region of Interest, ROI)

  - reco energy (1.1 TeV > E_{proxy} > 50 TeV)

  - zenith cuts (up-going), etc.

- After all cuts, expected number of s+b in two final signal regions: 1.46 and 5.4 events

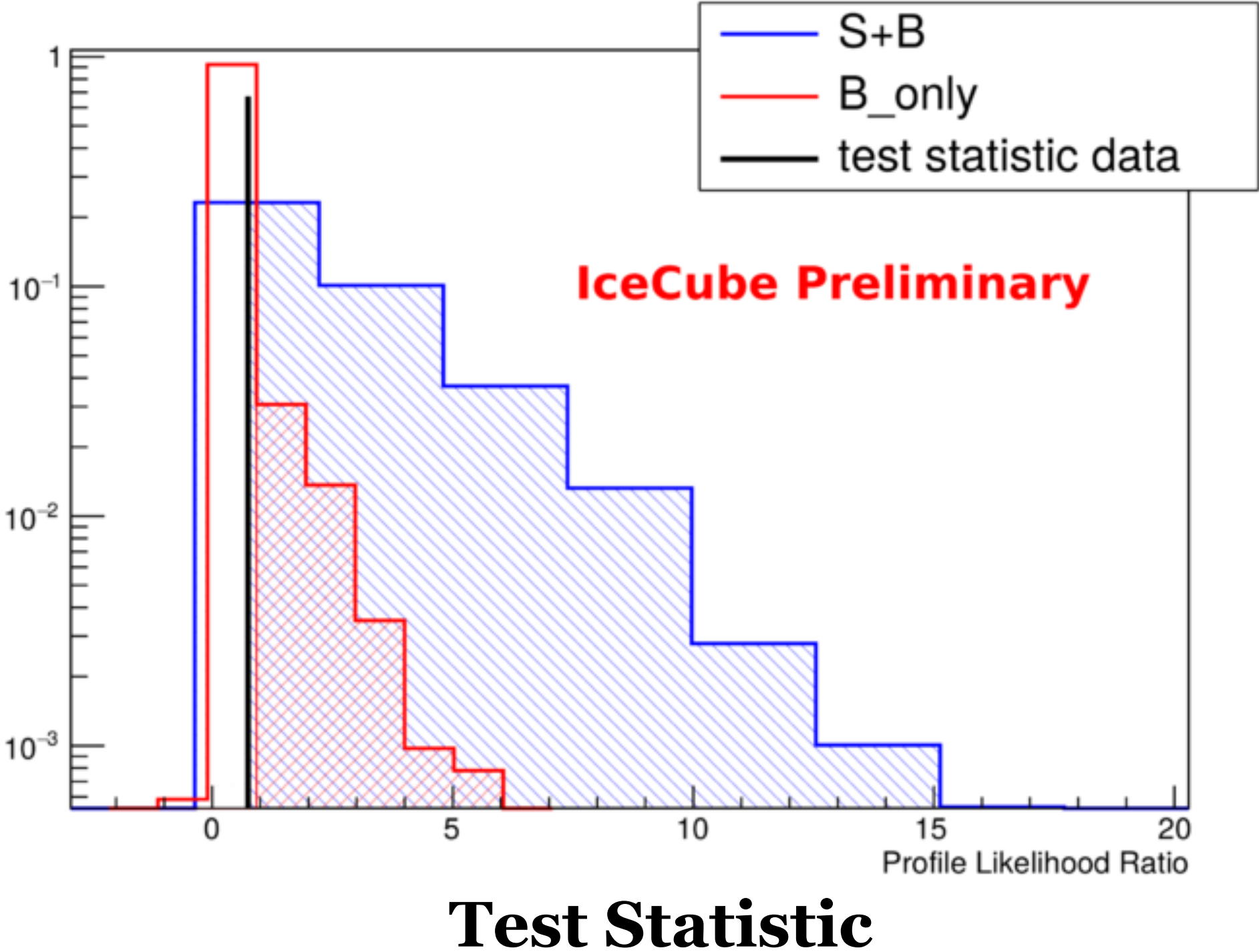https://ualberta.scholaris.ca/items/de2068d1-4f8b-40bd-b40b-e56b51c27591

MEOWS-2023 Dimuon Results

- Data reports 1 and 4 events, rejects background (no dimuons) at 1.3σ and 1.1σ

		Expectation	Data
SR1	Signal	1.25	1
	Background	0.21	
SR2	Signal	3.27	4
	Background	2.13	

IceCube Preliminary

Test Statistic

https://ualberta.scholaris.ca/items/de2068d1-4f8b-40bd-b40b-e56b51c27591
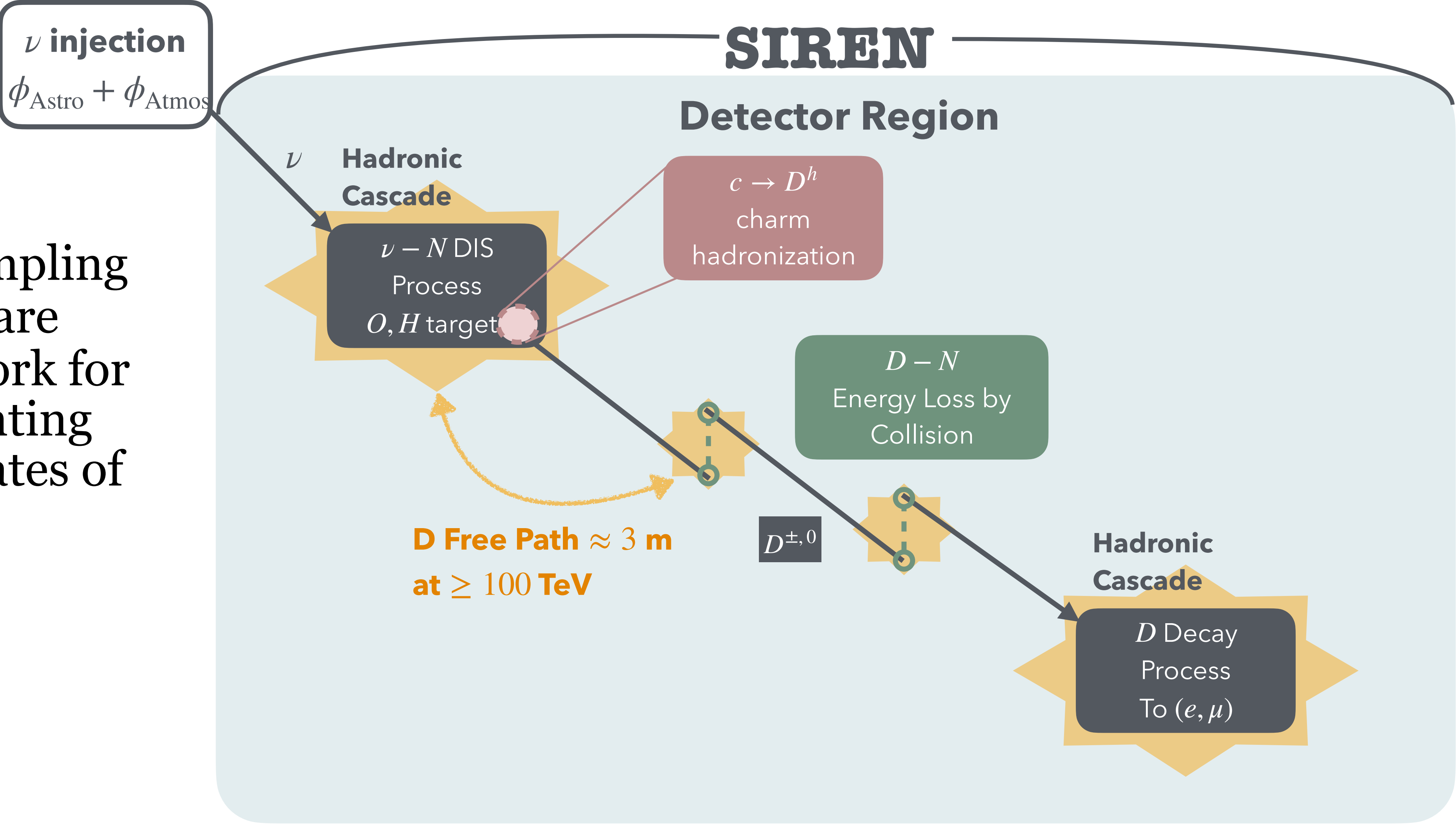
Plan for the talk

- Overview/motivation

- Results from most recent IceCube dimuon analysis (MEOWS-2023)

- **Current Icecube dimuon analysis using MEOWS-2026**

- Conclusion

New Additions in MEOWS-2026

- **New MC generator**
  (MEOWS-23 used leptoninjector+madgraph+pythia etc.; MEOWS-26 uses SIREN for all)

- **New reconstruction** techniques (GNN vs. transformer-based)

- **More sophisticated statistical analysis** using full profile binned likelihood instead of counting analysis

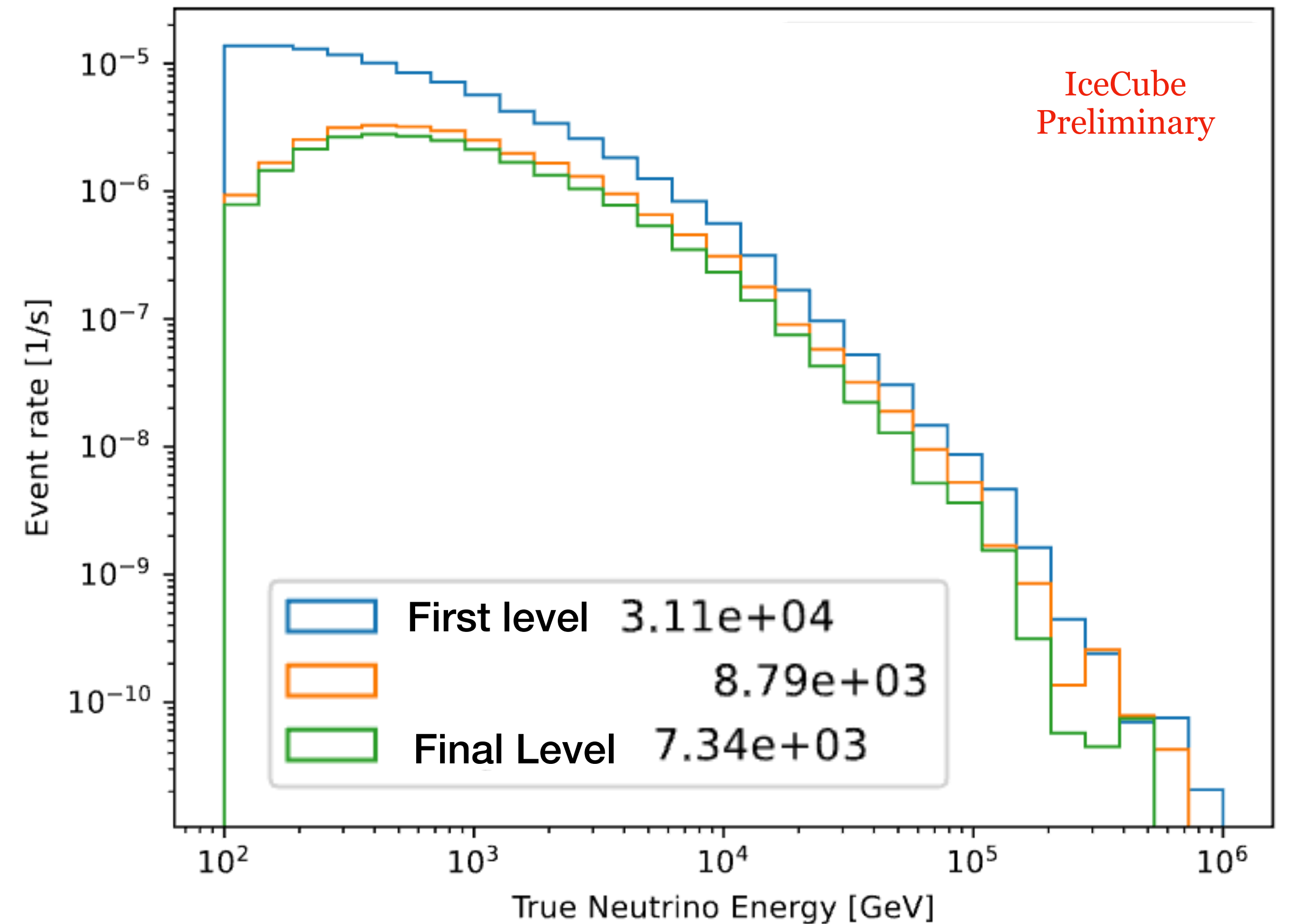- **MEOWS-2026 dataset** would have ~ 20% more data

MEOWS-2026 Dimuon MC Generation Stage

Using SIREN, (**S**ampling and **I**njection for **R**are **E**ve**N**ts), a framework for injecting and weighting interaction final states of complex topology

ν **injection**

$\phi_{\text{Astro}} + \phi_{\text{Atmos}}$

SIREN

Detector Region

ν **Hadronic Cascade**

$\nu - N$ DIS Process
O, H target

$c \to D^h$ charm hadronization

$D - N$ Energy Loss by Collision

D Free Path ≈ 3 **m at** ≥ 100 **TeV**

$D^{\pm, 0}$

Hadronic Cascade

D Decay Process
To (e, μ)

Schneider et al., arXiv:2406.01745

Thanks Andy Jin for both injection framework and this figure!

MEOWS-2026 Dimuon MC pipeline

- Pass to MEOWS pipeline (reduces cascade/atmospheric muon backgrounds < 0.1%)

- Pass final-level dimuon events to classifier/estimator next

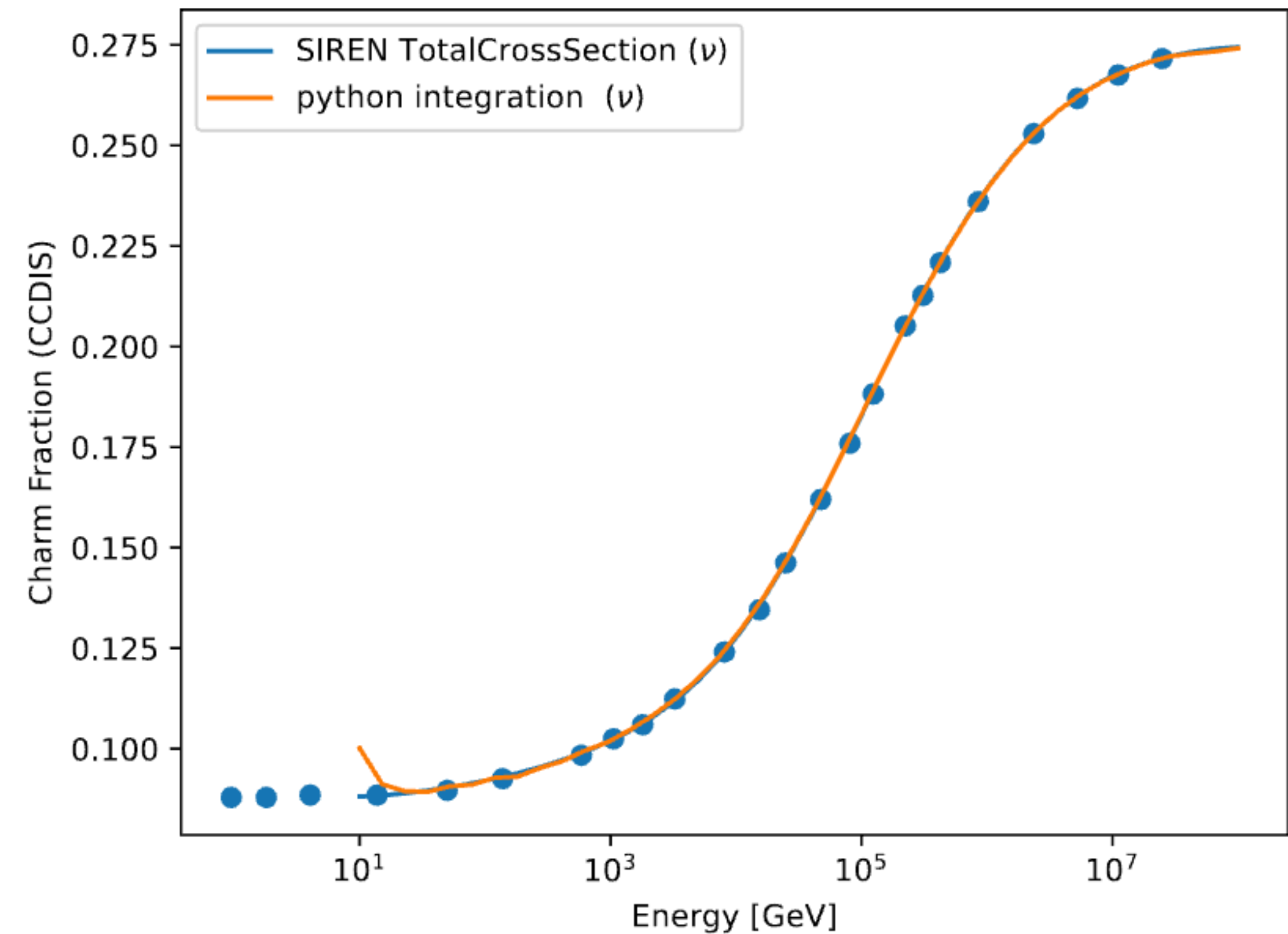- This is produced using no further cuts on data than already present in MEOWS-23

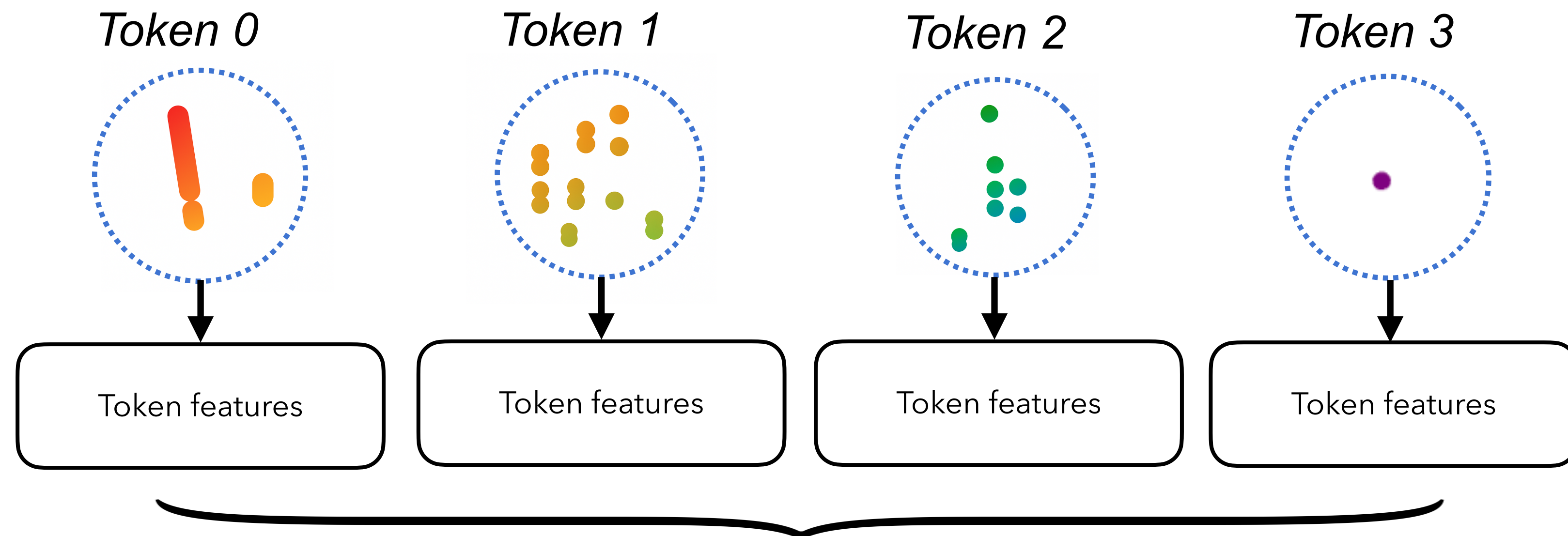Thanks to work by Niklas Franklin

MEOWS-2026 Dimuon Cross-Validation

- Cross validation of SIREN generator (cross sections, hard scattering kinematics, etc.) with PYTHIA and MadGraph

- Still a WIP but things are looking good so far

- Need to finalize checks

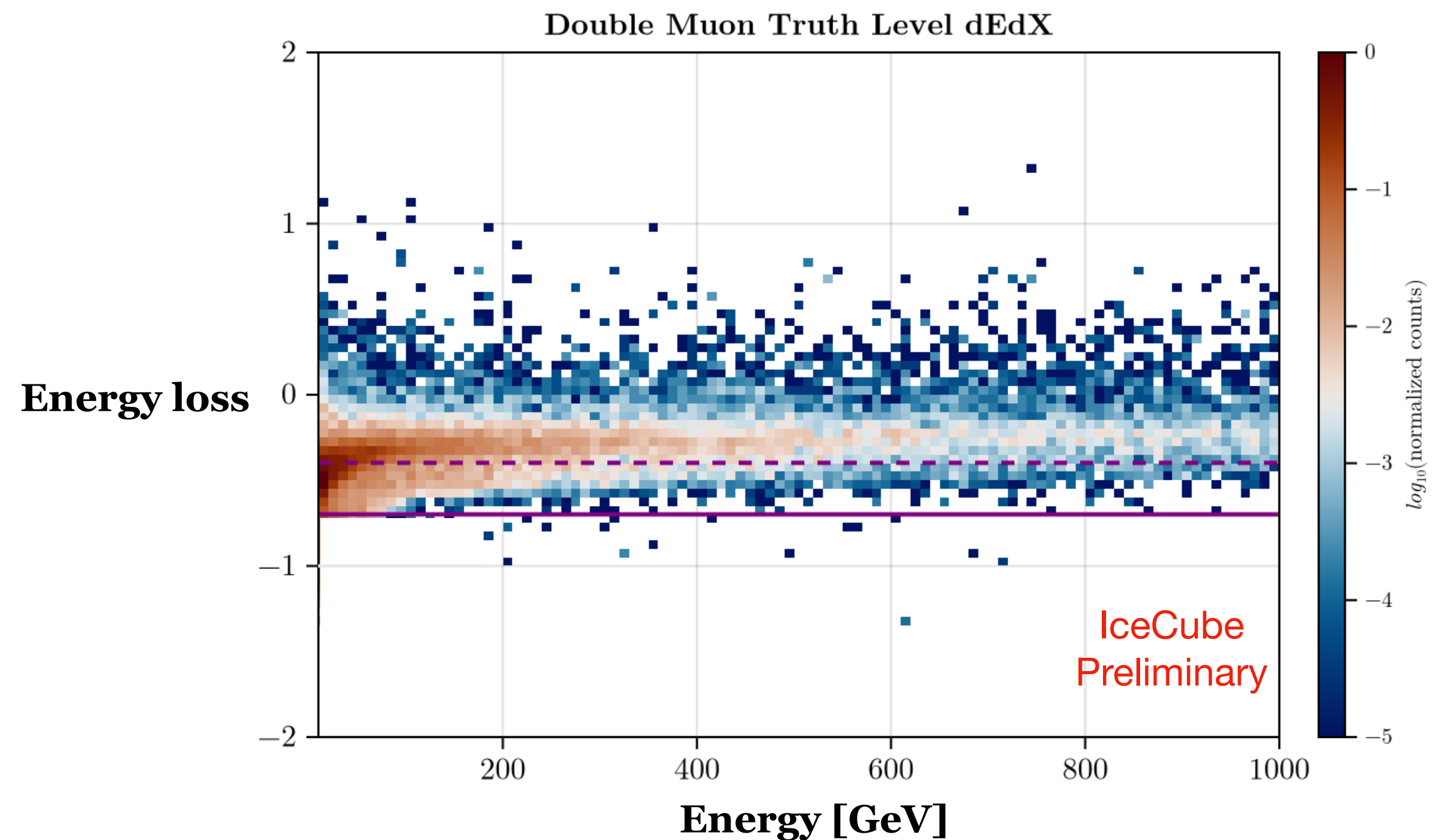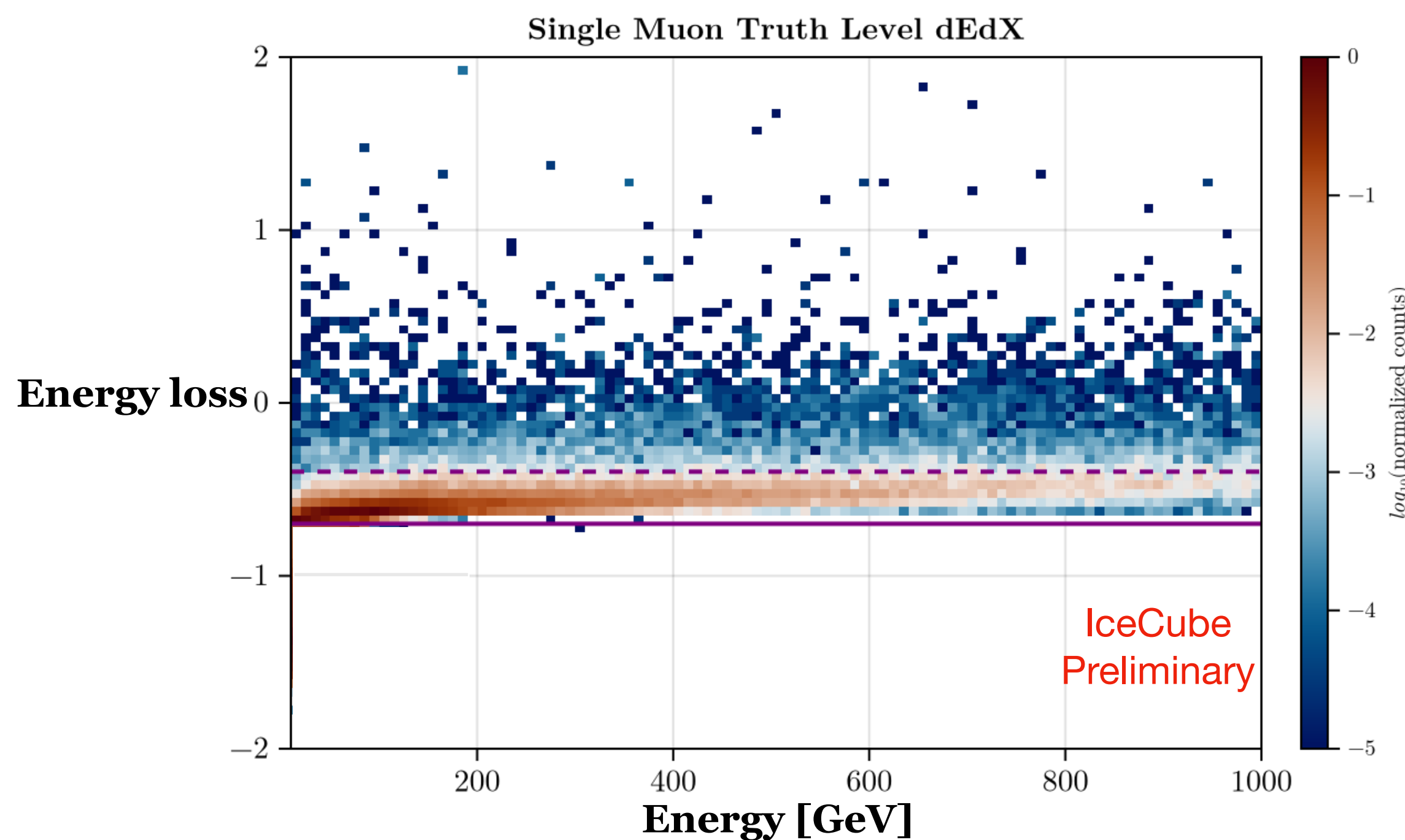# MEOWS-2026 Dimuon Reconstruction

- Using a transformer-based classifier/estimator with point-cloud tokenization: **neptune** (a**N** **E**fficient **P**oint **T**ransformer for **U**ltrarelativistic **N**eutrino **E**vents)

- Input data: spatial and temporal coordinates of pulses but also event features

- Hints of success in estimating > 100 GeV muon direction

- First classification has run into difficulties; need better features

Token 0   Token 1   Token 2   Token 3

Token features   Token features   Token features   Token features

Global context!

Yu et al., arXiv:2510.01733

A Better Feature Selection?

μ $\nearrow$ $200\,\dfrac{MeV}{m}$ $\mu\mu$ $\nearrow\!\!\!\nearrow$ $400\,\dfrac{MeV}{m}$
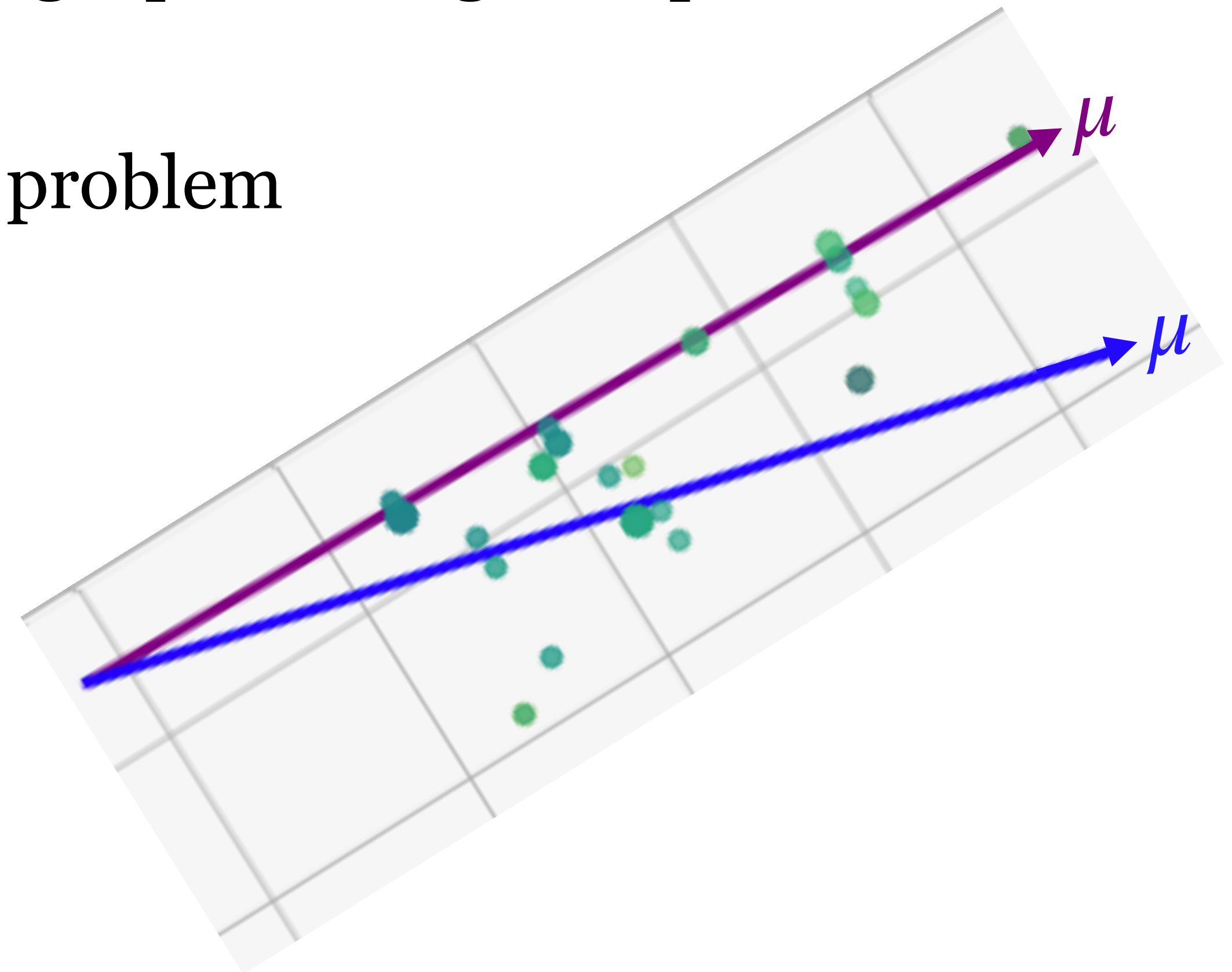

ENERGY vs. ENERGY LOSS

- dE/dX could be promising, for minimally ionizing muons the dE/dX distributions for dimuon events are different from single muon events (at truth level)

Plan for the talk

- Overview/motivation

- Results from most recent IceCube dimuon analysis (MEOWS-2023)

- Current Icecube dimuon analysis using MEOWS-2026

- **Conclusion**

Conclusion

- Dimuons are worthwhile to study: strange quark insights, opens the door to BSM analyses

- However it is a difficult reconstruction problem
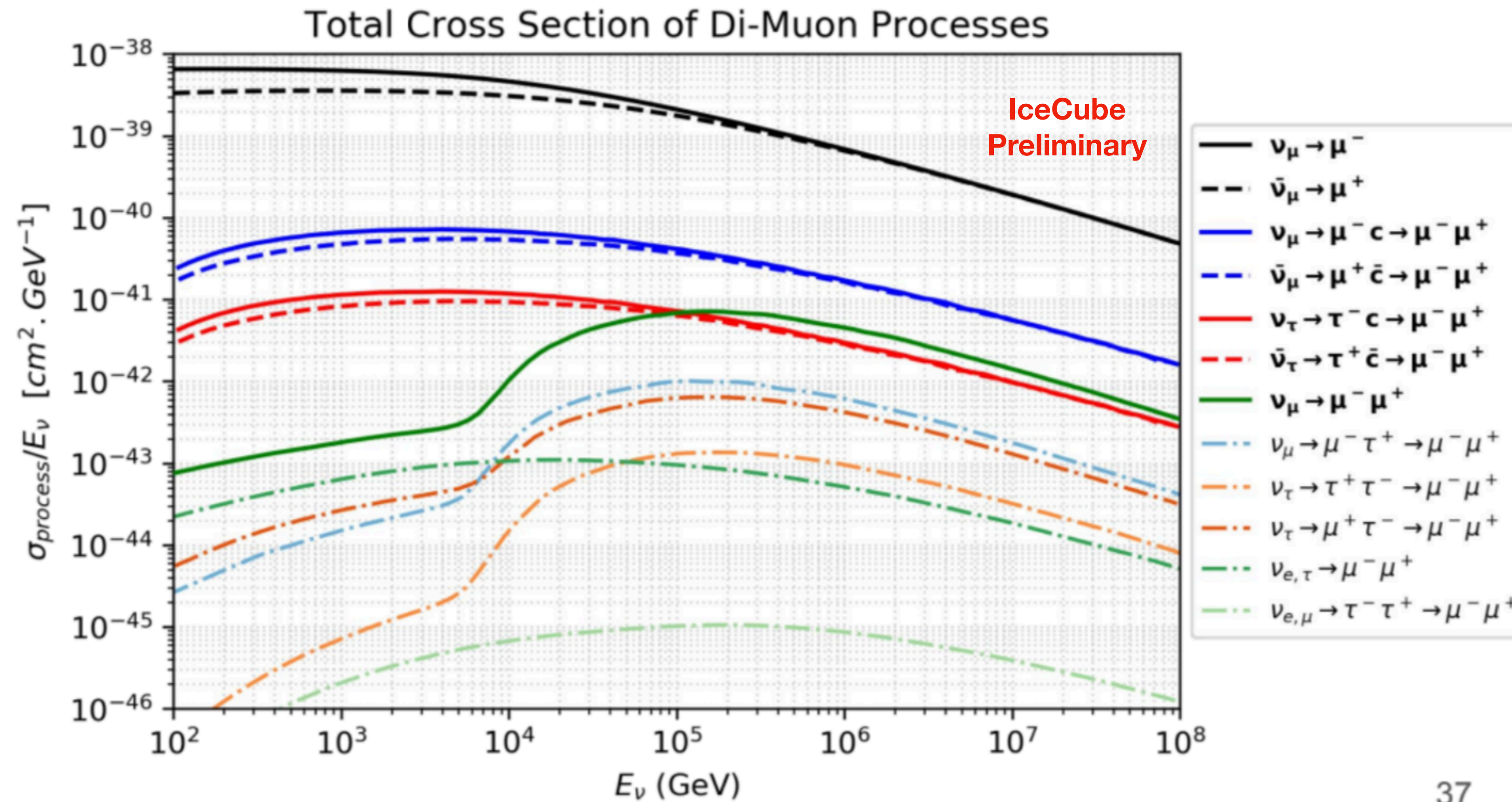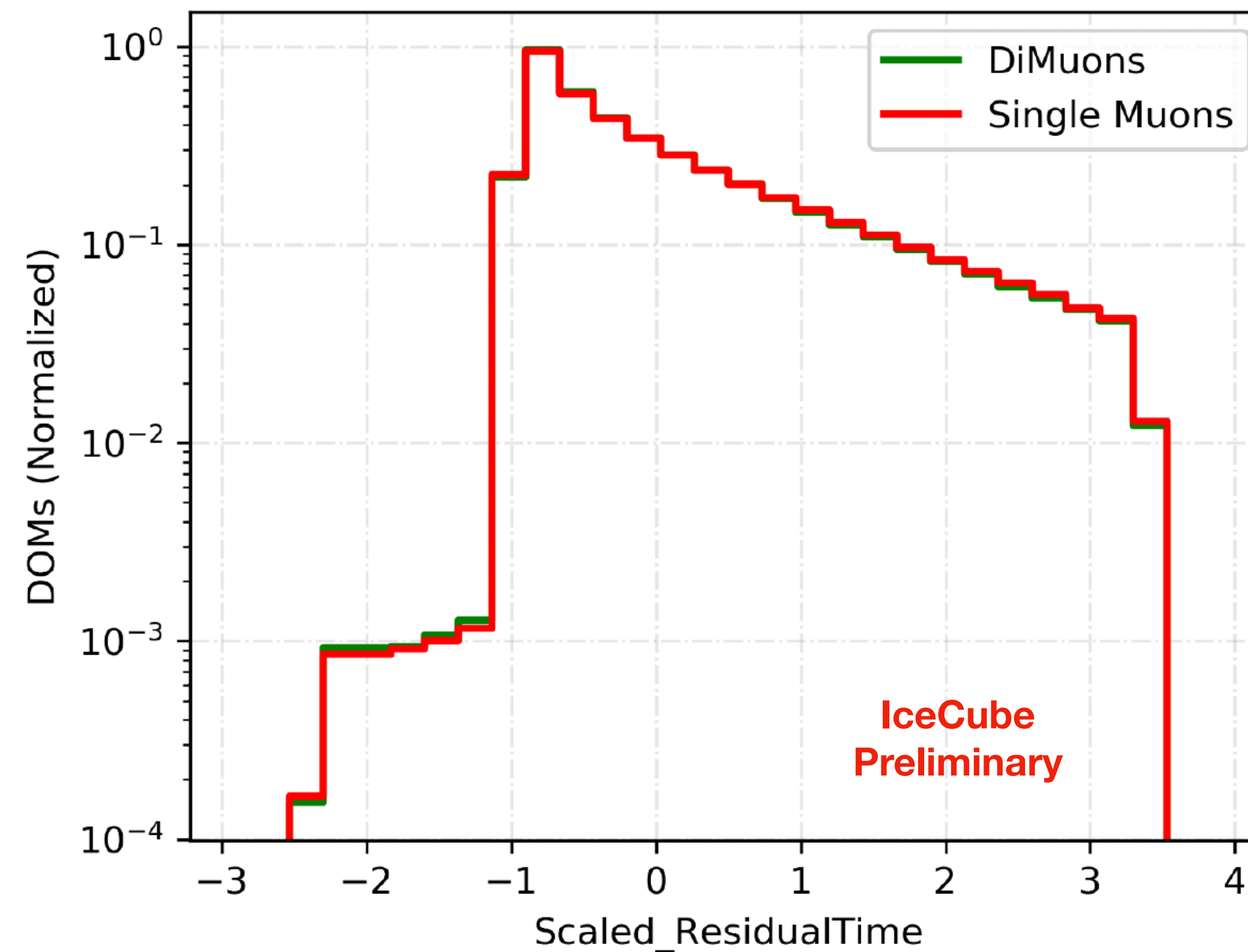
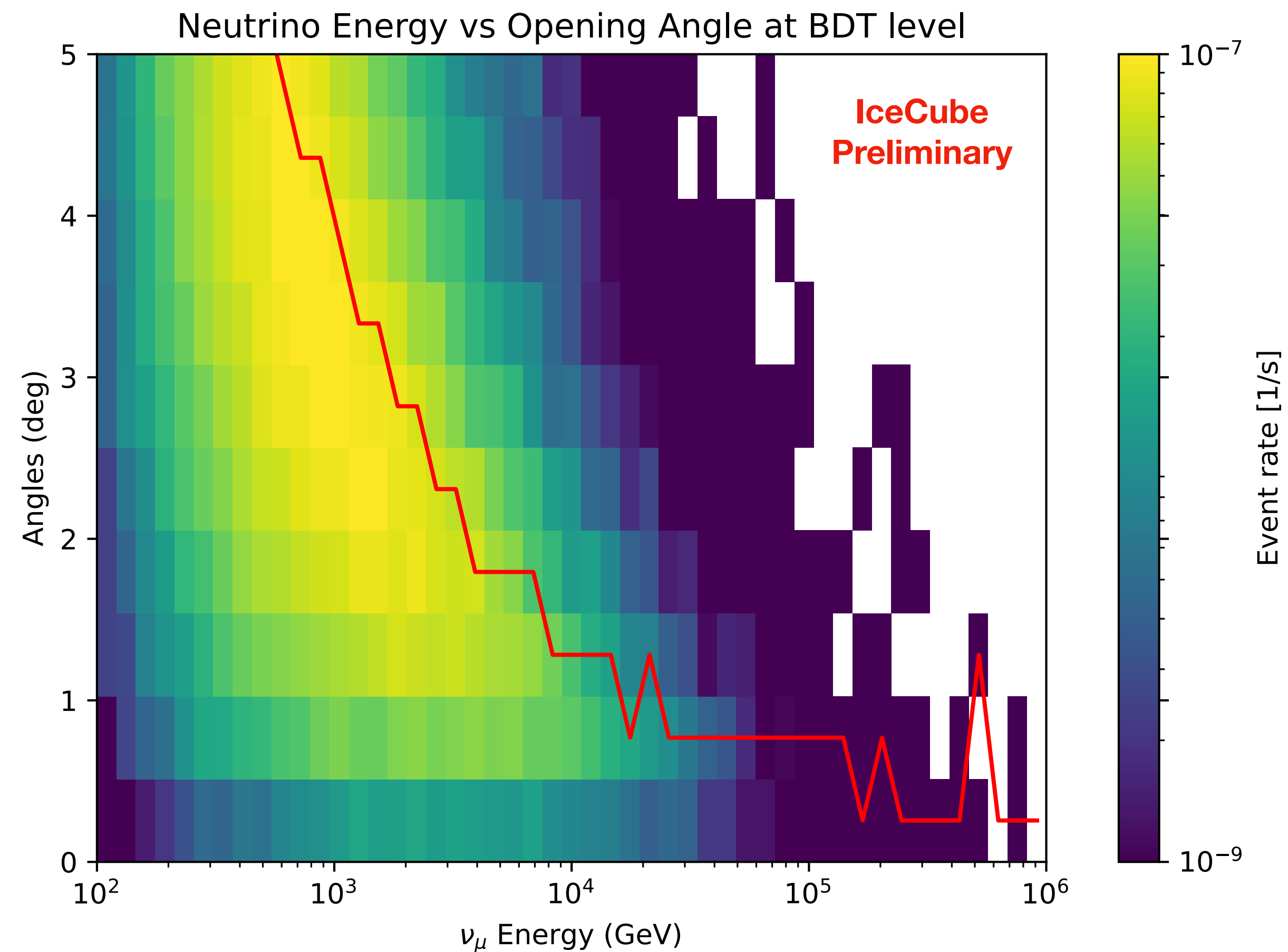- Wait for further results!

¡Gracias!

Appendix

Dimuon cross sections

Total Cross Section of Di-Muon Processes

IceCube Preliminary

37

Sourav Residual Time distribution

Opening angle with energy cut
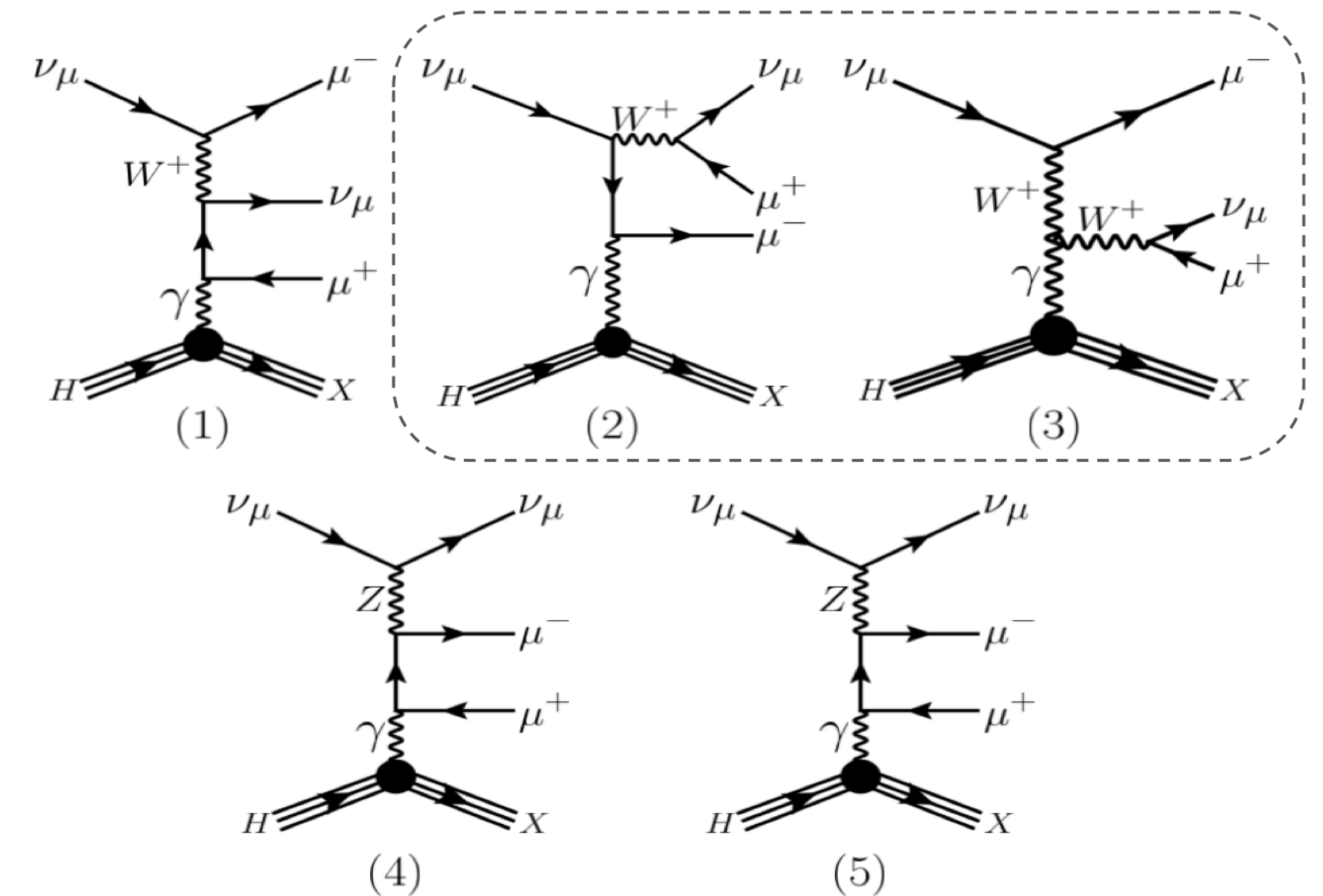

Neutrino Energy vs Opening Angle at BDT level

IceCube Preliminary

Tridents

- Neutrino scattering off Coulomb field nucleon

- low reco-inelasticity dimuon events

- Enhanced cross section from on-shell W-boson production

- Expectation is ~ 10 events in MEOWS MC sample

Neptune Architecture