Dimuons in Neutrino Telescopes: New Predictions and First Candidates in IceCube

Bei Zhou

Postdoctoral fellow, Dept. of Physics and Astronomy, Johns Hopkins University

arXiv: 2110.02974   ***Bei Zhou (JHU), John Beacom (OSU)***

Neutrino telescopes are very important

MeV—GeV neutrino telescopes

- Solar nu, Nobel prize 2002, 2015, and more to study
- Supernova nu, Nobel prize 2002, and more to study
- Atmospheric nu, Nobel prize 2015, and more to study
- All above have been used to test new physics

TeV—PeV neutrino telescopes

- Astrophysics:
  - Origin of high-energy cosmic rays (> 100-year problem)
  - Gamma ray sources, hadronic vs leptonic (~long-term problem)
- Particle physics:
  - Standard model (Glashow resonance, W-boson production)
  - Beyond SM (DM, nu properties, etc.)

Neutrino telescopes are very important

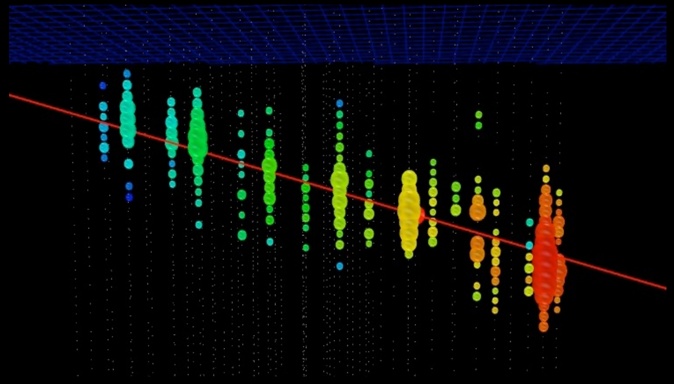
MeV—GeV neutrino telescopes

- Solar nu, Nobel prize 2002, 2015, and more to study
- Supernova nu, Nobel prize 2002, and more to study
- Atmospheric nu, Nobel prize 2015, and more to study
- All above have been used to test new physics

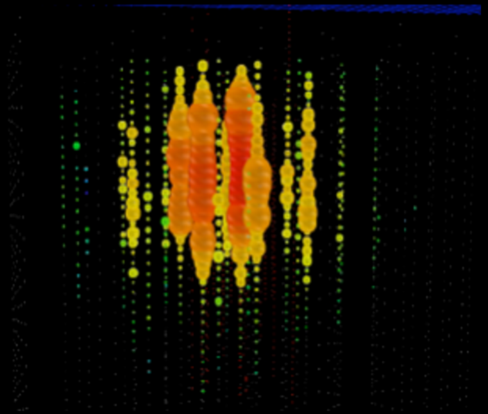
TeV—PeV neutrino telescopes

- Astrophysics:
  - Origin of high-energy cosmic rays (> 100-year problem)
  - Gamma ray sources, hadronic vs leptonic (~long-term problem)
- Particle physics:
  - Standard model (Glashow resonance, W-boson production)
  - Beyond SM (DM, nu properties, etc.)

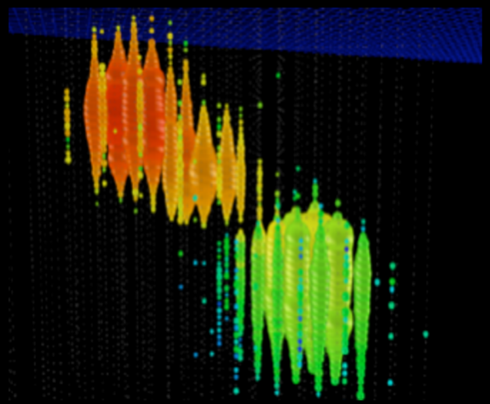
Very important to study new event classes



μ track



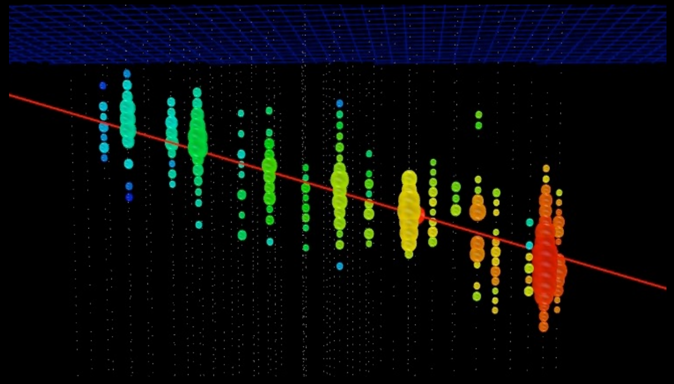
Shower (e or hadron)



Double shower/bang (τ)

- We are having more and more TeV—PeV neutrino detectors
  - IceCube, KM3NeT, BaiKal-GVD, P-ONE, IceCube-Gen2, …
- New event classes are needed to get more physics from the data

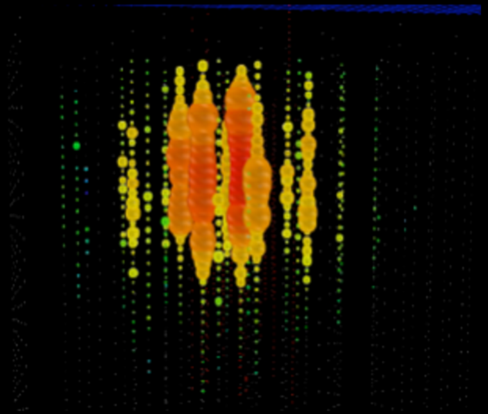
Very important to study new event classes: Dimuon



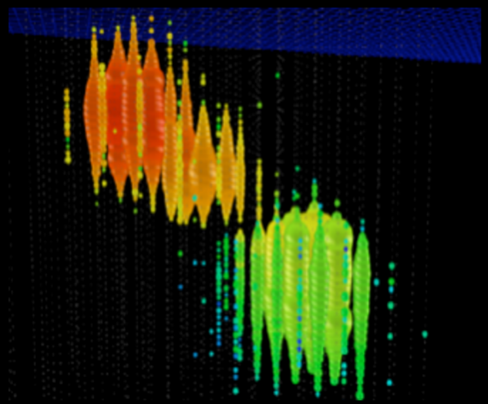
μ track

Double muons

(Dimuon)



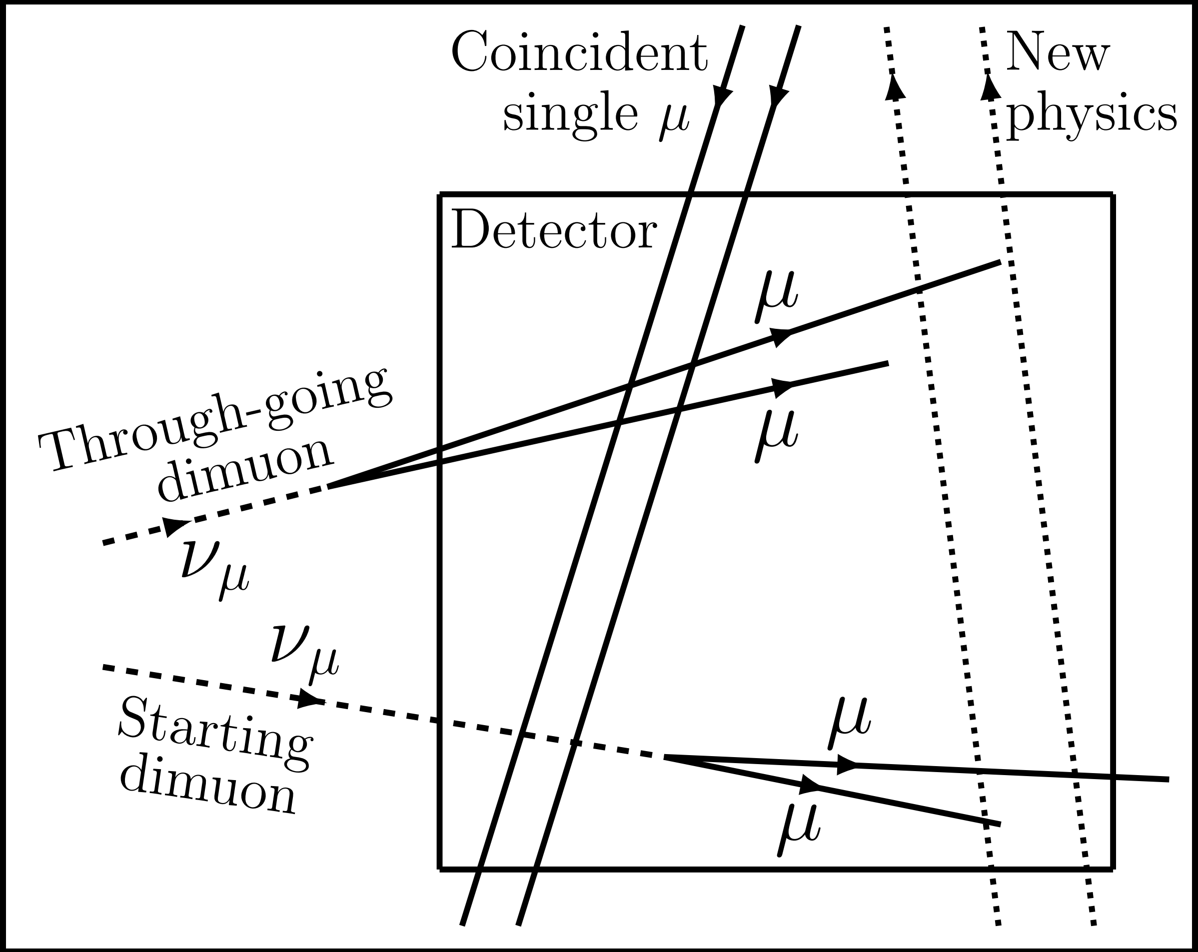
Shower (e or hadron)



Double shower/bang (τ)

- We are having more and more TeV—PeV neutrino detectors
  - IceCube, KM3NeT, BaiKal-GVD, P-ONE, IceCube-Gen2, …
- New event classes are needed to get more physics from the data

What is dimuon (double muon)

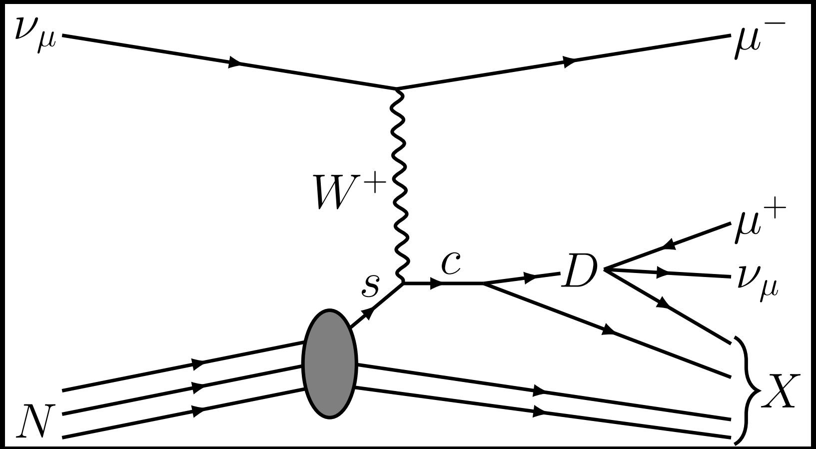


- Coincident single muons
  - background for dimuon,
  - negligible for most cases
- Standard model dimuon
  - Interesting, focus of our work
- BSM dimuon
  - E.g., double staus from SUSY models
  - More to be studied in this direction

(BZ, Beacom, 2110.02974)

How could one neutrino produce two muons

Deep inelastic scattering (DIS)

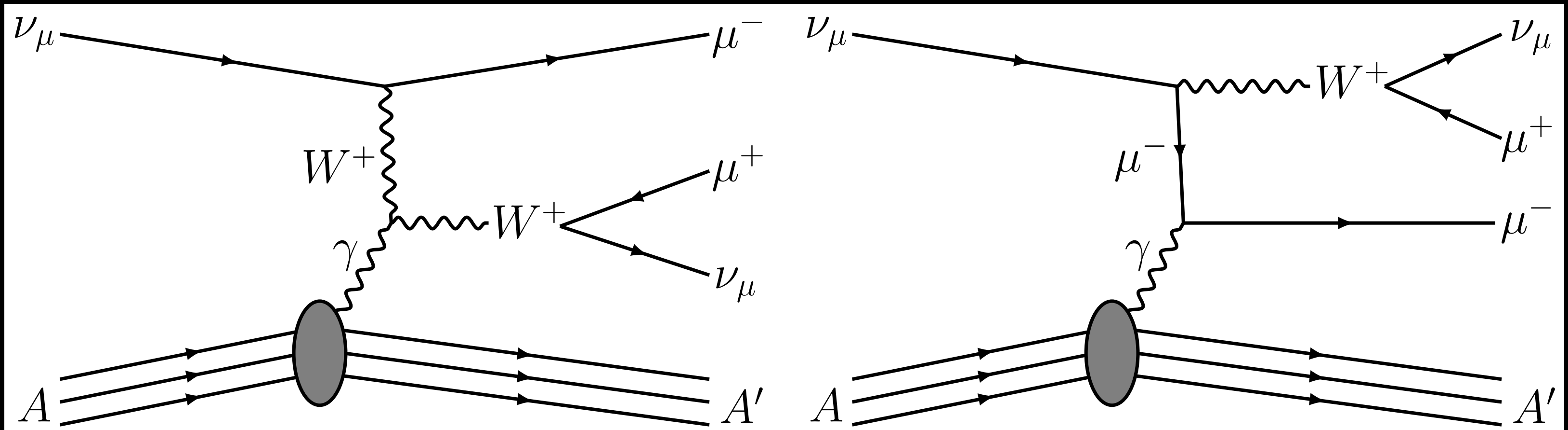


DIS is the dominate channel for detecting high-energy neutrinos.

Detected at tens—hundreds GeV, never above a TeV.

Important for QCD studies.

(On-shell) W-boson production (WBP)



(BZ, Beacom, 1910.08090, 1910.10720)

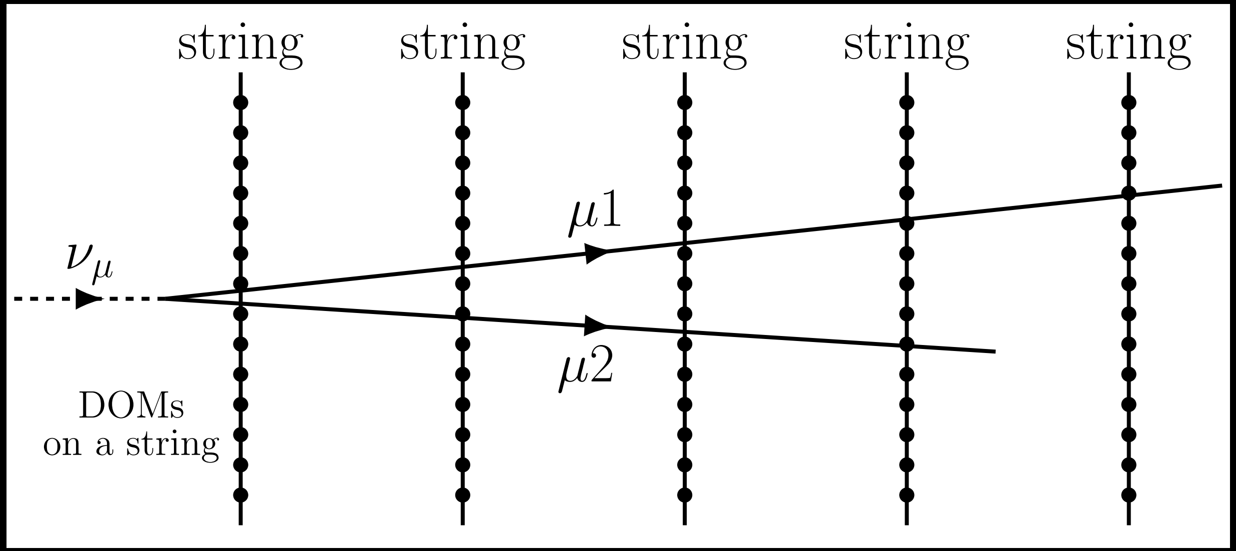
WBP is the 2nd most important channel for detecting high-energy neutrinos,

but never identified yet.

First hypothesized/calculated in 1960…

How to detect dimuons in TeV--PeV neutrino telescopes

Inside a HE neutrino detector



(BZ, Beacom, 2110.02974)

Angular threshold:

$$R_{\mu 2}\theta_{\mu\mu} > 2D_{\mathrm{v}}$$

μ1-μ2 separation

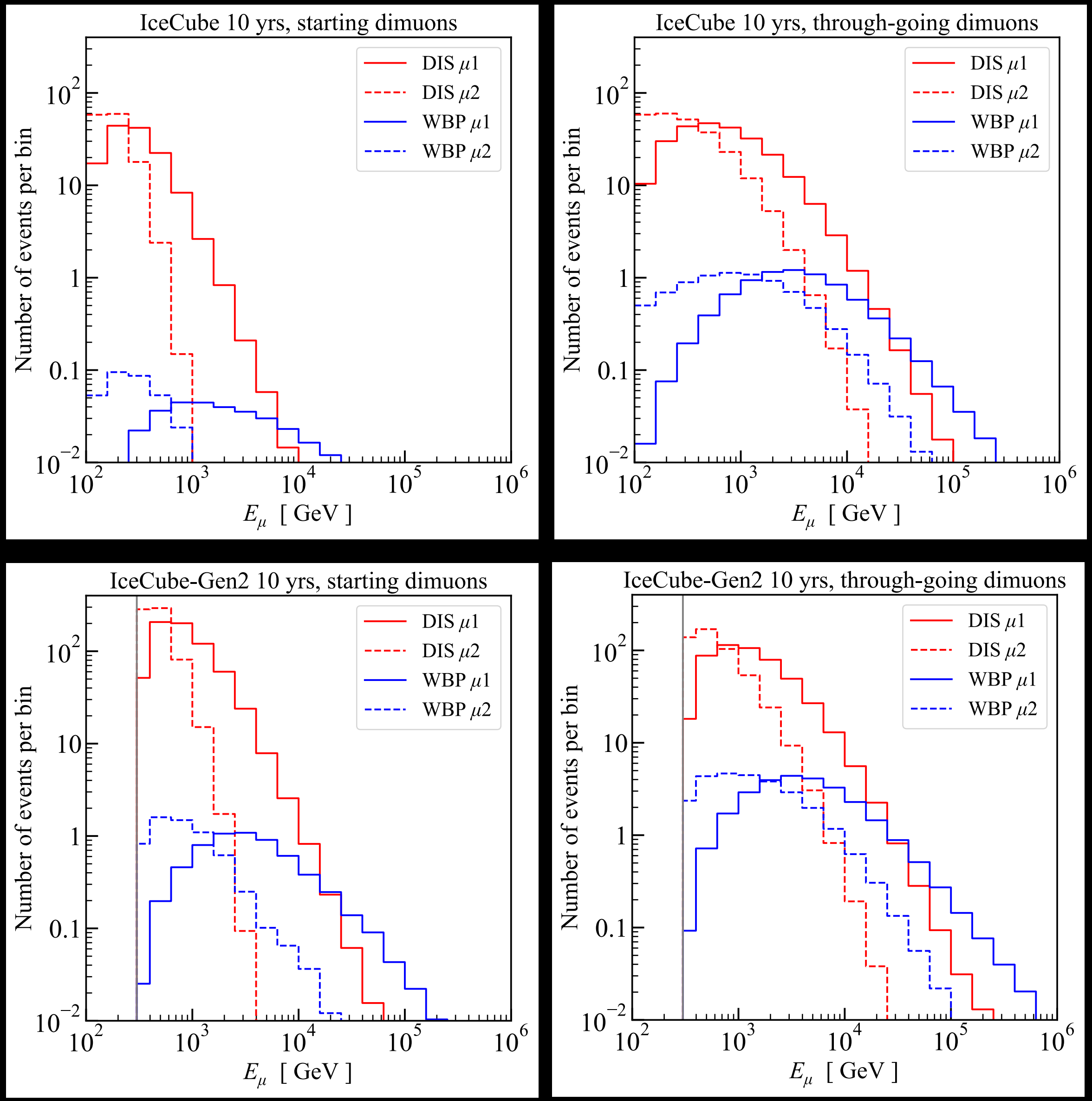
Spacing between adjacent DOMs

Energy Threshold:

100 GeV for IceCube
300 GeV for IceCube-Gen2

Dimuon rates in IceCube and IceCube-Gen2

Skipping all the calculational details (see *2110.02974*)…



Our predicted number of dimuons

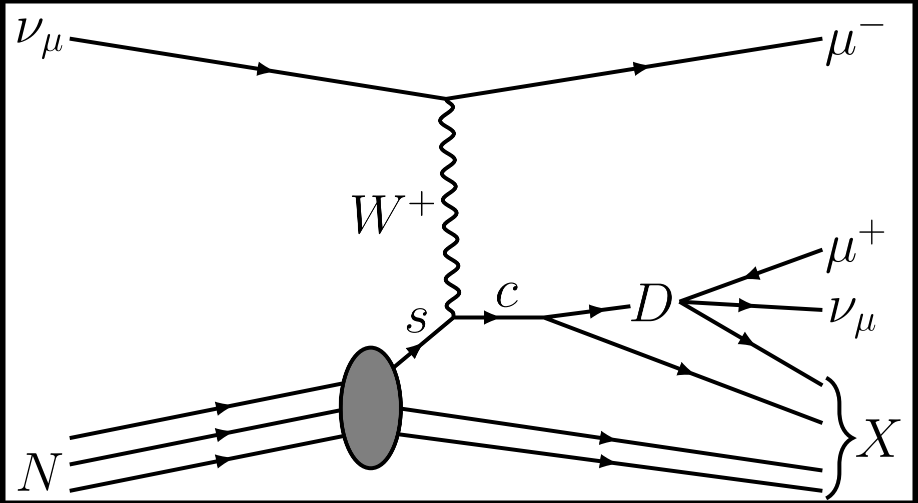
	Starting		Throughgoing	
	DIS	WBP	DIS	WBP
IceCube, 10 yrs	140	0.4	250	8
IceCube-Gen2, 10 yrs	680	6	510	27

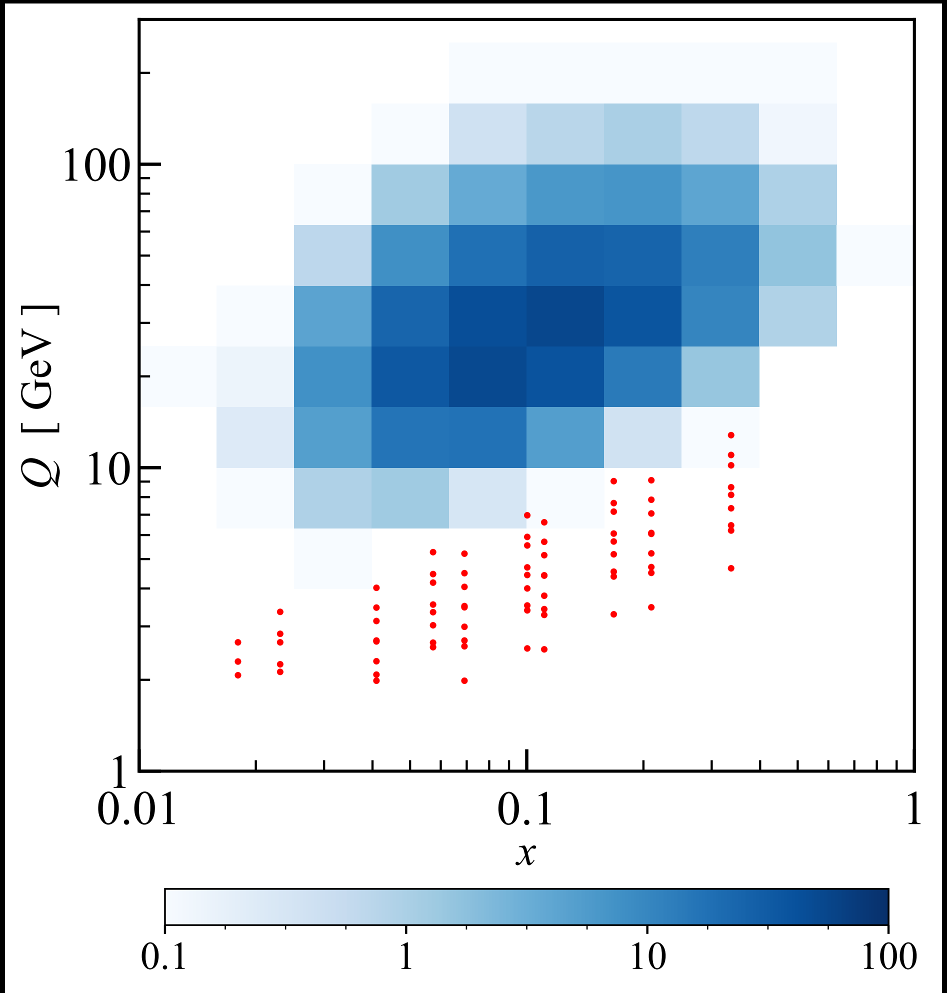
(Note IceCube has run for > 10 years)

Physics potential: measuring the strange-quark PDF

(Note this measurement can be done with current IceCube data)

Deep inelastic scattering (DIS)



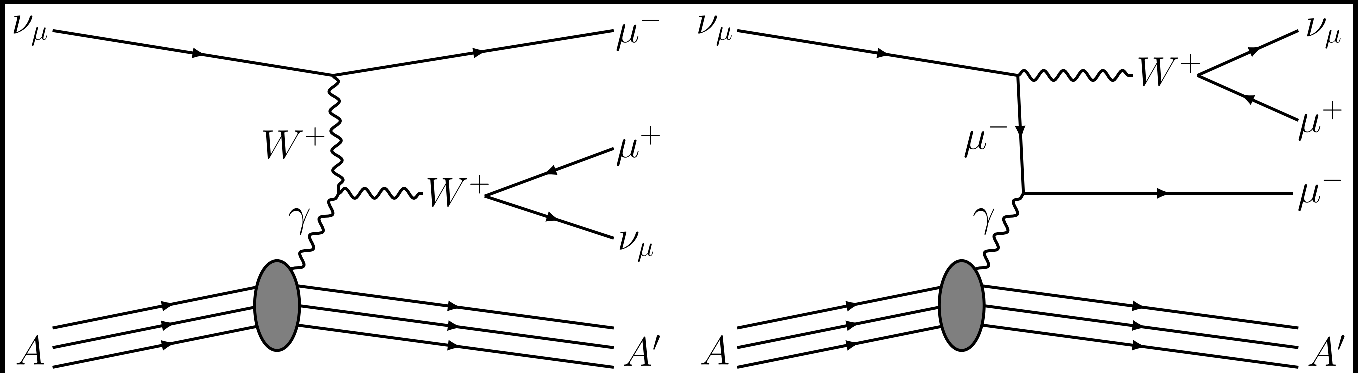


(BZ, Beacom, 2110.02974)

Physics potential: first detection of WBP

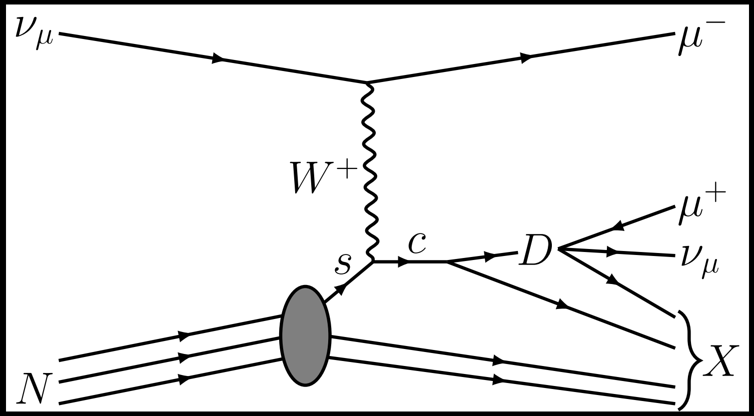
with showerless starting dimuons

Signal: W-boson production (WBP)

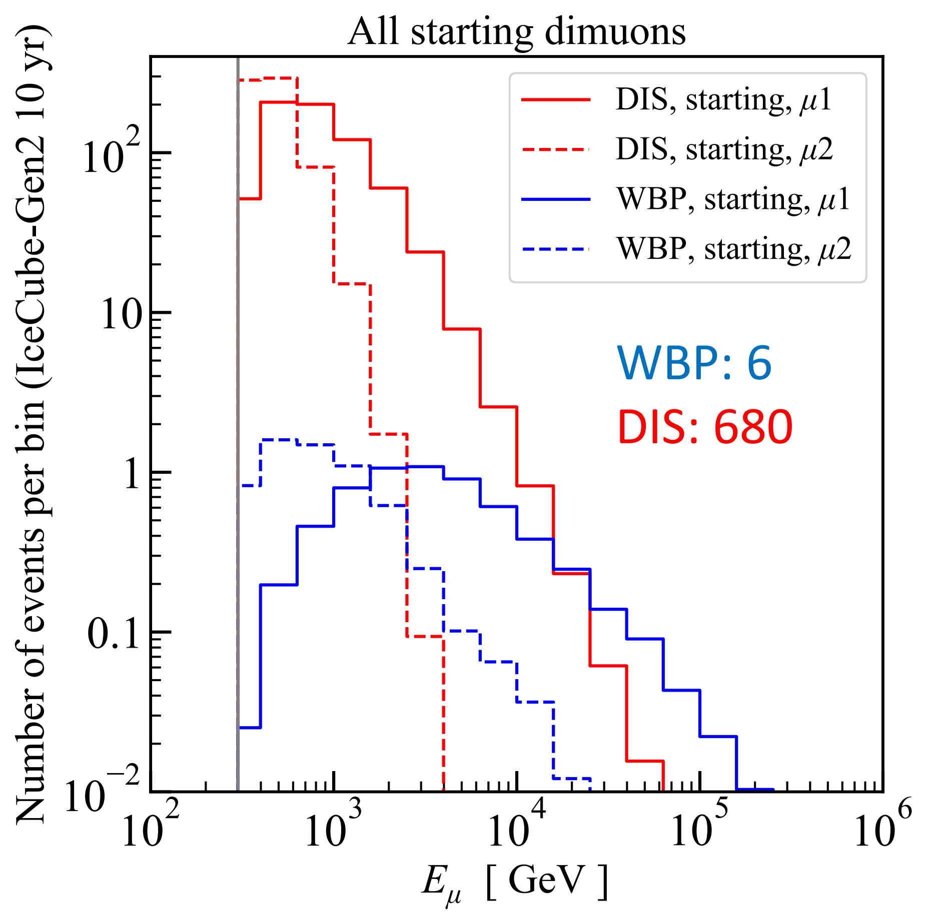


A': No shower

Background: deep inelastic scattering (DIS)



X: Mostly shower



(BZ, Beacom, 2110.02974)

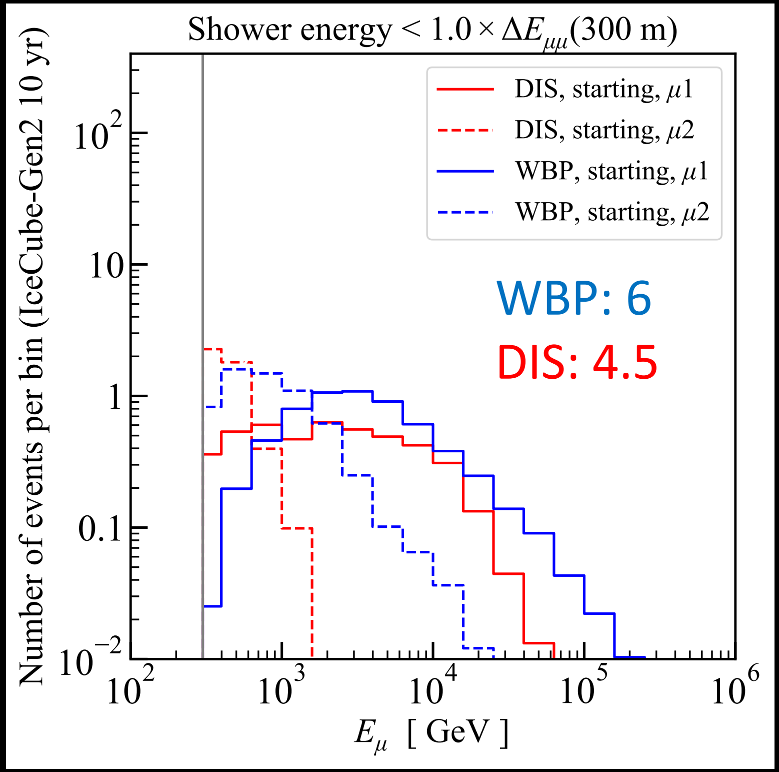
Physics potential: first detection of WBP

with showerless starting dimuons

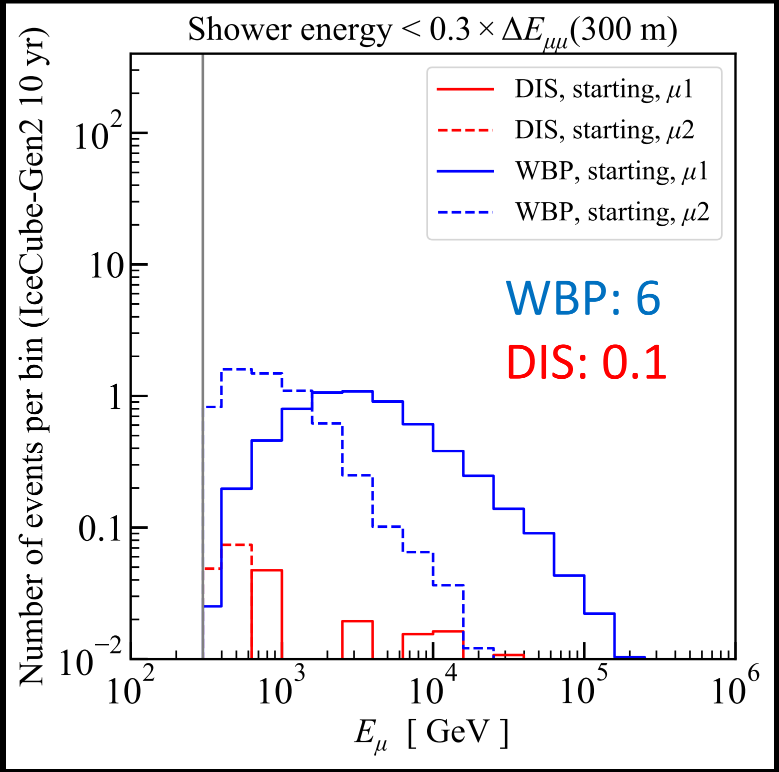
Shower energy threshold

$$E_{\text{shower}} < f \times \Delta E_{\mu\mu}(L)$$

L = 300 m >~ spatial resolution
f ~ energy resolution



f = 1.0



f = 0.3

(BZ, Beacom, 2110.02974)

Observation part: found 19 dimuon candidates

Dataset and analysis

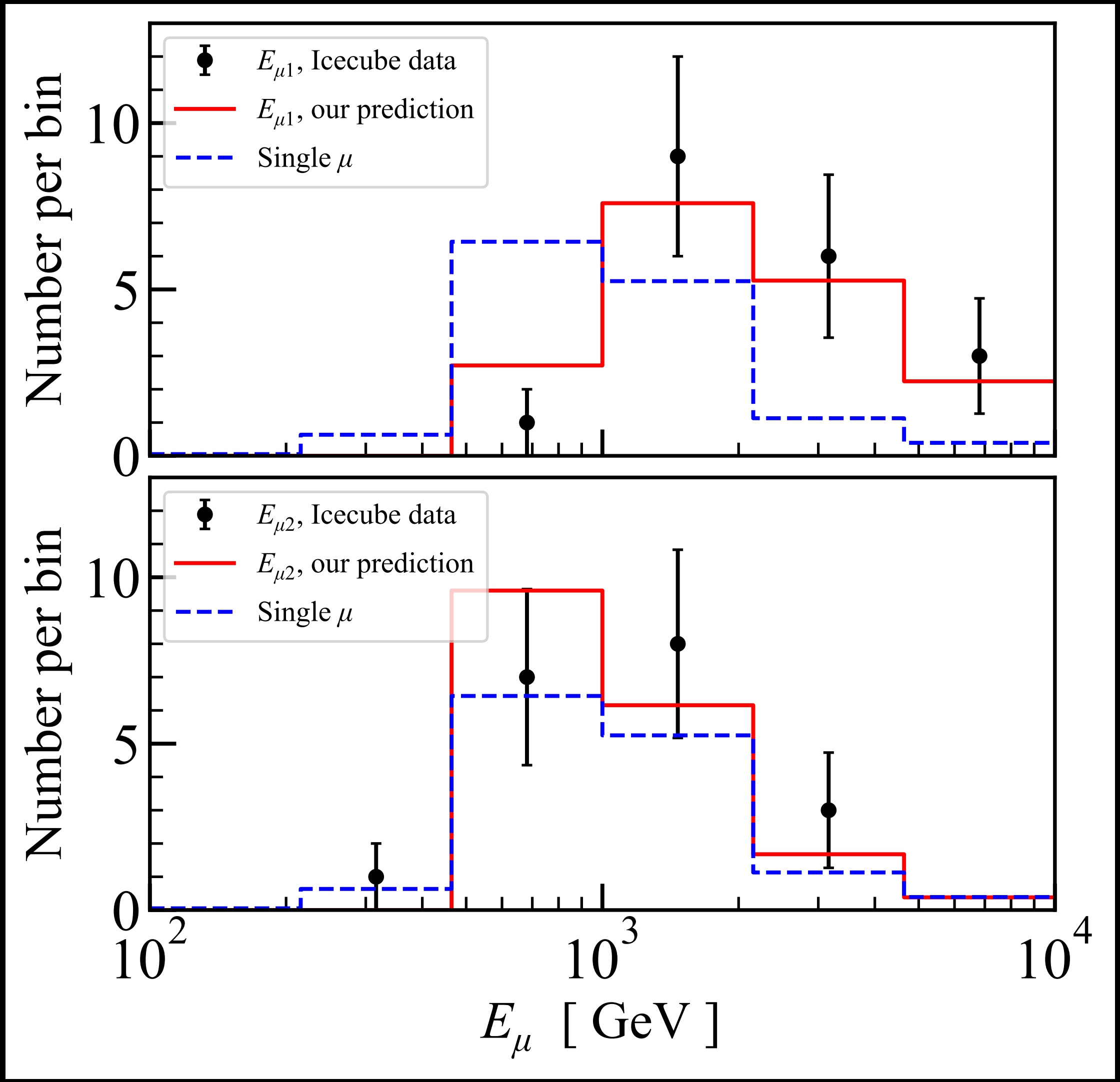
- Ten years of public IceCube data (1,134,450 muon events; 2008--2018)
- Data obtained after multiple strong cuts optimized for point-source search, not dimuon search.
- We analyze the data by looking for muon pairs arriving close in time and direction

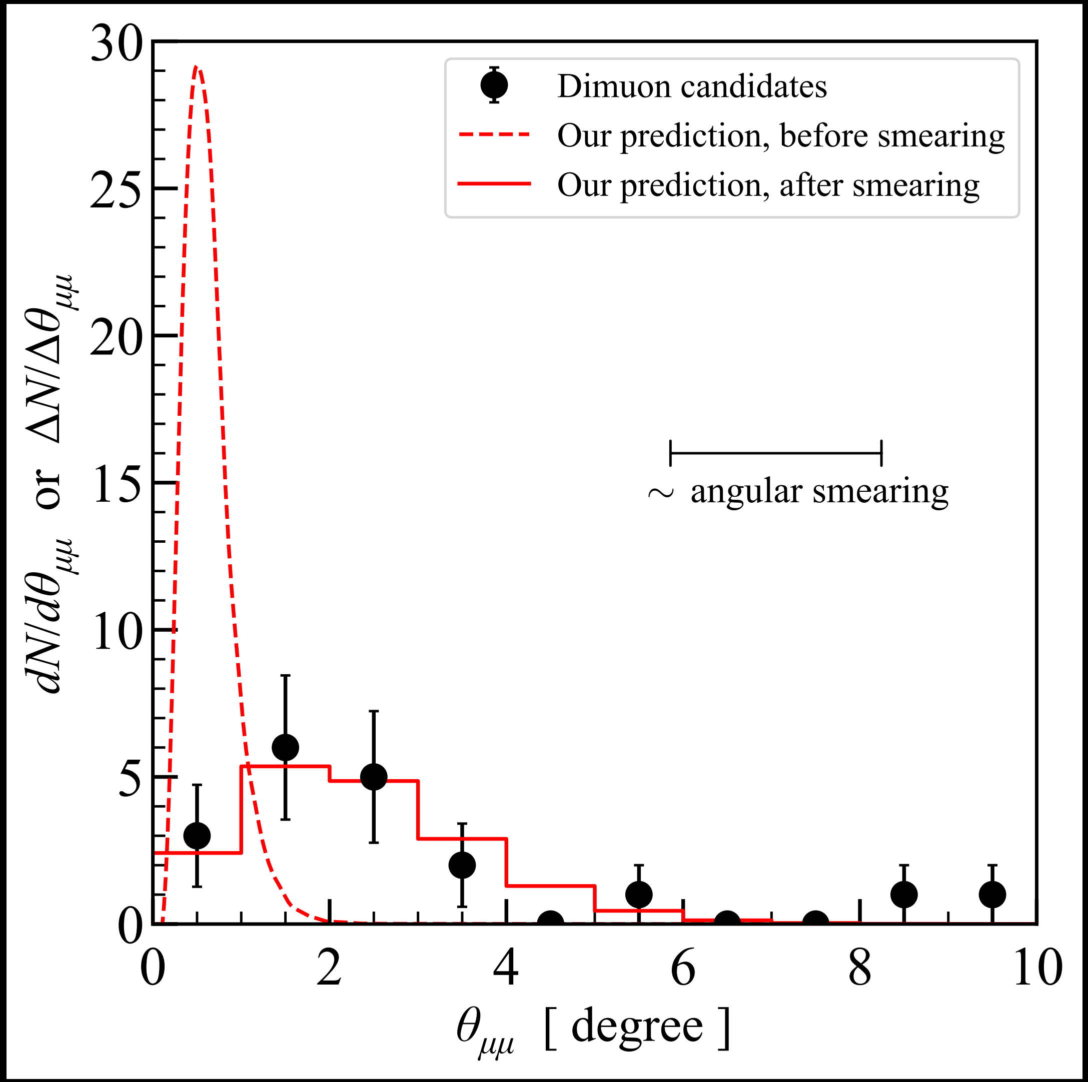
List of the 19 dimuon candidates we found

MJD1 [day]	MJD2 (= MJD1)	$E_{\mu 1}$ [TeV]	$E_{\mu 2}$	RA1 [deg]	RA2	Dec1	Dec2	AngErr1	AngErr2	AngDis	DisErr
56068.26557772	56068.26557772	1.23	1.05	25.065	25.860	18.168	18.466	0.38	1.85	0.81	1.89
56115.78056499	56115.78056499	2.29	0.65	296.835	296.891	41.777	46.922	3.10	0.41	5.15	3.13
56235.14756523	56235.14756523	2.19	2.19	179.781	185.182	20.271	28.274	2.50	1.57	9.39	2.95
56582.68675378	56582.68675378	2.29	1.35	120.687	121.892	26.630	24.994	1.47	0.78	1.96	1.66
56653.19502448	56653.19502448	3.31	1.48	48.106	47.781	30.840	30.100	0.75	1.19	0.79	1.41
56784.87114671	56784.87114671	1.35	0.35	126.690	126.357	69.524	70.871	1.97	2.83	1.35	3.45
56813.78701082	56813.78701082	0.91	0.83	184.136	181.708	31.627	31.957	3.01	0.83	2.09	3.12
56895.78341718	56895.78341718	1.91	0.79	295.288	303.817	14.387	16.670	1.94	1.61	8.53	2.52
56932.15214130	56932.15214130	1.70	0.98	175.546	173.549	36.710	35.972	1.17	0.86	1.77	1.45
56940.02405671	56940.02405671	5.13	3.72	1.404	0.541	11.716	9.353	3.13	2.38	2.51	3.93
57214.99298310	57214.99298310	1.51	0.83	13.089	14.760	39.101	39.034	3.50	0.85	1.30	3.60
57376.46221142	57376.46221142	1.66	1.55	326.795	328.022	17.543	15.199	2.11	1.15	2.62	2.40
57461.19606500	57461.19606500	1.35	1.10	308.771	307.274	31.268	30.077	1.08	1.37	1.75	1.74
57499.81363094	57499.81363094	5.89	1.70	199.430	201.527	16.454	15.029	2.55	1.30	2.47	2.86
57560.74070687	57560.74070687	1.74	0.79	219.566	219.023	12.582	13.008	1.62	0.74	0.68	1.78
57650.26270928	57650.26270928	6.17	2.40	256.189	255.088	19.588	20.293	2.03	0.77	1.25	2.17
57661.79317519	57661.79317519	1.45	0.91	24.276	21.095	23.145	24.317	1.72	2.22	3.14	2.81
58003.09416087	58003.09416087	2.29	1.23	349.095	345.586	21.328	19.554	2.17	1.30	3.74	2.53
58266.46093610	58266.46093610	2.63	1.48	296.881	294.994	19.596	20.896	1.57	1.45	2.20	2.14

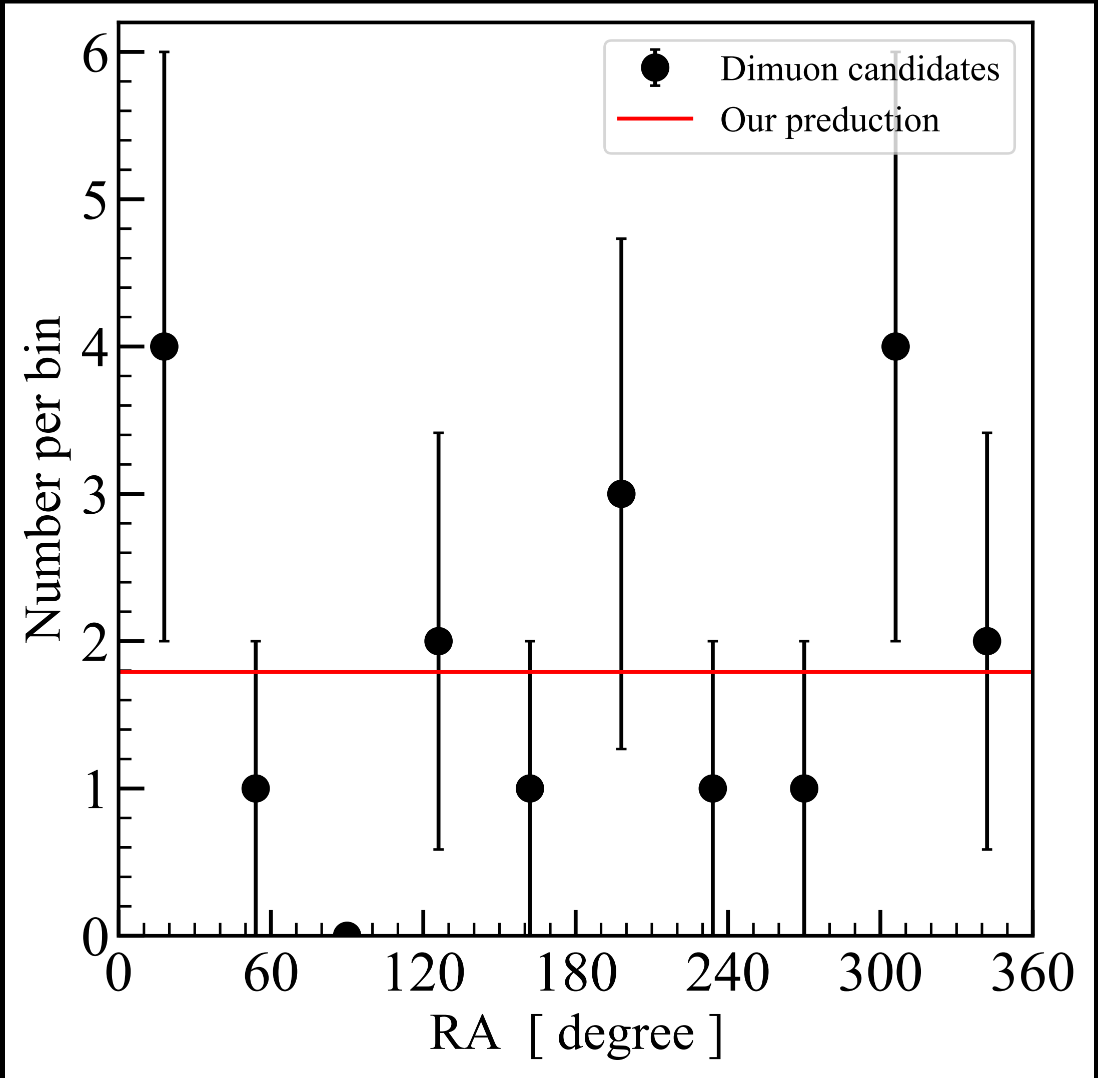
(BZ, Beacom, 2110.02974)

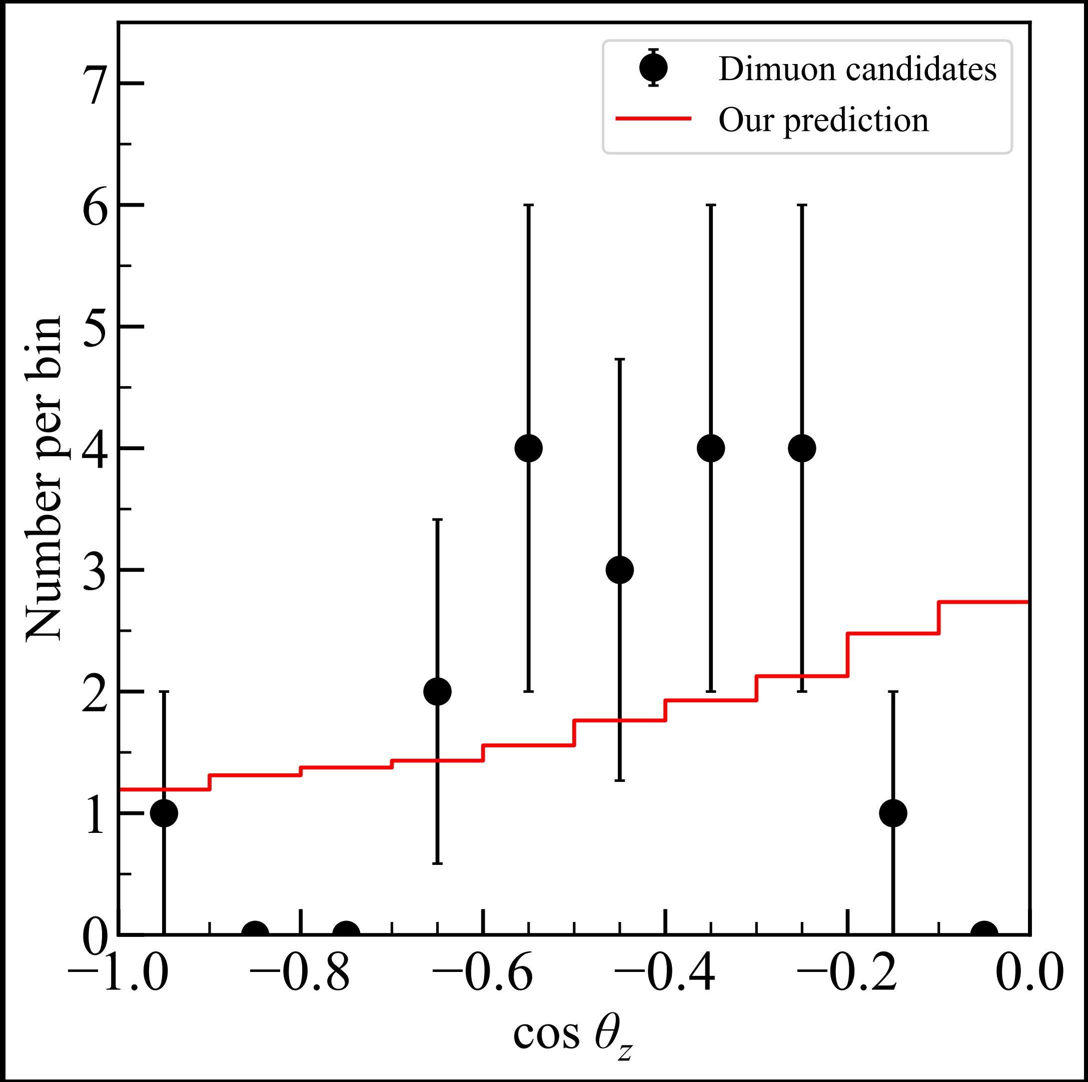
Agree with our prediction: energy & angular distribution





Agree with our prediction: sky distribution





Then, why they may not be dimuons…

Concerns

- DAQ system of IceCube
- Saves all the data within 10 microseconds as one event.
- However, we don't know if their algorithm identified the two muons in one event and reported them in the dataset.

Alternative explanation(s)

- Afterpulsing of photomultiplier tubes
- A photomultiplier triggers itself it shortly after being triggered
- However, this is unlikely because afterpulsing
  - is random, hard to be fit as a muon
  - is much less energetic.

Possible outcomes of the candidates

- The 19 dimuon candidates are found to be real
    - Then this will be the first detection of dimuons in a neutrino telescope or in any experiments above a TeV
- Some or all of them turn out to be something else
    - The candidates may be some unknown background (or signal!, new physics?)

- In any case, all the theoretical part in the previous slides are not affected
- A dimuon-optimized search in IceCube data should find much more dimuons than 19

Conclusion

- We studied dimuons as a new event class for high-energy neutrino telescopes
- IceCube has ≃400 events and IceCube-Gen2 will detect ≃1200 in 10 years
- Significant physic potentials, including but not limited to
  - Measuring strange quark PDF
  - Enabling the first detection of W-boson production
  - Better energy measurements
  - Background of new physics signatures
- We analyzed the limited IceCube public data and found 19 dimuon candidates
  - Could be first detection of dimuons in a neutrino telescopes or in any experiments above a TeV or could be some unknown background (or new signal!).
  - No matter what they turn out to be, it doesn't affect our theoretical studies above
- Dimuon may be a new direction for high-energy neutrinos

Thanks for your attention!

Glashow resonance vs. W-boson production

	Glashow resonance	W-boson production
Process	$\bar{\nu}_e + e^- \rightarrow W^-$	$\nu_x + A \rightarrow x^- + W^+ + A'$ $\bar{\nu}_\mathrm{x} + A \rightarrow x^+ + W^- + A'$
Neutrino energy	$E\nu \simeq$ 6.3 PeV	$E\nu$ > ~10 TeV
First predicted by	Sheldon L. Glashow	T. D. Lee & C. N. Yang
First predicted in	1960 (Phys. Rev.)	1960 (PRL)
First "Detected" in	March 2021, IceCube (2.3σ; *Nature*)	

WBP could produce ~10 times more W bosons in neutrino telescopes

(BZ, Beacom, 1910.10720, PRD)