“New” interactions and signatures for high-energy neutrinos

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Outline

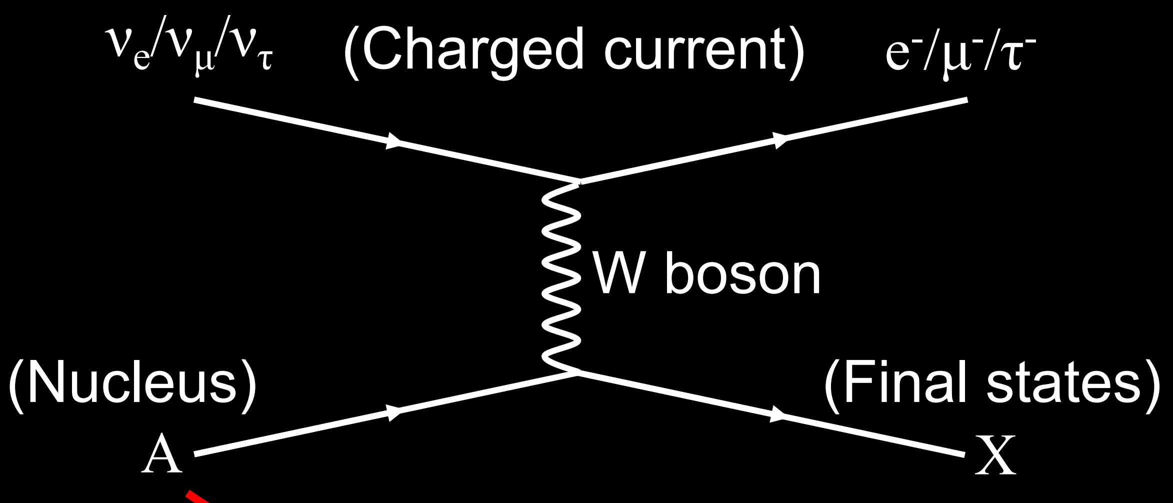
1. Neutrino-nucleus W-boson and trident production (1910.08090, 1910.10720)

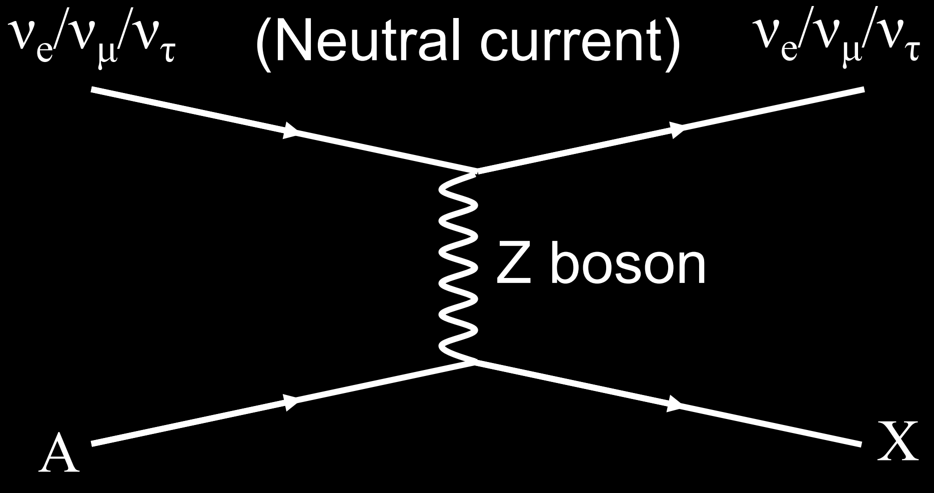
2. Dimuons from neutrino-nucleus interactions in neutrino telescopes (2110.02974)

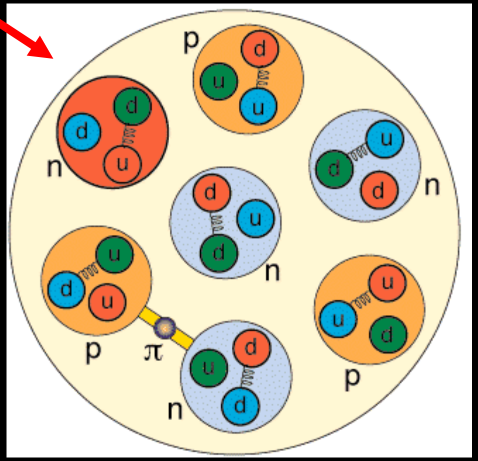
Part 1: W-boson and trident production for high-energy neutrinos

Detecting neutrinos through neutrino interactions

Deep inelastic scattering (DIS) dominates (≃1% precision)

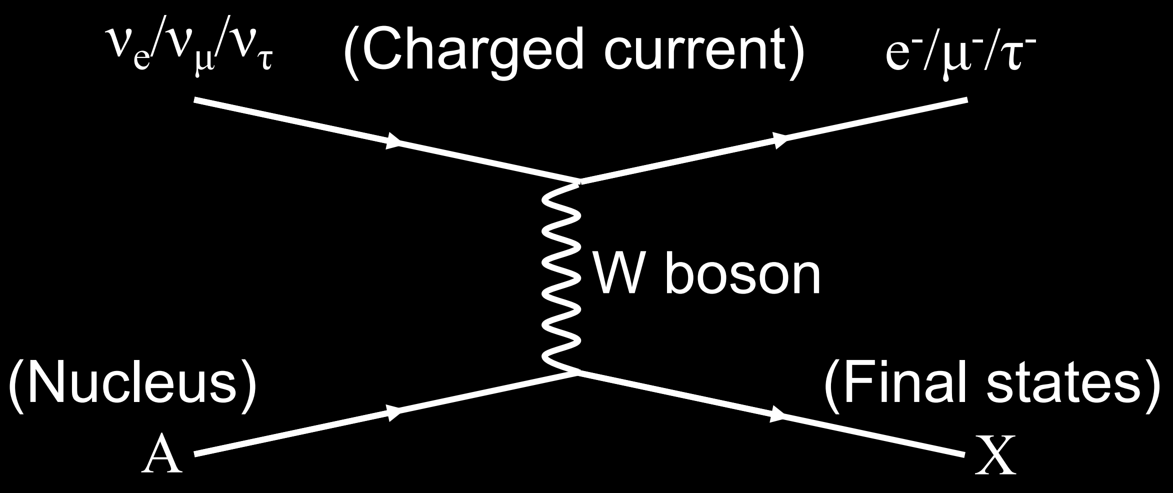


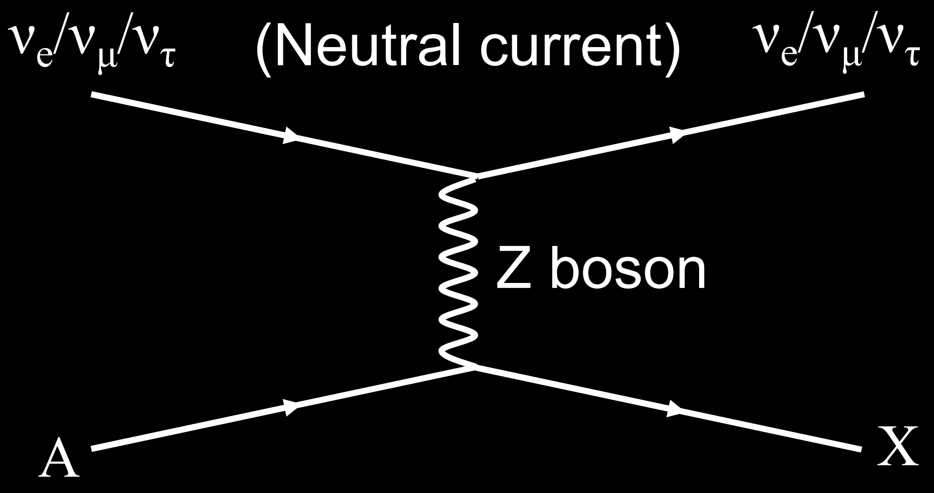




Much more data needs study subdominant interactions

Deep inelastic scattering (DIS) dominates (≃2% precision)



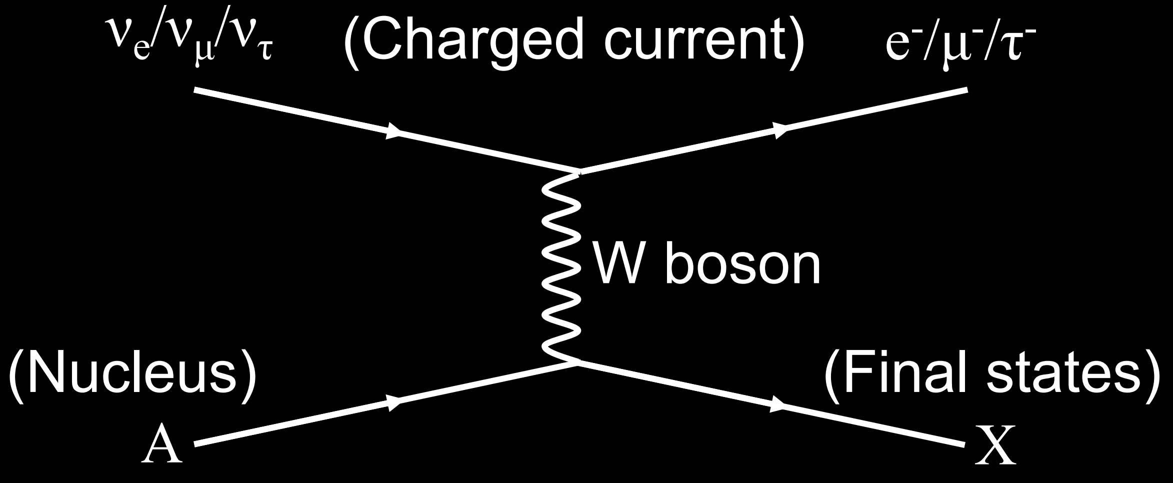


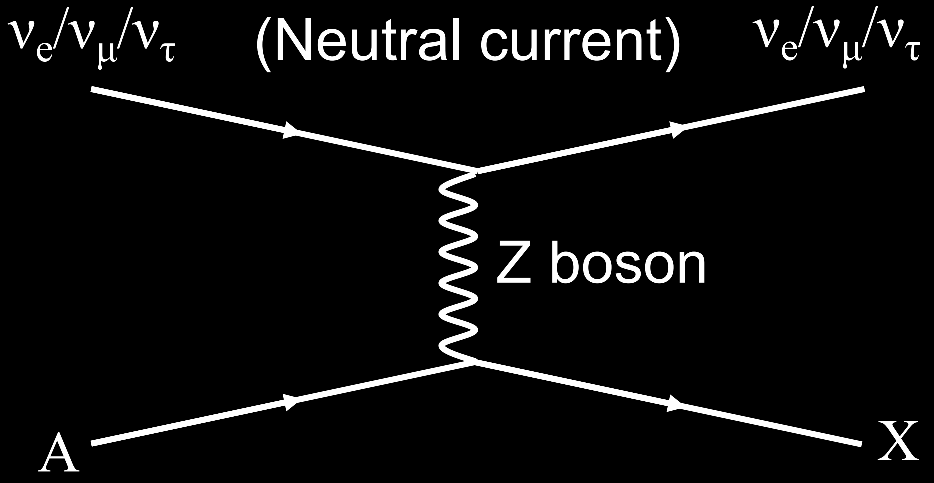
Increasing data demands studying subdominant interactions

Detector	Size	Status	Detector		Status
IceCube	1 km^3	Running for ~14 yrs	FASERν	Neutrino beam	Running
KM3NET	1 km^3	Running	FASERν2	Neutrino beam	Proposed
Baikal-GVD	1 km^3	Running, constructing			
P-ONE	multi-km^3	Proposed			
IceCube-Gen2	10 km^3	Proposed			

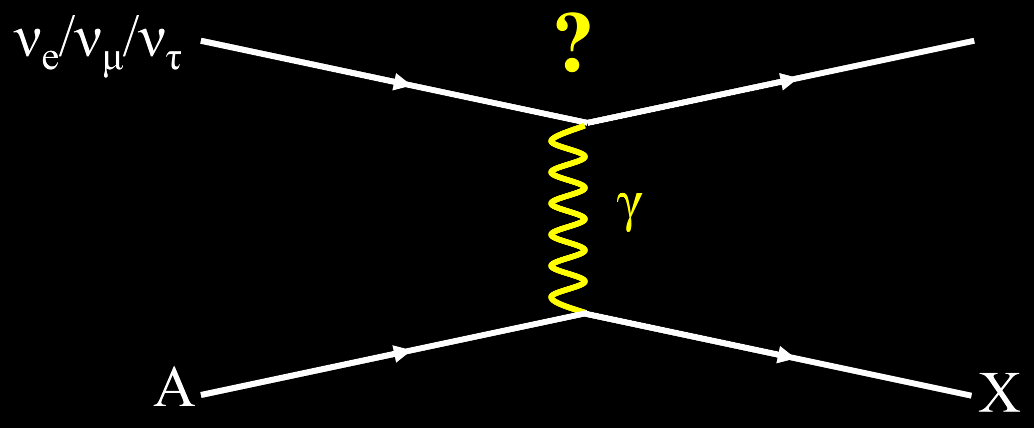
Photon coupling to nucleus

Deep inelastic scattering (DIS) dominates (≃2% precision)



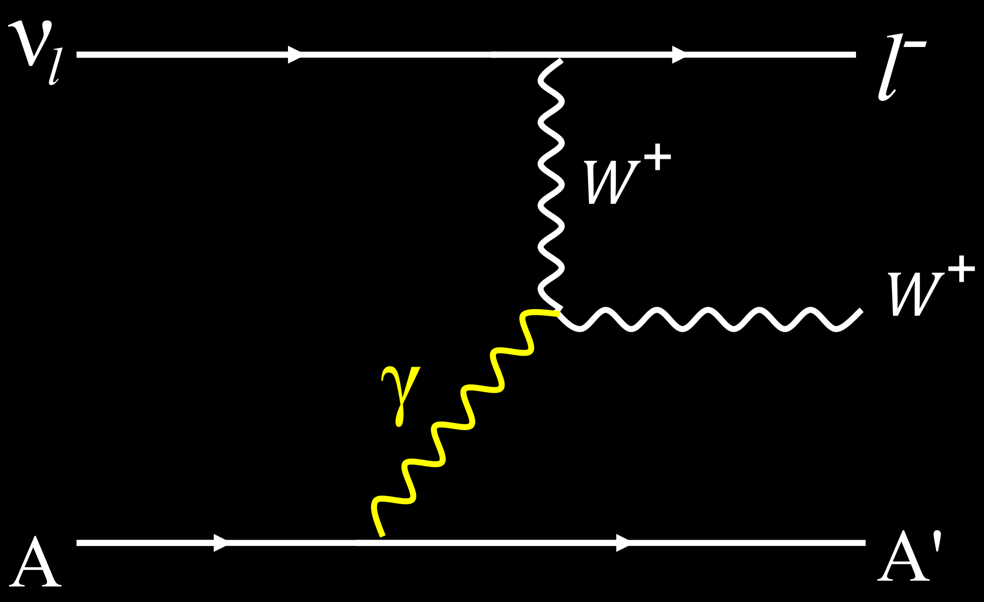


Subdominant interactions? Photon coupling to the nucleus!



Two other processes may matter

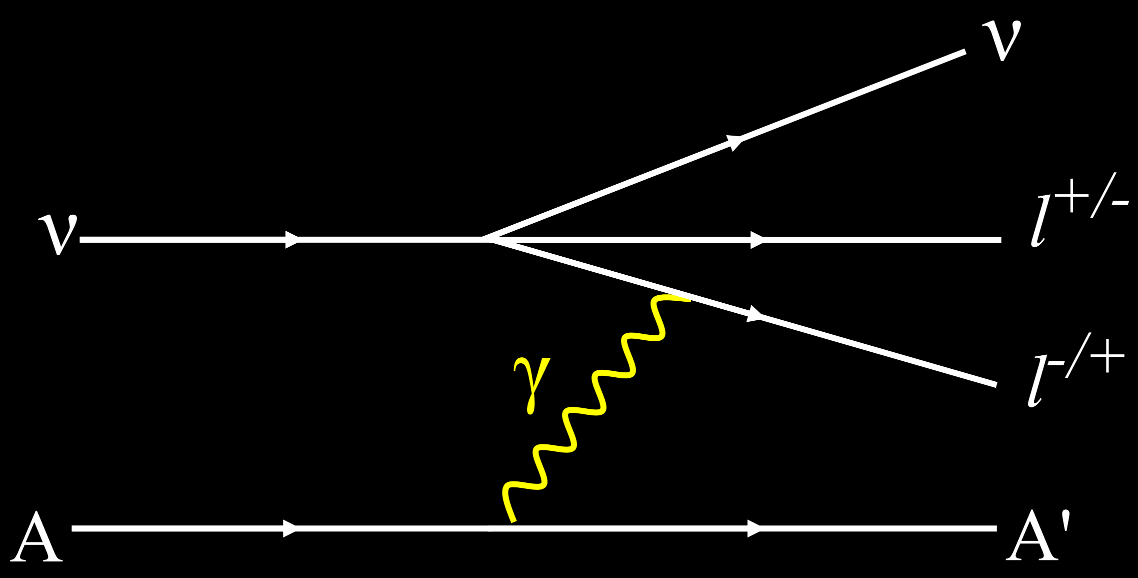
(on-shell) W-boson production



(Nucleus)

$$\nu_e + A \to e^- + W^+ + A'$$
$$\nu_\mu + A \to \mu^- + W^+ + A'$$
$$\nu_\tau + A \to \tau^- + W^+ + A'$$

Trident production

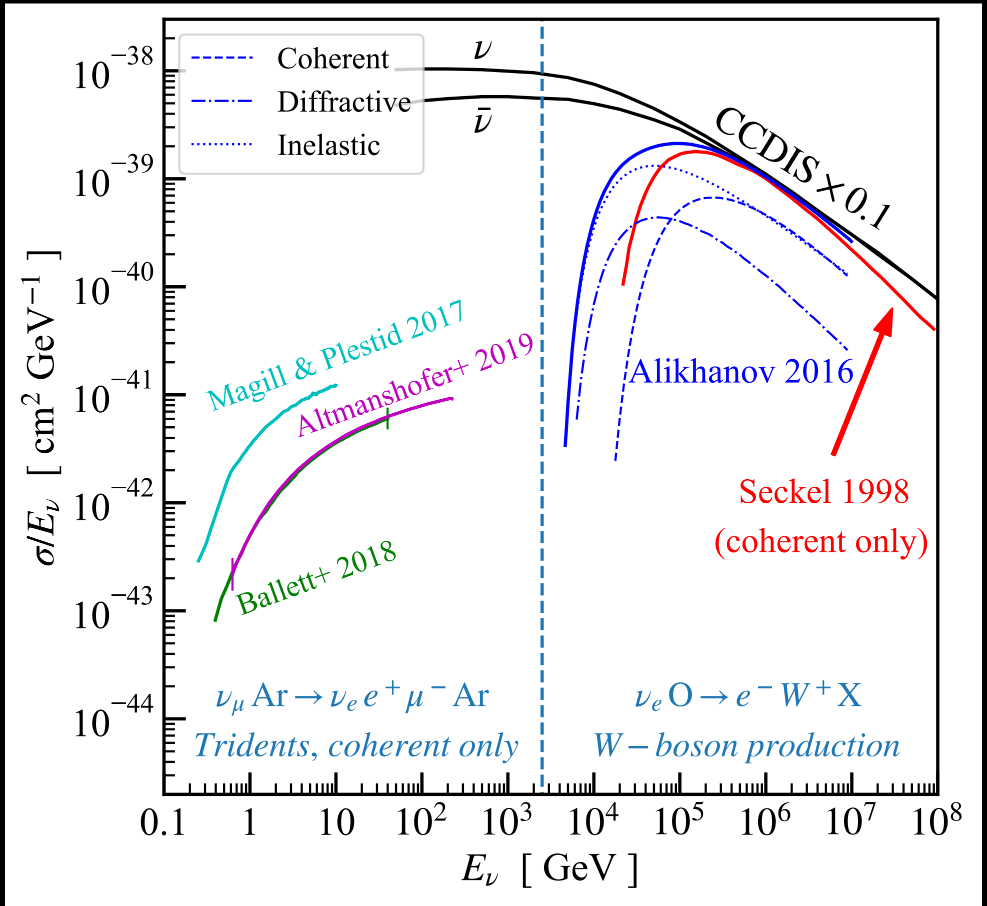


(Nucleus)

5 channels per flavor

Goals of our work

1. Cross sections

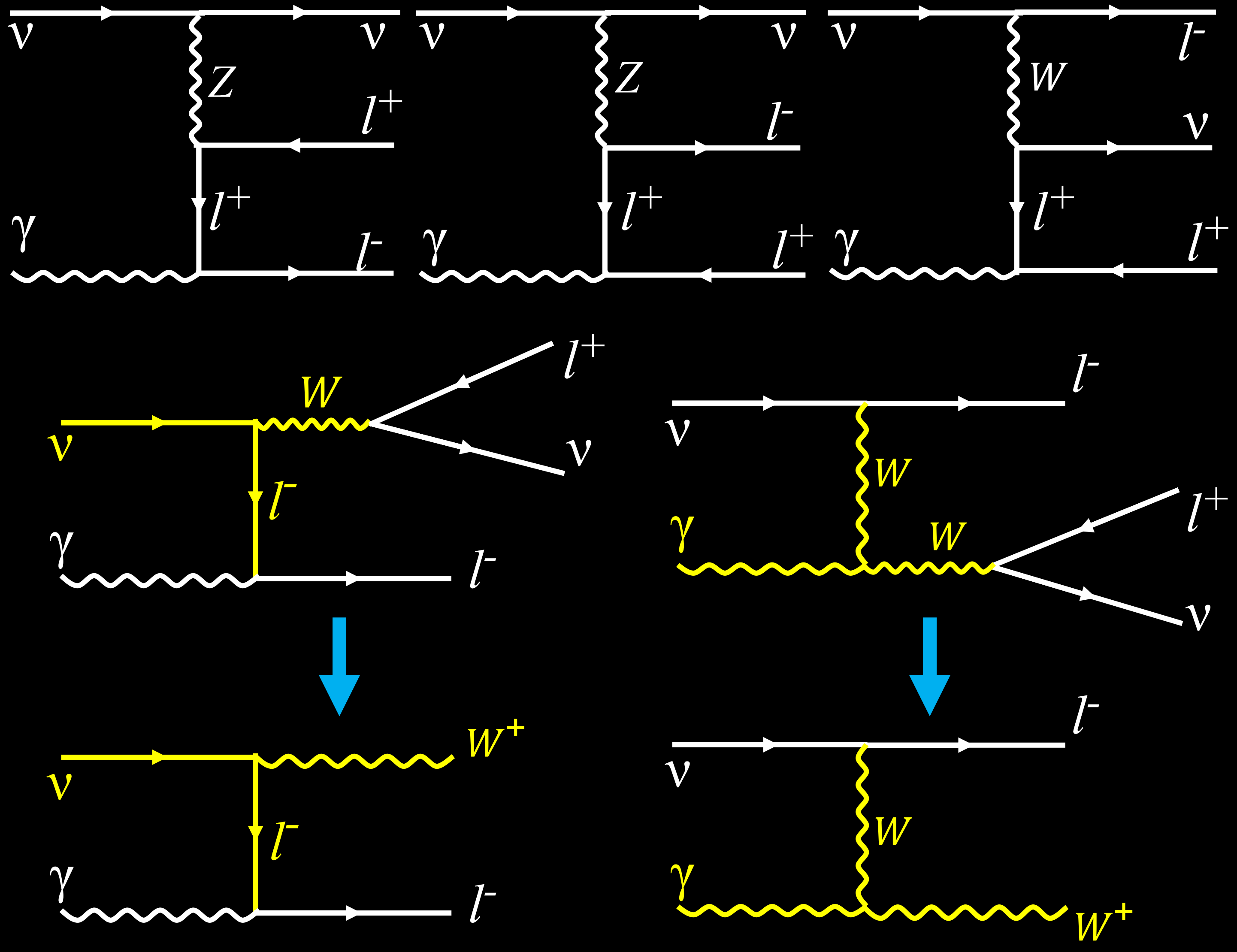


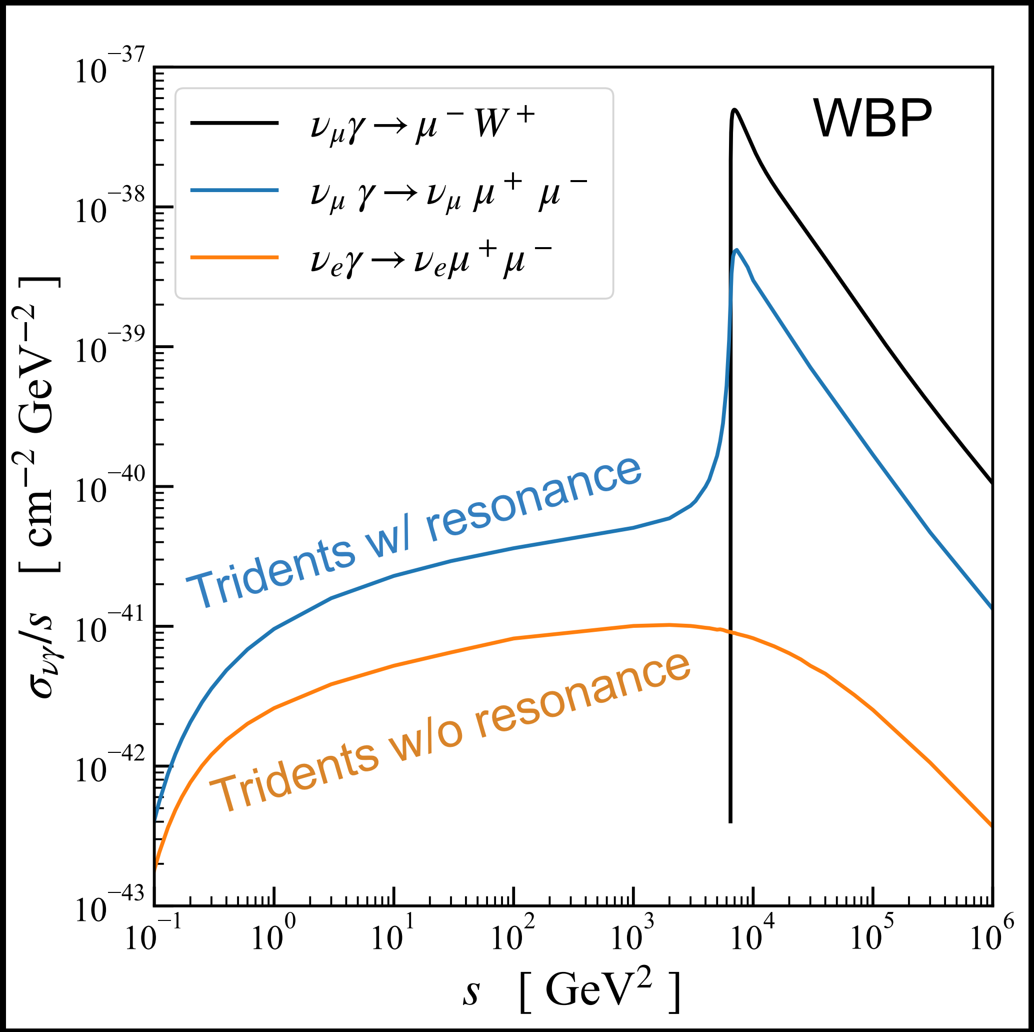
(BZ, Beacom, 1910.08090, PRD)

2. Effects on detections, etc. (Never studied before)

Part 1.1: Cross section calculations

Cross section with free photon, instead of nucleus

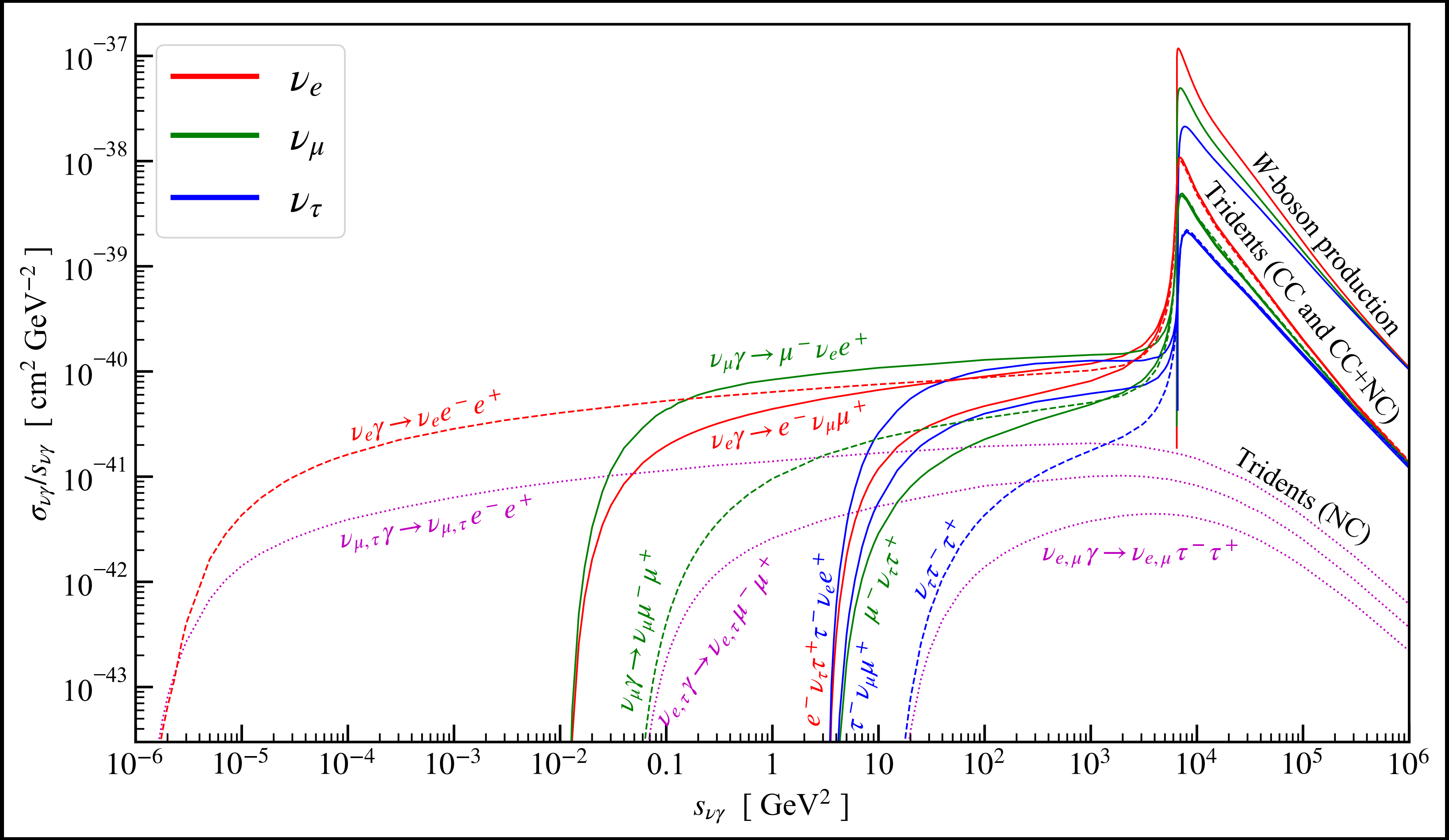




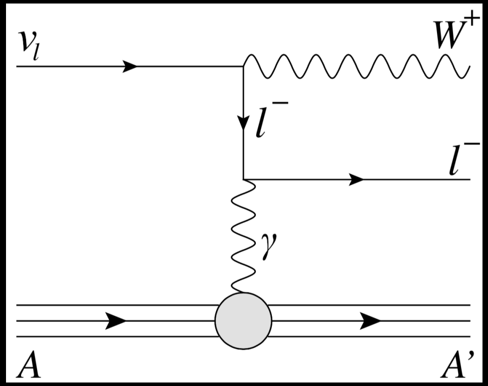
Tridents and W boson production are related

Cross section with free photon: different flavors

(BZ, Beacom, 1910.08090, PRD)

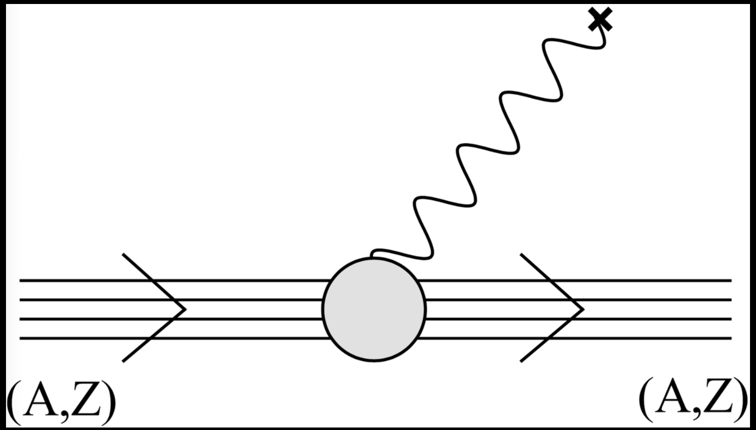


From cross section with photon to with nucleus

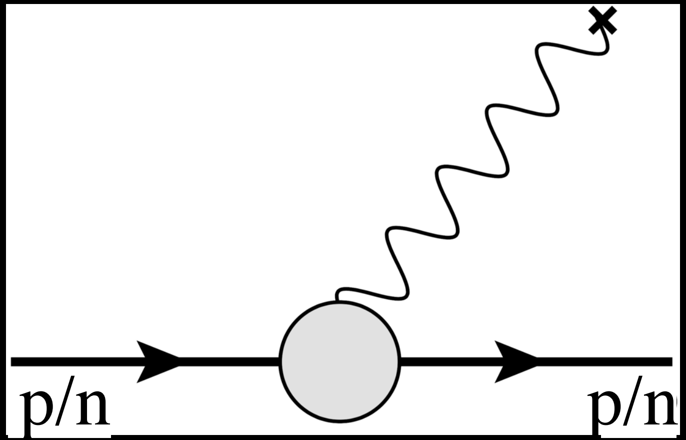


Photon from the nucleus → three kinetic regimes

Coherent (elastic)



Diffractive (elastic)



Inelastic

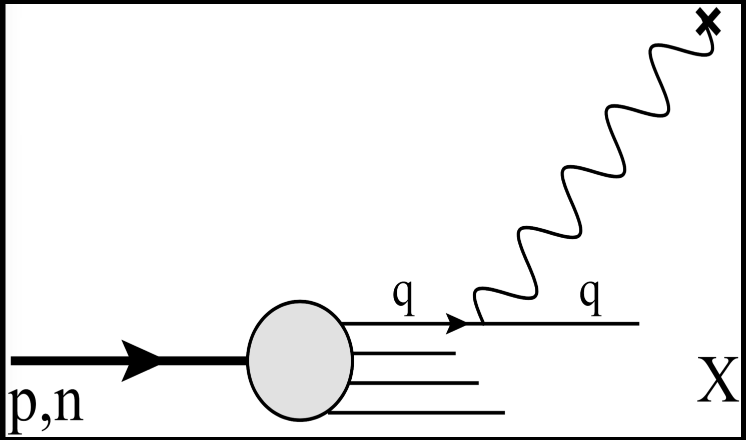
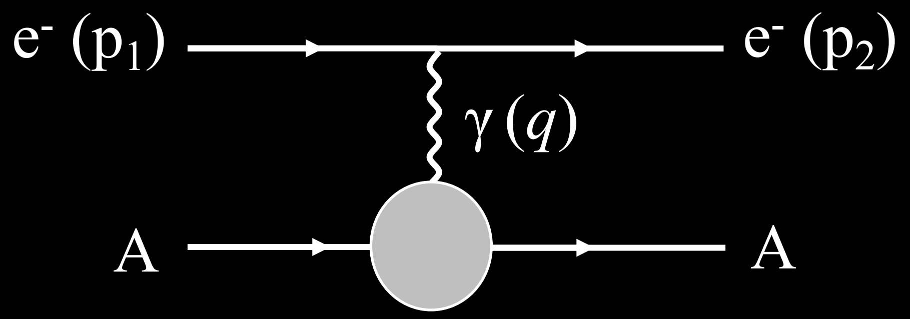


Figure from: Alikhanov, PLB, 2016 and modified

Coherent and diffractive: Invalidity of equivalent photon approximation

(or Weizsäcker-Williams approximation)

Equivalent photon approx.



$p_1 \simeq (E_1, 0, 0, E_1)$

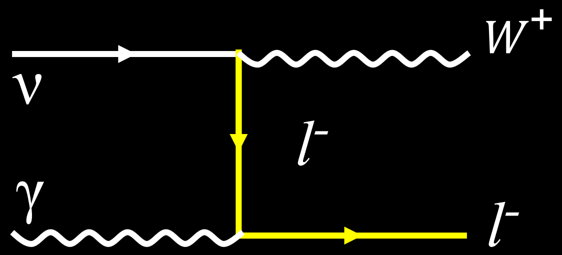
$p_2 \simeq (E_2, 0, E_2\sin\theta, E_2\cos\theta)$; $\cos\theta \simeq 1$

$q^2 = (p_2 - p_1)^2 = E_1E_2(1-\cos\theta) \simeq 0$, on shell photon.

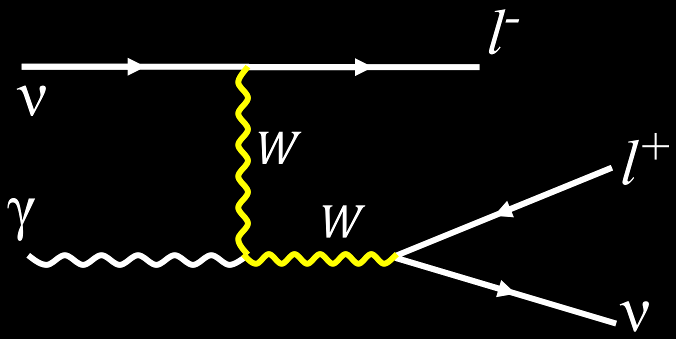
$$\sigma_{eA}(s) \simeq \int \sigma_{e\gamma}(s_{e\gamma})\, H_\gamma(s_{e\gamma}, q^2)$$

But not valid for us

W-boson production



Tridents



Ballett et al., 1807.10973 showed the invalidity of EPA for tridents.

We show invalidity for W boson production, for the first time

Coherent and diffractive: complete approach

$i\,M = L^{\mu}\frac{-ig_{\mu\nu}}{q^2}H^{\nu}$; $\frac{d^2\sigma_{\nu X}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_X^2)^2}\frac{H^{\mu\nu}L^{\mu\nu}}{q^4}$;

$$\frac{d^2\sigma_{\nu A}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}q^2}\left[\sigma_{\nu\gamma}^{T}(q^2,\hat{s})\,h_X^T(q^2,\hat{s}) + \sigma_{\nu\gamma}^{L}(q^2,\hat{s})\,h_X^L(q^2,\hat{s})\right]$$

Transverse Longitudinal

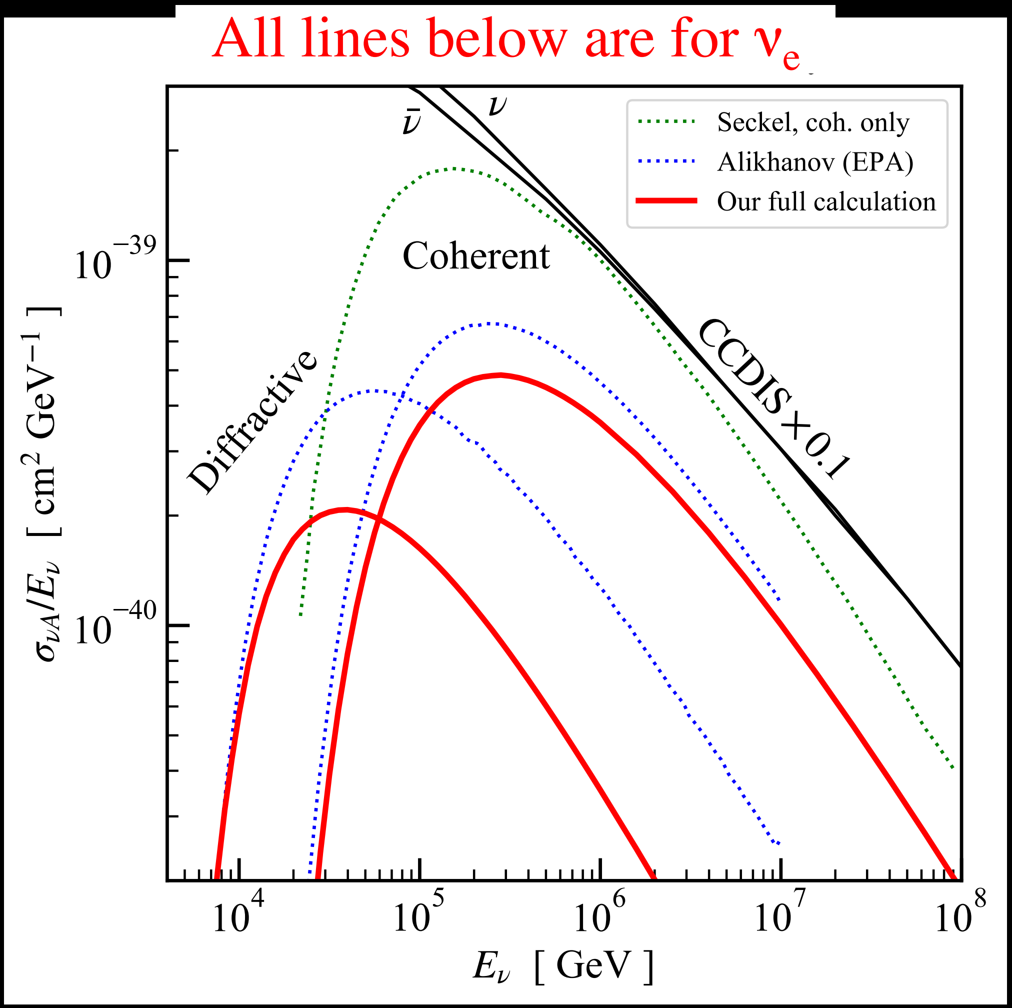
$$\sigma_{\nu\gamma}^{T}(\hat{s},\mathrm{q}^2) = -\frac{1}{2\hat{s}}\frac{1}{2}\left(g^{\mu\nu} - \frac{4Q^2}{\hat{s}^2}p_1^{\mu}p_1^{\nu}\right)L_{\mu\nu};$$

$$\sigma_{\nu\gamma}^{L}(\hat{s},\mathrm{q}^2) = -\frac{1}{\hat{s}}\frac{4Q^2}{\hat{s}^2}p_1^{\mu}p_1^{\nu}L_{\mu\nu};$$

$h_X^{T/L}$ inludes the form factors.

Diffractive regime: included Pauli-blocking effects for the first time assuming ideal Fermi gas of nucleons with equal density

(WBP as an example, similar for tridents)



EPA is not good. Pauli blocking should be included.

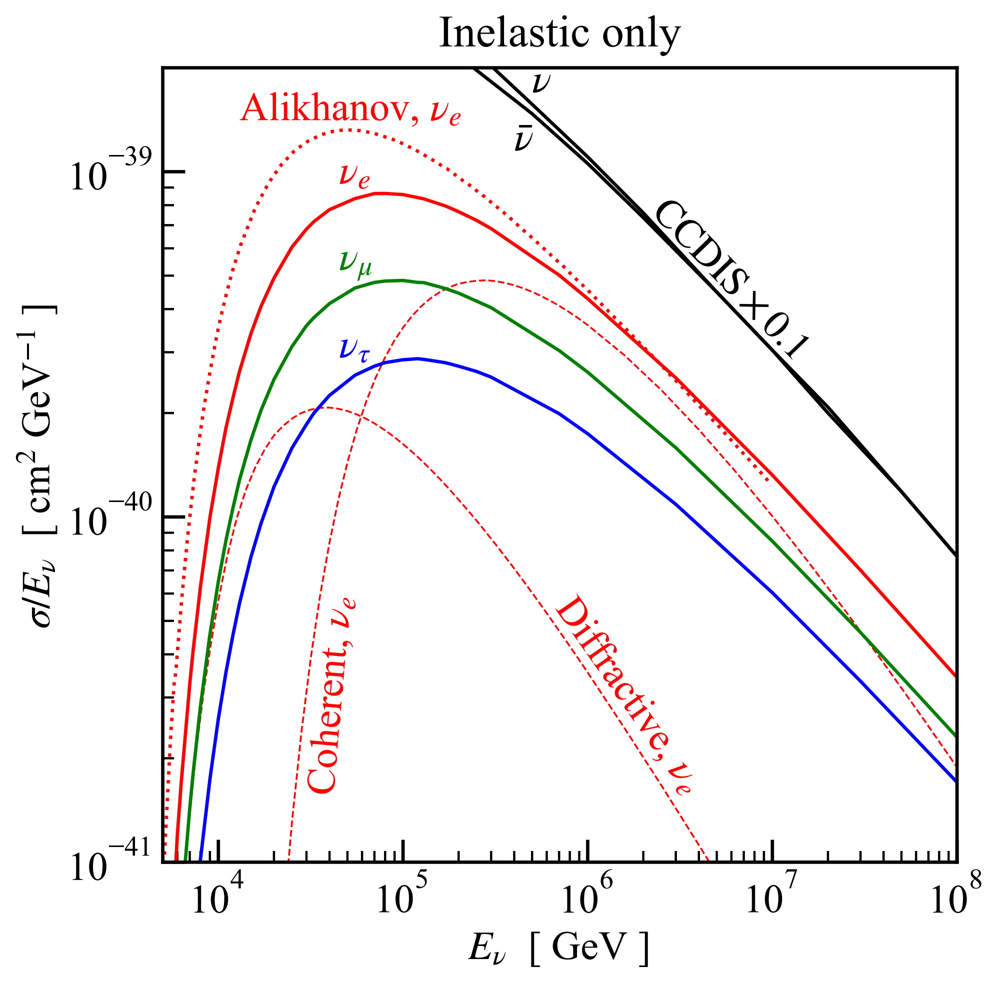
Inelastic

(BZ, Beacom, 1910.08090, PRD)

Use Photon PDF (CT14, *1509.02905*)

Use MadGraph for calculation.

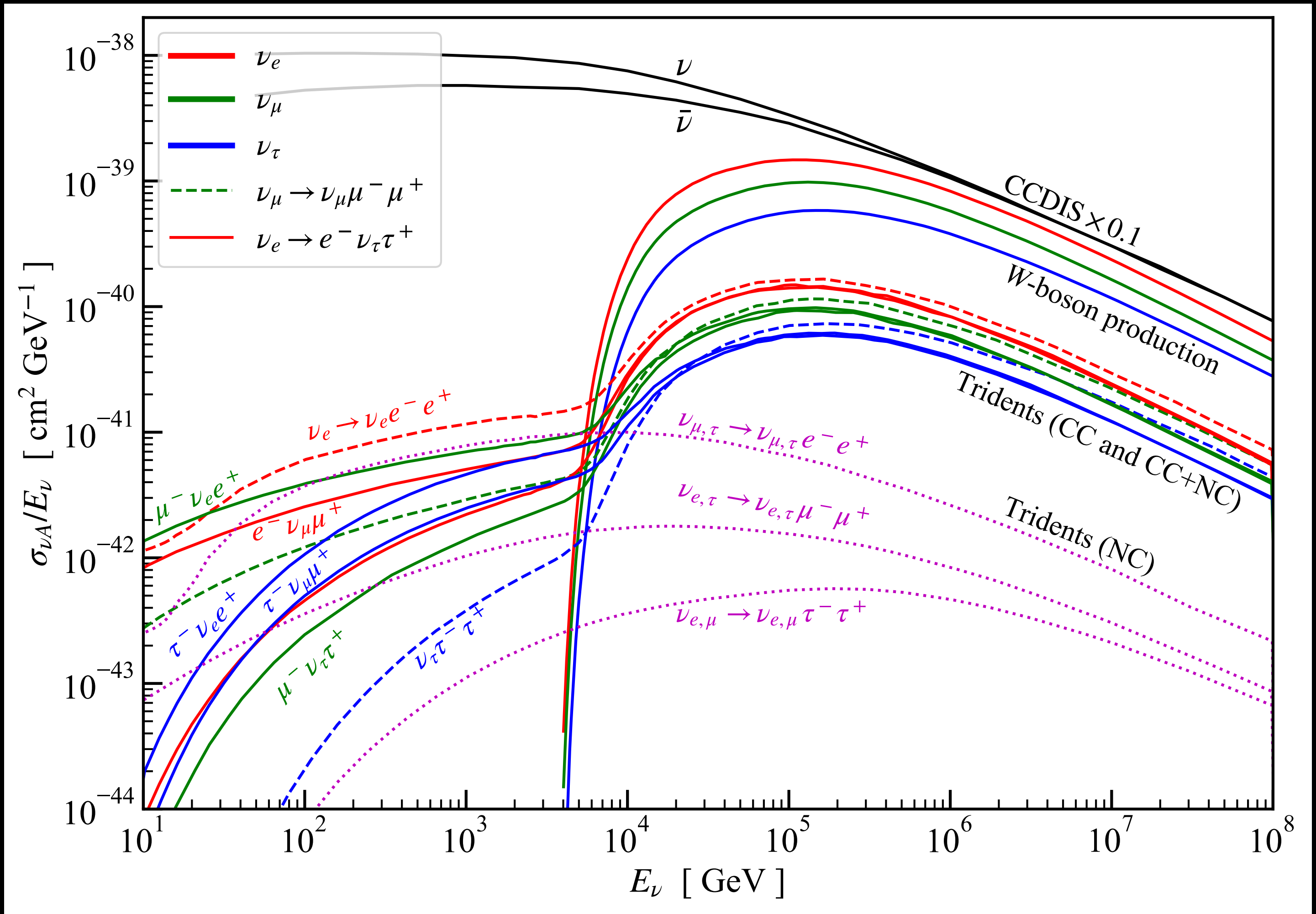
Choose $s_{\nu\gamma}$ as the factorization scale.



(WBP as an example, similar for tridents)

Total neutrino-nucleus (Oxygen) cross section

(BZ, Beacom, 1910.08090, PRD)

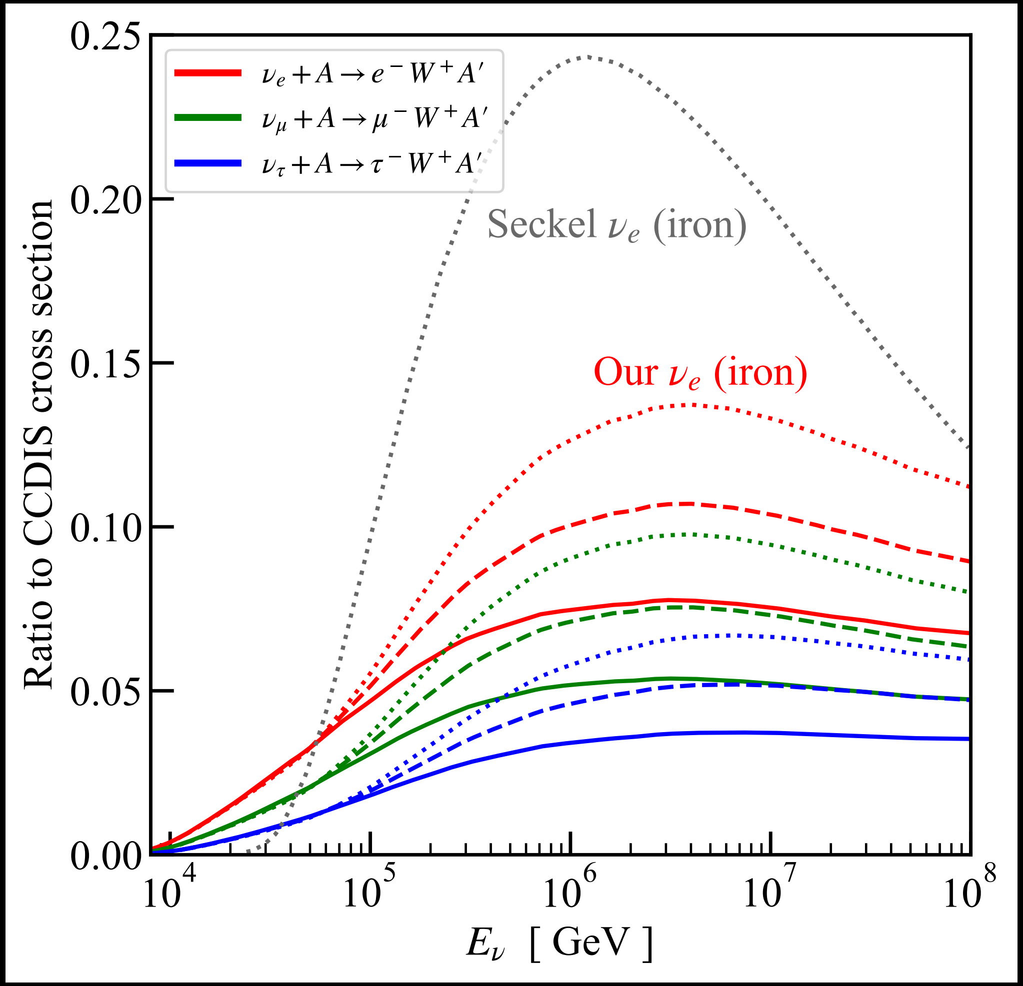


W-boson production:
First comprehensive calculation

Tridents:
First calculation at TeV—PeV

Part 1.2: Detections in IceCube/IceCube-Gen2

Ratios to CCDIS cross section



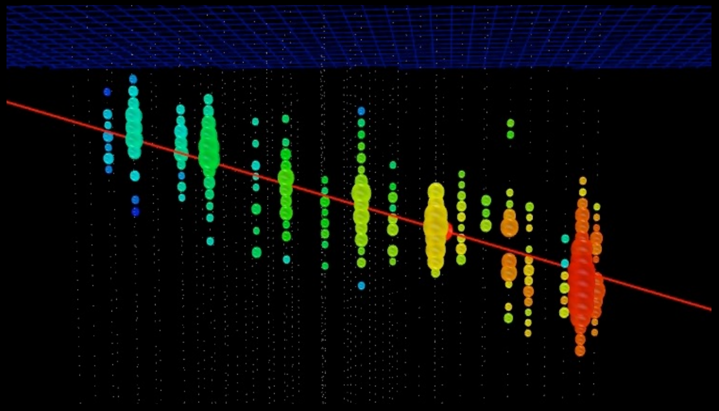
(BZ, Beacom, 1910.08090, PRD)

Implications:

1. Neutrino absorption in Earth (Increase as large as ≃15%)
2. Detections in IceCube, etc.

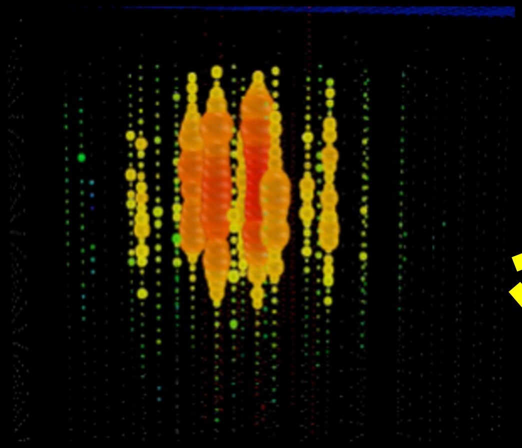
Brief review of IceCube detection

(BZ, Beacom, 1910.10720, PRD)



μ track

mainly $\nu\mu$ CCDIS

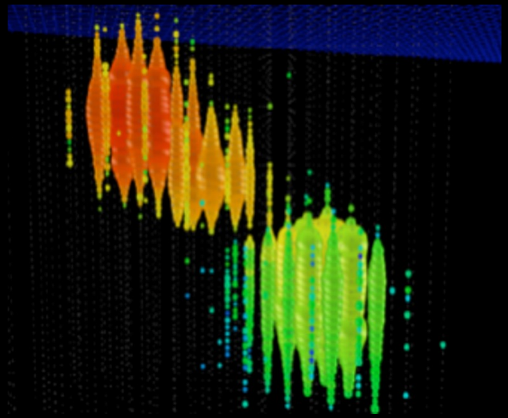


Shower

(e or hadron)

e: mainly from νe CCDIS

hadrons: All CC/NC DIS



Double bang/pulse (τ)

($\nu\tau$ CCDIS >~1e5 GeV)

EM shower (e)

vs

Hadronic shower

WBP/tridents mainly showers

(BZ, Beacom, 1910.10720, PRD)

$$\nu_e + \mathrm{A} \rightarrow e + W + A'$$

$$\nu_\mu + \mathrm{A} \rightarrow \mu + W + A'$$

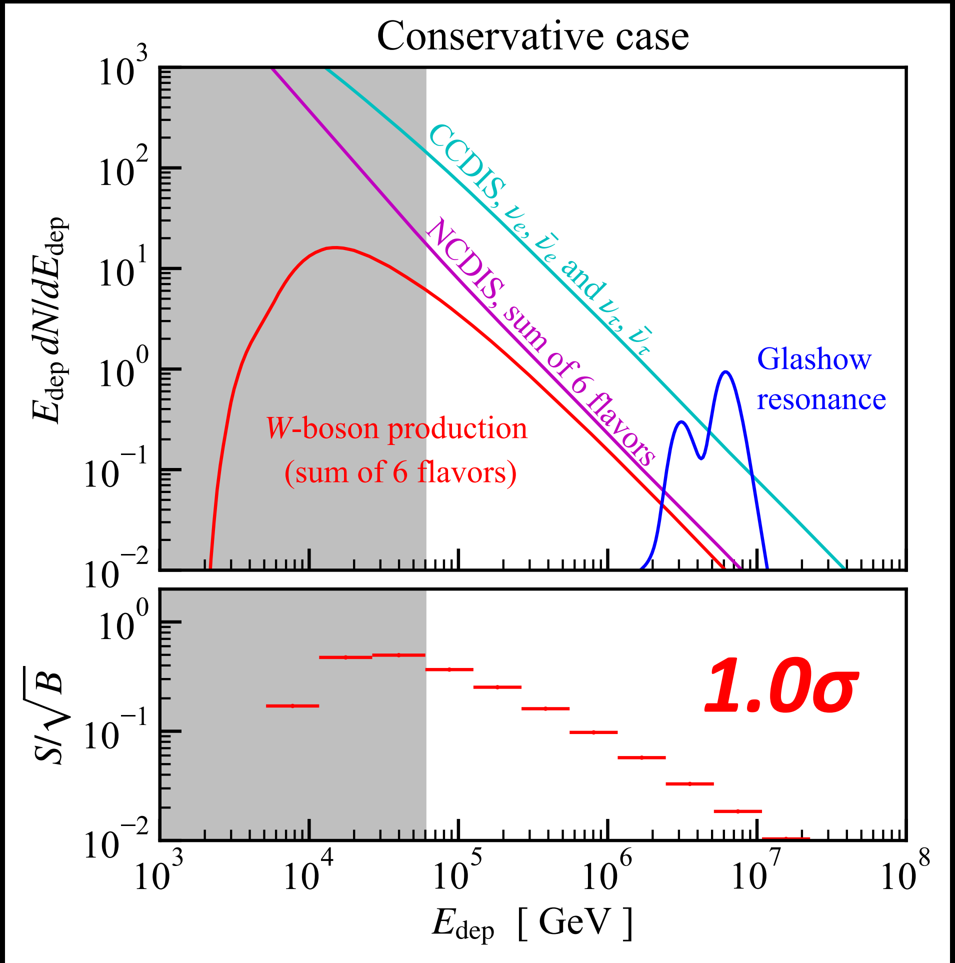
$$\nu_\tau + \mathrm{A} \rightarrow \tau + W + A'$$

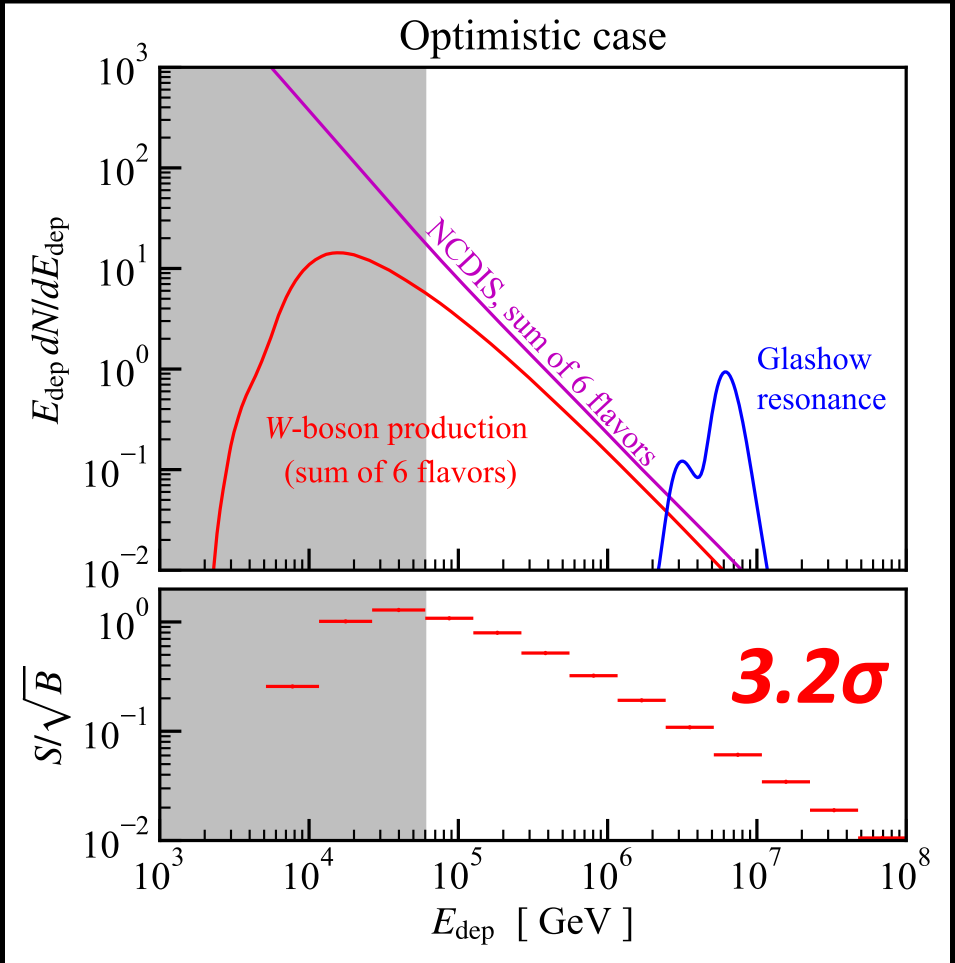
W decay

$\rightarrow e$	(11%)
$\rightarrow \mu$	(11%)
$\rightarrow \tau$	(11%)
$\rightarrow$ hadrons	(67%)

Shower spectrum: WBP/tridents detectable

For 10 years observation by IceCube (=1 year IceCube-Gen2)





$\simeq$ 6 WBP shower events (> 60 TeV)

(BZ, Beacom, 1910.10720, PRD)

Novel signatures from WBP/tridents

(BZ, Beacom, 1910.10720, PRD)

1. Double track/Dimuon (showerless) 0.34 events > 60 TeV, 10yrs IceCube or 1yr Gen2

   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$

2. Track without shower 0.96 events ……

   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$, and two tracks are inseparable
   $\nu_e + A \to e + W + A'$ with $W \to \mu$, and e energy is low

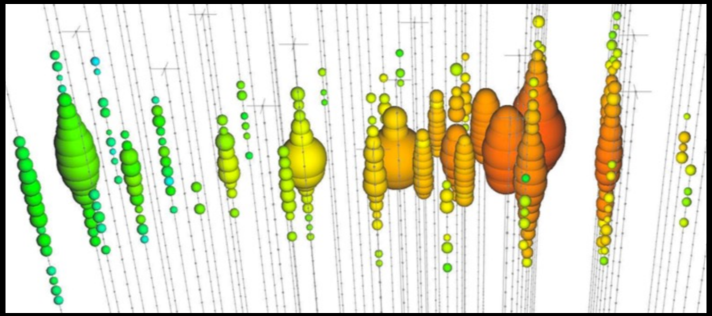
3. Pure EM shower 0.82 events ……

   Mainly from: $\nu_e + A \to e + W + A'$ with $W \to e$

Encouraging hints from current IceCube data

(BZ, Beacom, 1910.10720, PRD)

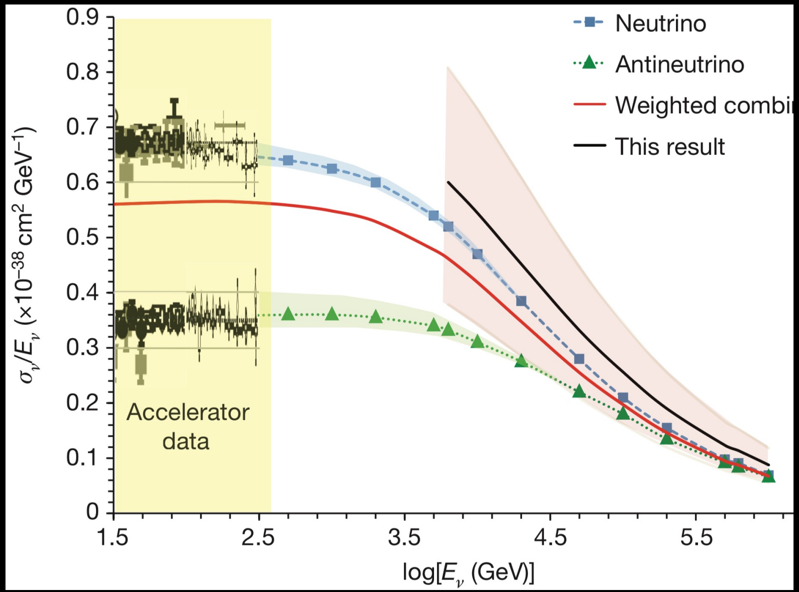
Event topology



Track without shower??

Event 5 of IceCube, 1311.5238, Science

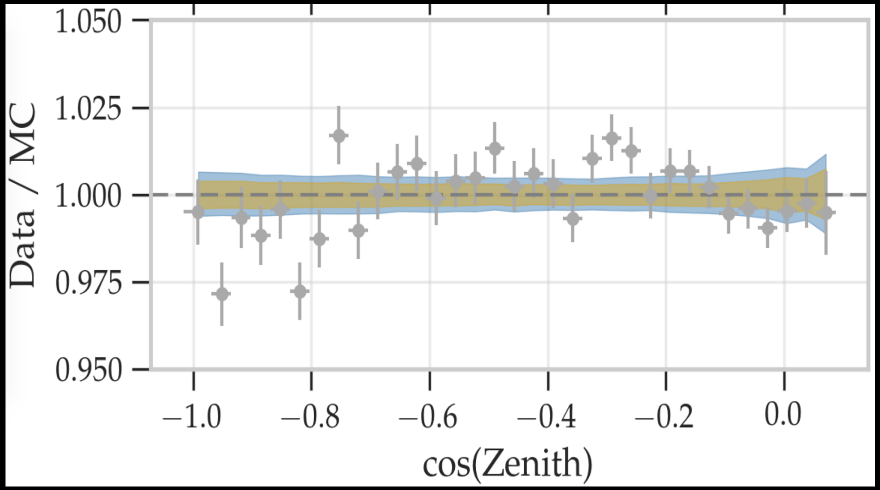
Measuring neutrino cross section



1.3±0.45 of SM prediction
but only DIS is included

IceCube, 1711.08119, Science

Diffuse Astrophysical νμ Spectrum



An unknown 2% deficit of straight up-going events

IceCube, 1908.09551
ICRC 2019

Summary of part 1

Cross sections

+ First comprehensive calculation of WBP (Xsec is ~ half of before)

+ First calculation of tridents at TeV—PeV

+ The two processes are related

(BZ, Beacom, 1910.08090, PRD)

Detectability of WBP/tridents (first study)

+ ν in-earth attenuation increased 15%

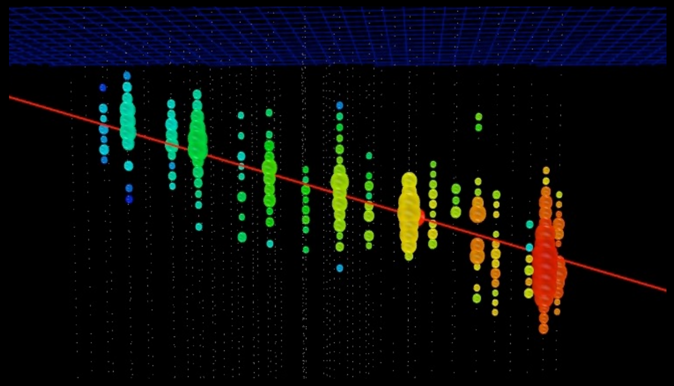
+ IceCube: detectable shower events and novel signatures

+ FASER:
Tridents detectable;
WBP, depends on the highest energy that the neutrino flux could reach.

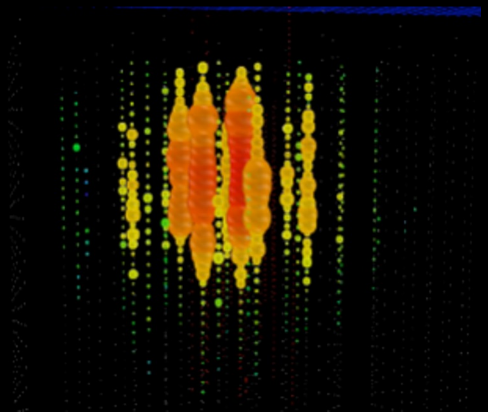
(BZ, Beacom, 1910.10720, PRD)

Part 2: Dimuons from neutrino-nucleus interactions in neutrino telescopes

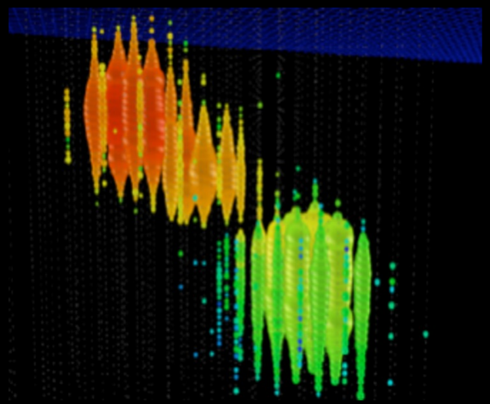
Very important to study new event classes



μ track



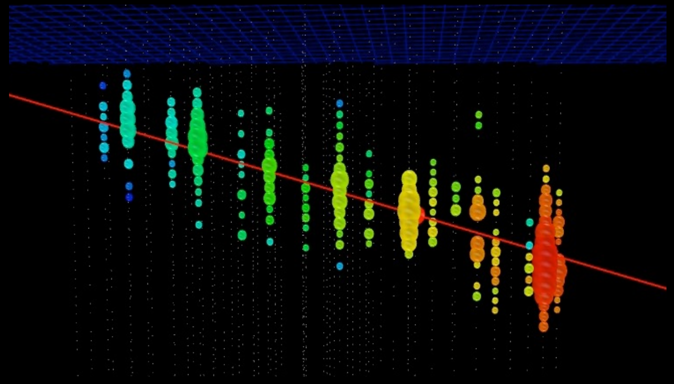
Shower (e or hadron)



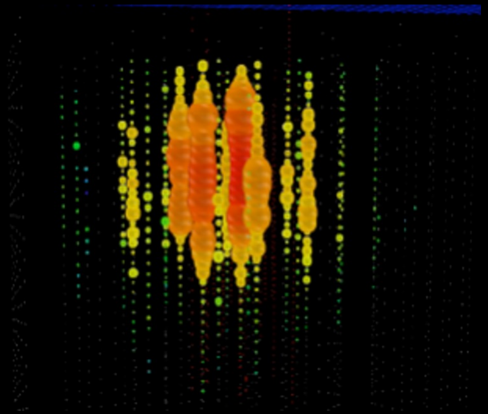
Double shower/bang ($\nu\tau$)

- 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



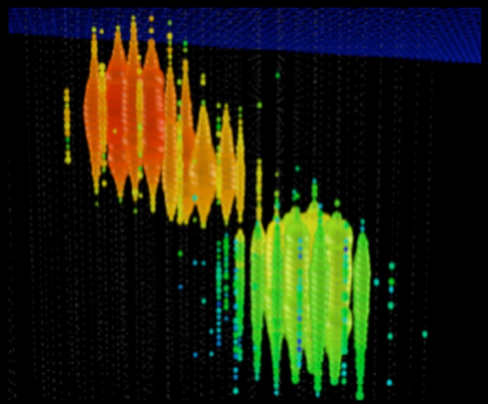
μ track



Shower (e or hadron)

Double muons

(Dimuon)

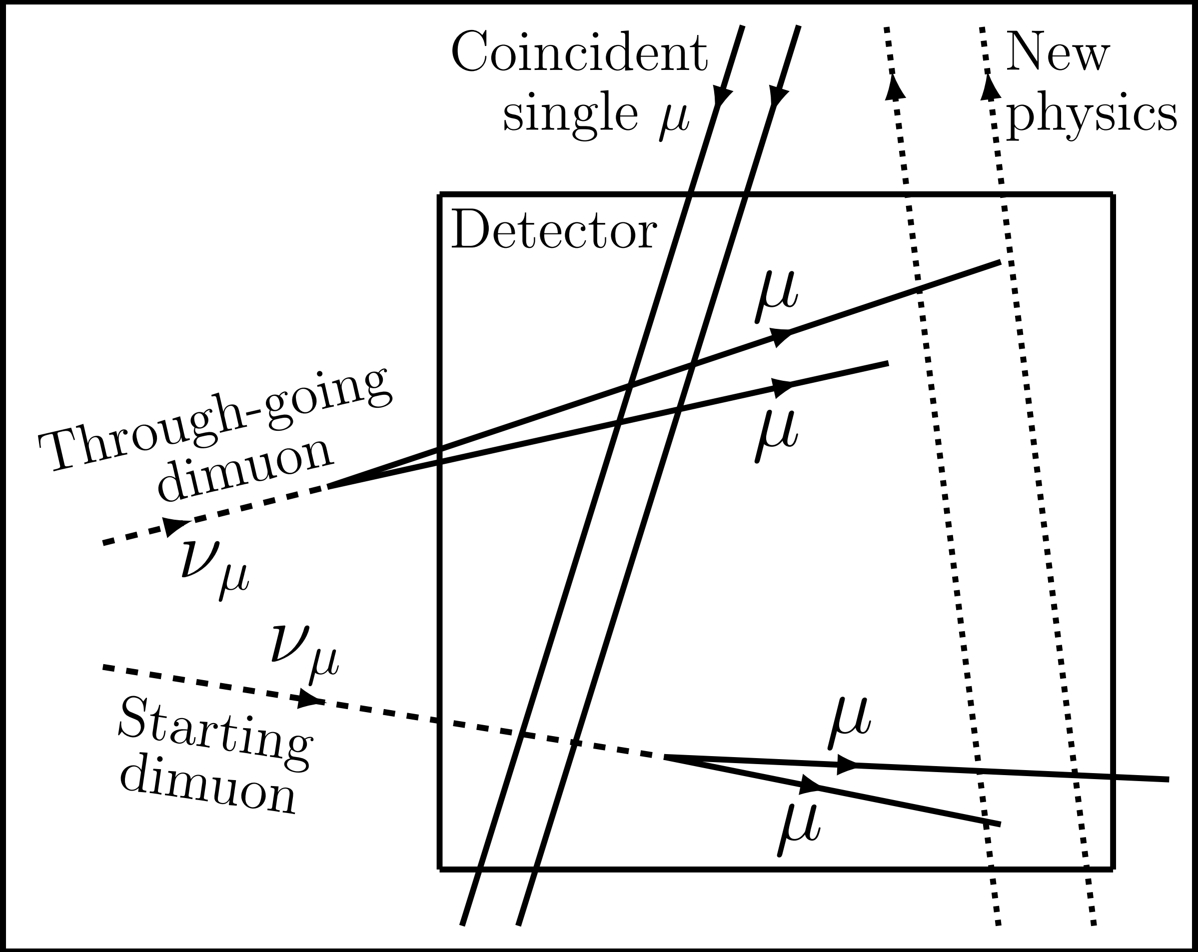


Double shower/bang ($\nu\tau$)

- 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

Part 2.1: theoretical work

What is dimuon (double muon)

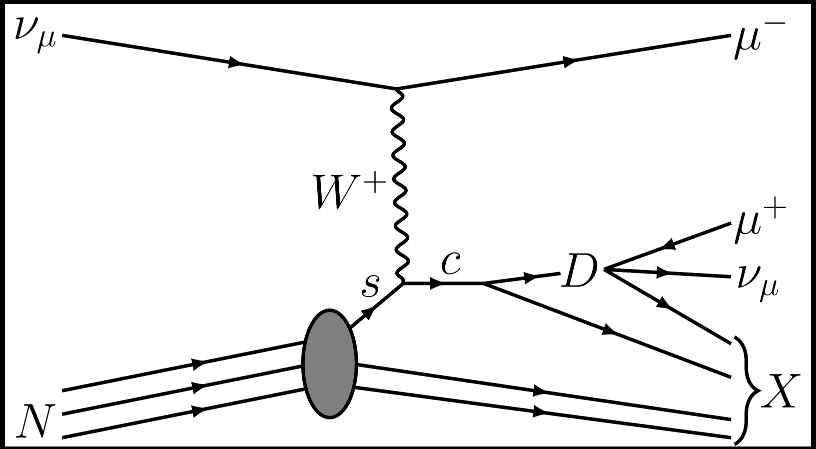


- Coincident single muons
  - background for dimuon,
  - negligible for most cases
- Standard model dimuon
  - Interesting, focus of our work
- BSM dimuon
  - E.g., double staus from SUSY models
  - More to be studied in this direction

(BZ, Beacom, 2110.02974)

How could one neutrino produce two muons

Deep inelastic scattering (DIS)

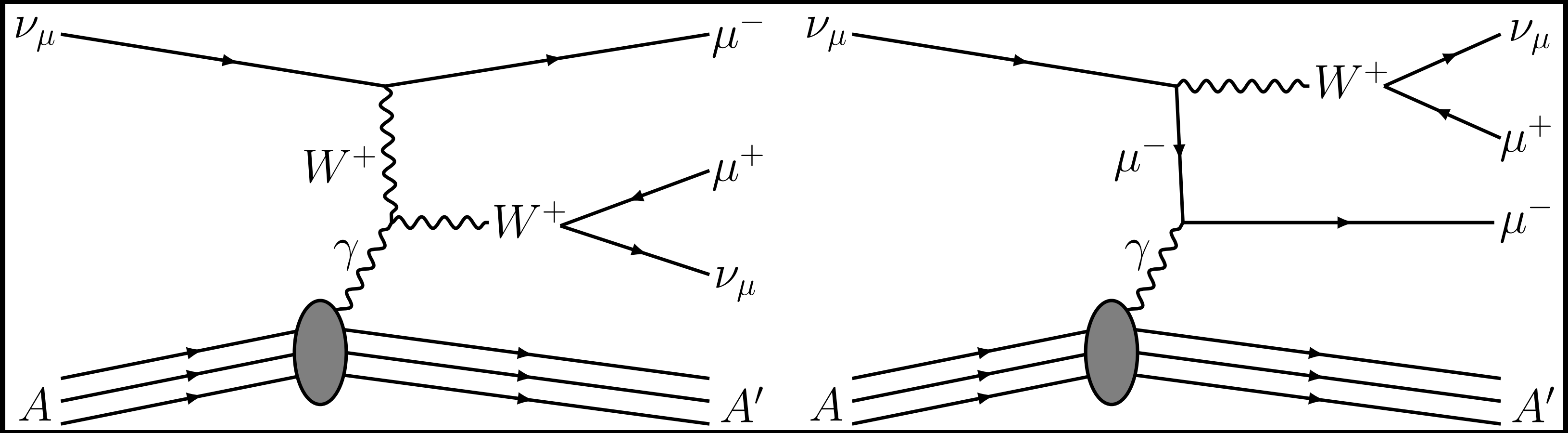


DIS is the dominate channel for detecting high-energy neutrinos.

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

Important for QCD studies.

(On-shell) Tridents/WBP



(BZ, Beacom, 1910.08090, 1910.10720)

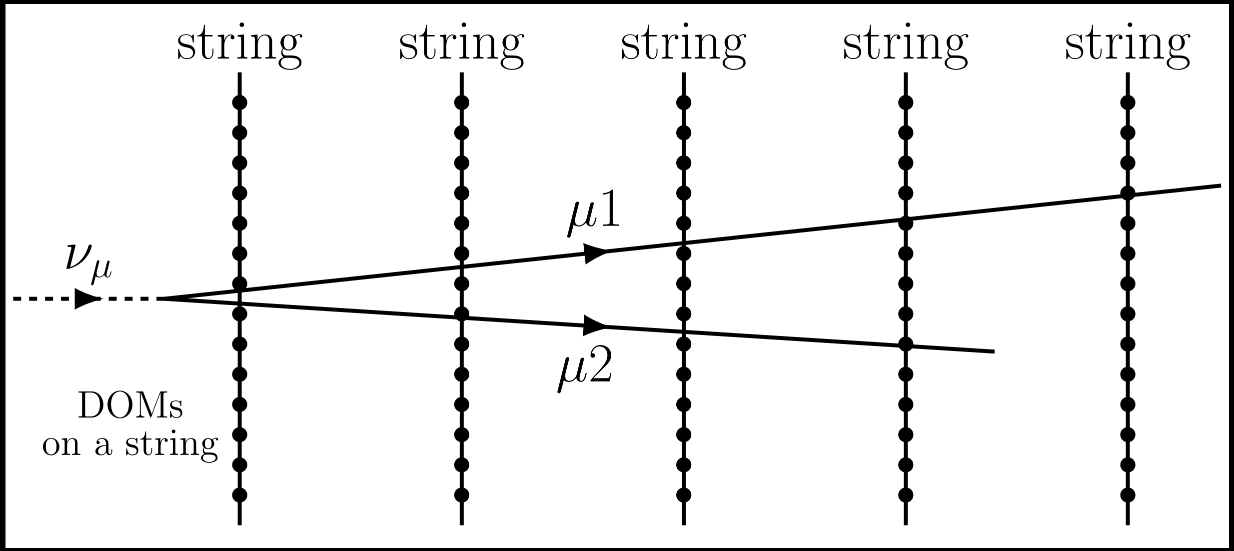
WBP is the 2nd most important channel for detecting high-energy neutrinos,

but never identified yet.

First hypothesized/calculated in 1960…

We propose a way to detect dimuons in IceCube-like detectors

Inside a HE neutrino detector



(BZ, Beacom, 2110.02974)

Angular threshold:

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

μ1-μ2 separation

Spacing between adjacent DOMs

Energy Threshold:

100 GeV for IceCube
300 GeV for IceCube-Gen2

First calculational framework for dimu in ν telescopes

(BZ, Beacom, 2110.02974)

Starting dimuons:

$$\frac{dN_{\mu\mu}^{\rm st}}{dE_{\mu1/2}} = N_t T \int_{E_{\rm th}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma_{\mu\mu}^{\rm cuts}}{dE'_{\mu1/2}}(E'_{\mu1/2}, E_\nu | E'_{\mu2} > E_{\rm th}) \,,$$

Throughgoing dimuons:

Flux

Interactions

Detector angular threshold

$$\frac{dN_{\mu\mu}^{\rm thr}}{dE_{\mu2}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu2}} \int_{E_{\mu2}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \int_{E_{\mu2}}^{E_\nu} dE'_{\mu2} \frac{d\sigma_{\mu\mu}^{\rm cuts}}{dE'_{\mu2}}(E'_{\mu2}, E_\nu) \,, \text{ and}$$

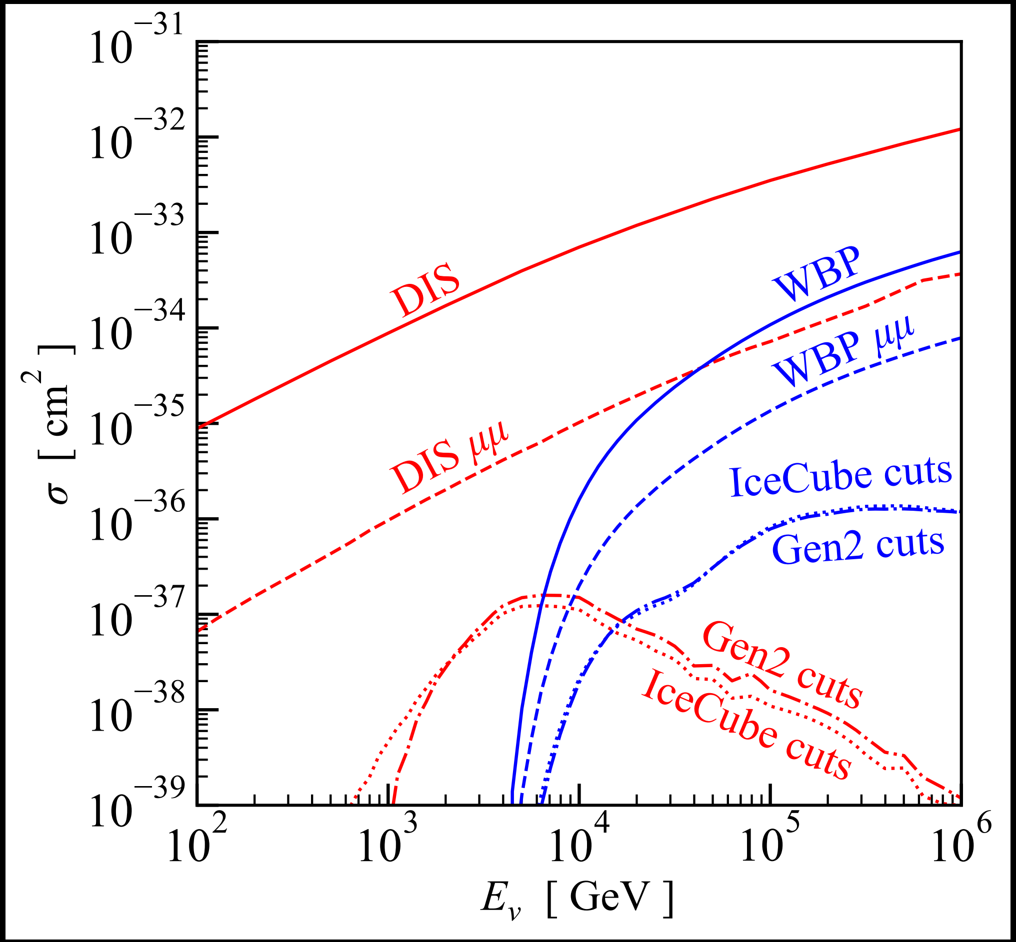
$$\frac{dN_{\mu\mu}^{\rm thr}}{dE_{\mu1}} = \frac{A_{\rm det} T N_A}{\alpha + \beta E_{\mu1}} \int_{E_{\mu1}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu} \int_{E_{\mu1}}^{E_\nu} dE'_{\mu1} \int_{E'_{\mu2,\rm th}}^{E'_{\mu1}} dE'_{\mu2} \frac{d^2\sigma_{\mu\mu}^{\rm cuts}}{dE'_{\mu1} dE'_{\mu2}}(E'_{\mu1}, E'_{\mu2}, E_\nu) \,,$$

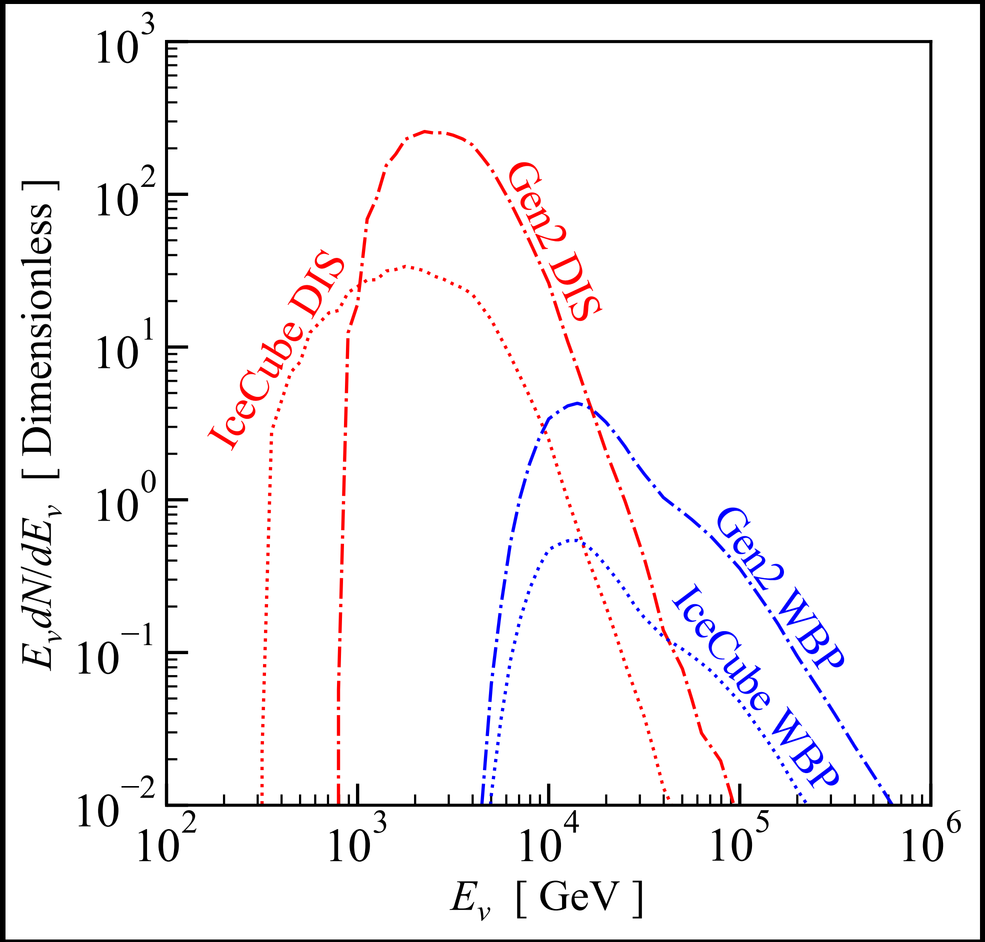
Energy losses

Detector energy threshold

$$E'_{\mu2,\rm th} = \left(\frac{E'_{\mu1} + \epsilon}{E_{\mu1} + \epsilon}\right)(E_{\rm th} + \epsilon) - \epsilon$$

Dimuon cross sections and parent ν distribution





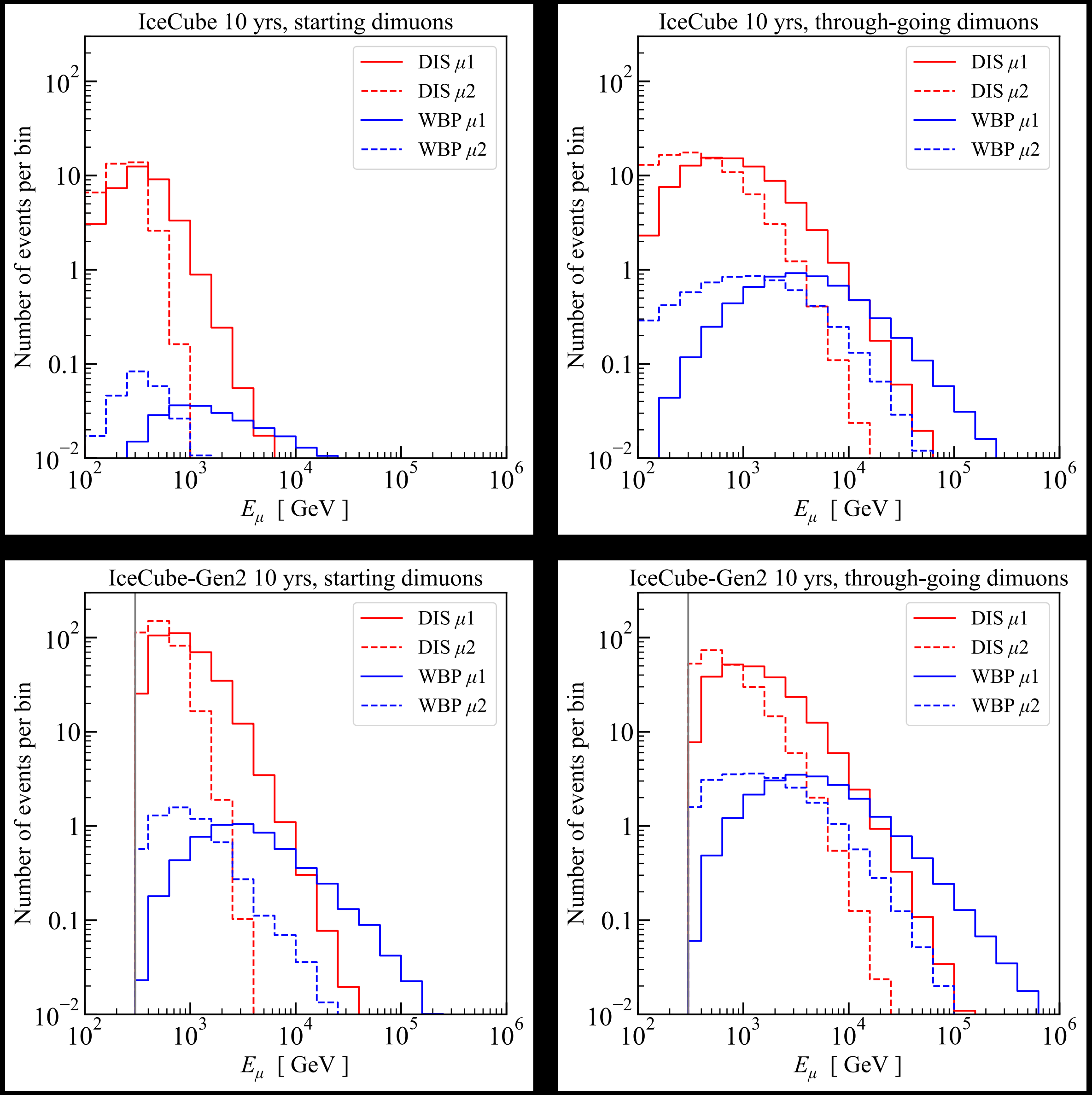
(BZ, Beacom, 2110.02974)

Dimuon rates in IceCube and IceCube-Gen2

Our predicted number of dimuons

	Starting		Throughgoing	
	DIS	WBP	DIS	WBP
IceCube, 10 yrs	37	0.3	85	6.0
IceCube-Gen2, 10 yrs	370	5.8	231	22

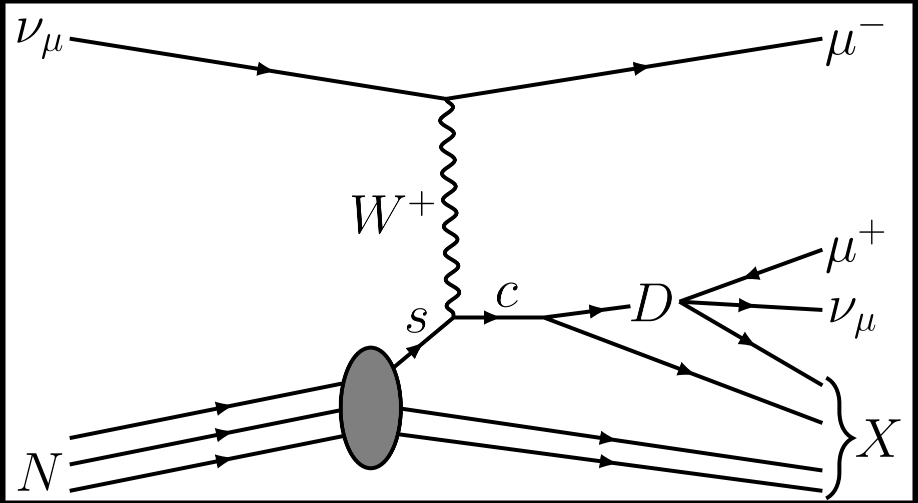
(Note IceCube has run for > 10 years)

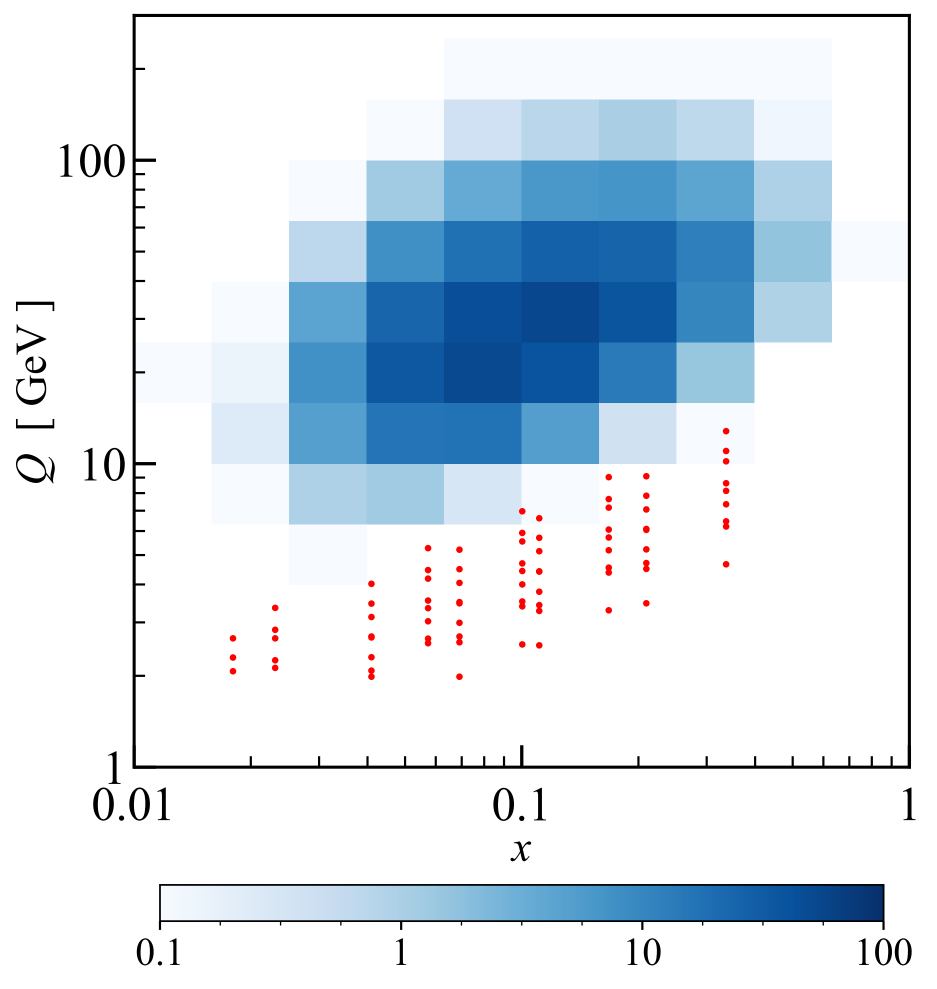


Physics potential: measuring the strange-quark PDF

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

Deep inelastic scattering (DIS)



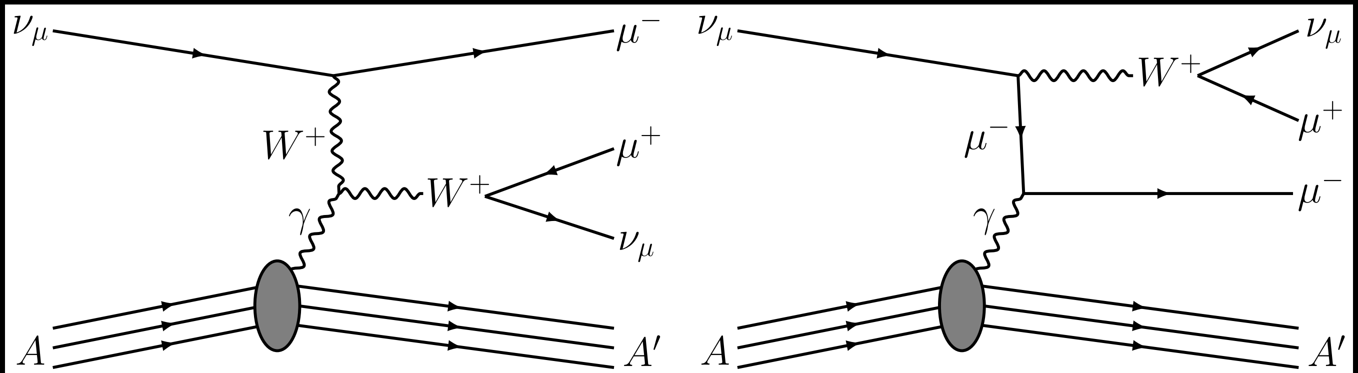


(BZ, Beacom, 2110.02974)

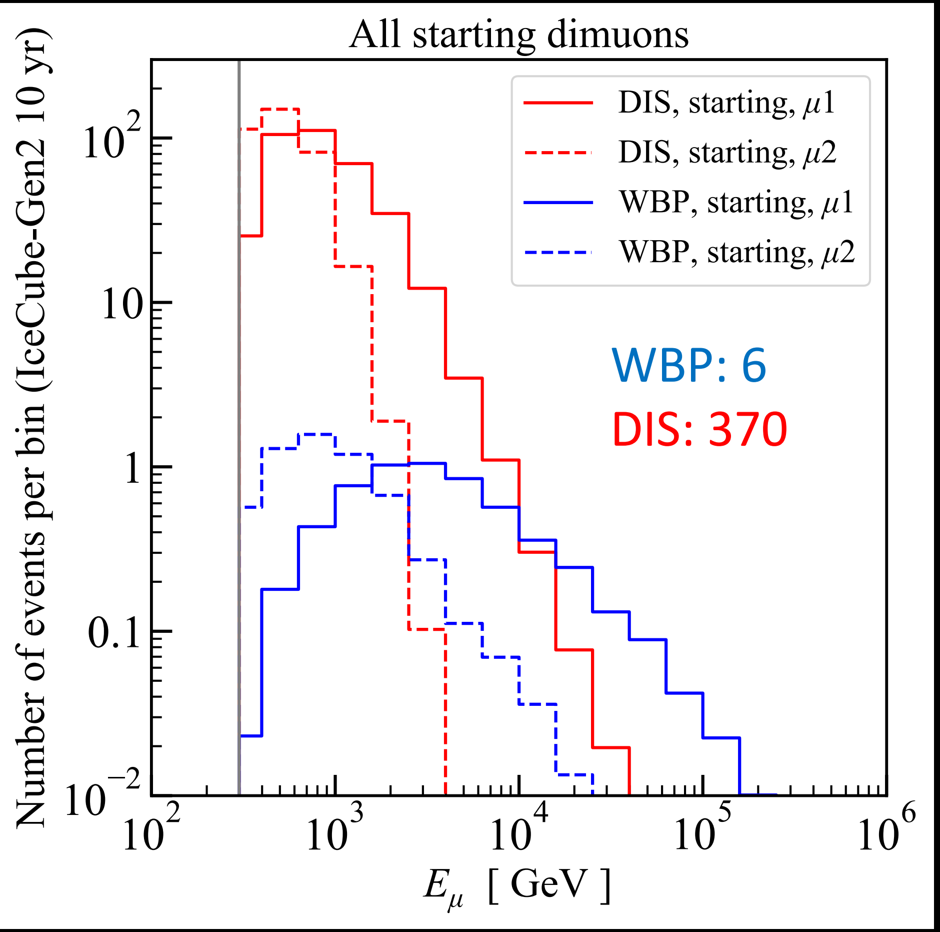
Physics potential: first detection of WBP

with showerless starting dimuons

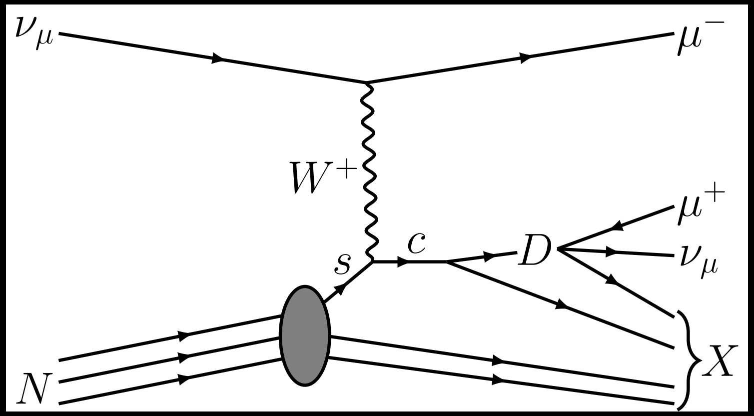
Signal: W-boson production (WBP)



A': No shower



Background: deep inelastic scattering (DIS)



X: Mostly shower

(BZ, Beacom, 2110.02974)

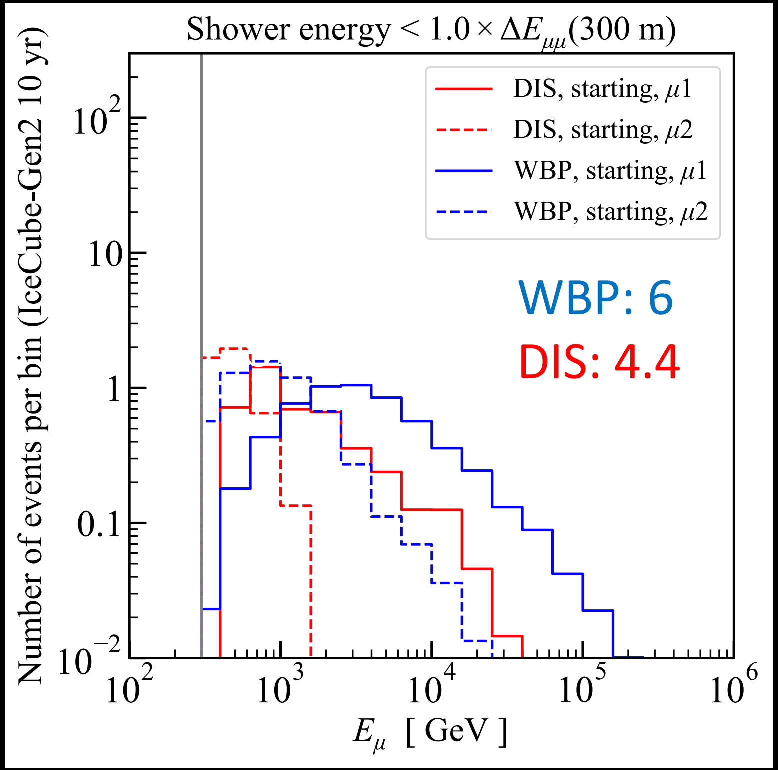
Physics potential: first detection of WBP

with showerless starting dimuons

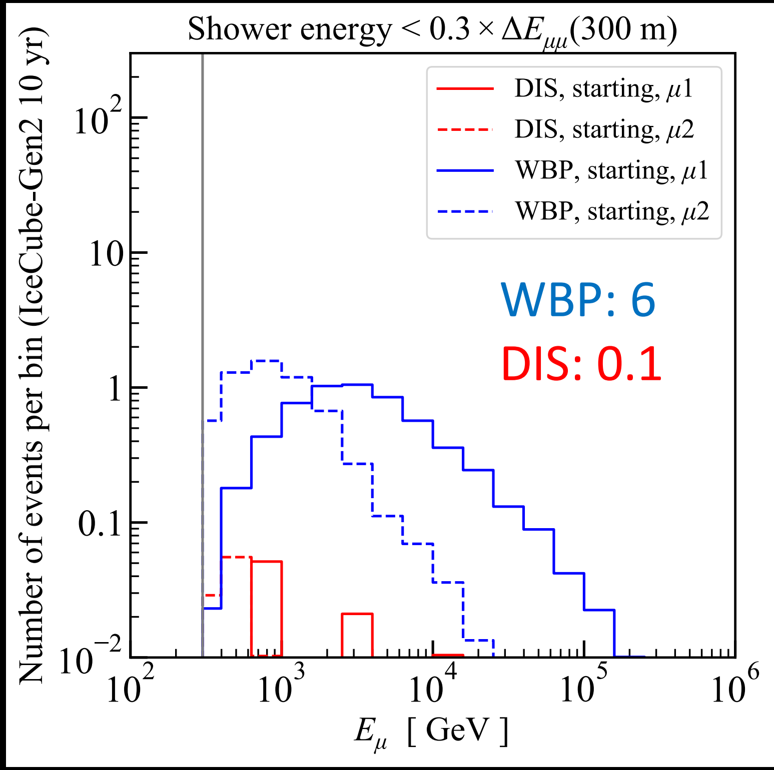
Shower energy threshold

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

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



f = 1.0



f = 0.3

(BZ, Beacom, 2110.02974)

Other implications

- Better energy measurements for throughgoing dimuons than single muons
  - Less energy losses before entering detector than single muon events
  - Hadronic part is partially measurable because μ2 takes some energy

- Background for new physics searches
  - E.g., neutrino induced di-staus from some SUSY models

Part 2.2: observational work: first search for dimuons in a neutrino telescope

Dataset and analysis

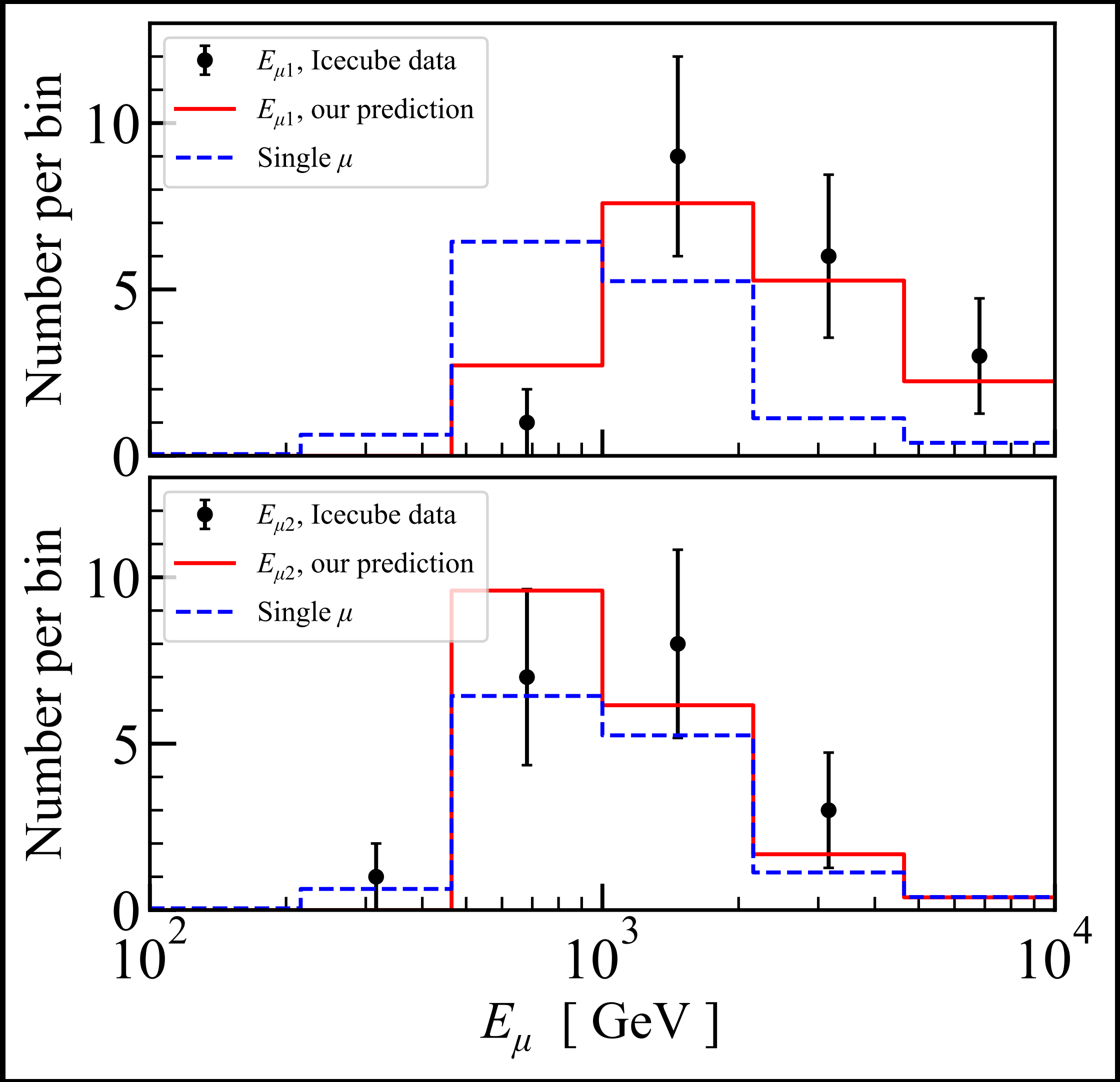
- Ten years of public IceCube data (1,134,450 muon events; 2008--2018)
- Data obtained after multiple strong cuts optimized for point-source search, not dimuon search.
- We analyze the data by looking for muon pairs arriving close in time and direction

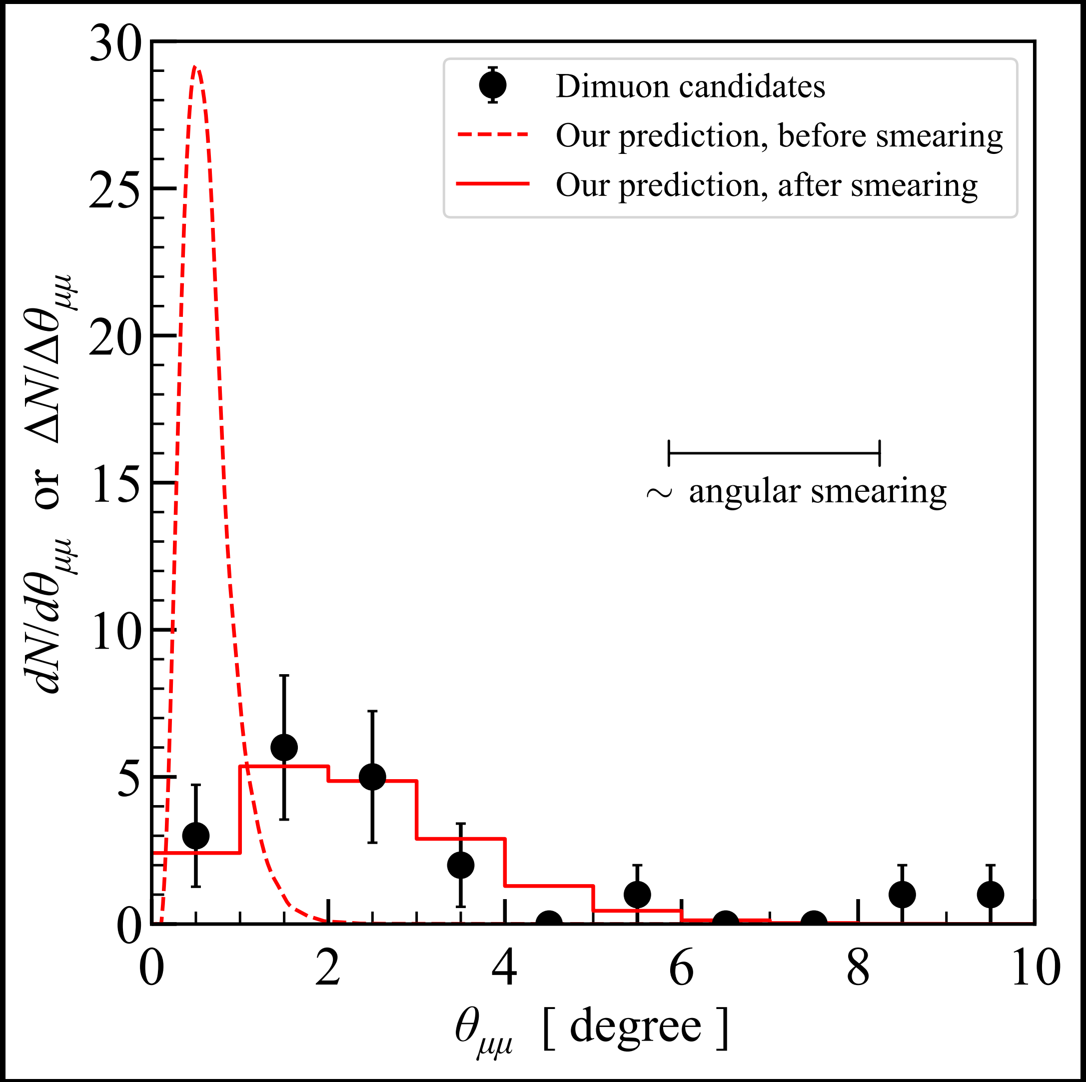
List of the 19 dimuon candidates we found

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

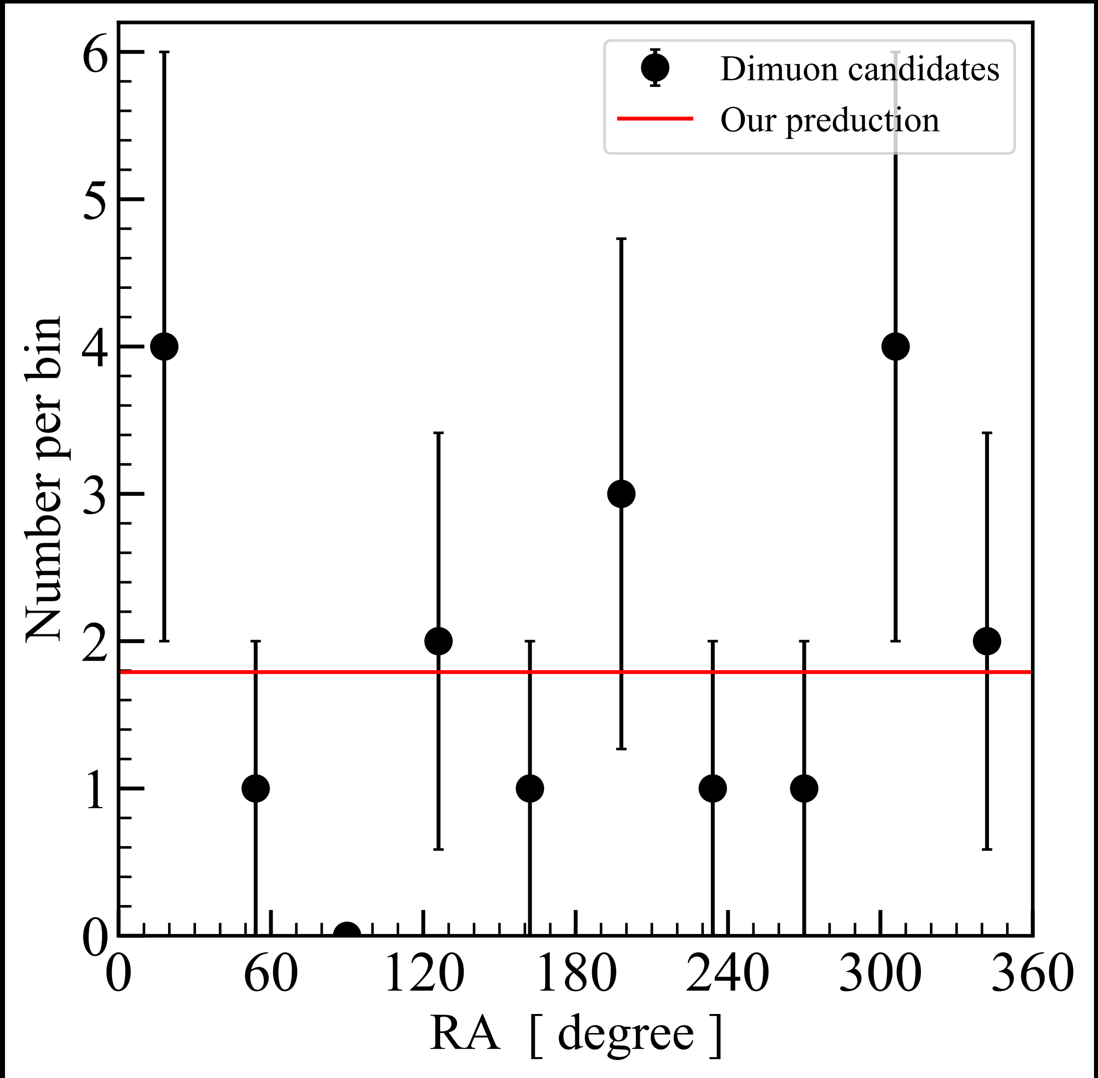
(BZ, Beacom, 2110.02974)

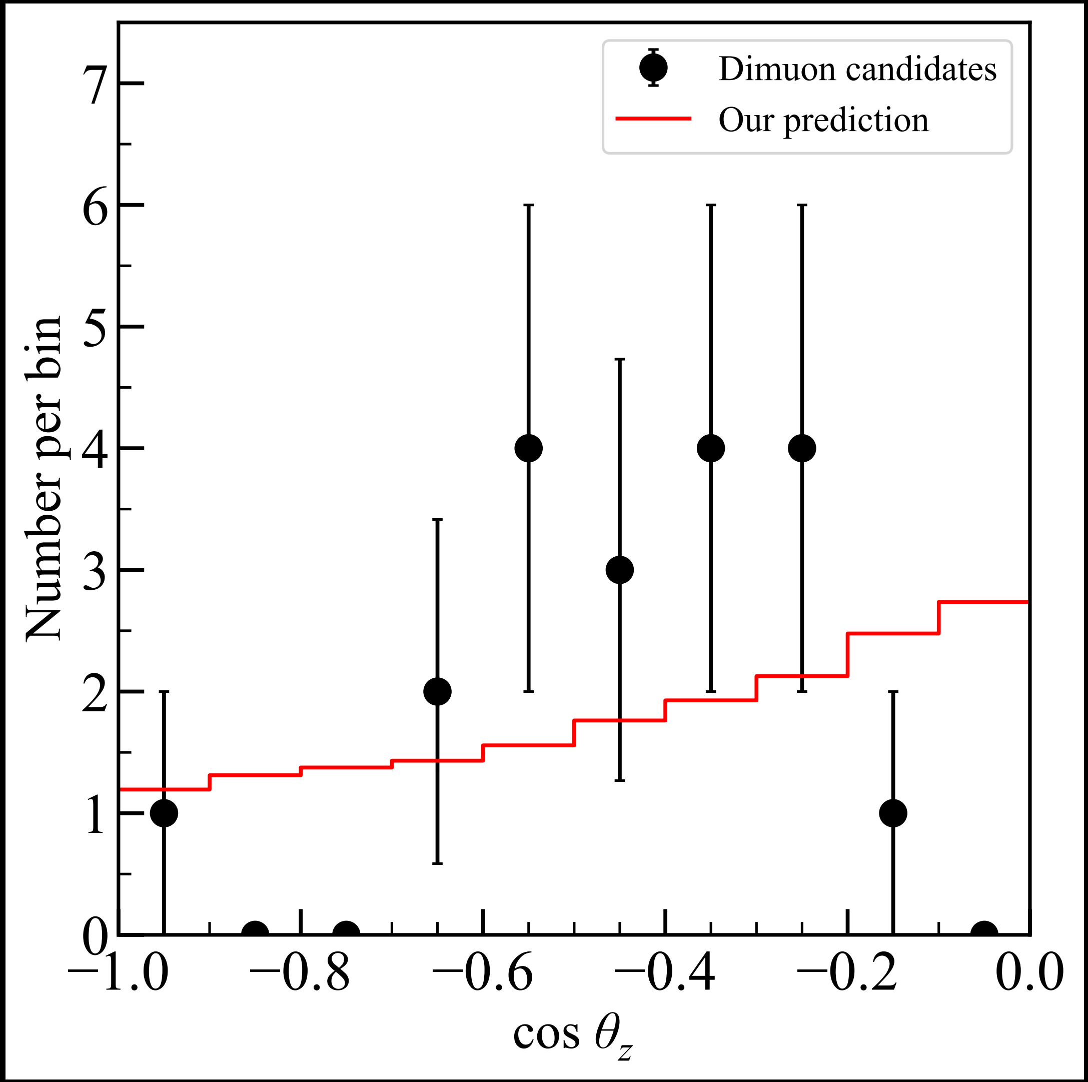
Agree with our prediction: energy & angular distribution





Agree with our prediction: sky distribution

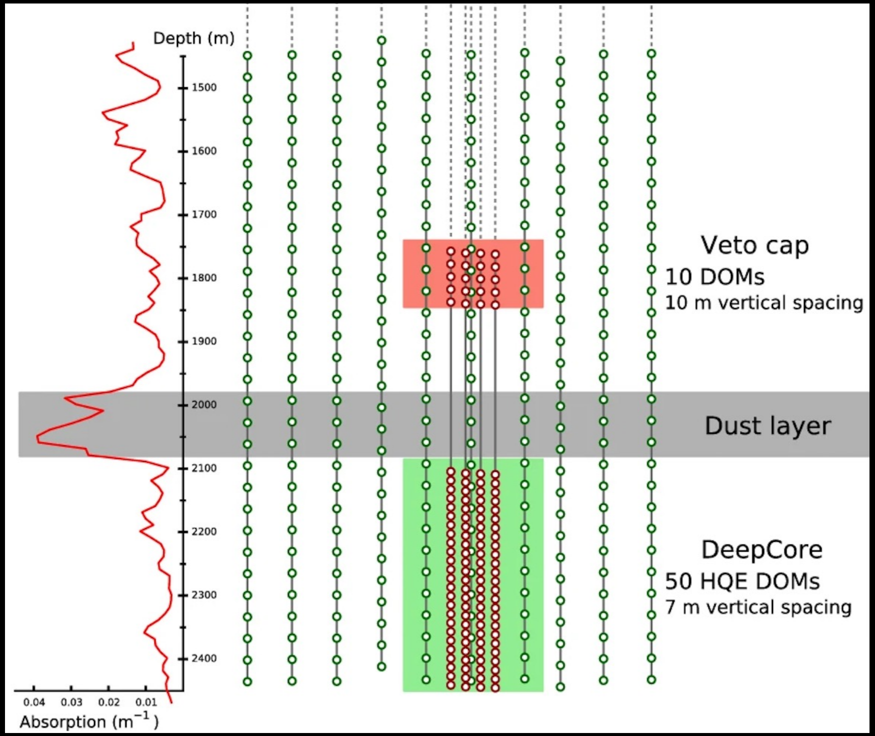




Outcome of these candidates

- After our paper out, IceCube collaboration did a visual inspection to these candidates, and found that they are not real dimuons.
- They are, instead, due to an internal reconstruction error that identifies some single muons crossing the dust layer as two separate muons.
- IceCube has started an analysis searching for dimuons events.
- The theoretical part of our work still holds.

Inside IceCube detector



Summary of part 2

- We studied dimuons as a new event class for high-energy neutrino telescopes
- IceCube has ≃130 events and IceCube-Gen2 will detect ≃620 in 10 years
- Significant physic potentials, including
  - Measuring strange quark PDF
  - Enabling the first detection of W-boson production
  - Better energy measurements
  - Background of new physics searches
- We did the first search of dimuons with IceCube publica data
  - Found 19 candidates, later turn out to be an important misconstruction error
  - We motivated IceCube to start their search for dimuons
- Dimuons may be a new direction for high-energy neutrinos

Thanks for your attention!

Neutrino telescopes are very important

MeV—GeV ν telescopes

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

High-energy (TeV--PeV) ν 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.)
    - high-energy, known direction, cosmic distance, extremely high column density (through Earth)

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Outline

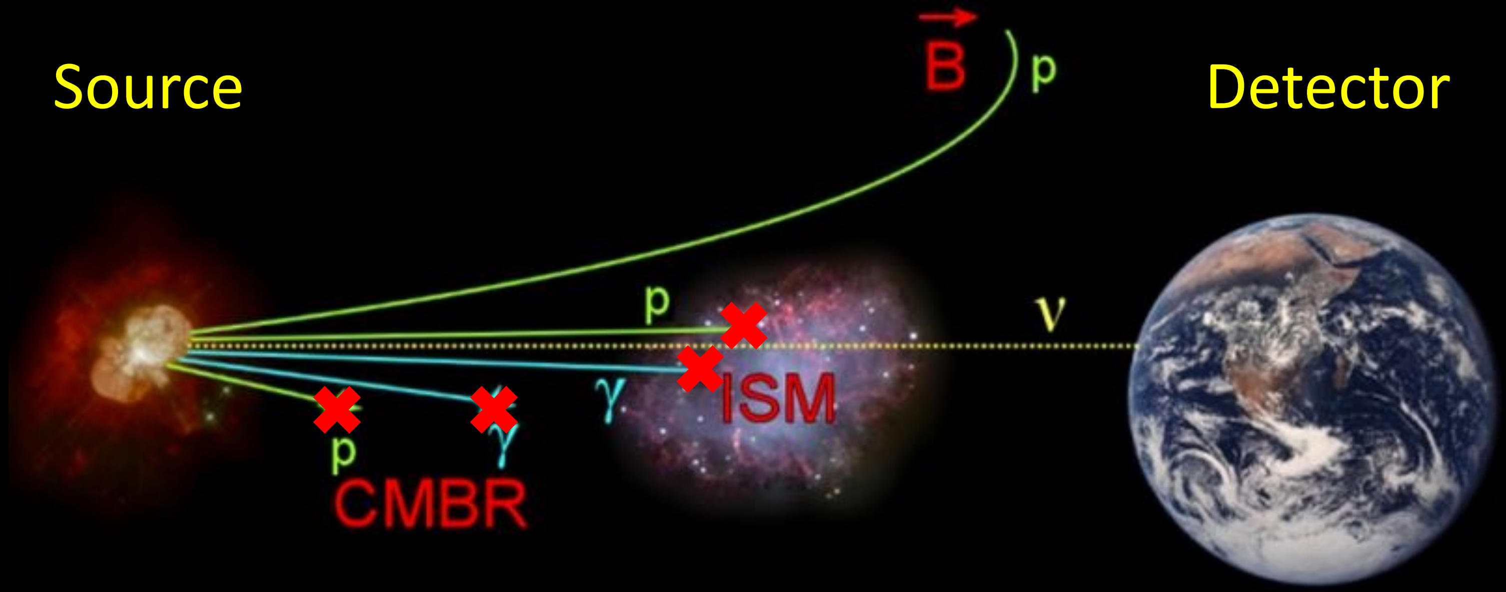
0. xxx

1. Search for high-energy neutrino emission from radio-bright AGN (2103.12813)
    1) Introduction
    2) Our work

2. W-boson and trident production for high-energy neutrinos (1910.08090, 1910.10720)
    1) Introduction
    2) Our work 1: cross section calculation
    3) Our work 2: important effects on detection in IceCube (IceCube-Gen2)

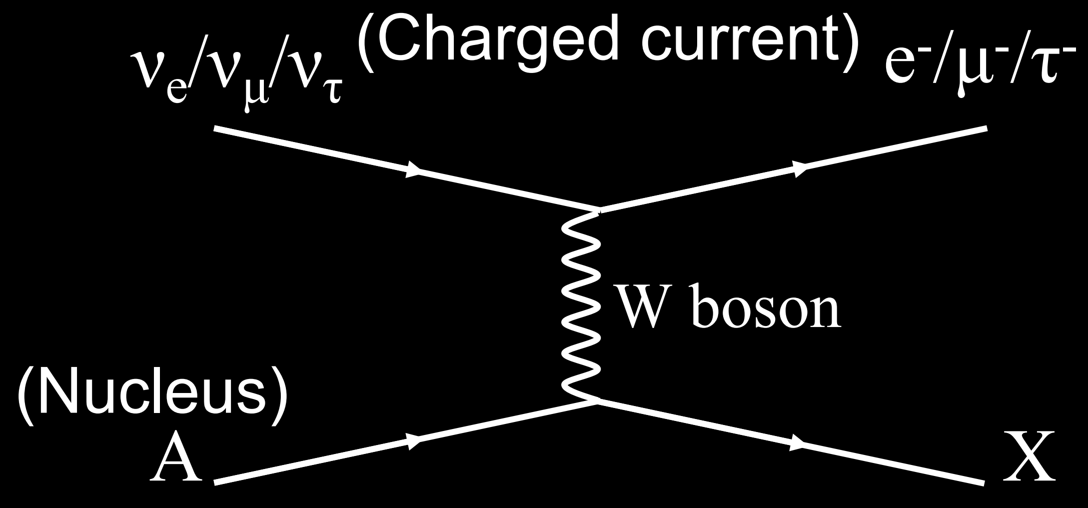
Why do we detect/study high-energy neutrinos

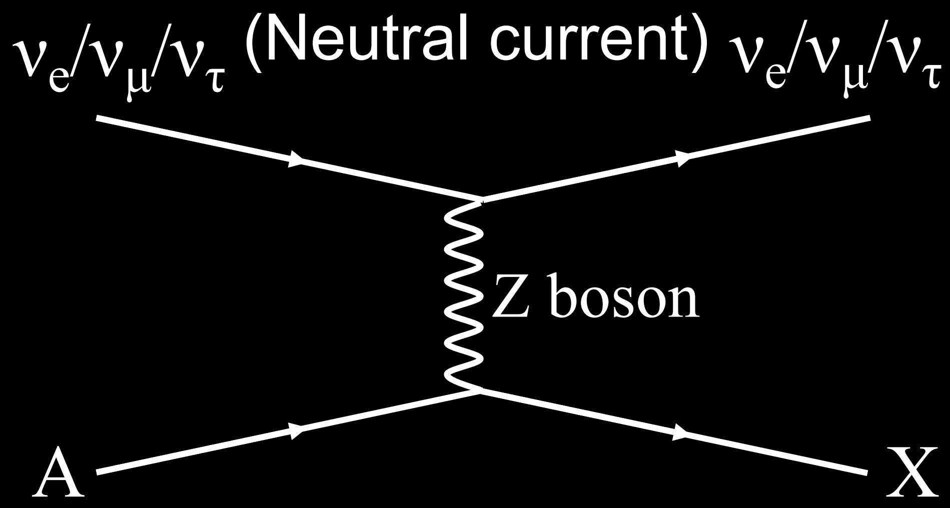
1. Astrophysics: origin of high-energy cosmic rays (~long-term problem)



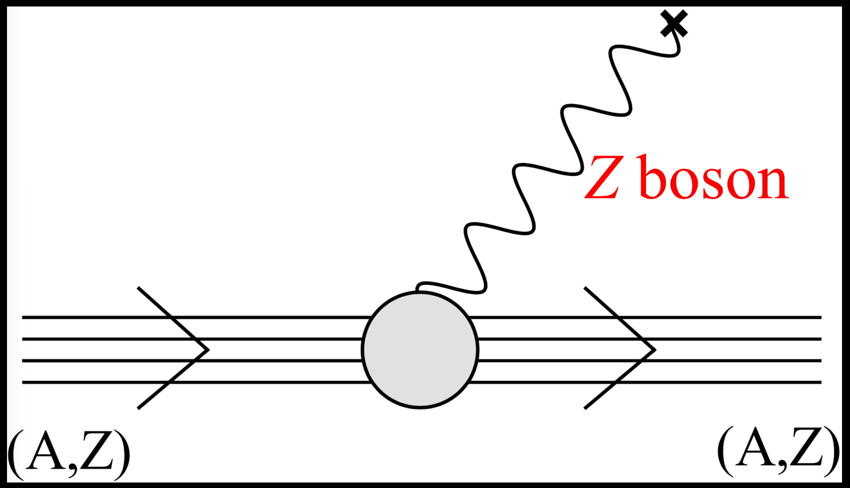
   - Particle acceleration mechanisms of those source
2. Gamma ray sources, hadronic vs leptonic (~long-term problem)
3. Particle physics: Neutrino properties, testing new physics (dark matter, etc.)
   - high-energy, known direction, cosmic distance, extremely high column density (through Earth)

Neutrino-nucleus interactions



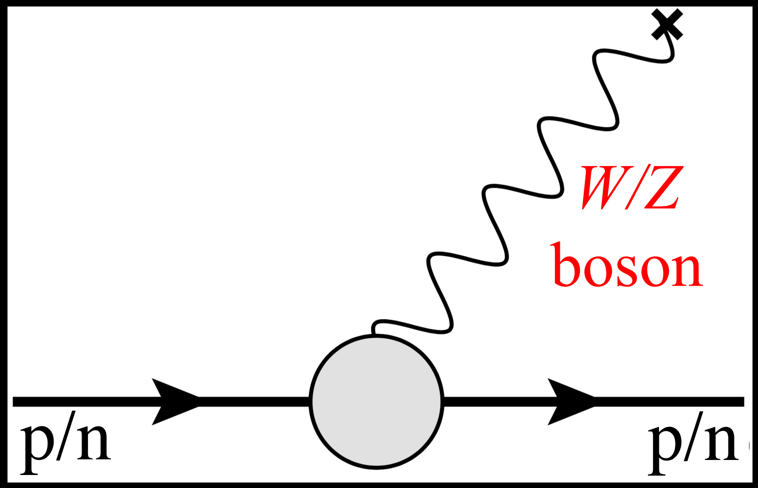


Coherent (elastic) scattering

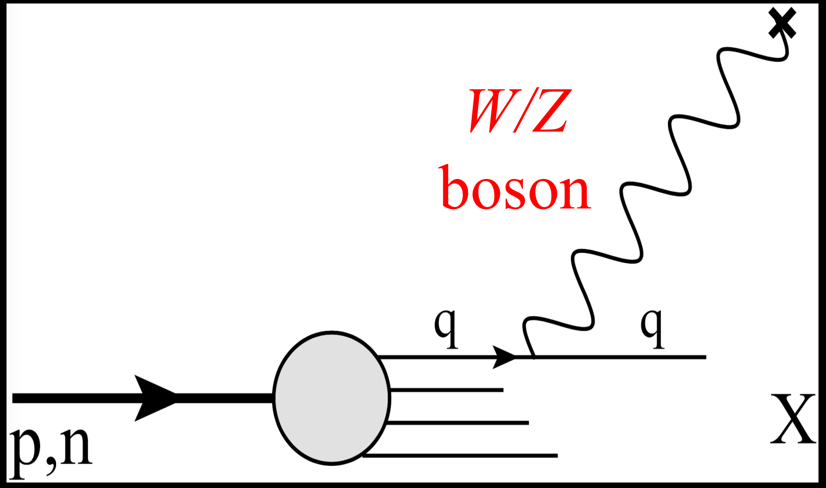


Dominates < ~100 MeV

Quasielastic scattering

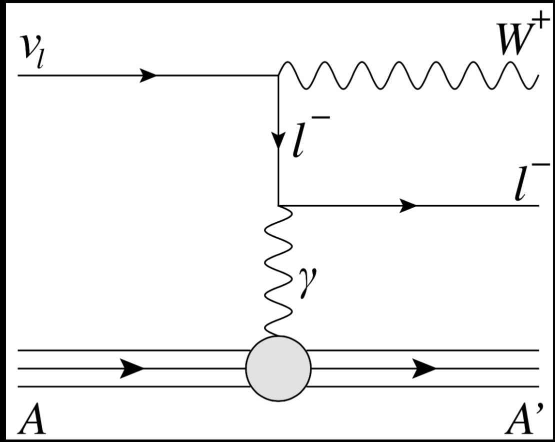


Inelastic



Dominates > ~10 GeV

Coherent and diffractive: Invalidity of equivalent photon approximation



Equivalent photon approx. $\sigma_{\nu A}(s) \simeq \int \sigma_{\nu\gamma}\left(s_{\nu\gamma}\right) H_\gamma(s_{\nu\gamma}, q^2)$

But not valid for us

Ballett et al., 1807.10973 showed the invalidity of this for tridents.

We show invalidity for W boson production, for the first time

Complete approach (for coherent and diffractive)

$$i\,M = L^{\mu}\frac{-ig_{\mu\nu}}{q^2}H^{\nu}$$

$$\frac{d^2\sigma_{\nu X}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_X^2)^2}\frac{H^{\mu\nu}L^{\mu\nu}}{q^4}\ ;\ L^{\mu\nu} = \int L^{\mu *}L^{\nu}\ \mathrm{d\,PS}$$

$$\frac{d^2\sigma_{\nu X}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}q^2}\left[\sigma_{\nu\gamma}^{T}(q^2,\hat{s})\ h_X^T(q^2,\hat{s}) + \sigma_{\nu\gamma}^{L}(q^2,\hat{s})\ h_X^L(q^2,\hat{s})\right]$$

$$\sigma_{\mathrm{T}}(\hat{s},\mathrm{q}^2) = -\frac{1}{2\hat{s}}\frac{1}{2}\left(g^{\mu\nu} - \frac{4Q^2}{\hat{s}^2}p_1^{\mu}p_1^{\nu}\right)L_{\mu\nu};$$ ~ transverse

$$\sigma_{\mathrm{L}}(\hat{s},\mathrm{q}^2) = -\frac{1}{\hat{s}}\frac{4Q^2}{\hat{s}^2}p_1^{\mu}p_1^{\nu}L_{\mu\nu};$$ ~ longitudinal

To calculate σ_{T} and σ_L:

For Real W production, the matrix element and 2 body phase space (PS) integration are relatively simple.

For trident, need to deal with both the complicated matrix element and full 3 body phase space.

Then convolve the hadronic part, $h_X^T(\mathrm{q}^2,\hat{s}), h_X^L(q^2,\hat{s})$; ~ hadronic current involving nucleus/nucleon form factors.

Czyz, Sheppey, Walecka, Nuovo Cim. 1964; J. Lovseth and M. Radomiski,, PRD 1971
K. Fujikawa, Annals Phys. 1971; Ballett et al. , 1807.10973

Other theoretical inputs

Coherent:

$h_{coherent}^{T/\mathrm{L}}(q^2, \hat{s}) \sim Z^2 e^2 |F(q^2)|^2$

$|F(q^2)| \sim$ Nucleus form factor: Use the Wood-Saxon F. F.

Diffractive:

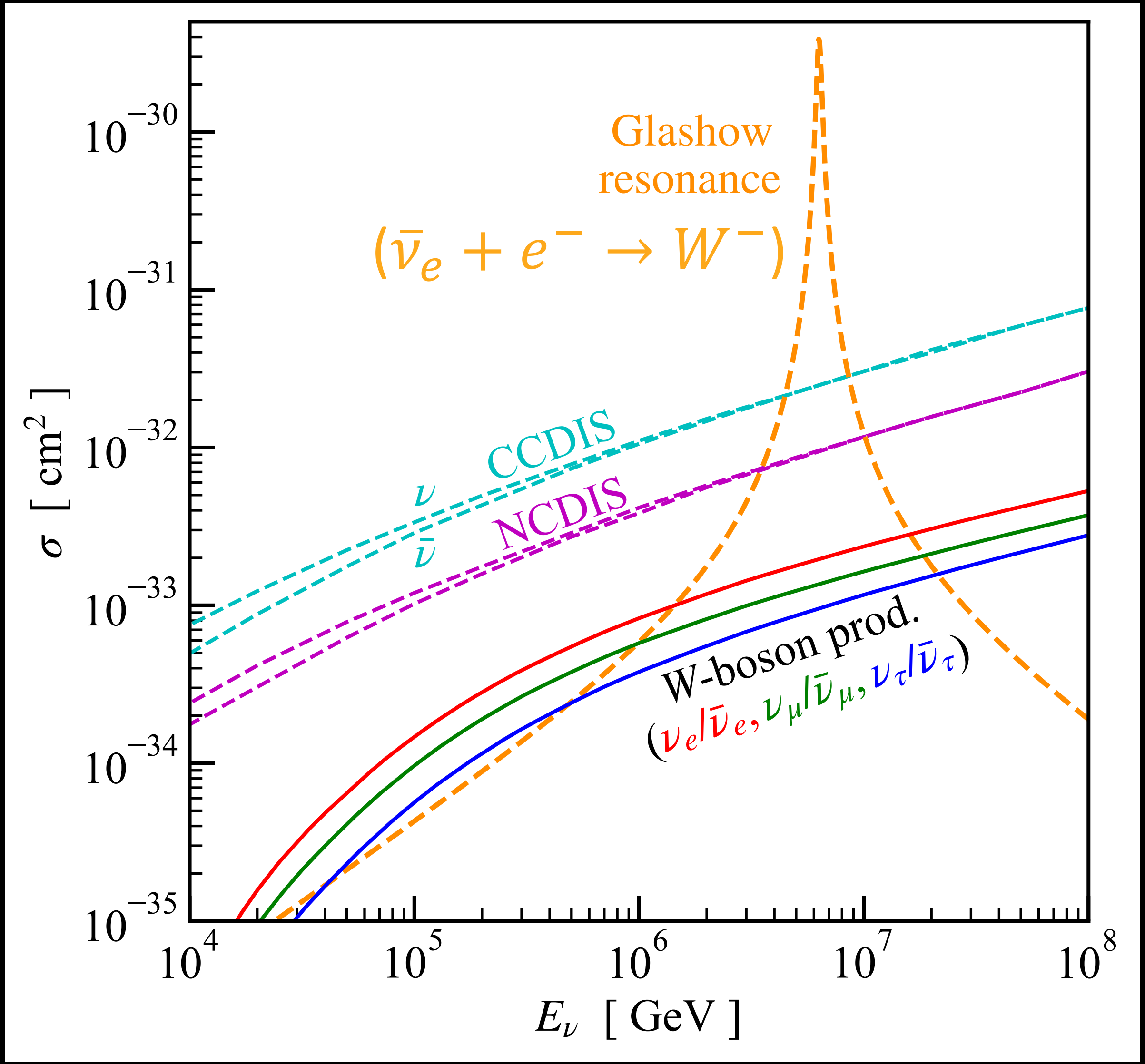
$h_{nucleon}^{T,L}(q^2, \hat{s}) \sim e^2 F_{nucleon}(q^2)$

Neutron's form factor has only magnetic part.

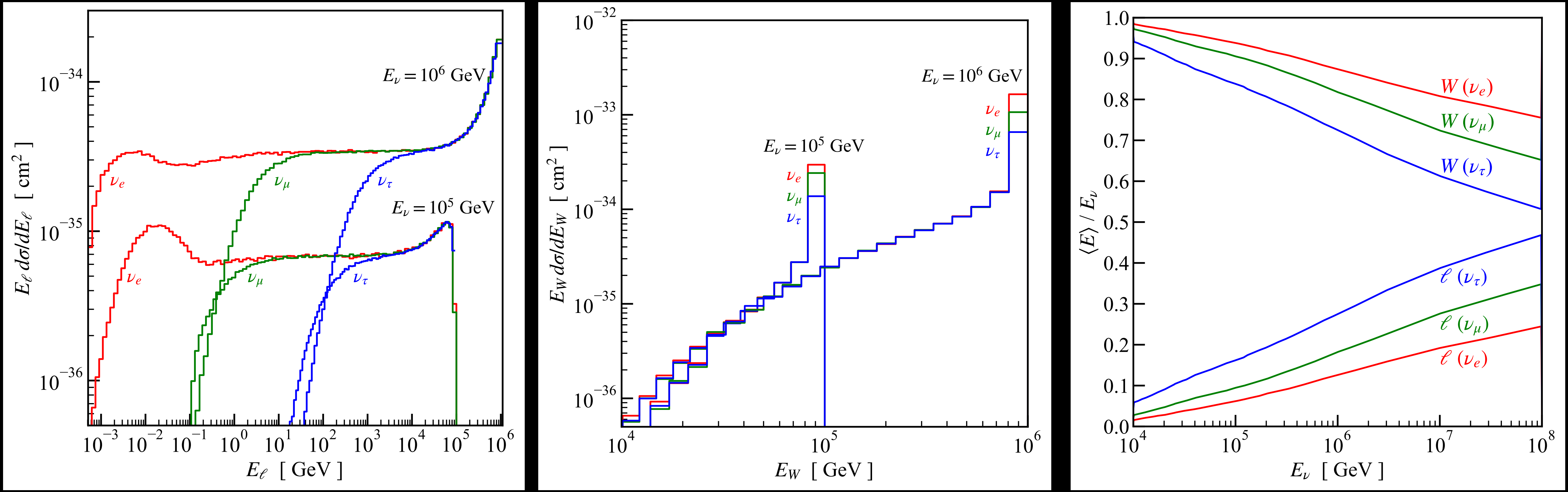
Proton's has both electric part and magnetic part.

DIS:

Use CT14 for PDFs.
Use MadGraph for calculation.



Glashow resonance
$(\bar{\nu}_e + e^- \rightarrow W^-)$
CCDIS
NCDIS
ν
$\bar{\nu}$
W-boson prod.
$(\nu_e/\bar{\nu}_e, \nu_\mu/\bar{\nu}_\mu, \nu_\tau/\bar{\nu}_\tau)$
σ [cm^2]
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^4
10^5
10^6
10^7
10^8
E_ν [GeV]



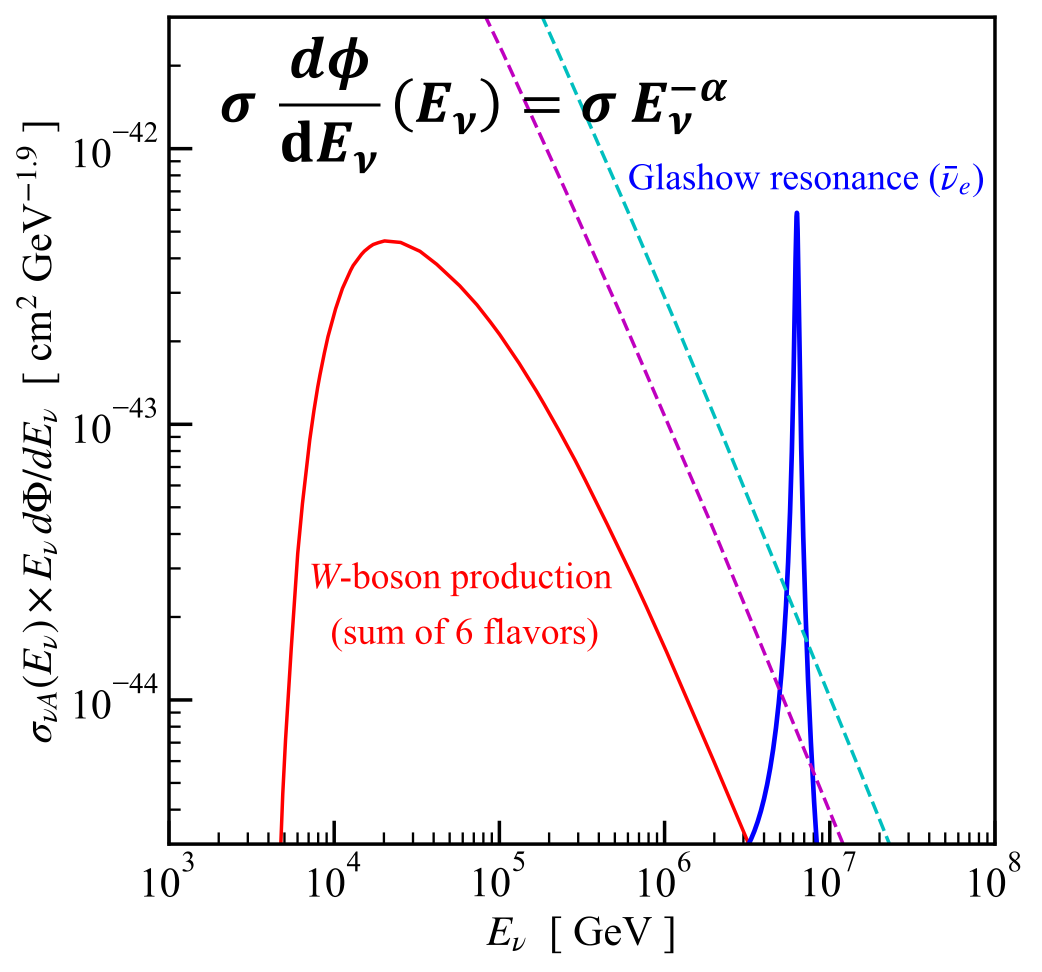
Features:

And W takes most of the energy

Energy transferred to nucleus is negligible

WBP produces more W's than Glashow resonance

(Zhou, Beacom, 1910.10720, PRD)



$\alpha = 2.9$ A factor of 20 (right figure →)
(2.9 is from fitting IceCube data)

$\alpha = 2.5$ A factor of 3.5
$\alpha = 2.0$ A factor of 0.5

So, WBP is the dominant source of on-shell W bosons unless the spectrum is extremely hard.

Increase neutrino attenuation in Earth

Neutrino flux ϕ, after attenuation is $\phi \times A$

Attenuation factor:

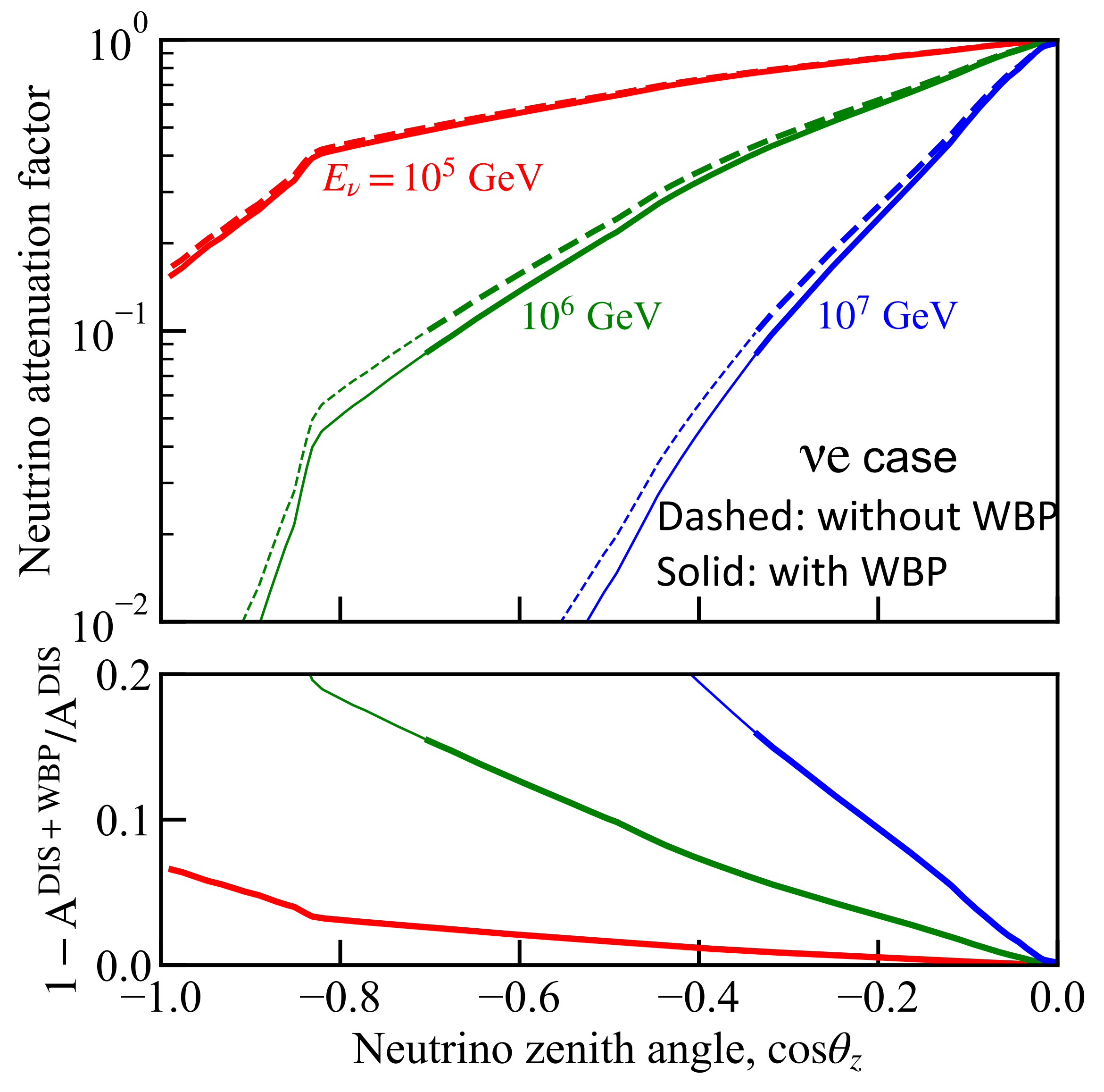
$$A = e^{-C(\cos\theta_z)\,\sigma(E_\nu)}$$

$C(\cos\theta_z)$: column density, well known

$\sigma(E_\nu)$: total xsec. WBP was not included.

Inseparable part of measuring xsec by IceCube.

1.3±0.45 of SM, but WBP not included



Channel	W decay	Final state	τ decay	Signature	Fraction	Counts
$\nu_e \to eW$ (7.5% rel. to CCDIS)	$e\nu_e$, 11%	e e		**Pure EM shower**	11%	0.34
	$\mu\nu_\mu$, 11%	e μ		**Track without**/with **shower**	11%	0.34
	$\tau\nu_\tau$, 11%	e τ	e, 18%	**Pure EM shower**	2.0%	0.06
			μ, 17%	**Track without**/with **(displaced) shower**	1.9%	0.06
			h, 65%	Shower	7.2%	0.22
	$q\bar{q}$, 67%	e h		Shower	67%	2.08
$\nu_\mu \to \mu W$ (5.0% rel. to CCDIS)	$e\nu_e$, 11%	μ e		**Pure EM shower**/Track with shower	11%	0.56
	$\mu\nu_\mu$, 11%	μ μ		**Single/Double tracks without shower**	11%	0.56
	$\tau\nu_\tau$, 11%	μ τ	e, 18%	**Pure EM shower/Track with (displaced) shower**	2.0%	0.10
			μ, 17%	**Single/Double tracks without shower**	1.9%	0.10
			h, 65%	Shower/**Shower with (displaced) track**	7.2%	0.36
	$q\bar{q}$, 67%	μ h		Shower/Shower with track	67%	3.41
$\nu_\tau \to \tau W$ (3.5% rel. to CCDIS)	$e\nu_e$, 11%	τ e	e, 18%	**Pure EM shower**	2.0%	0.02
			μ, 17%	**Pure EM shower/Track with (displaced) shower**	1.9%	0.02
			h, 65%	**Pure EM shower**/Shower	7.2%	0.09
	$\mu\nu_\mu$, 11%	τ μ	μ, 17%	**Single/Double tracks without shower**	1.9%	0.02
			e or h, 83%	**Track without shower/with (displaced) shower**	9.1%	0.11
	$\tau\nu_\tau$, 11%	τ τ	e e, 3%	**Pure EM shower**	0.4%	0.004
			μ μ, 3%	**Single/Double tracks without shower**	0.3%	0.004
			μ e/h, 29%	**Track without shower/with (displaced) shower**	3.1%	0.04
			h h/e, 65%	Shower/Double bang	7.2%	0.09
	$q\bar{q}$, 67%	τ h	e or h, 83%	Shower	56%	0.69
			μ, 17%	Shower/Shower with track	11%	0.14
Total counts						9.44

Unique signatures (background free)

$\nu_l + A \to l + W + A'$ (W takes most energy, l ~50% detectable, A' negligible energy)

1. Double track (no shower) 0.34 events per 10 years IceCube and > 60 TeV

   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$

2. Track without shower 0.96 events ……

   Mainly from: $\nu_\mu + A \to \mu + W + A'$ with $W \to \mu$, and two tracks are inseparable
   $\nu_e + A \to e + W + A'$ with $W \to \mu$, and e energy is low

3. Pure EM shower 0.82 events ……
   Mainly from: $\nu_e + A \to e + W + A'$ with $W \to e$
   $\nu_{\mu/\tau} + A \to \mu/\tau + W + A'$ with $W \to e$, and μ/τ energy is low

Glashow resonance vs. W-boson production

	Glashow resonance	W-boson production
Process	$\bar{\nu}_e + e^- \rightarrow W^-$	$\nu_x + A \rightarrow x^- + W^+ + A'$ $\bar{\nu}_x + A \rightarrow x^+ + W^- + A'$
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)