W-boson and trident production for high-energy neutrinos

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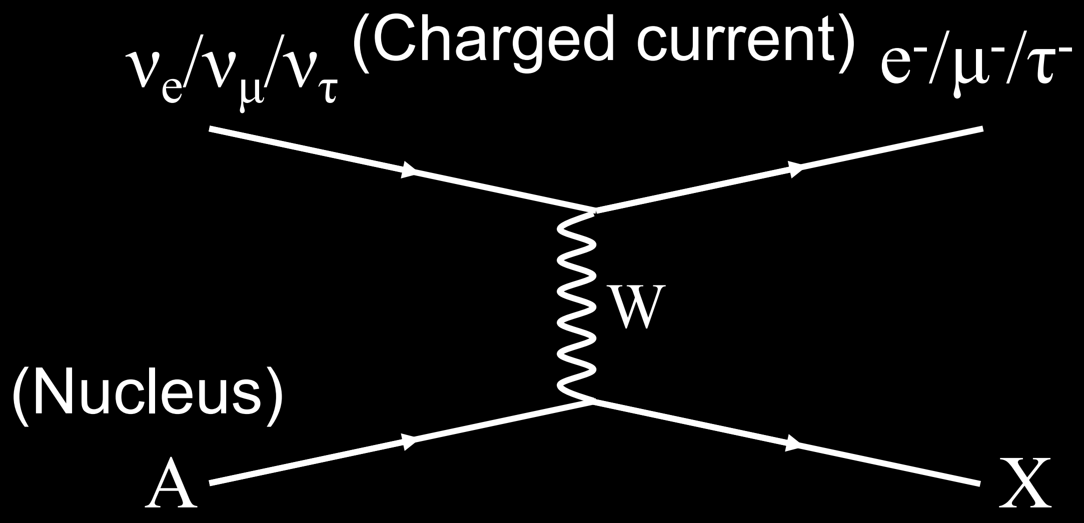
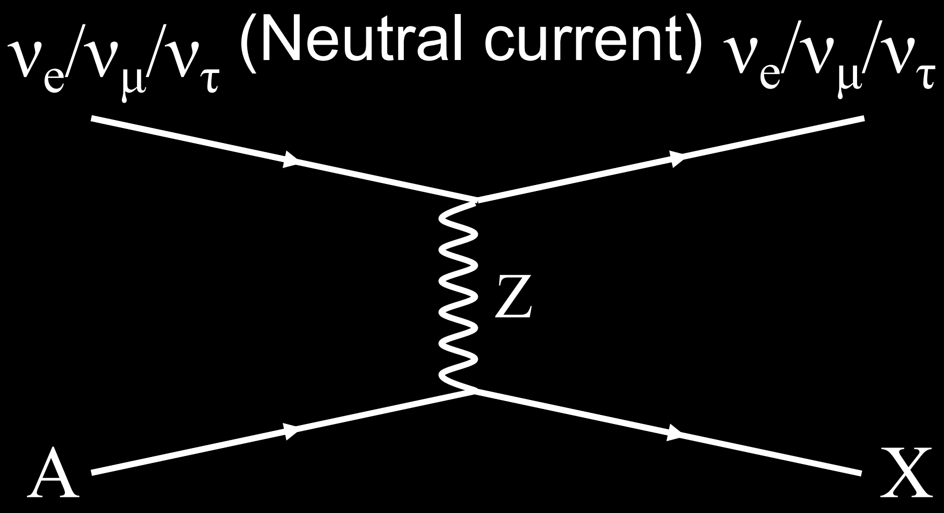
(Will be on arXiv in a few days)

TeV—PeV neutrinos

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



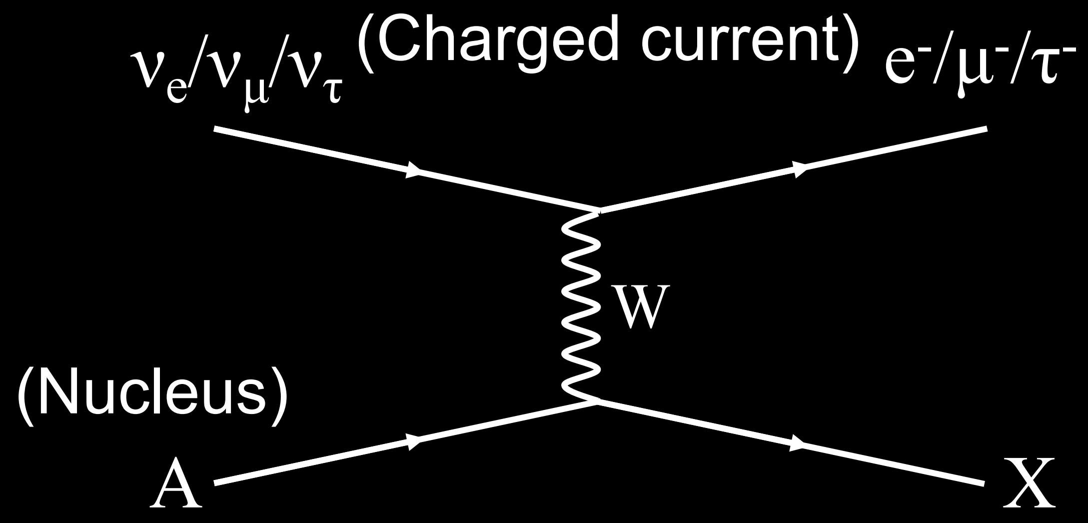


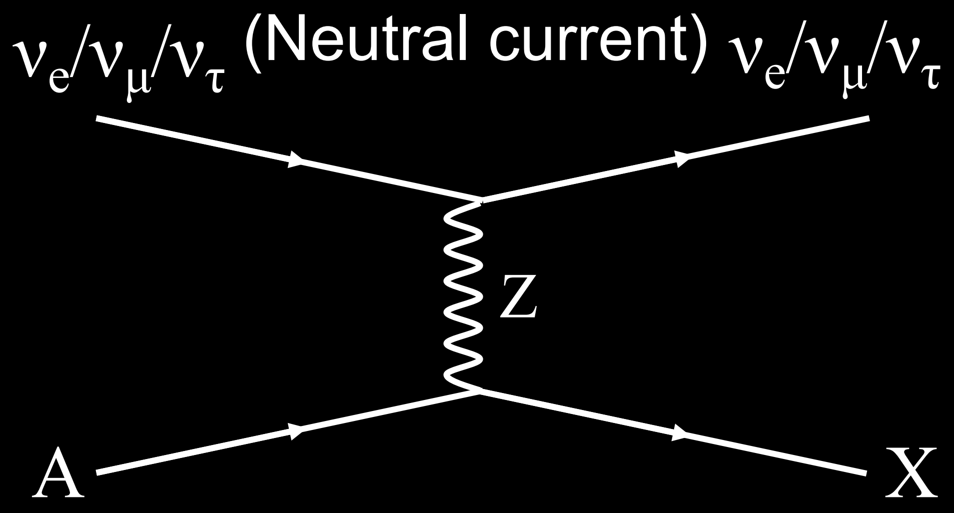
Increasing data demands studying subdominant interactions

Detector	Size	Status
IceCube	1 km^3	Running
KM3NET	1 km^3	Being constructed
IceCube-Gen2	10 km^3	Proposed

Photon coupling to nucleus

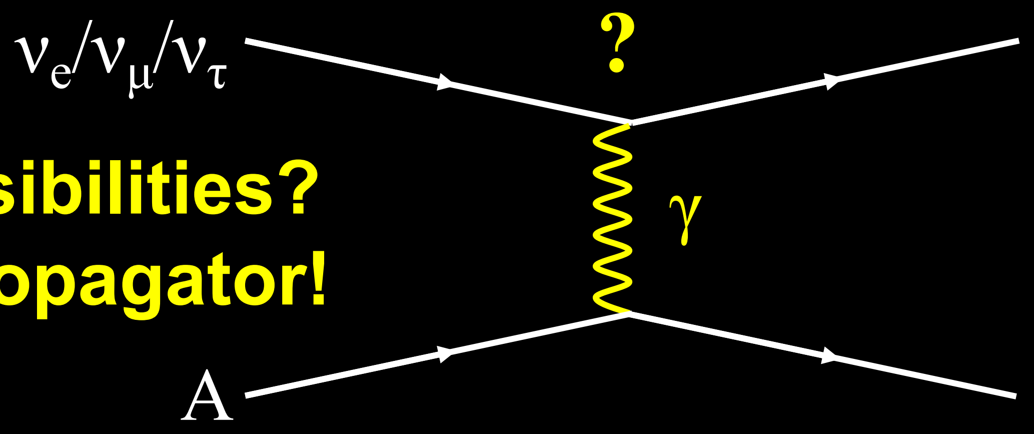
Deep inelastic scattering (DIS) dominates (~2% precision)





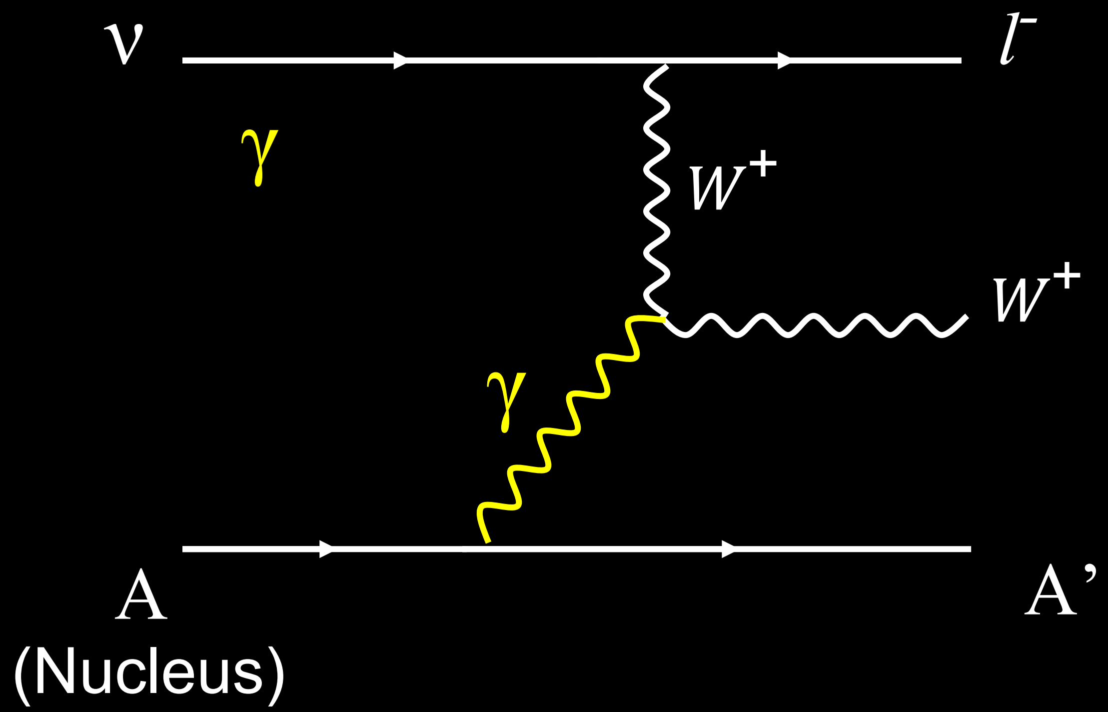
Subdominant interactions: photon coupling to the nucleus

Any other possibilities?
Yes, photon propagator!

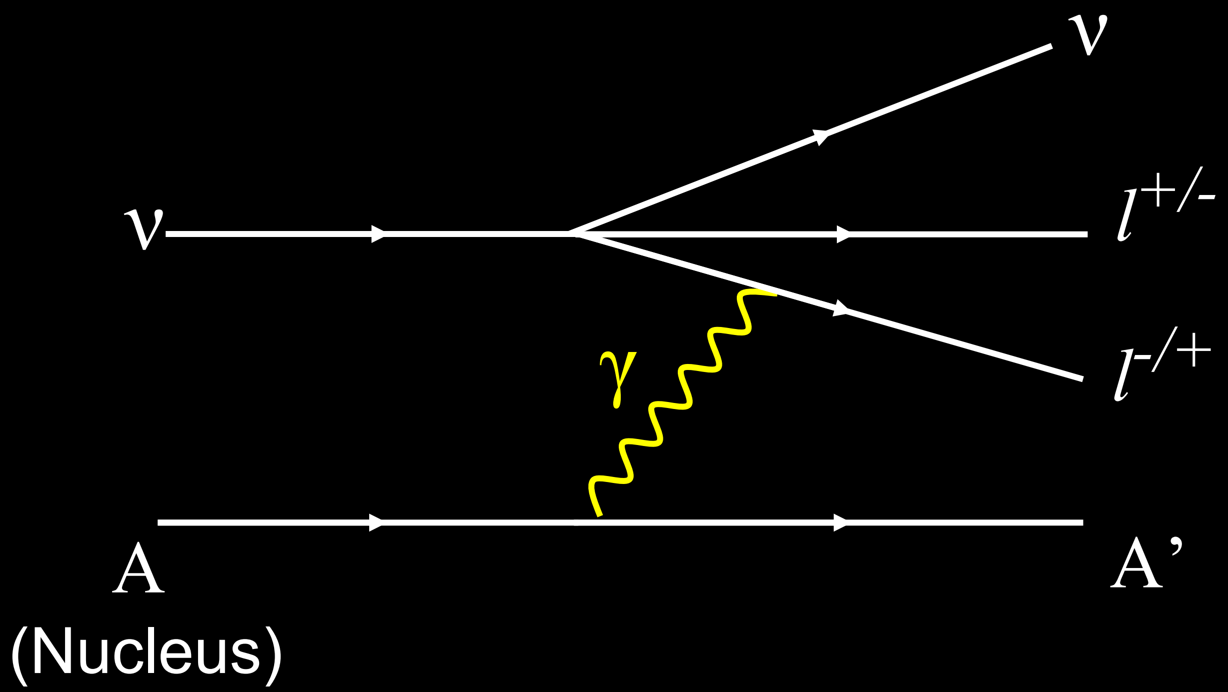


Two other processes may matter

(on-shell) W-boson production

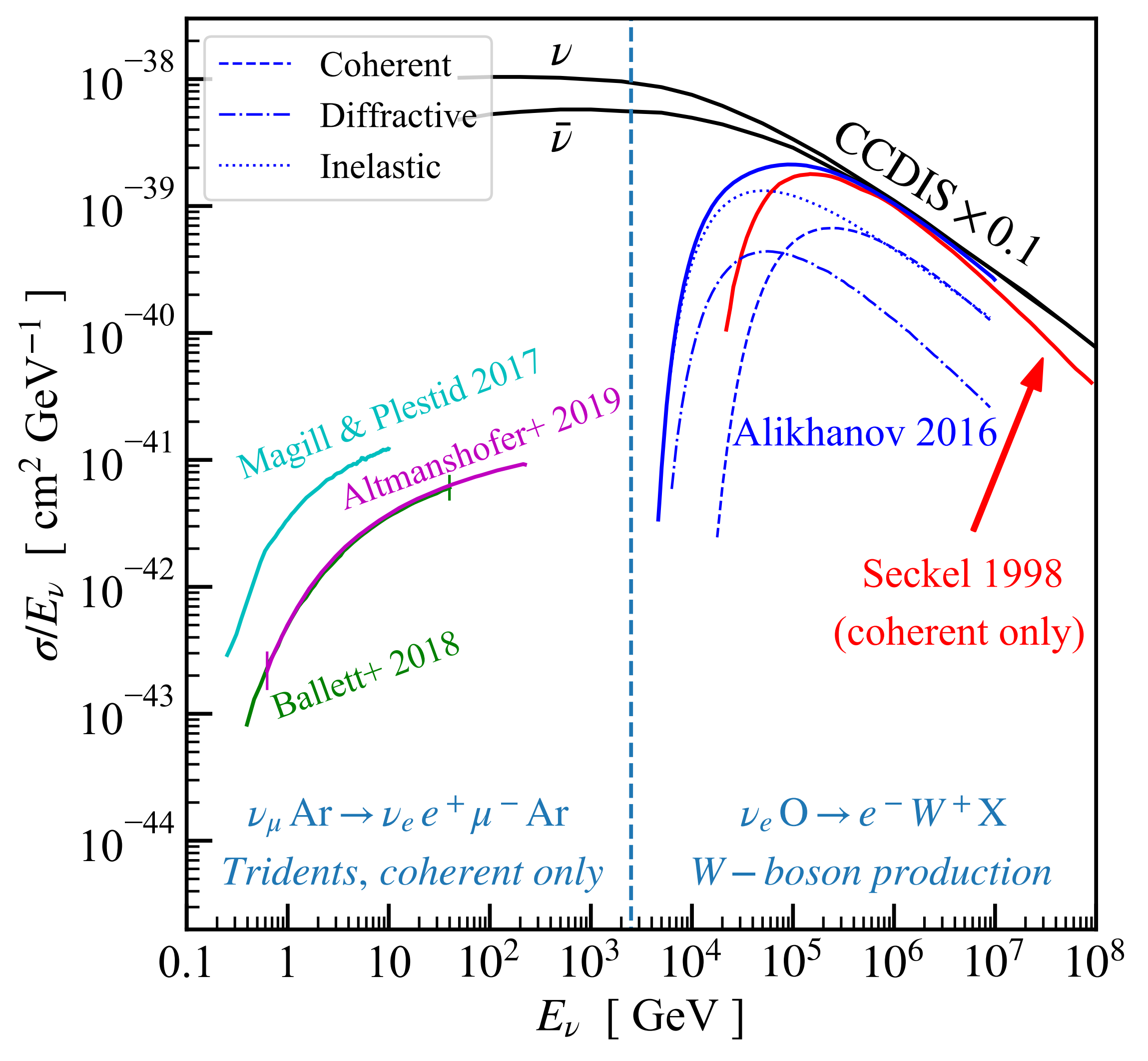


Trident production



Goals of our work

1. Cross section

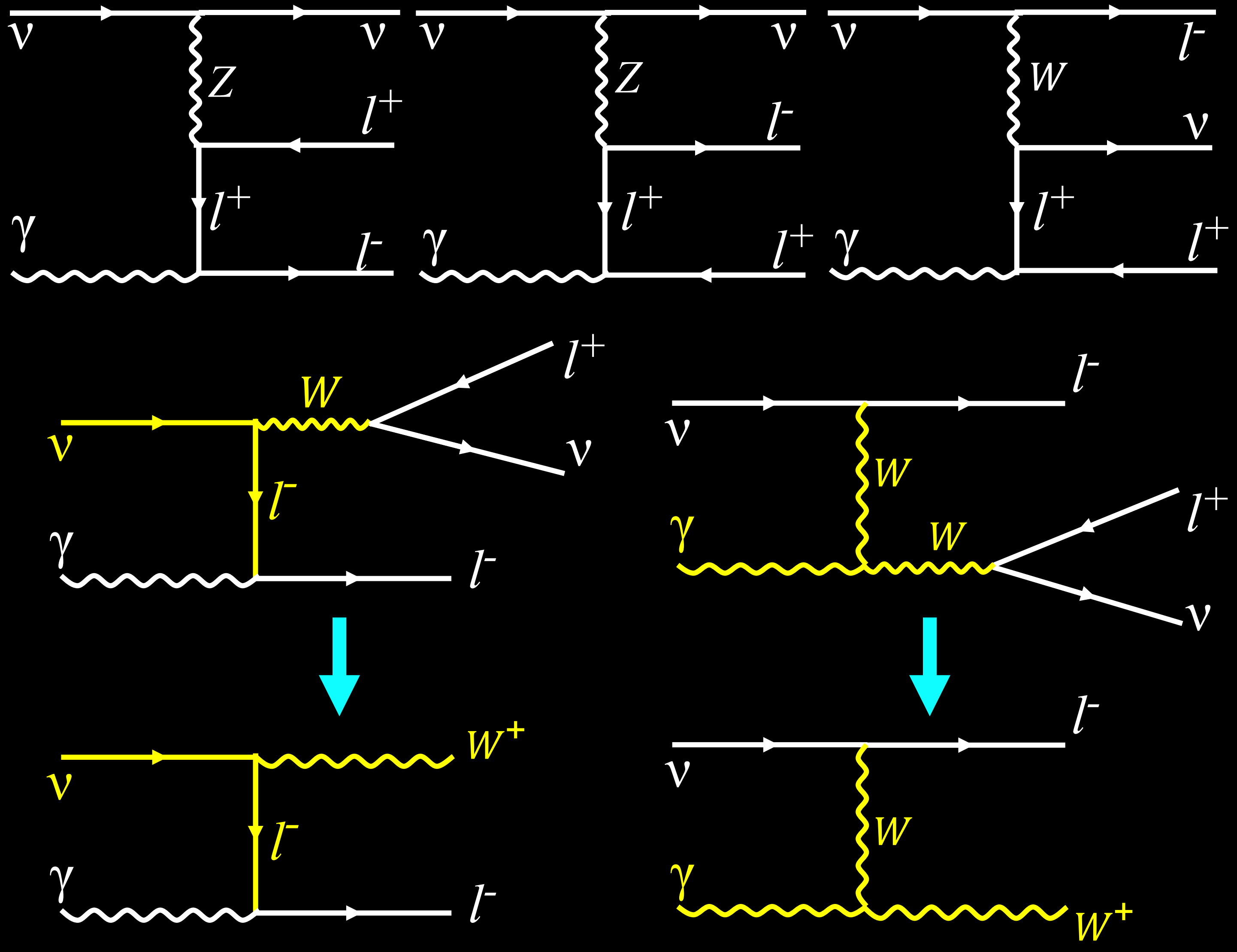


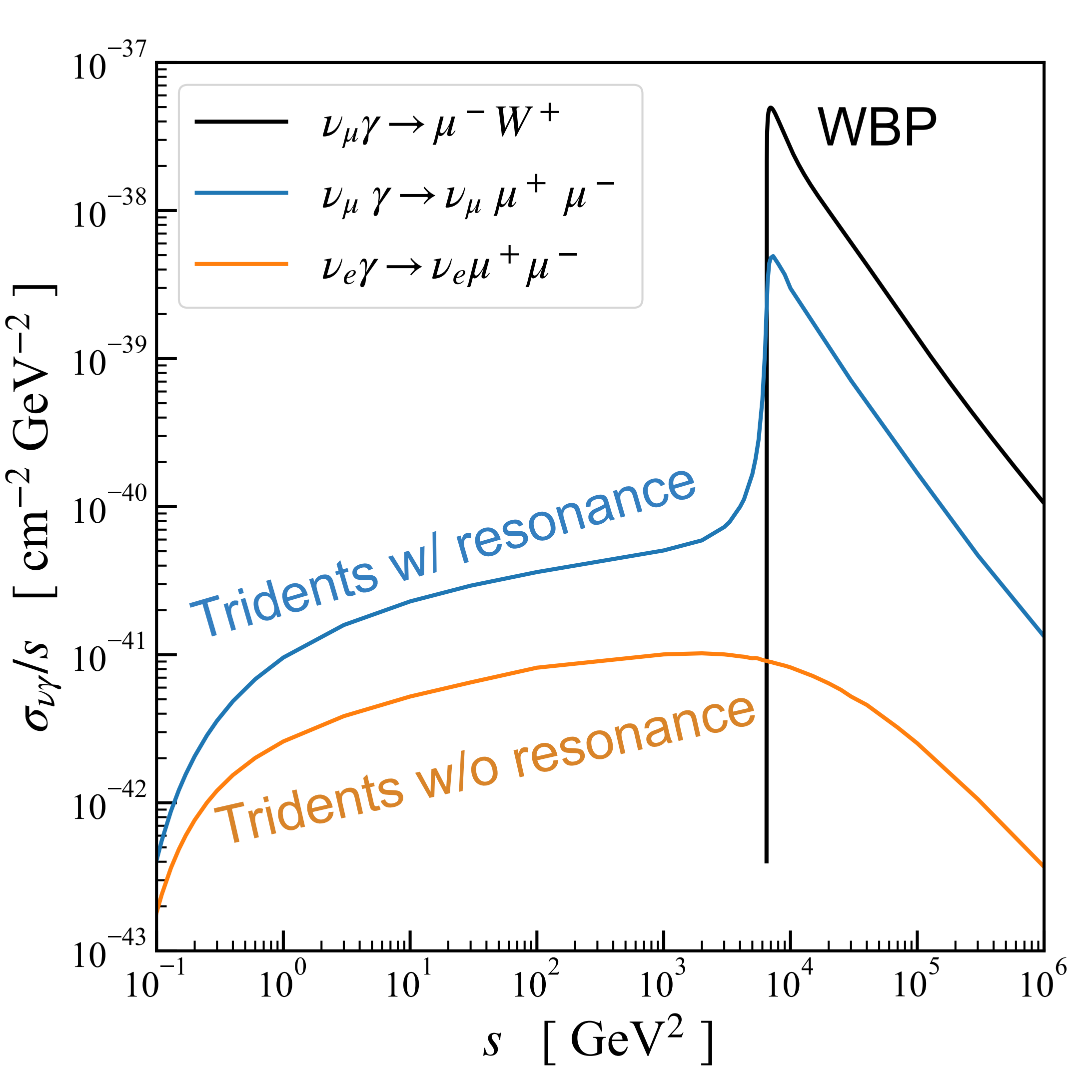
2. Effects on detections, etc. (No study before)

- Detections
- Unique signatures. E.g., dimuon

Part 1: Cross sections

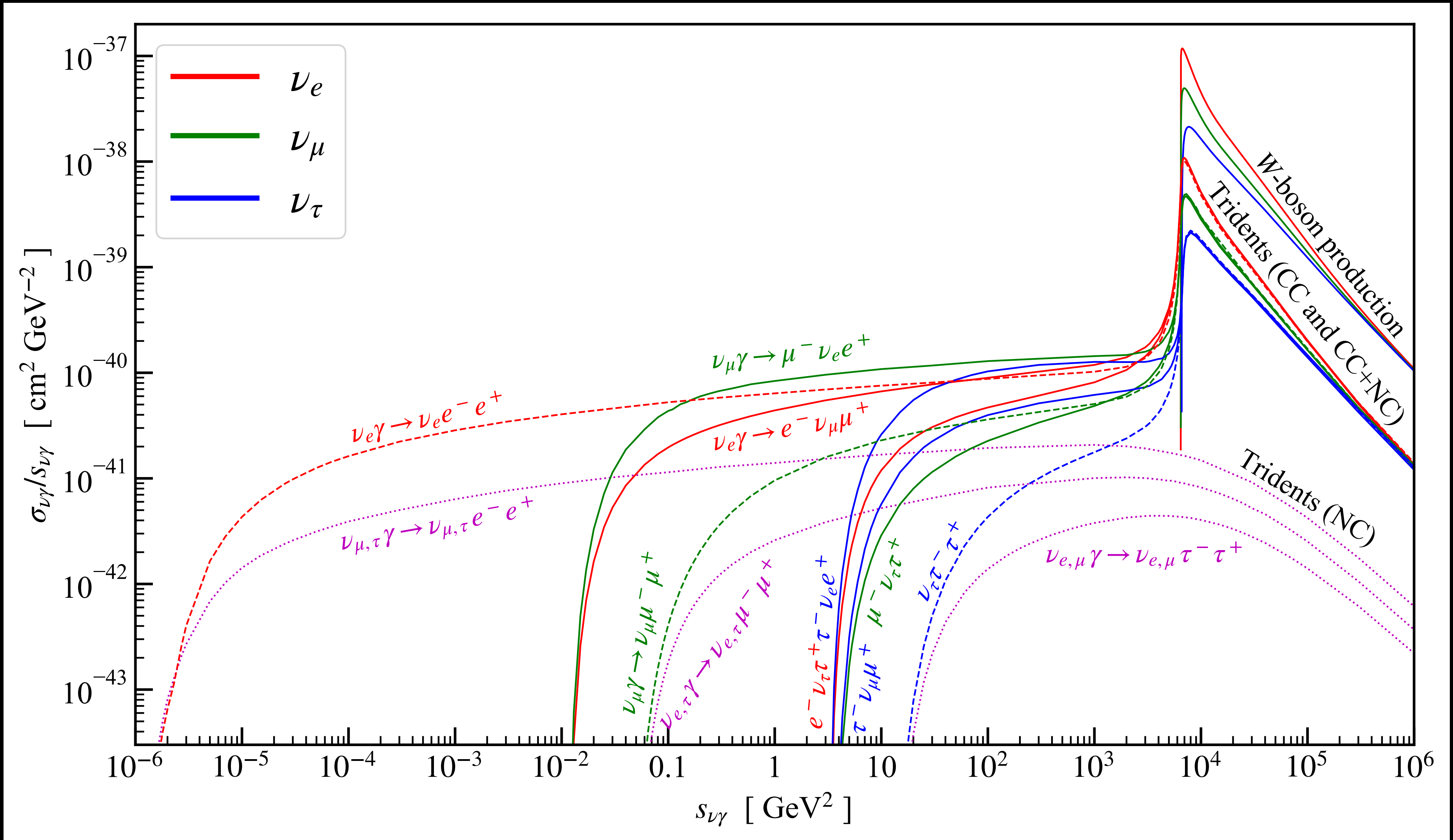
Cross section with free photon, instead of nucleus



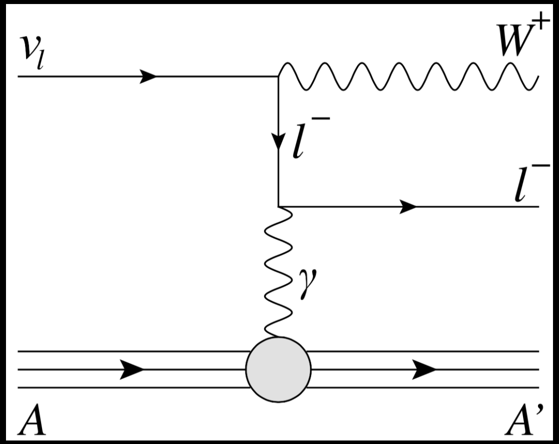


Tridents and W boson production are related!

Cross section with free photon: different flavors

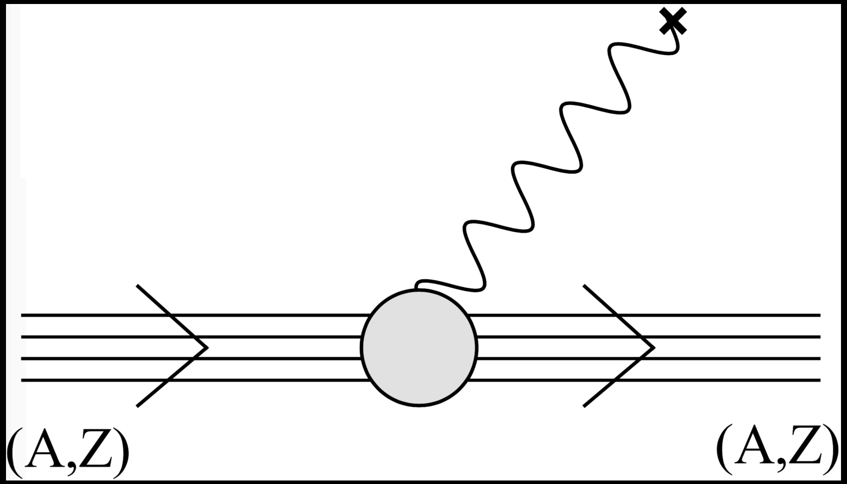


From cross section with photon to with nucleus

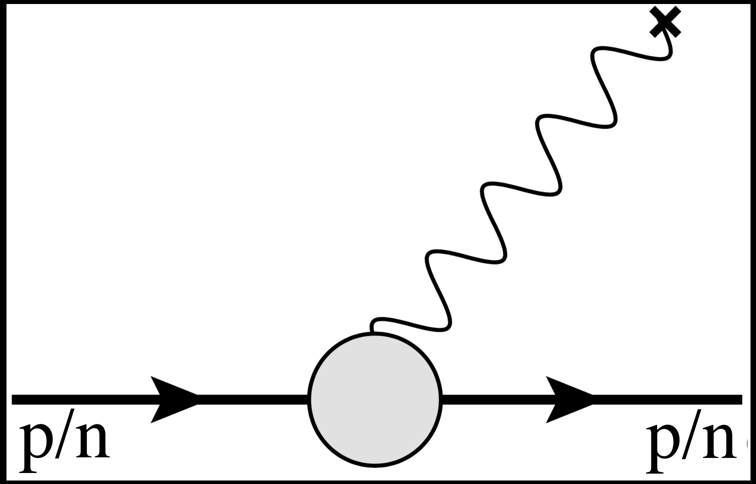


Photon from the nucleus → three kinetic regimes

Coherent (elastic)



Diffractive (elastic)



Inelastic

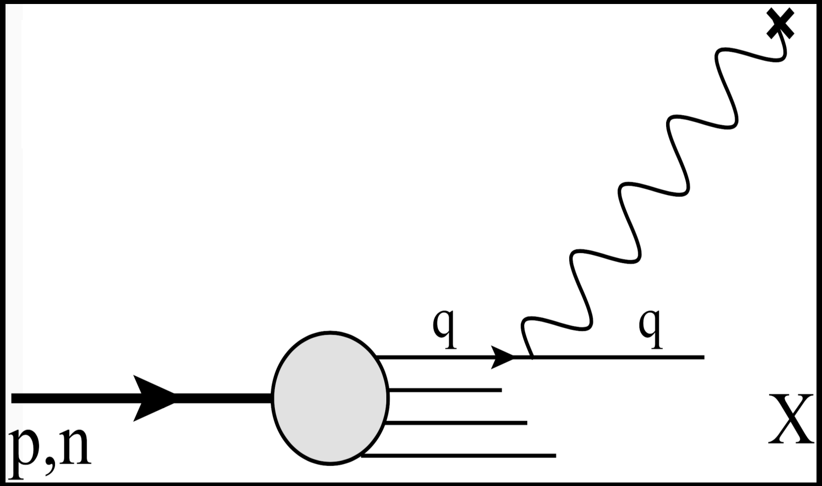
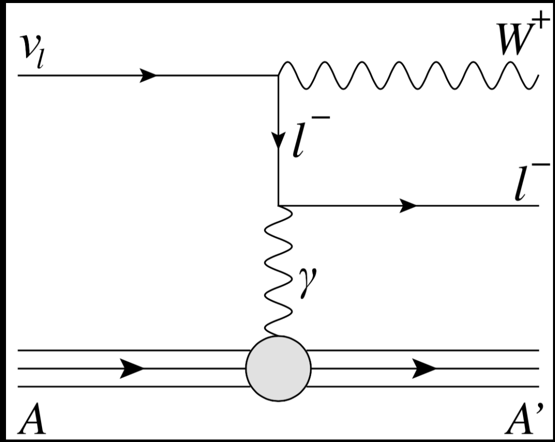


Figure from: Alikhanov, PLB, 2016 and modified

Coherent and diffractive: Invalidity of equivalent photon approximation



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

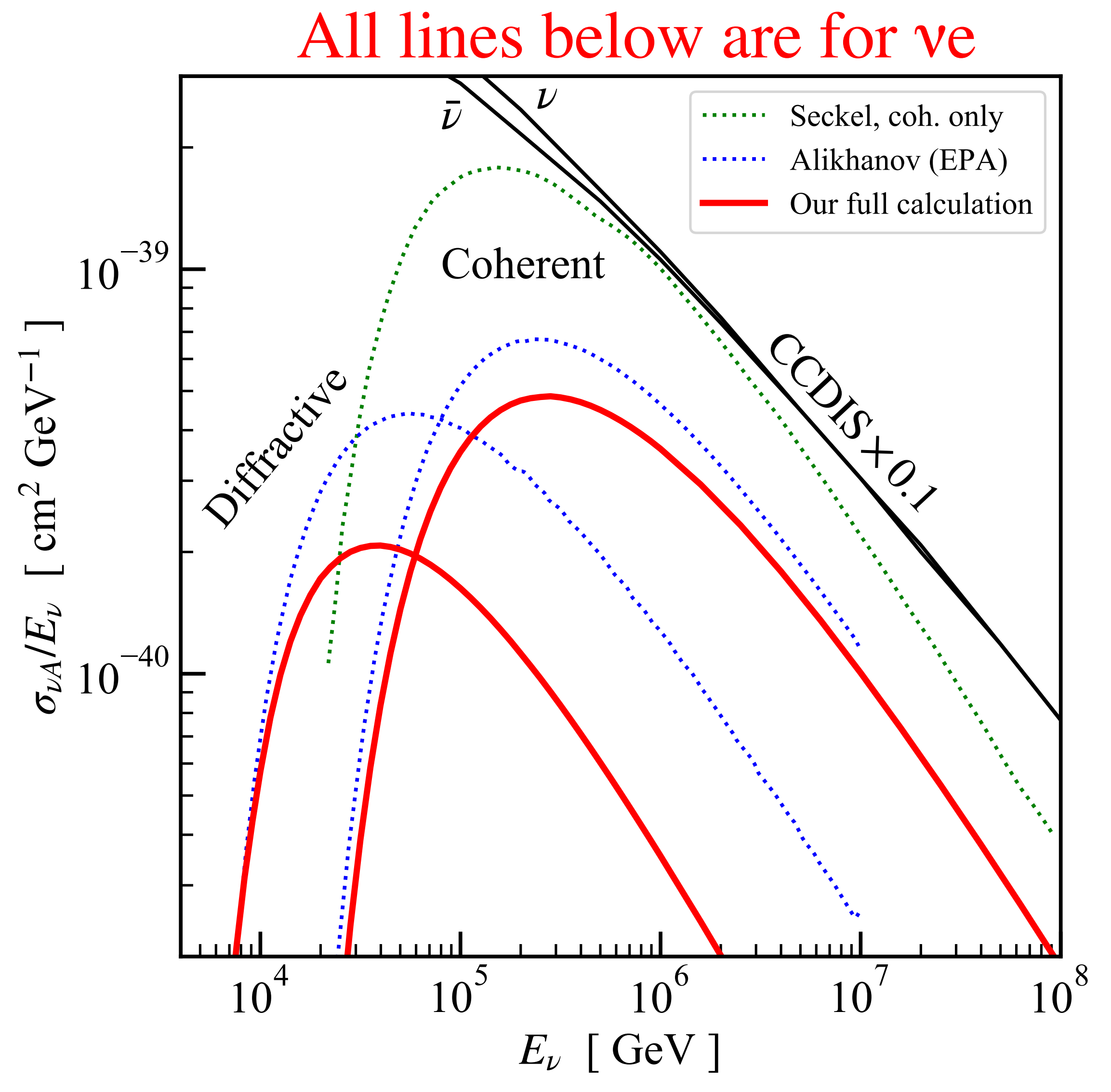
Coherent and diffractive: complete approach

$$\frac{d^2\sigma_{\nu A}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}q^2}\left[\sigma^T_{\nu\gamma}(q^2,\hat{s})\, h^T_X(q^2,\hat{s}) + \sigma^L_{\nu\gamma}(q^2,\hat{s})\, h^L_X(q^2,\hat{s})\right]$$

Transverse   Longitudinal

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

Czyz, Sheppey, Walecka, Nuovo Cim. 1964; Ballett et al. , 1807.10973



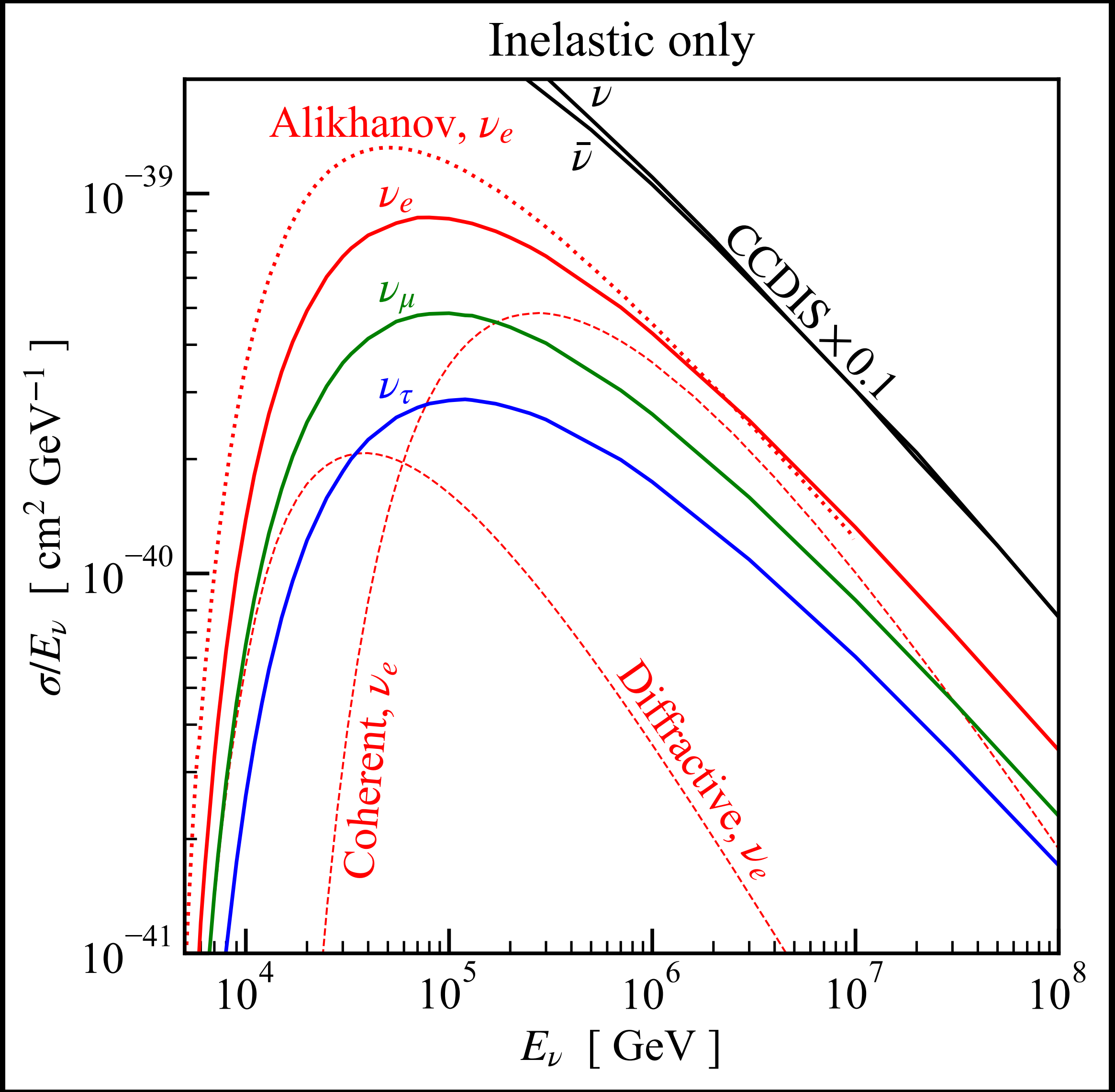
EPA is not good. Pauli blocking should be included.

Inelastic

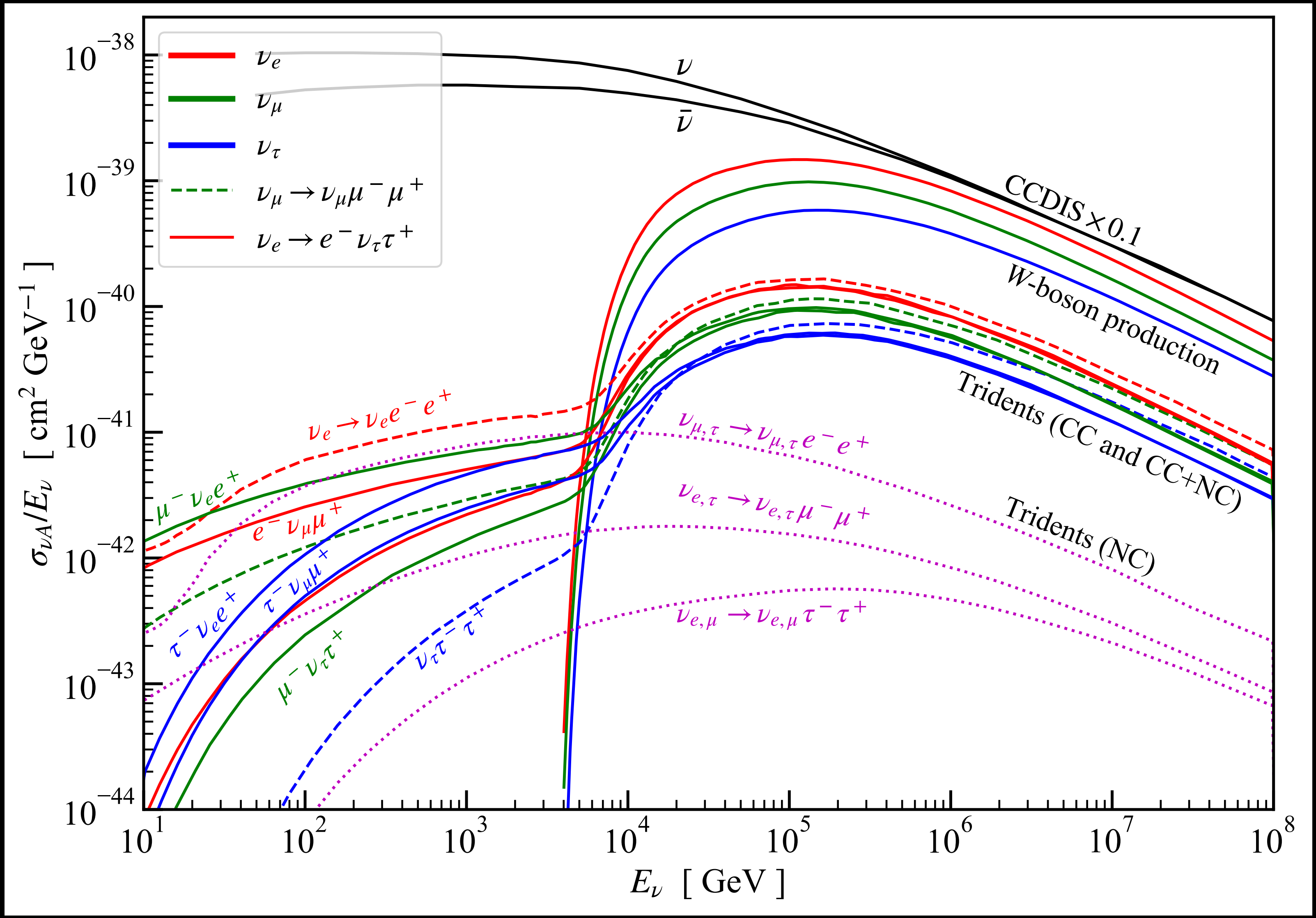
Use Photon PDF (CT14, *1509.02905*)

Use MadGraph for calculation.

Choose $\hat{s}_{\nu\gamma}$ as the factorization scale.



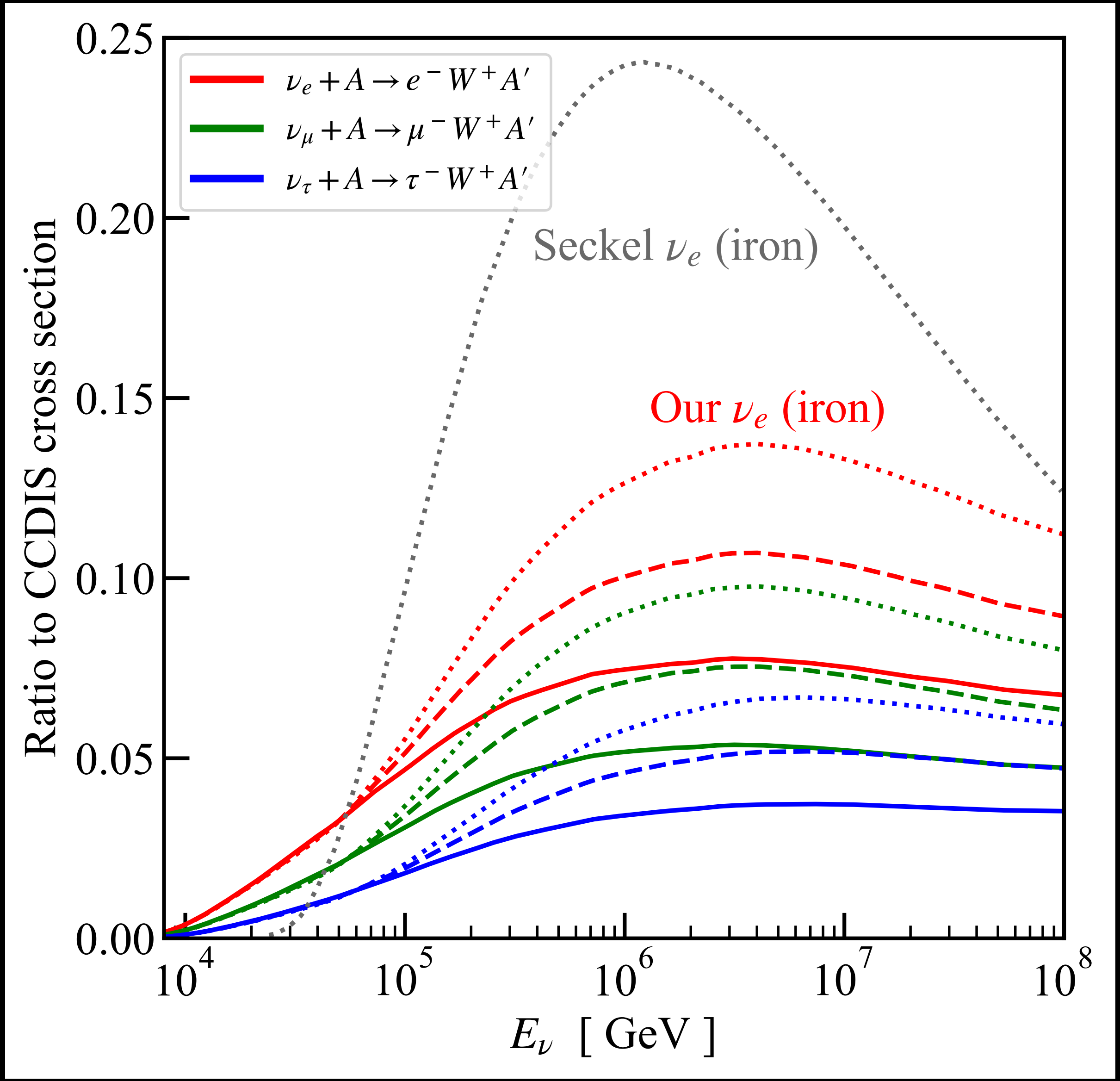
Total neutrino-nucleus cross section



W-boson production:
Much more complete calculation

Tridents:
First calculation at TeV—PeV

Ratios to CCDIS



Maximal ratios:

Water/ice targets (solid lines):
7.5% (νe), 5% (νμ), 3.5% (ντ)
Iron targets (dotted):
14% (νe), 10% (νμ), 7% (ντ)

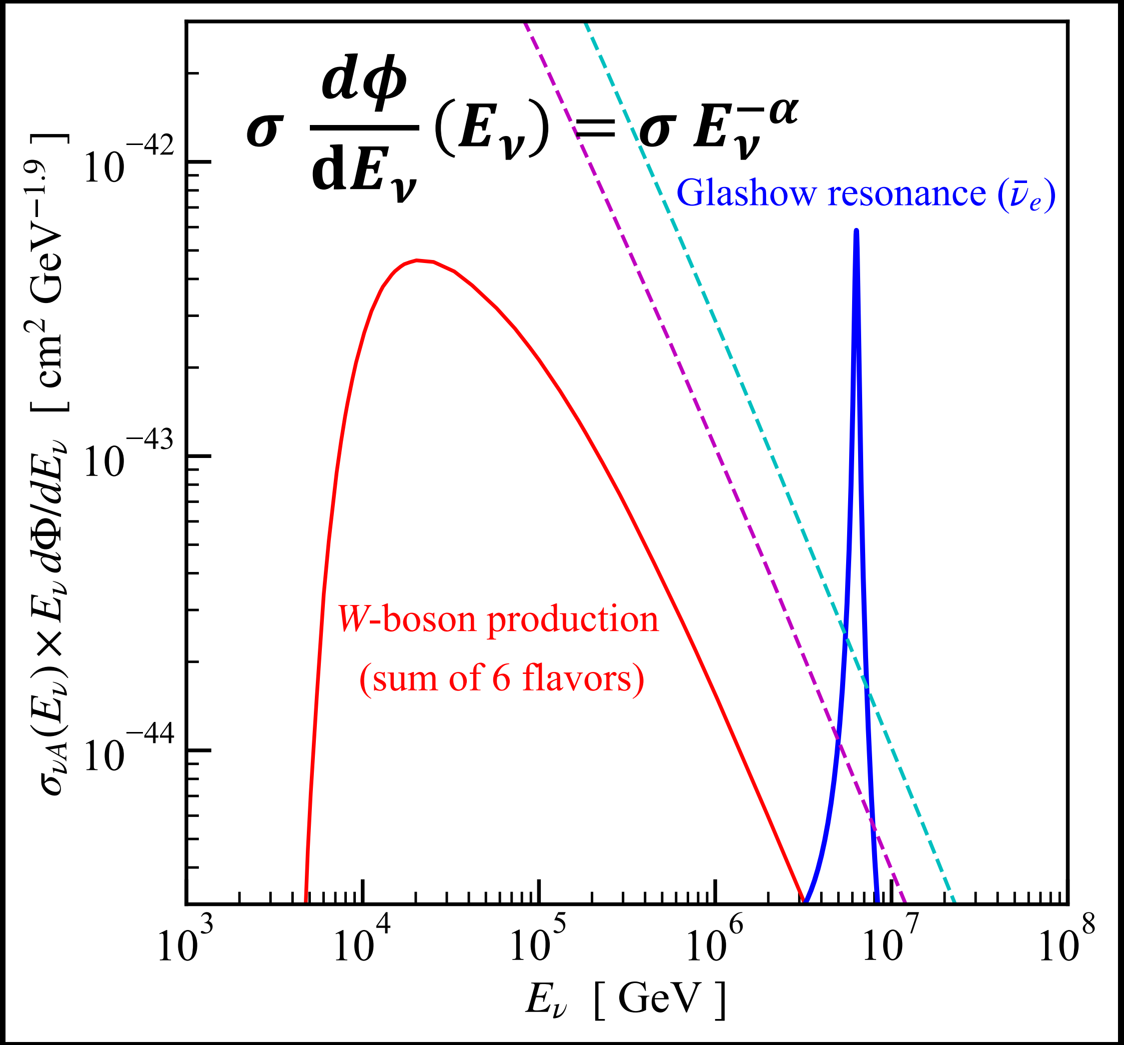
Implications

1. Neutrino absorption in Earth
   (In crease as large as ≃15%)

2. Detections in IceCube, etc.

Part 2: Detections

WBP produces more W's than Glashow resonance

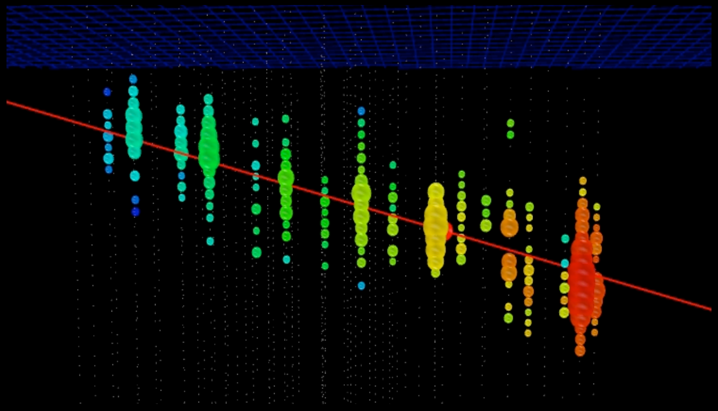


$\alpha = 2.9$ A factor of 20 (right figure →)
(2.9 is from fitting IceCube data)

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

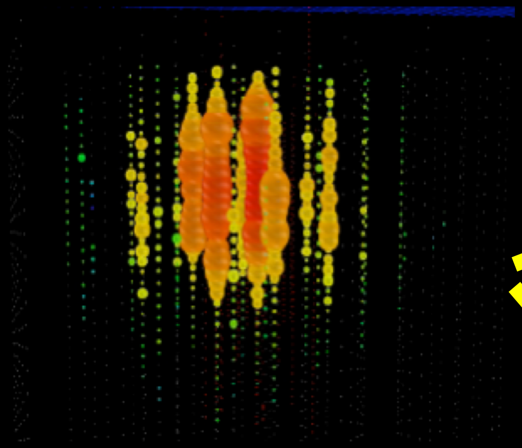
So, WBP is the dominant source of on-shell W bosons unless the spectrum is extremely hard.

Brief review of IceCube detection



μ track

mainly νμ CCDIS

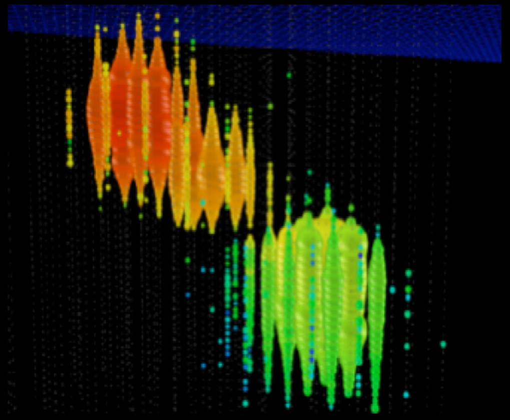


Shower

(e or hadron)

e: mainly from νe CCDIS

hadrons: All CC/NC DIS



Double bang/pulse (τ)

(ντ CCDIS >~1e5 GeV)

EM shower (e)

vs

Hadronic shower

Shower spectrum: WBP mainly showers

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

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

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

W decay

$\rightarrow e$ (11%)

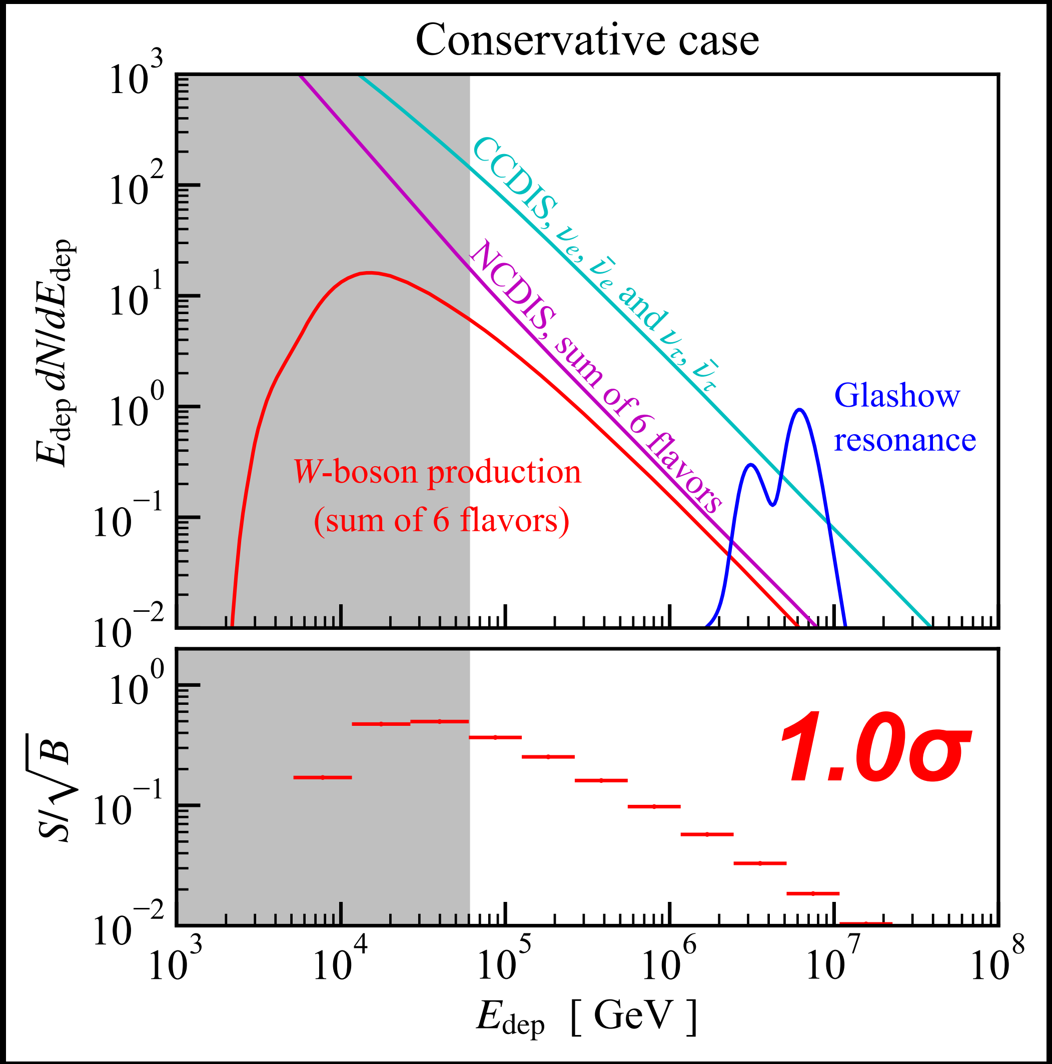
$\rightarrow \mu$ (11%)

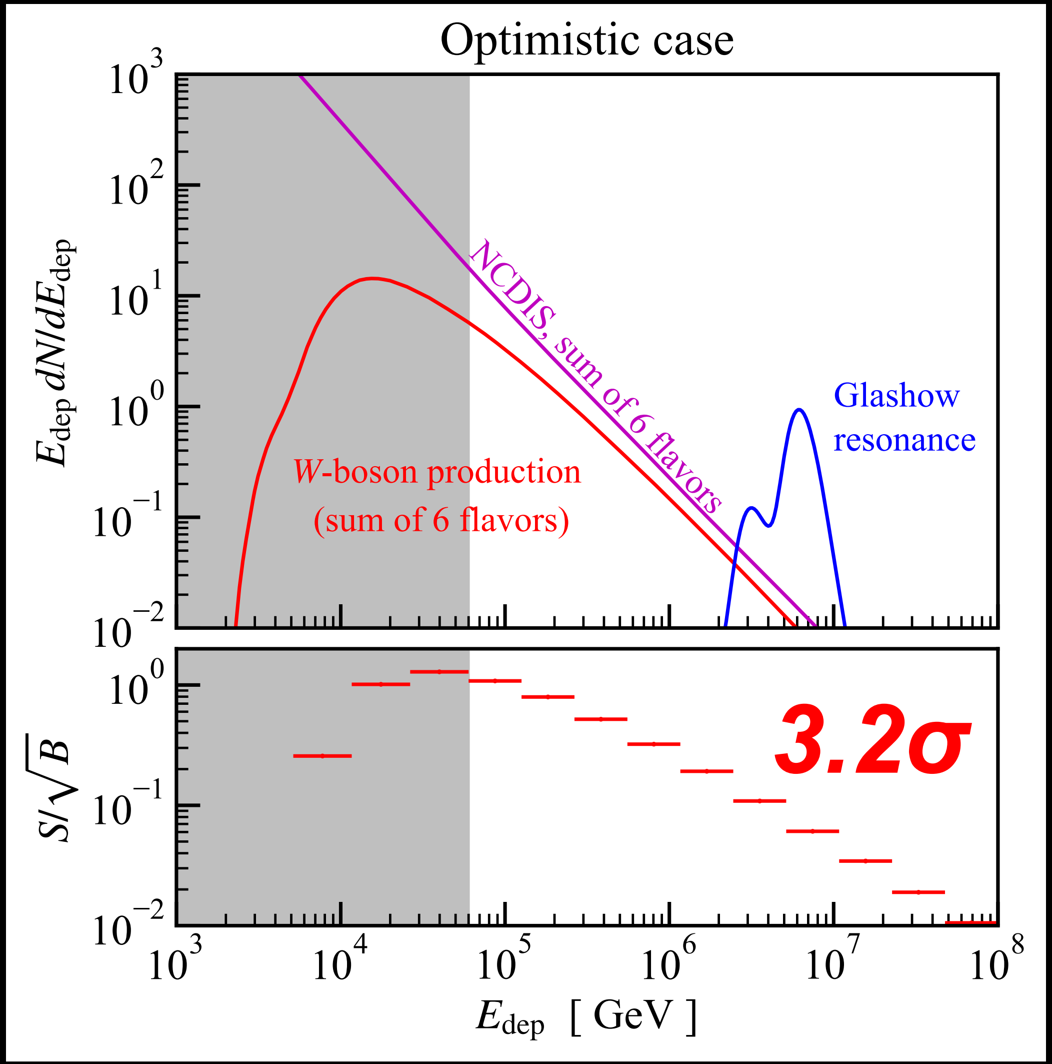
$\rightarrow \tau$ (11%)

$\rightarrow h$ (67%)

Shower spectrum: WBP contributes and detectable

For 10 years observation by IceCube (10 year for KM3NET and 1 year IceCube-Gen2)





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

Unique signatures (background free)

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

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

2. Track without shower 0.96 events ……

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

3. Pure EM shower 0.82 events ……

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

Conclusions

Cross sections

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

+ First calculation of tridents at TeV—PeV

+ The two processes are related

W-boson prod. affects detections

+ ν in-earth attenuation increased 15%

+ Produces 20 times more W's than Glashow resonance

+ Contributes $\simeq$6 shower events

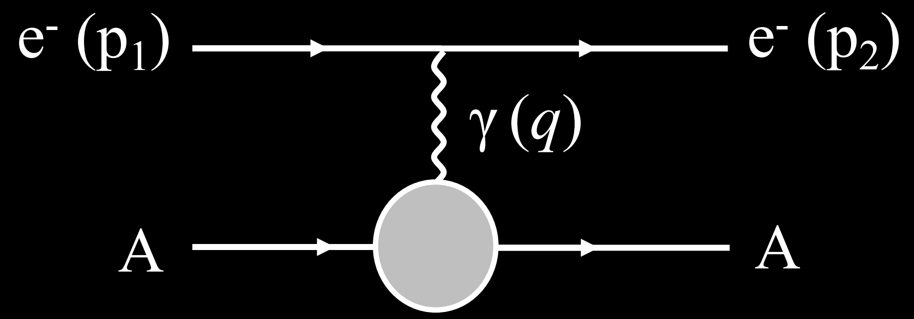
+ Gives background free signatures

Thanks for your attention!

6Coherent and diffractive: Invalidity of equivalent photon approximation

(or Weizsäcker-Williams approximation)

Equivalent photon approx.



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

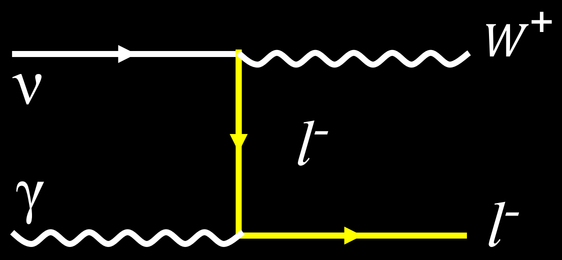
$p_2 \simeq (E_2, 0, E_2\sin\theta, E_2\cos\theta)$; $\cos\theta \simeq 1$

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

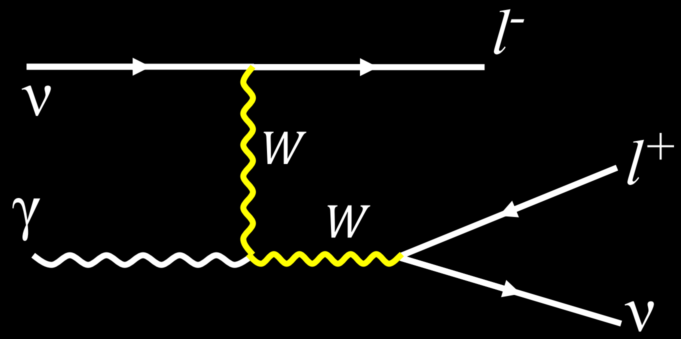
$$\sigma_{eA}(s) \simeq \int \sigma_{e\gamma}(s_{e\gamma})\, H_\gamma(s_{e\gamma}, q^2)$$

But not valid for us

W-boson production



Tridents



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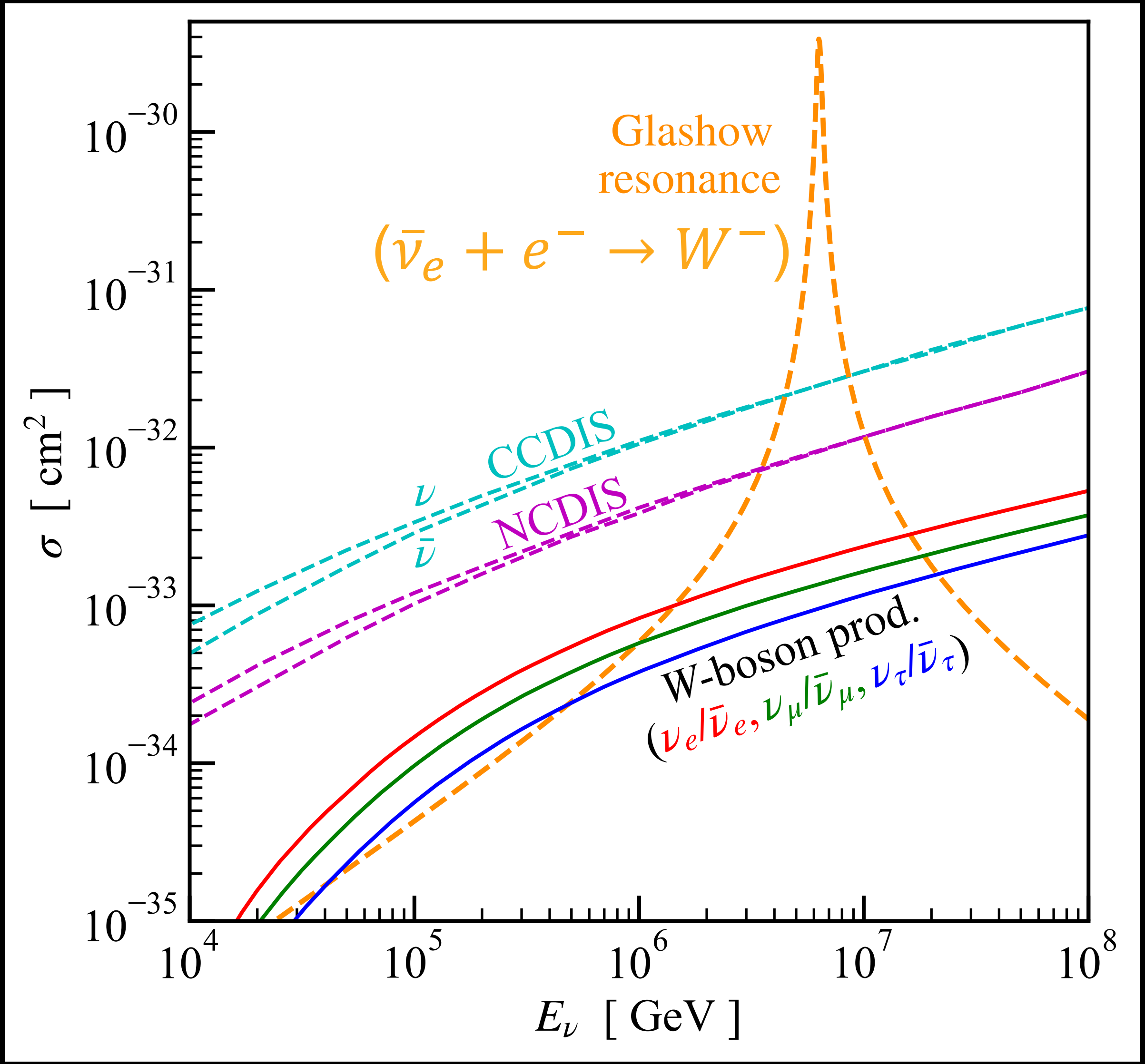
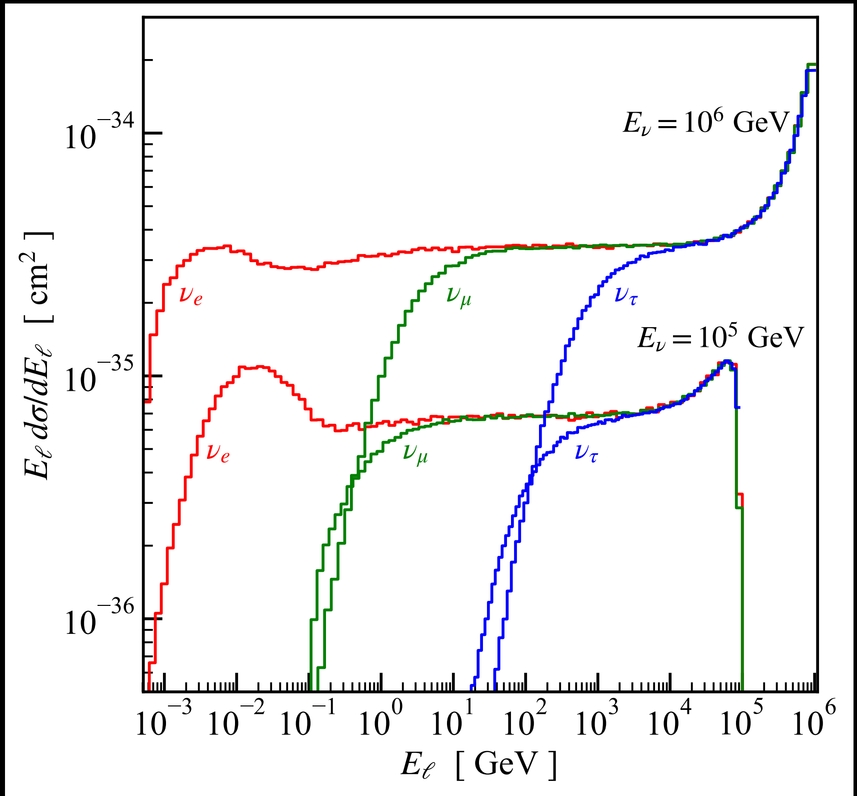
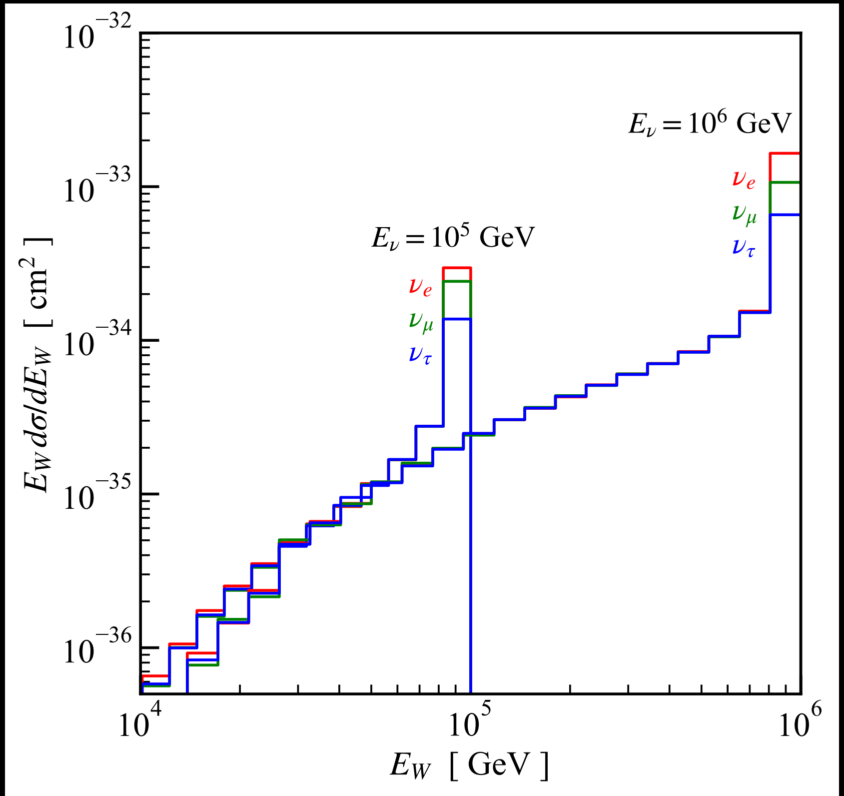
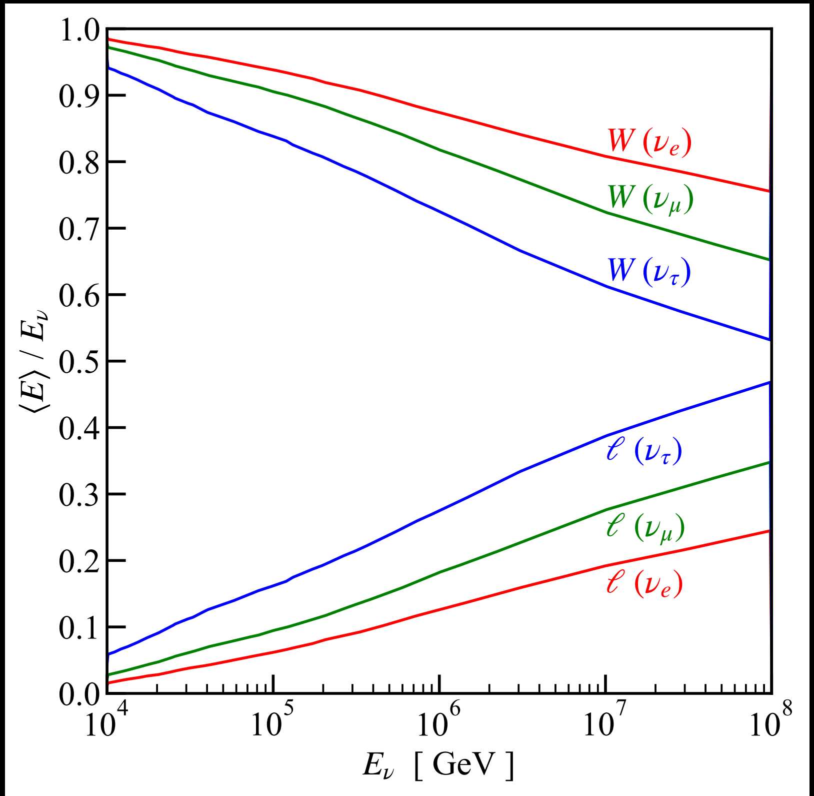

Glashow
resonance
$(\bar{\nu}_e + e^- \to W^-)$
CCDIS
NCDIS
ν
$\bar{\nu}$
W-boson prod.
$(\nu_e/\bar{\nu}_e, \nu_\mu/\bar{\nu}_\mu, \nu_\tau/\bar{\nu}_\tau)$
σ [cm^2]
E_ν [GeV]
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^4
10^5
10^6
10^7
10^8

15 Differential cross sections







Features:
And W takes most of the energy
Energy transferred to nucleus is negligible

Increase neutrino attenuation in Earth

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

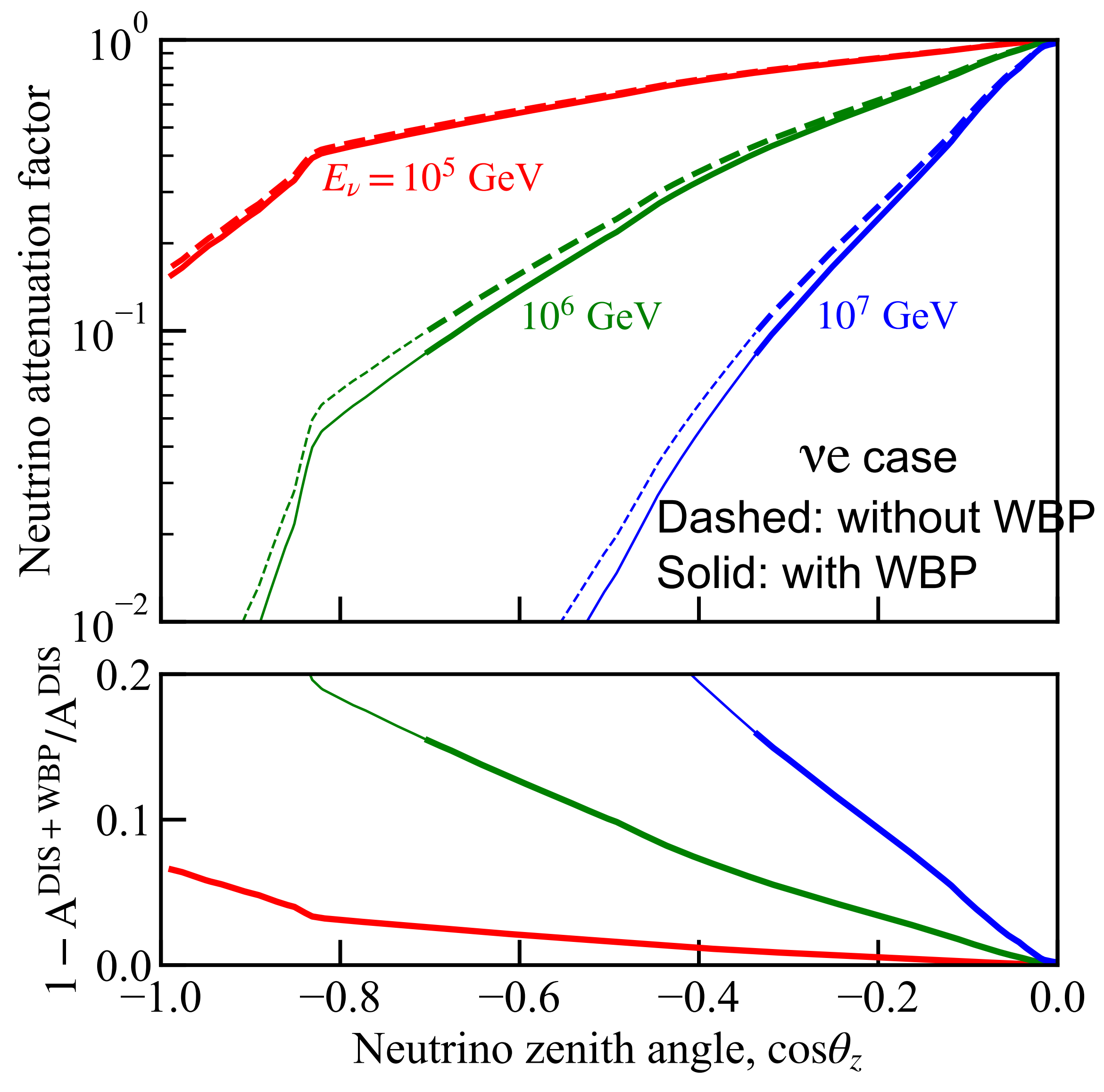
Attenuation factor:

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

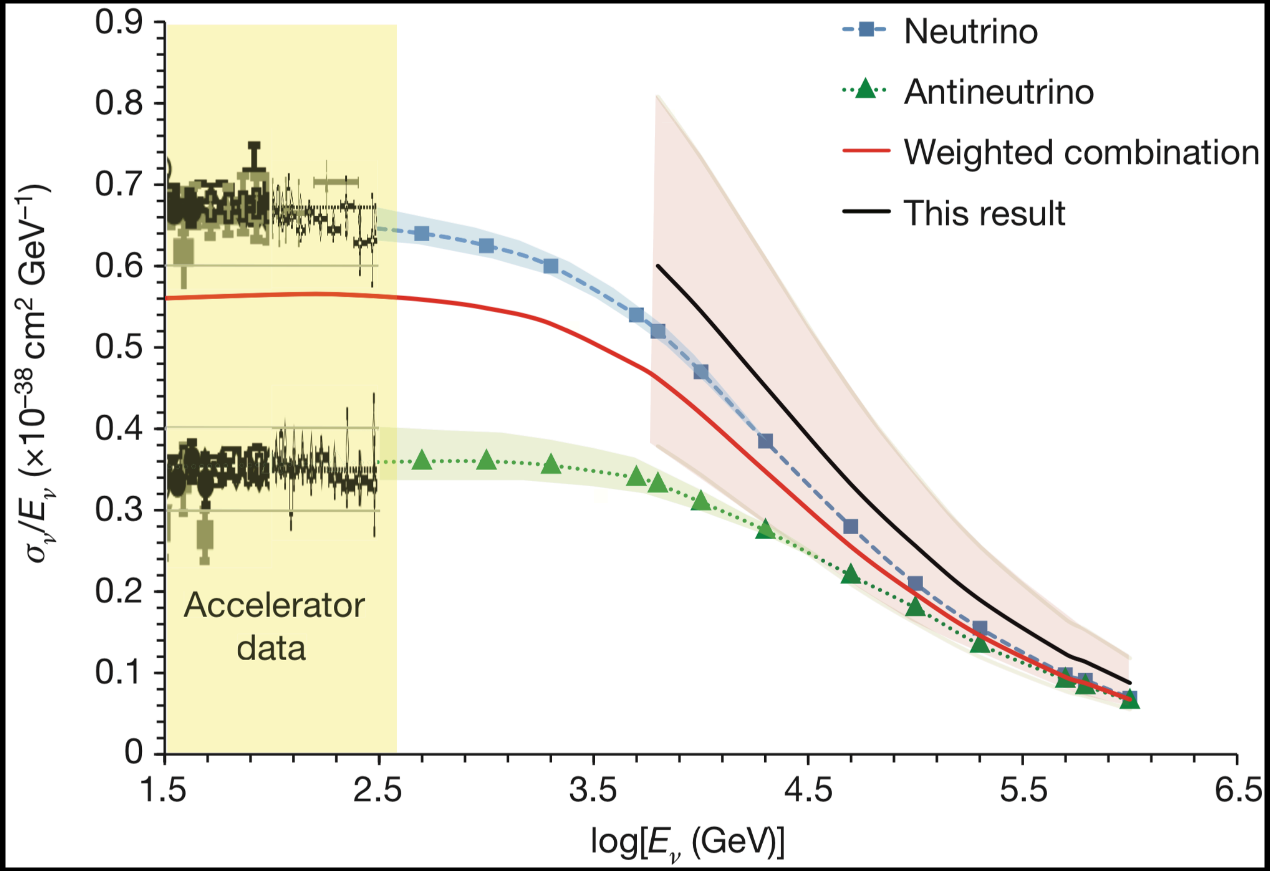
$C(\cos\theta_z)$: column density, well known

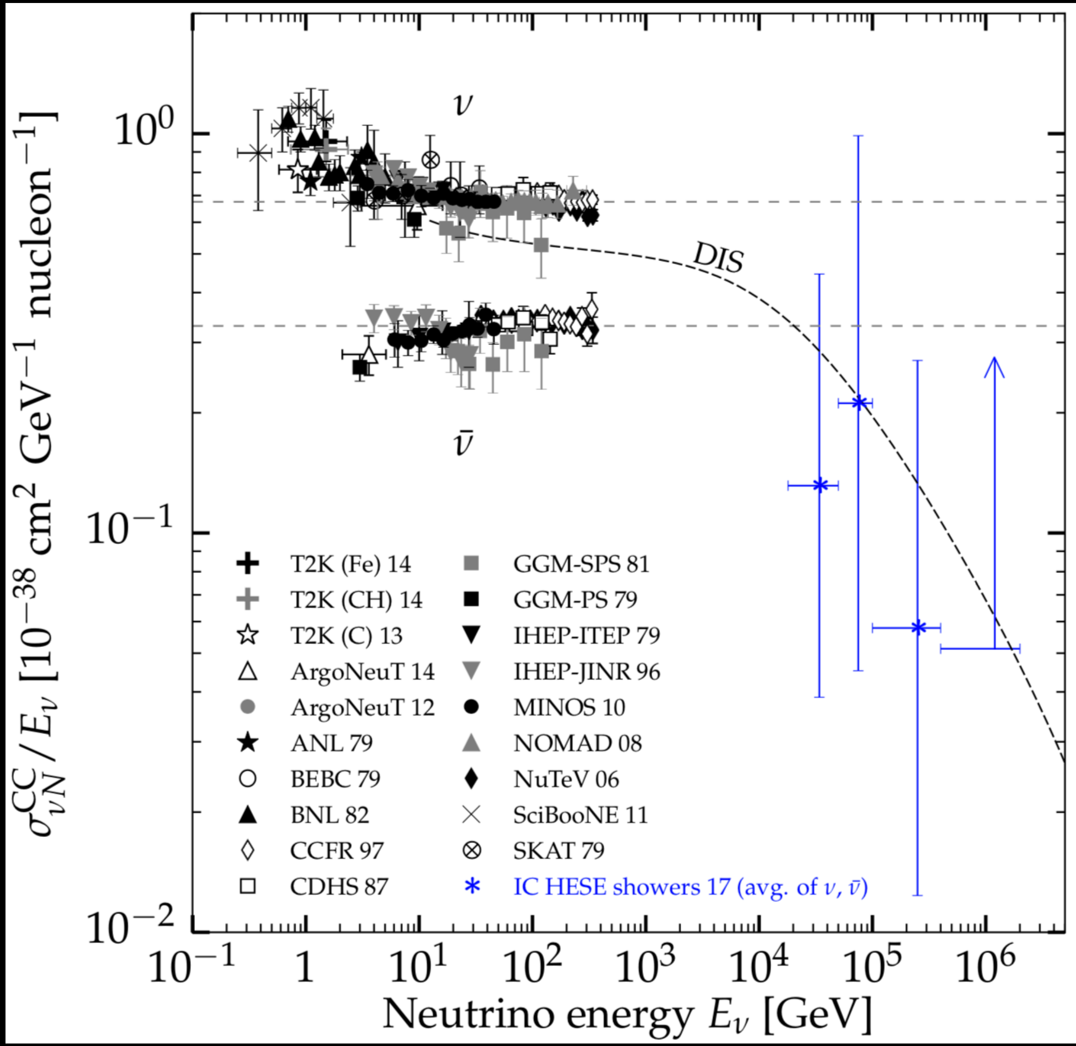
$\sigma(E_\nu)$: total xsec. WBP was not included.

Inseparable part of measuring xsec by IceCube.
1.3±0.45 of SM, but WBP not included



11 inseparable part of measured ν xsec





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

15 Unique signatures (background free)

$\nu_l + A \rightarrow l + W + A'$ (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: $\nu_\mu + A \rightarrow \mu + W + A'$ with $W \rightarrow \mu$

2. Track without shower 0.96 events ……

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

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