New scattering processes for HE neutrinos in the Standard Model

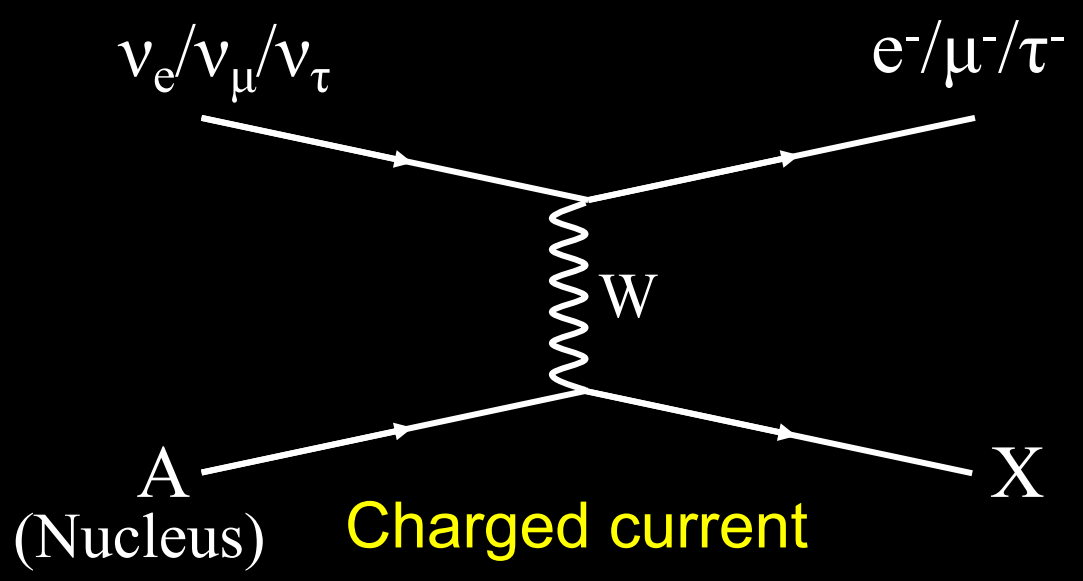
Bei Zhou

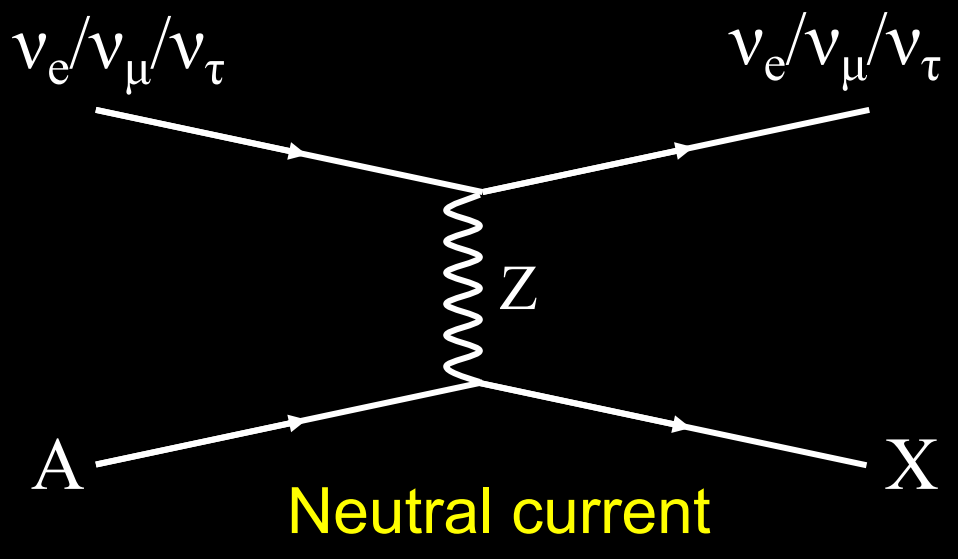
(with Prof. John Beacom)

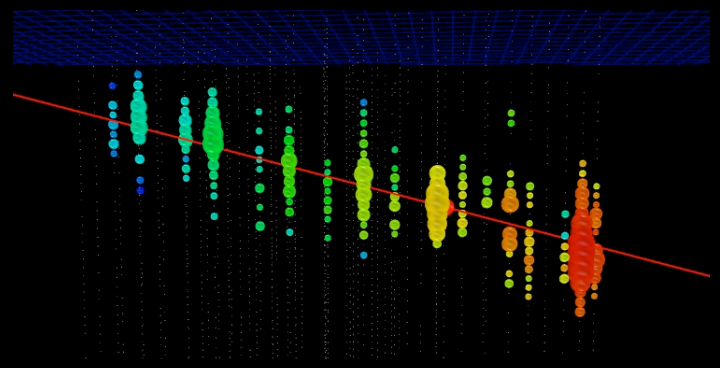
CCAPP, The Ohio State University

Pheno Symposium 2019 @ Pittsburgh, PA

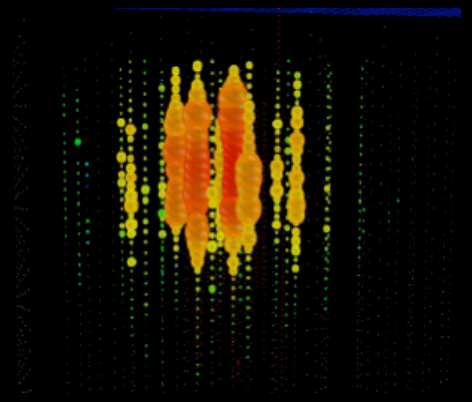
Deep inelastic scattering (DIS)



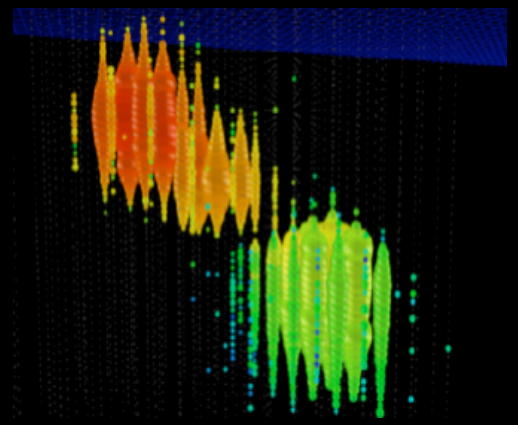




μ, track

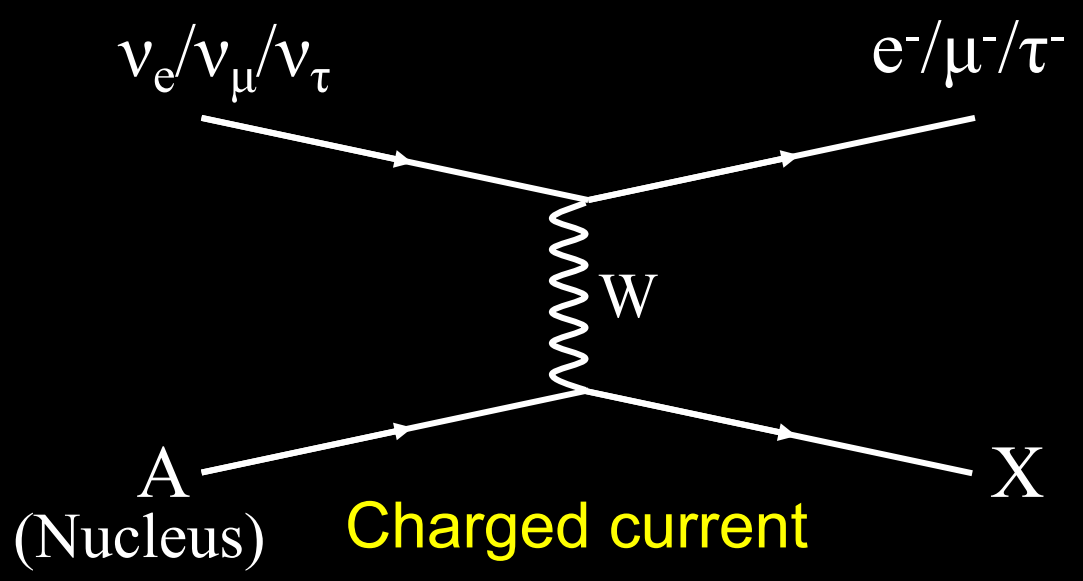


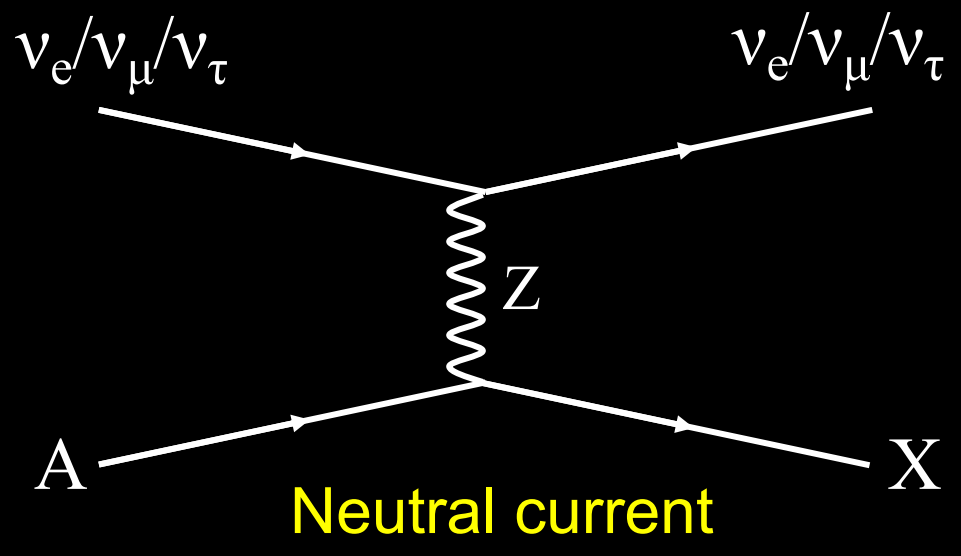
hadron/e/τ, shower



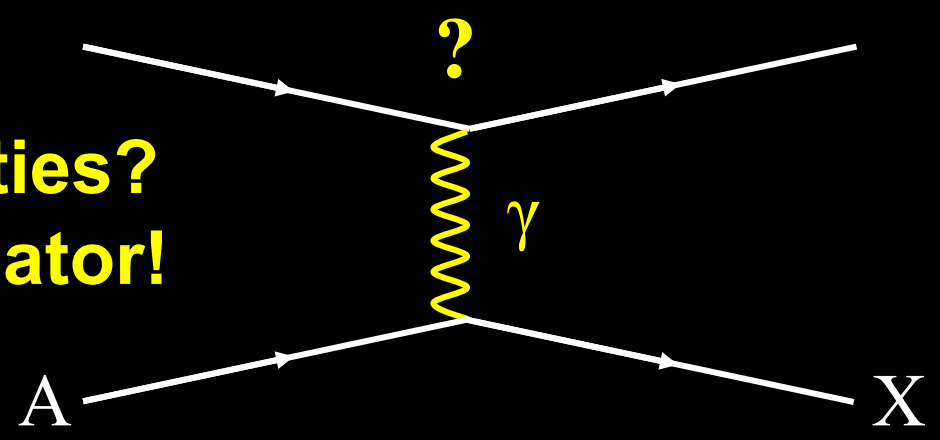
τ, double bang

Deep inelastic scattering (DIS)

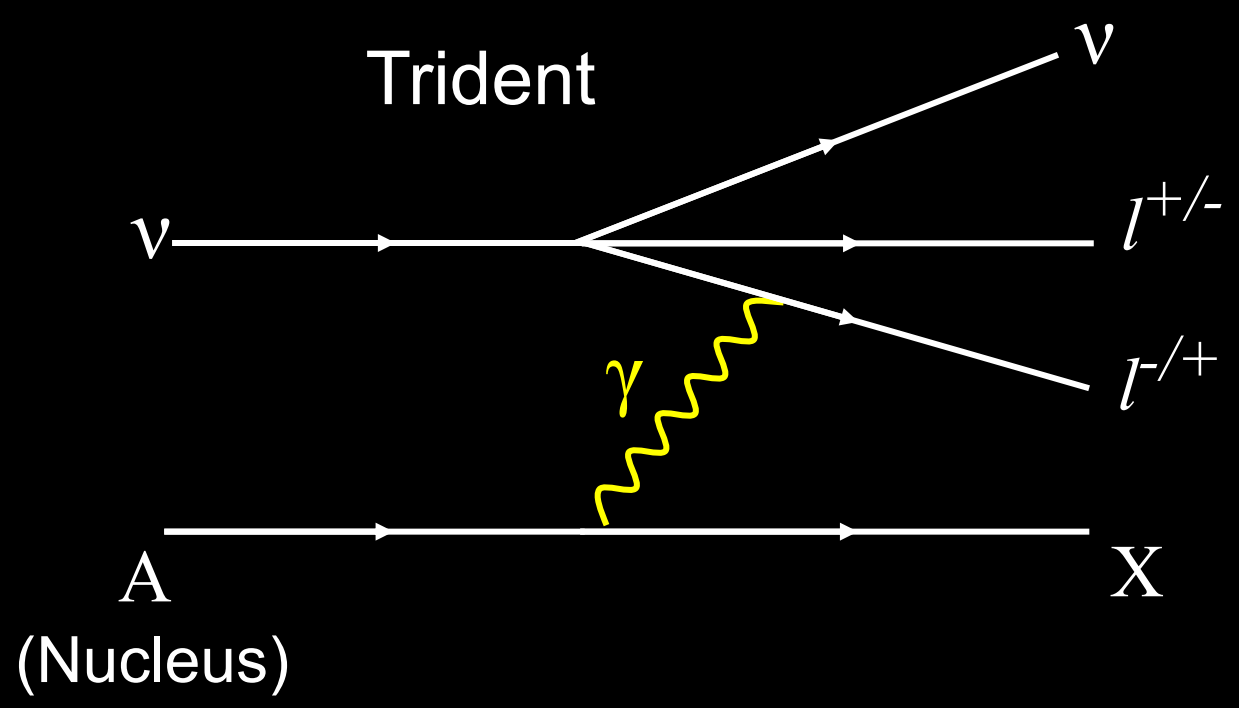


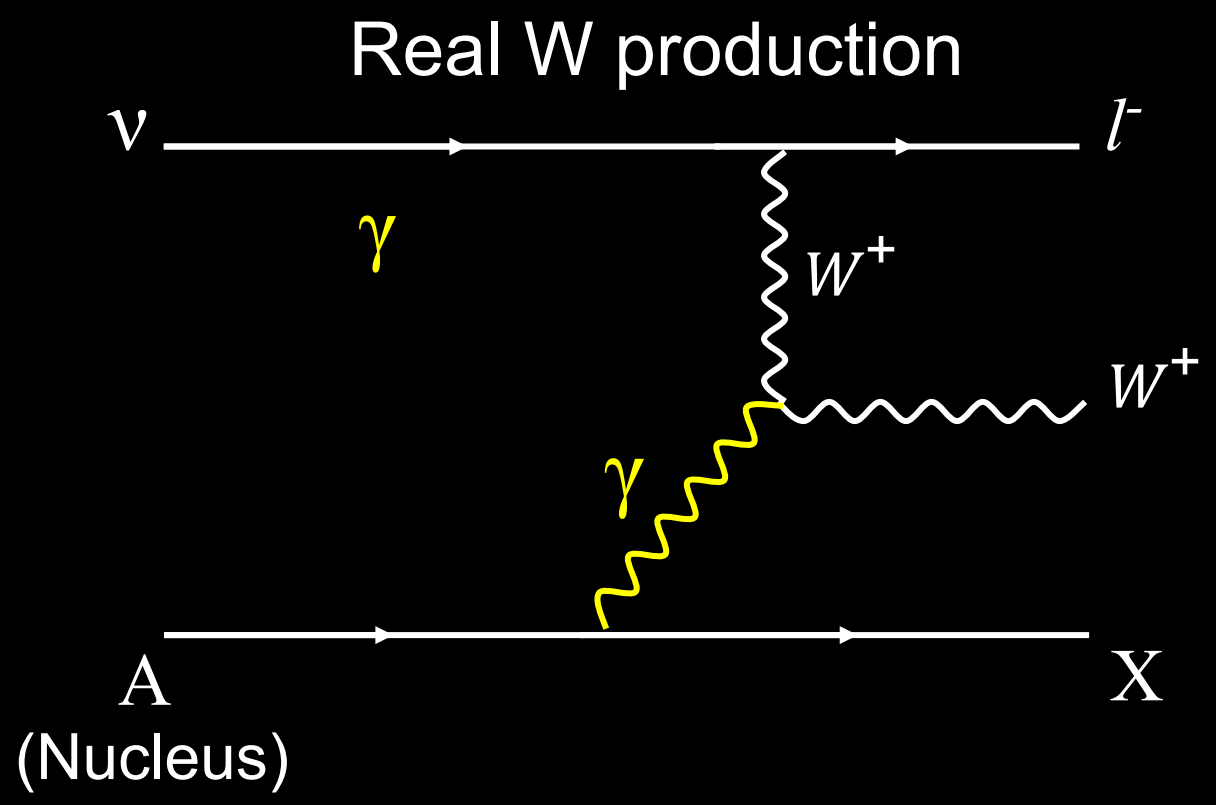


Any other possibilities?
Yes, photon propagator!



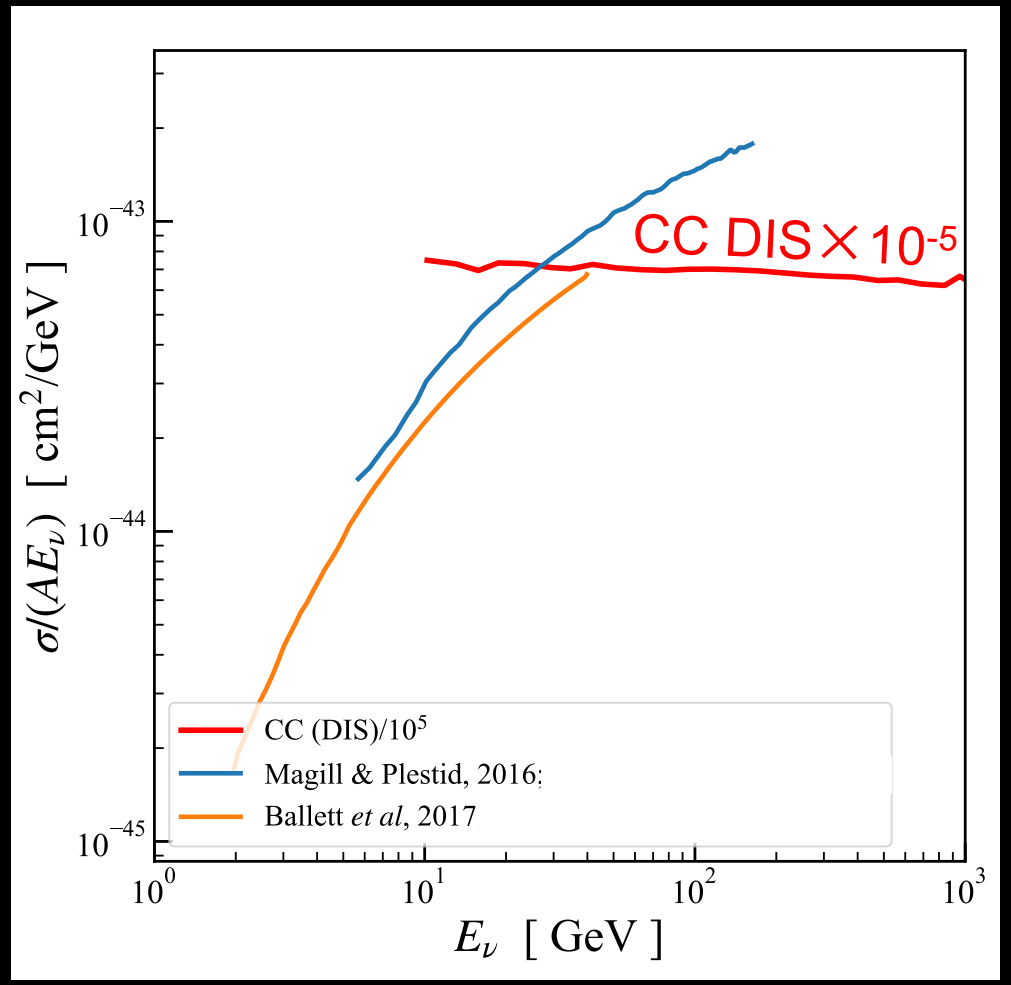
Two other processes may matter





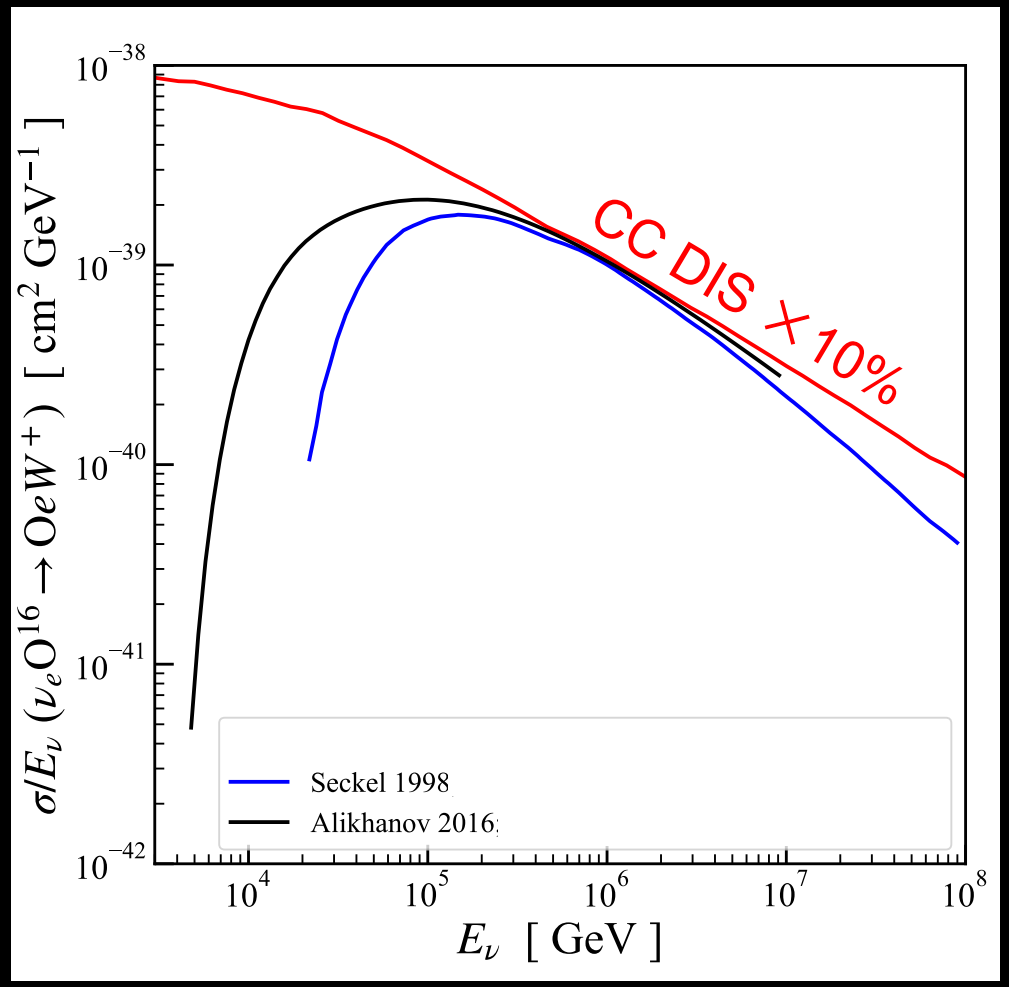
Goals of our work

Trident



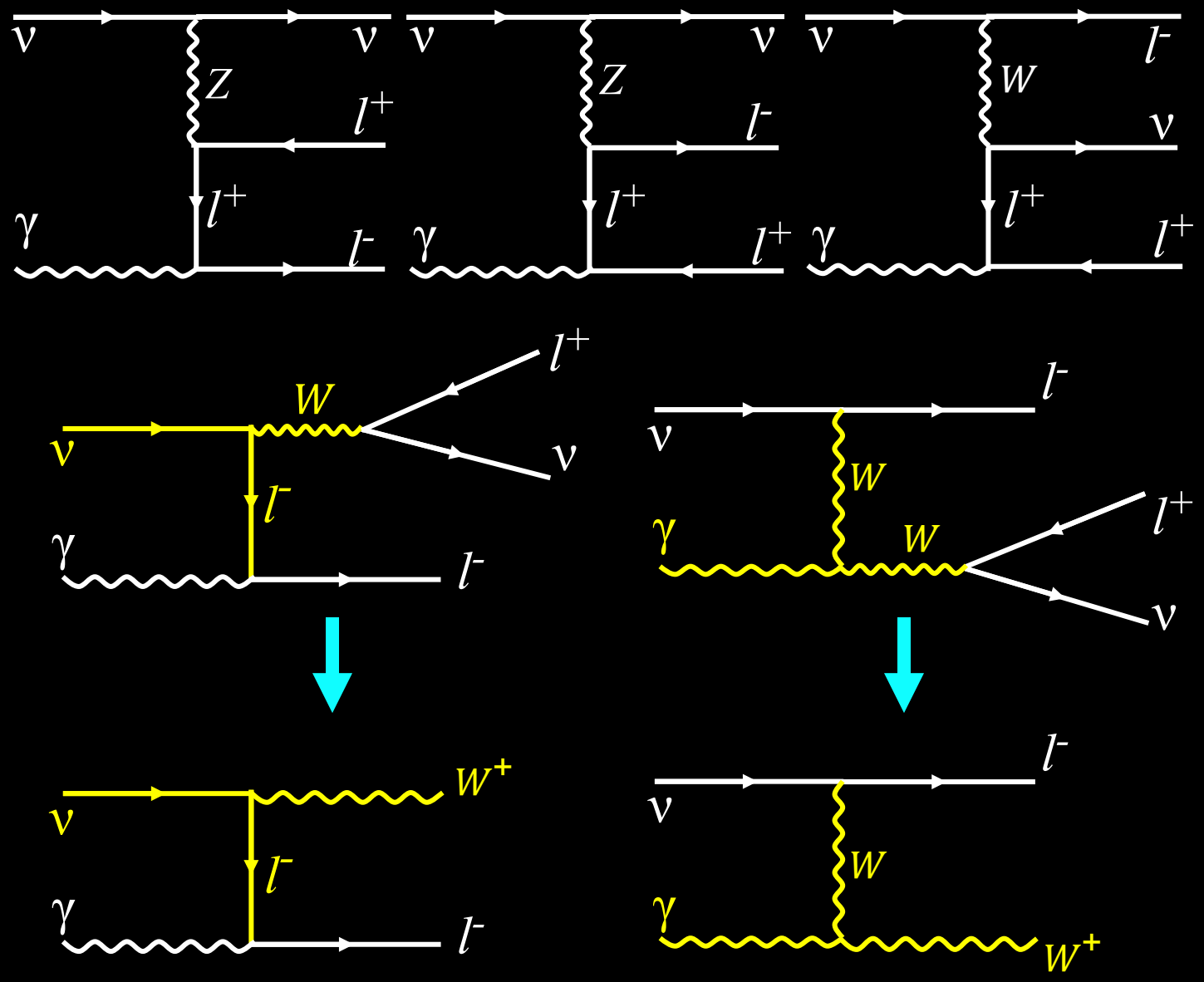
Increases much faster CC DIS.
Above 1 TeV should be calculated!

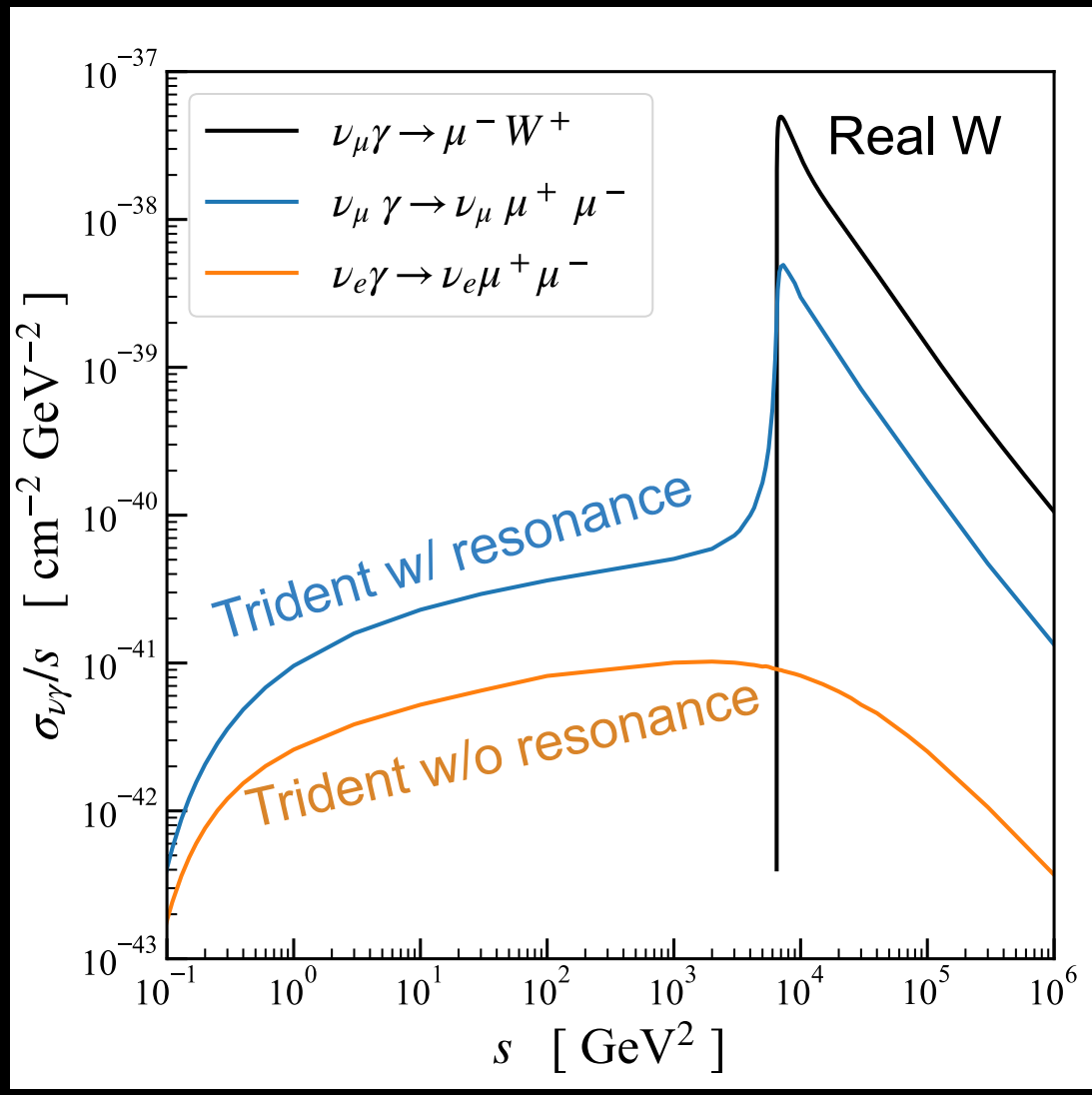
Real W production



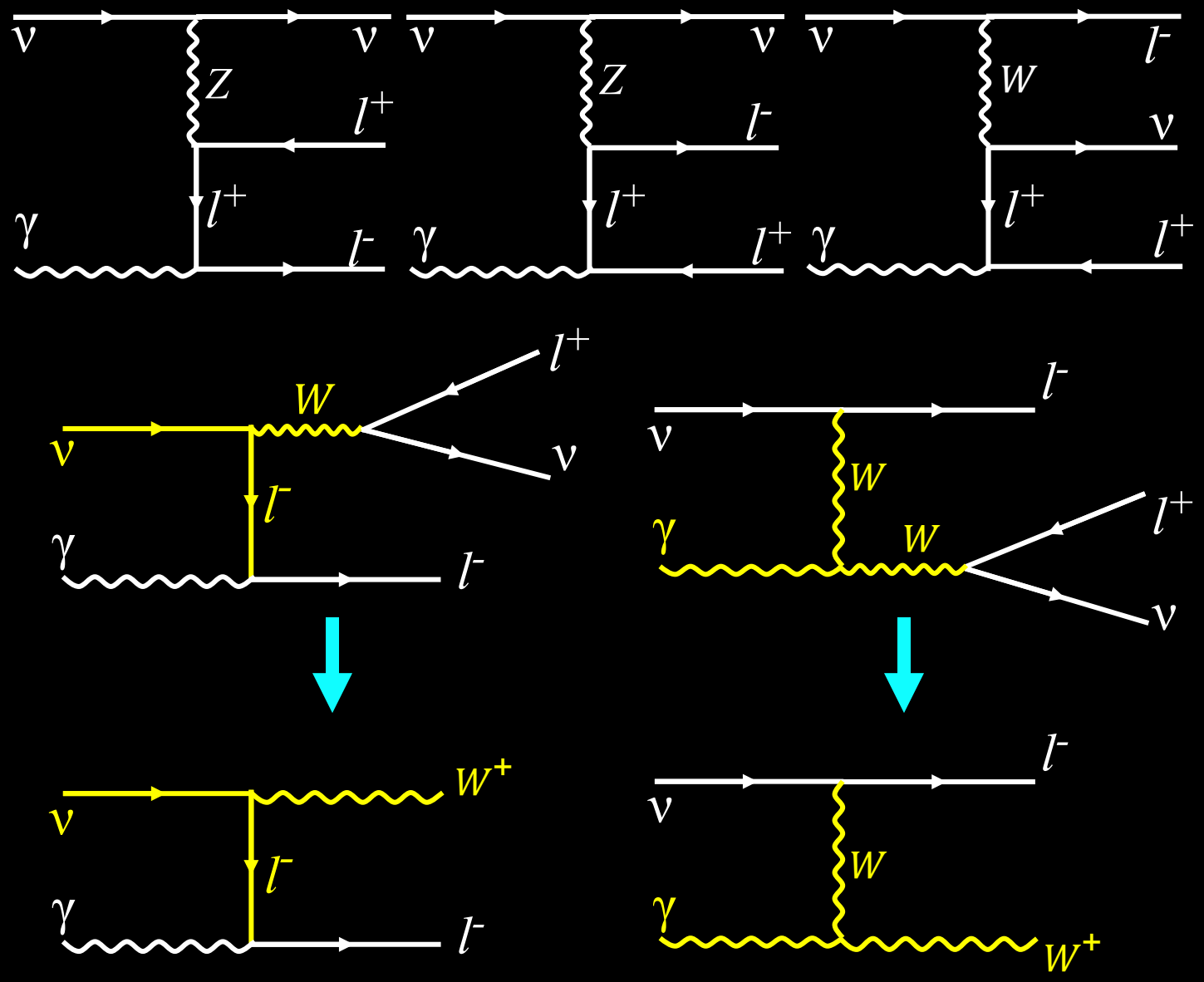
Real W production is important!
Need more careful calculation!

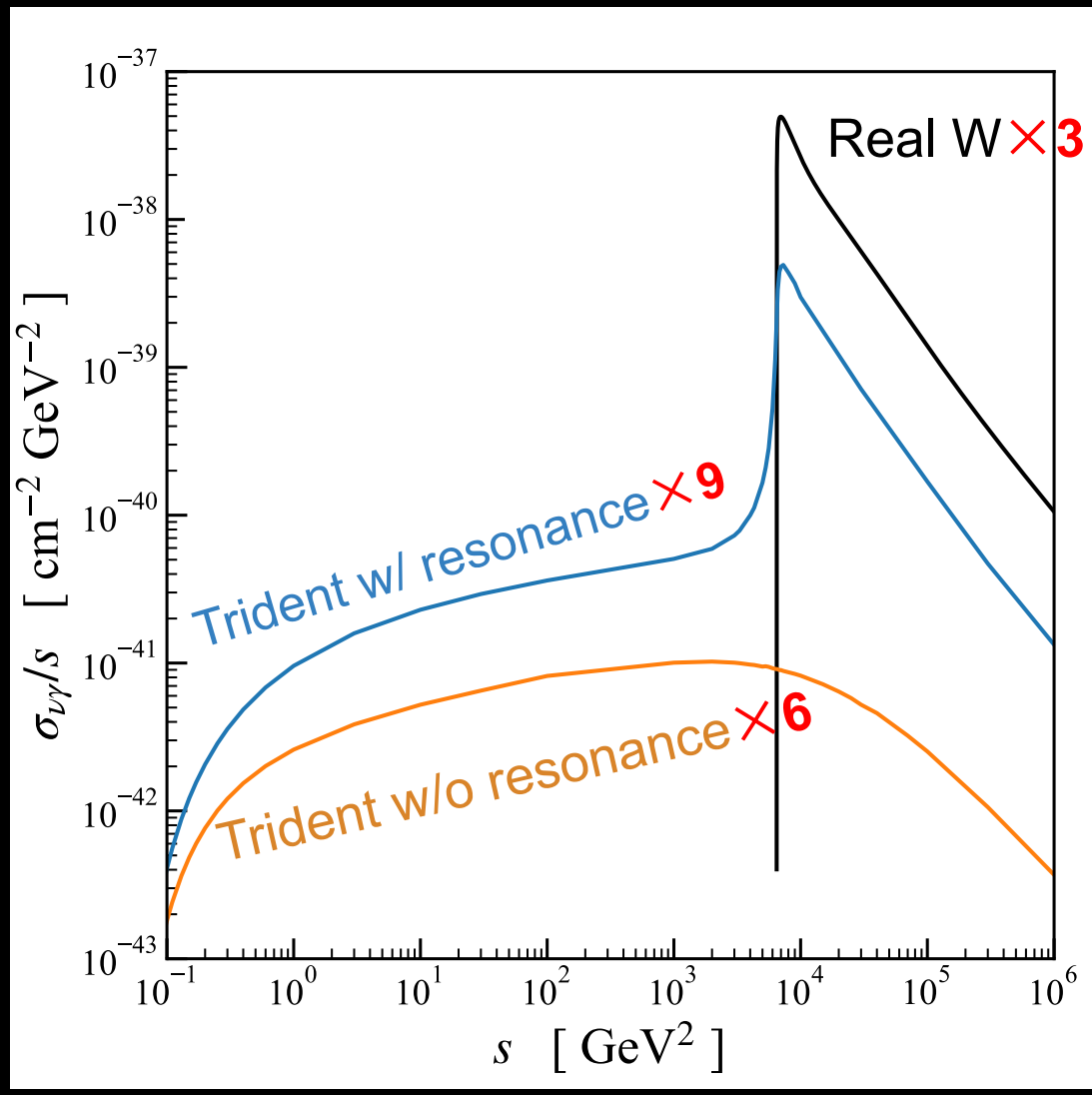
Cross section with free photon, instead of nucleus





Different flavors

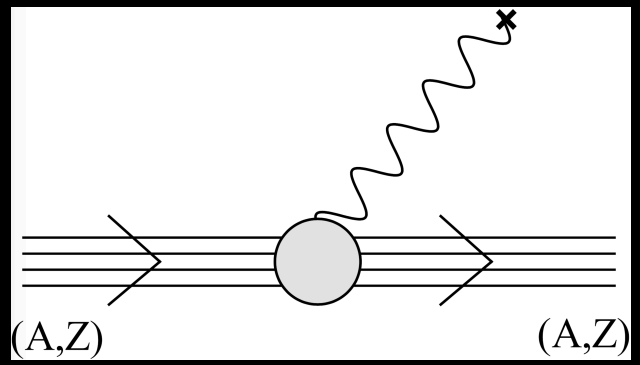




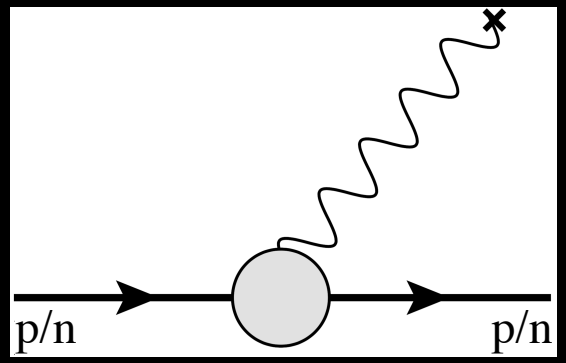
Hard part: from $\sigma_{\nu\gamma}$ to $\sigma_{\nu A}$

Photon from the nucleus → three regimes.

Coherent



Diffractive



DIS

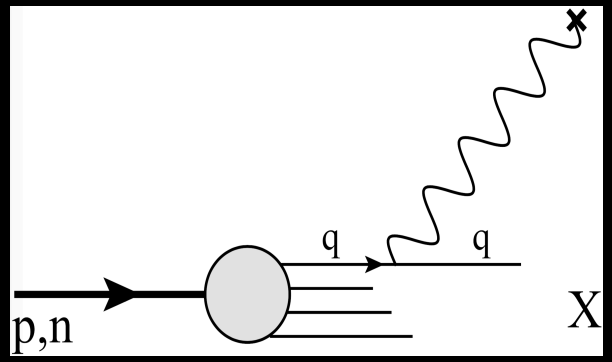
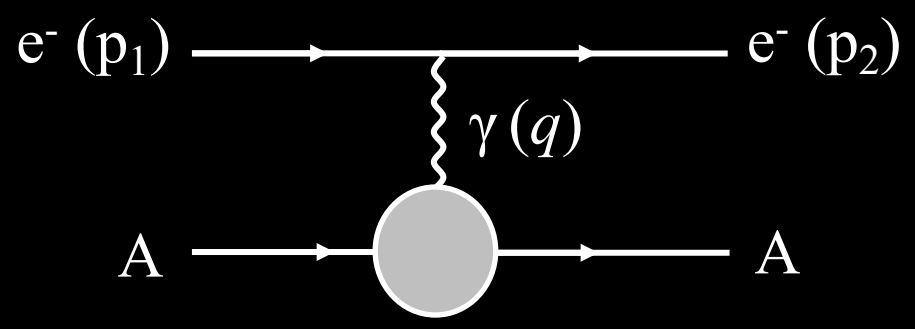


Figure from: Alikhanov, PLB, 2016 and modified

Invalidity of equivalent photon approximation

(or Weizsäcker-Williams approximation)

Equivalent photon approx.



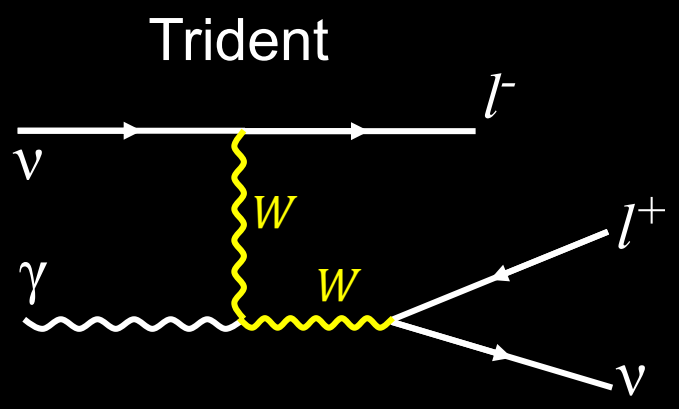
$p_1 \simeq (E_1, 0, 0, E_1)$

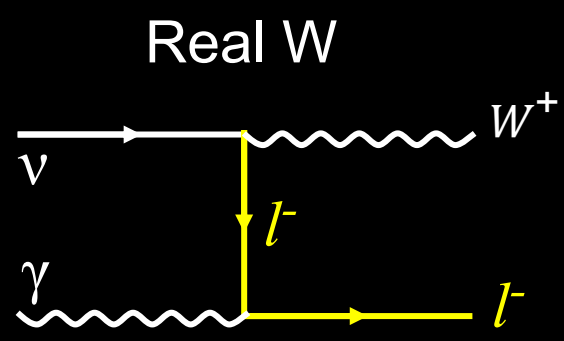
$p_2 \simeq (E_2, 0, E_2\sin\theta, E_2\cos\theta)$; $\cos\theta \simeq 1$

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

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

But not valid for us





Ballett et al. , 1807.10973 pointed out the EPA is not good for trident.

We will show that for real W.

Complete approach (for coherent and diffractive)

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

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

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

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

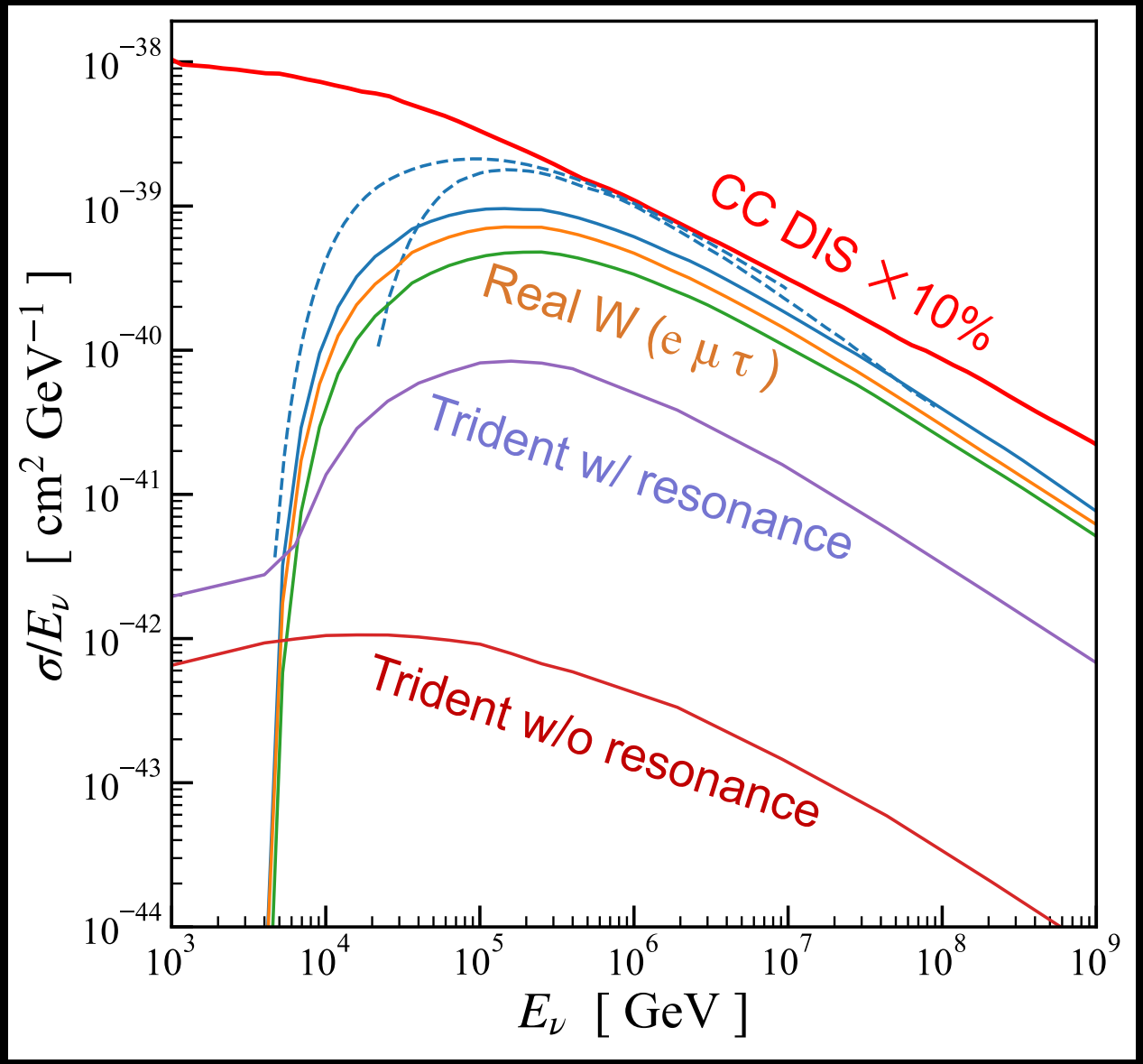
Proton's has both electric part and magnetic part.

DIS:

Use CT14 for PDFs.
Use MadGraph for calculation.

Total neutrino-nucleus cross section

$\nu + {}^{16}O$

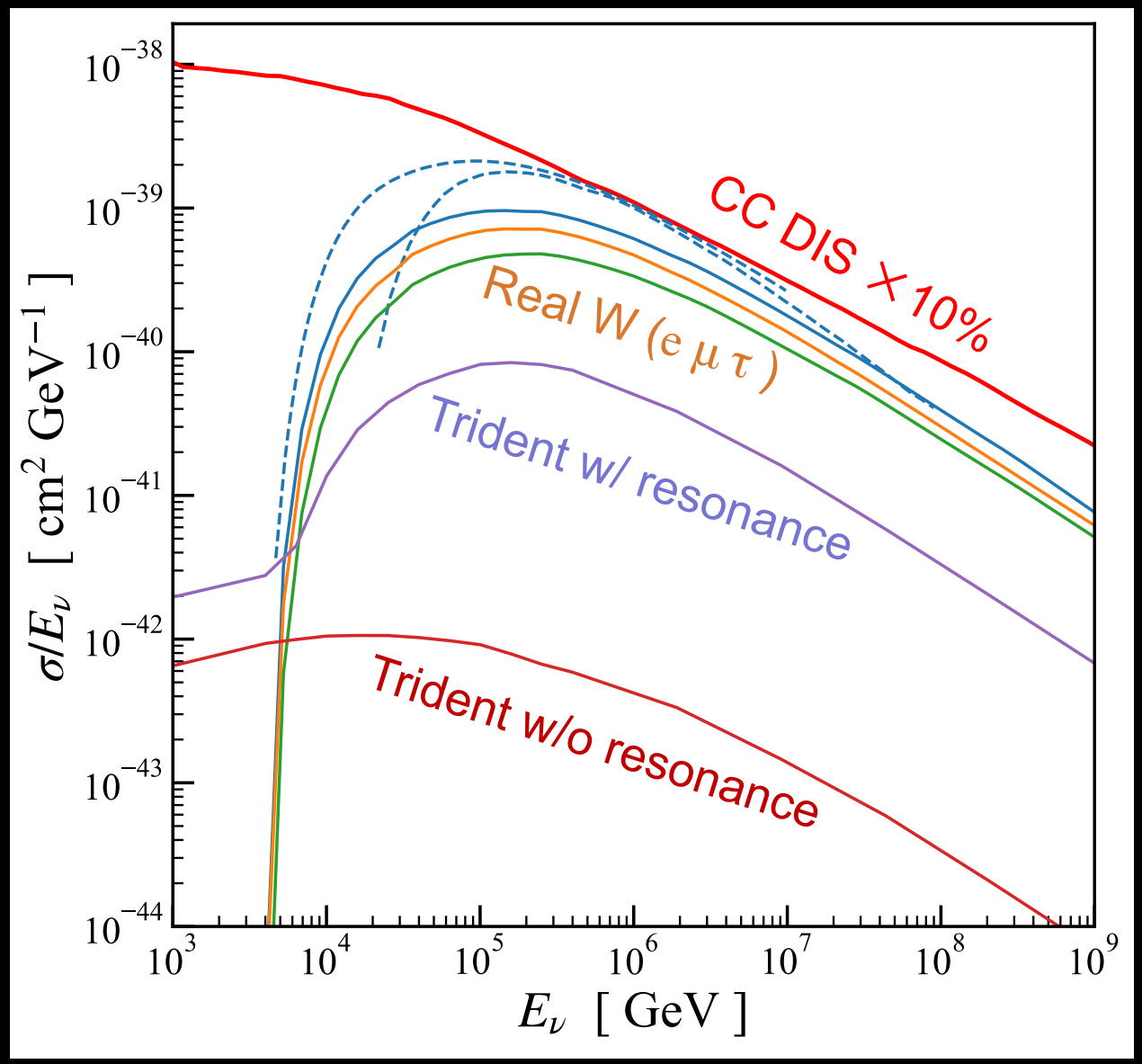


Dashed lines of the figure:
previous calculations by
Seckel 1998,
Alikhanov 2016

Conclusion: first complete calculation of trident and real W

- Trident
  - First calculation above 1 TeV.
  - First use full SM instead of 4-Fermi theory.
  - Cross sections approach 0.5% of CC DIS.
- Real W
  - (First) use the complete formalism instead of equivalent photon approximation.
  - Cross sections approach 5% of CC DIS.
- First use all possible photon sources from nucleus

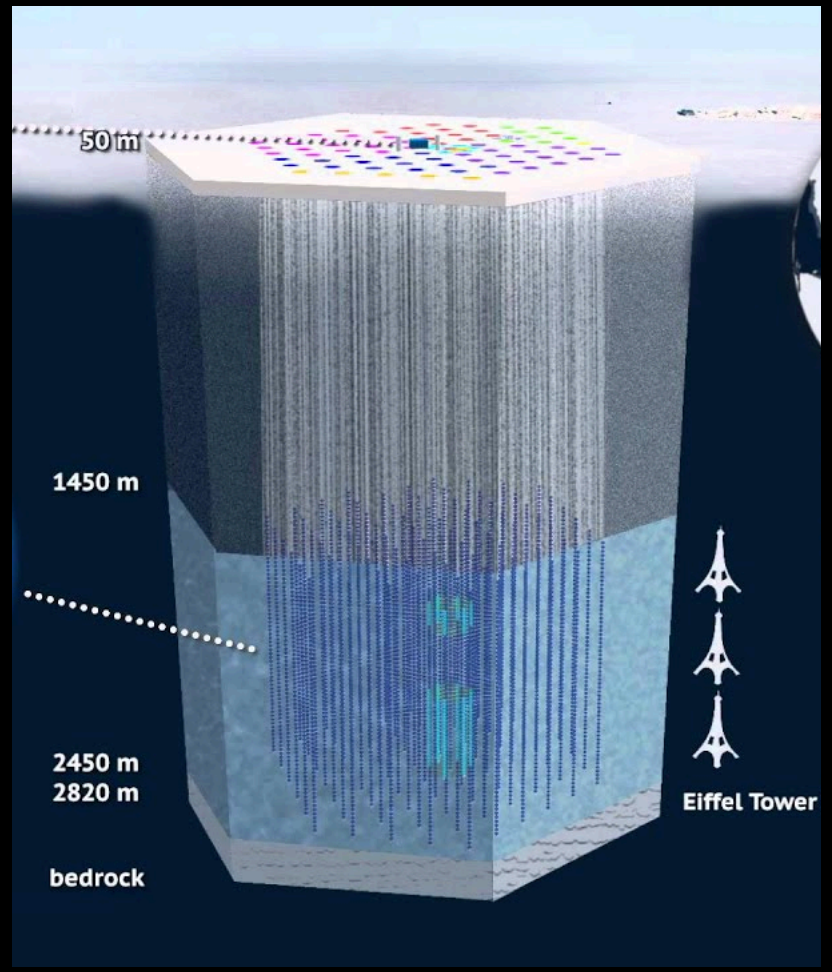
- Distinct signatures (examples)
  - $\nu A \rightarrow \nu \mu^+ \mu^-$ will give special signature involving two muon tracks.



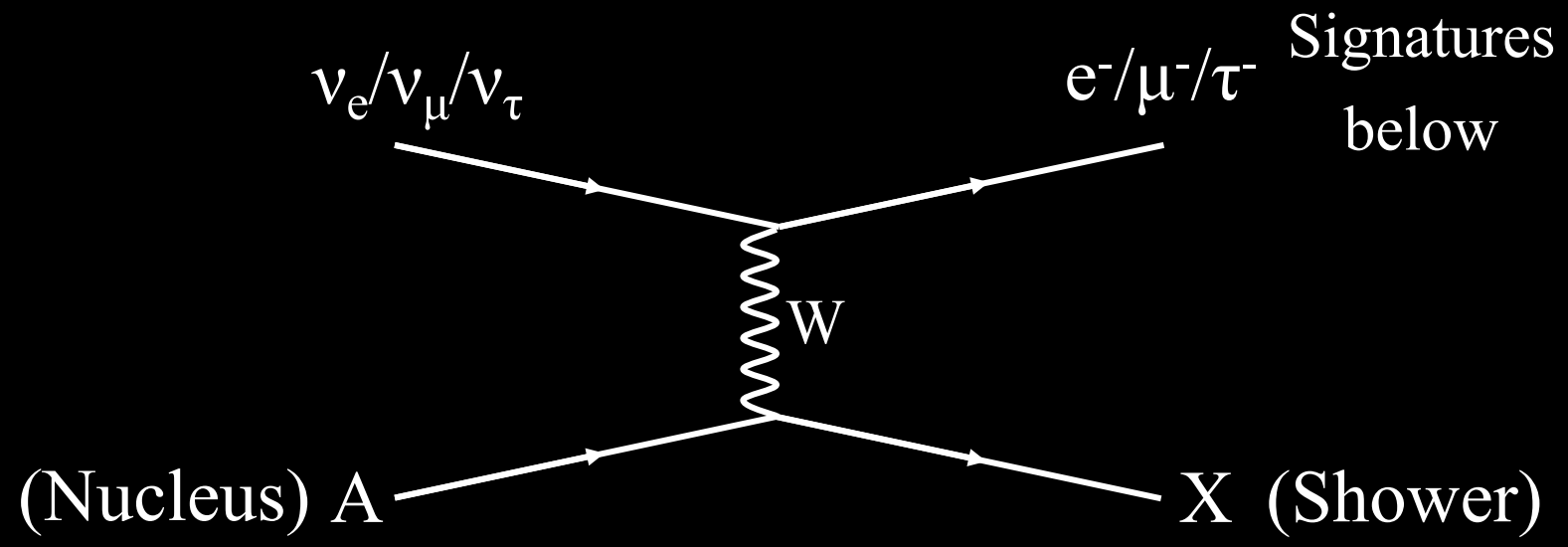
Bei Zhou (OSU)

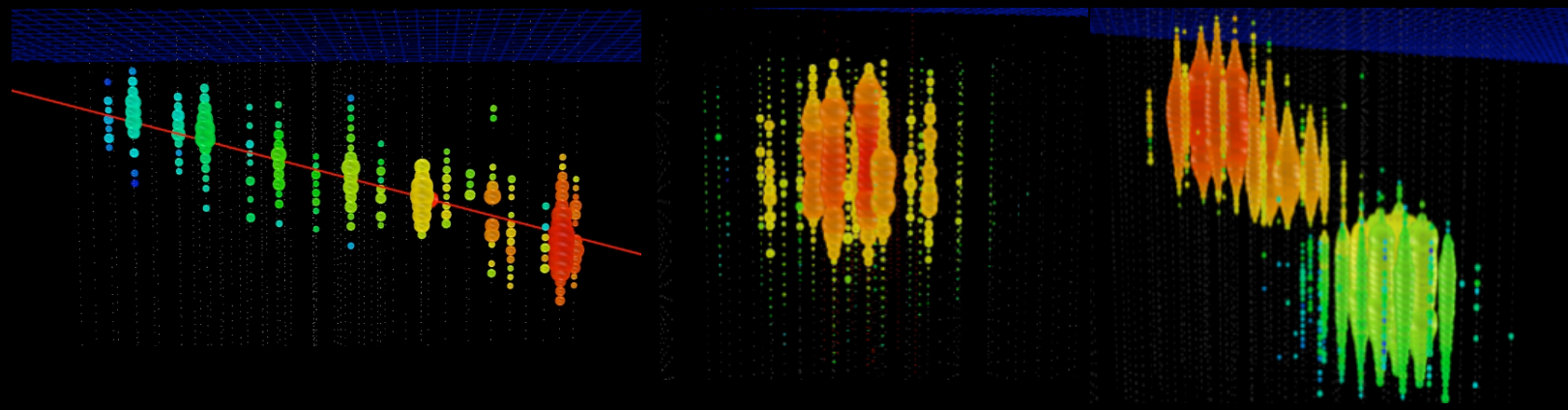
Thanks for your attention!

Detecting high-energy neutrinos



IceCube

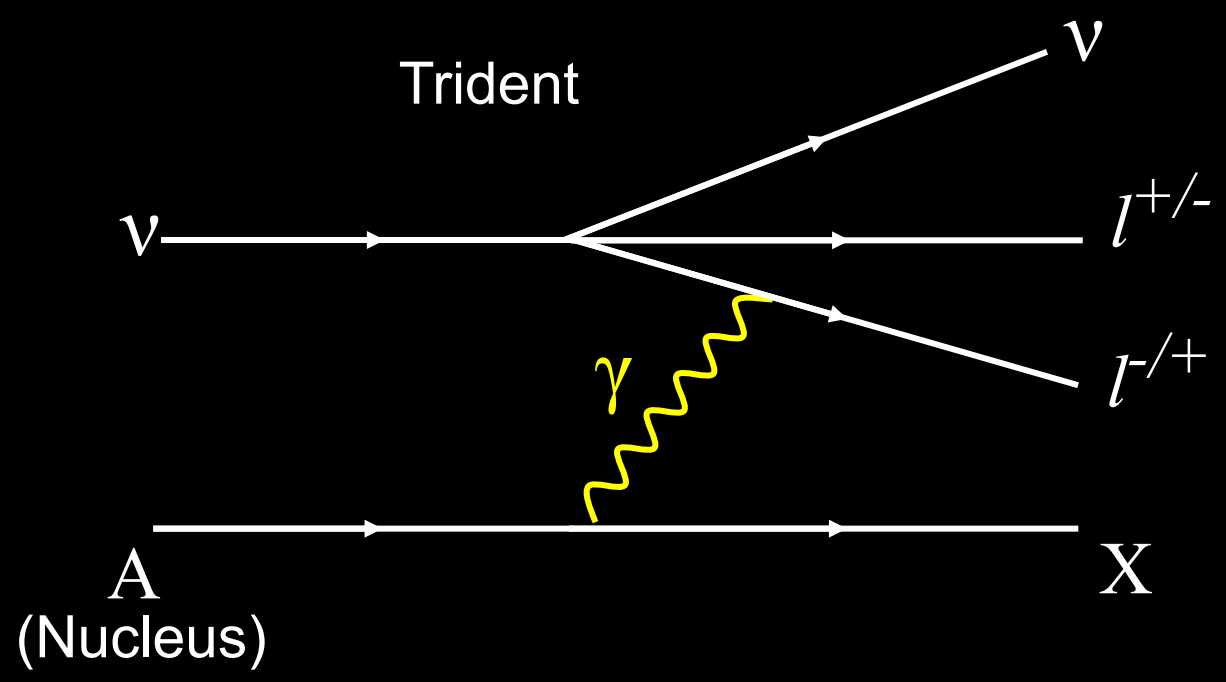


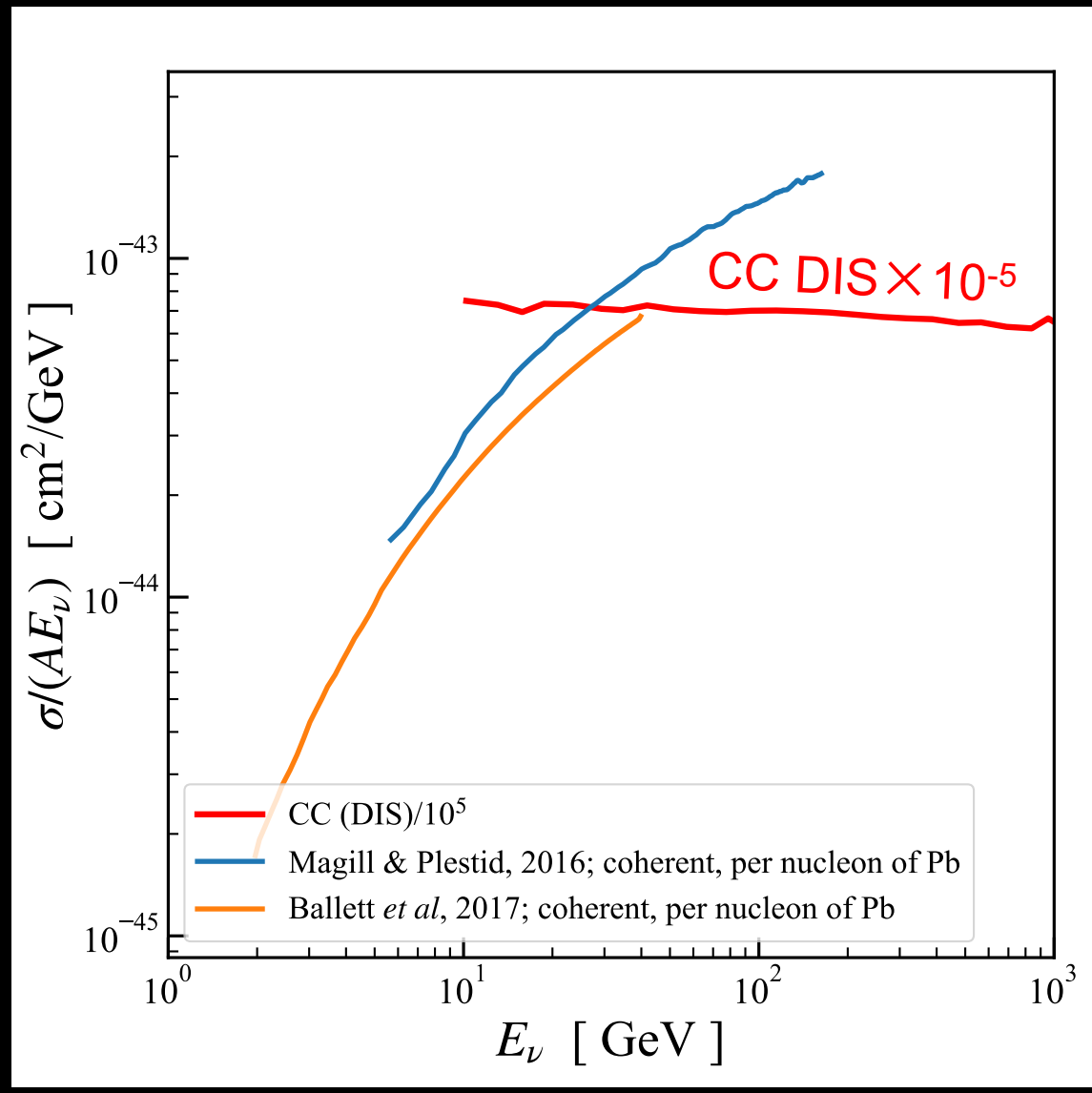


μ, track e/τ, shower τ, double bang

Figure from: Dawn Williams, 2012

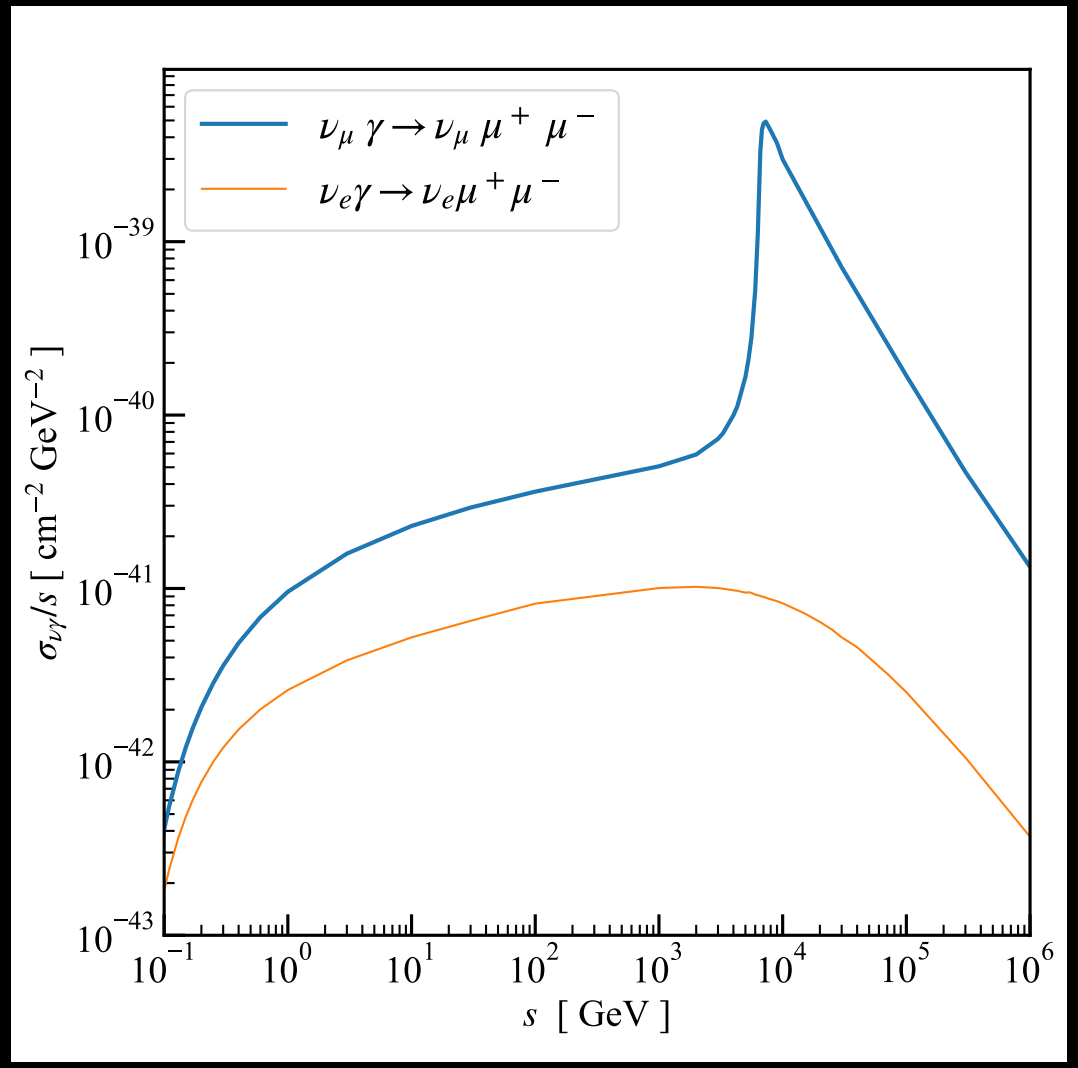
2 ν scatters photon from nucleus, an example



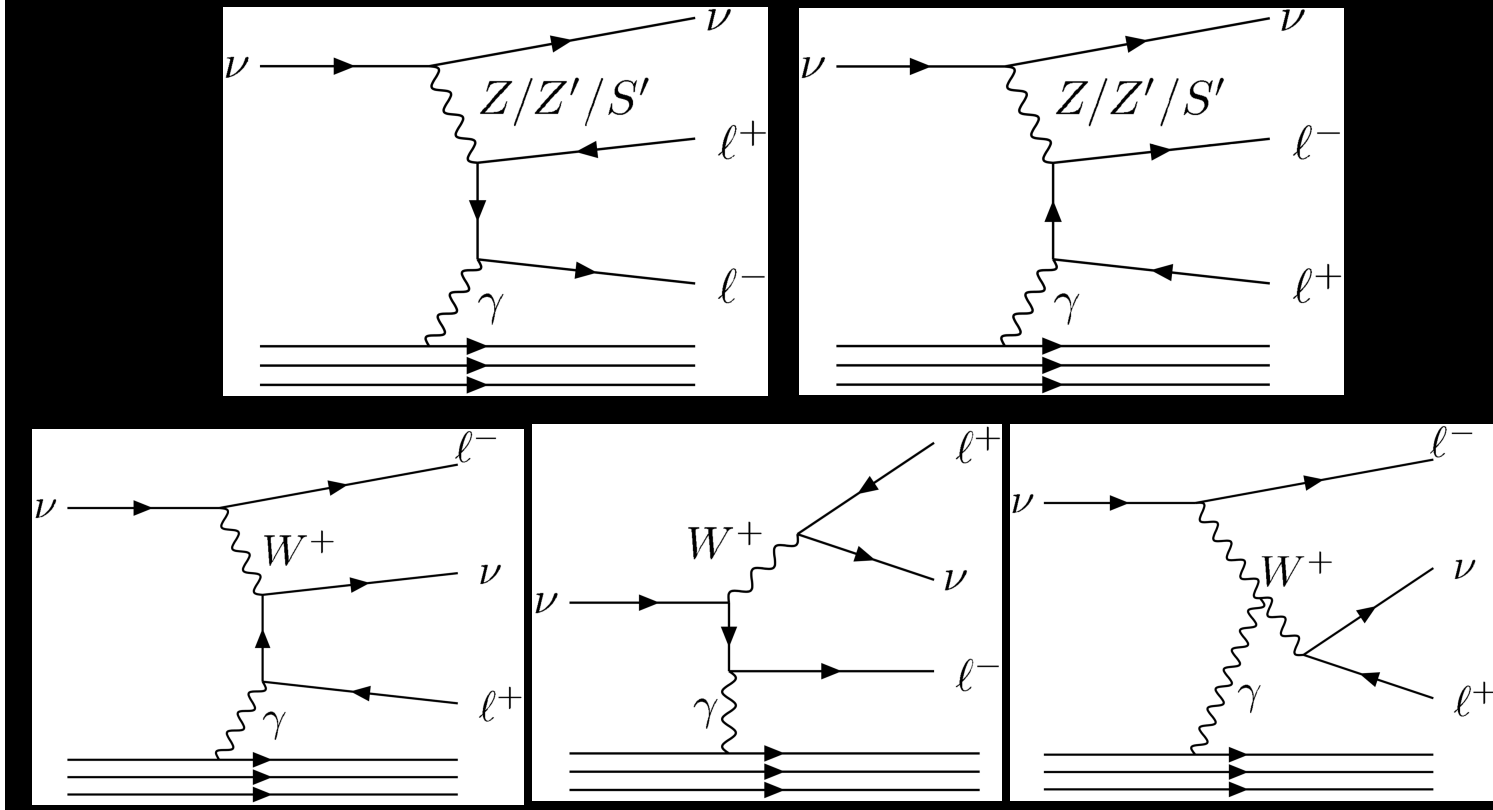


See also Altmannshofer et al. 1902.06765

What about higher energies? A quick look

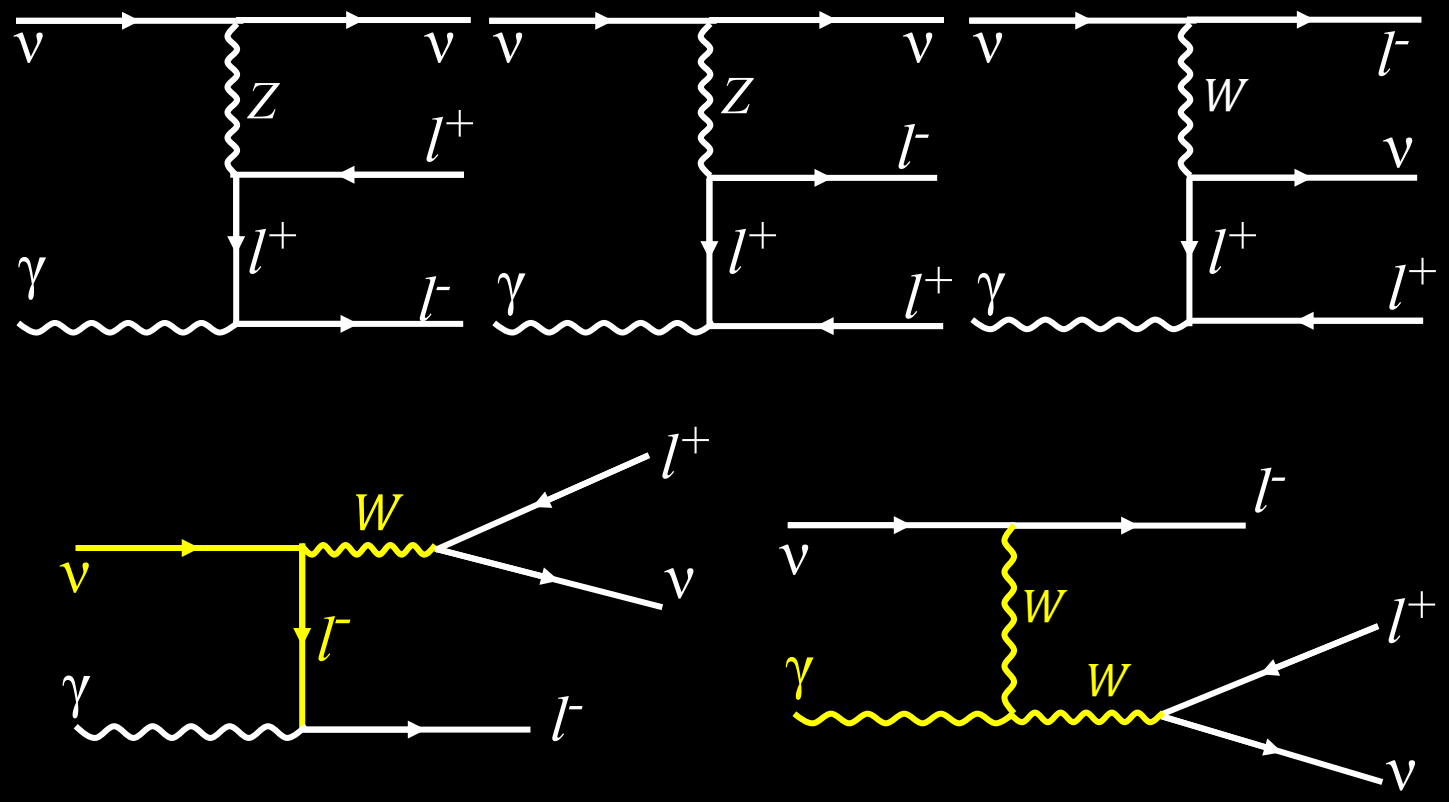


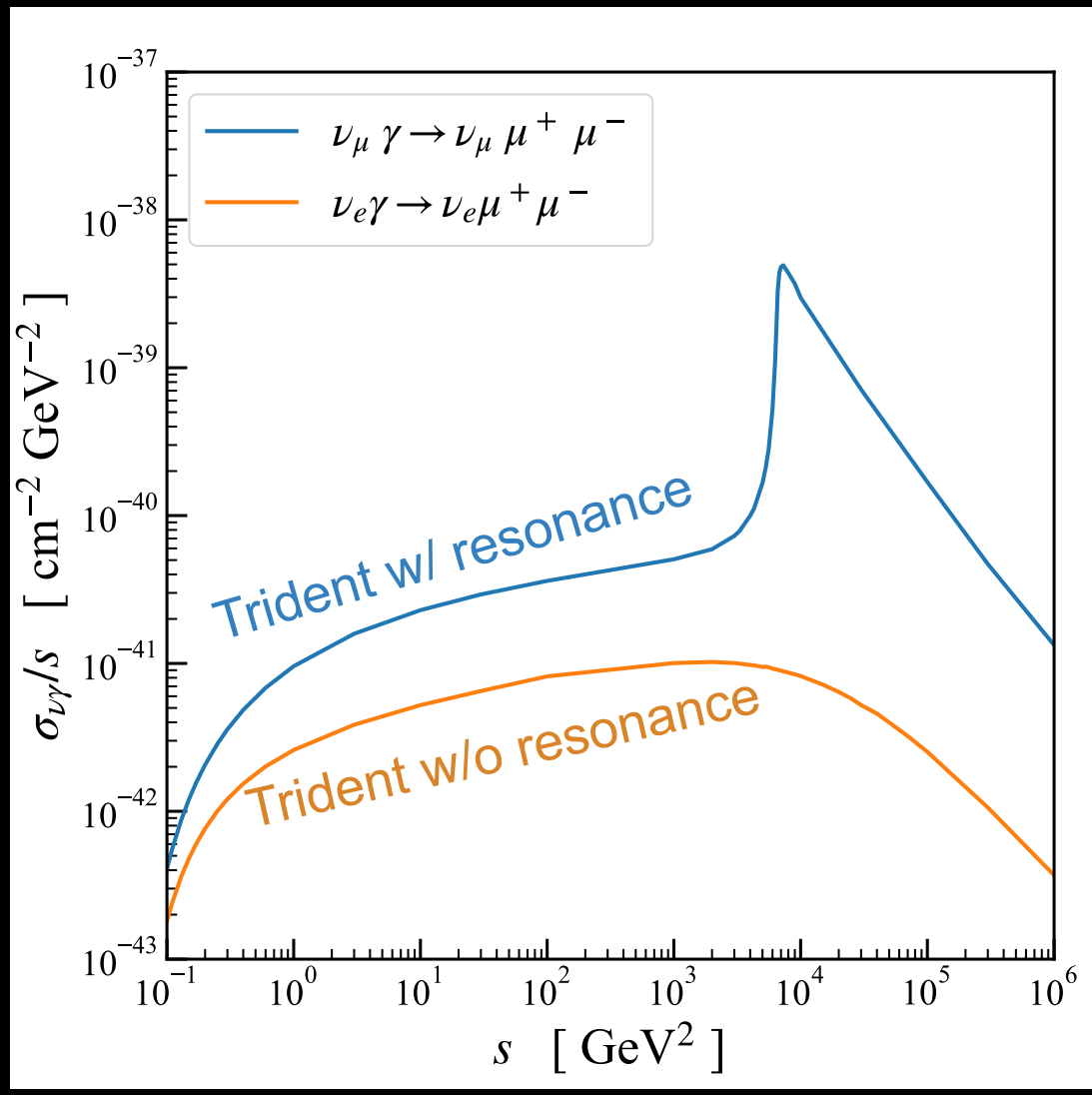
CC+NC: $\nu_\mu + \gamma \to \nu_\mu + \mu^- + \mu^+$



NC: $\nu_e + \gamma \to \nu_\mu + \mu^- \mu^+$

4 What about higher energies?

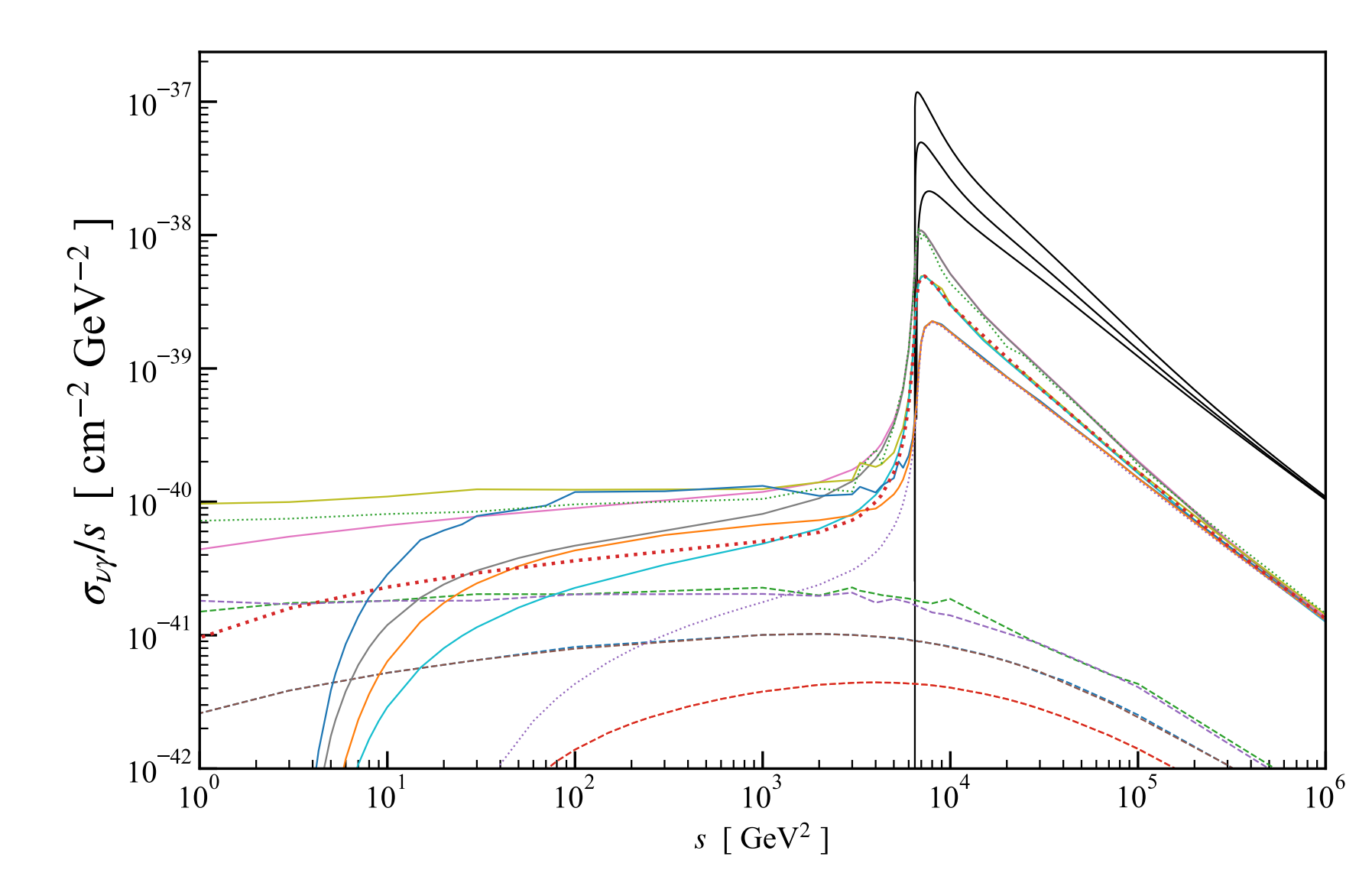




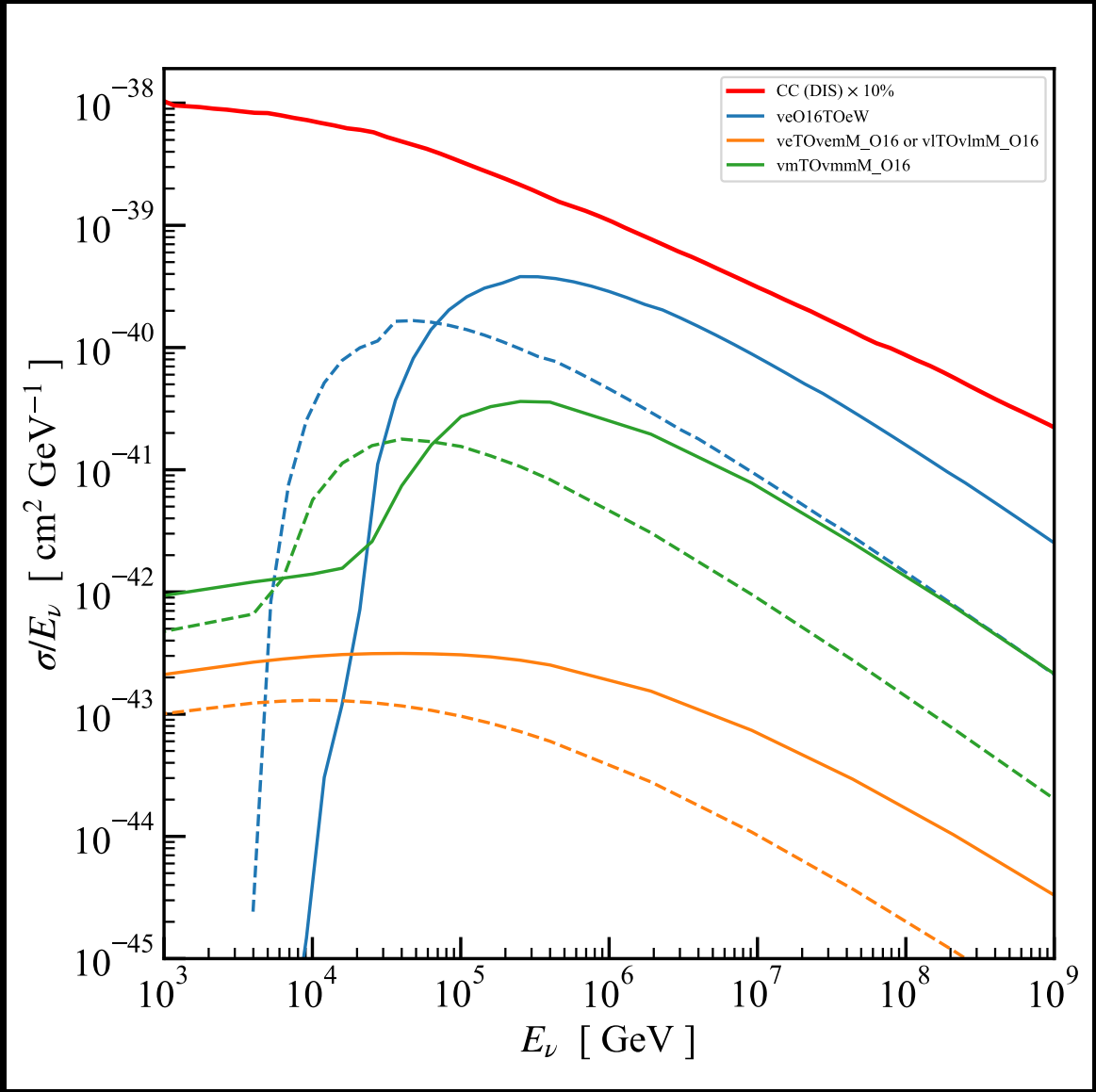
$\nu_\mu + \gamma \to \nu_\mu + \mu^- + \mu^+$ includes all five diagrams

$\nu_e + \gamma \to \nu_e + \mu^- + \mu^+$ not includes bottom two diagrams

All flavors, $\sigma_{\nu\gamma}$

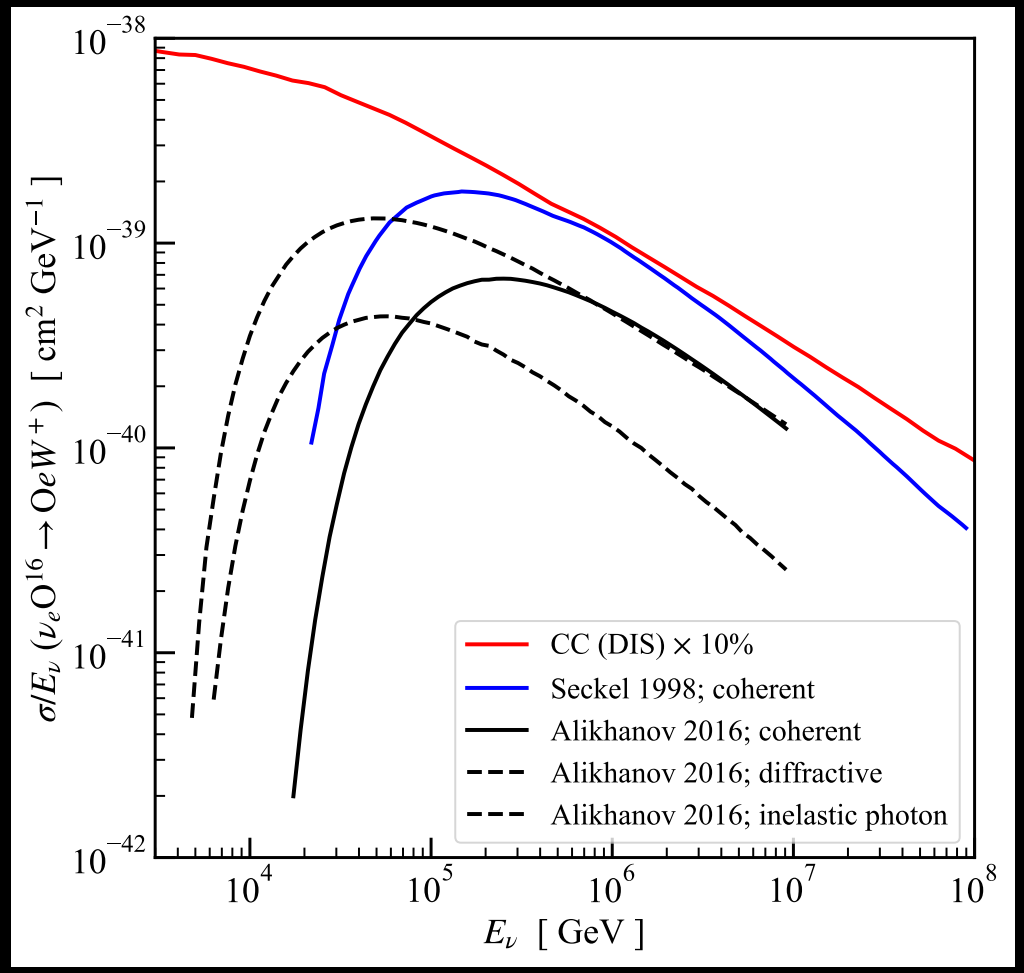


Coh vs. Diff


CC (DIS) × 10%
veO16TOeW
veTOvemM_O16 or vlTOvlmM_O16
vmTOvmmM_O16
σ/E_ν [cm^2 GeV^{-1}]
E_ν [GeV]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^3
10^4
10^5
10^6
10^7
10^8
10^9

Previous calculation and shortcomings

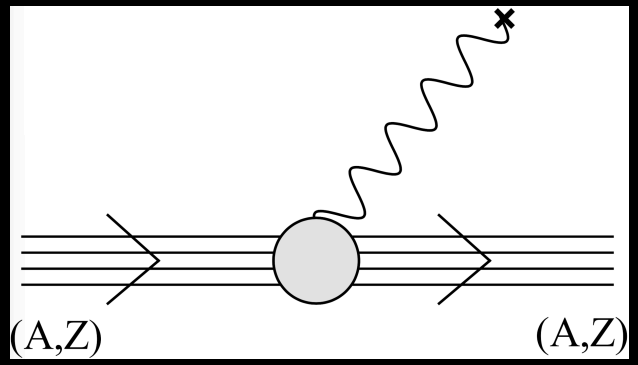
- Real W production



- Trident
  - No one calculated above 1 TeV
  - People always used FF, simplifying the calculation a lot.
  - People never considered inelastic photon.
  - The channels with $\nu\tau$ or τ are never calculated.

Coherent regime: elastic photon from nucleus

Coherent

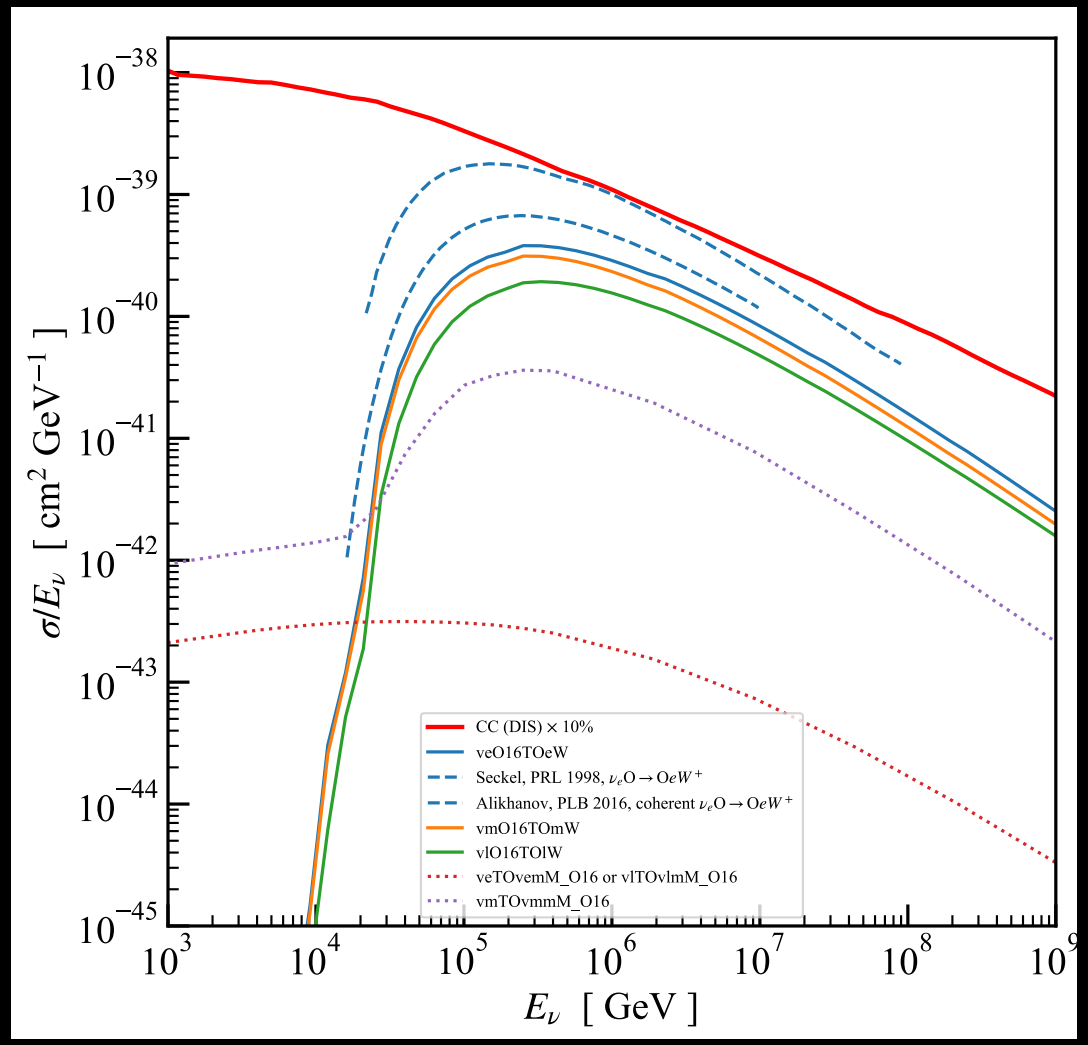


$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}Q^2}\left[\sigma^T_{\nu\gamma}(Q^2,\hat{s})\, h^T_X(Q^2,\hat{s}) + \sigma^L_{\nu\gamma}(Q^2,\hat{s})\, h^L_X(Q^2,\hat{s})\right]$$

$$h^T_{coherent}(Q^2,\hat{s}) = 8Z^2e^2\left(1 - \frac{\hat{s}}{2E_\nu M} - \frac{\hat{s}^2}{4E_\nu^2 Q^2}\right)|F(Q^2)|^2$$

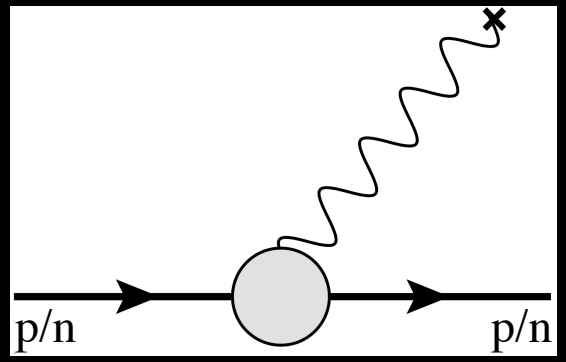
$$h^L_{coherent}(Q^2,\hat{s}) = 4Z^2e^2\left(1 - \frac{\hat{s}}{4E_\nu M}\right)^2 |F(Q^2)|^2$$

$|F(Q^2)|$ ~ Nucleus form factor: we use the Wood-Saxon Form factor



Diffractive regime: elastic photon from nucleon

Diffractive



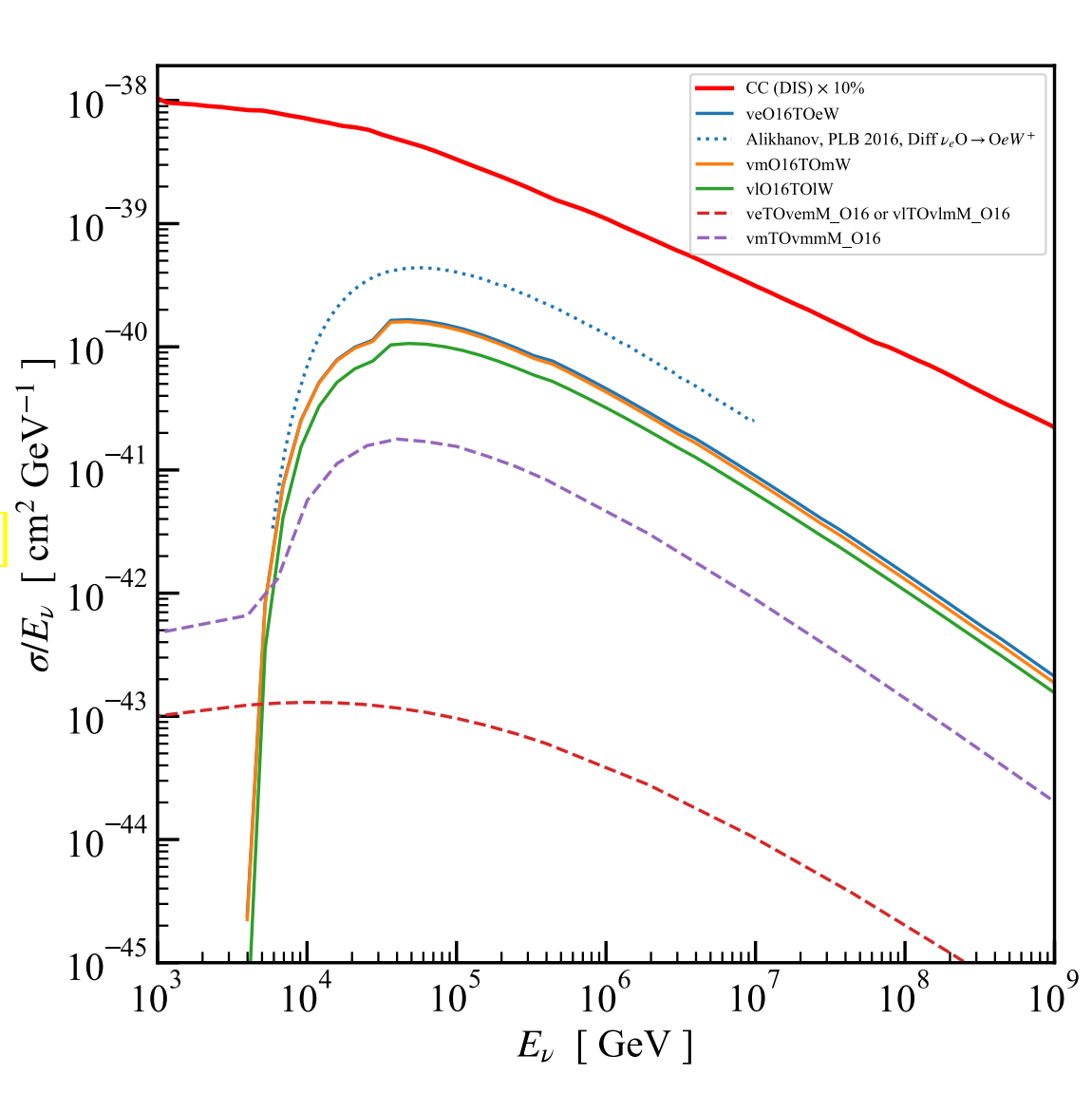
$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}Q^2}\left[\sigma^T_{\nu\gamma}(Q^2,\hat{s})\, h^T_X(Q^2,\hat{s}) + \sigma^L_{\nu\gamma}(Q^2,\hat{s})\, h^L_X(Q^2,\hat{s})\right]$$

$$h^{T,L}_{proton,neutron}(Q^2,\hat{s}) \sim Z^2 e^2 G_D(Q^2)$$

$$G_D(Q^2) = \left(1 + \frac{Q^2}{(0.84\ \mathrm{GeV})^2}\right)^{-2}$$

Proton's form factor has both electric part and magnetic part.

Neutron's form factor has only magnetic part.



Coherent and diffractive regimes: elastic photons

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

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

$h^{T,L}_{proton,neutron}(Q^2, \hat{s}) \sim e^2 G_D(Q^2)$

$G_D(Q^2) = (1 + Q^2/(0.84\ \mathrm{GeV})^2)^{-2}$

Neutron's form factor has only magnetic part.

Proton's has both electric part and magnetic part.