Neutrino Trident Production

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in collaborations with

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Review of Neutrino Trident Production

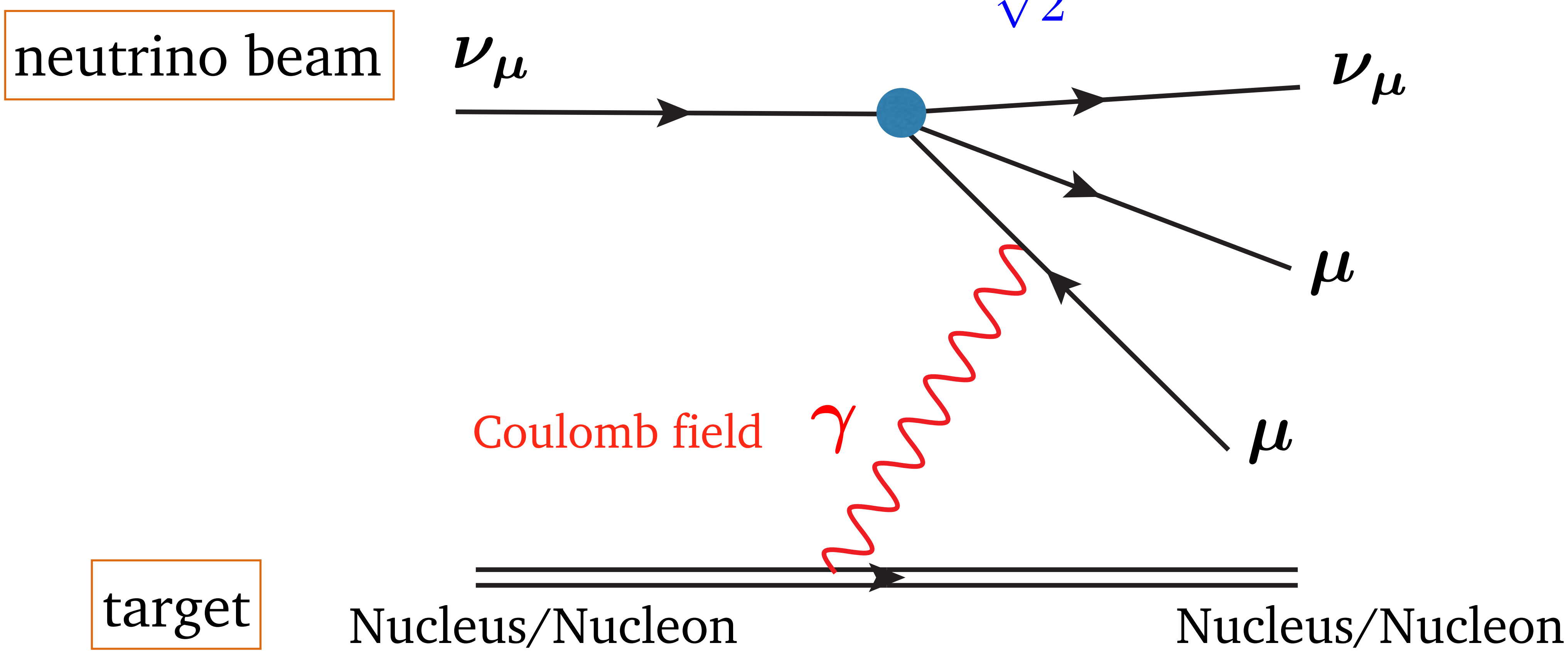
What is Neutrino Trident Production (NTP) Processes?

Charged lepton pair production by the scattering of a neutrino off *the Coulomb field* of a nucleus/nucleon

$$\boxed{\nu_\mu + N \to \nu_\mu + \mu + \mu + N}$$

N: Nucleus/Nucleon

weak int. $\mathcal{L} = \frac{G_F}{\sqrt{2}} \bar{l}\gamma_\mu (C_V - C_A\gamma_5) l \bar{\nu}\gamma^\mu (1-\gamma_5)\nu$



Brief History of the NTP's

Back in the early days,

	1934	Four Fermi interaction (Fermi)
	1956,7	Parity Violation discovered (Lee and Yang, Wu)
	1957	the V-A theory (Feynman, Gell-mann)
$\nu_\mu + N \to \mu^- + W^+ + N$, $W^+ \hookrightarrow e/\mu + \nu$	1964	Trident Production to examine the V-A theory (Czyz, Sheppey, Walecka)
	1967	Weinberg-Salam theory
$\nu_\mu + N \to \nu + \mu + \mu + N$	1971	Momentum and angular distribution of the NTP (Lovseth and Radomiski, Koike et al, Fujikawa)
	1972	Trident production to examine the WS theory (Brown, Hobbs, Smith and Stanko)
	1974	Neutral current (CERN)
	1983	*W* and *Z* boson discovered
	1990	CHARM-II
	1991	CCFR
	1995	NuTeV
revival $\longrightarrow$	2014	Trident production to constrain new physics (Altmannshofer, Gori, Pospelov, Yavin)

consistent with the SM prediction

Types of the NTPs and kinematical threshold

Mono-flavour

$$\nu_\mu + N \to \nu_\mu + \underline{\mu^+ + \mu^-} + N \qquad \text{(}W/Z\text{)}$$

$$\nu_\mu + N \to \nu_\mu + \underline{e^+ + e^-} + N \qquad \text{(}Z\text{)}$$

$$\nu_\mu + N \to \nu_\mu + \underline{\tau^+ + \tau^-} + N \qquad \text{(}Z\text{)}$$

Minimum neutrino energy: $E_{\nu,\text{thresh}} = 2m_l$ $(l=e,\mu,\tau)$

Multi-flavour

$$\nu_\mu + N \to \nu_e + \underline{e^+ + \mu^-} + N \qquad \text{(}W\text{)}$$

etc...

Minimum neutrino energy: $E_{\nu,\text{thresh}} = m_l + m_{l'}$ $(l,l'=e,\mu,\tau)$

The same processes exist for other flavours, and also exist for anti-neutrinos if *CP* is conserved.

The NTPs with atomic electrons

In principle, the NTPs can occur with bound electrons. But *these are negligible due to the high threshold and small cross sec.*

$$\boldsymbol{\nu_\mu + e^- \to \nu_\mu + \mu^+ + \mu^- + e^-} \qquad E_{\nu,\mathrm{thresh}} = \frac{2m_\mu}{m_e} m_\mu \simeq 43 \text{ GeV}$$

$$\boldsymbol{\nu_\mu + e^- \to \nu_e + e^+ + \mu^- + e^-} \qquad E_{\nu,\mathrm{thresh}} = \frac{m_\mu}{2m_e} m_\mu \simeq 11 \text{ GeV}$$

These do not occur for low energy neutrino beam.

The following process always occurs

$$\boldsymbol{\nu_e + e^- \to \nu_e + e^+ + e^- + e^-} \qquad E_{\nu,\mathrm{thresh}} = 4m_e \simeq 2\text{MeV}$$

The cross sec. of this process is much small and will be important for lower energy neutrino beams.

The NTP cross sections

Czyz et al (1964), Lovseth et al (1971), Brown et al (1972)

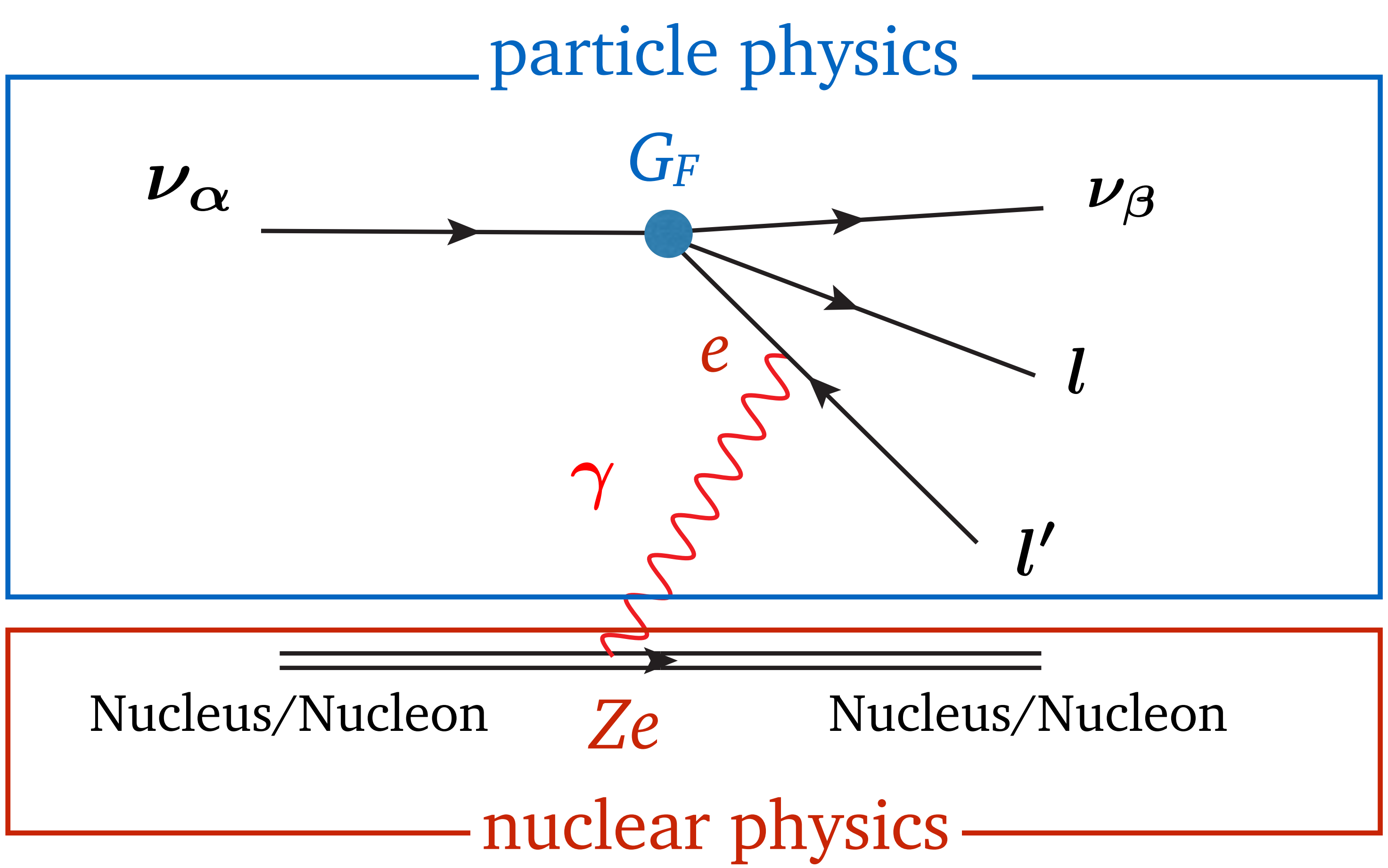
The cross section can be divided into two parts

$$\sigma = Z^2 \alpha^2 G_F^2 \int d\mathrm{LIPS}\ M_{\mu\nu} J^{\mu\nu} \frac{1}{q^4}$$ (Z : atomic number)

where

$$J^{\mu\nu} = \langle N'| J^{\mu} |N\rangle \langle N| J^{\nu} |N'\rangle$$

J^{μ} : nuclear electromagnetic current



Nuclear Electromagnetic Current

The nuclear electromagnetic current can be expressed in terms of form factors, *F*.

spin-0 particle (^{12}C, ^{56}Fe, ^{208}Pb, etc)

$$\langle N'|\, J^\mu \,|N\rangle = (Q+Q')^\mu F(q^2) \qquad\qquad (q = Q' - Q)$$

where $F(0) = 1$

spin-1/2 particle (p, n)

$$\langle N'|\, J^\mu \,|N\rangle = \bar{u}(Q') \left[\gamma^\mu F_1(q^2) + i\frac{\kappa\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2) \right] u(Q)$$

where *M* is the proton mass, and

$F_1(0) = 1,\ F_2(0) = 1,\ \kappa = 1.79$ for proton

$F_1(0) = 0,\ F_2(0) = 1,\ \kappa = -1.91$ for neutron

Nuclear Form Factor

The form factors in the literature are

the dipole fit

$$F(q^2) = \left(1 - \frac{q^2 R_0^2}{20}\right)^{-2} \quad \text{or} \quad \left(1 - 1.21\frac{q^2}{M_p^2}\right)^{-2}$$

M_p: proton mass

the exponential fit

$$F(q^2) = \exp\left(\frac{q^2 R_0^2}{10}\right)$$

where $R_0 = 1.21A^{1/3}$ fm

the Fermi fit (more realistic)

$$F(q^2) = \int \rho(\boldsymbol{r}) e^{i\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{r}/Q$$

$$\rho(\boldsymbol{r}) = (1 + \exp(r - R)/b)^{-1}$$

where

$$R = 1.07A^{1/3} \text{ fm} \quad \text{and} \quad b = 0.57 \text{ fm}$$

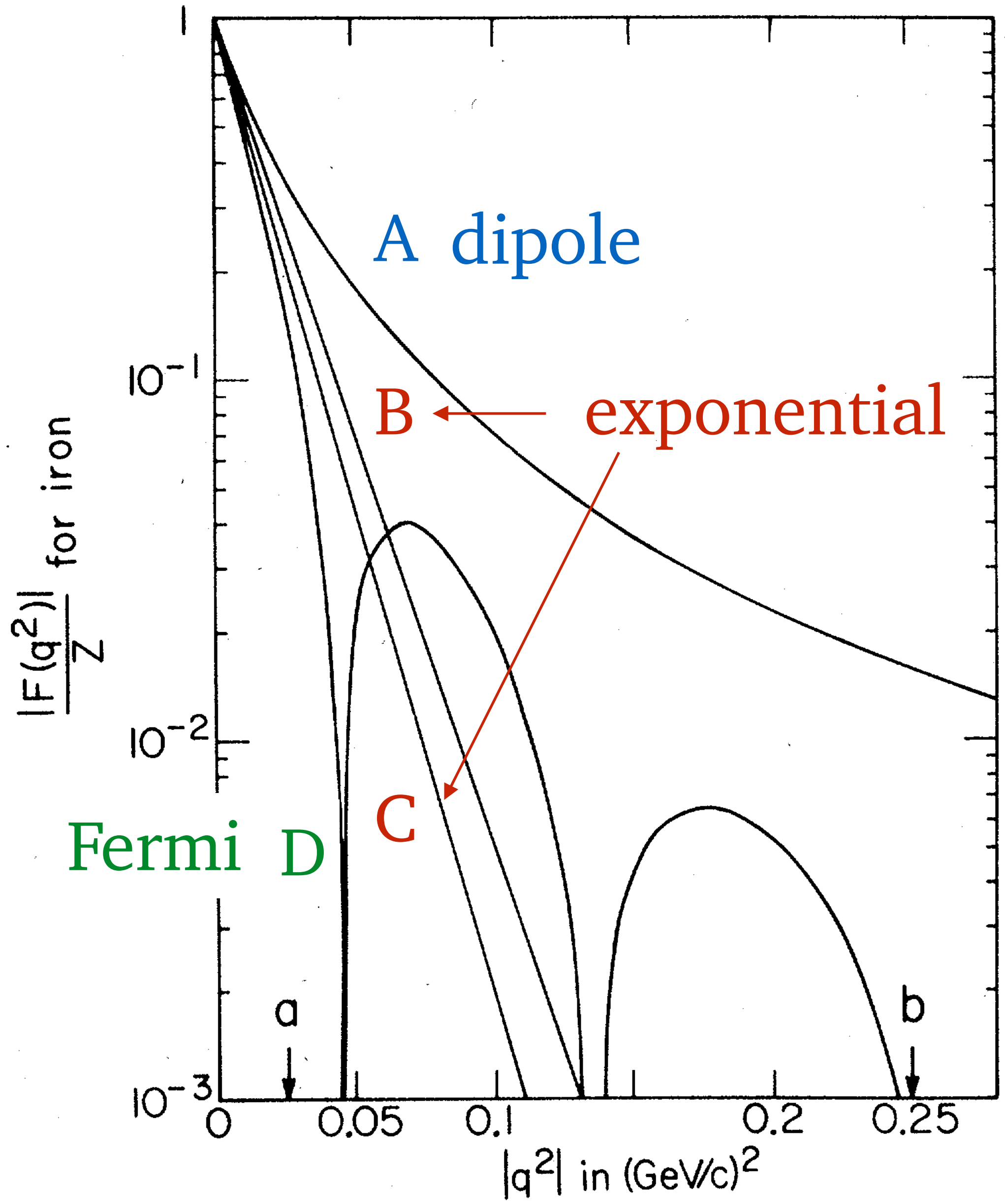
q^2 dependence of the form factors

The main contribution to the NTP comes from small q^2.

$B : R_0 = 1.21 A^{1/3}$ fm

$C : R_0 = 1.3 A^{1/3}$ fm

Iron nucleus



Brown et al, PRD(1972)

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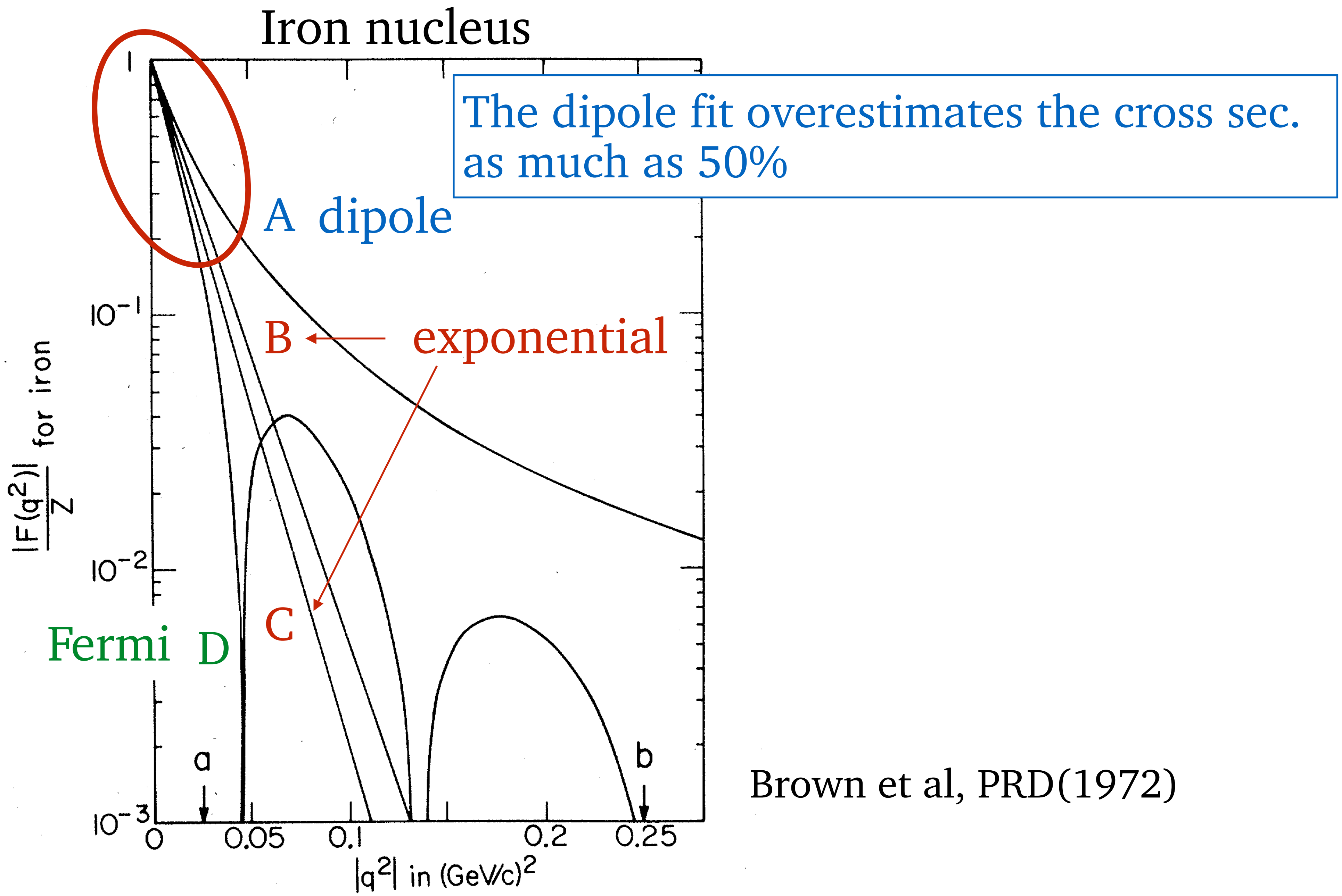

Brown et al, PRD(1972)

These form factors are almost the same for small q^2

The NTP cross sections (in the V-A theory)

1. NTP by the *coherent* scattering off *a nucleus*

$$\sigma_{\rm nucleus}(\mu\mu) \sim Z^2\alpha^2 G_F^2 \frac{E_\nu}{R_0}\log\left(\frac{E_\nu}{R_0 m_\mu^2}\right)$$

$$\sigma_{\rm nucleus}(ee) \sim Z^2\alpha^2 G_F^2 \frac{E_\nu}{R_0}\log\left(E_\nu R_0\right)$$

R_0: nuclear radius

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2. NTP by the *incoherent* scattering off *a nucleon*

$$\sigma_{\mathrm{nucleon}} \sim \alpha^2 G_F^2 E_\nu M_p \log\left(\frac{E_\nu M_p}{m_\mu^2}\right) (0.5Z + 0.1N)$$

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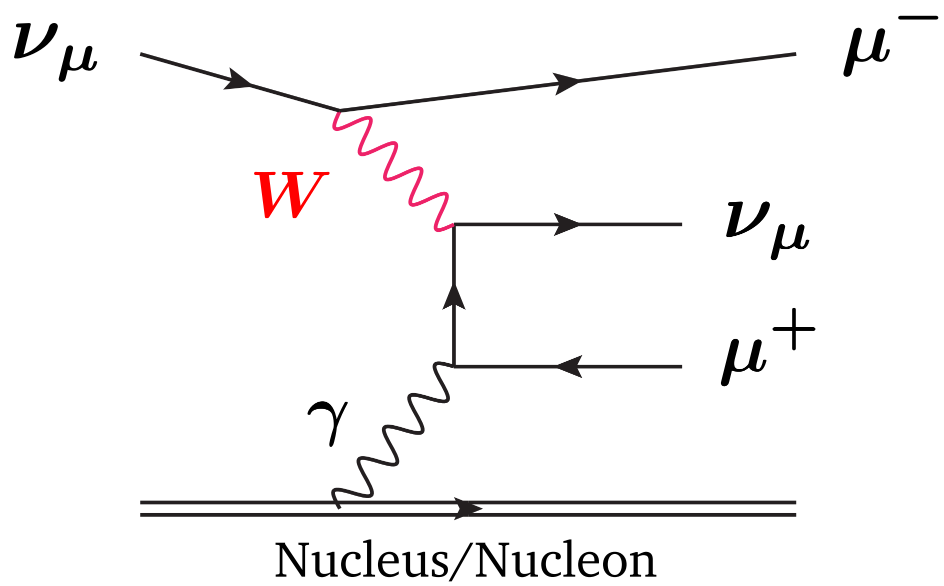
3. NTP by the *incoherent* scattering off *an atomic electron*

$$\sigma_{\text{electron}} \sim \alpha^2 G_F^2 E_\nu m_e \log^2\left(\frac{E_\nu}{m_e}\right)$$

The NTP cross sections (in the SM)

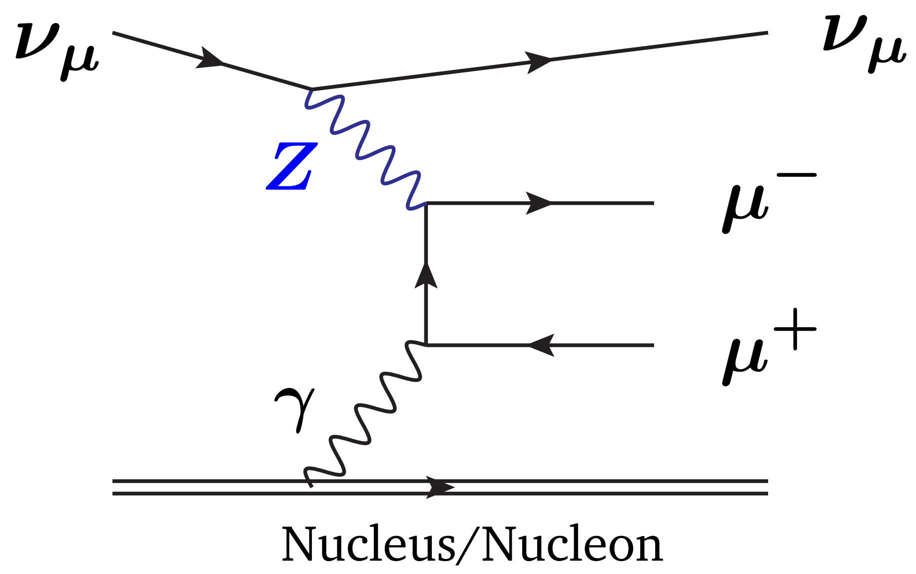
The neutrino trident production in the SM occurs via

W contrib. (*V-A*)



$+$

Z contrib.



The NTP cross sections (in the SM)

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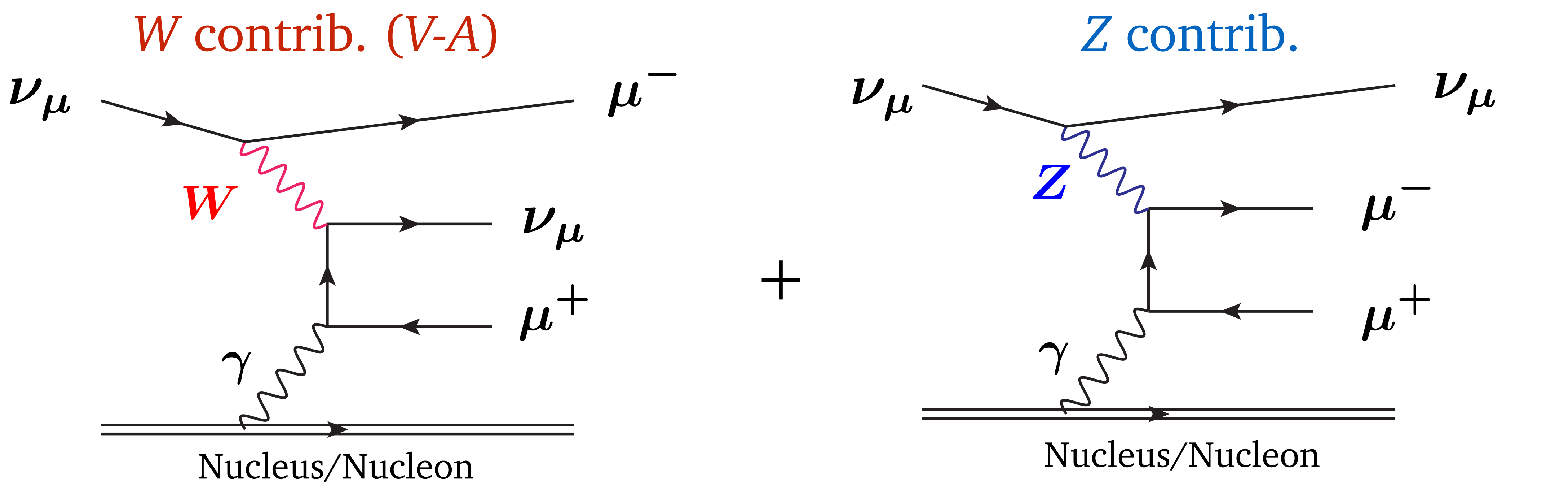


The Z boson contributes to the NTP cross section destructively,

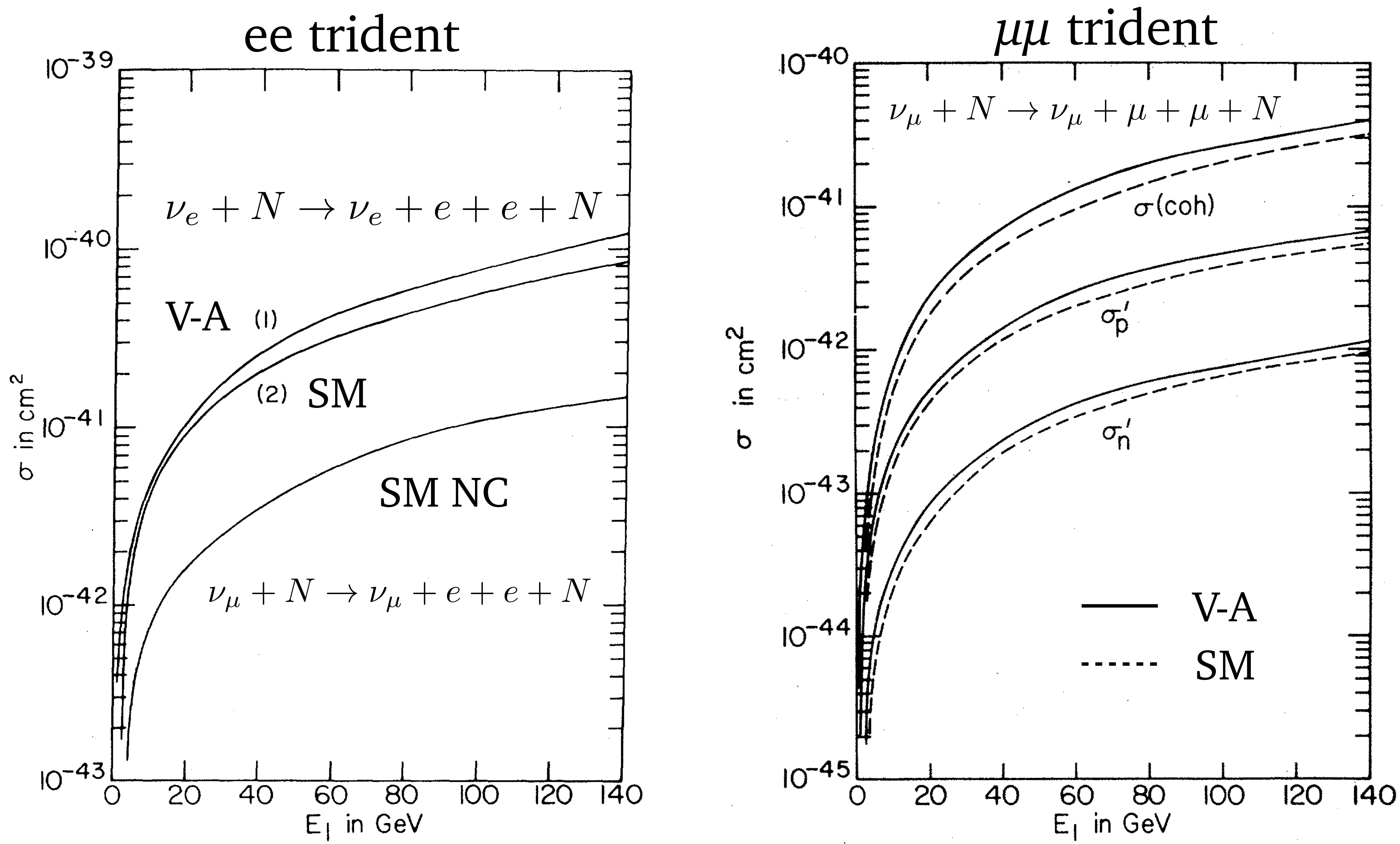
$$\mathcal{L} = \frac{G_F}{2}\left[\bar{\nu}\gamma^\mu(1-\gamma_5)\nu\right]\left[\bar{l}\gamma_\mu(C_V - C_A\gamma_5)l\right]$$

where $C_V = -\frac{1}{2} + 2\sin^2\theta_W\ (+1), C_A = -\frac{1}{2}\ (+1)$ (C_V=C_A=1 in V-A)

Then, the cross section is given by

$$\sigma_{\rm SM} \simeq (C_V^2 + C_A^2)\sigma_{V-A} \simeq 0.6\sigma_{V-A}$$

The NTP cross sections (in the SM)



The ν_e NTP is one order larger than the ν_μ NTP

Experimental Results of the NTP

- CHARM-II (CERN) PLB 245 (1990)

The first observation of the NTP using

$$\text{beam energy}: \quad \langle E_\nu \rangle = 23.8 \text{ GeV} \quad (\nu_\mu)$$
$$\langle E_\nu \rangle = 19.3 \text{ GeV} \quad (\bar{\nu_\mu})$$

Fiducial target mass : 547 t glass plates, $\langle Z^2 \rangle = 97.6$

Results (per nucleus)

$$\sigma_{\rm exp} = [3.0 \pm 0.9(\text{stat.}) \pm 0.5(\text{sys.})] \times 10^{-41} \text{ cm}^2$$

The result is consistent wit the SM prediction,

$$\sigma_{\rm theo} = [1.9 \pm 0.4] \times 10^{-41} \text{ cm}^2$$

which is consistent with the experimental results.

Theoretical uncertainty comes from

1. the uncertainty of the form factor
2. the estimation of diffractive contributions

Experimental Results of the NTP

- CCFR (FNAL) PRL 66 (1991)

The first observation of the destructive interference between *W* and *Z* using

beam energy : $\langle E_\nu \rangle = 160 \text{ GeV} \quad (\nu_\mu, \bar{\nu_\mu})$

Fiducial target mass : 324 t iron plates, $Z = 26$

Results

$$N_{\text{exp}} = 37.0 \pm 12.4$$
$$\sigma_{\text{exp}} = [7.5 \pm 2.6] \times 10^{-40} \text{ cm}^2$$

The expected numbers of events in the V-A and in the SM are

$$N_{V-A} = 78.1 \pm 3.9$$
$$N_{\text{SM}} = 45.3 \pm 2.3$$

The experimental result rules out the V-A theory at 99% C.L.

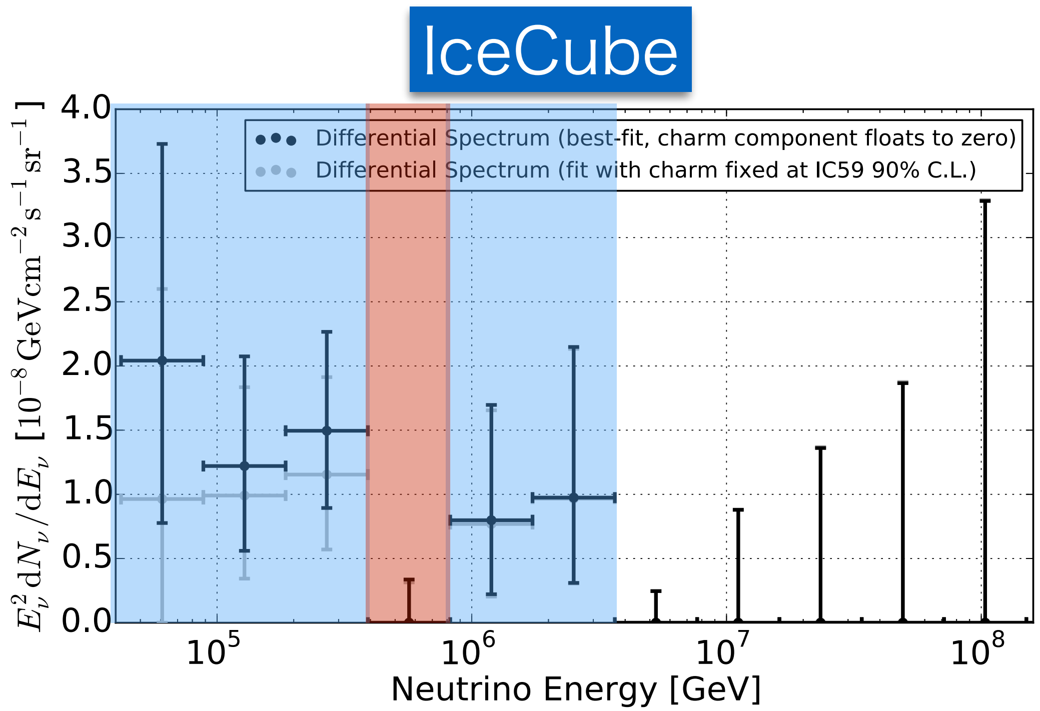
Short Summary of the NTP

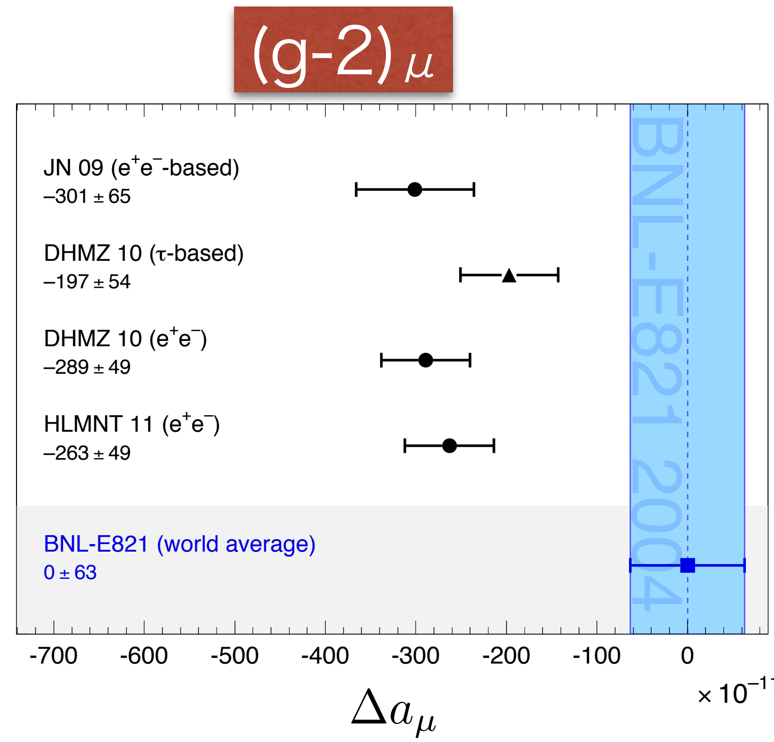
1. The neutrino trident production processes have been studied since 60's.
2. Nuclear form factors are necessary to compute the cross sections.
3. The NTP cross section is much smaller than the charged current one. Typically below 10^{-40} cm^2.
4. The latest results are more than 20 years ago, with large errors.
5. The experimental results are consistent with the SM so far within the error.

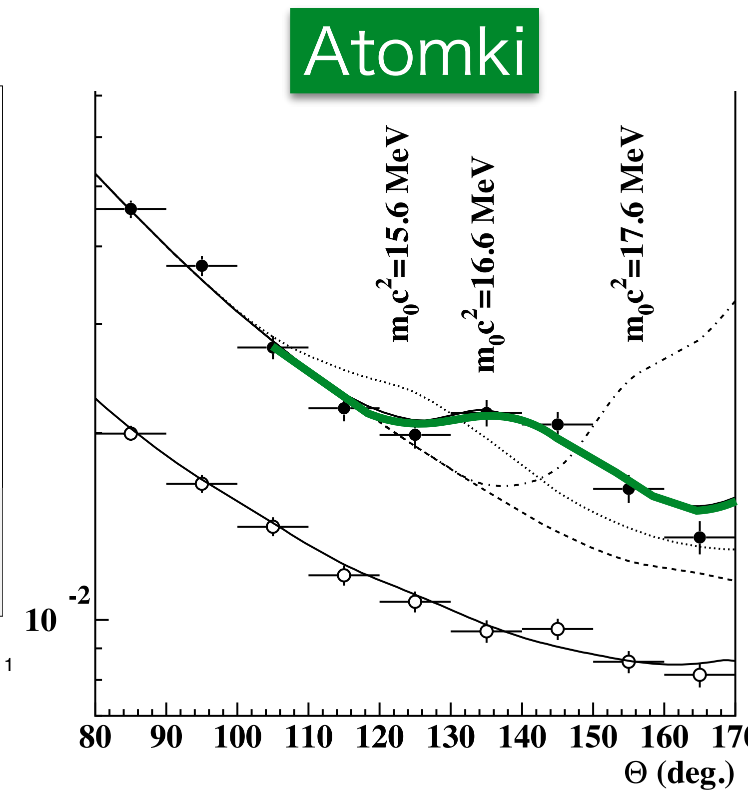
Neutrino Trident Production in a gauged L_μ-L_τ model

Light Gauge Boson as New Physics

Seto san's talk



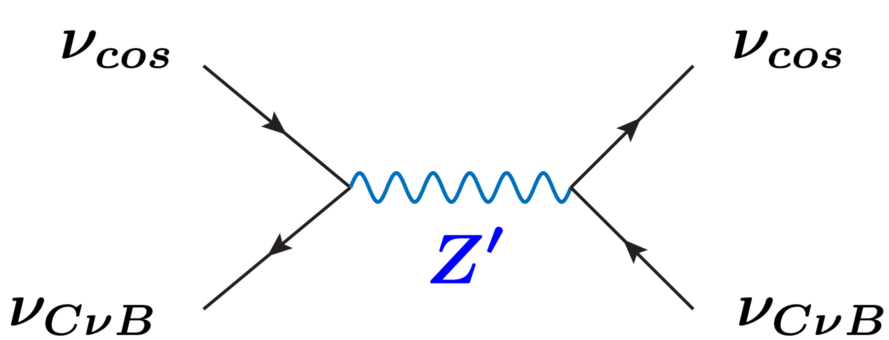


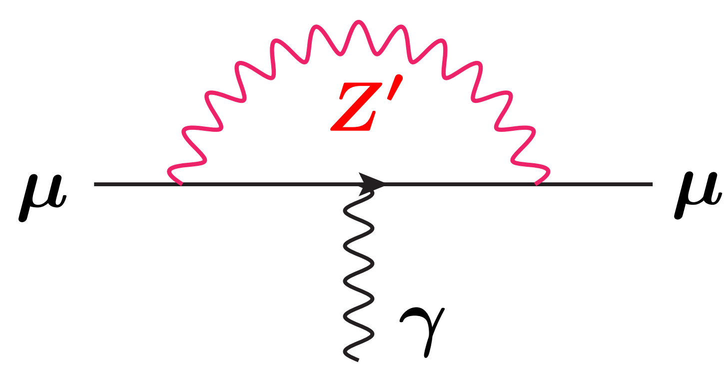


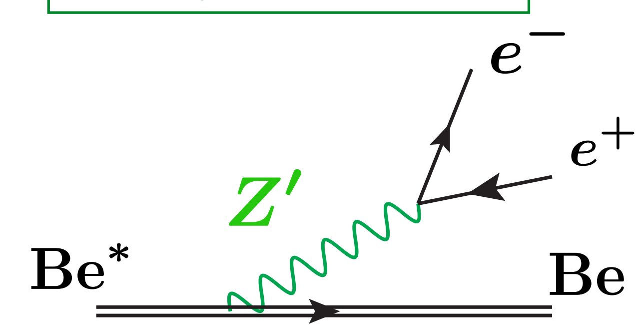
resonant absorption of cosmic ν

new int. with muon

decay into $e^+ e^-$







$E_\nu = 1$ PeV, $m_\nu = 0.1$ eV

$$M_{Z'} \simeq \sqrt{2E_\nu m_\nu}$$

$$\boxed{\simeq \mathcal{O}(10)\ \mathrm{MeV}}$$

For $m_{Z'} \ll m_\mu$ and $g' = 10^{-4}$

$$\Delta a_\mu \simeq \frac{g'^2}{8\pi^2} \simeq \mathcal{O}(10^{-9})$$

best fit

$$\boxed{m_{Z'} = 16.70\ \mathrm{MeV}}$$

Light Gauge Boson as New Physics

These anomalies/tensions can be explained by

$$m_{Z'} \simeq \mathcal{O}(10 - 100)\ \mathrm{MeV} \qquad g' \sim 10^{-4} - 10^{-5}$$

The origin of the mass = The spontaneous breaking of a symmetry

$$v = \frac{m_{Z'}}{g'} \sim \mathcal{O}(100 - 1000)\mathrm{GeV}$$

New Physics above the EW scale

Gauged $U(1)_{L\mu\text{-}L\tau}$ model

R. Foot, Mod.Phys.Lett. (1991),
He, Joshi, Lew, Volkas, PRD (1991)

- Minimal extension of the SM
- Anomaly free
- Large neutrino mixing

Choubey, Rodejohann, Eur.Phys.J, (2005)
Ota, Rodejohann, Phys.Lett. (2006)

	l_e	e_R	l_μ	μ_R	l_τ	τ_R
L_μ	0	0	1	1	0	0
L_τ	0	0	0	0	1	1

The Lagrangian without the kinetic mixing,

$$\mathcal{L} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu$$
$$+ g' Z'_\mu (\bar{\mu}\gamma^\mu \mu + \bar{\nu}_\mu \gamma^\mu \nu_\mu - \bar{\tau}\gamma^\mu \tau - \bar{\nu}_\tau \gamma^\mu \nu_\tau)$$

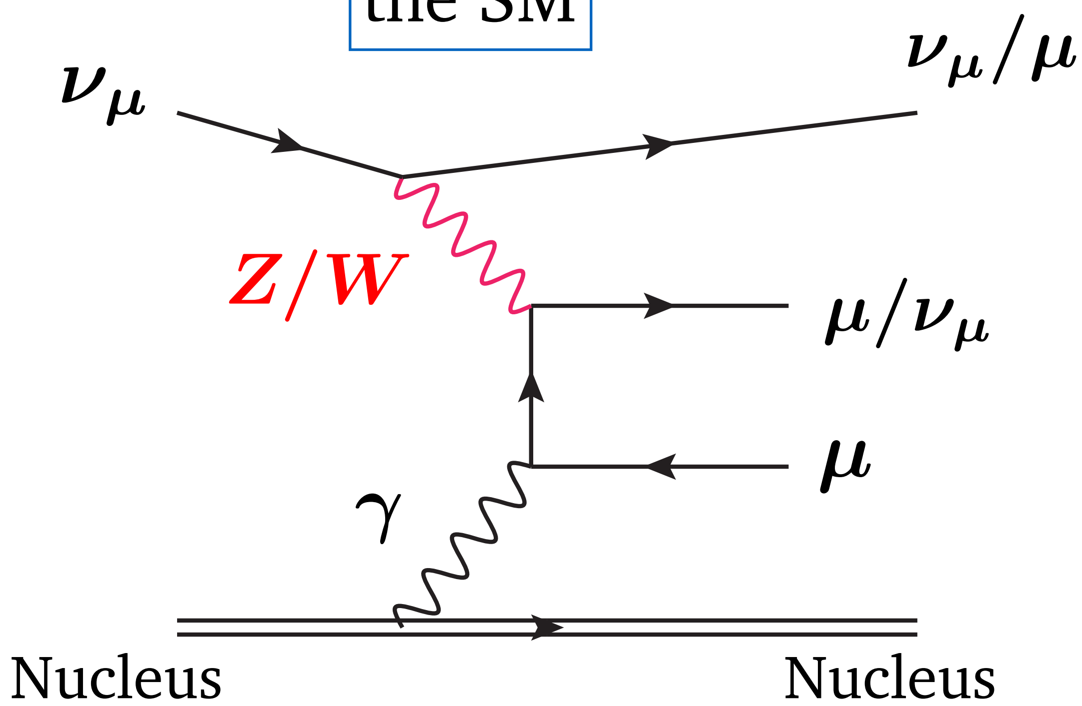
new interactions for μ and ν

- The IceCube gap can be explained by $O(10)$ MeV Z' with $g' \sim 10^{-4}$
- The muon (g-2) also can explain by the same mass and the coupling

Araki, Kaneko, Ota, Sato, T.S, PRD93 (2016)

Z' contribution to the NTP

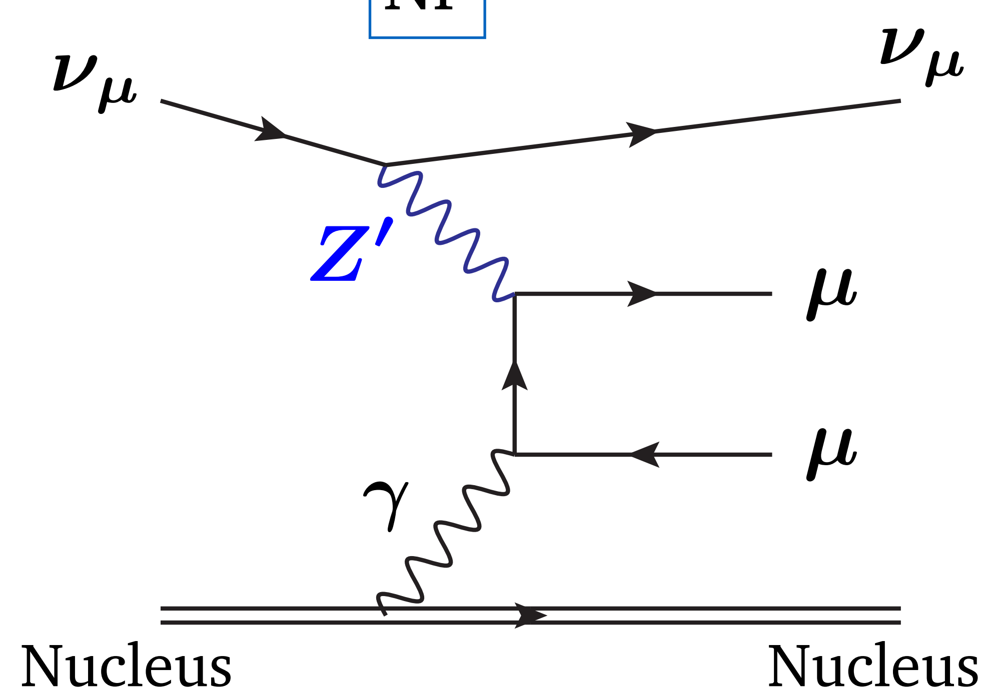
the SM



$$G_F = \frac{g_2^2}{m_Z^2}$$

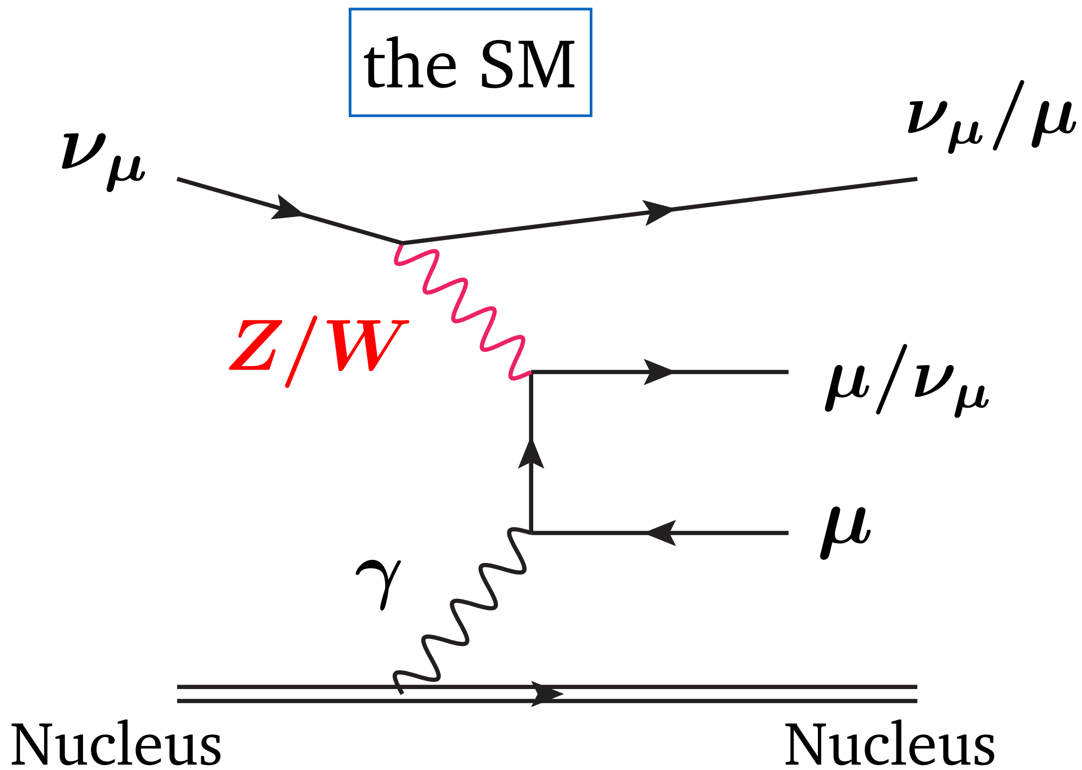
ONLY weak int.

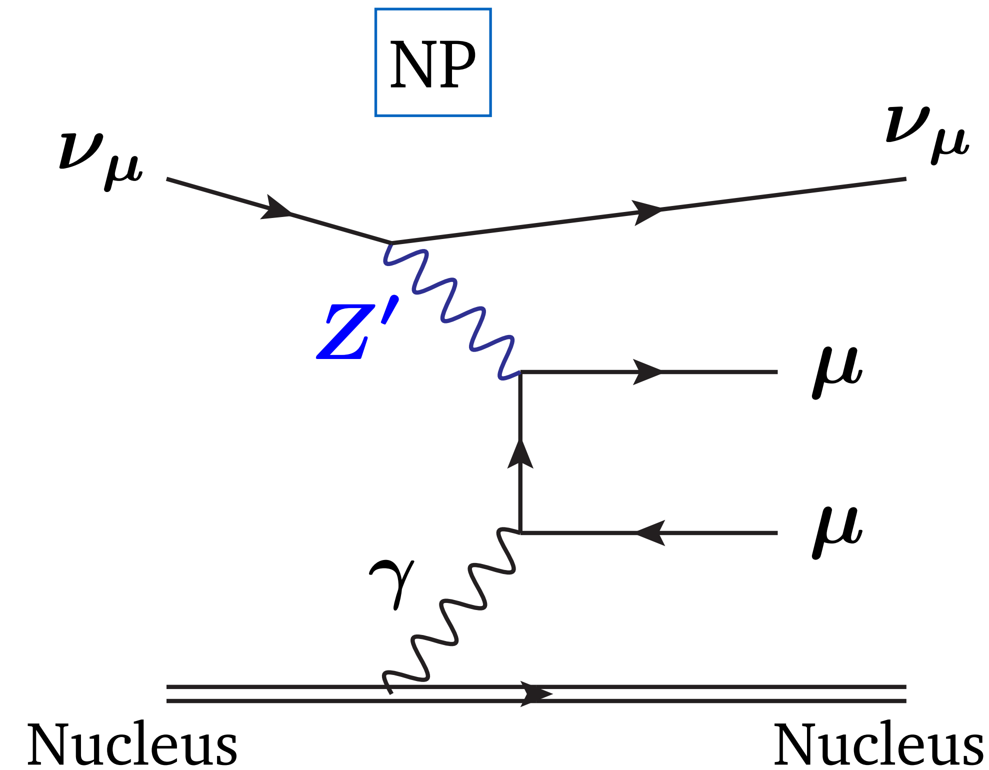
NP



$$\frac{g'^2}{q^2 - m_{Z'}^2}$$

Z' contribution to the NTP





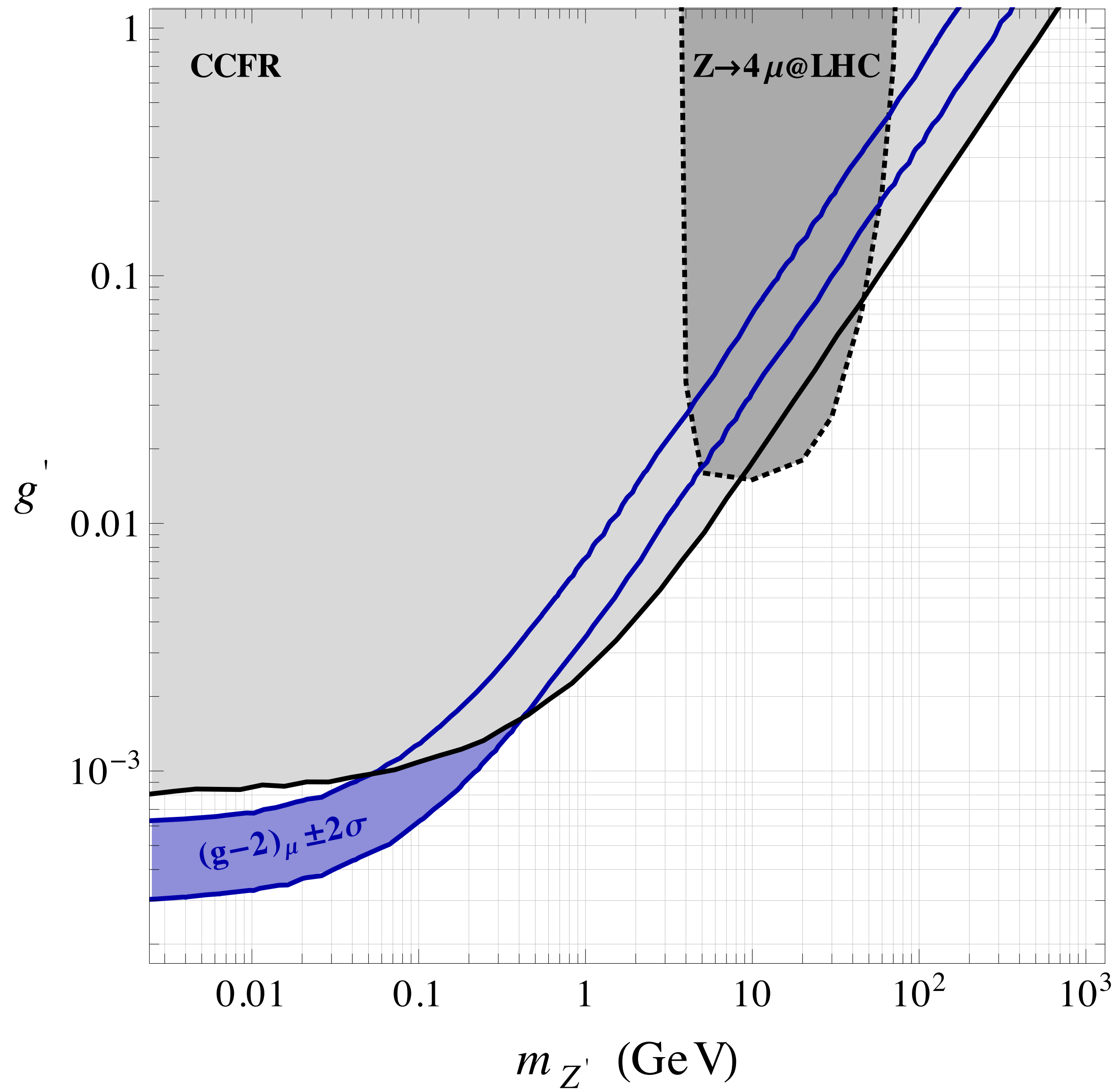
$$G_F = \frac{g_2^2}{m_Z^2} \qquad \frac{g'^2}{q^2 - m_{Z'}^2}$$

ONLY weak int.

$$\frac{g'^2}{m_{Z'}^2} \sim 10^{-5}\ \mathrm{GeV}^{-2} \qquad g' \sim 10^{-3} \quad @\ m_{Z'}=10\ \mathrm{MeV}$$

sensitive to small *g'* & $m_{Z'}$

Allowed parameter region



Altmannshofer, et al, PRL. 113 (2014)

$$\sigma_{\text{CHARM-II}}/\sigma_{\text{SM}} = 1.58 \pm 0.57 \text{ at } E_\nu \sim 20 \text{ GeV} \quad (1990)$$

$$\sigma_{\text{CCFR}}/\sigma_{\text{SM}} = 0.82 \pm 0.28 \text{ at } E_\nu \sim 160 \text{ GeV} \quad (1991)$$

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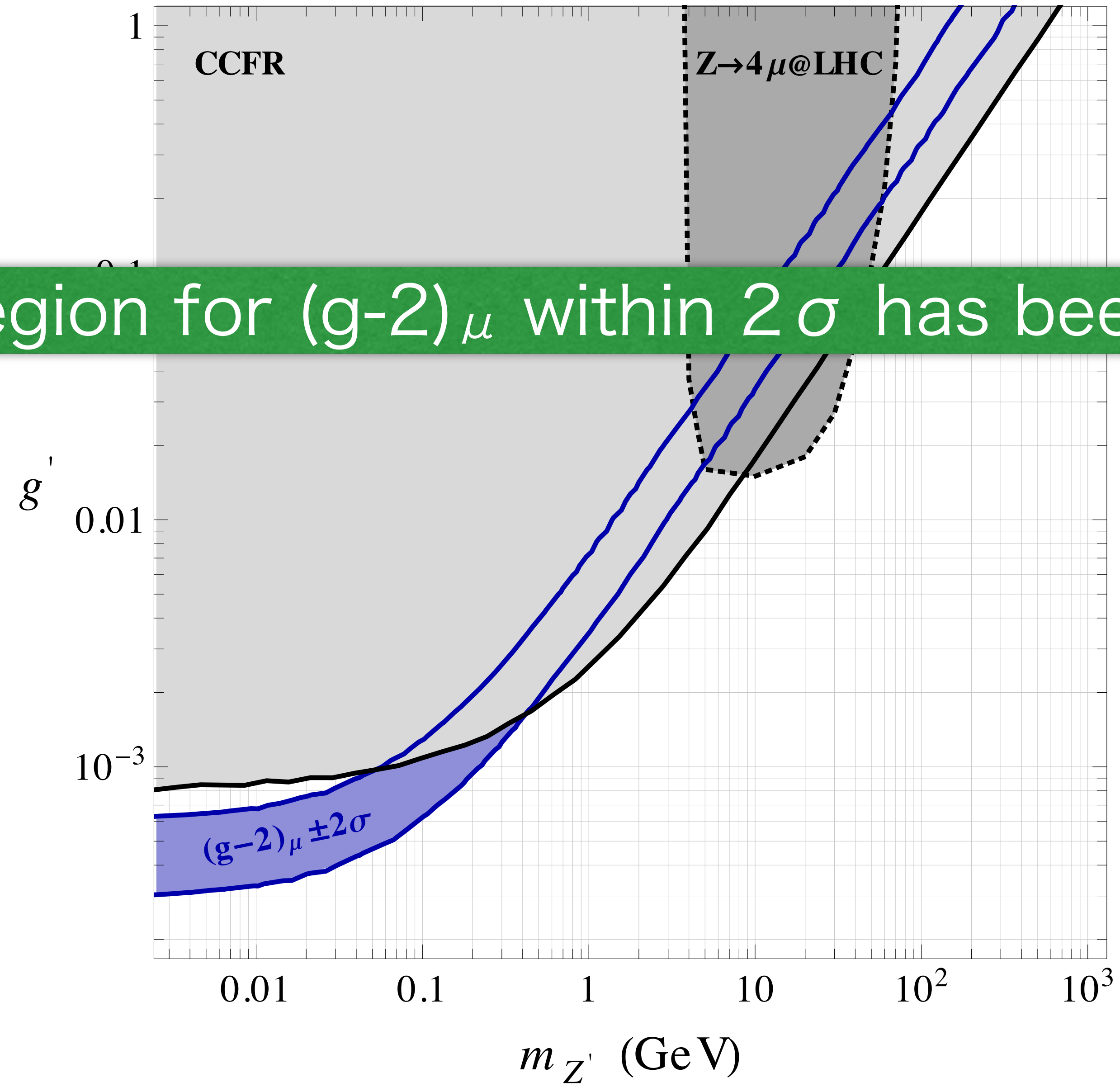

Most of region for $(g\text{-}2)_\mu$ within 2σ has been excluded!

Altmannshofer, et al, PRL. 113 (2014)

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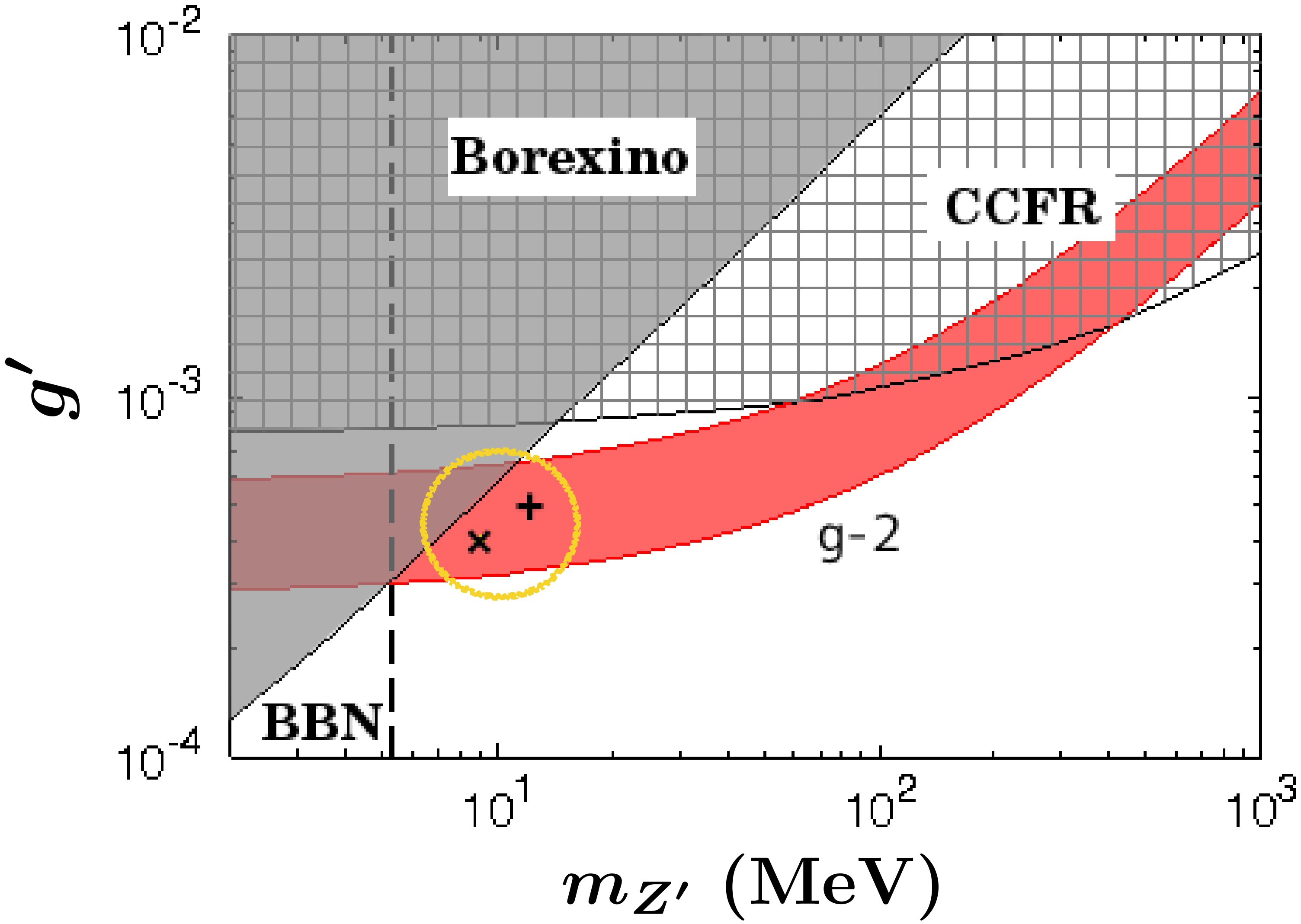

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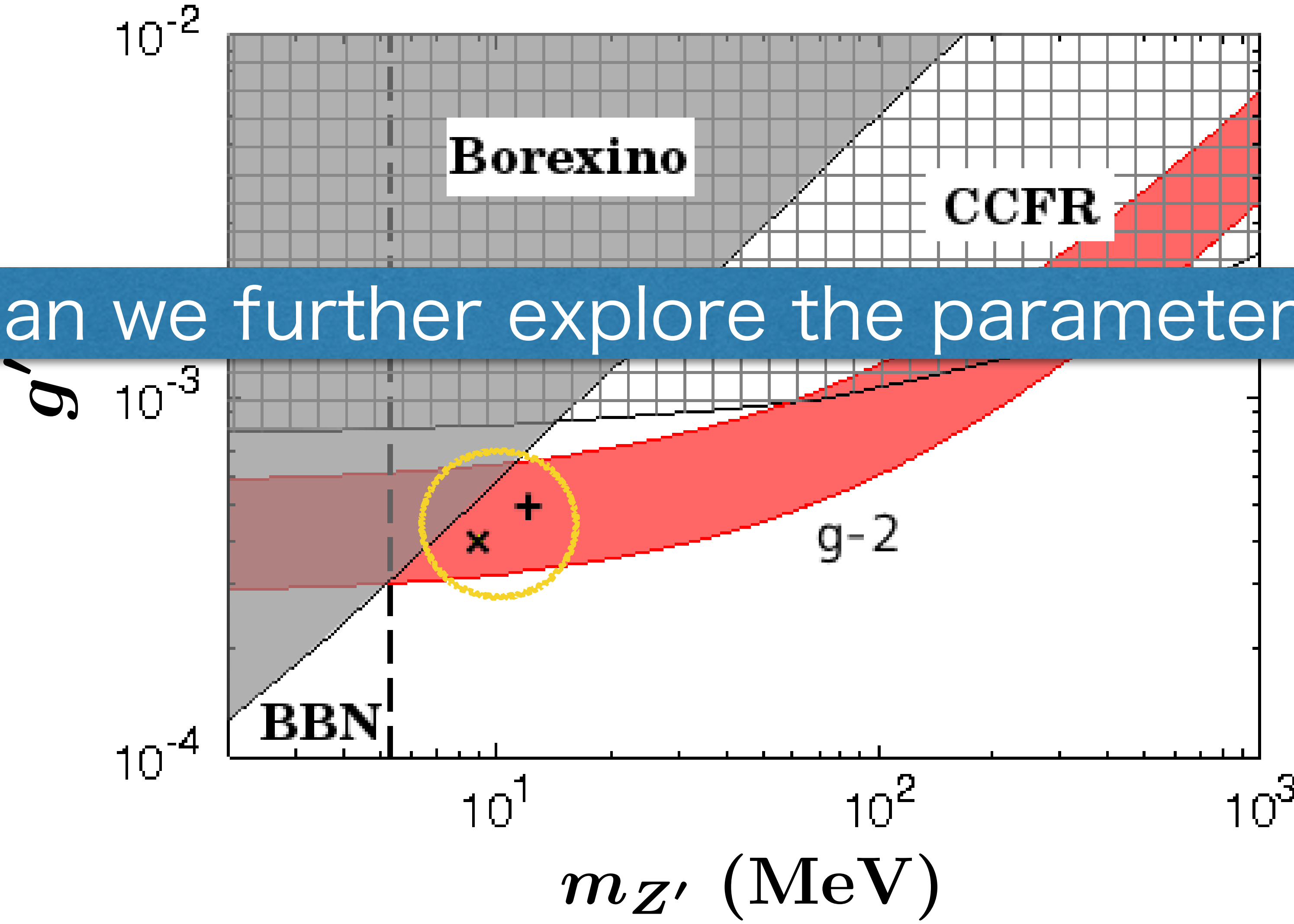

How can we further explore the parameter region?

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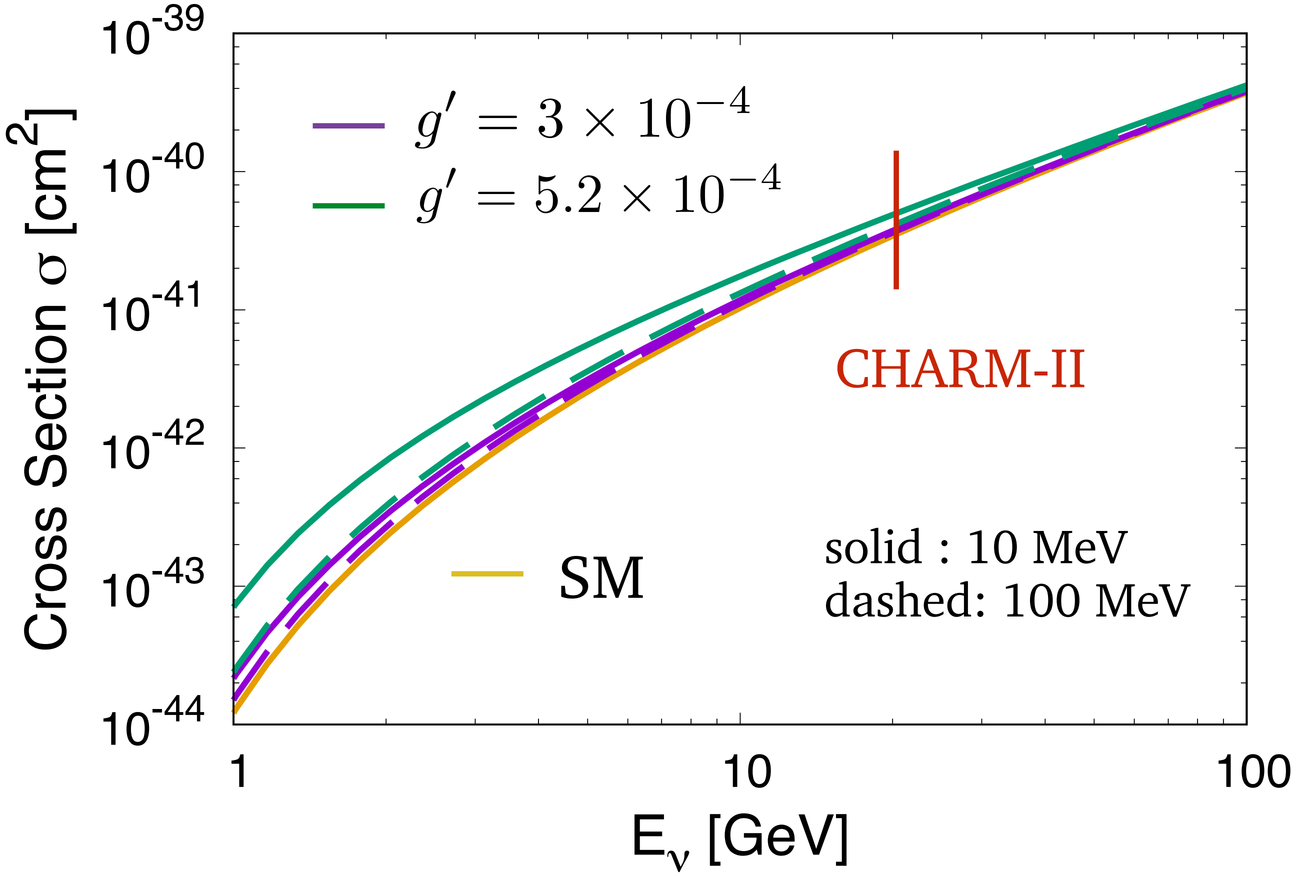
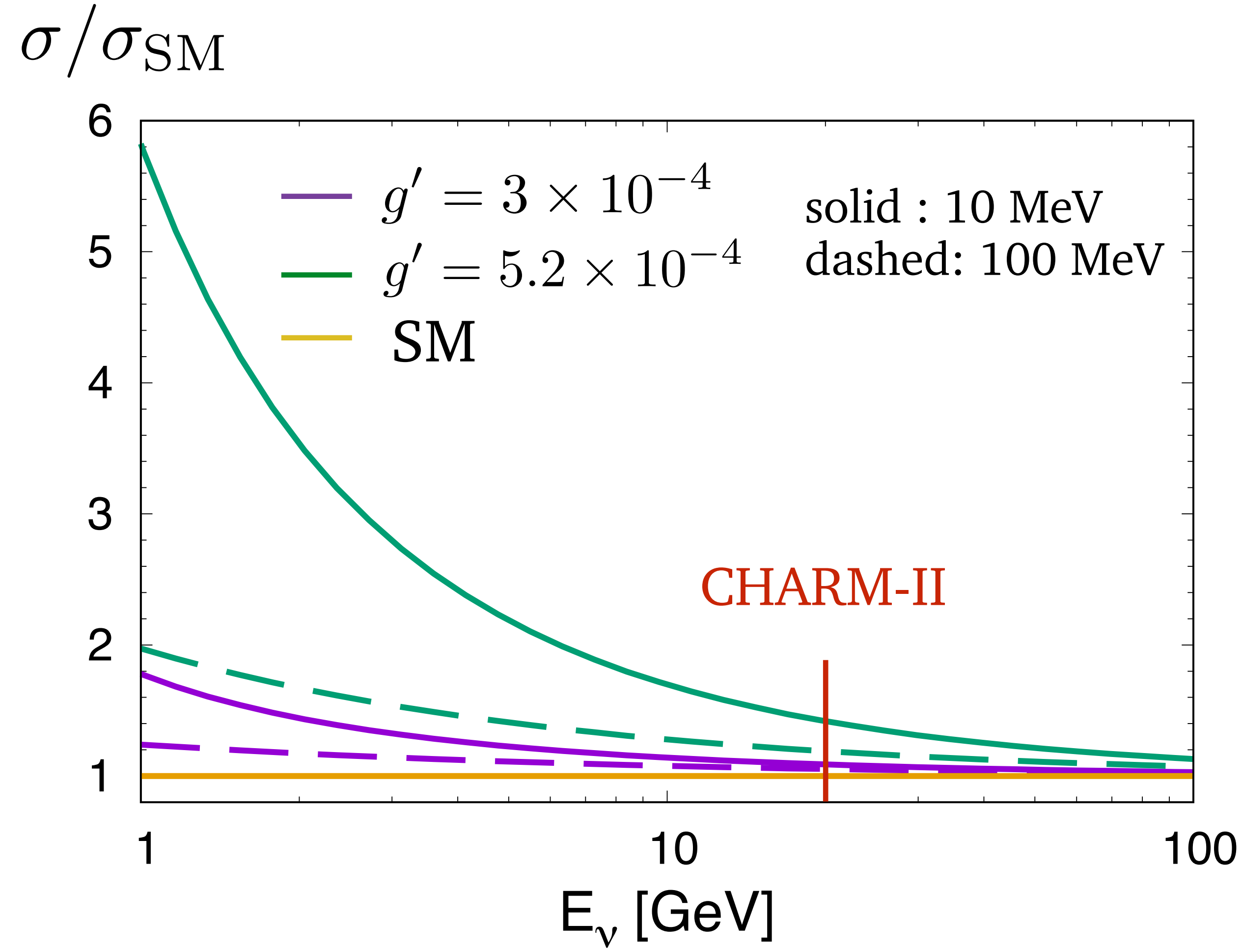
Energy dependence of the cross section





The cross section $\sigma = \sigma_{\rm SM} + \underline{\sigma_{\rm int} + \sigma_{Z'}}$

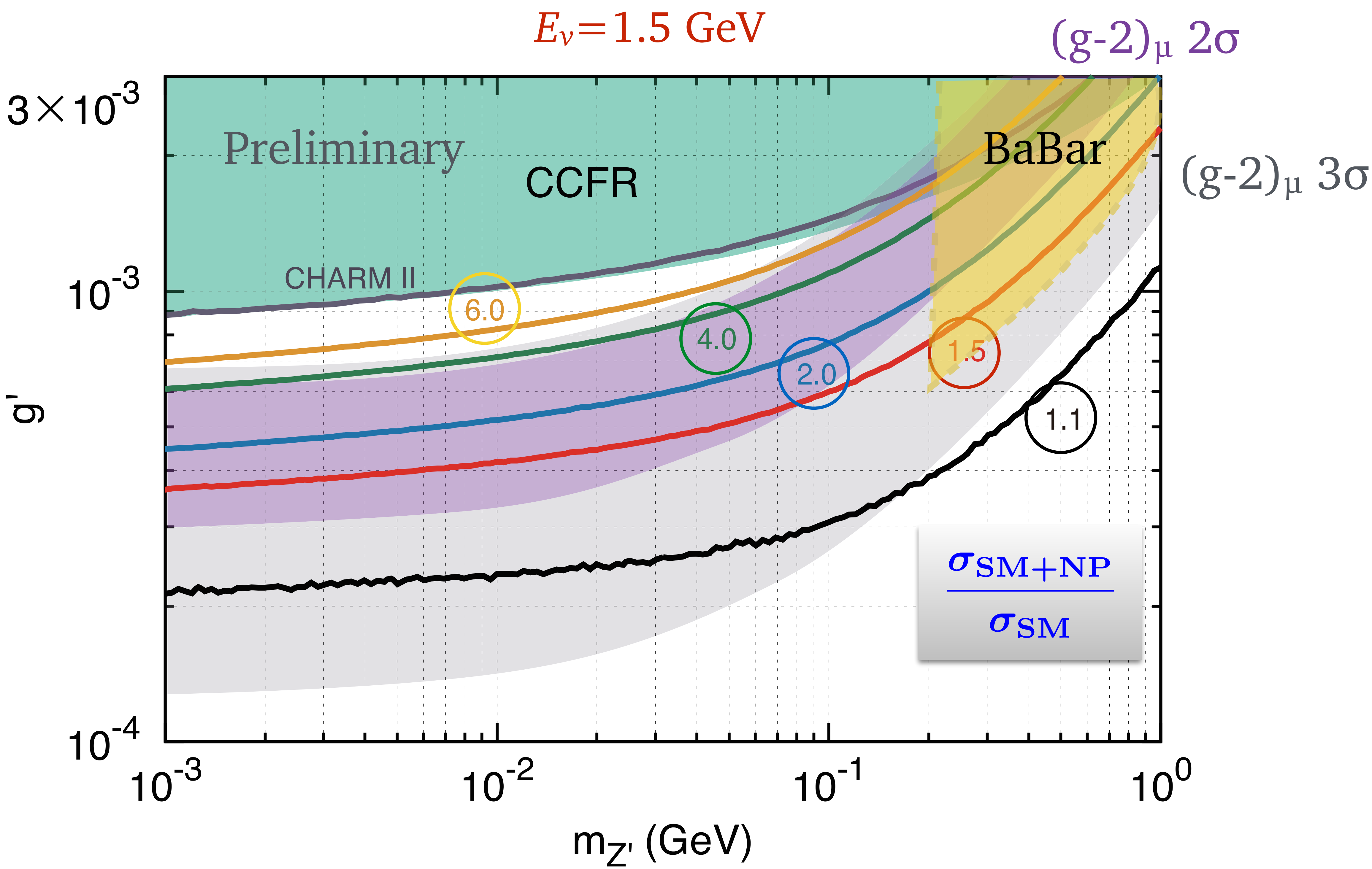
$$\sigma_{\rm SM} \propto G_F^2 \alpha^2 \frac{E_\nu}{R_0} \log\left(\frac{E_\nu}{R_0 m_\mu^2}\right)$$

$$\sigma_{\rm int} \propto G_F \alpha g'^2 \log^2\left(\frac{E_\nu}{R_0 m_\mu^2}\right)$$

$$\frac{\sigma_{\rm int}}{\sigma_{\rm SM}} \propto \frac{\log E_\nu}{E_\nu}$$

NP is enhanced at low E

Sensitivity to g' and $m_{Z'}$ in a gauged L_μ-L_τ model



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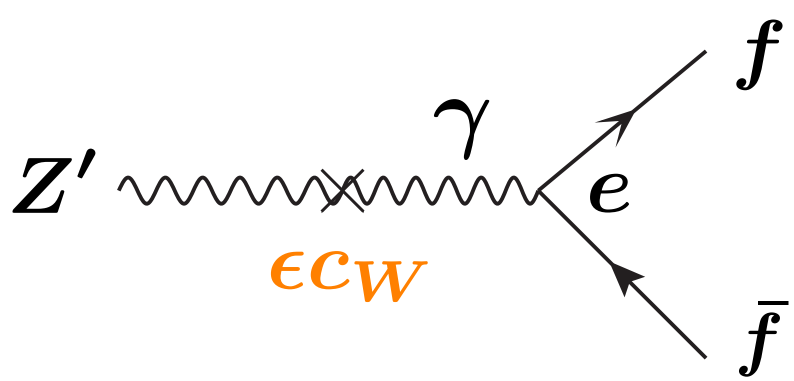
Gauged $U(1)_{L\mu\text{-}L\tau}$ model with kinetic mixing

In general, there are no reasons to forbid the kinetic mixing,

$$\mathcal{L}_{\mathrm{kin}} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}Z'^{\mu\nu}Z'_{\mu\nu} + \underline{\frac{\epsilon}{2}B^{\mu\nu}Z'_{\mu\nu}}$$

B : field strength of $U(1)_Y$

The kinetic mixing induces new interactions with *Z'* and fermions,

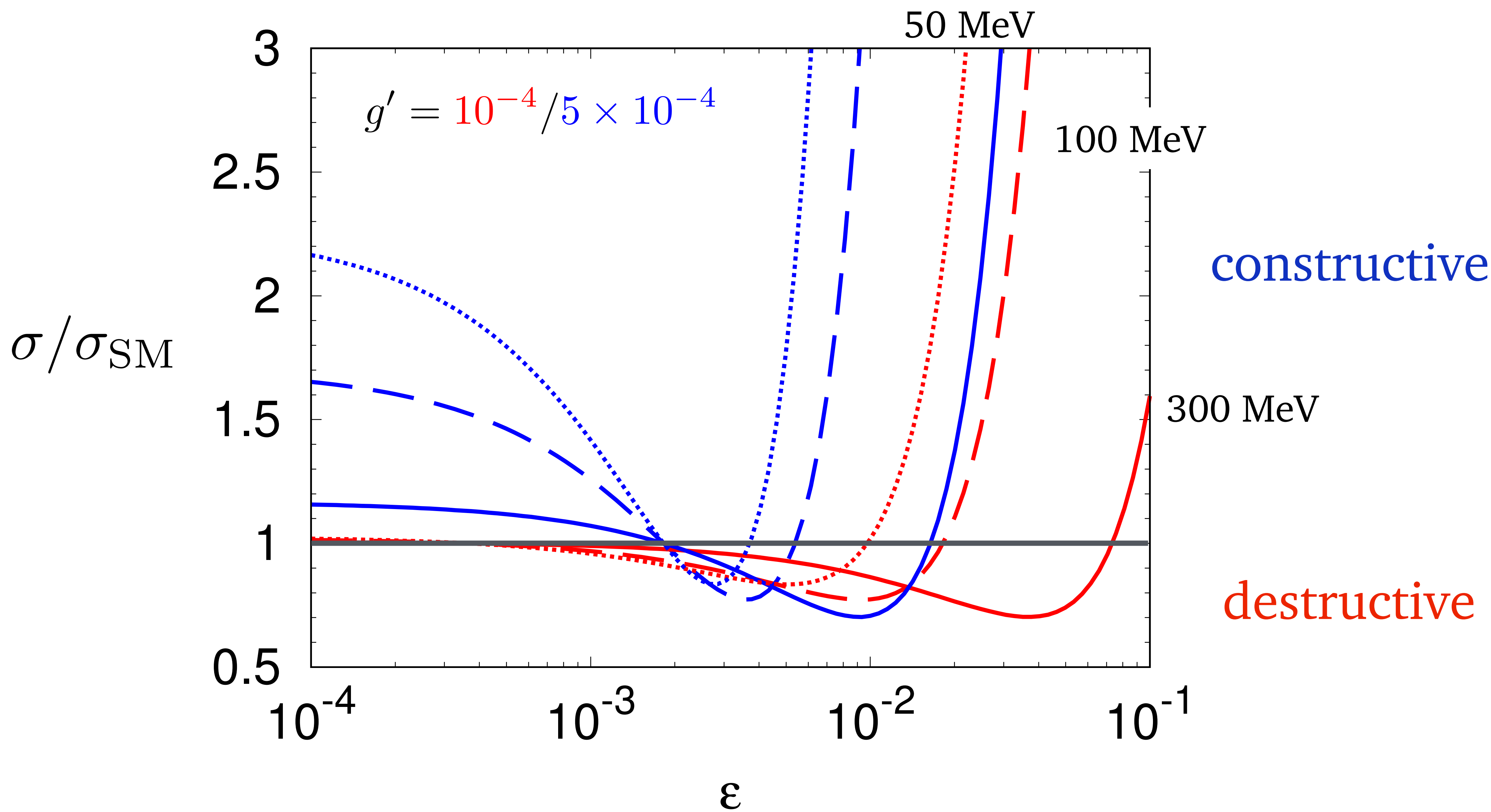


$(c_W = \cos\theta_W)$

$$\mathcal{L}_{\mathrm{int}} = Z'_\mu\left[-\varepsilon e c_W \bar{e}\gamma^\mu e + \underline{(g' - \varepsilon e c_W)}\bar{\mu}\gamma^\mu\mu + (-g' - \varepsilon e c_W)\bar{\tau}\gamma^\mu\tau \right.$$
$$\left. + \underline{g'}(\bar{\nu}_\mu\gamma^\mu\nu_\mu - \bar{\nu}_\tau\gamma^\mu\nu_\tau)\right]$$

- ✳ The muon coupling can be negative.
- ✳ The neutrino coupling is the same.

NTP Cross Section with kinetic mixing



The ratio >1 or <1 is also important information.

Summary

1. The new physics above the EW scale can appear as a light gauge boson.
2. The NTP is a powerful tool to search such a light gauge boson, especially a gauged L_μ-L_τ model.
3. Lower energy neutrino beams have better sensitivity to new physics search.

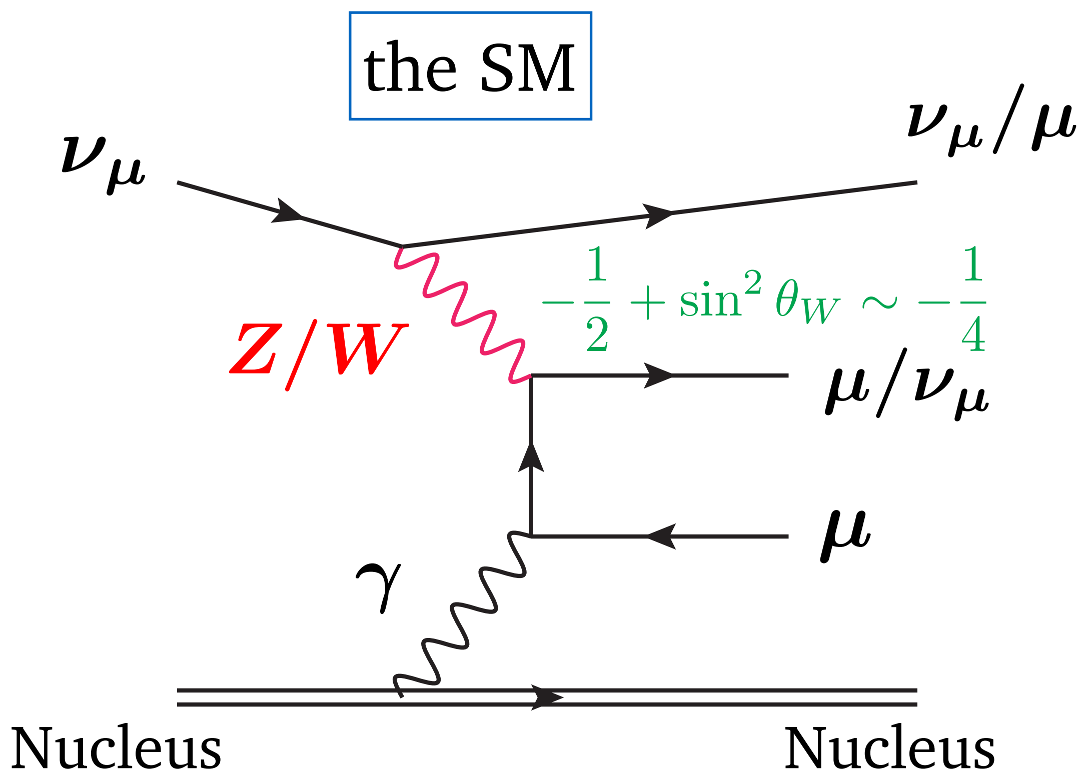
Future works (under progress)

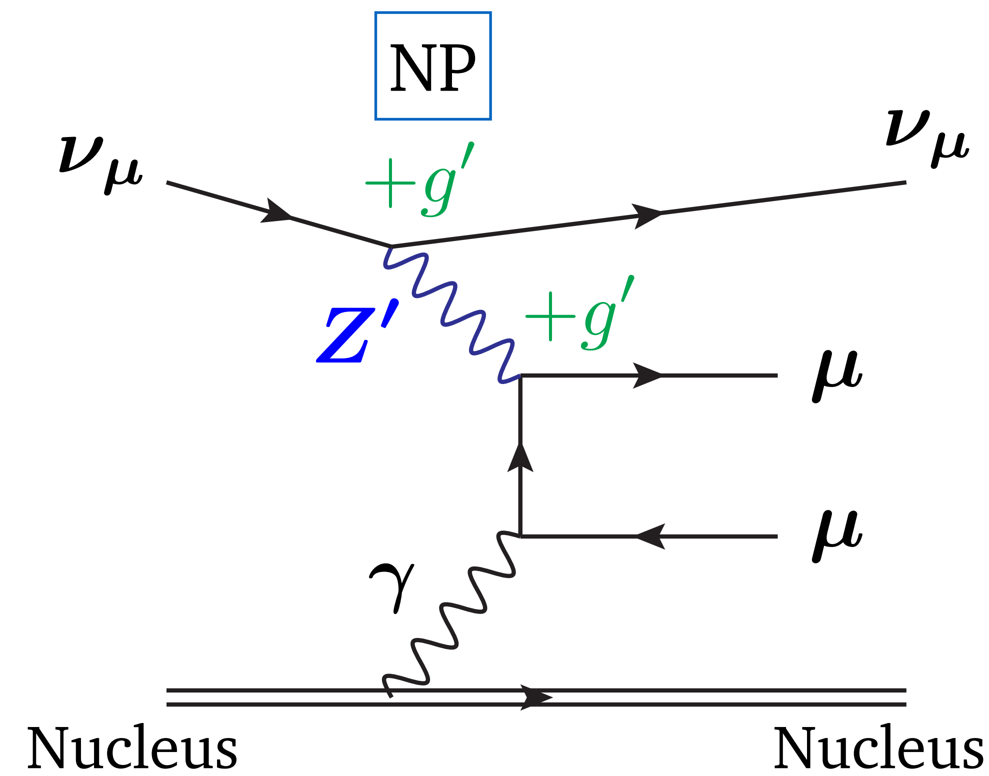
1. Backgrounds to the NTP come from leptonic decays of mesons (pi, K, rho, ...).

$$\nu_\mu + N \to \mu^- + X + N$$
$$\hookrightarrow X \to \mu^+ + \nu_\mu + \cdots$$

2. Momentum and angular distributions of the charged leptons are important to discriminate the signals from the backgrounds.

Z' contribution to the NTP





$$G_F = \frac{g_2^2}{m_Z^2}$$

$$\frac{g'^2}{q^2 - m_{Z'}^2}$$

Only weak int.

sensitive to small g' & $m_{Z'}$

The Z' contribution to this process is proportional to $(+g')^2$

always constructive

IceCube gap and muon g-2

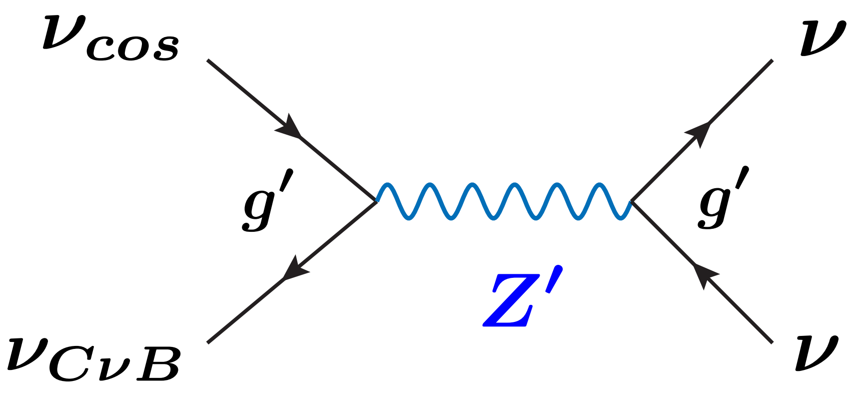
400TeV - 1PeV is resonantly scattered by cosmic ν background

- The resonant energy of comic ν is

$$E_{\mathrm{res}} \simeq \frac{m_{Z'}^2}{m_\nu}$$

For $m_{Z'} = 10$ MeV,

$$E_{\mathrm{res}} \simeq 1\ \mathrm{PeV}$$



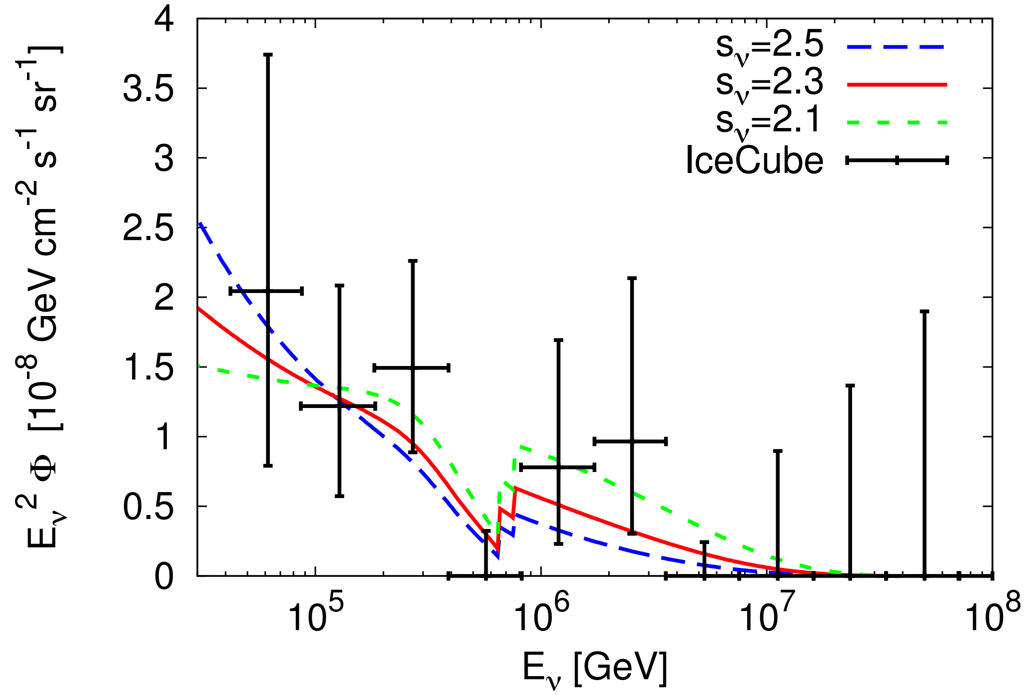
- The scattering cross section is

$$\sigma = \frac{2\pi g'^2}{M_{Z'}^2}\delta\left(1 - \frac{E_{\mathrm{res}}}{E_\nu}\right)$$

From numerical analysis,

$$g' \geq 10^{-4}$$

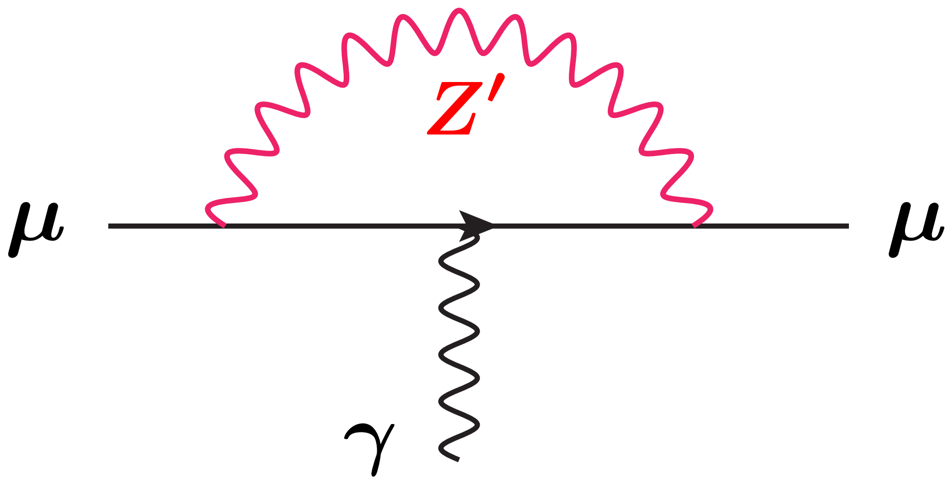
Araki, Kaneko, Ota, Sato, T.S, PRD93 (2016)



IceCube gap and muon g-2

Z' contribution to $(g\text{-}2)_\mu$

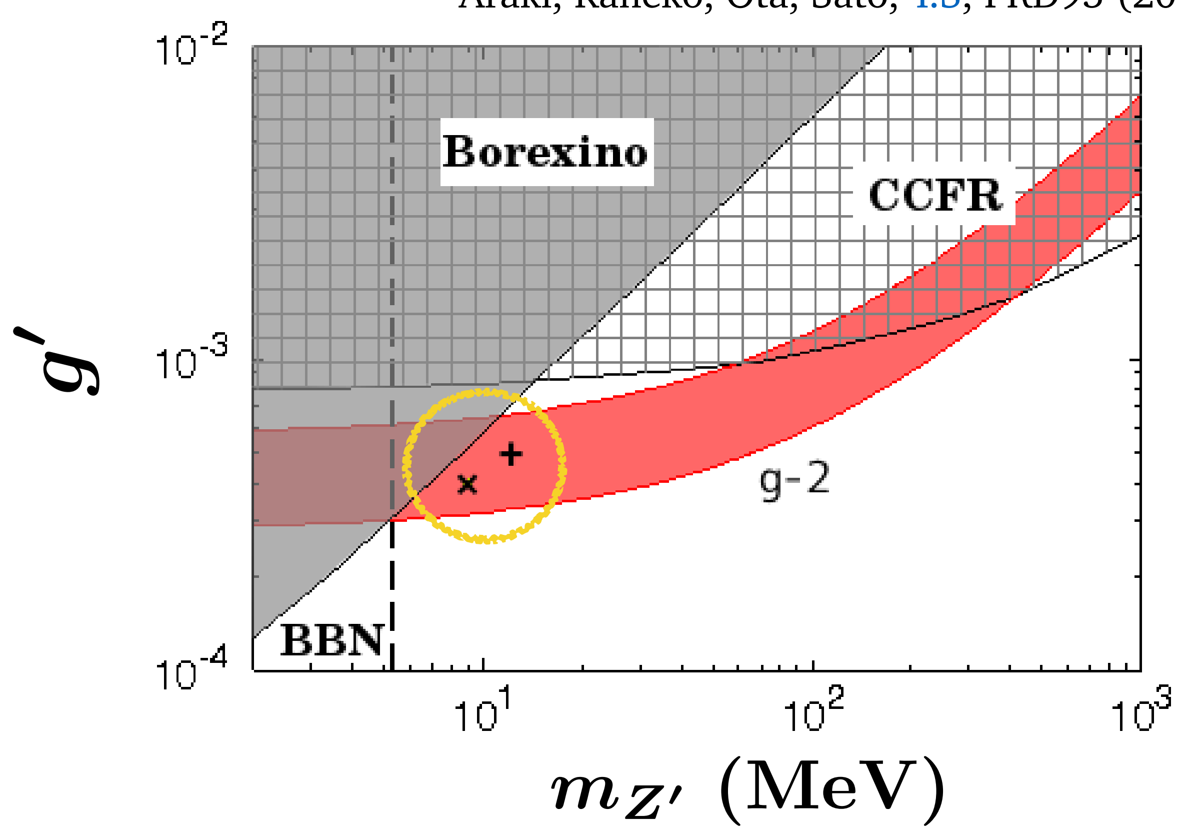
$$\Delta a_\mu = \frac{g'^2}{8\pi}\int_0^1 dx \frac{2m_\mu^2 x(1-x)^2}{x m_{Z'}^2 + (1-x)^2 m_\mu^2}$$



For $m_{Z'}$ =10 MeV and $g'=4\times10^{-4}$,

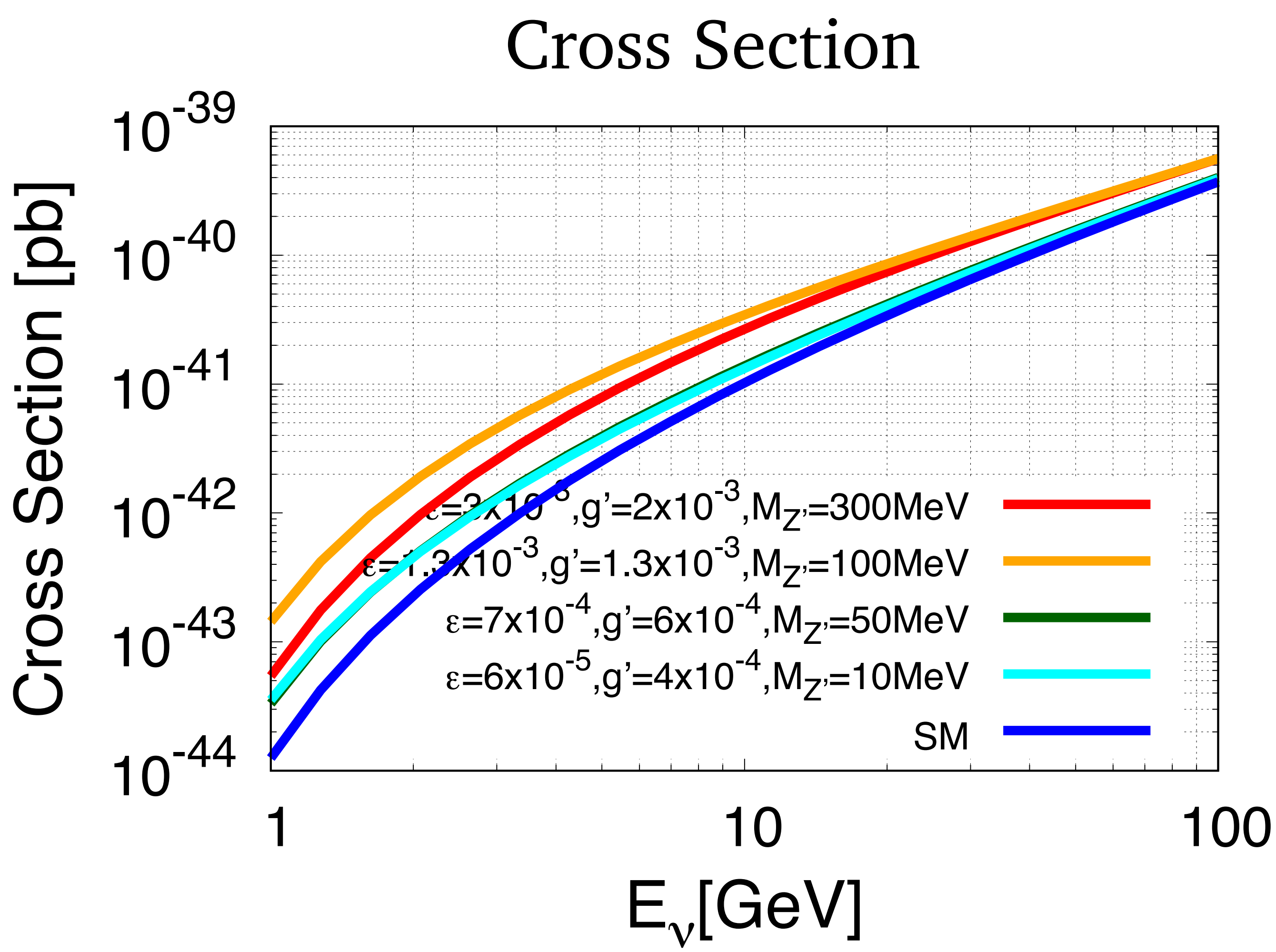
$$\Delta a_\mu \simeq \frac{g'^2}{8\pi^2} \simeq \mathcal{O}(10^{-9})$$

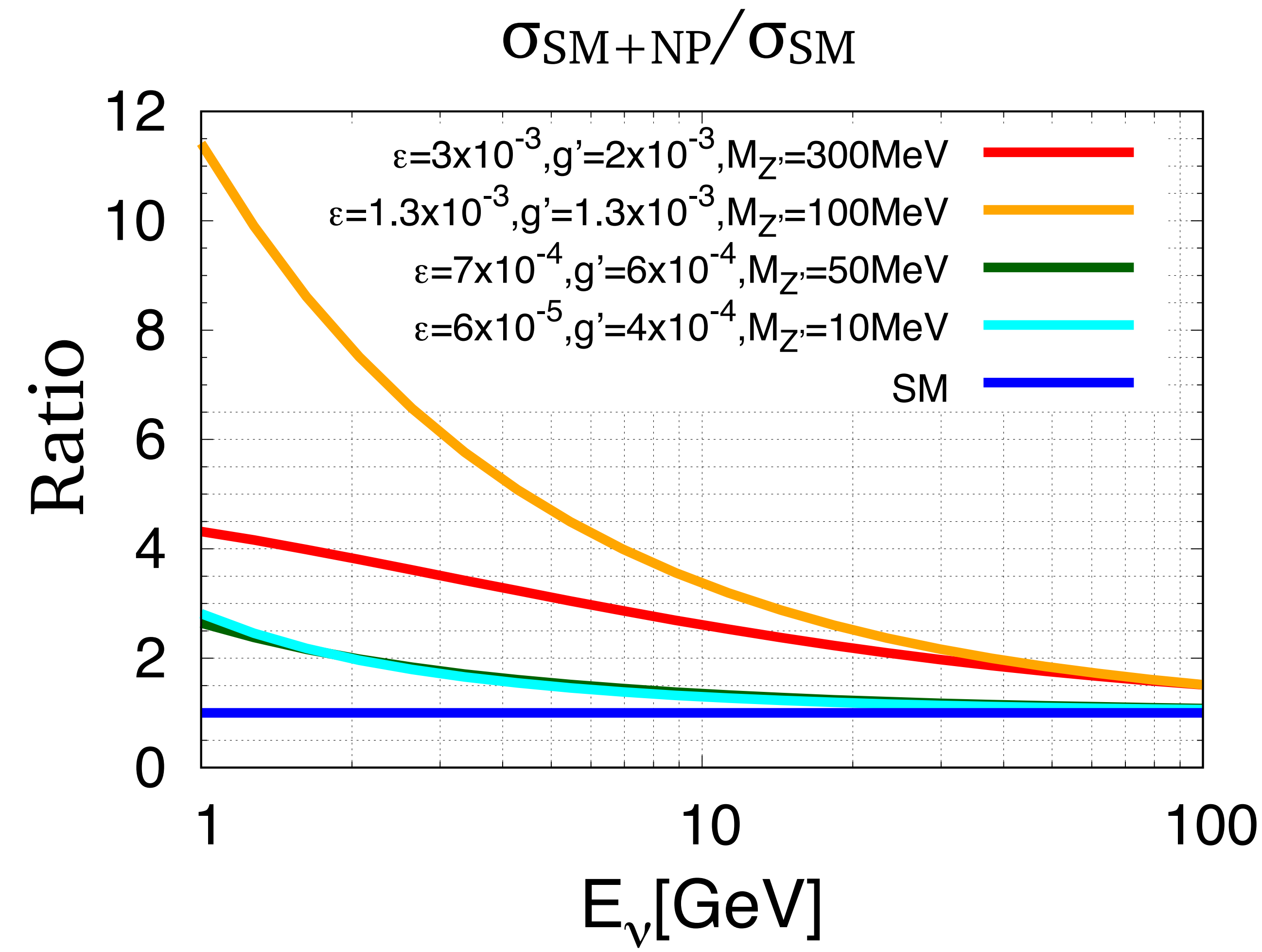
Araki, Kaneko, Ota, Sato, T.S, PRD93 (2016)



IceCube and $(g\text{-}2)_\mu$ can be explained

Energy dependence of Neutrino Trident Prod. Cross Section





The lower energy of neutrinos has smaller cross sections

The lower energy of neutrinos is more sensitive to NP.

cf

$$\sigma_{CC}/E_\nu \sim 10^{-38}\ \mathrm{cm^2 GeV^{-1}}$$