KAVLI IPMU
東京大学 国際高等研究所 カブリ数物連携宇宙研究機構
KAVLI INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

NEUTRINO TRIDENT PRODUCTION

A SHORT REVIEW

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CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

SCIENCE WITHOUT BORDERS

Outline

Intro

Neutrino trident scattering cross section

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Measurement in neutrino experiments (past, present and future)

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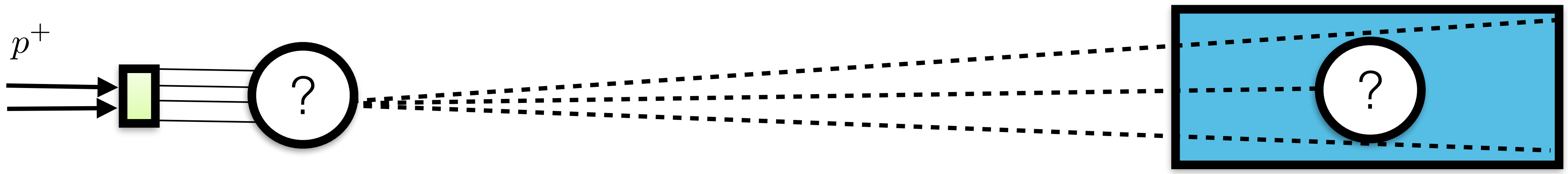
Neutrino trident scattering cross section

Measurement in neutrino experiments (past, present and future)

New physics
Z's and other sources of multi-lepton signatures

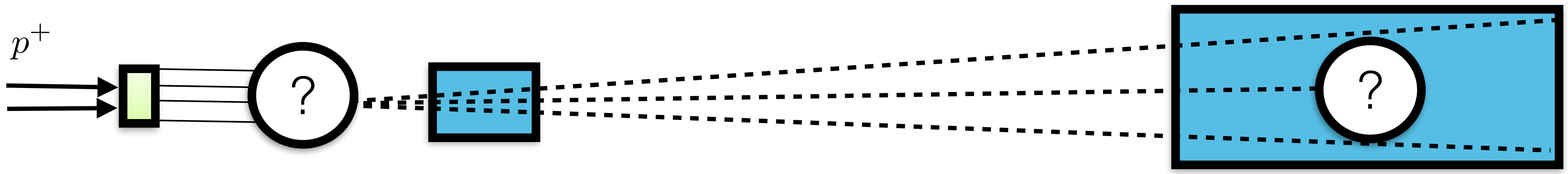
Oscillation experiments — precision era



Flux uncertainties are large
(hadro-production and focusing)
> 8% at the NuMI beam

Neutrino-nucleus cross sections:
nuclear physics + lack of data

Oscillation experiments — precision era



Flux uncertainties are large
(hadro-production and focusing)
> 8% at the NuMI beam

Neutrino-nucleus cross sections:
nuclear physics + lack of data

Beating systematics for precision on oscillation → Near detectors

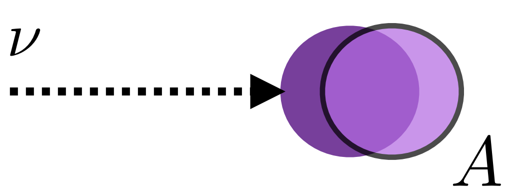
Typically $> 10^5$ interactions

Physics of the 70-90's… but harder.
(GeV neutrino energies/nuclear targets/precision)

Neutrino interactions

CEvNS

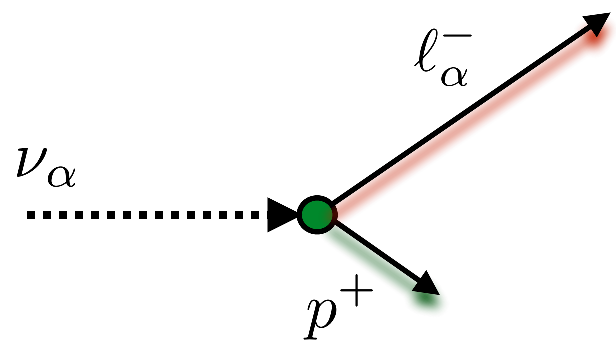
- Large cross section
- NC only
- Low energy recoil



$\sim 10^{-38}\ \mathrm{cm}^2$

Neutrino-nucleon

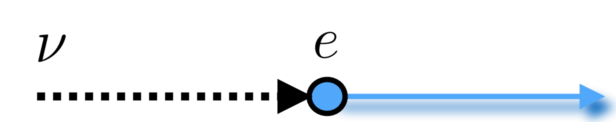
- Large statistics
- CC and NC on event-by-even
- Nuclear effects



$\sim 10^{-38}\ \mathrm{cm}^2$

Neutrino-electron

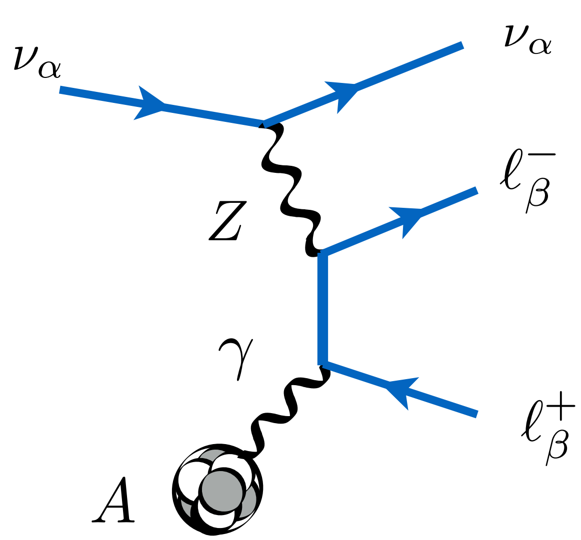
- Low statistics
- NC or NC+CC
- Fundamental couplings



$\sim 10^{-41}\ \mathrm{cm}^2$

- Weak force in isolation
- Small G_F — sensitive to light new physics

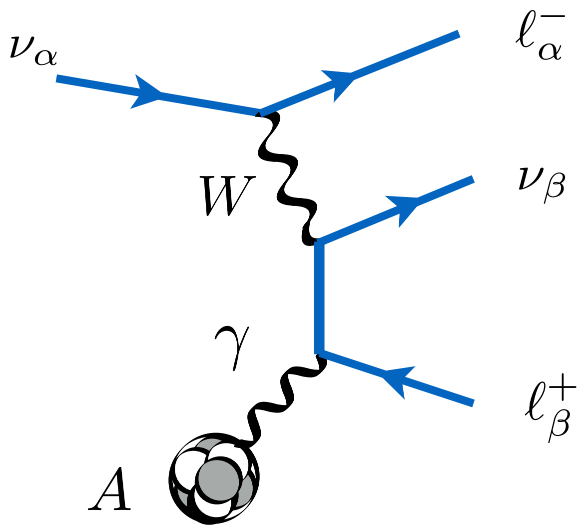
Neutrino trident production



Neutrino trident production/scattering:

Neutrino charged lepton production in the Coulomb field of a nucleus*.

$$\sim 10^{-44}\ \mathrm{cm}^2$$



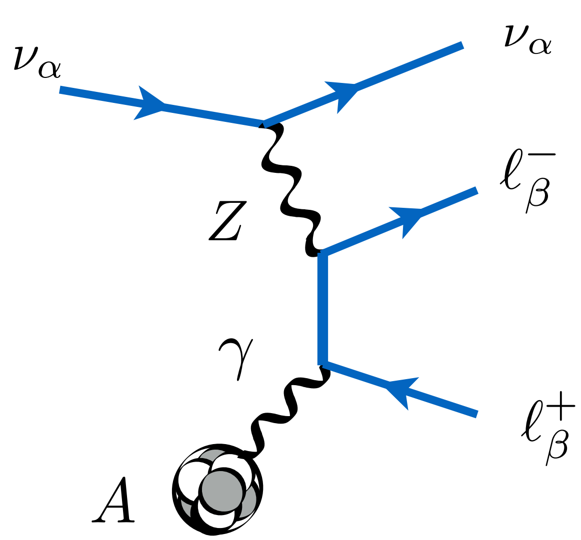
why?

1) Sensitive to neutrino interactions with the charged-leptons.

2) Well understood cross section with distinct final state.

* Usually extended to include contributions from nucleons and quarks.

Neutrino trident production



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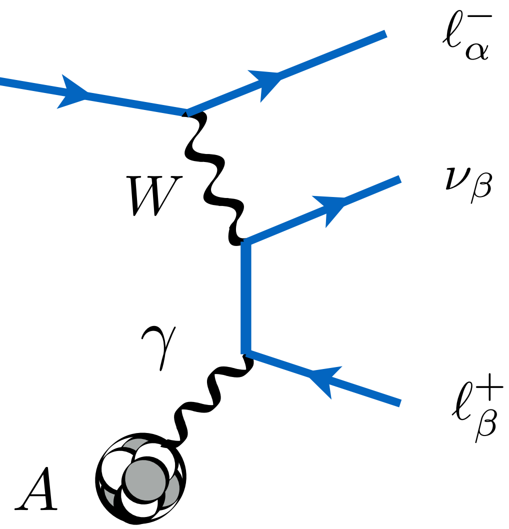


Very crude approximation for the total cross section:

$$\sigma_\Psi \approx (g_V^2 + g_A^2) \frac{Z^2 \alpha^2 G_F^2}{9\pi^3} \log\left(\frac{2E_\nu \Lambda_{\rm QCD}}{4 m_\ell^2 A^{1/3}}\right) \frac{2E_\nu \Lambda_{\rm QCD}}{A^{1/3}}$$

Channel	SM Contributions	g_V	g_A
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	CC, NC	$1/2 + 2s_{\rm w}^2$	$1/2$
$\nu_\mu \to \nu_\mu e^+ e^-$	NC	$-1/2 + 2s_{\rm w}^2$	$-1/2$
$\nu_\mu \to \nu_e e^+ \mu^-$	CC	1	1

$$\frac{(g_V^2 + g_A^2)_{\rm CC+NC}}{(g_V^2 + g_A^2)_{\rm CC}} \approx 0.60 \longrightarrow \text{NC+CC destructive interference.}$$

Old history

V-A theory

Total cross section calculation within V-A theory — W. Czyz et al, 1964 (Nuovo Cim. 34 404-435)

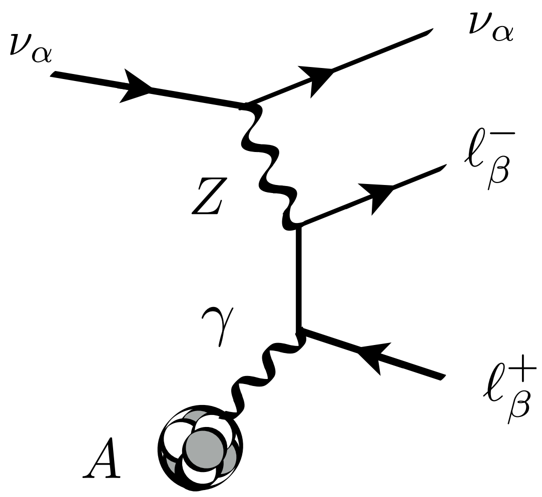
Kinematical distributions — J. Lovseth et al, 1971 Phys.Rev. D3 2686-2706; K. Fujikawa, 1971 Annals Phys. 68 102-162

Sensitive to CC and NC interference in the SM

Complete calculation in the (early stages of) SM — R.W. Brown et al, 1972 (Phys. Rev. D 6, 3273)

This was the goal of HE neutrino experiments in the 80's and 90's

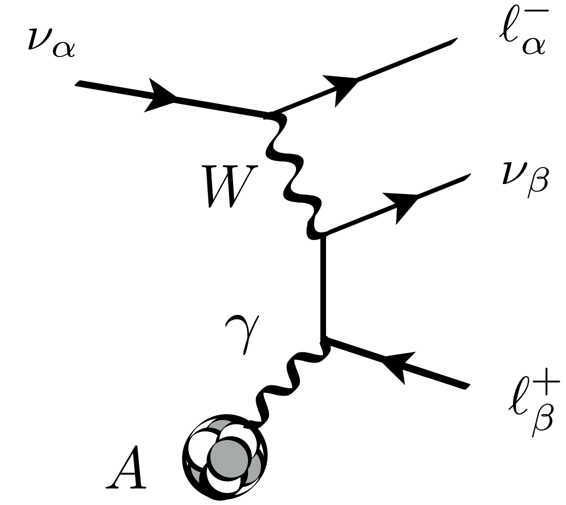
Standard Model contributions



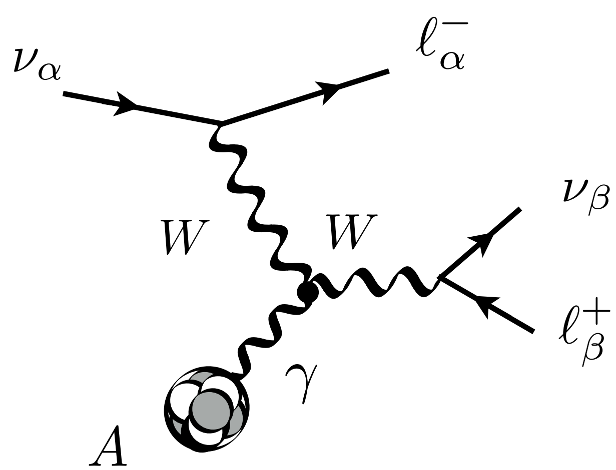
\+ crossed boson lines

Z exchange boson lines

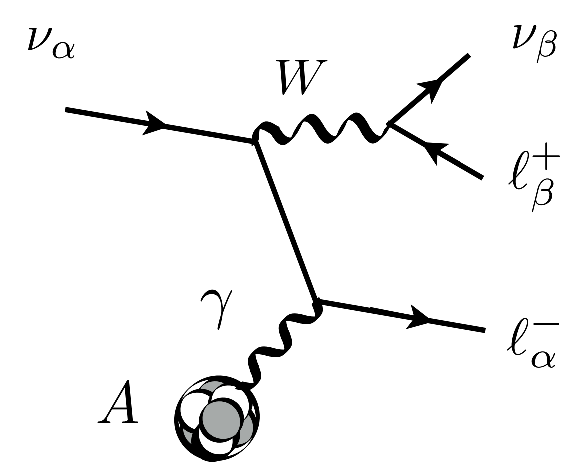
—Bethe-Heitler resembling photon pair production—



W exchange

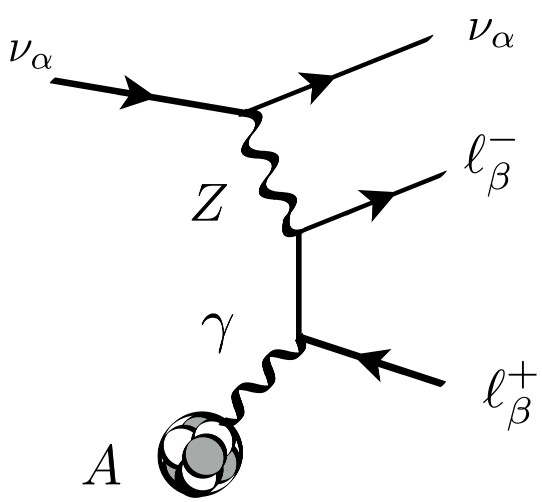


Triple gauge boson coupling
(order M_W^4)

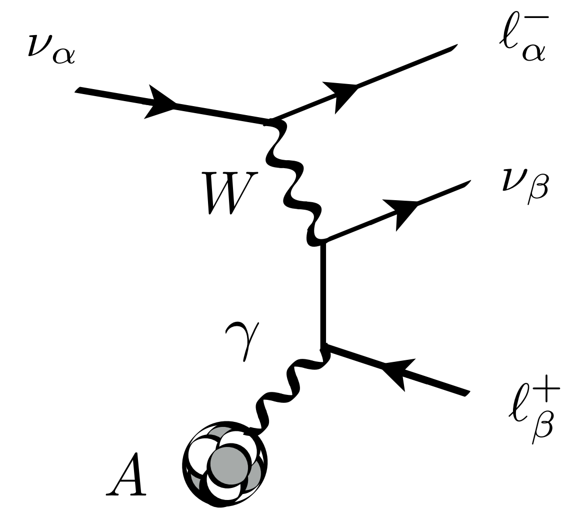


W radiation

Standard Model contributions

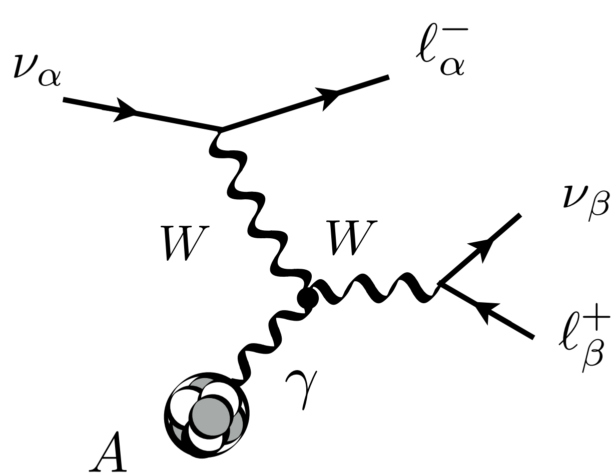


+ crossed boson lines

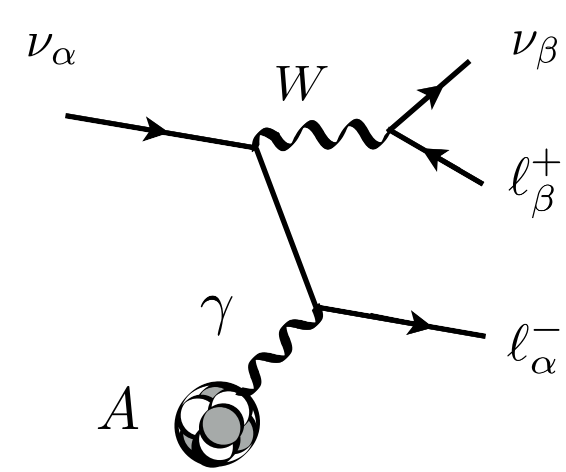


Z exchange boson lines
—Bethe-Heitler resembling photon pair production—

W exchange



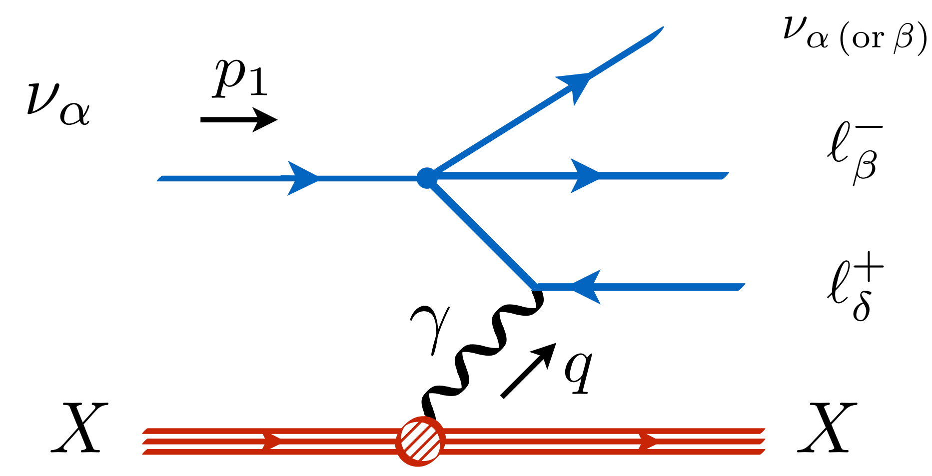
Resonant at high energies



Triple gauge boson coupling
(order M_W^4)

W radiation

Process in coherent, diffractive or DIS limit:



$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_X^2)^2}\frac{H_X^{\mu\nu}L_{\mu\nu}}{Q^4}$$

where $\hat{s} = 2\,(p_1\cdot q)$ and $Q^2 = \sqrt{-q^2}$.

Universal leptonic T and L cross sections.

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

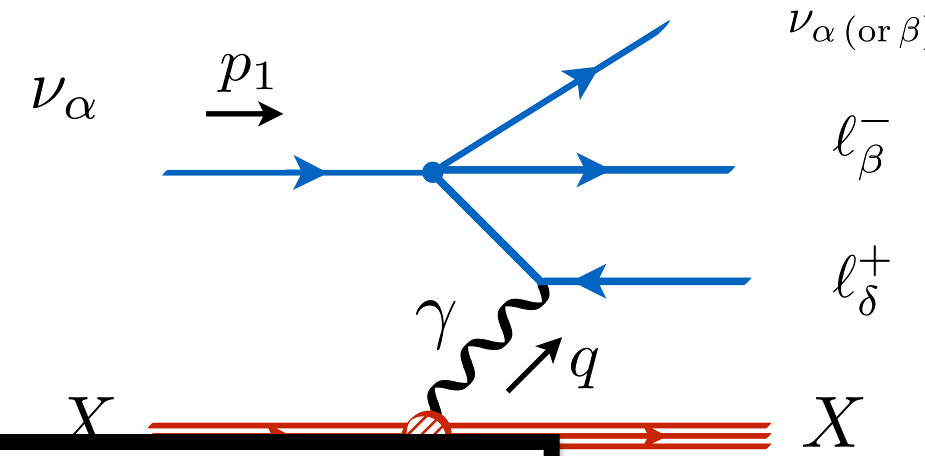
T and L photon flux function (**target** and **regime** dependent)

*On-shell photon (EPA or Weiszacker-Williams) is a bad approximation at LE (factors of 2 or 3 difference — unsuitable for diffractive scattering)

P. Ballett et al, JHEP 1901 (2019) 119.

Low energy cross sections

Process in coherent, diffractive or DIS limit:



$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_X^2)^2}\frac{H_X^{\mu\nu}L_{\mu\nu}}{Q^4}$$

where $\hat{s} = 2\,(p_1 \cdot q)$ ar

Well understood process.

Electromagnetic nuclear form factors

+

fundamental neutrino-lepton scattering

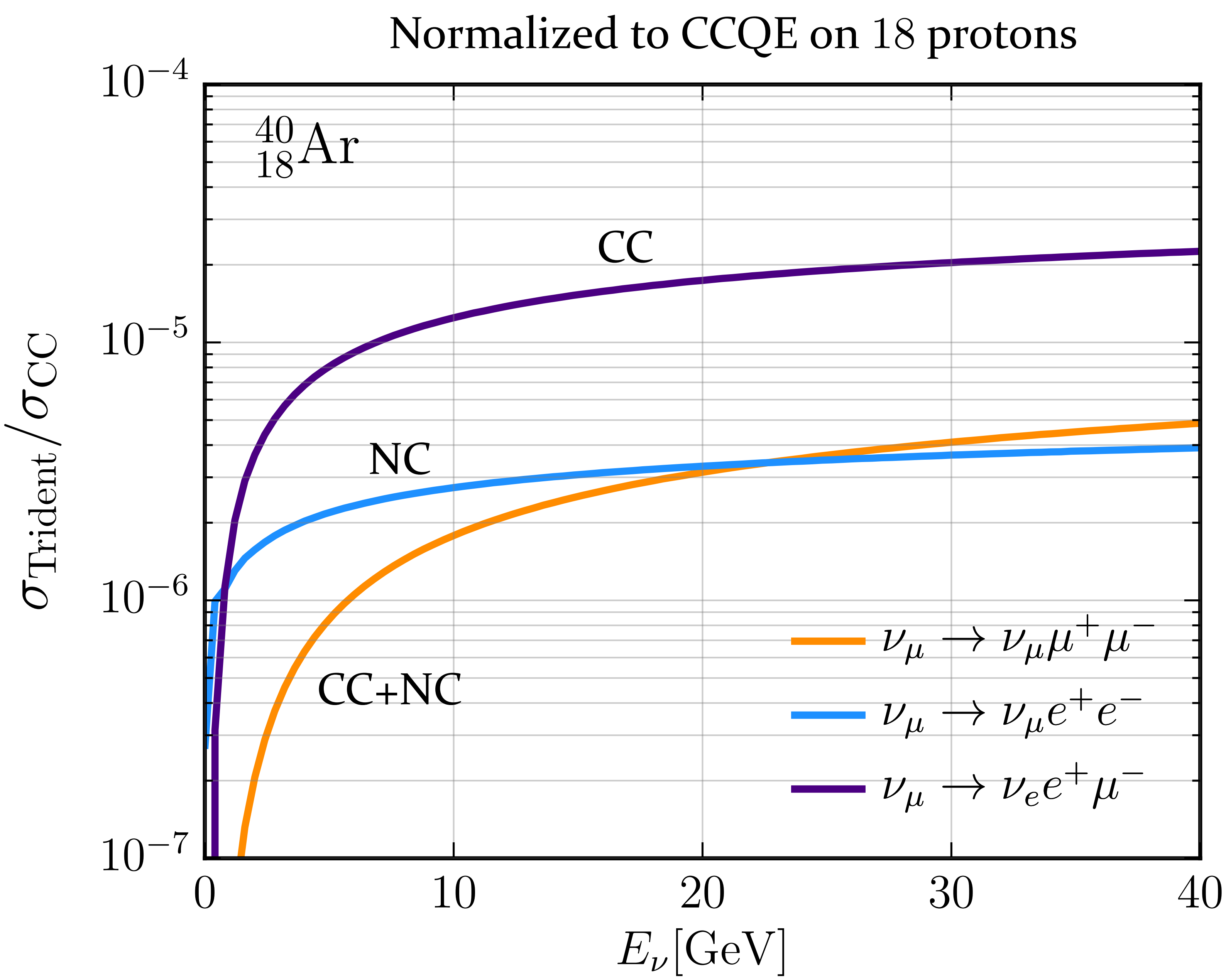
$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} =$$

T and L photon flux function (**target** and **regime** dependent)

*On-shell photon (EPA or Weiszacker-Williams) is a bad approximation at LE
(factors of 2 or 3 difference — unsuitable for diffractive scattering)

P. Ballett et al, JHEP 1901 (2019) 119.

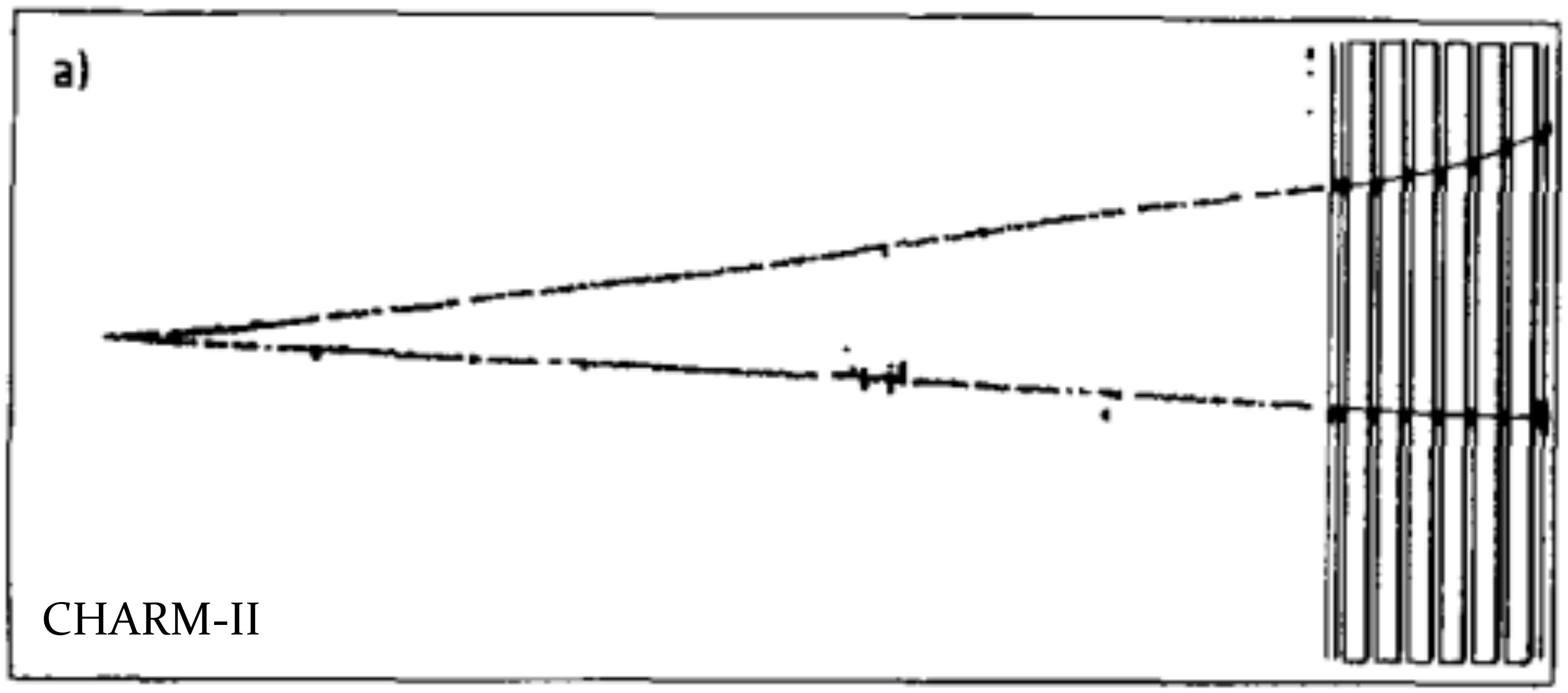
Cross sections



Need > 10^6 CCQE events to join the game at LE.

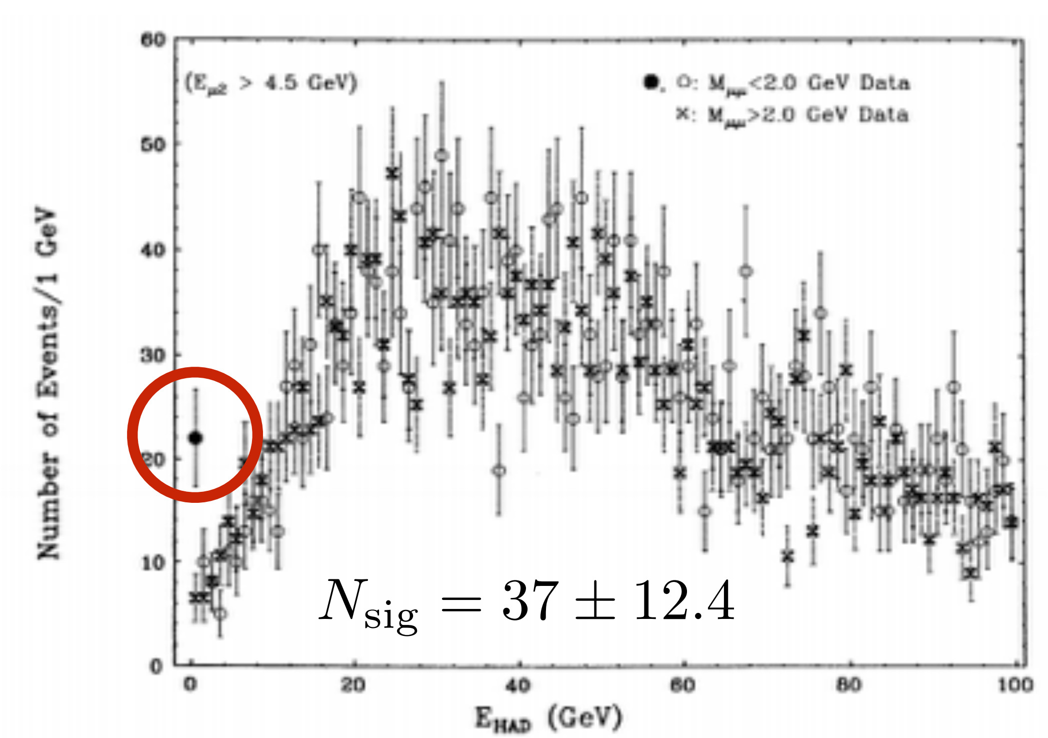
Production of taus is very small… not visible in the plot. If q is large, three propagator suppression.

Measurements



CCFR

Lab E detector at FNAL

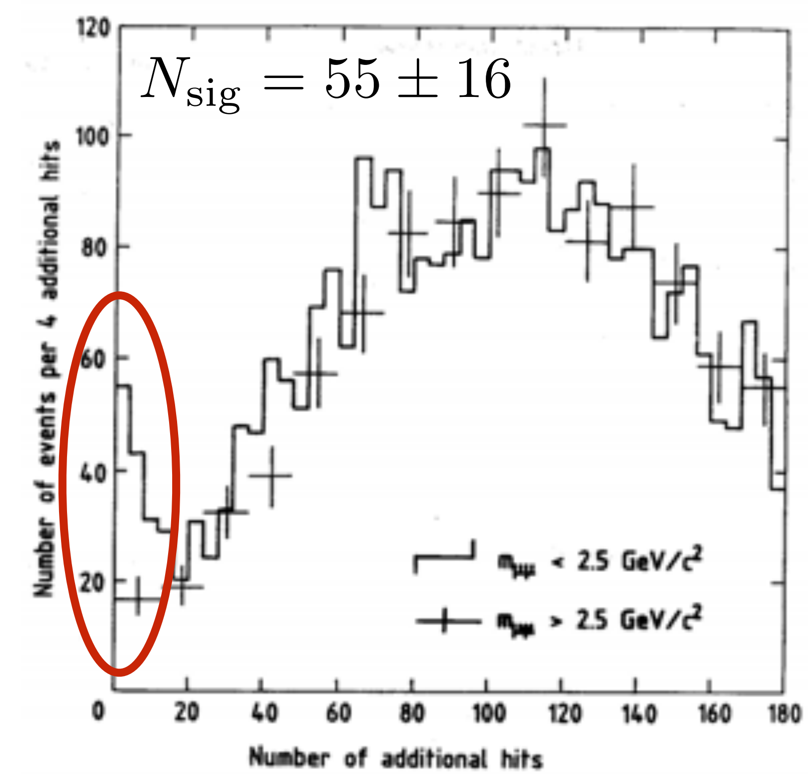


$$\langle E_\nu \rangle = 160 \text{ GeV}$$

$$\frac{\sigma_{\rm CCFR}}{\sigma_{\rm SM}} = 0.82 \pm 0.28$$

CHARM-II

WANF beam (CERN)



$$\langle E_\nu \rangle = 25 \text{ GeV}$$

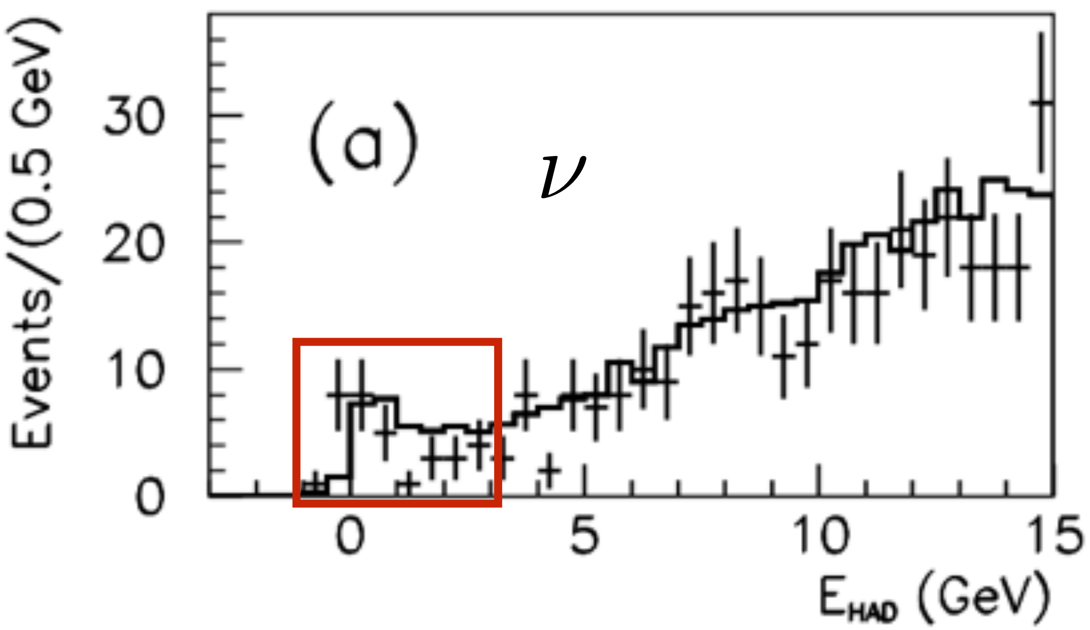
$$\frac{\sigma_{\rm CHARM-II}}{\sigma_{\rm SM}} = 1.58 \pm 0.57$$

Phys. Rev. Lett. 66, 3117 (1991).

Phys. Lett. B 245, 271 (1990)

Dimuon

NuTeV
Lab E detector at FNAL

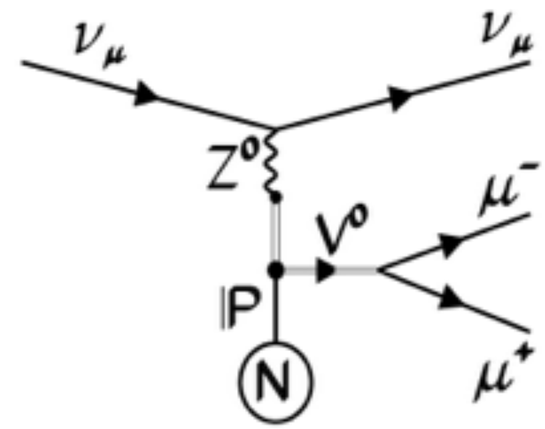


$$\langle E_\nu \rangle = 160 \text{ GeV}$$

$$\frac{\sigma_{\text{NuTeV}}}{\sigma_{\text{SM}}} = 0.72^{+1.73}_{-0.72}$$

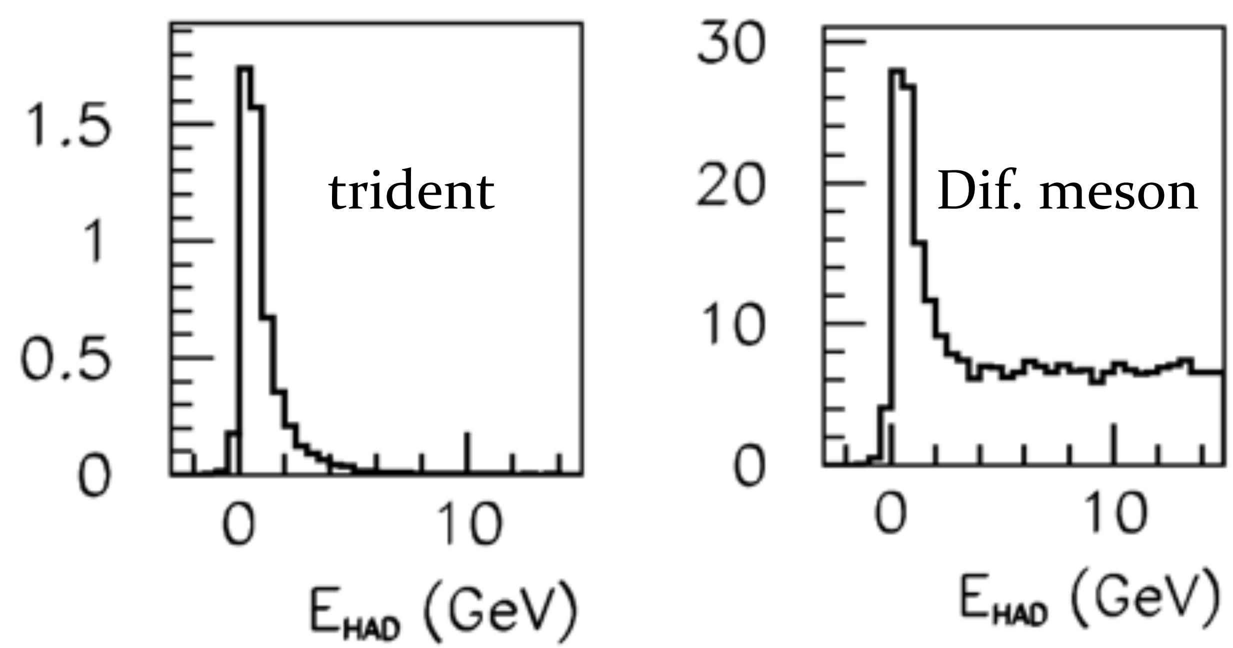
Inconclusive

Phys. Rev. D 61, 092001 (2000)



Diffractive vector meson contribution.

NuTeV MC



See discussion in
G. Krnjaic, arXiv:1902.07715

Other channels

Coherent-like production of

$$e^+e^- \qquad\qquad \mu^\pm e^\mp$$

Not yet observed or even searched for!

Challenging because of **PID** and **backgrounds**.

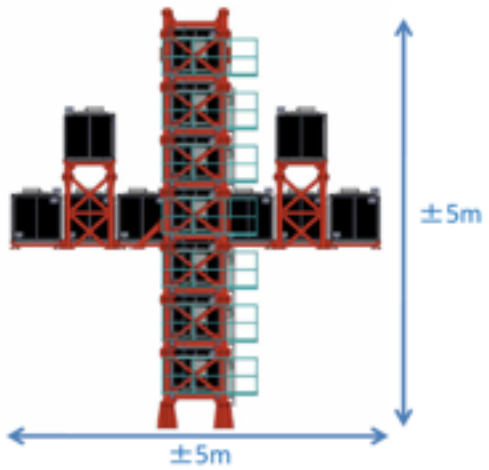
With new technology and large rates in current and future neutrino experiments we should consider these again.

G. Magill et al, Phys. Rev. D 95

Dilepton production in neutrino experiments is old physics, but trident is unique.

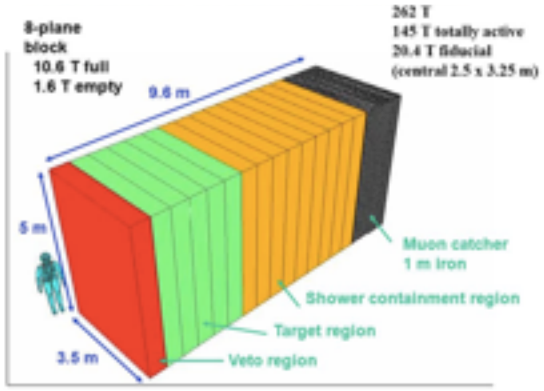
Present

INGRID

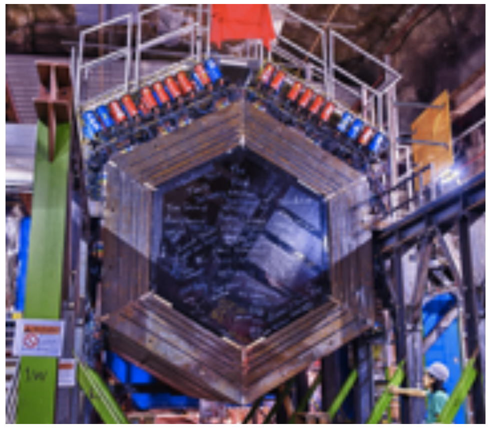


MINOS/+

NOvA



MINERvA



Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total e$^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)

100% efficiencies. Detector capability is the name of the game.

Future

Channel	SBND	μBooNE	ICARUS	DUNE ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)
	2	0.1	0.2	692 (530)
Total e^+e^-	6	0.4	0.7	1007 (800)
	0.7	0.0	0.1	143 (111)
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)
	0.4	0.0	0.0	196 (147)

Hyper-K? ND

Why is it hard?

Dilepton production is rare, usually alongside heavy resonances and had. E, but...

PID $\begin{cases} \mu^\pm/\pi^\pm \\ e^\pm/\gamma \end{cases}$

$\underline{\mu^+\mu^-}$

$\mathrm{CC}1\pi^\pm$ misID $\pi^\pm$.

$\underline{e^+e^-}$

$\mathrm{NC}1\pi^0$ and $\nu_e\mathrm{CC}\pi^0$.

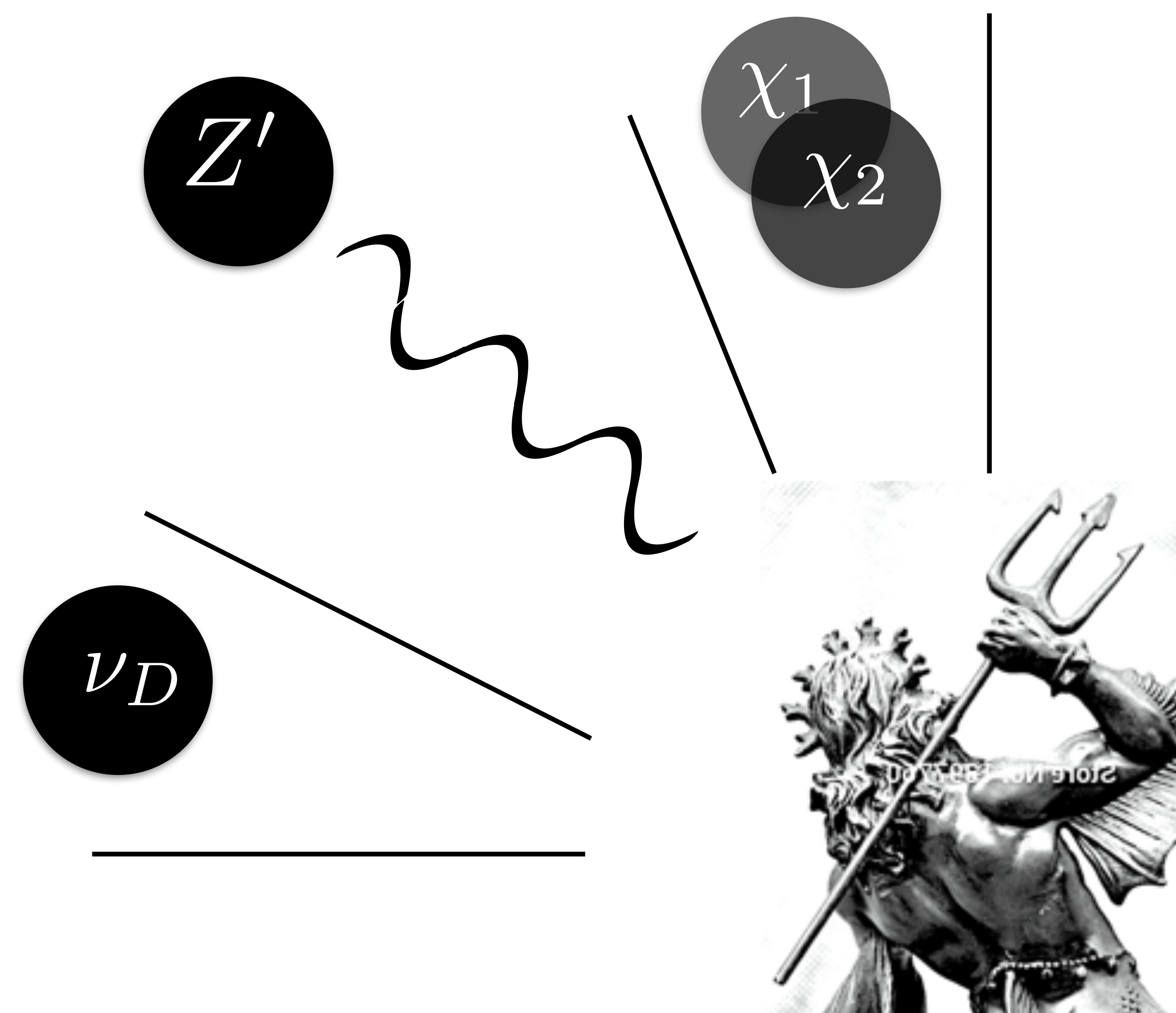
Even if misID is few %, there are just too many, we have to rely on kinematics.

$\underline{e^+\mu^-}$

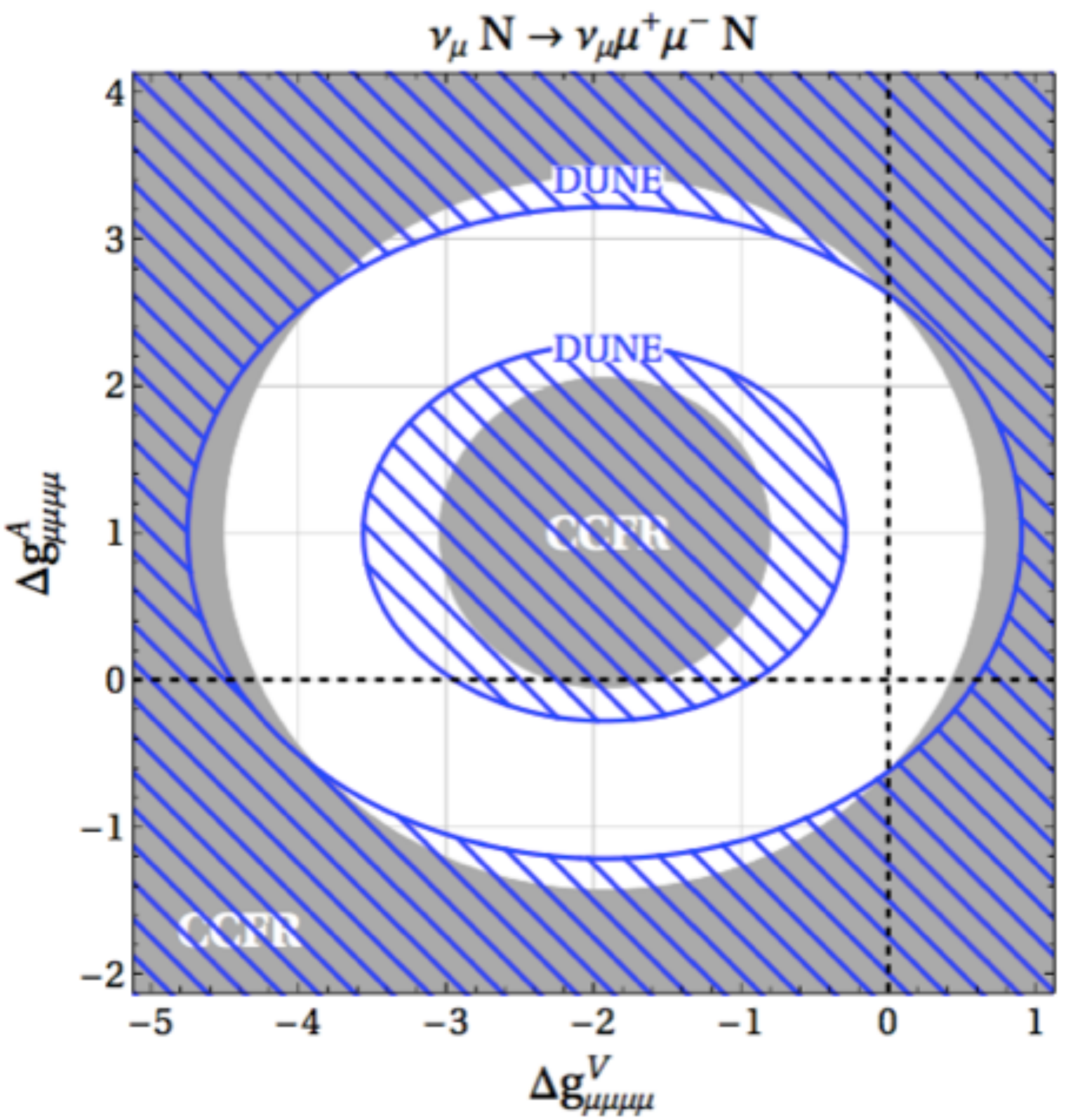
$\mathrm{CC}1\pi^0$ with misID γ .

See P. Ballett et al, JHEP1901(2019)119 for preliminary analysis in LAr for all channels
W. Altmannshoffer et al, arXiv:1902.06765 for more sophisticated dimuon projection in DUNE.

Smiting New Physics



Precision physics?



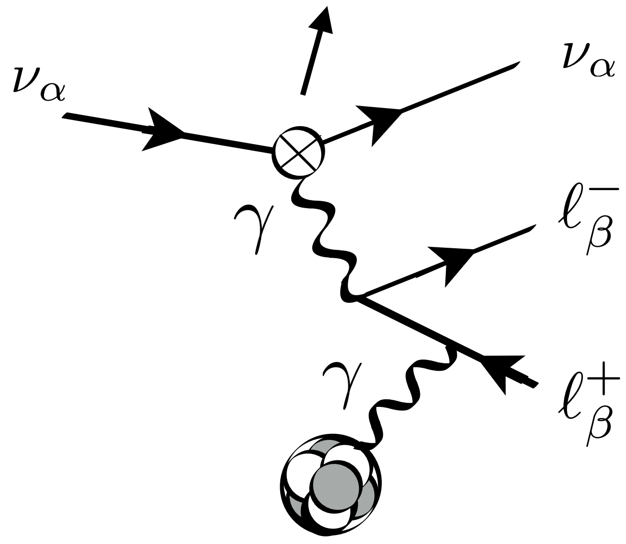
$$2g_V = 1 + 4\sin^2\theta_W + \Delta g^V_{\mu\mu\mu\mu} \qquad -2g_A = -1 + \Delta g^A_{\mu\mu\mu\mu}$$

W. Altmannshoffer et al, arXiv:1902.06765

Neutrino magnetic moments

Large neutrino magnetic moments?

$$\mu_\nu \, \overline{\nu} \, \sigma_{\alpha\beta} \, \nu \, A^\alpha \, q^\beta$$



$\mu_{\nu_\mu} \lesssim 4.0 \times 10^{-8} \mu_{\rm B}$ according to the CCFR data,

M.I. Vysotsky et al., Phys.Atom.Nucl.65(2002)1634

Bound from dimuon at large energies, but EPA used and **energy dependence** not studied.

As of now, unlikely to beat neutrino-electron scattering bounds.

$L_\mu - L_\tau$ model

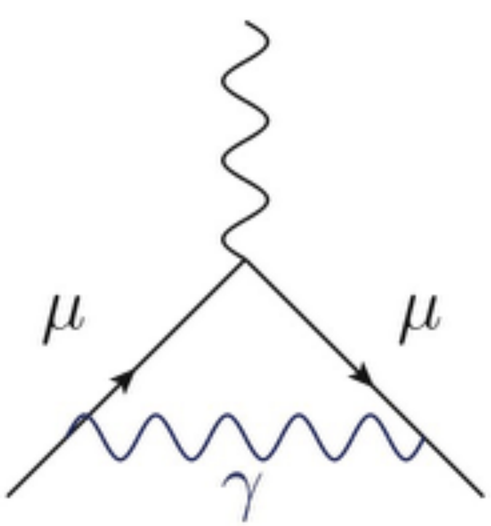
$$\text{SM} \times U(1)_{L_\mu - L_\tau}$$

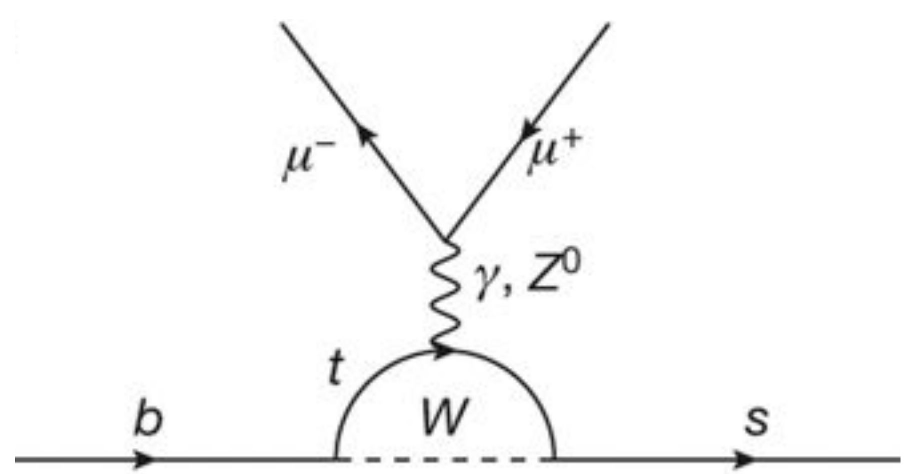
The model that revived the interest in dimuon tridents

W. Altmannshoffer et al, PRL113(2014)091801

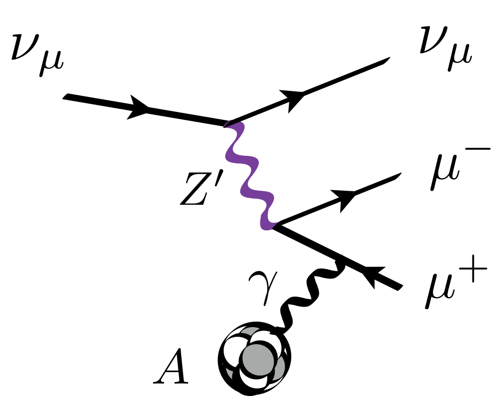
$$\mathscr{L}_{\text{int}} \supset g' Z'_\alpha \left(\overline{L}_\mu \gamma^\alpha L_\mu - \overline{L}_\tau \gamma^\alpha L_\tau + \overline{\mu}_R \gamma^\alpha \mu_R - \overline{\tau}_R \gamma^\alpha \tau_R \right)$$

Minimal **anomaly-free** extension that:
— can explain the muon (g-2) discrepancy.
— contains lepton non-universality (easily related to flavour anomalies in LHCb)
— allows to reproduce neutrino mixing data





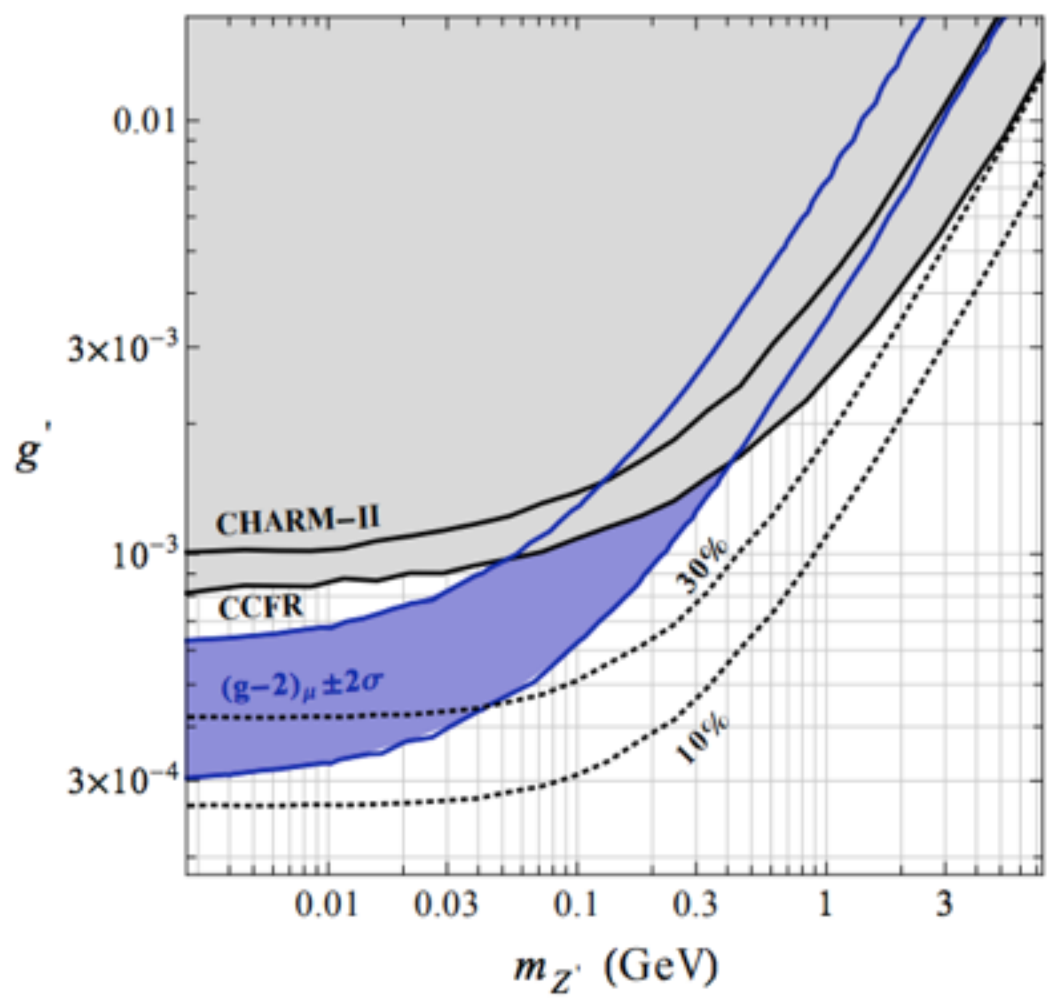
$L_\mu - L_\tau$ model



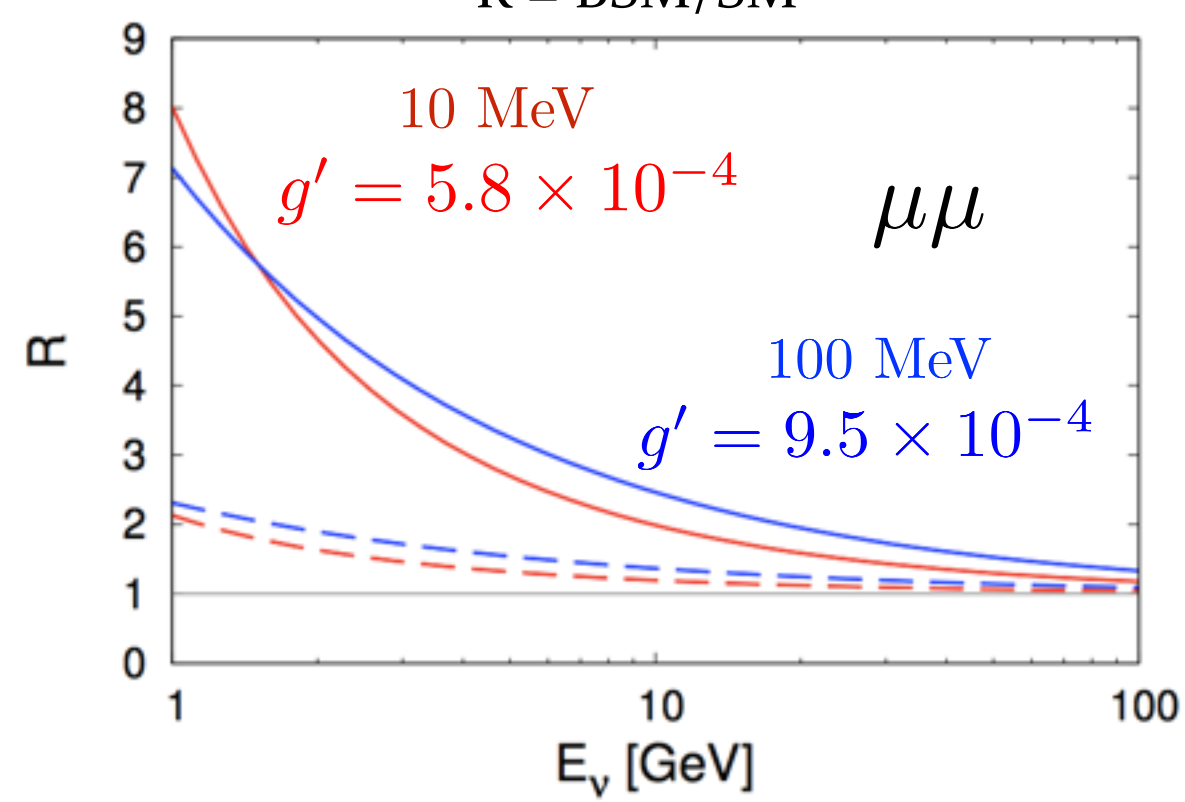
$$\text{SM} \times U(1)_{L_\mu - L_\tau}$$

The model that revived the interest in dimuon tridents

Measurement at low energies more sensitive



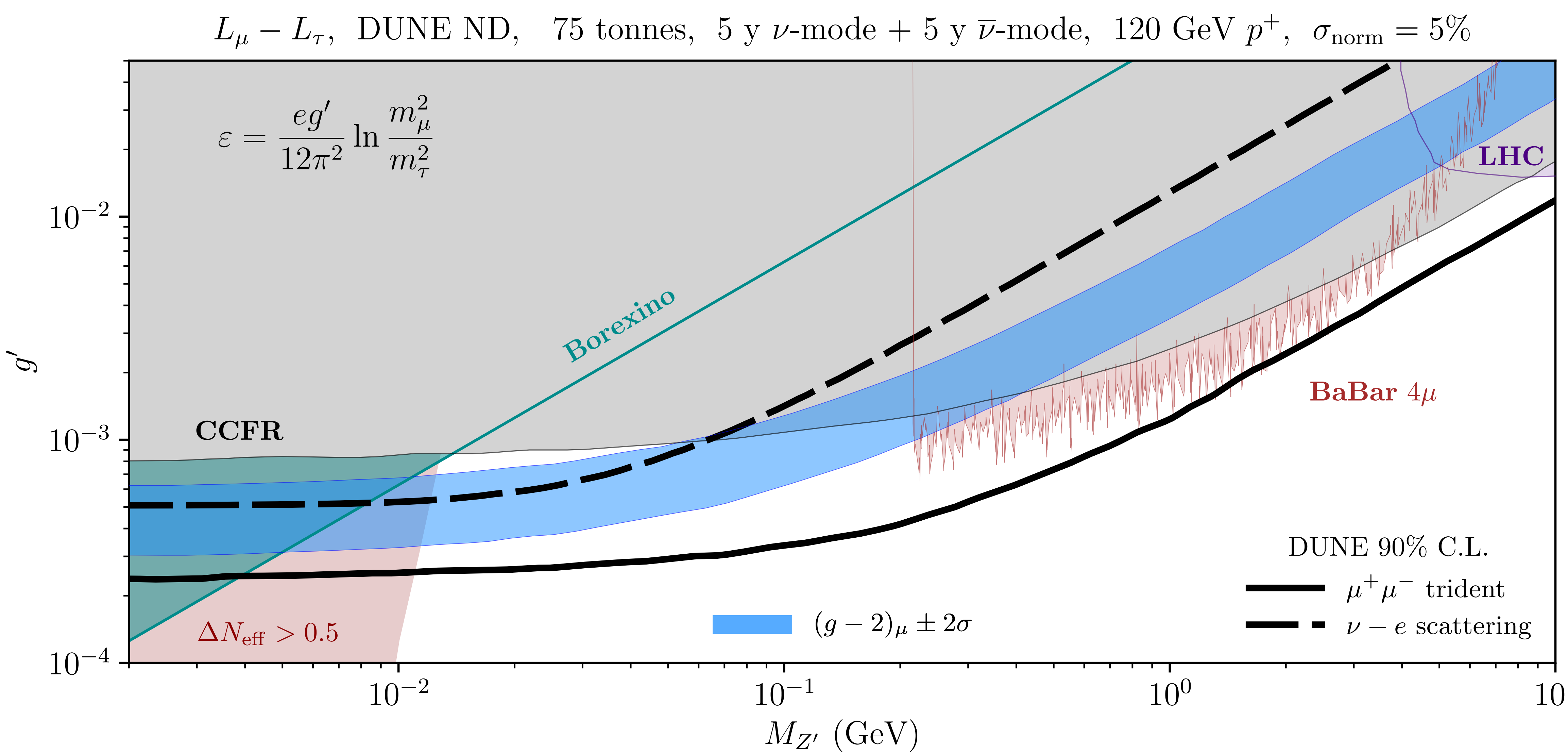
R = BSM/SM



W. Altmannshoffer et al, PRL113(2014)091801

Y. Kaneta et al, PTEP 2017 (2017) no.5, 053B04

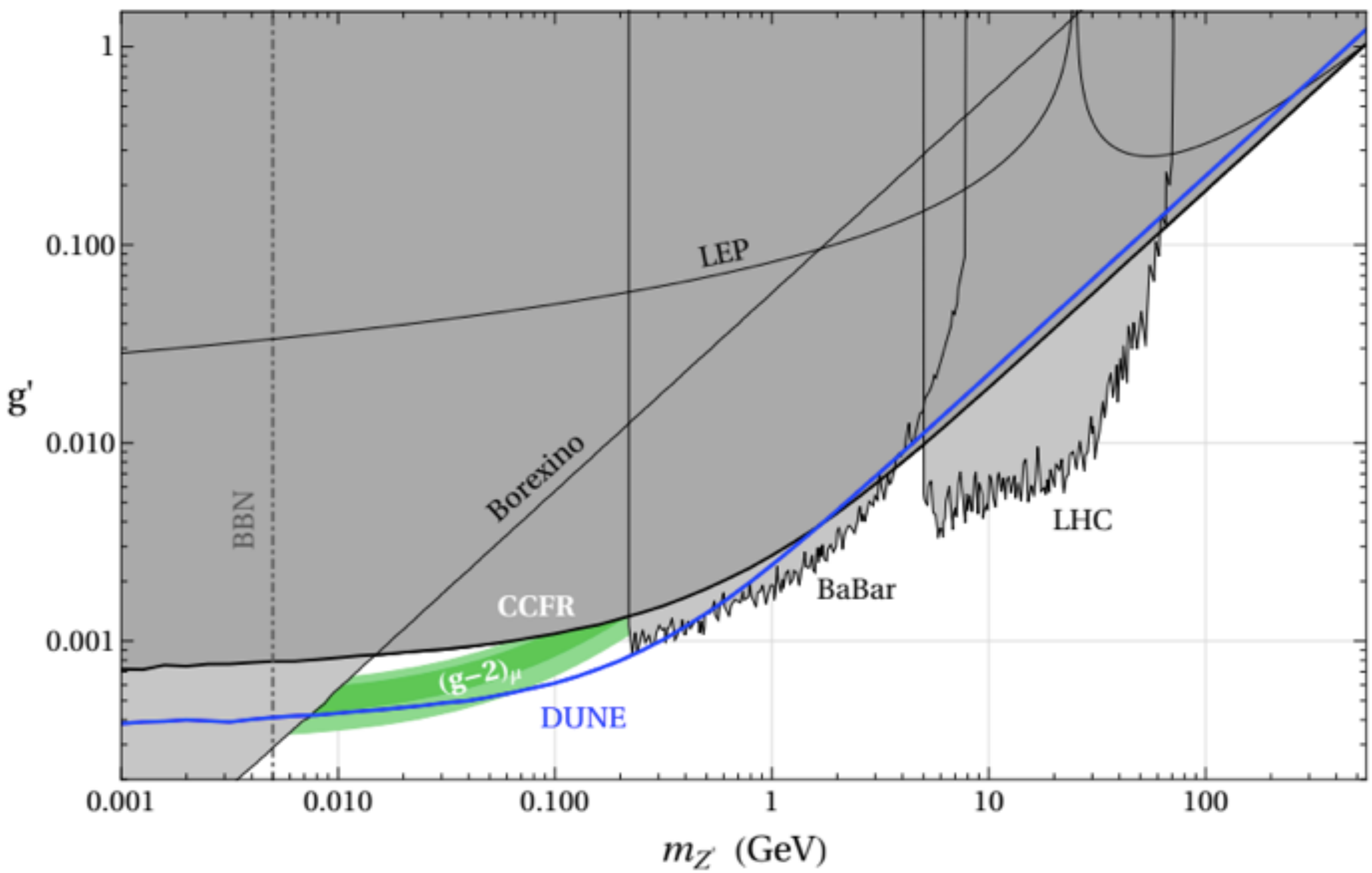
DUNE



No backgrouds, but kin. cuts on signal, eg. $\theta_{\mu\mu} < 20^\circ$

P. Ballett et al, arXiv:1902.08579

DUNE



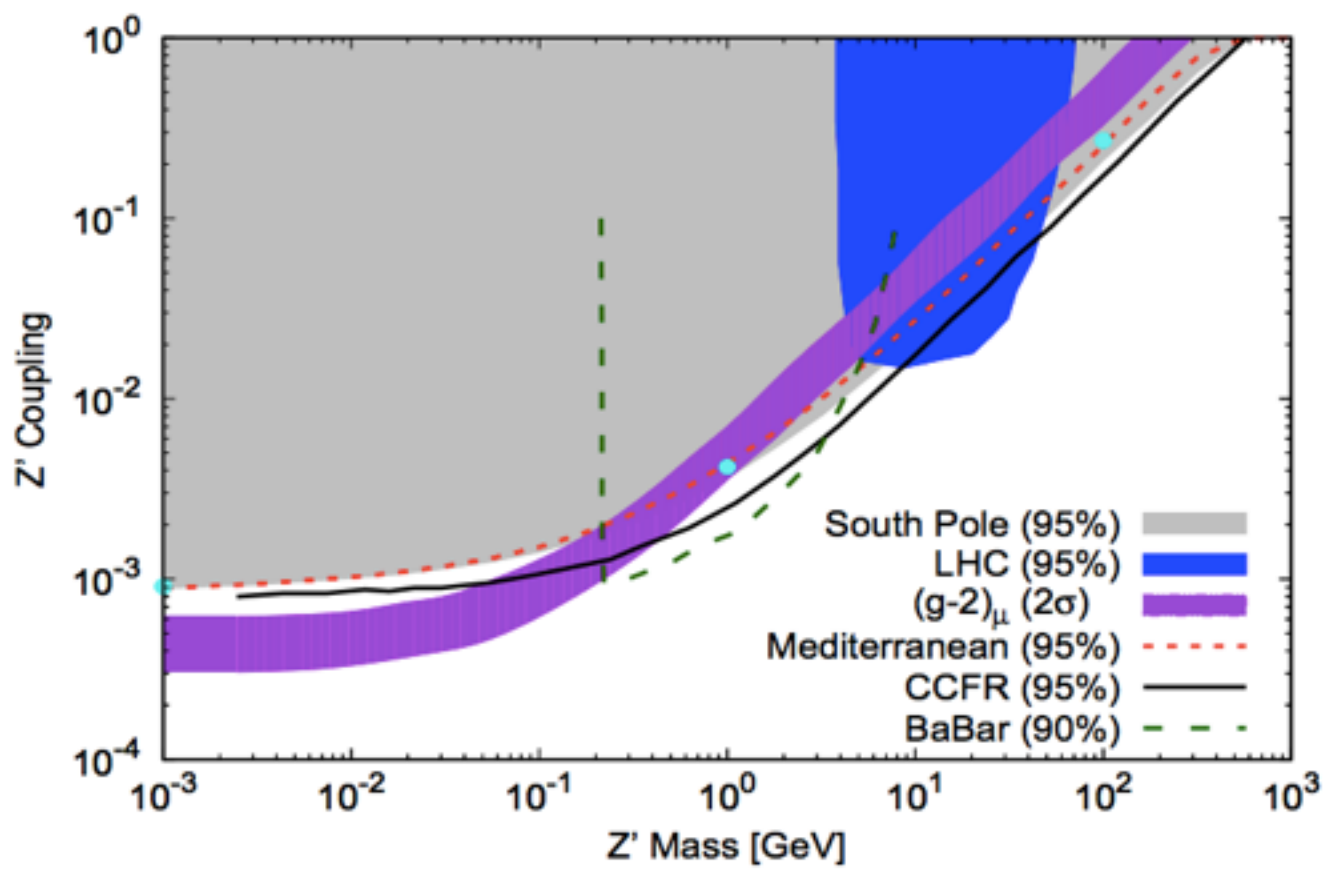
Backgrounds: $S/\sqrt{B} \sim 1.6$ per year, 25% measurement in ~ 6.5 years.

Tight kin. cuts (eg. $\theta_{\mu\mu} < 5^\circ$). Reducing pion misID can loosen it

W. Altmannshoffer et al, arXiv:1902.06765

Atmospheric neutrinos in the game

Trade off between # of events and BSM enhancement.



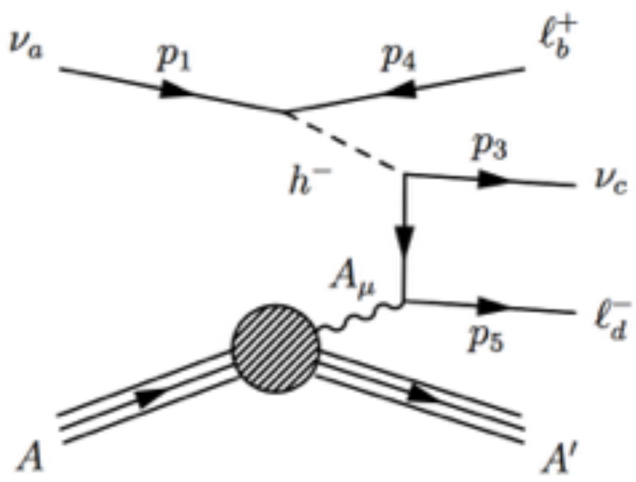
Total SM rate expected in 10 years:

7.4 (17, 63) at PINGU (DeepCore, IceCube)
16 (23) at ORCA (ARCA)

SF. Ge et al, PLB772(2017)164-168

Code available at:
https://gitlab.com/gesf/NuTrident_CompHEP

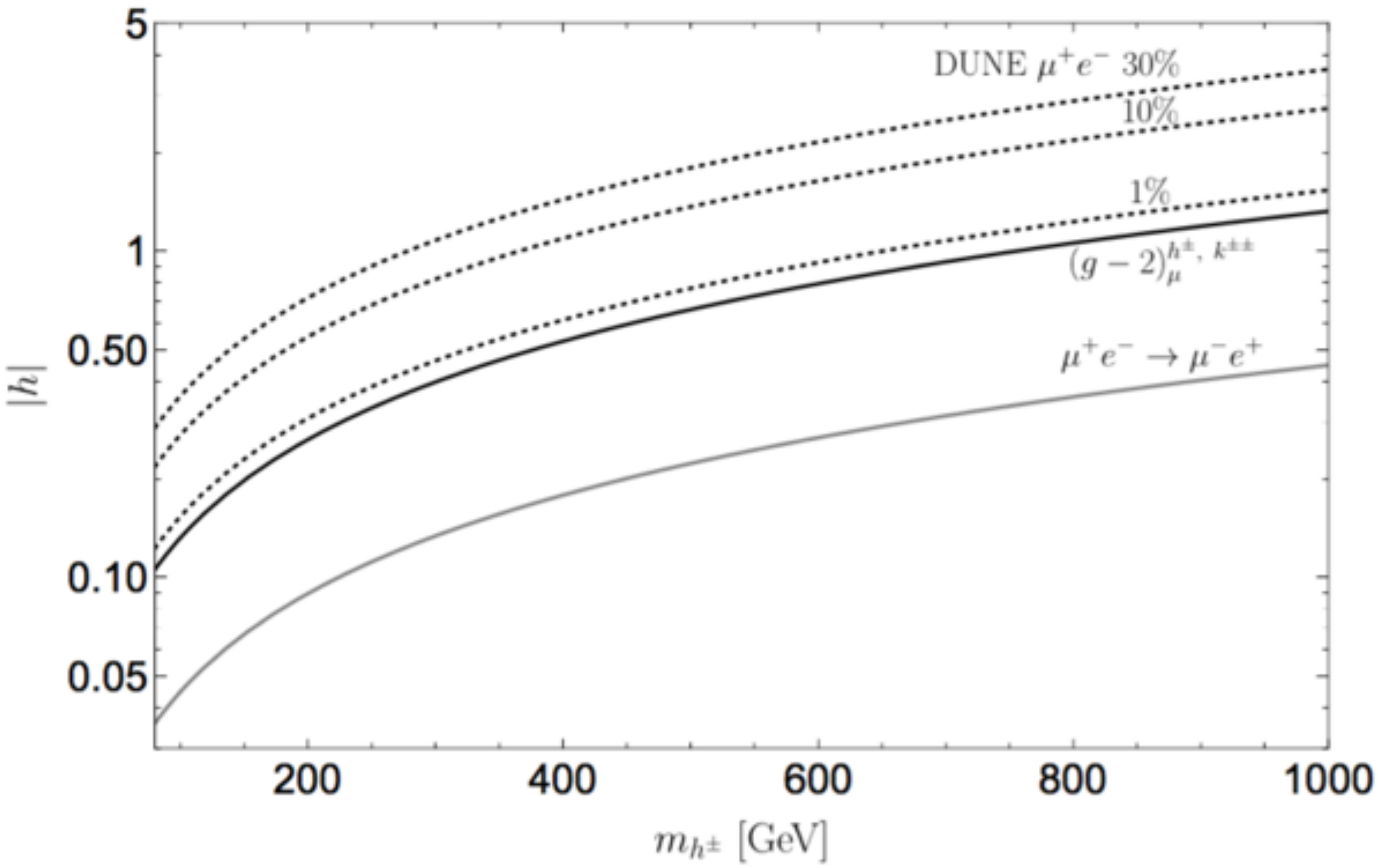
New physics in charge-current channels



G. Magill et al, PRD97 (2018)no.5,055003

Much harder — new physics more easily constrained otherwise.

$$\mathcal{L} \supset |\partial_\mu h|^2 - m_h^2 |h|^2 + \sqrt{2} h_{ab} \nu^a \ell^b h + k_{ab} \ell^a \ell^b k + c.c.$$

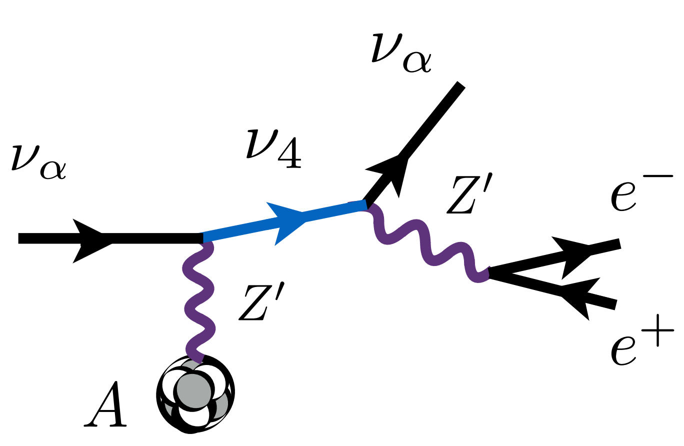


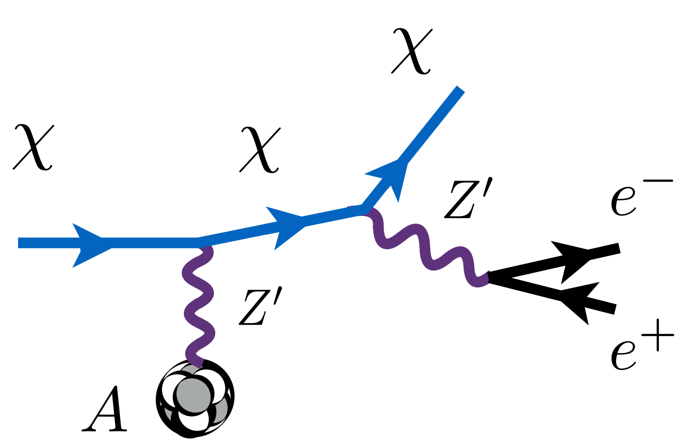
...but more data cannot harm!

Dielectron signatures

New forces that talk directly to electrons are can be bounded by neutrino-electron scattering data.

However, BSM e^+e^- signature still arise.





Dark neutrinos (U'(1) charged heavy neutrinos)
— MiniBooNE explanation
— Neutrino mass generation at low scales

E. Bertuzzo et al, PRL121.241801
P. Ballett et al, arXiv:1808.02915
P. Ballett et al, arXiv:1903.07589

Light DM (+ Inelastic DM)
— produced in the beam
— scattering or decay signature

E. Izaguirre, PRD96(2017)no.5, 055007
A. de Gouvea et al, JHEP1901(2019)001

Dielectron signatures

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However, BSM e^+e^- signature still arise.

ν_α χ

ν_α e^-

A e^+

Early days of a new kind of signature

— Distinct signature to avoid BKGS

— No detailed experimental studies for such signatures yet (separation angle of e pair?)

Dark neutrin

— MiniBooN

— Neutrino mass generation at low scales

ic DM)

produced in the beam

— scattering or decay signature

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Conclusions

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We can study it again at the DUNE ND, but no need to wait (see MINERvA, T2K).

Beyond tridents, what else are neutrinos doing at the **per mille of a per mille level of CCQE?**

THANK YOU

APPENDIX

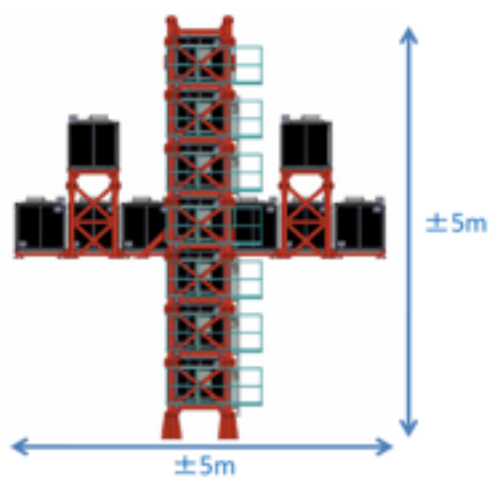
Coherent cross sections

SBND	110 m, 112 t	6.6×10^{20} P.O.T.
μBooNE	470 m, 89 t	13.2×10^{20} P.O.T.
ICARUS	600 m, 476 t	6.6×10^{20} P.O.T.

50 t LAr, assuming
$(2 + 2 \times 3) \times 1.83\text{e}21$ P.O.T.
in nu and nubar mode.

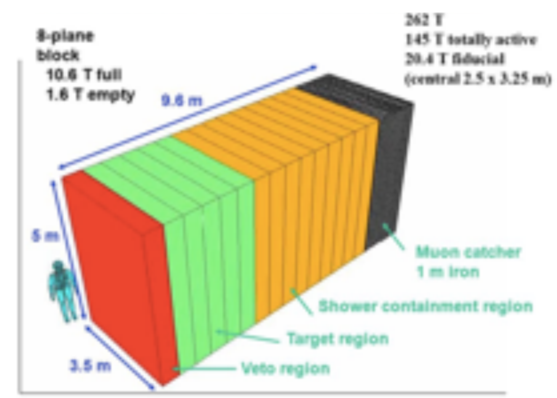
Coherent cross sections

INGRID

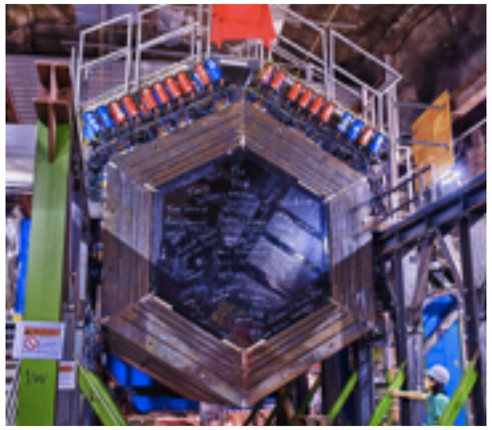


MINOS/+

NOvA



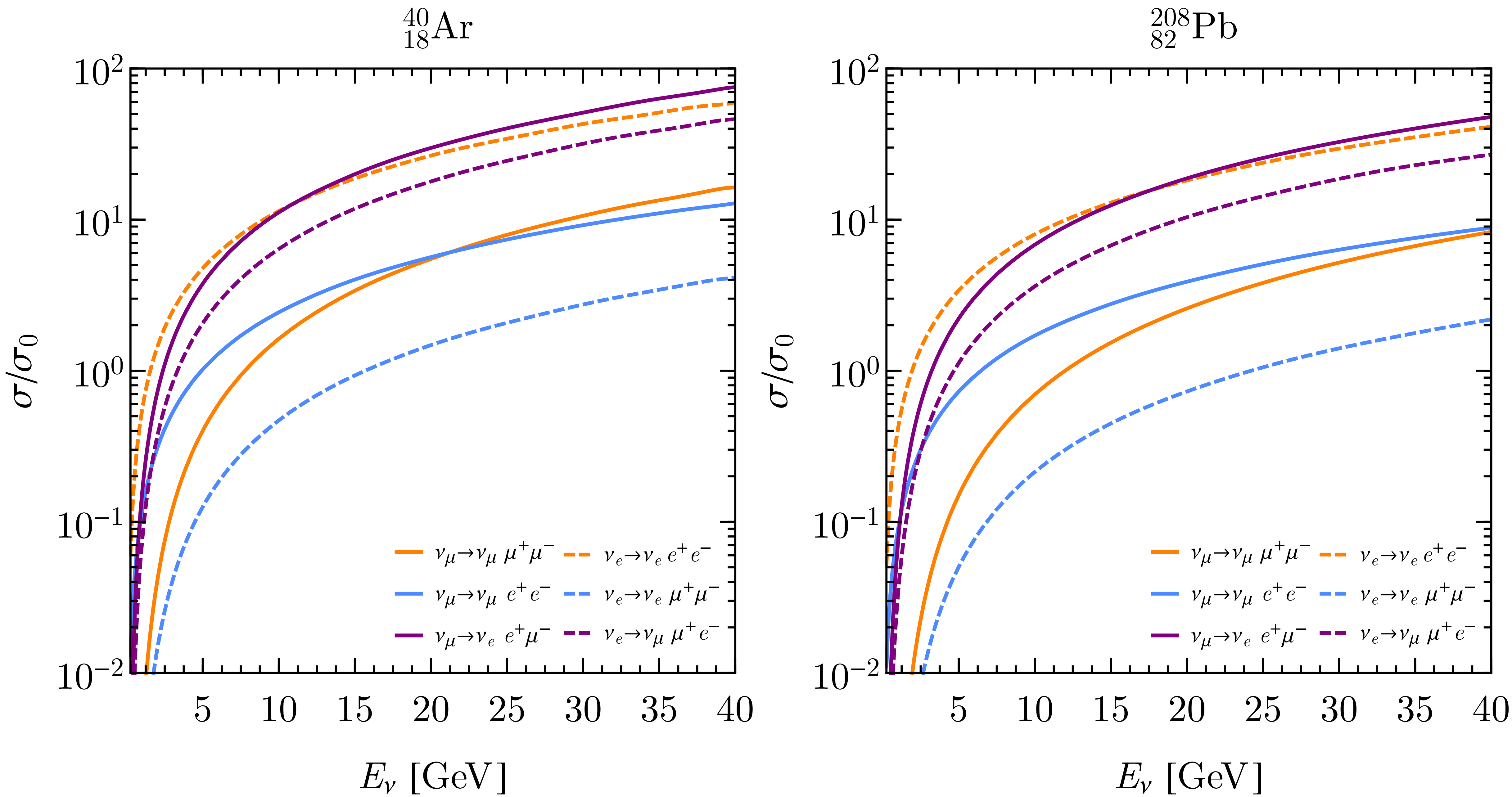
MINERvA



Experiment	**Material**	**Baseline (m)**	**Exposure (POT)**	**Fiducial Mass**
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12) \times 10^{20}$	7.98

POT in antineutrino mode in parentheses.

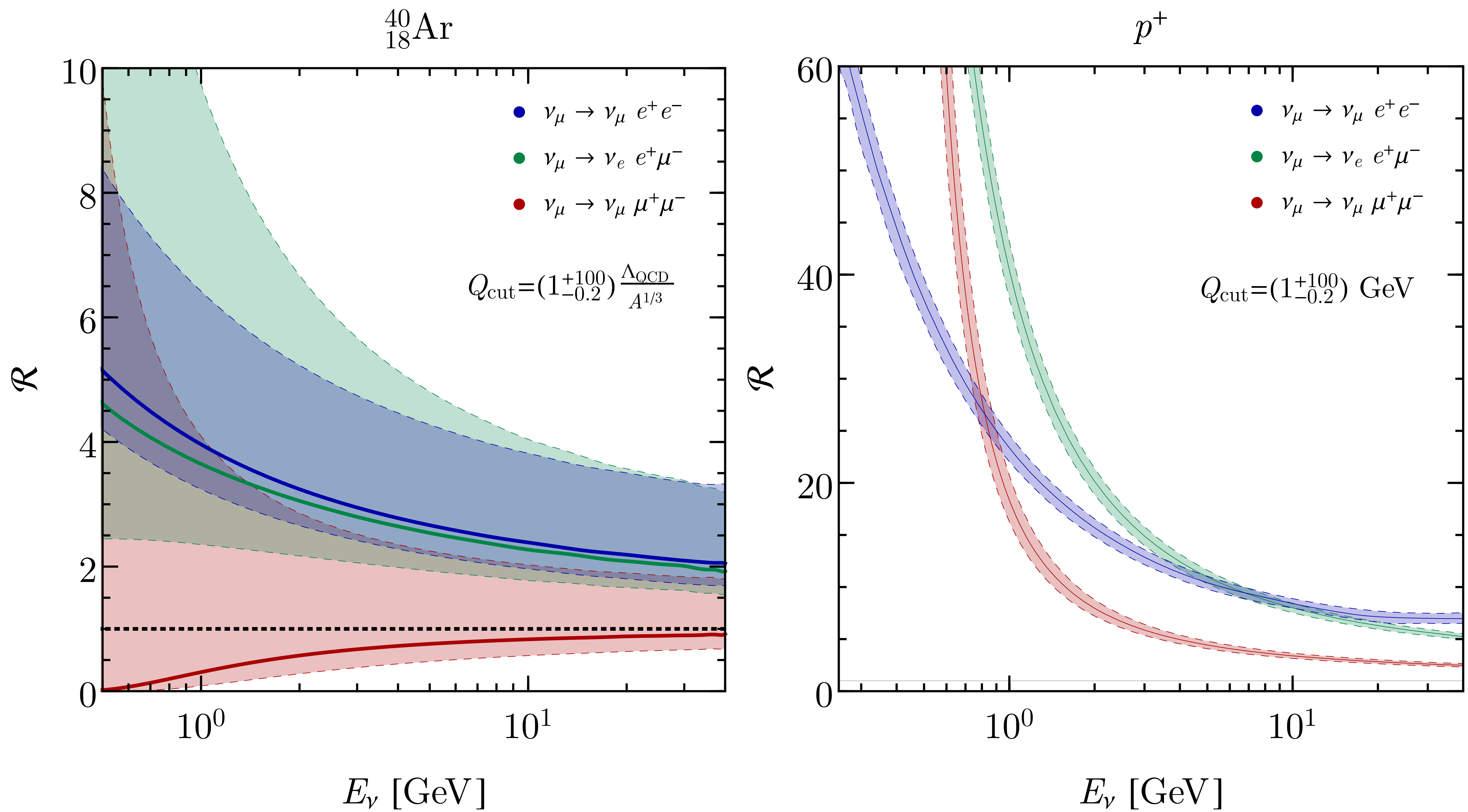
Coherent cross sections



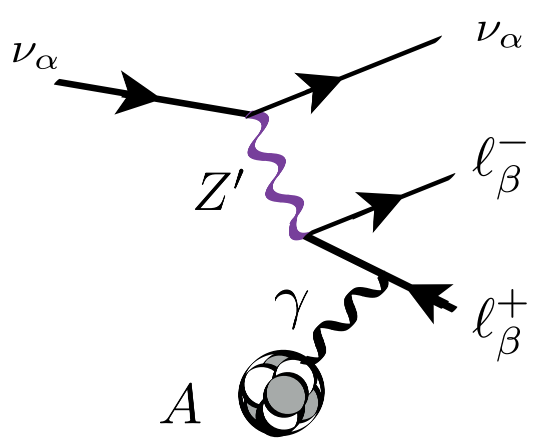
$$\sigma_0 = Z^2\, 10^{-44}\ \text{cm}^2$$

Equivalent Photon Approximation

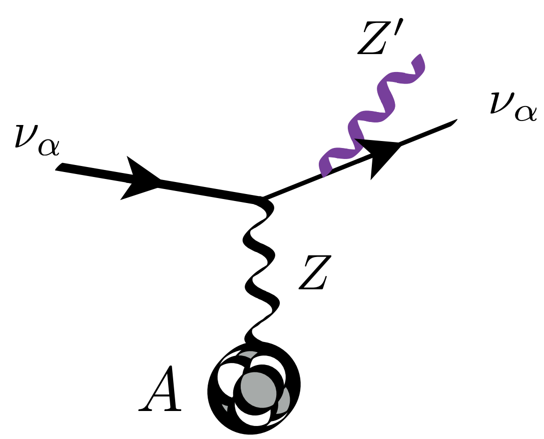
$$\mathcal{R} = \frac{\sigma_{\rm EPA}(E_\nu)|_{Q_{\rm max}}}{\sigma_{\rm 4PS}(E_\nu)}$$



BSM tridents @ DUNE

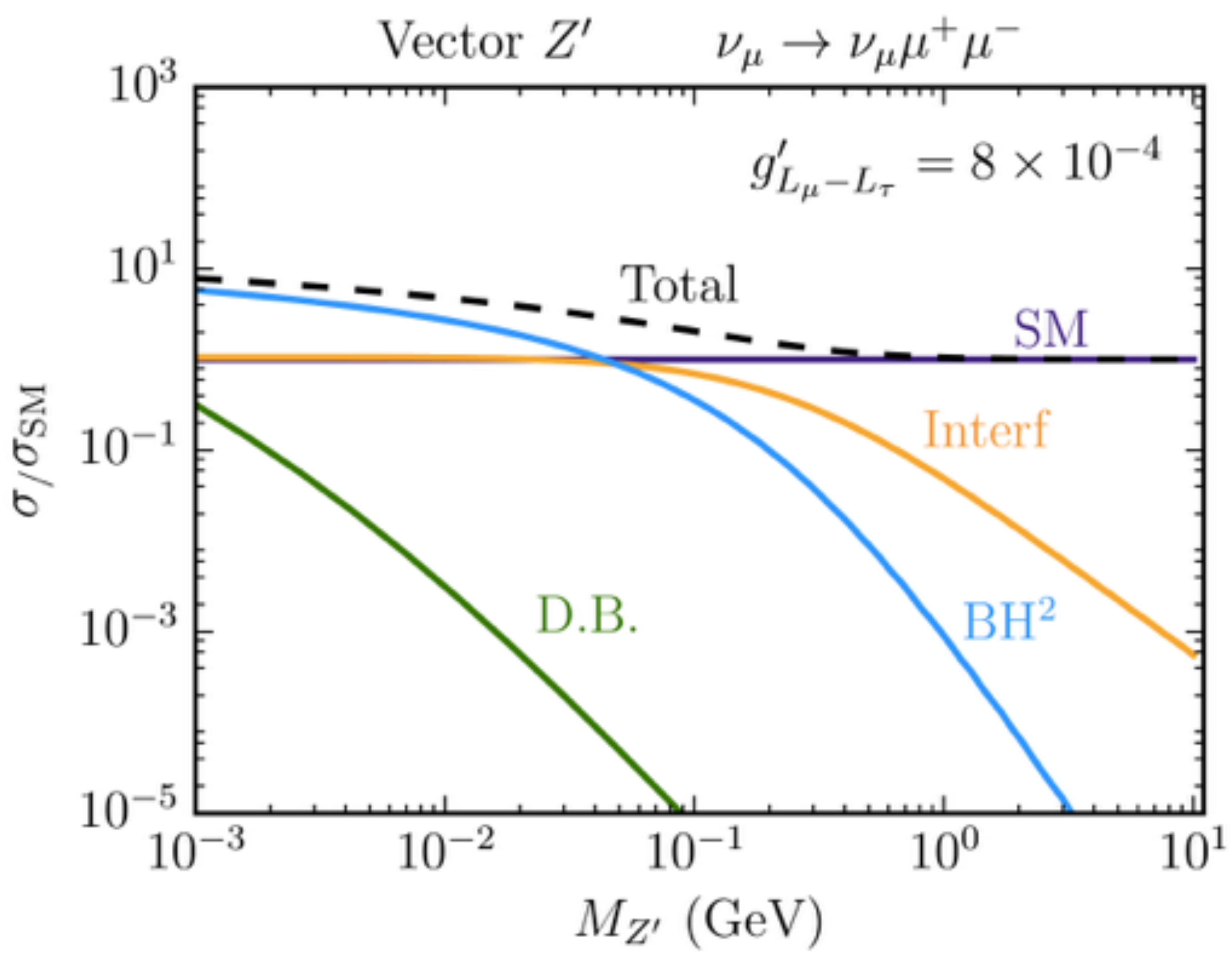


Bethe-Heitler (BH)



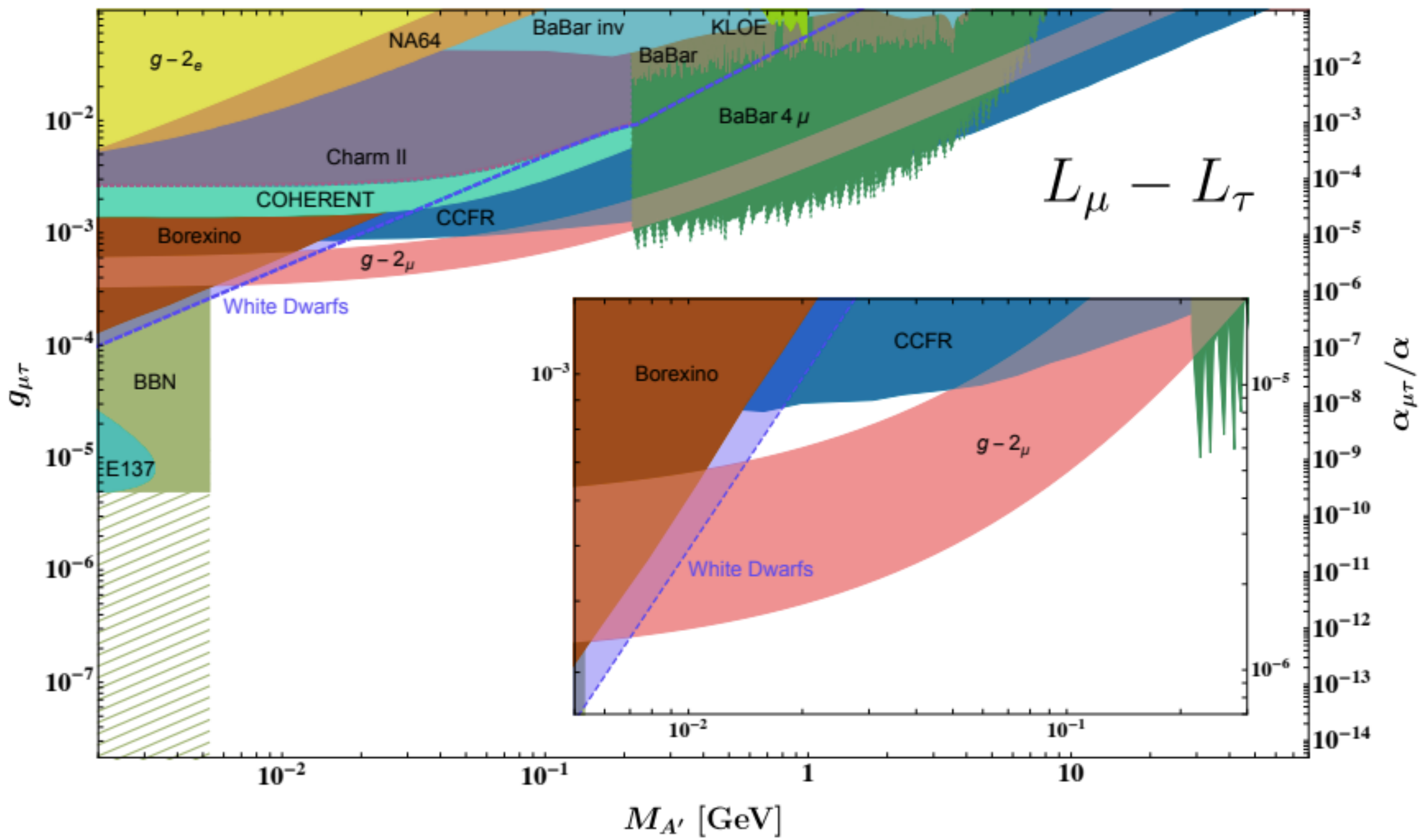
Dark-Bremsstrahlung (DB)
Calculation using NWA (negligible!)

$L_\mu - L_\tau$

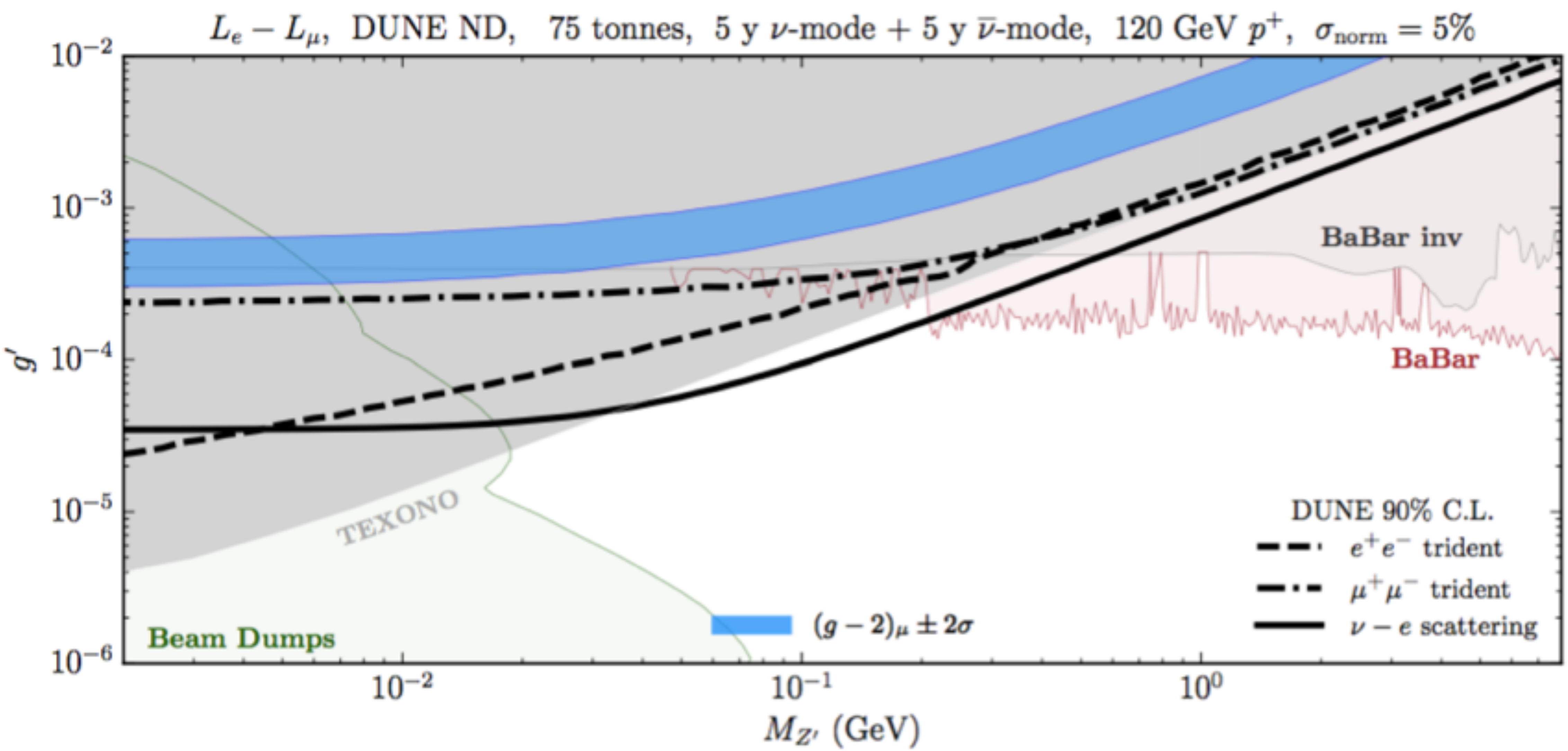


Other constraints

M. Bauer et al, 2018



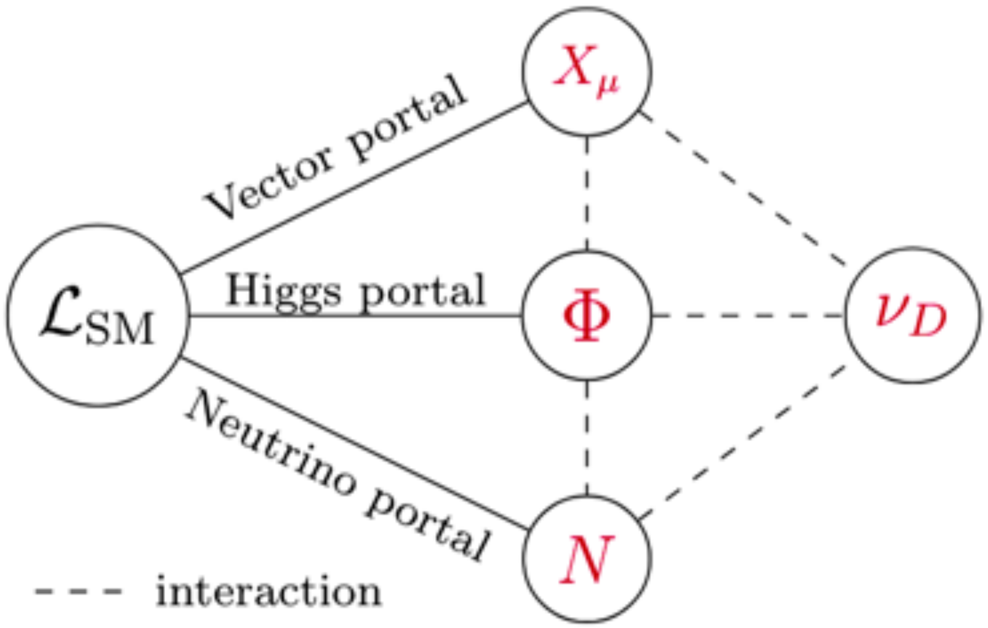
$L_e - L_\mu$ model



$L_e - L_\mu$, DUNE ND, 75 tonnes, 5 y ν-mode + 5 y $\bar{\nu}$-mode, 120 GeV p^+, $\sigma_{\rm norm} = 5\%$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
g'
BaBar inv
BaBar
TEXONO
Beam Dumps
$(g-2)_\mu \pm 2\sigma$
DUNE 90% C.L.
e^+e^- trident
$\mu^+\mu^-$ trident
$\nu - e$ scattering
10^{-2}
10^{-1}
10^{0}
$M_{Z'}$ (GeV)

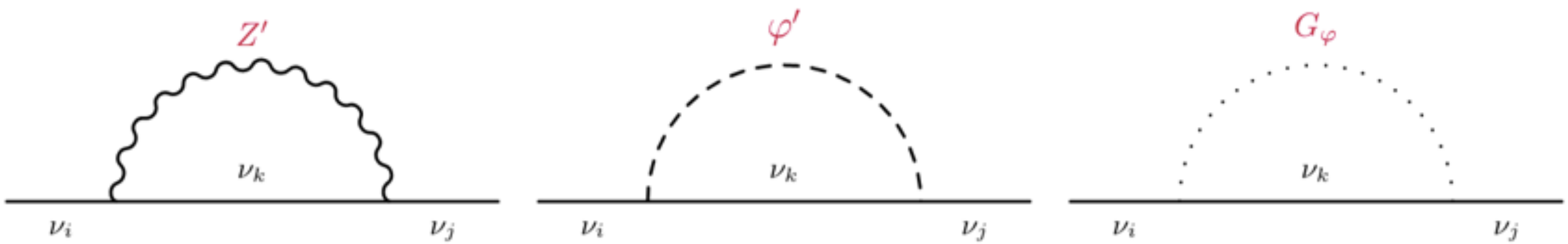
Dark Neutrinos

P. Ballett et al, arXiv:1903.07589



P. Ballett et al, arXiv:1903.07590

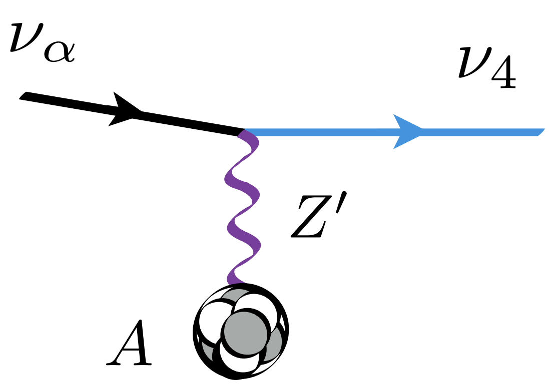
$$\mathcal{L}_{\text{mass}} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu}_\alpha & \overline{N} & \overline{\nu_D} \end{pmatrix} \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ N^c \\ \nu_D^c \end{pmatrix}$$

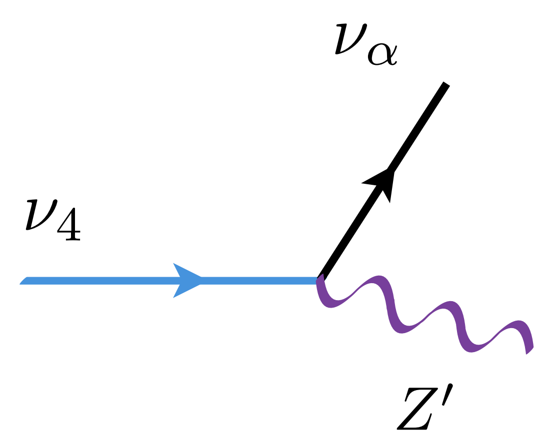


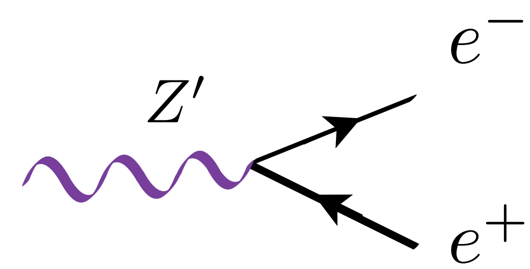
Dark Neutrinos

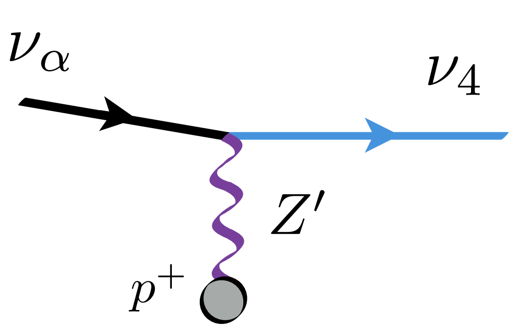
E. Bertuzzo et al. arXiv:1807.09877

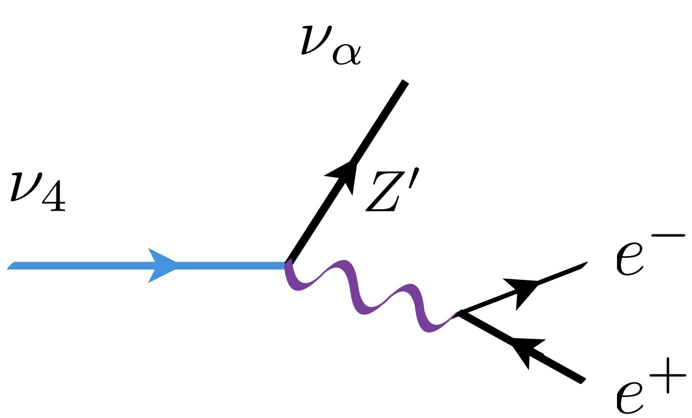
$$m_{Z'} < m_4$$











P. Ballett et al. arXiv:1808.02915

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