NEUTRINO TRIDENT PRODUCTION AT NEAR DETECTORS

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in collaboration with

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Durham University

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

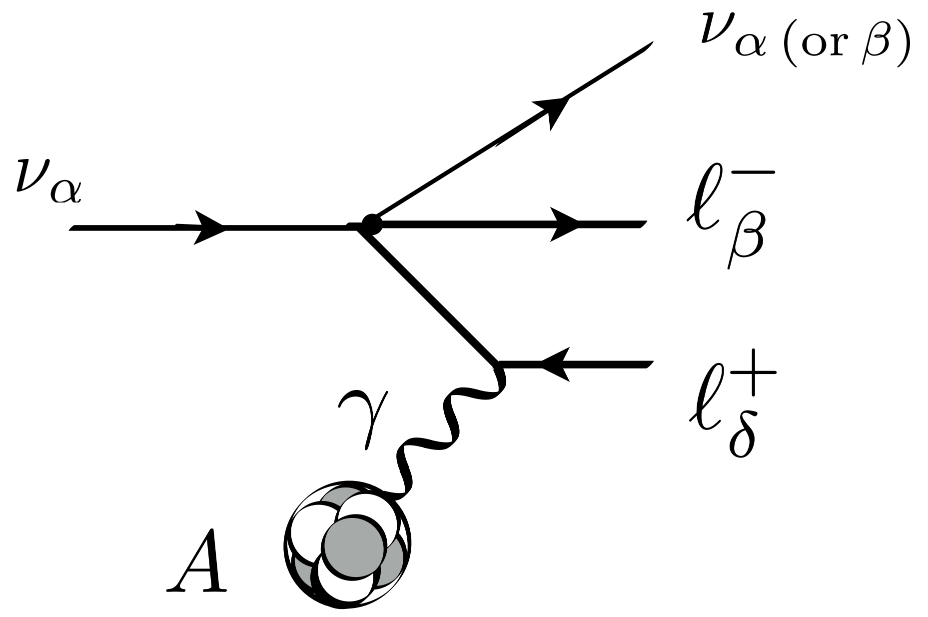
SCIENCE WITHOUT BORDERS

Neutrino trident production

neutrino trident production

or

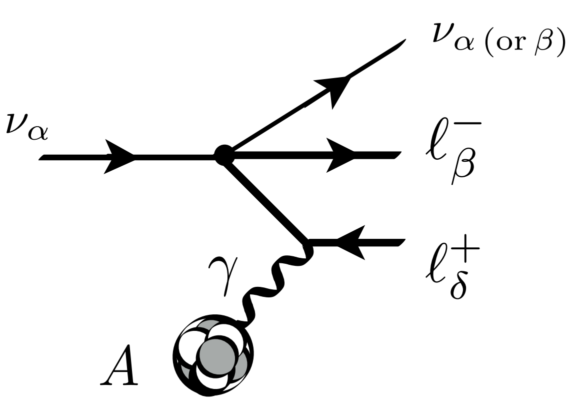
pair production by a neutrino

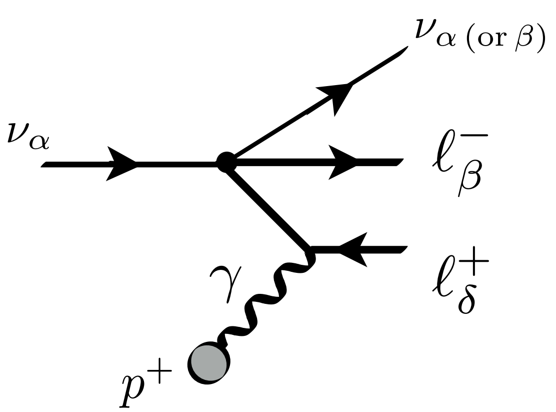


$$\nu_\alpha + \mathcal{N} \to \nu_\beta + \ell^+_\gamma + \ell^-_\delta + \mathcal{N}$$

Neutrino trident production

Pair production in the coulomb field of the **nucleus, nucleons or quarks.**



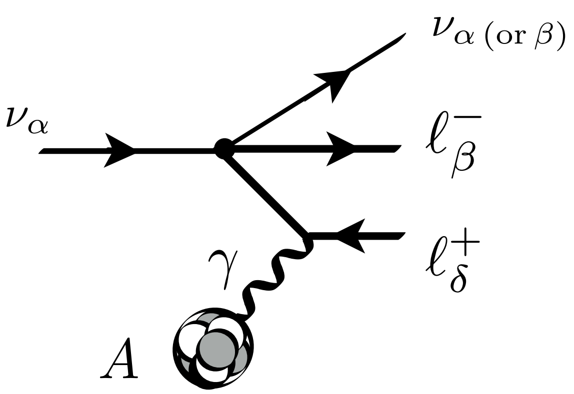


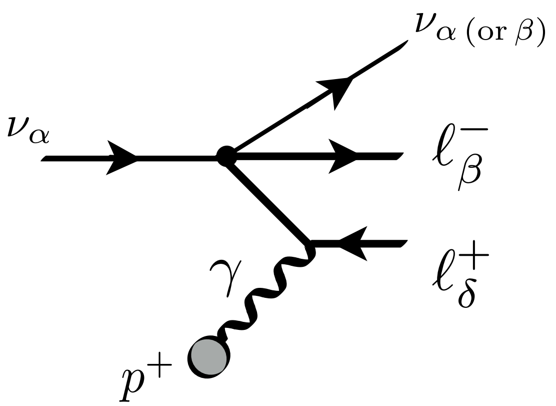
Neutrino	Antineutrino	SM Contributions
$\nu_\mu \to \nu_\mu \mu^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu \mu^+ \mu^-$	CC, NC
$\nu_\mu \to \nu_e e^+ \mu^-$	$\bar{\nu}_\mu \to \bar{\nu}_e e^- \mu^+$	CC
$\nu_\mu \to \nu_\mu e^+ e^-$	$\bar{\nu}_\mu \to \bar{\nu}_\mu e^+ e^-$	NC
$\nu_e \to \nu_e e^+ e^-$	$\bar{\nu}_e \to \bar{\nu}_e e^+ e^-$	CC, NC
$\nu_e \to \nu_\mu \mu^+ e^-$	$\bar{\nu}_e \to \bar{\nu}_\mu e^+ \mu^-$	CC
$\nu_e \to \nu_e \mu^+ \mu^-$	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	NC

CC/NC interference leads to a cancellation of 40%.

Neutrino trident production

Pair production in the coulomb field of the **nucleus, nucleons or quarks.**





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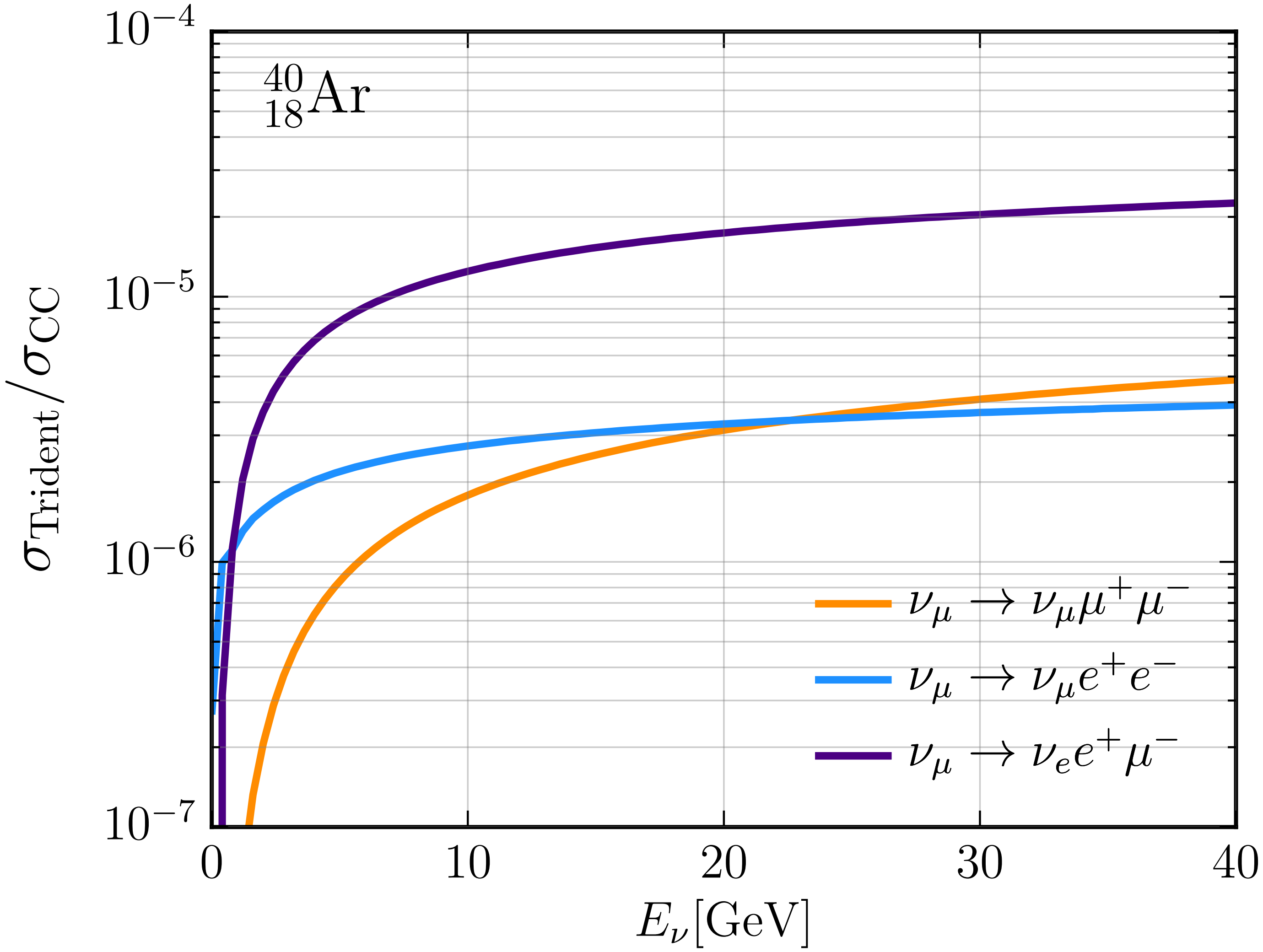
$\nu_e \to \nu_e \mu^+ \mu^-$	$\bar{\nu}_e \to \bar{\nu}_e \mu^+ \mu^-$	NC

Measured!

CC/NC interference leads to a cancellation of 40%.

Neutrino trident production

How rare is it?



Past

[Czys et al, 1964] — Full calculation of process in V - A theory.

[Brown et al, 1972] — Full calculation in V - A and SM.

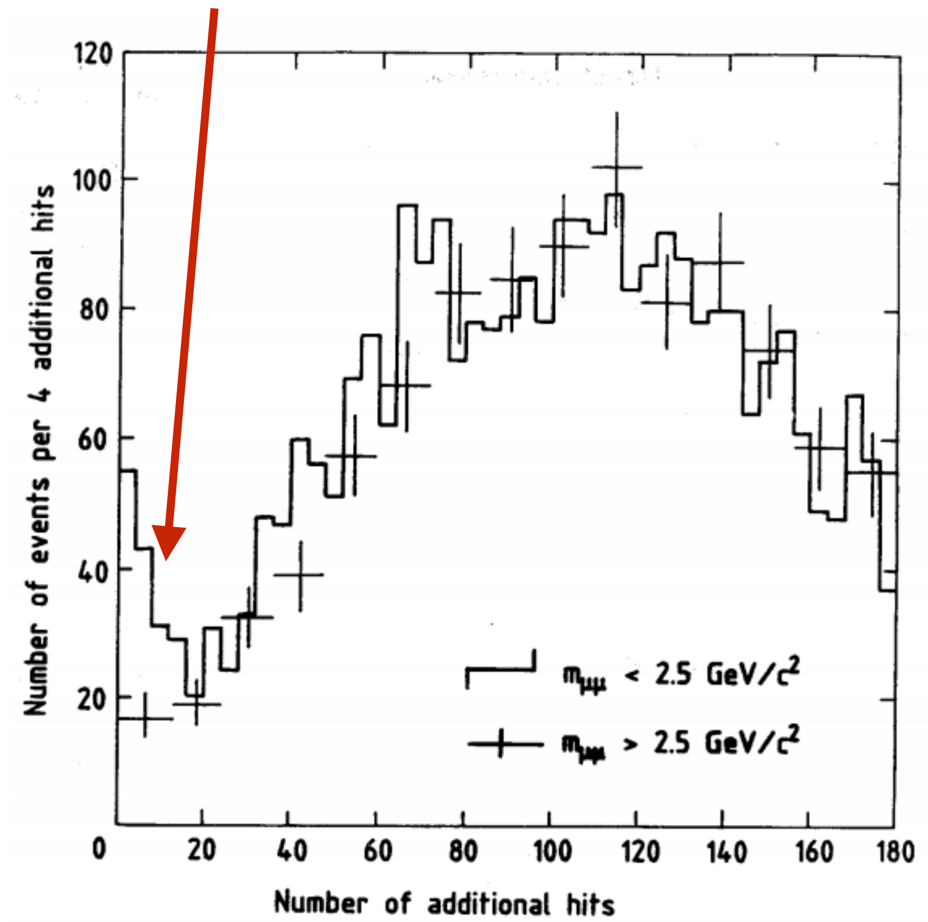
[CHARM II coll., 1990] — First measurement of $\mu^+\mu^-$ trident.

CHARM II

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

$$N_{\text{sig}} = 55 \pm 16$$

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



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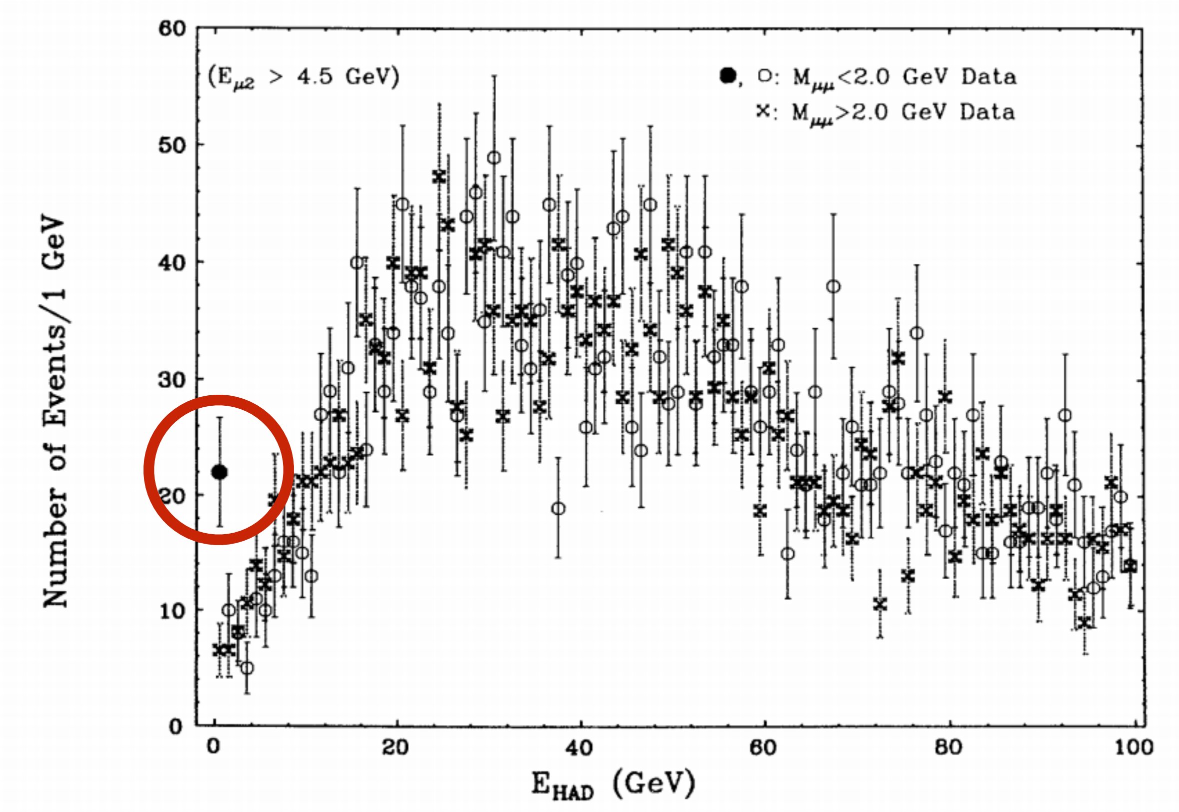
CCFR

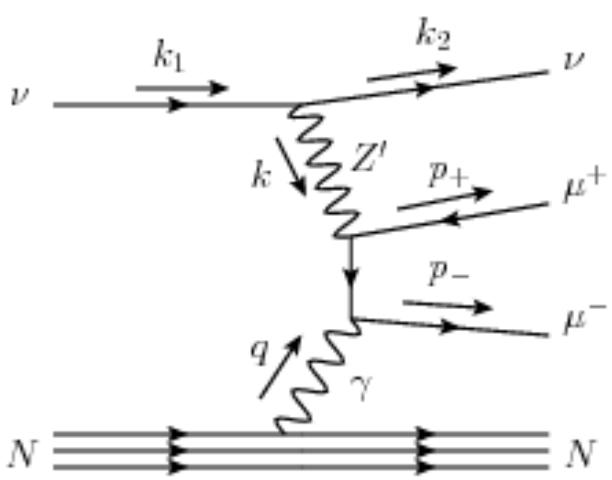
$$\langle E_\nu \rangle = 160 \text{ GeV}$$

$$N_{\text{sig}} = 37 \pm 12.4$$

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



Present



Renewed interest, especially due to NP potential. **[W. Altmannshoffer et al, 2014]**

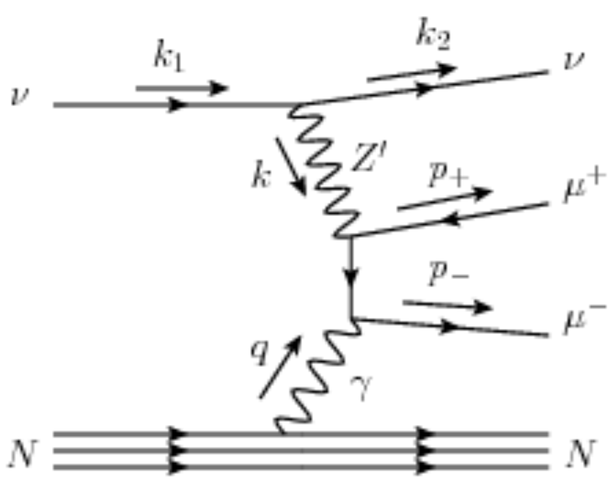
High rates for DUNE ND and SHiP for unobserved channels. **[G. Magill et al, 2016]**

Atmospheric neutrino trident production. **[SF Ge et al, 2017]**

Charged scalars influence on CC channels. **[G. Magill et al, 2017]**

Trident constraints on EFT **(see Giovanni's talk).** **[A. Falkowski et al, 2018]**

Present



Equivalent Photon Approximation (EPA)

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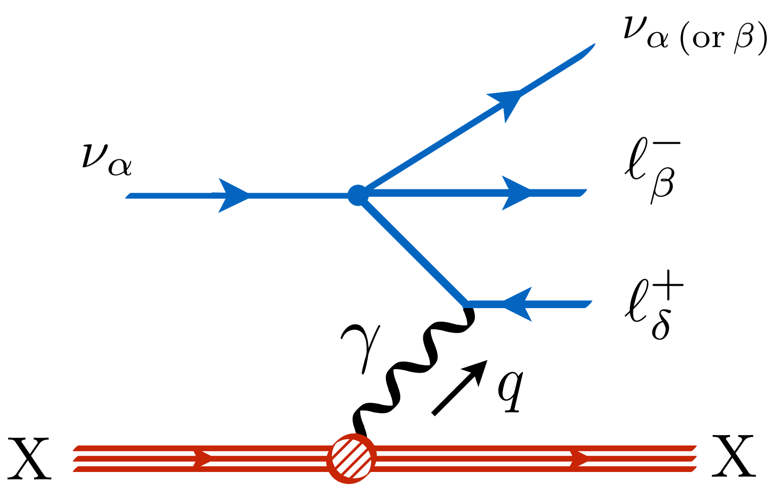
The cross section

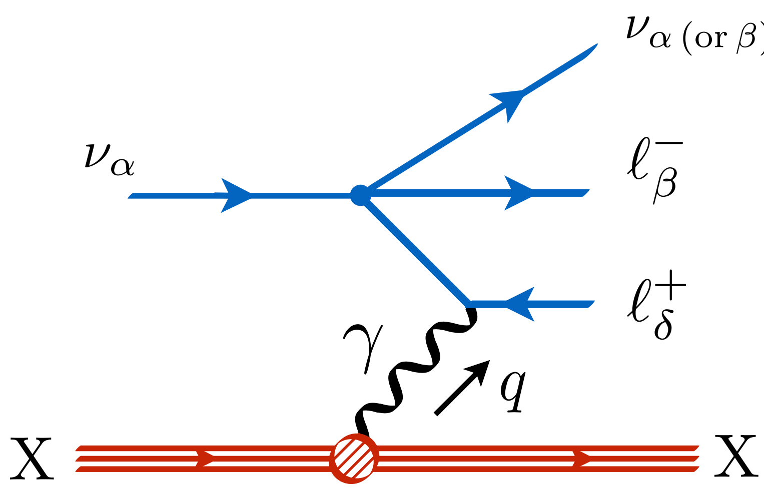


Let's calculate.

The cross section

Process can happen in a coherent, diffractive or DIS limit. Usual separation:

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



where $\hat{s} = 2\,(p_1 \cdot q)$. Would like to do more to understand the EPA.

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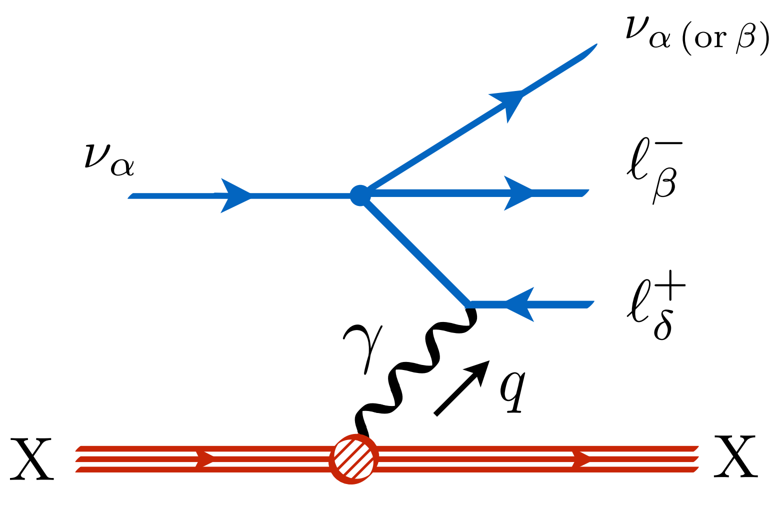


$$\frac{d^2\sigma_{\nu X}}{dQ^2 d\hat{s}} = \frac{1}{32\pi^2 (s - M^2_{\mathcal{H}})^2} \frac{H^{\mu\nu}_X L_{\mu\nu}}{Q^4}$$

where $\hat{s} = 2\,(p_1 \cdot q)$. Would like to do more to understand the EPA.

Universal leptonic T and L cross sections.

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

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

EPA

Equivalent Photon Approximation (EPA):

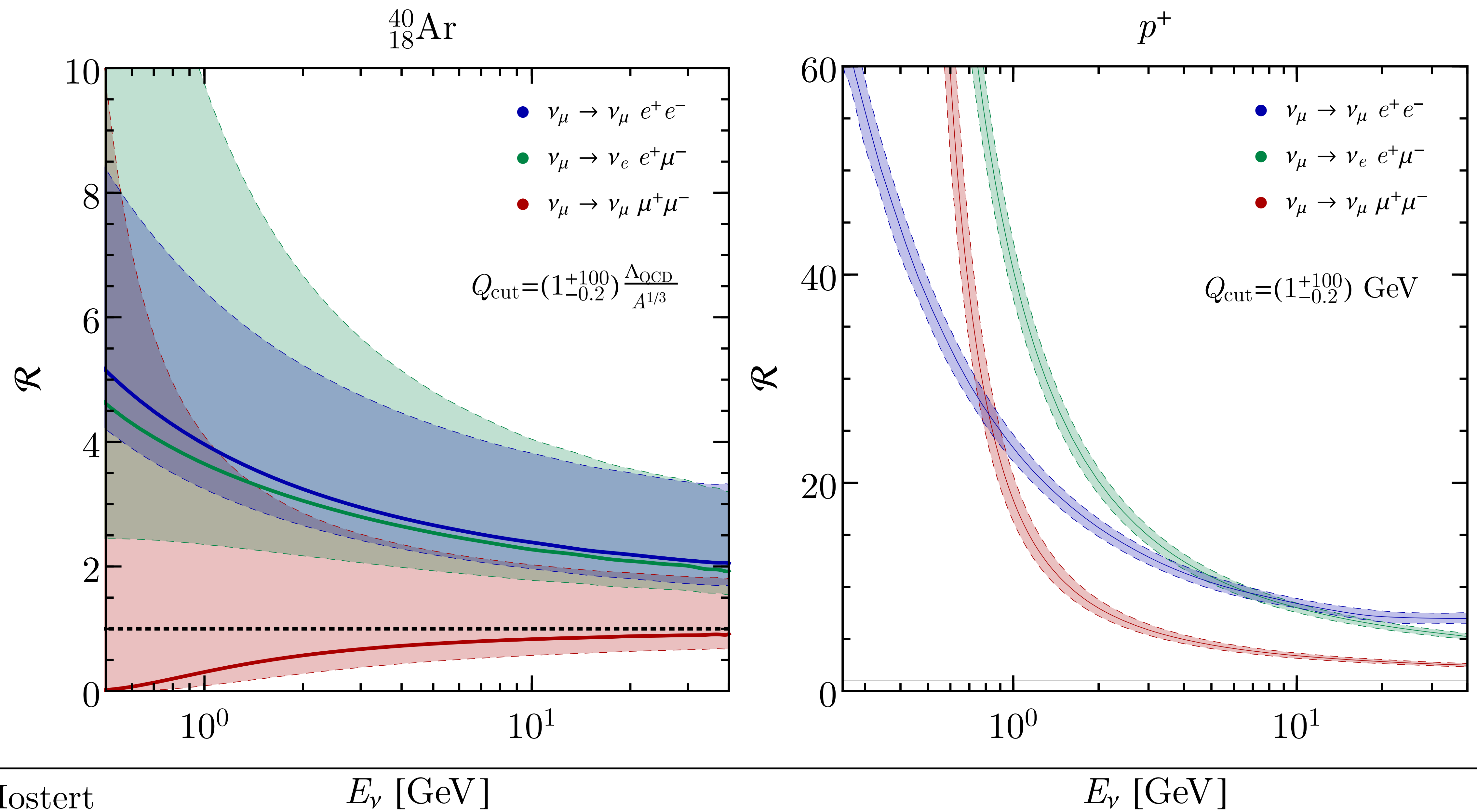
1) Neglecting the L contribution ($h^{\mathrm{L}}(q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(q^2,\hat{s}) \approx 0$).

2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

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

How bad is it?

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



EPA

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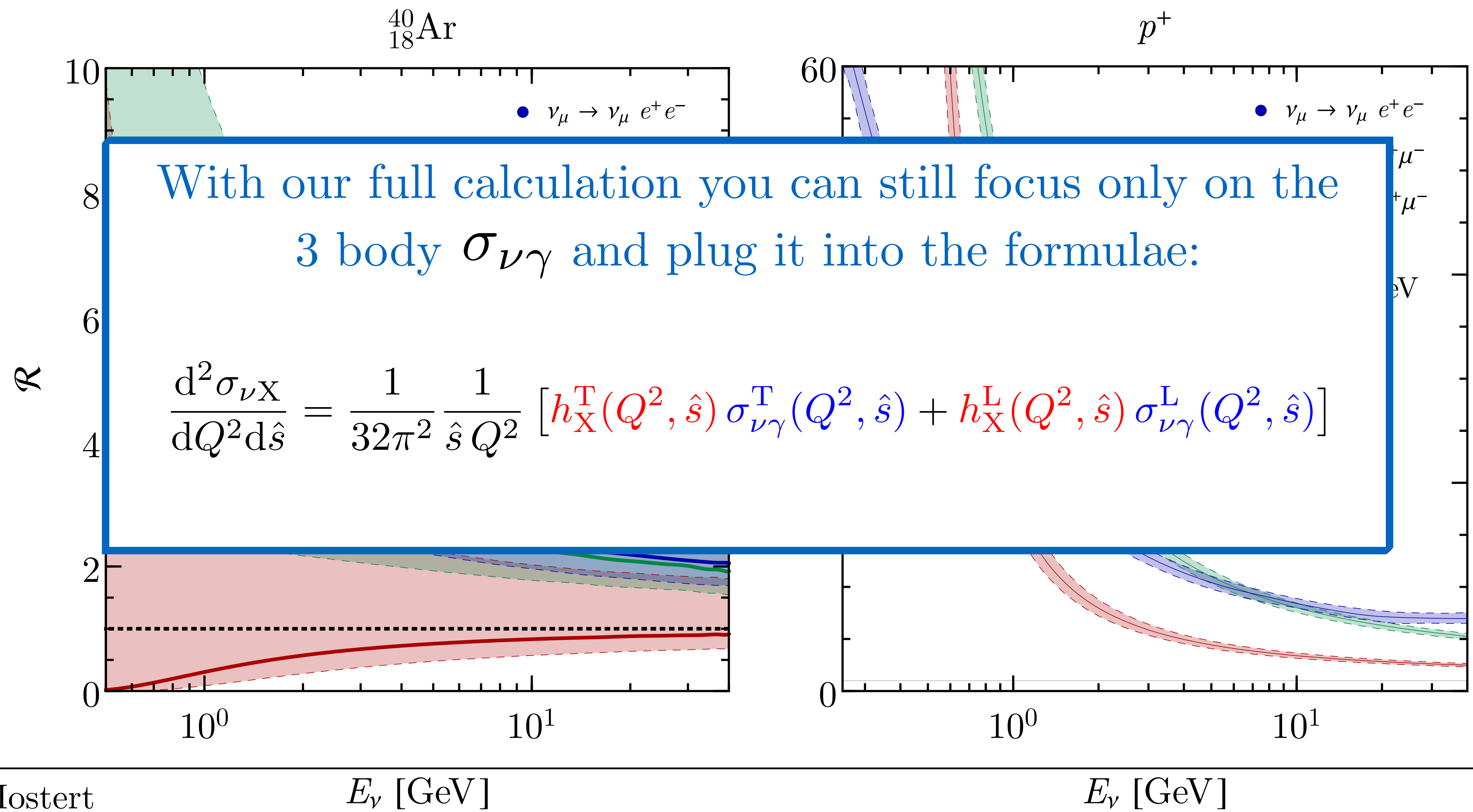
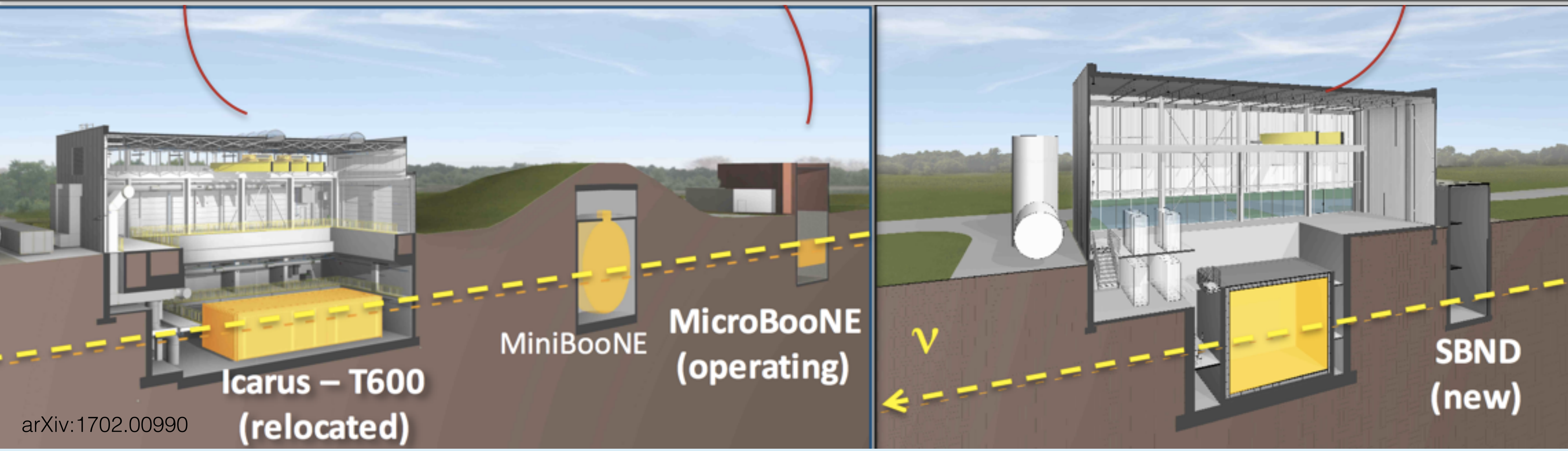
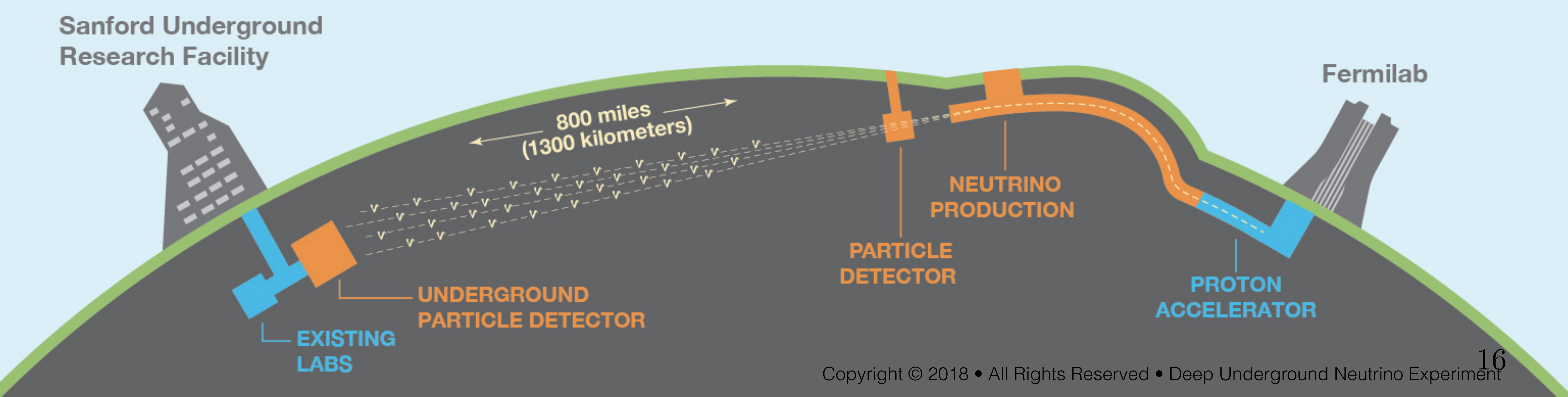


With our full calculation you can still focus only on the 3 body $\sigma_{\nu\gamma}$ and plug it into the formulae:

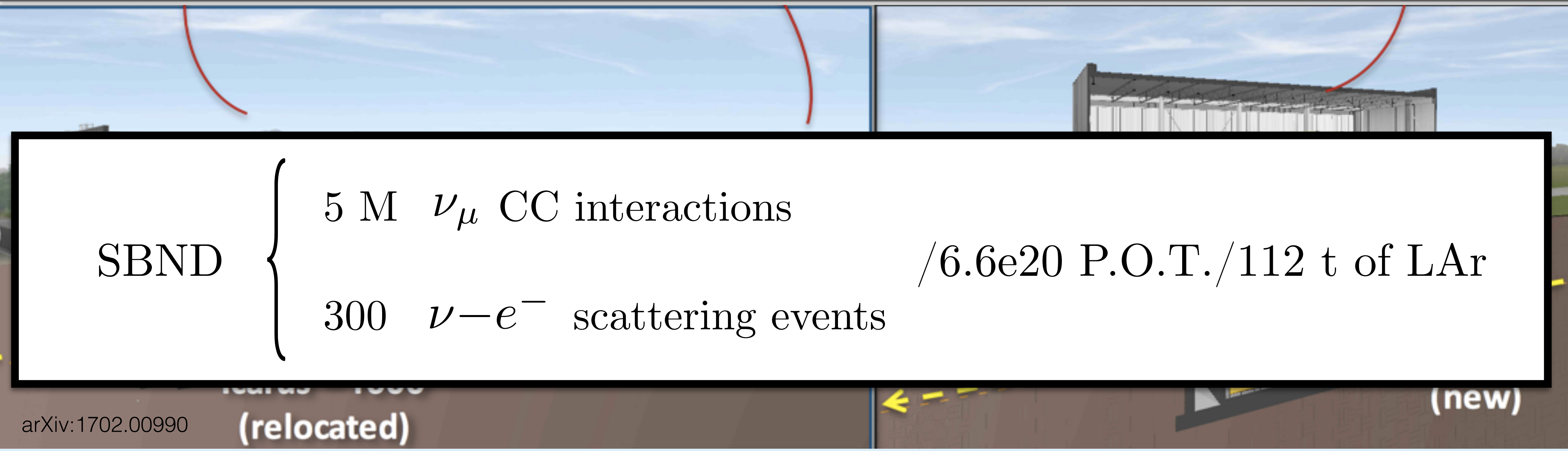
$$\frac{{\rm d}^2\sigma_{\nu{\rm X}}}{{\rm d}Q^2{\rm d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\left[h_{\rm X}^{\rm T}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\rm T}(Q^2,\hat{s}) + h_{\rm X}^{\rm L}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\rm L}(Q^2,\hat{s})\right]$$

Near detectors



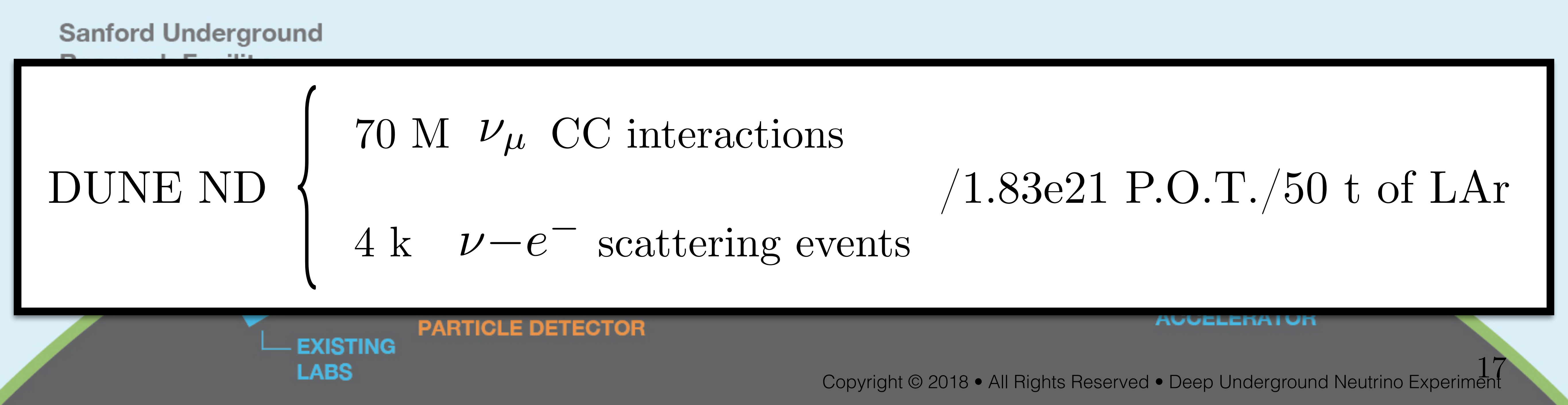


Near detectors



SBND $\left\{ \begin{array}{l} 5\ \text{M}\ \ \nu_\mu\ \text{CC interactions} \\ 300\ \ \nu{-}e^-\ \text{scattering events} \end{array} \right.$ /6.6e20 P.O.T./112 t of LAr

DUNE ND $\left\{ \begin{array}{l} 70\ \text{M}\ \ \nu_\mu\ \text{CC interactions} \\ 4\ \text{k}\ \ \nu{-}e^-\ \text{scattering events} \end{array} \right.$ /1.83e21 P.O.T./50 t of LAr



LAr rates

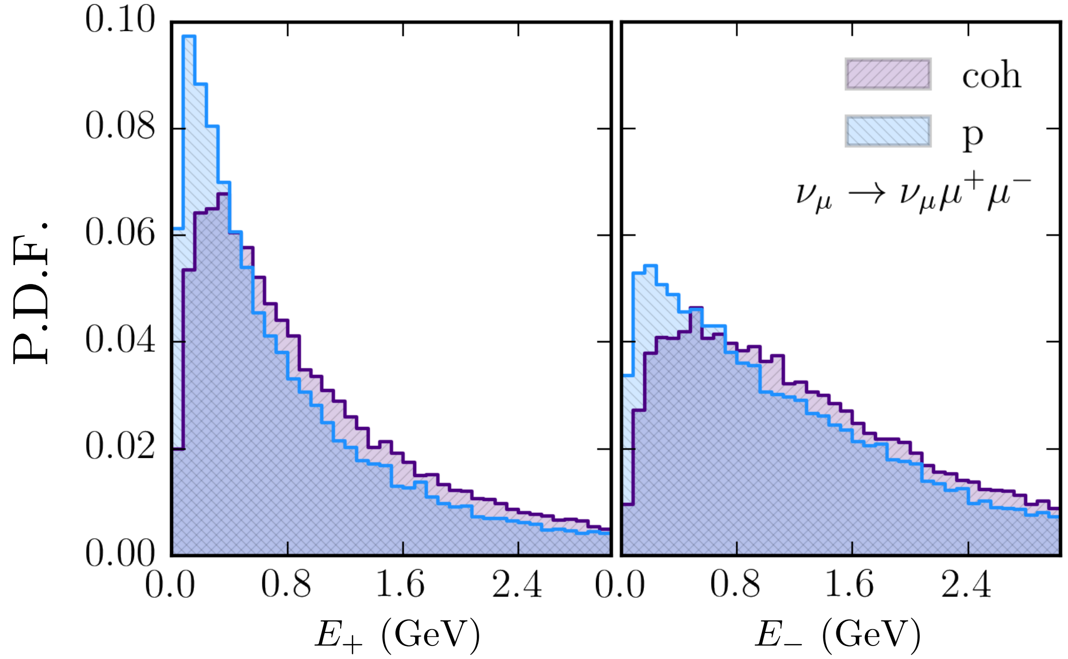
ν_e initiated channels?

See **K. Long**'s talk earlier this week.

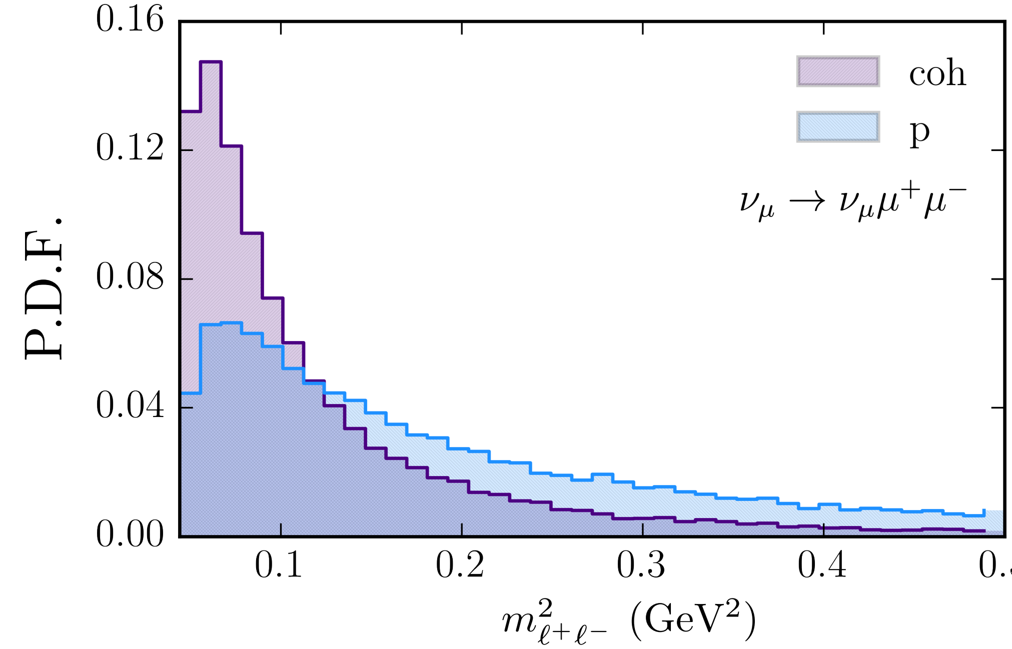
Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)	191
	2	0.1	0.2	692 (530)	41
Total $e^{+}e^{-}$	6	0.4	0.7	1007 (800)	114
	0.7	0.0	0.1	143 (111)	14
Total $\mu^{+}\mu^{-}$	0.4	0.0	0.0	286 (210)	11
	0.4	0.0	0.0	196 (147)	9

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

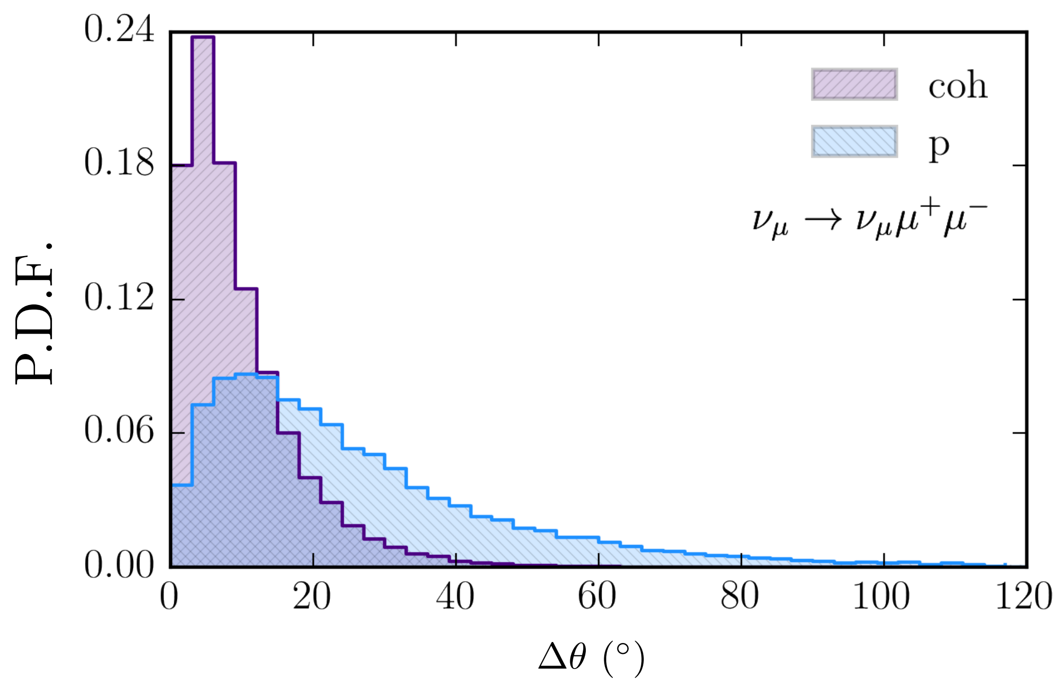
The signal @ DUNE



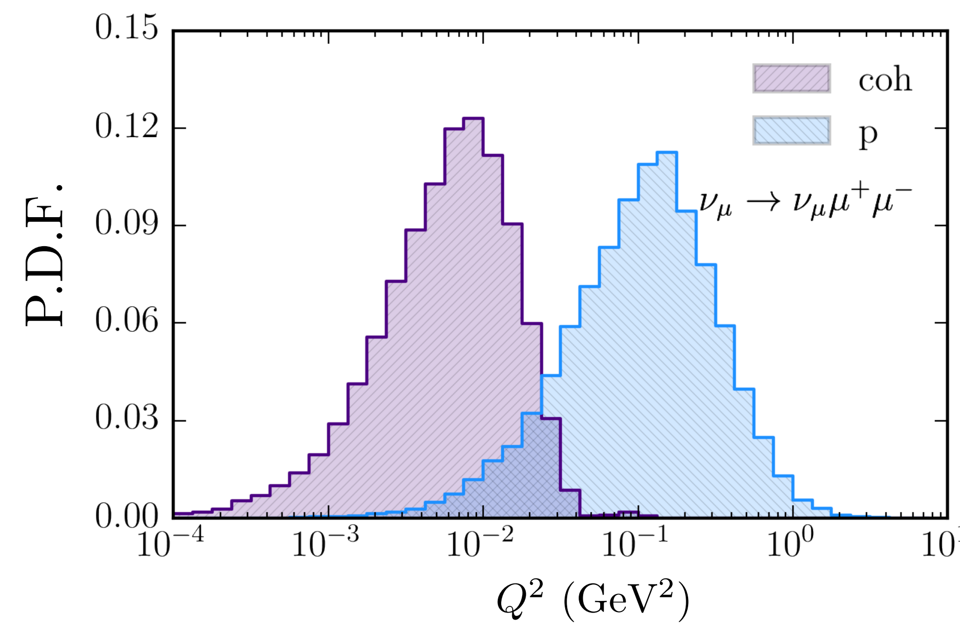
Not a problem.



Incredibly low invariant masses.



Collimated muons.



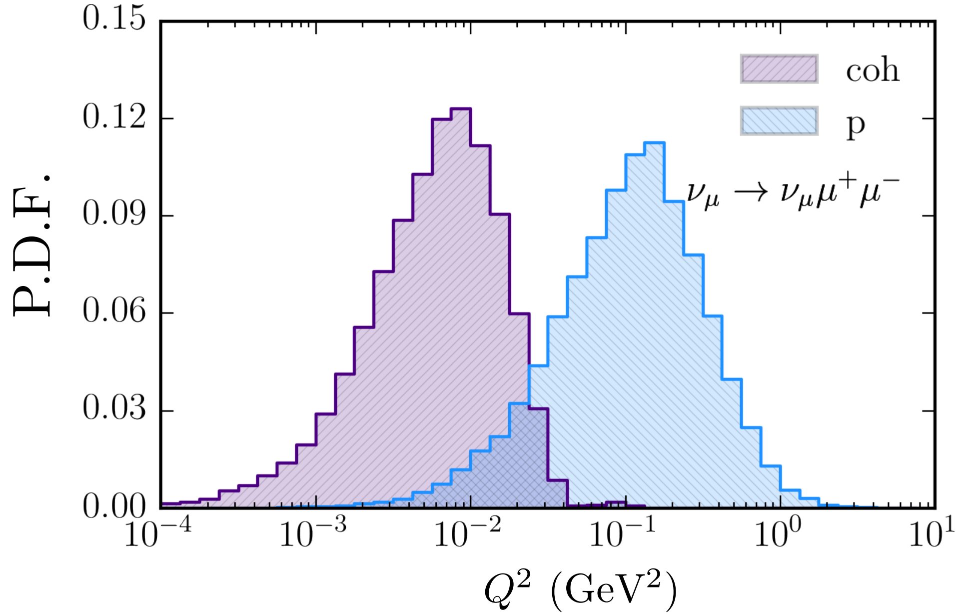
No hadronic activity at the vertex?

The signal @ DUNE

Perhaps biggest uncertainty of calculation!

What is the hadronic signature of diffractive tridents?

We include fermi blocking, but other effects at play.

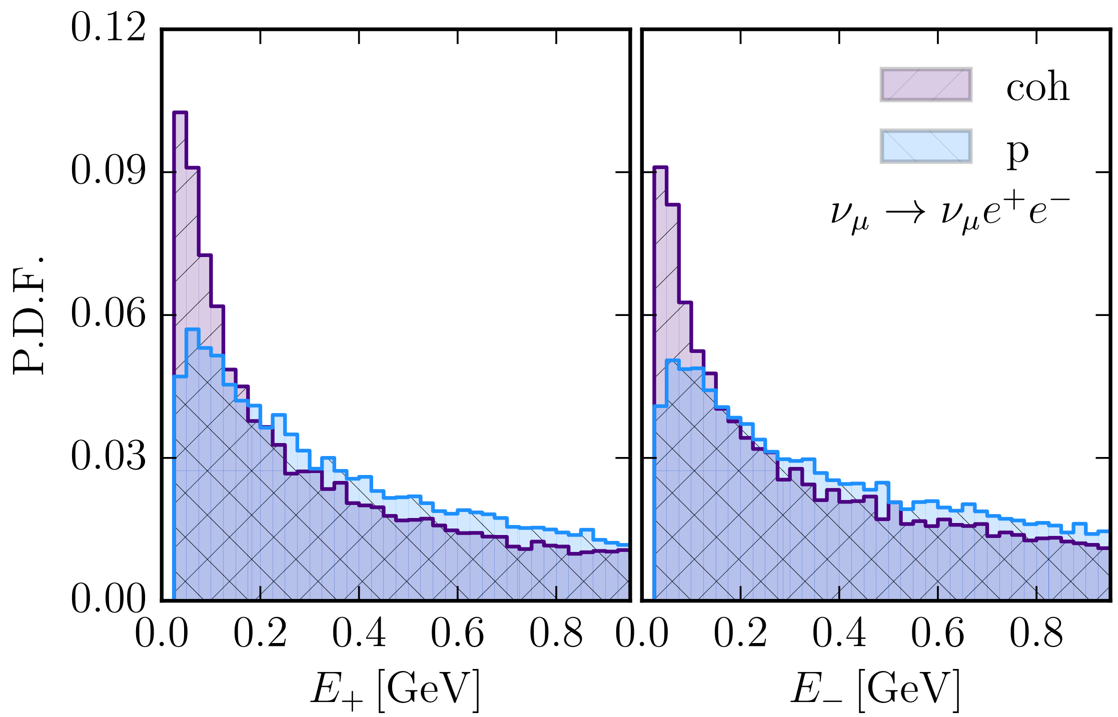


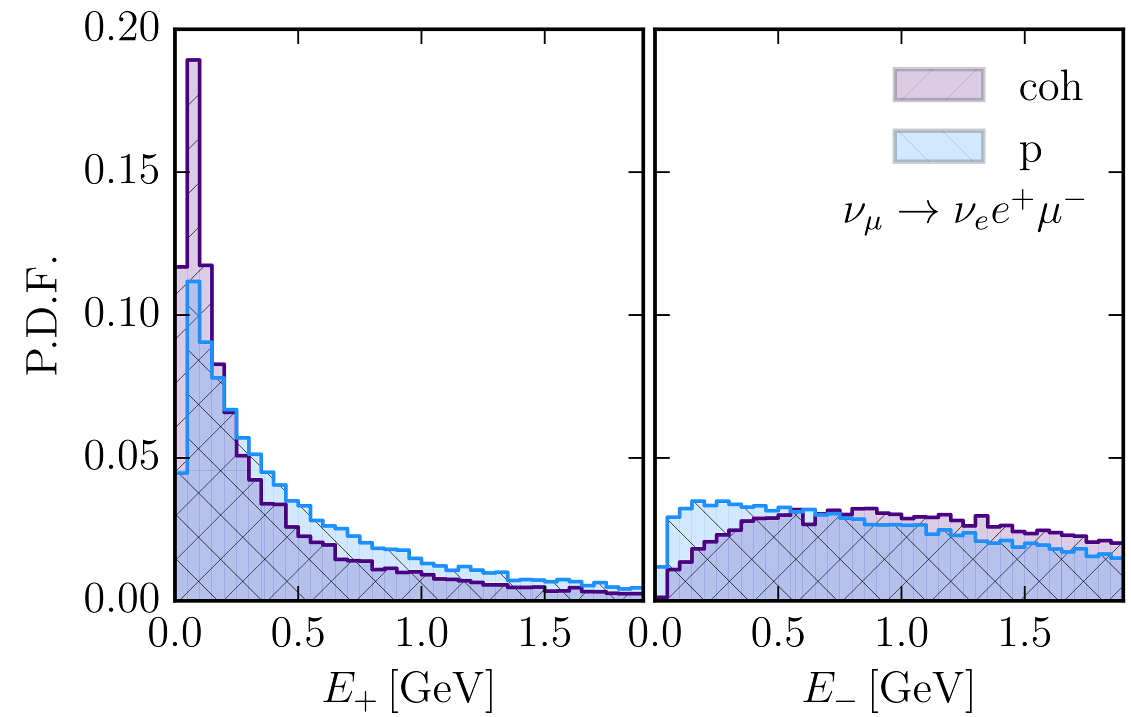
No hadronic activity at the vertex?

The signal @ DUNE

Electrons are produced with low energies.

Even with 30 MeV thresholds in LAr, still okay ⟶ 70% efficiencies.





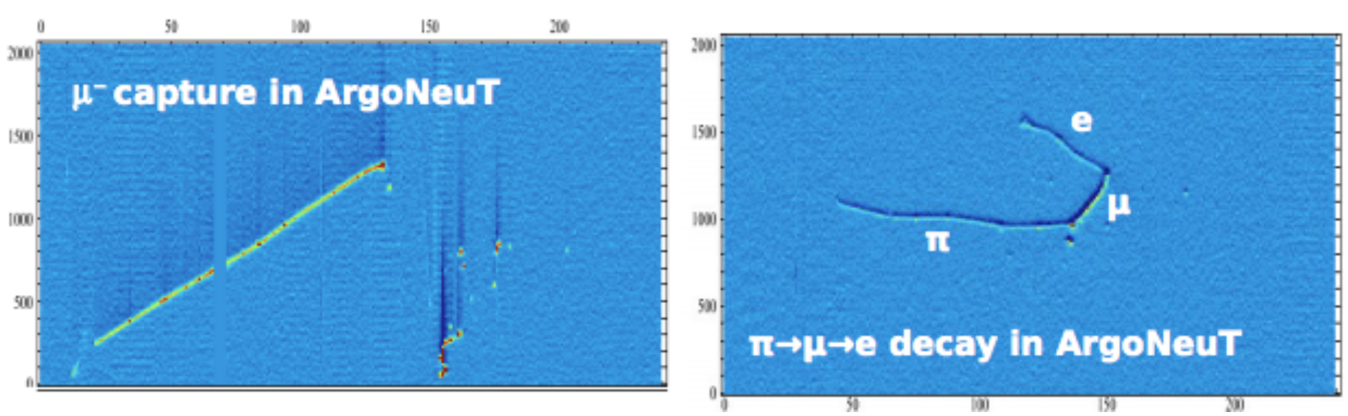
Backgrounds

Is it even observable?

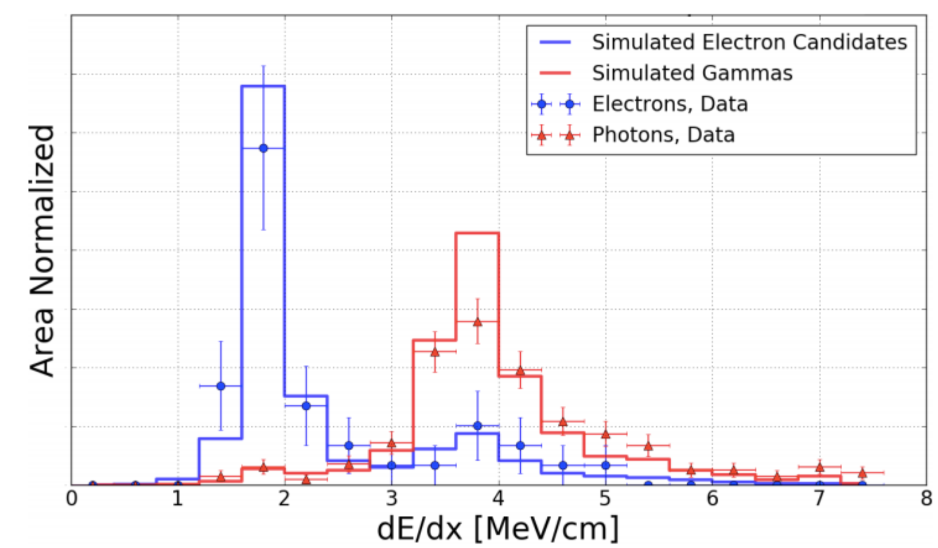
Genuine dilepton production is rare, but misID of particles is the problem.

$\mu^{\pm}/\pi^{\pm}$

$e^{\pm}/\gamma$



F. Blaszczyk - NuInt 2014



Escaping pion? No decay kink?

Successful separation in LAr (ArgoNeuT)

Backgrounds

Constant misID rates

misID	Rate
γ as $e^\pm$	0.05
γ as e^+e^-	0.1 (w/ vertex) 1 (no vertex/overlapping)
$\pi^\pm$ as $\mu^\pm$	0.1

From GENIE events, find most important bkgs. after vetoing protons (>21 MeV) are

$\mu^+\mu^-$

CC1$\pi^\pm$ misID $\pi^\pm$.

e^+e^-

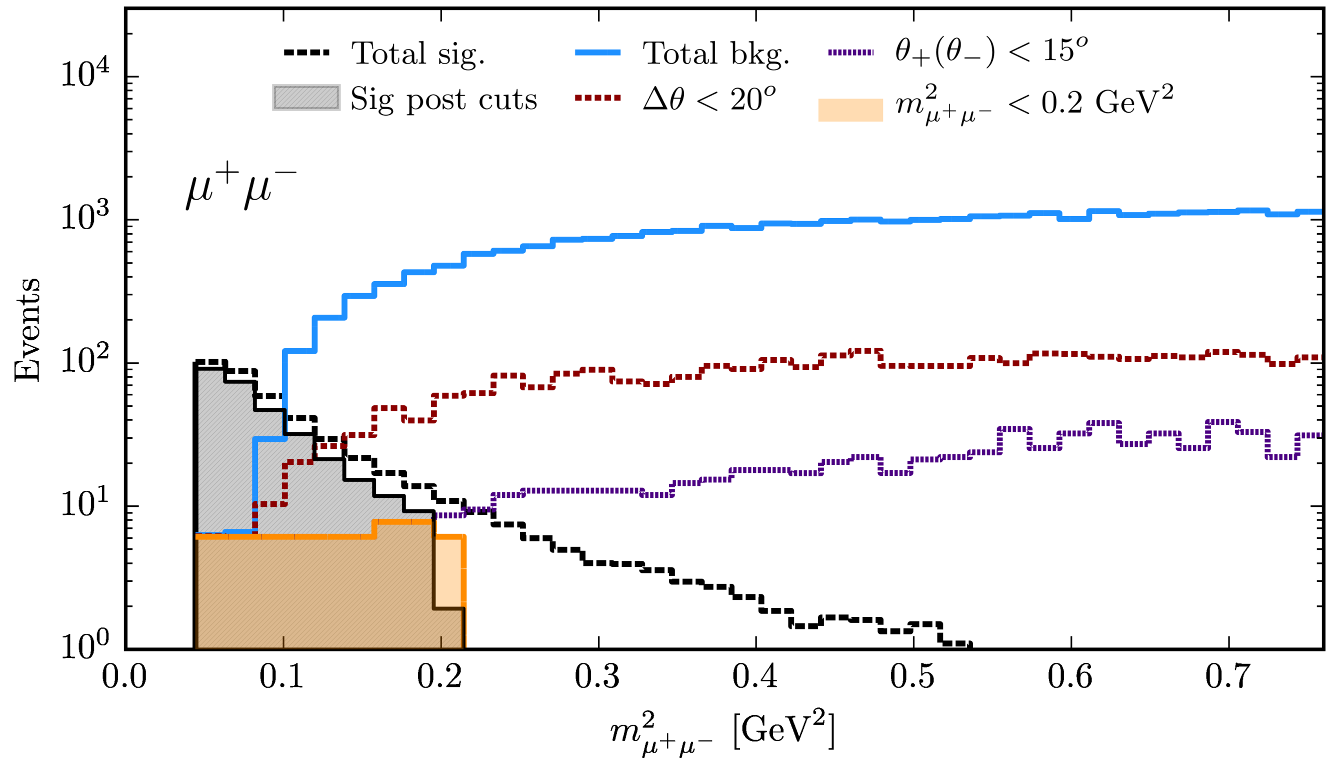
NC1π^0 and ν_eCCπ^0.

$e^+\mu^-$

CC1π^0 with misID γ .

Backgrounds

Apply simple 1D kinematical cuts based on the signal distributions.



Channel	$\mathbf{N}_{\rm B}^{\rm misID}/\mathbf{N}_{\rm CC}$	$\mathbf{N}_{\rm B}^{\rm had}/\mathbf{N}_{\rm CC}$	$\mathbf{N}_{\rm B}^{\rm kin}/\mathbf{N}_{\rm CC}$	$\epsilon_{\rm sig}^{\rm coh}$	$\epsilon_{\rm sig}^{\rm dif}$
$e^\pm\mu^\mp$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$	0.61 (0.61)	0.39 (0.39)
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$	0.48 (0.47)	0.21 (0.21)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)	0.17 (0.16)

Backgrounds

Apply simple 1D kinematical cuts based on the signal distributions.

Many caveats!

Detector effects?

De-excitation gammas? Internal bremsstrahlung? Dalitz decays?

6 orders of magnitude is a lot.

Channel					$\epsilon_{\rm sig}^{\rm dif}$
$e^\pm\mu^\mp$					0.39 (0.39)
e^+e^-					0.21 (0.21)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)	0.17 (0.16)

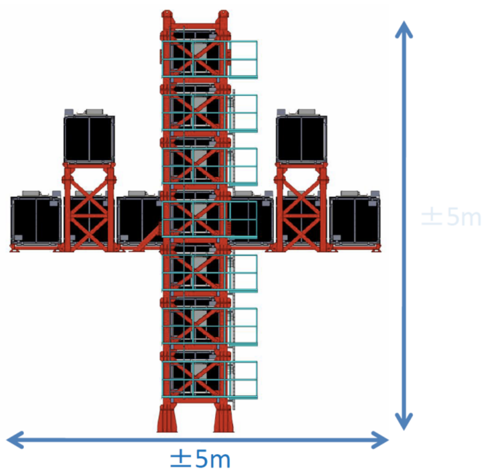
Other NDs

Despite LAr being a promising technology for measuring tridents, it is not the only one!

Could we measure it now?!

Other NDs

INGRID



MINOS/+

NOvA

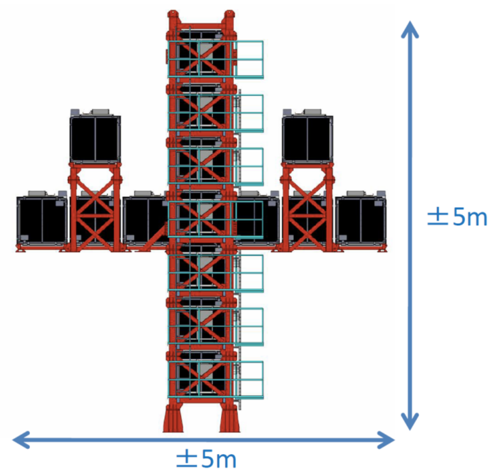
MINERvA

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)

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Other NDs

INGRID



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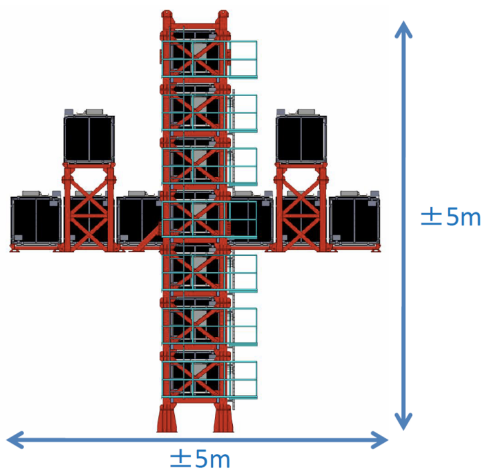
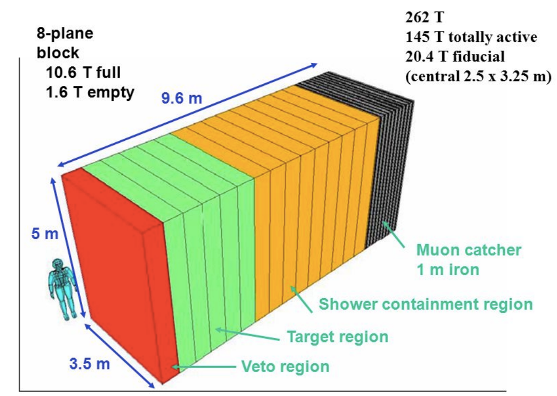


MINOS/+

NOvA



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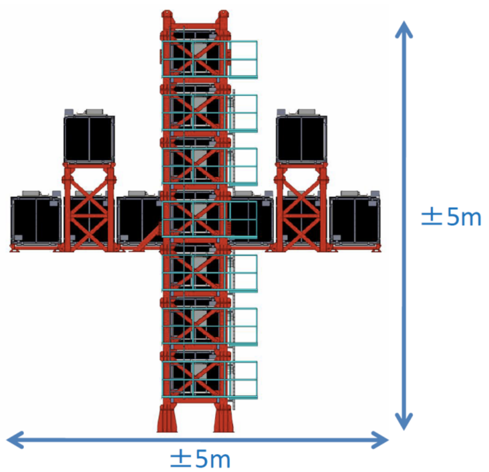
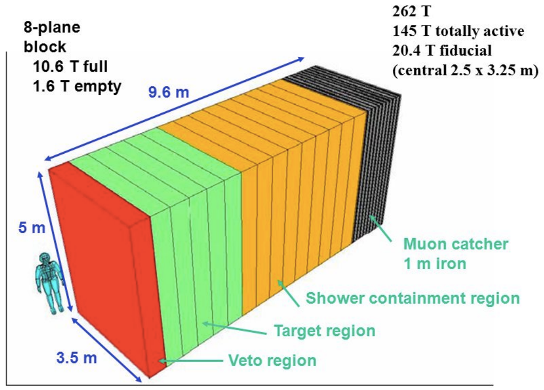
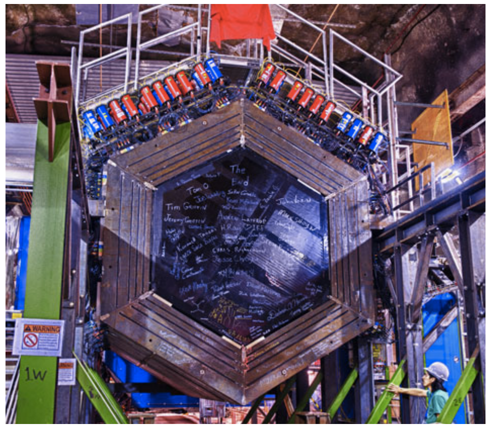


MINOS/+

NOvA



MINERvA

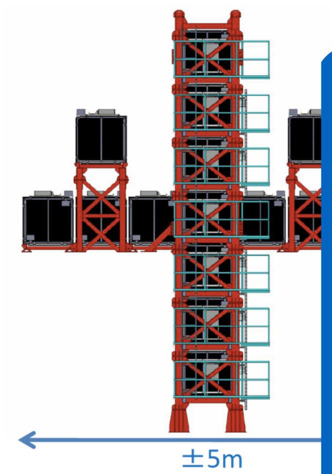


Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total $e^{+}e^{-}$	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^{+}\mu^{-}$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

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Other NDs

INGRID MINOS/+ NOvA MINERvA



Could INGRID and MINOS be in the game?

Detector performance study needed.

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)
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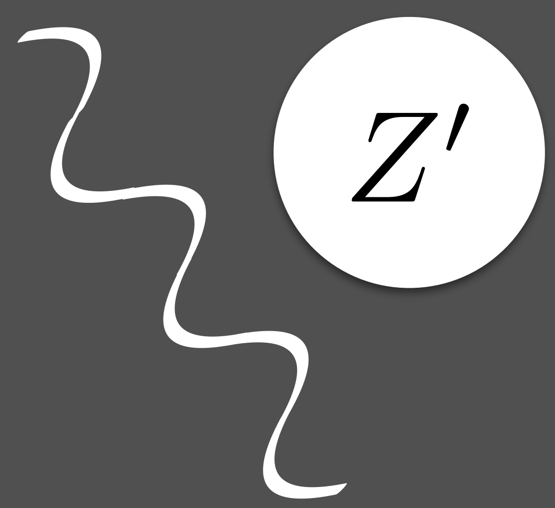
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

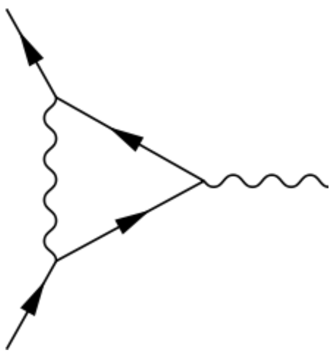
Smiting new physics



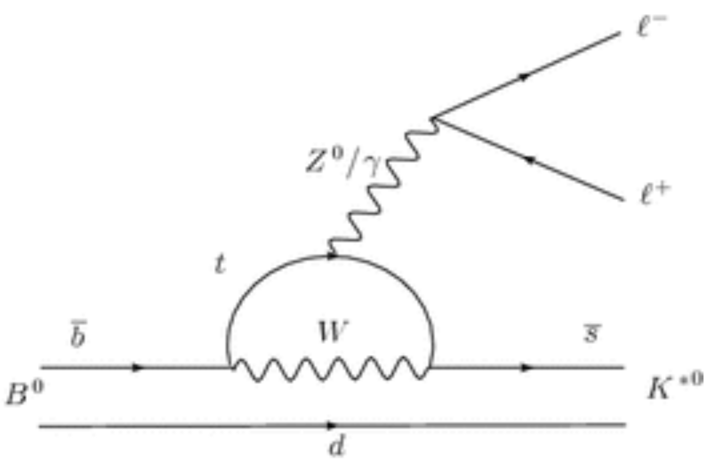
Work in progress

$L_\mu - L_\tau$ gauge

Consider first a new gauge boson gauged under the **anomaly free** group $U(1)_{L_\mu - L_\tau}$



Possible explanation of the **muon (g-2) anomaly**.



Recent interest due to hints of **flavour non-universality** in $b \to s\,\ell^+\,\ell^-$ decays.

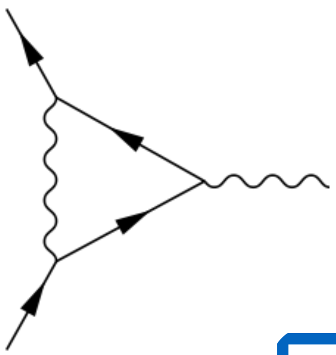
See **[Altmannshofer et al, 1403.1269]** for an extension for flavour anomalies.

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

[Altmannshofer et al, 1406.2332]

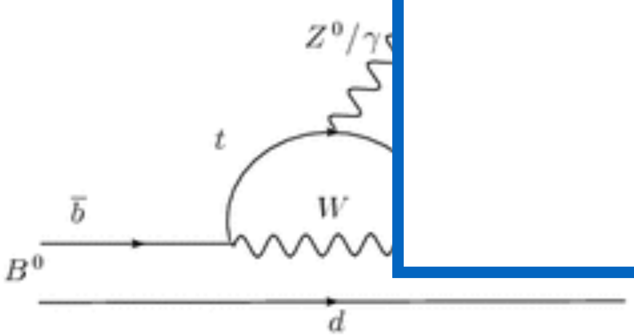
$L_\mu - L_\tau$ gauge

Consider first a new gauge boson gauged under the **anomaly free** group $U(1)_{L_\mu - L_\tau}$



Possible explanation of the **muon (g-2) anomaly**.

ersality



extension for flavour anomalies.

“Not the worst model.”

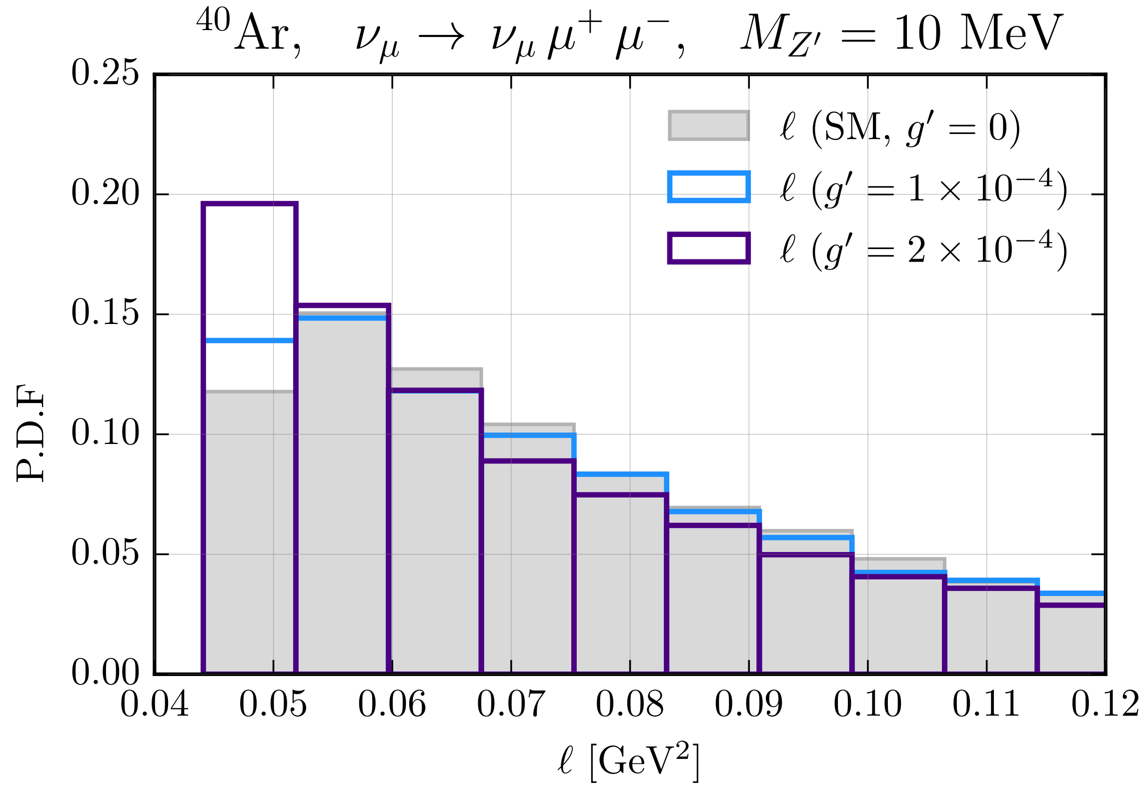
$$\mathscr{L}_{\rm int} \supset g' Z'_\alpha \left(\overline{L}_\mu \gamma^\alpha L_\mu - \overline{L}_\tau \gamma^\alpha L_\tau + \overline{\mu}_R \gamma^\alpha \mu_R - \overline{\tau}_R \gamma^\alpha \tau_R\right)$$

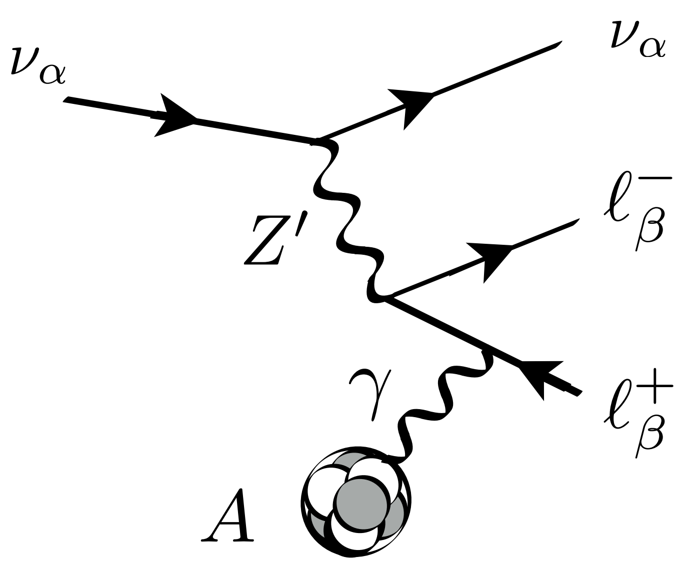
[Altmannshofer et al, 1406.2332]

$L_\mu - L_\tau$ gauge

Trident enhanced by light mediator mass, no QED contribution to compete with!

A single channel is affected: $\nu_\mu \to \nu_\mu \mu^+ \mu^-$

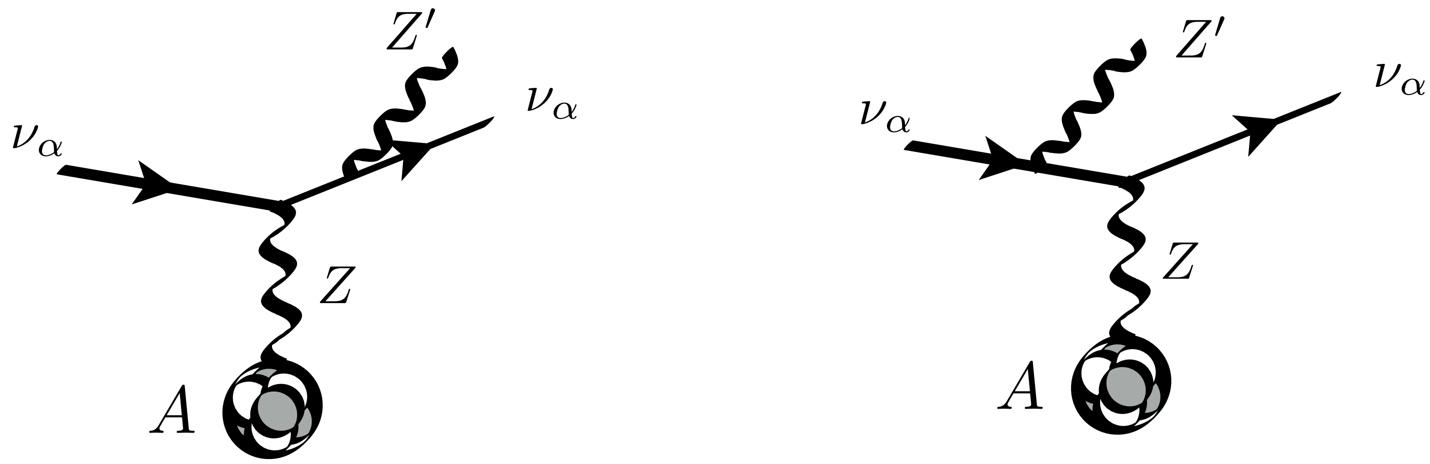




$L_\mu - L_\tau$ gauge

Other processes are also relevant if Z' decays visibly

"Dark bremsstrahlung"



Final state from $Z' \to \mu^+\mu^-$ looks nothing like trident.

Hunt invariant mass bump at $M_{Z'}$.

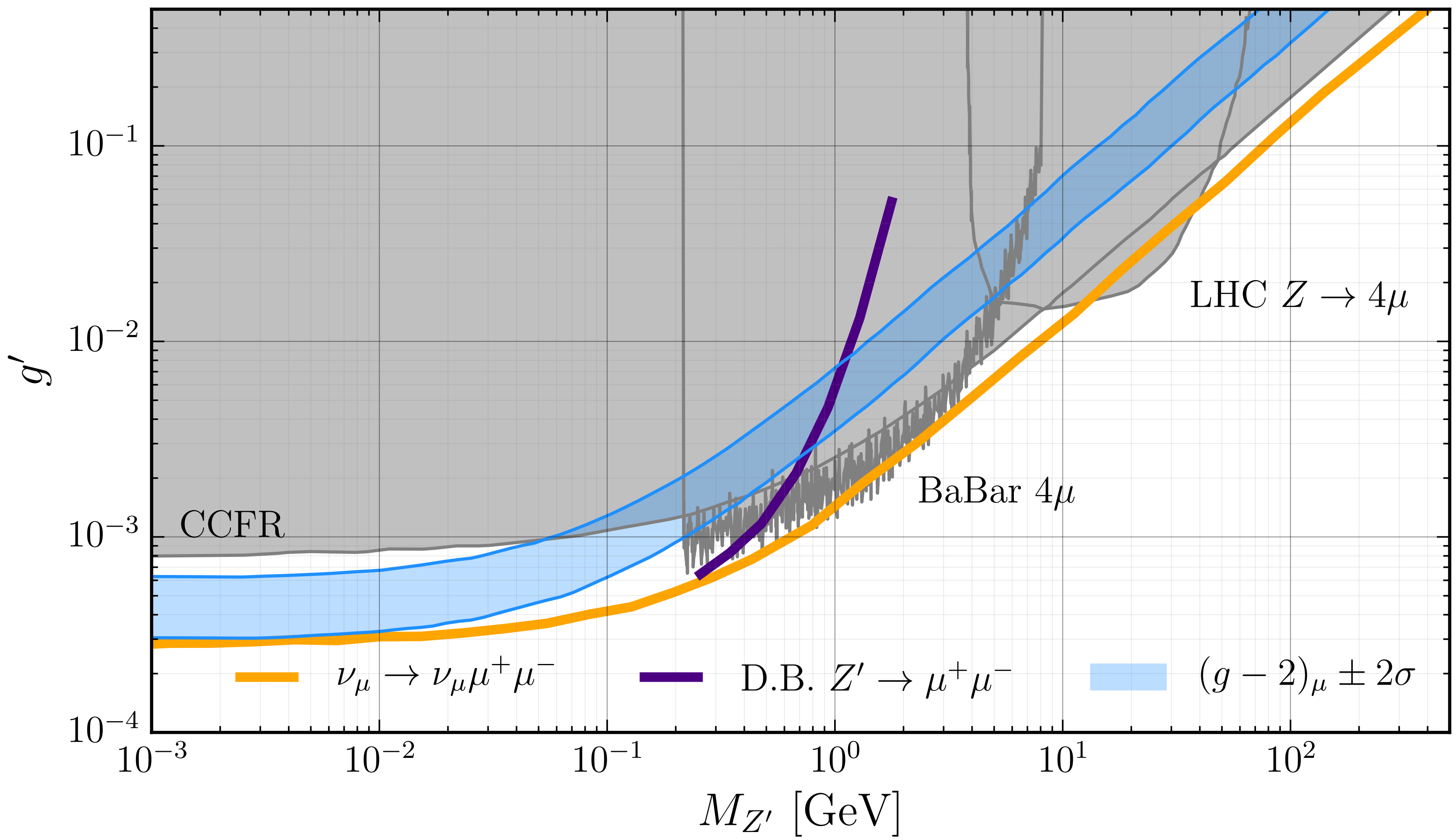
Experimental sensitivity

Sensitivity of DUNE ND

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

Enhancement is largest at **lower energies.**

Log sensitive to the Z' mass below 10 MeV.



DUNE near detector (**25 t**) at 90 % C.L.

Assume 10% normalisation systematics and no backgrounds.

Conclusions

Neutrino trident production measurement is an **attainable goal** of future LAr DUNE ND.

Trident events might hide in our current experiments. Can our detectors see them?

Incredibly sensitive to new physics. Leading constraint for $U(1)_{L_\mu - L_\tau}$.

Similar rates to tridents at DUNE?

To think: what can other rare processes teach us?

$$\nu_\alpha + \mathcal{N} \to \begin{cases} \ell^-_\alpha + \ell^+_\beta + \ell^-_\beta + \mathcal{N}' \\ \ell^-_\alpha + \nu_\beta + \overline{\nu}_\beta + \mathcal{N}' \\ \nu_\alpha + \nu_\beta + \overline{\nu}_\beta + \mathcal{N} \end{cases}$$

THANK YOU

APPENDIX

Near detectors

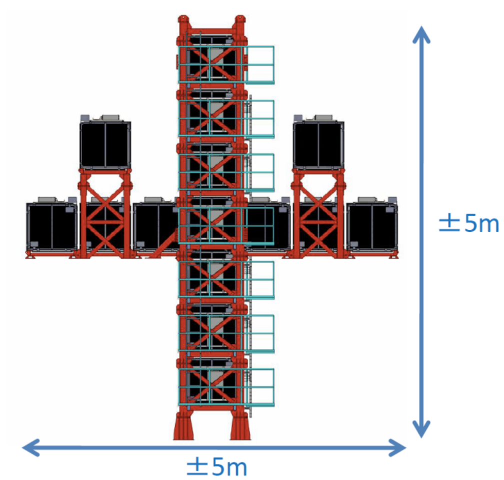
SBND	110 m, 112 t	6.6×10^{20} P.O.T.
μBooNE	470 m, 89 t	13.2×10^{20} P.O.T.
ICARUS	600 m, 476 t	6.6×10^{20} P.O.T.

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

50 m from the storage ring, 100 t LAr
assuming 10^{21} P.O.T.

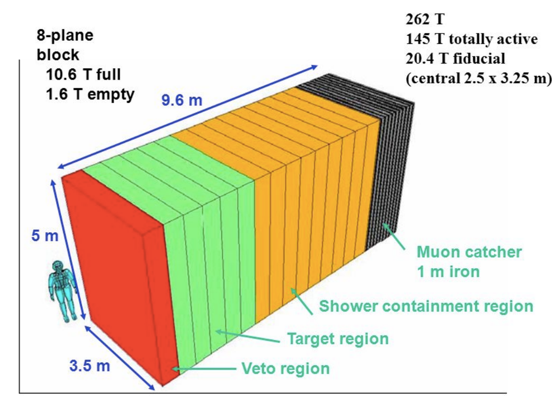
Near detectors

INGRID

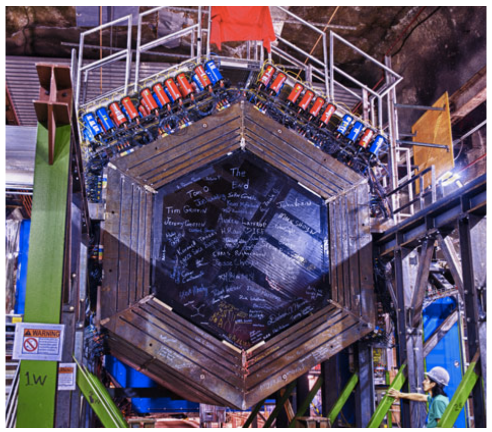


MINOS/+

NOvA



MINERvA



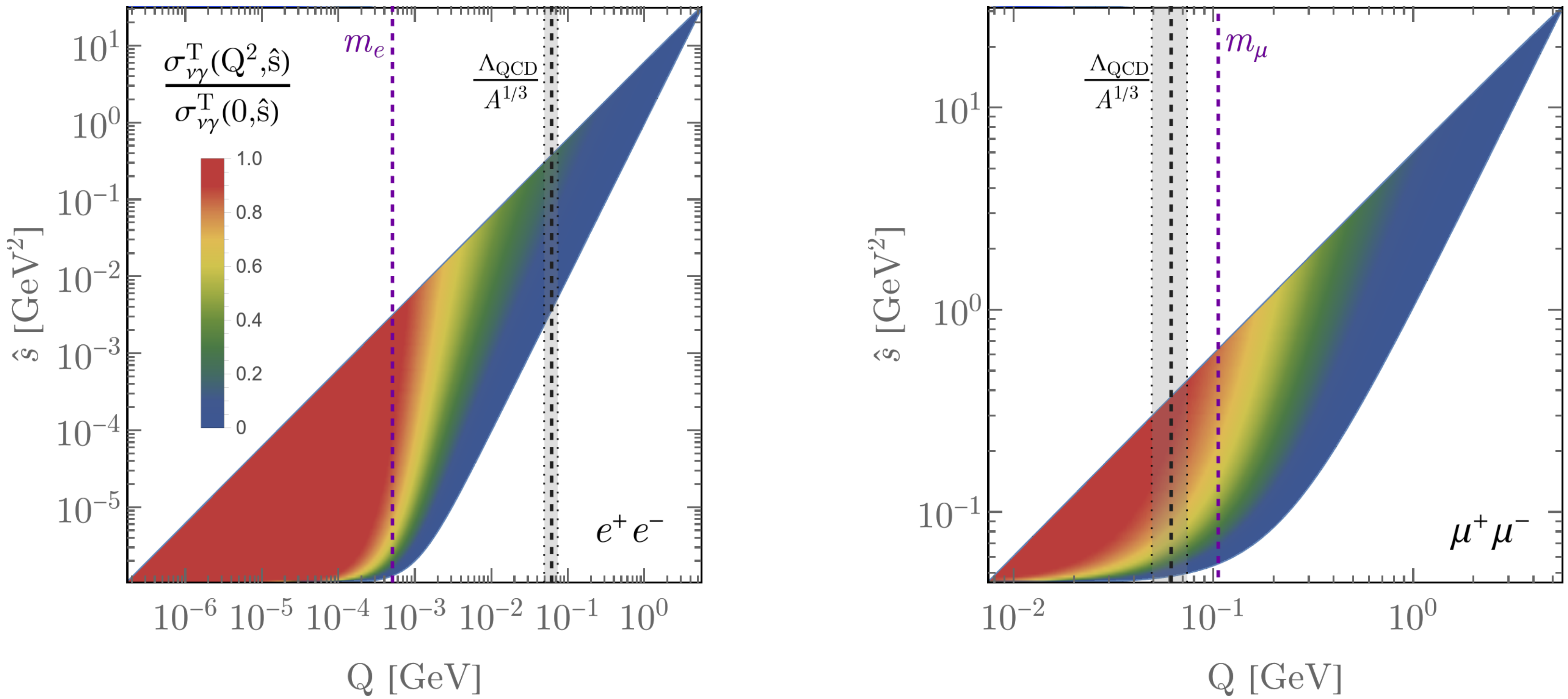
Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mas
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12)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

EPA

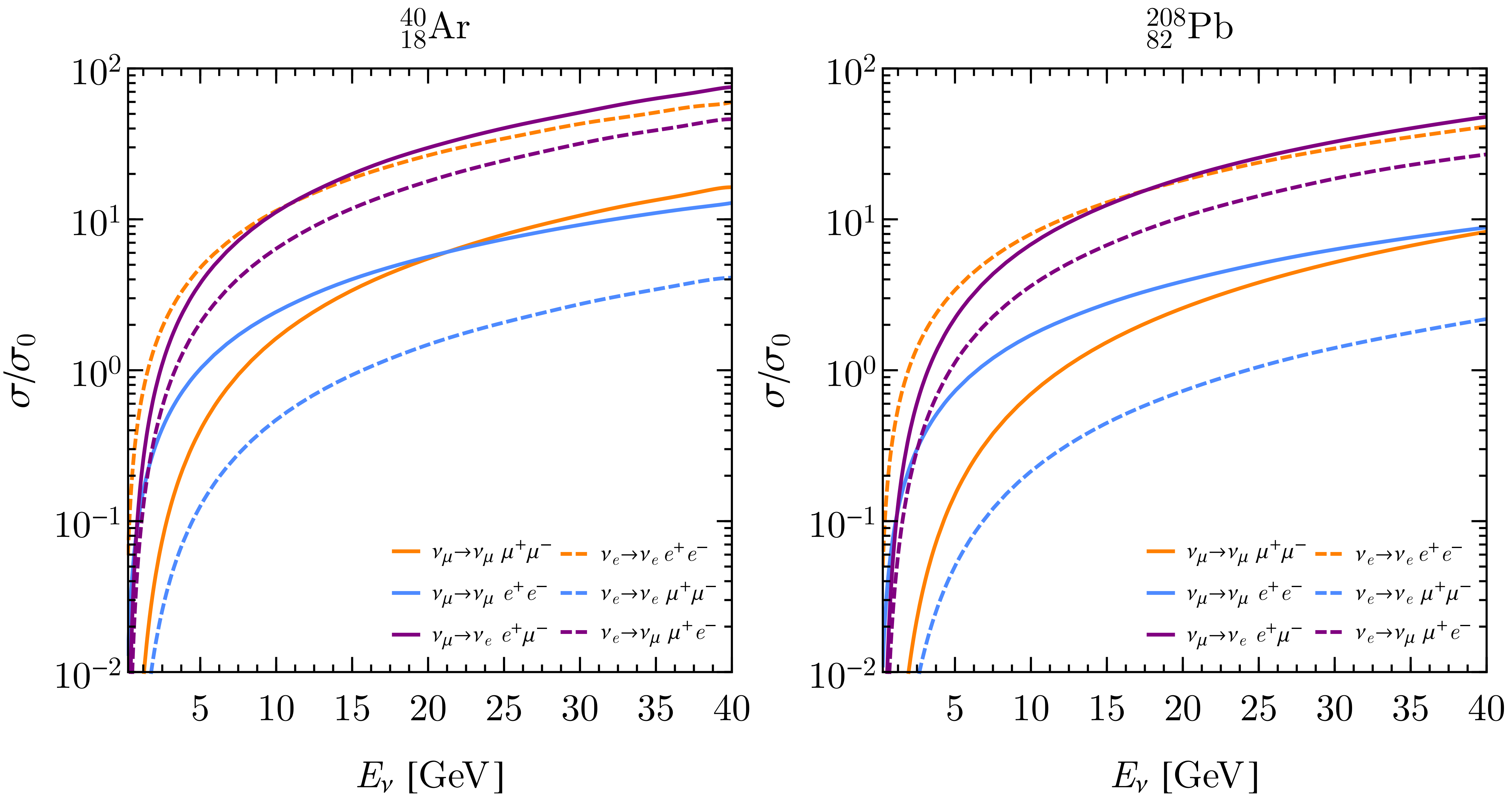
EPA assumptions

1) Neglecting the L contribution ($h^{\mathrm{L}}(q^2, \hat{s})\, \sigma^{\mathrm{L}}_{\nu\gamma}(q^2, \hat{s}) \approx 0$).

2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2, \hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0, \hat{s})$).



4PS cross sections



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