NEUTRINO TRIDENT PRODUCTION AT NEAR DETECTORS

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in collaboration with
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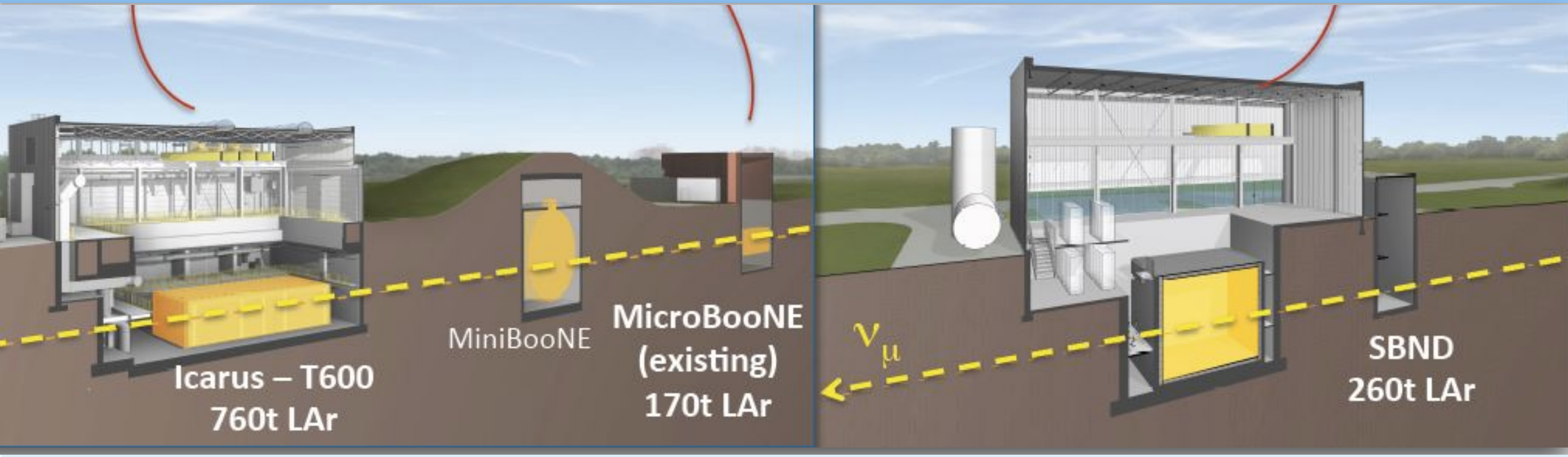
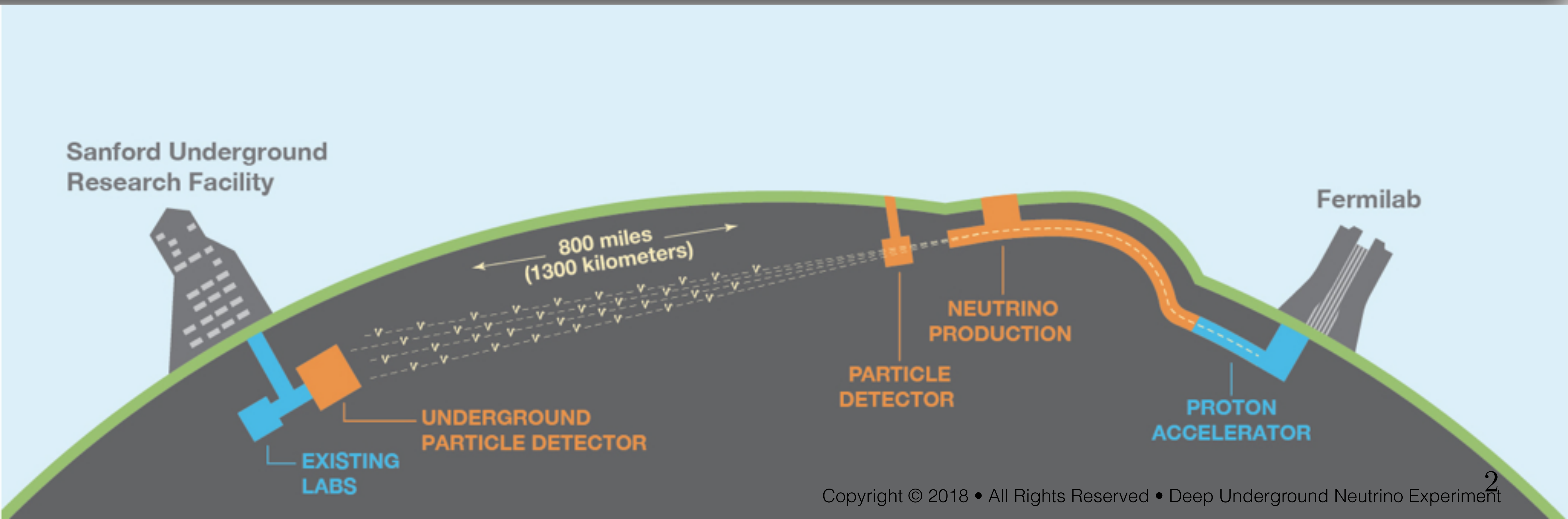
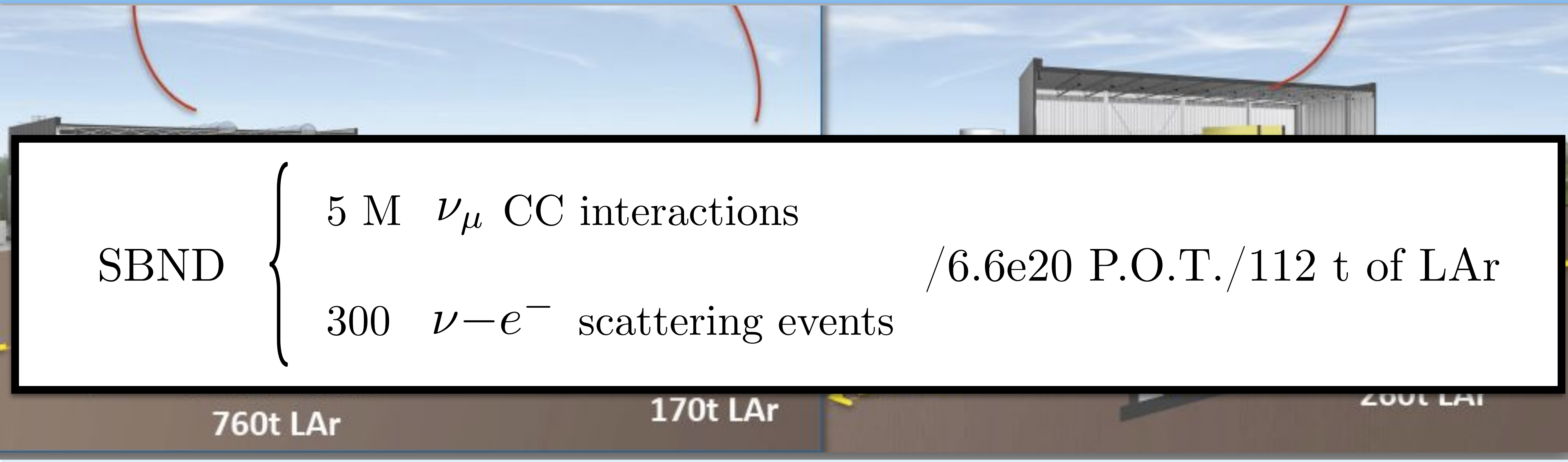
SCIENCE WITHOUT BORDERS

Near detectors

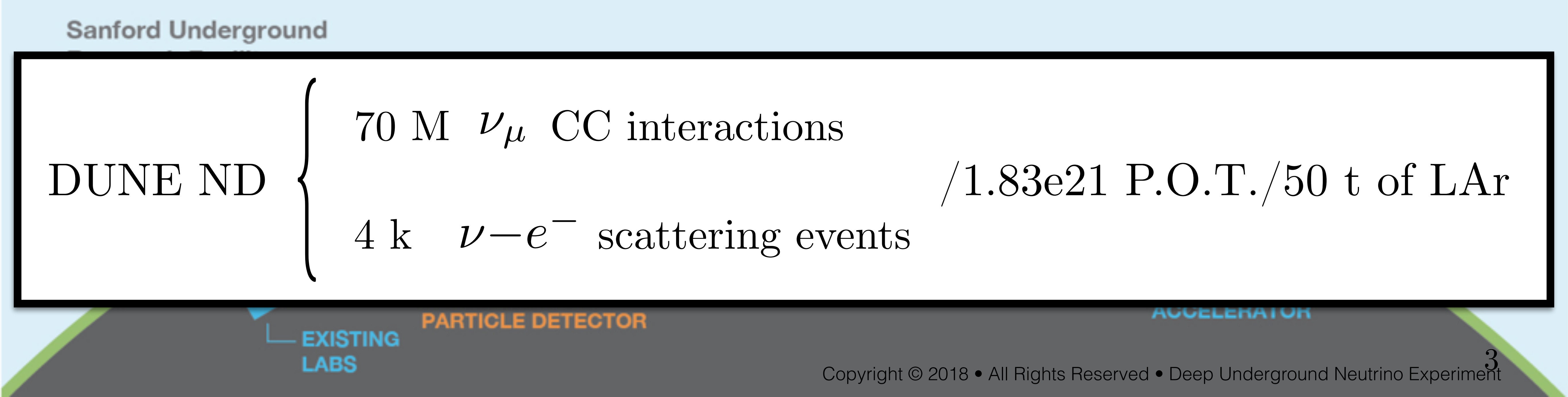




Near detectors



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



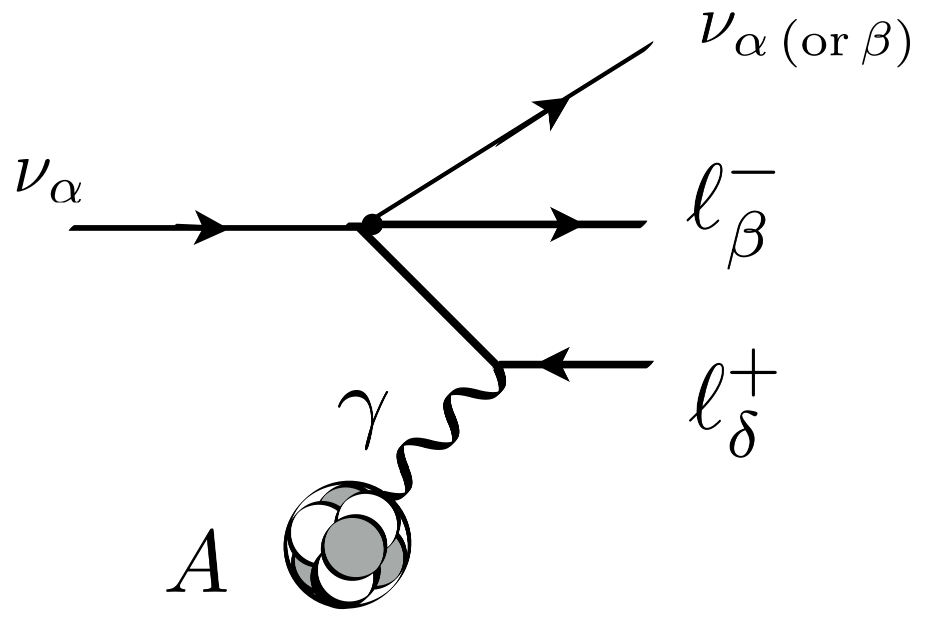
DUNE ND $\left\{ \begin{array}{l} 70\ \text{M}\ \ \nu_\mu\ \text{CC interactions} \\ 4\ \text{k}\ \ \nu{-}e^-\ \text{scattering events} \end{array} \right.$ /1.83e21 P.O.T./50 t of LAr

Neutrino trident production

neutrino trident production

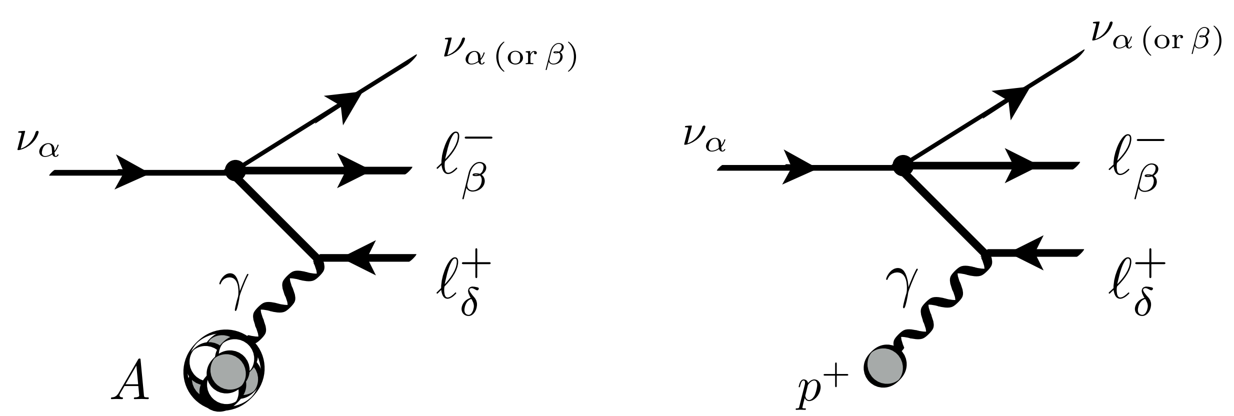
or

pair production by a neutrino



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

Neutrino trident production



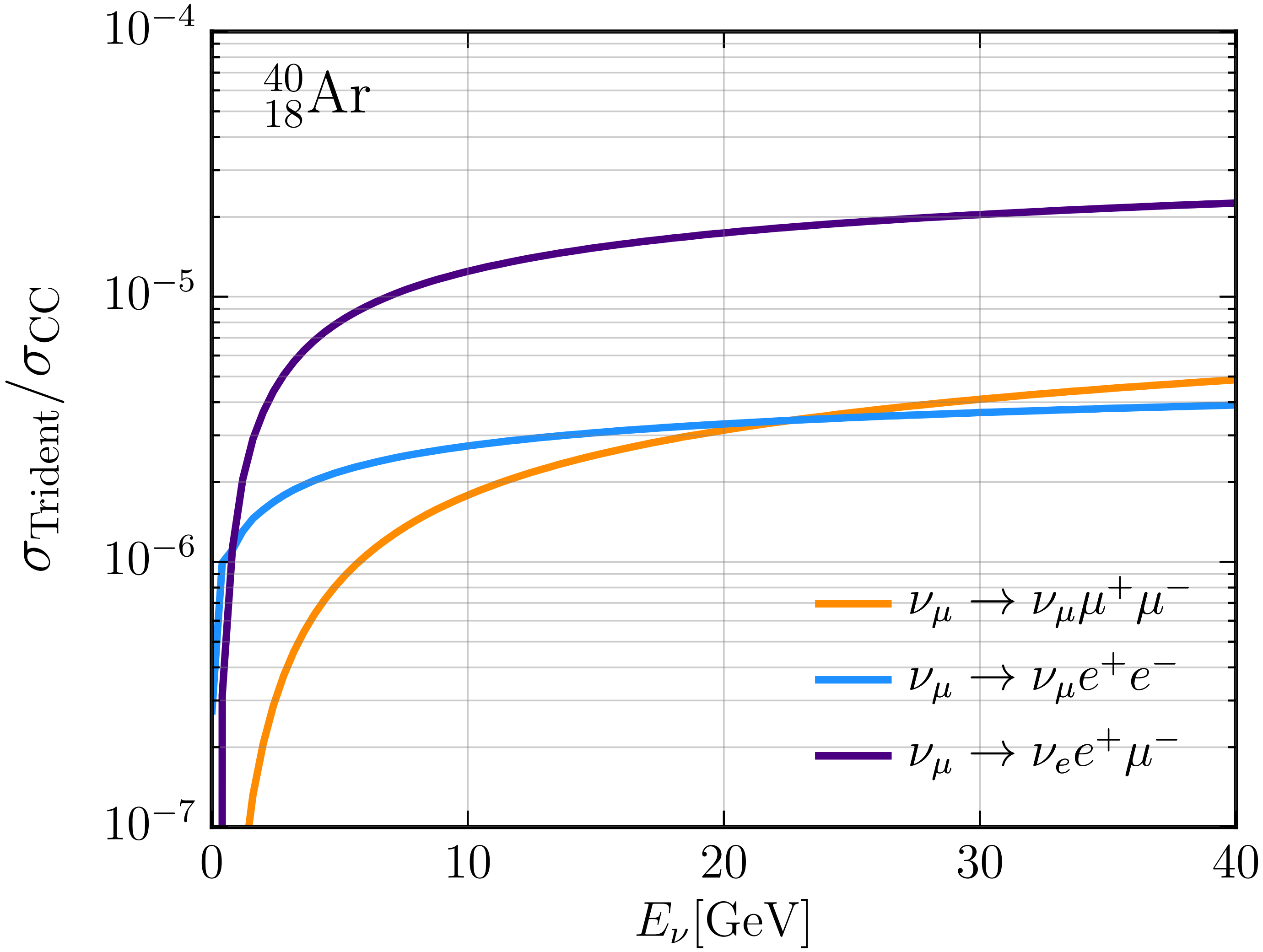
Pair production in the EM field of the
nucleus, nucleons or quarks.

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

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

Neutrino trident production

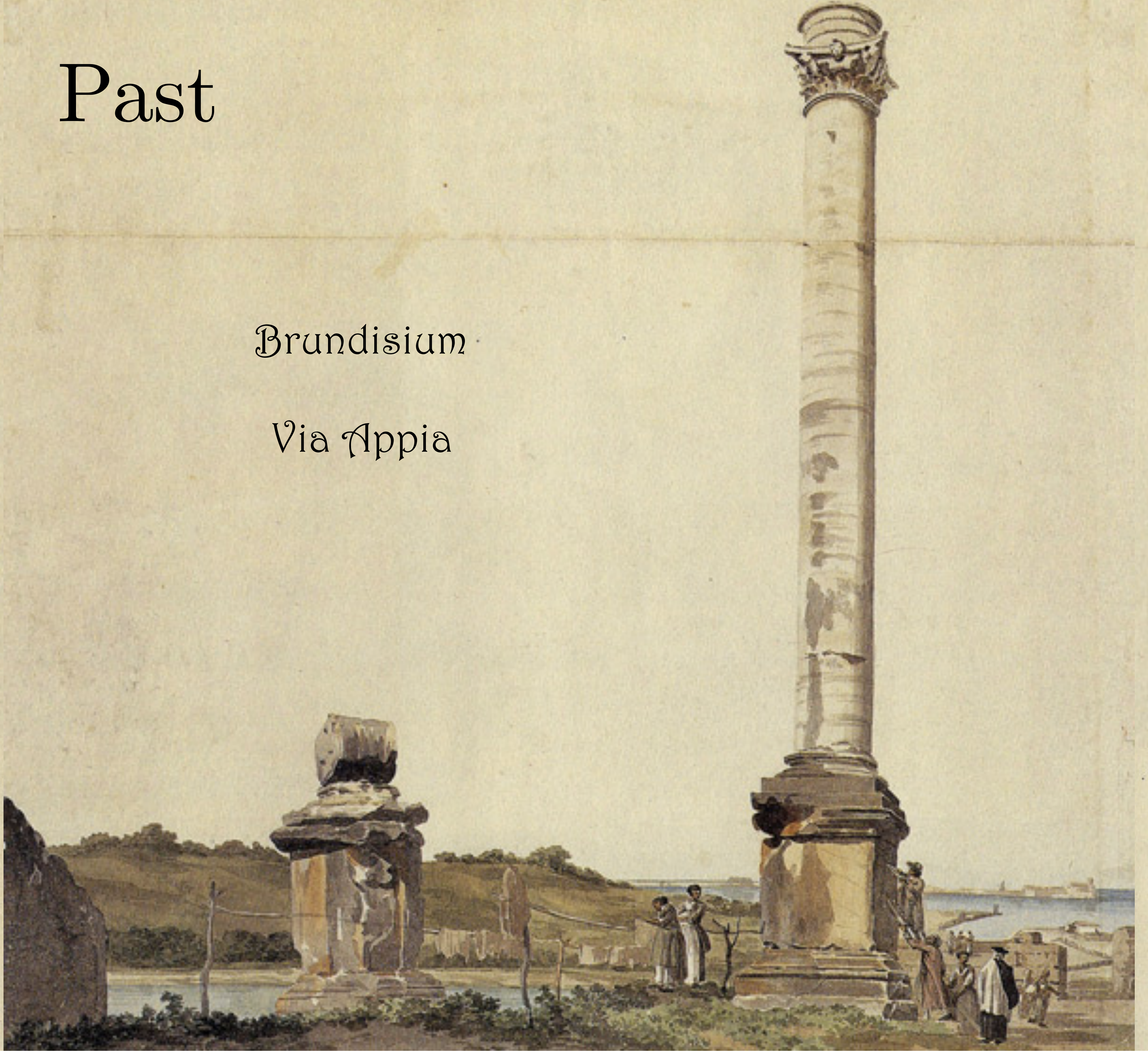
How rare is it?



Past

Brundisium

Via Appia



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 (1990)**] — First measurement of $\mu^+\mu^-$ trident.

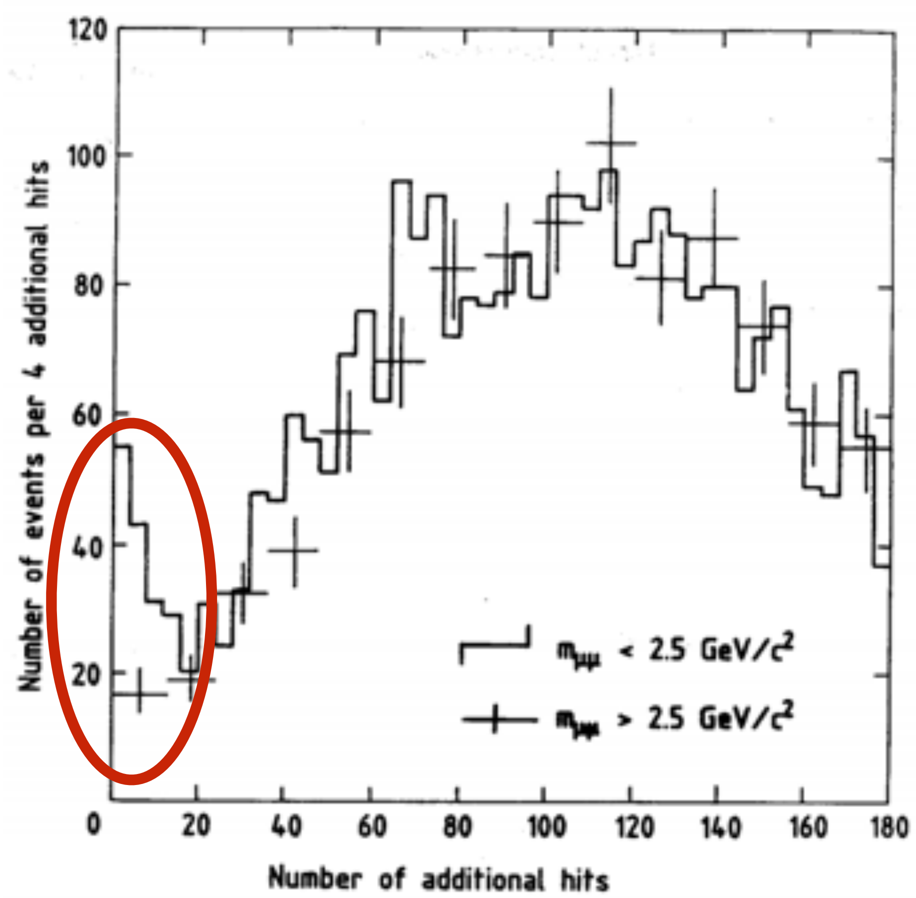
$$\langle E_\nu \rangle = 25 \text{ GeV}$$

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

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

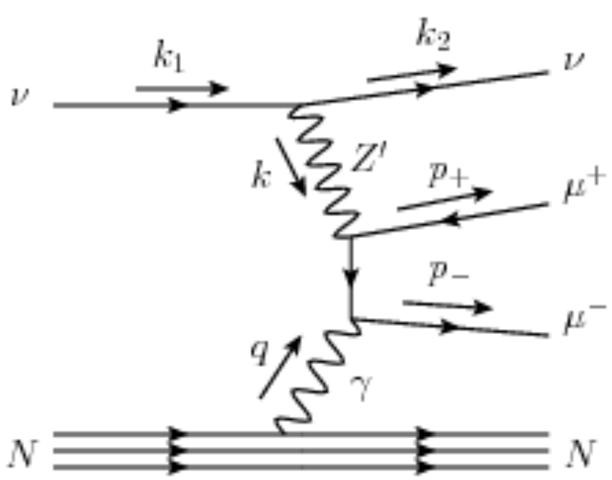
[CCFR, 1991]

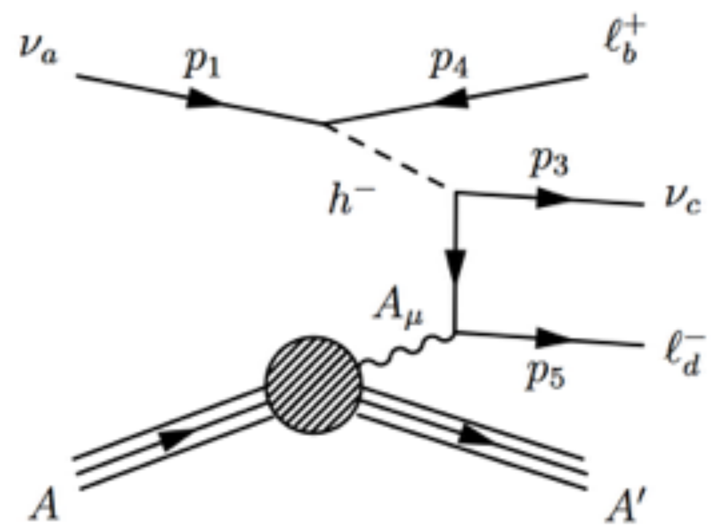
[NuTeV, 1998]



Present

Present





Renewed interest, leading bound in $U(1)_{L_\mu - L_\tau}$ model. [W. Altmannshoffer et al, 2014]

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

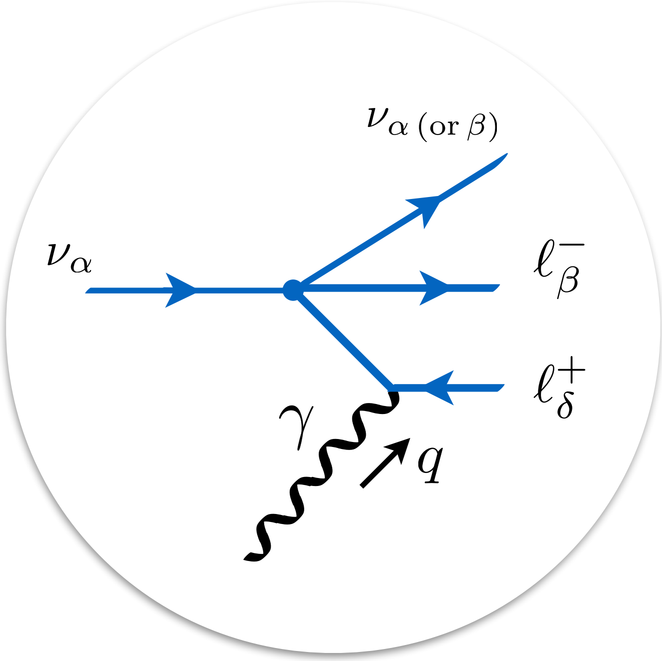
Atmospheric neutrino trident production. [SF Ge et al, 2017]

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

Trident constraints on EFT. [A. Falkowski et al, 2018]

Present

Equivalent Photon Approximation (EPA)



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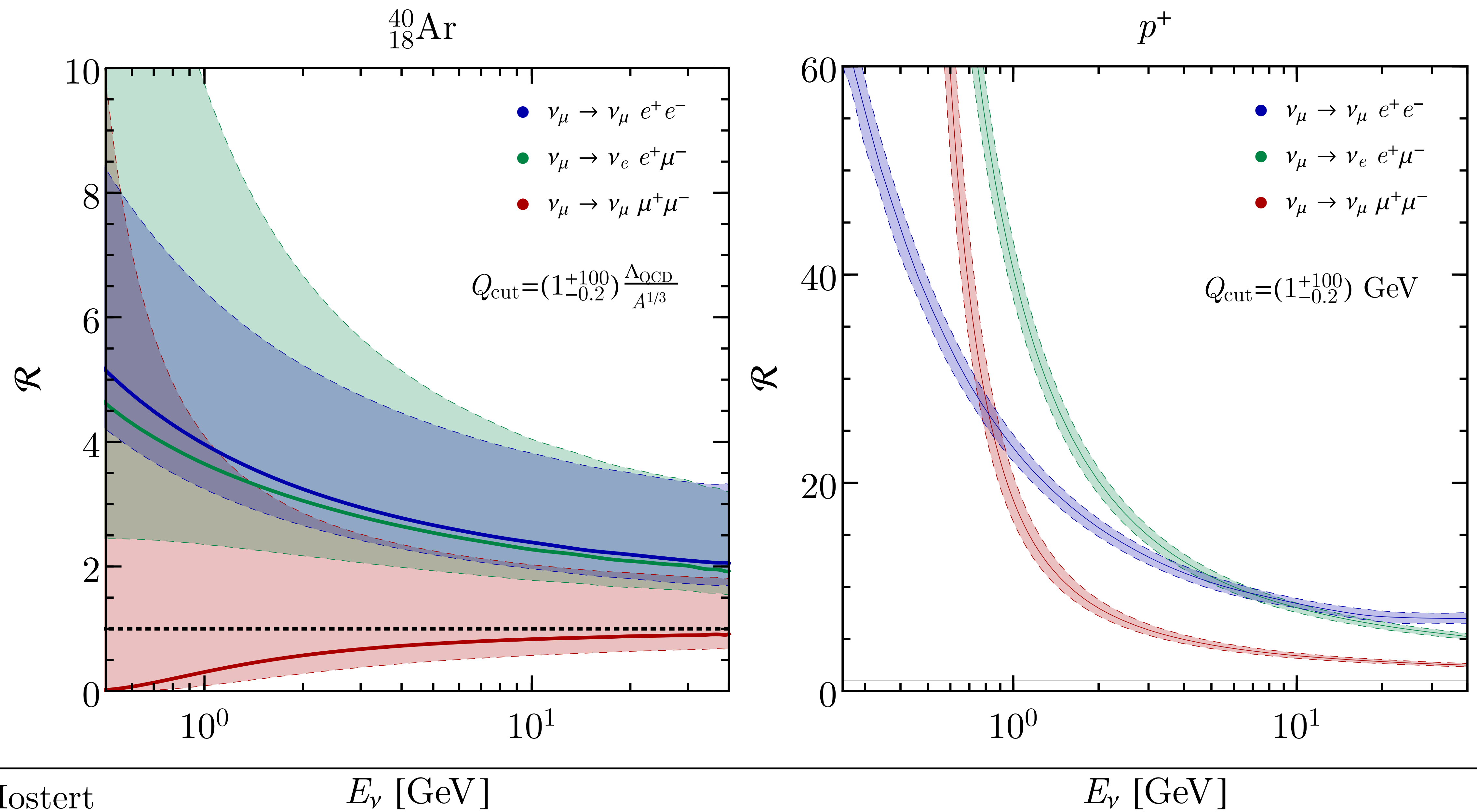
EPA

How bad is it?

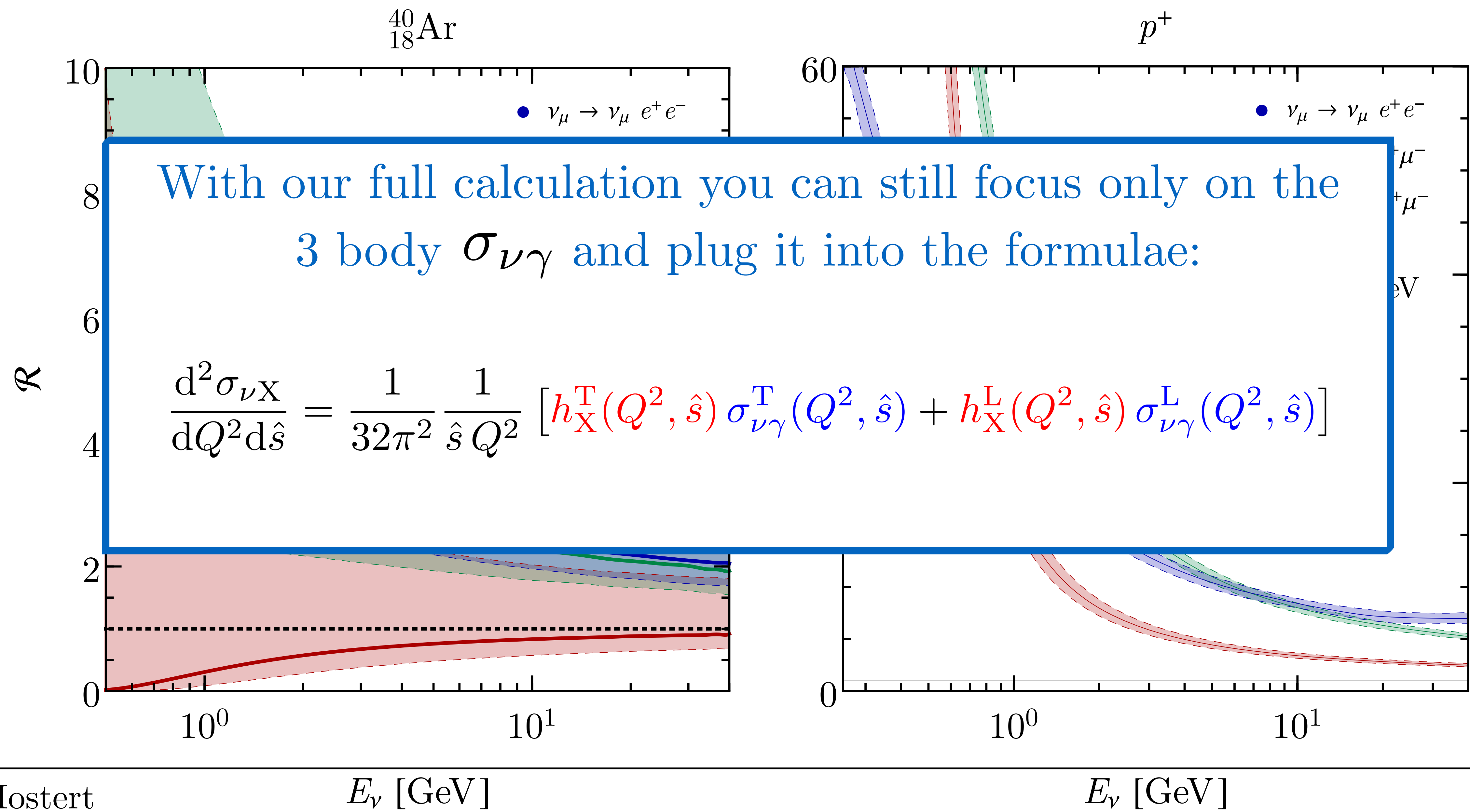
$$\mathcal{R} = \frac{\sigma_{\rm EPA}(E_\nu)|_{Q_{\rm max}}}{\sigma_{\rm 4PS}(E_\nu)}$$



EPA

How bad is it?

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



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

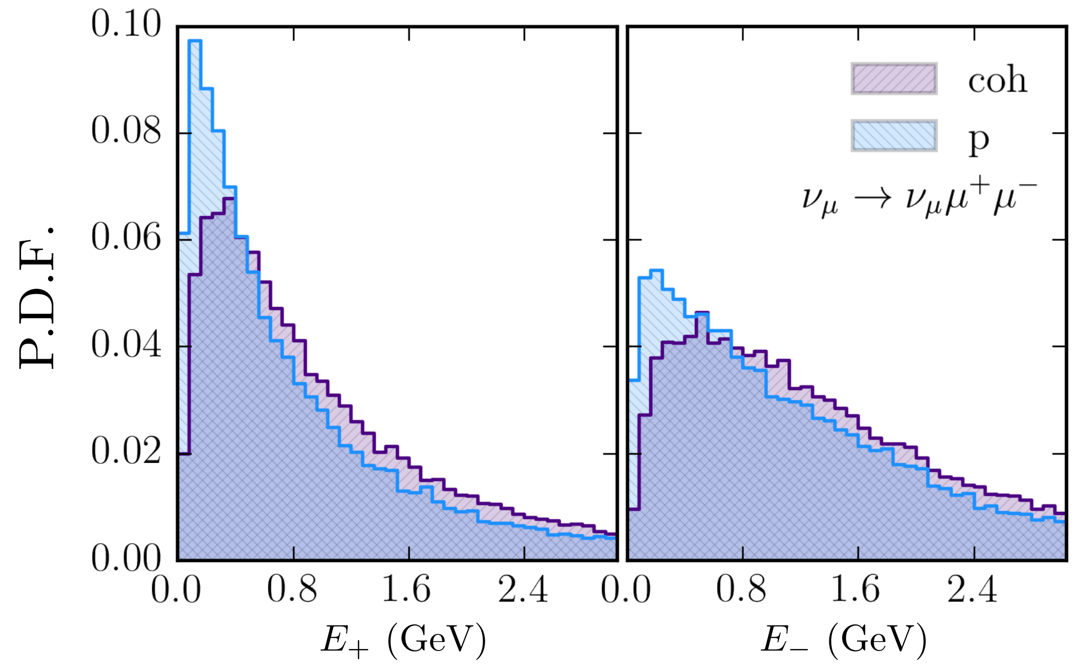
$$\frac{\mathrm{d}^2\sigma_{\nu\mathrm{X}}}{\mathrm{d}Q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,Q^2}\left[h_{\mathrm{X}}^{\mathrm{T}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{T}}(Q^2,\hat{s}) + h_{\mathrm{X}}^{\mathrm{L}}(Q^2,\hat{s})\,\sigma_{\nu\gamma}^{\mathrm{L}}(Q^2,\hat{s})\right]$$

LAr rates

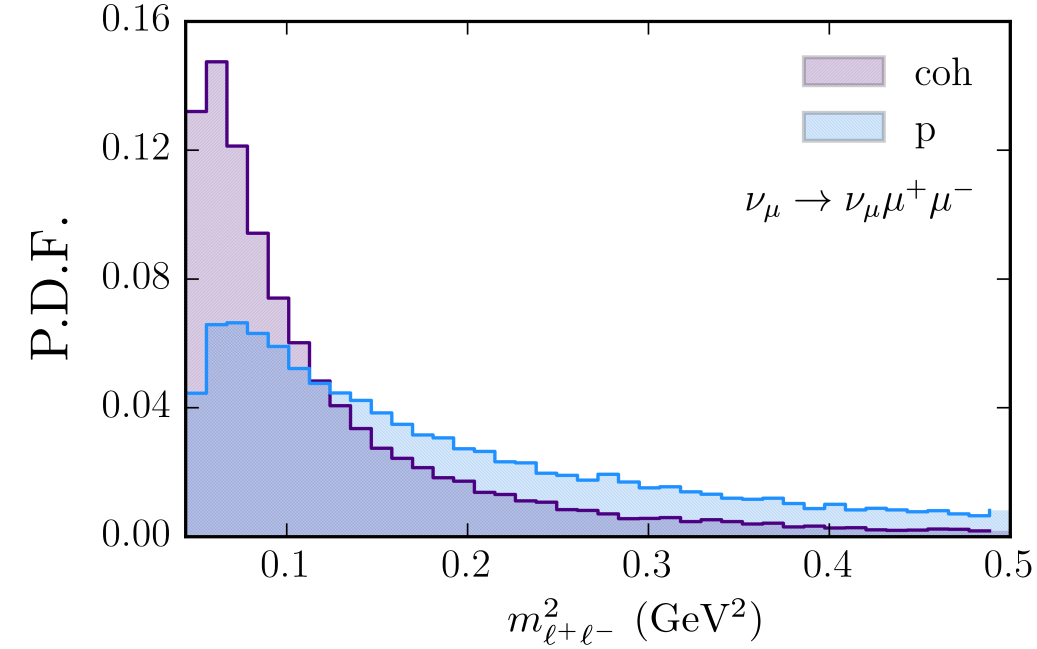
Channel	SBND	μBooNE	ICARUS	DUNE ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)
	2	0.1	0.2	692 (530)
Total e^+e^-	6	0.4	0.7	1007 (800)
	0.7	0.0	0.1	143 (111)
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)
	0.4	0.0	0.0	196 (147)

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode in the expected lifetime of the experiment.

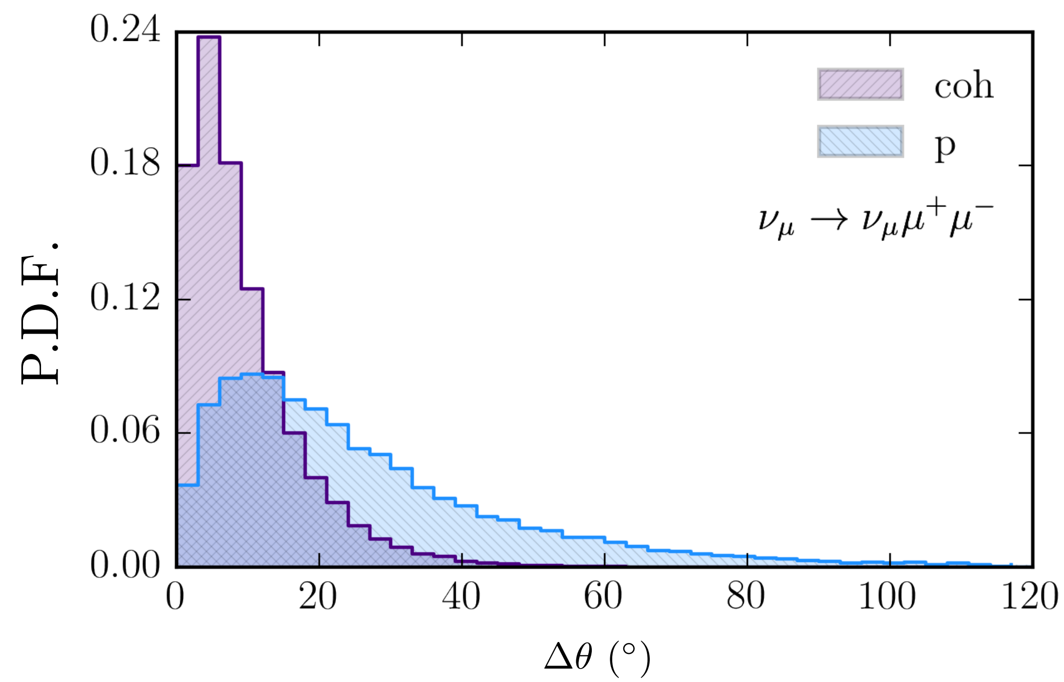
The signal @ DUNE



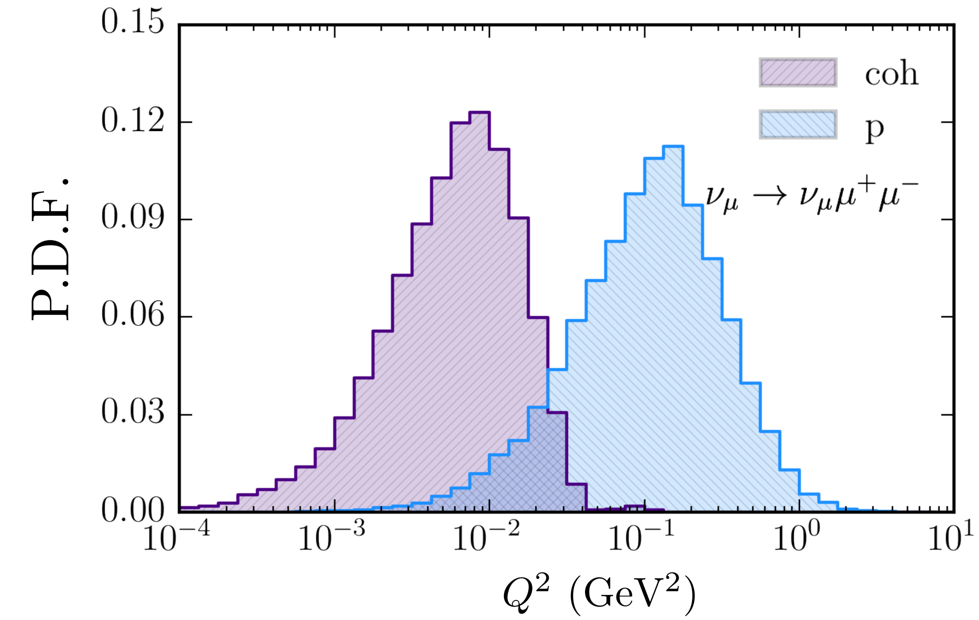
Not a problem.



Incredibly low invariant masses.



Collimated muons.



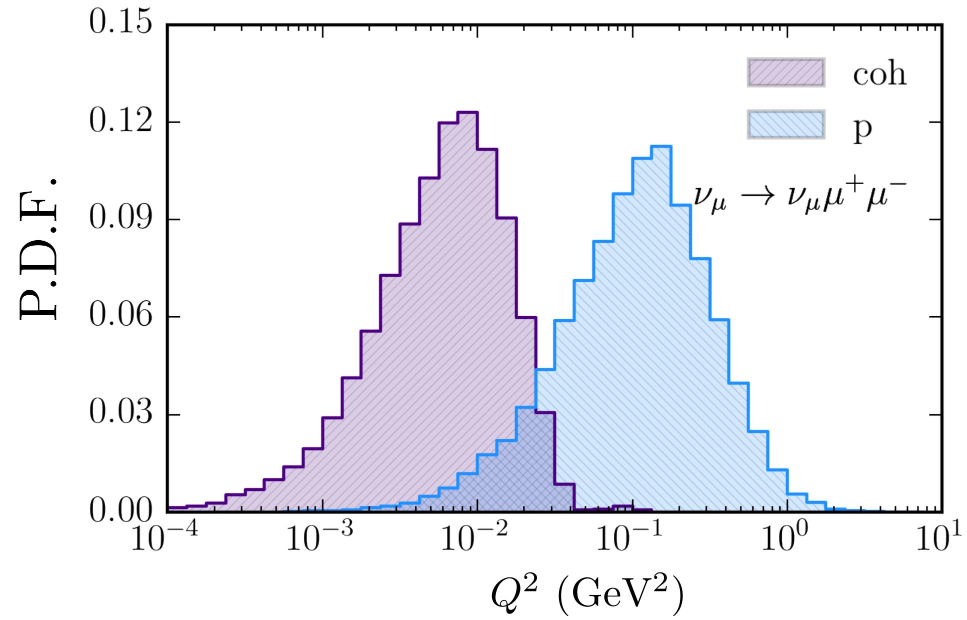
No hadronic activity at the vertex?

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.

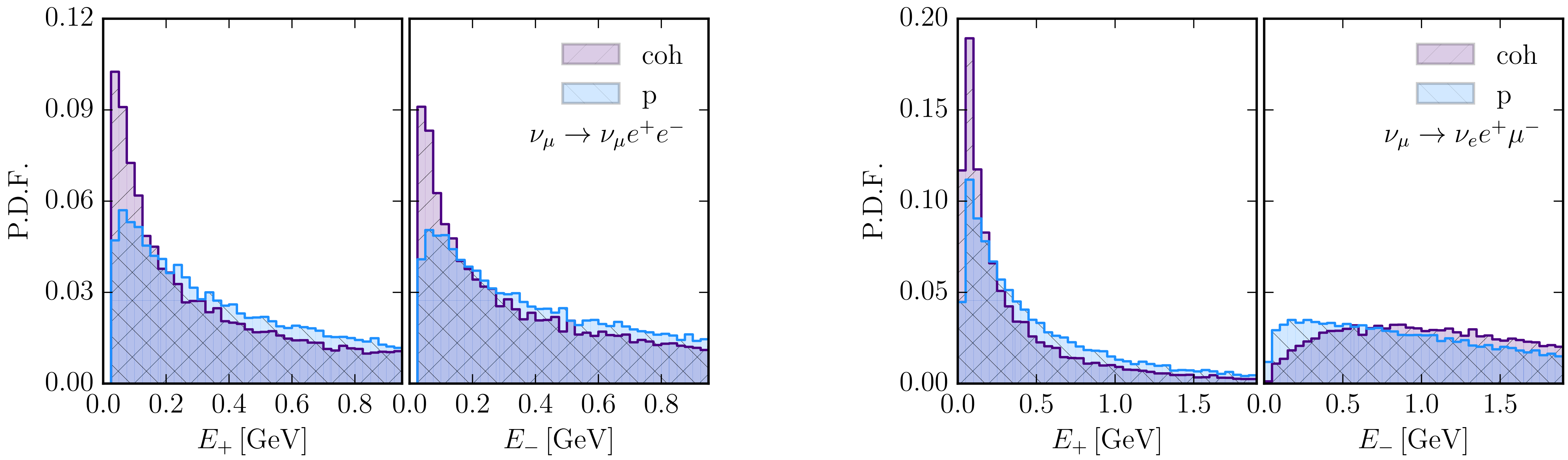


No hadronic activity at the vertex?

The signal @ DUNE

Electrons are produced with low energies.

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



Backgrounds

Genuine dilepton production with no hadronic activity is rare, but misID is the problem.

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

Constant misID rates

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

$\mu^+\mu^-$

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

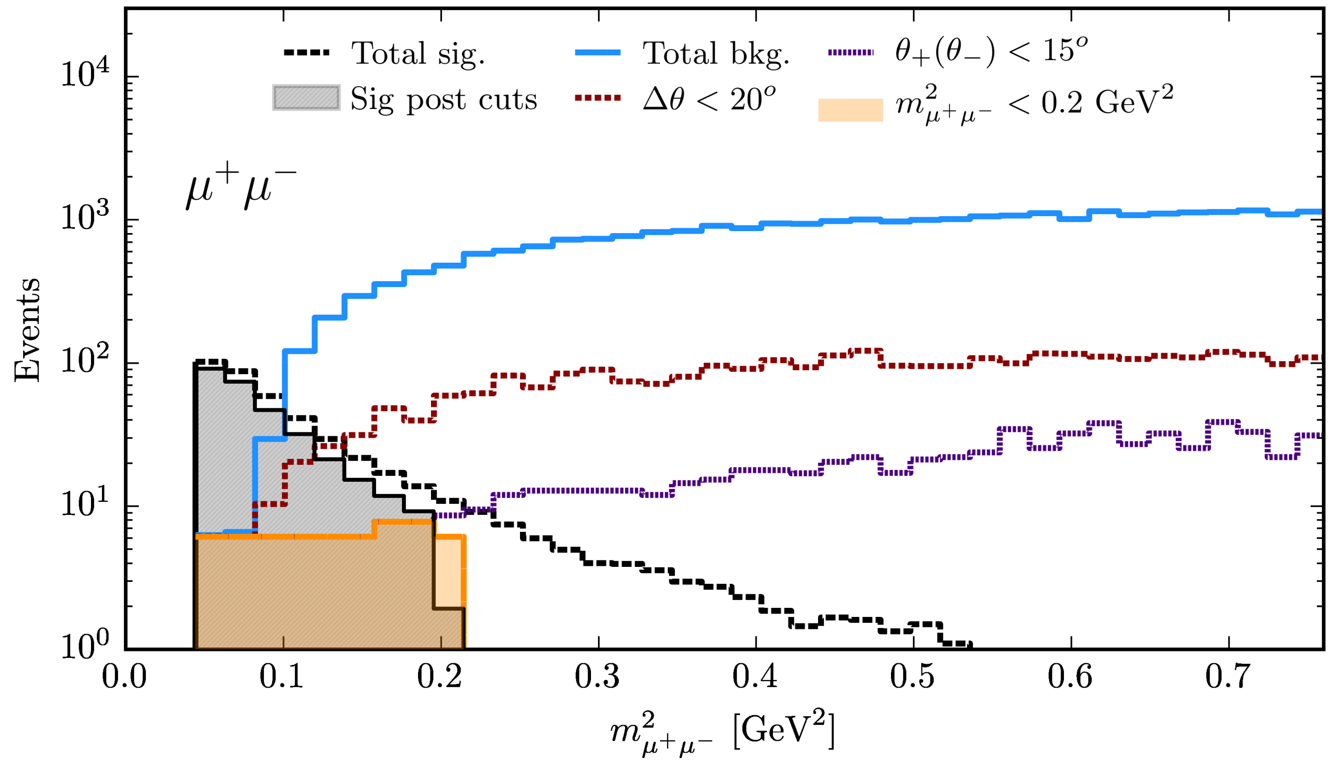
e^+e^-

NC1π^0 and ν_eCCπ^0.

$e^+\mu^-$

CC1π^0 with misID γ .

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



Channel	N_B^{misID}/N_{CC}	N_B^{had}/N_{CC}	N_B^{kin}/N_{CC}	ϵ_{sig}^{coh}	ϵ_{sig}^{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.

Caveats!

Detector effects? Efficiencies at lower energies?

De-excitation gammas? Internal bremsstrahlung?
Dalitz decays?

6 orders of magnitude is a lot.

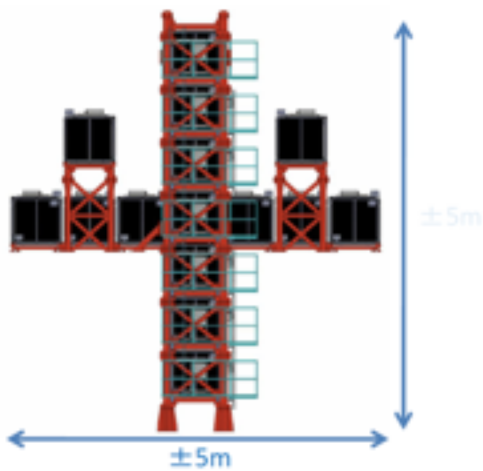
Channel					$\epsilon_{\rm sig}^{\rm dif}$
$e^\pm\mu^\mp$					0.39 (0.39)
e^+e^-					0.21 (0.21)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)	0.17 (0.16)

Other near detectors

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

Could we measure it now?!

Other near detectors

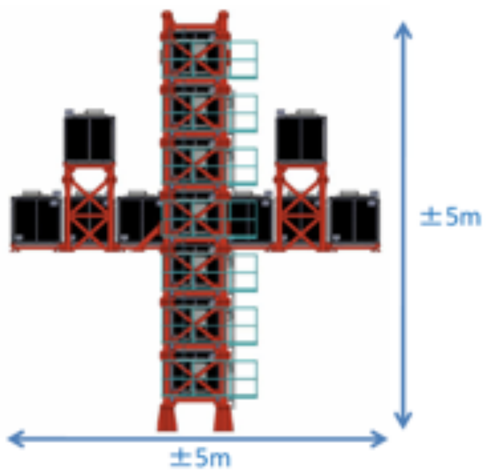
INGRID	MINOS/+	NOvA	MINERvA
			

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 near detectors

INGRID



MINOS/+

NOvA

MINERvA

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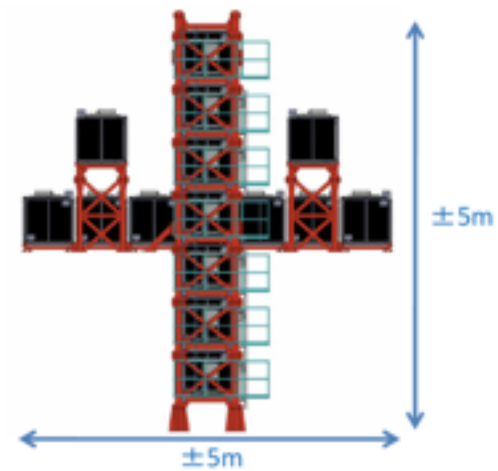
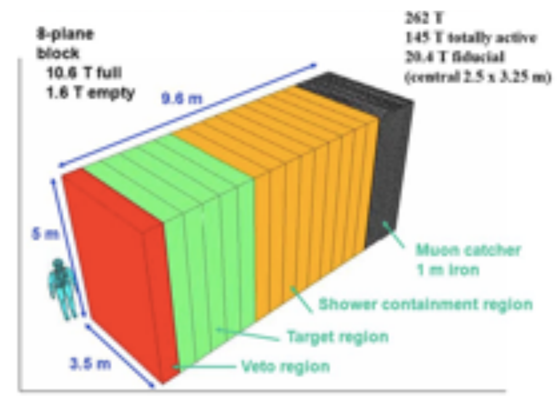


MINOS/+

NOvA



MINERvA

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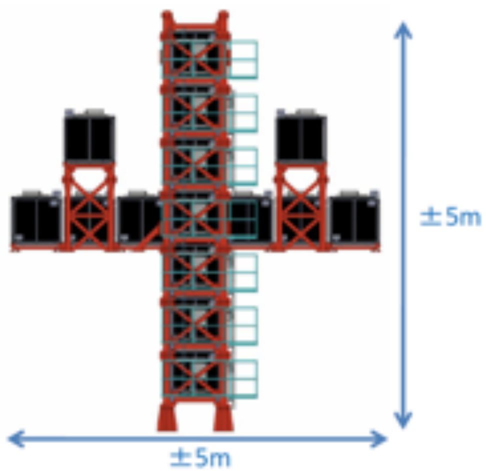
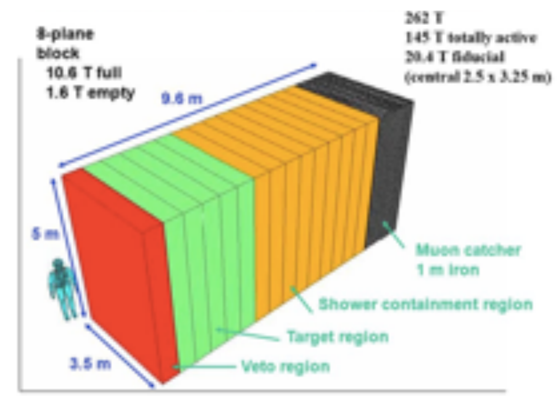
Other near detectors

INGRID

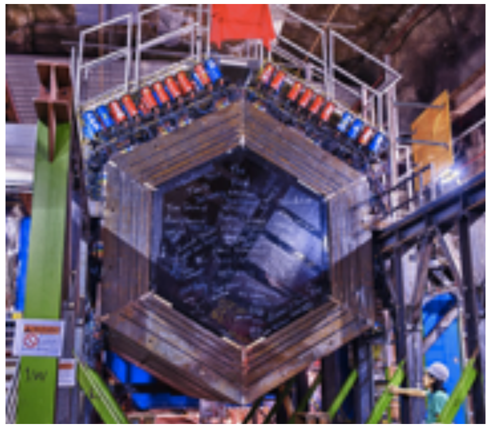


MINOS/+

NOvA



MINERvA



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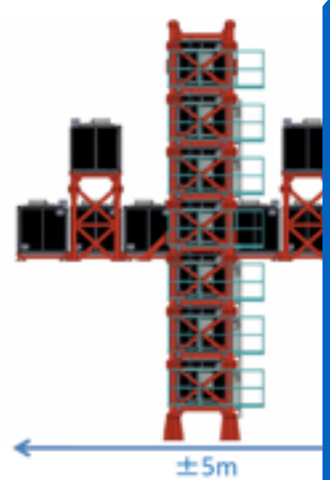
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Other near detectors

INGRID MINOS/+ NOvA MINERvA



Could these experiments be in the game?

Detector performance study needed.

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

Conclusions

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

Very first measurement of electron channels possible.

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

.

What else can trident and other rare processes teach us?

THANK YOU

APPENDIX

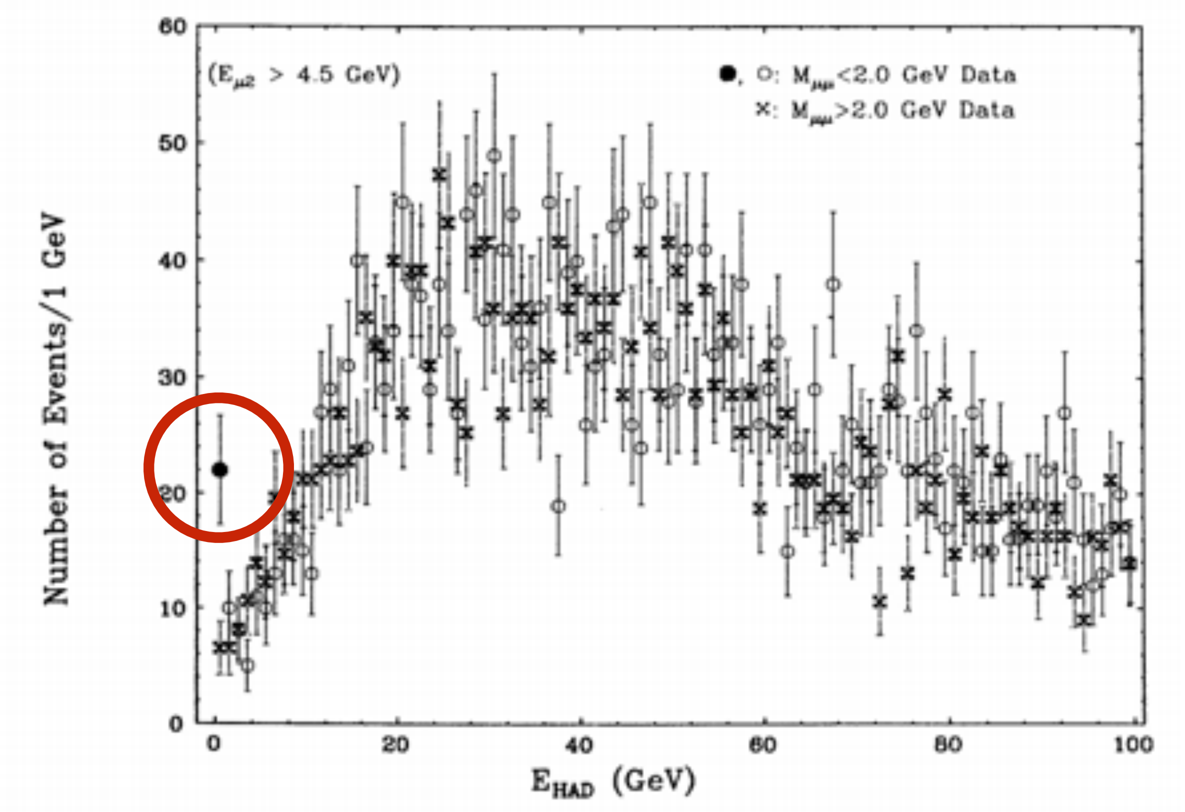
CCFR Measurement

CCFR (1991)

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

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

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



Parameters assumed for LAr rates

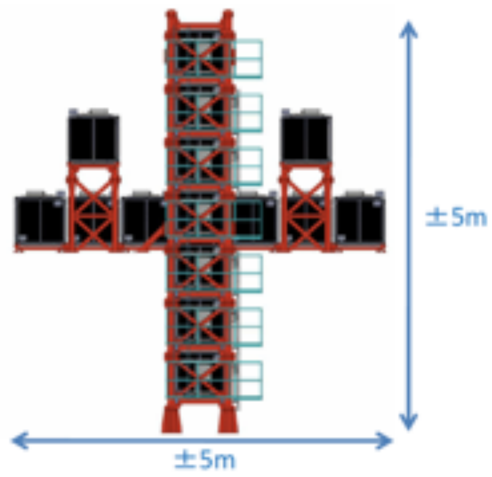
SBND	110 m, 112 t	6.6×10^{20} P.O.T.
μBooNE	470 m, 89 t	13.2×10^{20} P.O.T.
ICARUS	600 m, 476 t	6.6×10^{20} P.O.T.

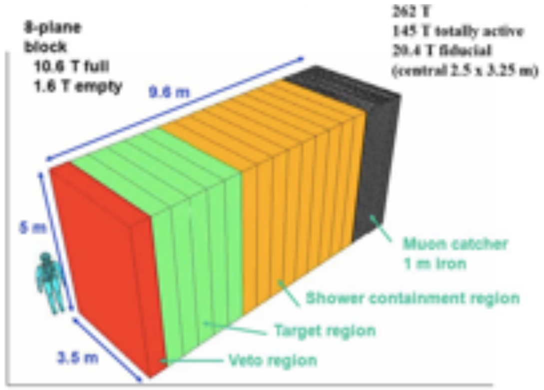
---

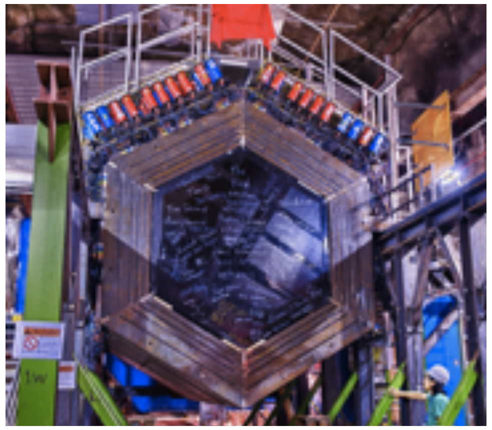
50 t LAr, assuming
$(2 + 2 \times 3) \times 1.83\text{e}21$ P.O.T.
in nu and nubar mode.

Parameters assumed for current rates

INGRID	MINOS/+	NOvA	MINERvA







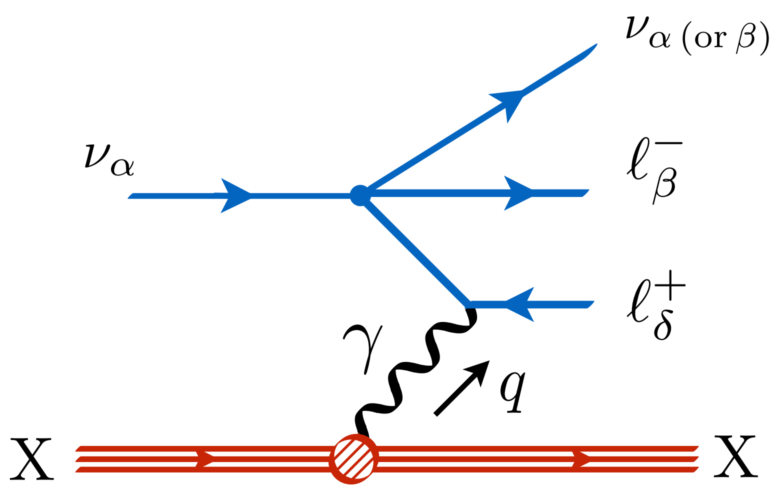
Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mass
INGRID	Fe	280	3.9×10^{21} $[10^{22}]$ T2K-I [T2K-II]	99.4
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12)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

POT in antineutrino mode in parentheses.

The cross section

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.

Universal leptonic T and L cross sections.

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

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

EPA breakdown

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 ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2, \hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0, \hat{s})$).

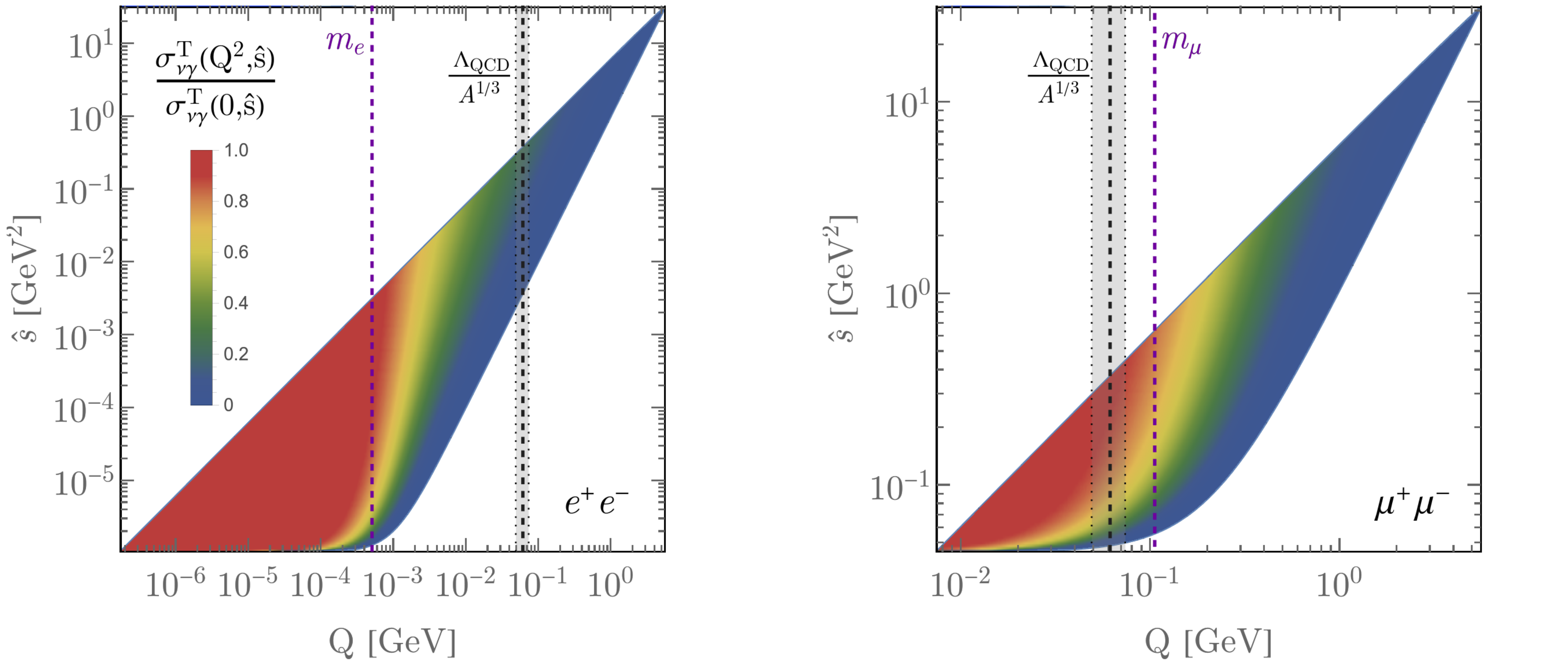
$$\frac{\mathrm{d}^2\sigma_{\nu \mathrm{X}}}{\mathrm{d}Q^2 \mathrm{d}\hat{s}} = \frac{1}{32\pi^2} \frac{1}{\hat{s}\, Q^2} \left[h^{\mathrm{T}}_{\mathrm{X}}(Q^2, \hat{s})\, \sigma^{\mathrm{T}}_{\nu\gamma}(Q^2, \hat{s}) + h^{\mathrm{L}}_{\mathrm{X}}(Q^2, \hat{s})\, \sigma^{\mathrm{L}}_{\nu\gamma}(Q^2,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

EPA breakdown

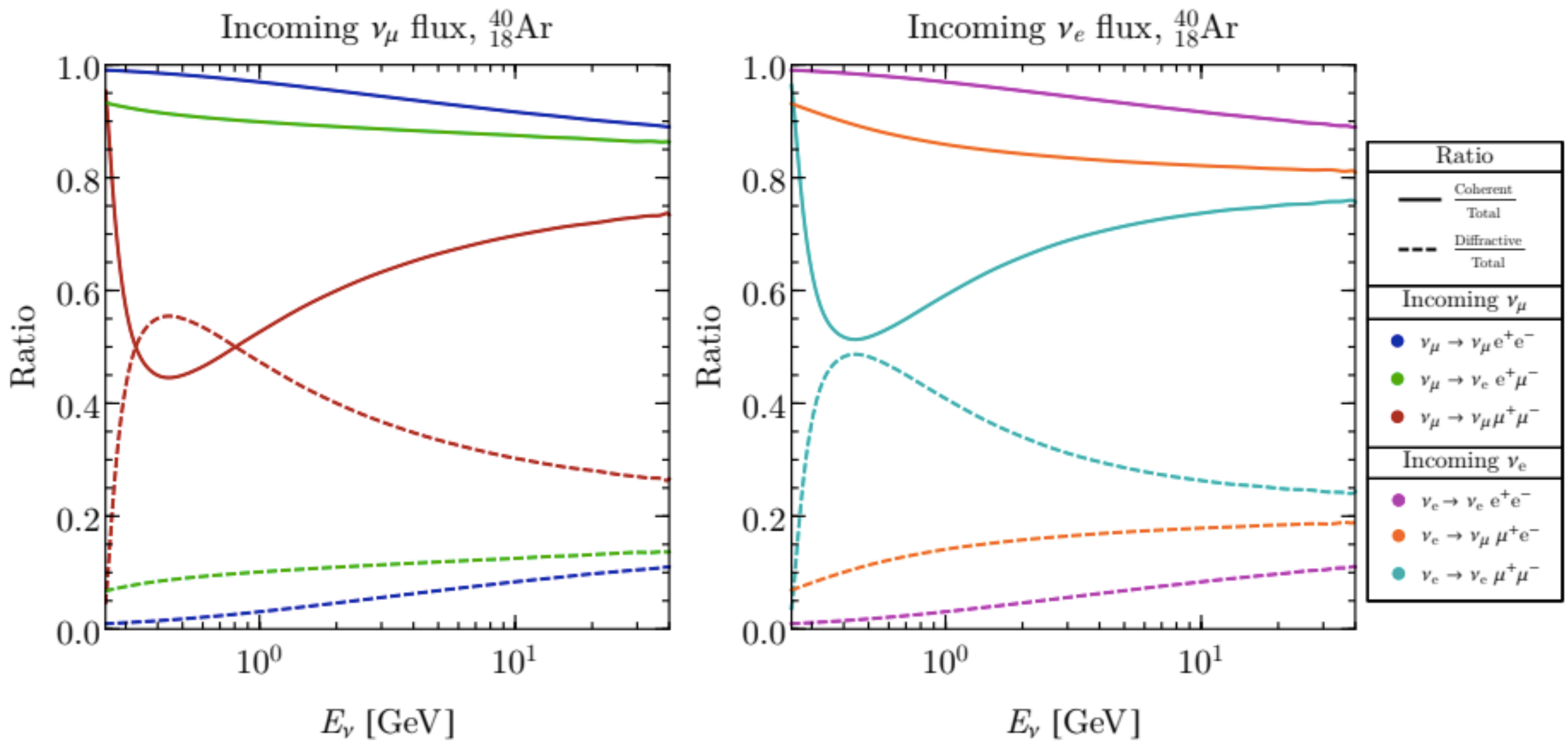
EPA assumptions

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

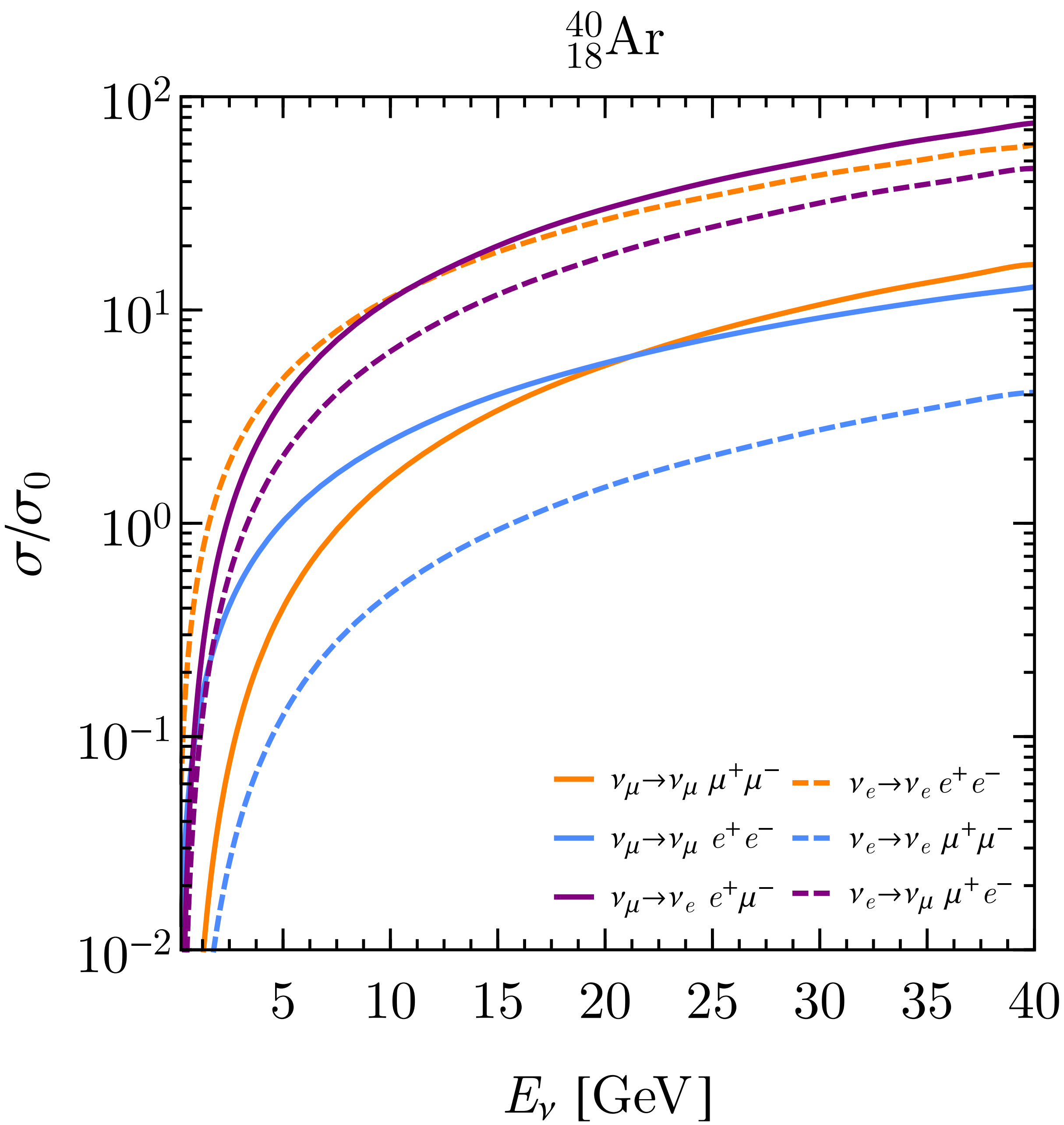
2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

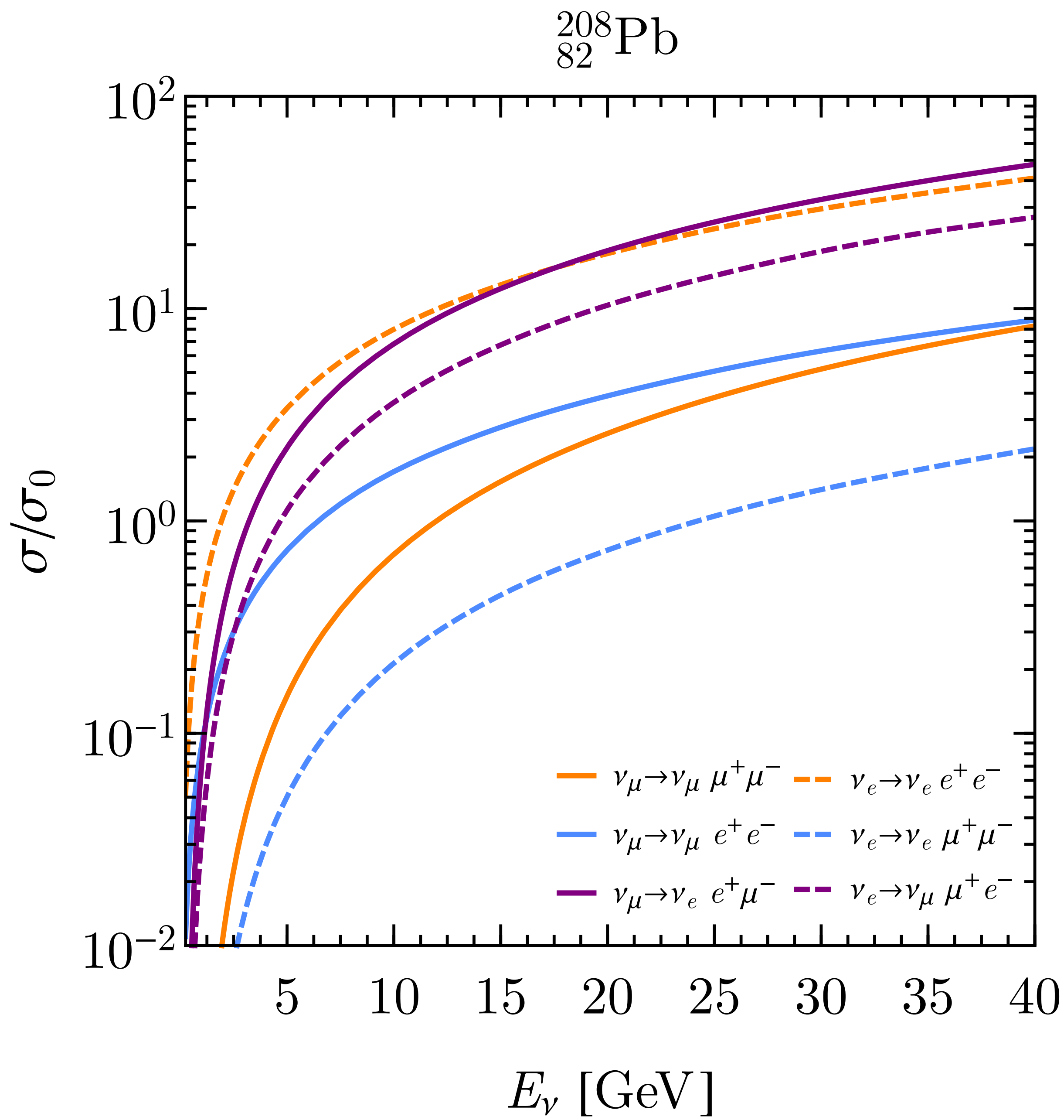


Coherent vs Diffractive



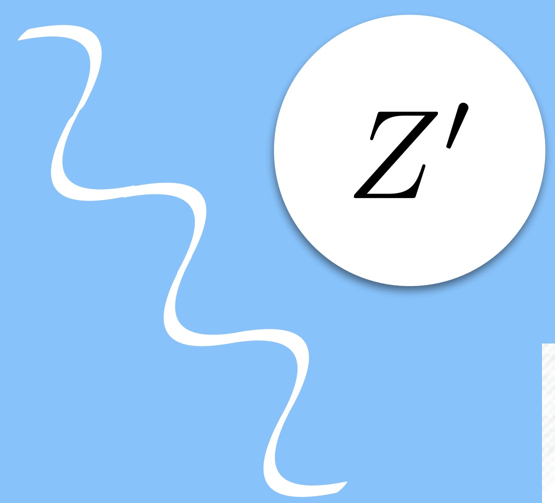
Coherent cross sections





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

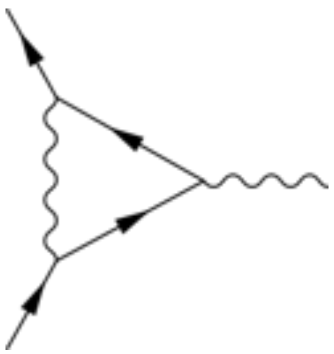
Smiting new physics



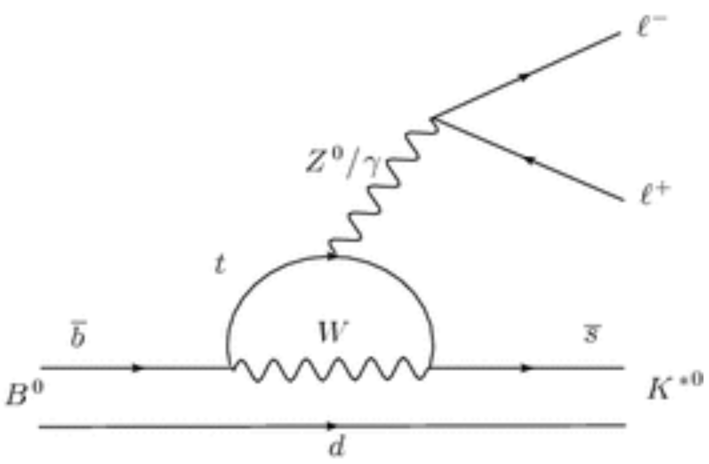
Work in progress

$L_\mu - L_\tau$ 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.

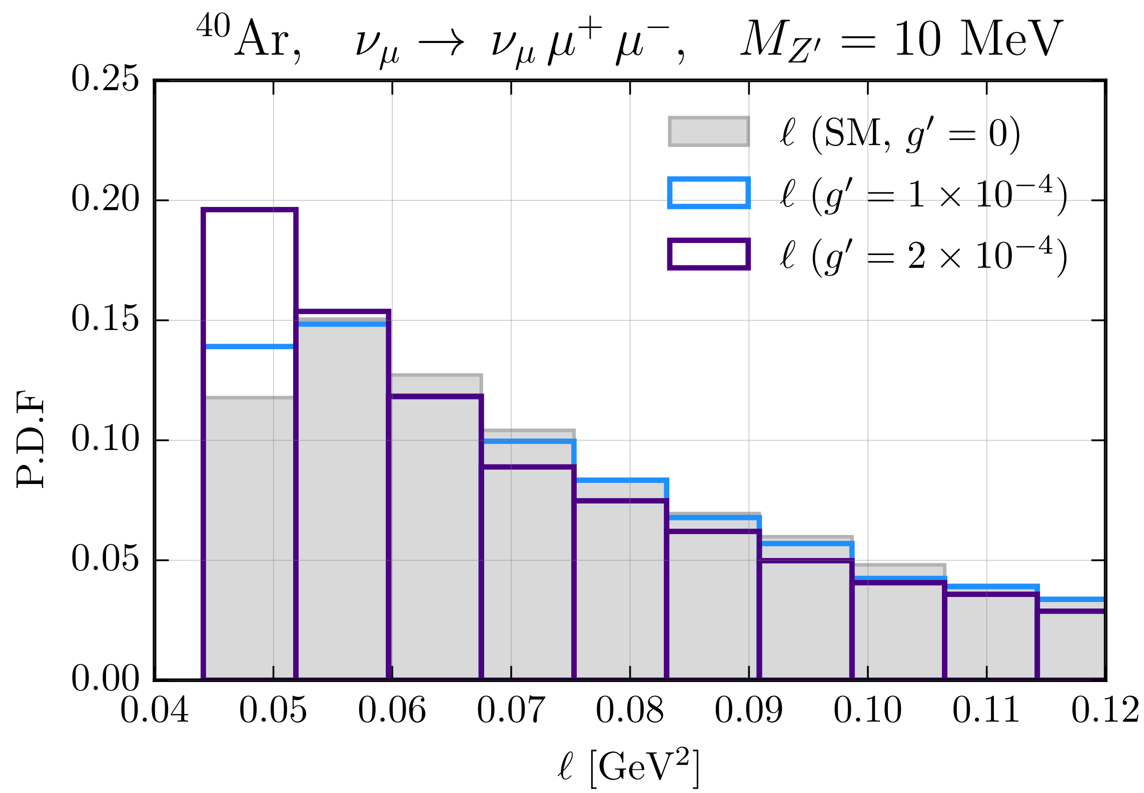
$$\mathscr{L}_{\rm int} \supset g' Z'_\alpha \left(\overline{L}_\mu \gamma^\alpha L_\mu - \overline{L}_\tau \gamma^\alpha L_\tau + \overline{\mu}_R \gamma^\alpha \mu_R - \overline{\tau}_R \gamma^\alpha \tau_R\right)$$

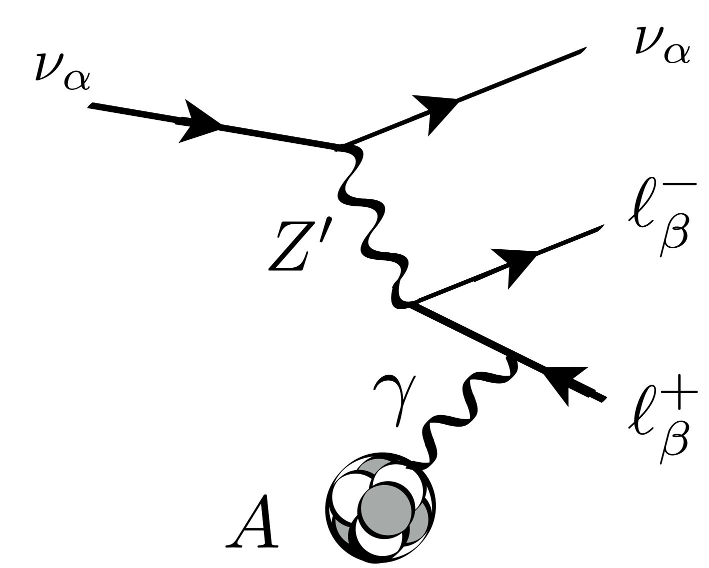
[Altmannshofer et al, 1406.2332]

$L_\mu - L_\tau$ gauge

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

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

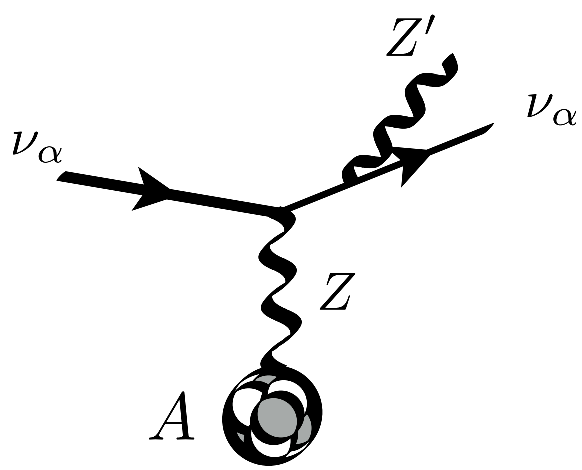


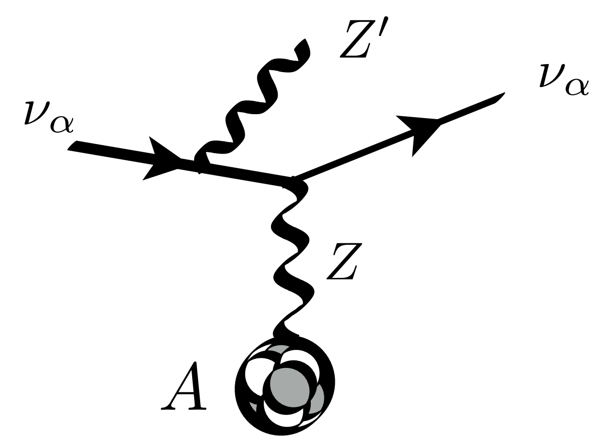


$L_\mu - L_\tau$ gauge

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 $M_{Z'}$.

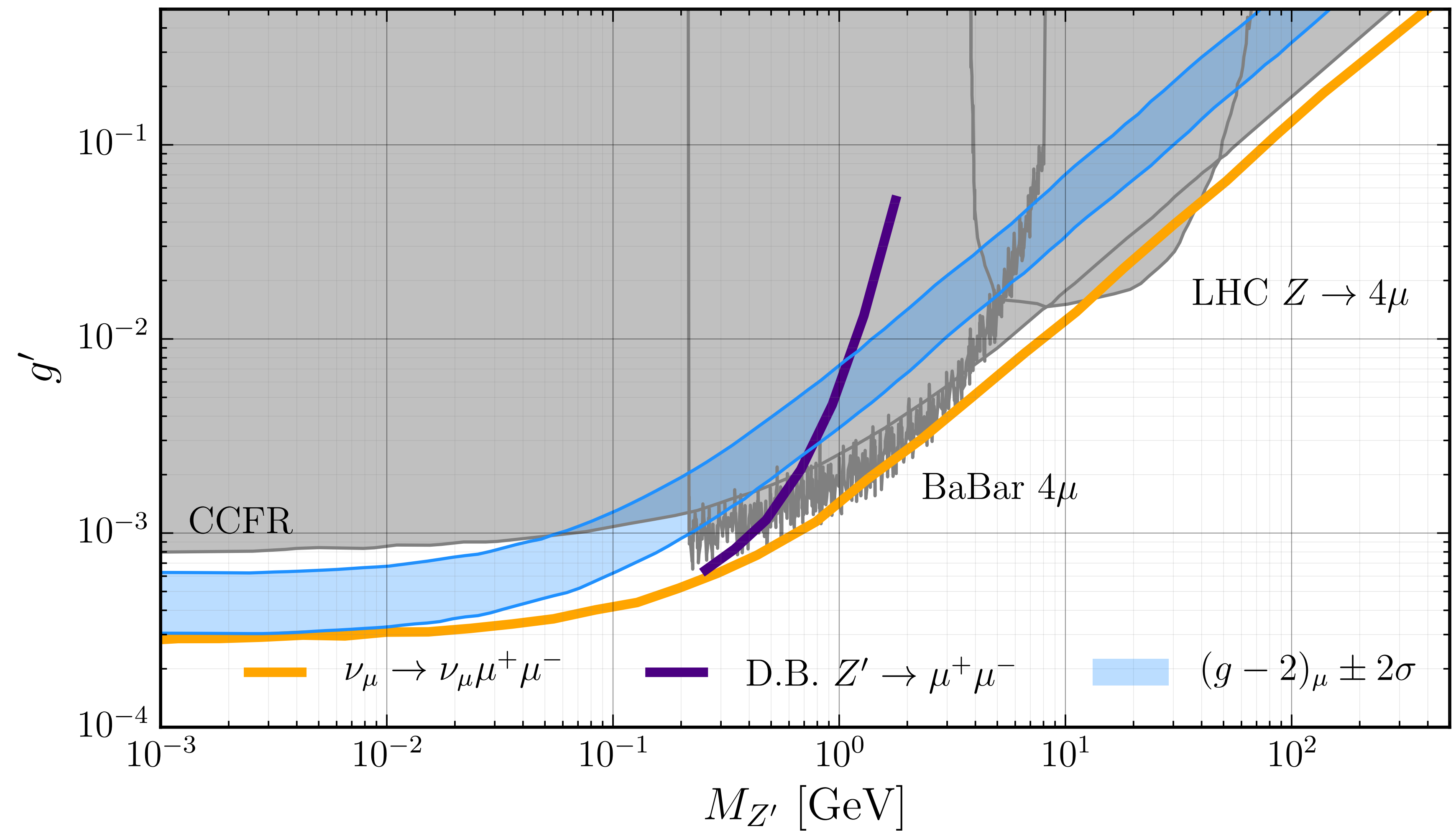
Experimental sensitivity

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.