NEUTRINO TRIDENT PRODUCTION AT NEAR DETECTORS

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in collaboration with
P. Ballett, S. Pascoli, Y. F. Perez-Gonzalez, Z. Tabrizi, T. Wang and R. Z. Funchal

IP3
CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico
SCIENCE WITHOUT BORDERS

Outline

- **Neutrino trident scattering in the SM.**

  Revisit calculation.

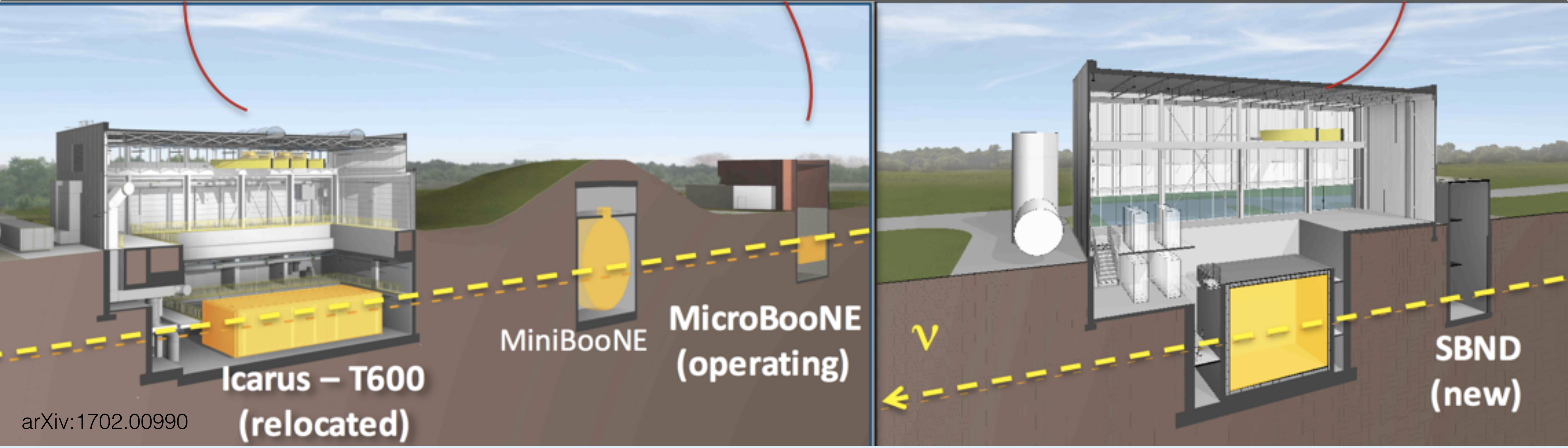
  Show revised rates for current and future experiments.

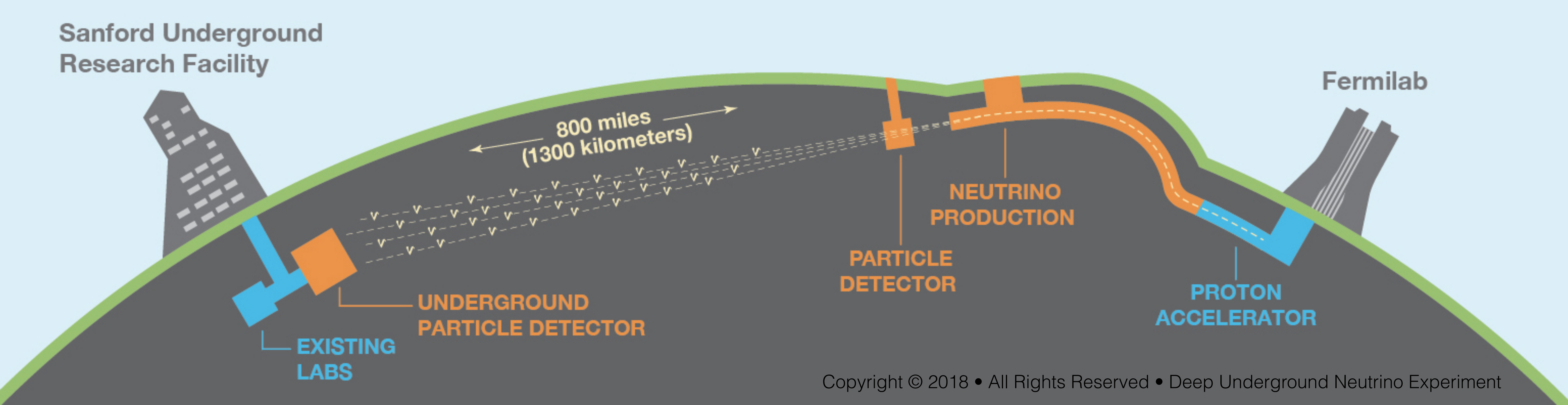
  Signal and backgrounds.

- **New physics in trident production.**

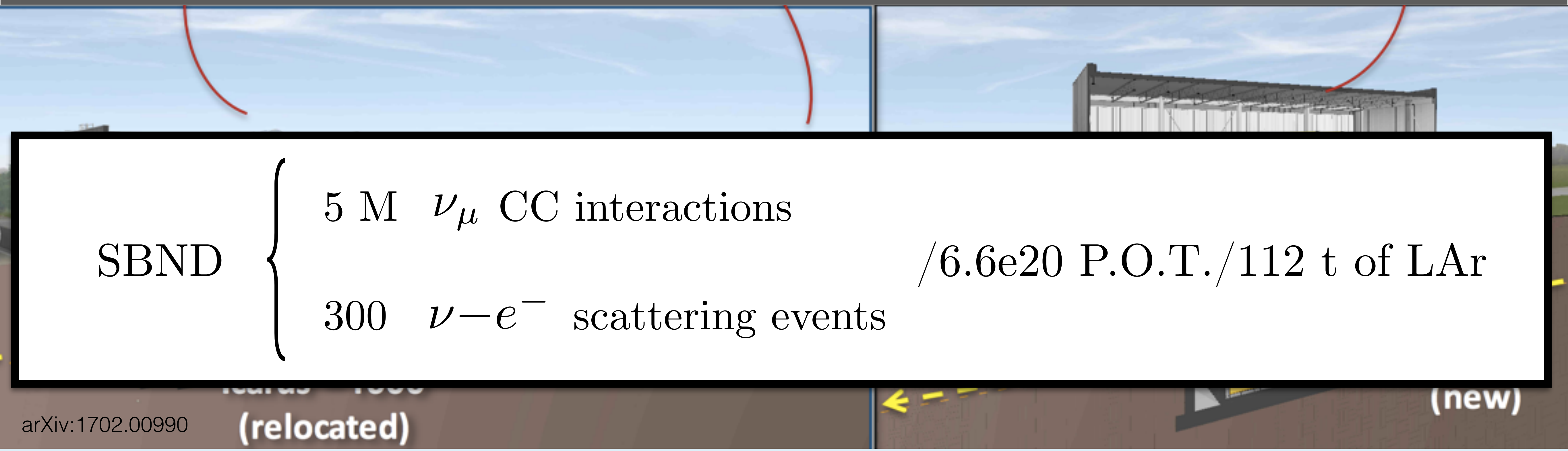
  Light Z's at DUNE ND.

Near detectors

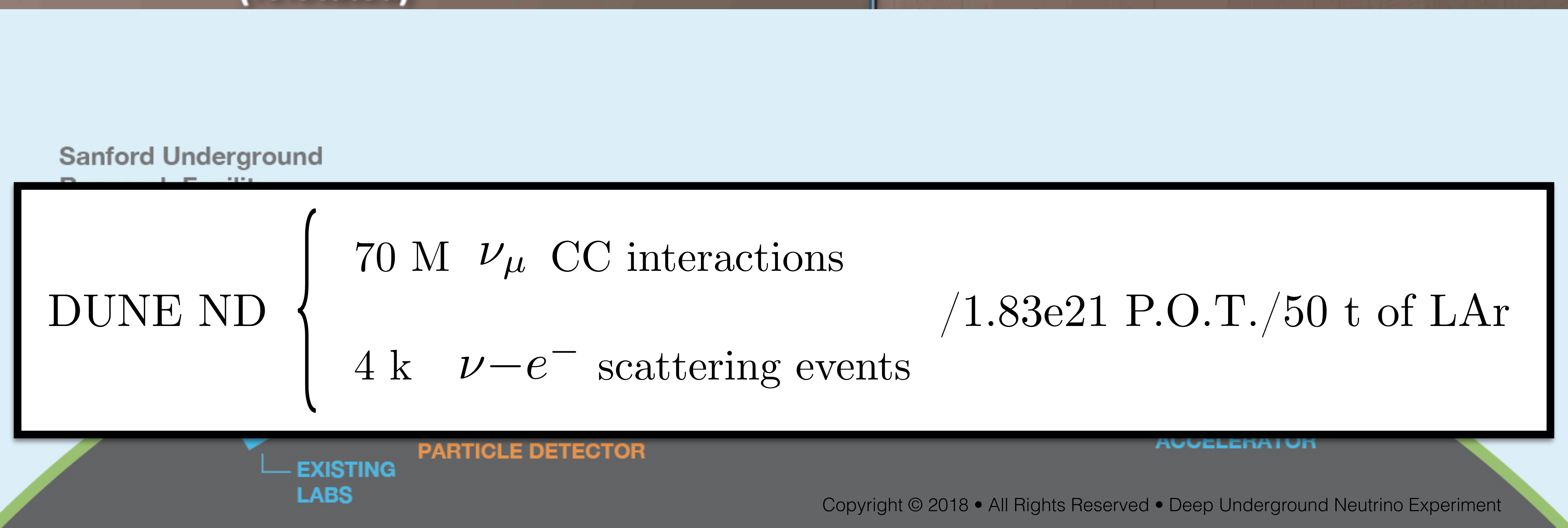




Near detectors



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



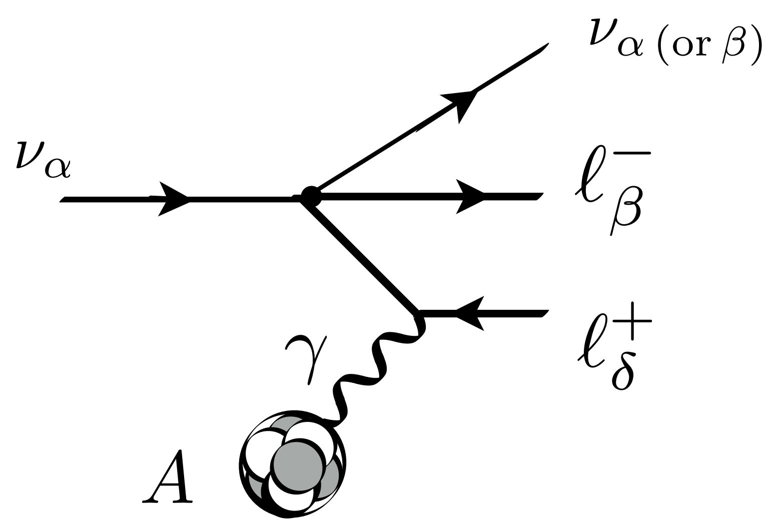
DUNE ND $\left\{ \begin{array}{l} 70\ \mathrm{M}\ \ \nu_\mu\ \mathrm{CC\ interactions} \\ 4\ \mathrm{k}\ \ \nu{-}e^-\ \mathrm{scattering\ events} \end{array} \right.$ /1.83e21 P.O.T./50 t of LAr

Neutrino trident production

Let us then study rare processes! In particular, will focus on

neutrino trident production

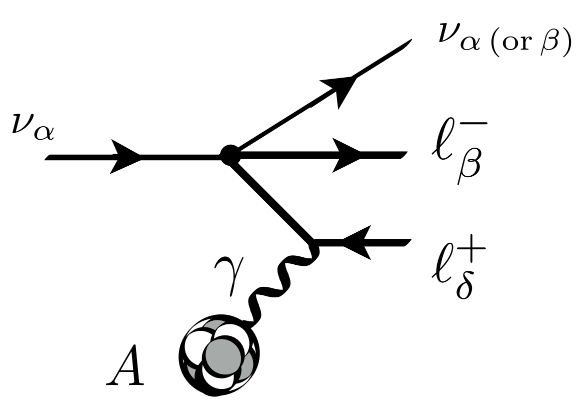
$$\nu_\alpha + \mathcal{N} \to \nu_\beta + \ell_\gamma^+ + \ell_\delta^- + \mathcal{N}$$

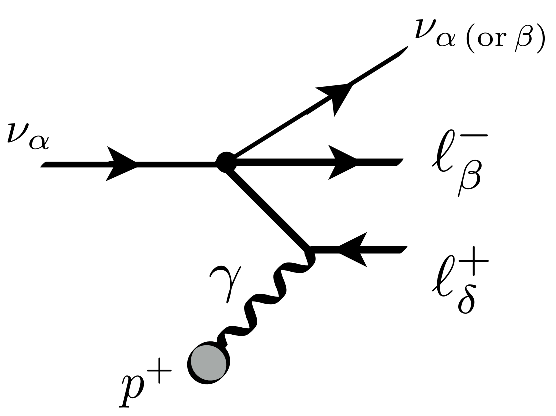


[W. Altmannshoffer, M. POSPELOV et al 2014] [G. MAGILL et al, 2016]

Neutrino trident production

Neutrino **charged lepton pair** production in a coulomb field.





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

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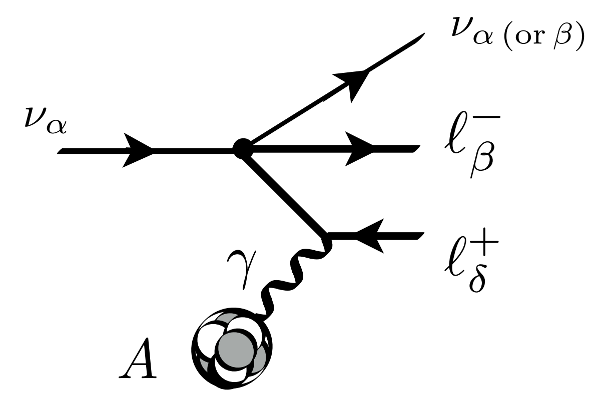

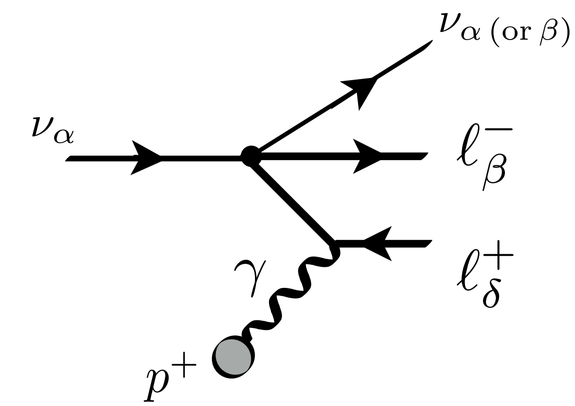

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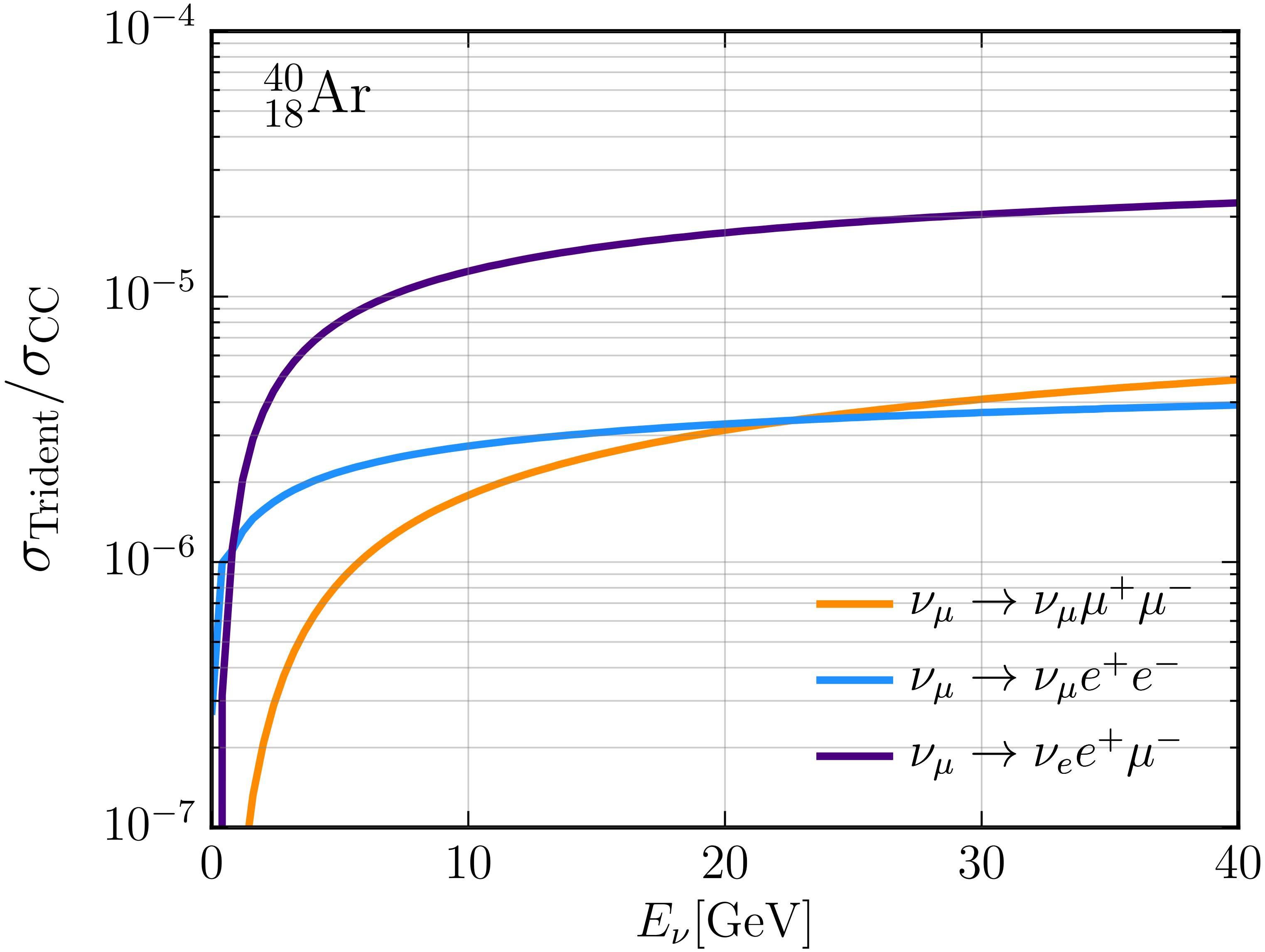
Measured!

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.

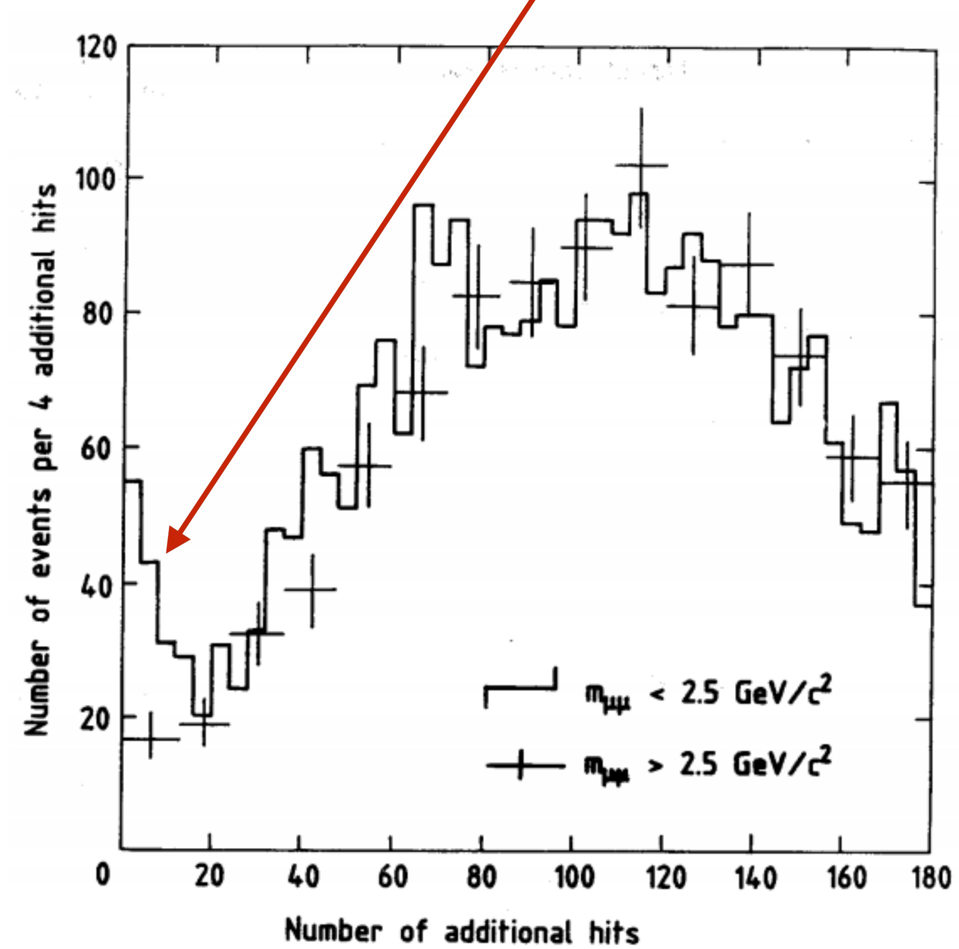
[CHARM II Collaboration, 1990] — First measurement of $\mu^+\mu^-$ trident.

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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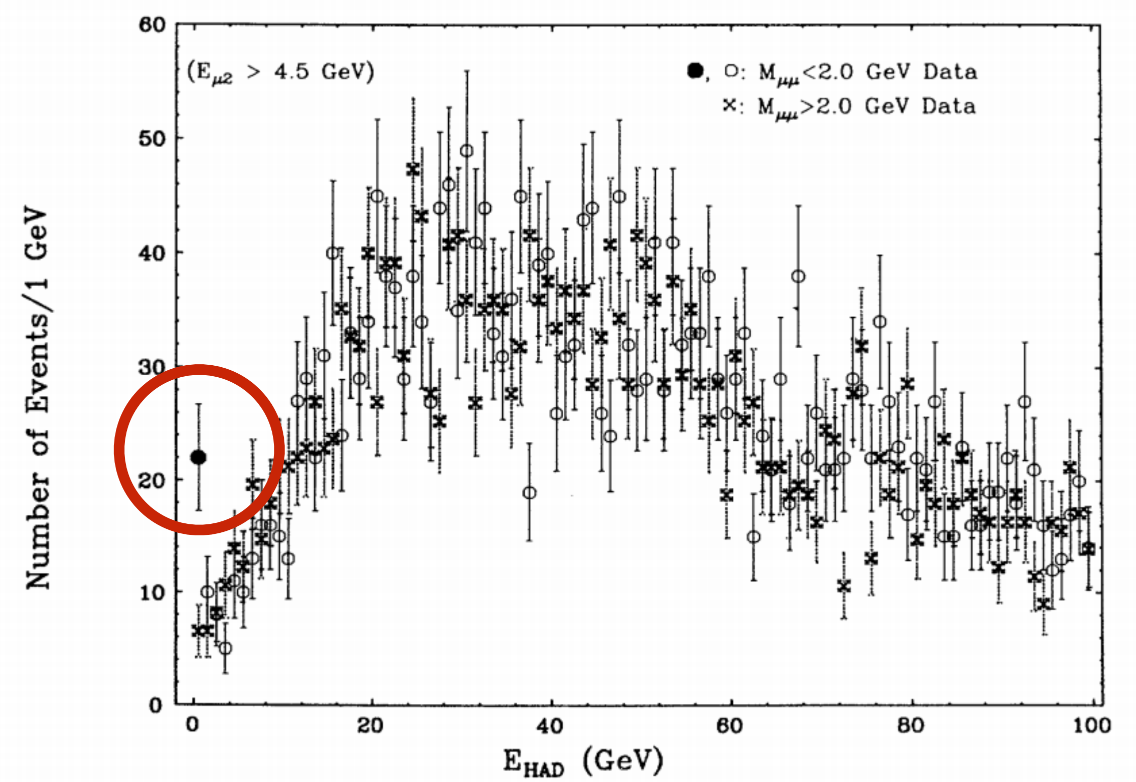
CCFR

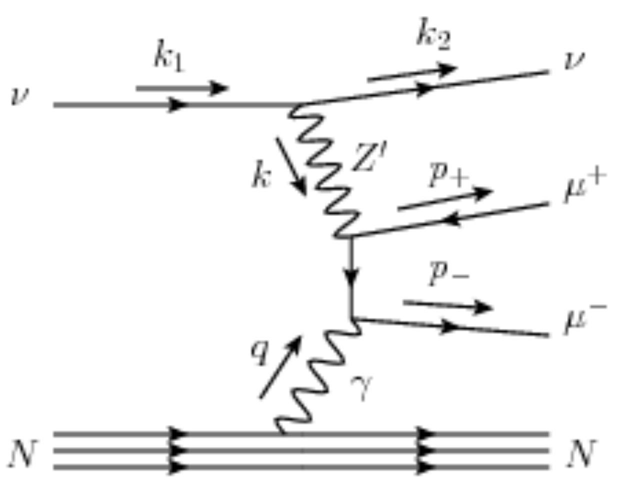
$$\langle E_\nu \rangle = 160 \text{ GeV}$$

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

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



Present



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

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

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

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

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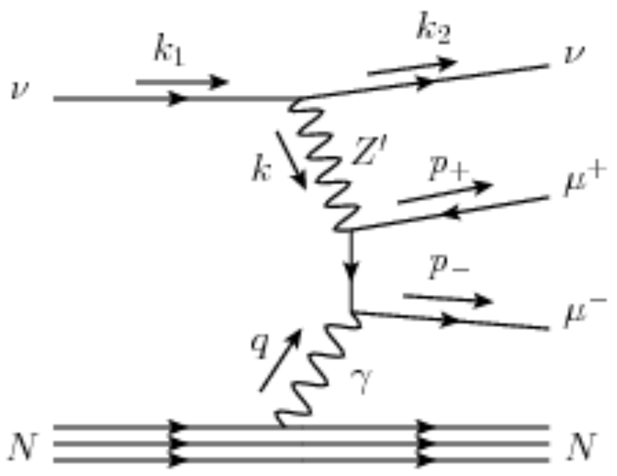

Equivalent Photon Approximation (EPA)

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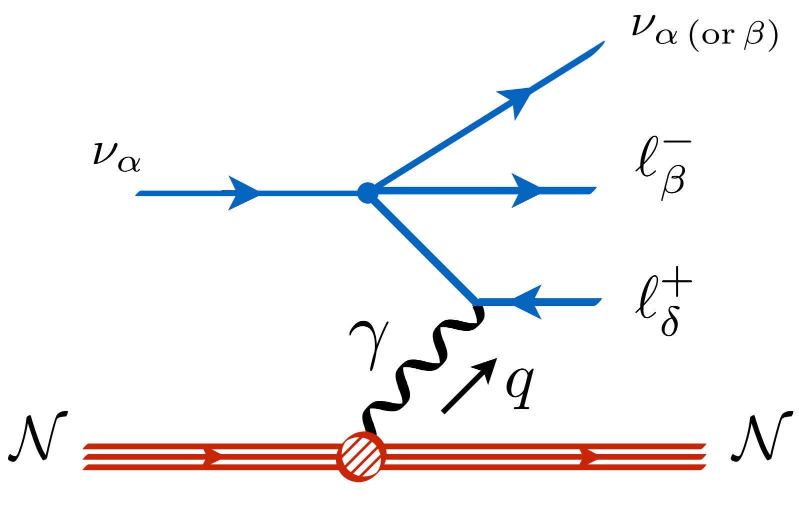
Understanding the cross section



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

$$\frac{d^2\sigma_{\nu\mathcal{N}}}{dq^2 d\hat{s}} = \frac{1}{32\pi^2(s-M_T^2)^2}\frac{H^{\mu\nu}L_{\mu\nu}}{q^4}$$

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

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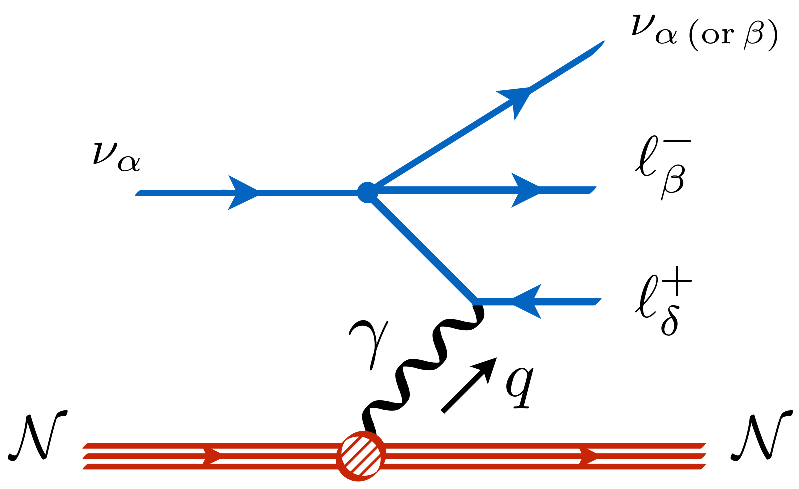

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Universal leptonic T and L cross sections.

$$\frac{\mathrm{d}\sigma_{\nu\mathcal{N}}}{\mathrm{d}q^2\mathrm{d}\hat{s}} = \frac{1}{32\pi^2}\frac{1}{\hat{s}\,(s-M_T^2)^2}\frac{1}{q^4}\left[h^{\mathrm{T}}(q^2,\hat{s})\,\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) + h^{\mathrm{L}}(q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(q^2,\hat{s})\right]$$

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

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

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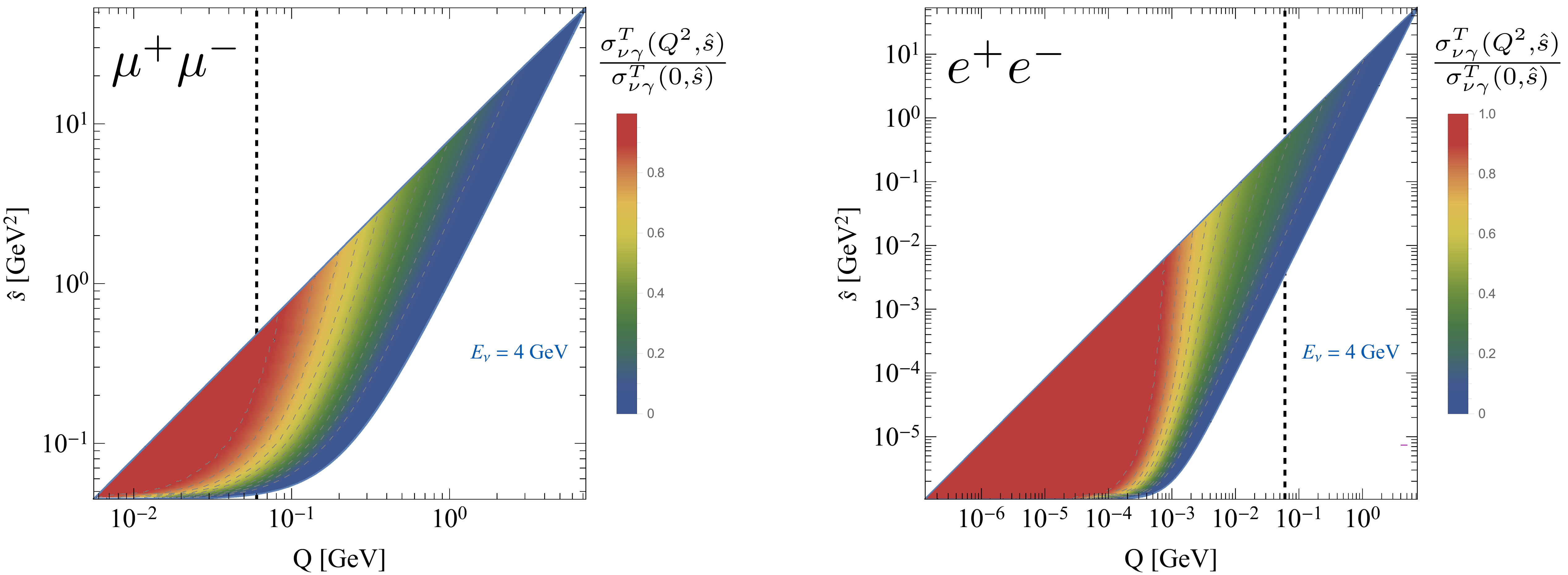
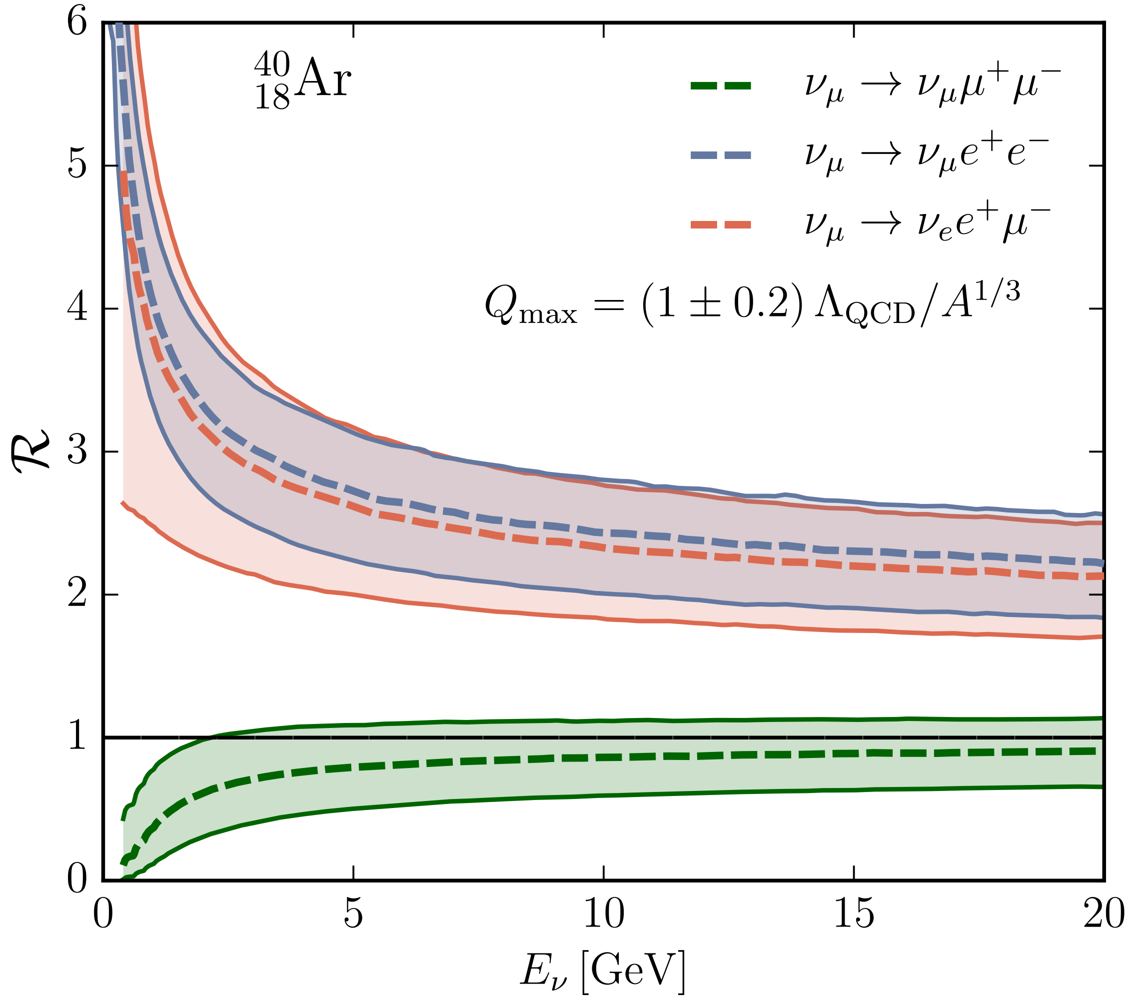


EPA

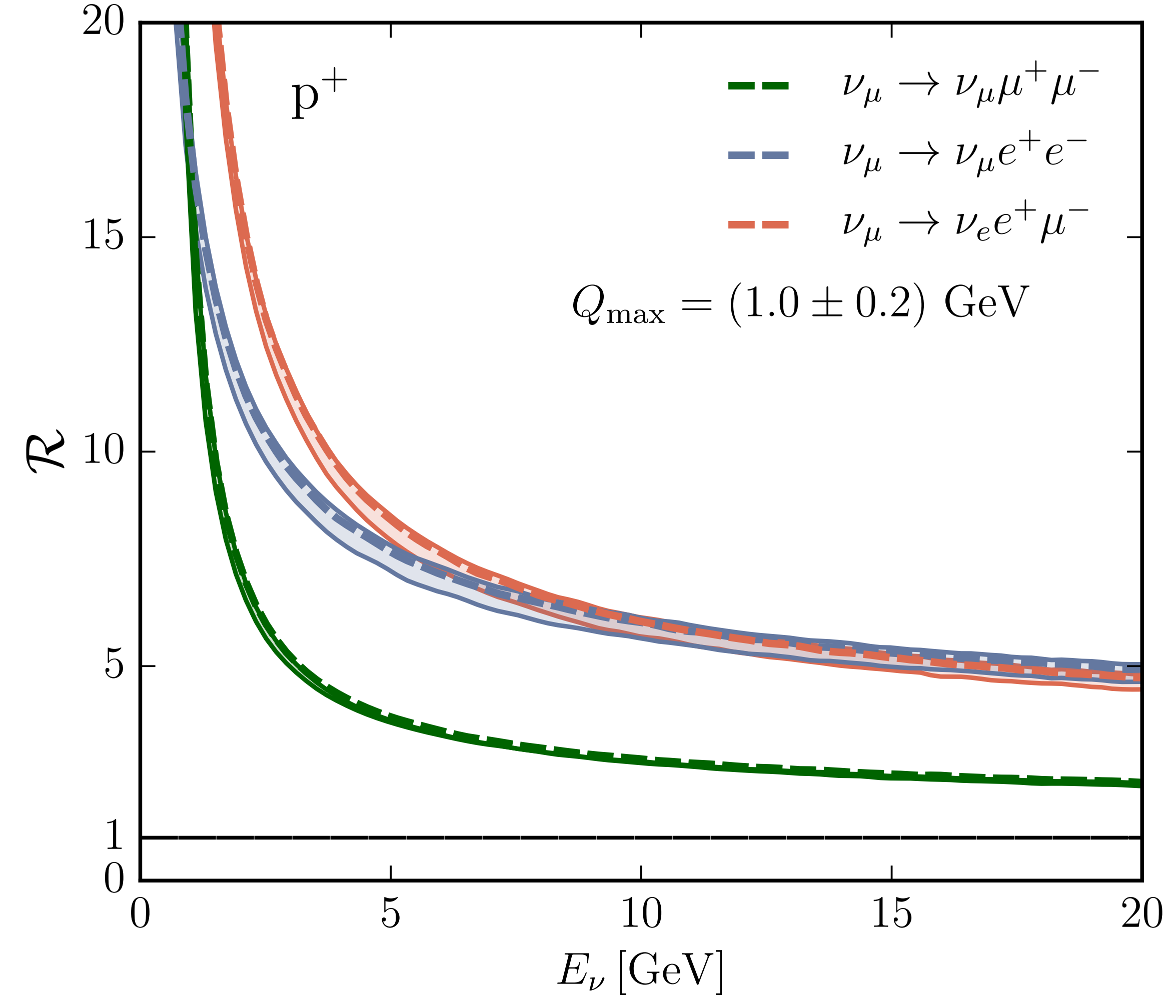
How bad is it?

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

Coherent



Diffractive



The signal

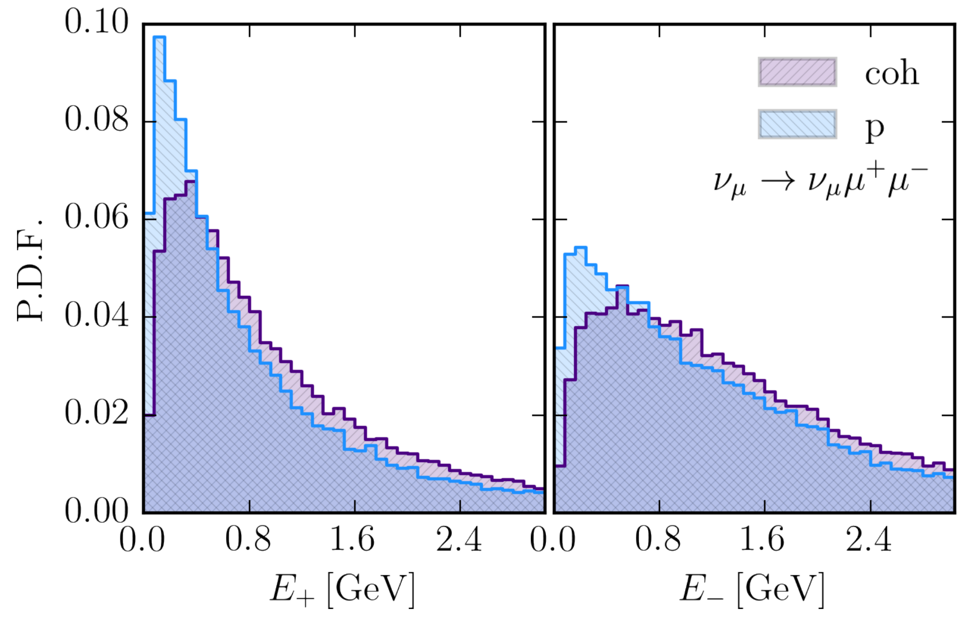
How many events in LAr at FNAL?

4PS calculation

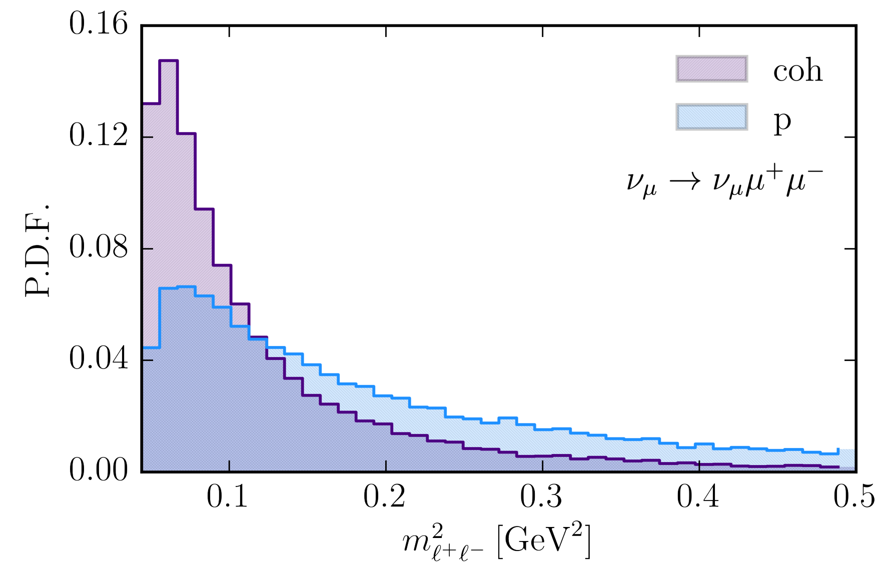
Channel		SBND	DUNE ND ν ($\overline{\nu}$)
$e^{\pm}\mu^{\mp}$	coh	10.1	2993.1 (2306.7)
	dif	2.2	691.7 (530.7)
$e^{+}e^{-}$	coh	6.6	1007 (800)
	dif	–	142.3 (111.5)
$\mu^{+}\mu^{-}$	coh	–	286.7 (210.3)
	dif	–	195.8 (146.7)

Assuming a 50 t LAr DUNE ND and $(2 + 2 \times 3) \times 1.83e21$ P.O.T. for neutrino and antineutrino mode.

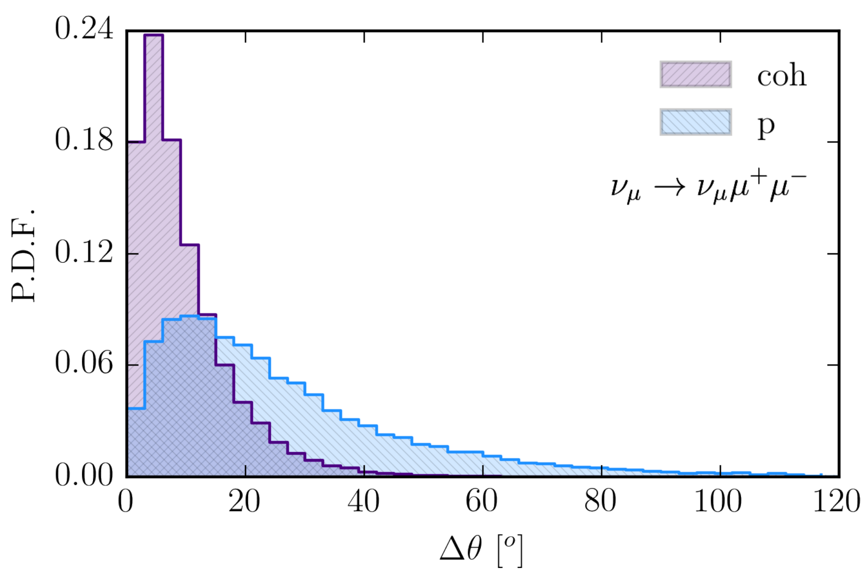
The signal



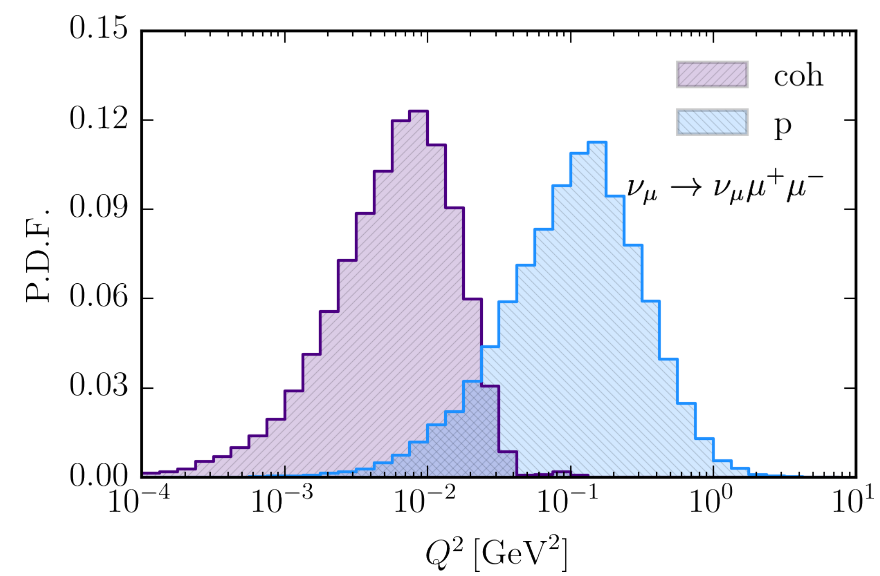
Not that energetic!



Incredibly low invariant masses.



Collimated muons.



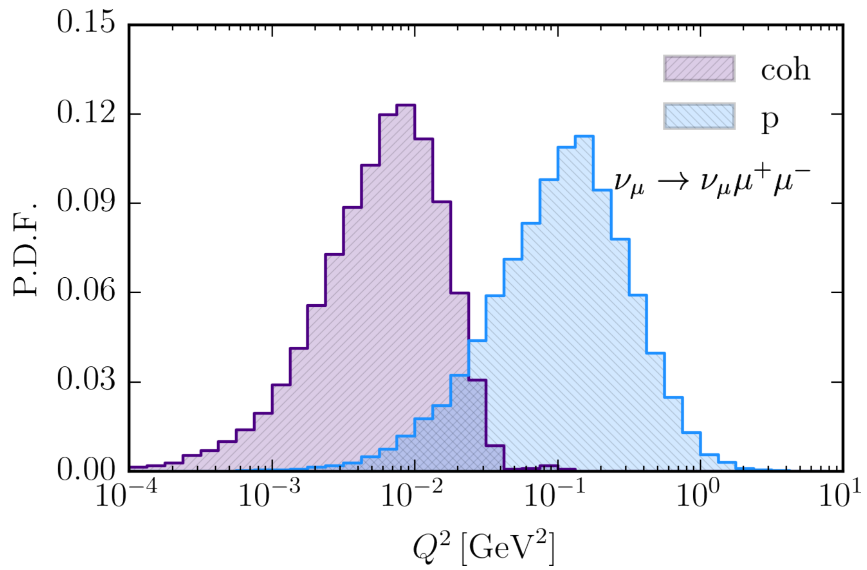
No hadronic activity at the vertex?

The signal

Perhaps biggest uncertainty of calculation!

What is the hadronic signature of diffractive tridents?

We include fermi blocking, but other effects at play.

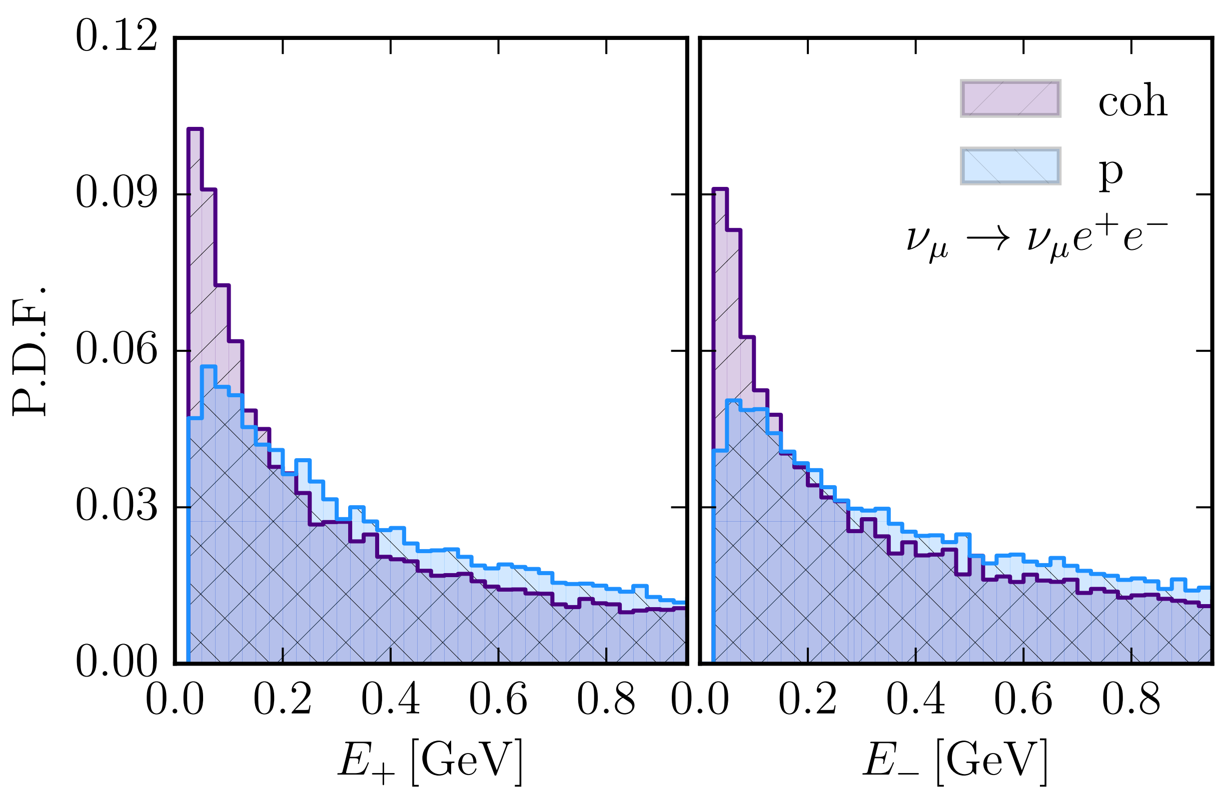


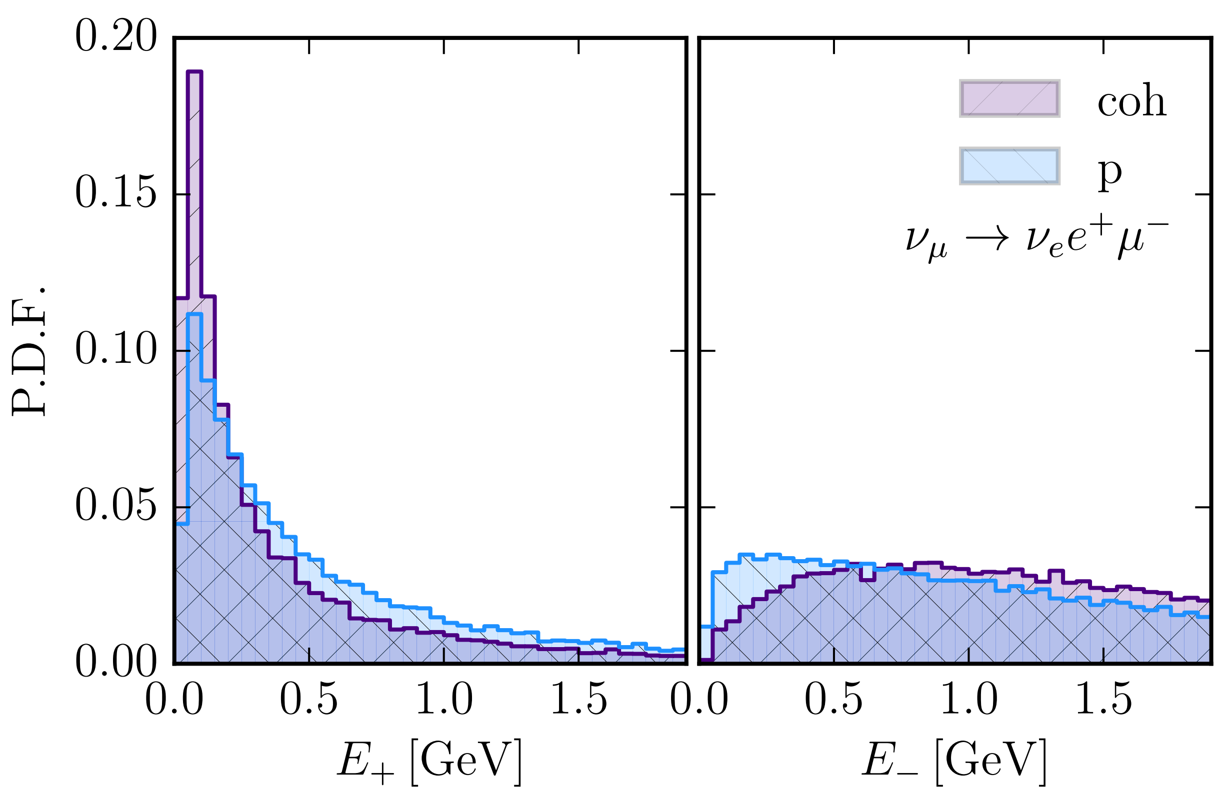
No hadronic activity at the vertex?

The signal

Thresholds are important! With 30 MeV detection threshold, find efficiencies of below 70% for mixed and electron channels.

Most electrons are soft!



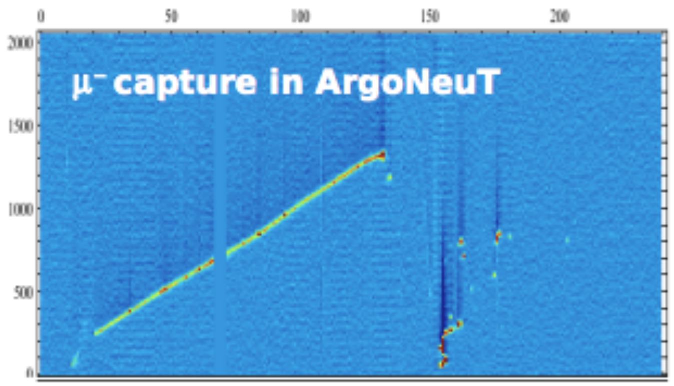


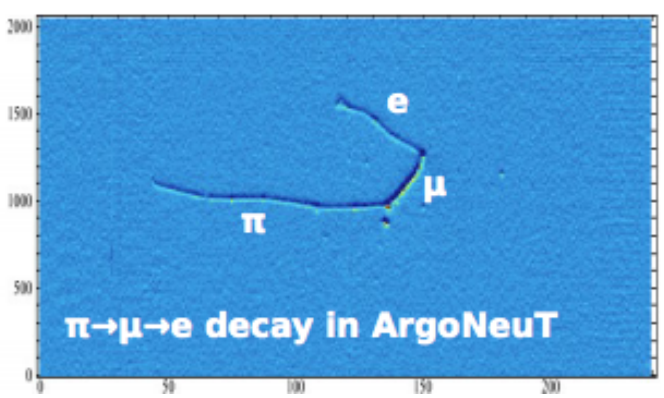
Backgrounds

Okay, is it even observable?

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

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

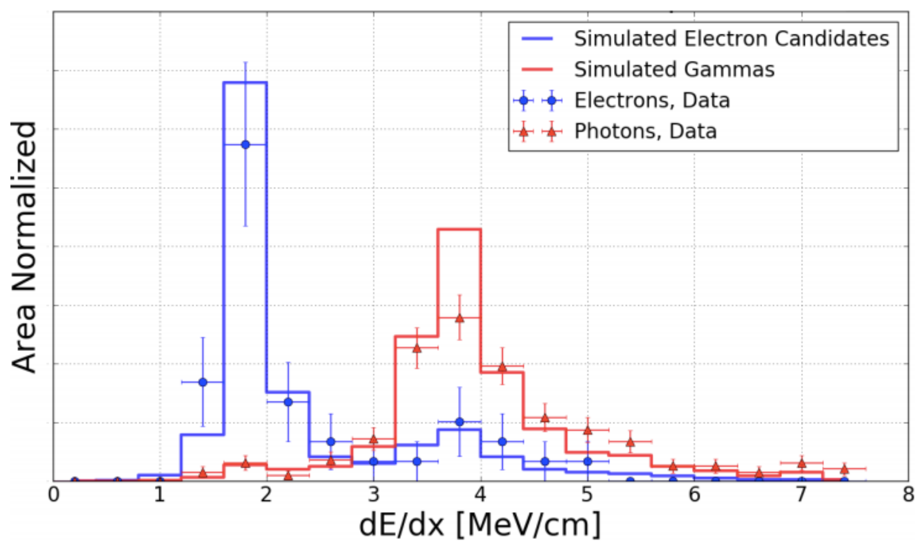




F. Blaszczyk - NuInt 2014

Escaping pion? No decay kink?

$e^{\pm}/\gamma$



Succesful separation in LAr (ArgoNeuT)

Backgrounds

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Genuine dilepton production is rare, but misID of particles 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

Naive estimates taken as constant.

Backgrounds

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

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

$CC1\pi^{\pm}$ misID $\pi^{\pm}$. Dimuons from charm production is rel. small.

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

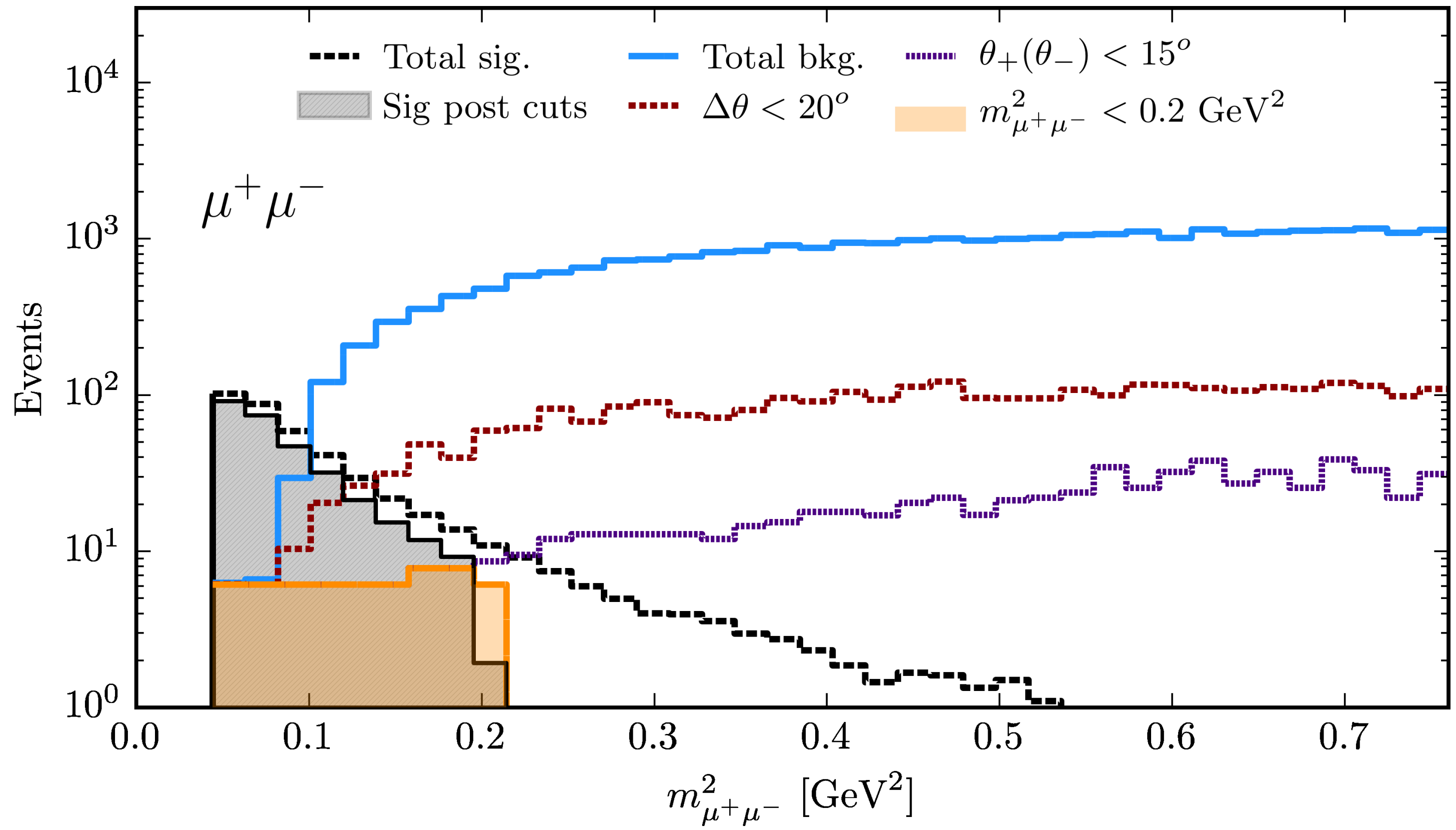
$\nu_e CC\pi^0$ and $NC1\pi^0$.

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

$CC1\pi^0$ with misID γ .

Backgrounds

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



Channel	$N_B^{\text{misID}}/N_{\text{CC}}$	$N_B^{\text{had}}/N_{\text{CC}}$	$N_B^{\text{kin}}/N_{\text{CC}}$	ϵ_{sig}
$e^\pm\mu^\mp$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$	0.63 (0.64)
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$	0.55 (0.56)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)

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.

Channe…				
$e^\pm\mu^\mp$	[illegible]	[illegible]	[illegible]	…3 (0.64)
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$	0.55 (0.56)
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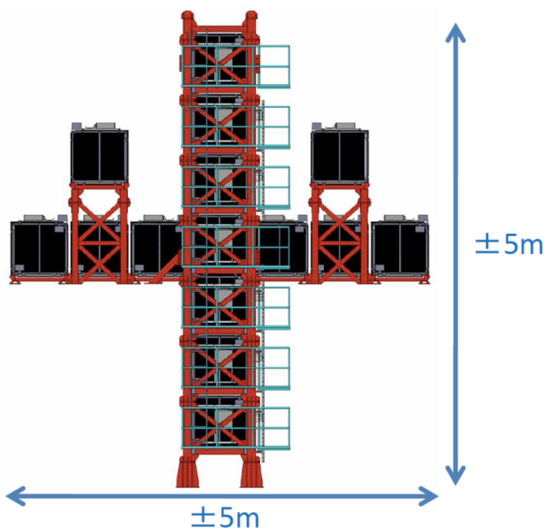
Other NDs

INGRID



Channel	T2K-I	T2K-II	MINOS ND	NOνA ND	MINERνA
Total $e^{\pm}\mu^{\mp}$	563.5	1444	210 (52.5)	57.4	148.5 (102.5)
	96.3	246.4	43.7 (11)	30.8	56.3 (39.5)
Total $e^{+}e^{-}$	277	711	58 (14.7)	19.4	38.6 (27.1)
	24	62.6	7.9 (2)	7.1	10 (6.8)
Total $\mu^{+}\mu^{-}$	30.3	78	23.4 (6.1)	6.2	18.1 (12.9)
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Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Other NDs

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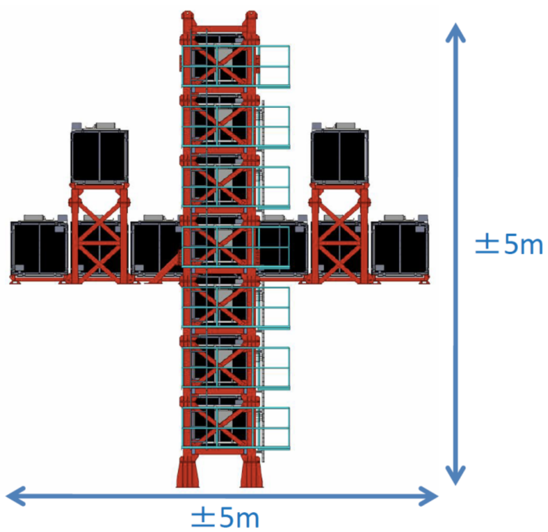

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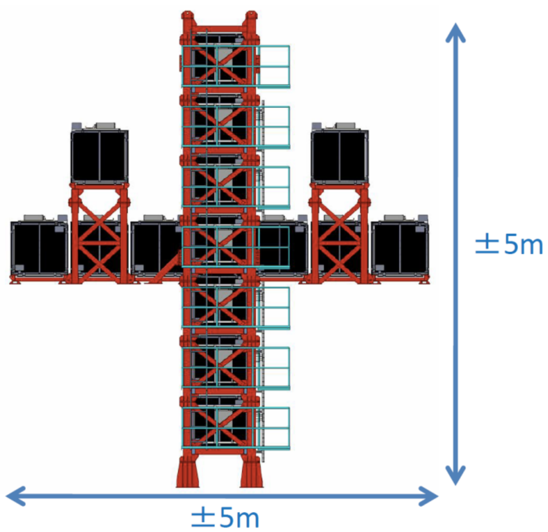

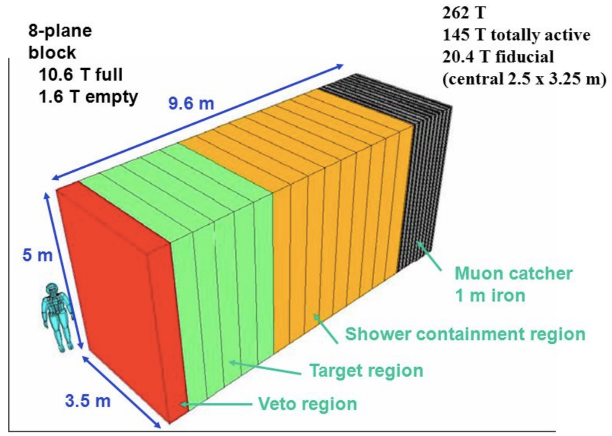

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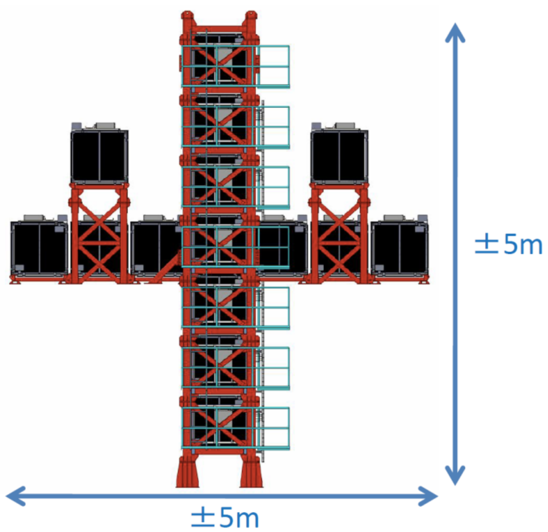
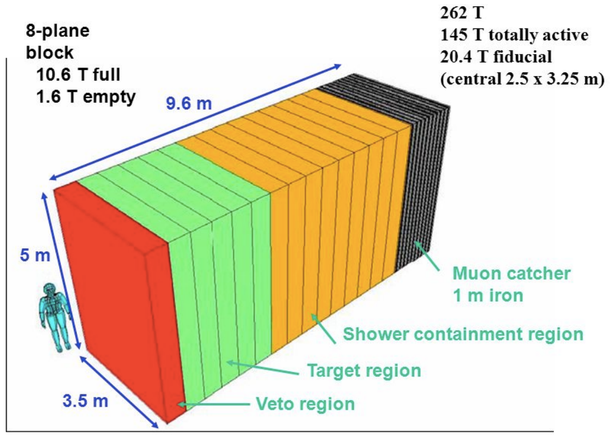
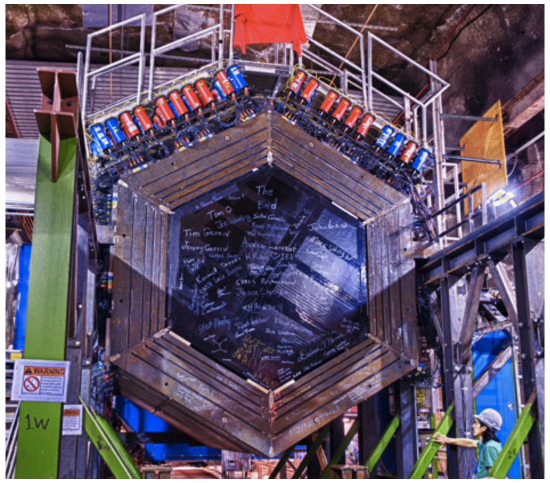


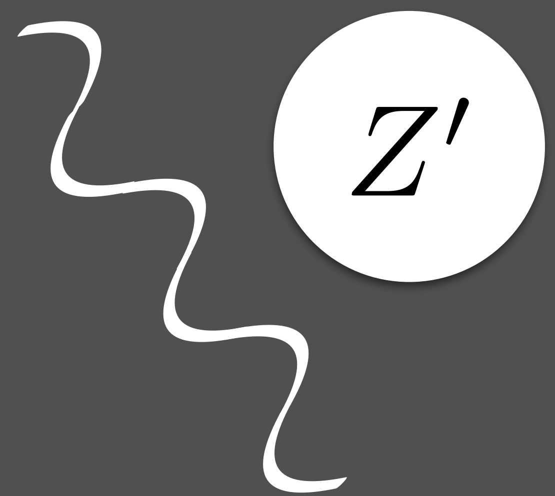




Channel	T2K-I	T2K-II	MINOS ND	NOνA ND	MINERνA
Total $e^{\pm}\mu^{\mp}$	563.5	1444	210 (52.5)	57.4	148.5 (102.5)
	96.3	246.4	43.7 (11)	30.8	56.3 (39.5)
Total e^+e^-	277	711	58 (14.7)	19.4	38.6 (27.1)
	24	62.6	7.9 (2)	7.1	10 (6.8)
Total $\mu^+\mu^-$	30.3	78	23.4 (6.1)	6.2	18.1 (12.9)
	21	54.4	13.8 (3.5)	8.2	18 (12.8)

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

Smiting new physics

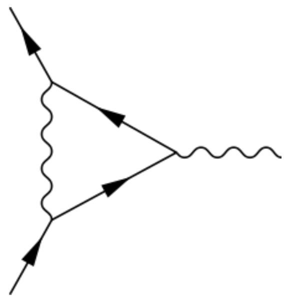


$L_\mu - L_\tau$ gauge

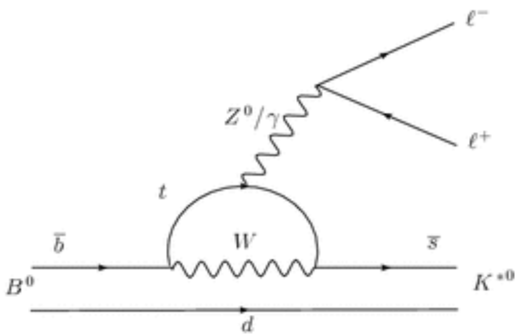
[Altmannshofer et al, 1406.2332]

Consider first a new gauge boson gauged under the **anomaly free**

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



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



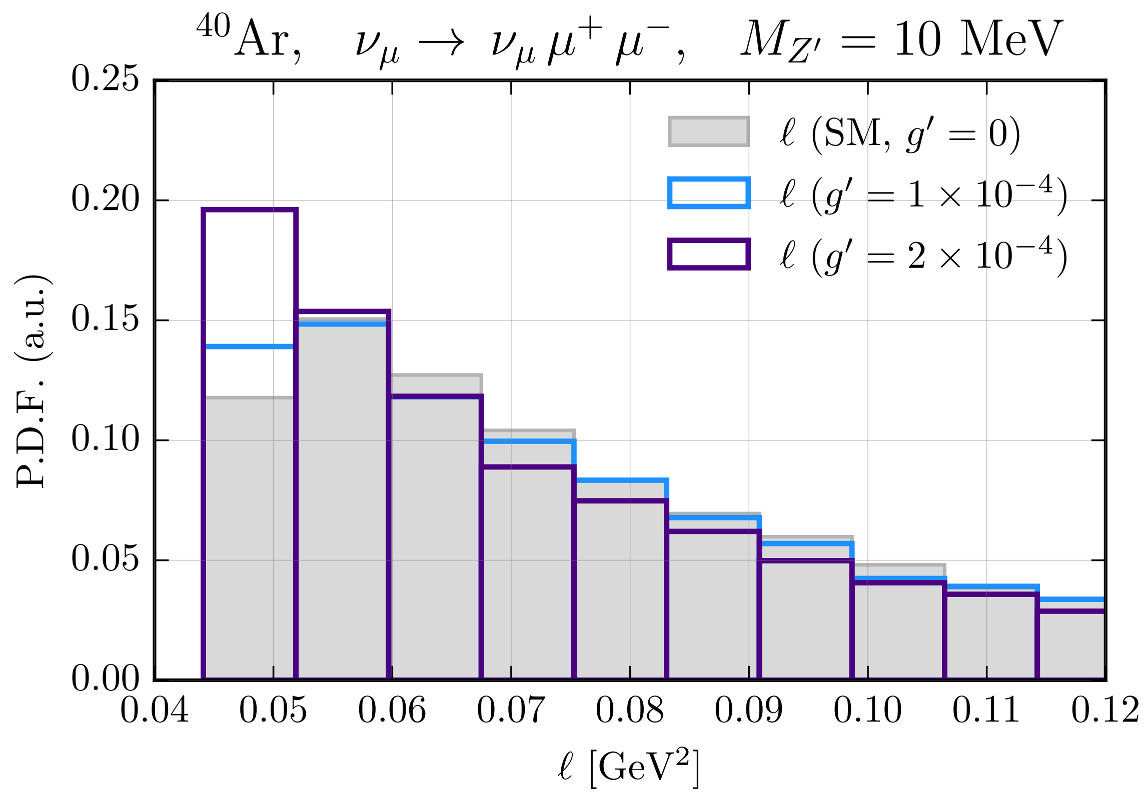
Recent interest due to hints of flavour non-universality in $b \to s\,\ell^+\,\ell^-$ decays. [Altmannshofer et al, 1403.1269]

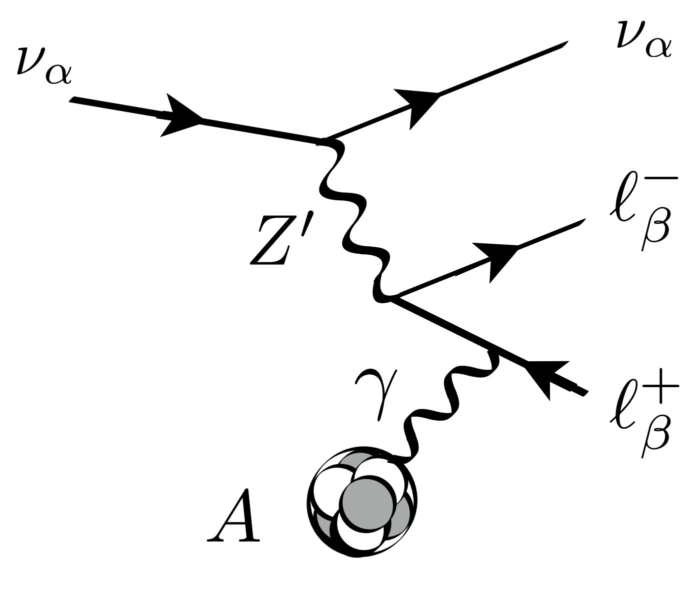
$$\mathscr{L}_{\rm int} \supset g' Z'_\alpha \left(\overline{L}_\mu \gamma^\alpha L_\mu - \overline{L}_\tau \gamma^\alpha L_\tau + \overline{\mu}_R \gamma^\alpha \mu_R - \overline{\tau}_R \gamma^\alpha \tau_R\right)$$

$L_\mu - L_\tau$ gauge

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

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

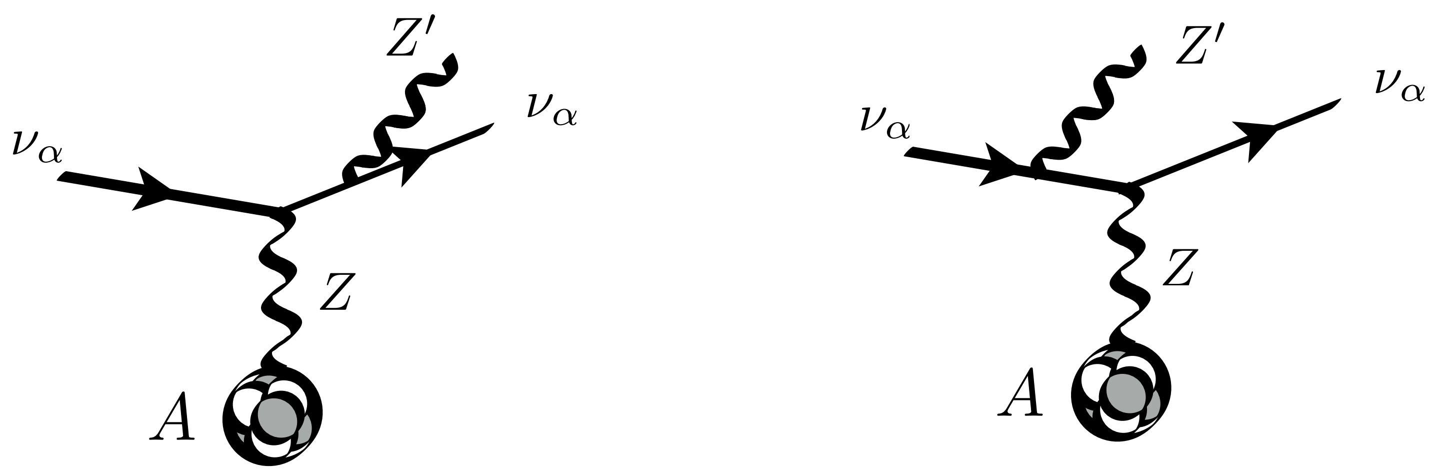




$L_\mu - L_\tau$ gauge

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 close to $M_{Z'}$.

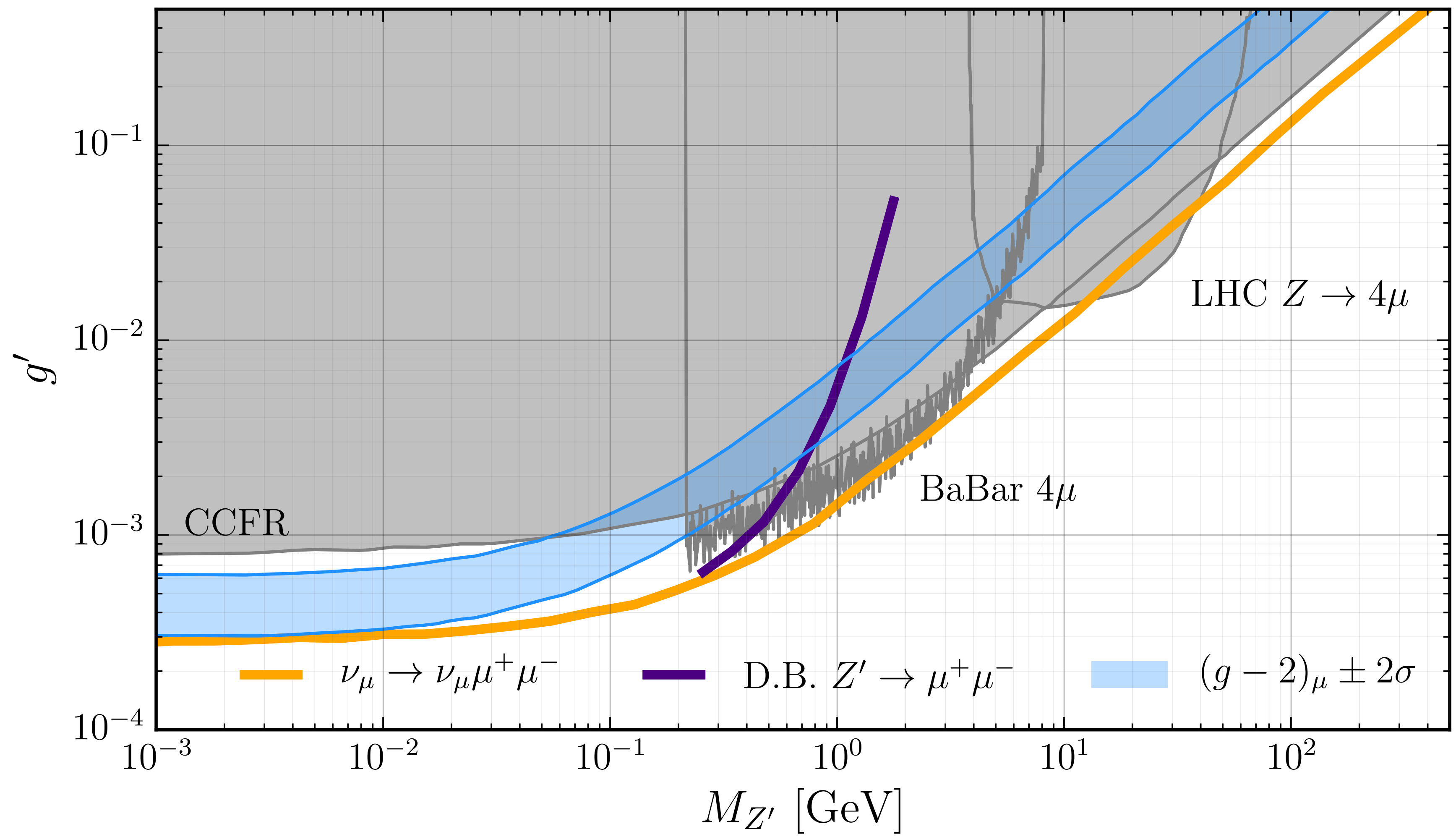
Experimental sensitivity

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.

Other rare processes?

How about the other leptonic currents?

What would them teach us?

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

Other rare processes?

How about the other leptonic currents?

What would them teach us?

Similar rates to tridents at 30 GeV.

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

Conclusions

- Even after re-evaluating cross section, neutrino tridents have a significant rate at DUNE ND. Small rates at other NDs suggest further study is needed.

- DUNE ND would be able to rule out all allowed region of (g-2) in a $L_\mu - L_\tau$ model, with additional signatures from Z' decays to look for.

What other rare events would be worth measuring?

THANK YOU