Tau Tridents at DUNE

Diego Lopez Gutierrez

In collaboration with Innes Bigaran, Bhupal Dev and Pedro Machado

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Pittsburgh
May 16, 2024

Washington University in St. Louis

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Precision era with next-gen neutrino experiments; probe **rare SM** and BSM processes

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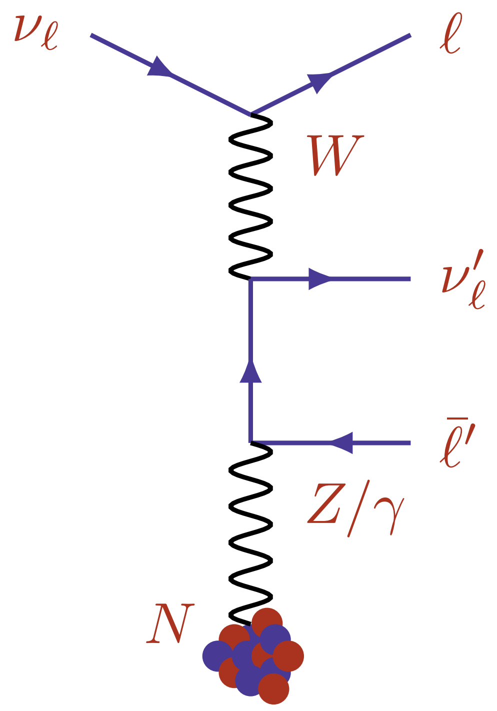
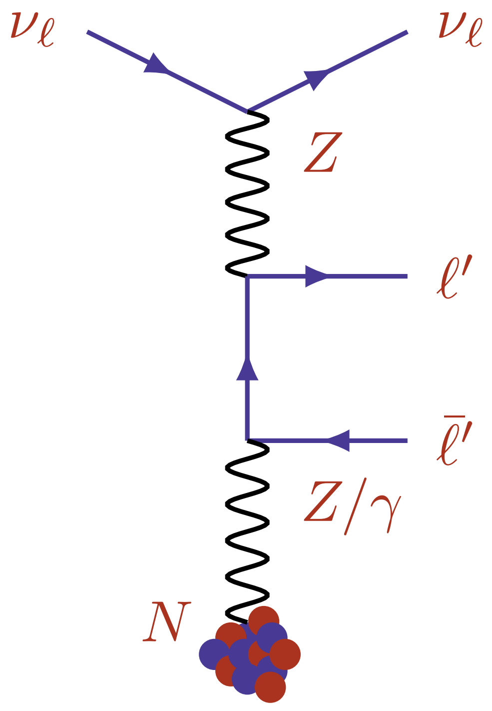
- Upper limit set by NuTeV.
- Results consistent with SM.



Charged-Current



Neutral-Current

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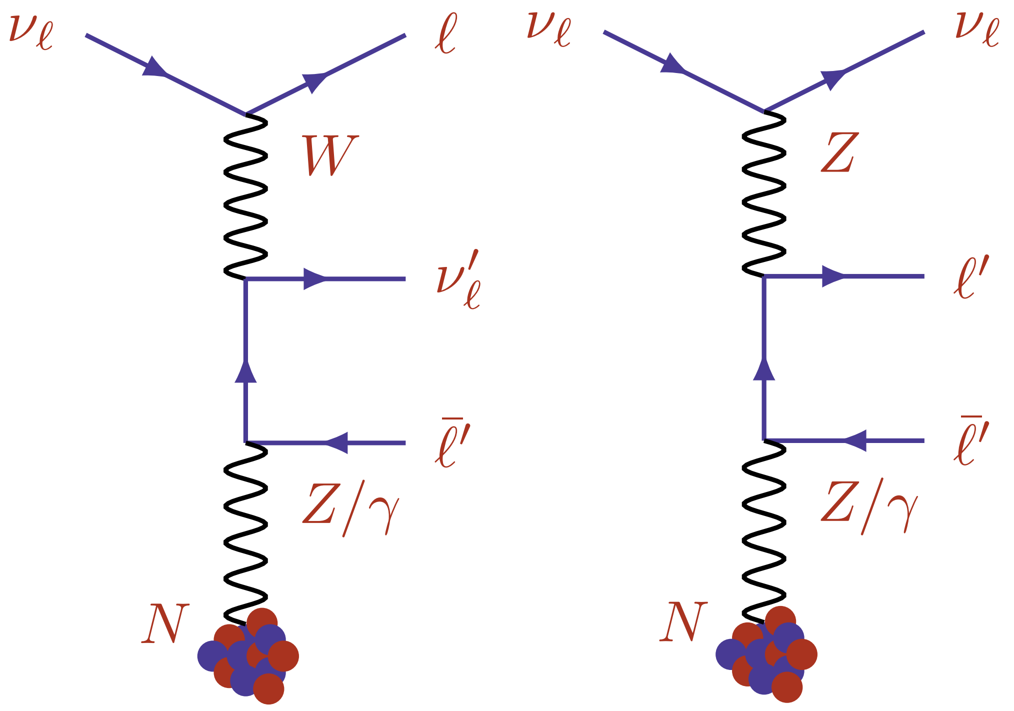

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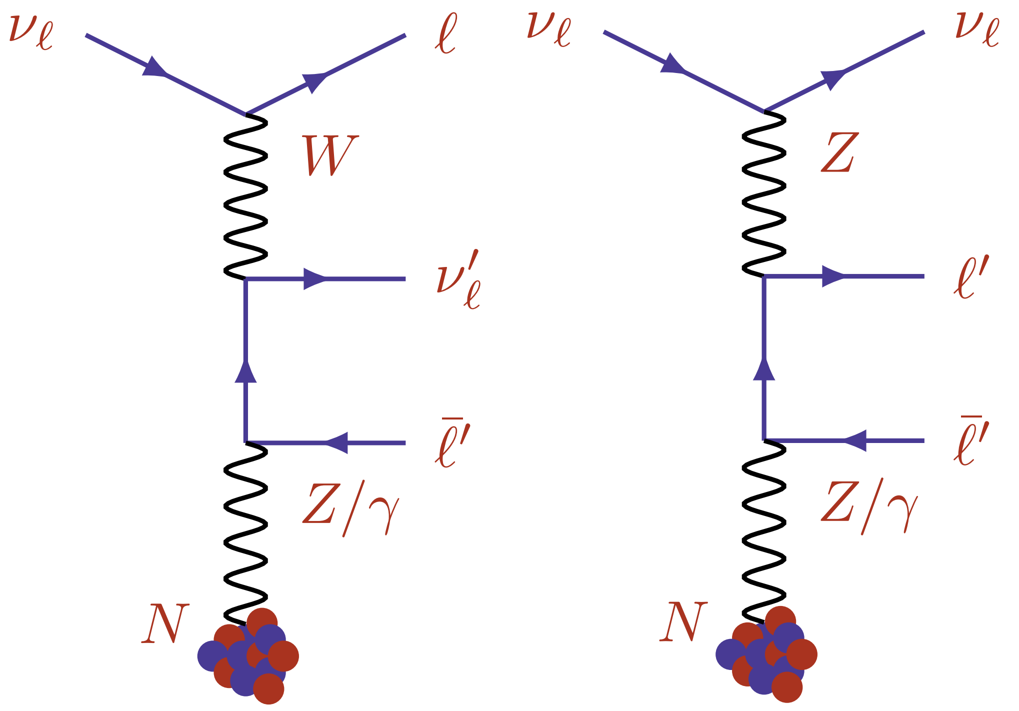
BSM: Potential background.

- SM production: decay of D mesons or ν-oscillations. *Anomalous* for DUNE.
- Abundance of BSM with ν_τ final states (e.g. sterile oscillations, $L_\mu - L_\tau$, $B - L$, Z', etc.)



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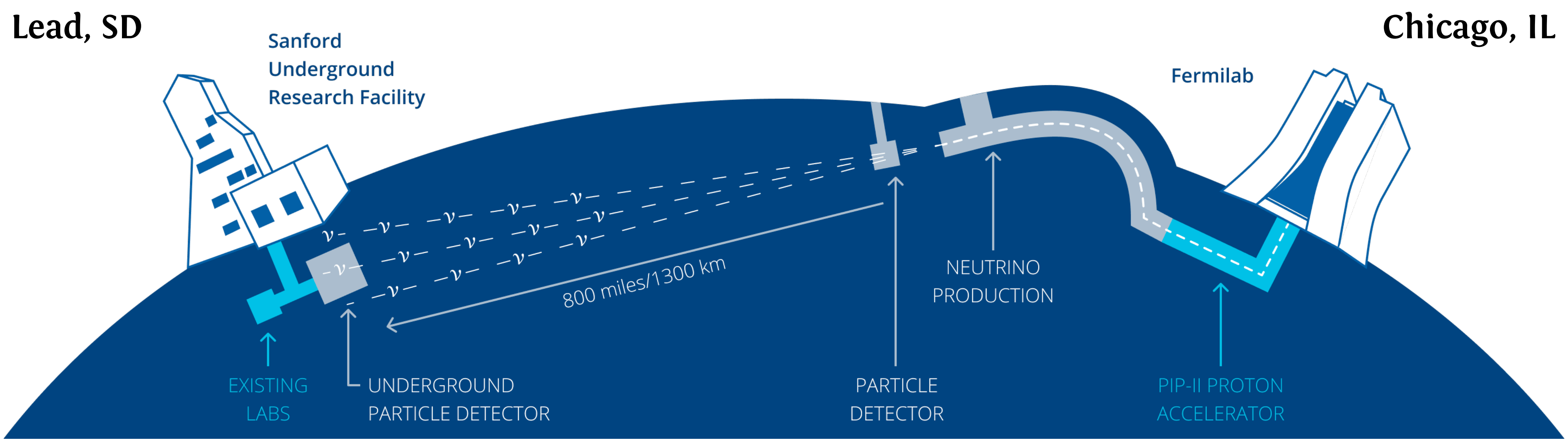
[6] P. Coloma et al., JHEP 2021, 65 (2021)
[7] B. Dev et al., arXiv:2304:02031 (2023)

Deep Underground Neutrino Experiment (DUNE)



- DUNE will start data taking ~2029.
- Long-baseline Liquid Argon (LAr) Time Projection Chamber (TPC) neutrino experiment:
    - Near Detector (ND): 574 m, 67t argon
    - Far Detector (FD): 1300 km, 40kt argon

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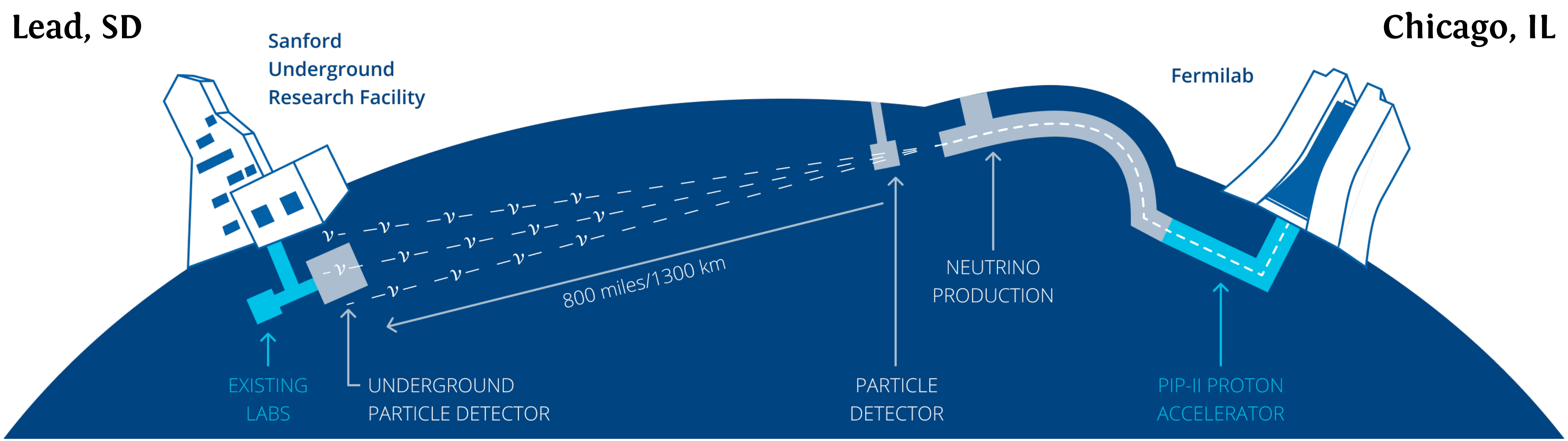

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- Long-baseline Liquid Argon (LAr) Time Projection Chamber (TPC) neutrino experiment:
    - Near Detector (ND): 574 m, 67t argon
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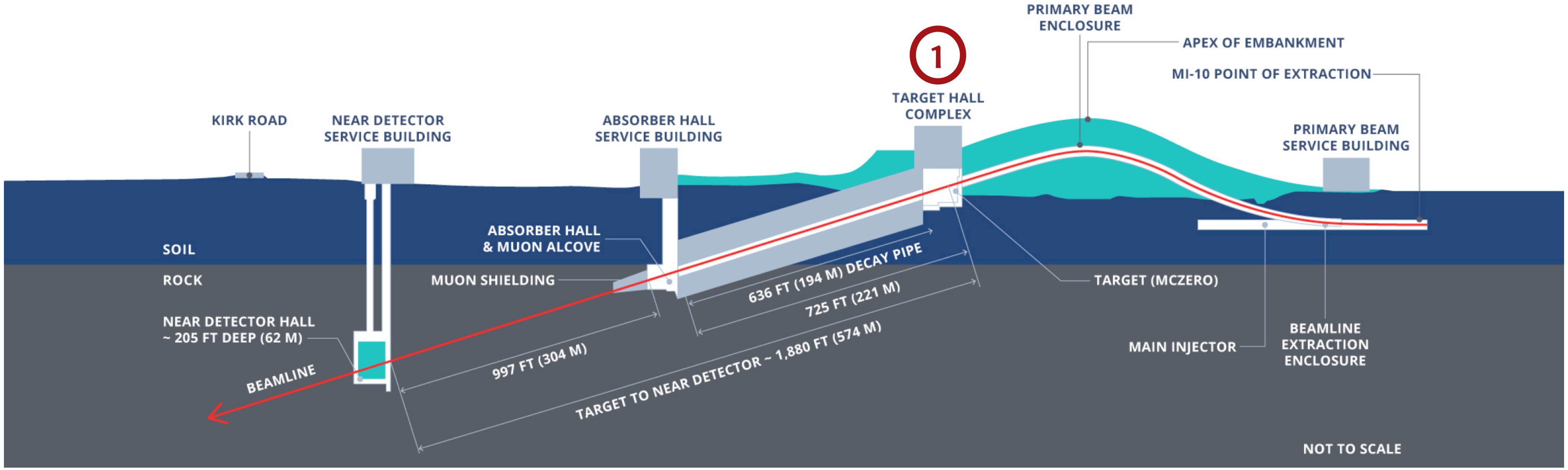
- Focus on DUNE ND; will detect ~10^6 ν events / (GeV·ton·MW·year).

DUNE Beam



1 120 GeV proton beam strikes on graphite target.

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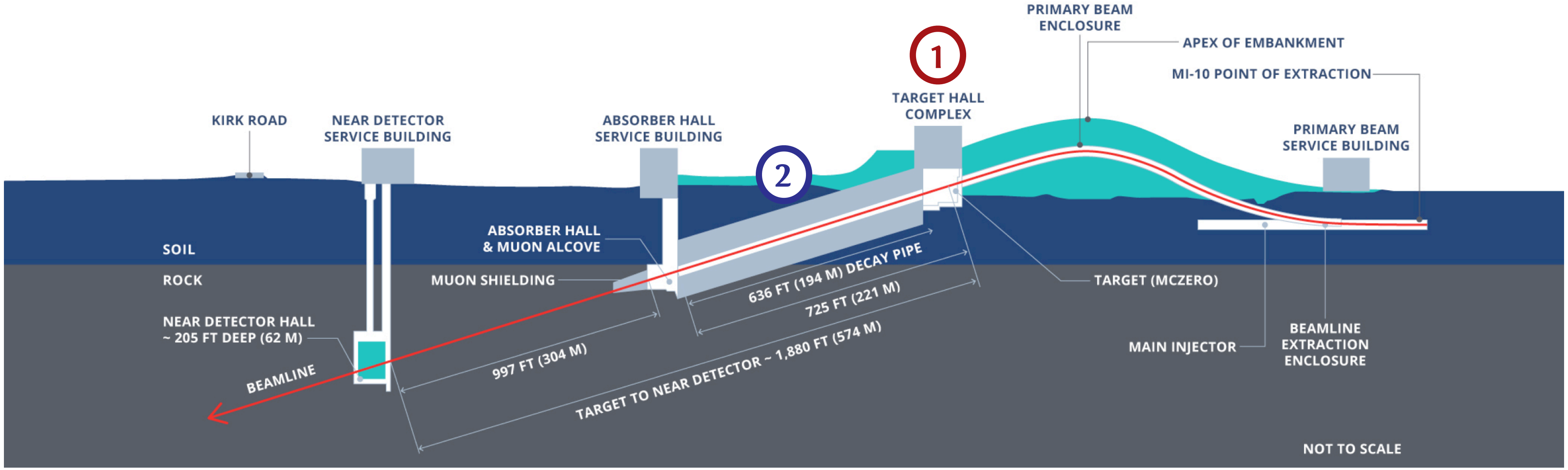

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2. π, K are focused by magnetic horns and travel through decay pipe producing μ, ν_μ.

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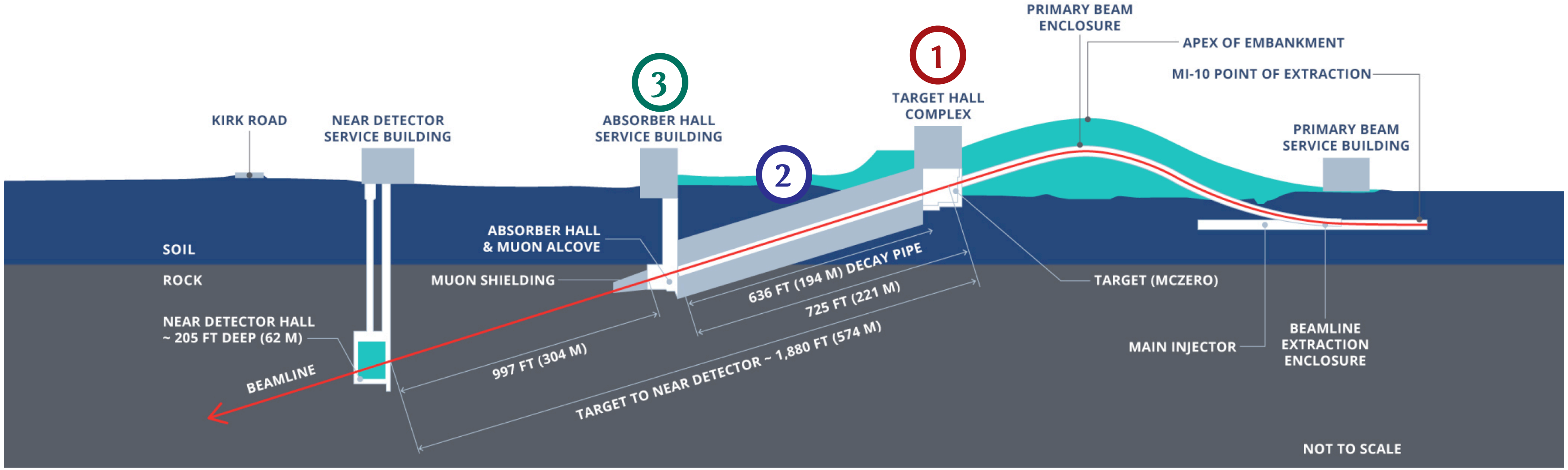

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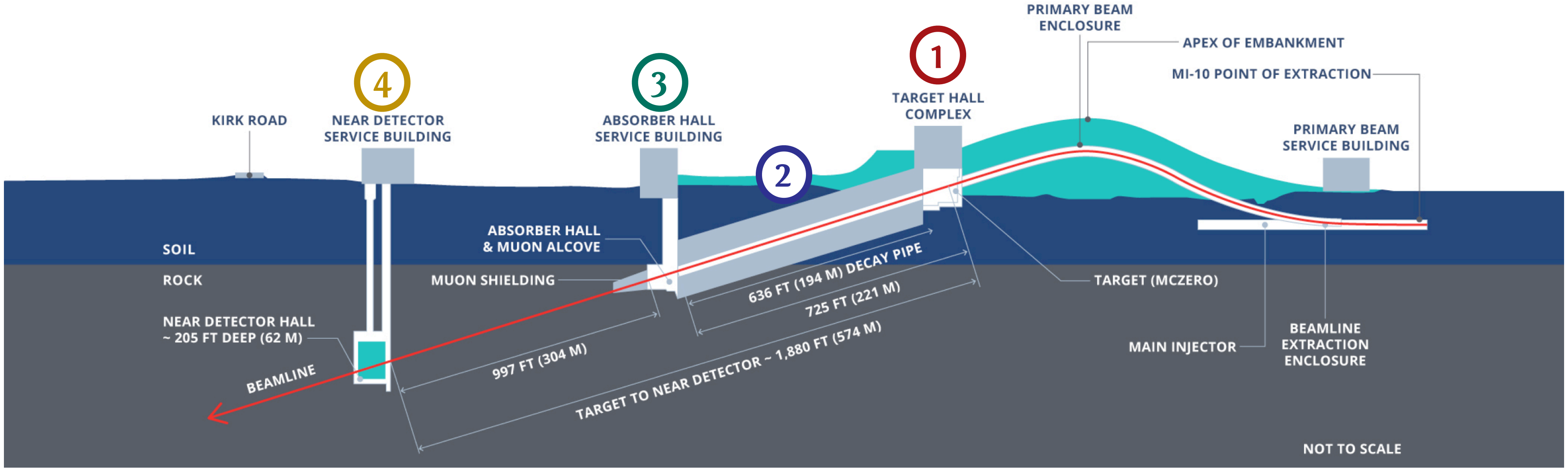

1. 120 GeV proton beam strikes on graphite target.
2. π, K are focused by magnetic horns and travel through decay pipe producing μ, ν_μ.
3. μ are stopped by a block of concrete and steel in the absorber hall.
4. ν_μ beam reaches the DUNE Near Detector 574 meters from the graphite target.

DUNE Near Detector Fluxes

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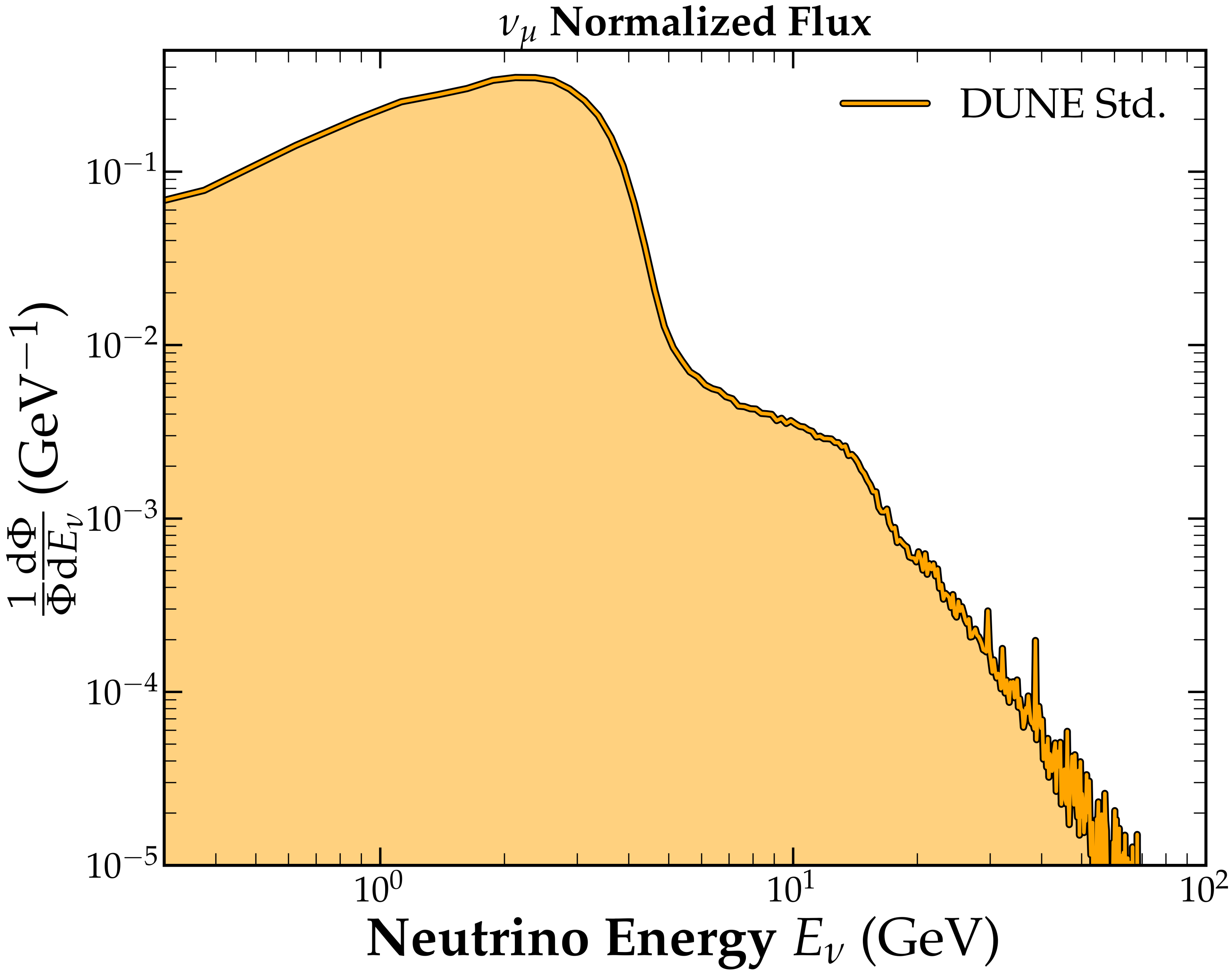
DUNE Standard (CP-optimized) mode:

- Magnetic horn configuration prioritizes less energetic π, K producing $1-5$ GeV range for $\delta_{\rm CP}$ measurements.
- $\langle E_\nu \rangle \sim 2$ GeV



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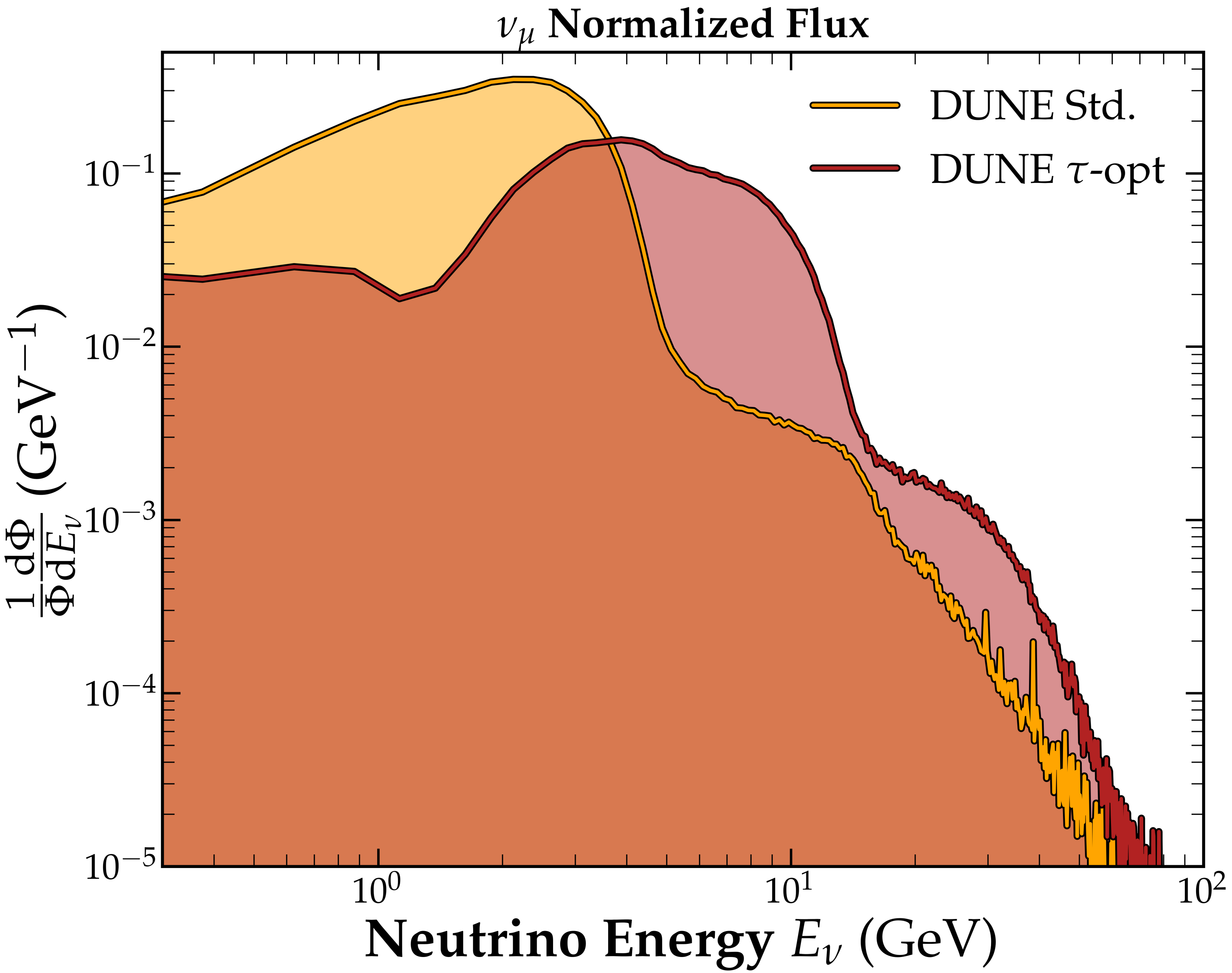
DUNE τ-optimized mode:

- Alternative horn configuration prioritizes focusing of more energetic π, K increasing the flux above 5 GeV for higher ν_τ measurements.
- $\left\langle E_\nu \right\rangle \sim 4$ GeV.



Trident Generator
(Based on work by Altmannshofer et al. (2019))

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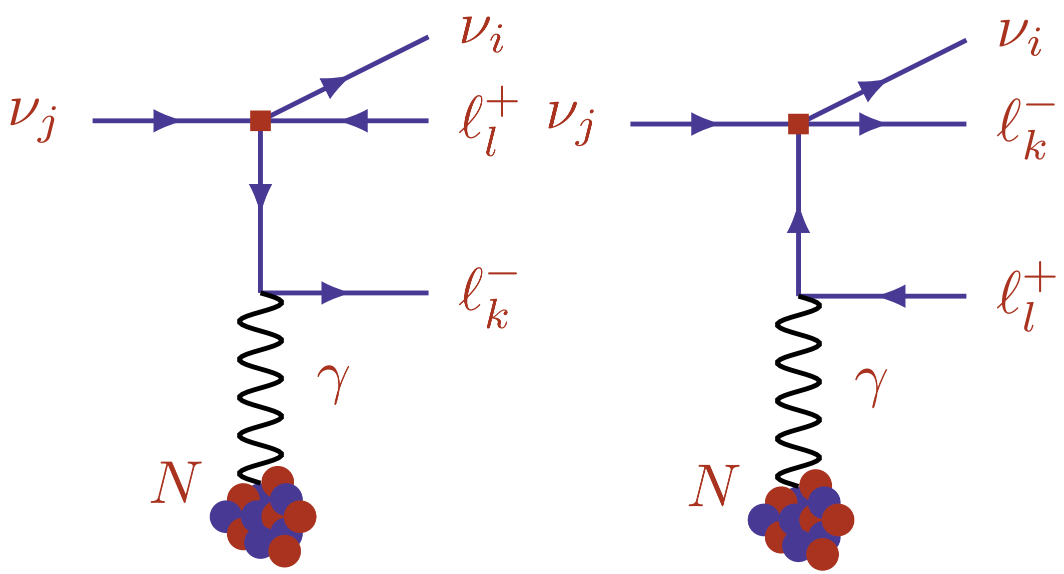
DUNE: $Q^2 \ll M^2_{W,Z} \rightarrow$ 4 Fermi interactions.

Only consider $\gamma - N$ contributions

Avoids Equivalent Photon Approximation (EPA)

- Shown to be unreliable for all but the coherent scattering of the $\nu_\mu \mu^+ \mu^-$ trident.



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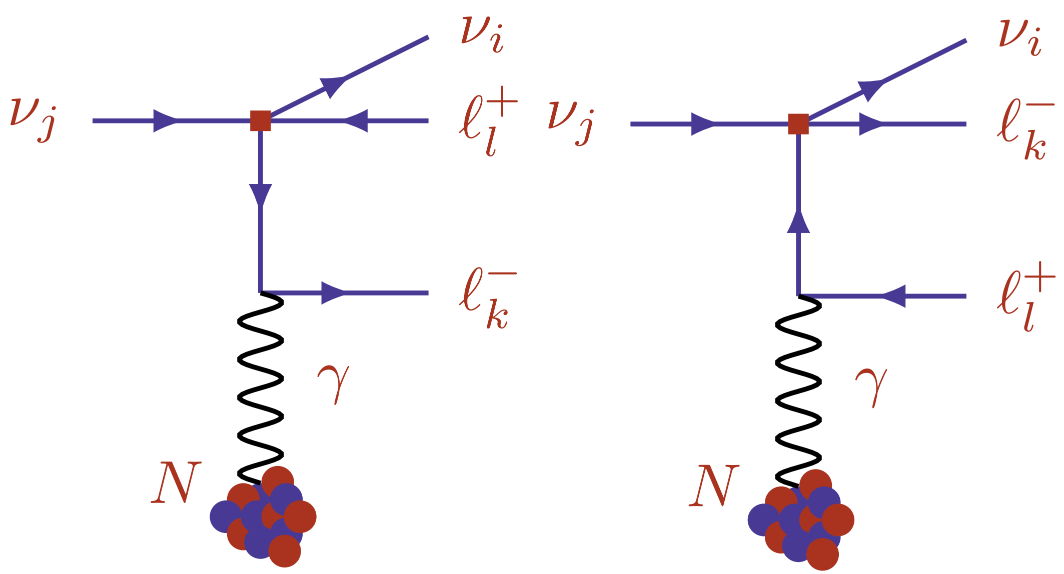

For DUNE, cross section divided into two regimes
- **Coherent scattering with argon nucleus.**
  - Nuclear form factor.
  - Scales as Z^2.
  - *Experimental signature*: oppositely charged leptons without any hadronic activity.

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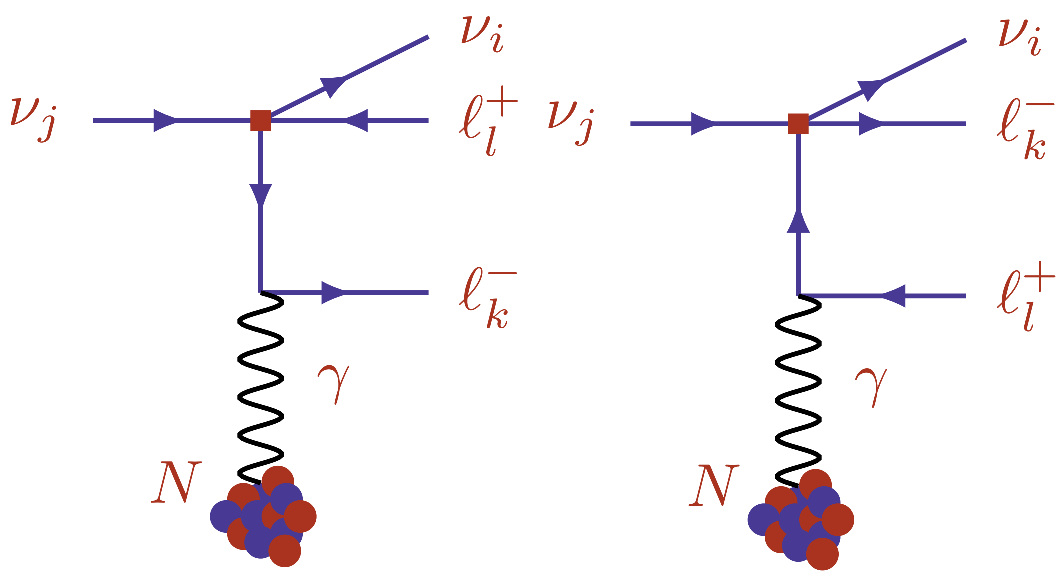

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- **Coherent scattering with argon nucleus.**
  - Nuclear form factor.
  - Scales as Z^2.
  - *Experimental signature*: oppositely charged leptons without any hadronic activity.
- **Incoherent (diffractive) scattering with individual nucleons.**
  - Nucleon form factors.
  - Fermi gas model; includes Pauli blocking factor.
  - Scales as Z.
  - *Experimental signature:* oppositely charged leptons + proton or neutron.

[8] Altmannshofer et al., Phys. Rev. D 100, 115029 (2019)

Cross Section Validation

Coherent scattering uncertainty ($\simeq 6\%$):

- Higher order QED corrections ($\simeq 3\%$)
- Nuclear form factors ($\simeq 1\%$)
- Higher order EW corrections ($\simeq 5\%$)

Incoherent scattering uncertainty ($\simeq 31\%$):

- Higher order QED corrections ($\simeq 3\%$)
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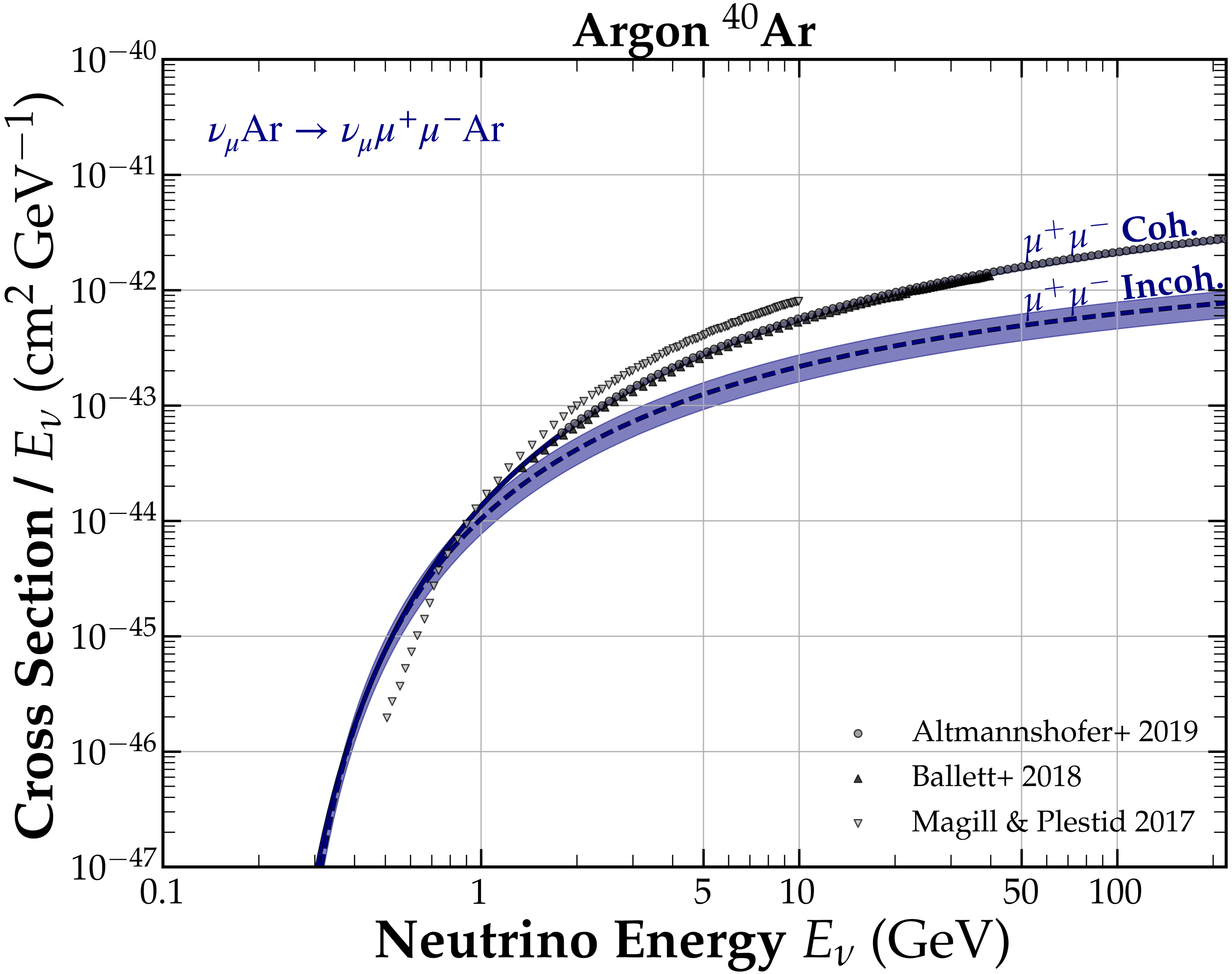
- Nuclear modeling ($\simeq 30\%$)



[9] P. Ballett et al., J. High Energy Phys. 01 119 (2019)

[10] Magill and Plestid, Phys. Rev. D95, 073004 (2017)

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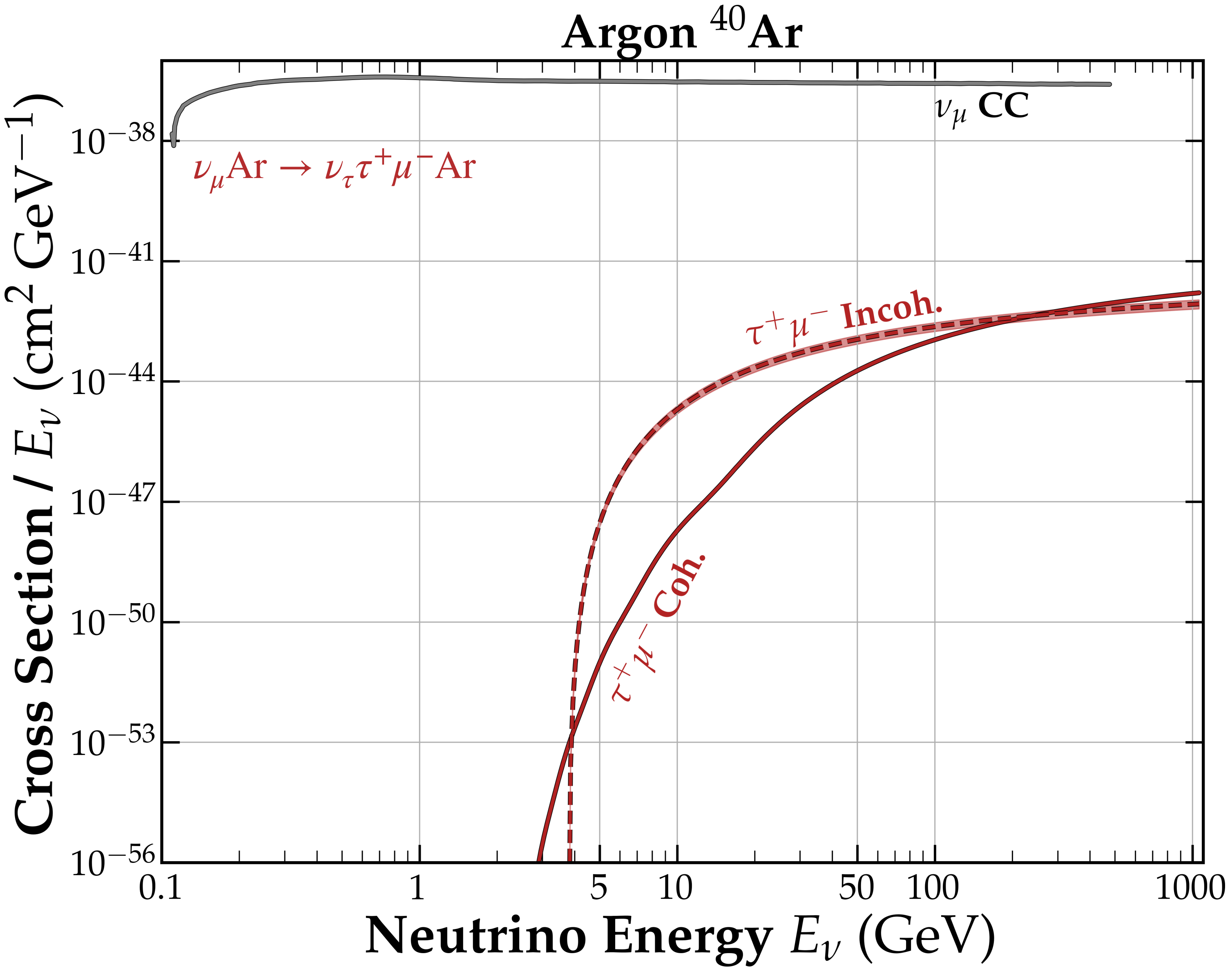

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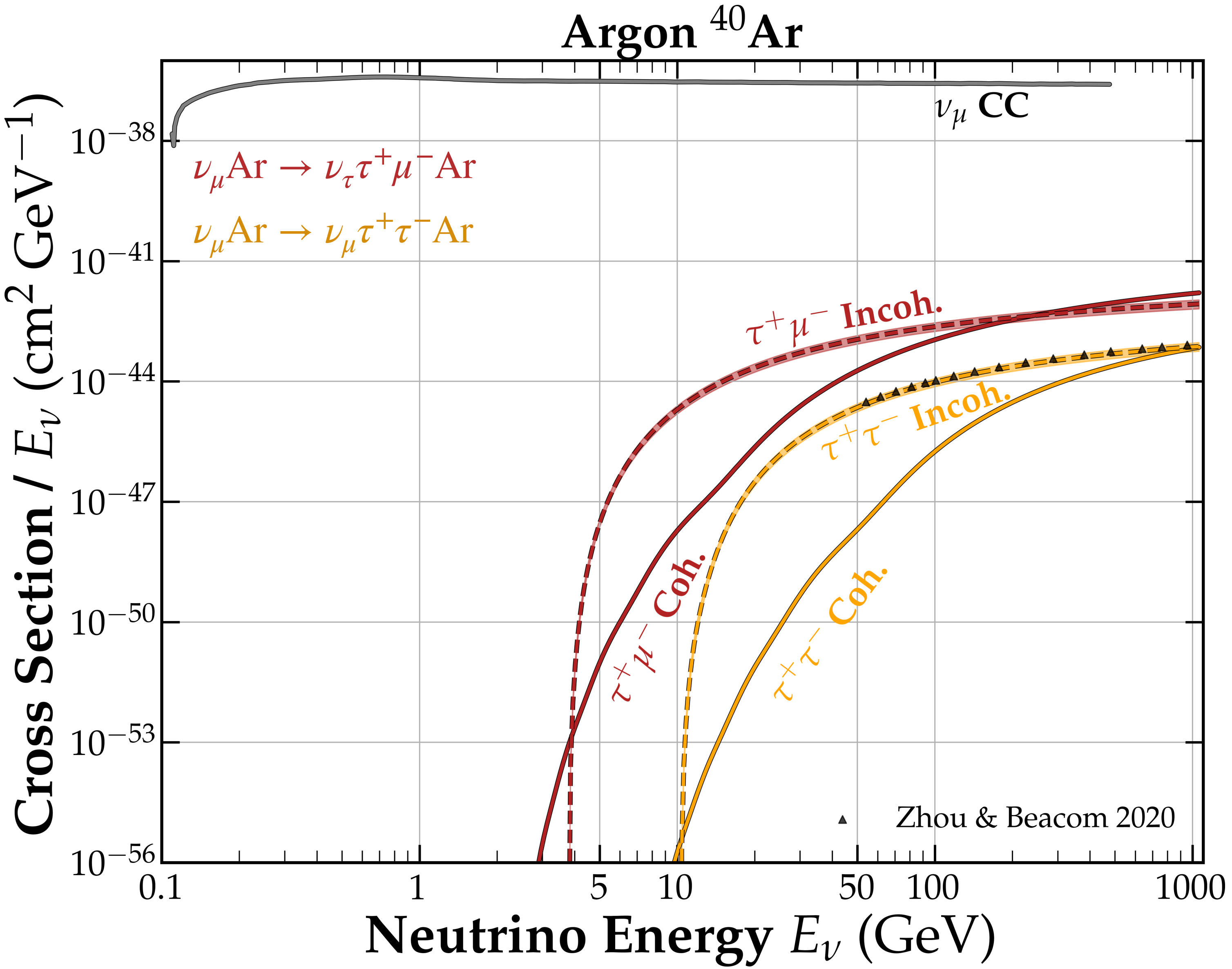

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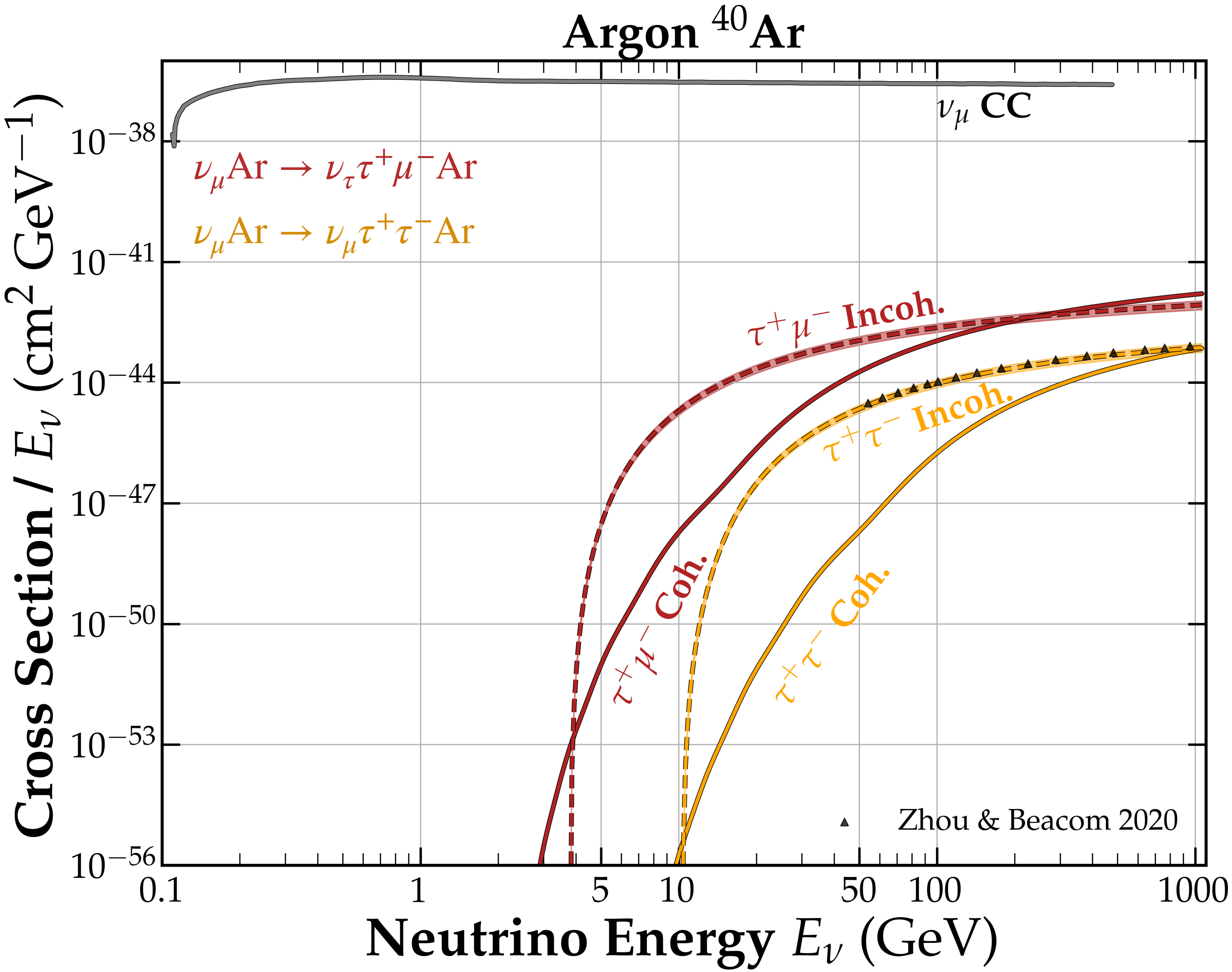
$$N_{\text{trident}} = \frac{M_{\text{det}}}{M_{\text{Ar}}} N_{\text{POT}} \int \frac{d\Phi}{dE} \sigma(E) dE$$



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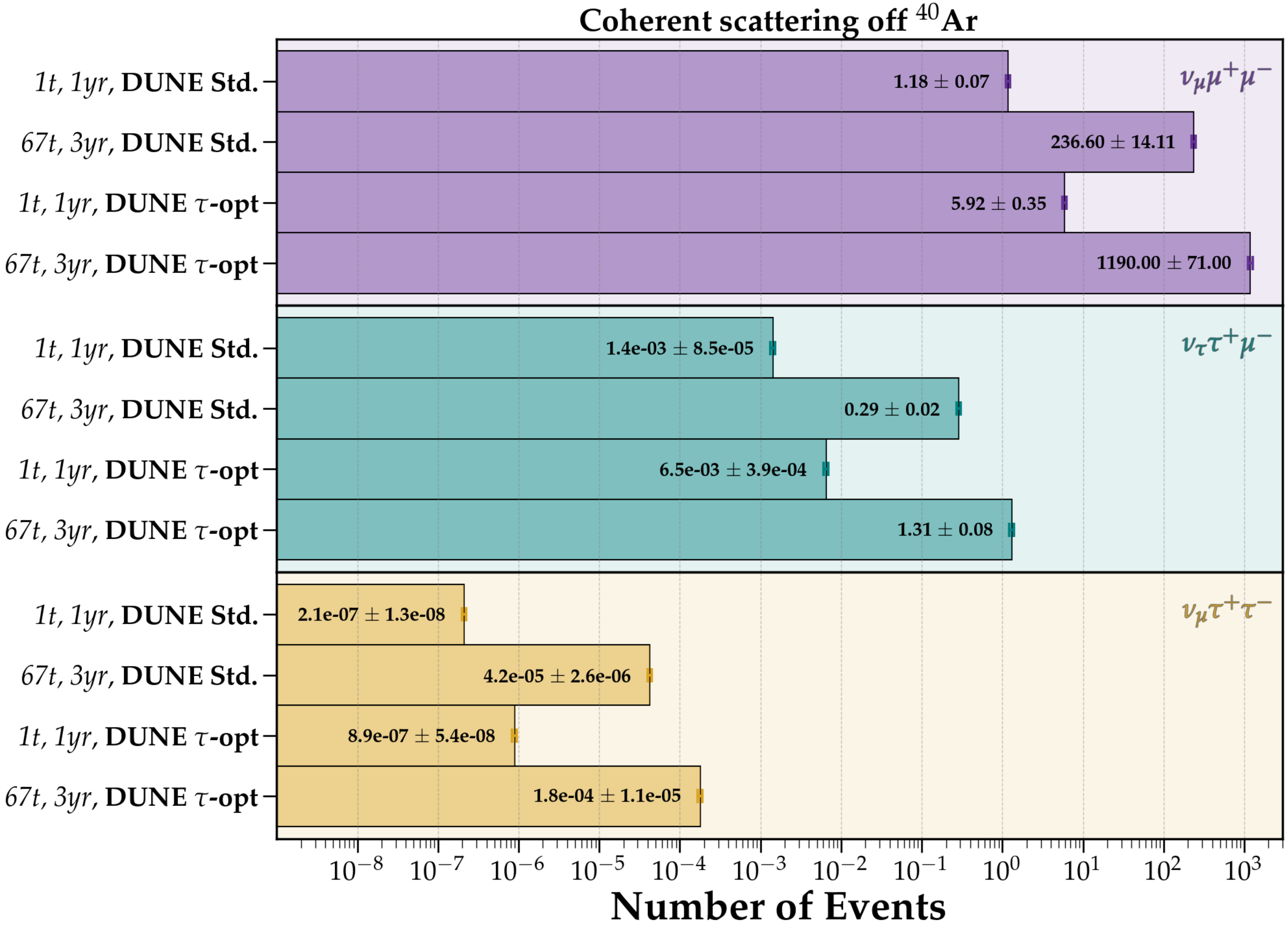
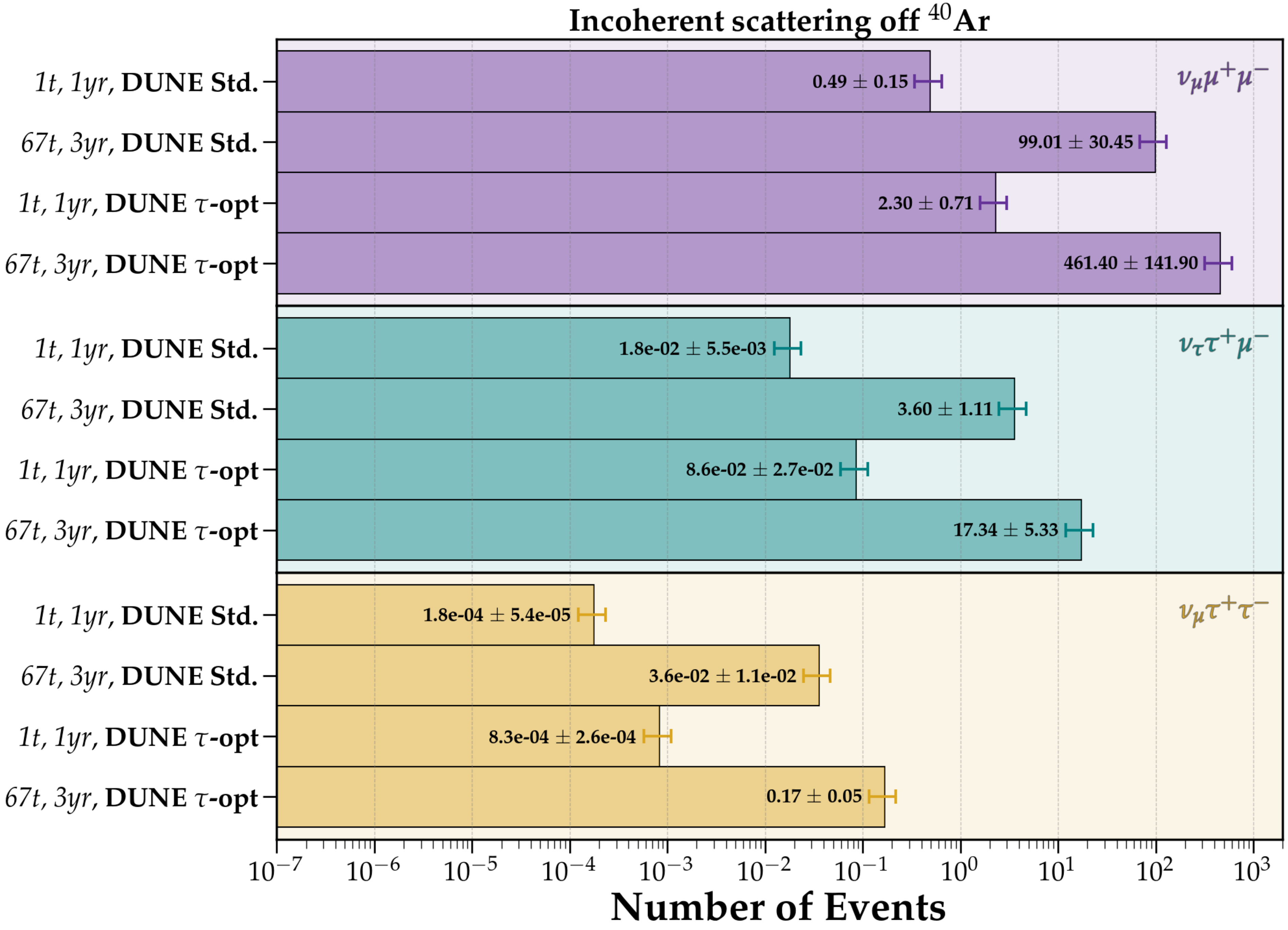


Coherent scattering off ^{40}Ar
1t, 1yr, DUNE Std.
67t, 3yr, DUNE Std.
1t, 1yr, DUNE τ-opt
67t, 3yr, DUNE τ-opt
1.18 ± 0.07
236.60 ± 14.11
5.92 ± 0.35
1190.00 ± 71.00
$\nu_\mu \mu^+ \mu^-$
1.4e-03 ± 8.5e-05
0.29 ± 0.02
6.5e-03 ± 3.9e-04
1.31 ± 0.08
$\nu_\tau \tau^+ \mu^-$
2.1e-07 ± 1.3e-08
4.2e-05 ± 2.6e-06
8.9e-07 ± 5.4e-08
1.8e-04 ± 1.1e-05
$\nu_\mu \tau^+ \tau^-$
Number of Events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1t, 1yr, DUNE Std.
67t, 3yr, DUNE Std.
1t, 1yr, DUNE τ-opt
67t, 3yr, DUNE τ-opt
0.49 ± 0.15
99.01 ± 30.45
2.30 ± 0.71
461.40 ± 141.90
$\nu_\mu \mu^+ \mu^-$
1.8e-02 ± 5.5e-03
3.60 ± 1.11
8.6e-02 ± 2.7e-02
17.34 ± 5.33
$\nu_\tau \tau^+ \mu^-$
1.8e-04 ± 5.4e-05
3.6e-02 ± 1.1e-02
8.3e-04 ± 2.6e-04
0.17 ± 0.05
$\nu_\mu \tau^+ \tau^-$
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
Number of Events

Summary and Outlook

- Importance of ν_τ as a SM signal and a BSM background.
- First results for coherent scattering on Argon for $\nu_\mu \mathrm{Ar} \to \nu_\tau \tau^+ \mu^- \mathrm{Ar}$ and $\nu_\mu \mathrm{Ar} \to \nu_\mu \tau^+ \tau^- \mathrm{Ar}$.

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- FASERν: High energy behavior of τ trident cross sections suggest larger N for detectors such as FASERν with E_ν in the $1 - 10$ TeV range. DIS will become relevant but coherent and incoherent contributions are still important. Expect results soon.

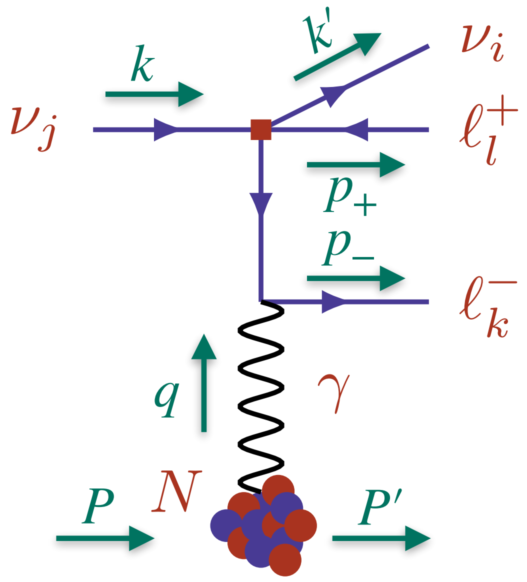
Thank you!

Back-up Slides

Coherent Trident Cross Section

Differential coherent scattering cross section off a nucleus of mass m_N; enhanced by Z^2.

$$d\sigma_{\text{coh}} = \frac{Z^2 \alpha_{\text{EM}}^2 G_F^2}{128\pi^6} \frac{1}{m_N E_\nu} \frac{d^3k'}{2E_{k'}} \frac{d^3p_+}{2E_+} \frac{d^3p_-}{2E_-} \frac{d^3P'}{2E_{P'}} \frac{H_N^{\alpha\beta} L_{\alpha\beta}}{q^4} \delta^4(k - k' - p_+ - p_- + q)$$



Leptonic Tensor $$L_{\alpha\beta} = \sum_{s,s',s_+,s_-} A_\alpha A_\beta^\dagger$$

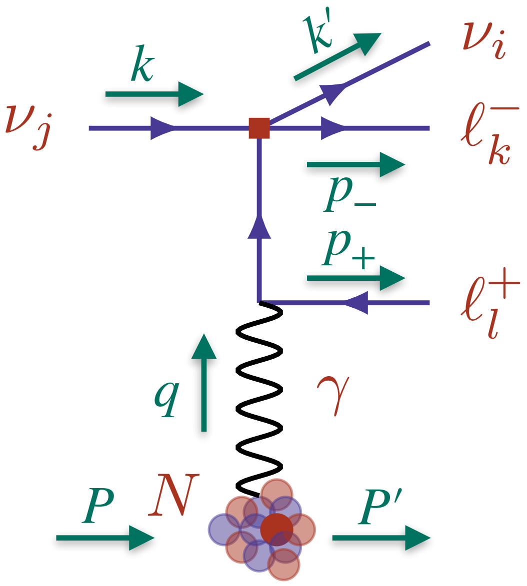
$$A_\alpha = (\bar{u}'\gamma_\mu P_L u)\left(\bar{u}_- \left[\gamma_\alpha \frac{(p_- - q)\cdot\gamma + m_-}{(p_- - q)^2 - m_-^2} \gamma^\mu (g_{ijkl}^V + g_{ijkl}^A \gamma_5) - \gamma^\mu (g_{ijkl}^V + g_{ijkl}^A \gamma_5) \frac{(p_+ - q)\cdot\gamma + m_+}{(p_+ - q)^2 - m_+^2} \gamma_\alpha \right] v_+ \right)$$

Hadronic Tensor $$H_N^{\alpha\beta} = 4P^\alpha P^\beta [F_N(q^2)]^2$$

Incoherent Trident Cross Section

Differential incoherent scattering cross section off an individual nucleon of mass $m_{p(n)}$.

$$d\sigma_{p(n)} = \frac{\alpha_{\rm EM}^2 G_F^2}{128\pi^6} \frac{1}{m_{p(n)}E_\nu} \frac{d^3k'}{2E_{k'}} \frac{d^3p_+}{2E_+} \frac{d^3p_-}{2E_-} \frac{d^3P'}{2E_{P'}} \frac{H^{\alpha\beta}_{p(n)}L_{\alpha\beta}}{q^4} \delta^4(k-k'-p_+-p_-+q)$$



Hadronic Tensor

$$H^{\alpha\beta}_{p(n)} = 4P^\alpha P^\beta \left(\frac{4m^2_{p(n)}[G_E^{p(n)}(Q^2)]^2}{Q^2+4m^2_{p(n)}} + \frac{Q^2[G_M^{p(n)}(Q^2)]^2}{Q^2+4m^2_{p(n)}} + g^{\alpha\beta}Q^2[G_M^{p(n)}(Q^2)]^2 \right)$$

Total incoherent cross section for $^A_Z N$

$$d\sigma_{\rm incoh} = \Theta(|\mathbf{q}|)(Z d\sigma_p + (A-Z)d\sigma_n)$$

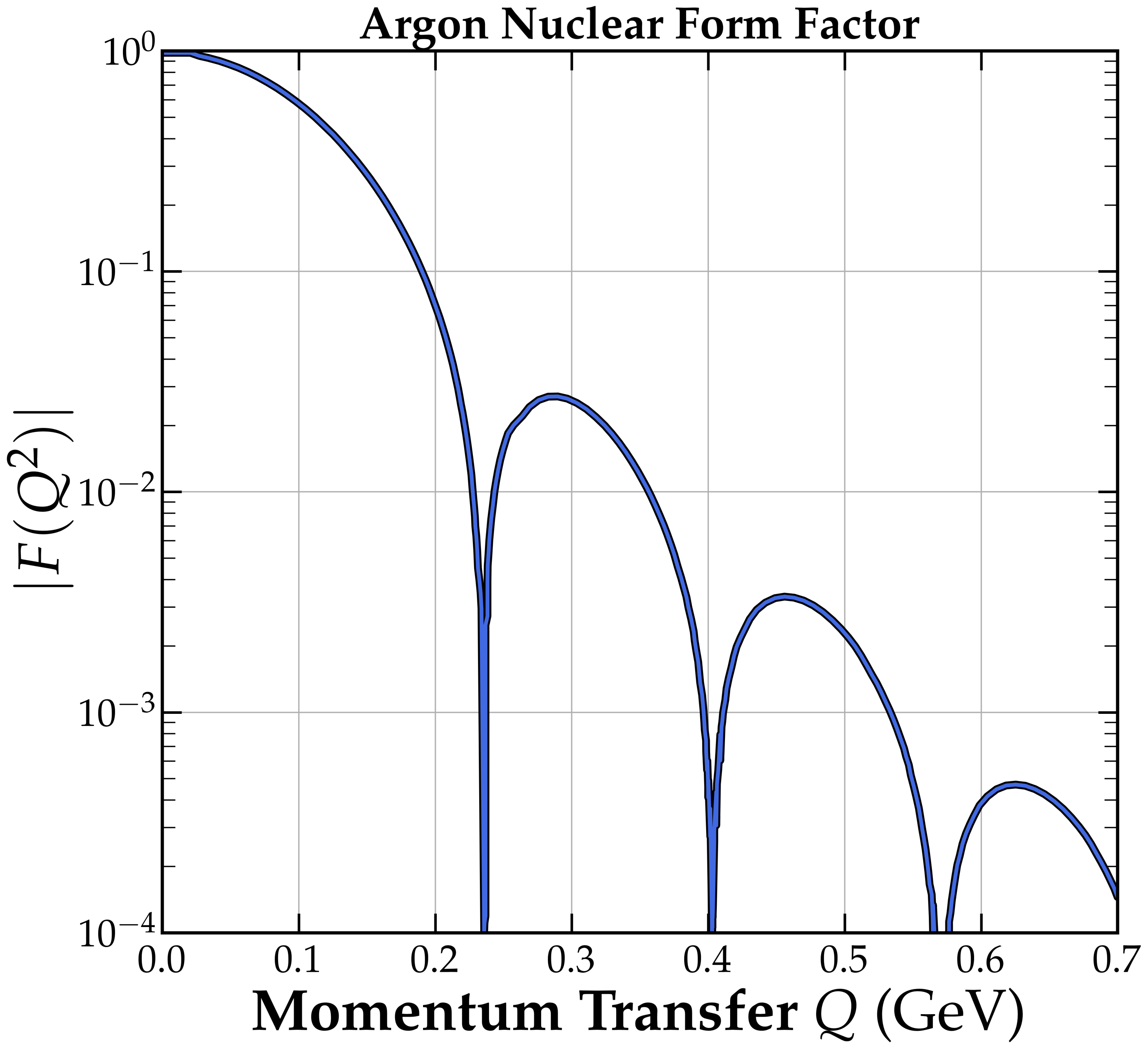
Pauli blocking: $\Theta(|\mathbf{q}|) = \begin{cases} \frac{3}{4}\frac{|\mathbf{q}|}{p_F} - \frac{|\mathbf{q}|^3}{16p_F^3} & \text{for } |\mathbf{q}| < 2p_F \\ 1 & \text{for } |\mathbf{q}| > 2p_F \end{cases}$ $\quad p_F = 235$ MeV

Argon Form Factor

$$F_N(Q^2) = \int \mathrm{d}r r^2 \frac{\sin(qr)}{qr} \rho_N(r)$$

Argon nuclear form factor using a 3-parameter Fermi parametrization for the charge distribution $\rho_N(r)$

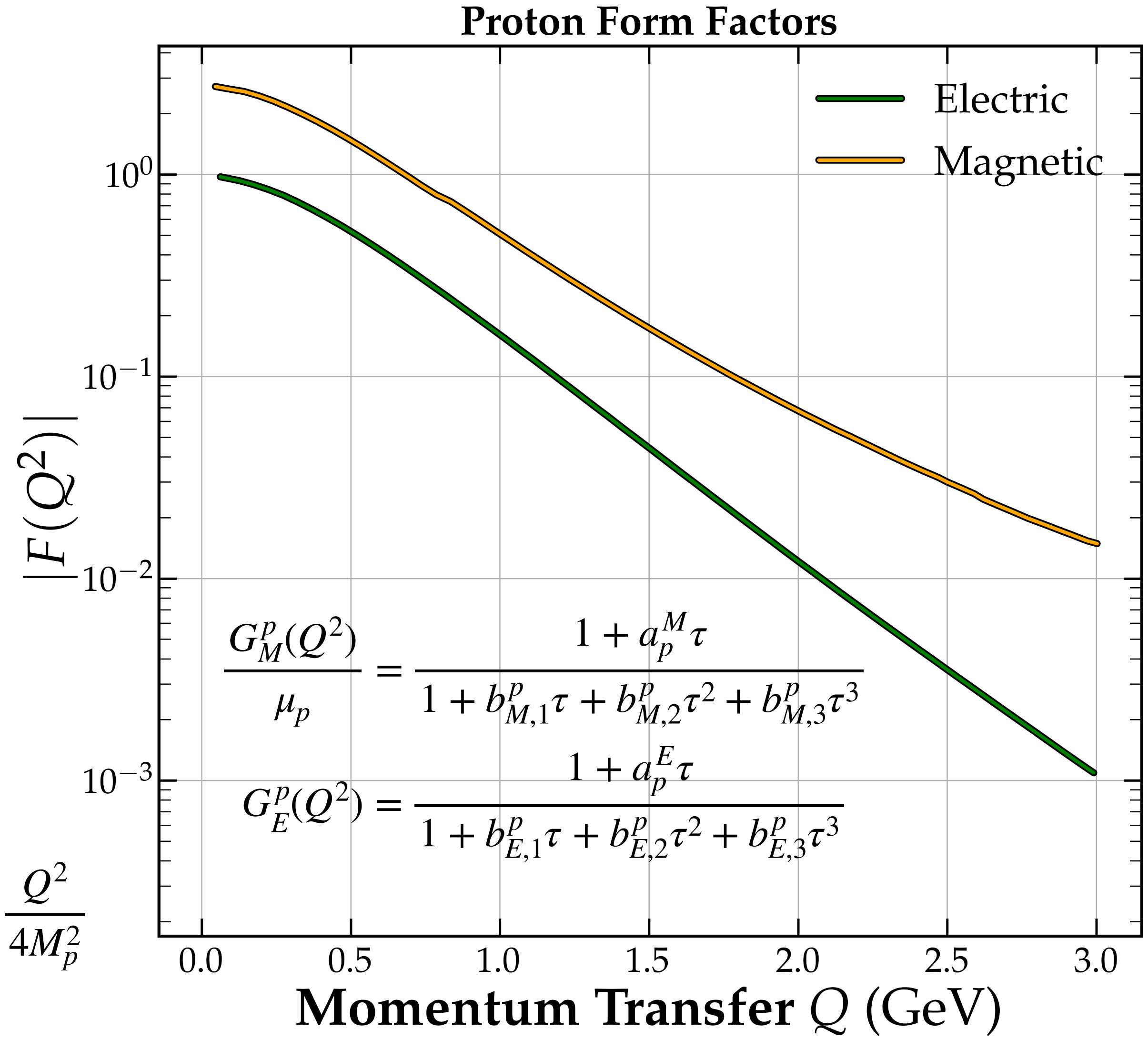
$$\rho_N(r) = \frac{\mathcal{N}\left(1 + w\frac{r^2}{r_0^2}\right)}{1 + \exp\left(\frac{r - r_0}{\sigma}\right)}$$



Nucleon Form Factors

Proton: electron-proton elastic scattering

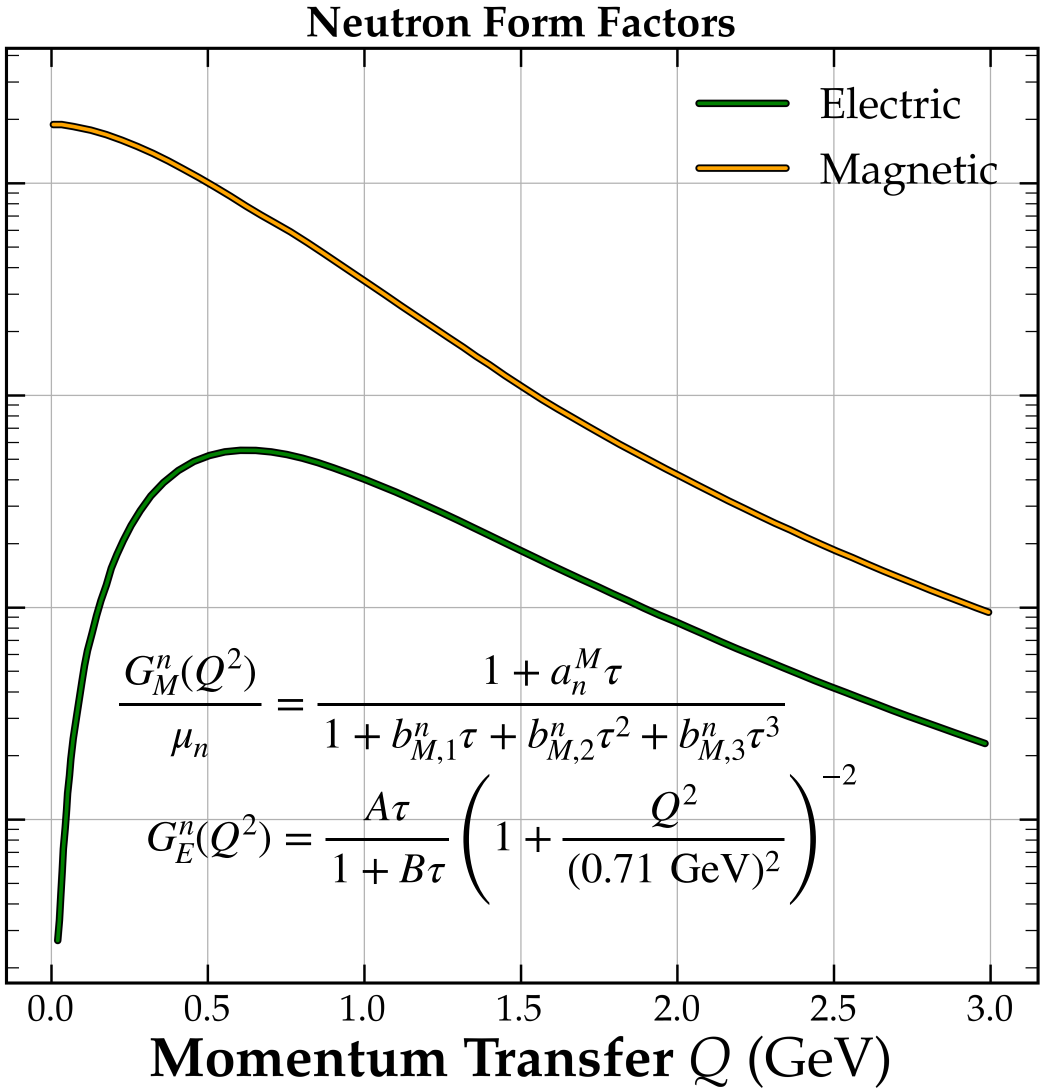
Neutron: electron-nucleus (deuterium and ^{3}He) scattering



$$\frac{G_M^p(Q^2)}{\mu_p} = \frac{1 + a_p^M \tau}{1 + b_{M,1}^p \tau + b_{M,2}^p \tau^2 + b_{M,3}^p \tau^3}$$

$$G_E^p(Q^2) = \frac{1 + a_p^E \tau}{1 + b_{E,1}^p \tau + b_{E,2}^p \tau^2 + b_{E,3}^p \tau^3}$$

$$\tau = \frac{Q^2}{4M_p^2}$$



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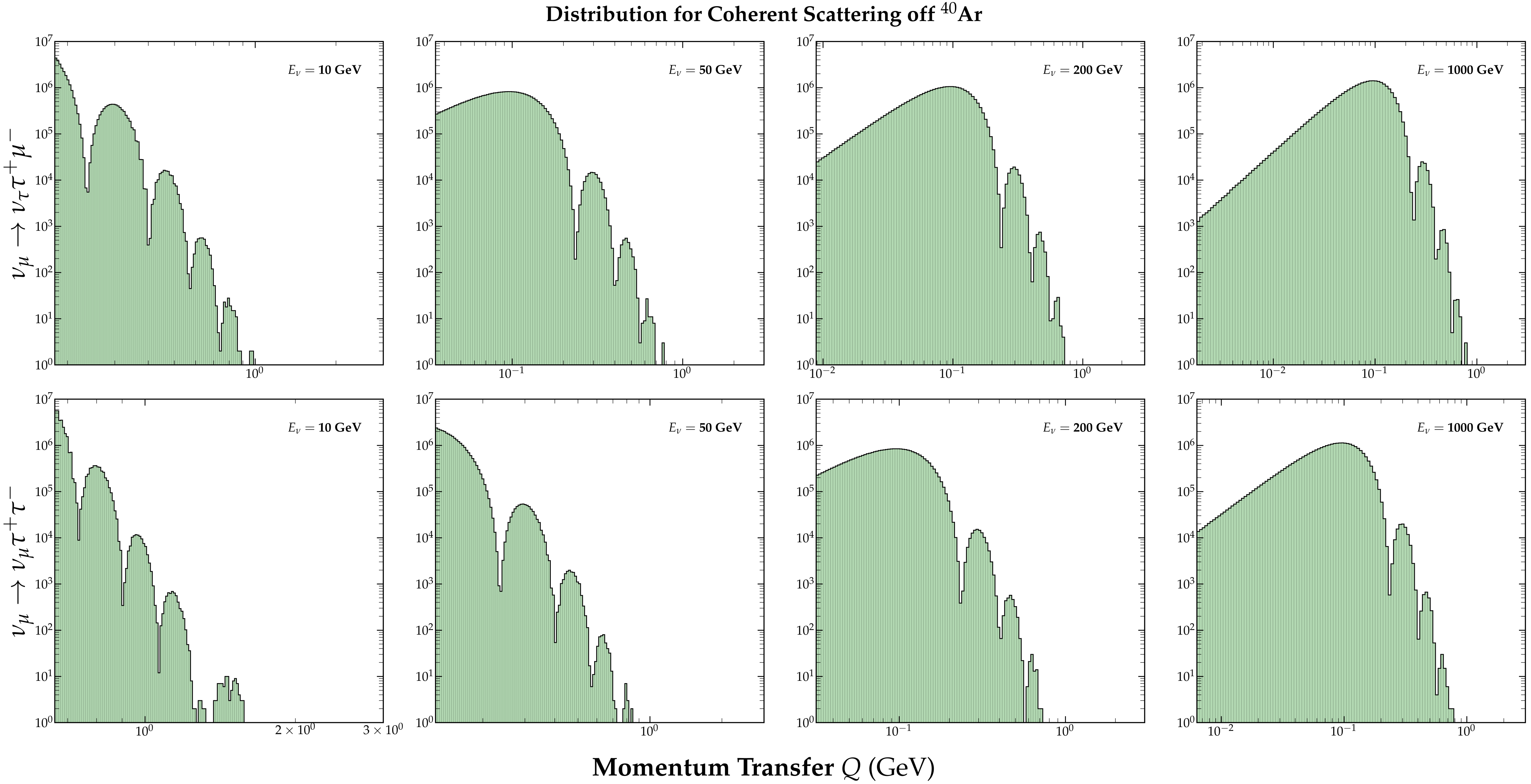
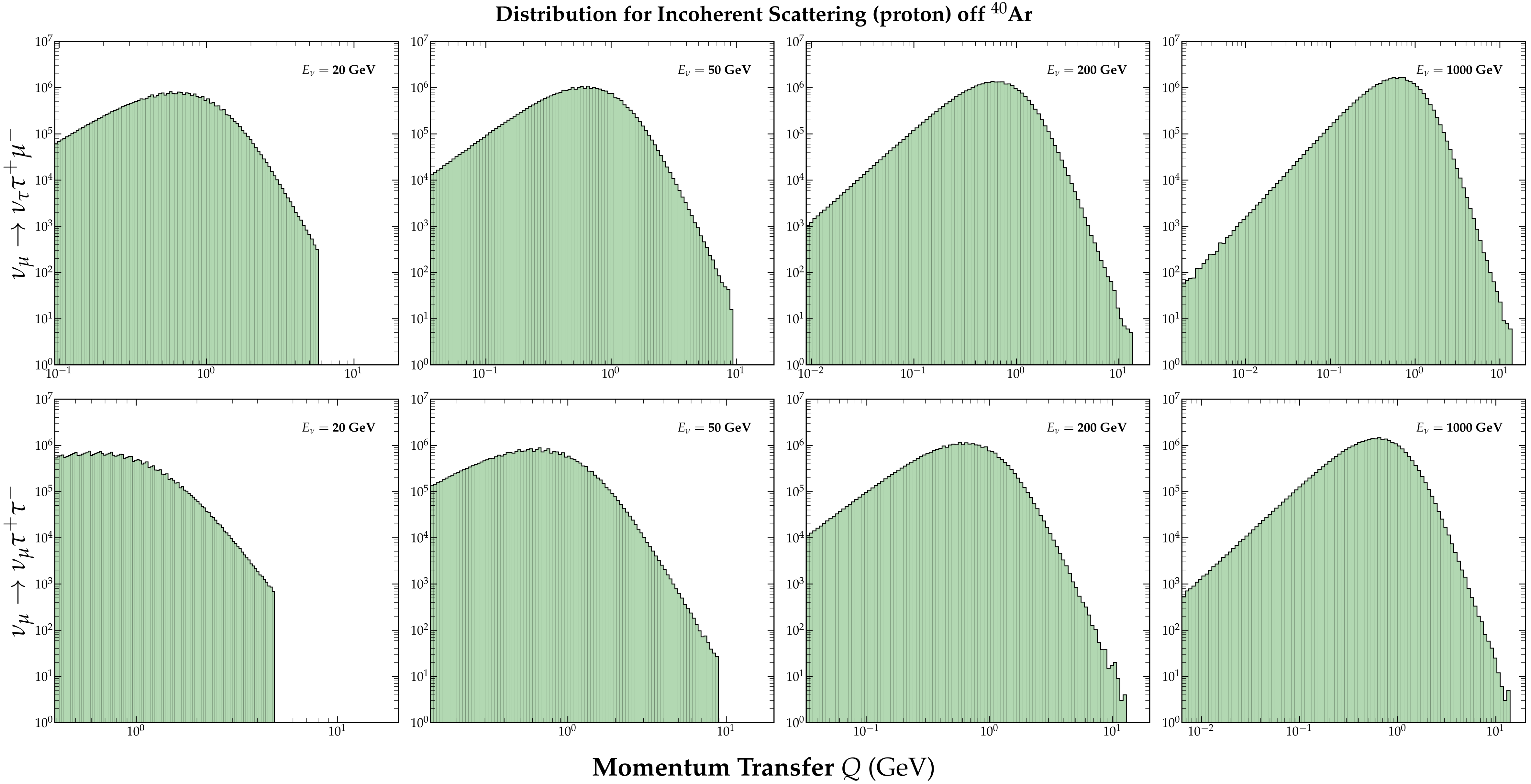
$$G_E^n(Q^2) = \frac{A\tau}{1 + B\tau}\left(1 + \frac{Q^2}{(0.71\ \mathrm{GeV})^2}\right)^{-2}$$

Momentum Transfer Distributions — Coherent



Momentum Transfer Distributions — Proton



Momentum Transfer Distributions – Neutron