

Neutrino Magnetic Moment, Charge Radius and Polarizability from MeV to GeV Neutrino Interactions

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Department of Physics and Astronomy,
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Based on:

Carey and Pandey, 2510.14015 [hep-ph];

Carey, Machado, Paz, Petrov, Sousa, Tammaro, and Zupan, 2508.16724 [hep-ph].



WAYNE STATE
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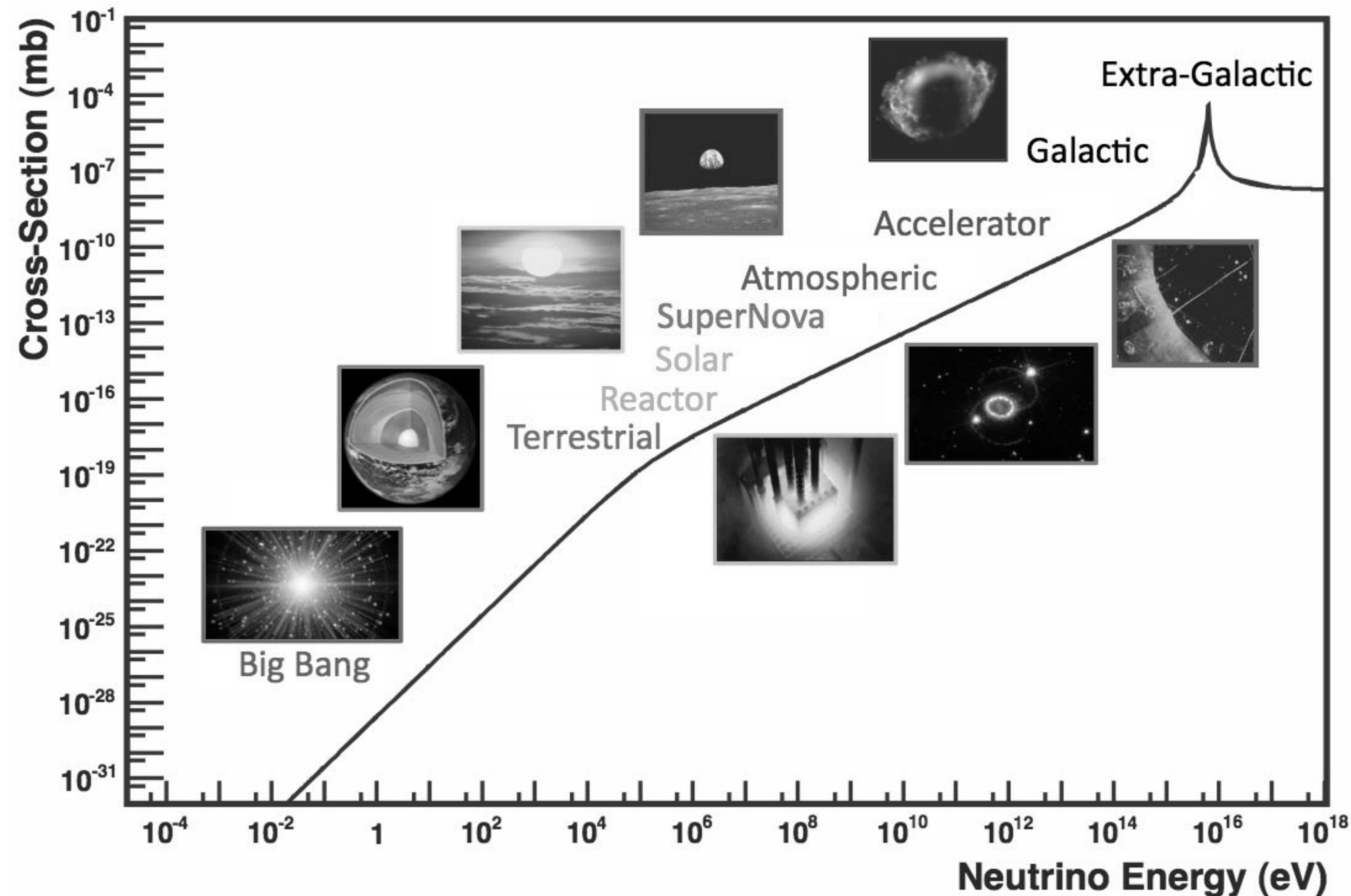
Overview

- ▶ Neutrino (Electromagnetic) Interactions
- ▶ Interaction at MeV: Magnetic Moment and Charge Radius
- ▶ Interaction at GeV: Enhanced Neutrino Polarizability in DUNE
- ▶ Summary

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Neutrino Interactions: Across Energies

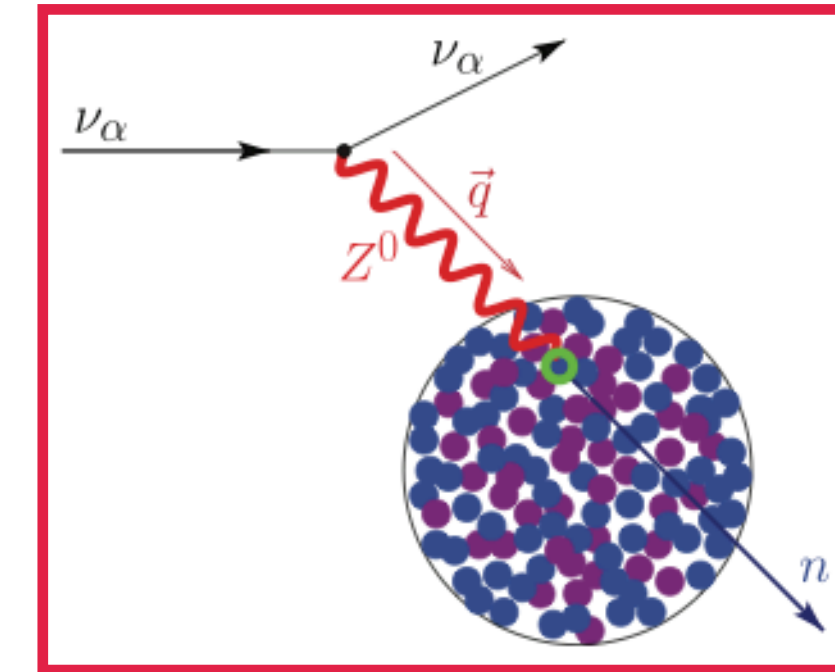
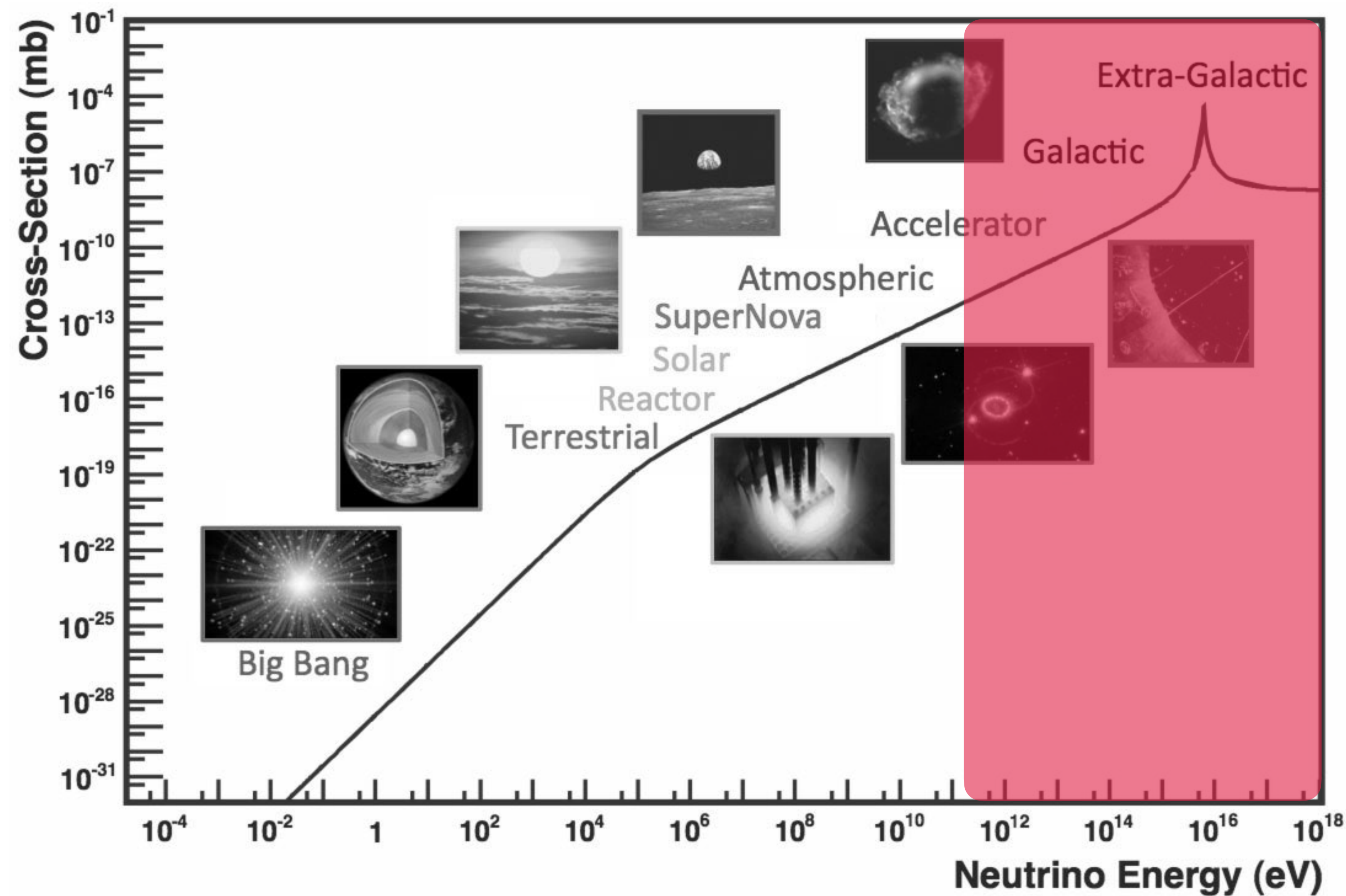


Total ν per nucleon CC cross sections and interaction with matter at different energies.

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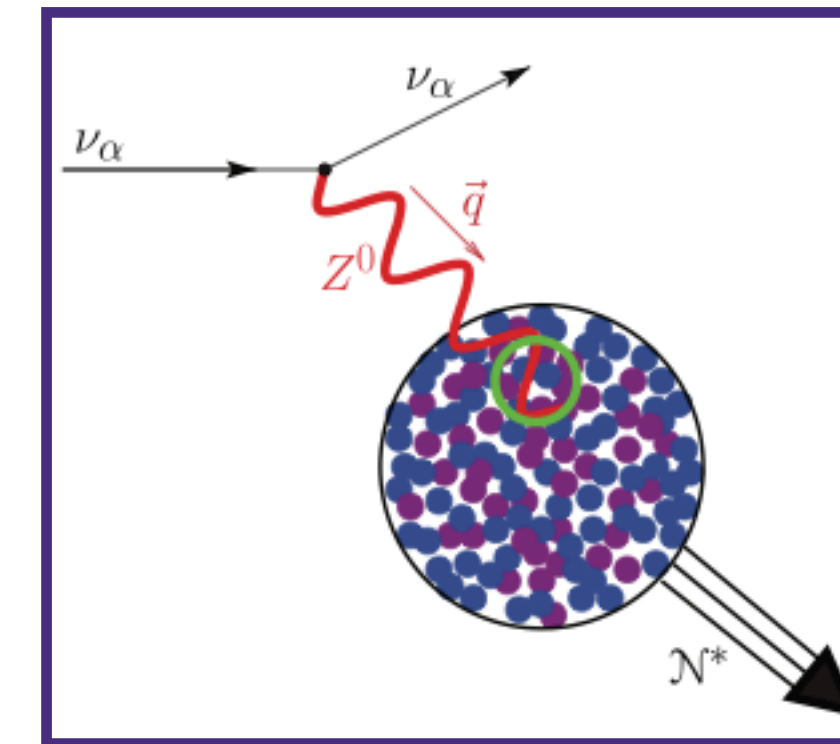
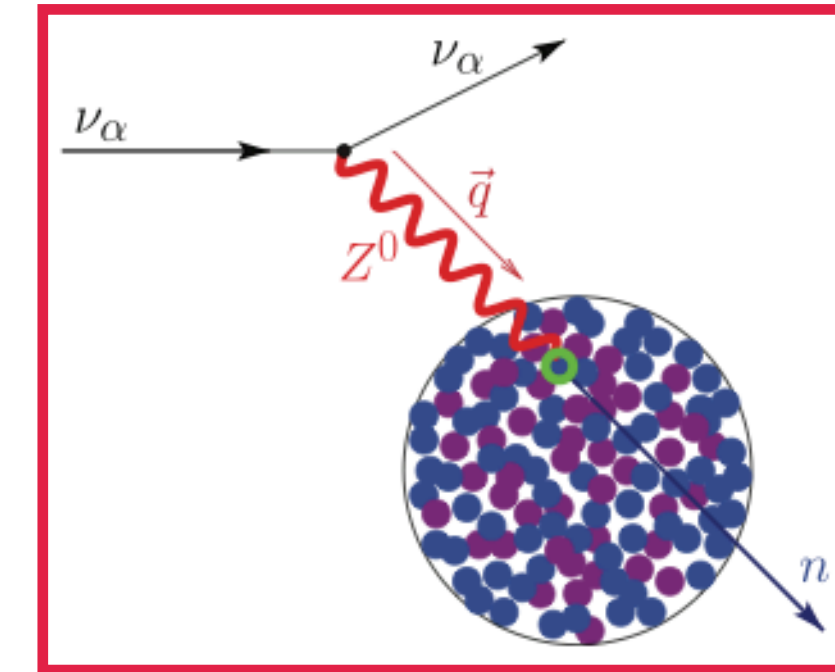
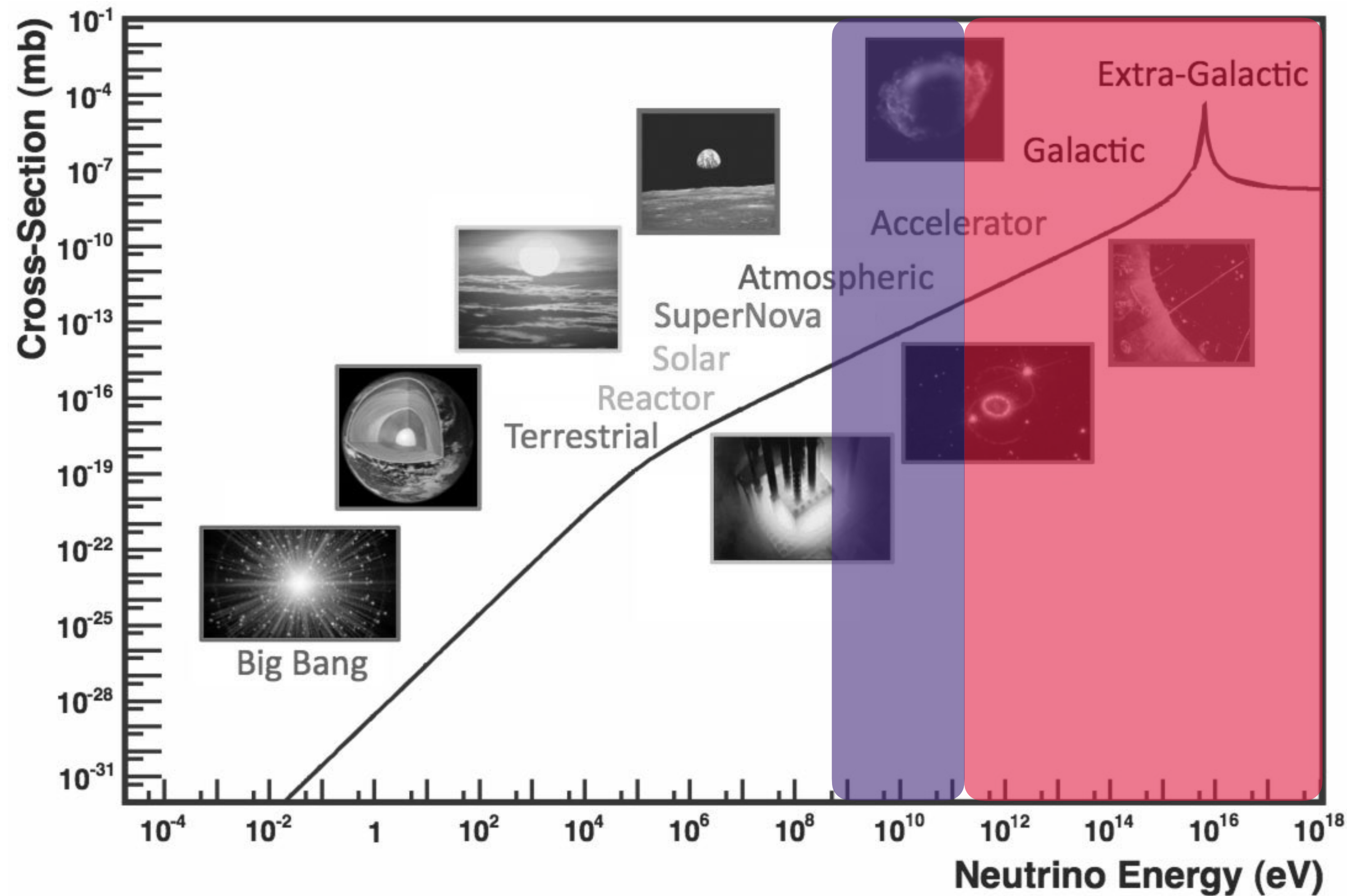


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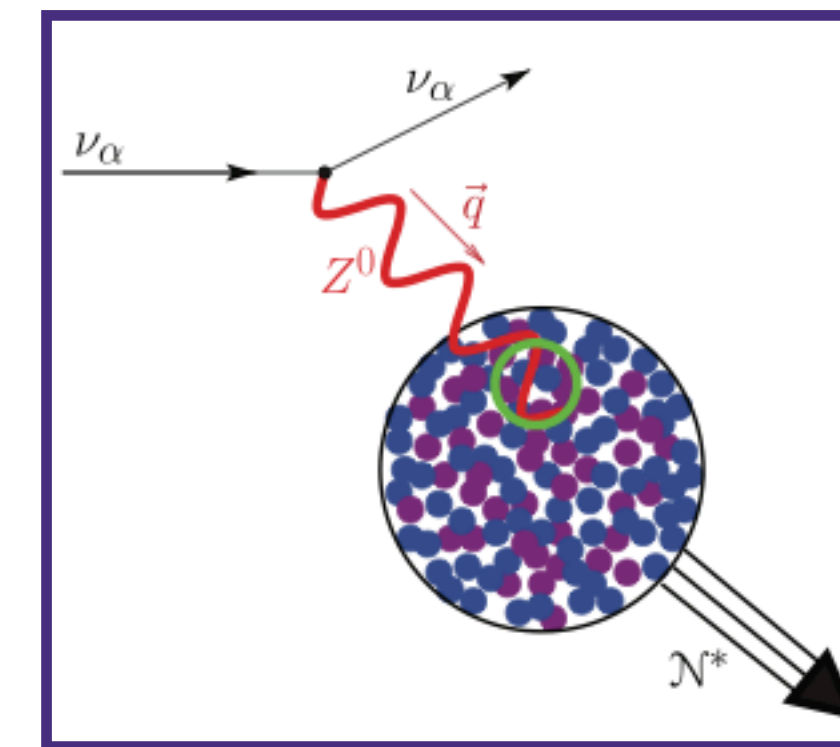
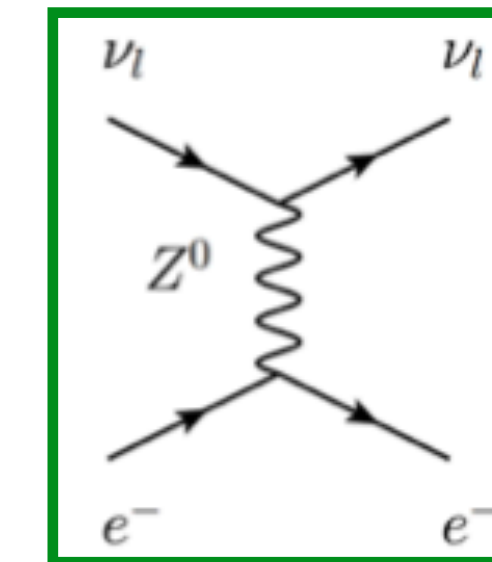
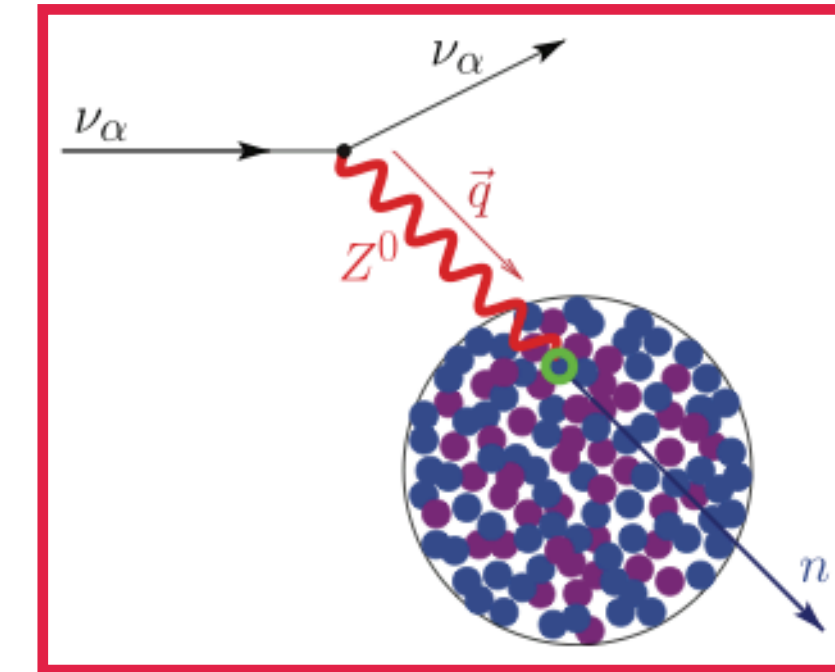
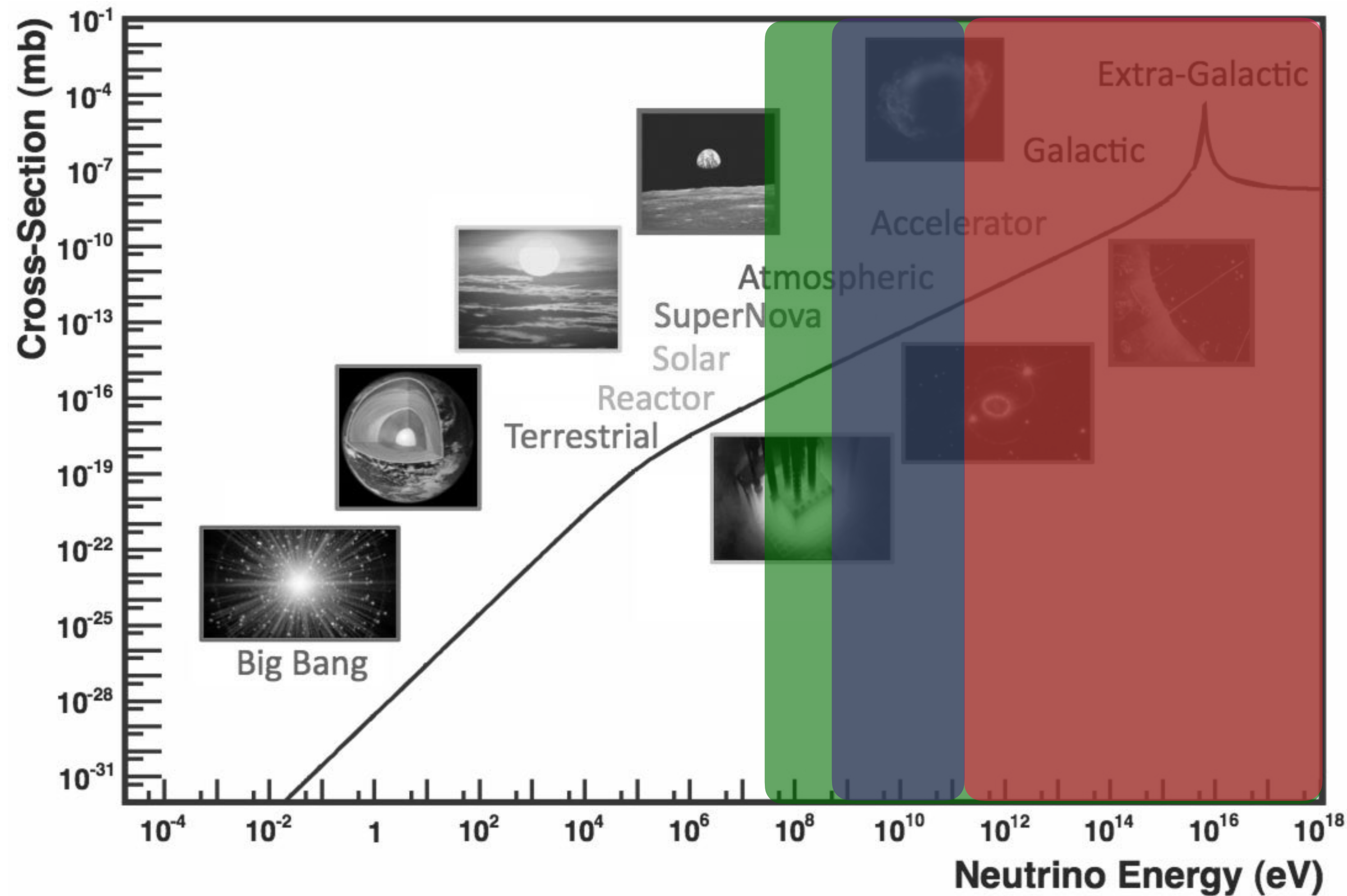


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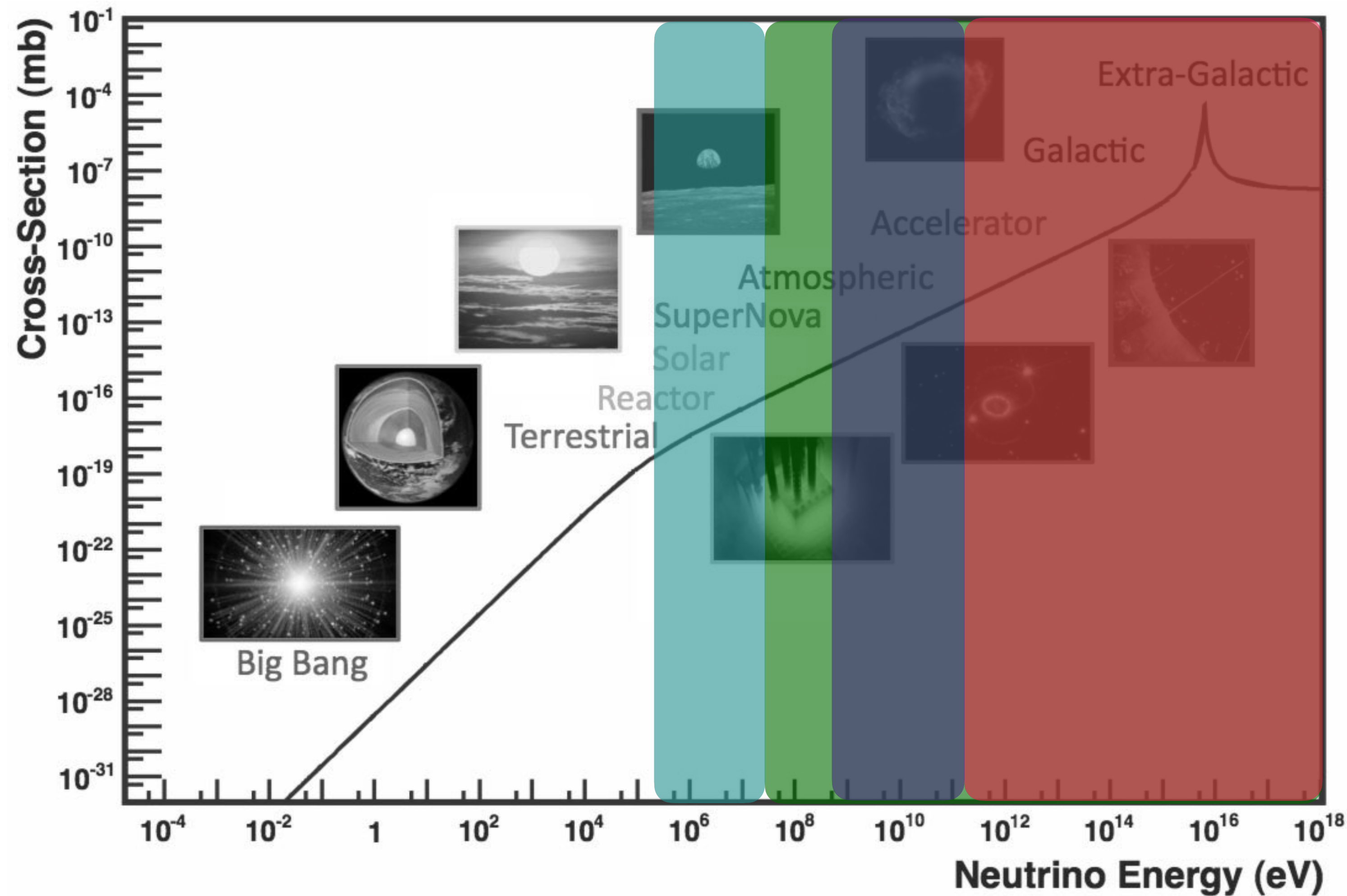


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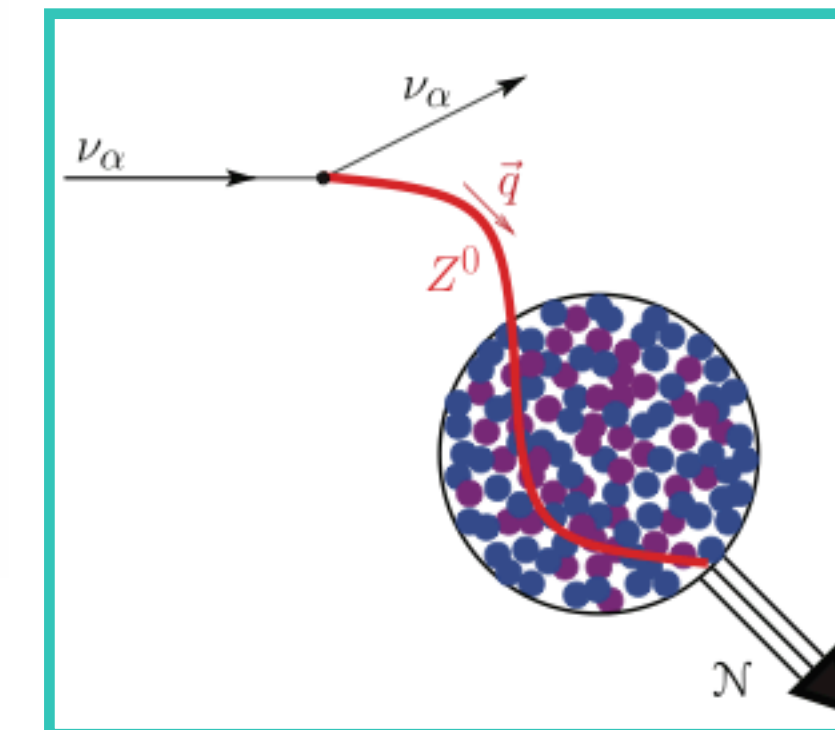
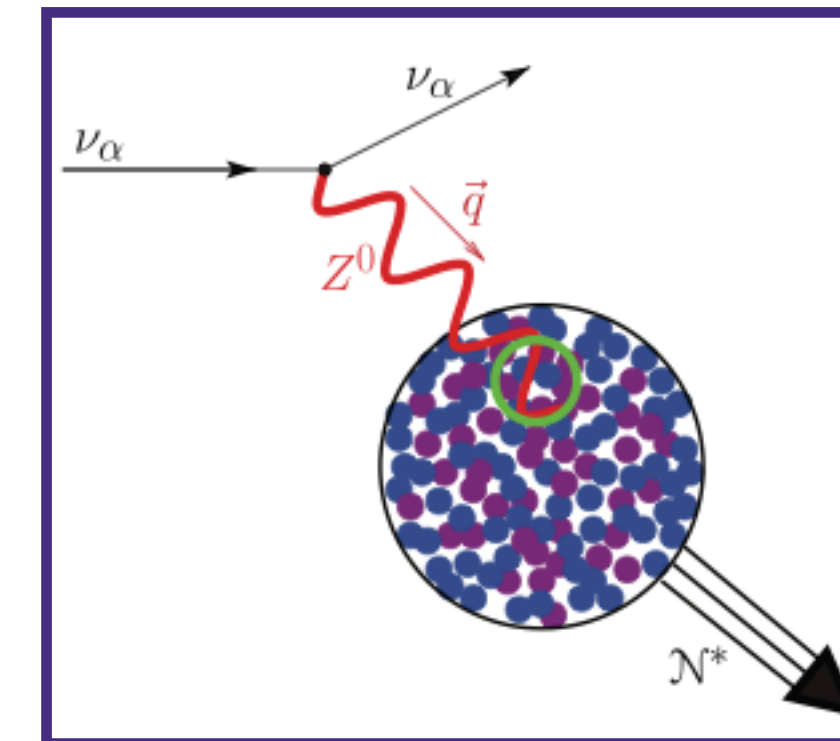
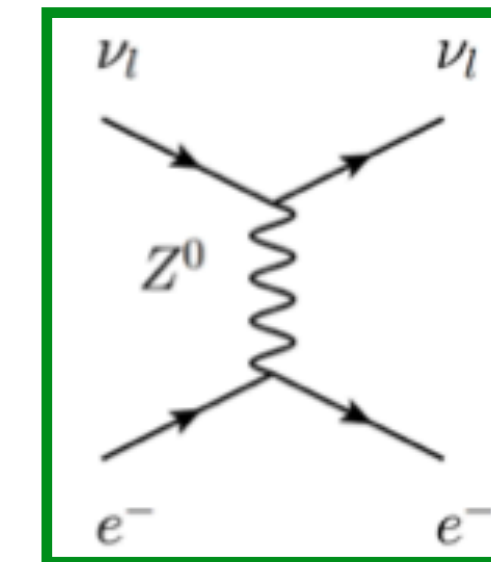
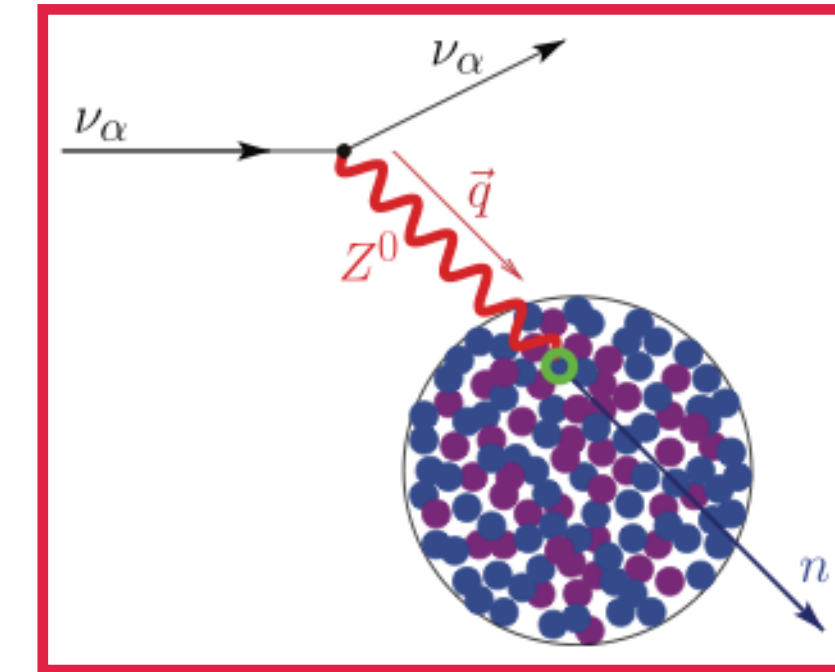
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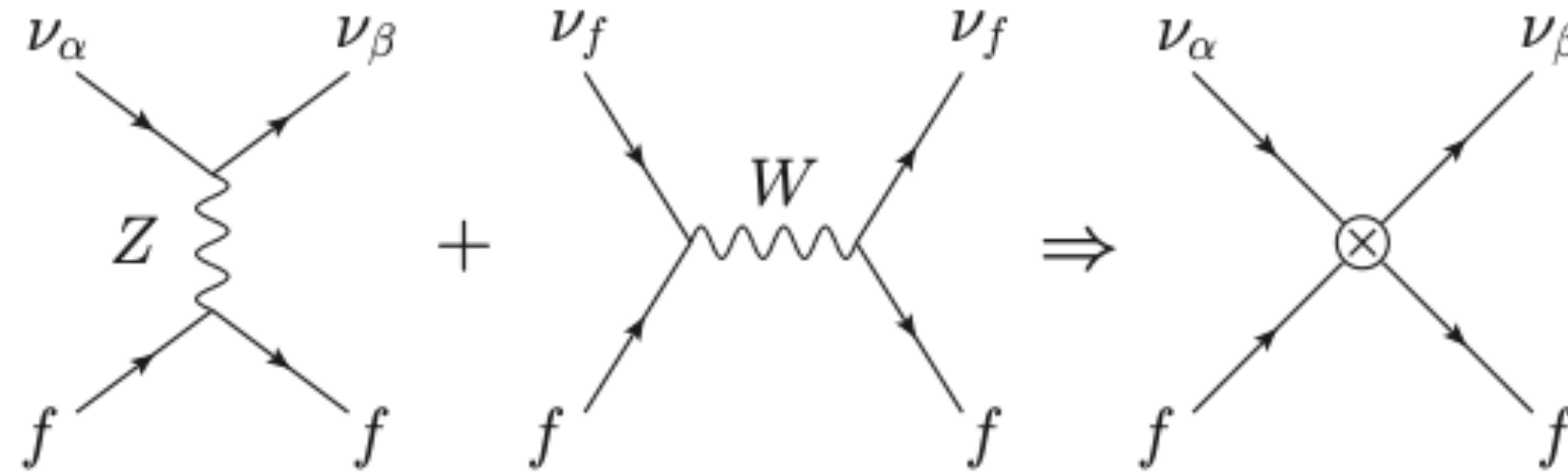
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- For $q \lesssim \mathcal{O}(100 \text{ MeV})$, neutrino-matter interactions described by an $\mathcal{L}_{\text{eff}}$ after integrating out heavy dof.

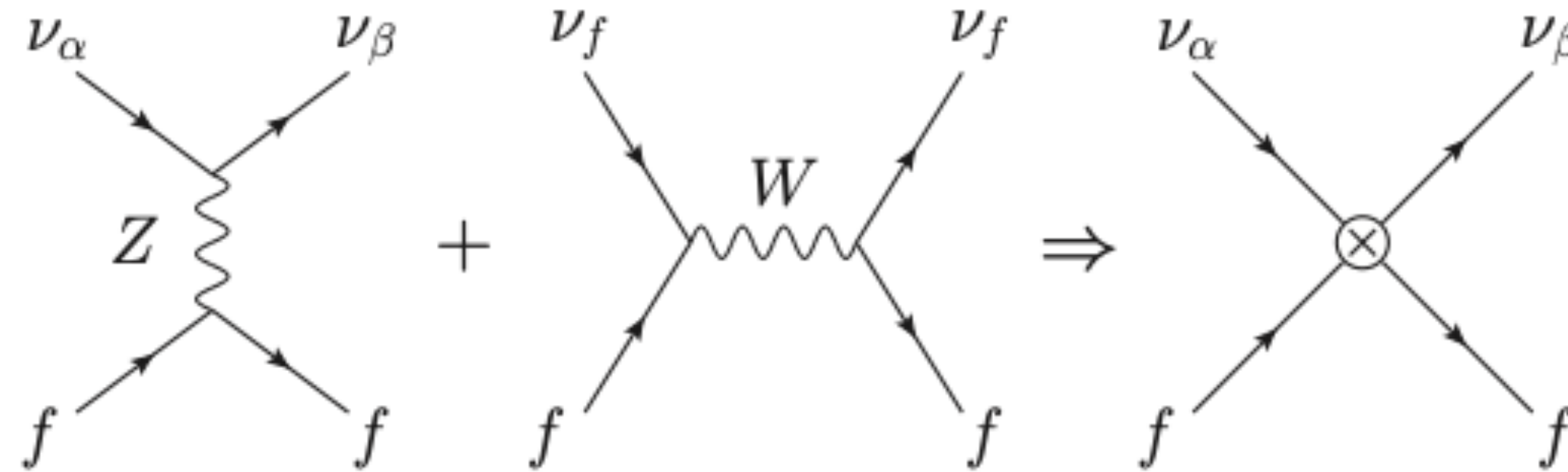


Integrating out the Z and W bosons at tree level NC and CC
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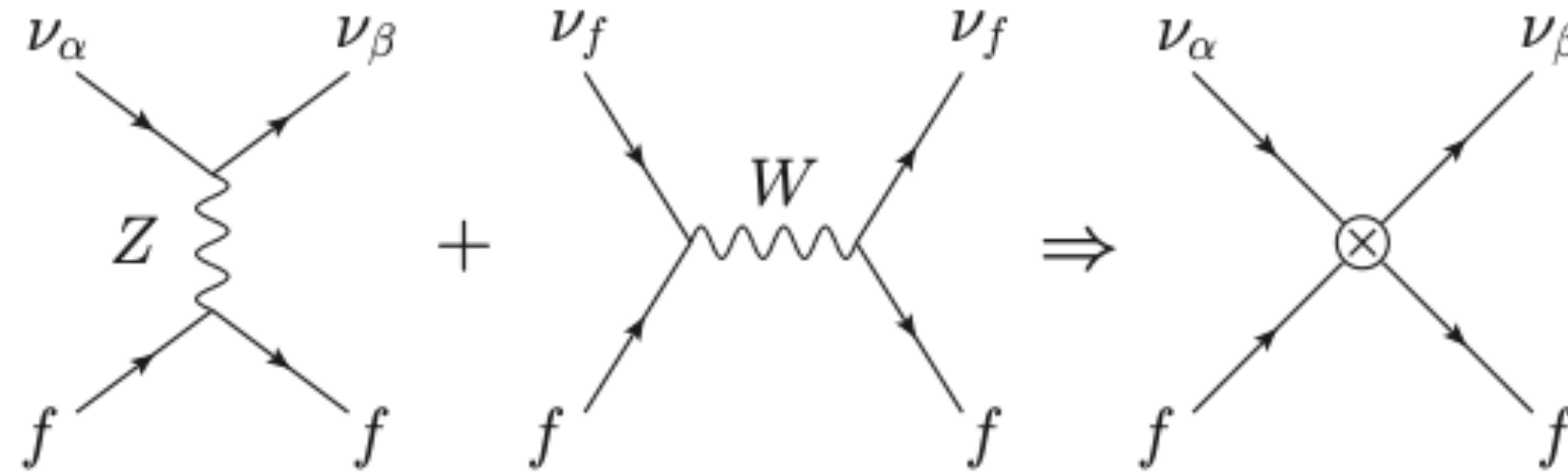
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- Non-Standard Interactions (NSIs): for characterizing potential new physics (NP) in the neutrino sector.

$$\mathcal{L}_{NSI} = \frac{G_F}{\sqrt{2}} \sum_{f, \alpha, \beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \left[\left(\delta_{\alpha\beta} g_V^f + \epsilon_{\alpha\beta}^{fV} \right) \bar{f} \gamma_\mu f + \left(\delta_{\alpha\beta} g_A^f + \epsilon_{\alpha\beta}^{fA} \right) \bar{f} \gamma_\mu \gamma^5 f \right]$$

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- First introduced to accommodate sub-leading effects in neutrino oscillations.

[Wolfenstein, Phys. Rev. D 17, 2369 (1978)]

Neutrino-Non-Standard (Photon) Interaction

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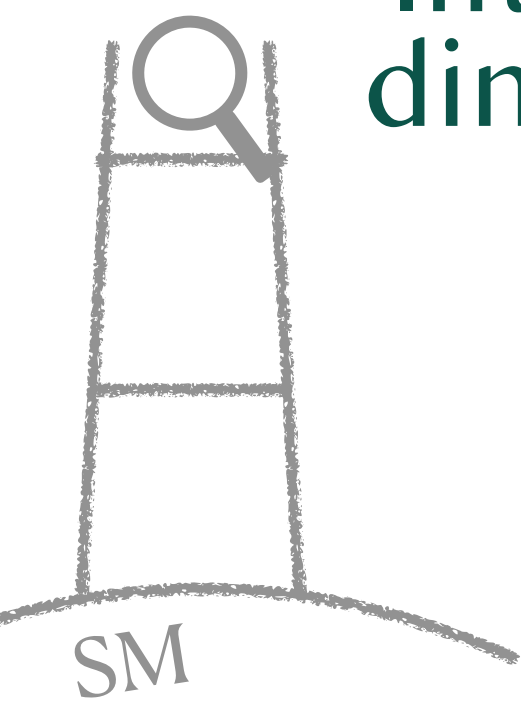
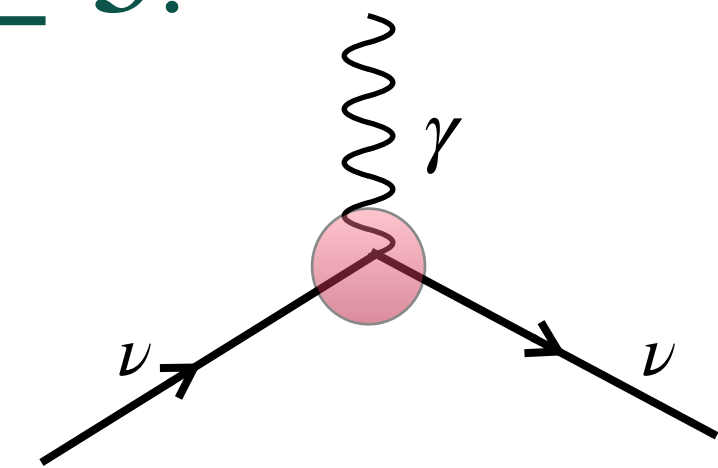
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$$\frac{1}{2} \lambda_{\nu,ij} (\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu} \quad \lambda_{\nu,ii} \sim \mathcal{O}(em_{\nu_i}/16\pi^2 v^2) \sim 10^{-18} (m_{\nu_i}/\text{eV}) \mu_B$$

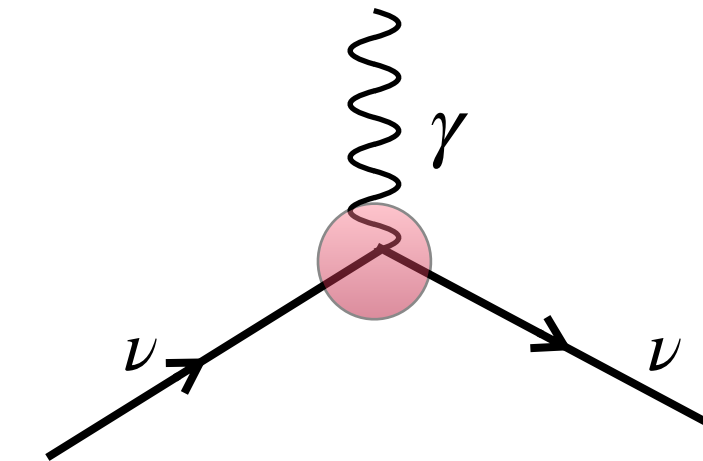


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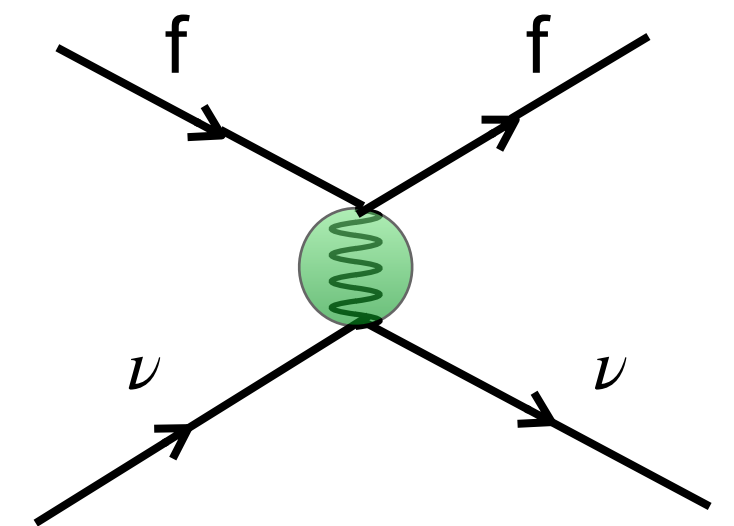
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dimension-6, anapole moment, NSI operator:

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$$\sum_{f,\alpha,\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \left[\left(\delta_{\alpha\beta} g_V^f + \epsilon_{\alpha\beta}^{fV} \right) \bar{f} \gamma_\mu f + \left(\delta_{\alpha\beta} g_A^f + \epsilon_{\alpha\beta}^{fA} \right) \bar{f} \gamma_\mu \gamma^5 f \right]$$



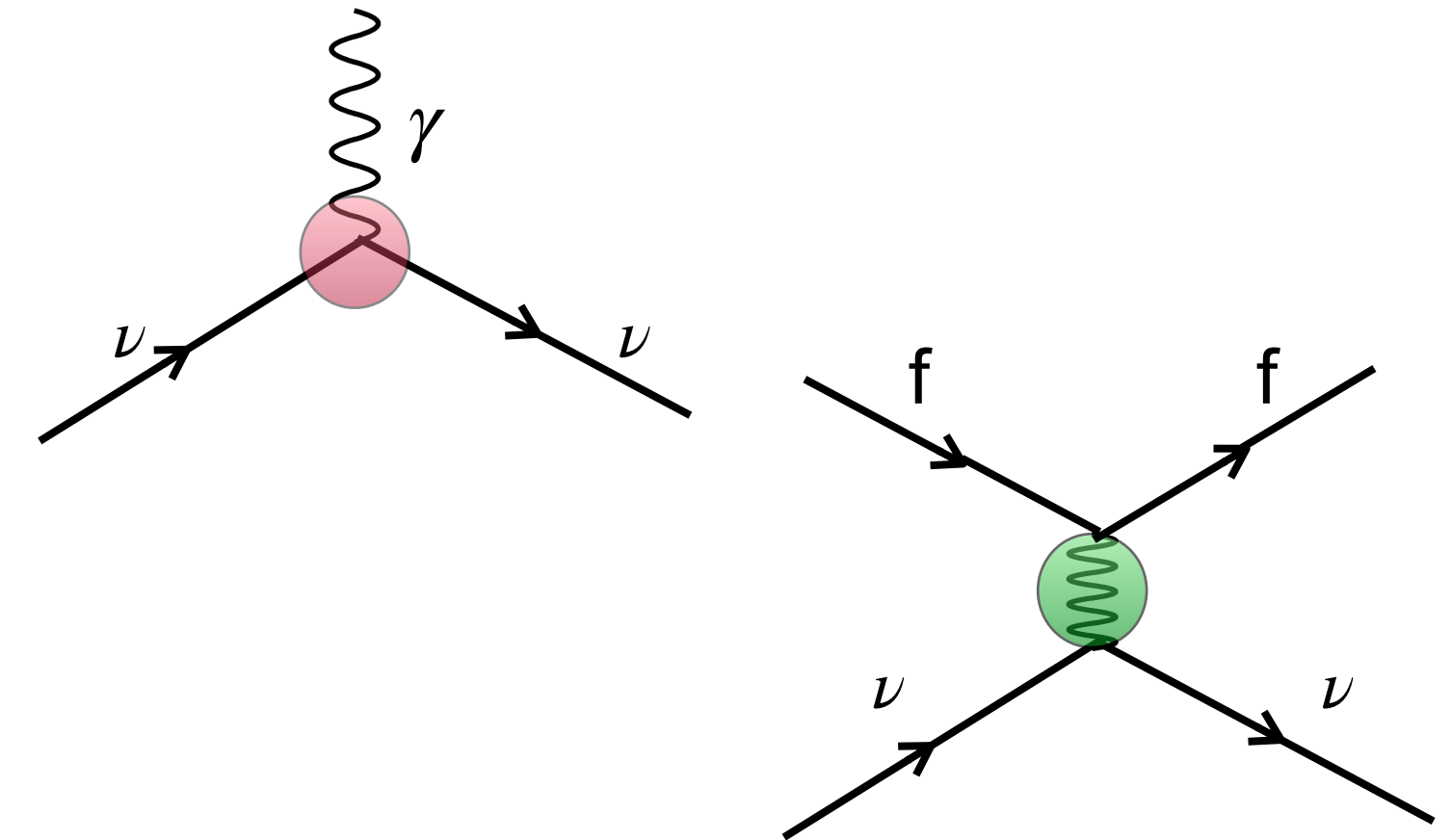
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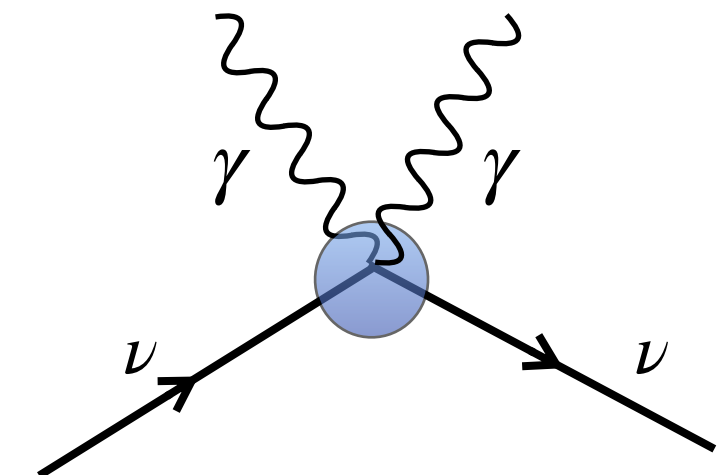


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dimension-7, polarizability operator:

$$\frac{1}{2} \alpha_{\nu,ij} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} F^{\mu\nu}, \quad \frac{1}{2} \tilde{\alpha}_{\nu,ij} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \alpha_{\nu,ii} \sim \mathcal{O}(e^2 m_{\nu_i}/16\pi^2 v^2).$$



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Magnetic Moment and Charge Radius from $CE\nu NS$

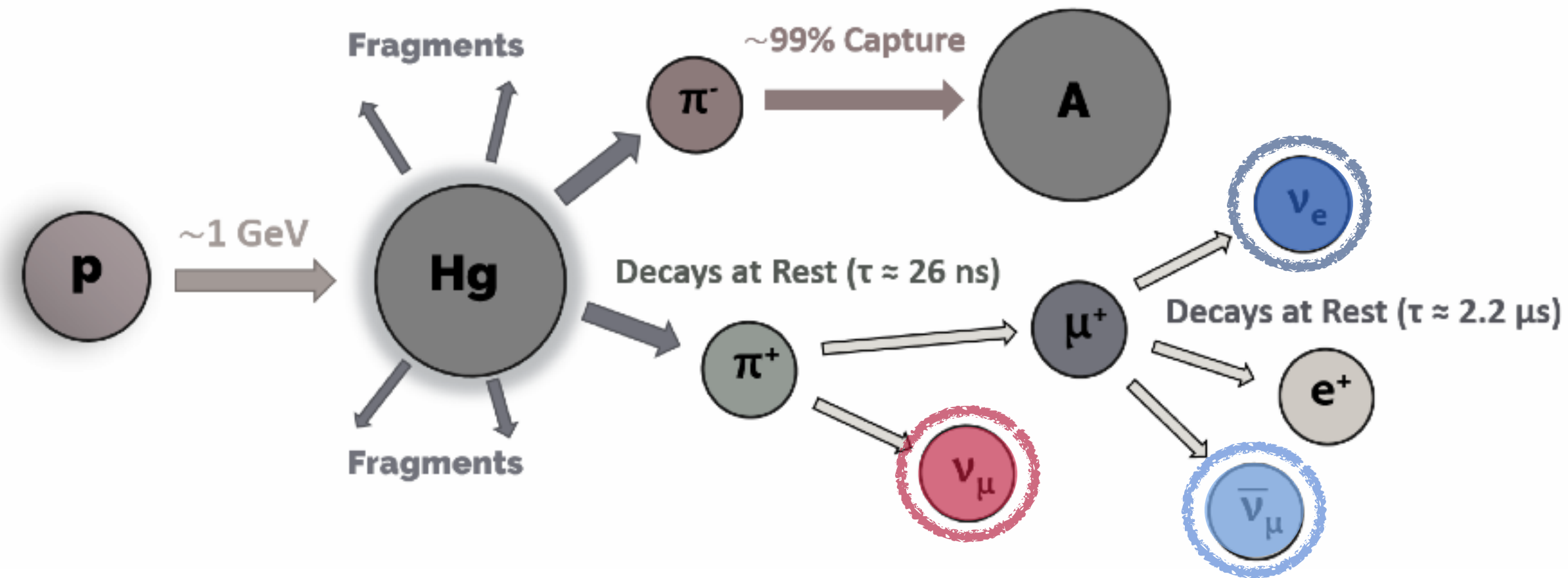
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Neutrino Source

- © Neutrino production (at SNS):

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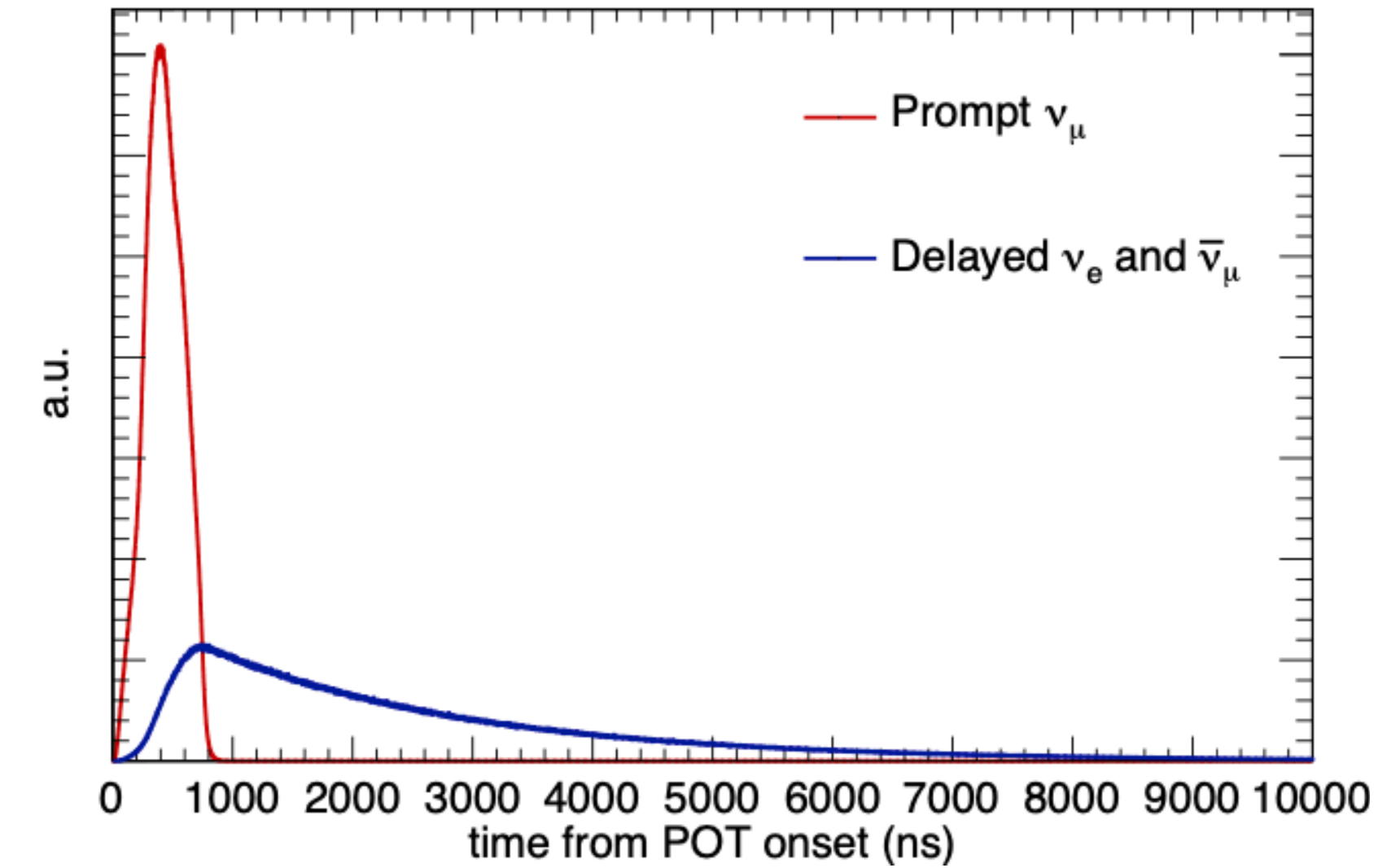
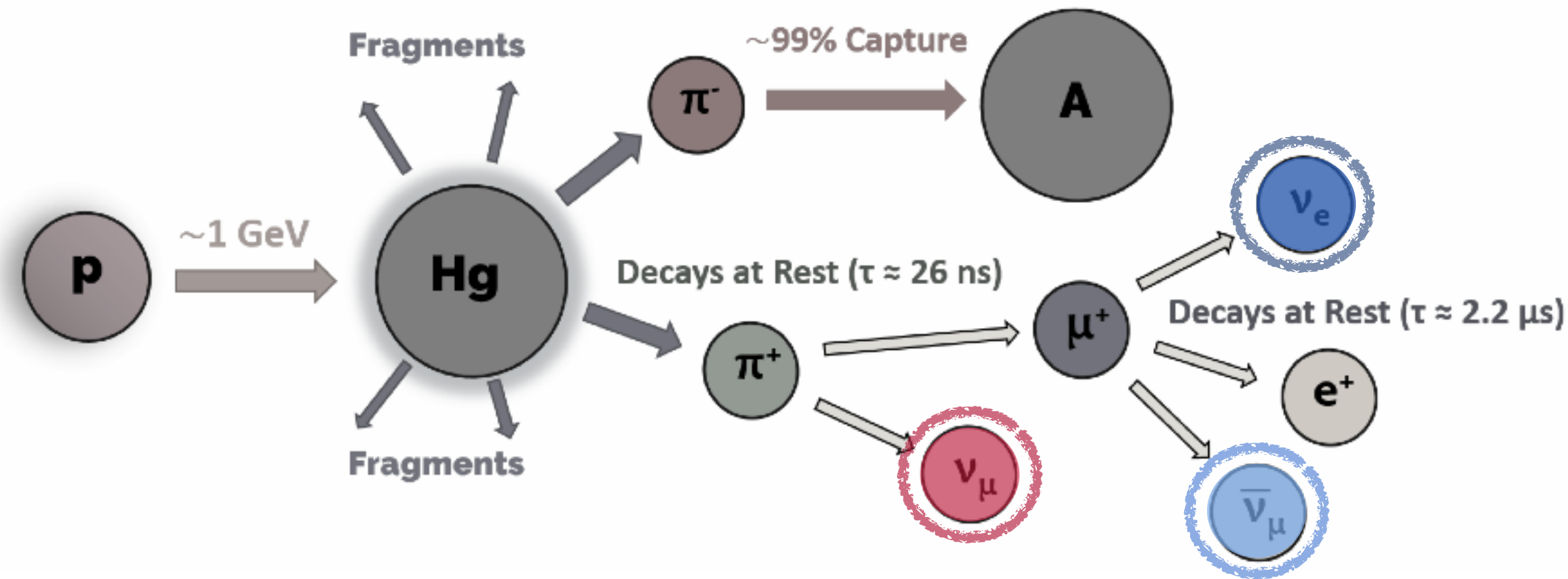
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Neutrino production via π -decay at rest
Green, Magnificent CEvNS (2025)

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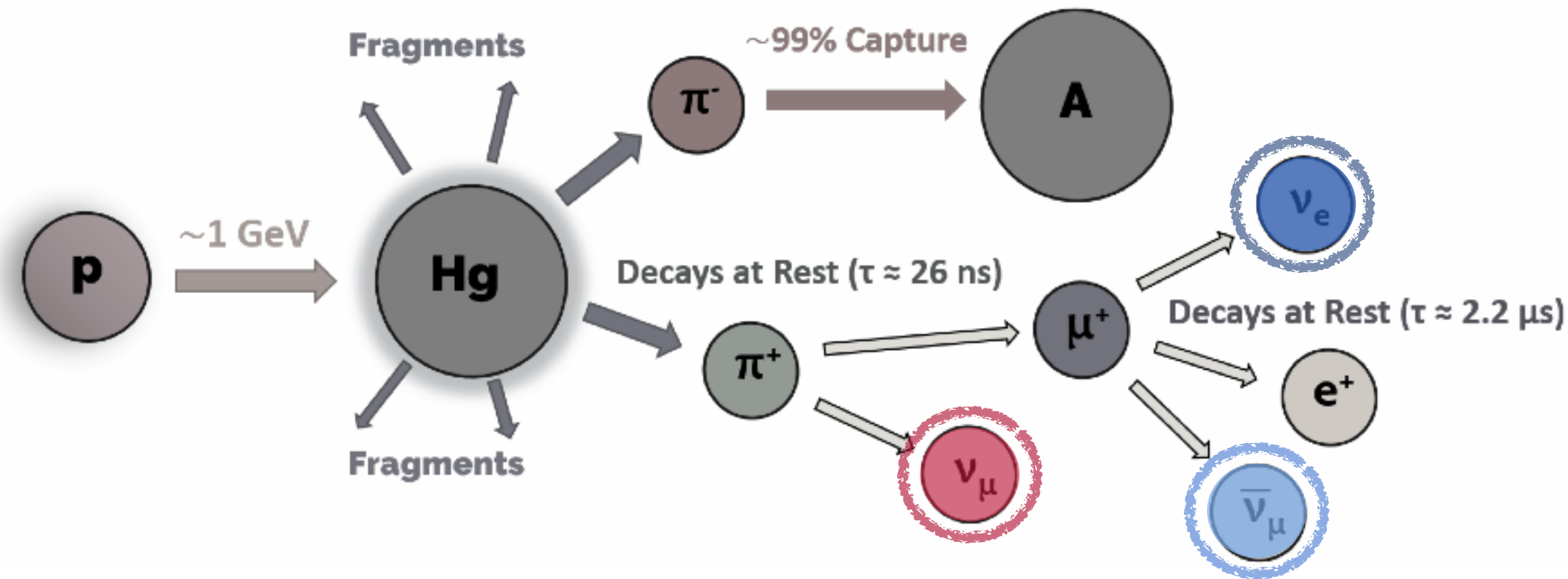
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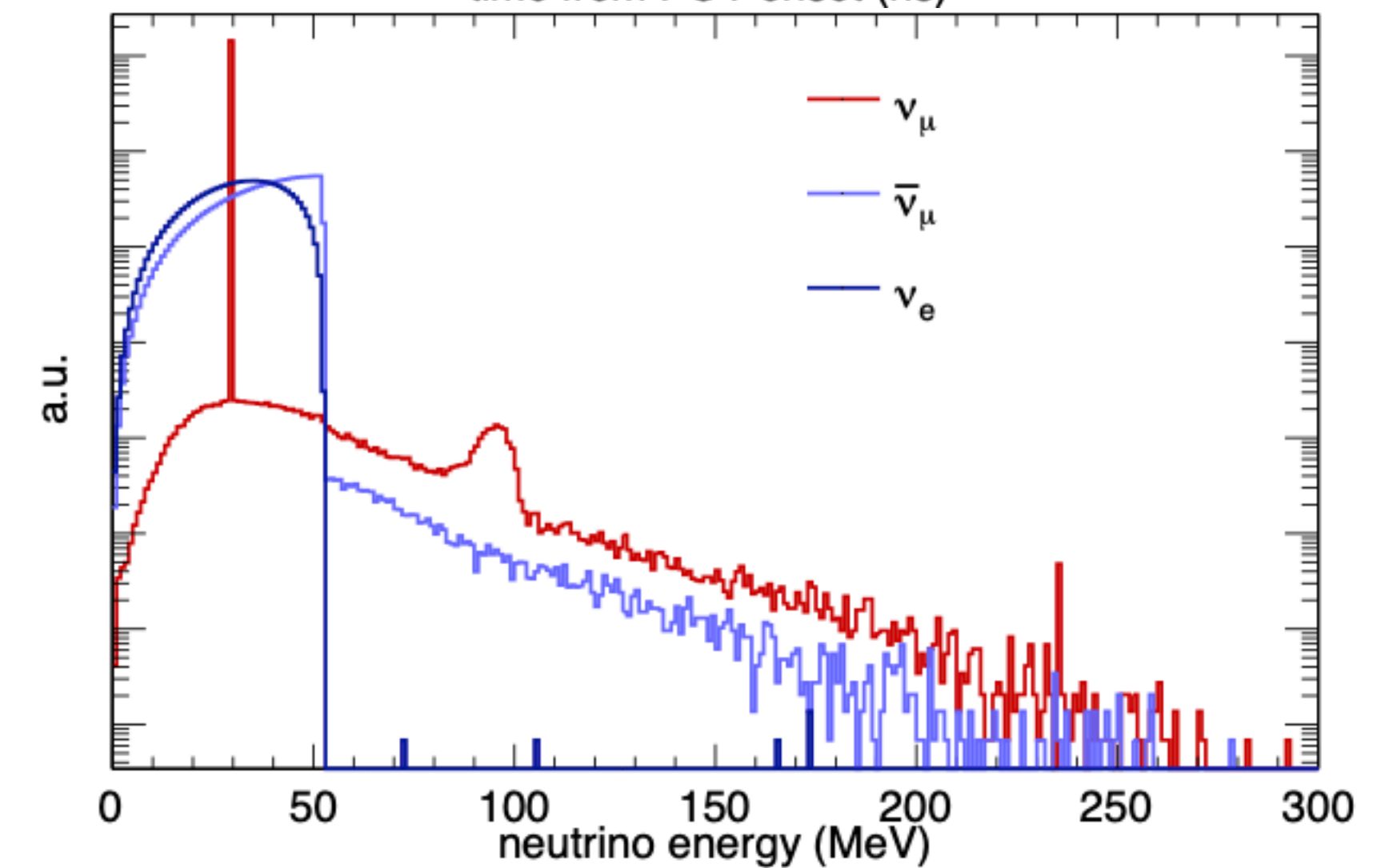
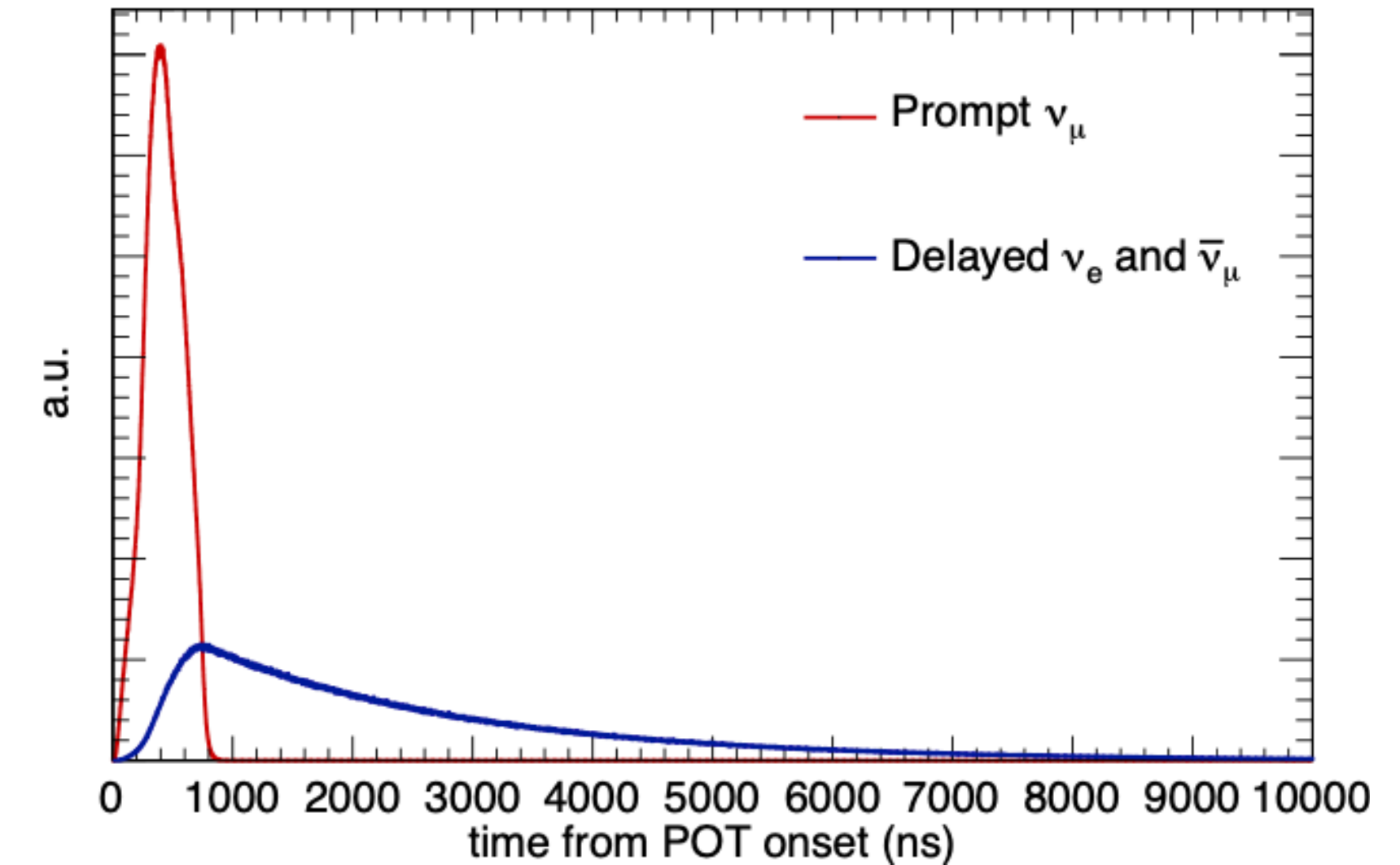
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Experiment	m_T (kg)	d (m)	POT (sec^{-1})
PIP2-BD at FNAL	100,000	20.0	2.75×10^{16}
CENNS10 at ORNL	24	27.5	1.0×10^{16}
CENNS750 at ORNL	610	27.5	7.6×10^{15}
CCM at LANL	10,000	20.0	5.6×10^{14}



Timing profile of the neutrinos and their fluxes
[Akimov, et. al., Science 357, 6356 (2017)]

Event Rate

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COHERENT reports data in reconstructed electron-equivalent recoil energy (T_{rec})

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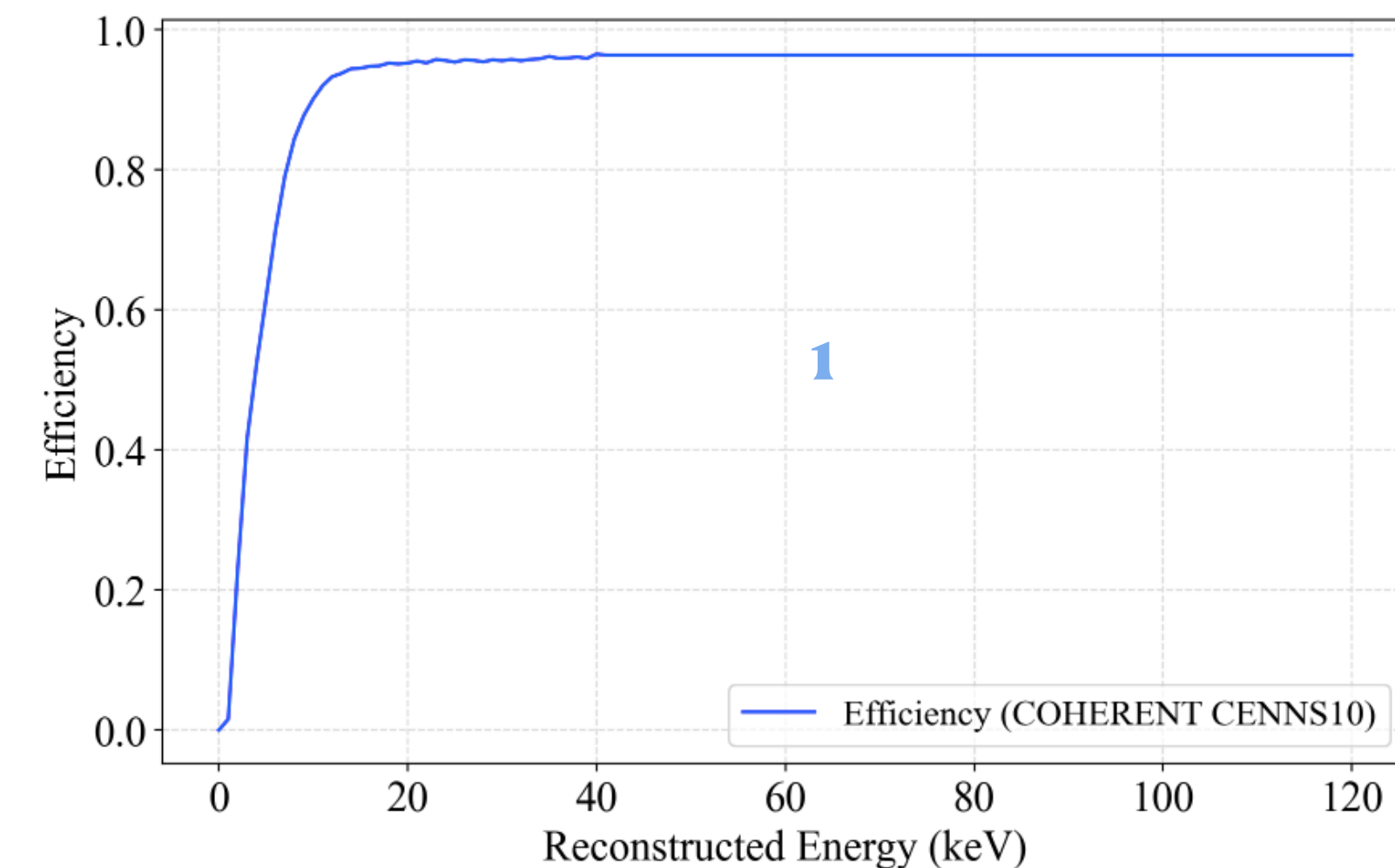
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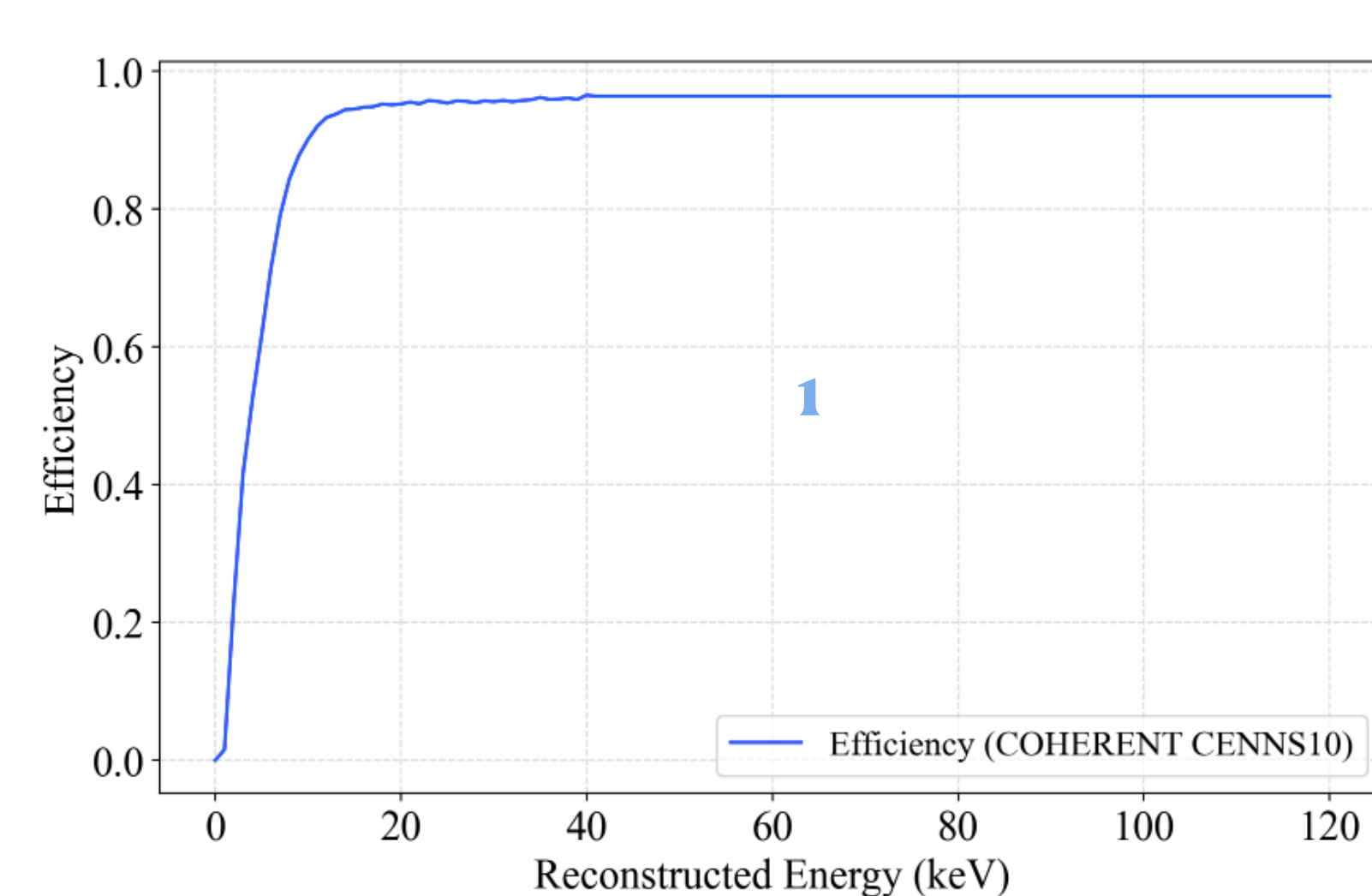


Detector efficiency as a function of T_{rec}
[Akimov et al., Phys. Rev. Lett. 126, 012002 (2021)]

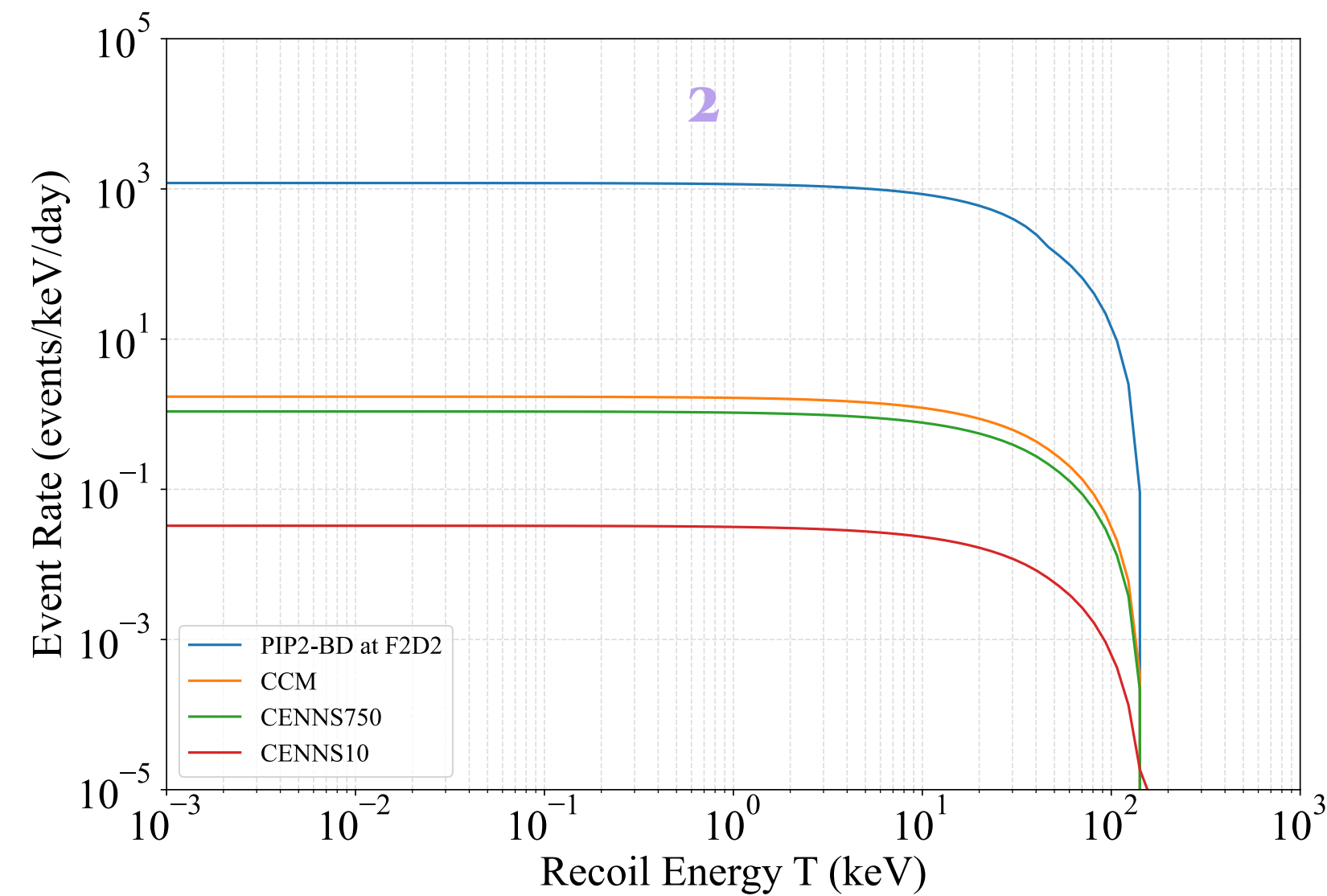
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Expected event rates as a function of T for all flux sources

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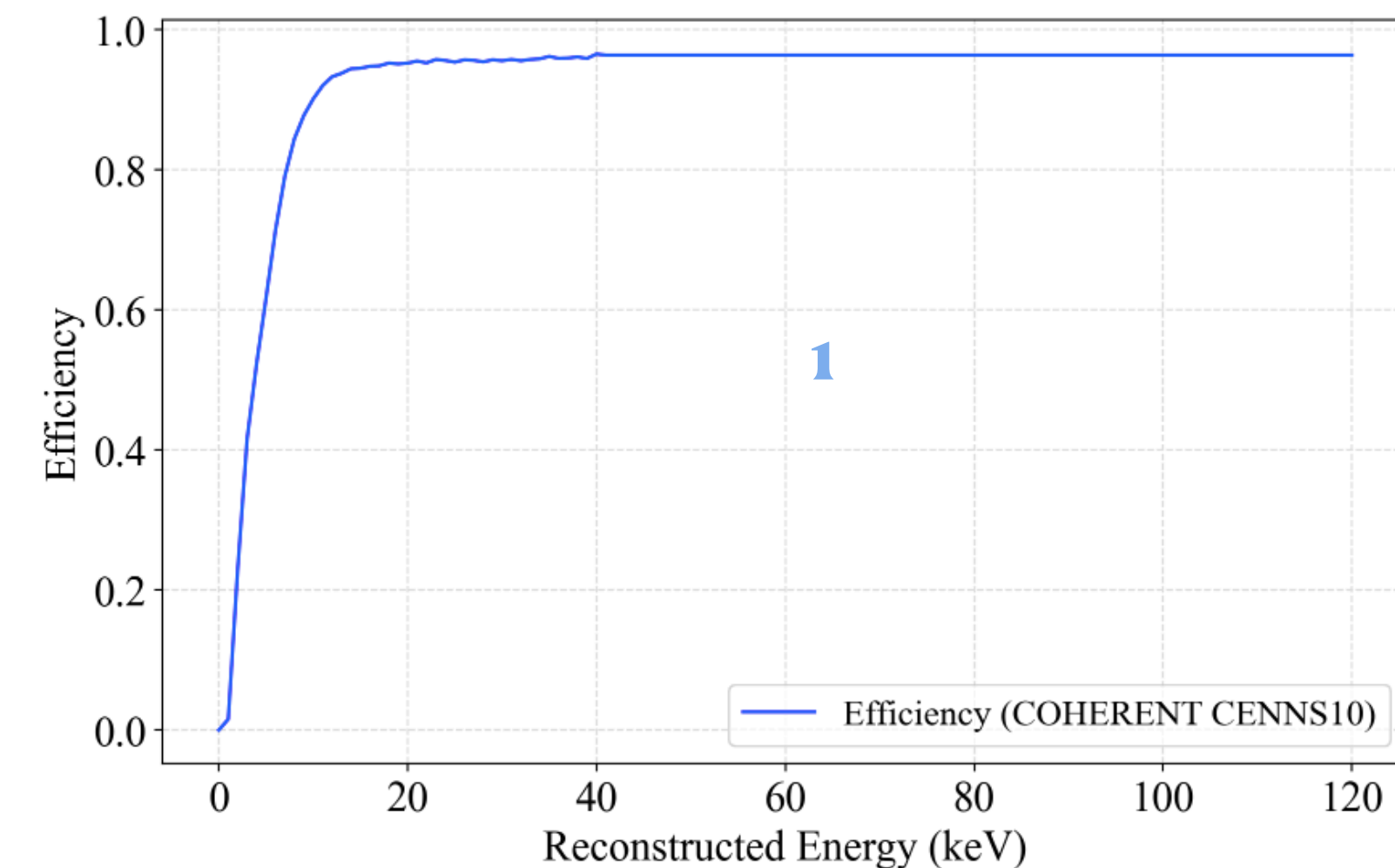
Detector resolution function:

solution function:

$$\mathcal{R}(T_{\text{rec}}, T_I; \sigma_I) = \frac{1}{\sqrt{2\pi}\sigma_I} e^{-\frac{(T_{\text{rec}} - T_I)^2}{2\sigma_I^2}}$$

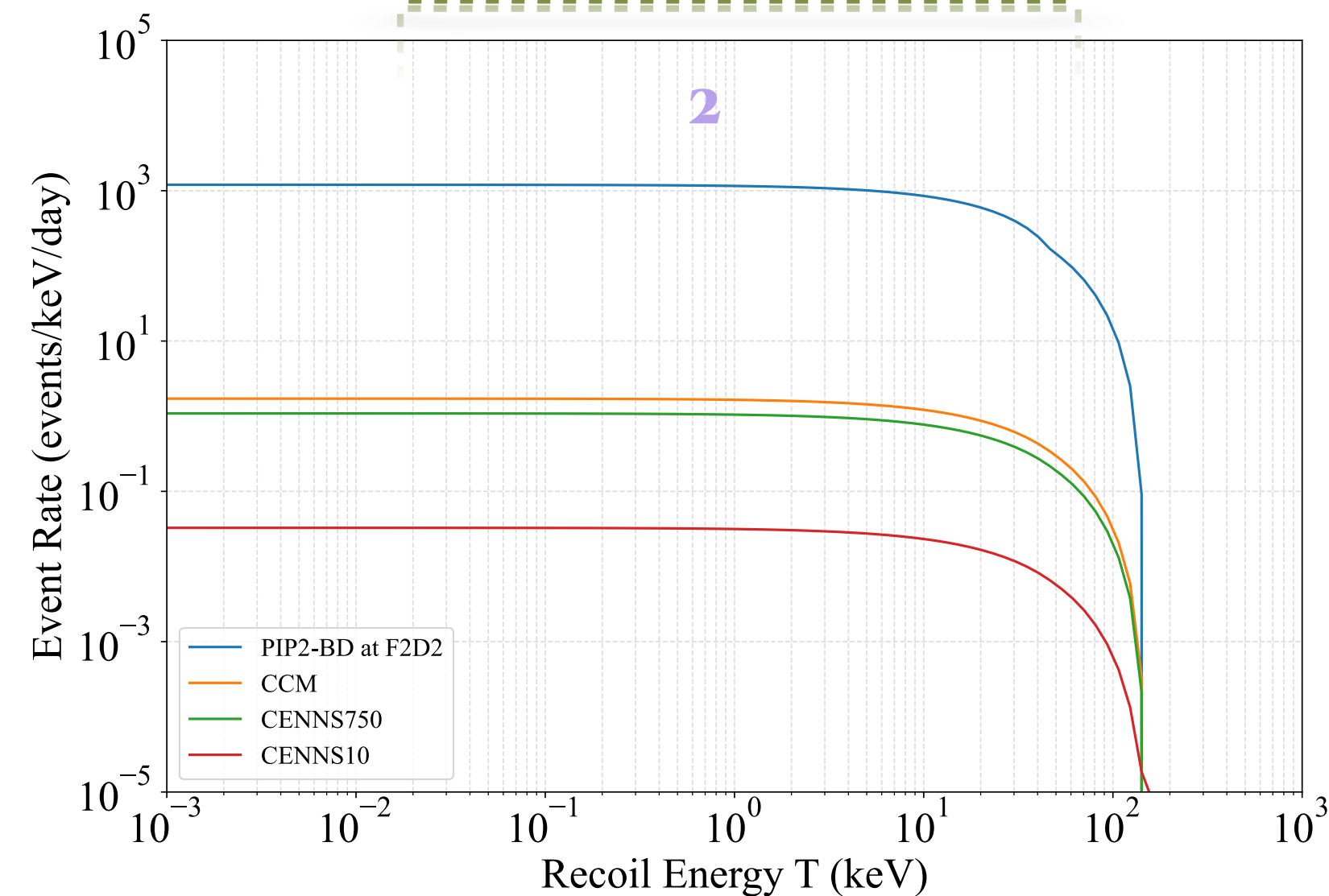
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$$\sigma_I = 0.58 \text{ keV} \sqrt{T_I / \text{keV}}$$



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True electron equivalent recoil energy:

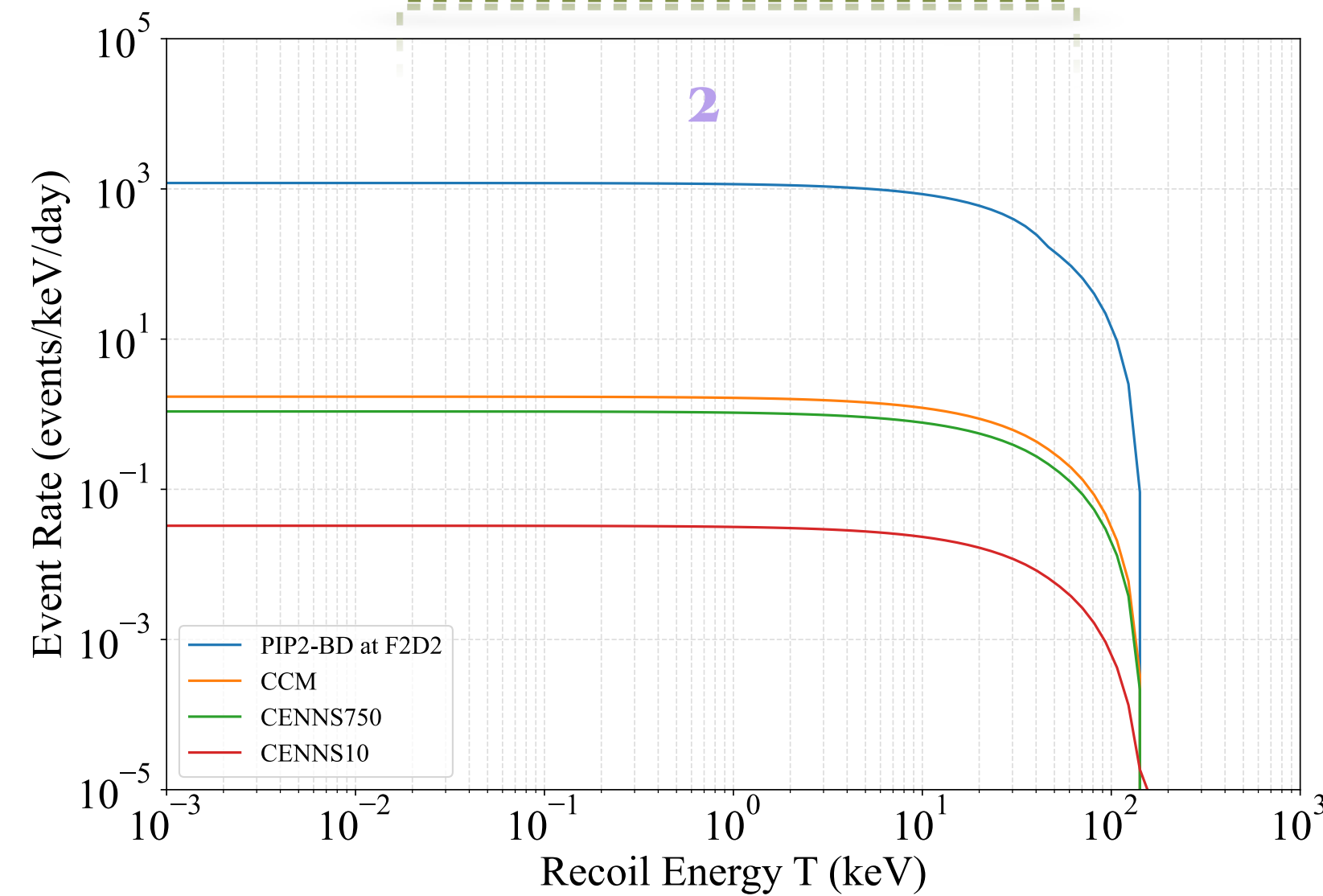
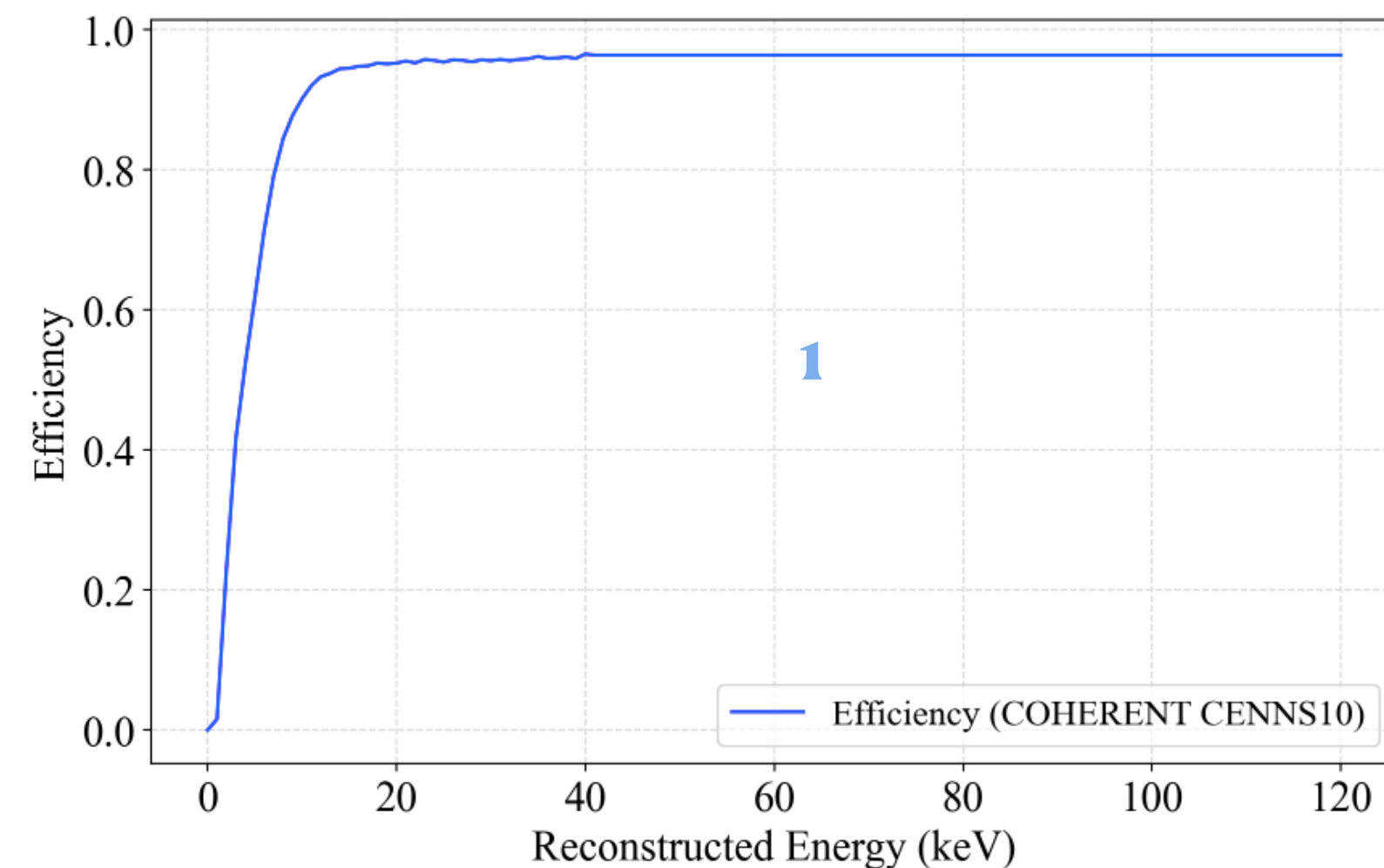
$$T_I = Q_F(T) T$$

Quenching factor:

$$Q_F = 0.246 + 0.00078 \text{ keV}^{-1}$$

Width:

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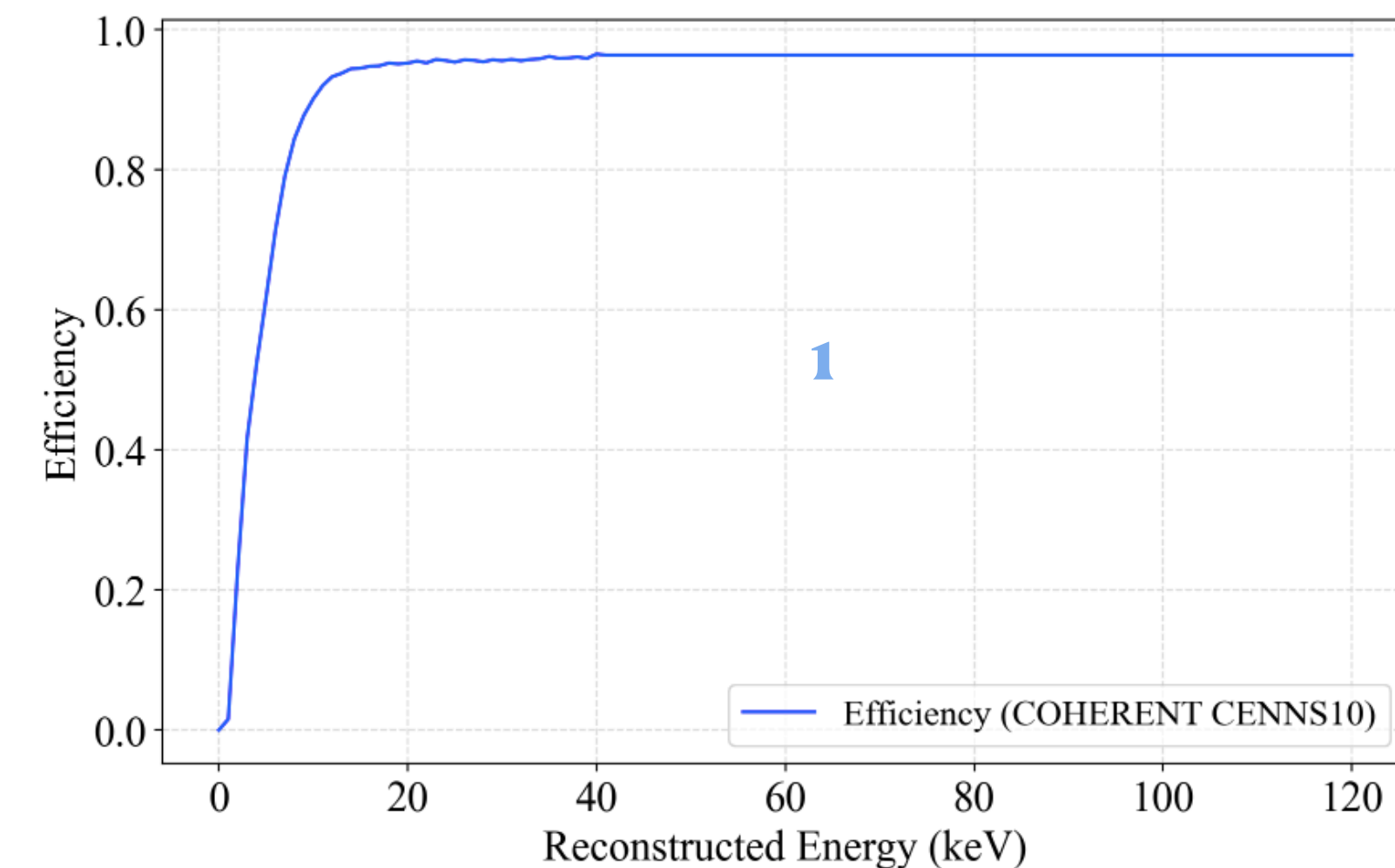
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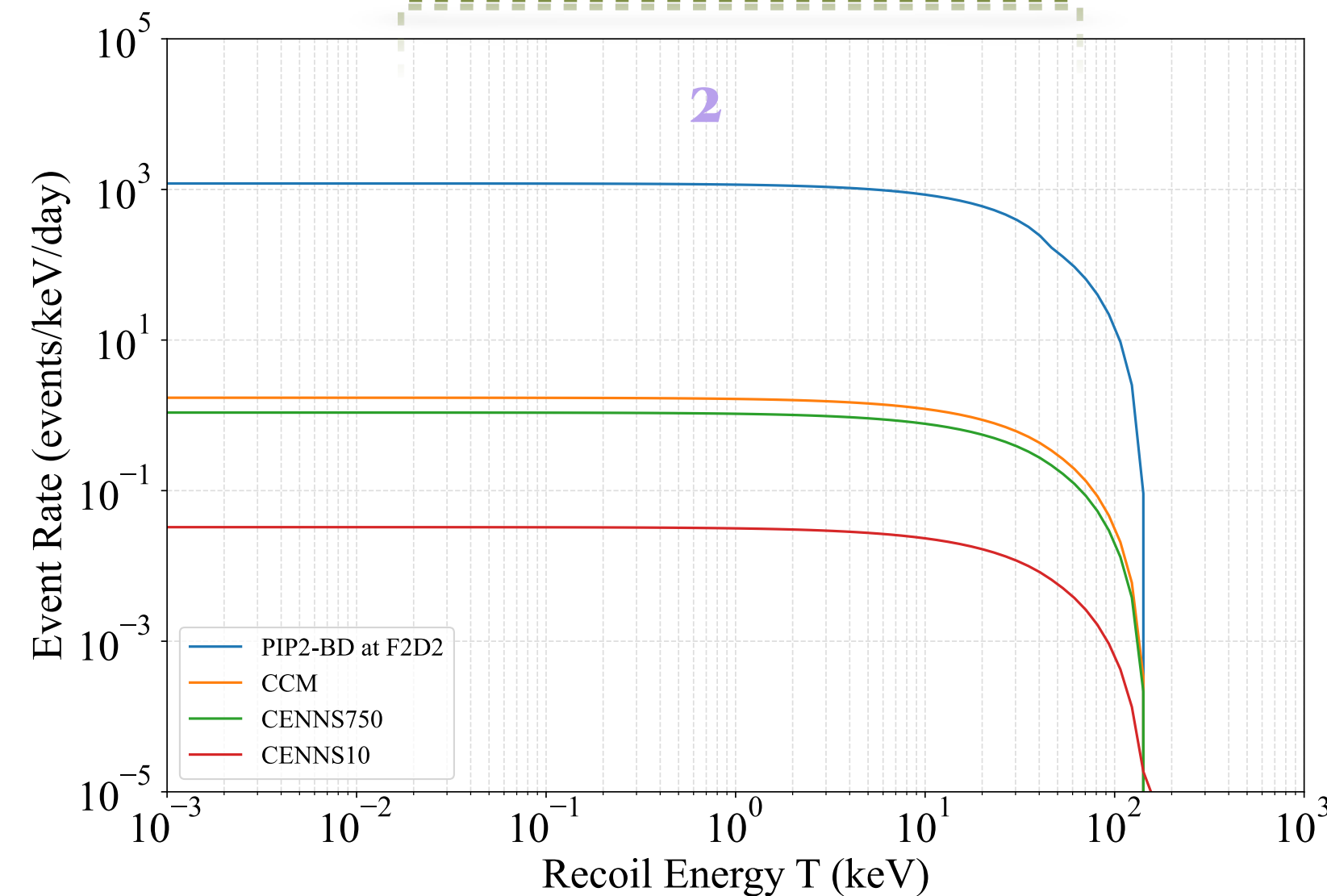
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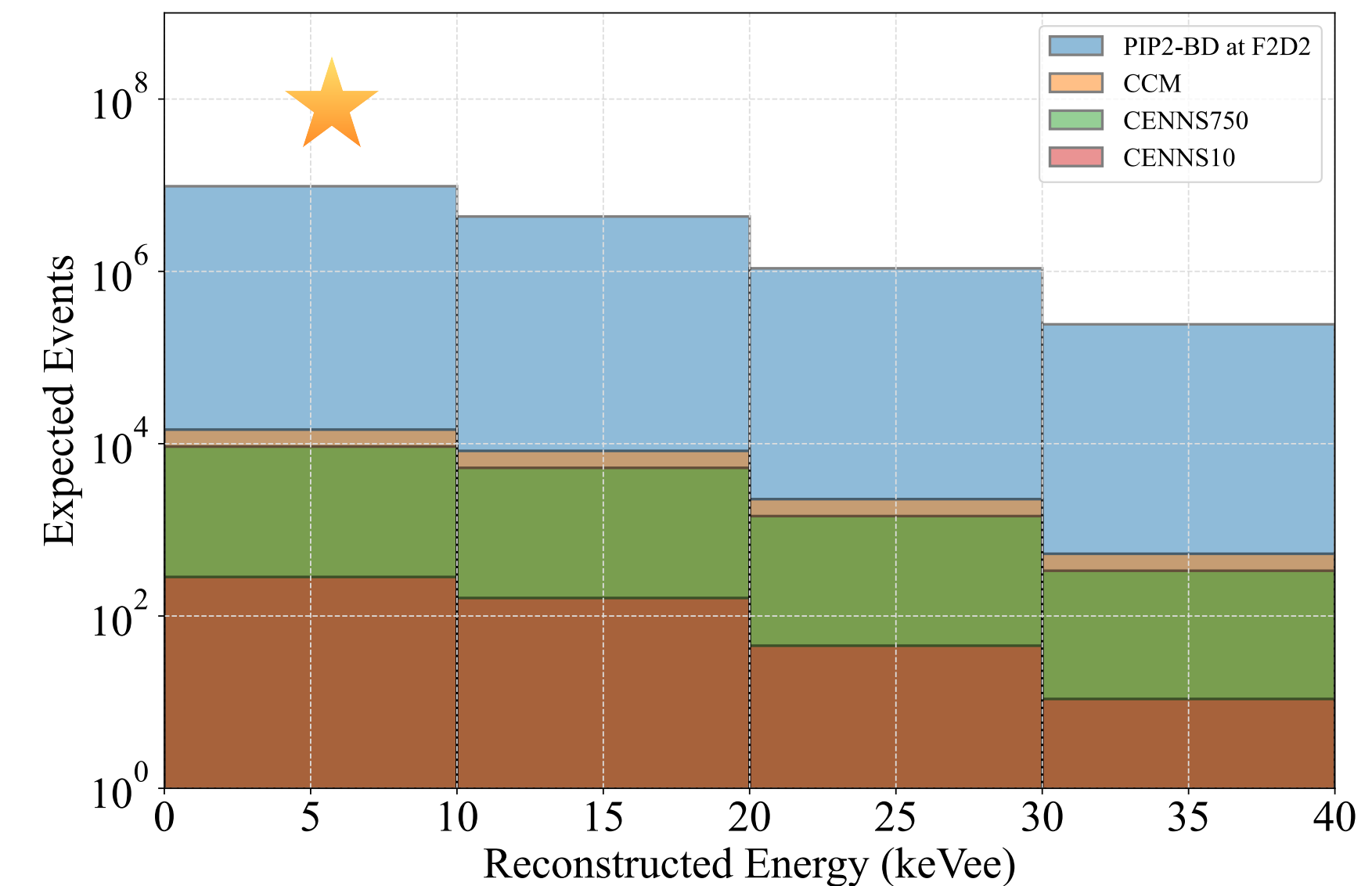
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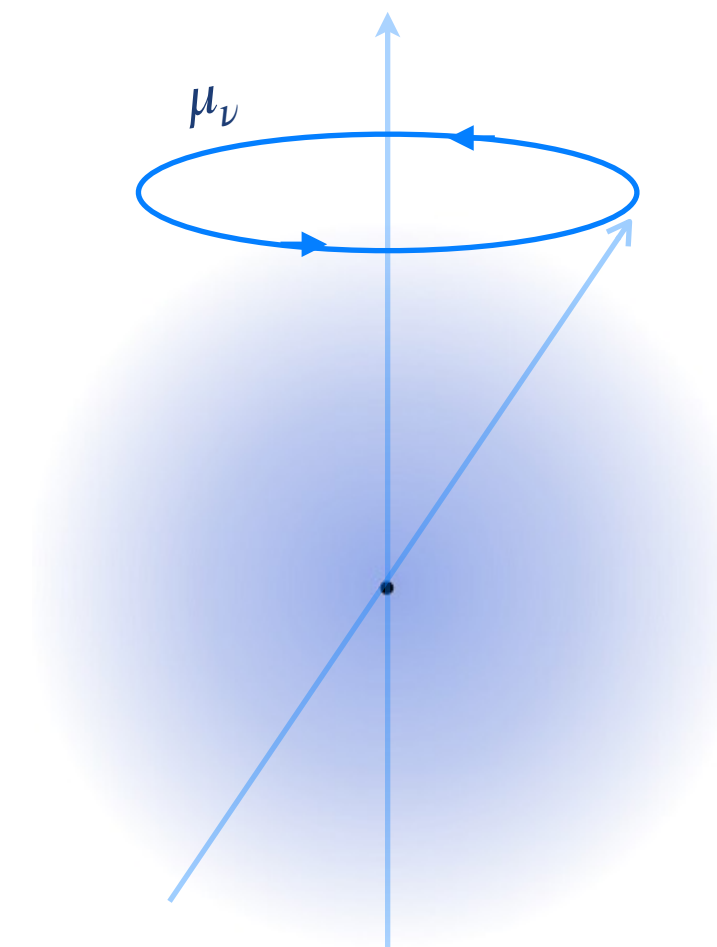
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[Carey and Pandey, arXiv: 2412.18055]

Magnetic Moment and Charge Radius

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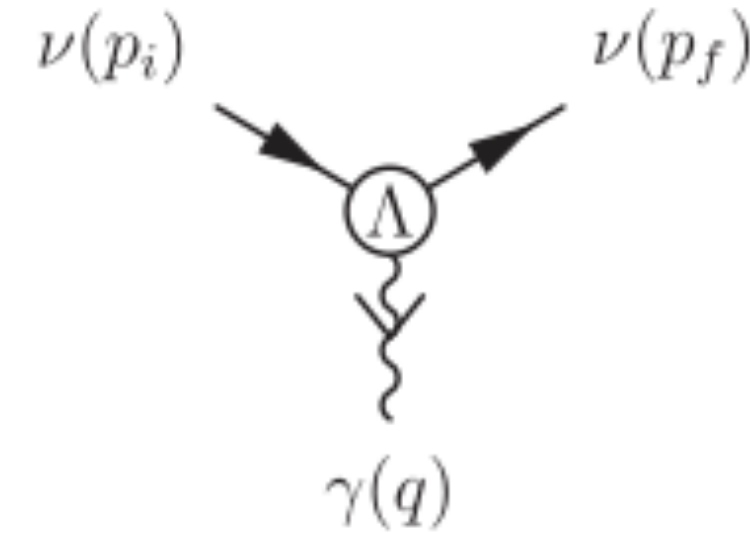


Magnetic Moment: Enhancement and Signature

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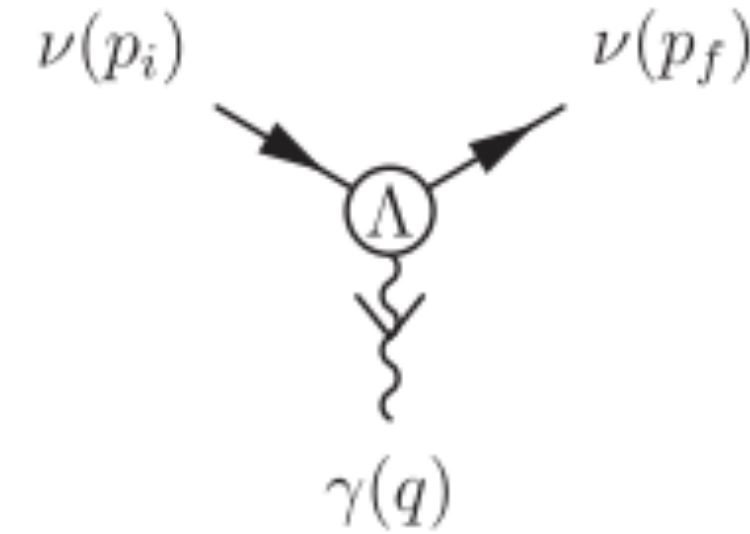
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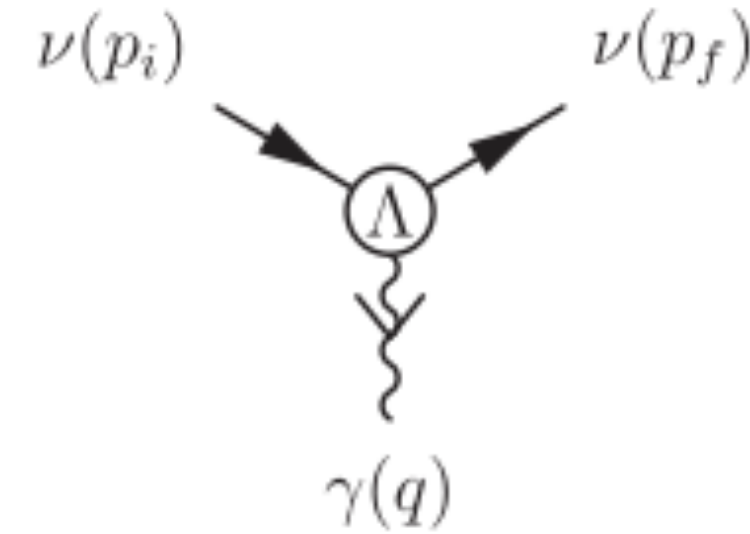
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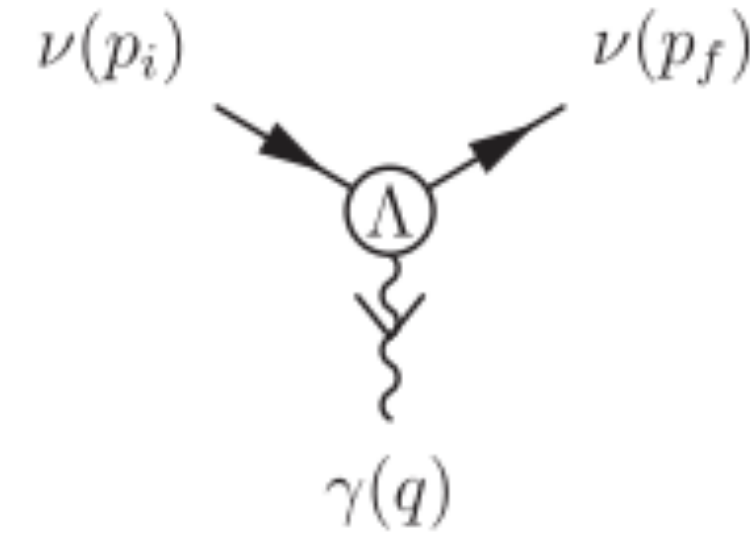
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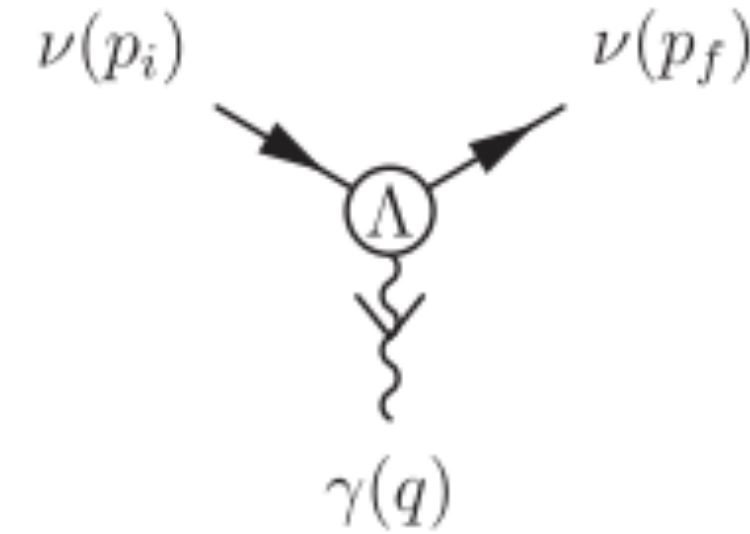


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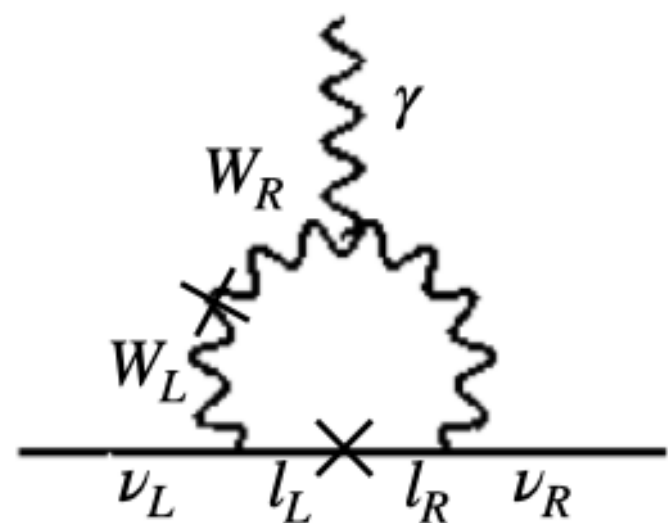
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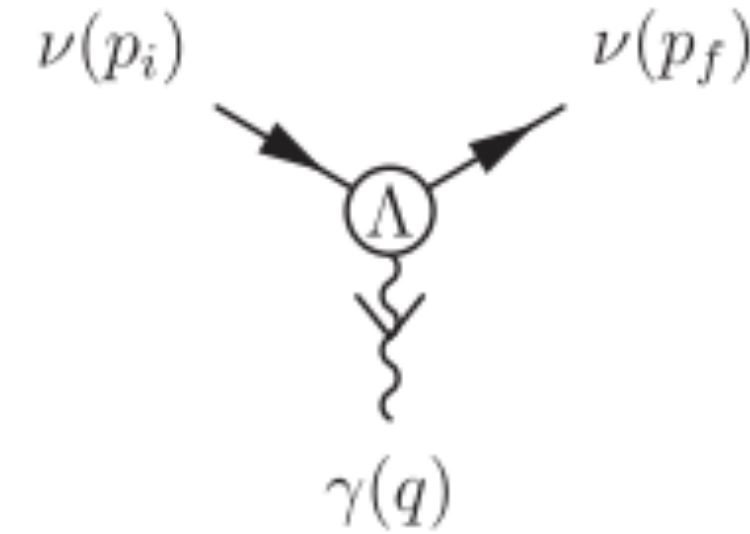
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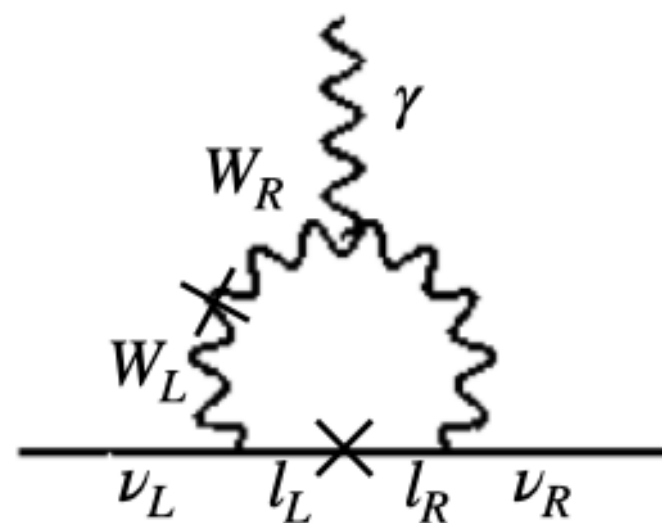
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Fine tuning: ξ to avoid “ $m_\nu - \mu_\nu$ conundrum”

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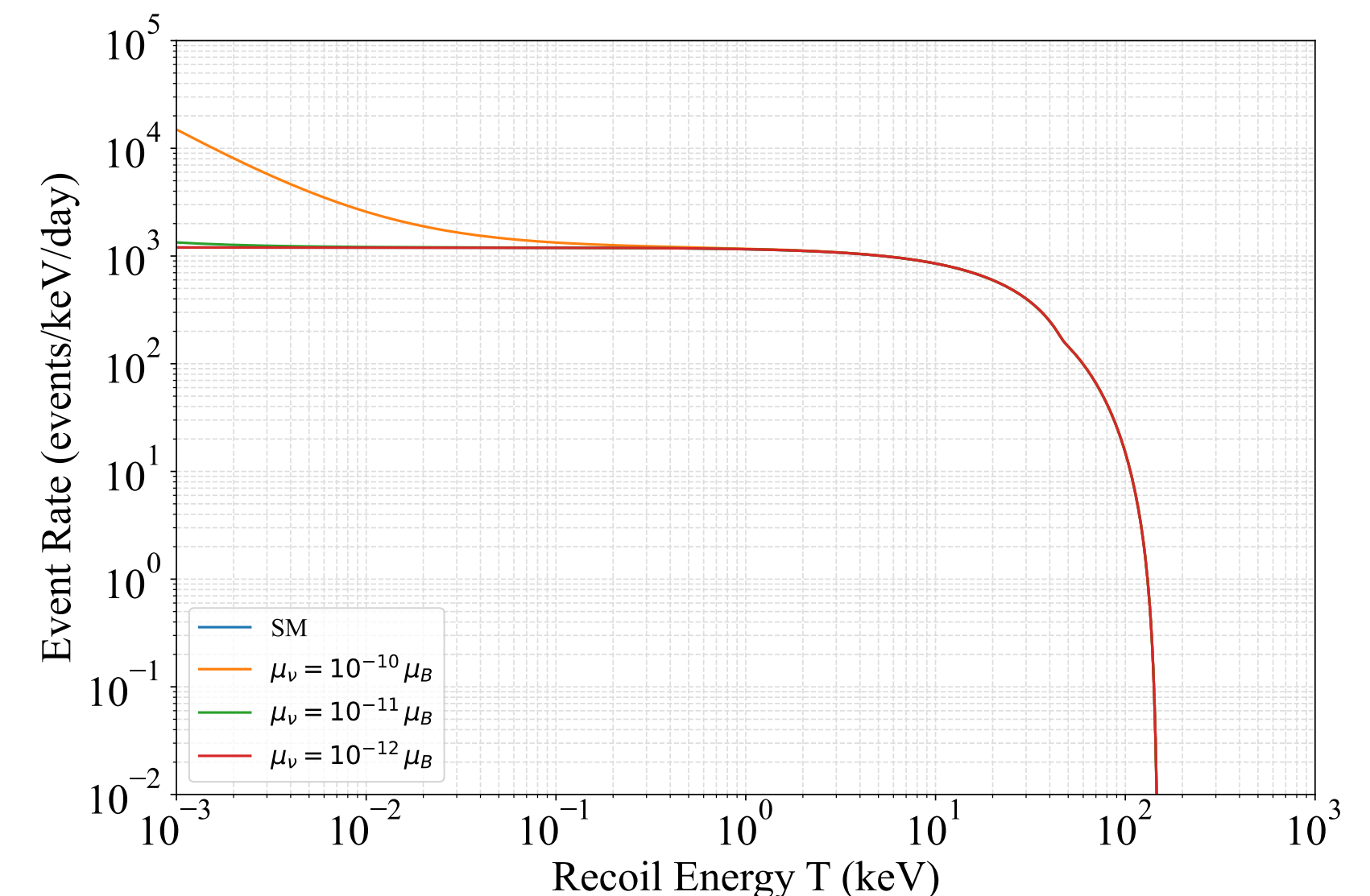
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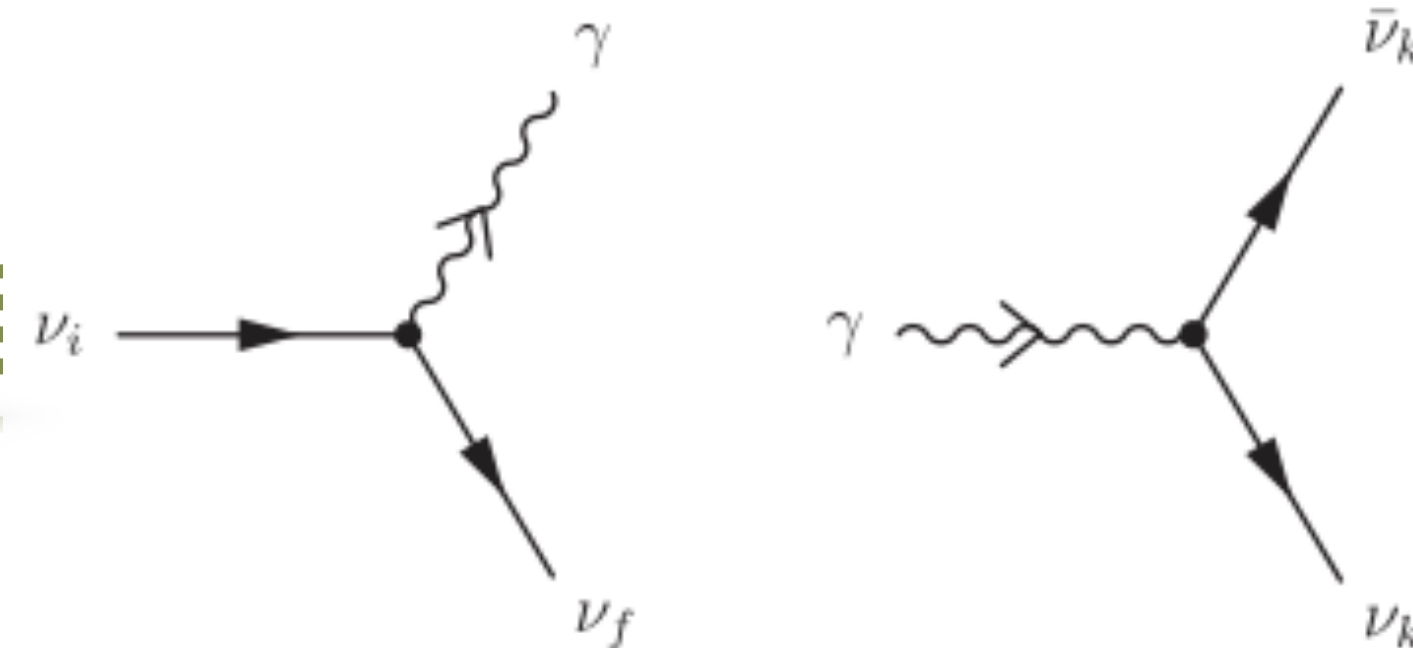
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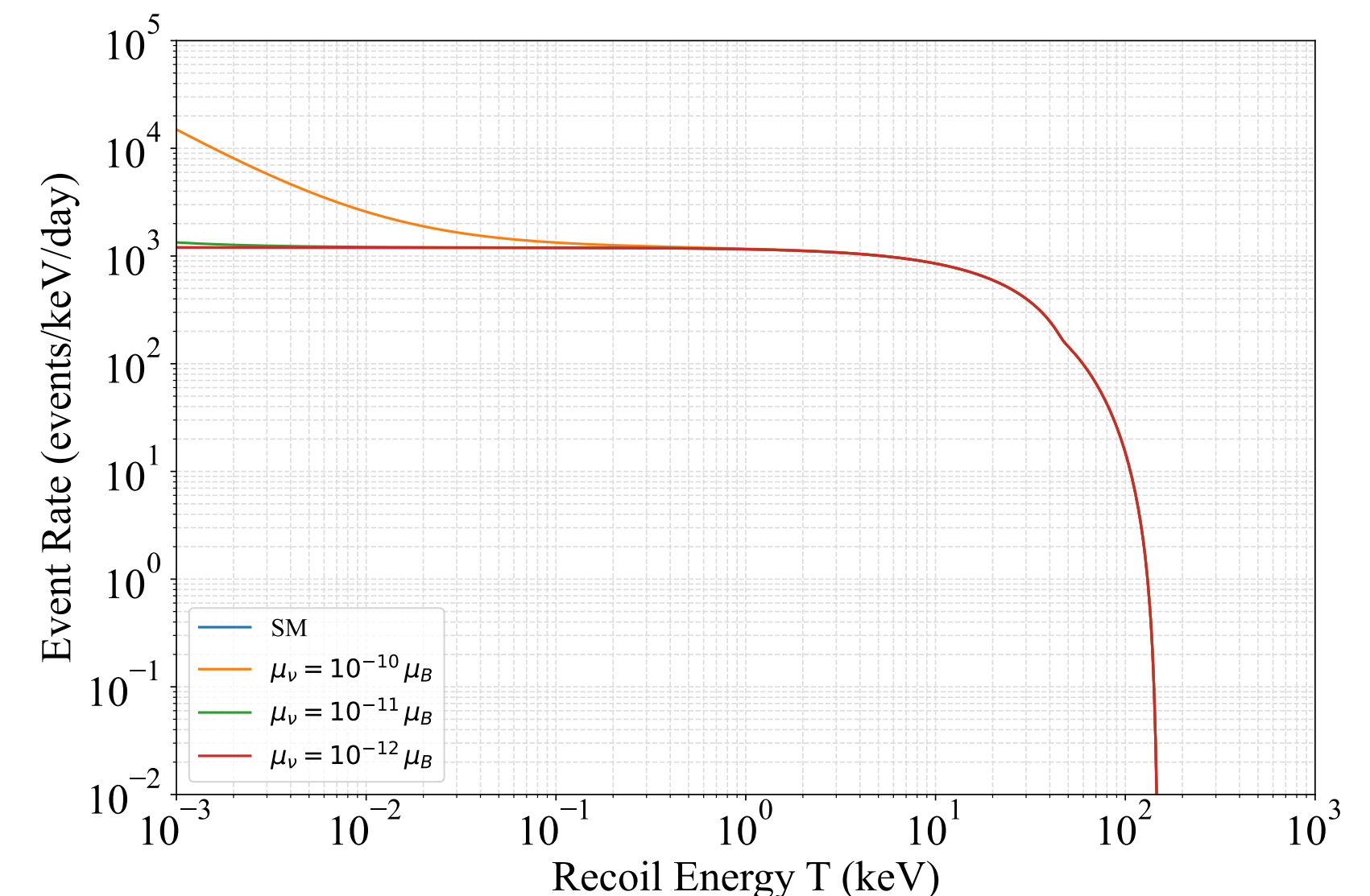
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Other signatures: $\rightarrow$

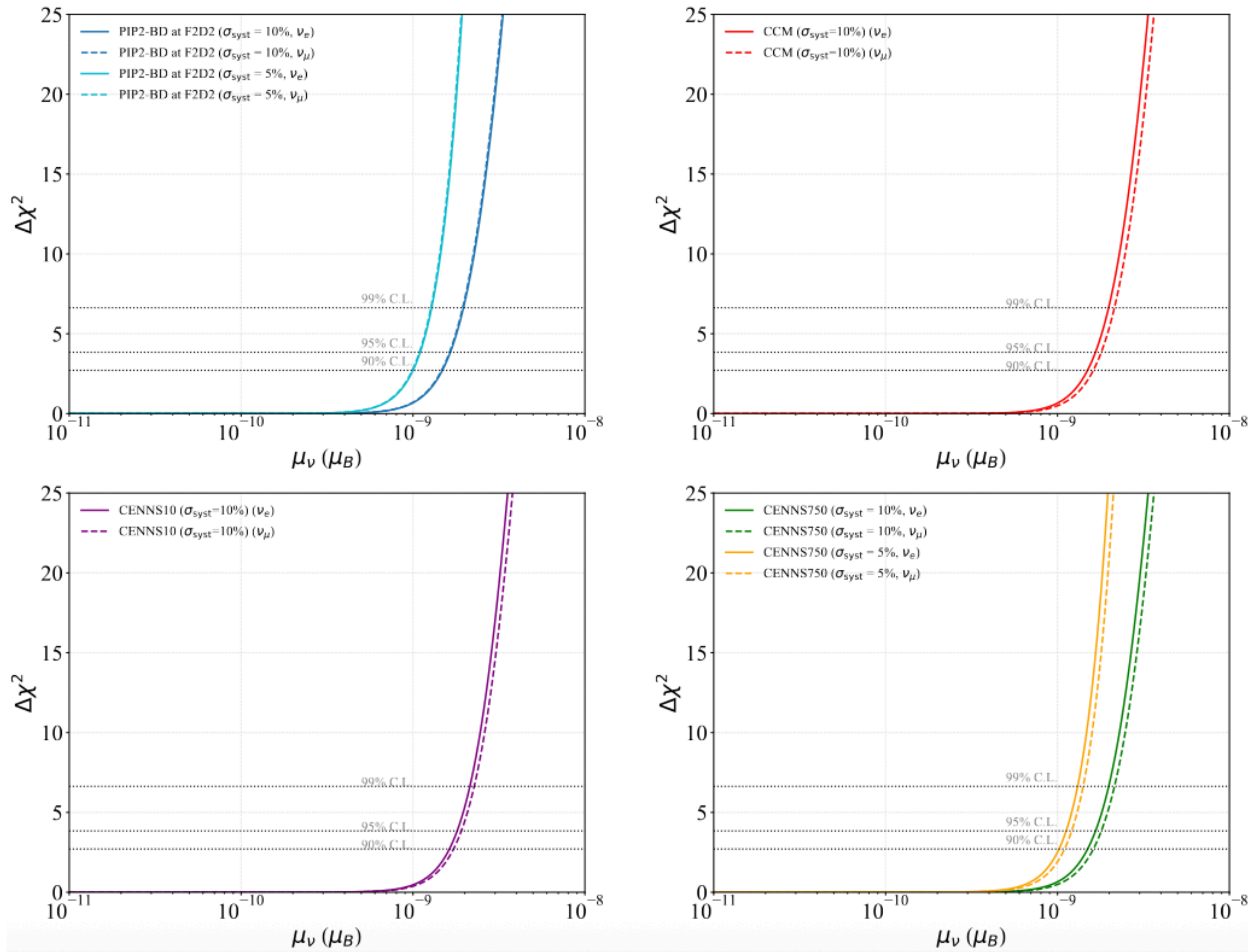


ν radiative decay: Cherenkov radiation (left) and Plasmon decay in stars (right)



Sensitivity to μ_ν

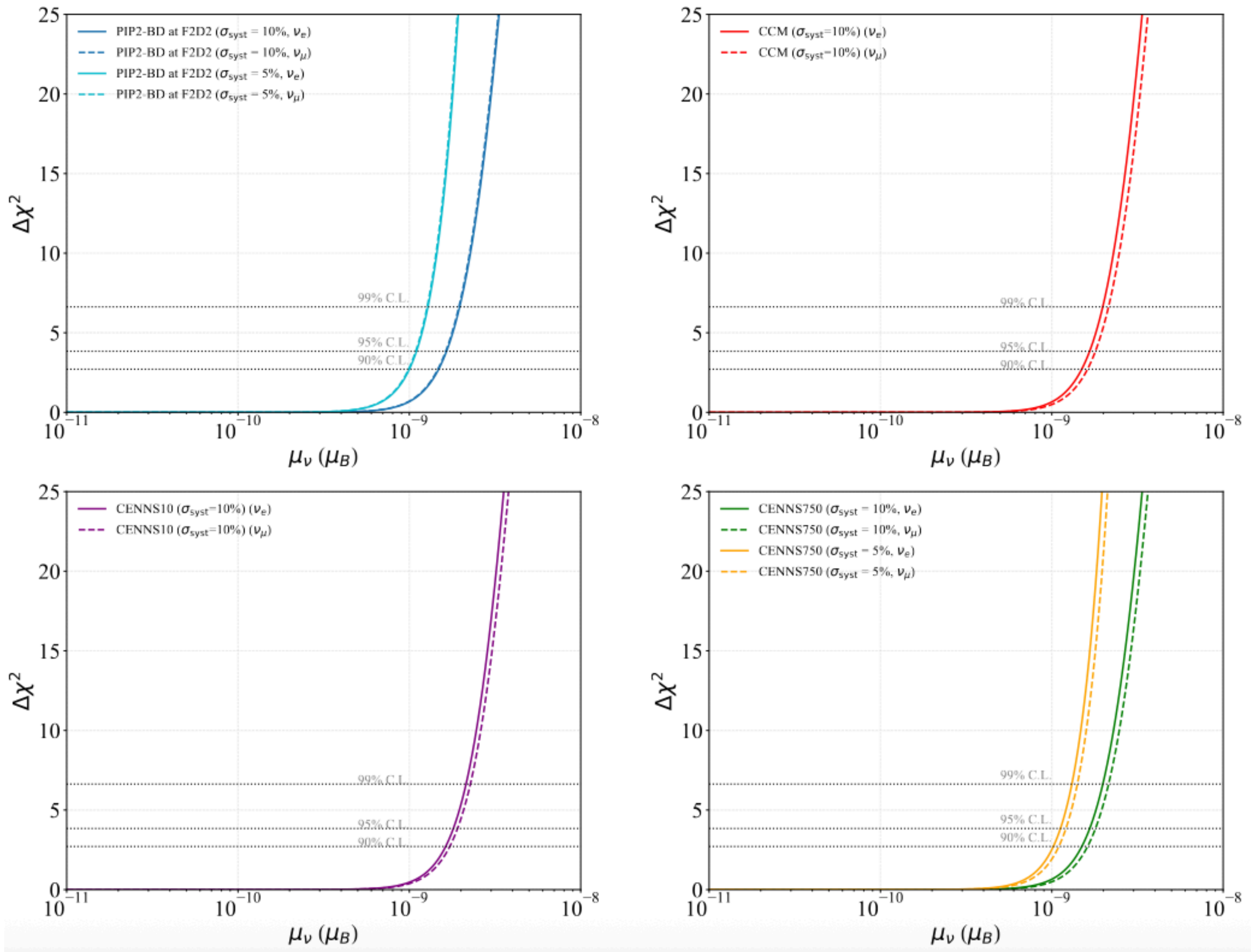
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Sensitivity on neutrino magnetic moment ($\mu_{\nu_e}, \mu_{\nu_\mu}$) for the different flux sources

[Carey and Pandey, arXiv: 2510.14015]

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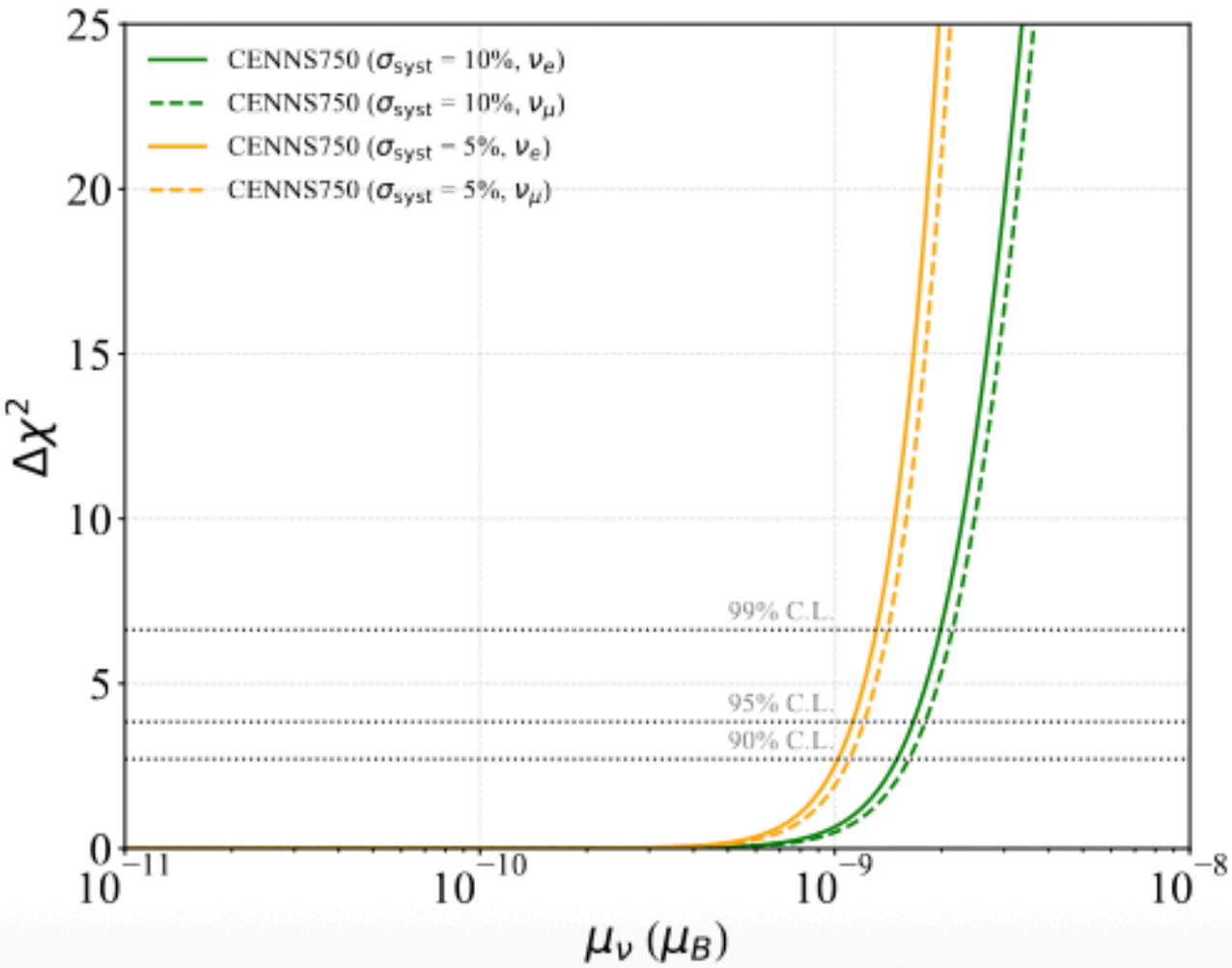
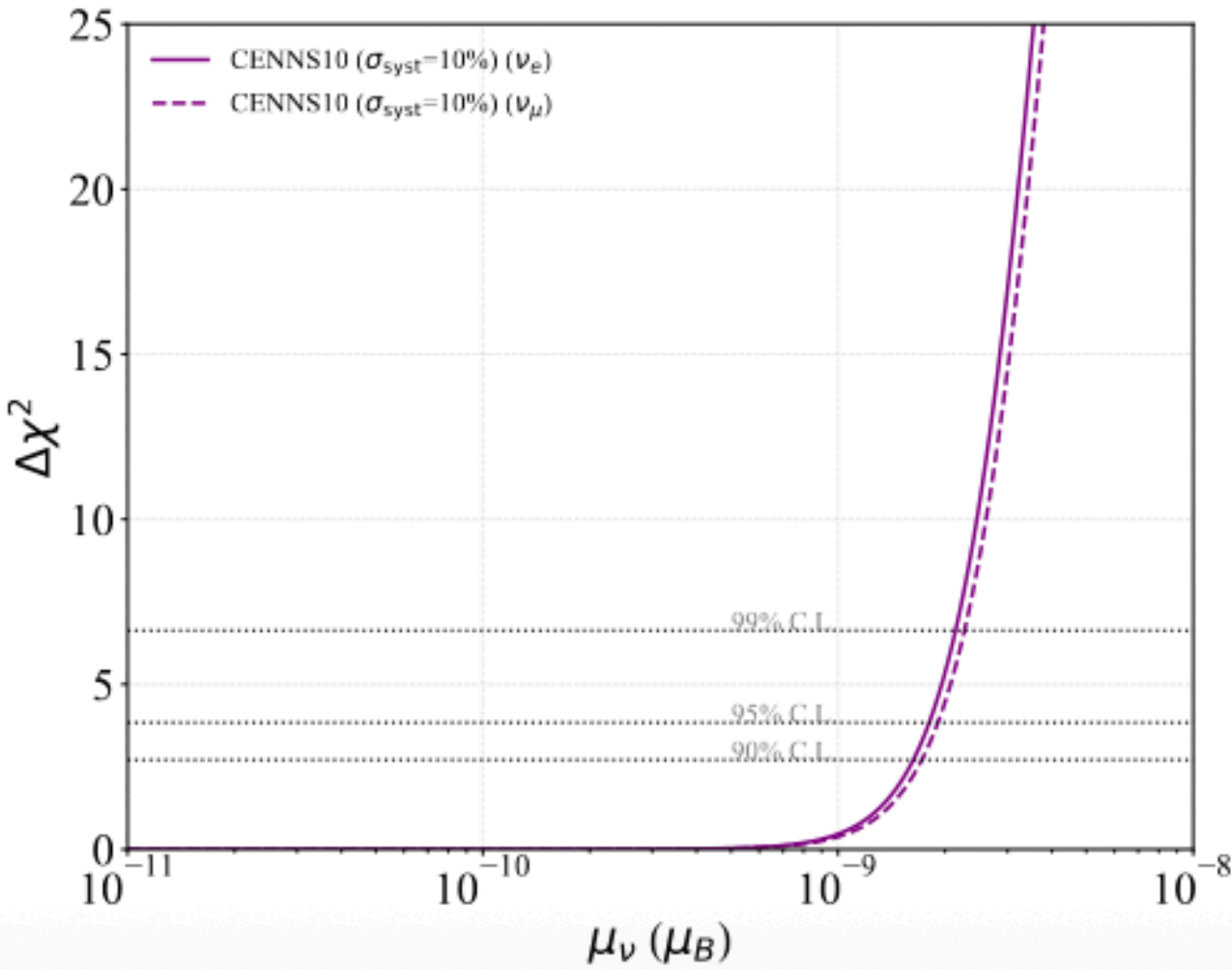
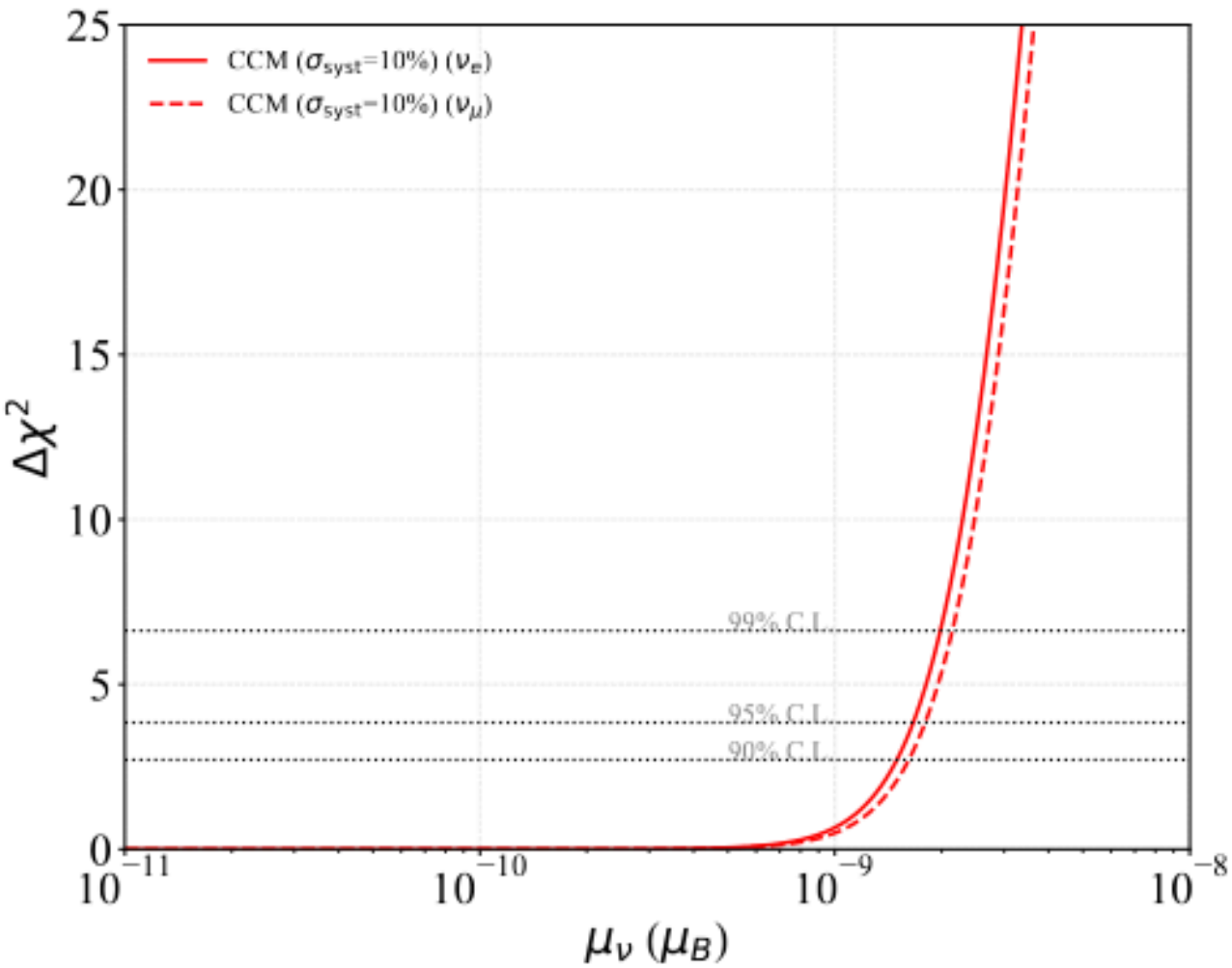
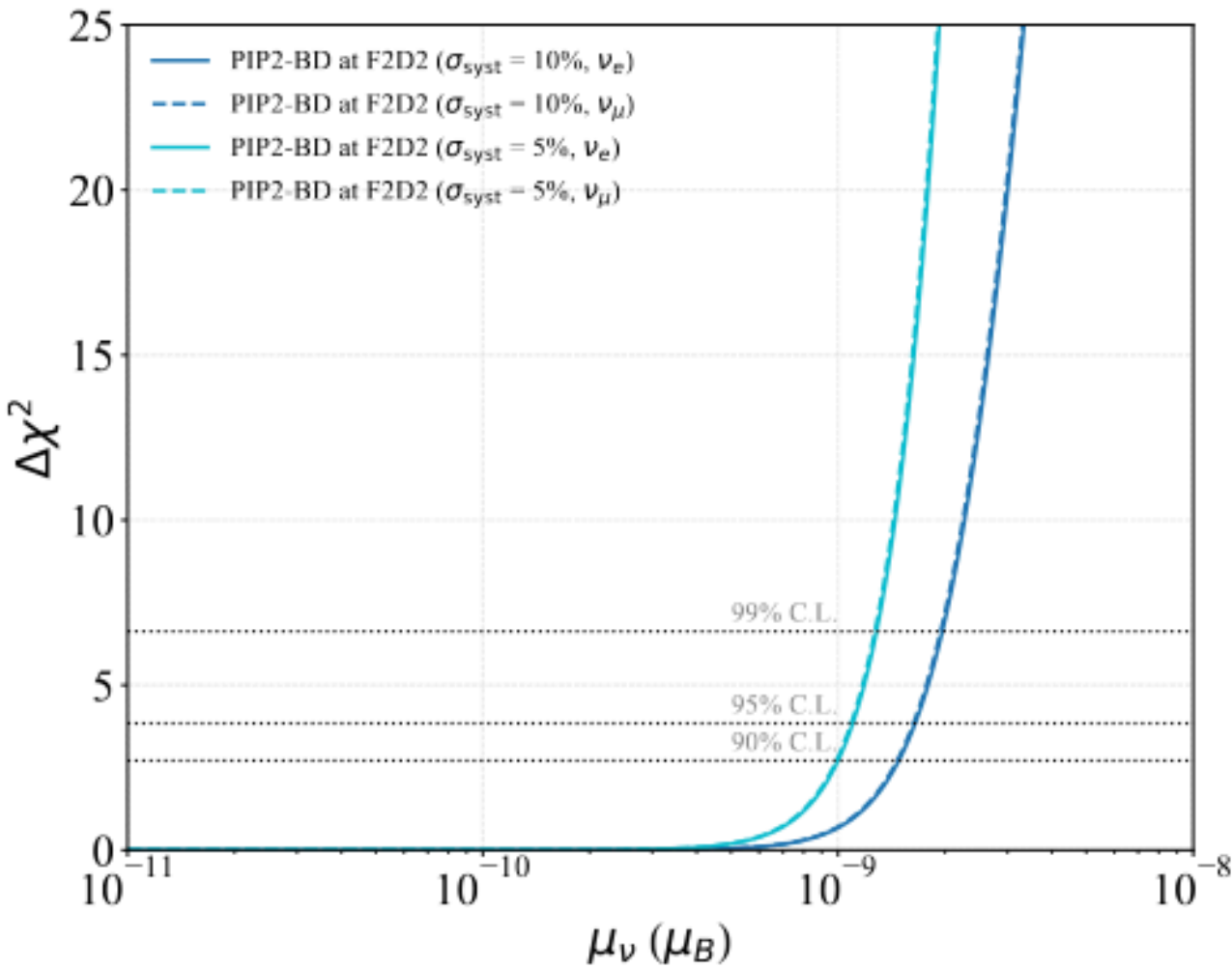


Flux Source (Syst. Unc.)	μ_ν	μ_{ν_e}	μ_{ν_μ}
PIP2-BD at F2D2 (10%)	14.7	14.8	14.7
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CENNS-10 (10%)	16.3	16.3	17.2
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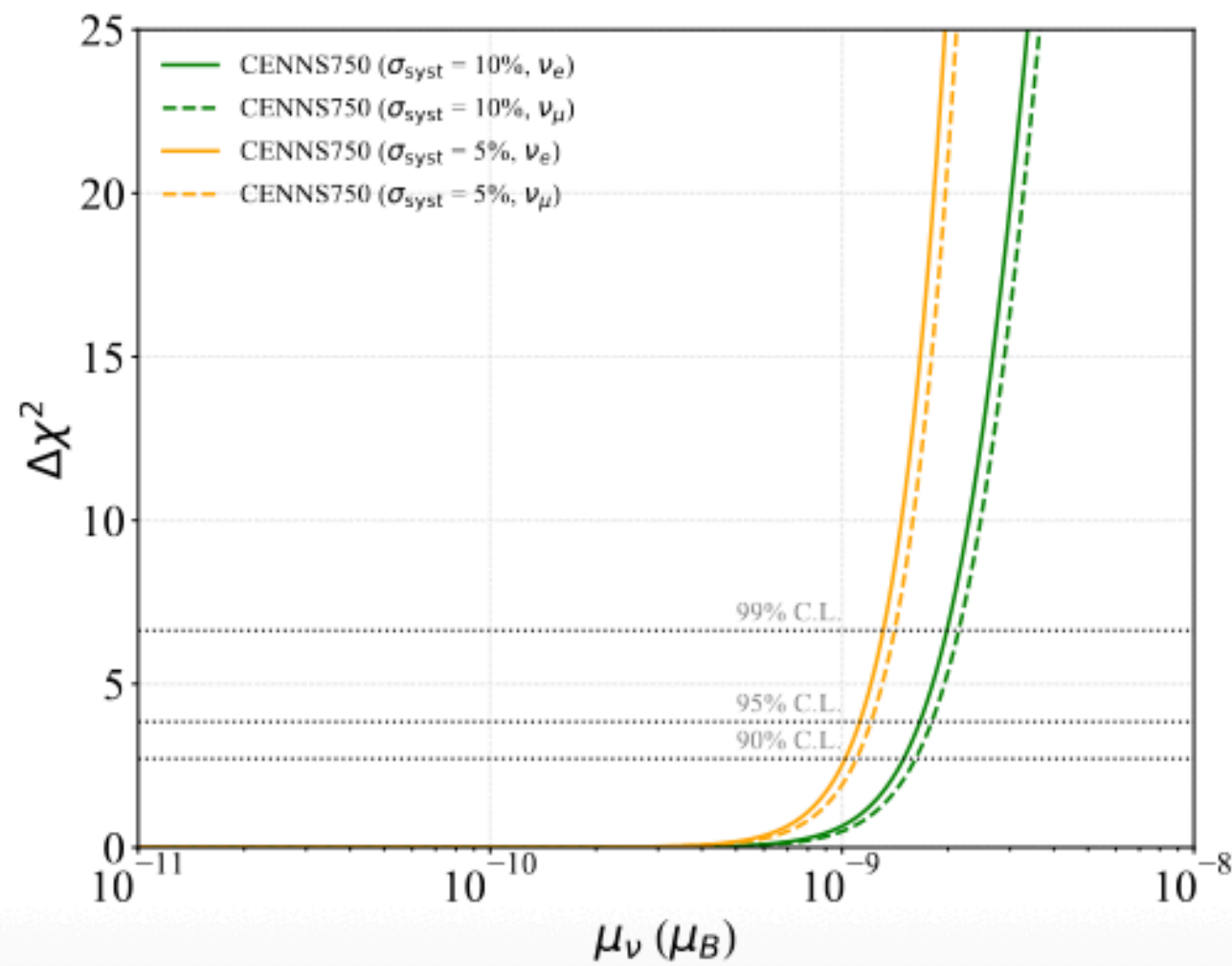
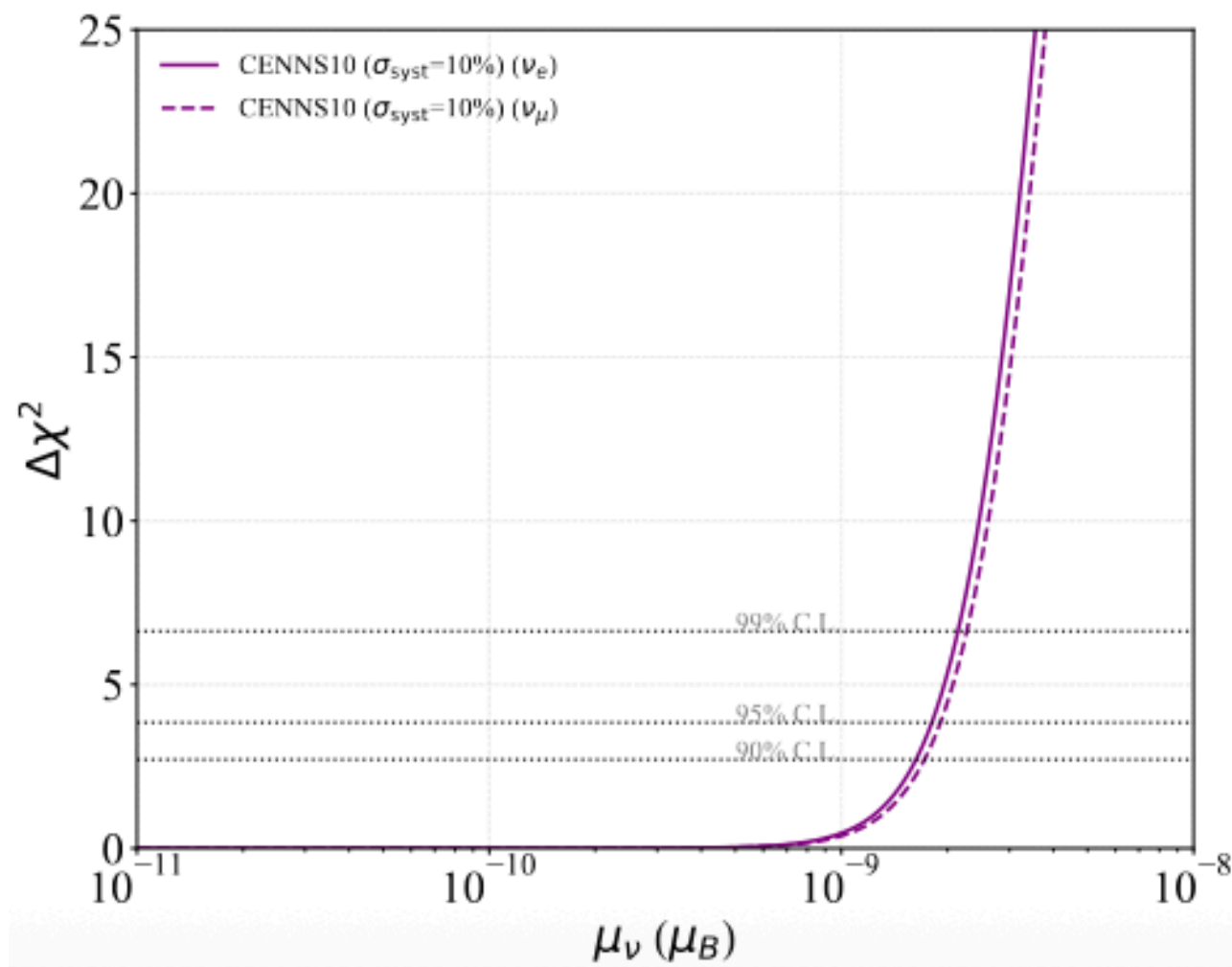
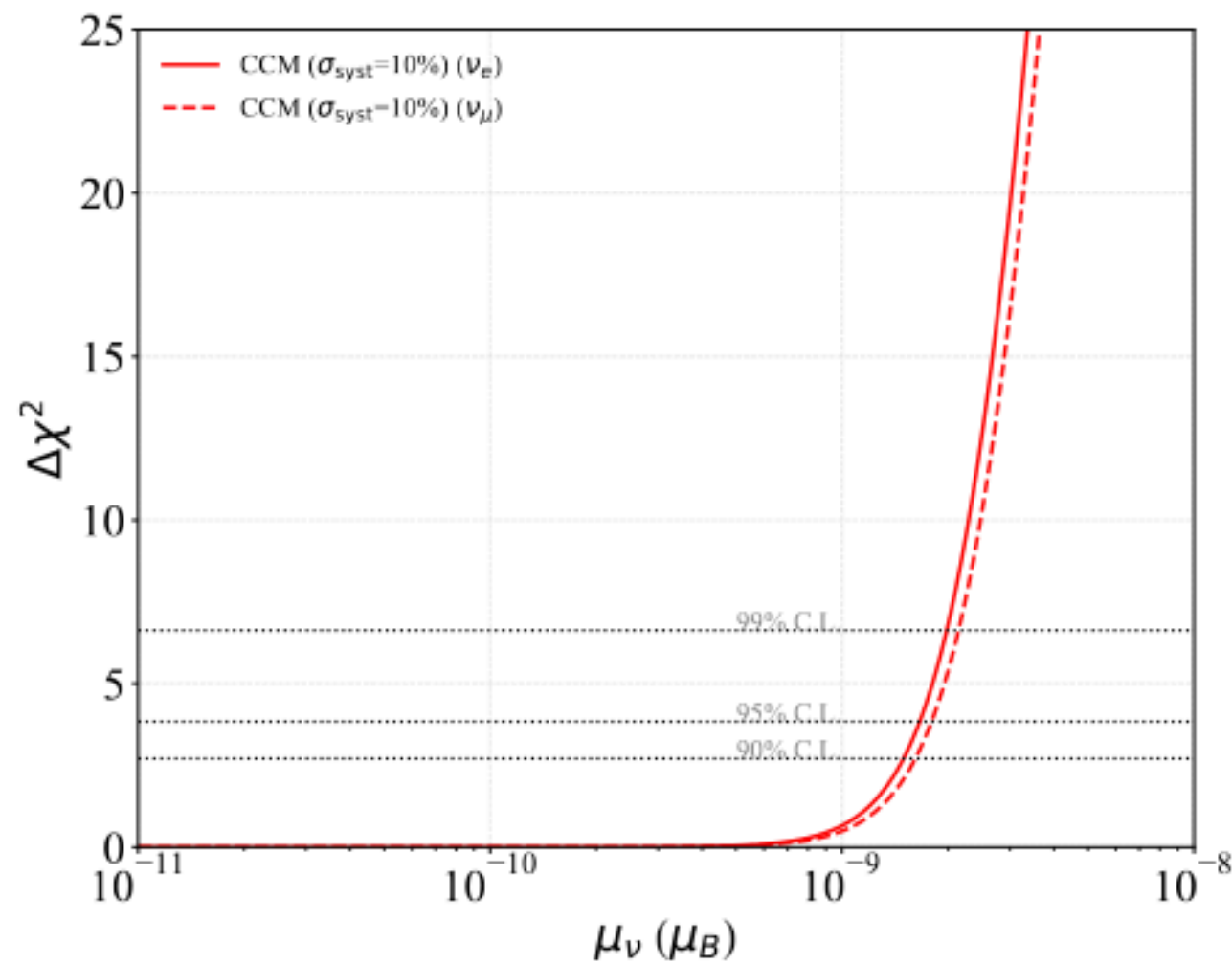
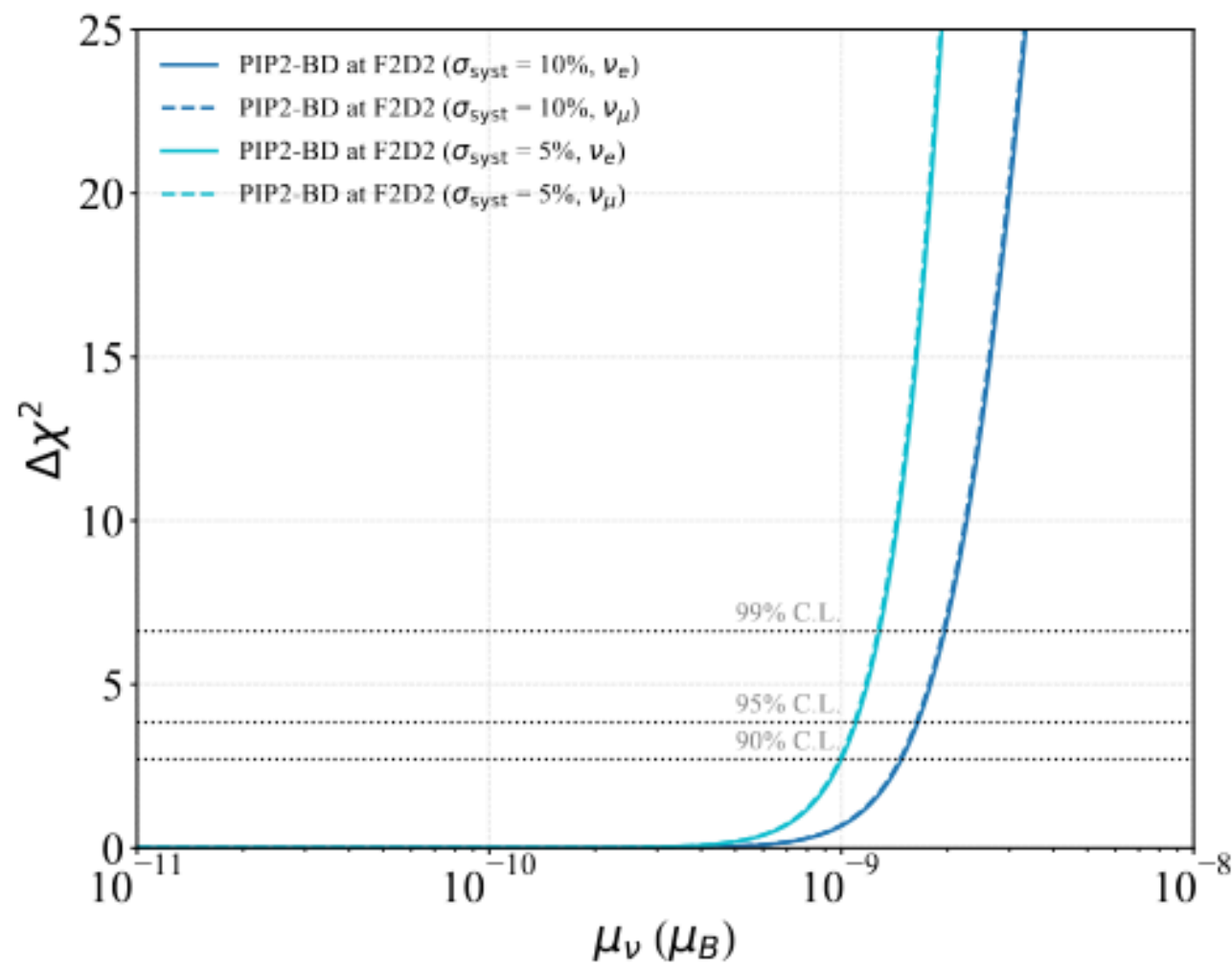
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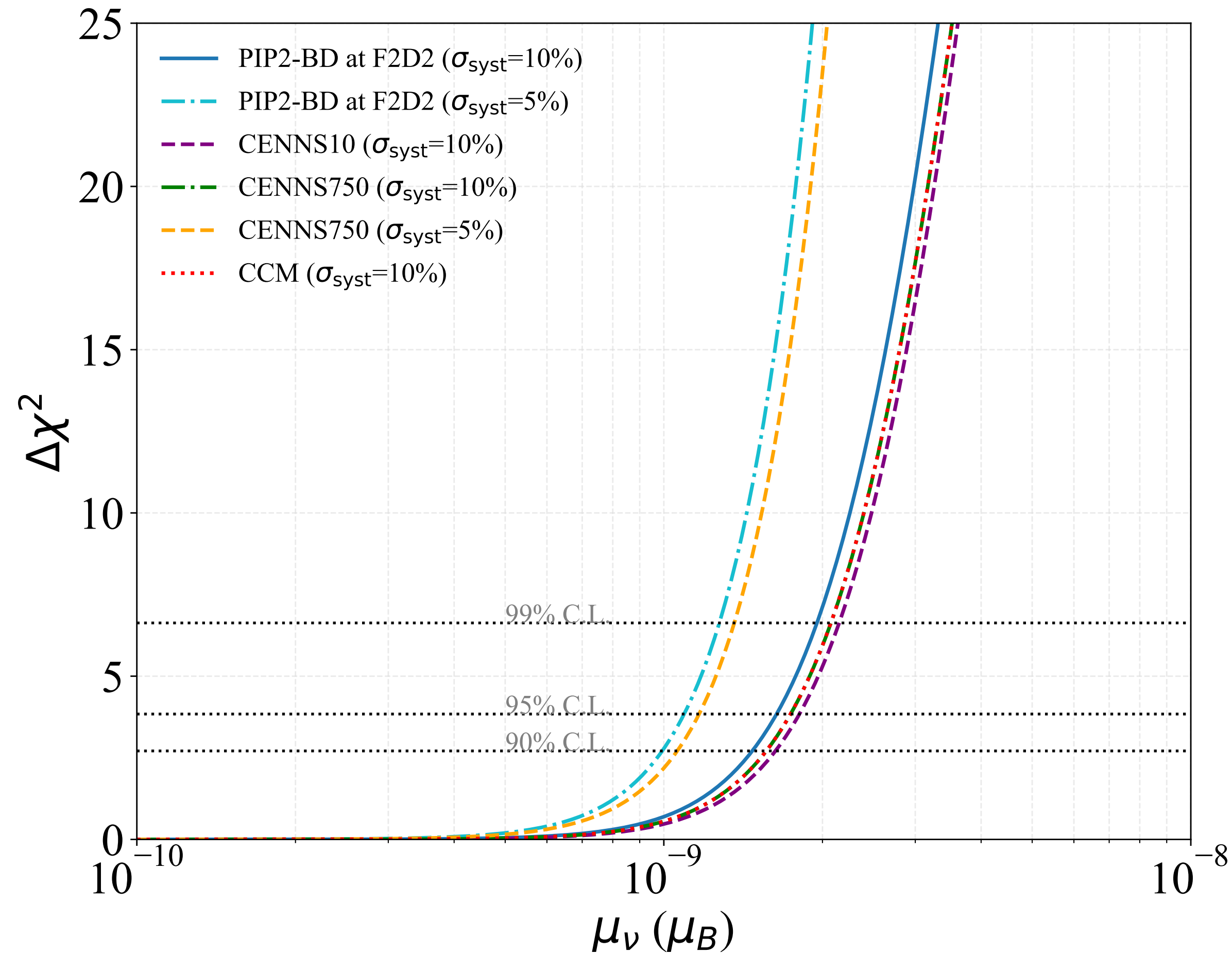
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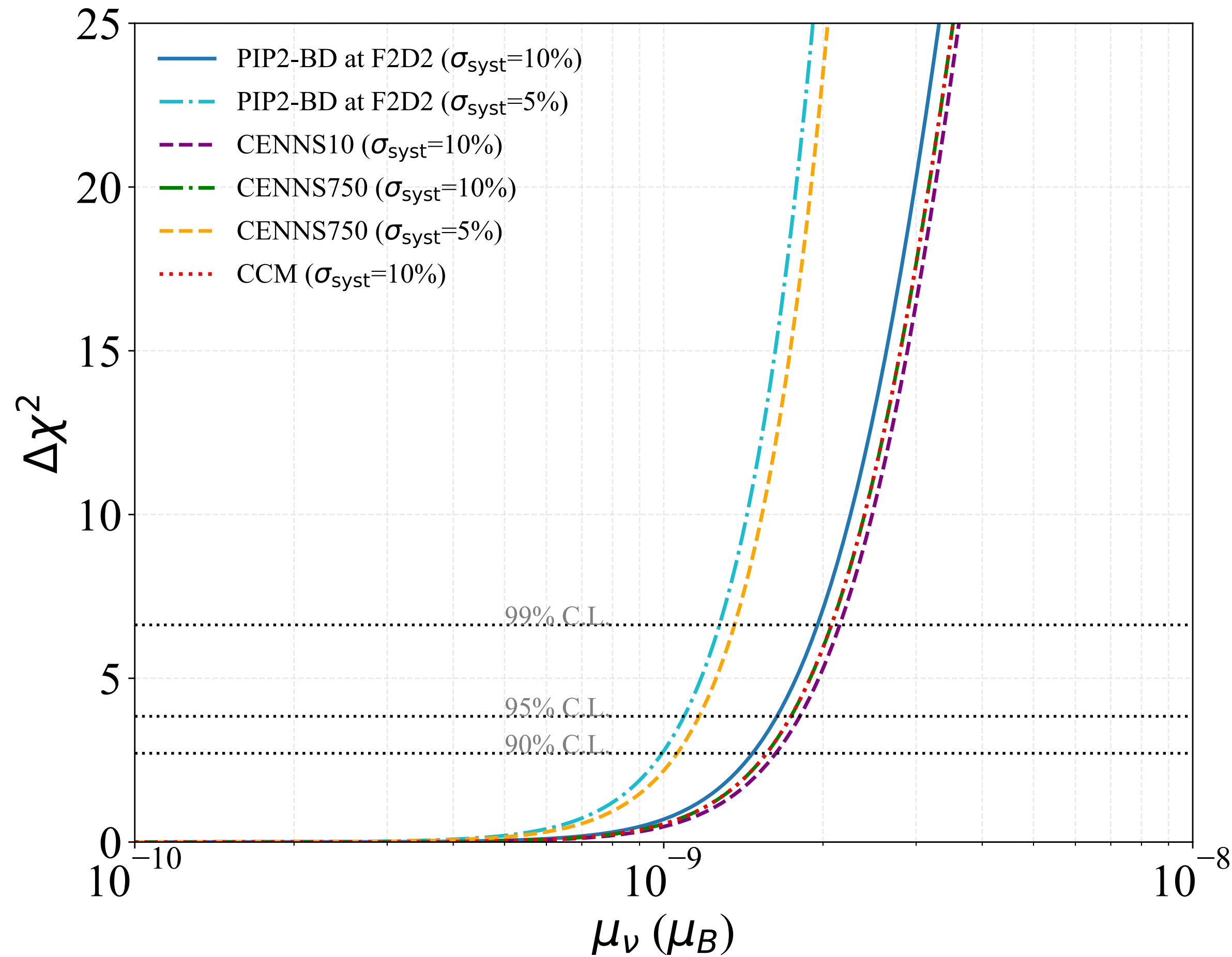
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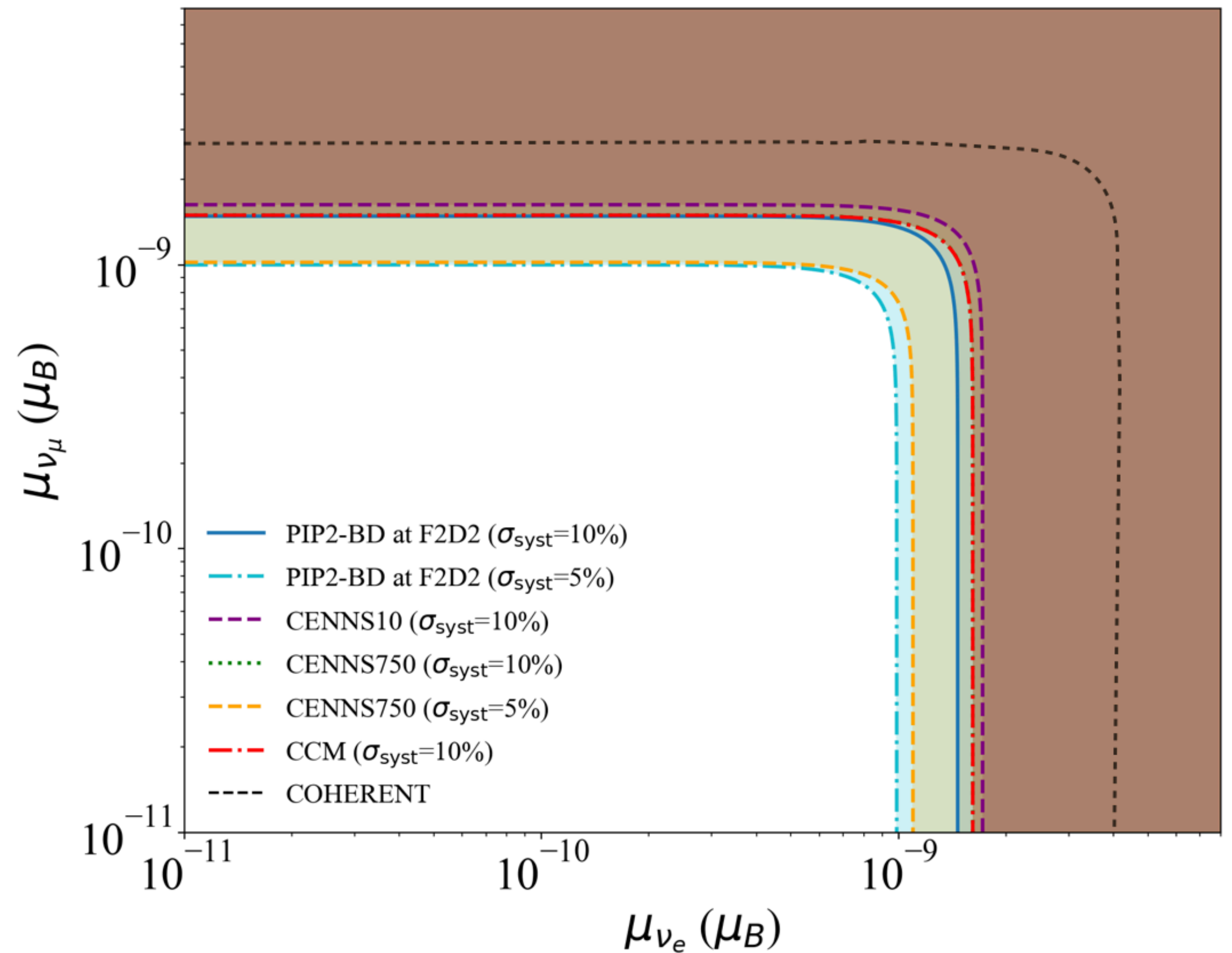


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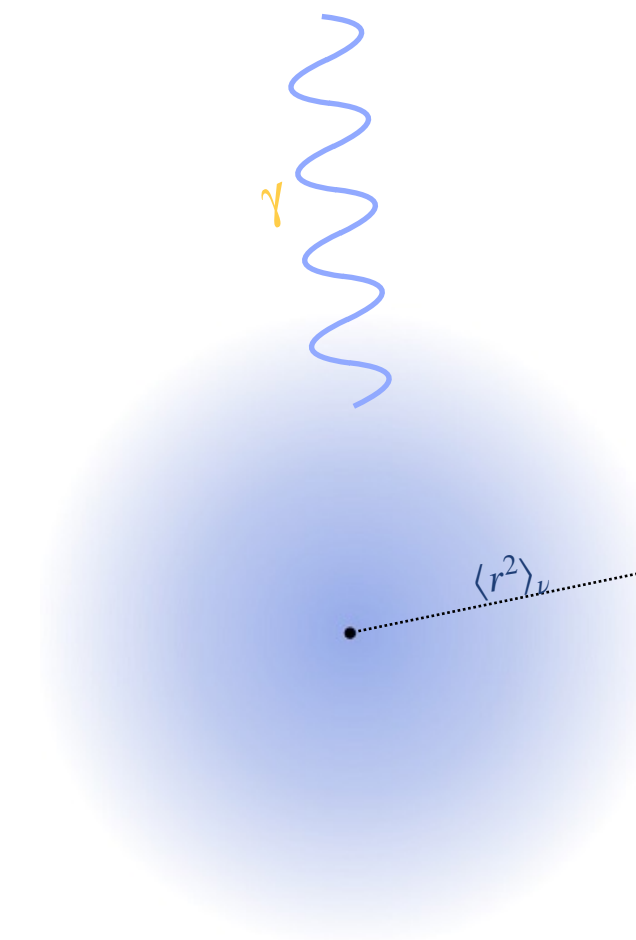
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Excluded regions at 90% CL in the plane of $\mu_{\nu_e} - \mu_{\nu_\mu}$ for the different flux sources in comparison to the COHERENT results
[Coloma, et. al., JHEP 05, 037 (2022)]
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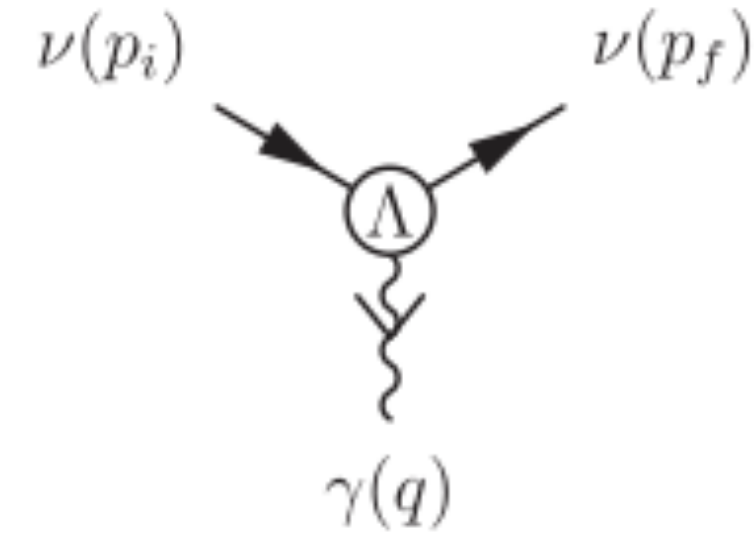
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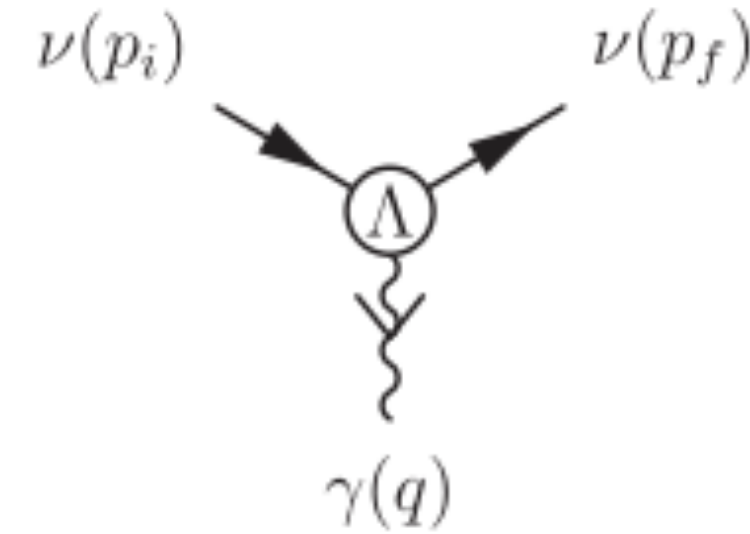
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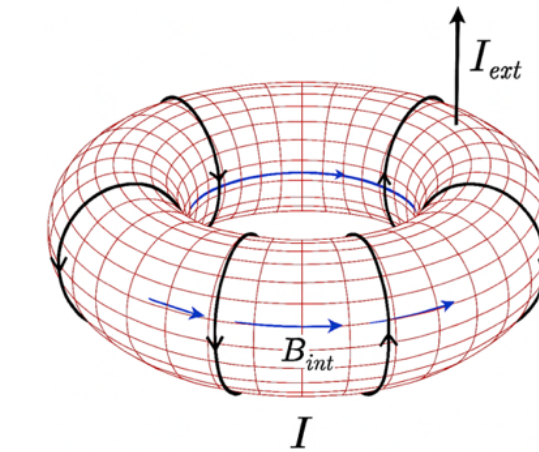
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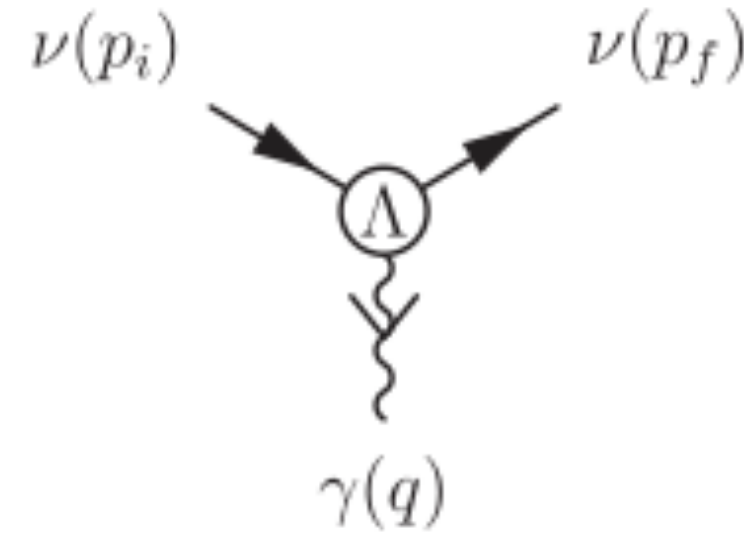
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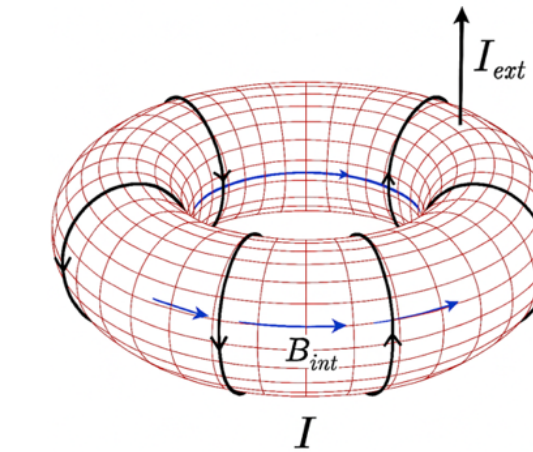
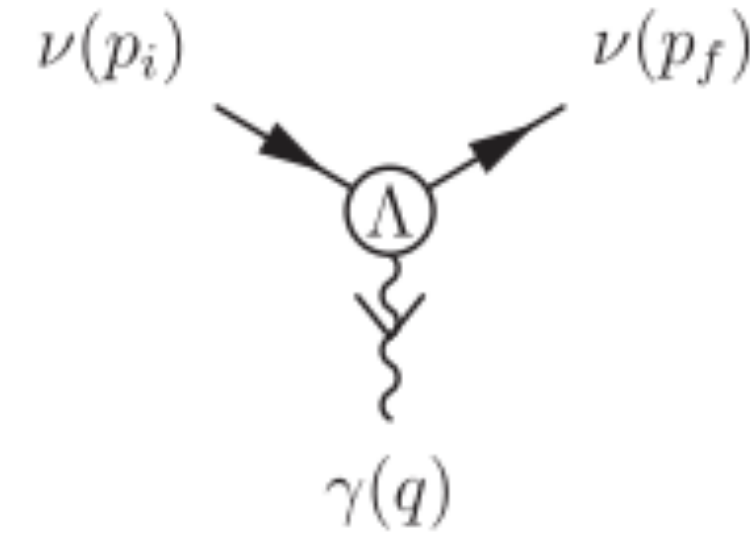
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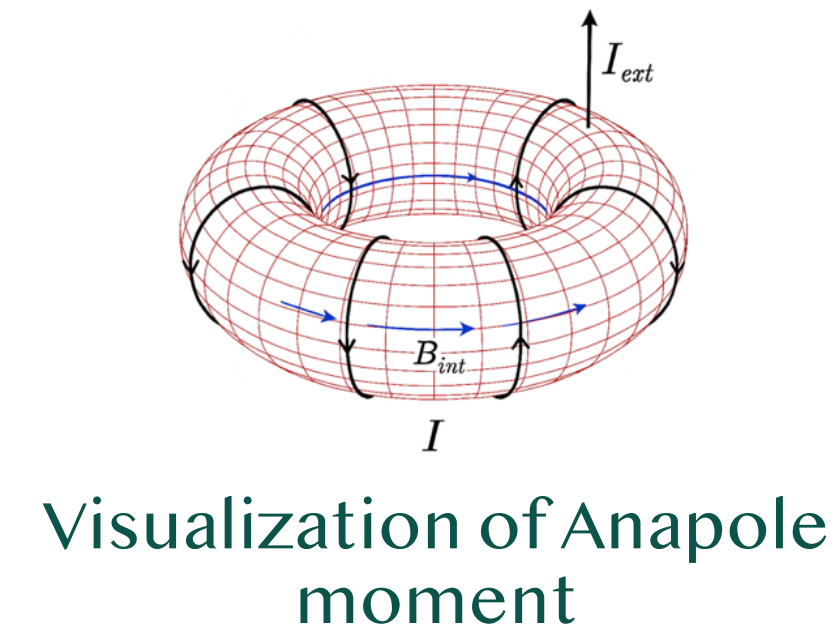
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- For ultra-relativistic ν : $F_A(q^2) \Leftrightarrow \langle r^2 \rangle_\nu$

$$a_\nu = \frac{1}{6}\langle r^2 \rangle_\nu$$

Anapole Moment and Charge Radius

- $\nu - \gamma$ interaction: $\bar{\nu}(x)\Lambda_\mu\nu(x)A^\mu(x)$

[Lee and Shrock, Phys. Rev. D 16, 1444 (1977)]

$$\Lambda_\mu(q) = -i\sigma_{\mu\nu}q^\nu [F_M(q^2)] + \left(\gamma_\mu - q_\mu\gamma^\nu q_\nu/q^2\right) [F_1(q^2) + F_A(q^2)q^2\gamma_5]$$

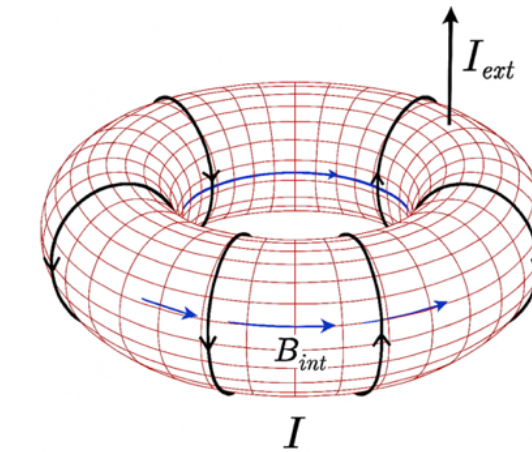
- **Zeldovich: anapole moment** ($\cancel{P}$) - coupling not with EM field but source. Effective one-photon coupling of a ν

$$\mathcal{L}_{\text{Dim-6}} \sim \epsilon_{ij}(\bar{\nu}_i\gamma^\mu\gamma_5\nu_j)(\bar{f}\gamma_\mu f)$$

[Zeldovich, JETP 6, 1184-1186 (1958)]

- Even if $q_\nu = 0$ (i.e. $F_1(0) = 0$), Taylor expansion:

$$F_1(q^2) = F_1(0) + \frac{1}{6}\langle r^2 \rangle_\nu q^2 + \dots$$



Visualization of Anapole moment

$$\text{SM Prescription: } \langle r_{\nu_i}^2 \rangle = \frac{G_F}{4\sqrt{2}\pi^2} \left[\frac{25}{6} - \log\left(\frac{m_i^2}{M_W^2}\right) \right] \rightarrow \approx 10^{-33}\text{cm}^2$$

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$\nu - e^-$ scattering: strongest constraint (at 90% CL)
 $([-2.1, 3.3] \times 10^{-32}\text{cm}^2)$ from TEXONA

Charge Radius Signature

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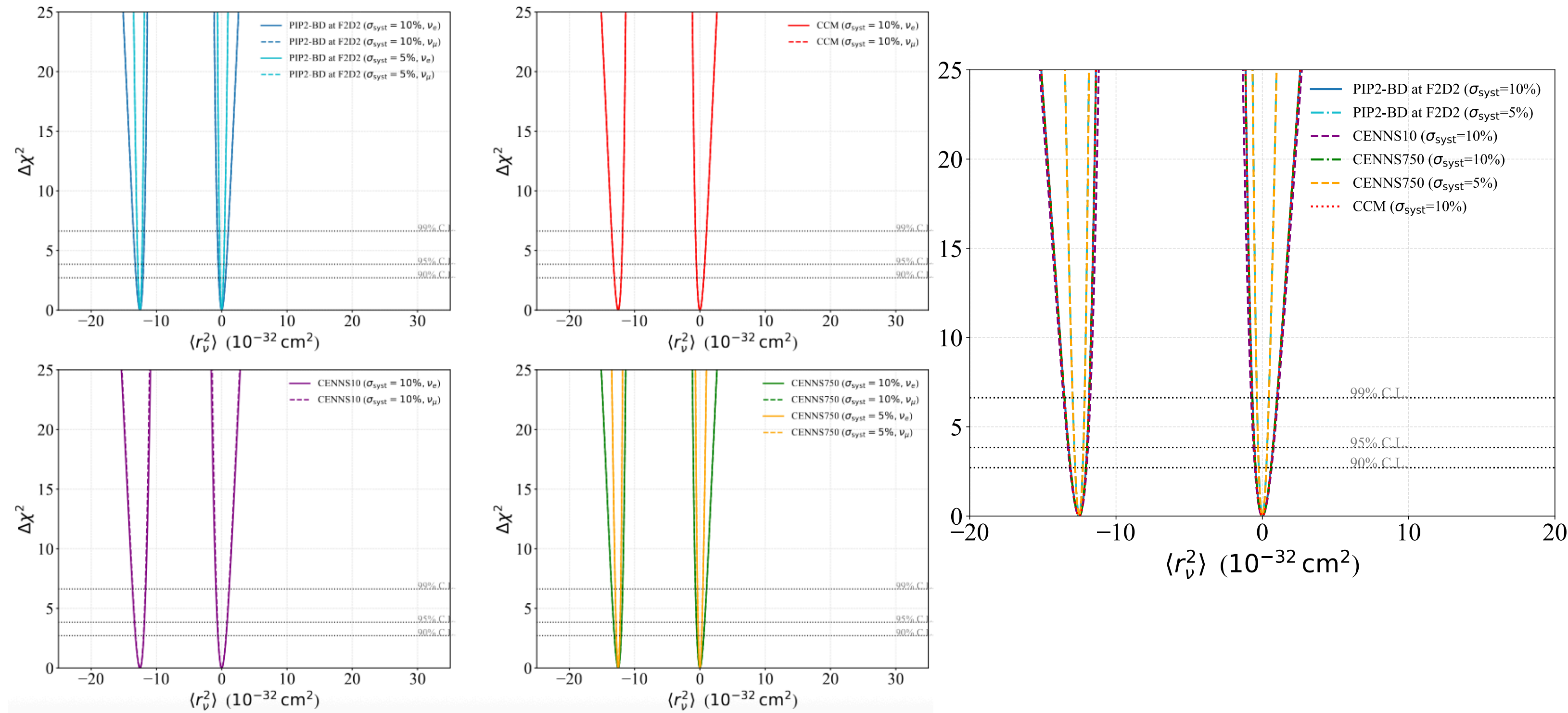
- Experimental signatures: finite $\langle r^2 \rangle_\nu$ leads to the redefinition of the θ_W as

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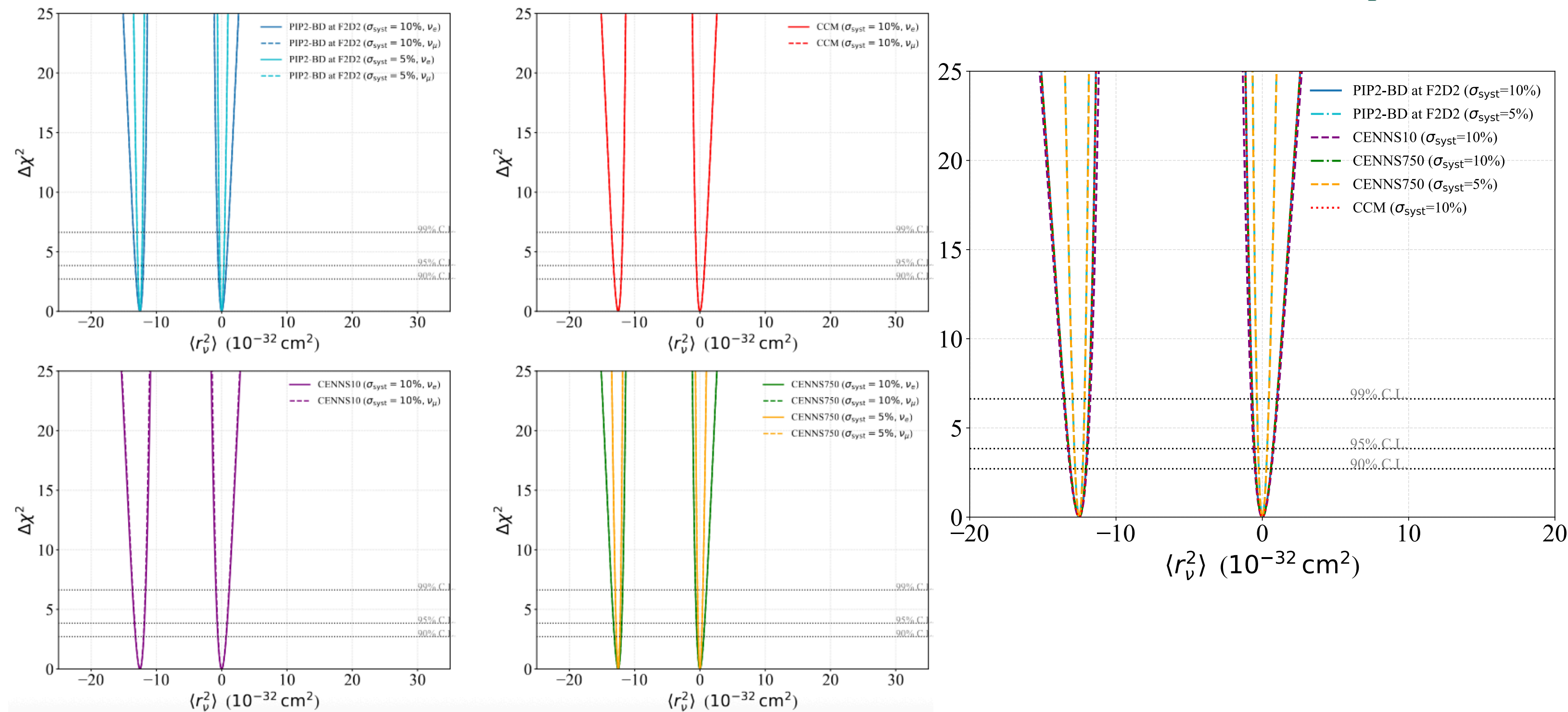


Sensitivity on neutrino charge radius
[Carey and Pandey, arXiv: 2510.14015]

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Flux Source (Syst. Unc.)	$\langle r^2 \rangle_{\nu\mu}$
PIP2-BD at F2D2 (10%)	$[-13.08, -12.08] \cup [-0.44, 0.56]$
PIP2-BD at F2D2 (5%)	$[-12.76, -12.28] \cup [-0.24, 0.24]$
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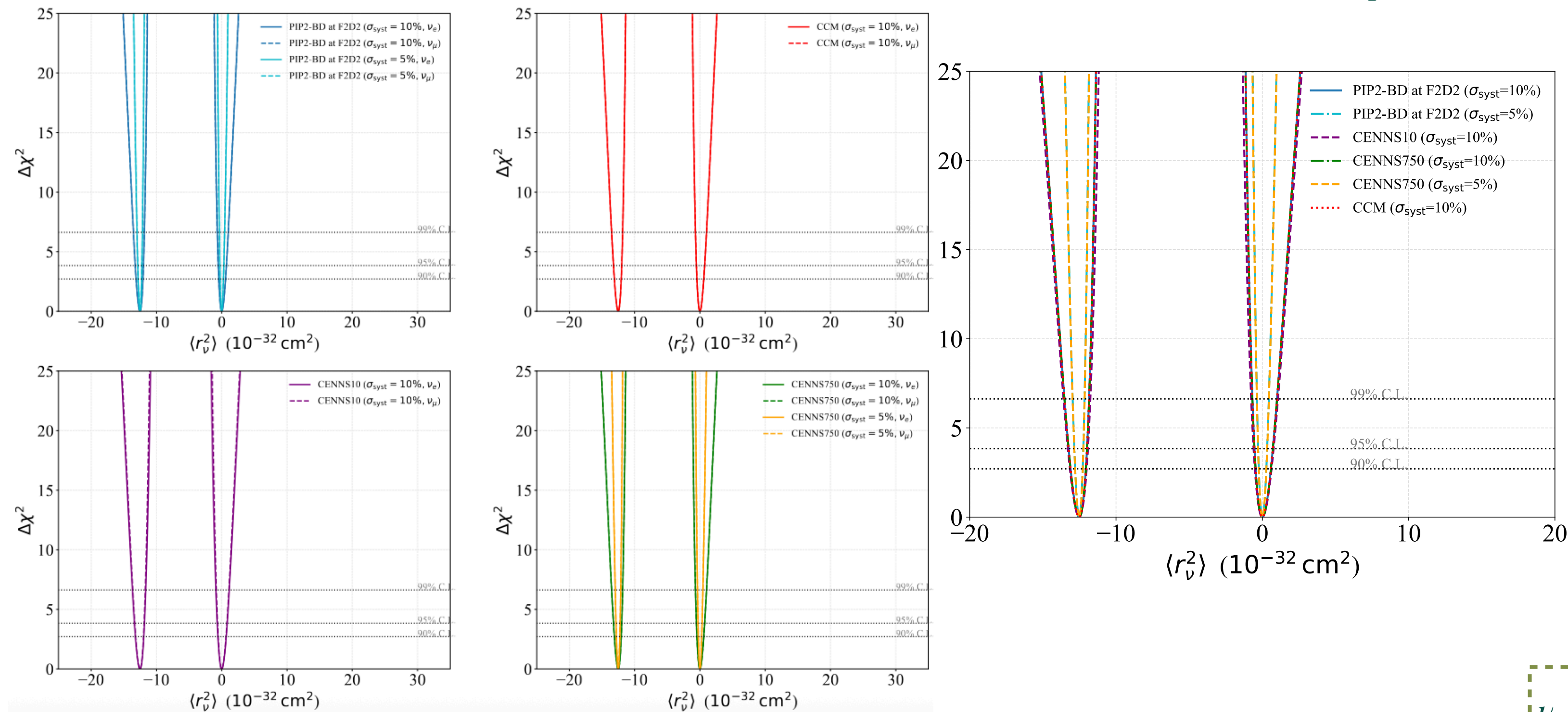
Estimated values of $\langle r^2 \rangle_\nu$ at 90% CL
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ν_μ – CsI scattering: strongest constraint
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Overview

✓ Neutrino (Electromagnetic) Interactions

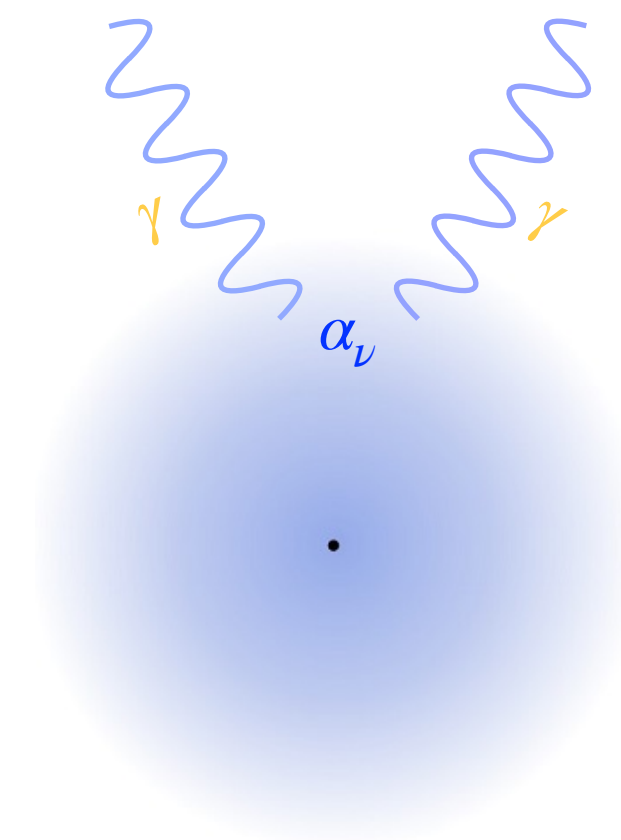
✓ Interaction at MeV: Magnetic Moment and Charge Radius

► Interaction at GeV: Enhanced Neutrino Polarizability in DUNE

► Summary

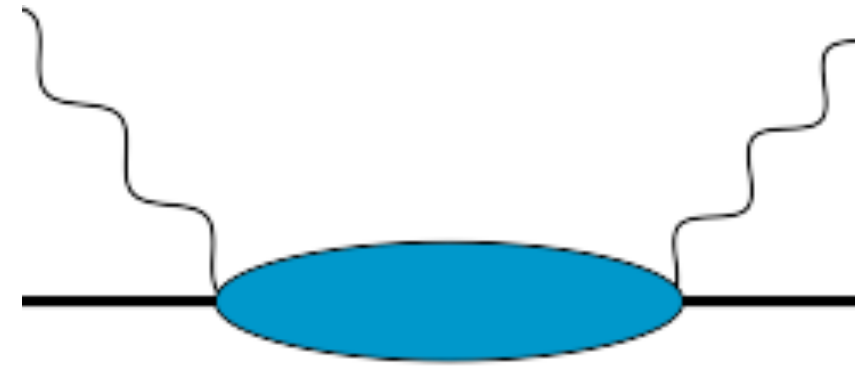
Enhanced Neutrino Polarizability in DUNE

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Polarizability

Polarizability

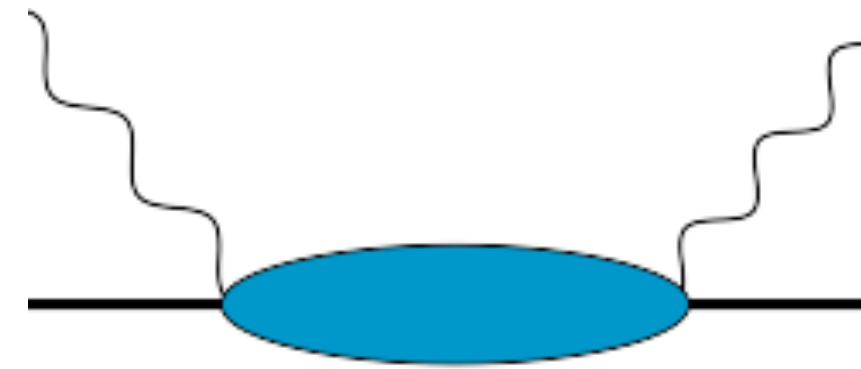


Polarizability in
Compton scattering

- © Idea: familiar from classical electrodynamics extended to Compton scattering

[Klein, Phys. Rev 99, 3 (1955)]

Polarizability



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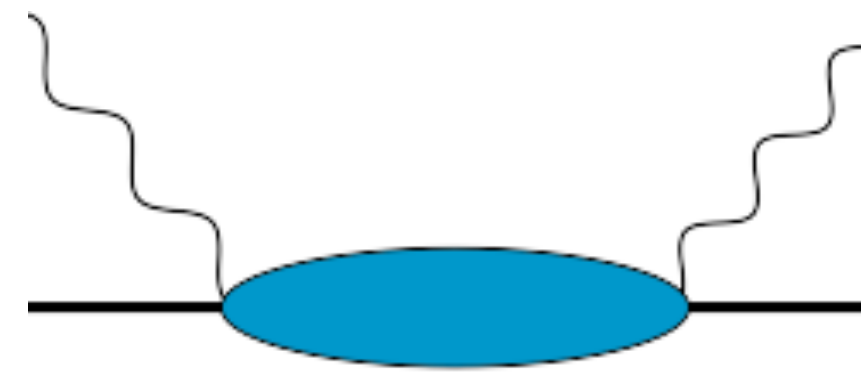
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- ν polarizability described by dim-7 operator:

$$\frac{1}{2}\tilde{\alpha}_{\nu,ij}\left(\bar{\nu}_i P_L \nu_j\right) F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{1}{2}\alpha_{\nu,ij}\left(\bar{\nu}_i P_L \nu_j\right) F_{\mu\nu} F^{\mu\nu} \longrightarrow \boxed{\vec{E}^2 - \vec{B}^2}$$

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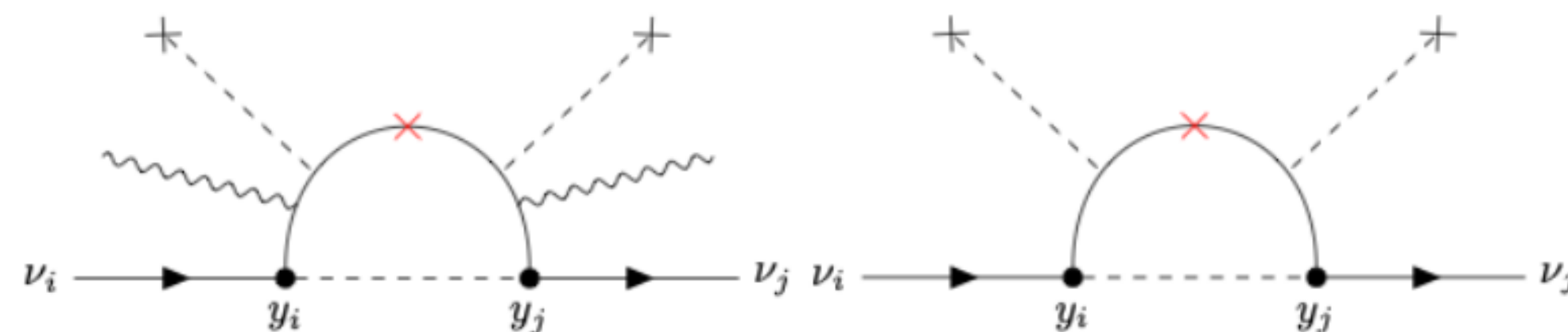
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- In generic new physics model (NP: heavy scale) polarizability highly suppressed:

$$\tilde{\alpha}_{\nu,ij} \approx m_\nu / M^4$$



One loop contributions to the (left:) polarizability and
(right:) neutrino mass matrix

[Bansal, Paz, Petrov, Tamaro and Zupan, JHEP 05, 142 (2023)]

Enhanced ν Polarizability

Enhanced ν Polarizability

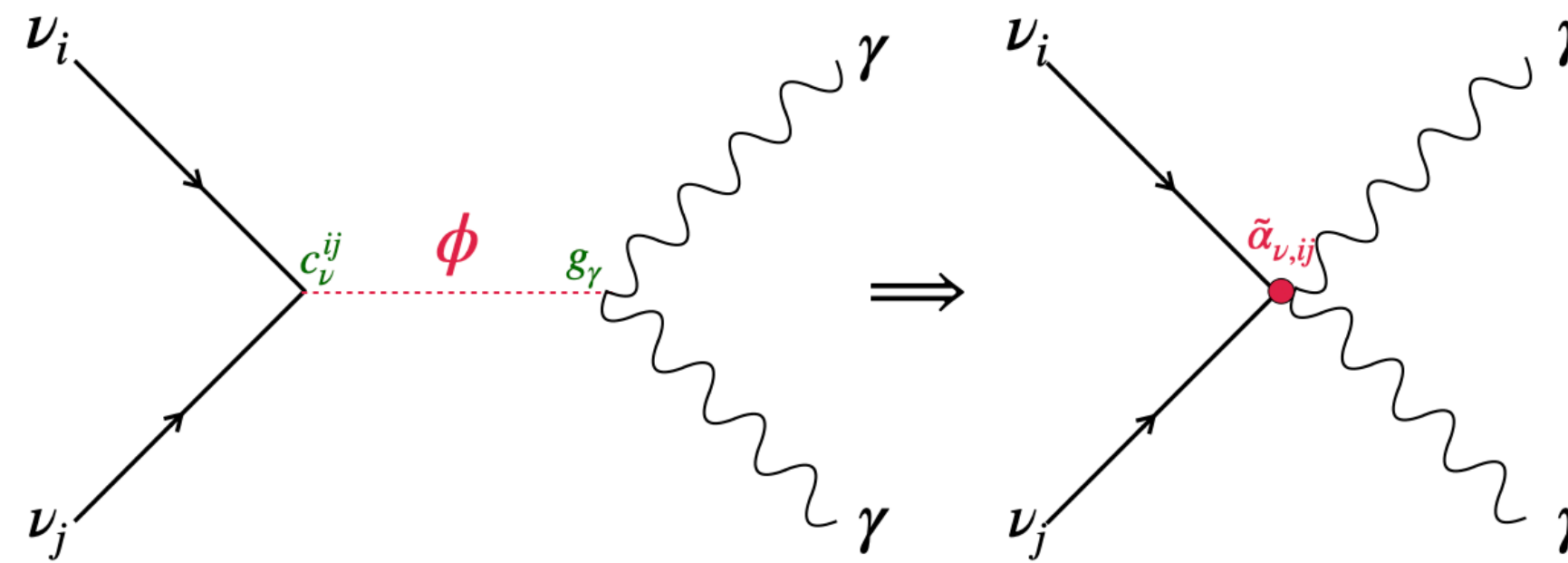
- Introduce light (pseudo-)scalar ϕ coupling to neutrinos and photons:

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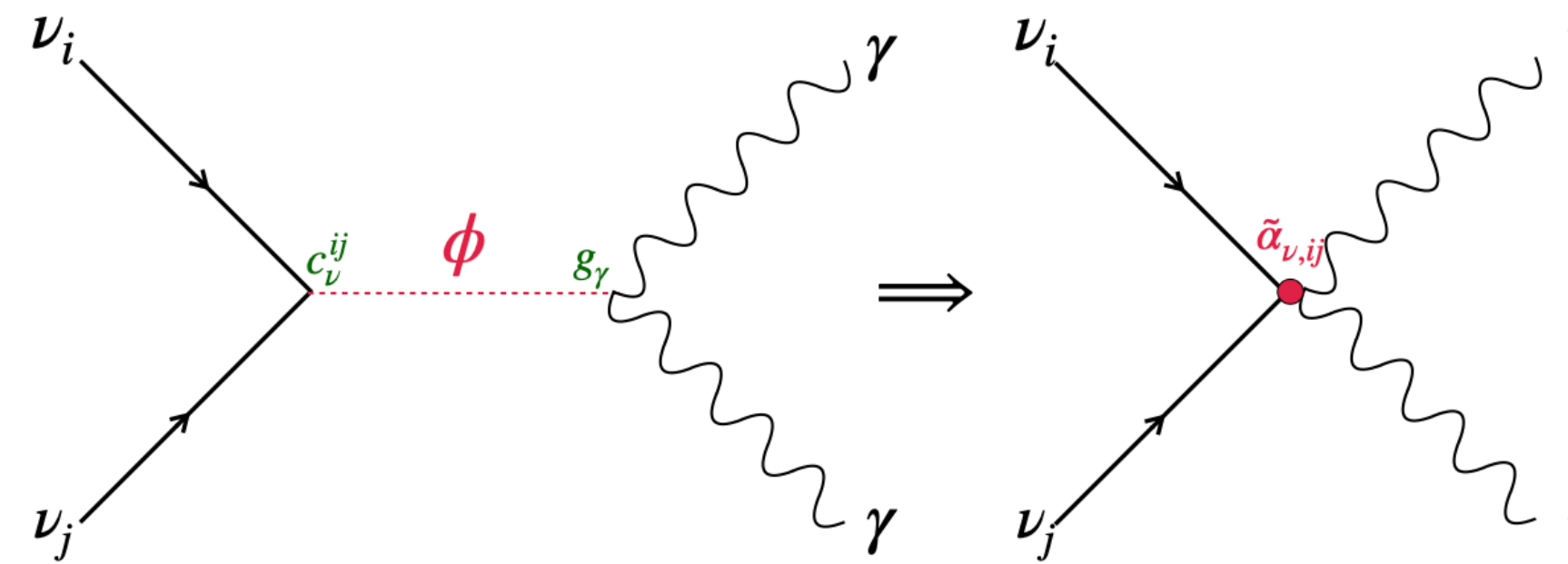
Neutrino-photon coupling mediated by light scalar

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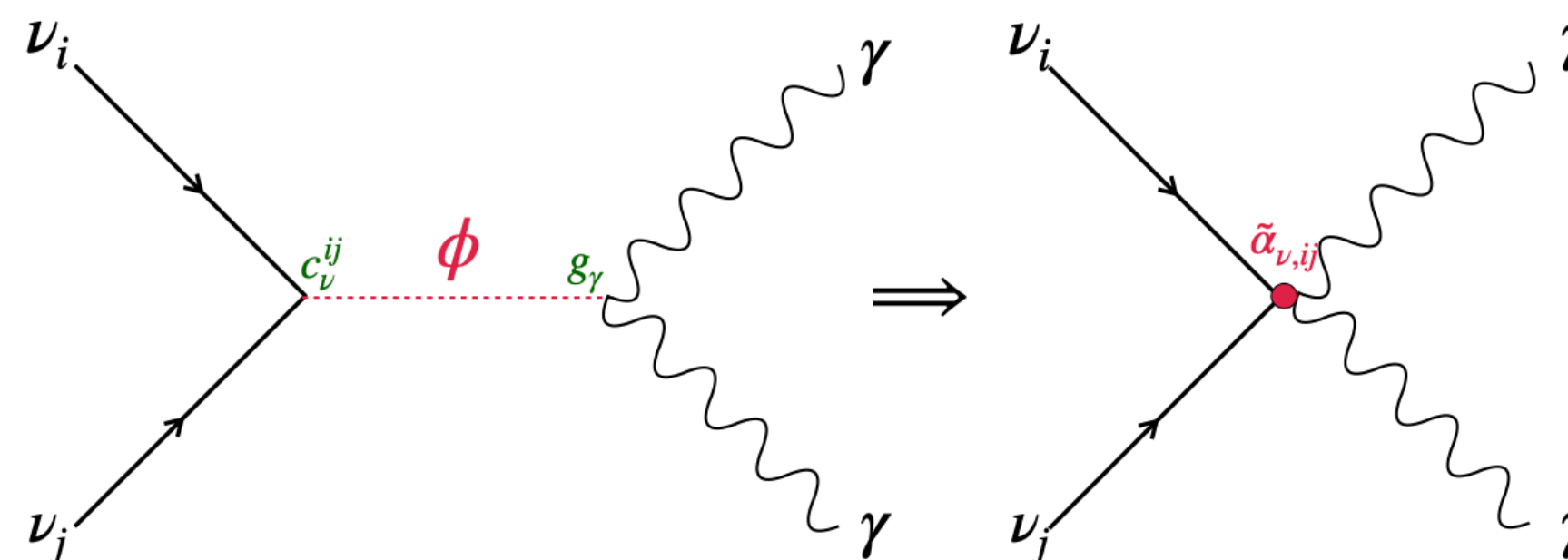
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For $q \ll m_\phi$: $\tilde{\alpha}_\nu \sim m_\nu / (\Lambda_\gamma f_\phi m_\phi^2) \rightarrow$ **Enhanced Neutrino Polarizability**

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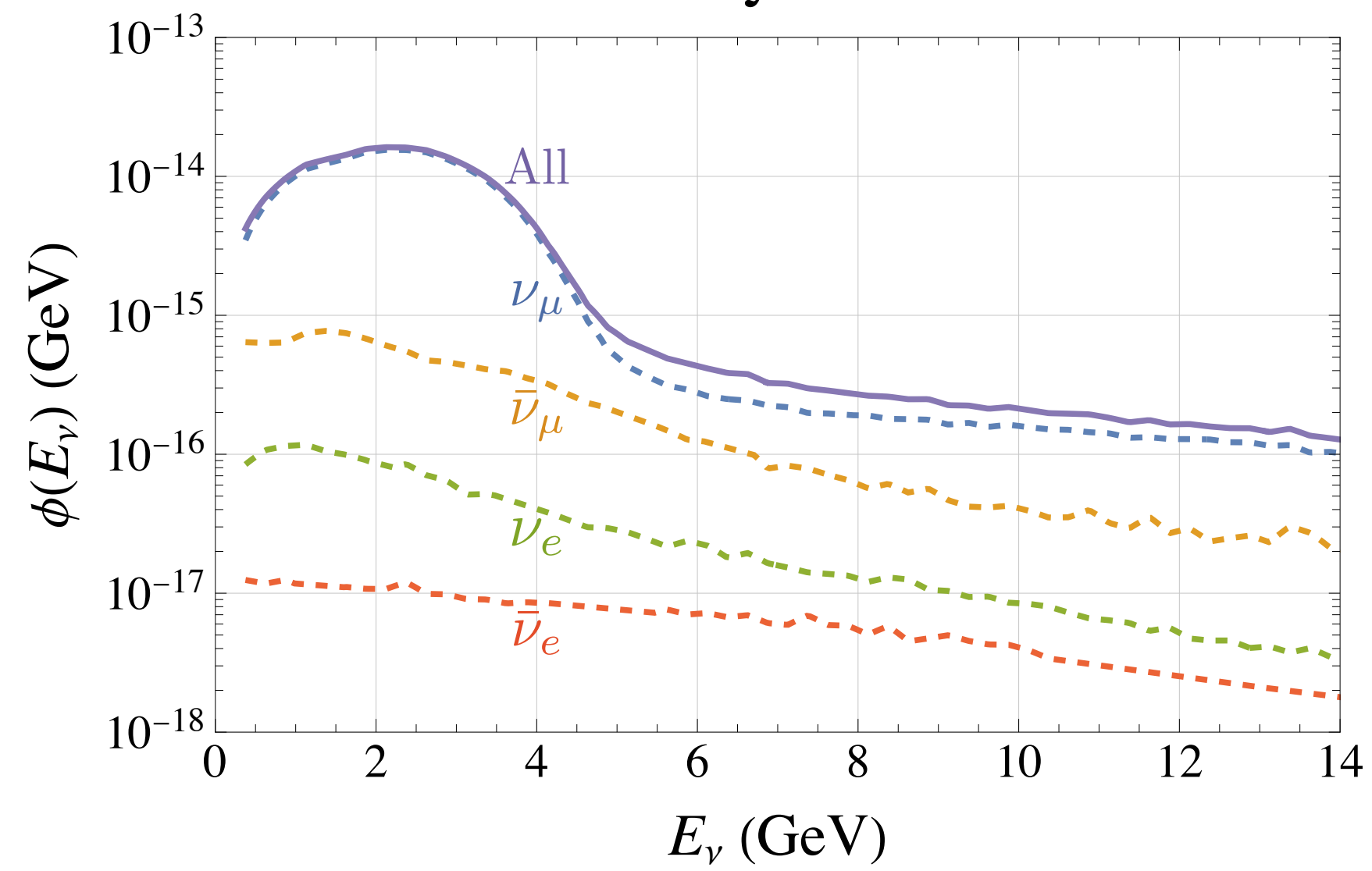
Three Energy regime:

- ♦ $|q^2| \ll m_\phi^2$: ϕ integrated out, EFT description.
- ♦ $q \sim m_\phi$: σ -interplay between q and m_ϕ .
- ♦ $|q^2| \gg m_\phi^2$: ϕ effectively massless, $\sigma \propto 1/q^2$.

Signal at DUNE-ND (1-EM)

Signal at DUNE-ND (1-EM)

1 year

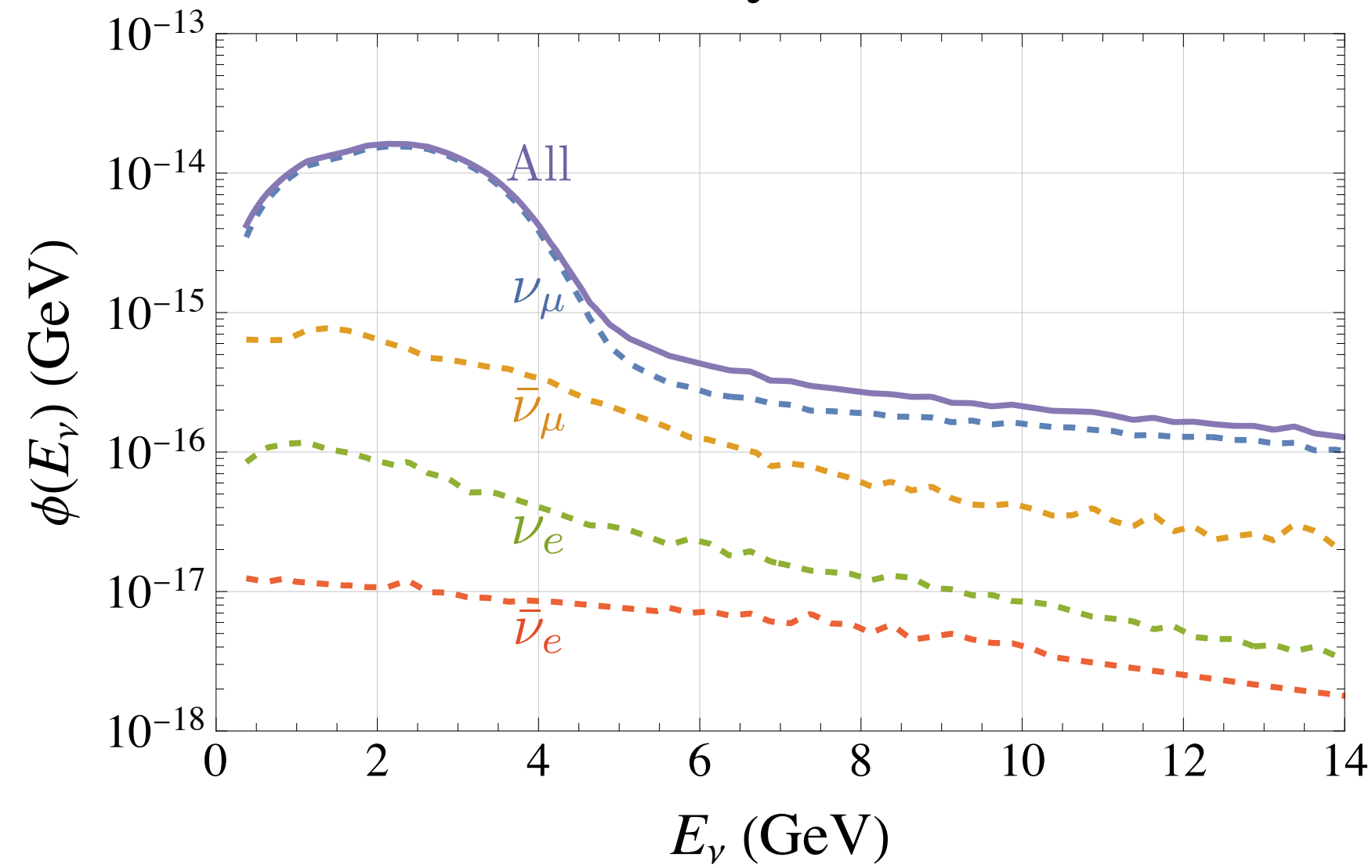


The ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ fluxes at ND

[DUNE collaboration - Abi, et. al., arXiv: 2103.04797]

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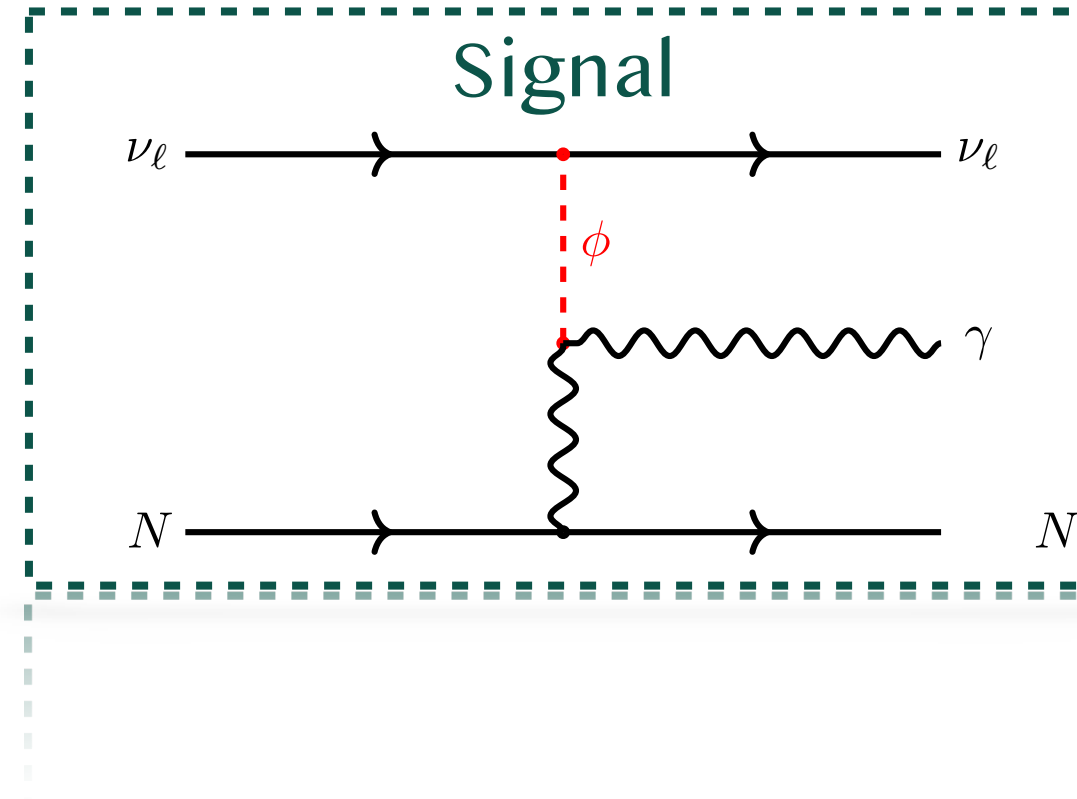
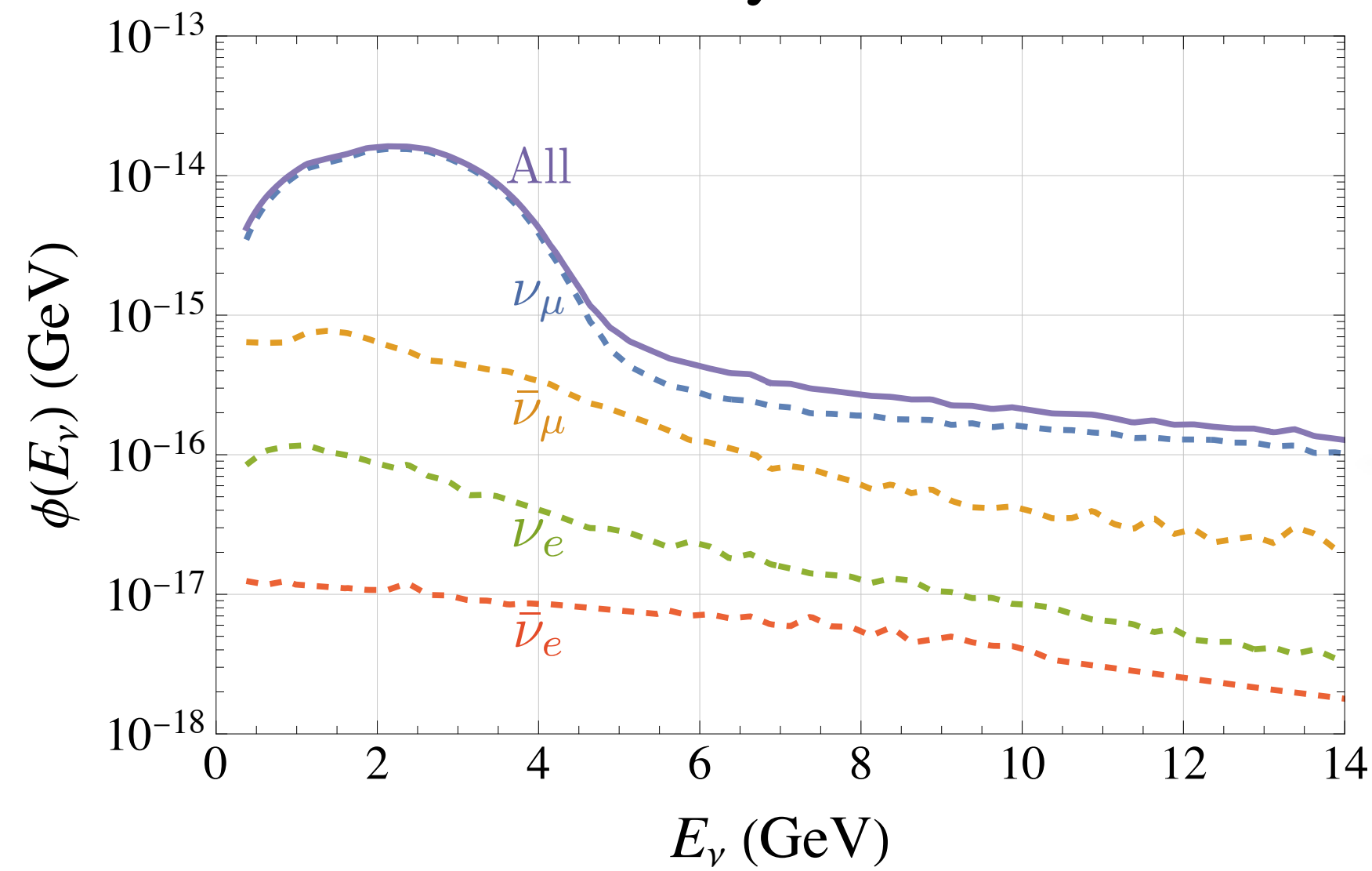
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Energy threshold and angular resolution:

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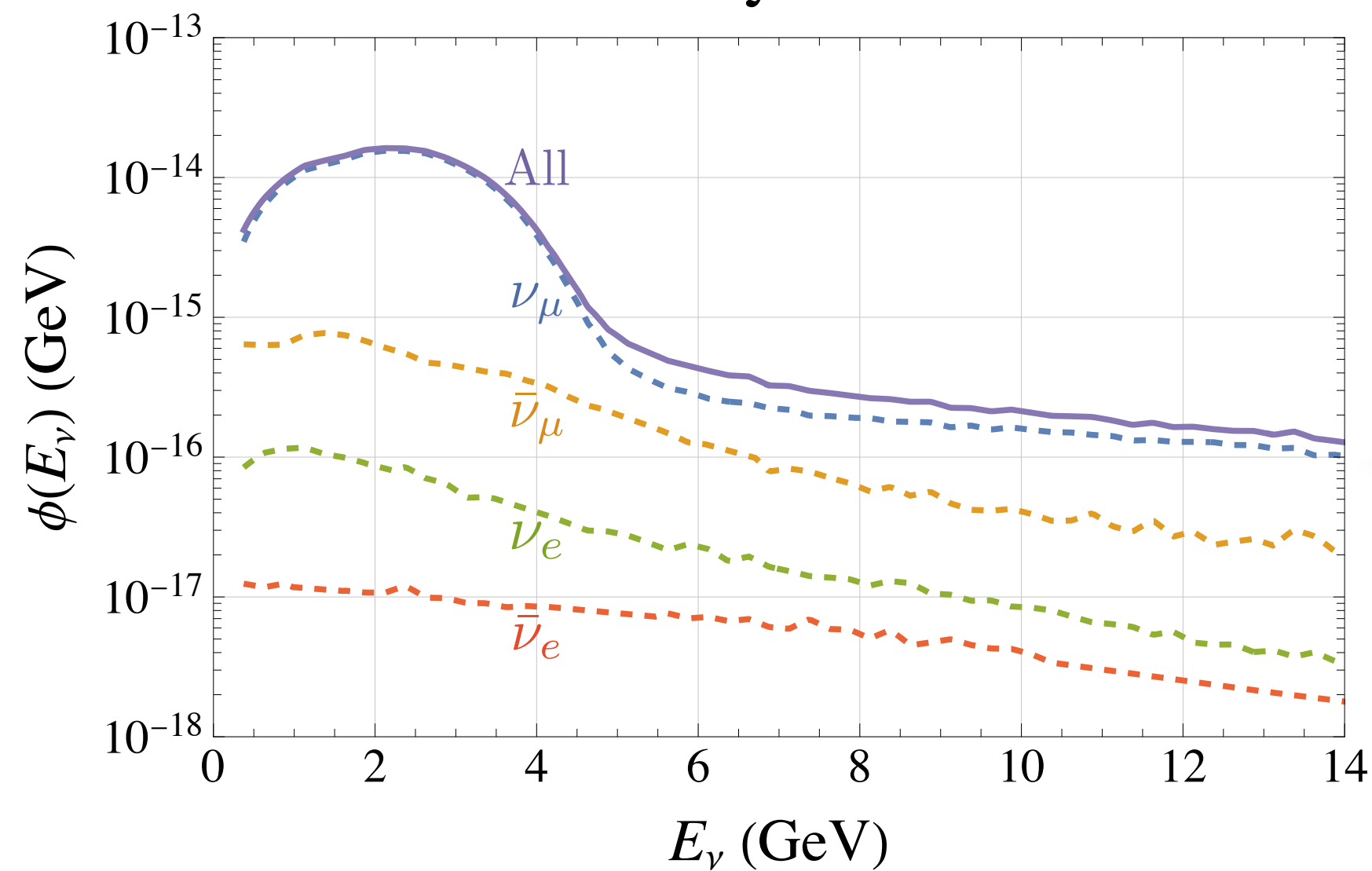
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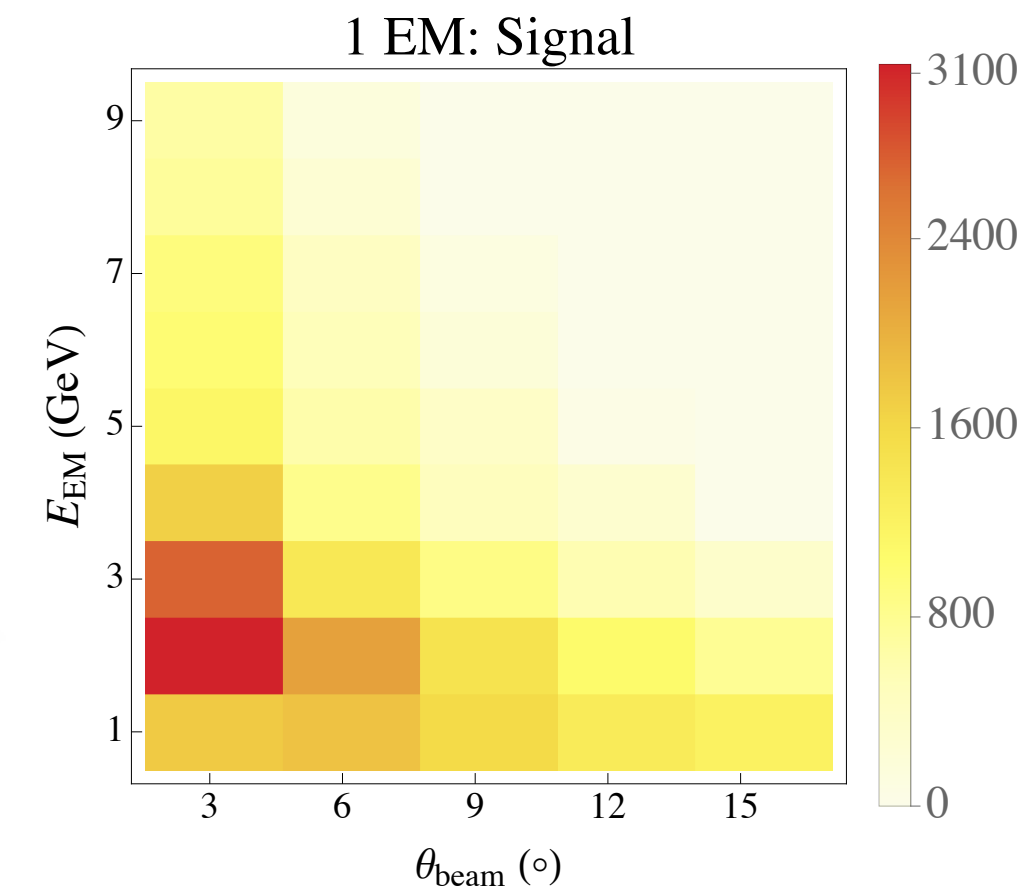
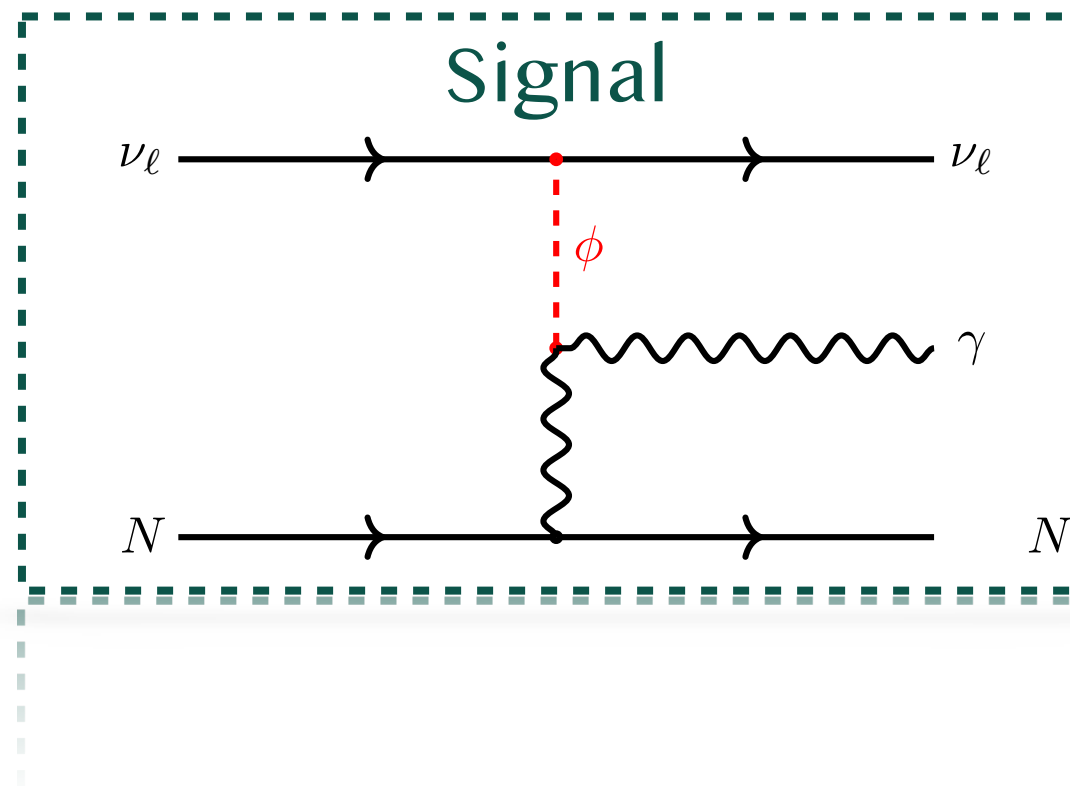
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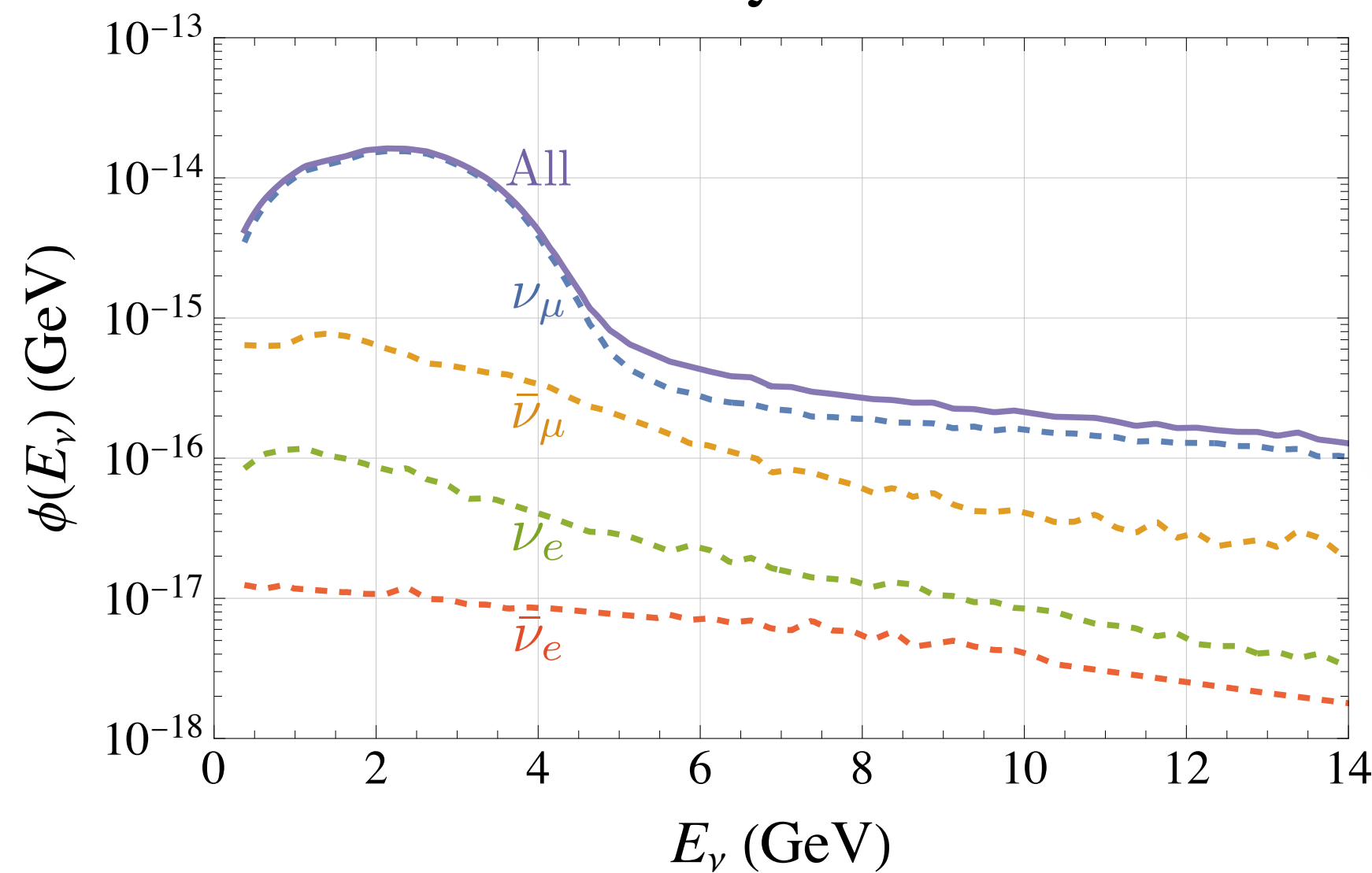
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Kinematical distributions for the 1EM shower topology
[Carey, Machado, Paz, Petrov, Sousa, Tammaro and Zupan, 2508.16724]

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1 year

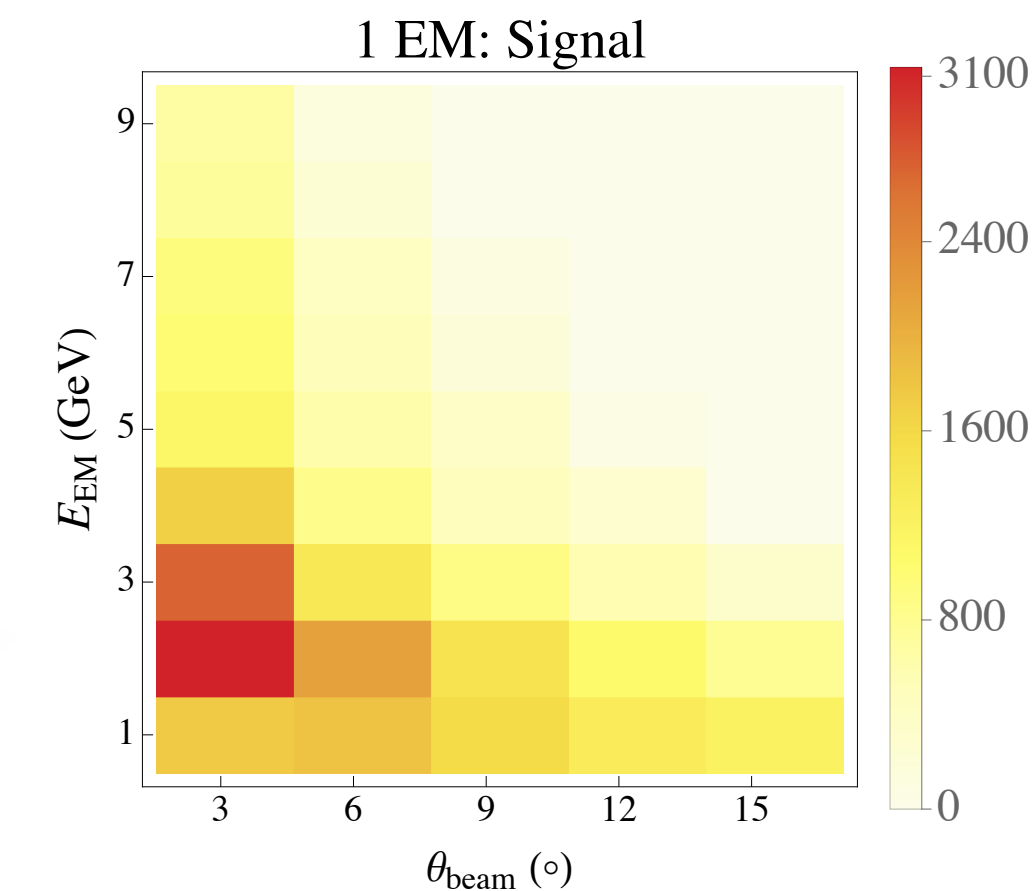
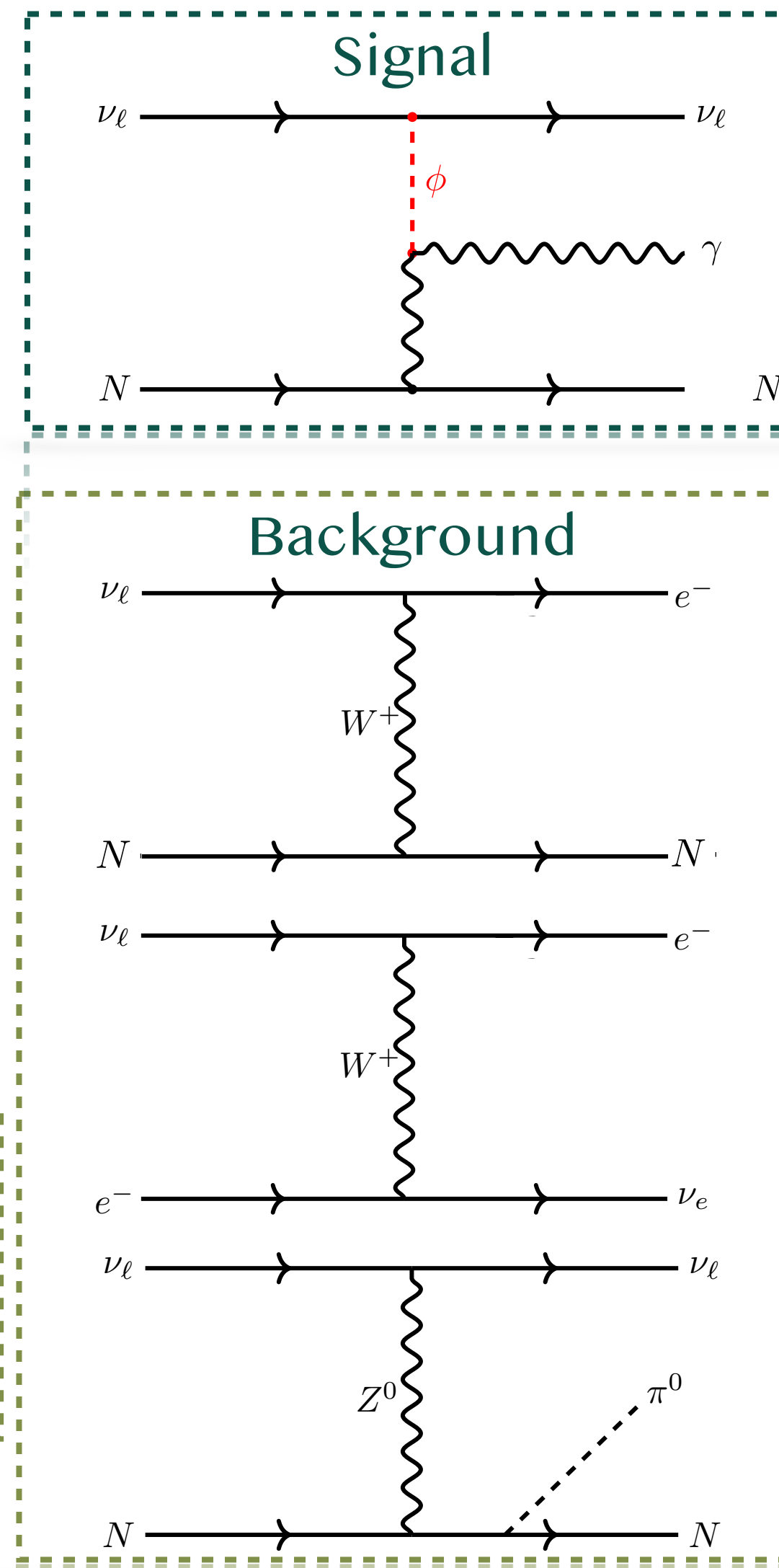


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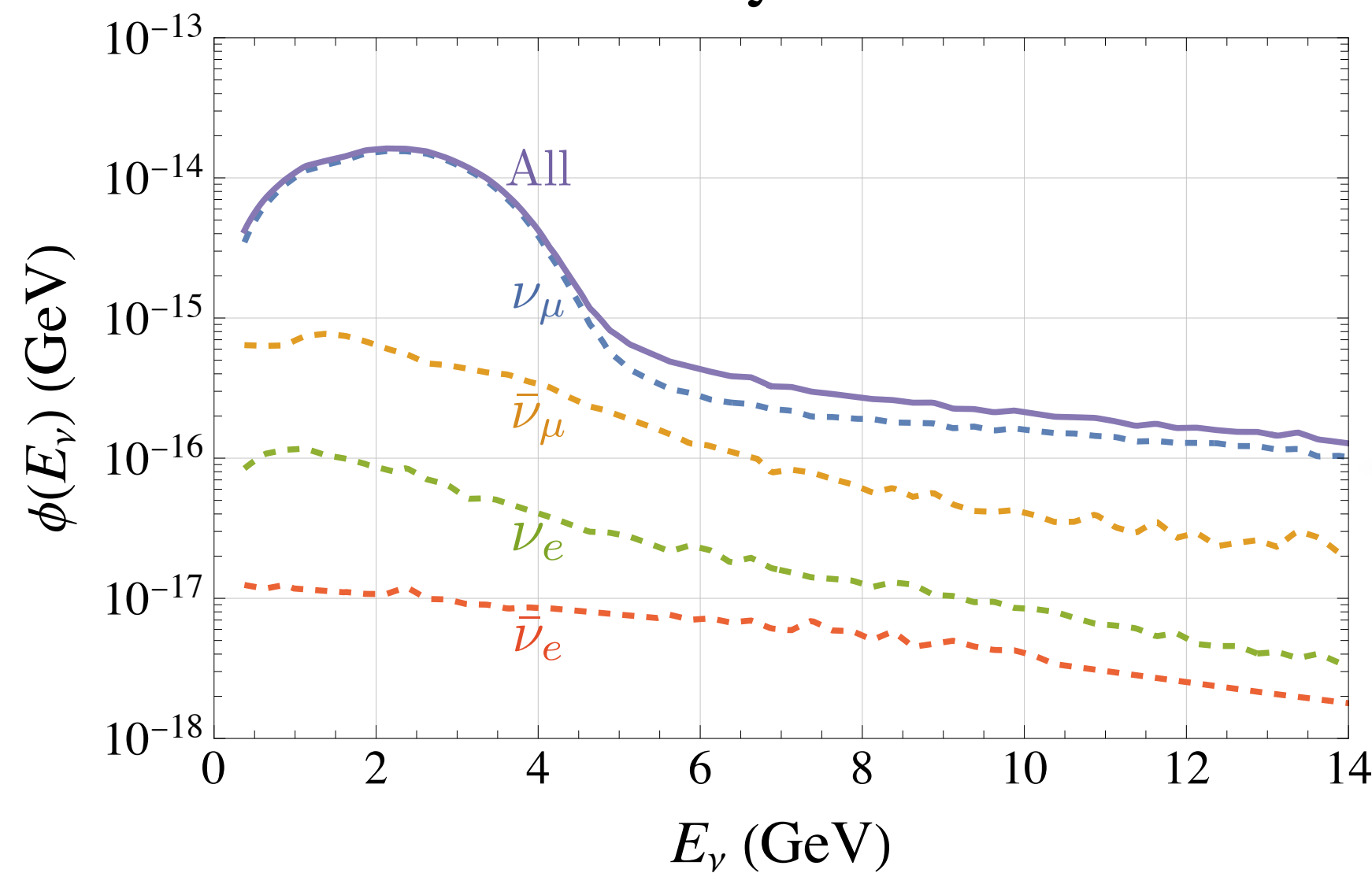
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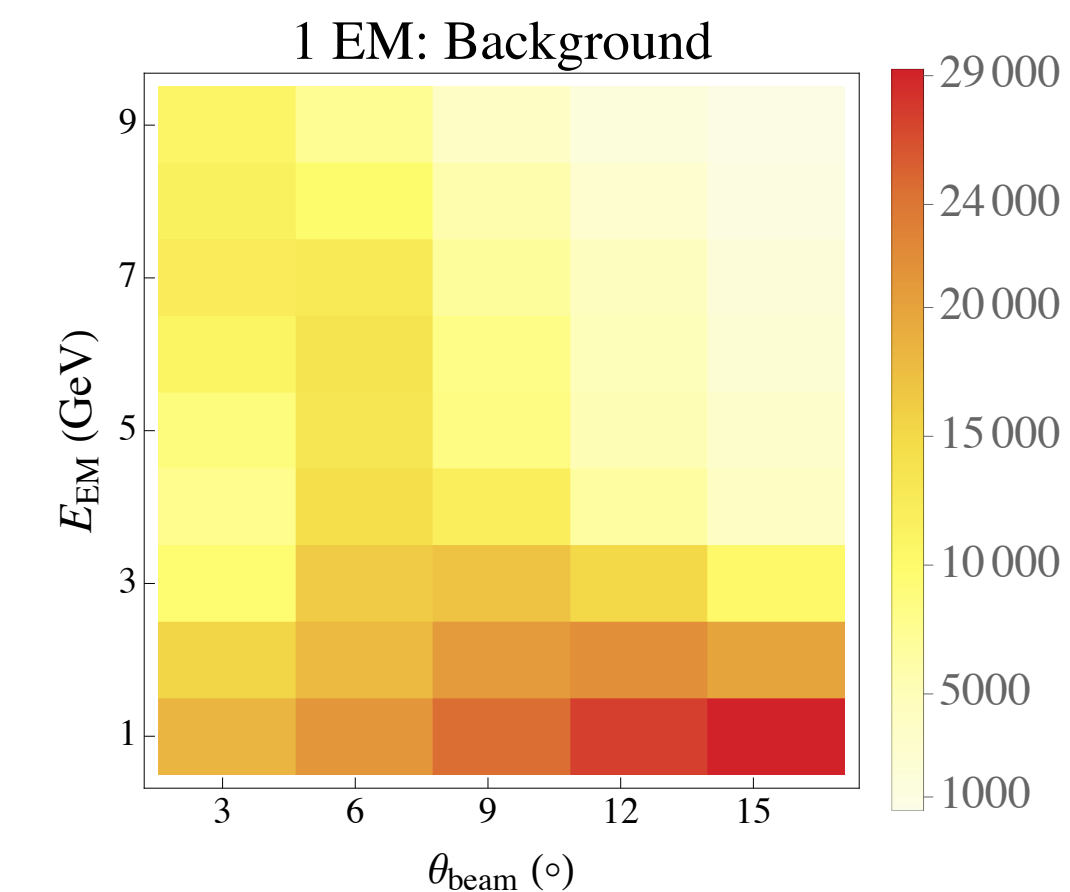
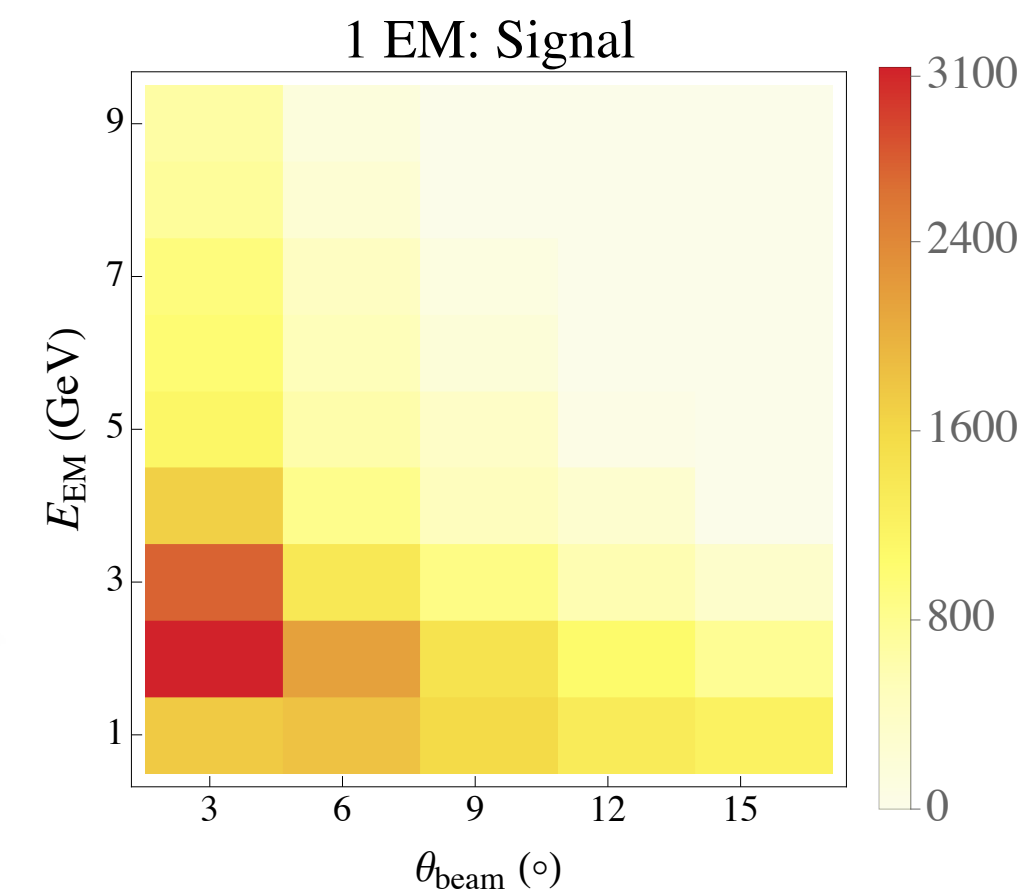
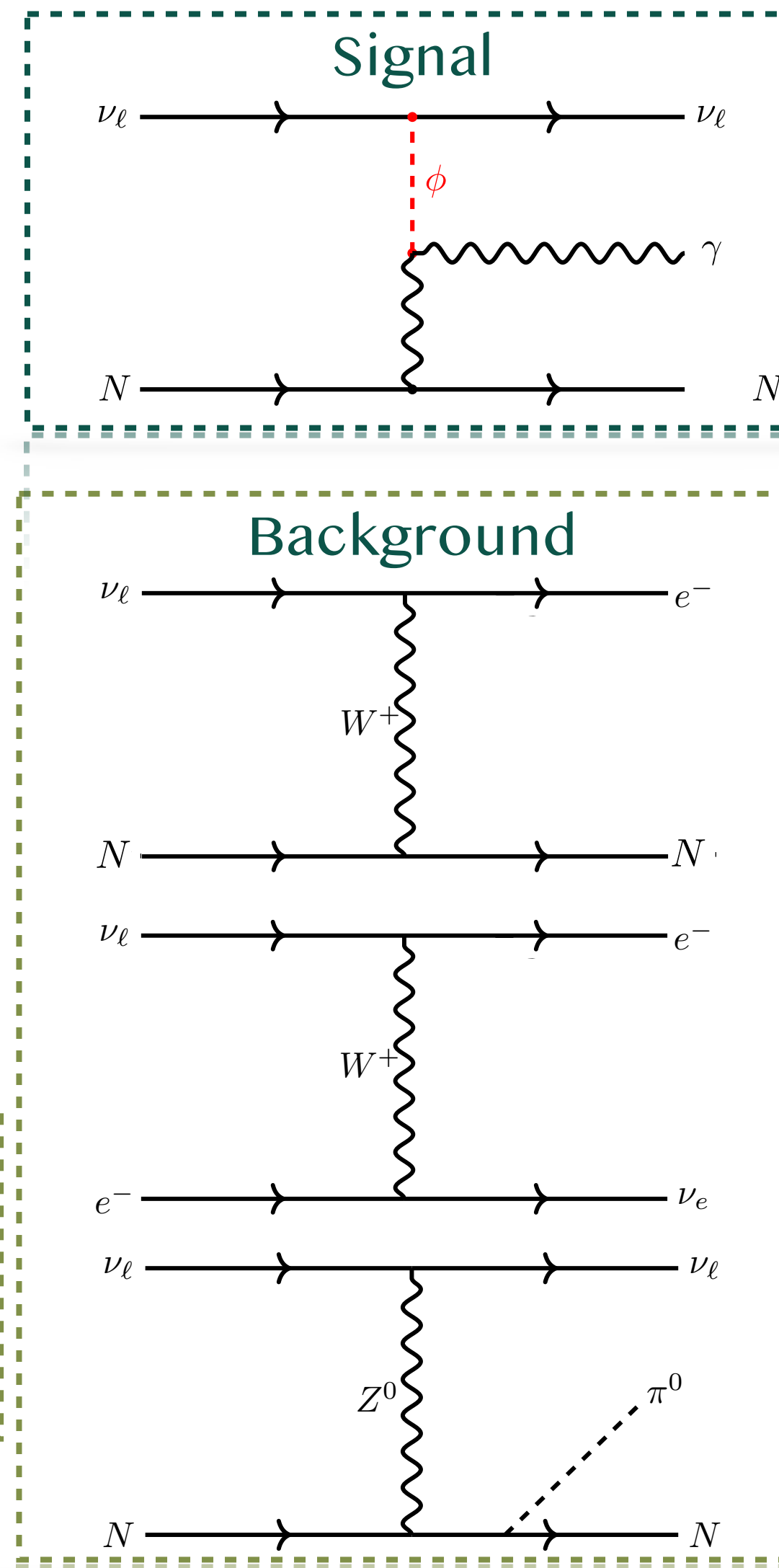
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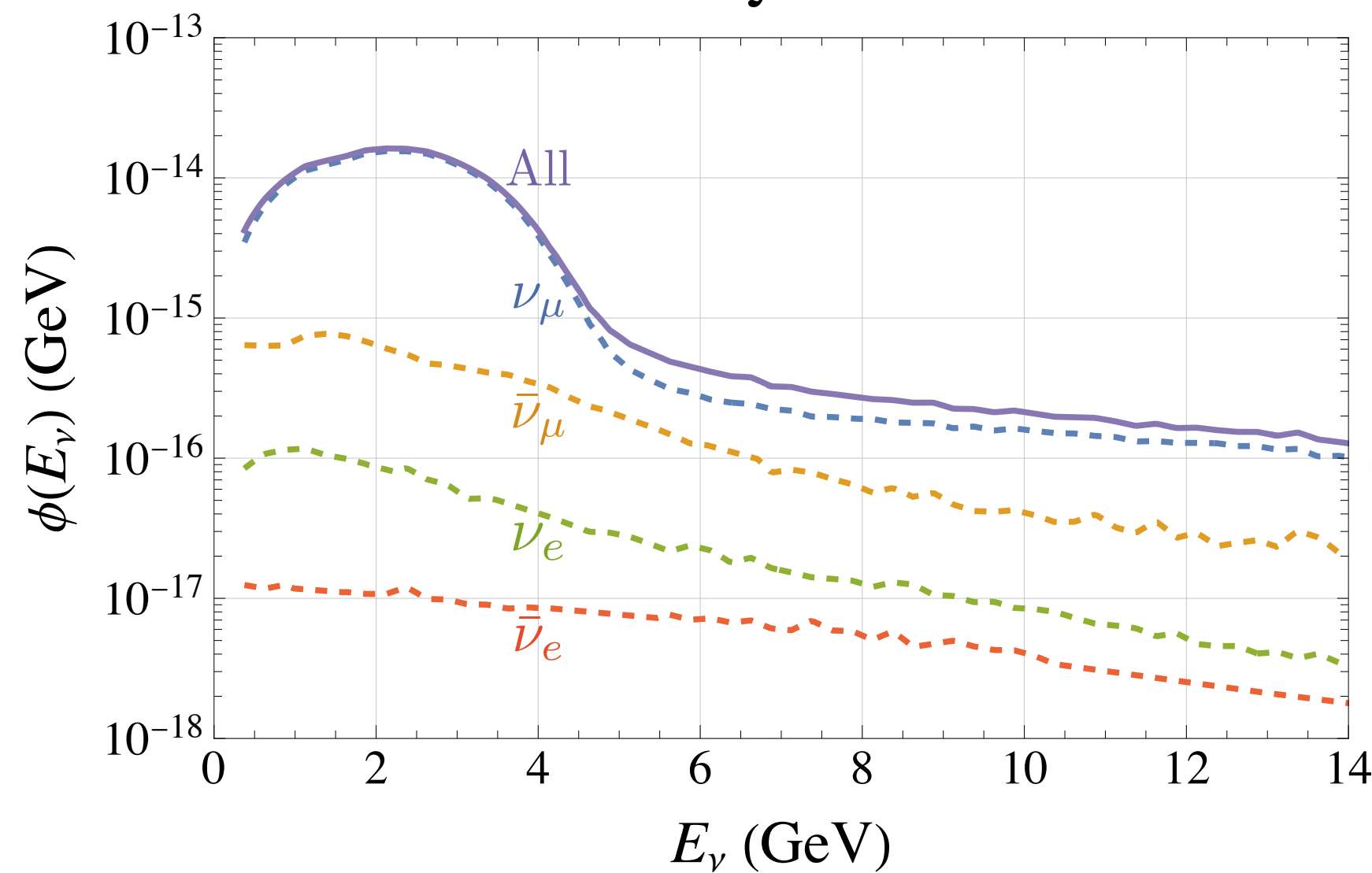
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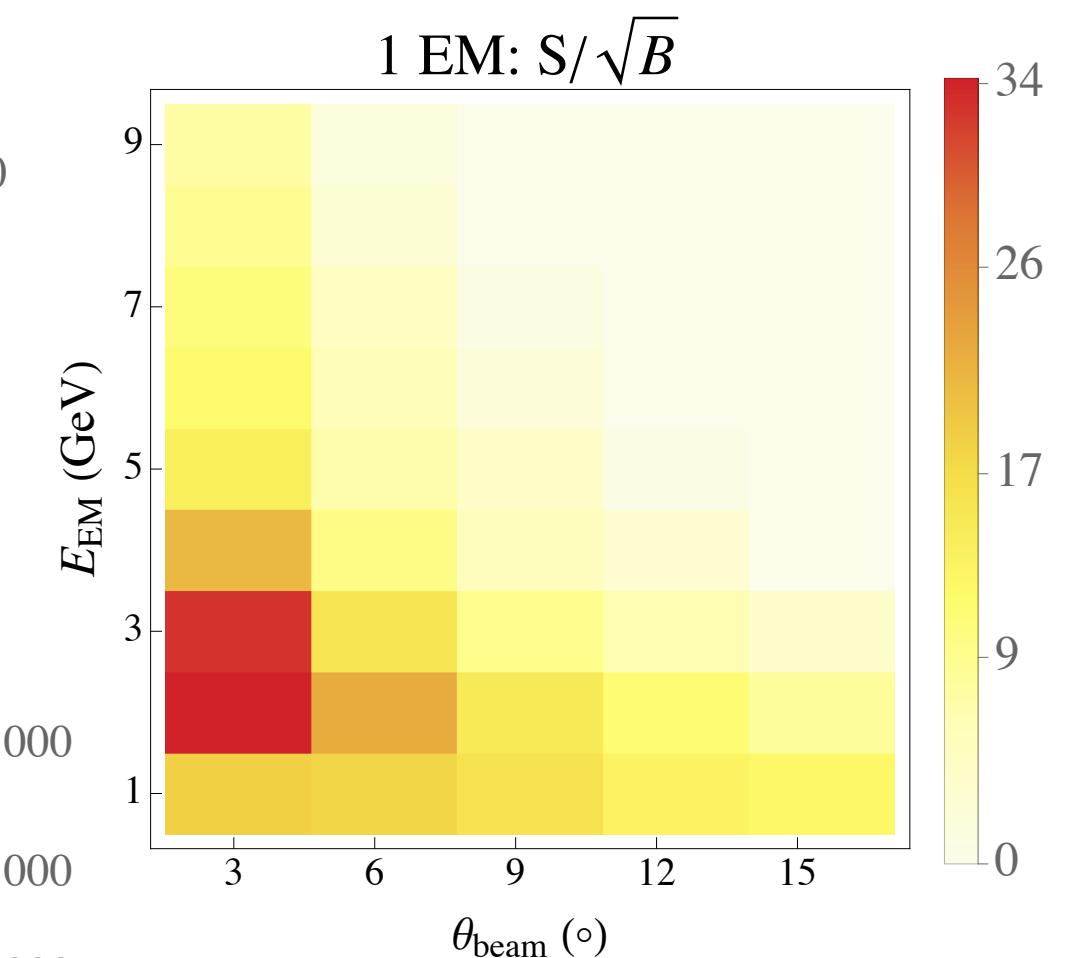
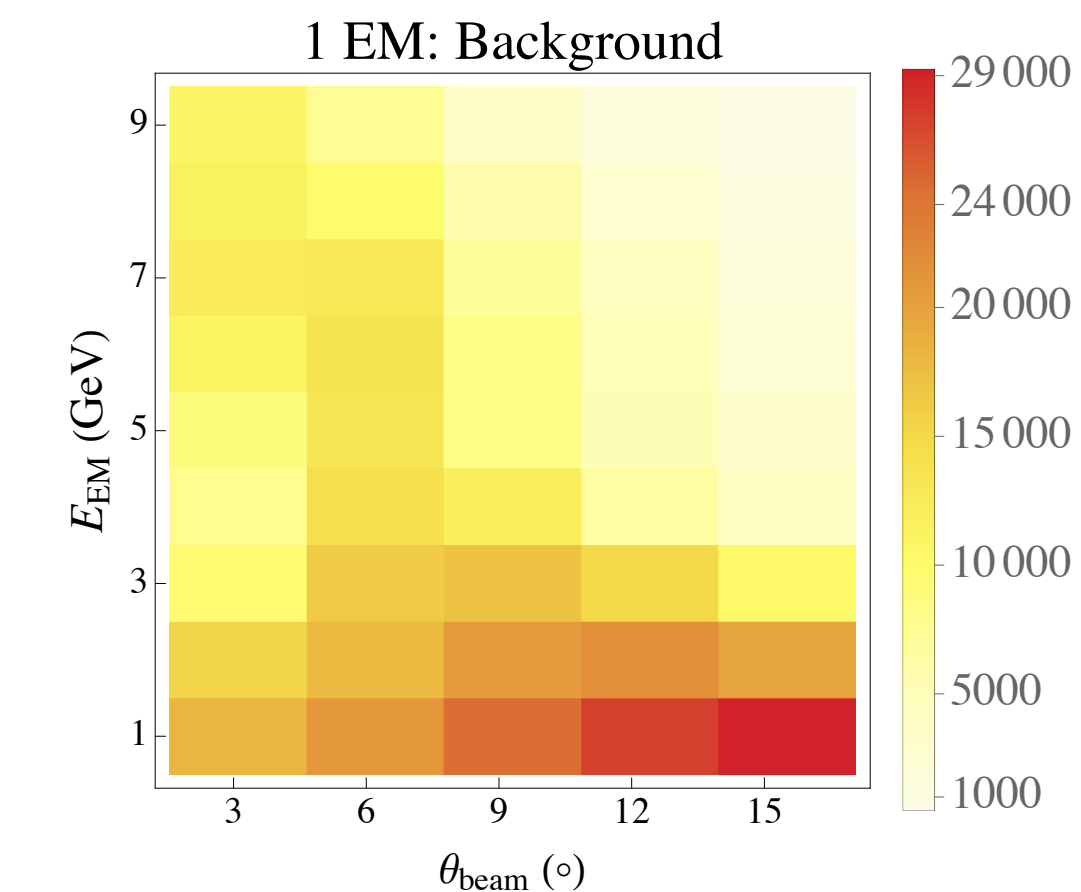
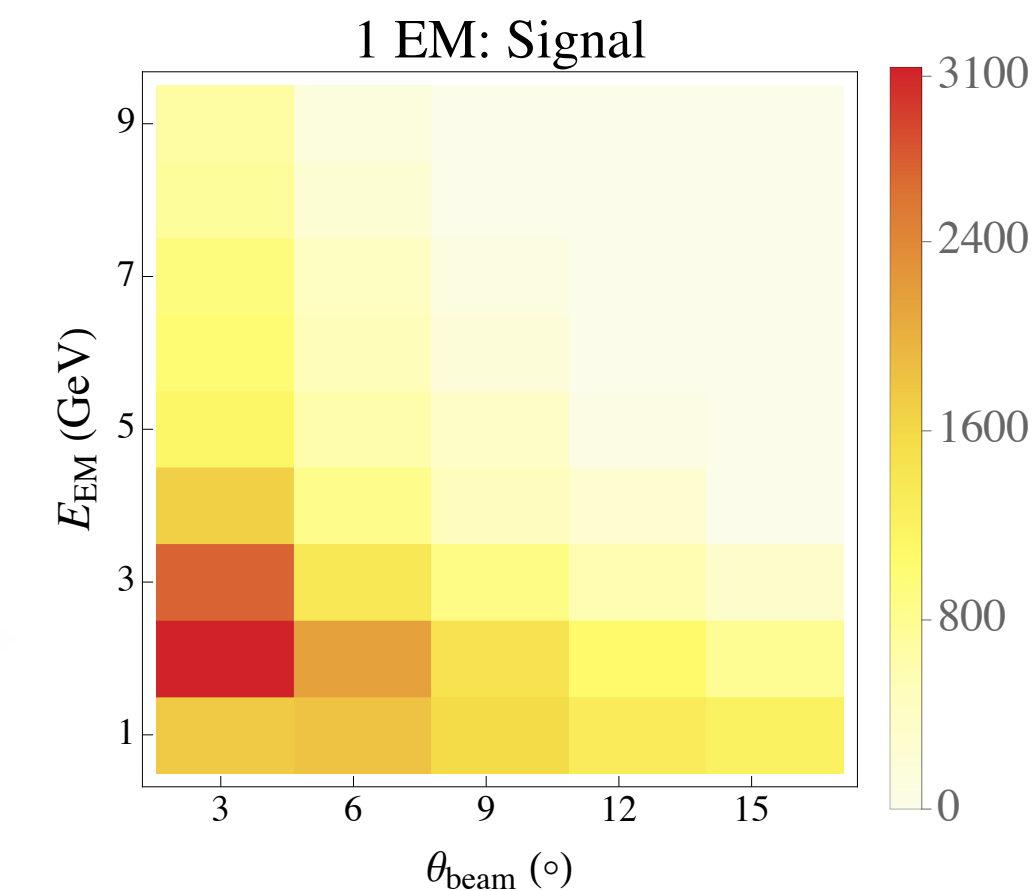
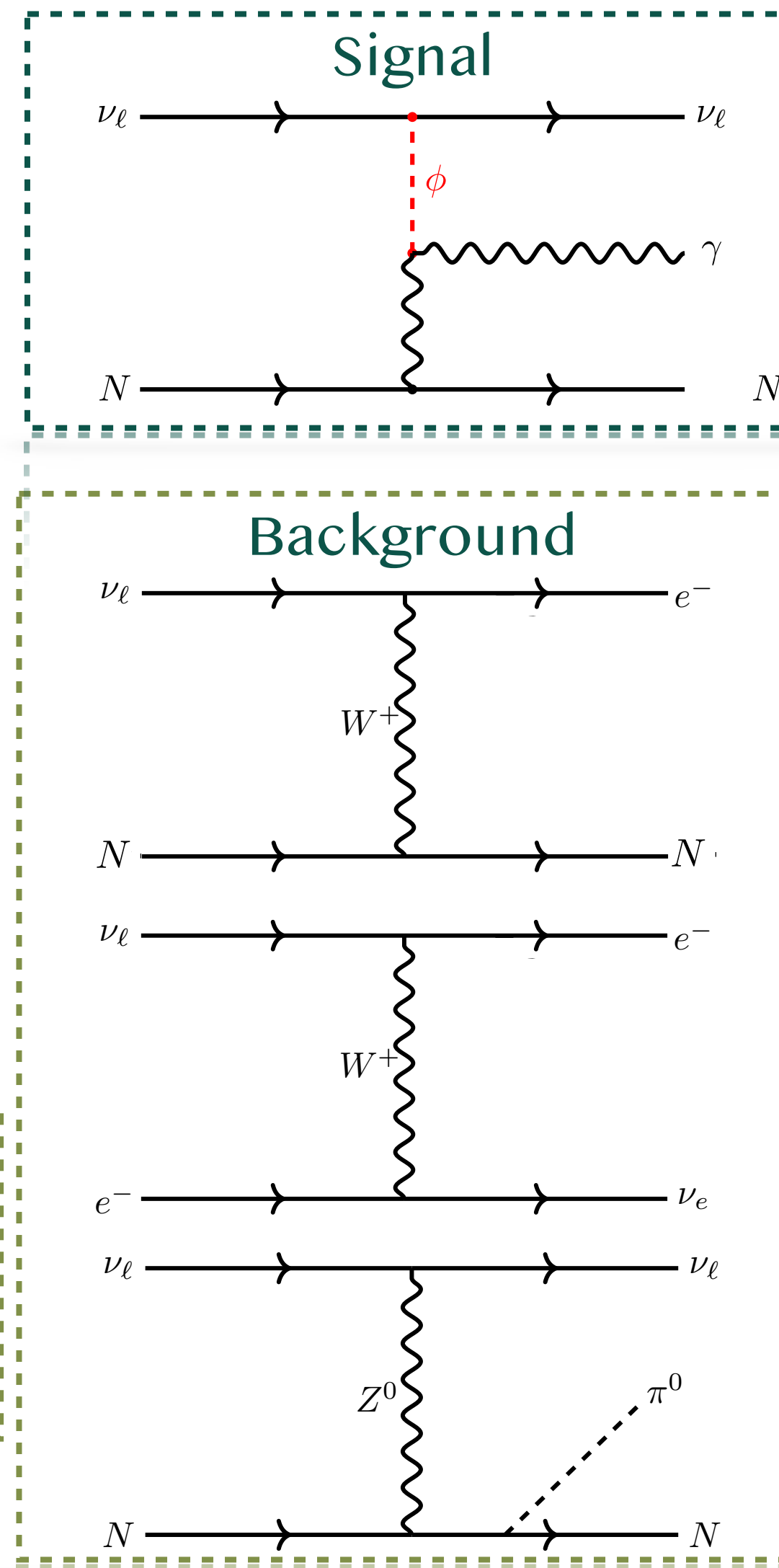


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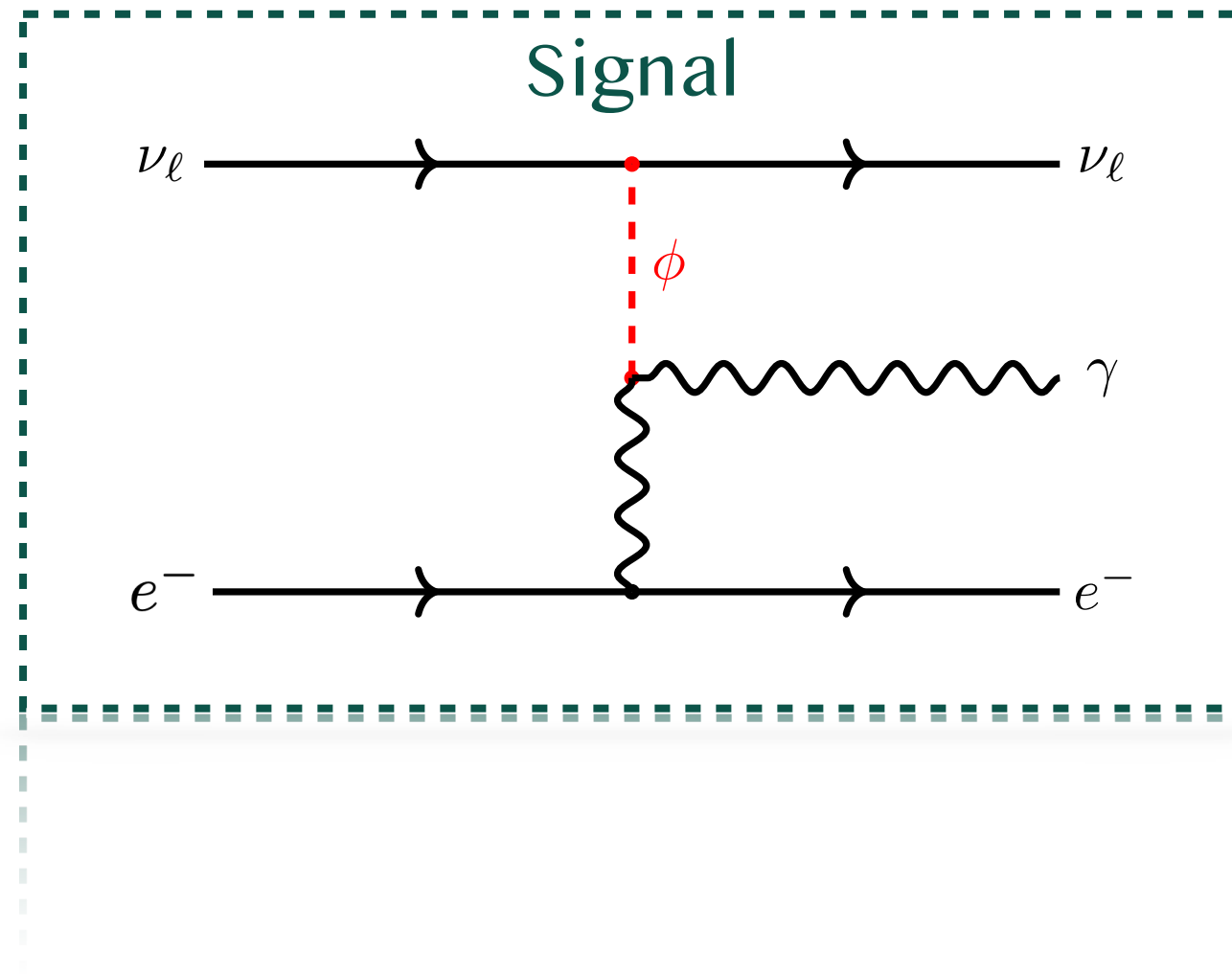
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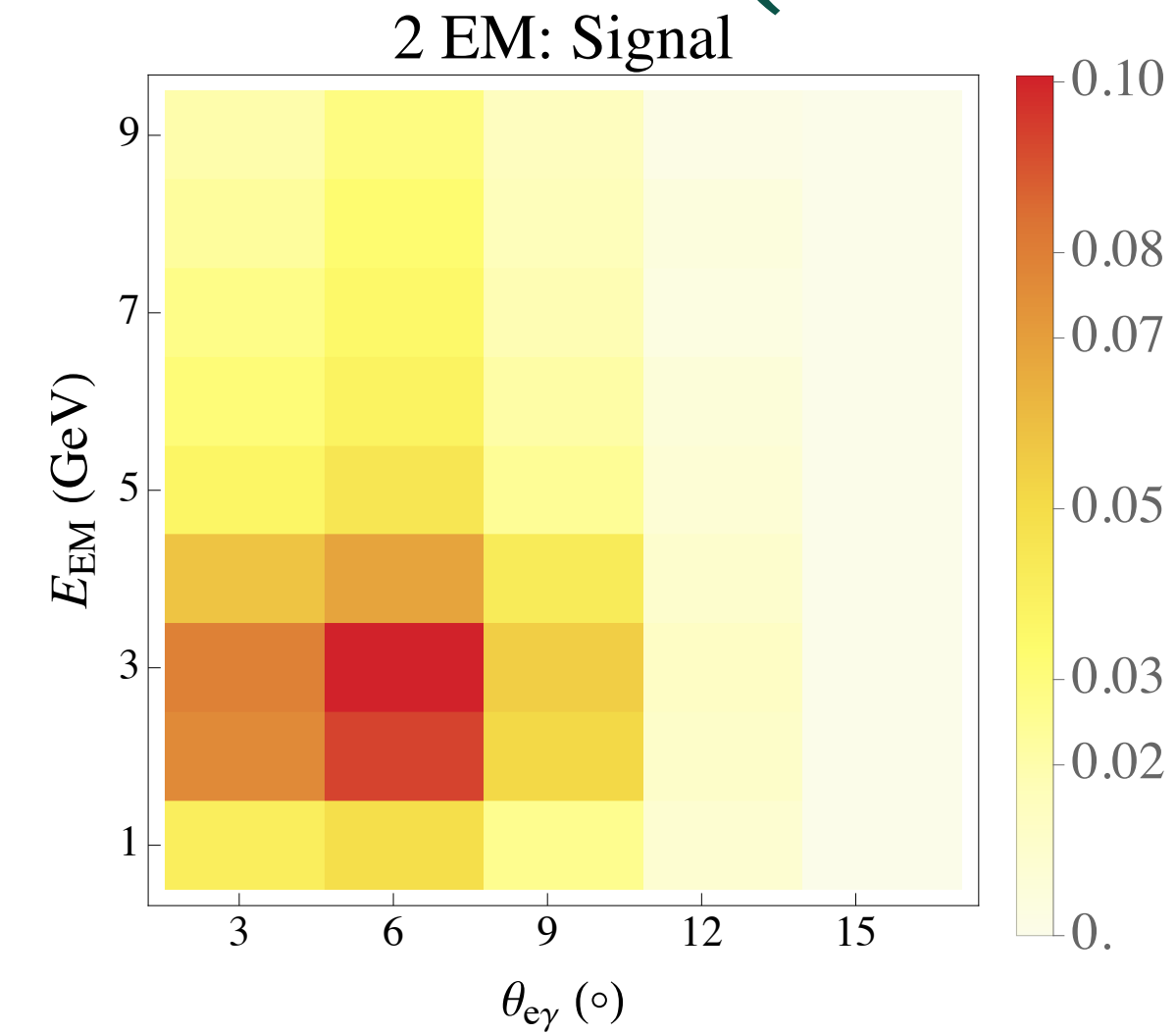
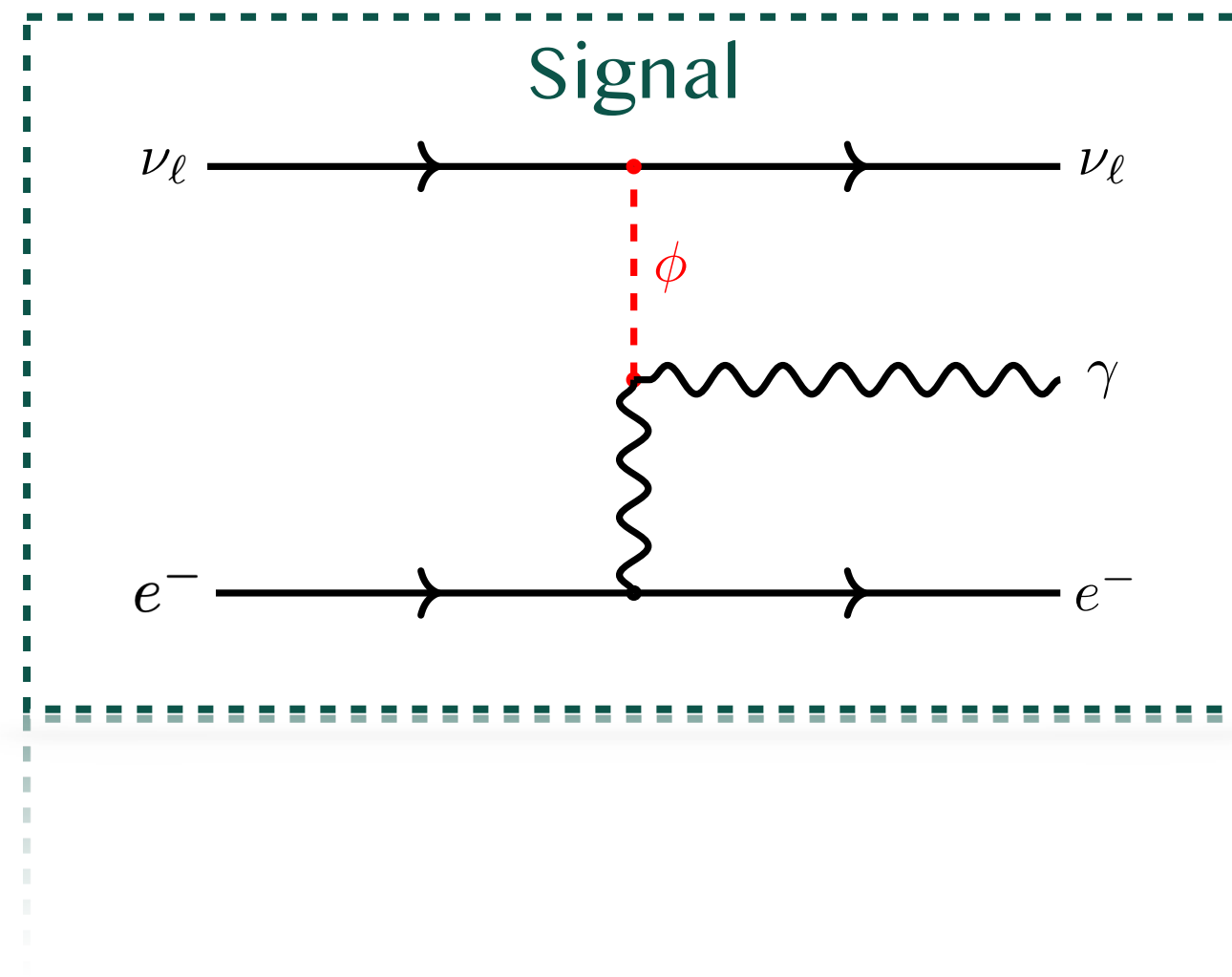
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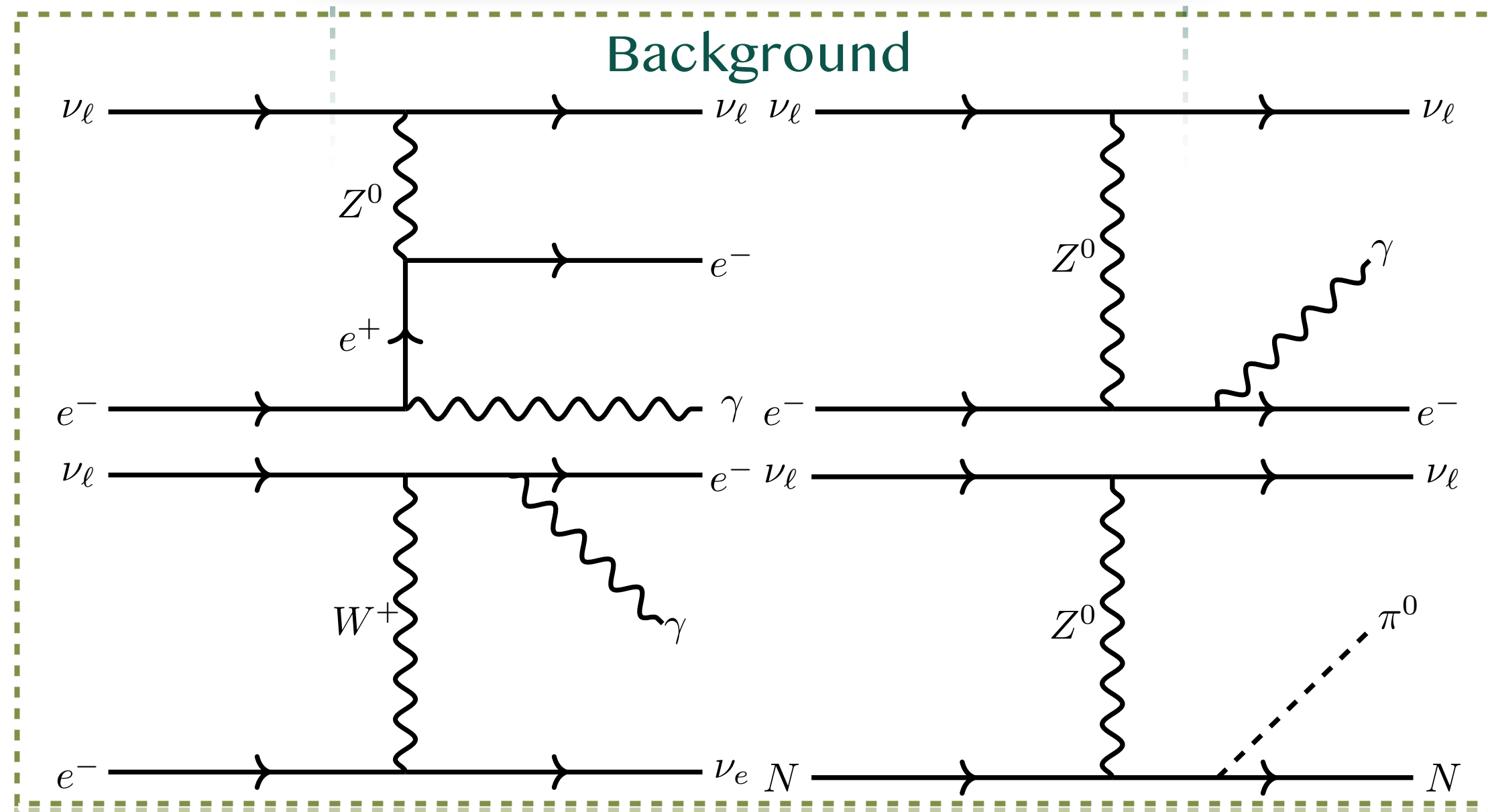
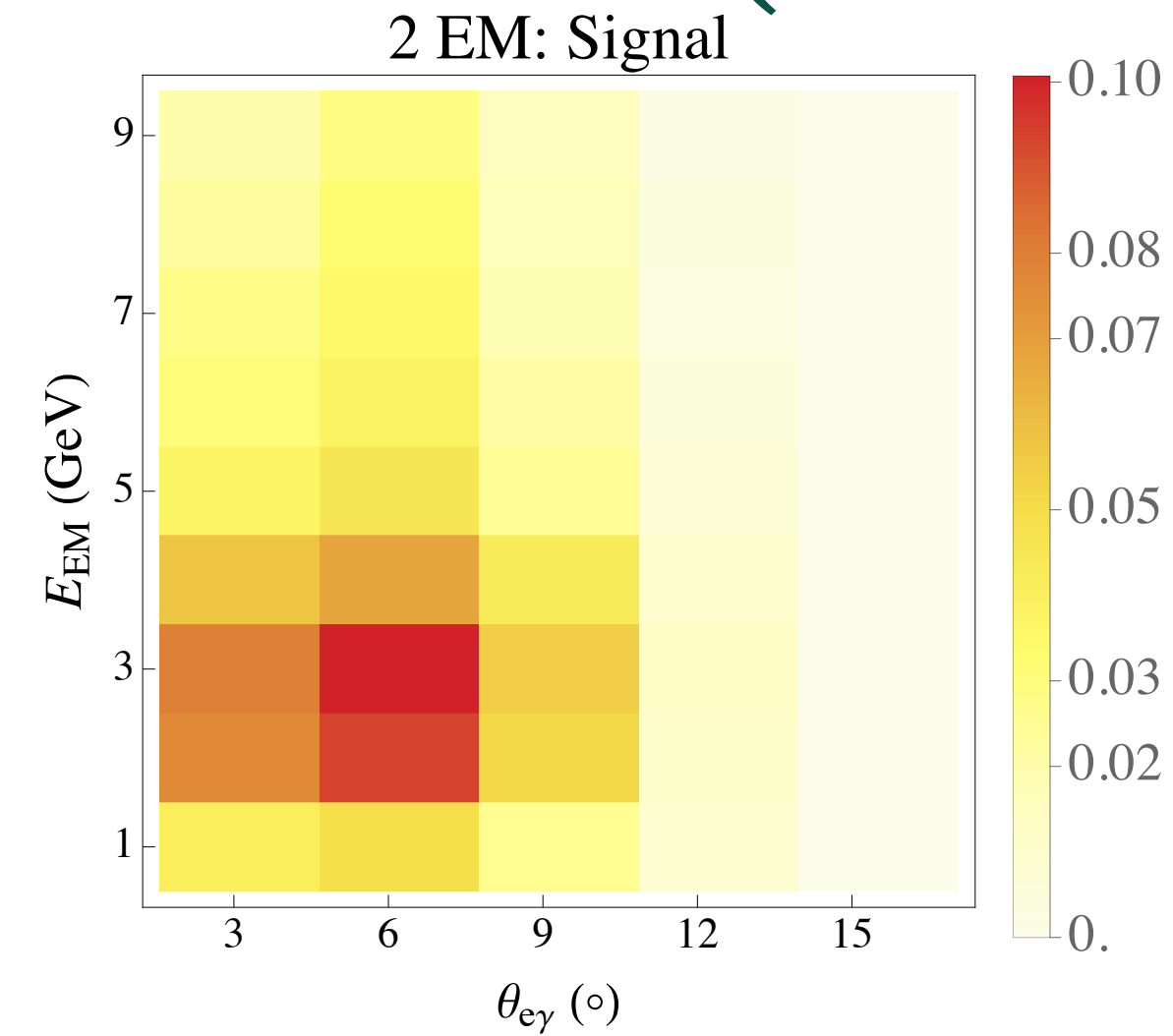
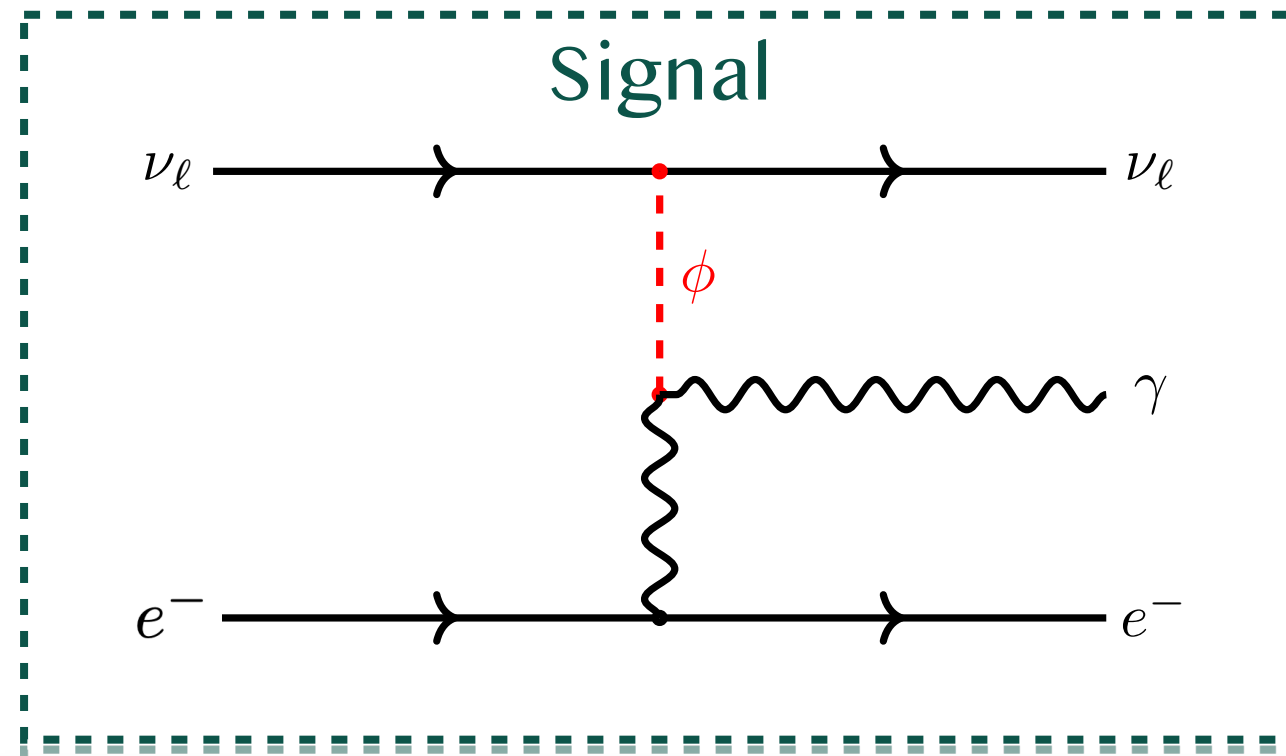


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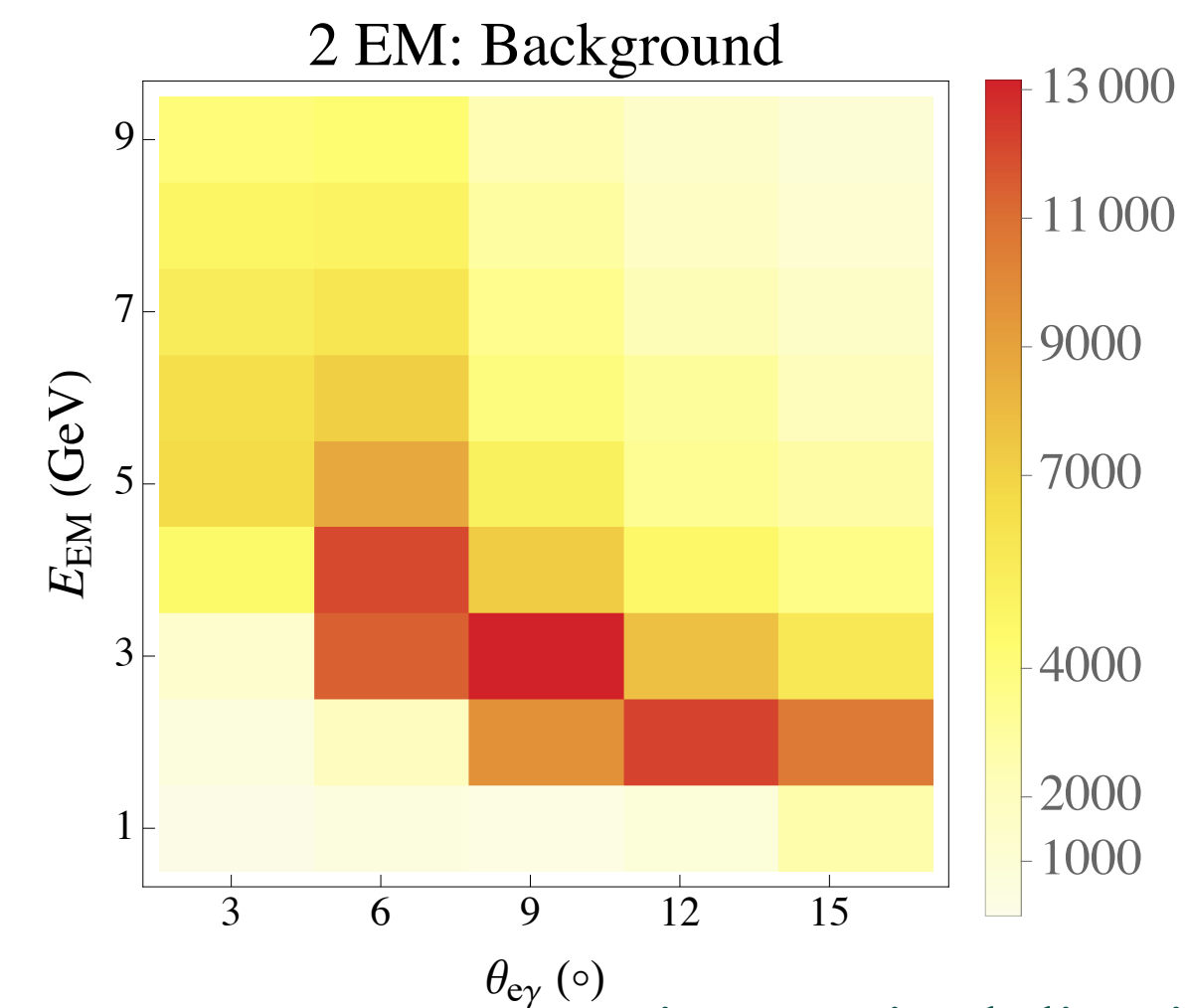
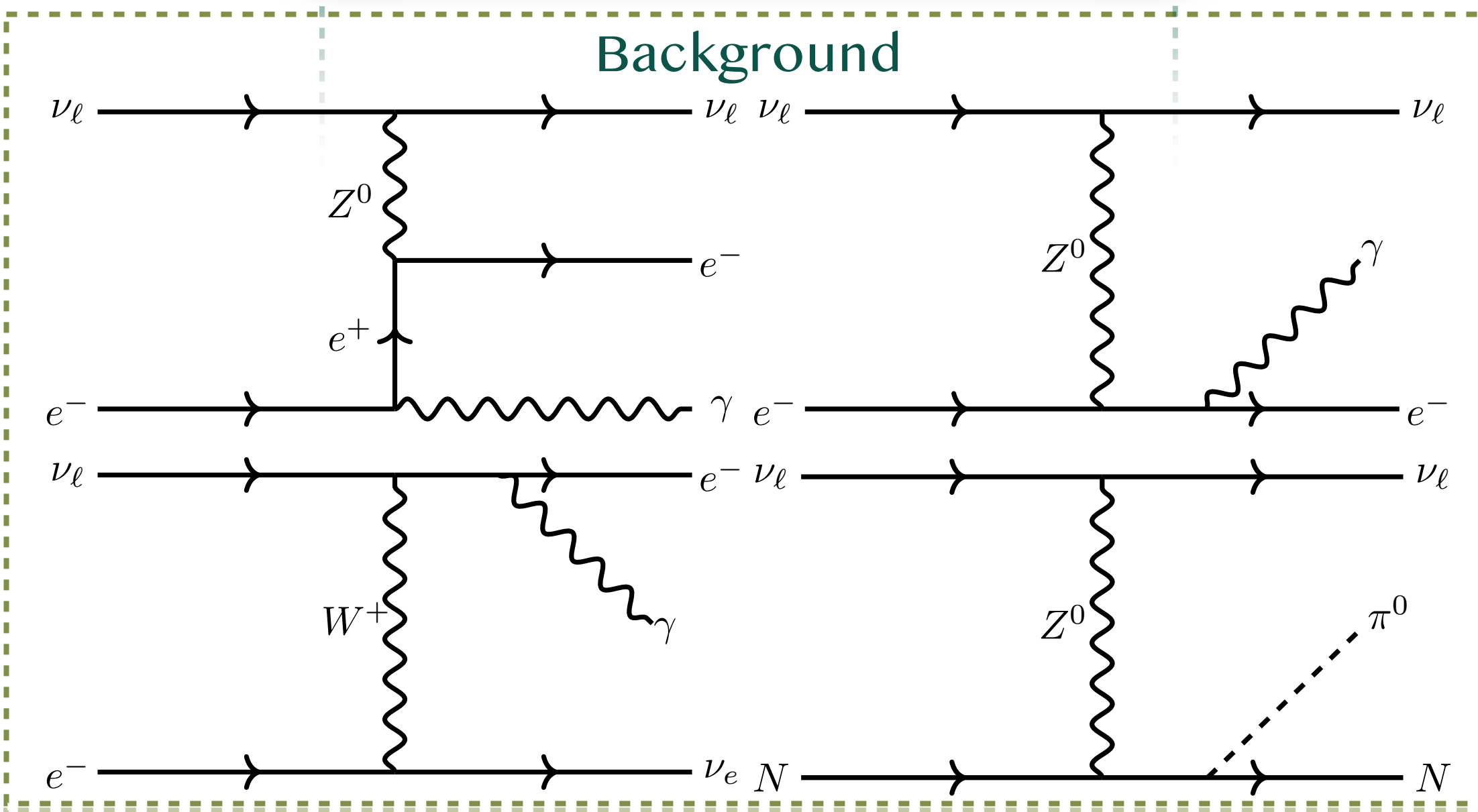
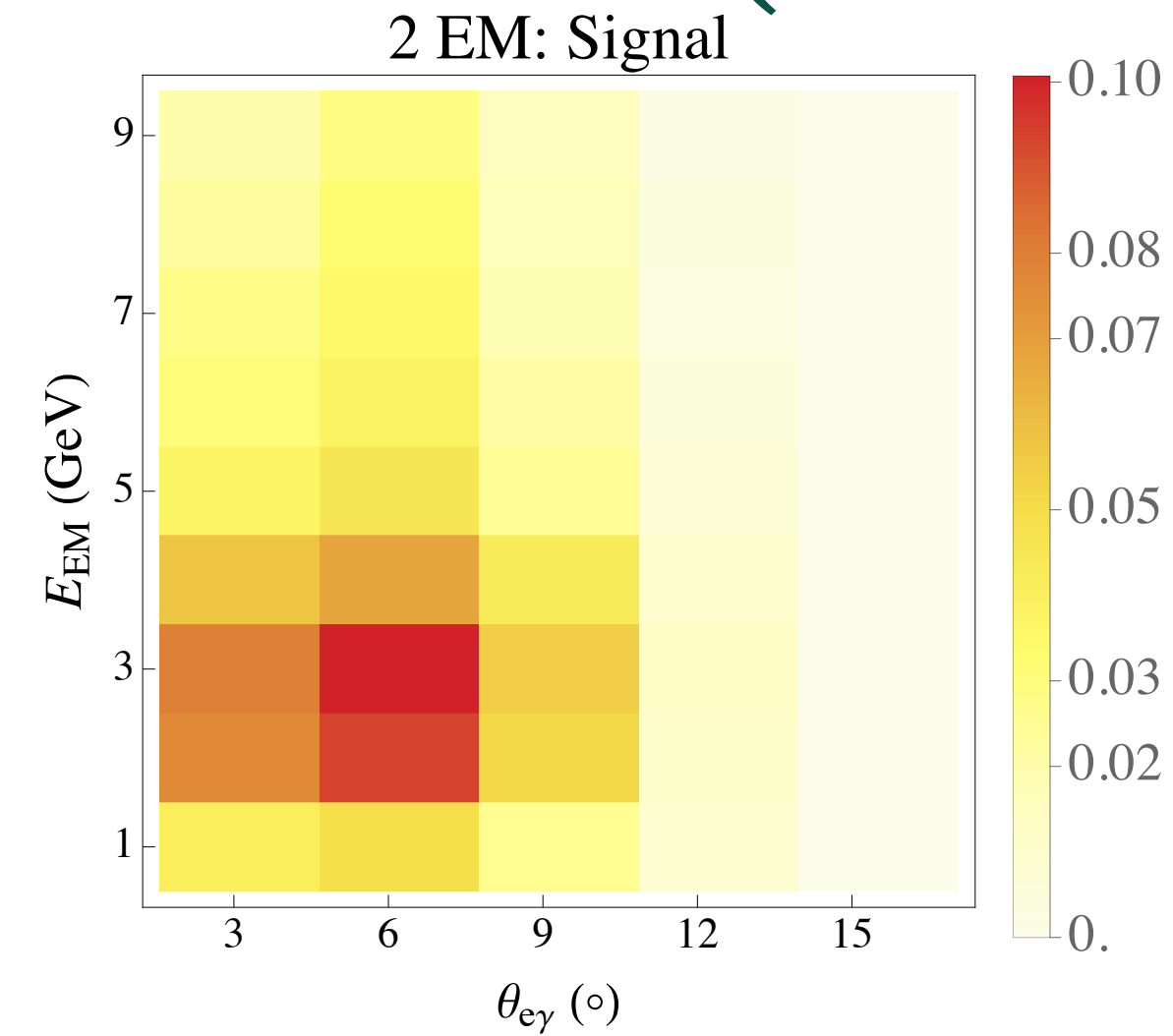
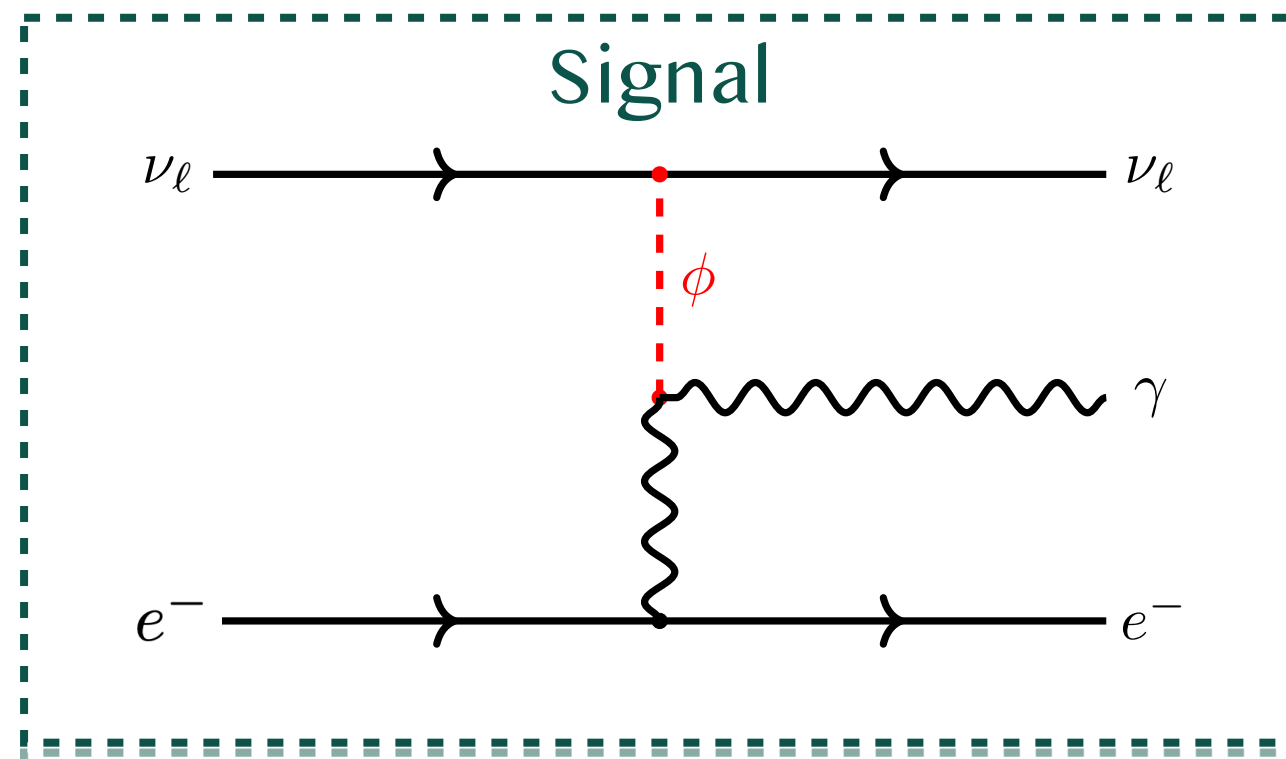
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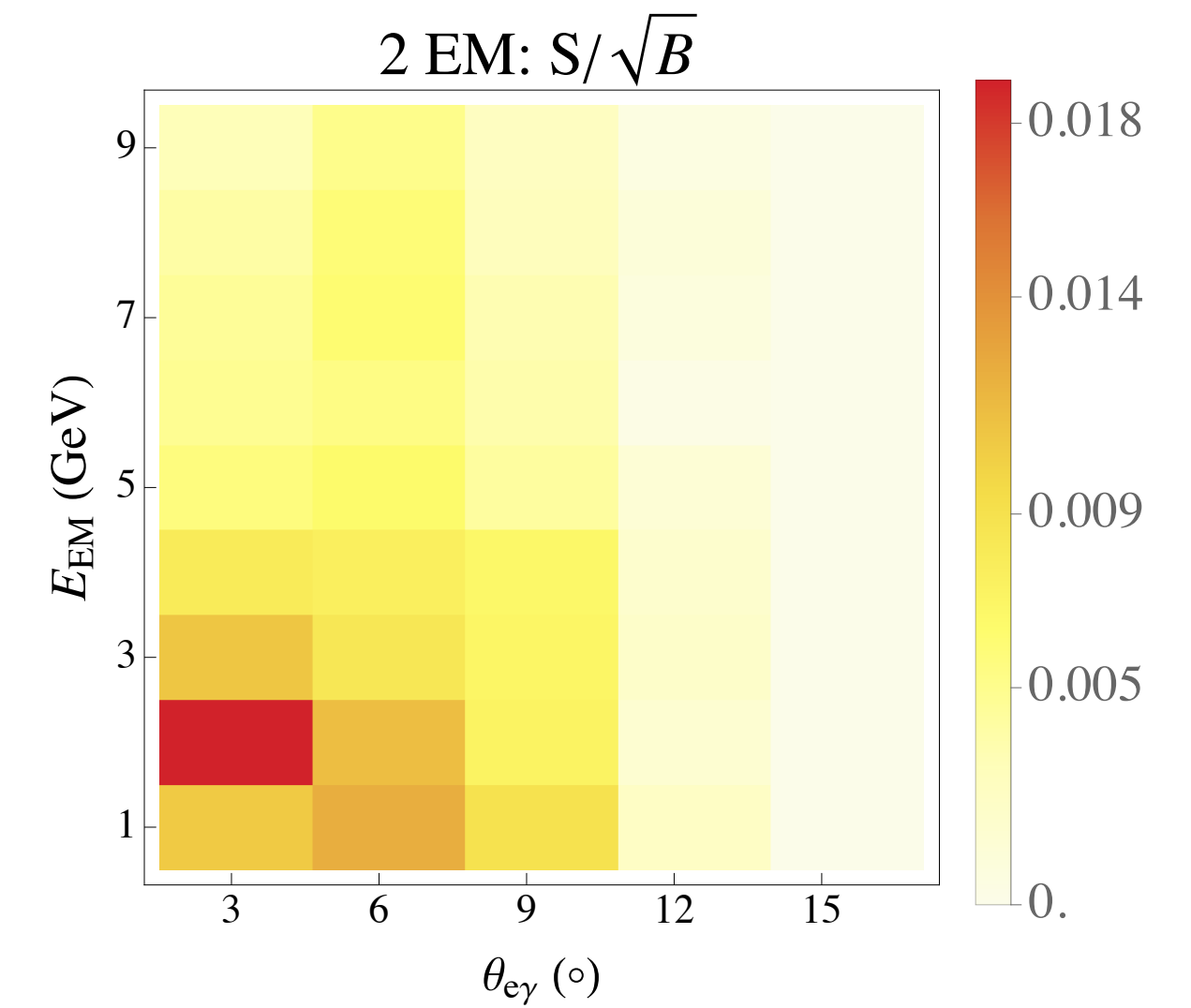
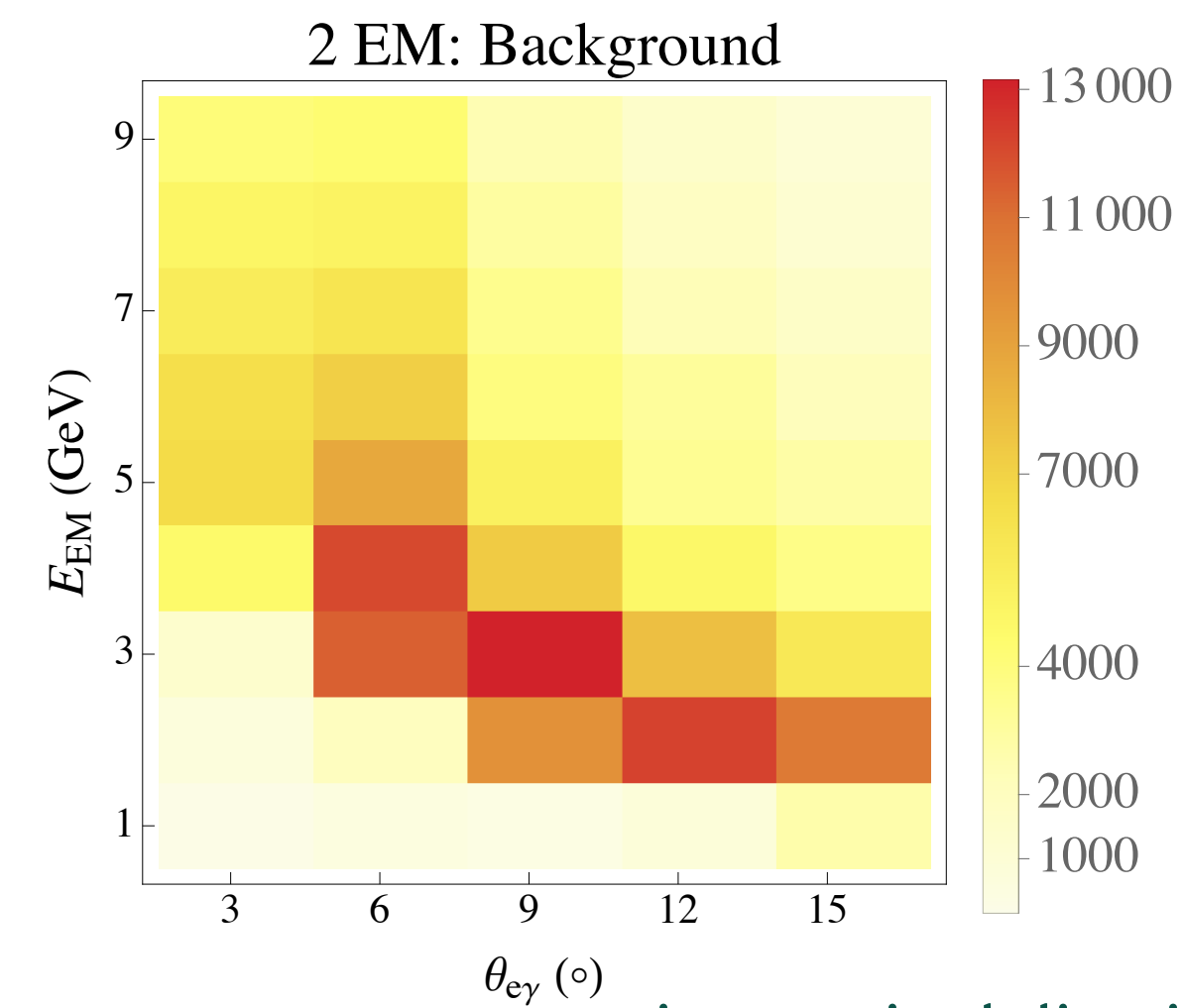
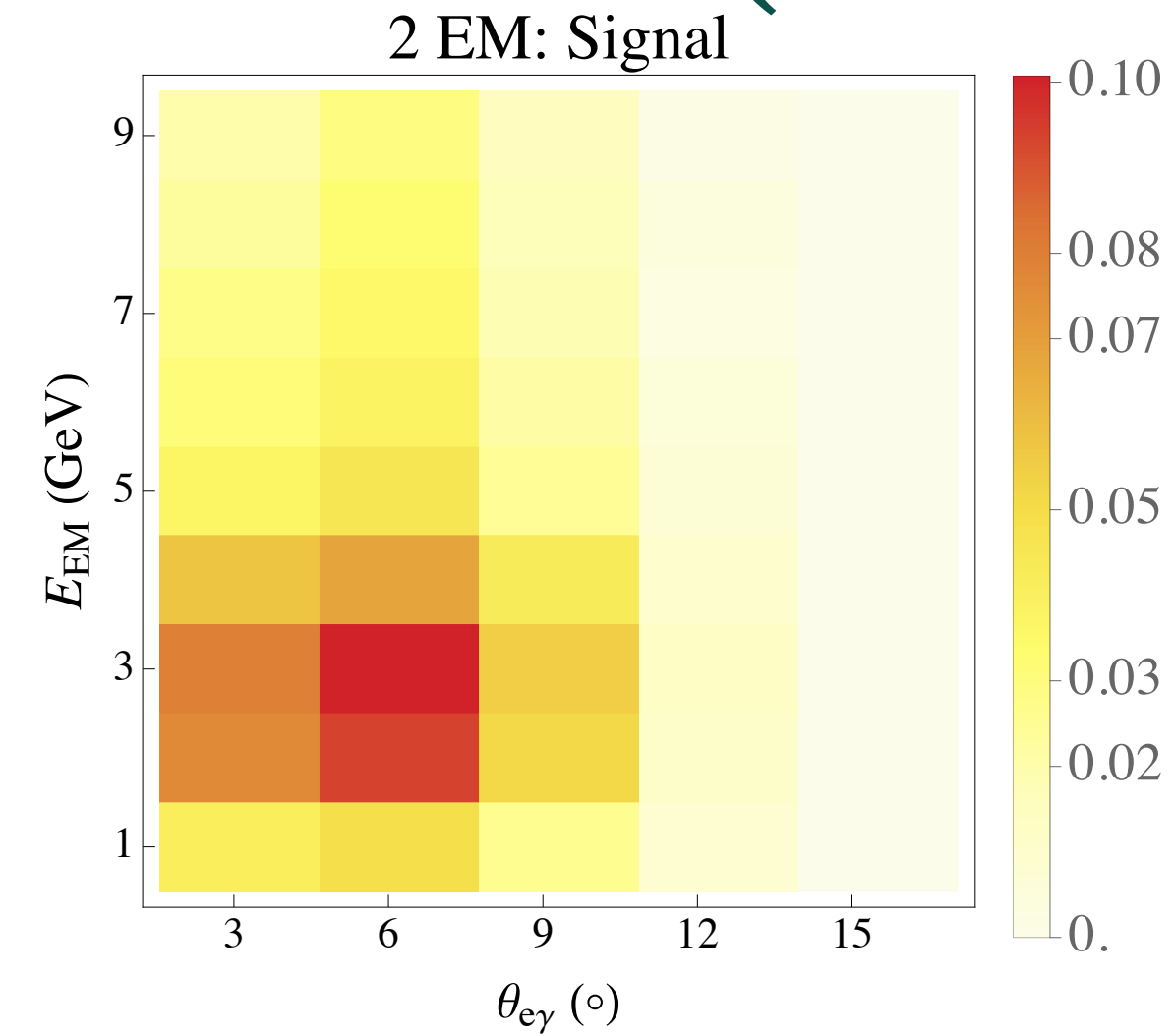
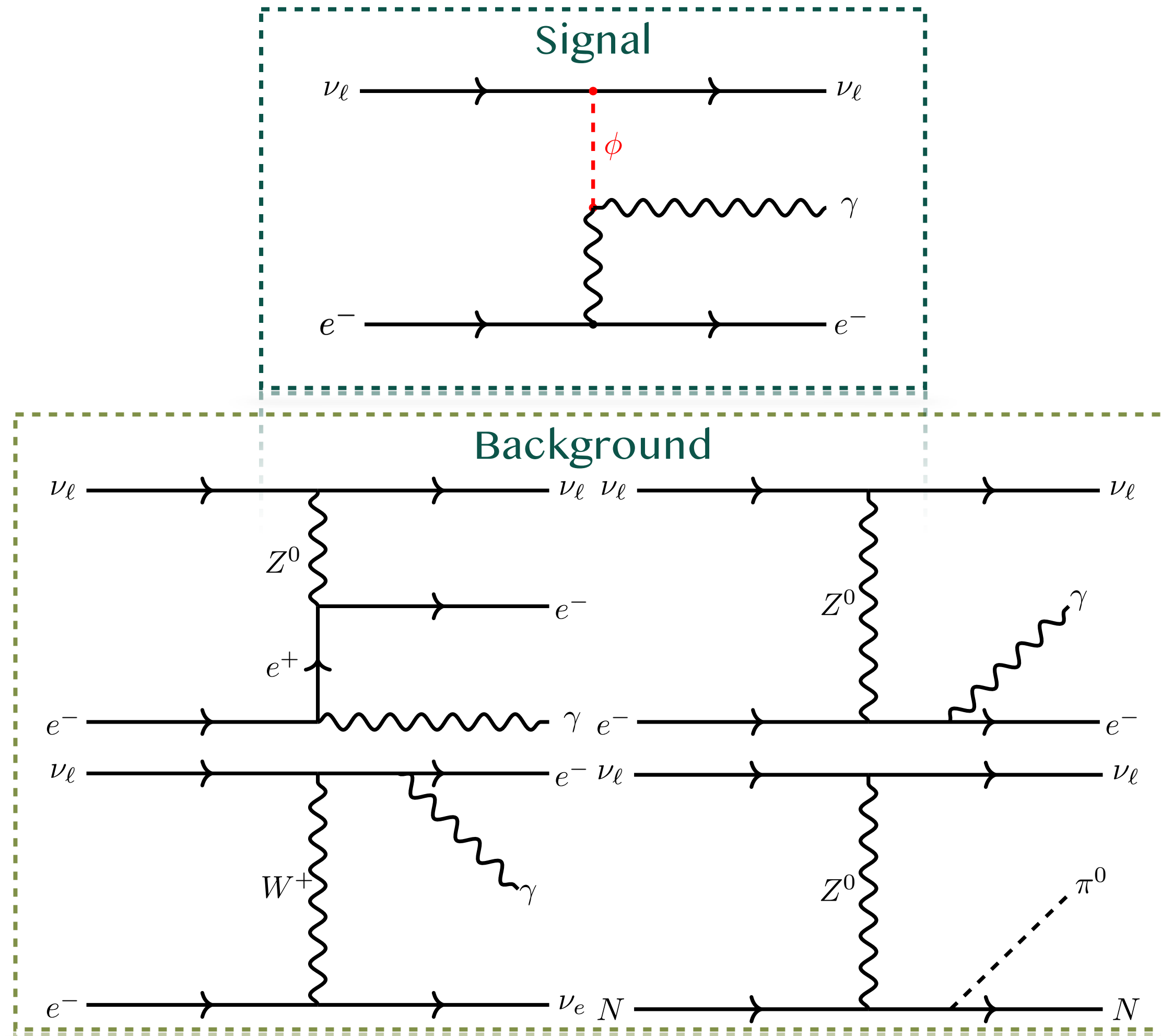
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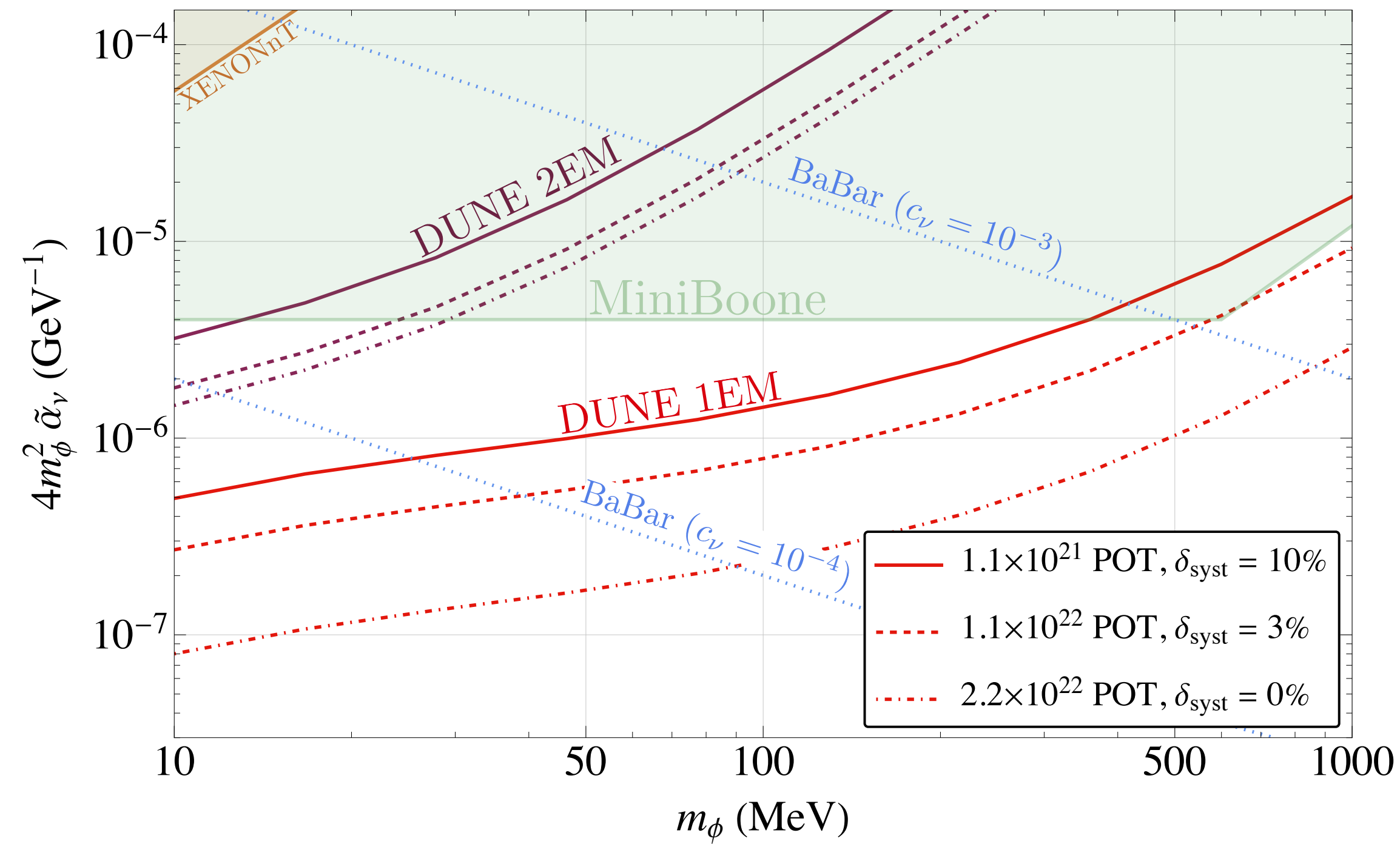
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DUNE Reach

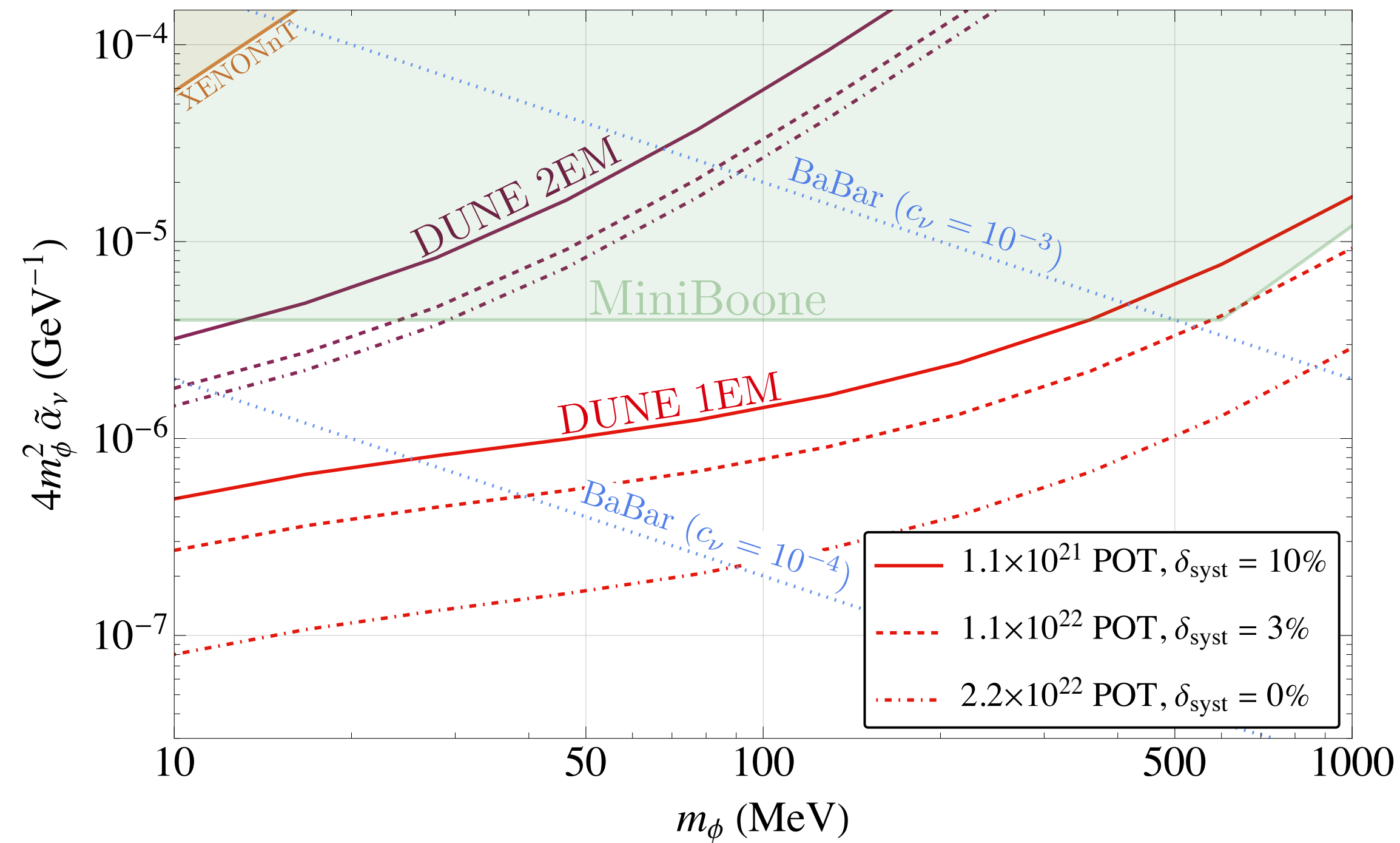
DUNE Reach



Bounds on rescaled neutrino polarizability as function of m_ϕ .

[Carey, Machado, Paz, Petrov, Sousa, Tammaro and Zupan, 2508.16724]

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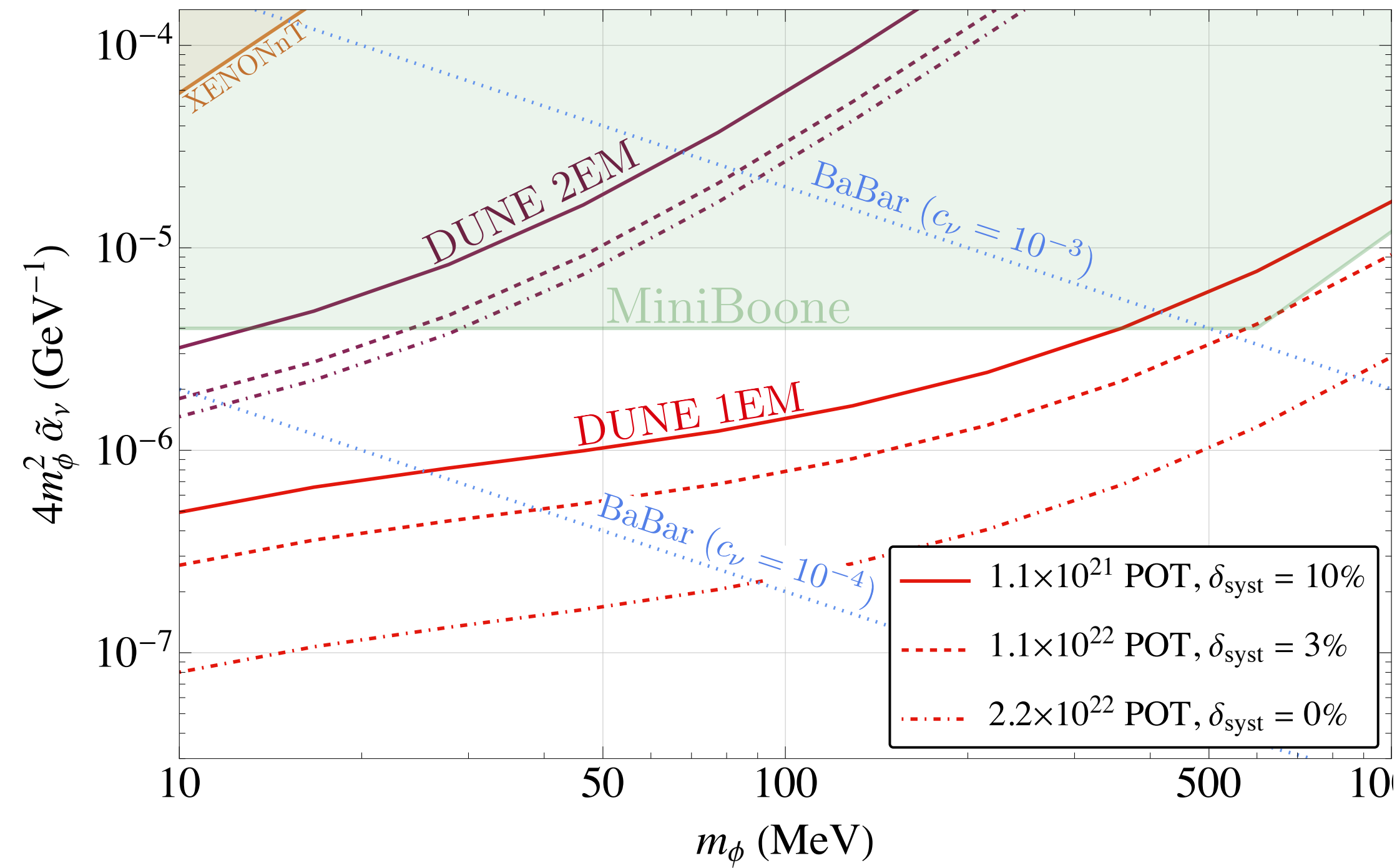
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Estimated values of the bound for $m_\phi = 50$ MeV

$$2\text{EM: } c_\nu g_\gamma = 4m_\phi^2 \times \tilde{\alpha}_\nu \leq (18, 10, 8.3) \times 10^{-6} \text{ GeV}^{-1}$$

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DUNE Reach



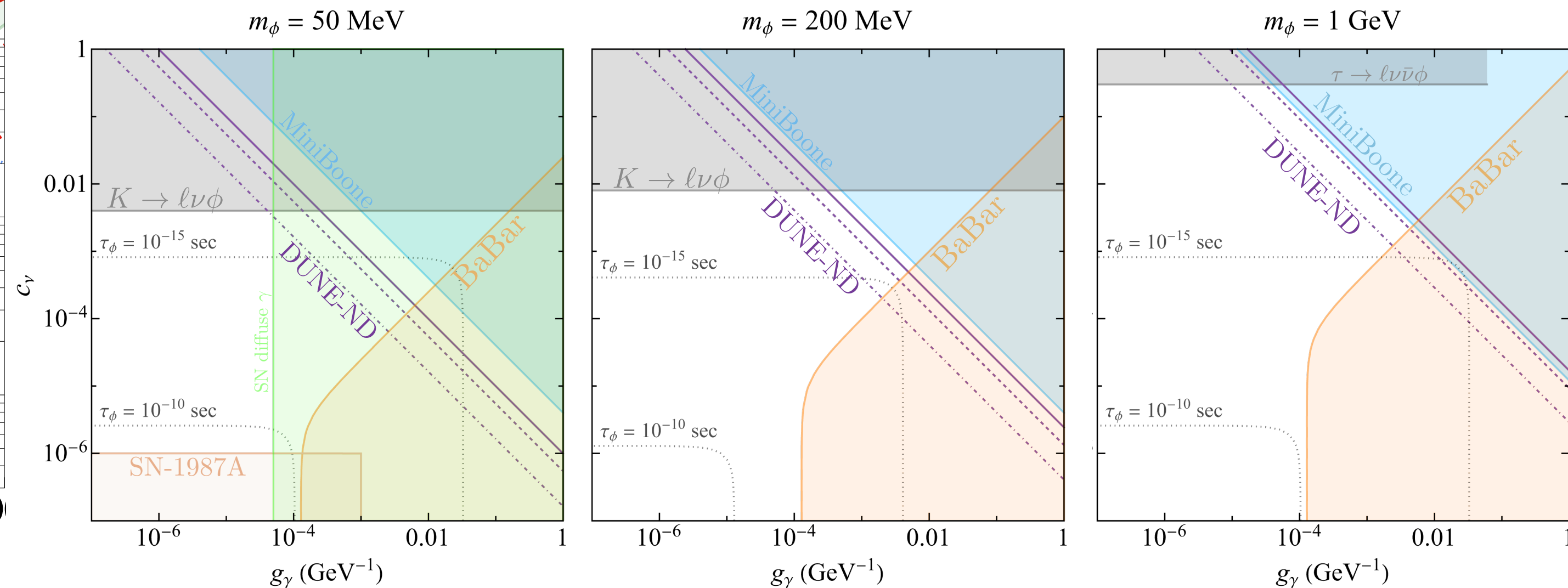
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Bounds on the neutrino and photon couplings, c_ν and $g_{\phi\gamma}$ for $m_\phi = 50, 200, 10^3$ MeV.

[Carey, Machado, Paz, Petrov, Sousa, Tammaro and Zupan, 2508.16724]

Summary

- ◉ At MeV: CE ν NS - unique probe for precision Standard Model and BSM searches.
- ◉ Future experiments - PIP2-BD at F2D2, other facilities - improve sensitivity to $\nu - \gamma$ physics (μ_ν , $\langle r^2 \rangle_\nu$)
- ◉ At GeV: further insight into enhanced neutrino polarizability.
- ◉ Though model-independently $\propto m_\nu$; parametrically enhanced with the introduction of ϕ .
- ◉ We show $\nu - e$ (or $\nu - N$) scattering via exchange of $\phi \implies$ distinct experimental signatures at DUNE: 1EM and 2 EM showers with no associated hadronic activity.

Thank You!

Backup- $\text{CE}\nu\text{NS}$ Cross-Section & Form Factor

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$$\left[\frac{d\sigma(E_\nu)}{dT} \right]_{\text{SM}} = \frac{G_F^2 Q_W^2 M_A}{4\pi} \left(1 - \frac{T}{E_\nu} - \frac{M_A T}{2 E_\nu^2} \right) F_{\text{Weak}}^2(Q^2)$$

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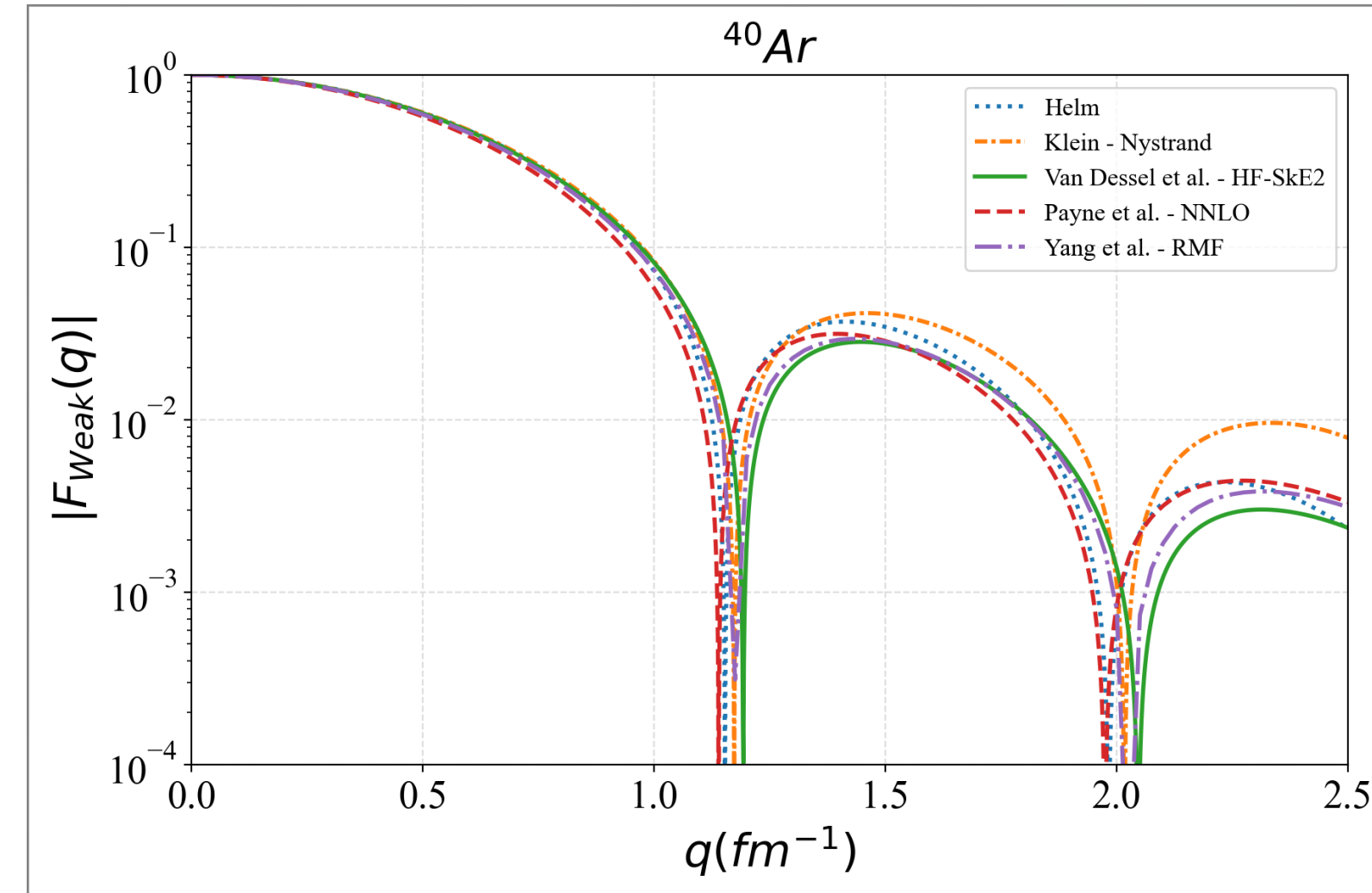
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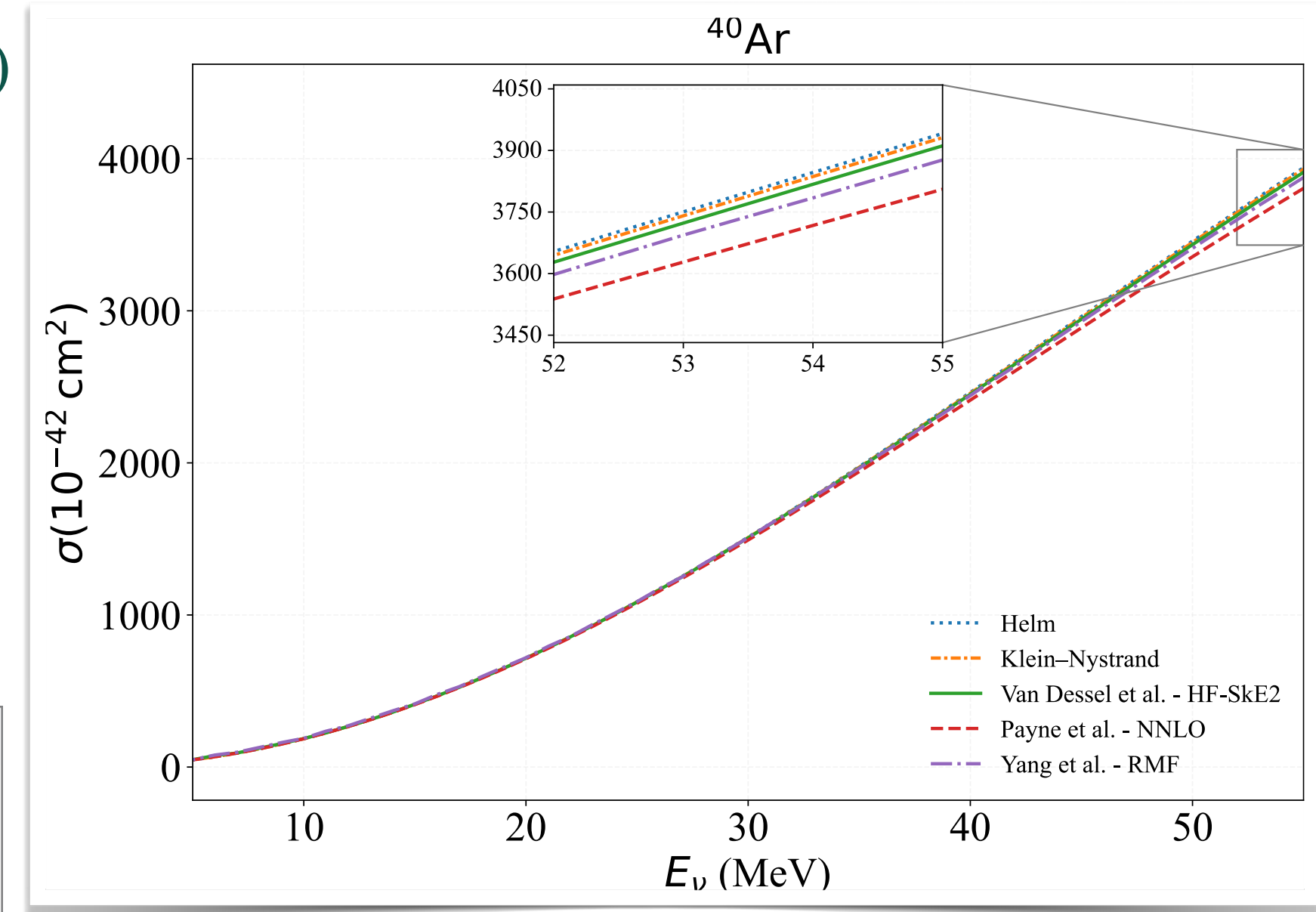
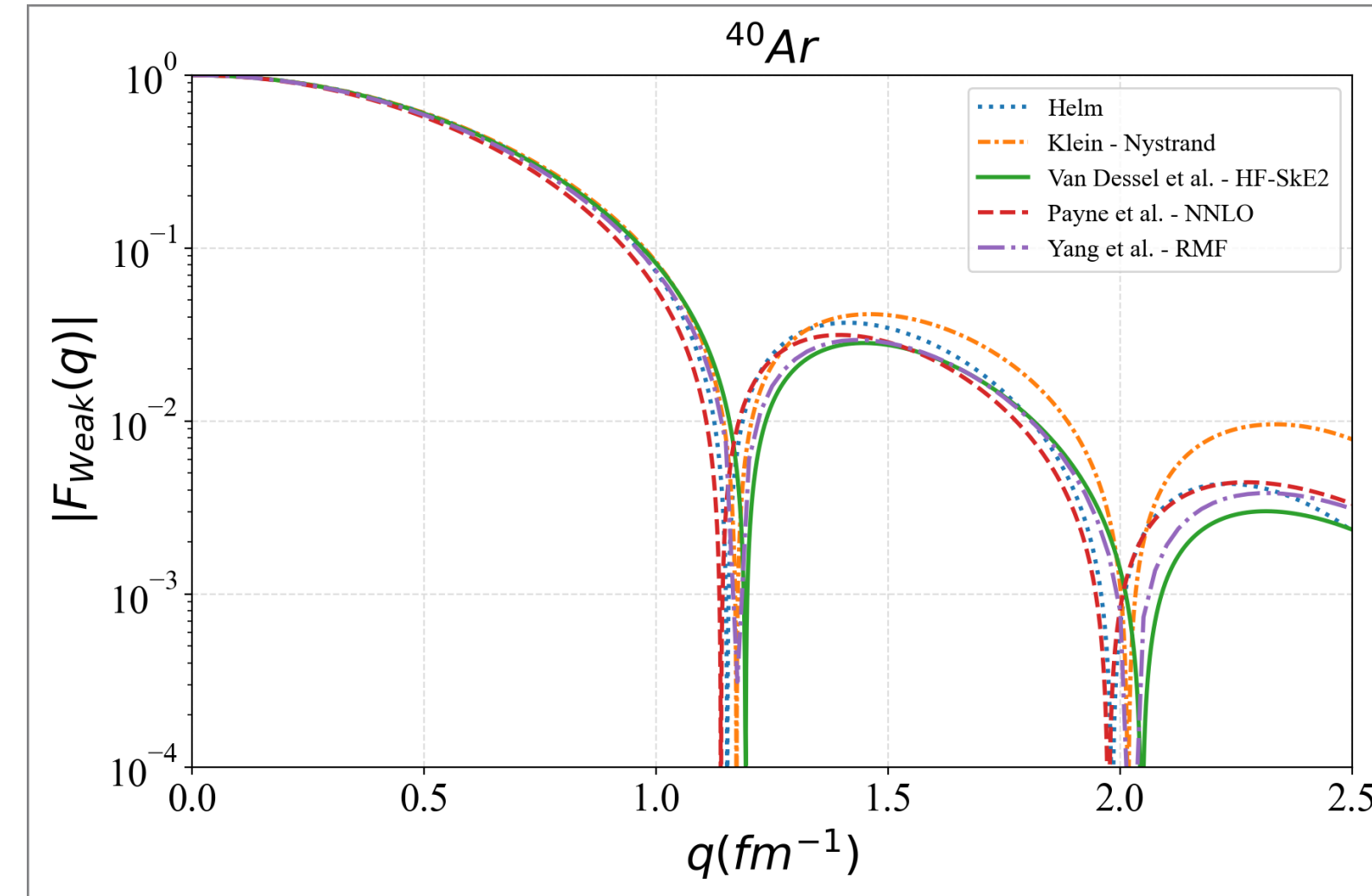
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Total cross-section comparison for different form factors

[Carey and Pandey, arXiv: 2510.xxxx]

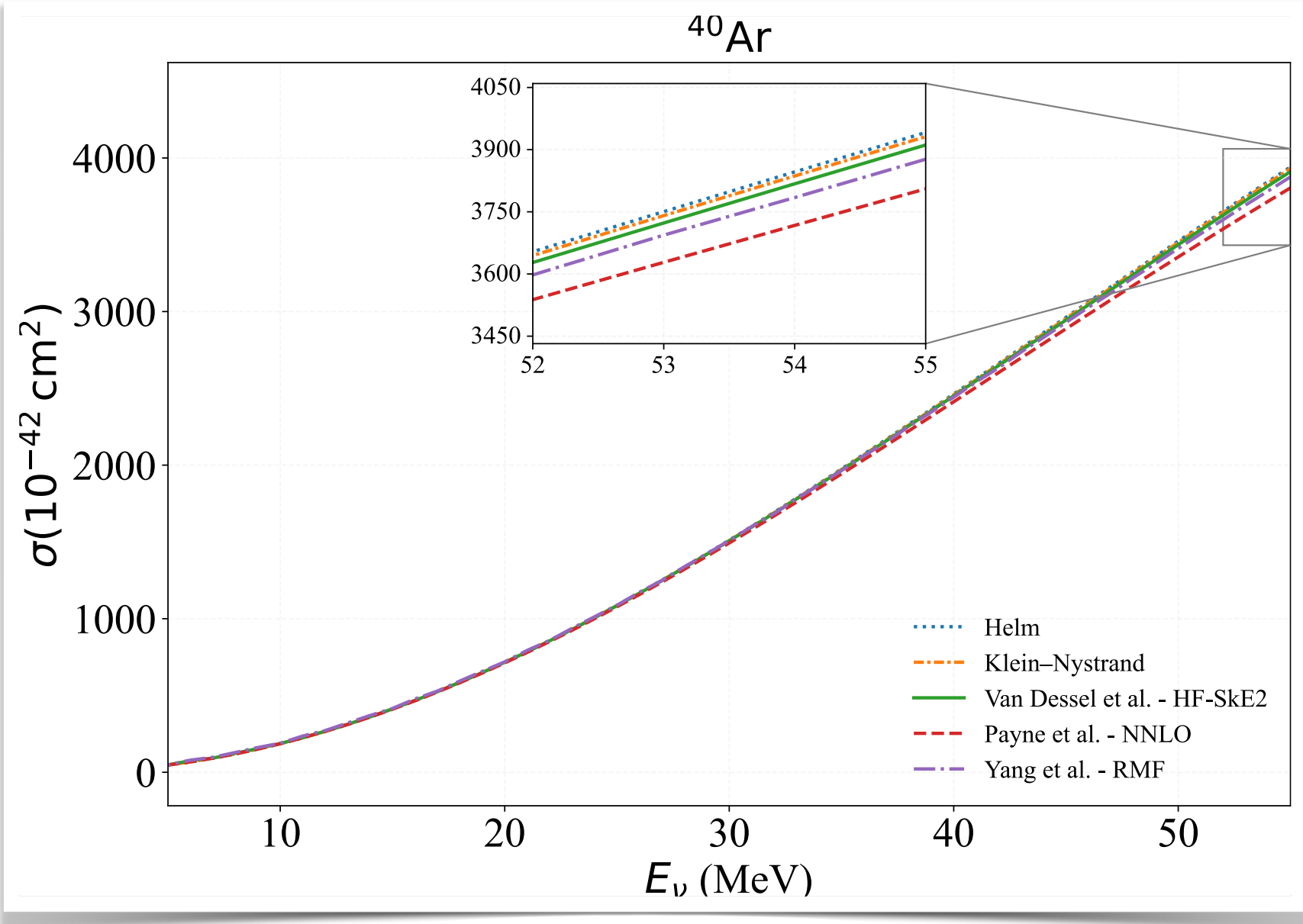
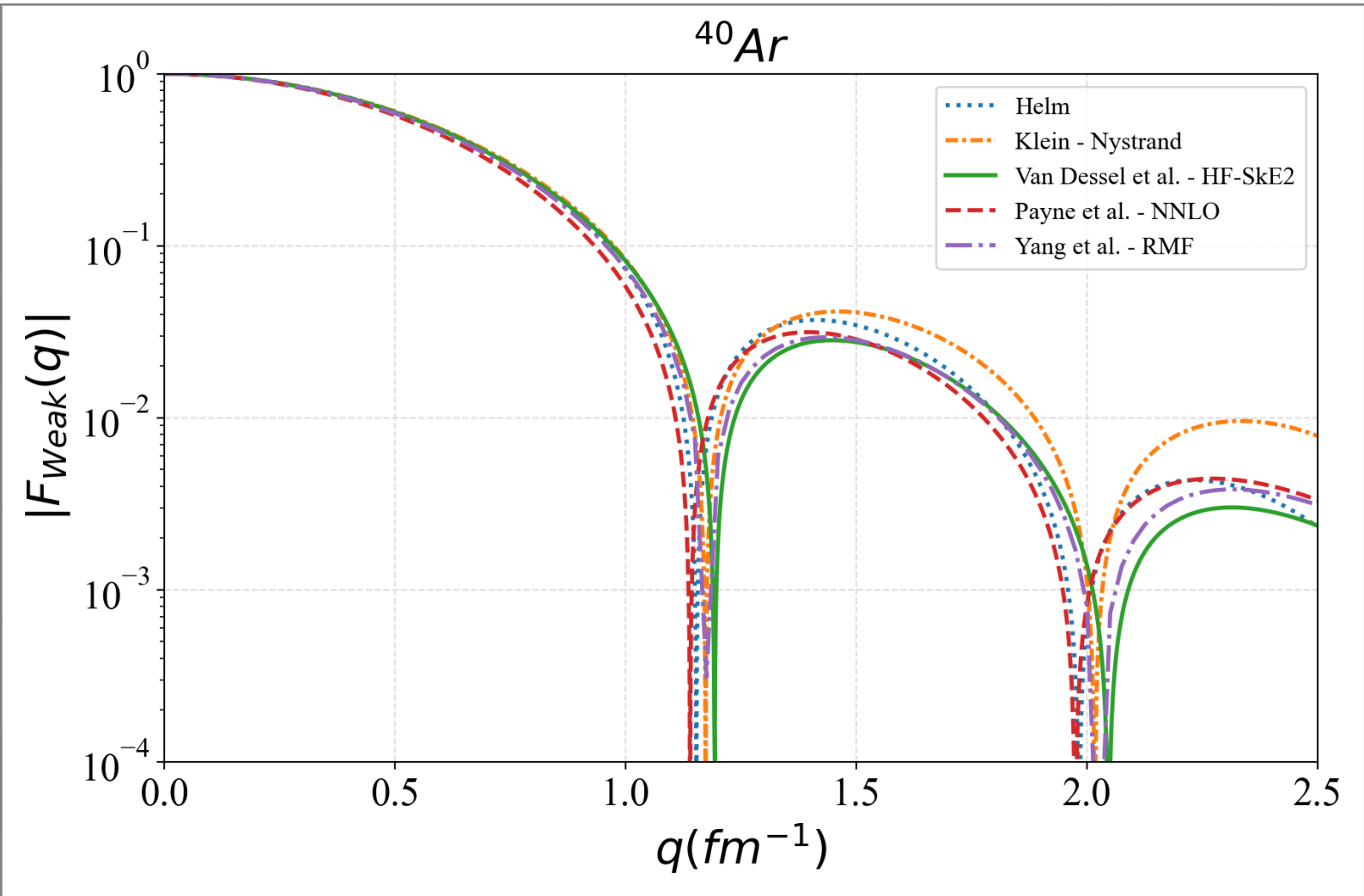
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Helm	5.131×10^6	—
Klein-Nystrand	5.117×10^6	0.28%
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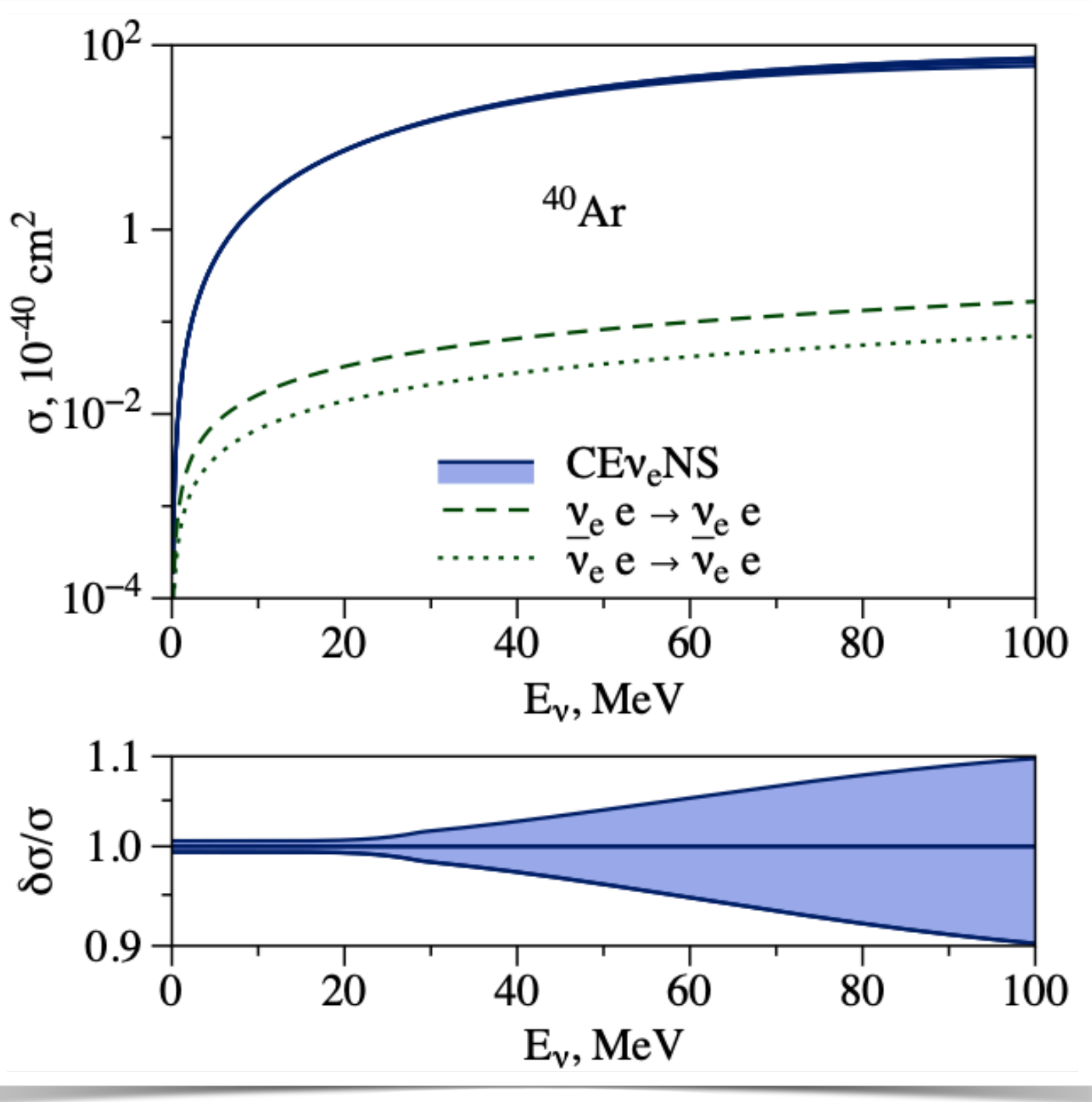
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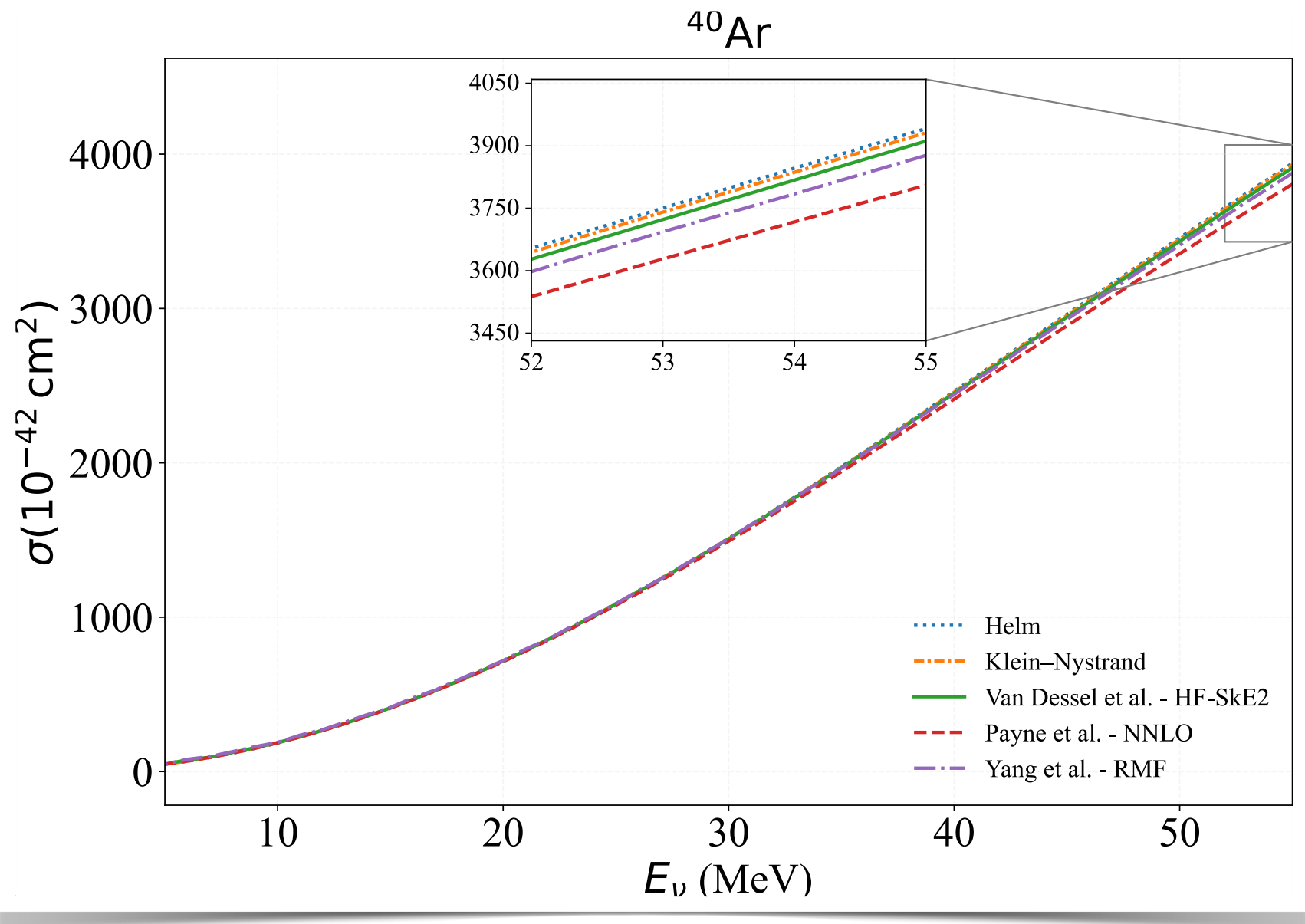
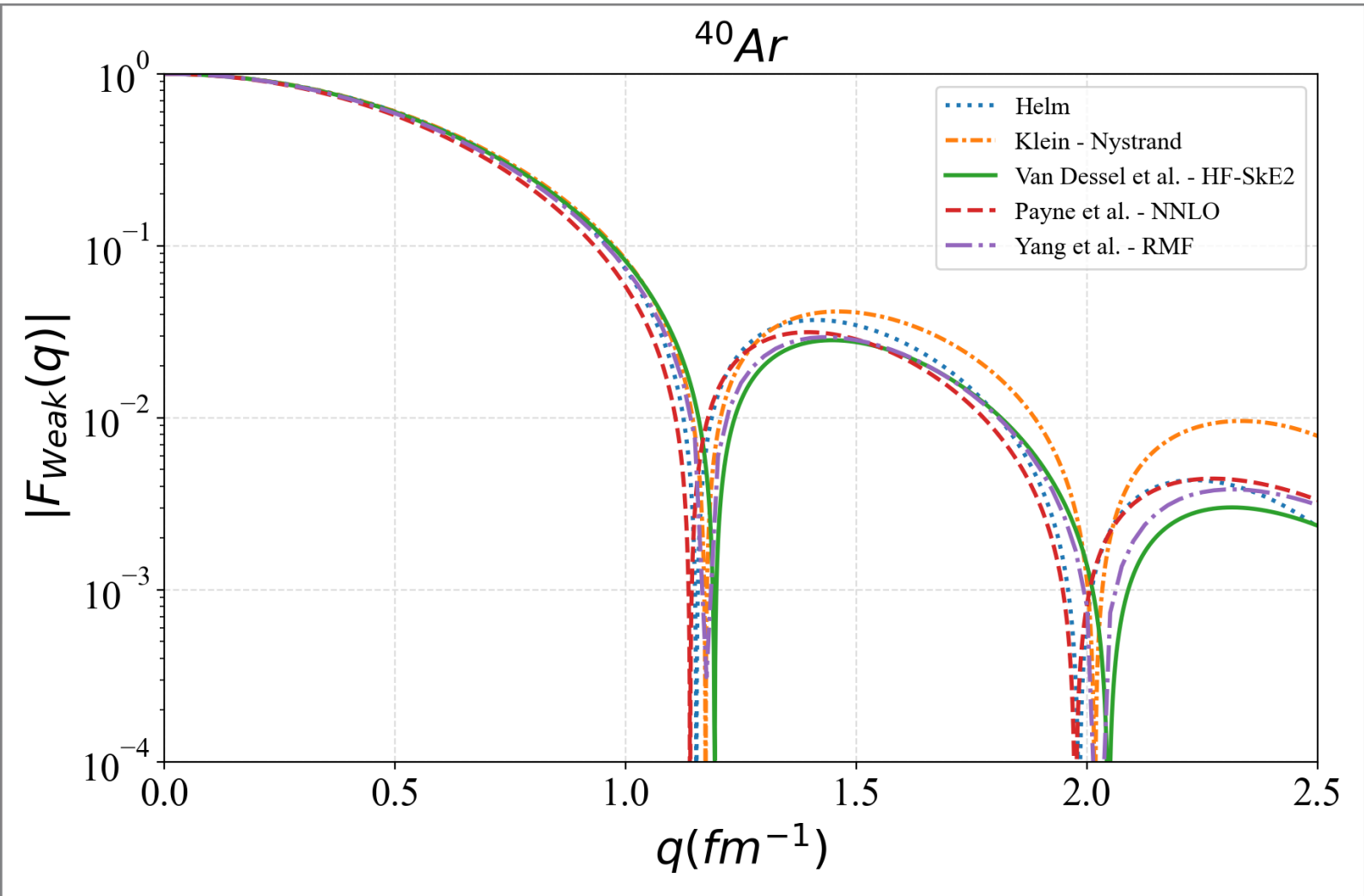
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Radiative correction to tree-level cross section
[Tomalak et al., JHEP 02, 097 (2021)]



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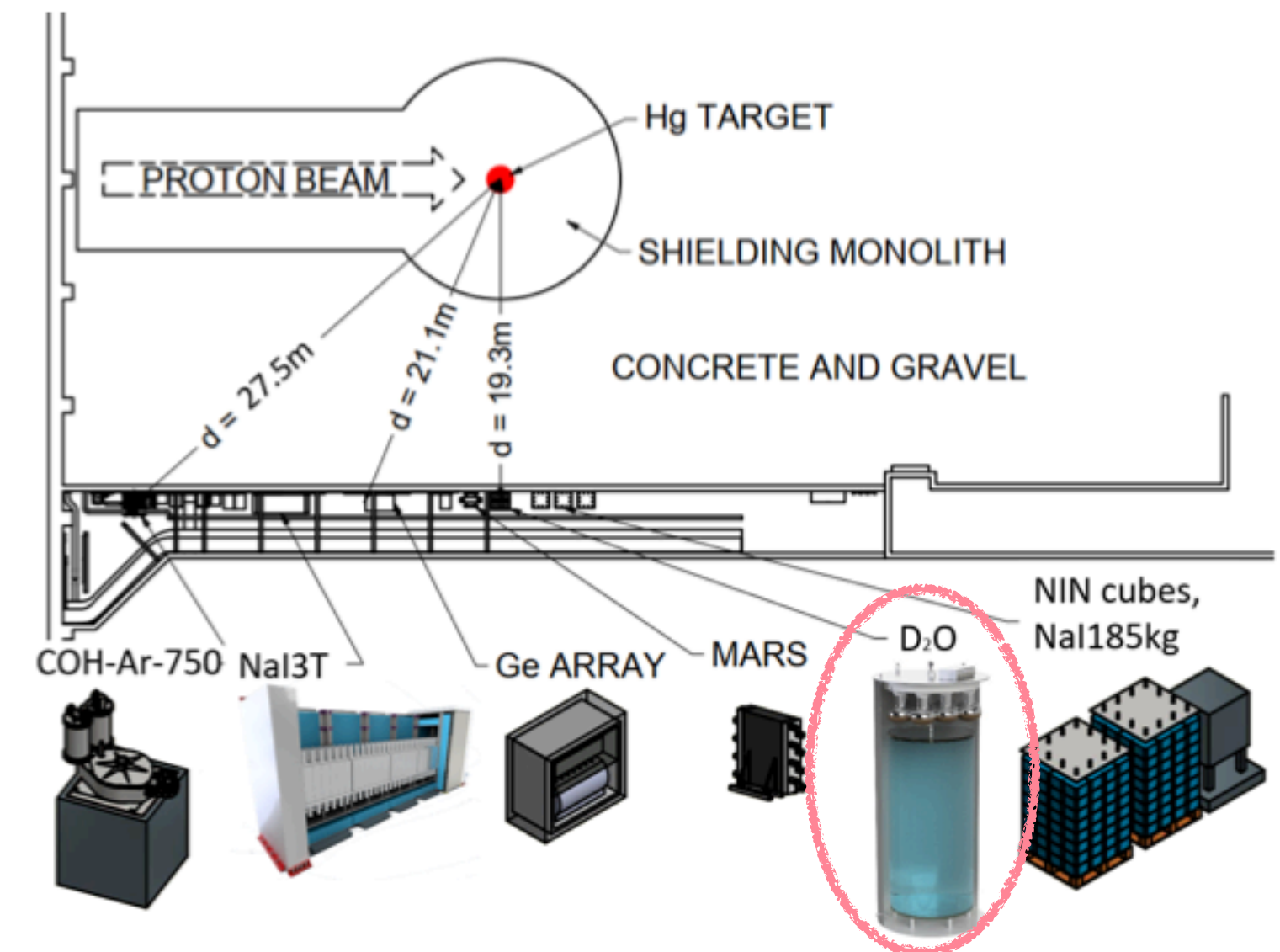
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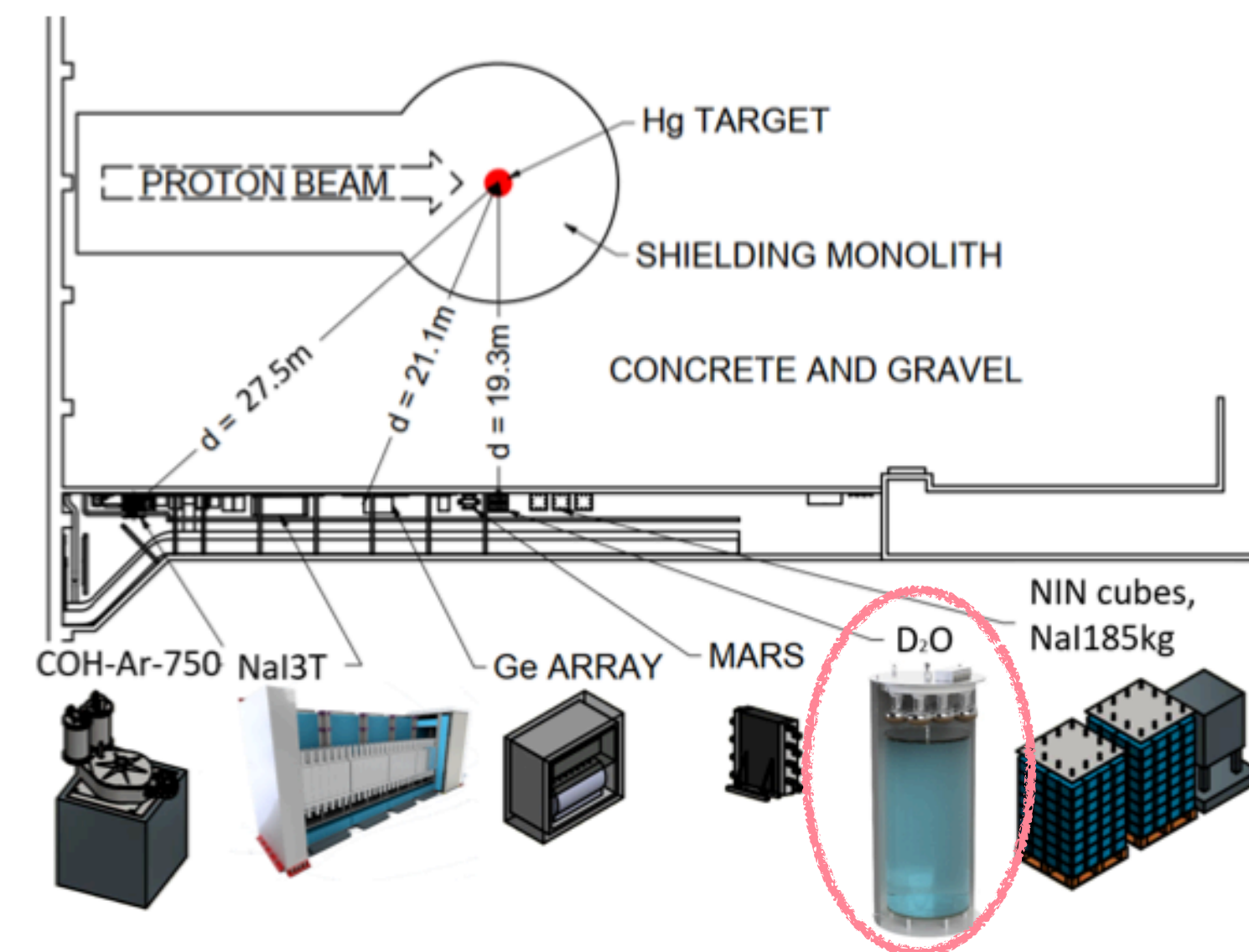


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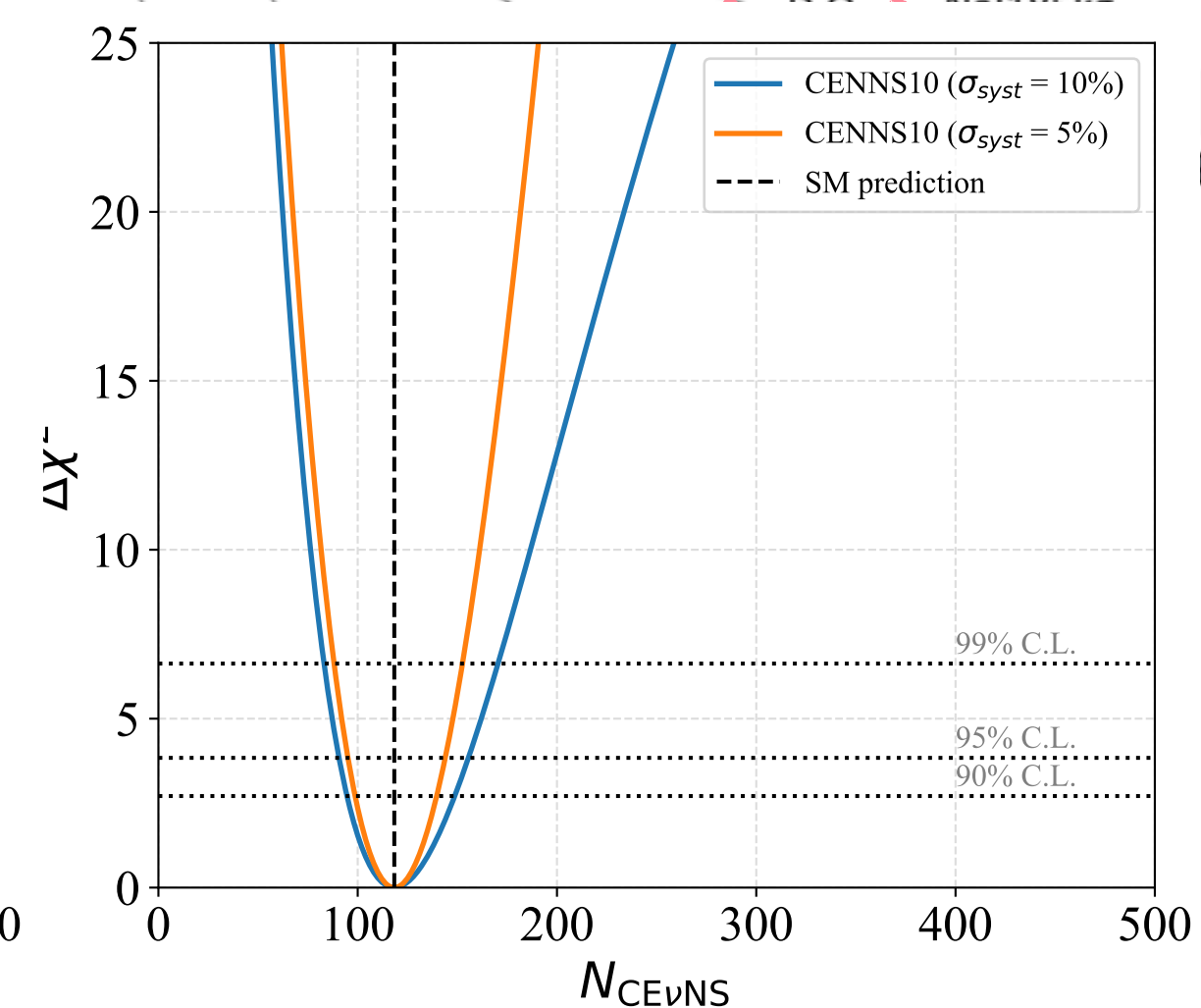
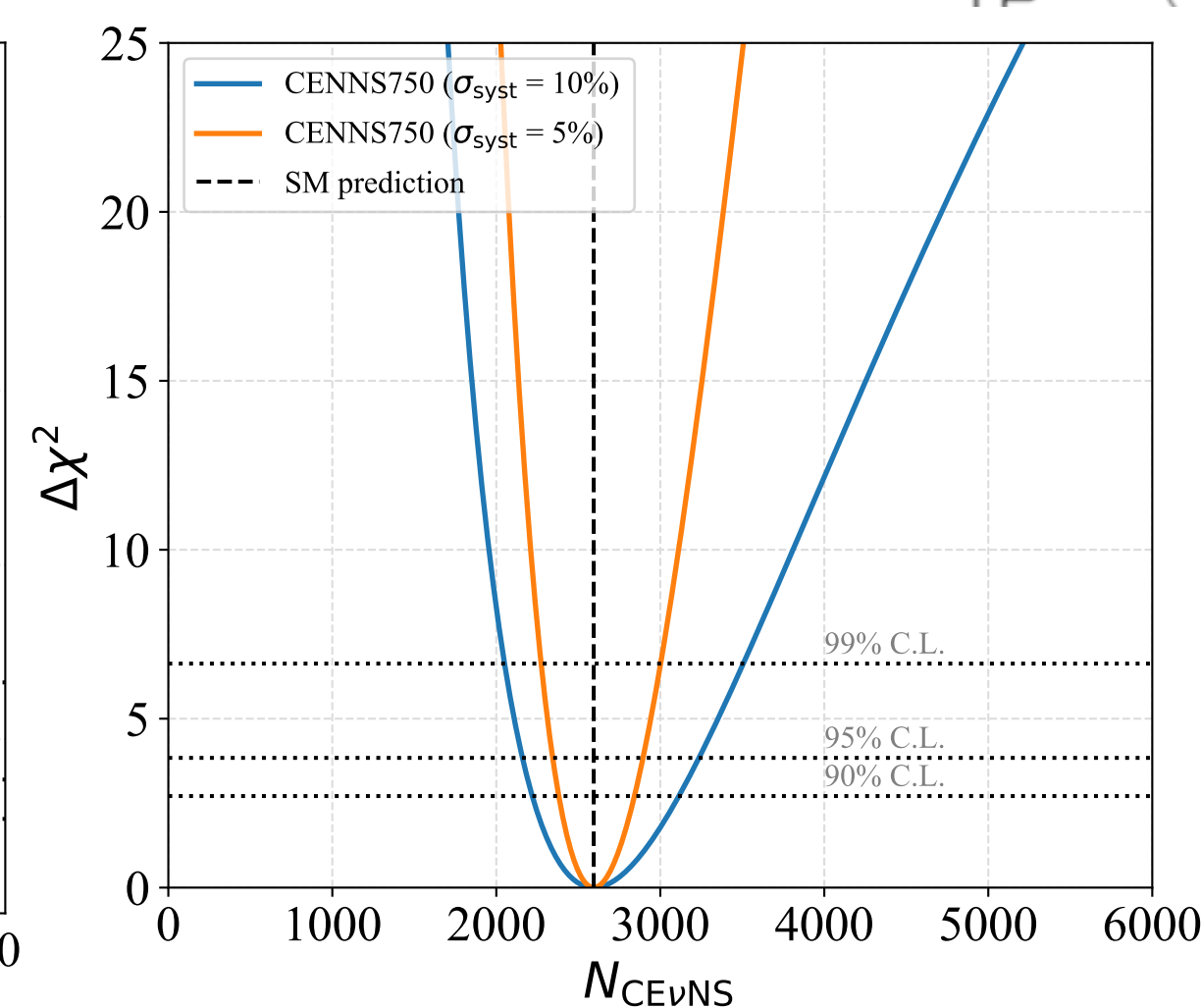
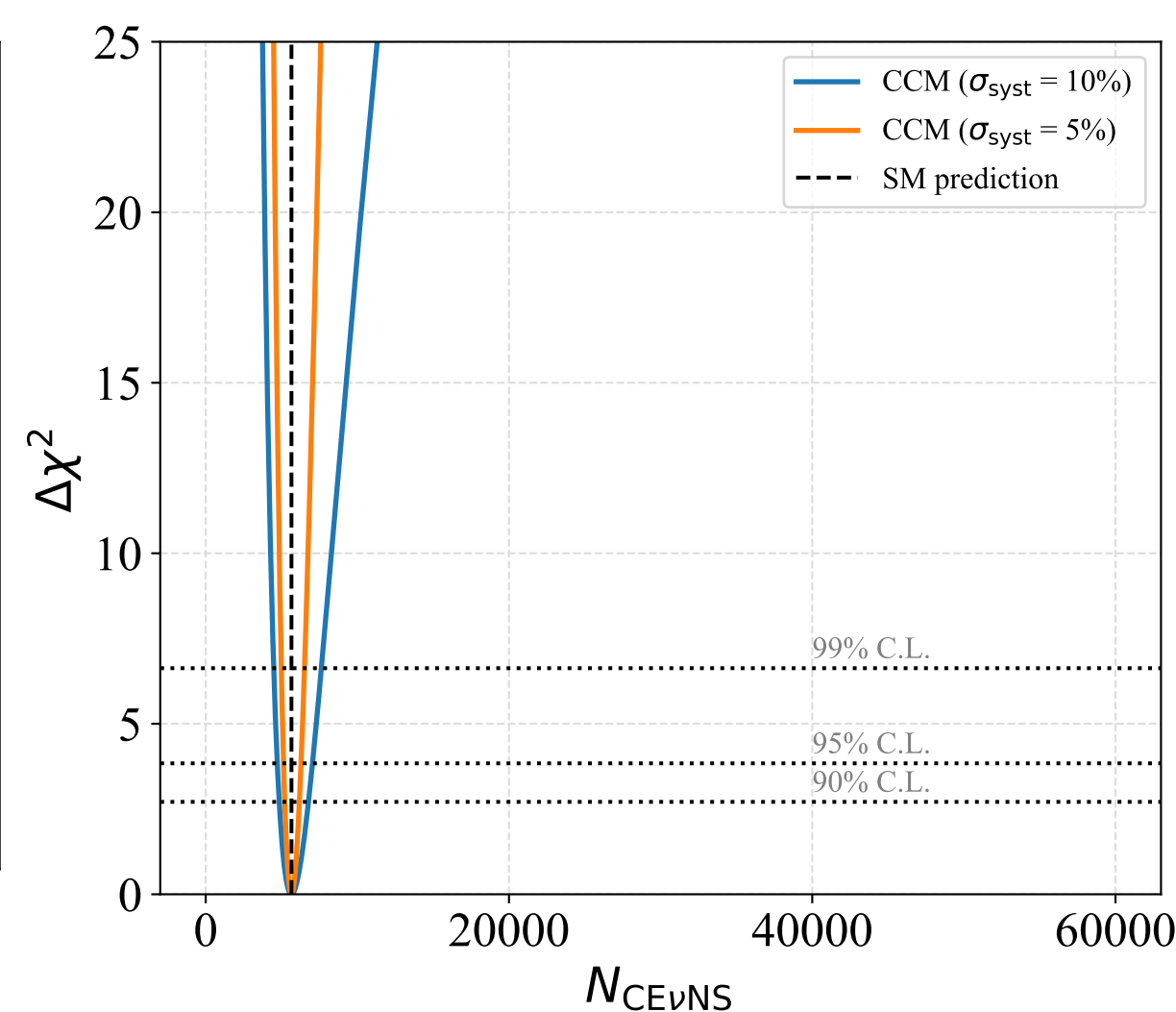
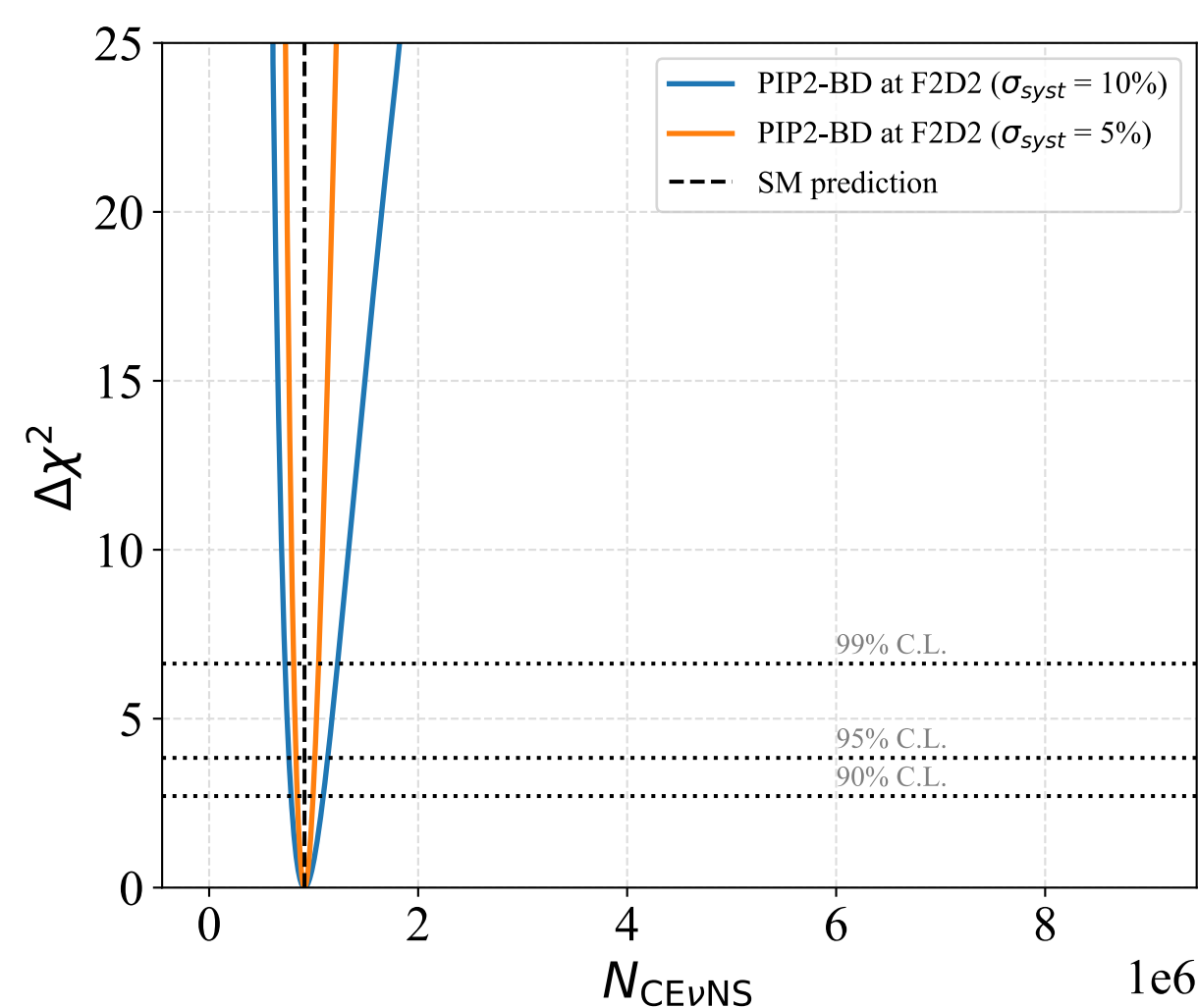
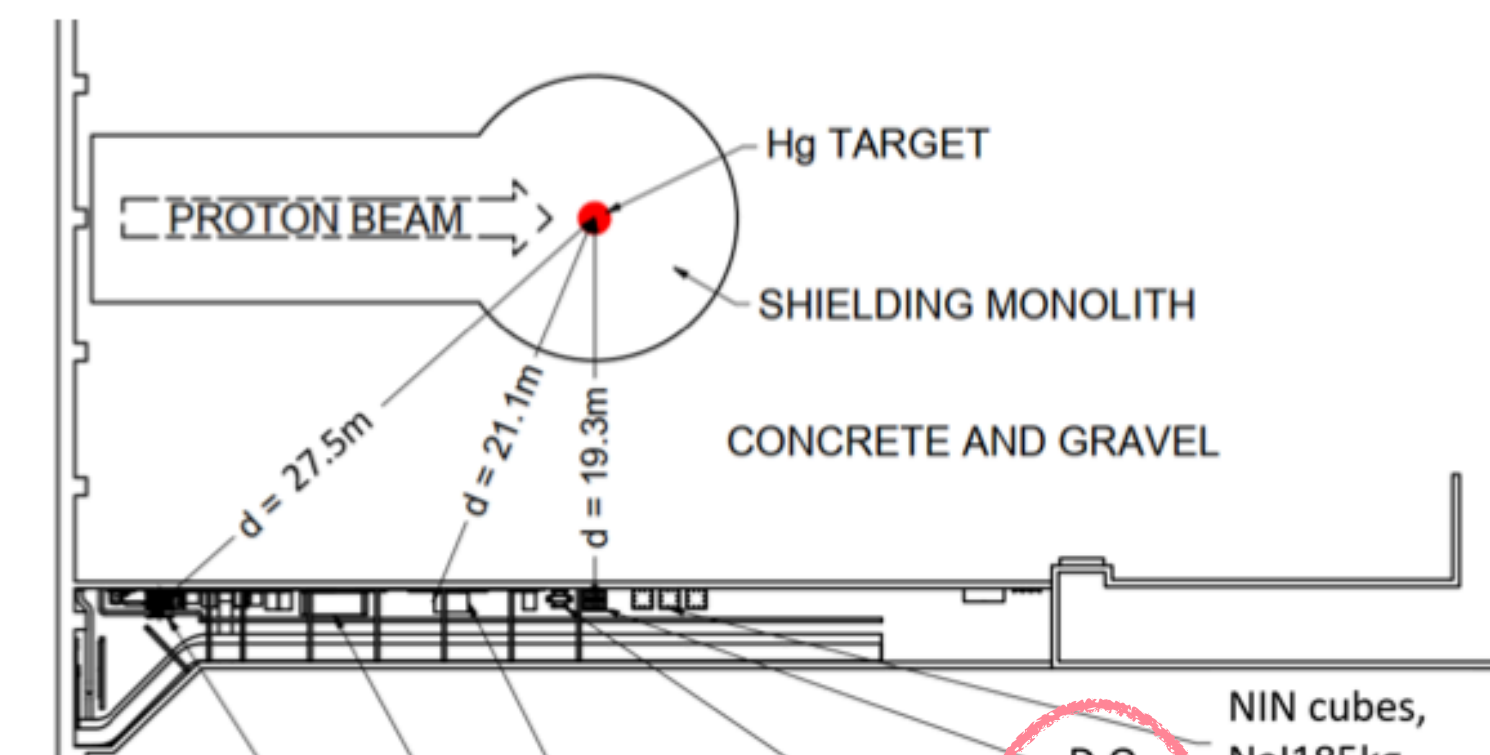


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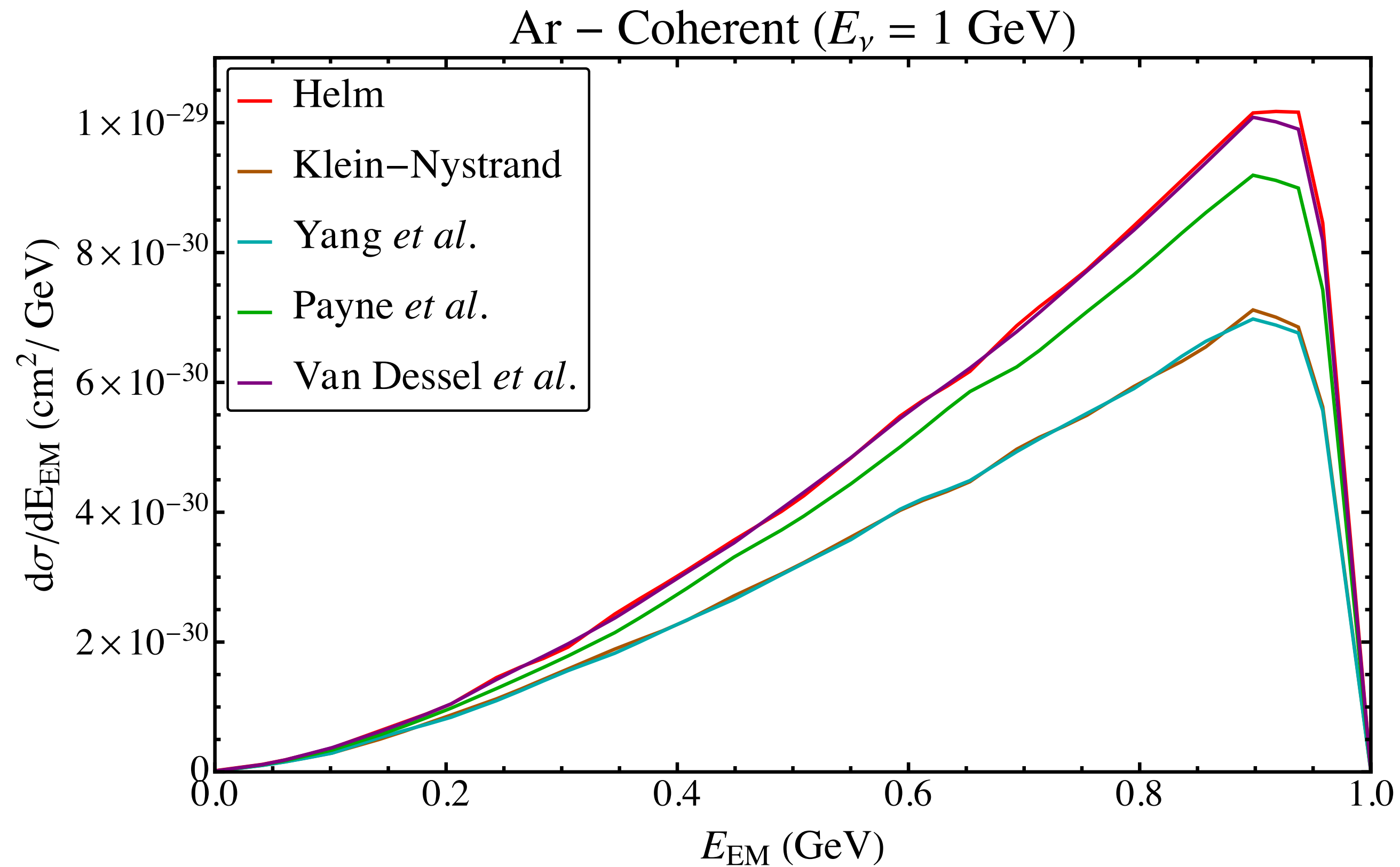
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$\Delta\chi^2$ vs the event deviation from the SM event count

Backup - Form Factor



Differential cross section in the emitted photon energy, for a neutrino with $E_\nu = 1$ GeV scattering coherently on argon.