New Physics via Neutrons at FASER

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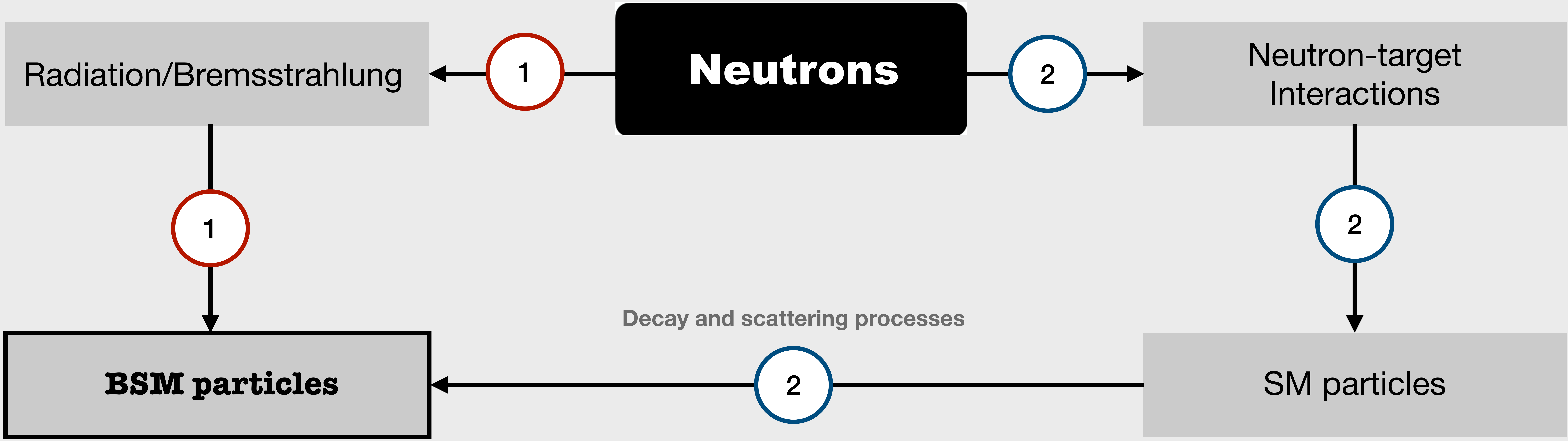
PHYSICS AND ASTRONOMY

Motivation

New physics from ***high-energy***, ***high-intensity*** neutrons at a ***dump***



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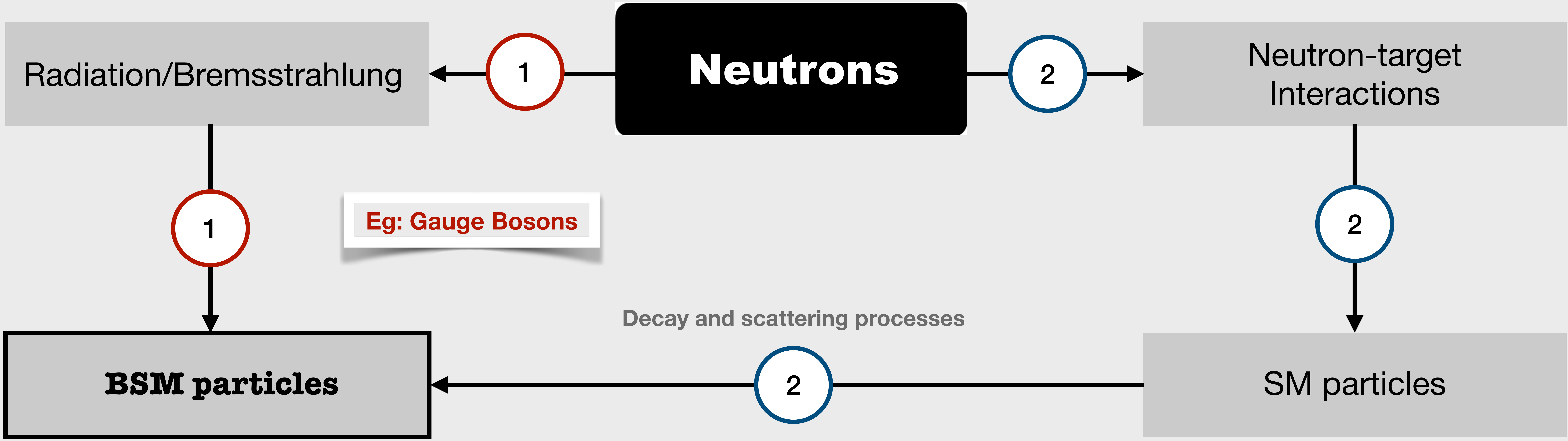

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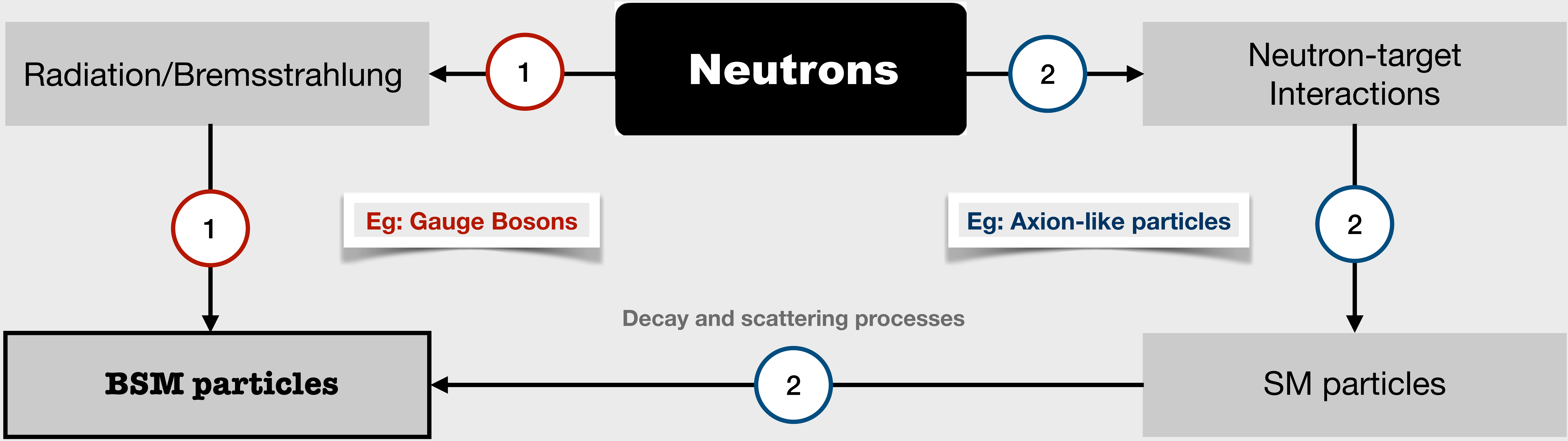
New physics from ***high-energy***, ***high-intensity*** neutrons at a ***dump***



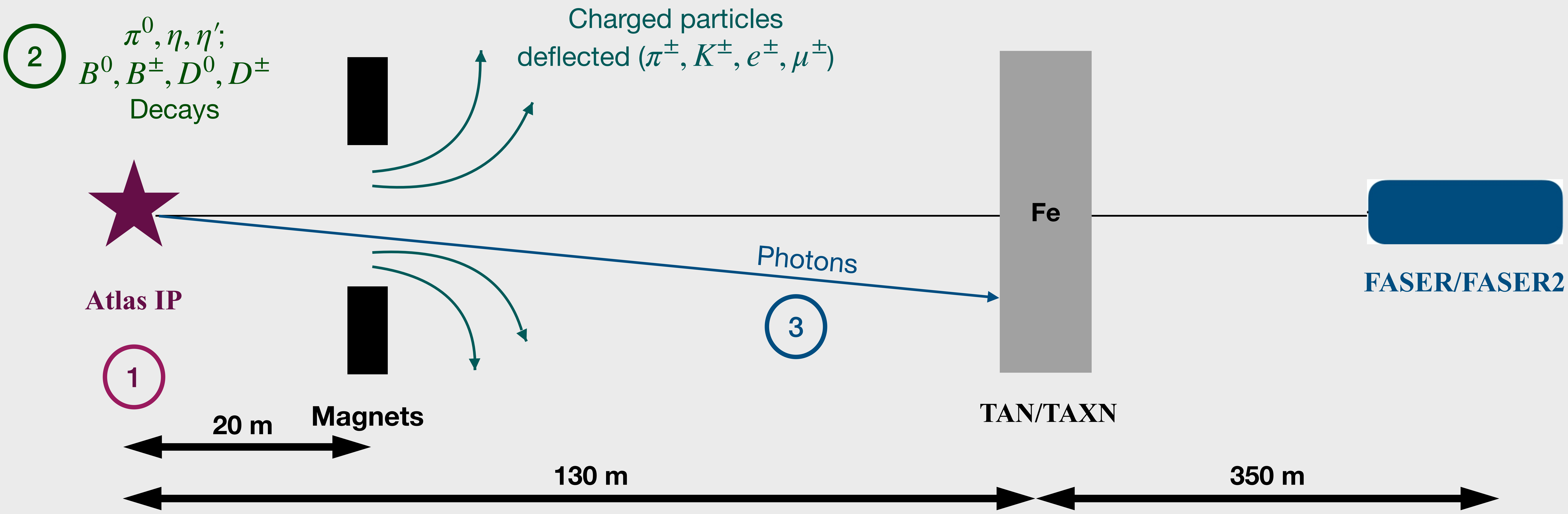
See also:
- arxiv.org/abs/1811.12522
- arxiv.org/abs/2212.06186
- arxiv.org/abs/1801.08947
- arxiv.org/abs/1806.02348
- arxiv.org/abs/2204.03599

FASER, FASER2: Existing studies

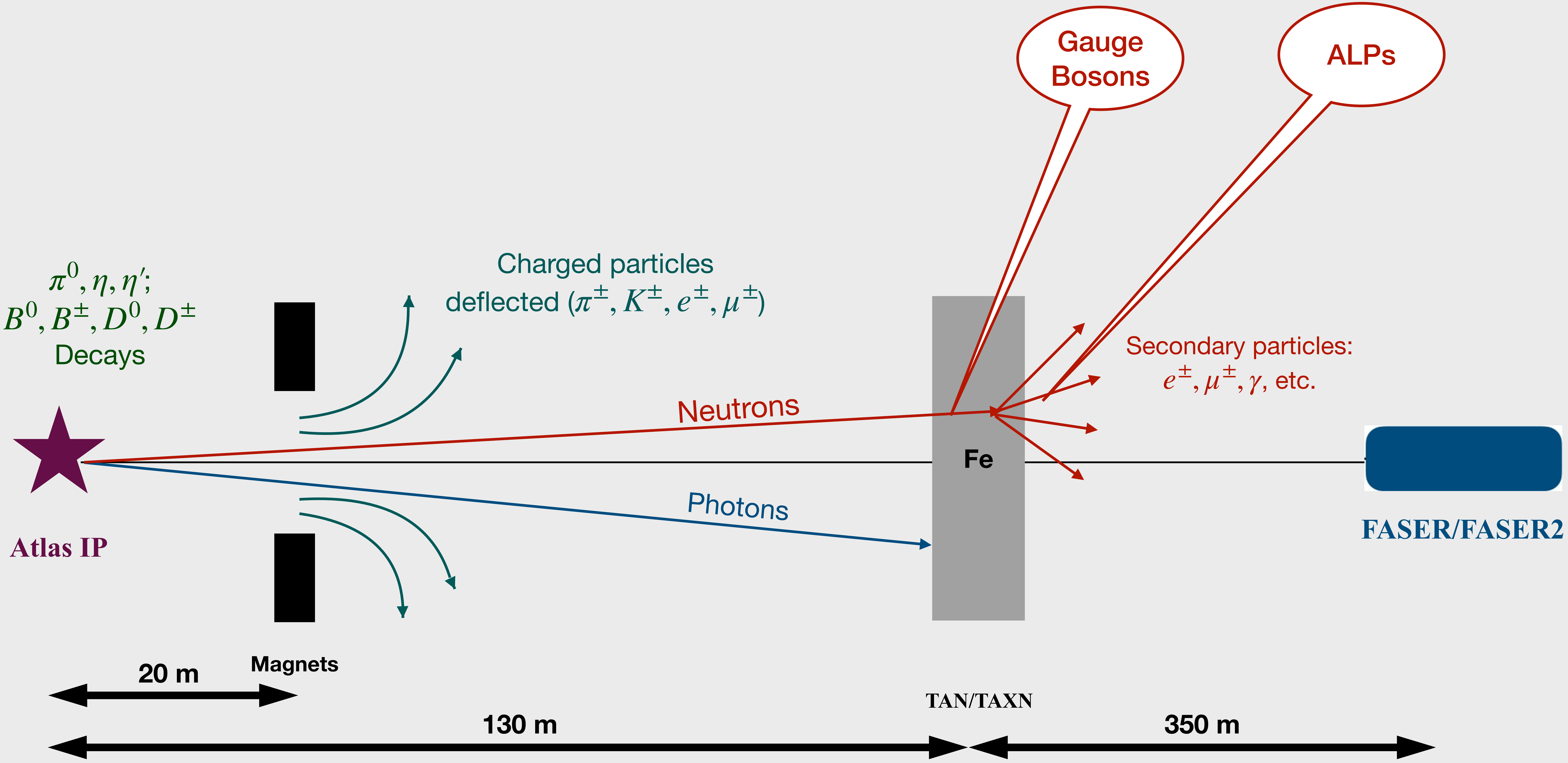
1. $U(1)_X$, $U(1)_{B-L}$, etc.

2. $U(1)_X$, $U(1)_{B-L}$, HPS, HNL

3. ALPs with photon couplings



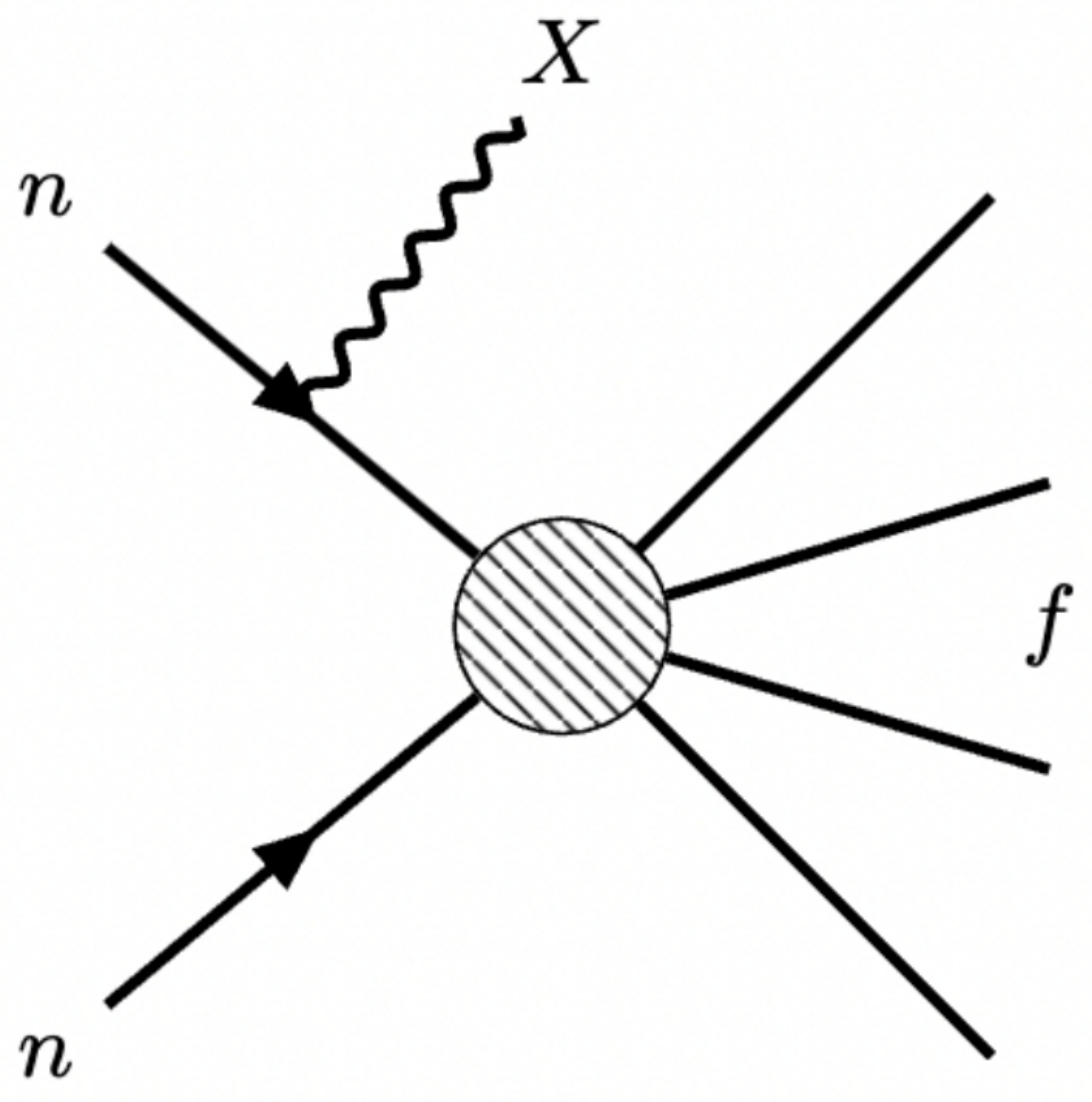
FASER, FASER2: Neutrons



Neutron Bremsstrahlung

Initial State Radiation

Radiation from Non-Standard Diffractive (NSD) neutron processes



$$\frac{d^2N_X}{dE_X d\cos\theta_X} = \int dE_n \frac{dN_n}{dE_n} n_T \lambda_T(E_n) \frac{d^2\sigma_{ISR}(E_n)}{dE_X d\cos\theta_X}$$

↓

$$d\sigma_{ISR}(E_n) = \sigma_{NSD}(s(E_n'))dP_{n\to n'X}$$

↓

$$\sigma_{NSD}(s) = 1.76 + 19.5\left(\frac{s}{\text{GeV}^2}\right)^{0.057} \text{mb}$$

n_T : No.of target atoms per unit volume.

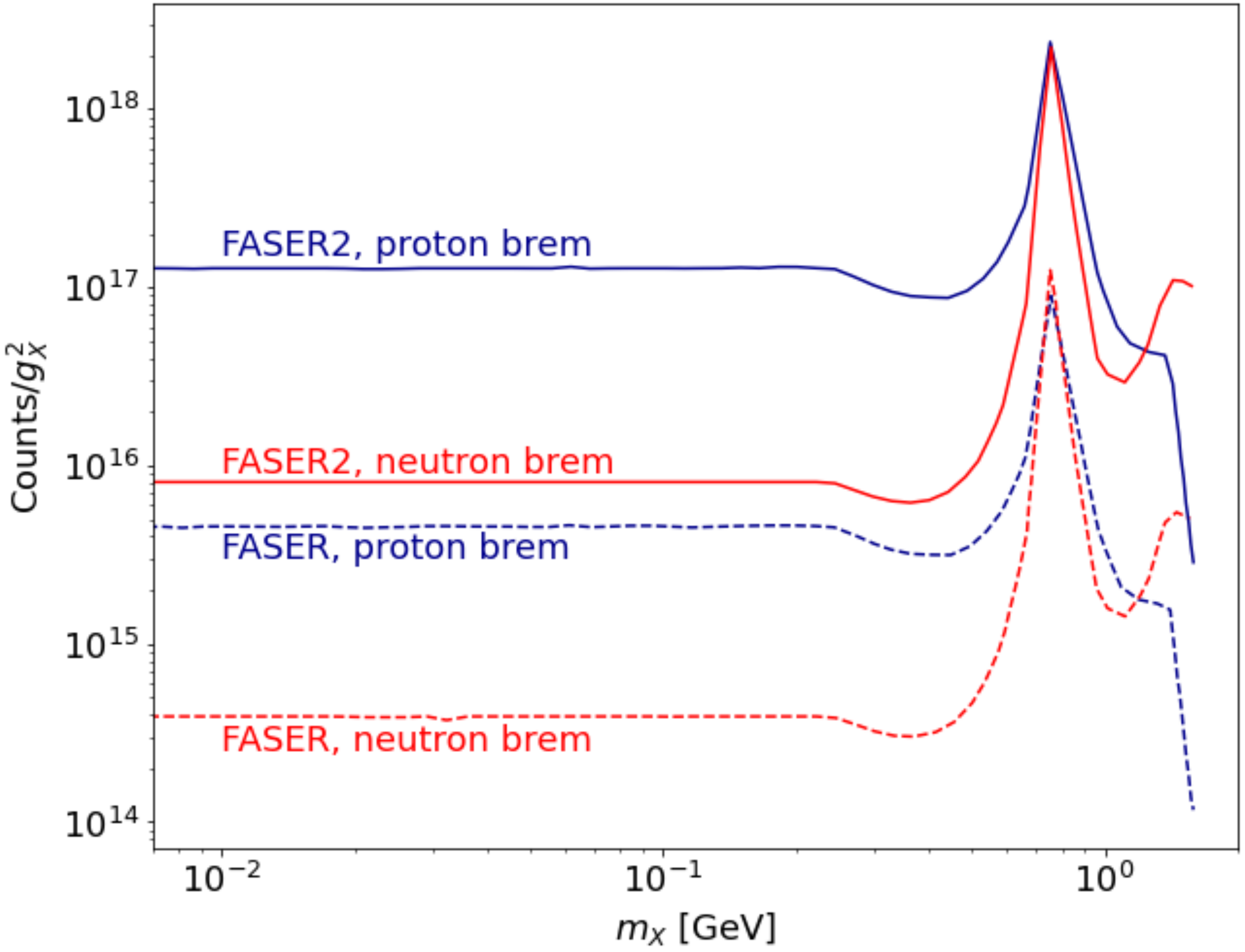
$\lambda_T(E_n)$: Mean free path length of a neutron with energy E_n in material T

Approximations for $dP_{n\to n'X}$:

- $E_n/2 < E_X < E_n$
- $\cos\theta_X \sim 1$

Formulation follows from:
Abari, Ritz, arxiv.org/abs/2108.05900

Generic model - proton and neutron couplings



Proton Bremsstrahlung:

- Enhanced as $\sqrt{s} = 14$ TeV
- Suppression due to p-p collision

Neutron Bremsstrahlung:

- Suppressed as $\sqrt{s} = 40$ GeV
- Enhanced due to neutron-dump interactions

Differences arise due to hadronic form factors (Vector Meson Dominance)

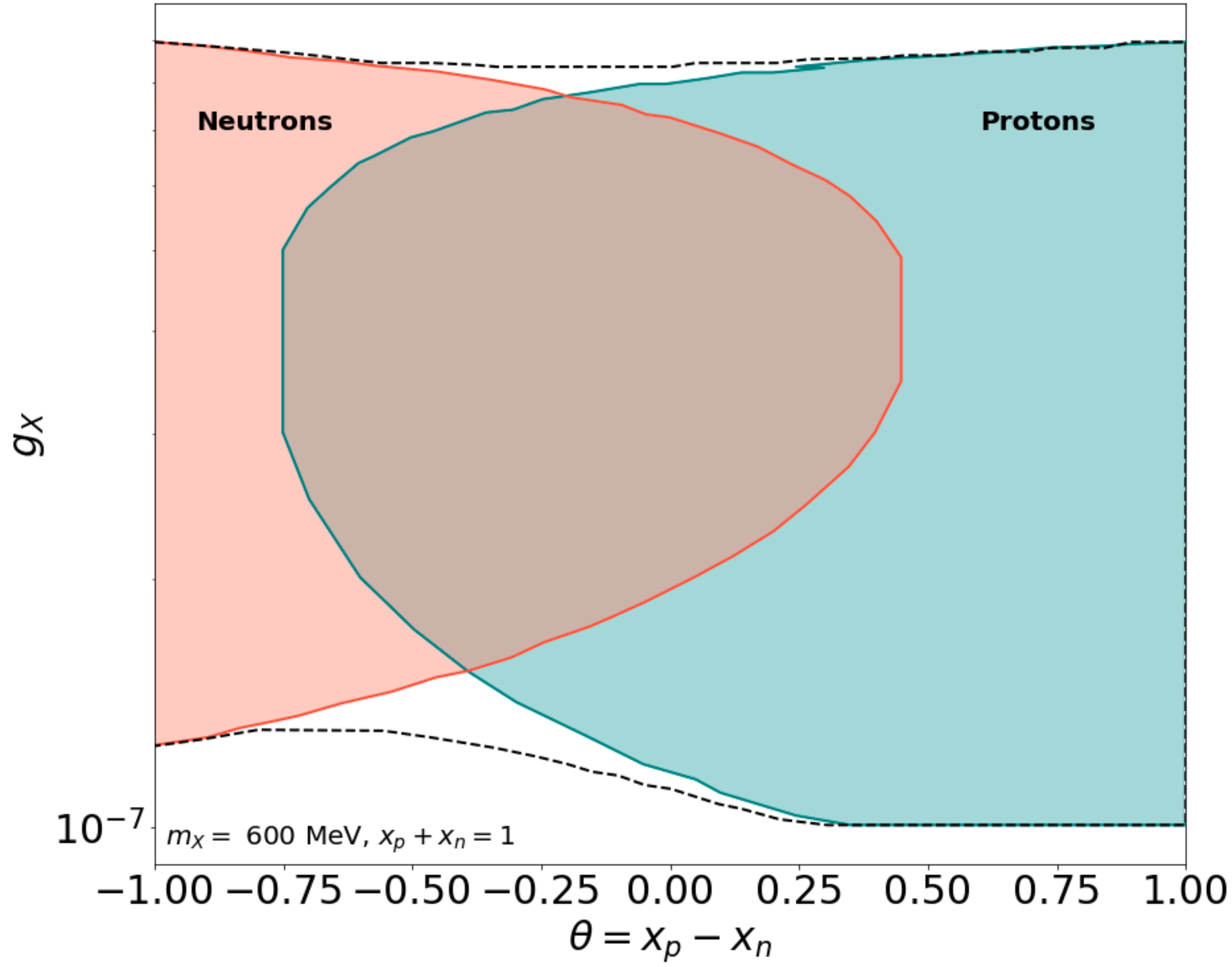
See for Form factors: arxiv.org/abs/0910.5589

Generic model - proton and neutron couplings

$$SU(2)_L \times SU(2)_L \times U(1)_X = 0$$

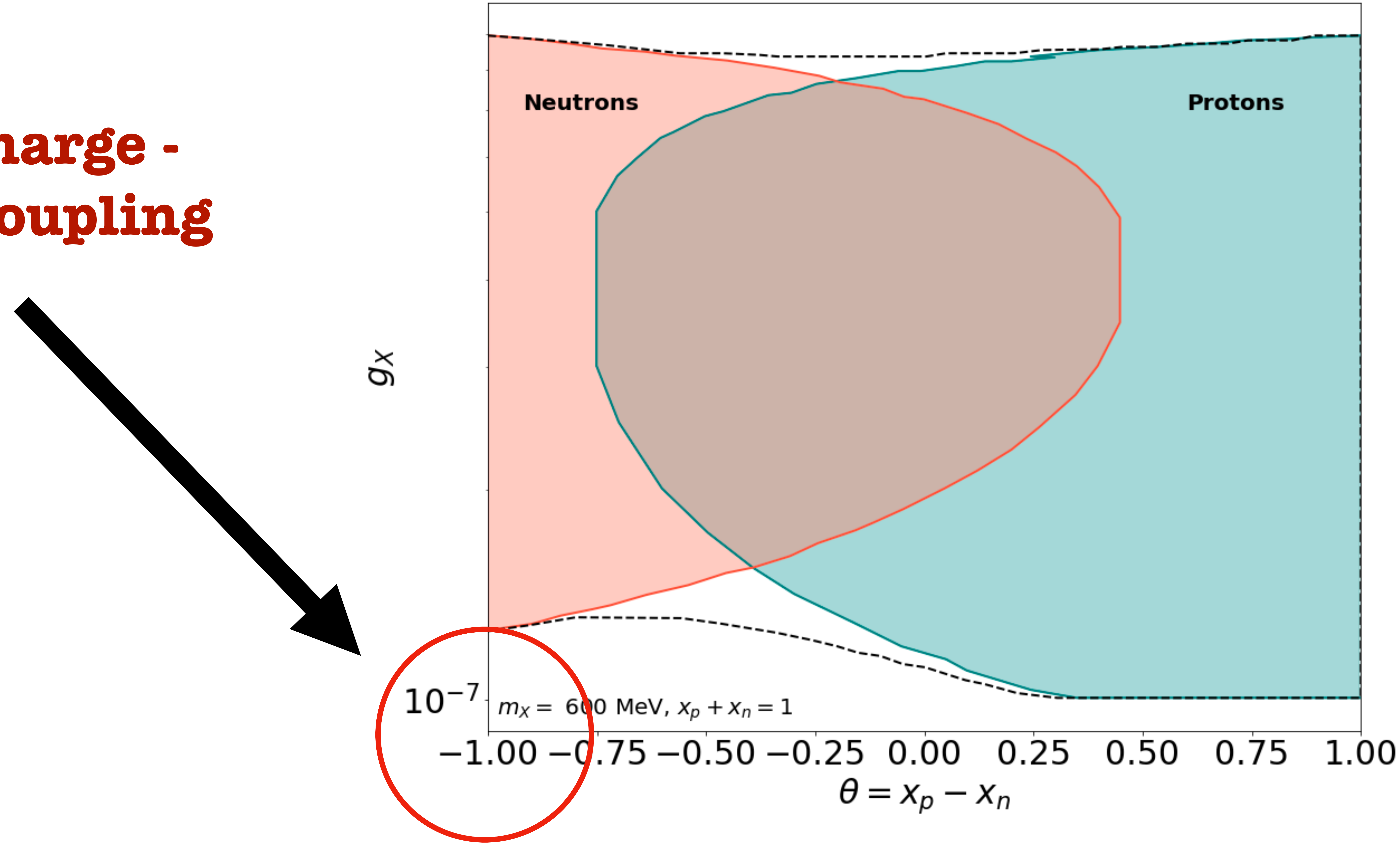
$$x_p + x_n + x_e + x_{\nu_e} = 0$$

$$\theta = x_p - x_n \quad x_e = -(x_p + x_n)$$



Generic model - proton and neutron couplings

Protophobic charge -
Pure Neutron coupling



Neutron Bremsstrahlung:

Protophobic gauge bosons

Protophobic model

$$x_p = 0$$
$$x_n = 1$$

$$\mathscr{L}_X = -\frac{1}{2}m_X^2 X_\mu X^\mu - g_X X_\mu \sum_f x_f \bar{f}\gamma^\mu f$$

f	x_f
u, c, t	-1/3
d, s, b	2/3
e, μ, τ	-1
ν_e, ν_μ, ν_τ	0

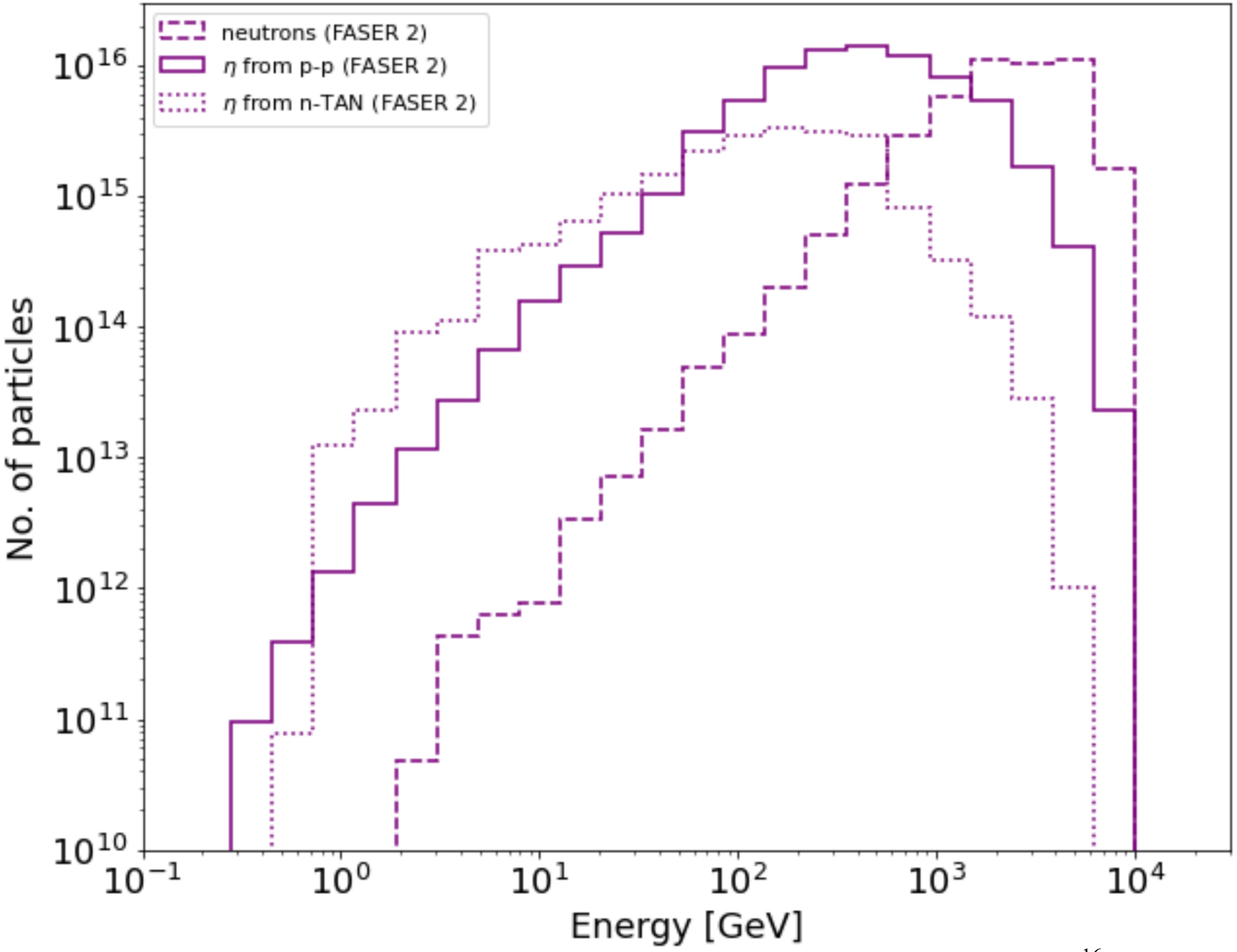
Sources:

1. Neutron Bremsstrahlung
2. Neutral meson decays (Dominantly η)

- BR$(\pi^0 \to X\gamma) = 0$
- At LHC, $N(\eta') < N(\eta)$

[1] Ilten, Soreq, et.al., arxiv.org/abs/1801.04847

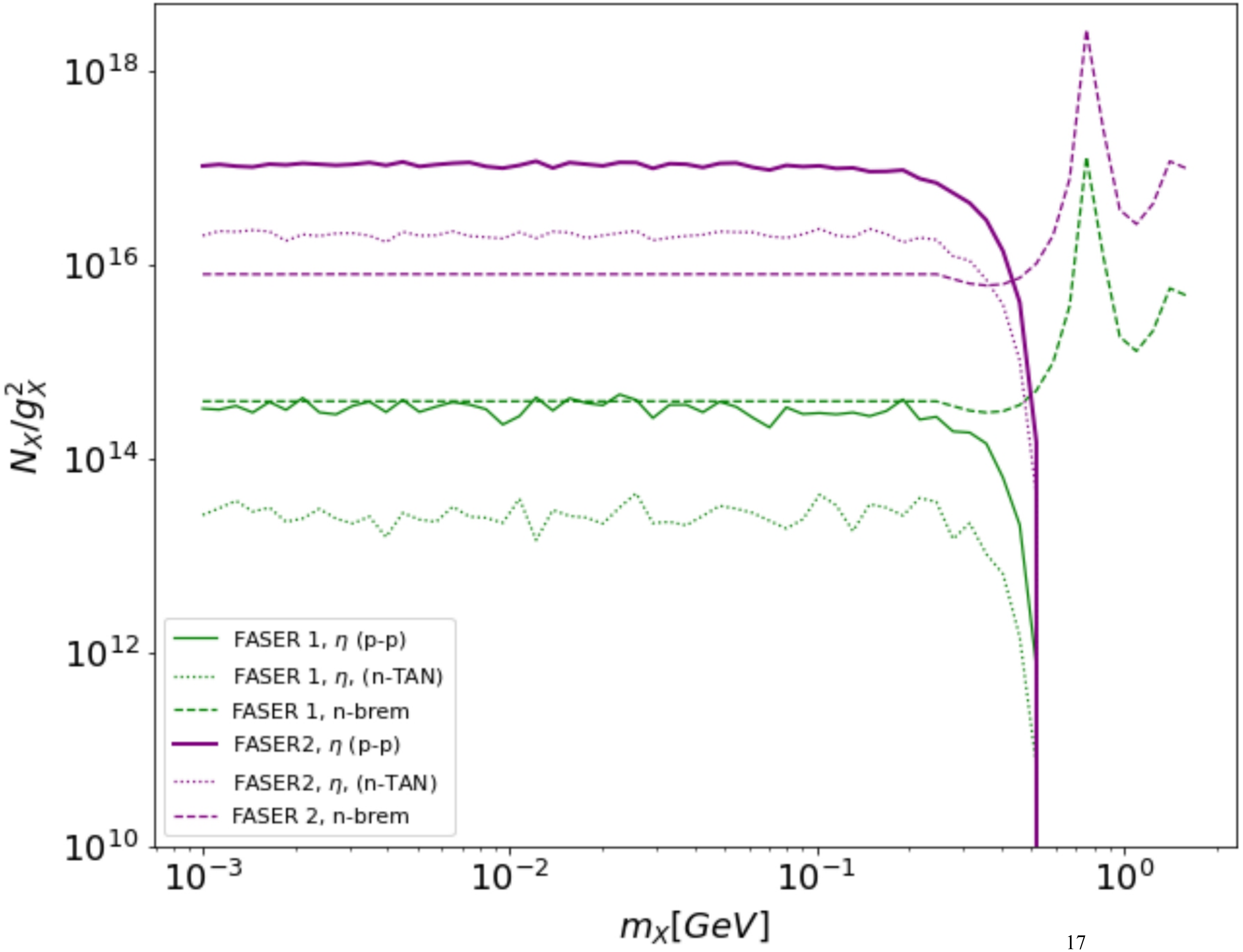
X Boson: Parent flux



- η mesons from IP [1] are higher in number and energy than those from n-TAN/TAXN [2]
- No. of neutrons ~ No. of η mesons
- We observe similar features at FASER, with $\mathcal{O}(10)$ lesser magnitude

[1] Neutron-TAN: GEANT4 simulations by Hyunyong Kim
[2] IP: FORESEE package, Kling, Trojanowski arxiv.org/abs/2105.07077

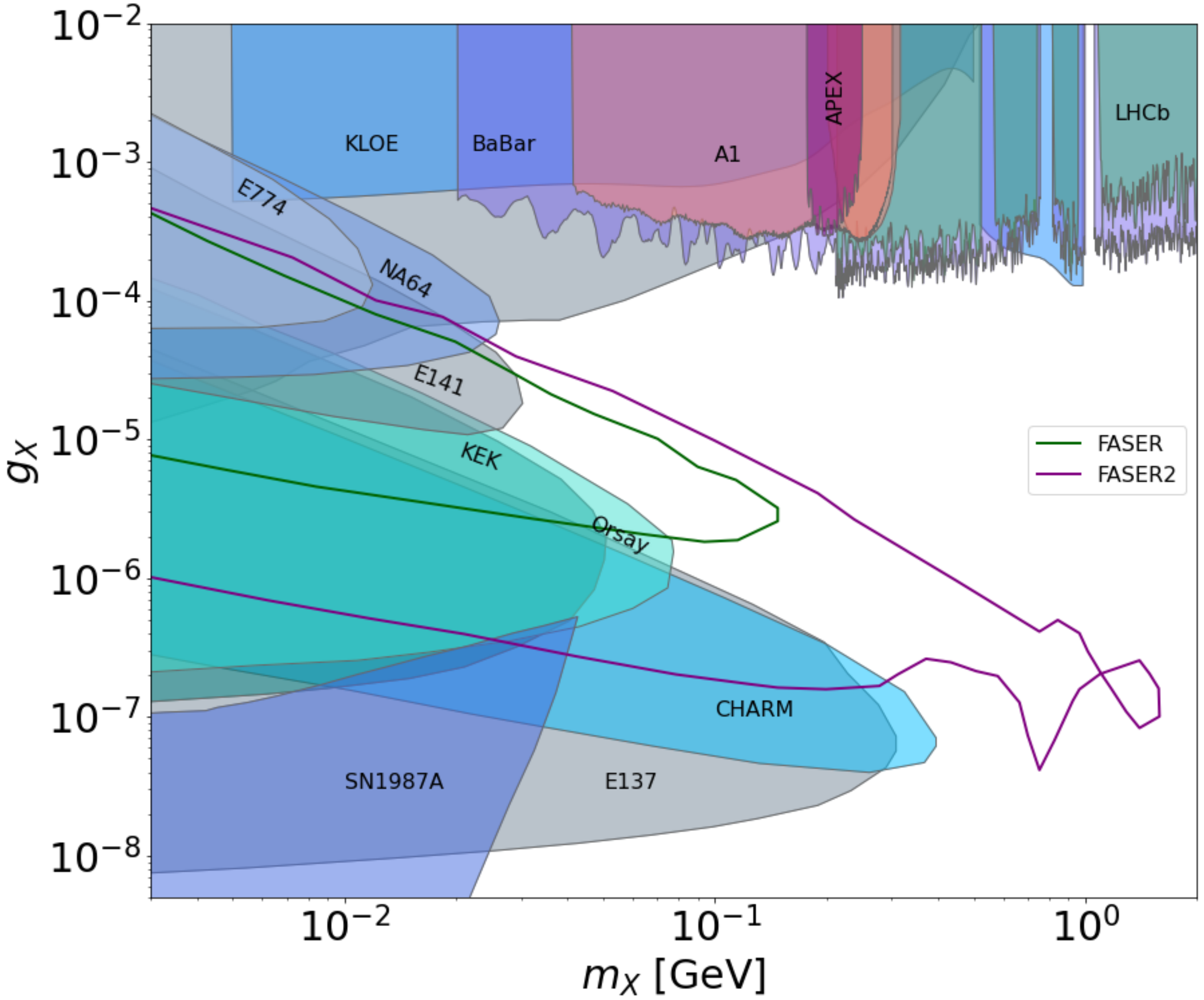
X Boson flux



- No. of bosons from η decays are higher in statistics
- X from neutron bremsstrahlung are higher in energy

Sensitivity

No. of events: 3



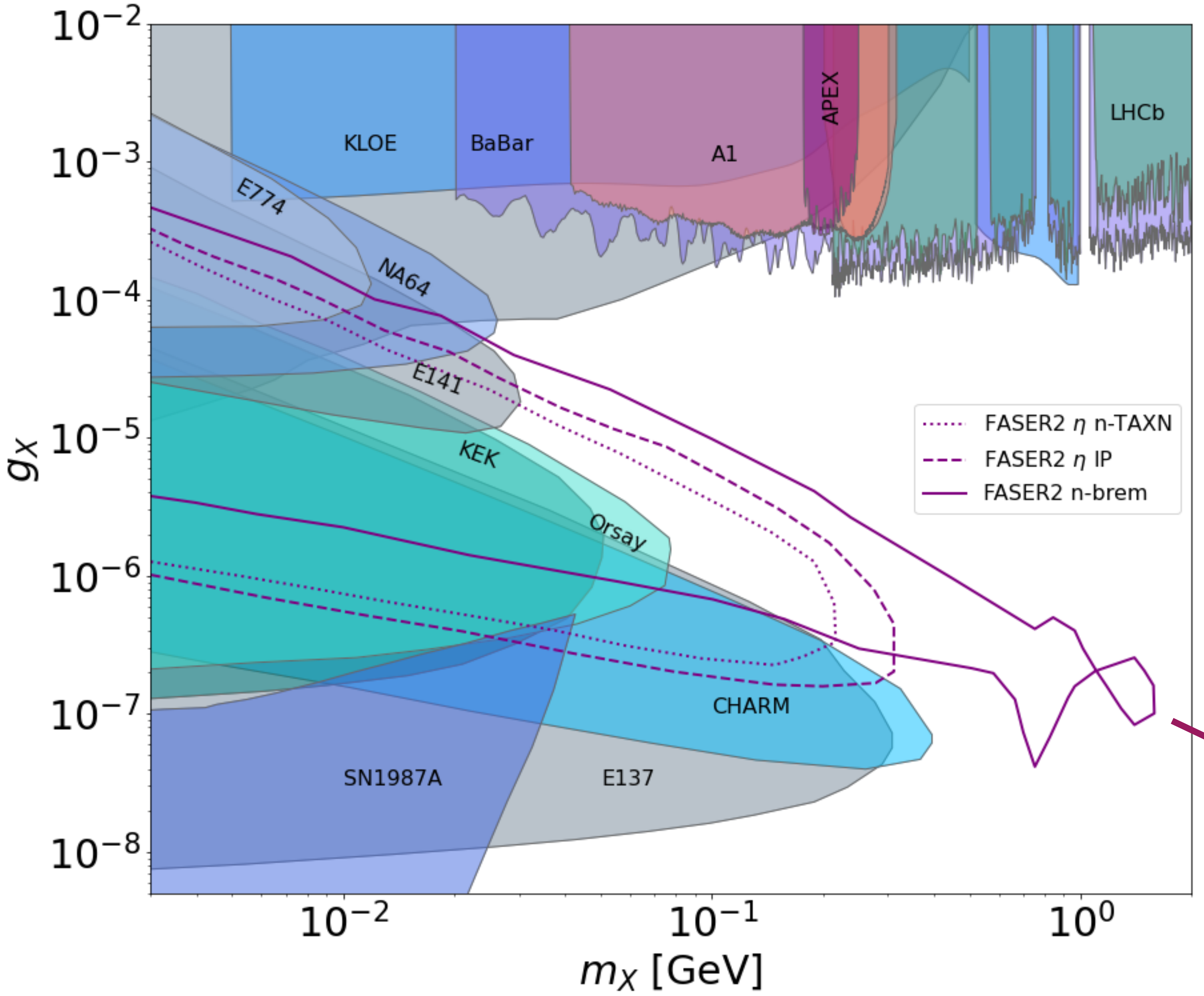
Constraints:

- Electron beam-dump: E137, E141, E774, NA64, Orsay
- Proton beam-dump: CHARM
- e^+e^- collider: BaBar
- pp collider: LHCb
- Others: A1, APEX, Υ, η, B decays

Final states: $e^+e^-, \mu^+\mu^-$, hadrons

Sensitivity

No. of events: 3



Inferences:

1. η decays: Pushes sensitivity to lower couplings $\mathcal{O}(10^{-6})$

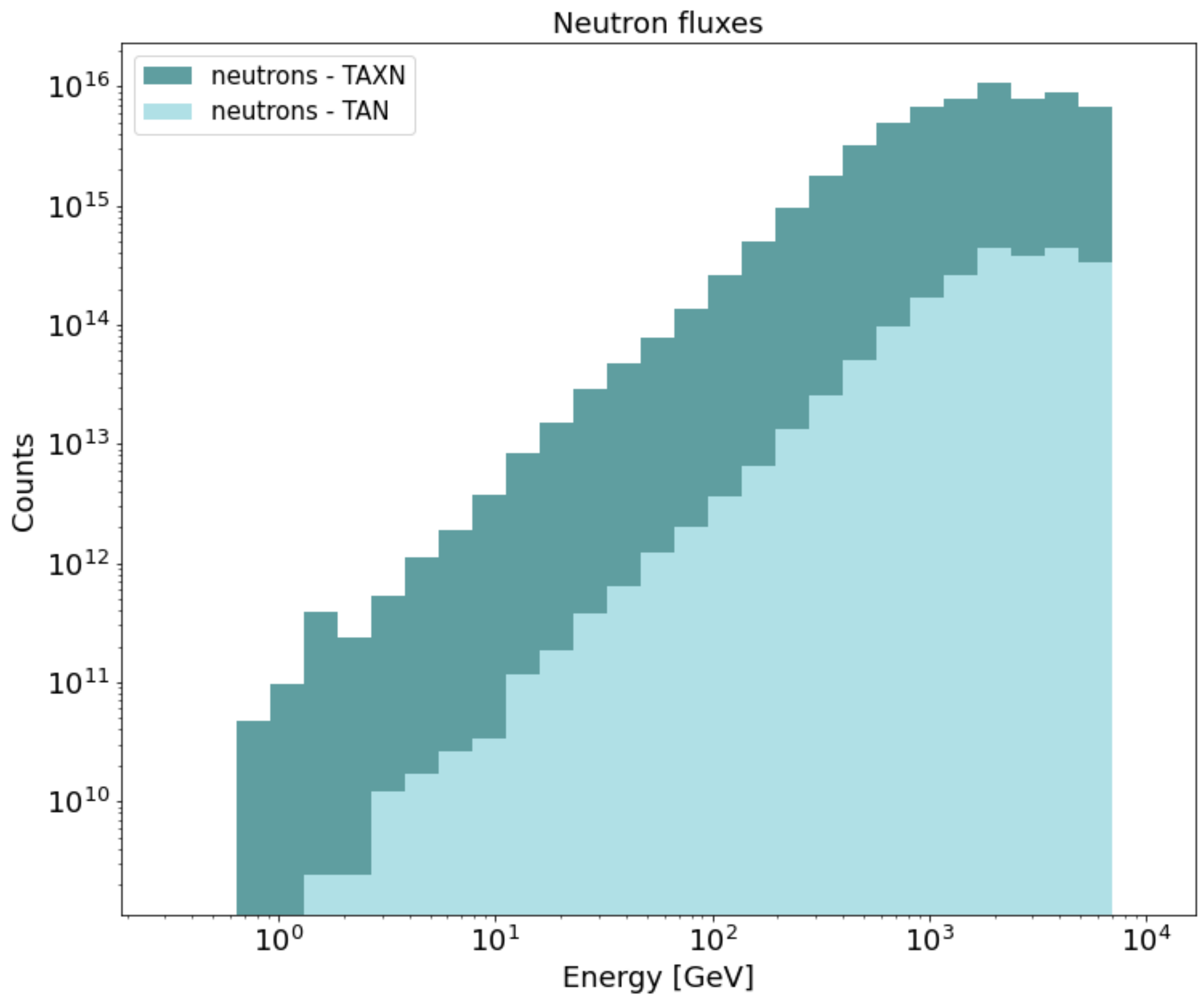
2. *Neutron Bremsstrahlung*: Extends to larger masses (> 1 GeV), as compared to *proton bremsstrahlung*.

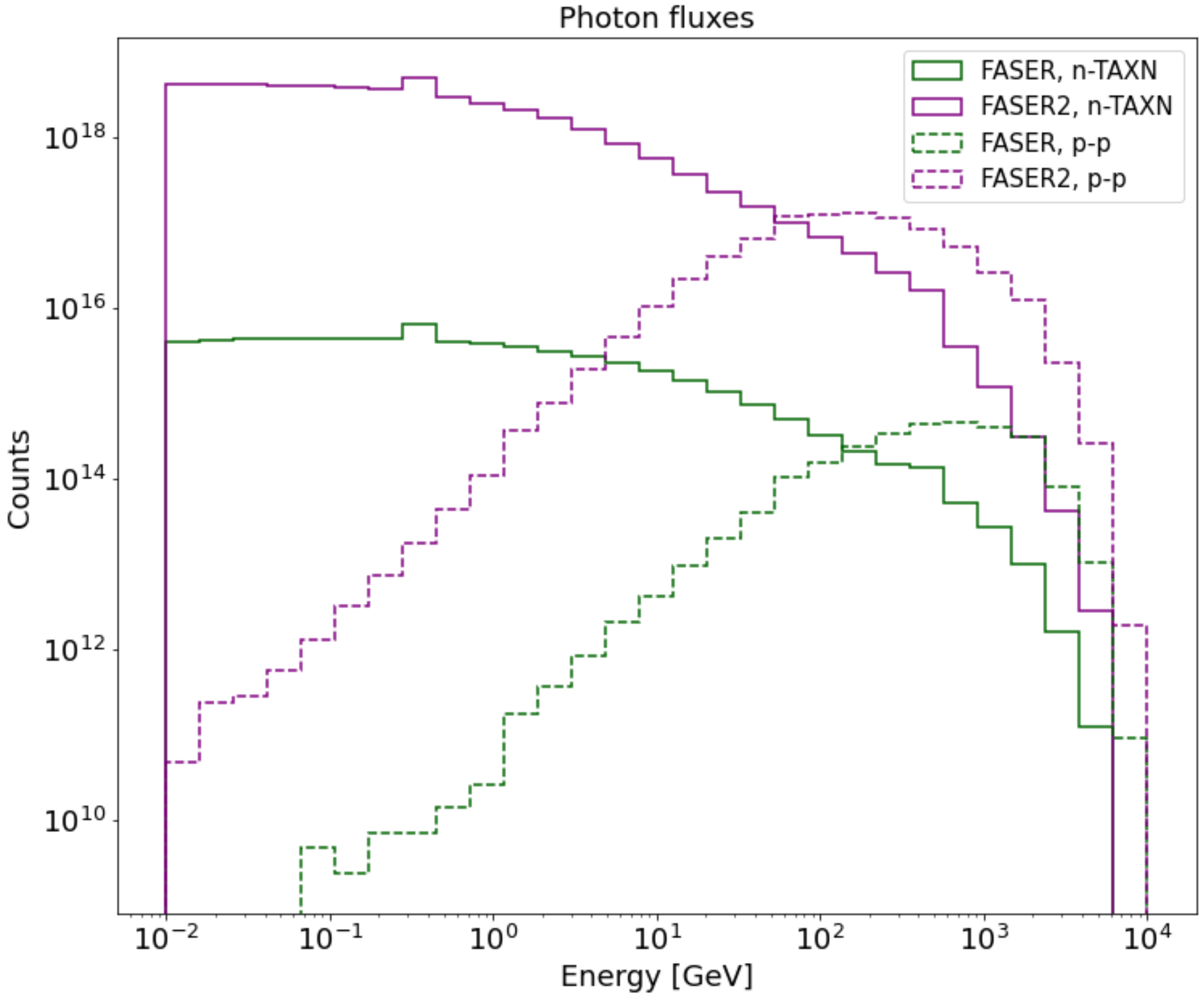
Feature in the neutron form factor

Secondary particles at neutron dump

Neutrons-on-target: Photons

Neutrons induce ***larger flux*** of ***soft*** photons



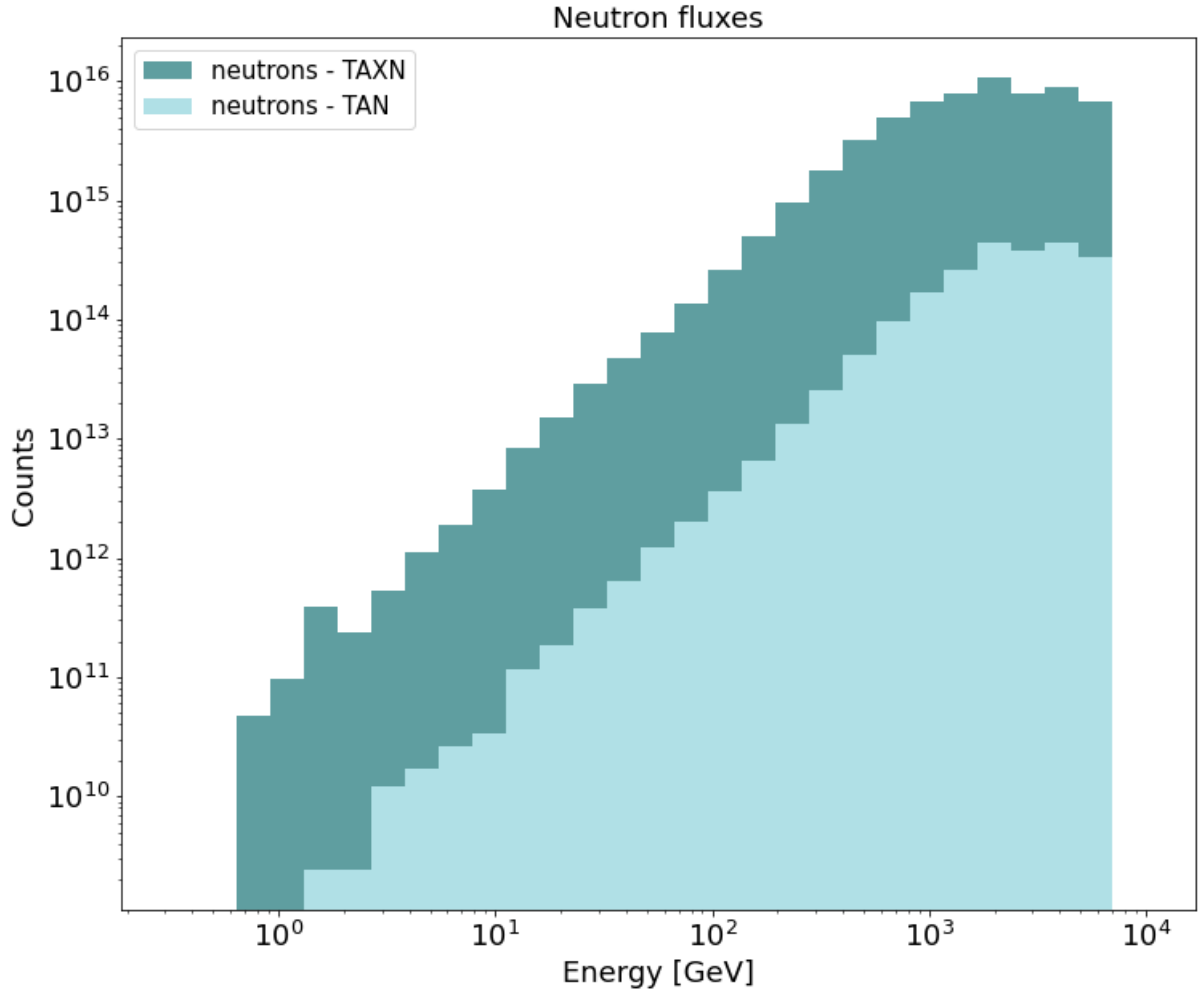


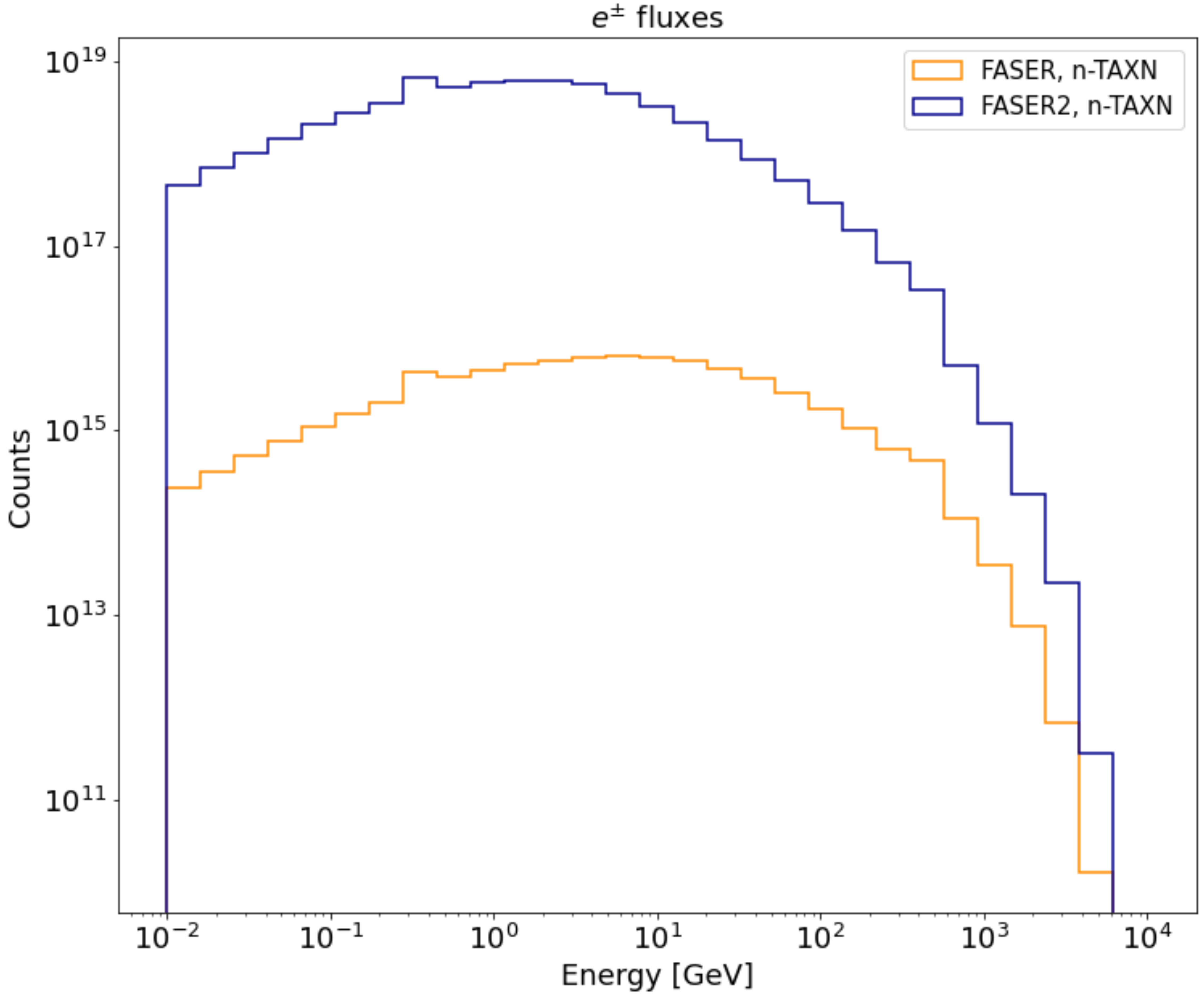
$L_{F1} = 150\ \text{fb}^{-1} \quad L_{F2} = 3\ \text{ab}^{-1}$

[1] Simulations by Hyunyong Kim
[2] FORESEE package, Kling, Trojanowski arxiv.org/abs/2105.07077

Neutrons-on-target: $e^{\pm}$

Neutrons are the ***only source*** of $e^{\pm}$





$L_{F1} = 150\ \text{fb}^{-1} \quad L_{F2} = 3\ \text{ab}^{-1}$

[1] Simulations by Hyunyong Kim
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Secondary particles at neutron dump:

Axion-like Particles

Axion-like Particles - electron couplings

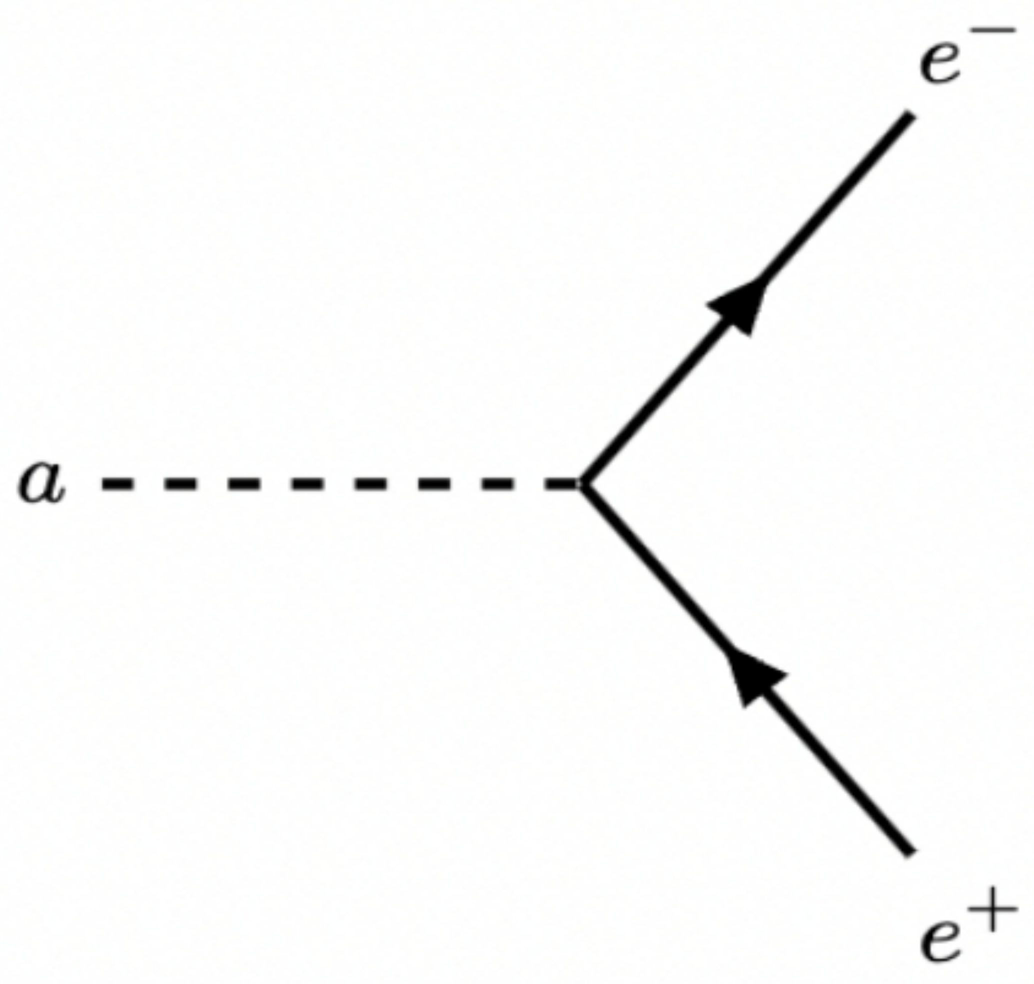
$$\mathcal{L}_{ae} \supset -\frac{1}{2}m_a^2 a^2 - i g_{aee}\bar{e}\gamma^5 e$$

ALP productions:

- Compton-like scattering : $\gamma e^- \to a e^-$
- Associated production : $e^- e^+ \to a\gamma$
- Resonance, electron-bremsstrahlung (subdominant)

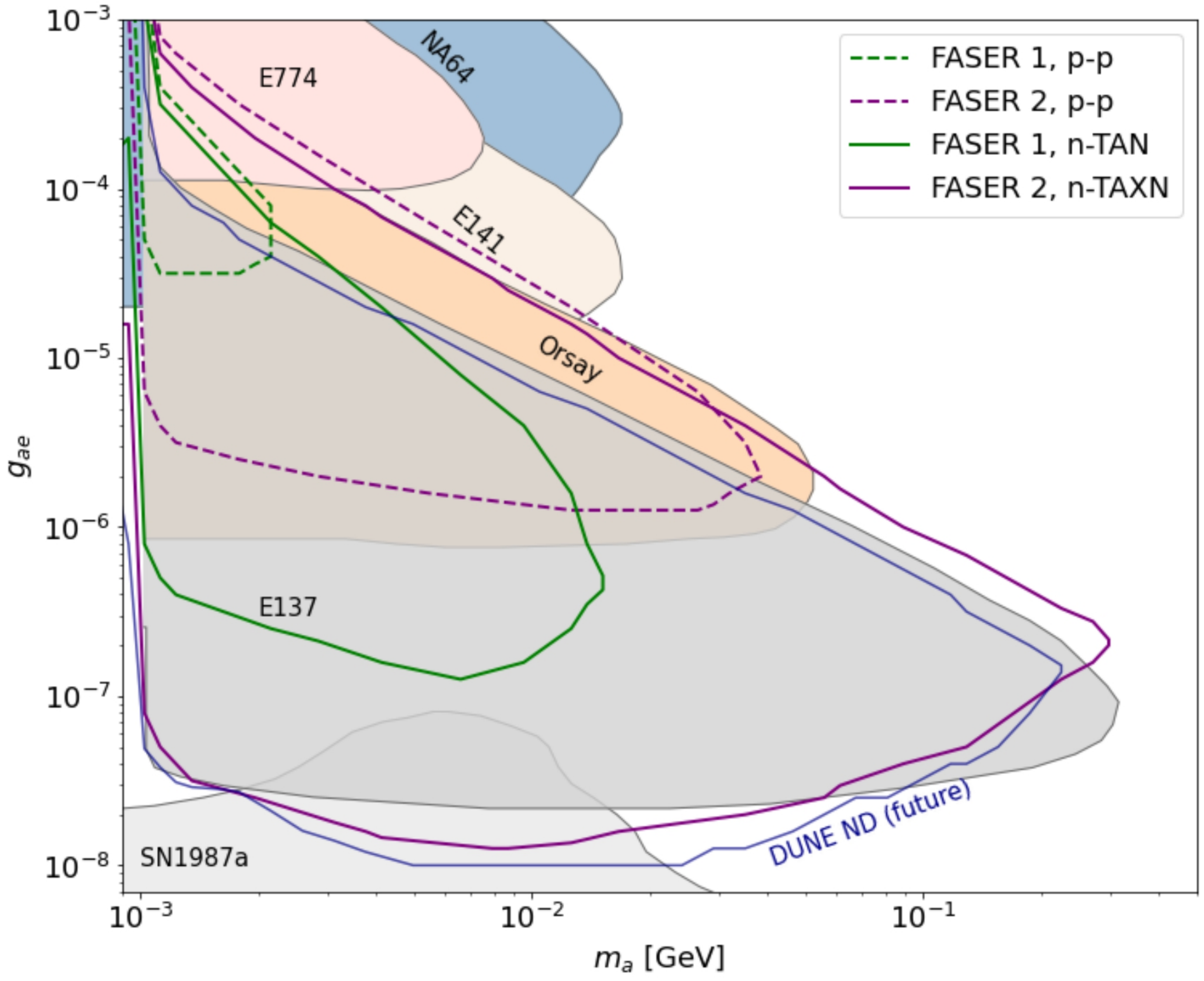
ALP detection:

- Decays : $a \to e^+ e^-$ for $m_a > 1$ MeV
- Scattering channels (subdominant)



See also:
· Feng, Galon, et.al, arxiv.org/abs/1806.02348
· Buonocore, Kling, Rottoli, arxiv.org/abs/2309.12793
· Kling, Quilez, arxiv.org/abs/2204.03599

Sensitivity - ALPs with electron coupling



No. of events = 3
$E_{threshold} = 30$ MeV

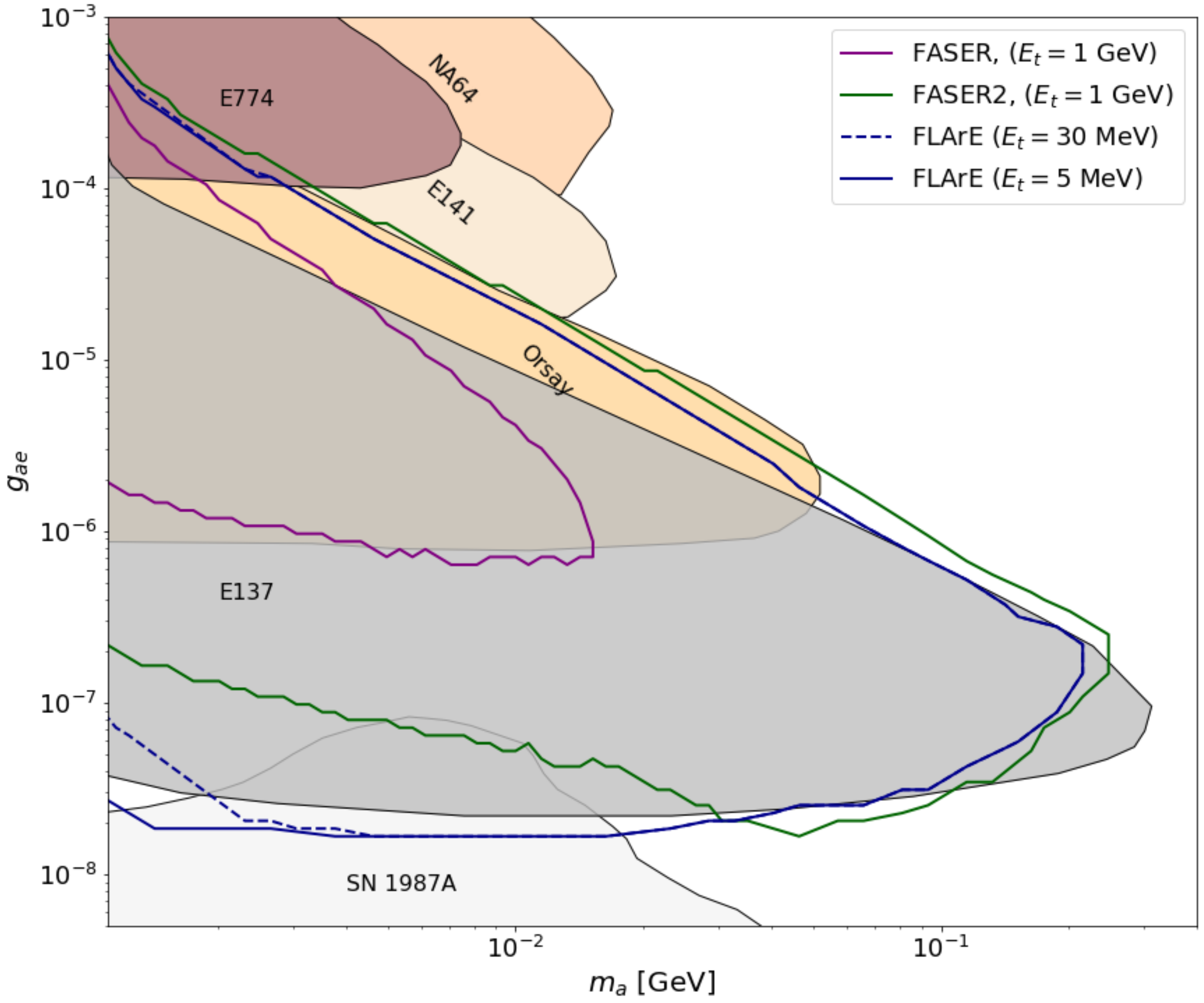
Features:

- Dotted lines: Photons from IP - Compton-like scattering.
- Solid lines: Photons, positrons from neutron interactions

Inferences:

- S-channel Compton-like scattering- favored for soft photons
- FASER2 can explore MeV scale ALPs with $\mathcal{O}(10^{-6})$ couplings.

ALPs with electron couplings at FLArE



Energy thresholds for FASER:

$E_{threshold} = 1$ GeV

Energy thresholds for FLArE:

Single electron:

$E_{threshold} = 30$ MeV

Two electron:

$E_{threshold} = 5$ MeV

For existing studies in FLArE:

- Feng, Kling, et.al., arxiv.org/abs/2203.05090
- Kling, Kuo, Trojanowski, Tsai, arxiv.org/abs/2205.09137
- Jodlowski, arxiv.org/abs/2305.16781

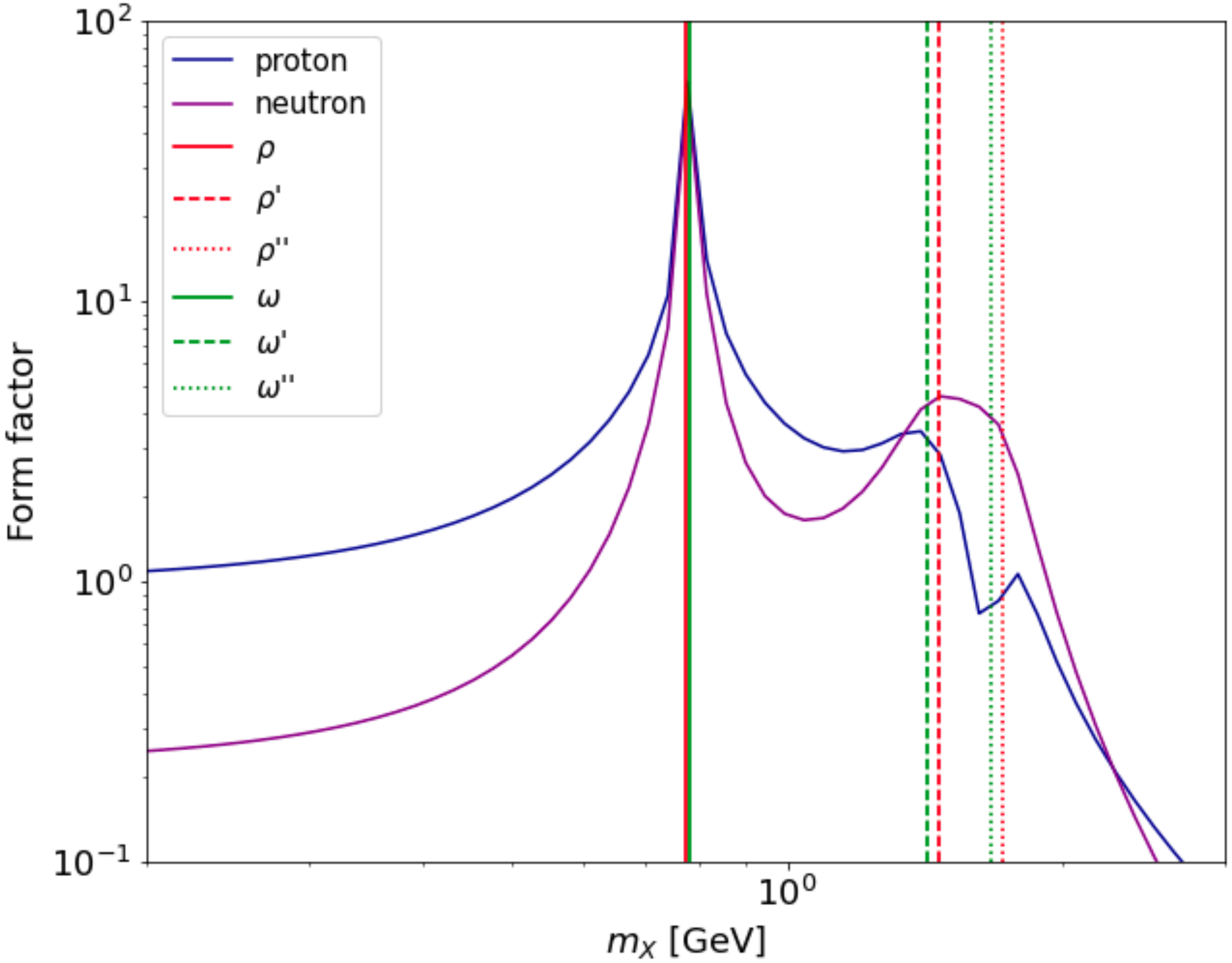
Conclusions

Neutrons - usually studied in the context of backgrounds - can be used to probe new physics.

1. **Neutron bremsstrahlung**
    - Probes *larger masses* than proton bremsstrahlung
    - Applied in other baryonic models which contain scalars, gauge bosons, etc.
2. **Neutron secondary particles**
    - Probing flavor-specific new physics - can extend to other leptophilic new physics particles.
    - FLArE - low energy neutron induced final states - complement FASER searches.

Backup

Proton and Neutron Form factors



$$F^n_{1,X}(p_X^2) = \sum_\omega \frac{f_\omega m_\omega^2}{m_\omega^2 - p_X^2 - i m_\omega \Gamma_\omega} - \sum_\rho \frac{f_\rho m_\rho^2}{m_\rho^2 - p_X^2 - i m_\rho \Gamma_\rho}$$

$$F^p_{1,X}(p_X^2) = \sum_\omega \frac{f_\omega m_\omega^2}{m_\omega^2 - p_X^2 - i m_\omega \Gamma_\omega} + \sum_\rho \frac{f_\rho m_\rho^2}{m_\rho^2 - p_X^2 - i m_\rho \Gamma_\rho}$$

Where,

$$f_\omega = \{1.011, -0.881, 0.369\}; f_\rho = \{0.616, 0.223, -0.339\}$$

Protophobic model

$$x_p = 0$$
$$x_n = 1$$

$$\mathcal{L}_X = -\frac{1}{2}m_X^2 X_\mu X^\mu - g_X X_\mu \sum_f x_f \bar{f}\gamma^\mu f$$

f	x_f
u, c, t	-1/3
d, s, b	2/3
e, μ, τ	-1
ν_e, ν_μ, ν_τ	0

$BR(\pi^0 \to X\gamma) = 0$; For choice of x_u, x_d

$$BR(\eta, \eta' \to X\gamma) = 2BR(\eta, \eta' \to \gamma\gamma)\beta_{\eta.\eta'}\left(1 - \frac{m_X^2}{m_{\eta,\eta'}}\right)$$

$$\beta_\eta = 0.26$$
$$\beta_{\eta'} = 1.22$$

$$BR(\eta \to \gamma\gamma) = 0.39$$
$$BR(\eta' \to \gamma\gamma) = 0.02$$

[1] Ilten, Soreq, et.al., arxiv.org/abs/1801.04847

Calculating beta for protophobic gauge bosons

$$\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \quad ; \quad \eta_0 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \quad \Rightarrow \quad \begin{bmatrix} \eta \\ \eta' \end{bmatrix} = \begin{bmatrix} \cos\theta_p & -\sin\theta_p \\ \sin\theta_p & \cos\theta_p \end{bmatrix} \begin{bmatrix} \eta_8 \\ \eta_0 \end{bmatrix}$$

$$\phi_\eta(V_1, V_2) = \left[\frac{1}{f_8}\cos\theta_p(x_1^u x_2^u + x_1^d x_2^d - 2x_1^s x_2^s) - \frac{\sqrt{2}}{f_0}\sin\theta_p(x_1^u x_2^u + x_1^d x_2^d + x_1^s x_2^s)\right]^2$$

$$\phi_{\eta'}(V_1, V_2) = \left[\frac{1}{f_8}\sin\theta_p(x_1^u x_2^u + x_1^d x_2^d - 2x_1^s x_2^s) - \frac{\sqrt{2}}{f_0}\cos\theta_p(x_1^u x_2^u + x_1^d x_2^d + x_1^s x_2^s)\right]^2$$

$$\beta_\eta = \frac{\phi_\eta(X,\gamma)}{\phi_\eta(\gamma,\gamma)} = 0.29 \quad ; \quad \beta_{\eta'} = \frac{\phi_{\eta'}(X,\gamma)}{\phi_{\eta'}(\gamma,\gamma)} = 1.20$$

This is the proportionality of the meson couplings with gauge boson X to meson couplings with SM photon

FLArE

- 10 ton Liquid Argon detector - 620 m away from ATLAS IP
- ***Low energy thresholds*** : 5 MeV for e^+e^- final states
- Existing studies: Millicharged particles, Dark matter up-scattering
- Sensitive to ***low-energy neutron induced new physics.***