BSM physics from neutrons at FASER

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Particle Physics On The Plains
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PHYSICS AND
ASTRONOMY

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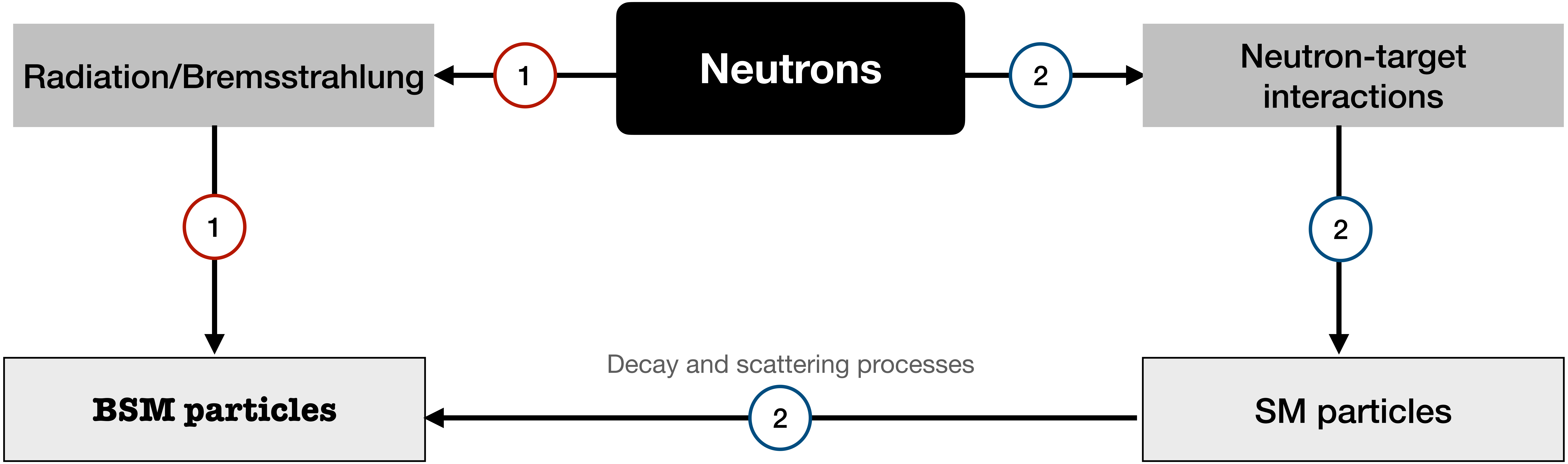
Motivation

Examples at FASER:
1. Gauge bosons
2. Axion-like Particles

BSM opportunities from **neutrons at FASER**



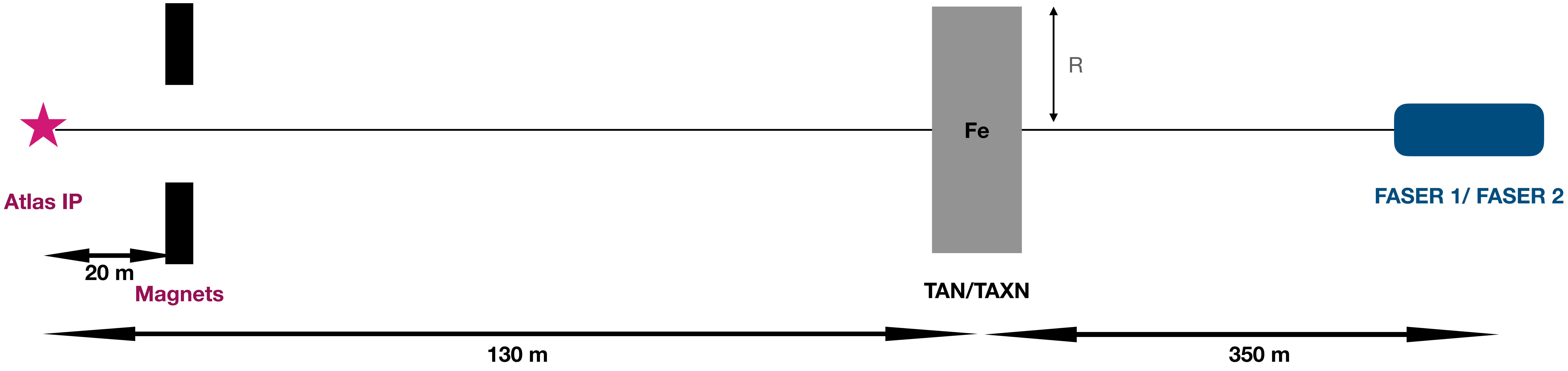
FASER TDR: arxiv.org/abs/1812.09139

FASER 1 and FASER 2

Detector	Radius (m)	Depth (m)	Material, R (m)	Luminosity
FASER 1	0.1	1.5	TAN, 0.06	$150\ fb^{-1}$
FASER 2	1	5	TAXN, 0.12	$3\ ab^{-1}$

Detection:
- Scintillators to separate charged particle tracks
- Calorimeter in the end of the detector

Primary signal:
- High energy electrons, muons and photons



FASER 1 and FASER 2 : Existing studies

$U(1)_X, U(1)_{B-L}$ gauge bosons;
Light scalars, Heavy neutral leptons.

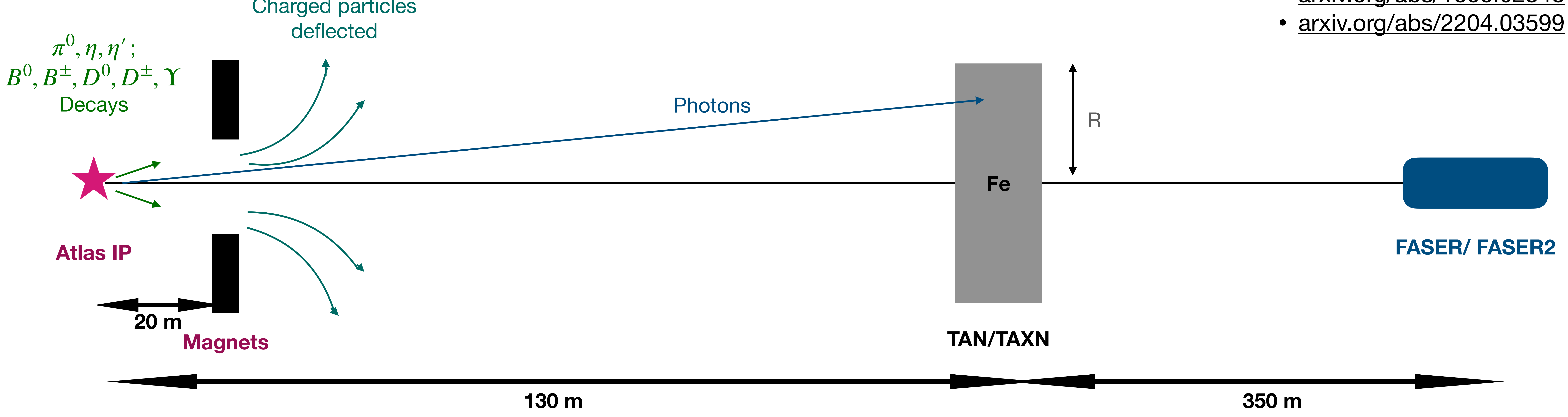
Deflected particles:
$\pi^\pm, K^\pm, e^\pm, \mu^\pm$, protons.

ALPs with photonic couplings

See also:

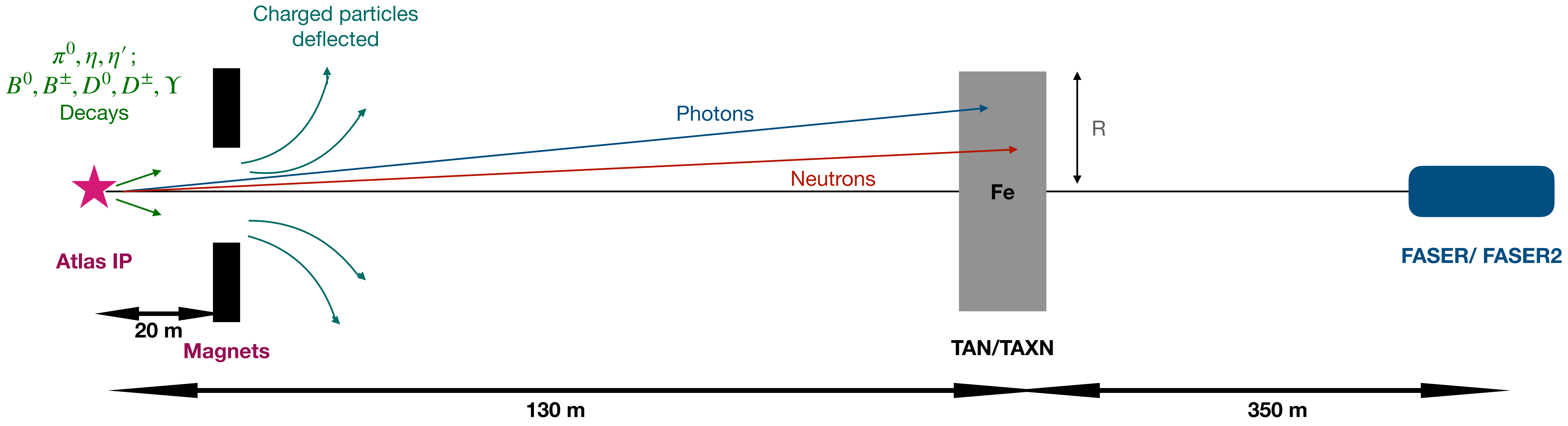
- arxiv.org/abs/1811.12522
- arxiv.org/abs/2212.06186
- arxiv.org/abs/1801.08947
- arxiv.org/abs/1806.02348
- arxiv.org/abs/2204.03599

Proton Bremsstrahlung



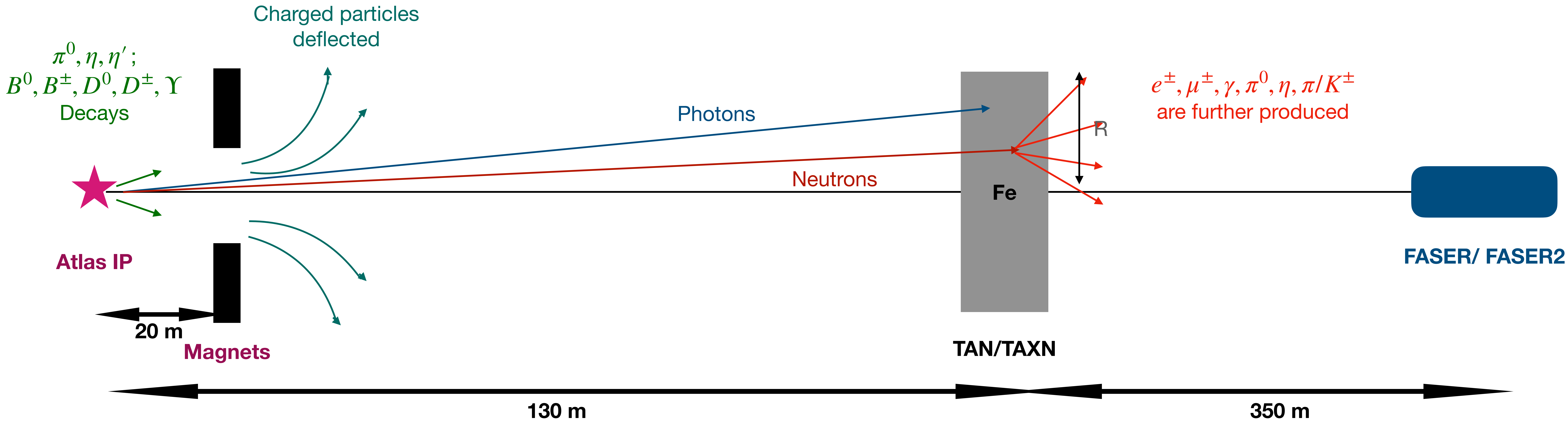
FASER 1 and FASER 2 : Neutrons

- Unaffected by the presence of magnets.



FASER 1 and FASER 2 : Neutrons

- Unaffected by the presence of magnets.
- Neutron-TAN/TAXN interactions - factory of particles



FASER 1 and FASER 2 : Neutrons

- Unaffected by the presence of magnets.
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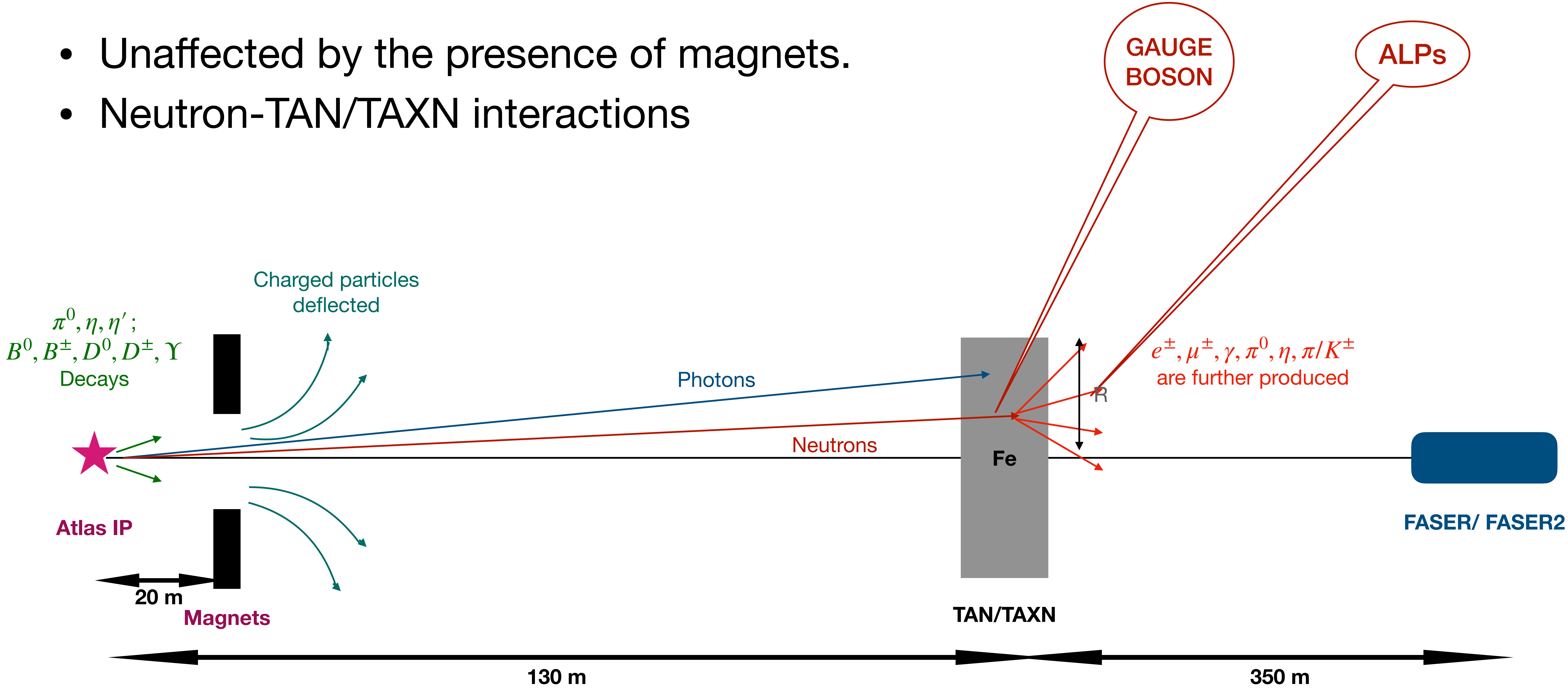
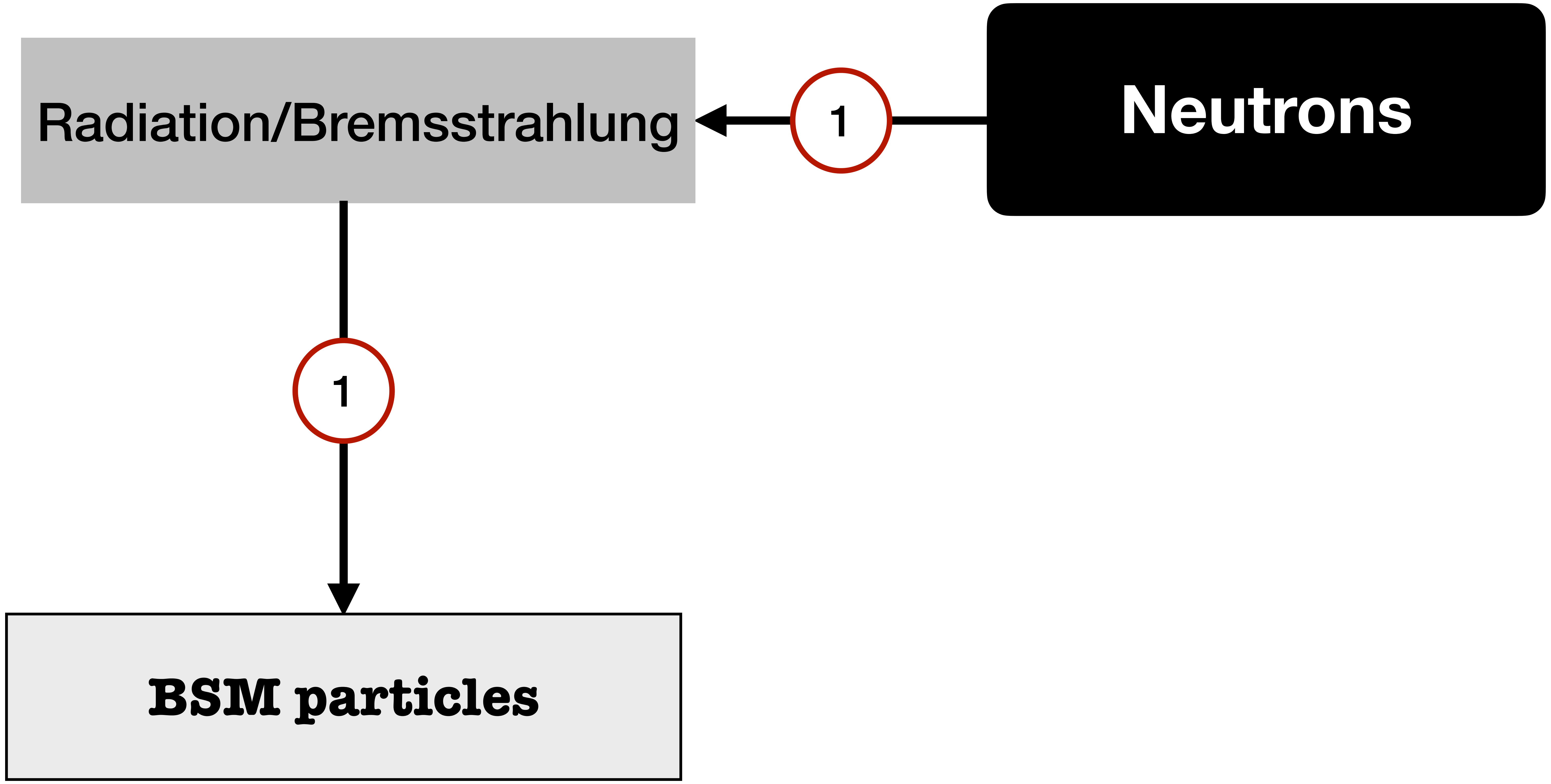




Radiation/Bremsstrahlung

1

Neutrons

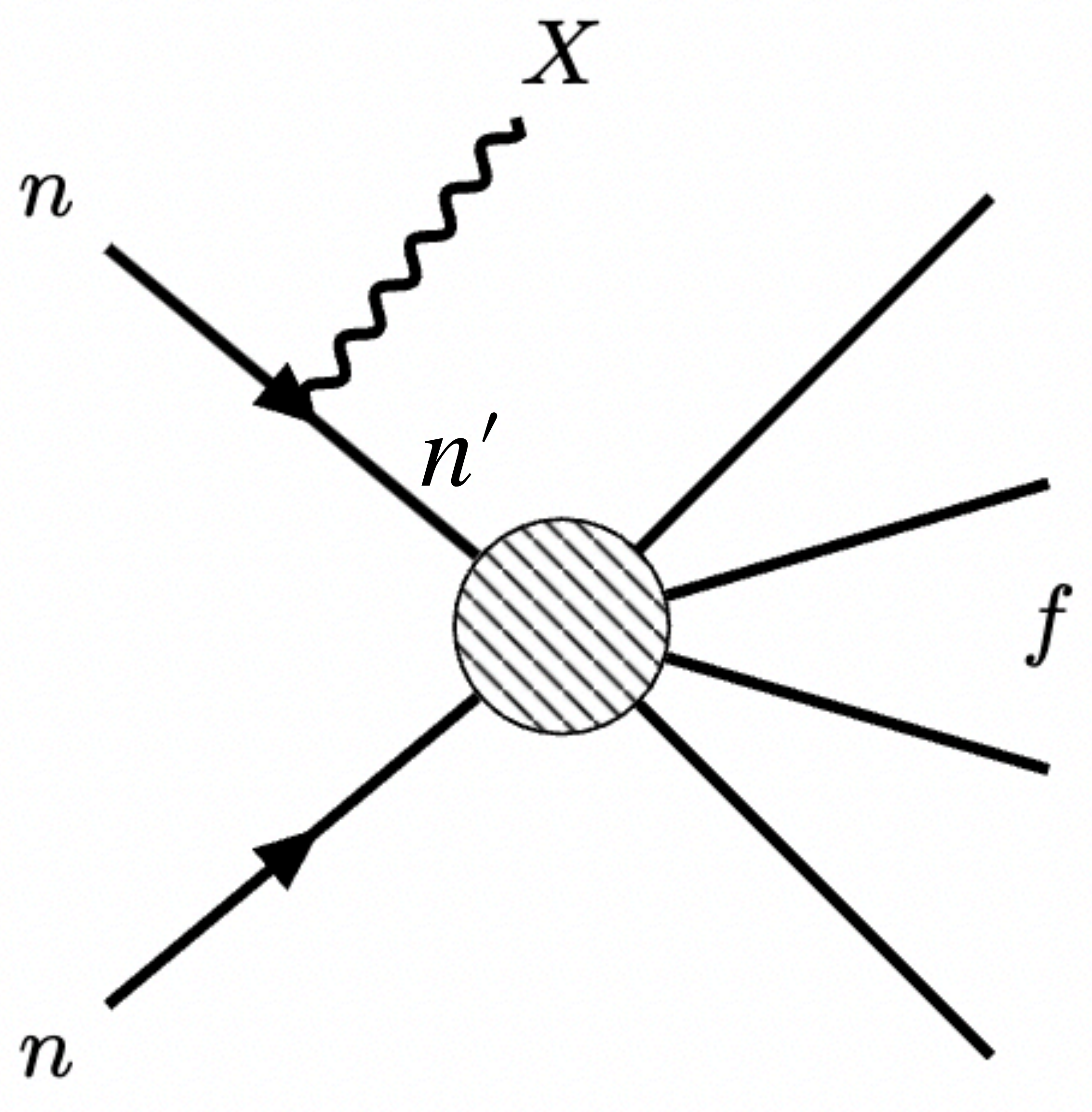
1

BSM particles

Neutron Bremsstrahlung

Initial State Radiation

Radiation from Non-Standard Diffractive (NSD) neutron processes



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

For more detals:
Abari, Ritz, arxiv.org/abs/2108.05900

Approximation for $dP_{n\to n'X}$:
$E_n/2 < E_X < E_n$
$\cos\theta_X \sim 1$

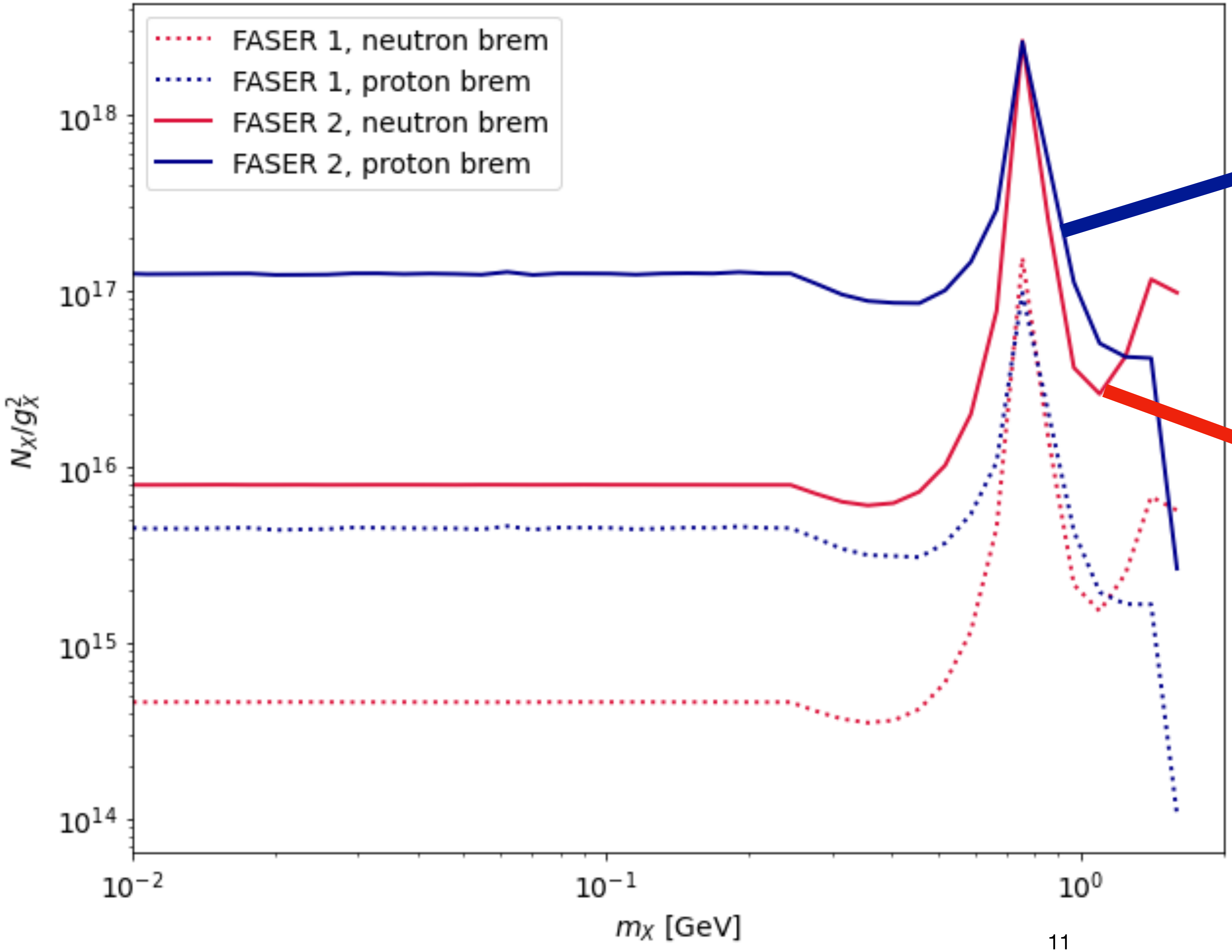
n_T : no.of target atoms per unit volume

λ_T: Mean free path length of neutron in material T

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

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

Generic model - proton and neutron couplings



Proton Bremsstrahlung:

- Enhanced due to high energy: $\sqrt{s} = 14\text{TeV}$
- Faces mild suppression from proton-proton collision

Neutron Bremsstrahlung:

- Suppressed as $\sqrt{s} \sim 40\text{GeV}$
- Enhancement due to larger availability of target neutrons

Different form factors - features near the peak

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

Generic model - proton and neutron couplings

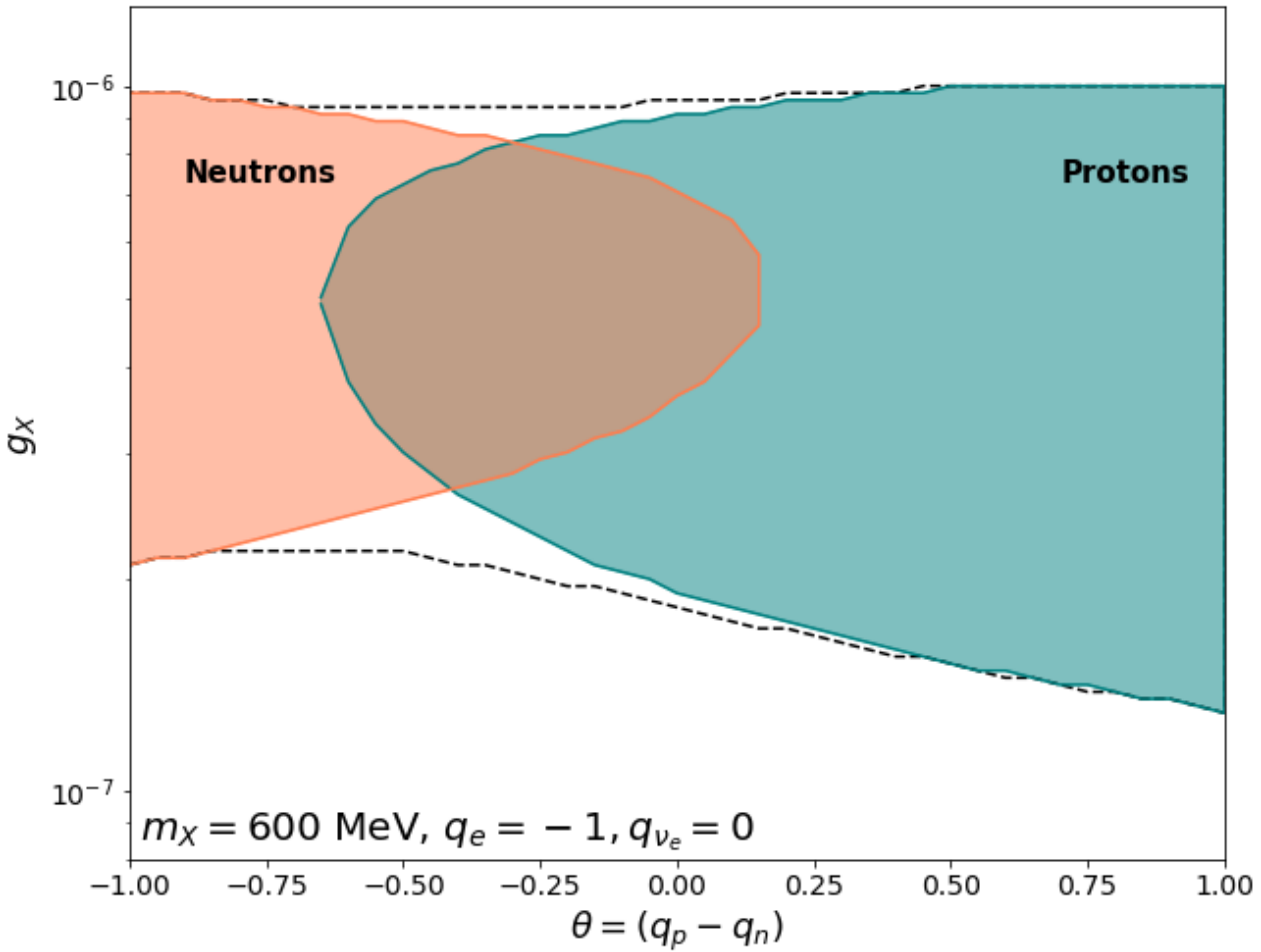
Anomaly free condition :

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

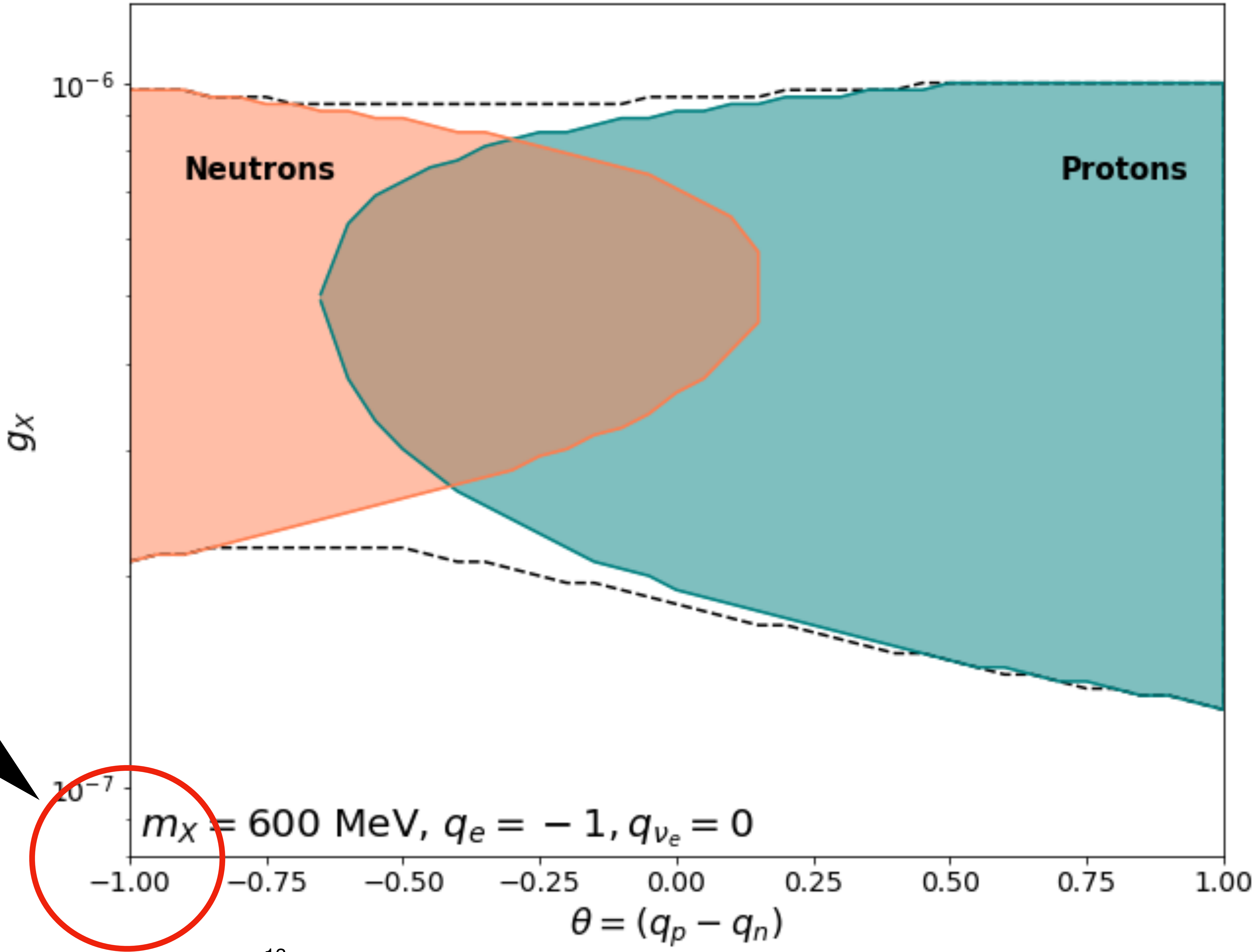
↓

$$q_p + q_n + q_e + q_{\nu_e} = 0$$

$$(q_p + q_n) = -q_e; \theta = (q_p - q_n)$$



Generic model - proton and neutron couplings



Protophobic charge -
Pure Neutron coupling

Neutron Bremsstrahlung: Protophobic Model

Protophobic model

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

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

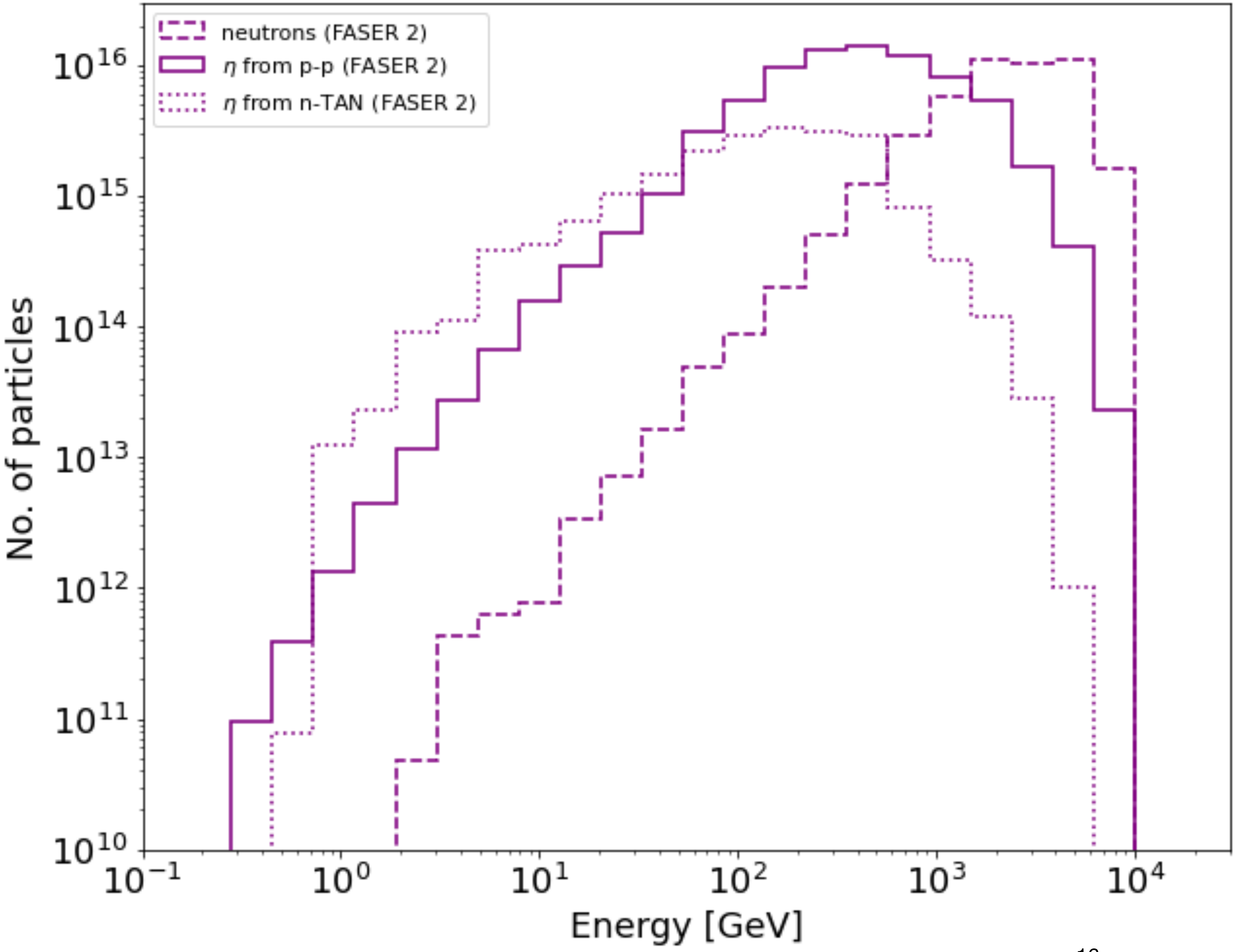
Sources:

1. Neutral Bremsstrahlung
2. Neutral meson decays ***(Dominantly*** η***)***
   - $BR(\pi^0 \to X\gamma) = 0$
   - At FASER, $N(\eta') < N(\eta)$

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

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

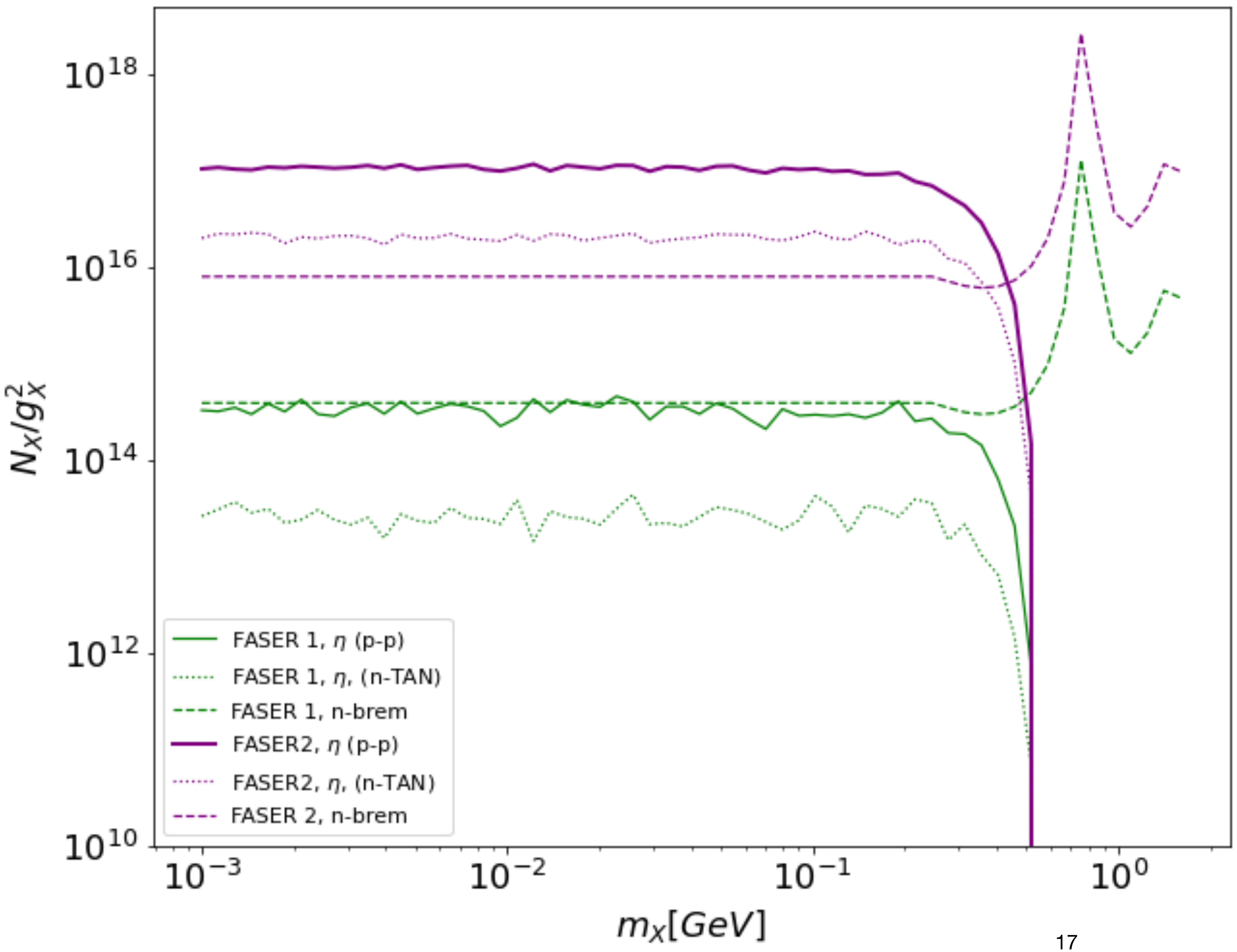
X boson flux : Parent flux



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

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

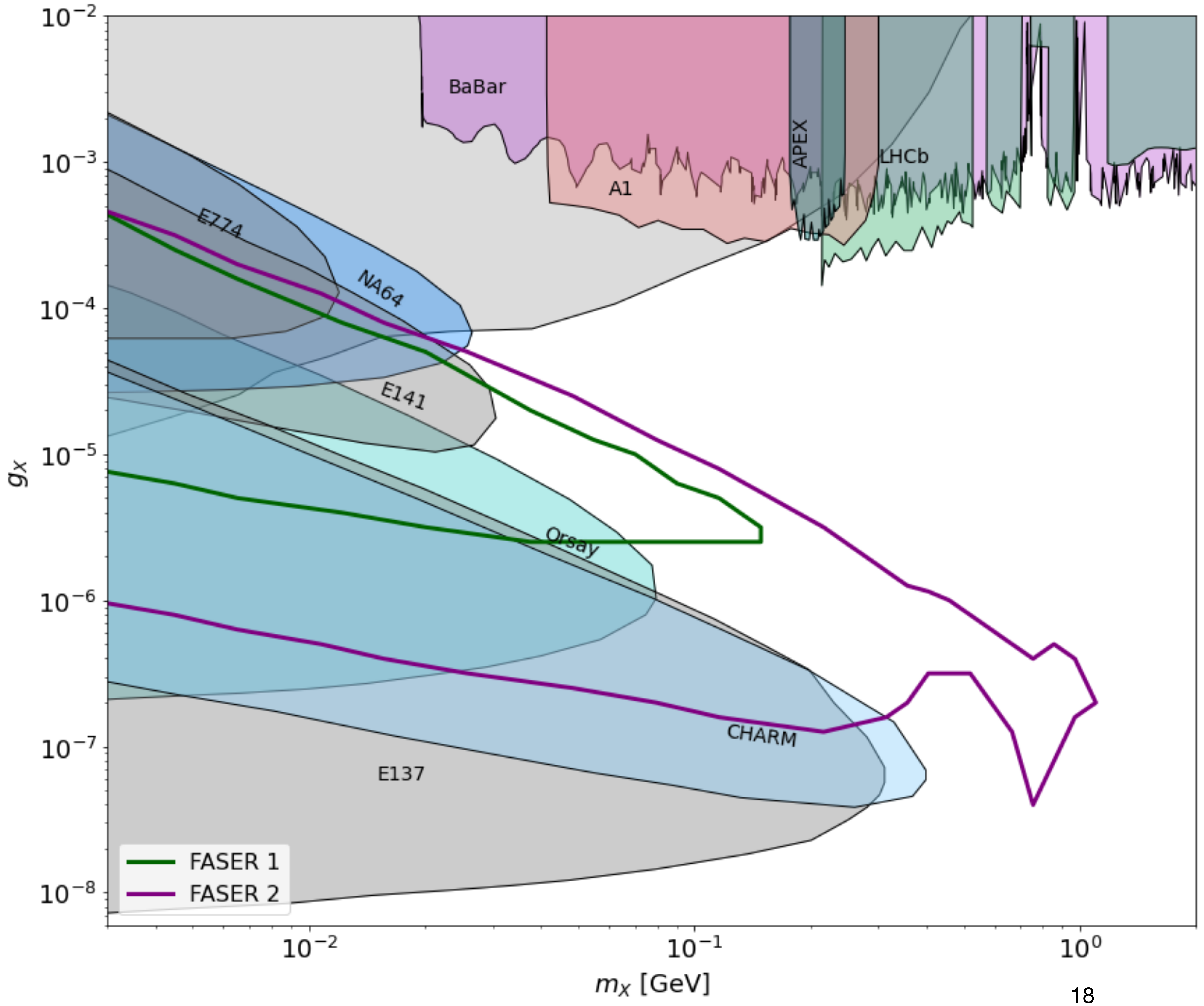
X boson flux



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

Sensitivity

No. events: 3



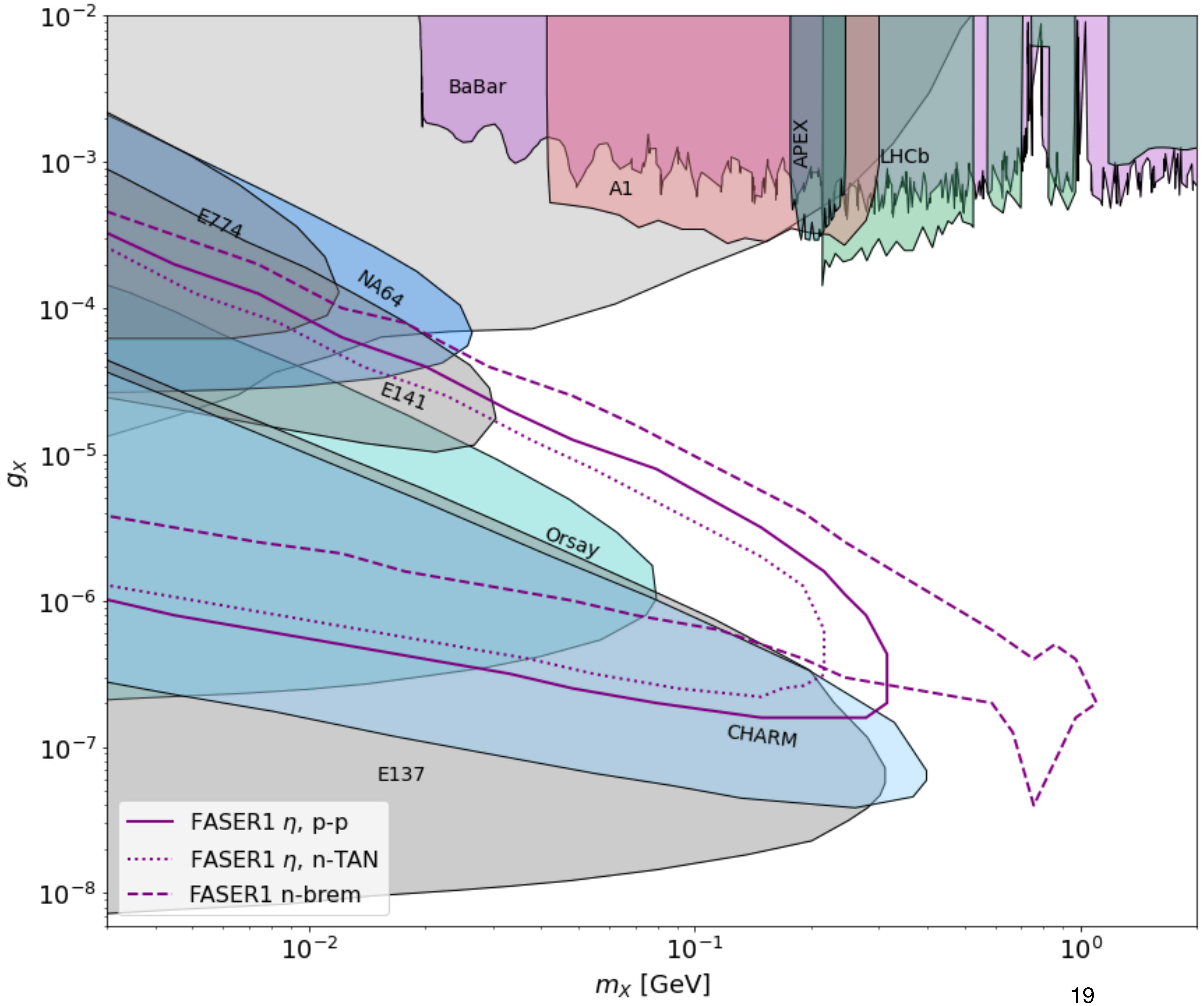
Constraints:

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

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

Sensitivity

No. events: 3



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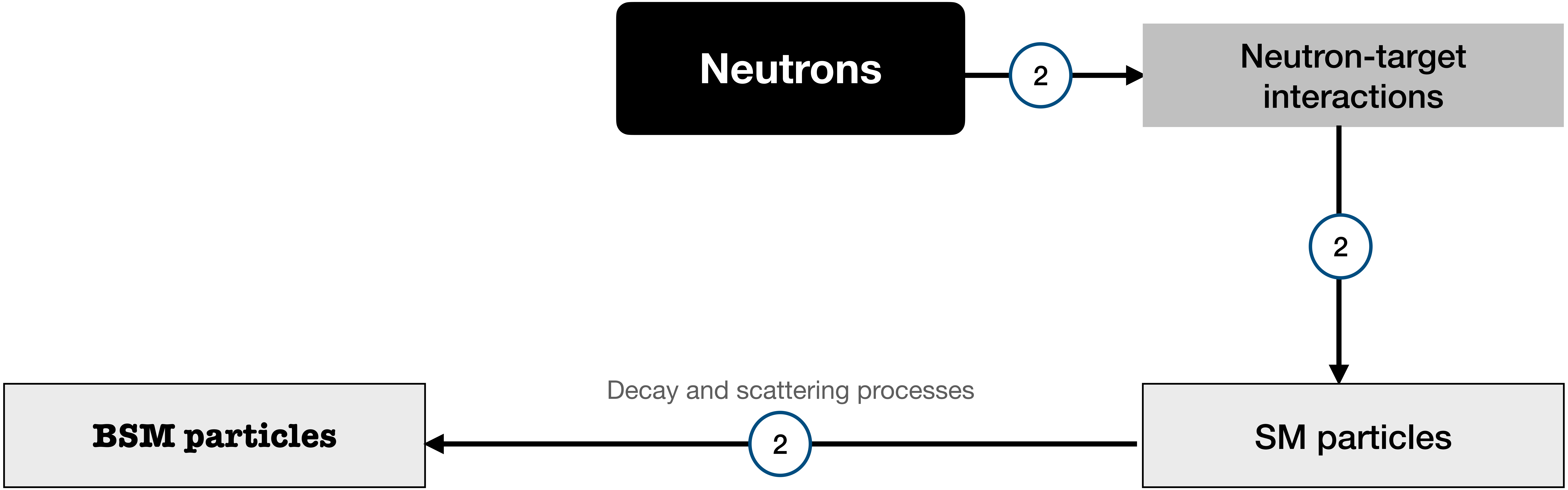
Inferences:

1. η *decays:* Facilitates FASER 2 to explore lower couplings $O(10^{-6})$
2. *Neutron Bremsstrahlung:* Extends to larger coupling and heavier masses



Neutrons

Neutron-target interactions

SM particles

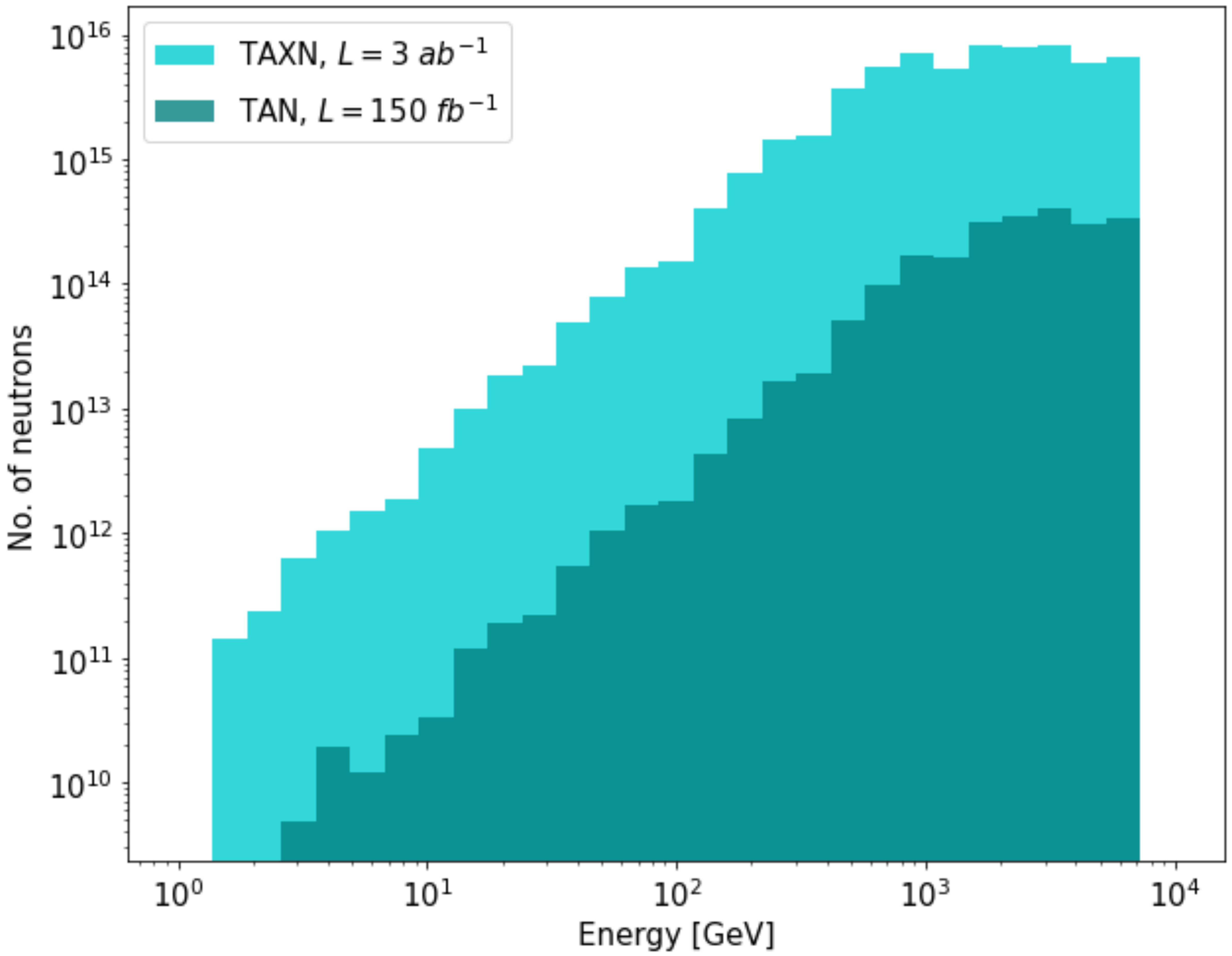
Decay and scattering processes

BSM particles

BSM from neutrons-on-target

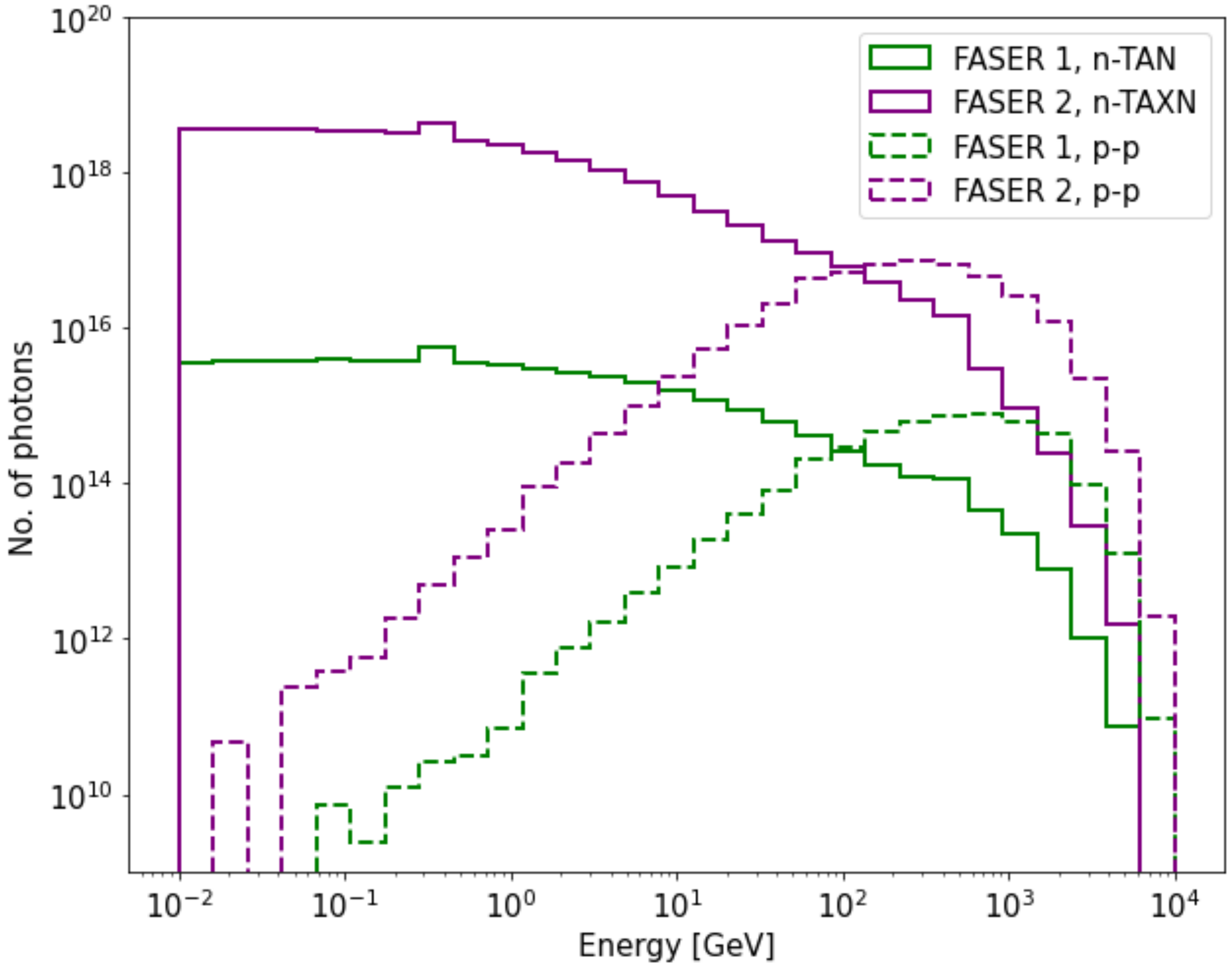
Neutron-on-target: Photons

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



$N_{TAN} = 2.2 \times 10^{15}$ $N_{TAXN} = 6.3 \times 10^{16}$

Photon fluxes from neutrons[1] and Atlas IP (EPOSLHC[2])



[1] GEANT4 simulations by Hyunyong Kim

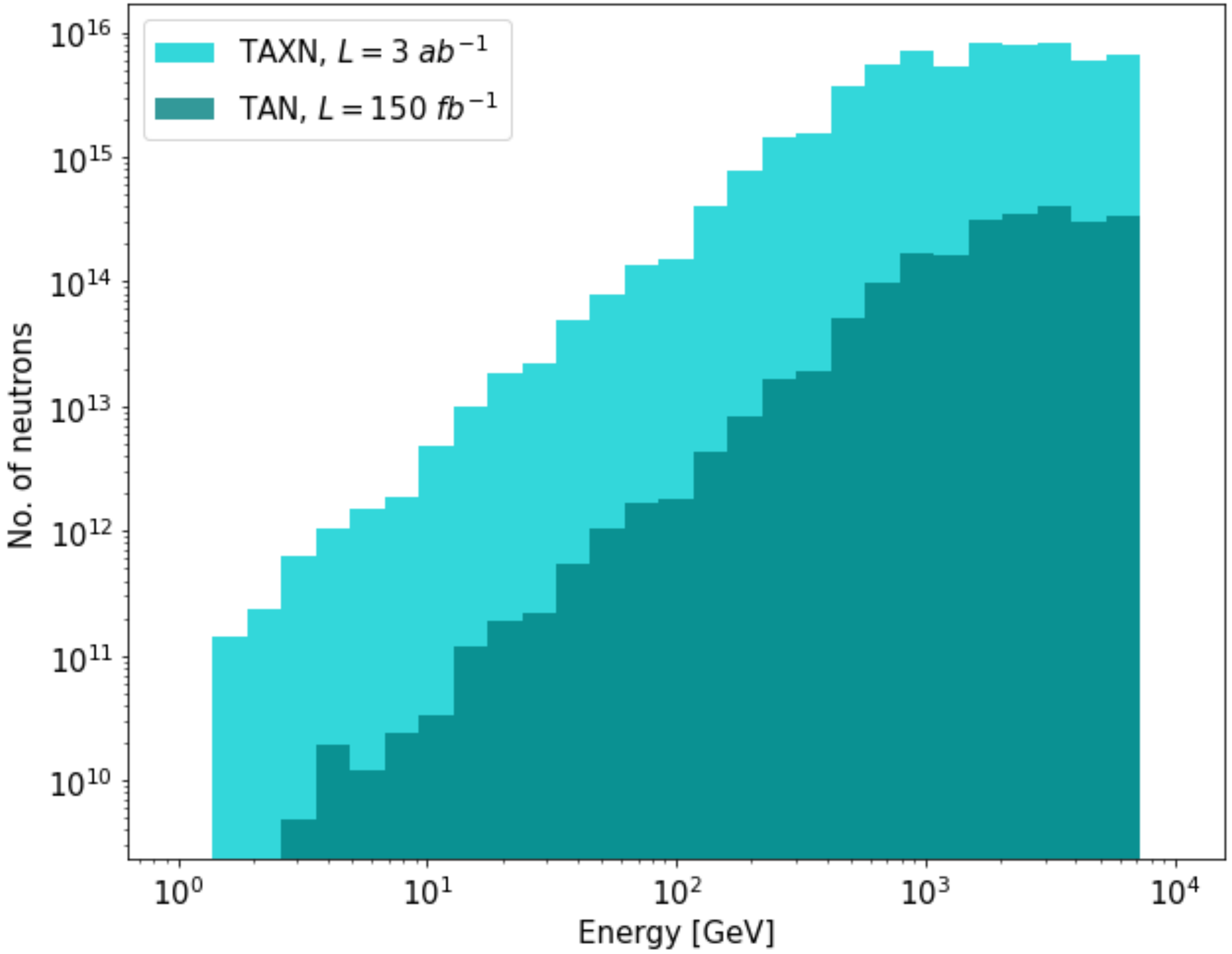
[2] FORESEE package, Kling, Trojanowski arxiv.org/abs/2105.07077

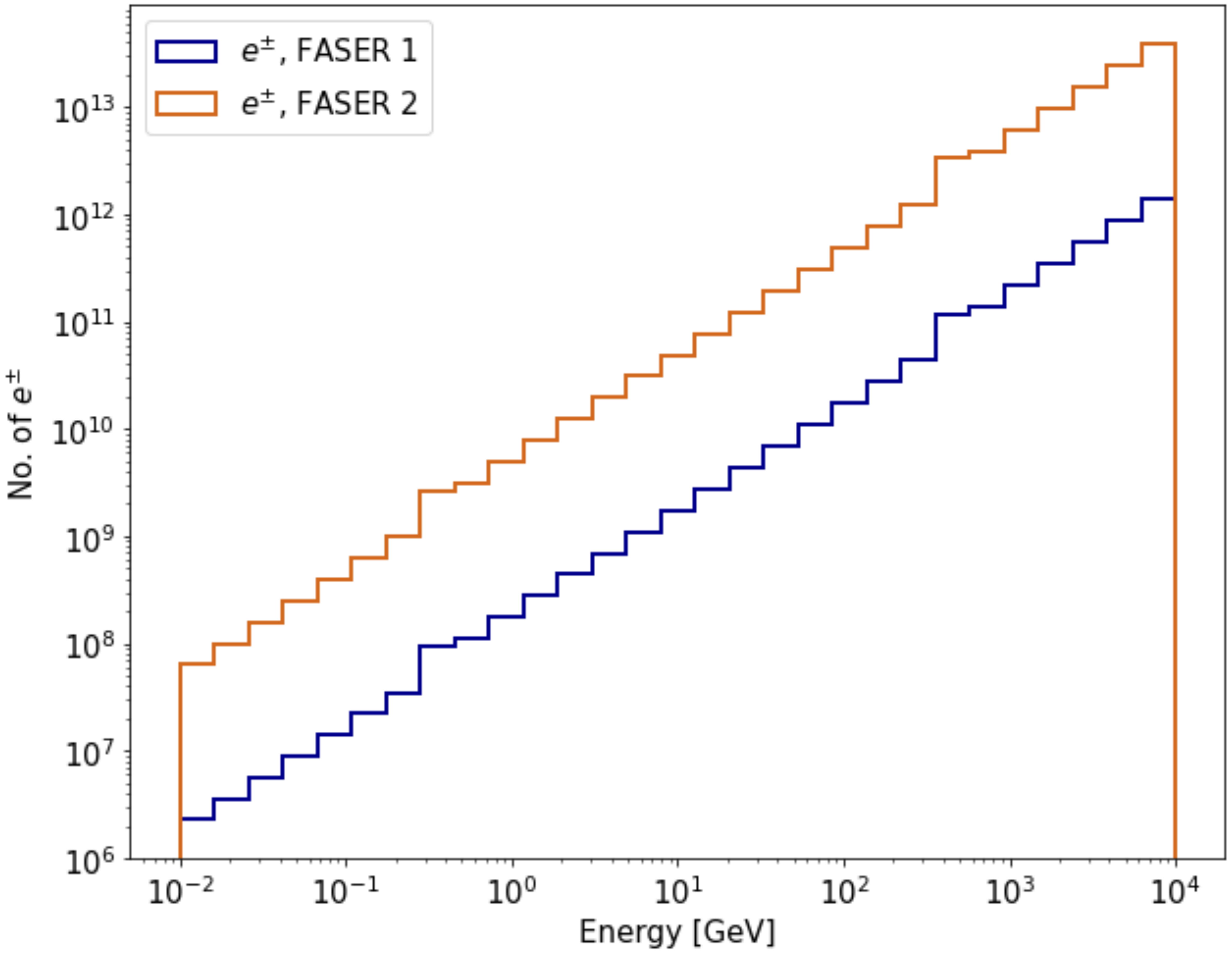
Neutron-on-target: $e^{\pm}$

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

$N_{TAN} = 2.2 \times 10^{15}$ $N_{TAXN} = 6.3 \times 10^{16}$

Electron, positron fluxes from neutrons[1]



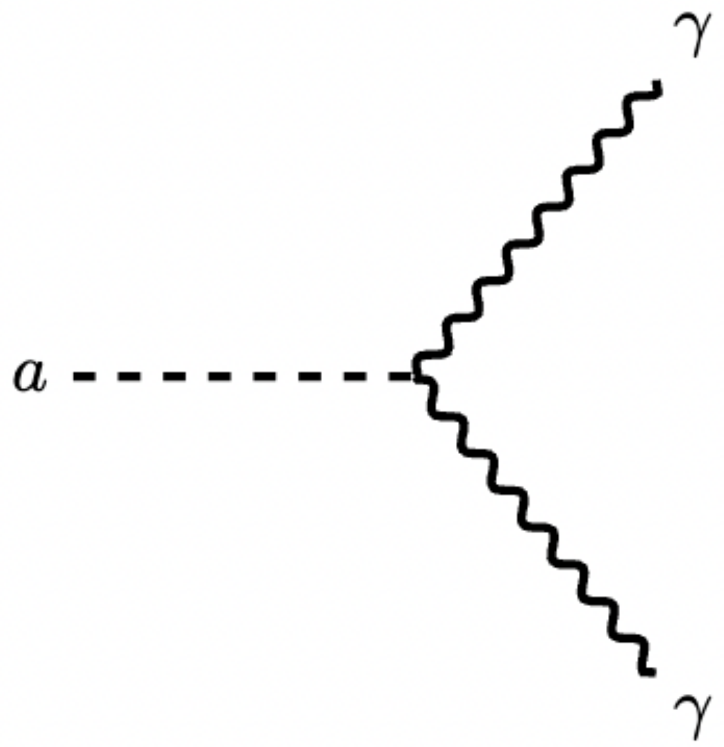


[1] GEANT4 simulations by Hyunyong Kim

BSM from neutrons-on-target: Axion-like Particles

Axion-like Particles (ALPs)

Photon couplings



$$\mathscr{L}_{a\gamma} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} F^{\mu\nu}\tilde{F}_{\mu\nu}$$

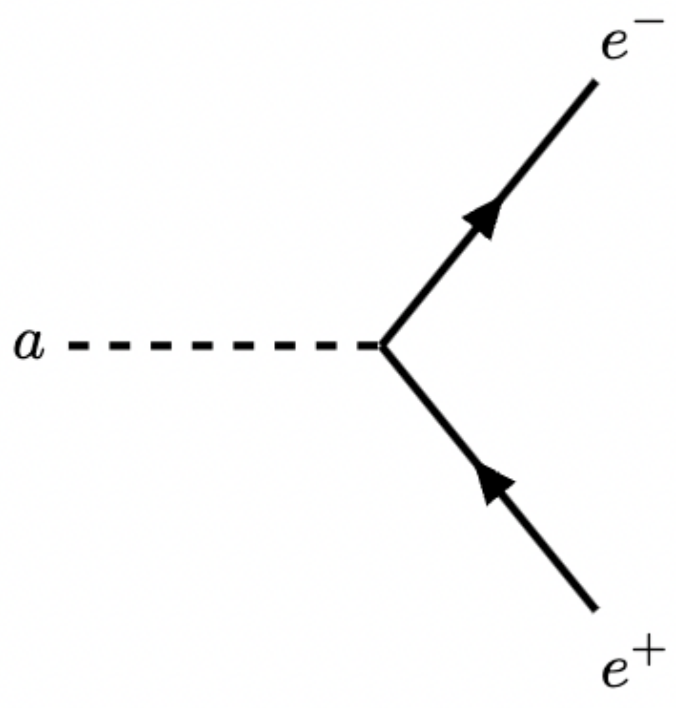
ALP production: *Primakoff process*

- $\gamma N \rightarrow aN$
- Coherently enhancement $\sim Z^2$

ALP detection:

- Decays $a \rightarrow \gamma\gamma$
- Inverse primakoff $aN \rightarrow \gamma N$ - subdminant for $m_a > 100$keV

Electron couplings



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

ALP production: ($\sim O(Z)$)

- Compton-like scattering - $\gamma e^- \rightarrow ae^-$
- Associated production - $e^+e^- \rightarrow a\gamma$

ALP detection:

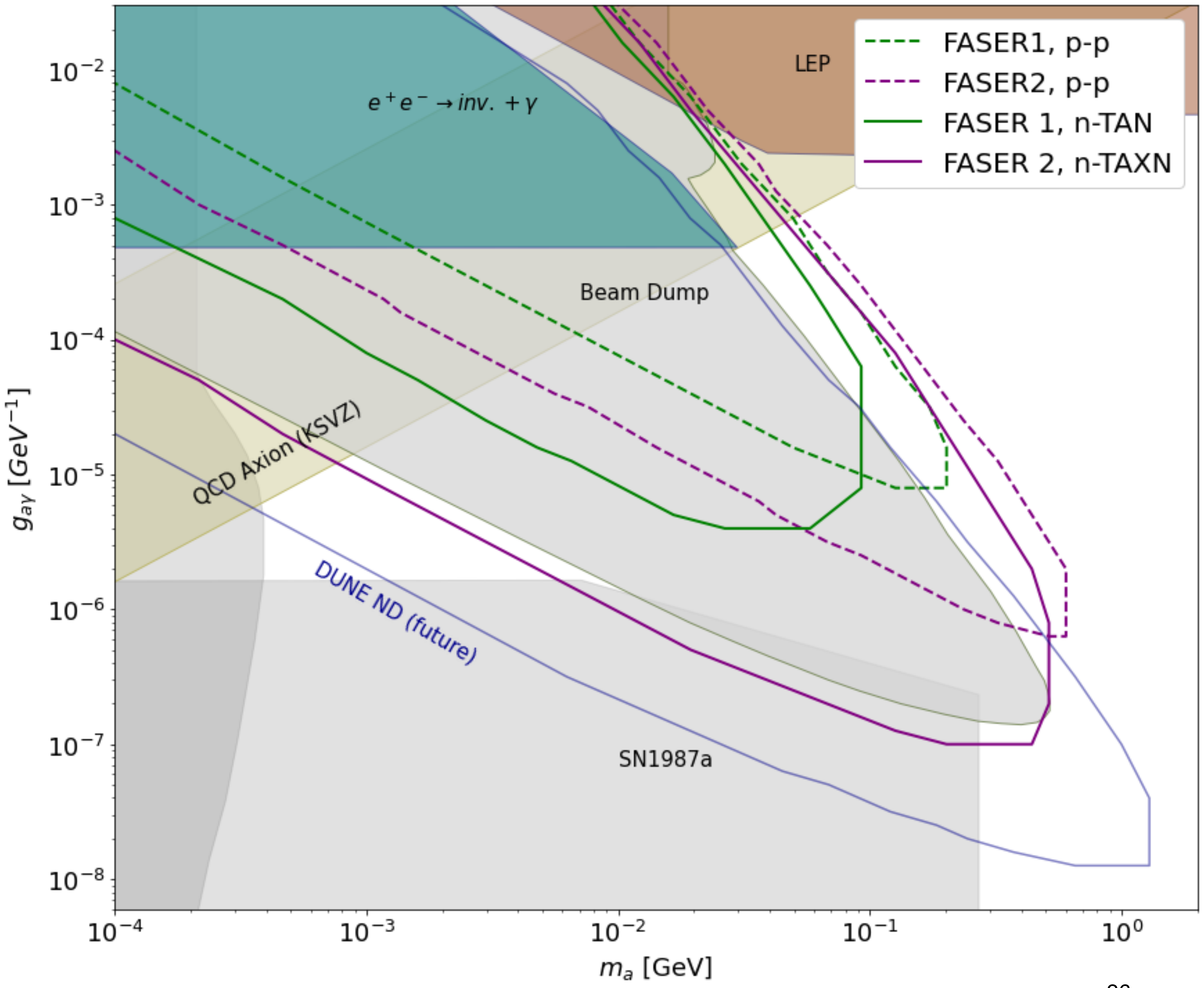
- Decays $a \rightarrow e^+e^-$ for $m_a > 1$MeV
- Scattering channels - subdominant at FASER

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

ALP sensitivity : Photon couplings

No. events: 3
Cutoffs: $E_\gamma > 20\text{MeV}$



Features:

- *Dotted lines:* Photons at IP (studied in [1])
- *Solid lines:* Photons from neutron interactions.

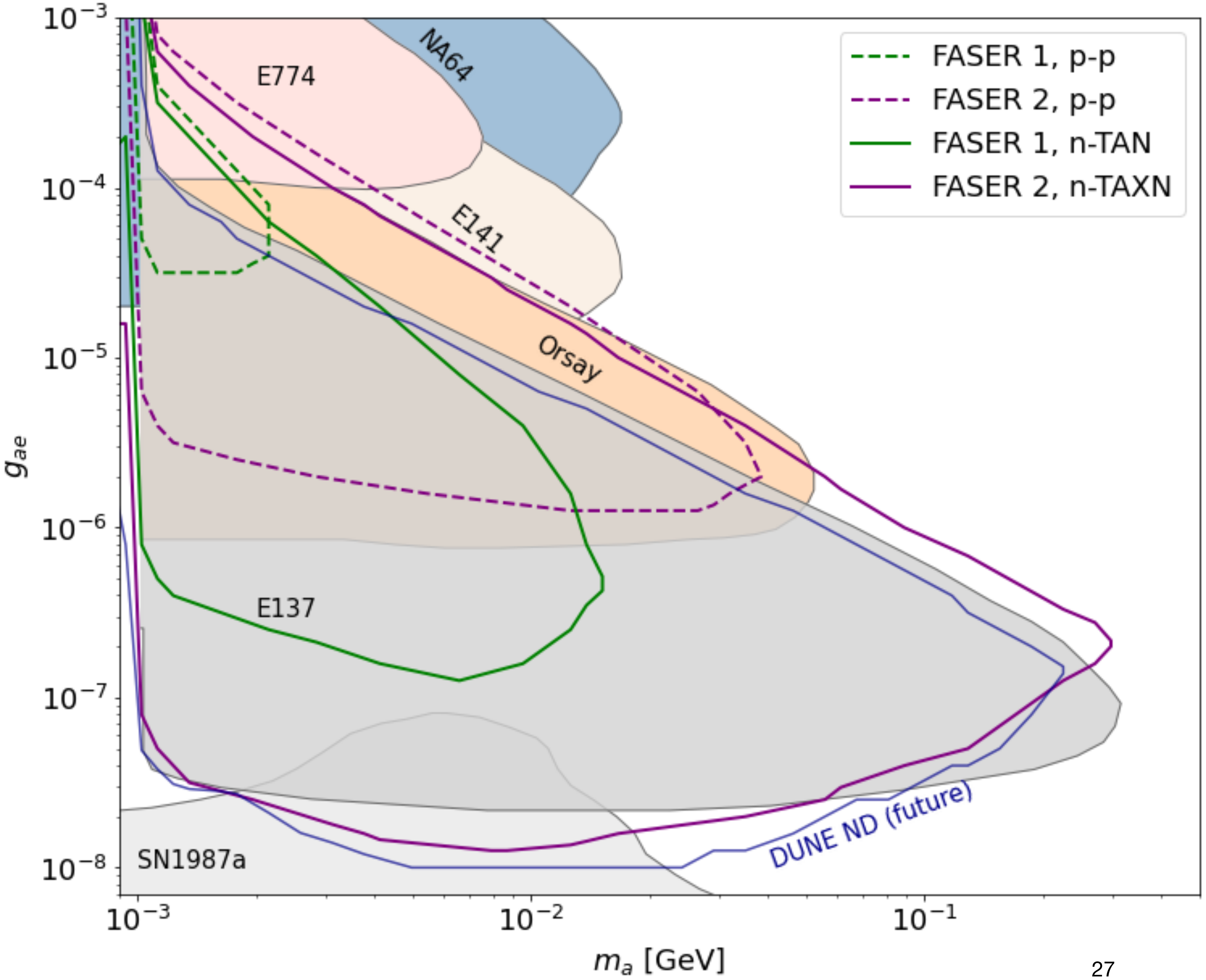
Inferences:

- Larger neutron-induced photons ⇒ FASER 2 reaches below beam dump constraints
- Neutron-induced fluxes complement fluxes from IP

[1]Feng, Galon, et.al, arxiv.org/abs/1806.02348

ALP sensitivity : Electron couplings

No. events: 3
Cutoffs: $E_\gamma > 20$MeV



Features:

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

Inferences:

- S-channel Compton-like scattering - favored for soft photons.
- Neutron-induced photons give maximum contribution
- Only FASER 2 can explore MeV scale ALPs with $O(10^{-6})$ couplings.

Conclusion

- Neutrons have been studied in the context of backgrounds, but they can provide considerable insights into BSM physics.
- Neutron Bremsstrahlung - More applications in Baryonic models containing scalars, gauge bosons.
- Neutrons beyond ALPs - Flavor-specific scalars, gauge bosons

Backup

Protophobic model

X: Protophobic gauge boson

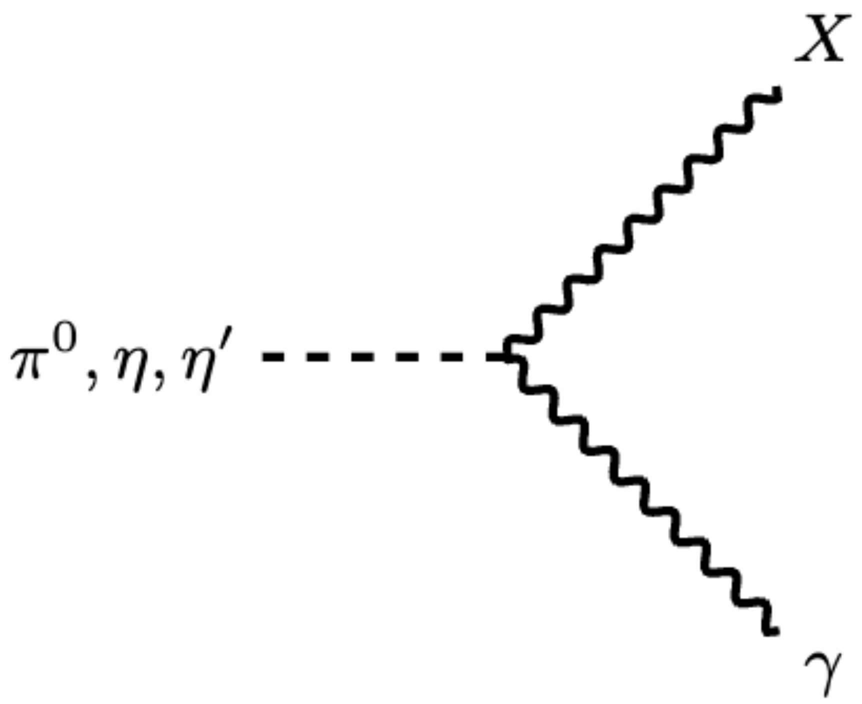
$$\mathcal{L}_X = -\frac{1}{2}m_X^2 X_\mu X^\mu - g_X X_\mu \sum_f x_f \bar{f}\gamma^\mu f$$

[1]

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. Neutral meson decays



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

$$BR(\eta, \eta' \to X\gamma) = 2BR(\eta, \eta' \to \gamma\gamma)\beta_{\eta,\eta'}\left(1 - \frac{m_X^2}{m_{\eta,\eta'}^2}\right)^3$$

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

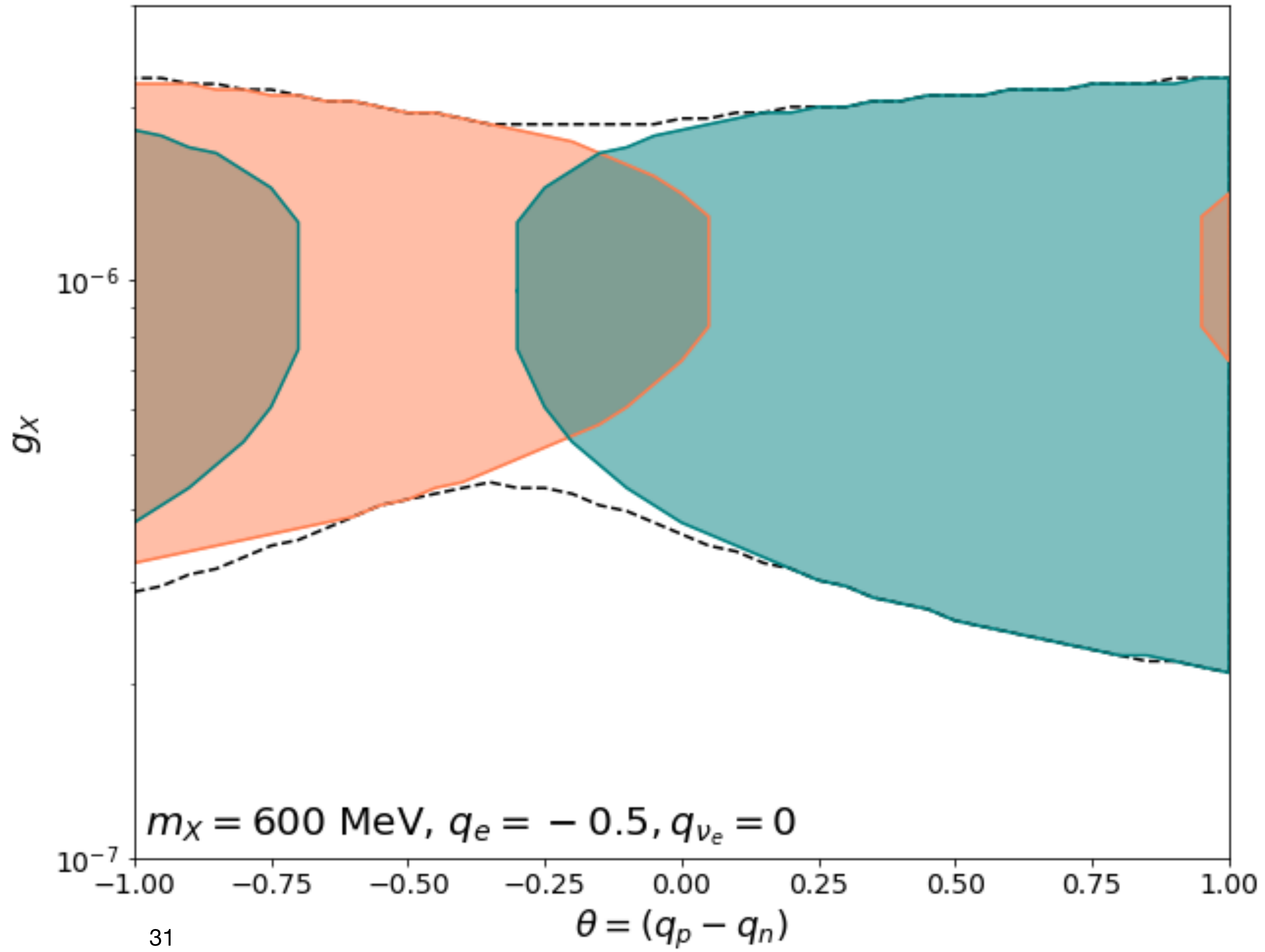
$BR(\eta \to \gamma\gamma) = 0.39$
$BR(\eta' \to \gamma\gamma) = 0.02$

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

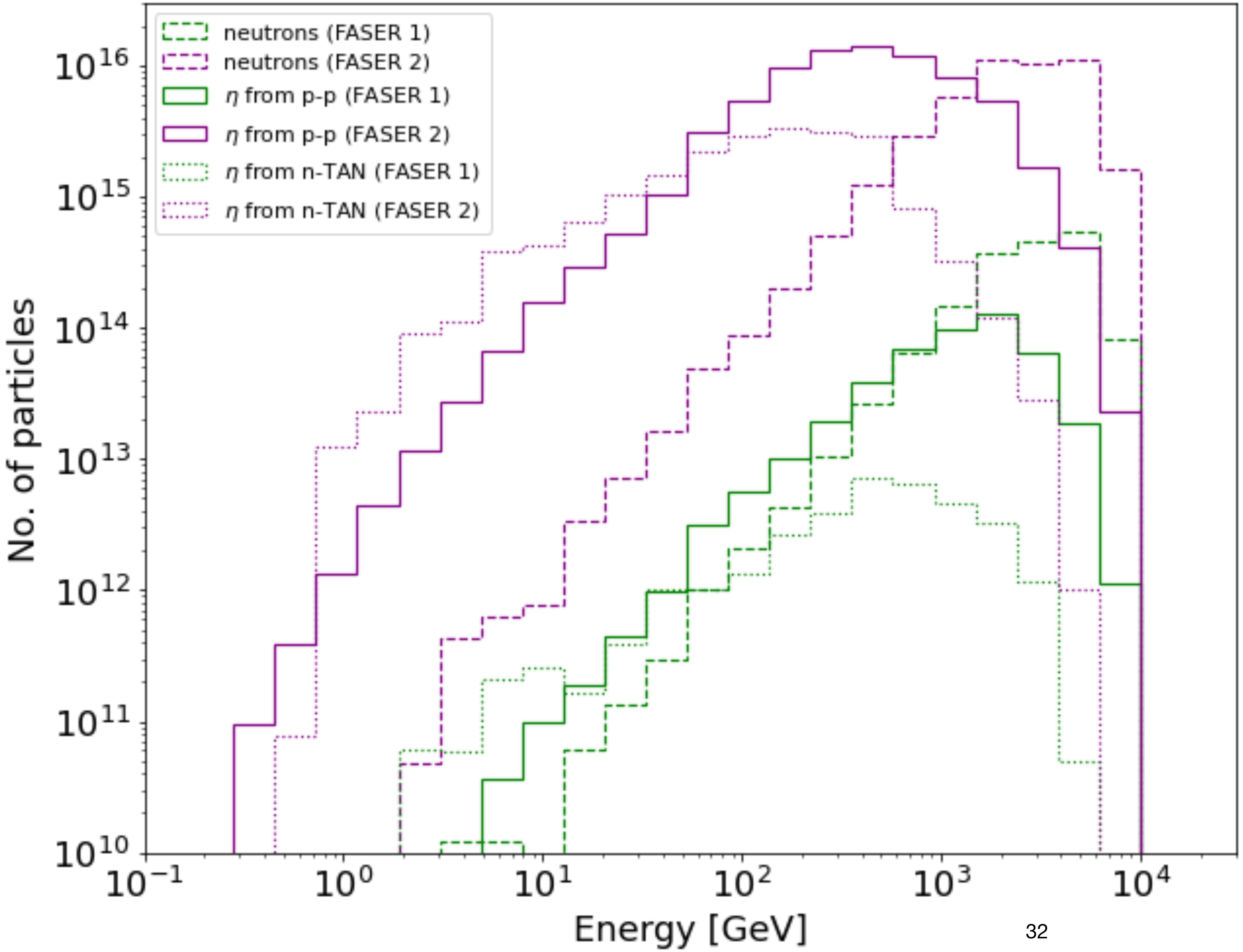
Generic model - proton and neutron couplings

Anomaly condition : $SU(2)_L \times SU(2)_L \times U(1)_X \Rightarrow q_p + q_n + q_e + q_{\nu_e} = 0$

Another scenario where $q_e = -0.5$



X boson flux : Parent flux



- η mesons from IP are higher in number and energy than those from n-TAN/TAXN
- No. of neutrons $\sim$ No. of η mesons

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[2] IP: FORESEE package, Kling, Trojanowski arxiv.org/abs/2105.07077

Calculating the beta factor for protophobic gauge bosons

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

$$\phi_\eta(x_u, x_d, x_s) = (\cos\theta_p(x_u q_u + x_d q_d - 2x_s q_s) - \sqrt{2}\sin\theta_p(x_u q_u + x_d q_d + x_s q_s))^2$$

$$\phi_{\eta'}(x_u, x_d, x_s) = (\sin\theta_p(x_u q_u + x_d q_d - 2x_s q_s) + \sqrt{2}\cos\theta_p(x_u q_u + x_d q_d + x_s q_s))^2$$

Therefore:

$$\beta_\eta(x_u, x_d, x_s) = \frac{\phi_\eta(x_u, x_d, x_s)}{\phi_\eta(q_u, q_d, q_s)} \quad ; \quad \beta_{\eta'}(x_u, x_d, x_s) = \frac{\phi_{\eta'}(x_u, x_d, x_s)}{\phi_{\eta'}(q_u, q_d, q_s)}$$

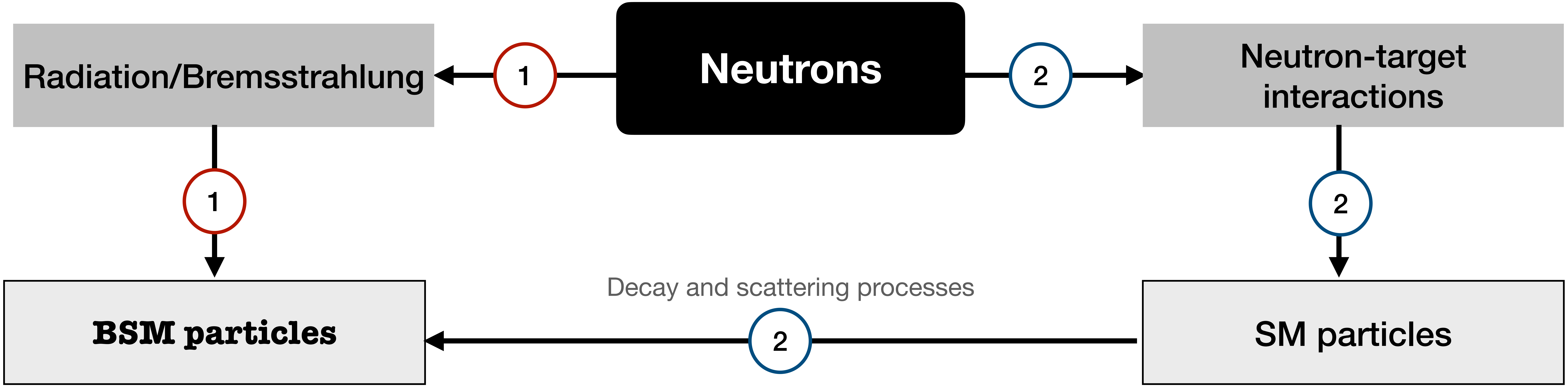
This is the proportionality of the meson couplings to the gauge boson X with the meson couplings to QED photon

Motivation

Examples:
1. Gauge bosons
2. Axion-like Particles

BSM physics from **neutrons at FASER**:

- Unaffected by the presence of magnets.
- Iron atoms at TAN/TAXN - factory of SM and BSM particles



Neutrons

Radiation/Bremsstrahlung

Neutron-target interactions

BSM particles

SM particles

Decay and scattering processes