

Long Lived Particles from photons and charged mesons at beam dumps

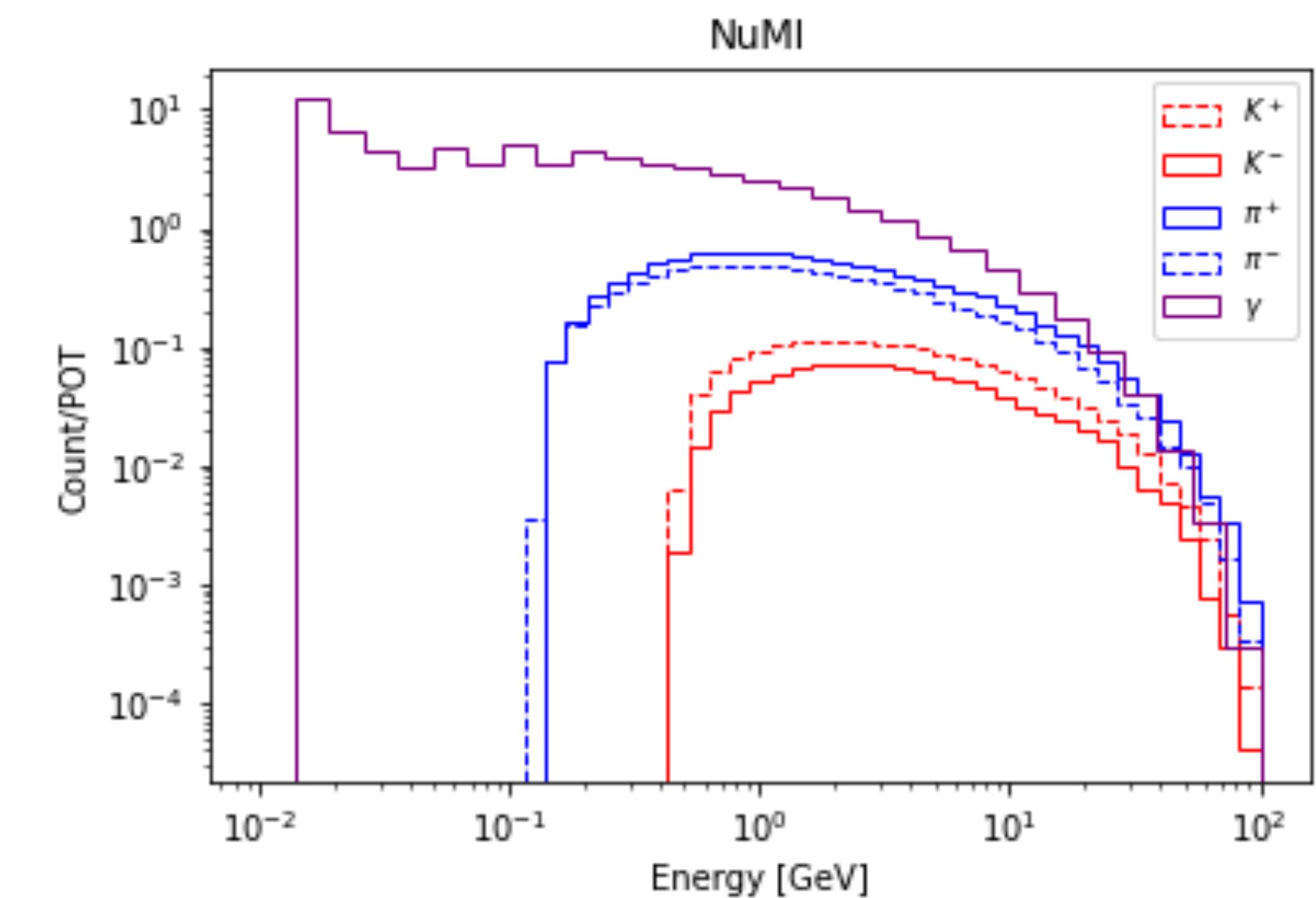
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Motivation

- Extended Higgs sectors in sub GeV regime through photon coupling and three body decay of charged mesons.
- Extend the study to $U(1)$ gauge bosons.

- Why Photons?**
1. At 120GeV $\sim 10^2$ photons per POT > 5 MeV
 2. Photons can undergo **Primakoff** scattering, $O(Z^2)$ enhancement
- Why Charged mesons?**
1. At 120GeV $\sim 10 \pi^\pm$ per POT and $\sim 2 K^\pm$ per POT
 2. Three body decays of K^\pm and π^\pm are phase space enhanced.^[1]



[1] Carlson, Rislow, Phys. Rev. D 86, 035013

Benchmark Models

1. Higgs Portal Scalars:

- Standard model Higgs (h) \leftrightarrow light scalar singlet S : $h \rightarrow h + \theta S$

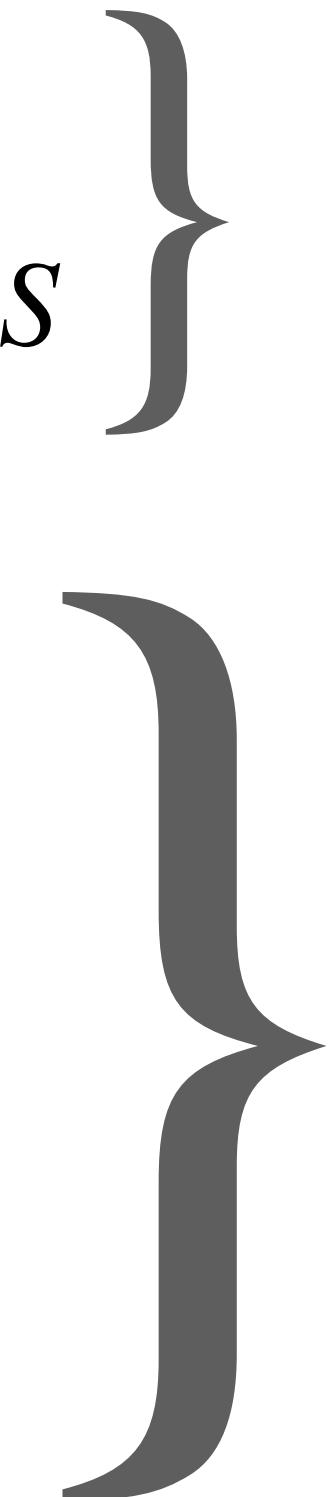
Explain Hidden
sector masses.

2. Muon-philic scalar models:

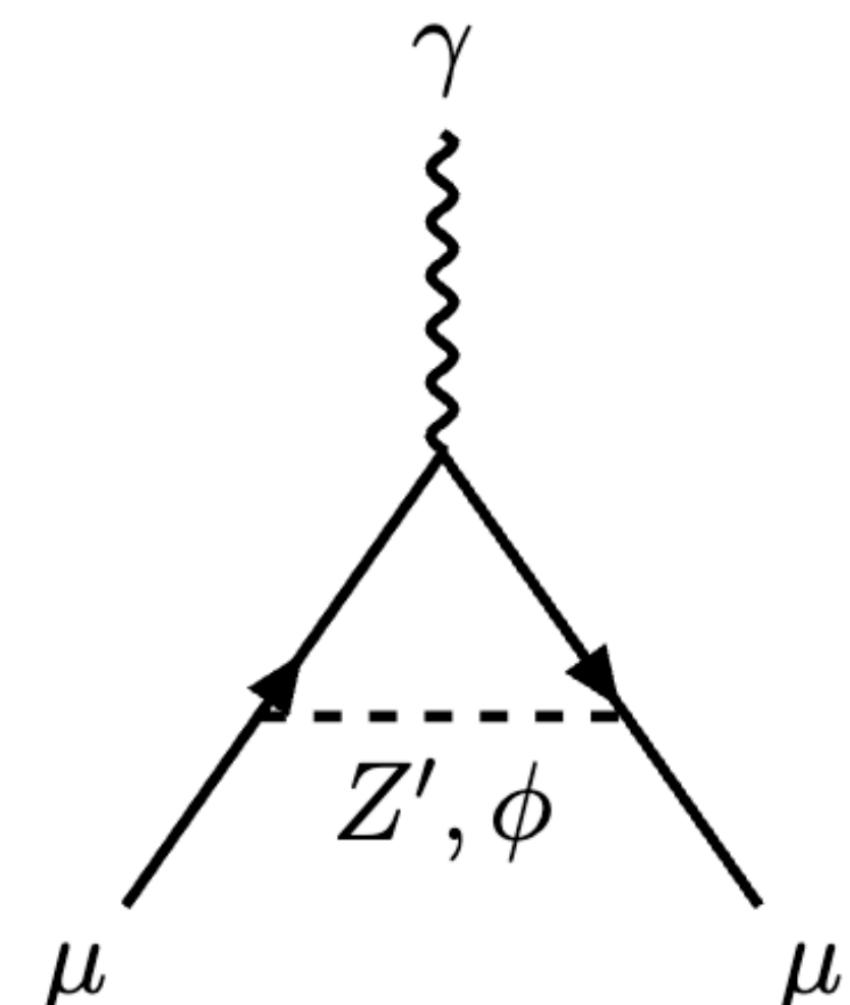
- Scalar ϕ in muon-specific EFTs, coupling strength : Y_{22}

3. $U(1)_{L_\mu - L_\tau}$ Gauged model:

- $U(1)$ massive gauge boson Z' , coupling strength : $(L_\mu - L_\tau)g_{\mu\tau}$



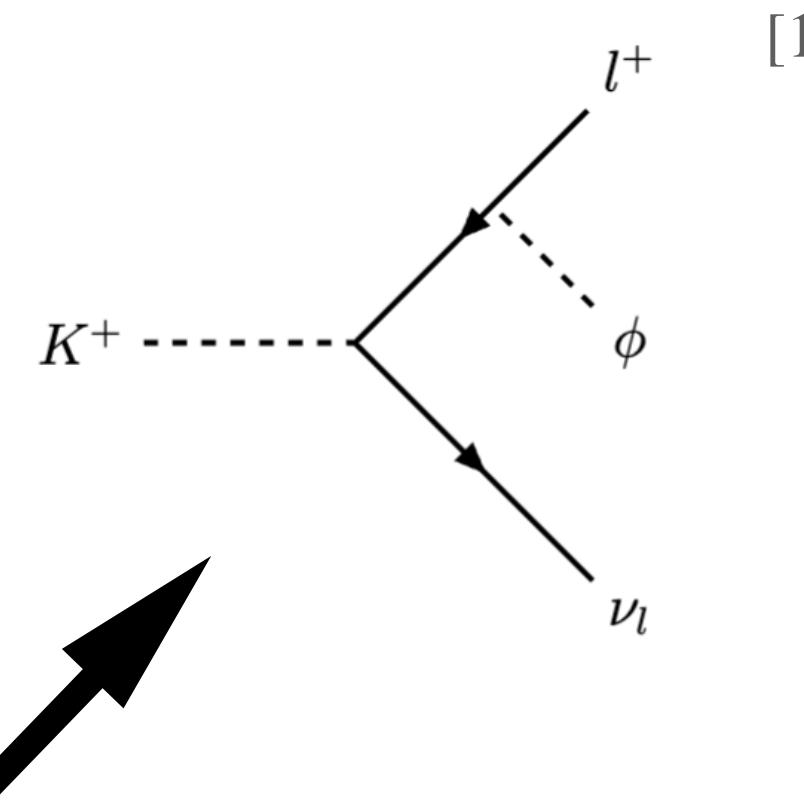
To explain
muon $g - 2$
discrepancy!



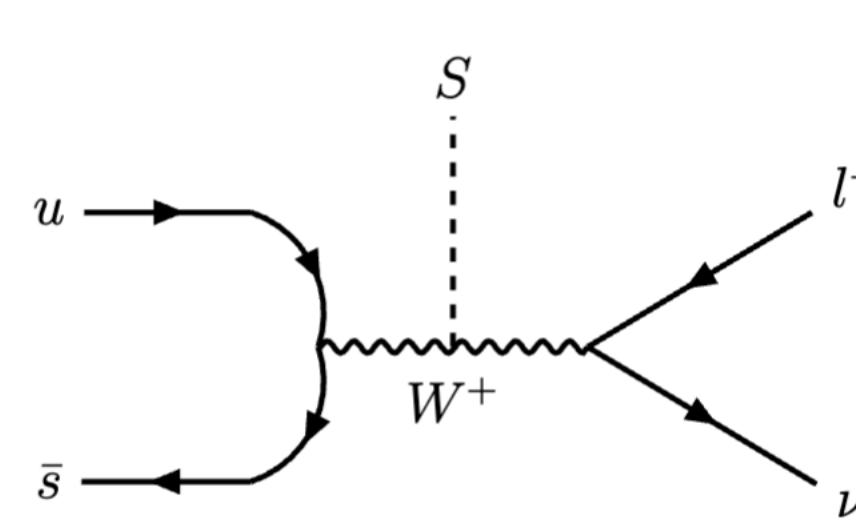
1. Patt, Wilczek, [arXiv:hep-ph/0605188](https://arxiv.org/abs/hep-ph/0605188)
2. Dutta, Ghosh, Li, [arXiv:2006.01319](https://arxiv.org/abs/2006.01319); Batell, Freitas et.al. Phys. Rev. D 98, 055026 (2018) [arXiv:1712.10022](https://arxiv.org/abs/1712.10022);
3. He, Joshi et.al. Phys. Rev. D 43 (1991) 22-24

Production from charged mesons

Scalars:



$$iM_{K \rightarrow \phi} = y_{ff} \frac{G_f f_K V_{us}}{(p_l + p_\phi)^2 - m_l^2} \bar{u}_{p_l} [(p_l + p_\phi)^2 + m_l p_K] (1 - \gamma^5) v(p_\nu)$$

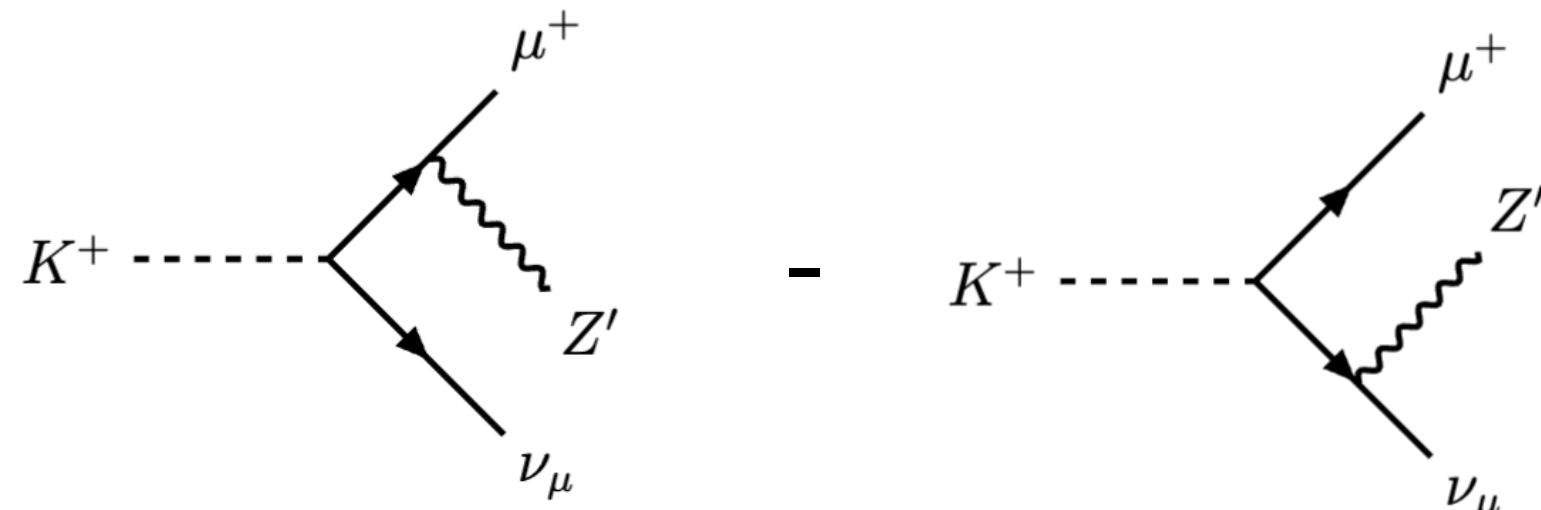


HPS:

$$y_{ff} = \theta \frac{m_f}{v} \quad y_{SW} = 2\theta \frac{m_W^2}{v}$$

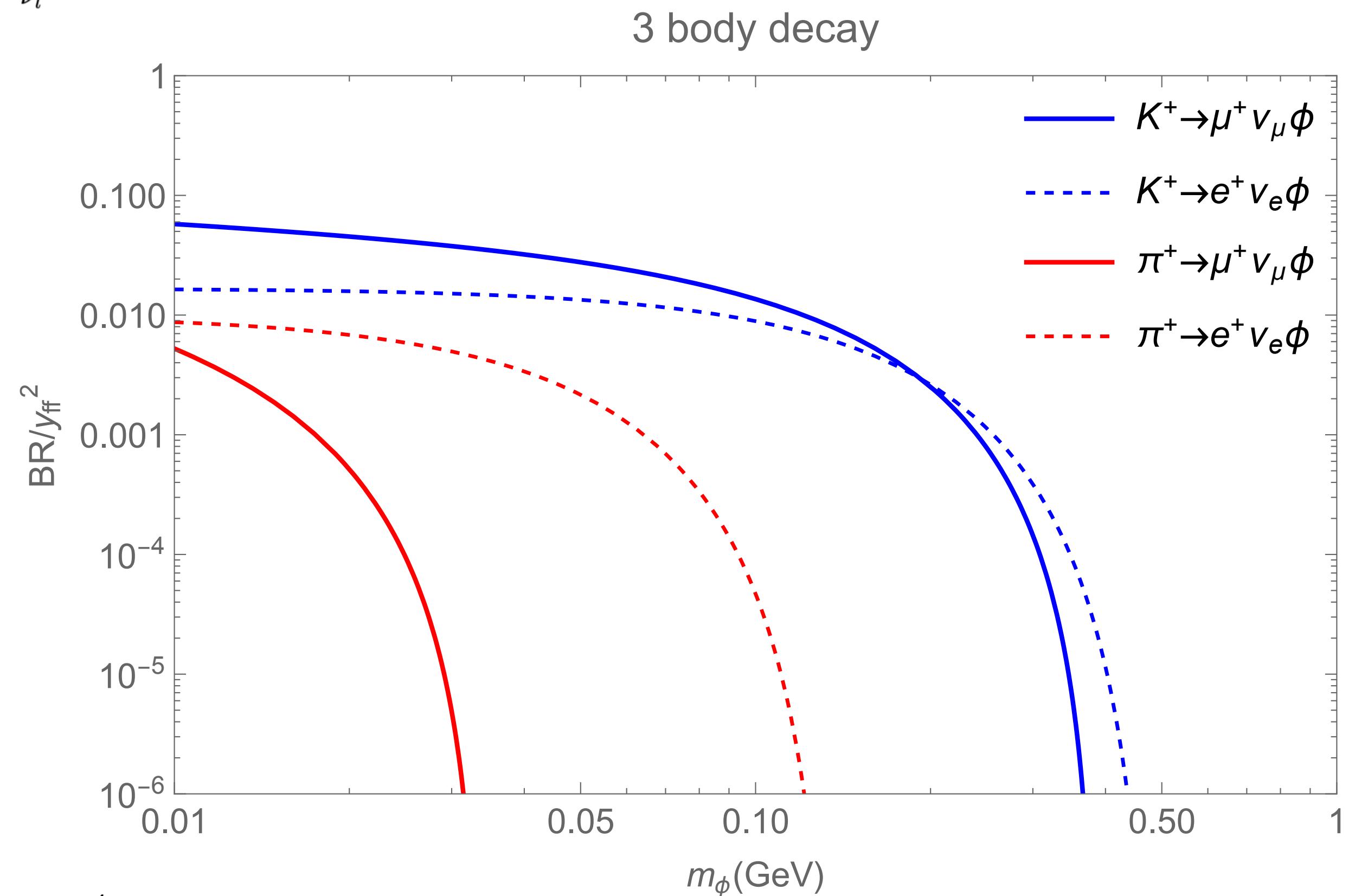
μ -philic scalar:
Only coupling $-\mu$ lepton
 $y_{ff} = y_{22} \quad y_{SW} = 0$

Gauge Bosons:

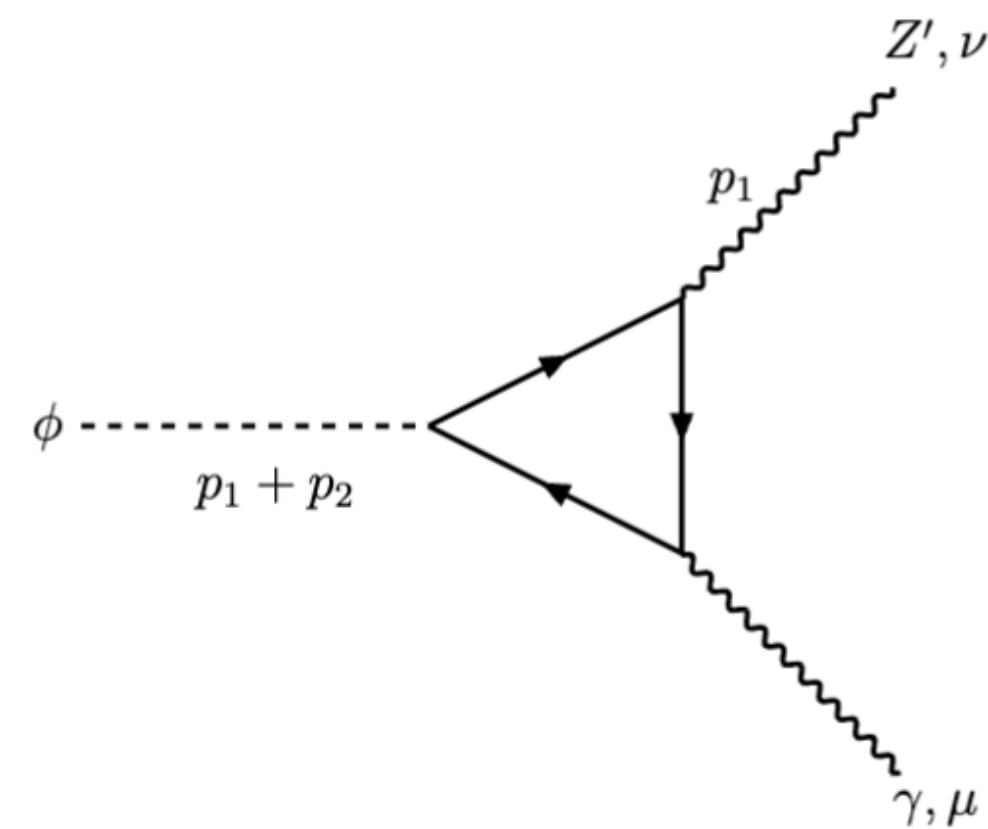


[1] Carlson, Rislow, Phys. Rev. D 86, 035013

[2] Chivukula, Manohar Phys.Lett.B 207 (1988) 86

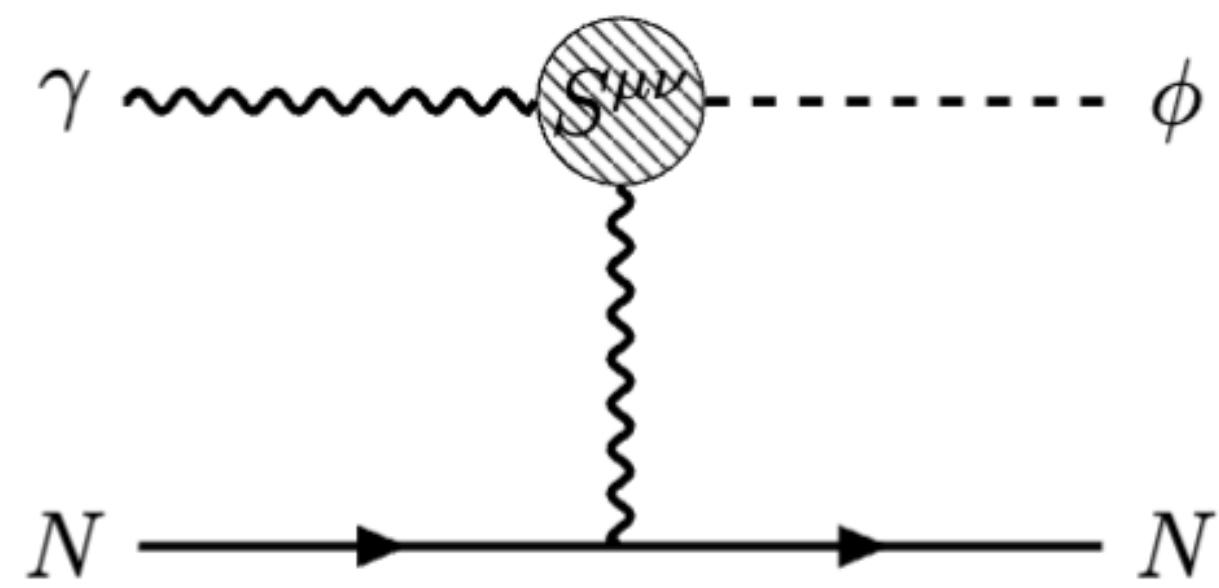


Production from photons (Scalars)



$$S^{\mu\nu} = 2 \times 10^{-3} (p_1 \cdot p_2 \eta^{\mu\nu} - p_1^\nu p_2^\mu) \sum_f y_{ff} \frac{N_c Q_f^2}{m_f} I(p_1 \cdot p_2, m_f^2)$$

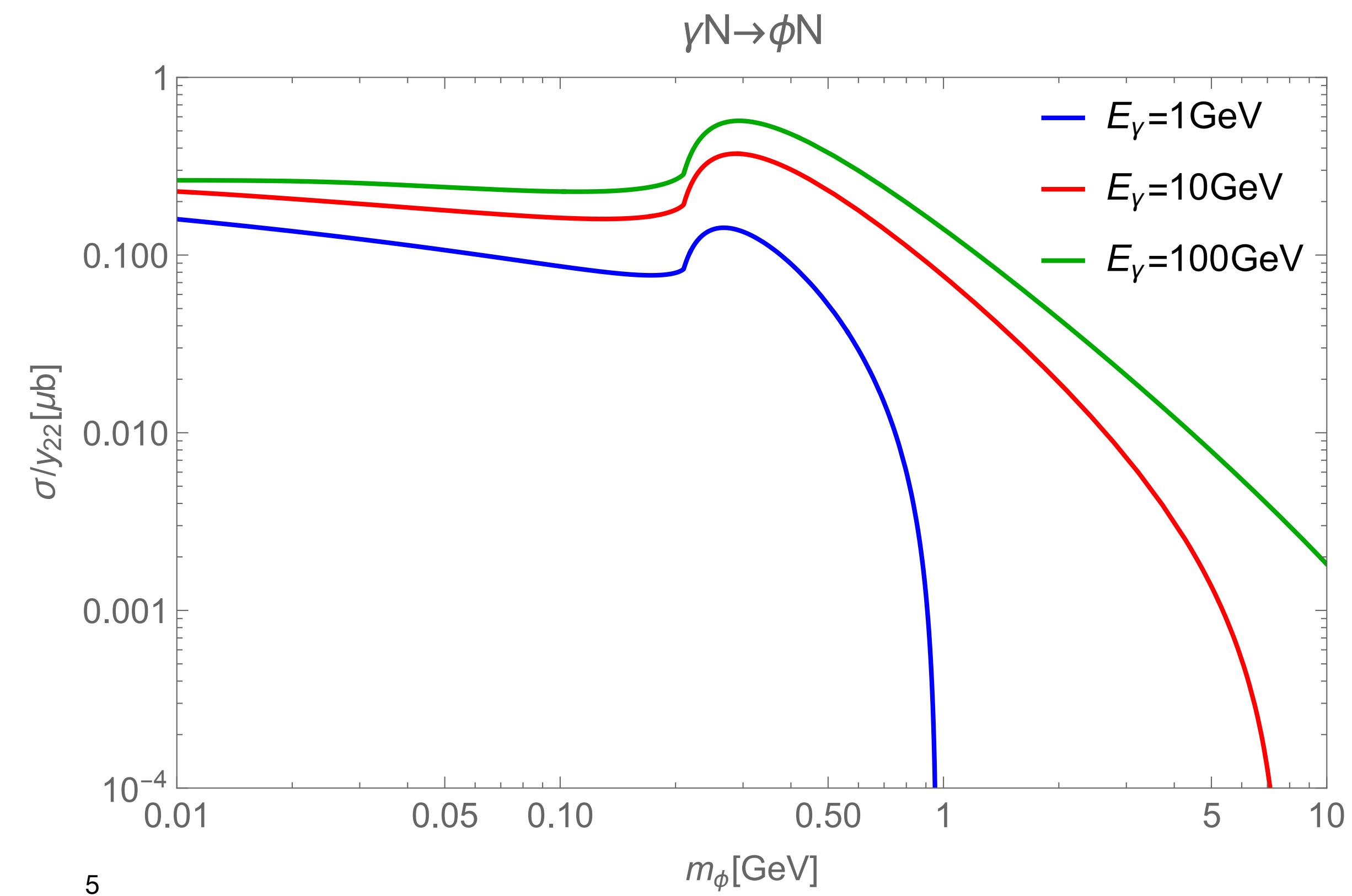
Primakoff scattering



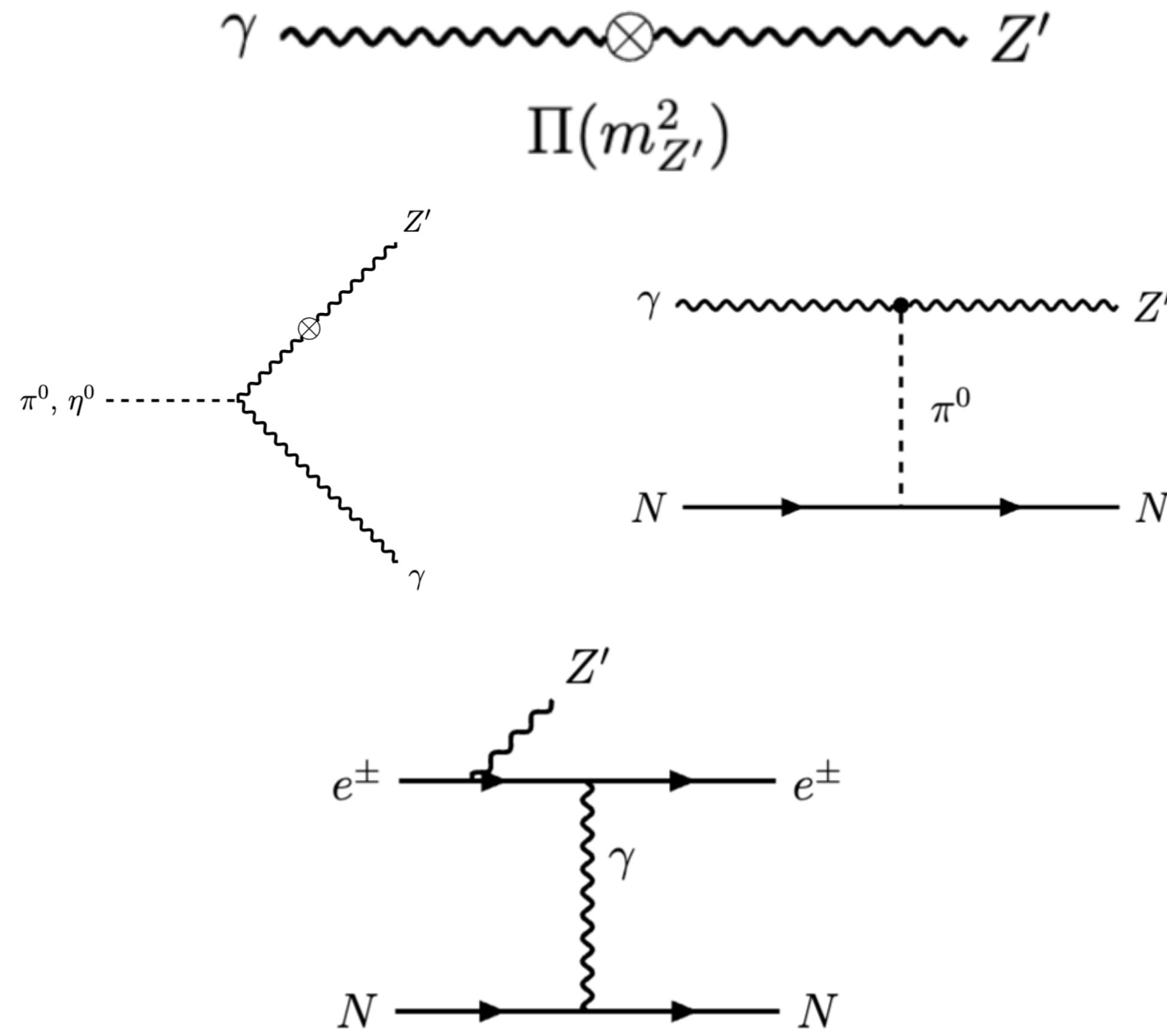
HPS:
Strongest coupling - **Top Quark**

$$y_{ff} = y_{tt} = \theta \frac{m_t}{\nu}$$

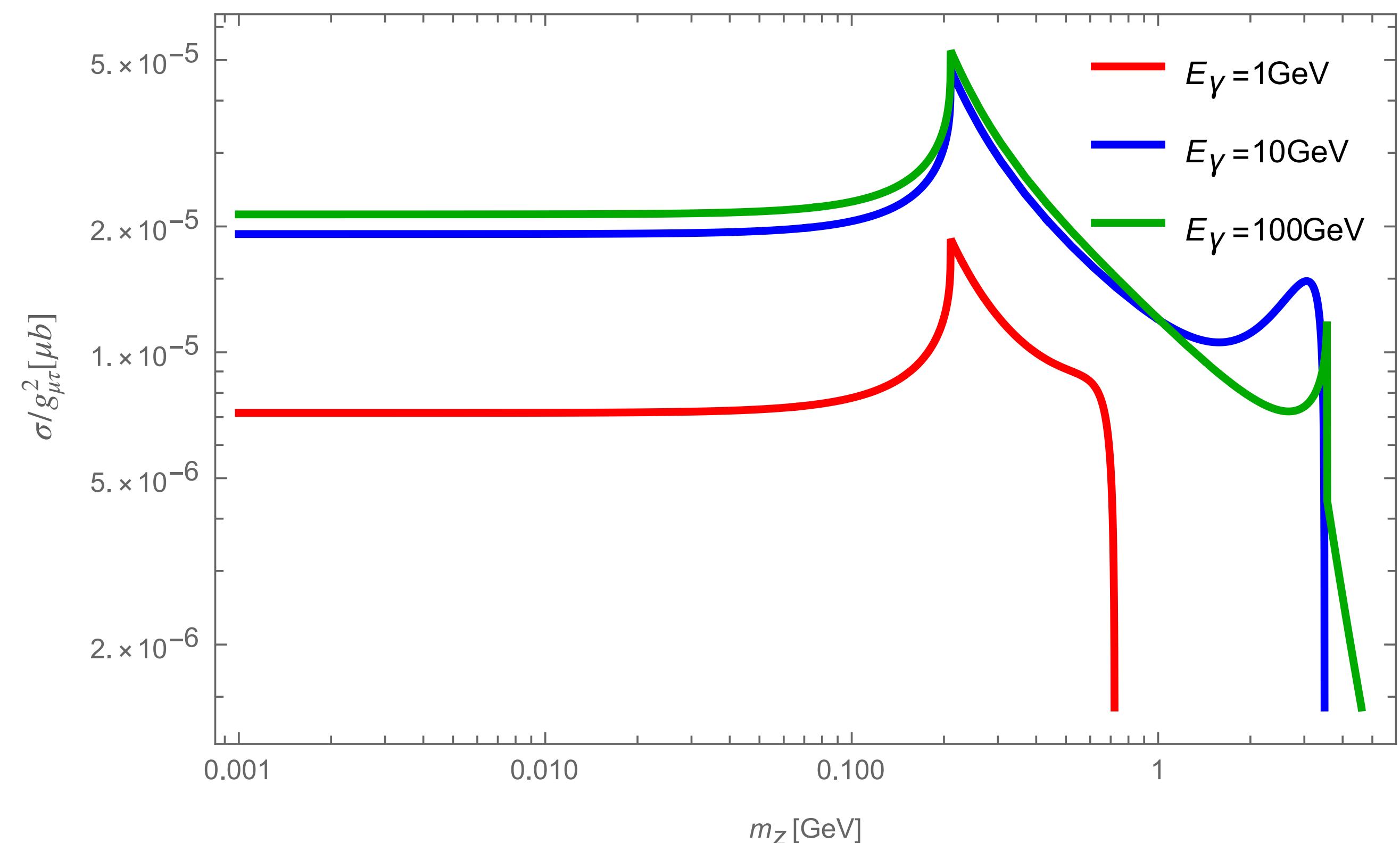
μ -philic scalar:
Only coupling $-\mu$ lepton
 $y_{ff} = y_{22}$



Production from photons (Gauge bosons)



$$\Pi(m_{Z'}^2) = \frac{g_{\mu\tau}e}{2\pi^2} \int_0^1 dx x(1-x) \log \left[\frac{m_\tau^2 - x(1-x)m_{Z'}^2}{m_\mu^2 - x(1-x)m_{Z'}^2} \right] \quad [1]$$



[1] Araki, Hoshino et.al. arXiv: 1702.01497

Experiments considered

Magnetic Horn system:

- Focuses K^+ , π^+
- Deflects K^- , π^-

Detectors	Beam Energy [GeV]	Distance from target [m]	Angle off-axis [degrees]	Detector volume (w x h x d) [m^3]	POTs
SBND	BNB (M) 8	110	0.3	4 x 4 x 5	6.6×10^{21}
DUNE ND	LBNF, 120 (M)	574	0	3 x 5 x 4	7×10^{21}
ArgoNeuT	NuMI, 120 (M)	1040	0	0.4 x 0.48 x 0.9	1.35×10^{20}
ICARUS	NuMI, 120	803	5.56	2.63 x 2.86 x 17	6.6×10^{20}
MicroBooNe	NuMI, 120(M) BNB (M) 8	685 470	8	2.26 x 2.03 x 10.4	6×10^{20}

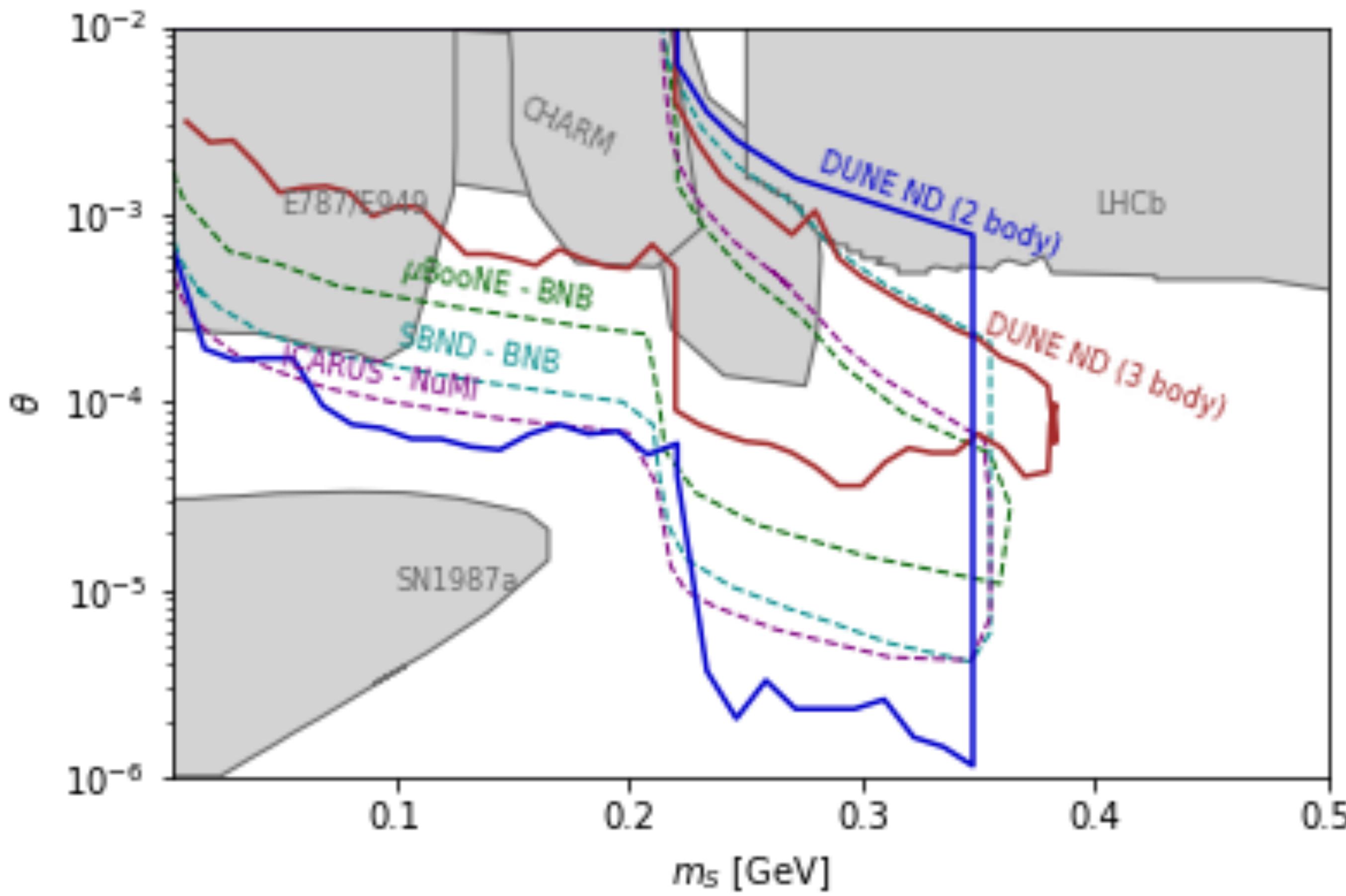
- ArgoNeuT observes the least amount of events- Distance from source and length
- ICARUS and MicroBooNe gets lower energy events as they are off-axis.

Completed
Ongoing
Upcoming

Sensitivity plots:

Preliminary; Zero backgrounds; 95% C.L

Sensitivity of HPS



Dotted lines are from:
Battel, Berger, Ismail Phys. Rev. D 100, 115039

Production:

1. $K^+ \rightarrow \pi^+ S$

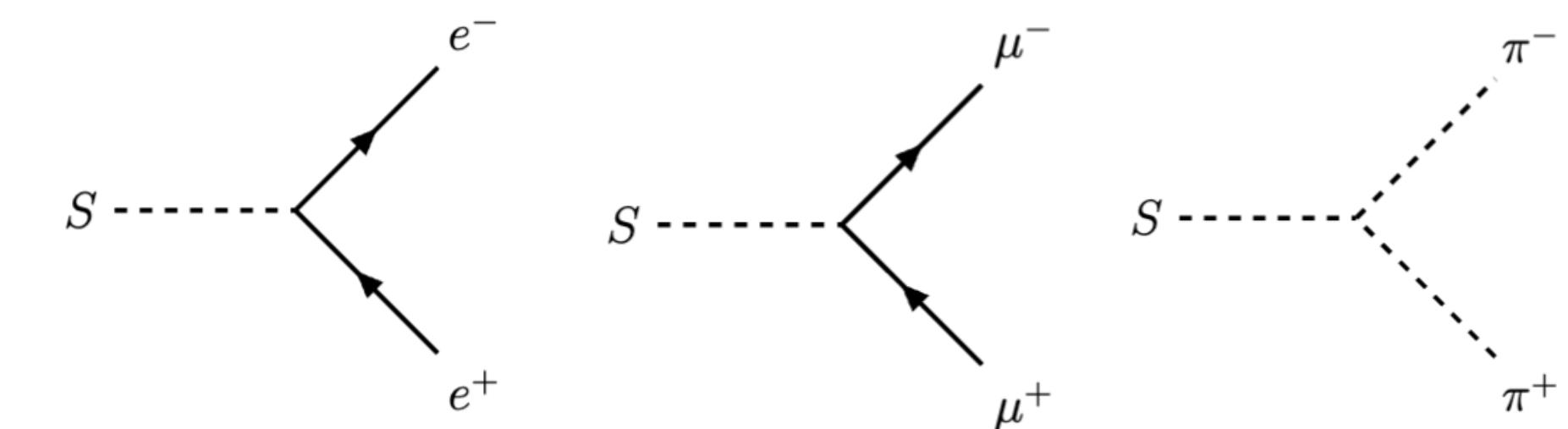
- constrain $m_S \leq m_{K^+} - m_{\pi^+}$ (354 MeV)

2. $K^+ \rightarrow e^+ \nu_e S$ (our study)

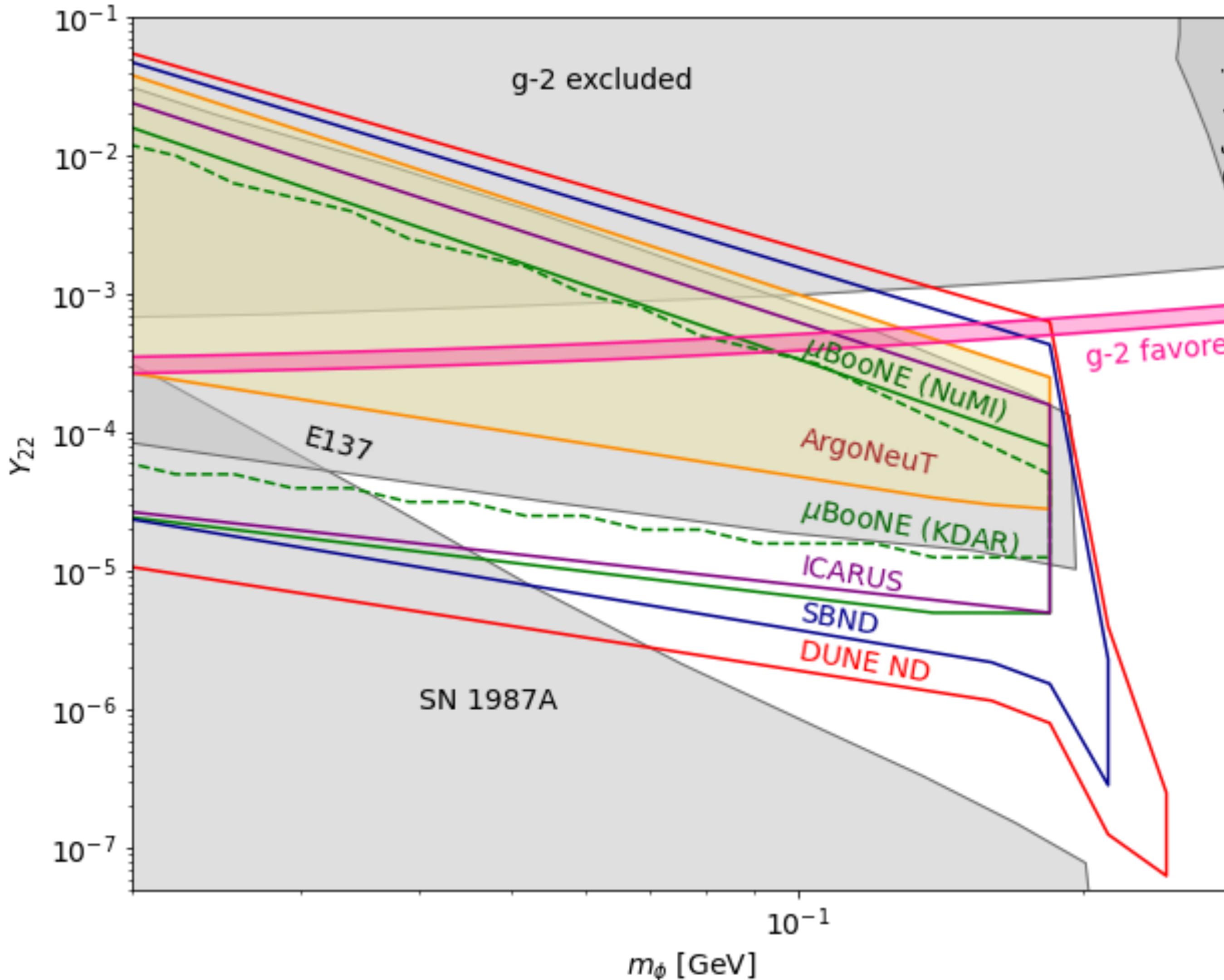
- Kinematically constrains $m_S \leq m_{K^+} - m_{e^+}$ (492 MeV)
- However **flux drops** after 370 MeV, therefore no sensitivity reach.

3. Photons (subdominant)

Detection:



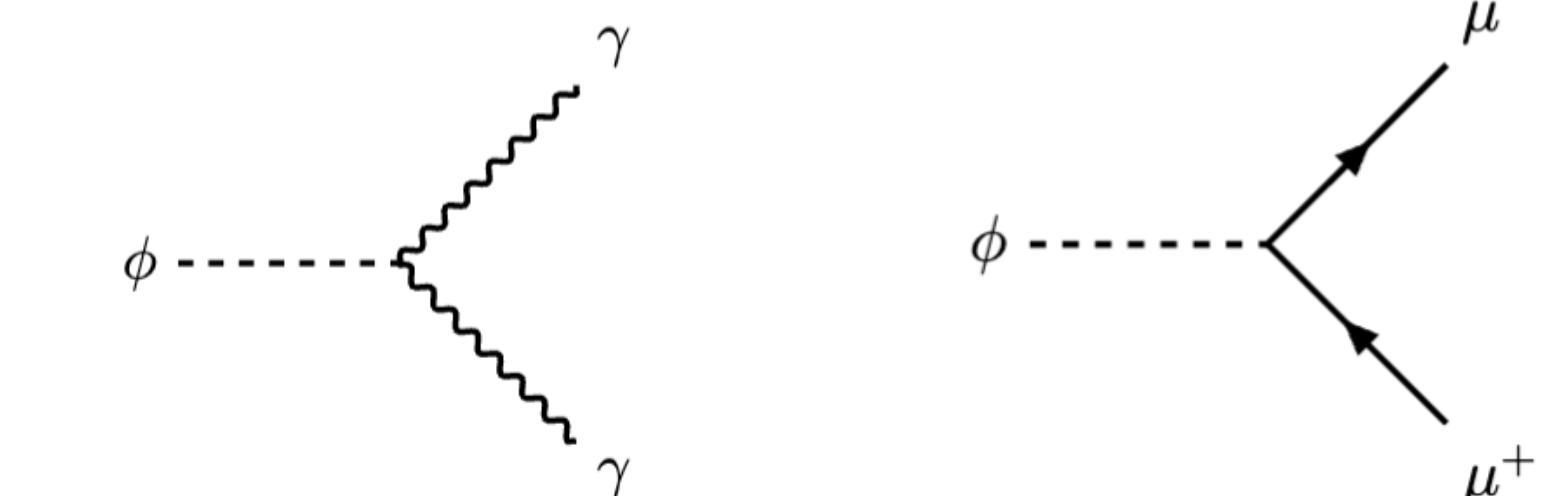
Sensitivity of muon-philic scalar



Production:

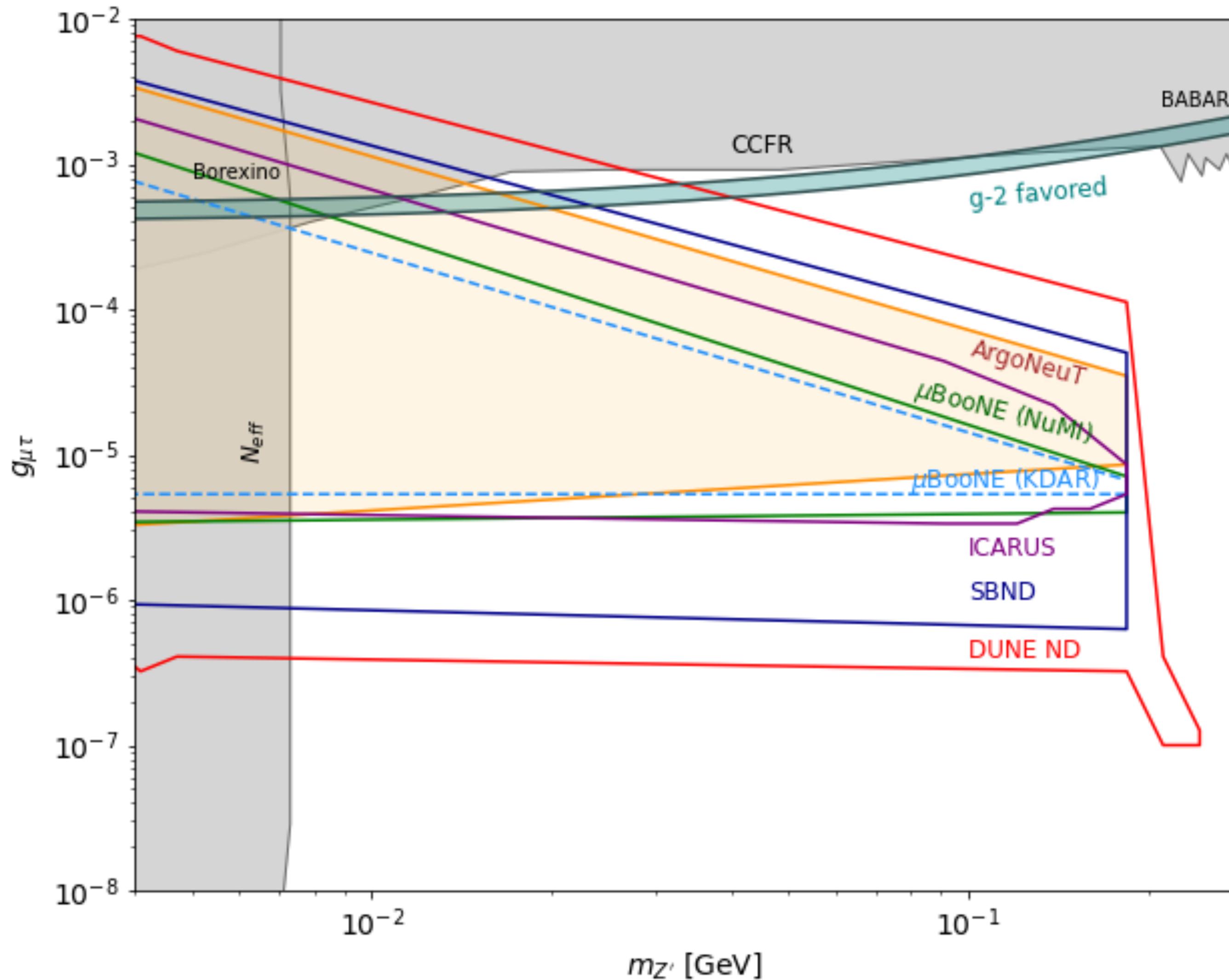
1. $K^+ \rightarrow \mu^+ \nu_\mu \phi$
2. $\gamma N \rightarrow \phi N$ (Primakoff)

Detection:



- Muon decay channels open up for DUNE, SBND.

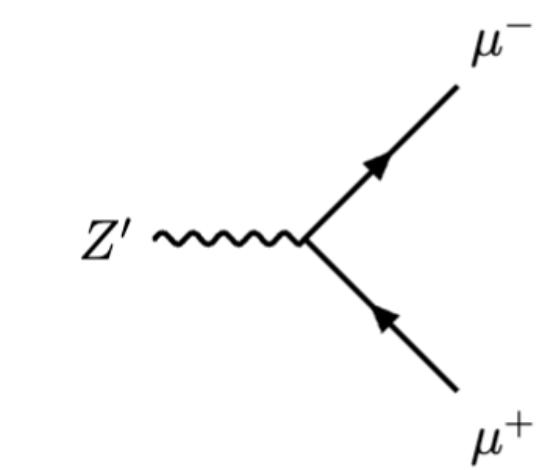
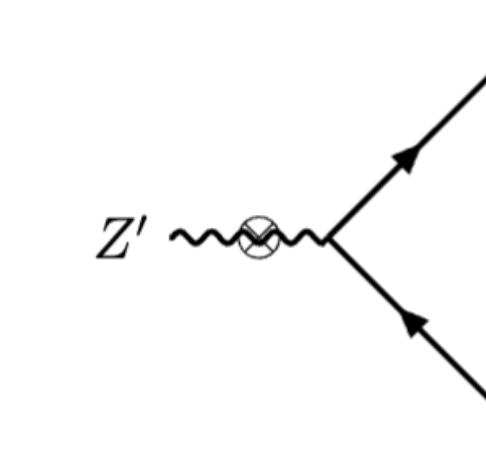
Sensitivity of $L_\mu - L_\tau$ model



Production:

- $K^+ \rightarrow \mu^+ \nu_\mu Z'$:from anti-muon and neutrino leg
- $\pi^0/\eta \rightarrow \gamma Z'$
- Electron-positron bremsstrahlung, annihilation
- $\gamma N \rightarrow Z' N$

Detection:



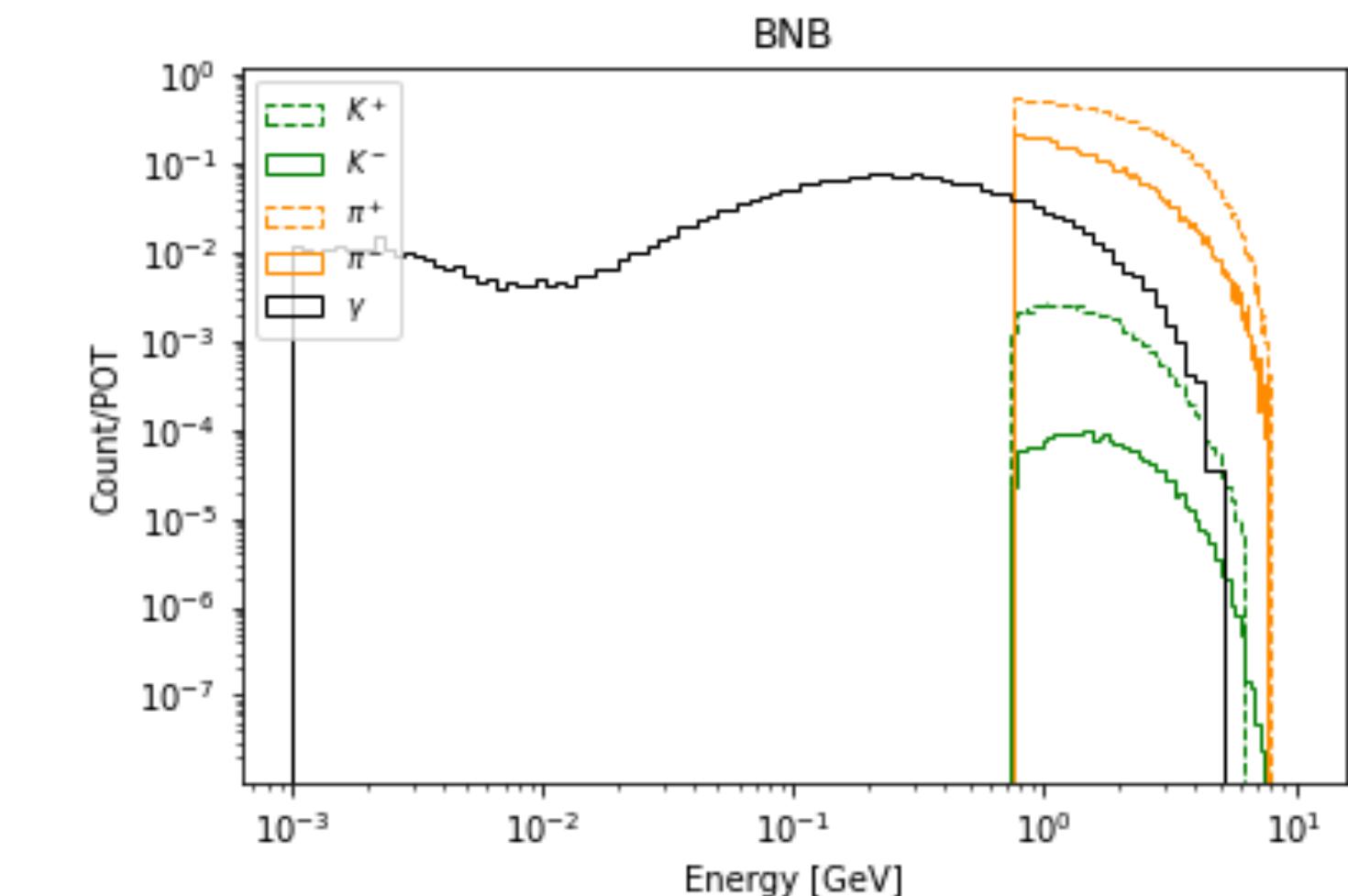
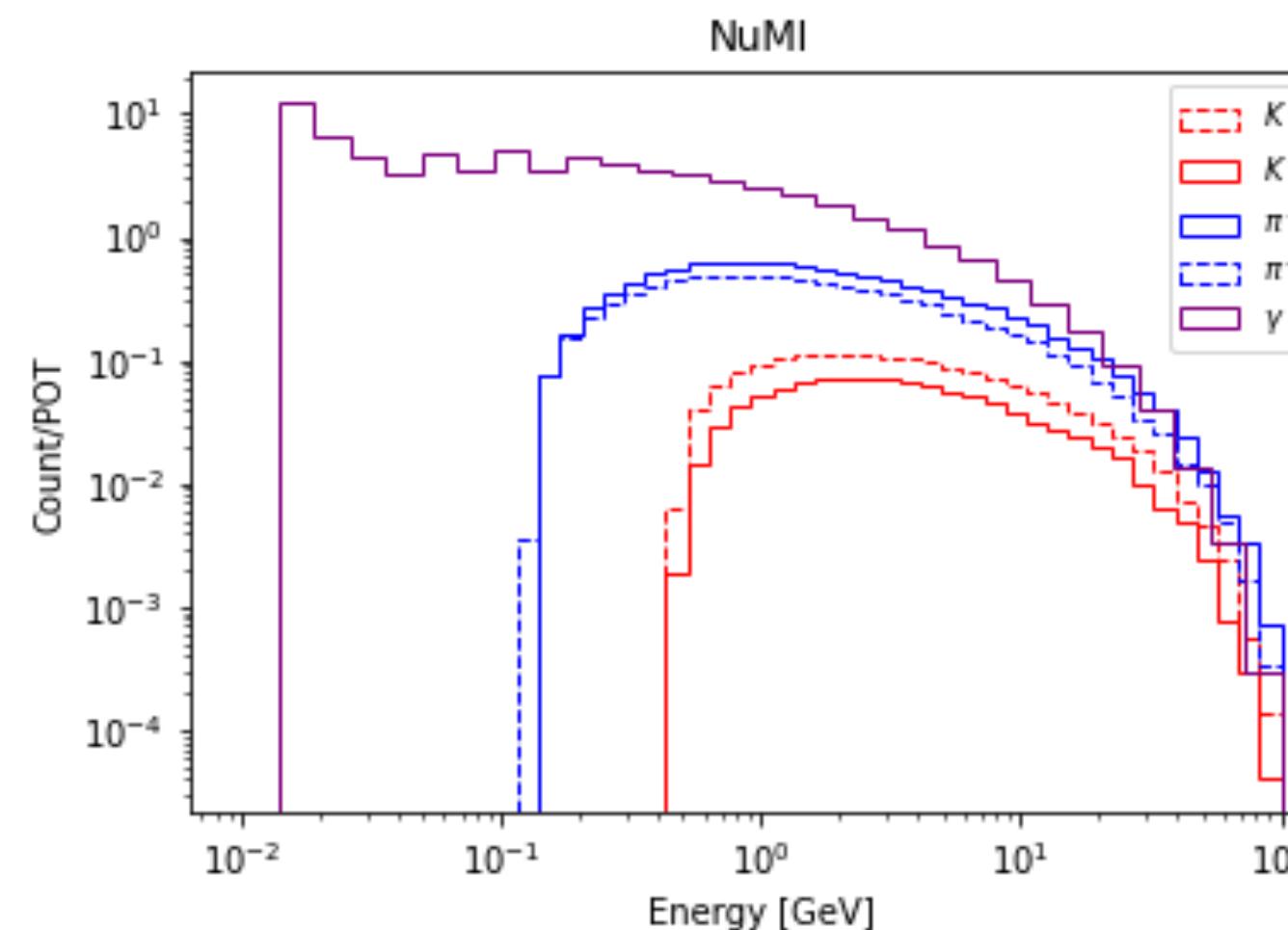
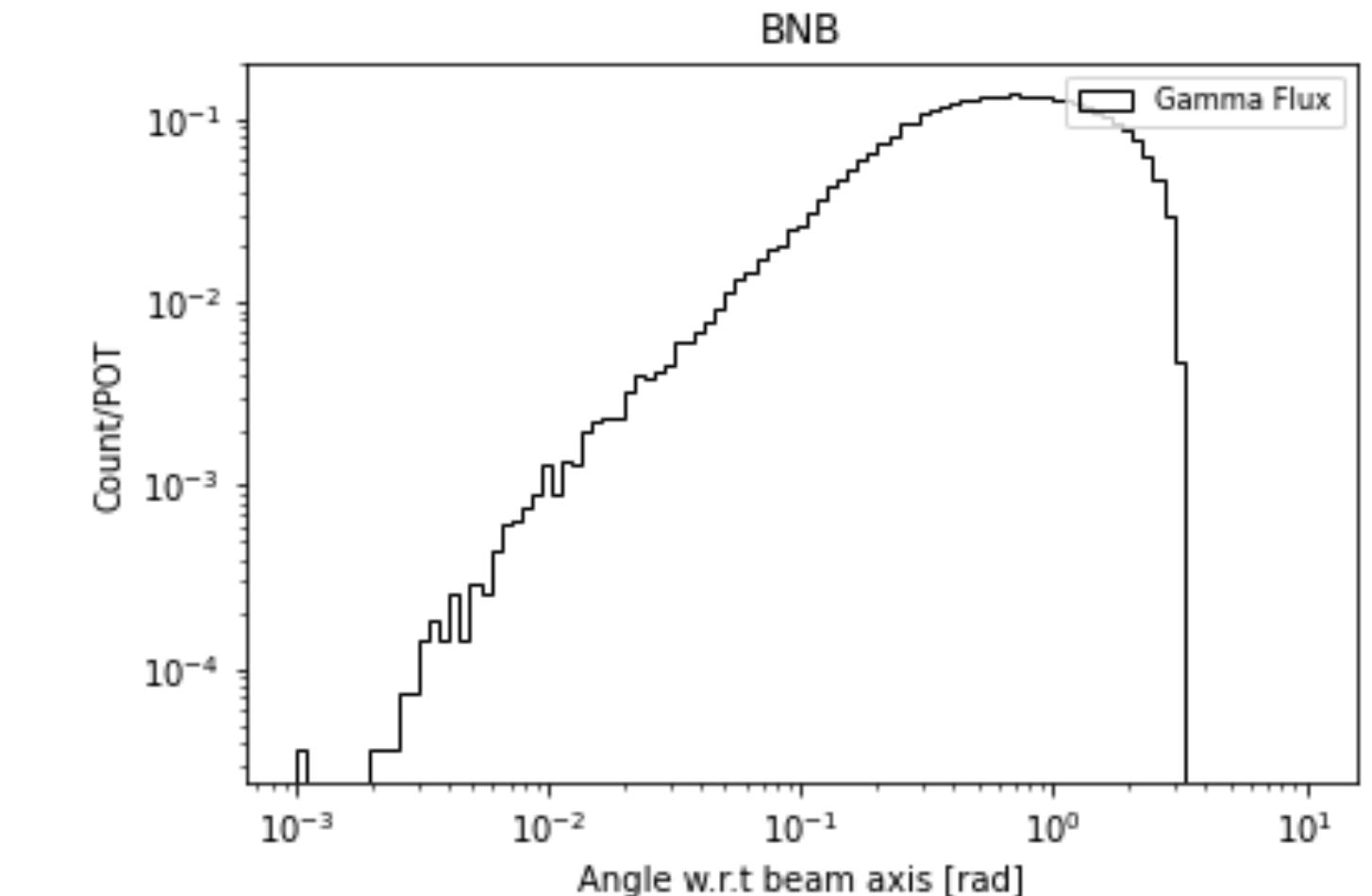
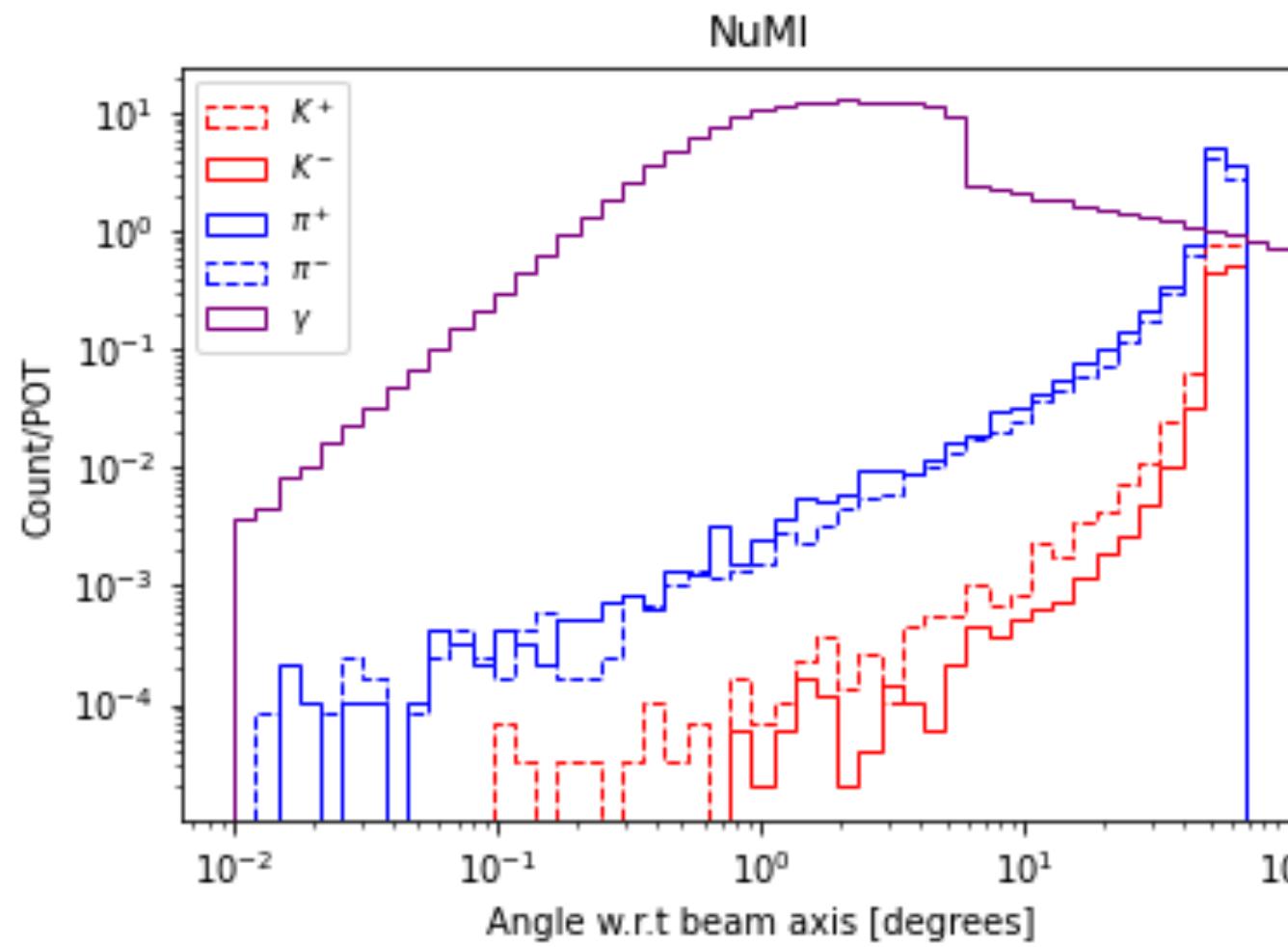
Discussions

- **Higgs Portal Scalars:** Three body Kaon decays can extend sensitivities to higher masses at the cost of flux.
- $g - 2$ **models:** Forward detectors (DUNE, ArgoNeuT) can probe parameters in the 2σ band.
- Analysis of backgrounds will give more accurate estimates.
- Upper edge of sensitivity plot doesn't change when event numbers are increased from 3 to 30.
- Above analysis can be extended to other models like $U(1)_{T_{3R}}$, $U(1)_{B-L}$, $U(1)_{L_e - L_\mu}$, can find parameter space complimentary to existing ones.
- Photon coupling can be exploited at LHC experimental facilities as well.

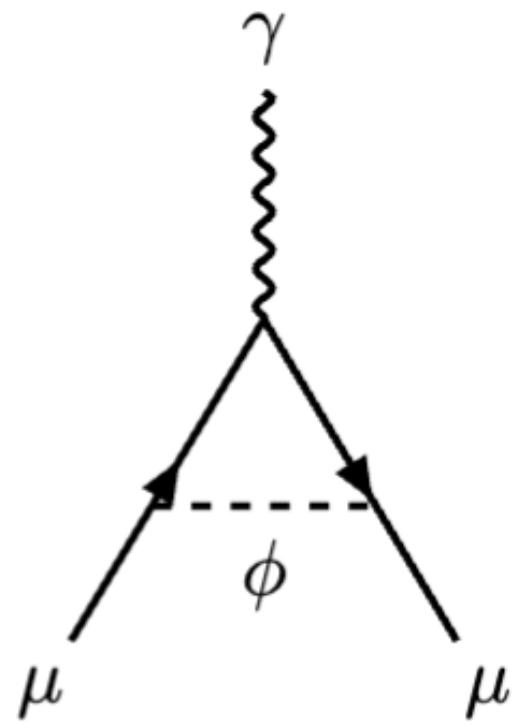
Backup

Fluxes at NuMI and BNB

- DUNE, ArgoNeuT uses the NuMI beam after focusing
- MicroBooNE uses both BNB and NuMI
- ICARUS uses the unfocused NuMI beam
- SBND uses the BNB beam after focusing



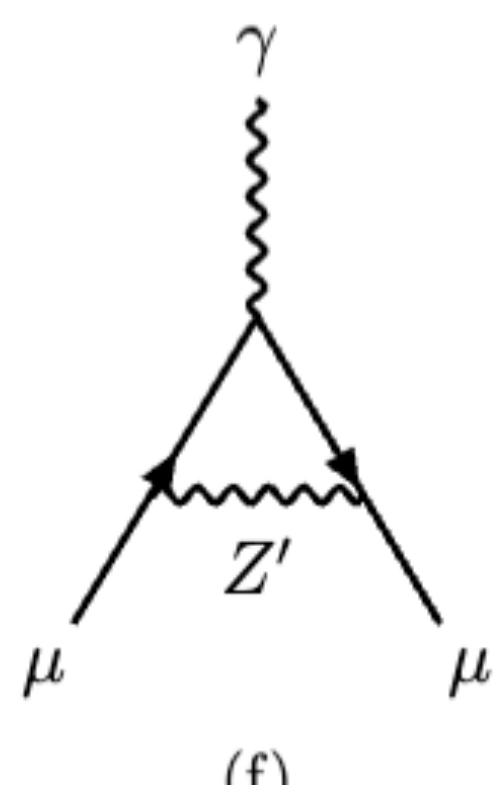
Correction to g-2



$$\Delta a_\mu^\phi = y_{22}^2 \frac{m_\mu^2}{4\pi^2} \int_0^1 dx \frac{2x^2 - x^3}{x^2 m_\mu^2 + (1-x)m_\phi^2}$$

$$\mathcal{L}_{HPS} \supset (AS + BS^2) H^\dagger H$$

$$\mathcal{L}_{\mu\phi} \supset y_{22} \bar{\mu} \mu \phi$$



$$\Delta a_\mu^{Z'} = g_{\mu\tau}^2 \frac{m_\mu^2}{4\pi^2} \int_0^1 dx \frac{x^2 - x^3}{x^2 m_\mu^2 + (1-x)m_\phi^2}$$

$$\mathcal{L}_{L_\mu - L_\tau} \supset \frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha - g_{\mu\tau} Z'_\alpha (\bar{\mu} \gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\tau} \gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha \nu_\tau)$$

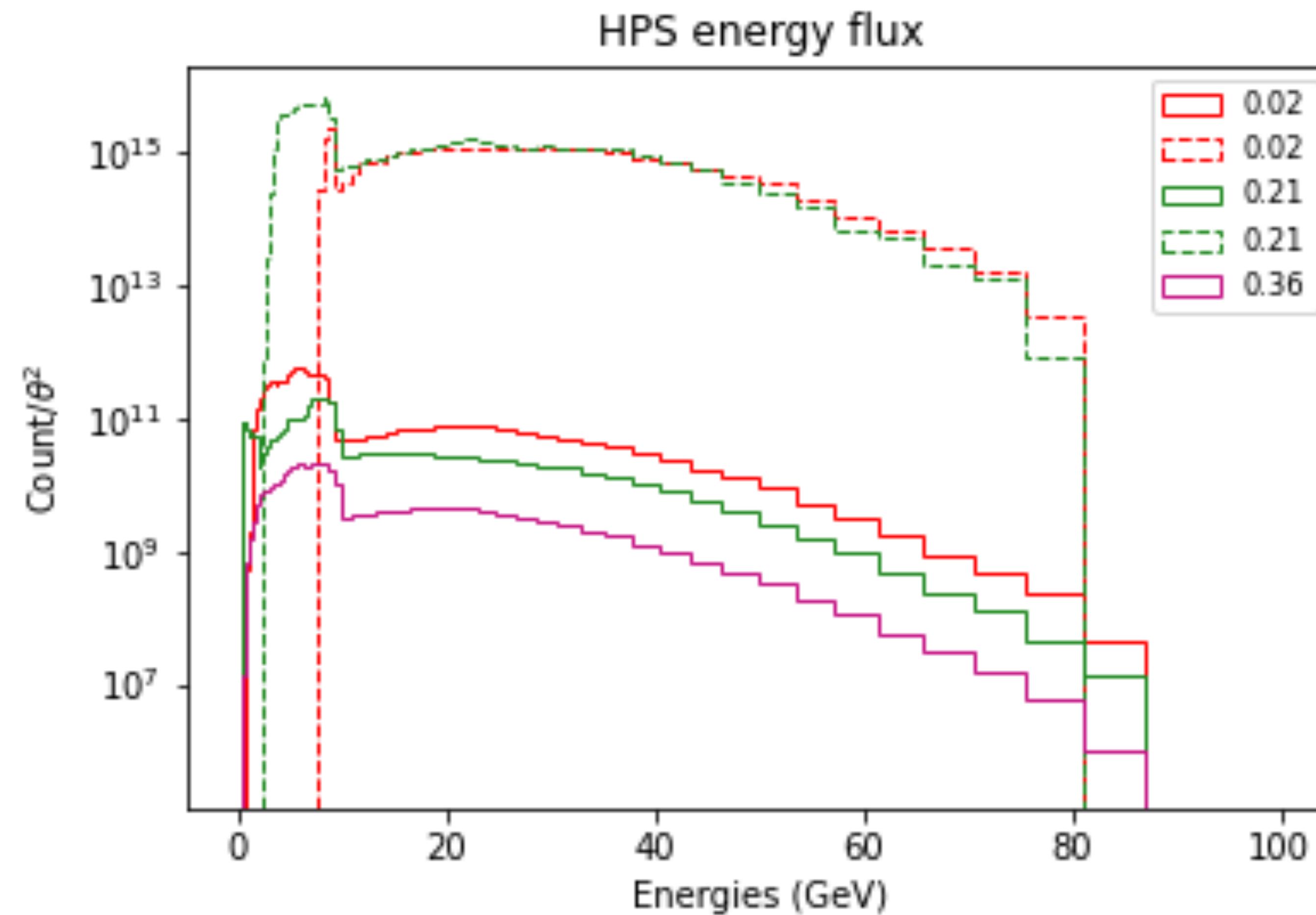
(f)

Number of events at the detector- Sensitivity

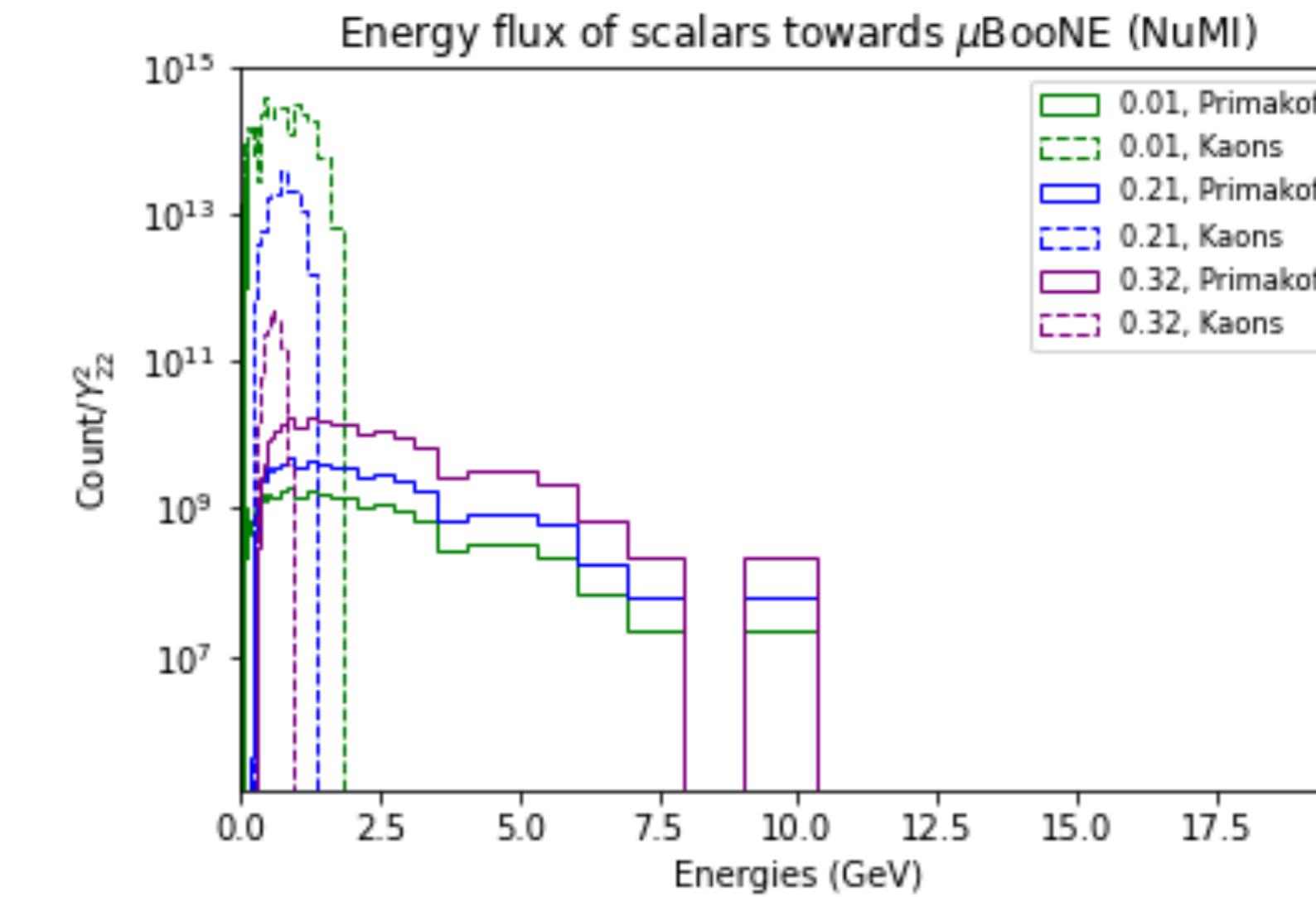
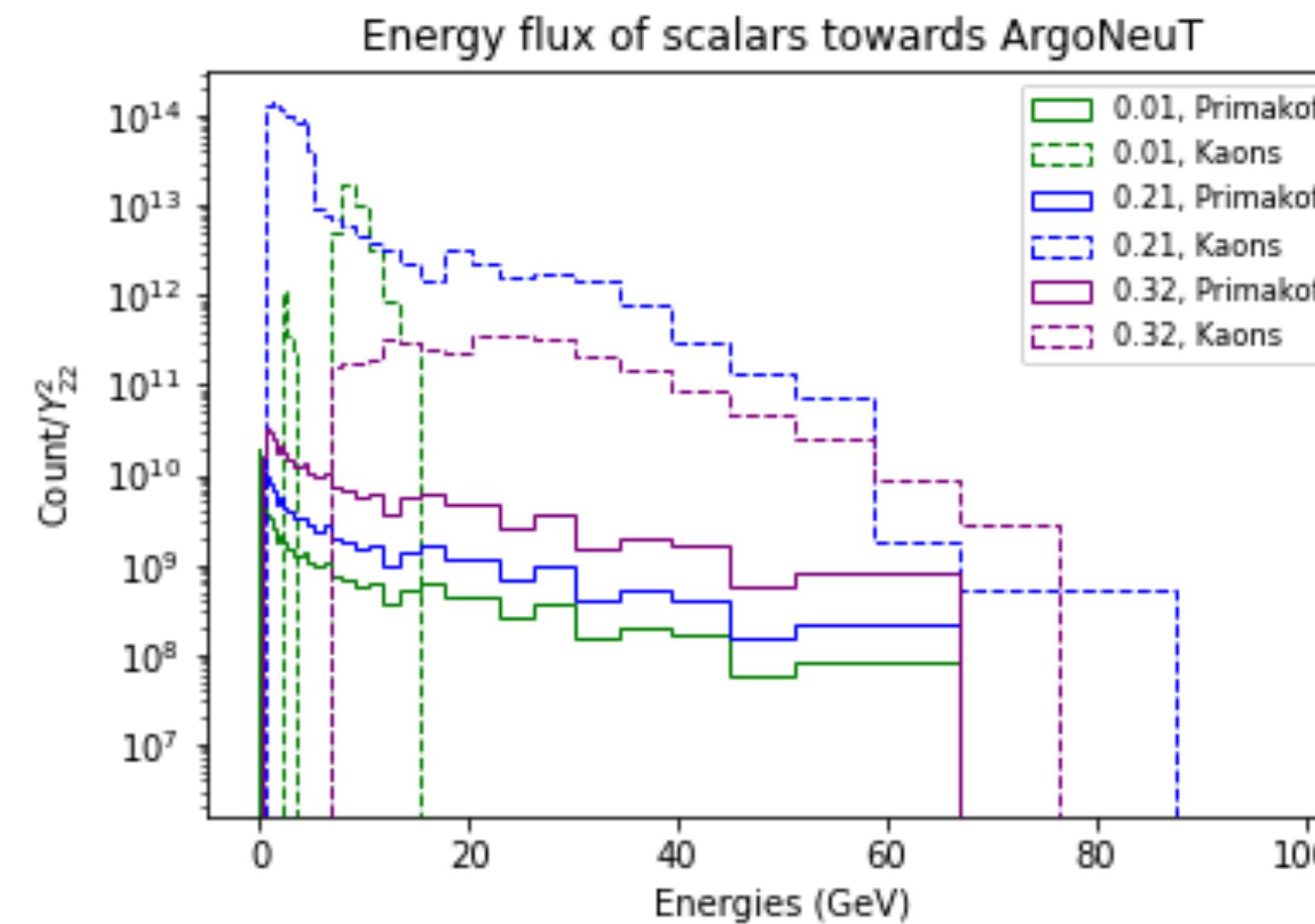
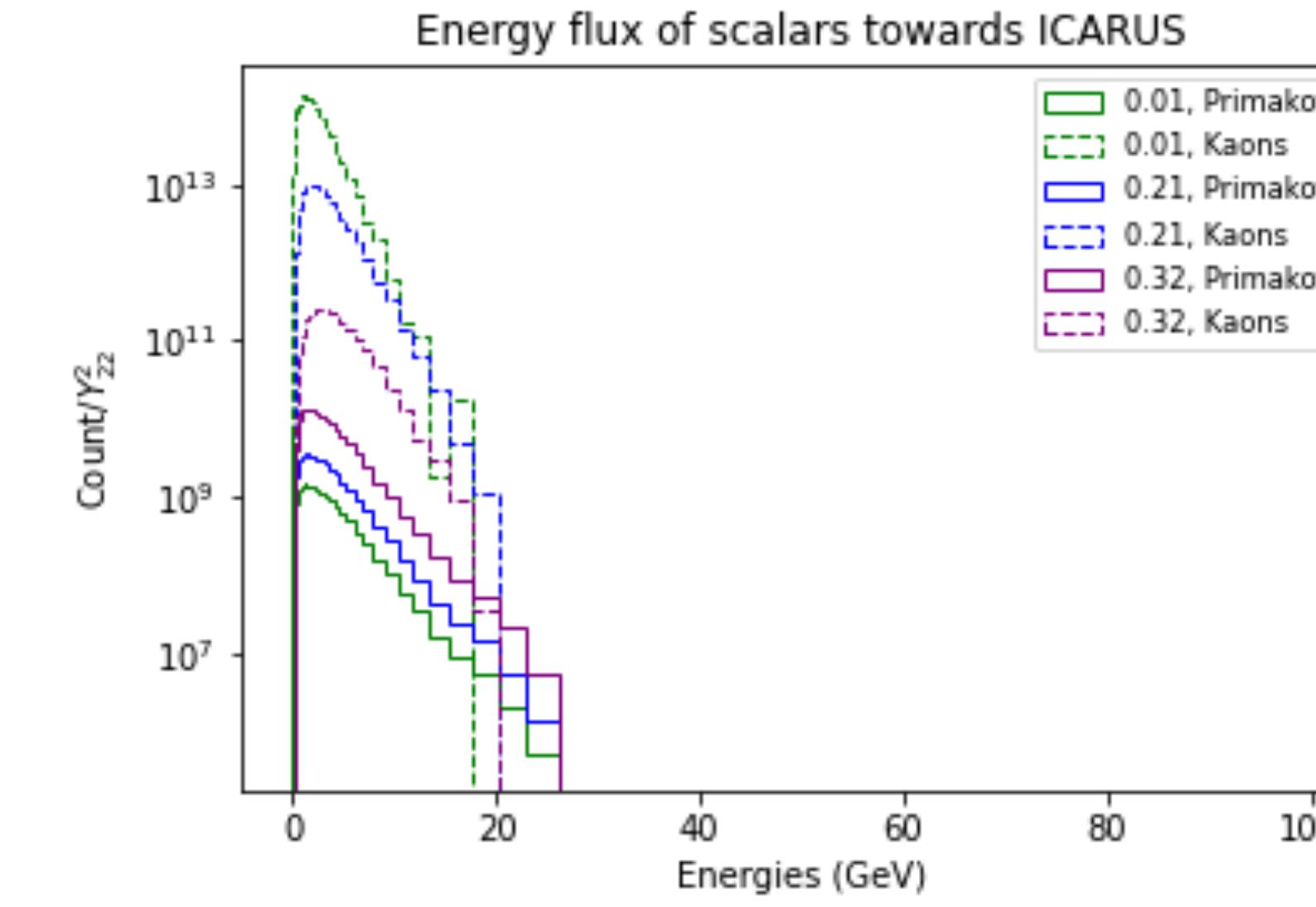
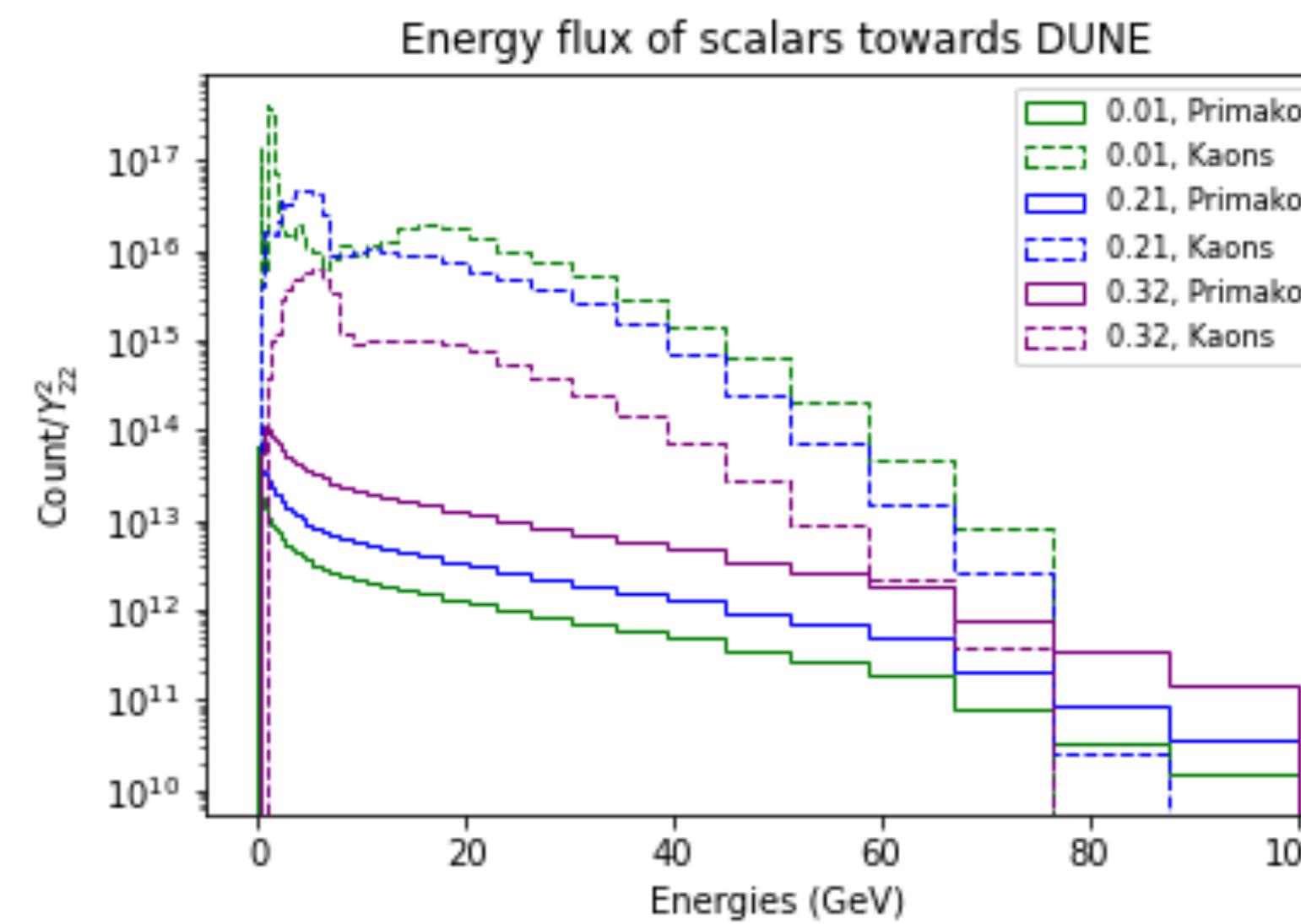
Assume a forward detector, source: 3 body decay

- $\frac{d^2N_D(E_D, \theta_D)}{dEd\cos\theta} = N_P \frac{d^2BR_{P\rightarrow D}}{dE_D d\cos\theta_D}$
- $P_{detector} = P_{survival}(L) \times (1 - P_{survival}(\Delta))$
- $N_{events} = \int dE_D \int d\theta_D \frac{d^2N_D(E_D, \theta_D)}{dEd\cos\theta} P_{detector} \Theta(\theta_D - \theta_{d,max})$
- L : distance from source to detector
- Δ : depth of the detector
- $\theta_{d,max}$: Maximum polar angle subtended by the detector
- $P_{survival}(d) = \exp(-d/\lambda_{decay})$
- $\lambda_{decay} = \hbar\beta c/\Gamma_{lab,decay}$
- $\Gamma_{lab,decay} = \gamma\Gamma_{rest,decay}$
- $\gamma = E_D/m_D$
- $\beta = p_D/E_D$

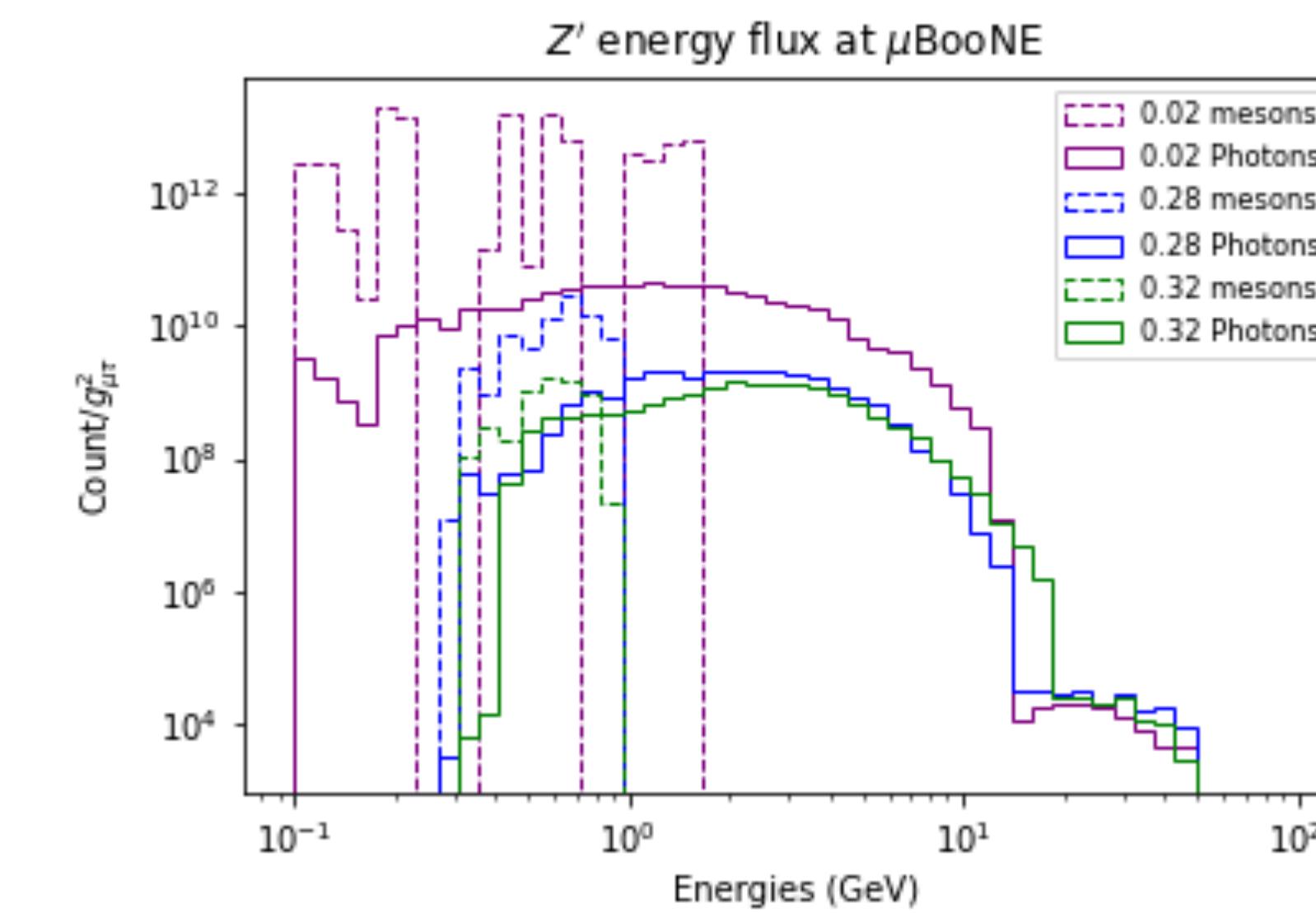
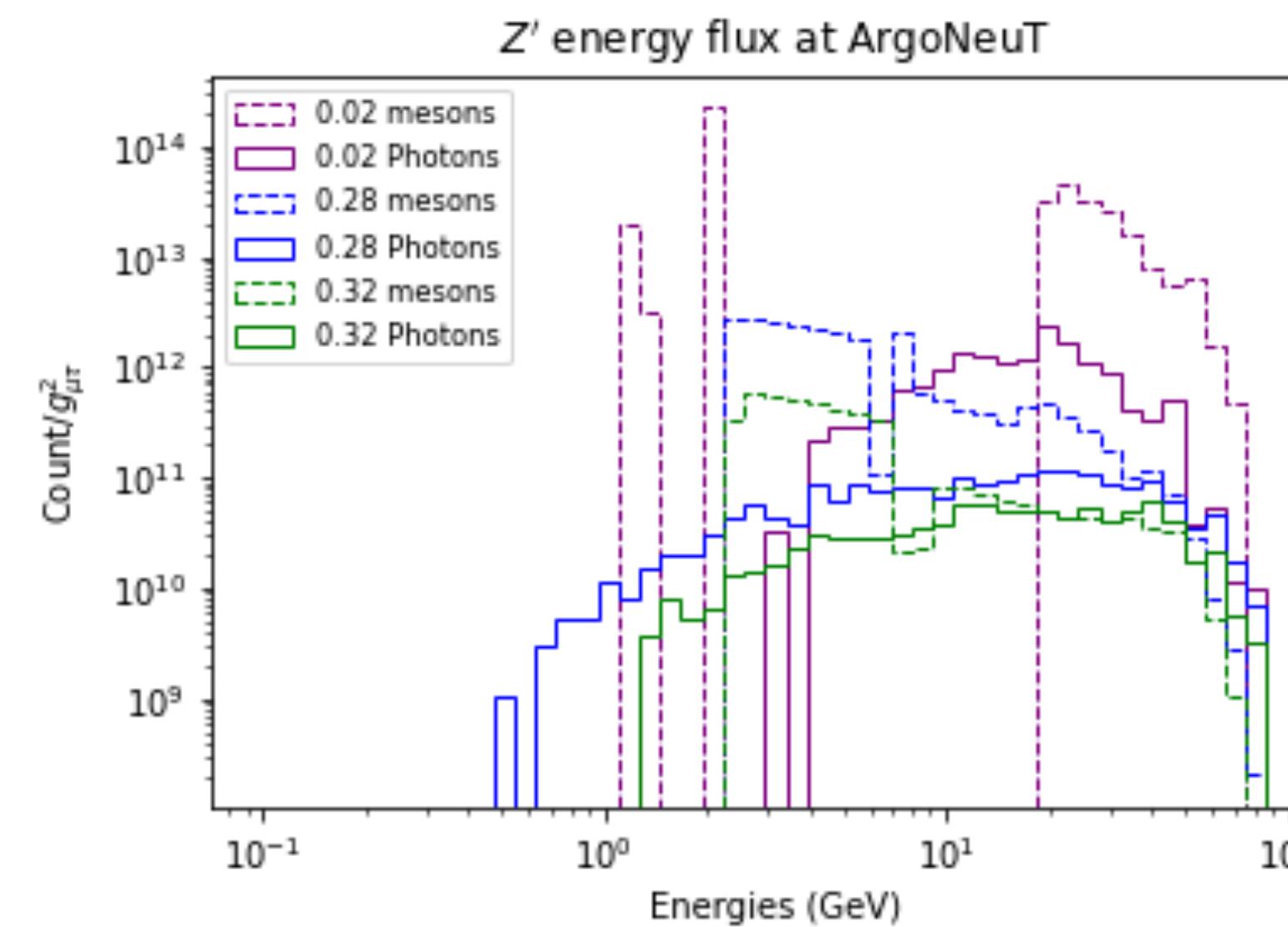
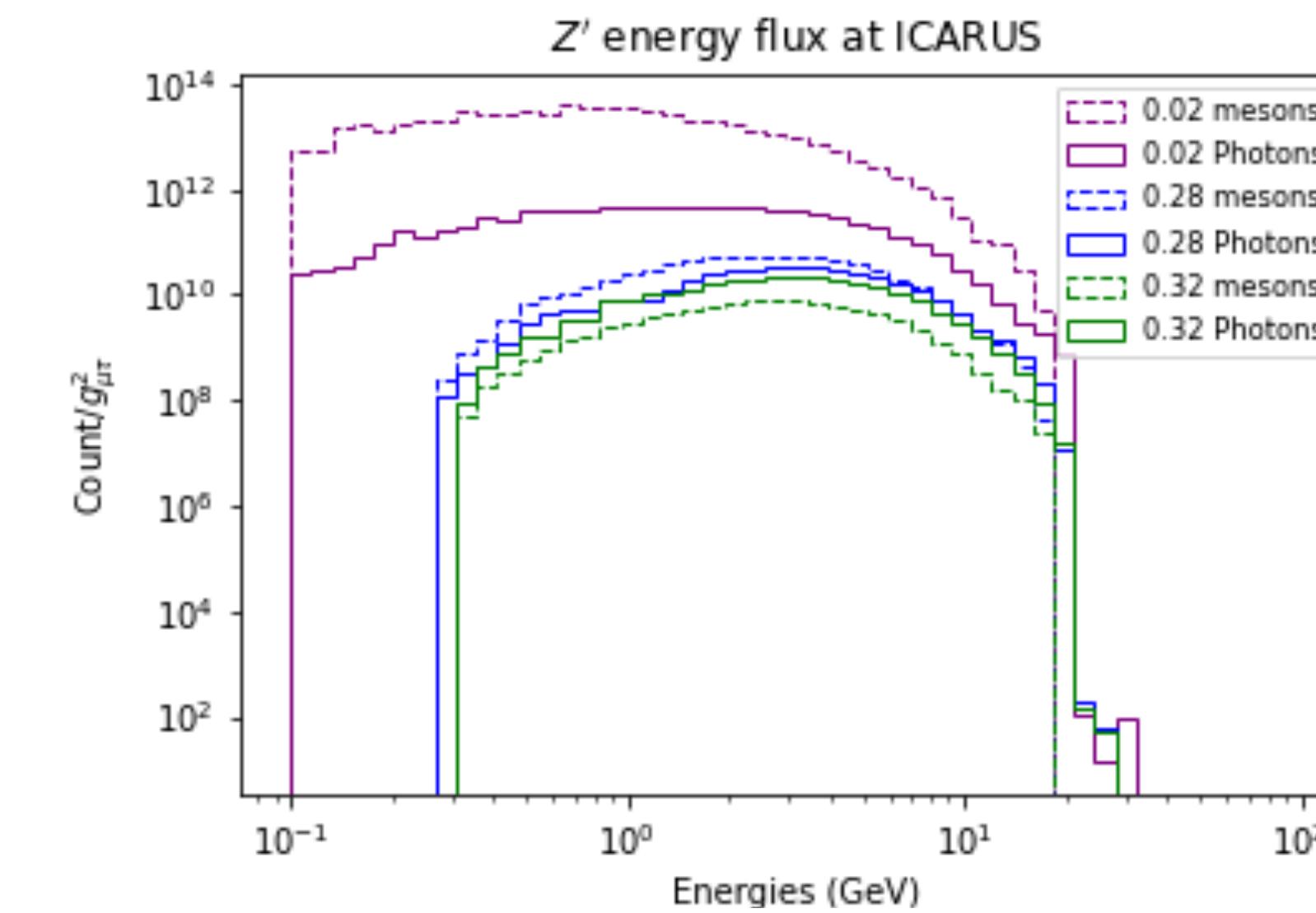
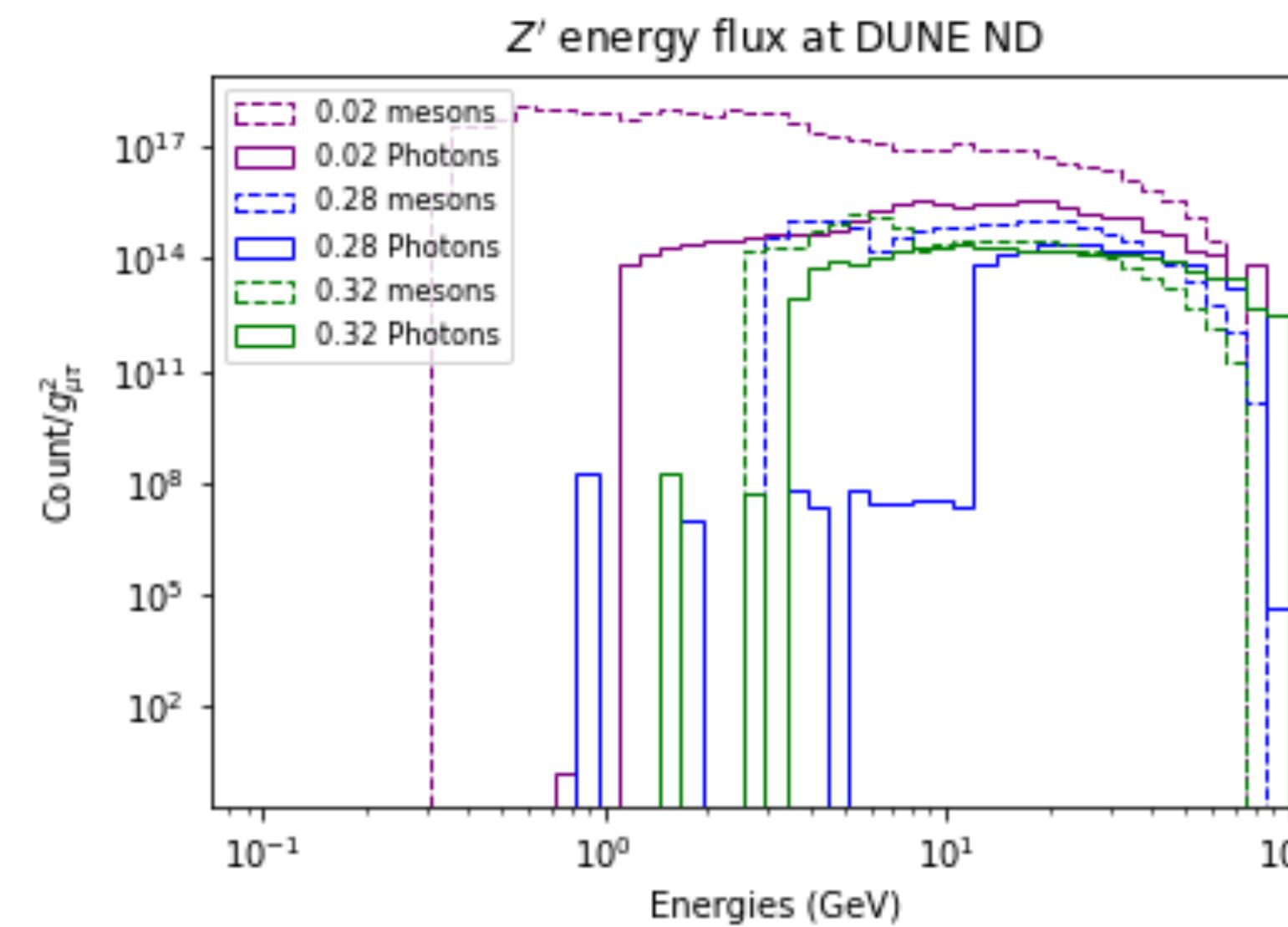
Energy flux of HPS



Energy flux of muonic scalars



Energy flux of $L_\mu - L_\tau$ bosons



Sensitivities with backgrounds for MicroBooNE

