Long-lived Vectors from Electromagnetic Cascades at SHiP

In collaboration with Nikita Blinov, Patrick J. Fox, Kevin J. Kelly, Pedro A.N. Machado, Ryan Plestid
arXiv:2412.01880

LIGHT DARK WORLD 2026
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Carleton University
Ottawa, Canada

Tao Zhou
Texas A&M University
taozhou@tamu.edu

Models

- Secluded dark photon

$$\mathcal{L} \subset -\frac{1}{4}F_{\mu\nu}{}'F^{\mu\nu\prime} \boxed{-\frac{\epsilon}{2}F_{\mu\nu}F^{\mu\nu\prime}} + \frac{1}{2}m_V^2 V_\mu V^\mu$$

Induces coupling with SM fermions $\epsilon e J_\mu V^\mu$

J_μ: SM electromagnetic current

V^μ: Dark photon field

Models

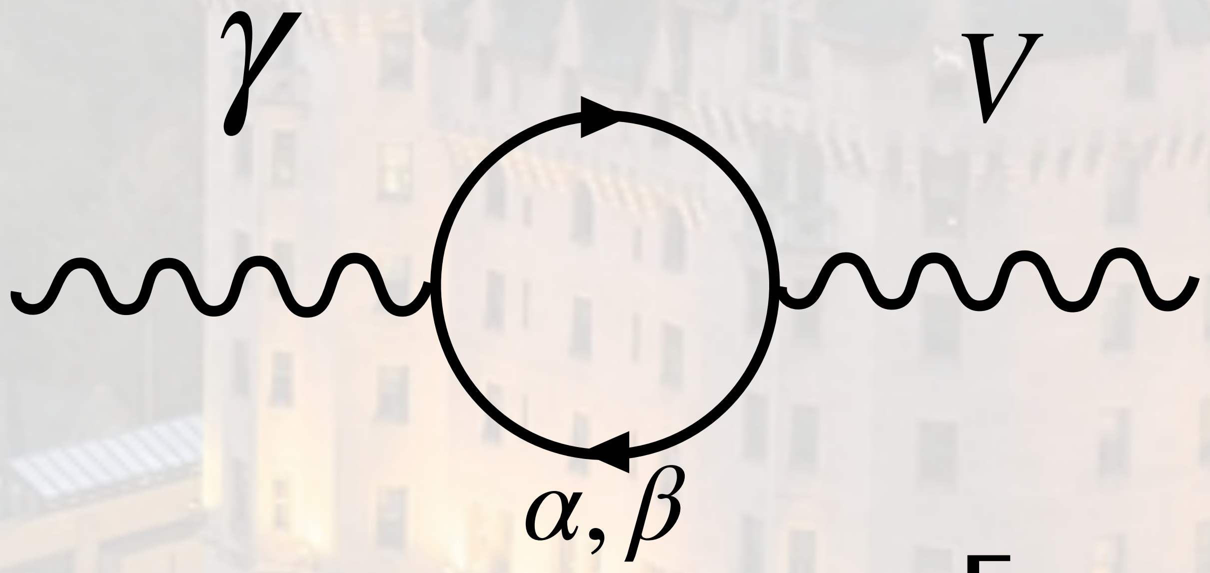
- Leptophilic gauge boson

$$\mathscr{L} \subset -\frac{1}{4}F_{\mu\nu}{}'F^{\mu\nu\prime} + \frac{1}{2}m_V^2 V_\mu V^\mu + g_V J_\mu V^\mu$$

$$L_e - L_\mu$$

$$L_e - L_\tau$$

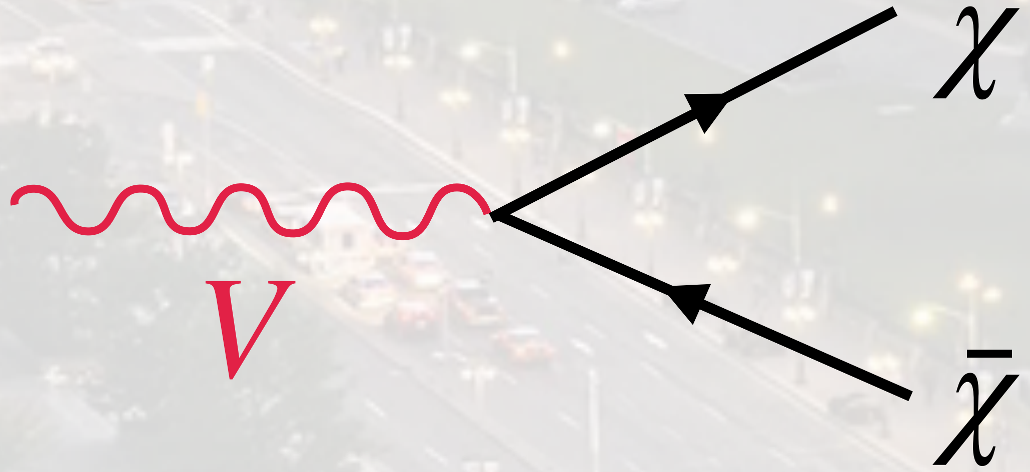
$$L_\mu - L_\tau$$

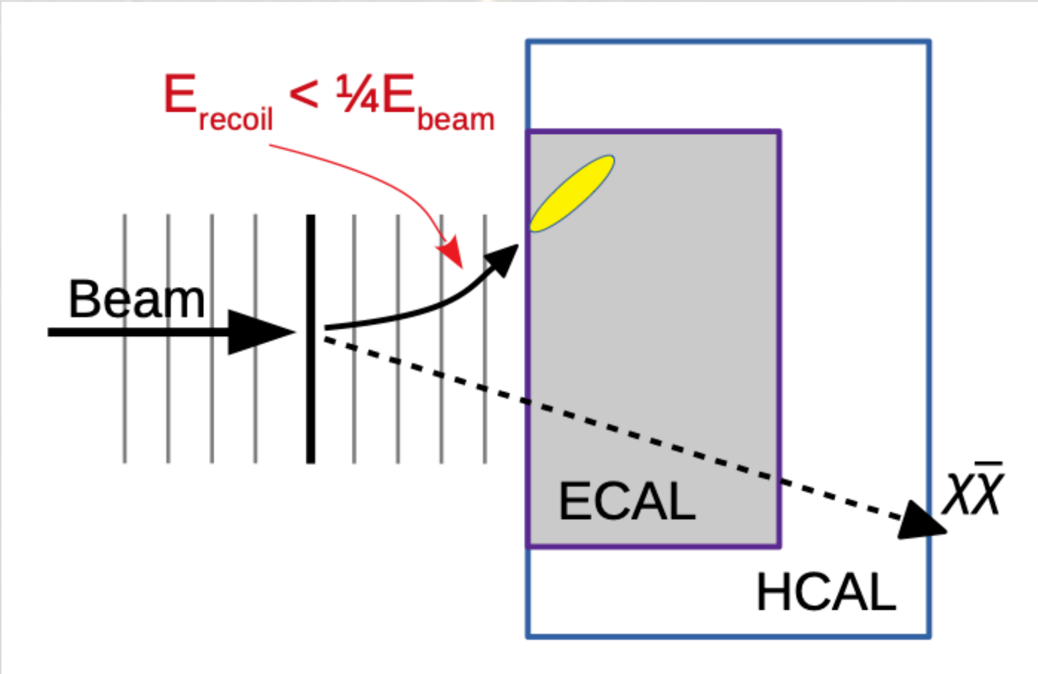


$$\varepsilon_{\alpha\beta}\left(q^2\right) = -\frac{e g_{\alpha\beta}}{2\pi^2}\int_0^1 x(1-x)\log\left[\frac{m_{\ell_\beta}^2 - x(1-x)q^2}{m_{\ell_\alpha}^2 - x(1-x)q^2}\right]dx$$

Search Strategies

- Fixed target experiments provides the most sensitive probes of dark sectors, especially long-lived and relatively low mass mediators.
- Invisible decay(LDMX, NA64, ...)

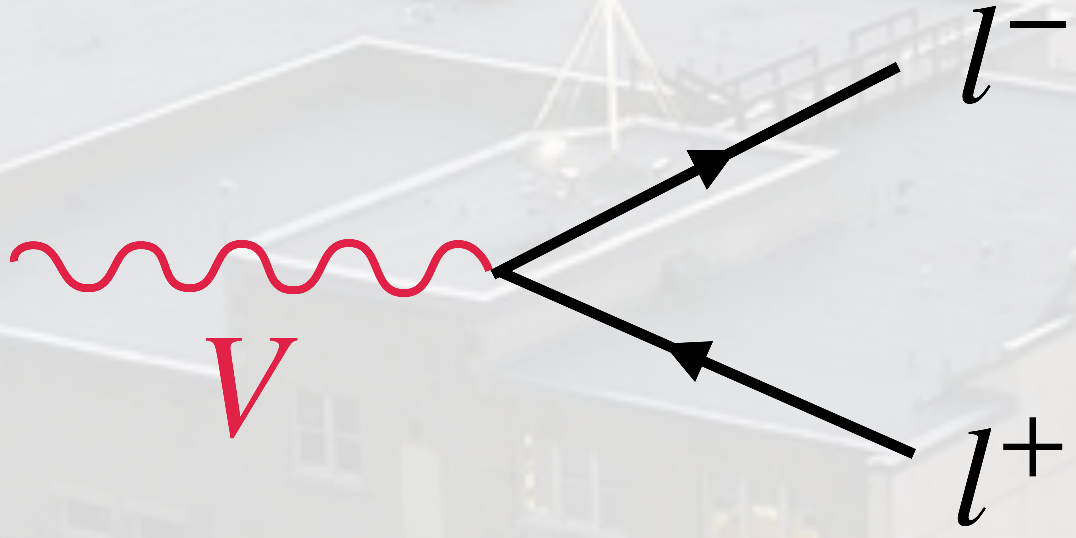


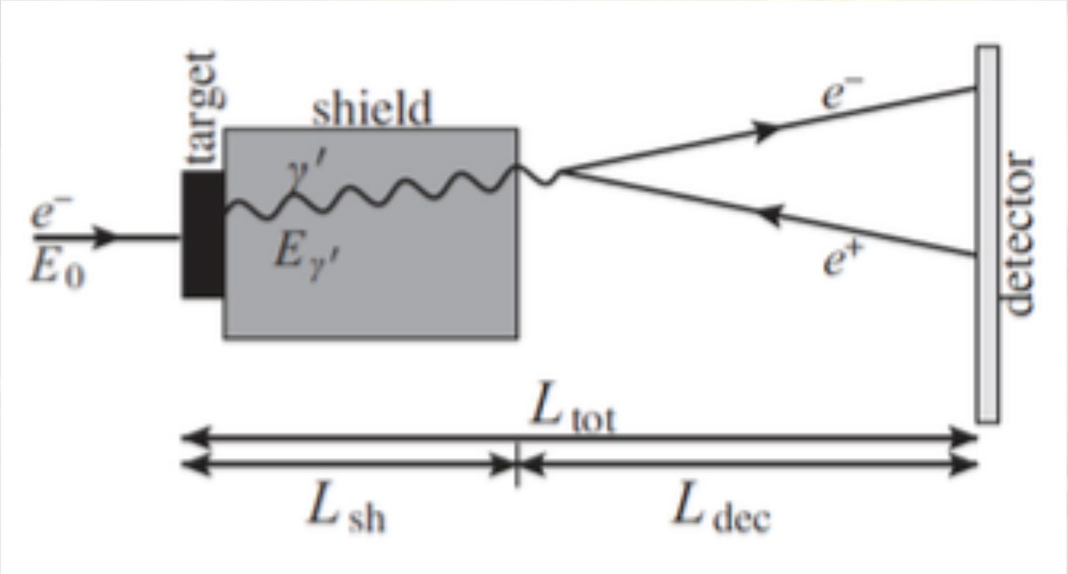


1808.05219

$$m_V > 2m_\chi$$

- Visible decay(SHiP, DarkQuest, ...)





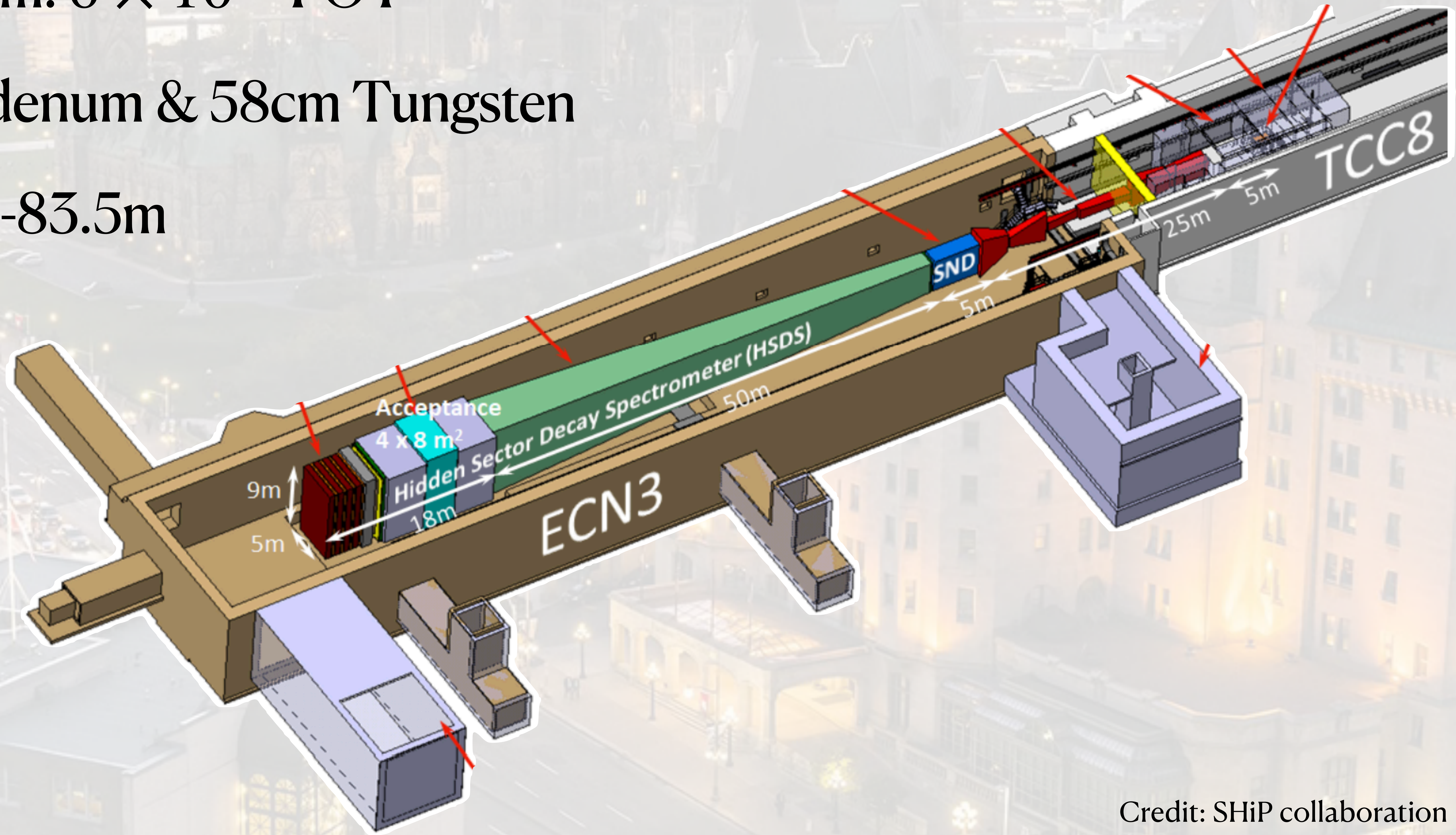
$$m_V < 2m_\chi$$

SHiP - Search for Hidden Particles

400 GeV proton beam. 6×10^{20} POT

Target: 58cm Molybdenum & 58cm Tungsten

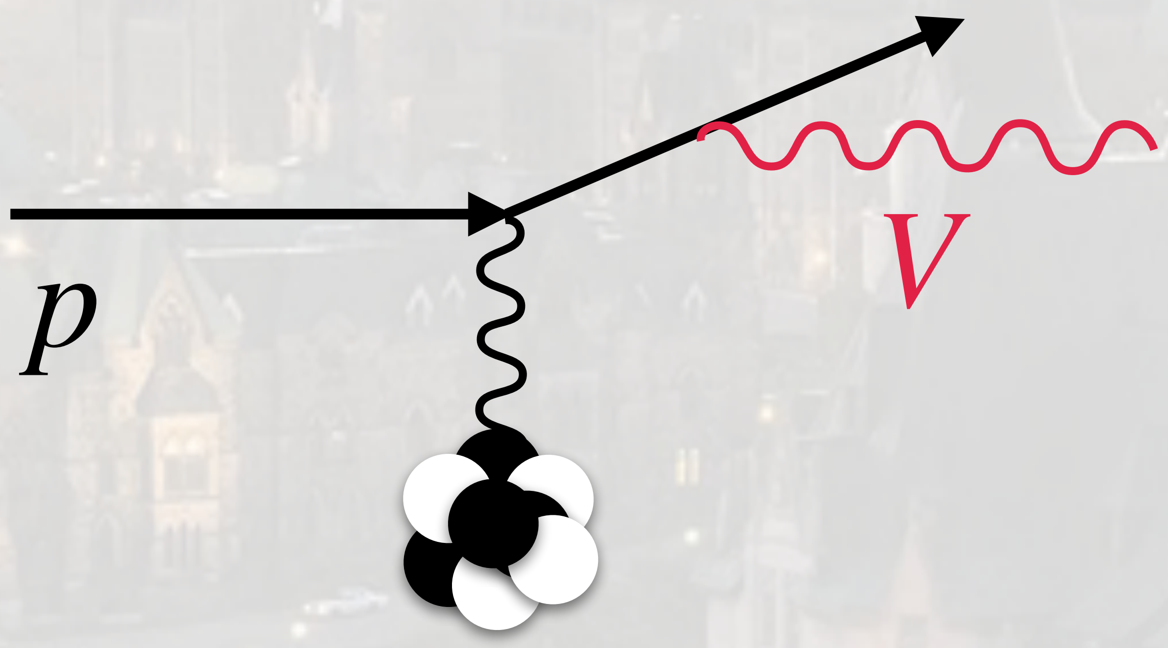
Decay chamber: 33.5-83.5m



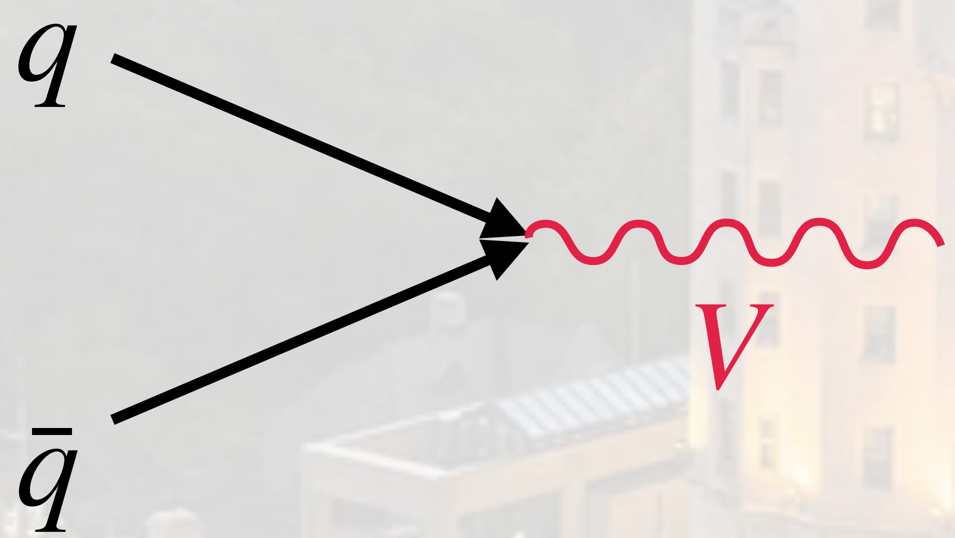
Credit: SHiP collaboration

Primary productions

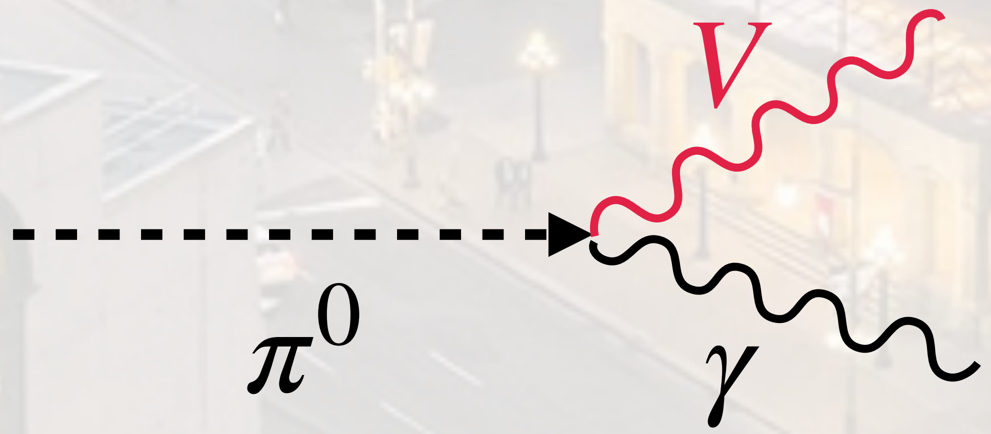
- Proton bremsstrahlung



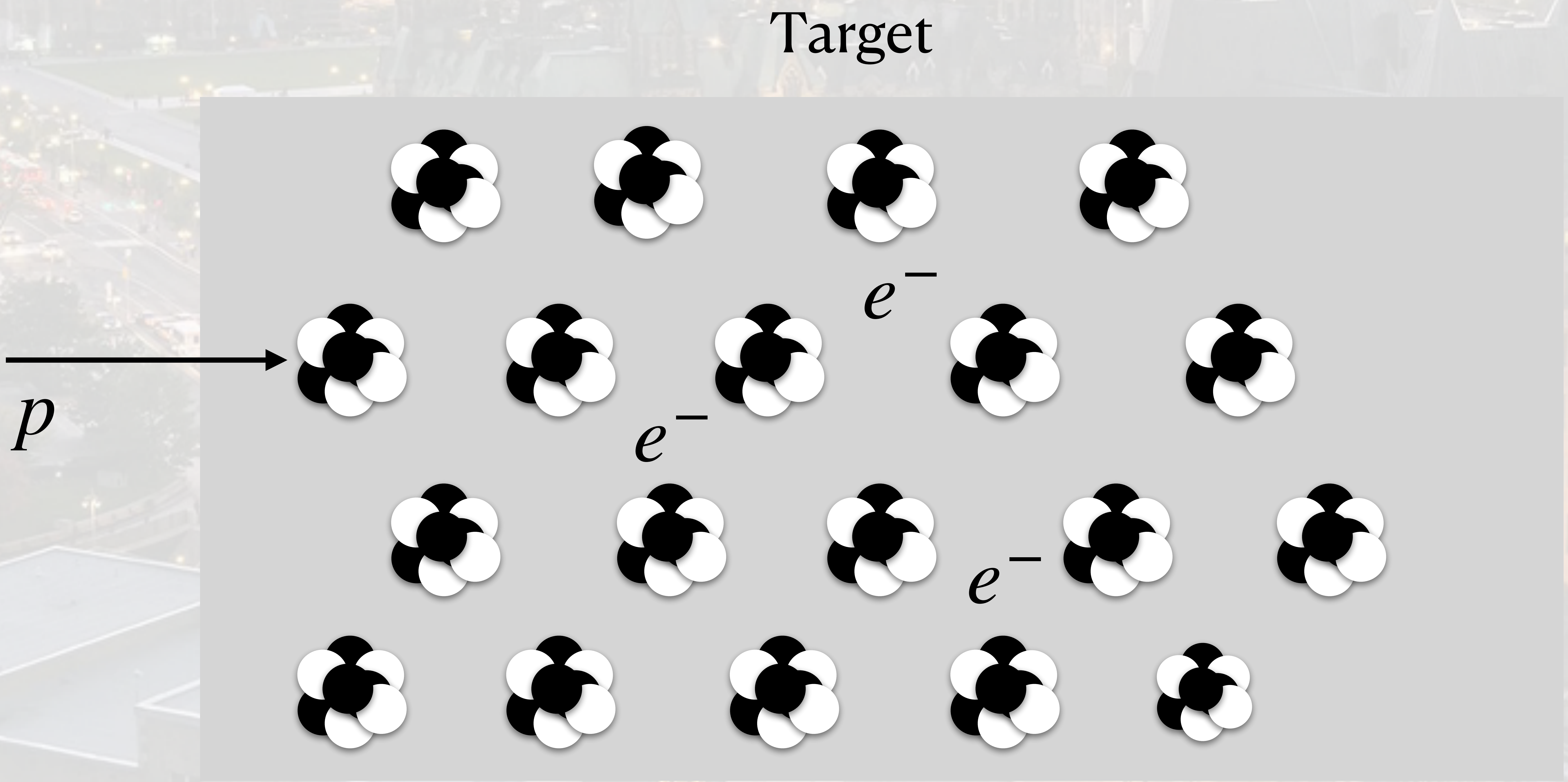
- Drell-Yan production



- Meson decay $(\pi^0, \eta, \omega, \eta')$

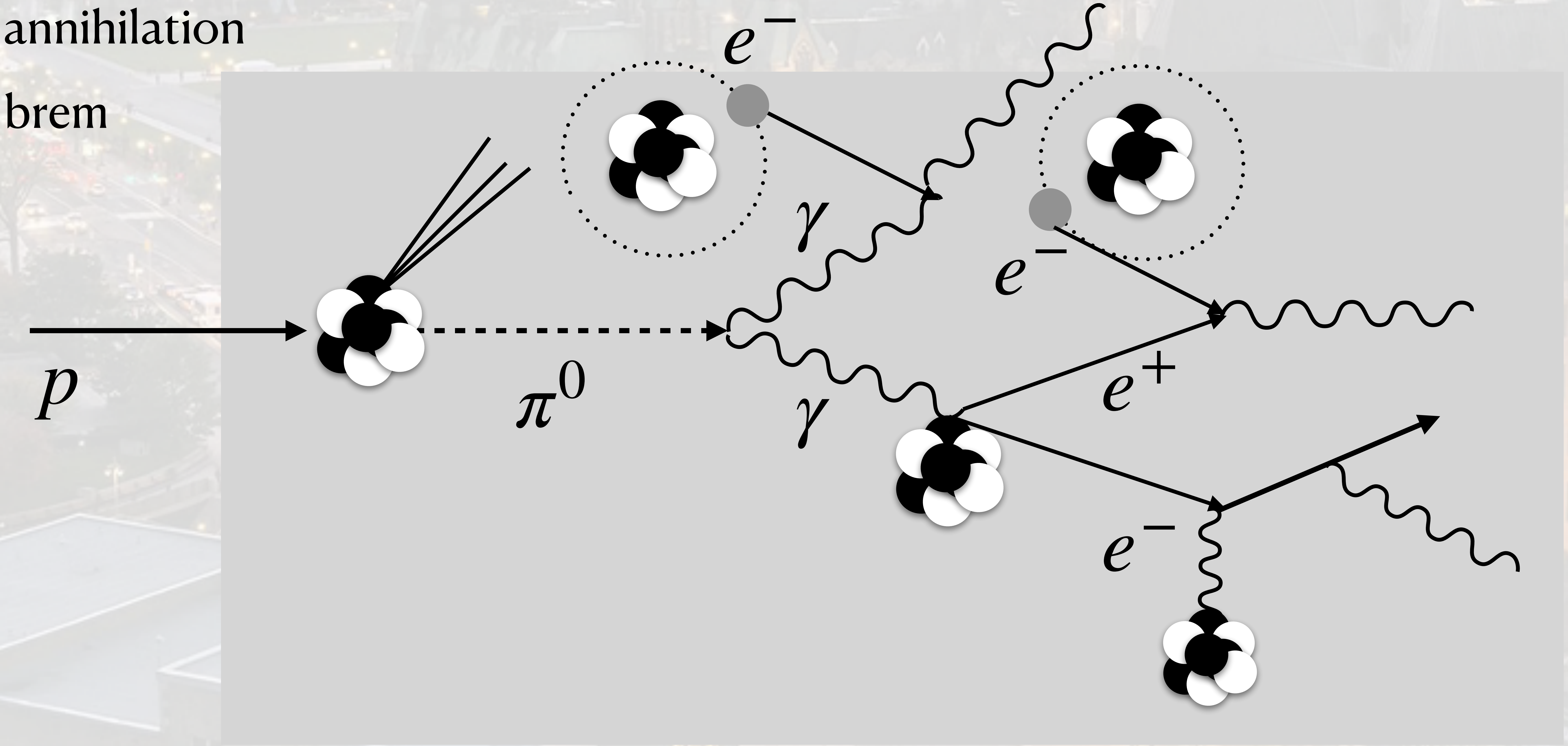


Electromagnetic secondaries



Electromagnetic secondaries

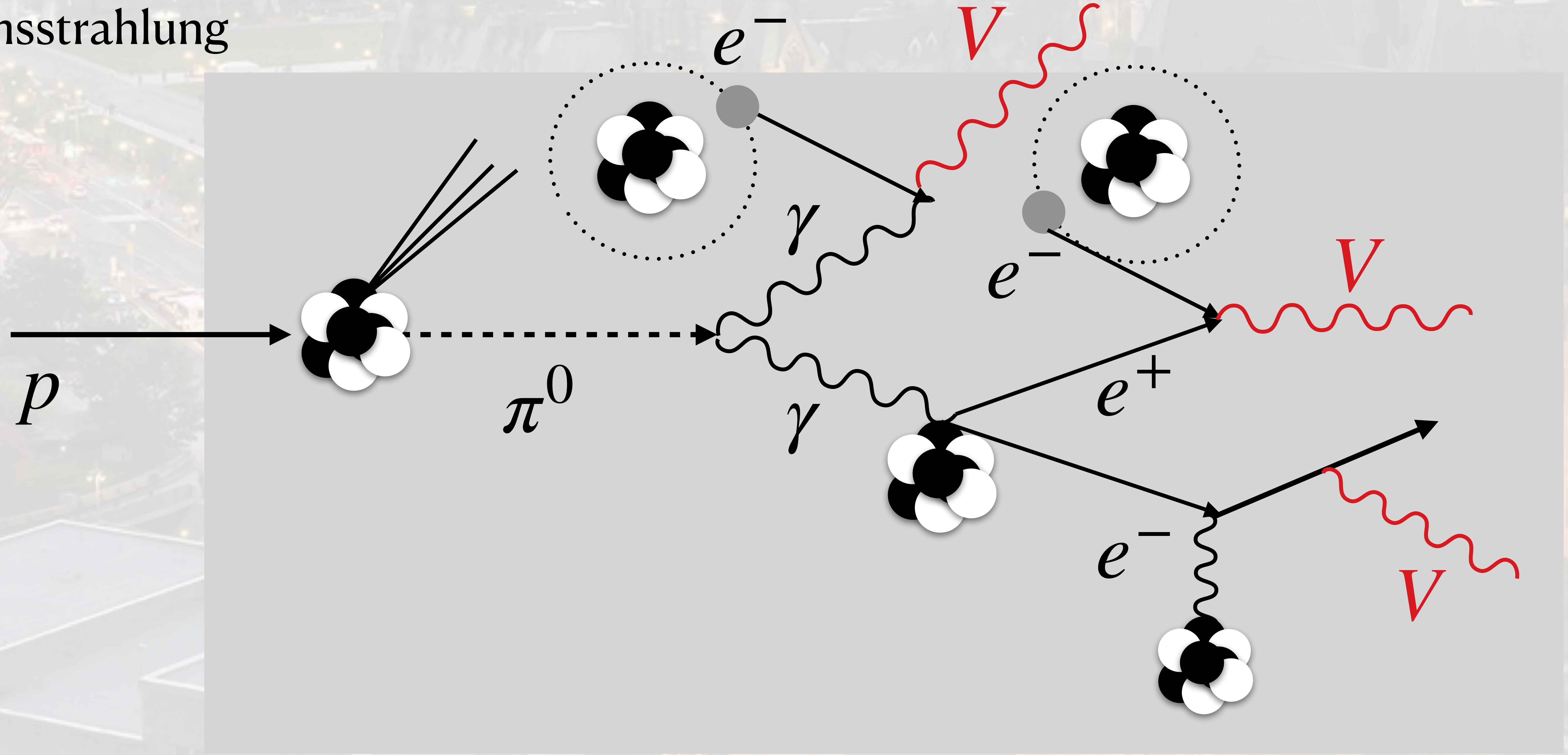
- Pair production
- Compton scattering
- Positron annihilation
- Electron brem



Each SM vertex in the shower can be BSM as well!

Electromagnetic secondaries

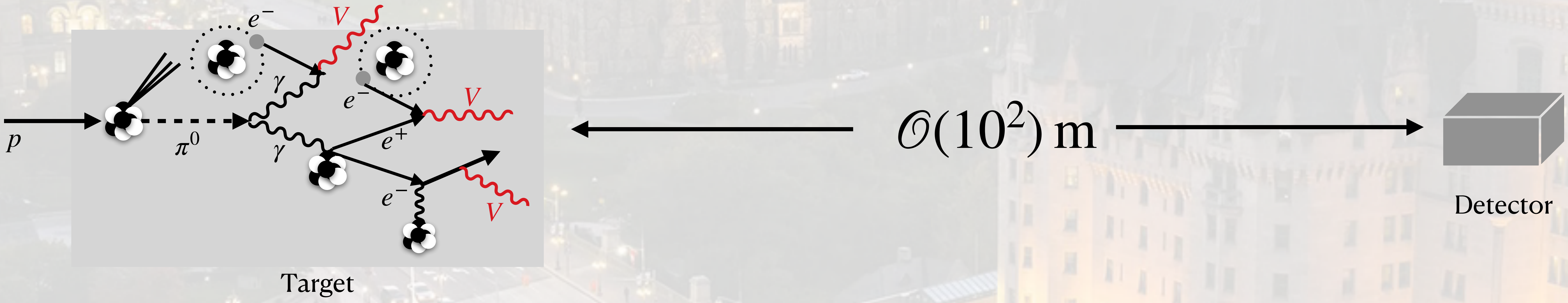
- Dark Compton scattering
- Dark annihilation
- Dark bremsstrahlung



Each SM vertex in the shower can be BSM as well!

Challenge - kinematics

- Experiments such as SHiP usually has a small detector acceptance.
- Small effect on directionality can be crucial for BSM production.



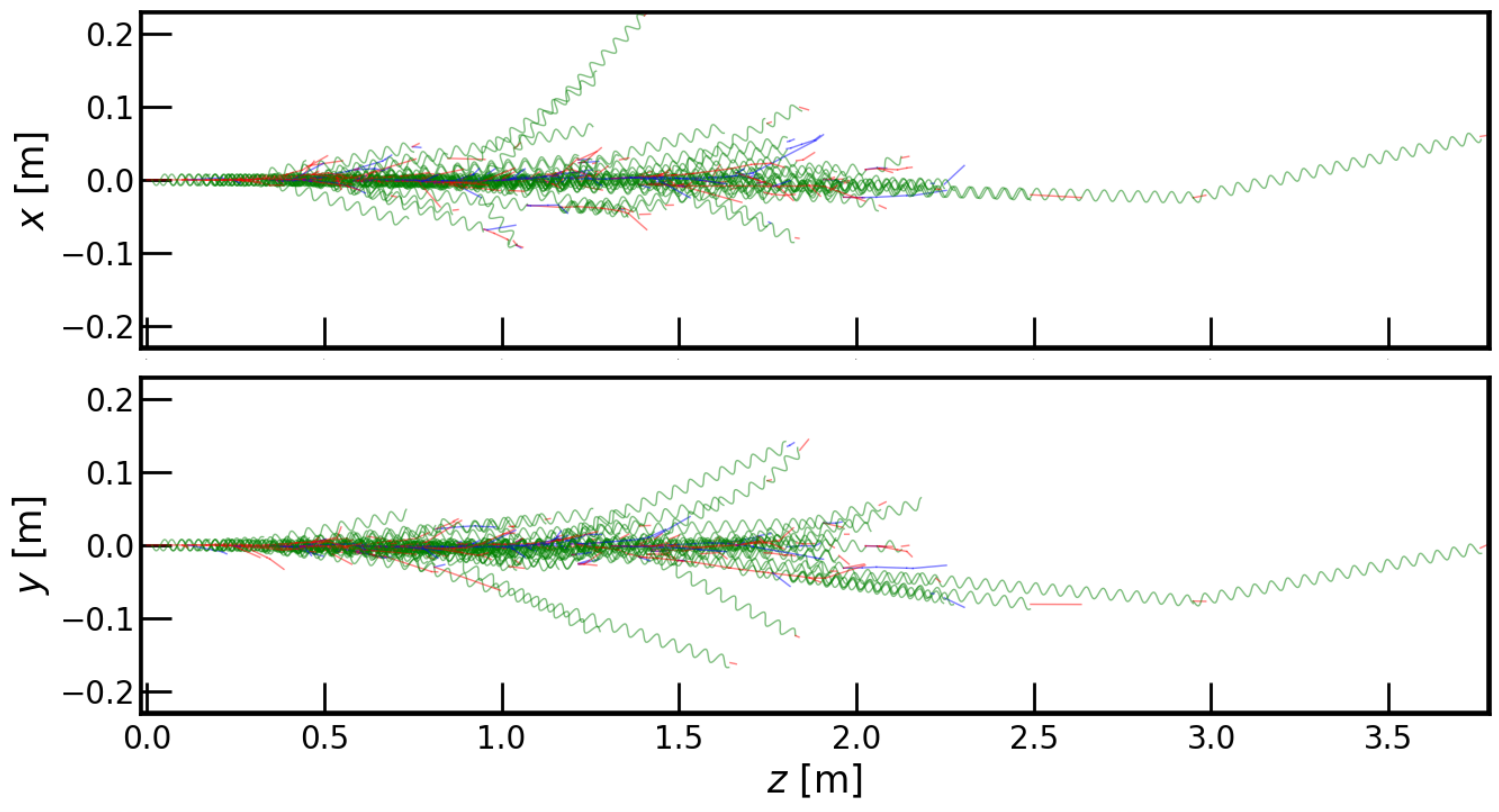
It would be nice if we can ...

- Generate SM shower
- Repurpose the SM shower to produce BSM states, tracking the kinematics.

PETITE (Package for Electromagnetic Transitions In Thick-target Environments)

Nikita Blinov, Patrick J. Fox, Kevin J. Kelly, Pedro A.N. Machado, Ryan Plestid, https://github.com/kjkellyphys/PETITE, 2401.06843

- **Fast** and **lightweight** Monte Carlo generator for production of dark sector objects in thick-target experiments.
- Generates electromagnetic showers for incoming electron, positron or photon propagating through a dense medium, and includes the possibility of dark sector particle production.



SM processes

- Bremsstrahlung $e^{\pm}Z \to e^{\pm}\gamma Z$
- Pair production $\gamma Z \to e^{+}e^{-}Z.$
- Compton scattering $\gamma e^{-} \to \gamma e^{-}$
- Pair-annihilation $e^{+}e^{-} \to \gamma\gamma$
- Moller Scattering $e^{-}e^{-} \to e^{-}e^{-}$
- Bhabha Scattering $e^{+}e^{-} \to e^{+}e^{-}$

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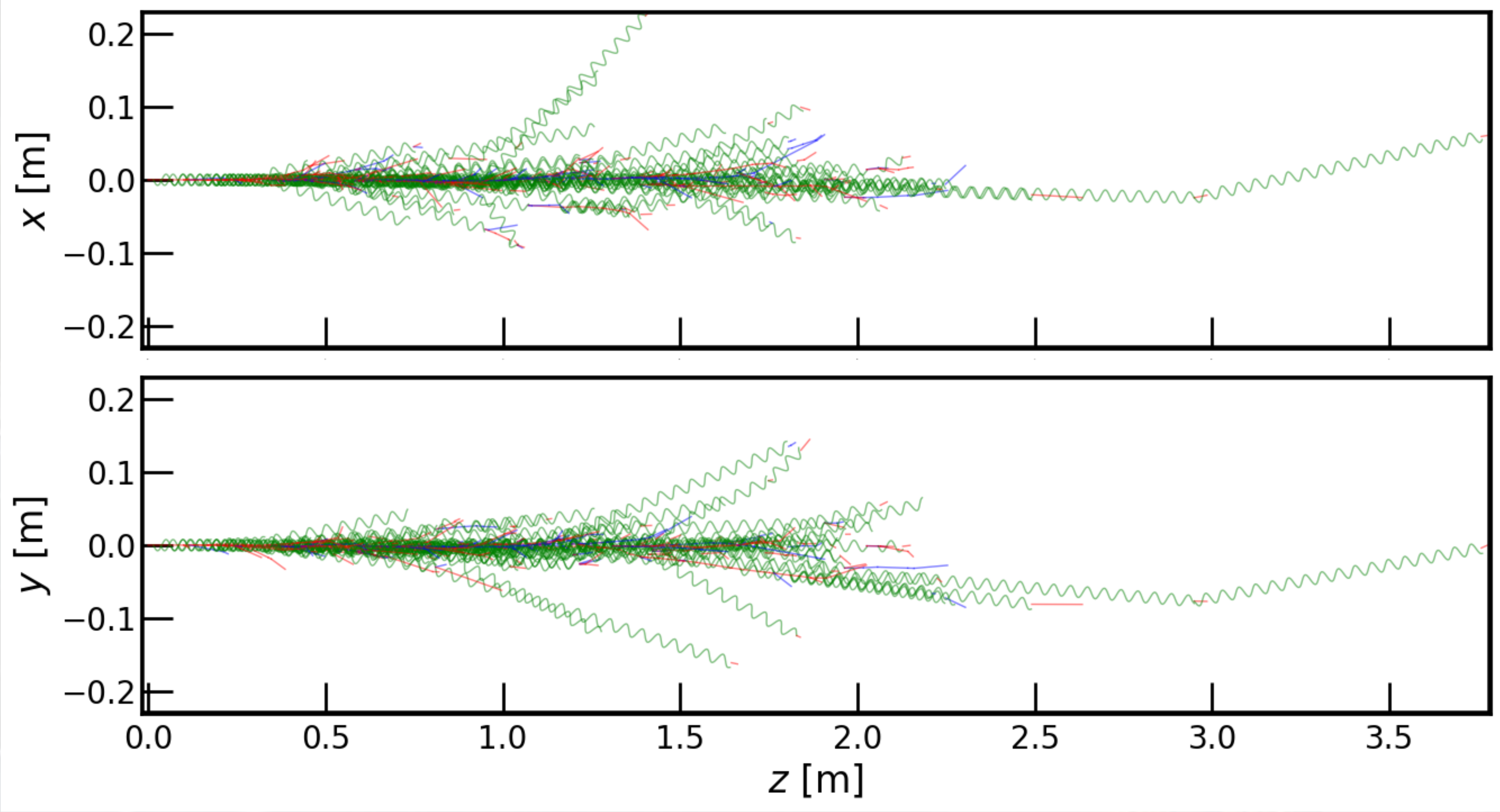
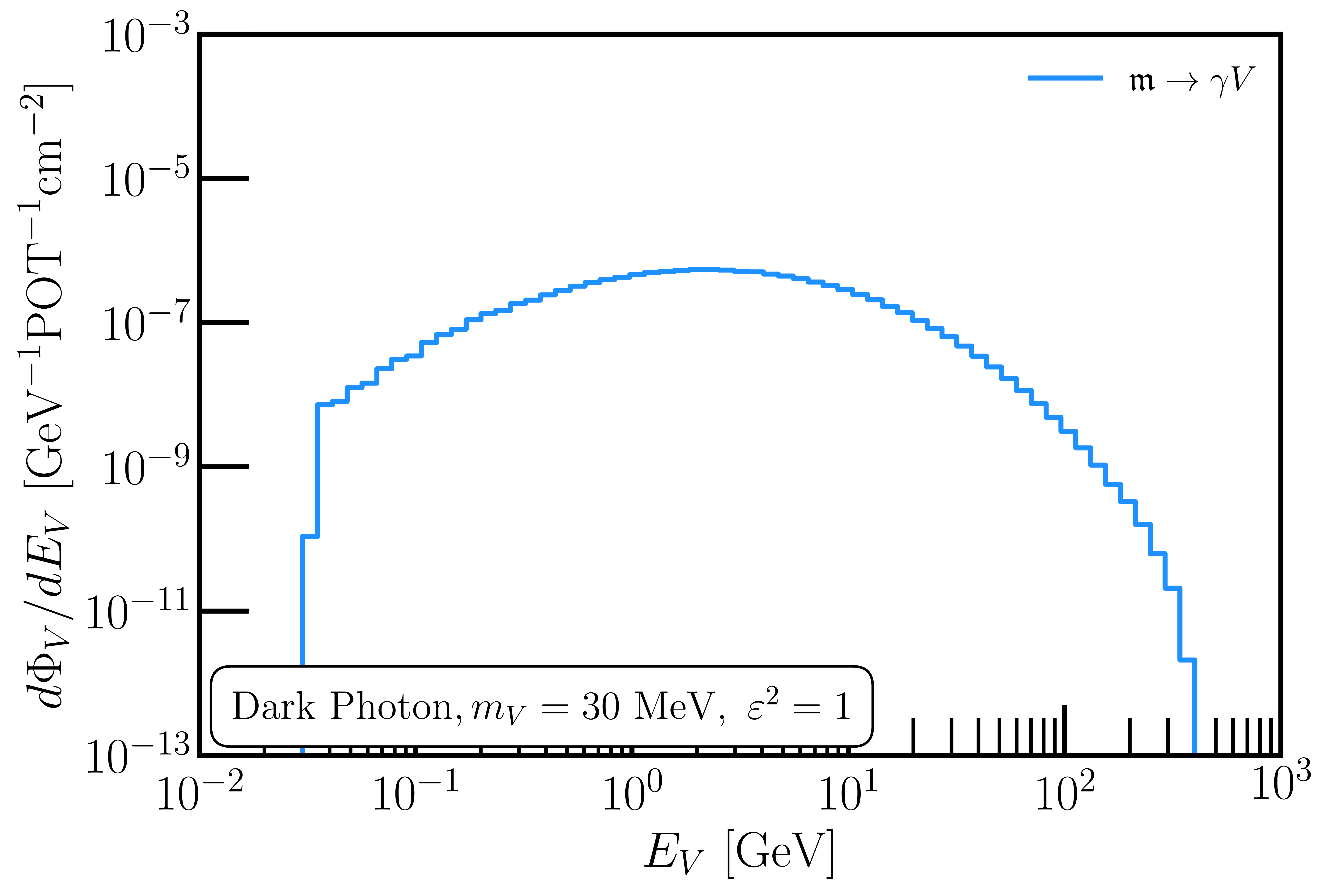


BSM processes

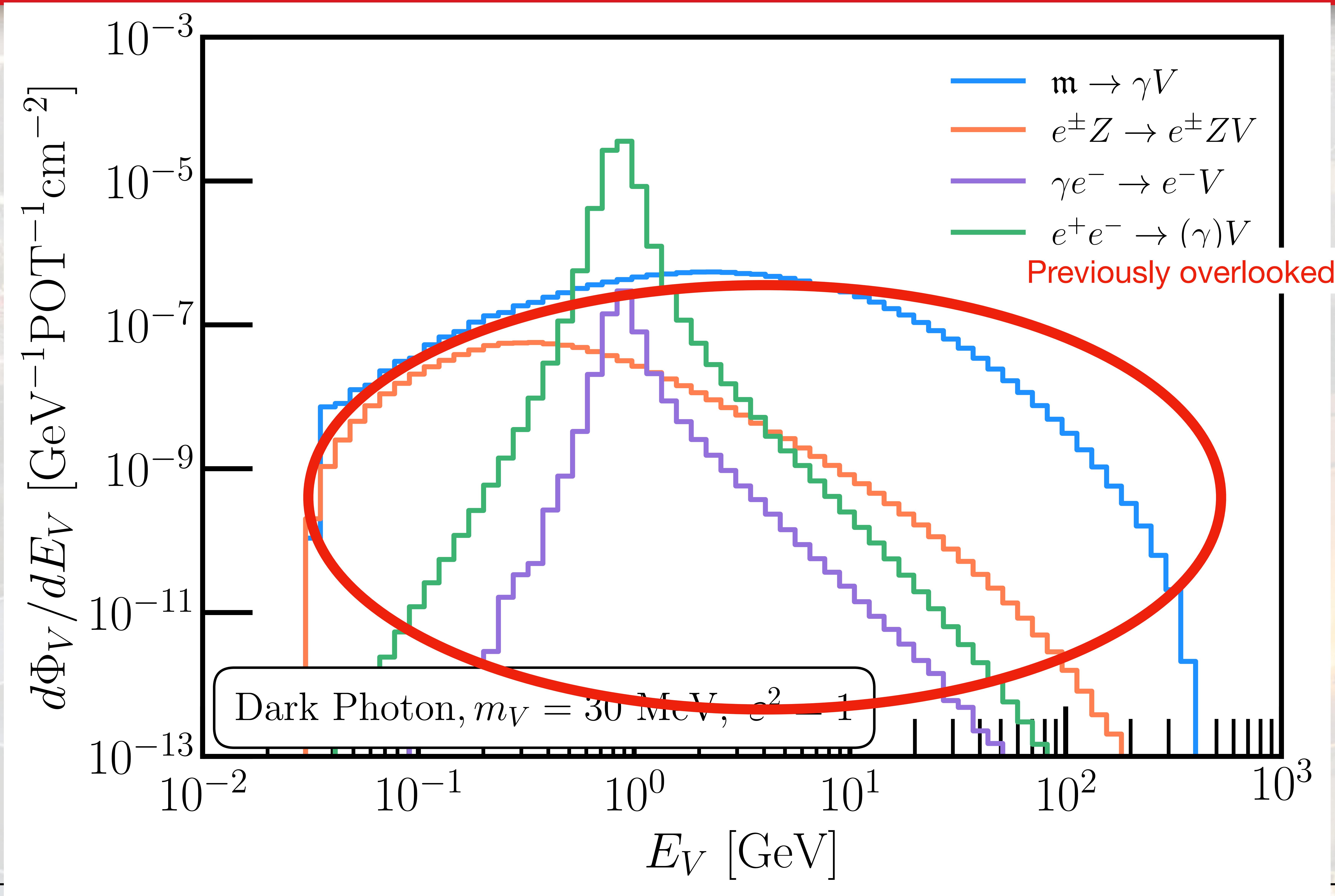
- Bremsstrahlung $Ze^{\pm} \to Ze^{\pm}V$
- Compton scattering $\gamma e^{-} \to e^{-}V$
- Pair-annihilation $e^{+}e^{-} \to (\gamma)V$

Flux



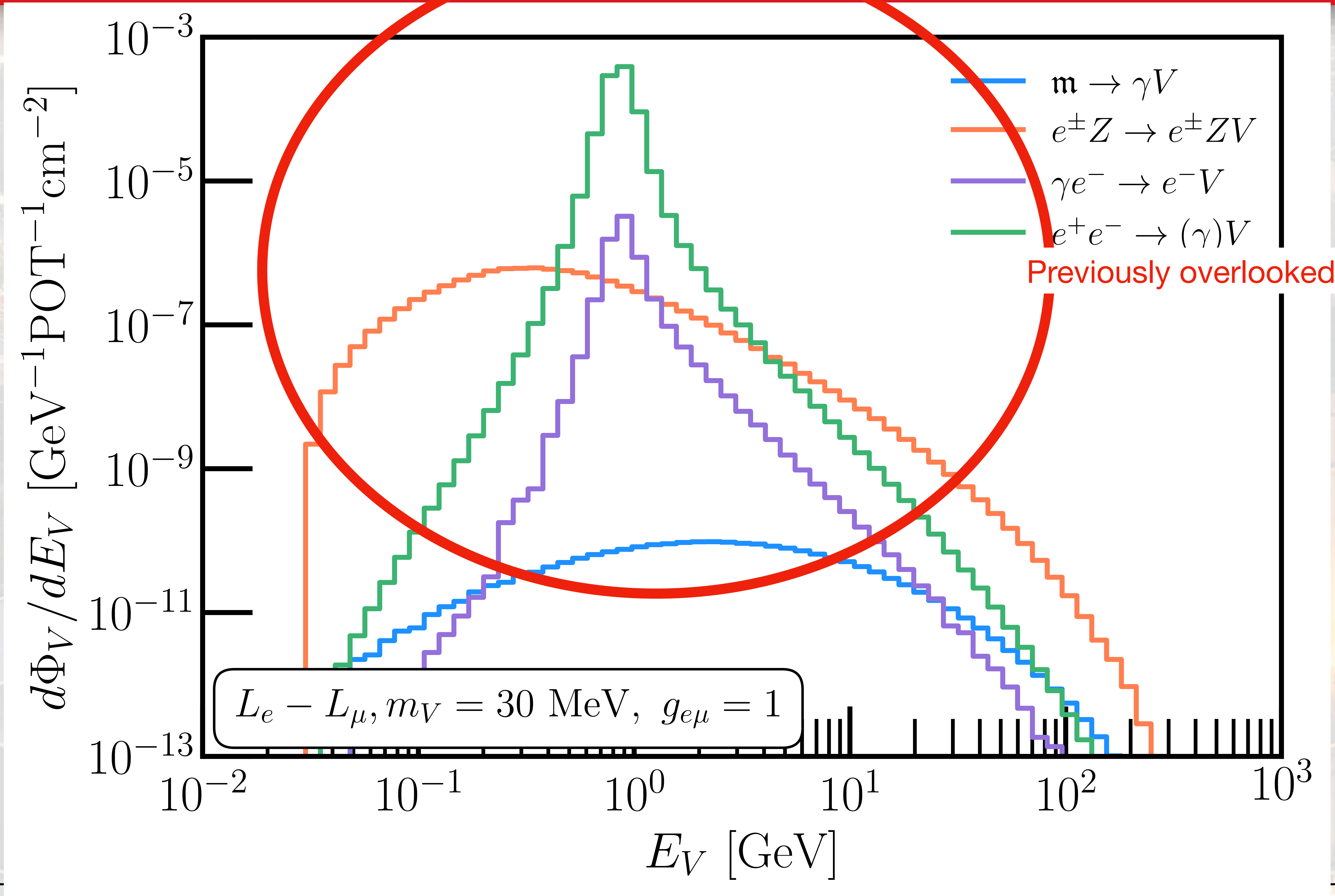
$\mathfrak{m} \to \gamma V$
Dark Photon, $m_V = 30$ MeV, $\varepsilon^2 = 1$
$d\Phi_V/dE_V$ [GeV^{-1}POT^{-1}cm^{-2}]
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E_V [GeV]

Flux



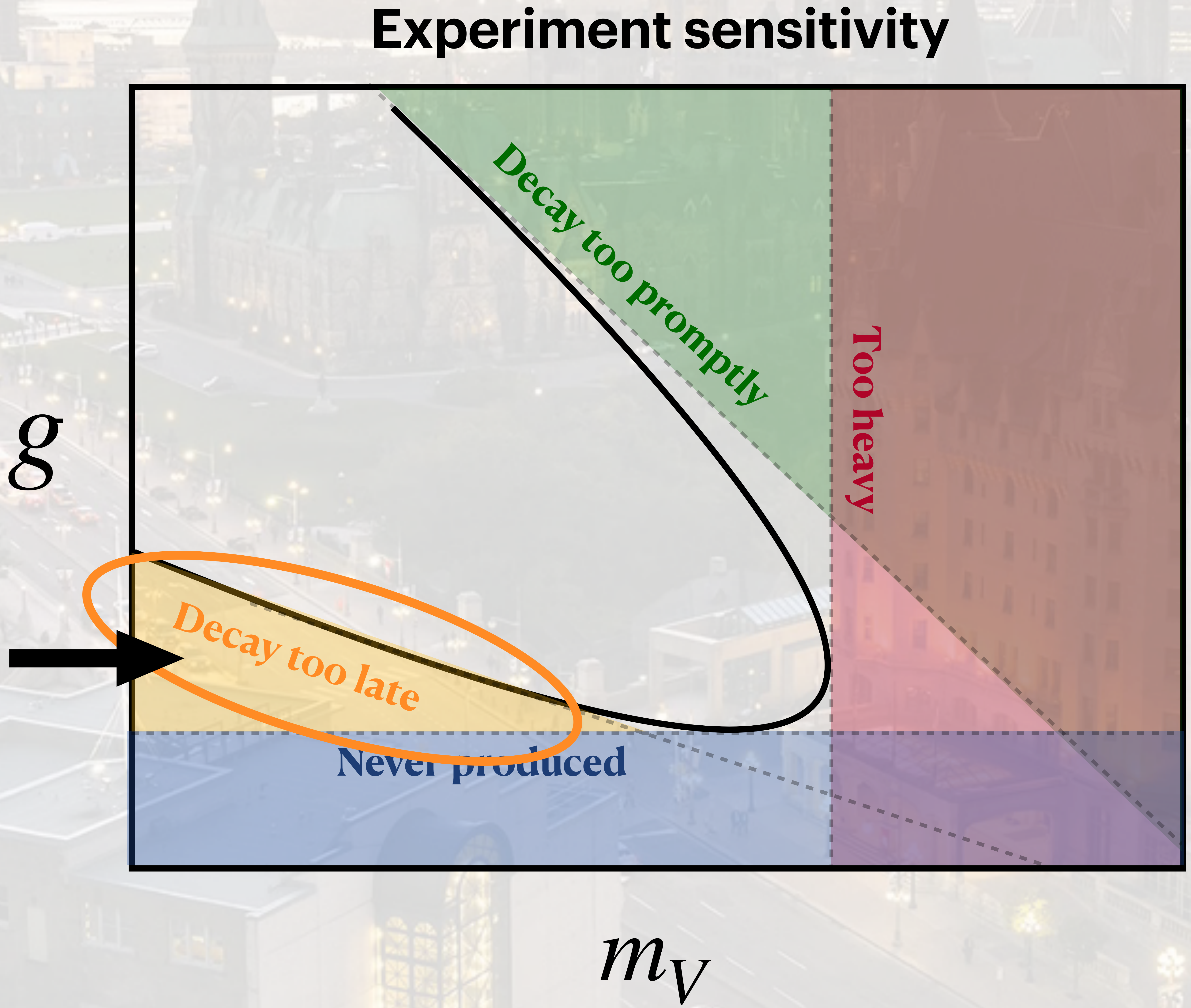
Previously overlooked production channels!

Flux



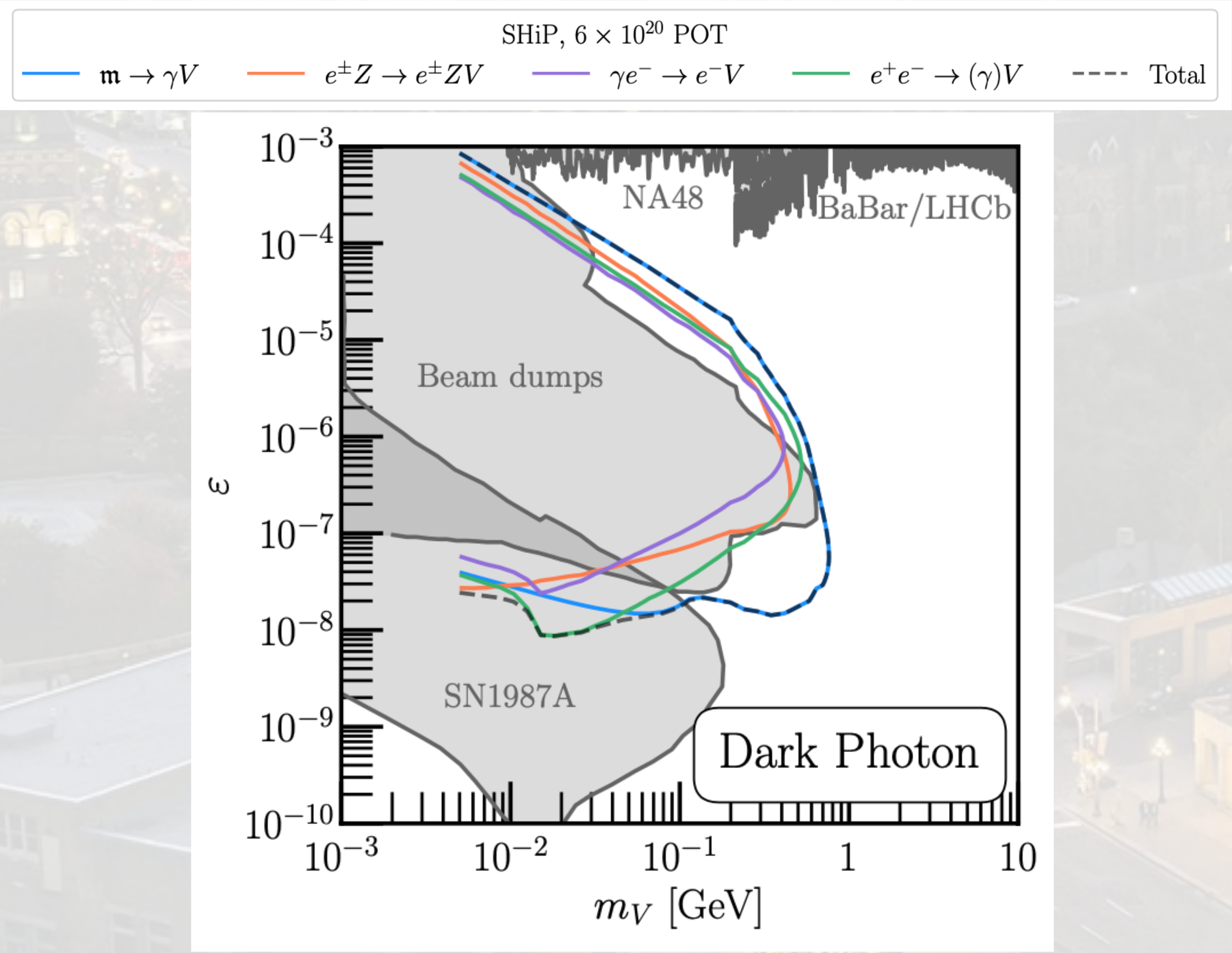
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
$d\Phi_V/dE_V\ [\mathrm{GeV}^{-1}\mathrm{POT}^{-1}\mathrm{cm}^{-2}]$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$E_V\ [\mathrm{GeV}]$
$\mathfrak{m} \to \gamma V$
$e^\pm Z \to e^\pm Z V$
$\gamma e^- \to e^- V$
$e^+e^- \to (\gamma)V$
$L_e - L_\mu, m_V = 30\ \mathrm{MeV},\ \ g_{e\mu} = 1$
Previously overlooked production channels!

Toy sensitivity plot



E&M secondaries can help with this!

Sensitivity - Dark Photon

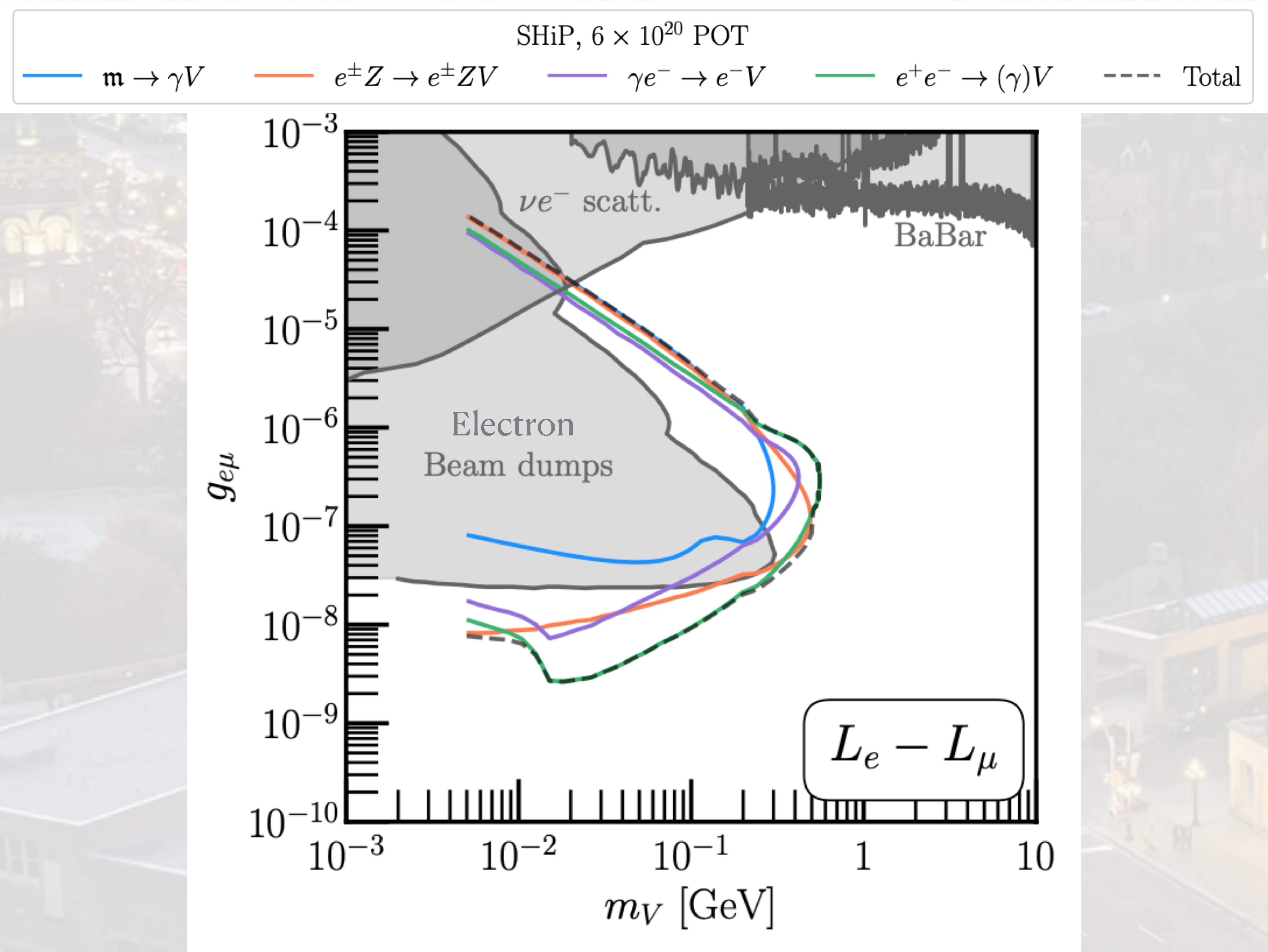


10 event contours

- Modest improvement of sensitivity at small couplings.
- Meson decay still dominate most of the parameter space.
- Positron annihilation pushes sensitivity at lower couplings down to 10^8
- SHiP will provide the strongest terrestrial constraints on dark photons in the ~10 MeV mass range surpassing E137 constraints

TZ, Plestid, Kelly, Blinov, Fox [2412.01880]

Sensitivity - Electrophilic gauge boson

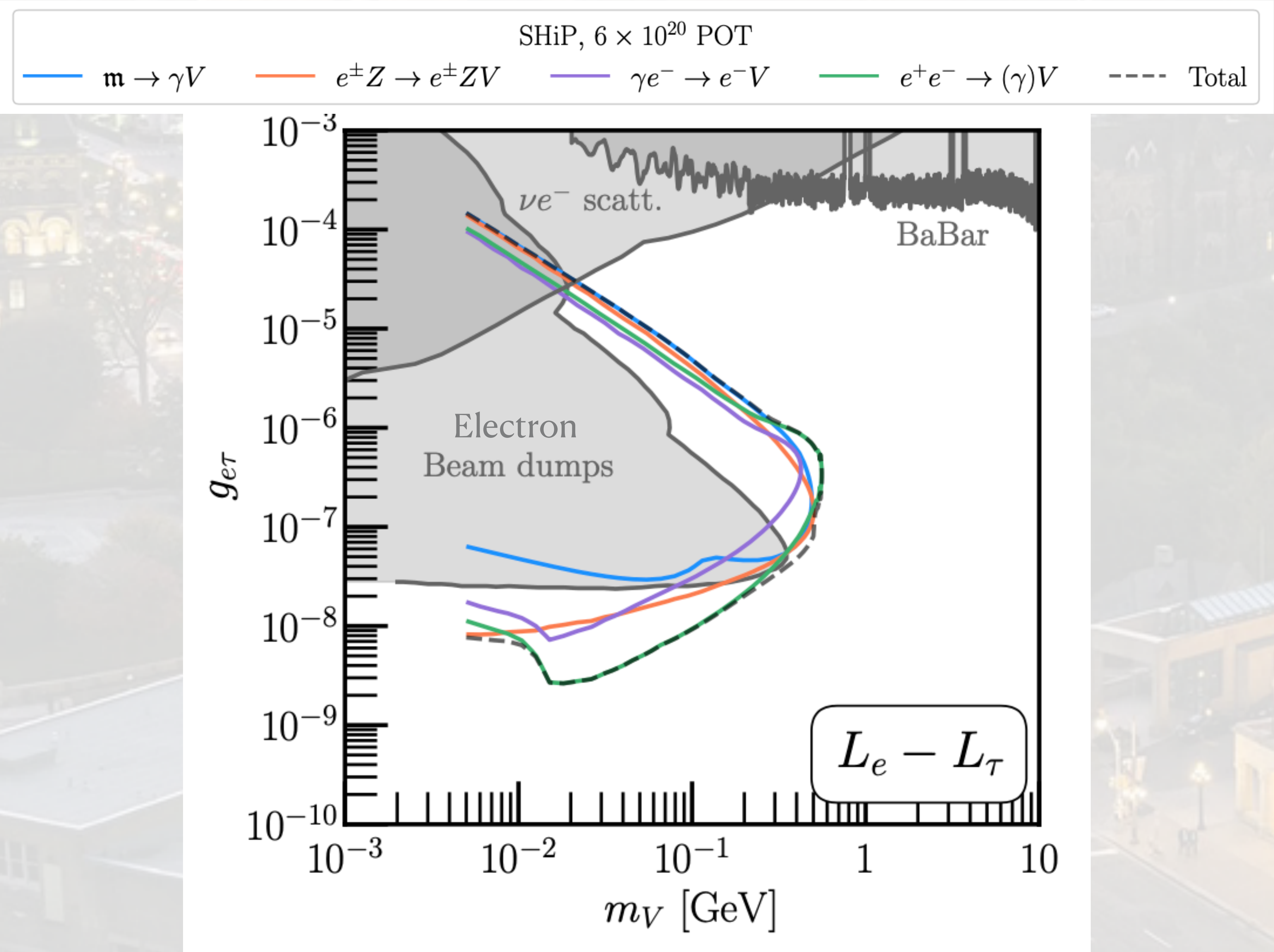


10 event contours

- Meson decay is loop-suppressed
- Enhanced sensitivity at small couplings (1 order of magnitude)
- Extended mass reach (3x)
- Event rate increased by 10^4
- Can probe more parameter space than current electron beam dump experiments. (large multiplicity and softer flux from electromagnetic secondaries)

TZ, Plestid, Kelly, Blinov, Fox [2412.01880]

Sensitivity - Electrophilic gauge boson



10 event contours

- Similar to $L_e - L_\mu$
- Meson decay changes due to different loop-induced kinetic mixing and different final states.

TZ, Plestid, Kelly, Blinov, Fox [2412.01880]

Takeaways

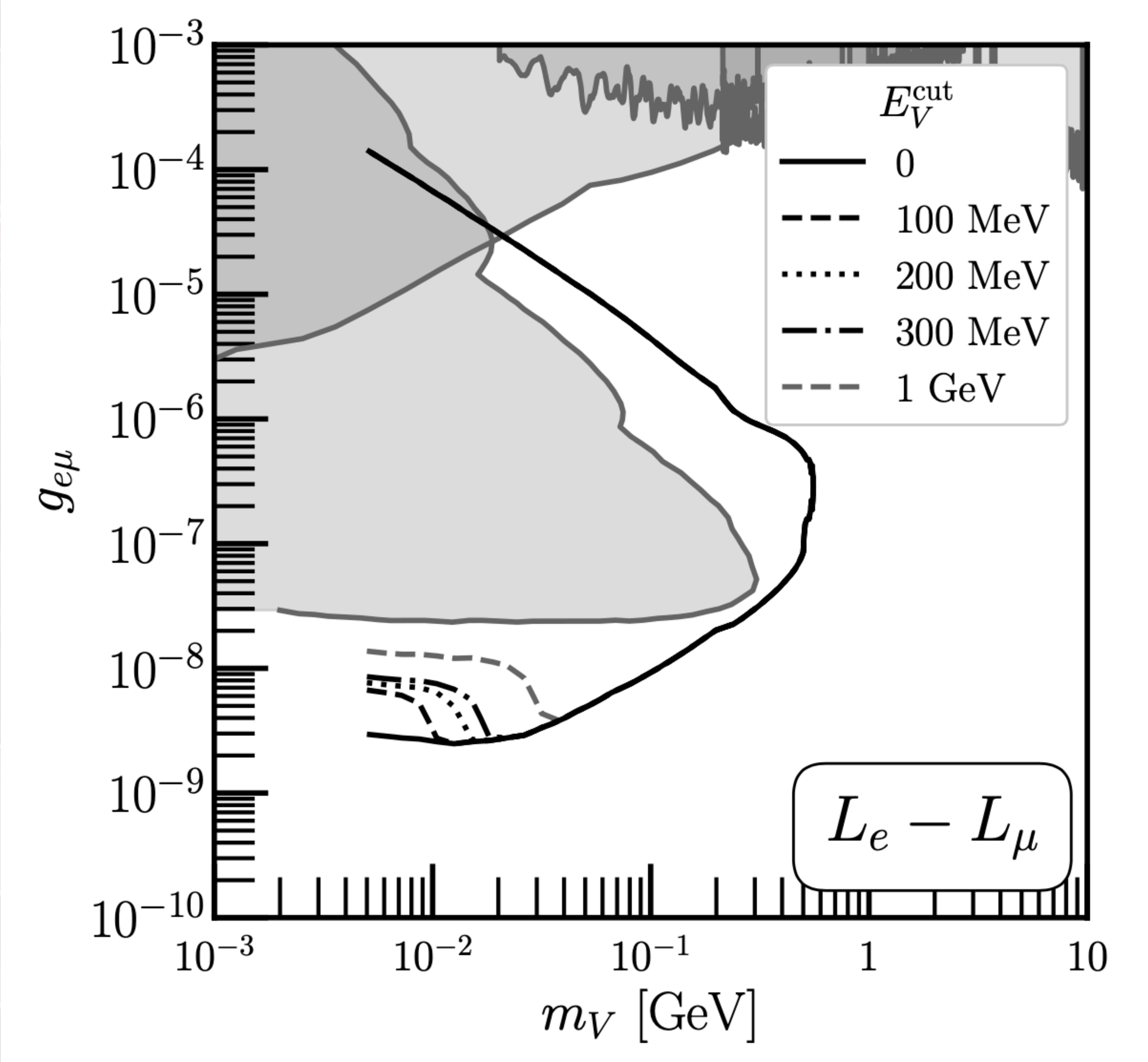
- Electromagnetic cascades expands sensitivity by an order of magnitude more than primary production at lifetime frontier.
- A proton fixed target experiment like SHiP is able to probe a large portion of parameter space that was not previously explored by current electron beam dump experiments.
- PETITE is a powerful tool to simulate E&M secondaries and it's robust against hadronic modeling.

Thank you!

Back-ups:


Evt. rate (SHiP), 2 × 10^20 POT
Dark photon, $m_V = 10$ MeV
π^0 Decay
Dark Brem.
Dark Ann.
Dark Comp.
Total
$e\varepsilon$
$L_e - L_\mu$, $m_V = 10$ MeV
$K^\pm$ Decay
π^0 Decay
Dark Brem.
Dark Ann.
Dark Comp.
Total
$g_{e\mu}$
$L_e - L_\tau$, $m_V = 10$ MeV
$K^\pm$ Decay
π^0 Decay
Dark Brem.
Dark Ann.
Dark Comp.
Total
$g_{e\tau}$
$L_\mu - L_\tau$, $m_V = 10$ MeV
$K^\pm$ Decay
π^0 Decay
Dark Brem.
Dark Ann.
Dark Comp.
Total
$g_{\mu\tau}$

Impact of energy cuts



10 event contours

- It's possible to go as low as $E_V \geq 100$ MeV, which lowers the point at which sensitivity is impacted by a further factor of 2.
- Our results call for a systematic investigation into low energy (i.e., sub-GeV energy) backgrounds and detection

TZ, Plestid, Kelly, Blinov, Fox [2412.01880]

PETITE Algorithm

PETITE algorithm

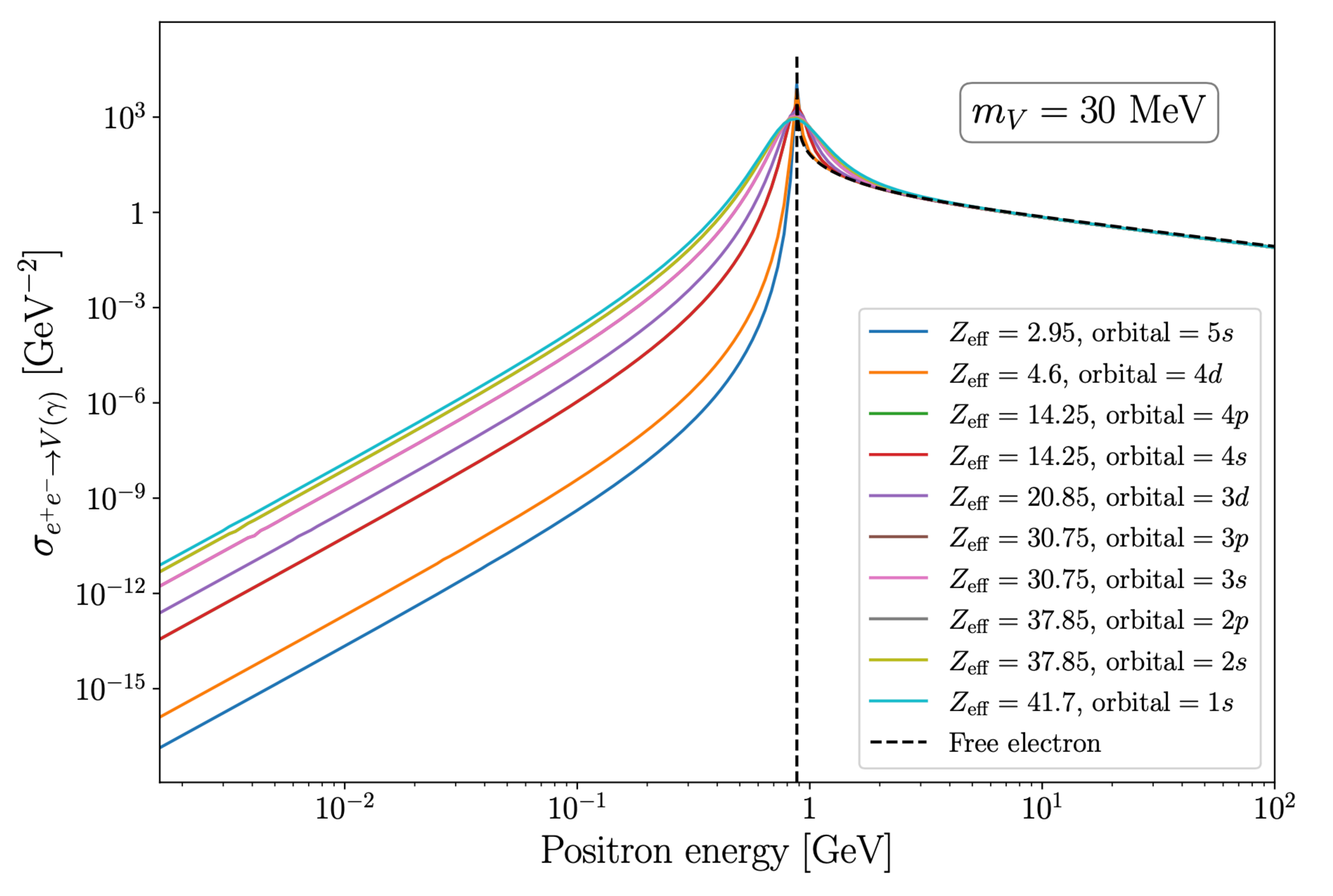
```
shower = existing Standard Model shower (e.g. as generated by PETITE)
for particle in shower do
    if particle = e+ then
        processlist = {Dark bremsstrahlung, Dark annihilation}
    else if particle = e− then
        processlist = {Dark bremsstrahlung}
    else if particle = γ then
        processlist = {Dark Compton}
    end if
    for p in processlist do
        if energy of particle is above energy threshold for process p then
            • determine the interaction position/energy by sampling from Eq. (3.2).
            • generate dark sector kinematics of the outgoing BSM particle by drawing from dσ^(p)_BSM.
            • compute weight w^(p) by integrating Eq. (3.2).
            • record the weight w^(p) position, momentum, and particle species.
        end if
    end for
end for
```

$$\frac{\mathrm{d}w^{(p)}}{\mathrm{d}z} = \boxed{n^{(p)}\sigma^{(p)}_{\mathrm{BSM}}(z)}\,\boxed{\exp\left(-\int_0^z \frac{\mathrm{d}z'}{\lambda^{\mathrm{SM}}_{\mathrm{MFP}}(z)}\right)}$$

Probability for the BSM process to occur

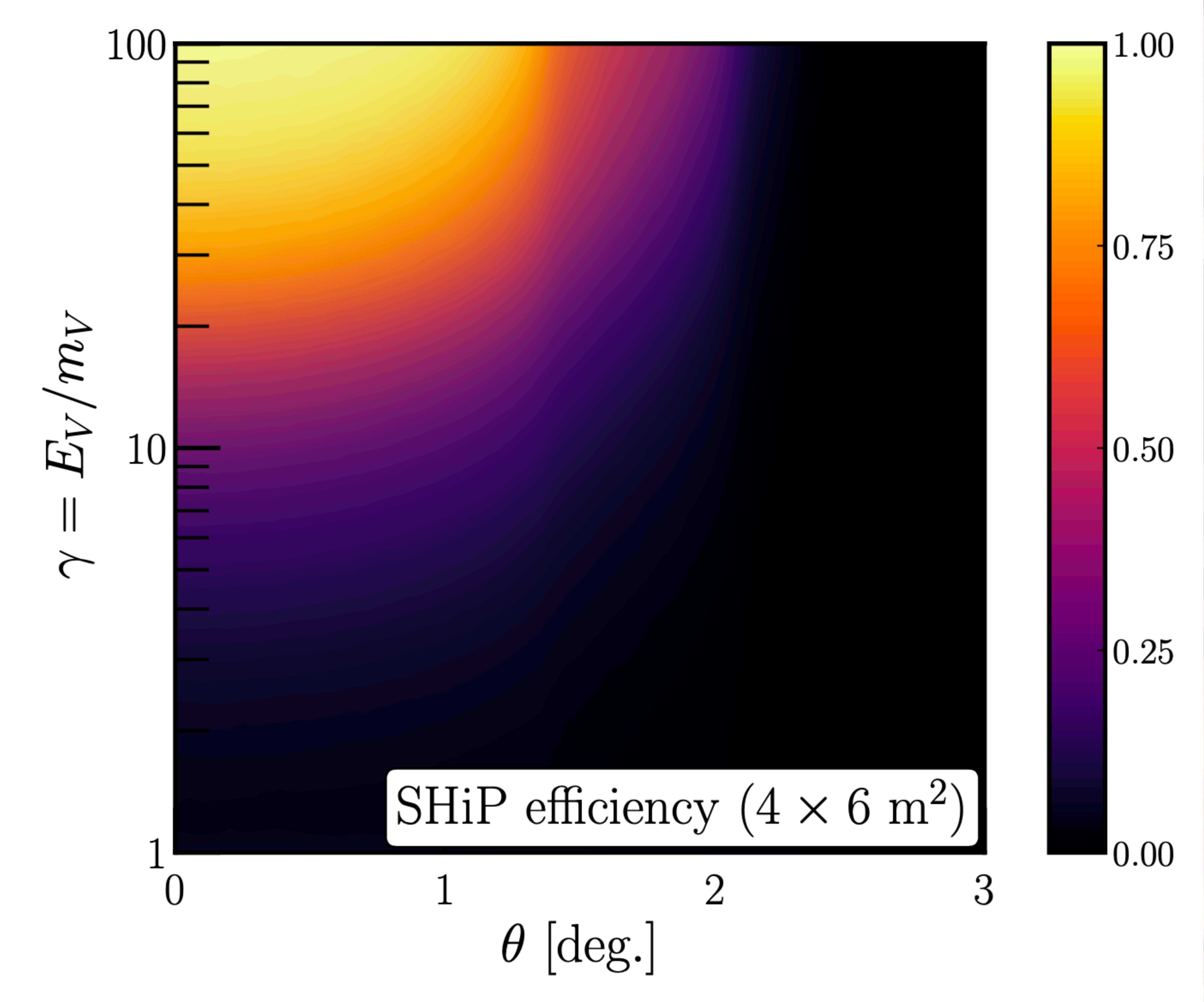
Probability of no SM process happening up to that point

Back-ups: Atomic Binding Corrections



Back-ups: Geometrical Efficiency

- We numerically simulate the efficiency given the latest SHiP detector geometry. Take into account difference for BSM particle's lifetime (in terms of where the decay is most likely to occur).
- For magnetic-field effects, we simply make a cut on — hope to encourage SHiP collaboration to explore lower-energy reconstruction and background rates to enhance sensitivity.

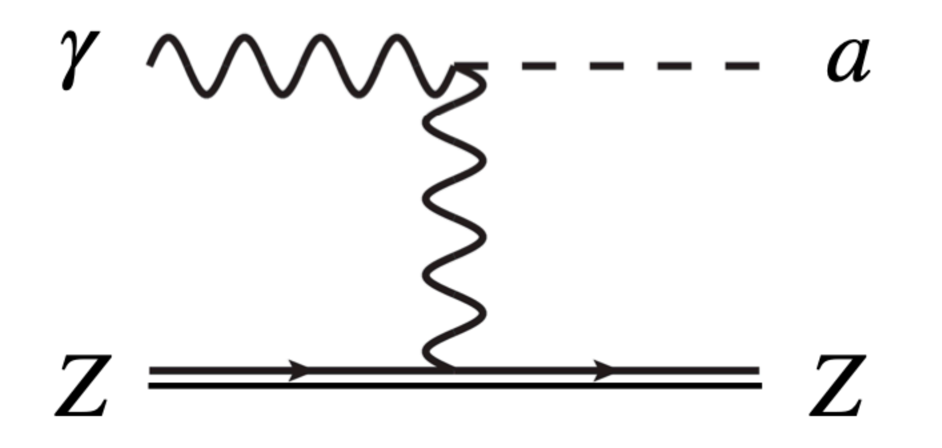


ALPs (Axion-Like Particles)

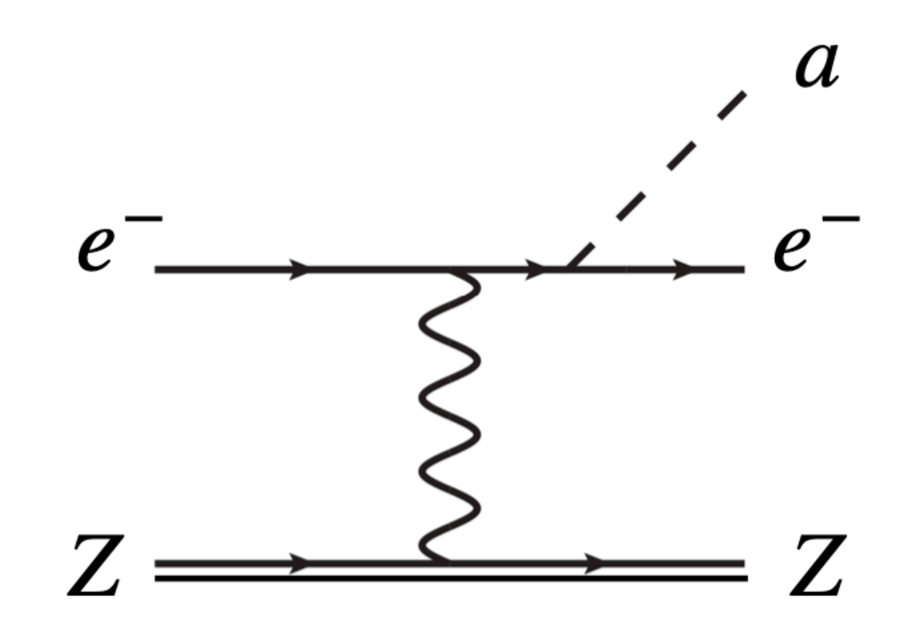
Patrone et al, 2509.14310

$$-\mathcal{L} \supset \frac{1}{2} m_a^2 a^2 - \frac{\alpha}{4\pi}\frac{c_{a\gamma\gamma}}{f} a F\tilde{F} - \frac{c_{aee}}{f}(\partial_\mu a)\bar{e}\gamma^\mu\gamma_5 e \ ,$$

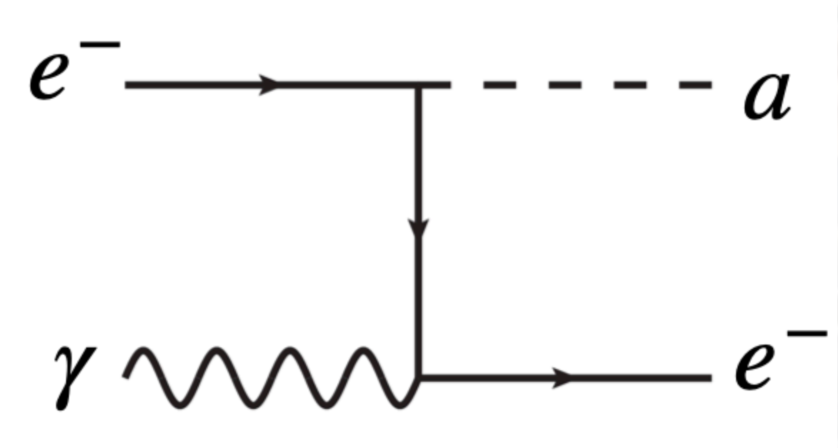
- Production channels:



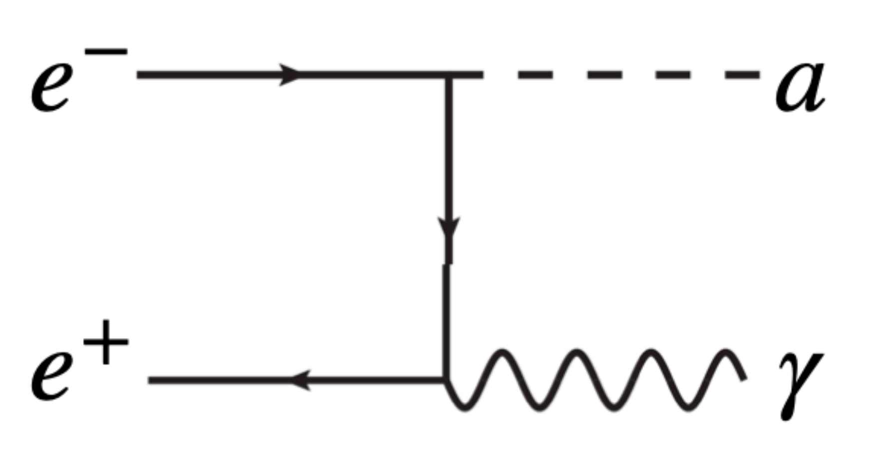
Primakoff



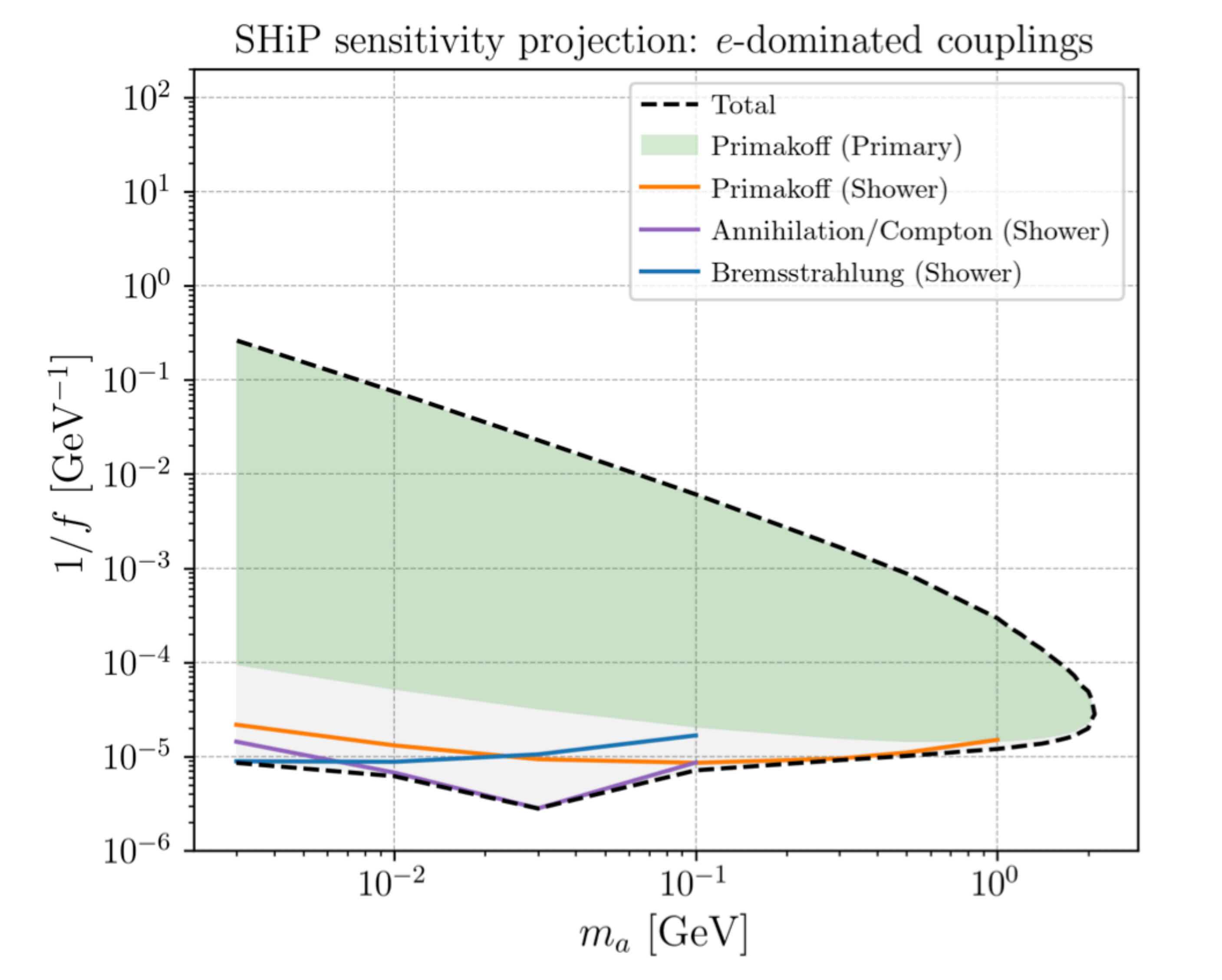
Bremsstrahlung

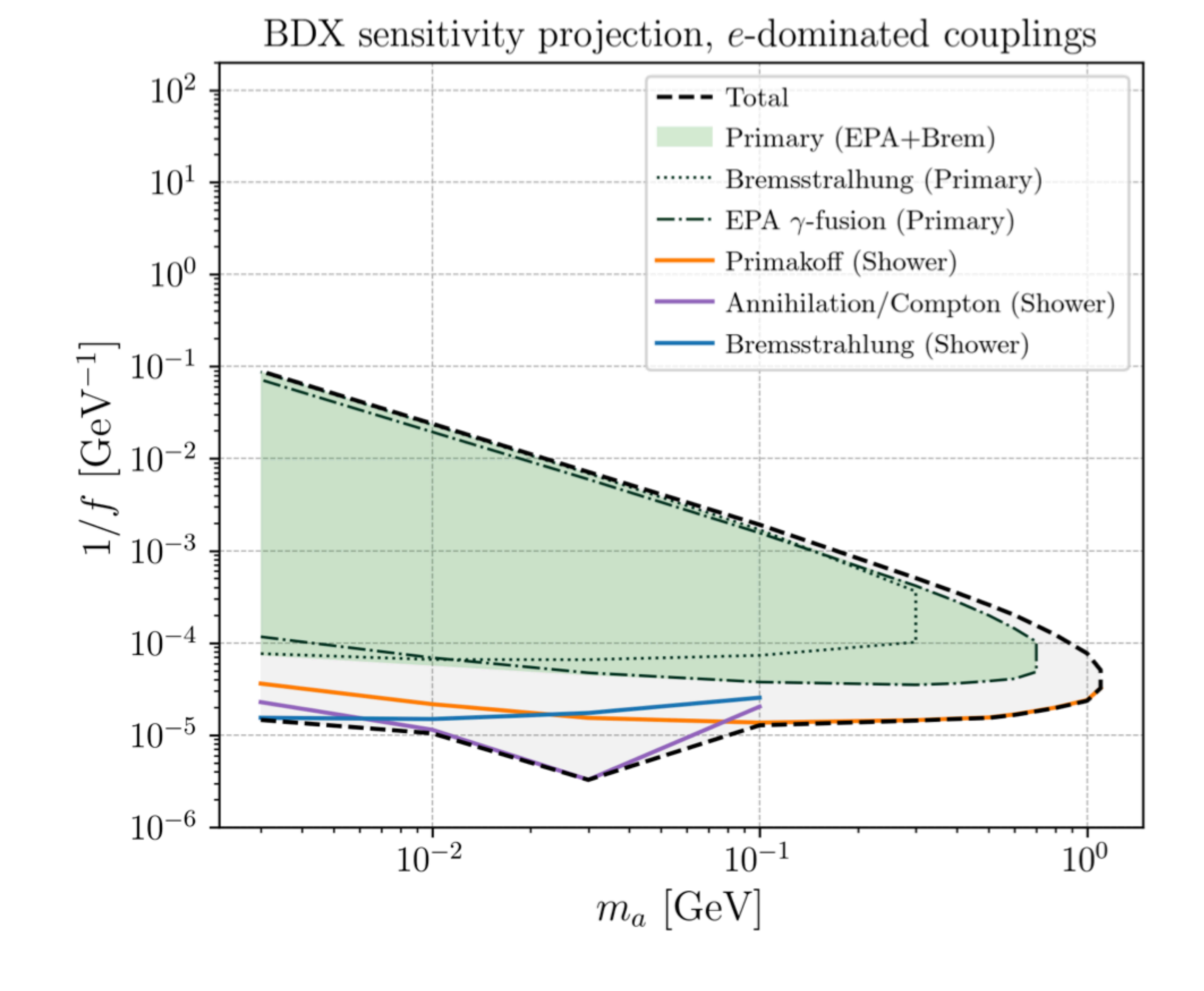


Compton



Annihilation

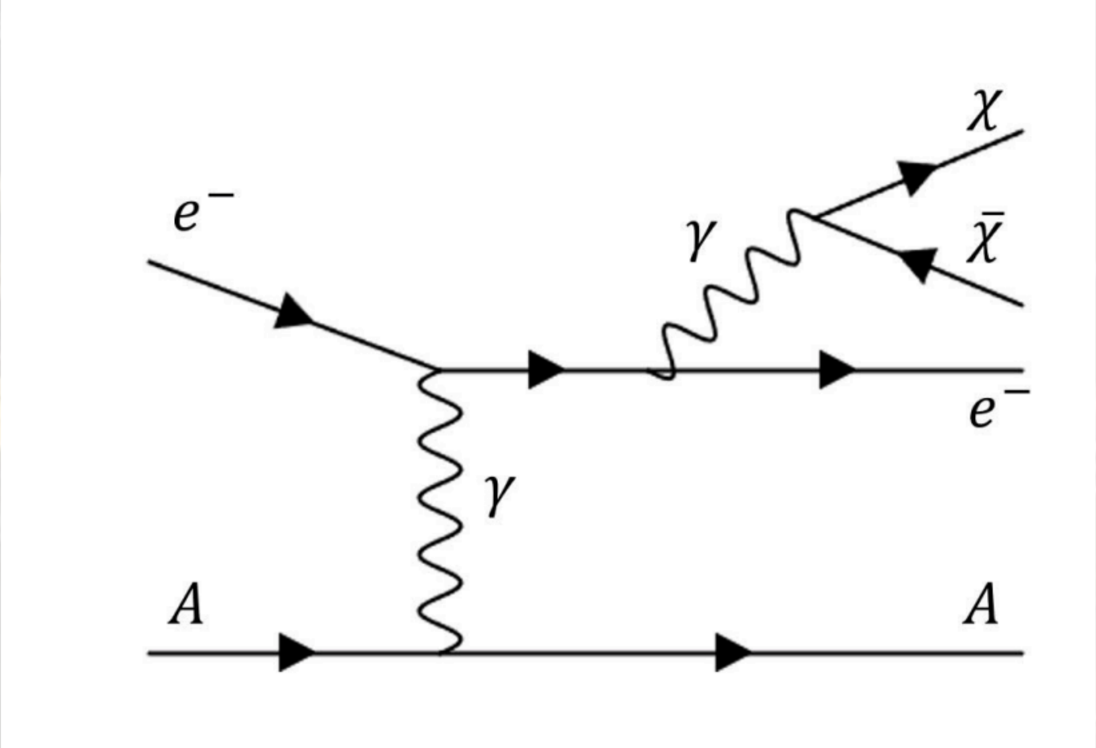


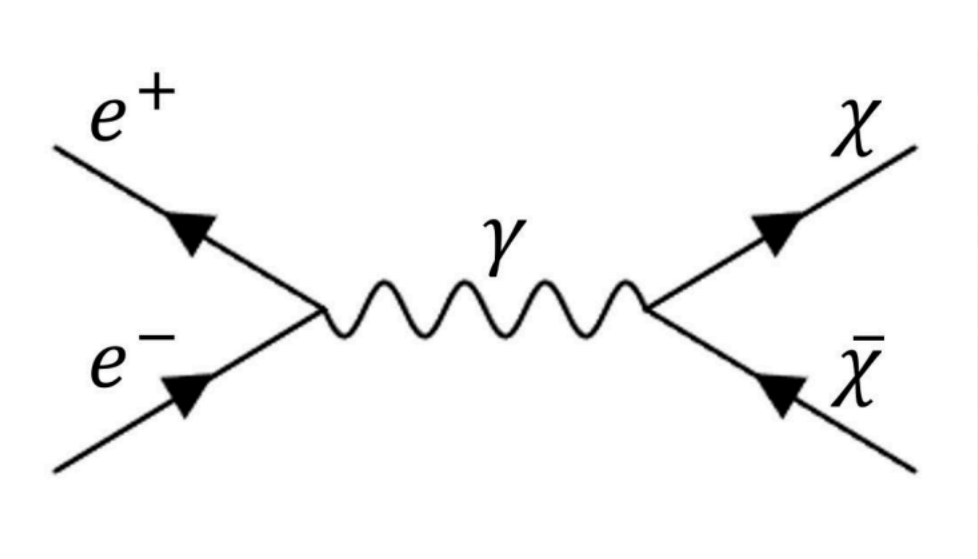


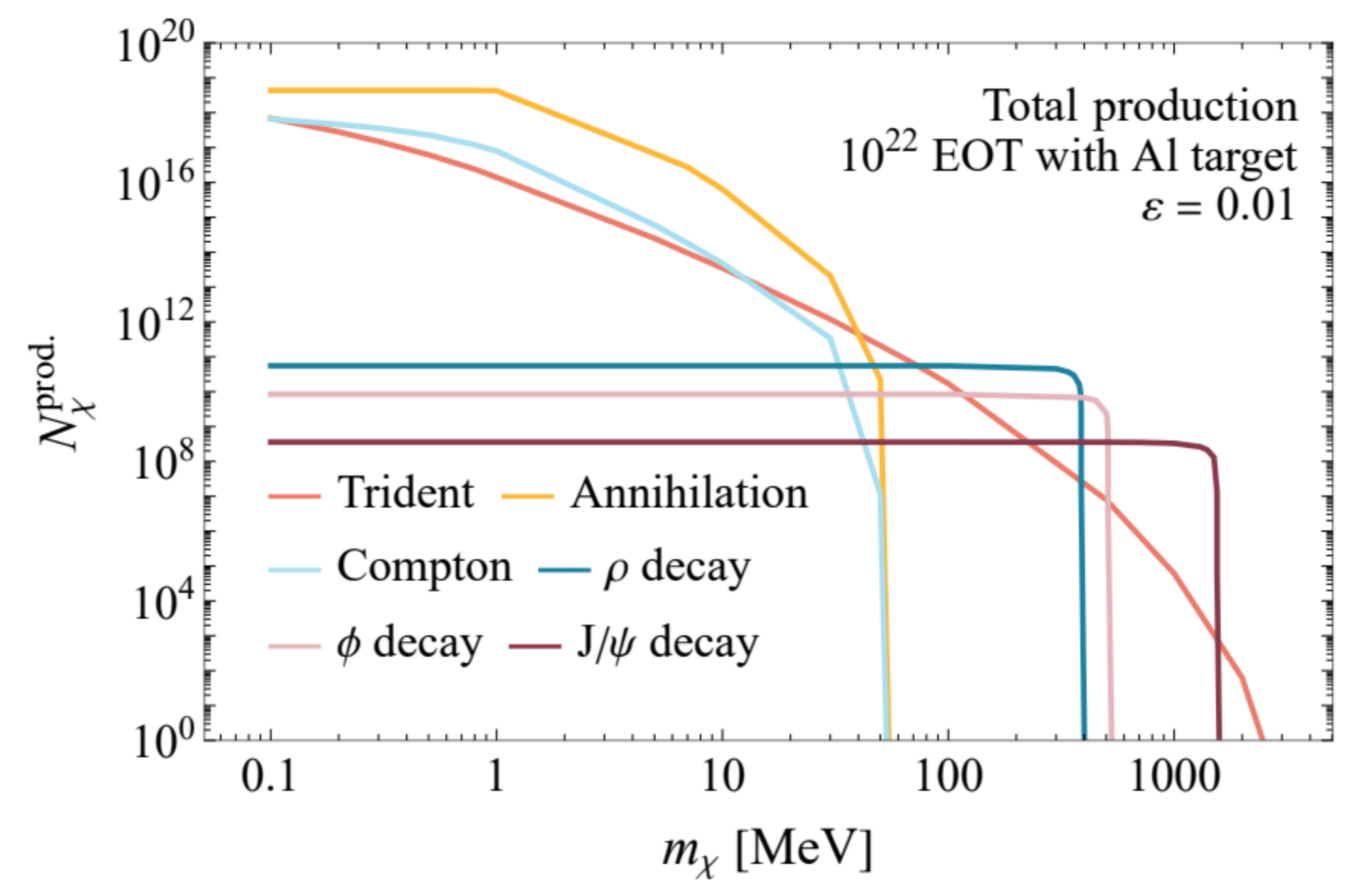
Millicharged particles

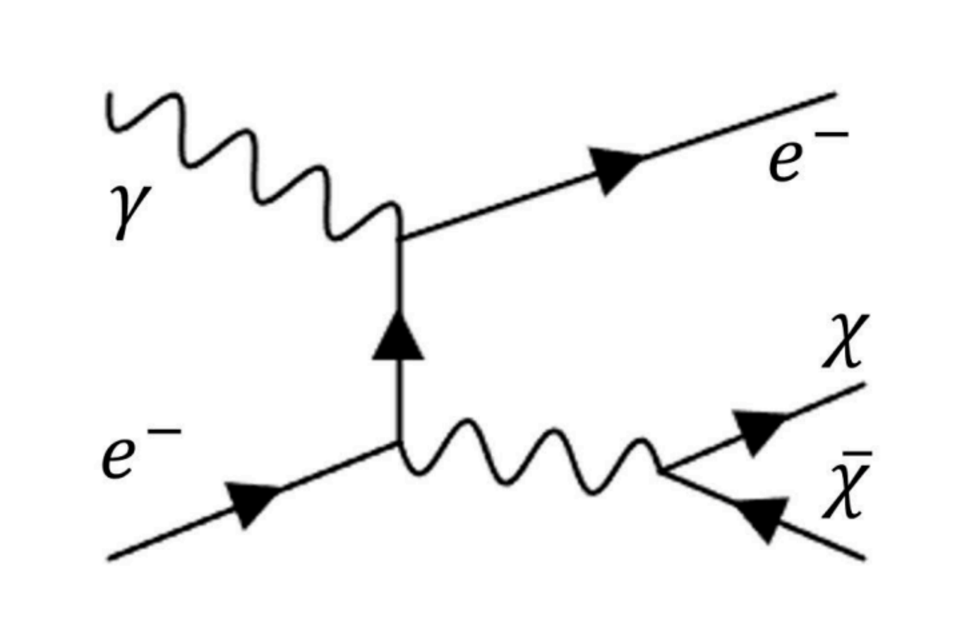
Essig et al, 2412.09652

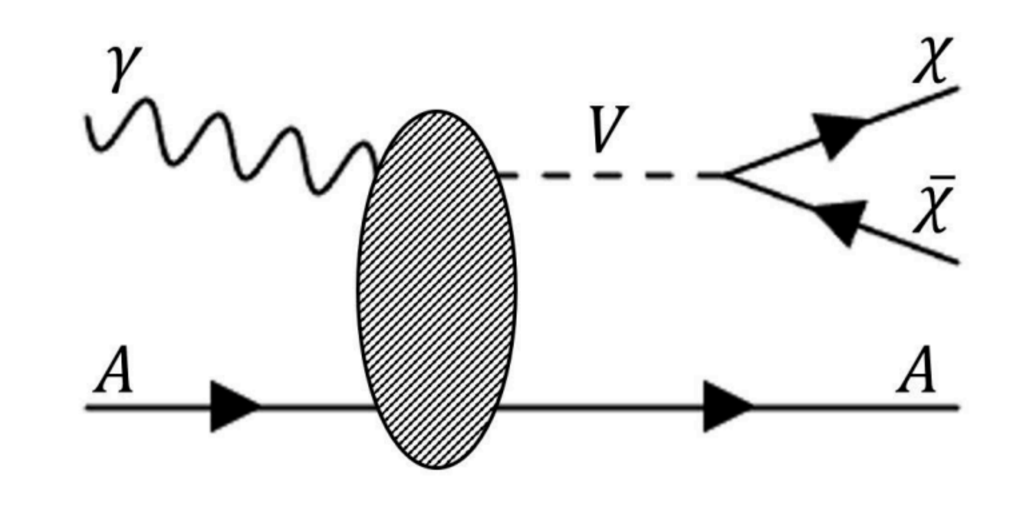
$$\mathscr{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \epsilon e A_\mu \bar{\chi}\gamma^\mu \chi$$

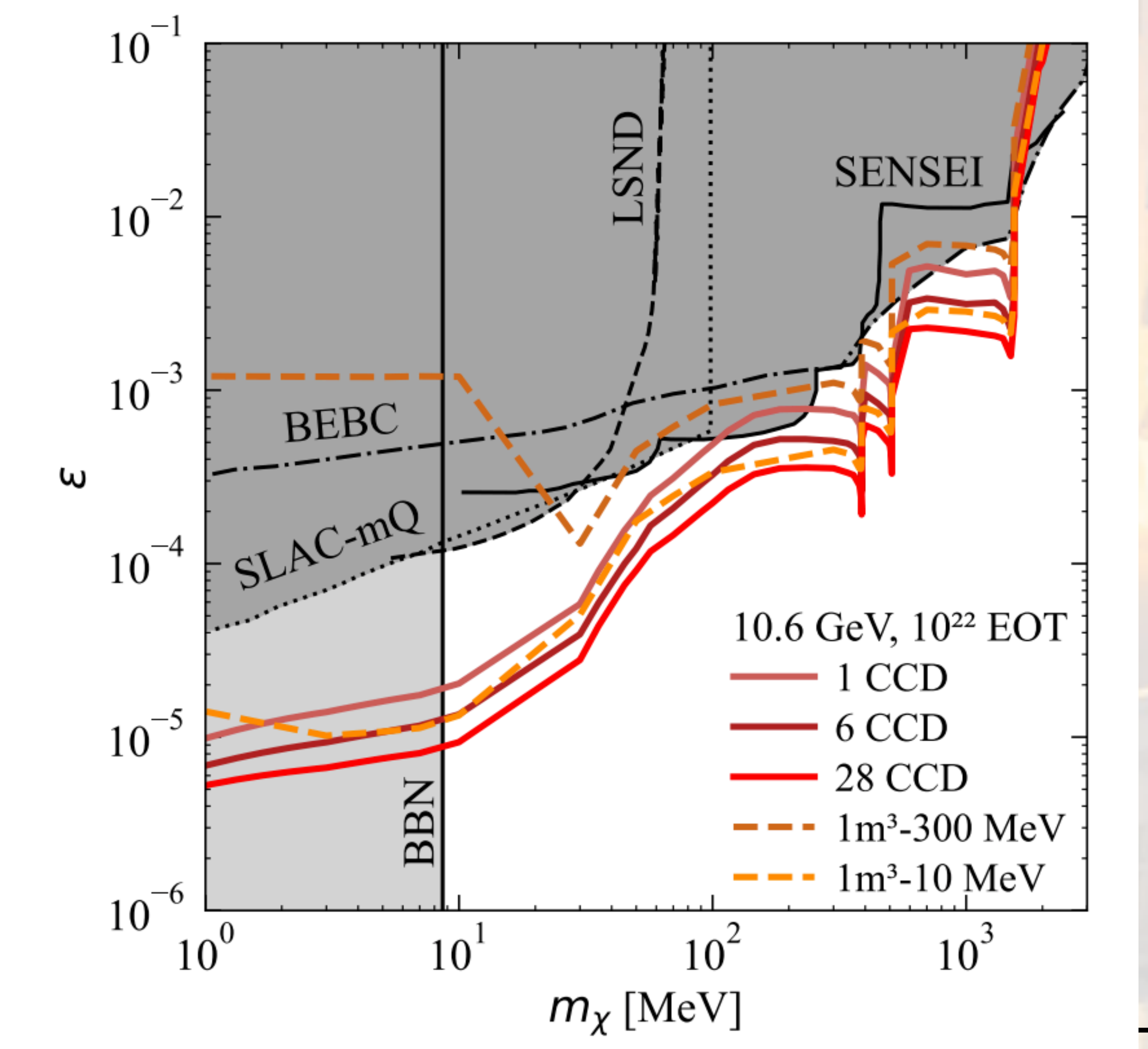








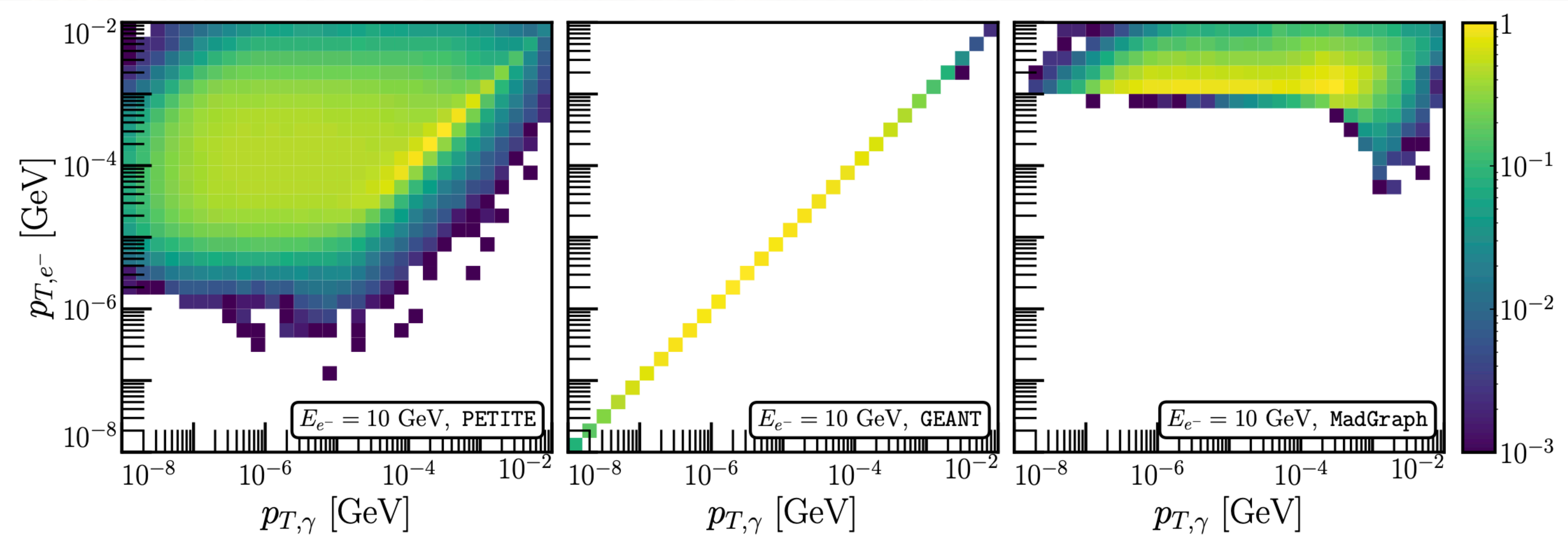




SM bremsstrahlung

- GEANT intrinsically assumes no momentum transfer to the nucleus
- MadGraph misses out on significant phase space at low pT

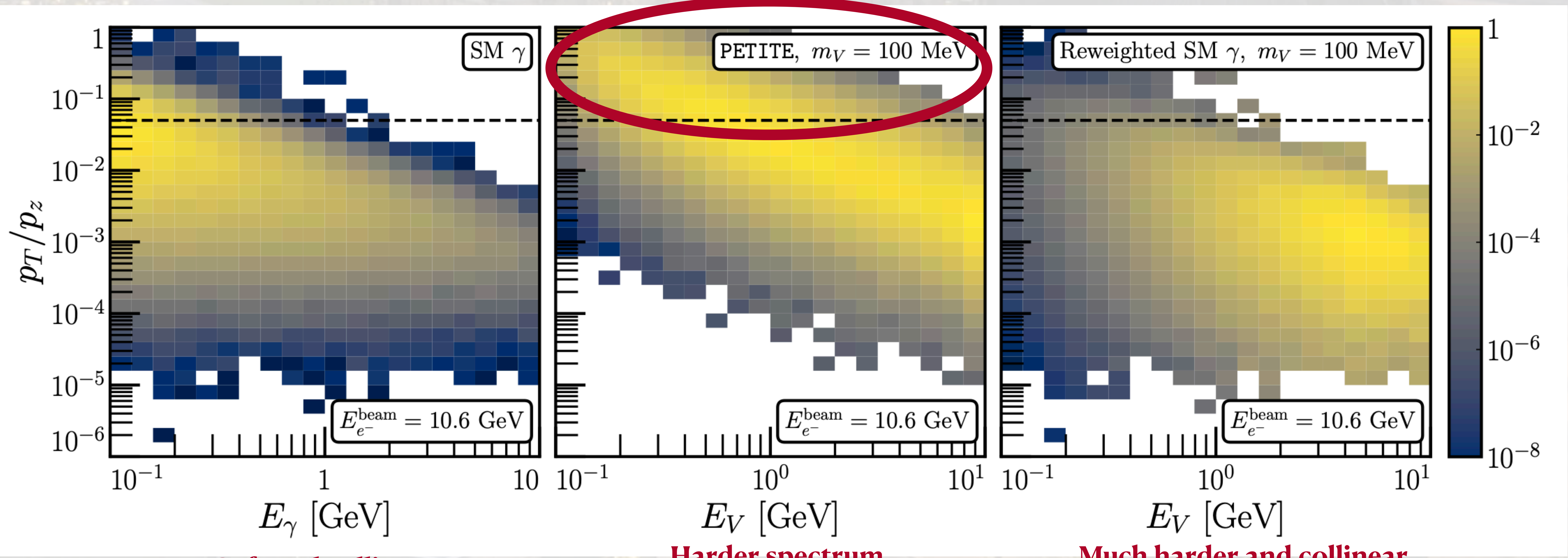
pT distribution of outgoing electrons and photons



SM vs. Dark bremsstrahlung

- Dashed line: geometrical acceptance of the BDX detector
- Turning SM photons to dark photons is tricky due to different kinematics

Miss the detector!



Soft and collinear

Harder spectrum,
Strong correlation

Much harder and collinear
Overestimation