

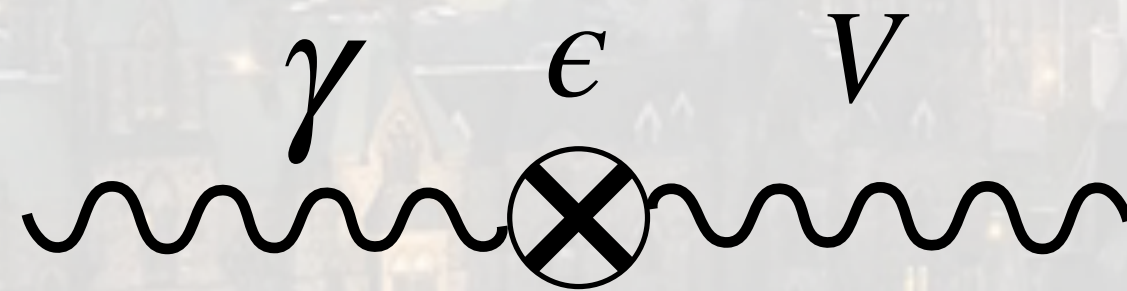
Long-lived Vectors from Electromagnetic Cascades at SHiP

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Models

- Secluded dark photon



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



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

J_μ : SM electromagnetic current

V^μ : Dark photon field

Models

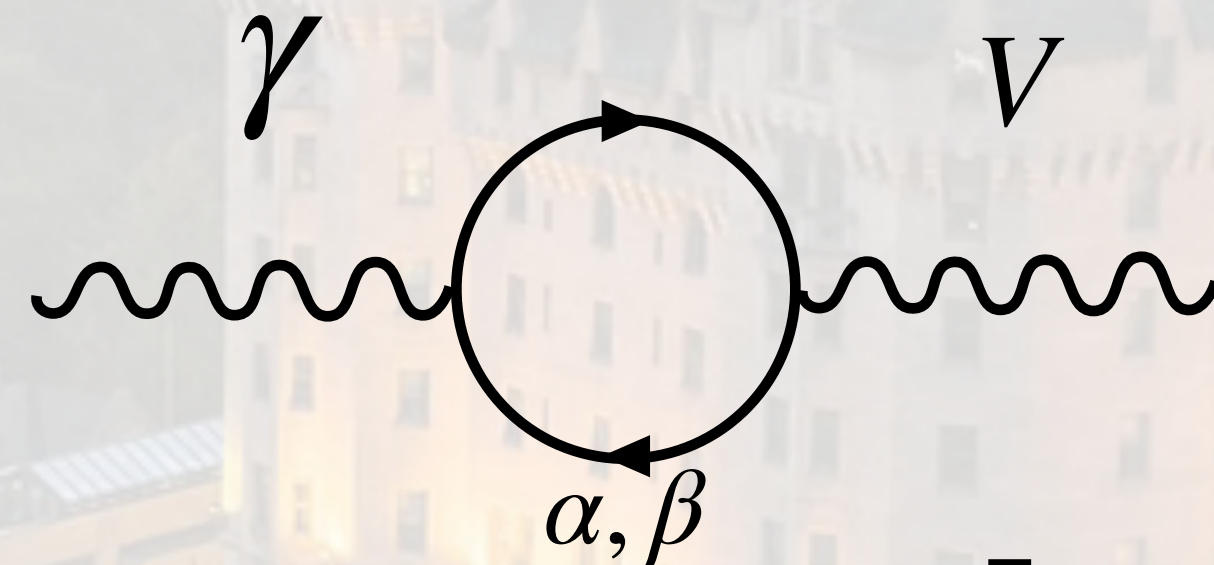
- Leptophilic gauge boson

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

$$L_e - L_\mu$$

$$L_e - L_\tau$$

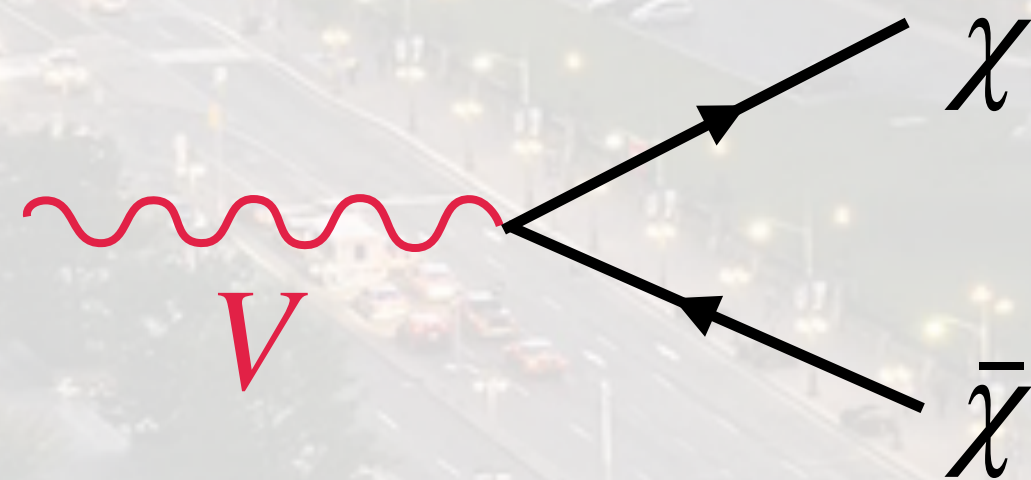
$$L_\mu - L_\tau$$



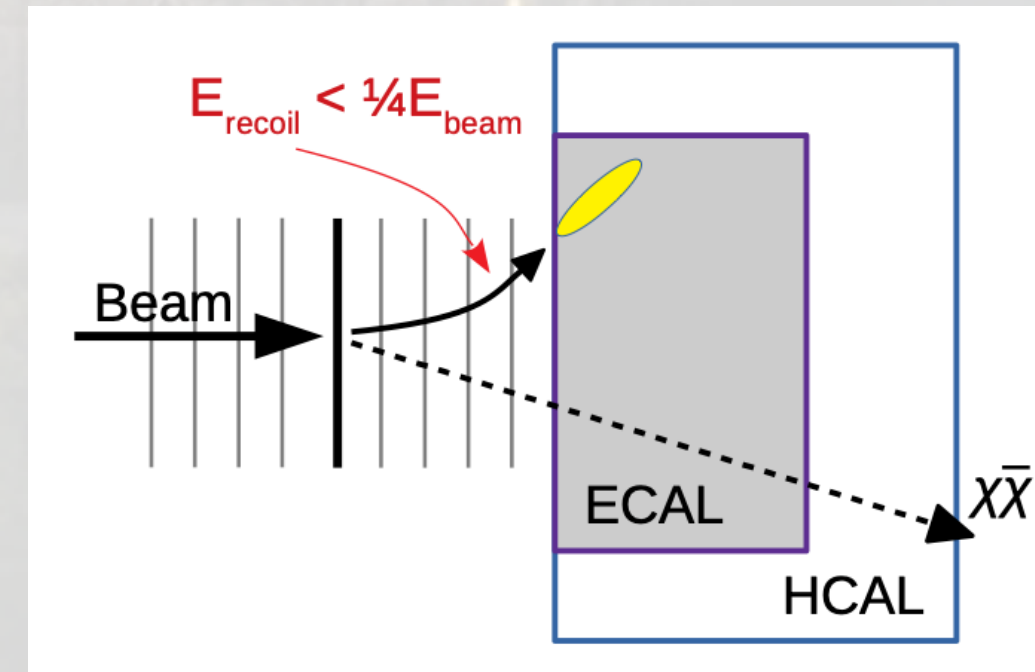
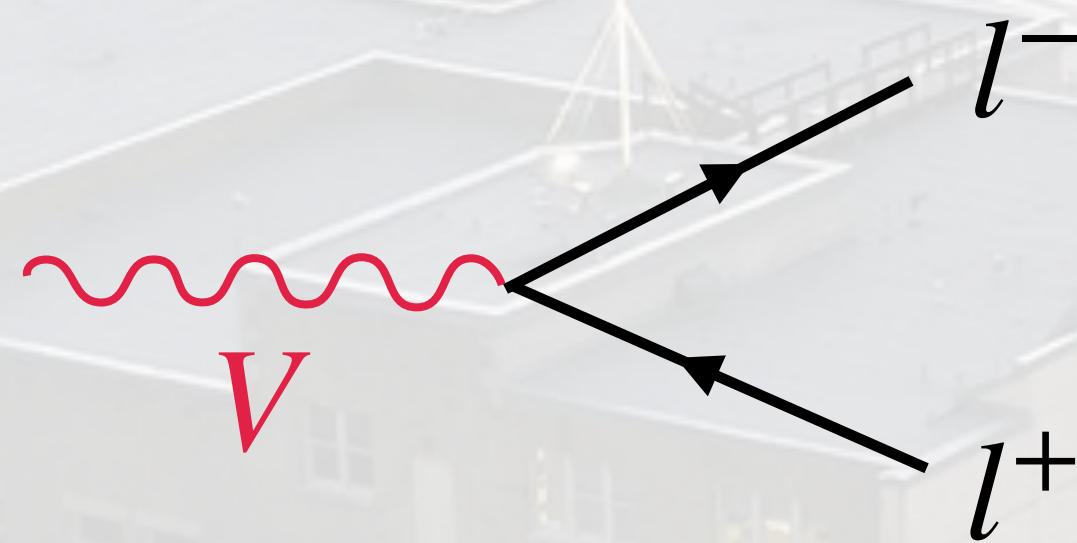
$$\varepsilon_{\alpha\beta}(q^2) = -\frac{eg_{\alpha\beta}}{2\pi^2} \int_0^1 x(1-x) \log \left[\frac{m_{\ell_\beta}^2 - x(1-x)q^2}{m_{\ell_\alpha}^2 - x(1-x)q^2} \right] dx$$

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, ...)

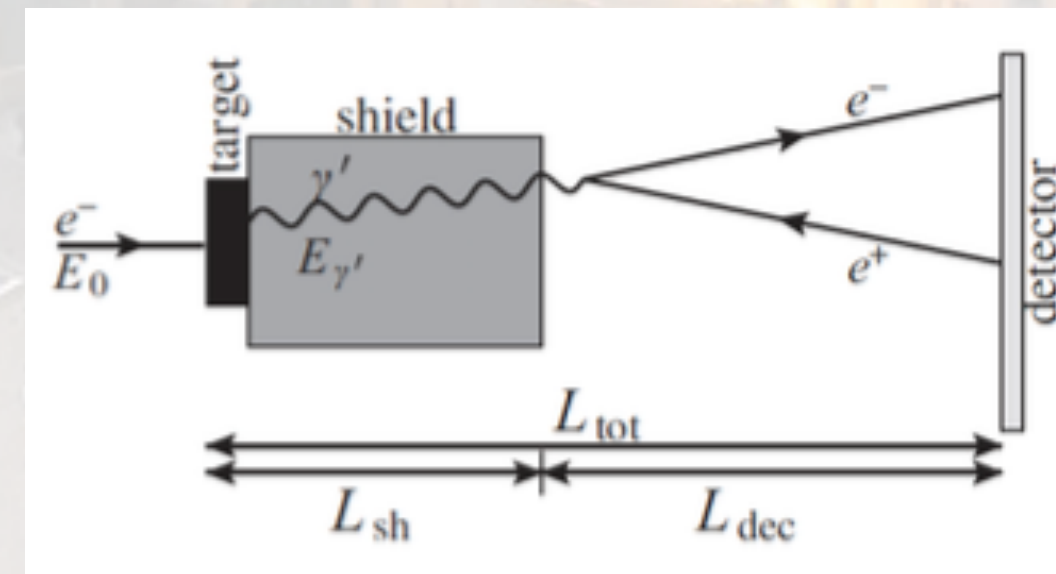


- Visible decay(SHiP, DarkQuest, ...)



1808.05219

$$m_V > 2m_\chi$$



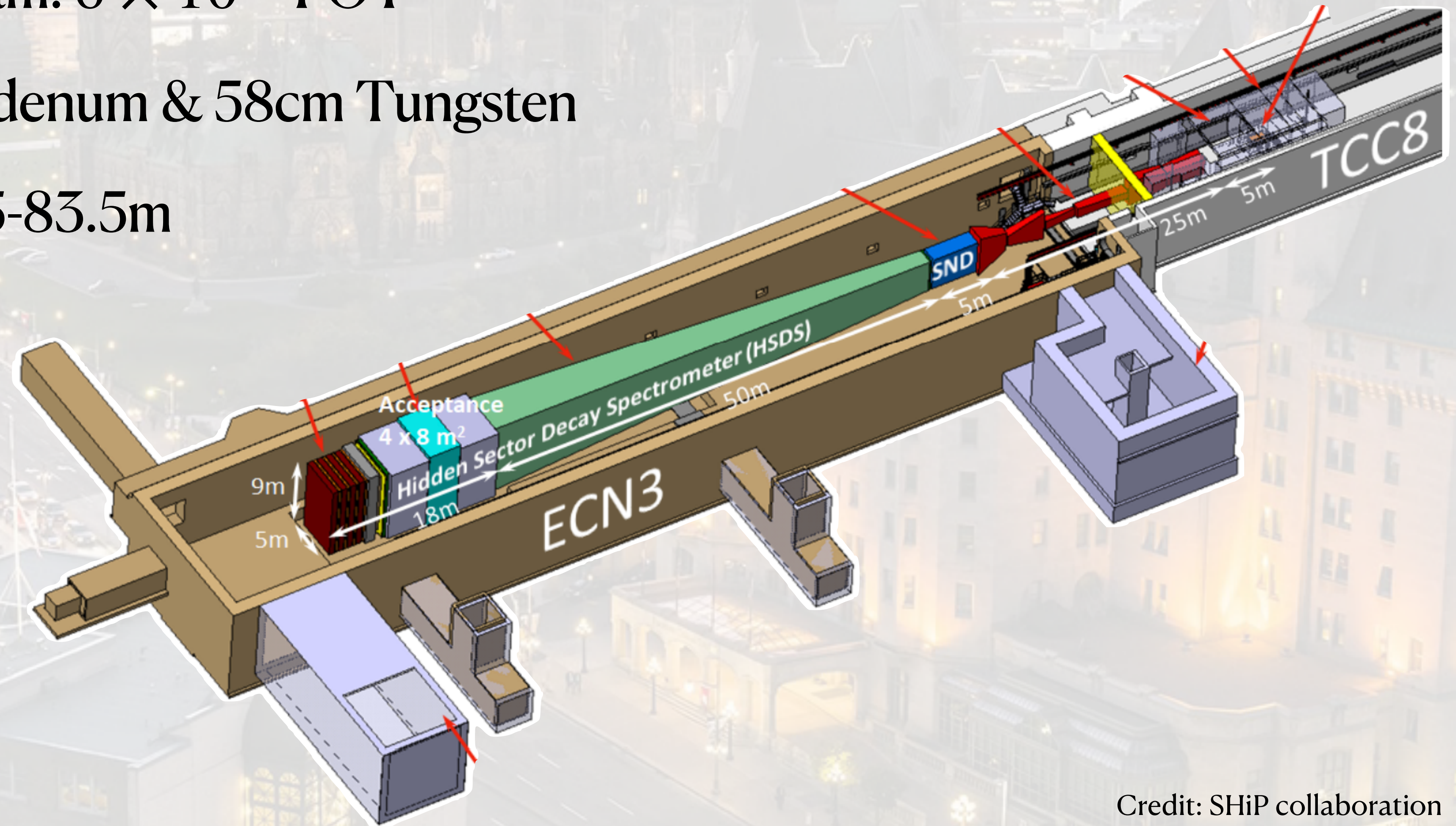
$$m_V < 2m_\chi$$

SHiP - Search for Hidden Particles

400 GeV proton beam. 6×10^{20} POT

Target: 58cm Molybdenum & 58cm Tungsten

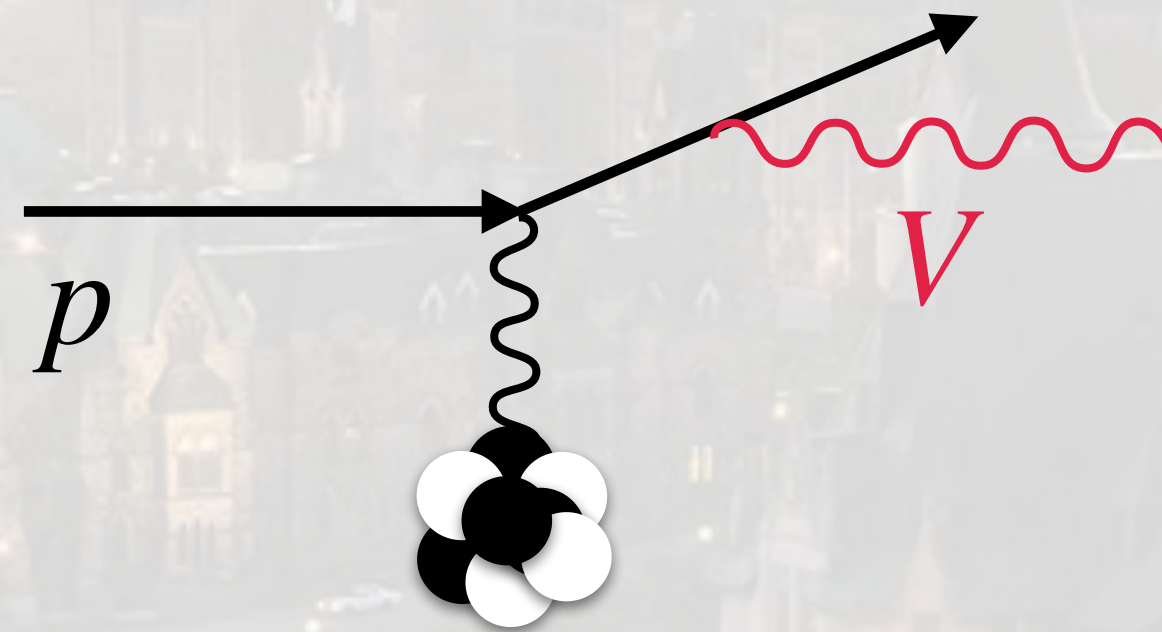
Decay chamber: 33.5-83.5m



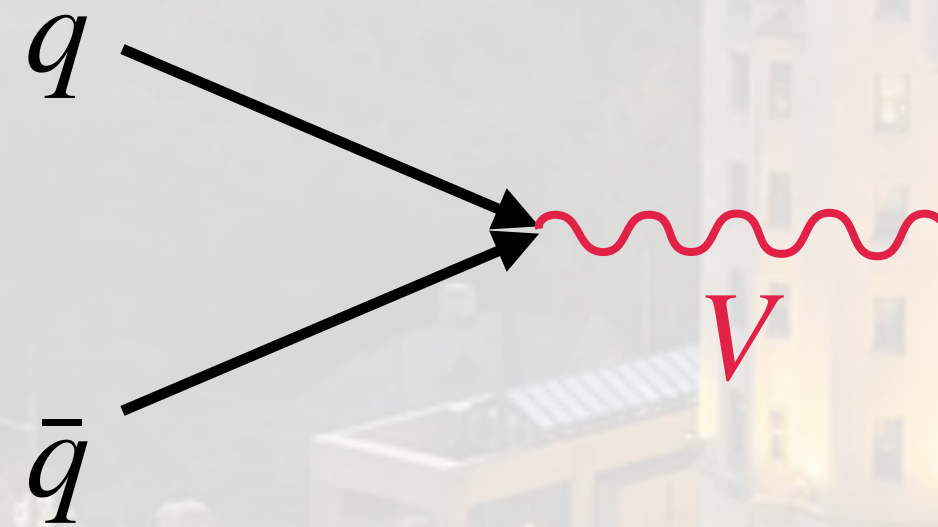
Credit: SHiP collaboration

Primary productions

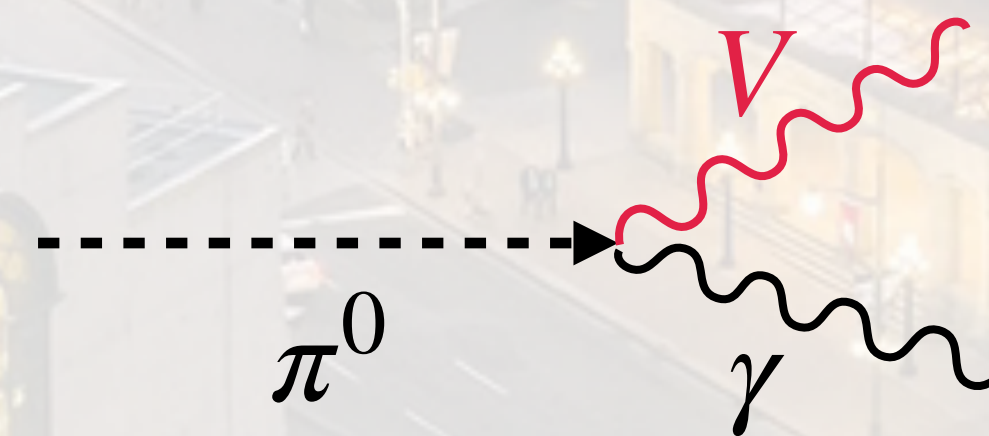
- Proton bremsstrahlung



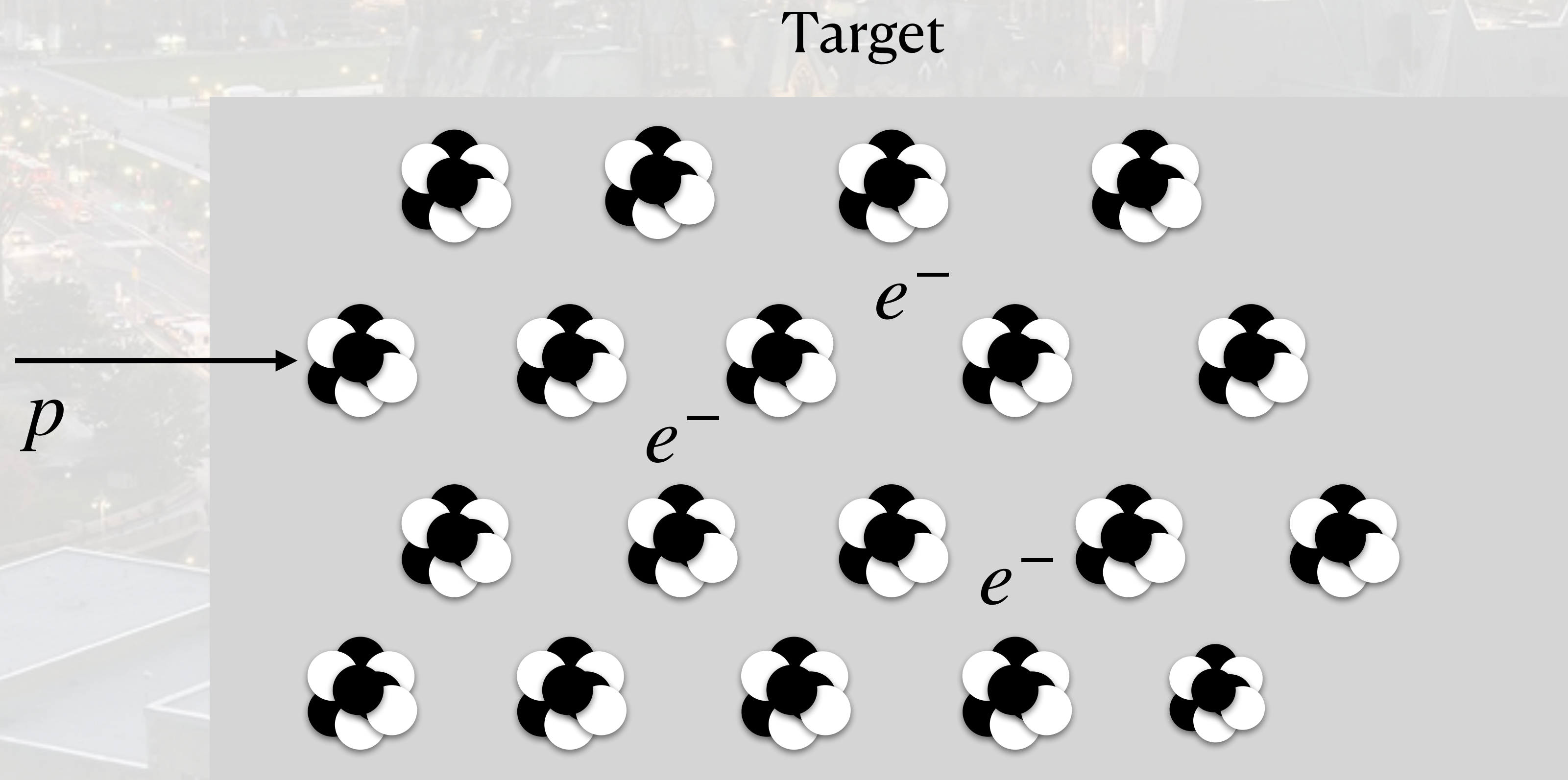
- Drell-Yan production



- Meson decay (π^0 , η , ω , η')

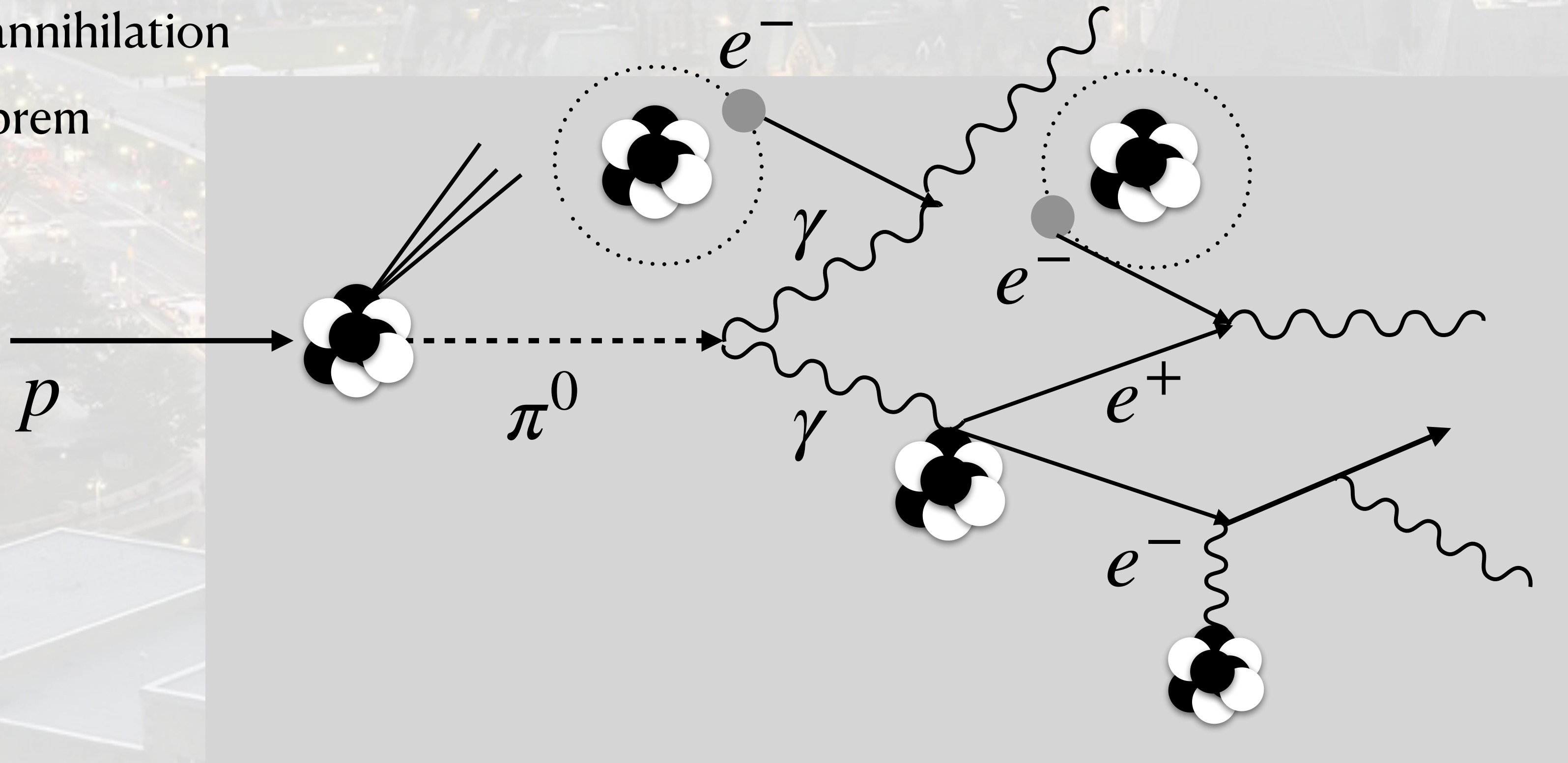


Electromagnetic secondaries



Electromagnetic secondaries

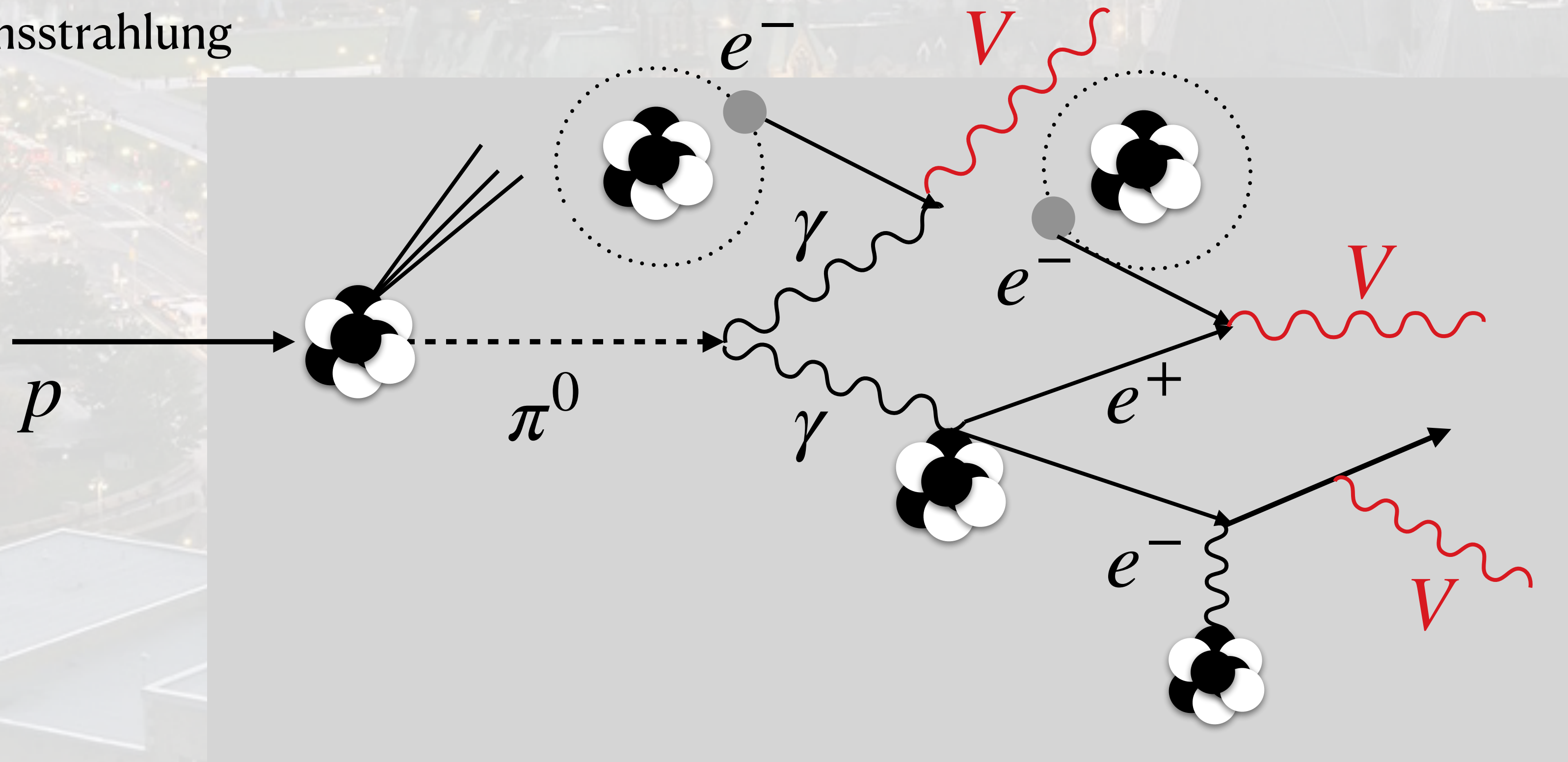
- Pair production
- Compton scattering
- Positron annihilation
- Electron brems



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.

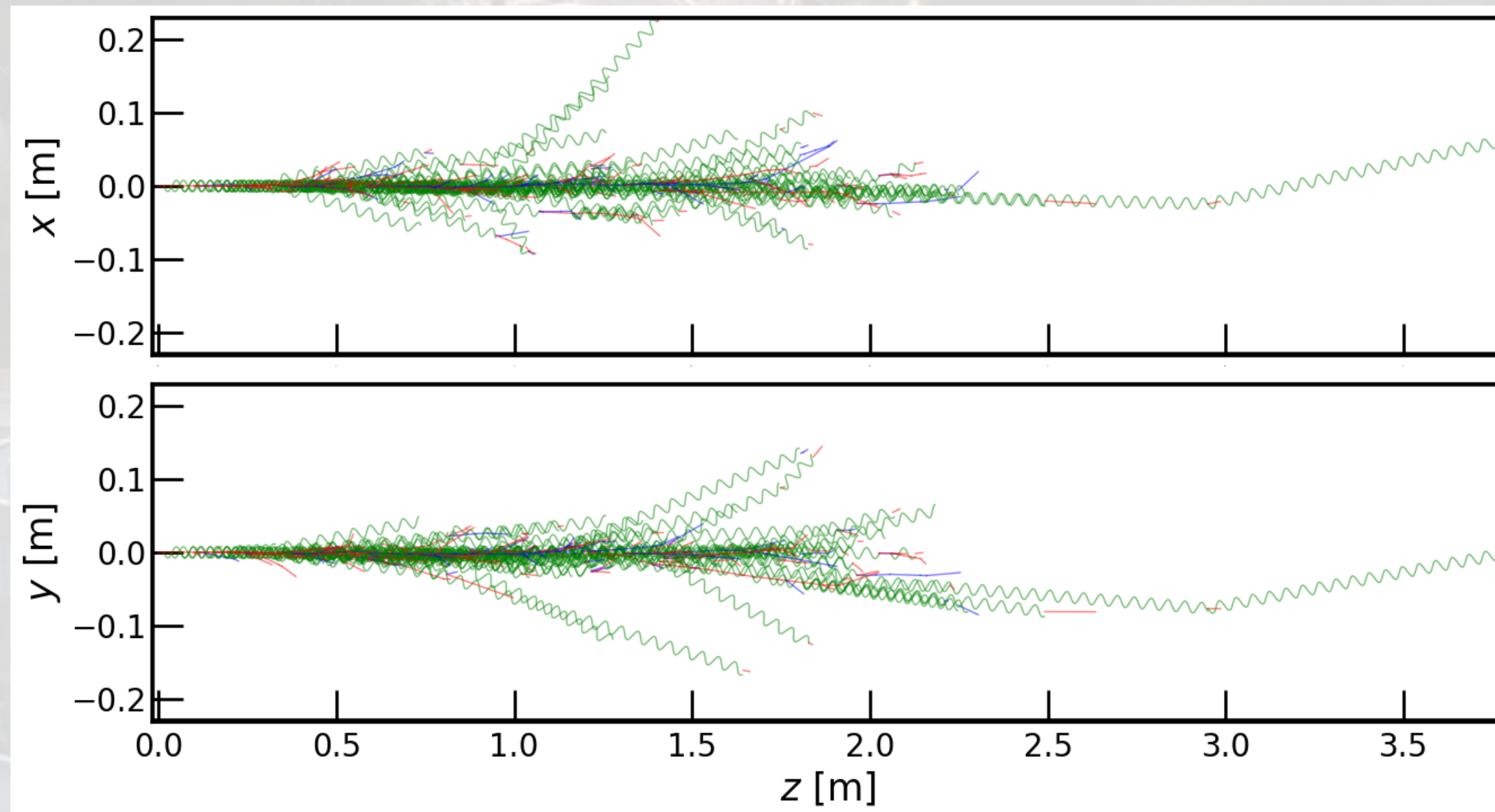
PETITE (Package for Electromagnetic Transitions In Thick-target Environments)

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

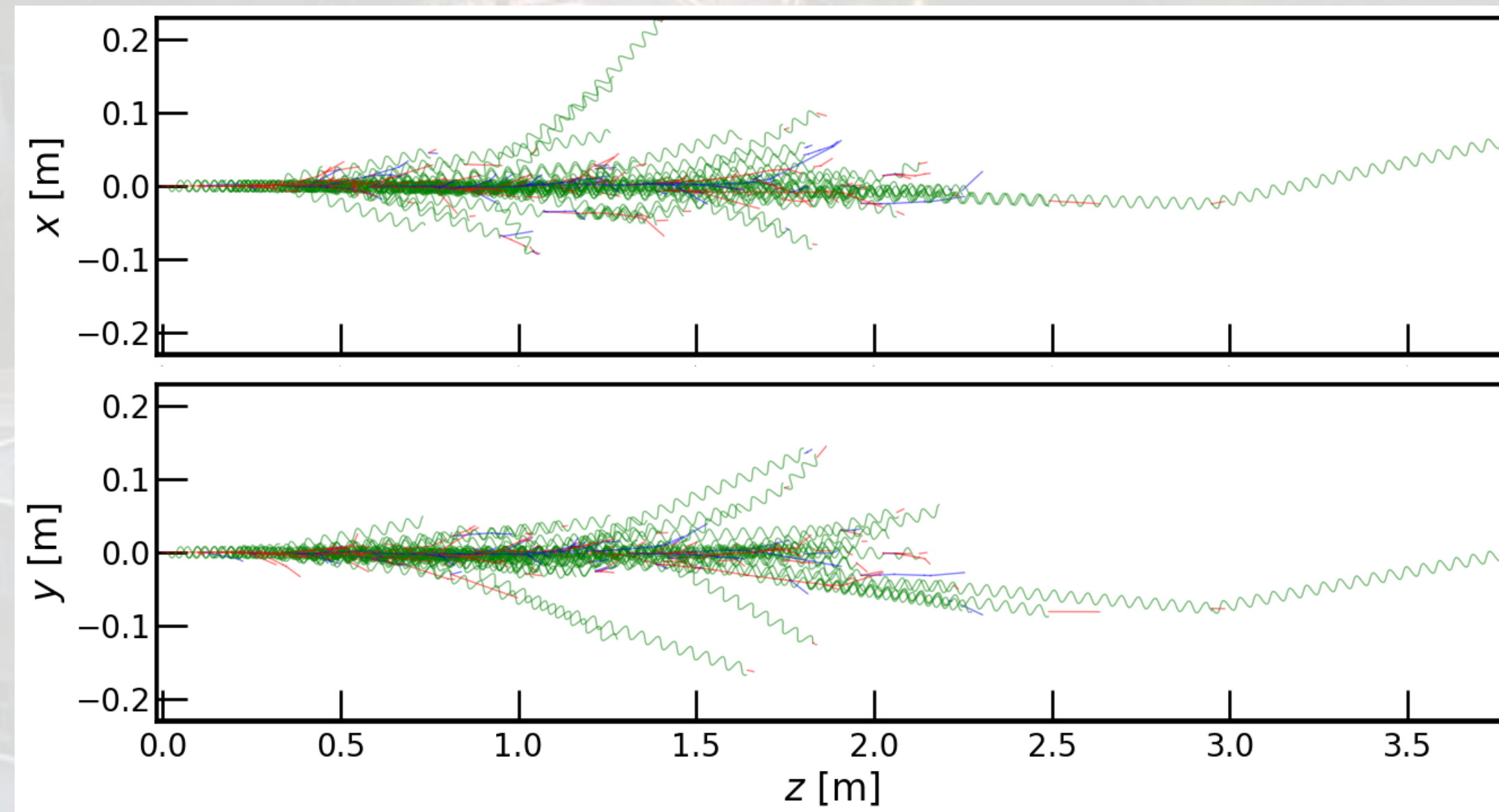
- Bremsstrahlung $e^{\pm}Z \rightarrow e^{\pm}\gamma Z$
- Pair production $\gamma Z \rightarrow e^{+}e^{-}Z$.
- Compton scattering $\gamma e^{-} \rightarrow \gamma e^{-}$
- Pair-annihilation $e^{+}e^{-} \rightarrow \gamma\gamma$
- Moller Scattering $e^{-}e^{-} \rightarrow e^{-}e^{-}$
- Bhabha Scattering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



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

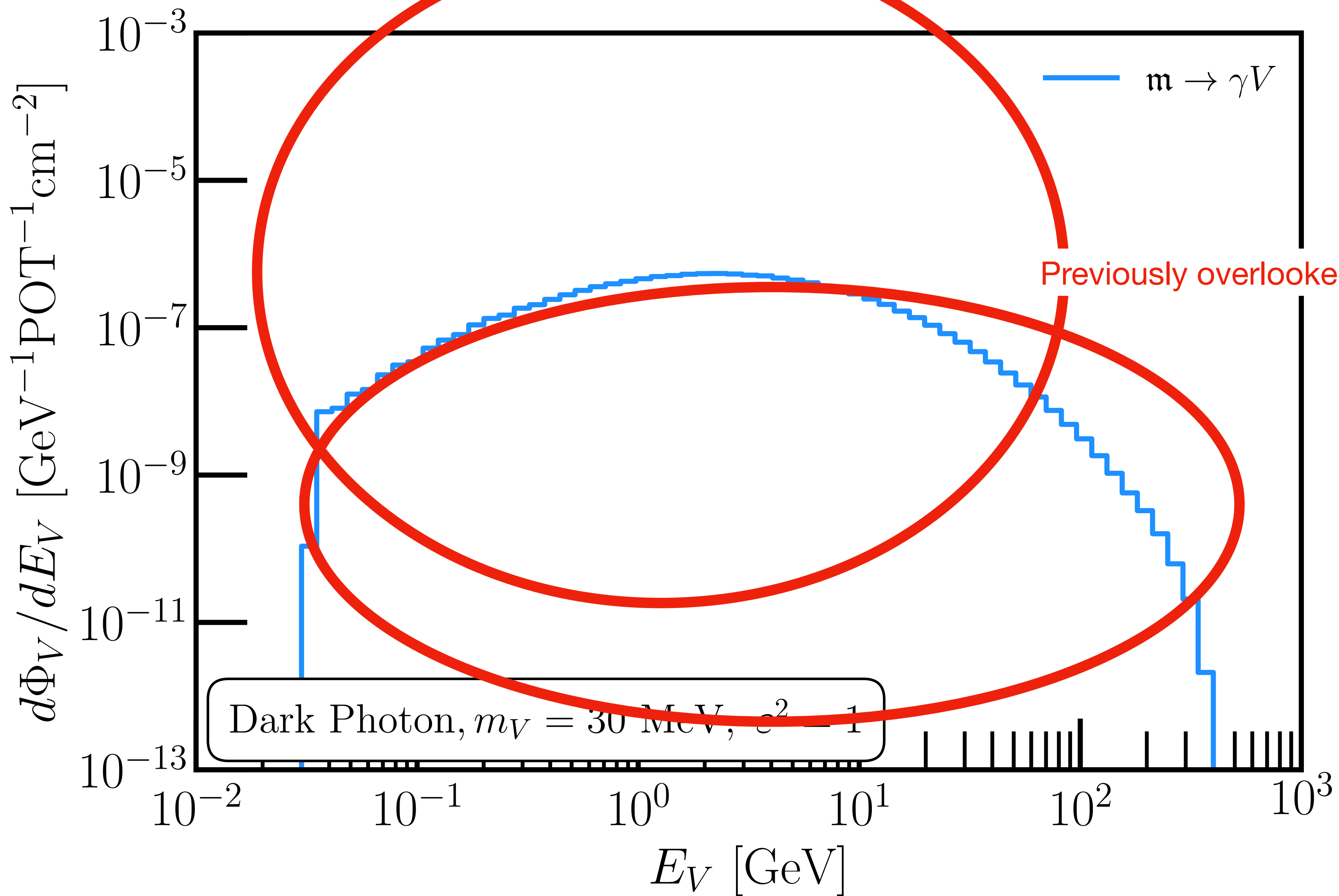
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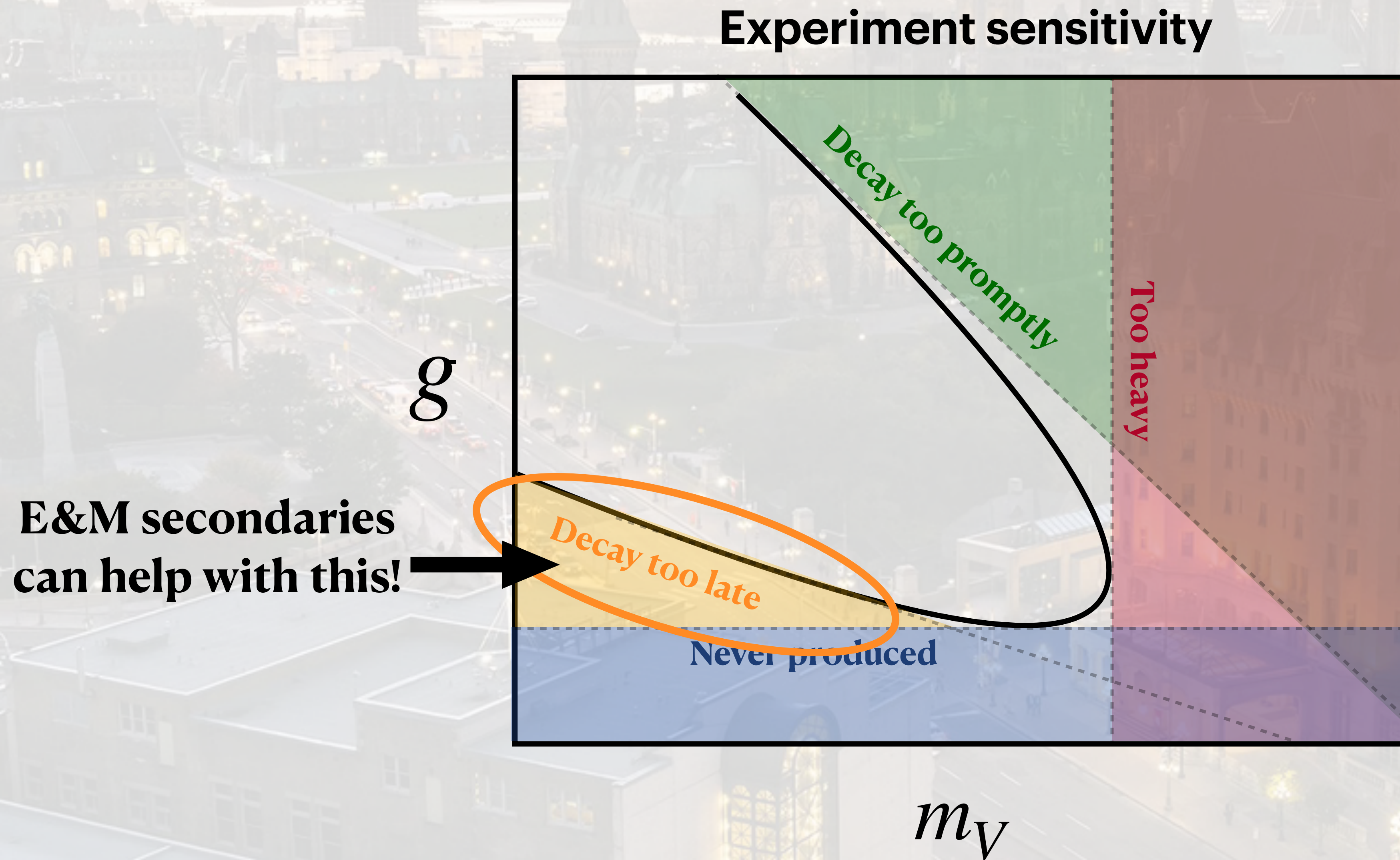


BSM processes

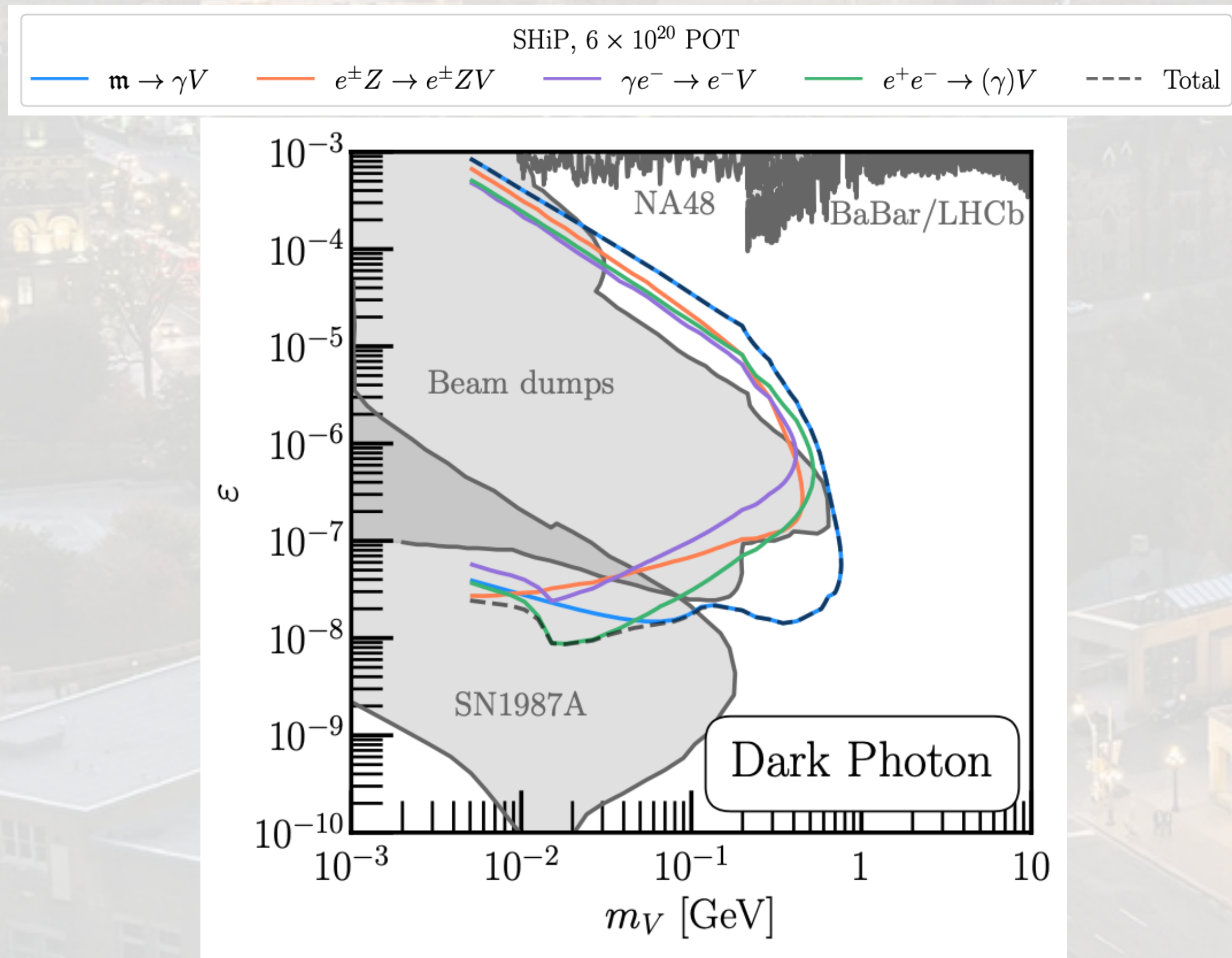
- Bremsstrahlung $Ze^{\pm} \rightarrow Ze^{\pm}V$
- Compton scattering $\gamma e^{-} \rightarrow e^{-}V$
- Pair-annihilation $e^{+}e^{-} \rightarrow (\gamma)V$



Toy sensitivity plot



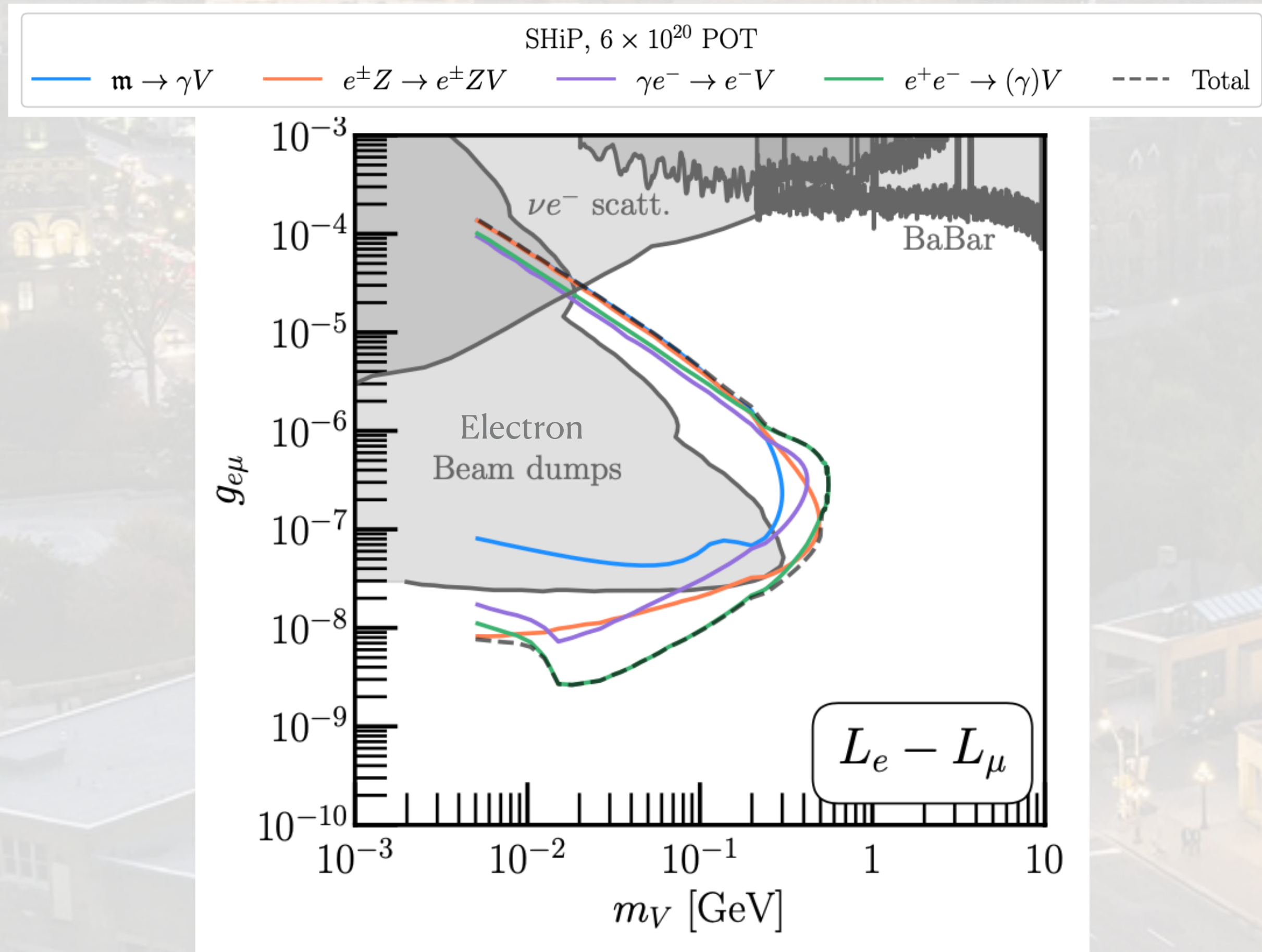
Sensitivity - Dark Photon



- 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

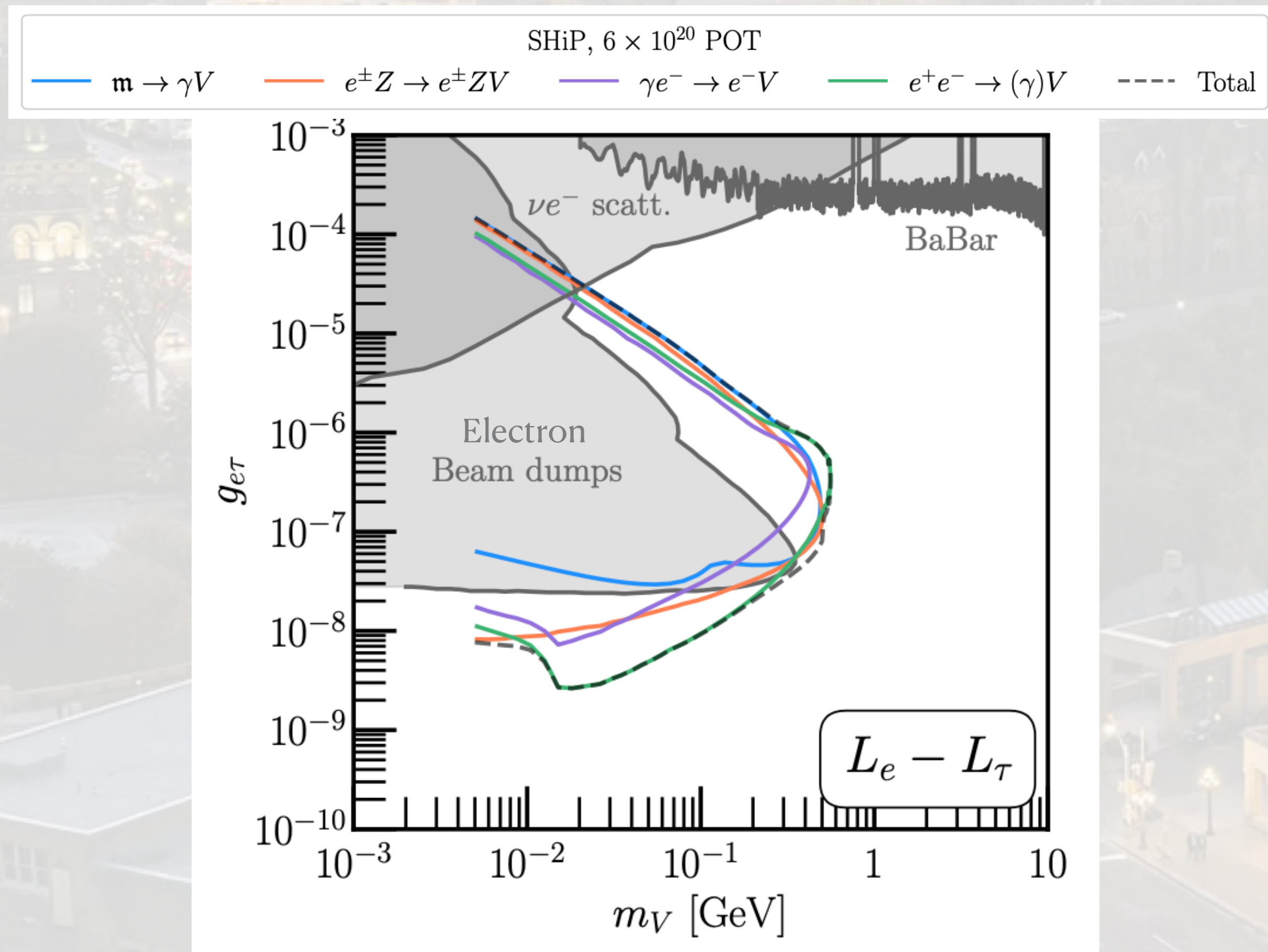


10 event contours

- 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



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

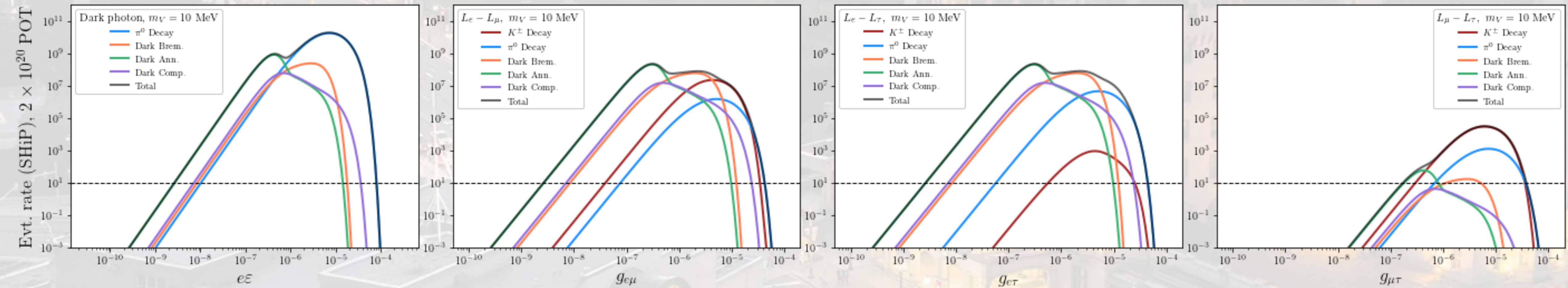
TZ, Plestid, Kelly, Blinov, Fox [\[2412.01880\]](#)

Takeaways

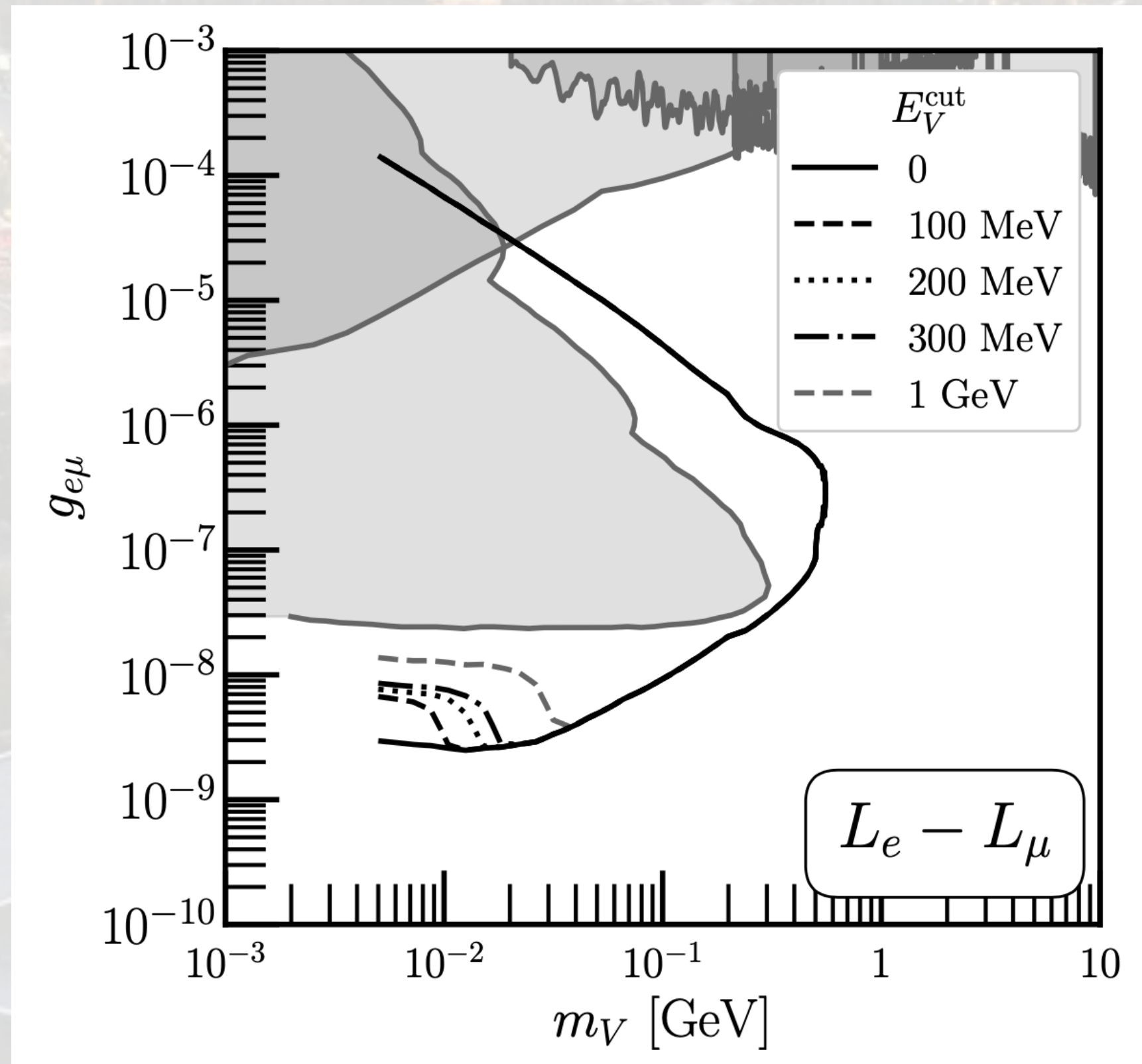
- Electromagnetic cascades expands sensitivity by an order of magnitude more than primary production at lifetime frontier.
- A proton fixed target experiment like SHiP is able to probe a large portion of parameter space that was not previously explored by current electron beam dump experiments.
- PETITE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

Thank you!

Back-ups:



Impact of energy cuts



- 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

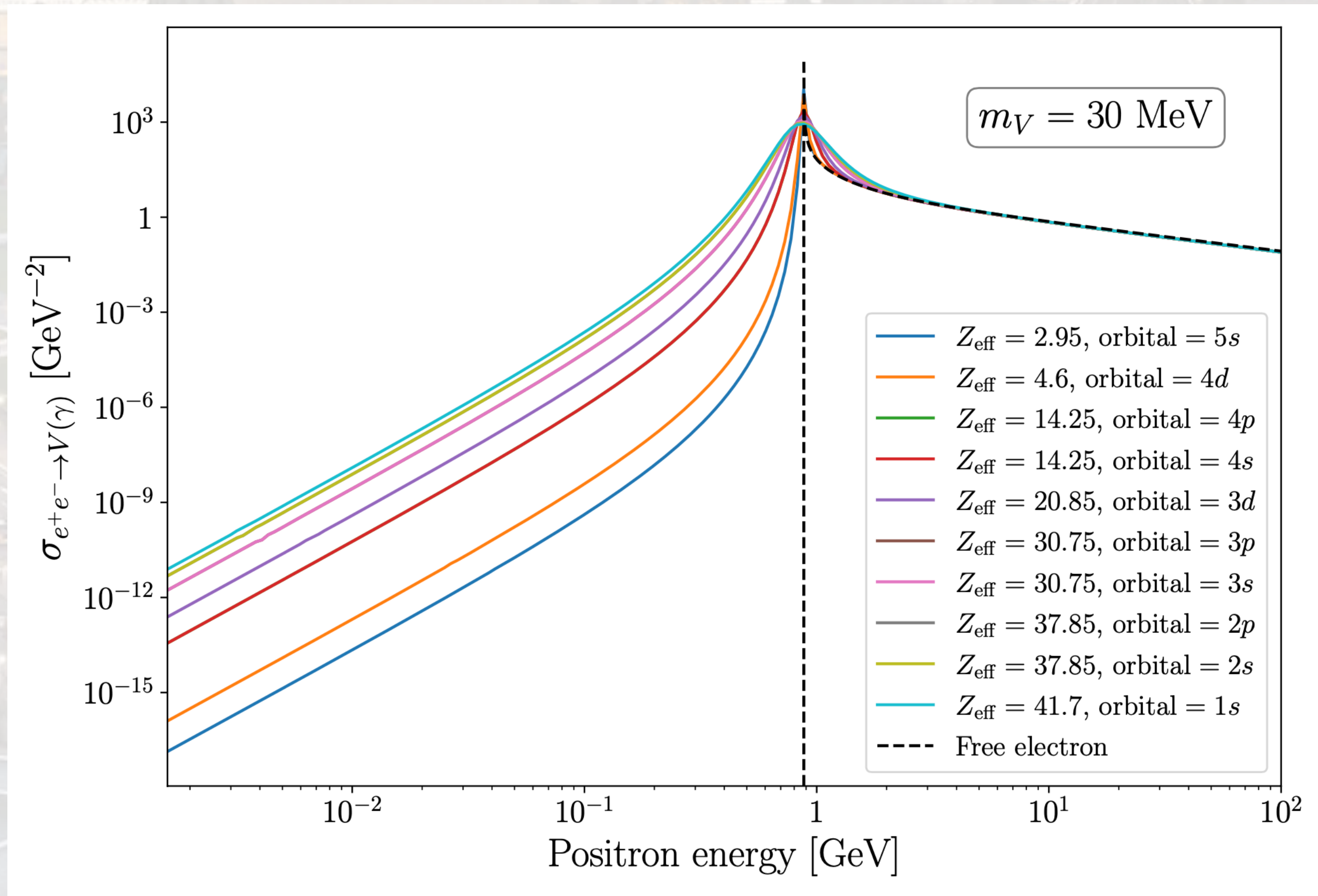
```
shower = existing Standard Model shower (e.g. as generated by PETITE)
for particle in shower do
  if particle =  $e^+$  then
    processlist = {Dark bremsstrahlung, Dark annihilation}
  else if particle =  $e^-$  then
    processlist = {Dark bremsstrahlung}
  else if particle =  $\gamma$  then
    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  $d\sigma_{\text{BSM}}^{(p)}$ .
      • 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
```

$$\frac{dw^{(p)}}{dz} = n^{(p)} \sigma_{\text{BSM}}^{(p)}(z) \exp \left(- \int_0^z \frac{dz'}{\lambda_{\text{MFP}}^{\text{SM}}(z')} \right)$$

Probability for the BSM process to occur

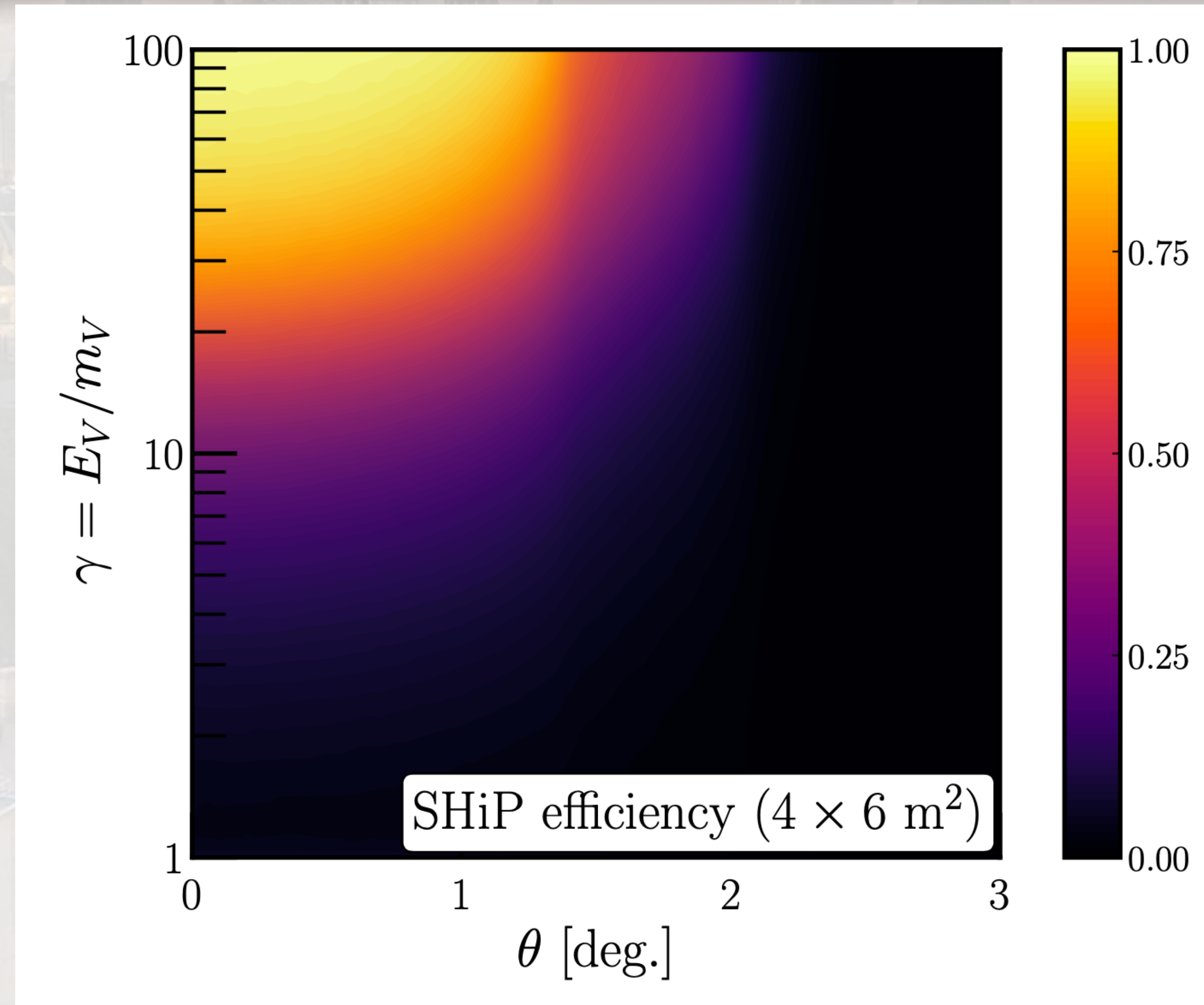
Probability of no SM process happening up to that point

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 γ — hope to encourage SHiP collaboration to explore lower-energy reconstruction and background rates to enhance sensitivity.

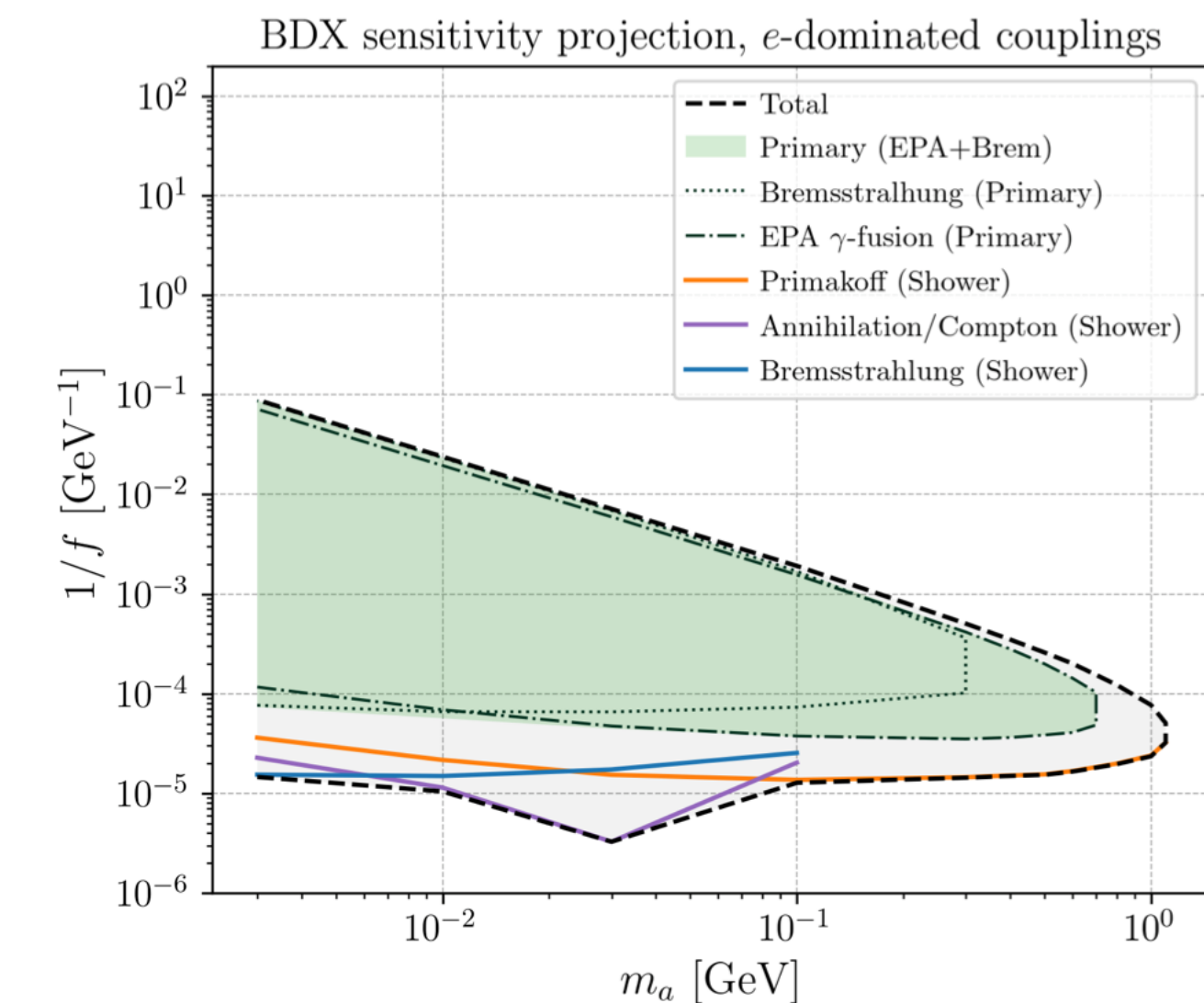
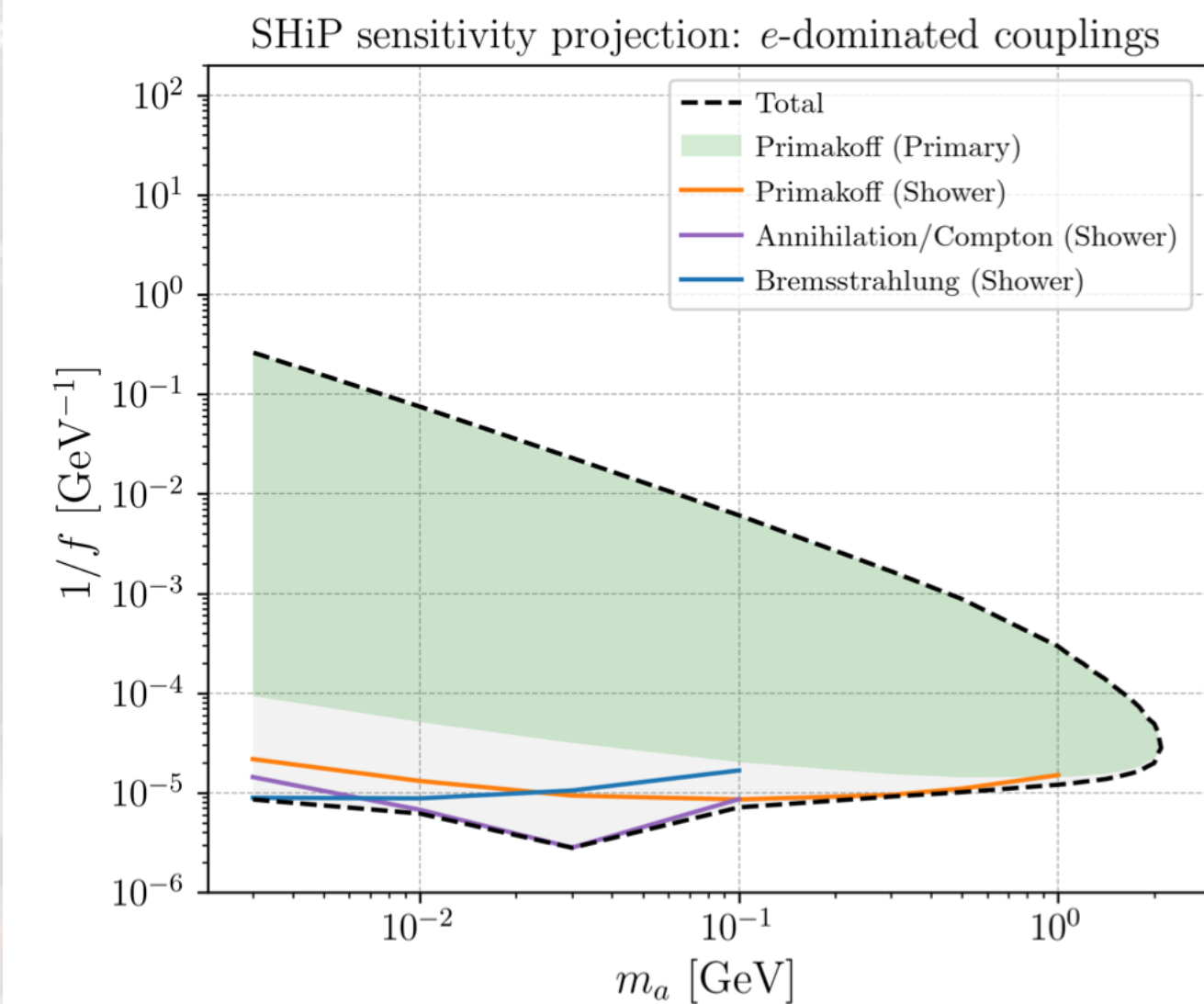
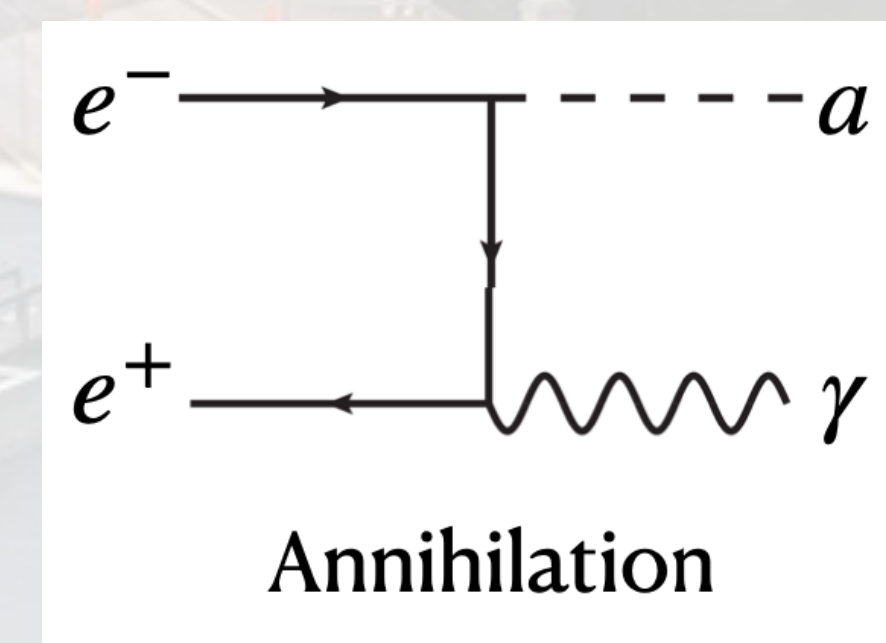
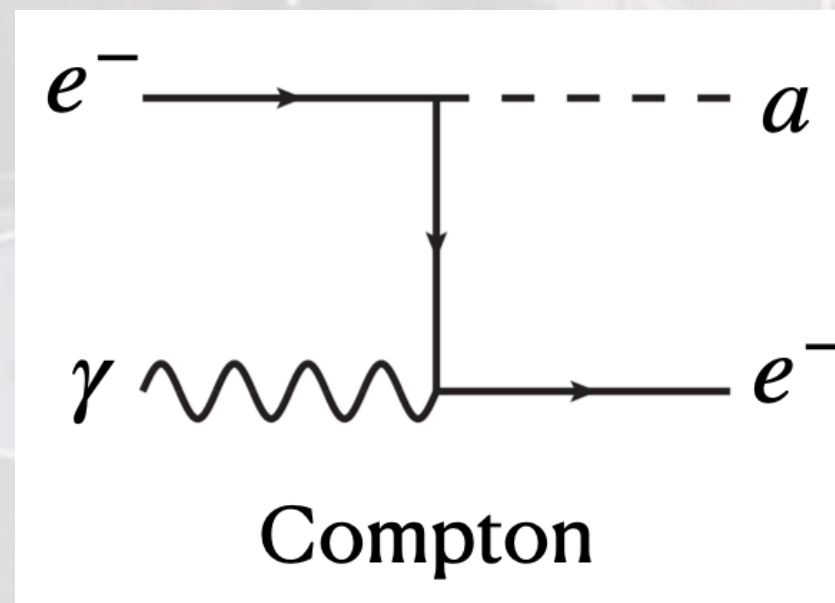
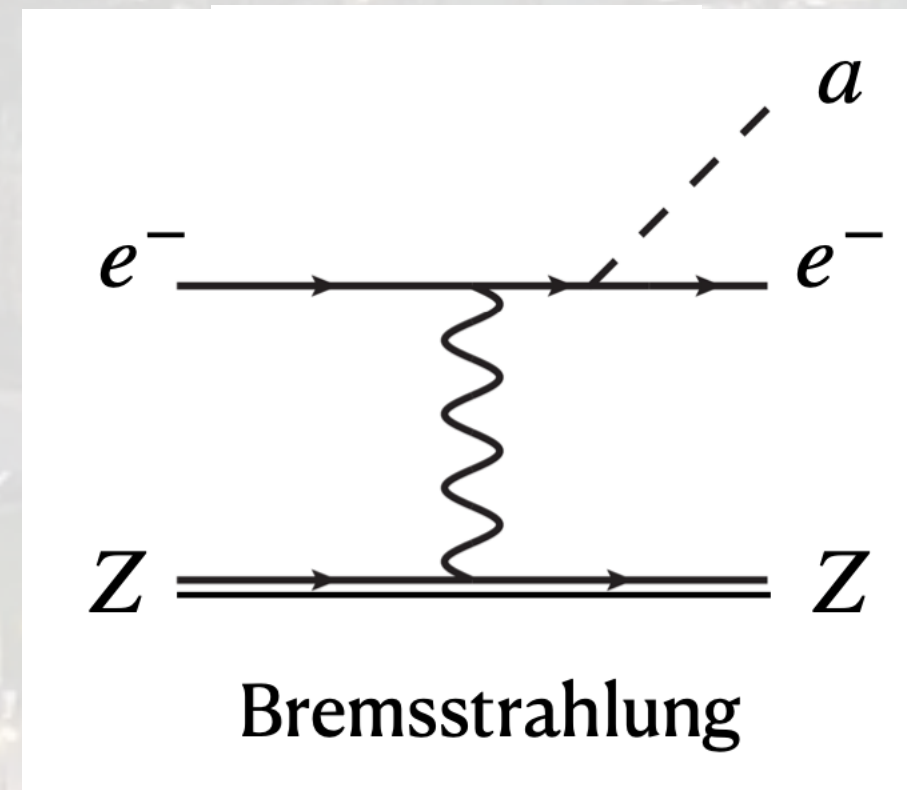
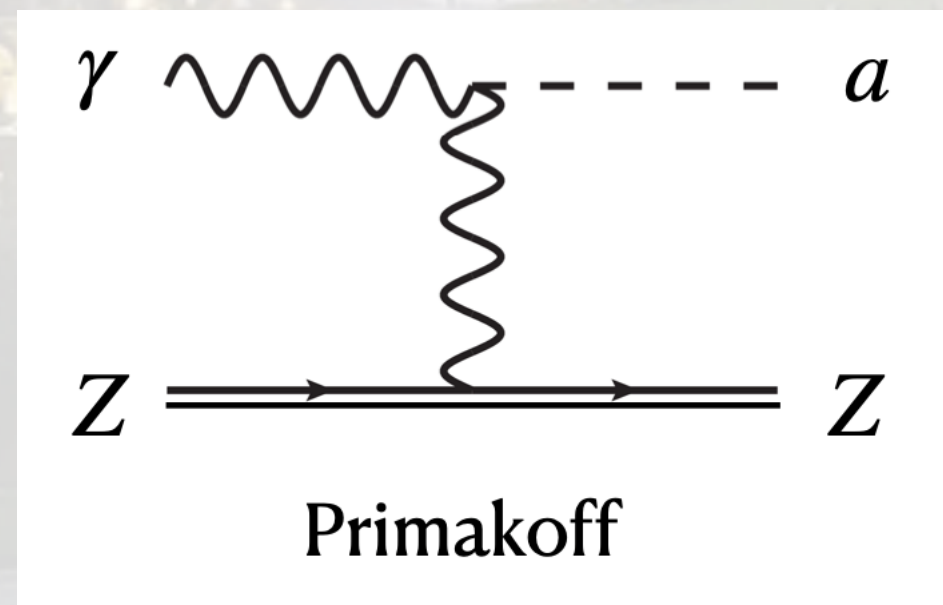


ALPs (Axion-Like Particles)

Patrone et al, 2509.14310

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

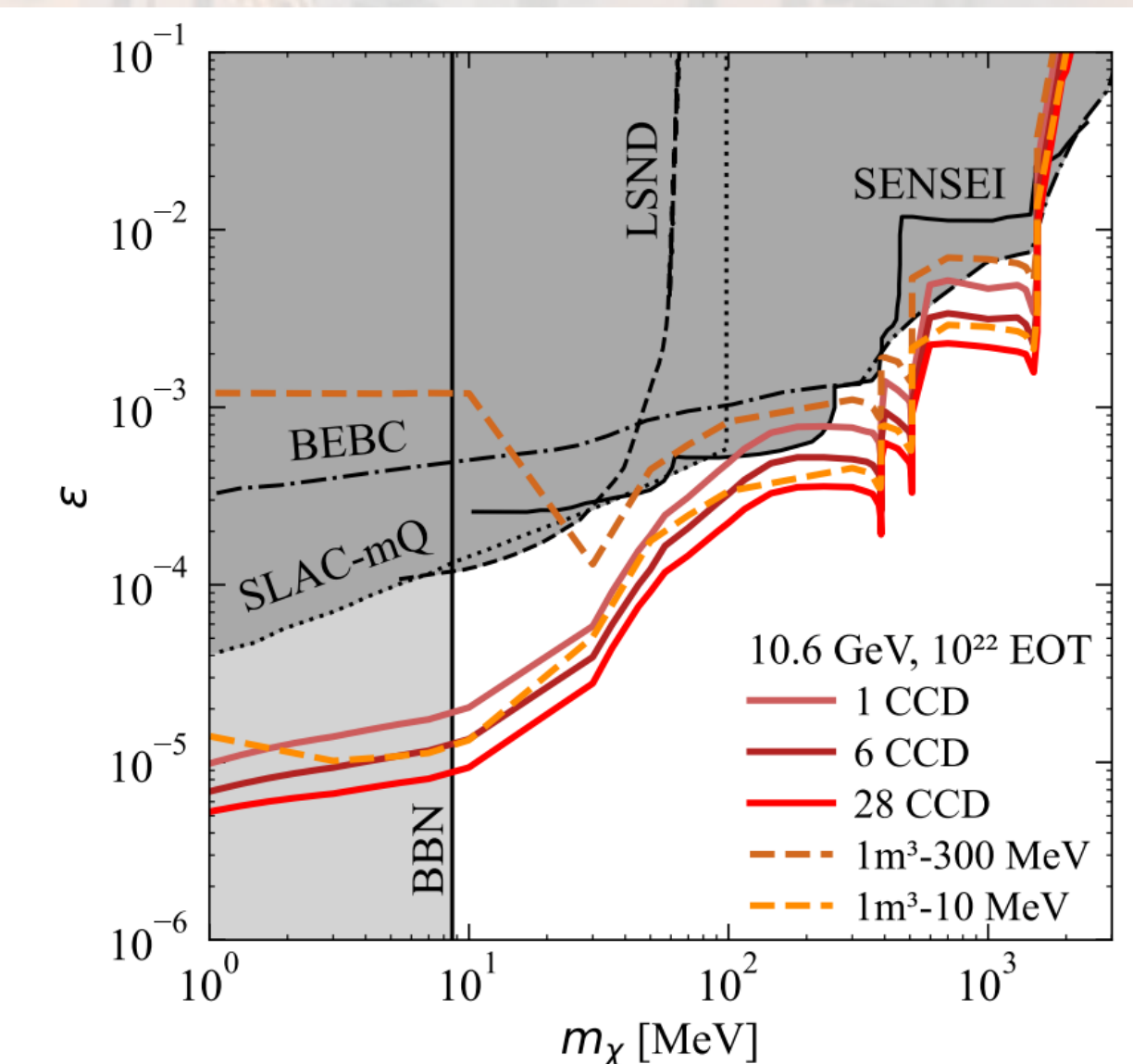
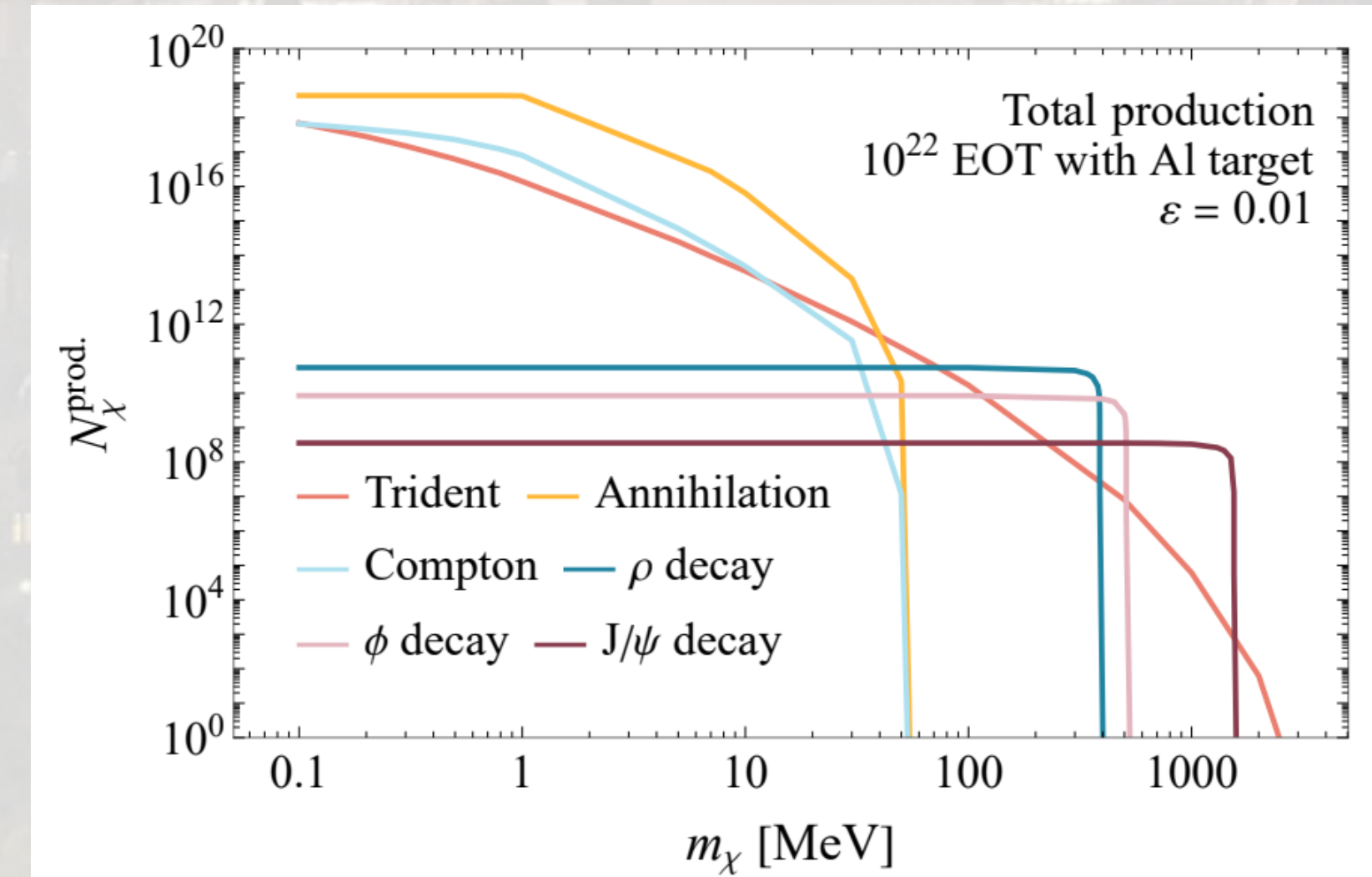
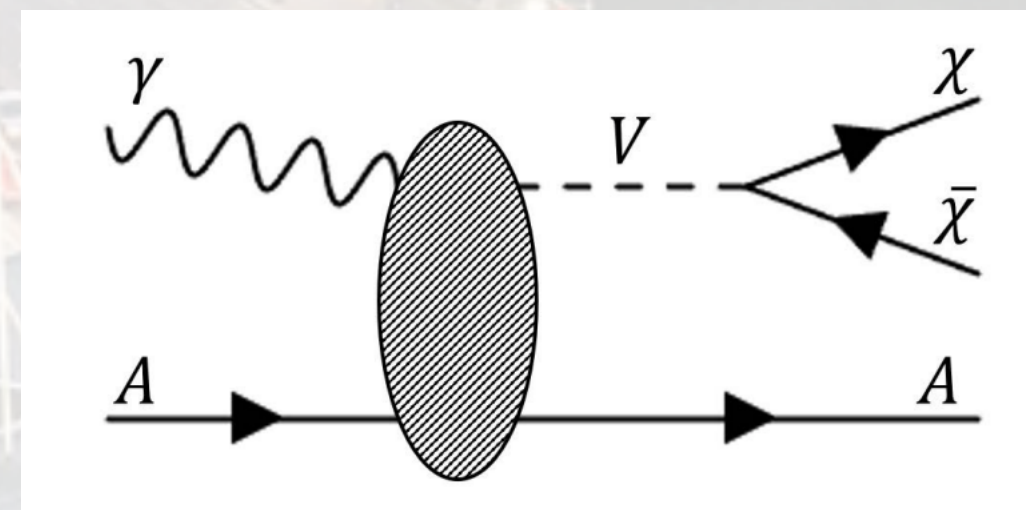
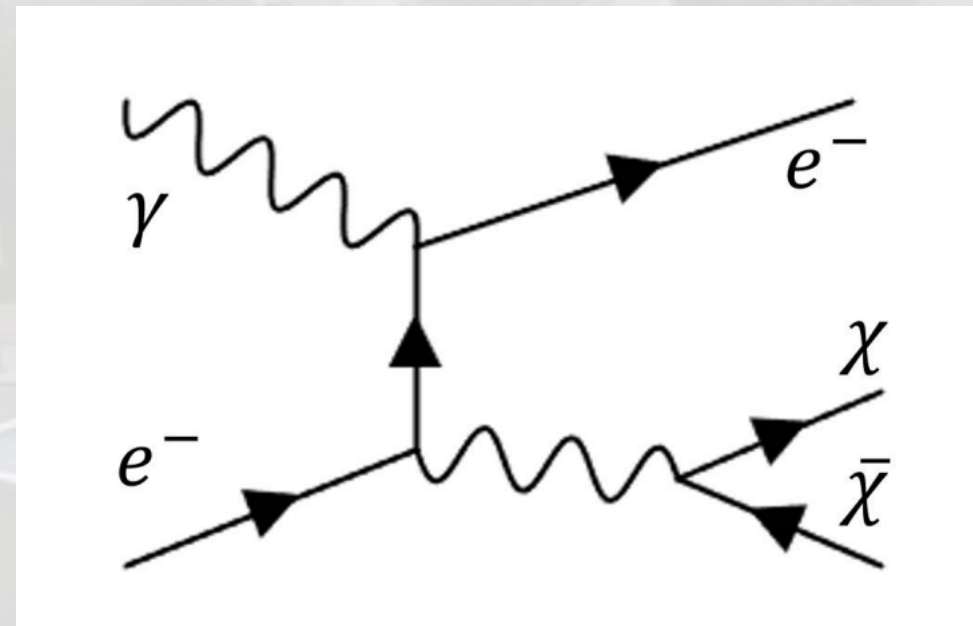
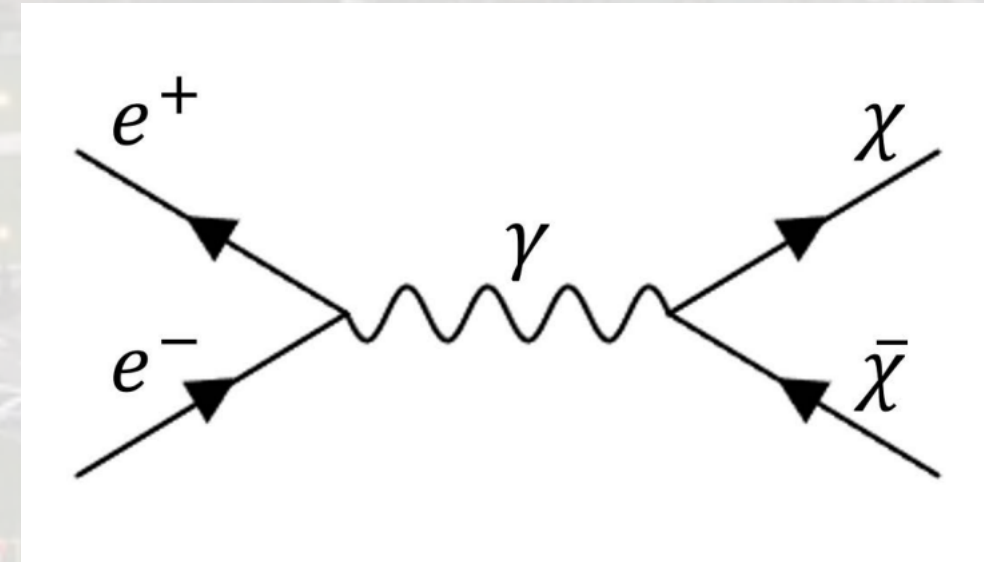
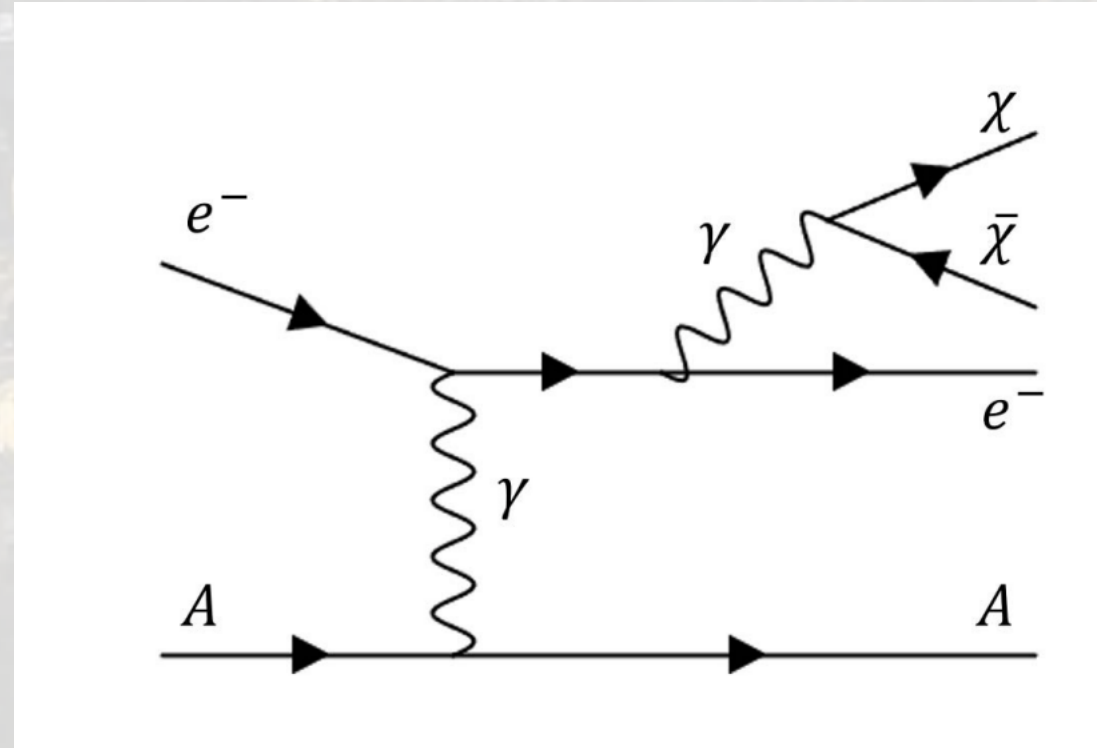
• Production channels:



Millicharged particles

Essig et al, 2412.09652

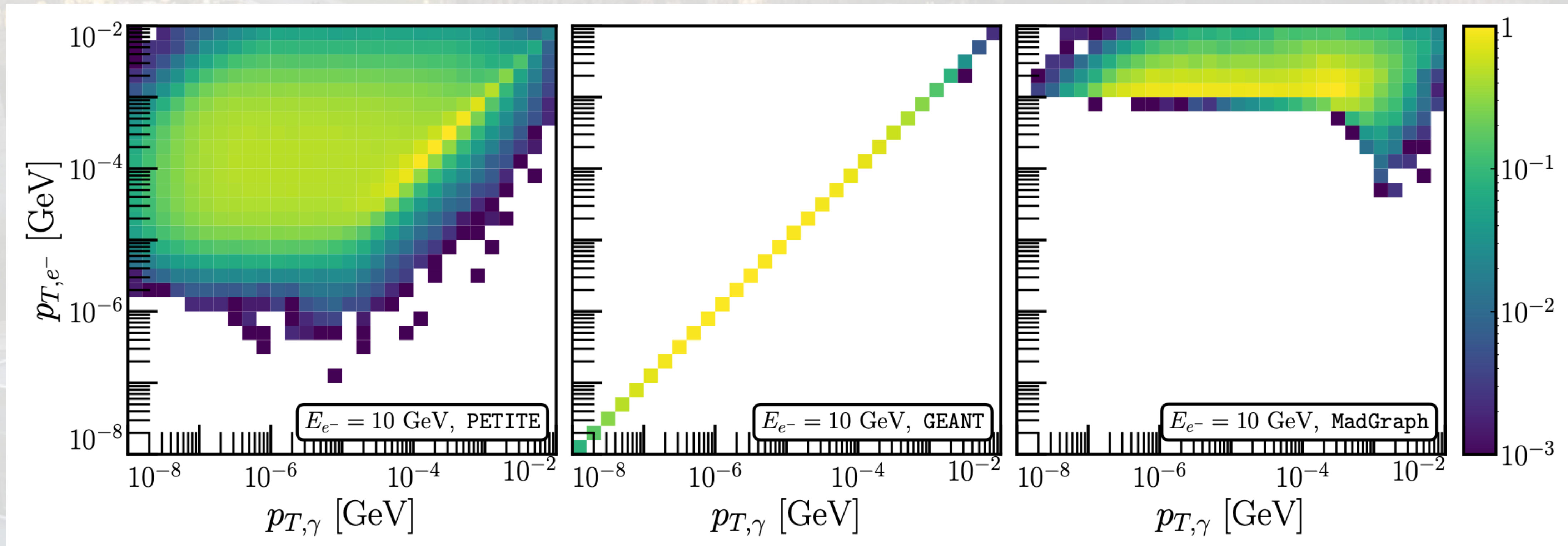
$$\mathcal{L} \subset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \epsilon e A_{\mu} \bar{\chi} \gamma^{\mu} \chi$$



SM bremsstrahlung

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

p_T 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

