ARXIV: 2401.06843 , ARXIV: 2410.XXXXX,

Enhanced Dark Sector Production In Beam Dumps From Electromagnetic Cascades

RYAN PLESTID | NTN FELLOW, BURKE INSTITUTE, CALTECH

COLLABORATORS | K.J. KELLY, T. ZHOU (TAMU) | N. BLINOV (YORK) | | P.A.N. MACHADO, PJ. FOX (FERMILAB) |

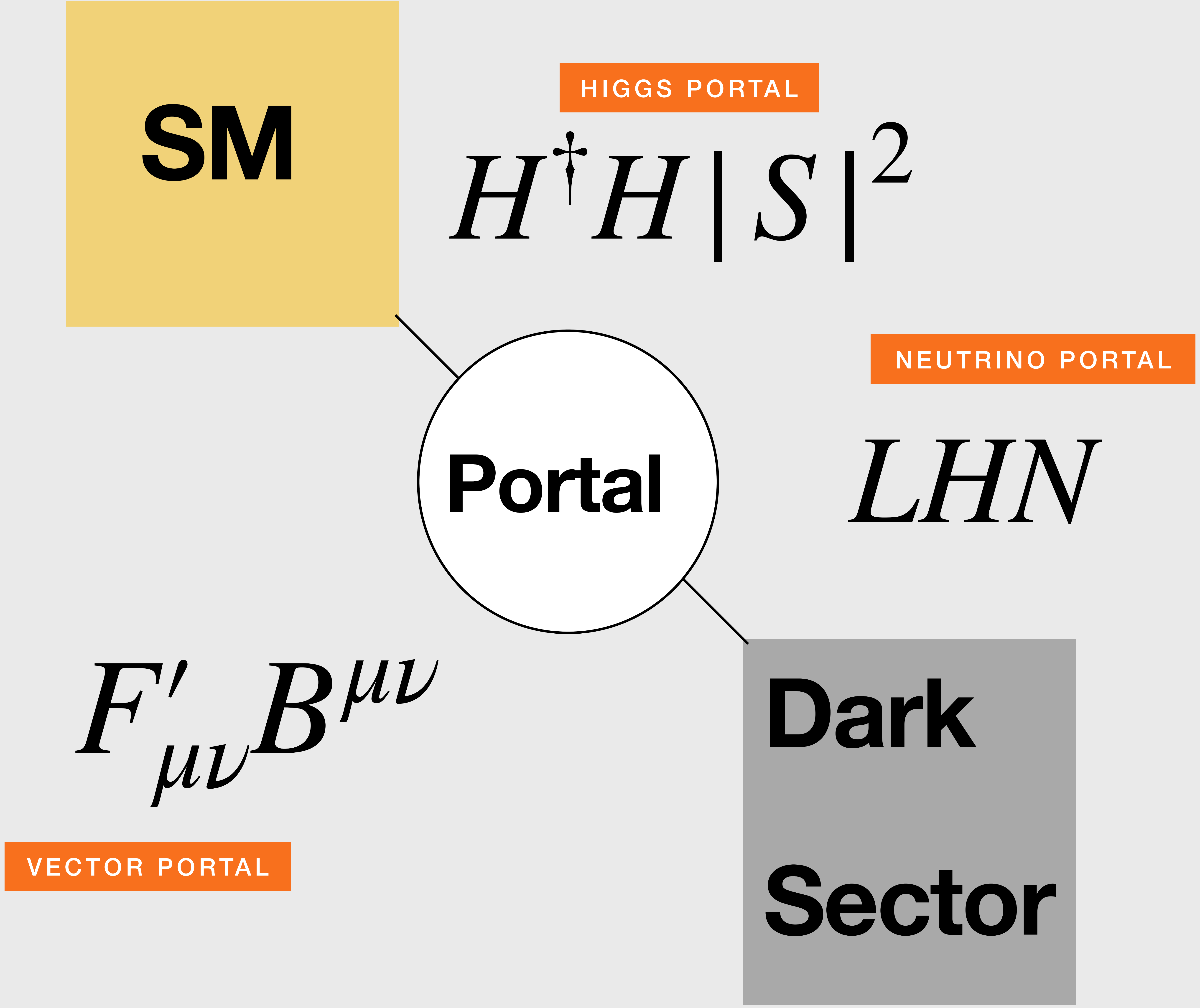
DARK INTERACTIONS | VANCOUVER, BRITISH COLUMBIA | OCTOBER 2024

Caltech

Neutrino Theory Network

Motivation & Context

- If light new physics exists it must be a gauge singlet.
- Possibly complex dark sector (e.g. SM-like).
- Few singlet operators available.
  Focus on "portals".



Motivation

- Q: How many ways can light new physics couple to the SM?
- A: Not many once you restrict to low-dim operators!

$$\mathcal{O}^{[4]}_{\text{singlet}} = \phi^2 |H|^2 \quad \text{or} \quad LHN \quad \text{or} \quad B^{\mu\nu} B'_{\mu\nu}$$

Scalars **HNLs** **Z-Prime**

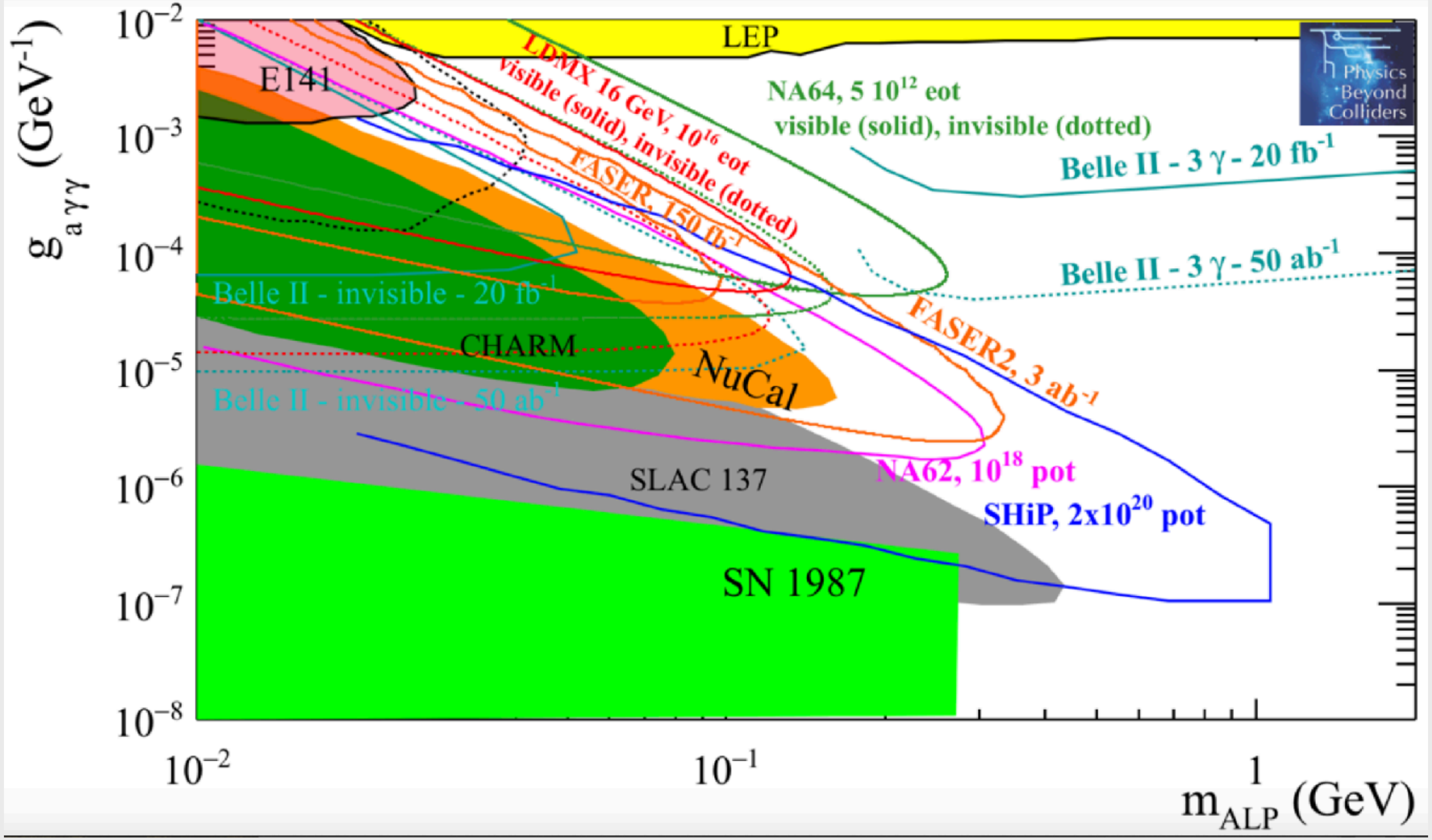
$$\mathcal{O}^{[5]}_{\text{singlet}} = \frac{1}{\Lambda} (\partial_\mu a)\, J^\mu \quad + \quad \dots$$

ALPs

Existing Searches

- Broad & competitive phenomenological landscape

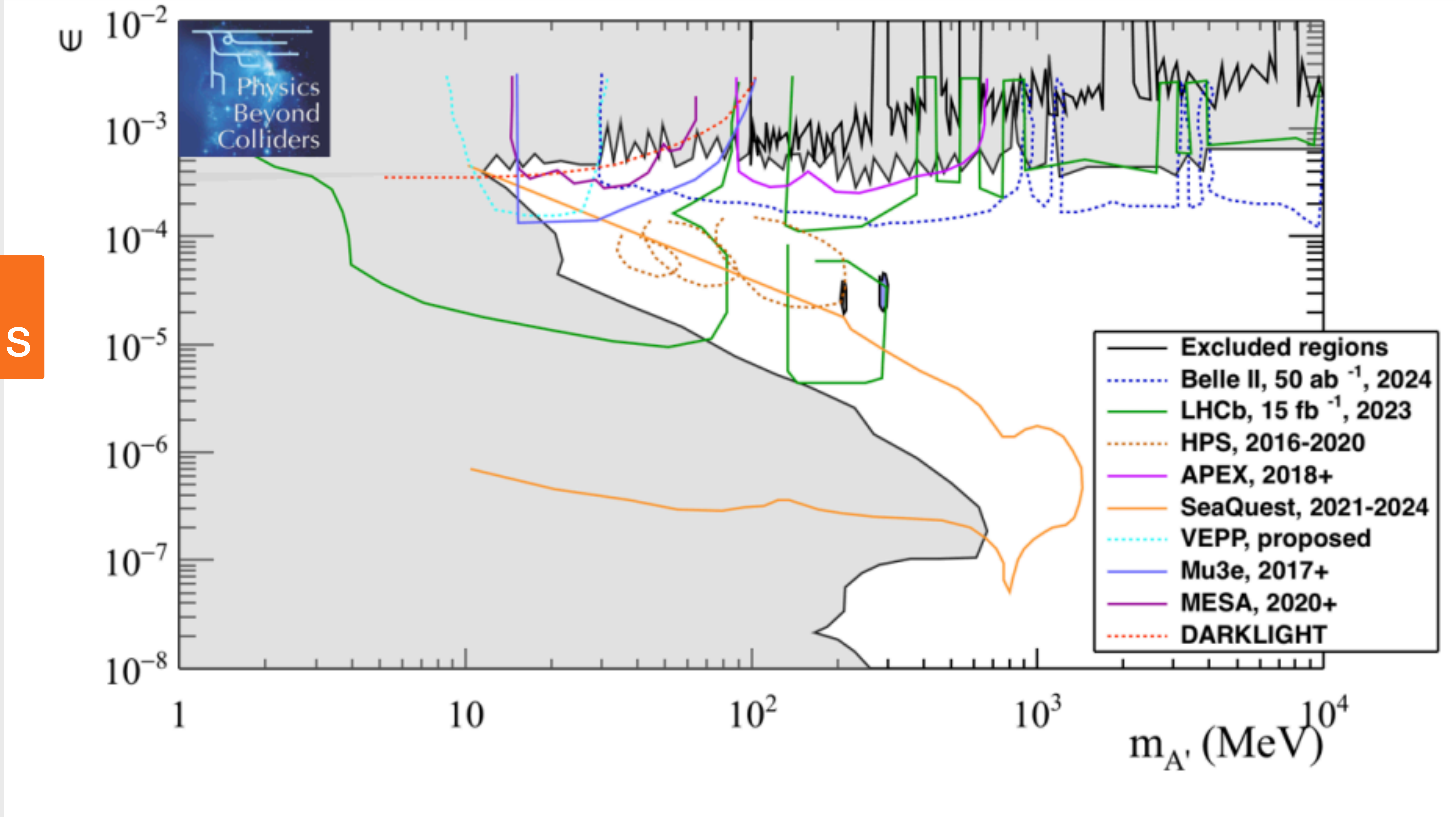
ALPS



Existing Searches

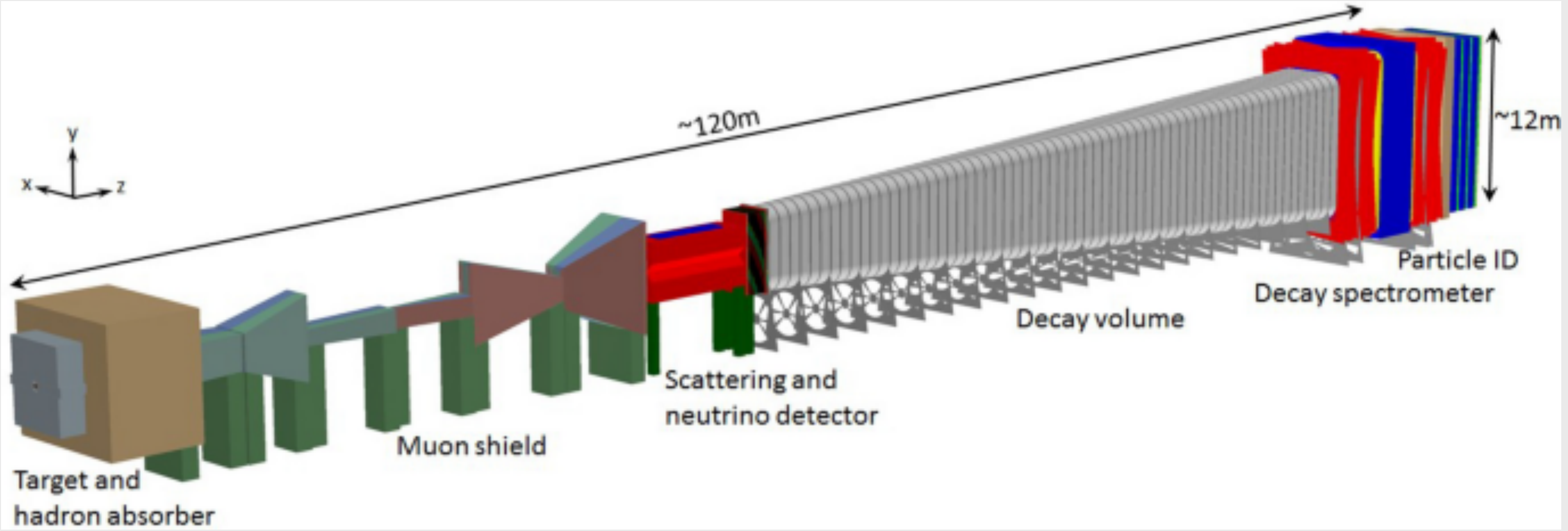
- Broad & competitive phenomenological landscape

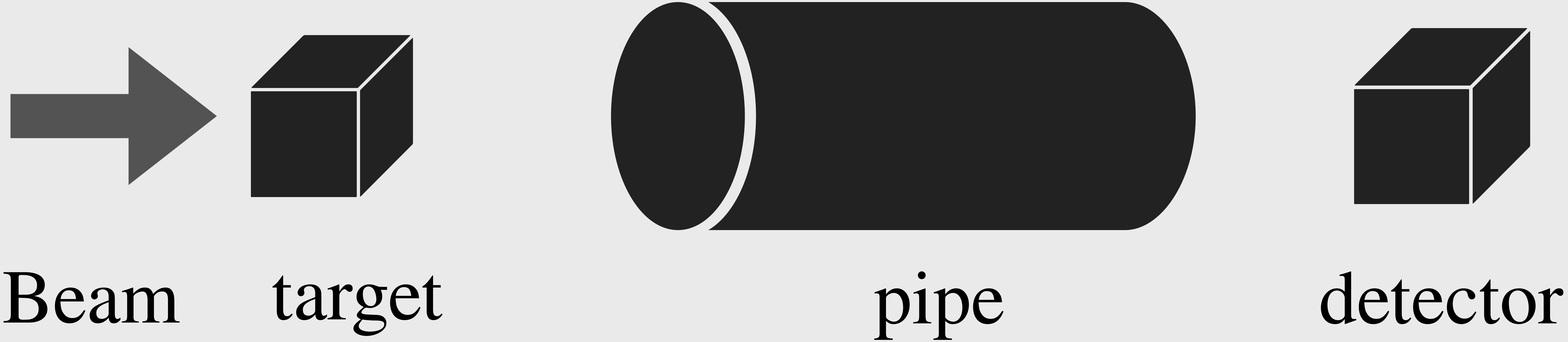
DARK PHOTONS



How Do These Experiments Work

HOW TO MAKE A BSM BEAM





Option 1: Meson Decays

IN NEUTRINO EXPERIMENTS

LONG LIVED

$$K^{\pm} \to \ell^{\pm} X$$

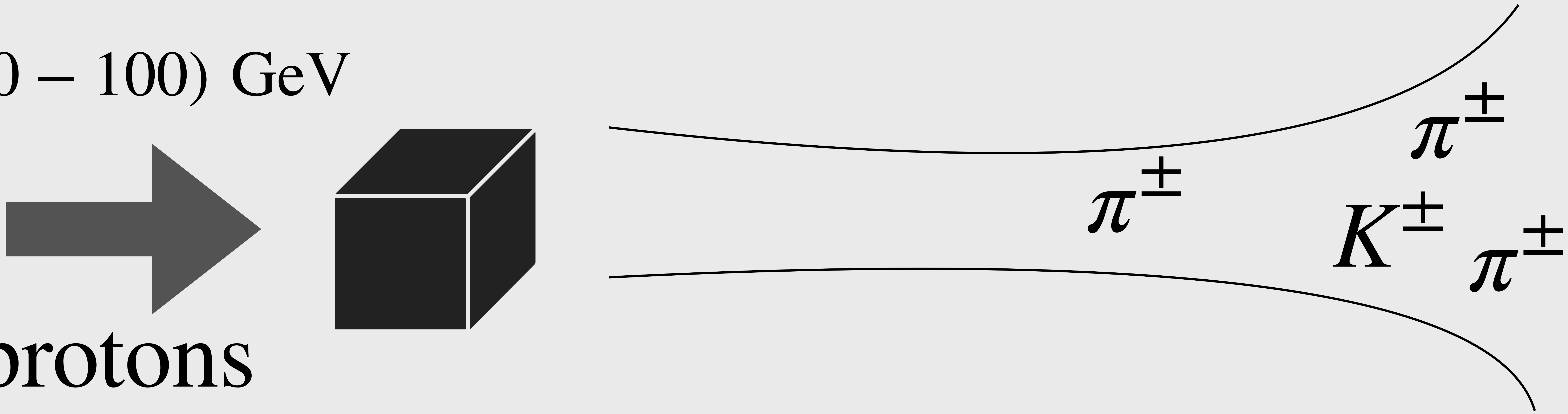
PROMPT

FROM BEAM STOP

$$D^{+} \to K^{+} X$$

$$\pi^{0} \to \gamma X$$

$\sim (10 - 100)$ GeV

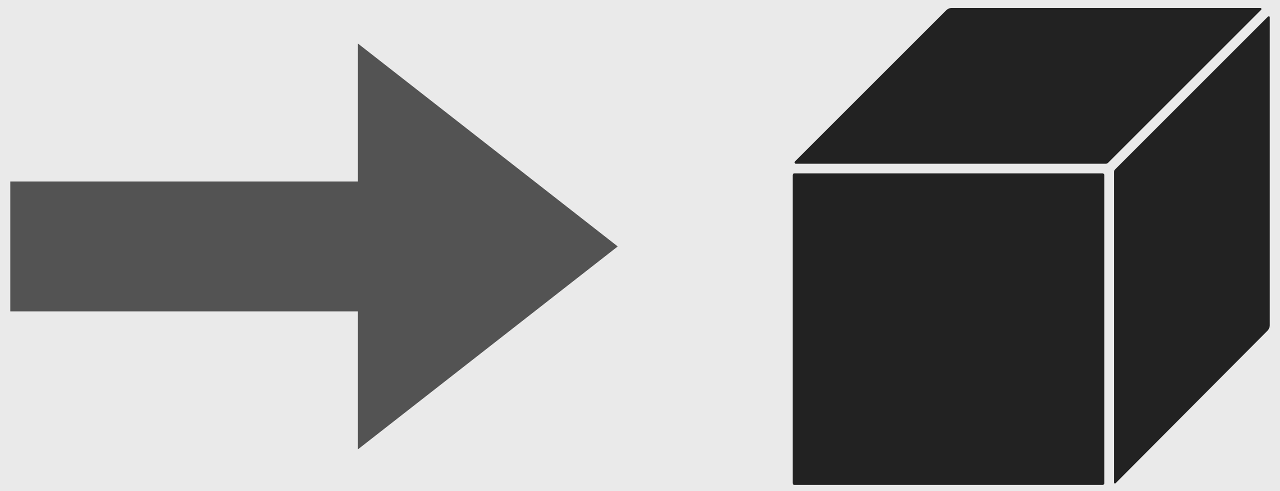


Option 2: Primary Production

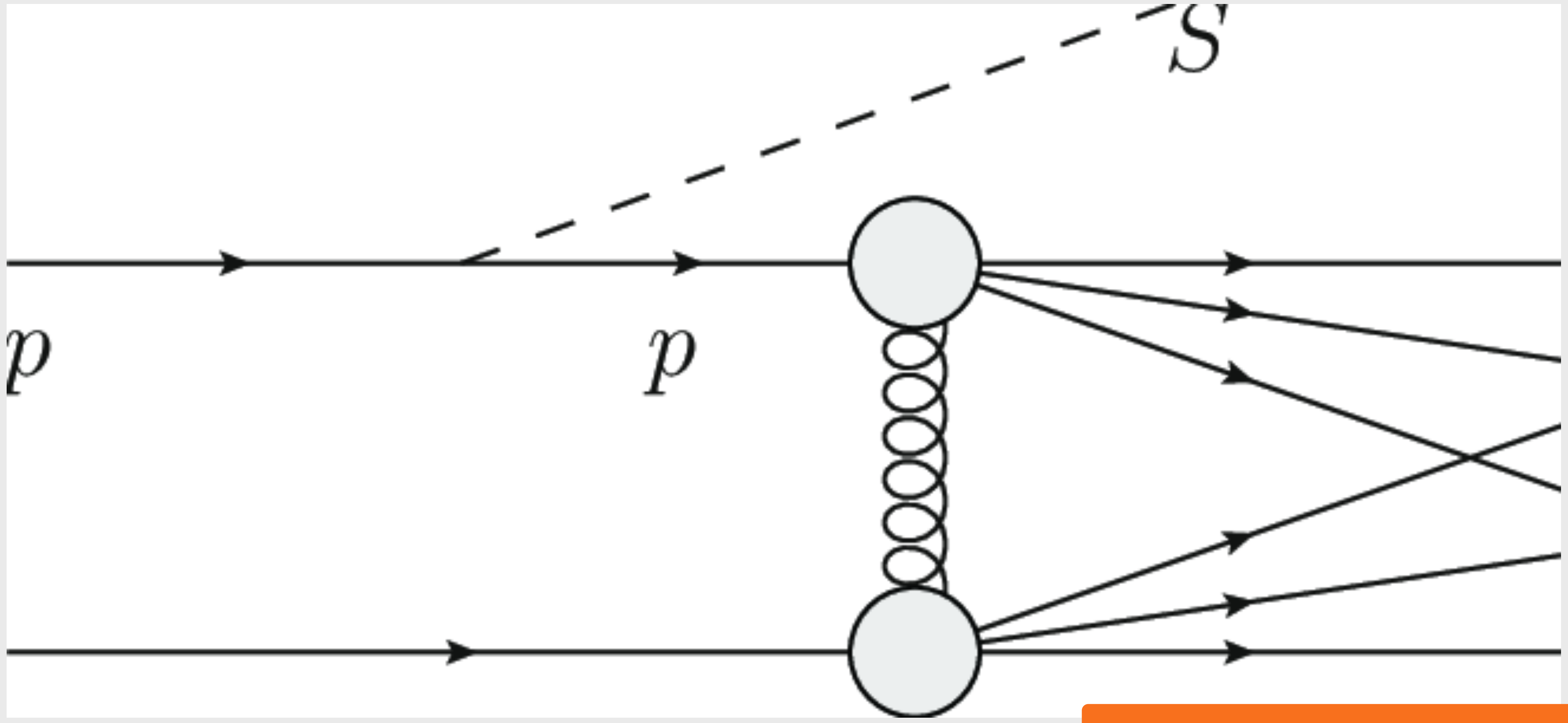
PROTON BREMMSTRAHLUNG

$$pp \to ppX$$

$\sim (10 - 100)$ GeV



protons



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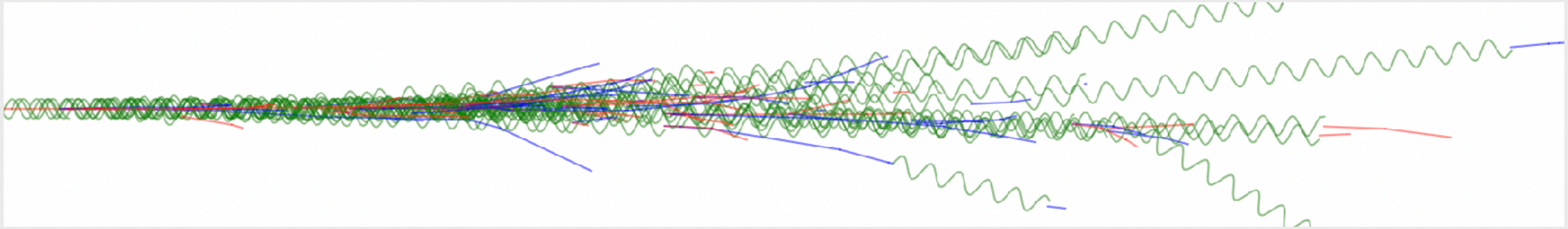
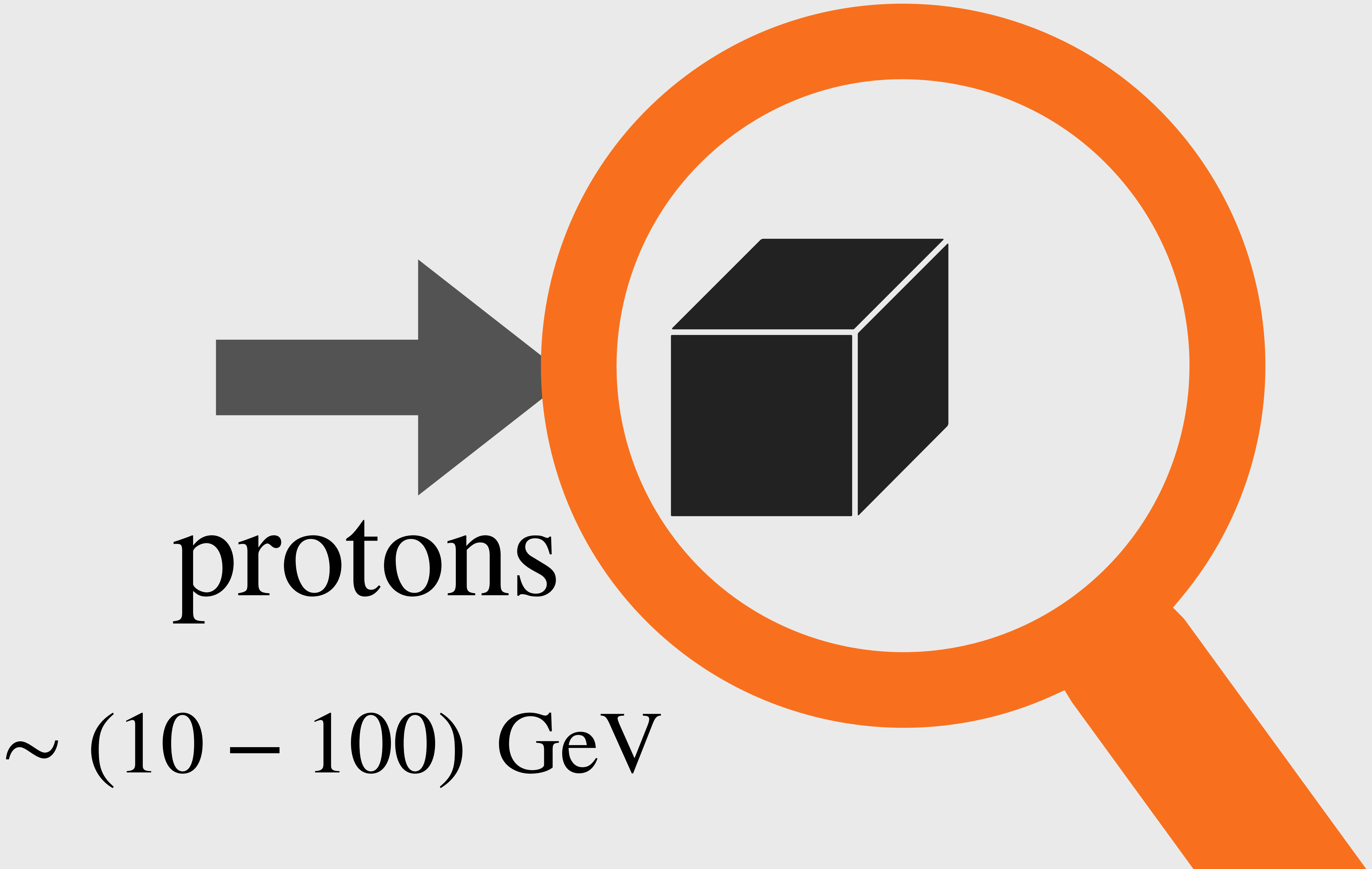
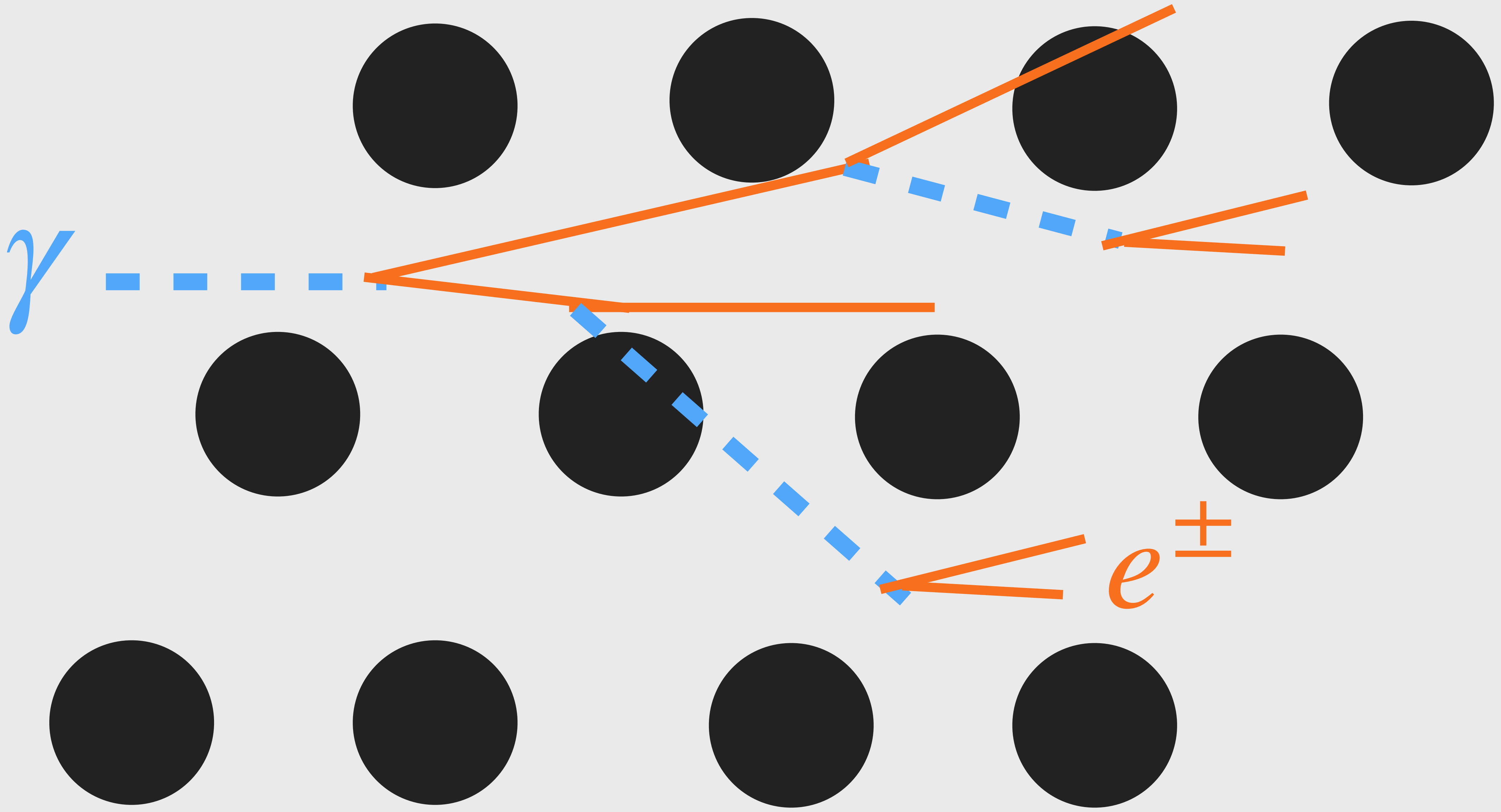
Option 3 : Secondary Production





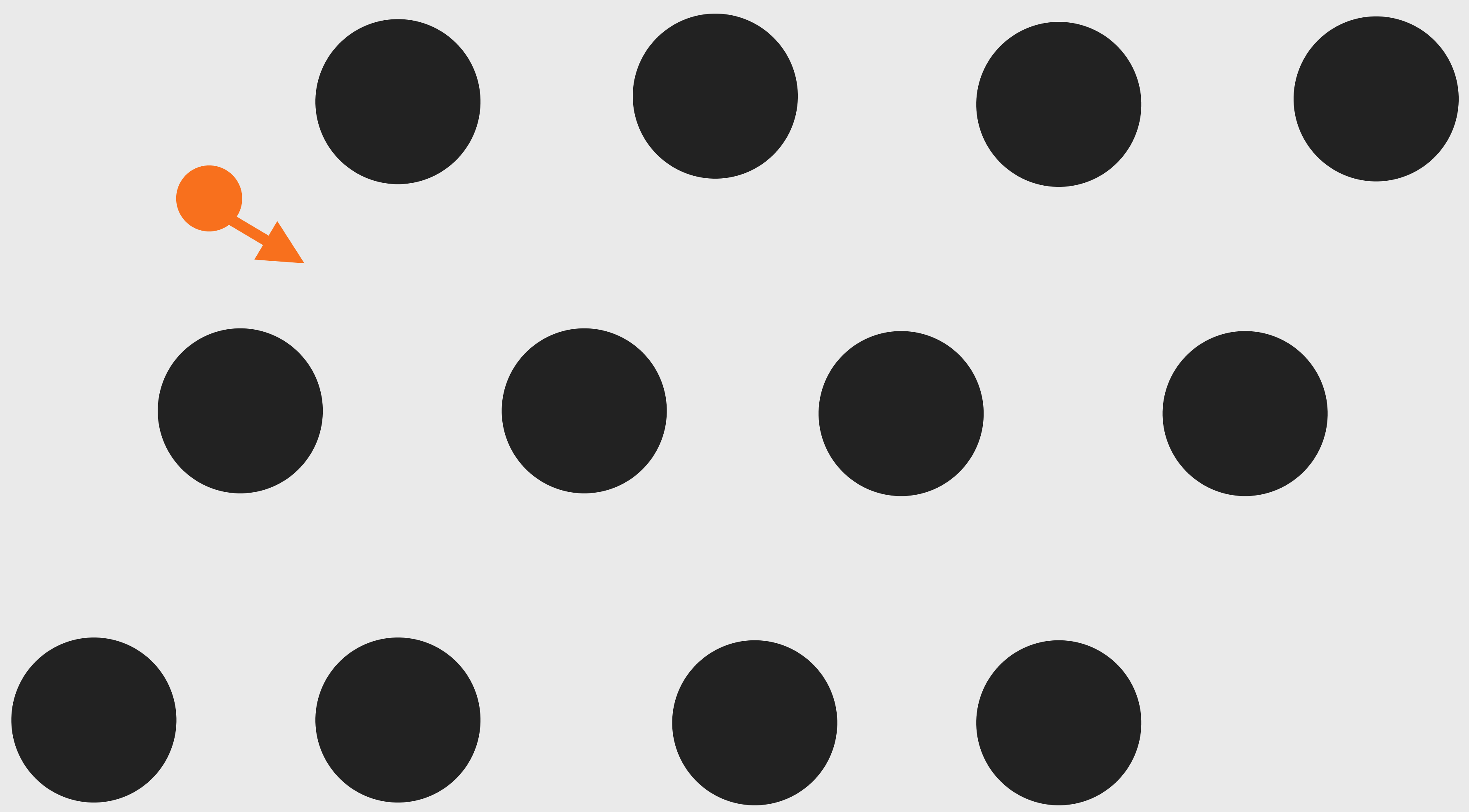


Electromagnetic Secondaries

Electrophilic Light New Physics

Hadronic And Electromagnetic Cascades

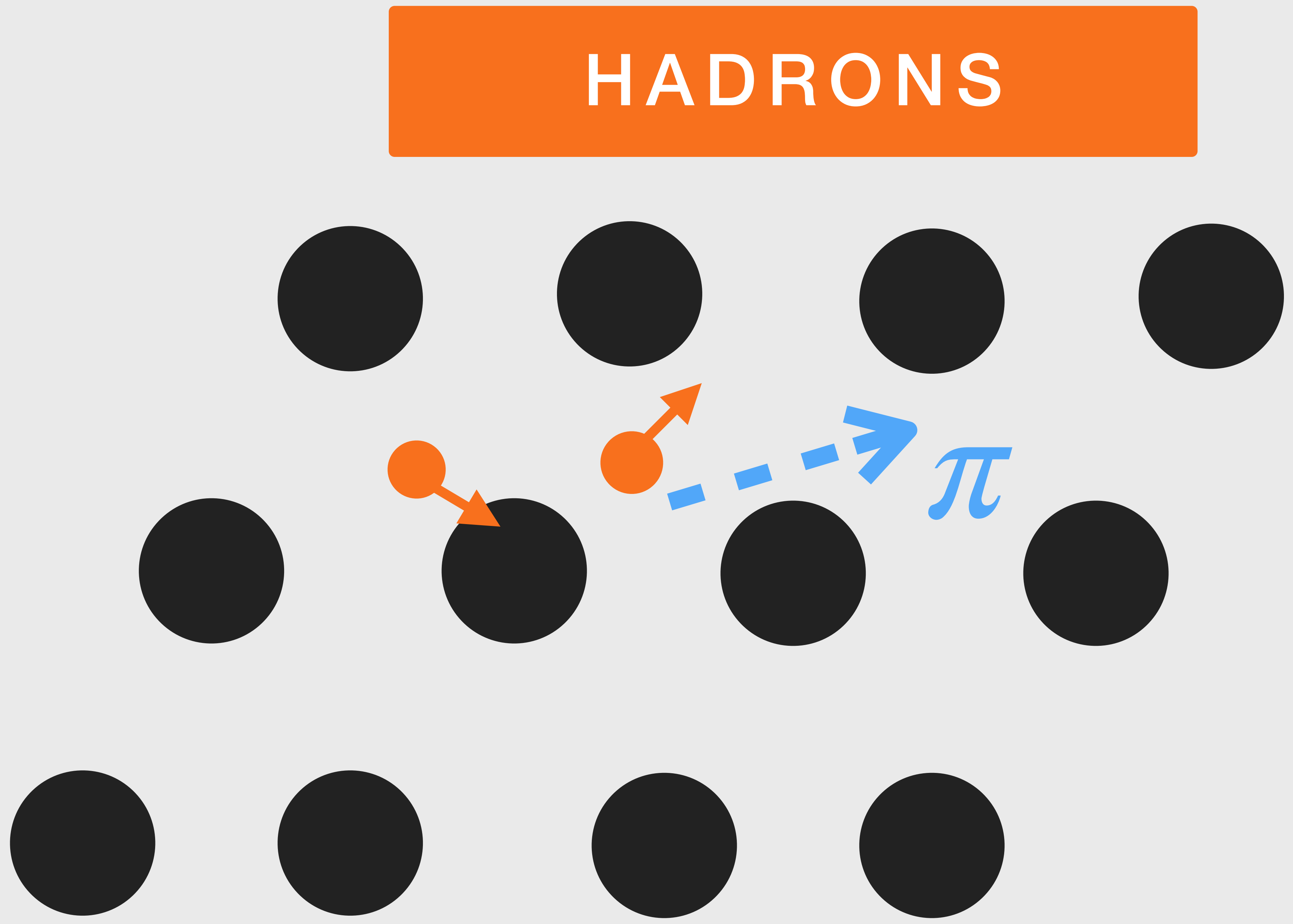
- Consider a particle propagating through medium



- Characteristic length between collisions λ_{MFP}

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium



- Hadrons "down convert" energy into pions.
- Every generation is a new chance to make a BSM particle.
- Multiplicity of interactions grows with energy.

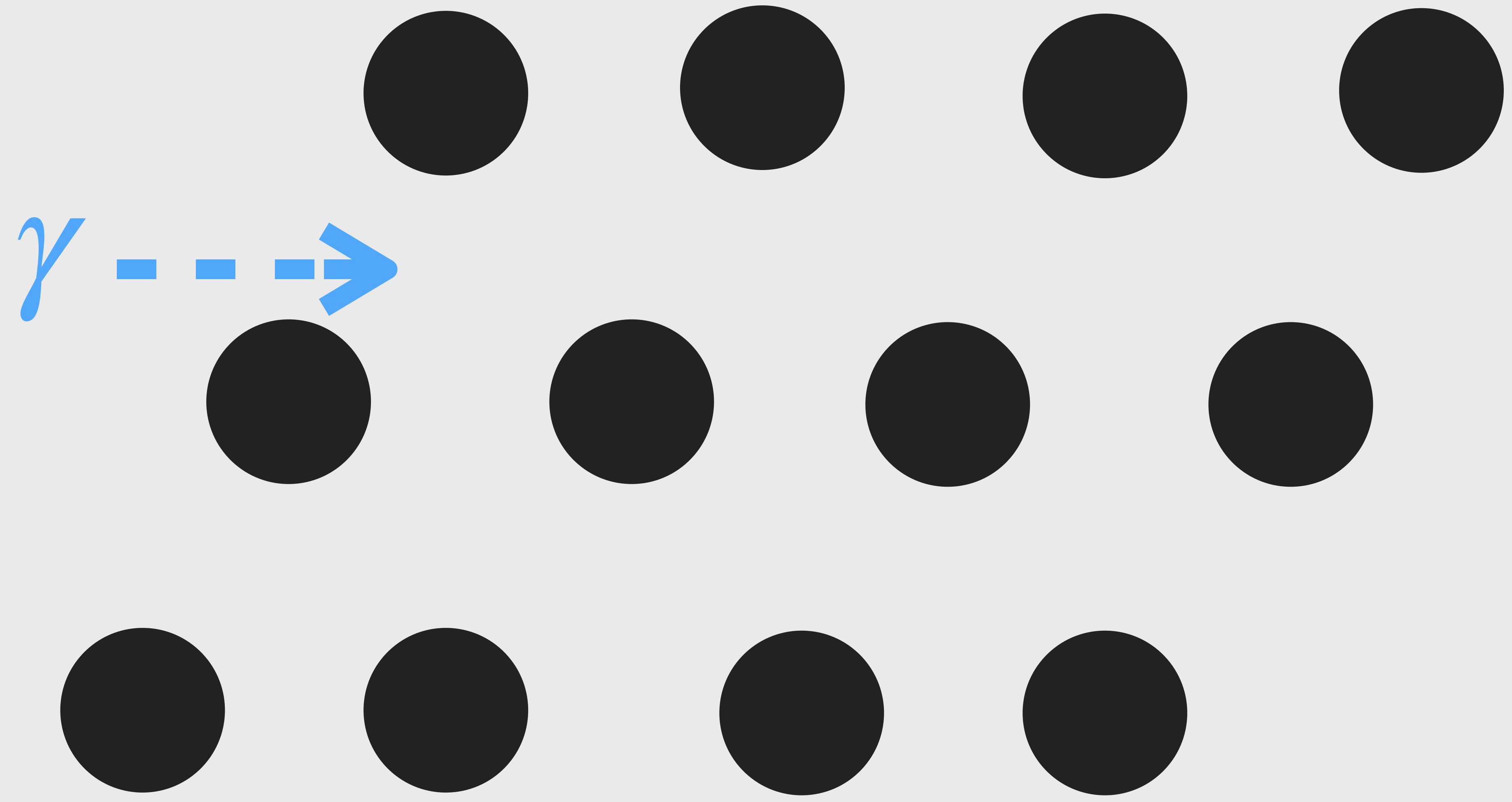
NEW RESOURCE BUT HARD TO STUDY SYSTEMATICALLY.

- Characteristic length between **hard** collisions X_H

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



- Main reactions are

$$\gamma Z \rightarrow e^+ e^- Z \quad e^\pm Z \rightarrow e^\pm \gamma Z$$

- Multiplicity of interactions grows with energy.

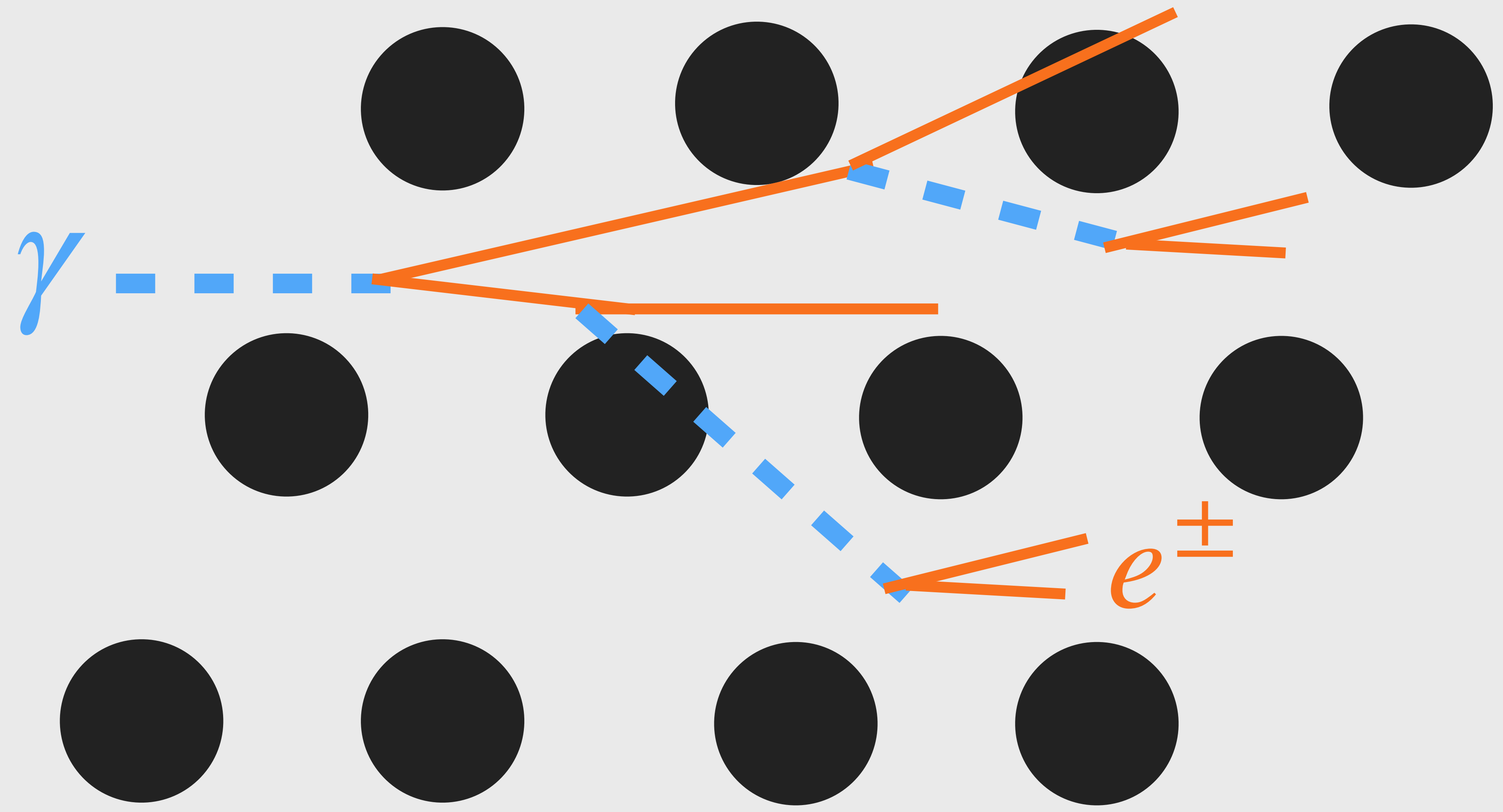
- Characteristic length between **hard** collisions X_0

- Radiation length

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



- Main reactions are

$$\gamma Z \to e^{+}e^{-}Z \quad e^{\pm}Z \to e^{\pm}\gamma Z$$

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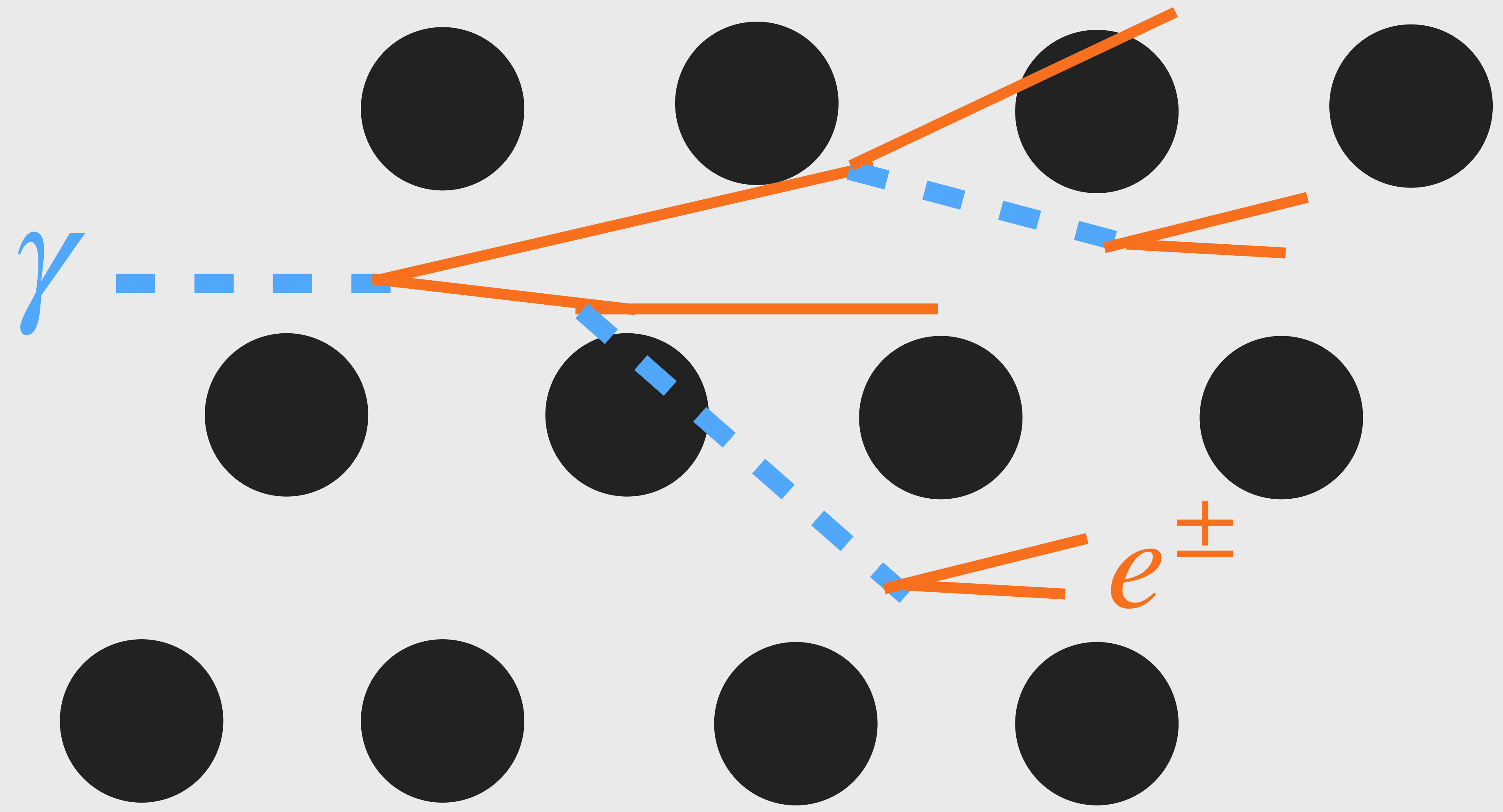
NEW RESOURCE FOR DARK SECTORS.
CAN BE COMPUTED PERTURBATIVELY.

- Characteristic length between **hard** collisions X_0
  - Radiation length

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



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NEW RESOURCE FOR DARK SECTORS.
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Previous Work On EM Secondaries

PHYSICAL REVIEW LETTERS **121**, 041802 (2018)

1807.05884

Novel Way to Search for Light Dark Matter in Lepton Beam-Dump Experiments

L. Marsicano,[1,2] M. Battaglieri,[1] M. Bondí,[3] C. D. R. Carvajal,[4] A. Celentano,[1] M. De Napoli,[3] R. De Vita,[1] E. Nardi,[5] M. Raggi,[6] and P. Valente[7]

PHYSICAL REVIEW D **102**, 075026 (2020)

2006.09419

New production channels for light dark matter in hadronic showers

A. Celentano,[1] L. Darmé,[2] L. Marsicano,[1] and E. Nardi[2]

PHYSICAL REVIEW D **98**, 015031 (2018)

1802.03794

Dark photon production through positron annihilation in beam-dump experiments

L. Marsicano,[1,2] M. Battaglieri,[1] M. Bondí,[3] C. D. R. Carvajal,[4] A. Celentano,[1] M. De Napoli,[3] R. De Vita,[1] E. Nardi,[5] M. Raggi,[6] and P. Valente[7]

Event generation for beam dump experiments

Luca Buonocore,[a,b] Claudia Frugiuele,[c] Fabio Maltoni,[d,e] Olivier Mattelaer,[d] Francesco Tramontano[b]

1812.06771

2108.03262

PHYSICAL REVIEW D **104**, 115010 (2021)

Extending the reach of leptophilic boson searches at DUNE and MiniBooNE with bremsstrahlung and resonant production

Francesco Capozzi,[1] Bhaskar Dutta,[2] Gajendra Gurung,[3] Wooyoung Jang,[3] Ian M. Shoemaker,[1] Adrian Thompson,[2] and Jaehoon Yu[3]

Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments ☆,☆☆

2101.12192

M. Bondi[a], A. Celentano[a], R.R. Dusaev[b], D.V. Kirpichnikov[c], M.M. Kirsanov[c], N.V. Krasnikov[c,d], L. Marsicano[a], D. Shchukin[e]

Previous Work On Electromagnetic Cascades

PHYSICAL REVIEW LETTERS 121, 041802 (2018)

1807.05884

Event generation for beam dump experiments

- Despite multiple groups and a reasonable amount of activity, no systematic comparison between results has been made.
- Naive comparisons suggest large differences (orders of magnitude in some cases)
- Want a systematic analysis to resolve discrepancies.

L. Marsicano,[1,2] M. Battaglieri,[1] M. Bondí,[3] C. D. R. Carvajal,[4] A. Celentano,[1] M. De Napoli,[3] R. De Vita,[1] E. Nardi,[5] M. Raggi,[6] and P. Valente[7]

M. Bondi[a], A. Celentano[a], R.R. Dusaev[b], D.V. Kirpichnikov[c], M.M. Kirsanov[c], N.V. Krasnikov[c,d], L. Marsicano[a], D. Shchukin[e]

Previous Work On EM Secondaries

PHYSICAL REVIEW LETTERS 121, 041802 (2018)

1807.05884

Event generation for beam dump experiments

- Despite multiple groups and a reasonable amount of

Dark fluxes from electromagnetic cascades

2401.06843

Nikita Blinov,[1,2] Patrick J. Fox,[3] Kevin J. Kelly,[4,5] Pedro A.N. Machado,[3] Ryan Plestid[6]

- Want a systematic analysis to resolve discrepancies.

Da

in

92

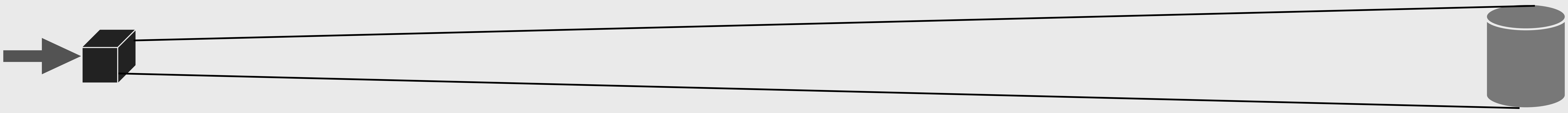
L. Marsicano,[1,2] M. Battaglieri,[1] M. Bondí,[3] C. D. R. Carvajal,[4] A. Celentano,[1] M. De Napoli,[3] R. De Vita,[1] E. Nardi,[5] M. Raggi,[6] and P. Valente[7]

M. Bondi [a], A. Celentano [a], R.R. Dusaev [b], D.V. Kirpichnikov [c], M.M. Kirsanov [c], N.V. Krasnikov [c,d], L. Marsicano [a], D. Shchukin [e]

Challenges With Far-Forward Detectors

SMALL ANGLES

$$\Phi(\theta, E) \quad \textbf{for} \quad \theta < \theta_c$$

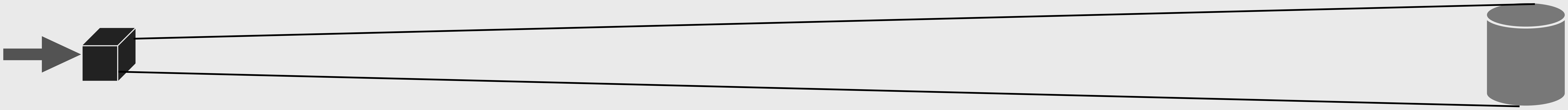


UNUSUALLY SENSITIVE TO ANGULAR SPREADING

Challenges With Far-Forward Detectors

LARGE HIERARCHY OF ENERGIES

$$E_{\text{beam}} \gg E_{\pi} \gg m_X \gg E_{\text{thr}}$$



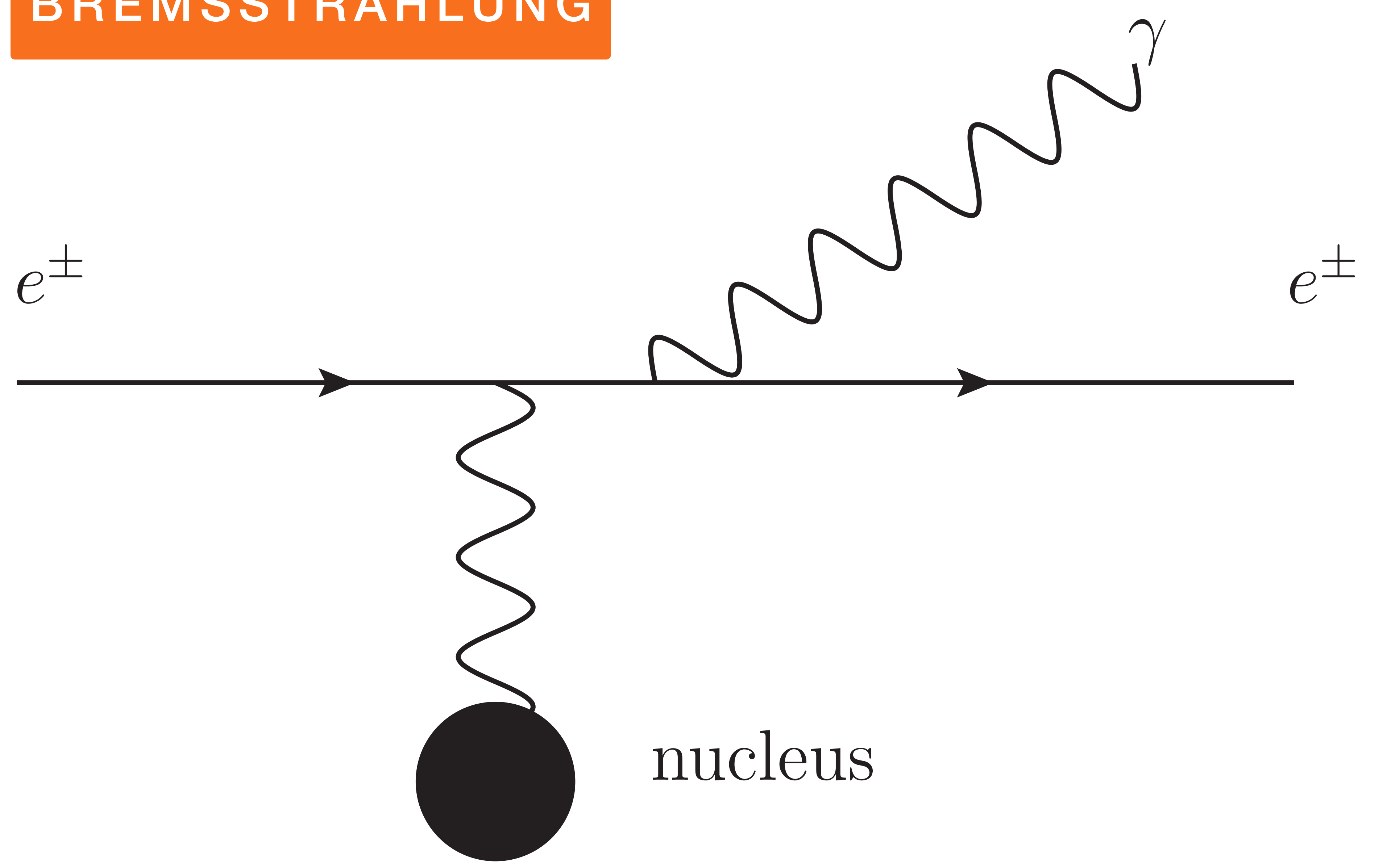
NEED TO WORRY ABOUT MANY GENERATIONS IN A SHOWER

Explicit Model: Dark Vector Boson

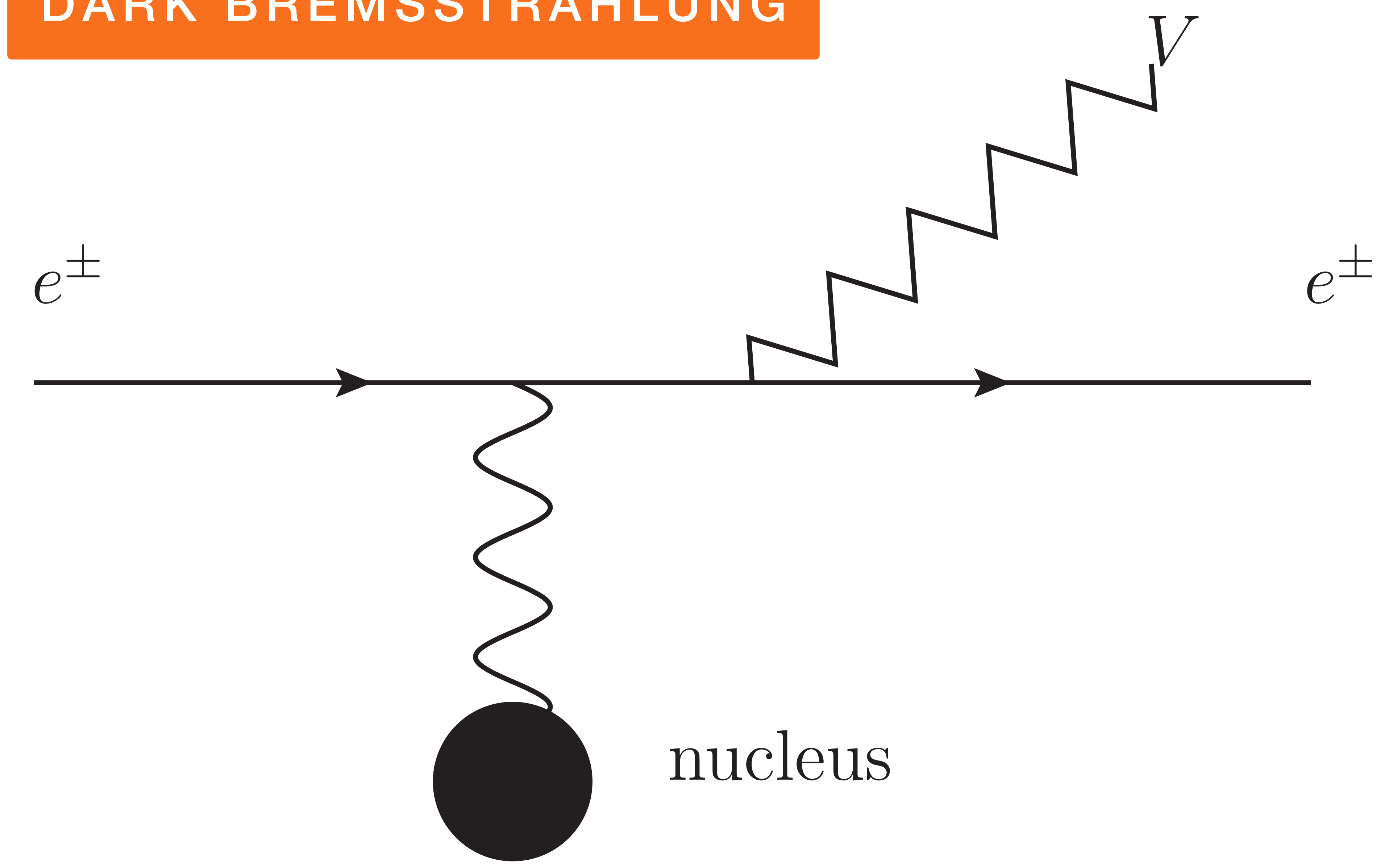
$$\mathscr{L} \supset g\bar{e}\gamma_\mu e V^\mu$$

- Vector boson of mass m_V couples to the electron vector current.

BREMSSTRAHLUNG



DARK BREMSSTRAHLUNG

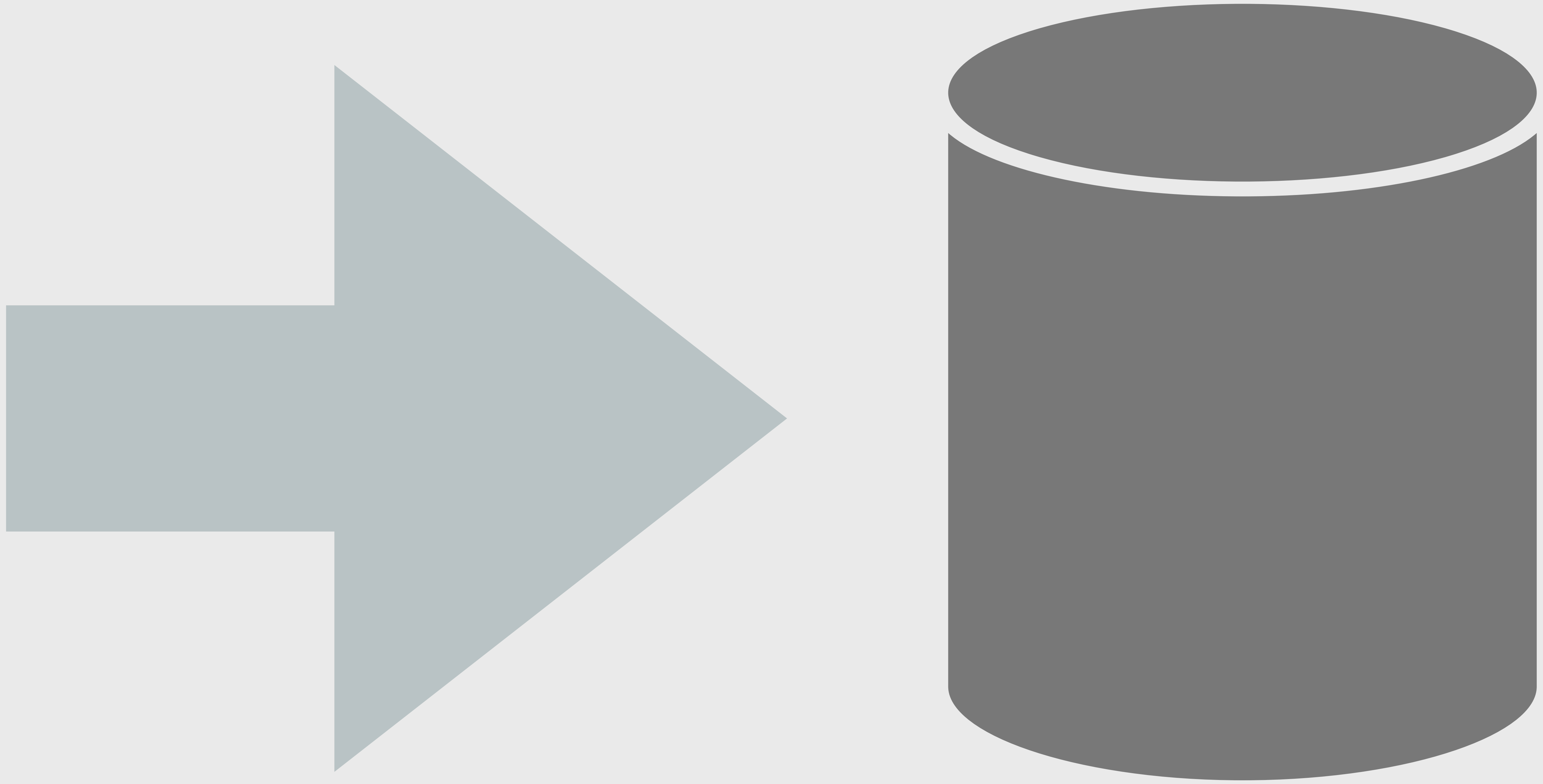


Explicit Model: Dark Vector Boson

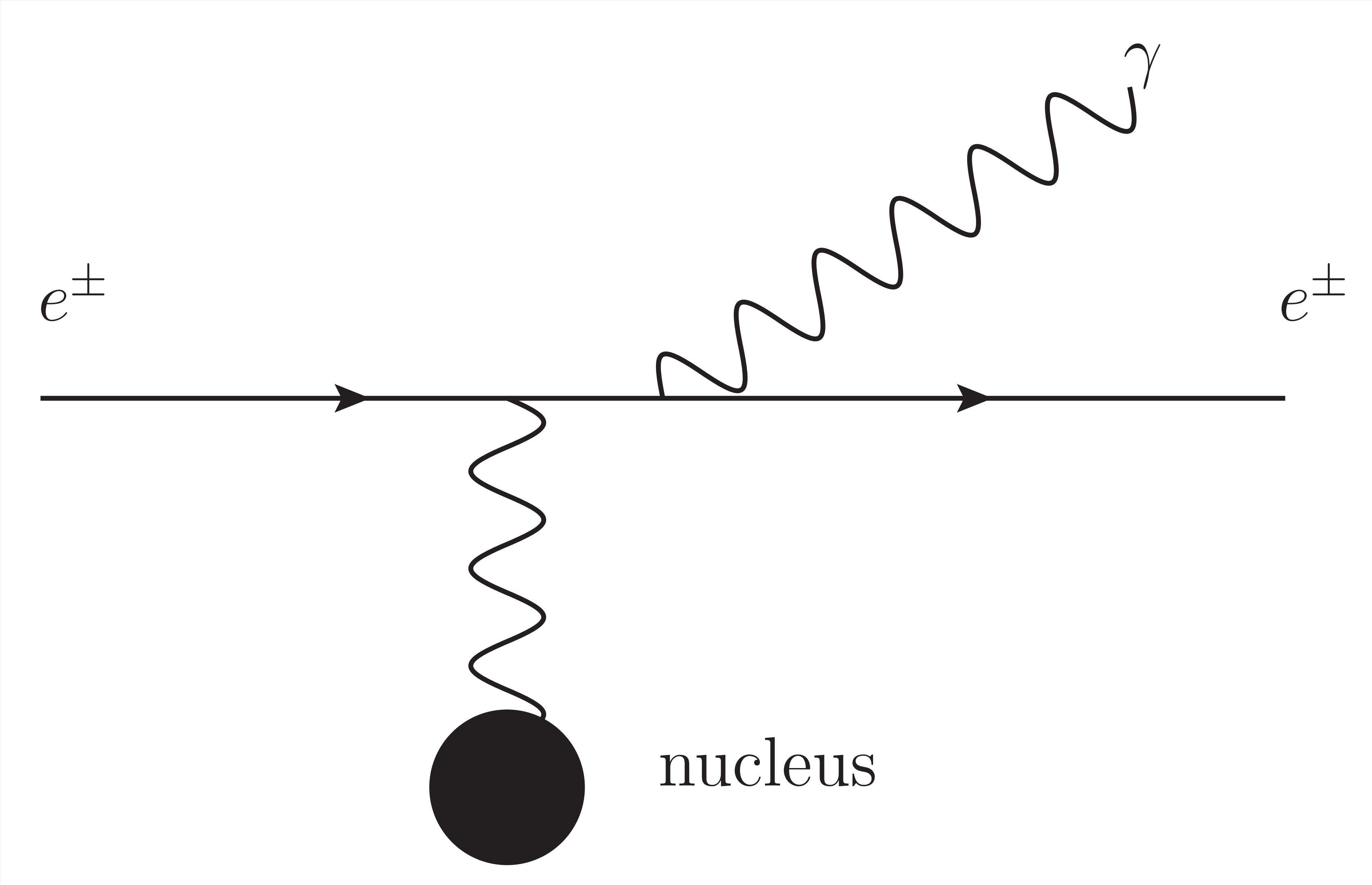
$$\mathcal{L} \supset g\bar{e}\gamma_\mu e V^\mu$$

- Our goal is to compute the flux from an EM cascade at the detector.

$$\Phi_{\mathrm{det}}(E_V)$$

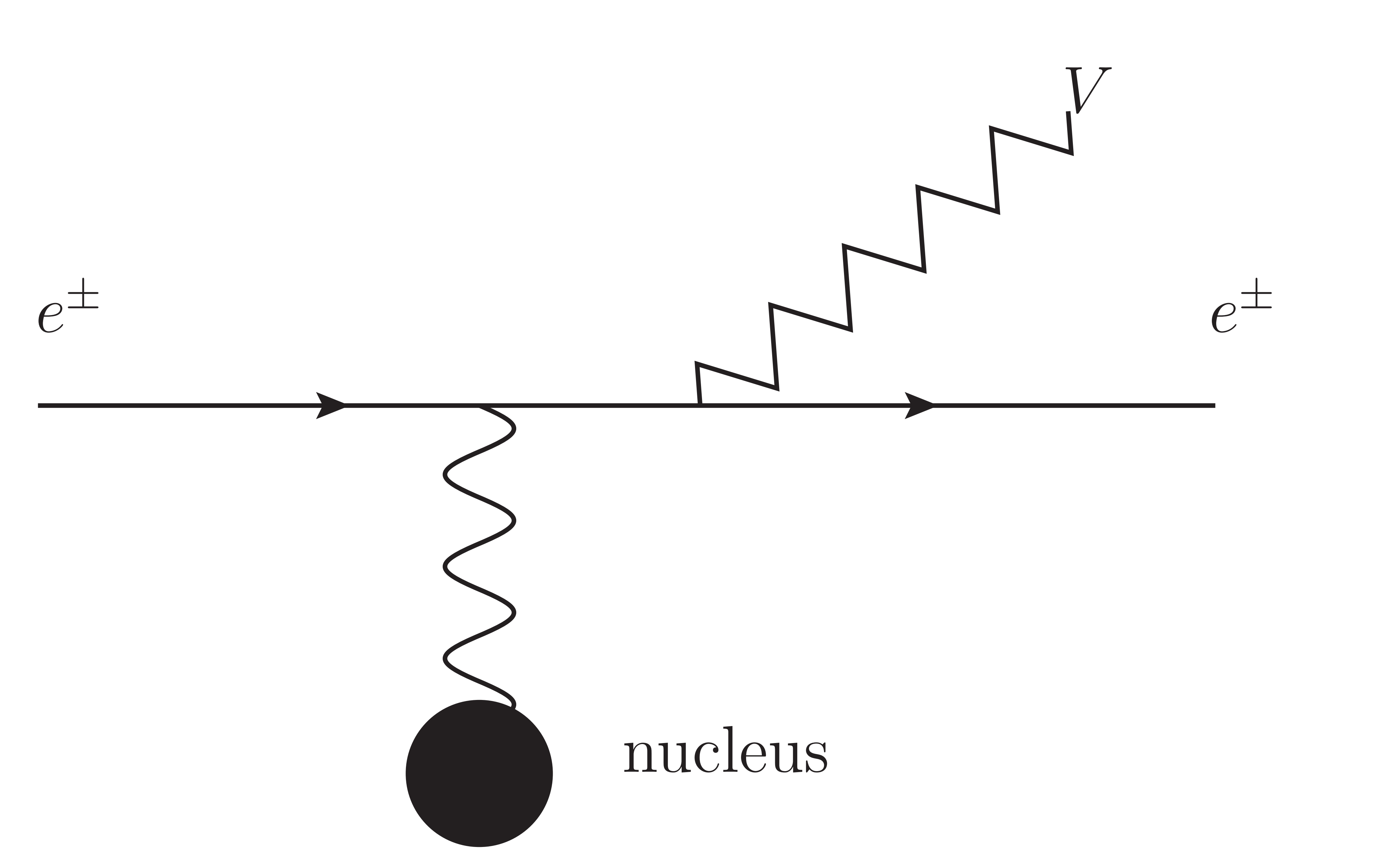


SM Event → BSM Event



- Consider an event in a MC event record.

$$(\mathbf{p},\mathbf{x})_e \rightarrow (\mathbf{p}',\mathbf{x})_e + (\mathbf{q}',\mathbf{x})_\gamma$$



- How do we use this to generate BSM event?

$$(\mathbf{p},\mathbf{x})_e \rightarrow (\mathbf{p}',\mathbf{x})_e + (\mathbf{q}',\mathbf{x})_V$$

SM Event → BSM Event

$$(\mathbf{p}, \mathbf{x})_e \to (\mathbf{p}', \mathbf{x})_e + (\mathbf{q}', \mathbf{x})_\gamma$$

FOCUS ON PARENT

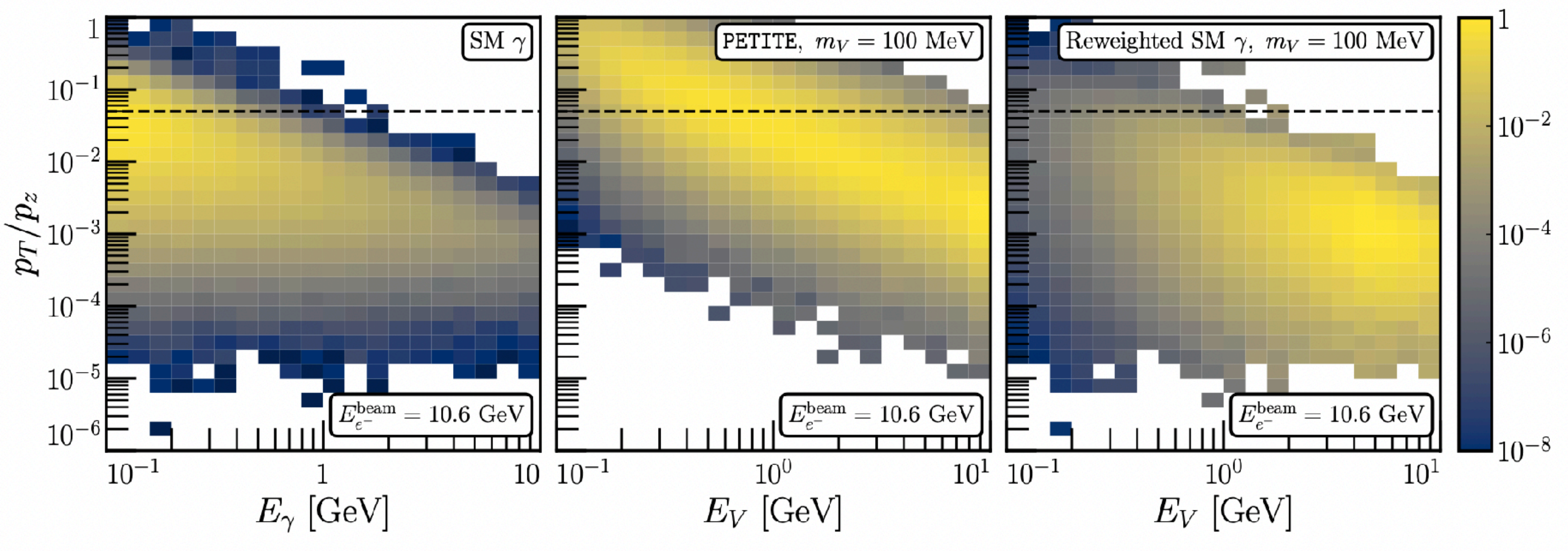
DRAW KINEMATICS FROM BSM DIST.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi} = (2\pi)^4 \delta^{(4)}(\Sigma P) \, |\mathcal{M}_{e\to eV}|^2$$

COMPUTE BRANCHING RATIO

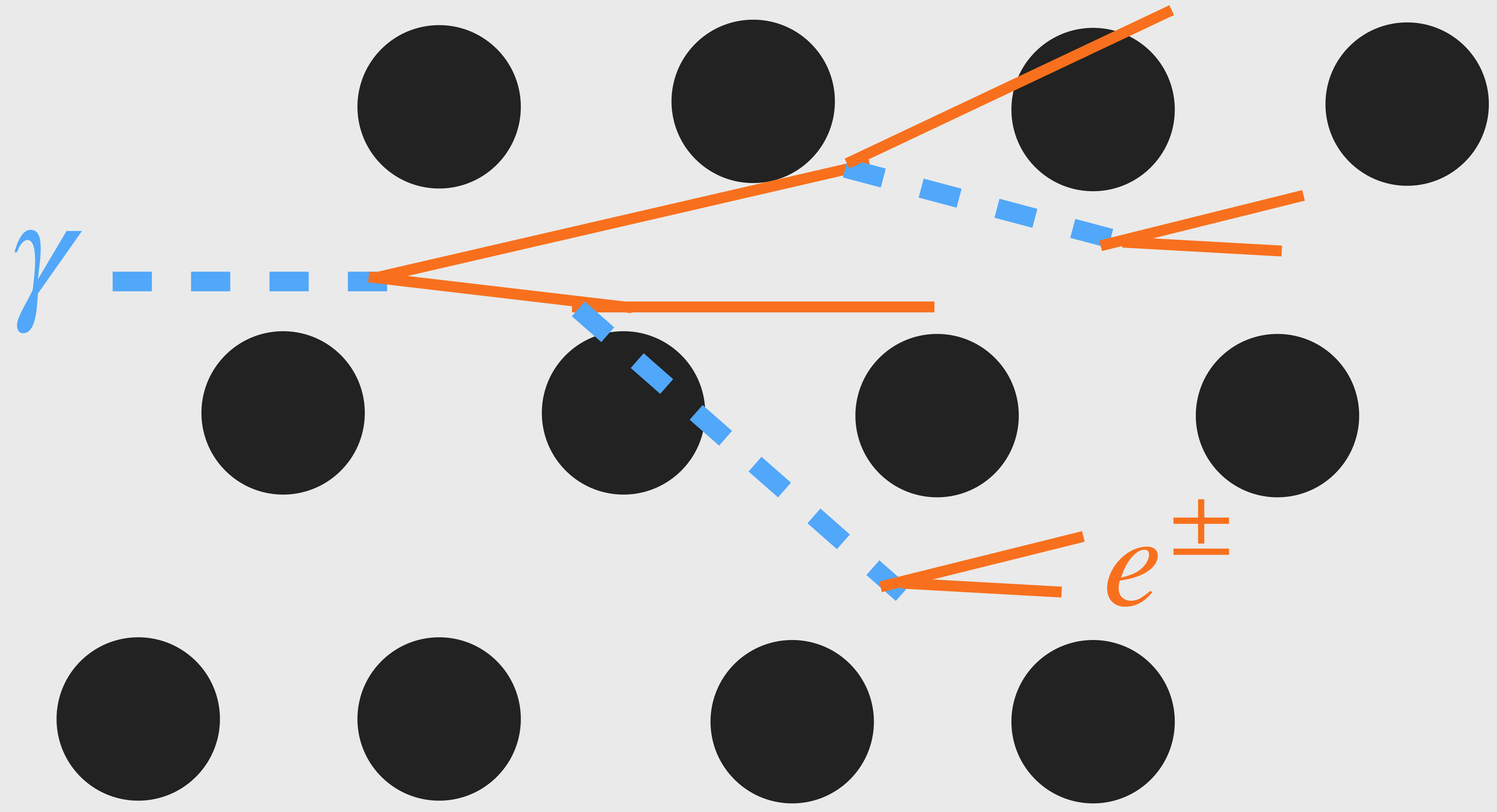
$$\mathrm{BR} = \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{tot}}} \approx \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{SM}}}$$

What Not To Do



- Trying to turn daughter photons into daughter dark photons is dangerous because of different distributions.

PETITE In A Nutshell



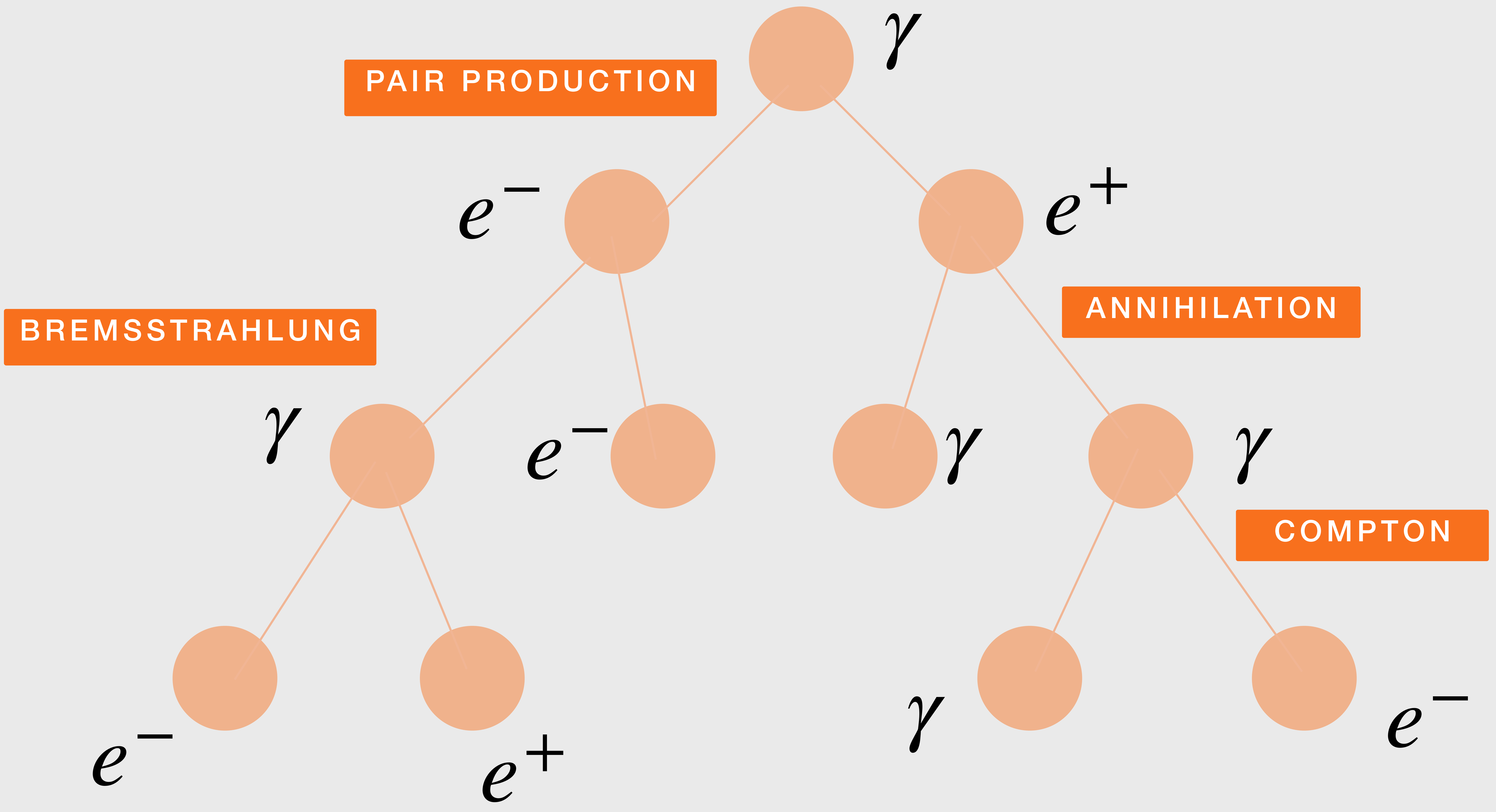
- Static nuclear centres source Coulomb fields.
- Electrons treated as a homogeneous gas of electrons at rest.
- Atomic screening included for bremsstrahlung and pair production.

PROCESSES INCLUDED

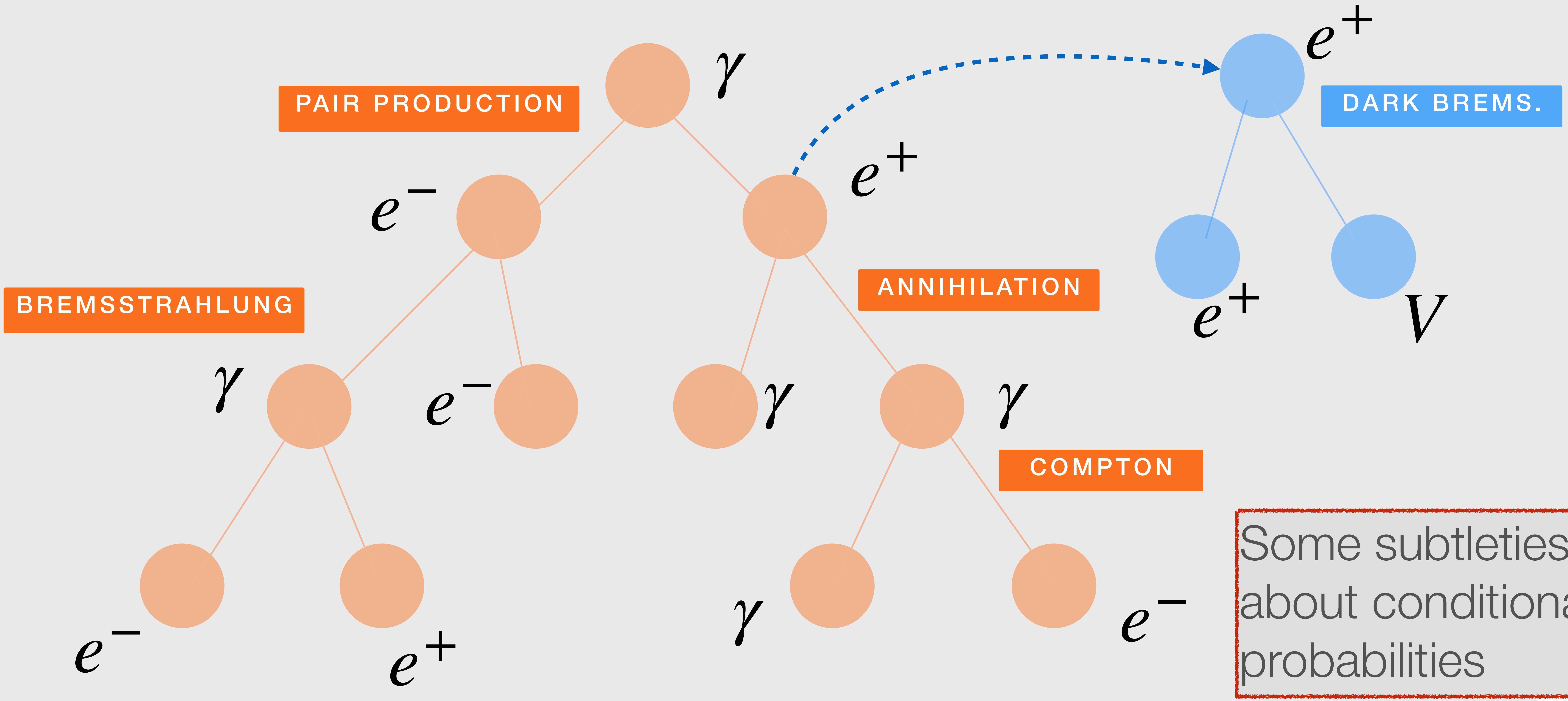
- $e^{\pm}Z \to e^{\pm}\gamma Z$
- $\gamma Z \to e^{+}e^{-}Z$
- $e^{\pm}e^{-} \to e^{\pm}e^{-}$
- $\gamma e \to \gamma e$
- $e^{+}e^{-} \to \gamma\gamma$

Continuous energy loss
&
Multiple Coulomb scattering.

SM Event Record → BSM Event Record



SM Event Record → BSM Event Record



Some subtleties about conditional probabilities

Implemented In PETITE

README

PETITE

PETITE: Package for Electromagnetic Transitions In Thick-target Environments Monte Carlo generator for production of dark sector objects in thick-target experiments PETITE generates electromagnetic showers for incoming electron, positron or photon propagating through a dense medium, and includes the possibility of dark sector particle production.

Installation

To install, from the top directory run

> pip install .

Dependencies

PETITE, its tutorials and tools require the following packages: numpy 1.24, vegas (>= 5.4.2), cProfile, pickle, matplotlib, scipy, datetime, tqdm, copy, sys, random and functools. Using `pip install .` should install all requirements, but if needed, you can manually install these packages with

> pip install <package_name>==<version_required>

HTTPS://GITHUB.COM/KJKELLYPHYS/PETITE

Join A Growing Community!

HTTPS://GITHUB.COM/KJKELLYPHYS/PETITE

The Lifetime Frontier

Lower Energies And Shorter Lifetimes

Particle Multiplicity

Lifetimes & Production Spectra

- Secondary, tertiary, etc. particles have ***<u>lower energies.</u>***
- This means they have decay faster in the lab frame

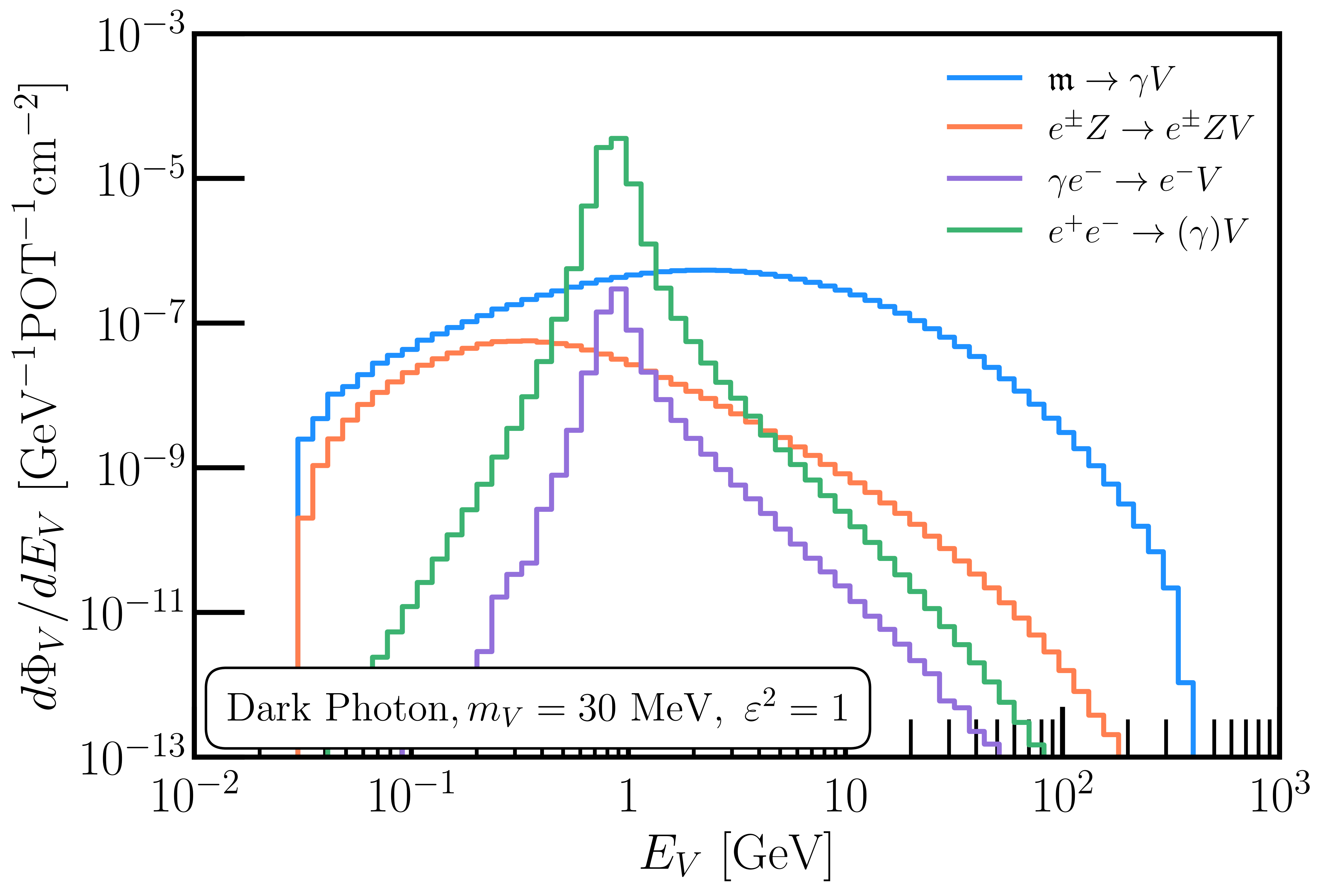
$$\lambda = c\beta\gamma\tau \propto E_V$$

- In the long-lifetime limit the probability of decay goes like

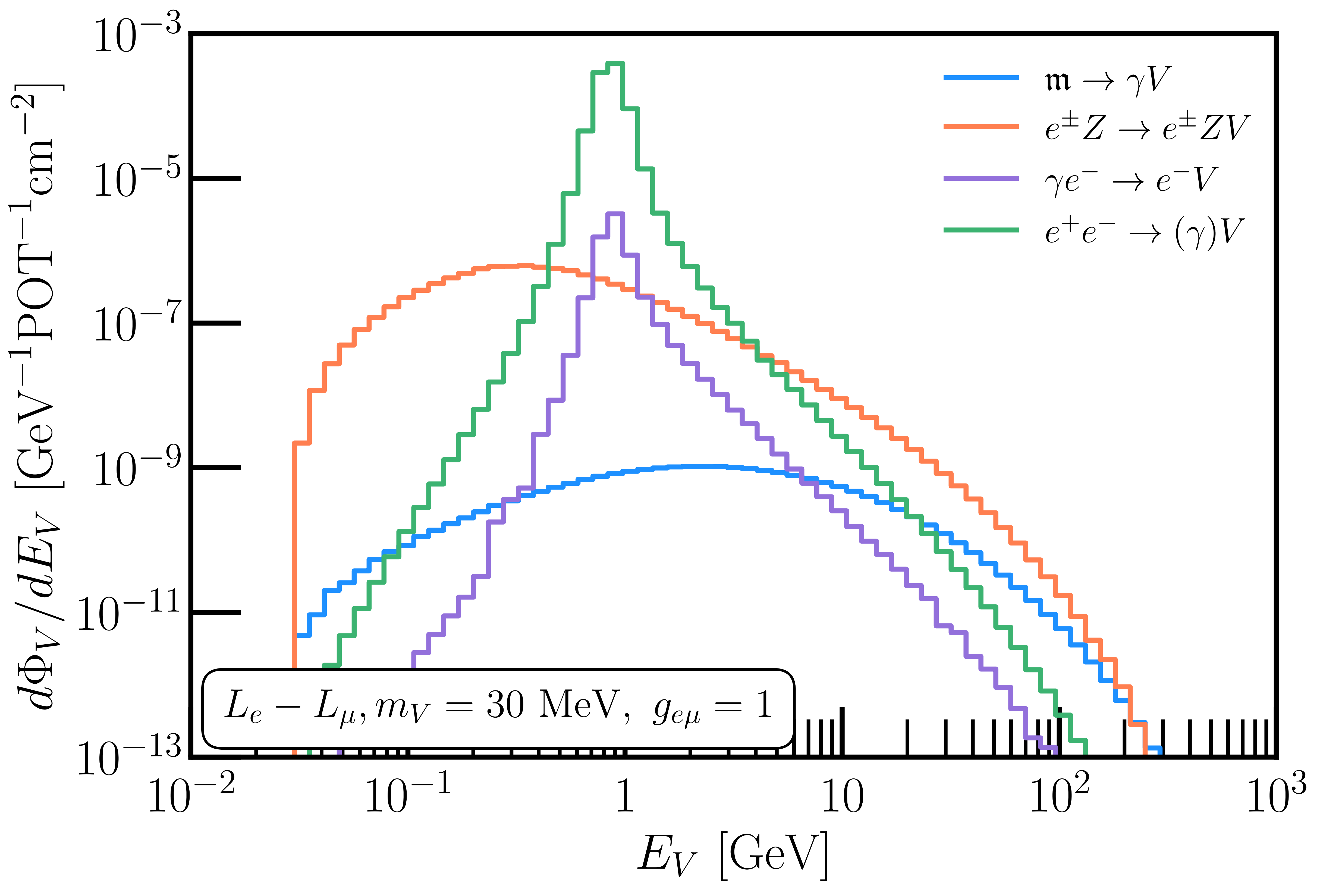
$$P_{\text{decay}} \simeq \frac{L_{\text{pipe}}}{\lambda}$$

Lifetimes & Production Spectra

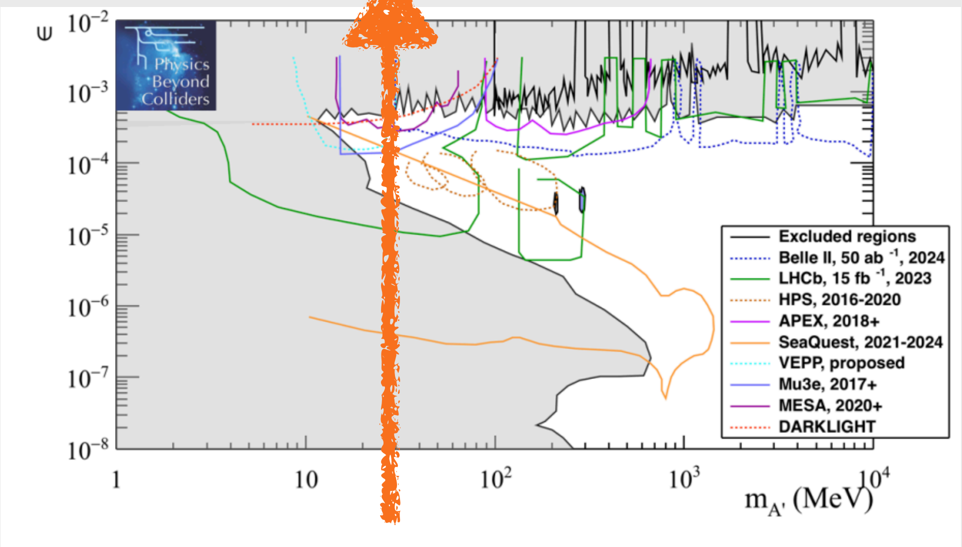
DARK PHOTON

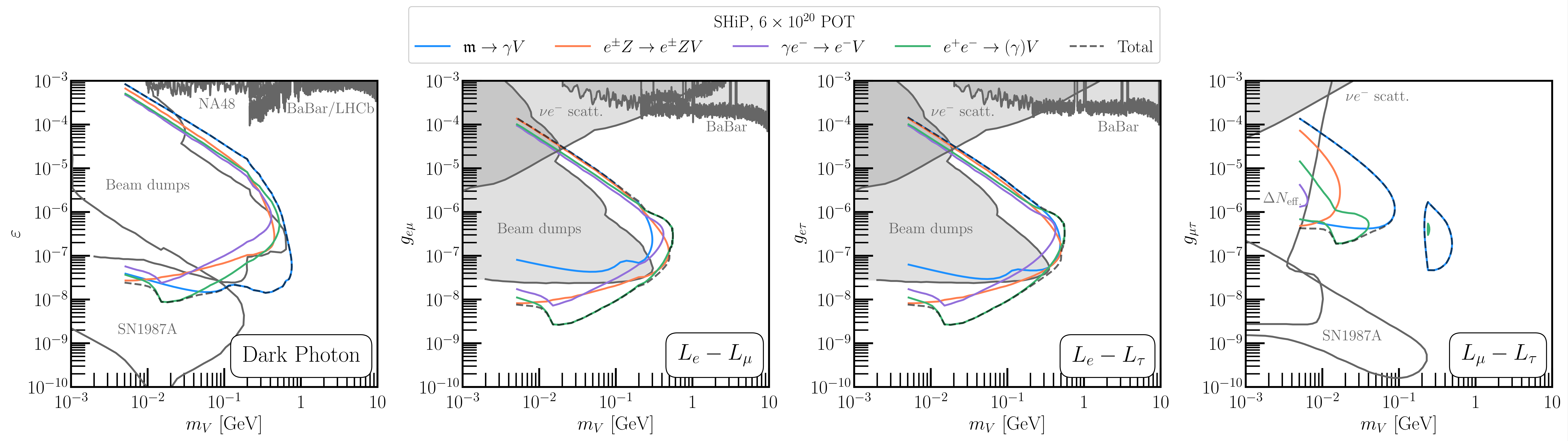


ELECTROPHILLIC



Impact For LLP Searches





Application To SHiP

Enhancements At The Lifetime Frontier

Quick Intro To SHiP

PROTON BEAM

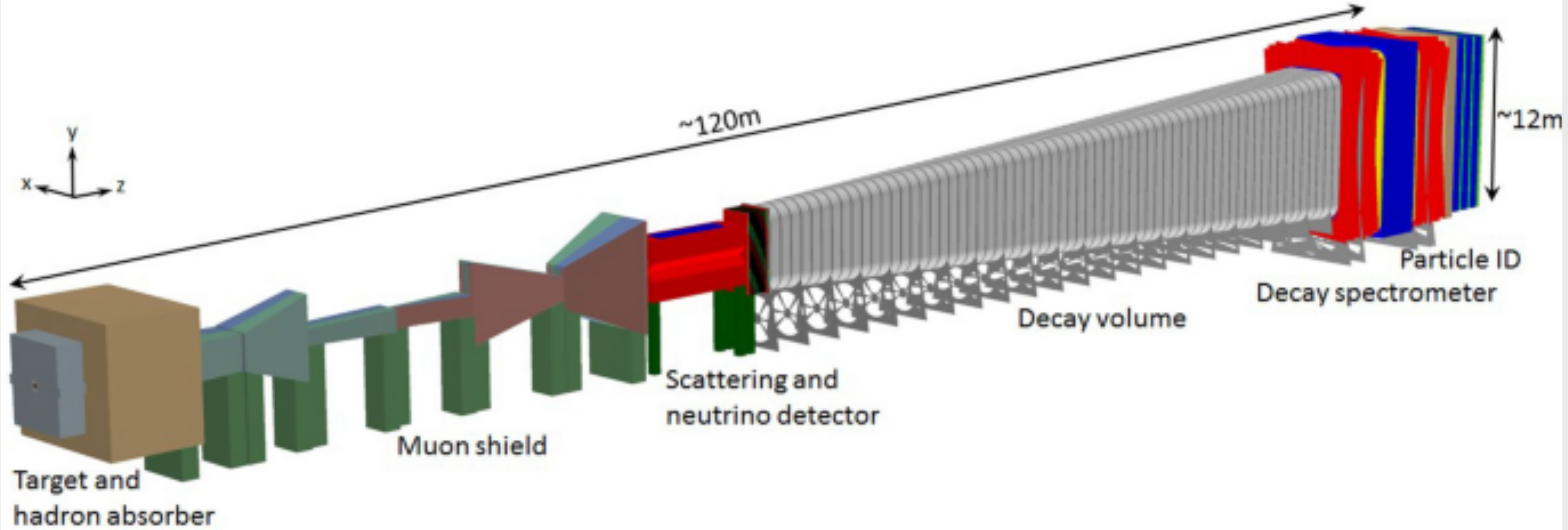
$$400 \text{ GeV}$$

PROTONS ON TARGET

$$6 \times 10^{20}$$

DECAY PIPE

$$\sim 30 - 80 \text{ m}$$



- Uses SPS beam at CERN.
- Excellent sensitivity to long-lived particles.
- Also has a scattering detector and tau-neutrino program.

Dark Vector Production In A Proton Beam Dump

PRIMARY MESONS

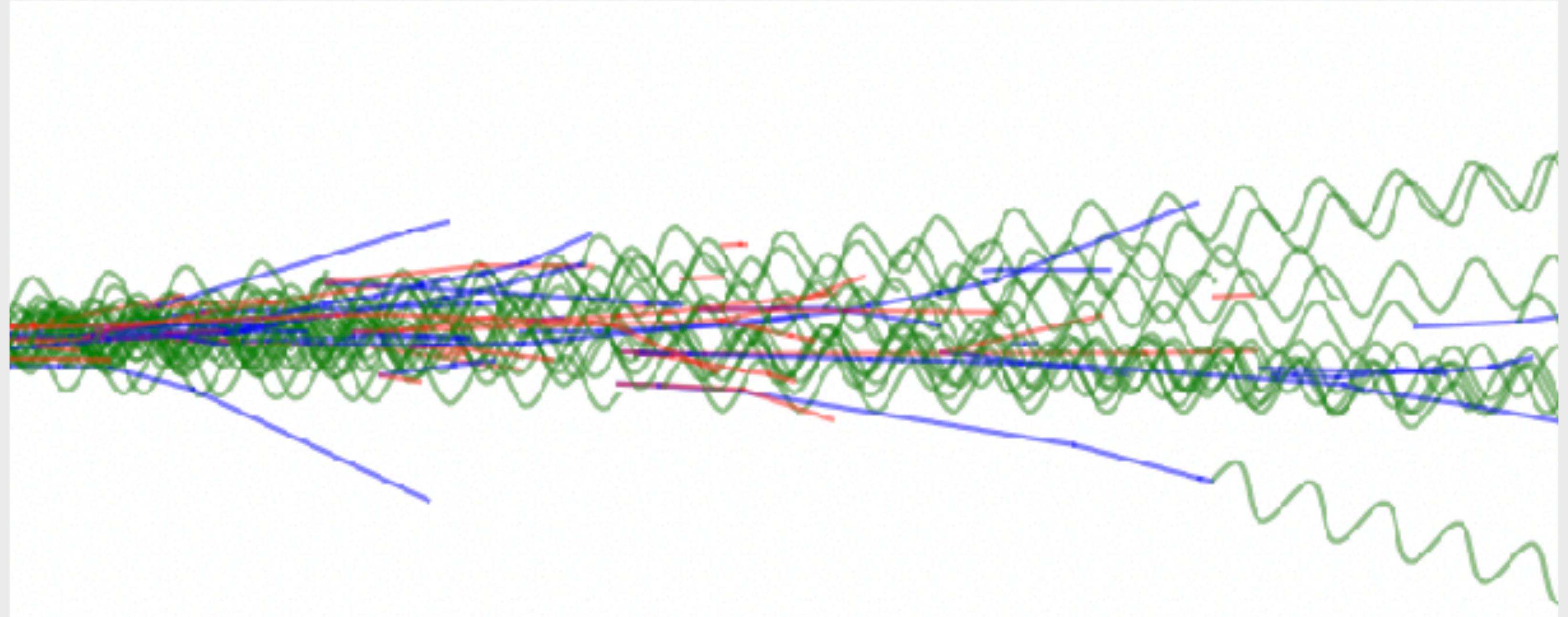
$$\pi^0 \rightarrow \gamma V$$
$$\eta \rightarrow \gamma V$$

PROTON BREMS.

$$pA \rightarrow pAV$$

PERTURBATIVE QCD

$$q\bar{q} \rightarrow V$$



CASCADE PRODUCTION

$$e^+e^- \rightarrow V(\gamma)$$
$$Ze^\pm \rightarrow Ze^\pm V$$
$$\gamma e^- \rightarrow e^- V$$

Dark Vector Production In A Proton Beam Dump

PRIMARY MESONS

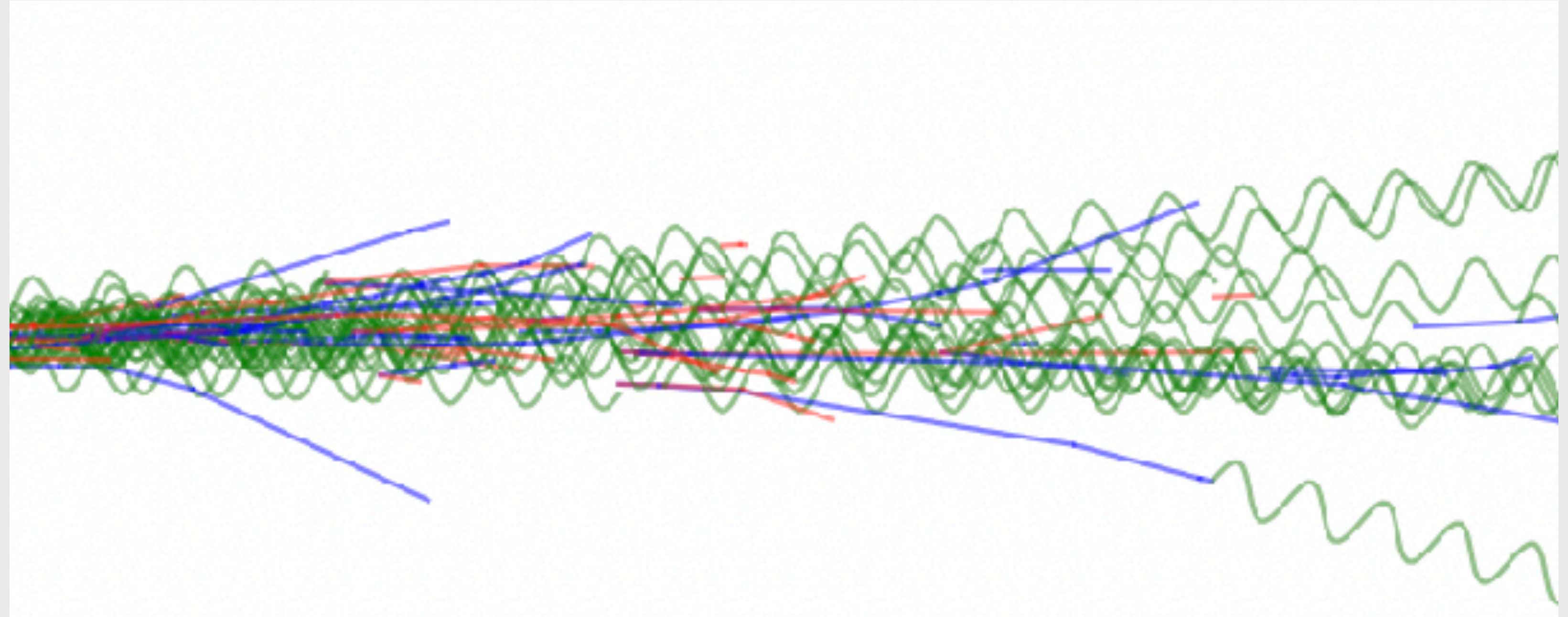
$$\pi^0 \to \gamma V$$
$$\eta \to \gamma V$$

PROTON BREMS.

$$pA \to pAV$$

PERTURBATIVE QCD

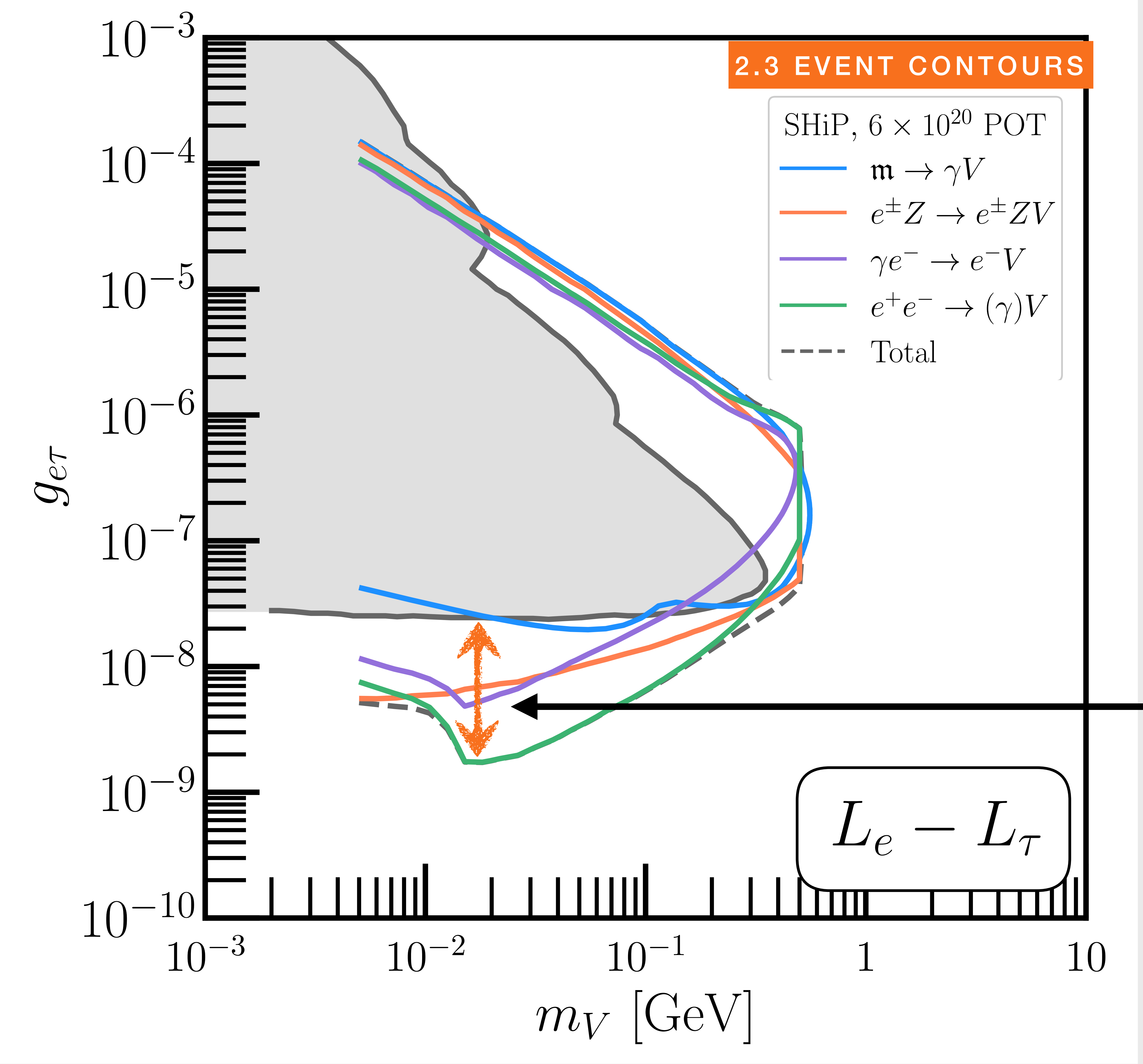
$$q\bar{q} \to V$$



CASCADE PRODUCTION

$$e^+e^- \to V(\gamma)$$
$$Ze^\pm \to Ze^\pm V$$
$$\gamma e^- \to e^- V$$

Gains In Sensitivity



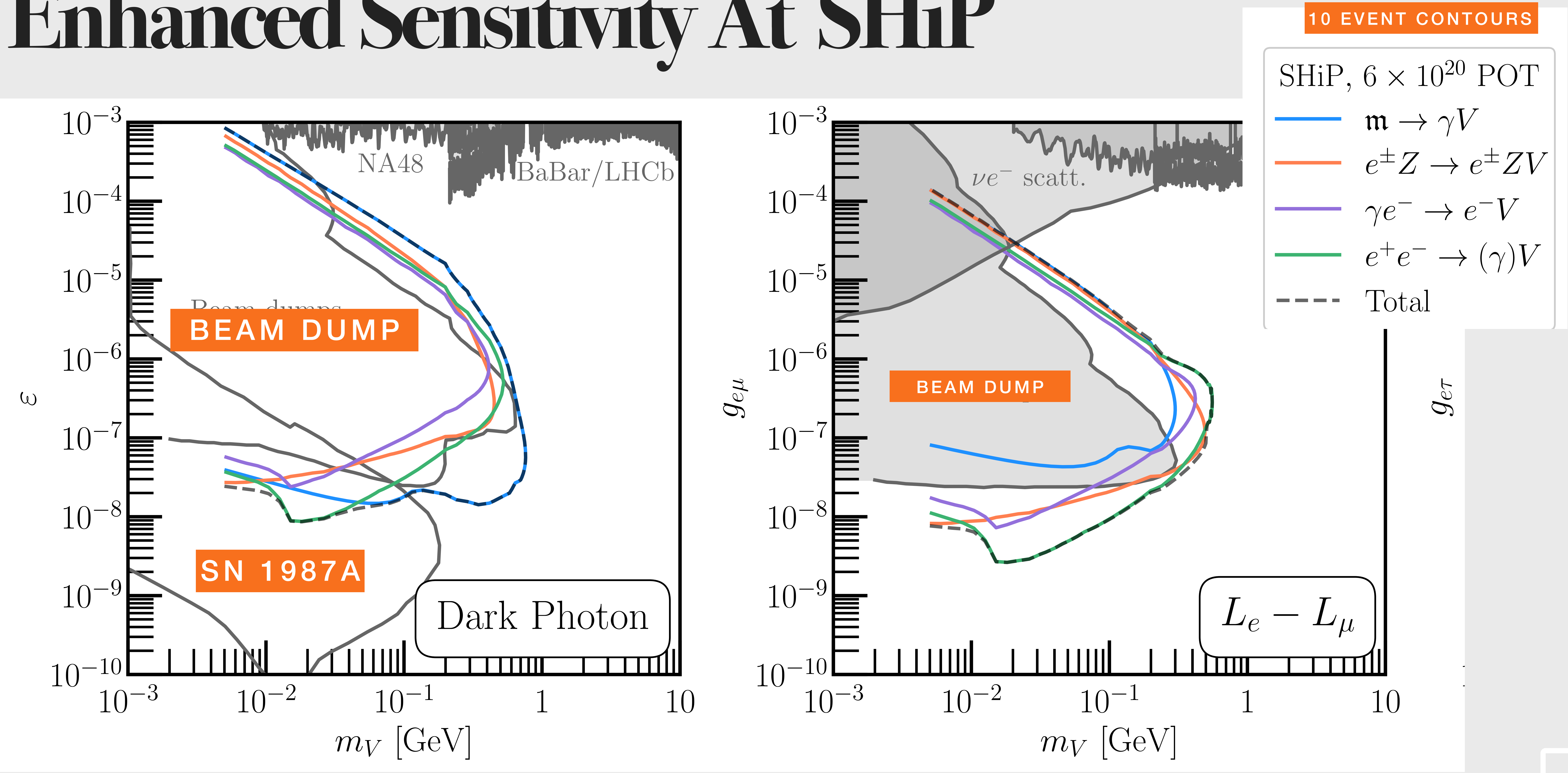
Huge Shift In Flux

~ FACTOR OF 10 IN $g_{e\tau}$

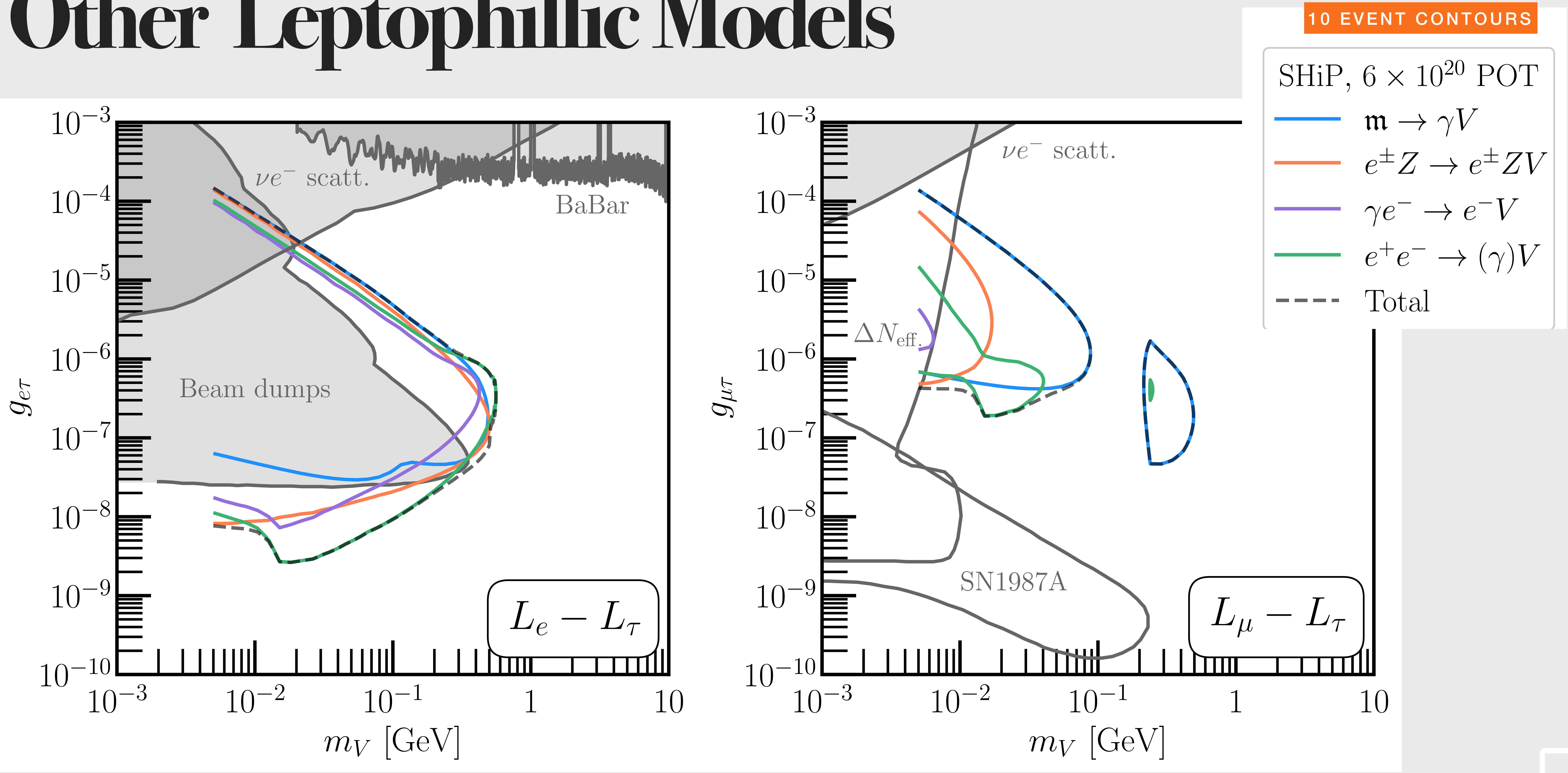
RATE $\sim g_{e\tau}^4$

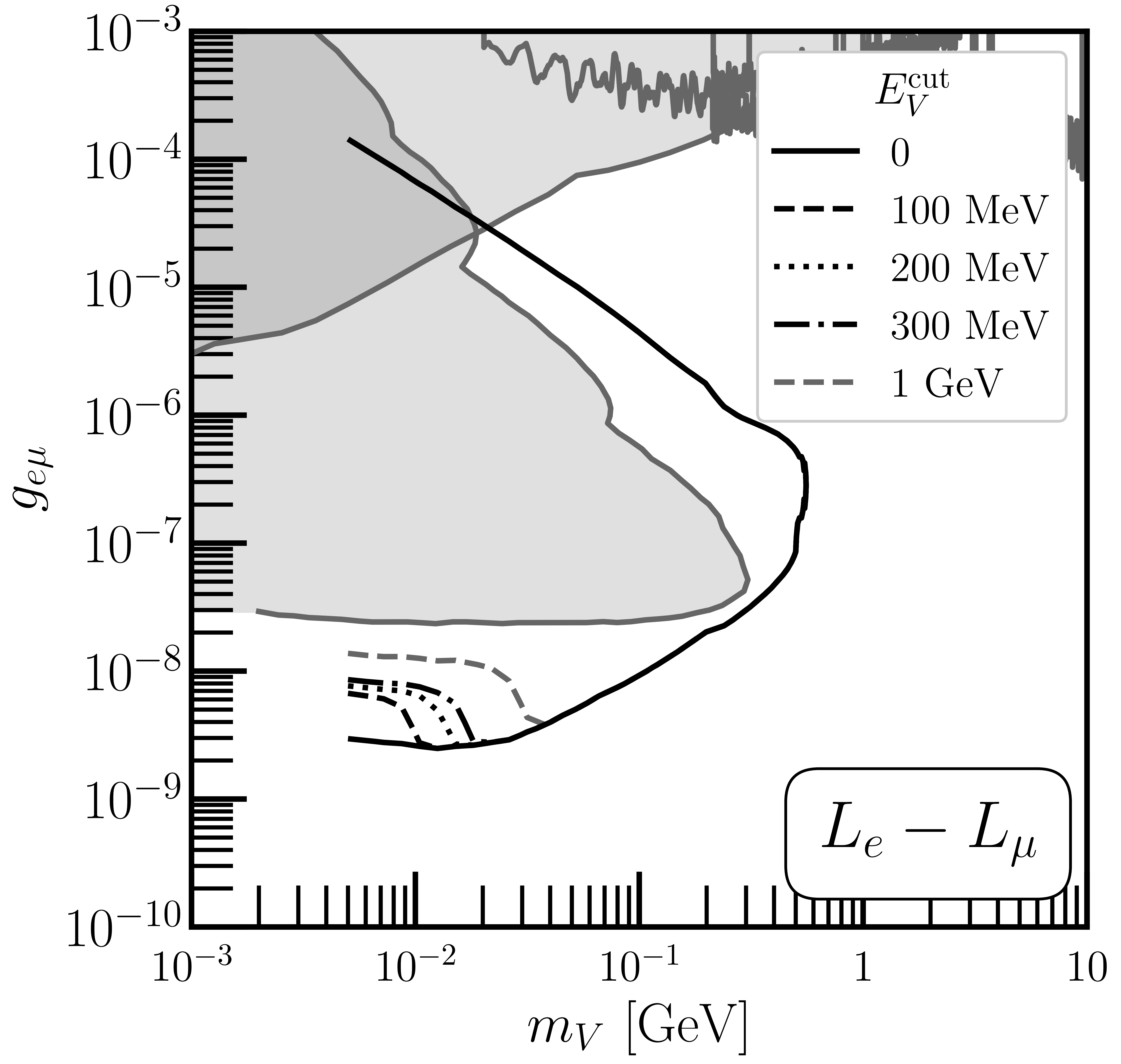
~ FACTOR OF 10^4 IN RATE!

Enhanced Sensitivity At SHiP



Other Leptophillic Models





Energy Threshold Dependence

$$e^+e^- \to V(\gamma)$$

$$E_{\text{res}} \simeq \frac{m_V^2}{2m_e}$$

- Motivates exploring lower thresholds at SHiP

Conclusions & Outlook

Conclusions

- SHiP can substantially extend its sensitivity to dark vectors by adding EM cascade production.
- There is an open source tool **PETITE** that can be used immediately to run simulations.
- Gains are per-$\pi^0 \implies$ robust against hadronic modelling.
- Biggest gains in sensitivity come at long-lifetimes.
- The smaller boost helps particles decay in the decay pipe.