Electromagnetic Secondaries With PETITE

ARXIV: 2401.06843

RYAN PLESTID | NTN FELLOW, BURKE INSTITUTE, CALTECH

COLLABORATORS | N. BLINOV, P. FOX, K. KELLY, P. MACHADO

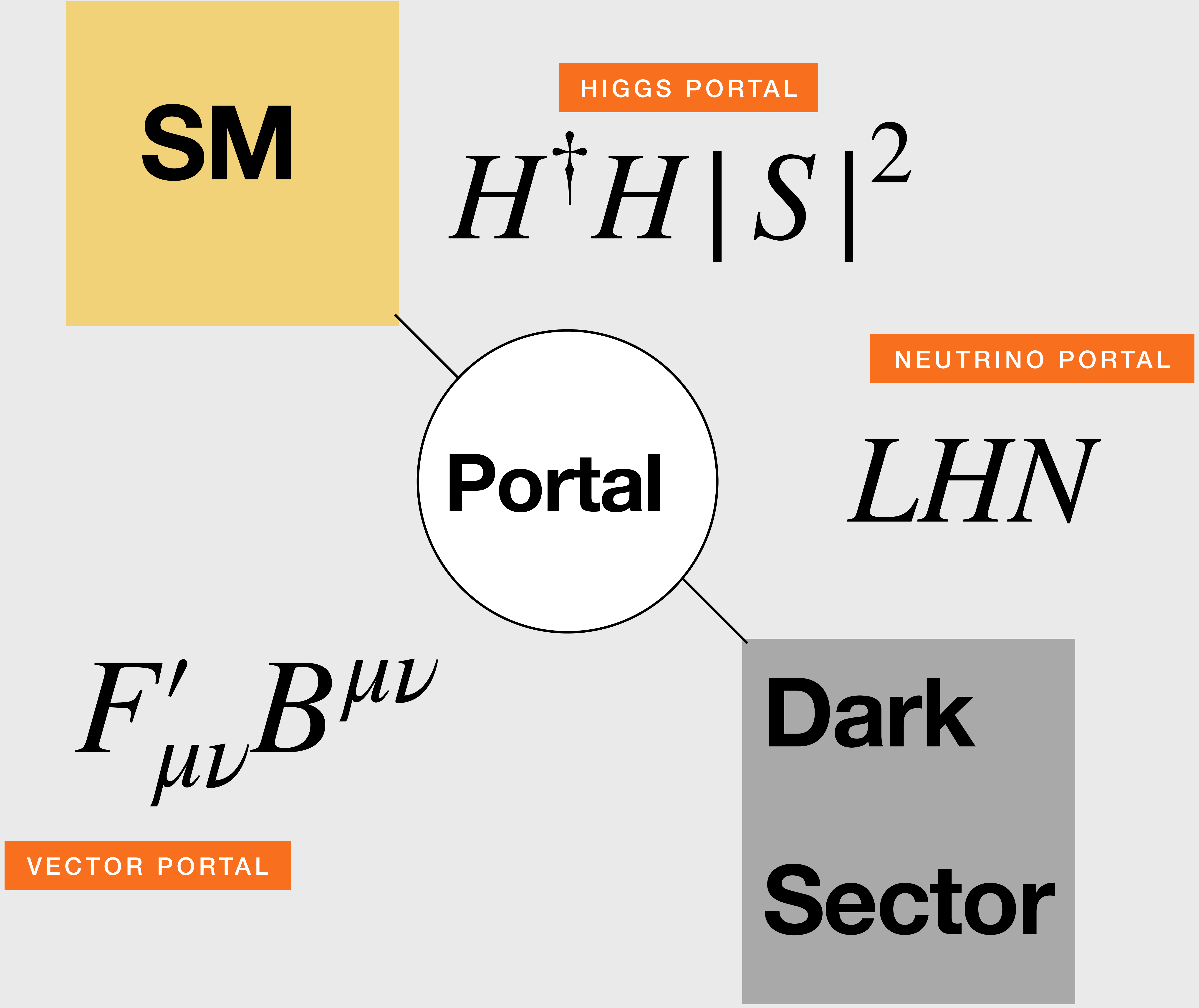
SBN TH+EXP WORKSHOP | SANTA FE, NM | FEBRUARY 2024

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!

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

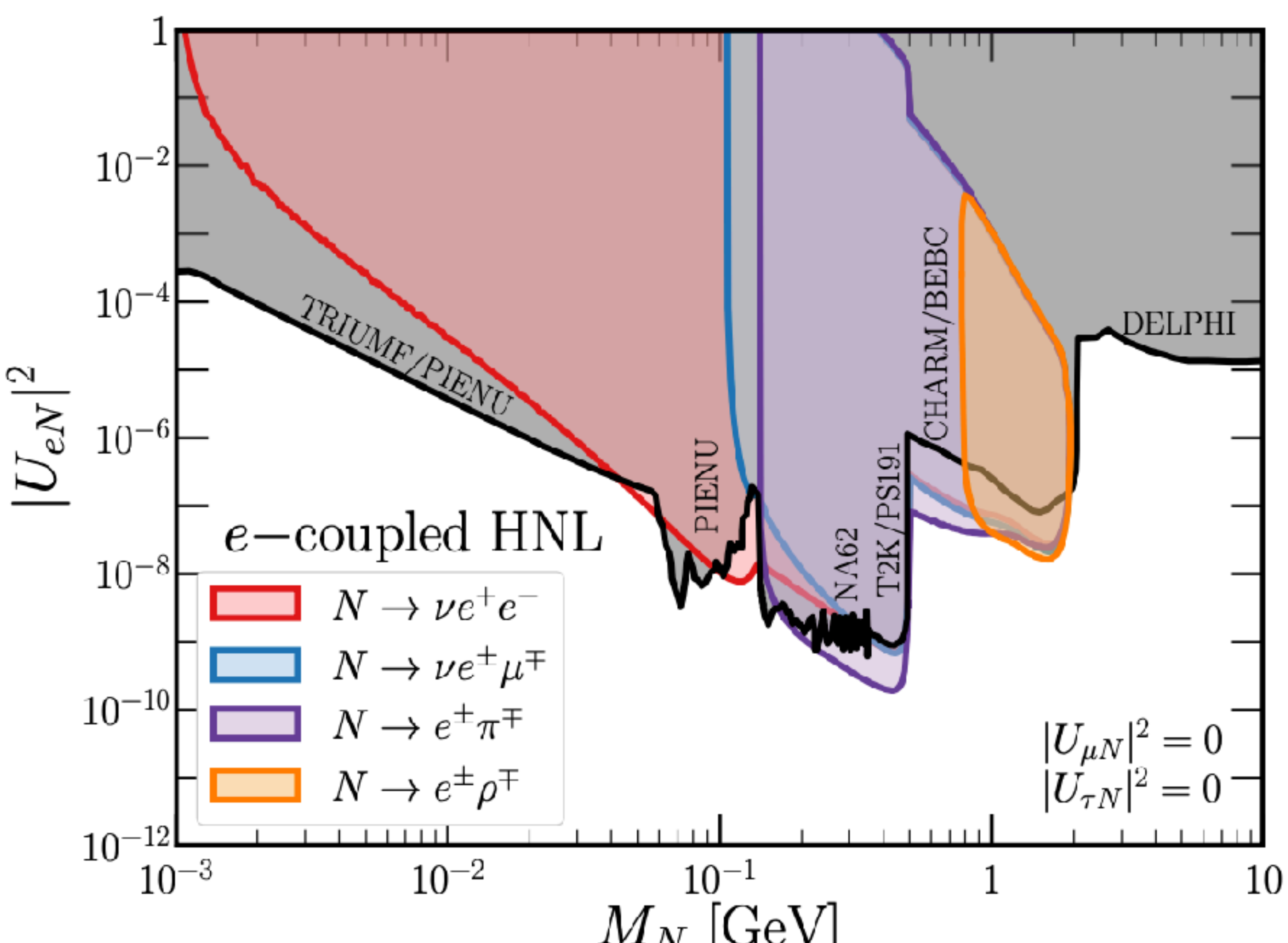
Scalars **HNLs** **Z-Prime**

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

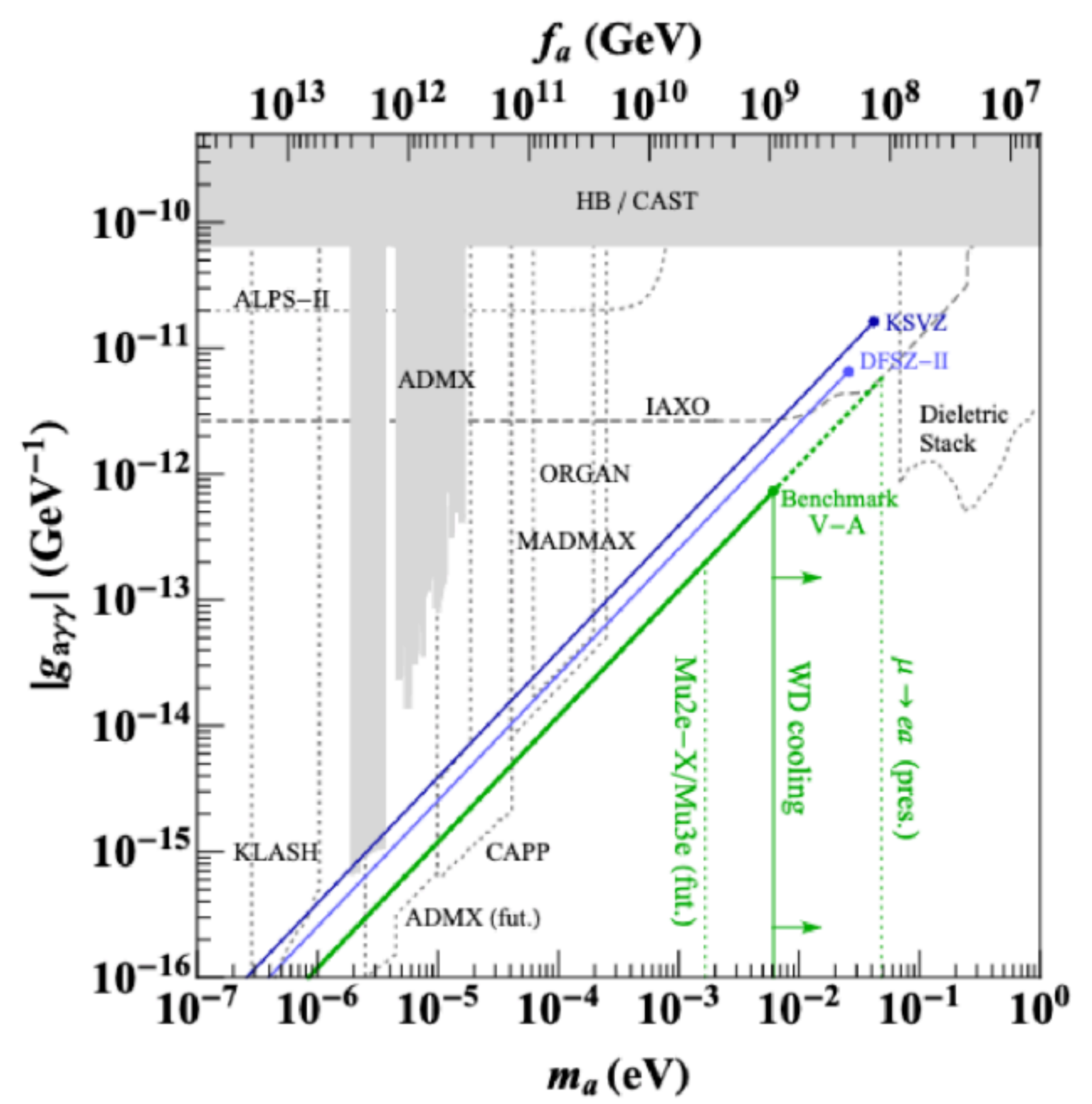
ALPs

Existing Searches

- Broad & competitive phenomenological landscape



BERRYMAN ET. AL. (2019)

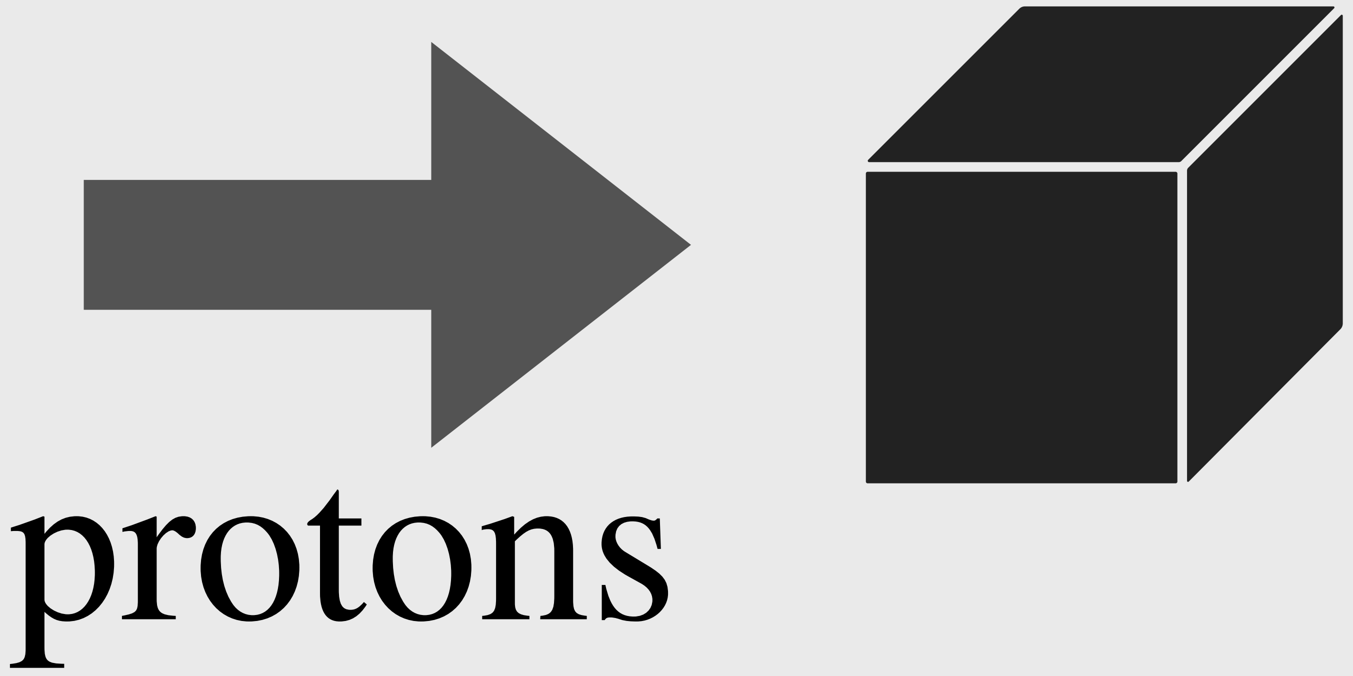


THIS WORK (CREDIT J. ZUPAN)

Neutrino Experiments

- One strategy is to precisely sculpt a signal.
- The other is to just win with brute force.

Neutrino Experiments



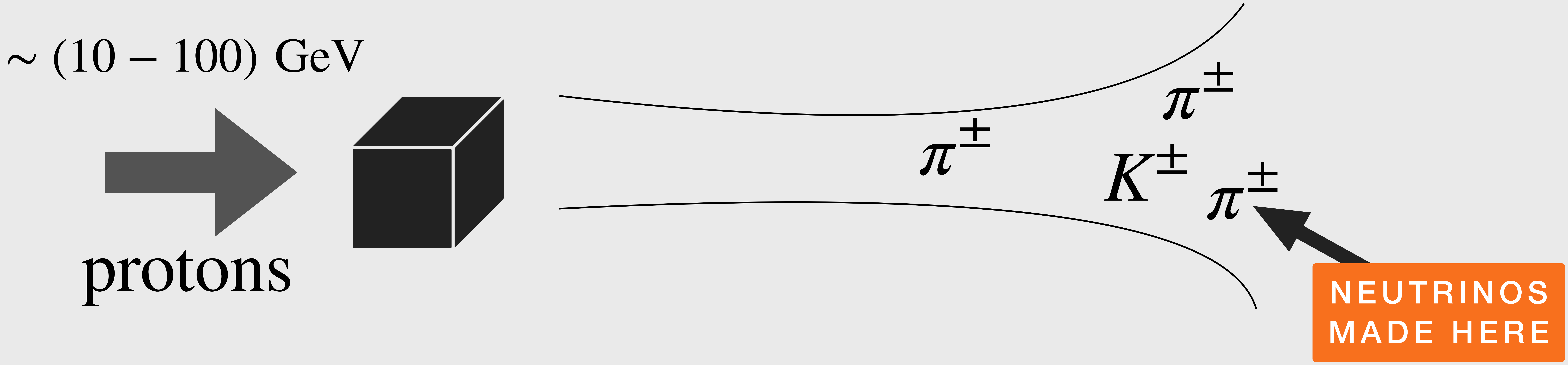
- Produce huge flux pions.
- Powerful neutrino beam.
- Powerful ***dark sector*** beam.

Electromagnetic Secondaries

Electrophilic Light New Physics

Dark Sector Production At Accelerator Energies

- The 3 GeV beam at JSNS is a far cry from the 120 GeV for DUNE.
- High energy protons make high energy pions and kaons etc.
- Many more production channels are available.



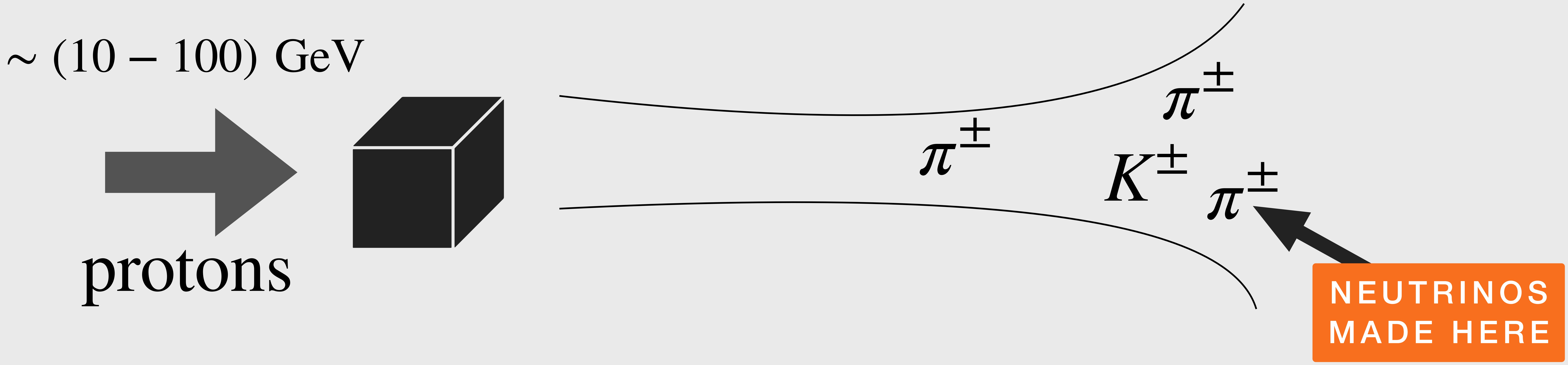
Option 1: Meson Decays

PROMPT

$$D^+ \to K^+ X$$
$$\pi^0 \to \gamma X$$

LONG LIVED

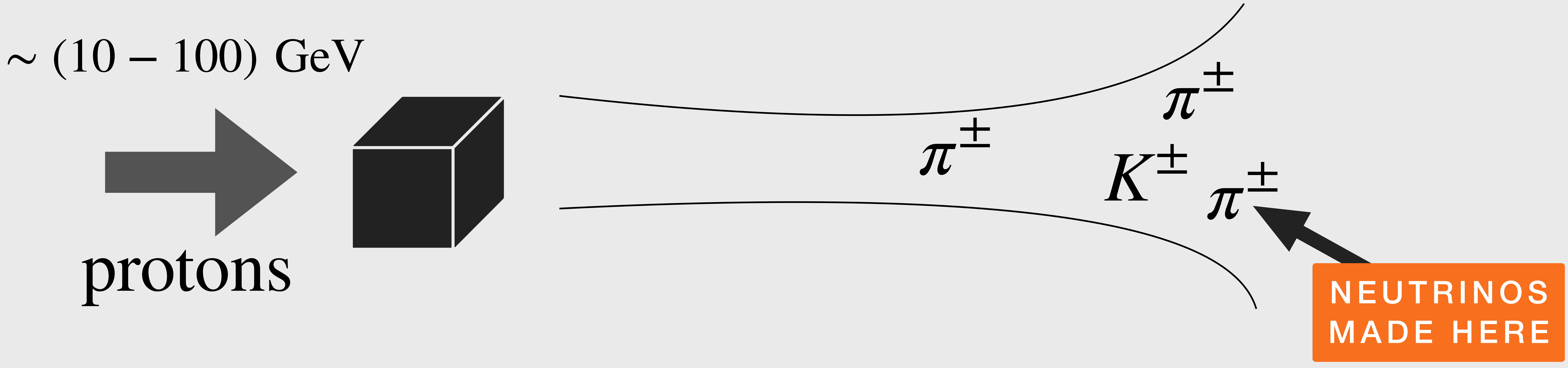
$$K^\pm \to \ell^\pm X$$



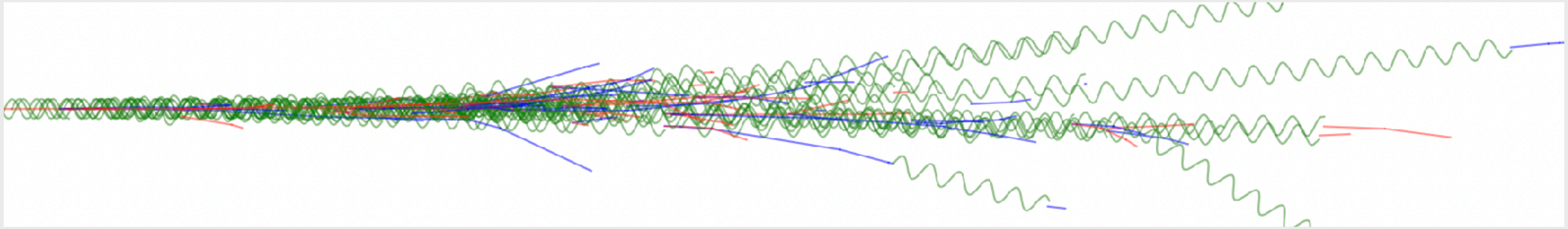
Option 2: Primary Production

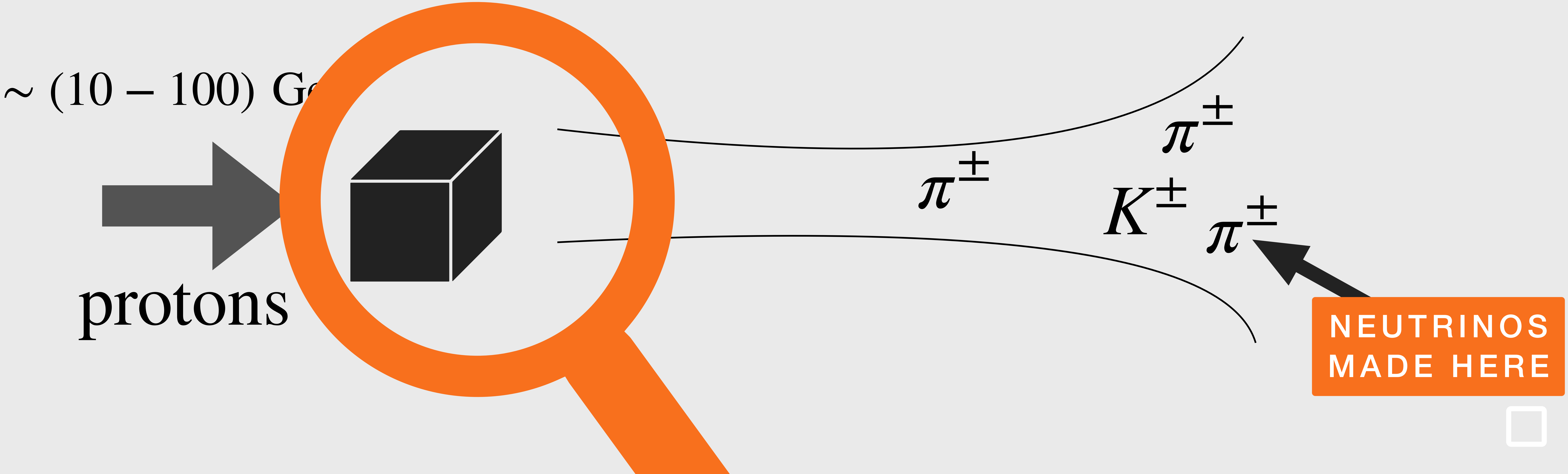
PROTON BREMMSTRAHLUNG

$$pp \to ppX$$



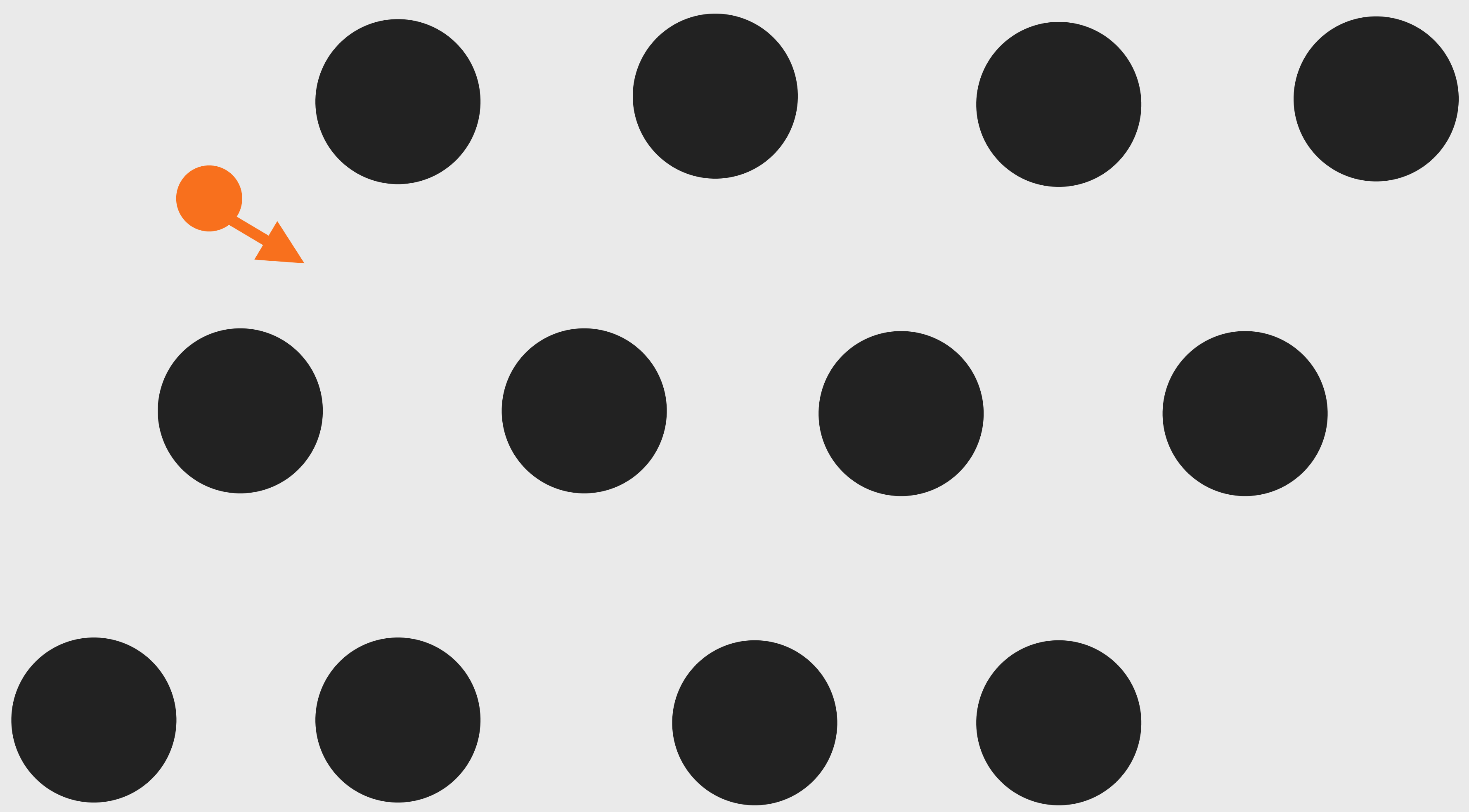
Option 3 : Secondary Production





Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium



- Characteristic length between collisions λ_{MFP}

Hadronic And Electromagnetic Cascades

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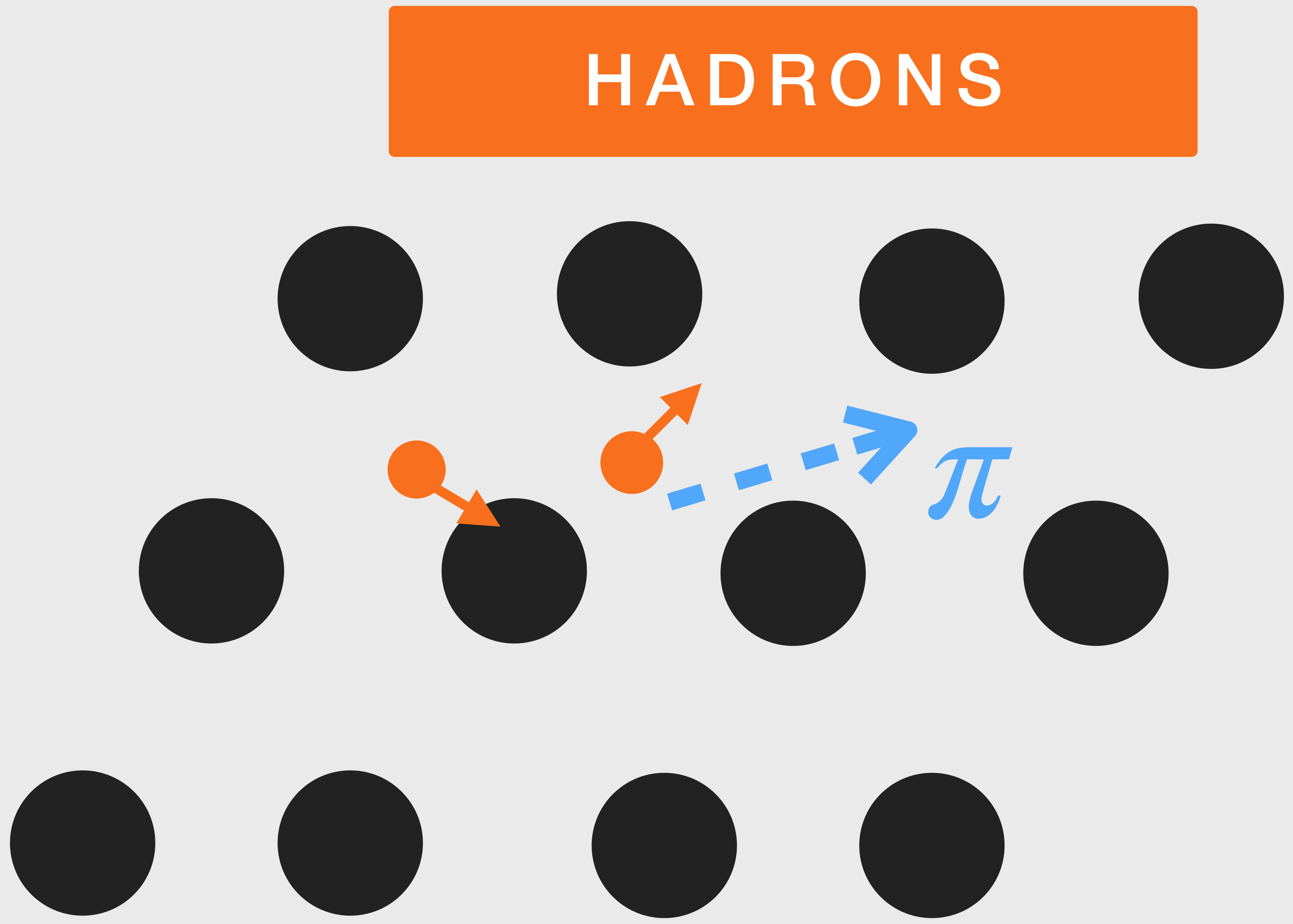


- Hadrons "down convert" energy into pions.
- Every generation is a new chance to make a BSM particle.
- Multiplicity of interactions grows with energy.

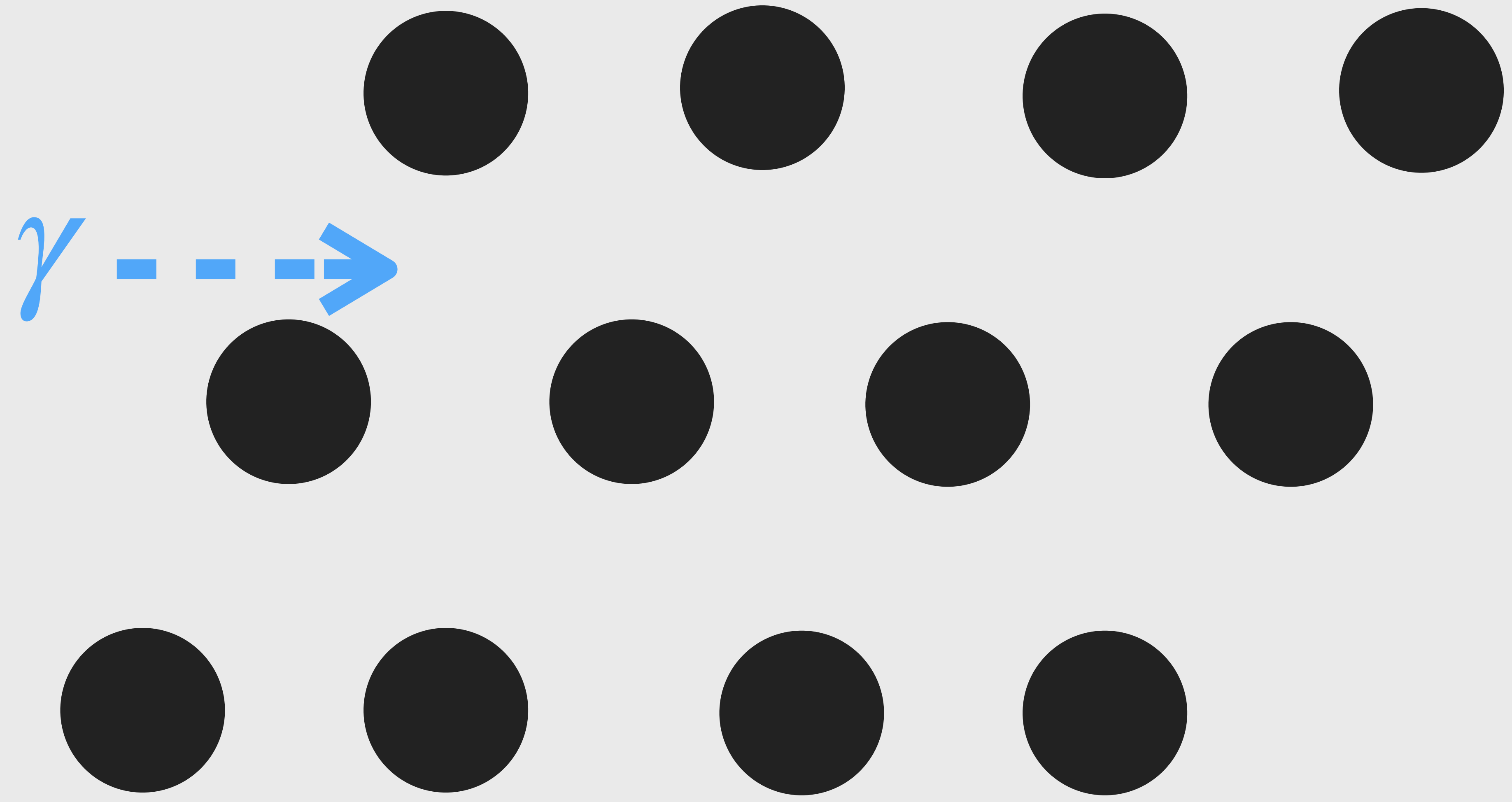
NEW RESOURCE BUT HARD TO STUDY SYSTEMATICALLY.

- Characteristic length between **hard** collisions X_H

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



- Main reactions are

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

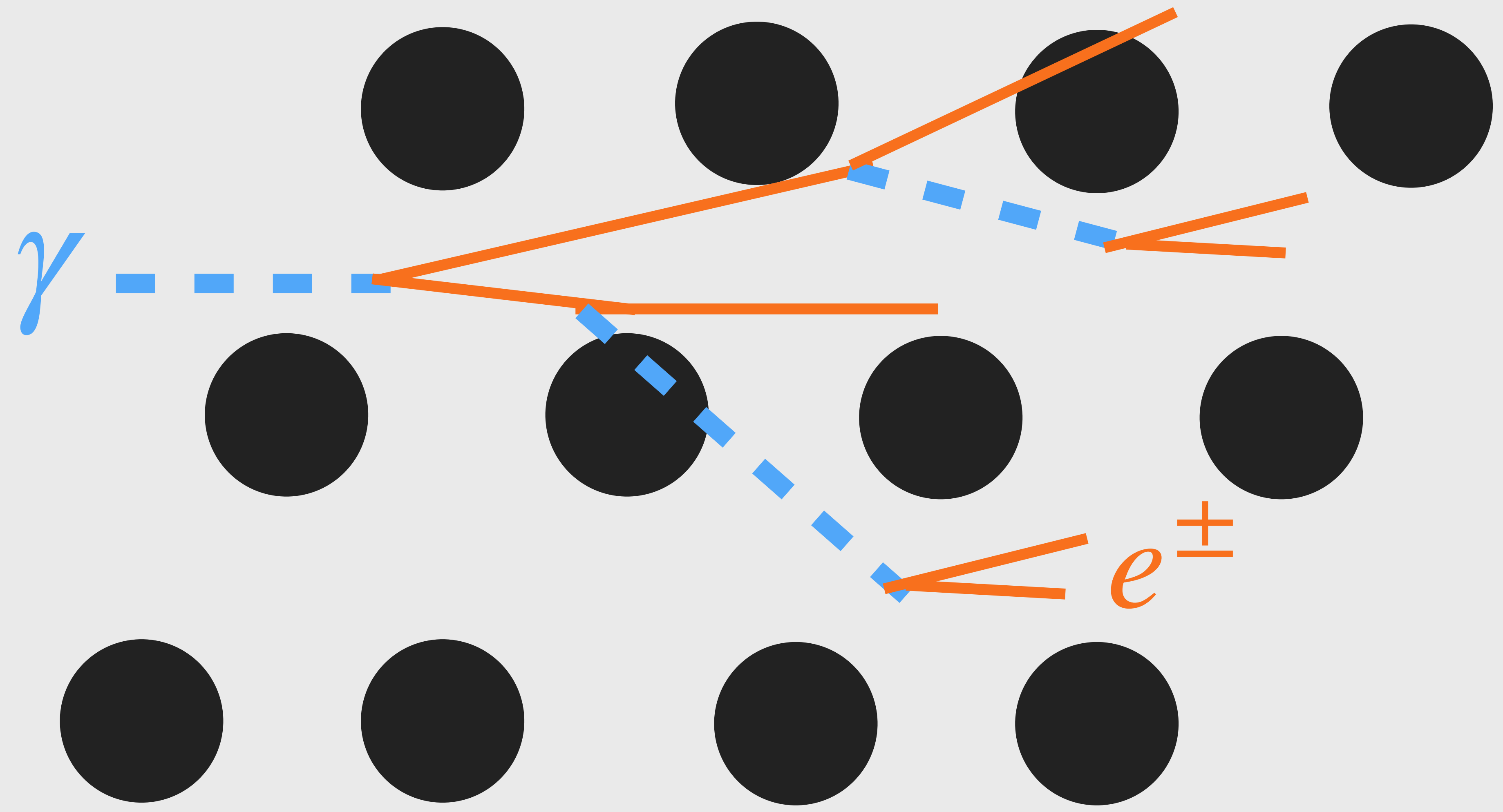
- Multiplicity of interactions grows with energy.

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

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



- Main reactions are

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**NEW RESOURCE FOR DARK SECTORS.
CAN BE COMPUTED PERTURBATIVELY.**

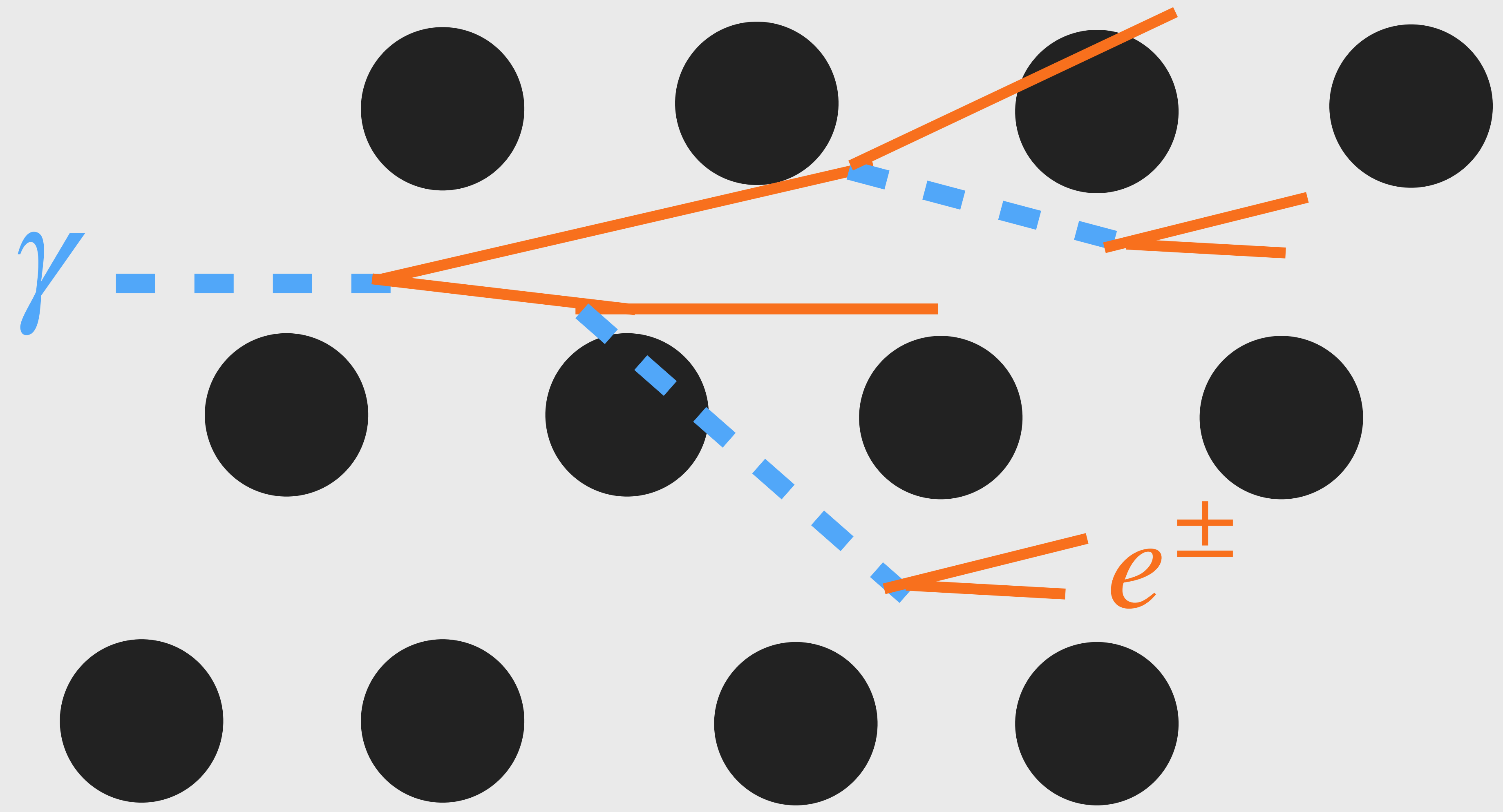
- Characteristic length between **hard** collisions X_0

- Radiation length

Hadronic And Electromagnetic Cascades

- Consider a particle propagating through medium

ELECTRONS & PHOTONS



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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]

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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

2401.06843

Dark fluxes from electromagnetic cascades

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.

Dar

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]

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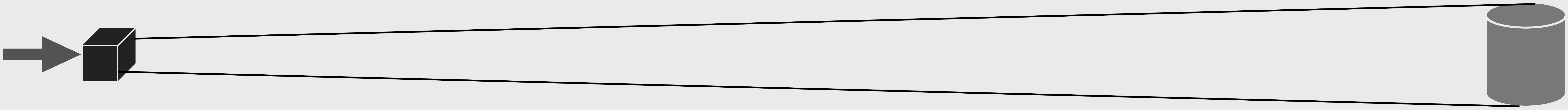
Challenges At Neutrino Experiments

SMALL ANGLES

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

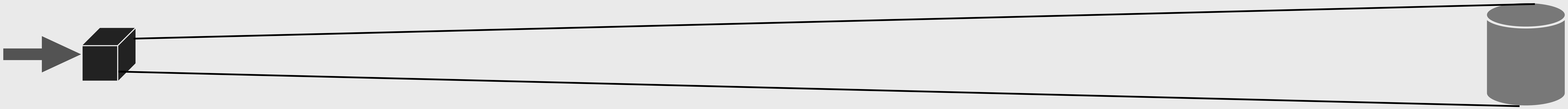


UNUSUALLY SENSITIVE TO ANGULAR SPREADING

Challenges At Neutrino Experiments

LARGE HIERARCHY OF ENERGIES

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

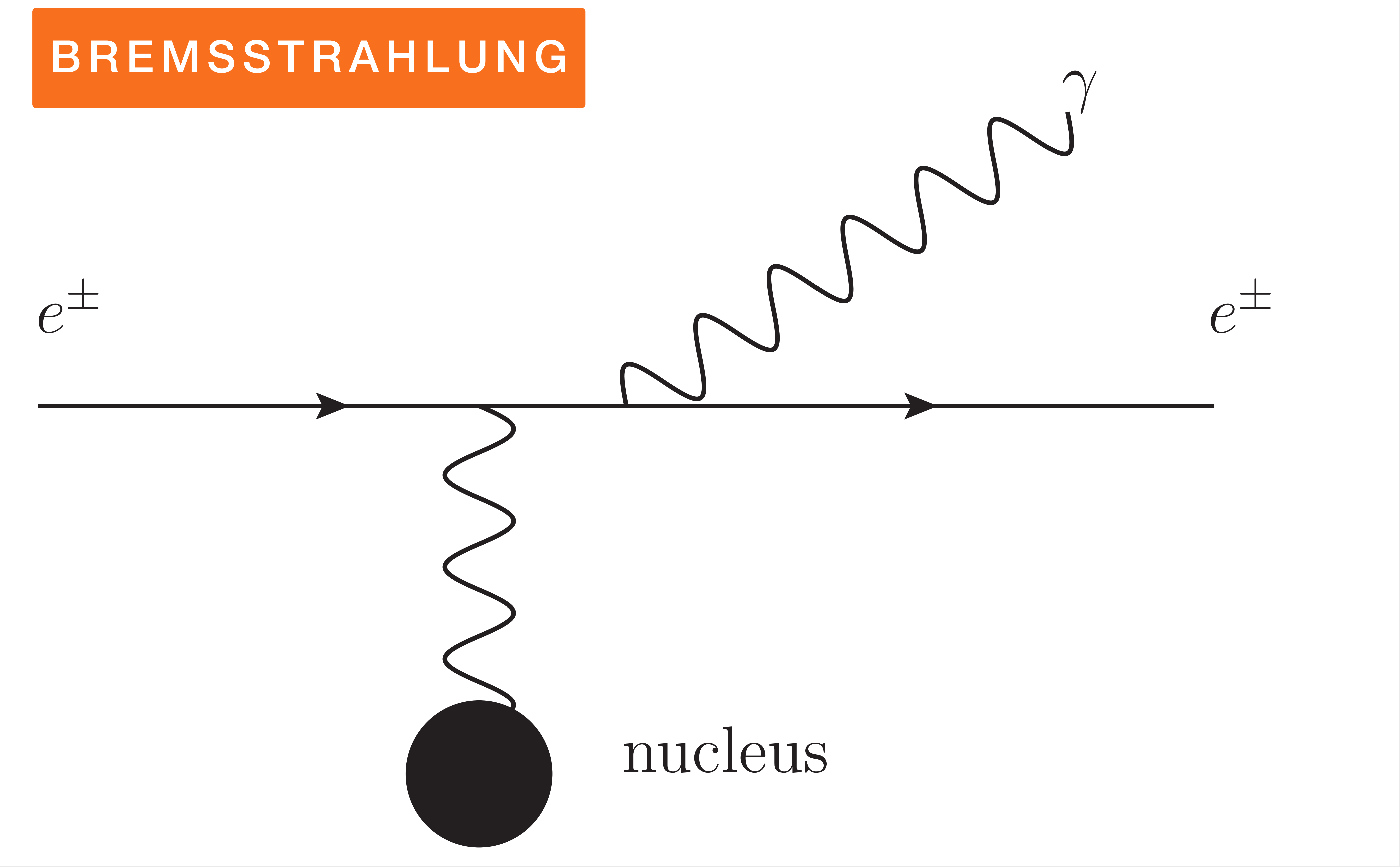


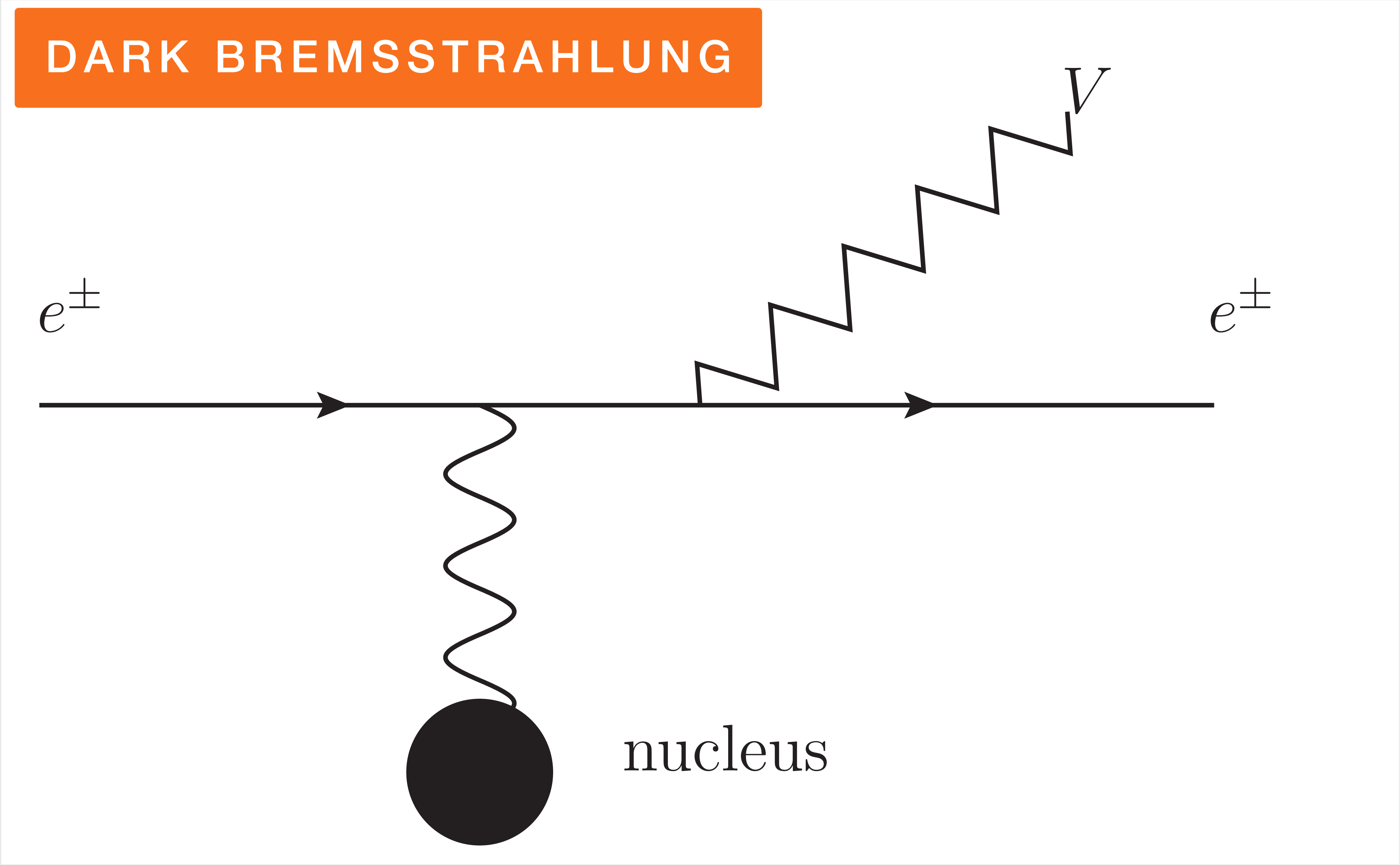
NEED TO WORRY ABOUT MANY GENERATIONS IN A SHOWER

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.



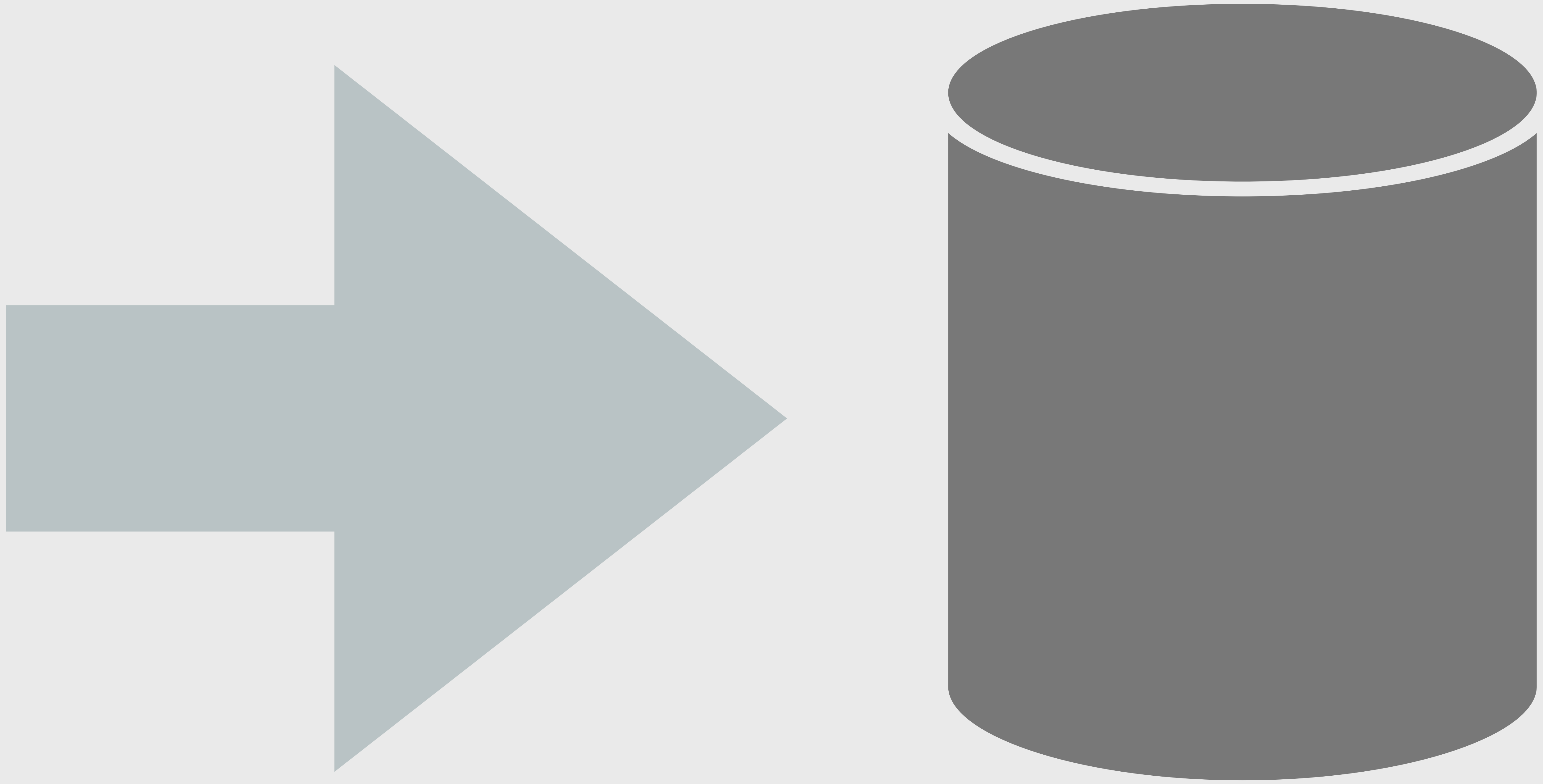


Explicit Model: Dark Vector Boson

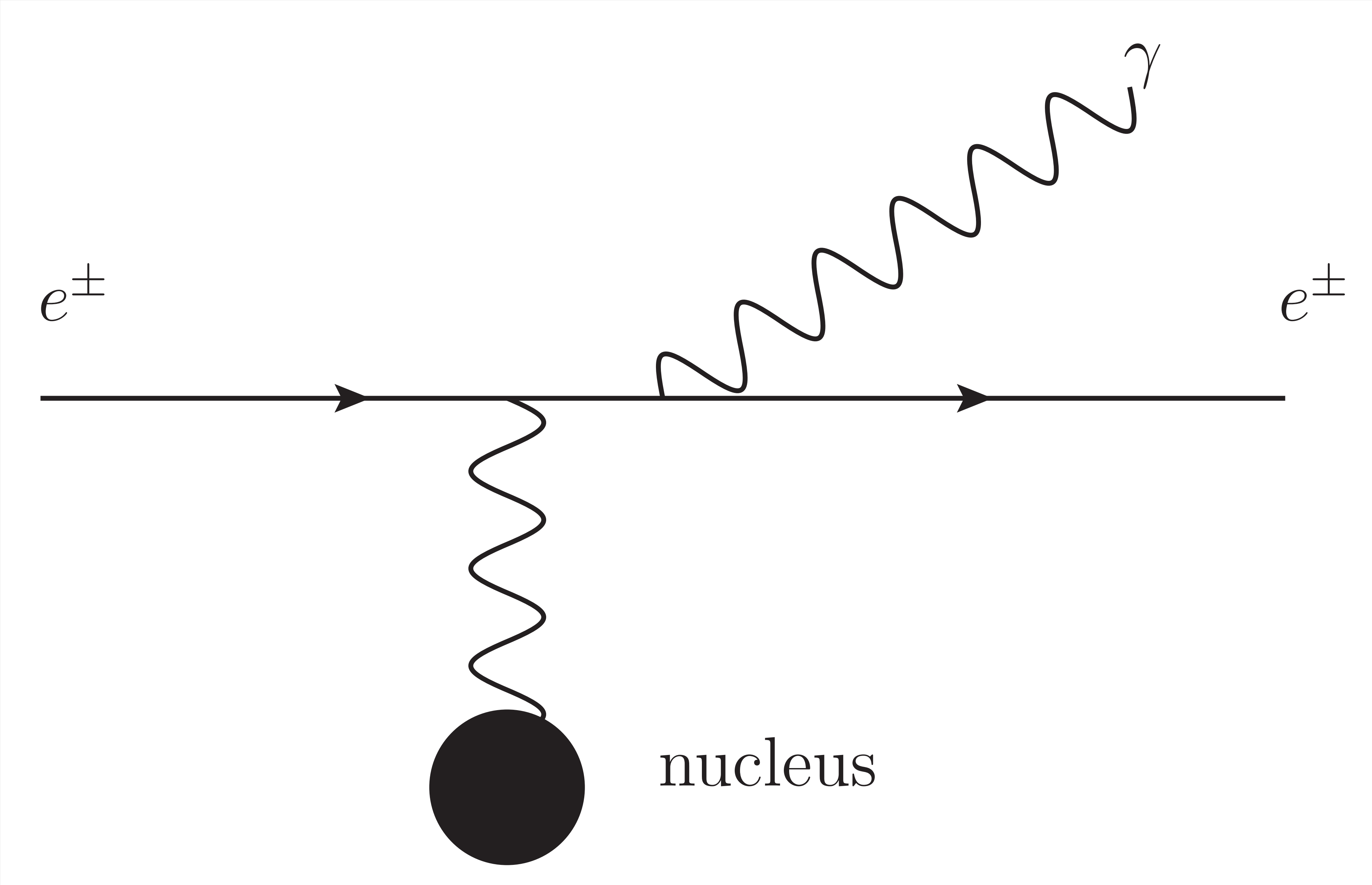
$$\mathscr{L} \supset g\bar{e}\gamma_\mu e V^\mu$$

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

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

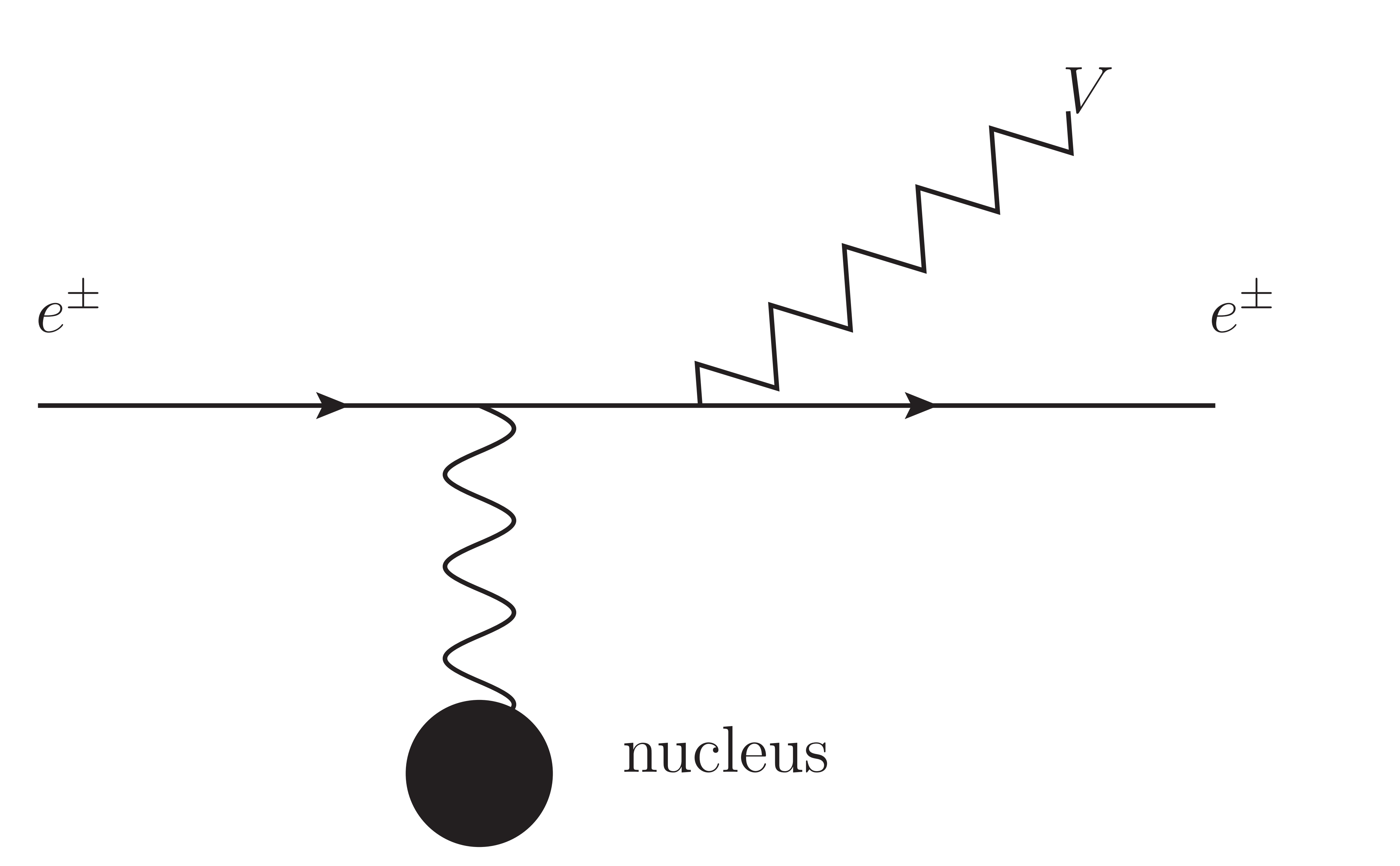


SM Event → BSM Event



- Consider an event in a MC event record.

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



- How do we use this to generate BSM event?

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

SM Event → BSM Event

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

FOCUS ON PARENT

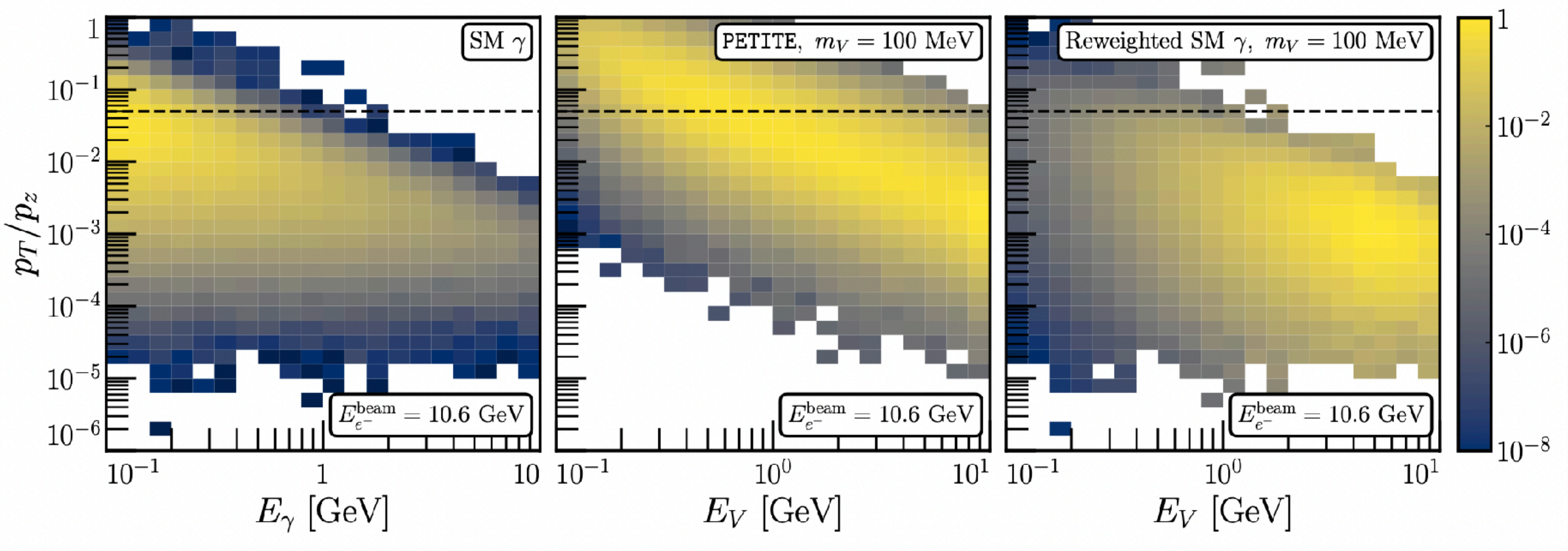
DRAW KINEMATICS FROM BSM DIST.

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

COMPUTE BRANCHING RATIO

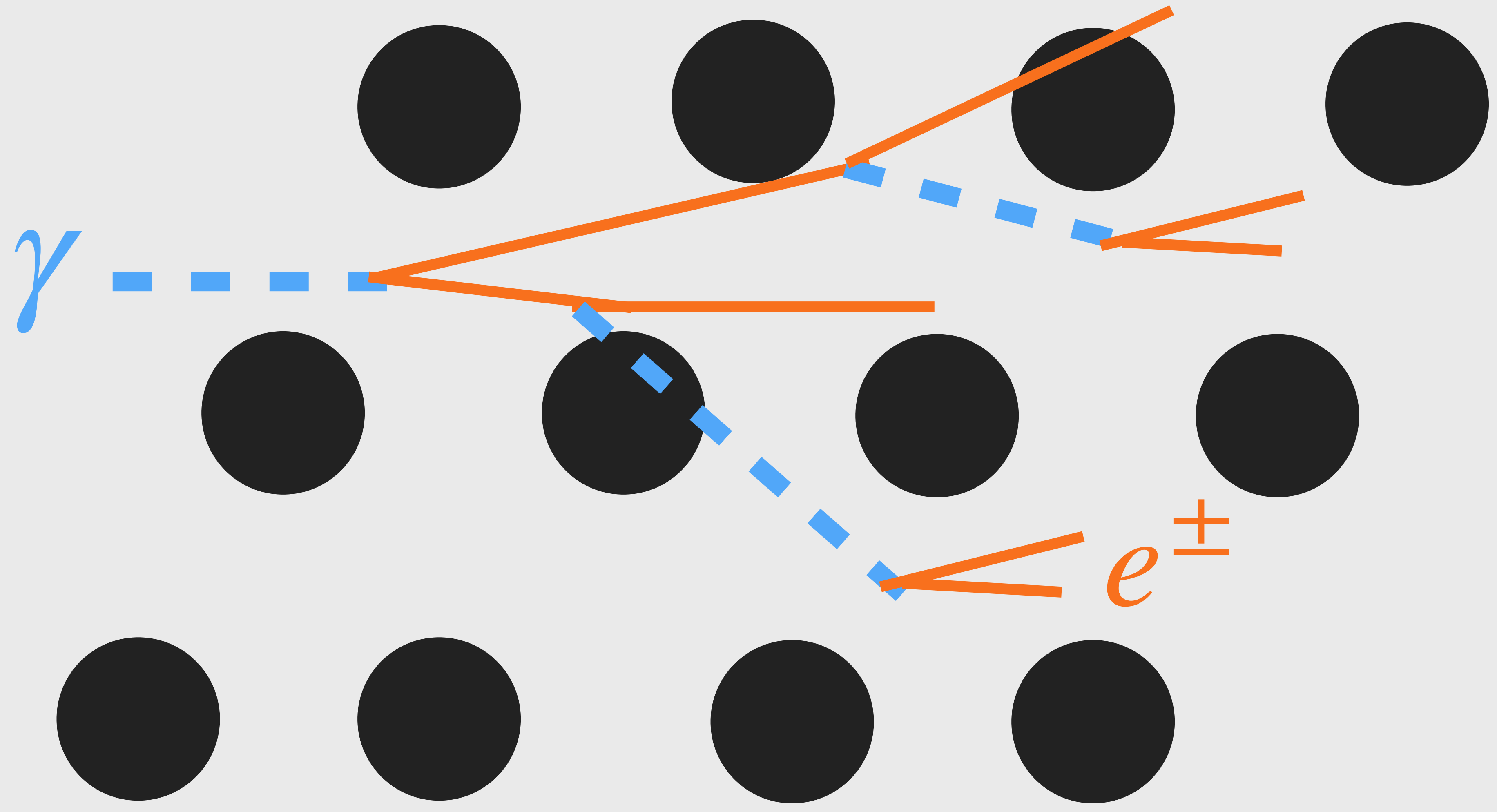
$$\mathrm{BR} = \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{tot}}} \approx \frac{\sigma_{\mathrm{BSM}}}{\sigma_{\mathrm{SM}}}$$

What Not To Do



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

PETITE In A Nutshell



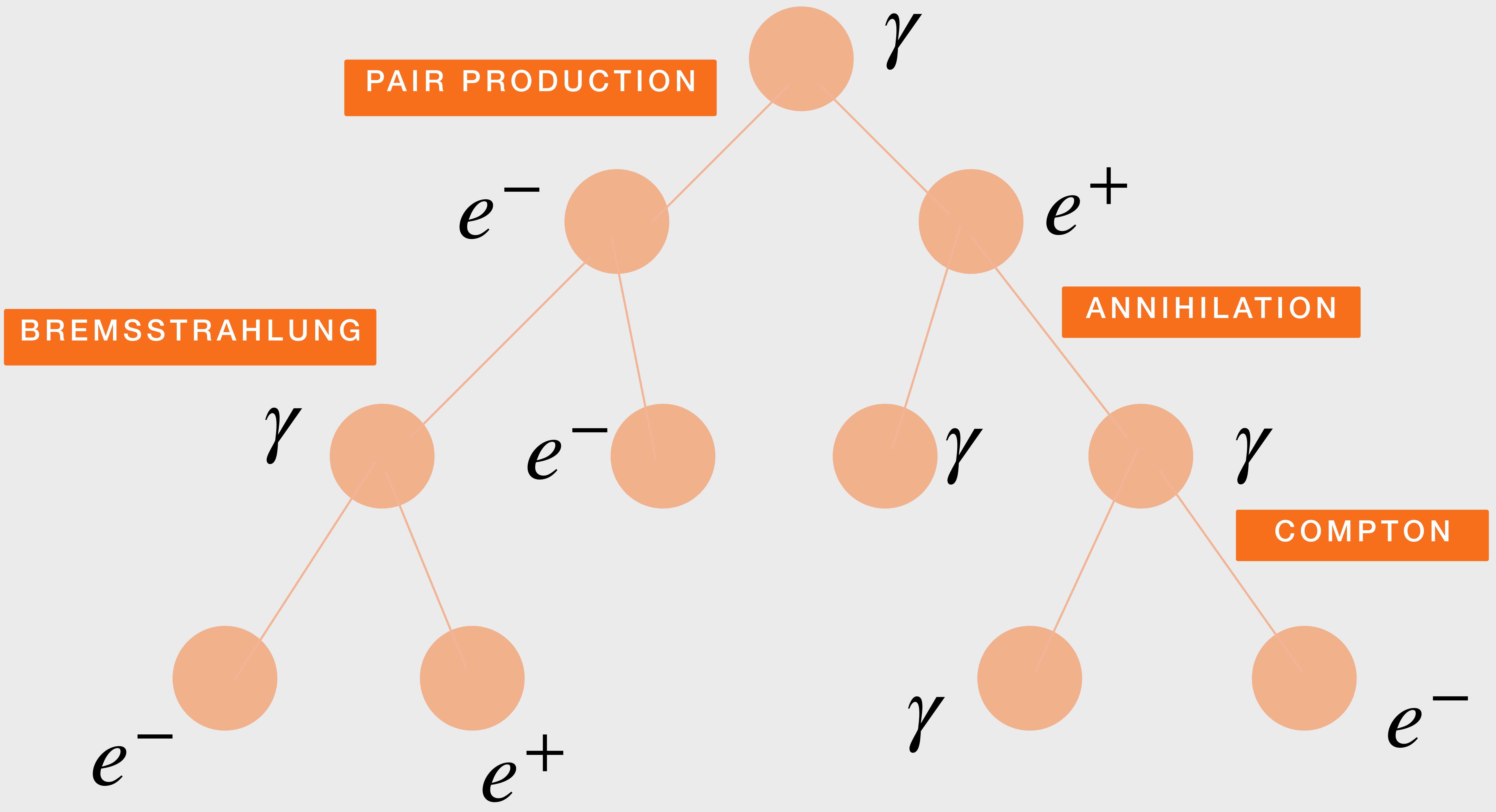
- Static nuclear centres source Coulomb fields.
- Electrons treated as a homogeneous gas of electrons at rest.
- Atomic screening included for bremsstrahlung and pair production.

PROCESSES INCLUDED

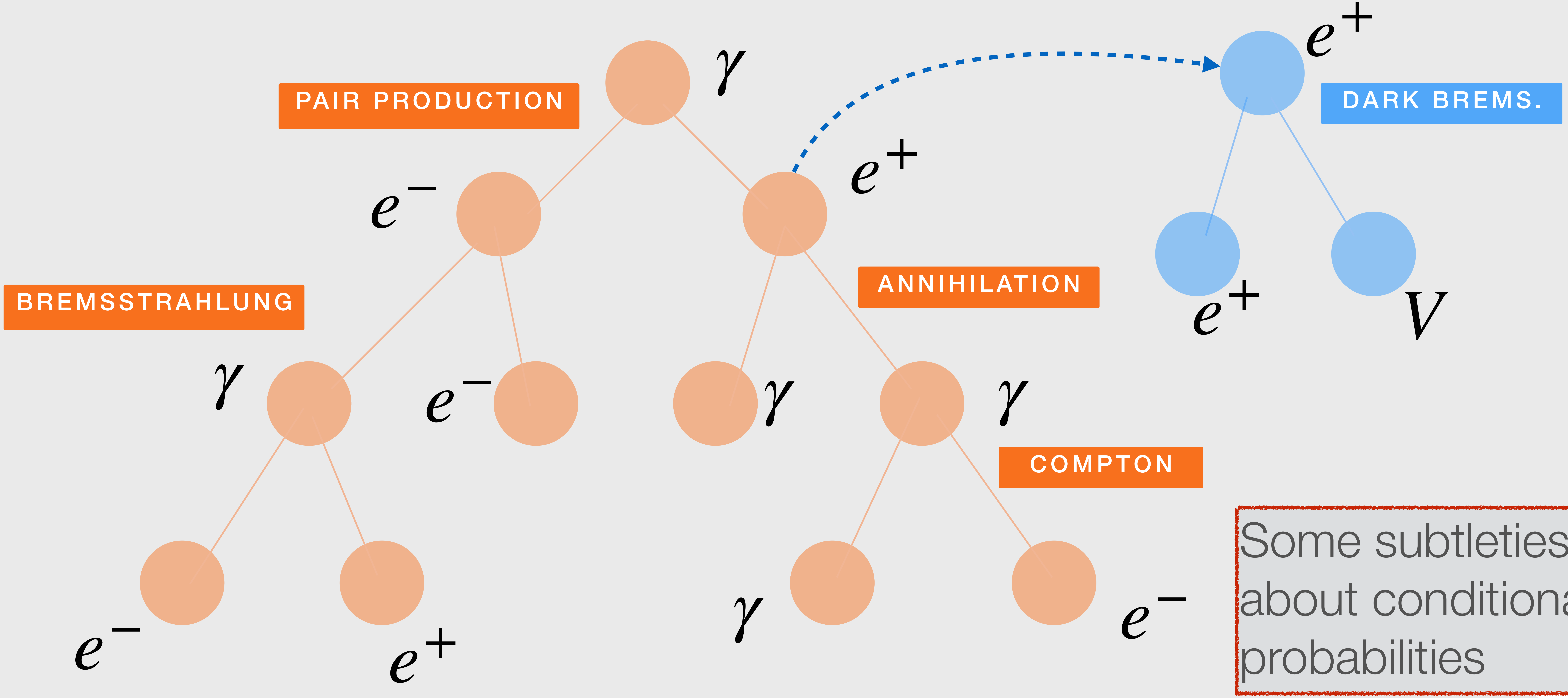
- $e^{\pm}Z \to e^{\pm}\gamma Z$
- $\gamma Z \to e^{+}e^{-}Z$
- $e^{\pm}e^{-} \to e^{\pm}e^{-}$
- $\gamma e \to \gamma e$
- $e^{+}e^{-} \to \gamma\gamma$

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

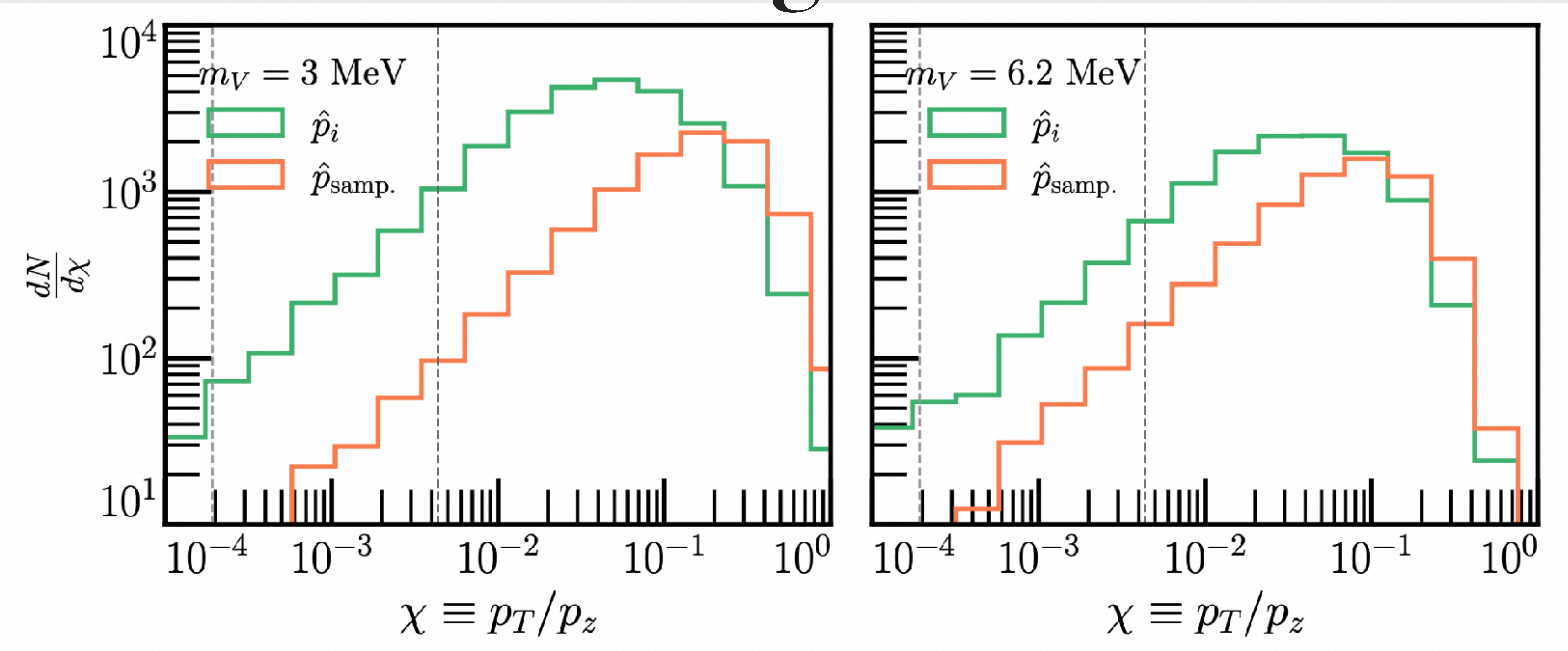
> pip install <package_name>==<version_required>

HTTPS://GITHUB.COM/KJKELLYPHYS/PETITE

Example Of Standard Model Uncertainty

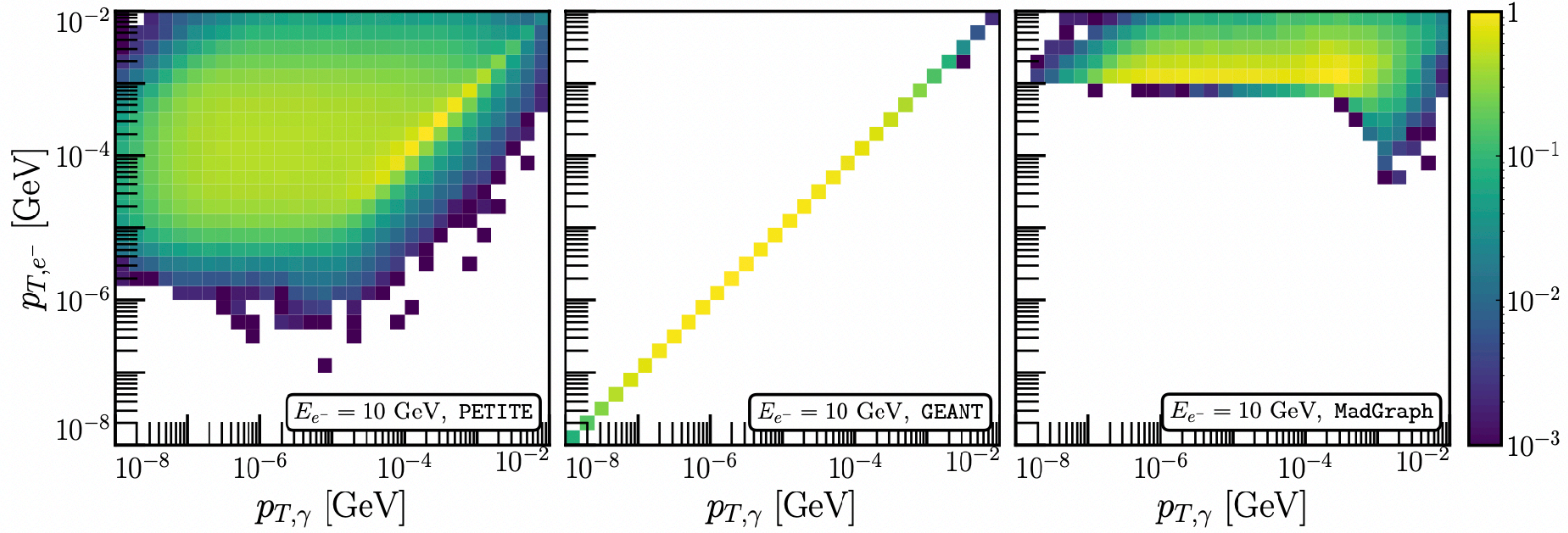
- We can quantify how different models of multiple Coulomb scattering affect BSM flux predictions.
- Alters angular distribution and therefore acceptance at detector.

Dark Annihilation Angular Distributions



- We find that $e^+e^- \to V(n\gamma)$ is very sensitive to multiple Coulomb scattering.
- One has to properly (i.e. carefully) sample the distance travelled by a positron.

Bremsstrahlung Mismodeling With Spurious Correlations



Comparison With Past Literature

- We find that we can reproduce, to within a factor of a few, all existing predictions by reproducing analysis choices within PETITE.
- Find that Celentano *et. al.* are closest to our predictions.
- PETITE is setup to easily support studies of systematic uncertainties.

Conclusions & Outlook

Conclusions

- Neutrino experiments are powerful factories for particles lighter than a few GeV.
- Reliable flux predictions are needed if one wants to go beyond conservative "rate $\gg$ background" constraints.
- We have a new framework for electromagnetic secondaries that is

  (I) Systematic.

  (II) Flexible.

  (III) Monte Carlo friendly.