Title: A PETITE Step Toward Accurate Predictions For Fixed-Target Experiments

Speakers: Nikita Blinov

Series: Particle Physics

Date: February 20, 2024 - 1:00 PM

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Abstract: An intense beam of Standard Model (SM) particles colliding with a fixed target is one of oldest types of accelerator-based experiments. With recent interest in production and detection of relatively light, weakly-coupled (``dark sector'') states, these set-ups are again playing a central role in the search for beyond-SM (BSM) physics. Signal rate prediction is often challenging in fixed-target experiments, requiring the simulation of many SM and BSM processes as the beam particle propagates through the target. Both play a key role in determining the flux of dark sector particles through a detector. An accurate description of these fluxes is needed, since small errors in angular and energy distribution predictions can lead to significant over or under estimates of signal rate in the detector. Focusing for simplicity on BSM particle production from electromagnetic cascades, I will describe how we can model production of BSM particles, highlighting some frequently-used approximations used in the past. I will then show that improvements in both SM and BSM modelling are desirable. We implemented several of these improvements in a code, PETITE. Using this tool we can show how mismodelling of SM or BSM processes can lead to orders of magnitude difference in signal rates at realistic experimental setups.

Zoom link

A PETITE Step Toward Accurate Predictions For Fixed-Target Experiments

Nikita Blinov

with Patrick Fox, Kevin Kelly, Pedro Machado & Ryan Plestid

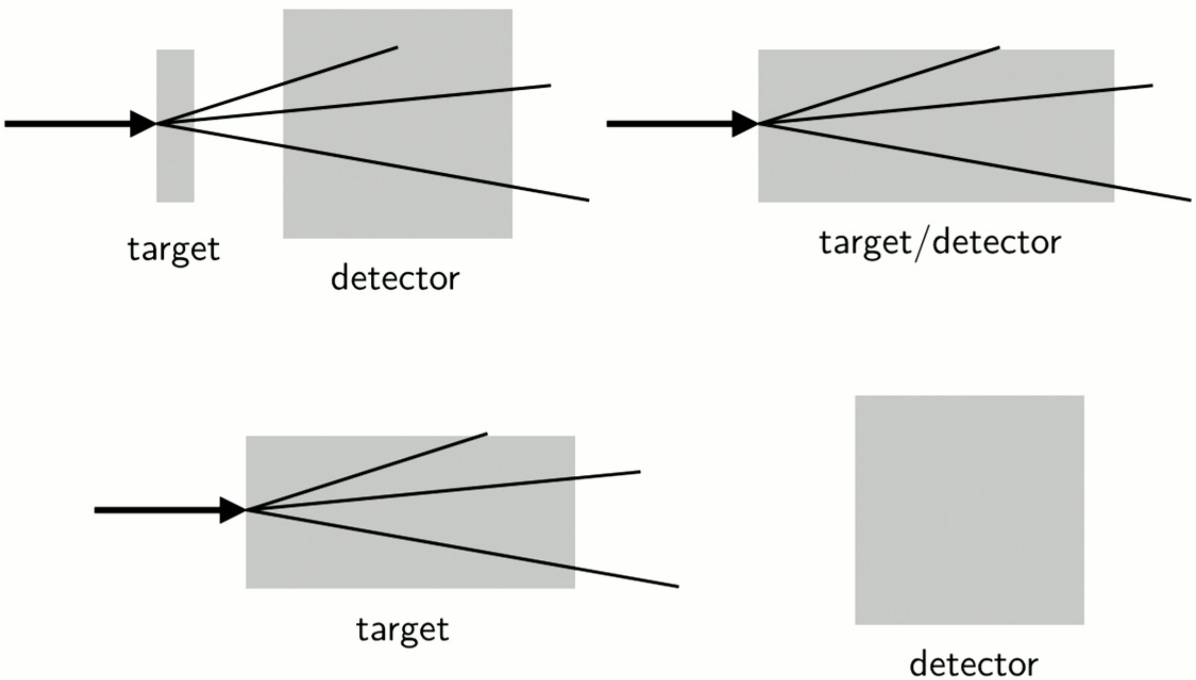
ArXiv: 2401.06843

Perimeter Institute, February 20, 2024

YORK U

Fixed-Target (FT) Experiments

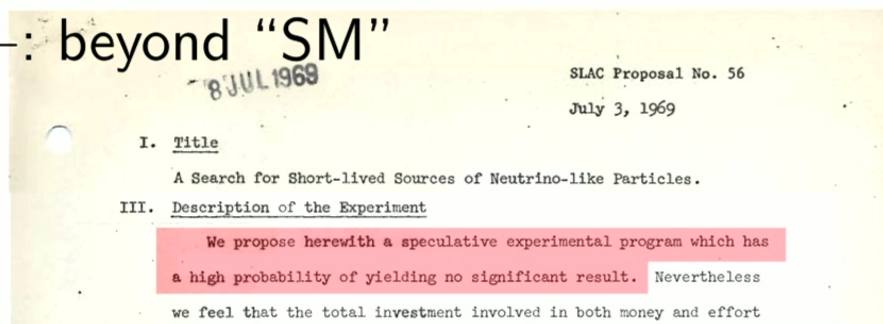
A classic experimental concept with many shapes and sizes



Some History

One of the oldest experimental tools:

- 1900s - Rutherford Gold Foil Experiments and discovery of the nucleus
- 1950s - Bubble chambers and meson spectroscopy
- 1960s - electron-proton deep inelastic scattering
- 1960s - searches for charges e/3 and 2e/3, ++
- 1960s+: beyond "SM"



8 JUL 1969

SLAC Proposal No. 56

July 3, 1969

I. Title

A Search for Short-lived Sources of Neutrino-like Particles.

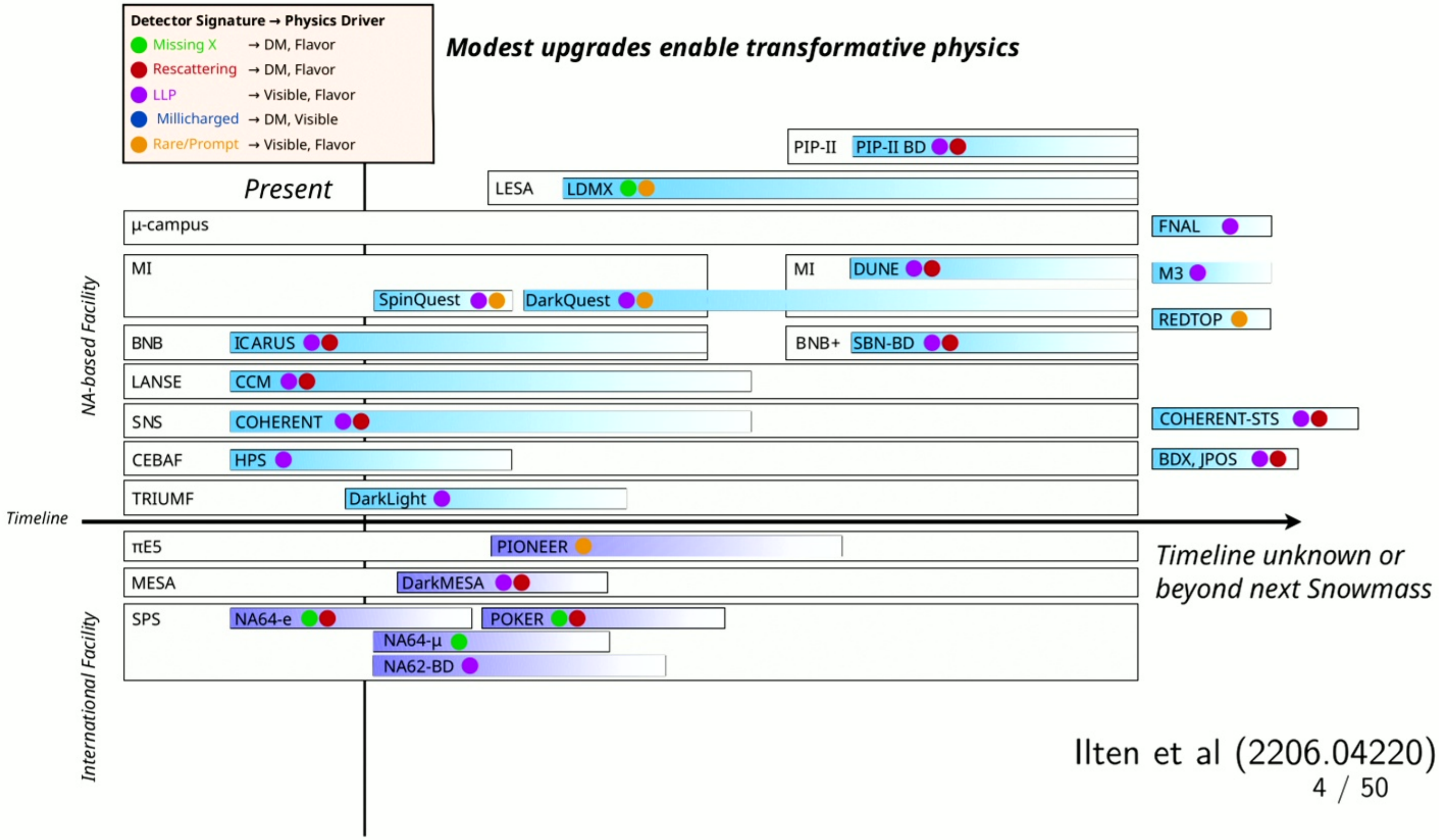
III. Description of the Experiment

We propose herewith a speculative experimental program which has a high probability of yielding no significant result. Nevertheless we feel that the total investment involved in both money and effort

3 / 50

Intensity Frontier Today

Many proposed or currently-running facilities



Ilten et al (2206.04220)

Beyond the Standard Model

The fixed target idea is well-trodden territory.

Why are they still relevant?

Recent(ish) insights about:

1) Light, feebly-coupled states + EFT

2) Simple Dark Matter Models

3) Testing solutions to exp. anomalies

Effective Field Theory

Only a handful of low-dimensional connections to potential new particles – study these first!

$A'_\mu J^\mu_{\rm EM}$ Dark photon $\Rightarrow$ Coupling to electromagnetism

$|H|^2\phi^2$ Higgs portal scalar $\Rightarrow$ Coupling to fermions

LHN_R Right-handed neutrino $\Rightarrow$ Coupling to neutrinos

$aF_{\mu\nu}\widetilde{F}^{\mu\nu}$ Pseudo-scalar $\Rightarrow$ Coupling to electromagnetism

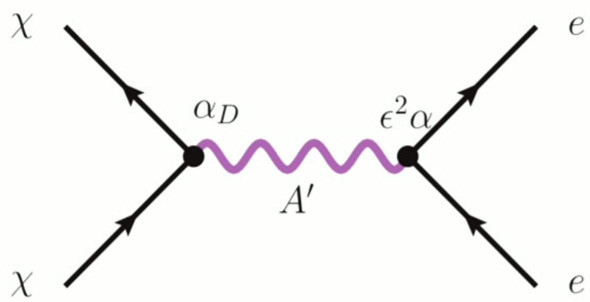
$\vdots$

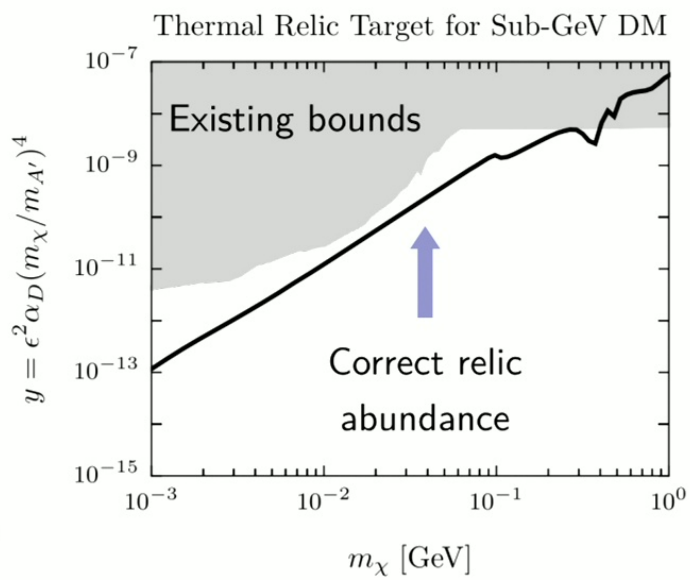
Batell, Pospelov & Ritz (2009)

FT experiments often provide best sensitivity for dim(O)$<\sim$6

Thermal DM: A Predictive Model

Dark matter coupled to the dark photon can annihilate directly into SM particles





$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha \alpha_D m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

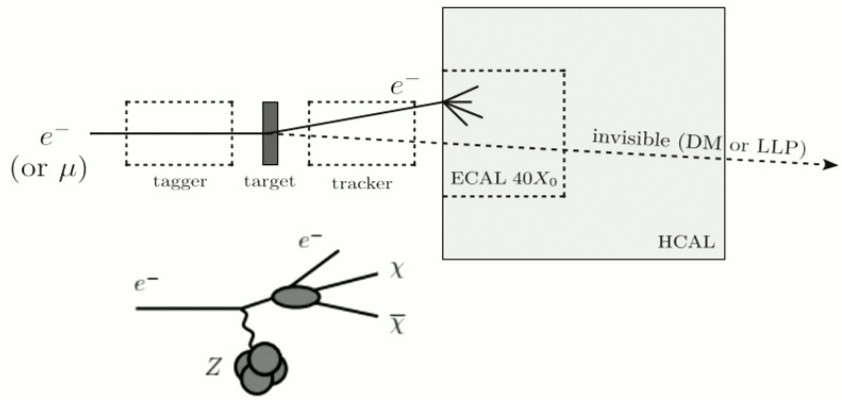
These models are weakly coupled, in the sense $\alpha_D < 1$

Concrete Example: LDMX

Detect DM production by observing recoiling SM particle.

Eder Izaguirre, Gordan Krnjaic, Philip Schuster, and Natalia Toro
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
(Dated: May 1, 2015)

(see also Andreas et al '13 $\rightarrow$ NA64 at CERN)



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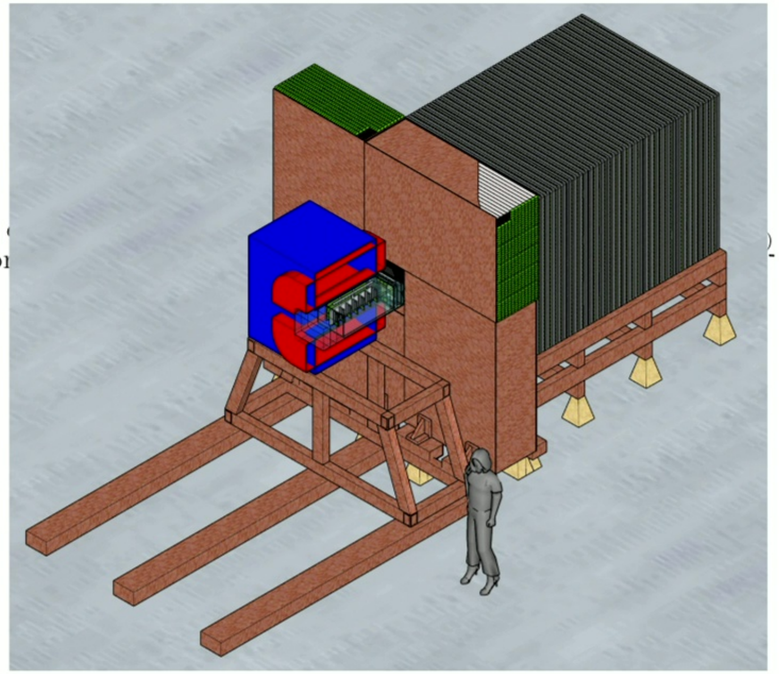
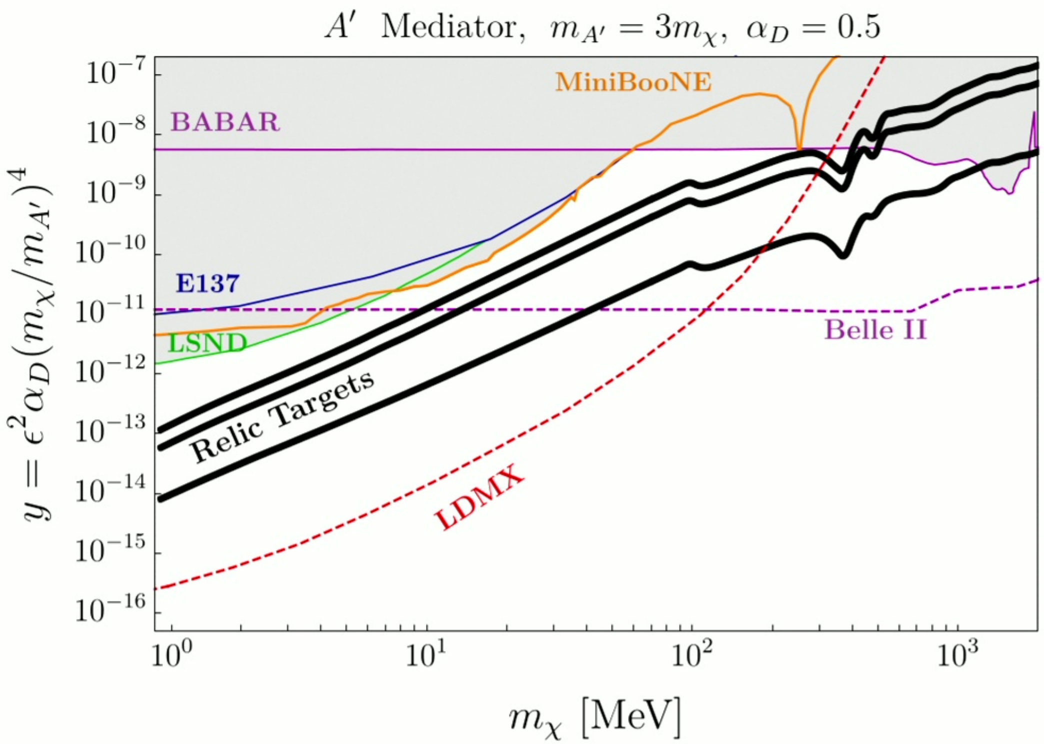


Åkesson et al '18, '22 ++

Discovery Prospects

Future FT experiments will test simple DM models



Berlin, NB, Krnjaic, Schuster & Toro '18

Other Approaches to Thermal DM

Many other implementations of light DM production

E.g. Strongly Interacting Massive Particles (SIMPs)

Carlson, Machacek and Hall (1992); Hochberg, Kuflik, Volansky and Wacker (2014)

Chemical equilibrium (within the DM) **Kinetic equilibrium (with the SM)**

These models are realized in strongly-coupled sectors

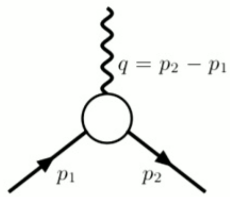
Qualitatively different signatures at FT experiments

Specific examples: see, e.g., Hochberg, Kuflik & Murayama (2015); Berlin, NB, Gori, Schuster & Toro (2018); Hochberg, Kuflik, McGehee, Murayama & Schutz (2018)++

Anomalies

Several experimental anomalies can be explained with new light physics. See, e.g., Harris, Schuster & Zupan '22

E.g. muon g-2:



$$\langle \mu_{p_2} | J^\mu(0) | \mu_{p_1} \rangle = \bar{u}_{p_2} \left[F_D(q^2)\gamma^\mu + F_P(q^2) \frac{i\sigma^{\mu\nu} q_\nu}{2m} \right] u_{p_1}$$

$$g - 2 \equiv F_P(0)$$

Melnikov & Vainshtein '06

$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{Theory}) = (251 \pm 59) \times 10^{-11}$$

(but see recent lattice results: Borsanyi et al '20)

Contributions from new scalars, vectors can resolve discrepancy

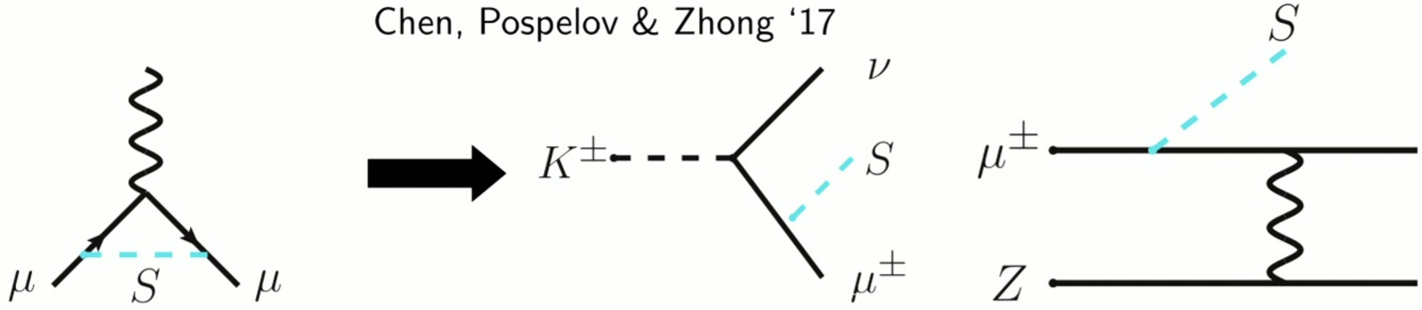
Kinoshita & Marciano '90

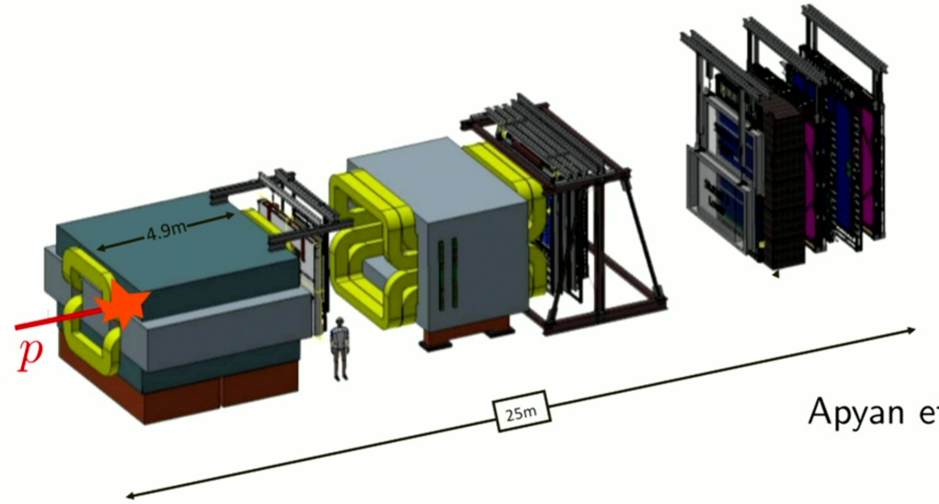
Concrete Example: DarkQuest

Low mass explanations of g-2 can be tested with FT.

Even minimal ones, **only** with couplings to muons

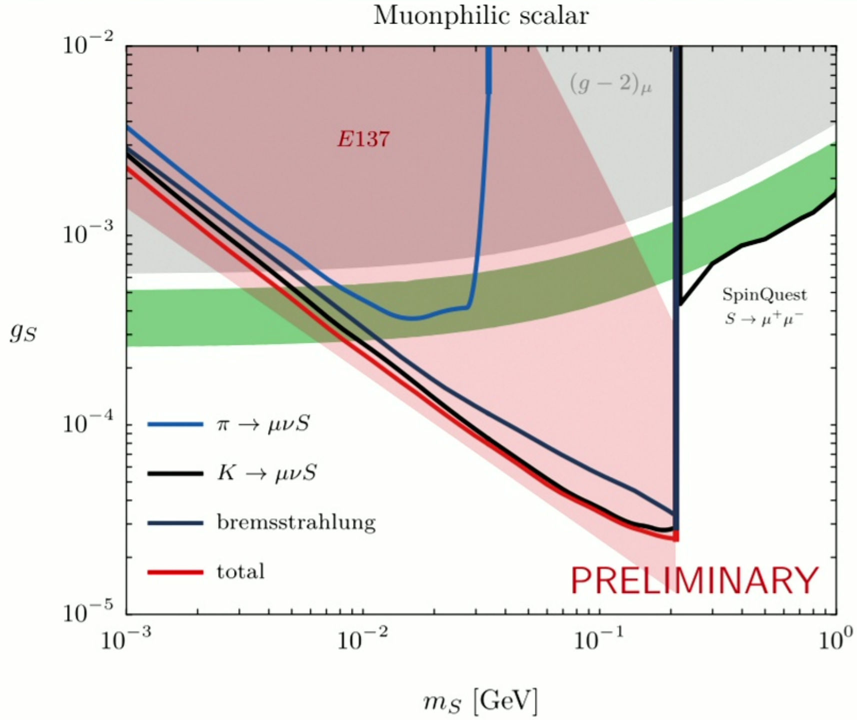
Chen, Pospelov & Zhong '17





Apyan et al '22

DarkQuest

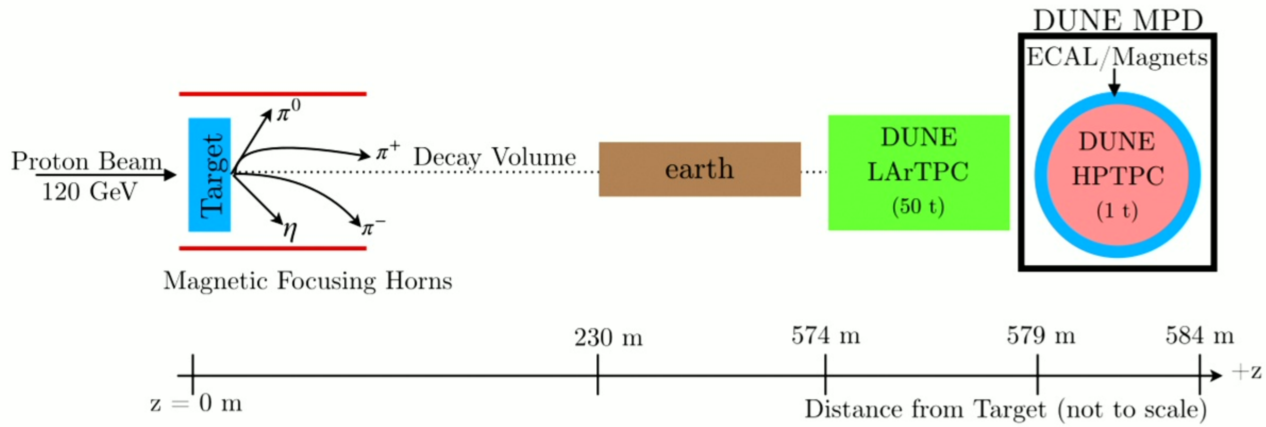


NB, Gori & Hamer (soon); see also Forbes et al '23

Short-baseline FT experiments like DarkQuest have many other BSM applications: DM, portals, etc.

DUNE and Other Neutrino Experiments

Neutrino sources are FT experiments



Applications of DUNE ND to BSM: Berryman et al '19

Beyond-SM searches for "free"!

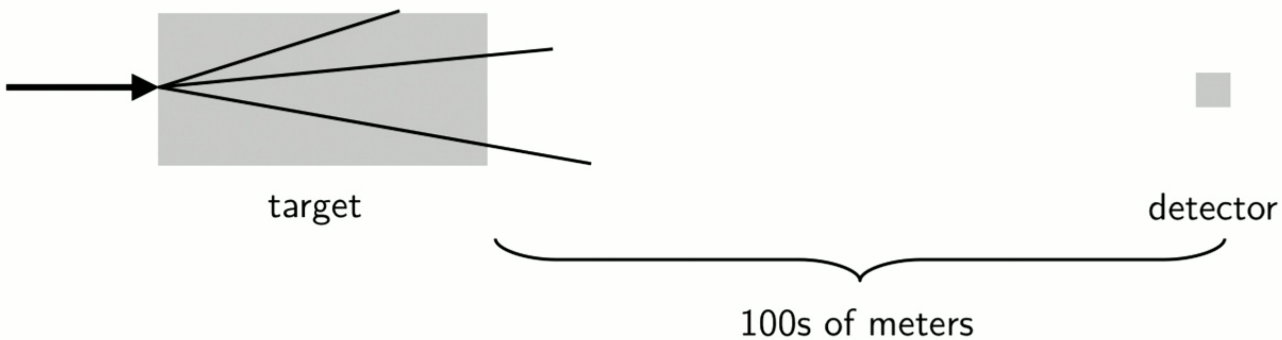
See also deNiverville, Pospelov & Ritz '11++; MiniBooNE DM Results '18, Batell, Berger & Ismail '19...

There is a well-developed science case for a new generation of fixed-target experiments

Many experiments are planned or are operating.

The Basic Challenge

Many detectors subtend tiny solid angles from target



E.g.: DUNE Near detector: size of ~2.5 m at a distance of ~ 600 m

Signal rates very sensitive to angular distribution!

Difficulties In Modeling Signal

Signal rate in a detector sensitive to both SM and BSM dynamics. Surprisingly challenging to predict:

1) **SM simulation effectively a black box**

   Many models/approximations in GEANT, FLUKA

2) **BSM processes often difficult for off-the-shelf codes**

   Kinematic singularities, in-medium propagation effects

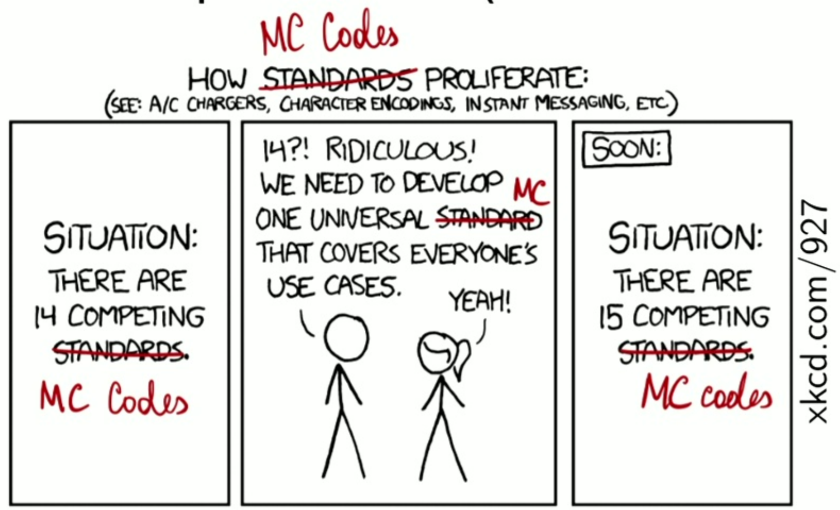
3) **No standard tool chain, a la collider physics:**

   MadGraph+Pythia+DELPHEs

PETITE

Package for **E**lectromagnetic **T**ransitions **I**n **T**hick-target **E**nvironment

Minimal set of SM and BSM processes to enable simulation of BSM production (in one model so far)



Not a replacement for existing generators!

A Simple Toy Model

Focus on electromagnetically-coupled new physics

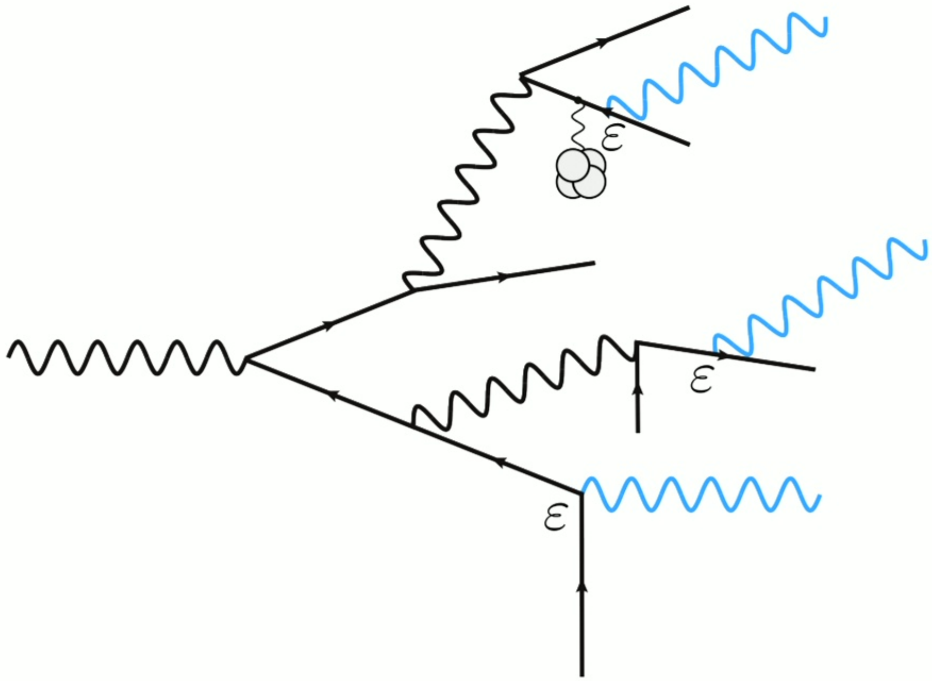
$$\mathcal{L} \supset e\varepsilon V^{\mu}\bar{e}\gamma_{\mu}e, \quad \varepsilon \ll 1$$

UV *incomplete*, but simple and illustrates many issues in a controlled setting:

- ✔ SM part of production is calculable (perturbative)
- ✔ Small set of production channels
- ✔ Relevant to many UV *complete* models

$$A', \;\; U(1)_{L_e - L_j}, \;\; U(1)_{B-L}, \;\; \ldots$$

BSM Emission from SM Shower



Previous experiments constrain $\varepsilon << 1$, so at most one emission per shower

SM and BSM production "factorize".

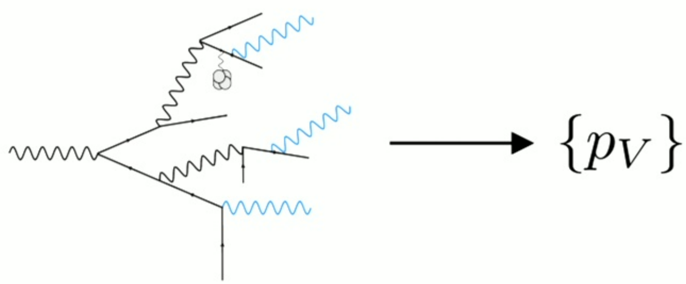
Small Coupling Regime

SM and BSM events can be simulated separately

(not always done, see Bondi et al '21 Eichlersmith et al '22)

Key advantage over doing SM and BSM simultaneously: efficiency

Large statistics w/o re-running expensive SM



Existing Tools for the SM Part

There are well-established tools for doing SM simulations: GEANT, FLUKA, EGS, etc

Typical algorithm: for each particle in the shower

1) Propagate it a small amount $x_{\text{step}} \sim$ MFP.
2) Determine if "hard" interaction took place. If it did, sample $d\sigma$ and add new particles to the shower
3) If not, update momentum using "continuous" processes (Coulomb, ionization, soft brem.)

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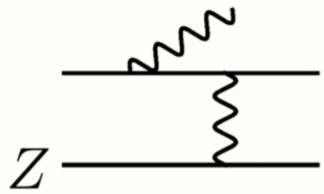
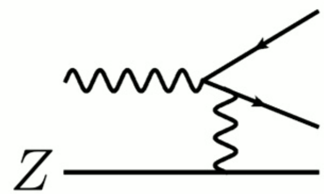
SM Processes

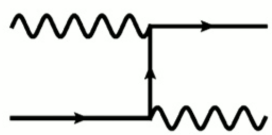
EM cascades of SM particles driven by:

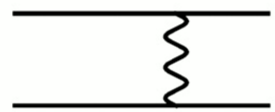
- Bremsstrahlung & Pair production



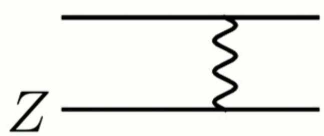


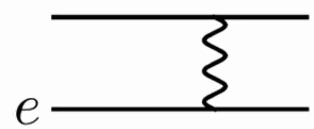
- Electron/Positron/Photon scattering on atomic e





- Coulomb scattering & Ionization





Simulation of a SM Shower

Differential rates for all of these can be perturbatively computed using standard QFT.

$$\frac{d\sigma_i}{dk_p d\Omega_p d \ldots}$$

Challenge: slow MC for peaky, high-dimensional integrands. Many approximations used.

Some processes are so frequent that they must be treated as quasi-continuous (ionization, Coulomb scatters; soft brem)

Example: Bremsstrahlung

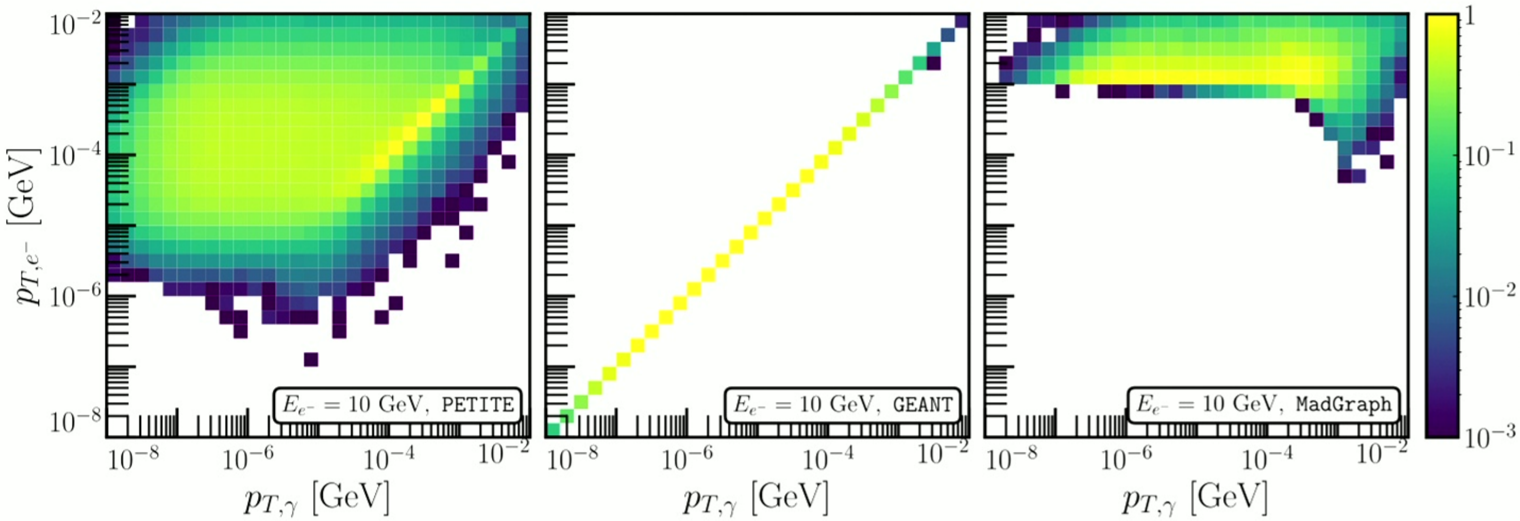
- 5D dimensional phase space (different for each incoming energy)
- Brute-force sampling using VEGAS: seconds/minutes *per event*
- Need to do this 100s of times per shower

Common approach: use marginalized distributions (1D for photon energy and angle)

Simulating SM Bremsstrahlung

Let's compare different implementations of

$$\frac{d\sigma_{\rm brem}}{dE_\gamma dp_{T,\gamma} dp_{T,e}}$$



What's going on?

What's going on with SM Bremsstrahlung?

The full differential cross-section looks like

$$d\sigma \propto \delta\delta' \times \left\{ \frac{\delta^2}{(1+\delta^2)^2} + \frac{\delta'^2}{(1+\delta'^2)^2} + \frac{\omega^2}{2\epsilon\epsilon'} \frac{\delta^2+\delta'^2}{(1+\delta^2)(1+\delta'^2)} - \left(\frac{\epsilon'}{\epsilon} + \frac{\epsilon}{\epsilon'} \right) \frac{\delta\delta' \cos\phi}{(1+\delta^2)(1+\delta'^2)} \right\}$$

$$\delta \sim p_{T,\gamma} \quad \delta' \sim p_{T,e}$$

Landau & Lifshitz

SM Monte Carlos (GEANT, FLUKA, ...) instead sample the photon from a 1D distribution and set

$$p_{T,e} = p_{T,\gamma}$$

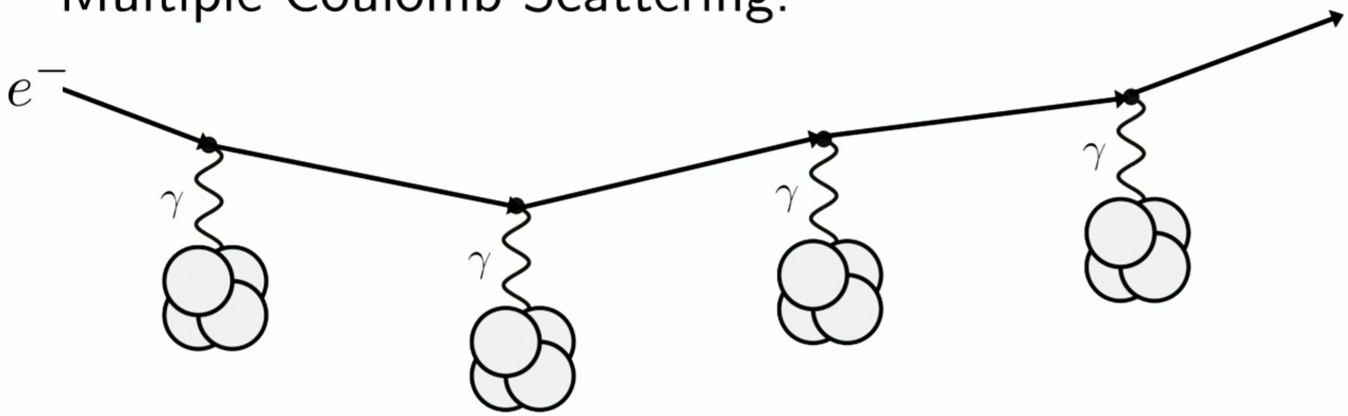
Angular distribution of recoil e is incorrect!

Is this important?

Is This Important?

It depends. Transverse evolution sensitive to

- Angular distributions of Brem, Compton, etc
- Multiple Coulomb Scattering:



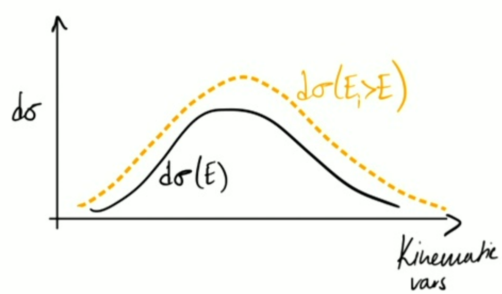
$$\theta_{\mathrm{MCS}} \sim 14 \left(\frac{\mathrm{MeV}}{p}\right) \sqrt{t/X_0} \quad \text{vs} \quad \theta_{\mathrm{Brem}} \sim \frac{m_e}{p}$$

Our Solution

- `PETITE` samples from the full 5D distribution each time
- We pre-train VEGAS on a grid of energies E_i:

  Fast sampling of a discrete set of $d\sigma(E_i)$

- Key observation: for an incident E, the phase space for any $E_i > E$ is a superset



Importance sampling at energy E is fast using the pre-trained integrand

Simulating BSM Processes

BSM processes come with their own challenges

Two examples:

1) **Bremsstrahlung of dark sector stuff**

Nearly singular ME, difficult to sample like in SM

2) **Positron annihilation**

Tight interplay with SM processes requires care

Is This Important?

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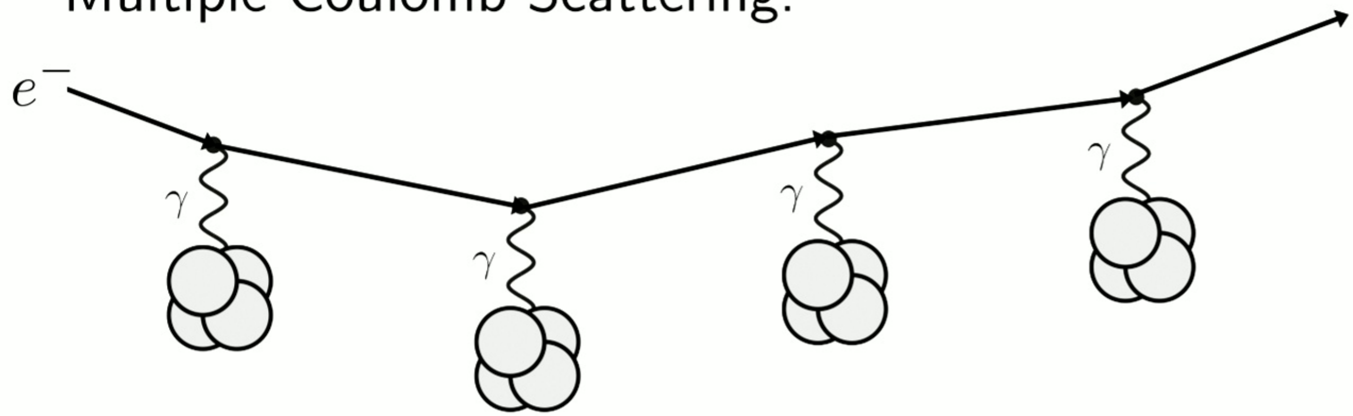

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BSM Bremsstrahlung

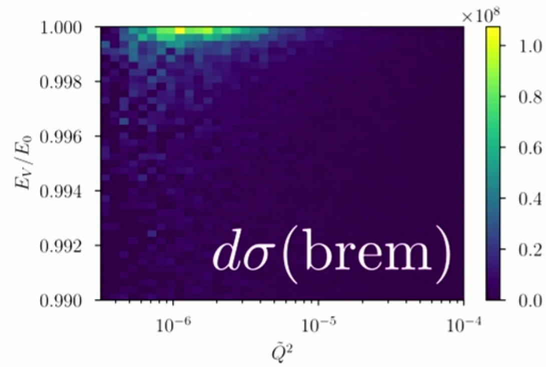
Ubiquotous channel for bosonic particle production

$$e + N \to e + N + V$$

Tsai '86, '89; Liu, McKeen & Miller '16++

Straightforward to write down matrix element:

$$\mathcal{M} \propto \frac{1}{Q^2}\left[(\not{P} + \not{P}')\frac{(\not{p} - \not{k} + m_e)}{m_V^2 - 2p\cdot k}\gamma^\mu + \gamma^\mu \frac{(\not{p}' + \not{k} + m_e)}{m_V^2 + 2p'\cdot k}(\not{P} + \not{P}')\right].$$

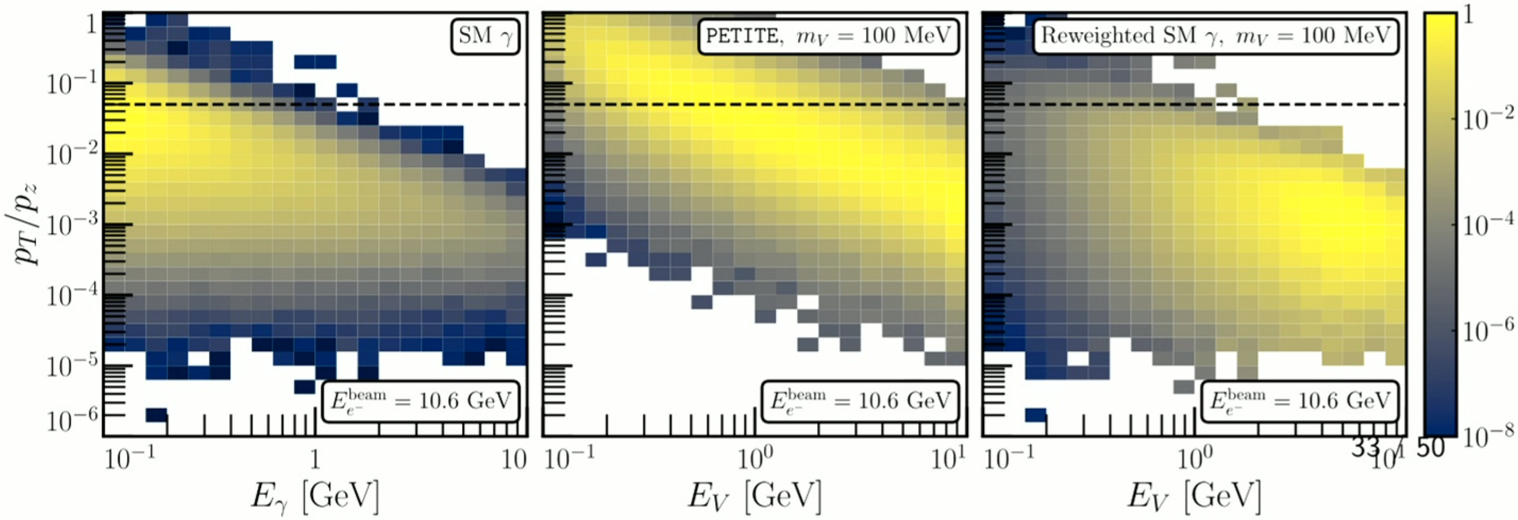


Problem: high dimensional, very peaked phase space

Distributions

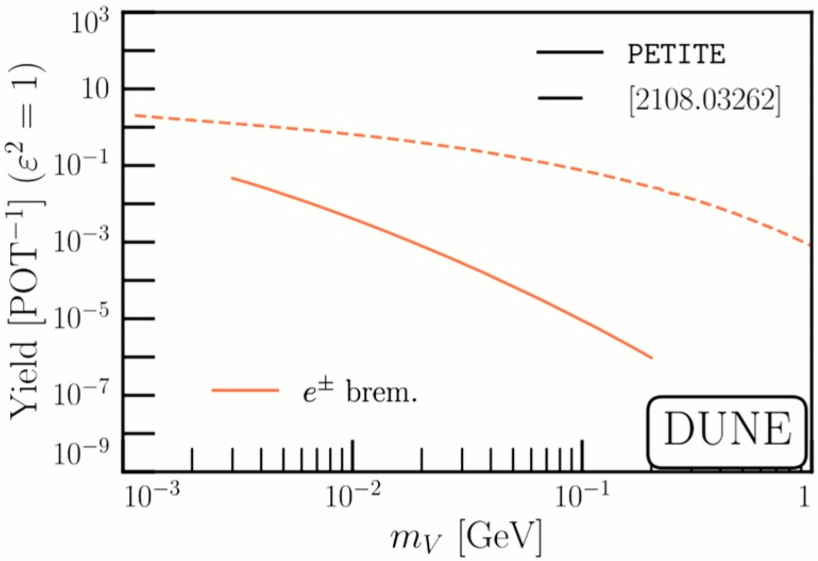
- Angular distributions make an important impact
- One trick used in the past: re-use SM photons from shower by re-weighing according to energy (not angle) $N_V(\theta_i, E_j) = \varepsilon^2 N_\gamma(\theta_i, E_j) \times f\left(\frac{m_V}{E_e}\right)$

Capozzi et al '21



Experimental Impact

- Close detector (e.g., BDX): geometric acceptance over-estimated by 40%
- Far-away detector (e.g., DUNE): over-estimated by ~1-2 orders of magnitude



What's Going On? (BSM Brem Edition)

Kinematics of SM and BSM brem are very different

$$\frac{d\sigma_V}{dE_V\,d\theta_V} \propto \frac{1}{(E_e E_V^2 \theta^2 + m_V^2(E_e - E_V) + m_e^2 E_V)^2}$$

SM Brem (mV=0): preferentially soft, collinear

BSM Brem (mV>me): $E_V = E_e$,

The new mass scale radically changes the emission pattern compared to SM

PETITE uses the exact tree-level differential cross-section

Other Approaches

- Weiszacker-Williams approx. for kinematics

  fast sampling of BSM state, but neglects nuclear recoil

  Bondi et al 2021

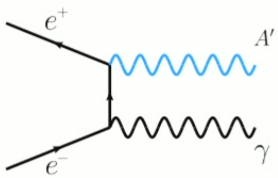
- Choose events from discrete set of MadGaph-simulations and rescale momenta

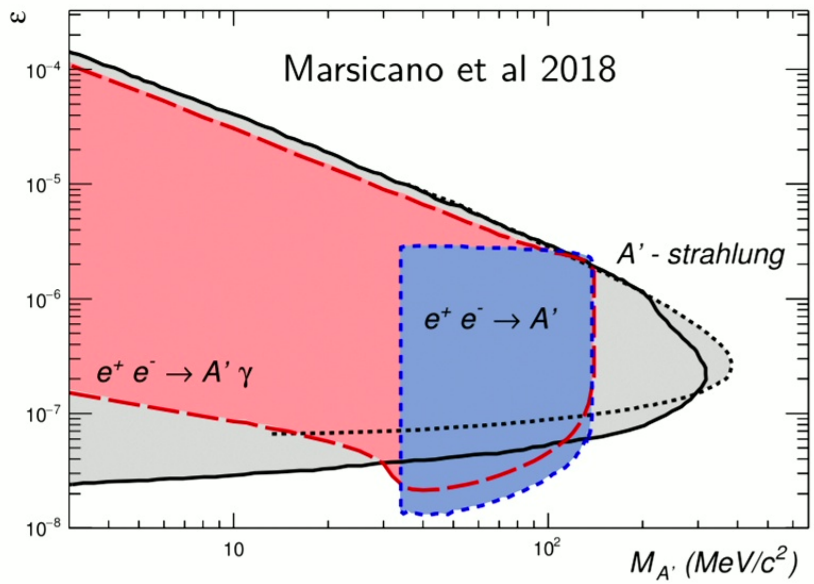
  MG not always reliable, different choices for the rescaling procedure possible

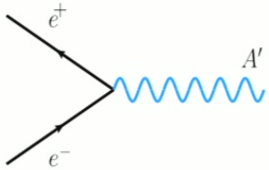
  Eichlersmith et al 2022

Annihilations

Recently realized to be an important contribution BSM production







$$\sigma_{\mathrm{res,tree}} = 4\pi^2\alpha\varepsilon^2\delta(s - m_V^2)$$

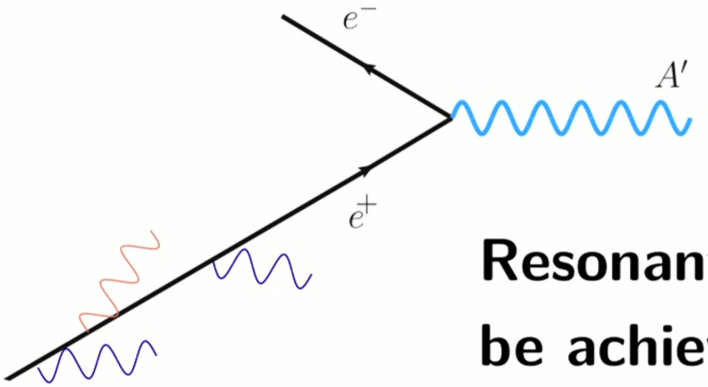
Soft and Collinear Emissions

$$N_{A'} = \frac{N_A}{A} Z\rho \int_{E^R_{min}}^{E_0} dE_e \, T_+(E_e)\, \sigma(E_e)$$

Marsicano et al 2018

Real energy losses proceed in steps: how do you hit an infinitesimally narrow resonance?

Charged particles radiate soft and collinear photons



Collinear emissions cost

$$\alpha \ln s/m_e^2 \sim 0.1$$

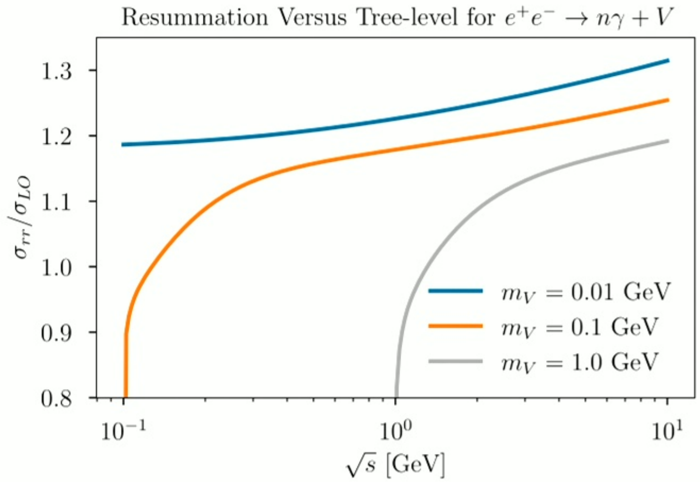
Resonant annihilation can always be achieved after some emissions!

Radiative Return

These emissions allow "resonant" production to occur for any sqrt(s)>m_V

See, e.g., Nicrosini & Trentadue '87

$$\sigma(e^+e^- \to V + n\gamma) = \left[\frac{4\pi^2\alpha\varepsilon^2}{s}\right]\int_{m_V^2/s}^{1}\frac{dx}{x}\underbrace{f_e(x,s)f_e\left(\frac{m_V^2}{xs},s\right)}$$



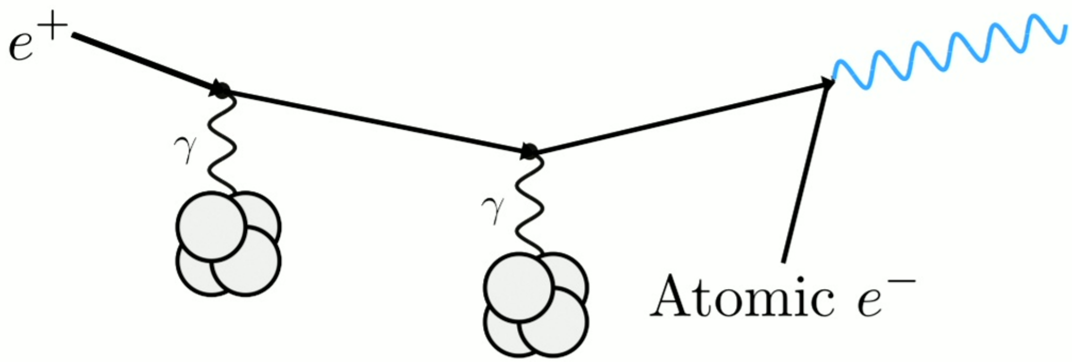
Electron PDFs

Probability for the electrons to Carry fraction x of original momentum (unlike QCD, these can be computed)

Enhanced rate compared to tree-level and clarity re: discrete energy losses

Interplay with Multiple Scattering

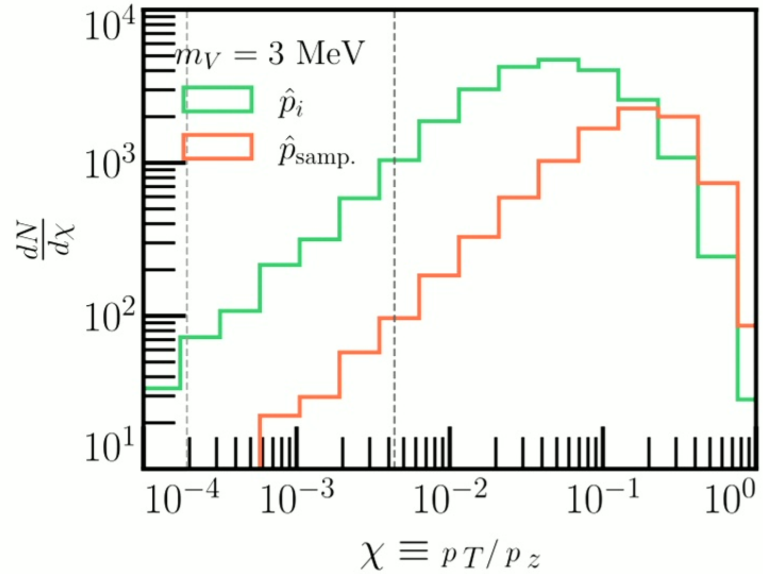
Atomic electrons effectively at rest: kinematics of V determined completely by e$^+$ at interaction point



Positron direction at production and interaction can be completely different!

Coulomb Scattering and Annihilation

Typical simulations so far: 1) Generate sample of positron momenta in a shower 2) convolve with annihilation cross-section



Choices in 1) can lead to order-of-magnitude changes in angular acceptance!

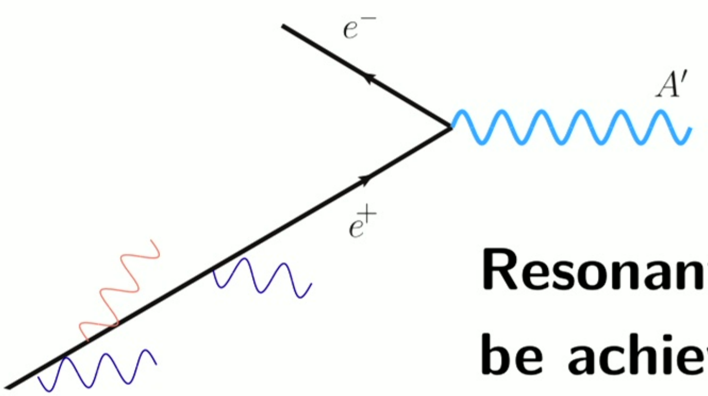
Soft and Collinear Emissions

$$N_{A'} = \frac{N_A}{A} Z\rho \int_{E^R_{min}}^{E_0} dE_e \, T_+(E_e)\, \sigma(E_e)$$

Marsicano et al 2018

Real energy losses proceed in steps: how do you hit an infinitesimally narrow resonance?

Charged particles radiate soft and collinear photons



Collinear emissions cost

$$\alpha \ln s/m_e^2 \sim 0.1$$

Resonant annihilation can always be achieved after some emissions!

Coulomb Scattering and Annihilation

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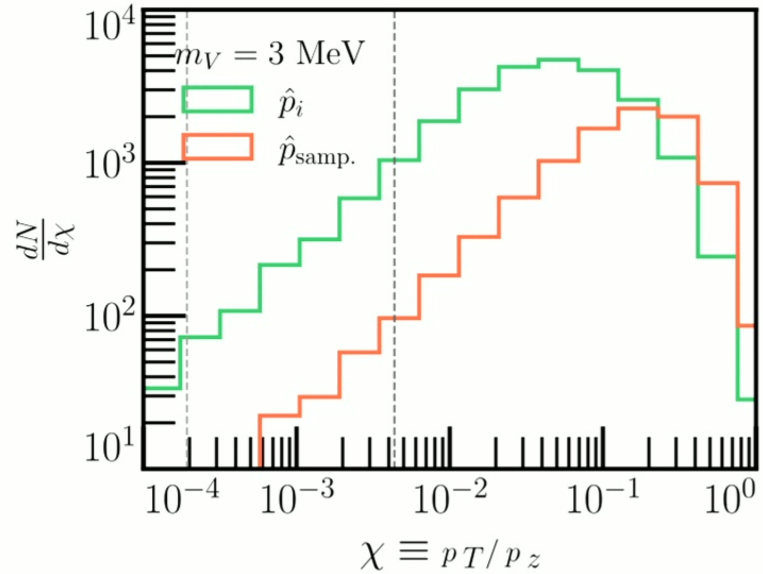


Choices in 1) can lead to order-of-magnitude changes in angular acceptance!

PETITE Solution

Given a positron momentum at production p_i

1) Generate an interaction position by sampling

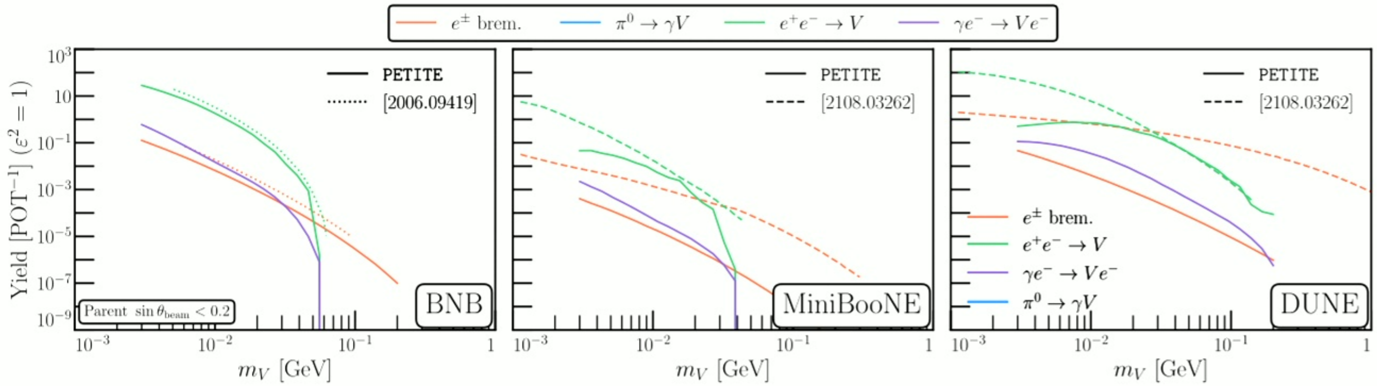
$$\frac{dw^{(p)}}{dz} = n^{(p)} \sigma^{(p)}_{\rm BSM}(z) \ \exp\left(- \int_0^z \frac{dz'}{\lambda^{\rm SM}_{\rm MFP}(z')} \right)$$

2) Apply energy loss and multiple scattering to get $p_{\rm samp}$

3) Generate kinematics for annihilation using $p_{\rm samp}$

This correctly assigns momentum to V!

Summary of Effects in Realistic Setups



Large variations in predicted signal rates arise from different approximations

Conclusion

- Fixed target experiments are useful

  New probes of DM, anomalies, EFT operators

- Signal (and background) simulation is tricky, even if only QED-type processes are involved

  Process multiplicity, numerous approx. used

- Better simulations needed for reliable predictions

  Some challenges addressed in `PETITE`

- Future work: applications to real experiments

Thank you!