Light Dark Matter Signatures at LDMX

A Likelihood-Based Statistical Framework and Ab Initio Nuclear Modelling

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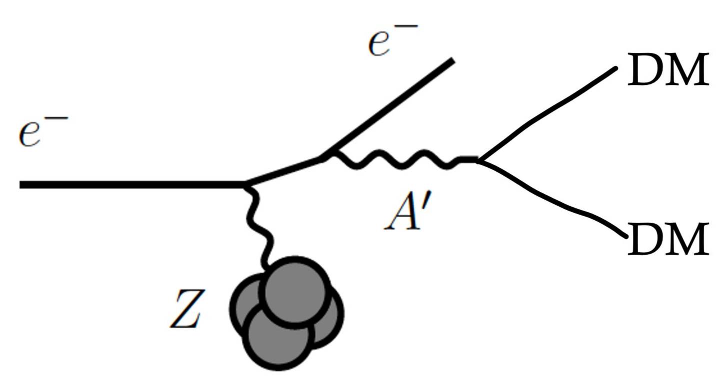
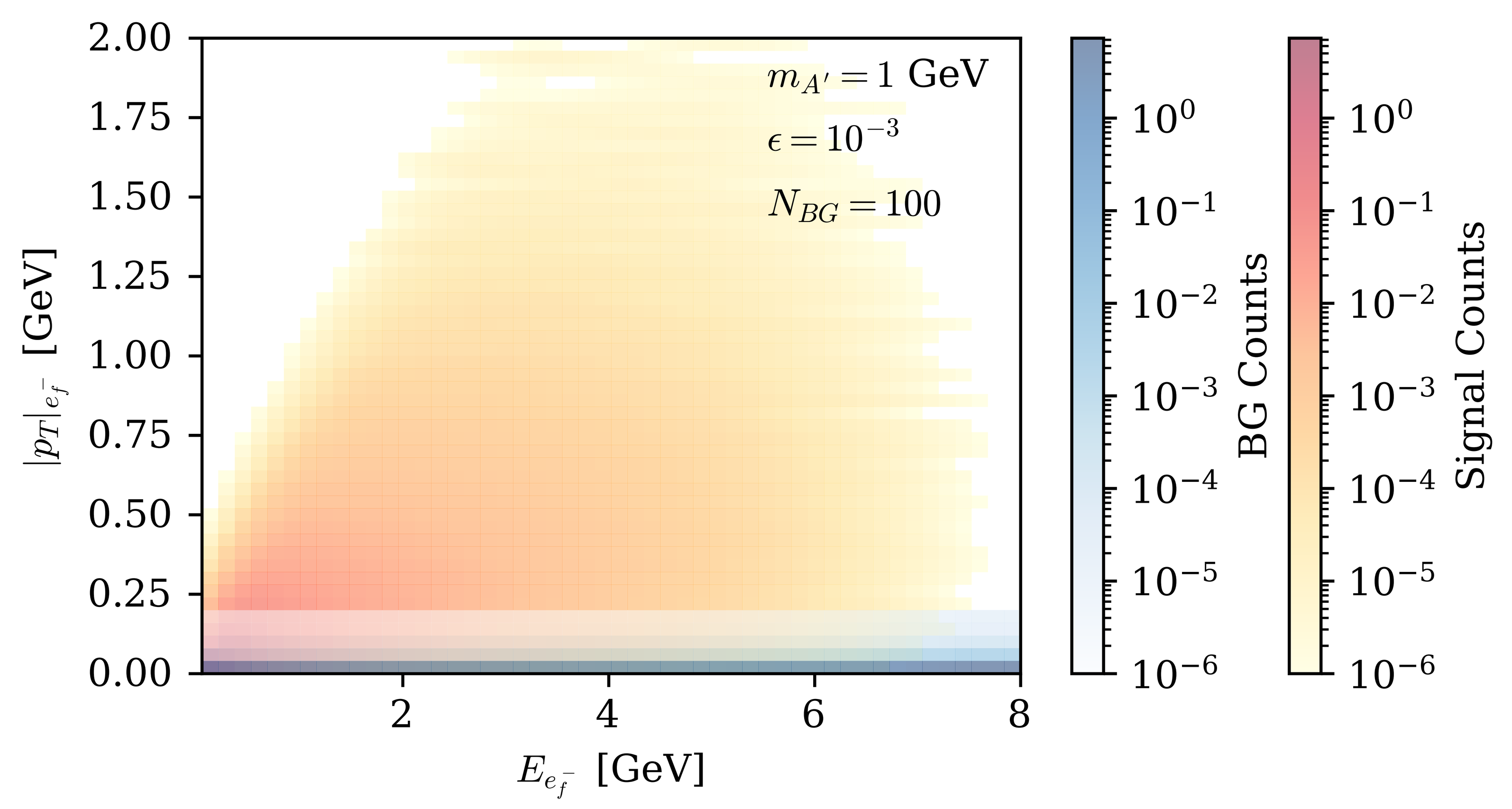
LDMX's Dark Matter Search



- The Light Dark Matter eXperiment (LDMX) is an electron fixed-target missing-momentum experiment with an 8 GeV beam and up to 10^{16} EOT.
- DM produced through dark bremsstrahlung via e^- target nucleus collisions.
- The **dark photon** A', the gauge boson of a new $U(1)'$ group and a DM mediator.

$$\mathscr{L}_{A'} = -\frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu} - \frac{1}{4}A'^{\mu\nu}A'_{\mu\nu} - \epsilon e A'^{\mu}\sum_f q_f \bar{f}\gamma_\mu f, \tag{1}$$

Signal & Background Modelling



- **Signal**: a recoil electron with **anomalously low energy** E **and large transverse momentum** p_T, from dark bremsstrahlung.
- **Background**: photo-nuclear processes producing neutral hadrons.
- The shape of the 2-D (E, p_T) distribution is dictated by $m_{A'}$.

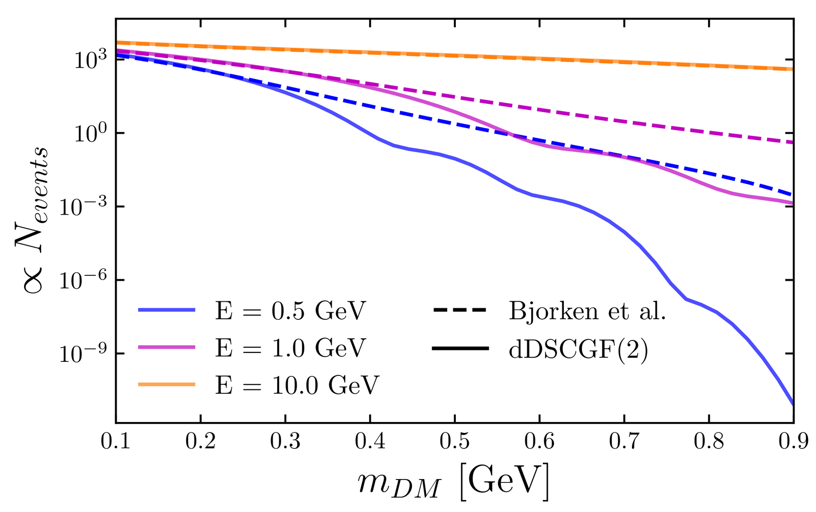
Ab Initio Nuclear Input

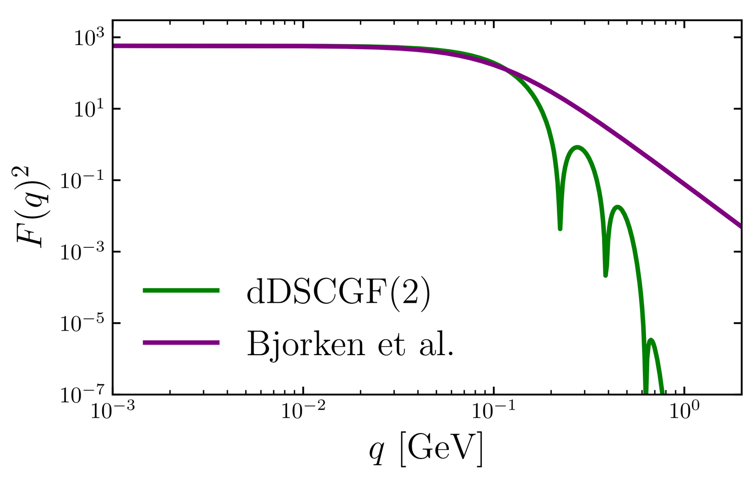
What is the impact of **nuclear structure**?

We use the **deformed Dyson Self-Consistent Green's Function** many-body method applied with chiral EFT interactions.

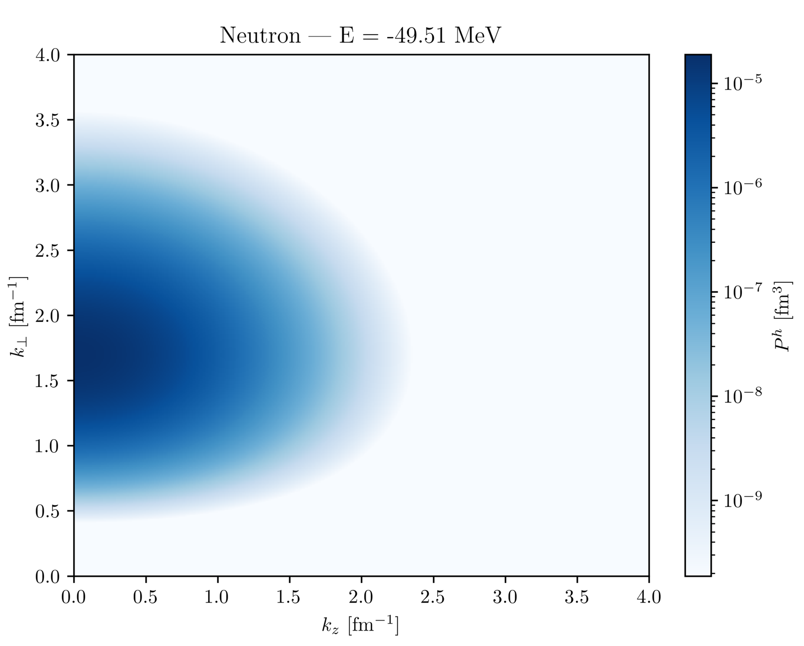
Elastic Scattering

$$N_{\text{events}} \propto \int dq \frac{q^2 - q^2_{\text{min}}}{q^3}|F(q)|^2, \qquad F(q) = \int d\vec{r}\, \rho_{\text{ch}}(\vec{r})\, e^{-i\vec{q}\cdot\vec{r}} \tag{2}$$





Quasi-Elastic Scattering



$$d\sigma_N = \int dE\, d^3k\, d\sigma_n\, P(\vec{k}, E) \tag{3}$$

$P(\vec{k}, E) \equiv$ Spectral Function

Likelihood Framework

We construct a **binned Poisson likelihood** over the 2D (E, p_T) space, incorporating signal and background uncertainties.

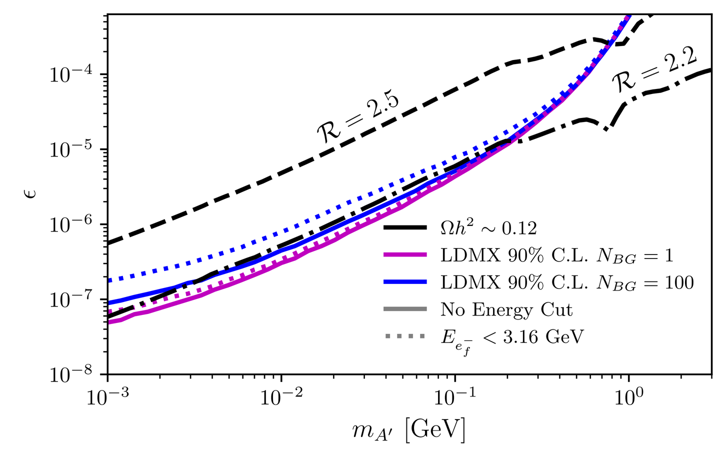
$$\mathcal{L}(\vec{d}|\epsilon, m_{A'}, \theta_S, \theta_B) = \prod_i^{N_E}\prod_j^{N_{PT}} \frac{\left[S_{ij}(\epsilon, m_{A'})\theta_S + B_{ij}\theta_B\right]^{d_{ij}}}{d_{ij}!} e^{-\left[S_{ij}(\epsilon, m_{A'})\theta_S + B_{ij}\theta_B\right]} \times \mathcal{P}(\theta_B|\sigma_B^2)\mathcal{P}(\theta_S|\sigma_S^2) \tag{4}$$

Asymptotic approximations **fail** at low bin counts $\Rightarrow$ full pseudo-experiment generation is essential for reliable exclusion and discovery.

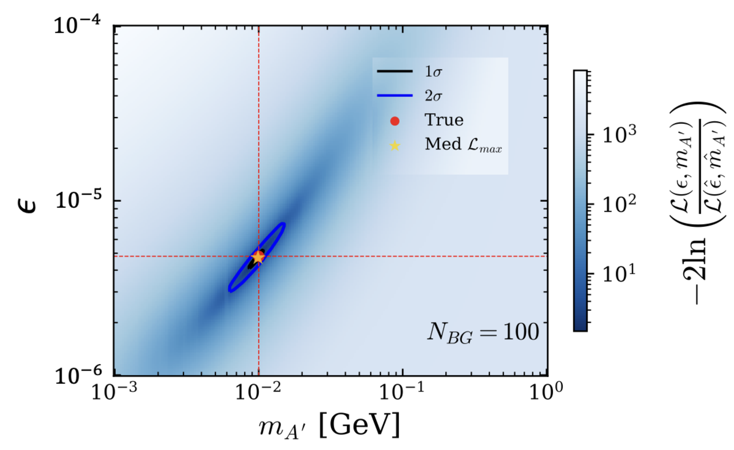
We take four **benchmarks** along the **complex scalar DM thermal relic targets** $R \equiv m_{A'}/m_{\text{DM}} = 2.5$ and 2.2 — which survive after recent DAMIC-M and PandaX-4T constraints.

Frequentist Analysis

- Exclusion:

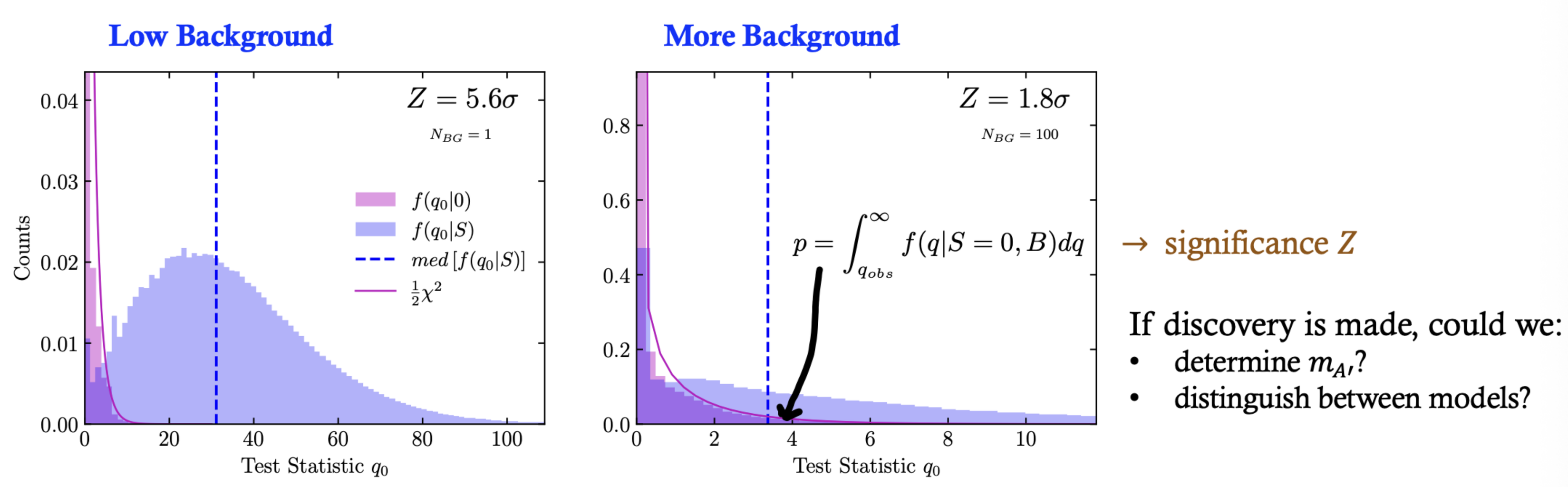


- Parameter Estimation:



- **Discovery:** Median expected significance from toy pseudo-experiments.

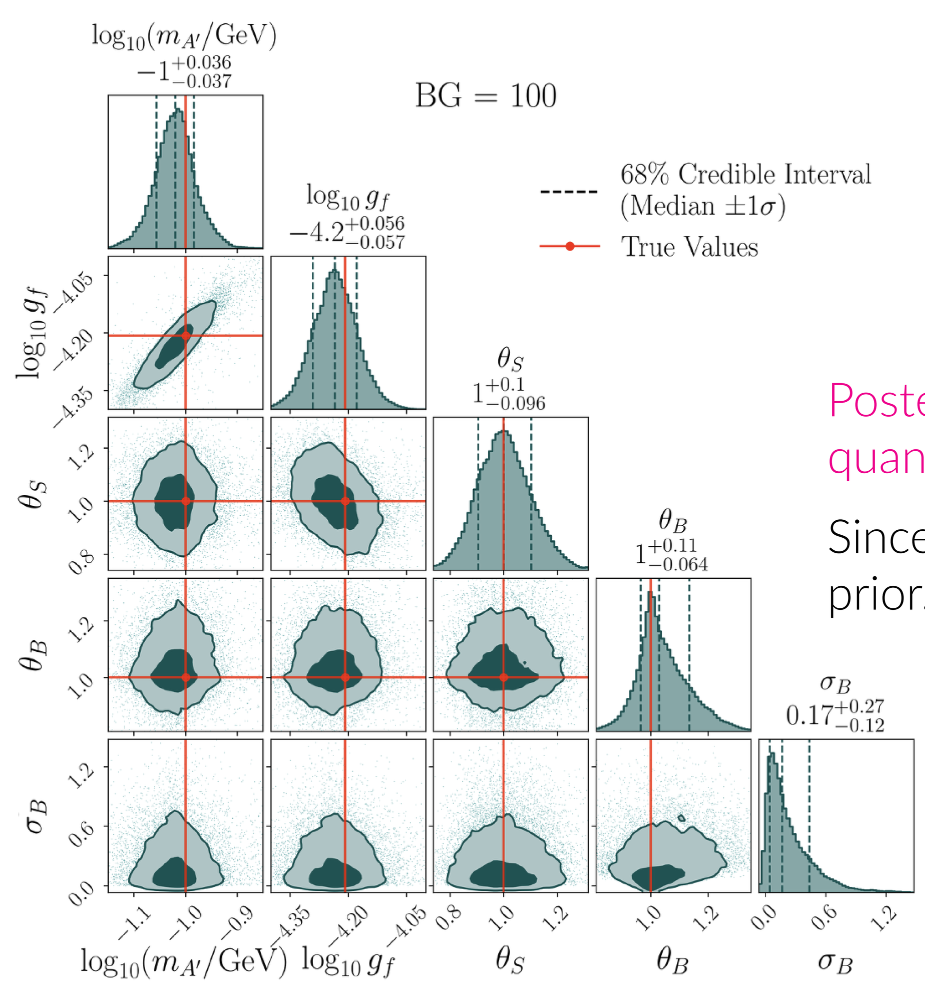
	$m_{A'}$ [GeV]	$\mathcal{R} \equiv \frac{m_{A'}}{m_{\text{DM}}}$	ϵ	S	$Z_{B=1}$	$Z_{B=100}$
BM 1	0.01	2.5	4.81×10^{-6}	425	$\gg 5$	$\gg 5$
BM 2	0.01	2.2	5.21×10^{-7}	5	5.6	1.8
BM 3	0.1	2.5	6.27×10^{-5}	333	$\gg 5$	$\gg 5$
BM 4	0.1	2.2	5.96×10^{-6}	3	5.1	2.9



Bayesian Analysis

$$p(m_{A'}, \epsilon, \vec{\theta} \mid \vec{d}) \propto \mathcal{L}(\vec{d} \mid m_{A'}, \epsilon, \vec{\theta})\, \pi(m_{A'}, \epsilon, \vec{\theta}) \tag{5}$$

Benchmark 1:



Posterior distributions give uncertainty quantification of inferred parameters!

Since σ_B is not known, we use a hyper-prior.

Summary

- It's an exciting time for Light DM searches!
  - Upcoming fixed-target experiments and recent bounds from direct detection via e^- recoils
- However, we need to:
  - Know how to deal with a potential signal using a **full statistical framework**
  - Properly model the signal + background
  - **Nuclear structure** plays a vital role