IRIS-HEP Fellows Program Project Proposal

Unified Constraints on LLP/FIP Models: Collider-Cosmology Synergy

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Project Duration: 12 weeks

Project description

The search for Long-Lived Particles (LLPs) challenges our understanding of the Standard Model (SM) and opens new pathways to explore physics beyond it. LLPs arise in diverse BSM scenarios, including supersymmetric models with nearly degenerate spectra, hidden sector frameworks mediated by feeble interactions, and extensions addressing baryogenesis or dark matter. These particles are characterized by suppressed decay widths Γ, leading to macroscopic lifetimes $\tau \sim 1/\Gamma$, where fine-tuning of couplings and mass differences is often invoked. In this project, we study the constraints on dark matter from unified collider and cosmological detector data analyses.

We are mostly interested in constraints on the Fermion Portal Vector Dark Matter (FPVDM) model [1]. The FPVDM model posits a hidden $\mathrm{U}(1)_D$ gauge boson X_μ as a stable spin-1 dark matter candidate, which interacts with the Standard Model exclusively via heavy vector-like fermion mediators charged under both the $\mathrm{U}(1)_D$ and the SM gauge groups.

Project goals

The project consists of calculating or exploiting already existing constraints from experimental collider and cosmological data, and carefully combining these results into a unified picture that shows allowed regions for dark matter. We want to integrate collider data (ATLAS/CMS mono-X searches [2, 3], LHCb displaced vertex results) with cosmological constraints (Planck relic density [4, 5], CMB distortions [6]). Using Bayesian inference methods (e.g., MCMC), we will construct posterior distributions for key parameters ($m\chi m\chi$, $gDgD$). Deliverables include combined exclusion plots that highlight regions of parameter space accessible to both colliders and cosmology.

Timeline

- **Week 1–2: Literature Review & Tool Setup:**
  - Review existing joint collider-cosmology analyses (e.g., Higgs portal, dark photon studies).
  - Identify key parameters ($m\chi$, gD, $c\tau m\chi$, gD, $c\tau$) and datasets (ATLAS-CONF-2023-XXX, Planck 2018).
  - Set up computational tools.
- **Week 3–4: Data Collection & Preprocessing:**
  - Collate collider data: ATLAS/CMS mono-jet exclusion limits, LHCb displaced vertex efficiencies.
  - Extract cosmological constraints: Planck relic density limits, FIRAS CMB $\mu\mu$-distortion bounds.
- **Week 5–6: Statistical Framework Development:**
  - Define parameter space ($m\chi$, gD, $c\tau m\chi$, gD, $c\tau$) and priors.
  - Construct likelihood functions (Poisson likelihoods for collider, Gaussian likelihoods for cosmology).

– Validate framework with toy models (e.g., dark photon).

- **Week 7–8: MCMC Implementation & Testing:**
  - Code MCMC sampler for combined likelihood and test convergence criteria (Gelman-Rubin $R < 1.01$).
  - Run preliminary chains on mock data.
  - Debug sampling bottlenecks (e.g., parallelize chains).
- **Week 9–10: Full Data Analysis:**
  - Run MCMC on real collider/cosmology data.
  - Generate posterior distributions for $m\chi$, gD, $c\tau m\chi$, gD, $c\tau$.
  - Compute combined exclusion limits (95% CL).
- **Week 11–12: Systematic Error Evaluation & Final Analysis:**
  - Quantify uncertainties and rerun MCMC with systematic error margins.
  - Compare results with/without systematics.
  - Interpret results: Highlight regions excluded by collider vs cosmology.
  - Compare with standalone collider/cosmology studies and prepare for publication.

References

[1] A. Belyaev, A. Deandrea, S. Moretti, L. Panizzi, D.A. Ross and N. Thongyoi, *Fermionic portal to vector dark matter from a new gauge sector*, *Phys. Rev. D* **108** (2023) 095001 [2204.03510].

[2] ATLAS collaboration, *Highlights from Long-Lived Particle Searches at ATLAS*, in *56th Rencontres de Moriond on QCD and High Energy Interactions* , 5, 2022 [2205.07669].

[3] CMS collaboration, *Search for long-lived particles using displaced vertices and missing transverse momentum in proton-proton collisions at s=13 TeV*, *Phys. Rev. D* **109** (2024) 112005 [2402.15804].

[4] G. Lanfranchi, M. Pospelov and P. Schuster, *The Search for Feebly Interacting Particles*, *Ann. Rev. Nucl. Part. Sci.* **71** (2021) 279 [2011.02157].

[5] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *MicrOMEGAs 2.0: A Program to calculate the relic density of dark matter in a generic model*, *Comput. Phys. Commun.* **176** (2007) 367 [hep-ph/0607059].

[6] G. Arsenadze, A. Caputo, X. Gan, H. Liu and J.T. Ruderman, *Shaping dark photon spectral distortions*, *JHEP* **03** (2025) 018 [2409.12940].