Model-Independent Simulations in Dark Vector Physics

Project Overview, Methods, and Current Progress

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Outline

- Introduction
- Theory
- Dark Sector Physics
- Dark Vector Models involved
- Beam Dump Experiments
- DarkCast
- My Work Using DarkCast
- ALPINIST- Framework
- Present Status
- Conclusions

Introduction

What We Do?

- Developing model-independent and model-dependent simulations.
- ALPINIST - framework for simulating exotics - ALPs, Dark Vector, HNLs and their behavior in proton beam dump experiments.

Why We Do it?

- Calculate production yields and acceptances for decay products - easier to test experimental sensitivities to various exotic models.
- Reinterpret searches for various models.

Theory

Dark Sector Physics - BSM Basis

Set of New Particles, which have properties:

- Very light, feebly interacting, below ~100GeV (weak) scale
- Mediator connecting - visible and dark sectors through a "portal".

Significance:

- Could explain phenomenon like dark matter.

BSM Theory Connection:

- If DS states are heavier than the mediator. The physics of the mediator is then characterized in a mass — coupling parameter space.

Gauge coupling constant for X

Fermionic field – quark/leptons

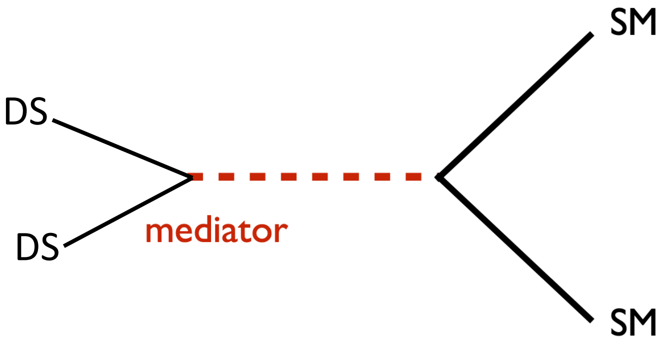
Mediator

DS particle

$$\mathcal{L} = g_X \sum_f \bar{f}\left(x_V^f \gamma^\mu + x_A^f \gamma^\mu \gamma^5\right) f X_\mu + \sum_\chi \mathcal{L}_{X_{\chi\bar{\chi}}}$$

Charge/coupling factor of fermion f

Current – coupling factor to X and f



Ref: [1] Serendipity in Dark Photon Searches, Ilten, P. et al. (2018)

Dark Vector Models

Generic Vector Bosons:

- Predicted BSM particles that may have unknown couplings, making them versatile dark sector mediator candidates.

Detection and SM Connection:

- These models predict unique decay modes and interaction strengths, allowing experiments to test for specific interactions with SM particles.

Extending SM with New Vector Bosons

Dark Photon(A'):

The dark photon couples to the SM photon via "kinetic mixing”.

B - L boson(Z'):

Arises from a gauge symmetry (Baryon – Lepton) numbers.

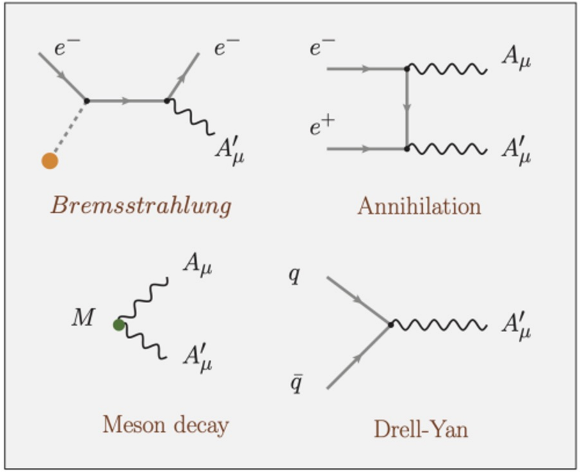
Leptophobic boson(B):

Couples directly to baryon number but not to leptons, hence it is termed "leptophobic."

Dark Photon

Dark Photon

- Hypothetical gauge boson, extension to the SM $U(1)_Y$ - hypercharge and new $U(1)_D$ – symmetry.
- Interacts with SM photon via Kinetic Mixing between the SM hypercharge and A' field strength tensors.



After EW sym. breaking

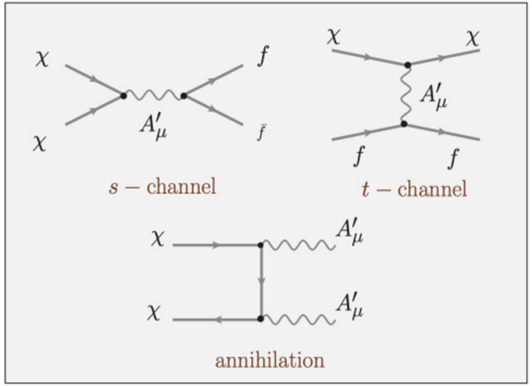
$$\mathcal{L} \ni -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} - i\bar{\chi}\gamma^\mu\partial_\mu\chi + m_\chi\bar{\chi}\chi + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + eQA_\mu\bar{f}\gamma^\mu f - y_\chi A'_\mu\bar{\chi}\gamma^\mu\chi,$$

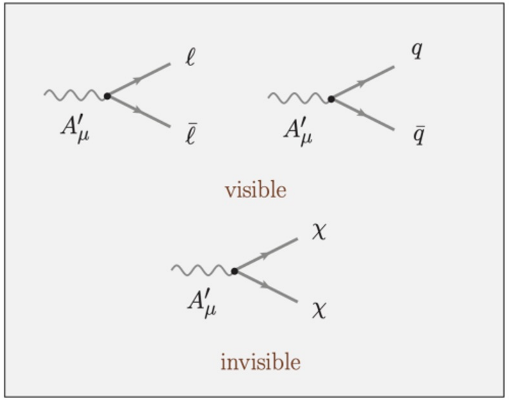
Before EW sym. breaking

$$\tilde{\mathcal{L}} = -\frac{\varepsilon}{2\cos\theta_W}\tilde{F}'_{\mu\nu}B^{\mu\nu}$$

Reference : [3] Fabbrichesi, M., Gabrielli, E. and Lanfranchi, G. (2020)

Dark Photon - Decays





- Visible decays: Dark photons with mass $m_{A'}$ <$2m_\chi$, decays into SM fermions.
- Dark photons are detected by reconstructing their decay products (e.g. $e^+e^-, \mu^+\mu^-$ pairs) within a defined decay volume.

Reference: [3] Fabbrichesi, M., Gabrielli, E. and Lanfranchi, G. (2020)

Phenomenology of DP

Parameters:

Mass ($m_{A'}$):

- Determines the kinematics of dark photon production and decay

Kinetic Mixing strength(ε):

Lifetime:

- The dark photon lifetime depends on its mass, momentum, and total decay width.
- For smaller (ε) or low $m_{A'}$, the lifetime can become significant, leading to displaced or long-lived decays

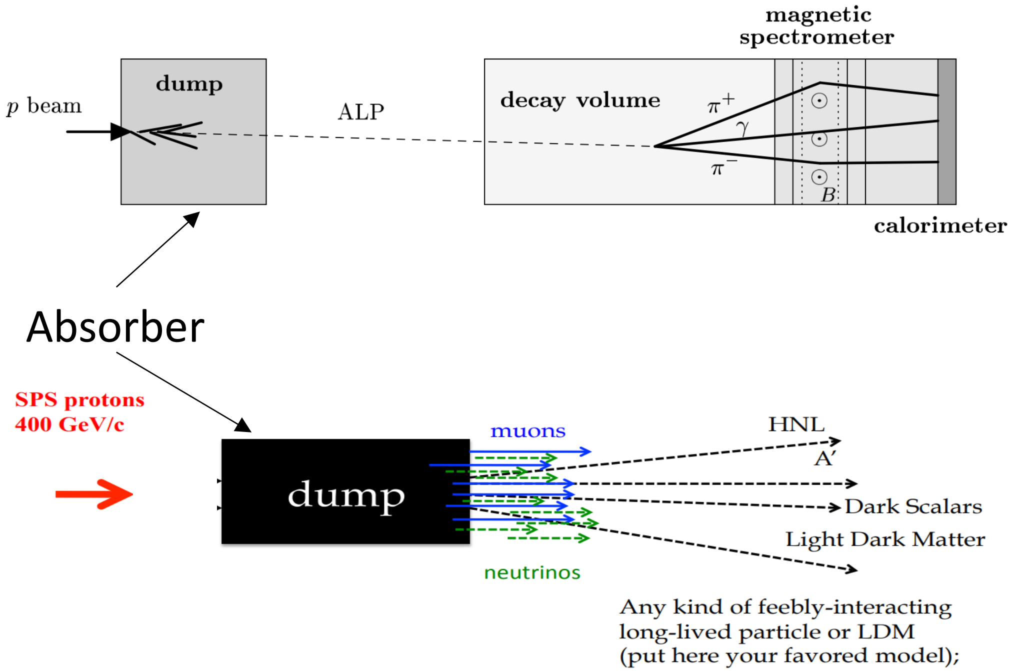
$$\tau_{A'} \propto \frac{1}{\epsilon^2 m_{A'}}$$

BR:

- The likelihood of decays into various final states.
- Depends on ($m_{A'}$), the available decay channels, and their respective coupling strengths.

Beam Dump Experiments

Beam Dump Experiments

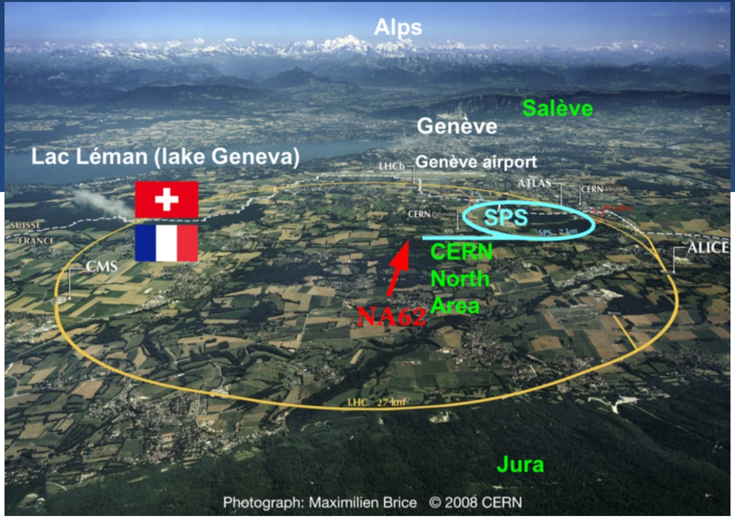


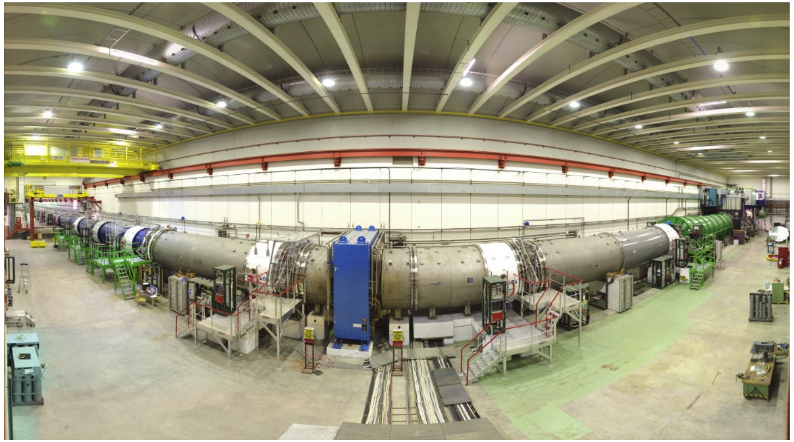
Reference: [2] Jerhot, J. et al. (2022) Alpinist: Axion-like particles in numerous interactions simulated and tabulated

NA62

- **Fixed target experiment** in CERN North Area (**400GeV SPS protons**)
- Main goal of experiment is to **measure the extremely rare decay**

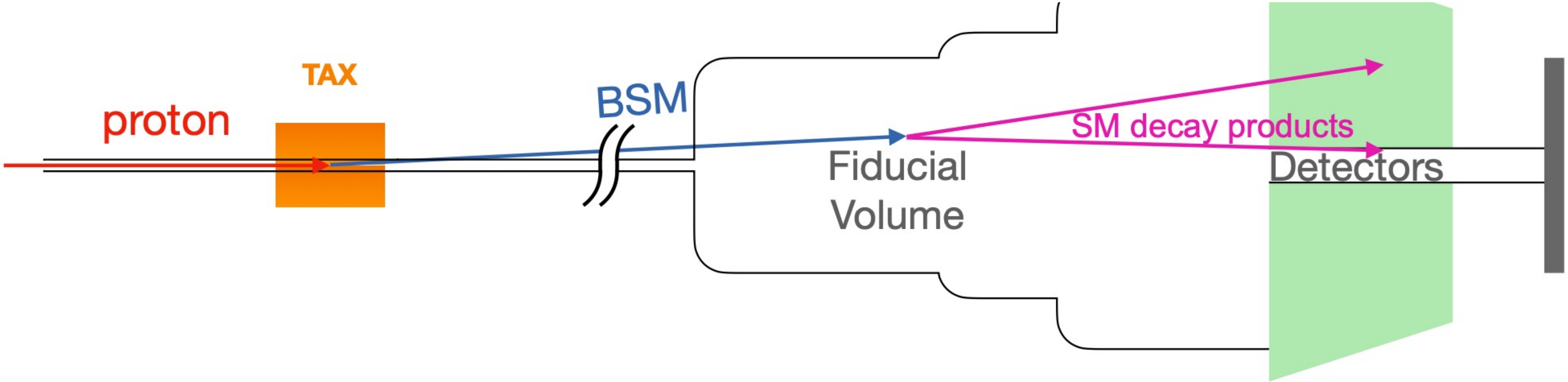
$$K^+ \to \pi^+ \nu \bar{\nu}$$





NA62 – Dump Mode

- 400 GeV proton beam from the CERN SPS accelerator is directed into a dense copper and iron target.
- Probability for production of DP with momentum above 10 GeV/c is of the order of $10^{-2} \times \varepsilon^2$ per proton.
- The long decay volume optimized for Kaon decay also allows sensitivity to long-lived BSM particles.



Comparison of Beam Dump Experiments

Feature	NA62 (Running)	CHARM (Past)	NuCAL (Past)
Beam Energy	400 GeV	400 GeV	70 GeV
Decay Volume Distance from Dump	105m(target)-180m(end of decay volume)	Starts ~480m(target)	64m(target)+23m(decay length)
Target Material	Copper + Iron	Copper	Iron
Physics focus	Flavour physics	Neutrino physics	Neutrino Physics

DarkCast

DarkCast - Framework

What is DarkCast?

- A framework for extending dark photon data to broader vector boson models.

Why Recast?:

- Existing experimental results focus on specific particles, such as the dark photon(A’).
- Other hypothetical particles, such as a vector boson (X), could have similar properties—like masses, lifetimes, or couplings to SM particles.
- Instead of running new experiments for each potential particle, DarkCast takes the data from dark photon experiments and adjust it to apply to different particles.

How it works?

$$\mathrm{BR}(X \to f) = \frac{\Gamma_{X\to f}}{\Gamma_X}$$

Cross-Section Scaling: Adjust production cross-sections to match new particles.

$$\frac{\sigma_{eZ\to eZX}}{\sigma_{eZ\to eZA'}} \approx \frac{(g_X x_e)^2}{(\epsilon e)^2}$$

Branching Ratios and Decay Widths: Recalculate decay probabilities.

Key Parameters for Recasting:

- Mass (mχ): Determines possible production channels and decay modes.
- Coupling Constants (g): Strength of the interaction which may vary for each particle.
- Branching Ratios - Br(Γ): Determine what fraction of X-bosons decay into specific particles.

Reference: [1] Serendipity in Dark Photon Searches, Ilten, P. et al. (2018)

Exclusion Plots - DarkCast

Physics of Decay Volume Geometry and Particle Sensitivity

- What is an Exclusion Plot?

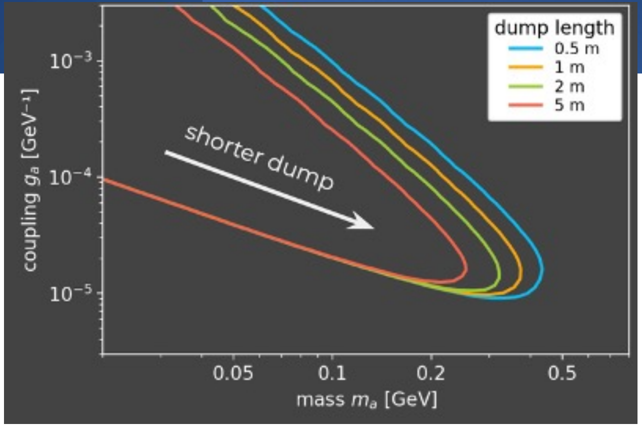
  Shows regions of parameter space (m, ϵ) that an experiment has ruled out with a given confidence level.

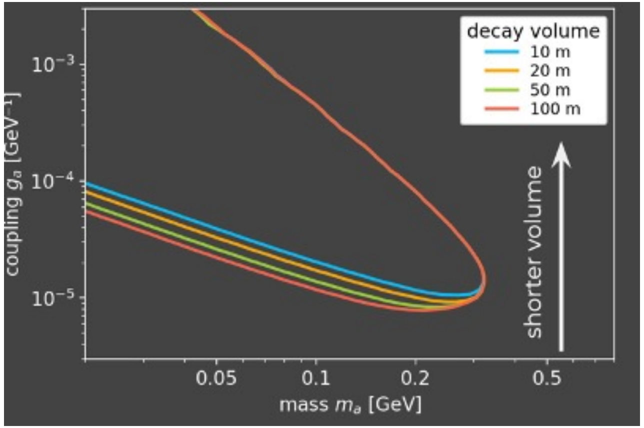
- Fixed Beam energies & decay lengths
  - Low energy – Short decay length
  - High energy – Longer decay length

- Modifying geometry changes/effect the sensitivity
  - Large g – short lived particles
  - Small g – long lived particles

- Past theory already constrained via experiments.

Reference: [5] Schulthess, I. (2024) *Opportunities at Future Collider Infrastructures*



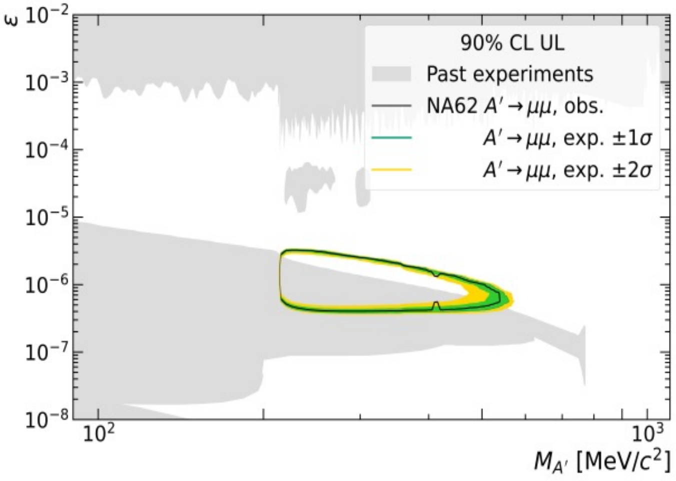


Physics of Decay Volume Geometry and Particle Sensitivity

The $m_{A'}$ and ε are the free parameters of the model.

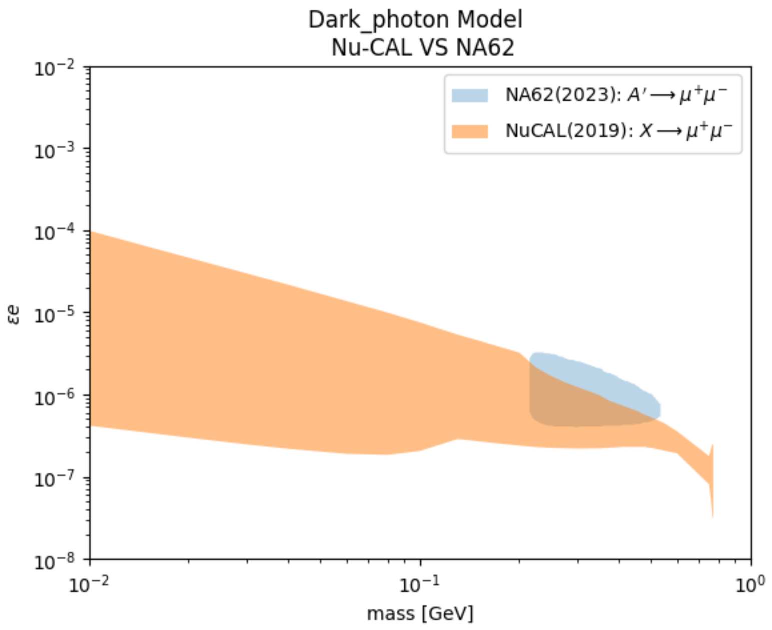
The relevant features of the DP- Model are:

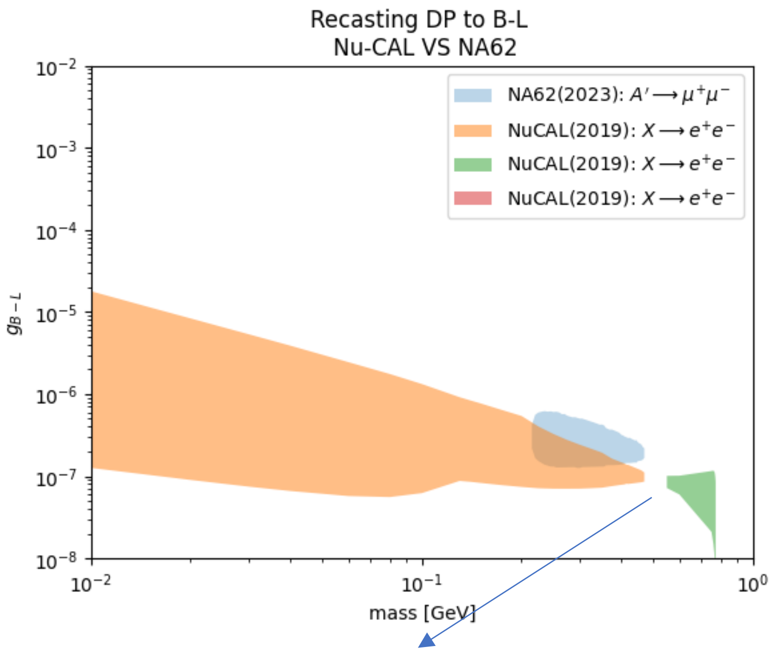
- Dark photons can be produced in proton-nucleus interactions via bremsstrahlung or decays of secondary mesons.
- For ε in the range from 10^{-5} to 10^{-7} and $m_{A'}$ in range ~ MeV, the decay lengths of DP with momenta above 10 GeV/c spans ~ tens of metres.
- For $m_{A'}$ below 700 MeV, the dark photon decay width is dominated by di-lepton final states.



Ref: [7] NA62 Collaborartion, Dobrich, B. (2023) *Search for dark photon decays to μ+μ− at NA62*

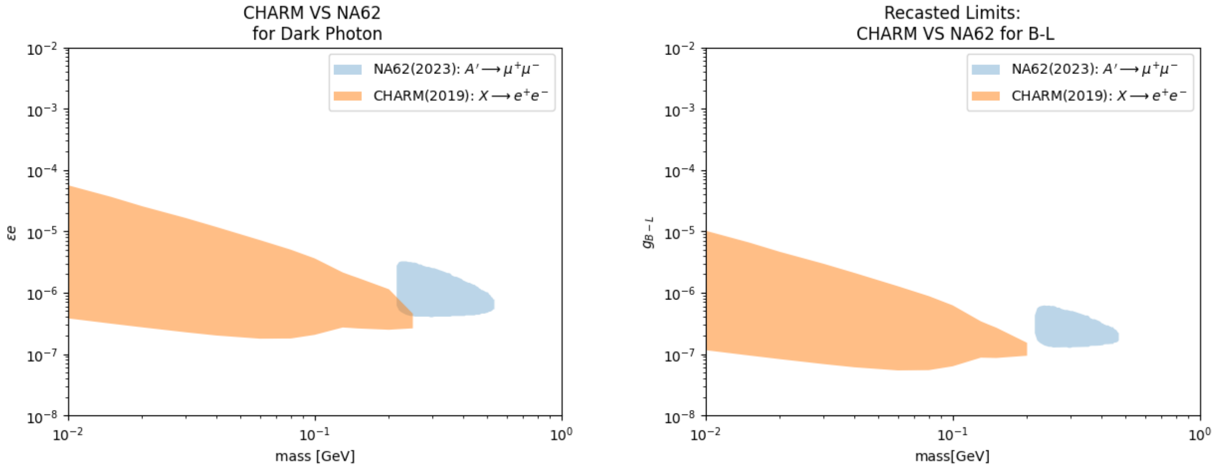
Recasting DP to B-L

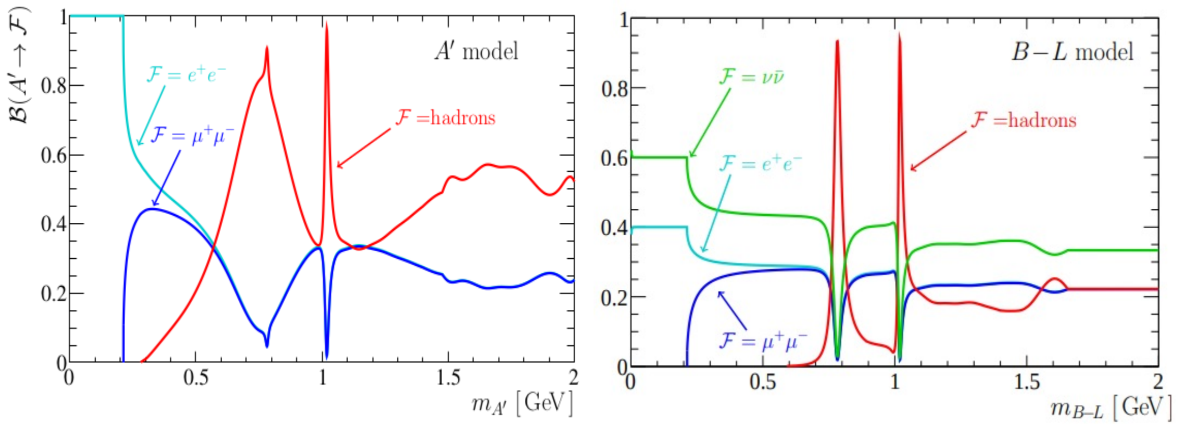




Since rho meson doesn't couple to B-L currents

Recasting DP to B-L





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Limitations of DarkCast

- Focuses on specific mass and coupling (m, ε) ranges based on available experimental data.
- Relies on data from existing experiments, applies assumptions of production and decay channels relevant to the model.
- Existing results of NA62 – produced only for A’, and now we want to extend to other models(ex: B-L).

ALPINIST

ALPINIST - Framework

- Simulating exotics - ALPs, Dark Vector, HNLs and their behavior in proton beam dump experiments
- Model-independent recasting of experimental results by combining MC simulations of particle production, propagation, and decay with a generalized rescaling mechanism.
- Flexible and adaptable to a wide range of particle models.

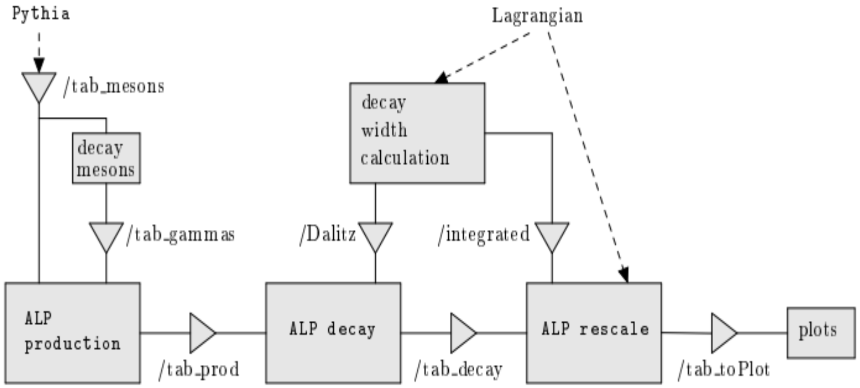
ALPINIST - Framework

Production:

- Simulates yield of exotic particles produced by a particle beam of given energy.
- Uses MC generator, like “Pythia” for SM meson production or external tables of mesons.

Decay:

- Loads tables from Production for given experiment and production mode and simulates chosen decay.
- Calculates yield for predefined parameter sets, mass, width.

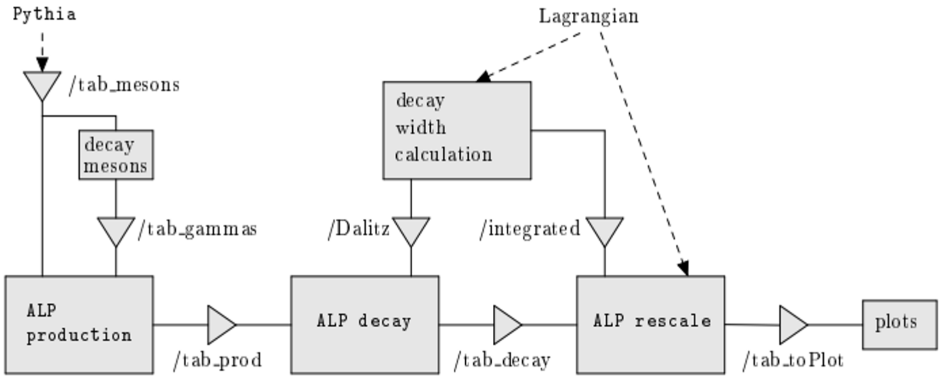


Ref: [2] Jerhot, J. et al. (2022) Alpinist: Axion-like particles in numerous interactions simulated and tabulated

ALPINIST - Framework

Rescale :

- Maps the prod and decay mode selected and calculates the number of predicted events for the model-independent & dependent parameters:
  - Mass | Lifetime | - Independent
  - BR | Coupling strength | - Dependent



Ref: [2] Jerhot, J. et al. (2022) Alpinist: Axion-like particles in numerous interactions simulated and tabulated

Production Mechanisms

Bremstrahlung:

- Dominates at intermediate masses above hundreds of MeVs and is resonantly enhanced ($m_{A'} \lesssim 1$ GeV).

Meson-Decay:

- Neutral vector mesons: $V \rightarrow A' + X$, where $V = \rho, \omega, \varphi$.
- Dominant for low masses (100s of MeVs).

Drell-Yan:

- In quark-antiquark annihilations ($q\bar{q} \rightarrow A'$), the A′ can be produced directly.
- This mechanism dominates for higher masses ($m_{A'} \gtrsim 1$ GeV).

Present Status

Meson - Mixing Production

- In VMD framework, photons interact with hadronic matter by first converting into intermediate vector mesons (ρ,ω,φ).
- This is possible because photons can couple to the same quark currents as these mesons.
- Through kinetic mixing (ϵ), A′ also couples to vector-mesons.
- There is **no direct mixing** between Xμ and A′ or vector mesons.
- Indirectly contribute to B−L boson production through their couplings to quark currents.

$$pN \to MX, \text{ where } M = \pi^0,\ \eta^{(\prime)},\ \rho,\ \omega,\ \phi$$

$$\begin{aligned} M &\to \gamma A' &&\text{for } M = \pi^0,\ \eta^{(\prime)}; \\ M &\to \pi^0 A' &&\text{for } M = \eta',\ \rho,\ \omega,\ \phi; \\ M &\to \eta A' &&\text{for } M = \rho,\ \omega,\ \phi. \end{aligned}$$

$$\mathcal{L}_{\text{VMD}} \supset eA_\mu J^\mu_{\text{em}} + g_\rho \rho_\mu J^\mu_\rho + g_\omega \omega_\mu J^\mu_\omega + g_\phi \phi_\mu J^\mu_\phi$$

$$\mathbf{J}^\mu_{\text{em}} = \sum_q Q_q \bar{q}\gamma^\mu q \qquad \mathbf{J}^\mu_{B-L} = \sum_f (B-L)_f \bar{f}\gamma^\mu f$$

$$\mathcal{L}_{\text{VMD}} = eA_\mu J^\mu_{\text{em}} \approx eA_\mu \left(\frac{m_\rho^2}{g_\rho}\rho^\mu + \frac{m_\omega^2}{g_\omega}\omega^\mu + \frac{m_\phi^2}{g_\phi}\phi^\mu \right)$$

$$\mathcal{L}_{A'} \approx \epsilon e A'_\mu J^\mu_{\text{em}} \qquad \mathcal{L}_X = g_{B-L} X_\mu \sum_V \frac{g_V}{m_V^2} V^\mu J^\mu_V$$

$$\Gamma_{\{V\to PA'\}} \sim \epsilon^2\ \Gamma_{\{V\to P\gamma\}}$$

Ref: [7] NA62 Collaborartion, Dobrich, B. (2023) *Search for dark photon decays to μ+μ− at NA62*

Separating Mixing Production of Dark Vector via Vector Meson Decays

We assume, in **DP model**, the kinetic mixing, couples universally to all vector mesons.

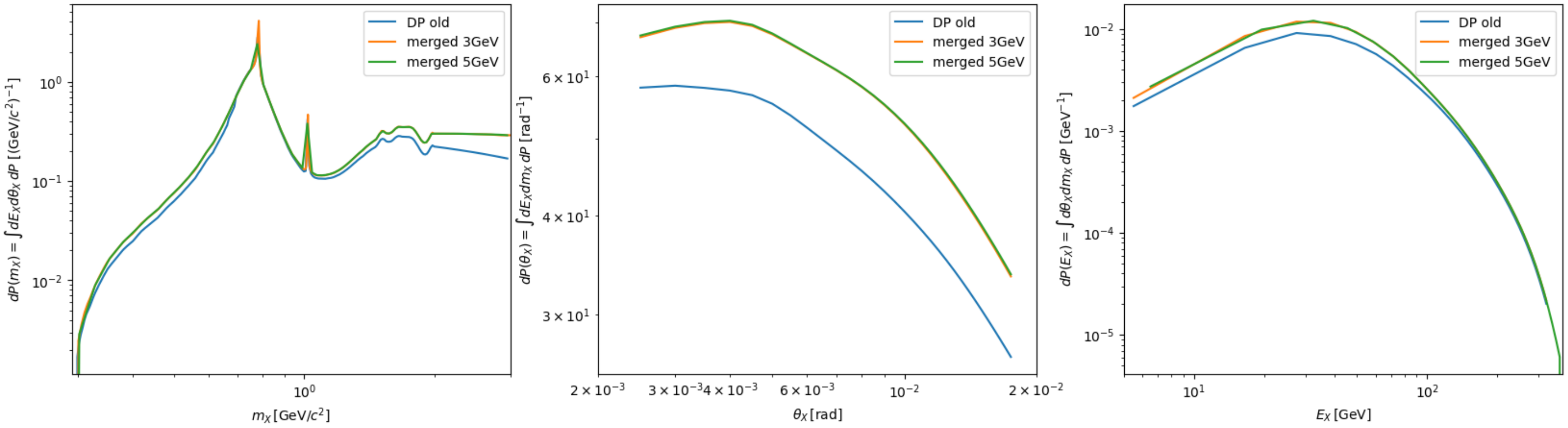
But in **B−L model**, the coupling depends on charges of quarks in the meson.

For ex., ρ meson (u & d) and the φ meson (s) will couple differently.

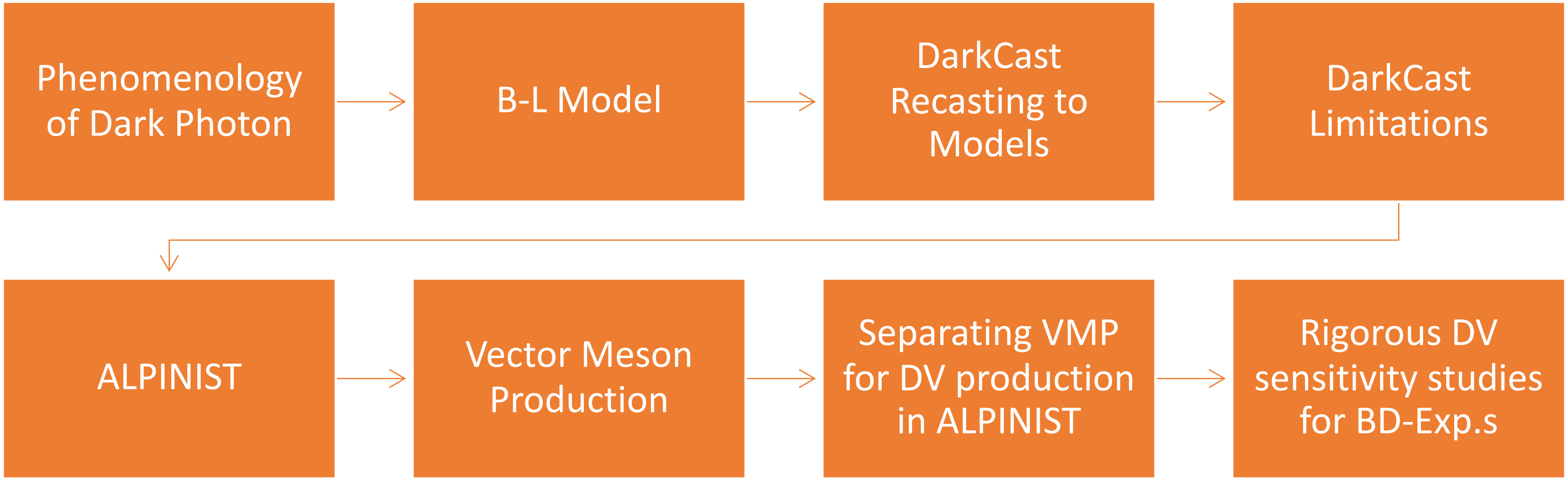
Reference: [1] Serendipity in Dark Photon Searches, Ilten, P. et al. (2018)

Integration Test:

Partially integrated probabilites DP-$\rho/\omega/\phi$ mixing | 1st dataset yield correction=1 | range: $\theta_X = [0.002, 0.02]$ | range: $E_X = [5, 380]$ | range: $m_X = [0.29, 3]$



Summary


Phenomenology of Dark Photon
B-L Model
DarkCast Recasting to Models
DarkCast Limitations
ALPINIST
Vector Meson Production
Separating VMP for DV production in ALPINIST
Rigorous DV sensitivity studies for BD-Exp.s

Q&A

References

[1] Ilten, P. et al. (2018) Serendipity in dark photon searches.

[2] Jerhot, J. et al. (2022) Alpinist: Axion-like particles in numerous interactions simulated and tabulated.

[3] Fabbrichesi, M., Gabrielli, E. and Lanfranchi, G. (2020) The Dark Photon.

[4] Batell, B. (2023) *Dark Sector Theory Lecture*. 14th International Neutrino Summer.

[5] Schulthess, I. (2024) *Opportunities at Future Collider Infrastructures*.

[6] Alonso-Monsalve, E. (2018) *Dark matter freeze-in via a kinetically mixed dark photon*.

[7] NA62 Collaborartion, Dobrich, B. (2023) *Search for dark photon decays to $\mu^+\mu^-$ at NA62*.