Dark Showers with the Z Portal

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HC, Lingfeng Li and Ennio Salvioni, arXiv:2110.10691 HC, Xuhui Jiang, Lingfeng Li and Ennio Salvioni, arXiv: 2401.08785 + 2407.xxxxx

supported by

PASCOS2024, Quy Nhon, Vietnam July 7-13, 2024

Introduction

- Motivated by many important physics questions: naturalness of EW scale, dark matter, …
- Novel experimental signatures: new targets and challenges for experimental searches.

Portal interactions

- Heavy states ($>$ TeV, X_{DK} , Z' , etc)
- Higgs or *Z*
- Dark photon kinetically mixed with photon
- Neutrinos

Z-portal Both *Z* and Higgs bosons are copiously produced at the LHC and other proposed energyfrontier experiments. For 13*,*(14)TeV, the anticipated total production rates of *Z* and *h*

• An interesting scenario which is less studied.

 $\sigma(pp \to Z) \approx 54.5$; (58.9); nb, $\sigma(pp \to h) \approx 48.6$; (54.7); pb **for 13(14)TeV**

- Light dark particles should be neutral under SM. How do they couple to Z? stringent (. 103) they couple to 72 from *Z* decays given the much larger production rate of *Z*. In models with a dark *Z*0
- 1. Light dark particles mix with heavy EW doublet **fermions.** (HC, L. Li, E. Salvioni, C.B. Verhaaren, 1906.02198, HC, L. Li, E. Salvioni, 2110.10691) 3. https://www.shown.com/signal yields depends on the signal yields on the signal yields o
- 2. Light dark particle are charged under a dark U(1) Which mixes with Z after EW breaking. (HC, X. Jiang, L. Li, E. Salvioni, 2401.08785) **Salvioni**, 2401.08785 hadron final states. There could be fewer dark hadrons and lower dark hadron energies if

EW Precision Constraints

• Heavy doublet mixing model: $Z = \overrightarrow{Q}$

- $\overline{ }$ - Other constraints comparable or weaker consider completions with a dark *Z*0 .
- Couplings of light eigenstates to Z suppressed by \mathbf{L} signex states to \mathbf{Z} even specifields. il digenstates to 2 suppressed by

$$
\frac{Y^2v^2}{M^2} \lesssim \text{few} \times 10^{-2}
$$

EW Precision Constraints angle in the absence of the dark sector and *Z*ˆ*^µ* = ˆ*c^W W*ˆ ³ are *Z* and photon fields without mixing with the dark gauge boson; *^L*(*R*)*ⁱ* are the dark fermions, with *xL*(*R*)*ⁱ* being their dark *U*(1)⁰ charges. The kinetic mixing between *U*(1)*^Y*

• $Z - Z'$ mixing model: Z pole data and low energy
absorption (for $M > Y$ mass) $\textsf{observals} \left(\textsf{for } M_{Z^{\prime}} \gtrsim \Upsilon \textsf{ mass} \right) . \tag{H^{\prime}}$ must be smaller than 1, to ensure positivity of the kinetic energy). The mass mixing *M*ˆ ² for \mathcal{R} . The mass eigenstates of the mass eigenstates of the neutral gauge of the neutral

Dark QCD

- Motivated by solutions to the hierarchy problem (neutral naturalness, cosmological relaxation) and dark matter (SIMP, dark baryon).
- Interesting collider signals from dark showers at LHC. If (some) light dark hadrons decay back to SM \Rightarrow semi-visible jets, emerging jets with displaced vertices, missing energies, depending on the lifetimes.
- The lightest dark hadrons are expected to be pseudo scalars (dark pions) if there are light dark quarks. [Focus of this talk]

Ga ^D,*μν*, *ψ*

Dark QCD

Dark Pion Decays

Dark pions: $\hat{\pi}_a \sim \overline{\psi}' i \sigma_a \gamma_5 \psi'$ (for N=2), ψ' : mass eigenstates

Z

 $\sum f$

 $-XVVVV$ SM

¯*f*

f • CP-odd dark pions behave like ALP and decay through mixing with the longitudinal mode of Z (and Z') with effective ALP decay α constants $f_a \gtrsim \textsf{PeV}$ for $f_{\hat{\pi}} \sim 1$ GeV $\alpha_{\hat{\pi} f \bar{f}} = -\frac{\partial_\mu \hat{\pi}_b}{\rho_0 \hat{\pi}_b}$ $f_a^{(b)}$ \sum *f* $a_f \bar{f} \gamma^\mu \gamma_5 f$

$$
\hat{\pi}_{1,3}
$$
, *CP* odd ($J^{PC} = 0^{-+}$) $\hat{\pi}_{1,3}$^Z

• CP-even dark pions decay through Higgs $(3.3 \times 10^{10} \text{ cm})$ cm \sim \sim \sim \sim

$$
\hat{\pi}_2
$$
, *CP* even ($J^{PC} = 0^-$) $\hat{\pi}_2$ ×...... $\left\{\n\begin{array}{c}\n\hat{\pi}_1 \\
\hat{\pi}_2\n\end{array}\n\right\}$

 $^*\!{\mathsf{Without}}\!$ a conserved $\mathsf{U}(\mathsf{I})$ flavor symmetry, $\hat\pi_1,\hat\pi_2$ are distinct states. *They will mix if CP is violated in the dark sector. ̂ nserved U(1) flavor symmetry, $\hat{\pi}_1, \hat{\pi}_2$ are distinct states.

Dark Pion Decays

(CP-odd) HC, Li, Salvioni, 2110.10691, using data driven method (Aloni et al, 1811.03474)

$$
\text{Br}(\hat{\pi} \rightarrow \mu^+ \mu^-) \gtrsim \text{few\% for } 2m_\mu < m_{\hat{\pi}} \lesssim 3 \text{ GeV}
$$

For $2m_{\mu} < m_{\hat{\pi}} < 3$ GeV, $f_a \sim 1$ PeV, dark pion decays through Z-portal at colliders.

Dark Shower Searches

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The final states of dark showers from *Z* decays are soft, therefore hard to trigger. On the other hand, dark pions are typically long-lived. Displaced decays give a great handle.

• CMS scouting search (2112.73169): Reduces the trigger threshold online. Data containing muon pairs that pass low-level triggers are recorded, keeping only simplified information of the events.

CMS Scouting Search becomes larger for a heavier dark pion since the average transverse boost decreases with Larger *m m m m m m scouting Search* $\mathbf{L}_{\mathcal{A}}$

• Recast CMS scouting search (using the Hidden Valley module in PYTHIA8), with some conservative assumptions. Model independent bounds (for 1 DV). equal to depend on the reach is only a few time better due to a lower position where inproperiacing the signal experimental reach \mathbf{v}_i .

CMS Scouting Search

• Future projections (with assumptions of improved trigger efficiency and extended l_{xy} reach 11 cm $\rightarrow \sim 90$ cm):

For 2DV, we assume each DV's trigger and detector efficiencies are independent, and the overall efficiency is the product of the two. It should be background free and is most effective when the dark pion lifetime makes the trigger efficiency optimal.

LHCb

• LHCb detector with low trigger thresholds and high vertex resolutions is powerful to look for dimuon DV's from dark showers, especially for lifetime smaller than O(cm). Recast follows the LHCb analysis, 2007.03923.

Auxiliary Detectors and Z-Factory efectors and *Z*-*Factory* produced in than the total HL-LHC yield, providing an immense opportunity to study exotic *Z* decays duviliary Detectors and 7-Factory needed for the optimal sensitivity is related to the auxiliary detector to the auxiliary de

• Auxiliary detectors are good for longer dark pion decay The *^e*+*e* ! *^Z* ! dark shower signal samples are generated at the *^Z* pole (p*^s* ⁼ *^mZ*). lengths. They are expected to be mostly background free.

based on original designs. They may \overrightarrow{f} 10⁻⁹ than the total of the total HL-LHC graduate opportunity to study experimental values opportunity to study experimental values of $\frac{1}{\alpha^2}$ **budget/space limitations.** θ θ θ θ ¹⁰⁻¹⁰ **A** For circuits the number of produced the number of produced the number of products the same of κ t_{rel} than the total HL-LHC yield, providing an immediate opportunity to study α to dark showers. Conversely, their *Z*0 budget/space limitations. need to be scaled down with the

\n
$$
\text{Tera-Z: } p_{T,\mu} > 0.5 \, \text{GeV, } |p_{\mu}| > 10 \, \text{GeV, and } |\eta_{\mu}| < 5 \, \text{M}_{\text{O}_4} \, \text{M}_{\text{O}_5} \, \text{M}_{\text{O}_7} \, \text{M}_{\text{O}_7
$$

 $V = \begin{bmatrix} \text{CIII} \end{bmatrix}$

Dark Hadron Production from FCNC + *AK*⇤ ² (*m*² ⇢ˆ) *m*² *^K*⇤ (*m^B* ⁺ *^mK*⇤)² ²*AK*⇤ ¹ (*m*² ⇢ˆ)*AK*⇤ ² (*m*² ⇢ˆ) **h**
 $=$ \bigcap

b $\left\{ u, c, t \right\}$ *s*

• Light dark hadrons can also be produced by W Meson (B, D, K) FCNC decays if the phase space is open. For dark pions, production $\frac{b_{\text{max}}}{a_{\text{max}}}$ mainly depend effective ALP decay constant f_a .

$$
BR(B^{+,0} \to \{K^+\hat{\pi}_b, K^{*0}\hat{\pi}_b\}) \approx \{0.92, 1.1\} \times 10^{-8} \left(\frac{1 \text{ PeV}}{f_a^{(b)}}\right)^2 \left(\frac{\mathcal{K}_t}{10}\right)^2 \left\{\lambda_{BK\hat{\pi}}^{1/2}, \lambda_{BK^*\hat{\pi}}^{3/2}\right\},\
$$

CMS Scouting LHCb

 10^{-5} ereas for decays involving data for decays in vector mesons one finds on 10^{-5} ereas for 10^{-5} ereas 10^{-5} 10^{-5} 101 fb⁻¹, 650 MeV ◆2✓*K^t* 10 ◆2 **z**
⊥
z 10^{−6} 1 fb^{-1} , 10^{-6} ---- 101 fb⁻¹, 2 GeV

3000 fb⁻¹, 650 MeV 10^{-6} \uparrow \downarrow \uparrow \downarrow \downarrow \downarrow \downarrow 300 fb^{-1} , 650 MeV 10^{-7} 10^{-7} $3000~{\rm fb}^{-1}$. 2 G ◆2✓*K^t* $\frac{1}{2}$ ✓ "*Zb/m*⇢^ˆ **BR** , (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.12), (6.1 10^{-8} 10^{-8} $\left(\begin{array}{c} \times \\ \times \\ \times \end{array}\right)$ 10^{-9} 10^{-9} where Eq. (6.12) was obtained by evaluating the second and third lines of Eq. (6.8) for 10^{-10} 10^{-10} $\frac{1}{\alpha}$ 10^{-11} 0.01 0.10 10^{-11} L
0.01 0.01 0.10 1 10 100 1000 0.01 0.01 0.10 1 10 100 1000 $c\tau$ [cm] $c\tau$ [cm]

Dashed: current; Solid: future HL-LHC projection

FCNC Reaches from Other Experiments

Auxiliary detectors B-factory and fixed target exp 10^{-6} FCNC, Codex-b & FASER: 300 ${\rm fb}^{-1}$ MATHUSLA & FASER II: 3000 ${\rm fb}^{-1}$ 650 MeV $\label{eq:BR} {\rm BR}(B\to K\hat\pi)\times {\rm BR}(\hat\pi\to X_{\rm sig})$ 900 MeV 10^{-7} -1.5 GeV 10^{-7} 2 GeV $BR(B\to K\hat\pi)$ 10^{-8} - Belle II, 2 Tracks ----- Belle II, $\pi^+\pi^-\pi^0$ 10^{-9}

650 MeV 2.0 GeV

 10^{-1}

FASER FASER II - Codex-b

MATHUSLA

1 10 100 100 100 10⁴ 10⁵ 10⁶

 $c\tau$ |cm

 10^{-10}

 10^{-2} 0.1 1 10 10^{2} 10³ 10⁴

 $c\tau(\hat{\pi})$ [cm]

Rare & Precision Frontier, FCNC

Charm, μ

Bounds on Benchmark Models if the benchmark models have the same *K^t* and the same decaying dark pions. Such

• To compare reaches of different experiments and production mechanisms, specific benchmark models are needed to obtain model-dependent bounds. $\frac{1}{\sqrt{1-\frac{1$ strengths of the dark shower constraints and FCNC constraints depend on *f*⇡ˆ. For *f*⇡^ˆ =

Fermion doublet mixing model: $Y = 0$, set $\tilde{\pi}_1, \tilde{\pi}_3$ lifetimes equal by choosing $y_{11} = y_{12}(1 + \sqrt{2}), y_{21} = y_{22} = 0$ *Fermion doublet mixing model:* $\tilde{Y} = 0$, set $\tilde{\pi}_1$, $\tilde{\pi}_3$ lifetimes equal $\overline{\mathcal{L}}$ and $\overline{\mathcal{L}}$ and $\overline{\mathcal{L}}$ reduce the production rate of the data showers and hence the data showers and $\overline{\mathcal{L}}$ by directing $y_{11} = y_{12}x_1 + y_2y_2 + y_{22}y_1 - y_{22}y_2 - y_1$

EMS scouting **for the filter of the EHCb**

The relative strengths of dark shower and FCNC reaches depends on $f_{\hat{\pi}}$. For $f_{\hat{\pi}} = 1$ GeV, DS > FCNC. Dark shower reaches decrease as $f_{\hat{\pi}}$ increases. \overline{A}

Reaches of Benchmark Models

• Higher f_a implies longer decay length. Experiments sensitive to longer decay lengths have strong reaches in f_a .

Auxiliary detectors

Intensity frontier

Conclusions

- The Z boson can be an interesting portal to the dark sector. More than 10¹¹ Z bosons will be produced at HL-LHC, providing a great opportunity to explore this scenario.
- Dark showers from Z-portal decays give exciting experimental signals, which are quite challenging. New search strategies and techniques (e.g. data scouting and parking) will be crucial to explore them.
- Additional auxiliary detectors at the LHC (FASER, MATHUSLA, CODEX-b) will be helpful for dark pions with longer decay lengths. A future *Z*-factory will be very powerful in extending the search reaches. Other fixed target experiments and Belle II provide complementary tests through FCNC meson decays.