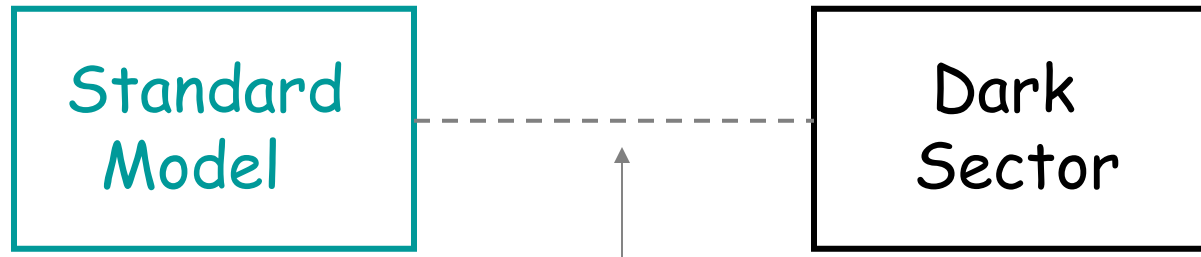


Dark Sectors at High Energy Colliders

Yuri Gershtein

David Shih

Scott Thomas



Messenger Interactions

Portals - (Local Operators)

Standard Model Portals:

$$D=2 \quad B_{\mu\nu} , H^* H$$

$$D=5/2 \quad LH$$

$$D=3 \quad Q^* \sigma^\mu Q , L \sigma^\mu L , \dots$$

$$D=4 \quad QHu , G^{\mu\nu} G_{\mu\nu} , H^* W_{\mu\nu} H , \dots$$

...

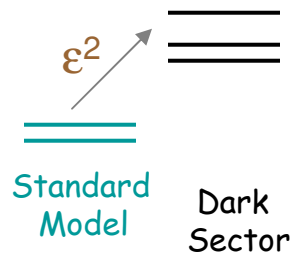


Portals Into and Out of the Dark Sector

Standard Model → Dark Sector → Standard Model

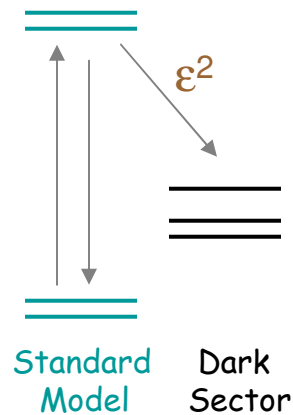
Dark Sector Production at High Energy Colliders

Direct Production



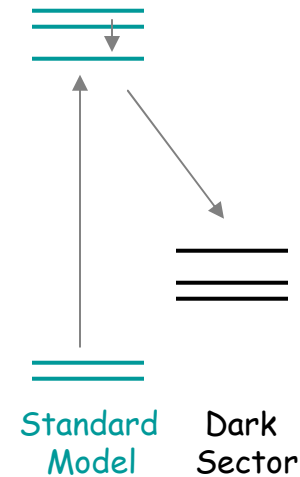
$$\sigma \sim O(\epsilon^2)$$

Indirect Production



$$Br \sim O(\epsilon^2)$$

Indirect Production
with Shared Conserved
Quantum Number



$$\sigma \cdot Br \sim O(\epsilon^0)$$

Which Dark Sector States Populated -
Depends on Production Portals

Portal $\sim \epsilon$

Dark Sector Production at High Energy Colliders

Direct Production

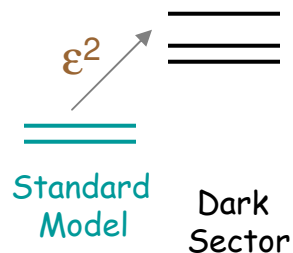
Indirect Production

Indirect Production
with Shared Conserved
Quantum Number

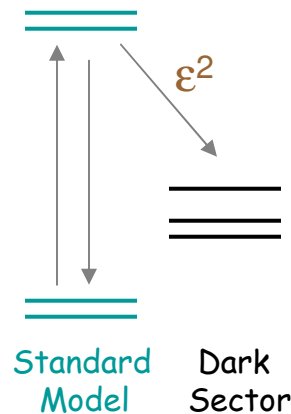
Resonant Dark DY

Higgs, Z Decay

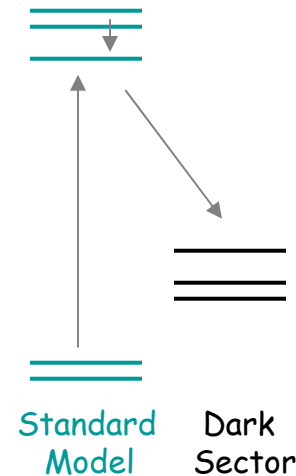
SUSY + R-Parity



$$\sigma \sim O(\epsilon^2)$$



$$Br \sim O(\epsilon^2)$$

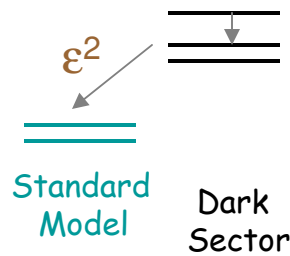


$$\sigma \cdot Br \sim O(\epsilon^0)$$

Which Dark Sector States Populated -
Depends on Production Portals

Portal $\sim \epsilon$

Dark Sector Decay to Standard Model



If No Dark Decay Mode Open - Dark Sector State Can Decay Back to Standard Model Through Portals

Guaranteed for LDSP if no Conserved Quantum #

All, Some, or None of the Dark Sector States May Have Prompt Decays Back to the Standard Model

Very Wide Range of Possibilities Depending On:

Production Portal

Dark Spectrum

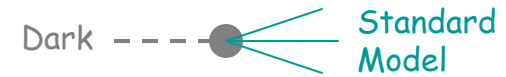
Dark Cascade Decays

Dark Showering

Decay Portal

Dark Sector Decay to Standard Model

Classify Dark Decay Modes According to Relevant Experimental Considerations:



1. Dark Object Content \supset {Leptons, Jets, MET} -
Decay Portals (No Decay = MET)

2. Dark Object Multiplicity / Isolation -

Dark Cascades and/or Dark Showering
(Confined Non-Abelian or Higgsed (Non)-Abelian Large g_D)

High Multiplicity \longleftrightarrow Low Multiplicity

Non-Isolated Object \longleftrightarrow Isolated Object
("Lepton Jets") (Di-muons)
"Difficult" "Easy"

* 3. Associated Objects from Production/Decay - {Leptons, Jets, MET}

Dark Sector \supset Abelian Gauge Symmetry

Standard Model Portals

Dark Sector Portals

$$D=2 \quad B_{\mu\nu}, H^*H$$

$$X_{\mu\nu}, H_D^*H_D$$

$$D > 2 \quad \dots$$

$$\dots$$

Marginal SM - Dark Interactions :

$$\frac{1}{2}\epsilon B_{\mu\nu}X^{\mu\nu} + \frac{1}{2}g'g_D \epsilon' (H^*H)(H_D^*H_D)$$

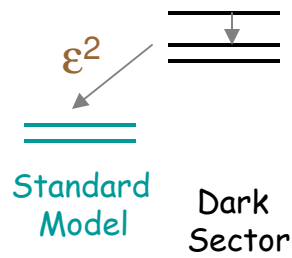
Photon - Dark Photon - Z Boson Mixing

$$e j_{EM}^\mu (A^\mu + \epsilon \cos \theta_W X_\mu) + g_Z j_Z^\mu Z_\mu + g_D j_D^\mu (X_\mu - \epsilon \sin \theta_W Z_\mu) + \mathcal{O}(\epsilon^2, \epsilon m_X^2/m_Z^2)$$

Higgs - Dark Higgs Mixing

$$\sin \theta_{hh_D} \simeq \epsilon' \frac{m_X m_Z \sin \theta_W}{m_h^2} \sim \mathcal{O}(\epsilon^{3/2})$$

Higgsed Abelian Dark Sector - Decay to Standard Model



Leading Decay Portals:

$$e \propto \cos \theta_W j_{EM}^\mu X_\mu$$

$$e' \propto \frac{m_X m_Z \sin \theta_W}{m_h^2} \mathcal{O}_{SM} h_D$$

Higgsed Abelian Dark Sector - Decay to Standard Model

Dark Photon Decay

$$e \epsilon \cos \theta_W j_{EM}^\mu X_\mu$$

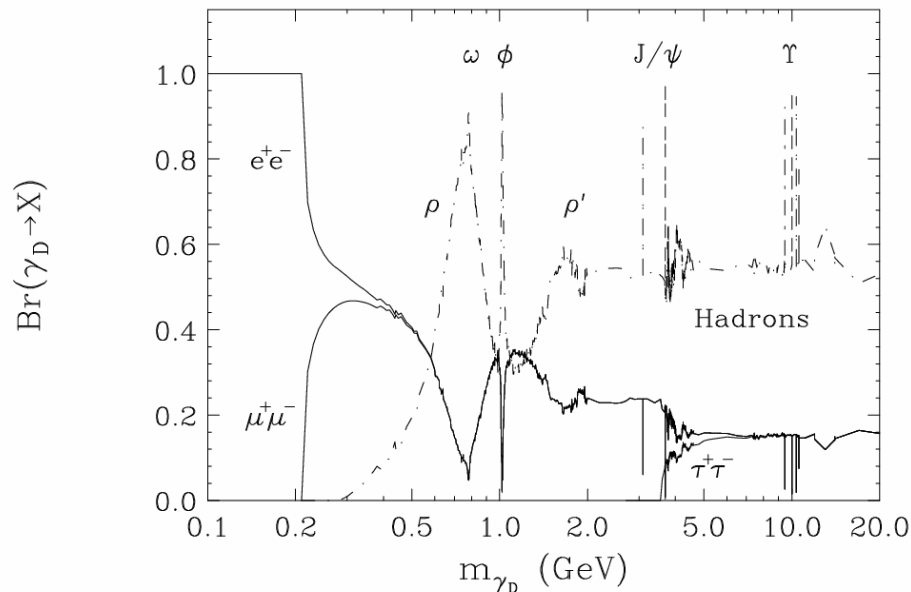


$$\Gamma(\gamma_D \rightarrow \text{All}) = -\epsilon^2 \cos^2 \theta_W m_{\gamma_D} \text{Im}\Pi(m_{\gamma_D}) = \frac{1}{3} \epsilon^2 \cos^2 \theta_W \alpha m_{\gamma_D} R(m_{\gamma_D})$$

Prompt

$$R(m_{\gamma_D}) \equiv \frac{\Gamma(\gamma^* \rightarrow \text{All})}{\Gamma(\gamma^* \rightarrow f^+ f^-)} = \frac{\sigma(e^+ e^- \rightarrow \gamma^* \rightarrow \text{All})}{\sigma(e^+ e^- \rightarrow \gamma^* \rightarrow f^+ f^-)} \Big|_{\sqrt{s}=m_{\gamma_D}}$$

Dark Photon Branching Ratio



Hadrons + Leptons

Higgsed Abelian Dark Sector - Decay to Standard Model

Dark Higgs Decay

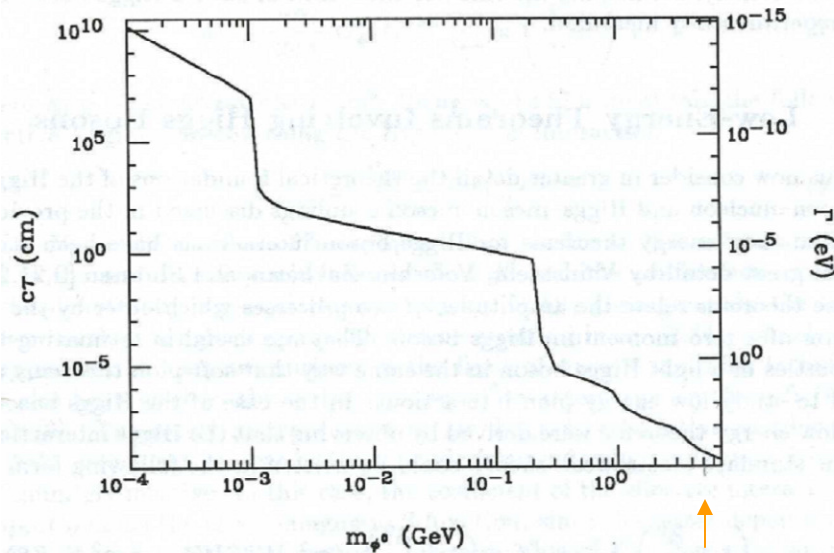
$$\epsilon' \frac{m_X m_Z \sin \theta_W}{m_h^2} \mathcal{O}_{SM} h_D$$



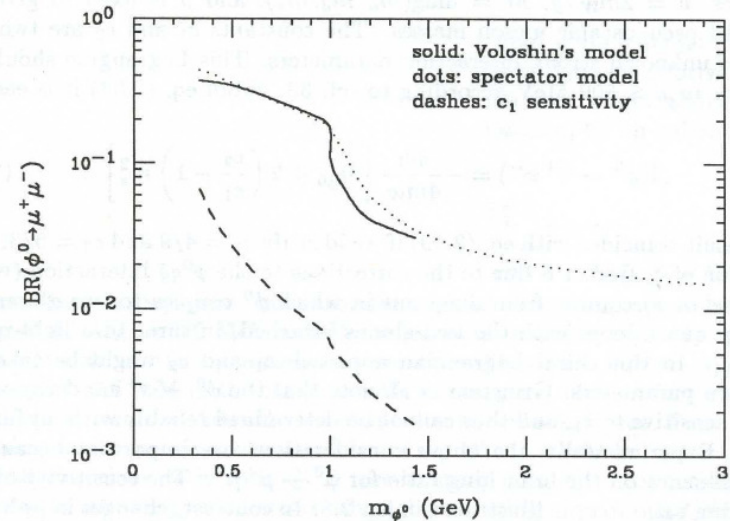
$$\Gamma(h_D \rightarrow \text{All}) \simeq \epsilon^2 \cos^2 \theta_W \frac{m_X^2 m_Z^2 \sin^2 \theta_W}{m_h^4} \Gamma(h \rightarrow \text{All})|_{m_h=m_{h_D}}$$

$$\text{Br}(h_D \rightarrow \text{final}) \simeq \text{Br}(h \rightarrow \text{final})|_{m_h=m_{h_D}}$$

Light Higgs Boson Lifetime and Width

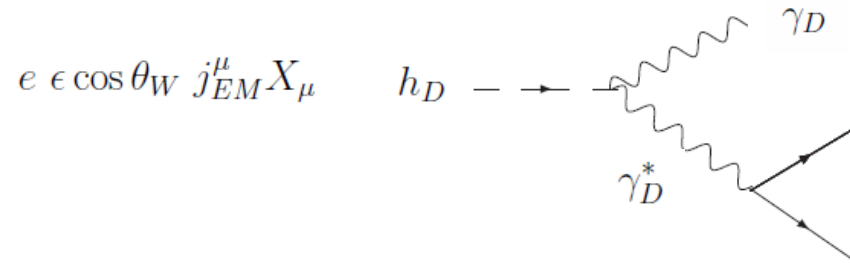


Higgs Branching Ratio to Muons



Higgsed Abelian Dark Sector - Decay to Standard Model

Dark Higgs Decay

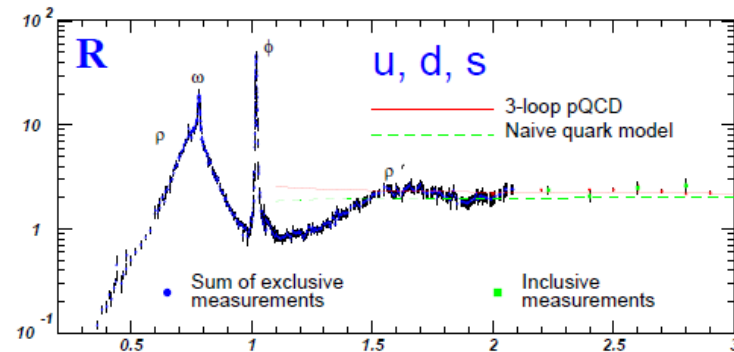


$$\Gamma(h_D \rightarrow \gamma_D \gamma_D^*) = \frac{3g_D^2 Q_D^2}{4\pi^2} f(m_{\gamma_D}^2/m_{h_D}^2) \Gamma(\gamma_D \rightarrow \text{All})|_{m=m_h}$$

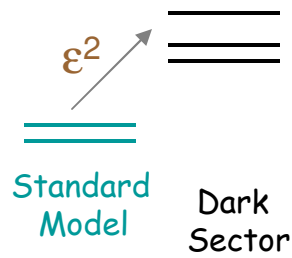
$$f(x) = x \int_0^{(1-\sqrt{x})^2} dy r(y) \frac{y \sqrt{(1-2(x+y) + (x-y)^2)}}{(x-y)^2} \left(1 - \frac{1}{3x} + \frac{(1+y-x)^2}{12xy}\right)$$

$$r(y) \equiv \frac{\Gamma(\gamma_D \rightarrow \text{All})|_{m=\sqrt{y}m_{h_D}}}{\sqrt{y} \Gamma(\gamma_D \rightarrow \text{All})|_{m=m_{h_D}}} = \frac{R(\sqrt{y}m_{h_D})}{R(m_{h_D})}$$

Most of the γ_D^* Goes
Through Hadronic Resonances



Higgsed Abelian Dark Sector - Direct Production



Leading Direct Production Portals:

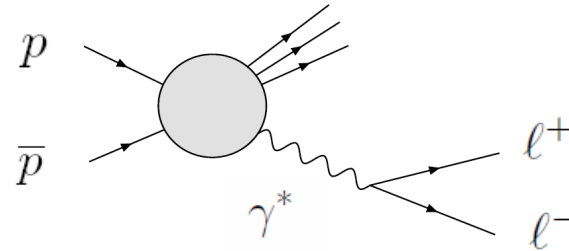
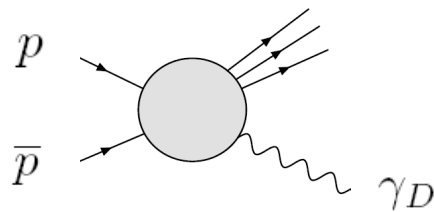
$$e \epsilon \cos \theta_W j_{EM}^\mu X_\mu$$

$$\epsilon' \frac{m_X m_Z \sin \theta_W}{m_h^2} \mathcal{O}_{SM} h_D \quad O(\epsilon^{3/2}) \cdot m_X / v_{SM}$$

Higgsed Abelian Dark Sector - Direct Production

Direct Dark Photon Production

$$e \epsilon \cos \theta_W j_{EM}^\mu X_\mu$$



$$\sigma(p\bar{p} \rightarrow X\gamma_D) = \epsilon_\gamma^2 \frac{3\pi m_{\gamma_D}}{2\alpha} \frac{d\sigma(p\bar{p} \rightarrow X\gamma^* \rightarrow X\ell^+\ell^-)}{dm_{\ell^+\ell^-}}$$

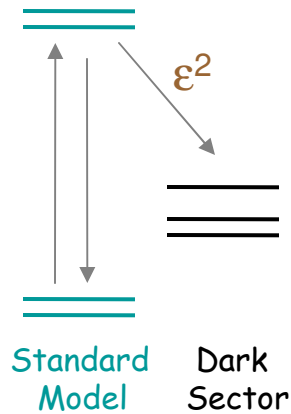
$$\int dx f(x) = 1$$

$$\frac{d\sigma(p\bar{p} \rightarrow X\gamma_D \rightarrow X\ell^+\ell^-)}{dm_{\ell^+\ell^-}} = \epsilon_\gamma^2 \text{Br}(\gamma_D \rightarrow \ell^+\ell^-) \frac{3\pi m_{\gamma_D}}{2\alpha \Gamma_{\ell^+\ell^-}} f\left(\frac{m_{\ell^+\ell^-} - m_{\gamma_D}}{\Gamma_{\ell^+\ell^-}}\right) \frac{d\sigma(p\bar{p} \rightarrow X\gamma^* \rightarrow X\ell^+\ell^-)}{dm_{\ell^+\ell^-}}$$

Assume $\gamma_D \rightarrow \text{SM}$: Resonance Search in $\mu^+ \mu^- \text{DY}$ (Background - Data)

Tevatron Sensitivity for $m \sim \text{few GeV}$ $\epsilon \sim 10^{-3}$

Higgsed Abelian Dark Sector - Indirect Production



Leading Indirect Production Portals → Two Universal Dark Portals

$$-\epsilon \sin \theta_W g_D j_D^\mu Z_\mu$$

$$j_D^\mu \supset m_X h_D X^\mu \simeq h_D \partial^\mu G_X$$

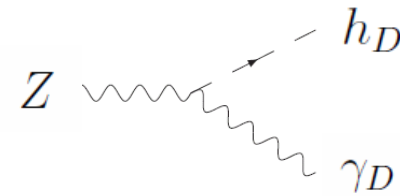
$$\epsilon' \frac{m_X m_Z \sin \theta_W}{m_h^2} h \mathcal{O}_D$$

$$\mathcal{O}_D \supset m_X^2 X^\mu X_\mu \simeq \partial^\mu G_X \partial_\mu G_X$$

(Focus on These Portals)

Higgsed Abelian Dark Sector - Indirect Production

Z Boson \rightarrow Dark Higgs + Dark Photon



$$\text{Br}(Z \rightarrow \gamma_{DL} h_D) = \frac{\epsilon^2 g_D^2 Q_{DH}^2}{g'^2} \left(\frac{103}{6} + \cot^2 \theta_W + \frac{21}{2} \cot^4 \theta_W \right)^{-1}$$

$$\text{Br}(Z \rightarrow \text{Dark}) = \frac{2\text{Tr}_F(Q_D^2) + \text{Tr}_B(Q_D^2)}{Q_{DH}^2} \text{Br}(Z \rightarrow \gamma_{DL} h_D)$$

Assume $\gamma_D \rightarrow \text{SM}$:

Inclusive Isolated $l^+ l^- + \pi^+ \pi^-$ Resonance Search in Z Decays

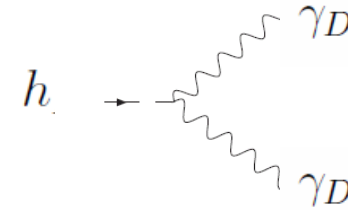
LEP: $O(10^7)$ Z's $E_{ll, \pi\pi} \simeq m_Z/2$ (Veto $l^+ l^- \gamma$)

Tevatron: $O(10^6)$ Z's

LHC: ...

Higgsed Abelian Dark Sector - Indirect Production

Higgs Boson \rightarrow Dark Photon + Dark Photon



$$\frac{\text{Br}(h \rightarrow \gamma_{DL} \gamma_{DL})}{\text{Br}(h \rightarrow b\bar{b})} = \frac{\epsilon'^2 g_D^2 Q_{DH}^2 m_Z^4 \sin^4 \theta_W}{3g'^2 m_b^2 m_h^2}$$

$$\epsilon' \sim 3 \times 10^{-3} \quad g_D \sim 4g' \quad \text{Br}(h \rightarrow \gamma_{DL} \gamma_{DL}) \simeq \text{Br}(h \rightarrow \gamma\gamma)$$

Assume $\gamma_D \rightarrow \text{SM}$:

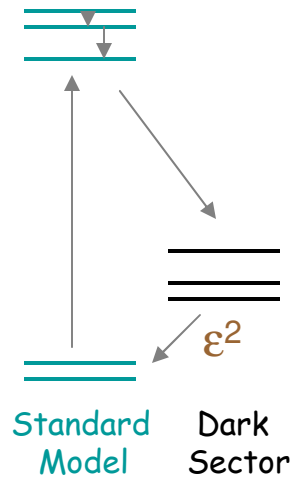
High p_T Isolated $(l^+ l^-)(l^+ l^-) + (l^+ l^-)(\pi^+ \pi^-)$? Di-Resonance Search

Tevatron: $h \rightarrow (\mu^+ \mu^-)(\mu^+ \mu^-)$ Search

LHC: $h \rightarrow (l^+ l^-)(l^+ l^-) + (l^+ l^-)(\pi^+ \pi^-)$? Search (c.f. $h \rightarrow \gamma\gamma$)

$$\text{For } m_h \simeq 120 \text{ GeV} \quad \epsilon' \simeq \epsilon \quad \frac{\sigma(pp \rightarrow h) \text{Br}(h \rightarrow \gamma_{DL} \gamma_{DL})}{\sigma(pp \rightarrow Z) \text{Br}(Z \rightarrow \gamma_{DL} h_D)} \sim \mathcal{O}(1)$$

Higgsed Abelian Dark Sector - Indirect Production With Shared Conserved Quantum Number



Supersymmetry with Conserved R-Parity

SUSY Dark Sector \supset SUSY Abelian Gauge Symmetry

Standard Model Portals

D=3/2

λ_B

D=2

$B_{\mu\nu}, H^*H$

D=5/2

$\Psi \phi^*$

...

Dark Sector Portals

λ_D

$X_{\mu\nu}, H_D^*H_D$

$\Psi_D \phi_D^*$

Leading Indirect Production Portal \rightarrow Universal Dark Portal

λ_B

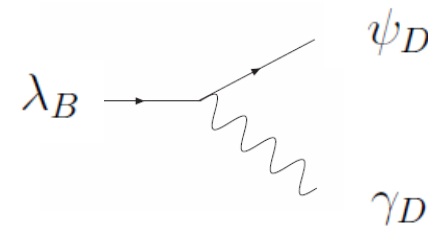
$\Psi_D G_D$

(Focus on This Portal)

Higgsed Abelian Dark Sector - Indirect Production With Shared Conserved Quantum Number

Bino \rightarrow Darkino + Dark Photon

$$\text{Br}(\lambda_B \rightarrow \psi_D \gamma_D) \leq \frac{1}{4}$$



Assume $\gamma_D \rightarrow \text{SM}$, $\psi_D \rightarrow \text{Blocked}$:

Inclusive High pT Isolated ($l^+ l^-$) ($l^+ l^-$) + ($l^+ l^-$) ($\pi^+ \pi^-$) ?
Di-Resonance Search in Association with MET

Inclusive High pT Isolated ($l^+ l^-$) ($l^+ l^- \rho^*$) + ($l^+ l^-$) ($\pi^+ \pi^- \rho^*$) ?
Di-Resonance Search in Association with MET

Assume γ_D , h_D , ψ_D , $\phi_D \rightarrow \text{SM} + \text{MET}$

Dark Object Search in Association with SUSY Cascade
(Non-Isolated MET)

...

SM Singlet + Higgsed Abelian Dark Sector - Indirect Production With Shared Conserved Quantum Number

Standard Model Portals

| | |
|-------|-------------------------------------|
| D=3/2 | λ_B , Ψ_S |
| D=2 | $B_{\mu\nu} , H^*H$ |
| D=5/2 | $\Psi \phi^*$ |
| D=7/2 | $\Psi_S \sigma^{\mu\nu} F_{\mu\nu}$ |
| ... | |

Dark Sector Portals

| |
|--|
| λ_D |
| $X_{\mu\nu} , H_D^*H_D$ |
| $\Psi_D \phi_D^*$ |
| $\lambda_D \sigma^{\mu\nu} X_{\mu\nu}$ |

Leading Indirect Production Portal \rightarrow Dark Portal

$$\Psi_S$$

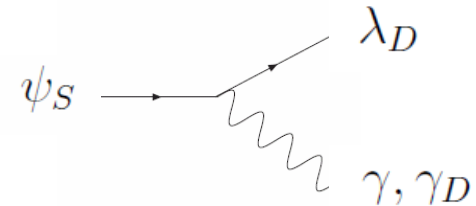
$$\Psi_S \sigma^{\mu\nu} F_{\mu\nu}$$

$$\lambda_D \sigma^{\mu\nu} X_{\mu\nu}$$

$$\lambda_D$$

SM Singlet + Higgsed Abelian Dark Sector - Indirect Production With Shared Conserved Quantum Number

Singletino \rightarrow Darkino + Photon , Dark Photon



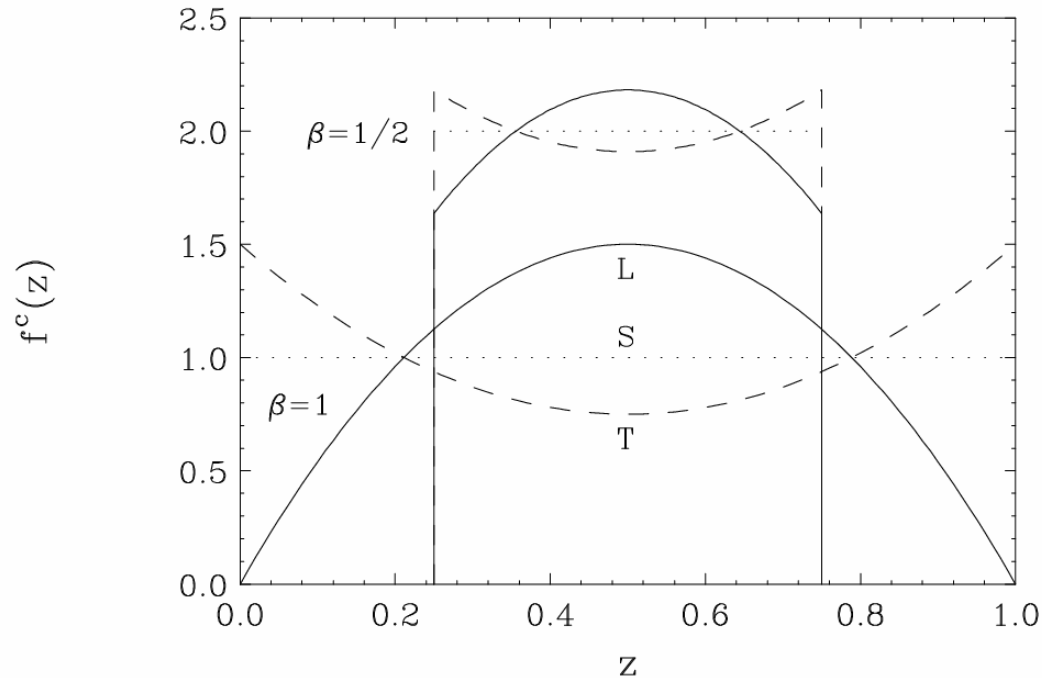
$$\text{Br}(\psi_S \rightarrow \lambda_D \gamma) + \text{Br}(\psi_S \rightarrow \lambda_D \gamma_D) \simeq 1$$

Assume $\gamma_D \rightarrow \text{SM}$, $\lambda_D \rightarrow \text{Blocked}$:

Inclusive High p_T Isolated $(l+l-)\gamma + (\pi^+\pi^-)\gamma$?
Resonance Search in Association with MET

...

Di-Lepton Resonance Spin + Polarization



$$z \equiv \frac{E_f}{E_f + E_{\bar{f}}}$$

$$\beta = \sqrt{1 - 4m_f^2/m_\gamma^2}$$

Goldstone Portals - Longitudinal

Transition Dipole Portals - Transverse

Dark Sectors at High Energy Colliders

Three production Mechanisms Available

Direct

Indirect

Indirect with Quantum Number

* Very Wide Range of Signatures ... (Examples)

Dark Object Content {Jets, Leptons, MET}

Dark Object Multiplicity / Isolation

Associated Objects {Jets, Leptons, MET}

Dark Sector \supset Higgsed Abelian Gauged Symmetry

Universal Portals \rightarrow High p_T Low Multiplicity Isolated Objects
(In Association with Other Objects)

Di-Lepton Resonance - Spin + Polarization

