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# Non-minimal composite dark matter *novel signatures*

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based on JHEP 2020, 128 (2020)

## The composite connection

- The WIMP scale

$$\Omega_{obs} h^2 \approx 0.1 \left( \frac{\alpha_w^2 / (100 \text{ GeV})^2}{\langle \sigma v \rangle_{th}} \right)$$

- Scalar dark matter is protected from the hierarchy problem.
- Interactions are fixed by symmetry.

$(H, \eta) \sim$  pseudo-Goldstones of the same  $\mathcal{G}/\mathcal{H}$

# Composite Higgs models with dark matter

$SO(n+1)/SO(n)$  :

- $n = 4$  MCHM

- $n = 5 \rightarrow (H, \eta)$

Frigerio et al (2012); Marzocca et al (2014)

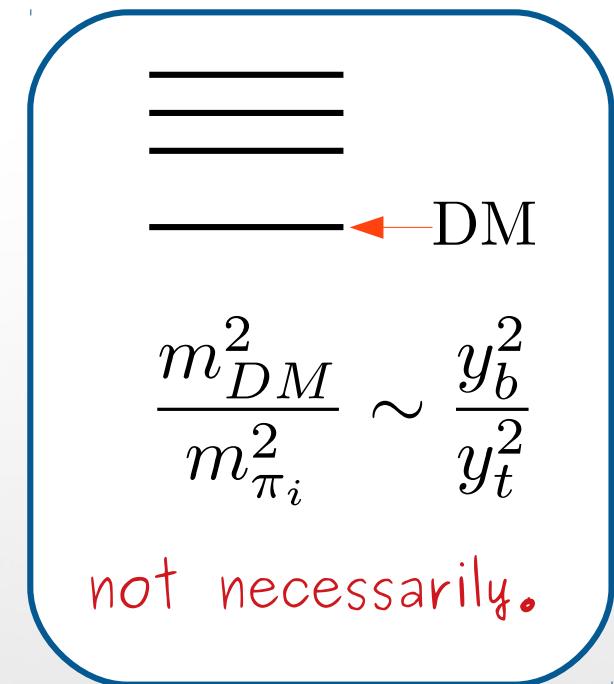
- $n = 6 \rightarrow (H, \kappa, \eta)$

Chala et al (2016); Balkin et al (2017)

Other possibilities:

$SO(7)/G_2 \rightarrow (H, \Phi_0), \dots$

Ballesteros et al (2017)



## Dark matter interactions

$$(1) \quad \mathcal{L}_G = \frac{1}{2} |\partial_\mu \Sigma|^2 \rightarrow \frac{(\eta \partial \eta) (h \partial h) + (\eta \partial \eta) (\kappa \partial \kappa)}{f^2}$$

$$(2) \quad \mathcal{L}_{\mathcal{G}} = \lambda \overline{q_L} \mathcal{O}_R^q \rightarrow \mathcal{L}_{yuk} \supset y_\psi h \overline{\psi} \psi \left[ \frac{\eta^2}{f^2} + i\gamma \frac{\kappa}{f} \right]$$

$$V_{1-loop} \supset m_\eta^2 \eta^2 + m_i^2 \pi^i + \lambda_{\eta i} \eta^2 \pi^i$$

Must necessarily respect

$$\mathbf{P}_\eta : \eta \rightarrow -\eta$$

In the MCHM+DM:

$$\mathcal{L}_{\partial^4} = \# \frac{\eta}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

## Dark matter interactions in $SO(1) / SO(6)$

$$(1) \quad \mathcal{L}_G = \frac{1}{2} |\partial_\mu \Sigma|^2 \rightarrow \frac{(\eta \partial \eta) (h \partial h) + (\eta \partial \eta) (\kappa \partial \kappa)}{f^2}$$

$$(2) \quad \mathcal{L}_{\mathcal{G}} = \lambda \bar{q} L \mathcal{O}_R^q \rightarrow \mathcal{L}_{yuk} \supset y_\psi h \bar{\psi} \psi \left[ \frac{\eta^2}{f^2} + i \gamma \frac{\kappa}{f} \right]$$

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## Global symmetry breaking

Embedding  $\overline{q_L} \oplus t_R$ :

$$\text{RegI: } V_{27} \supset V_{EW} + \frac{m_\eta^2}{2}\eta^2 + \frac{m_\kappa^2}{2}\kappa^2 + \frac{\lambda_H}{4}\eta^2 h^2$$

$(27 \oplus 1)$

$$\text{RegII: } V_7 \propto c_1 h^2 + c_2 \left[ \eta^2 + (1 - \gamma^2) \kappa^2 \right]$$

$(7 \oplus 7)$

In both:  $m_\eta \gtrsim m_\kappa$  ( $0 < \gamma < 1$ )

DM becomes unstable for  $\gamma \gtrsim 1.7$

## Global symmetry breaking

Embedding  $\overline{q_L} \oplus t_R$ :

$$\text{RegI: } \lambda_{\eta H} \sim \lambda_H, \quad \lambda_{\eta \kappa} \ll 1, \quad f \sim \frac{m_\eta}{\lambda_H} \sqrt{1 + \frac{m_\kappa^2}{m_\eta^2}}$$

$(27 \oplus 1)$

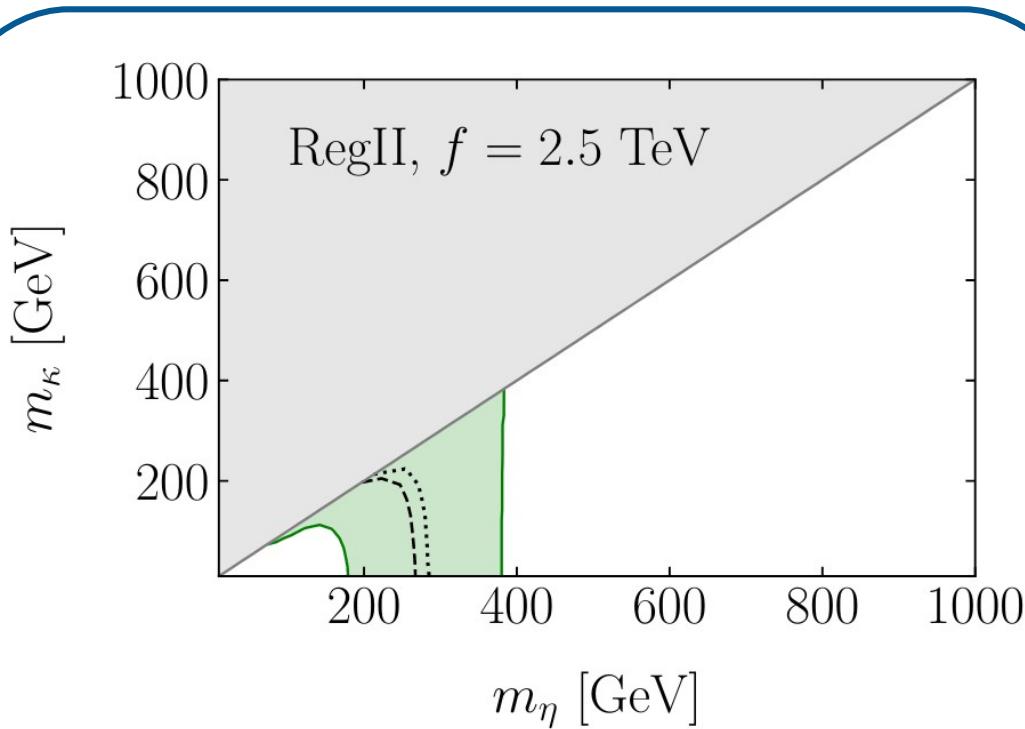
$$\text{RegII: } \lambda_{\eta H} \ll 1, \quad \lambda_{\eta \kappa} \sim \lambda_H, \quad f \sim 1, 2.5, 3, 4 \text{ TeV}$$

$(7 \oplus 7)$

In both:  $m_\eta \gtrsim m_\kappa$  ( $0 < \gamma < 1$ )

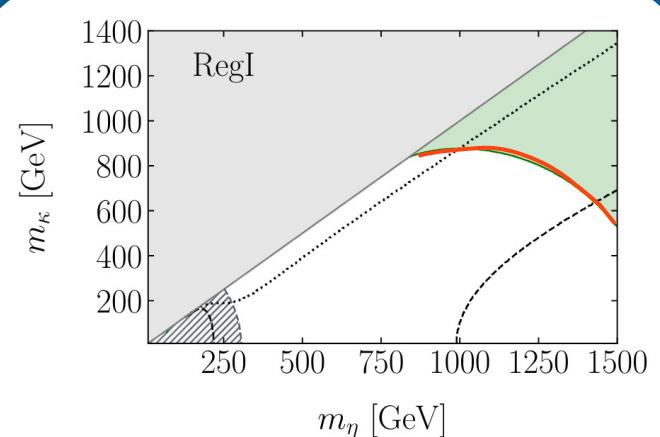
DM becomes unstable for  $\gamma \gtrsim 1.7$

## Composite phenomenology: annihilation



$$\sigma v \propto \left( \lambda - \frac{4m_\eta^2}{f^2} \right)^2$$

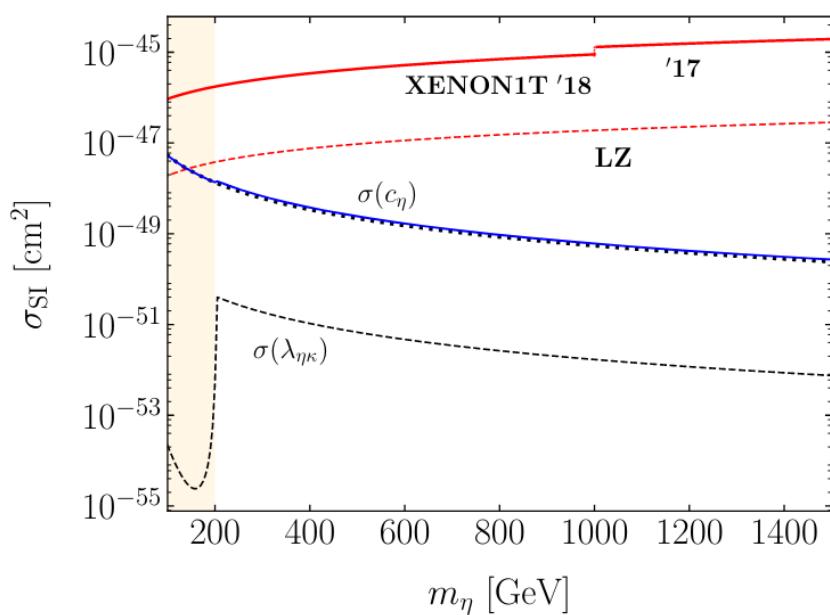
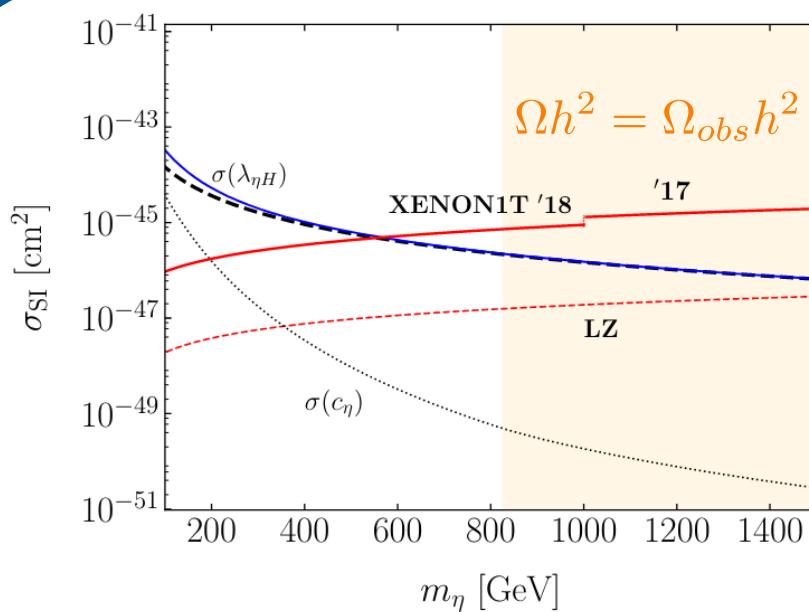
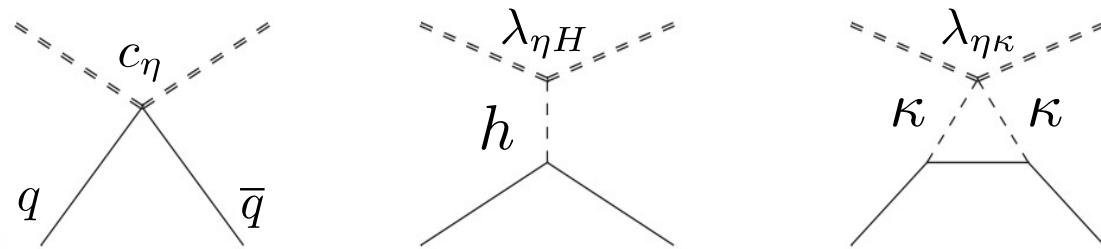
$\frac{(\eta \partial_\mu \eta)(\pi_i \partial^\mu \pi^i)}{f^2}$



Bound on fine-tuning:

$$2.8 \lesssim f \text{ [TeV]} \lesssim 3.3$$

# Composite phenomenology: direct detection



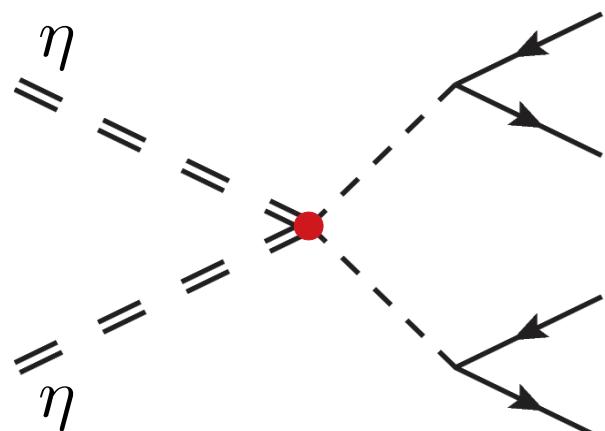
In the limiting case of  $\gamma = 0$ :  $\lambda_{\eta H} \sim 0$

Balkin et al (2018)

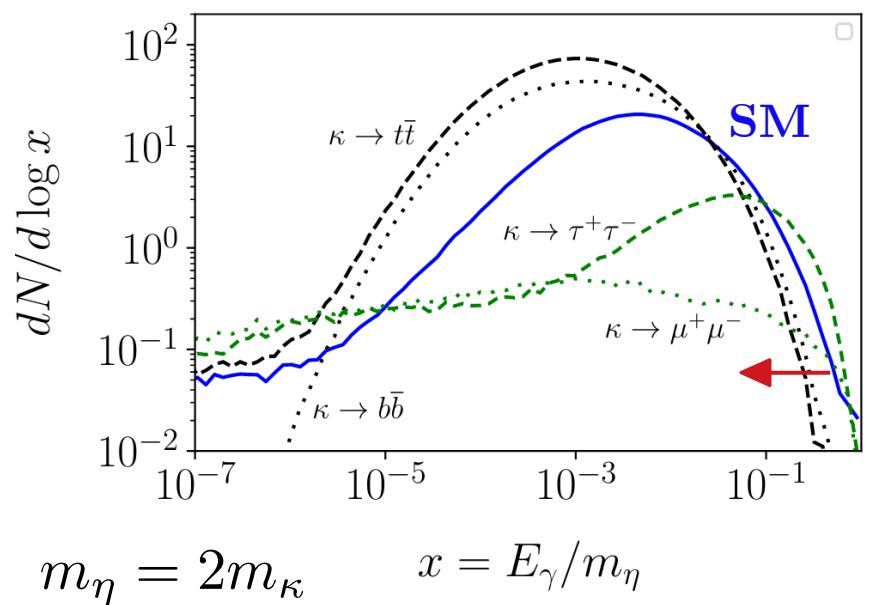
# Composite phenomenology: indirect detection

Shape effect:

$$\text{SM} \times 2^n$$

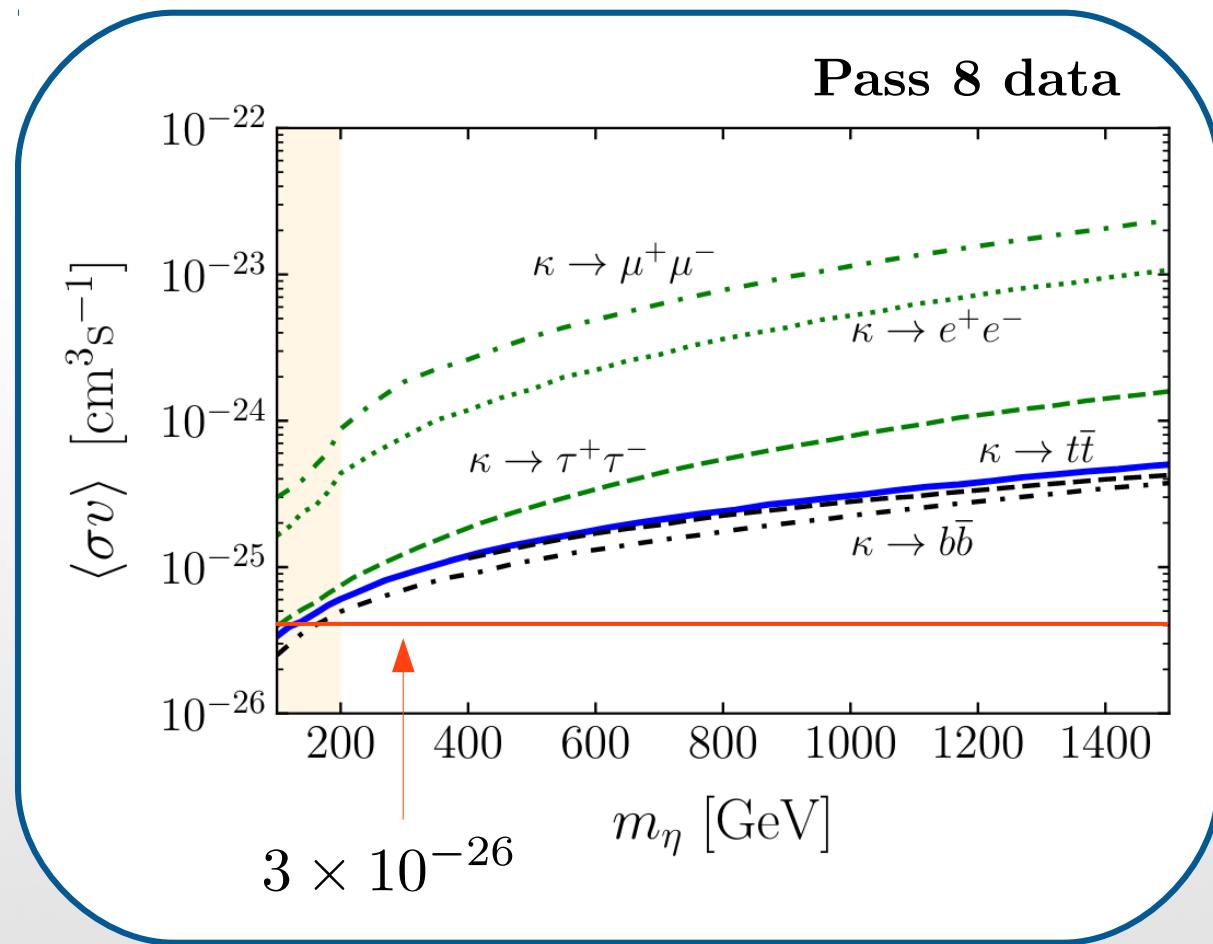


RegI with  $\Omega h^2 = \Omega_{obs} h^2$



$$\text{Gamma-ray flux} \propto \frac{\langle \sigma v \rangle}{m_\eta^2} \int \frac{dN_\gamma}{E_\gamma} dE_\gamma \text{ (J-factor)}$$

## New Fermi-LAT bounds



Future prospects:

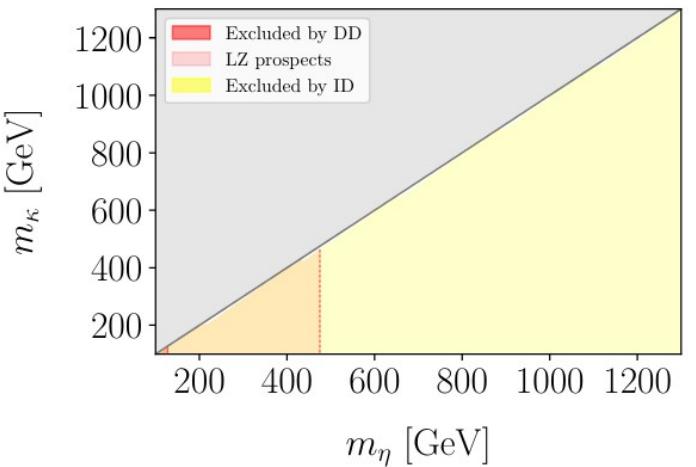
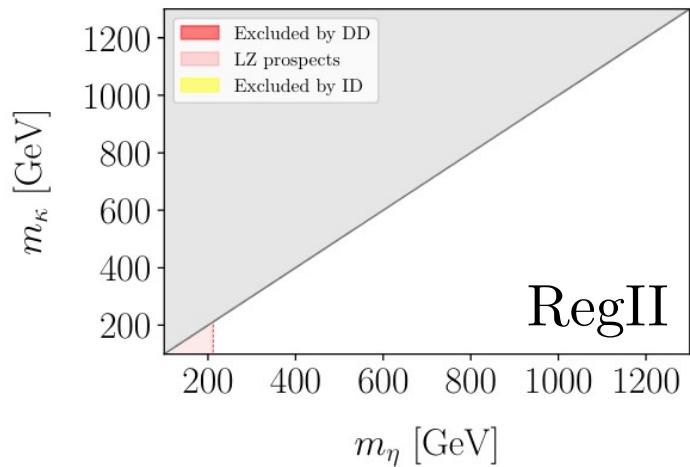
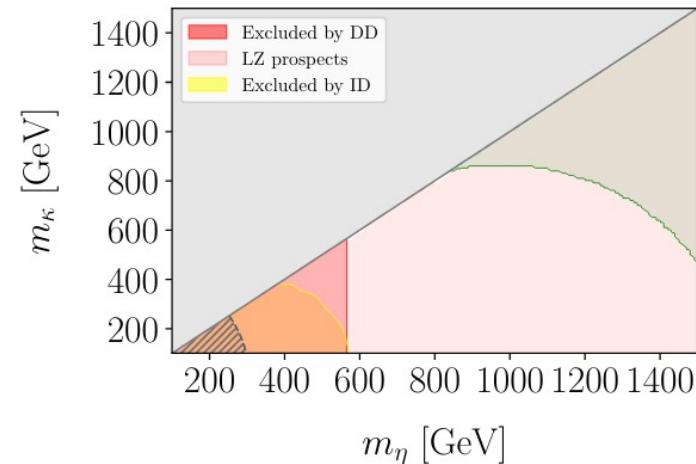
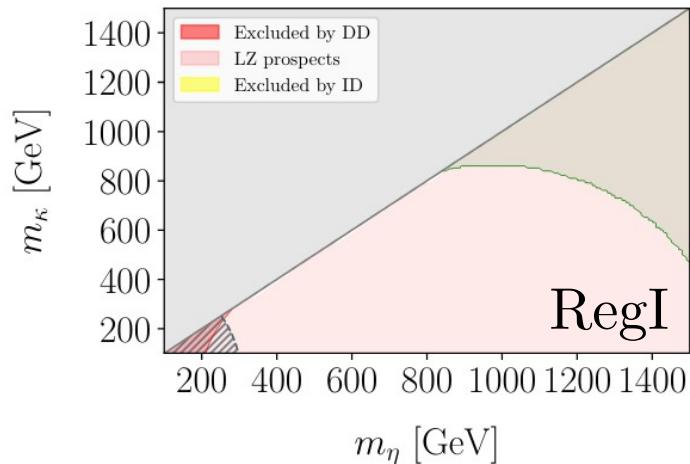
✓  $\eta\eta \rightarrow \kappa\kappa \rightarrow \ell^+\ell^-\ell^+\ell^-$

$$\kappa \xrightarrow{f} \begin{cases} f \\ \bar{f} \end{cases} \sim y_\ell \frac{v}{f} \gamma$$

$$\Rightarrow \gamma_q \approx 0, \quad \gamma_\ell \approx 1$$

unconstrained.

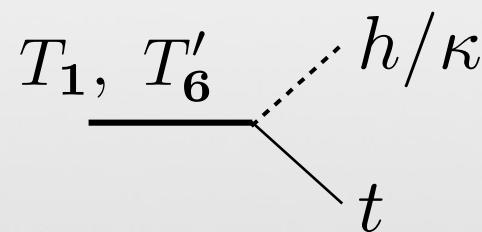
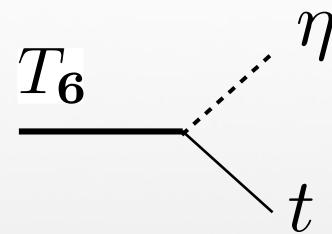
## All the dark matter bounds combined



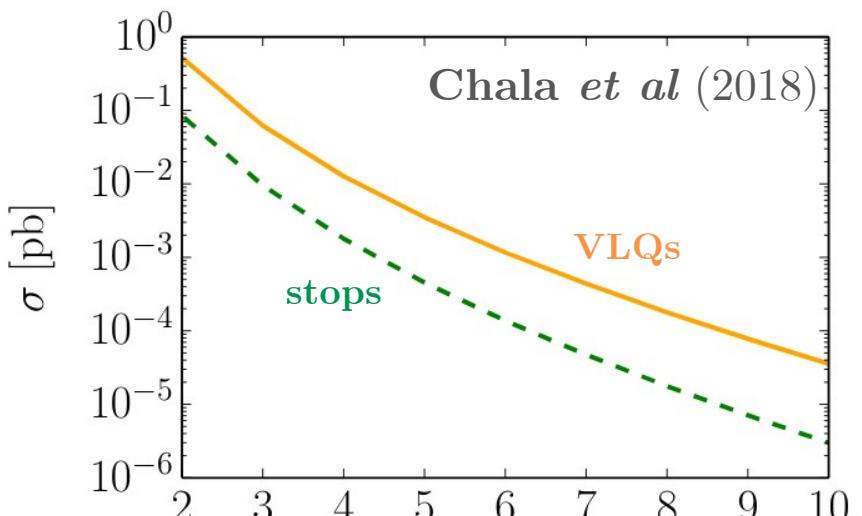
## Composite signatures at colliders

Top partner singlet as the *lightest* VLQ:

$$\text{e.g. } \mathbf{27} = \mathbf{1} \oplus \mathbf{6} \oplus \mathbf{20}$$



Pair Production @100TeV

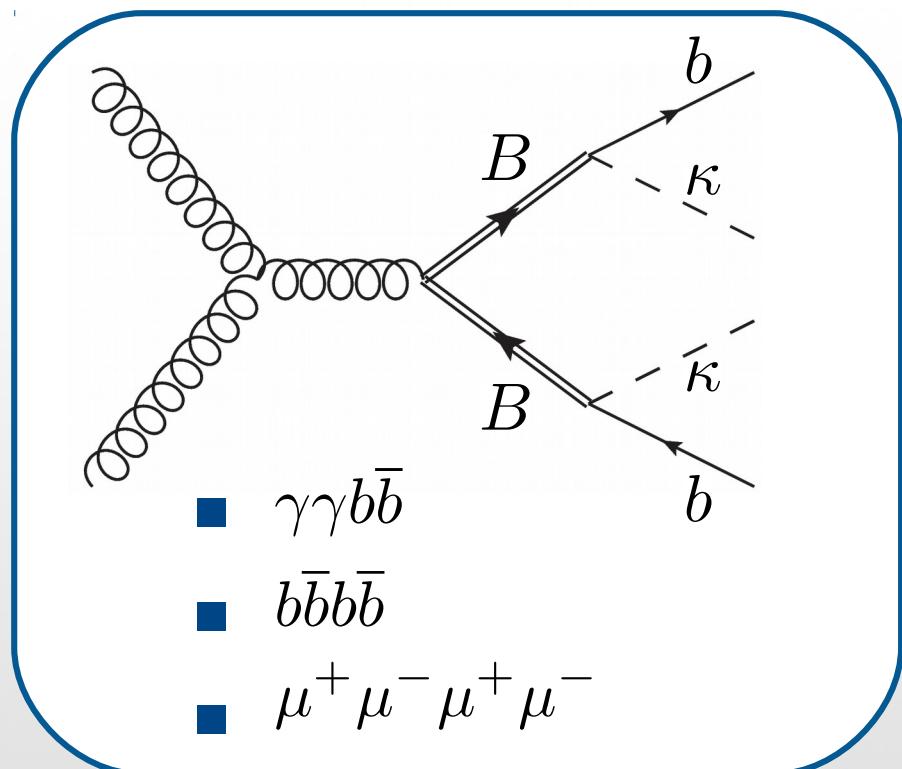


$$L = 1 \text{ ab}^{-1} : M \text{ [TeV]}$$

$$M \lesssim 9 \text{ TeV}, m_\eta \lesssim 3 \text{ TeV}$$

## Composite signatures at colliders

Non-minimality?  
singlet is the lightest?



Only prospects for the LHC,  
including:

$S \rightarrow b\bar{b}$  Chala (2017)

$a \rightarrow b\bar{b}/gg$  Cacciapaglia *et al* (2019)

Hierarchical parameter space:

$$m_\kappa \in [50, 400] \text{ GeV}$$

$$M_B \in [1, 9] \text{ TeV}$$

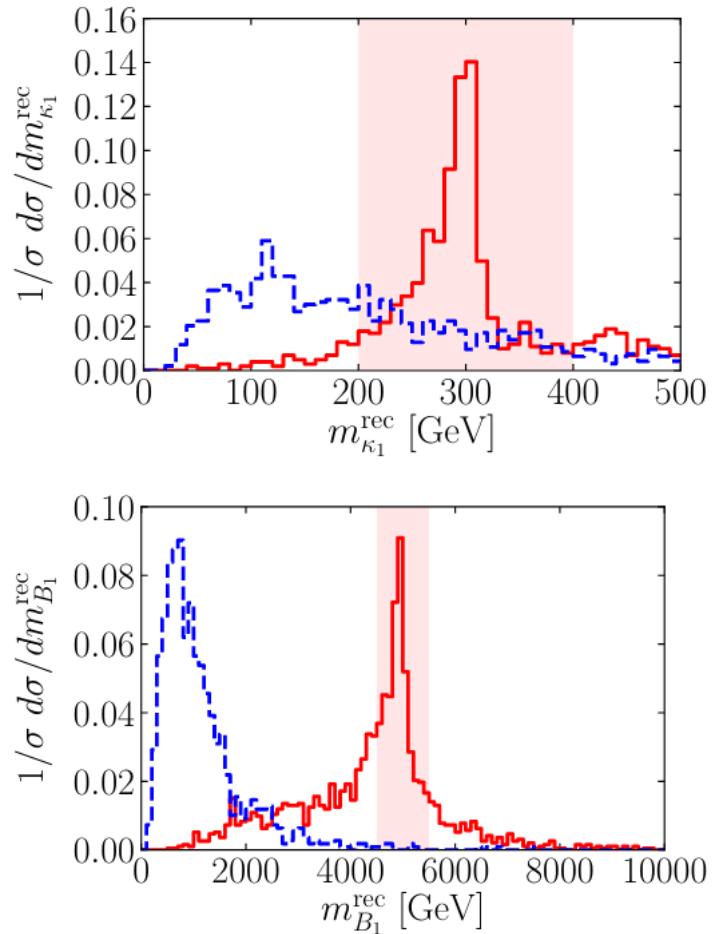
# Search for *six bottoms* in the final state

Main background:

$$pp \rightarrow b\bar{b}b\bar{b}, \ p_T^{b_1} > 500 \text{ GeV}$$

Selection Cuts:

- No isolated leptons;
- At least 6 *b*-jets;
- Scalar reconstruction from  
 $|m_{\kappa_1}^{\text{rec}} - m_{\kappa_2}^{\text{rec}}| < \Delta$
- Partners reconstruction from  
 $|m_{B_1}^{\text{rec}} - m_{B_2}^{\text{rec}}| < \Delta$



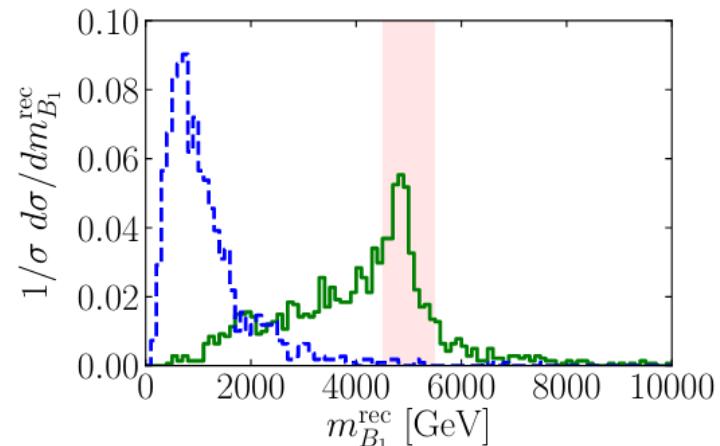
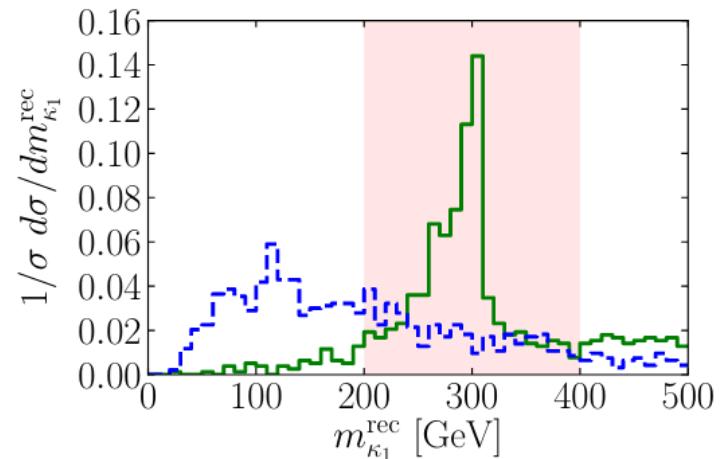
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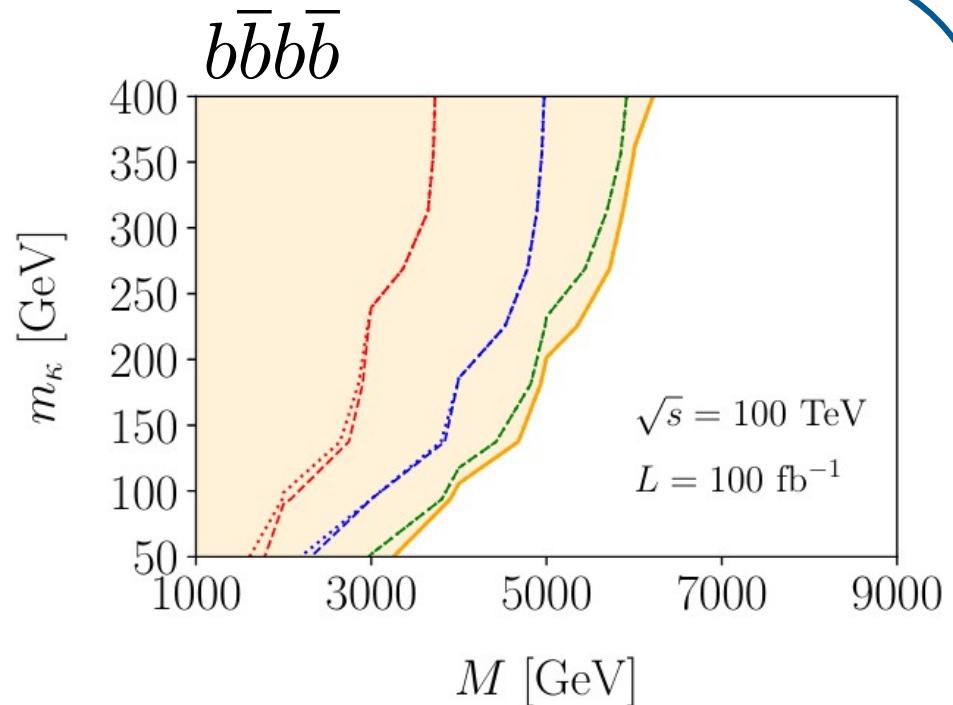
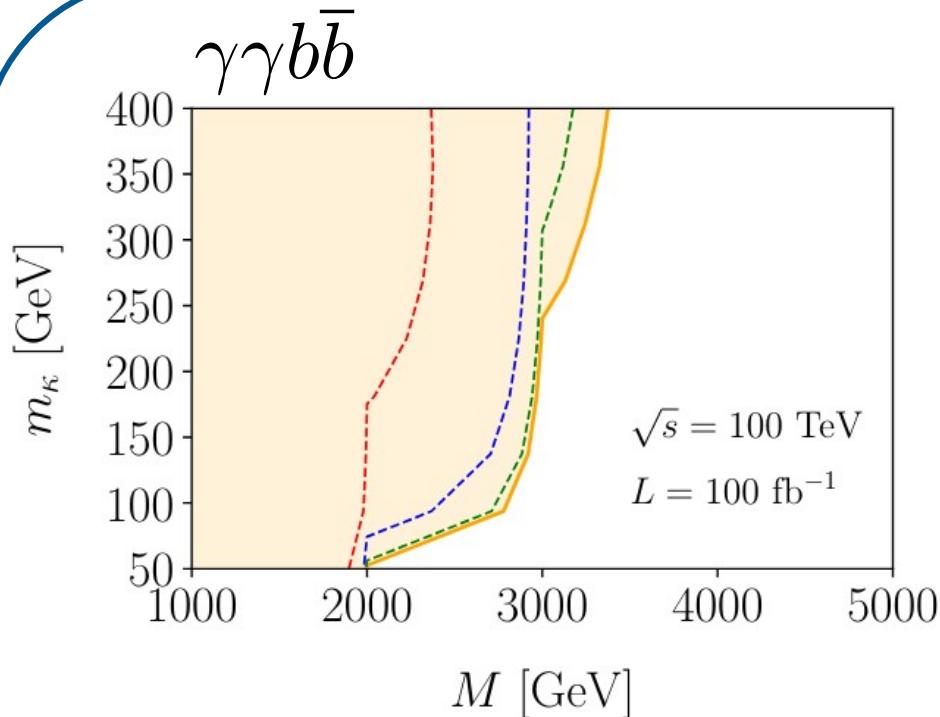
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# Prospects for a 100TeV collider



Muon analysis probes the entire parameter space @  $L = 1 \text{ ab}^{-1}$

# Conclusions

CHMs with dark matter are predictive frameworks which lead to a rich phenomenology:

- Dark matter can freeze-out even in the **absence of couplings to the SM**.
- Motivated regimes escape both current and future constraints from dark matter searches.
- (Non-minimal) collider searches are mandatory.

Dark matter in anomaly-free CHMs is far from being ruled out.

# Thank you!

(special thanks to M.Chala for useful discussions)

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