Phenomenology of Non-Minimal Composite Higgs Models

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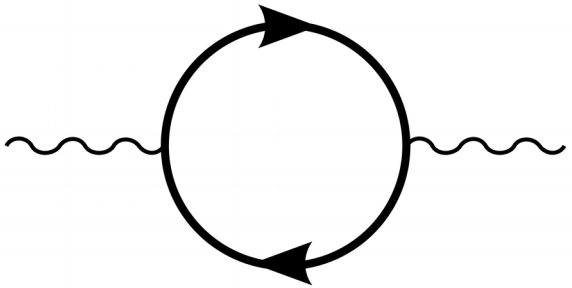
The SM is impressive, but still incomplete:

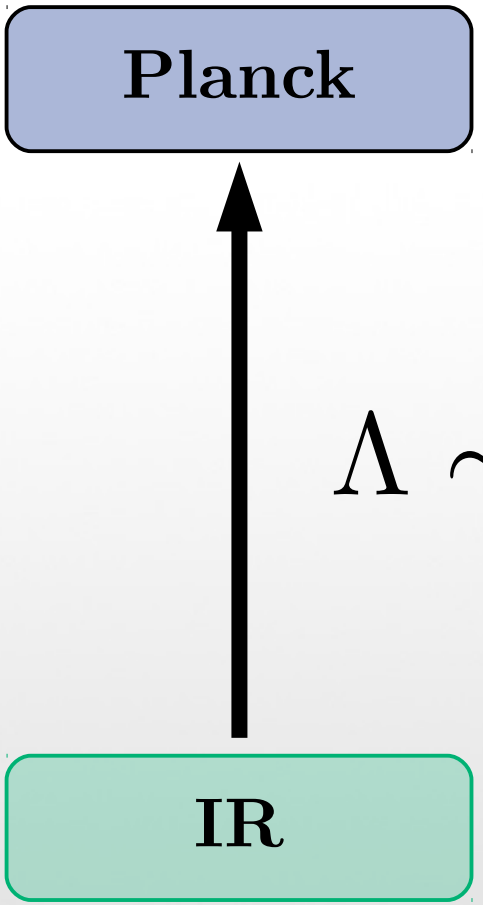
- Dark Matter
- Baryogenesis
- Neutrino Masses
- Flavour hierarchy
- Etc.

And then the Higgs...



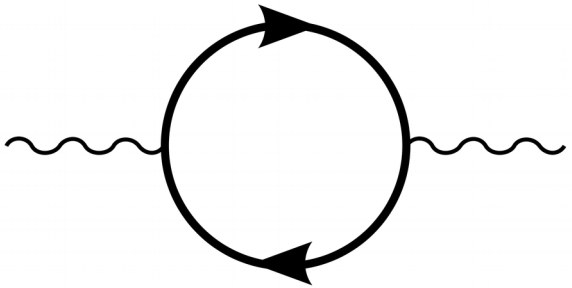
$$\delta m_H^2 \sim \frac{g^2}{(4\pi^2)}\Lambda^2$$

The SM is impressive, but still incomplete:



$$\Lambda \sim M_P!$$

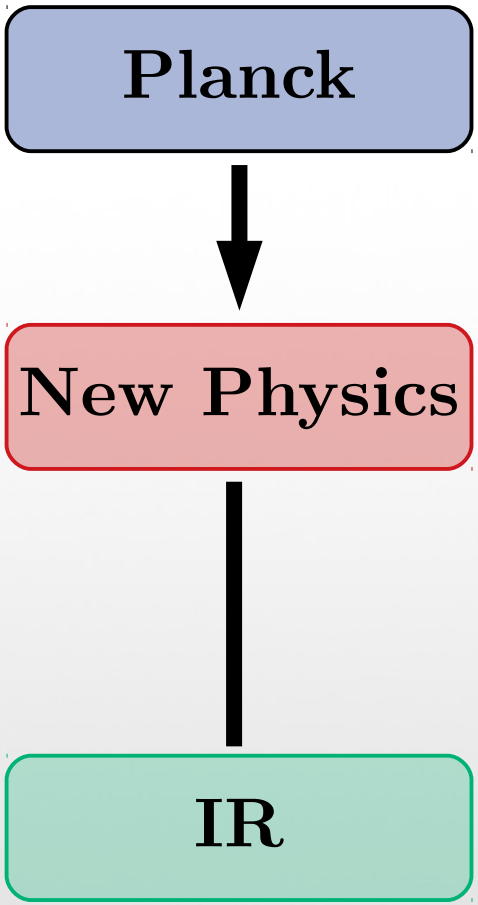
And then the Higgs...

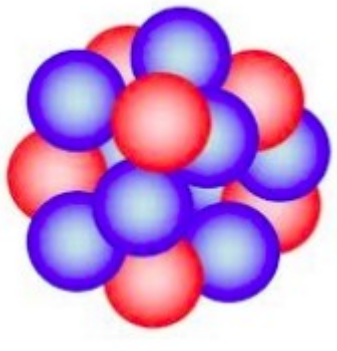


$$\delta m_H^2 \sim \frac{g^2}{(4\pi^2)}\Lambda^2$$

Something *should* be there...

A composite Higgs as a solution



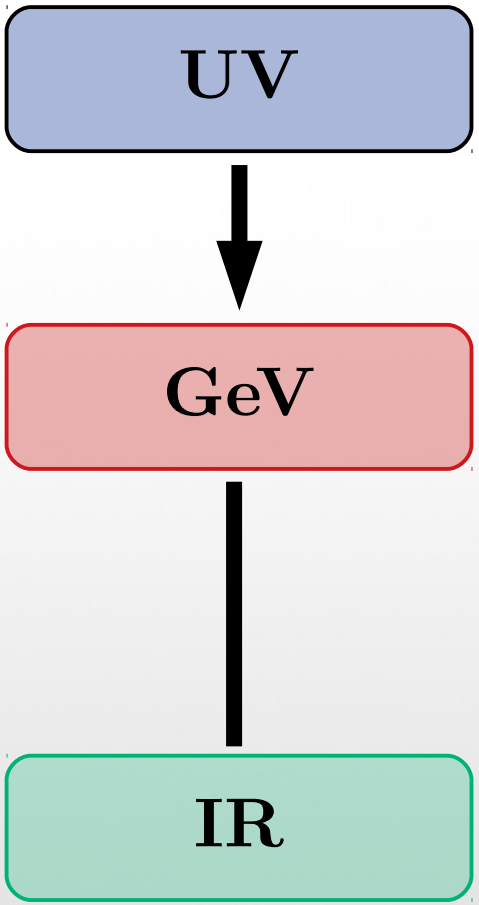


$$\left.\right] \sim \frac{1}{\text{TeV}}$$

The Higgs emerges as a *Goldstone boson* of

$$\mathcal{G}/\mathcal{H} \supset SO(4)$$

QCD-like at high energy



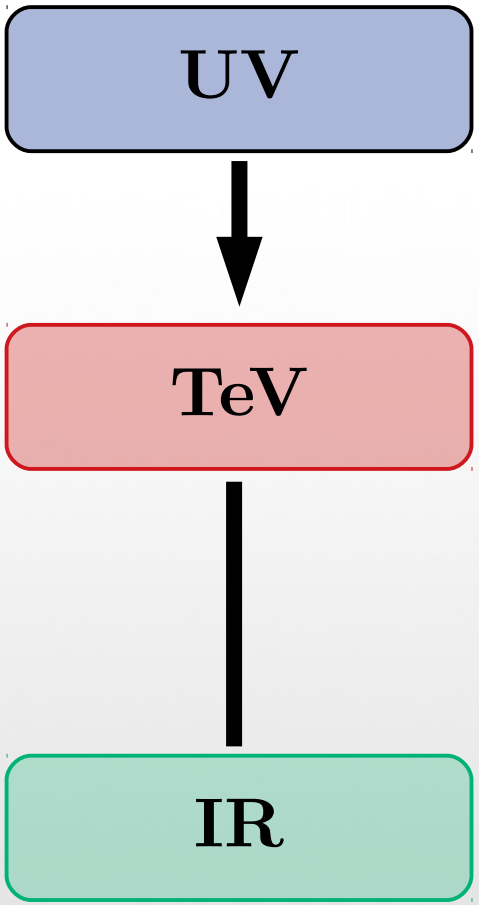
$$\mathcal{L} = m\bar{q}q + SU(2)_L \times SU(2)_R$$

$$p, n, \rho, \ldots$$

$$\pi^{\pm}$$
$$\pi^{0}$$

$$SU(2)_V$$

QCD-like at high energy



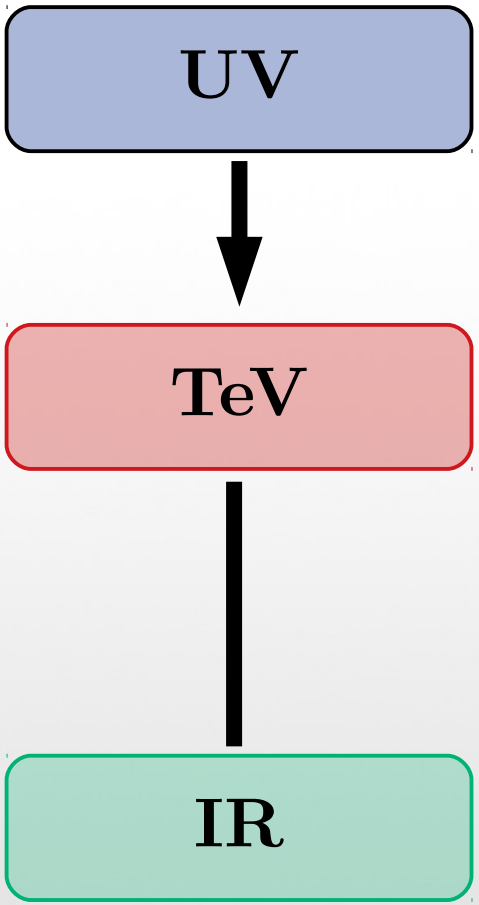
$$\mathcal{L} = \lambda \overline{q_i} \mathcal{O}_F^i + \text{global } \mathcal{G}\ [\mathrm{SO}(5)]$$

$$\lambda \overline{q_i} Q^i$$

$$\underline{\qquad\qquad} h$$

$$\mathcal{H}\ [SO(4)]$$

QCD-like at high energy



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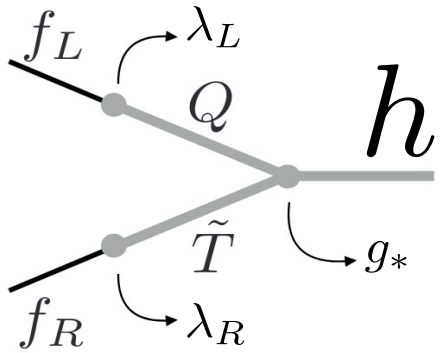

$$\mathcal{H}\ [SO(4)]$$

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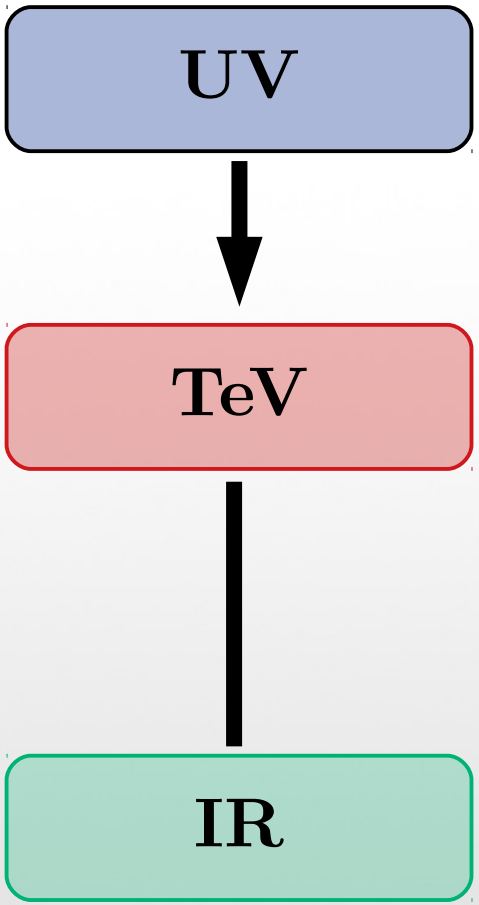
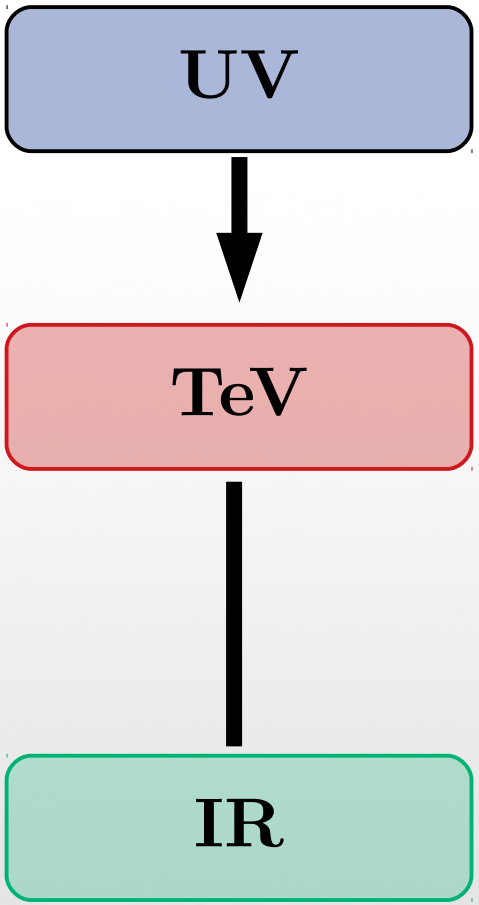


$$\mathcal{L} = \lambda \overline{q_i} \mathcal{O}_F^i + \text{global } \mathcal{G}\ [\text{SO}(5)]$$

$$\lambda \overline{q_i} Q^i$$

$$m_h^2 \sim \frac{y_i^2}{(4\pi)^2} m_Q^2 \qquad \mathcal{H}\ [SO(4)]$$

Non-minimal framework



$$\mathcal{L} = \lambda \overline{q_i} \mathcal{O}_F^i + \text{global } \mathcal{G}$$

Heavy resonances

$$\lambda \overline{q_i} Q^i$$

Group theory constraints: **VERY PREDICTIVE**

$$h, S, \eta^2 \ldots$$

Extra scalars

Focusing on a specific symmetry pattern

Let us focus on **SO(7)**

1. Breaking to SO(6) (if a condensate in the fundamental representation gains a VEV):
(a) dark matter, (b) light scalars

2. Breaking to G_2 (if the condensate transforms in the spinorial representation):
(c) triplet under SM gauge group

Extended Scalar Sector: SM triplet

$$V = \frac{1}{2}m_h^2 H^2 + \frac{1}{2}m_\phi \Phi^2 + \boxed{\lambda_{H\Phi} H^\dagger \Phi H} - \frac{\lambda_h}{4}H^4 + \frac{\lambda_\phi}{4}\Phi^4$$

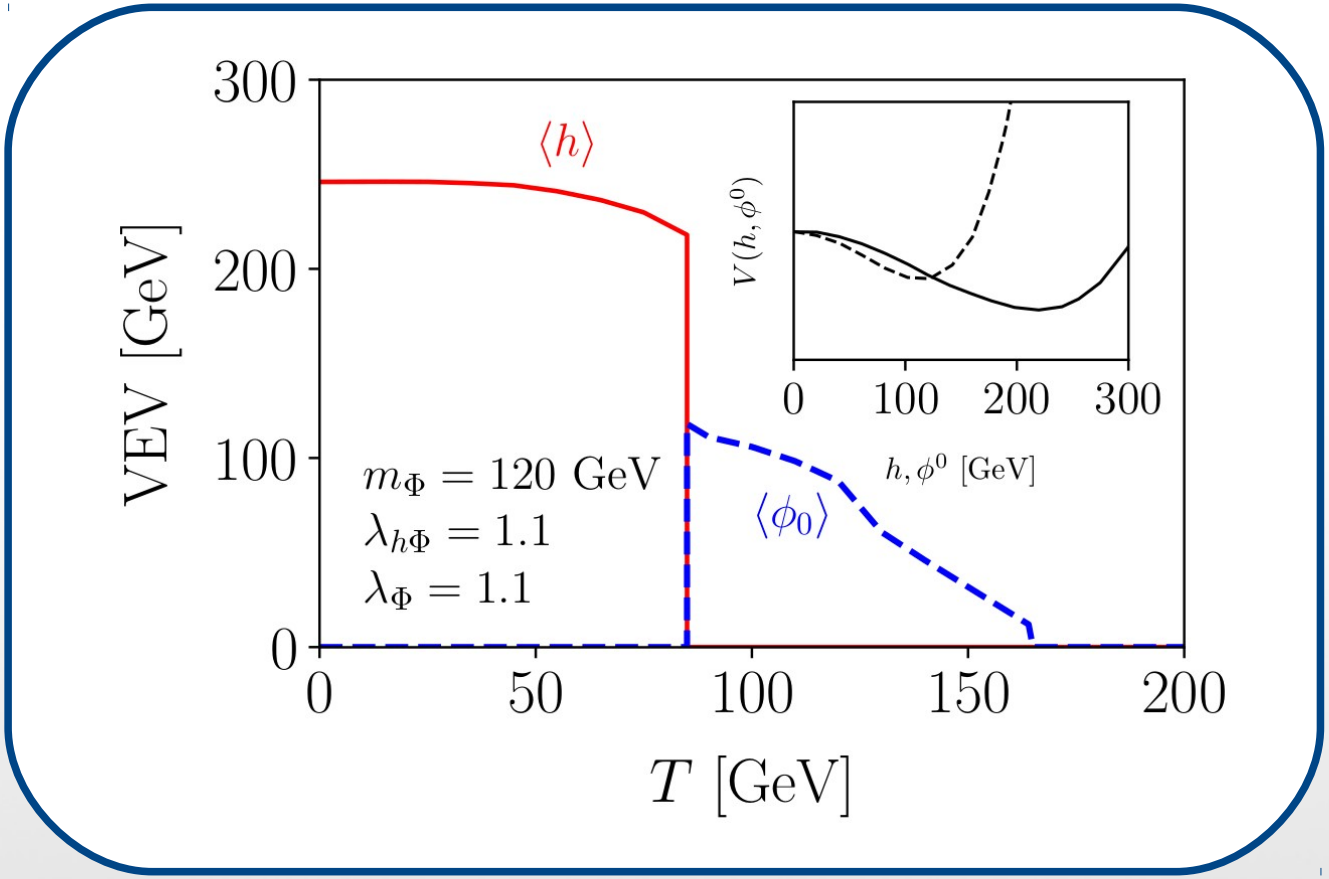
In conflict with: $\rho \equiv \frac{m_W^2}{m_Z^2 \cos\theta_w{}^2}$

$\Rightarrow \Phi$ *a pseudoscalar*

$$\sim \frac{ic}{f}\overline{q_L}\,(H\Phi)\,u_R$$

new collider phenomenology and might trigger baryogenesis

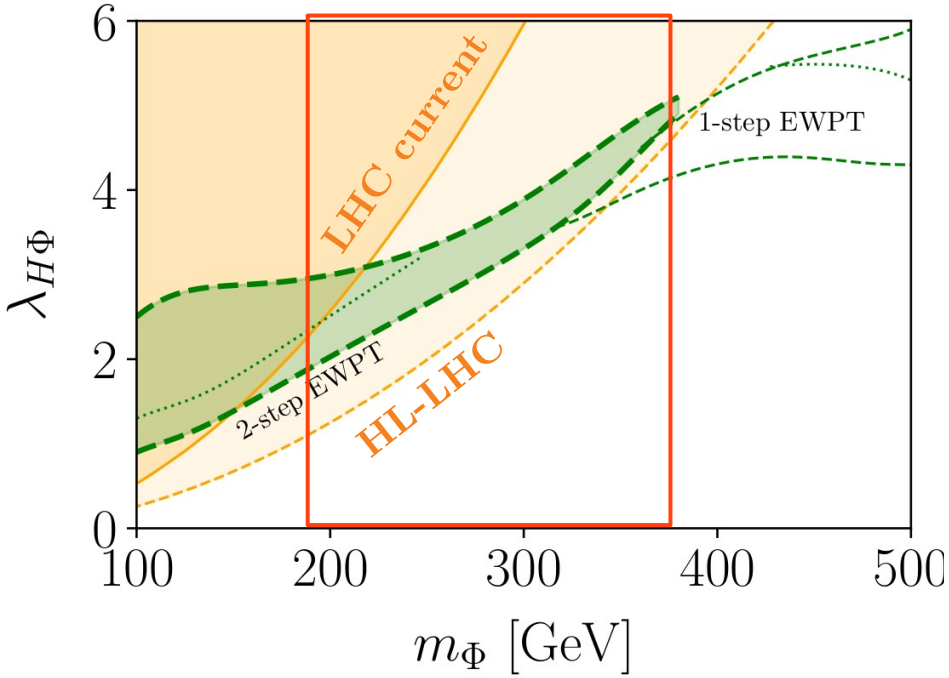
Extended Scalar Sector: SM triplet



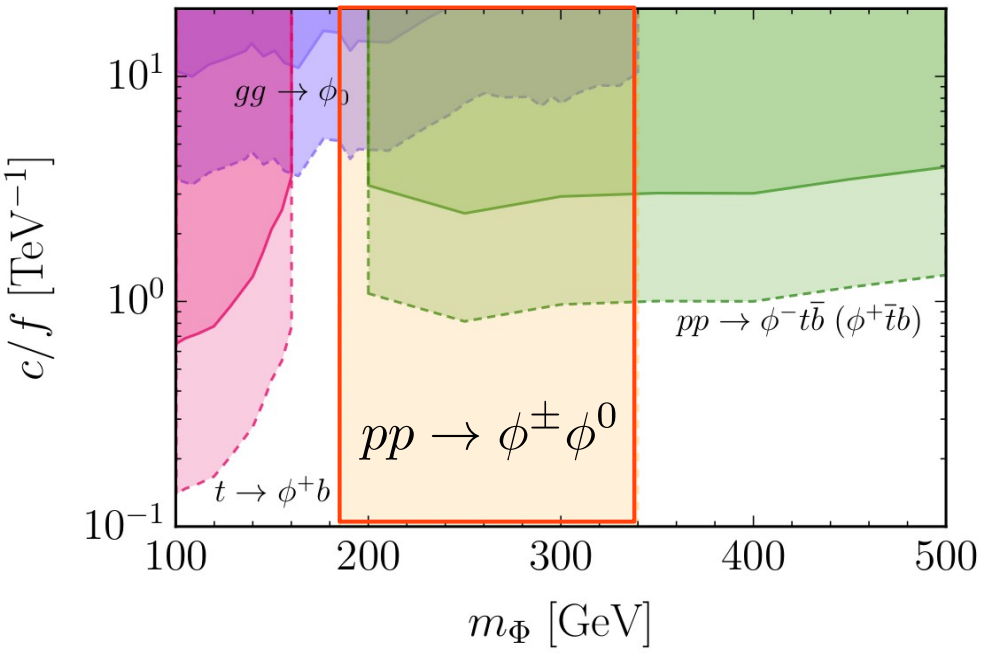
What are the consequences?

Extended Scalar Sector: SM triplet

Prospects for LISA

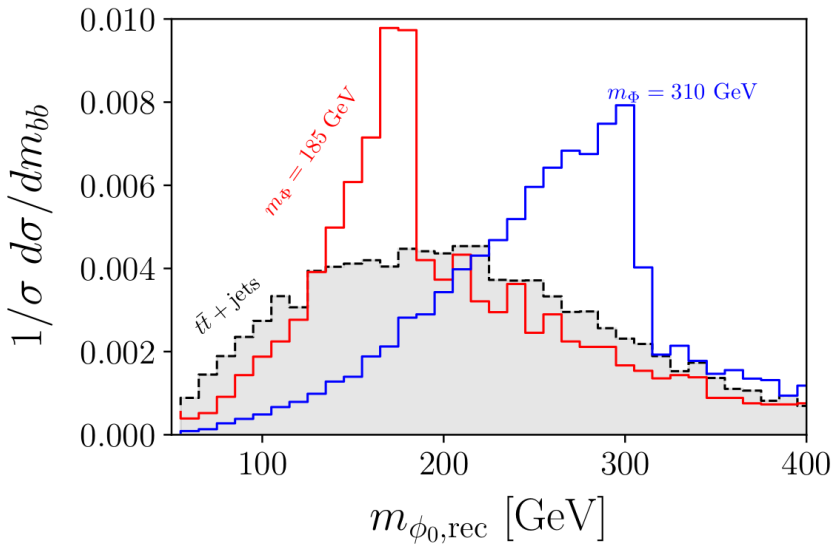


LHC Searches



Extended Scalar Sector: SM triplet

$$pp \to \phi^{\pm}\phi^{0} \to \bar{t}b(t\bar{b})\bar{b}b$$



- EW baryogenesis requires **CPV in the past.**
- Spontaneous CPV at finite temperature **implies a signal at the LHC.**
- The parameter space where EWB can occur **can be probed at the HL-LHC.**

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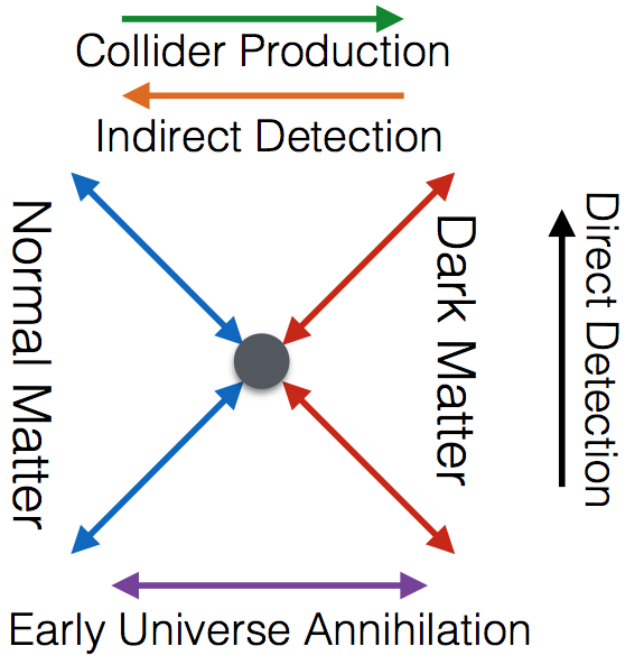
Composite Dark Matter: Novel Signatures

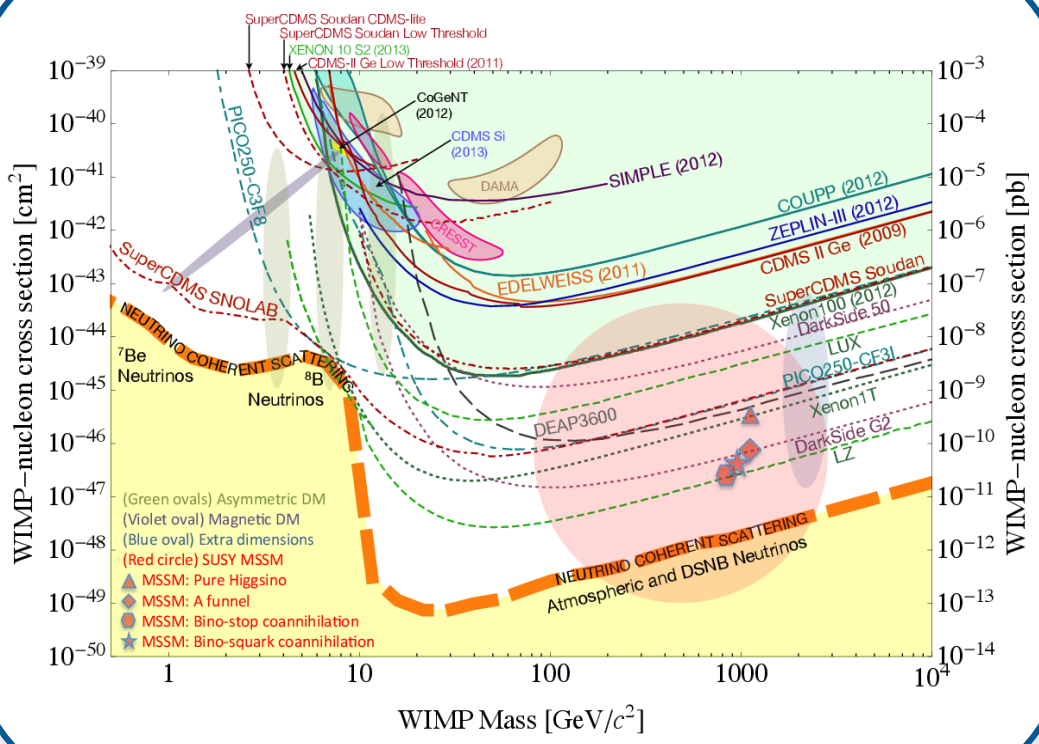


- Stable
- Electric Neutral
- If it is a thermal relic,

$$\Omega h^2 \approx 0.1 \left(\frac{\alpha_w^2 (200\text{GeV})^2}{\langle \sigma v \rangle} \right)$$

The WIMP miracle is no longer a coincidence.

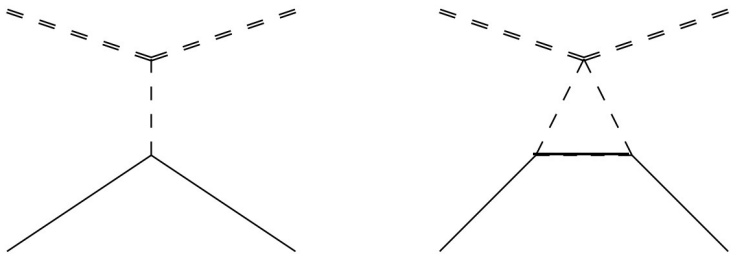
Composite Dark Matter: Novel Signatures



A revival of WIMPS ?

$$\mathcal{L}_{kin} \sim \frac{(\eta\partial_\mu\eta)(\pi_i\partial^\mu\pi^i)}{f^2}$$

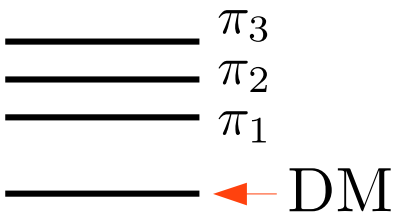
$$\lambda_{\eta H} \approx 0 \qquad \lambda_{\eta\pi_i} \sim \lambda_H$$



$(e.g.\ \overline{q_L} \oplus q_R = \mathbf{27} \oplus \mathbf{1})$

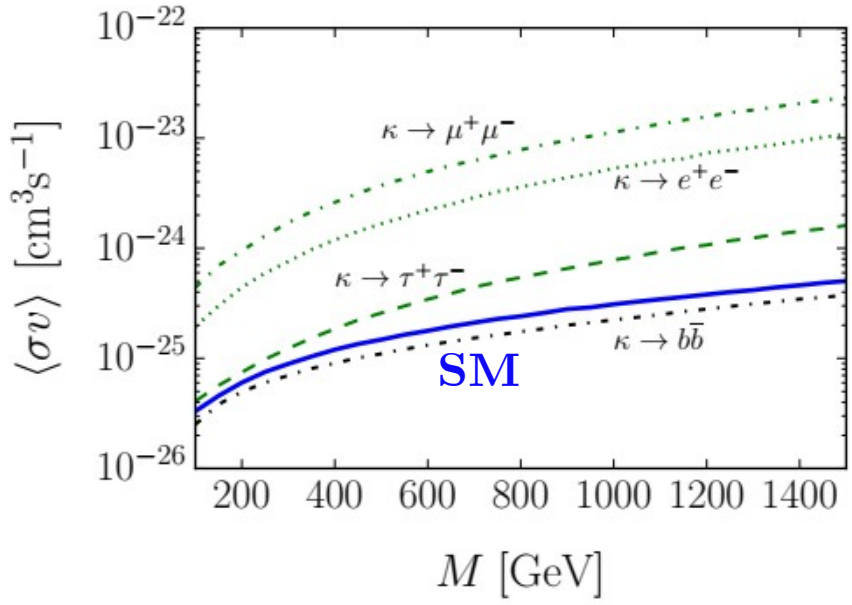
Composite Dark Matter: Novel Signatures

Traditionally



However,

$$\frac{M^2}{m_\pi^2} \sim \frac{y_t^2}{y_b^2}$$



- DM can freeze-out even in the **absence of couplings to SM**.

- Further **motivation for collider searches**, to test both:
  - Compositeness
  - Non-minimality

$$e.g.\ pp \to B\overline{B} \to \kappa\kappa b\bar{b}$$

Flavour Physics: Light Scalars at LHCb

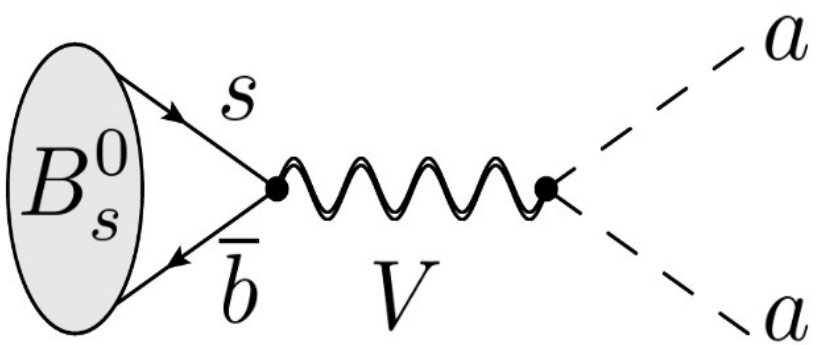
In many BSM frameworks,

V^μ ——— $\sim$ TeV

a - - - - - - - - - - - $\ll$ TeV

} CHMs reconcile scales and trigger couplings

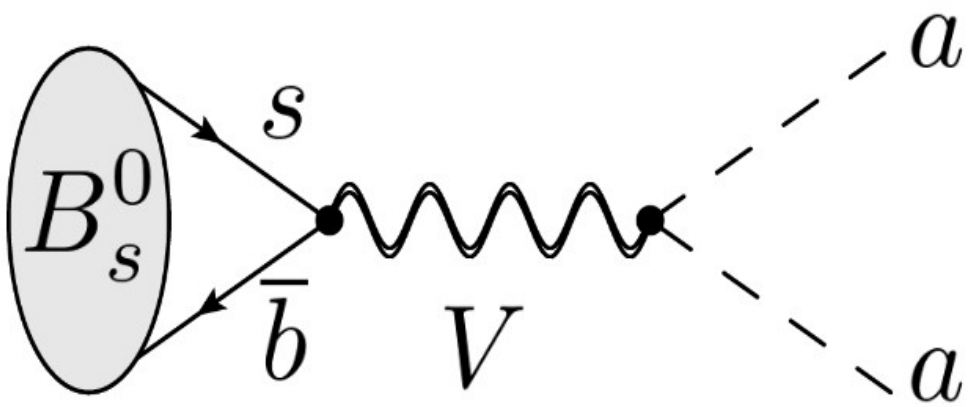
$$y_\ell a \ell^+ \ell^-, m^2 a^2, \ldots$$



Flavour Physics: Light Scalars at LHCb

$$\mathcal{B}\left(B_0^s \to 2\mu^+ 2\mu^-\right) < 2.5 \times 10^{-9} \quad \textbf{@ 8 TeV}$$

Ref. 1902.10156: $\mathcal{O}\left(10^{-11}\right)$ **@ end Upgrade-II**



Sensible probe of
SMEFT + a

Flavour Physics: Light Scalars at LHCb

V^μ

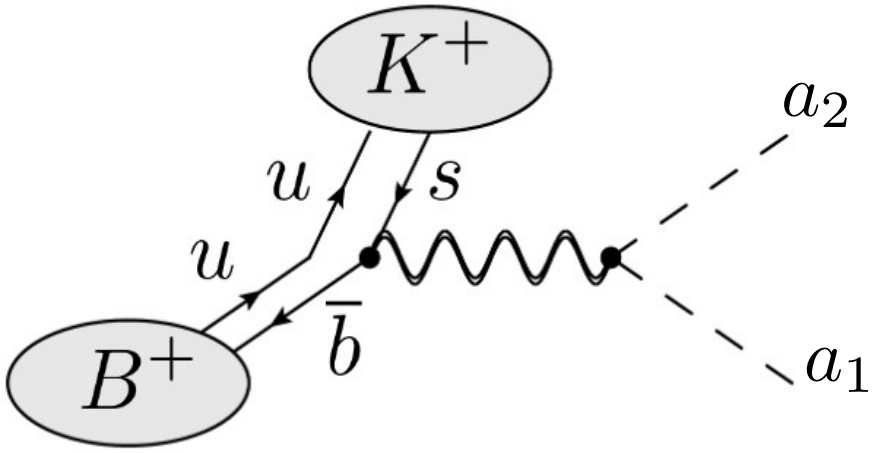
a_2 ----------

a_1 ----------

1. $\Gamma\left(a_2 \to a_1 a_1\right) > \Gamma\left(a_2 \to \ell^+\ell^-\right)$

2. $\mathcal{L}_{int} \propto V_\mu J^\mu$, with $J^\mu \sim a_1 \overleftrightarrow{\partial^\mu} a_2$

$\xrightarrow{m_1 = m_2} \Gamma\left(B_0^s \to a_1 a_2\right) = 0$



$\mathcal{B}_{3\mu^+3\mu^-} \sim 8 \times 10^{-9}$

$\mathcal{B}_{K^+3\mu^+3\mu^-} \sim 2 \times 10^{-9}$

Conclusions

CH is a predictive framework with a rich phenomenology:

- Link collider and astrophysical probes
- Rethink traditional BSM strategies
- Explore new regions of signal
- Test effects beyond SM (*e.g.* future project on rare top decays and FCNC)

Thank you very much for your attention!

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