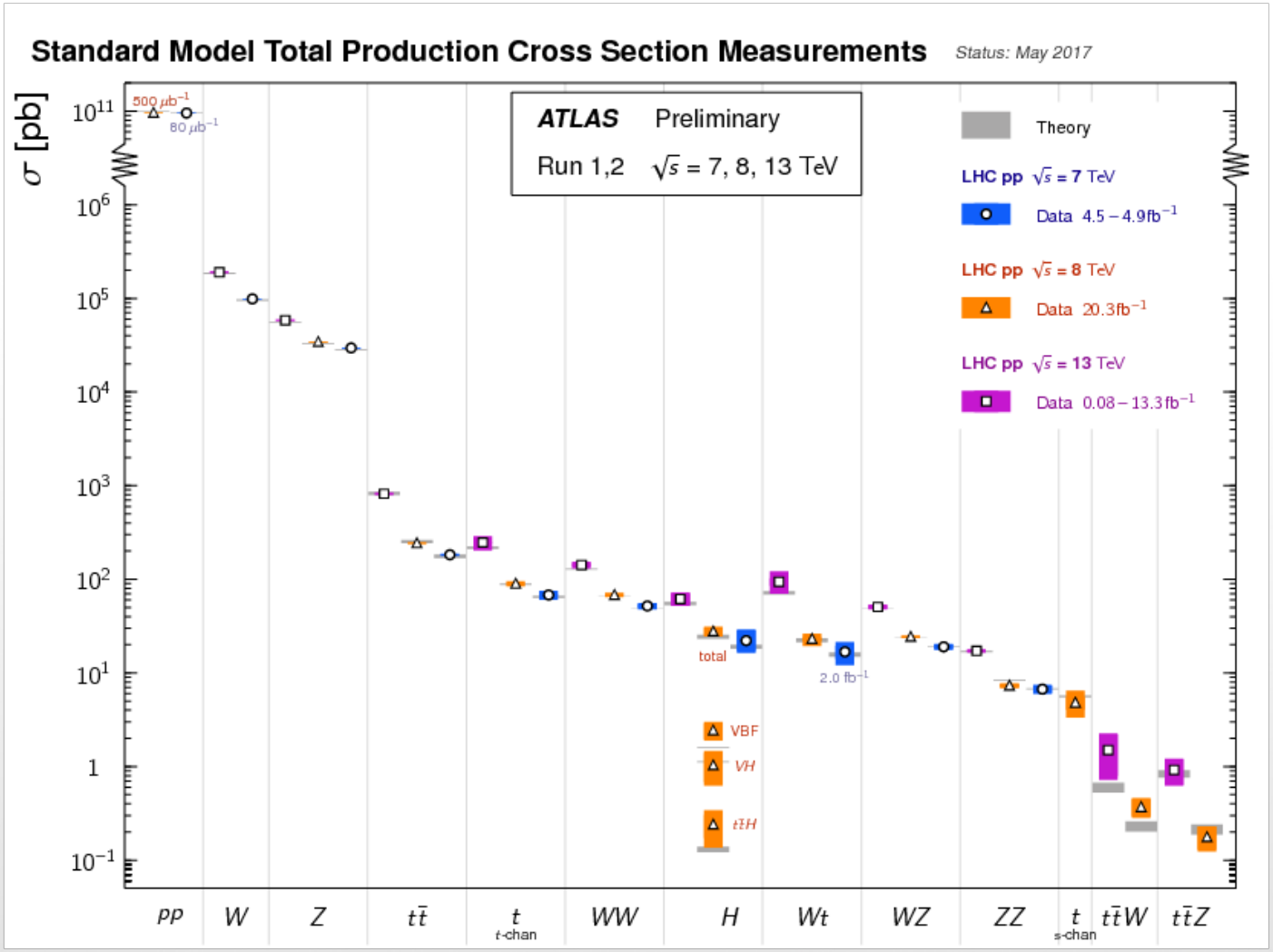
Composite signals of new physics

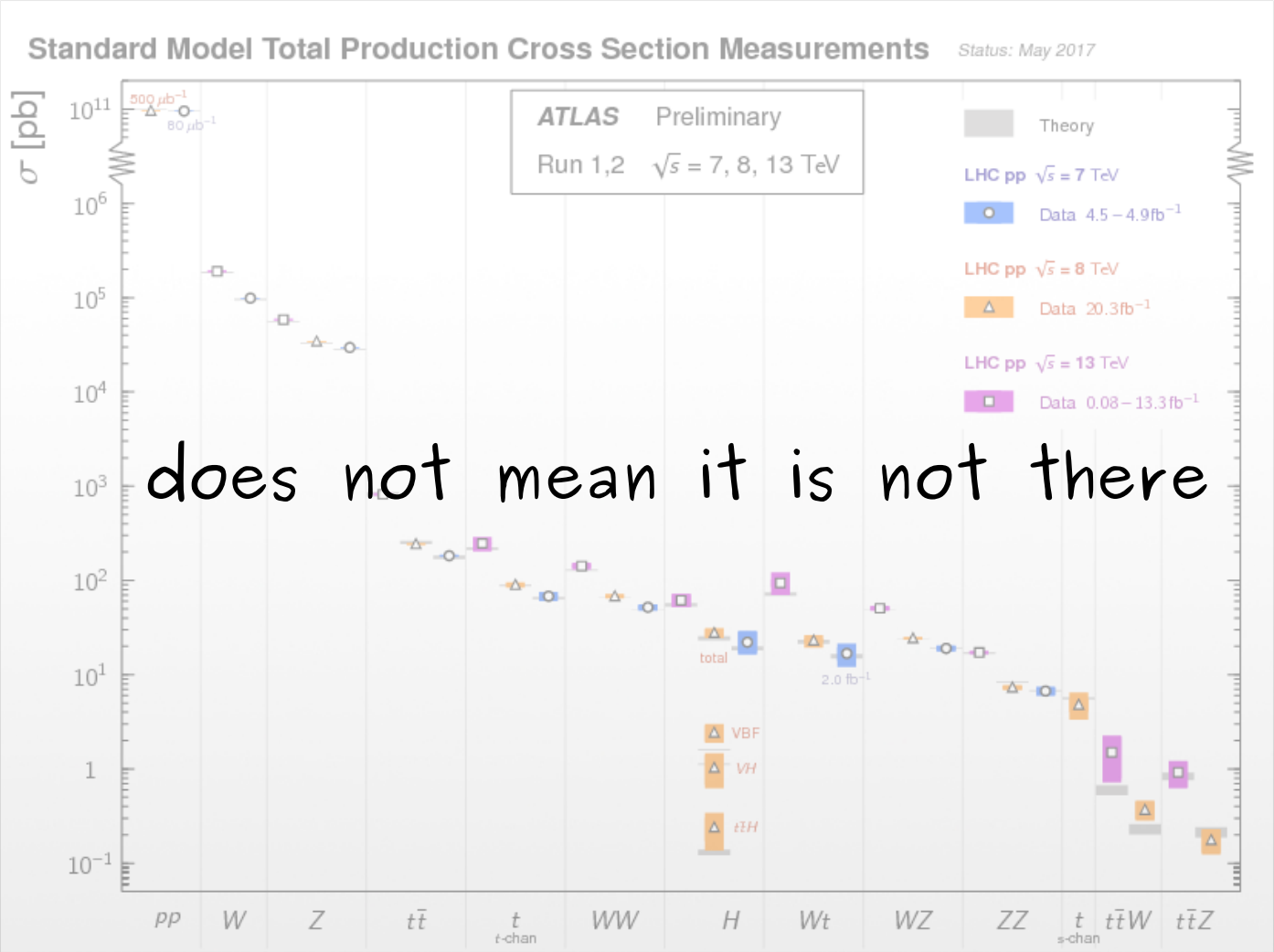
Maria Ramos

mariaramos@lip.pt

No evidence of new physics



No evidence of new physics



does not mean it is not there

Not the time to lose hope.

Actually, a very important time to **build** hope.

- **Do we know the Higgs boson?**
  Is the Higgs elementary? How much does it self-interact? ...
- **Are we posing the right questions?**
  What is the origin of the EW scale?
- **Have old strategies become non viable?**
  Does the Higgs fullfill naturalness?
- **Can Higgs physics point towards new physics?**
  Coincidence with dark matter, baryogenesis, LFU breaking scales?
- **Are we searching in the right places?**
  Are there directions into which we have not looked?
- **Are we interpreting well what data is telling us?**
  Does the absence of new physics means necessarily decoupling?

- Do we know the Higgs boson?

  Is the Higgs elementary?

- Are we posing the right questions?

  What is the origin of the EW scale?

- Have old strategies become non viable?

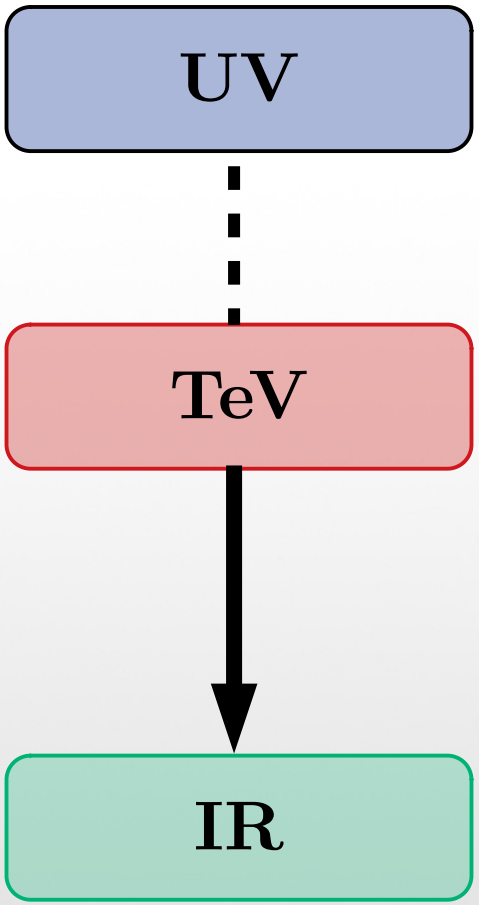
- Can Higgs physics point towards new physics?

- Are we searching in the right places?

- Are we interpreting well what data is telling us?

EWSB from a minimally coupled strong sector

G/H=SO(5)/SO(4)



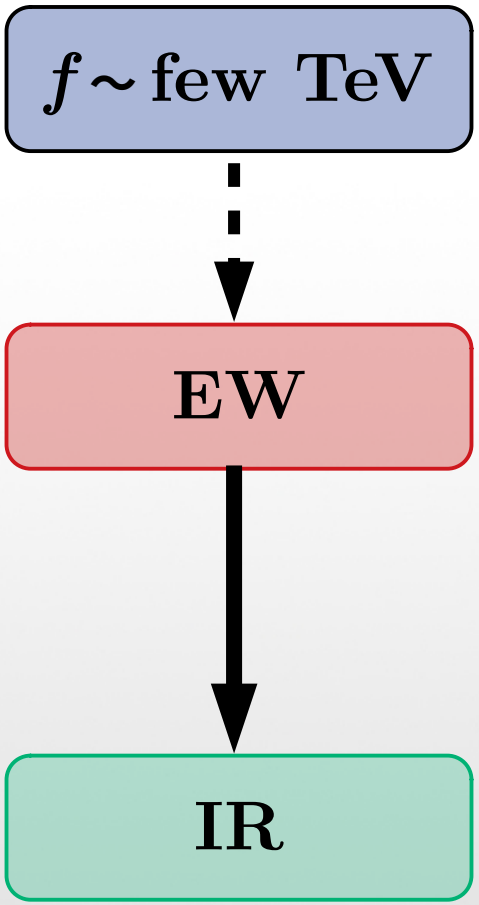
$\sim \rho_{\rm QCD}$ V_μ, L, Q

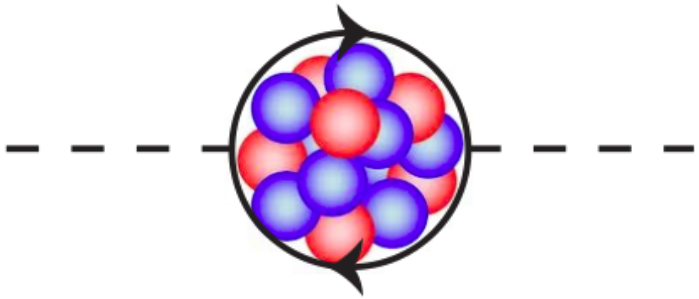
$\sim \pi_{\rm QCD}$

H ~ 4 NGBs of G/H

The strategy to make the Higgs lighter

...was already observed

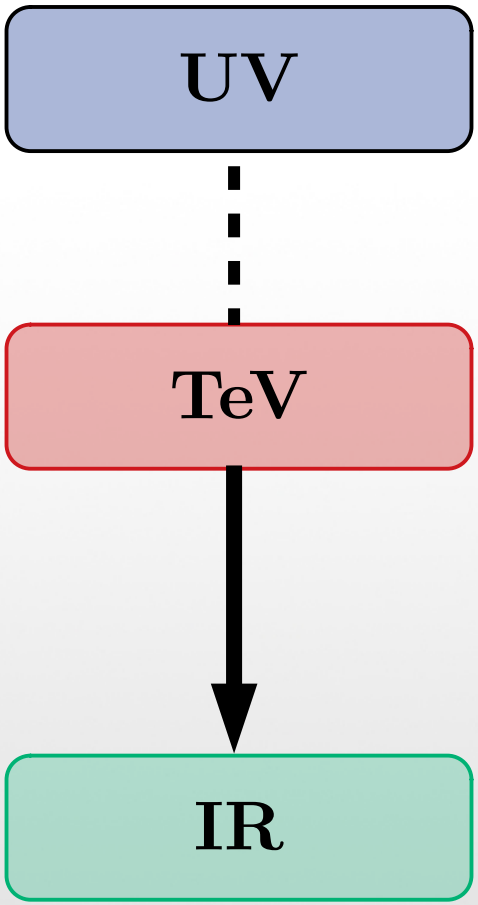




$$\delta m_h^2 \sim \frac{y^2}{(4\pi^2)} f^2$$

$$y = 0 : \;\; h \to h + \alpha f$$

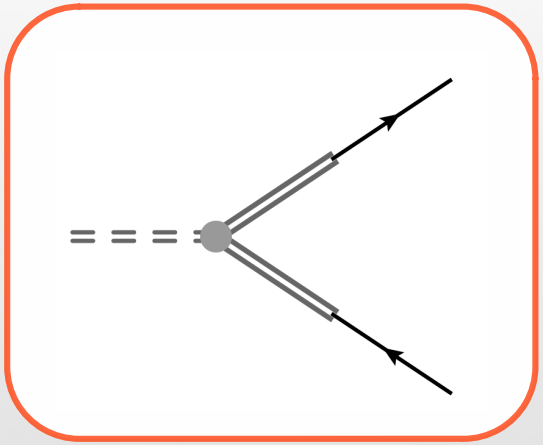
EWSB from a minimally coupled strong sector



Under partial compositeness,

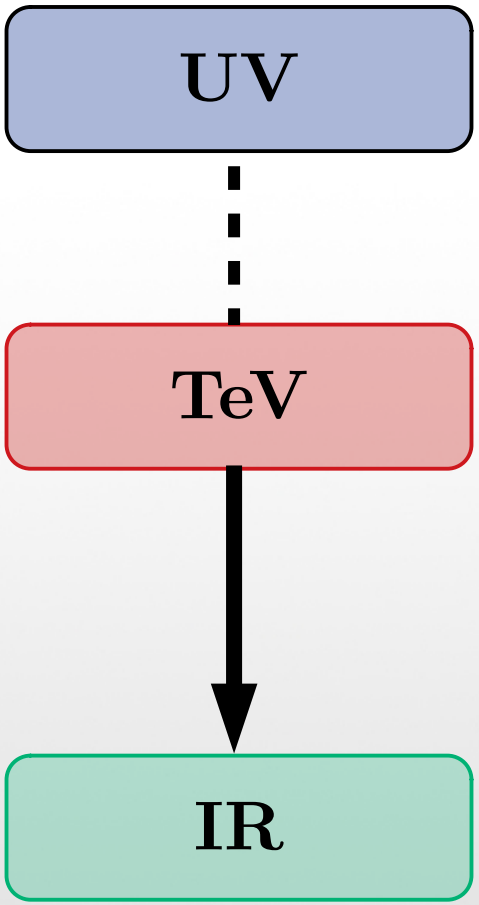
$\sim \rho_{\rm QCD}$ $V_\mu, L, Q \not\longleftrightarrow \ell, q$

$\sim \pi_{\rm QCD}$ H



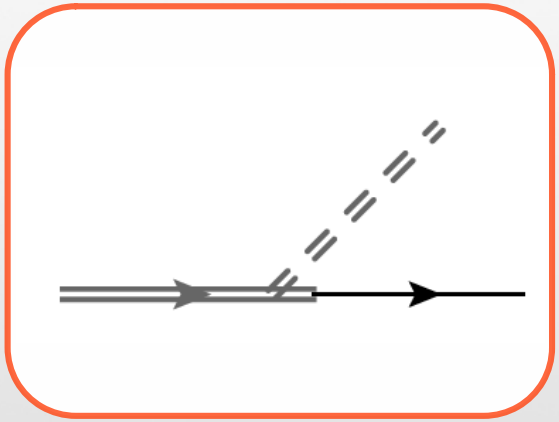
EWSB from a minimally coupled strong sector

VLQ pair production search in the Wt+X final state	EXOT	JHEP 08 (2018) 048
VLQ pair production search in the Ht+X final state	EXOT	JHEP 07 (2018) 089
VLQ pair production search in the Wb+X final state	EXOT	JHEP 10 (2017) 141
VLQ pair production search in the Zt+X decay with a 1 lepton plus MET plus jets final state	EXOT	JHEP 08 (2017) 052



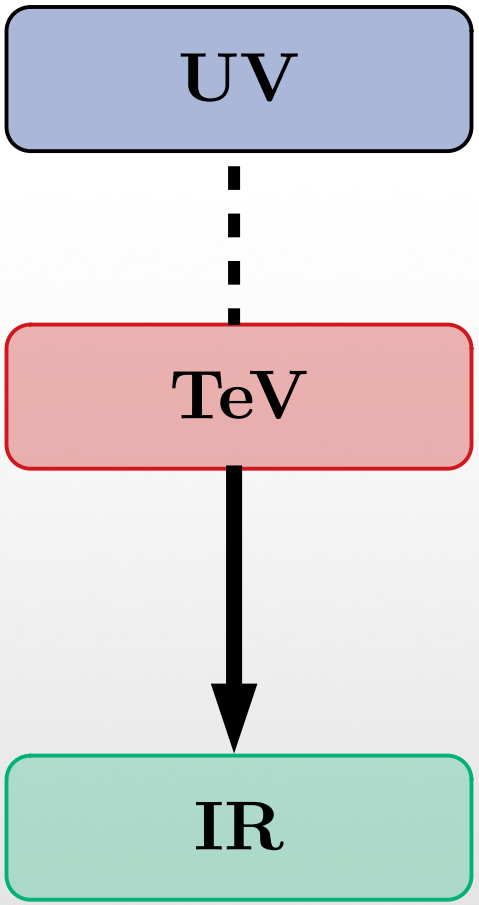
$\sim \rho_{\rm QCD}$ V_μ, L, Q $\not{G}$ ℓ, q

$\sim \pi_{\rm QCD}$ H



EWSB from a minimally coupled strong sector

unlikely



$\sim \rho_{\rm QCD}$ V_μ, L, Q $> 1\,(4)$ TeV

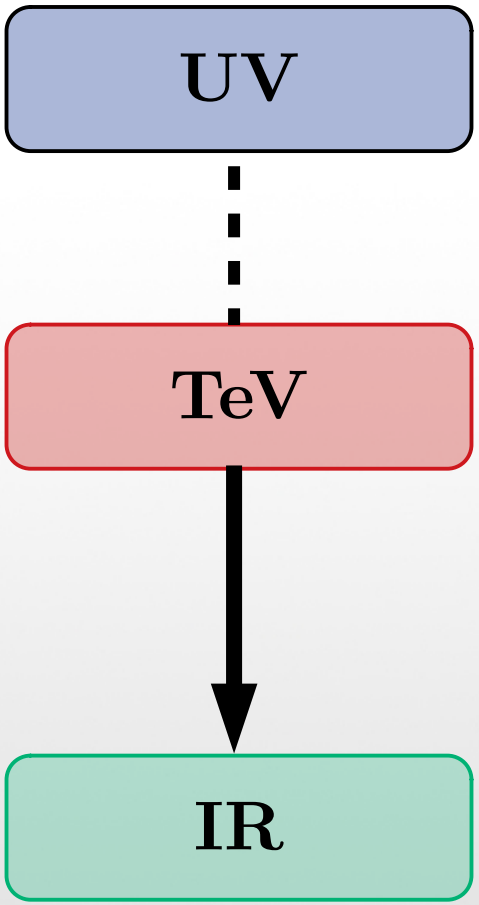
$\Delta \equiv \frac{v^2}{f^2} \lesssim 10^{-3}$

$\sim \pi_{\rm QCD}$ H

... with no extended purpose

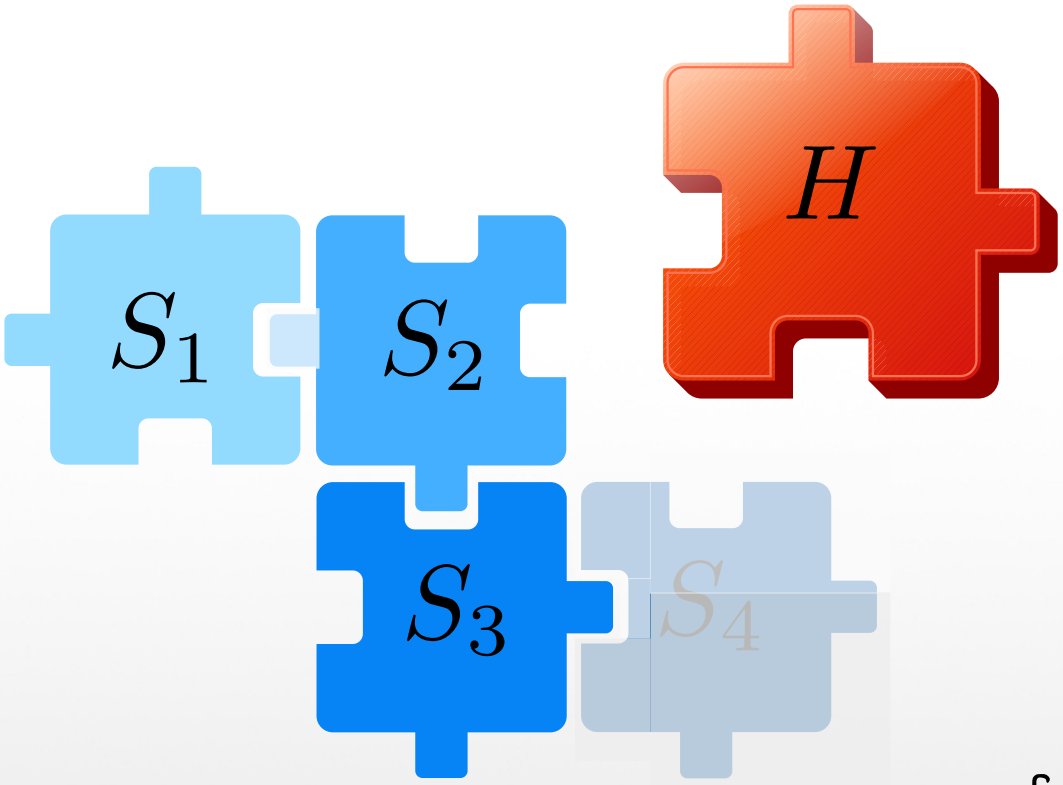
Beyond the minimal composite Higgs model

*UV completed in d=4, anomalous, natural, unique solutions



$\sim \rho_{\rm QCD}$ V_μ, L, Q $\not{G}$ ℓ, q

$\sim \pi_{\rm QCD}$ $H, S_1^q, S_2^\ell, S_3^2, \ldots$



focus of this talk

based on the SO(7)/G_2 CHM

$$\mathbf{7} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{3})$$

Triplet interactions

e.g. $q_L \oplus t_R = \mathbf{35} \oplus \mathbf{1}$ of SO(7)

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

$$\Leftrightarrow \Phi \to -\Phi$$

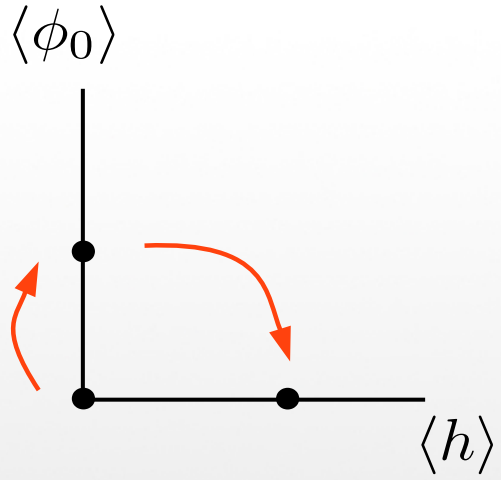
$$\sim \frac{ic}{f} y \overline{q_L} (H\Phi) u_R$$

No longer the inert triplet model, but a **much richer** framework.

Generation of the BAU

- Baryon number violation
- Departure from thermal equilibrium during a 1st order PT
- Extra sources of CP violation *in the past*, during the 1st order PT

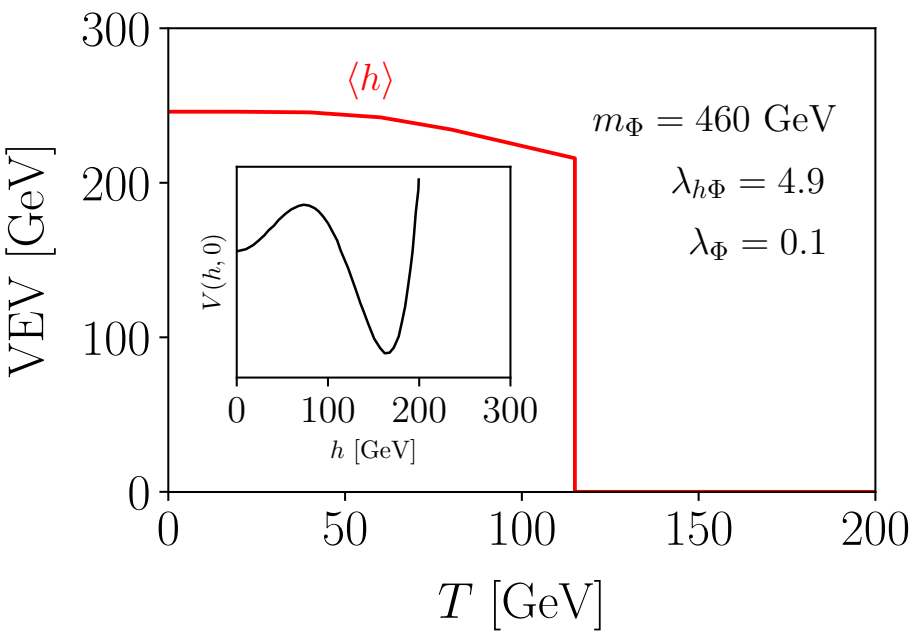
$$m_t \sim \langle h \rangle \left[y_t + i \frac{c}{f} \langle \phi_0 \rangle \right] = |m_t| e^{i\Theta_t}$$

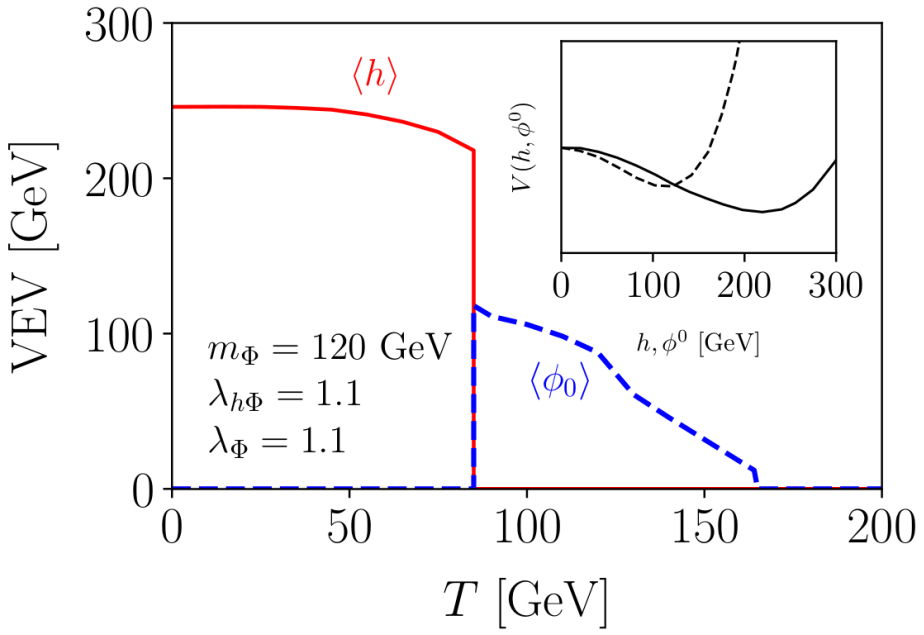


- $\frac{c\,\Delta v_\phi}{f} \sim 0.1 \Rightarrow \eta \equiv \frac{n_B - n_{\overline{B}}}{s} \sim 10^{-10}$

J.Espinosa,B.Gripaios,T.Konstandin,F.Riva (2011)

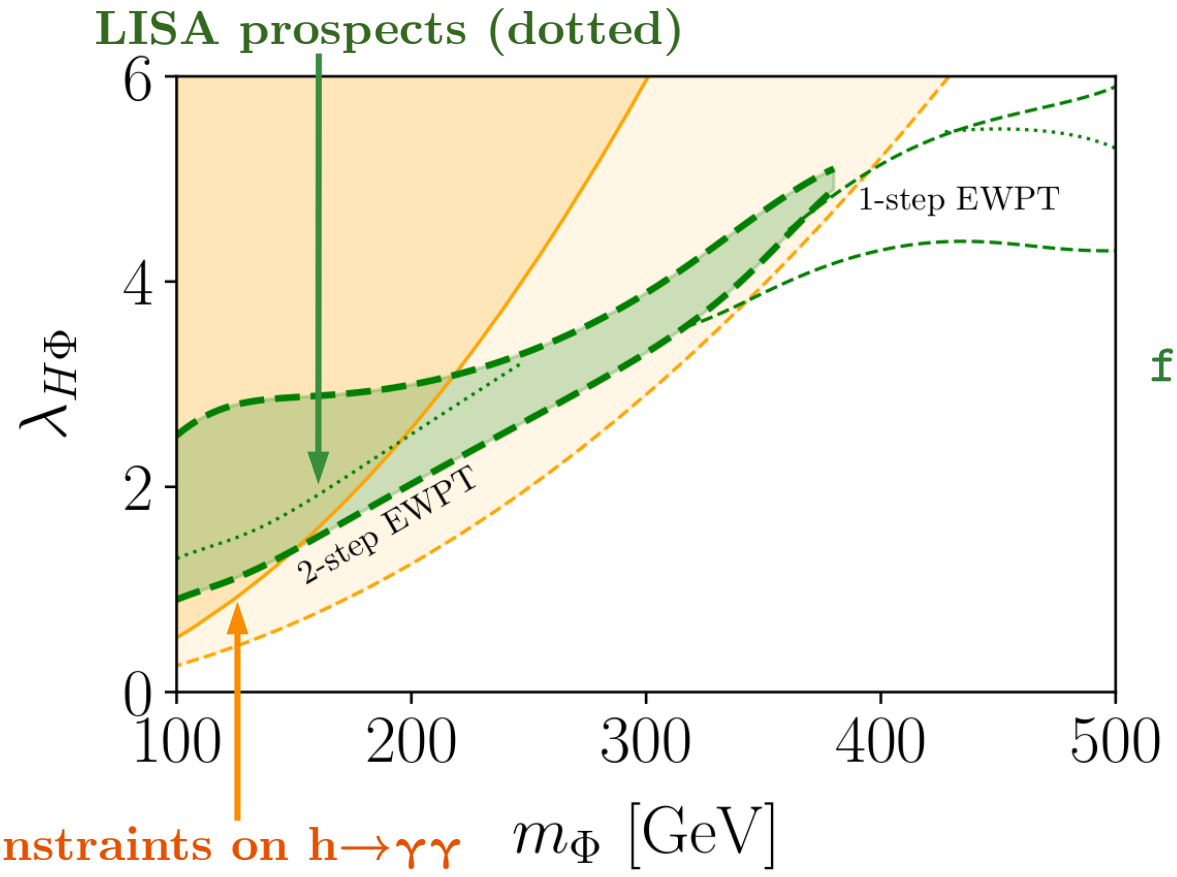
The EW phase transition





What are the low-energy consequences?

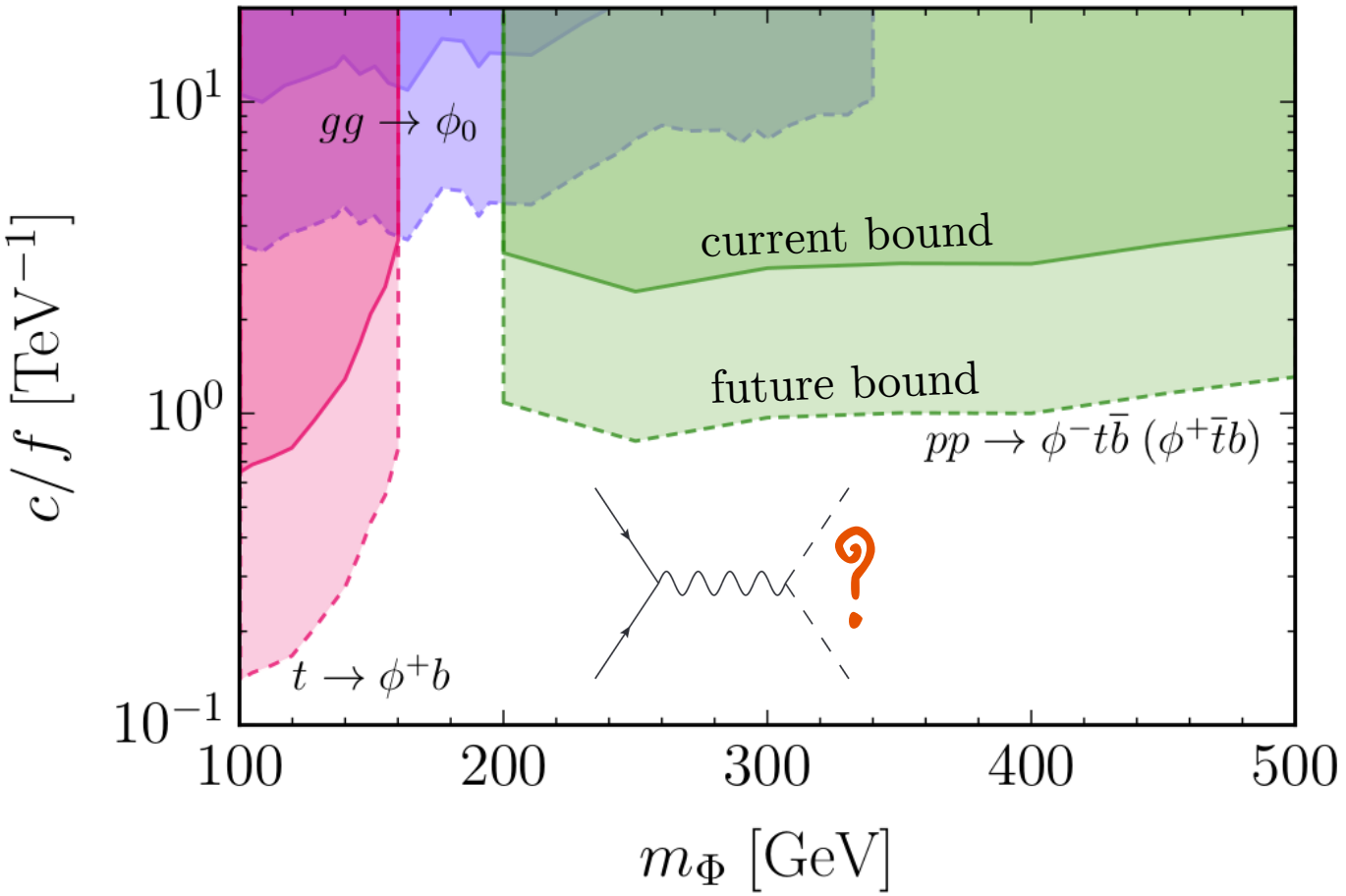
Constraints from the GW spectrum



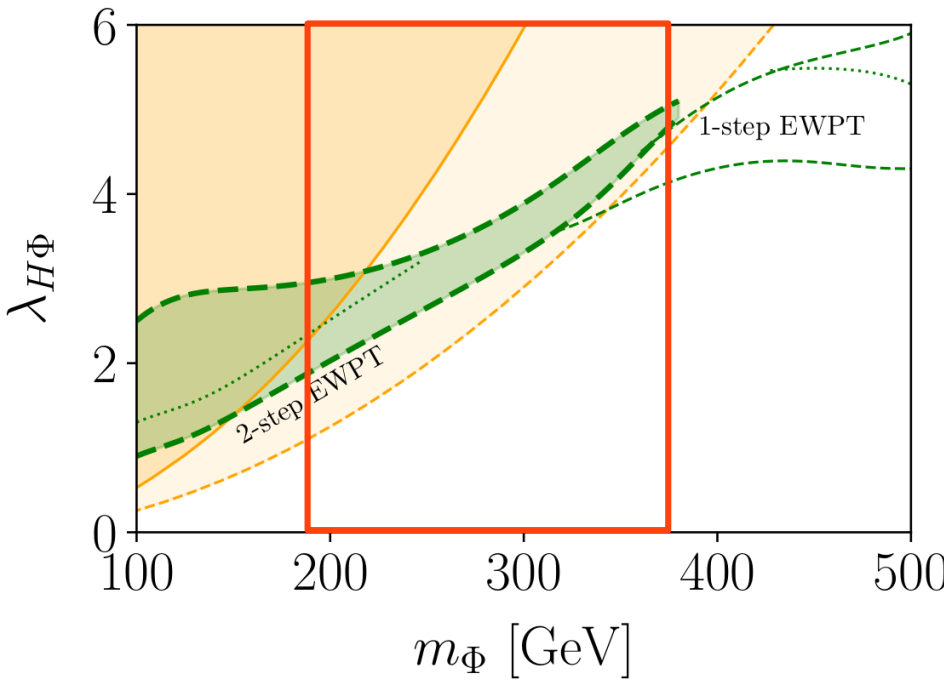
$$\frac{v_n}{T_n} \gtrsim 1$$

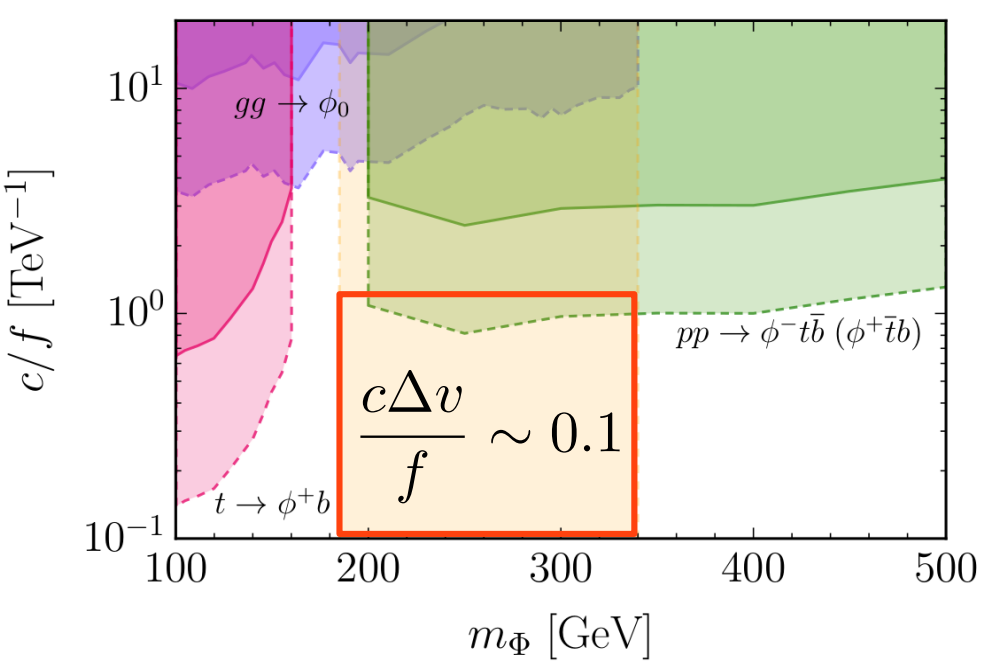
for strong PT

Constraints from collider data



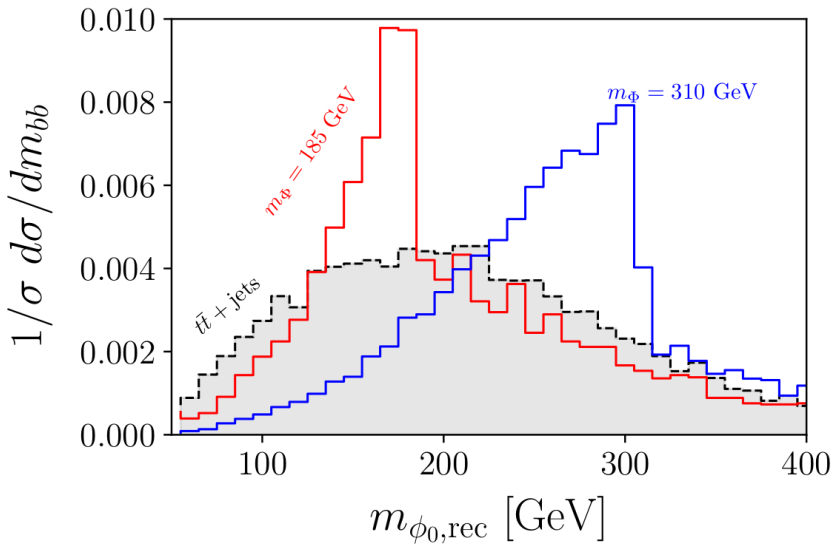
Complementarity of probes





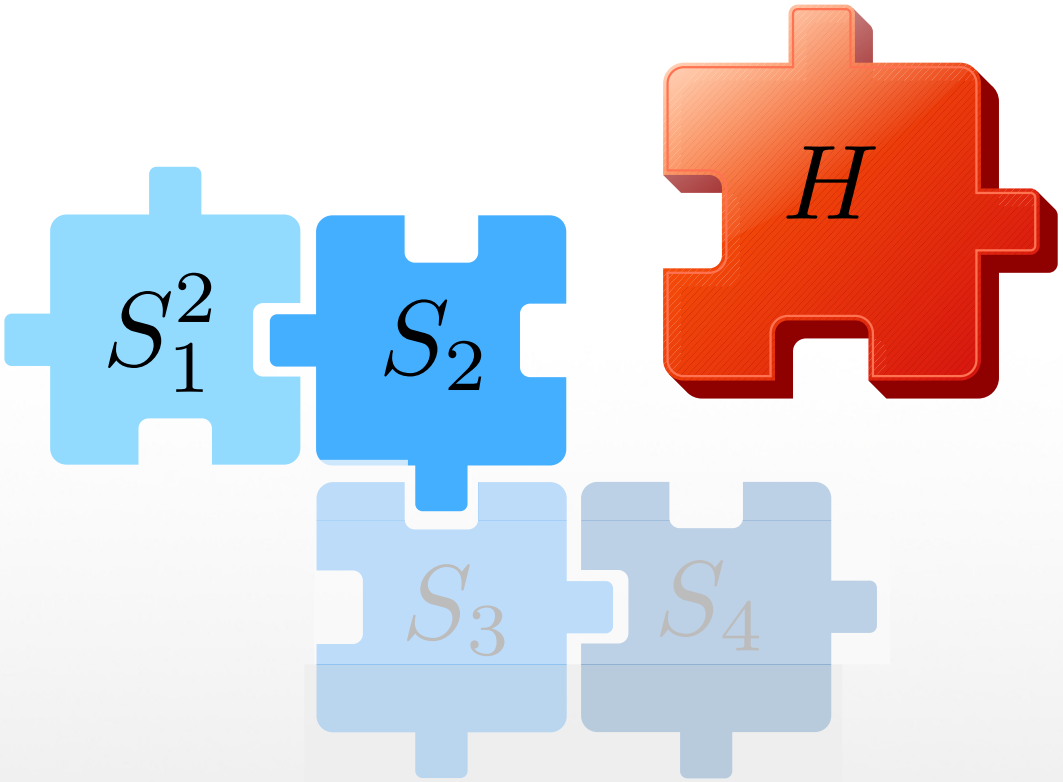
Outlook

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



- The entire parameter space where EWSB can occur **could be probed at the HL-LHC**
- Key search to establish constraints on other models
- Unique signature where the same operator responsible for CP violation in the past implies a clear collider signal in the present

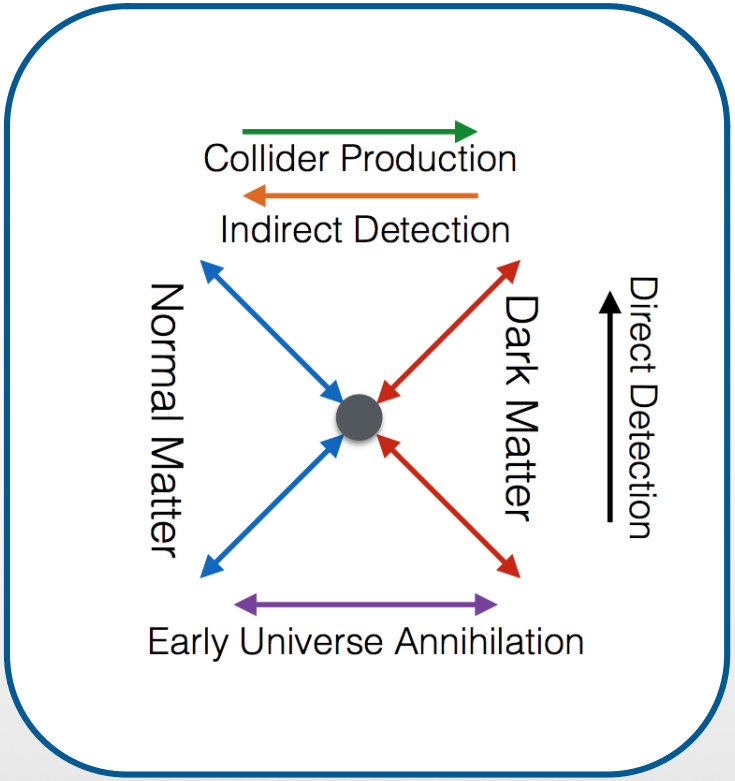
M.Chala,M.Ramos,M.Spannowsky (2019)



based on the SO(7)/SO(6) CHM

$$\mathbf{6} = (\mathbf{2},\mathbf{2}) \oplus 2 \times (\mathbf{1},\mathbf{1})$$

The composite-dark matter connection



- $\Lambda_{\rm DM} \sim$ EW

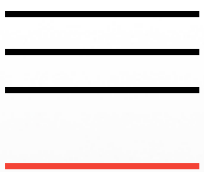
$$\Omega h^2 \approx 0.1 \left(\frac{\alpha_w^2/(100\ \text{GeV})^2}{\langle \sigma v \rangle_{\rm thermal}} \right)$$

- Protected from the HP
- No tension between relic density and direct searches, from

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

Dark matter stability symmetry

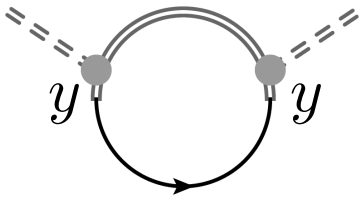
In non-anomalous composite dark matter models:



$$\begin{cases} SO(7)/SO(6) \to (H, \eta, \kappa) \\ SO(7)/G_2 \to (H, \phi_0, \phi^{\pm}) \end{cases}$$

Candidate for baryogenesis?

However, if



$$\frac{m_\eta^2}{m_\kappa^2} \sim \frac{y_t^2}{y_b^2} \longrightarrow$$

Minimal setup for the interplay

Dark matter interactions

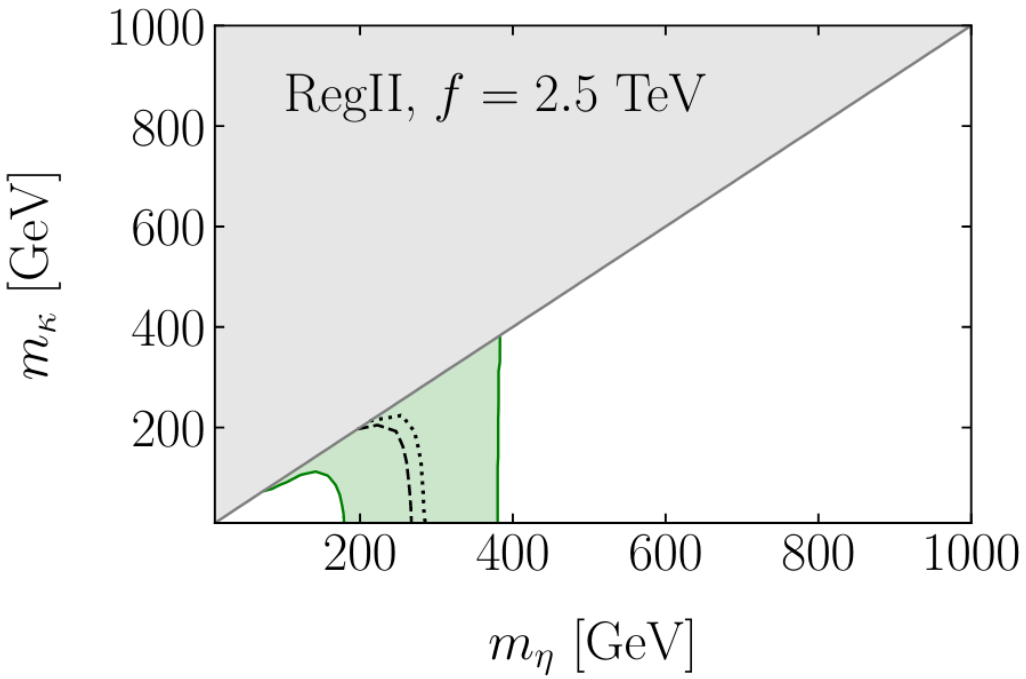
RegI: $(27 \oplus 1)$ $\lambda_{\eta H} \sim \lambda_H \ , \quad \lambda_{\eta\kappa} \ll 1 \ , \quad f \sim \dfrac{m_\eta}{\lambda_H}\sqrt{1+\dfrac{m_\kappa^2}{m_\eta^2}}$

RegII: $(7 \oplus 7)$ $\lambda_{\eta H} \ll 1 \ , \quad \lambda_{\eta\kappa} \sim \lambda_H \ , \quad f \sim 1, 2.5, 3, 4 \text{ TeV}$

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

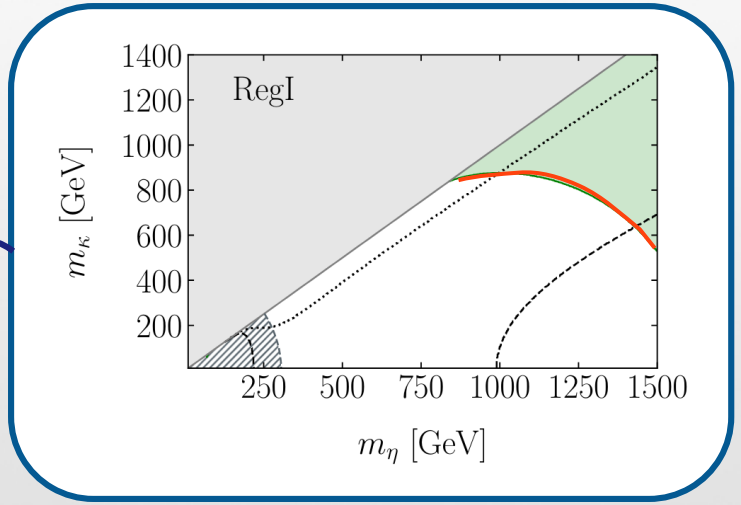
DM becomes unstable for $\gamma \gtrsim 1.7$

Annihilation scale



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

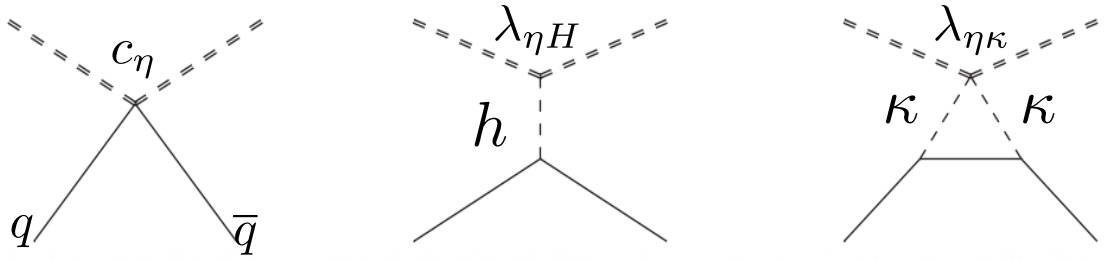
$$\frac{(\eta\partial_\mu\eta)(\pi_i\partial^\mu\pi^i)}{f^2}$$

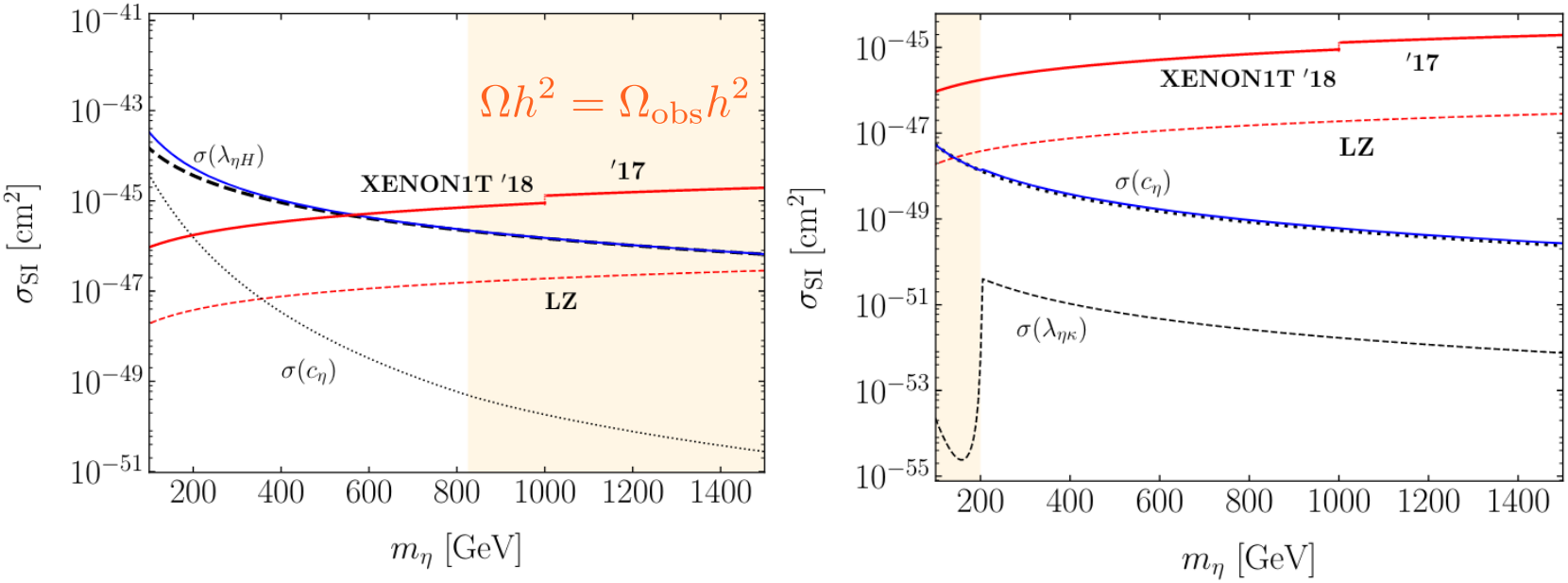


Real bound on fine-tuning:

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

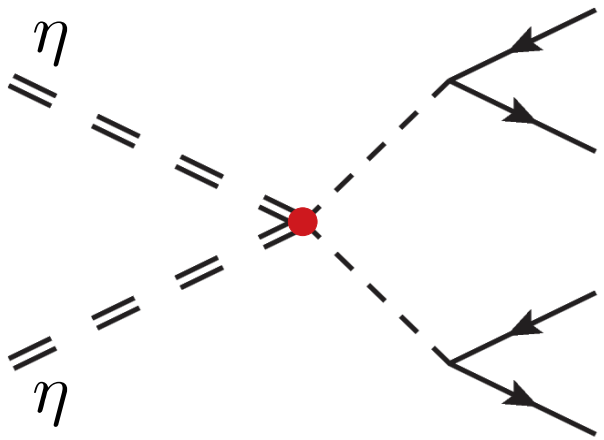
Direct detection scale



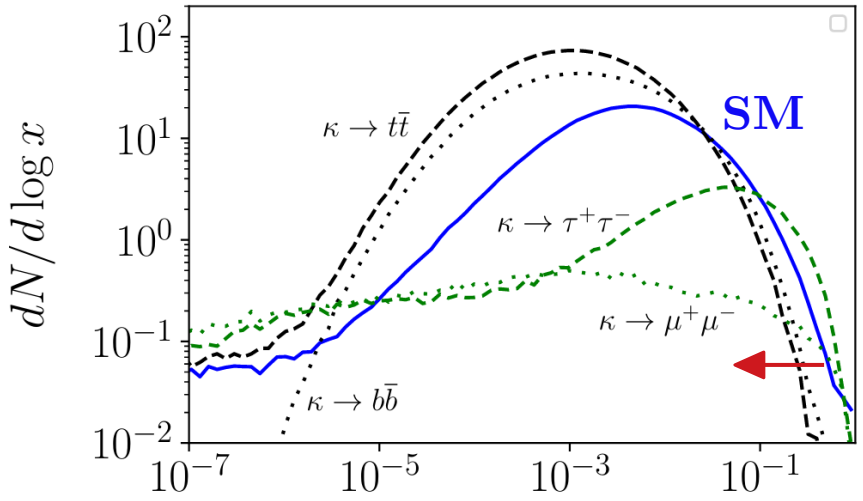


Indirect detection scale

Shape effect: $\mathrm{SM} \times 2^n$



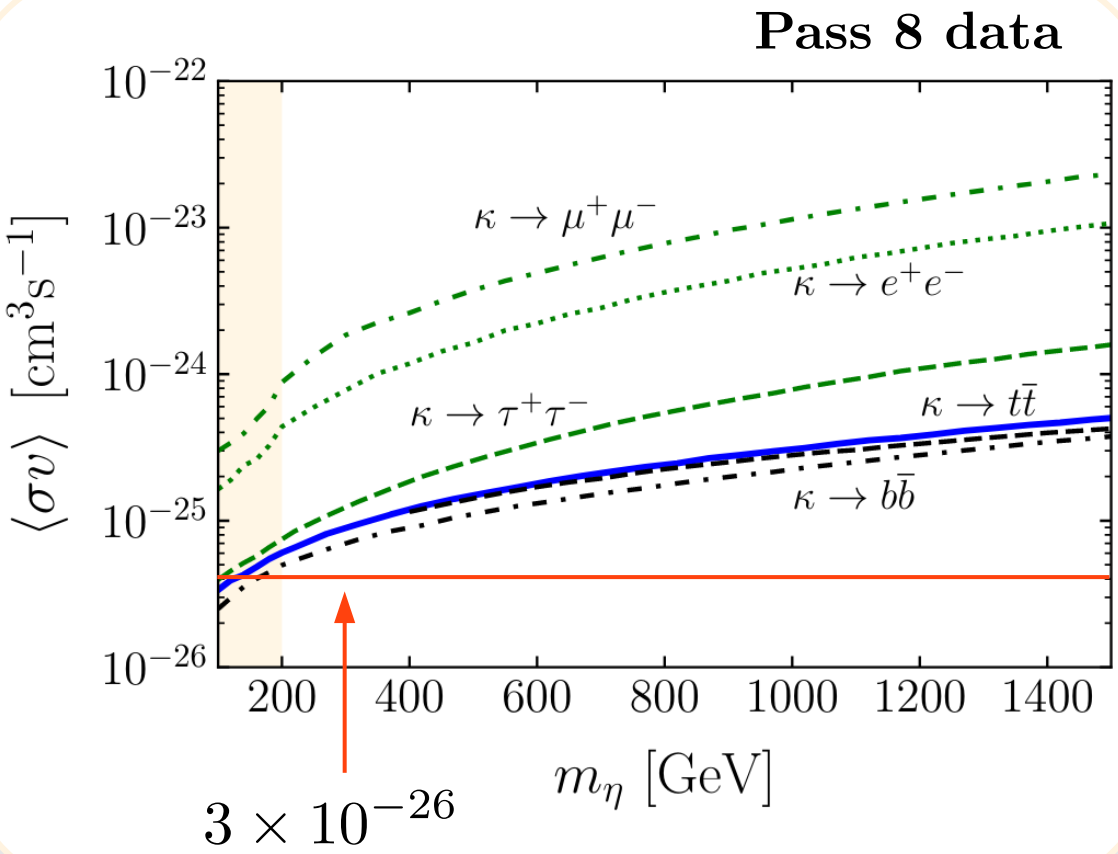
RegI with $\Omega h^2 = \Omega_{obs} h^2$



$m_\eta = 2m_\kappa$ $\quad x = E_\gamma/m_\eta$

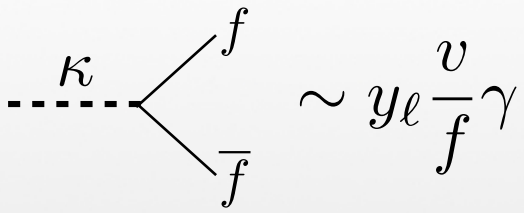
$$\Phi \propto \frac{\langle \sigma v \rangle}{m_\eta^2} \int \frac{dN_\gamma}{E_\gamma} dE_\gamma \, (J-\text{factor})$$

New Fermi-LAT bounds



Future prospects not sensitive to **leptophilic scenarios**:

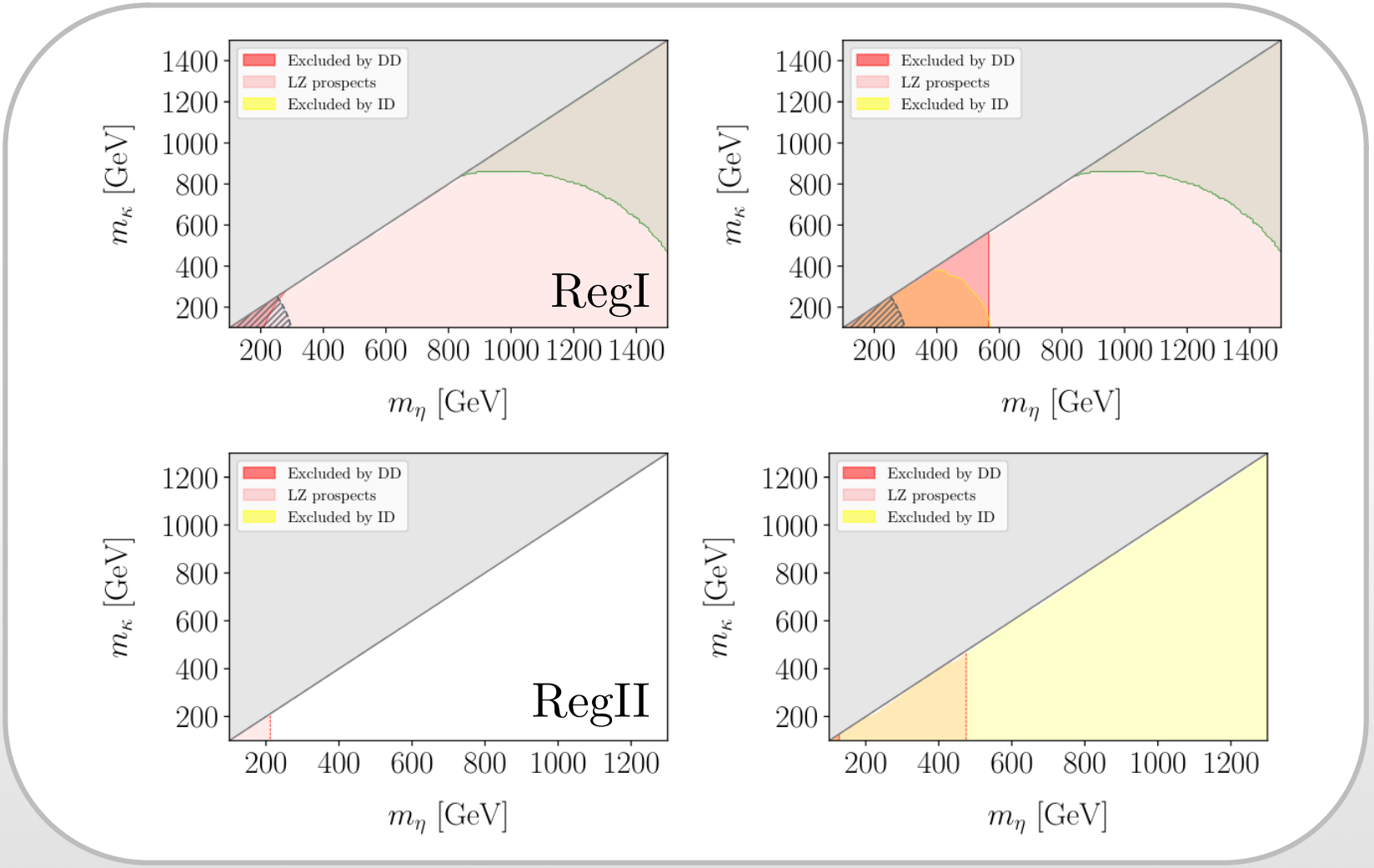
$$\eta\eta \to \kappa\kappa \to \ell^+\ell^-\ell^+\ell^-$$



$$\sim y_\ell \frac{v}{f}\gamma$$

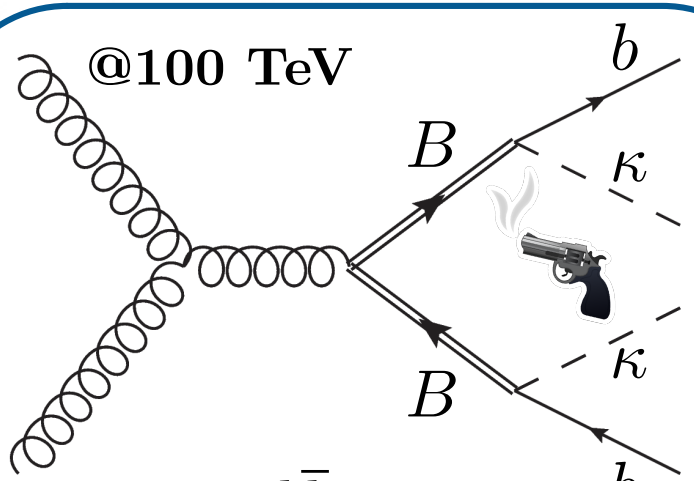
$$\Rightarrow \gamma_q \approx 0, \ \gamma_\ell \approx 1$$

Combining all dark matter bounds



Collider searches

Consider light vector-like quark singlets in the spectrum:



- $\gamma\gamma b\bar{b}$
- $b\bar{b}b\bar{b}$
- $\mu^+\mu^-\mu^+\mu^-$

Main background:

$$pp \to 2(\mu^+\mu^-)b\bar{b},\ p_T^{b_1} > 500 \text{ GeV}$$

Selection Cuts:

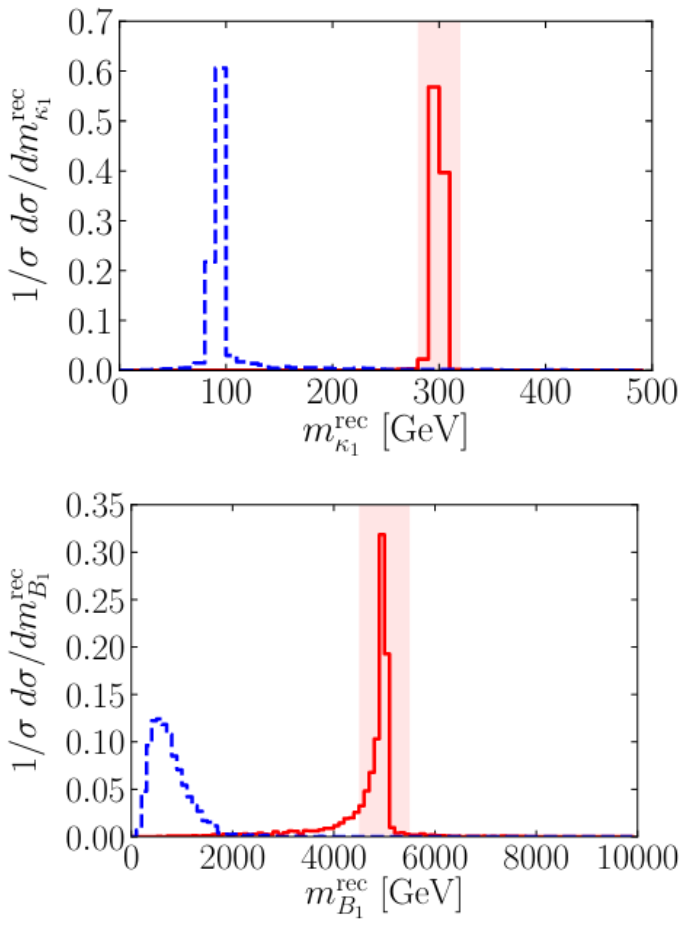
- Two neutral muon pairs;
- Exactly 2 b-jets;
- Scalar reconstruction from

$$|m_{\kappa_1}^{\text{rec}} - m_{\kappa_2}^{\text{rec}}| < \Delta$$

- Partners reconstruction from

$$|m_{B_1}^{\text{rec}} - m_{B_2}^{\text{rec}}| < \Delta'$$

Collider searches



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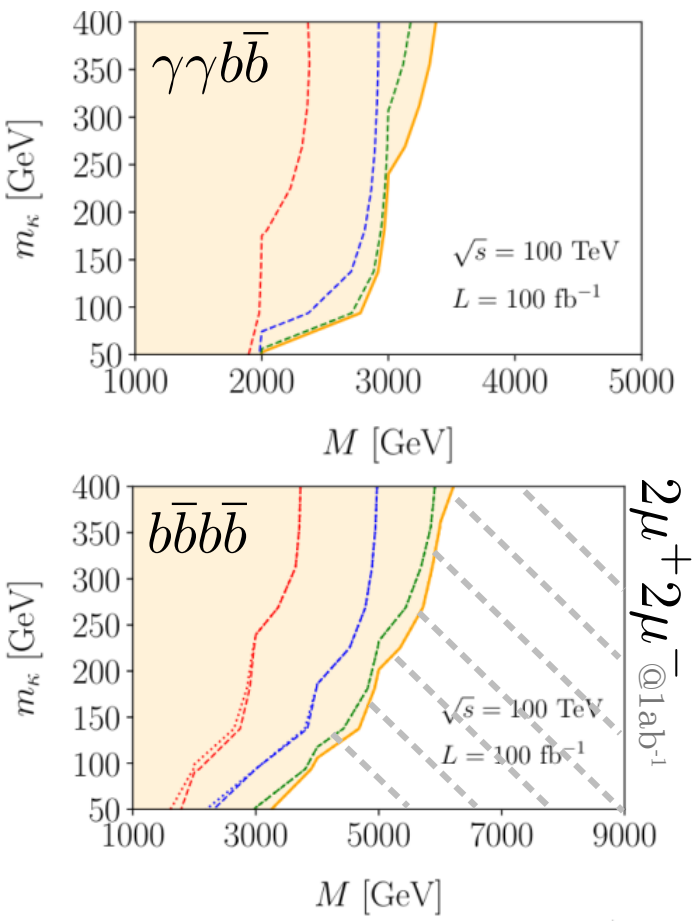
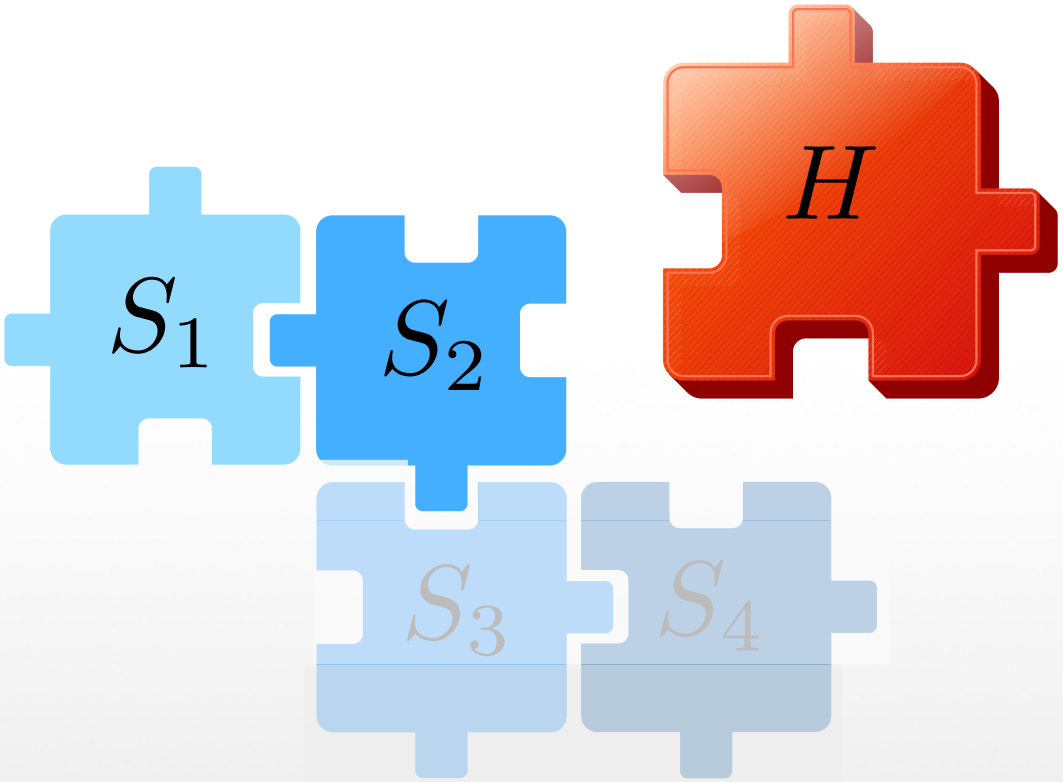
Outlook



- Non-minimal DM can freeze-out even in the **absence of couplings to SM**.
- Large regions of the phase space may escape all direct and indirect detection searches
- Further **motivation for collider searches**, to test both compositeness and non-minimality of the model

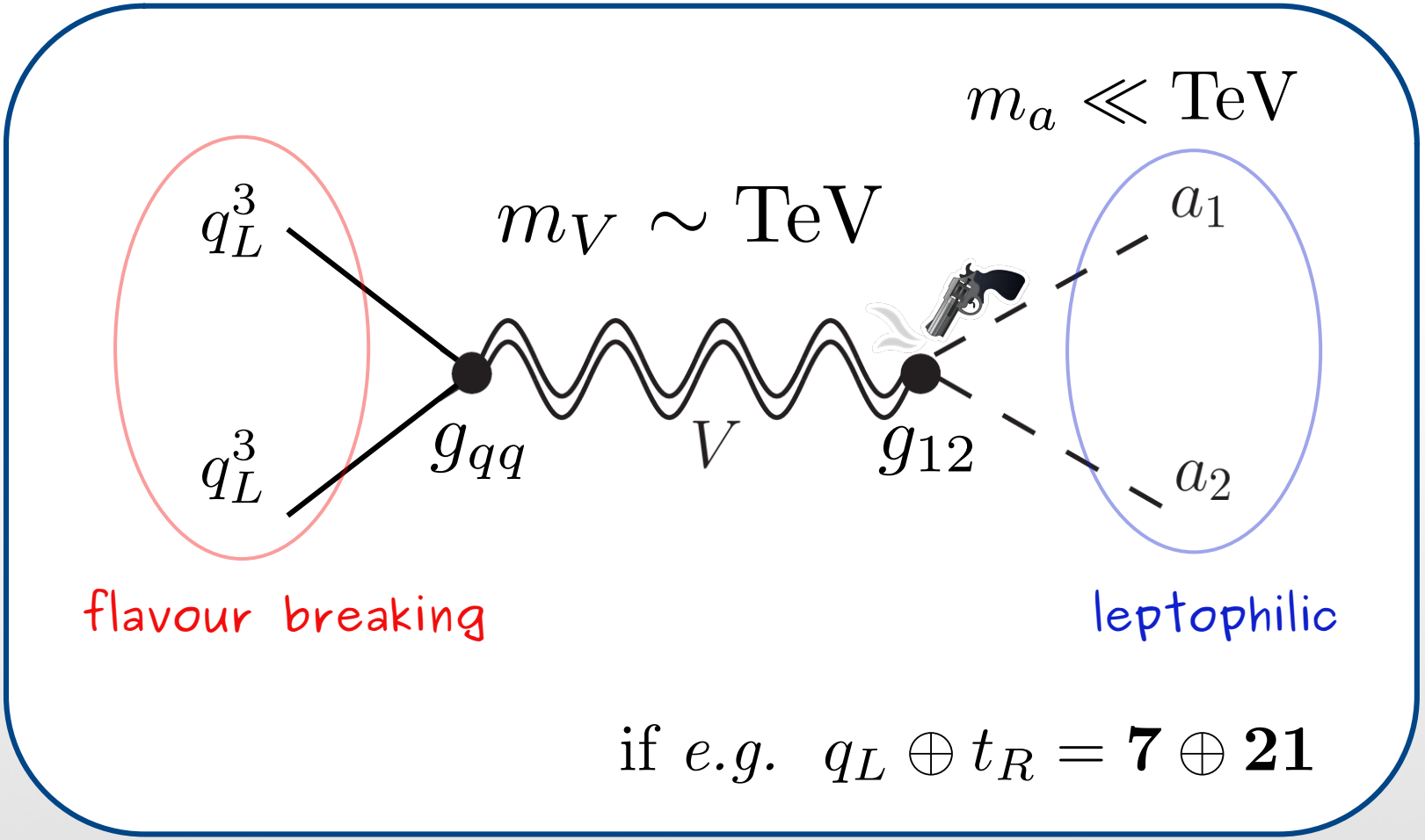
M.Ramos (2020)



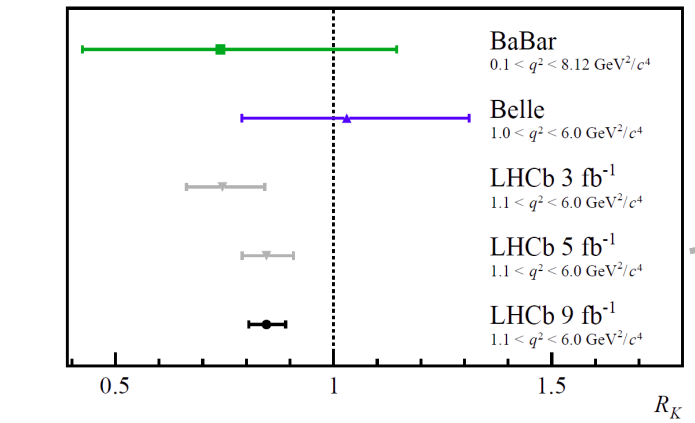
based on the SO(7)/SO(6) CHM

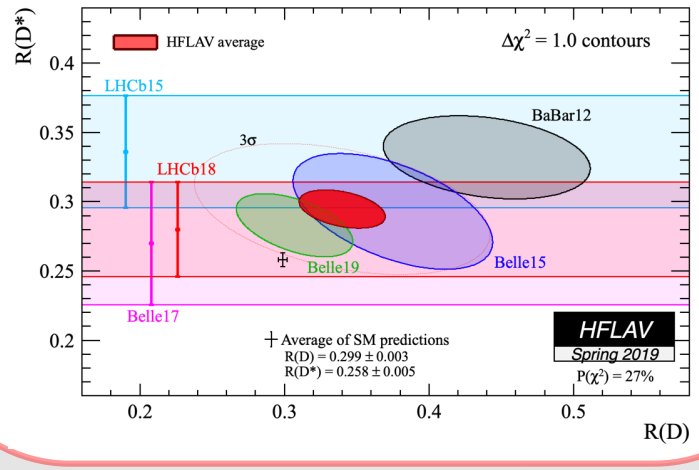
$$\mathbf{6} = (\mathbf{2},\mathbf{2}) \oplus 2 \times (\mathbf{1},\mathbf{1})$$

other composite interactions



Connection to the LFU anomalies

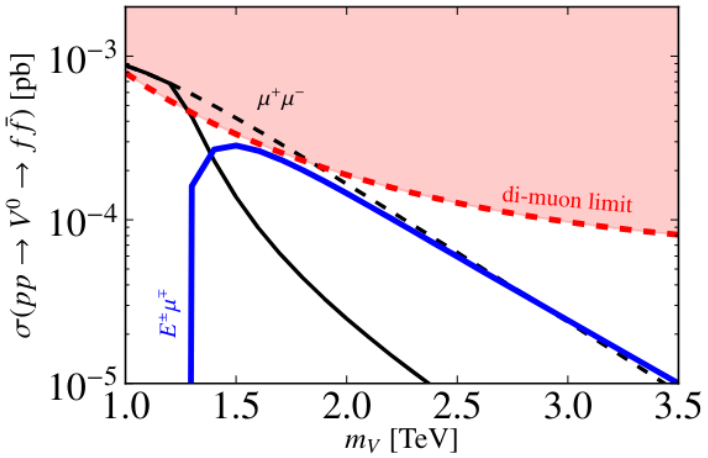




What data suggests:

$$\mathcal{O}_{LL} = \left(\overline{q_L}^{i}\gamma_\mu q_L^j\right)\left(\overline{\ell_L}^{\beta}\gamma_\mu \ell_L^\beta\right)$$

$$\lambda_{ij\alpha\beta} \sim \text{small} \times (\delta_{i3}\delta_{i3})\,(\delta_{\alpha 2}\delta_{\beta 2})$$

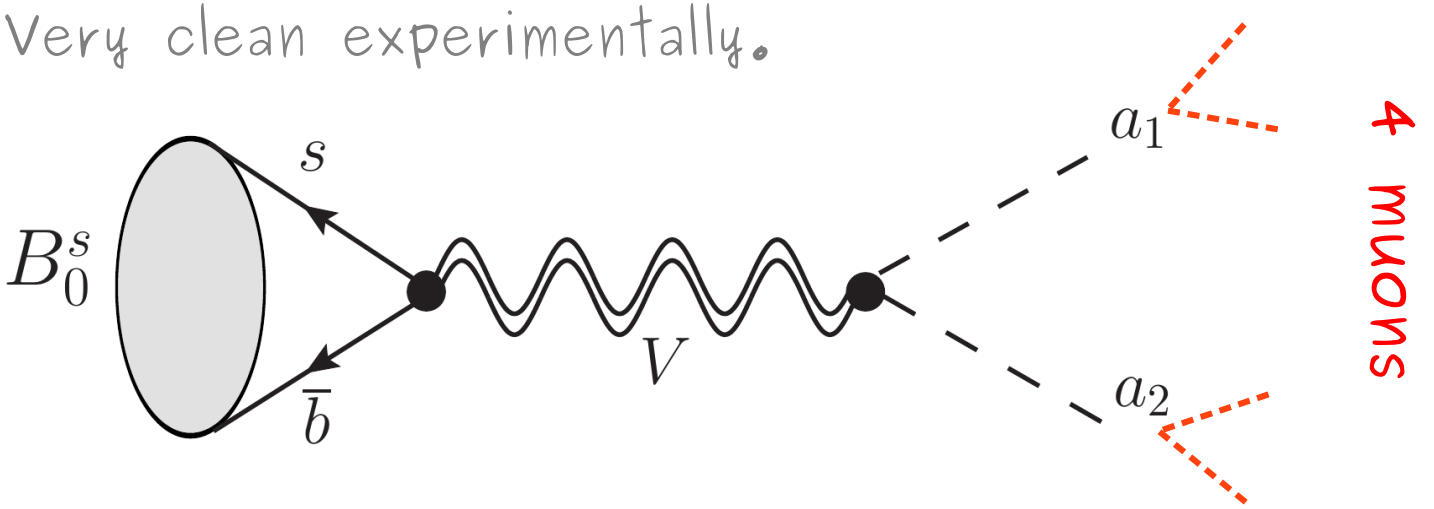


M.Chala,M.Spannowsky 2018

sizable couplings to taus if one includes R(D)

Low-energy signatures

Very clean experimentally.



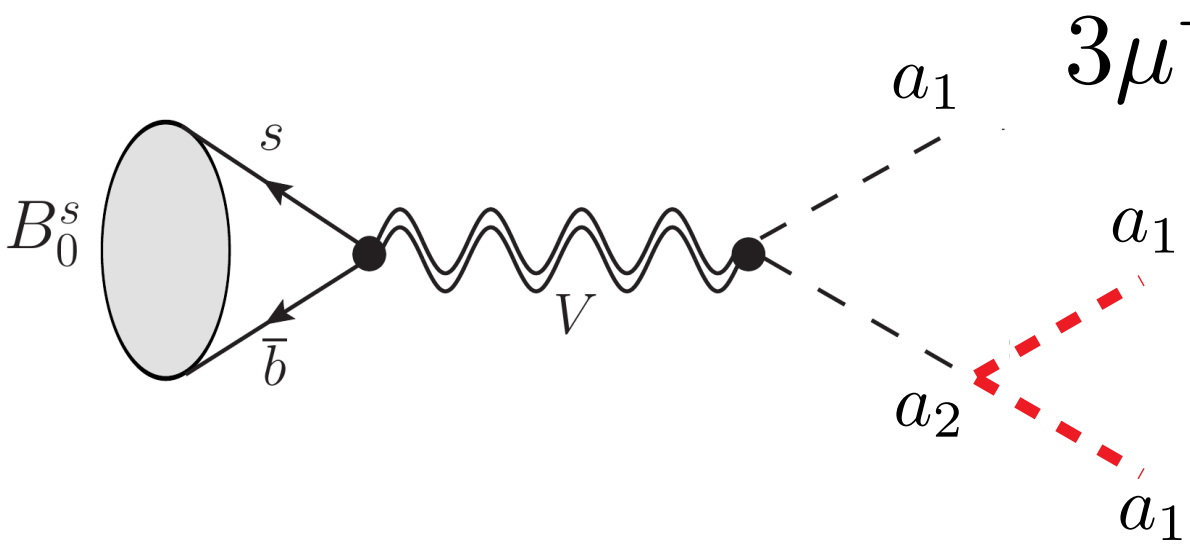
LHCb17 @8TeV with 3fb^{-1} data:

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 2.5 \times 10^{-9}$$

Motivation for alternative decays

#1 $\Gamma\left(a_2 \to \ell^+\ell^-\right) \ll \Gamma\left(a_2 \to a_1 a_1\right)$

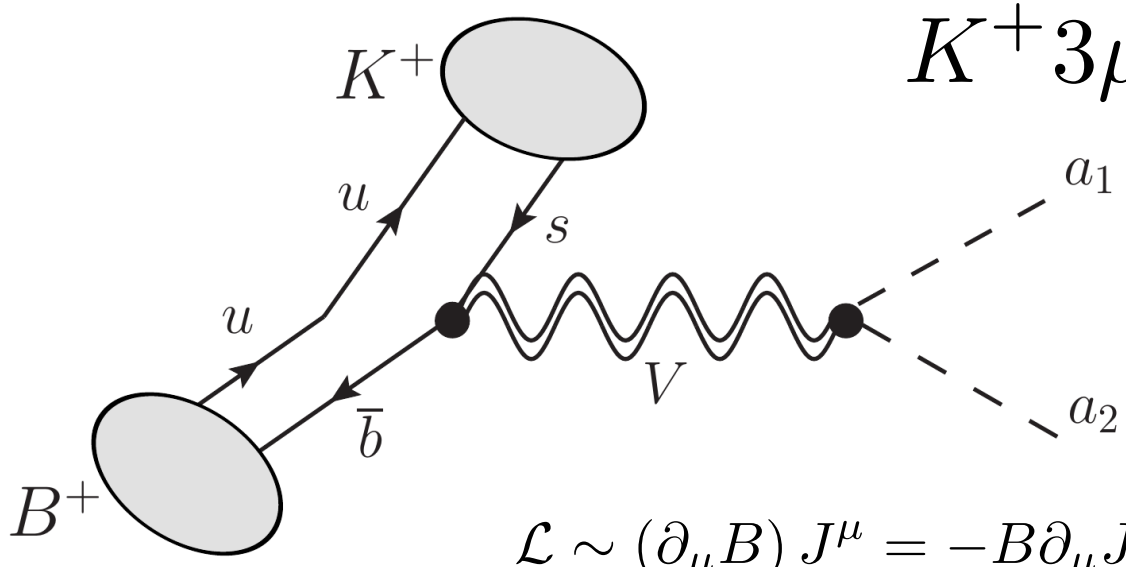
$3\mu^+3\mu^-$



Motivation for alternative decays

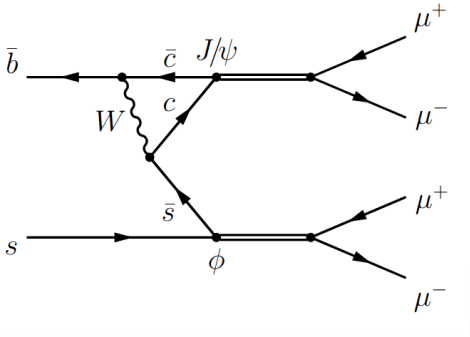
#2 $\Gamma\left(B_s^0 \to a_1 a_2\right) \propto \dfrac{|m_2^2 - m_1^2|}{m_B}$

$K^+ 3\mu^+ 3\mu^-$



$\mathcal{L} \sim (\partial_\mu B)\, J^\mu = -B \partial_\mu J^\mu \to 0$

Multi-muon analysis at LHCb



$\mathcal{B} \sim 10^{-8}$

[following 1611.07704]

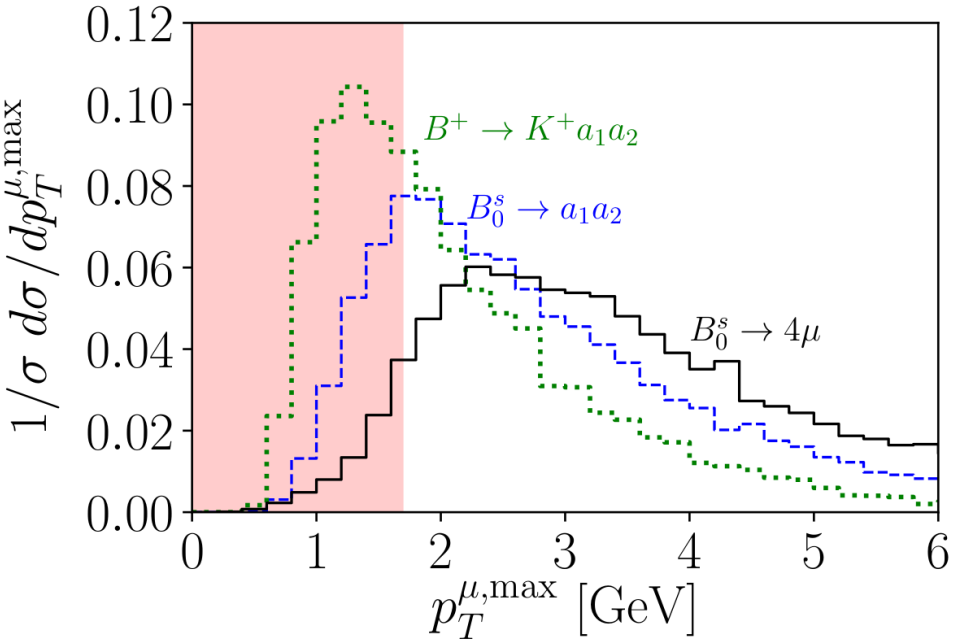
Veto around m_φ and $m_{J/\psi}$

$p_T^{\mu_1} > 1.7$ GeV

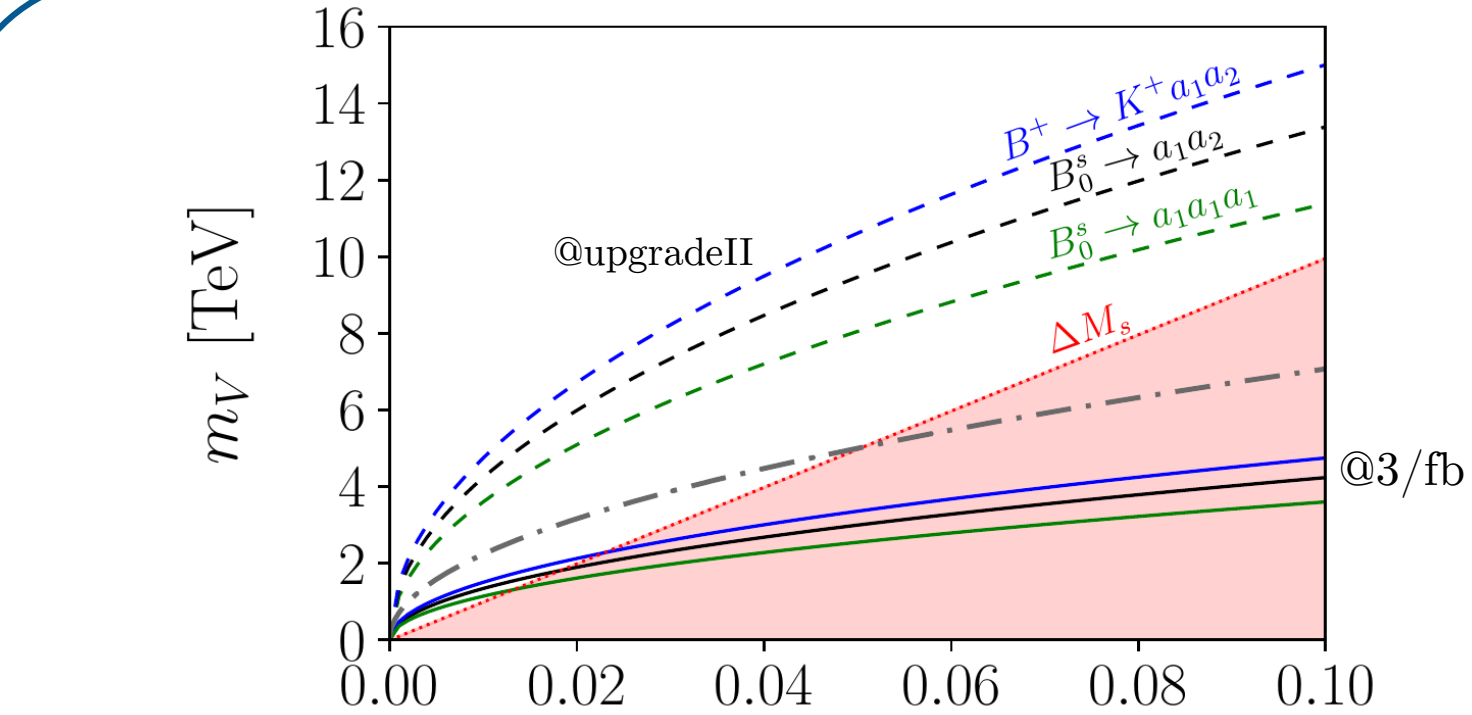
$p_T > 0.5$ GeV

$2.5 < \eta < 5.0$

$p^{\mu}_{\text{total}} > 2.5$ GeV



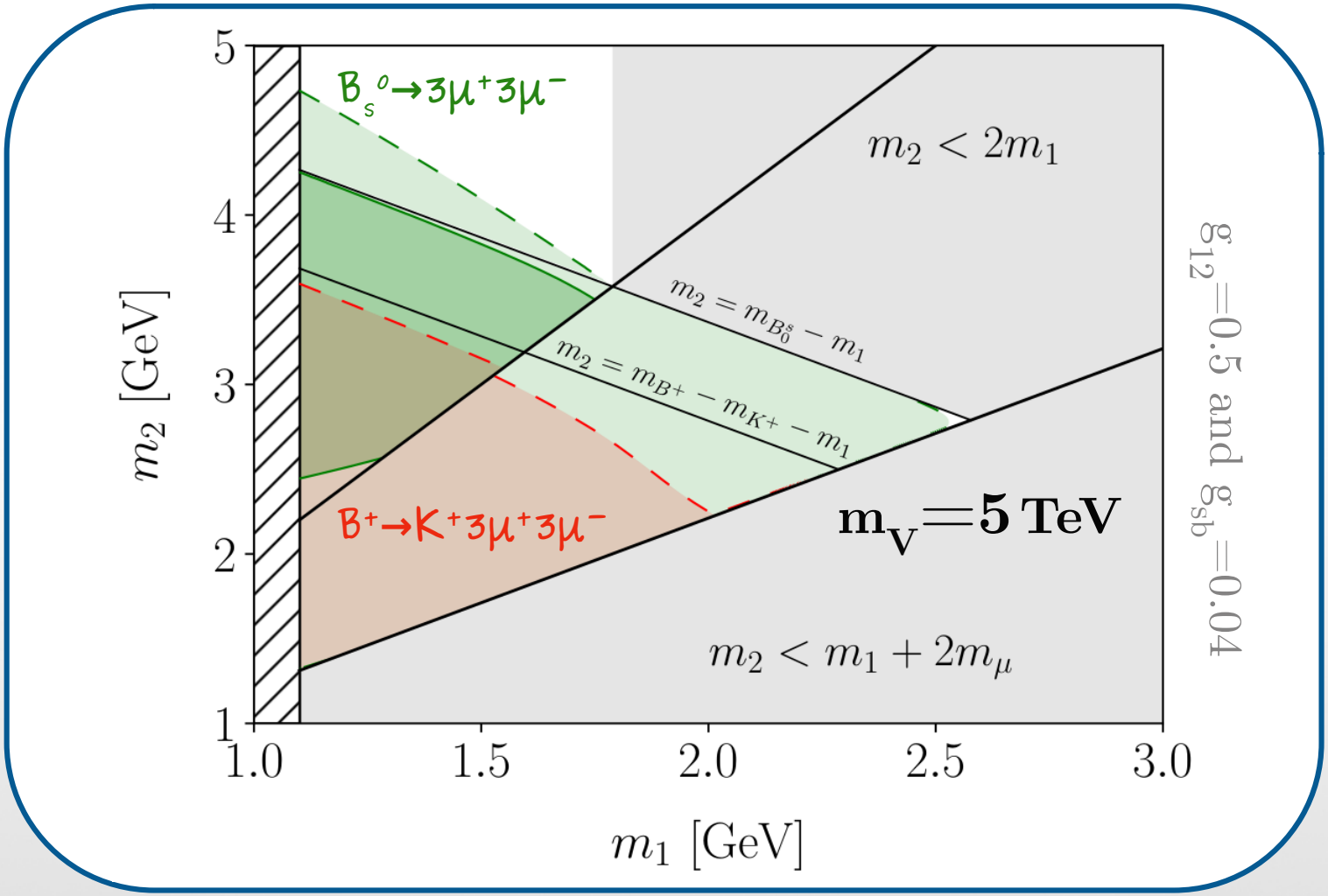
Maximum vector mass that can be tested



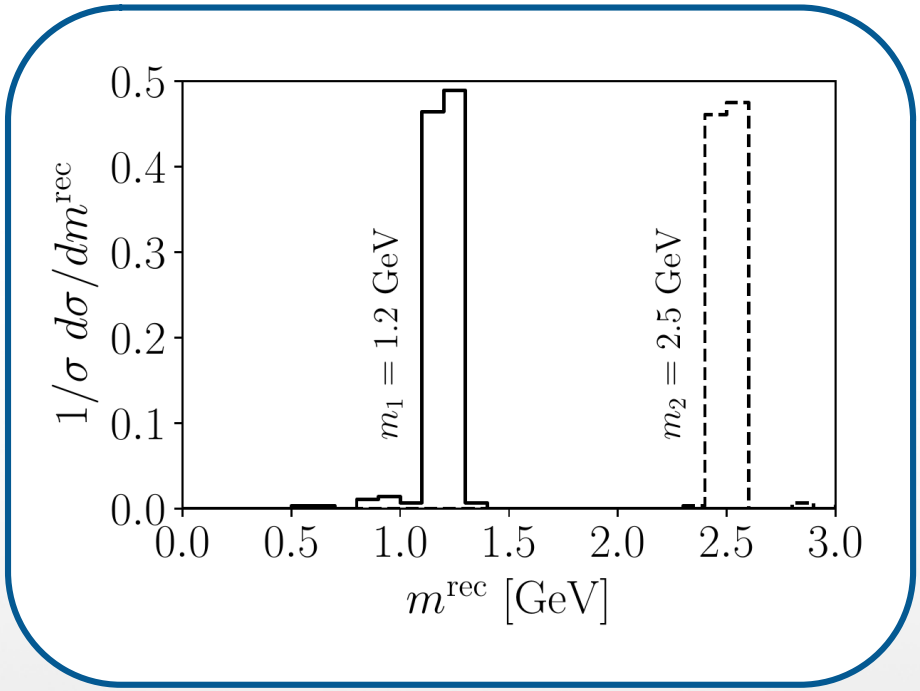
Explains the anomalies in R_K and R_{K*} at the 1σ level

g_{12}=0.5 and $m_1(m_2)$=1.2(2.0) GeV

Maximum scalar masses that can be tested



Outlook



$$\mathcal{L}_{\rm ALP} \sim \frac{1}{f^2} a^2 q q \bar{q} q$$

- Heavy-light coupling encodes interesting (composite) physics
- None of the six muon $(+K)$ signals has been explored experimentally
- Branching ratios $O(10^{-10})$ could be reached @Upgrade II of LHCb
- If a signal is observed, clean reconstruction
- **Sensible probe of effective 4F2S operators**

A.Blance,M.Chala,M.Ramos,M.Spannowsky (2019)

Take home lessons

- Is the Higgs elementary? **unknown**
- Does the Higgs fulfill naturalness strategy? **unknown**
- Can Higgs physics point towards new physics?
  Common origin to the hierarchy and other problems is not only possible, but *motivated*
- Are we searching in the right places?
  We have provided evidence of low sensitivity of current searches to non-oversimplified models
- Are we interpreting well what data is telling us?

New physics at the TeV scale requires significant efforts to be refuted

Instituto de Física Teórica UAM-CSIC

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