Composite Higgs Models

or: Collider probes of Composite Dark Matter

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based on work in collaboration with
M.Chala and M. Spannowsky,
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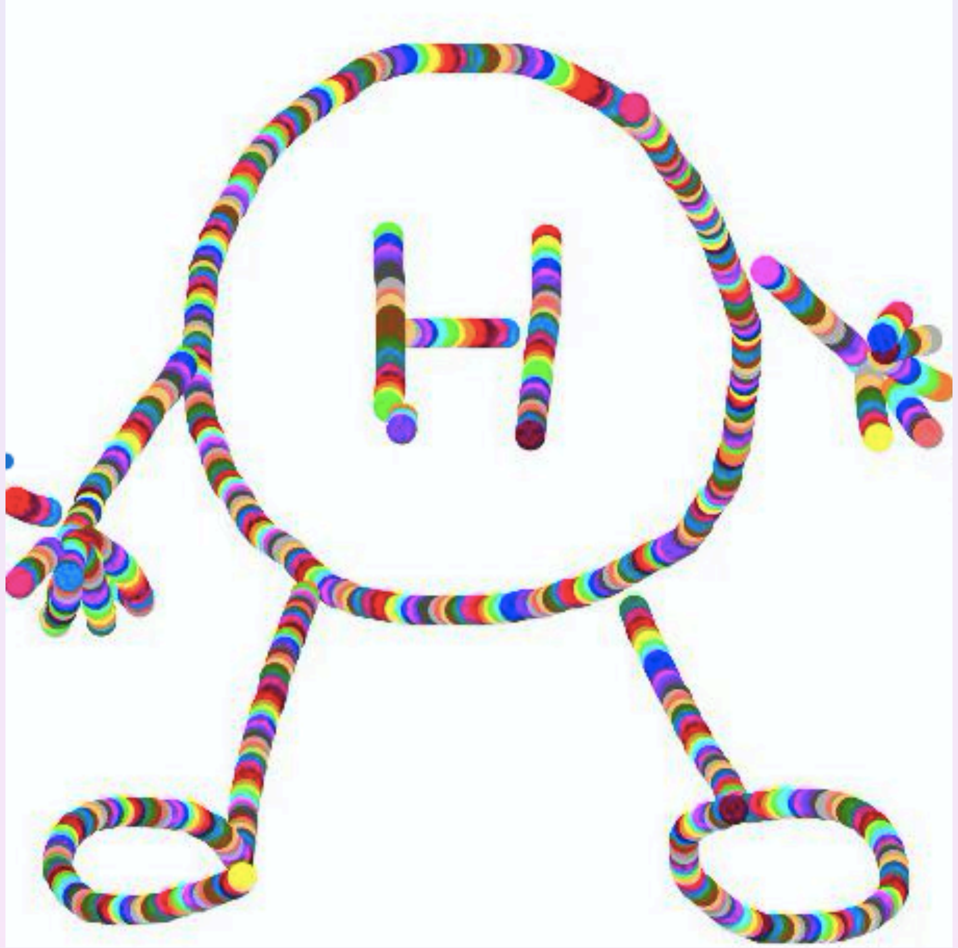

The Higgs boson discovery...

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...but is it the only Higgs boson? Is it elementary or composite? Is the Higgs sector really as predicted by the SM?

Open problems of the Standard Model

- Hierarchy the electroweak scale?
  Why is $m_H << \Lambda_{Planck}$?

  → connected to Higgs sector

- Dark matter

  → could there be a connection to the Higgs sector?

- ....

Open problems of the Standard Model

- Hierarchy the electroweak scale? → connected to Higgs sector

  Why is $m_H << \Lambda_{Planck}$?

Explain both within the same framework?

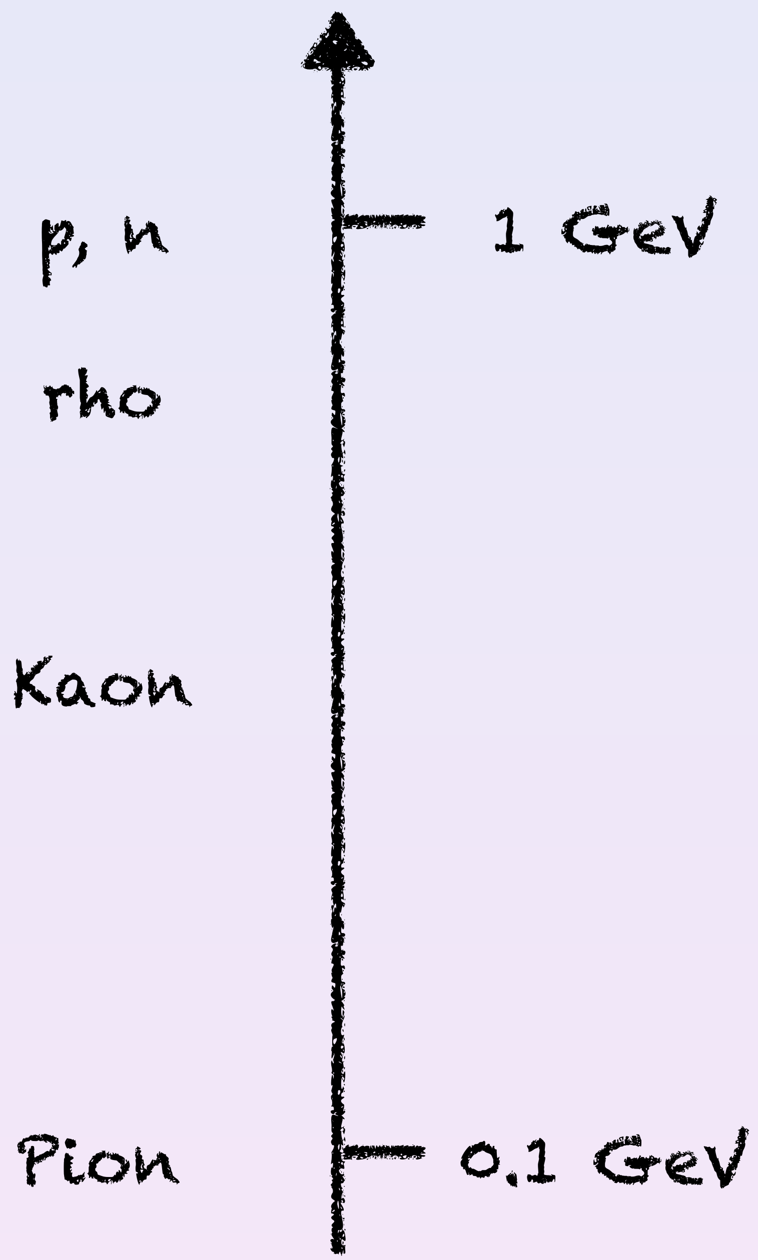
- Dark matter → could there be a connection to the Higgs sector?

- ....

Outline

- Introduction to Composite Higgs Models
- Parameterisation of Dark Matter in Composite Higgs Models
- Collider probes of Dark Matter in Composite Higgs Models

Composite Scalars in QCD



Spectrum of QCD:
Scalars without hierarchy problem

The QCD scale cuts their quantum corrections naturally off

Pions as pseudo-Nambu Goldstone bosons, naturally much lighter than QCD scale

QCD scale is natural,
can be largely separated from any high scale due to logarithmical running

Composite Higgs Models

[Georgi, Kaplan '84]

light, since pseudo-Goldstone boson

spin 0: H, ...

spin 1/2: T, B, $X^{5/3}$,...

spin 1: ρ, a,...

strongly interacting sector

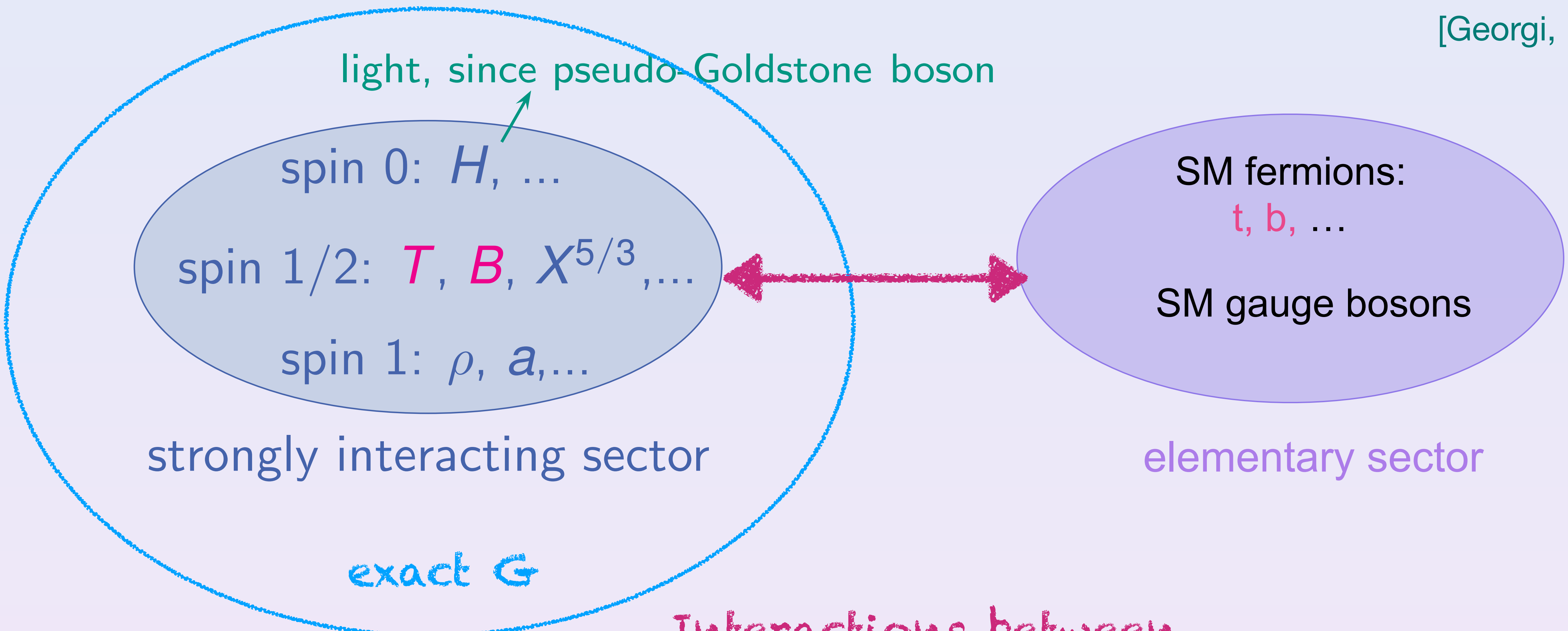
SM fermions:
t, b, ...

SM gauge bosons

elementary sector

Composite Higgs Models

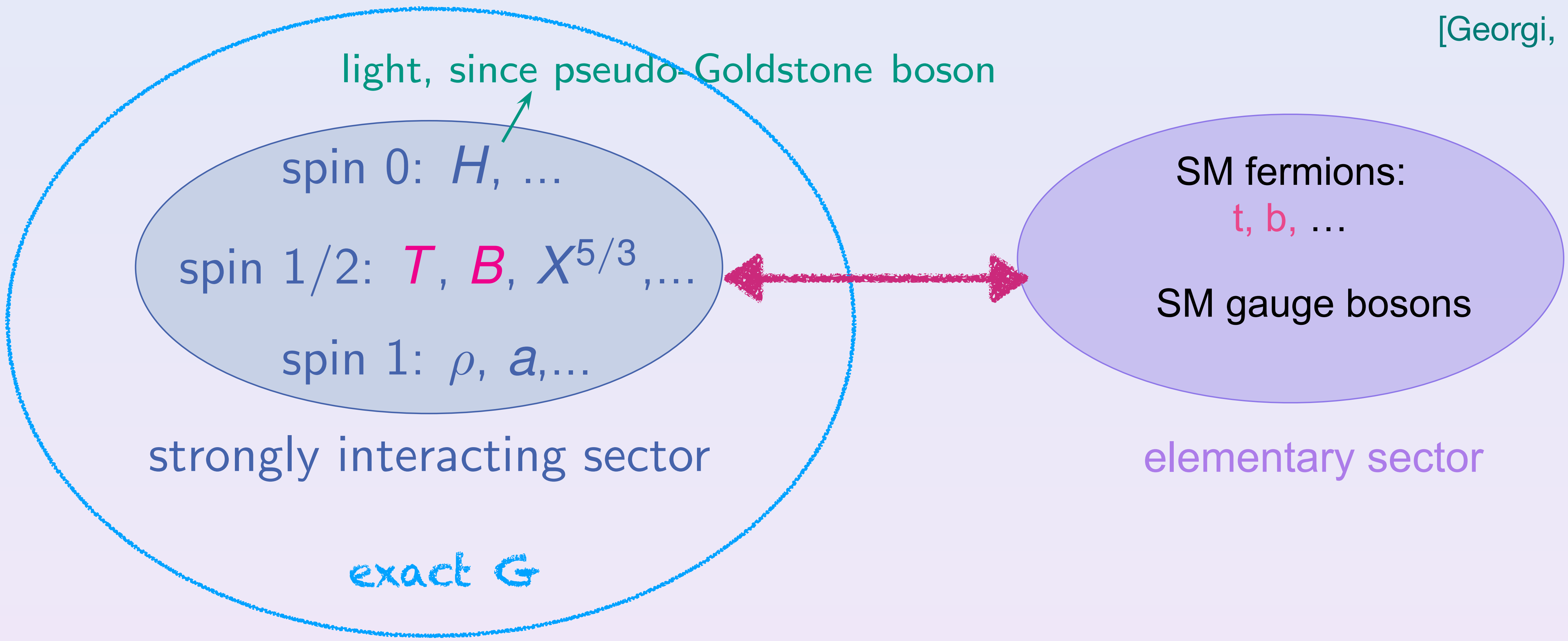
[Georgi, Kaplan '84]



Interactions between elementary and strongly interacting sector break G at scale f; coset G/H should contain the SM gauge group

Composite Higgs Models

[Georgi, Kaplan '84]



Higgs mass generated by quantum corrections

Partial compositeness: top quark mass generated by linear interactions with strongly interacting sector

Minimal Model: SO(5)/SO(4) [Agashe, Contino, Pomarol '04]

4 Goldstone bosons
(1 Higgs +3 usual would-be GBs)

Lagrangian for a Composite Higgs

Lagrangian from CCWZ construction: [Callan, Coleman, Wess, Zumino'69]

Goldstone matrix (X denote the broken generators) $U = e^{-i\frac{\sqrt{2}}{f}\pi^{\hat{a}}X^a}$

Defining

$$iU^{-1}\partial_\mu U = d_{\mu,a}X^a + e_{\mu,a}T^a$$

the Lagrangian is

$$\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}(d_\mu d^\mu)$$

more details in [Panico, Wulzer '15]

Minimal model: [Agashe, Contino, Pomarol '04]

We take a $\Sigma_0 = (0,0,0,0,1)^T$ to project on coset space.

Then

$$\mathcal{L} = \frac{f^2}{2}\left(D_\mu\Sigma\right)^\dagger D^\mu\Sigma, \quad \text{with } \Sigma = U\Sigma_0,$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\partial^\mu h + \frac{g^2}{4}f^2\sin^2\left(\frac{h}{f}\right)W_\mu^+W^{\mu-} + \frac{g^2}{8c_W^2}f^2\sin^2\left(\frac{h}{f}\right)Z_\mu Z^\mu.$$

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leads to non-linearities

$$\xi = \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

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$$\xi = \frac{v^2}{f^2} = \sin^2\frac{\langle h\rangle}{f}$$

$$\frac{g_{hVV}}{g_{hVV}^{SM}} = \sqrt{1-\xi}$$

Partial compositeness

[Kaplan '91]

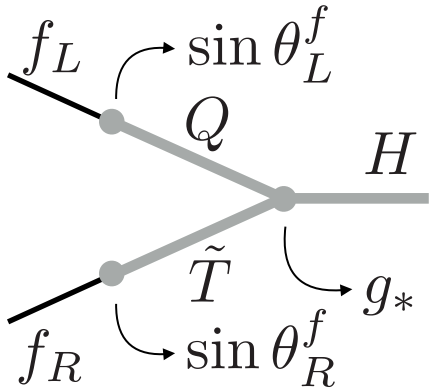
Elementary fermions mix with strong-interacting sector by linear couplings

$$\mathcal{L} = \lambda_L \bar{q}_L \mathcal{O}_R + \lambda_R \bar{t}_R \mathcal{O}_L$$

Mixing with top partners generate the top Yukawas

[Panico, Wulzer '15]

$y_t =$



$= g_* \cdot \sin\theta_L^f \cdot \sin\theta_R^f$

If we are only interested in the non-linearities:

Example : fermions transforming in the fundamental of SO(5)

$$Q_L^{2/3} = \frac{1}{\sqrt{2}}\left(d_L,\ -id_L,\ u_L,\ iu_L,\ 0\right)^T, \quad U_R = \frac{1}{\sqrt{2}}\left(0,\ 0,\ 0,\ 0,\ \sqrt{2}u_R\right)^T$$

$$\mathcal{L}_Y = f\left[-y_u(\overline{U_R}\Sigma)(\Sigma^T Q_L^{2/3}) - y_d(\overline{D_R}\Sigma)(\Sigma^T Q_L^{-1/3})\right] + \text{h.c.}$$

→ MCHM5: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \frac{1-2\xi}{\sqrt{1-\xi}}$ MCHM10: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \frac{1-2\xi}{\sqrt{1-\xi}}$ MCHM4: $\frac{g_{hf\bar{f}}}{g_{hf\bar{f}}^{SM}} = \sqrt{1-\xi}$

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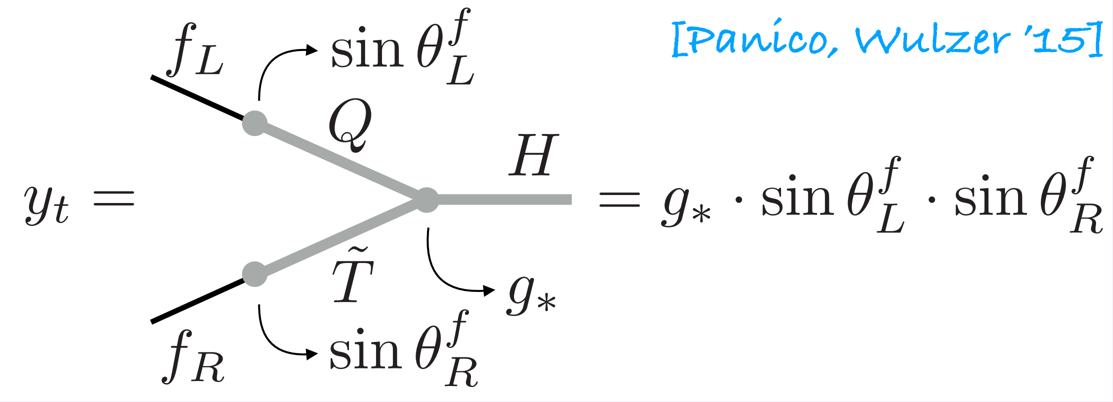

The couplings break the global symmetry explicitly

$\longrightarrow$ Connection between top partner masses and Higgs mass

$$\frac{m_h^2}{m_t^2} \simeq \frac{N_c}{\pi^2}\frac{m_\psi^2}{f^2}$$

Low tuning = light top partner masses

[Matsedonskyi, Panico, Wulzer '12, Marzocca, Serone, Shu '12, Pomarol, Riva '12, Panico, Redi, Tesi, Wulzer '12, Pappadopulo, Thamm, Torre '13]

Dark Matter in Composite Higgs Models

Non-minimal Composite Higgs Models

[Mrazek et al '11]

G	H	N_G	NGBs rep.$[H]$ = rep.$[SU(2) \times SU(2)]$	
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$	
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	[Gripaios et al '09; Frigerio et al '12; Marzocca, Urbano '14]
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2} + \bar{\mathbf{4}}_{-2} = 2 \times (\mathbf{2}, \mathbf{2})$	[Mrazek et al '11, De Curtis et al'16]
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$	[Balkin et al '17]
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	[Chala '12; Ballesteros et al '16]
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$	
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$	
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$	
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2 \times (\mathbf{2}, \mathbf{2})$	
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$	

Larger coset space ⟶ extended Higgs sector

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Larger coset space ⟶ extended Higgs sector

If new scalar stable ⟶ possible dark matter candidate

i.e. if there is a Z_2 or $U(1)$ symmetry

explanation why

WIMP mass scale ≈ electroweak scale

Composite Higgs Dark Matter

General parameterisation: [Chala, RG, Spannowsky '18]

$$L = |D_\mu H|^2 \left[1 - a_1 \frac{S^2}{f^2}\right] + \frac{a_2}{f^2}\partial_\mu |H|^2 (S\partial_\mu S) + \frac{1}{2}(\partial_\mu S)^2 \left[1 - 2a_3 \frac{|H|^2}{f^2}\right]$$
$$- m_\rho^2 f^2 \frac{N_c y_t^2}{(4\pi)^2} \left[-\alpha \frac{|H|^2}{f^2} + \beta \frac{|H|^4}{f^4} + \gamma \frac{S^2}{f^2} + \delta \frac{S^2 |H|^2}{f^4}\right] + \left[i\epsilon \frac{y_t}{f^2} S^2 \overline{q_L} H t_R + \text{h.c.}\right] + \cdots$$

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Annihilation cross section dominated by H^2S^2 interactions

Relic density $\Omega h^2 \sim m_S^2/V^2 \sim f^2/g_\rho^2$ using MicrOmegas

$a = a_1 = a_3 = a_3$

$$V \sim \frac{2iN_c m_\rho^2}{(4\pi)^2 f^2}\left[2(2a_1 + 2a_2 + a_3)\gamma - \delta\right]$$

Main difference to non-composite case: derivative interactions

Matching to concrete models

[Chala, RG, Spannowsky '18]

$\mathcal{G}/\mathcal{H}$	$q_L + t_R$	a_1	a_2	a_3	γ	δ
$SO(6)/SO(5)$	$\mathbf{6}+\mathbf{1}$ $\mathbf{6}+\mathbf{15}$ $\mathbf{15}+\mathbf{15}$ $\mathbf{20}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $\ll 1$ $\ll 1$ $1/4$	$-$ $\ll 1$ $\ll 1$ $1/5$
$SO(7)/SO(6)$	$\mathbf{7}+\mathbf{1}$ $\mathbf{7}+\mathbf{7}$ $\mathbf{27}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $-$ $\leq 1/4$	$-$ $-$ $\leq 1/5$
$SO(7)/G_2$	$\mathbf{8}+\mathbf{8}$ $\mathbf{35}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $1/4$	$-$ $1/5$
$SO(6)/SO(4)$	$\mathbf{6}+\mathbf{6}$	0	$1/6$	$1/3$	$-$	$-$
$SO(5)\times U(1)/SO(4)$	$\mathbf{5}+\mathbf{5}$	0	0	0	$\ll 1$	$\ll 1$
$SO(7)/SO(5)$	$\mathbf{7}+\mathbf{7}$	$< 1/3$	$< 1/3$	$1/3$	$-$	$-$
$SO(7)/SO(6)$ [complex case]	$\mathbf{27}+\mathbf{1}$	~ 0.3	~ 0.3	~ 0.3	$\sim 1/4$	$\sim \sqrt{2}/5$

Collider searches: Vector-like quarks

Bi-doublet under $SU(2)_L \times SU(2)_R$

$$\mathrm{BR}(T, X_{2/3} \to ht) \sim \mathrm{BR}(T, X_{2/3} \to Zt) \sim 0.5$$
$$\mathrm{BR}(B \to W^- t) \sim \mathrm{BR}(X_{5/3} \to W^+ t) \sim 1$$

Singlet

$$\mathrm{BR}(T' \to St) \sim 1$$

Current limits with `VLQlimits` [Chala '17]

$$m_\rho = g_\rho f < 1.2 \text{ TeV}$$

High luminosity LHC

$$m_\rho = g_\rho f < 1.7 \text{ TeV}$$

Vector-like quarks @ 100 TeV

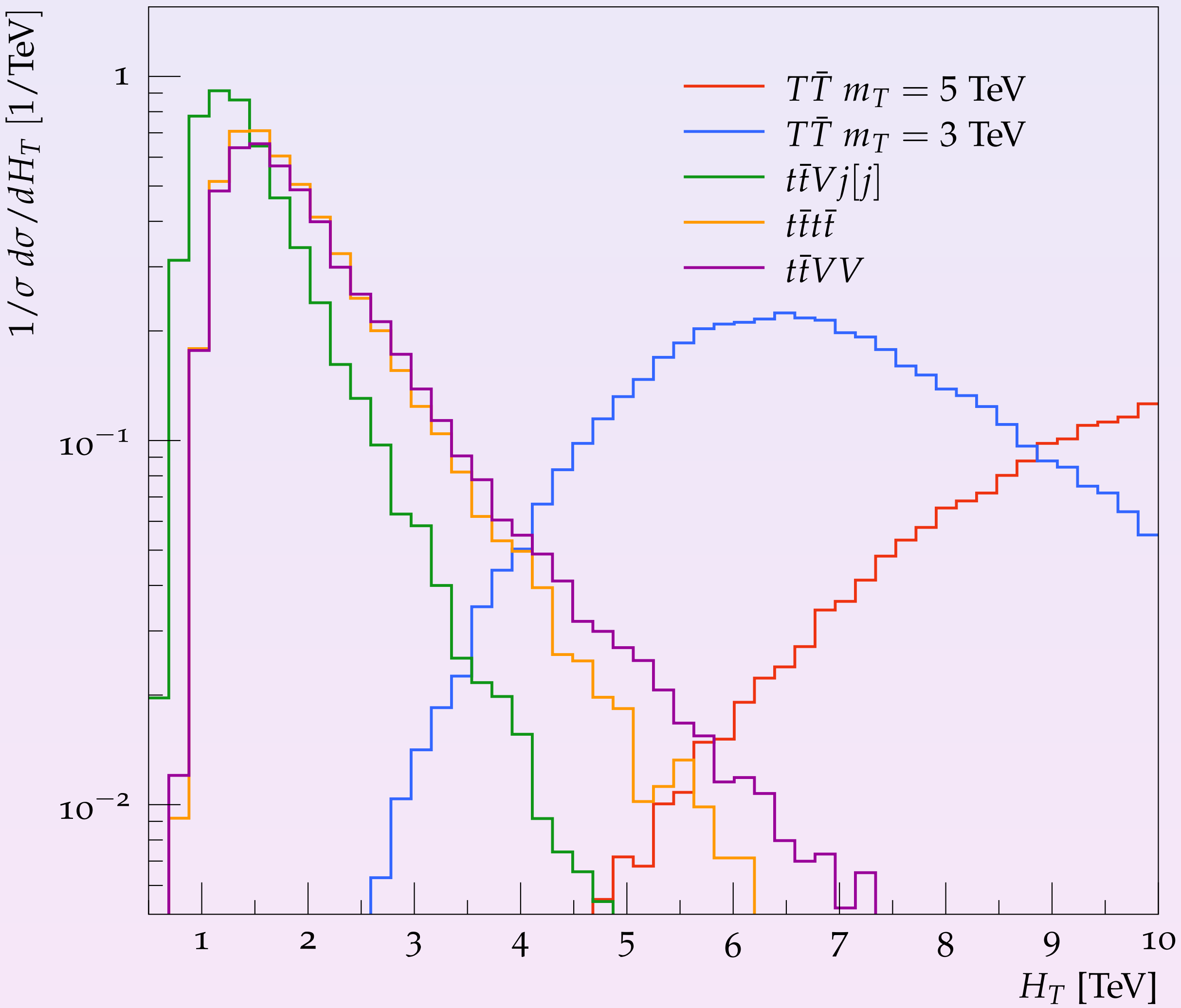
3-lepton final state

lepton cuts $|\eta_\ell| < 2.5$ $p_{T,\ell_1} > 250$ GeV $p_{T,\ell_2} > 100$ GeV $p_{T,\ell_3} > 20$ GeV

at least 4 jets with $p_{T,j} > 40$ GeV $|\eta_j| < 5$ $p_{T,j_1} > 70$ GeV

angular seperation $\Delta R(j,\ell) = \sqrt{\Delta\phi_{j\ell}^2 + \Delta\eta_{j\ell}^2} > 0.3$

exactly two b-jets $\Delta R(j,b) > 0.3.$ [Chala, RG, Spannowsky '18]



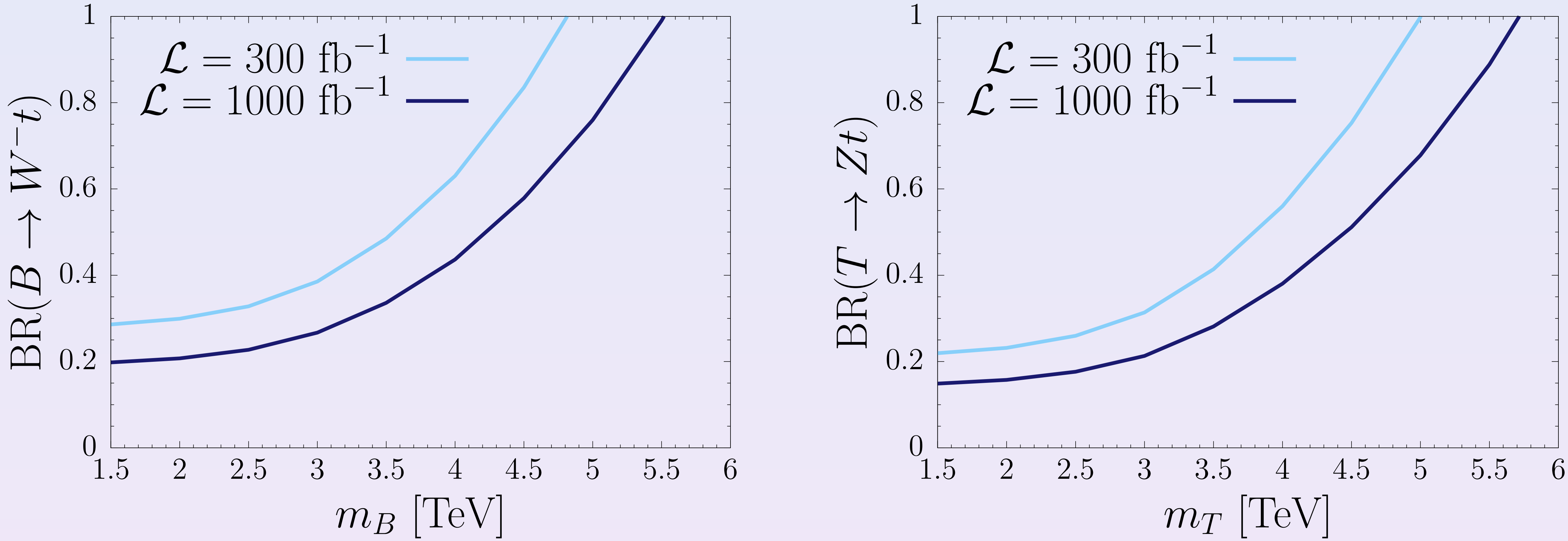
cut on $H_T > 6$ TeV

for top-partner also one reconstructed Z boson

$71 \text{ GeV} < M_{\ell^+\ell^-} < 111 \text{ GeV}$

using MG5_aMC@NLO, Herwig, Sherpa, Rivet

Vector-like quarks @ 100 TeV



VLQs can be excluded up to at $\mathcal{L} = 1000$ fb^{-1}

bottom-partner/(5/3)-charged $m_{X_{5/3}} = 5.5$ TeV

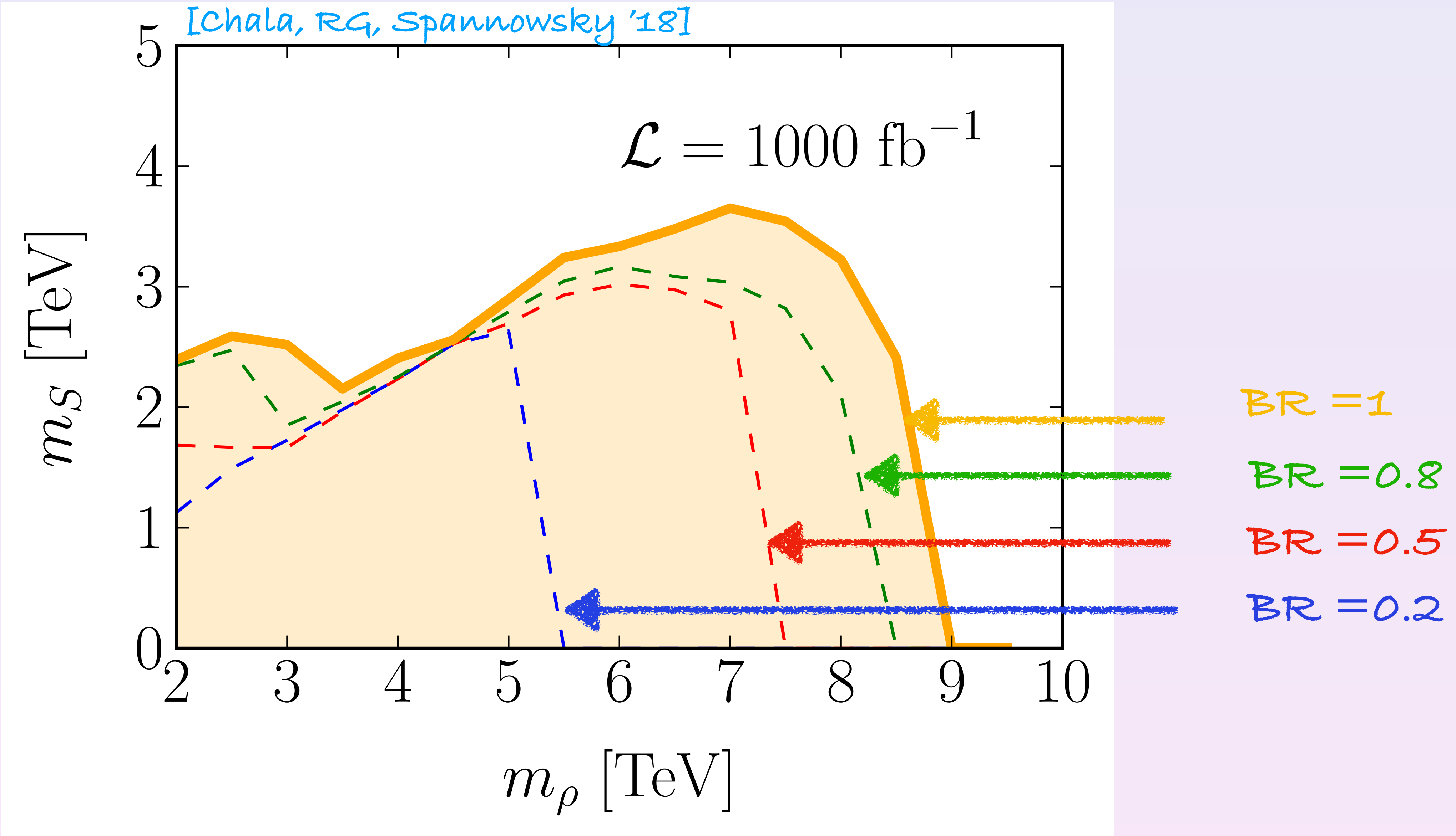
top-partner $m_T = 5.7$ TeV

4-plet $m_\rho = 6.4$ TeV

singlet VLQ can decay with BR ≈ 1 to S t

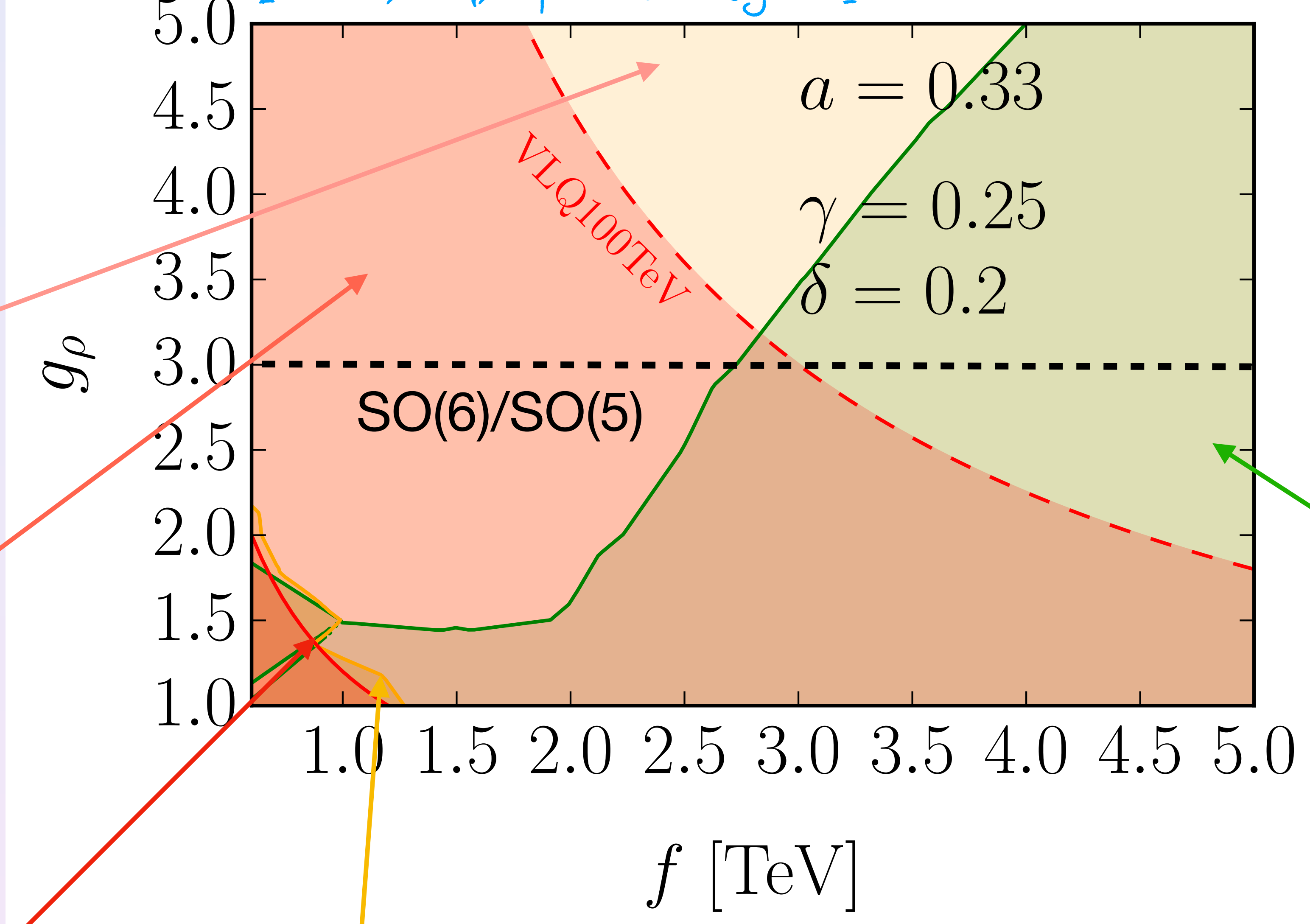
missing E_T and top quarks → SUSY searches for stops

recast sensitivity study of [Cohen, D'Angelo, Hance, Lou, Wacker '14]



more results in appendix

[Chala, RG, Spannowsky '18]



future LZ probed

FCC probed by searches for VLQs

Overabundance of dark matter

LHC excluded

LUX excluded

Summary Composite Higgs Models

- Non-minimal Composite Higgs Models can provide a framework addressing both the Hierarchy problem and Dark matter
- Explanation for similarity of WIMP scale and electroweak scale
- We proposed a model-independent framework to parameterise Composite Higgs Models with Dark Matter
- Dark Matter scenarios in Composite Higgs Models can be probed at future experiments

  - Collider experiments : searches for VLQs

    $m_\rho = 6.4$ TeV for VLQ decays to SM particles @ 100 TeV collider

    $m_\rho = 9$ TeV for VLQ decays to dark matter @ 100 TeV collider

  - dark matter direct detection

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Thanks for your attention!

More results

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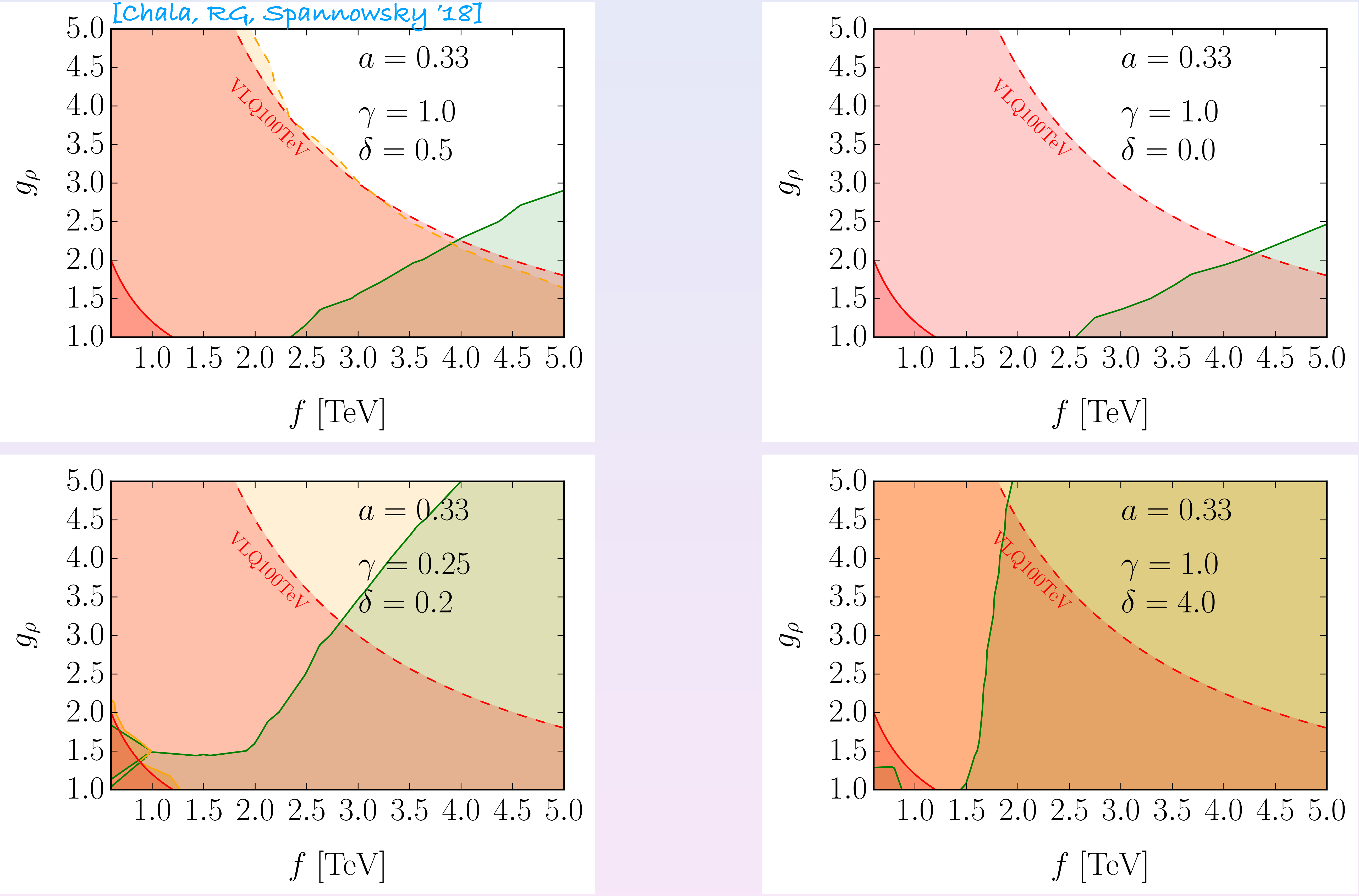

Effect fermion couplings

effect sizeable if there is a cancellation in the computation of the relic density

$$L = |D_\mu H|^2 \left[1 - a_1 \frac{S^2}{f^2}\right] + \frac{a_2}{f^2}\partial_\mu |H|^2 (S\partial_\mu S) + \frac{1}{2}(\partial_\mu S)^2 \left[1 - 2a_3 \frac{|H|^2}{f^2}\right]$$
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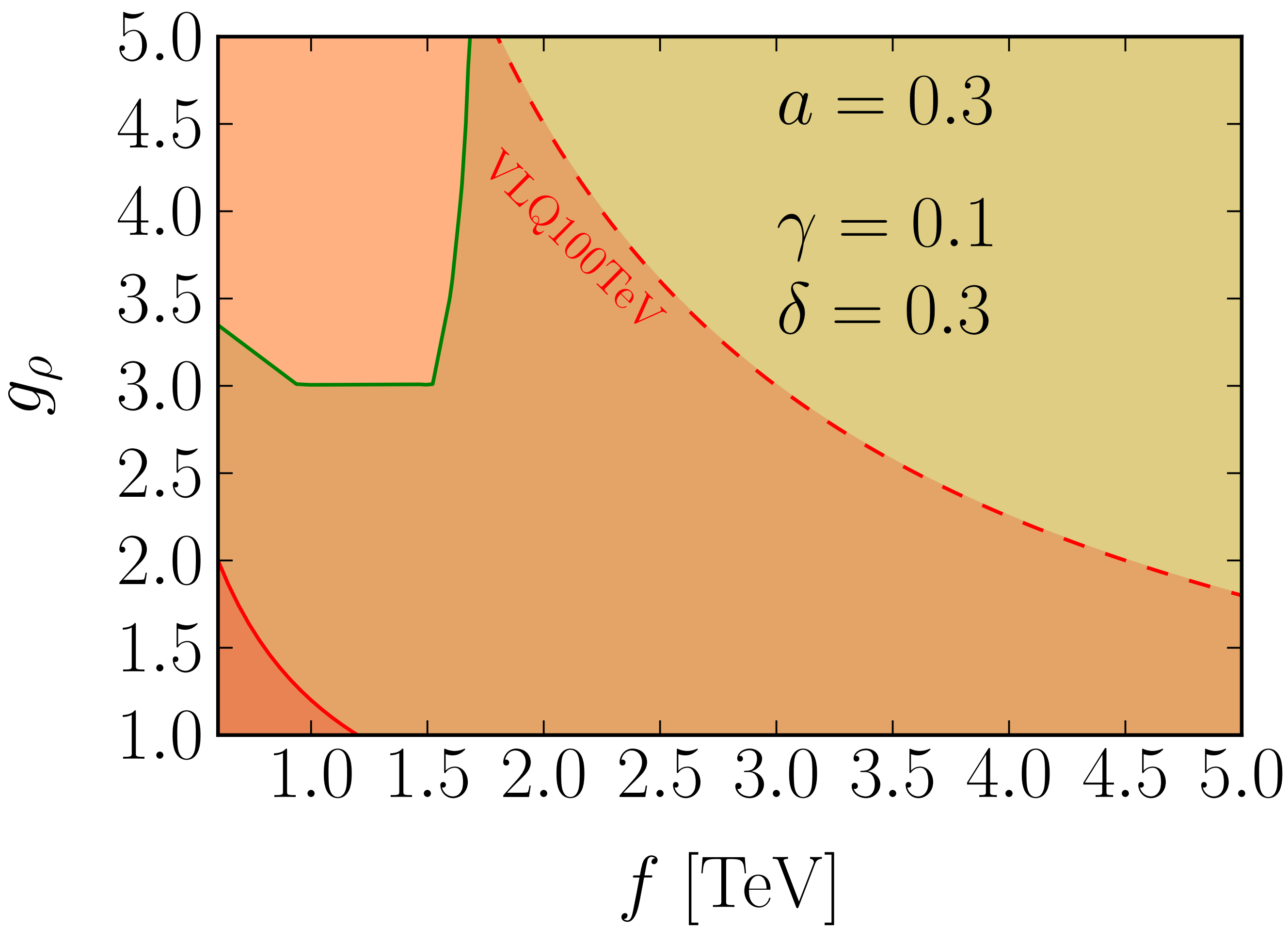
taking ϵ into account



$\epsilon = 0$