Search for Light Composite objects at the LHC

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HL/HE-LHC Workshop

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IPNL

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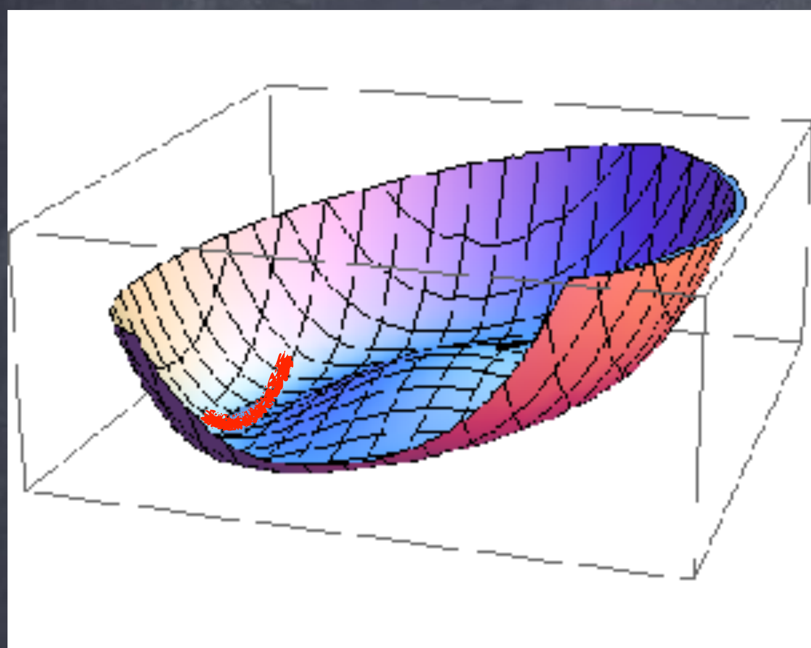
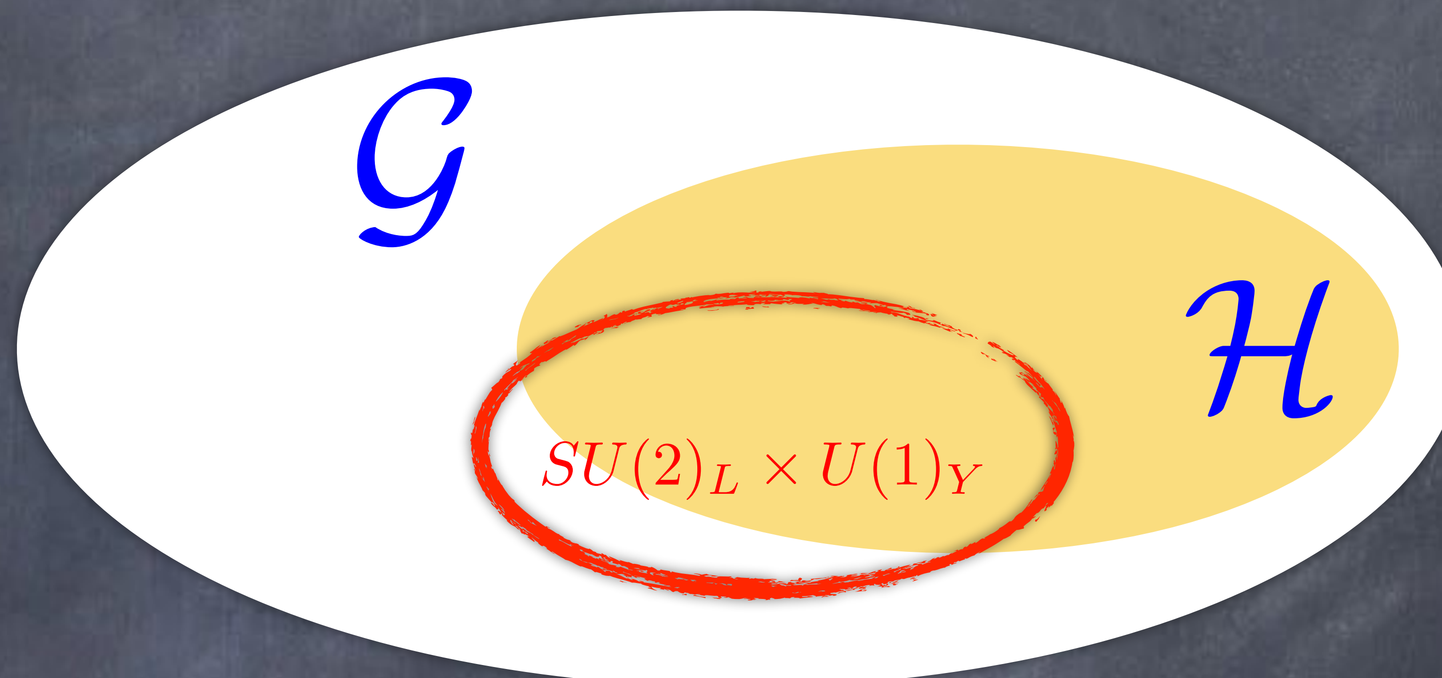
Compositeness, and the Higgs boson



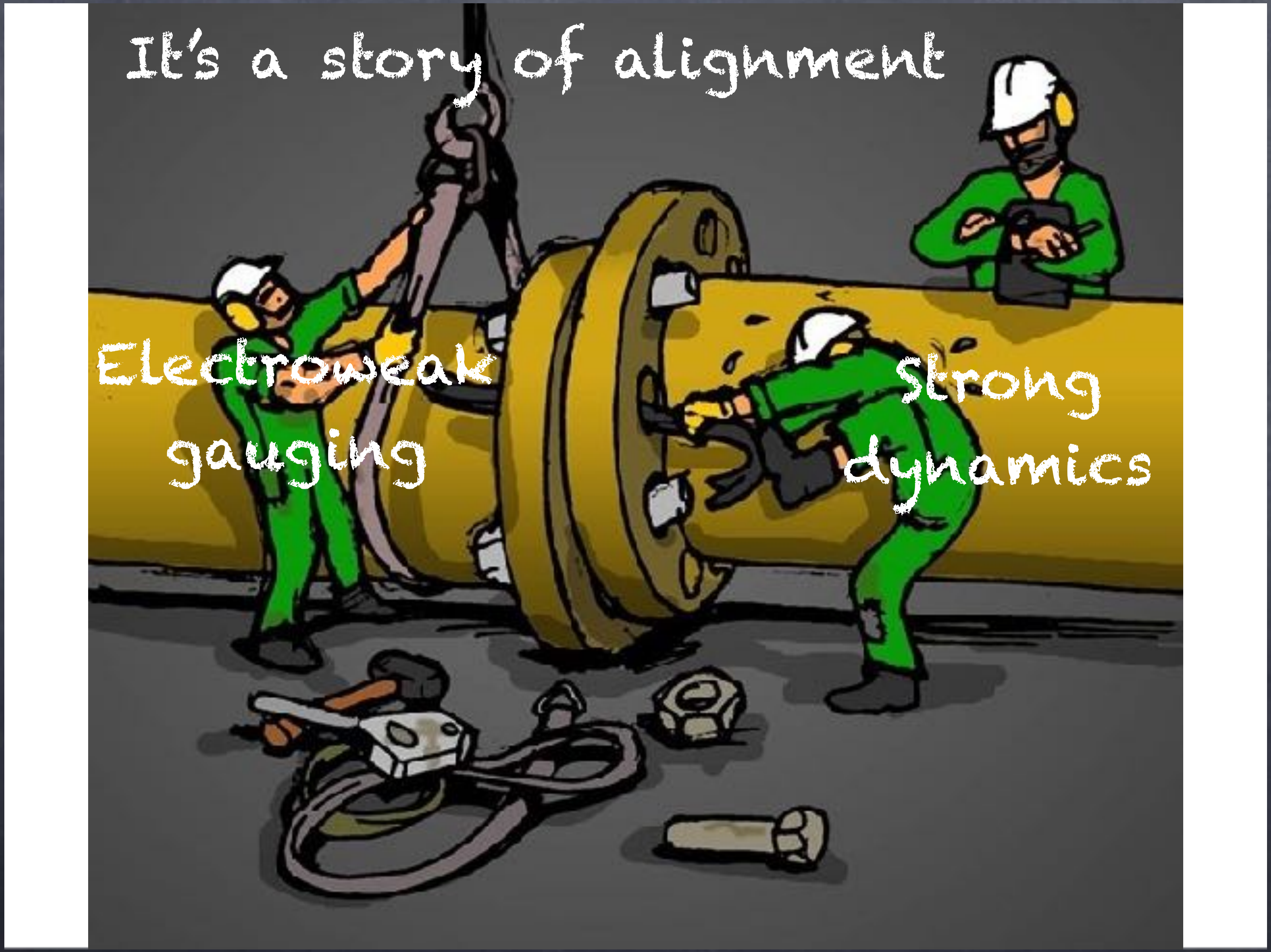


$\mathcal{G} \to \mathcal{H}$

QCD template:

- Goldstones include the longitudinal d.o.f. of W and Z — π pions
- the Higgs is a pseudo-Goldstone (pNGB) — σ sigma

Compositeness, and the Higgs boson



The hot potato: flavour!

100.000 TeV	Λ_{flavour}	Light fermions
		IR conformal region
10 TeV (Λ_{top})	$\Lambda \sim 4\pi f$	Vector resonances, top partners?
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB, Higgs

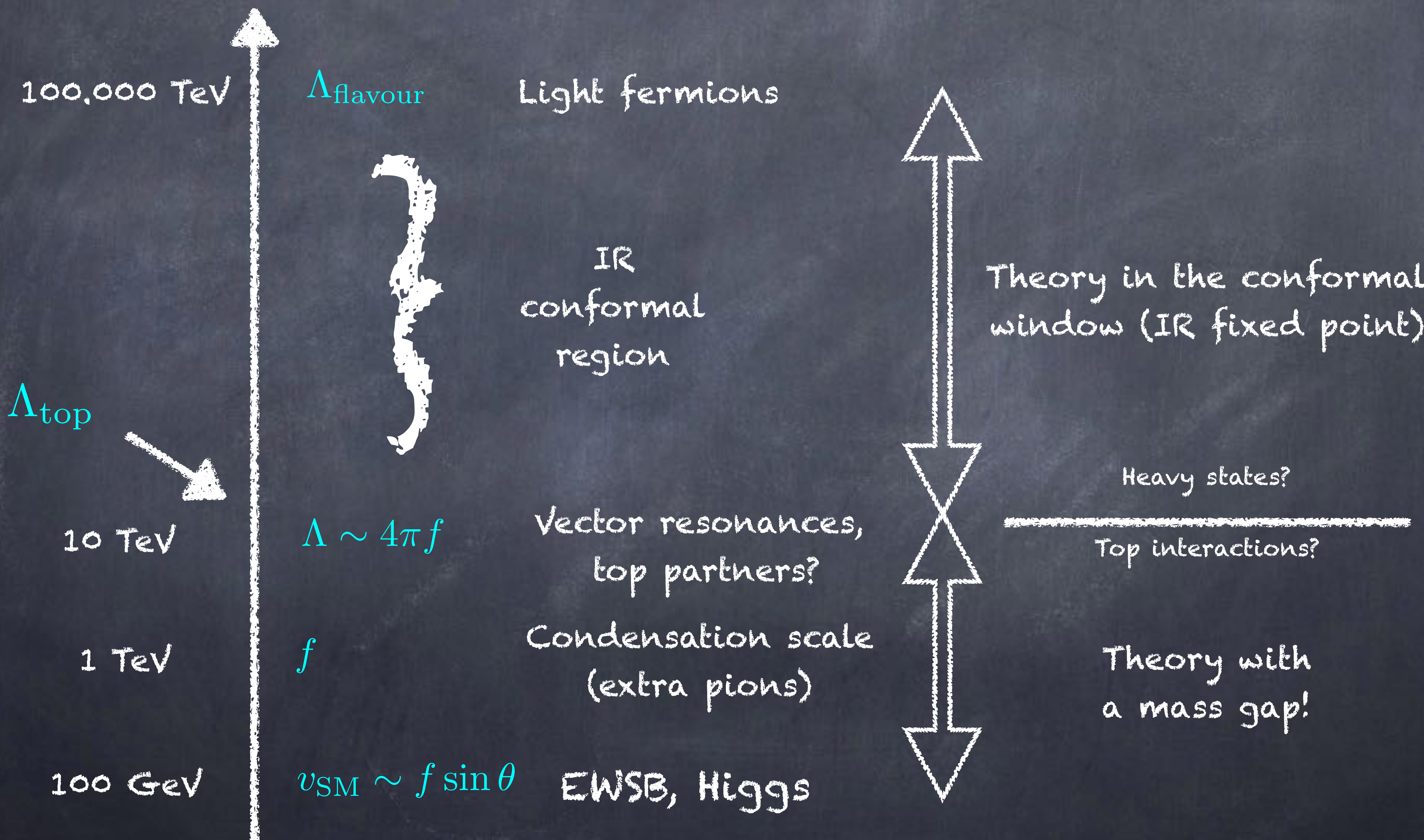
Multi-scale model

$$m_c \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-1} 4\pi f \sin\theta$$

Still, for the top, one would need:

$$\Lambda_{\text{top}} \sim 4\pi f$$

UV completion?



The FCD approach

G.C., F.Sannino
1402.0233

- Define a confining gauge group (GTC)
- Add in N fermions charged under the confining group GTC
- Assign SM quantum numbers to the fermions (thus providing embedding in the global symmetry)
- Couple them to SM fermions

↓

- Guides EFT construction!
- Lattice results can be used!

The new Minimal is non-minimal

coset	GTC	TF	Higgs doublets	pNGBs	
SU(4)/Sp(4)	Sp(2N)	fund	1	5	T.Ryttov, F.Sannino 0809.0713 Galloway, Evans, Luty, Tacchi 1001.1361 ← Minimal!
SU(5)/SO(5)	SU(4)	6	1	14	Dugan, Georgi, Kaplan 1985!!!
SU(4)xSU(4)/SU(4)	SU(N)	fund	2	15	G.C., T.Ma 1508.07014
SU(6)/Sp(6)	Sp(2N)	fund	2	14	G.C., C.Cai, H.Zhang 1805.07619

Where can light states come from?

- The spin-1 resonances expected to be heavy and difficult to see!
- The (minimal) cosets contain more scalars than the Higgs: opportunity for light states!
- The underlying theory can give us hints of the properties of the light states.

Typical top-partner scenario:

$\mathcal{G}_{\rm TC}$: rep R — rep R′

Q — χ

G.Ferretti, D.Karateev
1312.5330, 1604.06467

$T' = QQ\chi \quad \text{or} \quad Q\chi\chi$

SM : EW — colour + hypercharge

global : $\langle QQ \rangle \neq 0$

↓

pNGB Higgs
DM?

a) $\langle \chi\chi \rangle \neq 0$

coloured pNGBs
di-boson

b) $\langle \chi\chi \rangle = 0$

light (massless)
top partners?

Exception: 1506:00623

Predicting di-boson resonances

More precisely, the global symmetries are:

$$SU(N_Q) \times SU(N_\chi) \times U(1)_Q \times U(1)_\chi$$

EW states

QCD-coloured!

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

WZW term:

$$\mathcal{L} \supset \frac{g_i^2}{32\pi^2}\frac{\kappa_i}{f_a}\, a\, \epsilon^{\mu\nu\alpha\beta} G^i_{\mu\nu} G^i_{\alpha\beta} \,,$$

Coefficients depend
on the underlying dynamics!

Decays and production
only via WZW anomaly.

Model zoology

Ferretti
1604.06467

G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	$SU(5)/SO(5) \times SU(6)/SO(6)$				
$SO(N_{HC})$	$5 \times \mathbf{S_2}$	$6 \times \mathbf{F}$	$N_{HC} \geq 55$	$\frac{5(N_{HC}+2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{HC} \geq 15$	$\frac{5(N_{HC}-2)}{6}$	1/3	/	
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	1/3	$N_{HC} = 7, 9$	M1, M2
$SO(N_{HC})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	2/3	$N_{HC} = 7, 9$	M3, M4
	Real	Pseudo-Real	$SU(5)/SO(5) \times SU(6)/Sp(6)$				
$Sp(2N_{HC})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 12$	$\frac{5(N_{HC}+1)}{3}$	1/3	/	
$Sp(2N_{HC})$	$5 \times \mathbf{A_2}$	$6 \times \mathbf{F}$	$2N_{HC} \geq 4$	$\frac{5(N_{HC}-1)}{3}$	1/3	$2N_{HC} = 4$	M5
$SO(N_{HC})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{HC} = 11, 13$	$\frac{5}{24}, \frac{5}{48}$	1/3	/	
	Real	Complex	$SU(5)/SO(5) \times SU(3)^2/SU(3)$				
$SU(N_{HC})$	$5 \times \mathbf{A_2}$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 4$	$\frac{5}{3}$	1/3	$N_{HC} = 4$	M6
$SO(N_{HC})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$N_{HC} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{HC} = 10$	M7
	Pseudo-Real	Real	$SU(4)/Sp(4) \times SU(6)/SO(6)$				
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A_2}$	$2N_{HC} \leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{HC} = 11$	M9
	Complex	Real	$SU(4)^2/SU(4) \times SU(6)/SO(6)$				
$SO(N_{HC})$	$4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{HC} = 10$	$\frac{8}{3}$	2/3	$N_{HC} = 10$	M10
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$6 \times \mathbf{A_2}$	$N_{HC} = 4$	$\frac{2}{3}$	2/3	$N_{HC} = 4$	M11
	Complex	Complex	$SU(4)^2/SU(4) \times SU(3)^2/SU(3)$				
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{A_2}, \overline{\mathbf{A_2}})$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}-2)}$	2/3	$N_{HC} = 5$	M12
$SU(N_{HC})$	$4 \times (\mathbf{F}, \overline{\mathbf{F}})$	$3 \times (\mathbf{S_2}, \overline{\mathbf{S_2}})$	$N_{HC} \geq 5$	$\frac{4}{3(N_{HC}+2)}$	2/3	/	
$SU(N_{HC})$	$4 \times (\mathbf{A_2}, \overline{\mathbf{A_2}})$	$3 \times (\mathbf{F}, \overline{\mathbf{F}})$	$N_{HC} = 5$	4	2/3	/	

Ubiquitous colour octet

In all models there is a pNGB colour-octet!
(This is true in general)

The anomaly generated coupling to gluons,
but also gA (and gZ)

$$\mathcal{L} = a_1\ f_{abc} G^a_{\mu\nu} G^{b\mu\nu} \Phi^c + a_2\ f_{abc} f_{ade}\ \Phi^b\ \Phi^d\ G^c_{\mu\nu}\ G^e_{\mu\nu} + c\ G^a_{\mu\nu} \Phi^a F^{\mu\nu}$$

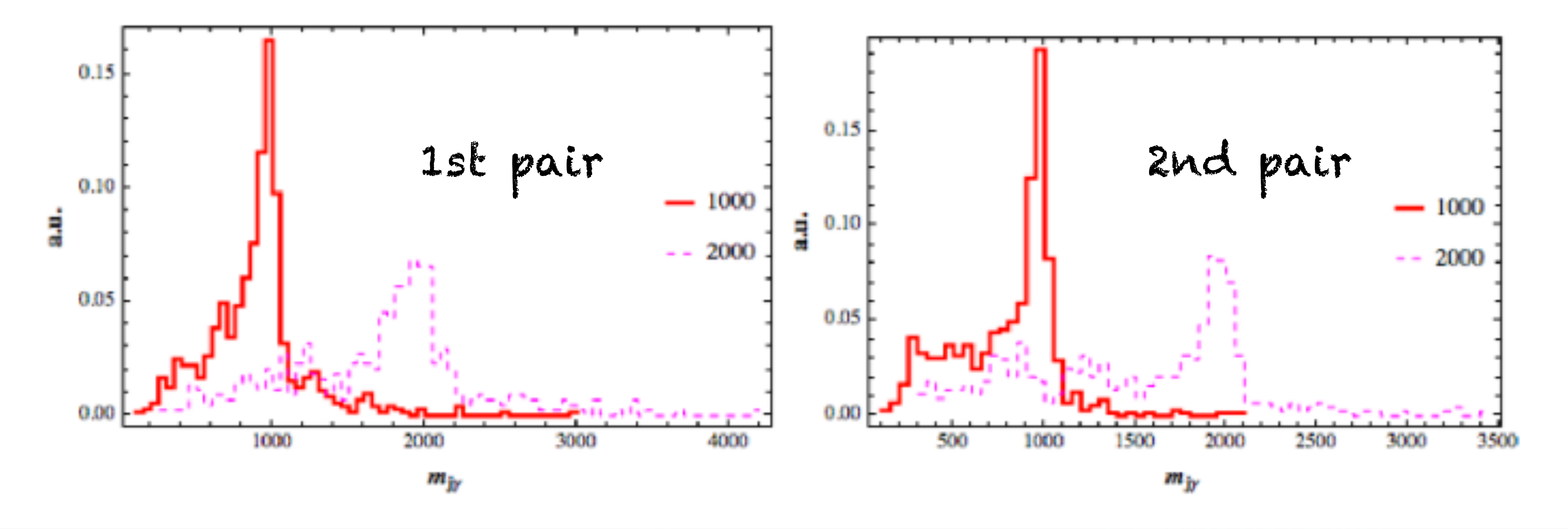
$$\frac{\mathrm{BR}(\Phi \to g\gamma)}{\mathrm{BR}(\Phi \to gg)} = 4.8\% \qquad \frac{\mathrm{BR}(\Phi \to gZ)}{\mathrm{BR}(\Phi \to gg)} = 1.4\% \qquad T = Q\chi\chi$$

$$\frac{\mathrm{BR}(\Phi \to g\gamma)}{\mathrm{BR}(\Phi \to gg)} = 19\% \qquad \frac{\mathrm{BR}(\Phi \to gZ)}{\mathrm{BR}(\Phi \to gg)} = 5.8\% \qquad T = QQ\chi$$

Ubiquitous colour octet

YR contrib. with A.Iyer and A.Deandrea

Pairs reconstructed by using angular separation.
Fair reconstruction efficiency.



$H_T > 500$ GeV

Cut flow	QCD (660 fb)	BP1	BP2
2 γ+2 jets	0.005	0.07	0.02

TABLE I: Pair production efficiencies for signal and background.

Di-bosons from the singlets

Belyaev, G.C., Cai, Ferretti, Flacke, Parolini, Serodio 1610.06591

- The two singlets mix!

η'

$$-\mathcal{L}_{\rm mass} = \frac{1}{2} m_{a_\chi}^2 a_\chi^2 + \frac{1}{2} m_{a_\psi}^2 a_\psi^2 + \frac{1}{2} M_A^2 (\cos\zeta a_\chi - \sin\zeta a_\psi)^2$$

fermion masses   anomaly

$$\left. \frac{m_a}{m_{\eta'}} \right|_{\rm max} = \sqrt{\frac{1-\cos\zeta}{1+\cos\zeta}} = \left| \tan\frac{\zeta}{2} \right| .$$

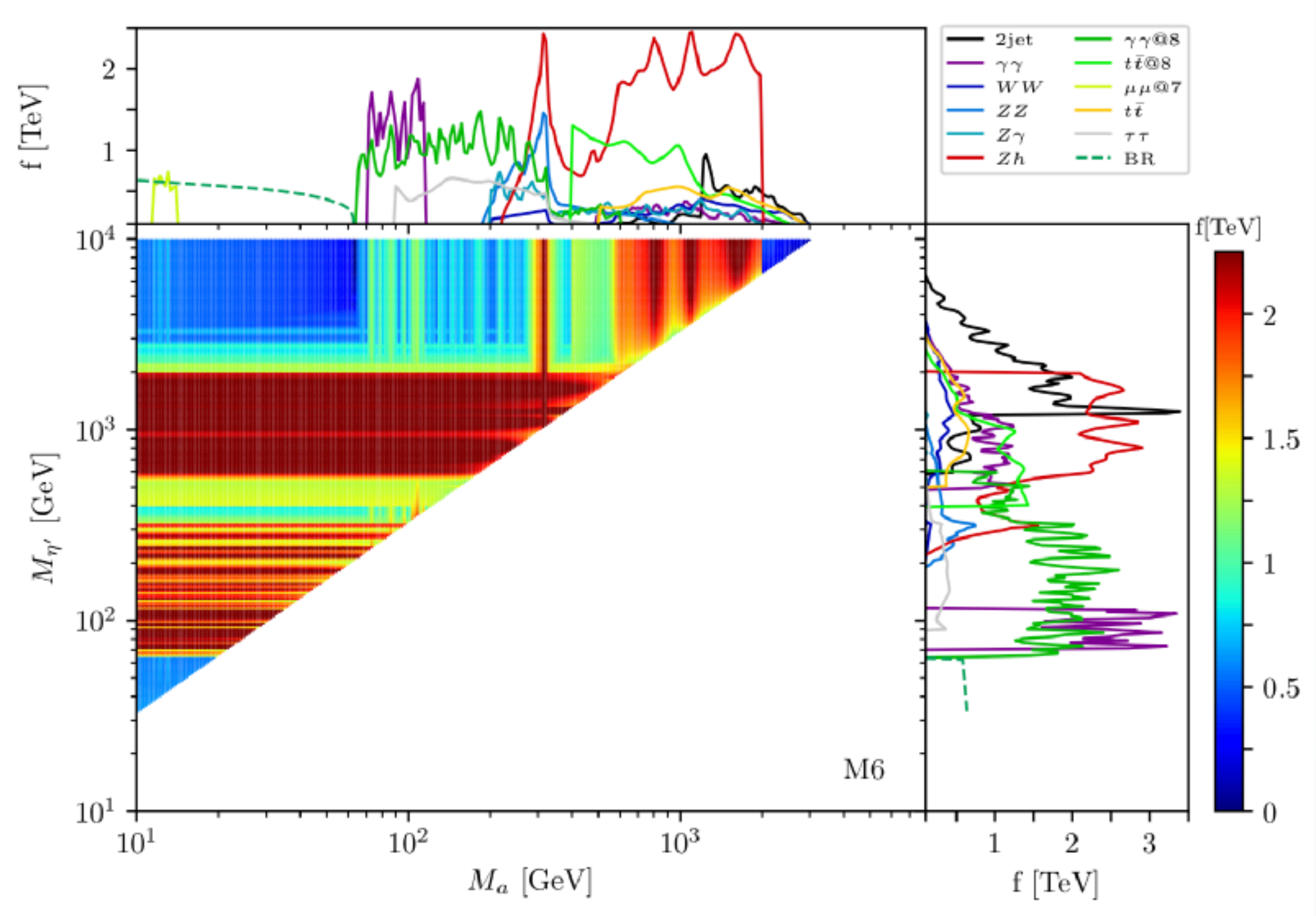
Minimum mass splitting!

- Couplings to tops are inevitable!

$$i c_5 \frac{m_{\rm top}}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}} \left((n_\psi q_\psi + n_\chi q_\chi)\, \tilde{a} + \left(n_\chi q_\psi \frac{f_{a_\psi}}{f_{a_\chi}} - n_\psi q_\chi \frac{f_{a_\chi}}{f_{a_\psi}} \right) \tilde{\eta}' \right) \bar{t} \gamma^5 t ,$$

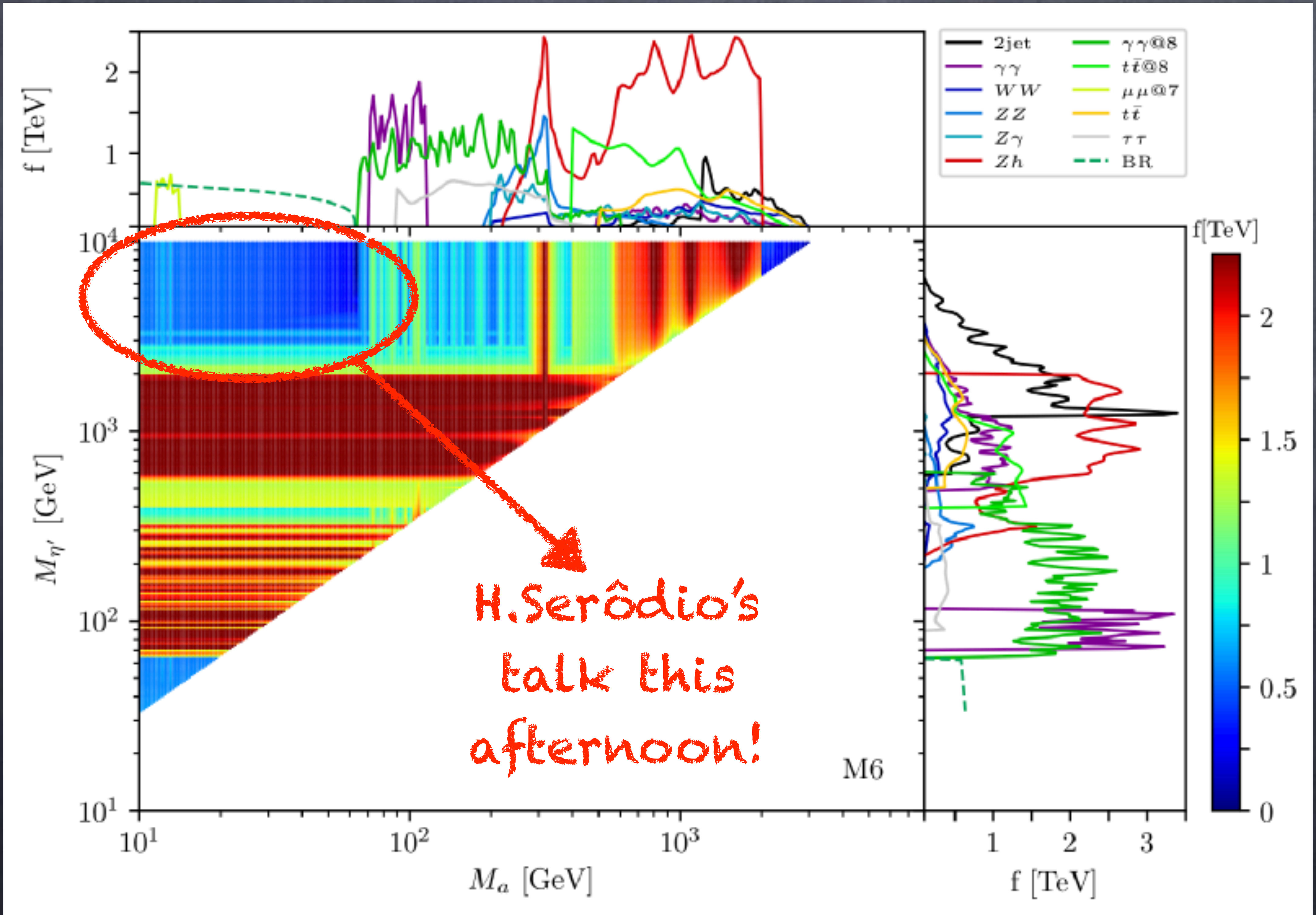
Bounds on f for M6

with H.Serôdio, G.Ferretti, T.Flacke



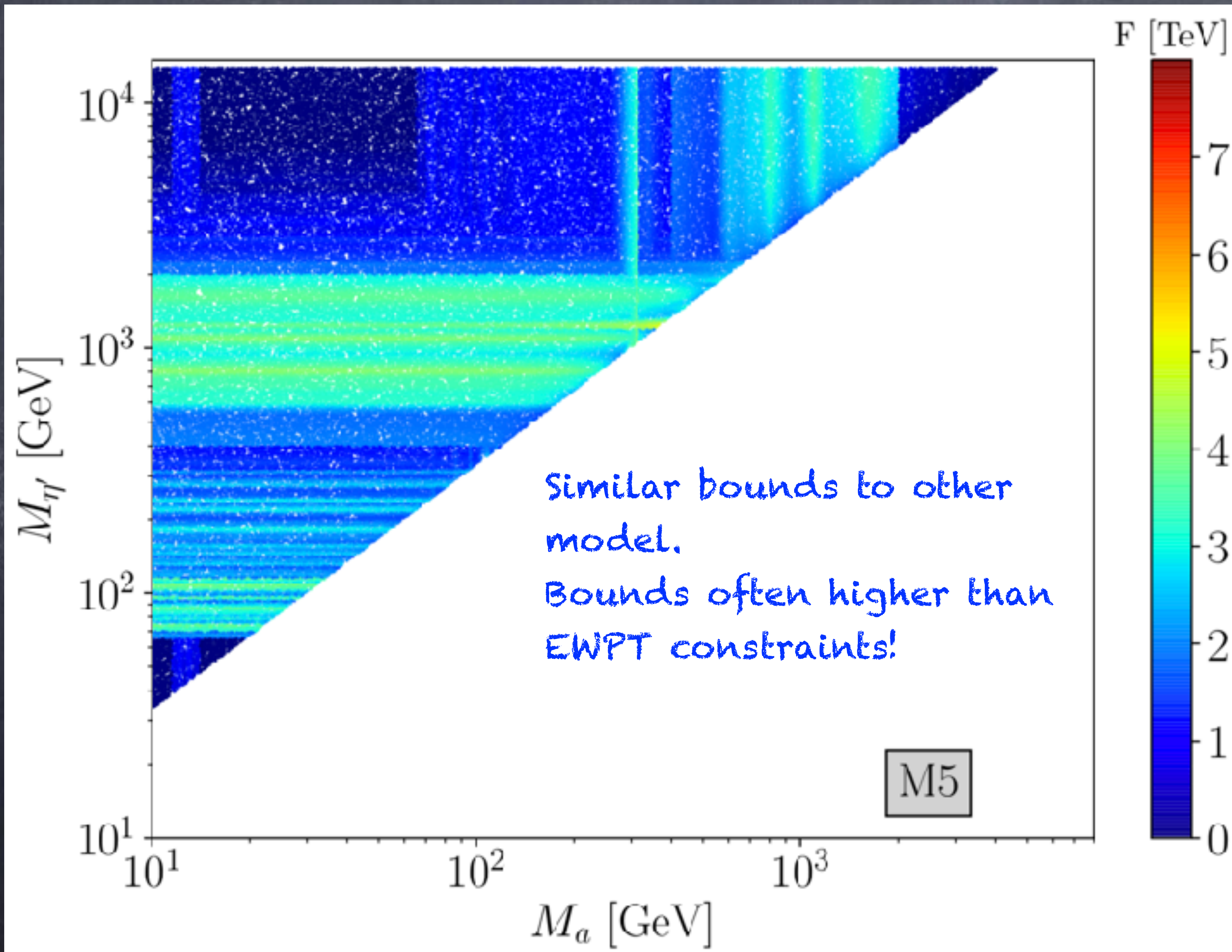
Bounds on f for M6

with H.Serôdio, G.Ferretti, T.Flacke



Bounds on f for M5

with H.Serôdio, G.Ferretti, T.Flacke



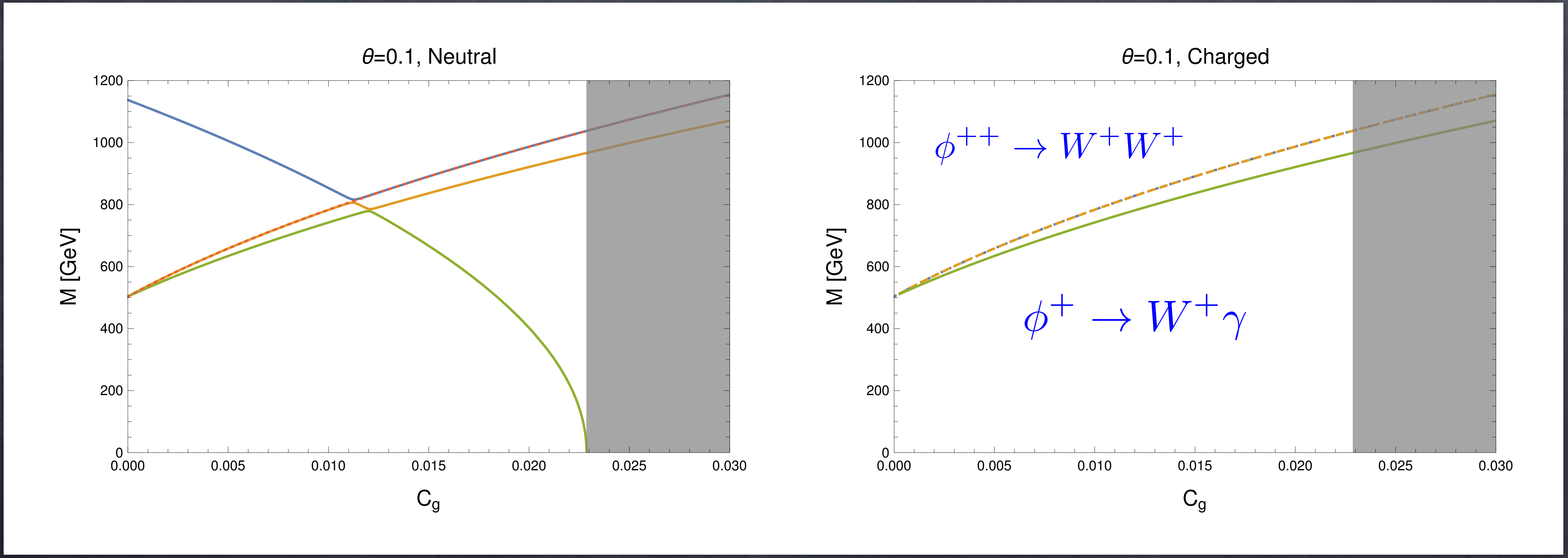
Different colour scale: sorry!

EWPTs

EW pNGBs

Work in progress with
A.Agugliaro, A.Deandrea, S.de Curtis

Spectrum of an SU(5)/SO(5) model: f ~ 2.4 TeV

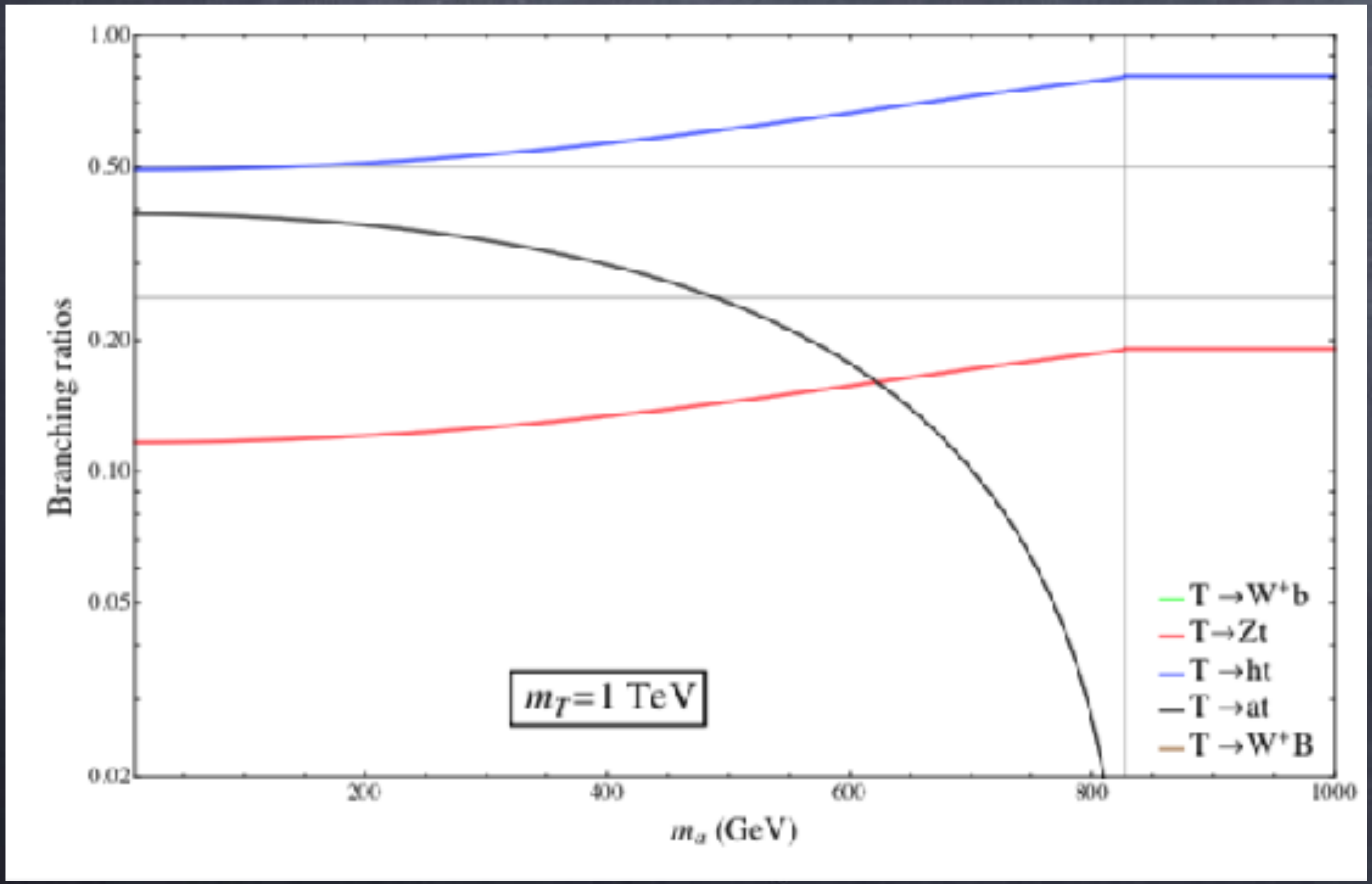


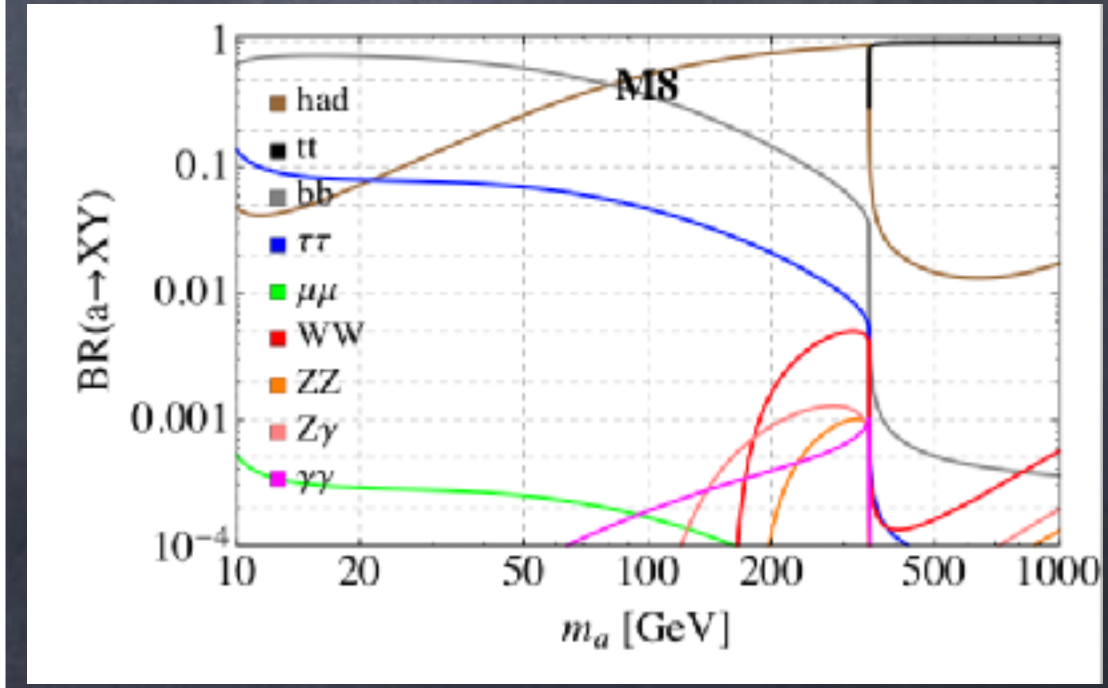
It's a composite Georgi-Machacek Model, but with peculiar spectra and properties.
No coupling to top/bottom, only to gauge boson via anomalies.

Opportunity for new searches:

- Production via top-partner decays!

N.Bizot, GC, T.Flacke
1803.00021



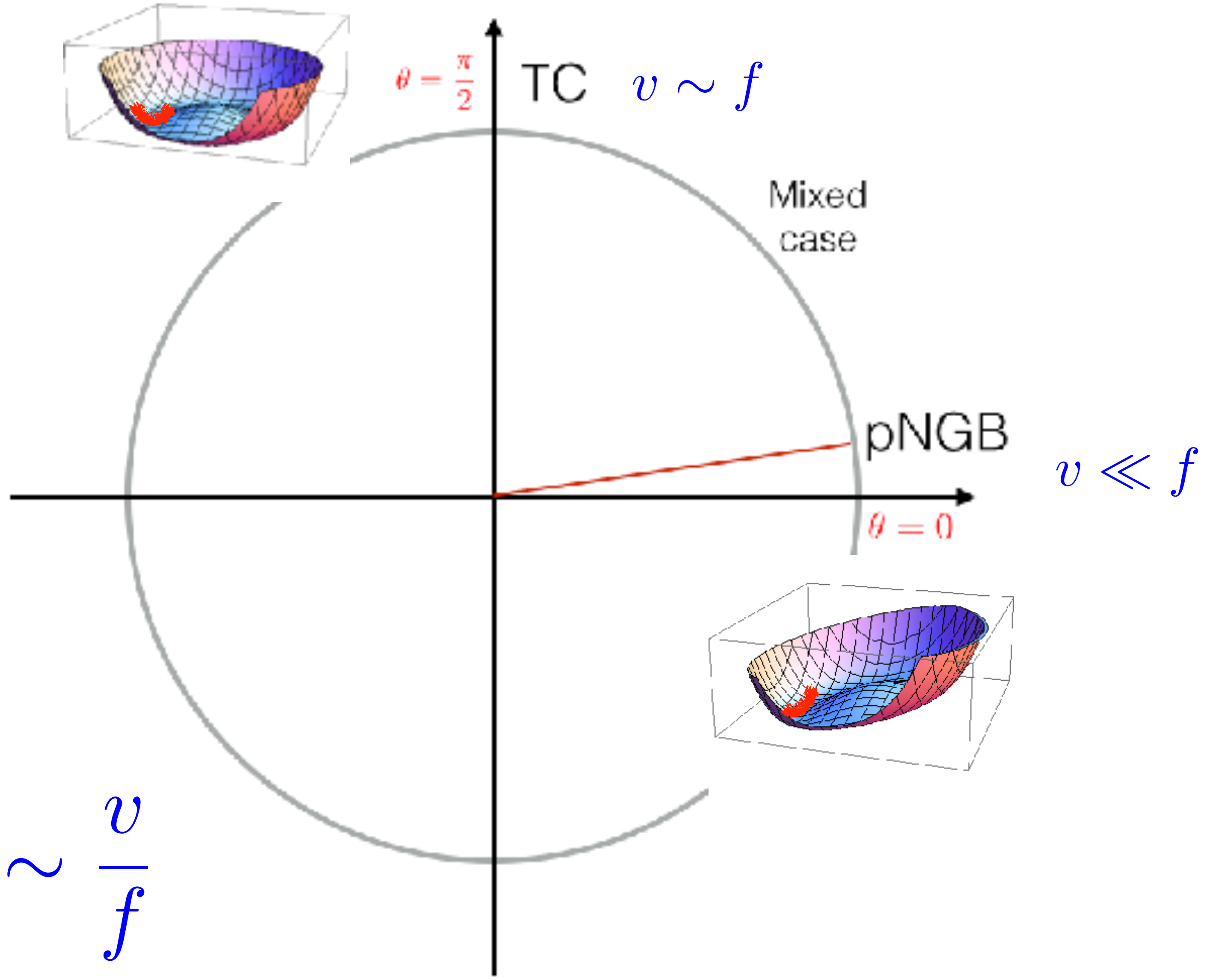


Conclusions and outlook

- UV completions indicate heavy resonances (several TeV): HE-LHC!
- Non-minimal coset is the new minimal! Additional "light" scalars to be studied!
- U(1) pNGB (di-bosons), coloured pNGBs (gluon photon), EW pNGBs (W photon, ...)
- New final states for top-partner searches

Bonus tracks

Compositeness, and the Higgs boson



$$\sin\theta \sim \frac{v}{f}$$

The FCD approach

- The symmetry breaking pattern determined by the irrep of the underlying fermions!
- The minimal case of SU(4)/Sp(4)!

R_{TC} is real: G_F =	$SU(N_\psi)$	$\langle \psi^i \psi^j \rangle$	$SU(N_\psi) \to SO(N_\psi)$
pseudo-real: G_F =	$SU(2N_\psi)$	$\langle \psi^i \psi^j \rangle$	$SU(2N_\psi) \to Sp(2N_\psi)$
complex: G_F =	$SU(N_\psi)^2$	$\langle \bar{\psi}^i \psi^j \rangle$	$SU(N_\psi)^2 \to SU(N_\psi)$

Model-dependent results

	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{HC})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{HC} \leq 36$	$\frac{1}{3(N_{HC}-1)}$	2/3	$2N_{HC} = 4$	M8
$SO(N_{HC})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{HC} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{HC} = 11$	M9

The EFT is the same!

Numerical value of couplings:

Model		κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g}$ (2,0)	$\frac{C_t}{\kappa_g}$ (0,2)	$\tan\zeta$
M8	a	$-0.77(-0.39)$	$-1.2(-2.5)$	$1.5(0.17)$	$-1.2(-2.5)$	$0.40(0.40)$	
	η'	$1.9(2.0)$	$0.20(0.096)$	$2.9(2.8)$	$0.20(0.0.96)$	$0.40(0.40)$	-0.41
	π_8	7.1	0	1.3	0	0.40	
M9	a	$-4.3(-2.7)$	$-0.55(-2.4)$	$2.1(0.26)$	$-0.068(-0.30)$	$0.18(0.18)$	
	η'	$1.3(3.6)$	$5.8(1.3)$	$8.5(4.0)$	$0.73(0.16)$	$0.18(0.18)$	-3.26
	π_8	16.	0	1.3	0	0.18	

Assuming $f_a = f_\psi = f_\chi$