

Search for Light Composite objects at the LHC

G.Cacciapaglia

with H.Serôdio, G.Ferretti, T.Flacke

2018/07/06 @ Seoul

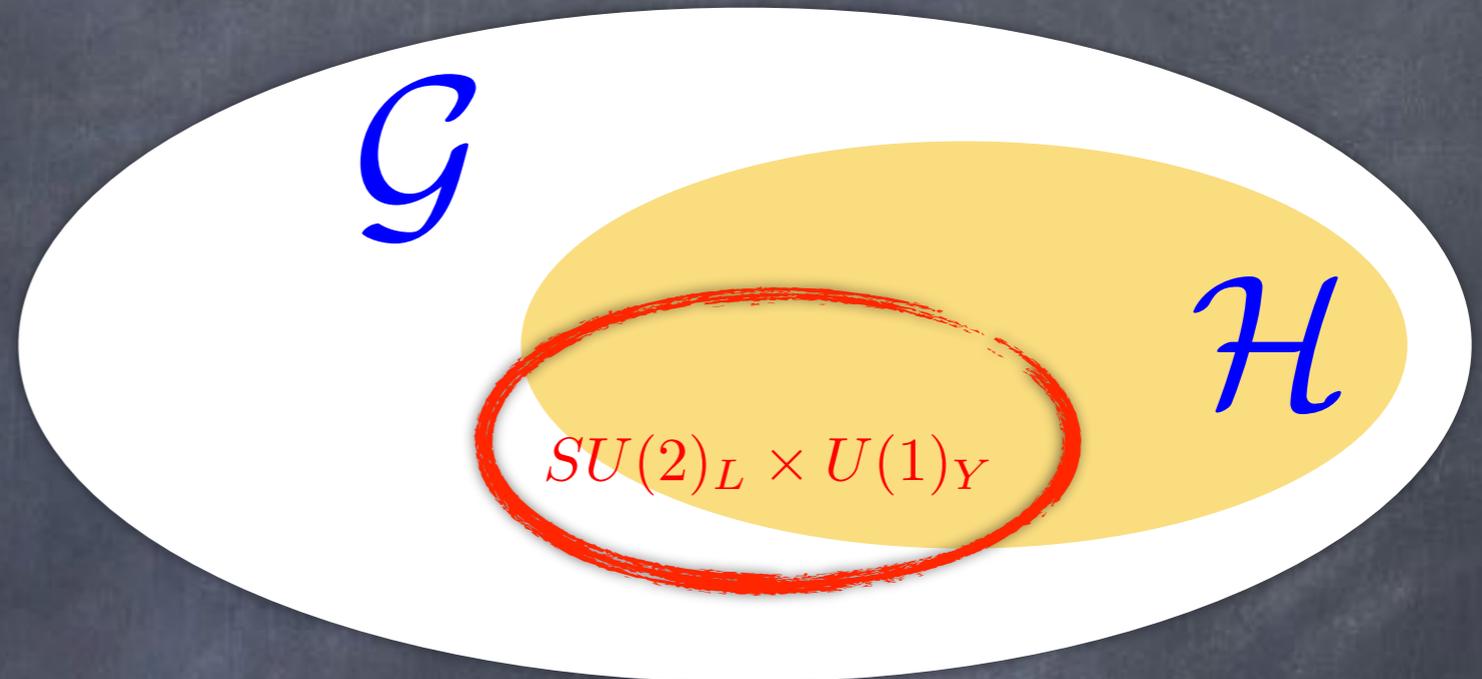
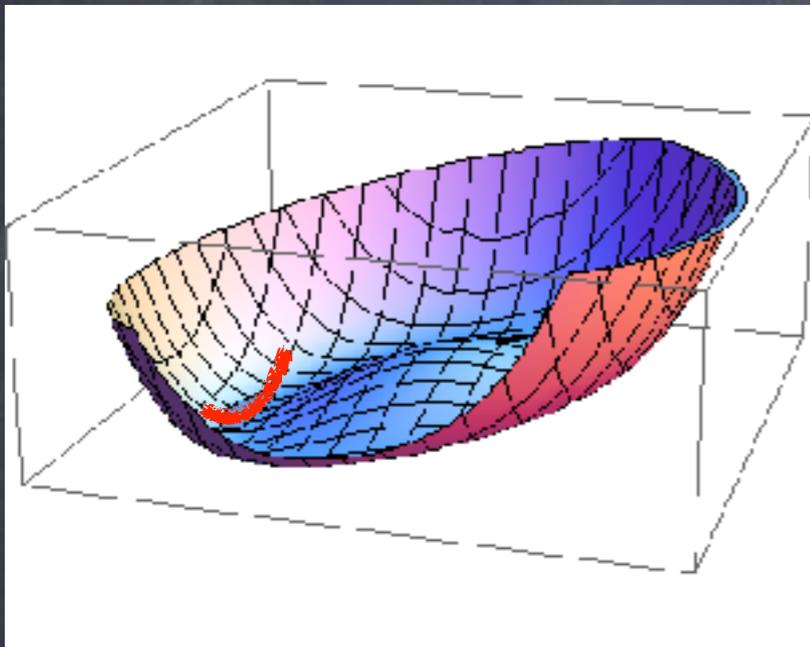
ICHEP2018



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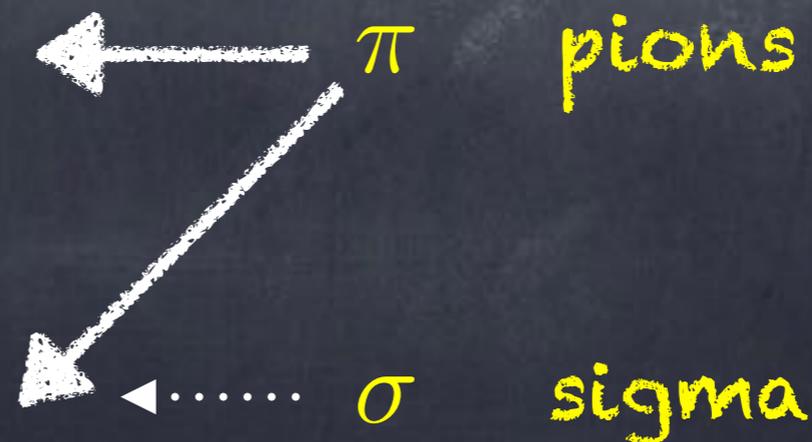
Compositeness, and the Higgs boson



$$G \rightarrow H$$

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

QCD template:

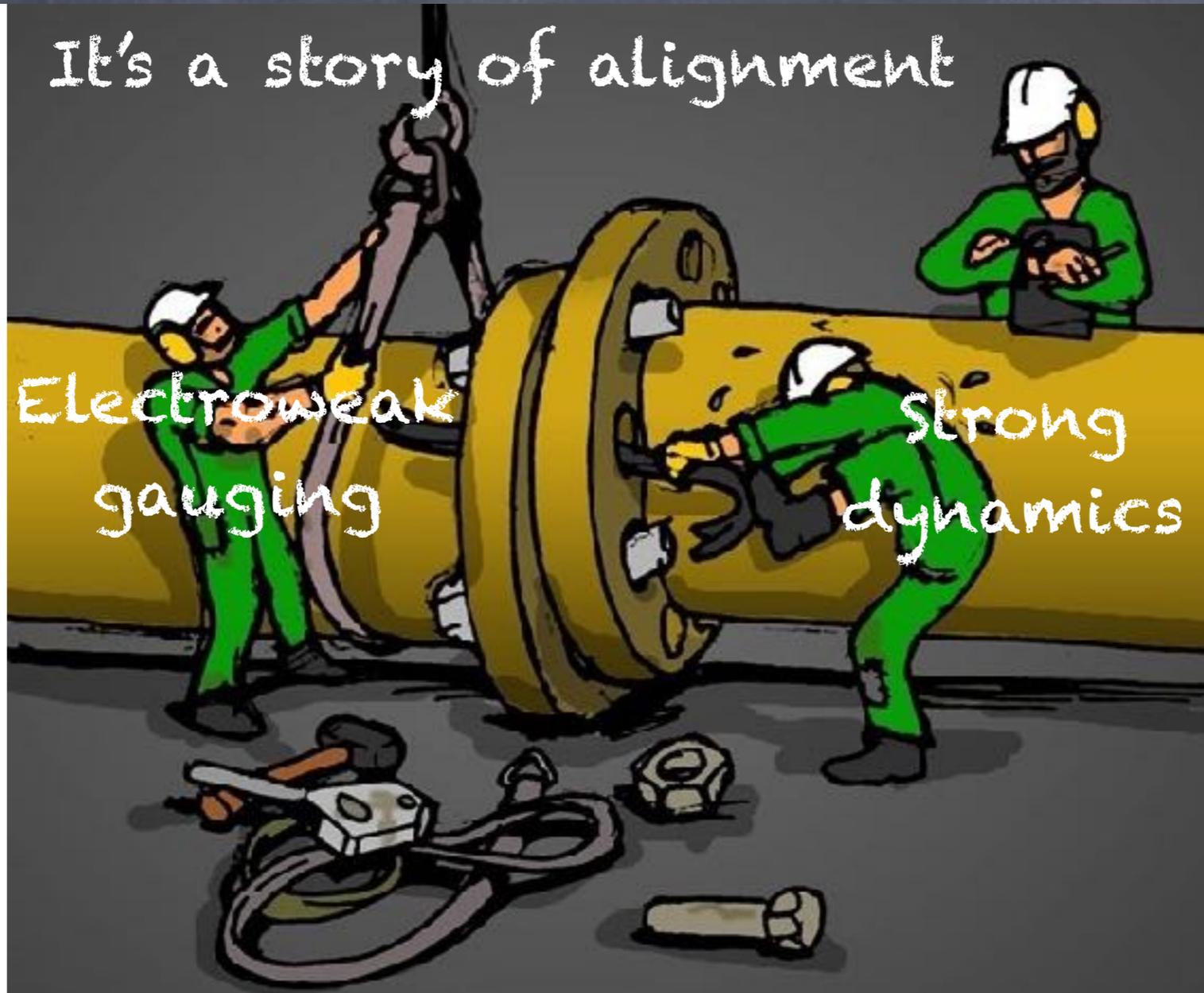


Compositeness, and the Higgs boson

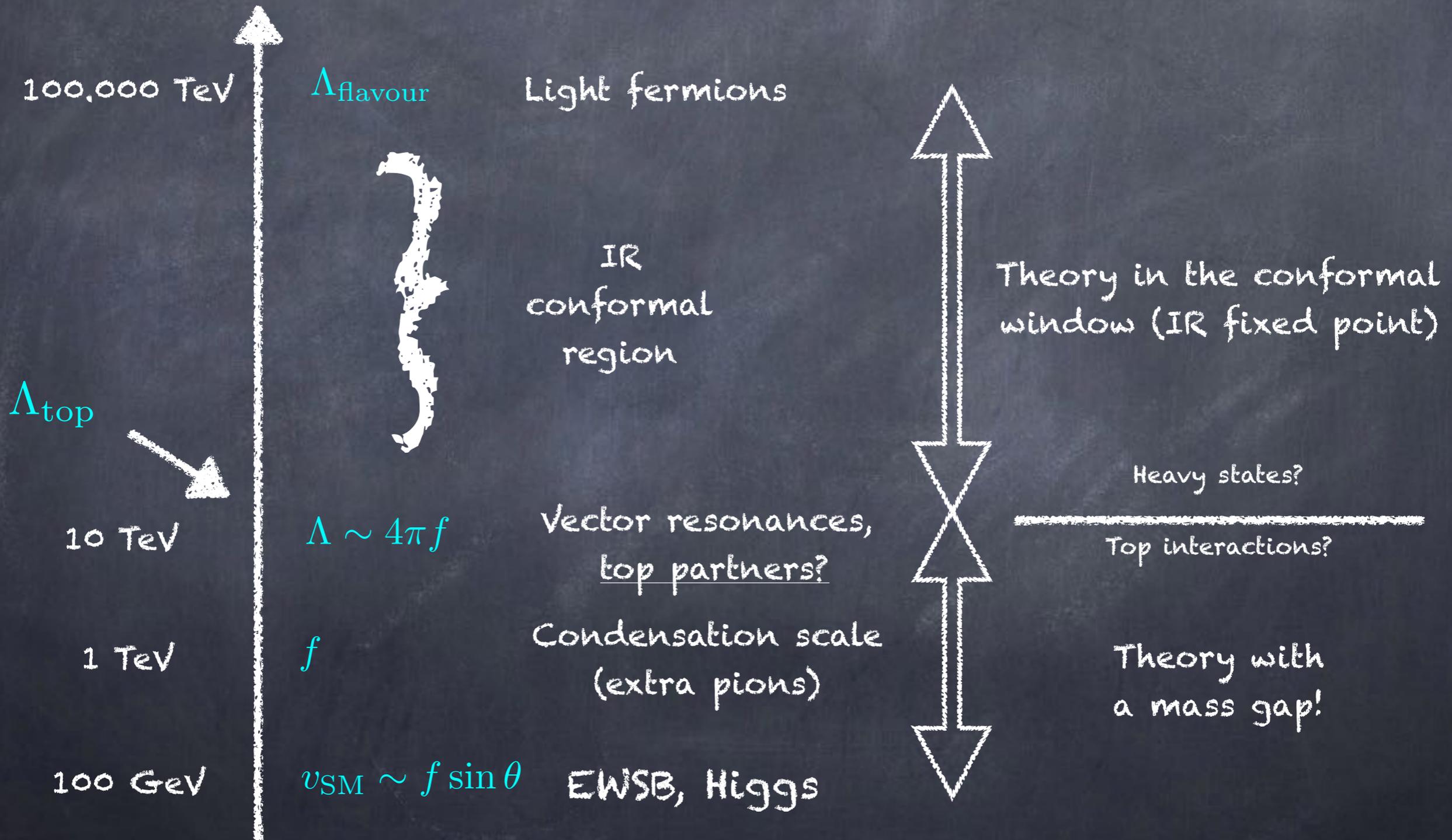
It's a story of alignment

Electroweak
gauging

Strong
dynamics



UV completion?



The new Minimal is non-minimal

coset	GTC	TF	Higgs doublets	pNGBs	
$SU(4)/Sp(4)$	$Sp(2N)$	fund	1	5	<p>T.Ryttov, F.Sannino 0809.0713 Galloway, Evans, Luty, Tacchi 1001.1361</p> <p>← Minimal!</p>
$SU(5)/SO(5)$	$SU(4)$	6	1	14	Dugan, Georgi, Kaplan 1985!!!
$SU(4) \times SU(4) / SU(4)$	$SU(N)$	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

Typical top-partner scenario:

G_{TC} :

rep R

rep R'

G.Ferretti, D.Karateev
1312.5330, 1604.06467

Q

χ

$T' = QQ\chi$ or $Q\chi\chi$

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:

$$SU(N_Q) \times SU(N_X) \times U(1)_Q \times U(1)_X$$



WZW term:

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

Coefficients depend on the underlying dynamics!

Anomalous U(1) → heavy η'

Orthogonal U(1) → pNGB a

Decays and production only via WZW anomaly.

Model zoology

G_{HC}	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
Real			SU(5)/SO(5) \times SU(6)/SO(6)				
$SO(N_{\text{HC}})$	$5 \times \mathbf{S}_2$	$6 \times \mathbf{F}$	$N_{\text{HC}} \geq 55$	$\frac{5(N_{\text{HC}}+2)}{6}$	1/3	/	
$SO(N_{\text{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$N_{\text{HC}} \geq 15$	$\frac{5(N_{\text{HC}}-21)}{6}$	1/3	/	
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\text{HC}} = 7, 9$	$\frac{5}{6}, \frac{5}{12}$	1/3	$N_{\text{HC}} = 7, 9$	M1, M2
$SO(N_{\text{HC}})$	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 7, 9$	$\frac{5}{6}, \frac{5}{3}$	2/3	$N_{\text{HC}} = 7, 9$	M3, M4
Real			Pseudo-Real		SU(5)/SO(5) \times SU(6)/Sp(6)		
$Sp(2N_{\text{HC}})$	$5 \times \mathbf{Ad}$	$6 \times \mathbf{F}$	$2N_{\text{HC}} \geq 12$	$\frac{5(N_{\text{HC}}+1)}{3}$	1/3	/	
$Sp(2N_{\text{HC}})$	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$2N_{\text{HC}} \geq 4$	$\frac{5(N_{\text{HC}}-1)}{3}$	1/3	$2N_{\text{HC}} = 4$	M5
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$N_{\text{HC}} = 11, 13$	$\frac{5}{21}, \frac{5}{48}$	1/3	/	
Real			Complex		SU(5)/SO(5) \times SU(3) ² /SU(3)		
$SU(N_{\text{HC}})$	$5 \times \mathbf{A}_2$	$3 \times (\mathbf{F}, \bar{\mathbf{F}})$	$N_{\text{HC}} = 4$	$\frac{5}{3}$	1/3	$N_{\text{HC}} = 4$	M6
$SO(N_{\text{HC}})$	$5 \times \mathbf{F}$	$3 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	$N_{\text{HC}} = 10, 14$	$\frac{5}{12}, \frac{5}{48}$	1/3	$N_{\text{HC}} = 10$	M7
Pseudo-Real			Real		SU(4)/Sp(4) \times SU(6)/SO(6)		
$Sp(2N_{\text{HC}})$	$4 \times \mathbf{F}$	$6 \times \mathbf{A}_2$	$2N_{\text{HC}} \leq 36$	$\frac{1}{3(N_{\text{HC}}-1)}$	2/3	$2N_{\text{HC}} = 4$	M8
$SO(N_{\text{HC}})$	$4 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 11, 13$	$\frac{8}{3}, \frac{16}{3}$	2/3	$N_{\text{HC}} = 11$	M9
Complex			Real		SU(4) ² /SU(4) \times SU(6)/SO(6)		
$SO(N_{\text{HC}})$	$4 \times (\mathbf{Spin}, \bar{\mathbf{Spin}})$	$6 \times \mathbf{F}$	$N_{\text{HC}} = 10$	$\frac{8}{3}$	2/3	$N_{\text{HC}} = 10$	M10
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$6 \times \mathbf{A}_2$	$N_{\text{HC}} = 4$	$\frac{2}{3}$	2/3	$N_{\text{HC}} = 4$	M11
Complex			Complex		SU(4) ² /SU(4) \times SU(3) ² /SU(3)		
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$	$N_{\text{HC}} \geq 5$	$\frac{4}{3(N_{\text{HC}}-2)}$	2/3	$N_{\text{HC}} = 5$	M12
$SU(N_{\text{HC}})$	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{S}_2, \bar{\mathbf{S}}_2)$	$N_{\text{HC}} \geq 5$	$\frac{4}{3(N_{\text{HC}}+2)}$	2/3	/	
$SU(N_{\text{HC}})$	$4 \times (\mathbf{A}_2, \mathbf{A}_2)$	$3 \times (\mathbf{F}, \mathbf{F})$	$N_{\text{HC}} = 5$	4	2/3	/	

Ferretti
1604.06467

Light scalar menu

- Light singlet pseudo-scalar

- Additional EW scalars from non-minimal cosets

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

- Coloured octet (ubiquitous), sextet and triplet

G.C., H. Cai, A. Deandrea, T. Flacke, S.J. Lee, A. Parolini,
1507.02283

- Dark Matter?

G.C., Y. Wu, T. Ma, B. Zhang, 1703.06903

G.C., C. Cai, H. Zhang, 1805.07619

G.C., T. Ma, Y. Wu, in prep.

Di-bosons from the singlets

- Couplings to tops are inevitable!

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

$$iC_5 \frac{m_{\text{top}}}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_\chi^2 f_{a_\chi}^2}} \left((n_\psi q_\psi + n_\chi q_\chi) \tilde{a} + \left(n_\chi q_\psi \frac{f_{a_\psi}}{f_{a_\chi}} - n_\psi q_\chi \frac{f_{a_\chi}}{f_{a_\psi}} \right) \tilde{\eta}' \right) \bar{t} \gamma^5 t,$$

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

Minimum mass splitting!

- Effective descriptions (but couplings are CALCULABLE)

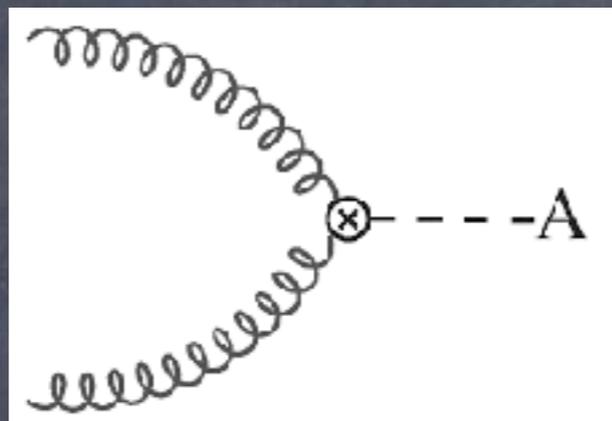
$$\begin{aligned} \mathcal{L}_a = & \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{1}{2} m_a^2 a^2 - \sum_f \frac{iC_f^a m_f}{f_a} a \bar{f} \gamma^5 f + \frac{g_s^2 K_g^a}{16\pi^2 f_a} a G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g^2 K_W^a}{8\pi^2 f_a} a W_{\mu\nu}^+ \tilde{W}^{-,\mu\nu} \\ & + \frac{e^2 K_\gamma^a}{16\pi^2 f_a} a A_{\mu\nu} \tilde{A}^{\mu\nu} + \frac{g^2 c_W^2 K_Z^a}{16\pi^2 f_a} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{egc_W K_{Z\gamma}^a}{8\pi^2 f_a} a A_{\mu\nu} \tilde{Z}^{\mu\nu}. \quad (2.4) \end{aligned}$$

$$\mathcal{L}_{hZa} = \frac{3C_t m_t^2 g_A}{2\pi^2 f_a v} (\kappa_t - \kappa_V) \log \frac{\Lambda^2}{m_t^2} h(\partial_\mu a) Z^\mu,$$

Higgs coupling kappas

Di-bosons from the singlets

The pseudo-scalars are produced via gluon fusion:



+ top loops

$t\bar{t}$, $b\bar{b}$ via partial compositeness

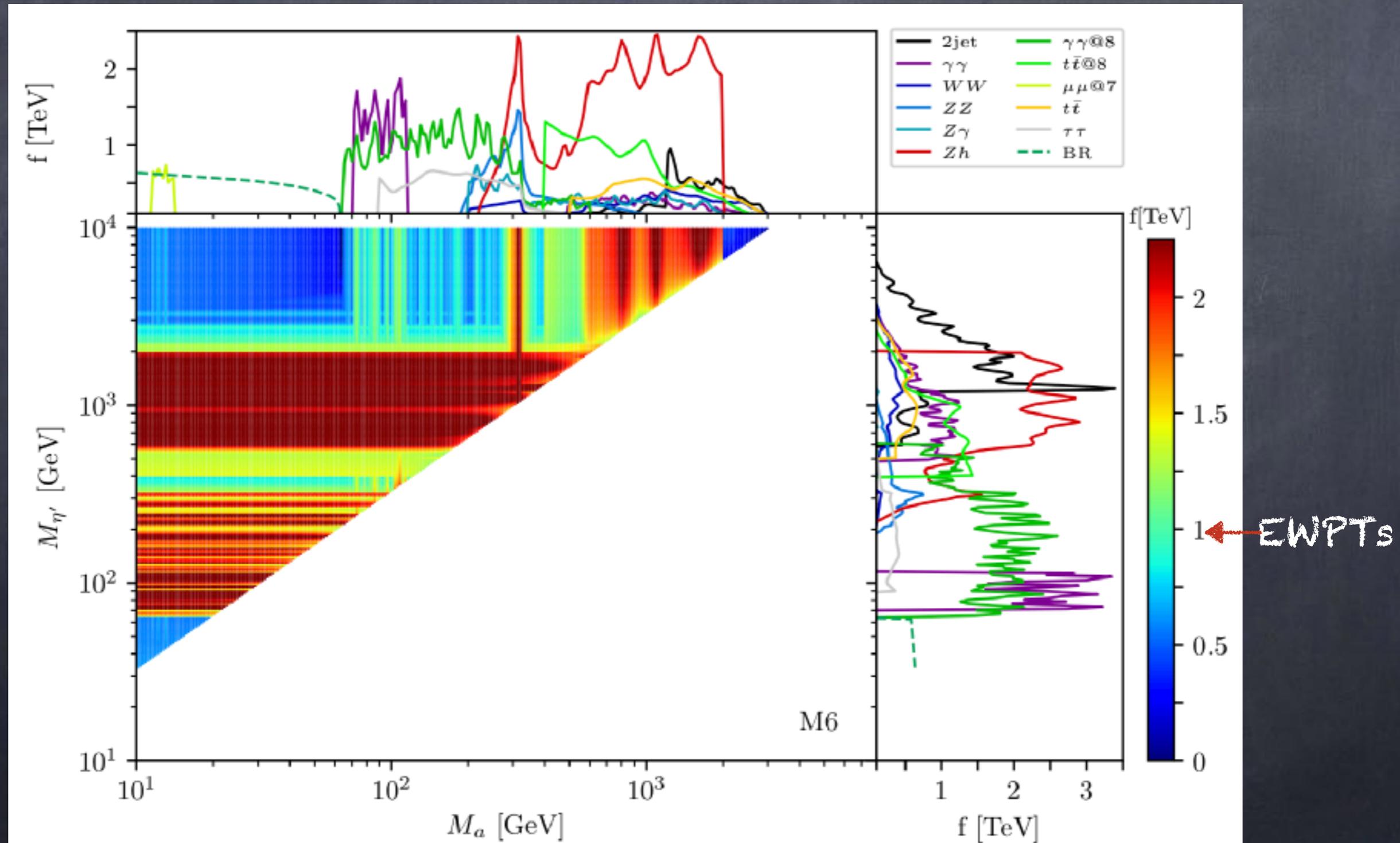
$q\bar{q}$, $l\bar{l}$ via bi-linear couplings (effective Yukawas)

gg , VV via WZW anomalies (and top loops)

Zh via top loops

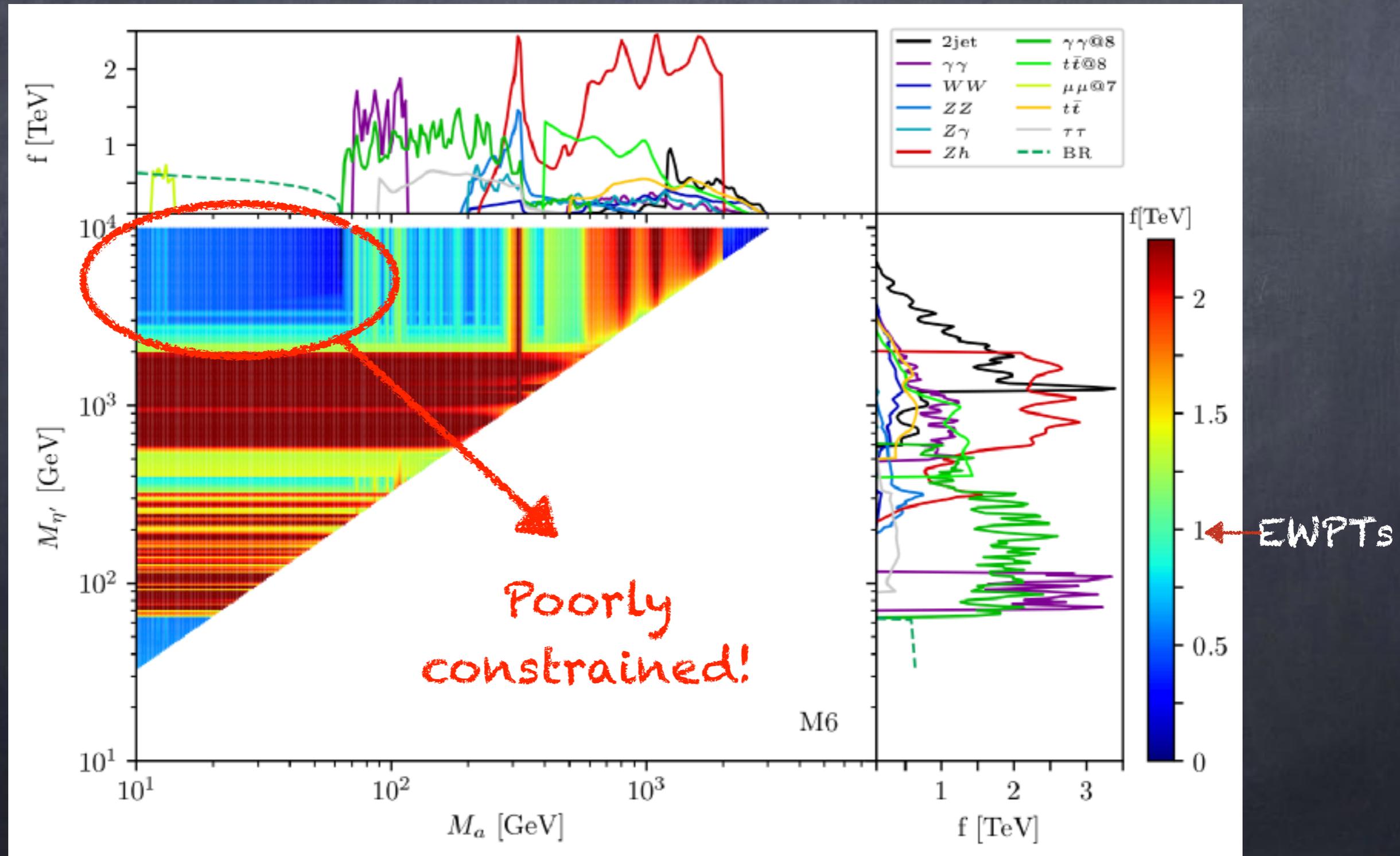
Bounds on f for M6

with H.Serôdio, G.Ferretti, T.Flacke



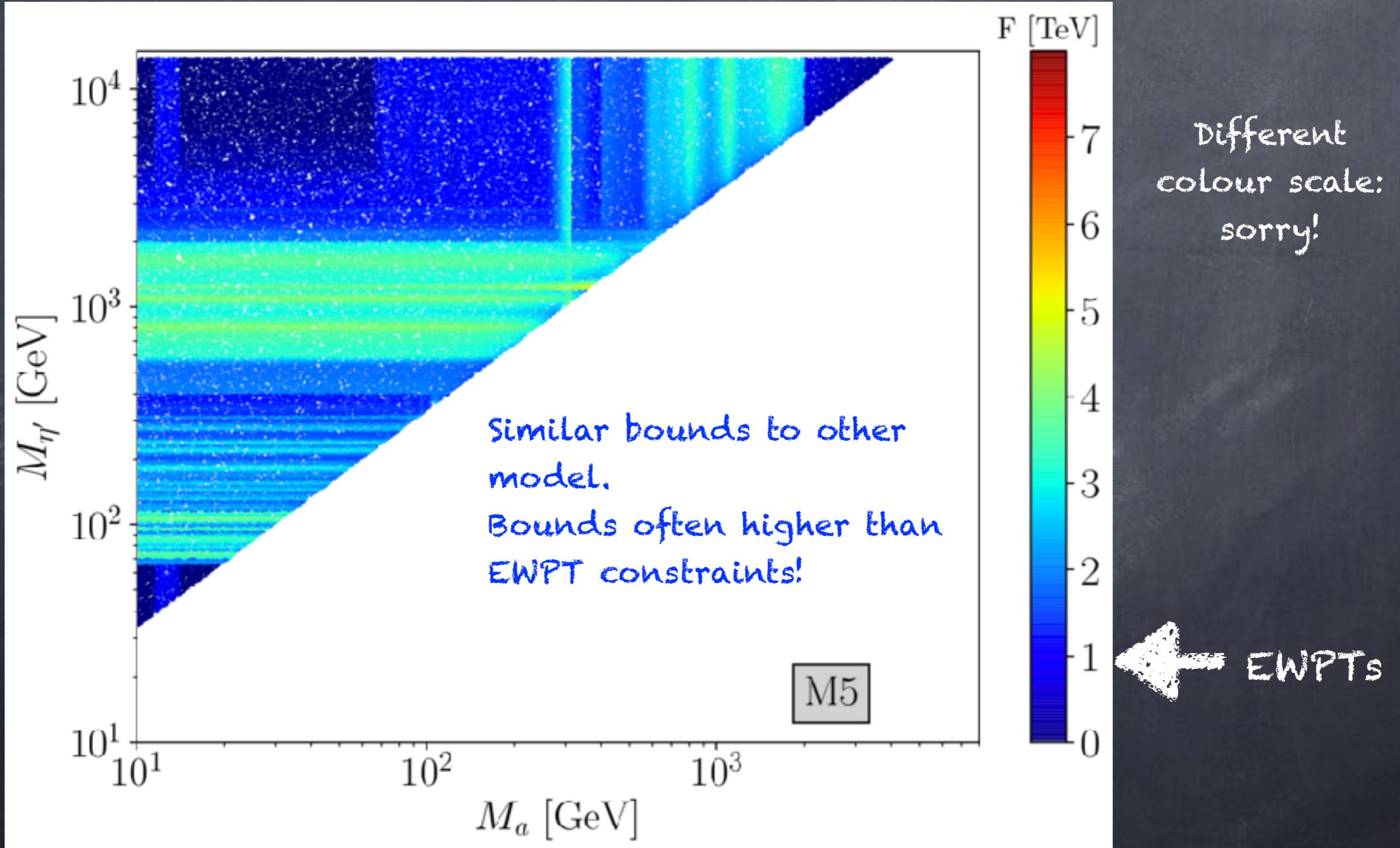
Bounds on f for M6

with H.Serôdio, G.Ferretti, T.Flacke



Bounds on f for M5

with H.Serôdio, G.Ferretti, T.Flacke



Low mass region

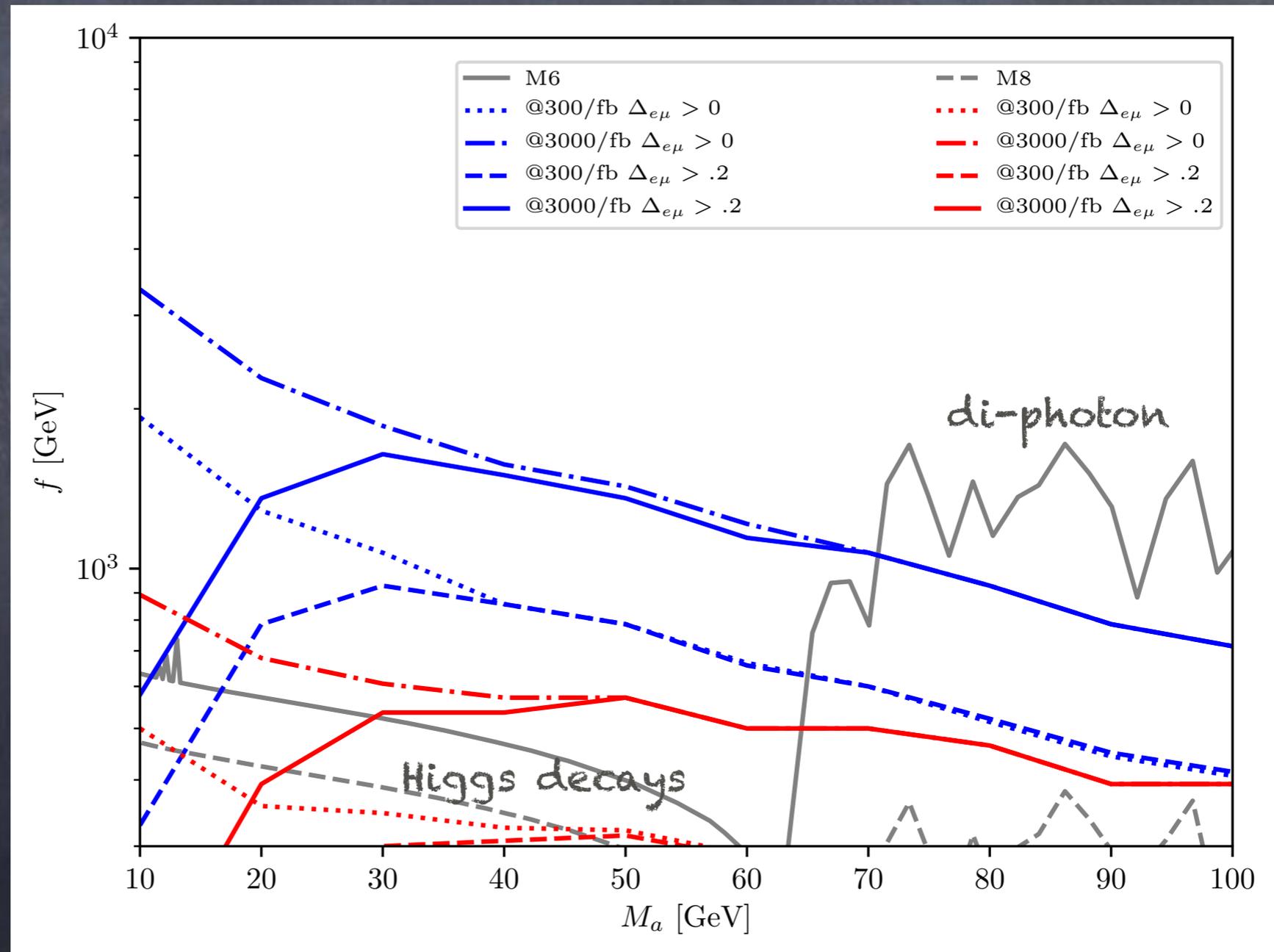
G.C., H.Serôdio, G.Ferretti, T.Flacke
1710.11142

We propose a new search for boosted di-taus:

We analyse leptonic decays: non-isolated e-mu pairs.

Semi-leptonic channel also promising.

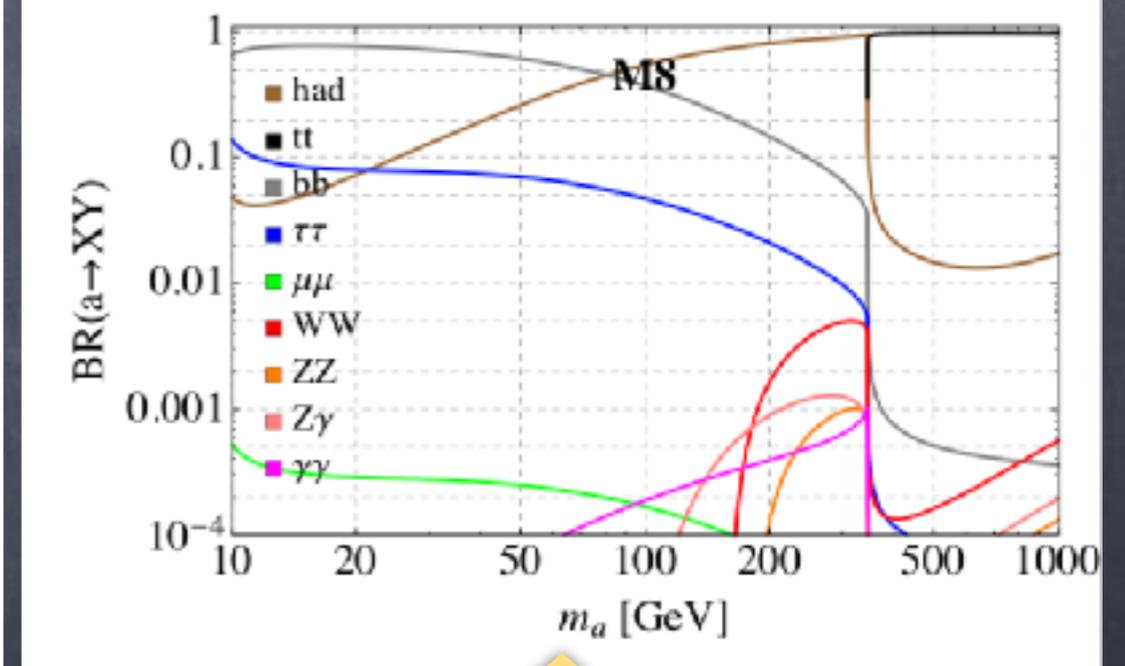
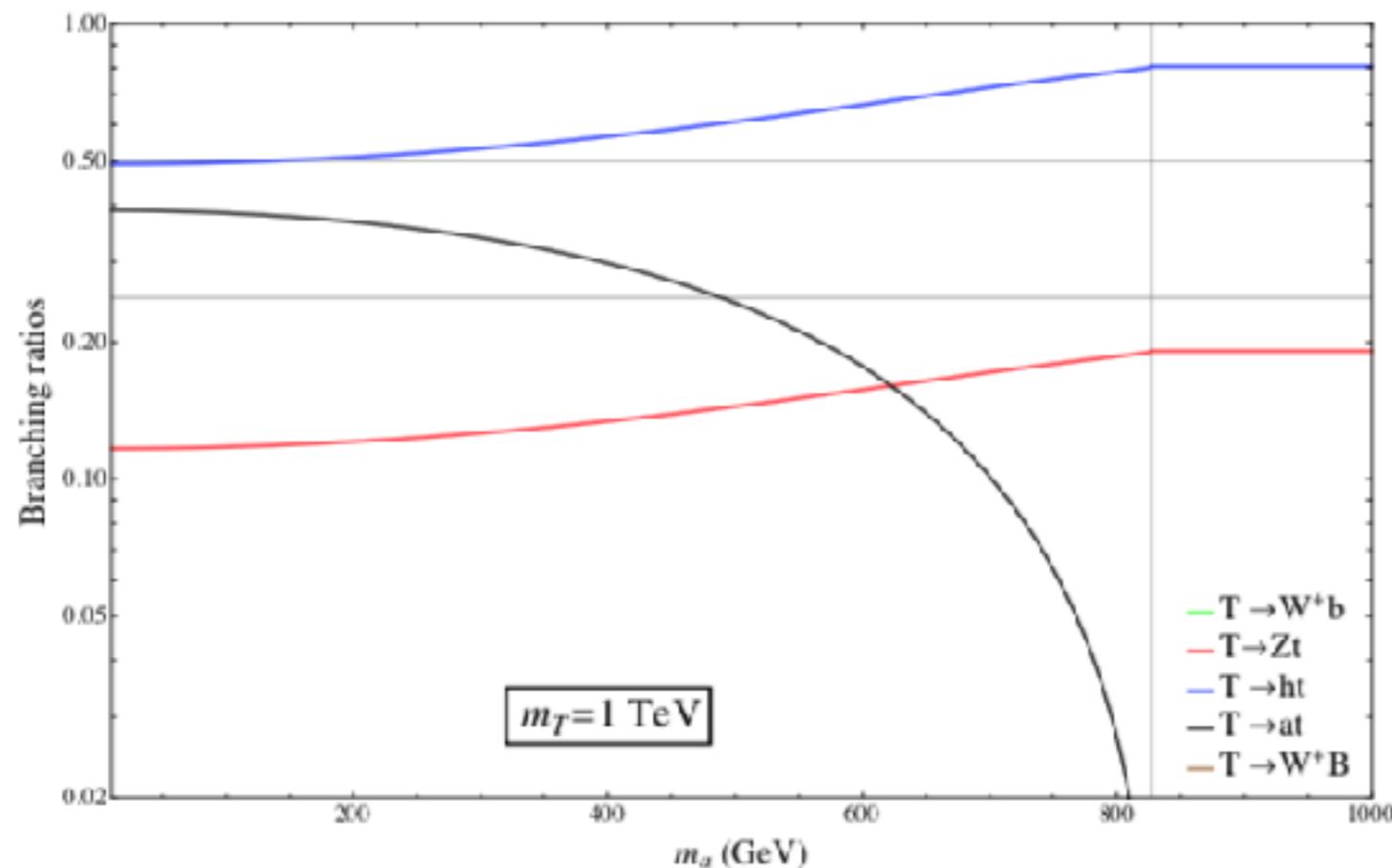
LHCb di-muon search close to BSM Higgs width bound.



Opportunity for new searches:

- Production via top-partner decays!

N.Bizot, GC, T.Flacke
1803.00021



Talk by T.Flacke
yesterday (BSM)

Conclusions and outlook

- UV completions indicate heavy resonances (several TeV): HE-LHC and FCC
- 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

Di-bosons from the singlets

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

- The two singlets mix!

$$-\mathcal{L}_{\text{mass}} = \underbrace{\frac{1}{2}m_{a_x}^2 a_x^2}_{\text{fermion masses}} + \underbrace{\frac{1}{2}m_{a_\psi}^2 a_\psi^2}_{\text{fermion masses}} + \frac{1}{2}M_A^2 \overbrace{(\cos \zeta a_x - \sin \zeta a_\psi)^2}^{\eta'}$$

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

Minimum mass splitting!

- Couplings to tops are inevitable!

$$ic_5 \frac{m_{\text{top}}}{\sqrt{q_\psi^2 f_{a_\psi}^2 + q_x^2 f_{a_x}^2}} \left((n_\psi q_\psi + n_x q_x) \tilde{a} + \left(n_x q_\psi \frac{f_{a_\psi}}{f_{a_x}} - n_\psi q_x \frac{f_{a_x}}{f_{a_\psi}} \right) \tilde{\eta}' \right) \bar{t} \gamma^5 t,$$

Model-dependent results

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

The EFT is the same!

Numerical value of couplings:

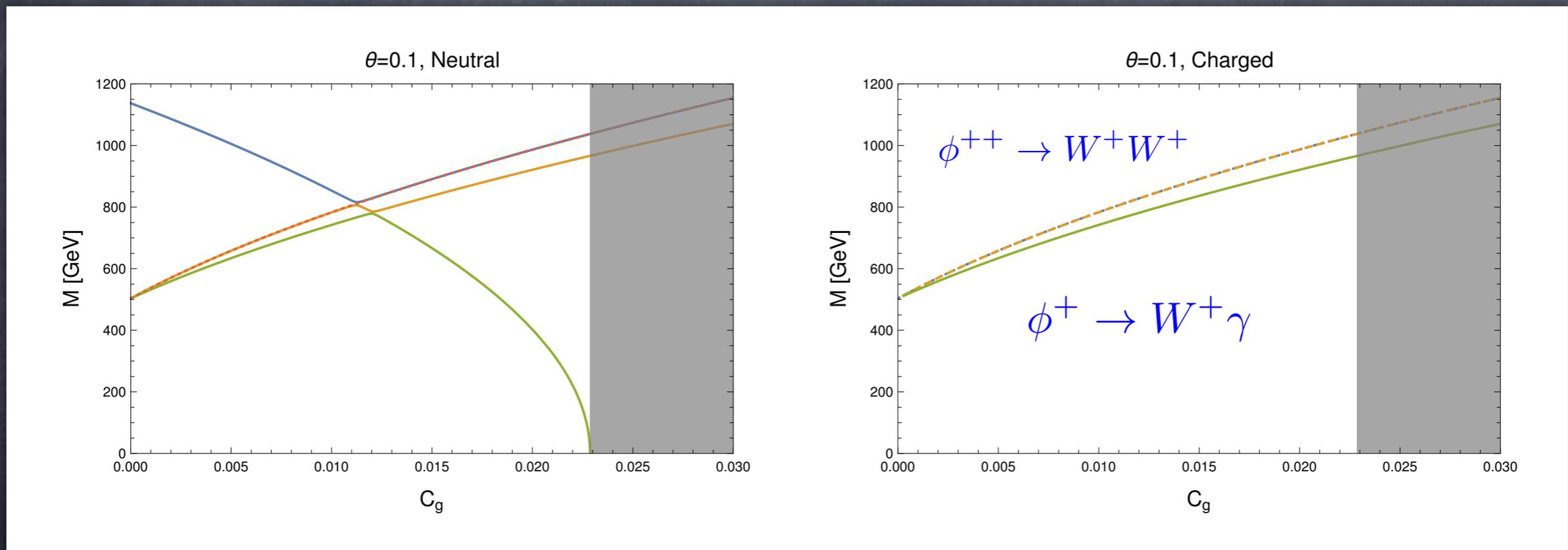
Model		κ_g	$\frac{\kappa_W}{\kappa_g}$	$\frac{\kappa_B}{\kappa_g}$	$\frac{C_t}{\kappa_g} (2, 0)$	$\frac{C_t}{\kappa_g} (0, 2)$	$\tan \zeta$
M8	a	-0.77(-0.39)	-1.2(-2.5)	1.5(0.17)	-1.2(-2.5)	0.40(0.40)	-0.41
	η'	1.9(2.0)	0.20(0.096)	2.9(2.8)	0.20(0.096)	0.40(0.40)	
	π_8	7.1	0	1.3	0	0.40	
M9	a	-4.3(-2.7)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

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

EW pNGBs

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

Spectrum of an $SU(5)/SO(5)$ model: $f \sim 2.4$ 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.

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)

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

$$\frac{\text{BR}(\Phi \rightarrow g\gamma)}{\text{BR}(\Phi \rightarrow gg)} = 4.8\%$$

$$\frac{\text{BR}(\Phi \rightarrow gZ)}{\text{BR}(\Phi \rightarrow gg)} = 1.4\%$$

$$T = Q\chi\chi$$

$$\frac{\text{BR}(\Phi \rightarrow g\gamma)}{\text{BR}(\Phi \rightarrow gg)} = 19\%$$

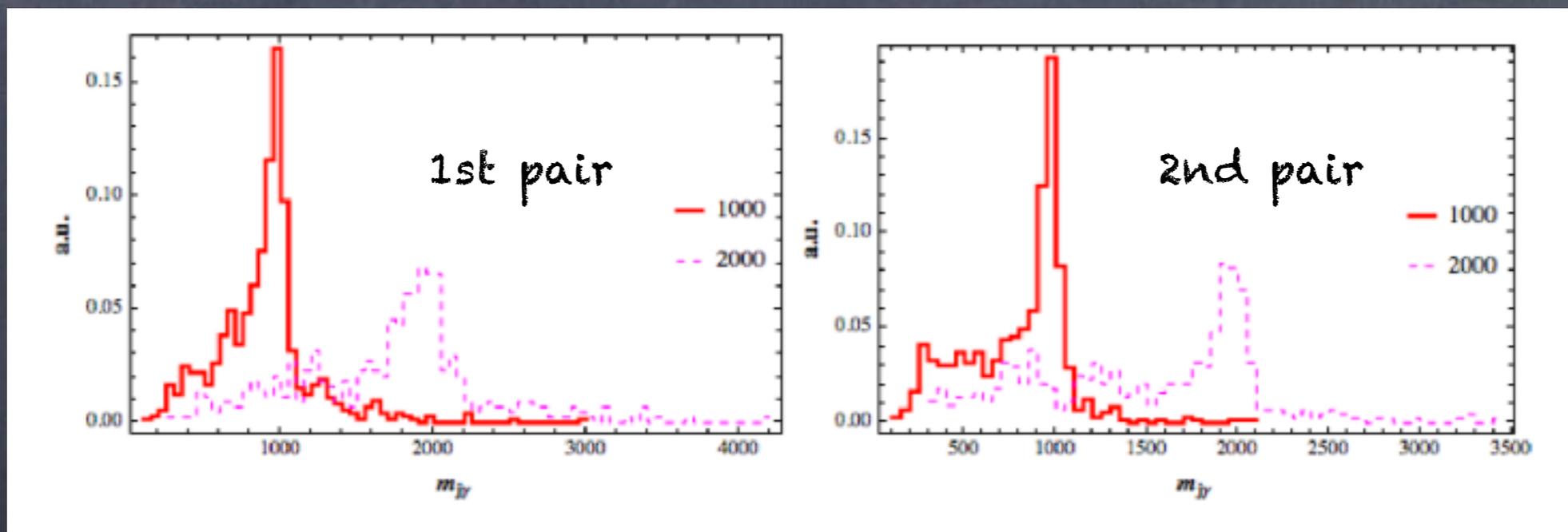
$$\frac{\text{BR}(\Phi \rightarrow gZ)}{\text{BR}(\Phi \rightarrow gg)} = 5.8\%$$

$$T = QQ\chi$$

Ubiquitous colour octet

Work in progress with A.Iyer and A.Deandrea

Pairs reconstructed by using angular separation.
Fair reconstruction efficiency.



$H_T > 500 \text{ GeV}$

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.