Signatures of UV-complete composite Higgs models

(mainly direct ones)

G.Cacciapaglia

2018/01/16 @ CERN
2nd FCC Workshop

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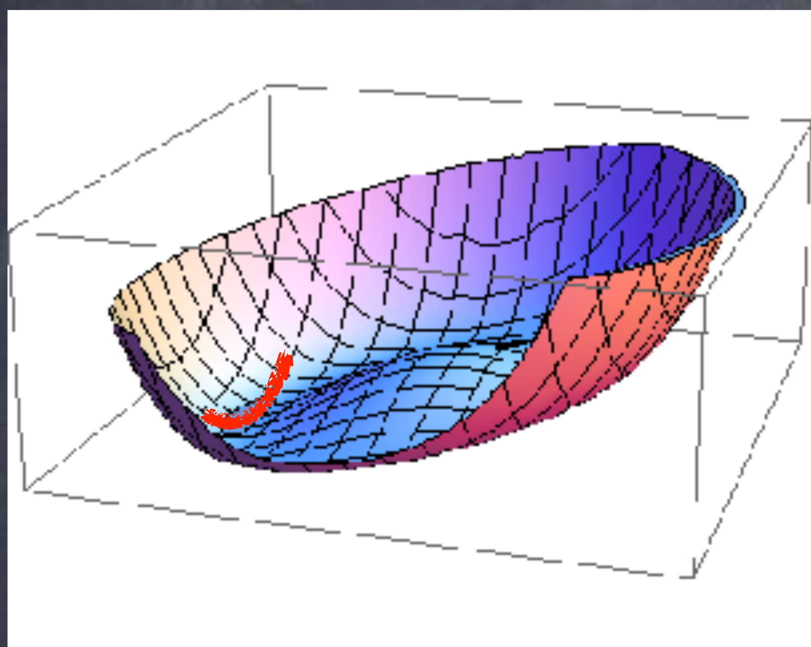
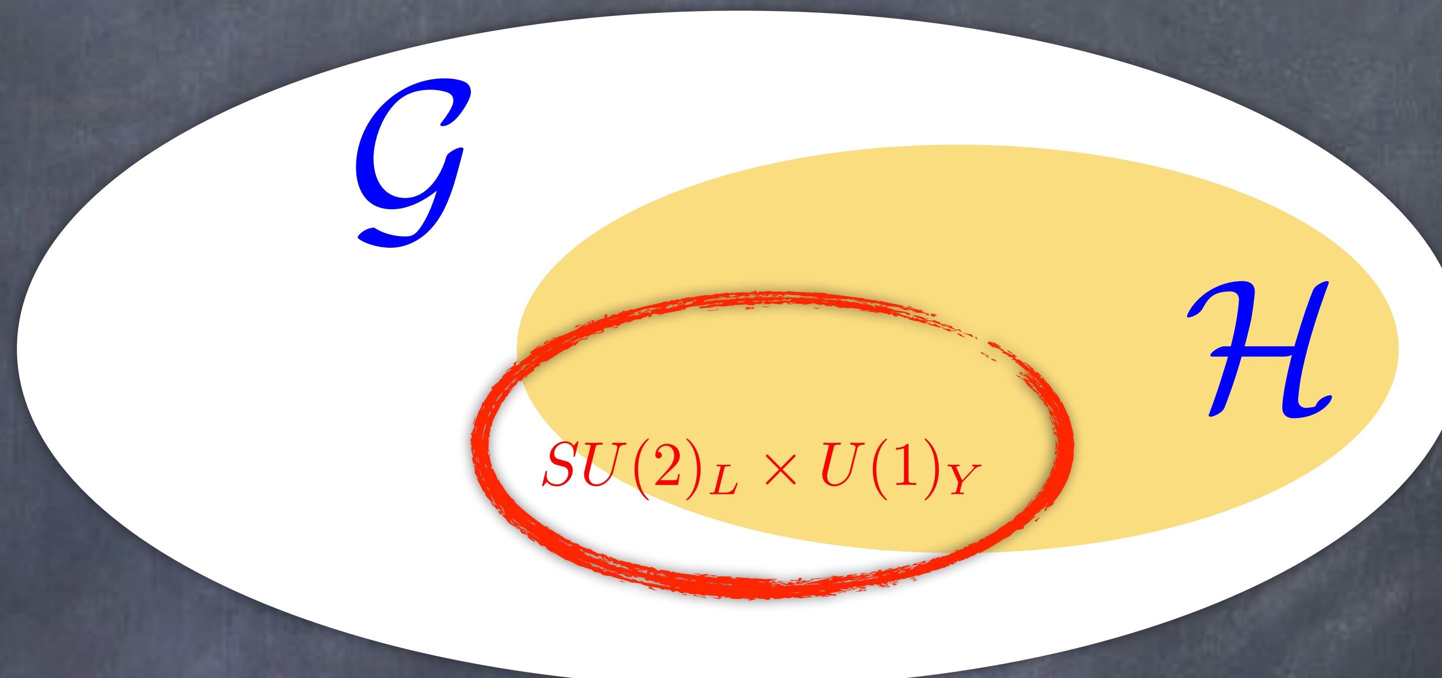
Compositeness, and the Higgs boson



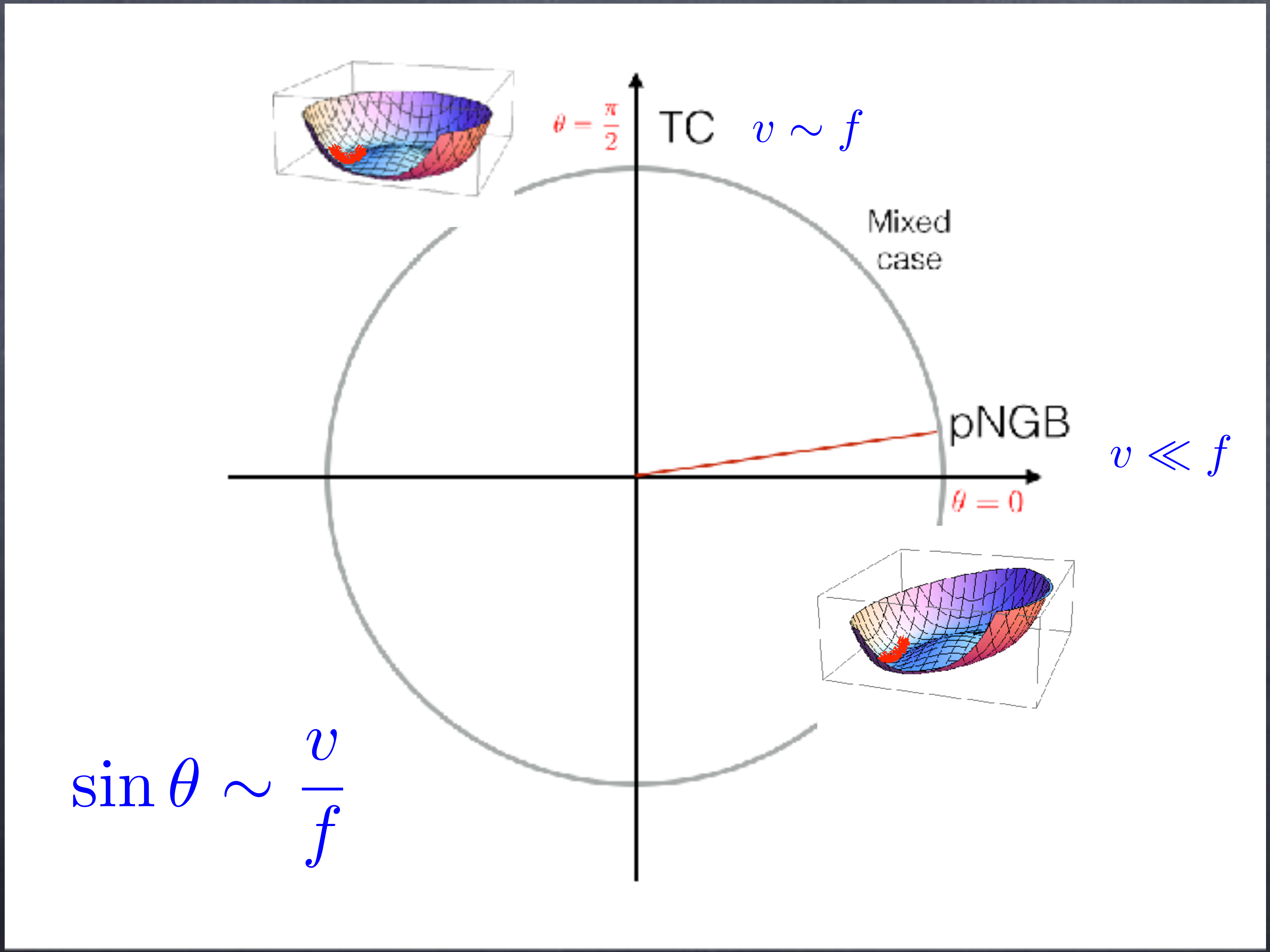


$\mathcal{G} \rightarrow \mathcal{H}$

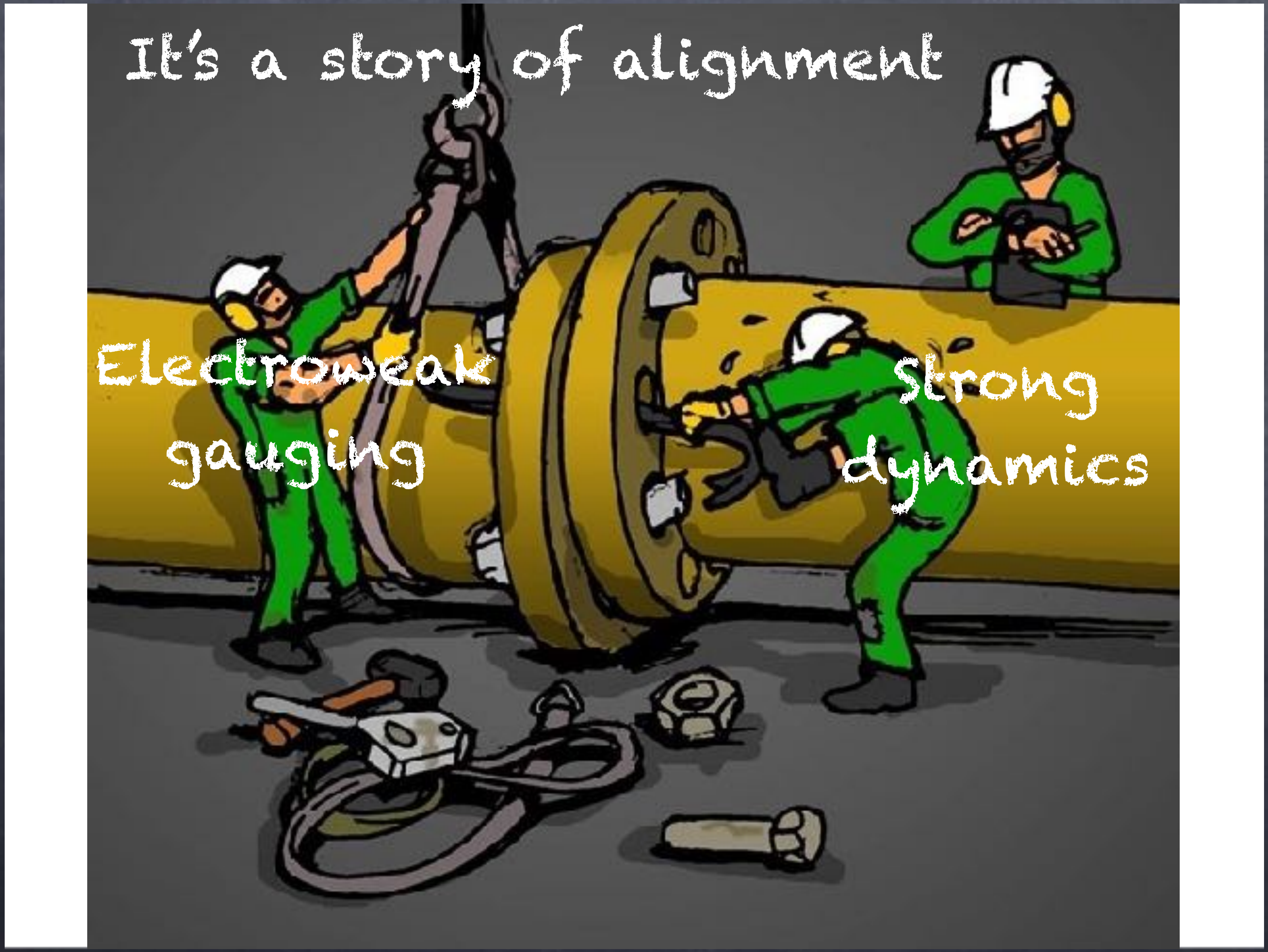
QCD template:

- 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



Compositeness, and the Higgs boson



The hot potato: flavour!

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

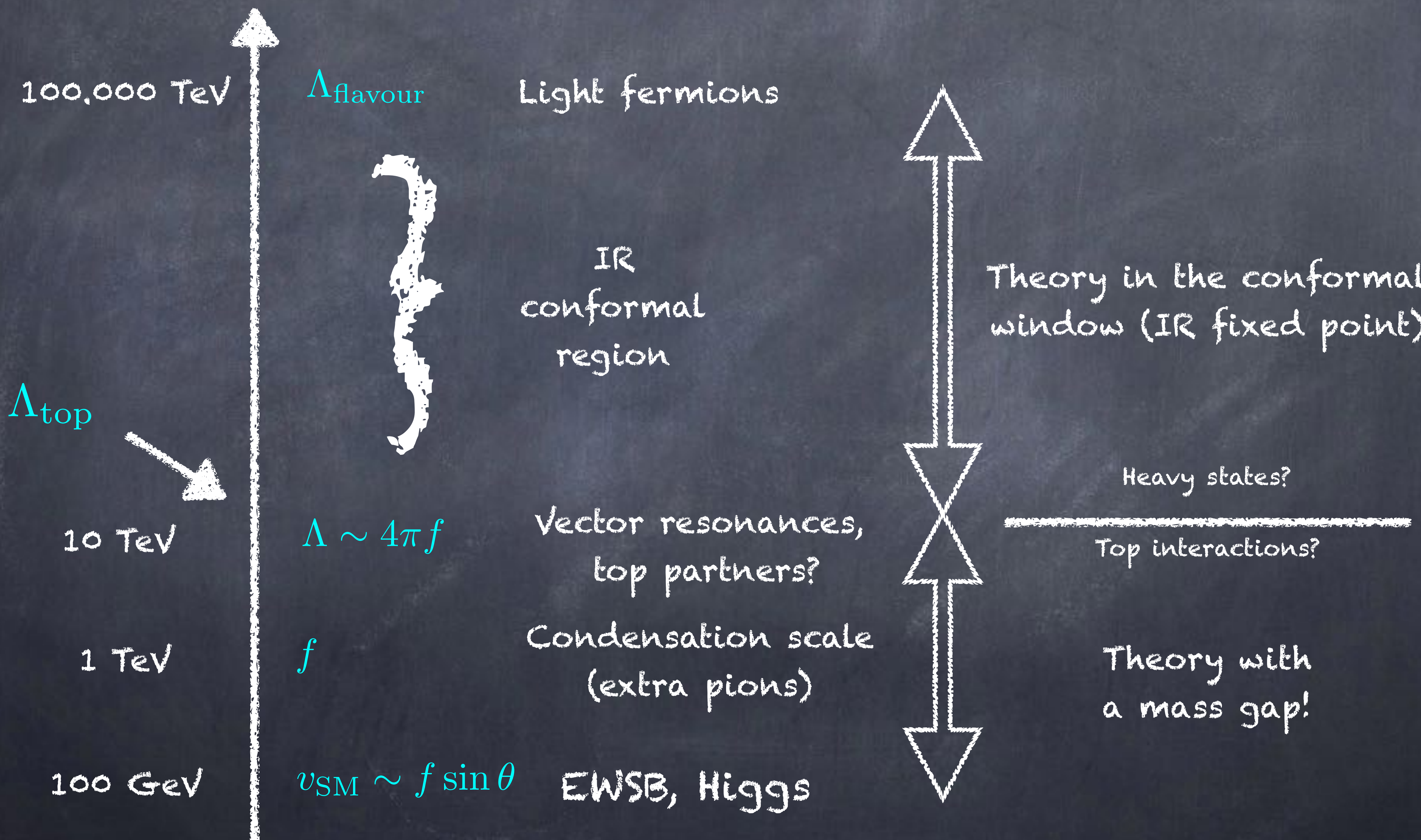
Multi-scale model

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

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 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 =	$SU(N_\psi)^2$	$\langle \bar{\psi}^i \psi^j \rangle$	$SU(N_\psi)^2 \to SU(N_\psi)$

A minimal case

T.Ryttov, F.Sannino 0809.0713
Galloway, Evans, Luty, Tacchi 1001.1361

	$SU(2)_{TC}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1\\ \psi^2\end{pmatrix}$	$\square$	$\square$	**2**	0
ψ^3	$\square$		**1**	-1/2
ψ^4	$\square$		**1**	1/2

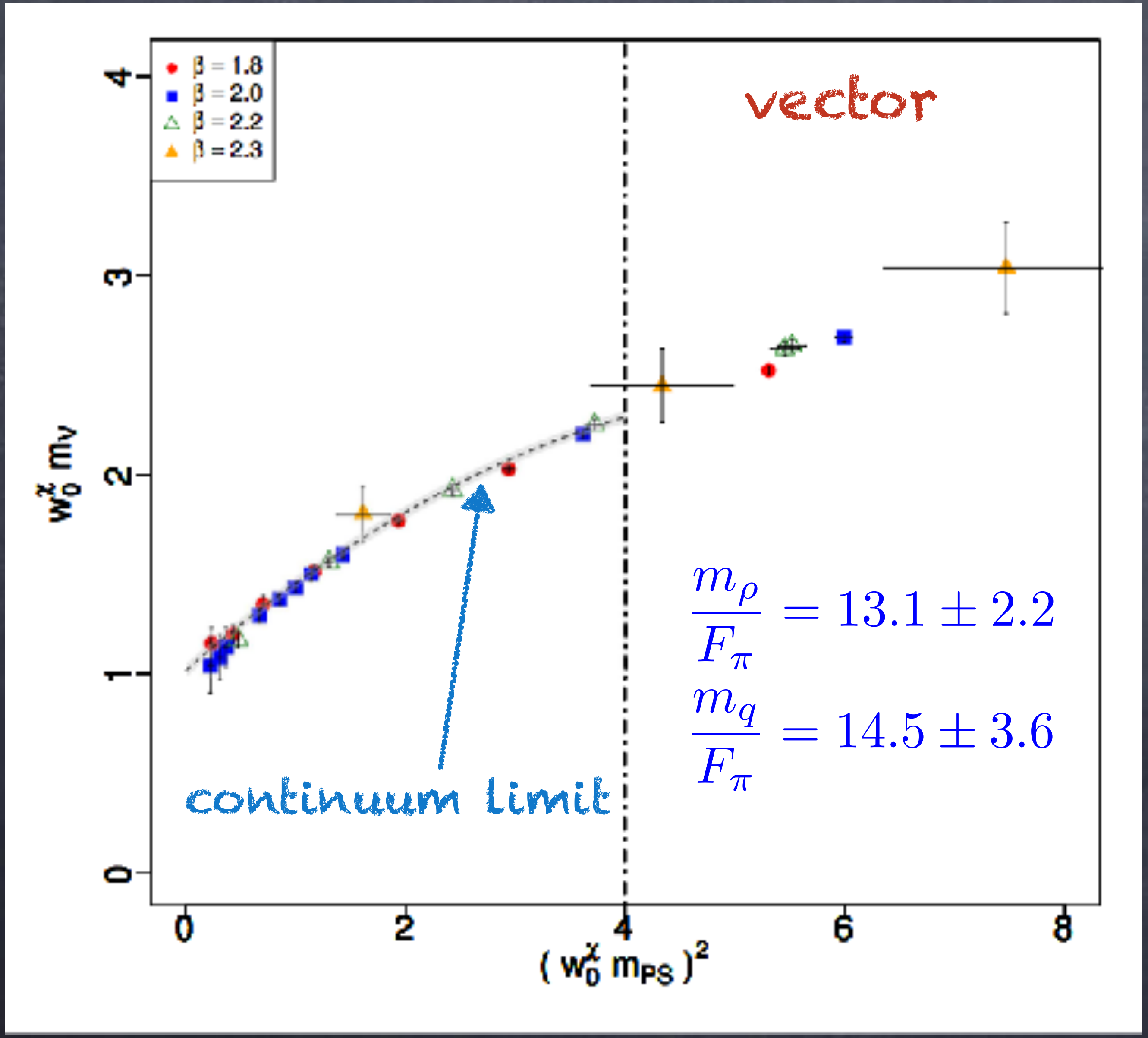
The EW symmetry
is embedded in the global
flavour symmetry
SU(4) !

Generators of SU(4) corresponding to $SU(2)_L \times SU(2)_R$

$$S^{1,2,3} = \frac{1}{2}\begin{pmatrix}\sigma_i & 0\\ 0 & 0\end{pmatrix}, \qquad S^{4,5,6} = \frac{1}{2}\begin{pmatrix}0 & 0\\ 0 & -\sigma_i^T\end{pmatrix},$$

The vector resonance

Lattice results:



Arthur, Drach, et al. 1602.06559

$\sin\theta \leq 0.2$

$$m_a = \frac{3.6 \pm 0.9 \text{ TeV}}{\sin\theta} \gtrsim 18 \text{ TeV}$$

$$m_\rho = \frac{3.2 \pm 0.5 \text{ TeV}}{\sin\theta} \gtrsim 16 \text{ TeV}$$

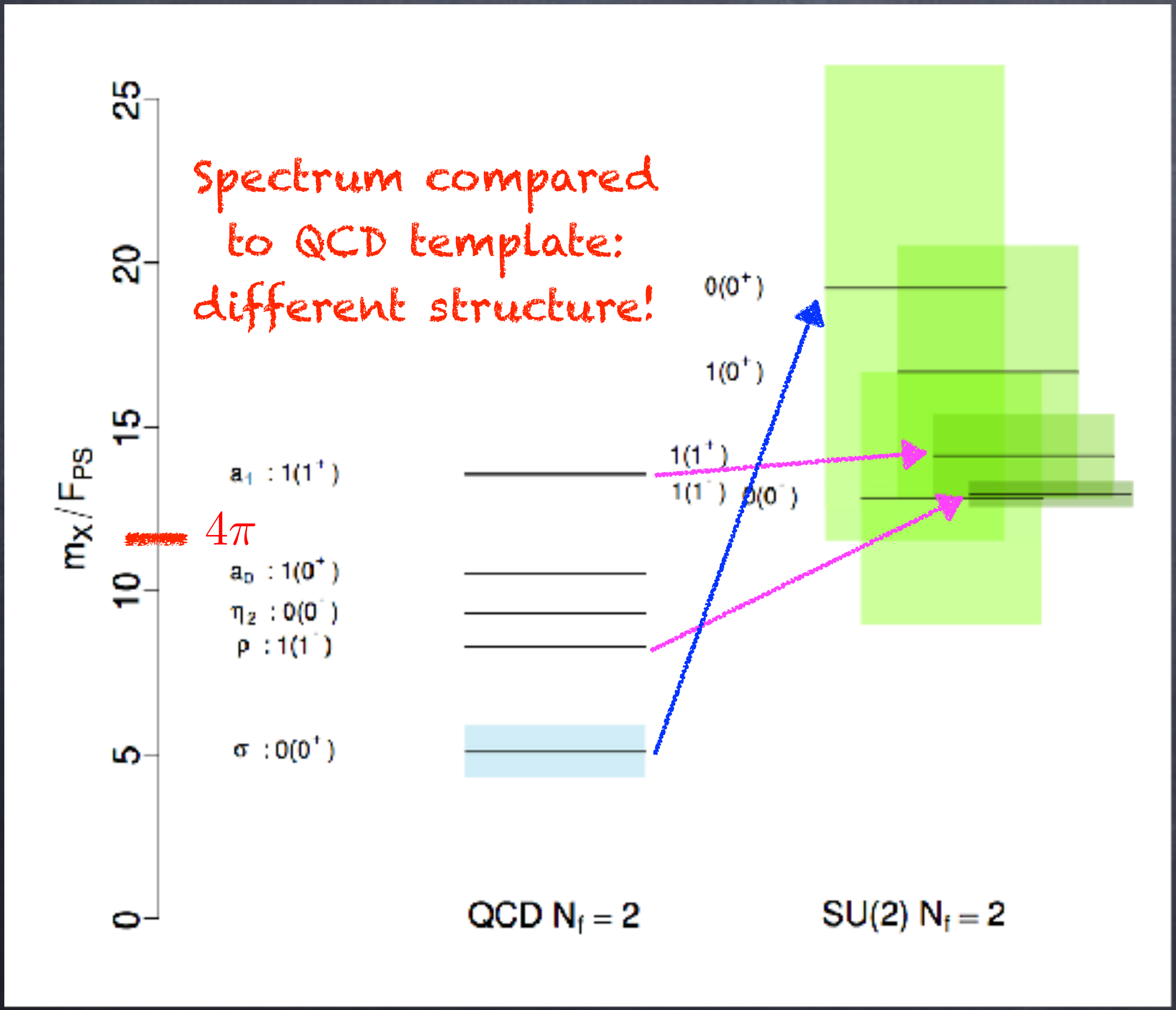
$$m_\sigma \sim ???$$

$$m_\eta \sim \frac{m_h}{\sin\theta} \gtrsim 600\ GeV$$

$$m_h = 125\ GeV$$

The spectrum

Lattice results:



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$$m_h = 125 \; GeV$$

The vector resonances

(@ FCC-hh)

D.Buarque Franzosi, G.C., H.Cai,
A.Deandrea, M.Frandsen
1605.01363

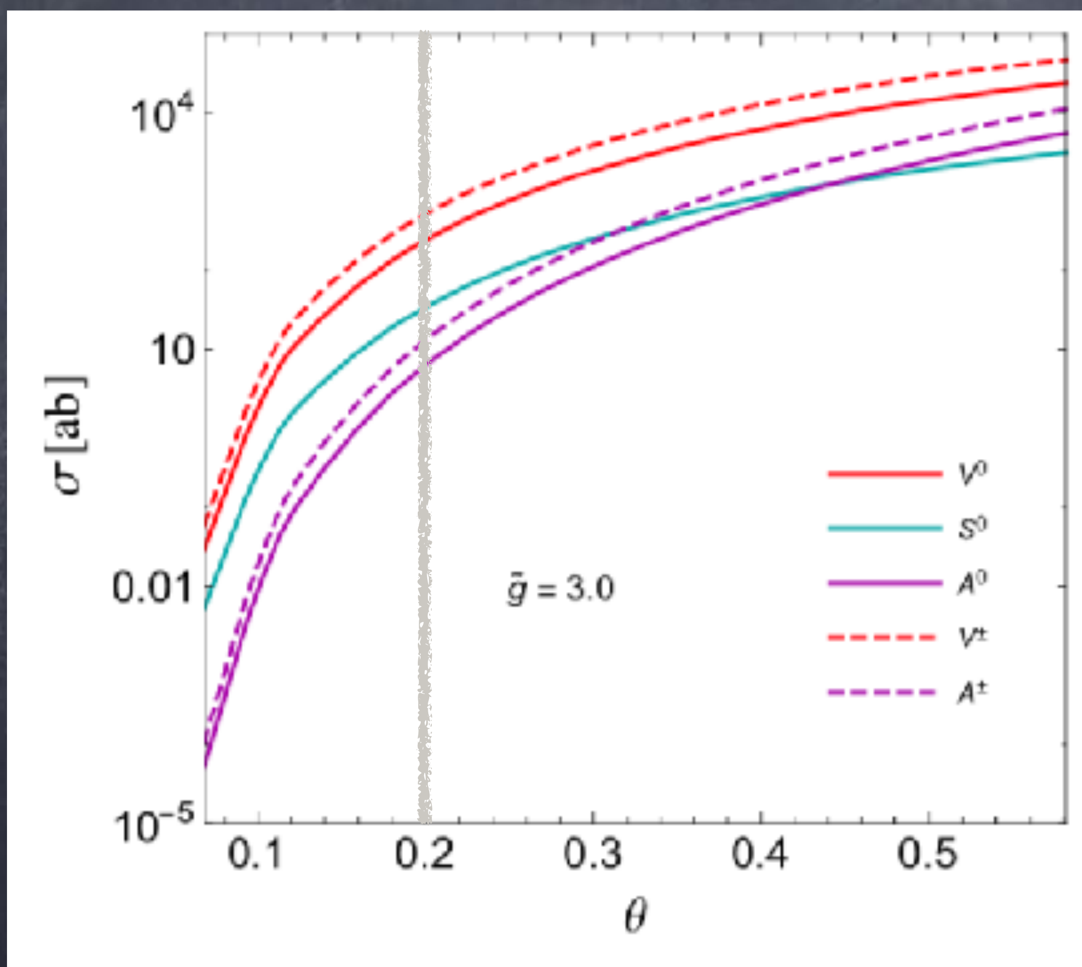
		$SU(2)_V$	$SU(2)_L \times SU(2)_R$	TC	CH
$\mathcal{V}$	$v_\mu^{0,\pm}$	3	(3,1)⊕(1,3)	$\vec{\rho}_\mu$	$\vec{\rho}_\mu$
	$s_\mu^{0,\pm}$	3			$\vec{a}_\mu$
	$\tilde{s}_\mu^{0,\pm}$	3	(2,2)		
	$\tilde{v}_\mu^{0}$	1			
$\mathcal{A}$	$a_\mu^{0,\pm}$	3	(2,2)	$\vec{a}_\mu$	
	x_μ^{0}	1			
	$\tilde{x}_\mu^{0}$	1	(1,1)		

- The model contains many spin-1 resonances!
- Some of them (~) only couple to the singlet pNGB! Pair-production!
- Others mix, and can be singly-produced.

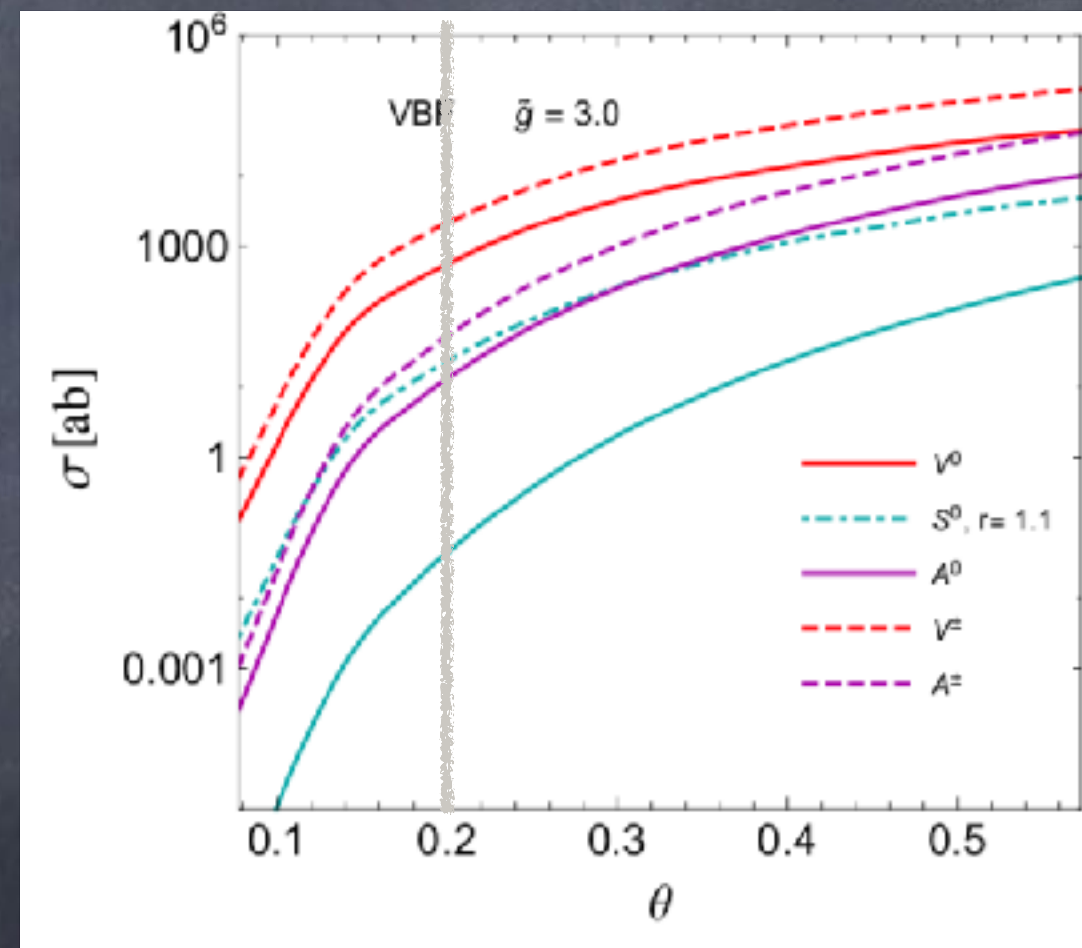
The vector resonances

(@ FCC-hh)

Drell-Yan



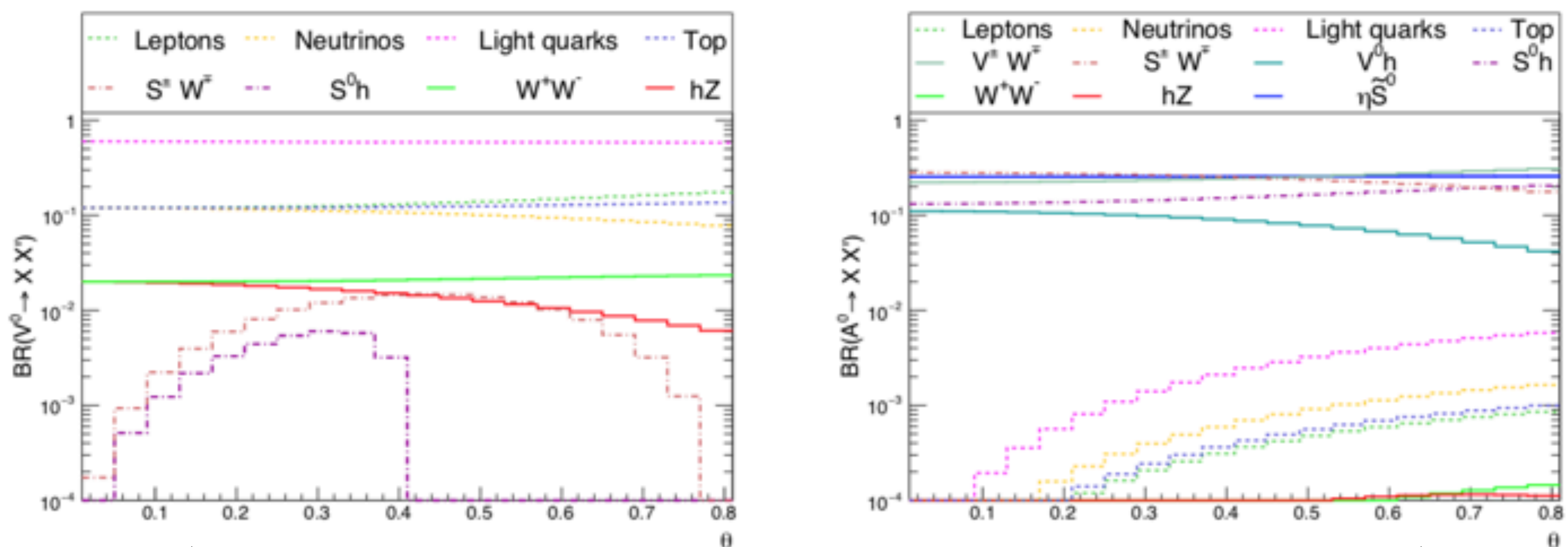
VBF



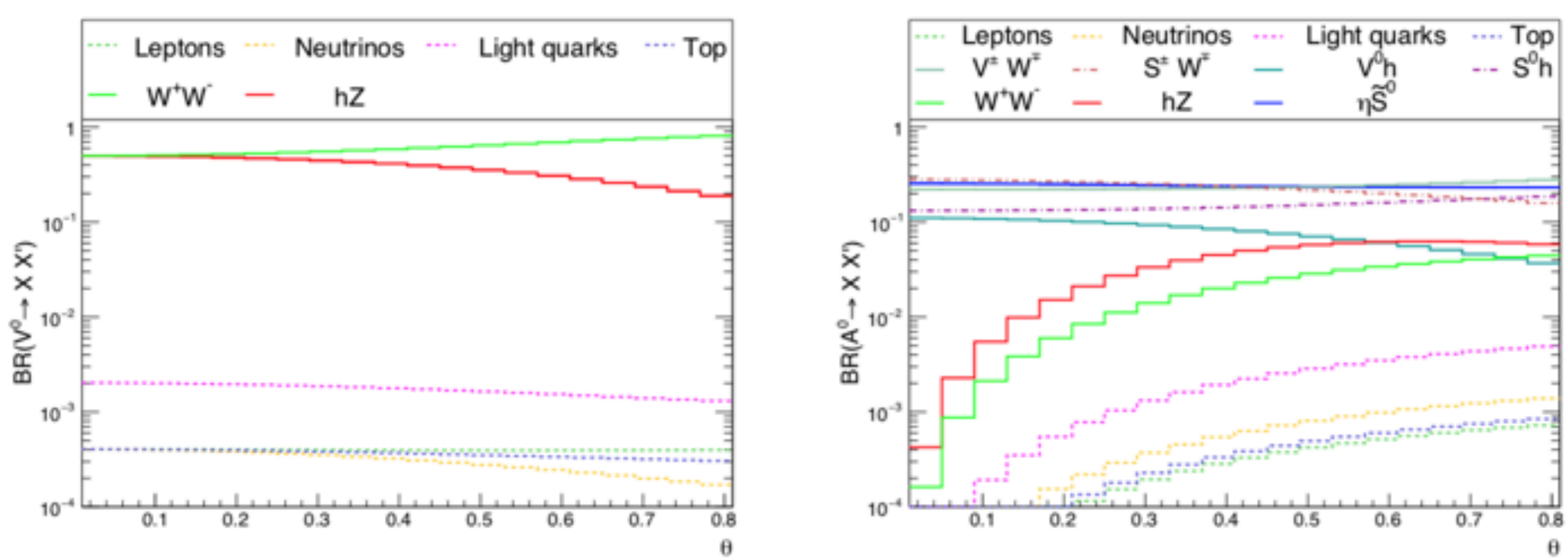
$$\sqrt{s} = 100 \text{ TeV}$$

The vector resonances

(@ FCC-hh)



The BRs depend on the mixing!

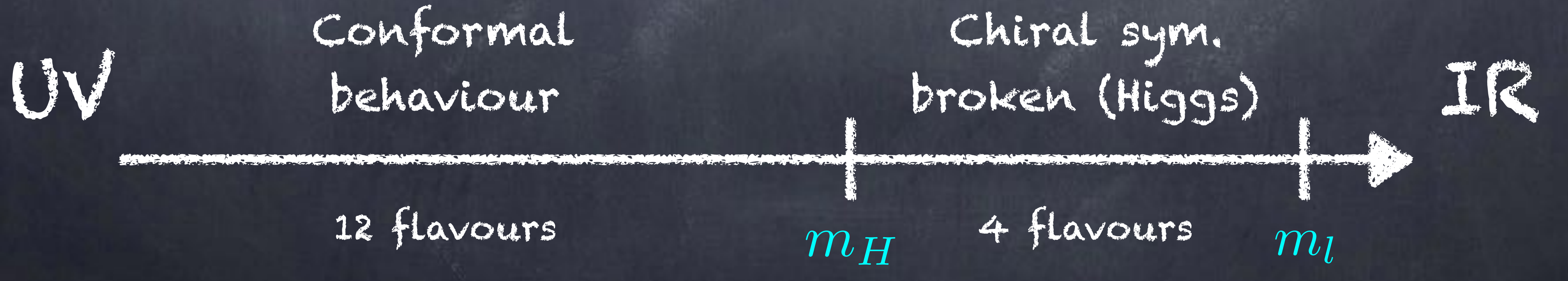


Entering the conformal window

A.Hasenfratz, C.Rebbi, O.Witzel
1609.01401, 1611.07427

Study QCD (i.e. SU(3) gauge theory) with 12 flavours.

4 flavours are light, with mass m_l
8 flavours are heavy, with mass m_H



Entering the conformal window

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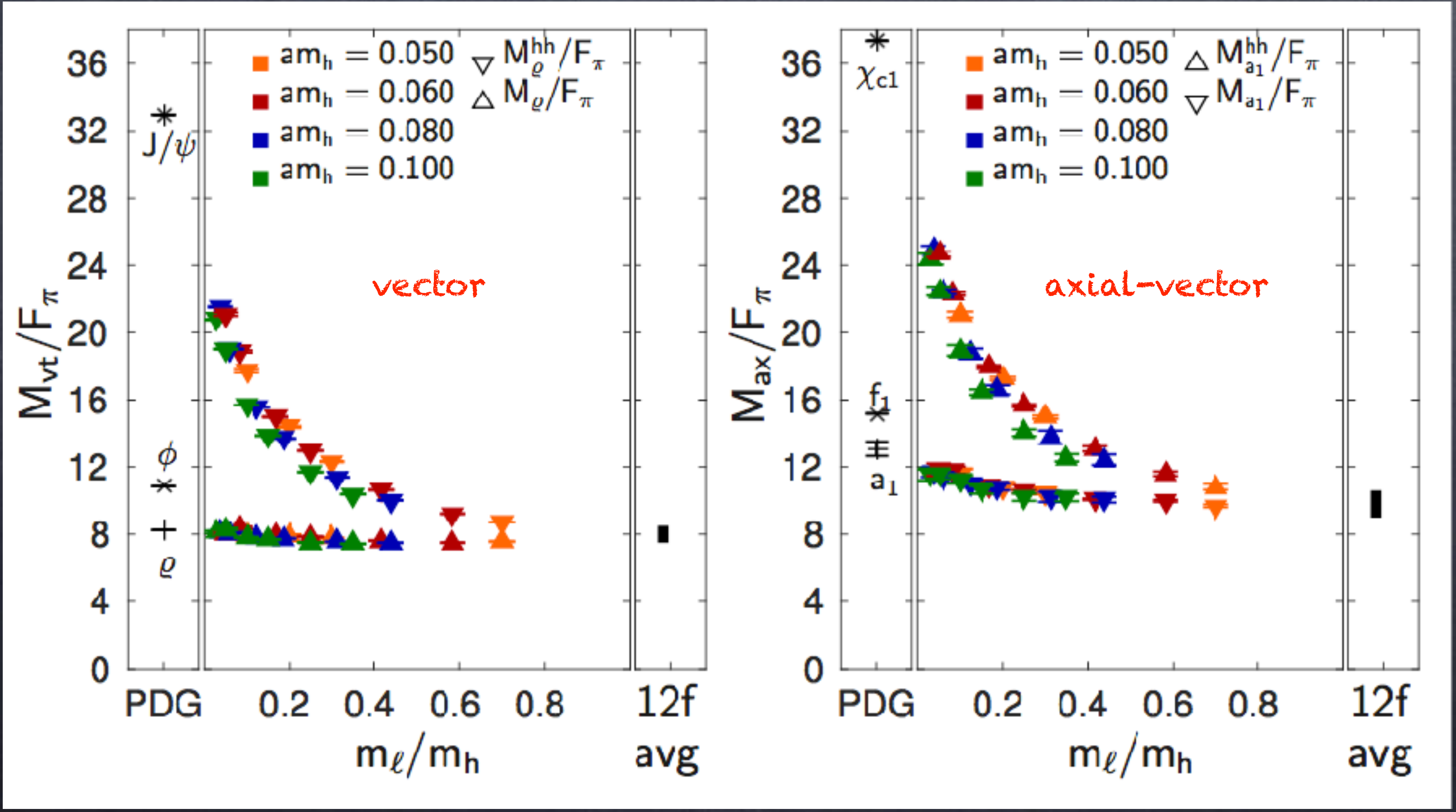

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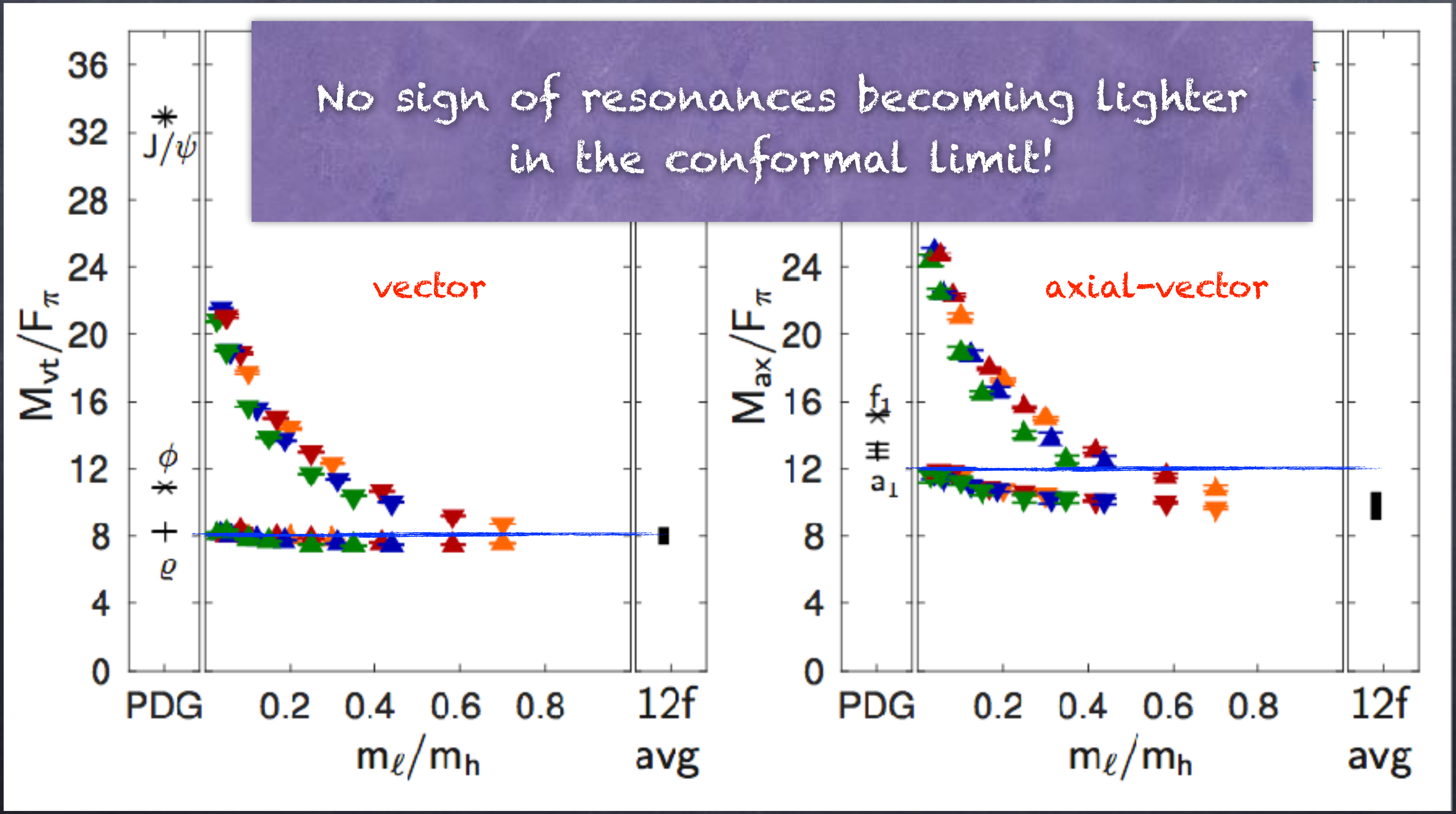


Take-home message

- The spin-1 resonances expected to be heavy and difficult to see!
- The (minimal) cosets contain more scalars than the Higgs: <u>opportunity for light states!</u>
- Challenge: masses and mixings are very model-dependent!

Typical top-partner scenario:

G.Ferretti, D.Karateev
1312.5330, 1604.06467

	rep R	rep R'
$\mathcal{G}_{\rm TC}$:	Q	χ
SM :	EW	colour + hypercharge

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

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

↓

pNGB Higgs
DM?

Exception: 1506:00623

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

coloured pNGBs
di-boson

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

light top partners

Predicting di-boson resonances

More precisely, the global symmetries are:

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

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!

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

Decays and production
only via WZW anomaly.

Predicting di-boson resonances

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

- The two singlets mix!

$$-\mathcal{L}_{\text{mass}} = \frac{1}{2}m^2_{a_\chi}a^2_\chi + \frac{1}{2}m^2_{a_\psi}a^2_\psi + \frac{1}{2}M^2_A(\underbrace{\cos\zeta a_\chi - \sin\zeta a_\psi}_{\eta'})^2$$

fermion masses — anomaly

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

Minimum mass splitting!

- Couplings to tops are inevitable!

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

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) × 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) × 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) × 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) × 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) × 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) × 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	/	
$SU(N_{HC})$	$4 \times (\mathbf{A}_2, \mathbf{A}_2)$	$3 \times (\mathbf{F}, \mathbf{F})$	$N_{HC} = 5$	4	2/3	/	

Model-dependent results

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

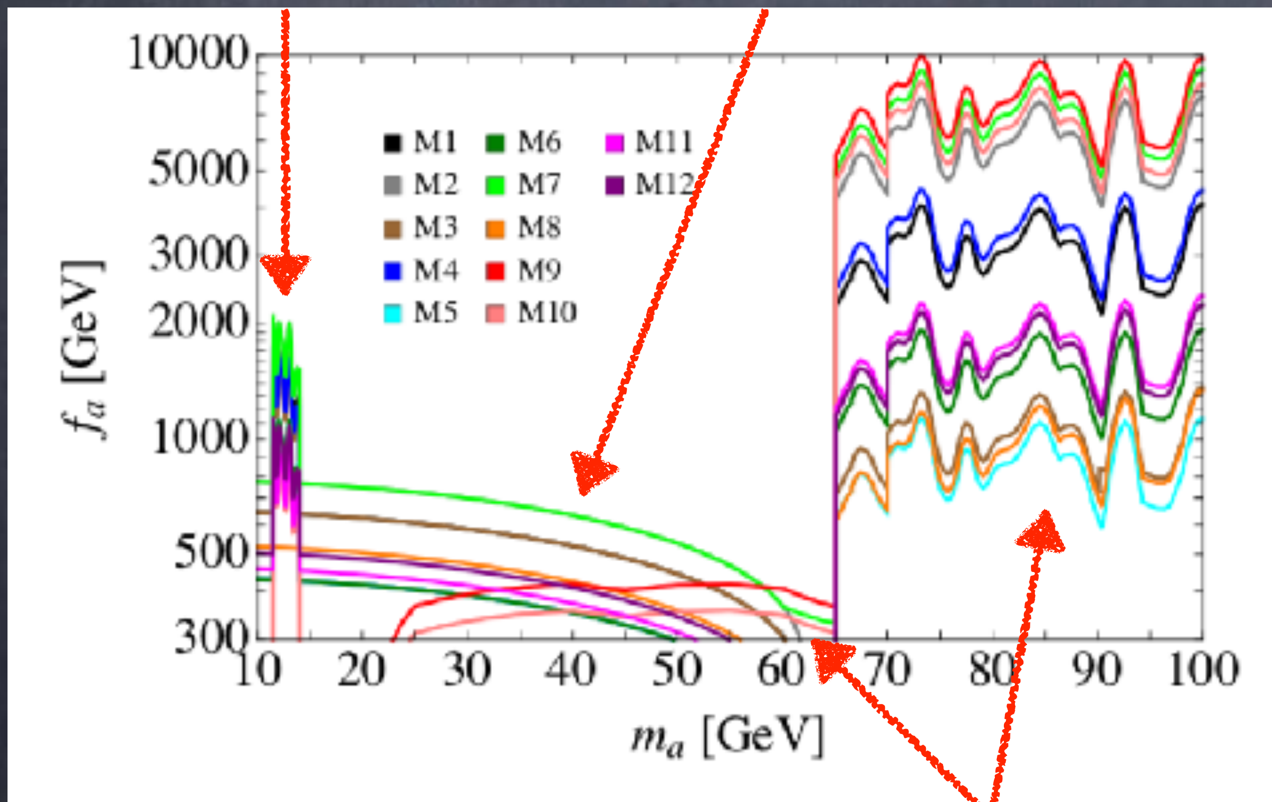
Assuming $f_a = f_\psi = f_\chi$

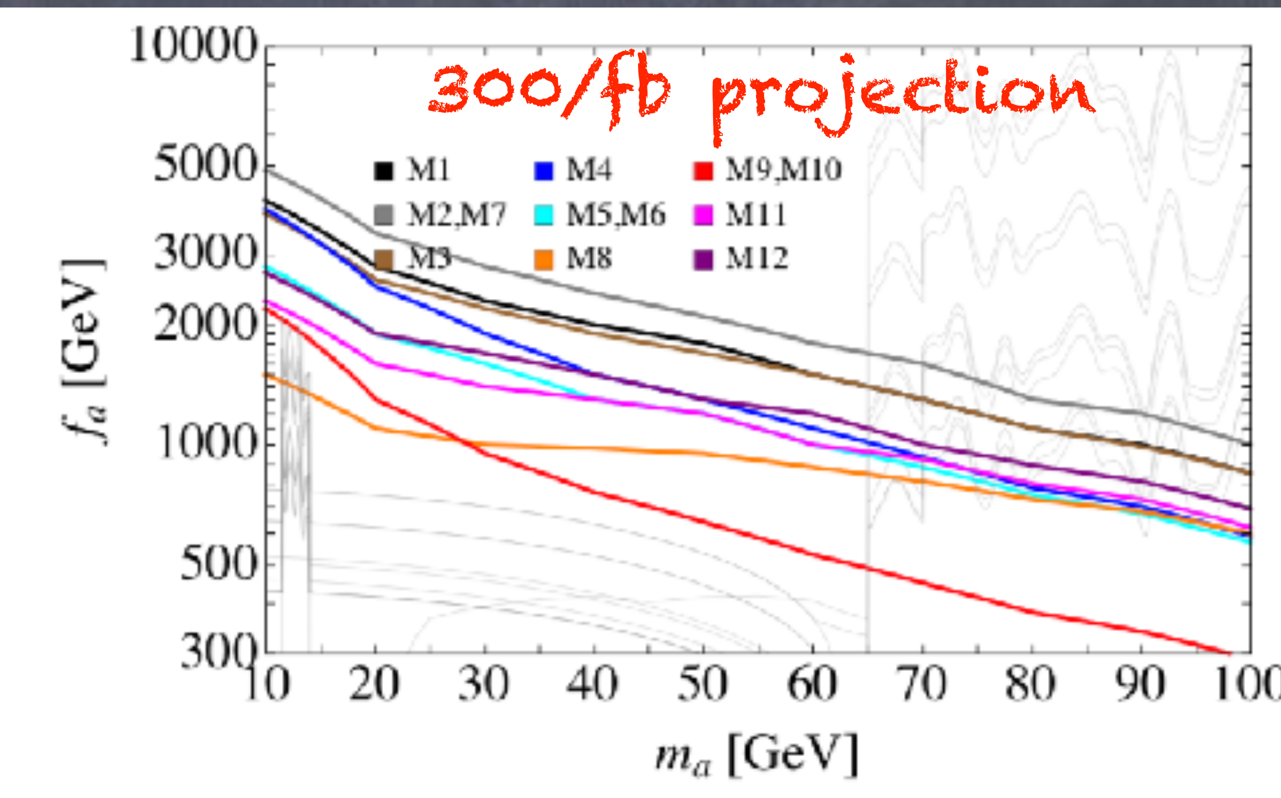
Light mass range @ LHC

Higgs width

di-muon

Boostes di-tau





di-photon

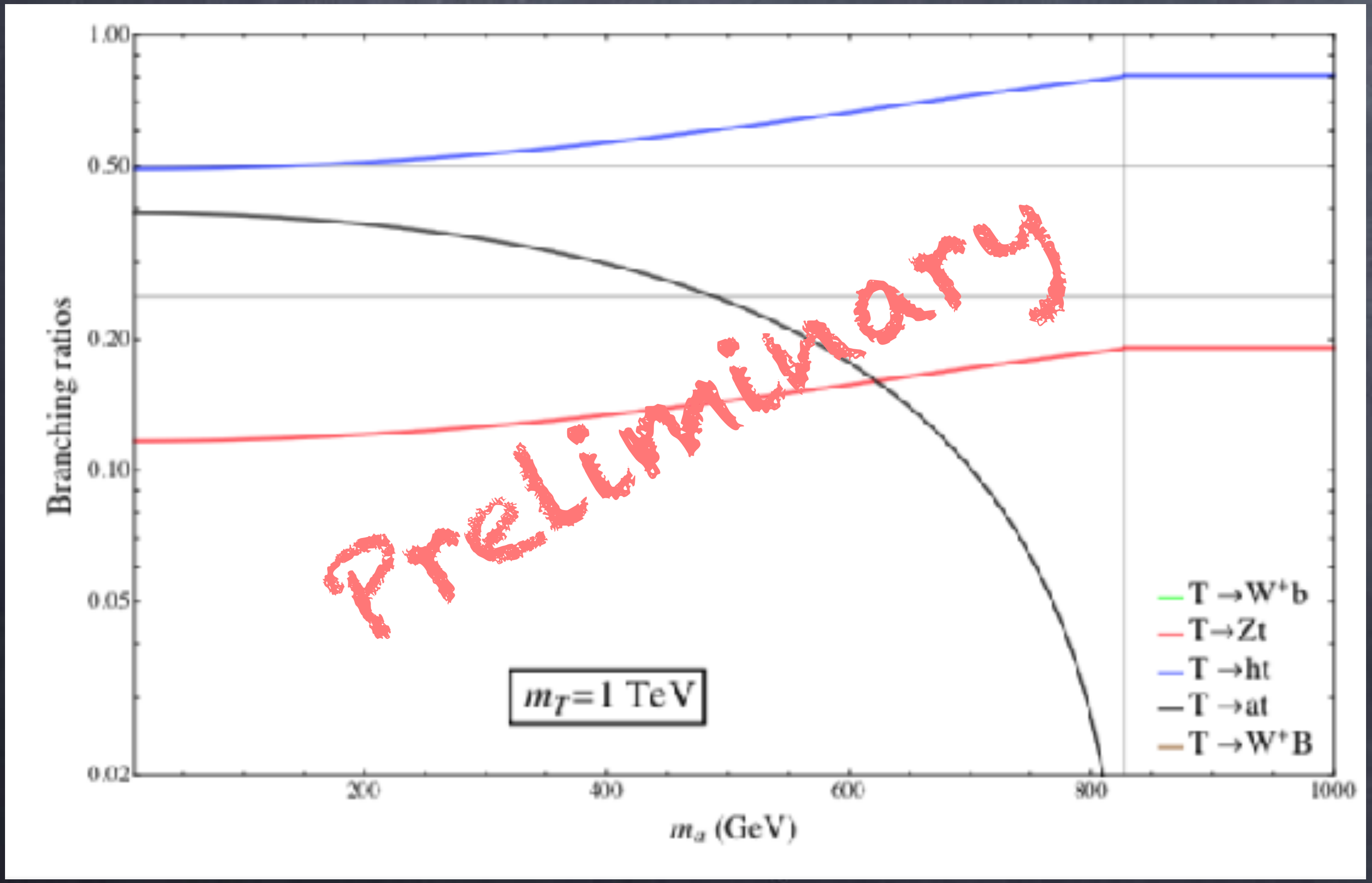
G.C., Ferretti, Flacke, Serodio 1710.11142

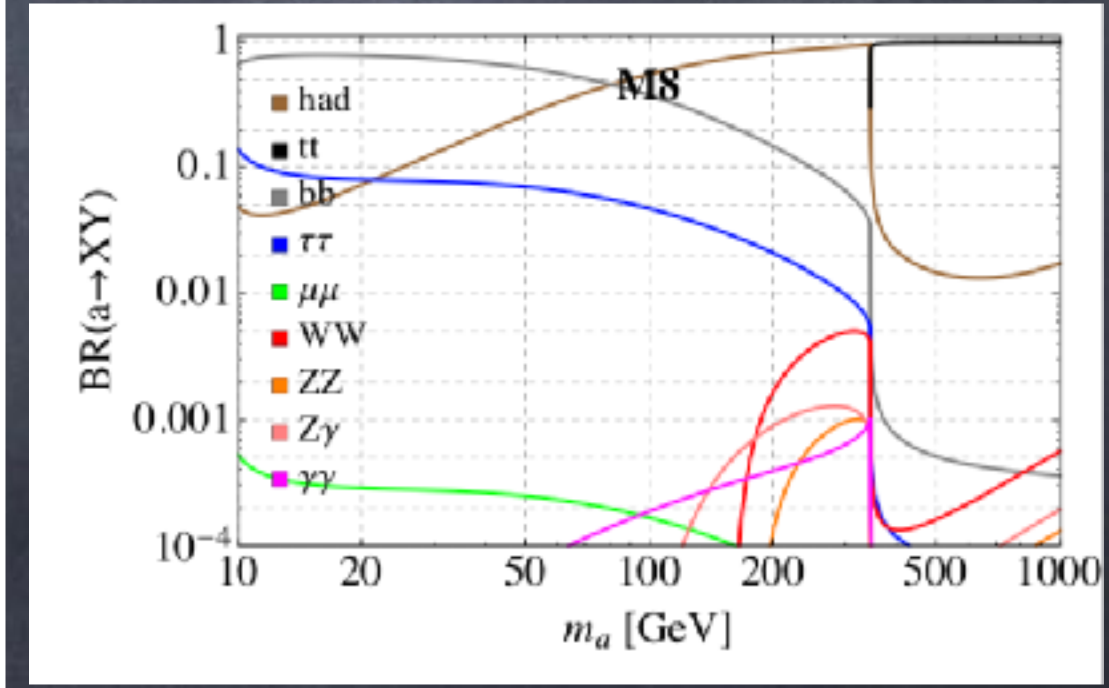
F.Sala this afternoon!

FCC-hh opportunity:

- Production via top-partner decays!

N.Bizot, GC, T.Flacke
in preparation





Conclusions and outlook

- UV completions indicate heavy resonances (>10 TeV): FCC-hh!
- Non-minimal coset is the new minimal! Additional "light" scalars to be studied!
- Example: U(1) pNGB sensitive to details of the UV model -> unique opportunity!
- High precision in Higgs coupling determination will be crucial!

Bonus tracks

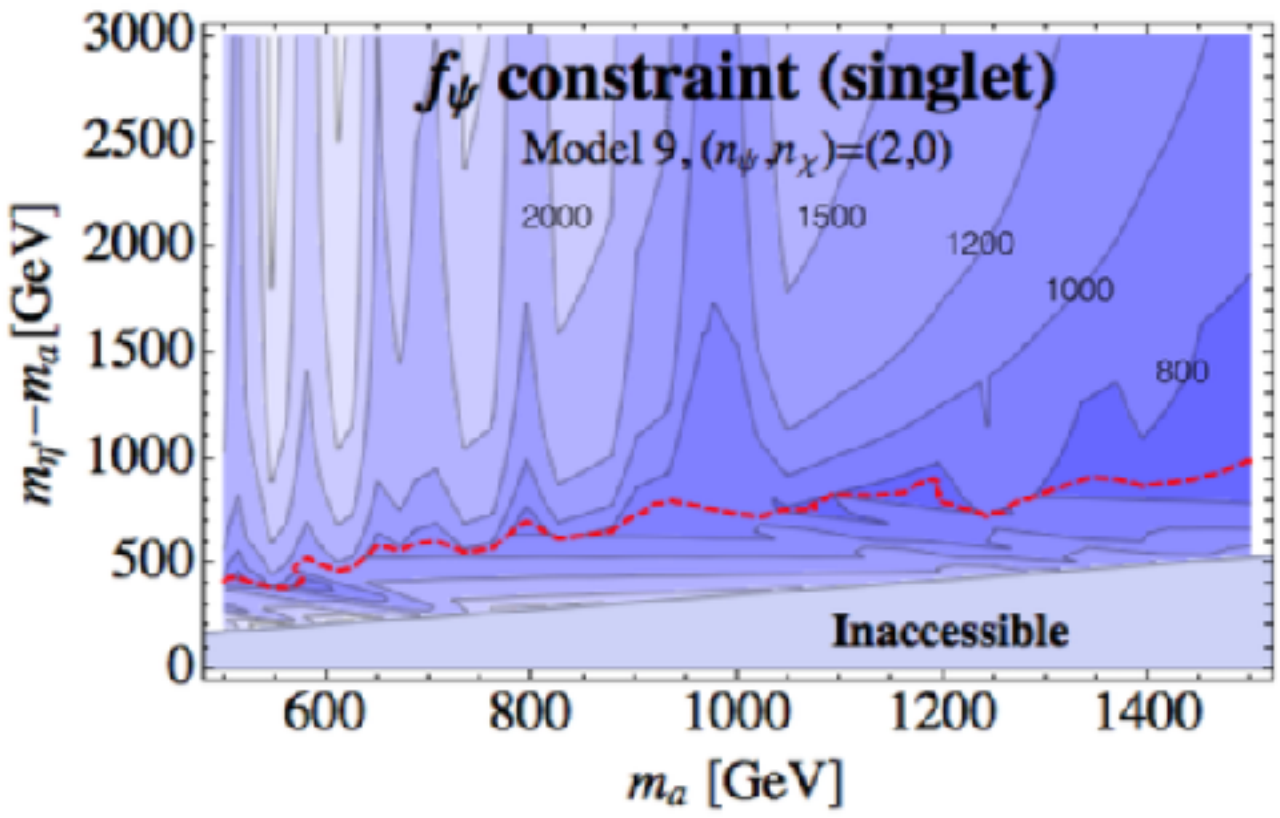
Minimal models

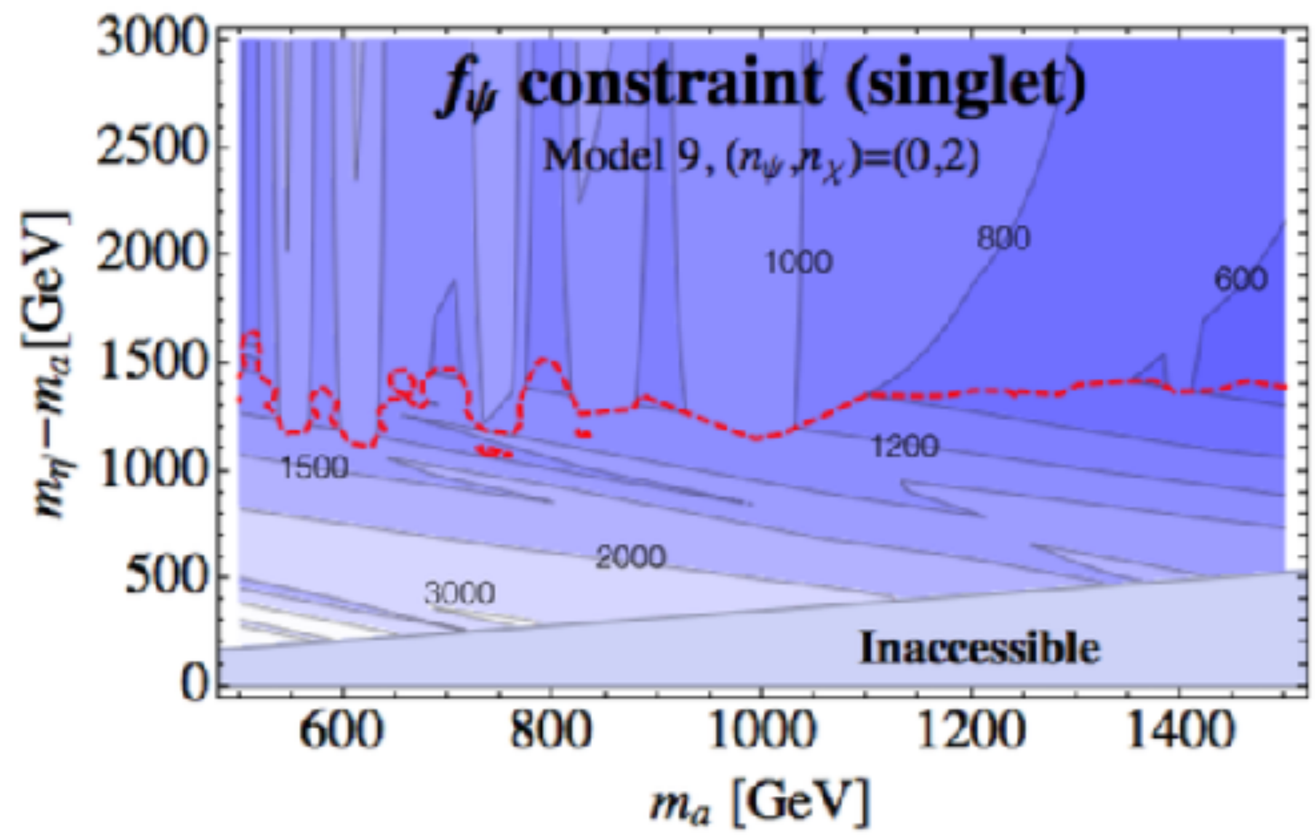
coset	GTC	TF	Higgs doublets	pNGBs	
SU(4)/Sp(4)	Sp(2N)	fund	1	5	← Minimal!
SU(5)/SO(5)	SU(4)	6	1	14	Dugan, Georgi, Kaplan 1985!!!
SU(4)xSU(4)/SU(4)	SU(N)	fund	2	15	G.C., T.Ma 1508.07014
SU(6)/Sp(6)	Sp(2N)	fund	2	14	G.C., M.Lespinasse in prep.

Model M9

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

$$\left.\frac{m_a}{m_{\eta'}}\right|_{\max} = 0.74$$





Above red line, bound driven by "a"!

Bounds stronger than EW precision in most of the parameter space!