Composite Goldstone Higgs models

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@ BSM models in VBS processes
Lisboa, 5/12/2019

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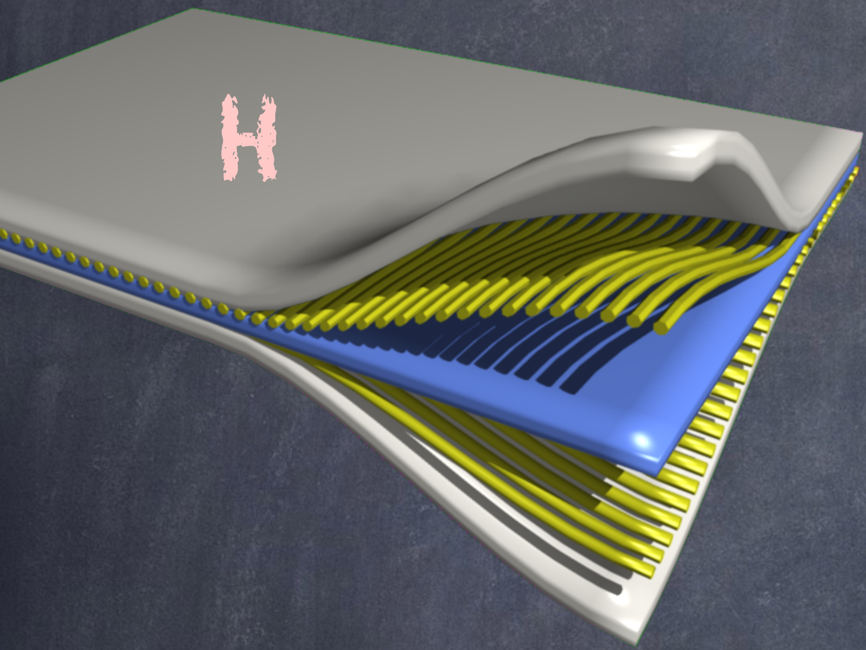
Why compositeness?



- The Higgs field may be made of more fundamental fields
- We have seen this in Nature: low-energy QCD!
- Symmetries can be broken dynamically without generating hierarchies of scales!
- Very simple models can be built.

Non-minimal is the new minimal!

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

	$SU(2)_{\rm TC}$	$SU(4)_\psi$	$SU(2)_L$	$U(1)_Y$
$\begin{pmatrix}\psi^1\\ \psi^2\end{pmatrix}$	$\square$	$\square$	**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) !

- The global symmetry is broken: SU(4)/Sp(4)

  Witten, Kosower

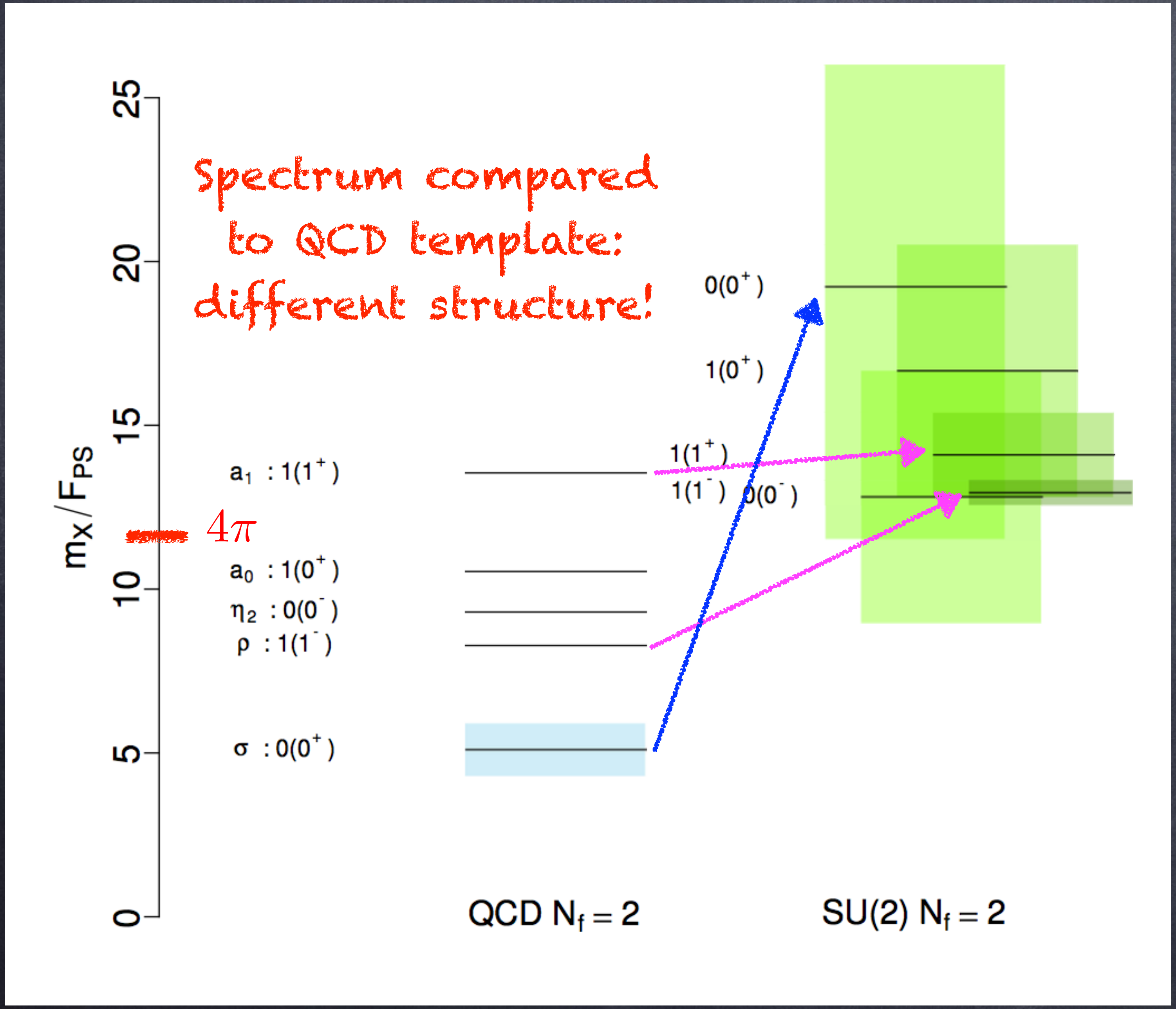
- 5 Goldstones (pions) arise:

$$\mathbf{5}_{\rm Sp(5)} \to (2,2) \oplus (1,1)$$

Higgs ↗ (2,2); additional singlet ↖ (1,1)

The spectrum

Lattice results:



$\sin\theta \leq 0.2$

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

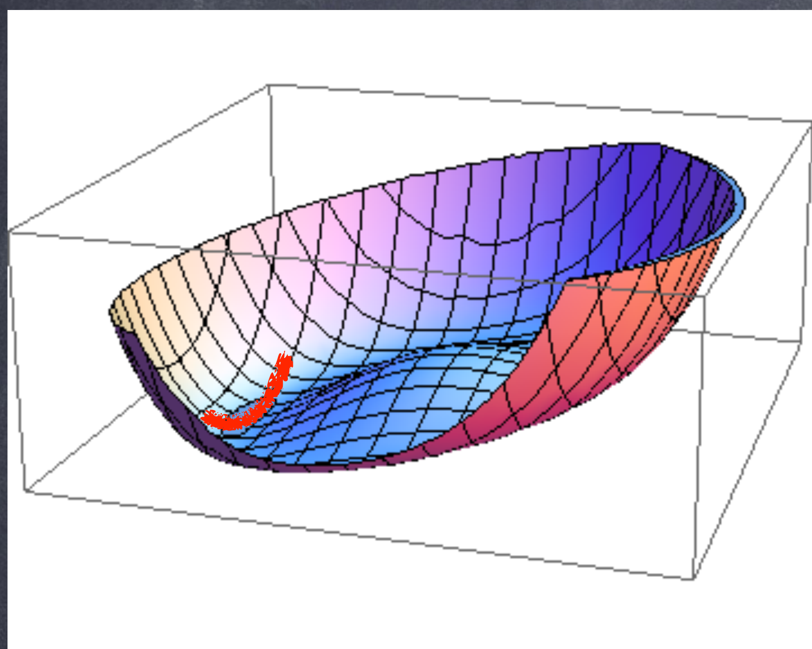
$$m_\rho = \frac{3.2 \pm 0.5 \text{ TeV}}{\sin\theta} \gtrsim 16 \text{ TeV}$$

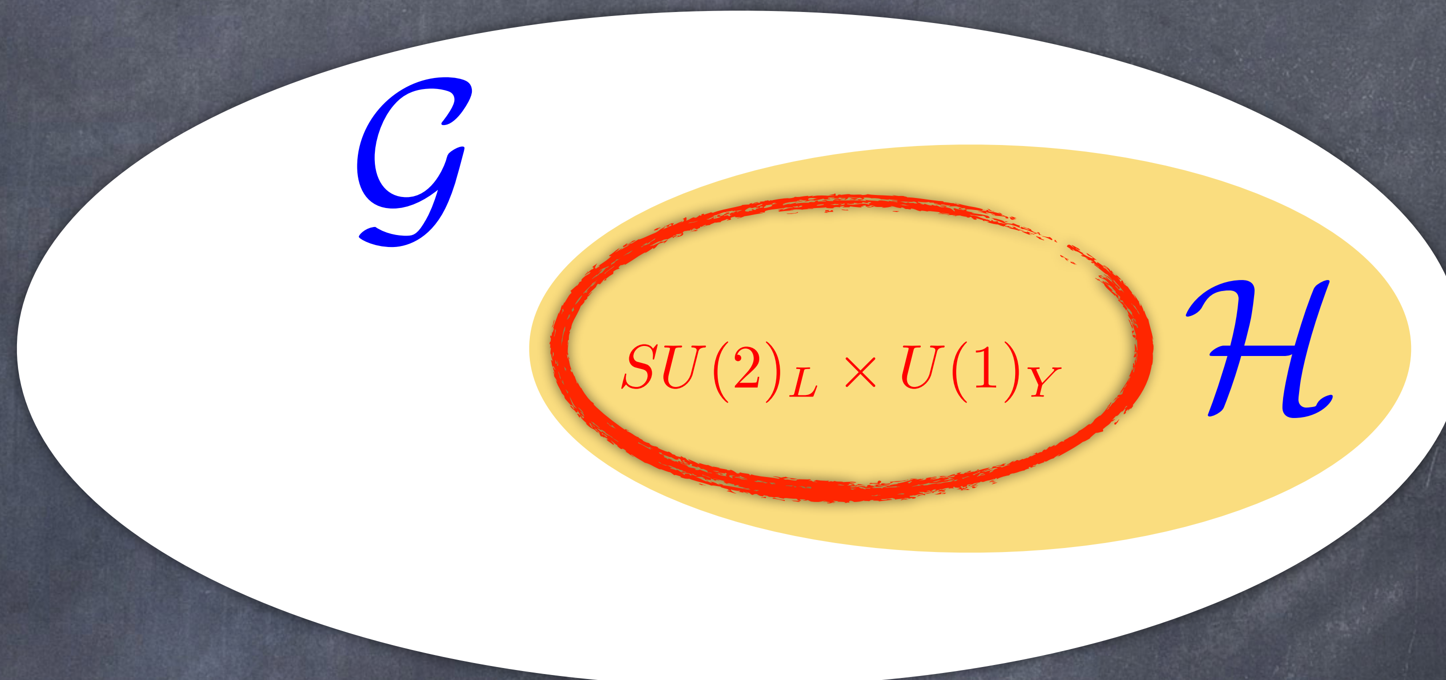
$$m_\sigma \sim ???$$

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

$$m_h = 125\ GeV$$

Compositeness, and the Higgs boson



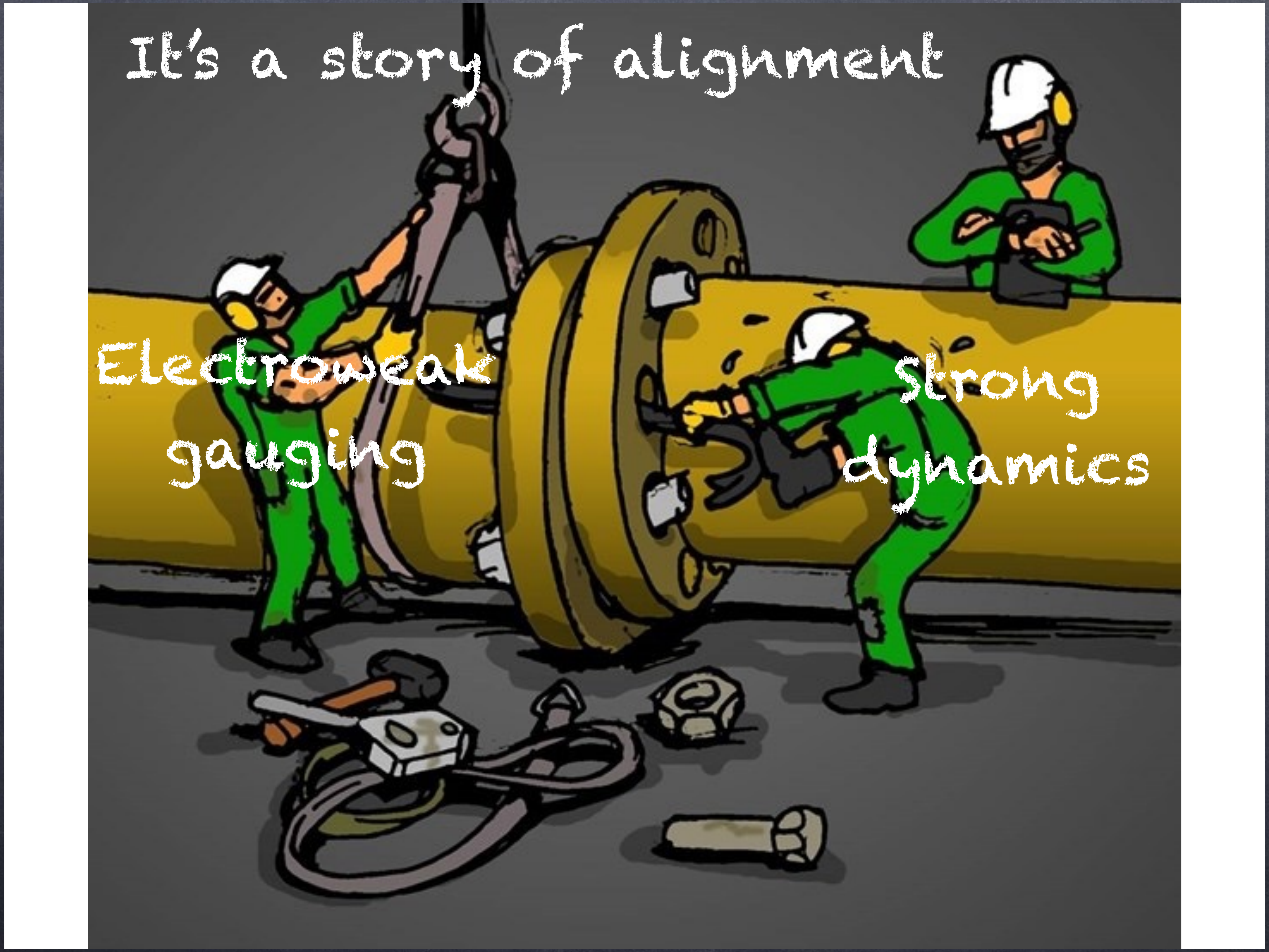


$\mathcal{G} \to \mathcal{H}$

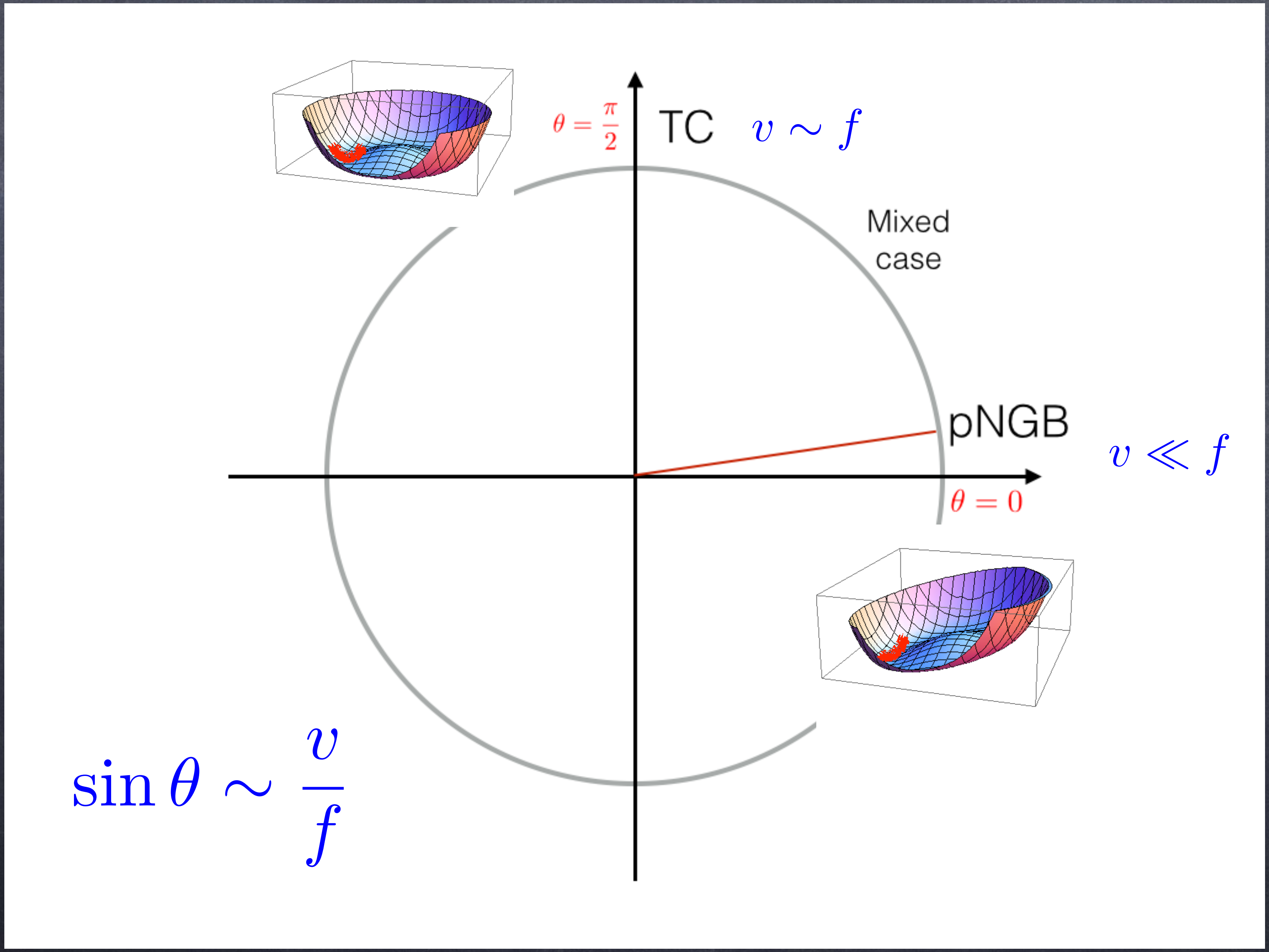
QCD template:

- 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



Compositeness, and the Higgs boson



The hot potato: flavour!

100.000 TeV	Λ_{flavour}	Scale of fermion mass generation
		How can this hierarchy be generated?
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

Higgs

$$\mathcal{L}_{\text{fermions}} = \frac{1}{\Lambda^2_{\text{fl.}}}(\psi\psi)(q^c_L q_R)$$

$$+\frac{1}{\Lambda^2_{\text{fl.}}}(q^c_L q_R)(q^c_L q_R) + \frac{1}{\Lambda^2_{\text{fl.}}}(\psi\psi)^2$$

FCNCs

Higgs mass

$$m_{\text{top}} \sim \frac{(4\pi f)^3}{\Lambda^2_{\text{fl.}}}\sin\theta$$

Too small!

The hot potato: flavour!

Scale		
100.000 TeV	Λ_{flavour}	Scale of fermion mass generation
		Intermediate conformal region
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions)
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

$$(\psi\psi) \to \mathcal{O}_H$$

$$\dim[\mathcal{O}_H] = d_H$$

effective Yukawa:

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R$$

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

$$d \sim 1.$$

The hot potato: flavour!

100.000 TeV — Λ_{flavour} — Light fermions

Conformal region

Λ_{top}

10 TeV — $\Lambda \sim 4\pi f$ — Vector resonances, ...

1 TeV — f — Condensation scale (extra pions) + 0++ state?

100 GeV — $v_{\text{SM}} \sim f \sin\theta$ — EWSB

Multi-scale model

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

$$\sim 0.01 \Rightarrow d \sim 1.5$$

Still, for the top, one would need:

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

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}}\mathcal{O}_H q_L^c q_R \qquad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-4} f^2$$

Both irrelevant if

we assume: $d_H > 1$ $\quad d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}}(\tilde{y}_L\, q_L\mathcal{F}_L + \tilde{y}_R\, q_R\mathcal{F}_R)$$

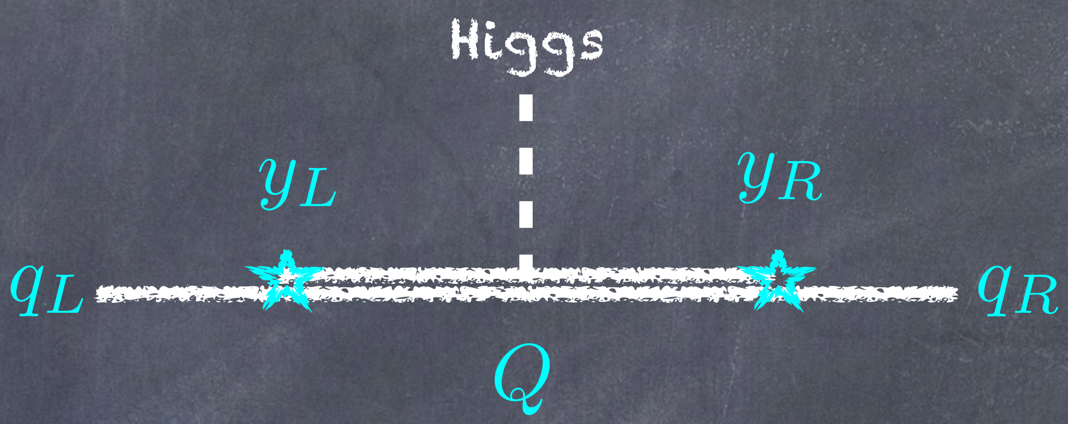
This dimension is not related to the Higgs!

↓

$$f(y_L\, q_L Q_L + y_R\, q_R Q_R)$$ with $$y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$$

The partial compositeness paradigm

$$f(y_L\, q_L Q_L + y_R\, q_R Q_R)$$



$$m_q \sim \frac{y_L y_R f^2}{M_Q^2} f \sin\theta$$

$$M_Q \sim f \Rightarrow y_L, y_R \sim 1$$

Top can cancel top loop, PUVC

$$M_Q \sim 4\pi f \Rightarrow y_L, y_R \sim 4\pi$$

Partial compositeness

100,000 TeV	Λ_{flavour}	Flavour scale
		Conformal region
10 TeV	$\Lambda \sim 4\pi f$	Vector resonances, ...
1 TeV	f	Condensation scale (extra pions) + 0++ state?
100 GeV	$v_{\text{SM}} \sim f \sin\theta$	EWSB

Top partners

- Are large baryon anomalous dimensions consistent with QFT?
- What are they composite of? (QCD colour...)
- What generates the Yukawas?

Top partners as baryons

Gauge-fermion underlying theory

$$\frac{1}{\Lambda_{\text{fl.}}} q \underbrace{\sigma^{\mu\nu}\psi G_{\mu\nu}}_{T}$$

$$d_T^{\text{naive}} = 7/2$$

- typically loop-suppressed
- psi need to carry colour and flavour quantum numbers

$$\frac{1}{\Lambda_{\text{fl.}}^2} q \underbrace{\psi\psi\psi}_{T}$$

$$d_T^{\text{naive}} = 9/2$$

- higher dimension, but easier to generate
- Note: issue with other 4-Fermion interactions non avoided!!! Anomalous dimensions are crucial!

Sequestering QCD

$\mathcal{G}_{\rm TC}$: rep R rep R′

G.Ferretti, D.Karateev
1312.5330, 1604.06467

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

SM : EW colour + hypercharge

global : $\langle QQ \rangle \neq 0$ a) $\langle \chi\chi \rangle \neq 0$

↓

pNGB Higgs
DM?

coloured pNGBs
di-boson

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

light top partners
from t Hooft anomaly
conditions?

An example

Baryons: $QQ\chi$

Barnard, Gherghetta, Ray 1311.6562

G_{TC} Global symmetries

Q

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(4)$	$SU(6)$	$U(1)$
Q_1 Q_2	$\square$	$\mathbf{1}$	$\mathbf{2}$	0	$\mathbf{4}$	$\mathbf{1}$	$-\frac{6N_c}{2N_c+1}q_\chi$
Q_3	$\square$	$\mathbf{1}$	$\mathbf{1}$	$1/2$			
Q_4	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

Global symmetries

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!

G = A, W, Z, g !!!

Cai, Flacke, Lespinasse 1512.04508

Anomalous U(1) -> heavy η'

Orthogonal U(1) -> pNGB a

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

Model zoology

The EFT is the same!

$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	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

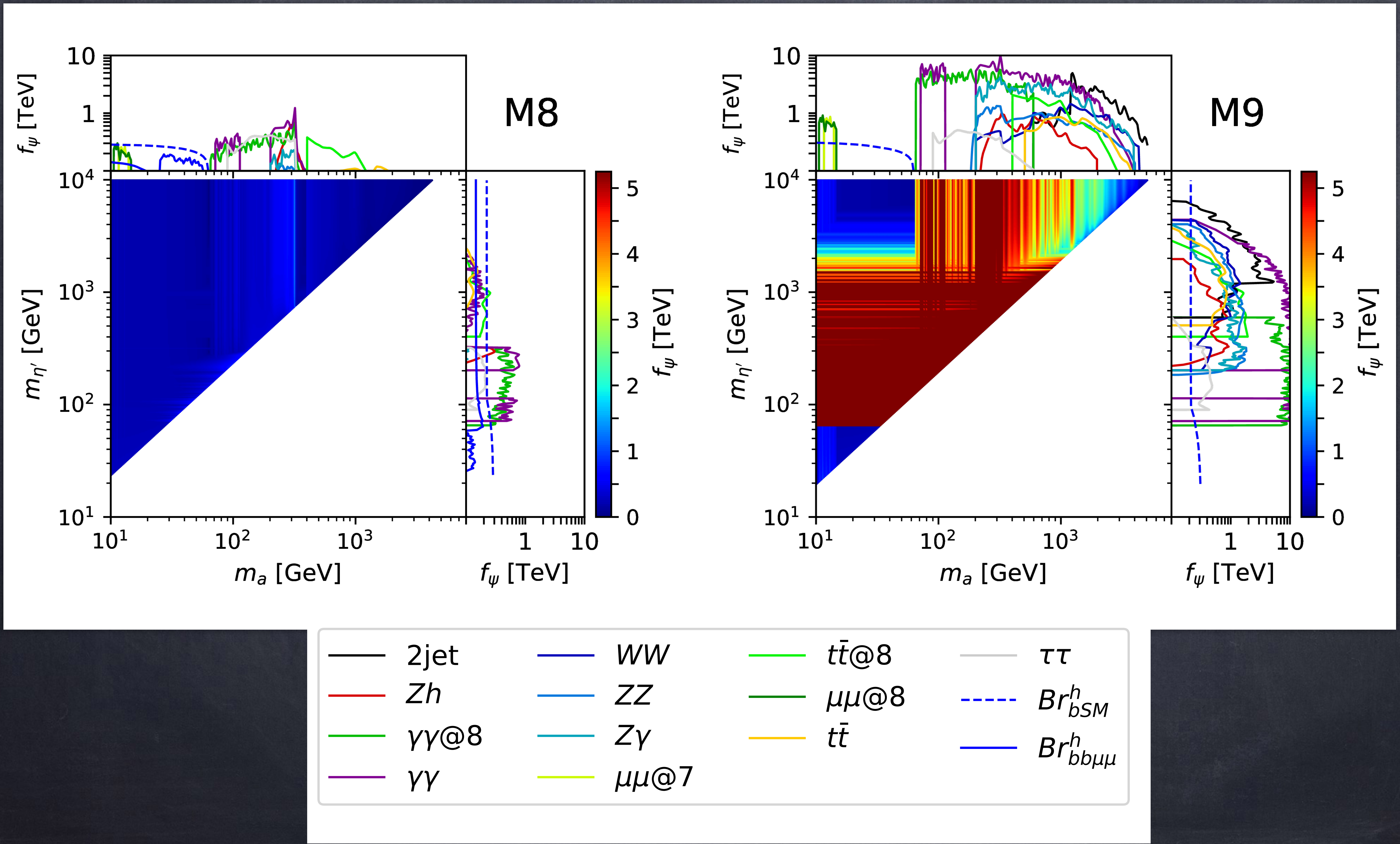
Defines $\tan\zeta$

Theory confines!

$T' = \psi\psi\chi$

Note: there is enough baryons to give mass to the top (and bottom) only!

Example of predictions: di-boson resonances



Take-home box

- Non-minimal models are the norm: additional light pNGBs (mesons)
- Conformal symmetry needed by flavour: light-ish dilaton?
- Top (fermion) partial compositeness: light-ish fermions (baryons)

Composite Higgs VBS

- Most analyses so far done in EFT

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right) \text{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$
$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3 \lambda v h^3 - d_4 \frac{\lambda}{4} h^4 + \cdots$$

-

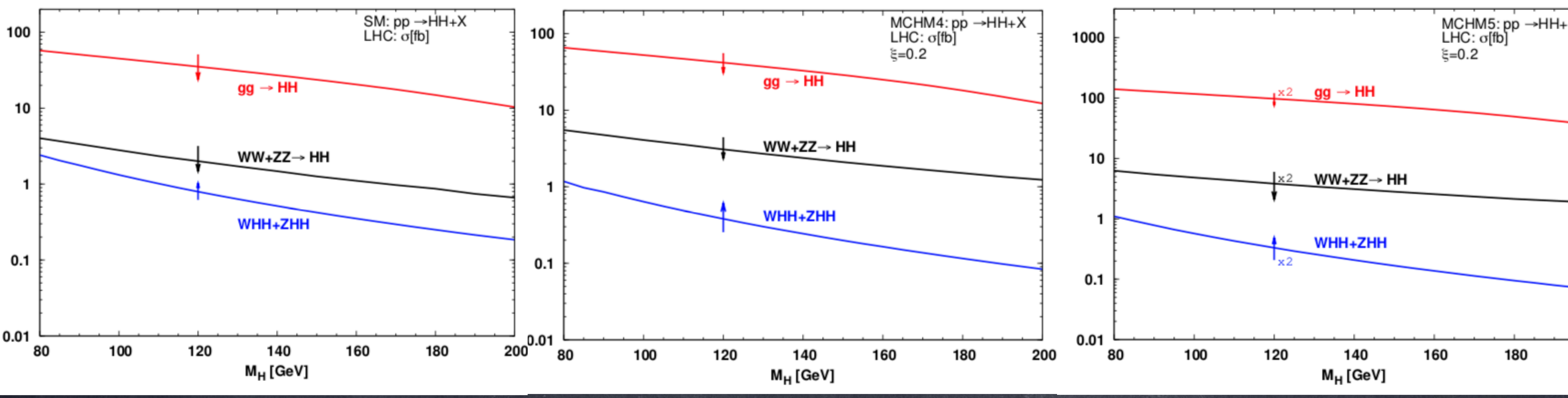
Model/Coupling	HVV	$HHVV$	Hff	HHH
MCHM4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
MCHM5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

$$\xi = \frac{v^2}{f^2}$$

Composite Higgs VBS

Gröber, Mühleitner
1012.1562

- Most analyses so far done in EFT



Model/Coupling	HVV	$HHVV$	Hff	HHH
MCHM4	$\sqrt{1-\xi}$	$1-2\xi$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
MCHM5	$\sqrt{1-\xi}$	$1-2\xi$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

Similar results for VV

Composite Higgs VBS

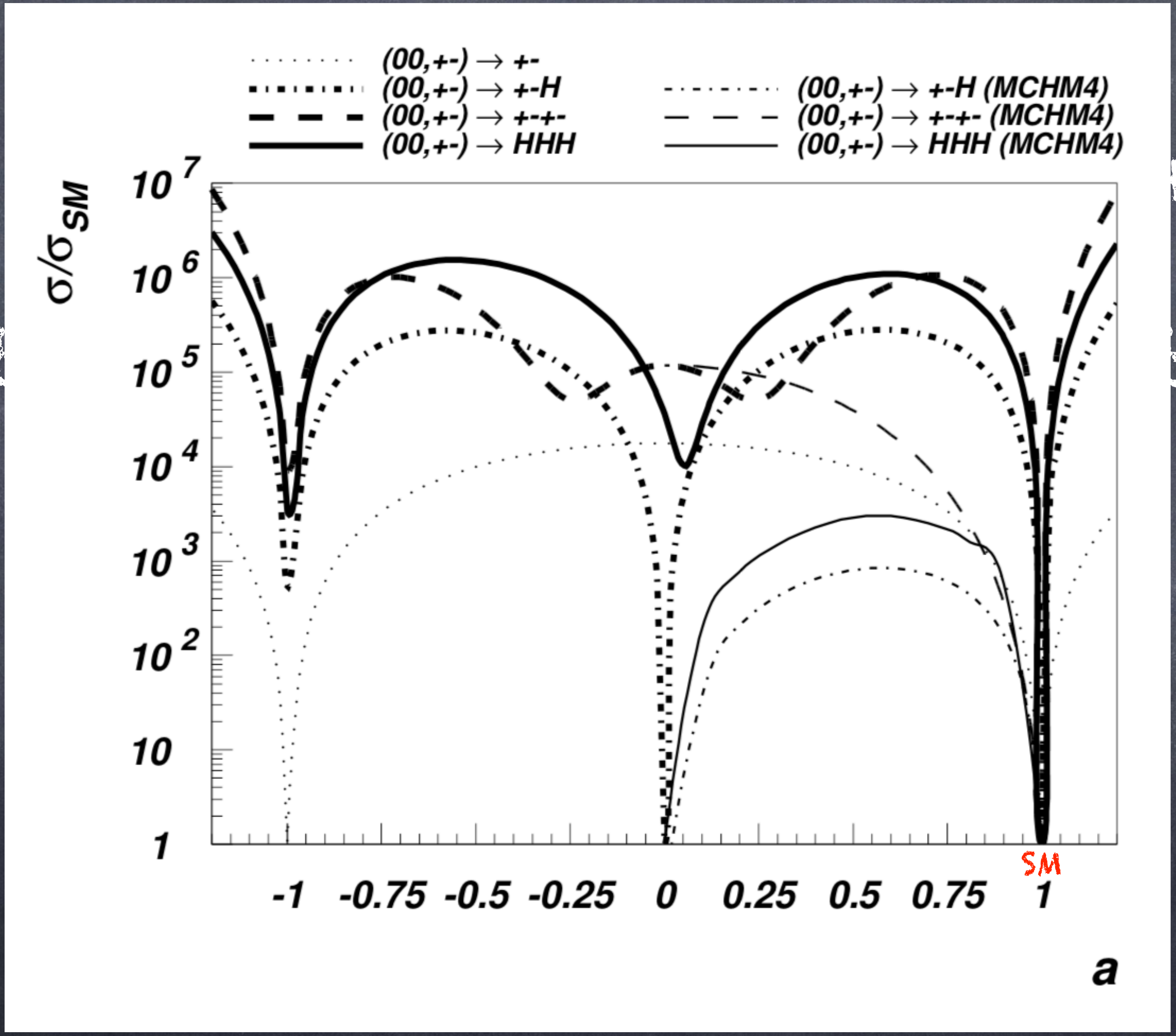
Belyaev et al
1212.3860

- Most analyses so far done in EFT
- Multi-V or H could be the way to go!
-

Composite Higgs VBS

Belyaev et al
1212.3860

- Mos[...]FT
- Mul[...]to go!
-



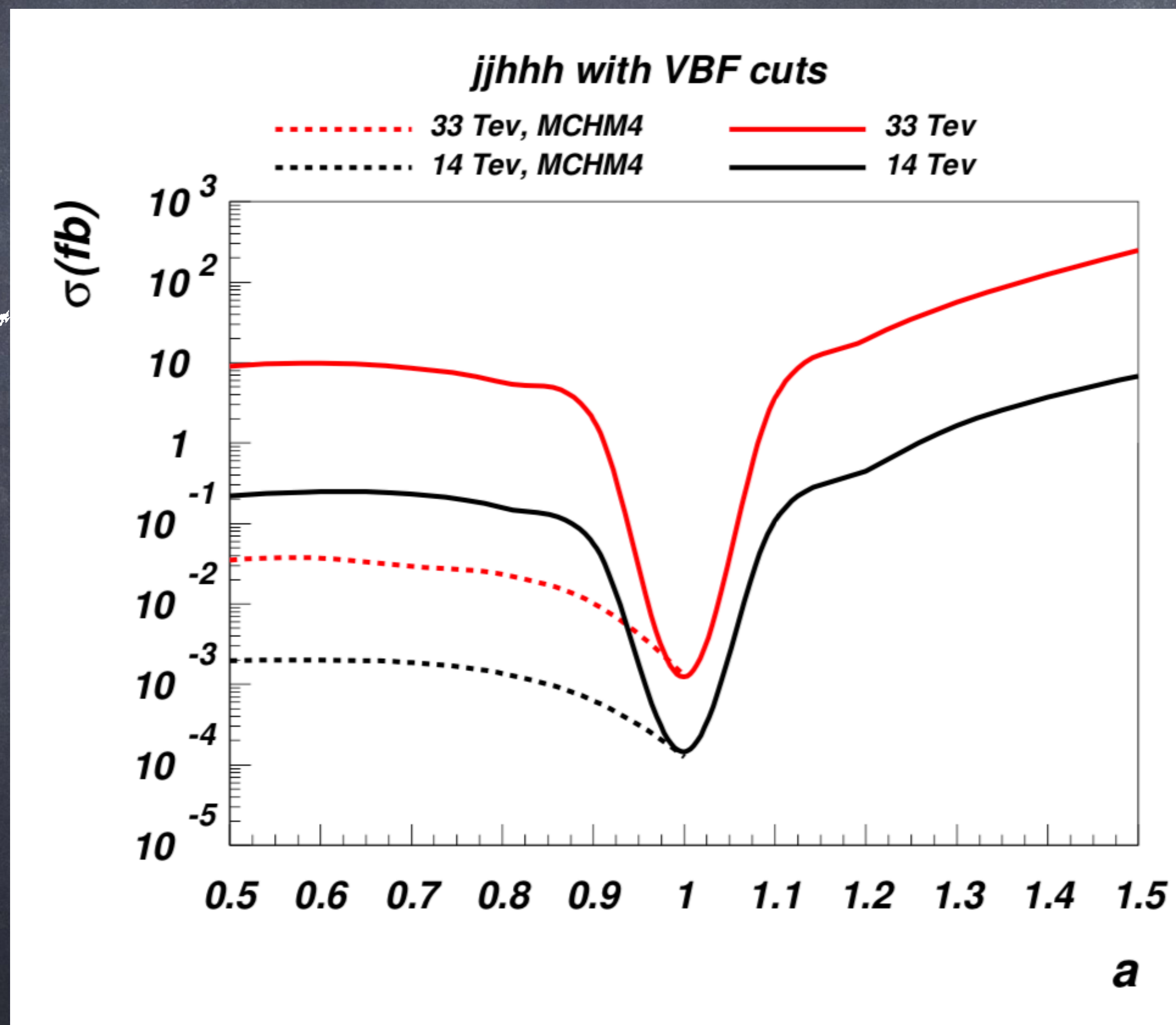
HVV modifier

partonic $\sqrt{s} = 2$ TeV

Composite Higgs VBS

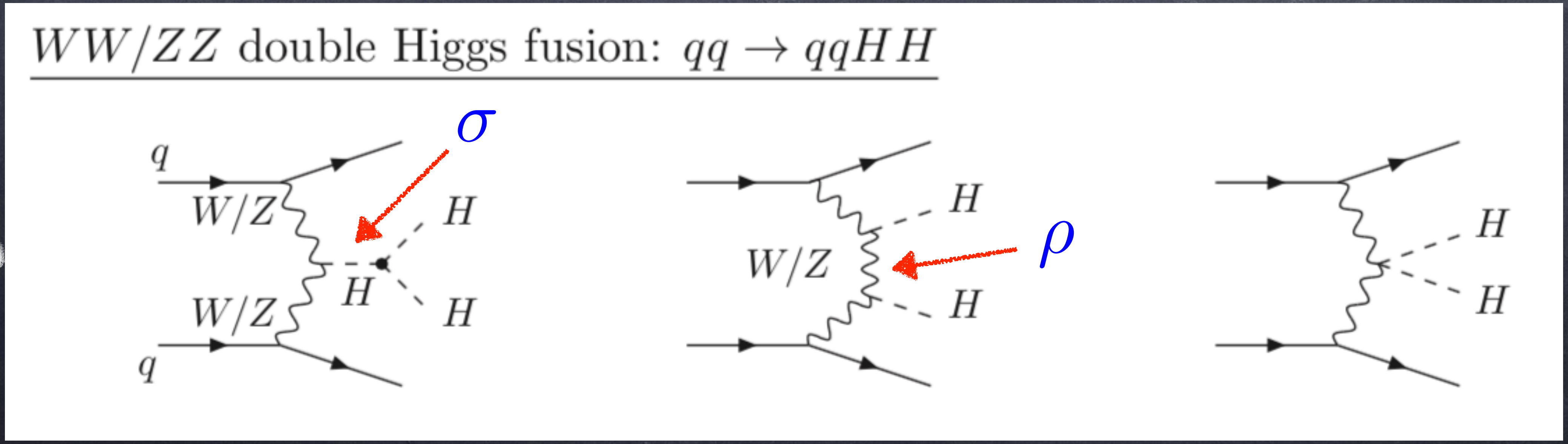
Belyaev et al
1212.3860

- Most … EFT
- Multi… to go!



see also:
Contino et al
1309.7038

Composite Higgs VBS

- Most analyses so far done in EFT
- Multi-V or H could be the way to go!
- Resonances need to be added!!!
- 

A QCD example:

Harada, Sannino, Schechter
hep-ph/9511335

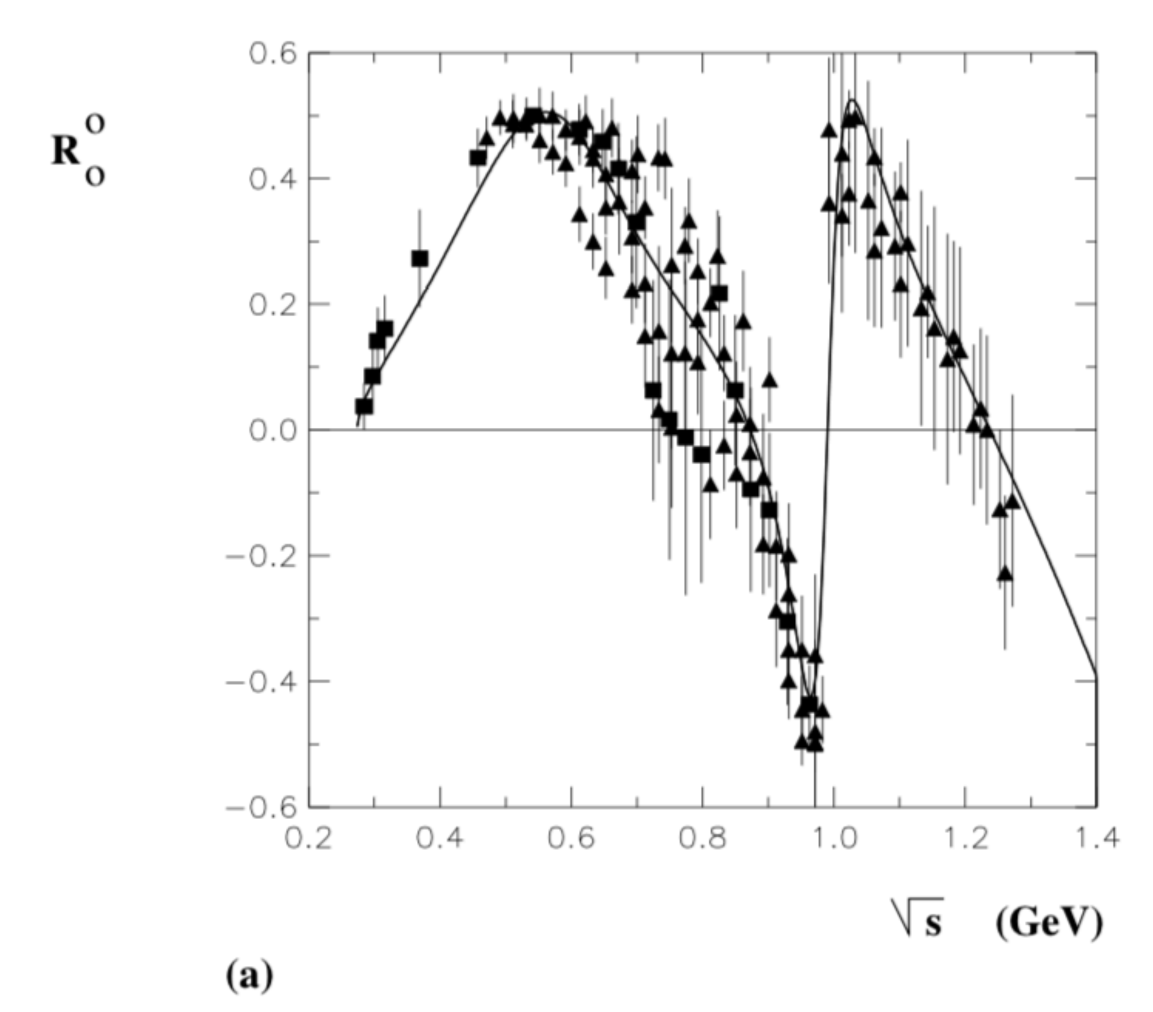
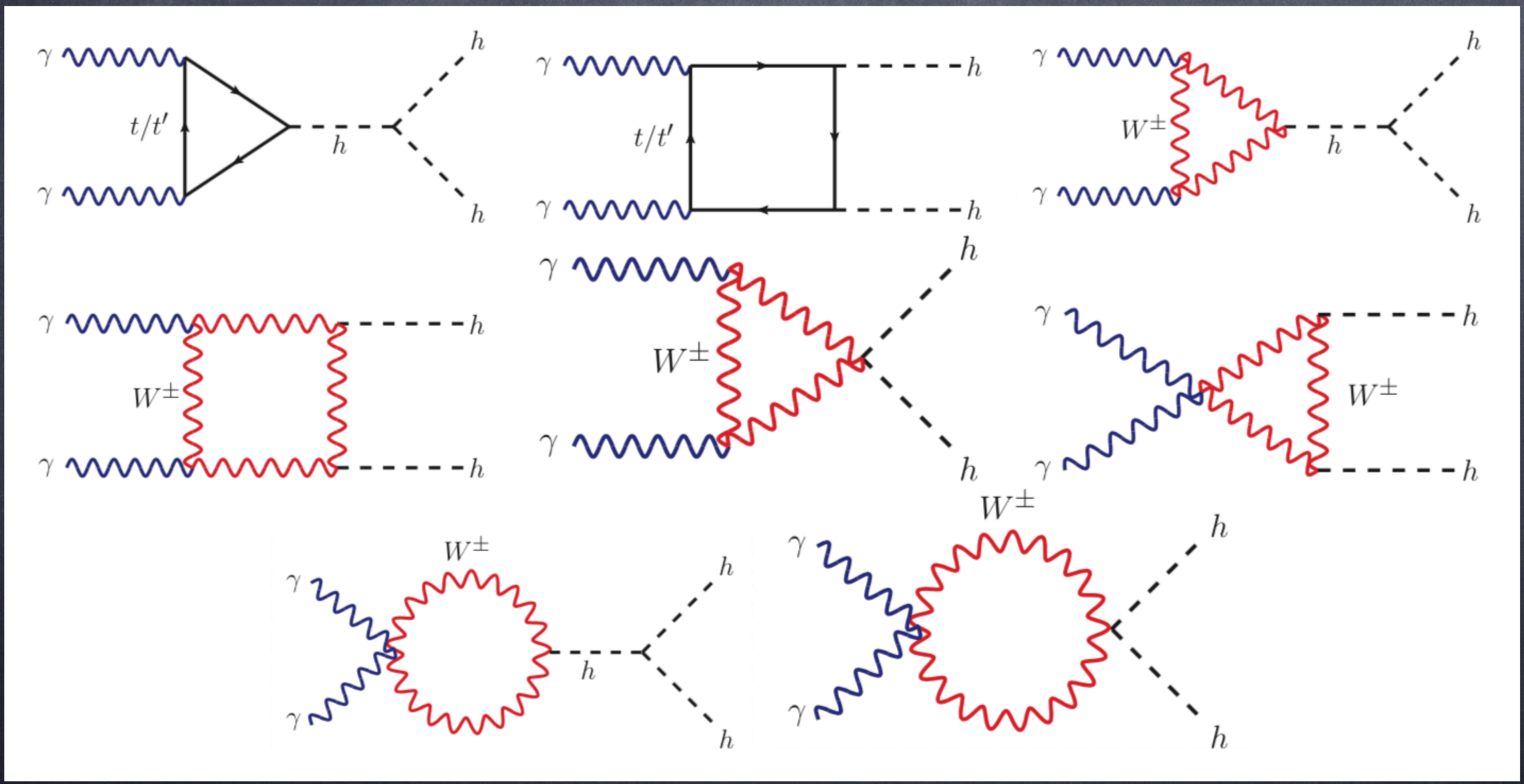


Figure 4: (a): The solid line is the *current algebra* + ρ + σ + $f_0(980)$ result for R_0^0 obtained by assuming column 1 in Table 2 for the σ and $f_0(980)$ parameters ($Br(f_0(980) \rightarrow 2\pi)$ = 100%).

Composite Higgs VBS

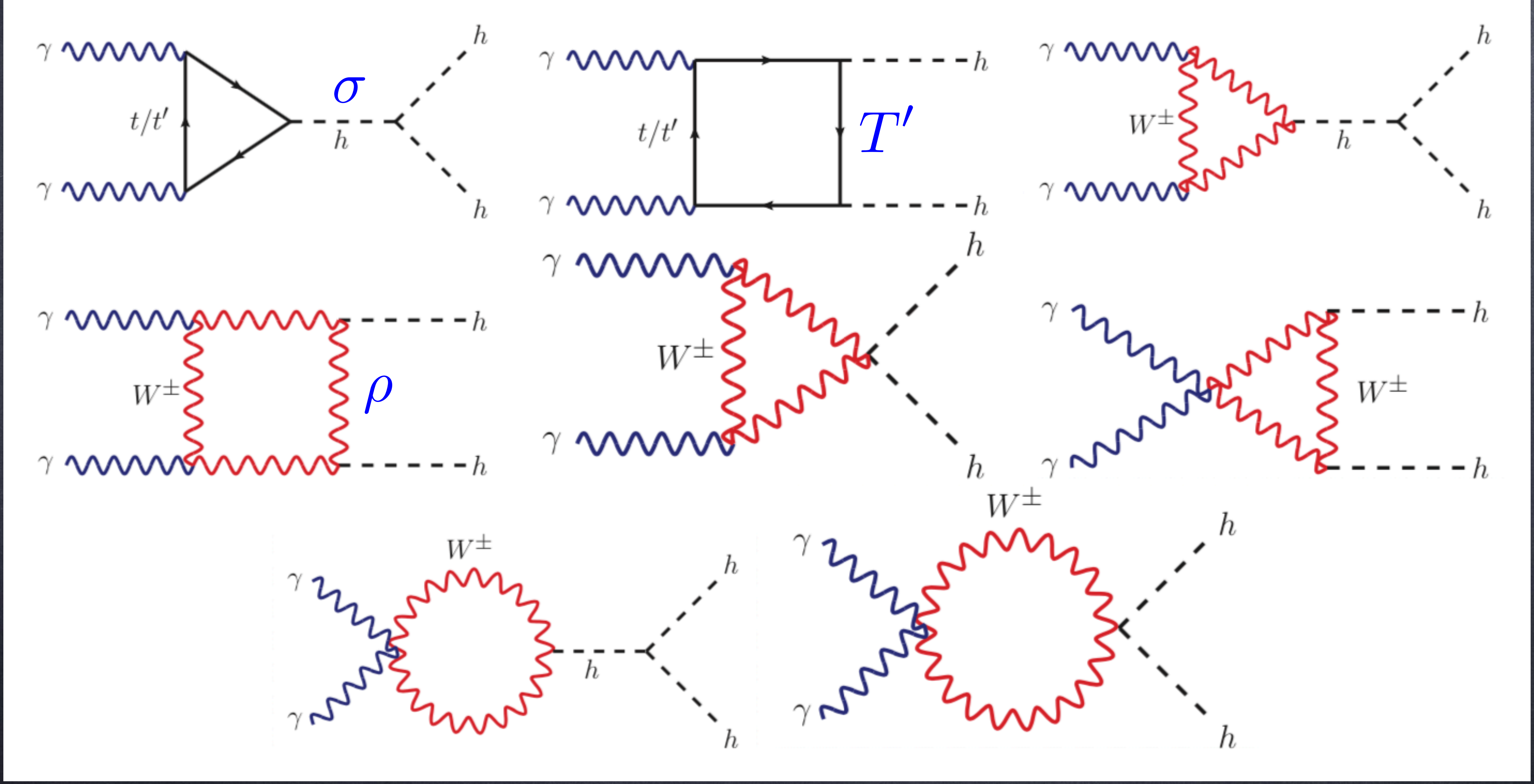
- Most analyses so far done in EFT
- Multi-V or H could be the way to go!
- Resonances need to be added!!!
- How about photons?
-

Composite Higgs VBS



Loops: sensitive to many couplings!

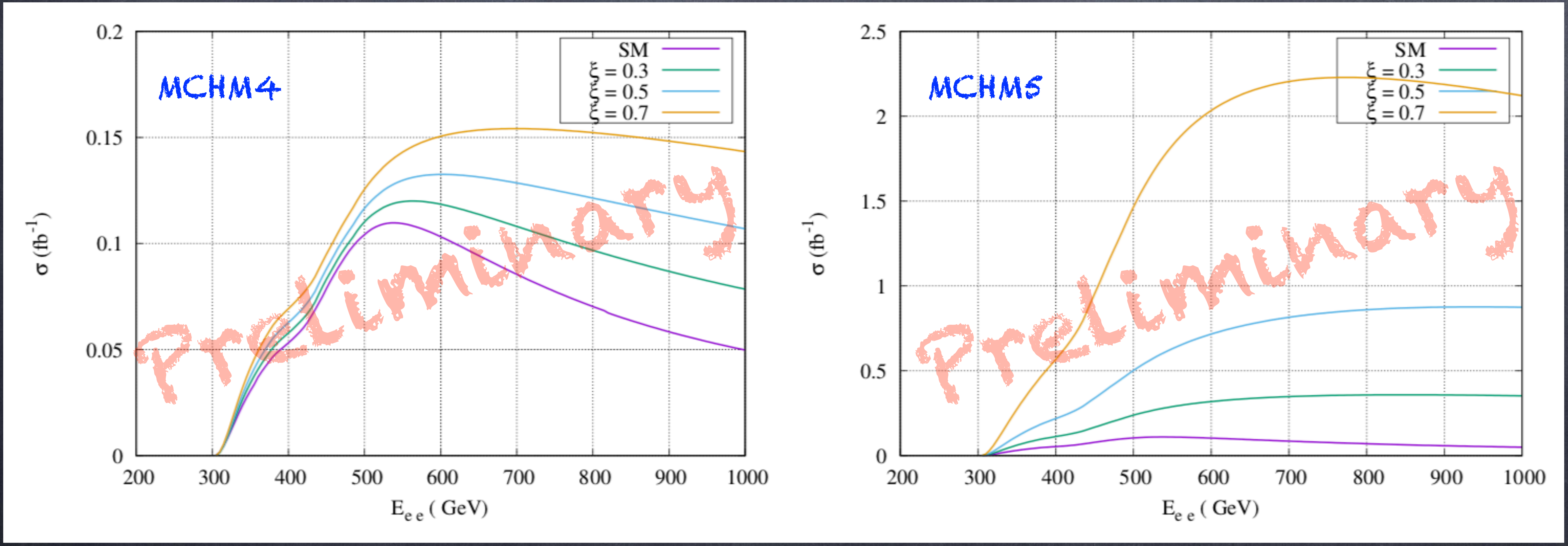
Composite Higgs VBS



... and to resonances!

$\gamma\gamma \to HH$ at FCCee

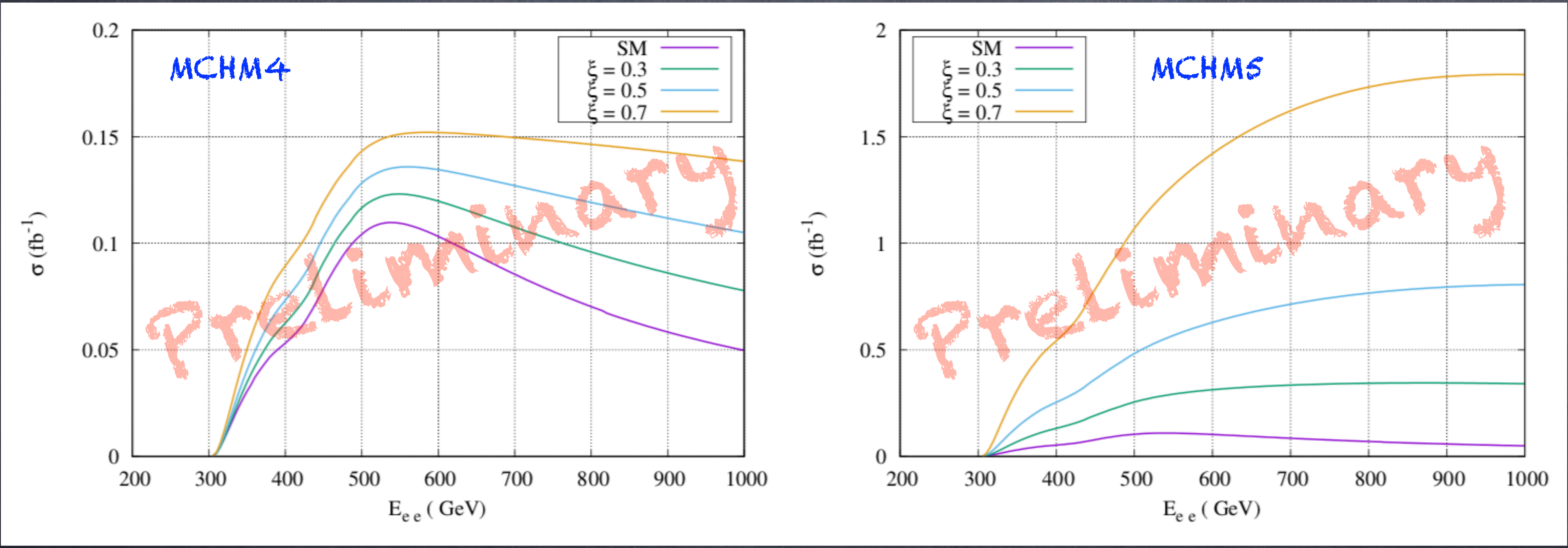
Gaur, Harada, G.C. et al
work in progress



Top coupling modified

$\gamma\gamma \to HH$ at FCCee

Gaur, Harada, G.C. et al
work in progress



Trilinear coupling modified

Composite Higgs VBS

- Most analyses so far done in EFT
- HHH could be the way to go!
- Resonances need to be added!!!
- How about photons? (HH)
- FCCee and FCChh crucial players