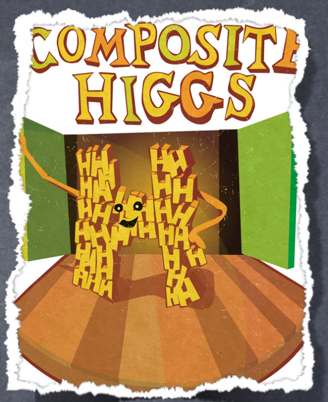
Phenomenology of composite resonances in realistic composite Higgs models

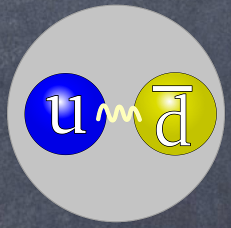
Giacomo Cacciapaglia
IP2I Lyon, France

@ PNU workshop, 2024/02/22
Busan

Composite Higgs models 101



- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)



Scales:

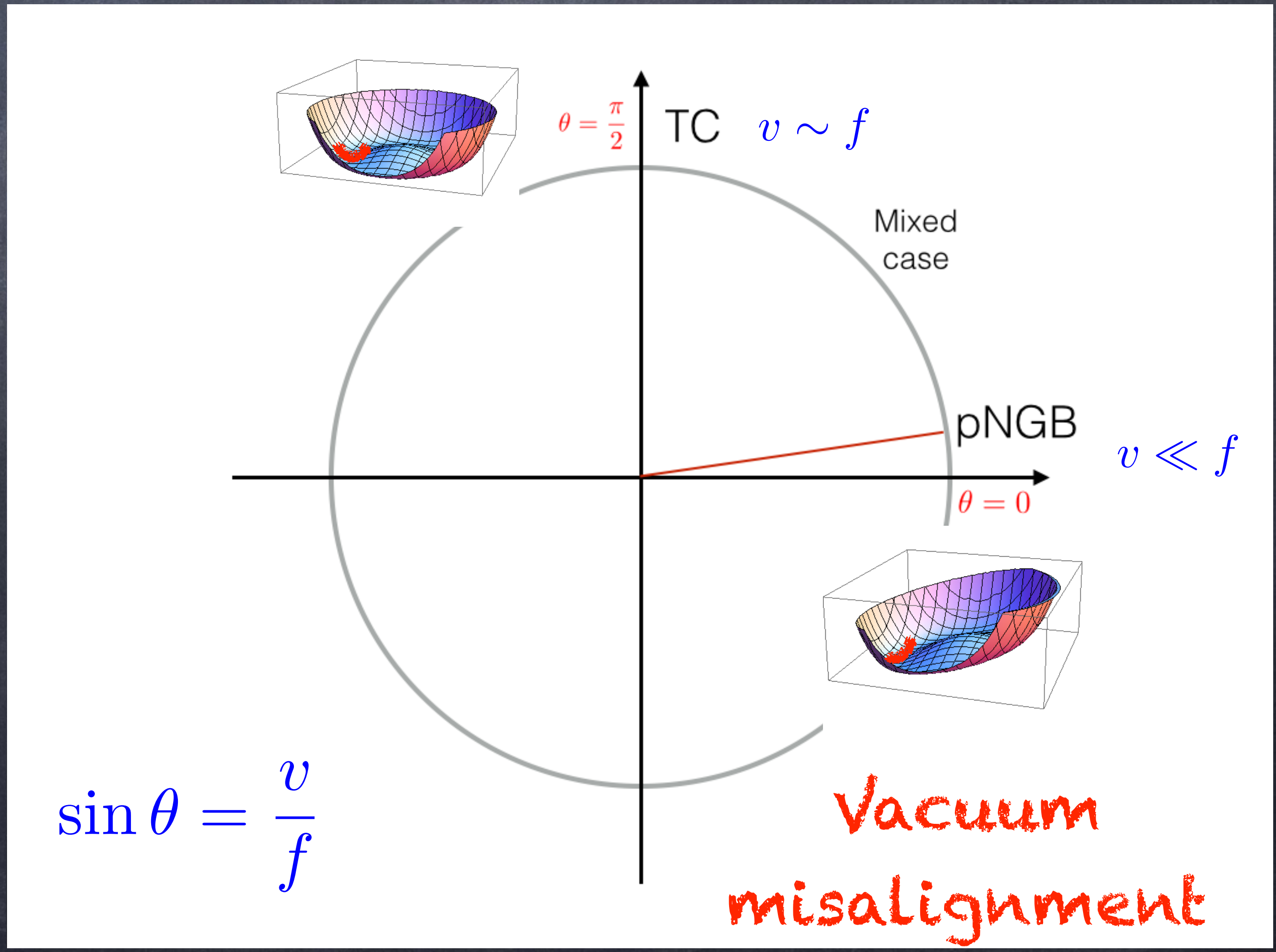
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

EWPTs + Higgs coupl. limit:

$$f \gtrsim 4v \sim 1 \text{ TeV}$$



Composite Higgs models 101

How can light states emerge?

Top loops

Gauge loops

TC-fermion masses

	Top loops	Gauge loops	TC-fermion masses
ϕ	$\sim y_t^2 f^2$	$\sim g^2 f^2$	$\sim m_\psi f$
h (h massless for vanishing v)	$\sim y_t^2 f^2 s_\theta^2 = y_t^2 v^2$	$\sim g^2 f^2 s_\theta^2 = g^2 v^2$	X
a	X	X	$\sim m_\psi f$ This can be small!

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

$$y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$$

Sequestering QCD in Partial compositeness

G.Ferretti, D.Karateev
1312.5330, 1604.06467

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

$T = \psi\psi\chi$ or $\psi\chi\chi$

global : $\langle \psi\psi \rangle \neq 0$ → pNGB Higgs, DM?

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

coloured pNGBs
di-boson

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

~~light top partners from 't Hooft anomaly conditions?~~

Composite models at various scales

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

Condensation scale

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

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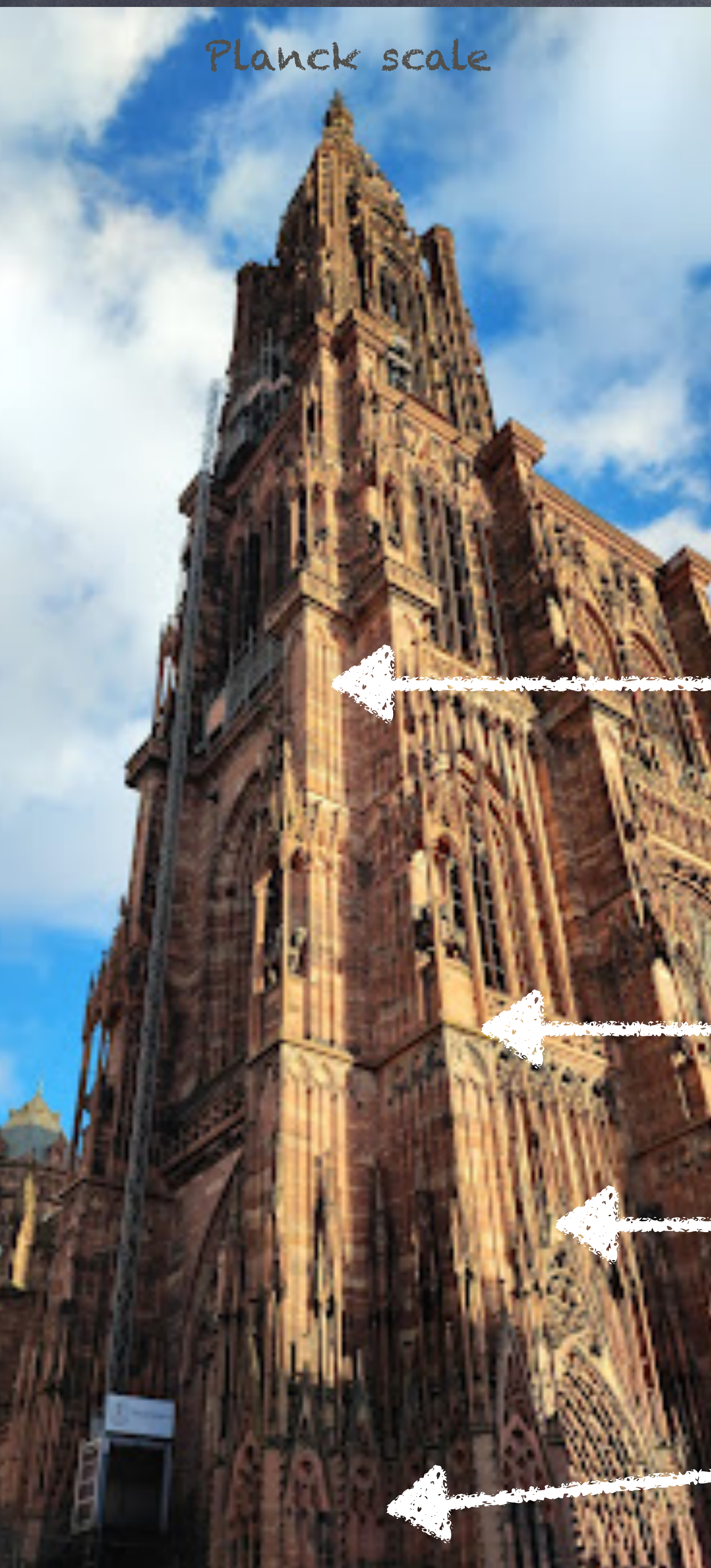

Conformal window
(large scaling dimensions)

One of Ferretti
models +
additional fermions

Condensation scale

Usual low energy description
of composite Higgs models

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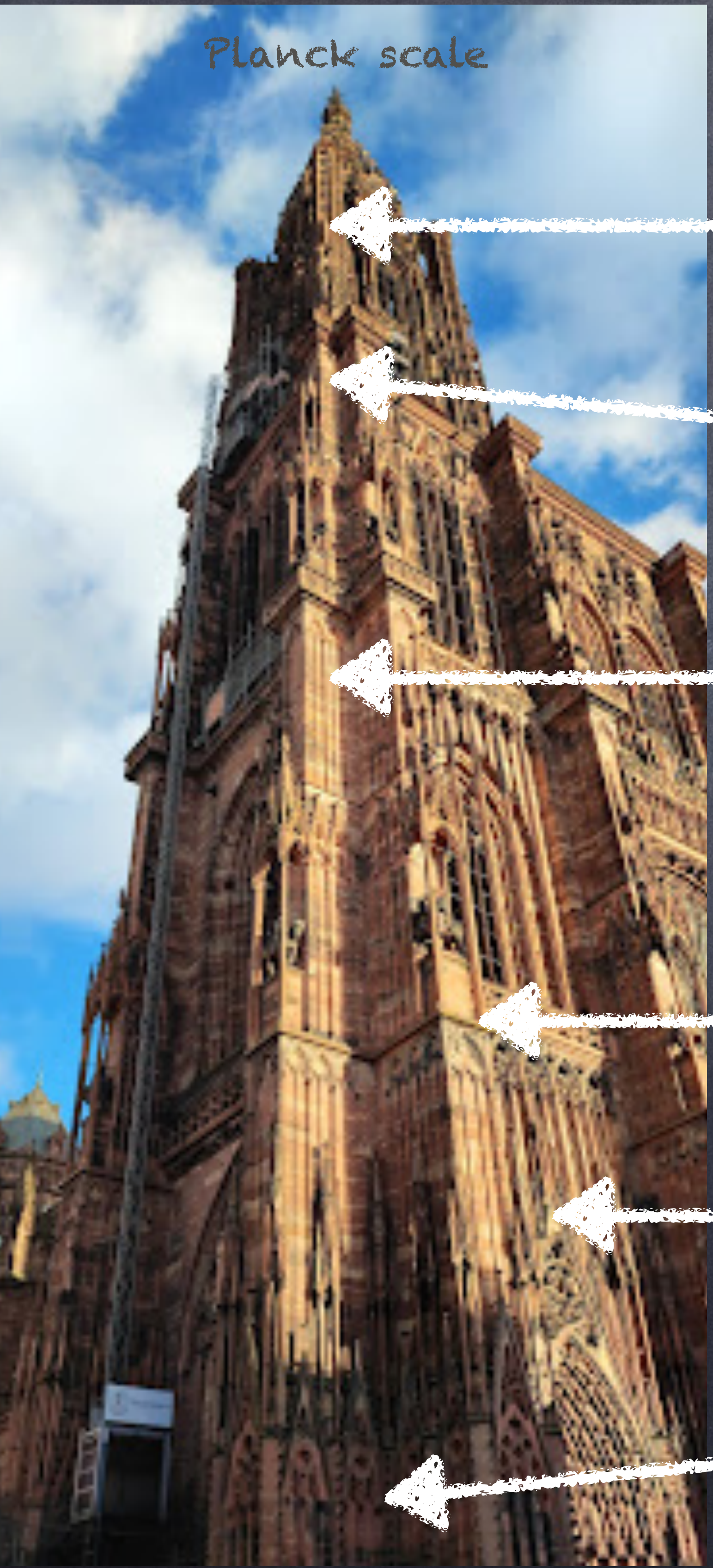
Composite models at various scales



HC and SM gauge groups partially unified

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

Symmetry breaking by scalars — 4-fermion Ops generated!

Conformal window (large scaling dimensions) — One of Ferretti models + additional fermions

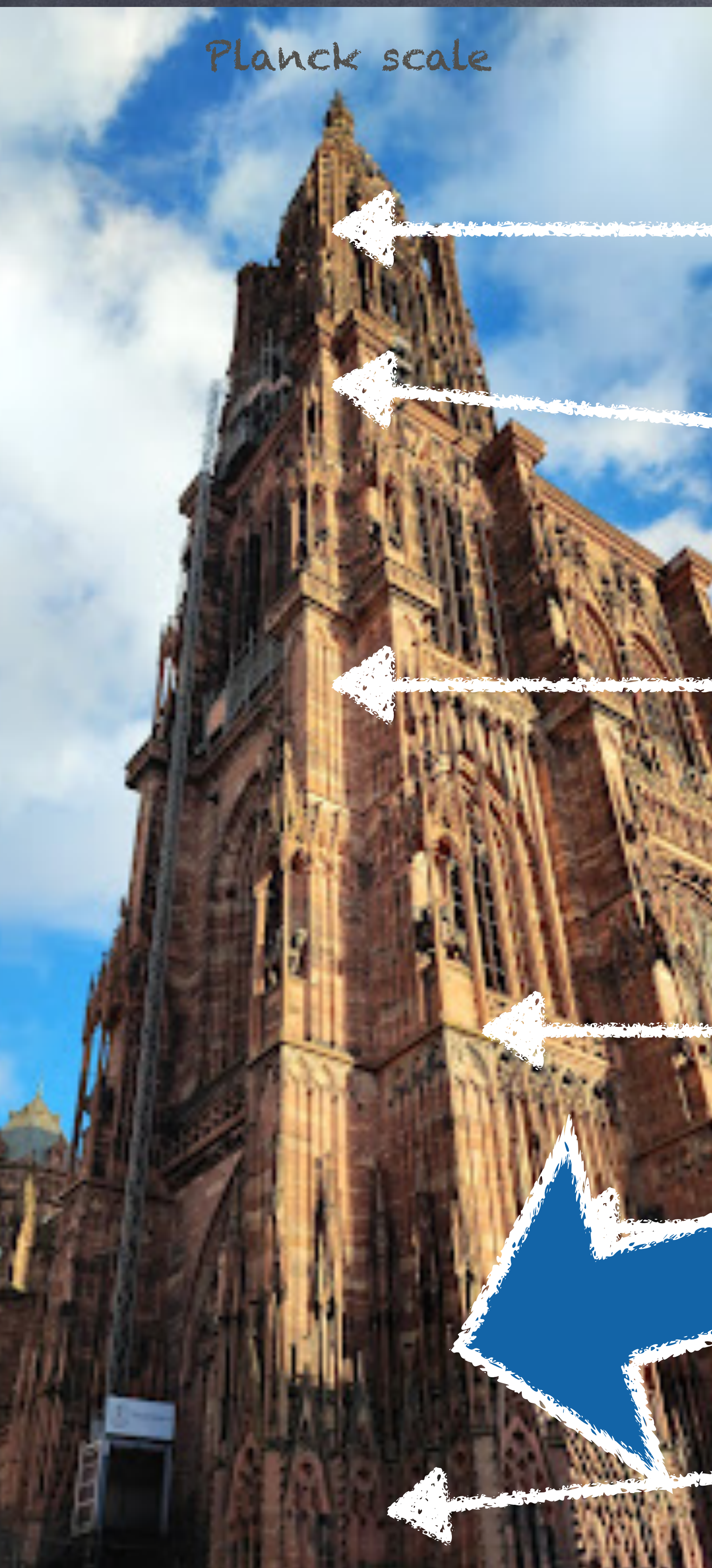
Condensation scale

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

Composite models at various scales



HC and SM gauge
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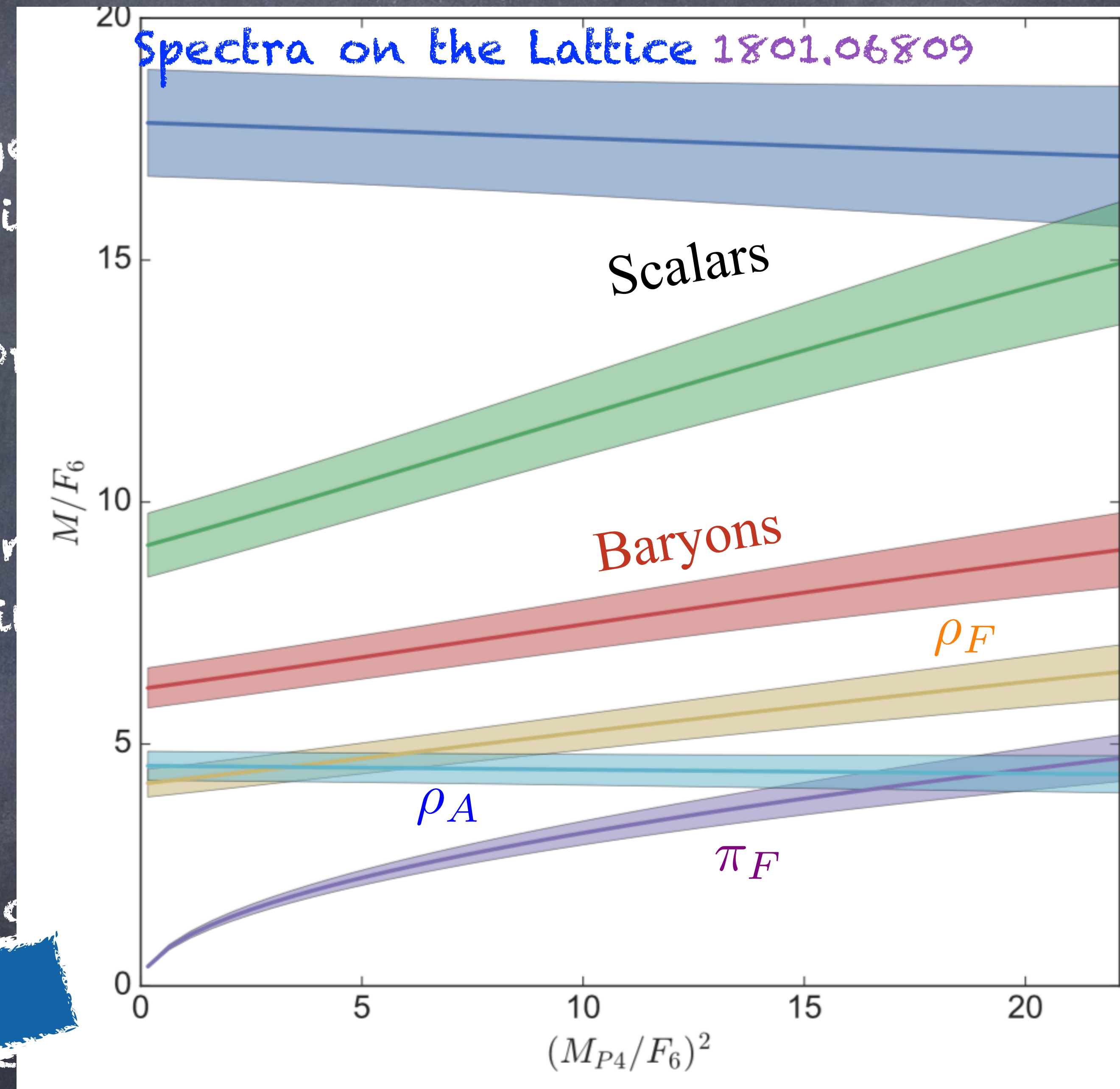
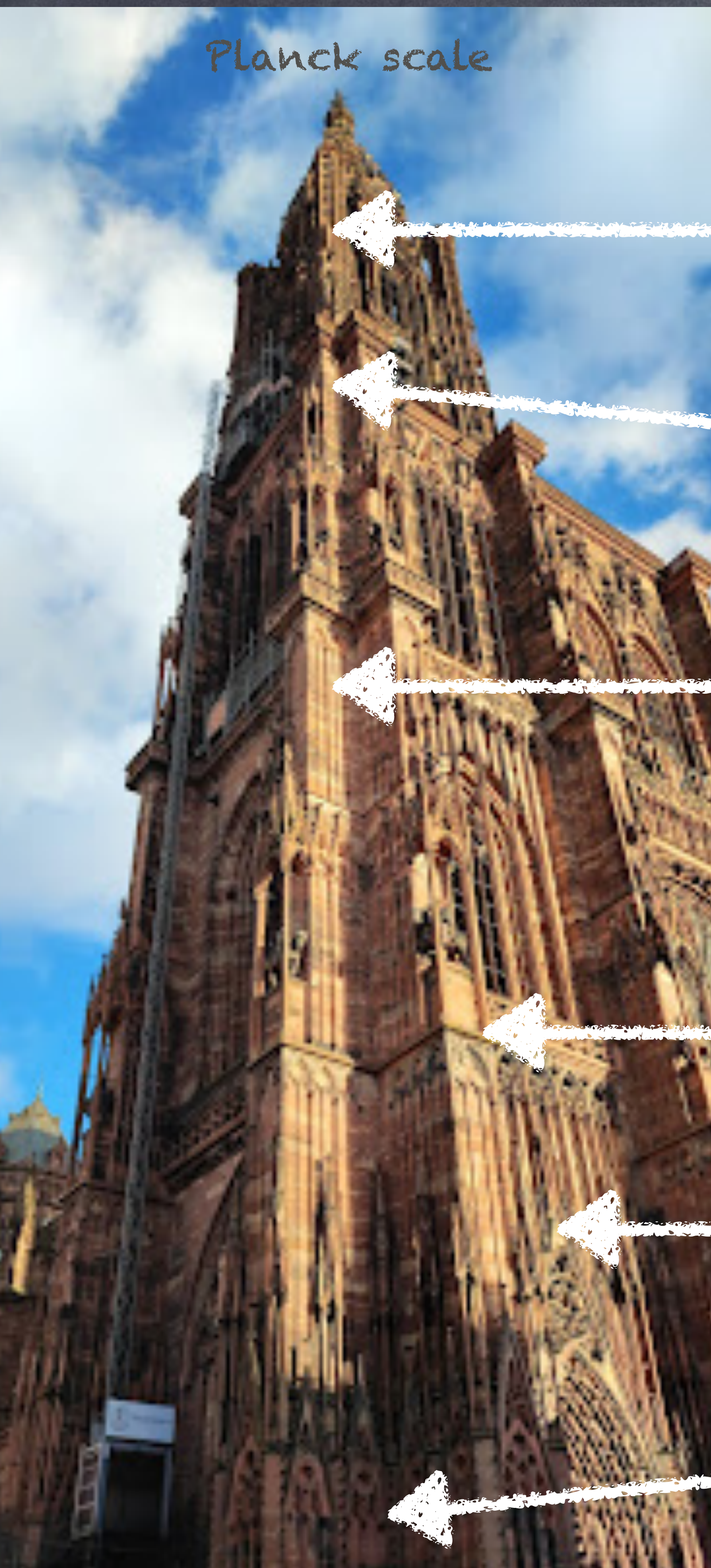


of composite Higgs models

models

Standard Model

Composite models at various scales



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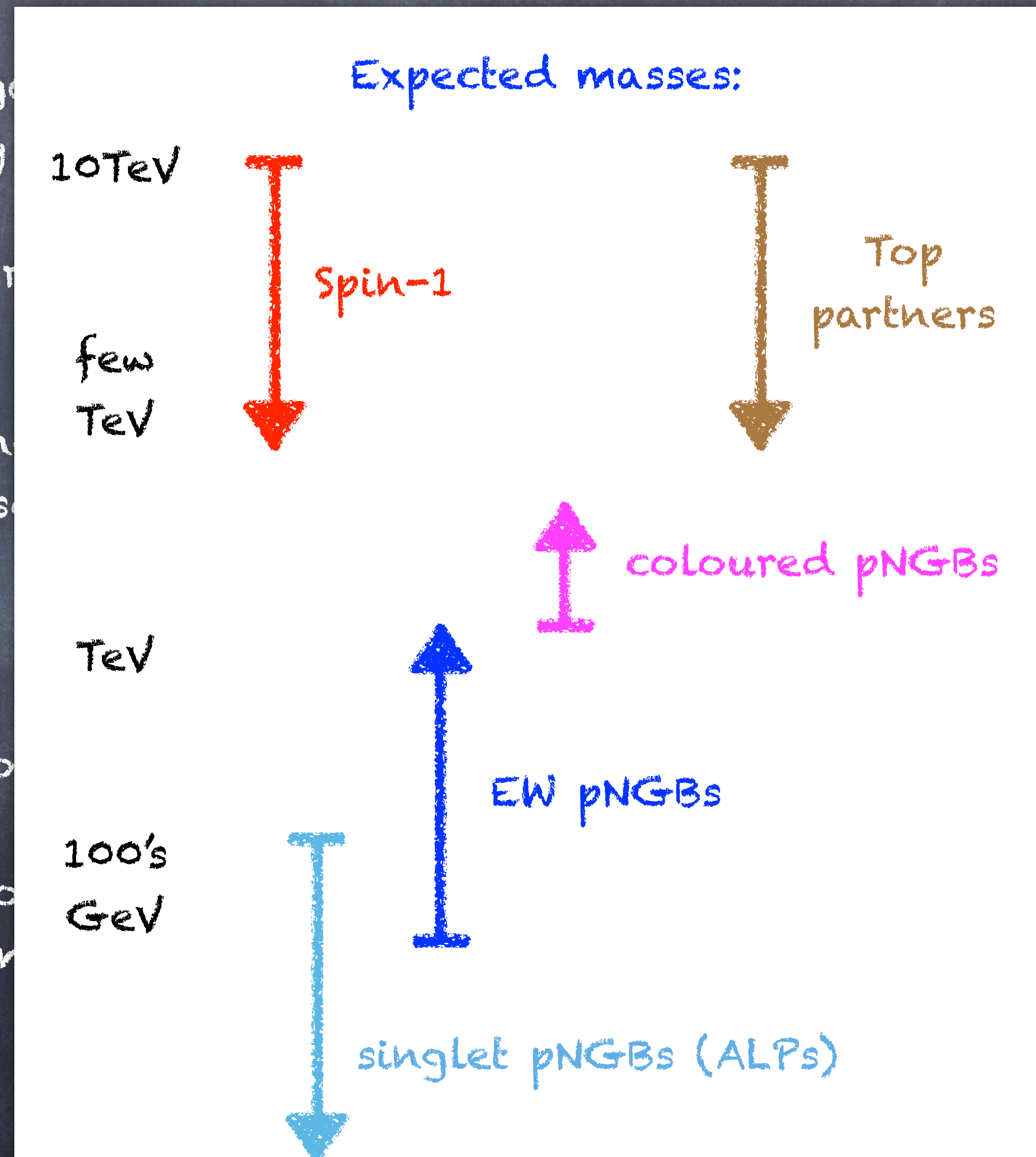

The composite Higgs wilderness

- Very light ALPs (below the Z)
- Singlets (Thomas' talk)
- Electroweak pNGBs (Thomas' talk)
- Coloured scalars
- Common exotic top partner decays
- Exotic-colour top partners
- Spin-1 resonances

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EW and Higgs precision!!!

	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	$2/3$	/	

Sp(4) with (N_F, N_A) Dirac fermions

$M8: \quad (2,3)$

~~$M5: \quad (3,\frac{5}{2})$~~

Next-to-minimal

$(3,3)$

Describes $M8^*$ and $M5^*$

On the conformal windowsill: many possibilities

The models

QCD \ EW	SU(4)/Sp(4)	SU(5)/SO(5)	$SU(4)^2/SU(4)$
SU(6)/Sp(6)		M5 ($\psi\chi\chi$)	
SU(6)/SO(6)	M8-9 ($\psi\psi\chi$)	M3-4 ($\psi\psi\chi$) M1-2 ($\psi\chi\chi$)	M10-11 ($\psi\psi\chi$)
$SU(3)^2/SU(3)$		M6-7 ($\psi\chi\chi$)	M12 ($\psi\psi\chi$)

7 classes of models!

Focusing on QCD-charged states:

	Models	χ (R, Y, B)	π	$\mathcal{V}^\mu$	$\mathcal{A}^\mu$	Ψ	di-quark
C1	M1-2	(R,$-\frac{1}{3}$,$\frac{1}{6}$)	8_0, $6_{-2/3}$	8_0, 1_0, $3_{2/3}$	8_0, $6_{-2/3}$	8, 1, 3, 6	none
C2	M3-4, M8-11	(R,$\frac{2}{3}$,$\frac{1}{3}$)	8_0, $6_{4/3}$	8_0, 1_0, $3_{-4/3}$	8_0, $6_{4/3}$	3	π_6, $\mathcal{V}_3^\mu$, $\mathcal{A}_6^\mu$
C3	M5	(Pr,$-\frac{1}{3}$,$\frac{1}{6}$)	8_0, $3_{2/3}$	8_0, 1_0, $6_{-2/3}$	8_0, $3_{2/3}$	8, 1, 3, 6	none
C4	M6-7	(C,$-\frac{1}{3}$,$\frac{1}{6}$)	8_0	8_0, 1_0	8_0	8, 1, 3, 6	none
C5	M12	(C,$\frac{2}{3}$,$\frac{1}{3}$)	8_0	8_0, 1_0	8_0	3	none

Red: $B = 1/3$ Blue: $B = 2/3$

Coloured pNGBs

- They are always present in models.
- They are relatively light (TeV scale)

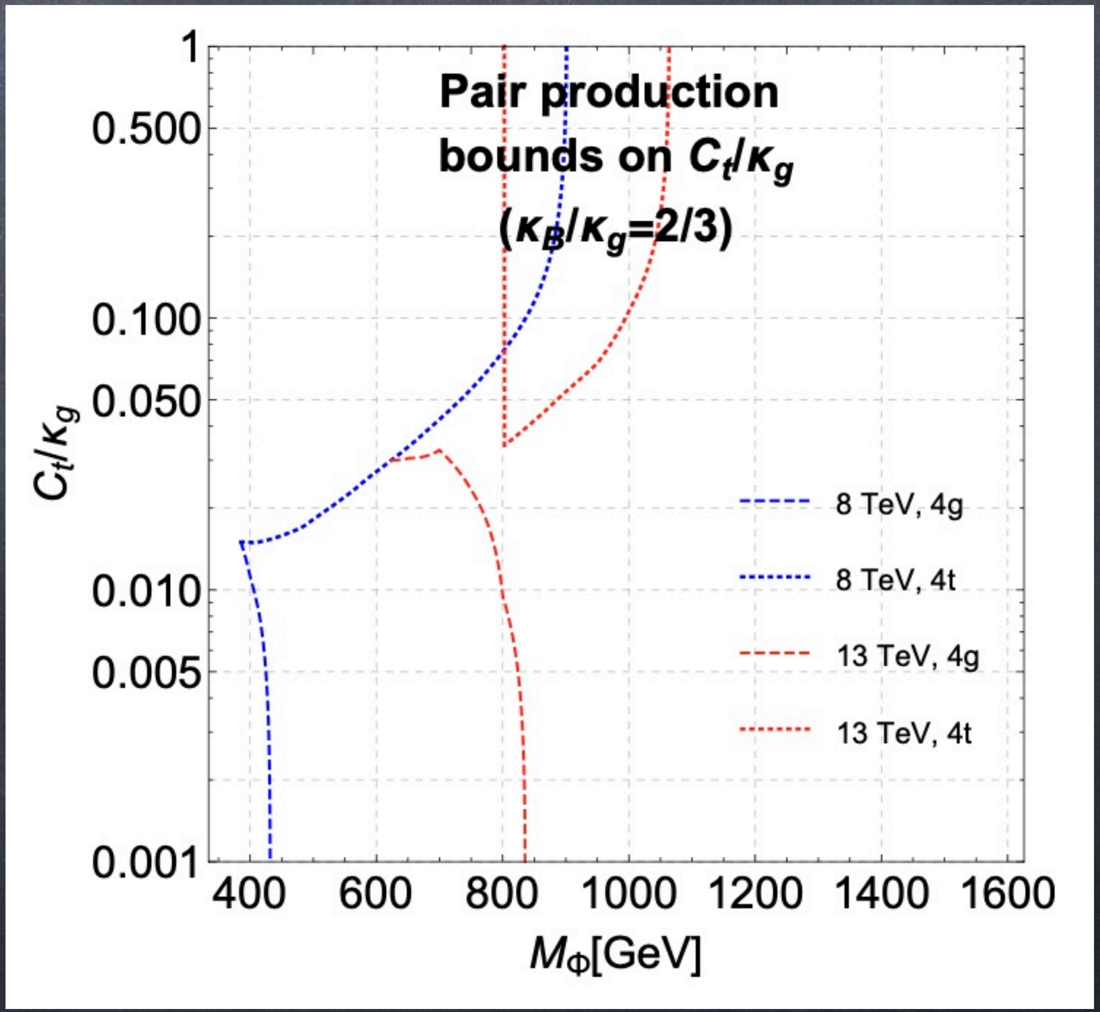
C1 :	$\pi_8 \to t\bar{t},\, gg;\ \pi_6 \to bb\,,$
C2 :	$\pi_8 \to t\bar{t},\, gg;\ \pi_6 \to tt\,,$
C3 :	$\pi_8 \to t\bar{t},\, gg;\ \pi_3 \to \bar{b}\bar{s}$ or $t\bar{\nu},\, b\tau^+\,,$
C4-5 :	$\pi_8 \to t\bar{t},\, gg\,.$

2002.01474

Octet $\begin{cases} \pi_8 \to t\bar{t} & \text{(sgluon-like)} \\ \pi_8 \to gg\,, g\gamma \end{cases}$

Triplet $\begin{cases} \pi_3 \to b\bar{s} \\ \pi_3 \to t\chi \end{cases}$ (stop-like)

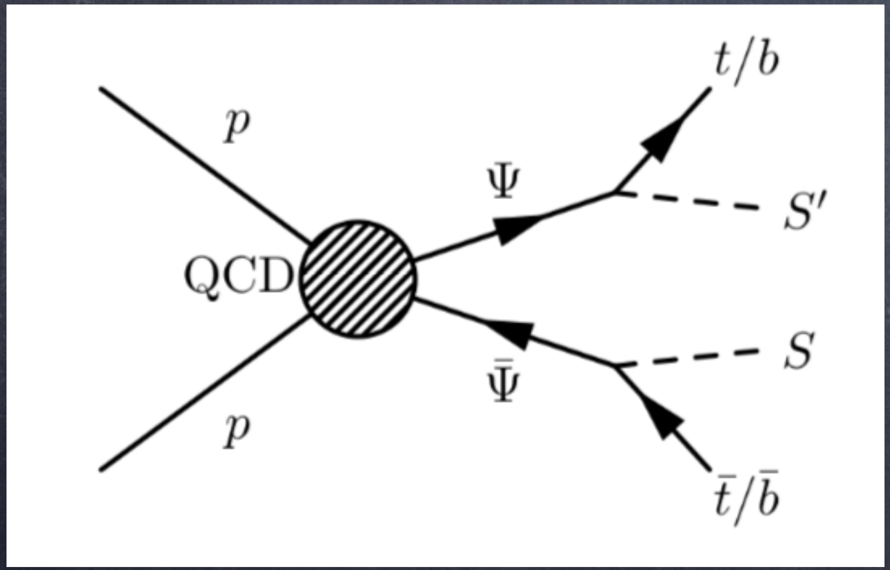
Sextet $\begin{cases} \pi_6 \to tt \\ \pi_6 \to bb \end{cases}$



Top partner pheno revisited

A.Banerjee et al
2203.0727 (Snowmass LOI)

- Dedicated searches in SM final states: tZ, bW, tH...
- pNGBs lighter than the top partners are to be expected in all composite models



The S decays are model-dependent, but they can be classified:

$$S_i^{++} \to W^+W^+$$
$$S_i^{+} \to W^+\gamma,\ W^+Z$$
$$S_i^{0} \to W^+W^-,\ \gamma\gamma,\ \gamma Z,\ ZZ.$$

Calculable ratios (from anomalies) and always present for all models.

$$S^{++} \to W^+ t\bar{b},$$
$$S^{+} \to t\bar{b},$$
$$S^{0} \to t\bar{t},\ b\bar{b}.$$

Dominant, if present for the specific S.

Common exotic top partner decays

$$\mathcal{L}_{\Psi f V} = \frac{e}{\sqrt{2} s_W} \kappa^W_{T,L} \overline{T} \not{W}^+ P_L b + \frac{e}{2 c_W s_W} \kappa^Z_{T,L} \overline{T} \not{Z} P_L t + \frac{e}{\sqrt{2} s_W} \kappa^W_{B,L} \overline{B} \not{W}^- P_L t$$
$$+ \frac{e}{2 c_W s_W} \kappa^Z_{B,L} \overline{B} \not{Z} P_L b + \frac{e}{\sqrt{2} s_W} \kappa^W_{X,L} \overline{X} \not{W}^+ P_L t + L \leftrightarrow R + \text{h.c.} \qquad (14)$$

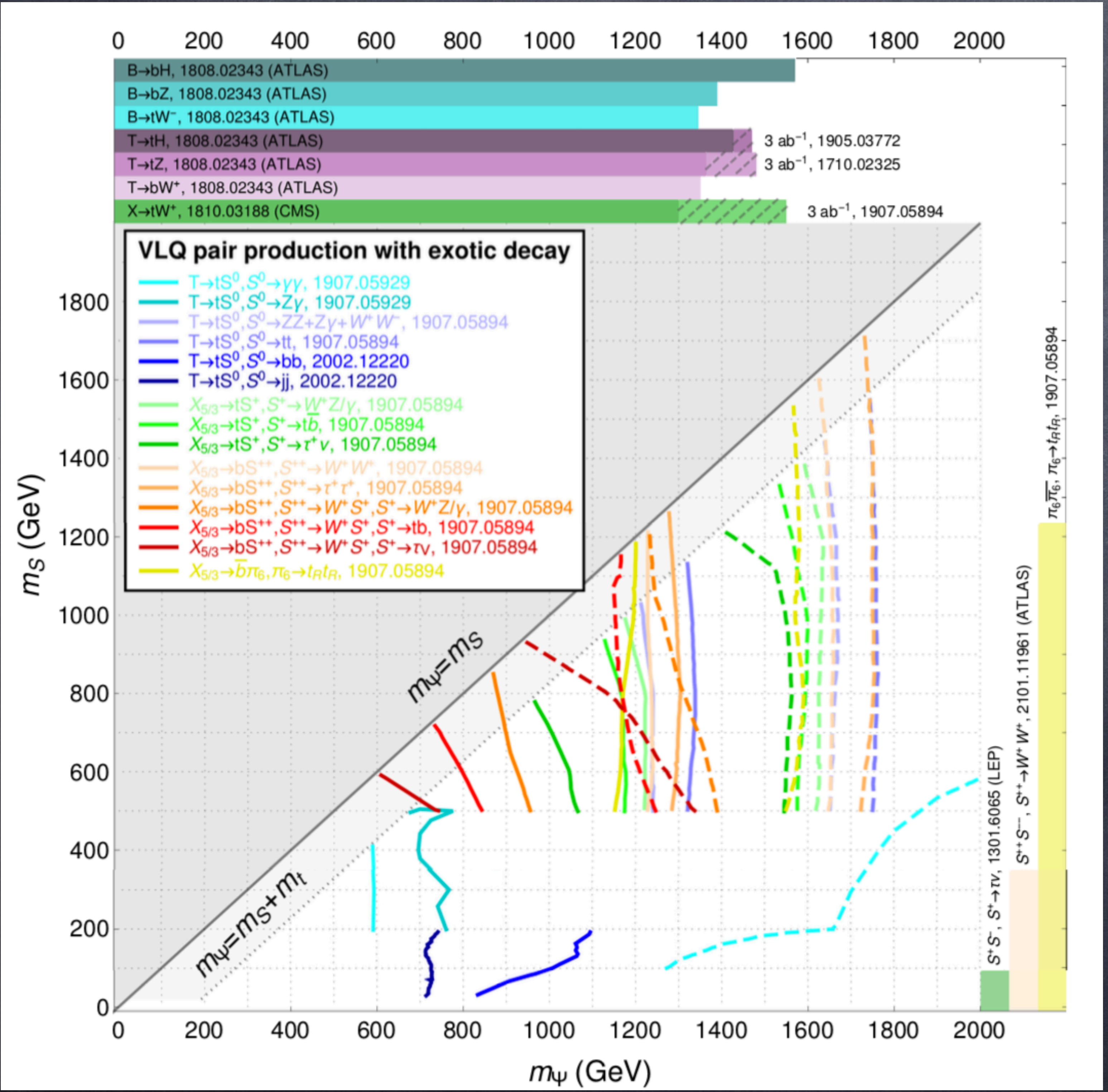
$$\mathcal{L}_{\Psi f S} = \sum_i S_i^+ \left[\kappa^{S_i^+}_{T,L} \overline{T} P_L b + \kappa^{S_i^+}_{X,L} \overline{X} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^- \left[\kappa^{S_i^-}_{B,L} \overline{B} P_L t + L \leftrightarrow R \right] + \text{h.c.}$$
$$+ \sum_i S_i^0 \left[\kappa^{S_i^0}_{T,L} \overline{T} P_L t + \kappa^{S_i^0}_{B,L} \overline{B} P_L b + L \leftrightarrow R \right] + \text{h.c.}$$
$$+ \sum_i S_i^{++} \left[\kappa^{S_i^{++}}_{X,L} \overline{X} P_L b + L \leftrightarrow R \right] + \text{h.c.} \qquad (15)$$

- Possible to write a Master-Lagrangian containing all possible couplings, implemented at NLO in MG (FSMOG)

Work in progress (??)

Common exotic top partner decays

A.Banerjee et al
2203.0727 (Snowmass LOI)



- Dedicated searches may be useful to push up the limits.
- Projections for FCC-hh are needed...
- in combination with scalar direct production.

Exotic top partners

	Models	$\chi\ (R,Y,B)$	π	$\mathcal{V}^\mu$	$\mathcal{A}^\mu$	Ψ	di-quark
C1	M1-2	$(\mathrm{R},-\frac{1}{3},\frac{1}{6})$	8_0, $6_{-2/3}$	8_0, 1_0, $3_{2/3}$	8_0, $6_{-2/3}$	8, 1, 3, 6	none
C2	M3-4, M8-11	$(\mathrm{R},\frac{2}{3},\frac{1}{3})$	8_0, $6_{4/3}$	8_0, 1_0, $3_{-4/3}$	8_0, $6_{4/3}$	3	$\pi_6, \mathcal{V}^\mu_3, \mathcal{A}^\mu_6$
C3	M5	$(\mathrm{Pr},-\frac{1}{3},\frac{1}{6})$	8_0, $3_{2/3}$	8_0, 1_0, $6_{-2/3}$	8_0, $3_{2/3}$	8, 1, 3, 6	none
C4	M6-7	$(\mathrm{C},-\frac{1}{3},\frac{1}{6})$	8_0	8_0, 1_0	8_0	8, 1, 3, 6	none
C5	M12	$(\mathrm{C},\frac{2}{3},\frac{1}{3})$	8_0	8_0, 1_0	8_0	3	none

Models in C1, C3 and C4 contain top-partners as octet and sextet!

$\psi\chi\chi$ types

Larger production than the triplets!

Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

- A specific model: M5 of Ferretti's classification

Hyper-fermions

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$			
$\psi_{3,4}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
ψ_5	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1							
χ_2	$\Box$	$\mathbf{3}$	$\mathbf{1}$	$-x$			
χ_3							
χ_4					$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_5	$\Box$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			
χ_6							

$x = -1/3$

Chimera Baryons (top partners)

	$SU(5)\times SU(6)$	$SO(5)\times Sp(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^1_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_1$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar\chi\bar\chi$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^2_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_1$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar\psi\bar\chi\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^3_{14}$
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_1$

$$\mathbf{14} \to \mathbf{8}_0 + \mathbf{3}_{-2x} + \bar{\mathbf{3}}_{2x}\,,$$

$$\mathbf{21} \to \mathbf{8}_0 + \mathbf{6}_{2x} + \bar{\mathbf{6}}_{-2x} + \mathbf{1}_0$$

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ψ_5	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1							
χ_2	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$			
χ_3							
χ_4					$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_5	$\square$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			
χ_6							

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	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar\chi\bar\chi$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^2_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_{1}$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar\psi\bar\chi\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^3_{14}$
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_{1}$

$$\mathbf{14} \to \mathbf{8_0} + \mathbf{3_{-2x}} + \bar{\mathbf{3}}_{\mathbf{2x}}$$

$$\mathbf{21} \to \mathbf{8_0} + \mathbf{6_{2x}} + \bar{\mathbf{6}}_{\mathbf{-2x}} + \mathbf{1_0}$$

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$\psi_{3,4}$	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{smallmatrix}\square\\ \square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1, χ_2, χ_3	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4, χ_5, χ_6	$\square$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			

$x = -1/3$

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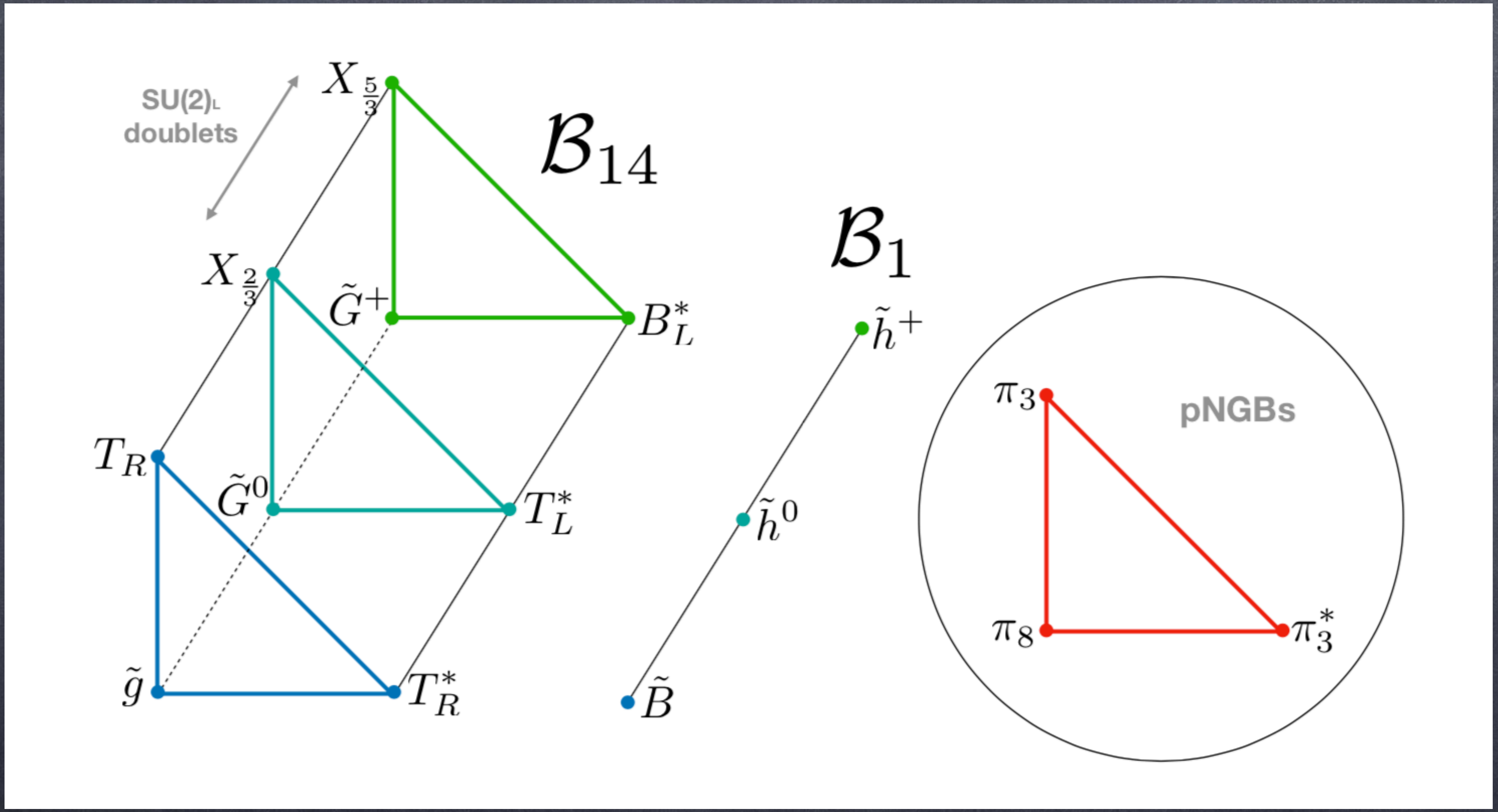
$\psi\bar\chi\bar\chi$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^2_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_{1}$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar\psi\bar\chi\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^3_{14}$
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_{1}$

$\mathbf{14} \to \mathbf{8_0} + \mathbf{3_{-2x}} + \bar{\mathbf{3}}_{\mathbf{2x}}$

$\mathbf{21} \to \mathbf{8_0} + \mathbf{6_{2x}} + \bar{\mathbf{6}}_{\mathbf{-2x}} + \mathbf{1_0}$

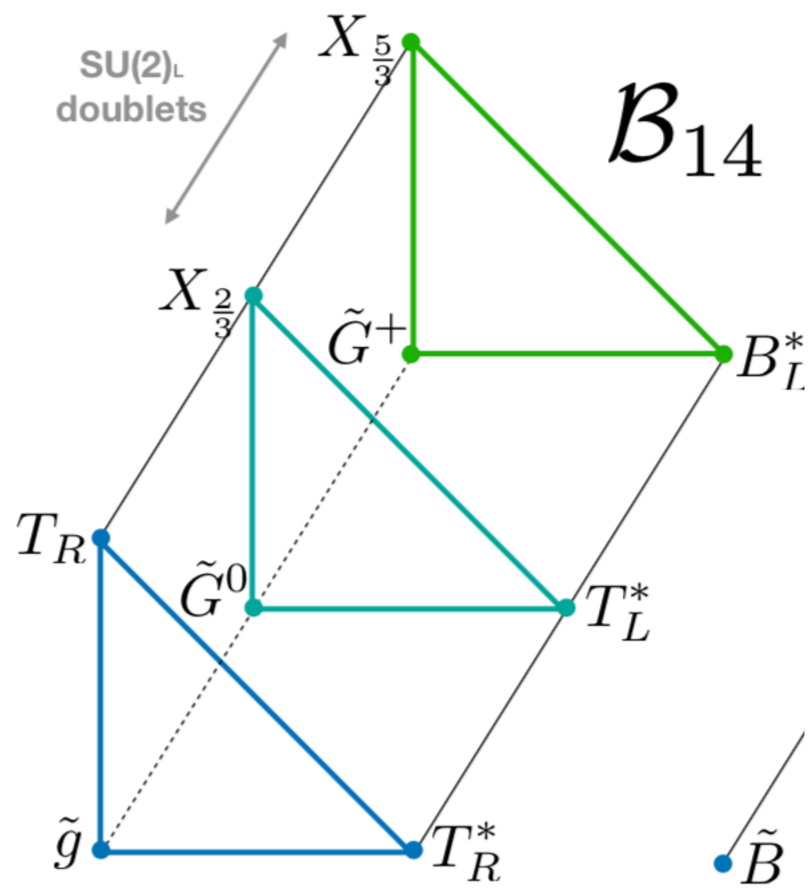
Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019



Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019



$$\text{Octoni (Dirac):}\quad \tilde{G}^+ = \begin{pmatrix} \tilde{G}_u^+ \\ \bar{\tilde{G}}_d^- \end{pmatrix}\,,\quad \tilde{G}^0 = \begin{pmatrix} \tilde{G}_u^0 \\ \bar{\tilde{G}}_d^0 \end{pmatrix}\,,$$

$$\text{Gluoni (Majorana):}\quad \tilde{g} = \begin{pmatrix} \tilde{g} \\ \bar{\tilde{g}} \end{pmatrix}\,;$$

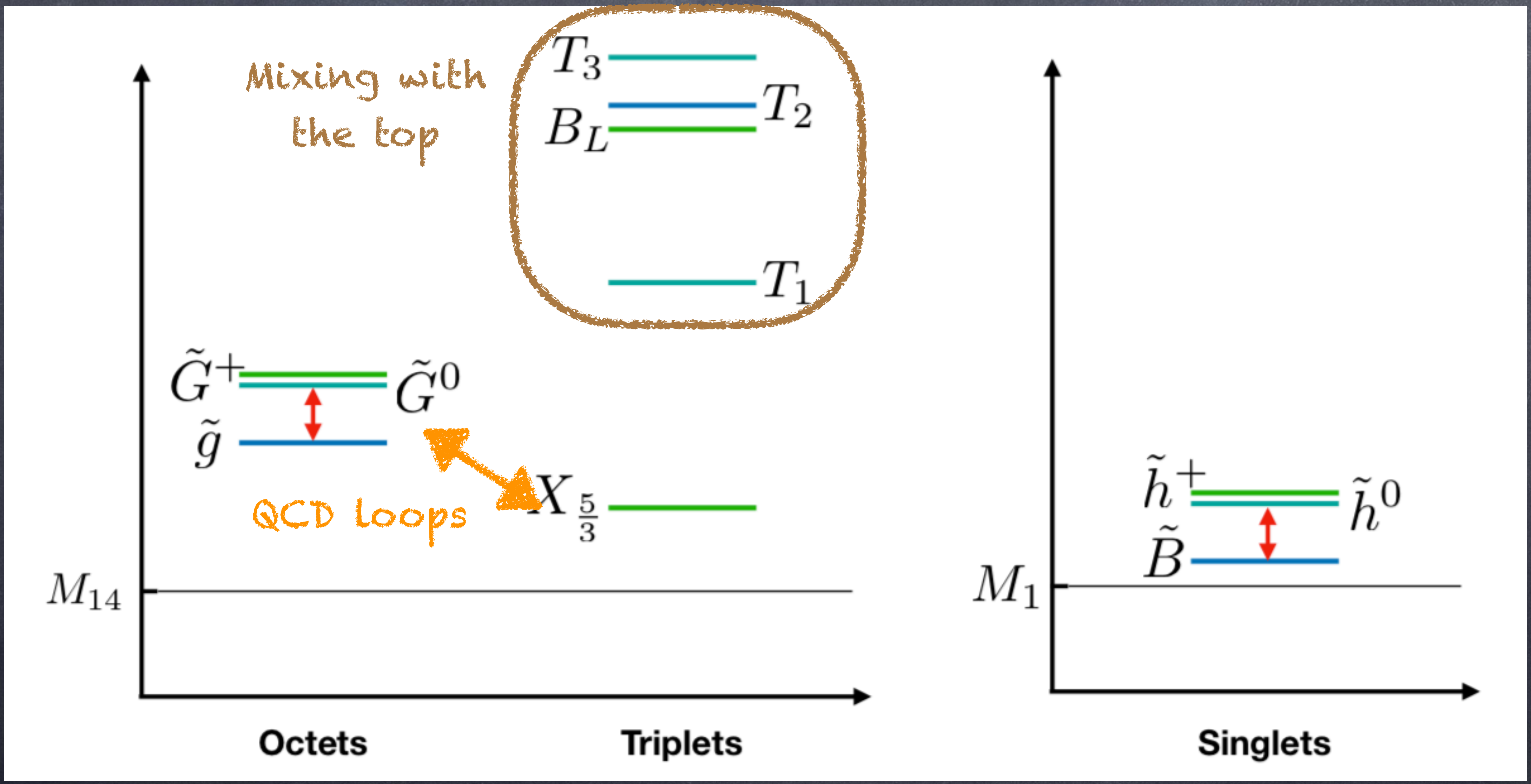
$$\text{Higgsoni (Dirac):}\quad \tilde{h}^+ = \begin{pmatrix} \tilde{h}_u^+ \\ \bar{\tilde{h}}_d^- \end{pmatrix}\,,\quad \tilde{h}^0 = \begin{pmatrix} \tilde{h}_u^0 \\ \bar{\tilde{h}}_d^0 \end{pmatrix}\,,$$

$$\text{Boni (Majorana):}\quad \tilde{B} = \begin{pmatrix} \tilde{B} \\ \bar{\tilde{B}} \end{pmatrix}\,.$$

The baryon content looks ironically SUSY-like!

Exotic top partners

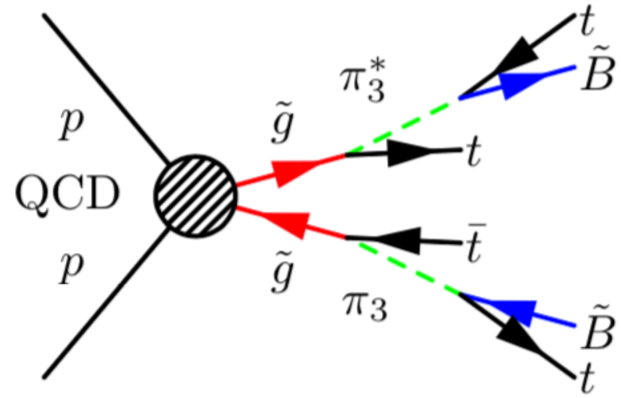
G.Cacciapaglia et al.
2112.00019



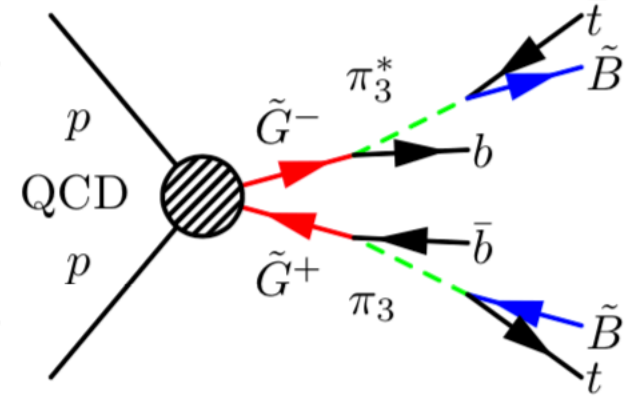
Octoni bounds

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

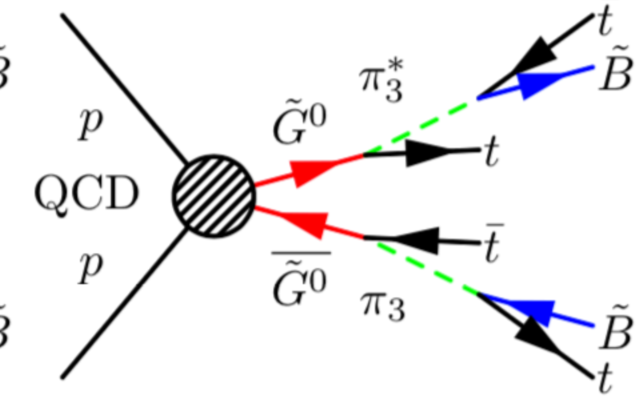
- Model implemented in MG.
- Check limits from searches in MadAnalysis and CheckMate.
- Strongest bound from gluino and stop searches!



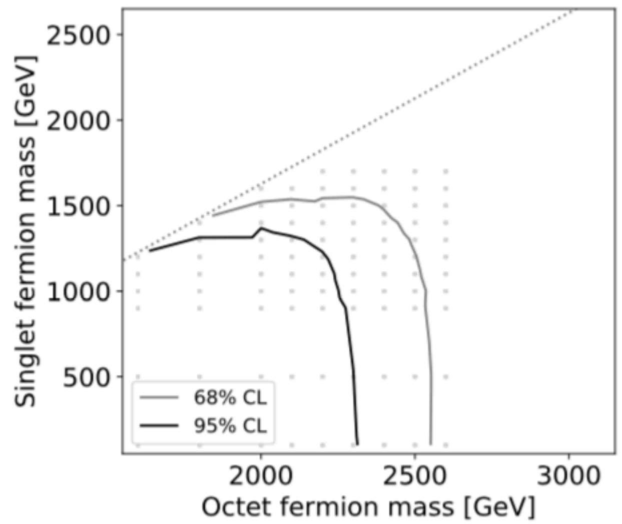
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$



(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$

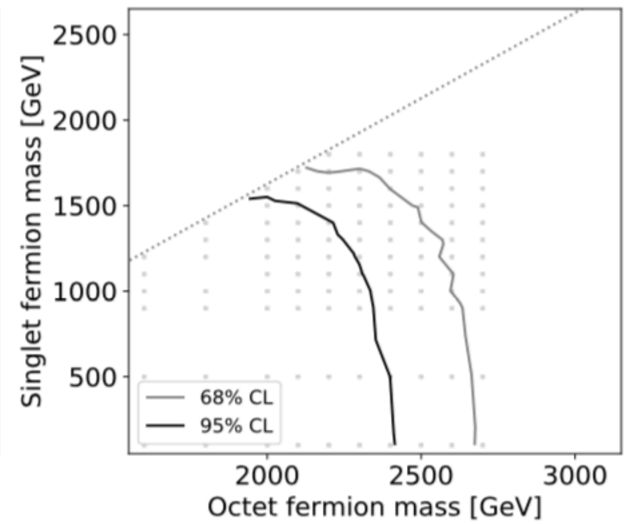


(c) $\tilde{G}^0 \to \bar{t}\pi_3 \to \bar{t}t\tilde{B}$



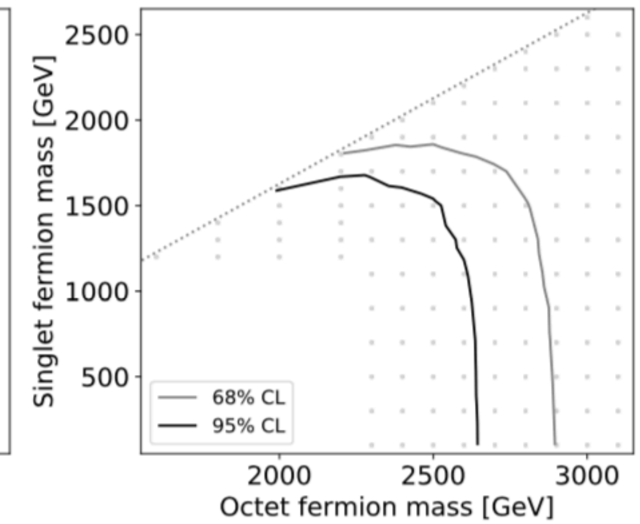
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

$m_{\tilde{g}} - m_{\pi_3} = 200$ GeV



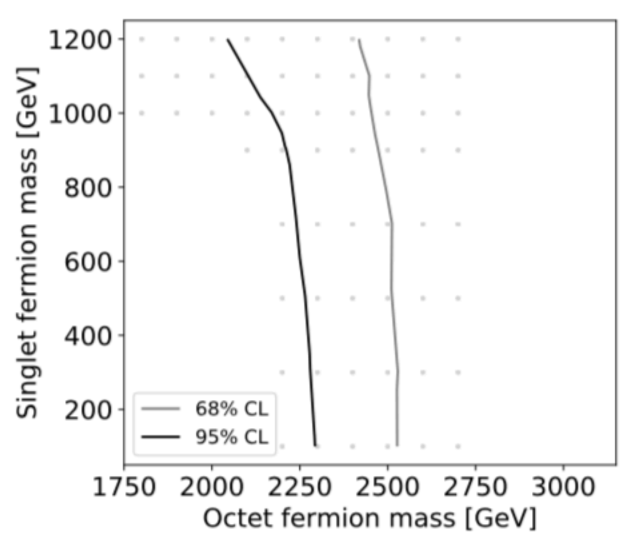
(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

$m_{\tilde{G}^+} - m_{\pi_3} = 200$ GeV



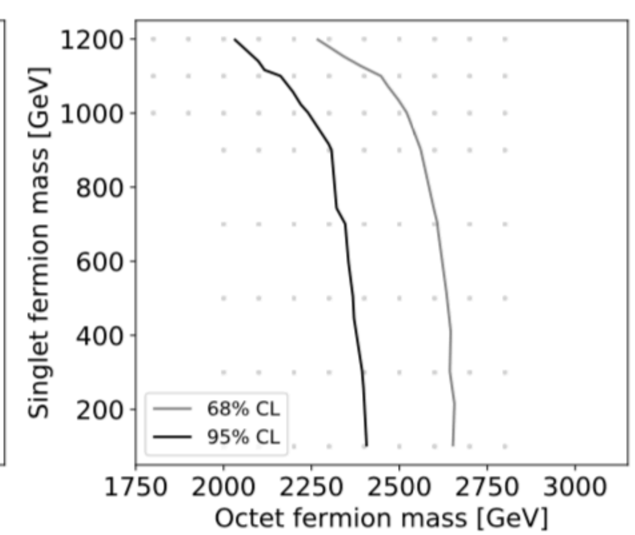
(c) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

$m_{Q_8} - m_{\pi_3} = 200$ GeV



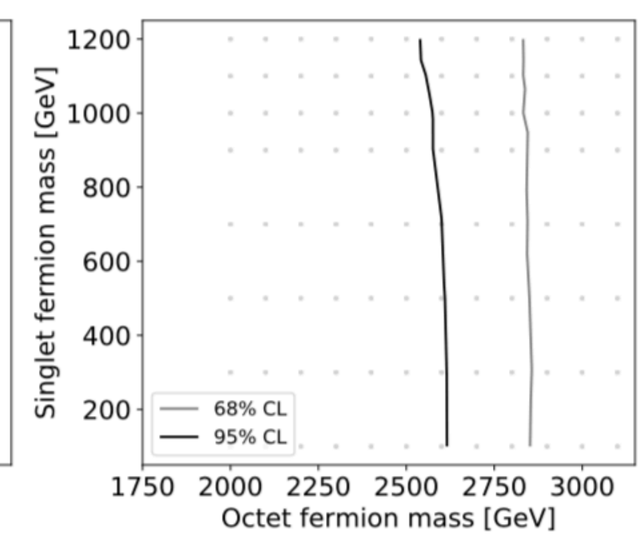
(d) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV



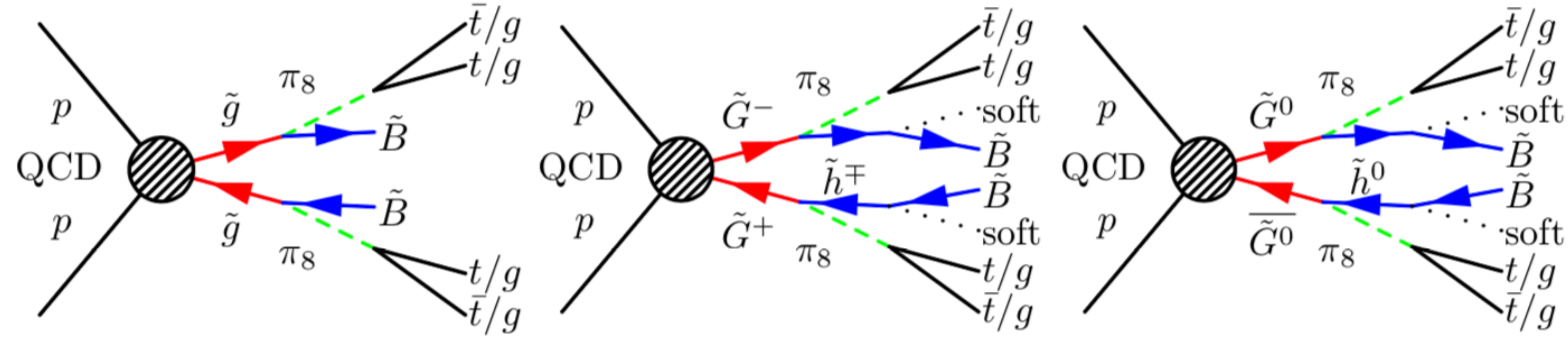
(e) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV

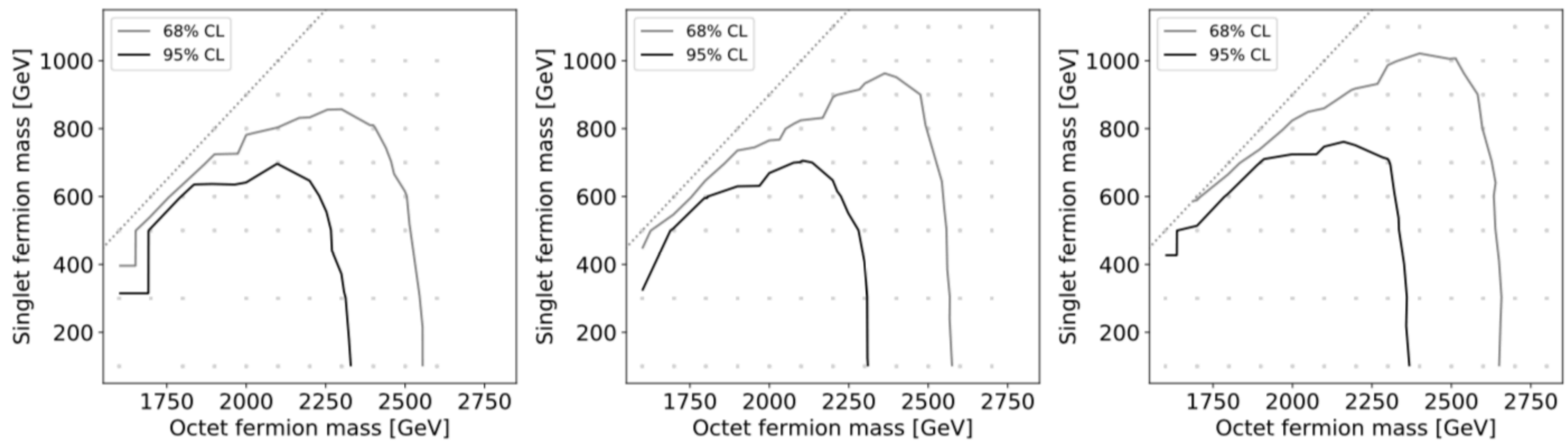


(f) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

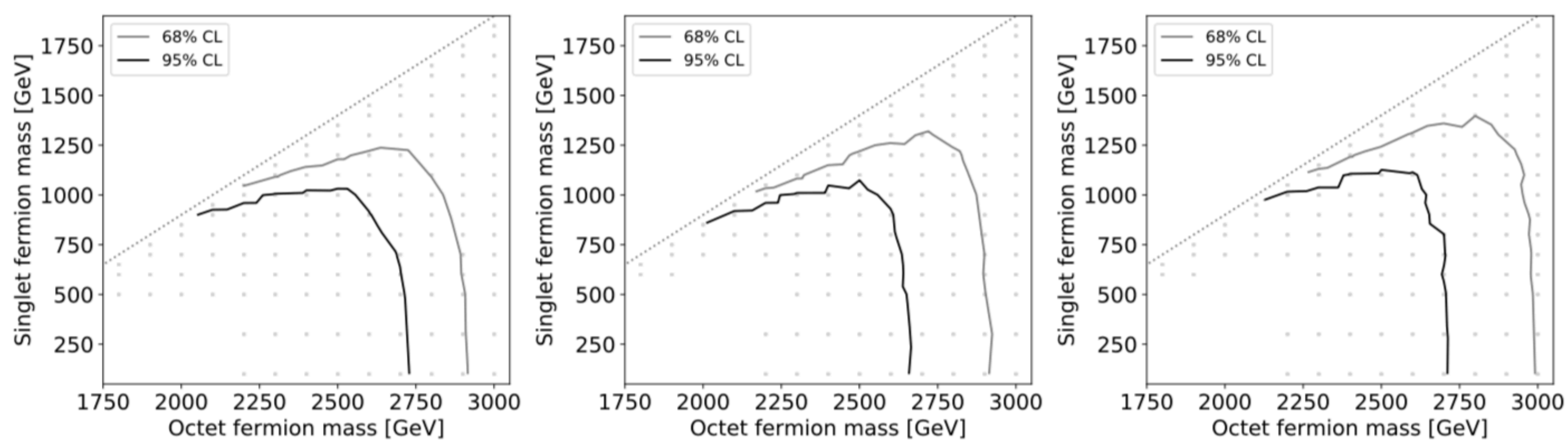
$m_{\pi_3} = 1.4$ TeV



(a) $\tilde{g} \to \tilde{B}\pi_8,\ \pi_8 \to \bar{t}t/gg.$ (b) $\tilde{G}^+ \to \tilde{h}^+\pi_8,\ \pi_8 \to \bar{t}t/gg.$ (c) $\tilde{G}^0 \to \tilde{h}^0\pi_8,\ \pi_8 \to \bar{t}t/gg.$



(a) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg$ (b) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg, t\bar{t}$ (c) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to t\bar{t}$



(d) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to gg$ (e) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to gg, t\bar{t}$ (f) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to t\bar{t}$

Spin-1 resonances

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

	Models	$\chi\ (R,Y,B)$	π	$\mathcal{V}^\mu$	$\mathcal{A}^\mu$	Ψ	di-quark
C1	M1-2	$(\mathrm{R},-\frac{1}{3},\frac{1}{6})$	8_0, $6_{-2/3}$	8_0, 1_0, $3_{2/3}$	8_0, $6_{-2/3}$	8, 1, 3, 6	none
C2	M3-4, M8-11	$(\mathrm{R},\frac{2}{3},\frac{1}{3})$	8_0, $6_{4/3}$	8_0, 1_0, $3_{-4/3}$	8_0, $6_{4/3}$	3	$\pi_6, \mathcal{V}_3^\mu, \mathcal{A}_6^\mu$
C3	M5	$(\mathrm{Pr},-\frac{1}{3},\frac{1}{6})$	8_0, $3_{2/3}$	8_0, 1_0, $6_{-2/3}$	8_0, $3_{2/3}$	8, 1, 3, 6	none
C4	M6-7	$(\mathrm{C},-\frac{1}{3},\frac{1}{6})$	8_0	8_0, 1_0	8_0	8, 1, 3, 6	none
C5	M12	$(\mathrm{C},\frac{2}{3},\frac{1}{3})$	8_0	8_0, 1_0	8_0	3	none

- Octets (and one singlet) ubiquitous
- V_8 always mixes with the gluon (V_1 with hypercharge)
- Triplets and sextets present in C1, C2 and C3.

Spin-1 resonances

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

Professionally implemented via hidden symmetry:

$$\mathcal{L} = -\frac{1}{2}\,\mathrm{Tr}\,\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu} + \frac{f_0^2}{2}\,\mathrm{Tr}\,d_{0,\mu}d_0^{\mu} + \frac{f_1^2}{2}\,\mathrm{Tr}\,d_{1,\mu}d_1^{\mu} + \frac{f_K^2}{2}\,\mathrm{Tr}\,D^{\mu}K(D_{\mu}K)^{\dagger} + r f_1^2\,\mathrm{Tr}\,d_{0,\mu}K d_1^{\mu}K^{\dagger} + \mathcal{L}_{\mathrm{fermions}}$$

G_0/H_0 $\quad$ G_1/H_1 $\quad$ $H_0 \times H_1/H$

Spin-1 resonances

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

Professionally implemented via hidden symmetry:

$$\begin{aligned}\mathcal{L} = &-\frac{1}{2}\,\mathrm{Tr}\,\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu}\\ &+\frac{f_0^2}{2}\,\mathrm{Tr}\,d_{0,\mu}d_0^{\mu} + \frac{f_1^2}{2}\,\mathrm{Tr}\,d_{1,\mu}d_1^{\mu}\\ &+\frac{f_K^2}{2}\,\mathrm{Tr}\,D^{\mu}K(D_{\mu}K)^{\dagger} + r f_1^2\,\mathrm{Tr}\,d_{0,\mu}K d_1^{\mu}K^{\dagger}\\ &+\mathcal{L}_{\mathrm{fermions}}\end{aligned}$$

G_0/H_0 $\qquad$ G_1/H_1 $\qquad$ $H_0 \times H_1/H$

SM gauging

$SU(3)_c \times U(1)_Y$

Spin-1 resonances

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

Professionally implemented via hidden symmetry:

$$\mathcal{L} = -\frac{1}{2}\,\mathrm{Tr}\,\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{2}\,\mathrm{Tr}\,\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu}$$
$$+ \frac{f_0^2}{2}\,\mathrm{Tr}\,d_{0,\mu}d_0^{\mu} + \frac{f_1^2}{2}\,\mathrm{Tr}\,d_{1,\mu}d_1^{\mu}$$
$$+ \frac{f_K^2}{2}\,\mathrm{Tr}\,D^{\mu}K(D_{\mu}K)^{\dagger} + r f_1^2\,\mathrm{Tr}\,d_{0,\mu}K d_1^{\mu}K^{\dagger}$$
$$+ \mathcal{L}_{\mathrm{fermions}}$$

G_0/H_0

SM gauging

$SU(3)_c \times U(1)_Y$

G_1/H_1

Full gauging

Resonances

Masses for V

$H_0 \times H_1/H$

Connects the two sectors

Masses for A

Spin-1 resonances

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Work in progress

Professionally implemented via hidden symmetry:

$$\mathcal{L} = -\frac{1}{2}\operatorname{Tr}\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu} - \frac{1}{2}\operatorname{Tr}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} - \frac{1}{2}\operatorname{Tr}\boldsymbol{\mathcal{F}}_{\mu\nu}\boldsymbol{\mathcal{F}}^{\mu\nu} + \frac{f_0^2}{2}\operatorname{Tr} d_{0,\mu} d_0^\mu + \frac{f_1^2}{2}\operatorname{Tr} d_{1,\mu} d_1^\mu + \frac{f_K^2}{2}\operatorname{Tr} D^\mu K (D_\mu K)^\dagger + r f_1^2 \operatorname{Tr} d_{0,\mu} K d_1^\mu K^\dagger + \mathcal{L}_{\text{fermions}}$$

5 indep. parameters : $\tilde{g}, \quad g_{\rho\pi\pi}, \quad M_{\mathcal{V}_8}, \quad \xi, \quad f_\chi .$

$$g_{\rho\pi\pi} = C_{\mathcal{V}_8}|_{\beta_8\to 0} = C_{\mathcal{V}_{3/6}} = \frac{\tilde{g}(r^2-1) f_K^2}{f_0^2\,(1-R^2)}$$

$$\xi = \frac{M_{\mathcal{A}}}{M_{\mathcal{V}_8}}$$

$$f_\chi = \sqrt{f_0^2 - r^2 f_1^2}.$$

Spin-1 resonances: decays

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

- Couplings to pNGBs

$$\mathcal{O}_V = i\,\mathrm{Tr}([\boldsymbol{\pi}, \partial_\mu \boldsymbol{\pi}]\boldsymbol{V}^\mu),$$
$$\mathcal{O}_\mathcal{A} = \mathrm{Tr}([\boldsymbol{\pi}, [\boldsymbol{\pi}, \partial_\mu \boldsymbol{\pi}]]\boldsymbol{\mathcal{A}}^\mu),$$

$V \to \pi\pi$

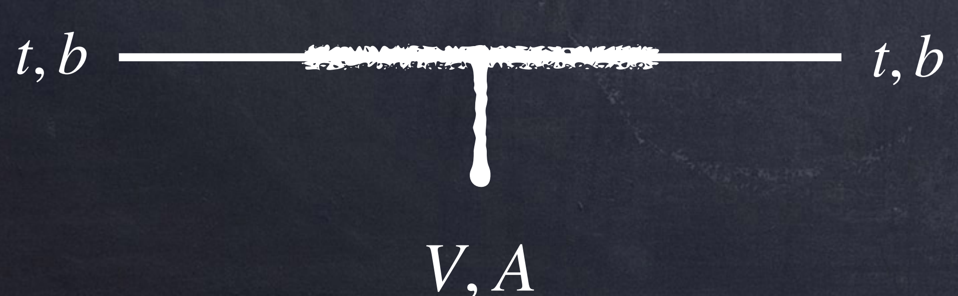
$A \to \pi\pi\pi$

Determined by $g_{\rho\pi\pi}$

- Octet couplings to quarks via mixing

Determined by $\tilde{g}$

- Couplings to tops via Partial Compositeness



Determined by $g_{\rho BB}$

Spin-1 resonances: decays

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

- Couplings to pNGBs

$$\mathcal{O}_V = i\,\mathrm{Tr}([\boldsymbol{\pi}, \partial_\mu \boldsymbol{\pi}]\boldsymbol{V}^\mu),$$
$$\mathcal{O}_A = \mathrm{Tr}([\boldsymbol{\pi}, [\boldsymbol{\pi}, \partial_\mu \boldsymbol{\pi}]]\,\boldsymbol{A}^\mu)$$

$V \to \pi\pi$

$A \to \pi\pi\pi$

Determined by $g_{\rho\pi\pi}$

- Oct

C1-2 :	$\mathcal{V}_8 \to$	$q\bar{q},\ b\bar{b},\ t\bar{t},\ \pi_8\pi_8,\ \pi_6\pi_6^c,$
C3 :	$\mathcal{V}_8 \to$	$q\bar{q},\ b\bar{b},\ t\bar{t},\ \pi_8\pi_8,\ \pi_3\pi_3^c,$
C4-5 :	$\mathcal{V}_8 \to$	$q\bar{q},\ b\bar{b},\ t\bar{t},\ \pi_8\pi_8,$

- Couplings to tops via Partial Compositeness

Determined by $g_{\rho BB}$

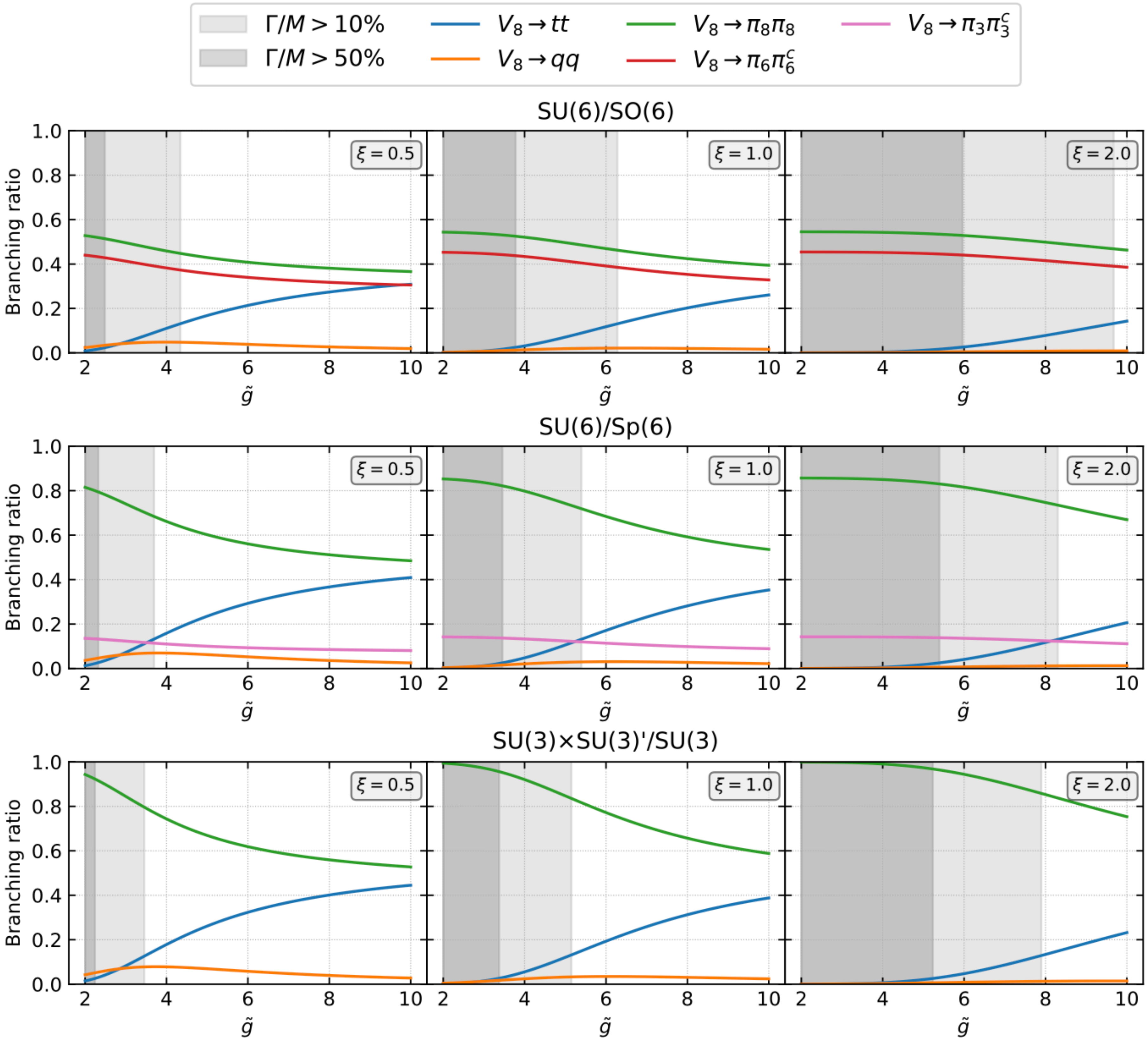


Figure 2: Sample branching ratios for $g_{\rho\pi\pi} = 1$ and $M_{\mathcal{V}_8} = 4.5$ TeV.

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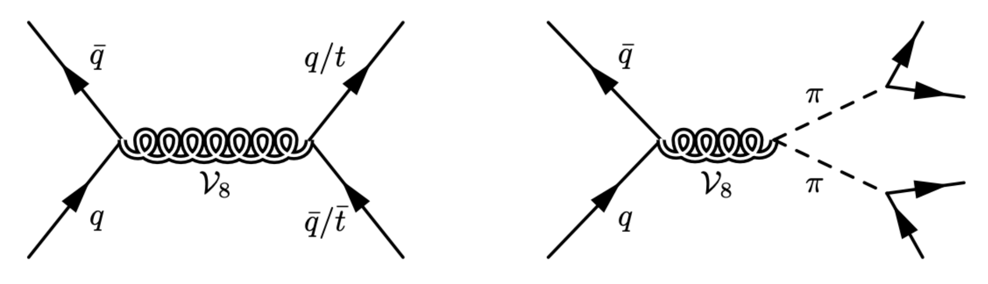
Work in progress

Spin-1 resonances: LHC bounds



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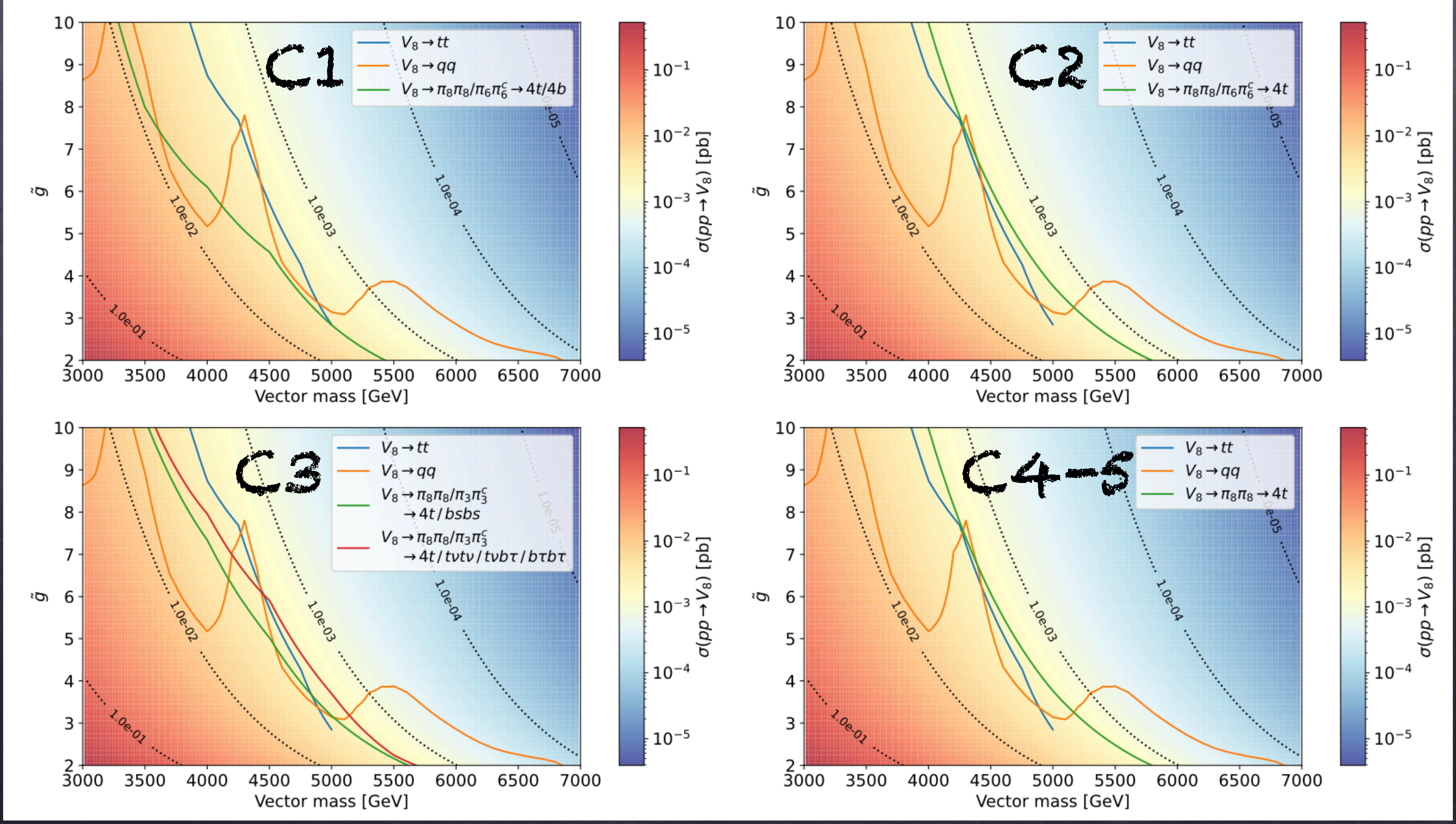
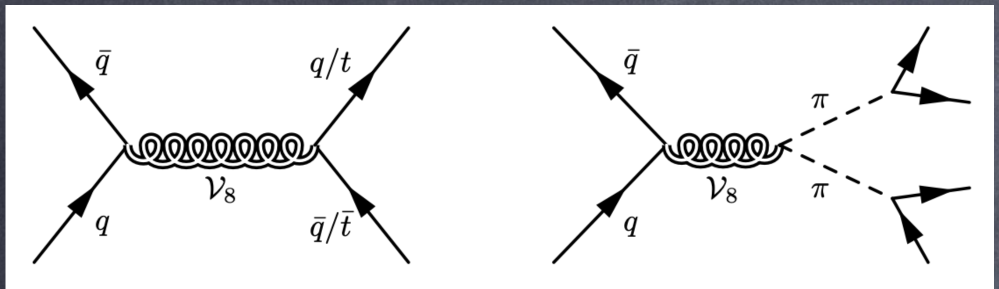
Work in progress



Spin-1 resonances: LHC bounds



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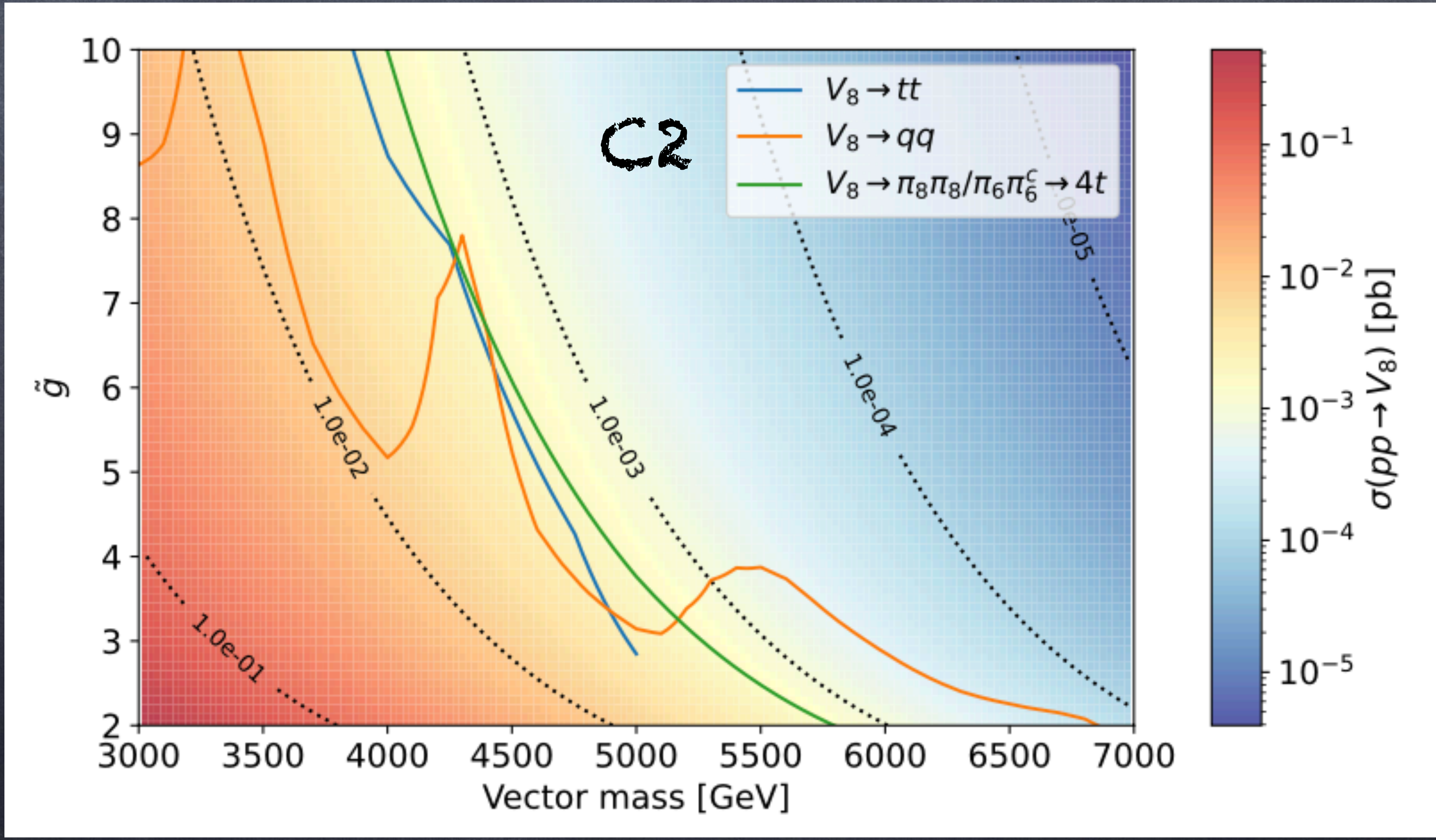
Work in progress



Spin-1 resonances: FCC-hh

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Work in progress

- Pair production becomes relevant
- Dominant channel is the sextet (when present)
- Note: the octet should be discovered in single production channel!

$$\mathcal{V}_6 \to \pi_8 \pi_3^\dagger \to (t\bar{t})(\bar{b}\bar{s} \text{ or } ql) \quad \text{in C3}$$

$$\mathcal{A}_6 \to \pi_8 \pi_8 \pi_6 \ (t\bar{t}t\bar{t}bb) \text{ and } \pi_6^\dagger \pi_6 \pi_6 \ (\bar{b}\bar{b}bbbb) \quad \text{in C1}$$

$$\mathcal{A}_6 \to tt \text{ or } \pi_8 \pi_8 \pi_6 \ (t\bar{t}t\bar{t}tt) \text{ and } \pi_6^\dagger \pi_6 \pi_6 \ (\bar{t}\bar{t}tttt) \quad \text{in C2}$$

The composite Higgs wilderness

- Light un-coloured pNGBs (Thomas' talk)
- Coloured scalars (2 or 4 tops)
- Spin-1 resonances
- Exotic top partners
- Lattice can help!

Spectra! $g_{\rho\pi\pi}$ $g_{\rho BB}$ ...

BONUS TRACKS

Typical ALP Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu},$$

Composite Higgs scenario:

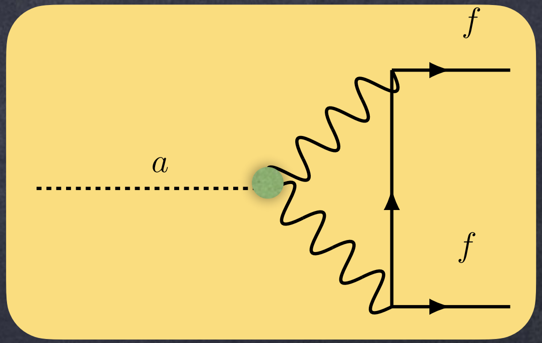
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\mathrm{TC}}}{64\sqrt{2}\,\pi^2 f}$$

$$\frac{C_{GG}}{\Lambda} = 0$$

(Poor bounds at the LHC)

$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

$\mathbf{C}_F$ is loop-induced:



M.Bauer et al, 1708.00443

Typical ALP Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW} \frac{a}{\Lambda} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB} \frac{a}{\Lambda} B_{\mu\nu} \tilde{B}^{\mu\nu},$$

Composite Higgs scenario:

$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

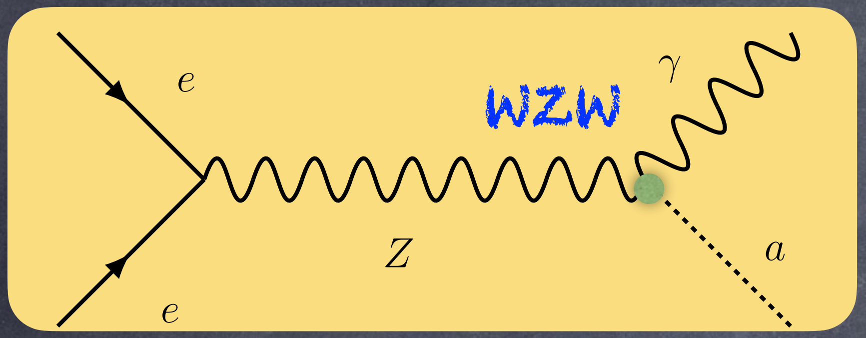
$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

Free parameters:

f, m_a

We will consider two scenarios:
Photo-philic and
Photo-phobic

Tera-Z portal to compositeness (via ALPs)

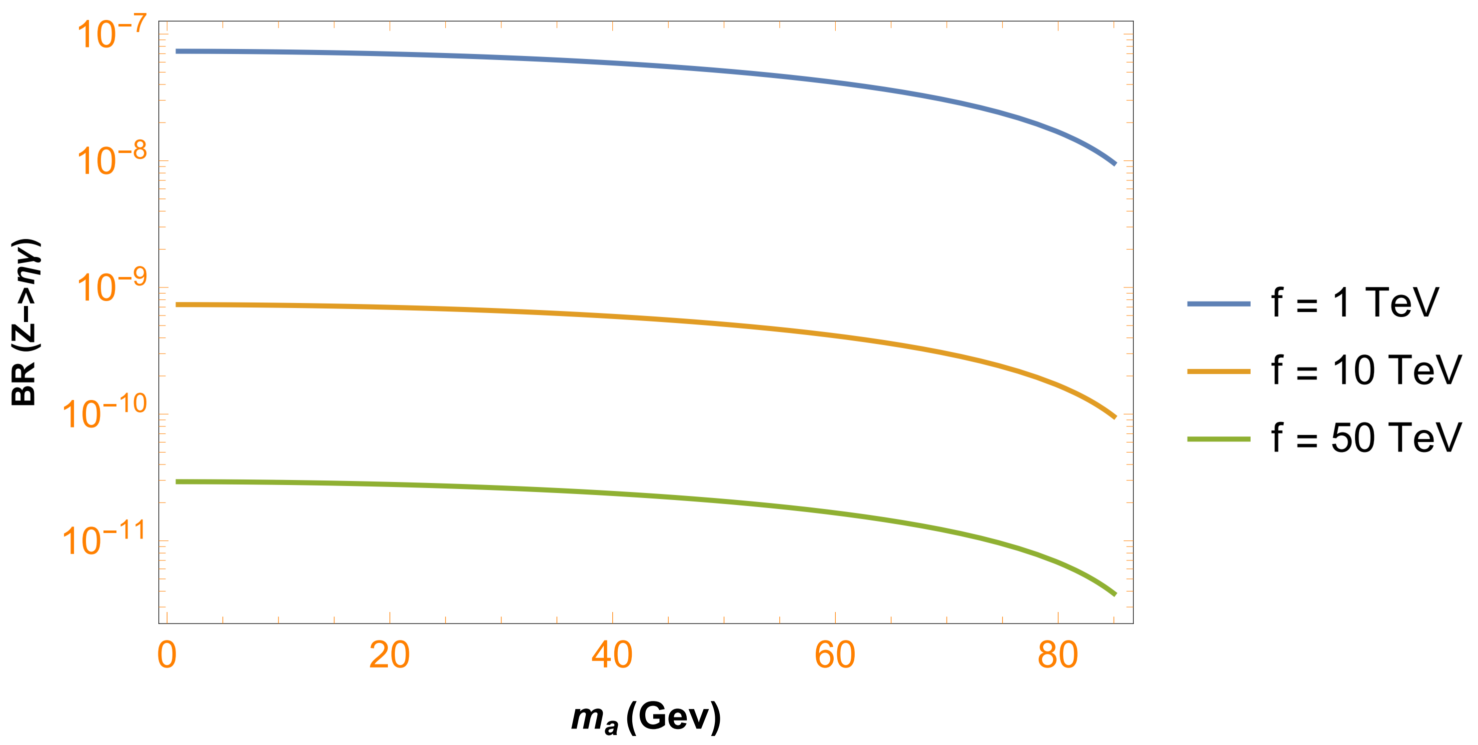


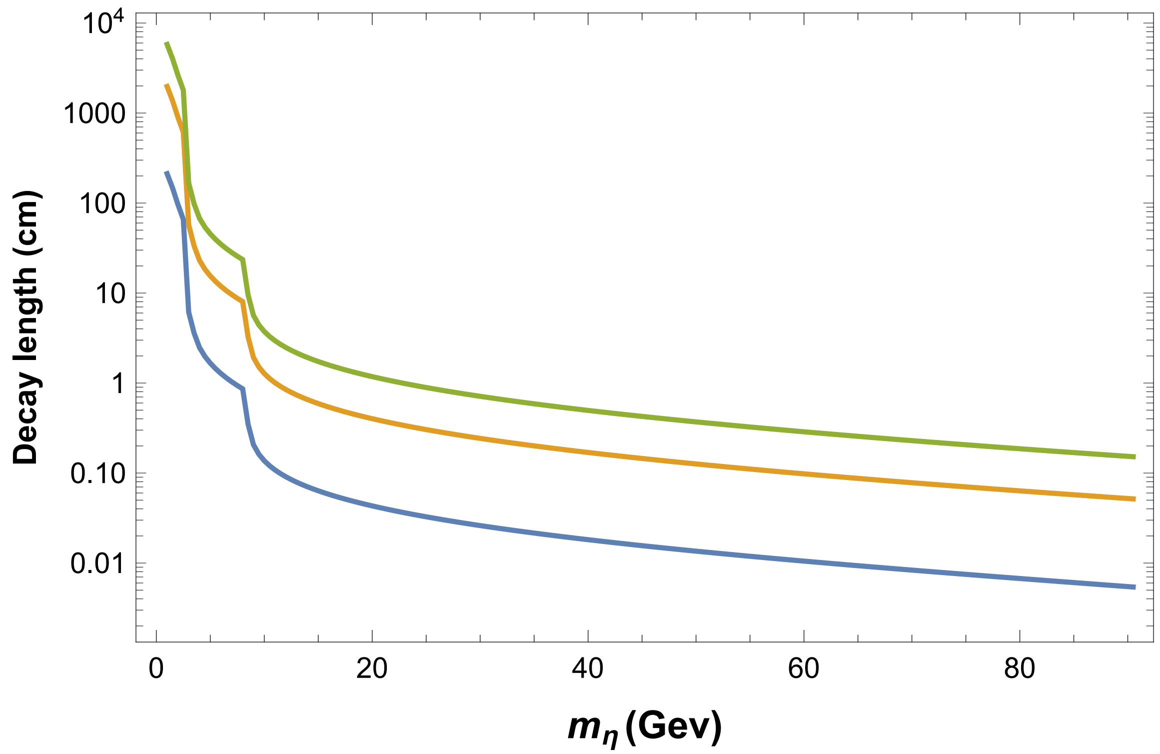
G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

This process is always associated with a monochromatic photon.

Tera Z phase of FCC-ee will lead to 5-6 10^12 Z bosons at the end of the run.

Ideal test for rare Z decays!!

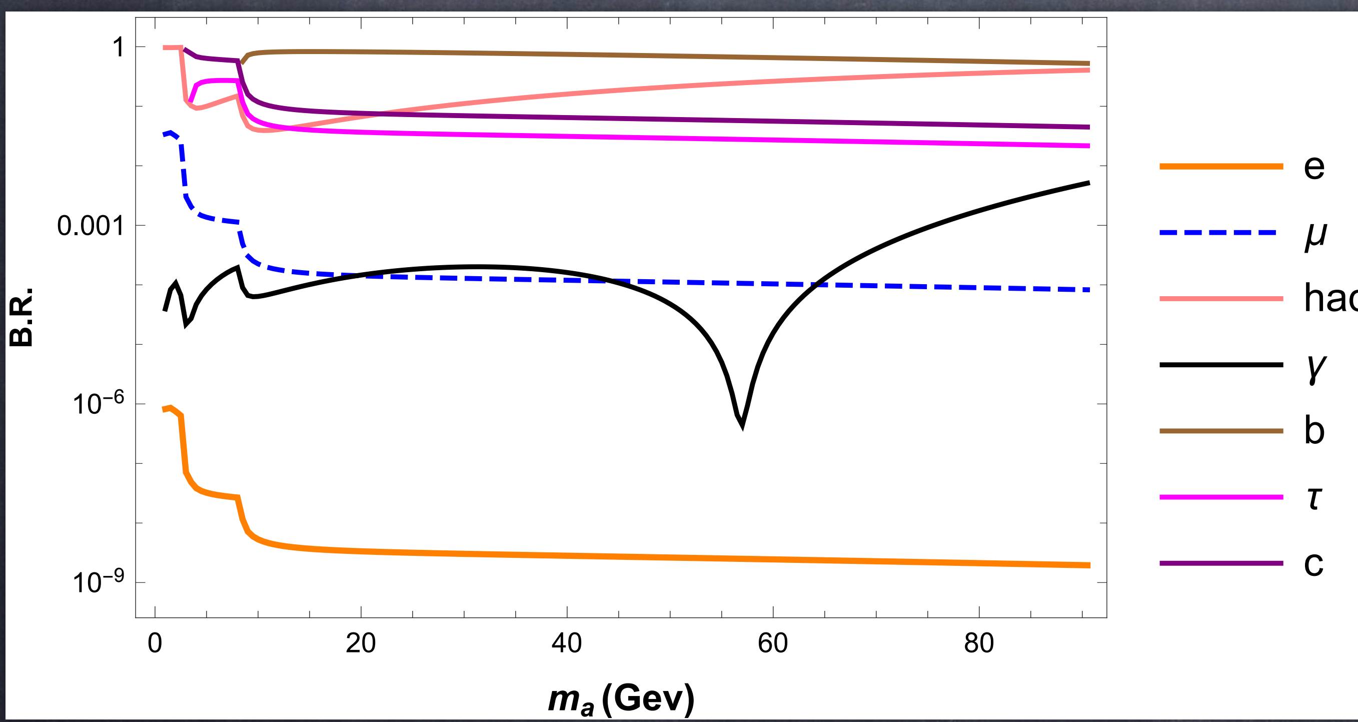




Tera-Z portal to compositeness (via ALPs)

G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

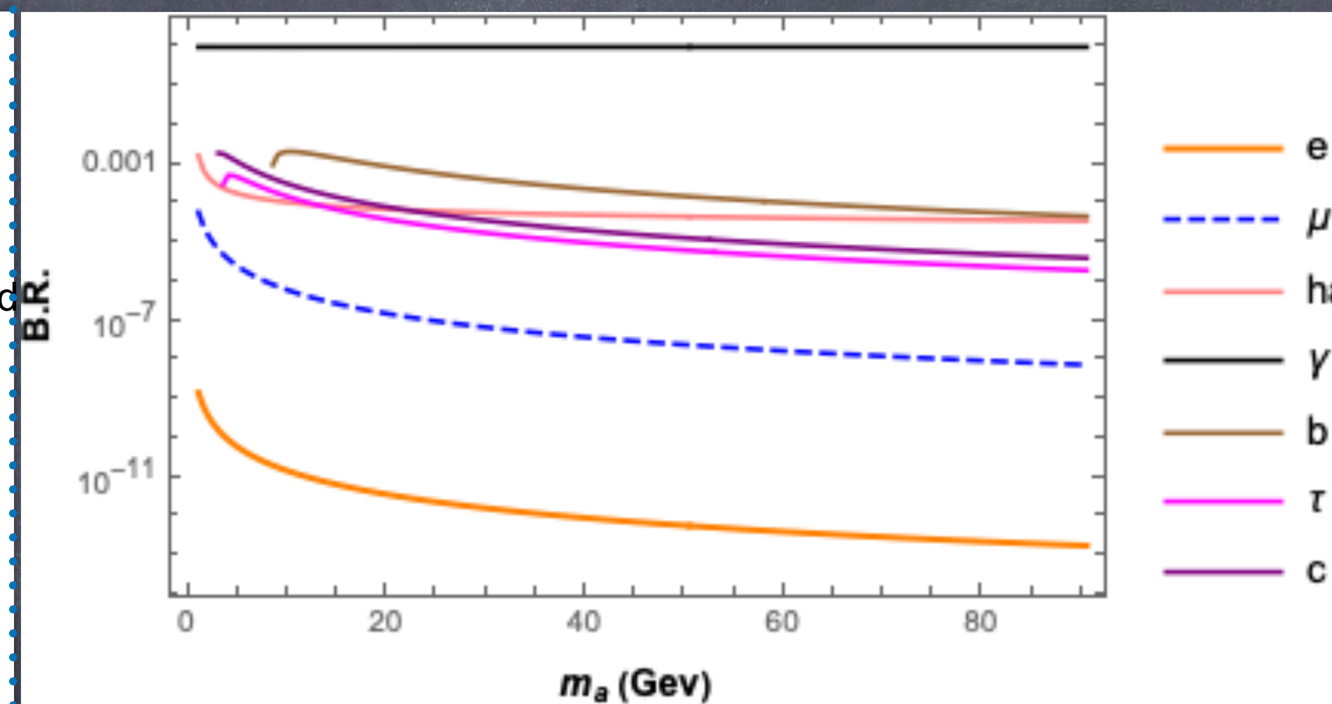
Photo-phobic



No leading order coupling to Photons (WZW interaction is Zero!!)

eg. SU(4)/SP(4), SU(4)xSU(4)/SU(4)

Photo-philic



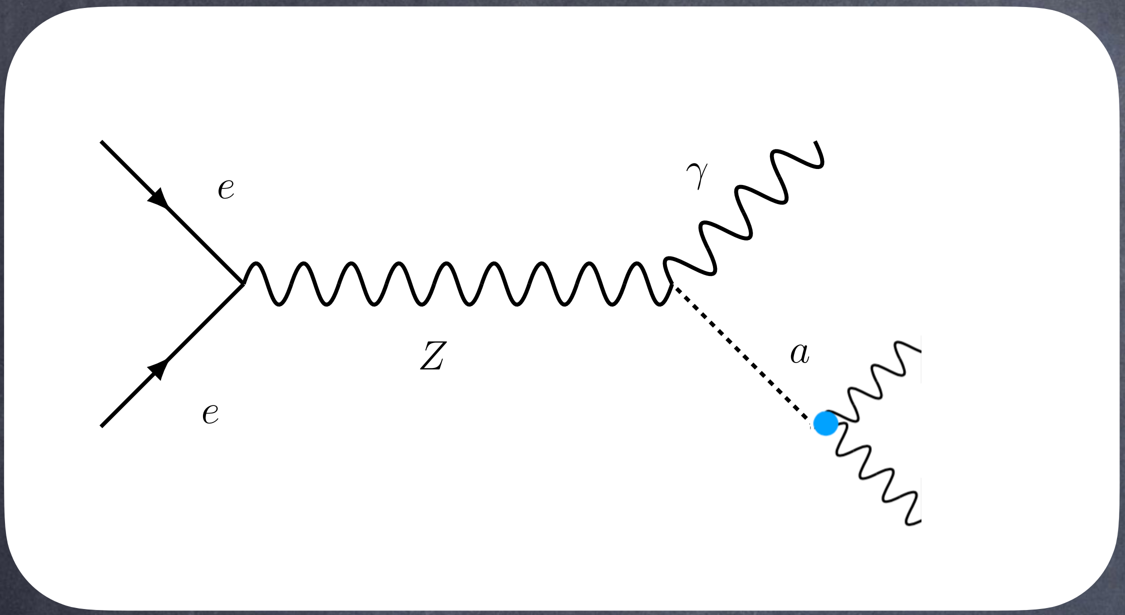
WZW interaction to photons (like the pion)

eg. SU(5)/SO(5), SU(6)/SO(6)

Phenomenology-Prompt Decays

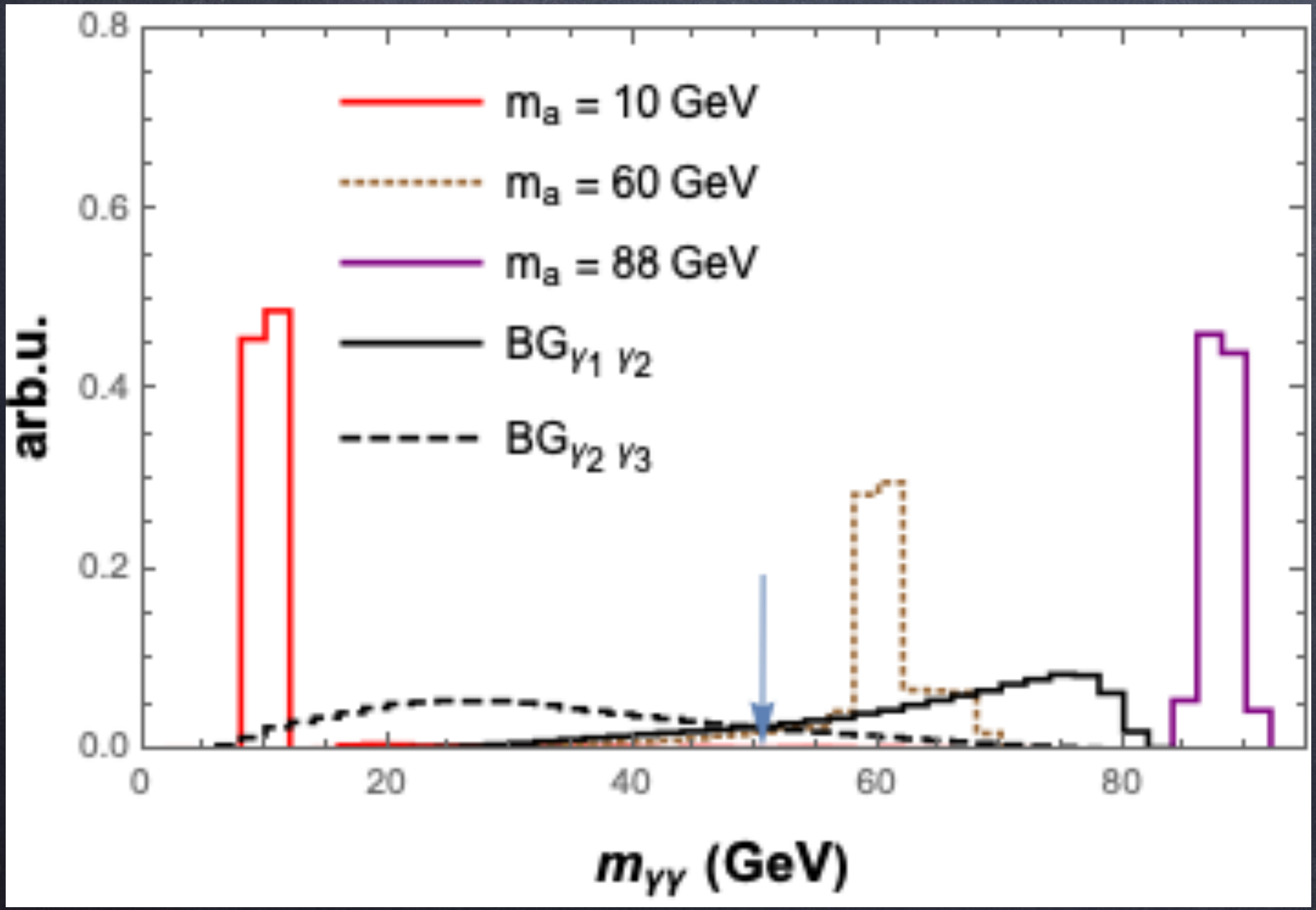
Photo-philic

G.C. et al.
2104.11064



- Three isolated photons

$$BR(Z \to 3\gamma)_{\text{LEP}} < 2.2 \cdot 10^{-6}$$



Discriminating variable: invariant mass

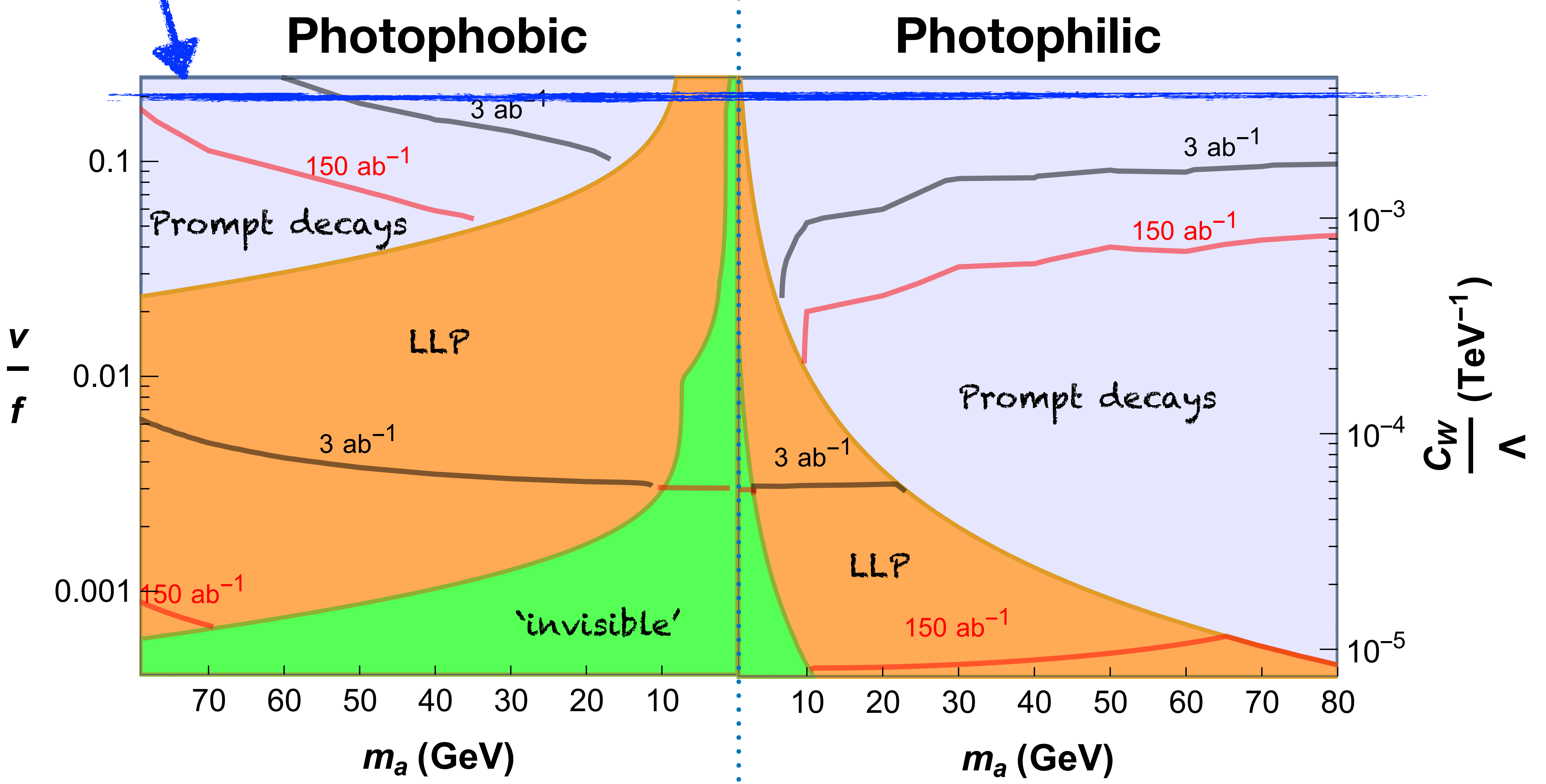
Photon ordering changes at inv. mass 50 GeV

Bins above 80 GeV populated by fakes: hard to estimate!

Money plot

G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

Typical EWPT bound



What if FCC-ee discovers $Z \to \gamma a$?

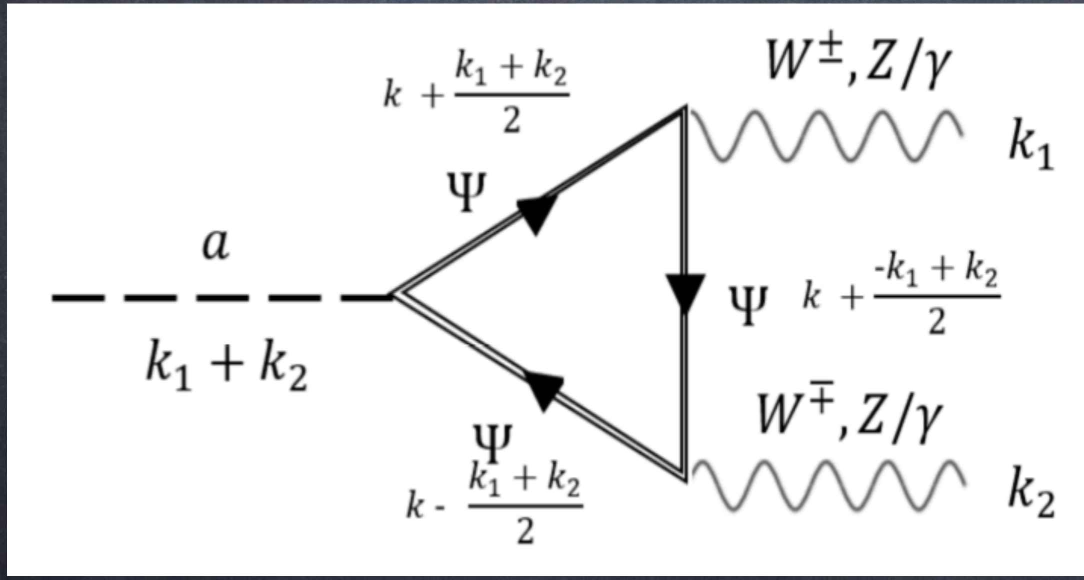
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

- Is it possible to distinguish the composite scenario, from an elementary mock-up model?

$\Phi = H + i\,a$

Singlet scalar

Ψ = doublet + singlet



Triangle loops can mimic the WZW interactions of the composite ALP:

doublet + singlet = photo-phobic case

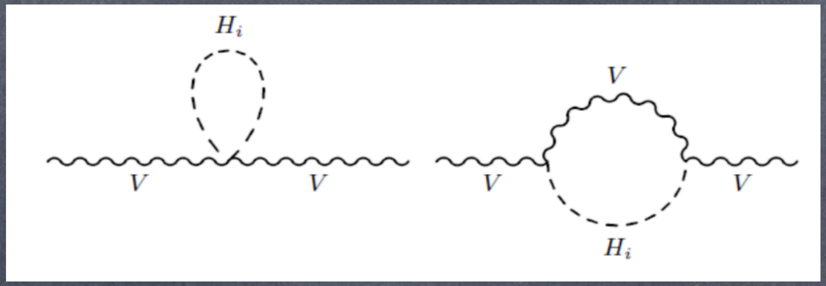
- Note: fermion masses of the order of TeV, potentially discoverable at HL-LHC or FCC-hh (QCD-neutral)

What if FCC-ee discovers Z > γa?

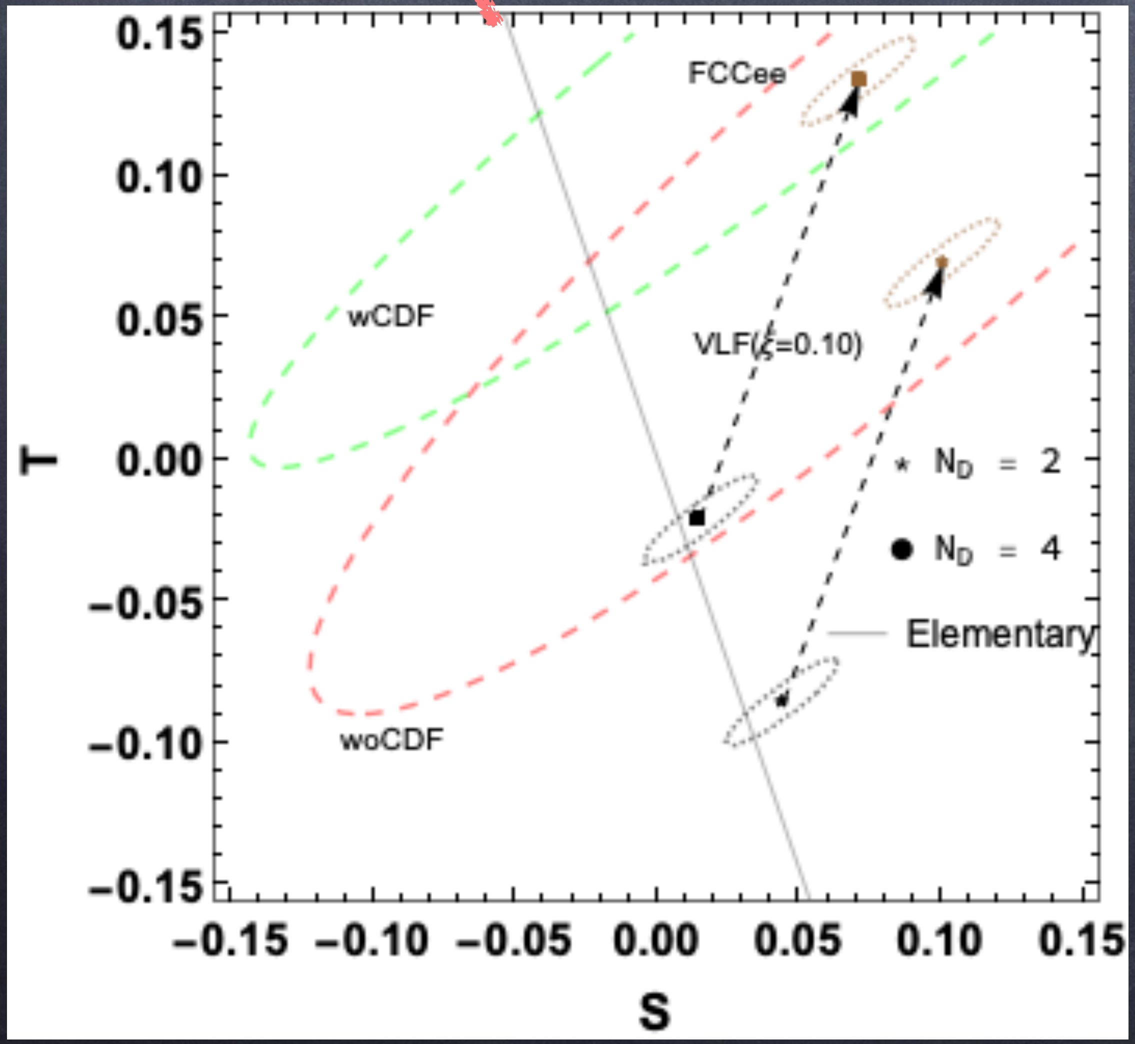
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

- Is it possible to distinguish the composite scenario, from an elementary mock-up model?

EWPT only depend on H loops



composite case: see 1502.04718



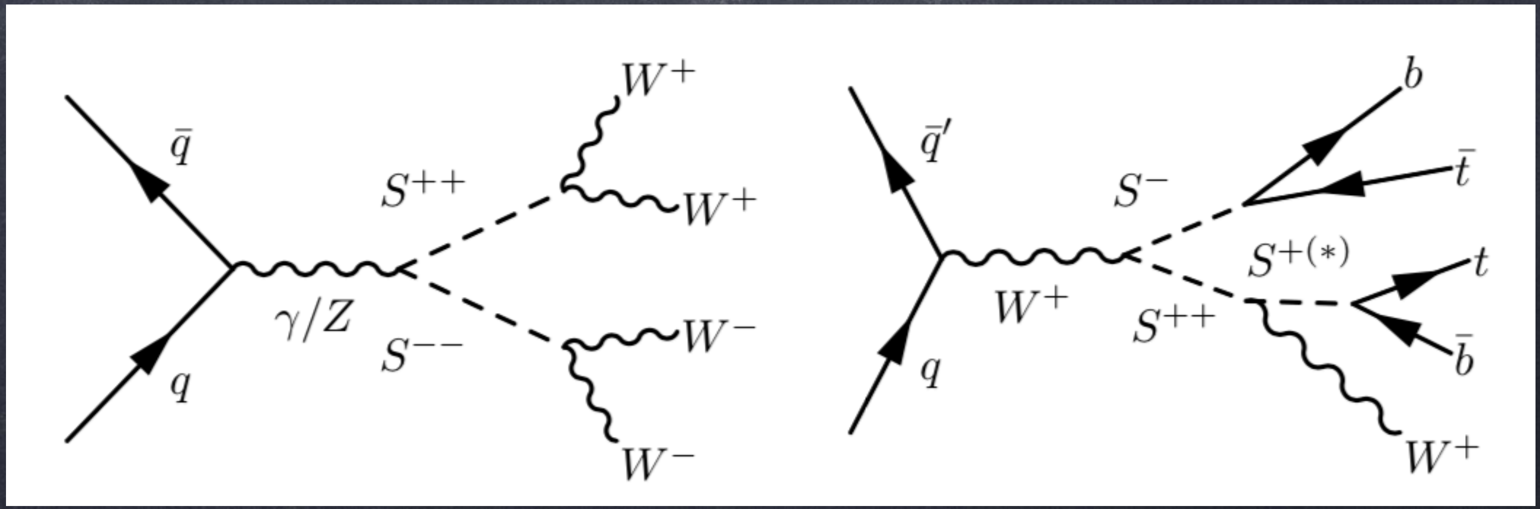
For fixed BR = 10^-8, i.e. discovery.

Arrows: naive contribution of top partner loops.

EW pNGB direct production

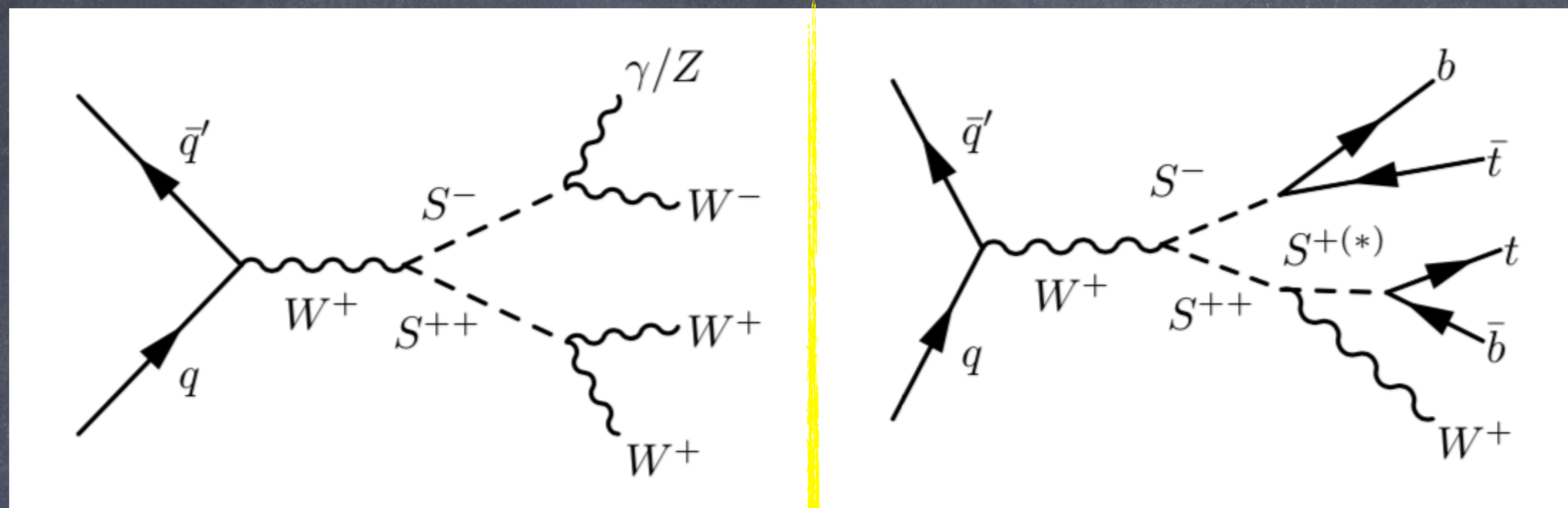
G.C., W.Porod, T.Flacke, L.Schwarze
2210.01826

- Dominantly pair-produced (no VEVs except for the doublet)
- Couplings to two EW gauge bosons via WZW
- Couplings to two fermions via partial compositeness
- Few dedicated direct searches (WWWW and WWWZ via doubly-charged scalar)



EW pNGB direct production

W.Porod et al.
2210.01826

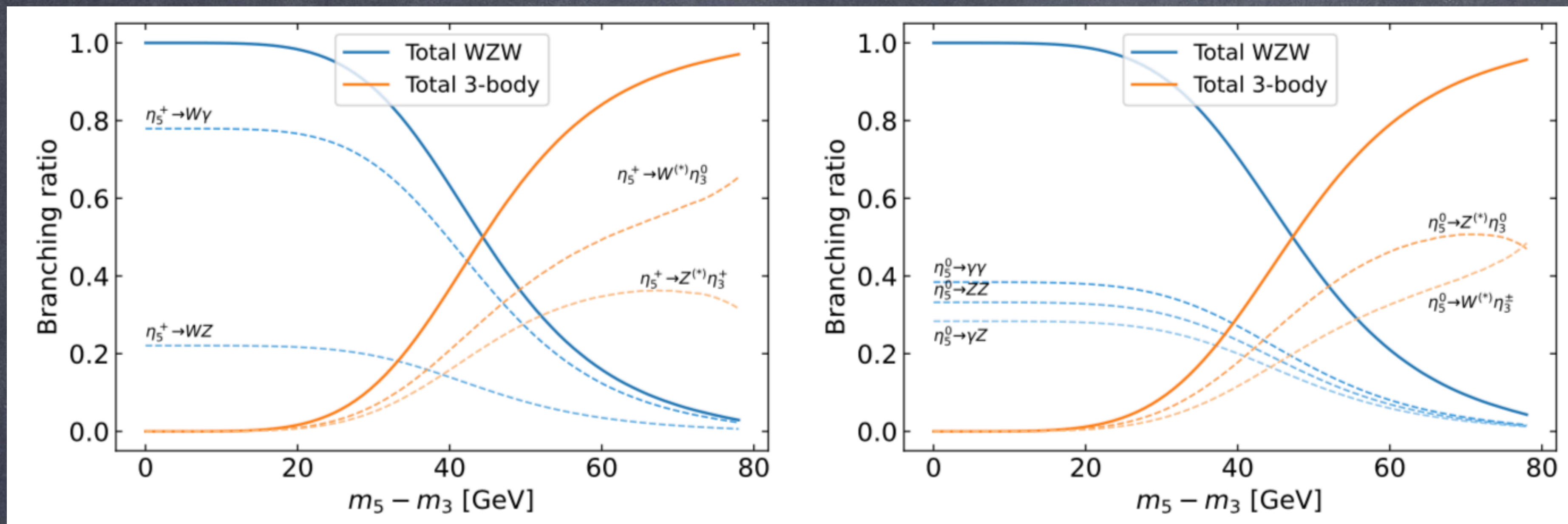


- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
- Photon-rich final states!

- Typically sizeable couplings to top and bottom
- Always dominate if present!
- They may be absent - model dependence!

Fermio-phobic SU(5)/SO(5) model

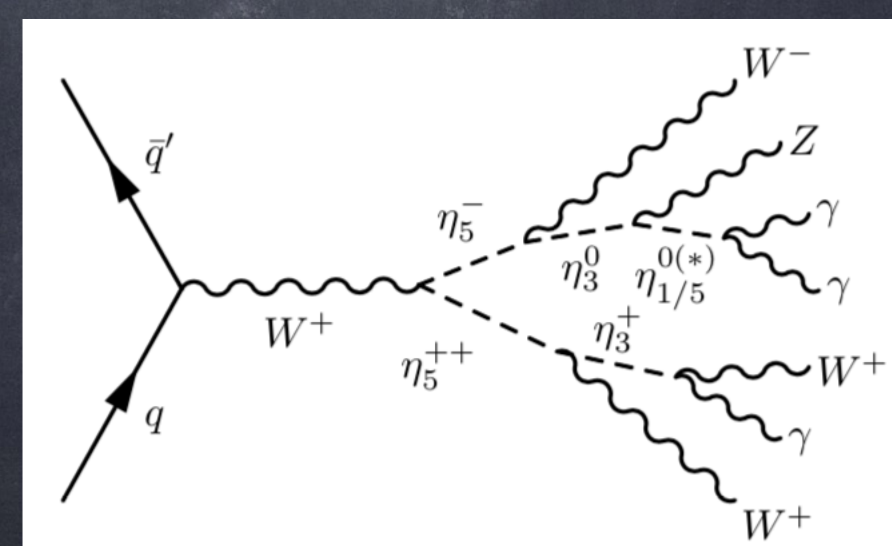
W.Porod et al.
2210.01826



(c) Decays of η_5^+ for $m_5 = 600$ GeV $> m_3$ (d) Decays of η_5^0 for $m_5 = 600$ GeV $> m_3$

- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
- Photon-rich final states!

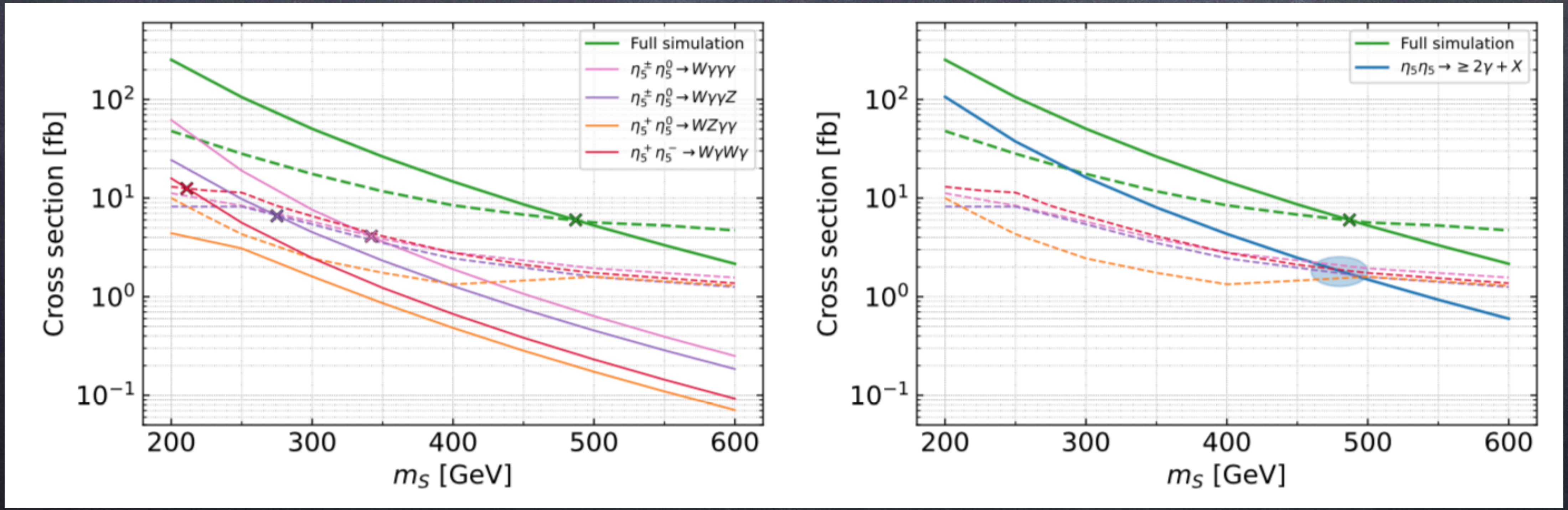
Cascade decays competitive for mass splits around 50 GeV



SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

- Run all searches in MadAnalysis, Checkmate and Contur on all di-scalar pair production channels.
- Best limits from multi-photon searches (ATLAS generic analysis)
- Many channels contribute to the same signal region!



SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

Exclusion from multi-photon search

S++ cascade decays

Change in dominant SR