A Collider Roadmap to Composite Higgs Models

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Motivation

- Composite models 'solve' the Hierarchy problem...
- with new scale in the multi-TeV!

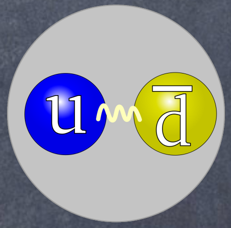
multi-TeV mountain

- What are we looking for?

-> Precision EW + Higgs observables
-> light composite scalars
-> multi-TeV resonances (top partners, pNGBs, spin-1)

Composite Higgs models 101

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



Scales:

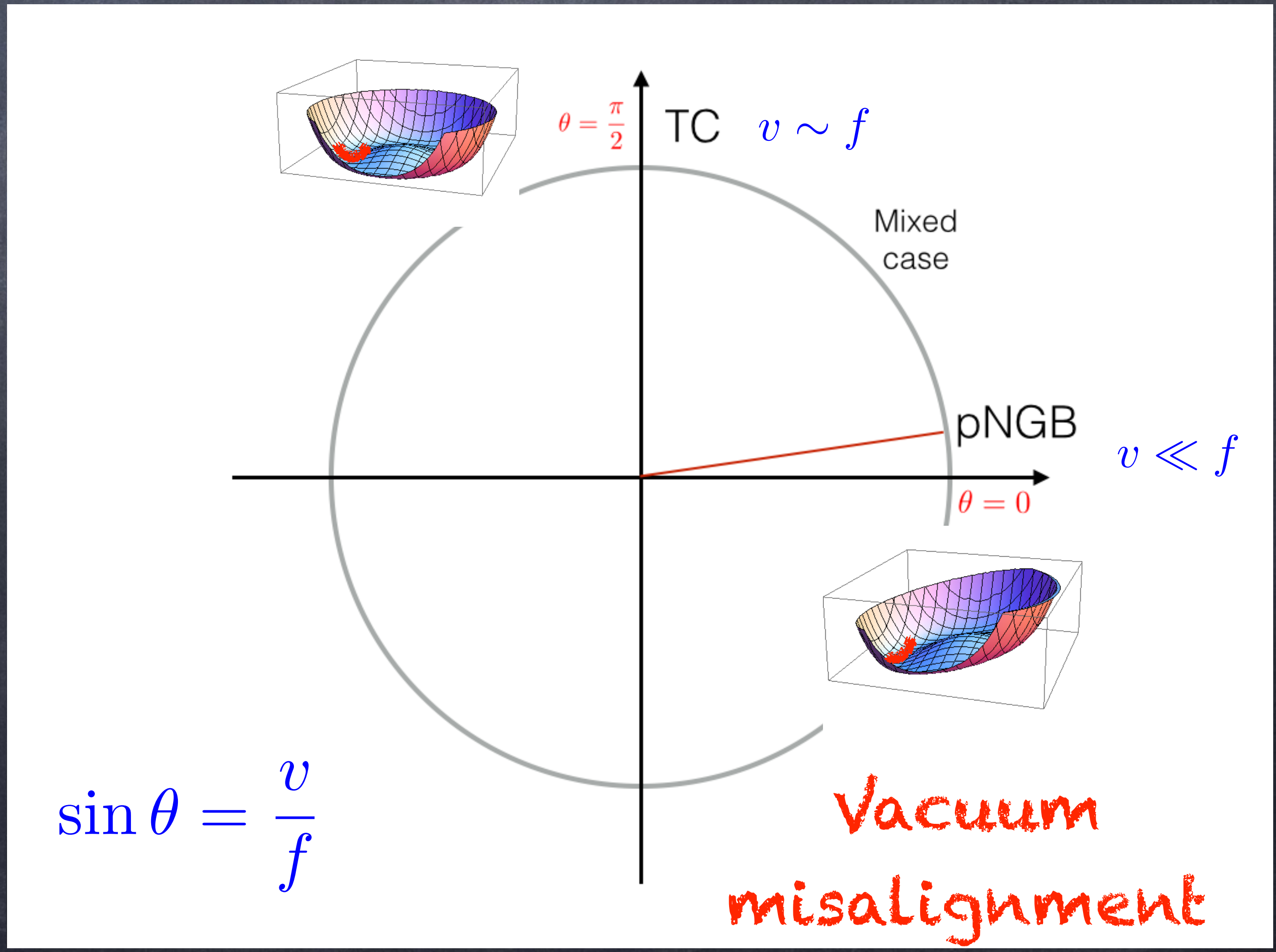
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

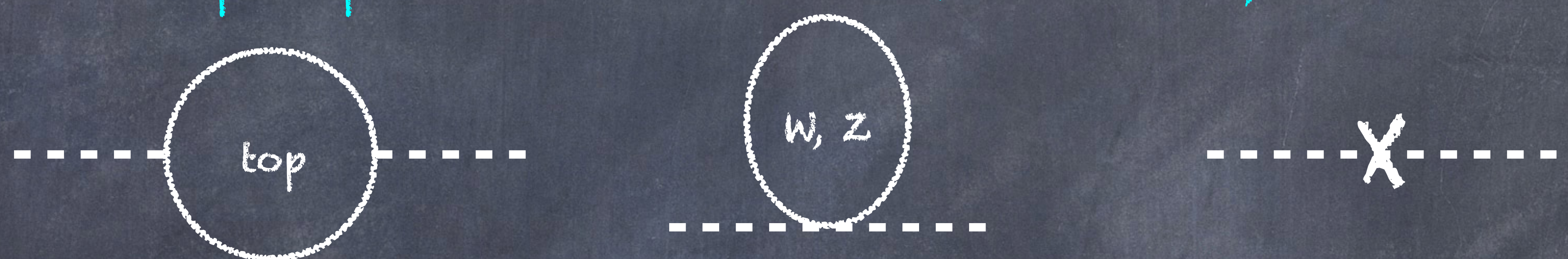
EWPTs + Higgs coupl. limit:

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



Composite Higgs models 101

How can light states emerge?



	Top loops	Gauge loops	TC-fermion masses
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

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

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

Let's postulate the existence of fermionic operators:

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

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

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

SM : EW — colour + hypercharge

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 $\Lambda_{TC} \sim 4\pi f$

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

Composite models at various scales

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

HC and SM gauge groups partially unified

Symmetry breaking by scalars — 4-fermion Ops generated!

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

Condensation scale $\Lambda_{TC} \sim 4\pi f$

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

Composite models at various scales

HC and SM g
partially

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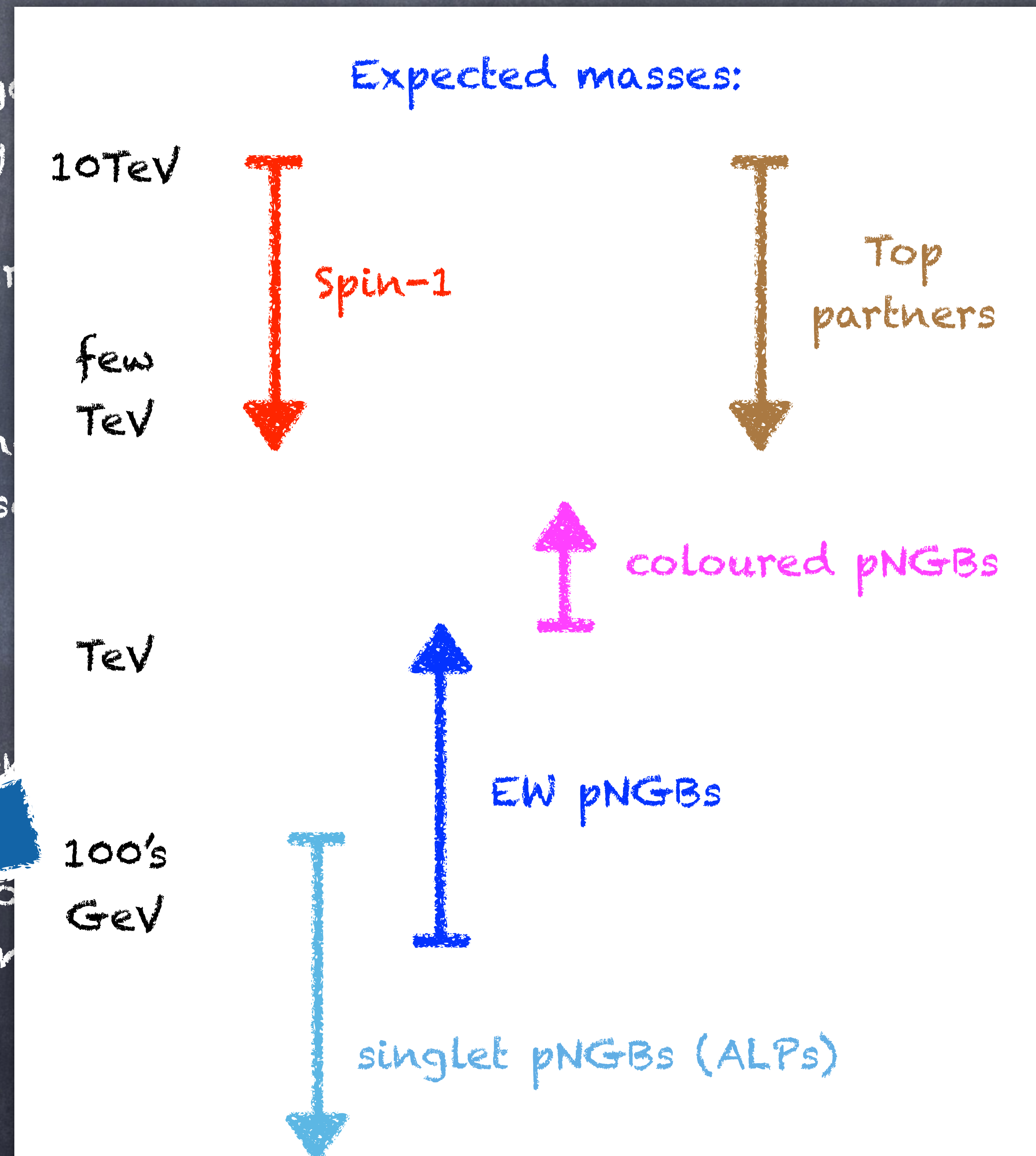


Roadmap to Higgs compositeness

- The HL-LHC will leave an important legacy, but NOT covering the whole interesting parameter space! (i.e. 10TeV is the target)

- A Tera-Z run will fully test the presence of a light composite ALP -> well beyond the 10 TeV mark

- Case 1 : discovery + EWPTs can fix the scale

- Case 2 : non-discovery + EWPTs

- In both cases, the results will strongly constraint the model building, providing testable predictions for a high energy pp collider, which will fully cover the scenario.

* Not including flavour, cosmology, ...

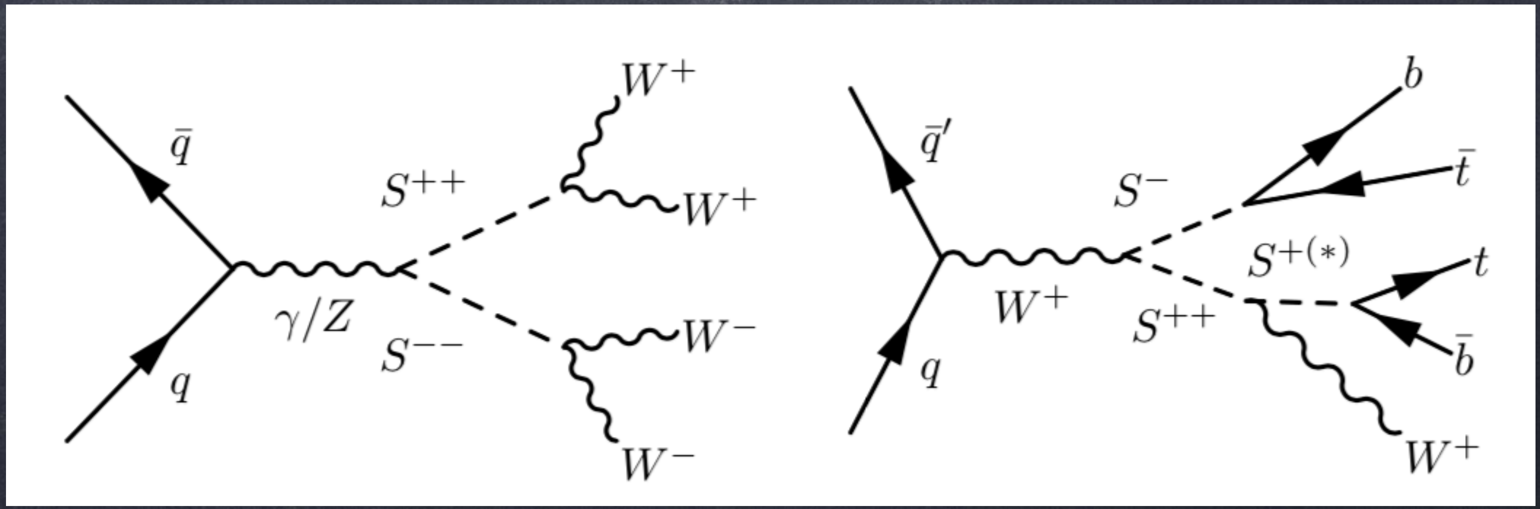
The LHC legacy

- The Higgs - couplings
- EW-charged scalars (few 100's GeV)
- Singlets (ALPs) that couple to gluons
- Spin-1 resonances (EW)
- Coloured states (QCD)

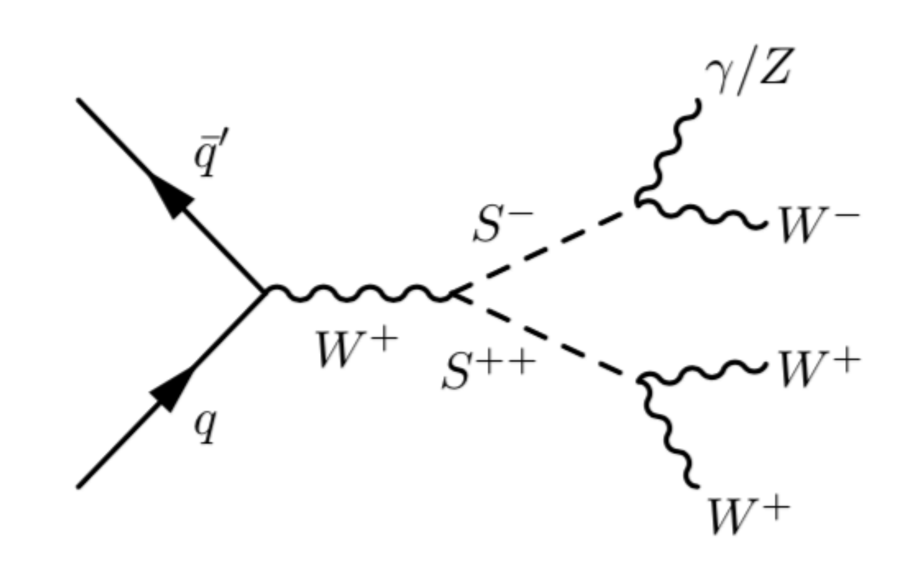
EW pNGB direct production

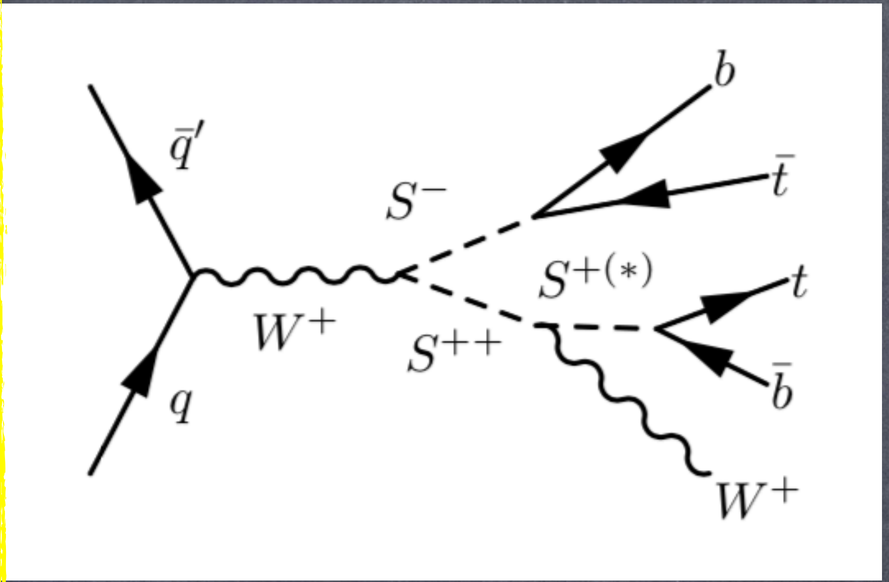
G.C., W.Porod, T.Flacke, L.Schwarze
2210.01826

- Dominantly pair-produced (no VEVs except for the doublet)
- Couplings to two EW gauge bosons via topological anomalies, not VEVs -> photons are present!!!
- Couplings to two fermions via partial compositeness
- Few dedicated direct searches (WWWW and WWWZ via doubly-charged scalar)



EW pNGB direct production





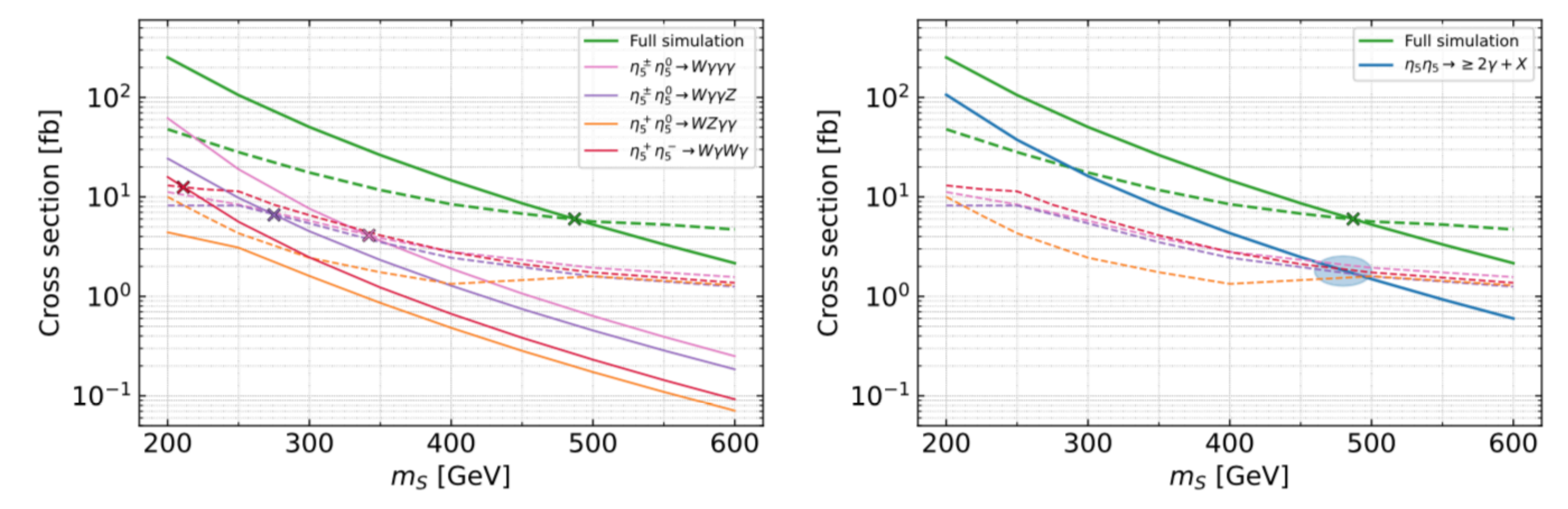
W.Porod et al.
2210.01826

- Decays to two GBs from 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!

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!

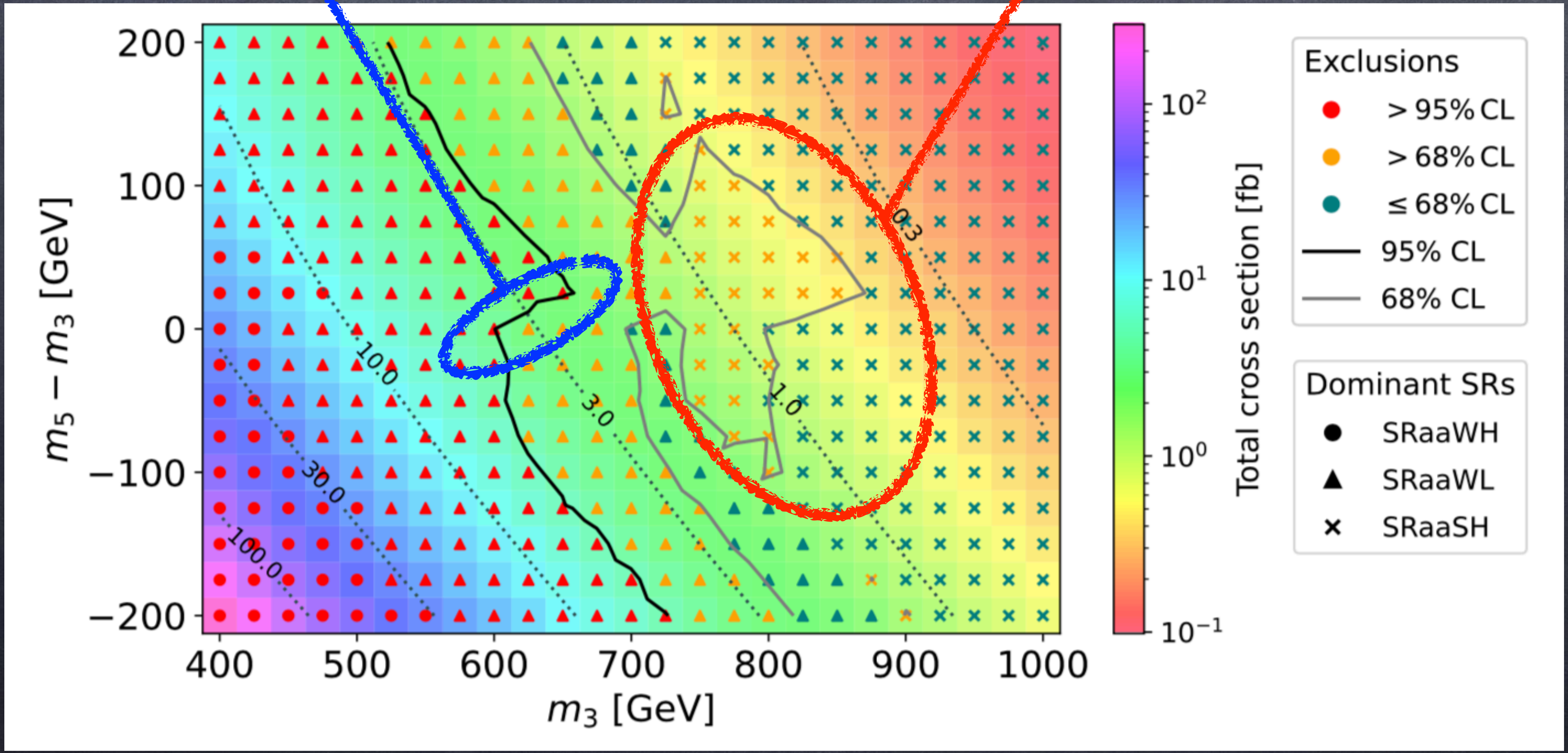
SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

Exclusion from multi-photon search

S++ cascade decays

Change in dominant SR



The QCD sector

(Above the TeV scale)

- Coloured pNGBs
- Top partners
- Spin-1 resonances

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	$(\mathrm{R}, -\frac{1}{3}, \frac{1}{6})$	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	π_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

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

Coloured pNGBs

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

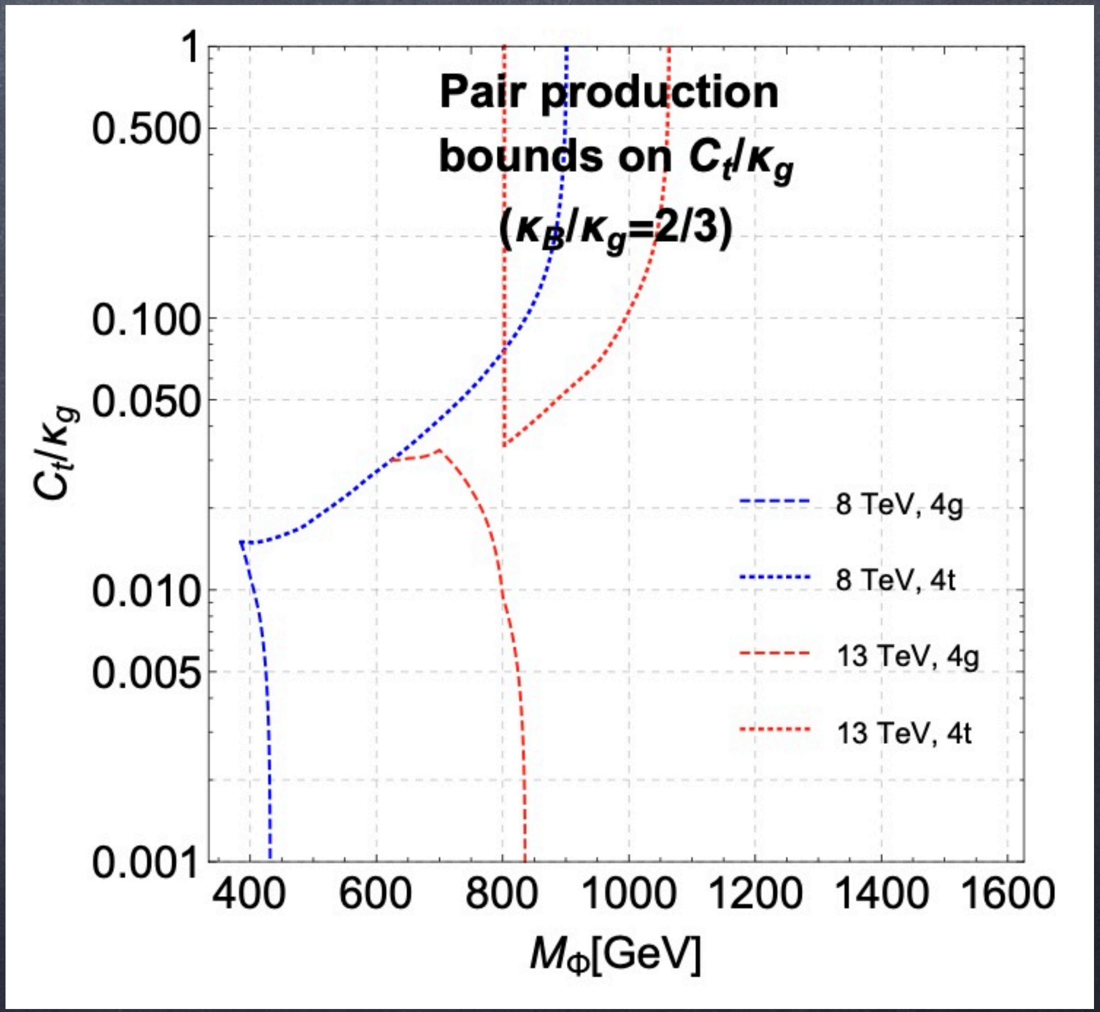
C1 :	$\pi_8 \to t\bar{t},\ gg;\ \pi_6 \to bb\,,$
C2 :	$\pi_8 \to t\bar{t},\ gg;\ \pi_6 \to tt\,,$
C3 :	$\pi_8 \to t\bar{t},\ gg;\ \pi_3 \to \bar{b}\bar{s}$ or $t\bar{\nu},\ b\tau^+\,,$
C4-5 :	$\pi_8 \to t\bar{t},\ gg\,.$

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)

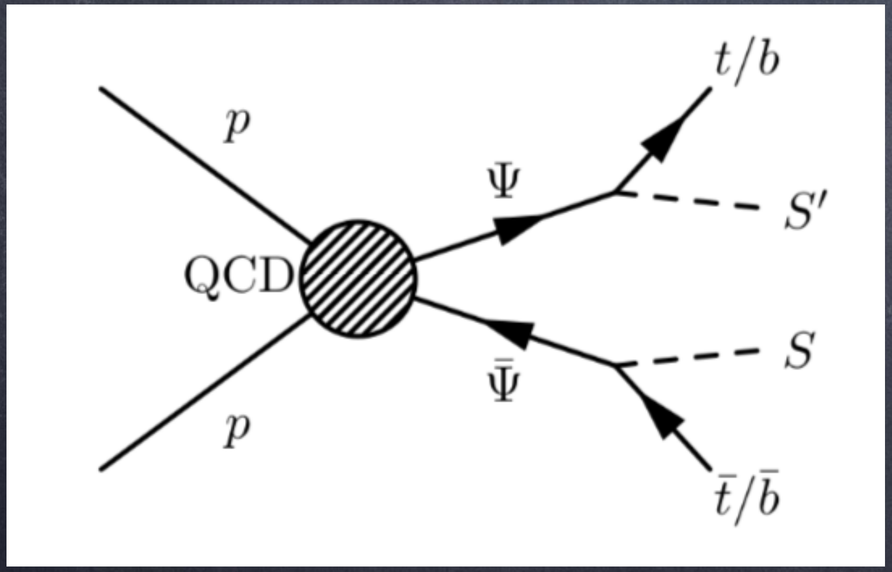
Sextet $\begin{cases} \pi_6 \to tt \\ \pi_6 \to bb \end{cases}$



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:

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

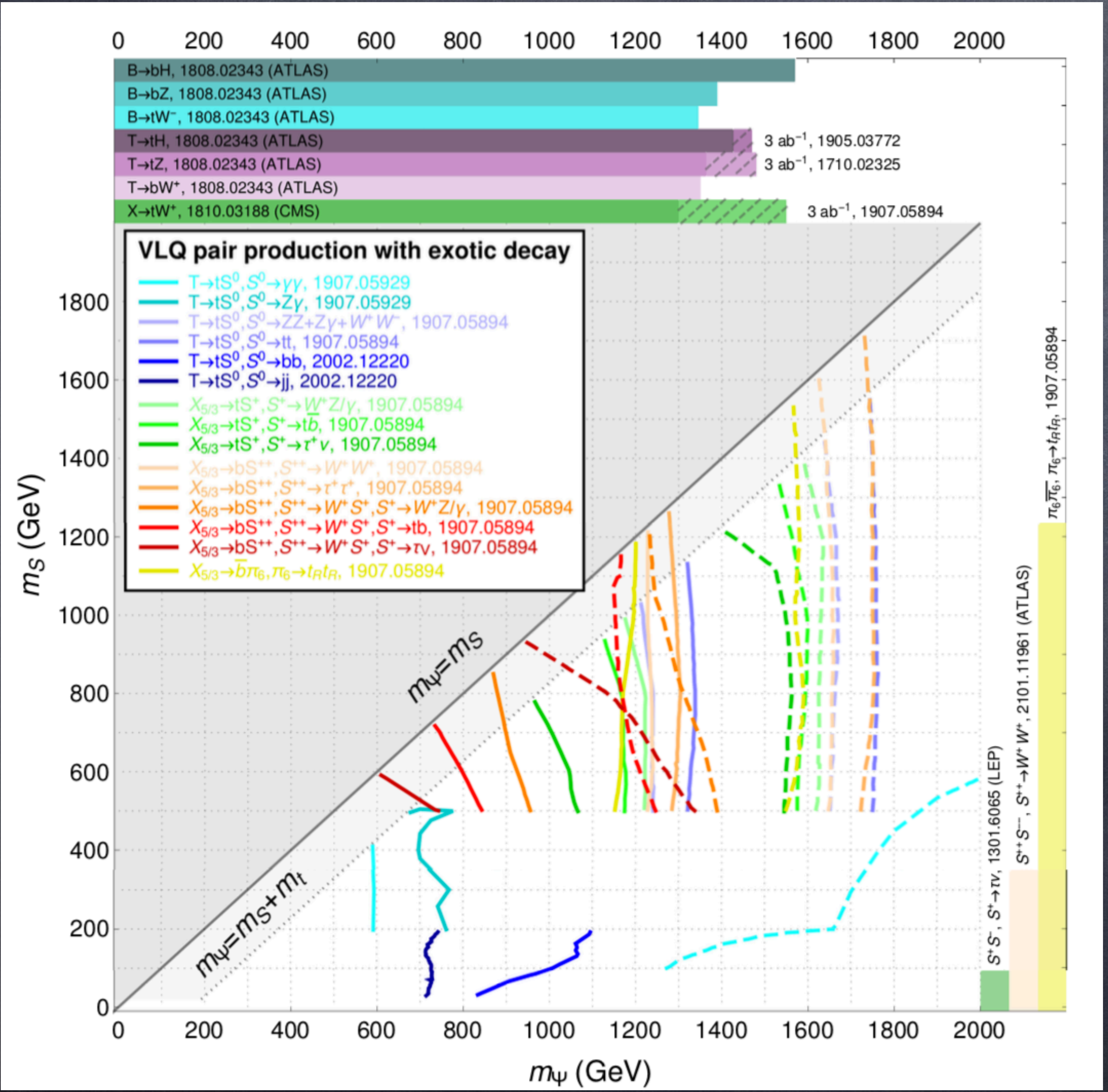
Calculable ratios (from anomalies) and always present for all models.

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

Dominant, if present for the specific S.

Common exotic top partner decays

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

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$			
$\psi_{3,4}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
ψ_5	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{1}$	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							

$x = -1/3$

Chimera Baryons (top partners)

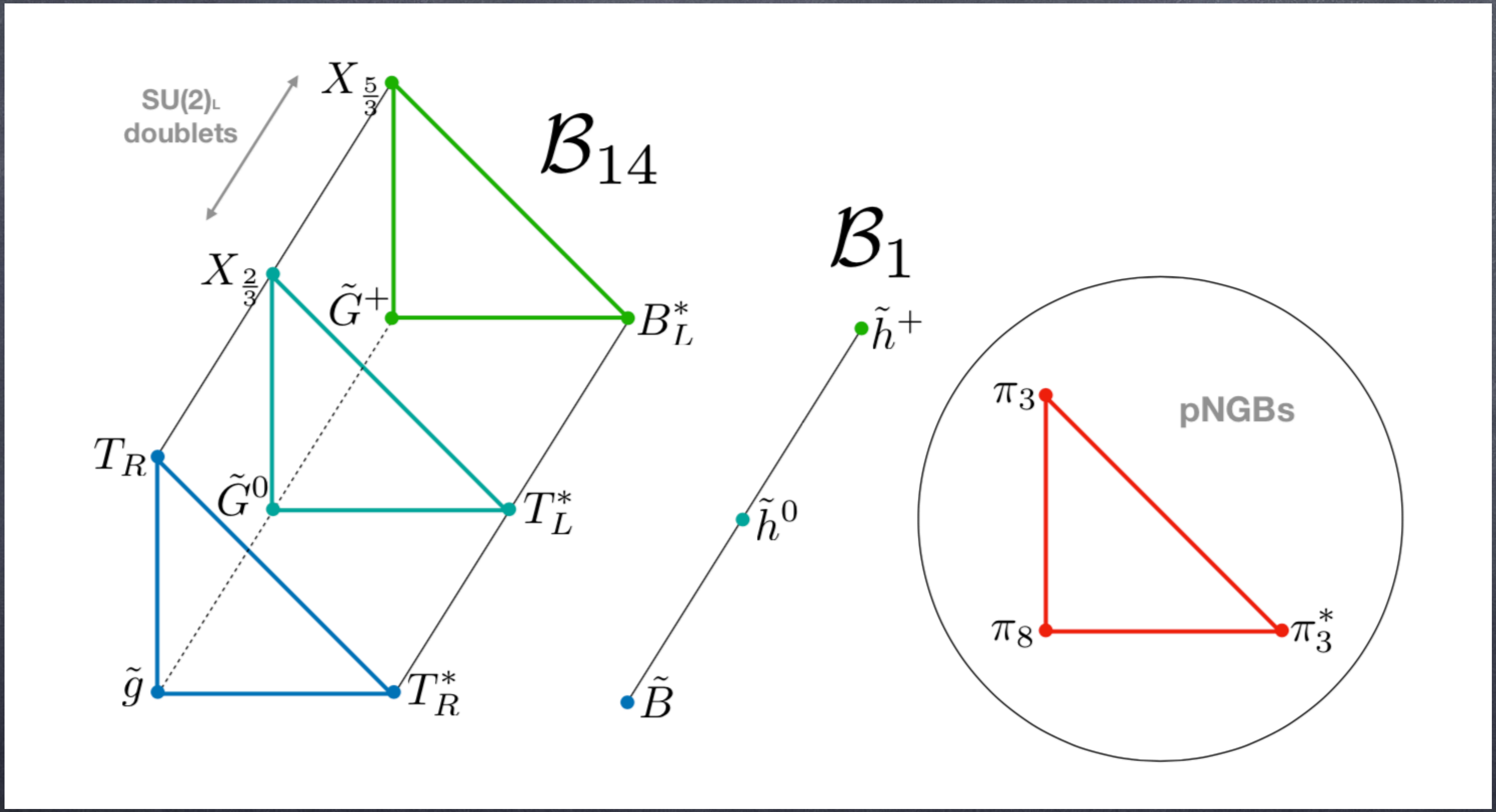
	$SU(5)\times SU(6)$	$SO(5)\times Sp(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^1_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_{1}$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar\chi\bar\chi$	$(\mathbf{5},\overline{\mathbf{15}})$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

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

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

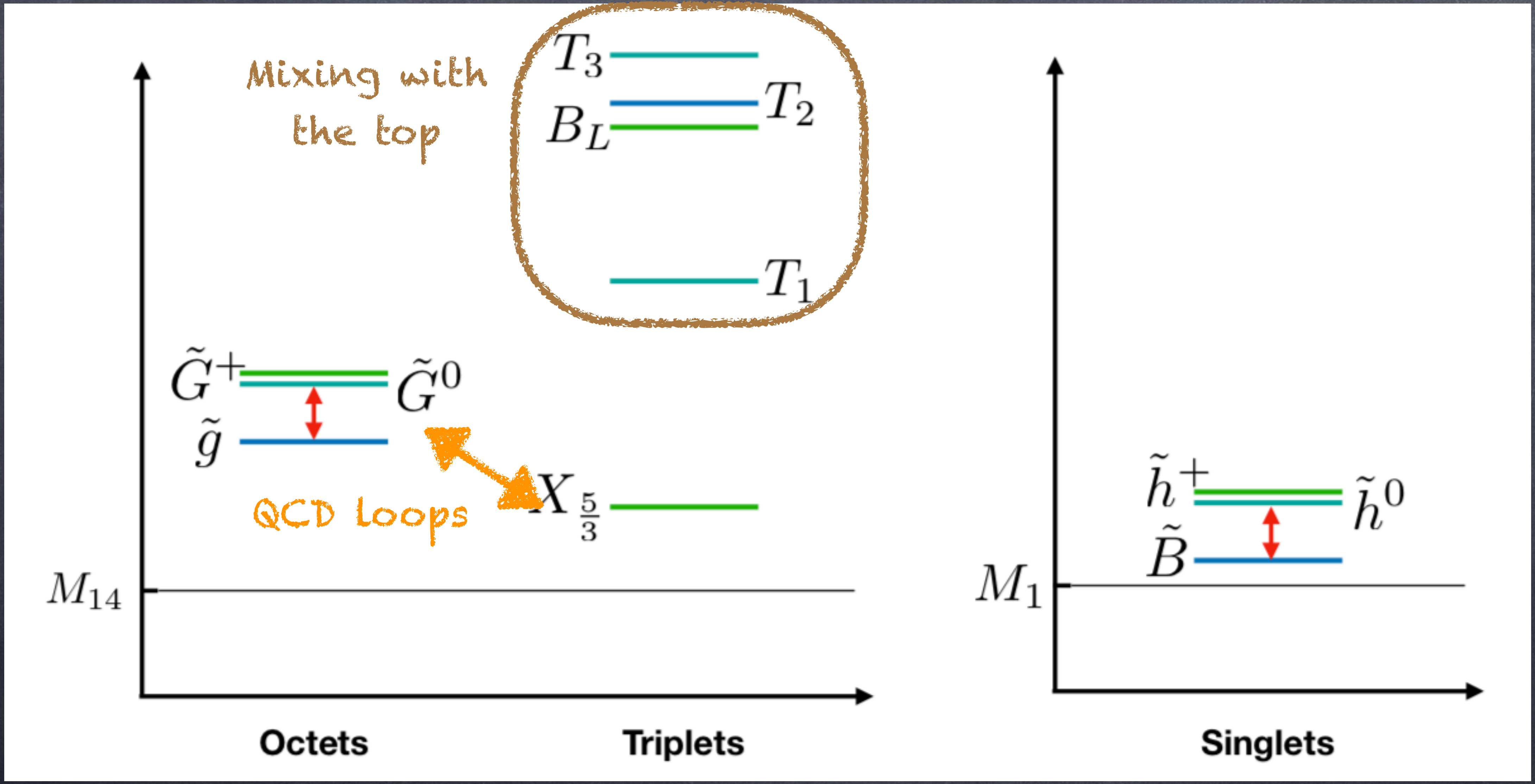
Exotic top partners

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



Exotic top partners

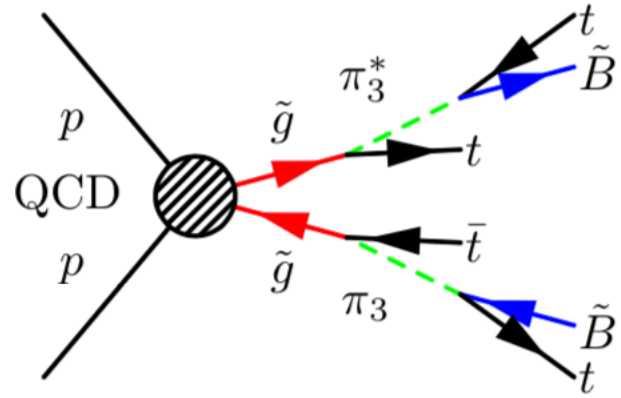
G.Cacciapaglia et al.
2112.00019



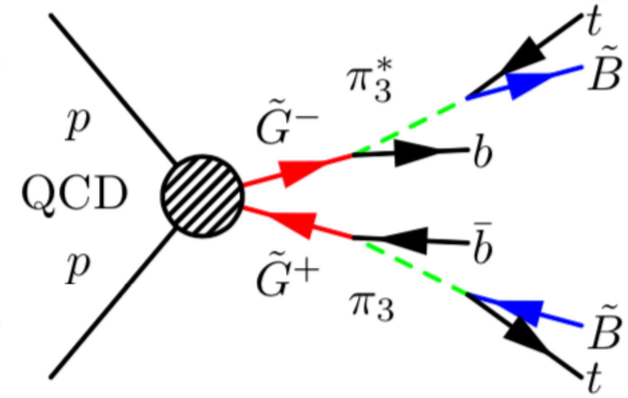
Octoni bounds

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

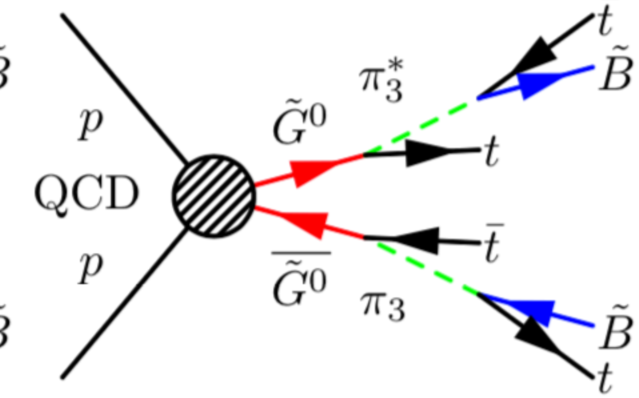
- Model implemented in MG.
- Check limits from searches in MadAnalysis and CheckMate.
- Strongest bound from gluino and stop searches!



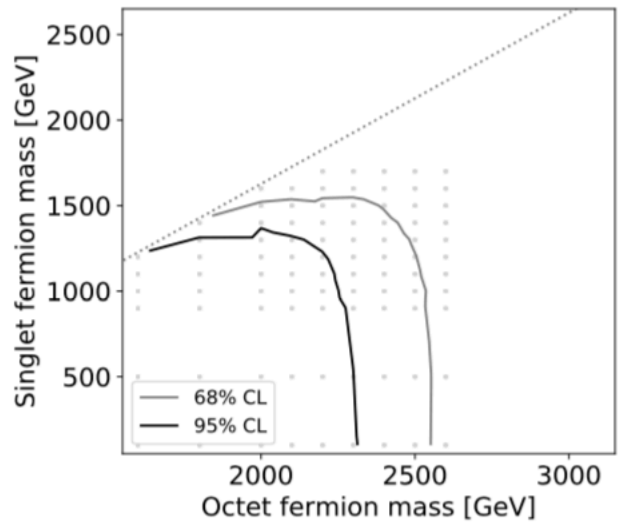
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$



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

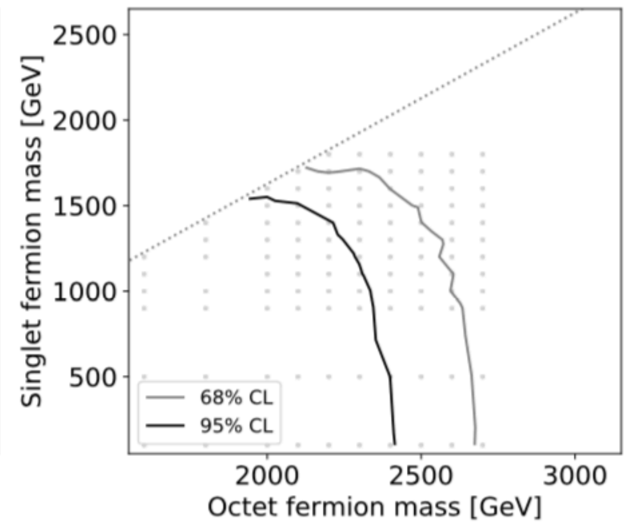


(c) $\tilde{G}^0 \to \bar{t}\pi_3 \to \bar{t}t\tilde{B}$



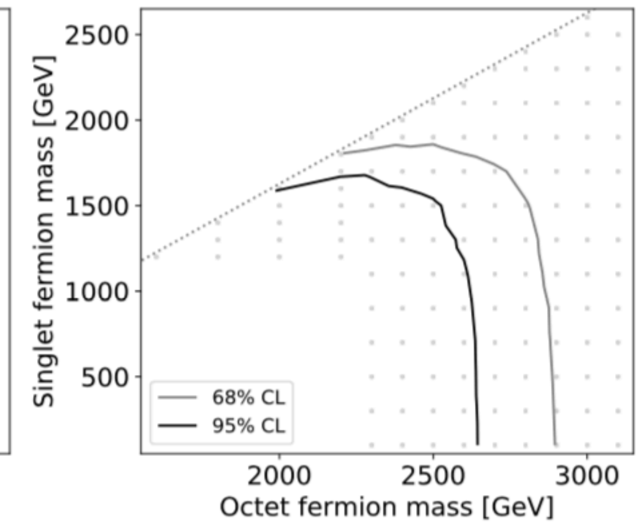
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

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



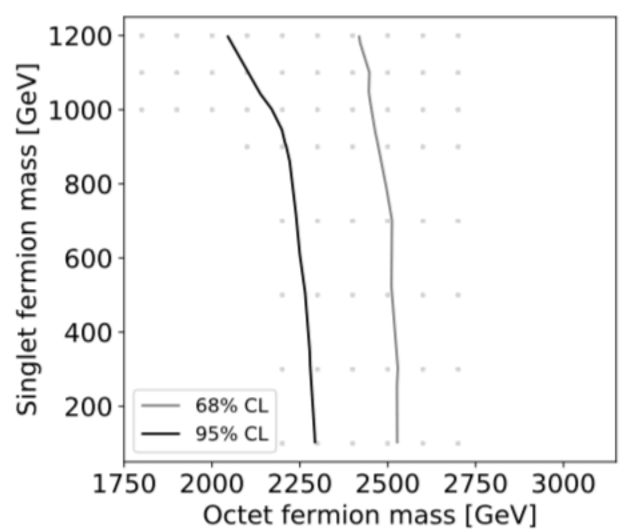
(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

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



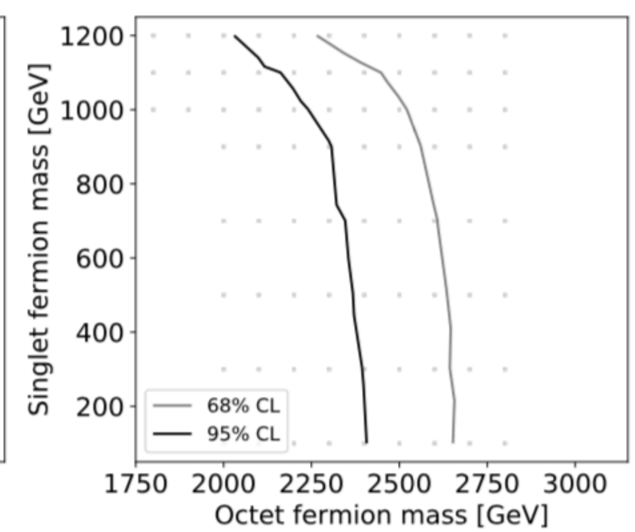
(c) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

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



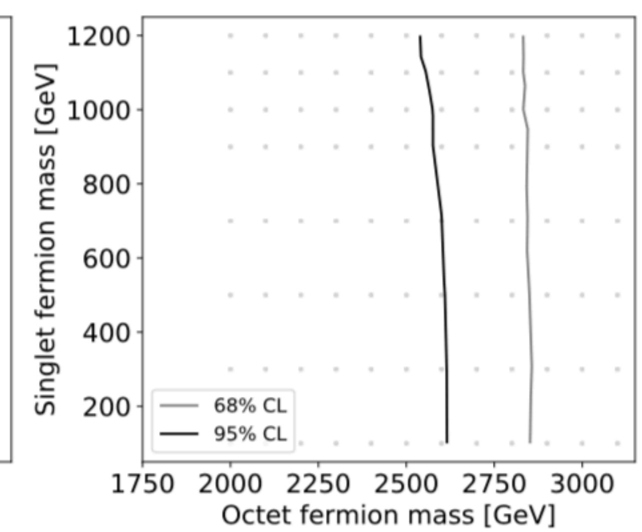
(d) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV



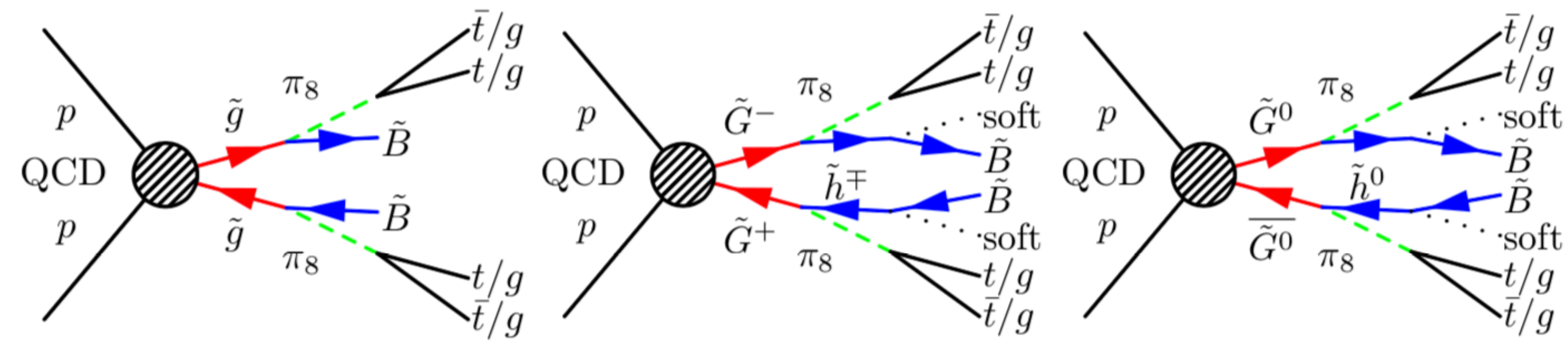
(e) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV

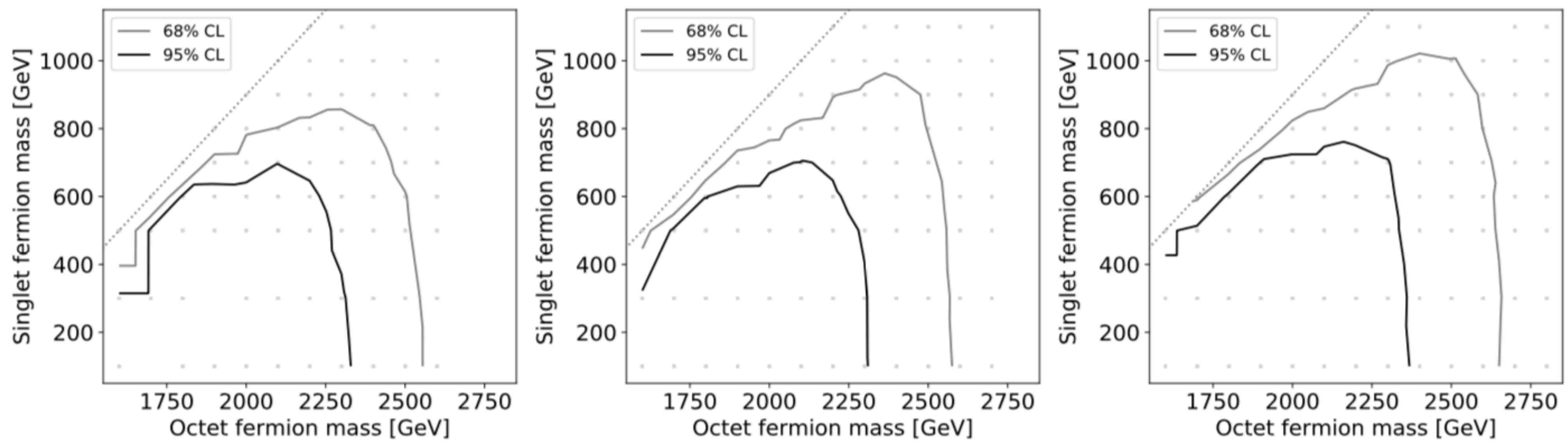


(f) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

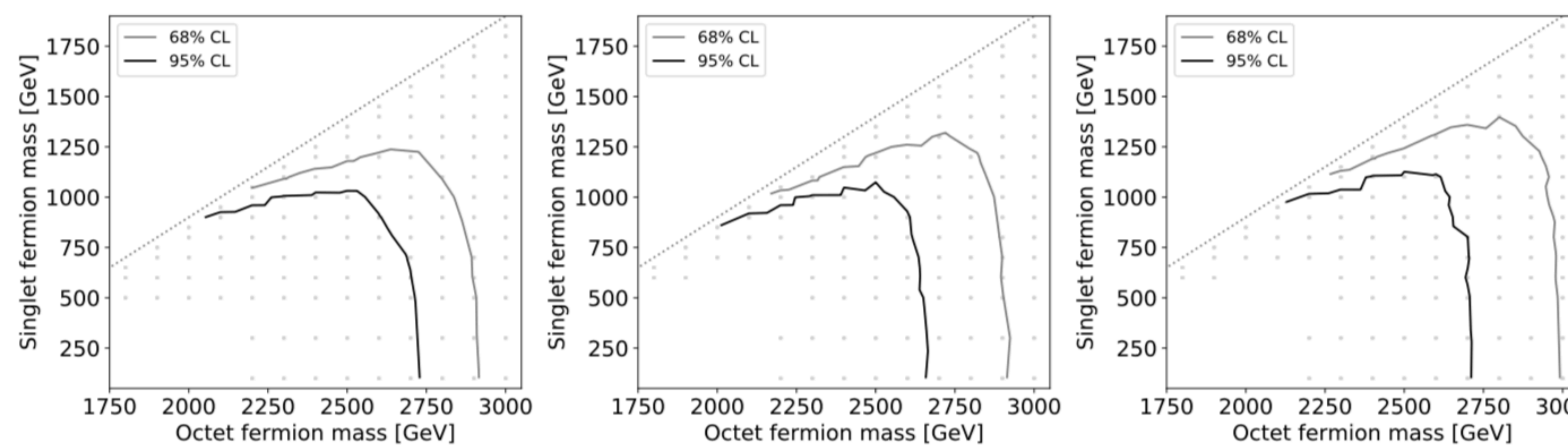
$m_{\pi_3} = 1.4$ TeV



(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
2404.02198

	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

- 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: decays

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
2404.02198

- Couplings to pNGBs

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

$V \to \pi\pi$

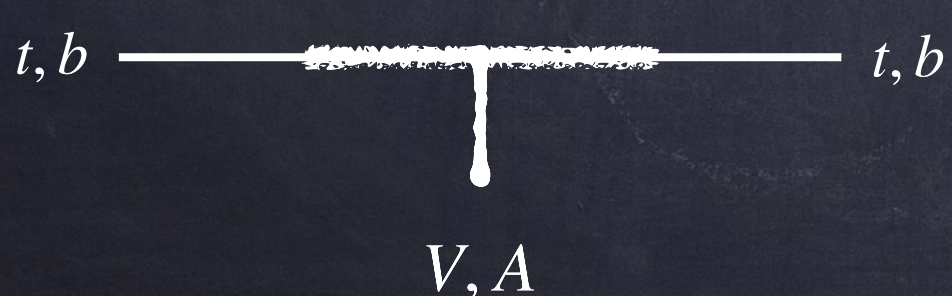
$A \to \pi\pi\pi$

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
2404.02198

- Couplings to pNGBs

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

$\mathcal{O}_\mathcal{A} = \mathrm{Tr}(\ldots$

$V \to \pi\pi$

$A \to \ldots$

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

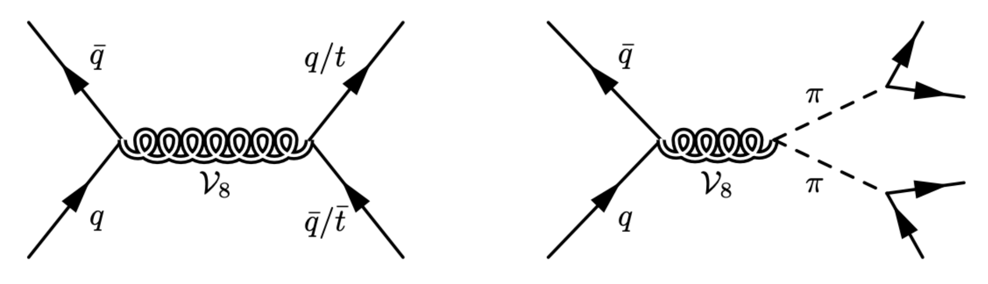
- Oct

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 $g_{\rho BB}$

Spin-1 resonances: LHC bounds



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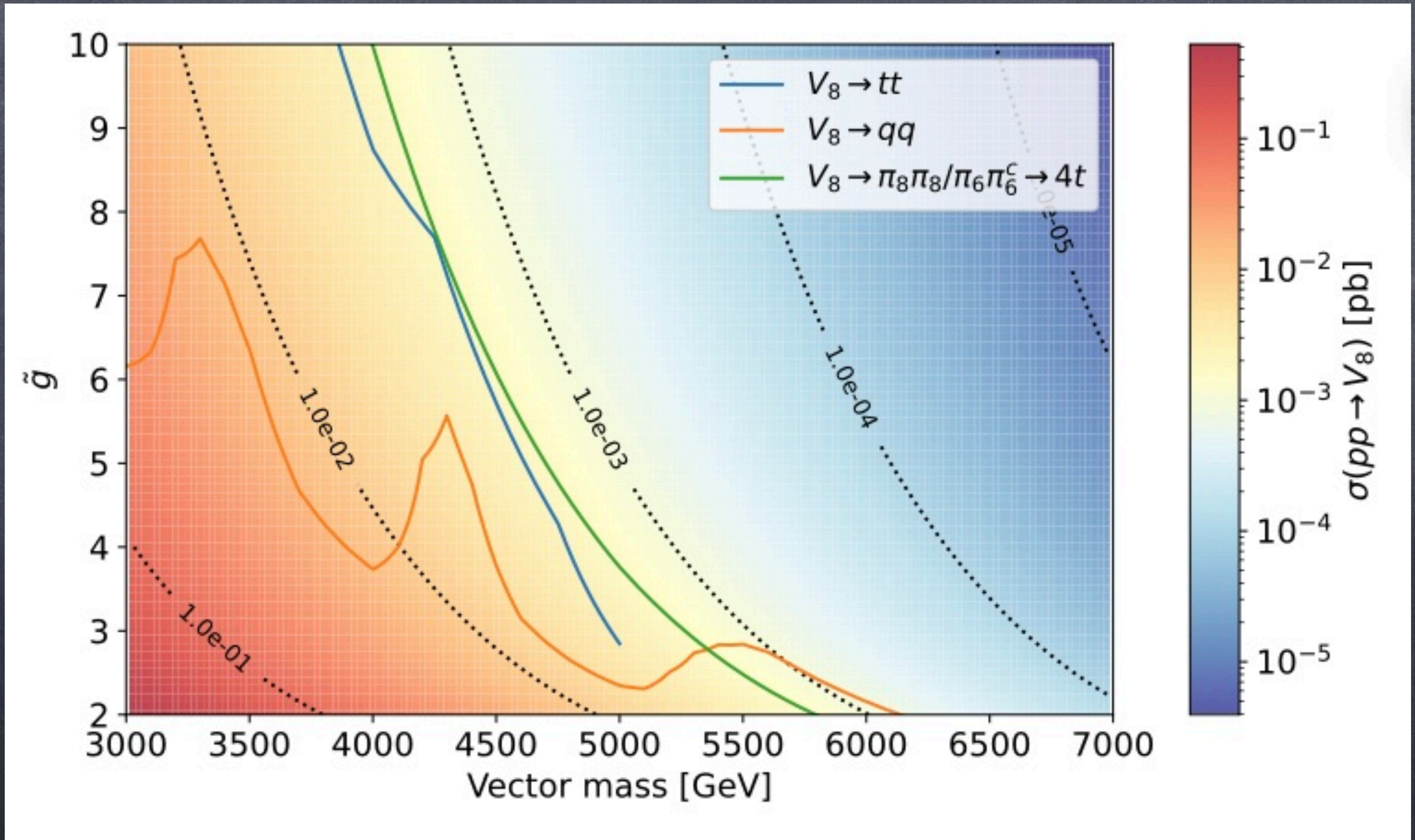
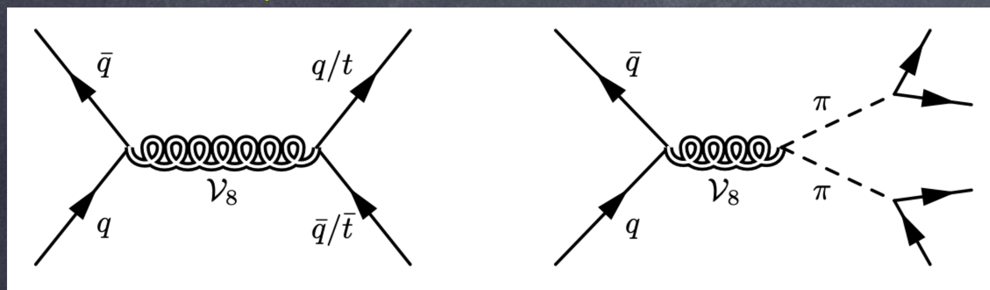
2404.02198

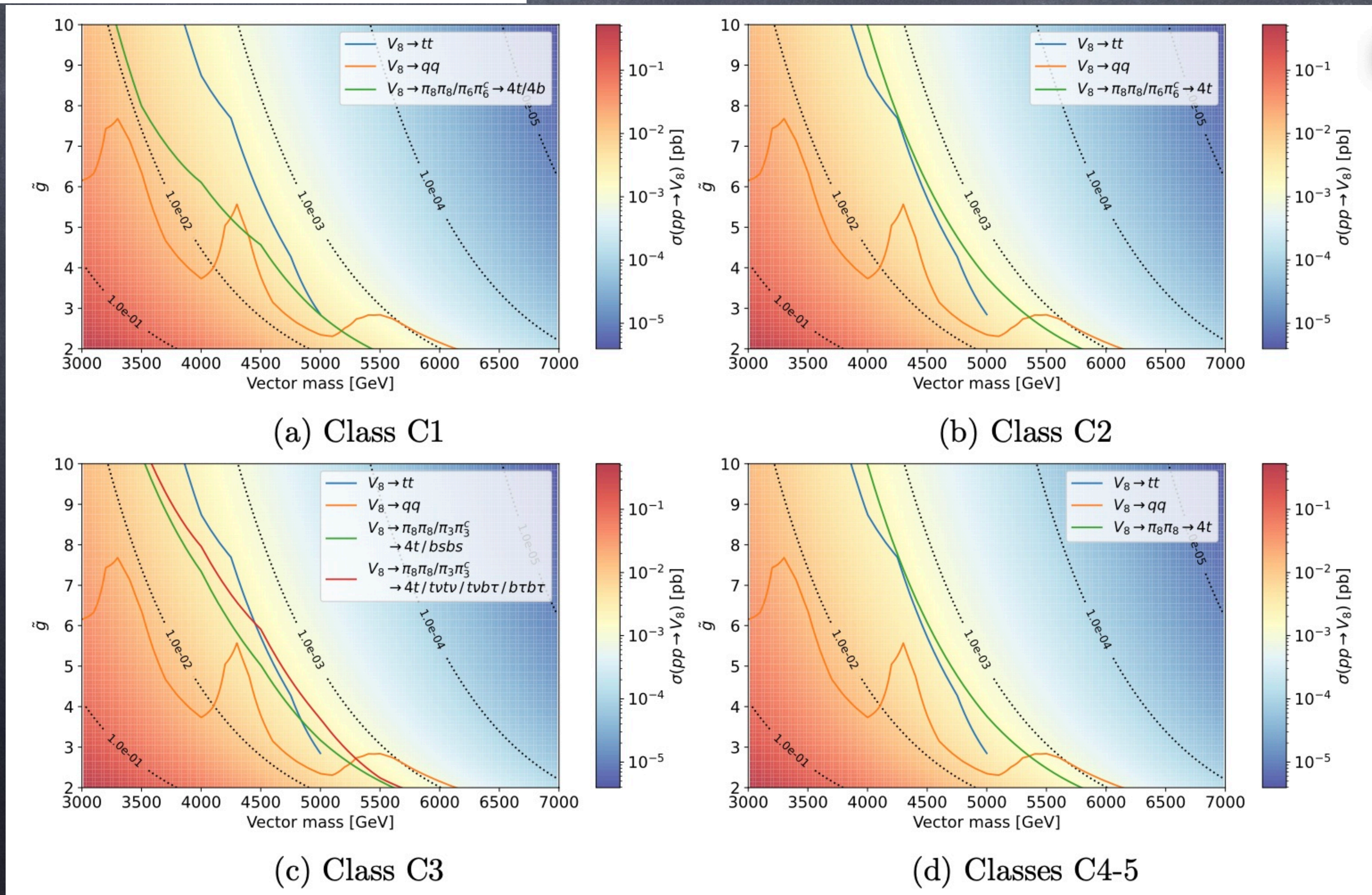


(b) Class C2

Spin-1 resonances: LHC bounds

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
2404.02198





(a) Class C1

(b) Class C2

(c) Class C3

(d) Classes C4-5

The FCC-ee* legacy

(* aka CEPC, ILC, ...)

- The Higgs (precision)
- EW precision tests
- Light singlets (ALPs) below the Z mass

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:

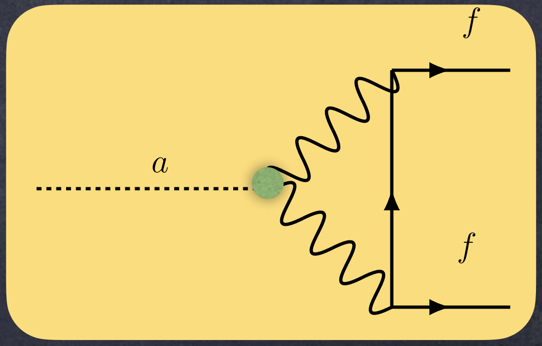
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

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

(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:

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$$+ g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde G^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + g'^2\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde B^{\mu\nu}\,,$$

Composite Higgs scenario:

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

Free parameters:

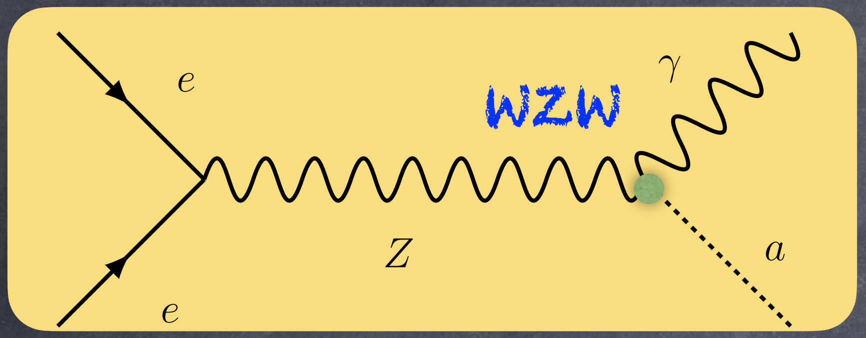
$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

f, m_a

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

Tera-Z portal to compositeness (via ALPs)

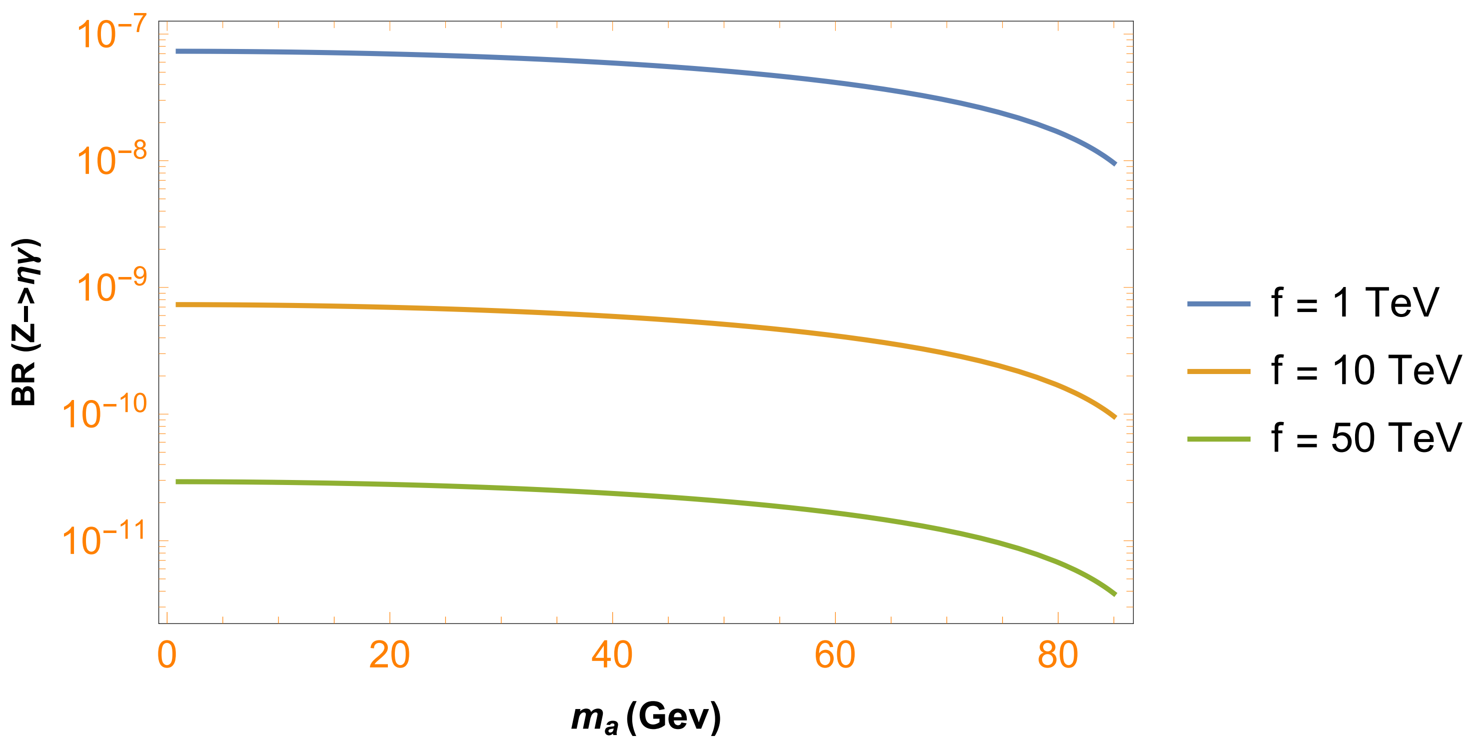
G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

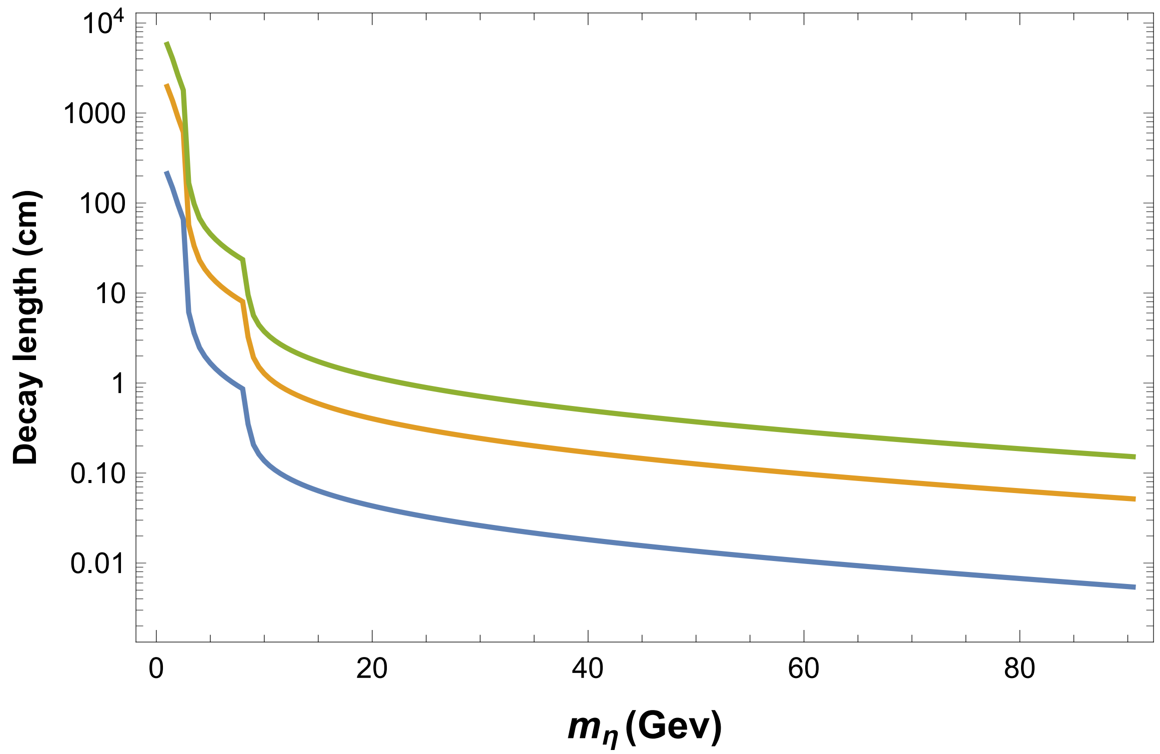


This process is always associated with a monochromatic photon.

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)

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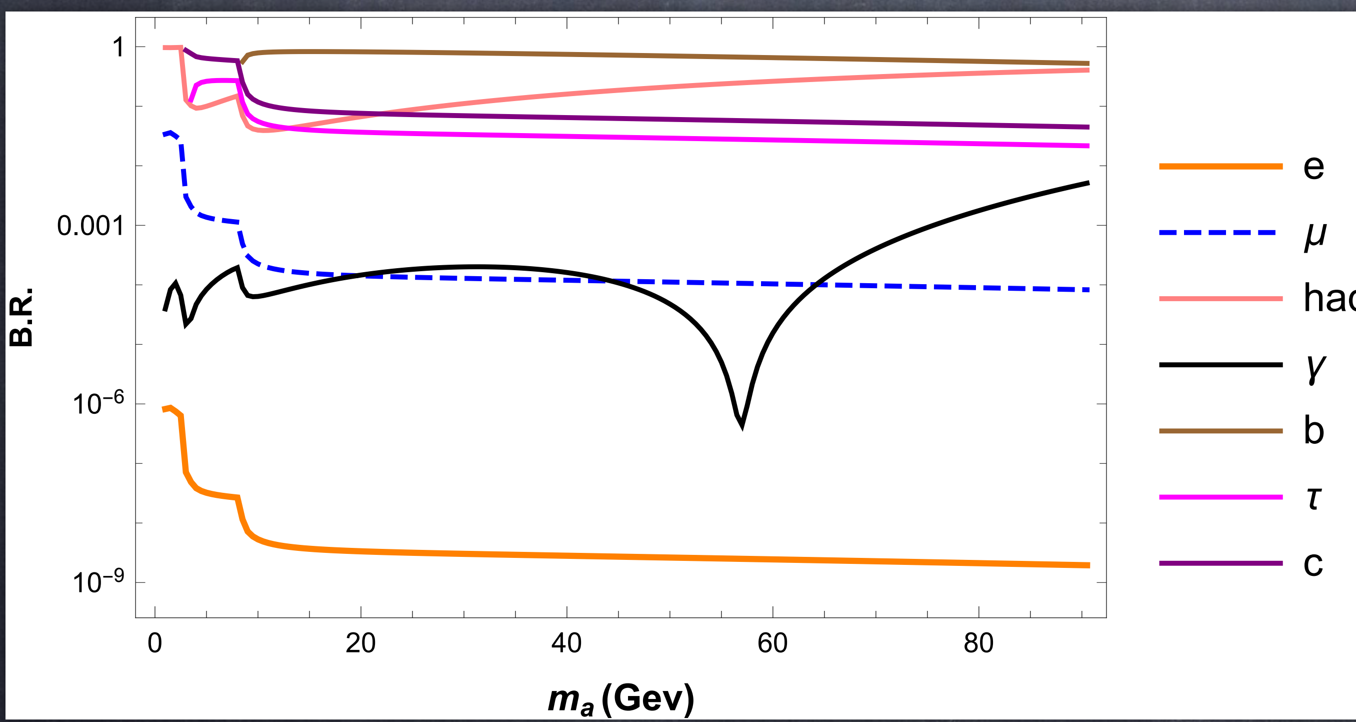
2104.11064

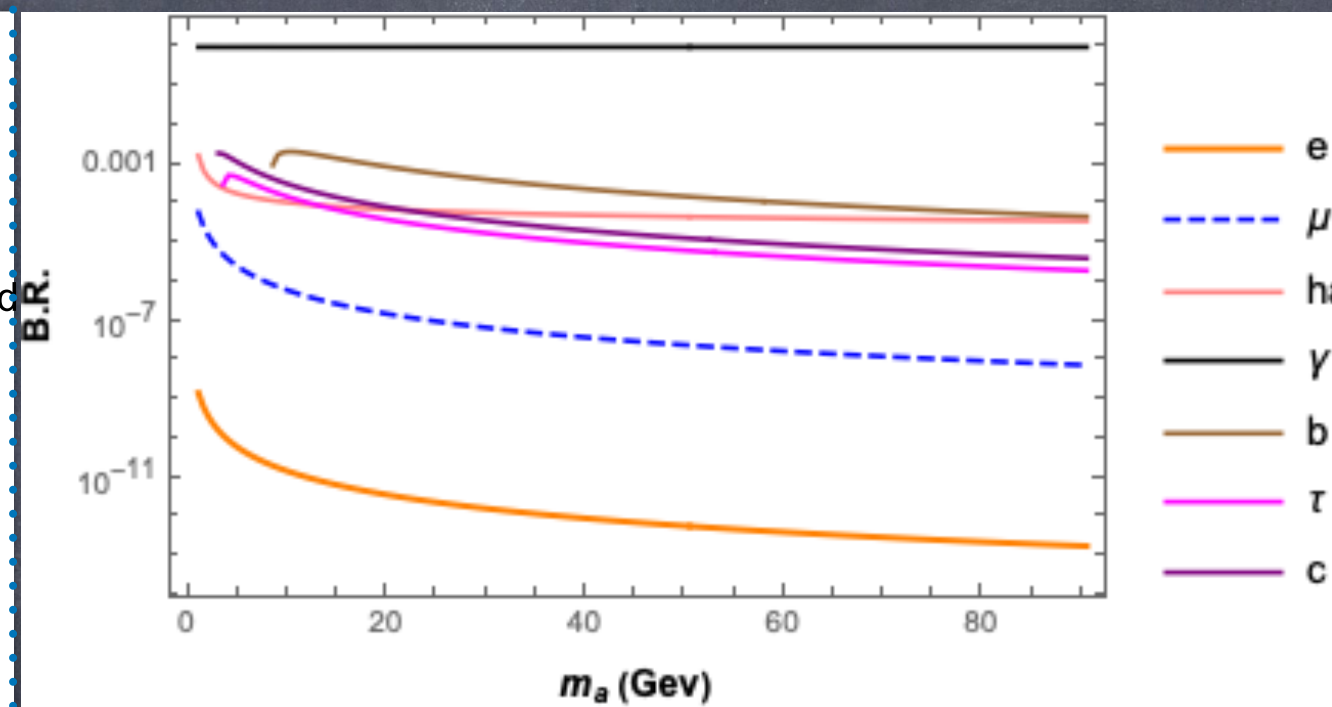
Photo-phobic



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

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

Photo-philic



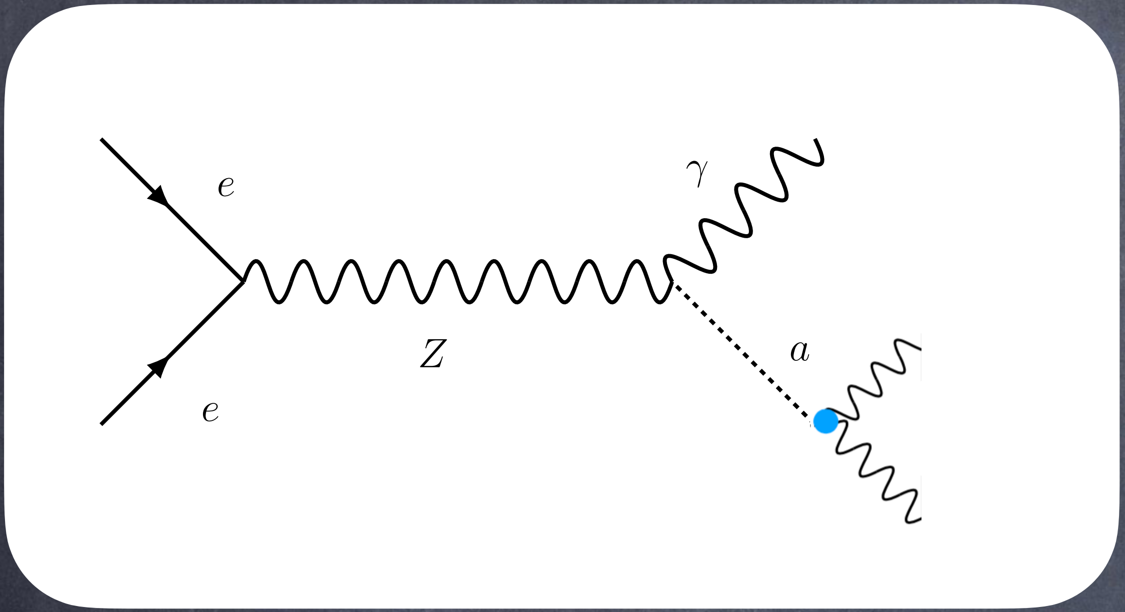
WZW interaction to photons (like the pion)

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

Phenomenology-Prompt Decays

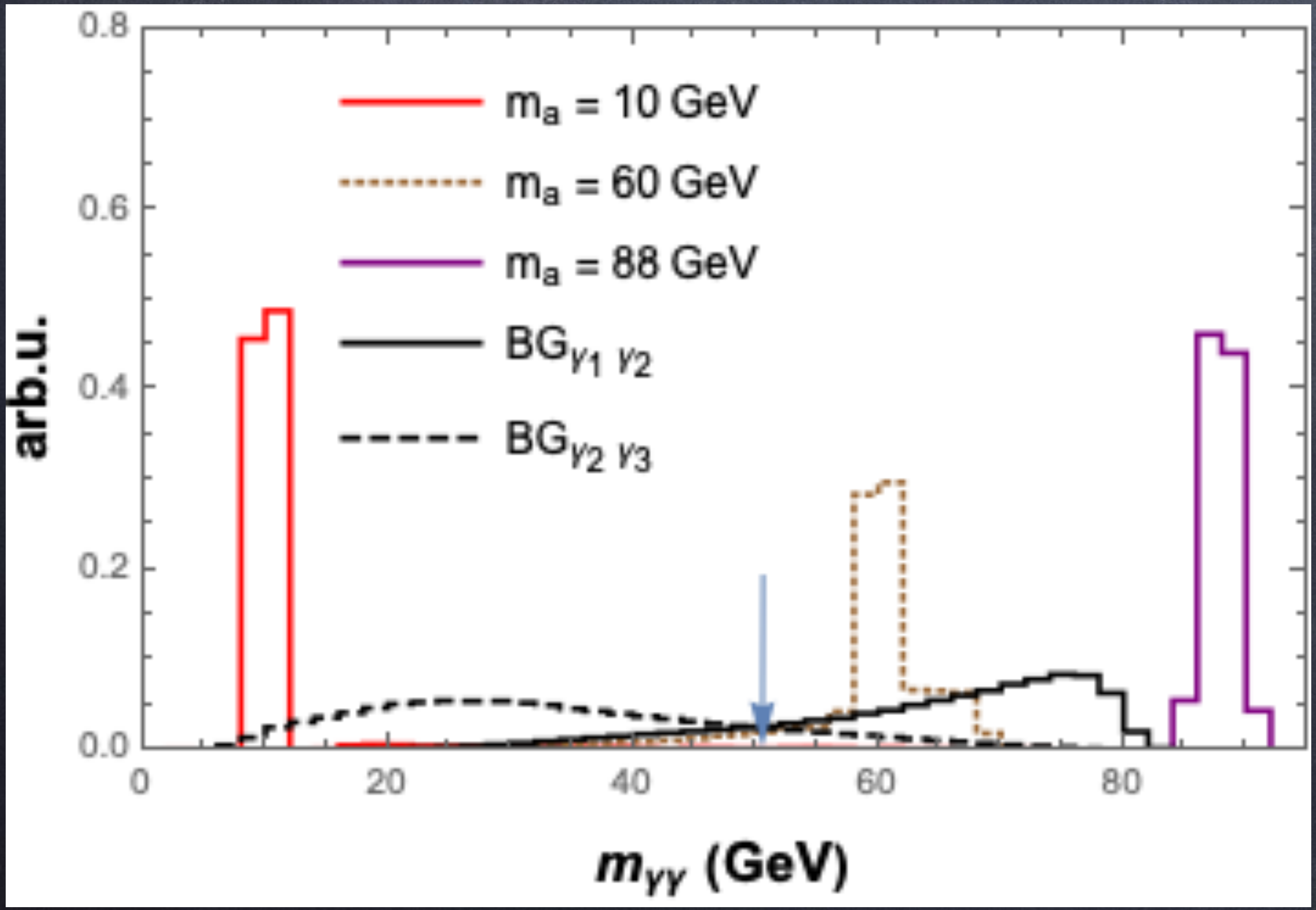
Photo-philic

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

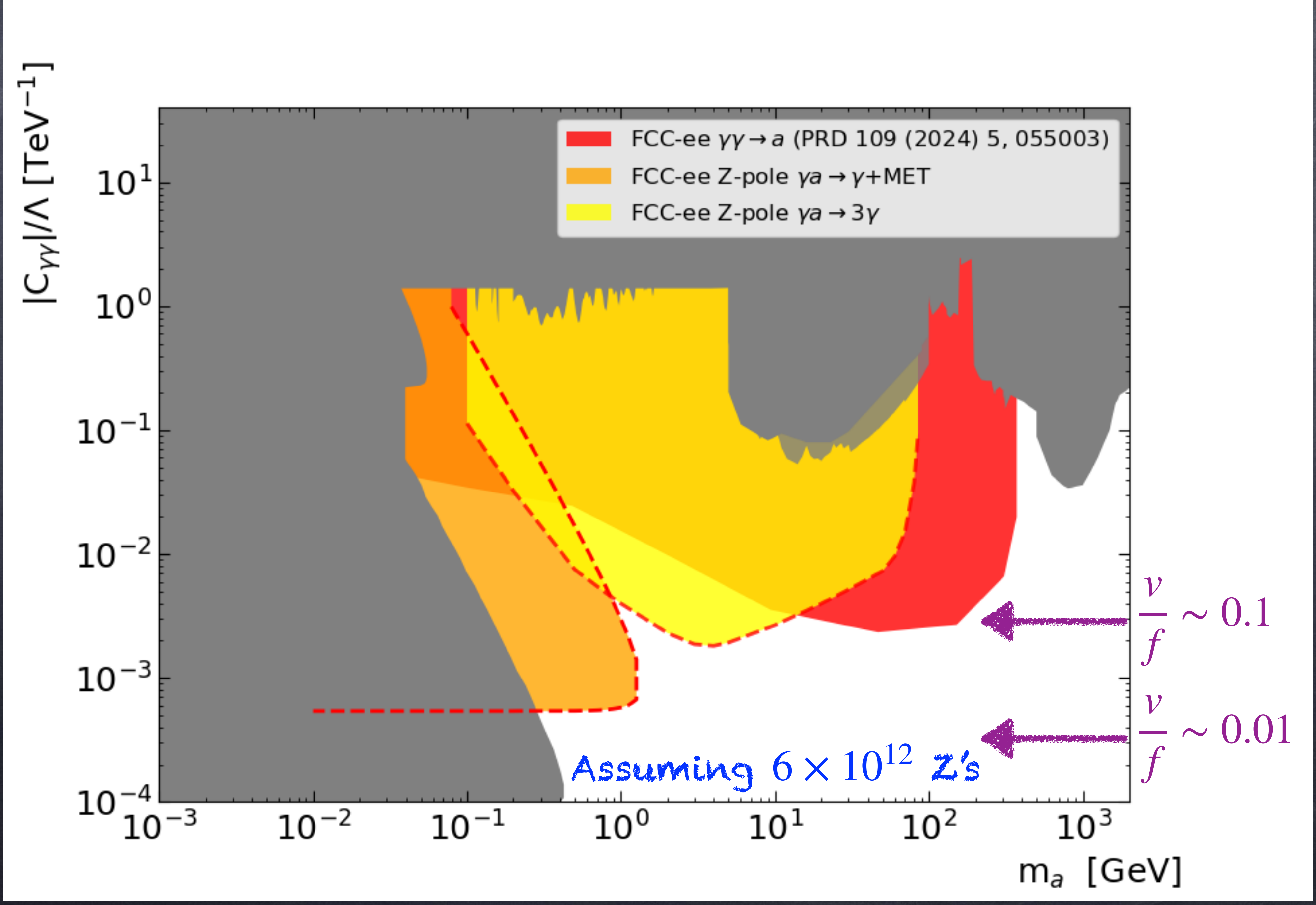
Bins above 80 GeV populated by fakes: hard to estimate!

Phenomenology

G.Polesello, 2502.08411
+ work in progress

Photo-philic

Two searches:
- prompt decays to photons;
- Decay outside the detector.



What if FCC-ee discovers Z > γa?

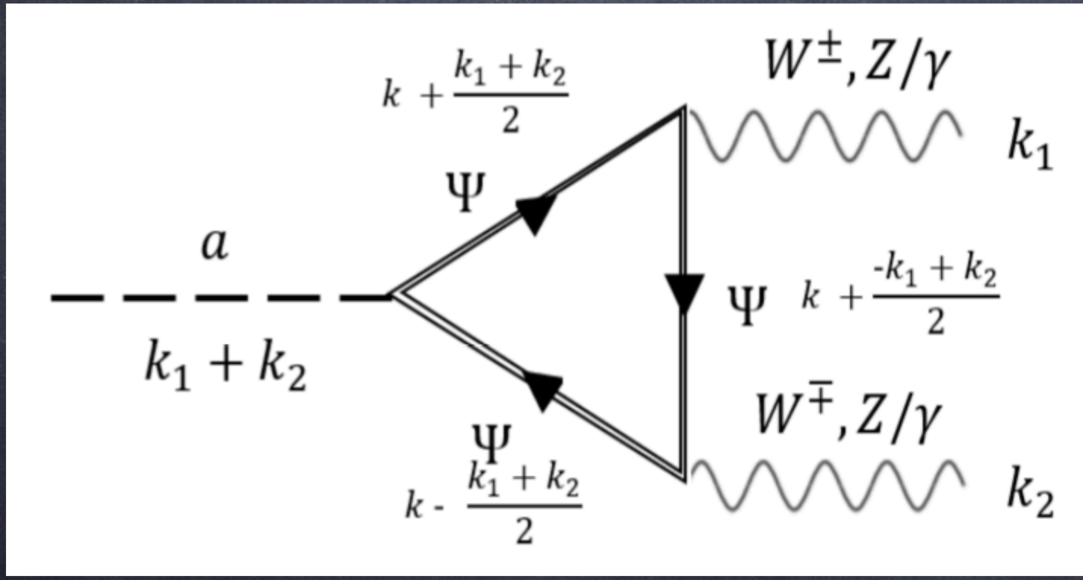
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

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

$\Phi = H + i\, a$

Singlet scalar

Ψ = doublet + singlet



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

doublet + singlet = photo-phobic case

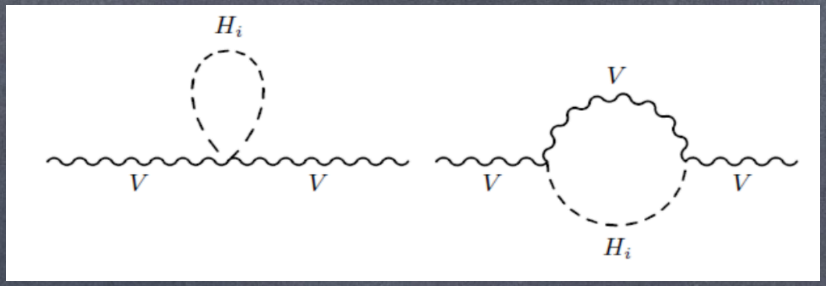
- Note: fermion masses of the order of TeV, potentially discoverable at HL-LHC or FCC-hh (QCD-neutral)

What if FCC-ee discovers Z > γa?

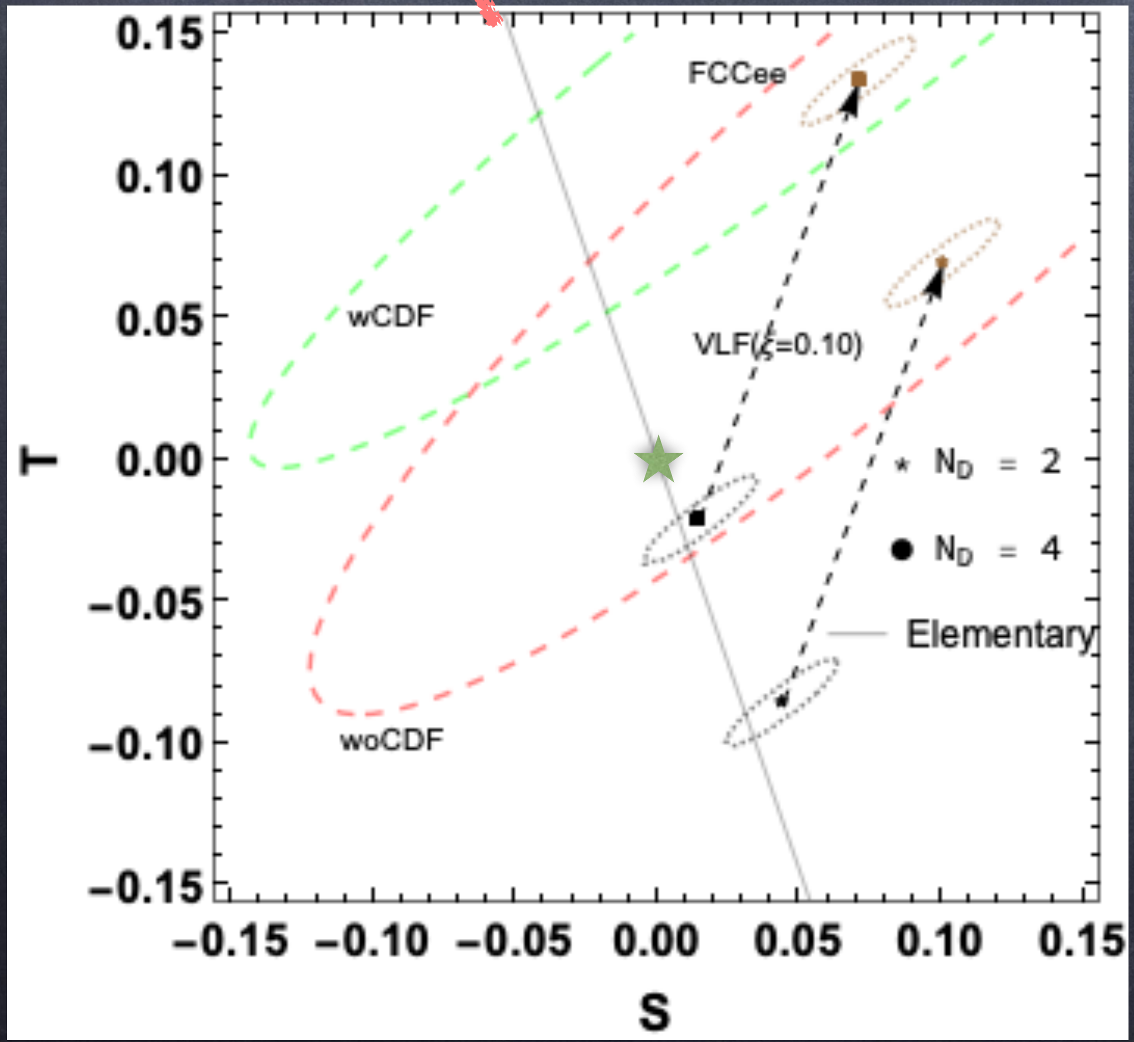
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

- 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.

The FCC-hh* legacy

(* aka CEPC, ILC, ...)

- The Higgs potential (trilinear)
- Heavy resonances
- Multi-boson production (precursors of techni-jets)

Spin-1 resonances: FCC-hh

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
2404.02198

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

$$\mathcal{V}_6 \to \pi_8 \pi_3^\dagger \to (t\bar{t})(\bar{b}\bar{s} \text{ or } ql) \quad \text{in C3}$$
$$\mathcal{A}_6 \to \pi_8 \pi_8 \pi_6 \; (t\bar{t}t\bar{t}bb) \text{ and } \pi_6^\dagger \pi_6 \pi_6 \; (\bar{b}\bar{b}bbbb) \quad \text{in C1}$$
$$\mathcal{A}_6 \to tt \text{ or } \pi_8 \pi_8 \pi_6 \; (t\bar{t}t\bar{t}tt) \text{ and } \pi_6^\dagger \pi_6 \pi_6 \; (\bar{t}\bar{t}tttt) \quad \text{in C2}$$

Multi-boson production

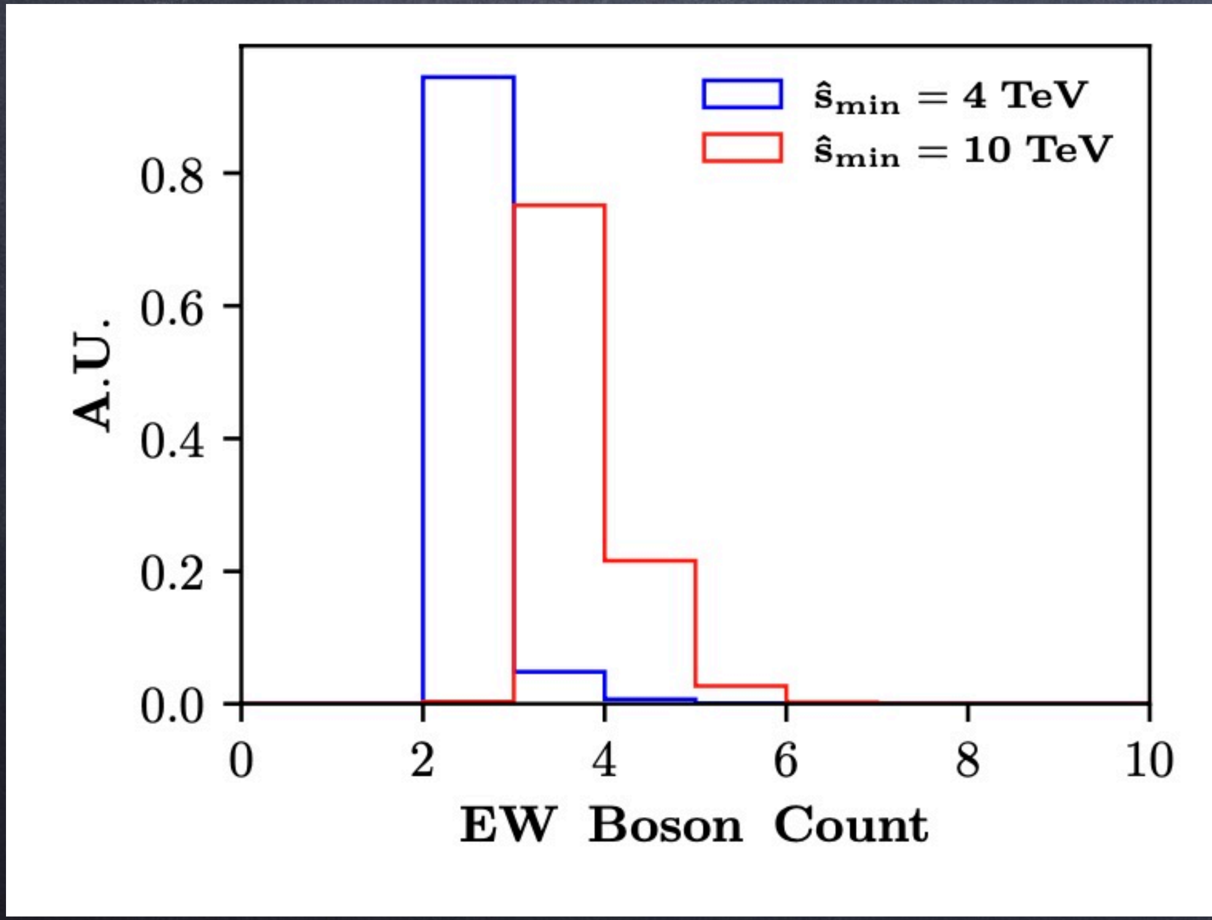
G.C., A.Deandrea, A.Iyer, S.Kulkarni, A.Singh
Work in progress

- Study high-energy multi-boson production via techni-quark Drell-Yan

We simulated events with

$$m_Q = \Lambda_{TC} = 2\ TeV$$

Multiboson dominant at large energies



$\hat{s}_{min}$ (TeV)	3 Bosons		4 Bosons	
	σ_{SM} (ab)	σ_{sig} (ab)	σ_{SM} (ab)	σ_{sig} (ab)
10	685.18	122.03	140.88	33.54
20	23.30	0.1542	6.49	0.2052
30	1.41	0.0014	0.47	0.0015

The composite Higgs Roadmap

- LHC: Higgs, EW scalars, coloured states
- FCC-ee: EW precision + Higgs, light ALPs -> Indications on the compositeness scale and top partner structures
- FCC-hh: discovery up to 10 TeV, jetty structures
- Complementary programme: flavour experiments, gravitational waves (LISA), …