Exploring extended Higgs sectors via pair production at the LHC

Giacomo Cacciapaglia
IP2I Lyon, France

@ IRN Terascale Grenoble

Motivation

- Scalar fields acquire VEV (2HDM, GM, ...)

-> Single production + decays to massive bosons/fermions

- Scalars do not acquire VEV: common scenario in composite Higgs models!

SU(4)/Sp(4)	SU(5)/SO(5)	SU(4)xSU(4)/SU(4)
5 Goldstones	14 Goldstones	15 Goldstones

-> Vacuum alignment induces VEV for the 'Higgs' doublet only!

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

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

Both irrelevant if

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

Let's postulate the existence of fermionic operators:

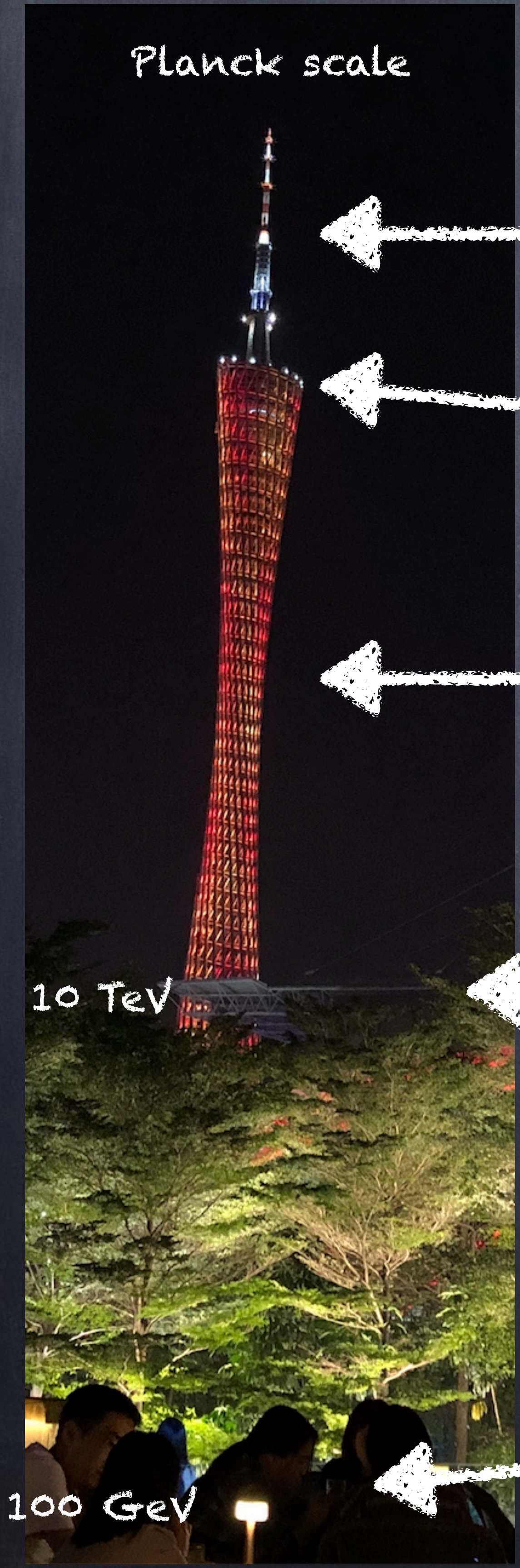
$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}} (\tilde{y}_L\, q_L \mathcal{F}_L + \tilde{y}_R\, q_R \mathcal{F}_R)$$

This dimension is not related to the Higgs!

↓

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

Composite models at various scales



HC and SM gauge groups partially unified

Symmetry breaking by scalars — 4-fermion Ops generated!

Conformal window (large scaling dimensions) — Low energy model + additional fermions

Condensation scale

Usual low energy description of composite Higgs models

Standard Model

Phenomenology accessible to colliders

Composite models at various scales

HC and SM g

partially

Symmetr

Con

(large s

Condensation scal

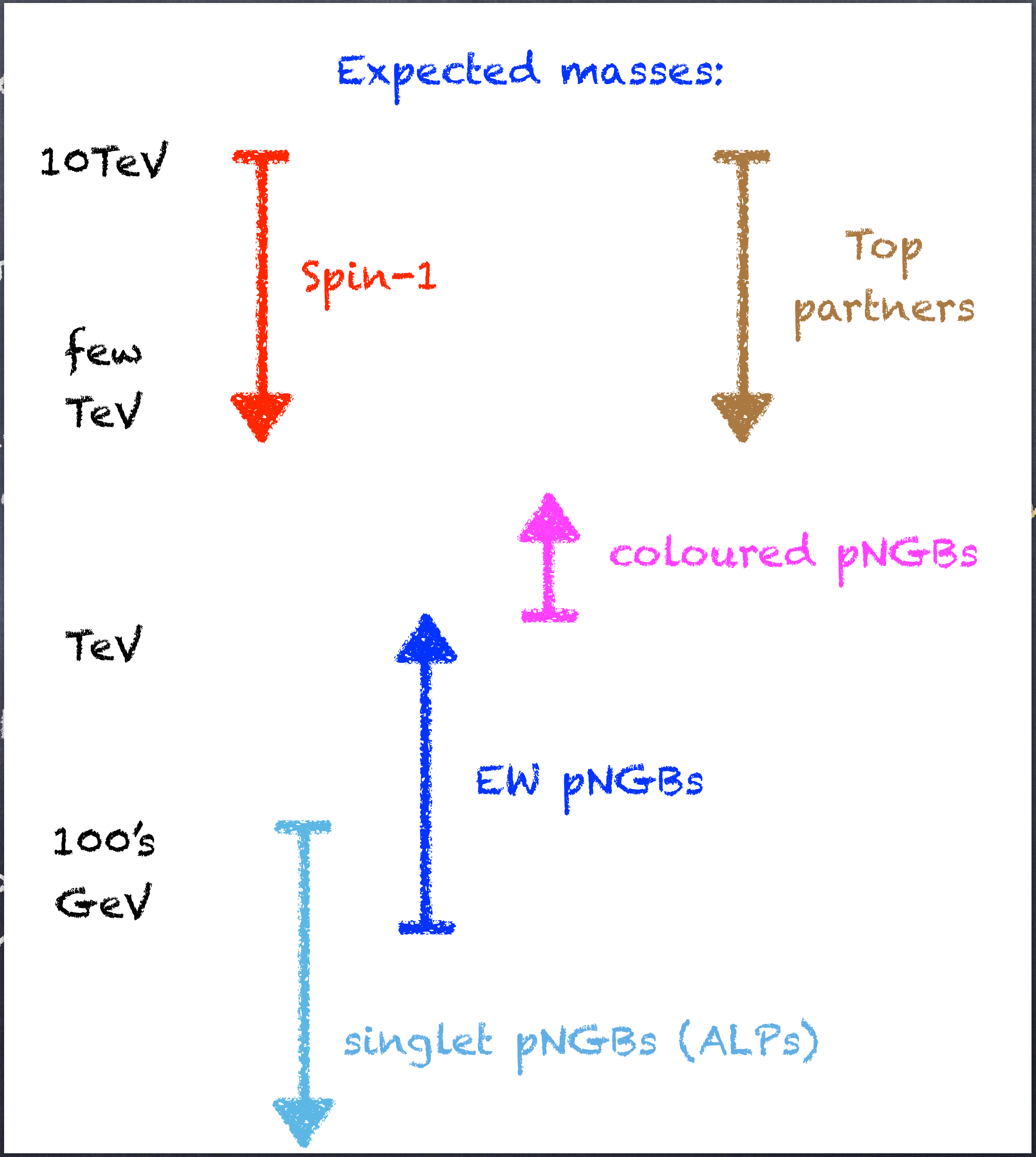
Usual lo

of com

Standard

+

ns



Expected masses:

10TeV

few TeV

TeV

100's GeV

Spin-1

Top partners

coloured pNGBs

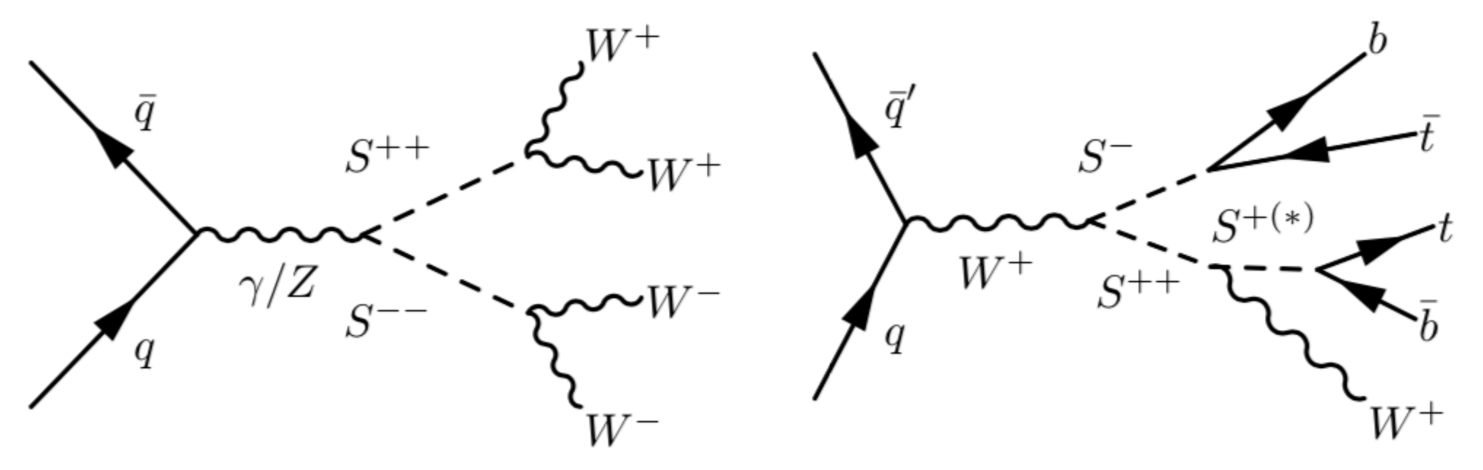
EW pNGBs

singlet pNGBs (ALPs)

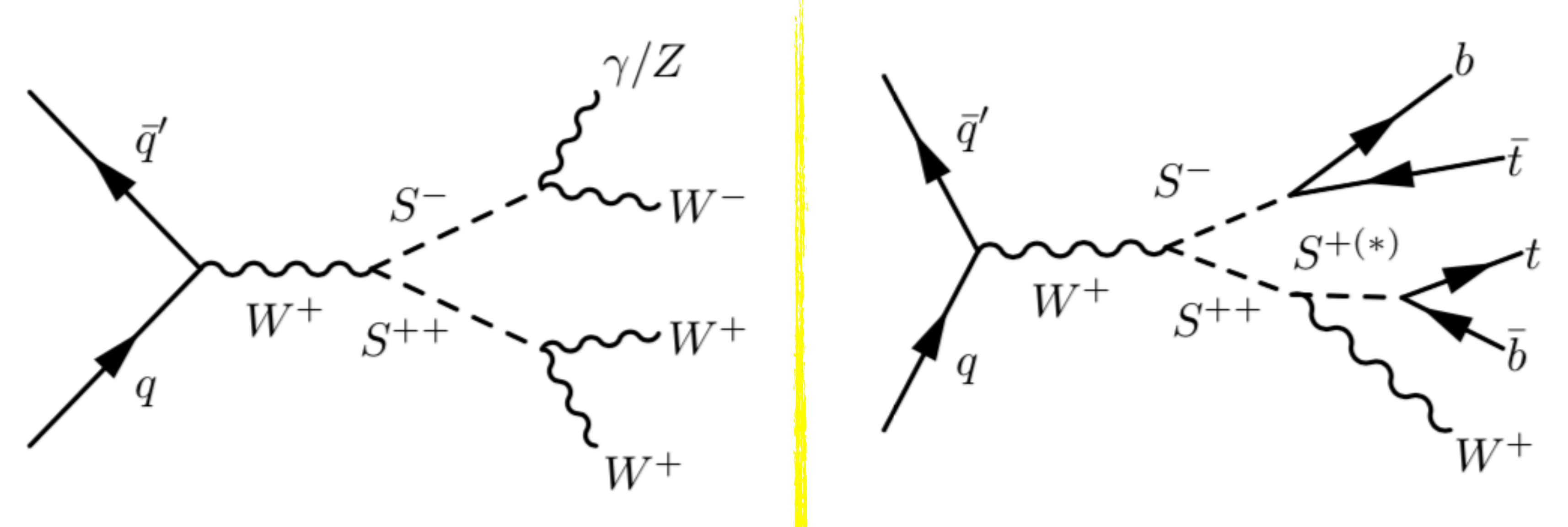
EW pNGB direct production

W.Porod et al.
2210.01826

- Dominantly pair-produced via EW gauge interactions
- Couplings to two EW gauge bosons via WZW (including photons!!!)
- Couplings to two fermions via partial compositeness
- Few dedicated direct searches (WWWW and WWWZ via doubly-charged scalar)



EW pNGB direct production

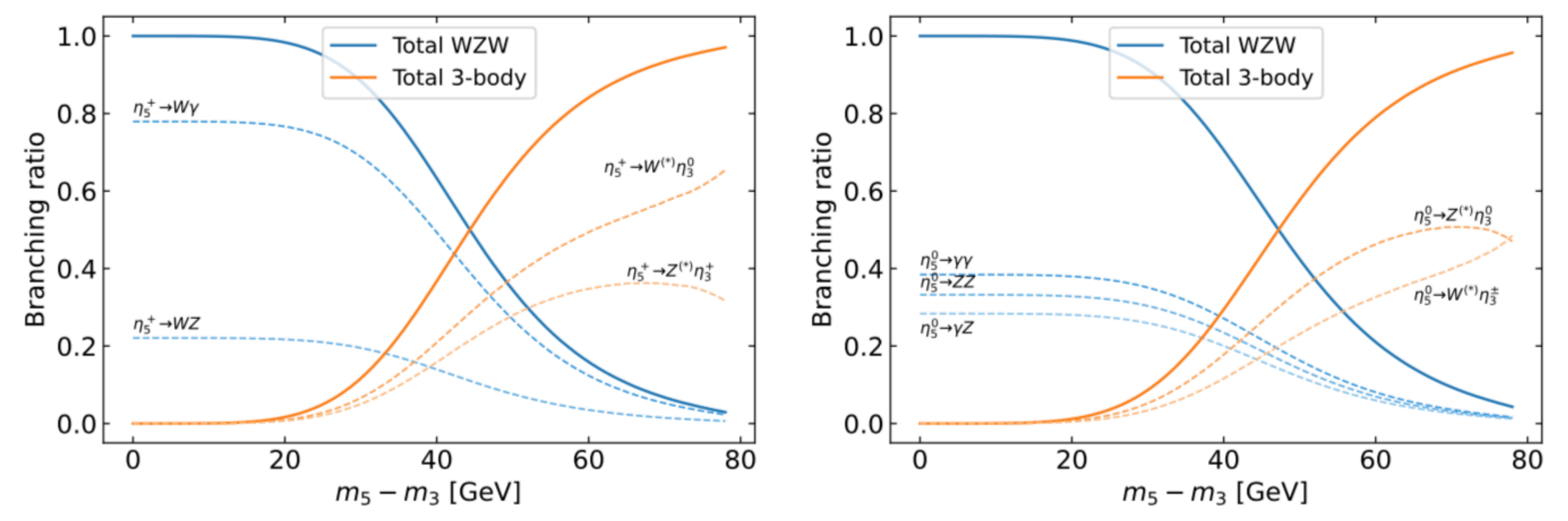


Porod et al.
2210.01826

- Decays to two GBs from WZW anomaly
- Very 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



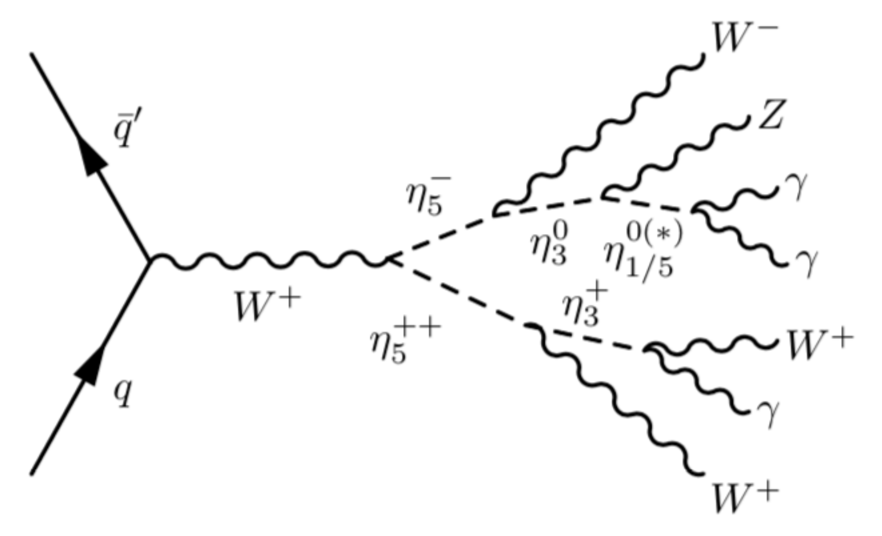
(c) Decays of η_5^+ for $m_5 = 600$ GeV $> m_3$

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

W.Porod et al.
2210.01826

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

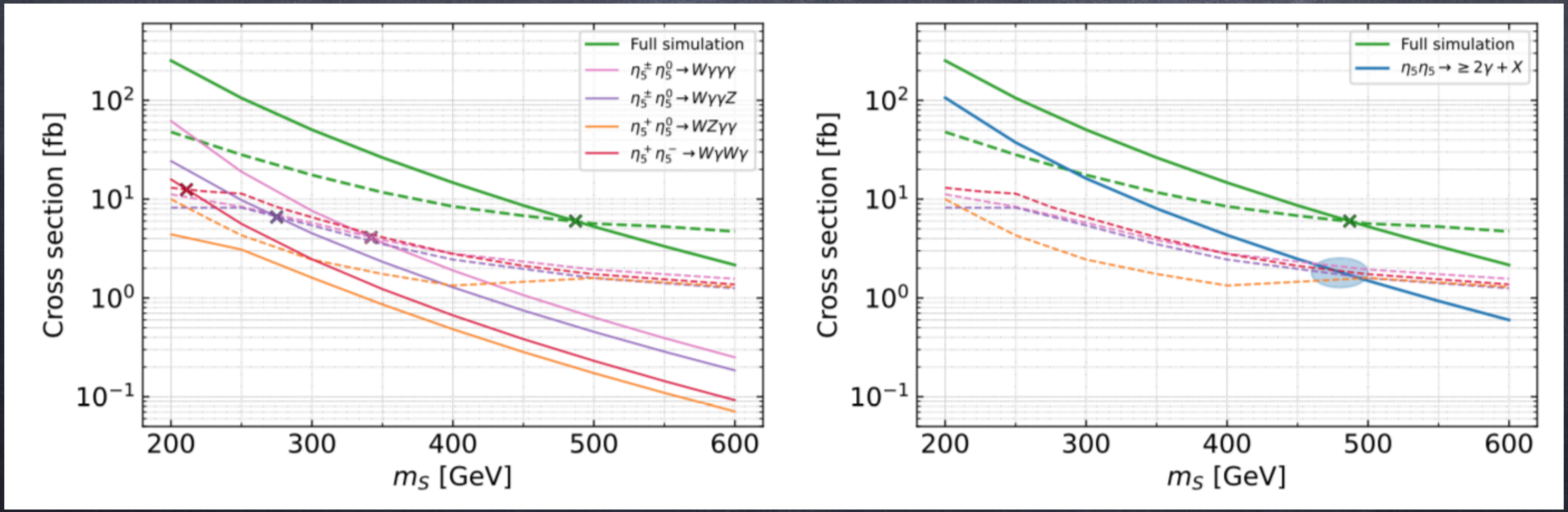
Cascade decays competitive for mass splits around 50 GeV



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!



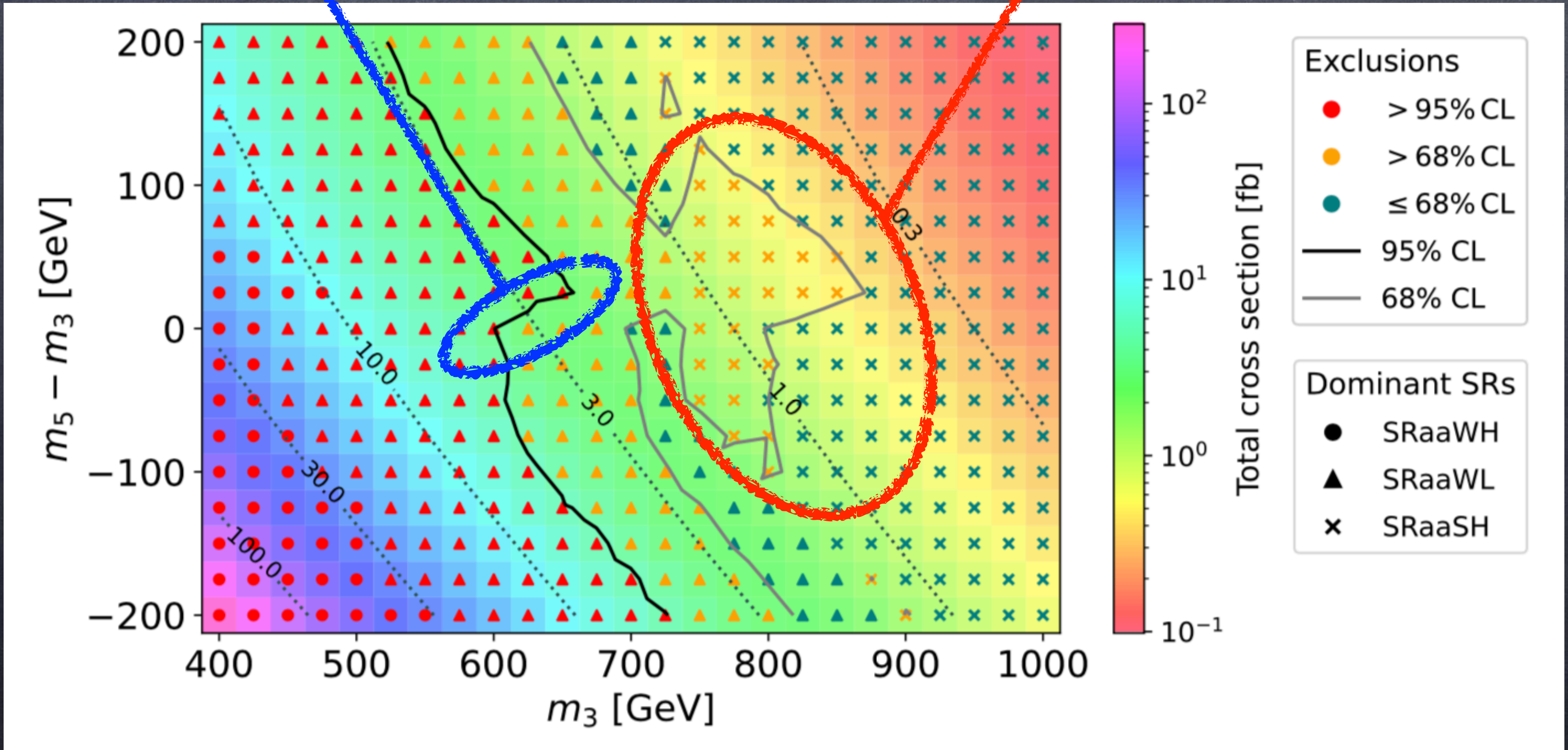
SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

Exclusion from multi-photon search

S++ cascade decays

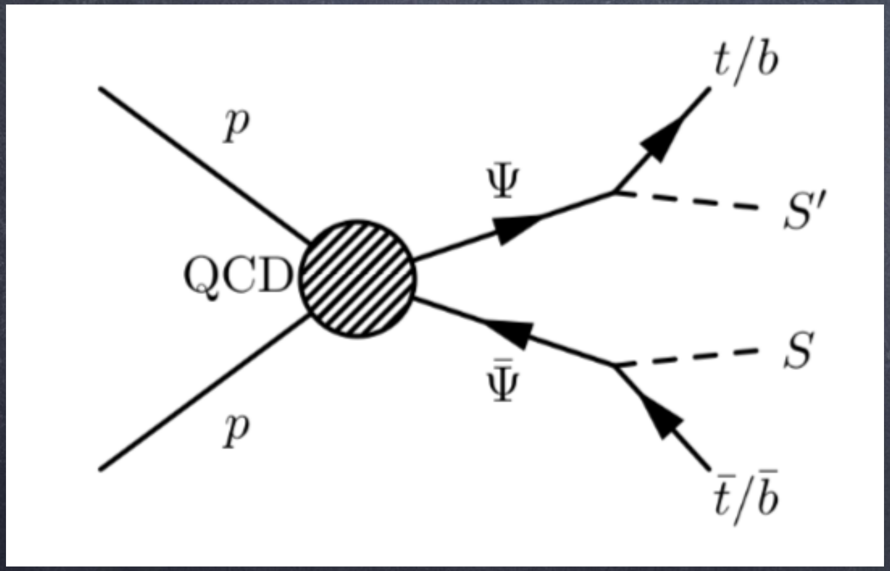
Change in dominant SR



Top partner pheno revisited

A.Banerjee et al
2203.0727 (Snowmass LOI)

- 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:

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

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

$$\begin{aligned} S^{++} &\to W^+t\bar{b}, \\ S^{+} &\to t\bar{b}, \\ S^{0} &\to t\bar{t},\, b\bar{b}. \end{aligned}$$

Dominant, if present for the specific S.

Common exotic top partner decays

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

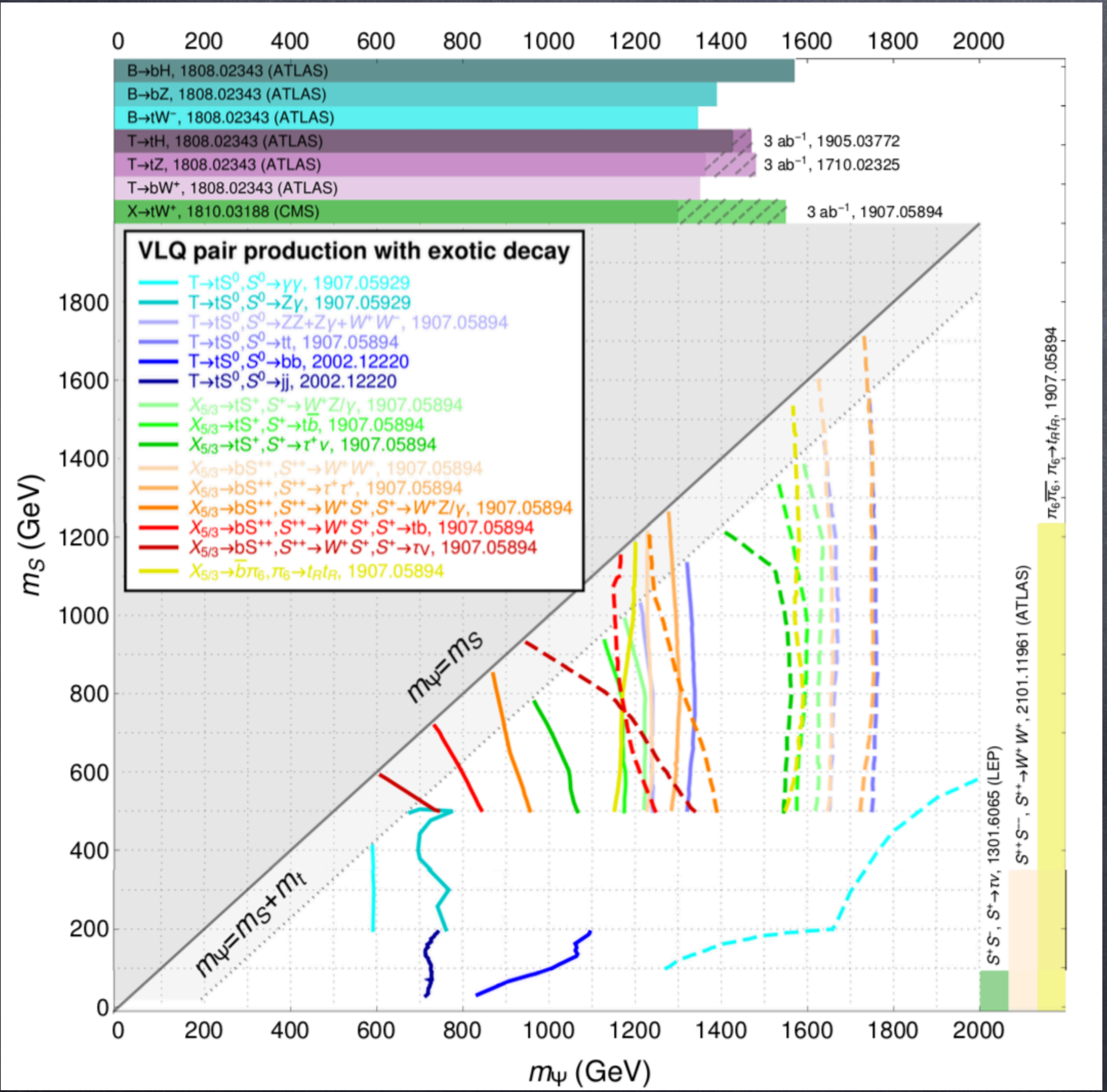
$$\mathcal{L}_{\Psi f S} = \sum_i S_i^+ \left[\kappa^{S_i^+}_{T,L} \overline{T} P_L b + \kappa^{S_i^+}_{X,L} \overline{X} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^- \left[\kappa^{S_i^-}_{B,L} \overline{B} P_L t + L \leftrightarrow R \right] + \text{h.c.}$$
$$+ \sum_i S_i^0 \left[\kappa^{S_i^0}_{T,L}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

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

Work in progress by A.Deandrea and B.Fuks

Common exotic top partner decays

A.Banerjee et al
2203.0727 (Snowmass LOI)



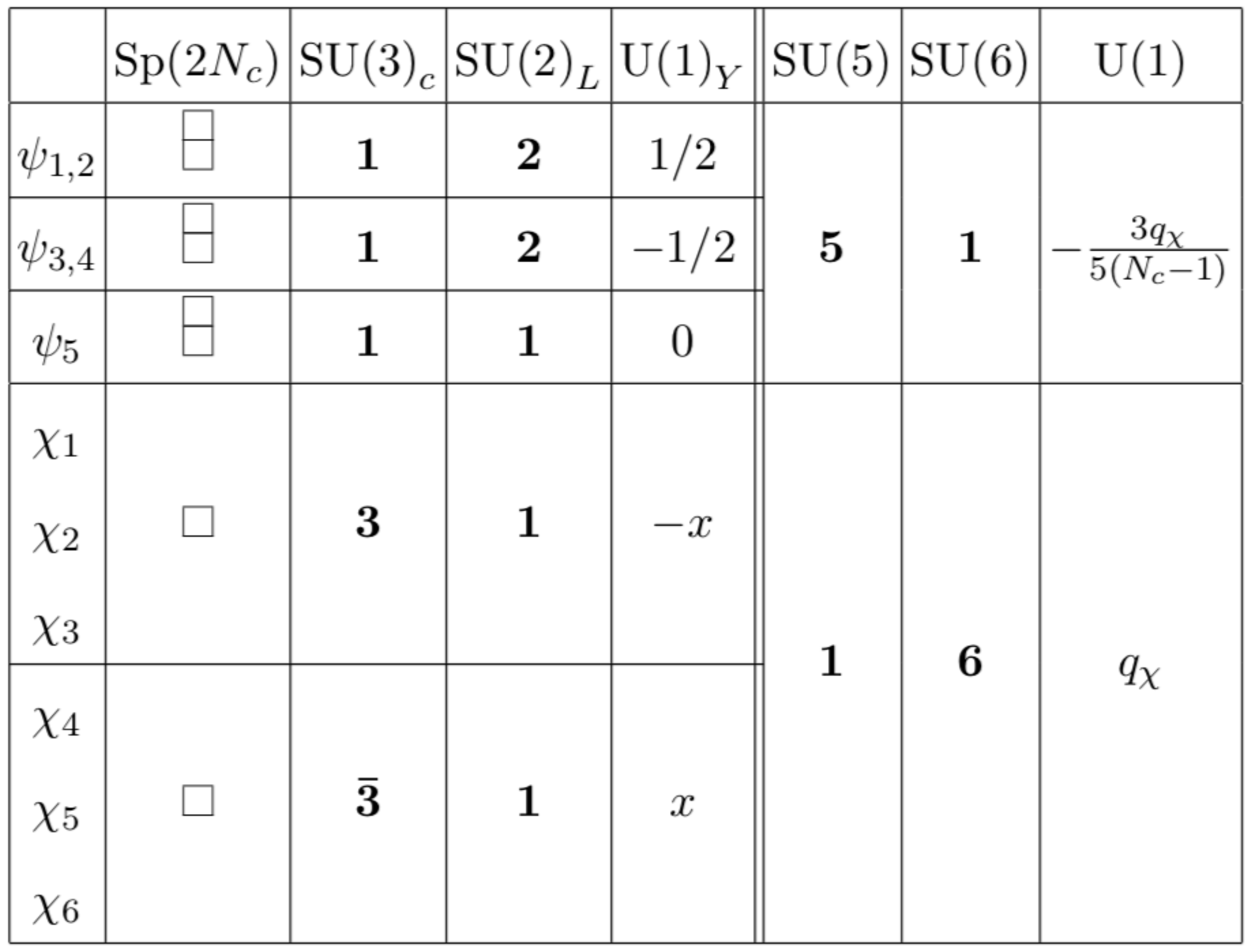
- Dedicated searches may be useful to push up the limits.
- Projections for FCC-hh are needed...
- in combination with scalar direct production.

Exotic top partners

G.Cacciapaglia et al.
2112.00019

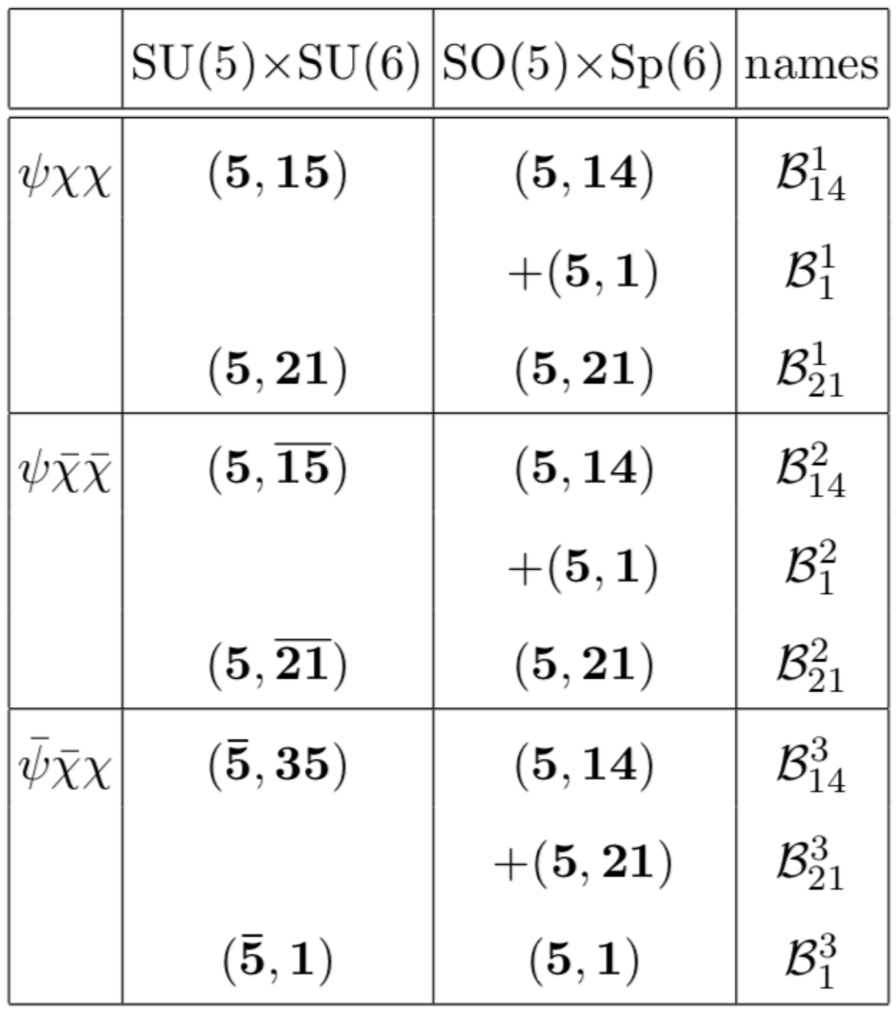
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)

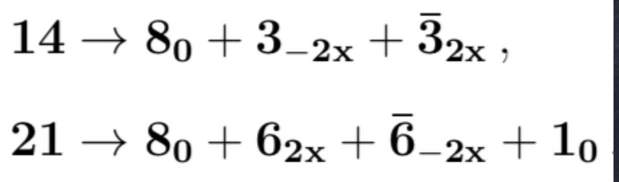


	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$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

Baryons (top partners)



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



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

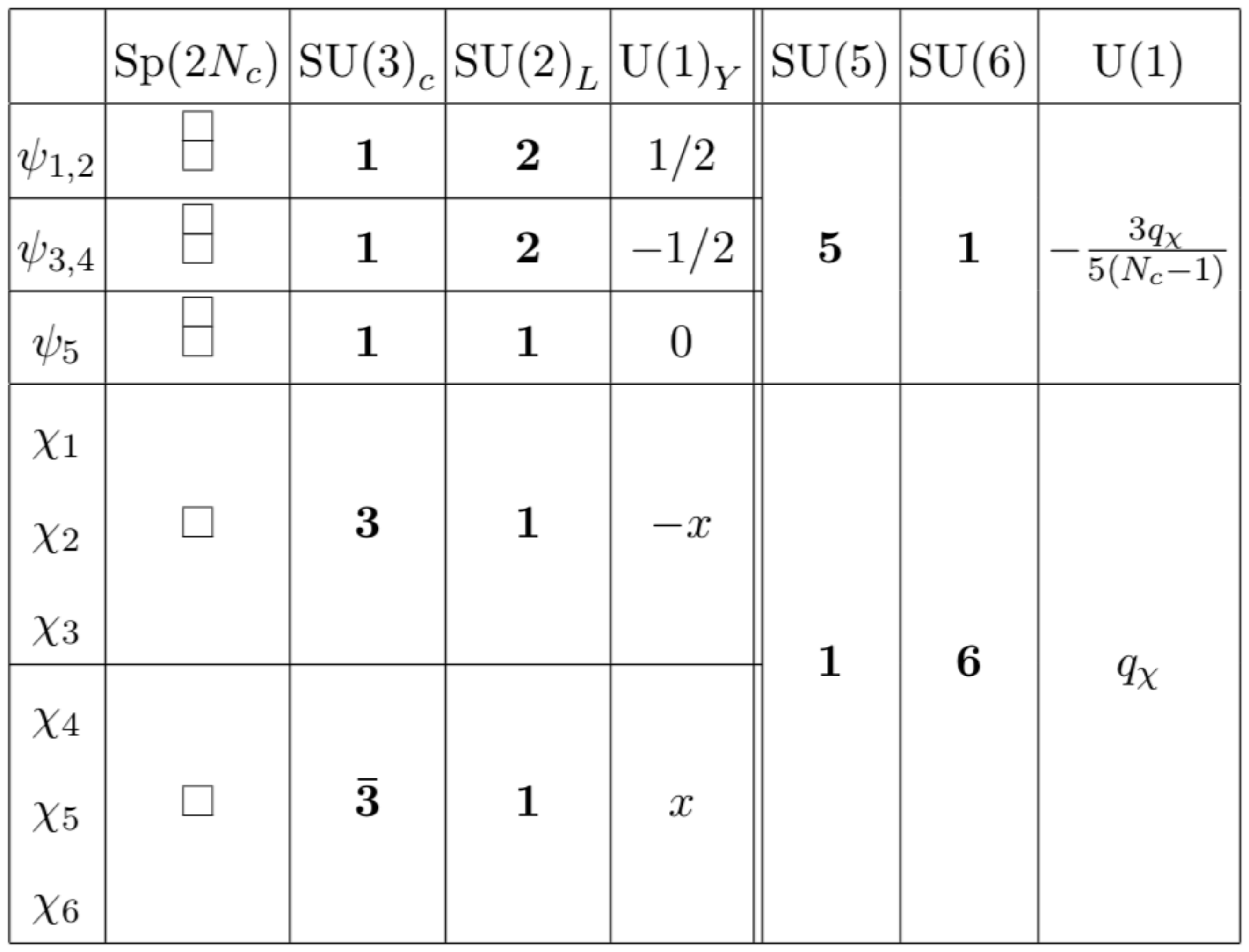
$$\mathbf{21} \to \mathbf{8_0} + \mathbf{6_{2x}} + \bar{\mathbf{6}}_{\mathbf{-2x}} + \mathbf{1_0}$$

Exotic top partners

G.Cacciapaglia et al.
2112.00019

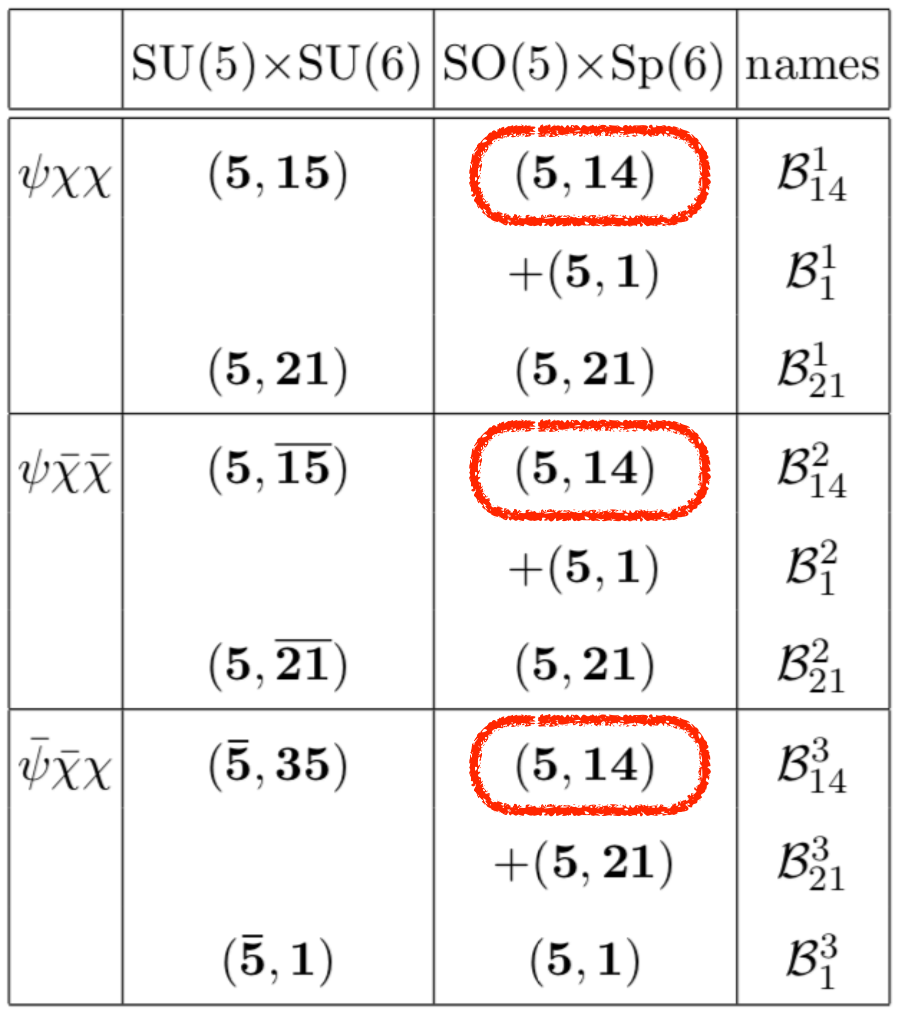
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)



	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(5)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
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			

Baryons (top partners)



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

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

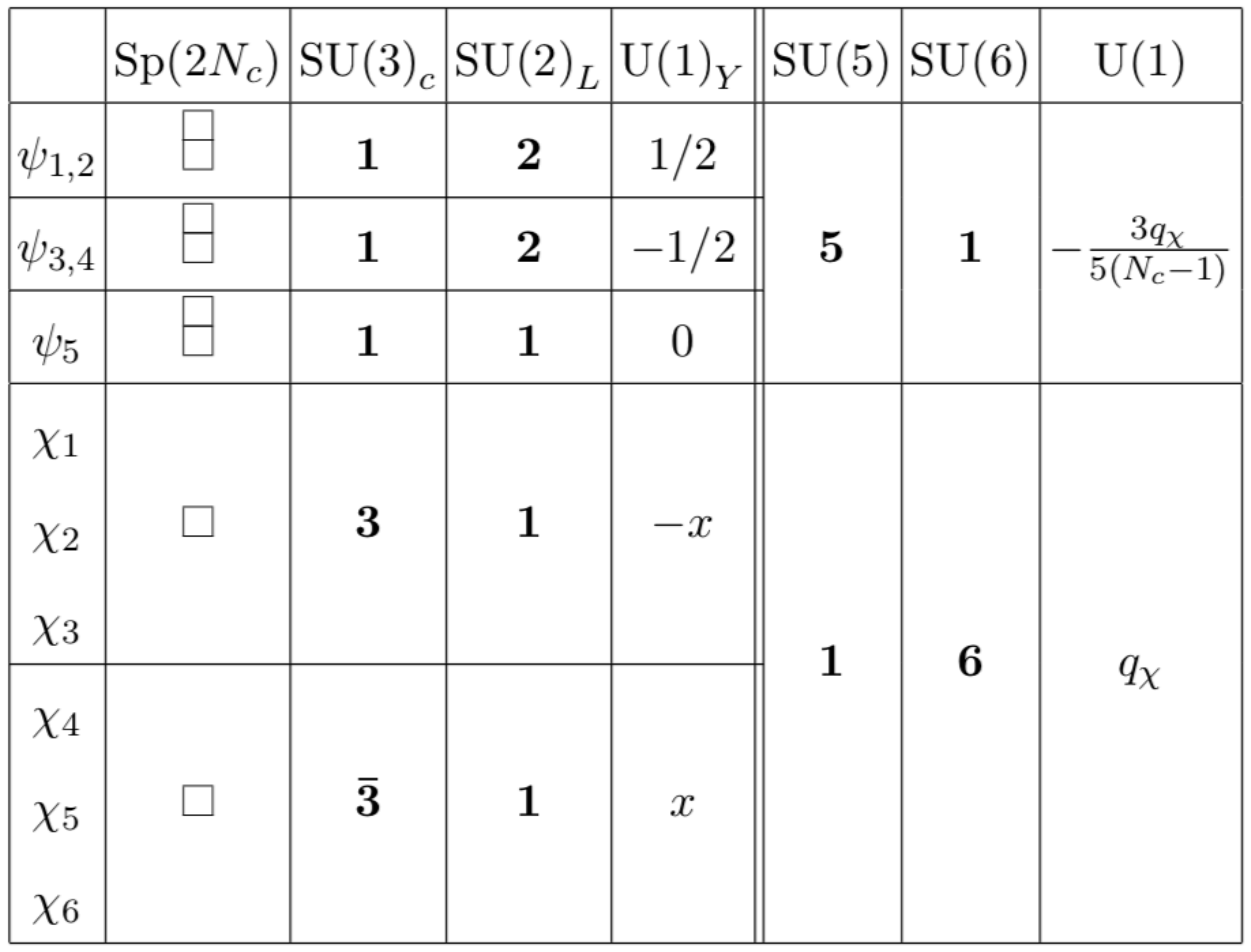
$$\mathbf{21} \to \mathbf{8}_0 + \mathbf{6}_{2x} + \bar{\mathbf{6}}_{-2x} + \mathbf{1}_0$$

Exotic top partners

G.Cacciapaglia et al.
2112.00019

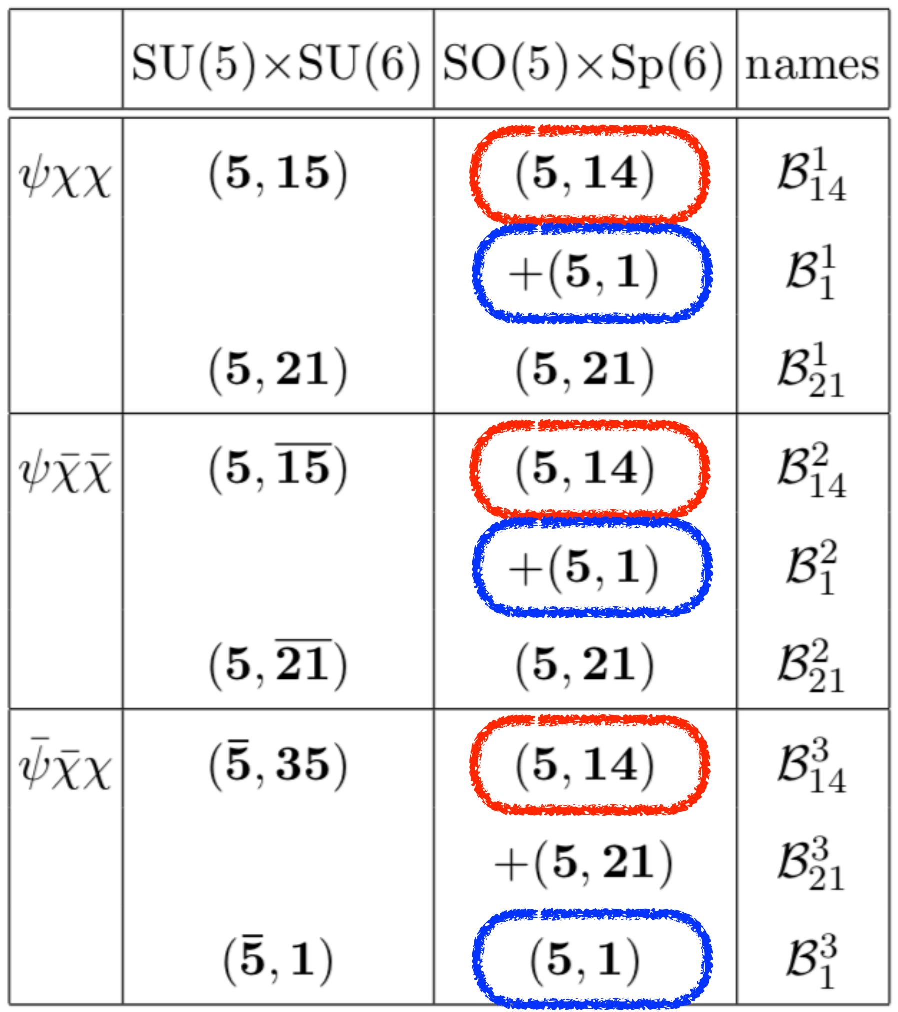
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)

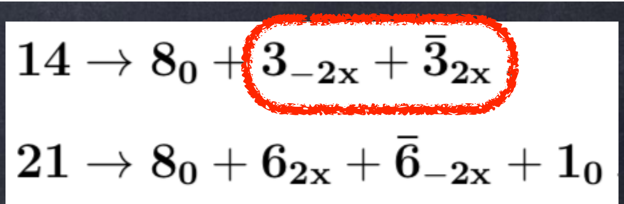


	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$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

Baryons (top partners)



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

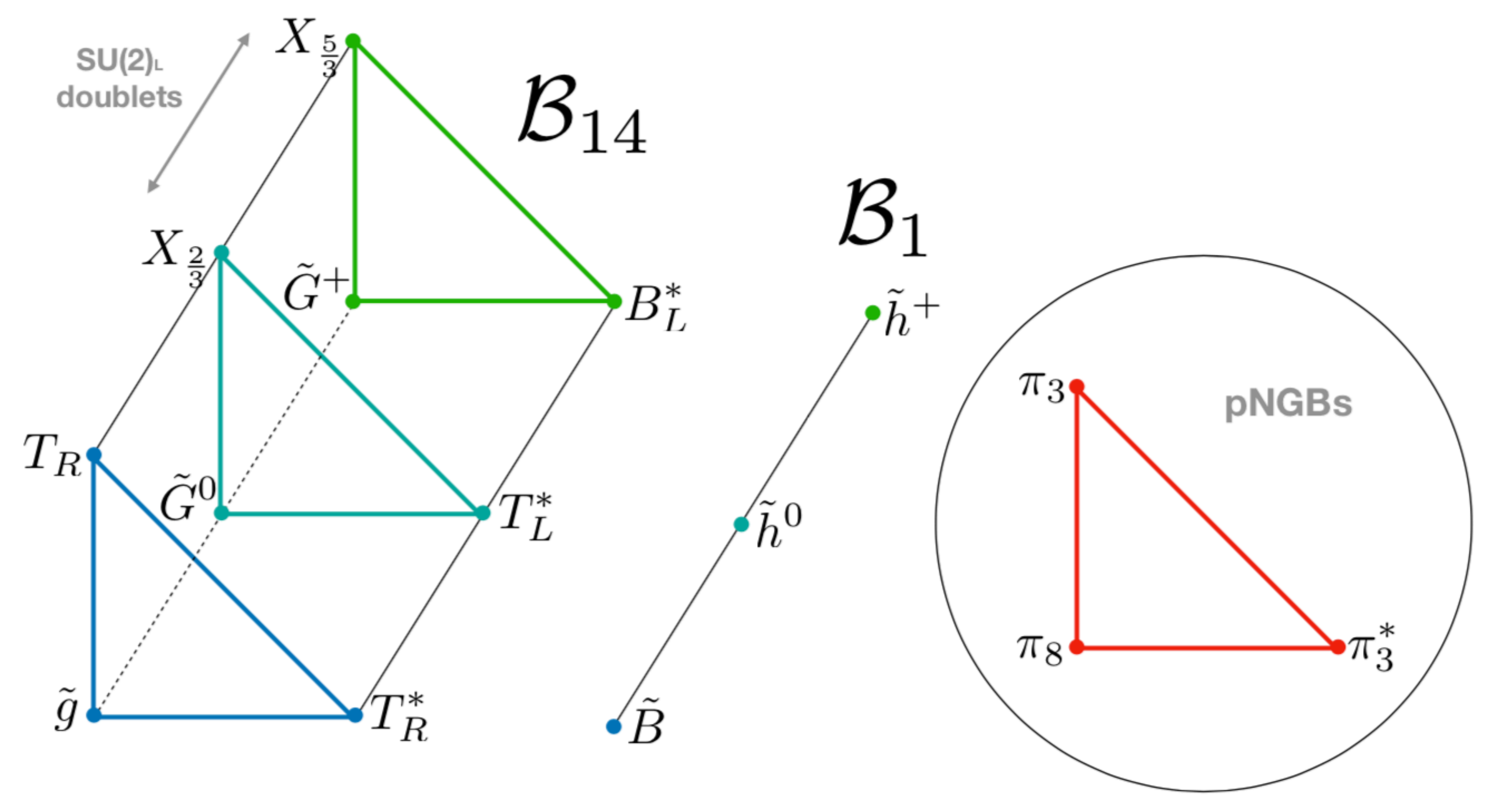


$$\mathbf{14} \to \mathbf{8_0} + \boxed{\mathbf{3_{-2x}} + \bar{\mathbf{3}}_{\mathbf{2x}}}$$

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

Exotic top partners

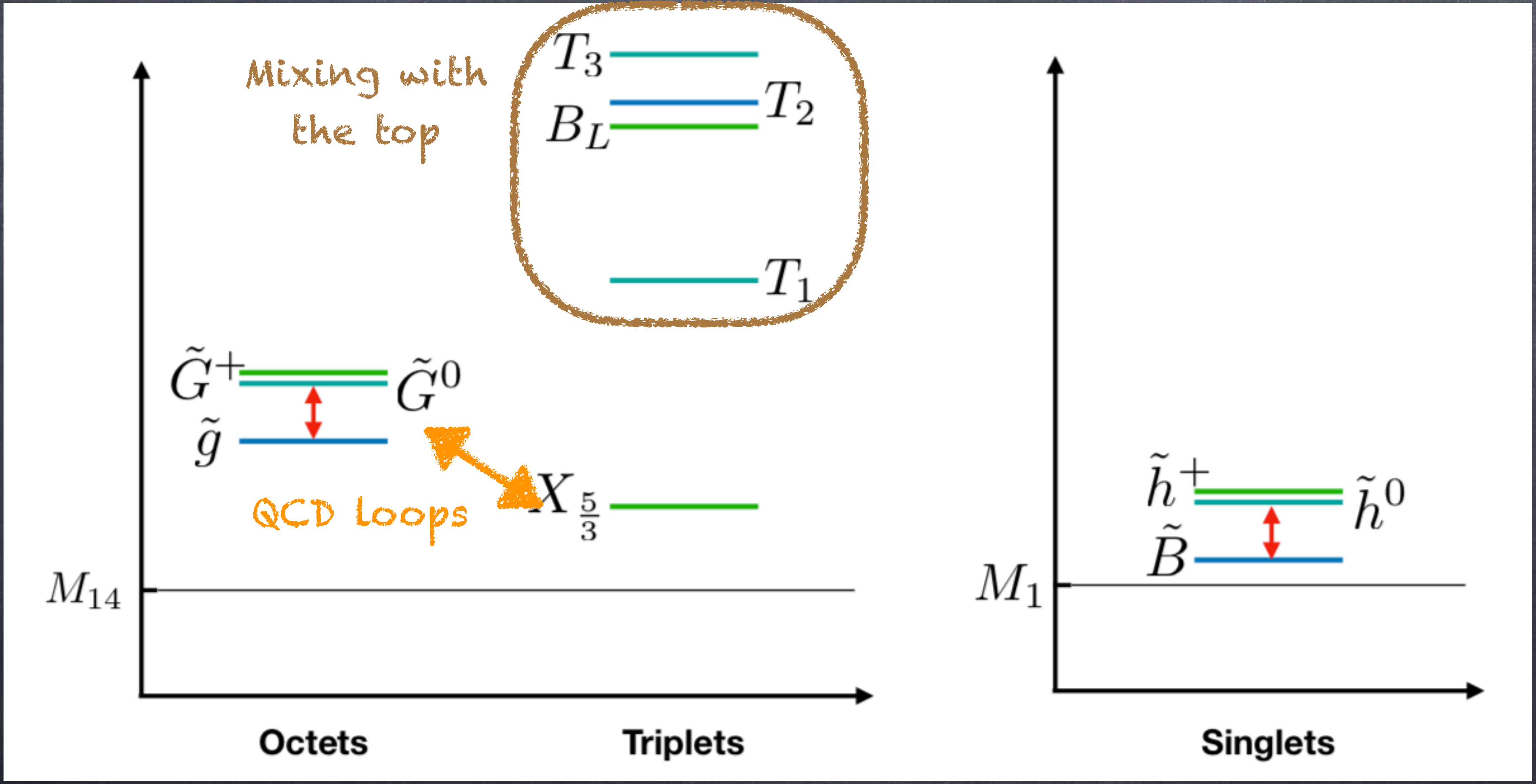
G.Cacciapaglia et al.
2112.00019

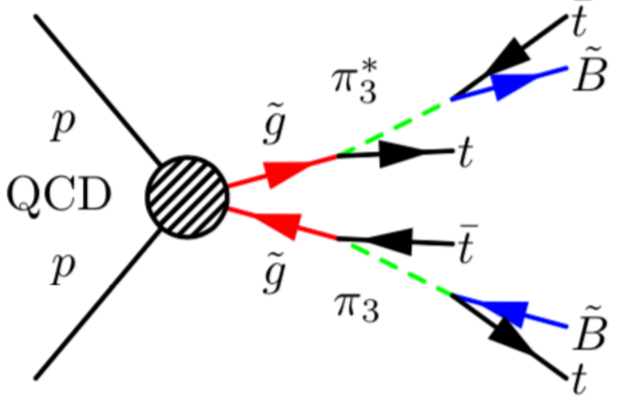


The new particle content looks ironically SUSY-like!

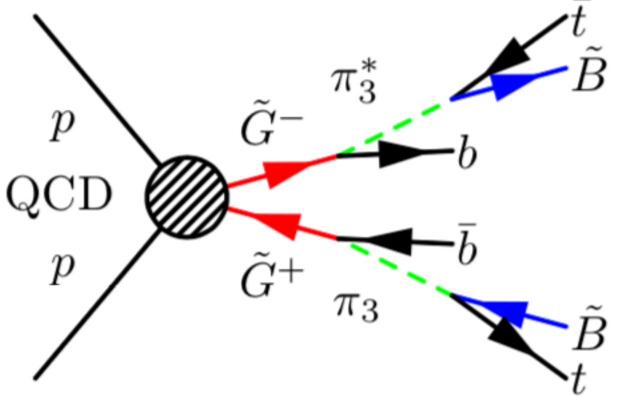
Exotic top partners

G.Cacciapaglia et al.
2112.00019

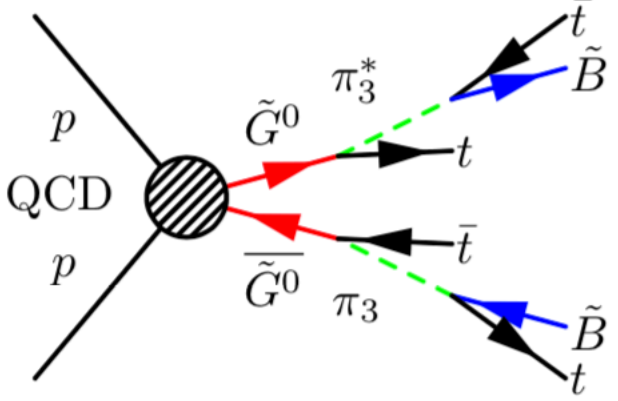




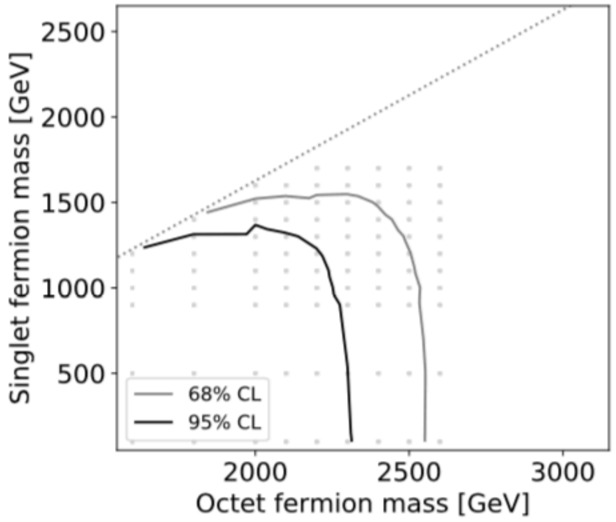
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$



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

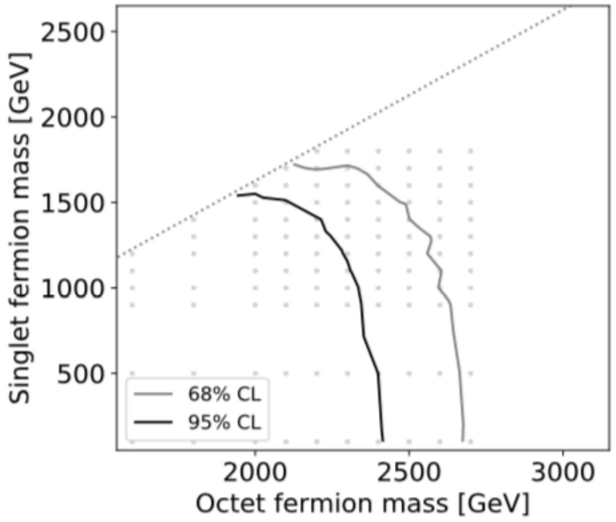


(c) $\tilde{G}^0 \to \bar{t}\pi_3 \to \bar{t}t\tilde{B}$



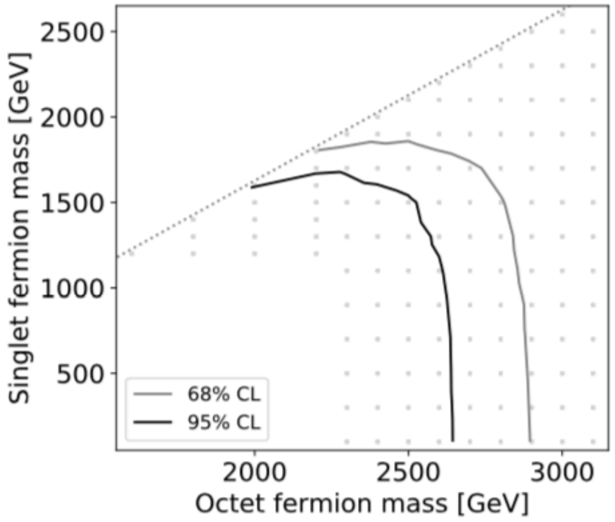
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

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



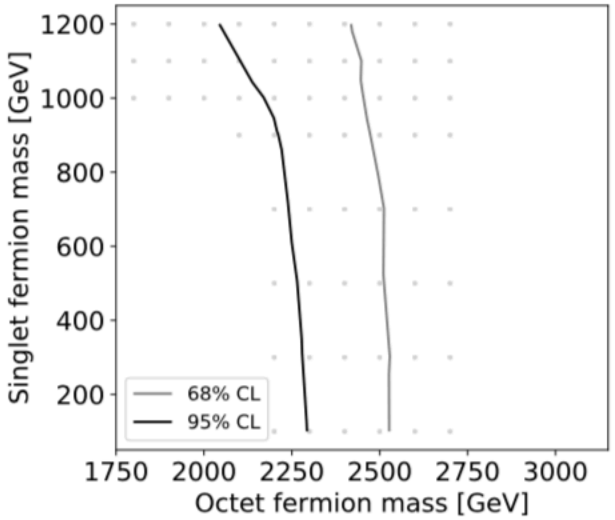
(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

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



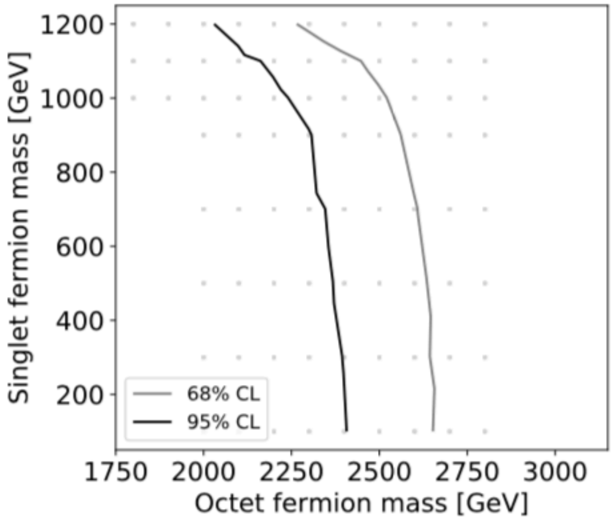
(c) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

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



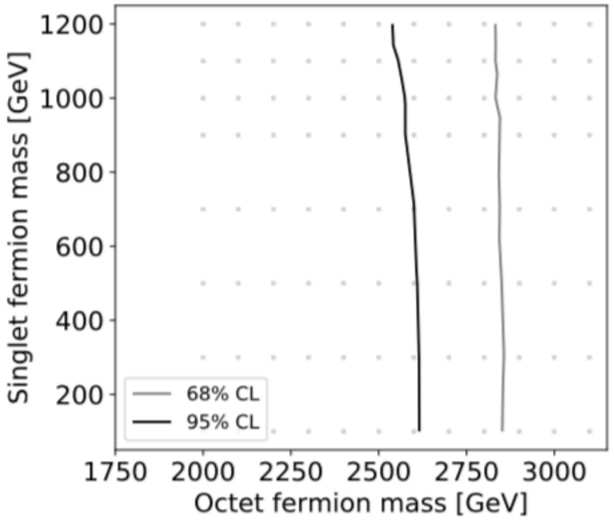
(d) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV



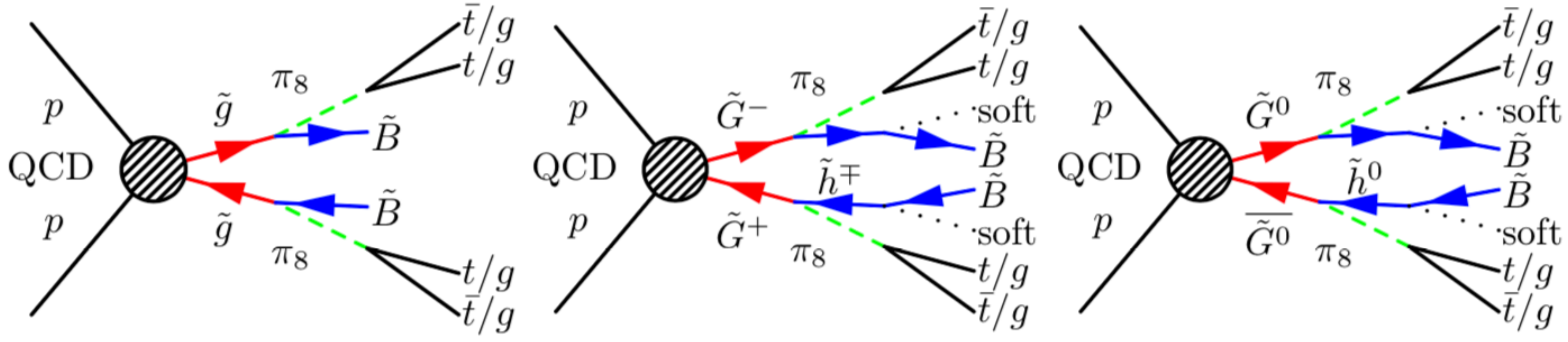
(e) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

$m_{\pi_3} = 1.4$ TeV

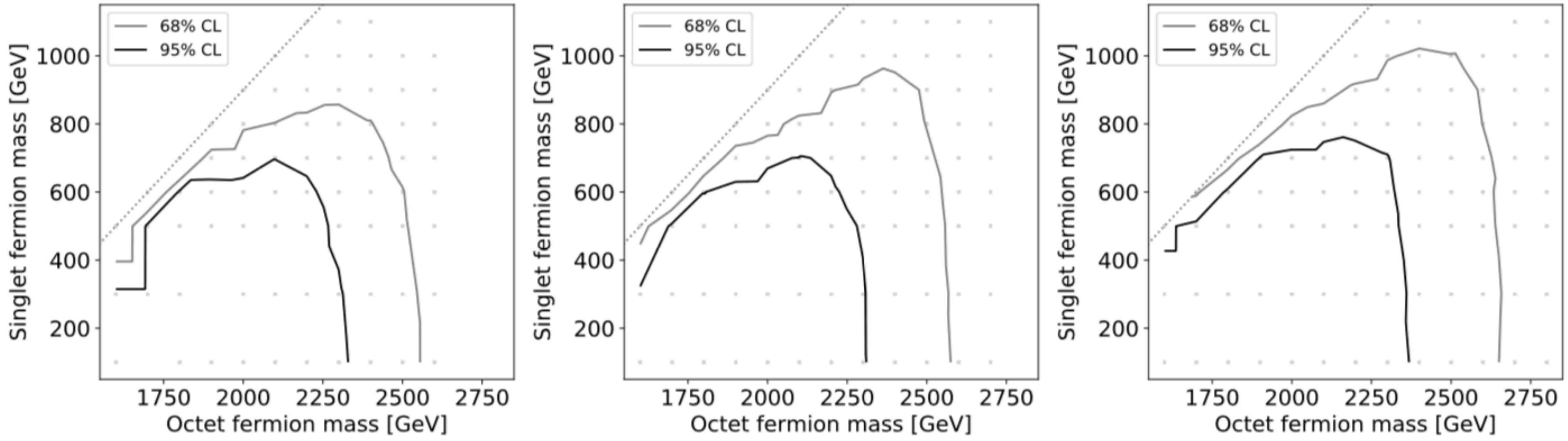


(f) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

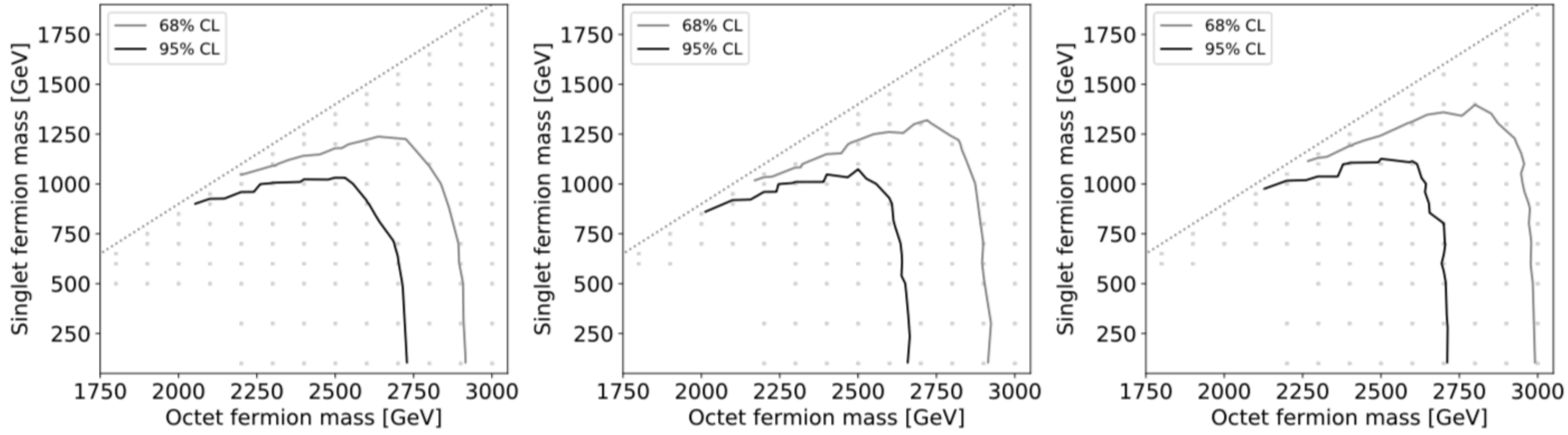
$m_{\pi_3} = 1.4$ TeV



(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) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to t\bar{t}$

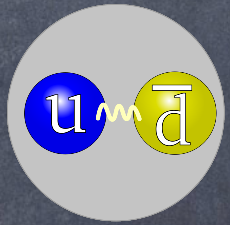
Conclusions

- Scalar pair production is characteristic of composite Higgs models (and beyond)
- Dedicated searches can improve reach
- Production via heavier states: top partners ('standard' and 'exotic')
- Heavy spin-1 states under study

Bonus tracks

Composite Higgs models 101

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



Scales:

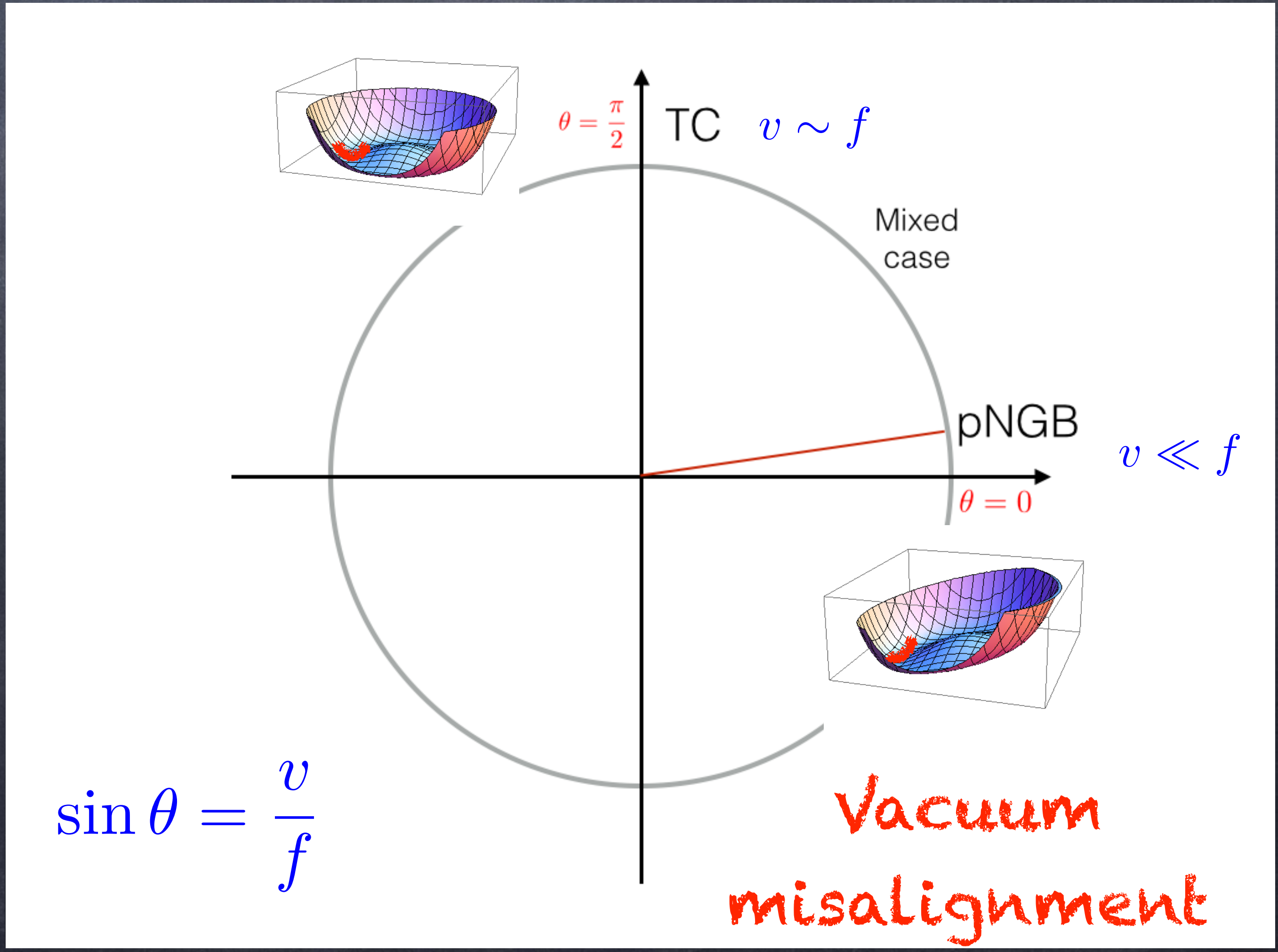
f : Higgs decay constant

v : EW scale

$$m_\rho \sim 4\pi f$$

EWPTs + Higgs coupl. limit:

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



$$\sin\theta = \frac{v}{f}$$

Vacuum misalignment

Composite models at various scales

HC and SM gaug
partially uni

Symmetry b

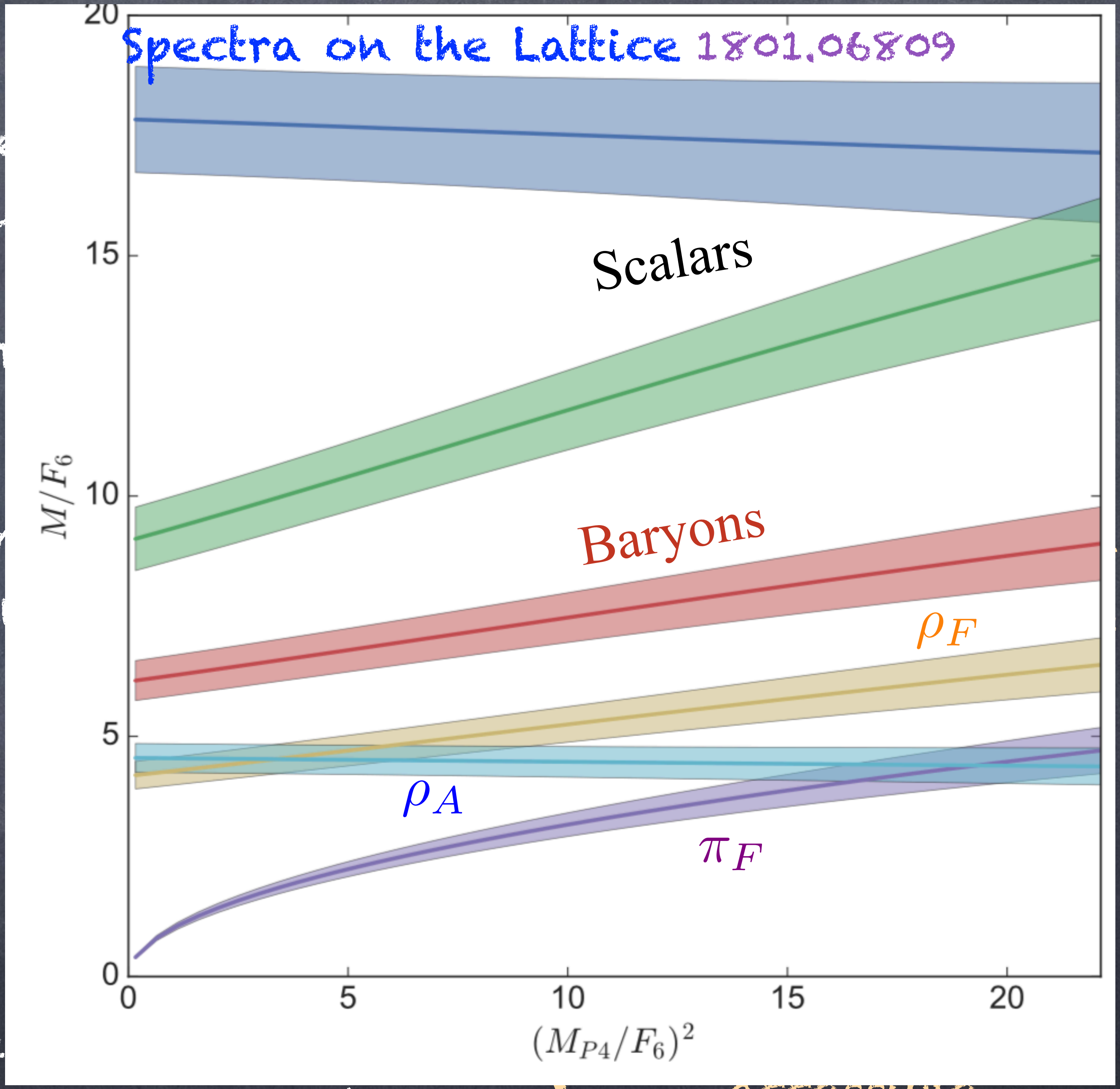
Confor
(large scali

Condensation scale

Usual low e
of composite Higgs models

Standard Model

accessible
to colliders


Spectra on the Lattice 1801.06809

Typical ALP Lagrangian:

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

Composite Higgs scenario:

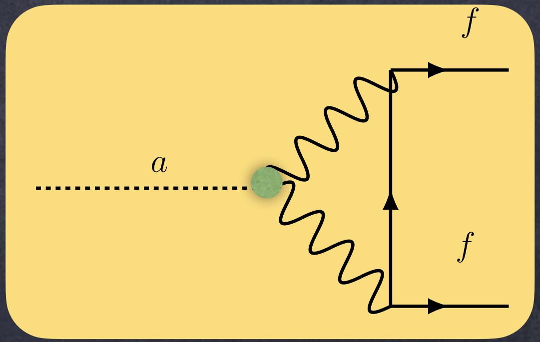
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\rm TC}}{64\sqrt{2}\,\pi^2 f}$$

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

(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:

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

Composite Higgs scenario:

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

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

Free parameters:

$$f, m_a$$

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

Money plot

Typical EWPT bound

G.Cacciapaglia et al.
2104.11064