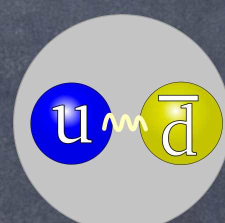
Composite Models

Giacomo Cacciapaglia
IP2I Lyon, France

Composite Higgs models 101

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



Scales:

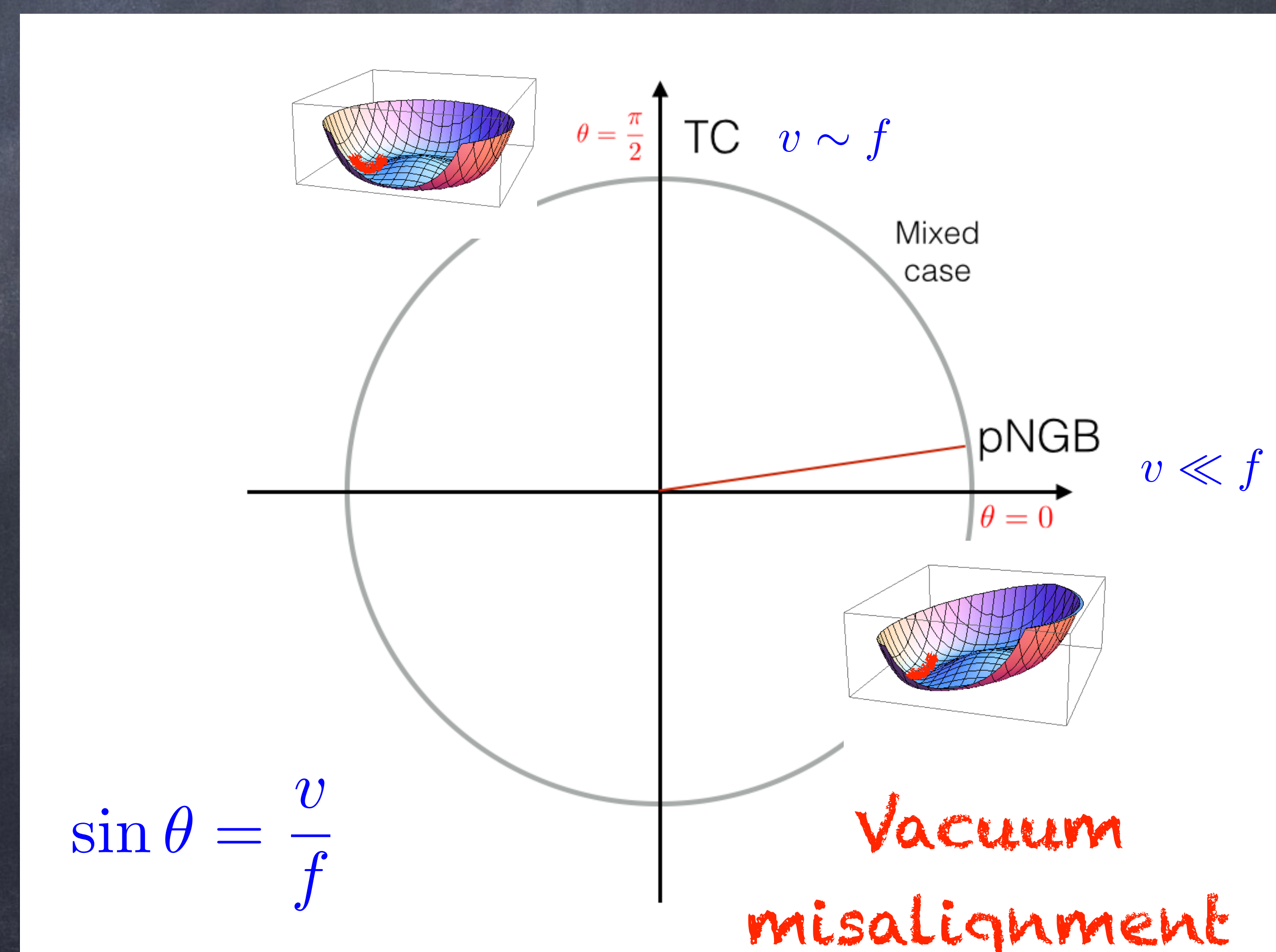
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

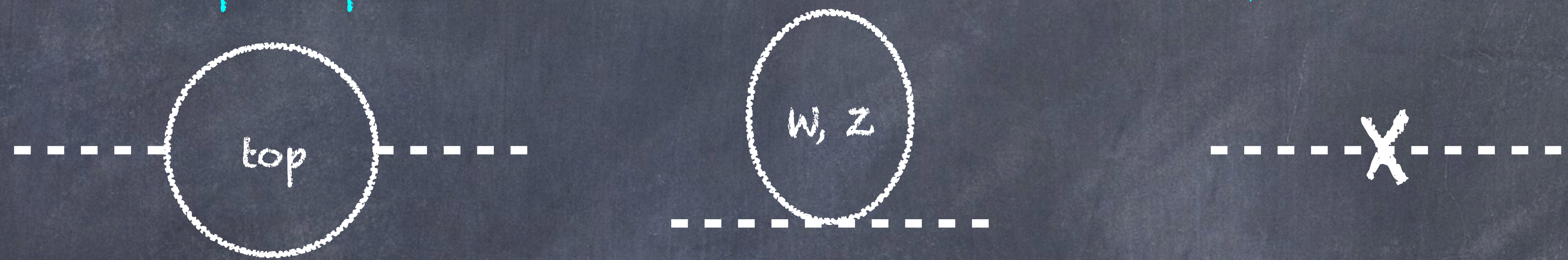
EWPTs + Higgs coupl. limit:

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



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!

Composite Higgs models 101

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

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

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

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

  Witten, Kosower

- 5 Goldstones (pions) arise:

$$\mathbf{5}_{\mathrm{Sp}(4)} \to (2,2) \oplus (1,1)$$

Higgs — additional singlet

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

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

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

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 QCD colour and flavour quantum numbers: too many!
- too many adjoint fermions!

Top partners as baryons

Gauge-fermion underlying theory

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

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

- higher dimension, but easier to generate
- More freedom in choosing the fermion representations

Sequestering QCD in Partial compositeness

$\mathcal{G}_{\rm TC}$: rep R, Q ; rep R′, χ

G.Ferretti, D.Karateev
1312.5330, 1604.06467

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

SM : EW ; colour + hypercharge

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

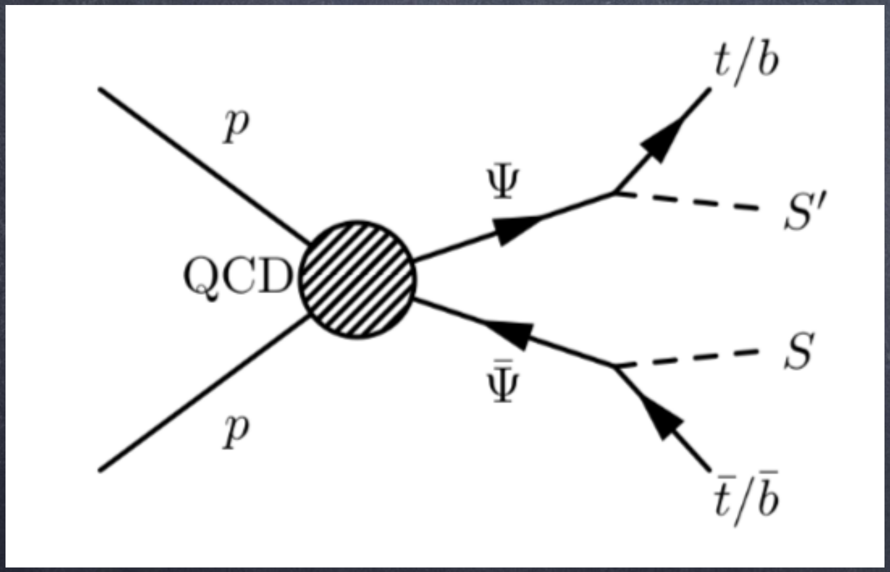
Composite phenomenology in 2022

- Light ALPs (not in this talk)
- Coloured scalars -> 4 top final states
- Common exotic top partner decays
- Exotic top partners
- What are muon anomalies trying to tell us?

Common exotic top partner decays

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

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

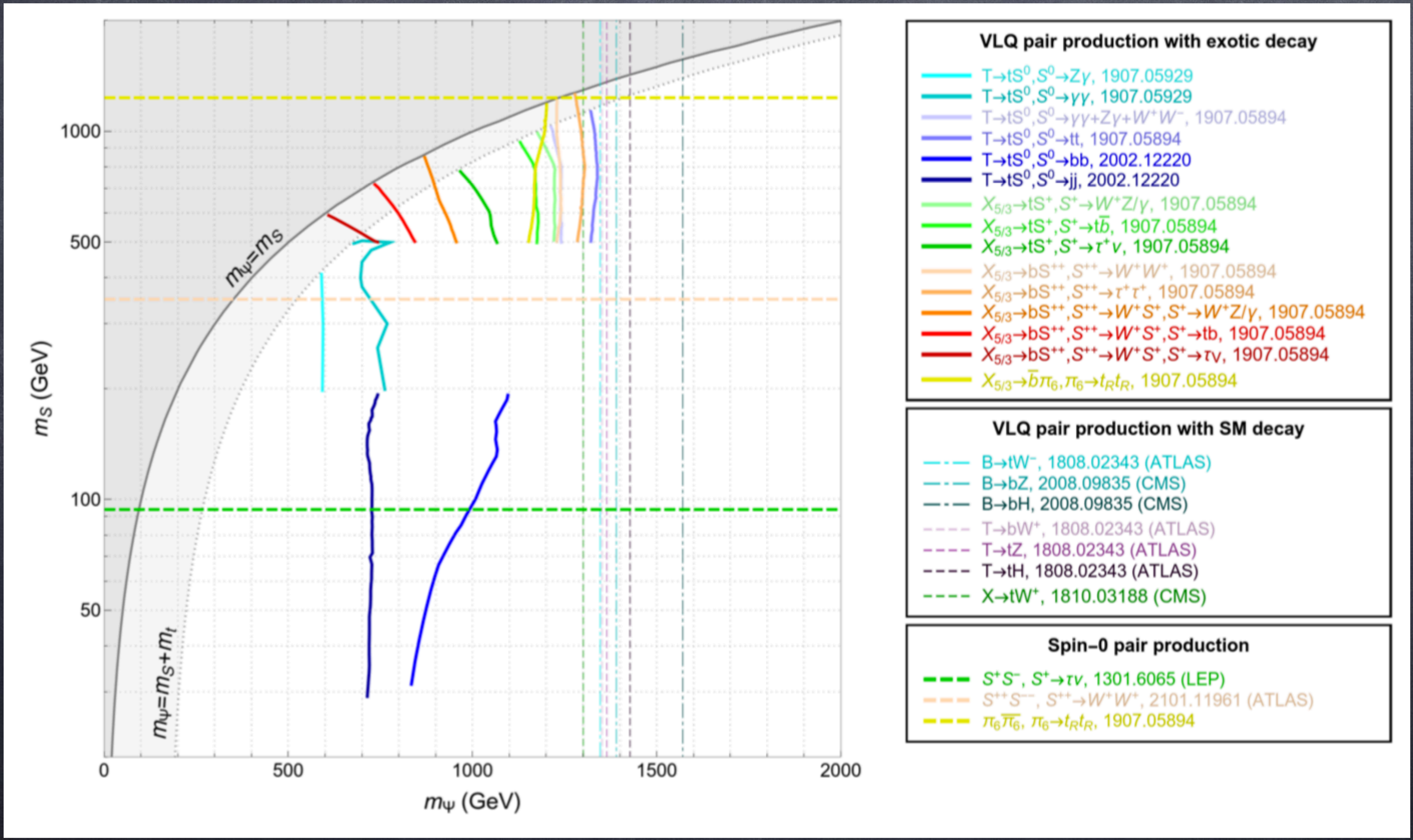
$$\mathcal{L}_{\Psi f S} = \sum_i S_i^+ \left[\kappa^{S_i^+}_{T,L} \overline{T} P_L b + \kappa^{S_i^+}_{X,L} \overline{X} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^- \left[\kappa^{S_i^-}_{B,L} \overline{B} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^0 \left[\kappa^{S_i^0}_{T,L}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

- 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)



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

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

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

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χ_3							
χ_4					$\mathbf{1}$	$\mathbf{6}$	q_χ
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χ_6							

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Exotic top partners

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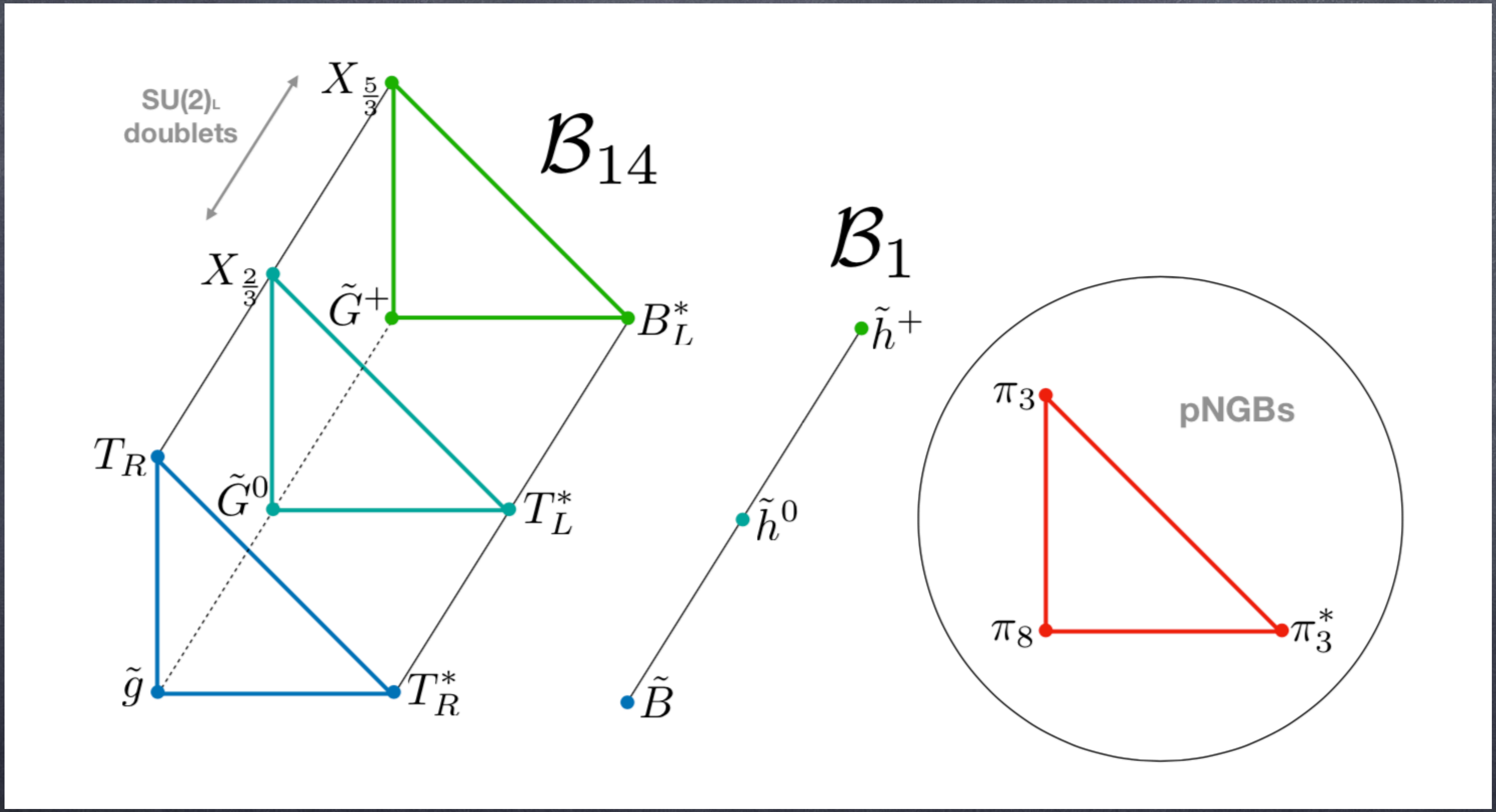

Exotic top partners

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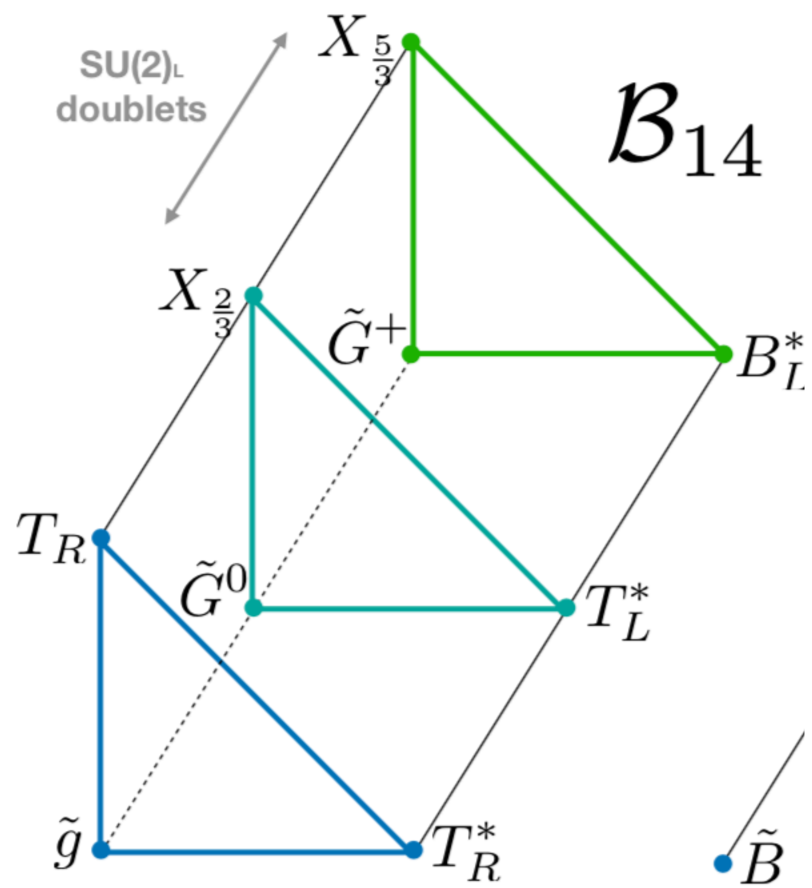

$$\text{Octoni (Dirac):} \quad \tilde{G}^+ = \begin{pmatrix} \tilde{G}_u^+ \\ \bar{\tilde{G}}_d^- \end{pmatrix}, \quad \tilde{G}^0 = \begin{pmatrix} \tilde{G}_u^0 \\ \bar{\tilde{G}}_d^0 \end{pmatrix},$$

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

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

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

The baryon content looks ironically SUSY-like!

Exotic top partners

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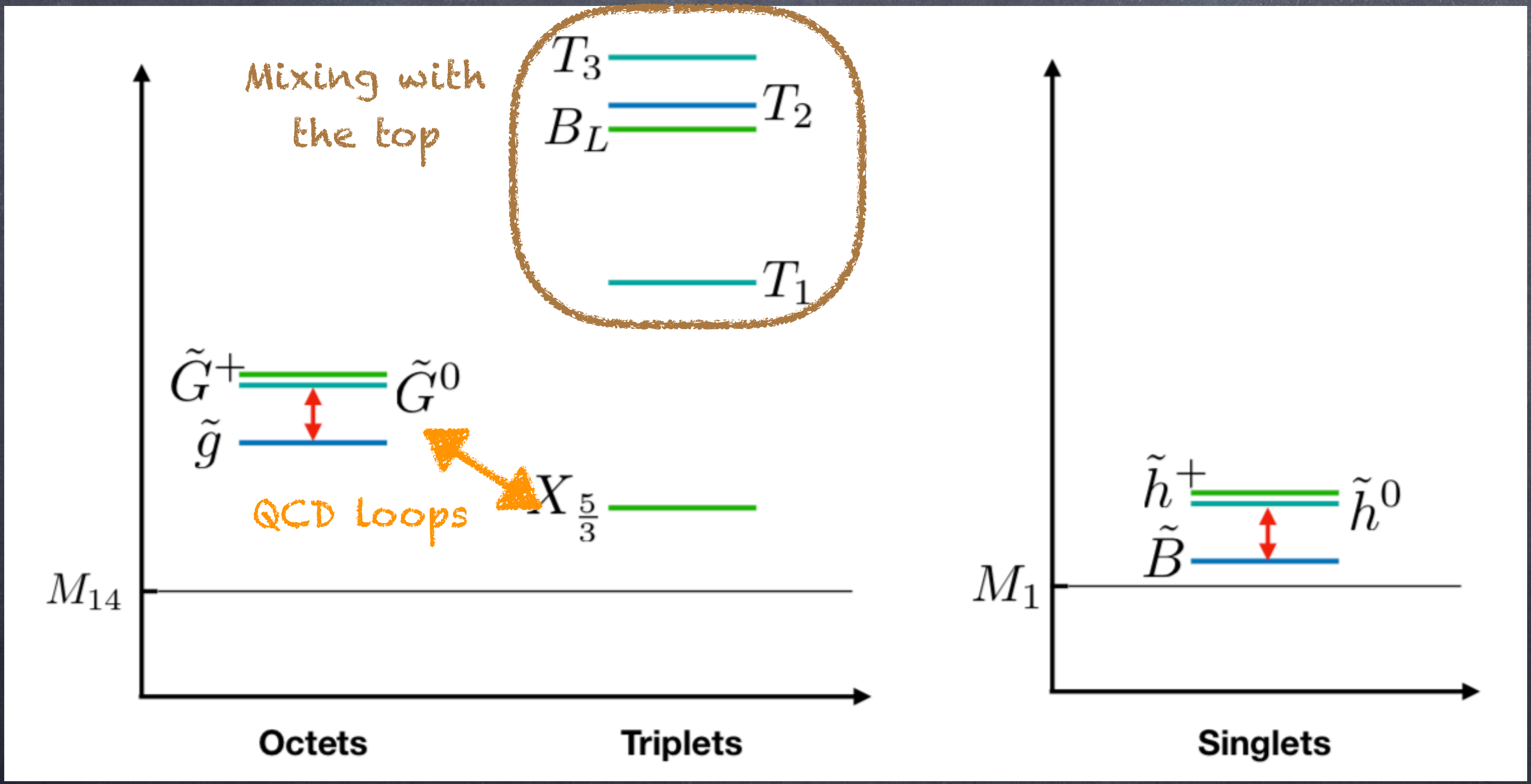

Octoni bounds

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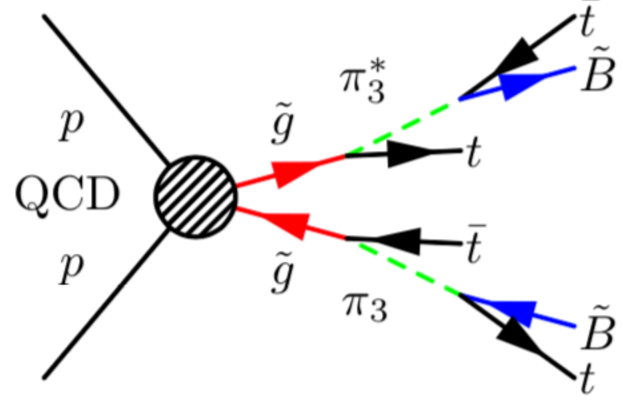
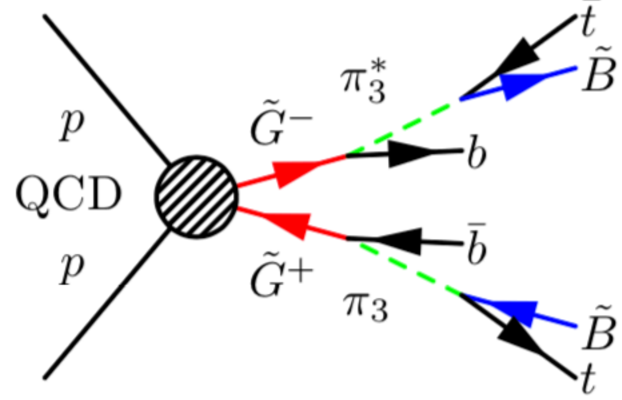
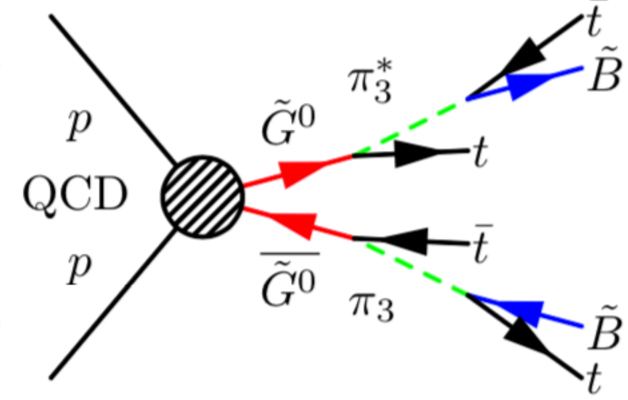
- Model implemented in MG.
- Check limits from searches in MadAnalysis and CheckMate.
- Strongest bound from gluino and stop searches!



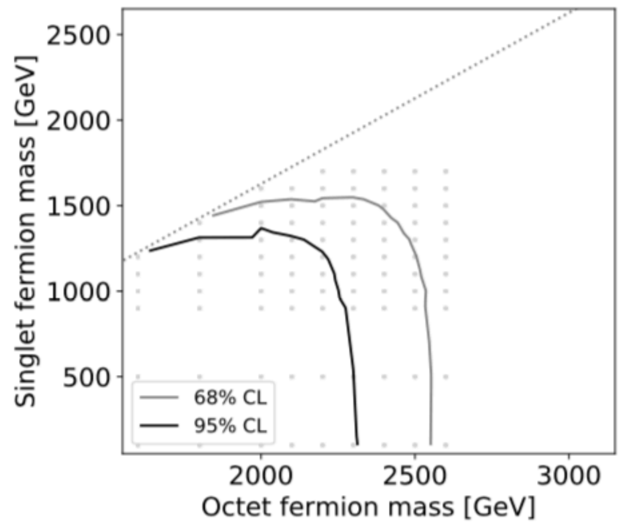
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$



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

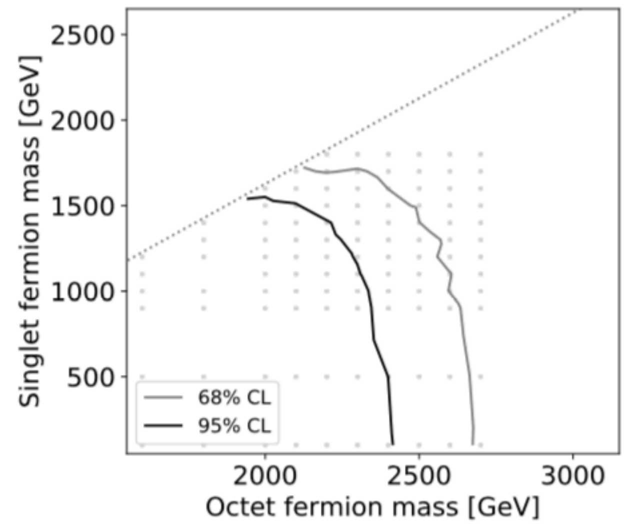


(c) $\tilde{G}^0 \to \bar{t}\pi_3 \to \bar{t}t\tilde{B}$



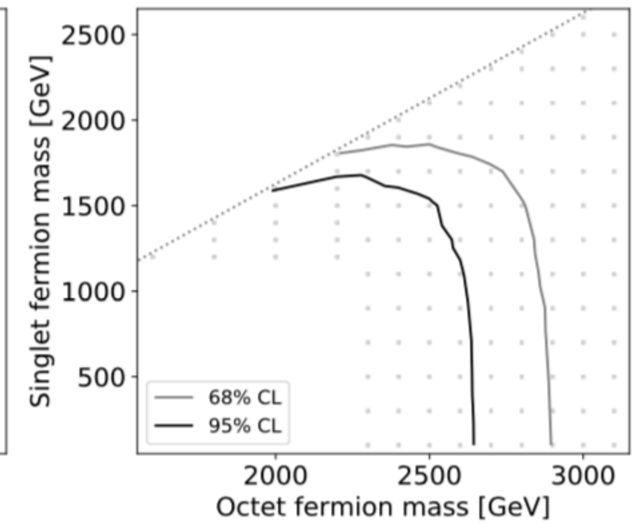
(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

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



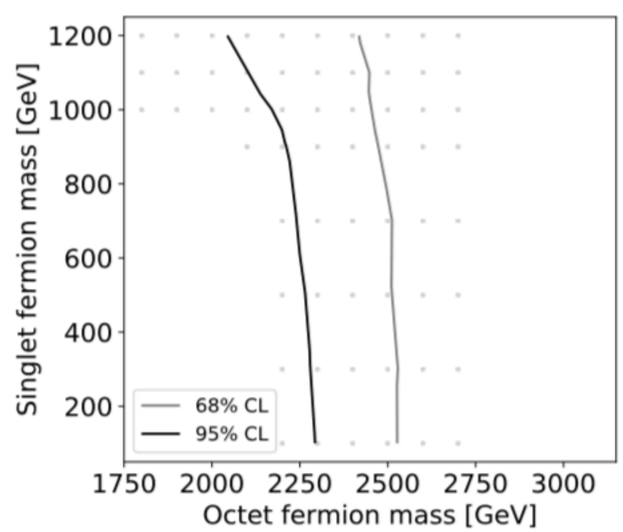
(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

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



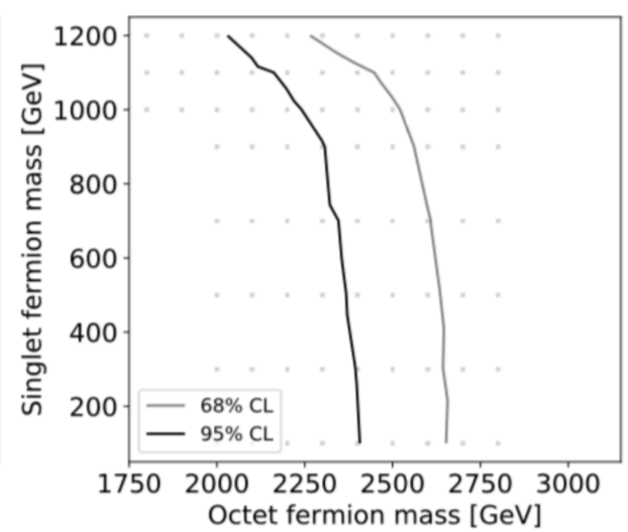
(c) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

$m_{Q_8} - m_{\pi_3} = 200$ 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) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

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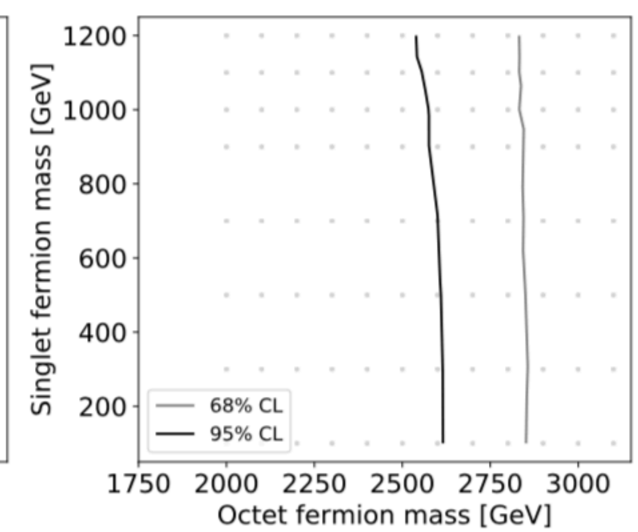

(f) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

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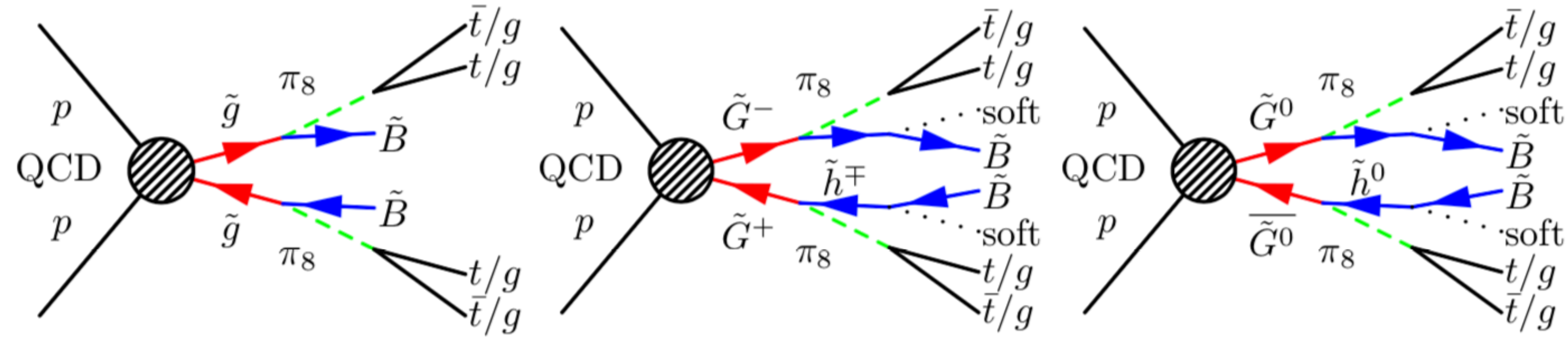
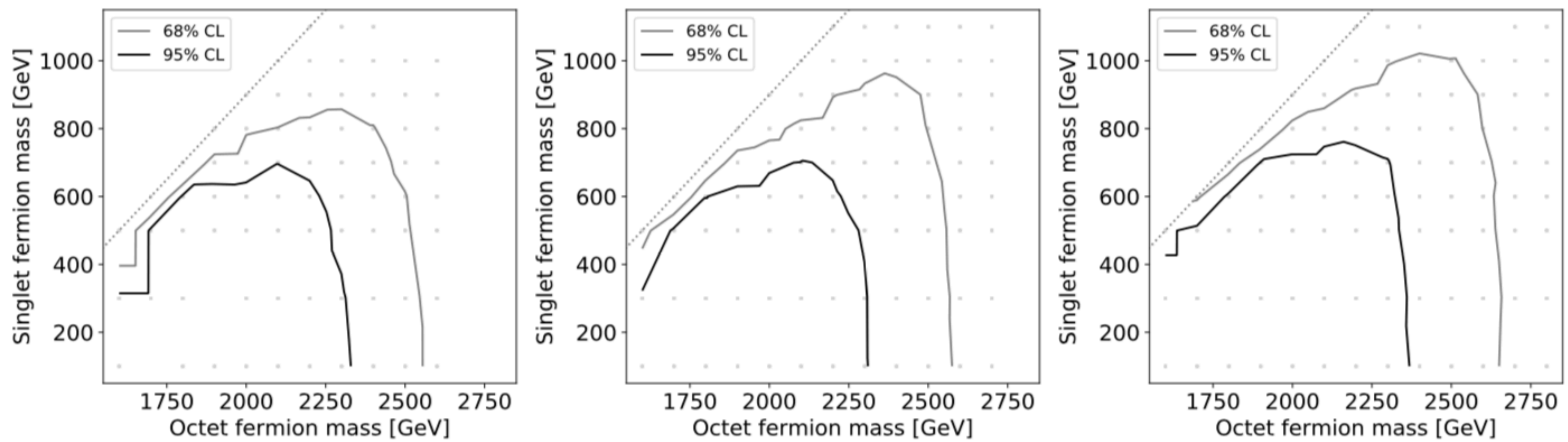
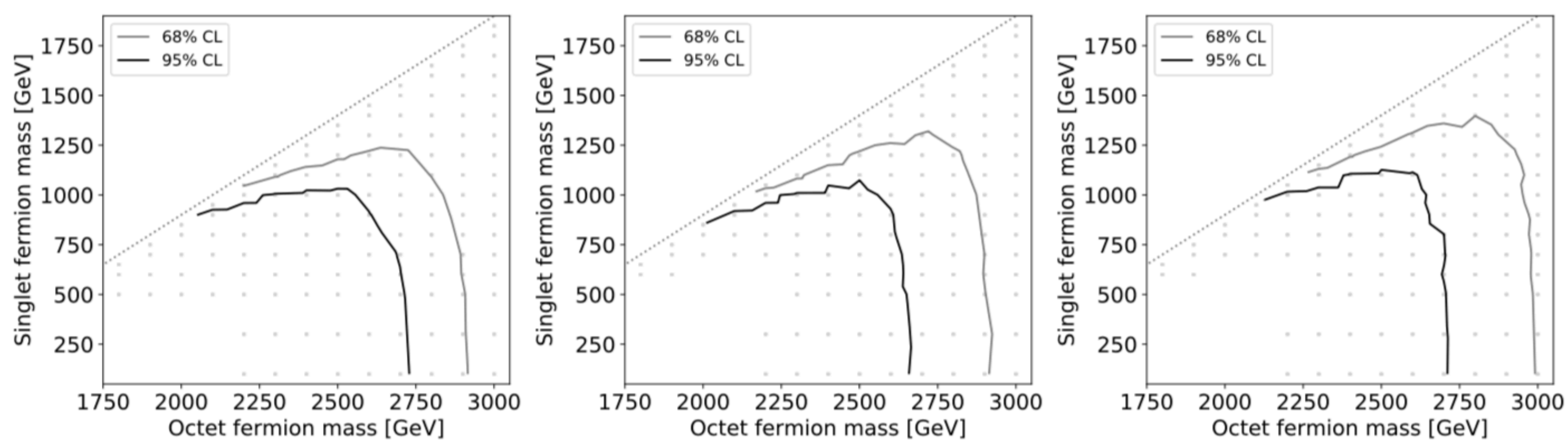


(a) $\tilde{g} \to \tilde{B}\pi_8$, $\pi_8 \to \bar{t}t/gg$. (b) $\tilde{G}^+ \to \tilde{h}^+\pi_8$, $\pi_8 \to \bar{t}t/gg$. (c) $\tilde{G}^0 \to \tilde{h}^0\pi_8$, $\pi_8 \to \bar{t}t/gg$.

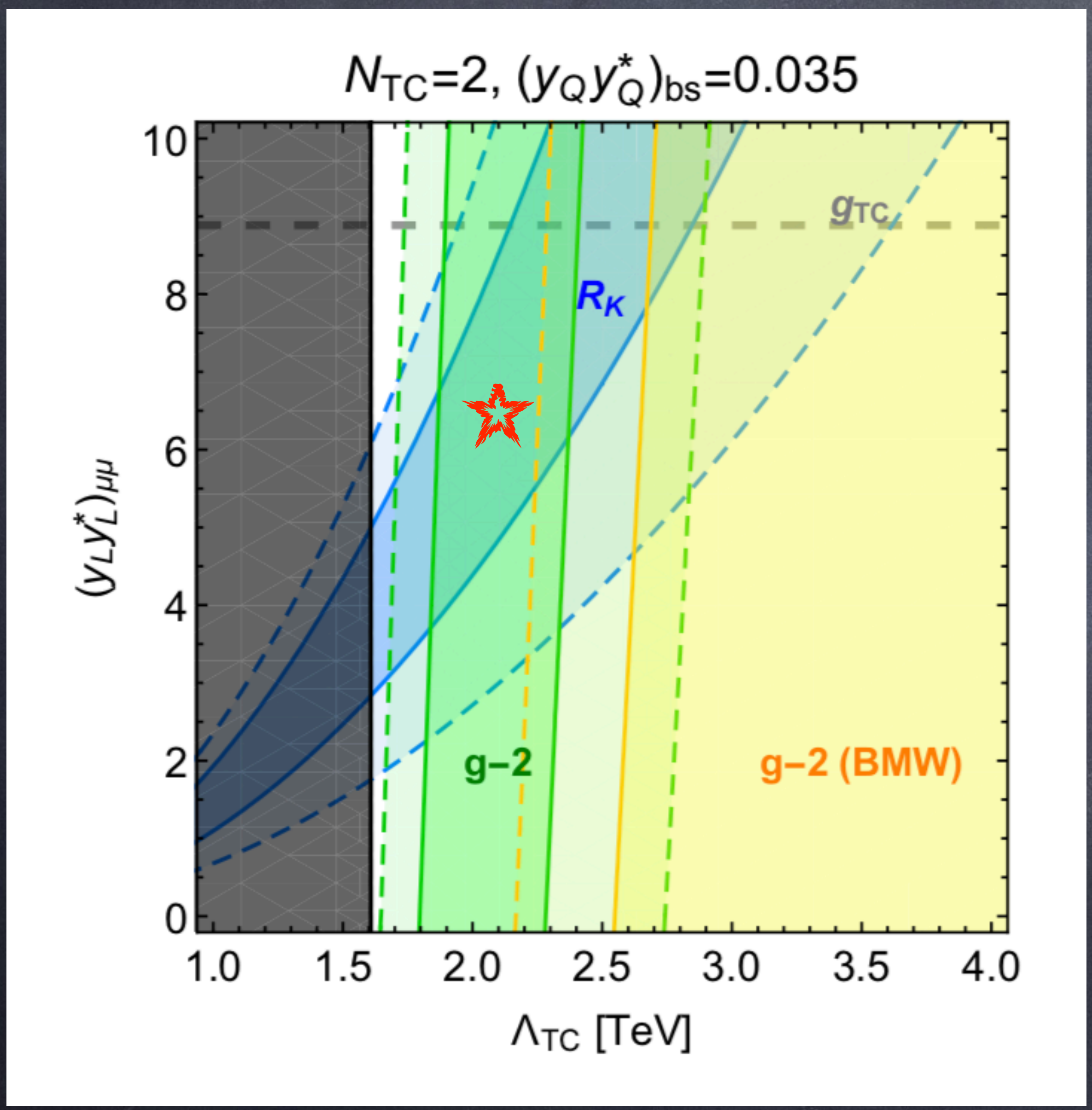


(a) $\tilde{g} \to \pi_8\tilde{B}$, $\pi_8 \to gg$ (b) $\tilde{g} \to \pi_8\tilde{B}$, $\pi_8 \to gg, t\bar{t}$ (c) $\tilde{g} \to \pi_8\tilde{B}$, $\pi_8 \to t\bar{t}$



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

There's something about Muons



$$R_K = \frac{\mathrm{BR}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{BR}\left(B^+ \to K^+e^+e^-\right)} = 0.846^{+0.044}_{-0.041}$$

- g-2 fixes the scale of new physics
- natural values for TC-like theories!
- RK requires large muon couplings (attainable in strong dynamics)

These anomalies will be further probed in the near future!