Exploring Composite Higgs Models at FCC

Giacomo Cacciapaglia
IP2I Lyon, France

Motivation

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

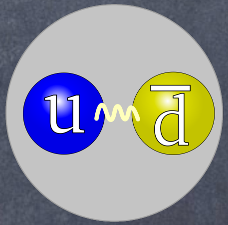
multi-TeV
mountain

- 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:

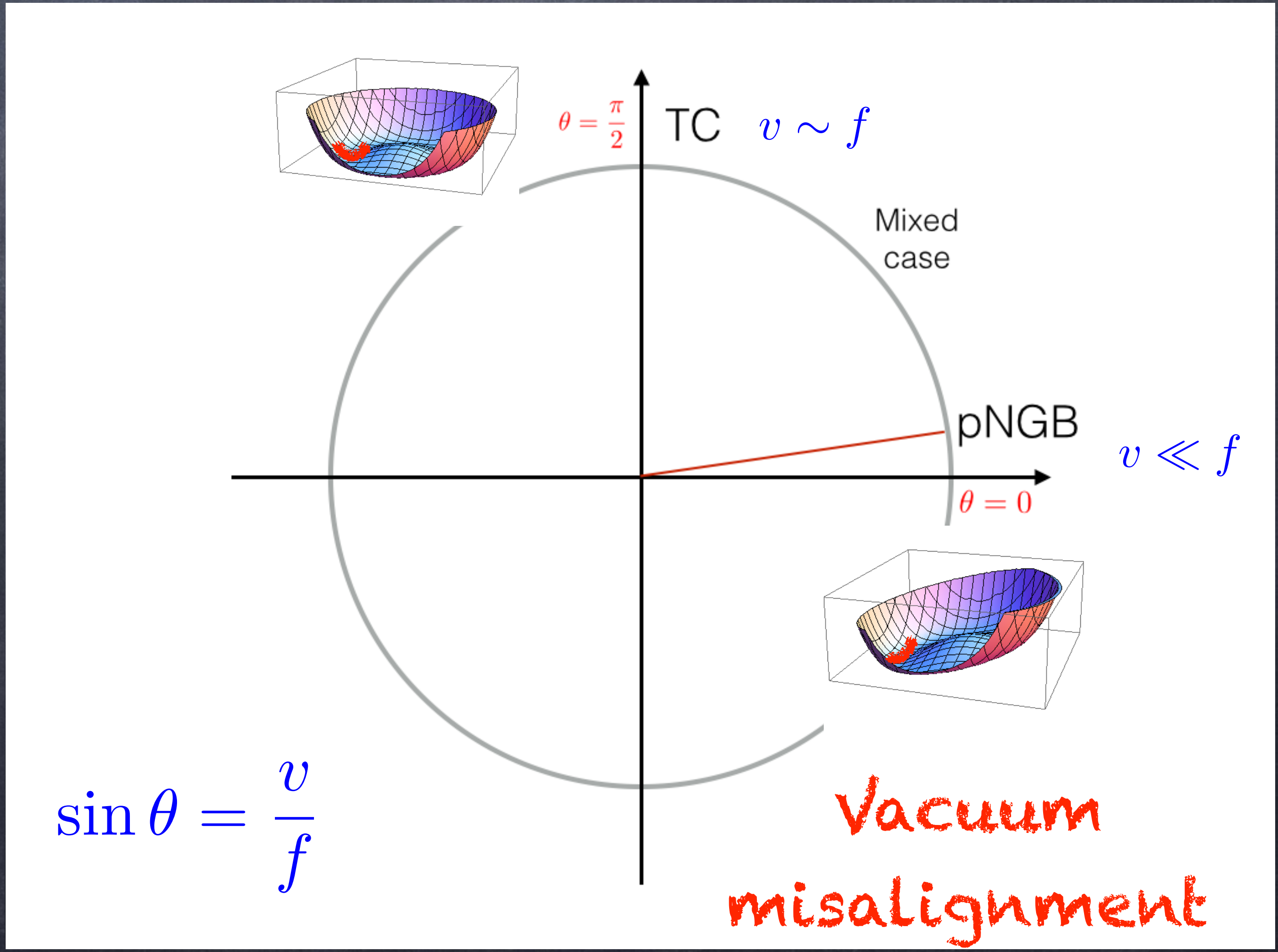
f : Higgs decay constant

v : EW scale

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

EWPTs + Higgs coupl. limit:

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



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

Vacuum misalignment

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:

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

This dimension is not related to the Higgs!

↓

$$f\left(y_L\; q_L Q_L + y_R\; q_R Q_R\right)$$

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 gaug
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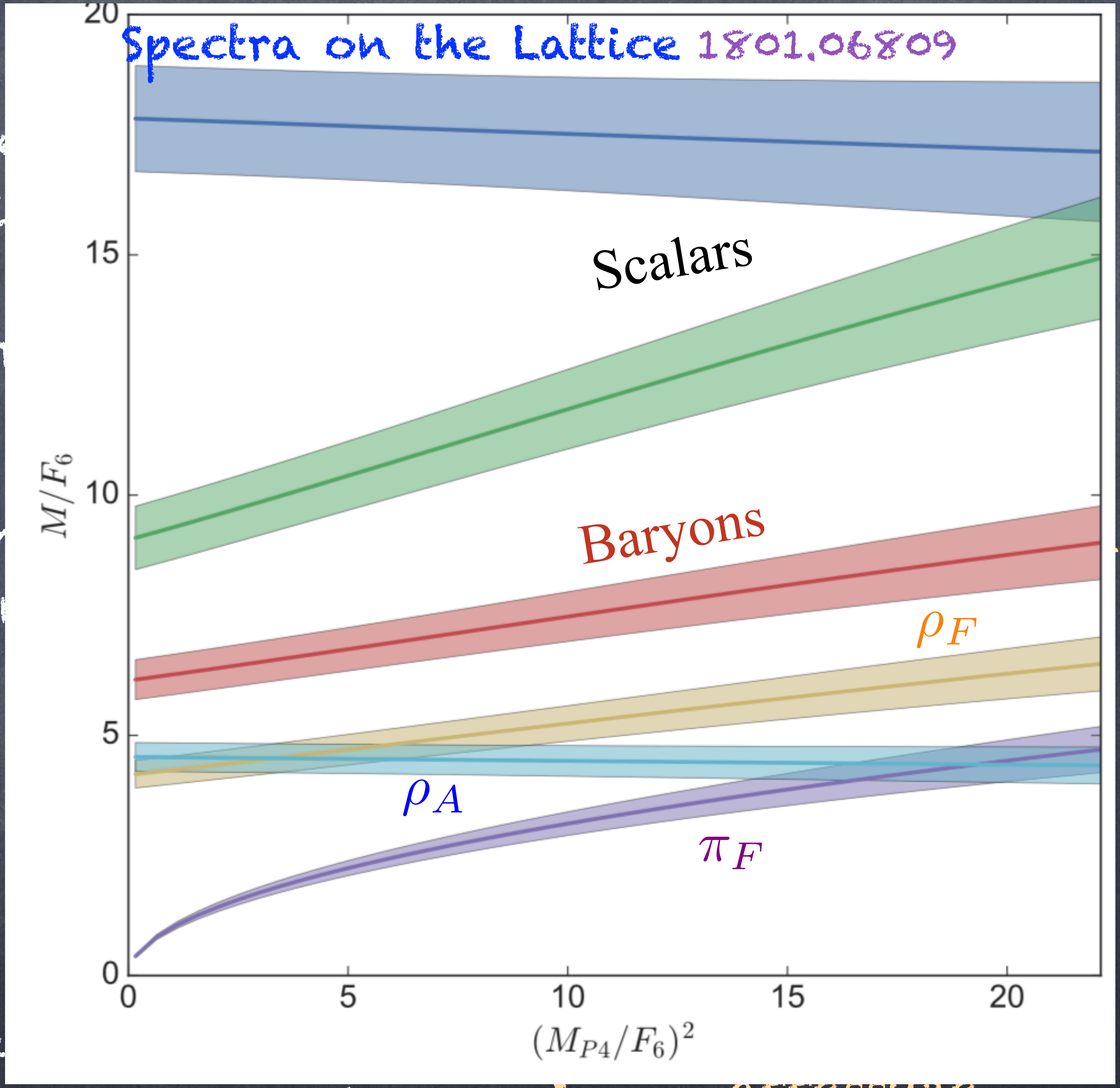

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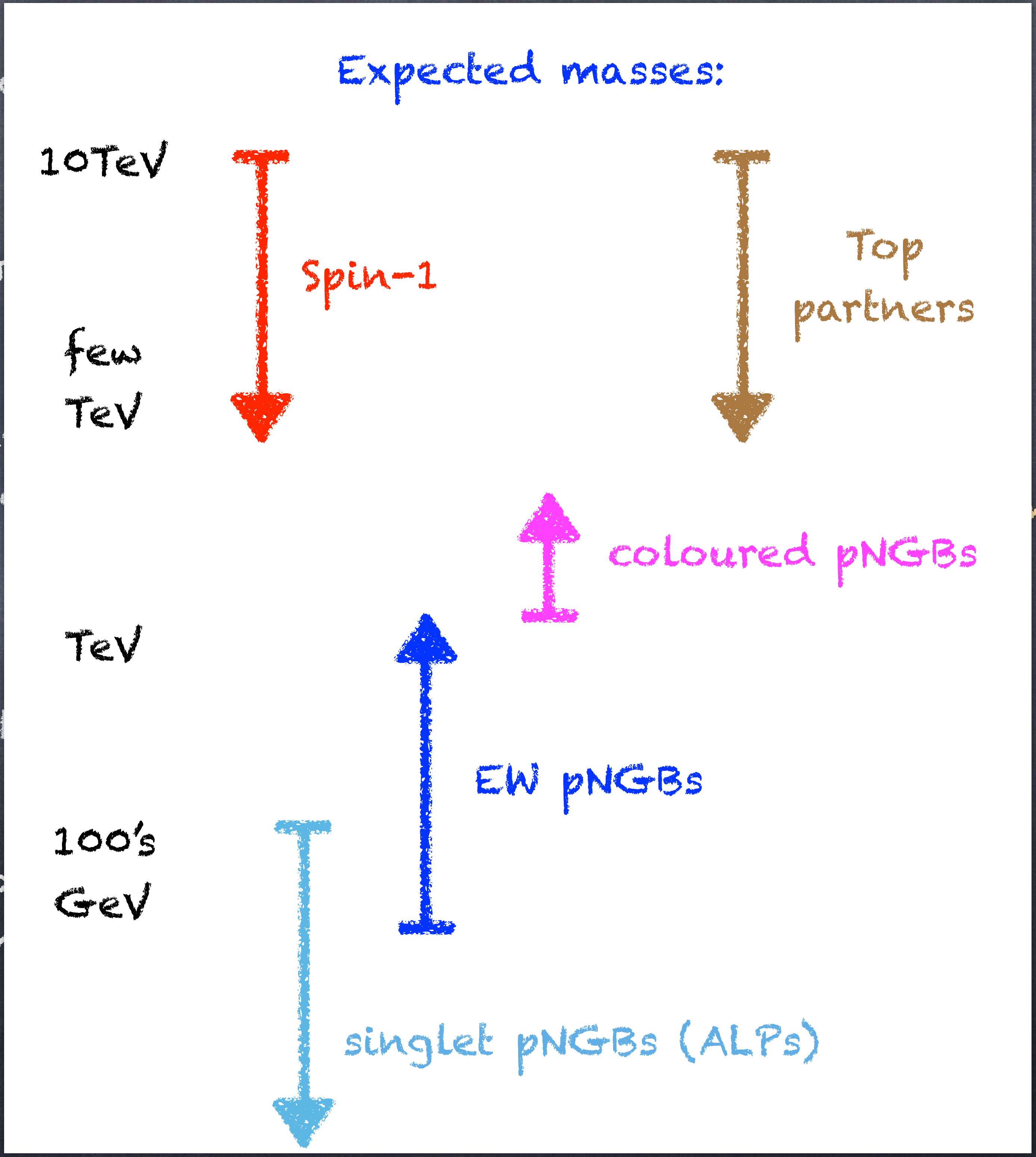

Expected masses:

10TeV

few TeV

TeV

100's GeV

Spin-1

Top partners

coloured pNGBs

EW pNGBs

singlet pNGBs (ALPs)

+

ns

The composite Higgs wilderness

- Light ALPs
- Electroweak pNGBs
- Coloured scalars (not in this talk)
- Common exotic top partner decays
- Exotic top partners
- Spin-1 resonances (not in this talk)
- What are muon anomalies trying to tell us?

The composite Higgs wilderness

EW and Higgs precision!!!

- Light ALPs
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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:

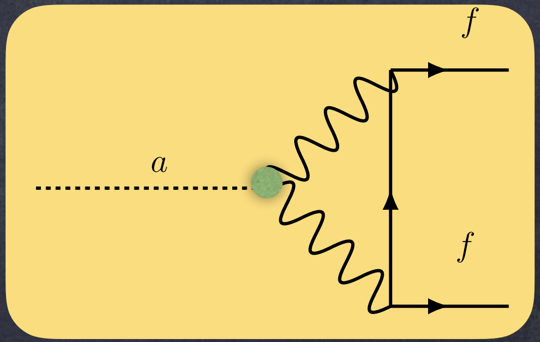
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

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

(Poor bounds at the LHC)

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

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



M.Bauer et al, 1708.00443

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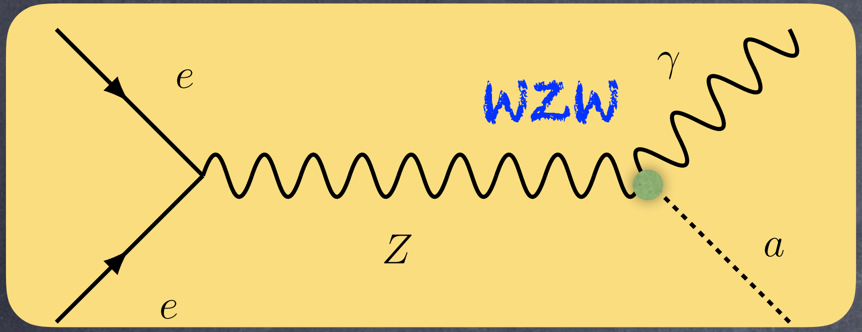
We will consider two scenarios:
Photo-philic and
Photo-phobic

Free parameters:

$$f, m_a$$

Tera-Z portal to compositeness (via ALPs)

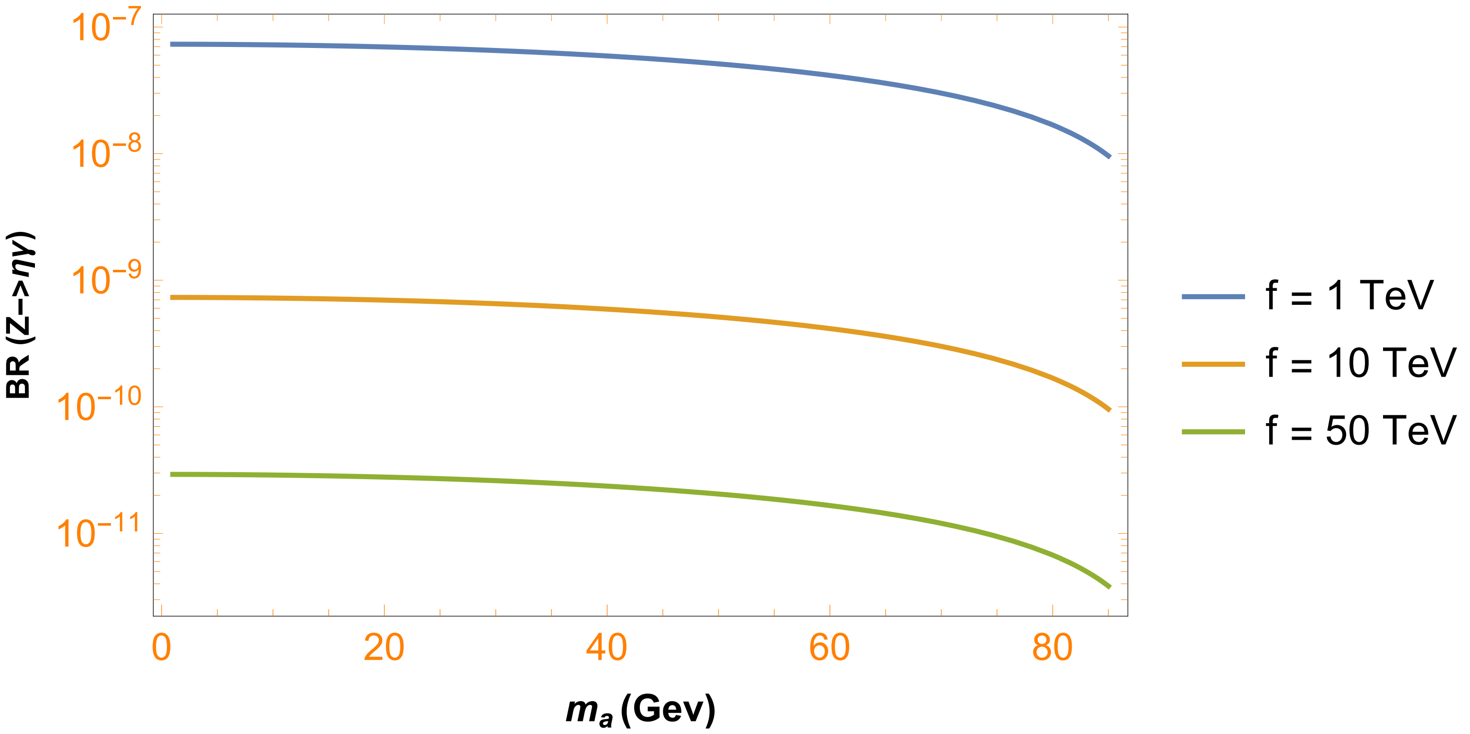


G.Cacciapaglia et al.
2104.11064

This process is always associated with a monochromatic photon.

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

Ideal test for rare Z decays!!



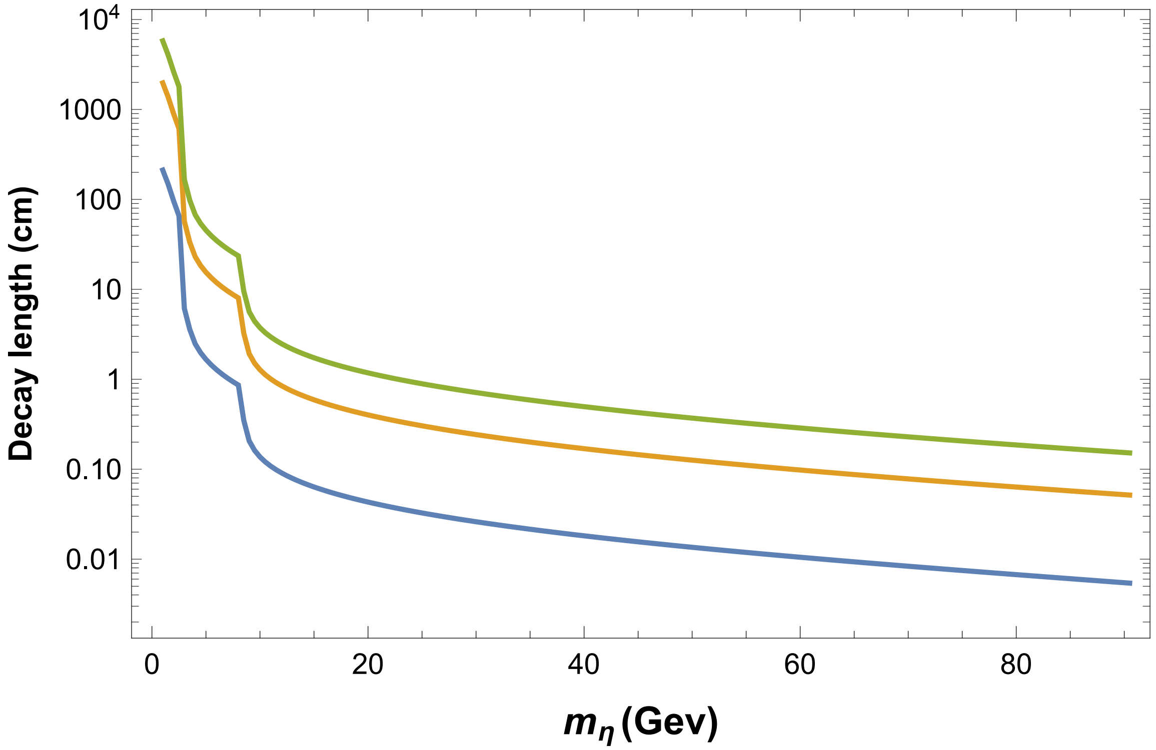


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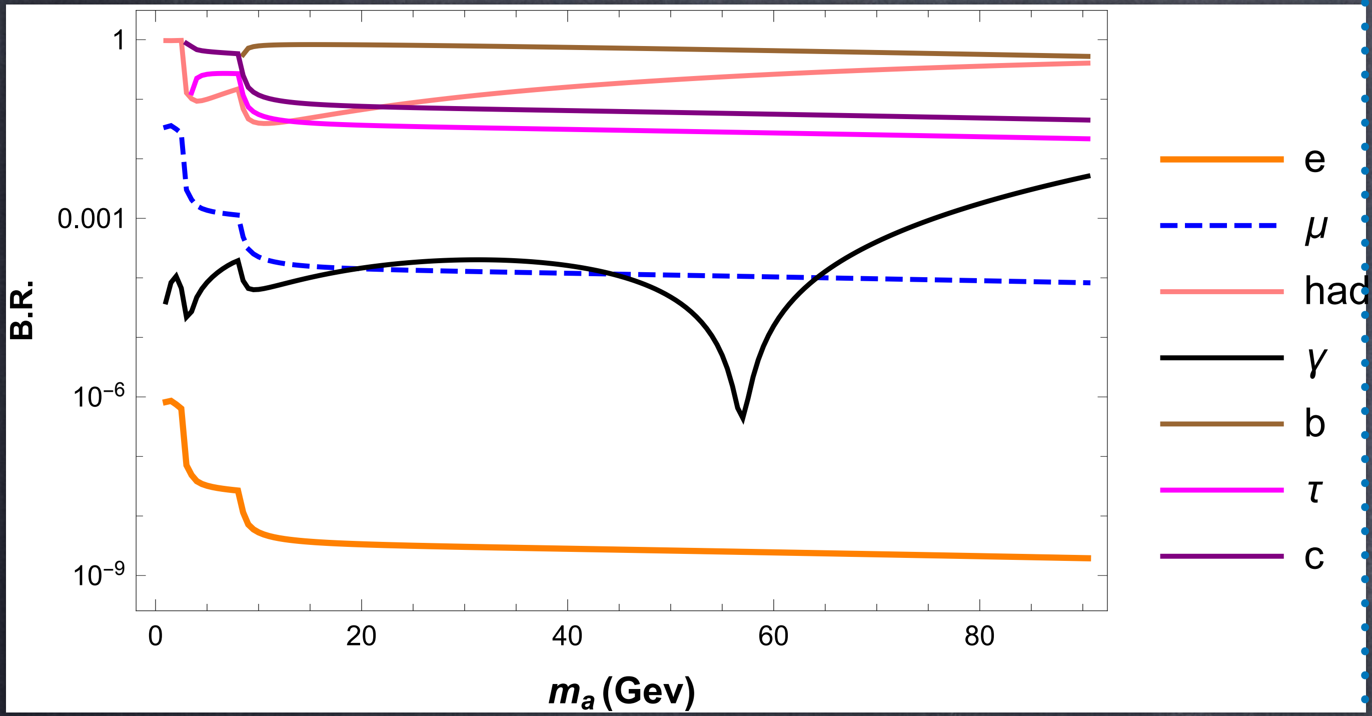
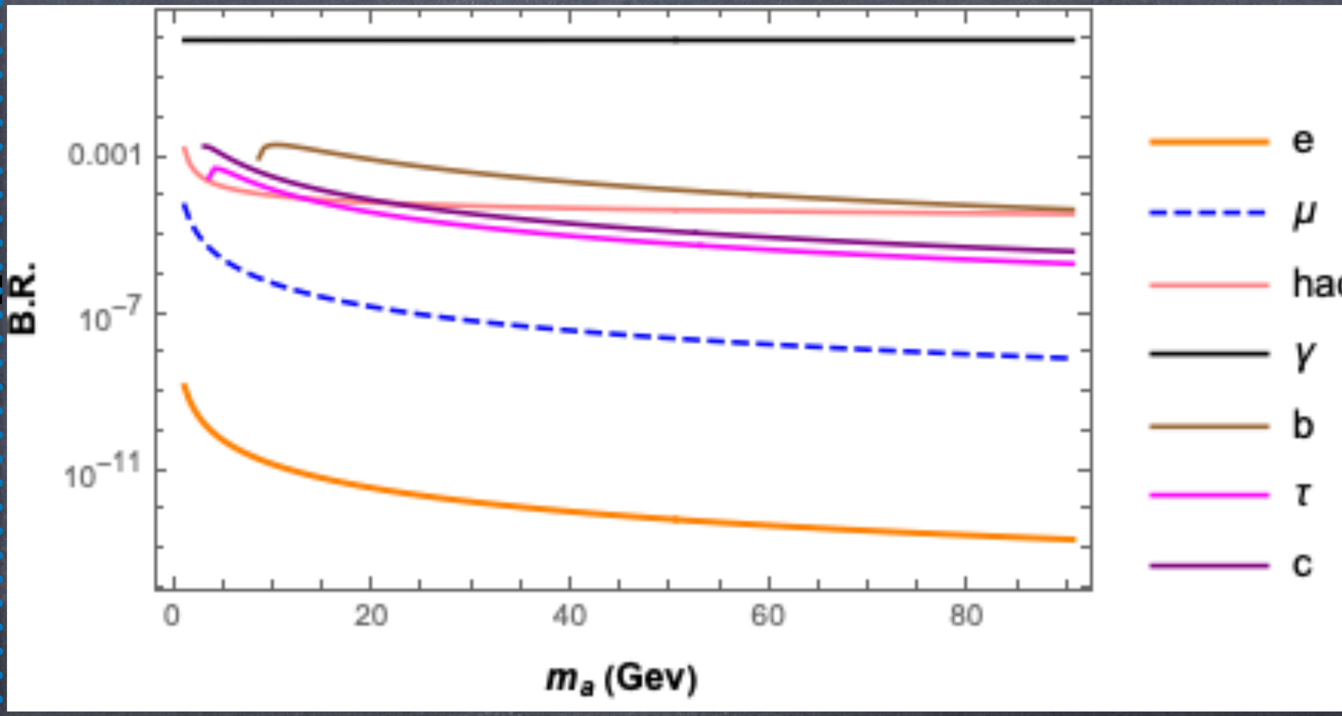
Photo-phobic



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

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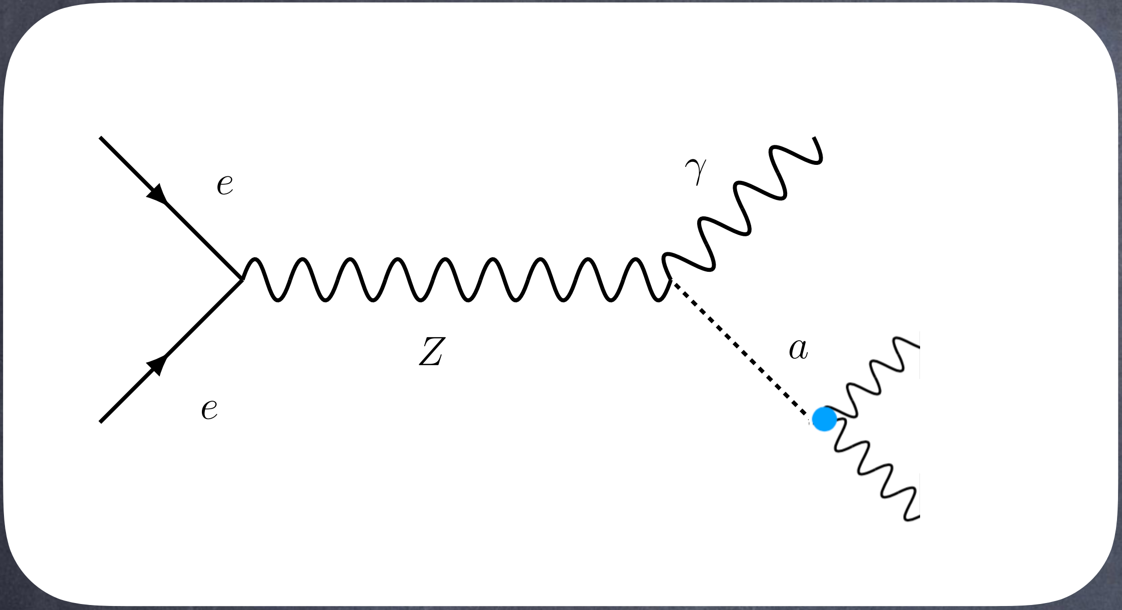
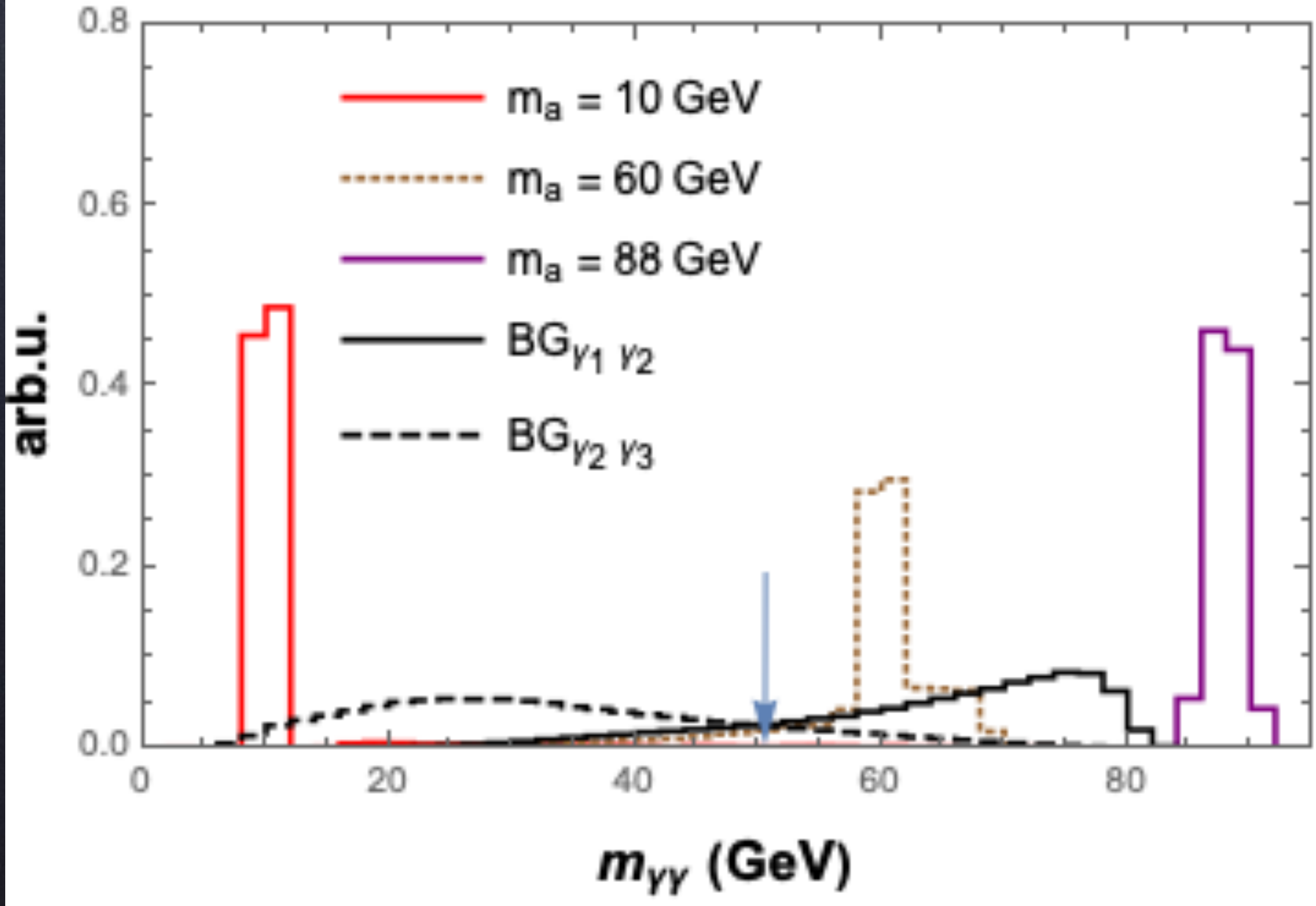


- Three isolated photons

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



Discriminating variable:
invariant mass

Photon ordering changes
at inv. mass 50 GeV

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

Money plot

Typical EWPT bound

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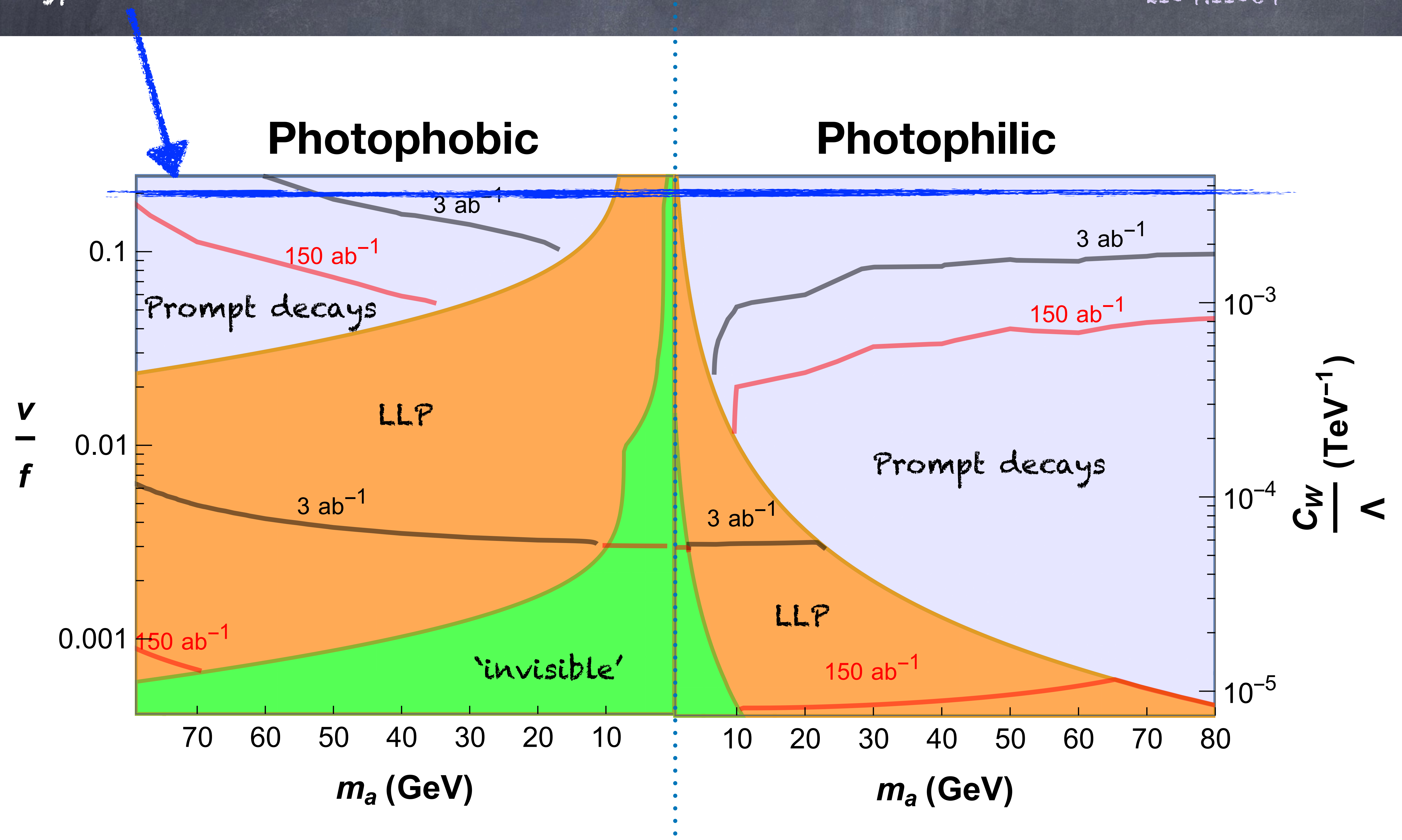
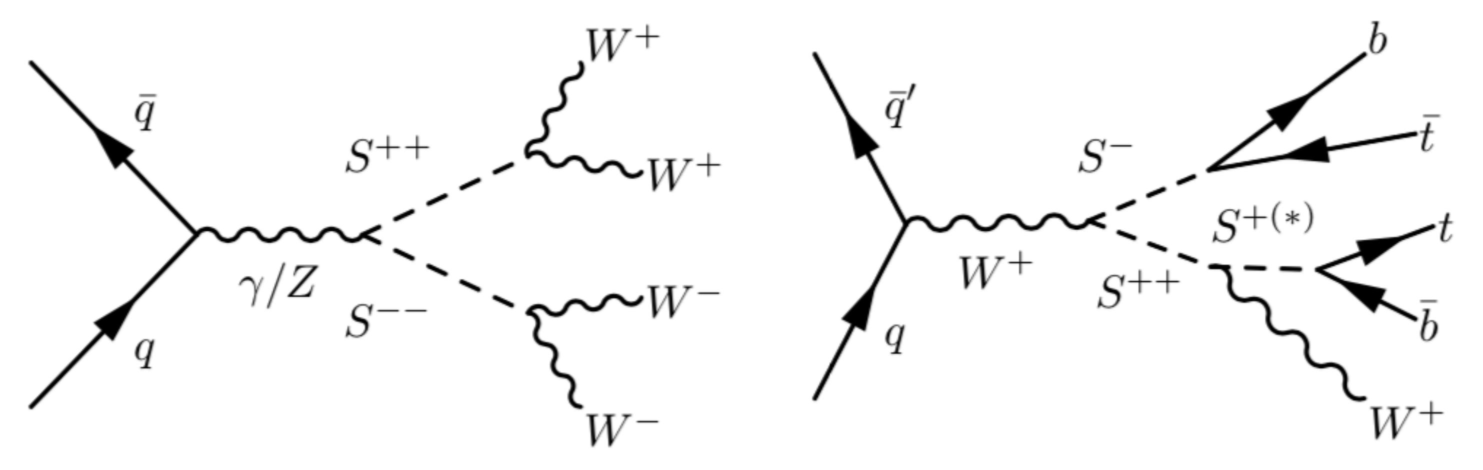


EW pNGB direct production

W.Porod et al.
work in progress

- 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

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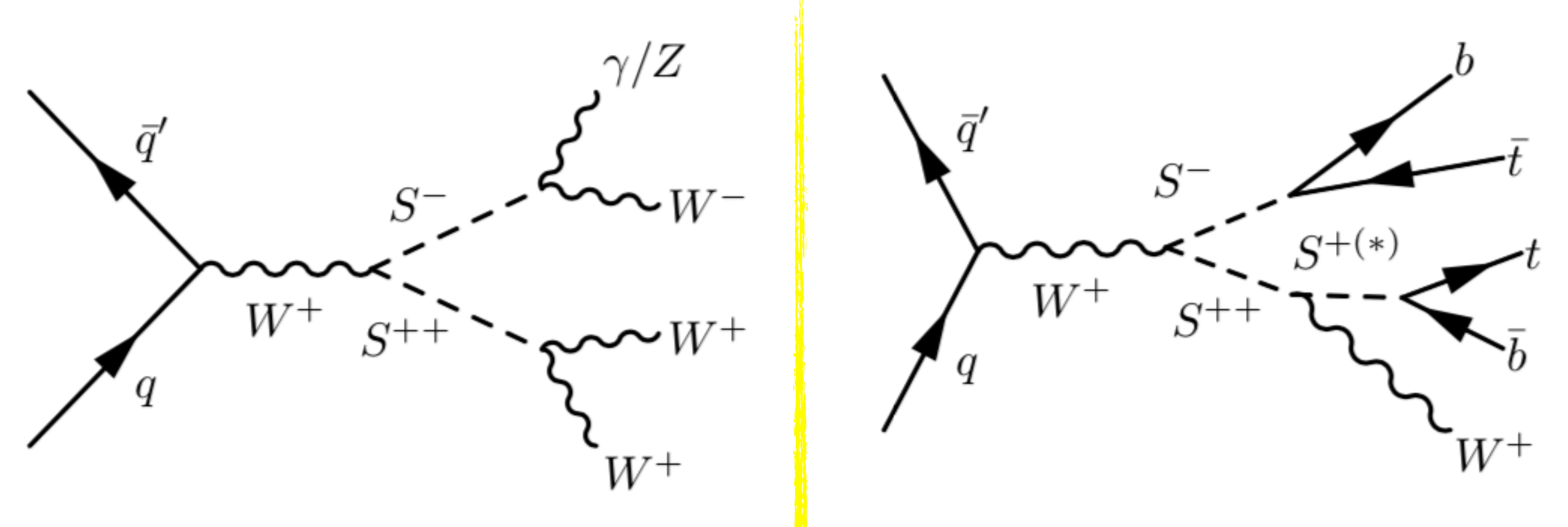
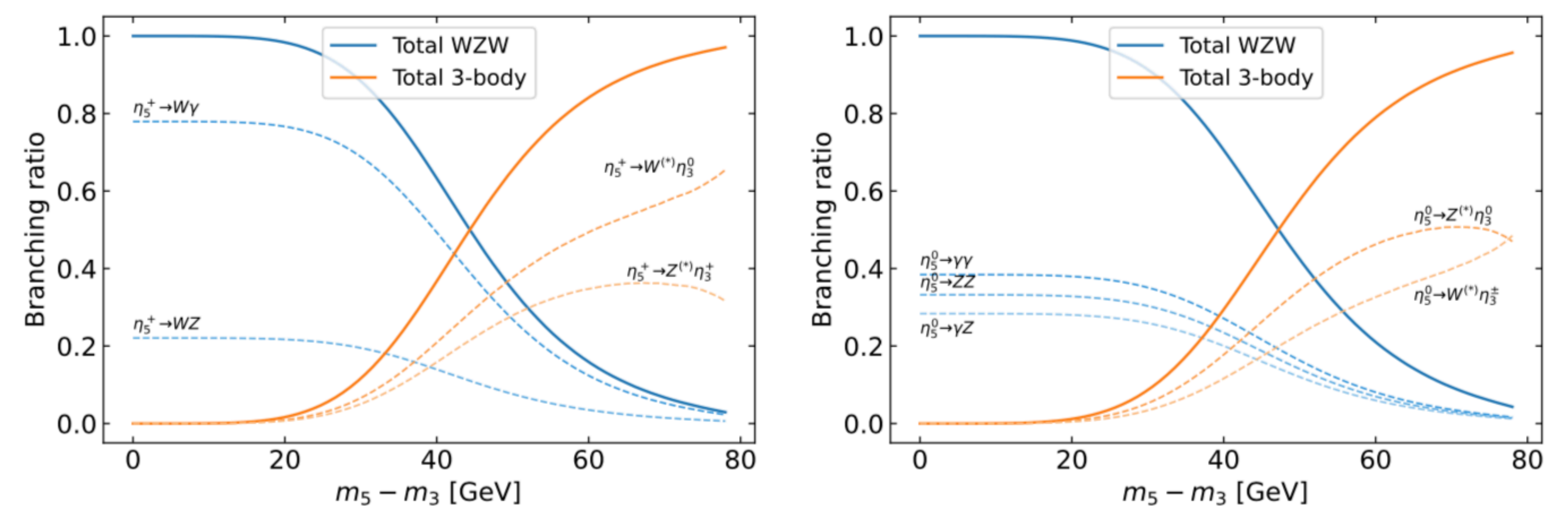


- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
- Photon-rich final states!

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

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



(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.
work in progress

- Decays to two GBs from WZW anomaly
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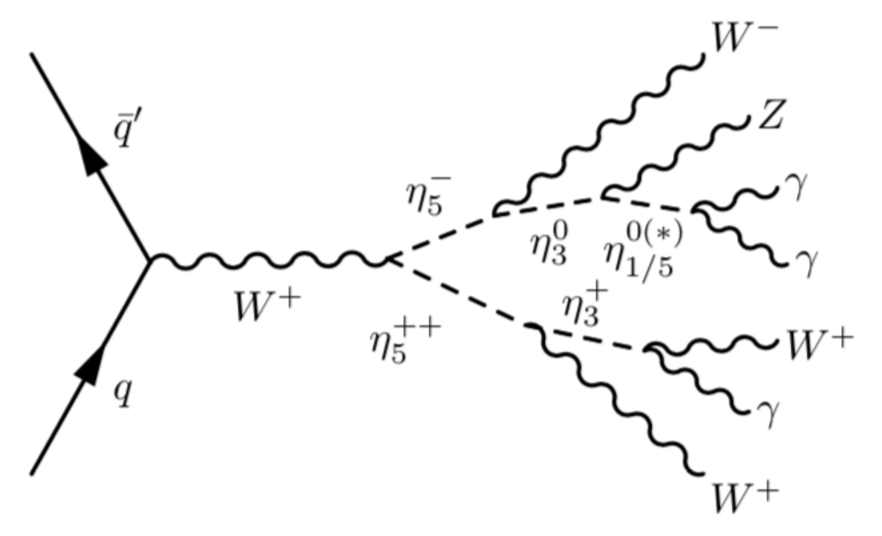
- Photon-rich final states!

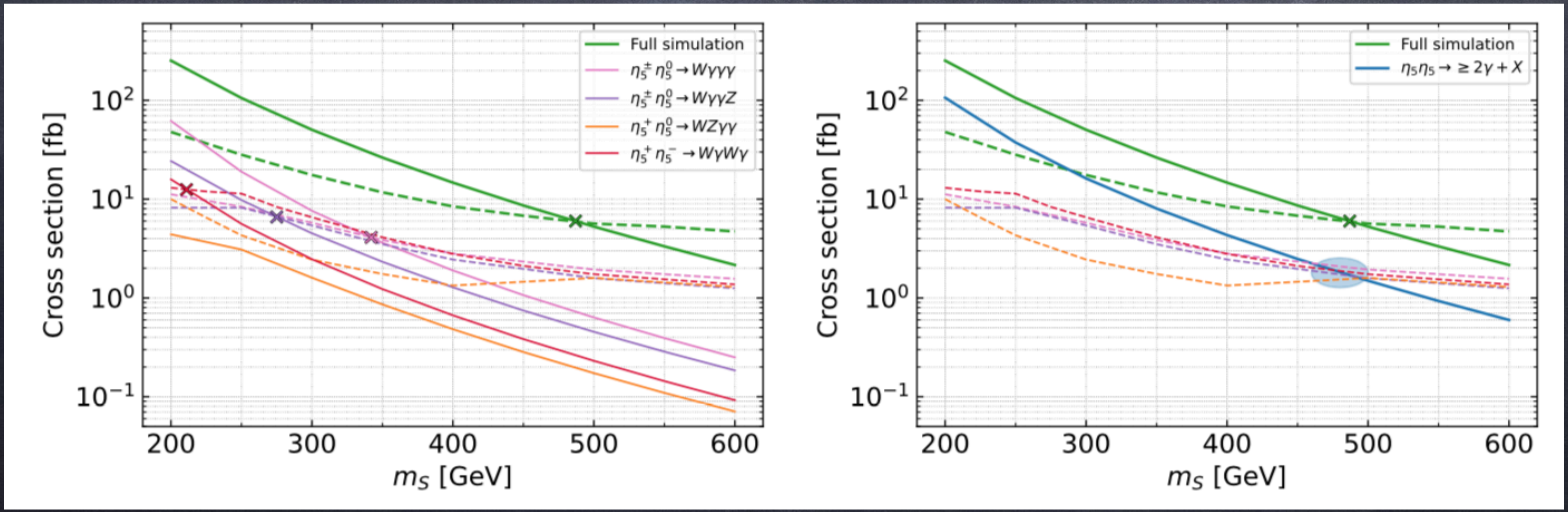
Cascade decays competitive for mass splits around 50 GeV



SU(5)/SO(5) benchmark

W.Porod et al.
work in progress

- 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!



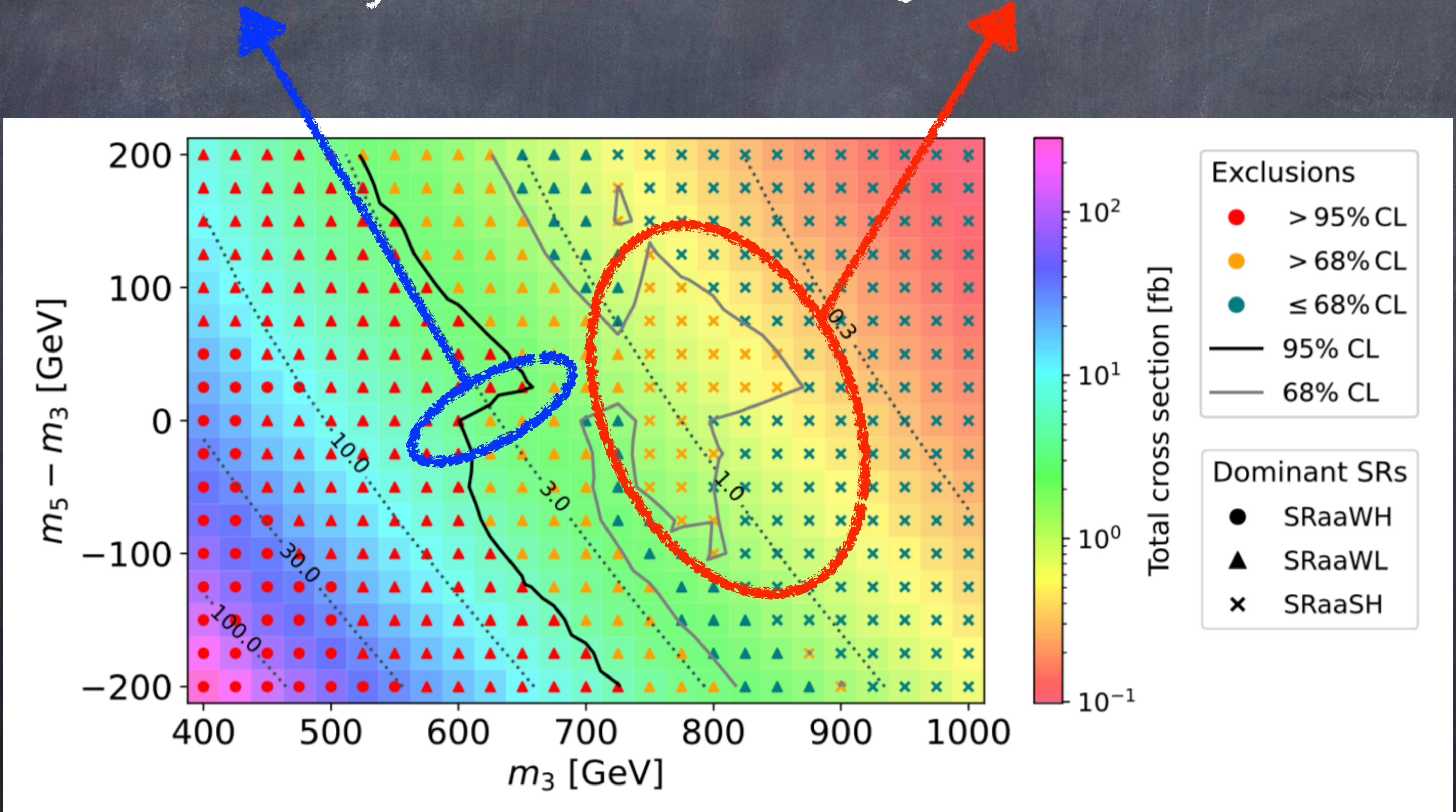
SU(5)/SO(5) benchmark

W.Porod et al.
work in progress

Exclusion from multi-photon search

S++ cascade decays

Change in dominant SR

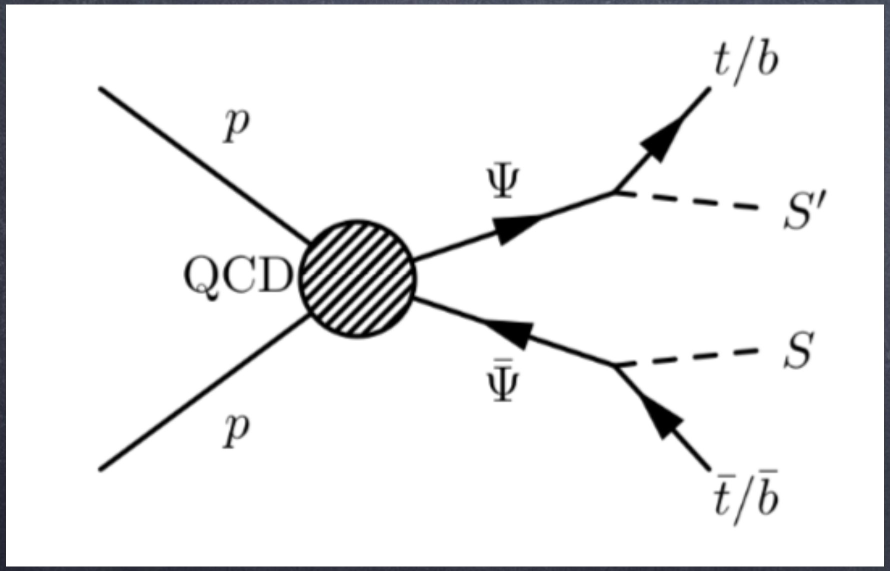


Top partner pheno revisited

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:



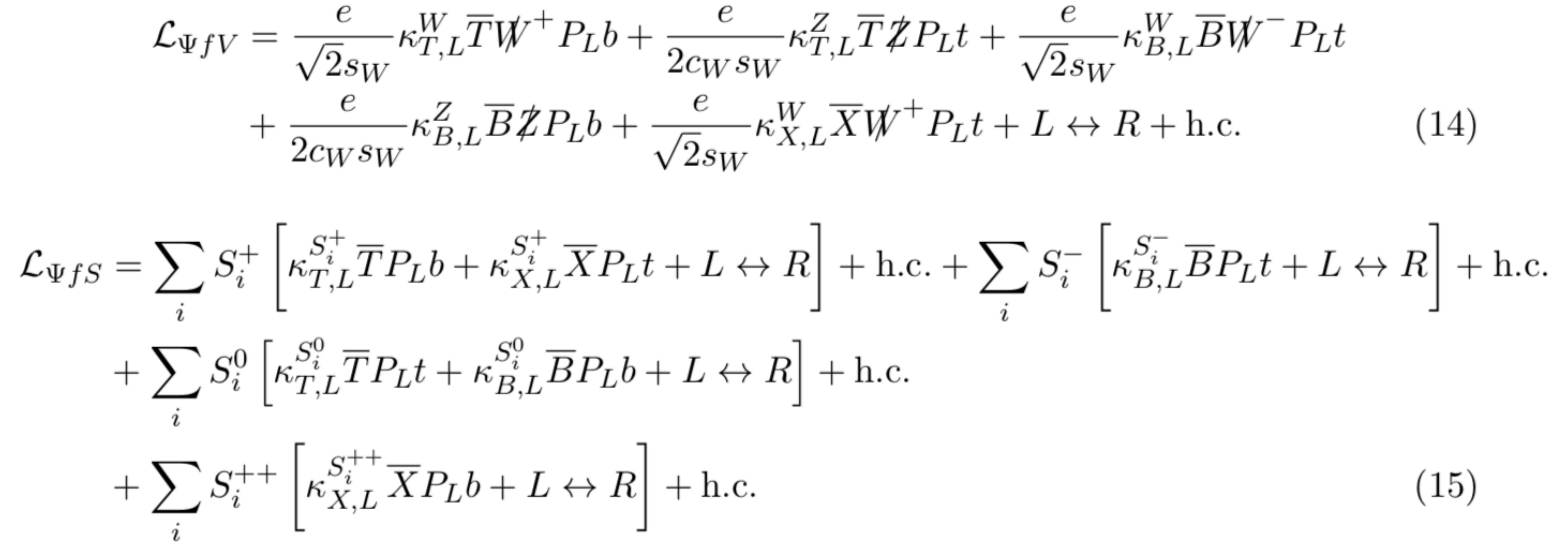
$$\begin{aligned} S_i^{++} &\to W^+W^+ \\ S_i^{+} &\to W^+\gamma,\ W^+Z \\ S_i^{0} &\to W^+W^-,\ \gamma\gamma,\ \gamma Z,\ ZZ. \end{aligned}$$

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



$$\begin{aligned}\mathcal{L}_{\Psi f V} = {} & \frac{e}{\sqrt{2} s_W} \kappa^{W}_{T,L} \overline{T} \not{W}^{+} P_L b + \frac{e}{2 c_W s_W} \kappa^{Z}_{T,L} \overline{T} \not{Z} P_L t + \frac{e}{\sqrt{2} s_W} \kappa^{W}_{B,L} \overline{B} \not{W}^{-} P_L t \\ & + \frac{e}{2 c_W s_W} \kappa^{Z}_{B,L} \overline{B} \not{Z} P_L b + \frac{e}{\sqrt{2} s_W} \kappa^{W}_{X,L} \overline{X} \not{W}^{+} P_L t + L \leftrightarrow R + \text{h.c.}\end{aligned} \tag{14}$$

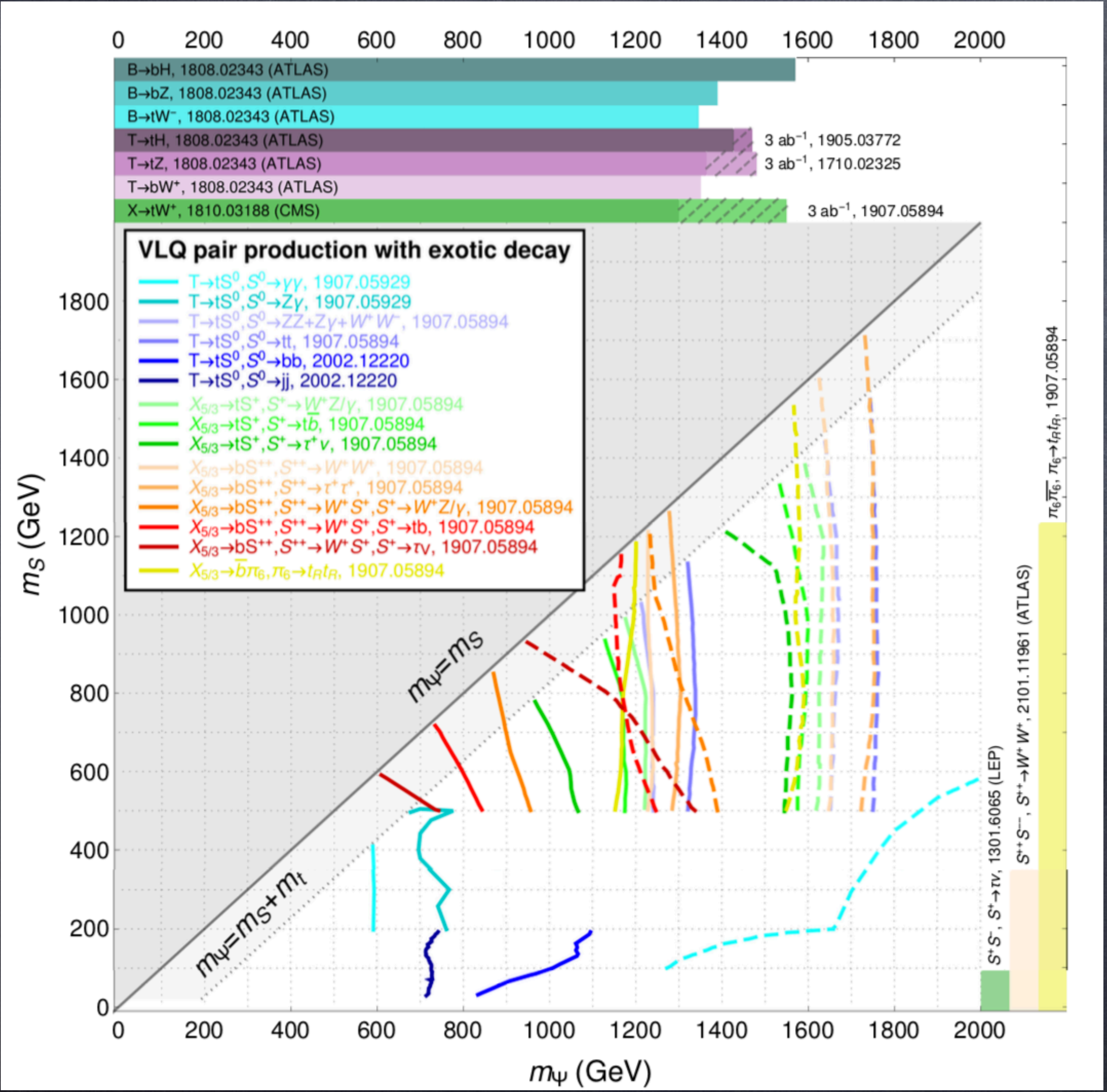
$$\begin{aligned}\mathcal{L}_{\Psi f S} = {} & \sum_i S_i^{+} \left[\kappa^{S_i^{+}}_{T,L} \overline{T} P_L b + \kappa^{S_i^{+}}_{X,L} \overline{X} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^{-} \left[\kappa^{S_i^{-}}_{B,L} \overline{B} P_L t + L \leftrightarrow R \right] + \text{h.c.}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

- 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)



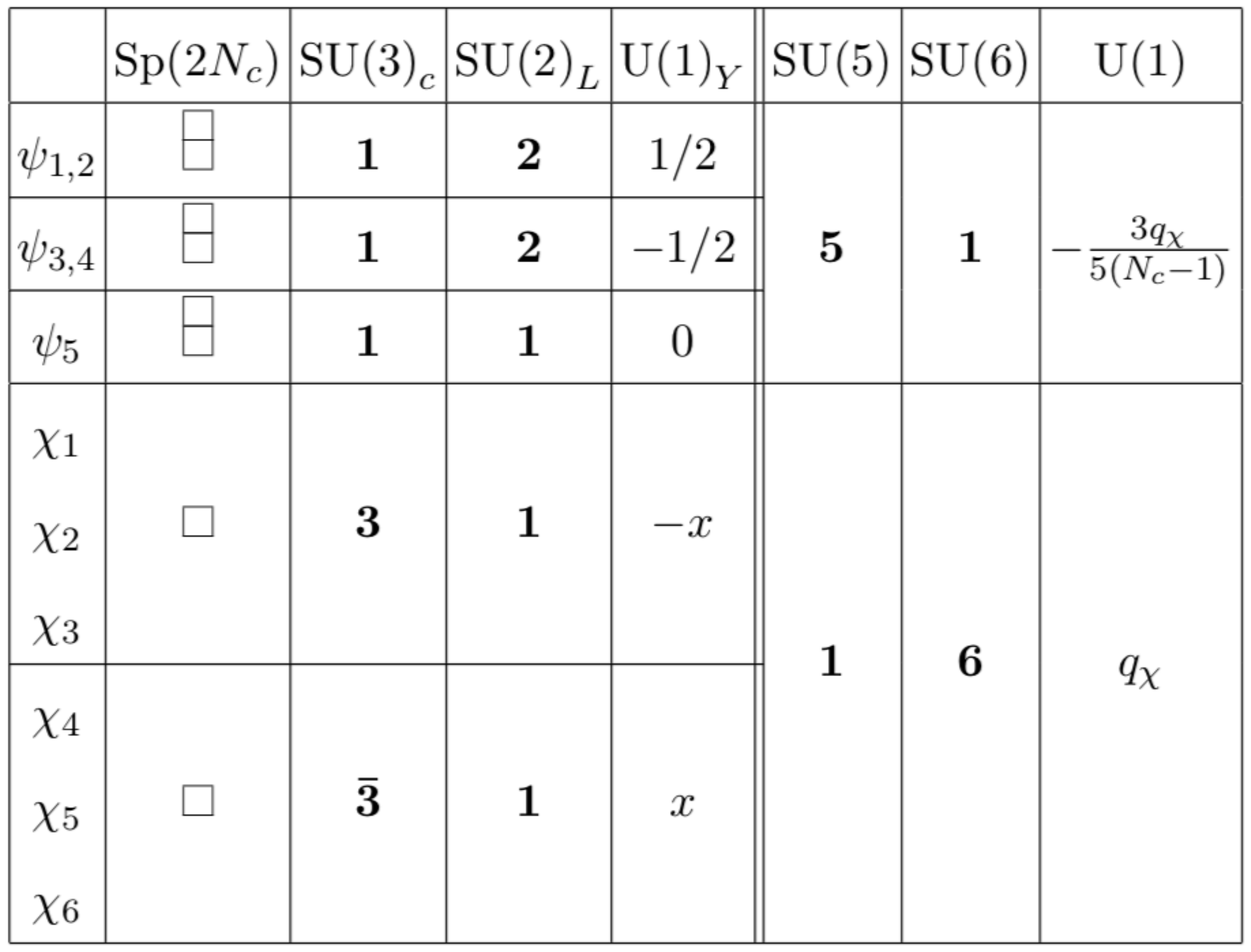
- Dedicated searches may be useful to push up the limits.
- Projections for FCC-hh are needed…
- in combination with scalar direct production.

Exotic top partners

G.Cacciapaglia et al.
2112.00019

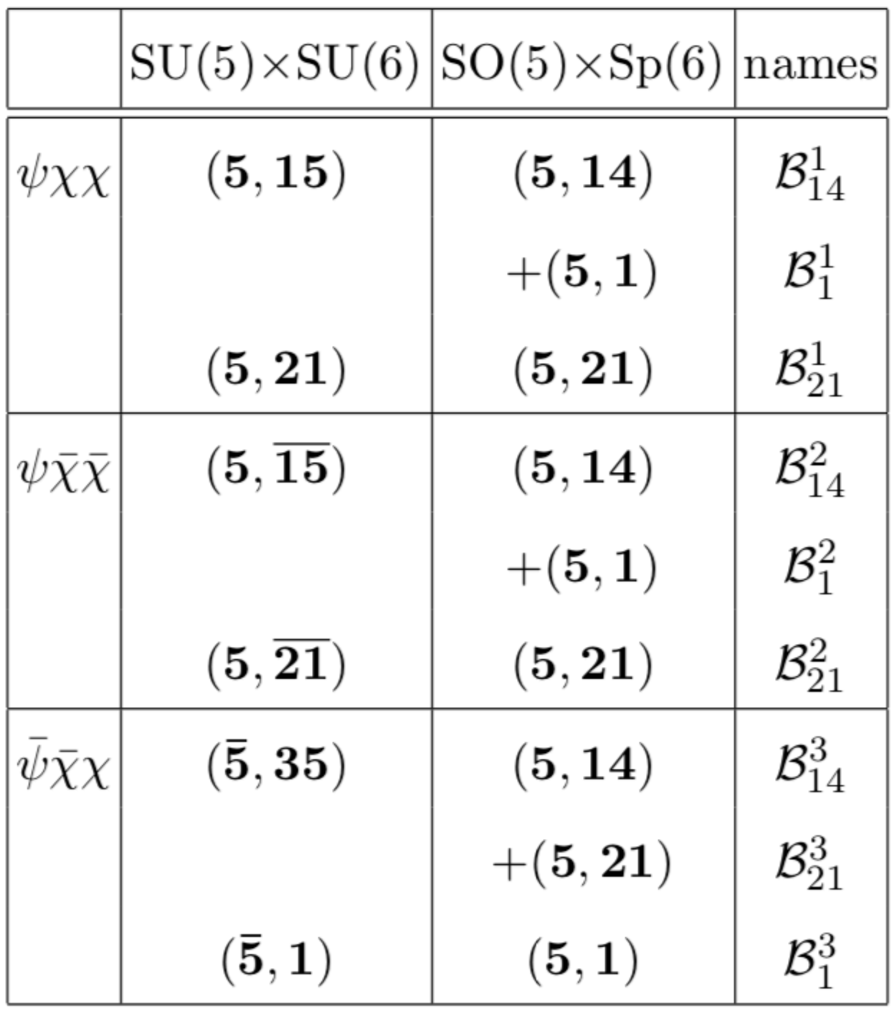
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)

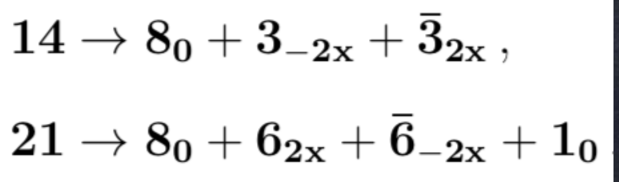


	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{matrix}\square\\\square\end{matrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{matrix}\square\\\square\end{matrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			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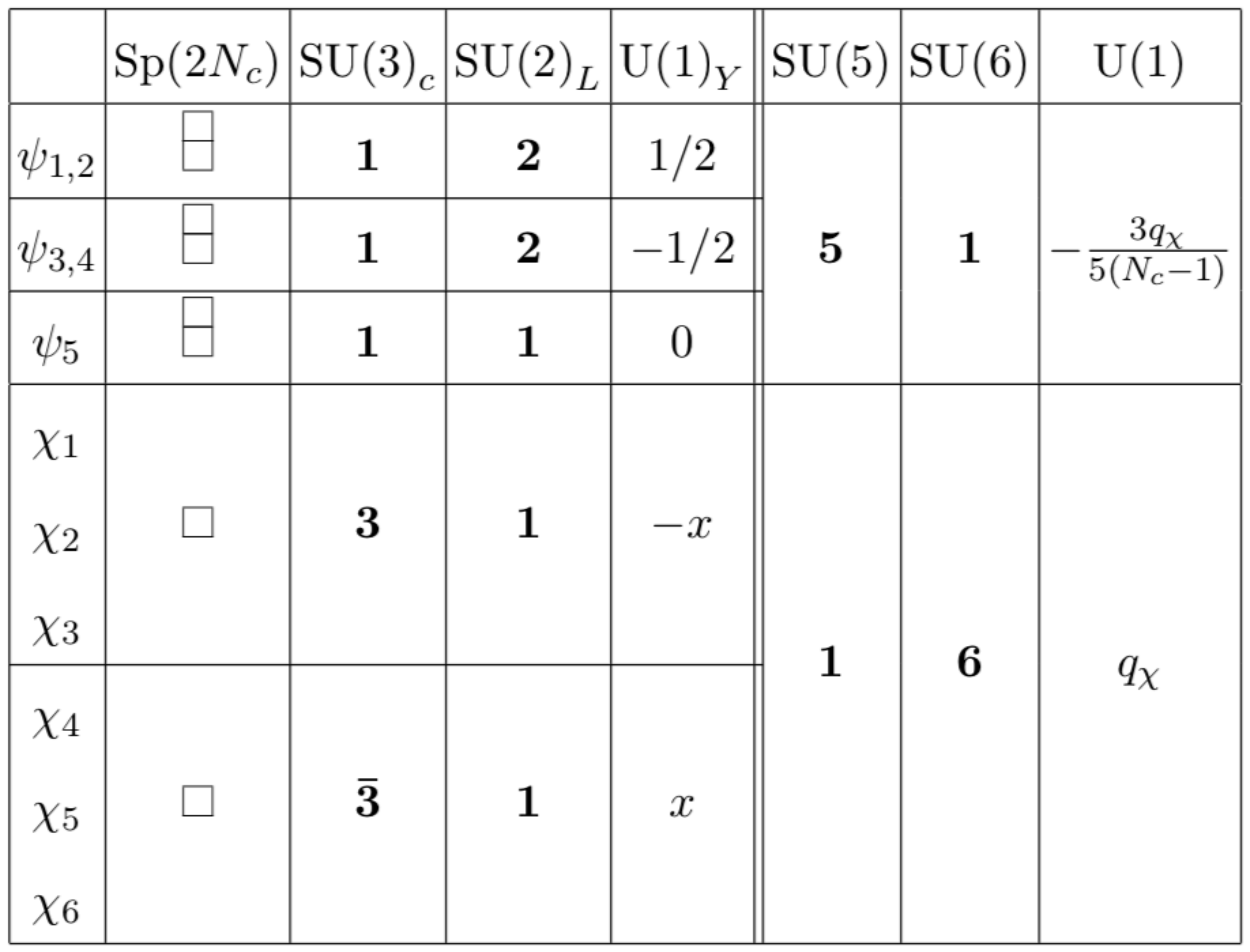

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χ_5							
χ_6							

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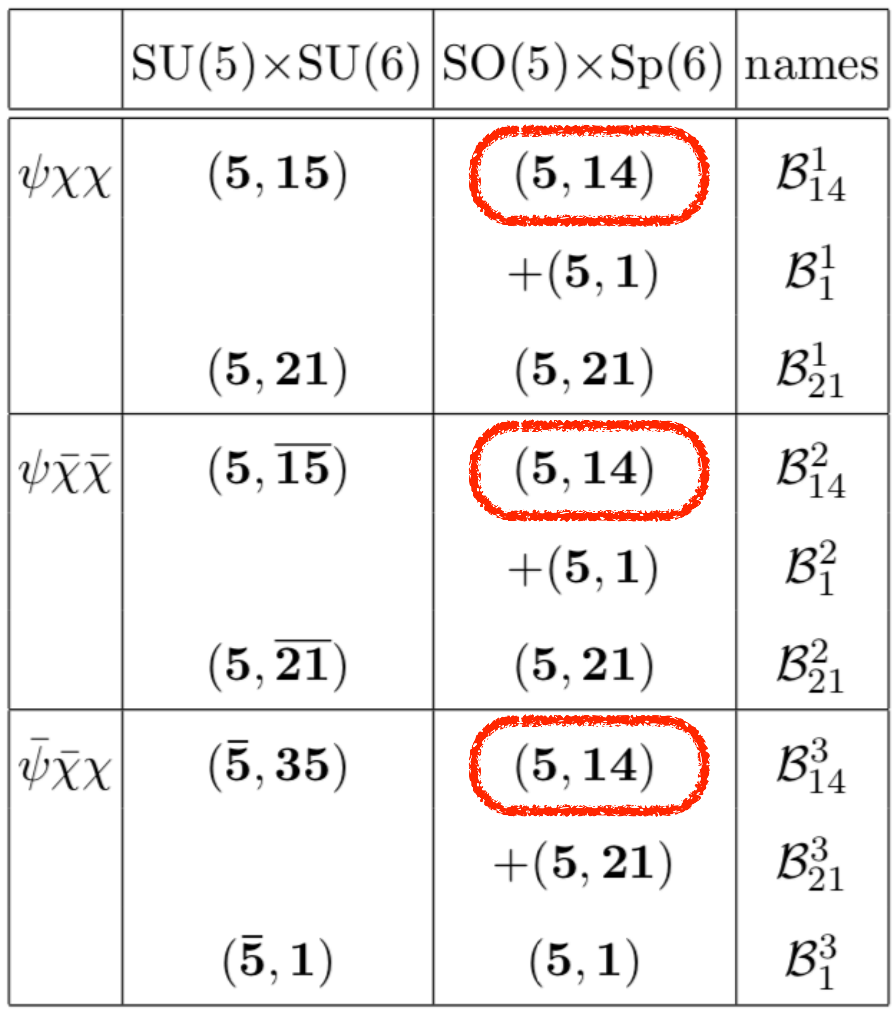

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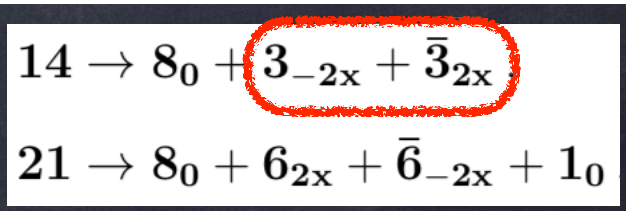
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_1$



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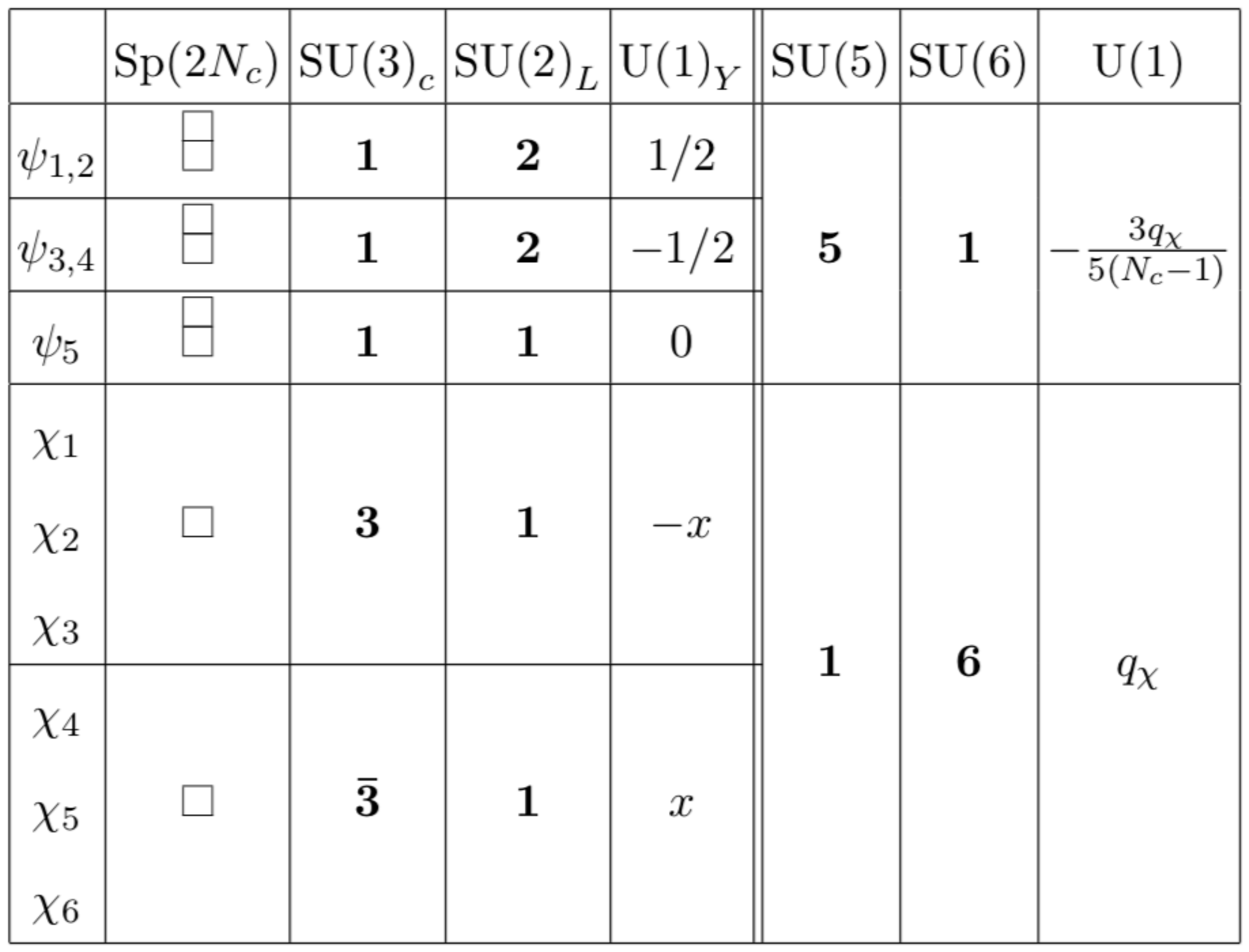
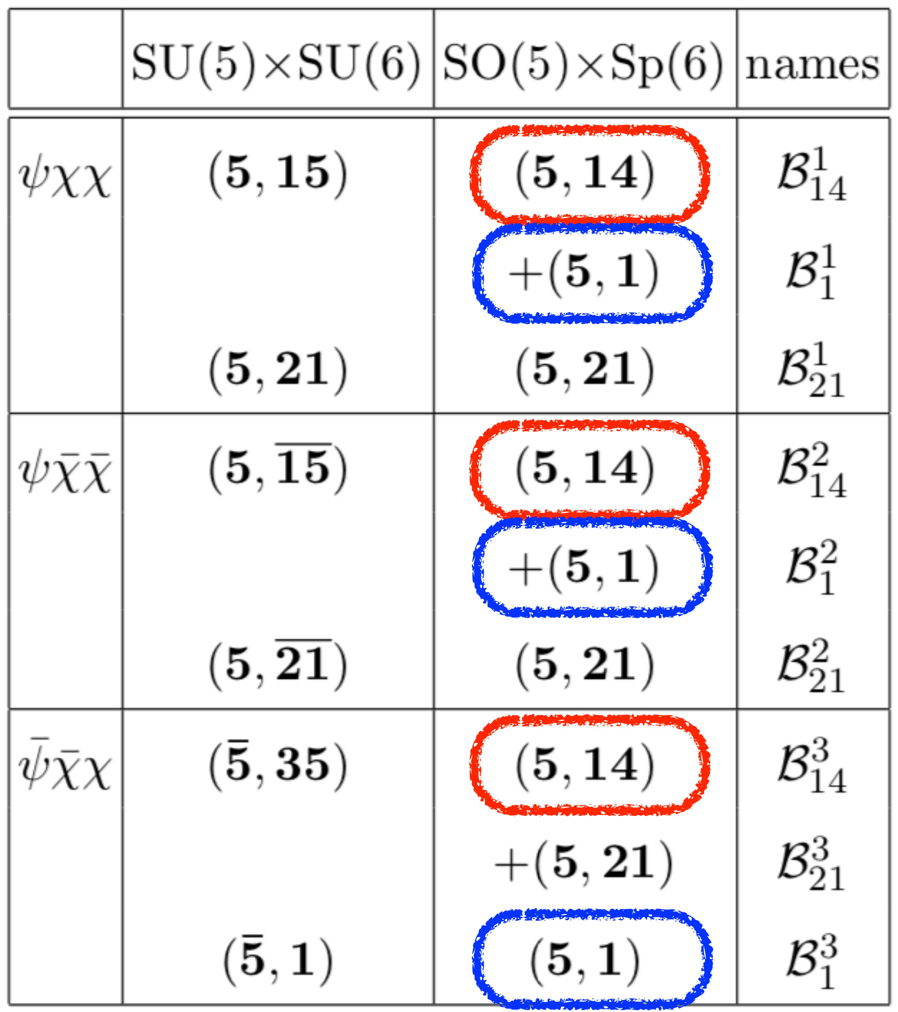


	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{SU}(5)$	$\mathrm{SU}(6)$	$\mathrm{U}(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$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

Baryons (top partners)



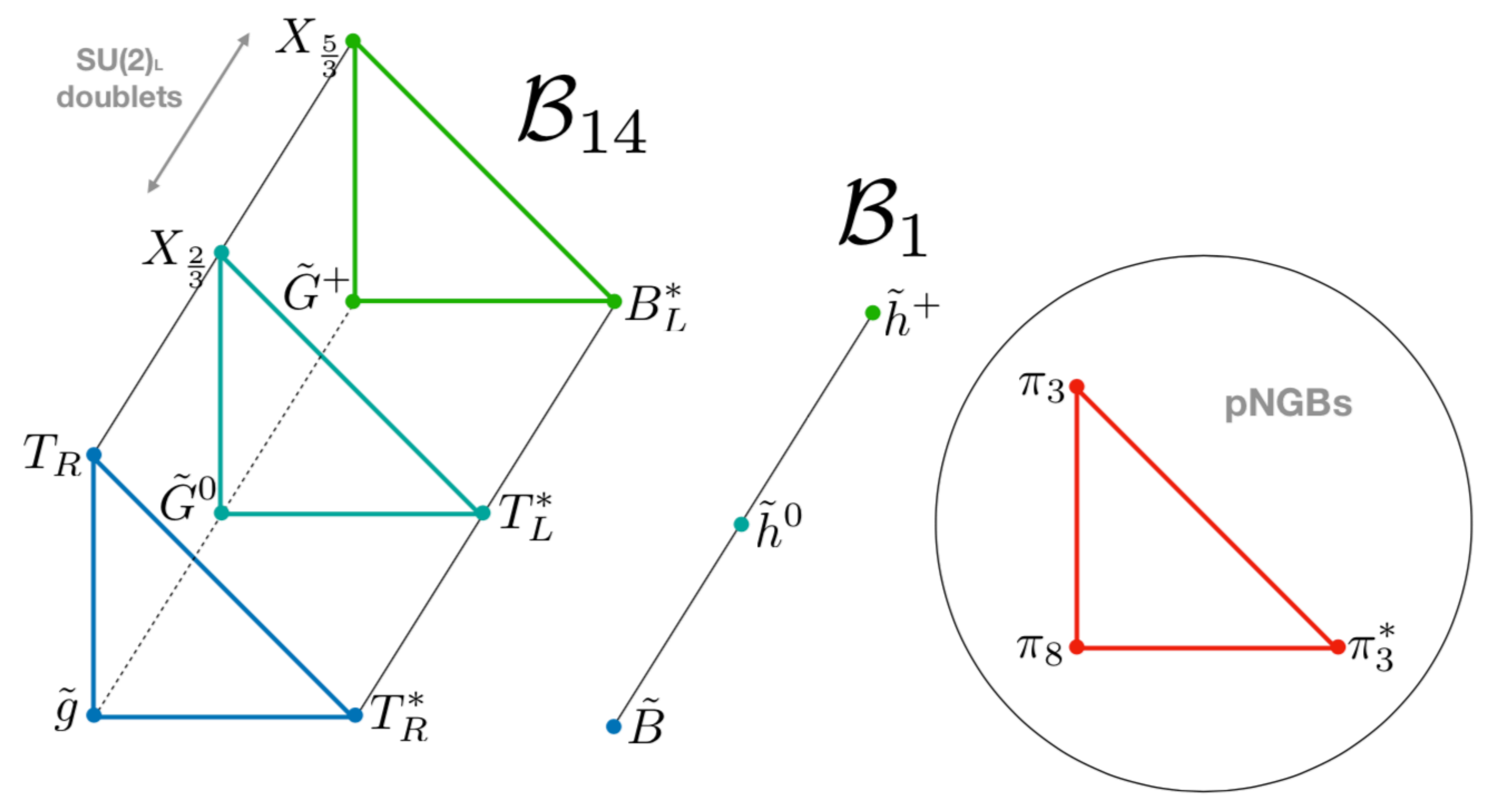
	$\mathrm{SU}(5)\times\mathrm{SU}(6)$	$\mathrm{SO}(5)\times\mathrm{Sp}(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^1_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_{1}$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar\chi\bar\chi$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

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

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

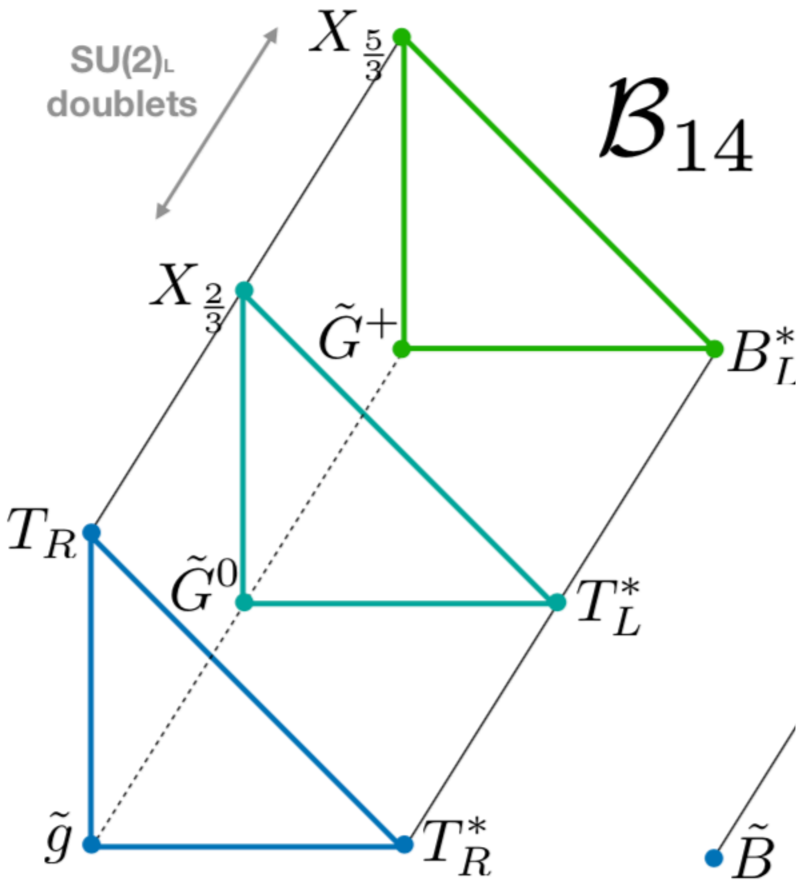
Exotic top partners

G.Cacciapaglia et al.
2112.00019



Exotic top partners

G.Cacciapaglia et al.
2112.00019



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

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

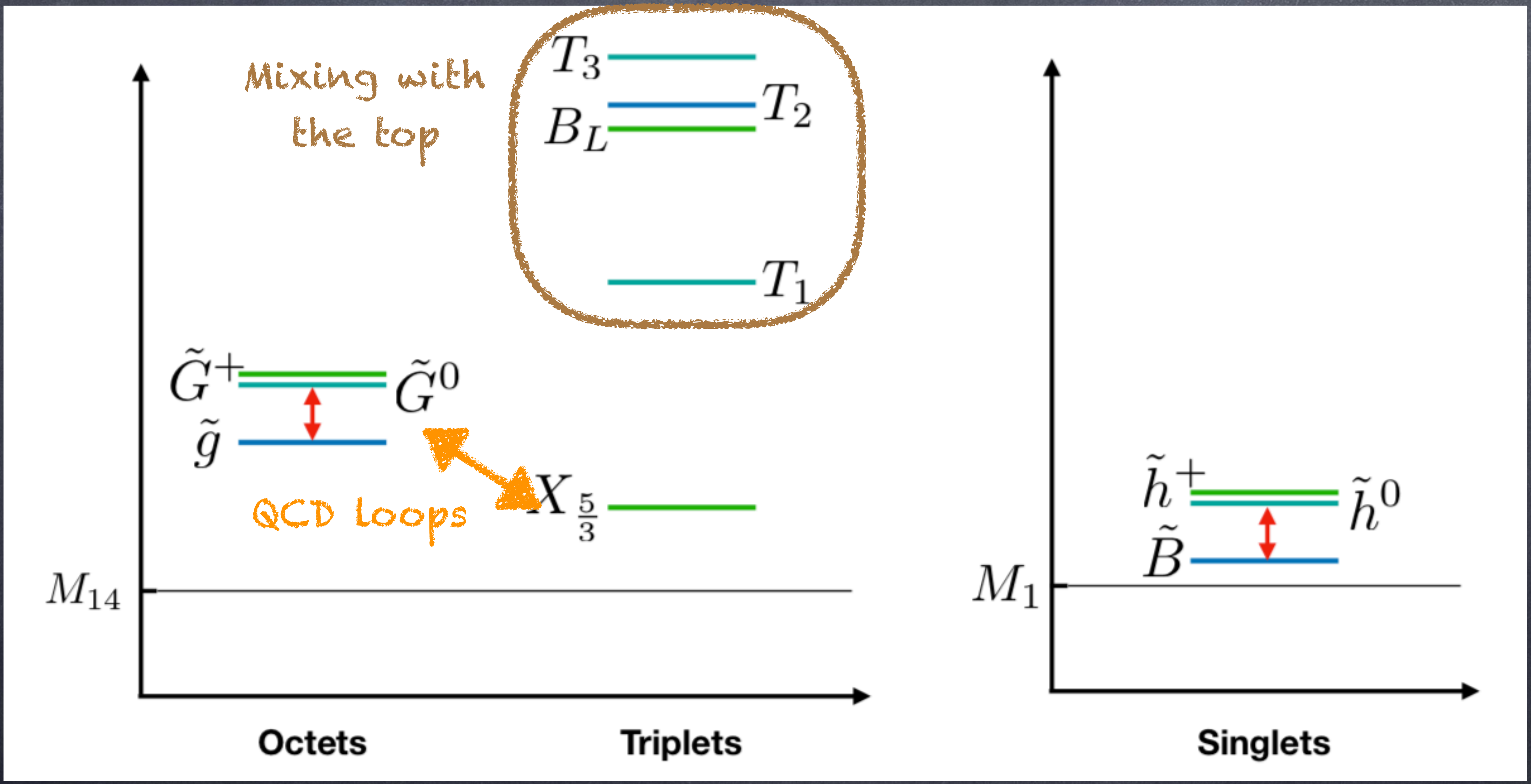
Higgsoni (Dirac): $\tilde{h}^+ = \begin{pmatrix} \tilde{h}_u^+ \\ \bar{\tilde{h}}_d^- \end{pmatrix}$, $\tilde{h}^0 = \begin{pmatrix} \tilde{h}_u^0 \\ \bar{\tilde{h}}_d^0 \end{pmatrix}$,

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

The baryon content looks ironically SUSY-like!

Exotic top partners

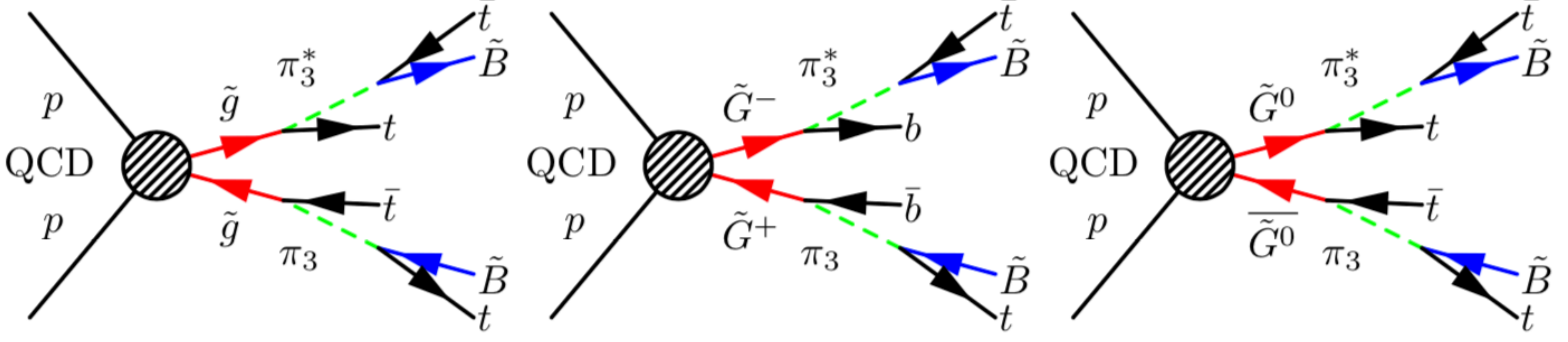
G.Cacciapaglia et al.
2112.00019



Octoni bounds

G.Cacciapaglia et al.
2112.00019

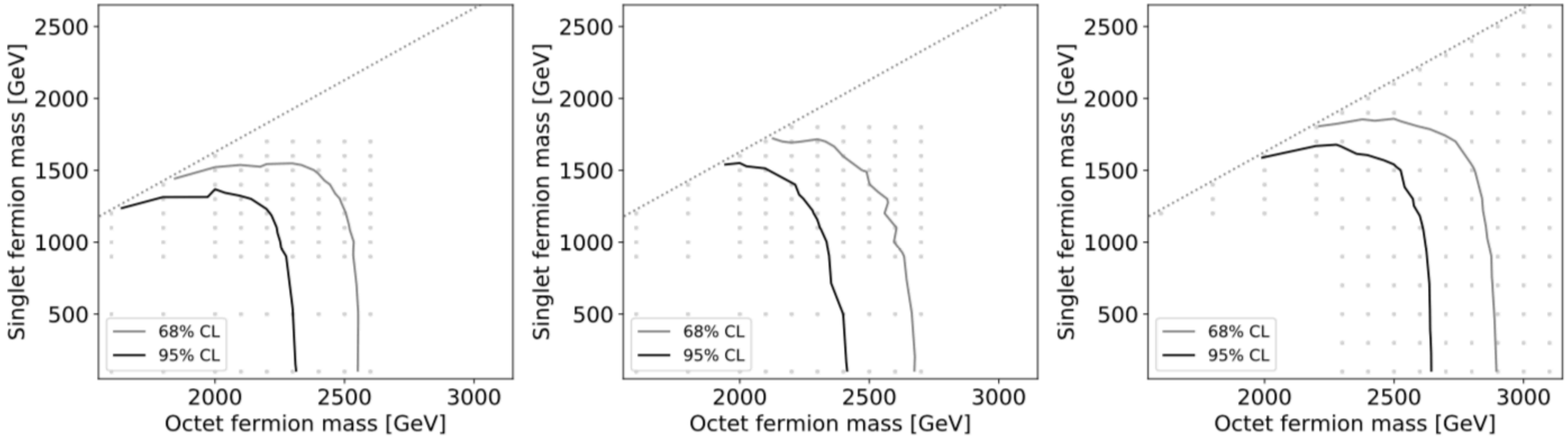
- Model implemented in MG.
- Check limits from searches in MadAnalysis and CheckMate.
- Strongest bound from gluino and stop searches!



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

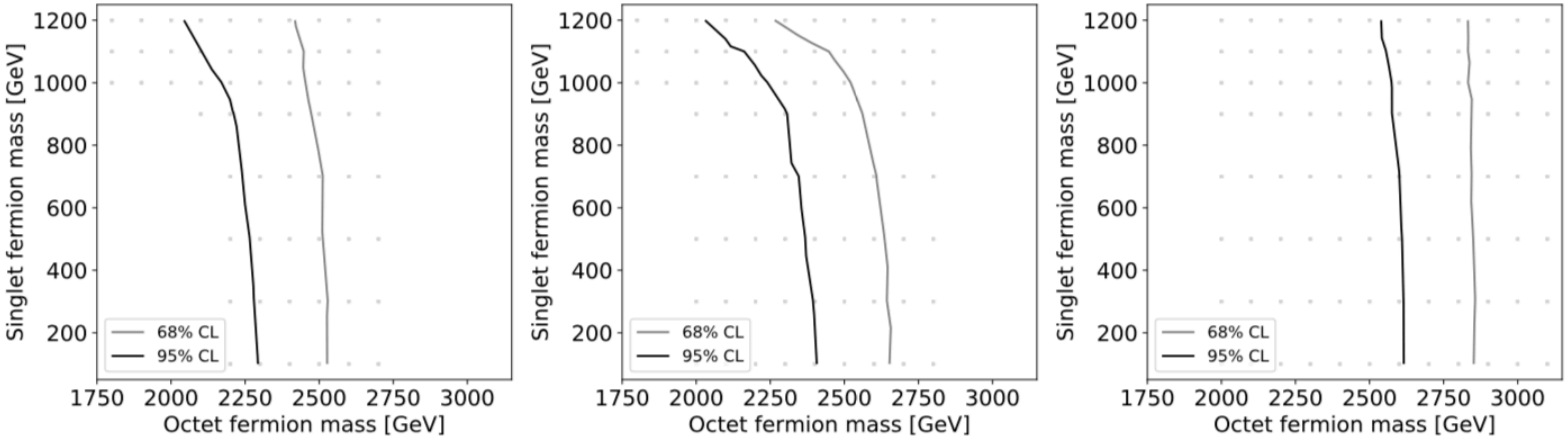
$m_{\tilde g} - m_{\pi_3} = 200$ GeV

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

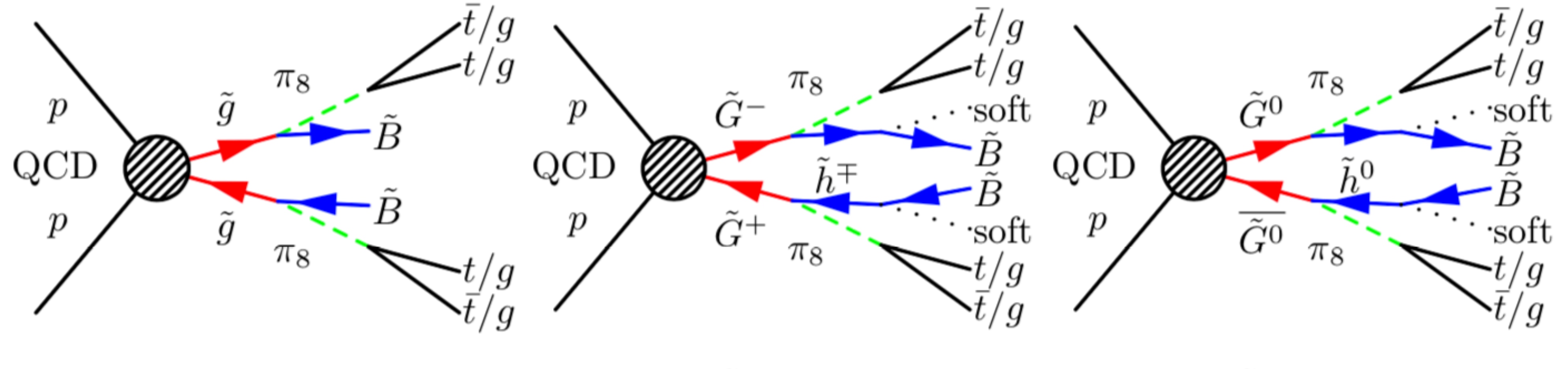
$m_{\pi_3} = 1.4$ TeV

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

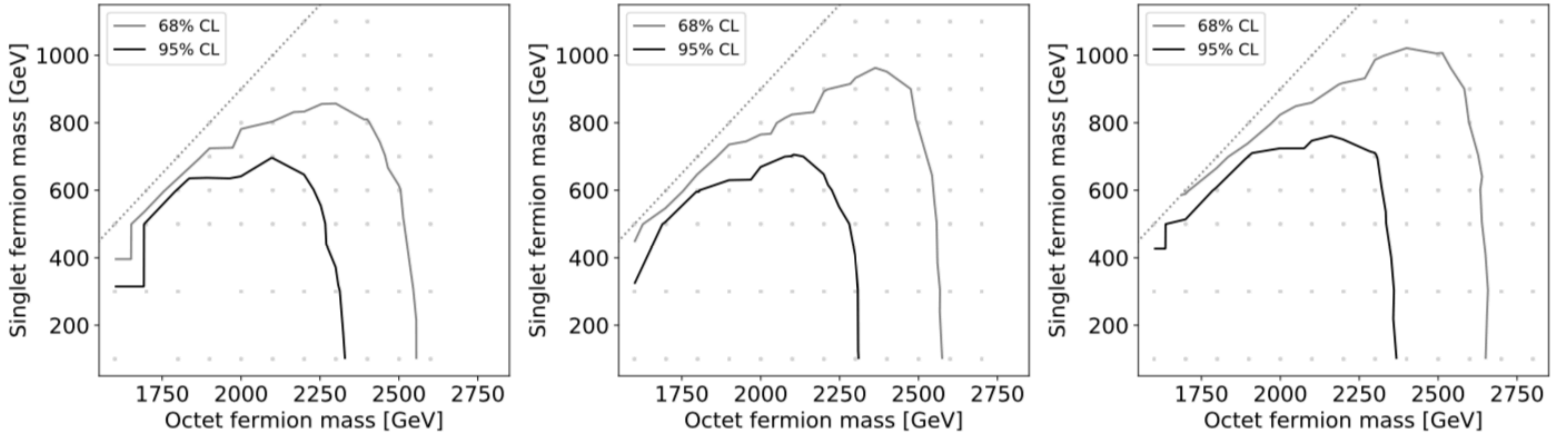
$m_{\pi_3} = 1.4$ TeV

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

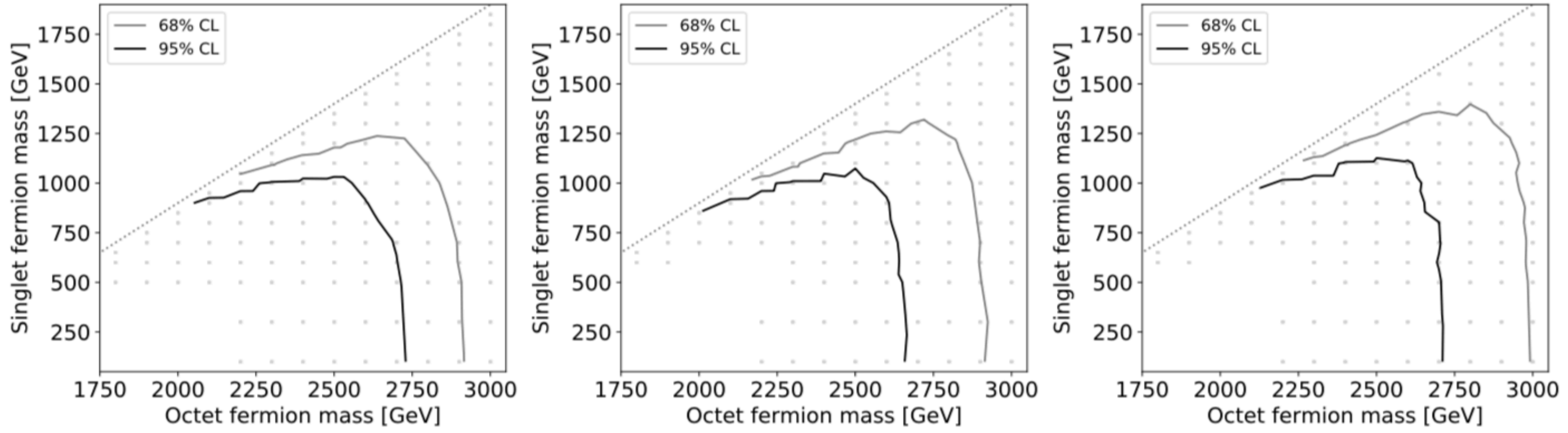
$m_{\pi_3} = 1.4$ TeV



(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) $\tilde{G}^0 \to \tilde{h}^0\pi_8,\ \pi_8 \to \bar{t}t/gg.$

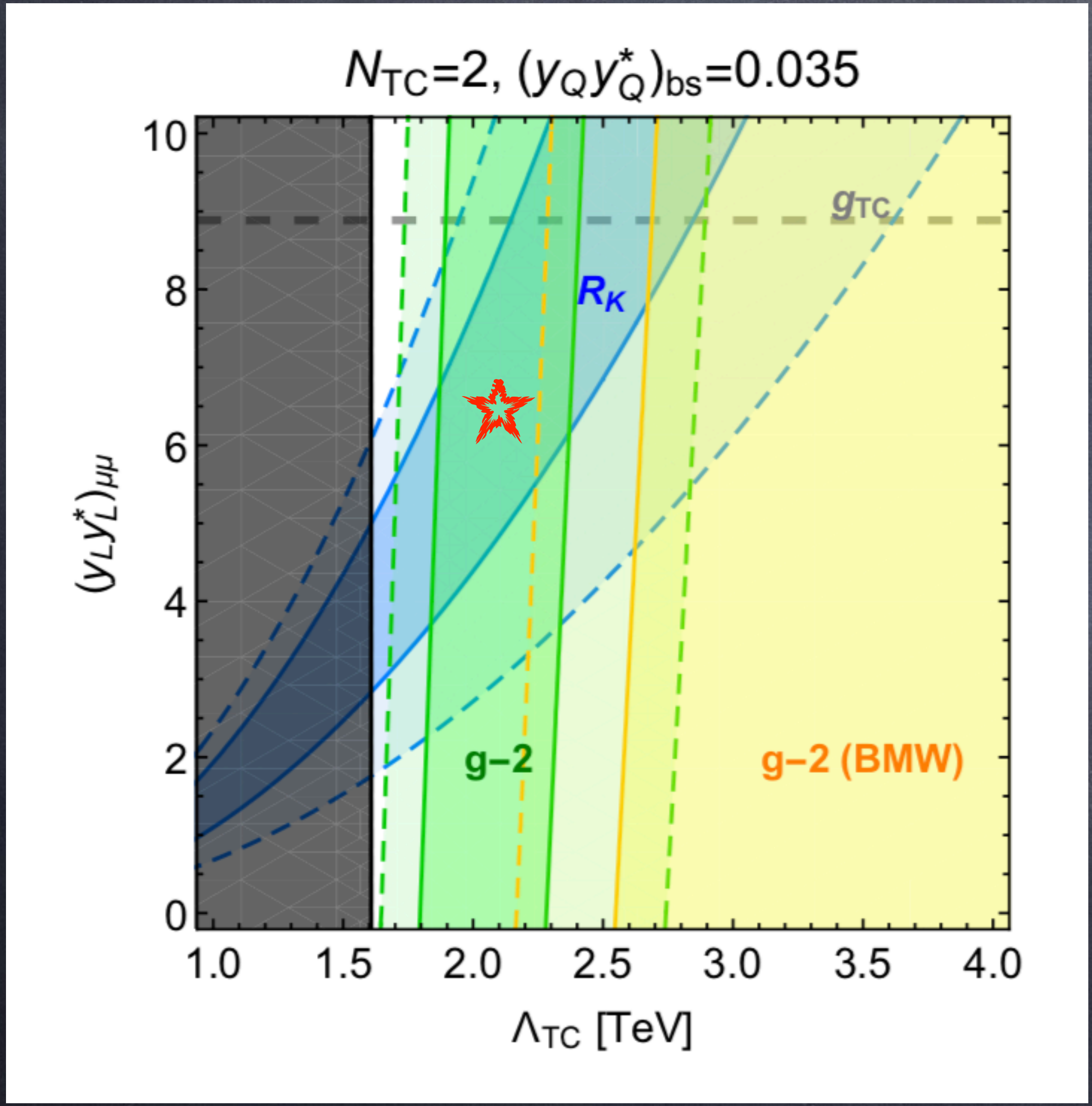


(a) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg$ (b) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg, t\bar{t}$ (c) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to t\bar{t}$



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

There's something about Muons



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

- 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!

Bonus tracks

What if FCC-ee discovers Z > γa?

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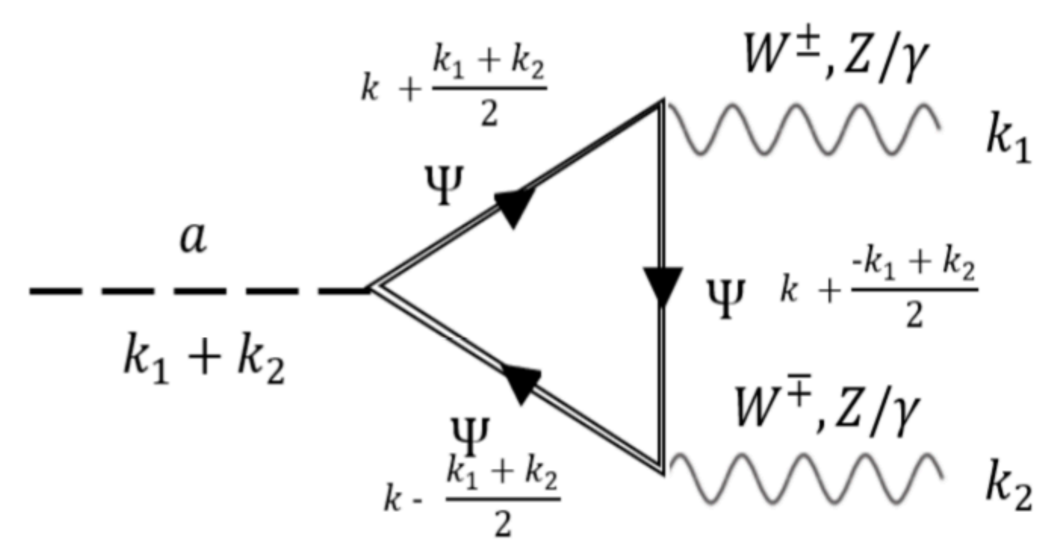
work in progress

- 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?

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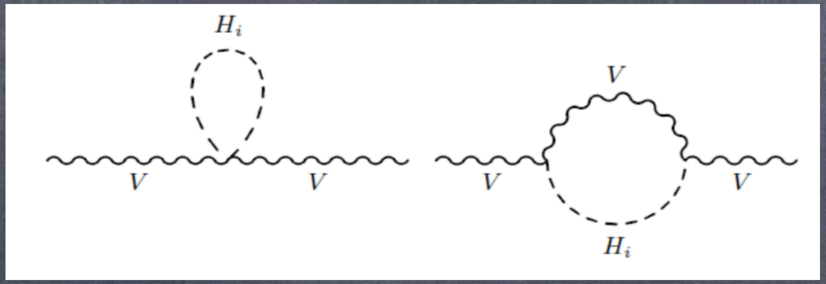
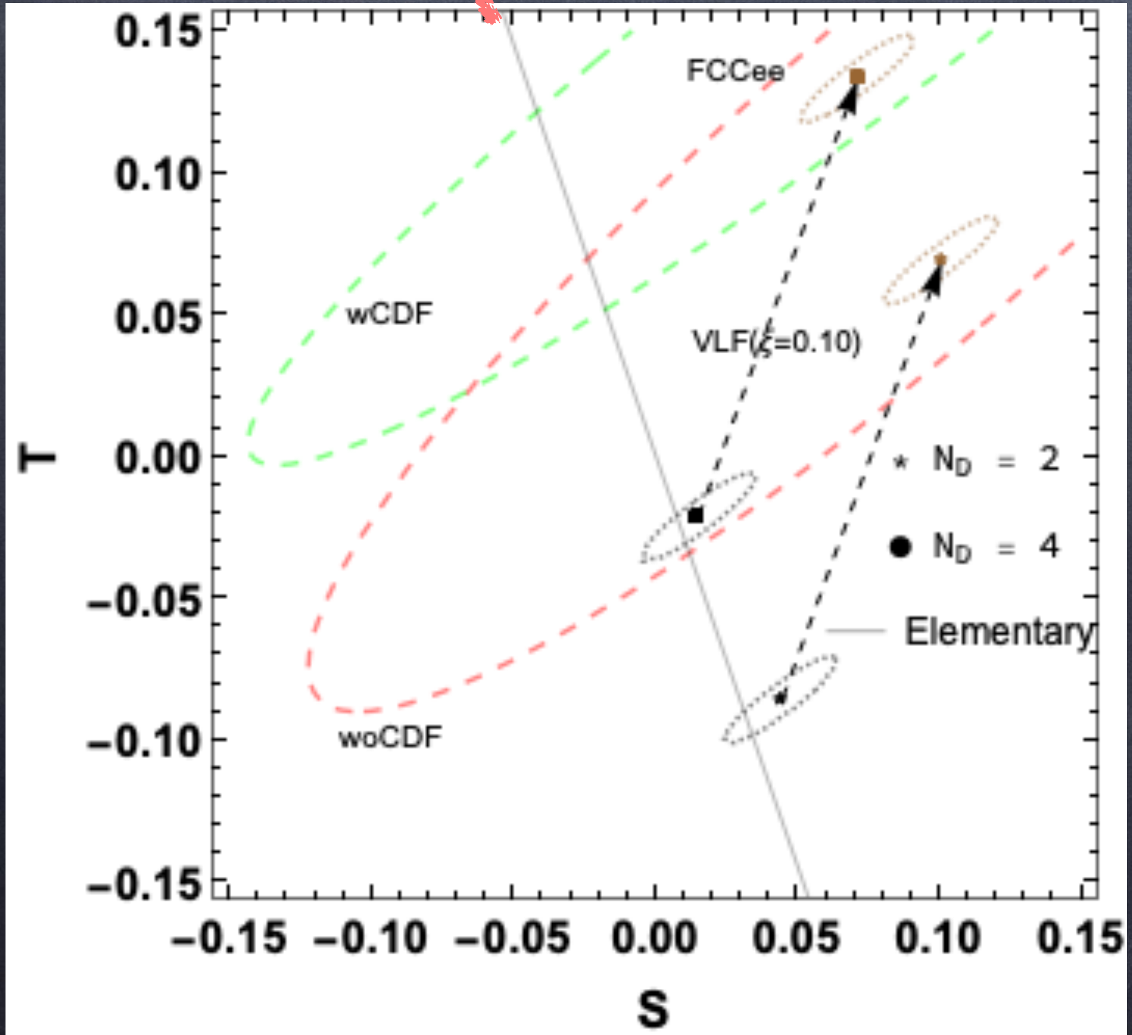
work in progress

- 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.