Searching for light scalars and ALPs from Z-decays

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IP2I Lyon, France

Second ECFA Workshop on e+e- Higgs/EW/Top Factories

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 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

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partially

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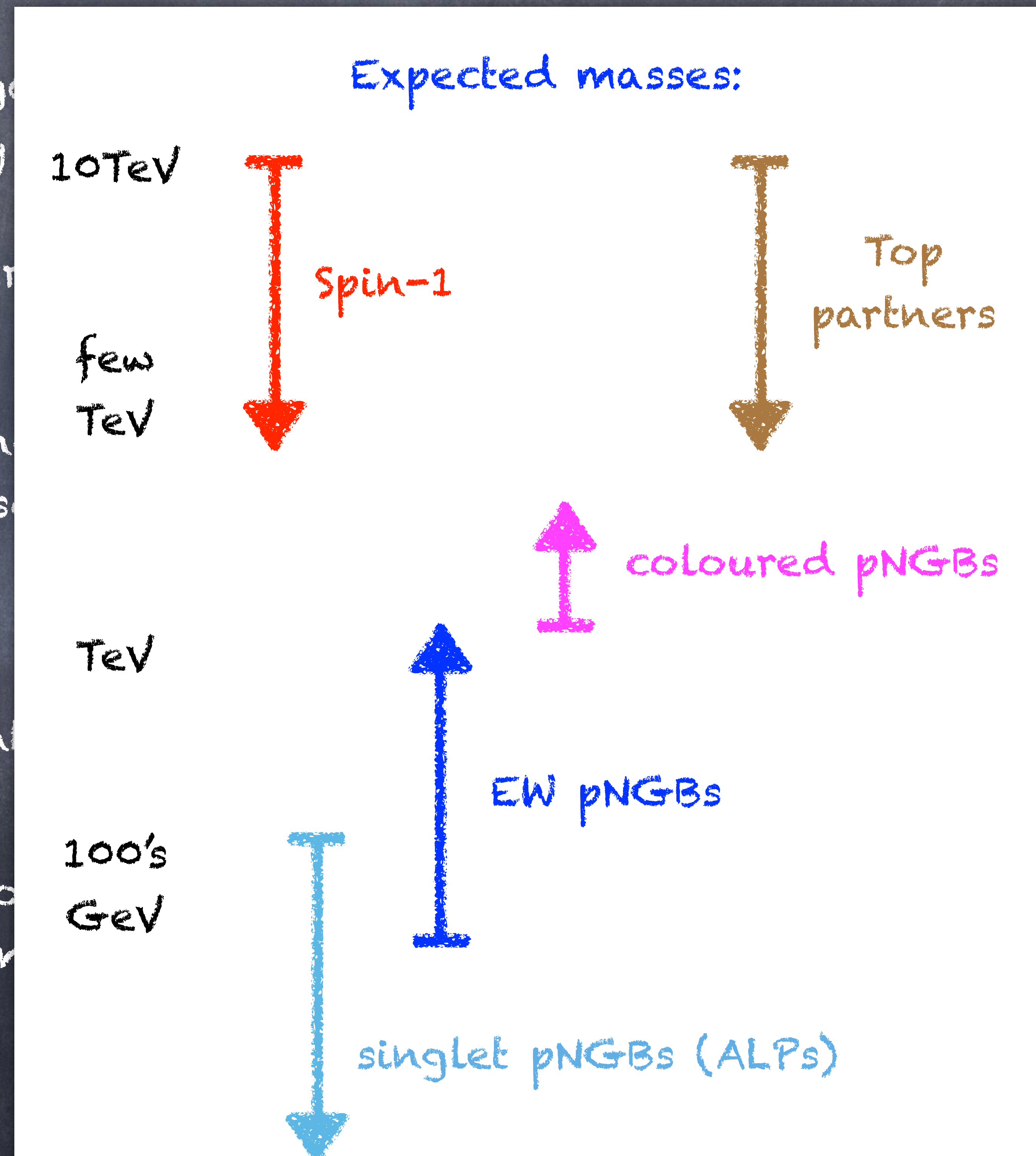

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Composite models at various scales

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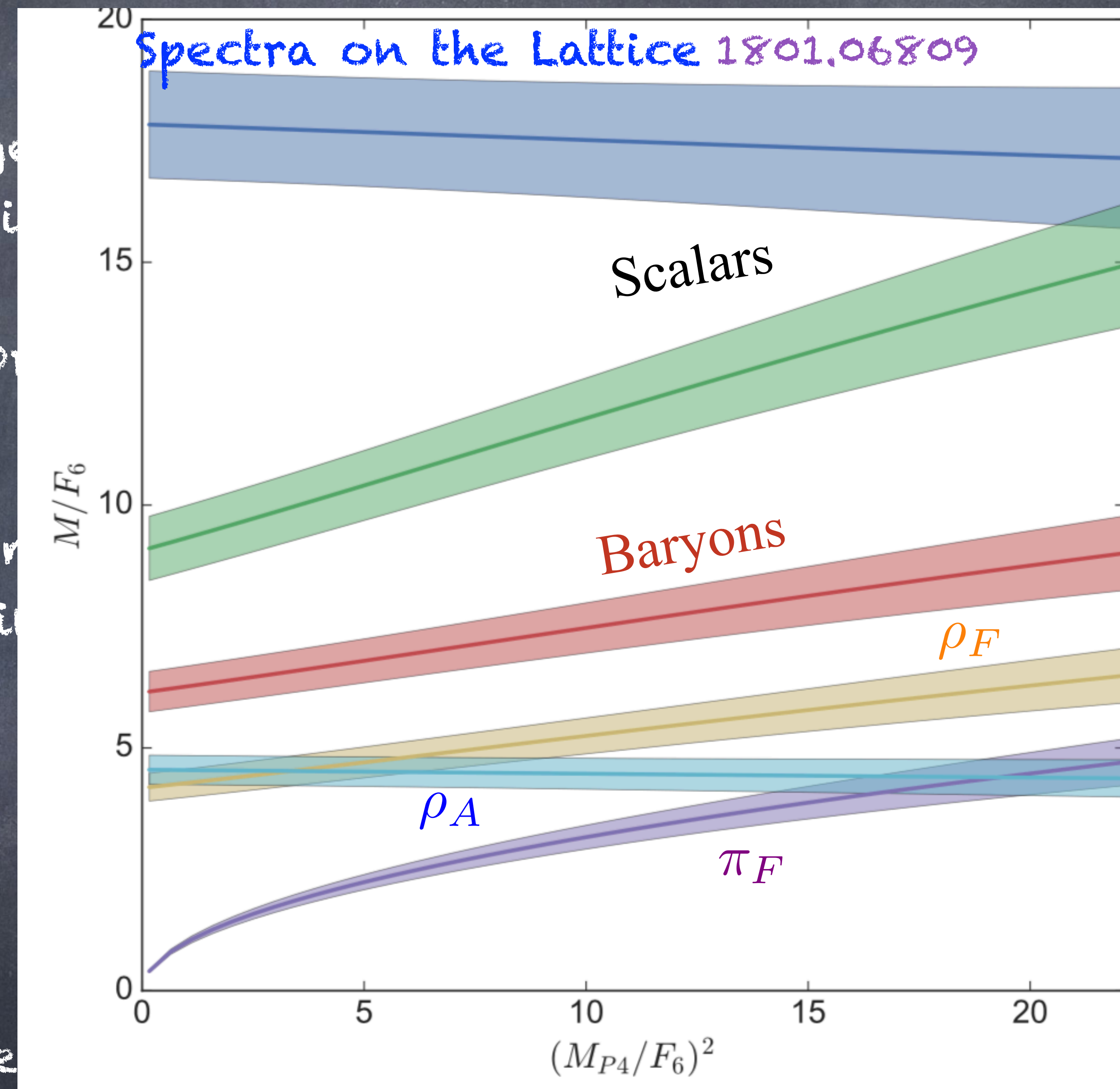
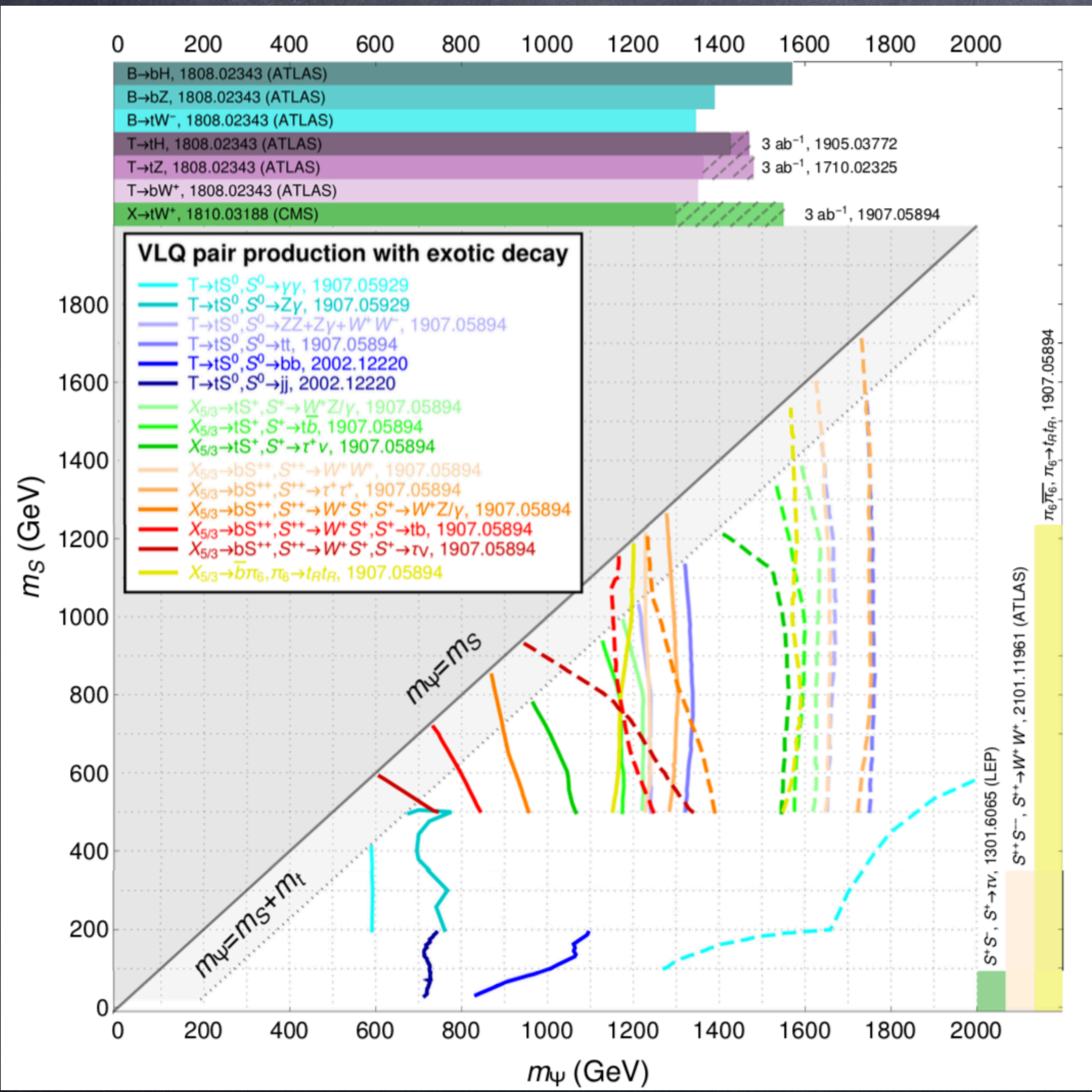
Standard Model



accessible
to colliders

The LHC legacy: top partner searches (for example)

A.Banerjee et al
2203.0727 (Snowmass LOI)

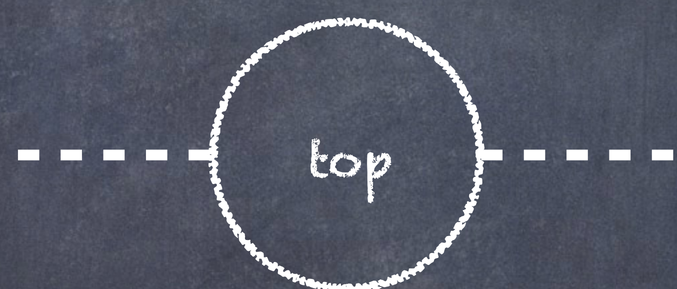


- The LHC's best target are top-partners.
- Dedicated searches useful to push up the limits, but barely touching 2 TeV!
- Projections for FCC-hh are needed...
- in combination with scalar direct production.

Low-hanging fruits: scalars!

How can light states emerge?

Top loops



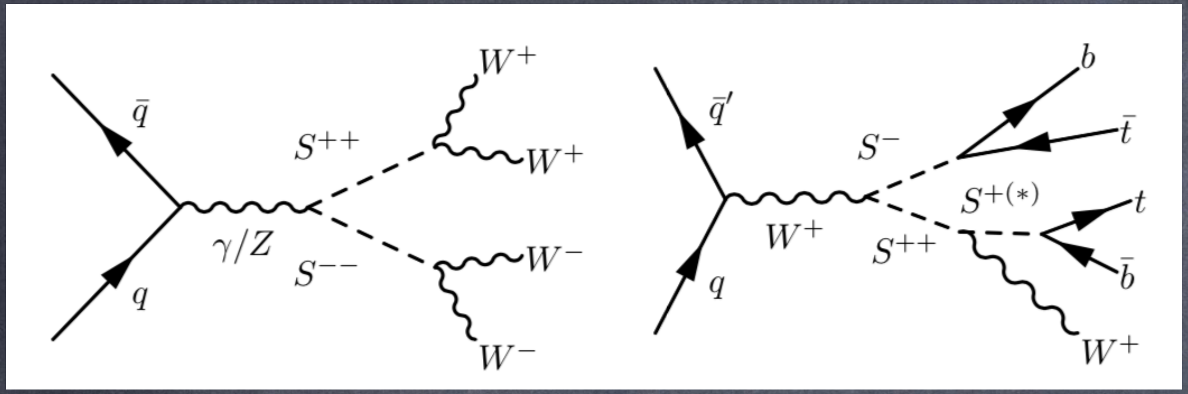
Gauge loops

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!

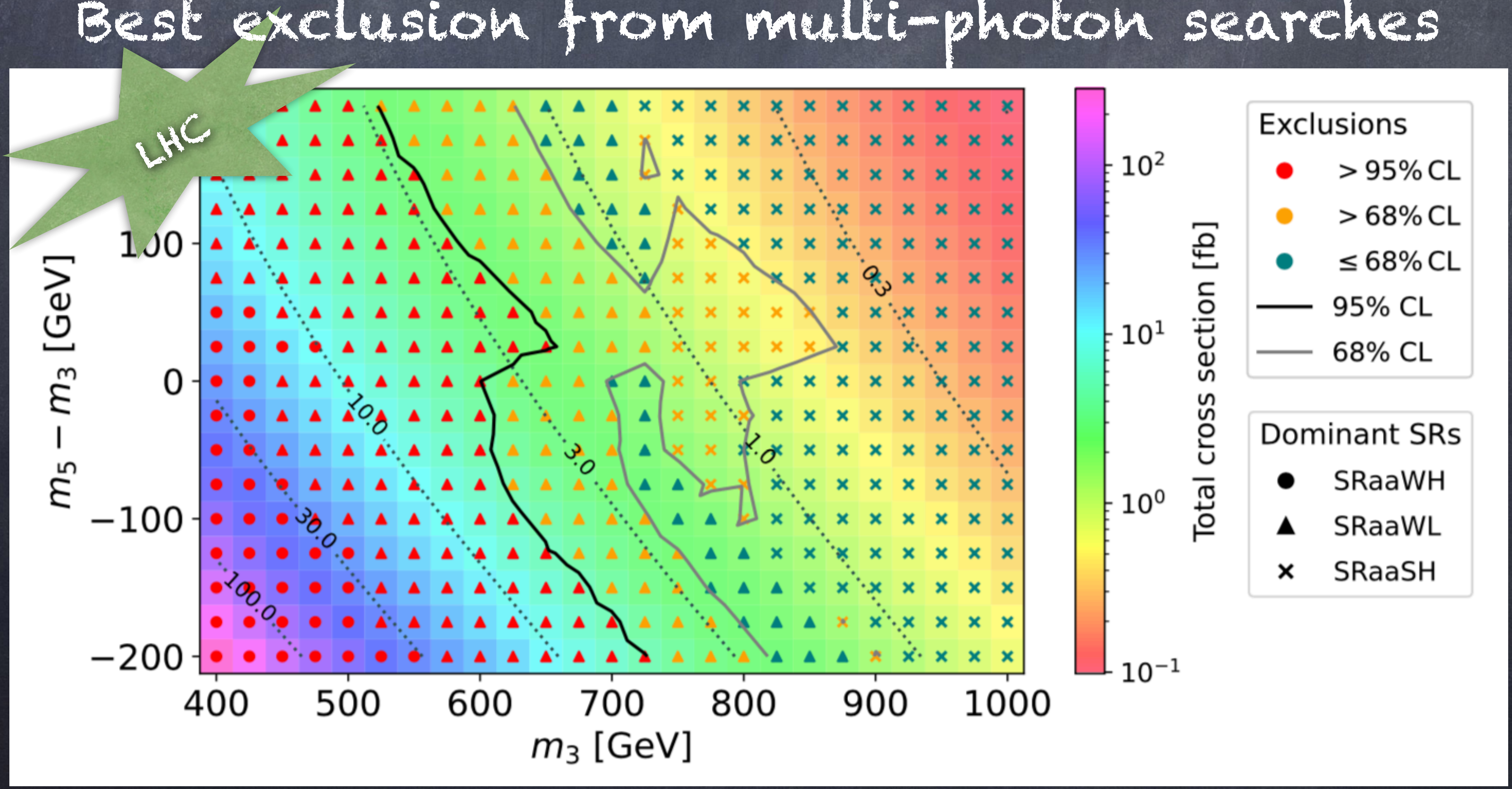
EW scalars: SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826



Dominantly EW pair-prod.
Good targets for ee colliders?

Best exclusion from multi-photon searches



Typical ALP Lagrangian:

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

Composite Higgs scenario:

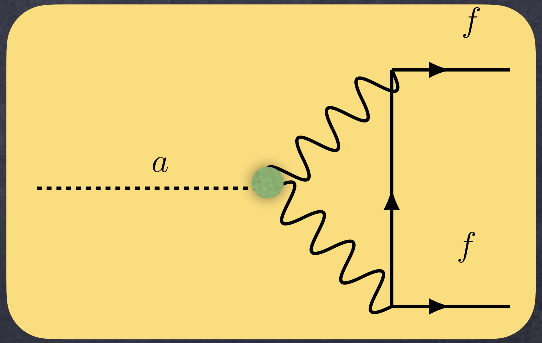
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\rm TC}}{64\sqrt{2}\,\pi^2 f}$$

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

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

(Poor bounds at the LHC)

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



M.Bauer et al, 1708.00443

Typical ALP Lagrangian:

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

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Free parameters:

$$f, m_a$$

We will consider two scenarios:

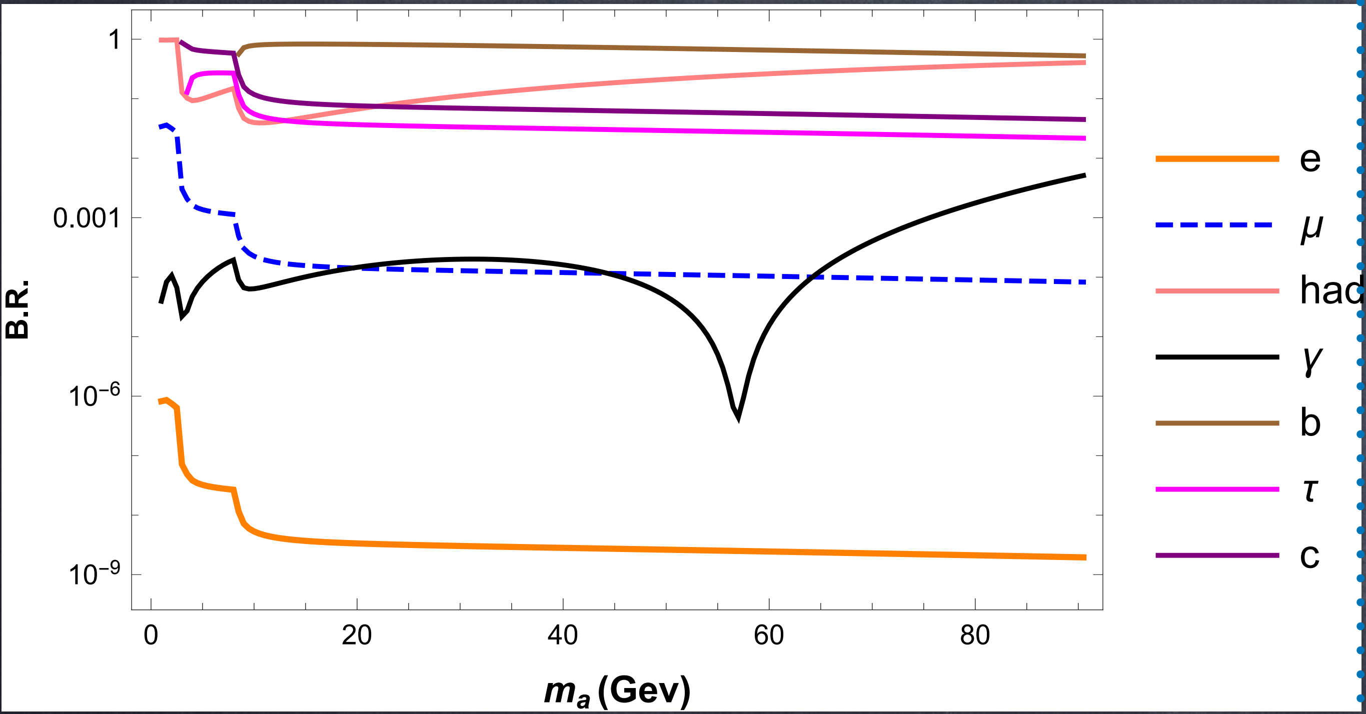
Photo-philic and

Photo-phobic

Tera-Z portal to compositeness (via ALPs)

G.Cacciapaglia et al.
2104.11064

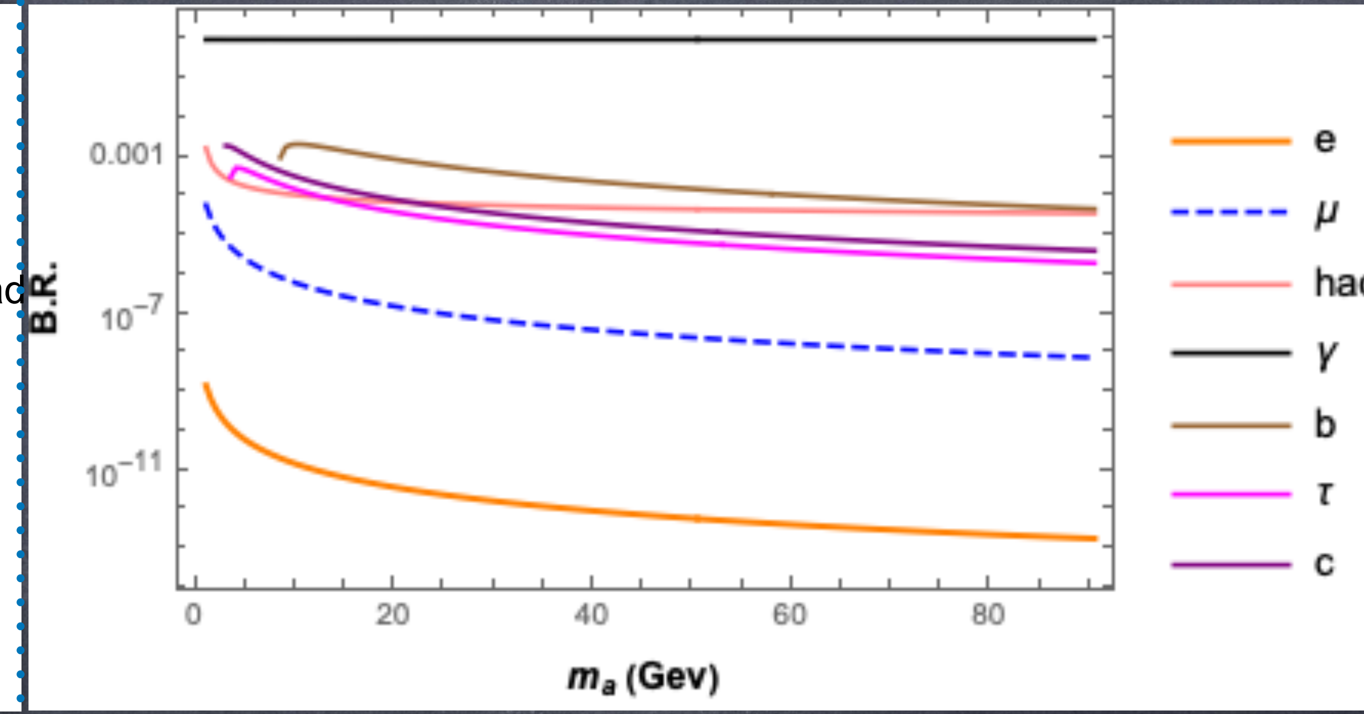
Photo-phobic



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

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

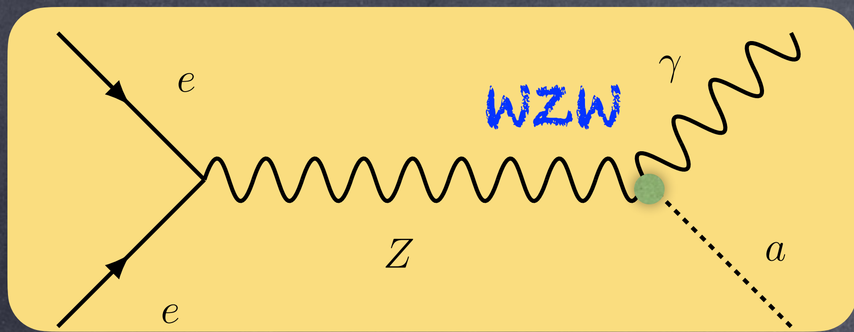
Photo-philic



WZW interaction to photons (like the pion)

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

Tera-Z portal to compositeness (via ALPs)

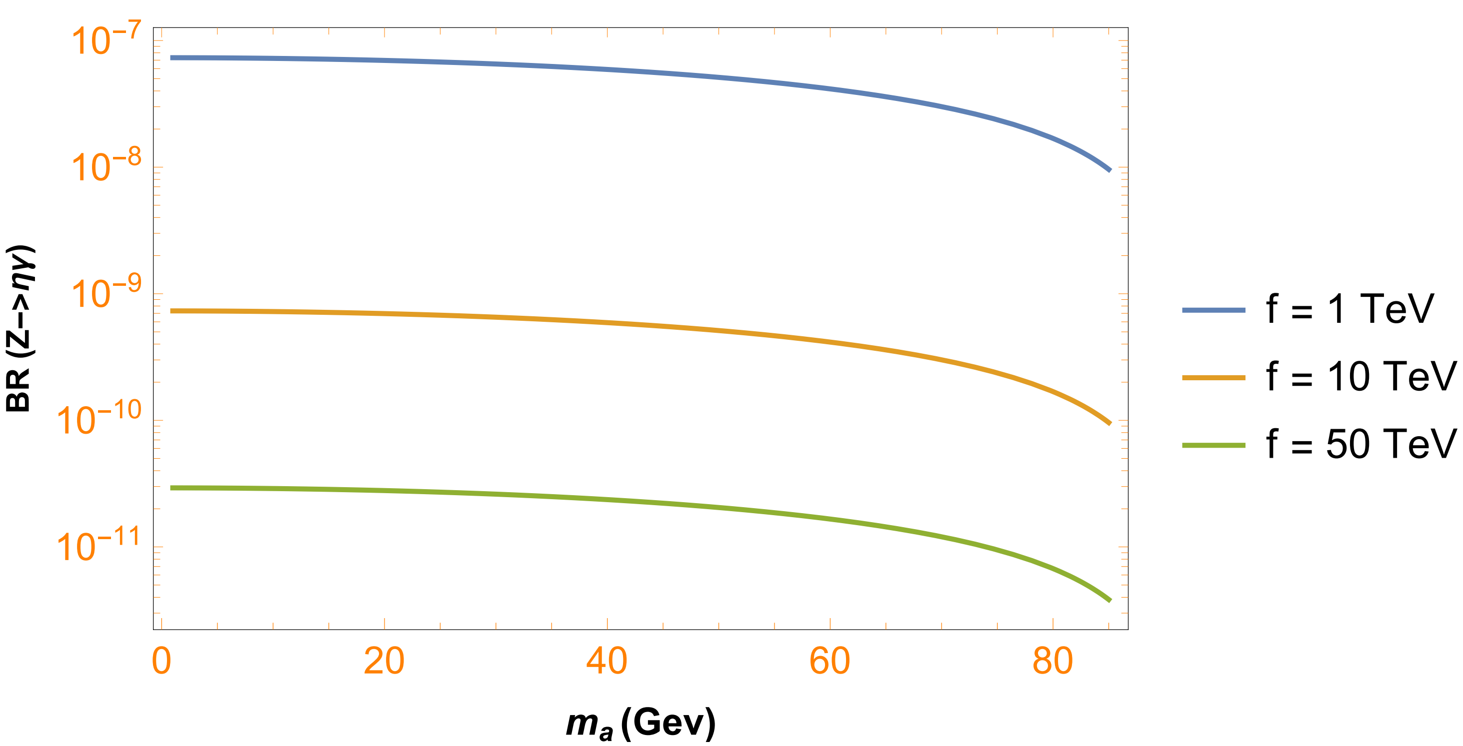


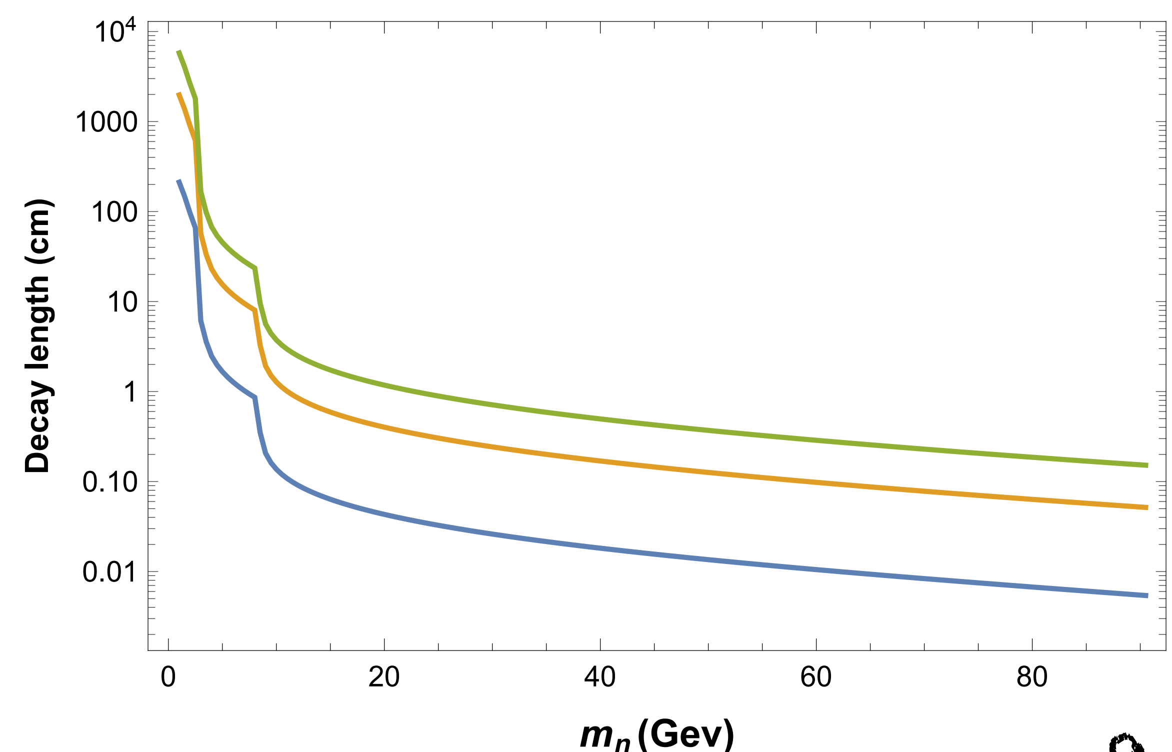
G.Cacciapaglia et al. 2104.11064

This process is always associated with a monochromatic photon.

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

Ideal test for rare Z decays!!

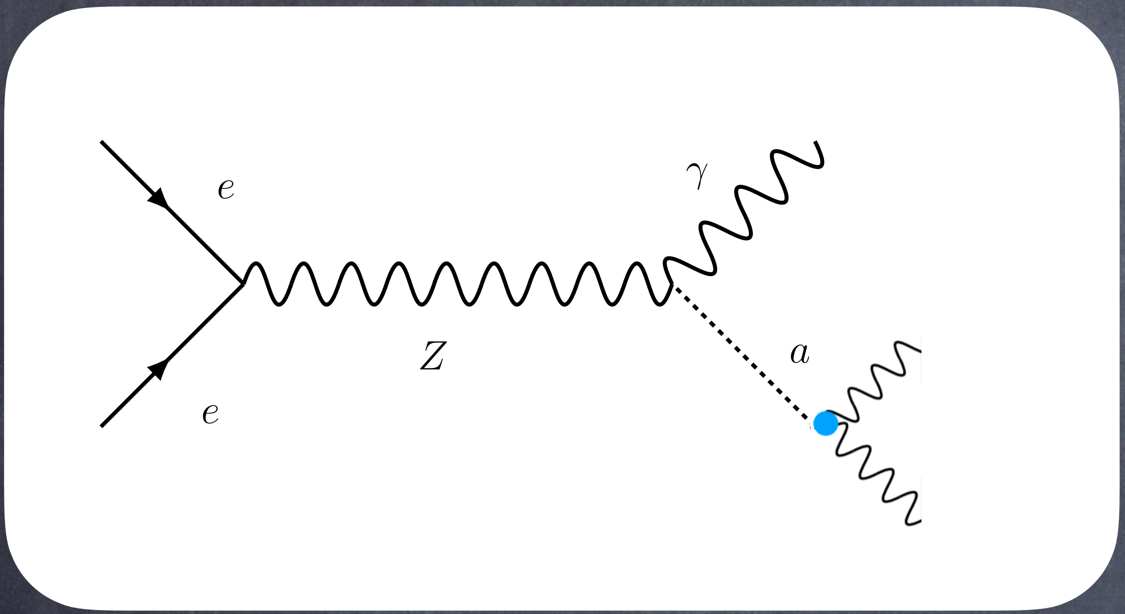




Phenomenology-Prompt Decays

Photo-philic

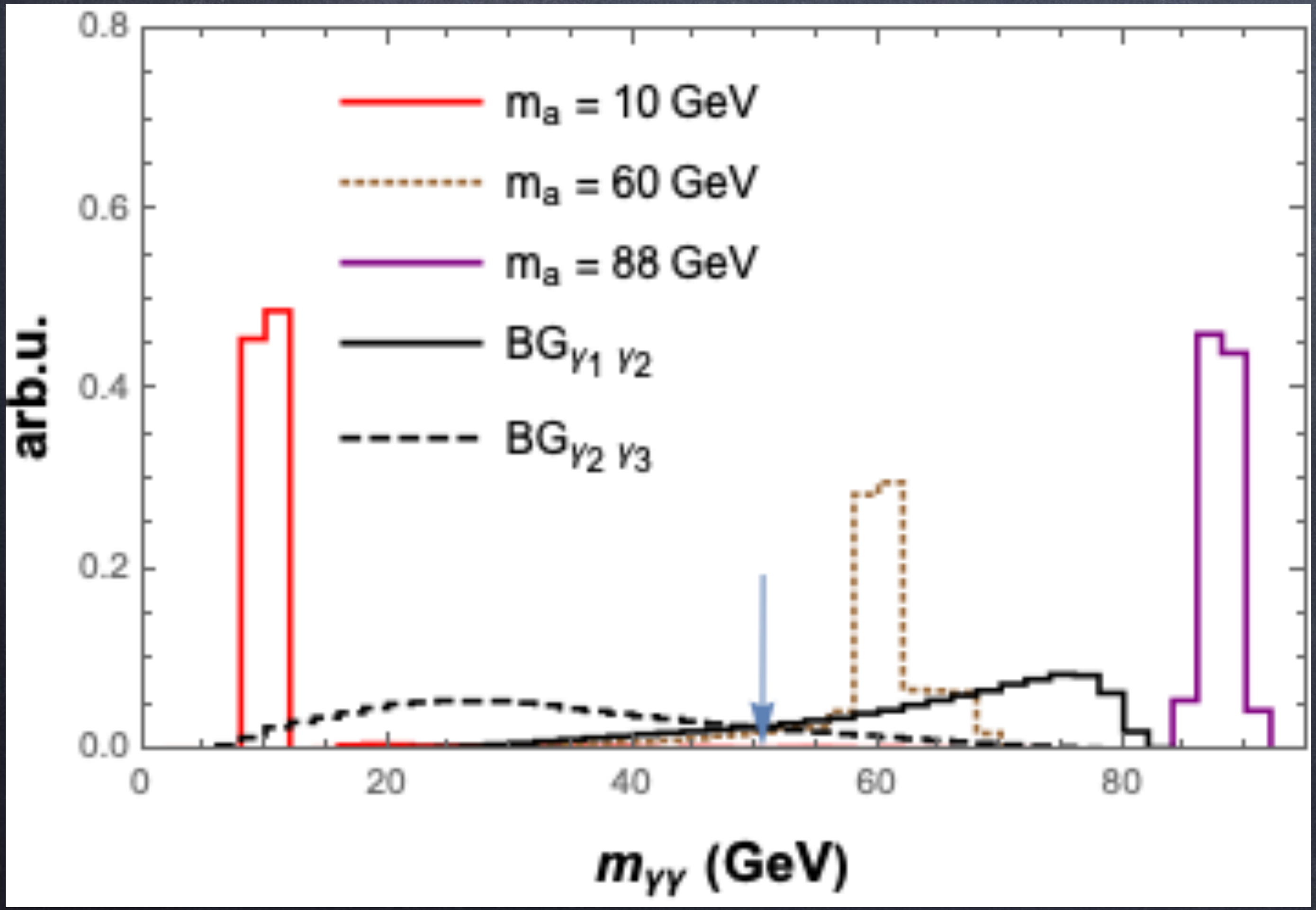
G.Cacciapaglia et al.
2104.11064



- Three isolated photons

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

Similar from ATLAS.
Reach of HL-LHC? Work in progress...



Discriminating variable: invariant mass

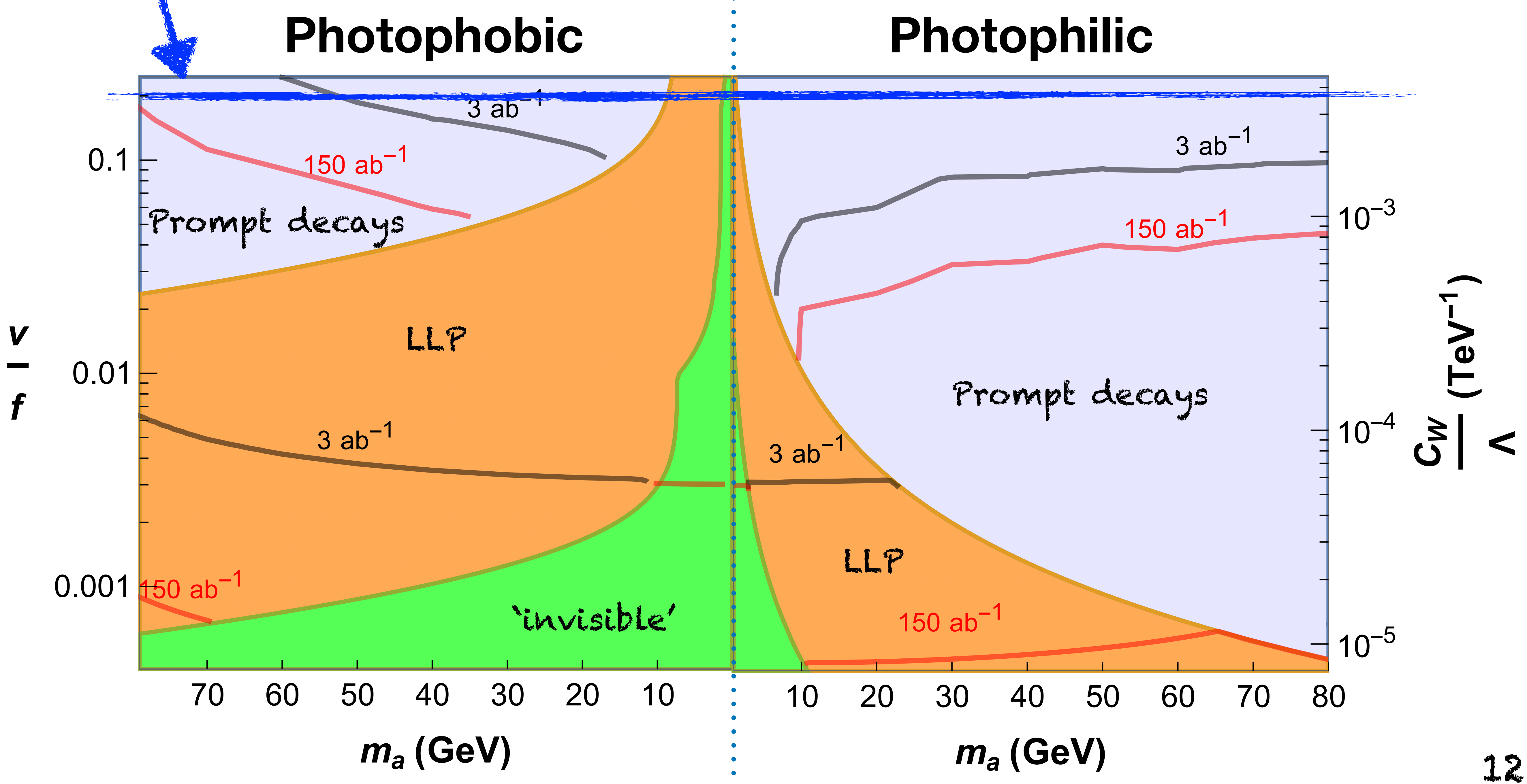
Photon ordering changes at inv. mass 50 GeV

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

Money plot

Typical EWPT bound

G.Cacciapaglia et al.
2104.11064



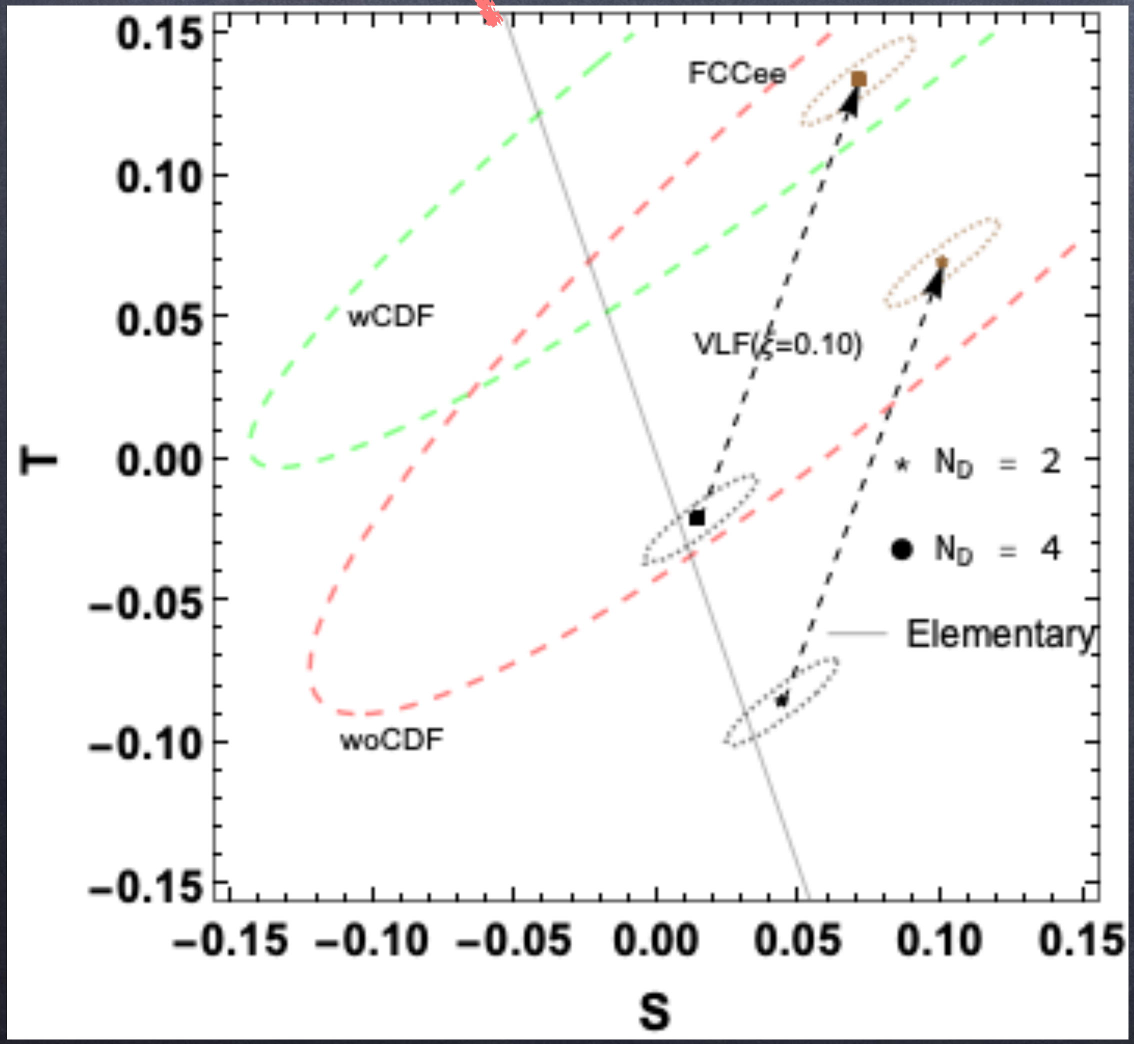
What if FCC-ee discovers $Z \to \gamma a$?

G.Cacciapaglia et al.
2211.00961

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

EWPT only depend on H loops in the elementary case

composite case: see 1502.04718



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

Arrows: "naive" contribution of top partner loops.

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

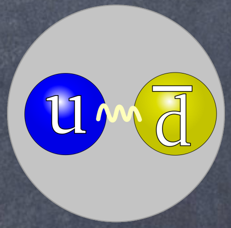
- Case 2 : non-discovery + EWPTs

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

Bonus tracks

Composite Higgs models 101

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



Scales:

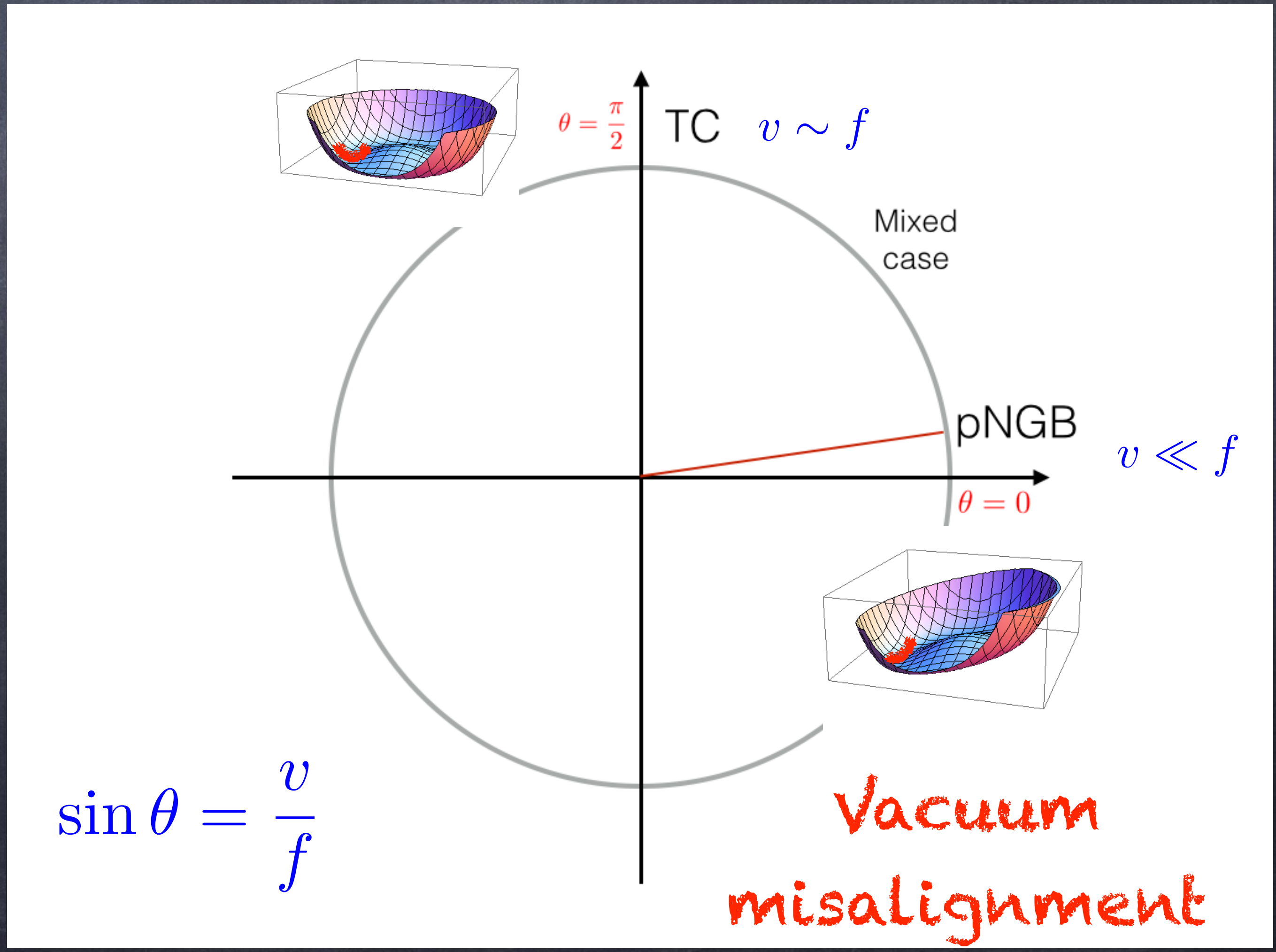
f : Higgs decay constant

v : EW scale

$m_\rho \sim 4\pi f$

EWPTs + Higgs coupl. limit:

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



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

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

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?

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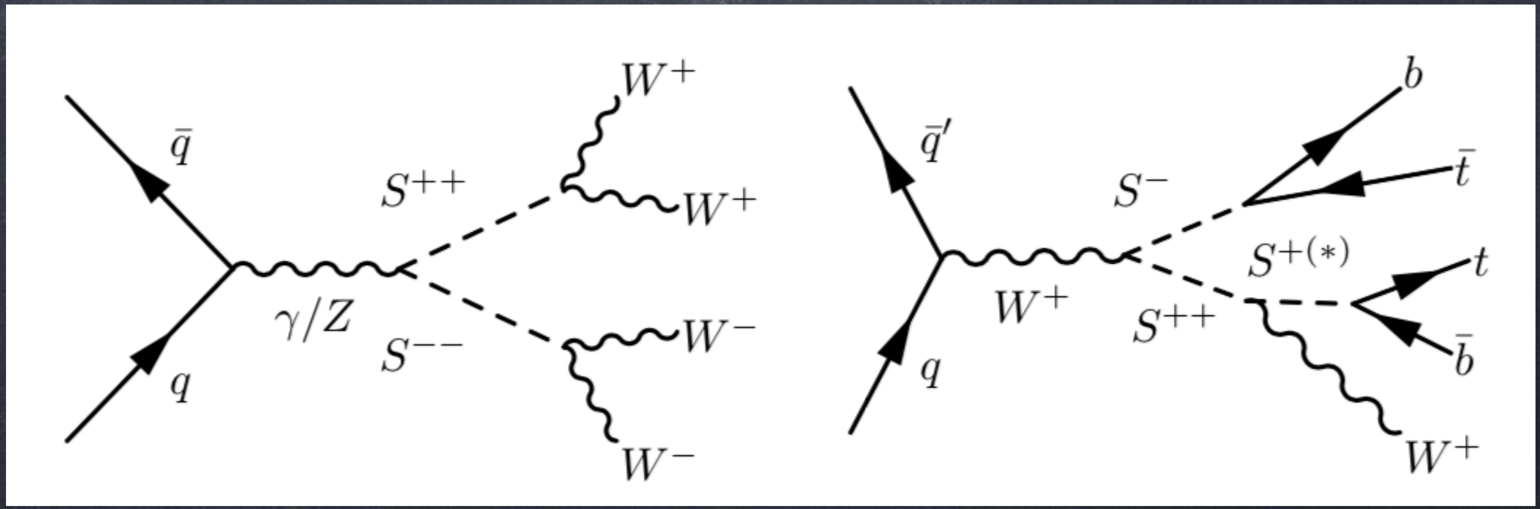
EW and Higgs precision!!!

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)



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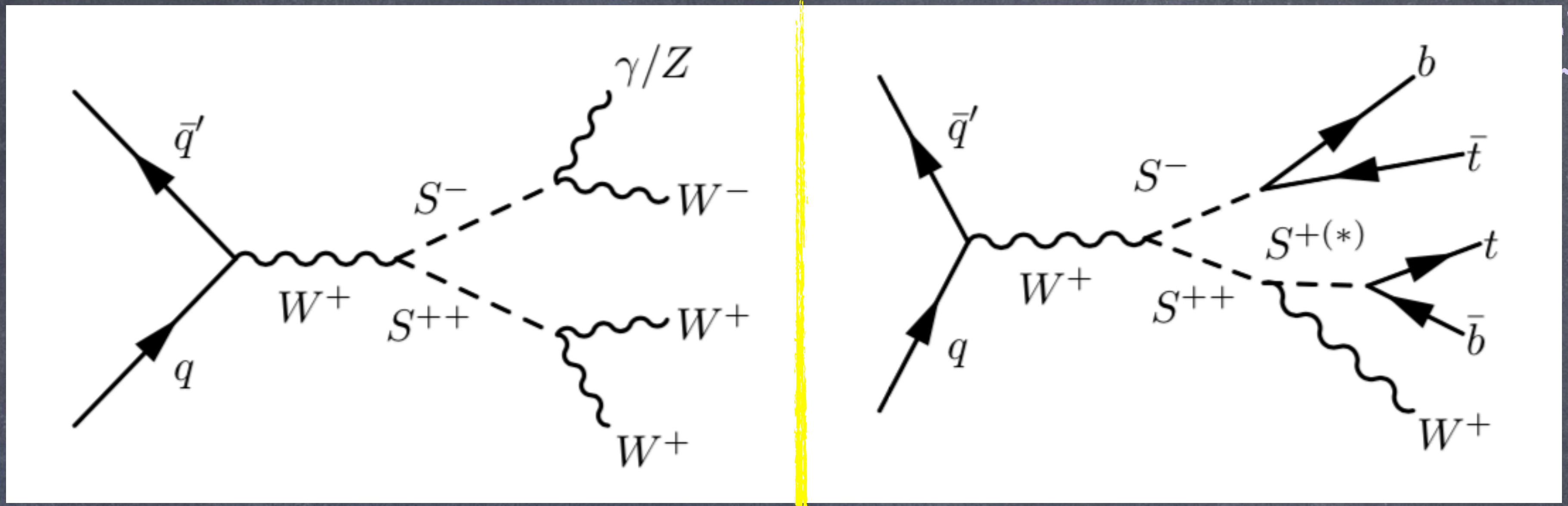
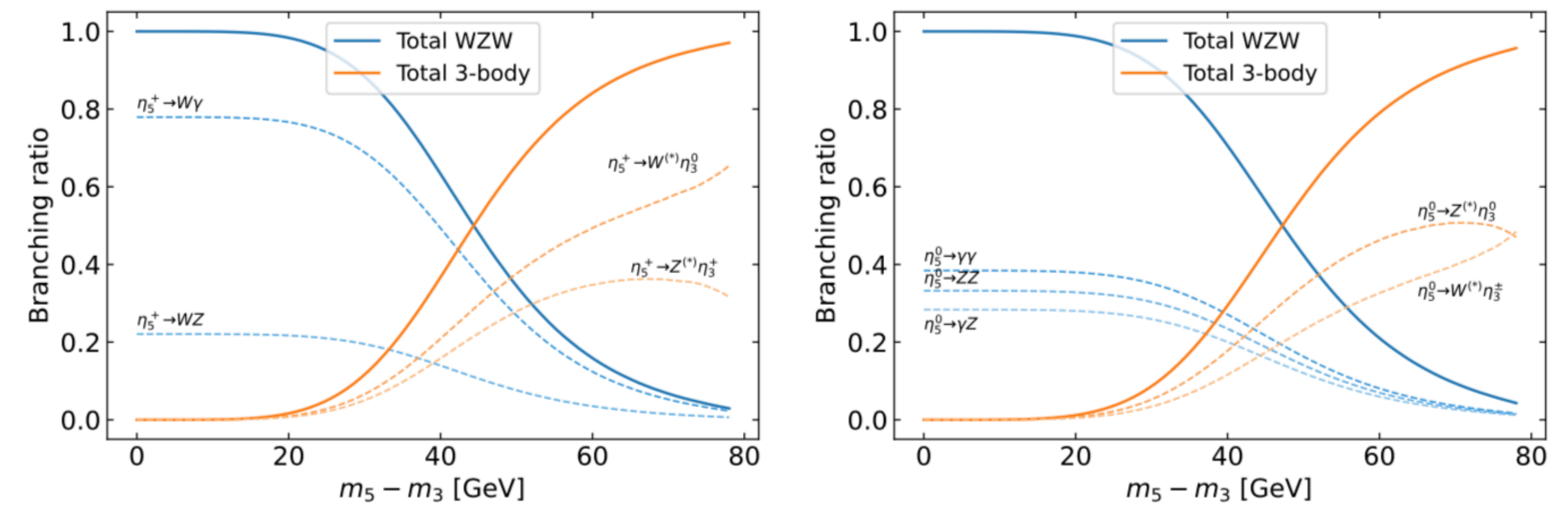


- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
- Photon-rich final states!

- 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

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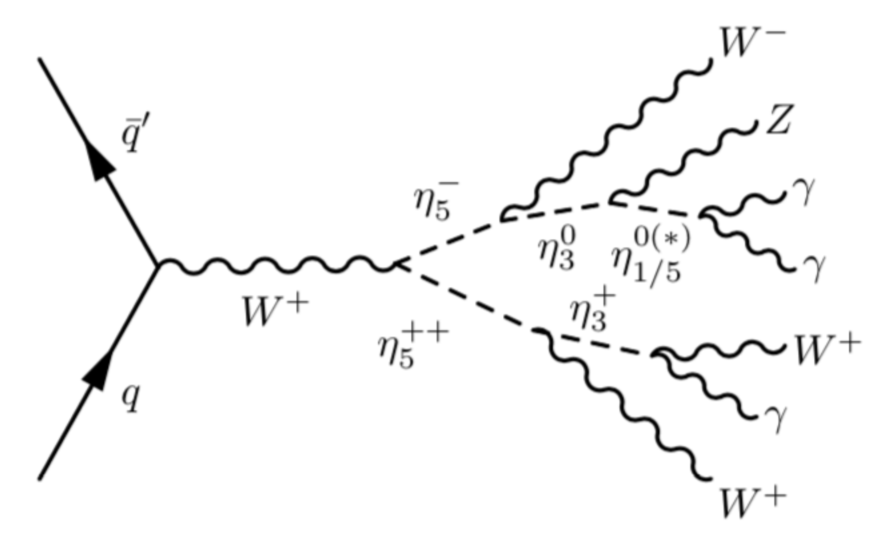
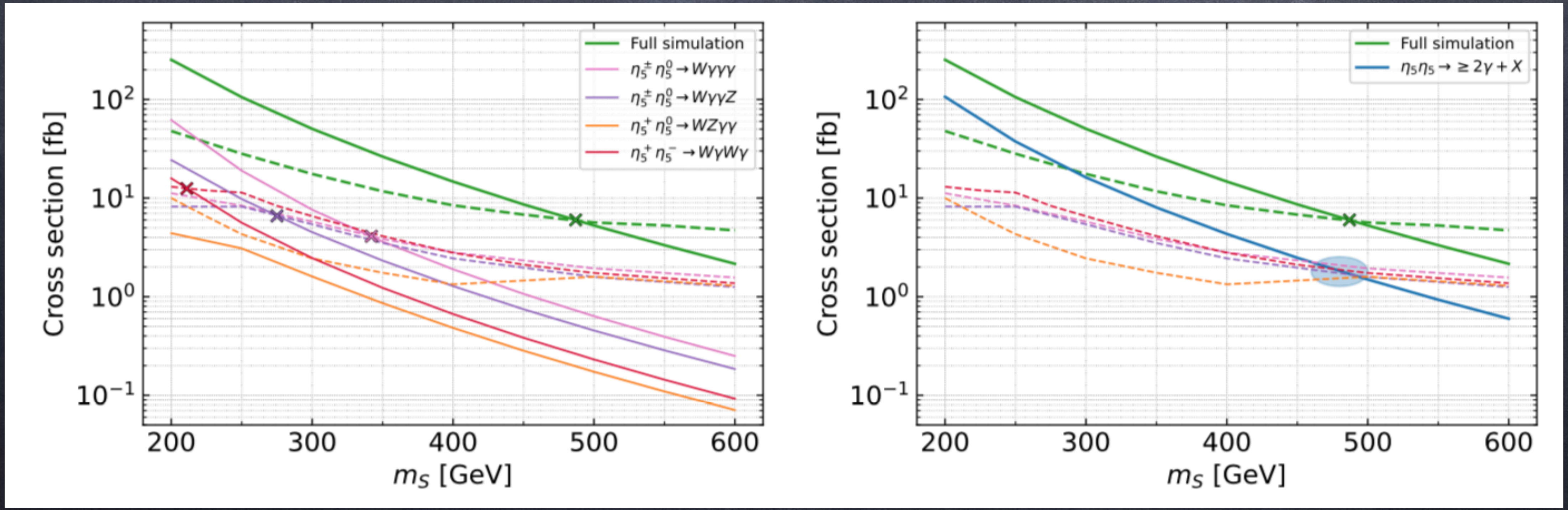
Cascade decays competitive for mass splits around 50 GeV



SU(5)/SO(5) benchmark

W.Porod et al.
work in progress

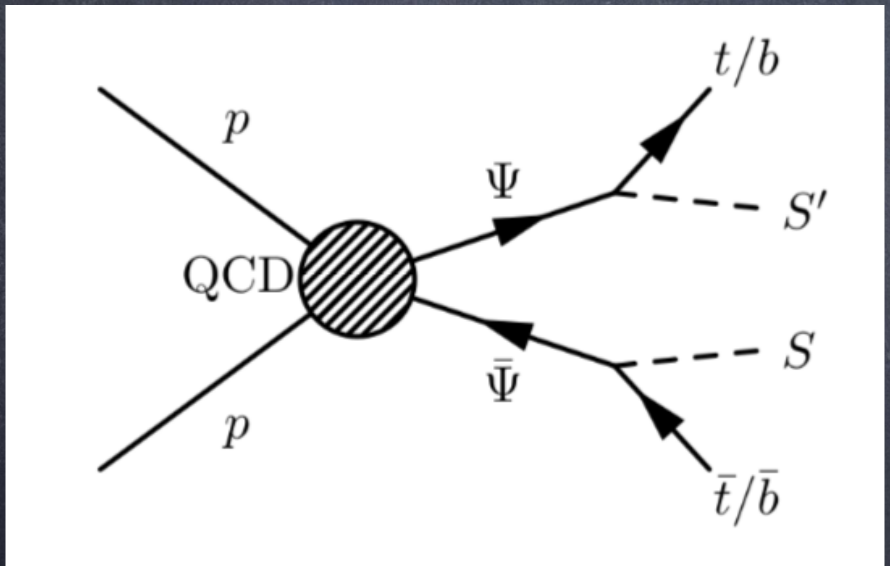
- Run all searches in MadAnalysis, Checkmate and Contur on all di-scalar pair production channels.
- Best limits from multi-photon searches (ATLAS generic analysis)
- Many channels contribute to the same signal region!



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:

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

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.