Extended Higgs Models: How to test them at FCC-ee?

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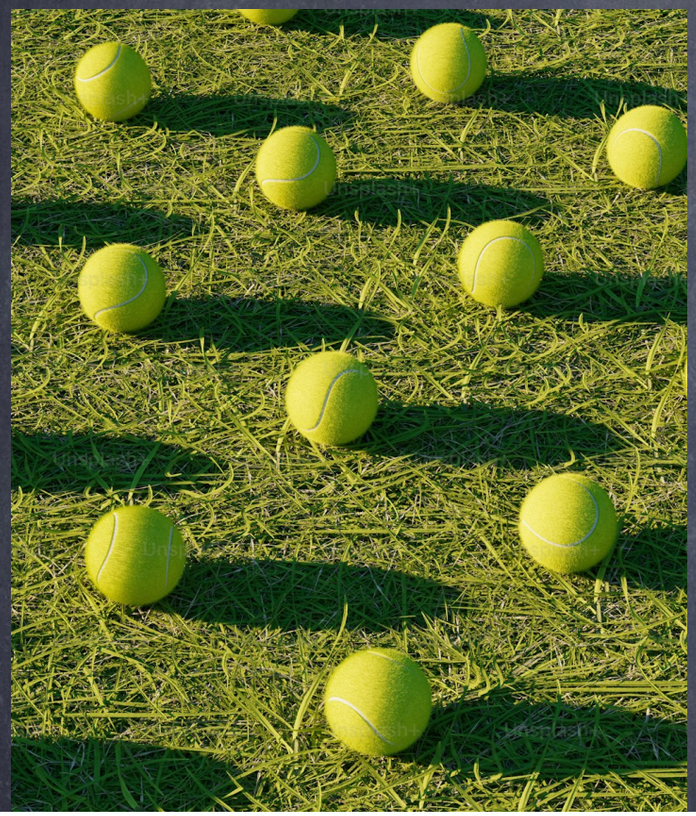
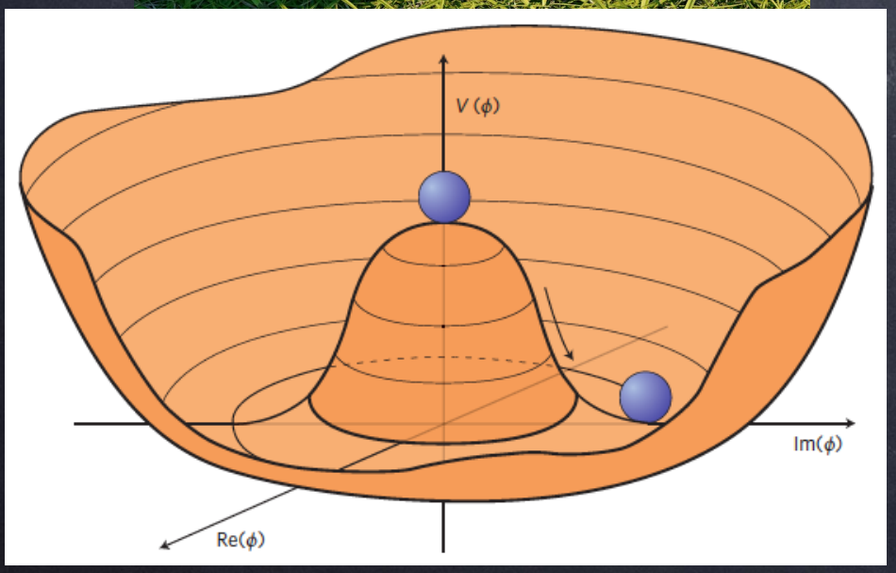
IP2I Lyon, France

7th FCC Physics Workshop
Annecy, 2024

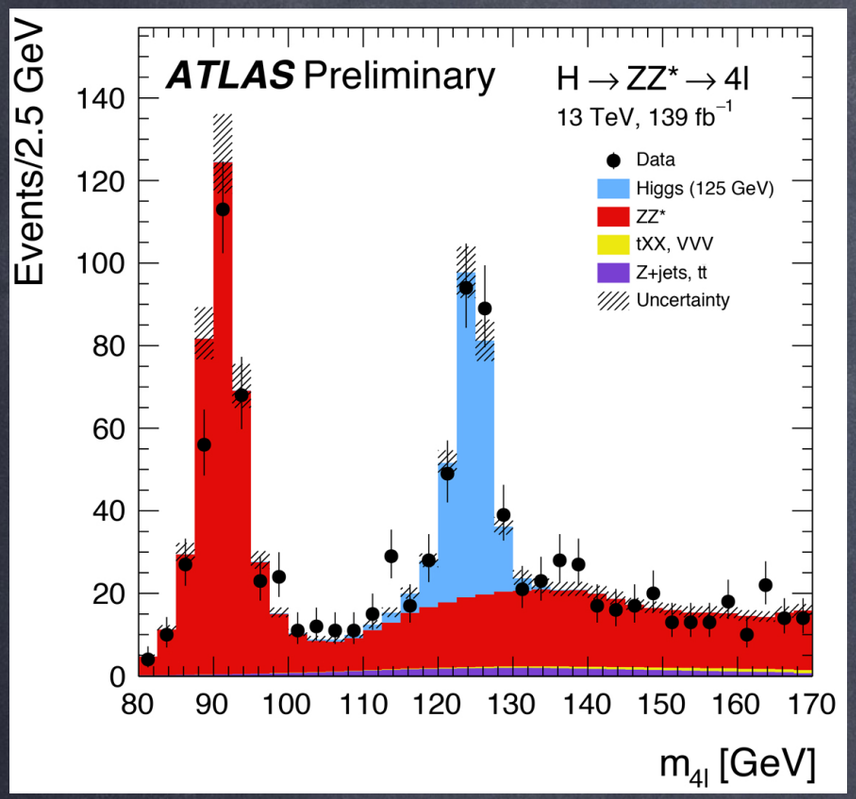
Scalar fields
and where to find them





- Scalars are the simplest spinless fields
- Used in many contexts: EFTs, inflation, symmetry breaking, ...
- Share the same quantum numbers of the vacuum
- At the origin of EWSB in the Standard Model!

Scalar fields
and where to find them



- Yet, the only 'fundamental' scalar seen is the youngest particle of the lot!
- Now, the LHC contains 'weak' hints for other scalars. What to do with them?

Scalar fields
and where to find them

- The SM is NOT minimal: 3 gauge symmetries, 3 families... why only one scalar sector?

- Extra scalars may be required by symmetries: SUSY, compositeness, ...

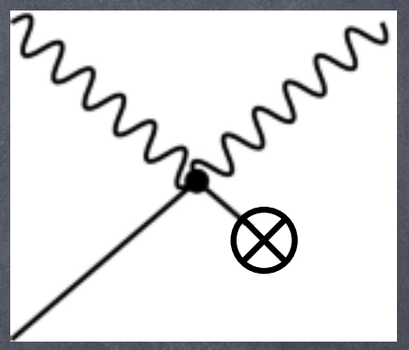
- Broadly speaking, they can be classified as:

    1. Taking part to EWSB

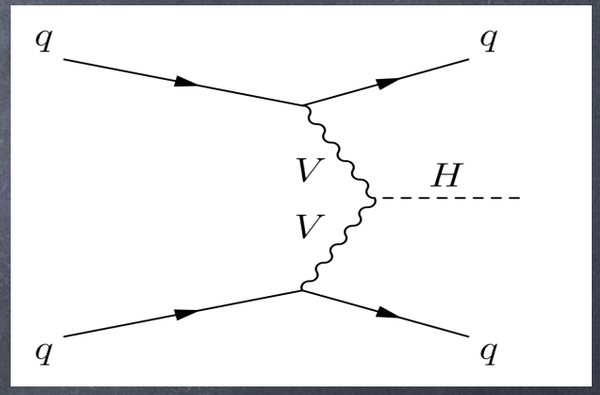
    2. or not.

EWSB partakers

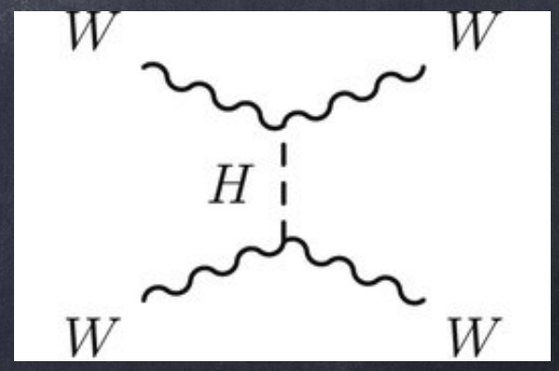
- Will have couplings to two EW gauge bosons, WW, ZZ, WZ



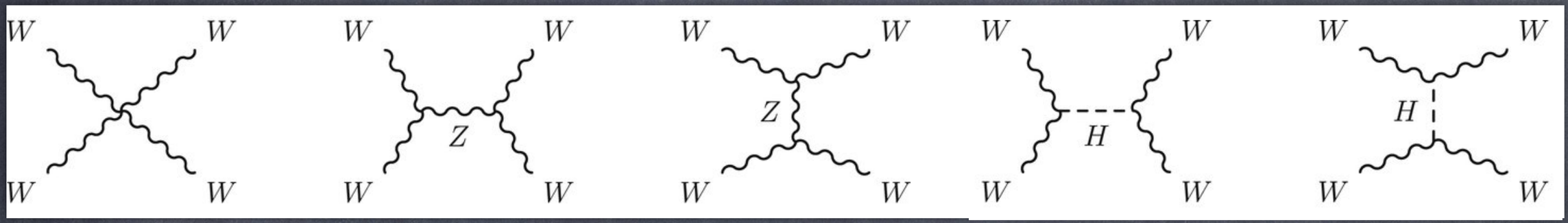
- Production via VBF @ LHC



- Contributions to VBS (Vector Boson Scattering)



Tales from the EW sum rules



Haber et al, 1991

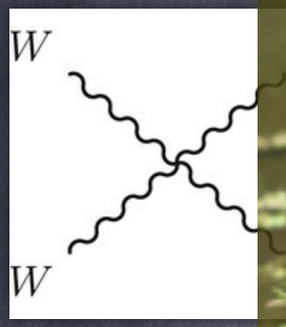
$$0 \approx g^2 m_W^2 - g_{WWh}^2 = \sum_k g_{WWH^0}^2 - \sum_l g_{WWH^{\pm\pm}}^2$$

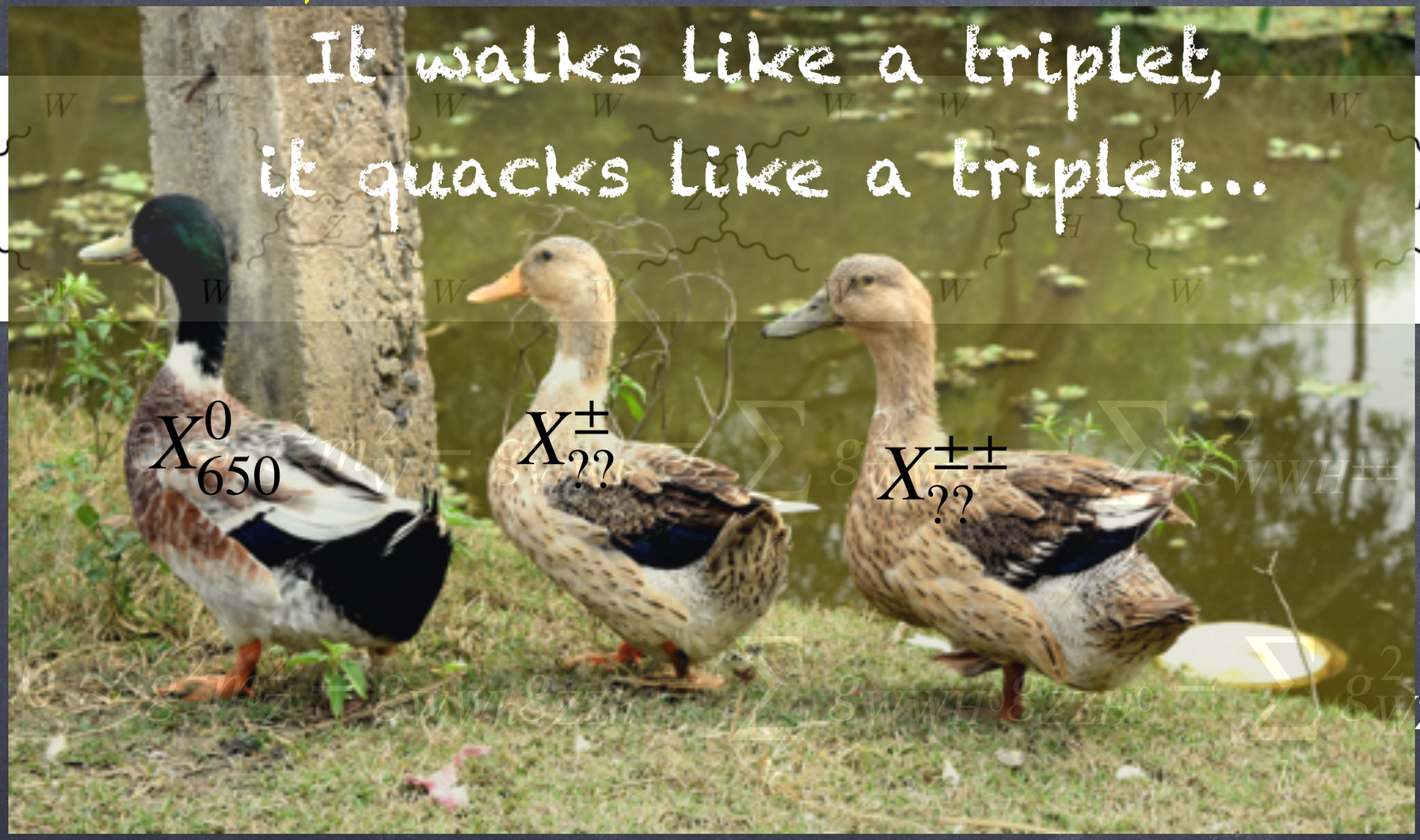
$$0 \approx g^2 m_Z^2 - g_{WWh} g_{ZZh} = \sum_k g_{WWH^0} g_{ZZH^0} - \sum_l g_{WZH^{\pm}}^2$$

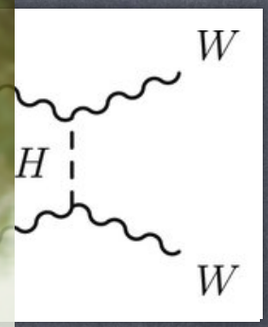
Hence, $X_{650} \to WW$ (and ZZ) requires the existence of a charged and a doubly-charged scalar (at least!)

F.Richard et al, 2308.12180, ...

Tales from the EW sum rules







$WZH^\pm$

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The painless triplets: GM

Georgi, Machacek, 1985

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

- Preserves custodial symmetry (no ρ parameter) if:

$$\langle \phi^0 \rangle = v \cos\theta_H, \;\; \langle \chi^0 \rangle = \langle \eta^0 \rangle = v \sin\theta_H$$

$$SU(2)_L \times SU(2)_R \to SU(2)_D$$

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h	$z^0, w^{\pm}$	$\eta_5^0, \eta_5^{\pm}, \eta_5^{\pm\pm}$	ϕ^0
	$\eta_3^0, \eta_3^{\pm}$		
	Isotriplets	Isoquintuplet	Isosinglet

$$SU(2)_L \times SU(2)_R \to SU(2)_D$$

The painless triplets: GM

h $\quad$ $z^0, w^\pm$ $\quad$ $\eta_5^0, \eta_5^\pm, \eta_5^{\pm\pm}$ $\quad$ ϕ^0

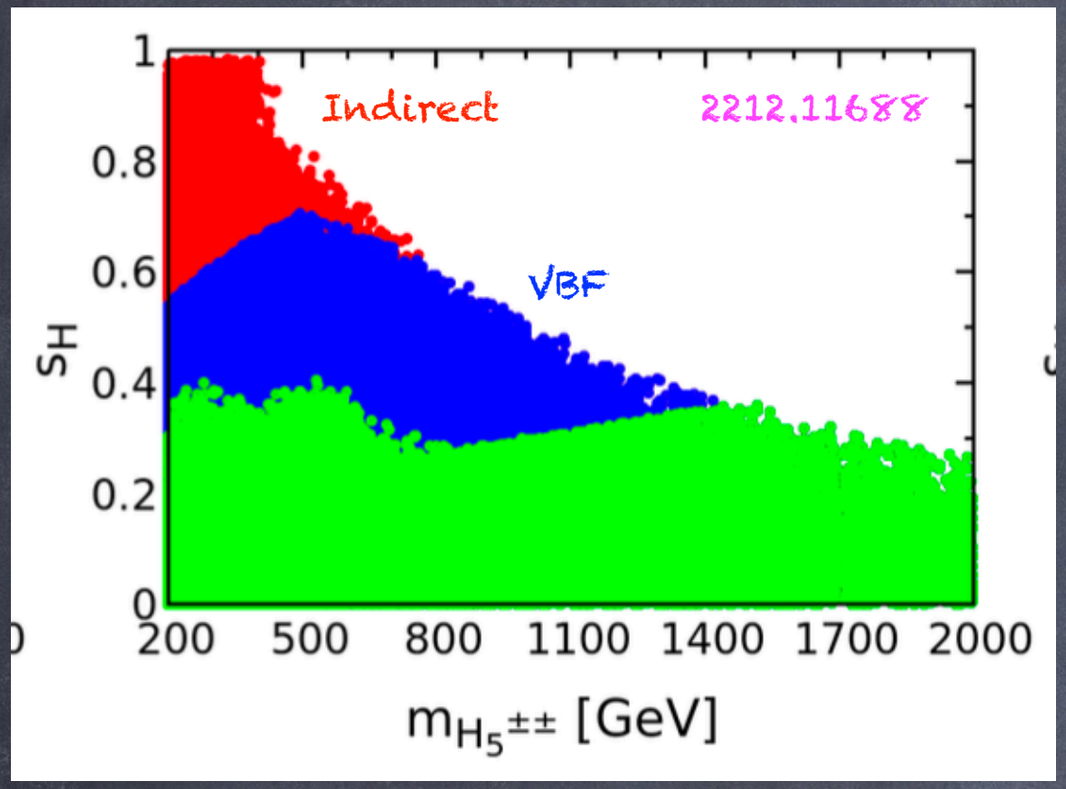
$\eta_3^0, \eta_3^\pm$ $\quad$ Isoquintuplet $\quad$ Isosinglet

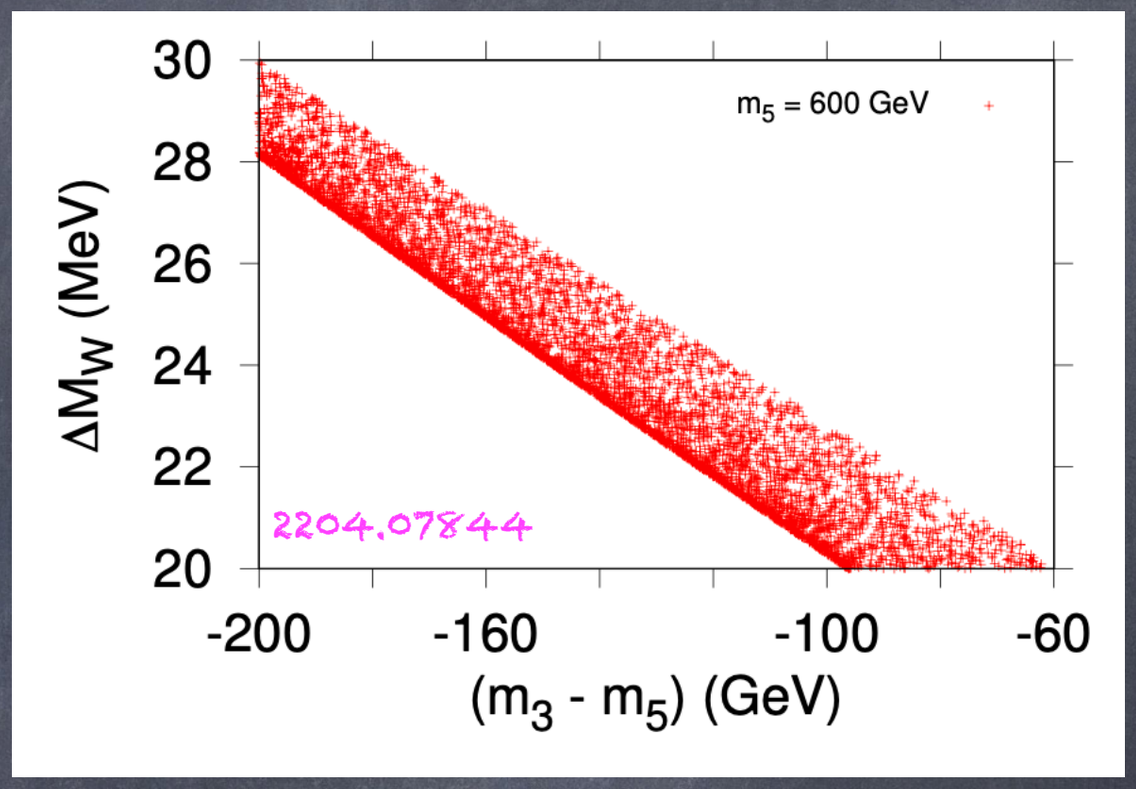
Isotriplets

- It's tempting to identify $X_{650} \equiv \eta_5^0$ (fermiophobic, hence produced only via VBF)... however it does not work!
- GM predicts $BR(ZZ) = 2 \times BR(WW)$, hence excluded by ZZ searches!
- Proposal of an extended GM with an extra doublet... under investigation.

F.Richard et al, 2308.12180, ...

The painless triplets: GM





- Wide parameter space stole open
- "Predicts" sizeable deviations in EW precision!
- However, they are model dependent!!!!

Towards a composite GM

Agugliaro et al, 1808.10175

- Naturally emerges in SU(5)/SO(5) models
- The 14 "pions" can be organised as

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}, \quad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}, \quad \pi_S$$

h

$z^0, w^{\pm}$

$\eta_3^0, \eta_3^{\pm}$

Isotriplets

$\eta_5^0, \eta_5^{\pm}, \eta_5^{\pm\pm}$

Isoquintuplet

η_1^0

η_S^0

Isosinglets

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h

$z^0, w^\pm$

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Isotriplets

$\eta_5^0, \eta_5^\pm, \eta_5^{\pm\pm}$

Isoquintuplet

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η_S^0

Isosinglets

CP-odd

"Wrong" CP parities!

Towards a composite GM

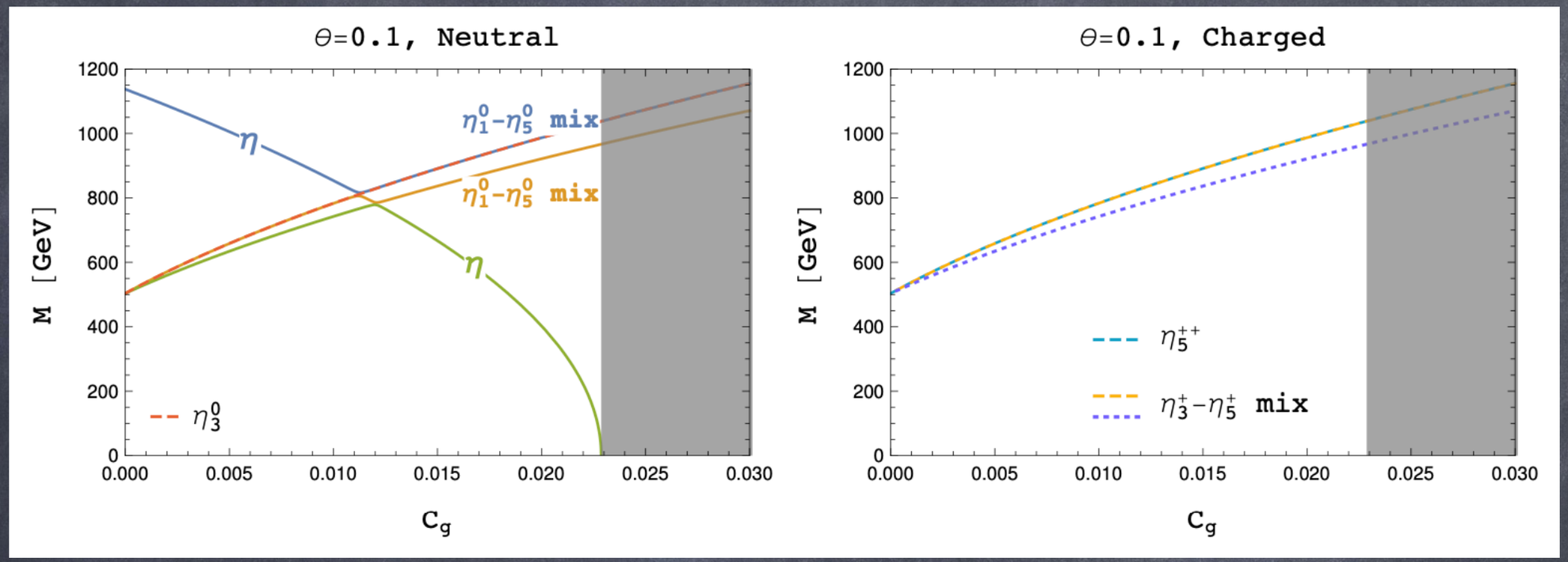
Agugliaro et al, 1808.10175

- Potential generated by top interactions (and gauge loops)
- Properties of the pions can be classified...
- ...and shown to differ from GM (i.e., fermiophilic isoquintuplets are possible)
- However, generating a custodial VEV requires CPV!!!

Work in progress...

Towards a composite GM

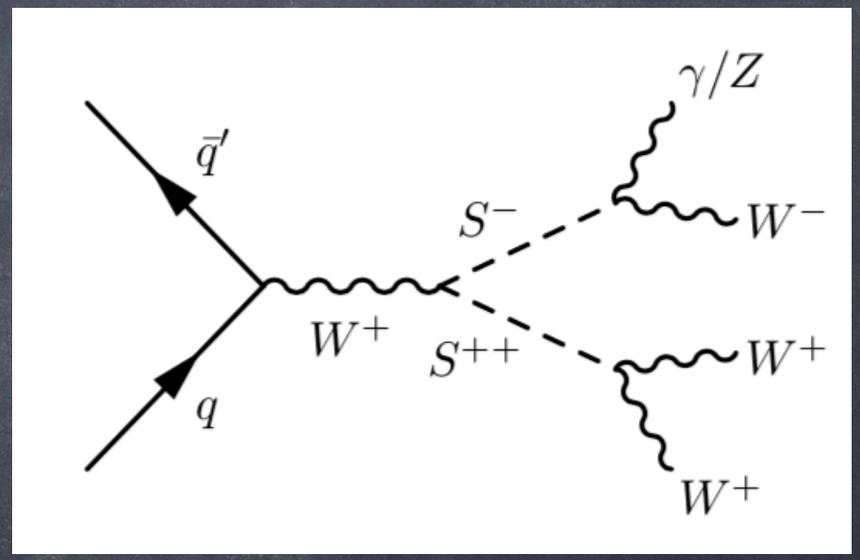
Agugliaro et al, 1808.10175



- Typical spectrum implies light singlet!
- Predicts deviations in the Higgs couplings and EWPOs : however, not directly related to scalars!
- FCC-ee precision in Higgs and EW couplings will allow to pin down the specific model (together with LHC discoveries).

Non-EWSB partakers

- Couplings to two gauge bosons generated by fermion loops, $WW, ZZ, WZ, W\gamma, Z\gamma, \gamma\gamma, gg$



- Mainly pair-produced via DY @ LHC
- ...or ggF for singlets!

- Couplings involve equally massless and massive GBs!!!

Non-EWSB partakers

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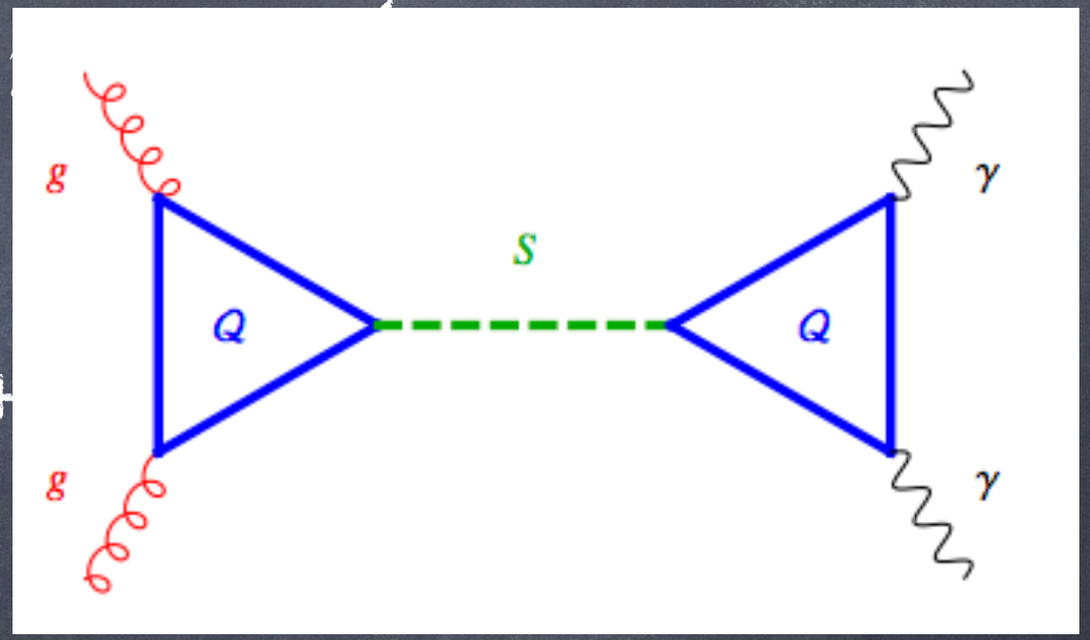


- Mainly pair-produced via DY @ LH
- ...or ggF for singlets!

Ideal candidate for X_{95}!!

- Couplings involve equally massless and massive GBs!!!

Phenomenology-Prompt Decays

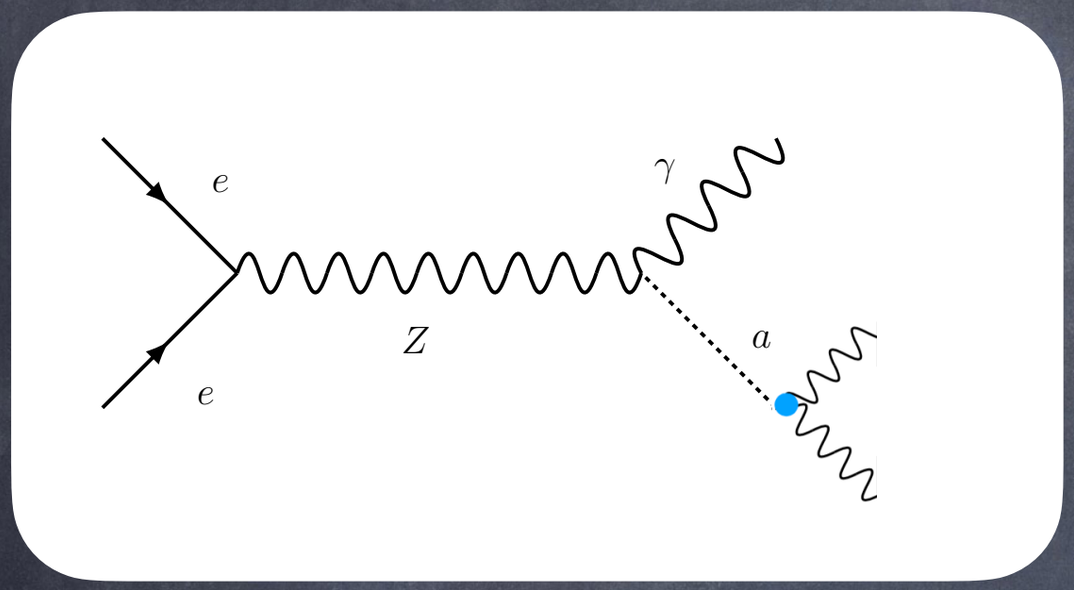


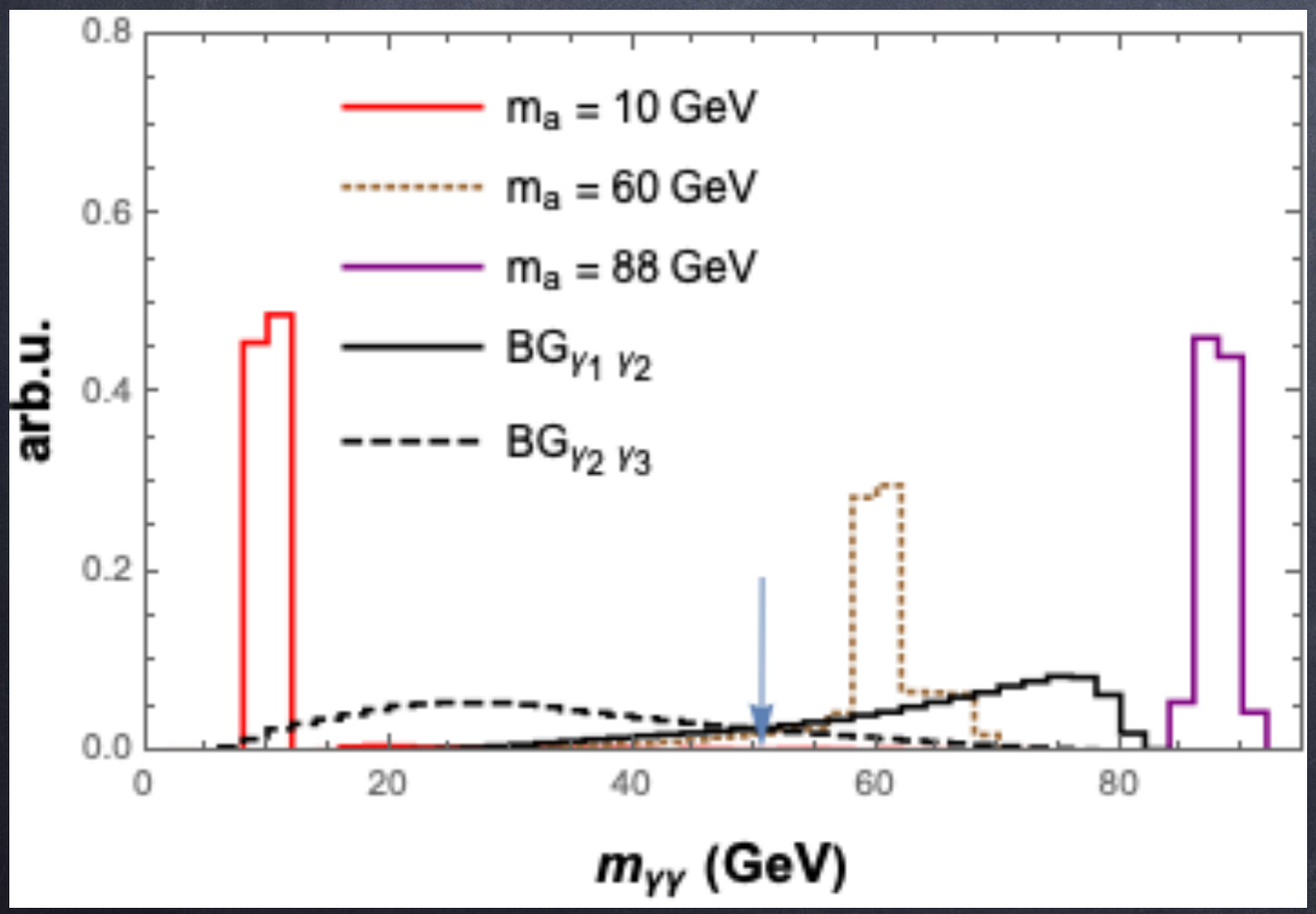
Photo-philic

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

Ongoing Les Houches project
with S.Gascon et al.

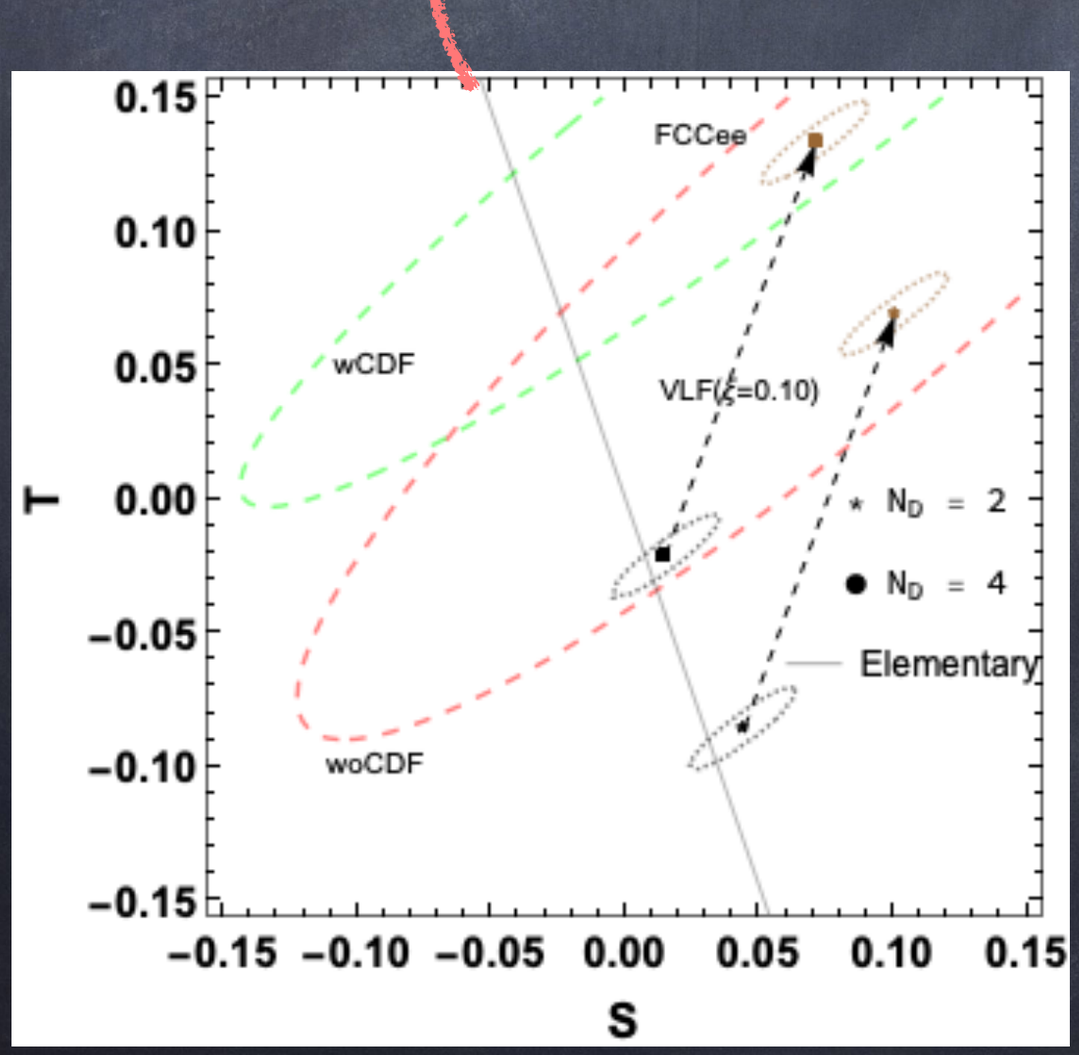
What if FCC-ee discovers Z > γa?

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.

Outlook

- No model-independent predictions for FCC-ee from LHC scalars...
- FCC-ee can disentangle models via precision Higgs and EW studies!
- Direct access to light singlets (see also Juliette's talk)
- En passant: let's not forget scalar pair production searches at the LHC!!!

May the FCC be with you (us)

Let's find a cool name, FCC is in the present!

BONUS

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!