Composite Higgs with partial compositeness in the top sector

LoI for Snowmass 2021 EF08 - BSM: Model specific explorations

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A general picture

All models of composite Higgs predict **new scalars** in the form of pNGBs
(with the notable exception of the MCHM)

In models of partial compositeness, **new vector-like fermions** are also predicted

$$\frac{\lambda_R}{\Lambda^{d_{\mathcal{B}}-5/2}}\mathcal{O}_{\mathcal{B}} t_R \dashrightarrow y_L f\, \bar{T}_L\, t_R \quad \text{with} \quad \mathcal{O}_{\mathcal{B}} = \psi\psi\psi, d_{\mathcal{B}} = 9/2$$

pNGBS

Neutral: light but with weak couplings
Electrically charged: heavier, possibly $\mathcal{O}$(1 TeV)
Coloured: even heavier, above $\mathcal{O}$(1 TeV)

Fermions

Vector-like quarks
Vector-like leptons

Both expected to be $\mathcal{O}$(TeV)

Some of these objects can function as DM candidates in some models

A large spectrum of **potential signatures** at the LHC and future colliders
from the production, decay and interactions of these objects.

How can we constrain these models at the LHC or FCCs?
Which parameters can we use for high-level plots?

pNGBs in composite models

Underlying gauge theories with two fermionic representations:

· ψ, carrying EW

· χ, carrying QCD and hypercharge

Condensates:

· pNGBs as $\langle\psi\psi\rangle$ and $\langle\chi\chi\rangle$

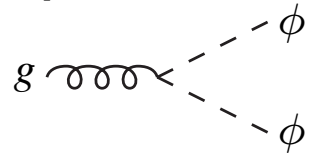
· T as $\langle\psi\psi\chi\rangle$ or $\langle\psi\chi\chi\rangle$

pNGBS

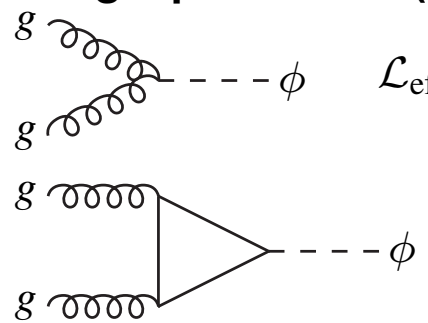
Model	EW coset					QCD coset					a	η'
	$\mathbf{2}_{\pm1/2}$	$\mathbf{3}_0$	$\mathbf{3}_{\pm1}$	$\mathbf{1}_0$	$\mathbf{1}_{\pm1}$	$\mathbf{8}_0$	$\bar{\mathbf{3}}_{2/3}$	$\bar{\mathbf{3}}_{4/3}$	$\mathbf{6}_{2/3}$	$\mathbf{6}_{4/3}$		
M1	1	1	1	1	-	1	-	-	1	-	1	1
M2	1	1	1	1	-	1	-	-	1	-	1	1
M3	1	1	1	1	-	1	-	-	-	1	1	1
M4	1	1	1	1	-	1	-	-	-	1	1	1
M5	1	1	1	1	-	1	1	-	-	-	1	1
M6	1	1	1	1	-	1	-	-	-	-	1	1
M7	1	1	1	1	-	1	-	-	-	-	1	1
M8	1	-	-	1	-	1	-	-	-	1	1	1
M9	1	-	-	1	-	1	-	-	-	1	1	1
M10	2	1	-	2	1	1	-	-	-	1	1	1
M11	2	1	-	2	1	1	-	-	-	1	1	1
M12	2	1	-	2	1	1	-	-	-	-	1	1

1902.06890

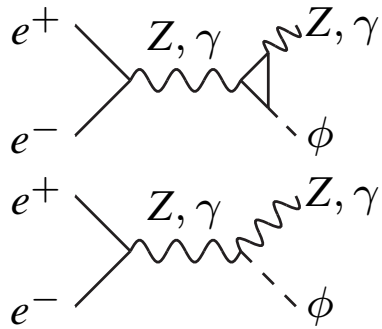
QCD pair production (LHC, FCC-hh)



Single production (LHC, FCC-hh, FCC-ee)



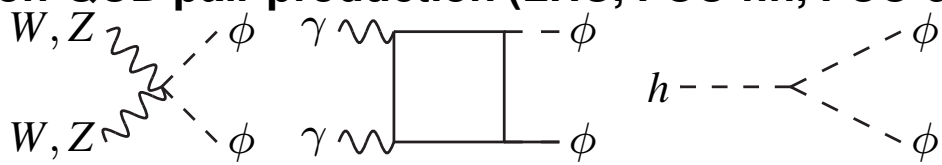
$$\mathcal{L}_{\text{eff}} \supset \frac{\phi}{16\pi^2 f_\phi} g_s^2 K_{gg}^{\phi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$



$$\mathcal{L}_{\text{eff}} \supset \sum_{\text{f}} \frac{iC_f m_f}{f_\phi} \phi \bar{f} \gamma^5 f$$

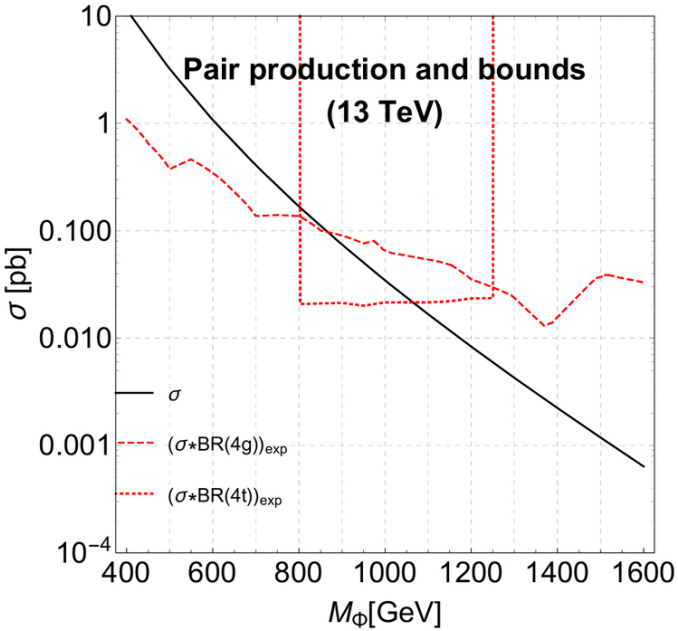
$$\mathcal{L}_{\text{eff}} \supset \frac{\phi}{16\pi^2 f_\phi} \frac{e^2}{c_W^2 s_W^2} K_{ZZ}^{\phi} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Non-QCD pair production (LHC, FCC-hh, FCC-ee)

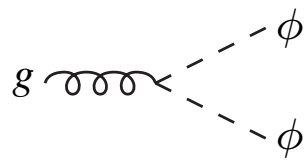


QCD pair production

$SU(3)_c$ triplets, octects, sextets



2002.01474
Bounds on the octet
Reinterpretation of di-jet-pair
and 4 top searches

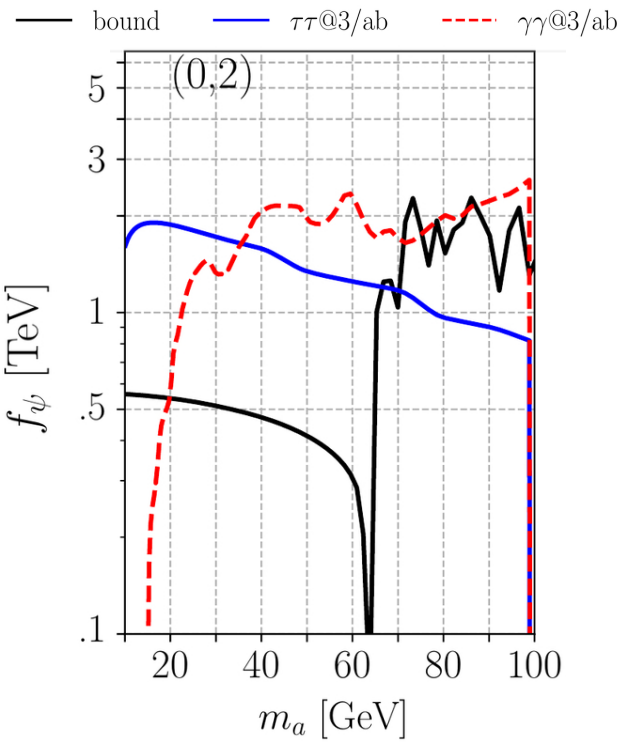


Production only depends on the mass,
and if the pNGBs are not broad,
the BRs can be factorised

$$\sigma_{QCD}(m_\phi) \times BR \times BR$$

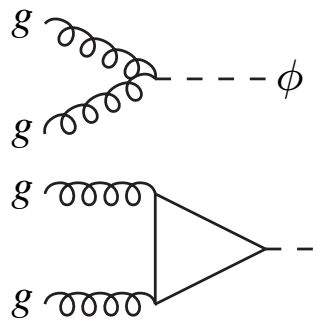
Bounds in the $\{m_\phi, \sigma \times BR \times BR\}$ plane for each decay channel

Single production



1902.06890

Bounds on the lightest $U(1)$ singlet
Reinterpretation of multiple searches for a specific benchmark



$$\mathcal{L}_{\text{eff}} \supset \frac{\phi}{16\pi^2 f_\phi} g_s^2 K_{gg}^{\phi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\mathcal{L}_{\text{eff}} \supset \sum_{\text{f}} \frac{i C_f m_f}{f_\phi} \phi \bar{f} \gamma^5 f$$

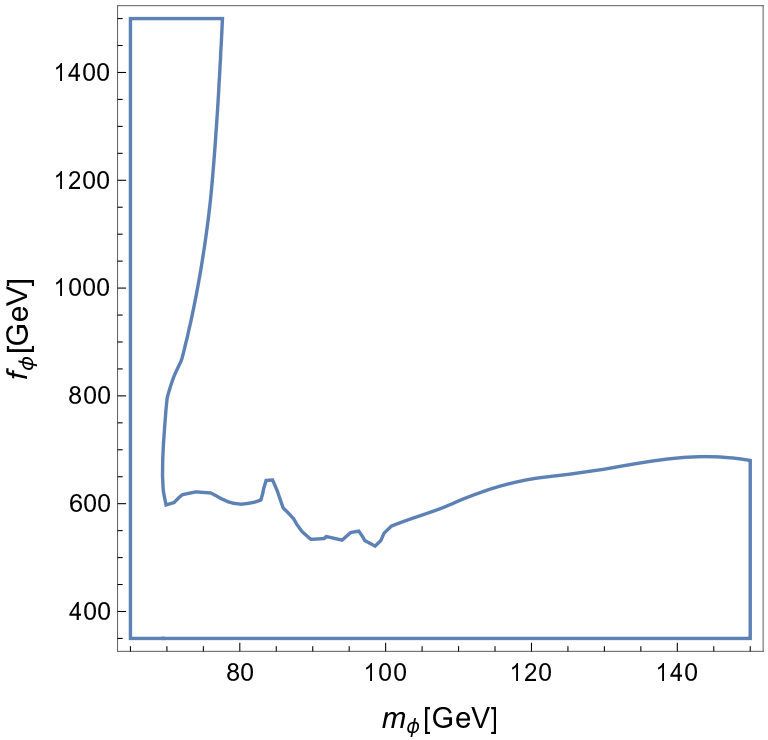
For each model the couplings K^ϕ and C_f are function of the decay constant f_ϕ (some assumptions apply) and of the quantum numbers of the underlying dynamics

The cross-section is function of m_ϕ and f_ϕ

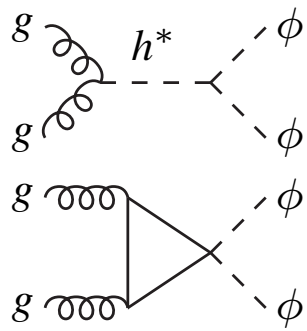
$$\sigma = F(m_\phi, f_\phi)$$

Bounds in the $\{m_\phi, f_\phi\}$ plane for each decay channel and for benchmark choices of K^ϕ and C_f

Non-QCD pair production



From 2005.13578 with inverted y-axis Projection for HL-LHC based on a dedicated analysis for a pNGB of the EW coset



$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{2}\sqrt{1-\frac{v^2}{f_\phi^2}}\,\frac{m_h^2}{v}\,h\phi^2$$

$$\mathcal{L}_{\text{eff}} \supset \frac{m_t}{2f_\phi^2}\,\phi^2\bar{t}t$$

The production cross-section is again a function of m_ϕ and f_ϕ

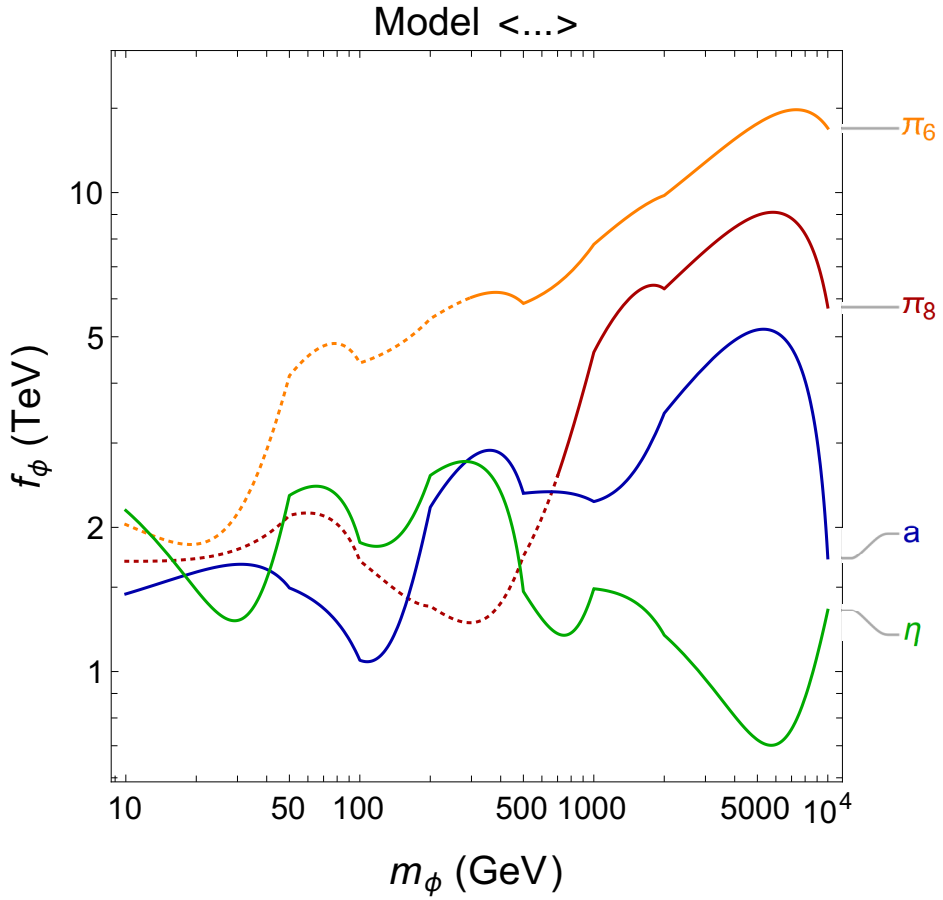
The BRs will define benchmarks characterised by coupling values

Analogous representation of results for processes of non-QCD pair production

Bounds in the $\{m_\phi, f_\phi\}$ plane for each decay channel and for benchmark choices of the couplings

Combining the bounds for pNGBs

Template example



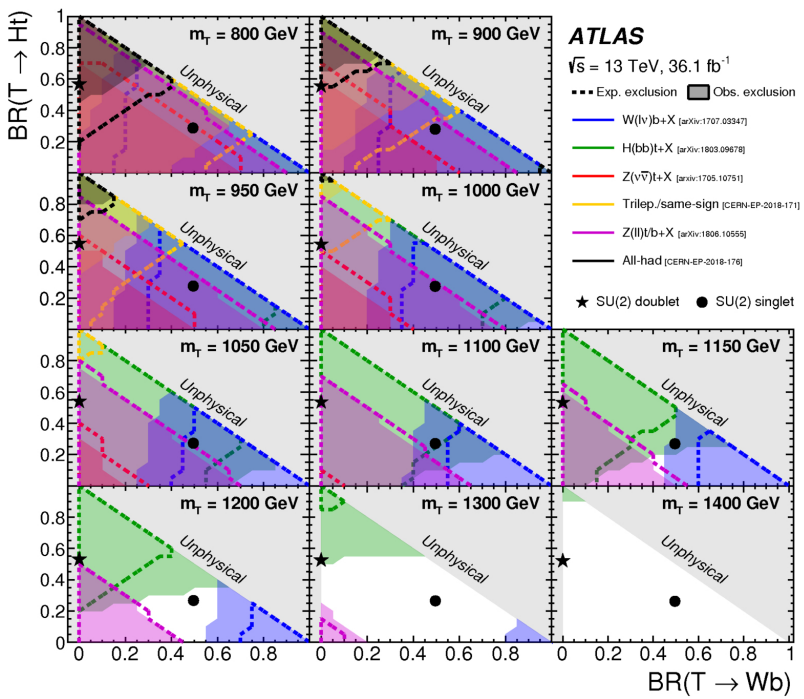
Notice
it's just an illustration
with random numbers

Envelope of all bounds in the $\{m_\phi, f_\phi\}$ plane for each decay channel and for all the particles of a specific composite realisation

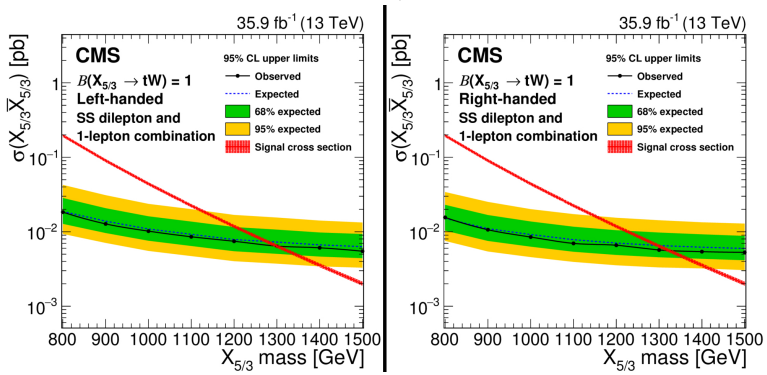
QCD mass limits (only on m_ϕ) exclude the dotted lines.

VLQs - SM decays

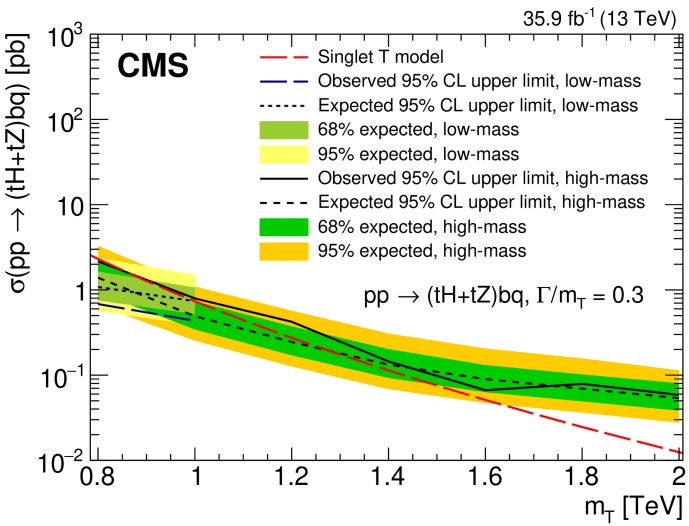
ATLAS T pair



CMS $X_{5/3}$ pair



CMS T single with large width



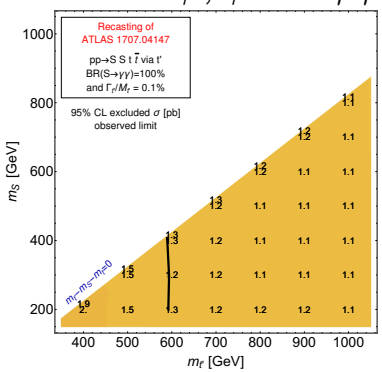
Bounds of the order of the TeV, but the VLQs could also decay to new scalars

VLQs - exotic decays

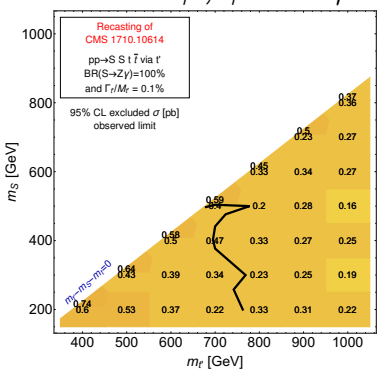
No dedicated experimental searches so far

Constraints can be reduced (BRs to SM do not add up to 1)
and potential for discoveries can be achieved with dedicated searches

$T \to t\phi, \phi \to \gamma\gamma$

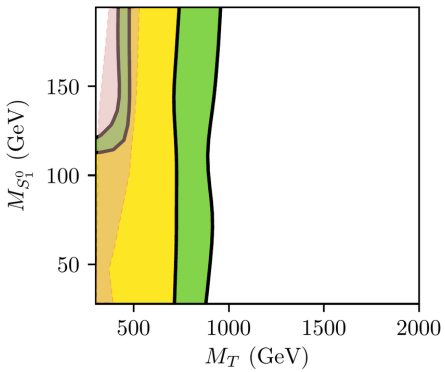


$T \to t\phi, \phi \to \gamma Z$

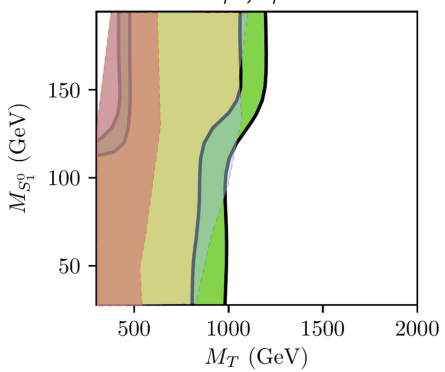


1907.05929
Recasting of direct searches

$T \to t\phi, \phi \to gg$



$T \to t\phi, \phi \to bb$



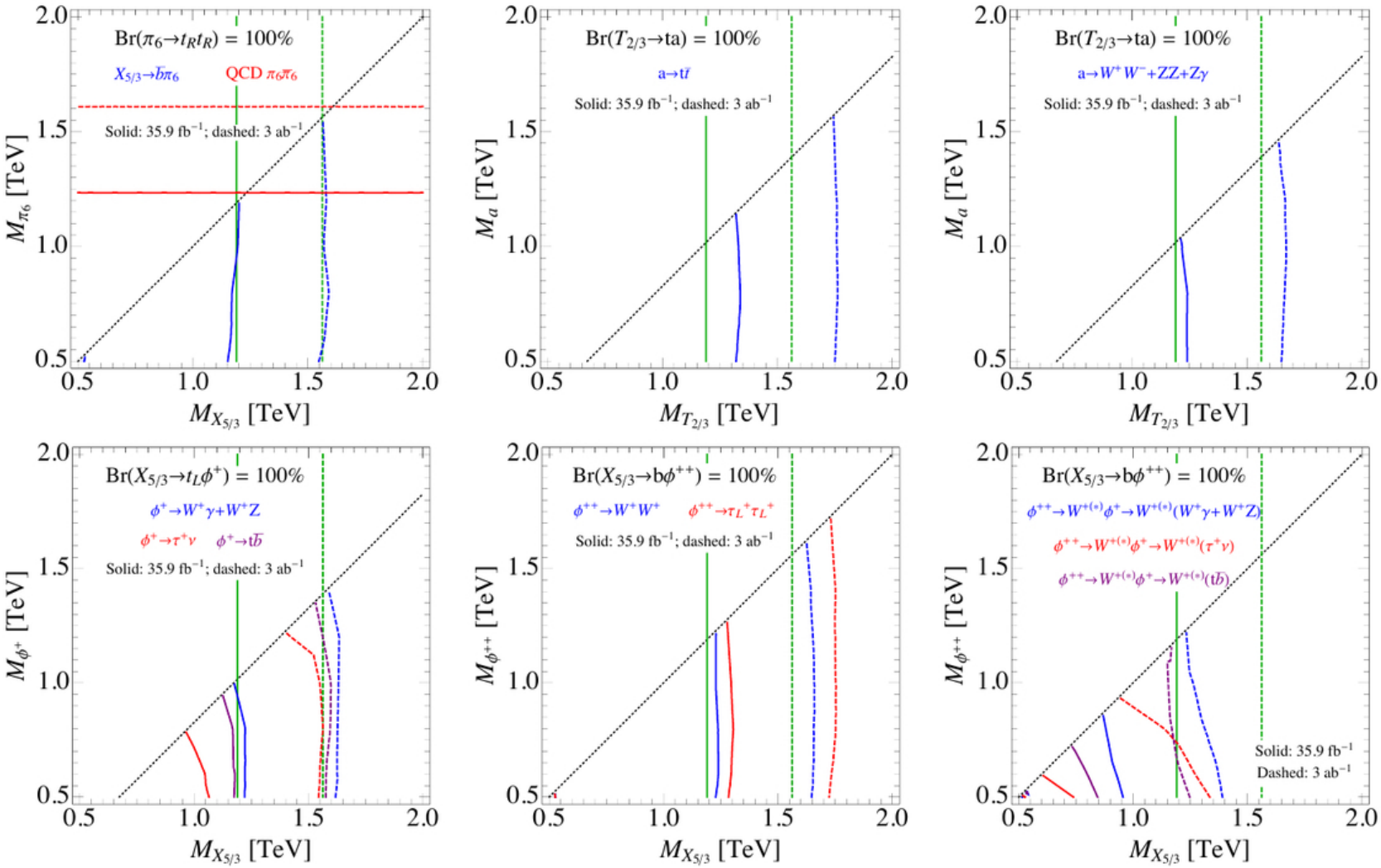
2002.12220
Recasting of direct searches and SM measurements

Bounds from pair production of VLQs decaying to new scalars in the $\{M_{VLQ}, M_\phi\}$ plane for each scalar decay channel

Also, bounds from single production of VLQs decaying to new scalars in the $\{M_{VLQ}, M_\phi\}$ plane for specific benchmarks

VLQs - exotic decays

bounds and projections from 1907.05894

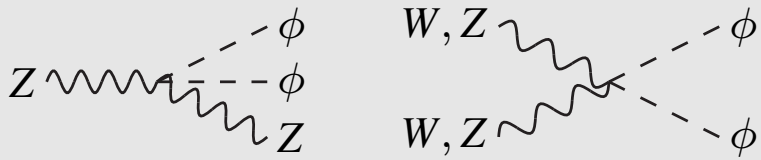


Our goals

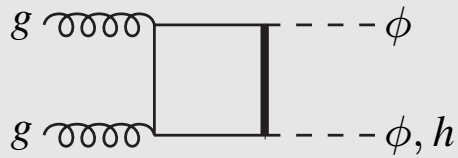
(and what can enter in the Snowmass report)

pNGBs

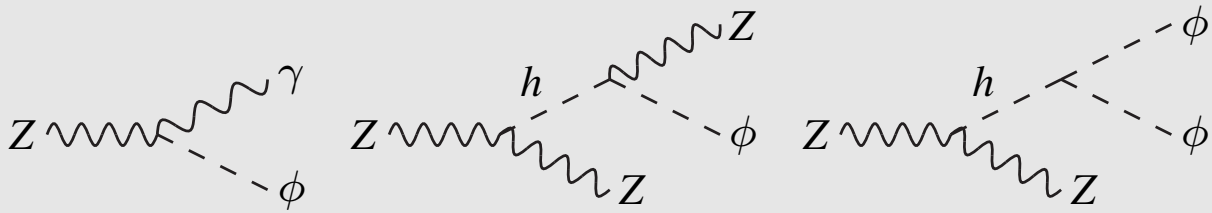
- Pair production through double pNGB-strahlung off Z (FCC-ee) or W or via VBF (LHC, FCC-hh), relevant if ϕ does not get a VEV



- Pair production or single production in association with the Higgs boson via loops of coloured particles at LHC and FCC-hh, relevant if ϕ does not couple to gluons via anomaly



- $Z \to \gamma\phi$, $h \to Z\phi$ and $h \to \phi\phi$ in a clean background environment at FCC-ee
  Very light ϕ would require dedicated strategies (2004.09825)



Constraints from less-explored scenarios, or where LHC has low sensitivity

Our goals

(and what can enter in the Snowmass report)

VLQs

- Exotic decay of top partners $T \to b\phi^+$
- Inclusion of NLO corrections and large-width effects
- Systematic recasting of VLQ searches with projections for HL-LHC
- development of dedicated analyses for FCC-hh

Bounds and reaches in the mass-mass plane for different VLQ widths

Interplay with other groups

which kind of data is needed

The activity of our collaboration fits in the
"Composite/Extra-dimension Resonance Benchmark" working group

Most of the plots presented in the previous slides cannot be unfolded for reinterpretation in different models. To do them, alongside others for different benchmarks/scenarios, **model-independent information** is required:

- Updated settings for FCC detectors (*i.e.* Delphes or SFS (2006.09387) cards)
- Background data for FCC
- Upper limits on the cross-sections as function of m_ϕ (QCD pair), in the $\{m_\phi, \text{coupling}\}$ (non-QCD pNGB) or $\{m_T, m_\phi\}$ planes (VLQ to pNGB) for individual processes with BR=100% (where relevant, also interference plots)

Model-dependent information can also be very useful for validation or recasts and for FCC projections:

- Cutflows for signal benchmarks and for specific signal regions
- Differential distributions for signal benchmarks

Interaction with experimental groups to assess which information to share