Testing charge-radius coupling of the composite Higgs boson at hadron colliders

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Models with composite Higgs

- The idea that the Higgs sector may be composite is as old as the SM itself.
- At first, built with the same principle as QCD.
- Now such models present solutions to some of the SM issues as the hierarchy and naturalness issues, dark matter or matter-antimatter asymmetry.
- Present new particles that may be discovered !

What are we searching for here ?

- collider relevance of a coupling of the composite Higgs boson being sensitive to the electromagnetic and weak isospin structure of its constituents
- the Higgs boson emerges as a light pseudo-Nambu-Goldstone boson (pNGB)
- interested in a production of the Higgs boson in association with a new light composite pseudo-scalar η
- explore cut-and-count analysis at hadron colliders
- work with with G. Cacciapaglia, S. Gascon-Shotkin, N. Manglani and K. Sridhar; more details in arXiv:2108.03005

Fundamental Composite Dynamics

Technicolor (TC)

- Consider a new strong gauge symmetry $G_{TC} = \mathcal{SU}(N_T)_{TC}$ with new "technigluons" and "technifermions" transforming under G_f.
- Technifermion condensates can appear a lower energy scale breaking G_f in a subgroup $F \subset G_f$.
- $dim(G_f) - dim(F) = n$ Goldstone bosons, massless or pNGB if symmetry is explicitly broken.
- Need another mechanism for the fermions to acquire a mass.

Composite Higgs (CH)

- As in TC, new strong sector associated to G_f symmetry for fermions.
- G_f broken in F containing the electroweak symmetry.
- $dim(G_f) - dim(F) = n$ bosons de Goldstone, pNGB with a small mass.
- Fermion mass is obtained through partial compositeness.

Fundamental Composite Dynamics (FCD)

- Two main differences between TC and CH: electroweak symmetry is broken along G_f in TC but preserved in CH, and the particle discovered in 2012 comes from a condensate in TC whereas considered as a pNGB which is part of $\mathcal{SU}(2)_L$ in CH.
- Can combine these theories in FCD so that this particle is a mix of a condensate and a pNGB.
- Done in considering a fundamental state combining the vacuum from the two theories.

Minimal model with $SU(4)/Sp(4)$ symmetry breaking, used to obtain a dark matter candidate ϕ in the TC limit.
In a more general FCD model, two pNGB h (SM Higgs) and a singlet η:

$$\phi = \frac{h + i\eta}{\sqrt{2}}$$

The TC and CH limits are represented through:

$$\sin\theta = \frac{v_{SM}}{f}$$

We want to focus on anomalous couplings of photons because typical signatures for compositeness in the electroweak sector.
In the TC limit, this coupling is given by:

$$\mathcal{L} \supset ie\frac{d_B}{\Lambda^2}\left(\phi^* \overset{\leftrightarrow}{\partial}_\mu \phi\right)\partial_\nu F^{\mu\nu}$$

Which can be rewritten in FCD:

$$\mathcal{L} \supset ie\frac{d_B}{\Lambda^2}\sin\theta\left(\eta \overset{\leftrightarrow}{\partial}_\mu h\right)\partial_\nu F^{\mu\nu}$$

$$\mathcal{L} \supset ie\frac{d_B}{\Lambda^2}\sin\theta\left(\eta\overleftrightarrow{\partial}_\mu h\right)\partial_\nu F^{\mu\nu}$$

- Generated by the components of the neutral pNGBs h and η that carry electromagnetic charges: charge-radius coupling
- Λ is the new physics energy scale
- d_B is a parameter, can be associated to the masses of spin-1 resonances

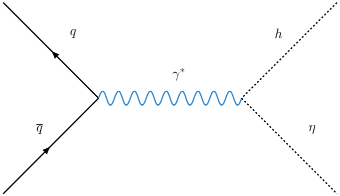
For better understanding: let's consider a new hyper-colour gauge group $Sp(2\mathrm{N}_c)$ with two Dirac hyper-fermions U and D.

In this context, we have with the masses of the spin-1 resonances ρ:

$$\frac{d_B}{\Lambda^2} = \frac{m_{\rho_U}^2 - m_{\rho_D}^2}{2m_{\rho_U}^2 m_{\rho_D}^2} \sim \frac{\delta m_\rho}{m_\rho^3}$$

Only interested in couplings with photon (although Z is possible and would give an additional contribution) $\Longrightarrow$ focus on the phenomenology consequences of this coupling.

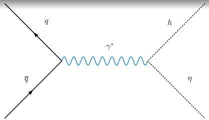
- Previous coupling vanishes for on-shell photons $\Longrightarrow$ it won't generate any decay of h or η
- Need a novel production mechanism for the pNGBs, i.e. production of η in association with a Higgs boson e^+e^-; $pp \to h\eta$
- This is generated with an off-shell photon

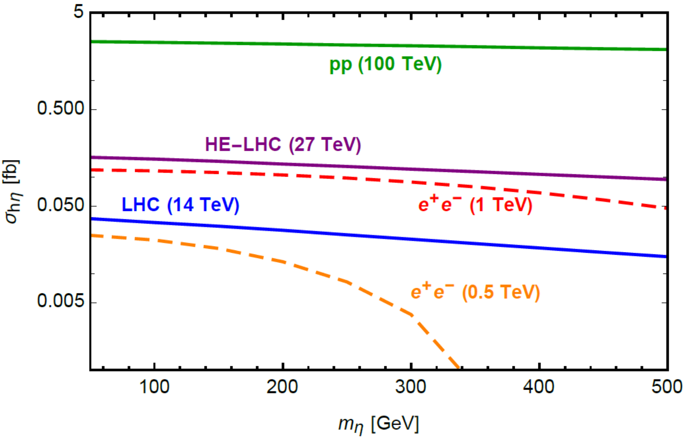


The mass of the pseudo-scalar η can acquire very different values.

- If $m_\eta < m_Z$, the dominant constraint will come from $Z \to \eta\gamma$.
- Here focus on $m_\eta > m_Z$ with the $\eta \to Z\gamma$ decay.

$e^+e^-; pp \to h\eta$



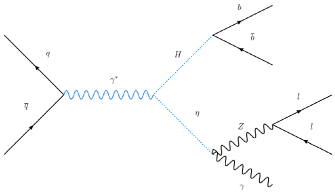


- $\frac{d_B \sin\theta}{\Lambda^2} = 0.011\ \text{TeV}^{-2}$
- $\sigma_{h\eta} \propto \Lambda^{-4}$
- $\sigma_{h\eta}$ are feeble $\Longrightarrow$ need for high luminosity

HL-LHC

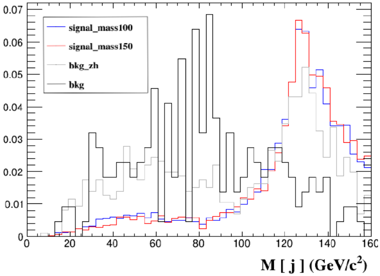
Study $pp \to \gamma^* \to H\eta$ events at 14 TeV.

- Signal m_η>90 GeV, $\eta \to Z\gamma$, $H \to bb$, Z to leptons
- Irreducible background $pp \to b\bar{b}l^+l^-\gamma$ and $Z \to ZH$
- Reducible background $jjl^+l^-\gamma$



Reconstruction with Pythia and FastJet, and dedicated cuts to discriminate s/b:

* 1 fat jet with $m_j \in$ [100,170] GeV
* $p_{T,j} > 380$ GeV
* $p_{T,\gamma} > 85$ GeV
* $m_{ll} \in$ [86,96] GeV
* $\Delta(l,\gamma) < 1.2$ and $\Delta(j,\gamma) > 2.0$
* Simple b-tagging efficiency
* $m_{ll\gamma}$ must reconstruct the signal mass



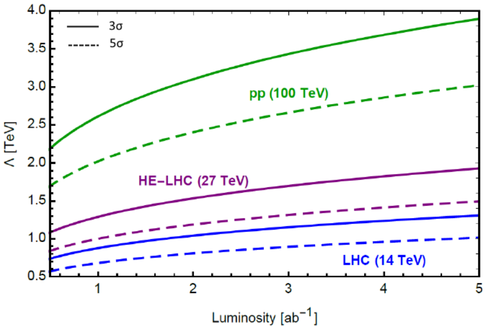
Cuts	jjlla	cclla	bblla	hza	$h\eta$
σ_{fid} (ab)	590	96	93	19	1.23
Events	10^5	10^6	10^6	10^6	10^4
Higgs reco.	337	856	3411	4913	1621
$p_T^\eta > 380$	242	695	2572	4625	1566
$p_T^\gamma > 85$	231	665	2497	4416	1274
$\Delta R_{\gamma Z} < 1.2$	57	187	636	1260	1259
m_{ll}	41	128	431	1037	1129
$m_{ll\gamma}$	2	1	9	29	1085
b-tags	0.0002	0.04	4.41	14.2	532
HL-LHC	$3.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	0.0012	0.0008	0.20

- Not a lot of signal events remaining...
- but can distinguish signal from background

Cuts based analysis results for hadron colliders

- Construct a simple figure of merit as a function of $\mathcal{L}$ and Λ
- $\mathcal{L}$ is the expected integral luminosity
- Λ is the scale of the new physics ($\sigma_{XS} \propto \Lambda^{-4}$)

$$Z(\mathcal{L}, \Lambda) = \frac{S}{\sqrt{S+B}}$$

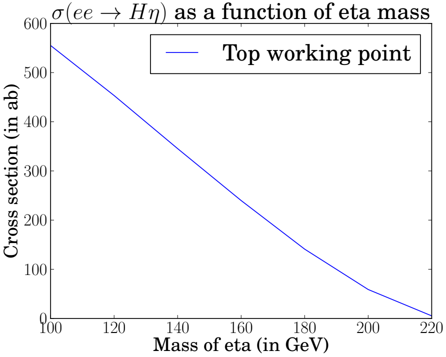


Discovery potential at $\Lambda \sim 1$ TeV (1.5 TeV) for HL-LHC (HE-LHC). Possibility to go up to 3 TeV for collisions at 100 TeV at FCC-hh.

Simple analysis with no systematic, no real detector simulation and simple cuts. The sensitivity could be improved using ML tools.

FCC-ee

Electron colliders are interesting because cleaner experimental conditions.
With the highest COM energy at 350 GeV:
Study $e^+e^- \to \gamma^* \to h\eta$ events.



XS is too small even with optimistic setup...
Solution: try photon fusion production mode or look at another e^+e^- collider.

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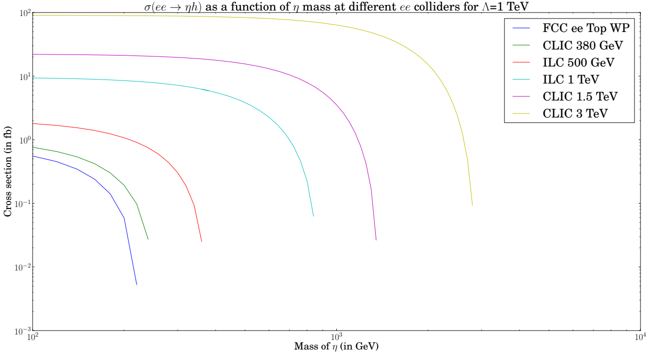

Conclusion

- Presented a search for a new pseudo-scalar particle
- A simple cut-and-count analysis has shown that signal can be distinguished from background
- Need to add systematics, realistic detector and a ML tool to enhance s/b
- Still this signature looks promising to look at at FCC-hh

Thanks for your attention !

Backup