Axionic signals at colliders with a dynamical Higgs

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In collaboration : Brivio, Gavela, Mimasu, Merlo, No, Sanz. Paper to appear.

Why an extra Goldstone?

$$\frac{a(x)}{f_a}$$

GBs are included in many BSM proposals.

Eg. The Peccei-Quinn $U(1)_A$ axion that solves the Strong CP problem.

... but also Majoron, ALPS, etc.

We will analyse at colliders for scales lower than the QCD axion scale.

=> Look for derivative couplings

Why a composite Higgs?

It is a solution to the Hierarchy Problem.

Is the Higgs···

Elementary?	Composite?
As in certain solutions of the Hierarchy problem. e.g. SUSY...	e.g. a pseudo-Goldstone Boson (GB) in SO(5)
LINEAR EWSB	NON-LINEAR EWSB

The composite Higgs appears as the pseudo-GB of a spontaneously broken symmetry ... this explains its "lightness".

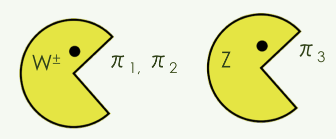
Linear

The Higgs is a **doublet.**
The doublet structure determines much of its phenomenology.

- The Higgs appears in the Lagrangian as $(v+h(x))^n$.

$$\Phi(x) = \frac{v+h(x)}{\sqrt{2}} e^{i\vec{\pi}\vec{\sigma}/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad e^{i\vec{\pi}\vec{\sigma}/v} \equiv \mathbf{U}(x) \Longrightarrow$$

The "pions" are parametrised by a dimensionless matrix.
(As in the QCD Non-linear Sigma model)



Non-linear

The Higgs is **not necessarily a doublet,** and can be inserted as a gauge singlet.

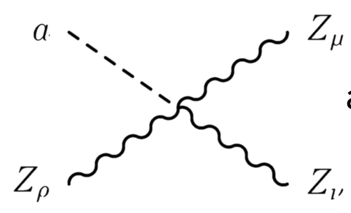
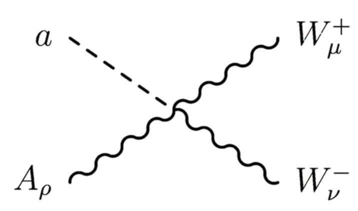
- $(v+h(x))^n$ *is replaced by a more general expansion*

$$\Downarrow$$

$$\mathcal{F}_i(h) = 1 + 2a_i\frac{h}{v} + b_i\left(\frac{h}{v}\right)^2 + \ldots$$

- F(h) and **U**(x) are separate building blocks in the EFT
→ Generically, one obtains a larger NLO basis.

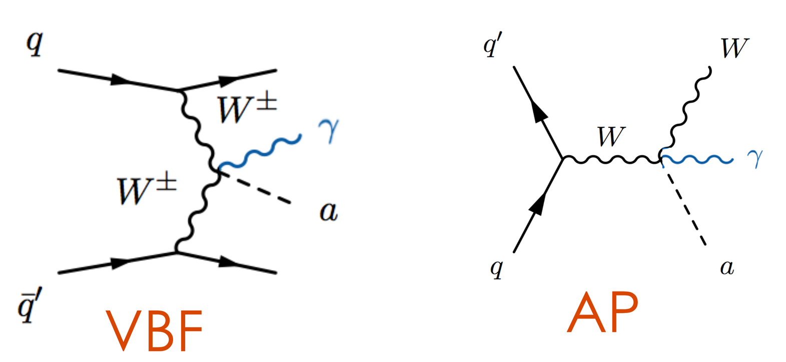
Main differences in scalar couplings:

Linear [Georgi, Randall, Kaplan -1984]		Non-Linear [Us – to appear]
$\mathcal{A}_\Phi = \Phi^\dagger i \overleftrightarrow{D}_\mu \Phi \frac{\partial^\mu a}{f_a}$ is NLO in linear (d=5)	→ **New LO couplings** for example aZh, aZhh...	$\mathcal{A}_{2D} = \frac{iv^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\frac{\partial^\mu a}{f_a}\mathcal{F}_{2D}(h)$ becomes LO (2 derivatives)
$i(D^\mu\Phi^\dagger\Box\Phi - \Box\Phi^\dagger D^\mu\Phi)\frac{\partial_\mu a}{f_a}$ doesn't appear in linear until d=7	→ **New NLO couplings**  and aAh^n, WWah...	$\mathcal{A}_9 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)^2\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\frac{\partial^\nu a}{f_a}\mathcal{F}_9(h)$ becomes NLO (4 derivatives)
$\epsilon^{\mu\nu\rho\alpha}p_{\alpha\sigma}$	→ **New Lorentz structures at NLO**  And also for aWW, aZWW...	$(g^{\mu\rho}p_a^\nu + g^{\nu\rho}p_a^\mu)$, $g^{\mu\nu}p_a^\rho$

$$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger \qquad \mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger$$

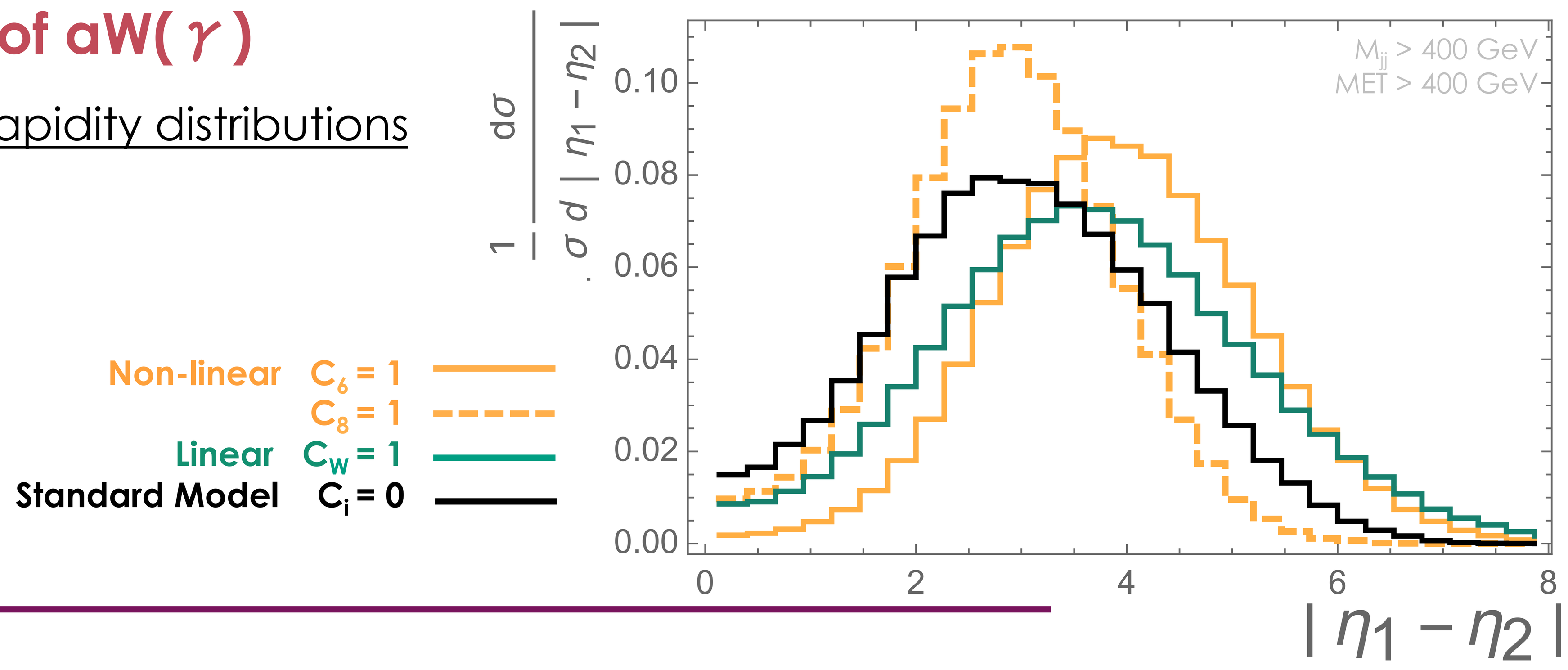
Distinctive signatures of non-linearity at colliders

1 Vector Boson Fusion – ajj(γ) – & Associated Production of aW(γ)

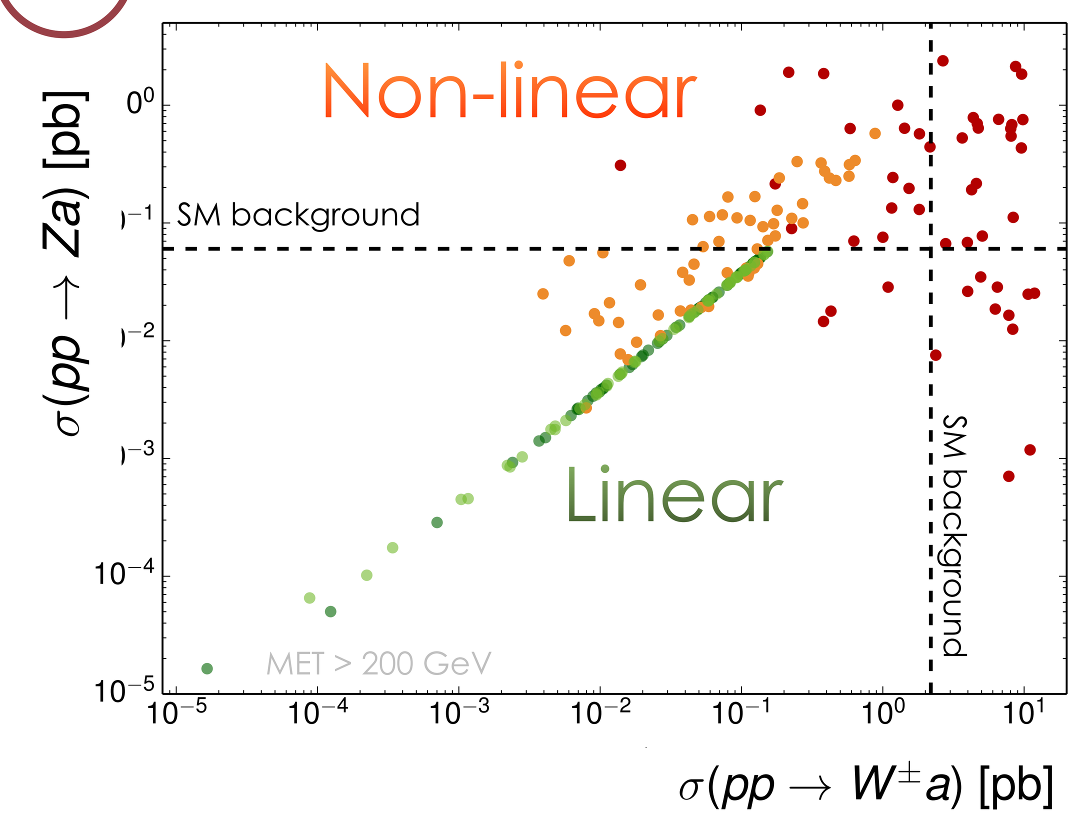


for example: VBF rapidity distributions

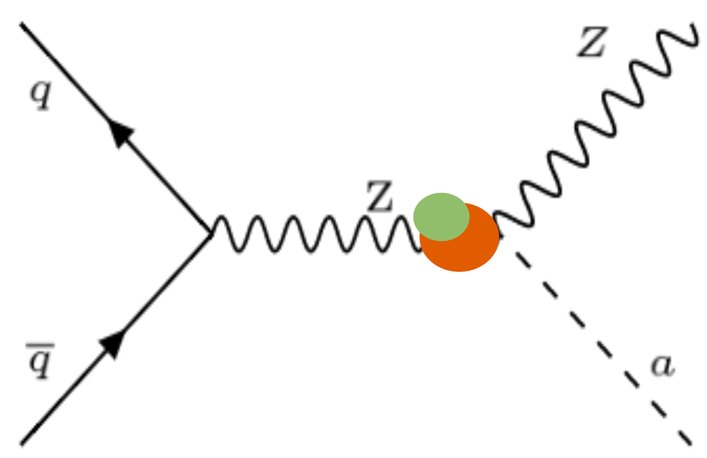
4 signals depending on 4 Wilson coefficients offer a possibility to **disentangle!**



2 Mono-Z and mono-W (and mono-h) signatures

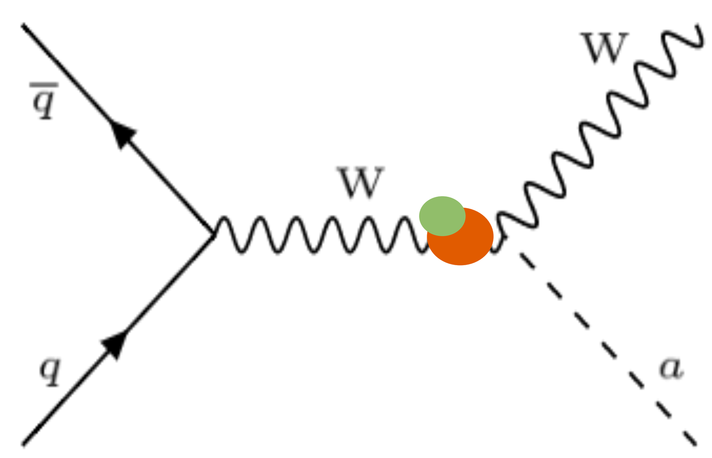


mono-Z:
2 operators in linear



+3 new ones in non-linear...

mono-W:
1 of the previous 2



+2 more!

More operators: can "escape" axion-photon constraint and break correlations.

Decorrelation of signals which are linearly correlated are **smoking guns** for non-linearity!

We have derived the **effective chiral Lagrangian** for **ALPs + bosonic sector** with a **dynamical Higgs.**

300 fb^{-1} of **LHC data** can test for **new GBs** with **$f_a \geq$ TeV.**