Di-Higgs production at HL/HE-LHC

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Motivation

Is the mechanism responsible for EWSB and fermion mass generation in the SM minimal?

What we know:

- One complex scalar doublet acquires a vev, breaks EW symmetry and gives W/Z and third generation fermions (most) of their masses

What we don't know:

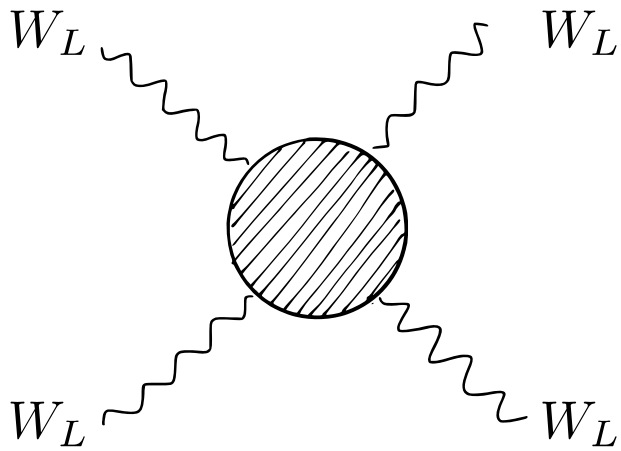
- Do the first and second generation fermions also get their masses from the same doublet?
- Is this Higgs vev the only source of EWSB?

HL(HE)-LHC are crucial steps towards answering these questions!

Perturbative unitarity: a lamppost

$$g_{hVV} \equiv c_V g_{hVV}^{\rm SM}, \qquad g_{hhVV} \equiv c_{2V} g_{hhVV}^{\rm SM}$$

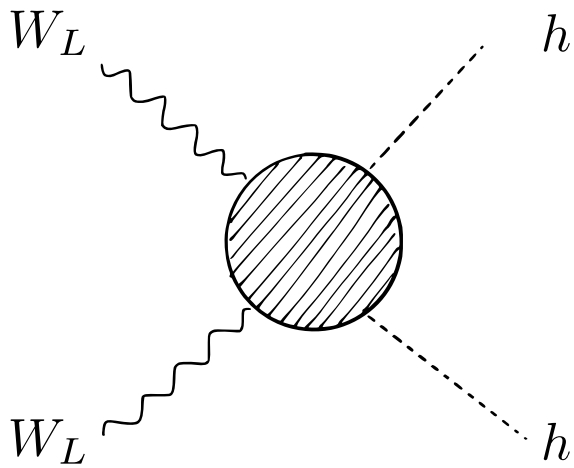
VBS



$$\propto \frac{\hat{s}}{v^2}\left(1 - c_V^2\right)$$

$$\sqrt{\hat{s}} \gg m_W$$

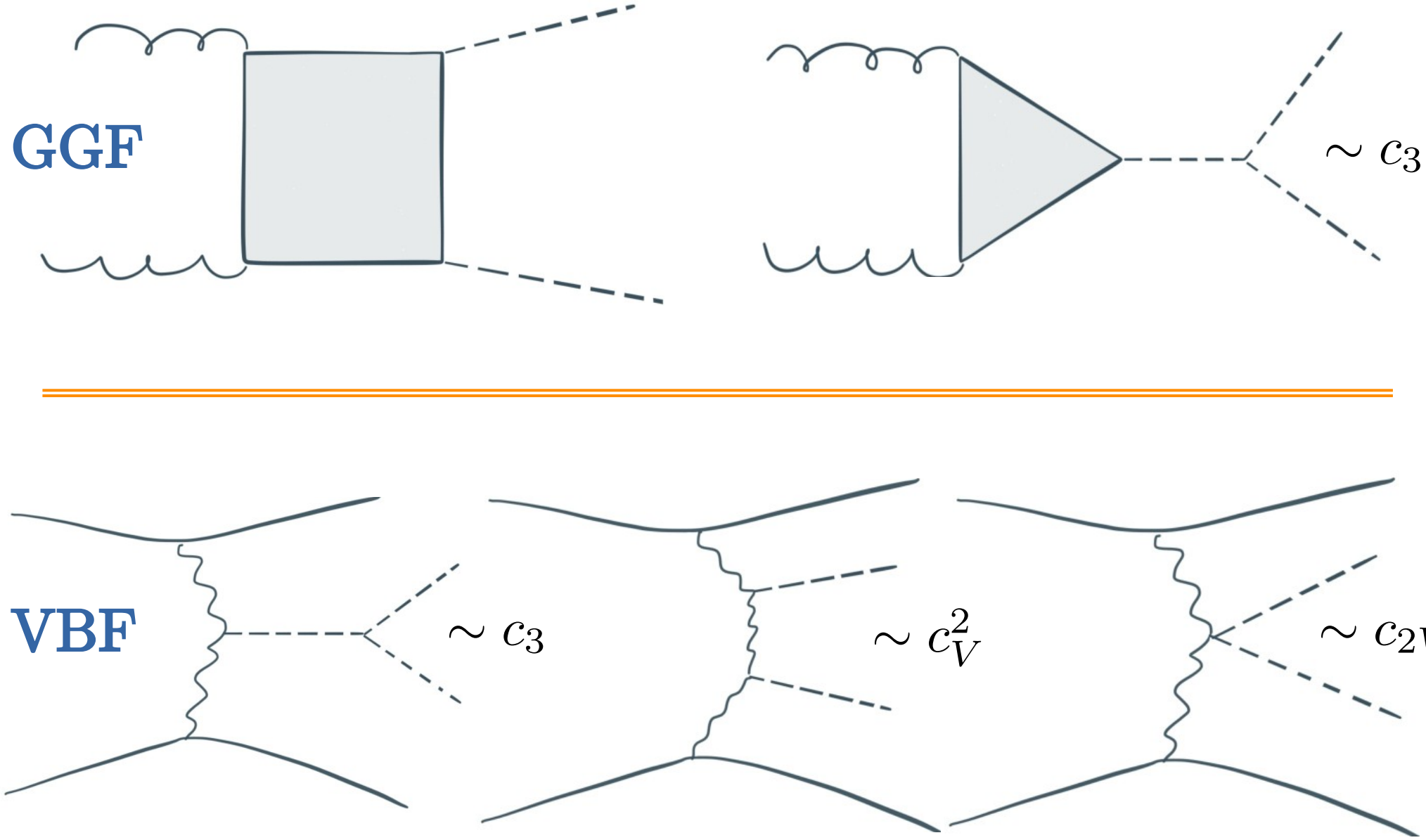
di-Higgs



$$\propto \frac{\hat{s}}{v^2}\left(c_{2V} - c_V^2\right)$$

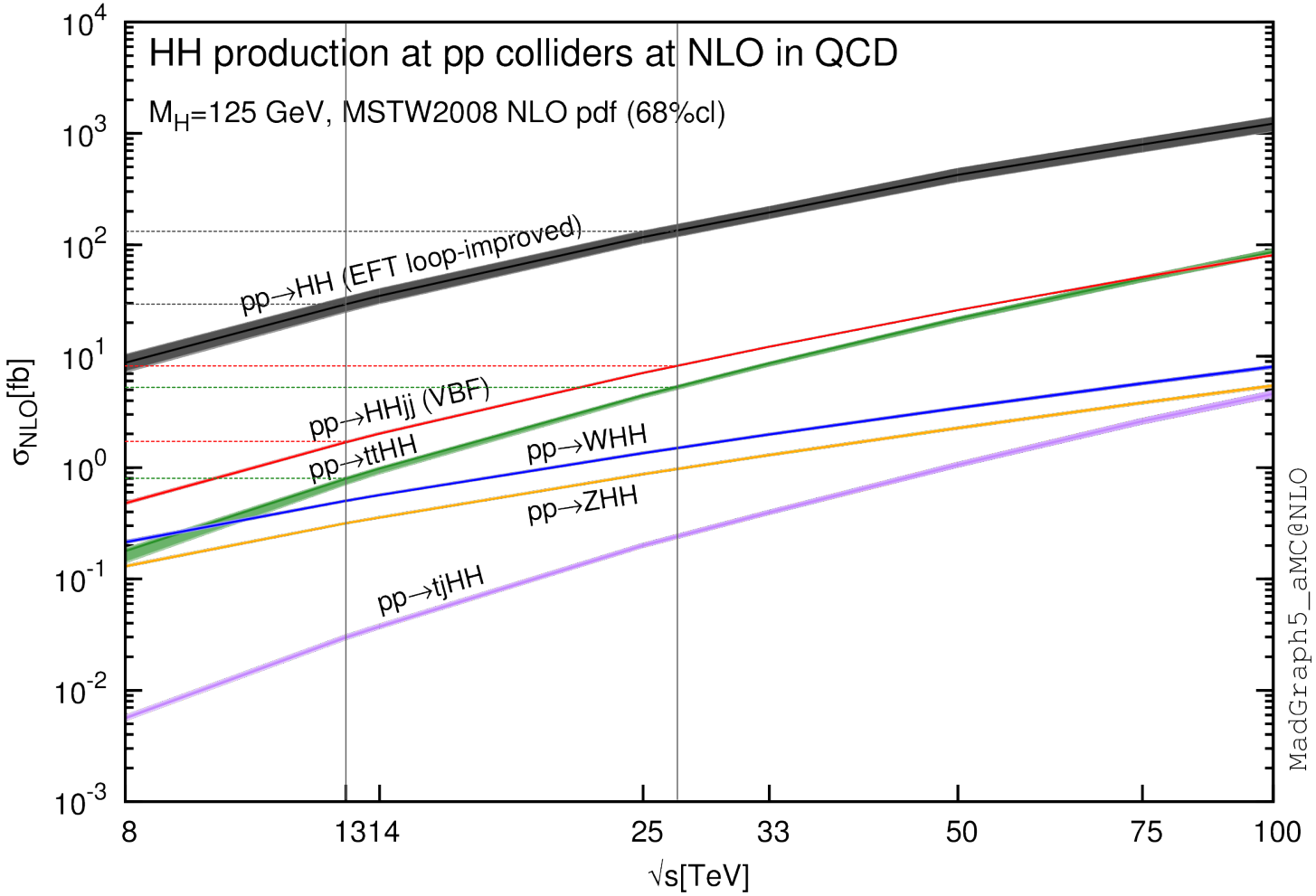
Deviations = new physics at some scale

Double Higgs production



HH production at pp colliders

- VBF cross-section at the LHC is small ~ 2 [fb] w/o $\mathcal{BR}$s
- But, it is a unique probe of the EWSB mechanism



Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro: 1401.7340

Is EWSB (non-)linearly realised?

[Grinstein and Trott: [0704.1505]
[Contino, Grojean, Moretti, Piccinini, Rattazzi: 1002.1011]

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu h)^2 - V(h)$$
$$+ \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \ldots\right]$$
$$- m_i\, \bar{\psi}_{Li}\, \Sigma \left(1 + c_\psi \frac{h}{v} + \ldots\right) \psi_{Ri} + \text{h.c.},$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + c_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \ldots$$

- In the minimal SM, linear realization
  → $c_V = c_{2V} = c_3 = 1$ and all … terms vanish
- Measuring $c_{2V} \neq 1$ → non-linearity!

A concrete example

- In minimal SO(5)/SO(4) models, the couplings c_V and c_{2V} are given by

Agashe et al. [hep-ph/0412089]
Contino et al. [hep-ph/0612048]

$$c_V = \sqrt{1-\xi}\,, \qquad c_{2V} = 1 - 2\xi$$

where $\xi = v^2/f^2$

- And, looking at the longitudinal vector boson scattering we see that

$$\mathcal{A}(V_L V_L \to hh) \simeq \frac{\hat{s}}{v^2}(c_{2V} - c_V^2)$$

- Choose a benchmark with $c_{2V} = 0.8$ (to roughly correspond to $\xi = 0.1$ which is at the boundary of exclusion by ATLAS)

ATLAS: [1509.00672]

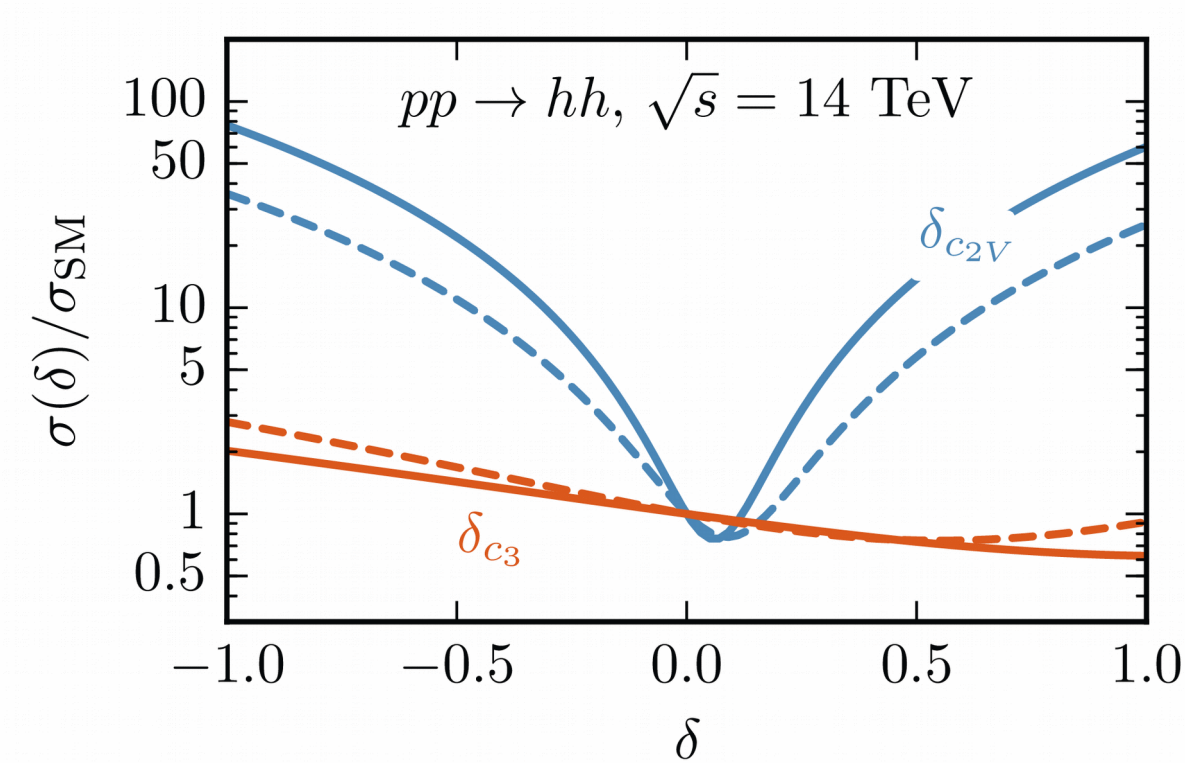
Sensitivity to δ_{c_3} and $\delta_{c_{2V}}$

- To illustrate, consider total σ before and after cuts with $\boxed{\sigma/\sigma_{\rm SM} = 1 + a\,\delta + b\,\delta^2}$

- Sensitivity to $\delta_{c_{2V}}(\delta_{c_3})$ is enhanced (suppressed) by the cuts

$$\boxed{\delta_i \equiv c_i - 1}$$

dashed : before cuts
solid : after cuts



FB, Contino, Rojo [1611.03860]

Kinematic cuts & b-tagging

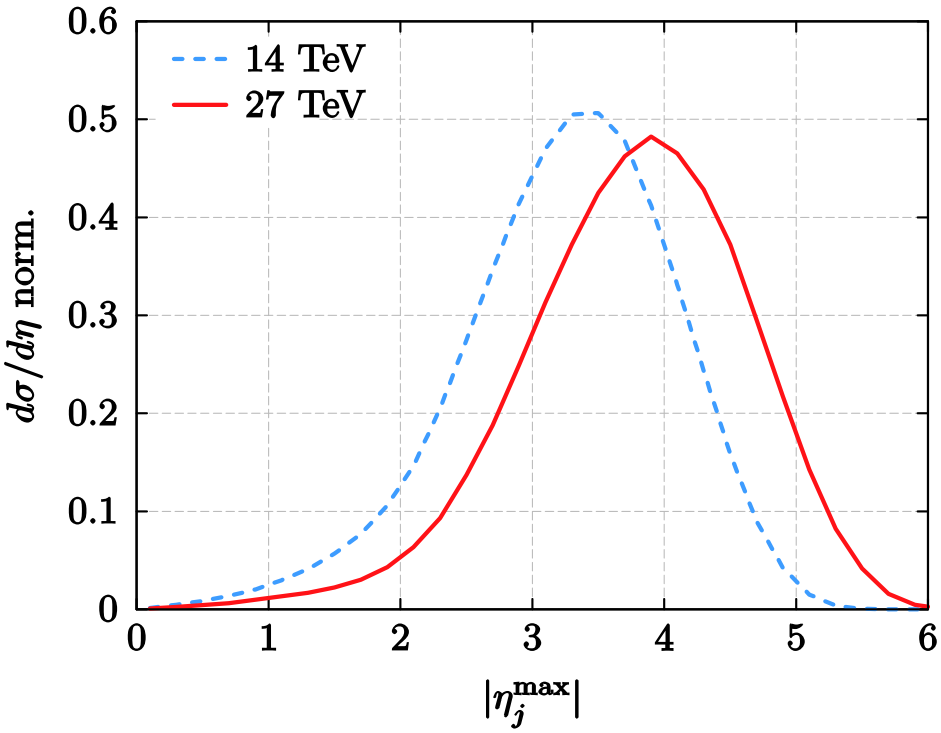
Final cuts:

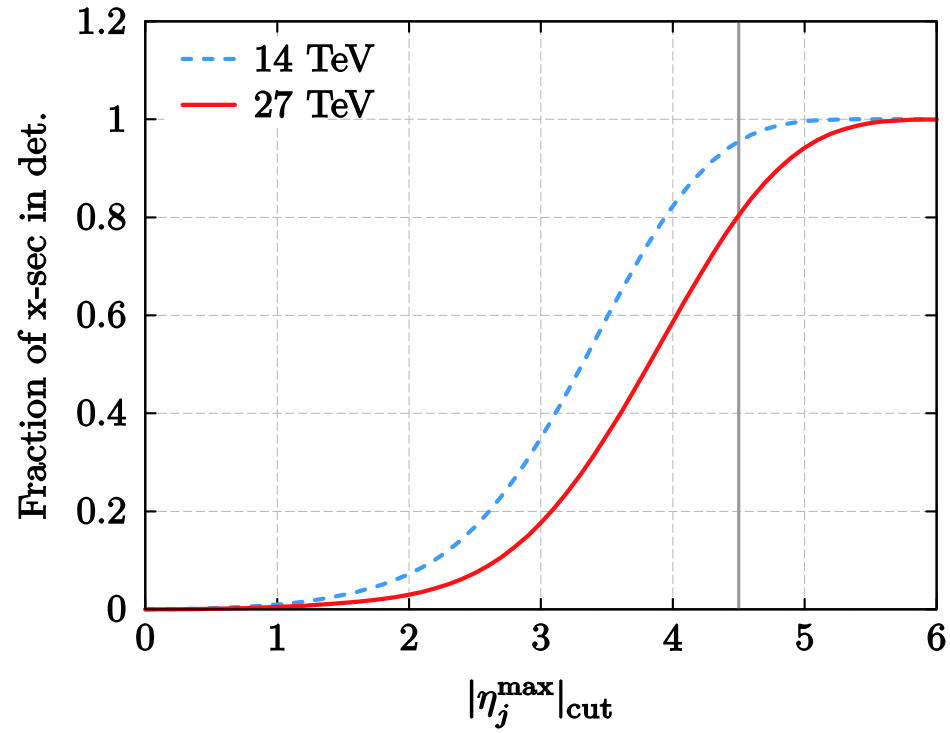
			14 TeV	100 TeV	27 TeV
Acceptance cuts		p_{T_j} (GeV) $\geq$	25	40	?
		p_{T_b} (GeV) $\geq$	25	35	?
		$\lvert\eta_j\rvert \leq$	4.5	6.5	?
		$\lvert\eta_b\rvert \leq$	2.5	3.0	?
VBF cuts		$\lvert\Delta y_{jj}\rvert \geq$	5.0	5.0	?
		m_{jj} (GeV) $\geq$	700	1000	?
	Central jet veto:	$p_{T_{j_3}}$ (GeV) $\leq$	45	65	?
		m_{hh} (GeV) $\geq$	500	1000	

B-tagging parameters:

$$\varepsilon(b\text{-tag}) = 0.75\,, \quad \varepsilon(c\text{-mistag}) = 0.1\,, \quad \varepsilon(q, g\text{-mistag}) = 0.01$$

Detector acceptance



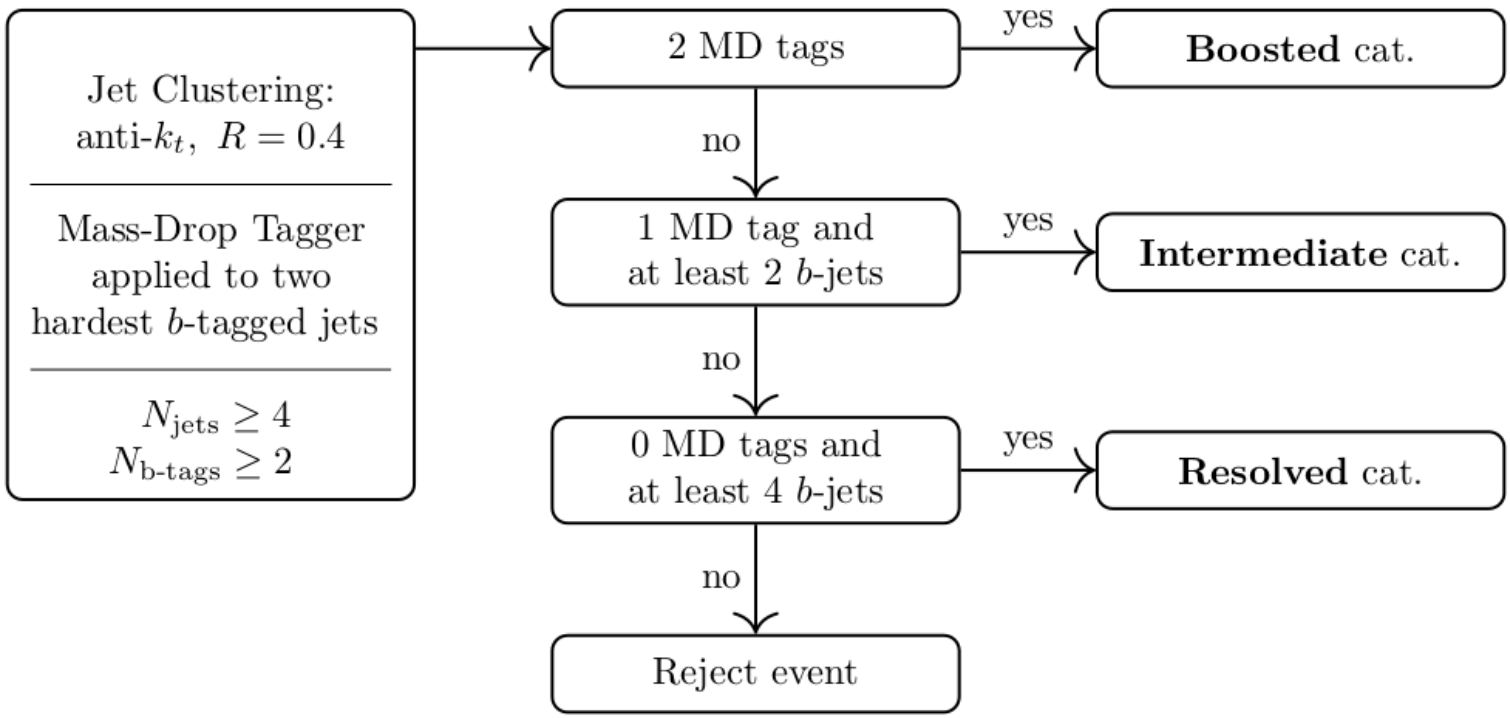


- At 14 TeV, $|\eta_j^{\max}| < 4.5$ retains 95% of the cross-section
- At 27 TeV, $|\eta_j^{\max}| < 4.5$ retains 80% of the cross-section

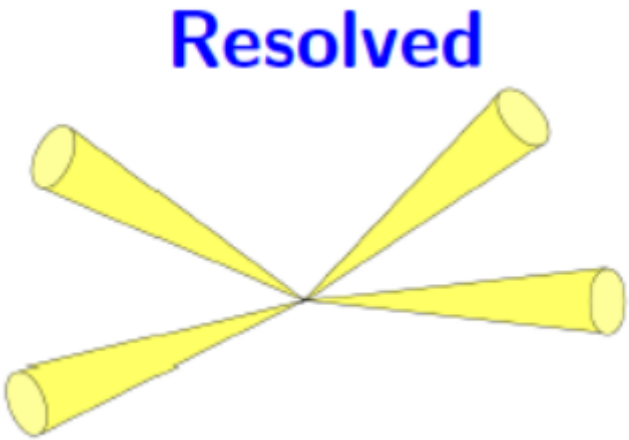
Scale invariant tagging

Gouzevitch et al. [1303.6636]

- Key feature: m_{hh} tail is harder when $c_V^2 \neq c_{2V}$
- Signal events will have boosted Higgs pairs $\rightarrow$ handle to reduce background



Higgs reconstruction



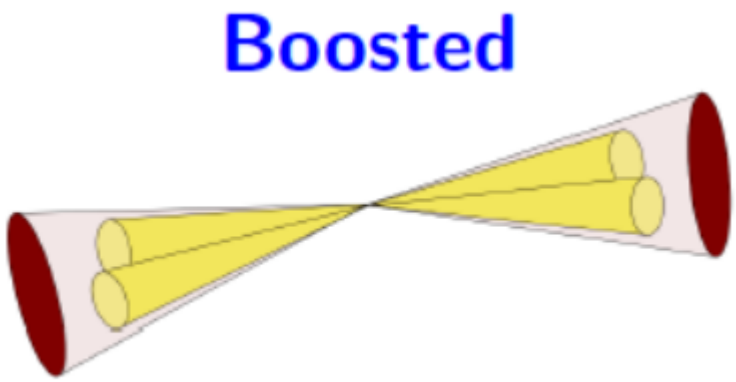
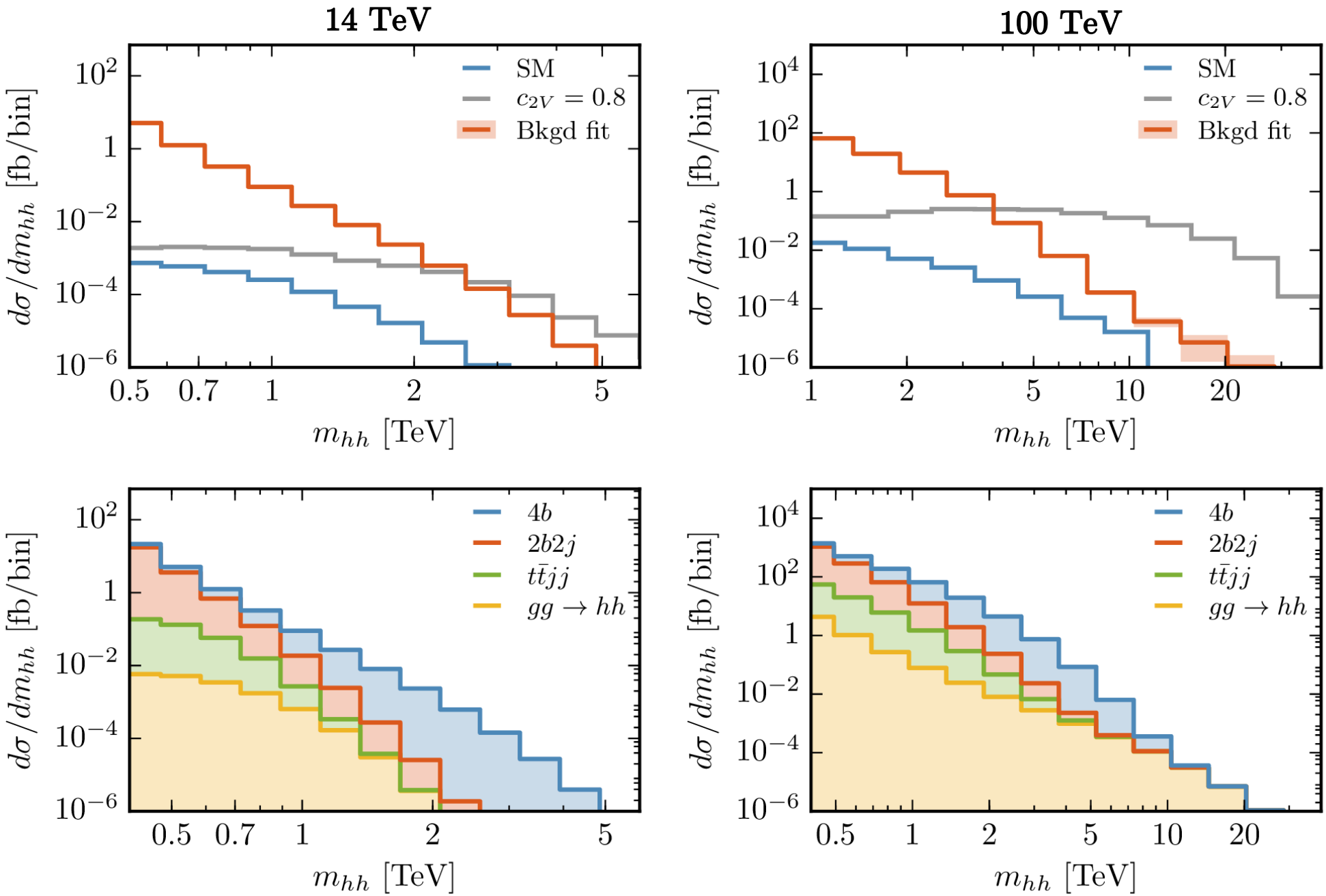


Figure credit: Juan Rojo

- ▷ 4 small-R b-tagged jets
- ▷ Consider hardest 6
- ▷ $h_1 \leftrightarrow$ b-jet pair with $\min\{|m_{bb} - 125|\}$
- ▷ $h_2 \leftrightarrow$ b-jet pair with $\min\{|m_{bb} - m_{h_1}|\}$

- ▷ 2 large-R jet $\supset$ 2 b-quarks each
- ▷ $h_1 \leftrightarrow$ large-R jet with $\min\{|m_j - 125|\}$
- ▷ $h_2 \leftrightarrow$ large-R with $\min\{|m_{j_2} - m_{j_1}|\}$

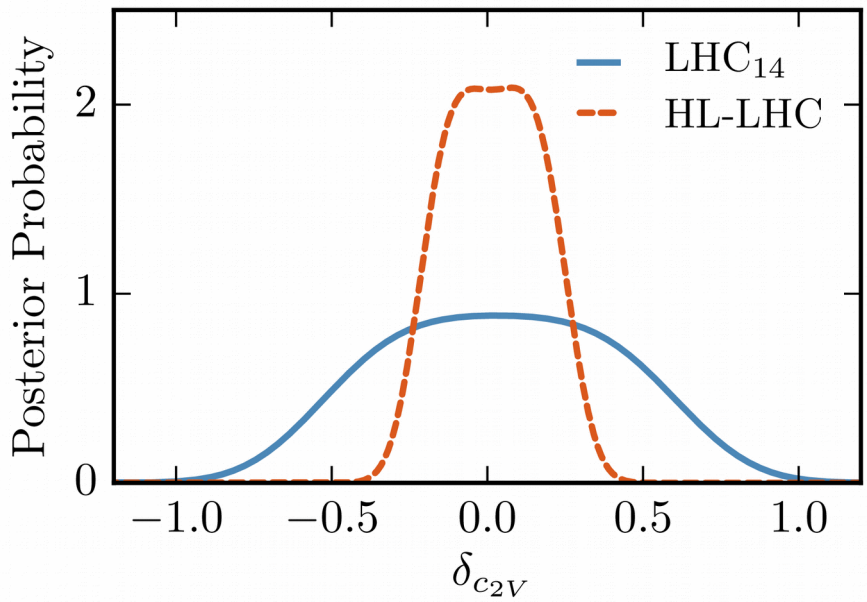
The hh invariant mass distribution

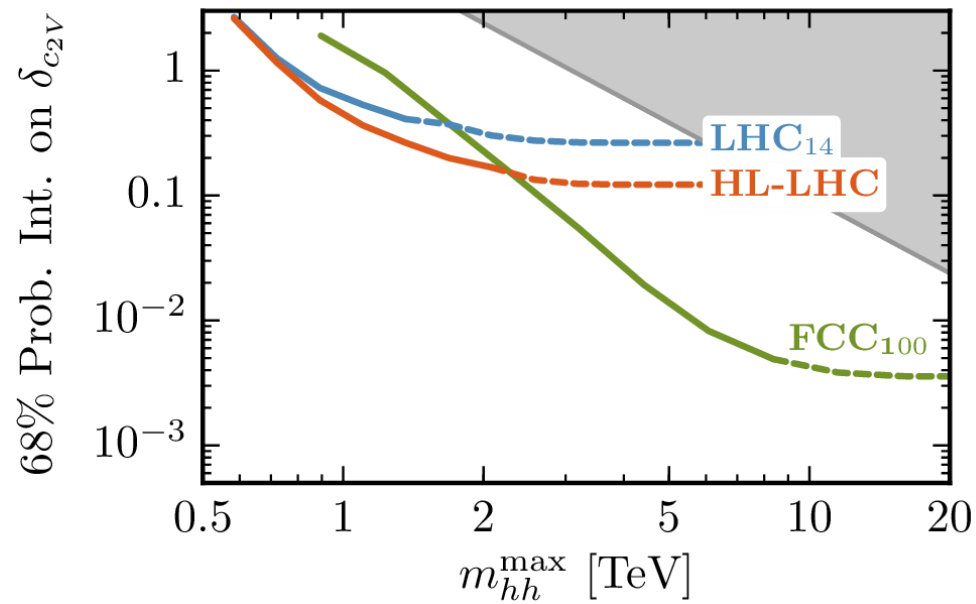


Results: probability intervals on δc_{2V}

FB, Contino, Rojo [1611.03860]

$$\delta_{c_{2V}} \equiv c_{2V} - 1$$





	68% probability interval on $\delta_{c_{2V}}$	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC$_{14}$	$[-0.37, 0.45]$	$[-0.43, 0.48]$
HL-LHC	$[-0.15, 0.19]$	$[-0.18, 0.20]$
FCC$_{100}$	$[0, 0.01]$	$[-0.01, 0.01]$

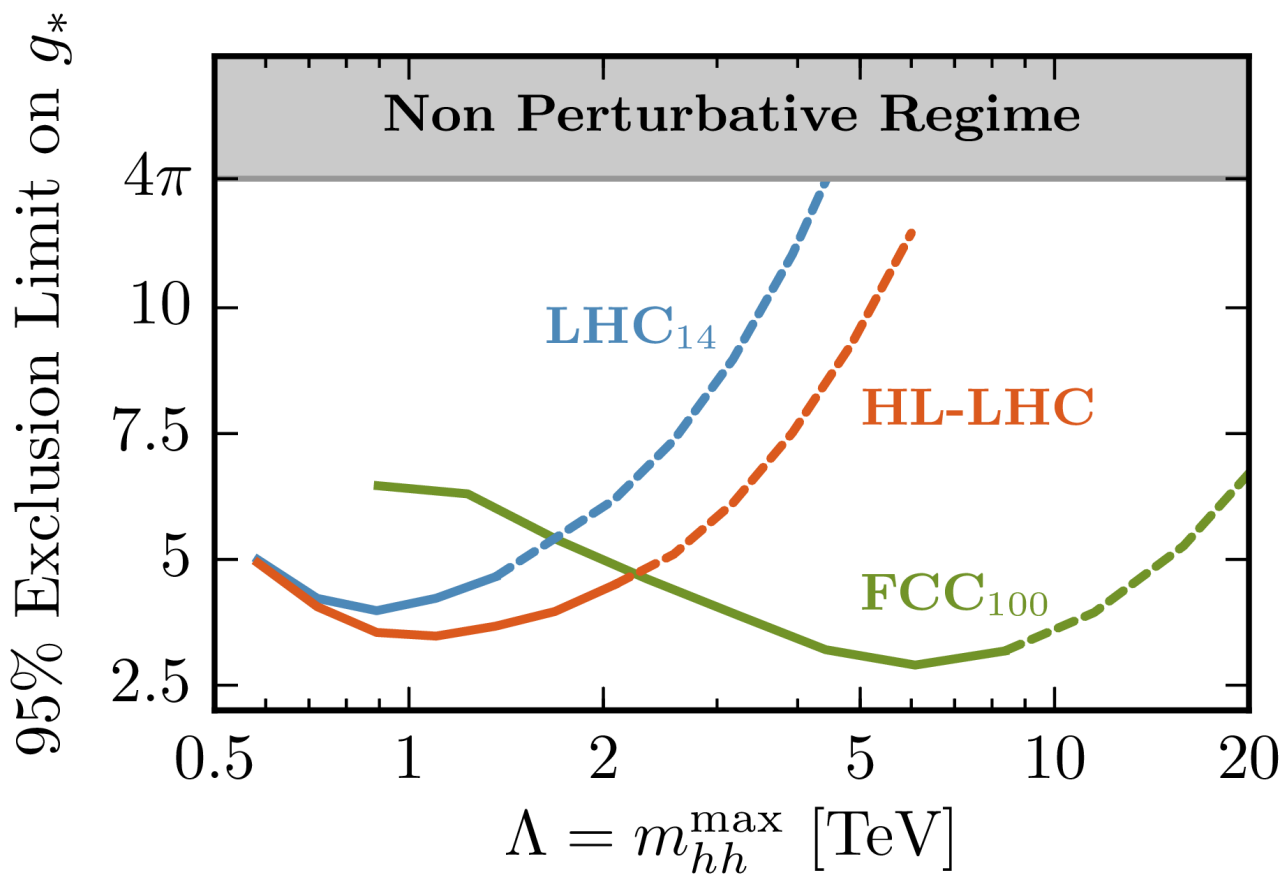
	95% probability upper limit on μ	
	$1 \times \sigma_{\rm bkg}$	$3 \times \sigma_{\rm bkg}$
LHC$_{14}$	109	210
HL-LHC	49	108
FCC$_{100}$	12	23

Results for HE-LHC (27 TeV) will be available shortly

Validity of the EFT description

- If NP is characterized by couping g_* and scale Λ
- One expects $\delta_{c_{2V}} \approx g_*^2 v^2/\Lambda^2$ See, e.g., [Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]
- Saturating the strong coupling limit then gives $\delta_{c_{2V}} \approx 16\pi^2 v^2/\Lambda^2$

This procedure was outlined in [Contino, Falkowski, Goertz, Grojean, Riva: 1604.06444]



FB, Contino, Rojo [1611.03860]

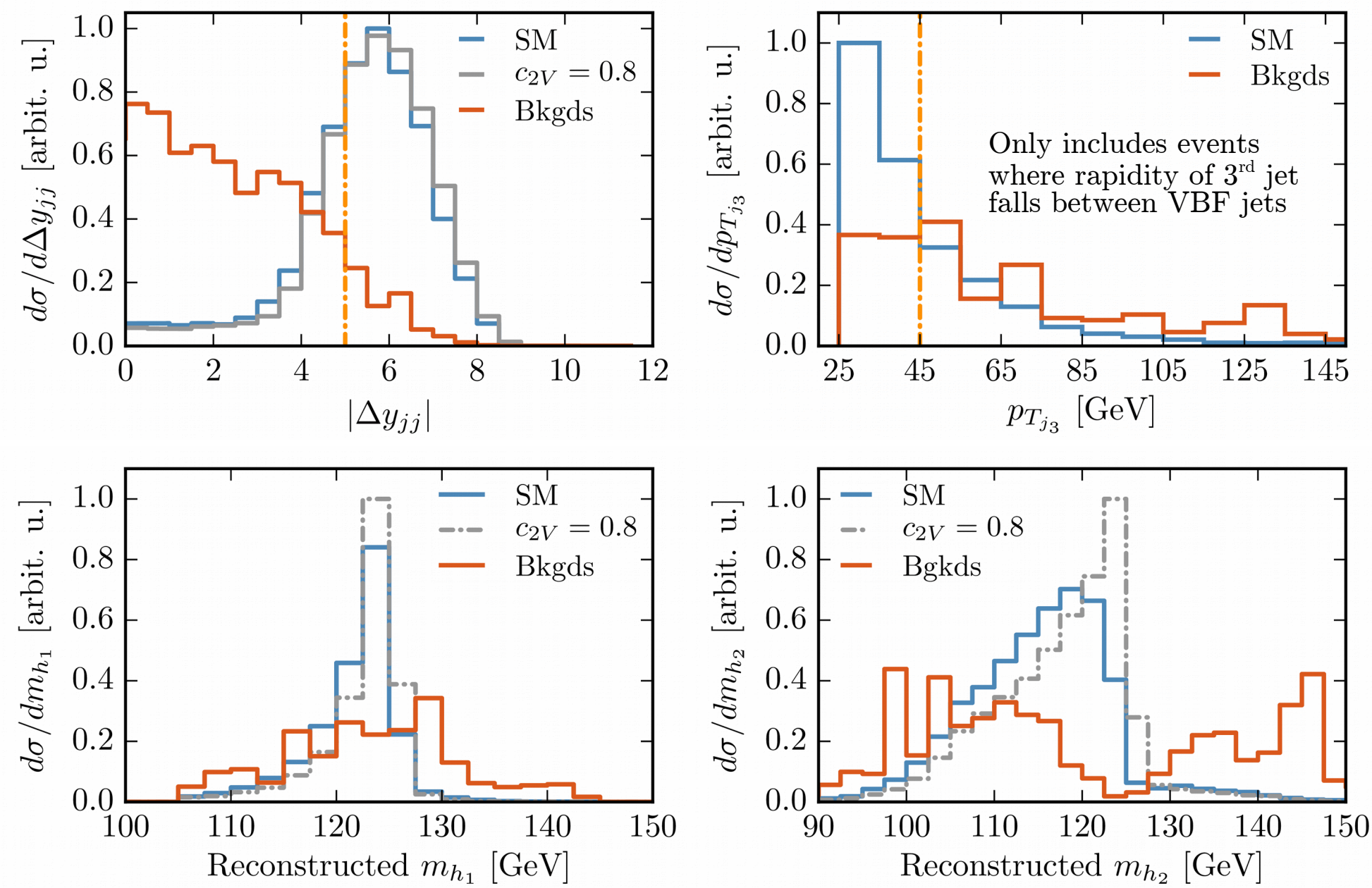
Summary

- Double Higgs production in VBF will constrain deviations, if present, in hhVV couplings
- Boosted kinematics gives a crucial handle to tame backgrounds
- 20% precision achievable at the HL-LHC and projections for HE-LHC will be available shortly

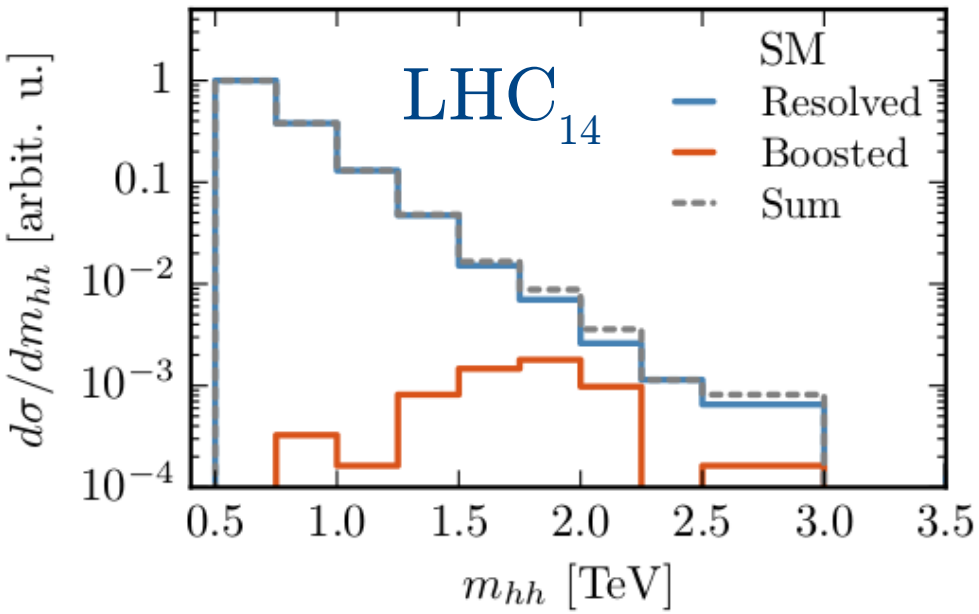
This is a crucial probe of the EWSB sector of the SM

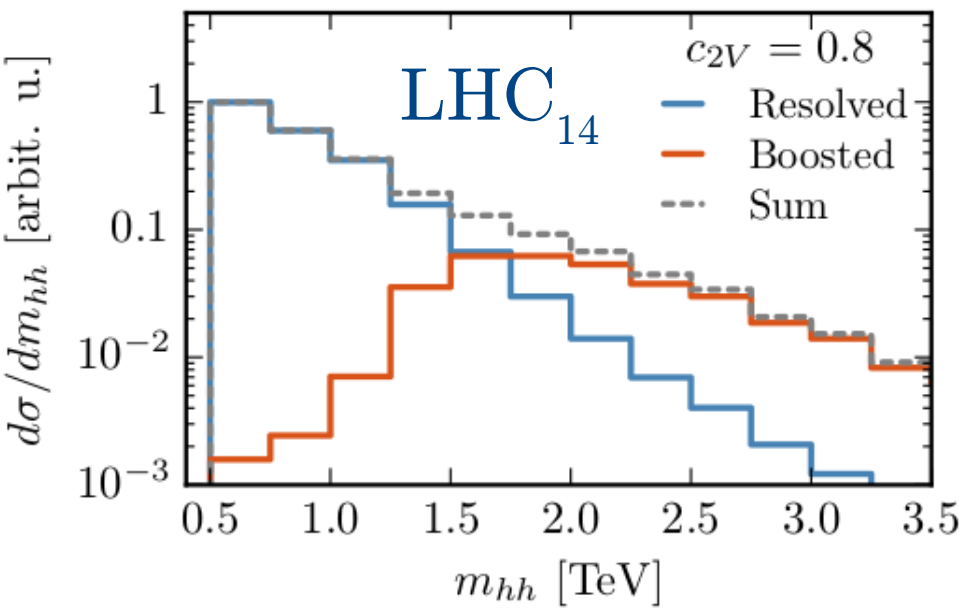
Thank you!

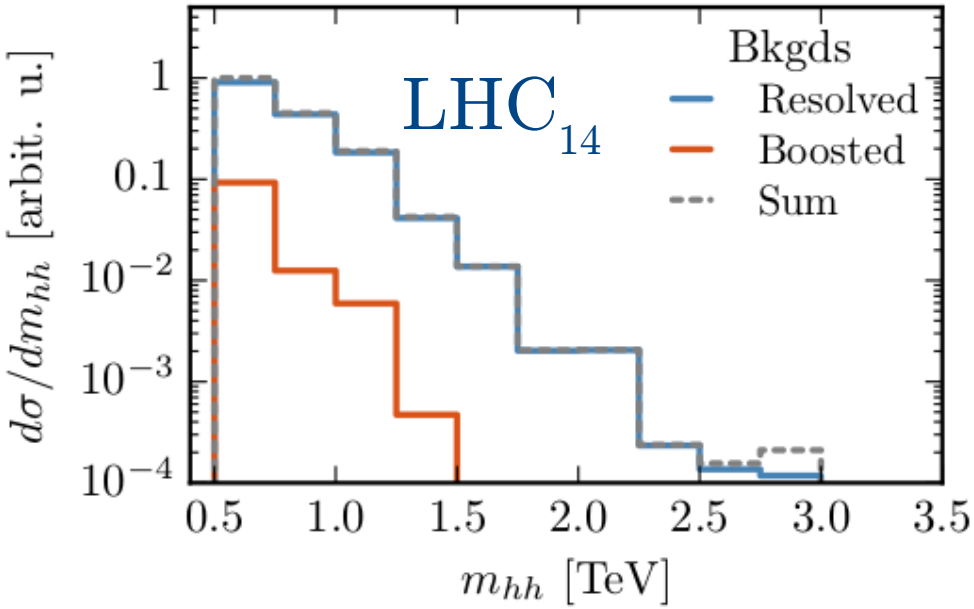
Taming the background

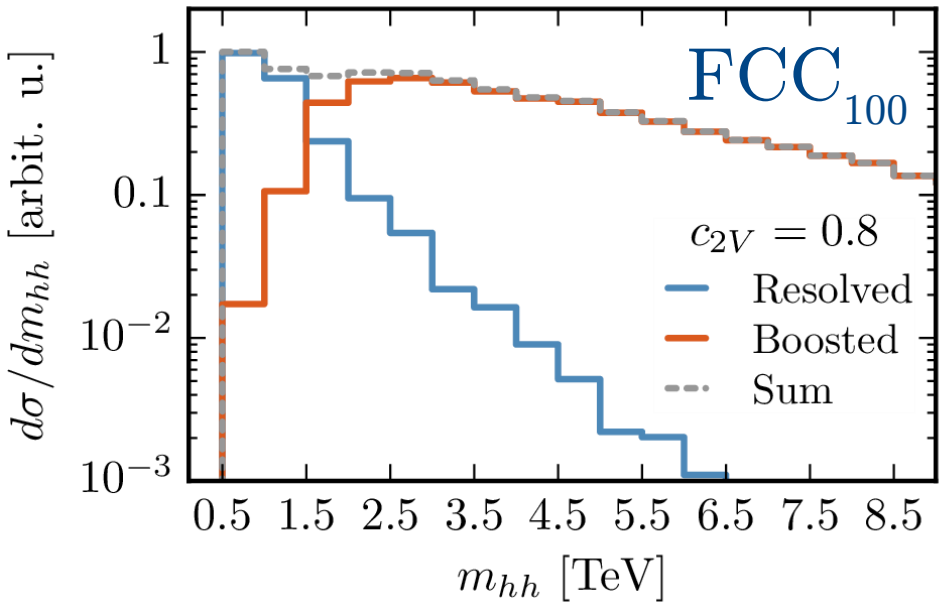


Scale invariant tagging



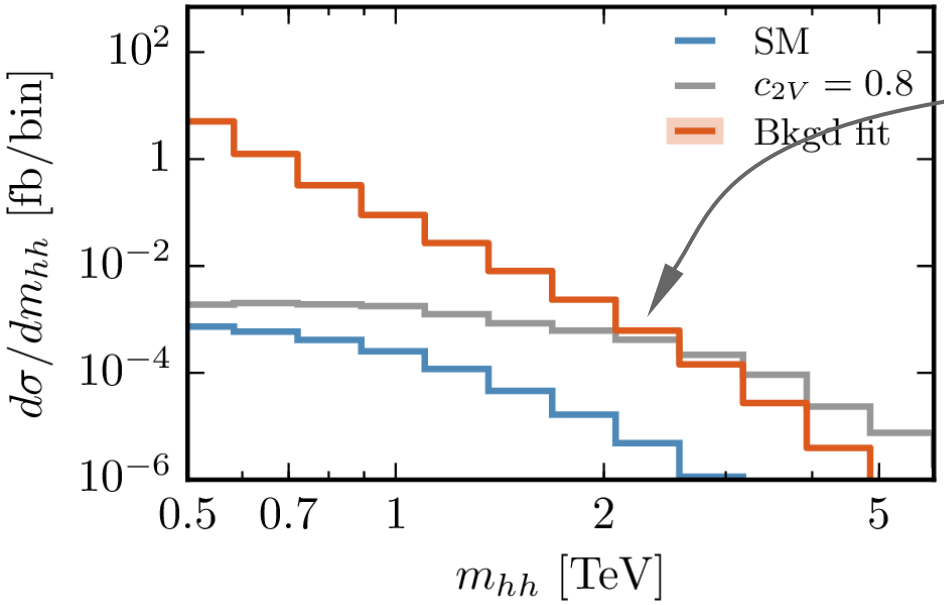






Populating the tail in our analysis

- Sensitivity is driven by the tail. Therefore good modelling is imperative



$d\sigma/db_j/(\sum_i d\sigma/db_i) \sim 10^{-6}$
$\rightarrow$ need 1M events to get 1 event in this bin.
$\rightarrow$Accounting for efficiency of all cuts and requiring 100 events here means need to generate 10^{12} events!

- Solution: generate weighted events and fit the background
- For signal, can also put generation cut on m_{hh} but this does not work for background