Higgs pair production in vector boson fusion at the LHC and beyond

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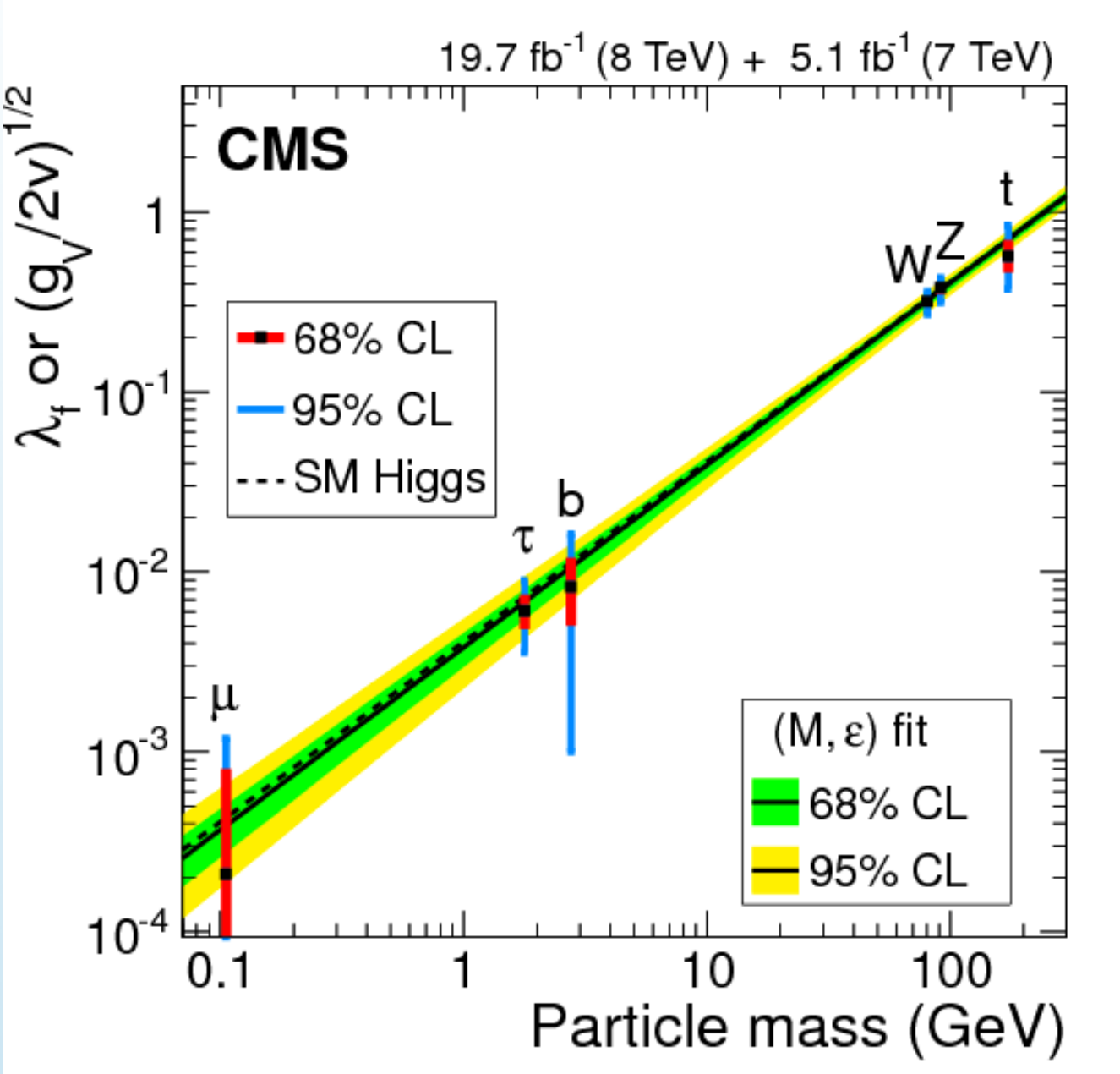
F. Bishara, R. Contino and J. Rojo, arxiv:1611.03860

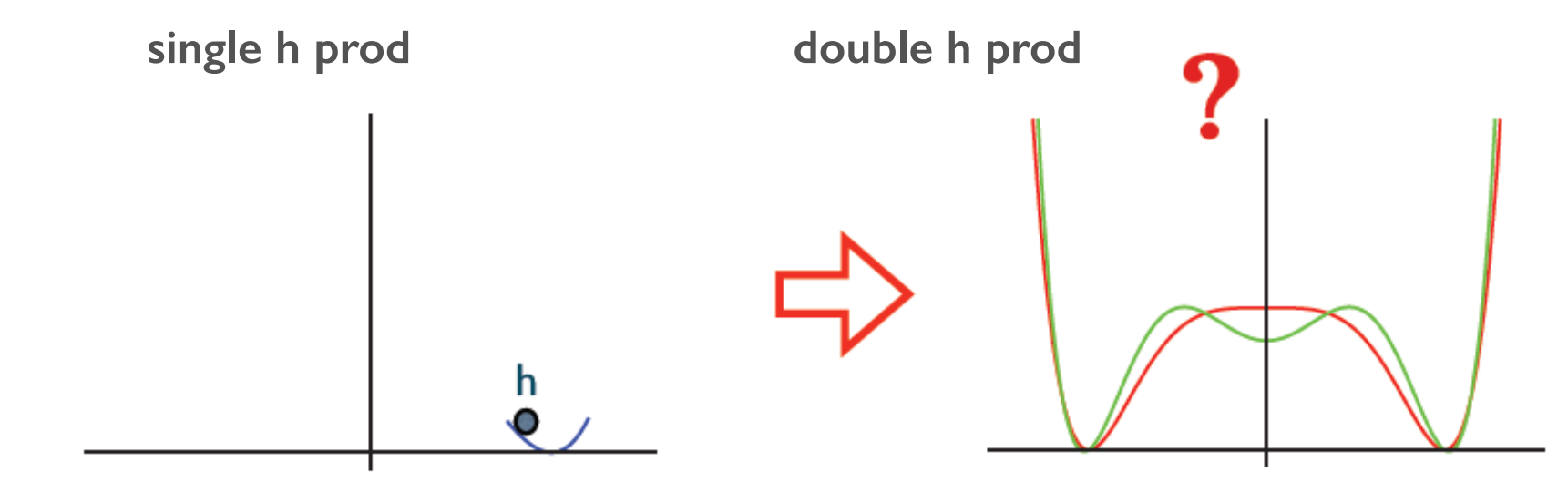
EW symmetry breaking: what do we know



- **Yukawa/Couplings** between Higgs and SM particles **proportional to mass**
- The Higgs boson is **responsible to break EW symmetry and give particles mass**
- However, we still lack understanding of ***why and how*** EWS is broken
- What are the **dynamics** underlying EW symmetry breaking?

EW symmetry breaking: what we don't know

- **Current measurements** (couplings in single Higgs production) probe **Higgs potential close to minimum**
- **Double Higgs production** essential to **reconstruct the full Higgs potential** and clarify EWSB mechanism
- The Higgs potential is *ad-hoc*: **many other EWSB mechanisms conceivable**



Higgs mechanism

$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda (h^\dagger h)^2$$

Coleman-Weinberg mechanism

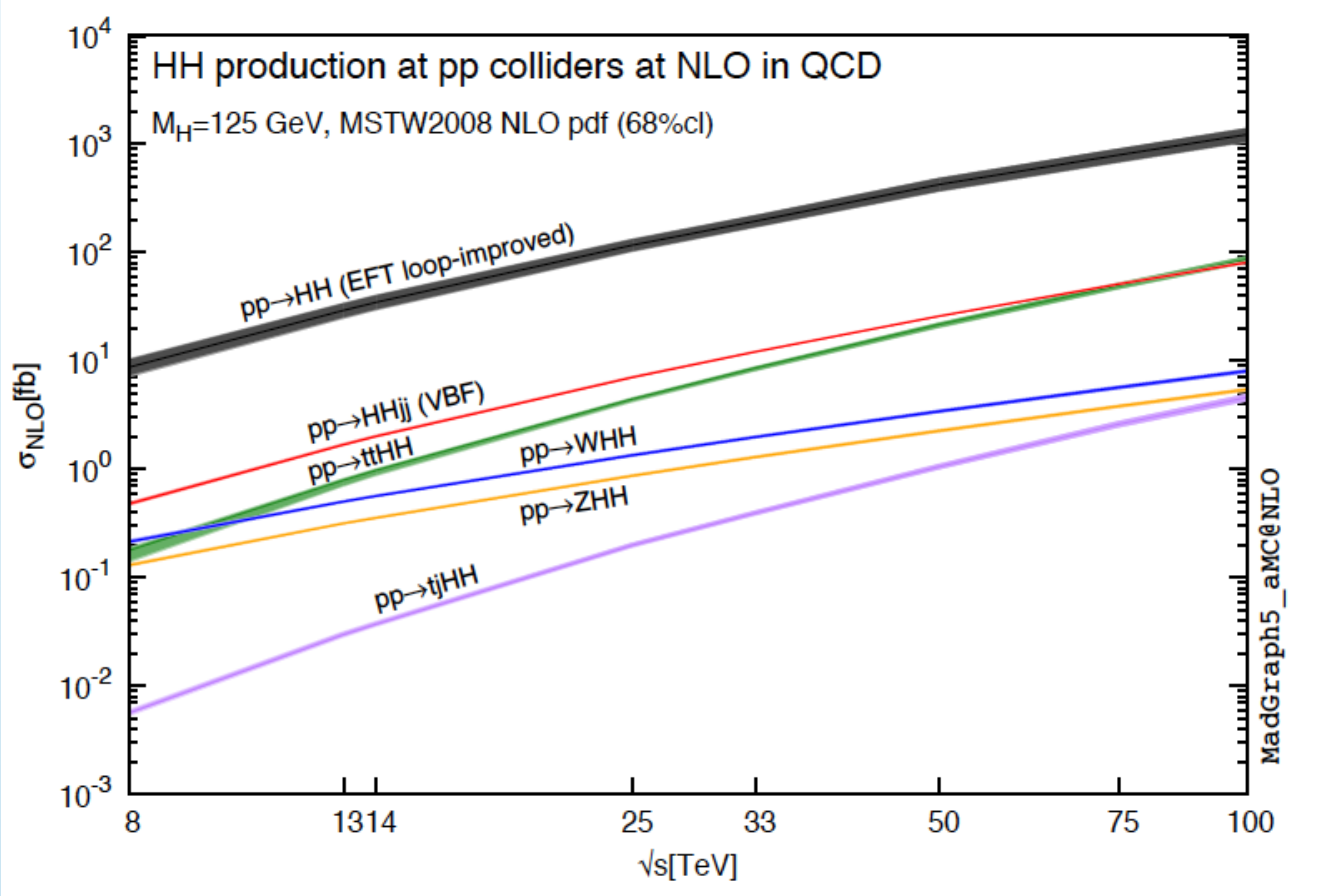
$$V(h) \to \frac{1}{2}\lambda (h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Each possibility associated to **completely different EWSB mechanism**, with crucial implications for the **hierarchy problem**, the structure of quantum field theory, and **New Physics at the EW scale**

Arkani-Hamed, Han, Mangano, Wang, arxiv:1511.06495

Higgs Pair Production at the LHC

- **Double Higgs production** allows accessing **crucial components of the Higgs sector**:
  - ☑ Reconstruct the **full electroweak symmetry breaking potential**
  - ☑ Probe the **Higgs self-interaction**
  - ☑ Probe the **doublet nature** of the Higgs by means of the **hhVV coupling**
- In the SM, **hh rates are small:** in the leading gluon-fusion production mode, the **cross-section at 14 TeV** is only **40 fb,** further suppressed by branching fractions



Higgs pair production in gluon fusion

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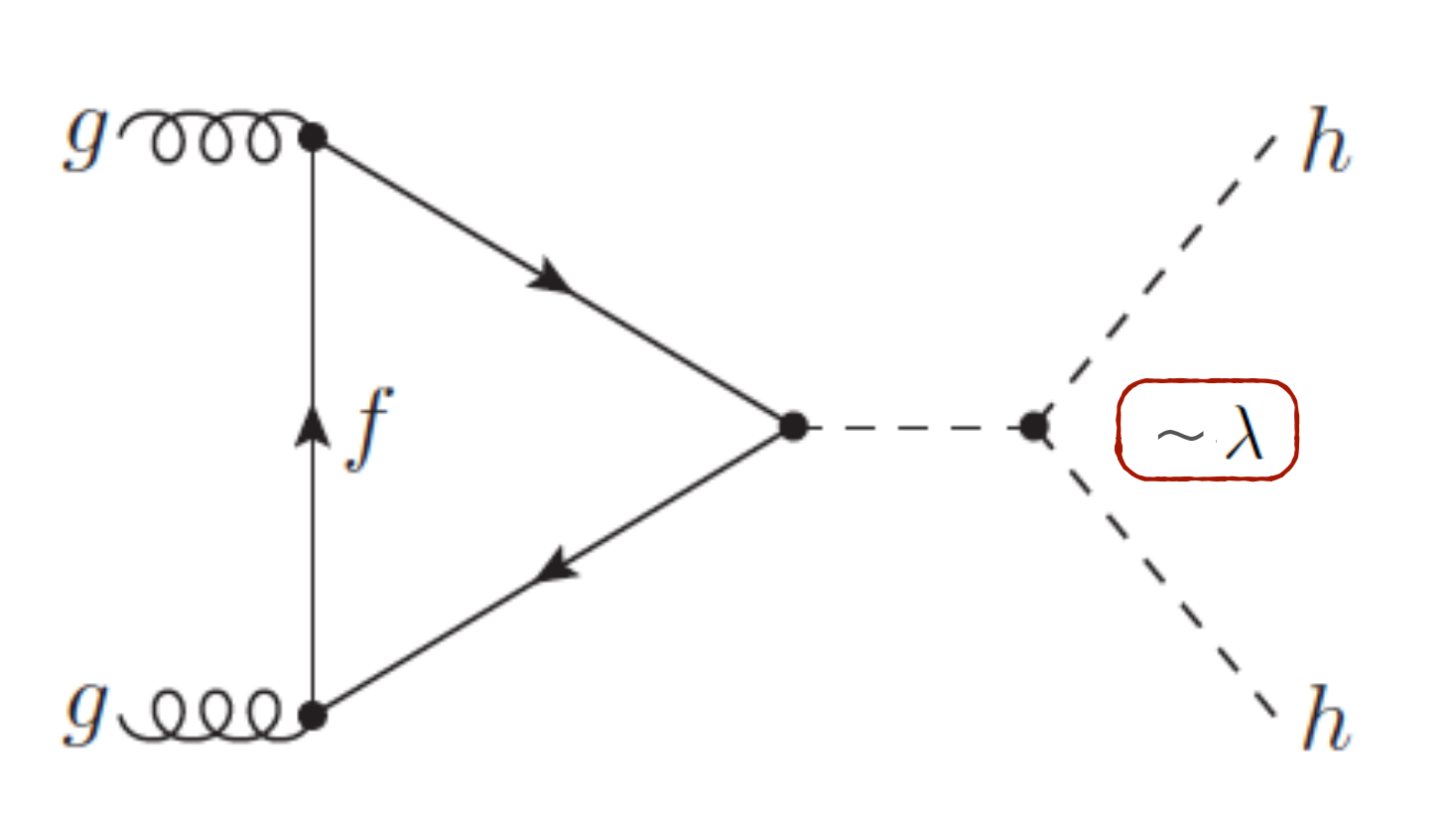
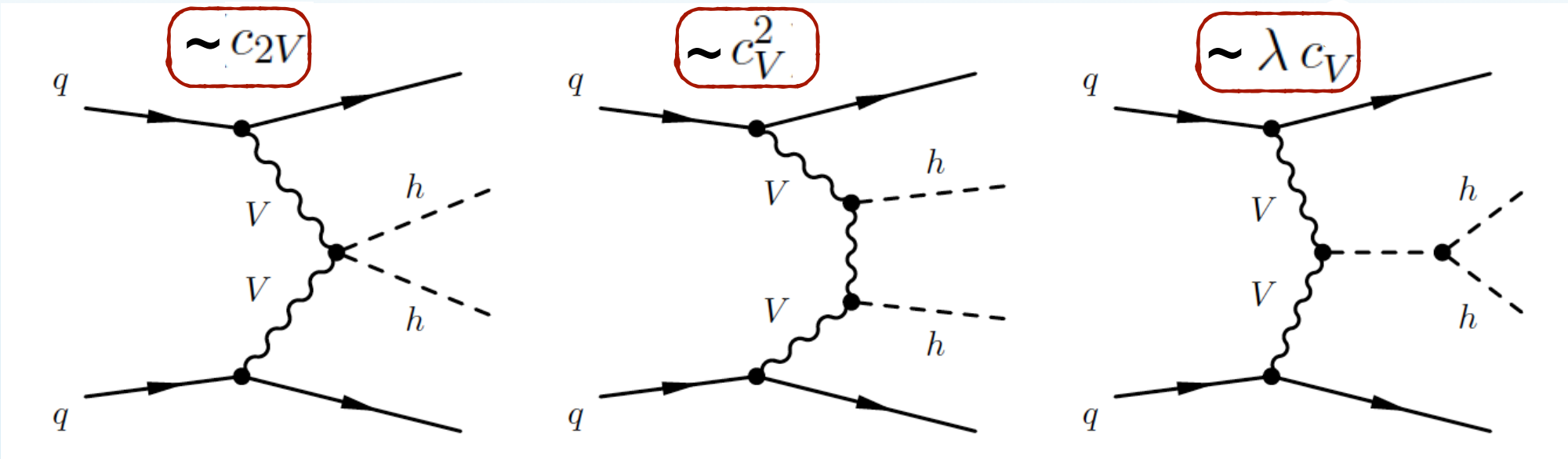


$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda (h^\dagger h)^2$$

Higgs pair production in VBF

- In the absence of the Higgs boson, the amplitude for **vector-boson scattering** (VBS) **grows** with the partonic center-of-mass energy, until eventually **unitarity is violated**
- In the SM, the Higgs boson **unitarizes the high-energy behaviour** of VBS amplitudes



at high energies $\longrightarrow$

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

Is this **cancellation exact** (as in SM, $c_{2V} = c_V^2$) or only **approximate (BSM, $c_{2V} \neq c_V^2$)?**

No model-independent information on c_{2V} available so far at the LHC

Even for small deviation of the SM couplings, **striking signals within the reach of Run II!**

EW symmetry breaking: what we don't know

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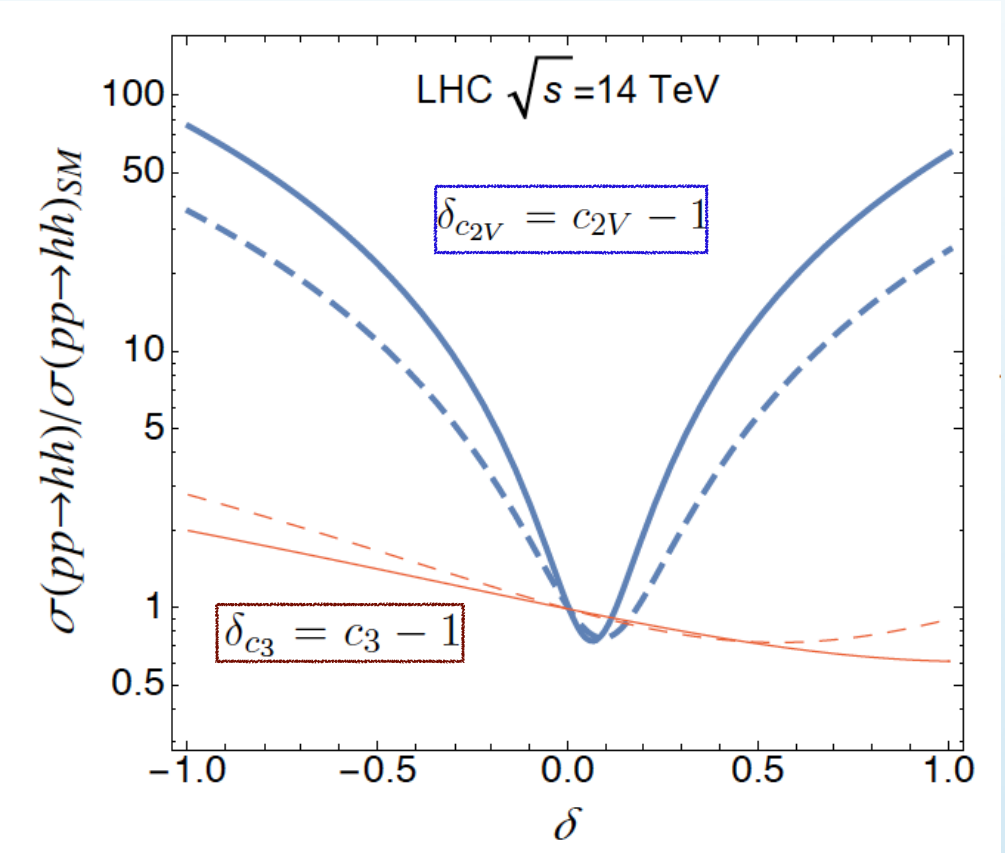


On the other hand, VBF production has **very little sensitivity to the Higgs self-coupling …**

at high energies →

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

Exploiting the VBF channel for di-Higgs

- Signal generation with **MadGraph5** using customized UFO model
- **Event rates** can increase by **up to a factor 30** as compared to SM if new physics is present
- At a 100 TeV collider, **10^5 events before cuts** even for SM couplings

Signal: VBF $hh \to b\bar{b}b\bar{b}$					
$\{c_V, c_{2V}, c_3\}$		LHC 14 TeV		FCC 100 TeV	
		σ (fb)	$N_{ev}(\mathcal{L} = 3\,\mathrm{ab}^{-1})$	σ (fb)	$N_{ev}(\mathcal{L} = 10\,\mathrm{ab}^{-1})$
{1,1,1}	SM	0.26	780	14.8	$1.5 \cdot 10^5$
{1,0,1}		4.4	$1.3 \cdot 10^4$	593	$5.9 \cdot 10^6$
{1,2,1}		2.5	$7.5 \cdot 10^3$	471	$4.7 \cdot 10^6$
{1,0,0}		5.8	$1.7 \cdot 10^4$	656	$6.6 \cdot 10^6$
{1,0,-1}		7.5	$2.3 \cdot 10^4$	731	$7.3 \cdot 10^6$
{1,1,0}		0.64	$1.9 \cdot 10^3$	29.8	$3.0 \cdot 10^5$
{0.84,0.40,0.48}	MCHM5 $\xi = 0.3$	0.78	$2.3 \cdot 10^3$	75.7	$7.6 \cdot 10^5$

Exploiting the VBF channel for di-Higgs

- Generation of **QCD multijet backgrounds** highly CPU time-intensive
- Generated at LO with **Sherpa** (weighted and unweighted events), **cross-checked with ALPGEN**
- **Gluon-fusion di-Higgs** production now background to VBF production
- The **irreducible 4b multijet background** is **seven orders of magnitude larger than the SM signal** at the generation level. How to overcome this huge difference?

Background processes						
Process	Program	Generation	$\sigma_{\rm LO}$ (fb)		K–factor	
			LHC14	FCC100	LHC14	FCC100
$4b$	Sherpa2.2	$N_{\rm ev} = 50$M weighted	$1.1 \cdot 10^6$	$1.6 \cdot 10^7$	1.7	1.7
$2b2j$	Sherpa2.2	$N_{\rm ev} = 50$M weighted	$2.6 \cdot 10^8$	$3.8 \cdot 10^9$	1.3	1.3
$t\bar{t}jj$	Sherpa2.2	$N_{\rm ev} = 10$M weighted	$1.9 \cdot 10^4$	$1.6 \cdot 10^6$	1.6	1.6
$4b2j$	ALPGEN	$N_{\rm ev} = 6$M(2M) unweighted	$5.4 \cdot 10^4$	$2.4 \cdot 10^6$	1.7	1.7
$2b4j$	ALPGEN	$N_{\rm ev} = 260$k unweighted	10^7	$5.2 \cdot 10^8$	1.3	1.3
$gg \to hh \to b\bar{b}b\bar{b}$	aMC@NLO	$N_{\rm ev} = 1$M unweighted	6.2	272	2.4	2.2

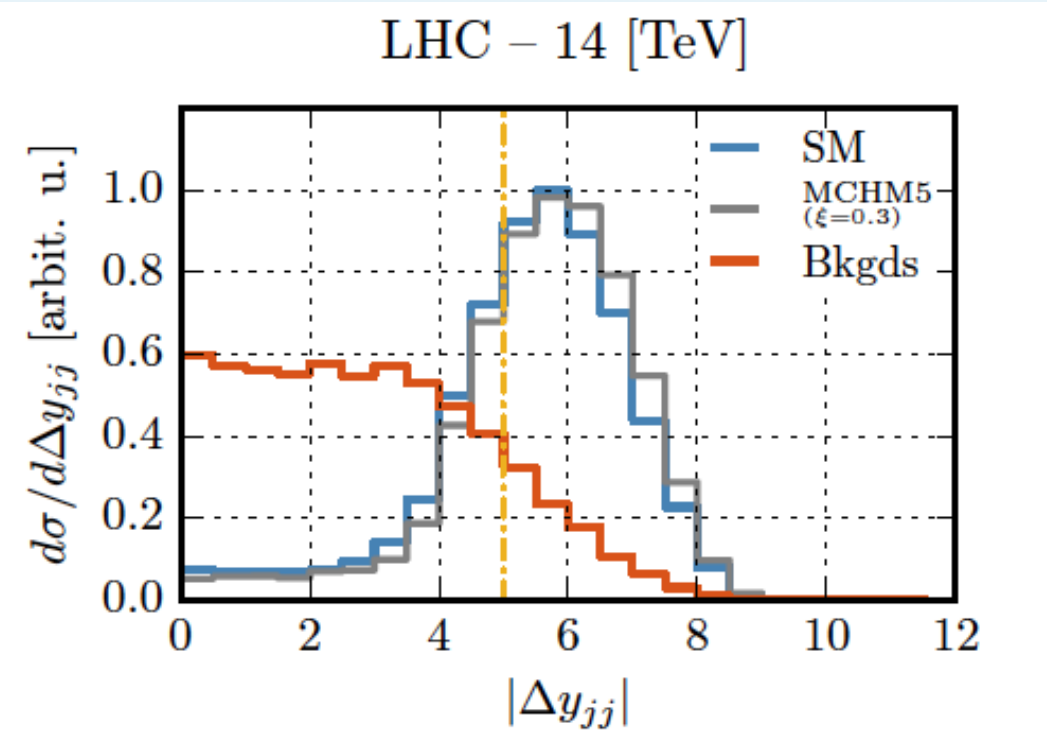
Killing backgrounds with VBF topology

The huge QCD jet backgrounds can be **reduced by exploiting the VBF topology**

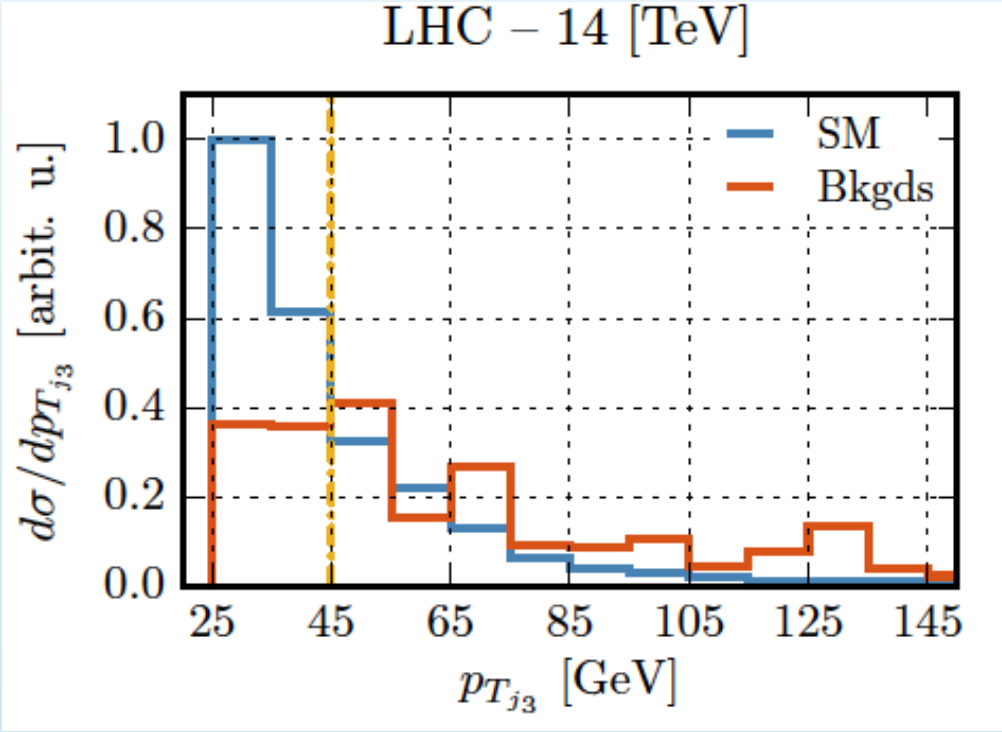
Require **two forward jets, separated in rapidity**, plus a **veto in hadronic activity** in the central region

Additional cuts in the **reconstructed Higgs invariant mass** and the **di-Higgs invariant mass m_{hh}** further reduce the QCD multijet cross-sections

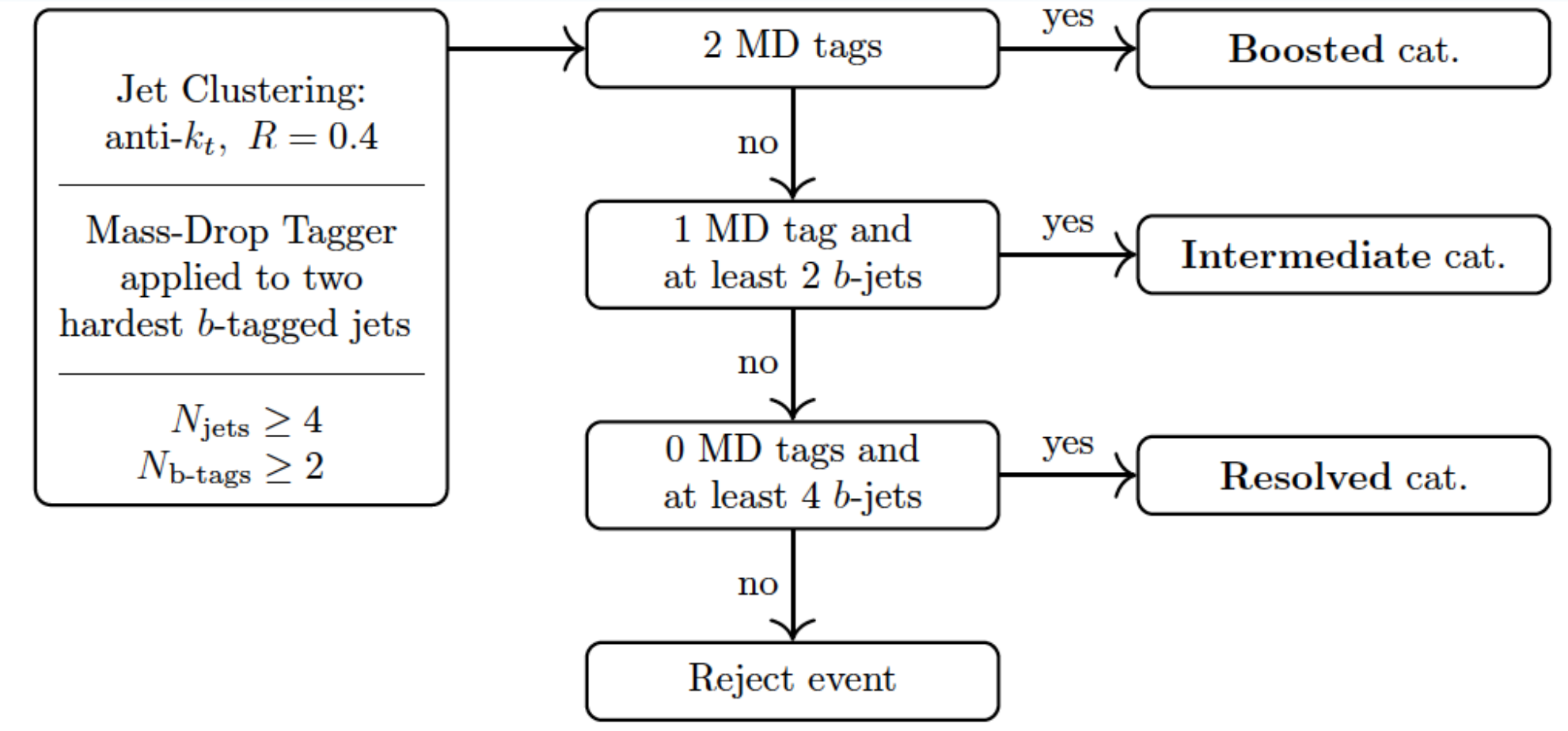
Dijet rapidity separation cut



Central jet veto cut



Scale-invariant Tagging

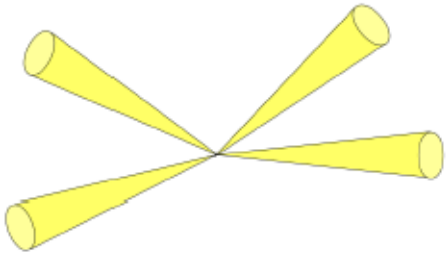


Same strategy as that used for the **analysis of the gluon-fusion channel**

Determine, **event-by-event**, degree of **boost of di-Higgs system** and optimise selection accordingly

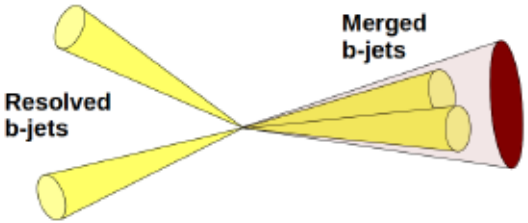
Scale-invariant Tagging

Resolved



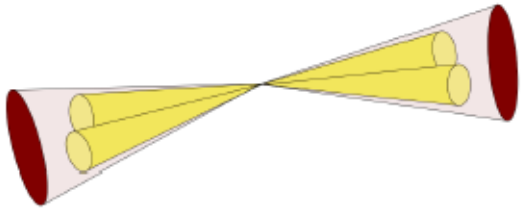
- ≥ 4 b-tagged small-R jets
- Higgs reconstruction from leading 4 jets
- Choice that minimises mass difference between dijet systems

Intermediate



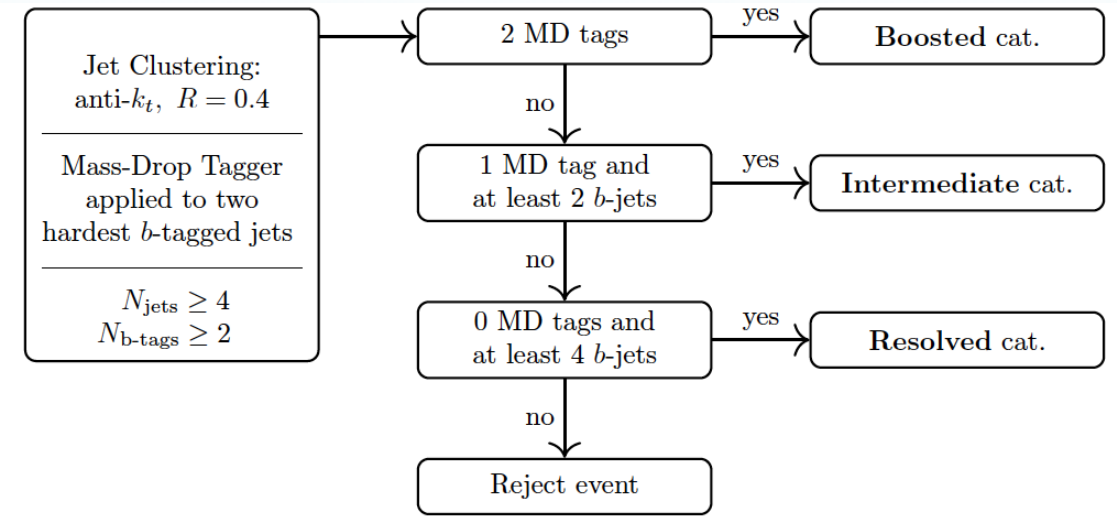
- $= 1$ large-R jet (Higgs-tagged + b-tagged) (leading Higgs)
- ≥ 2 b-tagged small-R jets
- $\Delta R > 1.2$ w.r.t. large-R jet
- Higgs reconstruction from leading 2 small-R jets
- Choice that minimises mass difference of dijet system and large-R jet

Boosted

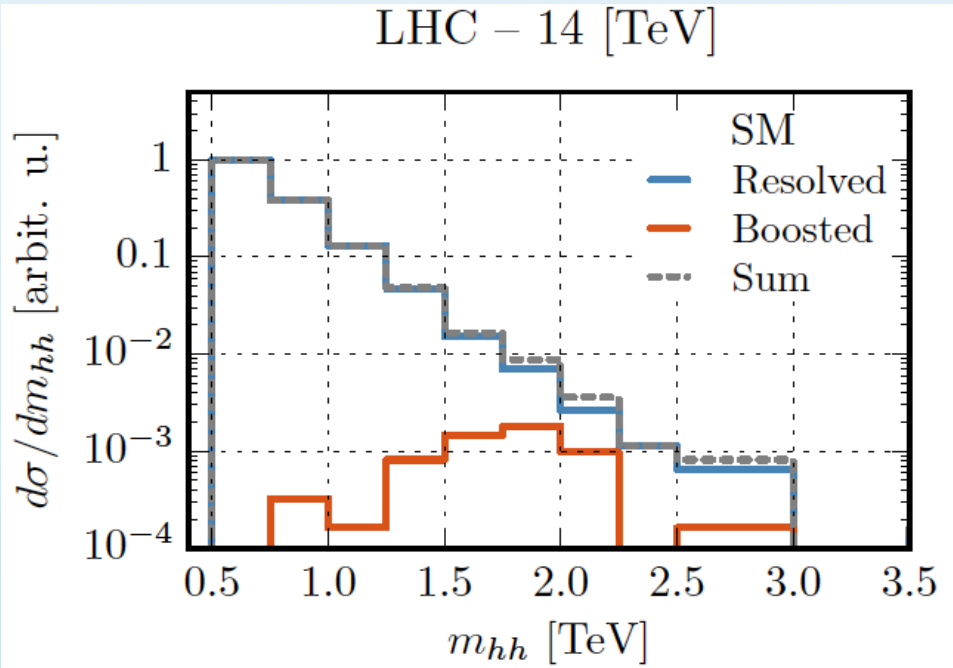


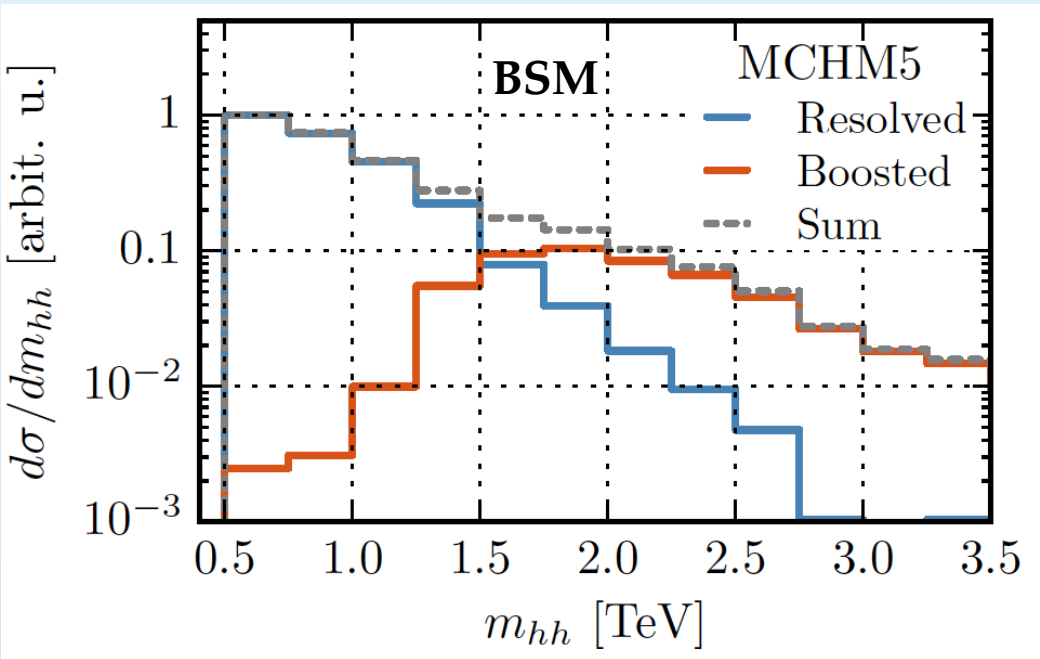
- ≥ 2 large-R jets (Higgs-tagged + b-tagged)
- Leading two jets taken as Higgs candidates

Scale-invariant Tagging



In the **SM, resolved selection** dominates, but for **BSM couplings**, **boosted topology** important



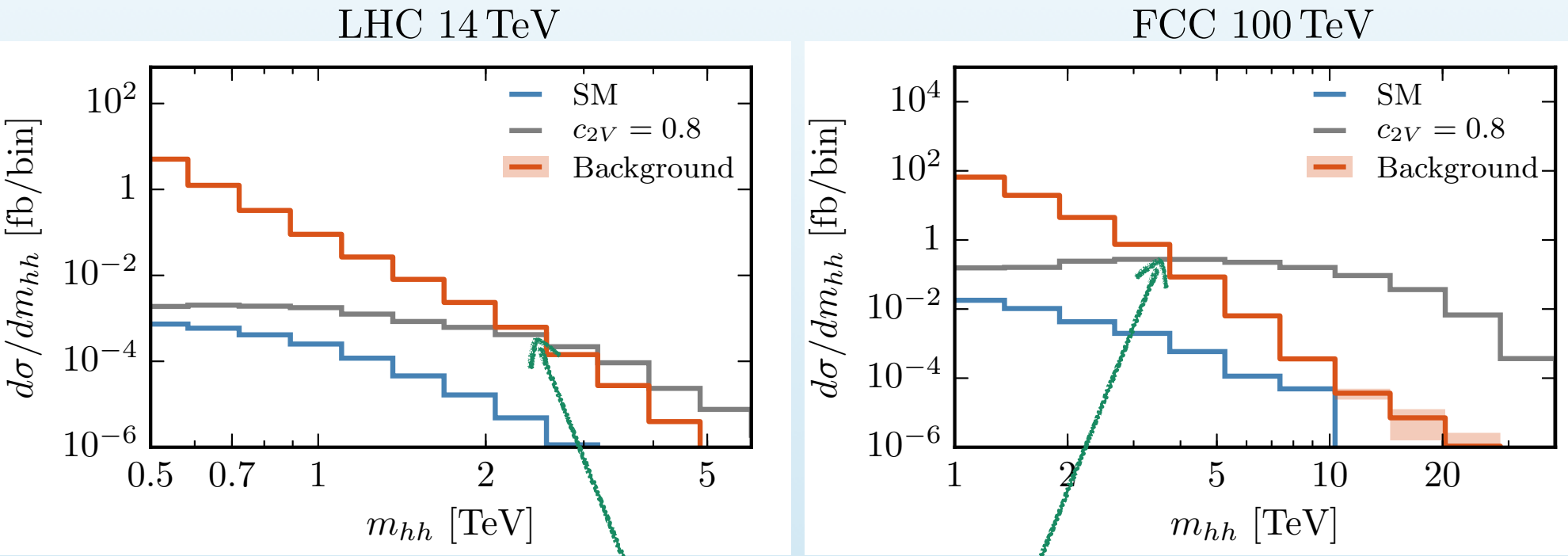


Probing the high-energy regime

After selection and analysis cuts, backgrounds are still **overwhelmingly large for m_{hh} close to threshold**

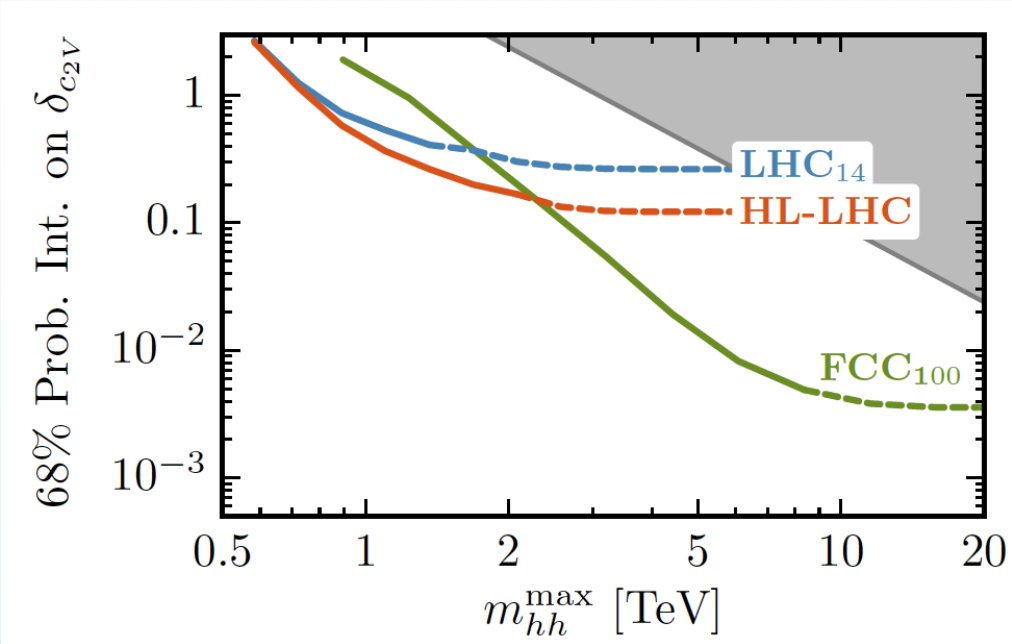
For BSM couplings, the ratio of cross-sections **between BSM and SM increases dramatically** as we probe the regions of **large m_{hh}**, eventually dominating over backgrounds

This is the key of **the sensitivity to c_{2V}** despite the tiny SM cross-sections



BSM signal (c_{2V}=0.8 benchmark point) dominates over background

Sensitivity to the hhVV coupling



	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}	$[0, 0.01]$	$[-0.01, 0.01]$

The **sensitivity to c_{2V}** improves significantly the **higher the values of m_{hh} that can be probed**

In the absence of new resonances, c_{2V} can be constrained **down to 45% (20%) of its SM value at the 1-sigma level** at the LHC (HL-LHC), assuming SM couplings

Take-away message

Searches for **di-Higgs production in the vector-boson-fusion channel** should start already during **Run II**, without waiting for the HL-LHC!

The di-Higgs frontier at the LHC

- Higgs pair production is a **cornerstone of the LHC program** for the coming years, allowing us to reconstruct the **EWSB potential** and to test the nature of the **EWSB mechanism**
- The **4b final state** offers the highest yields, but requires **clever analysis techniques** for taming the **overwhelming QCD background**, both theoretically and experimentally
- In the Vector-Boson-Fusion channel, the **steep rise of the cross-section with the di-Higgs invariant mass in the case of deviations from the SM couplings** is the key for the high sensitivity of this process to $\mathbf{c_{2V}}$
- For such complex final sates like 4b, the **ultimate signal optimization** of the extraction of the Higgs couplings requires the use of **Machine Learning methods** such as **Multivariate Analysis**

Higgs pair production holds unique potential
to uncover BSM dynamics at the LHC!

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Thanks for your attention!

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