Pinning down the hhVV coupling from Higgs boson pair production in vector-boson fusion

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Based on ongoing work in collaboration with
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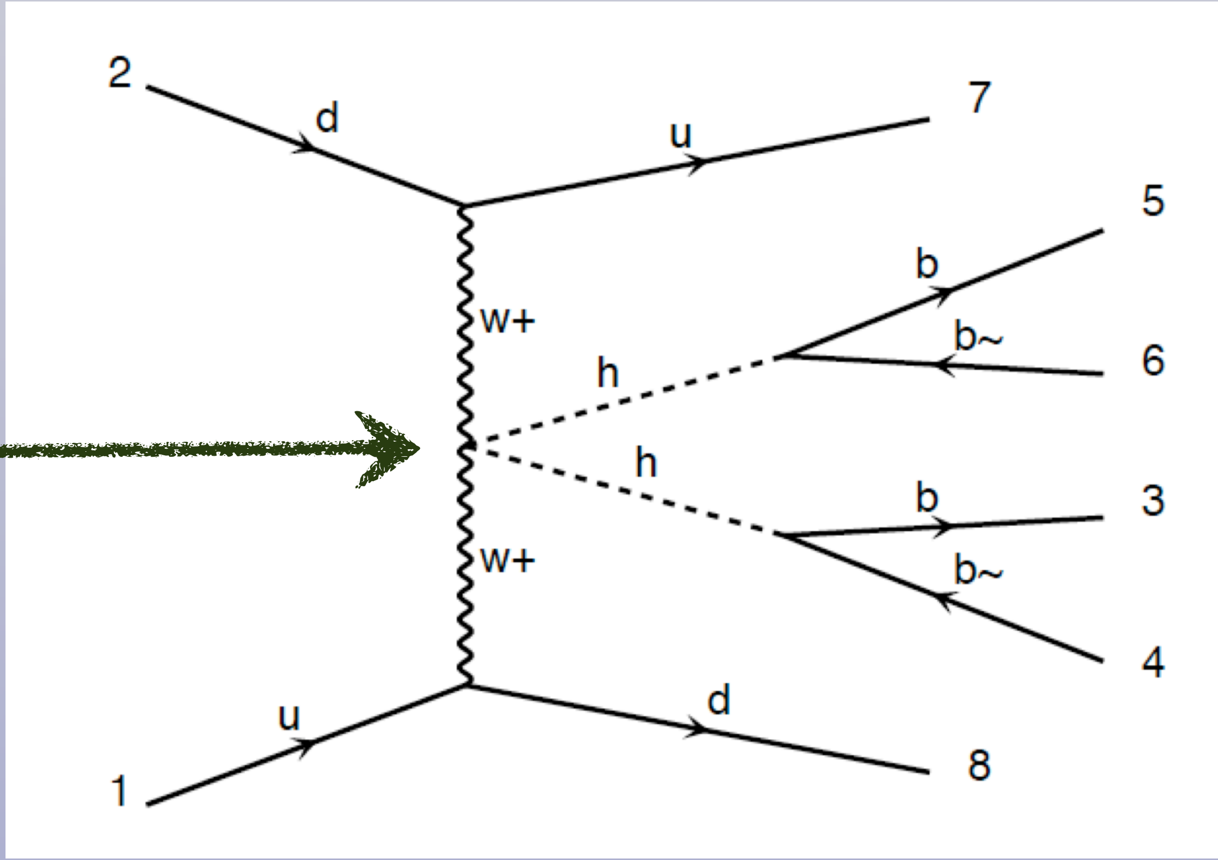
Motivation

- **Higgs pair production** is one of the most crucial processes for future LHC runs, since it allows to perform stringent tests of our understanding of electroweak symmetry breaking
- In the SM, the dominant process is gluon fusion, with **~33 fb (~1.5 pb)** at 14 TeV (100 TeV): direct sensitivity to the **Higgs trilinear coupling λ_3** (J. Baglio's talk)
- Higgs pair production in **Vector-Boson Fusion** is small in the SM: **2 fb (80 fb)** at 14 TeV (100 TeV), yet provides unique information on the **hhVV coupling**
- VBF Higgs pair production can be **substantially enhanced** in scenarios where electroweak symmetry breaking is broken by new **strong dynamics** (like in composite Higgs models)

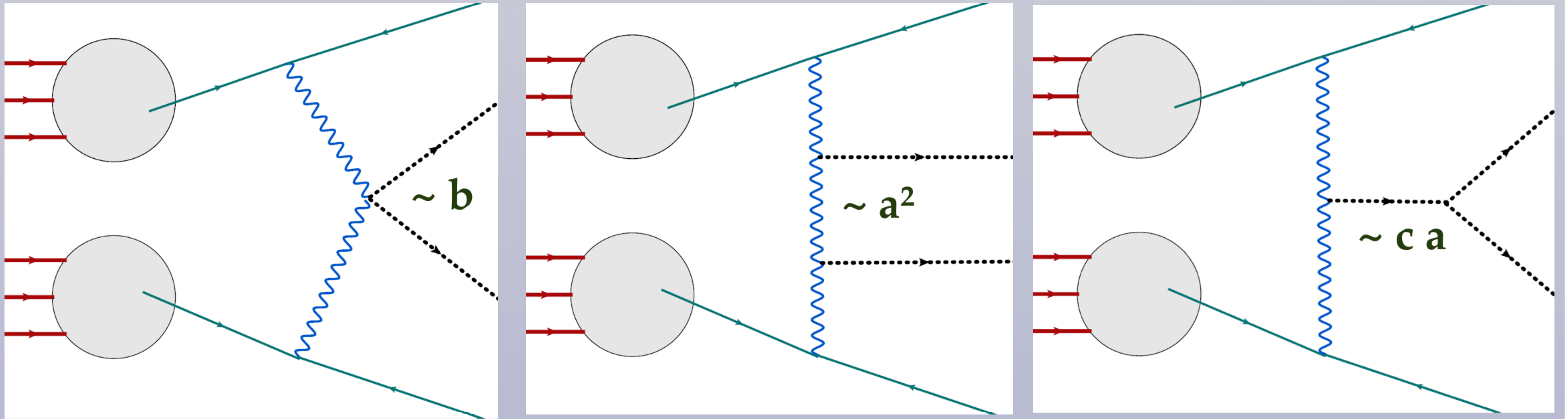
Unique direct sensitivity to the hhVV coupling



Strong Double Higgs Pair production

- In **composite Higgs models** with **new strong dynamics**, the predictions for VBF Higgs pair production at the hadron colliders can be substantially enhanced as compared to their SM values

$$
\begin{aligned}
\mathcal{L} =& \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right] \\
& - m_i\, \bar{\psi}_{Li}\, \Sigma \left(1 + c\,\frac{h}{v} + \dots\right) \psi_{Ri} + \mathrm{h.c.}\,,
\end{aligned}
$$



- In the SM, **a=b=c=1**
- The **hVV coupling** is constrained from single Higgs production up to **O(10-20%)**
- No model independent direct constraints available on the **hhVV and hhh couplings** yet

Strong Double Higgs Pair production

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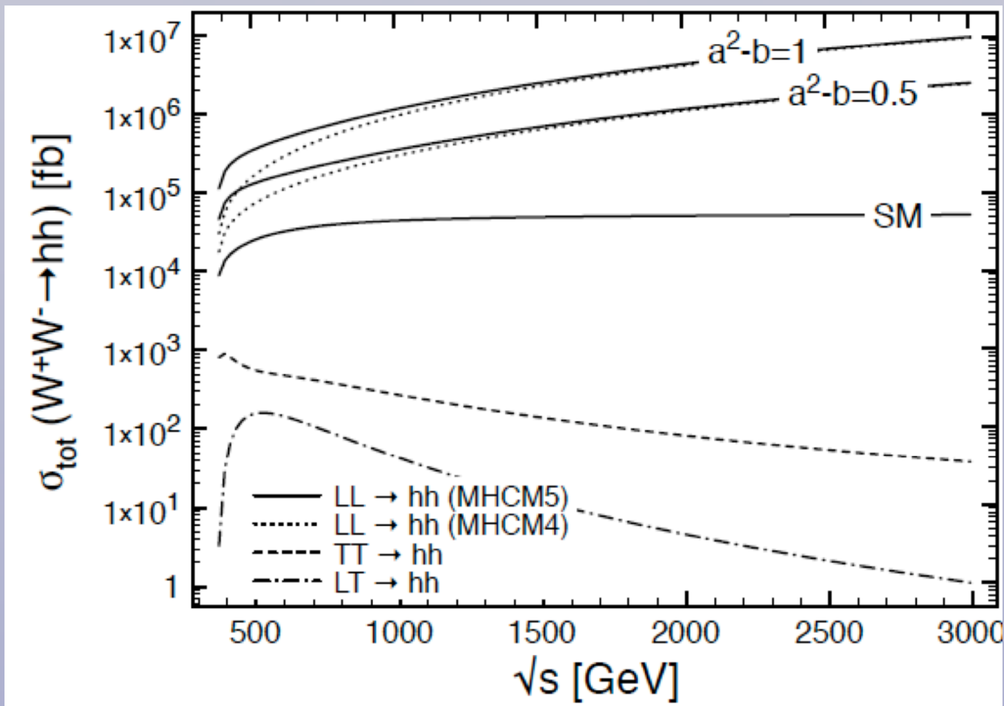
$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left[1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right] - m_i\,\bar{\psi}_{Li}\,\Sigma\left(1 + c\,\frac{h}{v} + \dots\right)\psi_{Ri} + \text{h.c.}\,,$$

$$\frac{d\sigma_{LL\to hh}}{dt} \simeq \frac{(b-a^2)^2}{32\pi\,v^4}\,, \qquad \frac{d\sigma_{TT\to hh}}{dt} \simeq \frac{g^4(a^4 + (b-a^2)^2)}{64\pi\,s^2}\,,$$



- Most **striking signature** is that the **new strong dynamics** lead to a much harder distribution in **M_{HH}** as compared to the SM
- Original feasibility study by **Contino, Grojean, Moretti, Piccinini and Rattazi in arxiv:1002.1011** assumed a **180 GeV Higgs** and focused on the dominant **WW final state**
- Our goal is to revisit the analysis for **m_H=125 GeV** for the final states with larger BR.
- For **b ≠ a**, Higgs pair produced with **large boosts: jet substructure techniques** needed

Event Generation

- The low rates for Higgs pair production in VBF emphasize the need for final states with large branching fractions: we use here the **4b2j** and **2b2τ2j** final states.

- **Signal events** have been generated with **MadGraph5_aMC@NLO**, with the **hhV, hhVV and hhh couplings** rescaled in a way that $c_V = c_{2V} = c_3 = 1$ are the SM values

$$C_V \kappa_{hhV} hhV \,, \qquad C_{2V} \kappa_{hhVV'} VV' \,, \qquad C_3 \kappa_{hhh} hhh$$

- Analytical dependence of the cross-section in these parameters given by **(R. Contino et al, arxiv:1309.7038)**

$$\sigma = c_V^4 \sigma_{\rm SM} \left(1 + A\delta_{c_{2V}} + B\delta_{c_3} + C\delta_{c_{2V}}\delta_{c_3} + D\delta_{c_{2V}}^2 + E\delta_{c_3}^2\right) \qquad \delta_{c_{2V}} \equiv 1 - \frac{c_{2V}}{c_V^2} \qquad , \delta_{c_3} \equiv 1 - \frac{c_3}{c_V}$$

- Background events have been generated with **Alpgen and MadGraph5**
  - ☑ **4b2j final state** QCD multijet production of **4b2j and 2b4j**
  - ☑ **2b2τ2j final state: ttjj** dominant background, **2b4j** also relevant when light jets fake **τ** leptons

- **Signal and background** parton level events are then showered and hadronized with **Pythia8.** Jet clustering is performed using **FastJet** with the anti-kT algorithm with **R=0.4**

- **Realistic b-tagging and τ-tagging,** including mistag rates, along the lines of ATLAS/CMS, has been implemented.

- We have studied the results both at the **LHC 14 TeV with 300 fb^{-1} and 3000 fb^{-1}** and at an **FCC at 100 TeV with 3000 fb^{-1}**

Selection and analysis cuts

Our basic selection cuts, including the **vector-boson fusion cuts** to suppress background, are

Basic acceptance cuts

$$p_{Tj} \geq 25 \text{ GeV}\,, \quad p_{Tb} \geq 25 \text{ GeV}\,, \quad p_{T\tau} \geq 25 \text{ GeV}$$

$$|\eta_j| \leq 4.5\,, \quad |\eta_b| \leq 2.5\,, \quad |\eta_\tau| \leq 2.5$$

$$\Delta R_{j\tau} \geq 0.4\,, \quad \Delta R_{b\tau} \geq 0.4\,, \quad \Delta R_{\tau\tau} \geq 0.2\,,$$

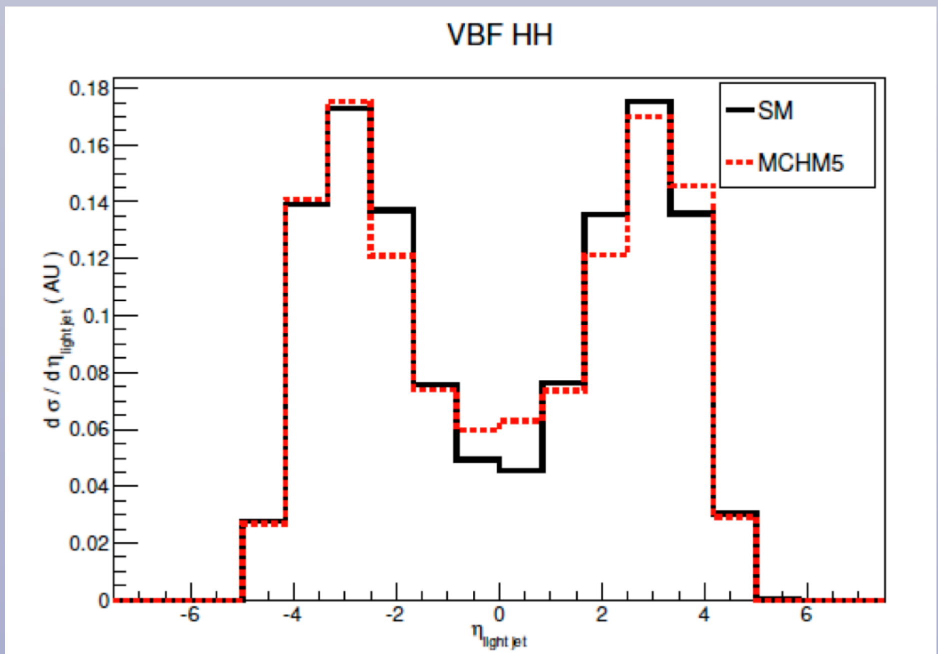
VBF cuts

$$m_{jj} \geq 1000 \text{ GeV}\,, \qquad \Delta y_{jj} \geq 5.0\,.$$

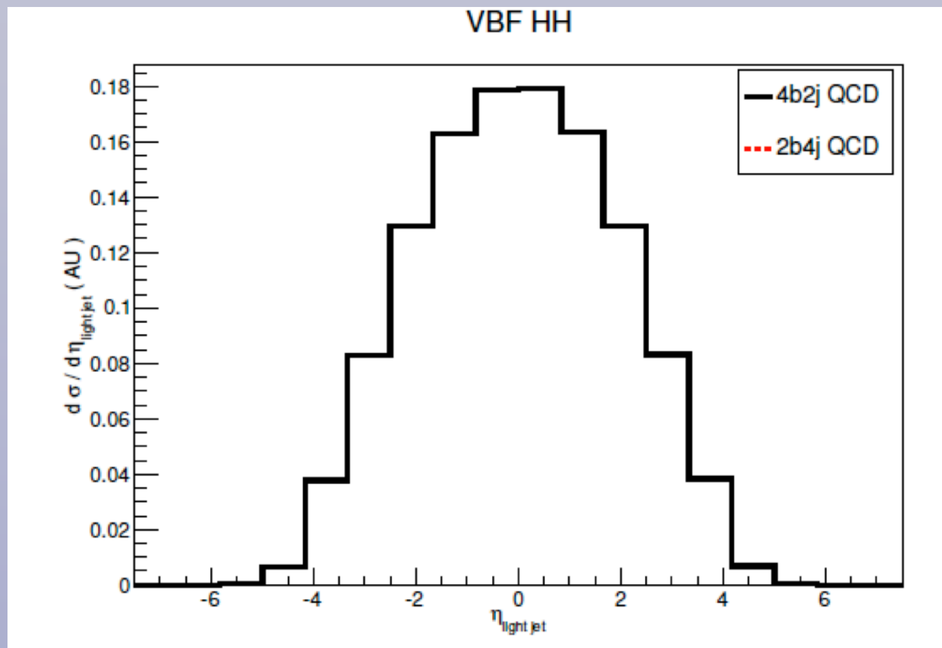
Central jet veto

$$p_{Tj,3} \leq 30 \text{ GeV} \quad \text{if} \quad \eta_{j,\min} \leq \eta_{j,3} \leq \eta_{j,\max}$$

VBF tagging jets rapidity - Signal



VBF tagging jets rapidity - Background



Event rates at the LHC and beyond

LHC 14 TeV	$\sigma(4b)$ (fb)	$N_{\rm ev}(3\,{\rm ab}^{-1})$
Standard Model	0.10	300
$c_V, c_{2V}, c_3 = 1.0, 0.0, 1.0$	2.45	7380
$c_V, c_{2V}, c_3 = 1.0, 2.0, 1.0$	1.59	4770
$c_V, c_{2V}, c_3 = 1.0, 1.0, 0.0$	0.29	870
$c_V, c_{2V}, c_3 = 1.0, 1.0, 3.0$	0.27	810
MCHM5 with $\xi = 0.3$ $c_V, c_{2V}, c_3 = 0.84, 0.40, 0.48$	0.41	1230

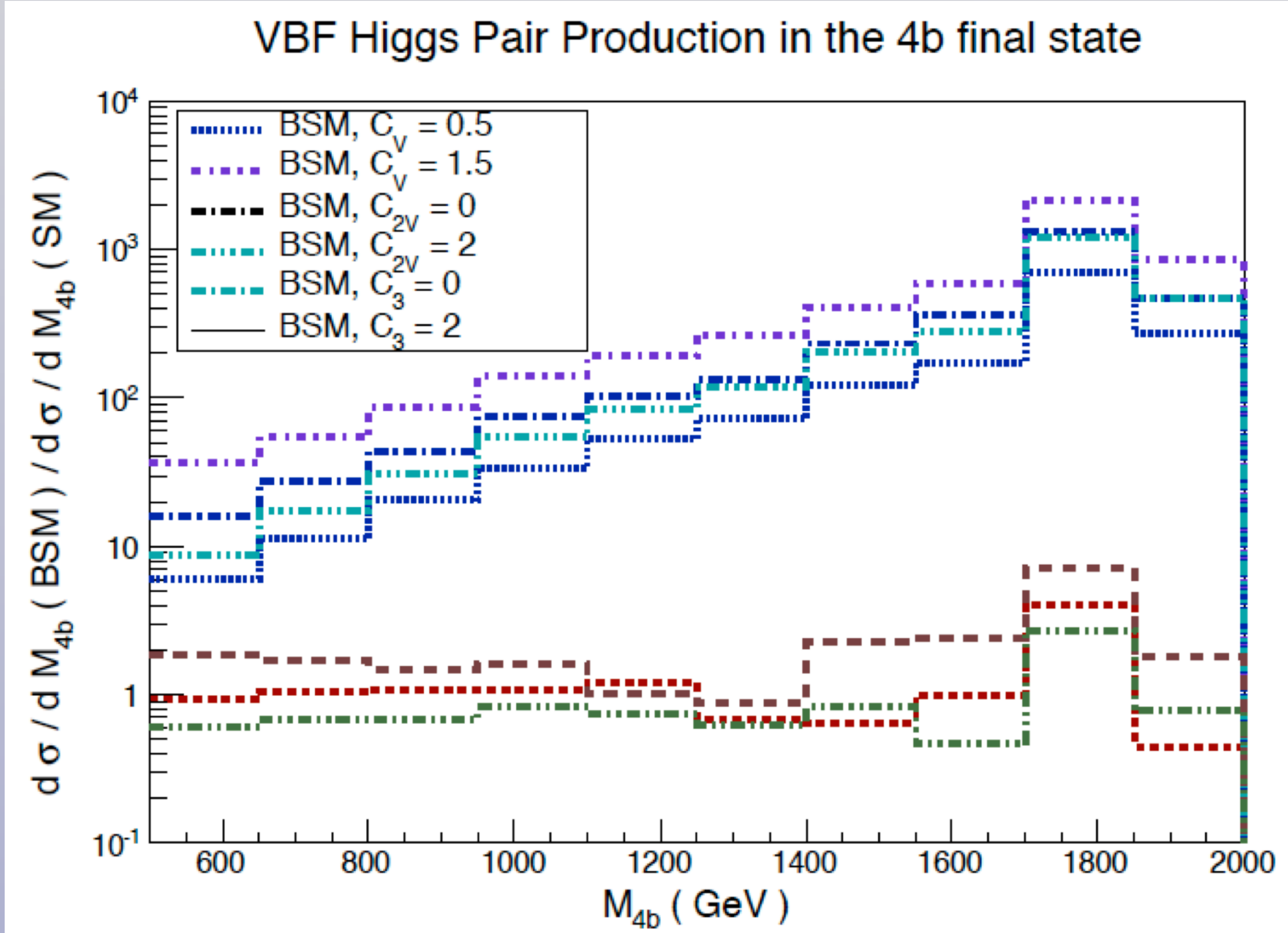
- Cross-sections for the **4b final state** after basic selection cuts
- Event rates very substantially enhanced when the **hhVV** coupling departs from its SM value: high sensitivity to **new strong BSM dynamics**
- Large increase in events rates when going up to **100 TeV**: greatly improved sensitivity

FCC 100 TeV	$\sigma(4b)$ (fb)	$N_{\rm ev}(10\,{\rm ab}^{-1})$
Standard Model	4.53	45.3K
$c_V, c_{2V}, c_3 = 1.0, 0.0, 1.0$	327	3.3M
$c_V, c_{2V}, c_3 = 1.0, 2.0, 1.0$	280	2.8M
$c_V, c_{2V}, c_3 = 1.0, 1.0, 0.0$	11.0	110K
$c_V, c_{2V}, c_3 = 1.0, 1.0, 3.0$	9.2	92K
MCHM5 with $\xi = 0.3$ $c_V, c_{2V}, c_3 = 0.84, 0.40, 0.48$	39	390K

Boosting the diHiggs final state

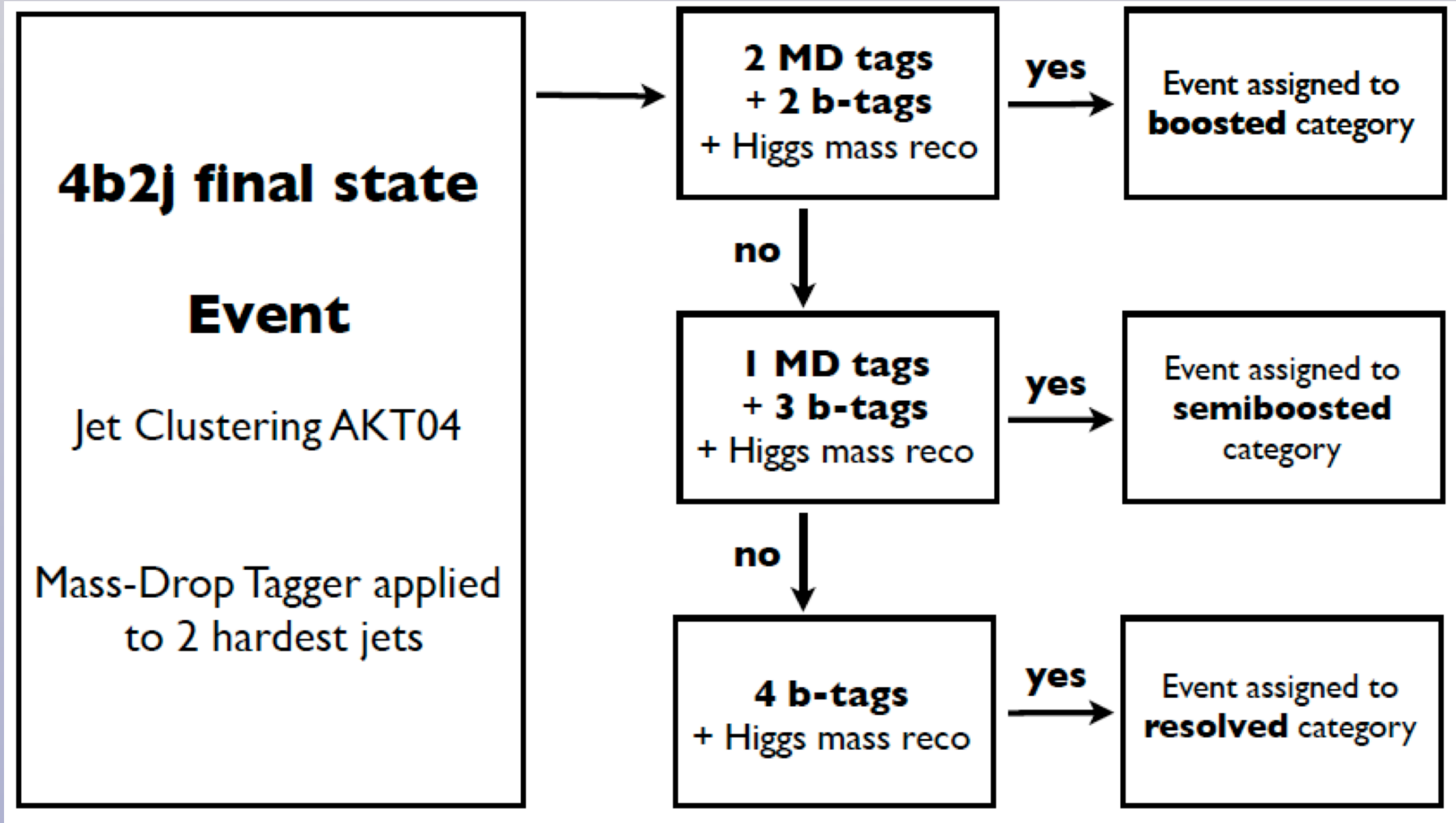
- The ratio of BSM/SM cross-sections **grows strongly** as a function of **M_{HH}**

- Exploiting the **hardness of the M_{HH} distribution** in composite Higgs models is the key to tame the overwhelming QCD backgrounds, and requires the use of **boosted jet techniques**



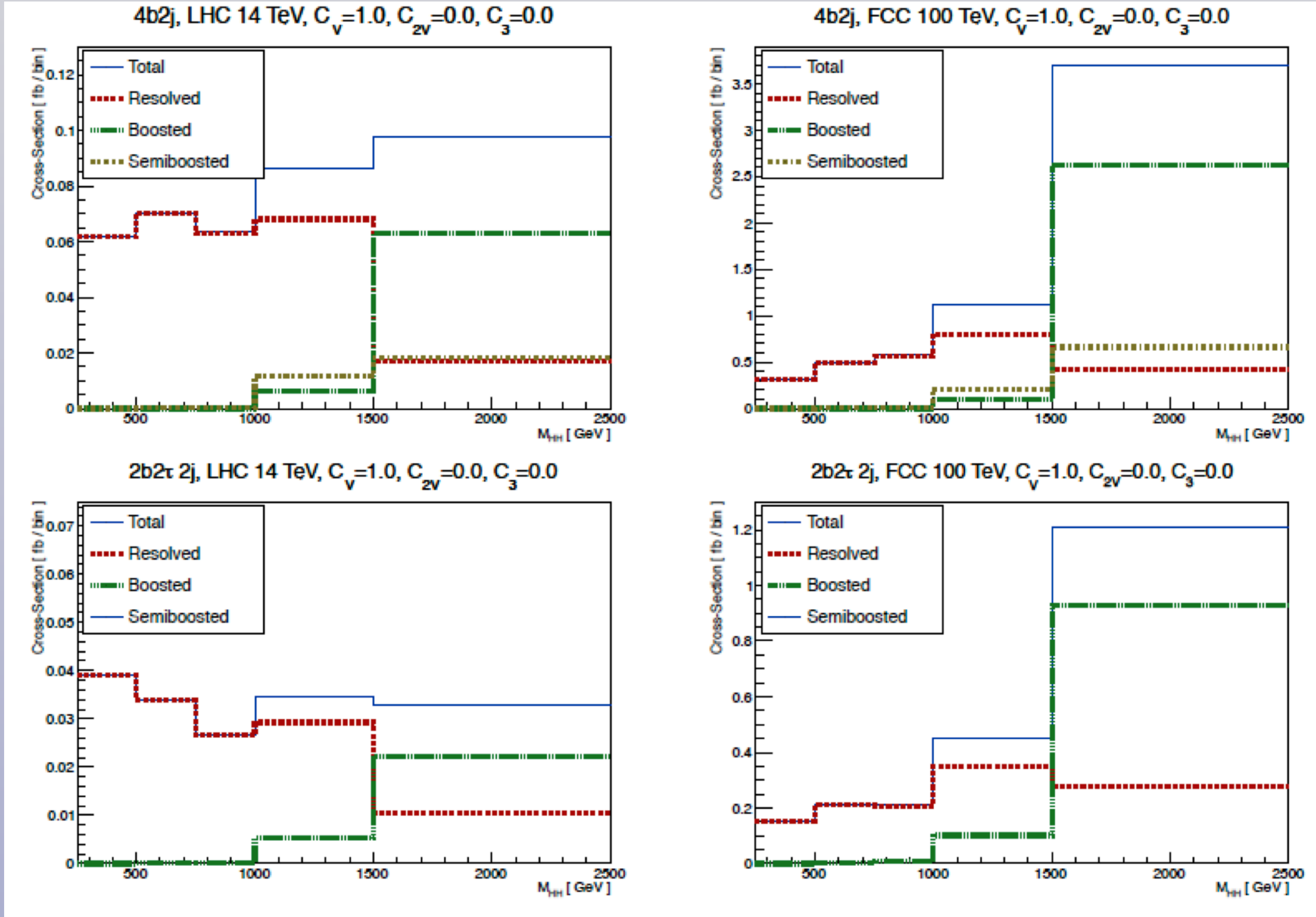
Analysis strategy

- An efficient analysis technique requires to simultaneously explore, on a event-by-event basis, **all possible signal topologies: boosted, semiboosted and resolved**
- This can be achieved with the so-called **scale-invariant resonance tagging**, which provides a smooth matching between boosted and resolved kinematics **(Gouzevitch, Oliveira, Rosenfeld, JR, Salam, Sanz, arxiv:1303.6636)**
- For jet substructure, we use the **BDRS mass-drop tagger (Butterworth, Davidson, Rubin, Salam, arxiv:0802.2470)**



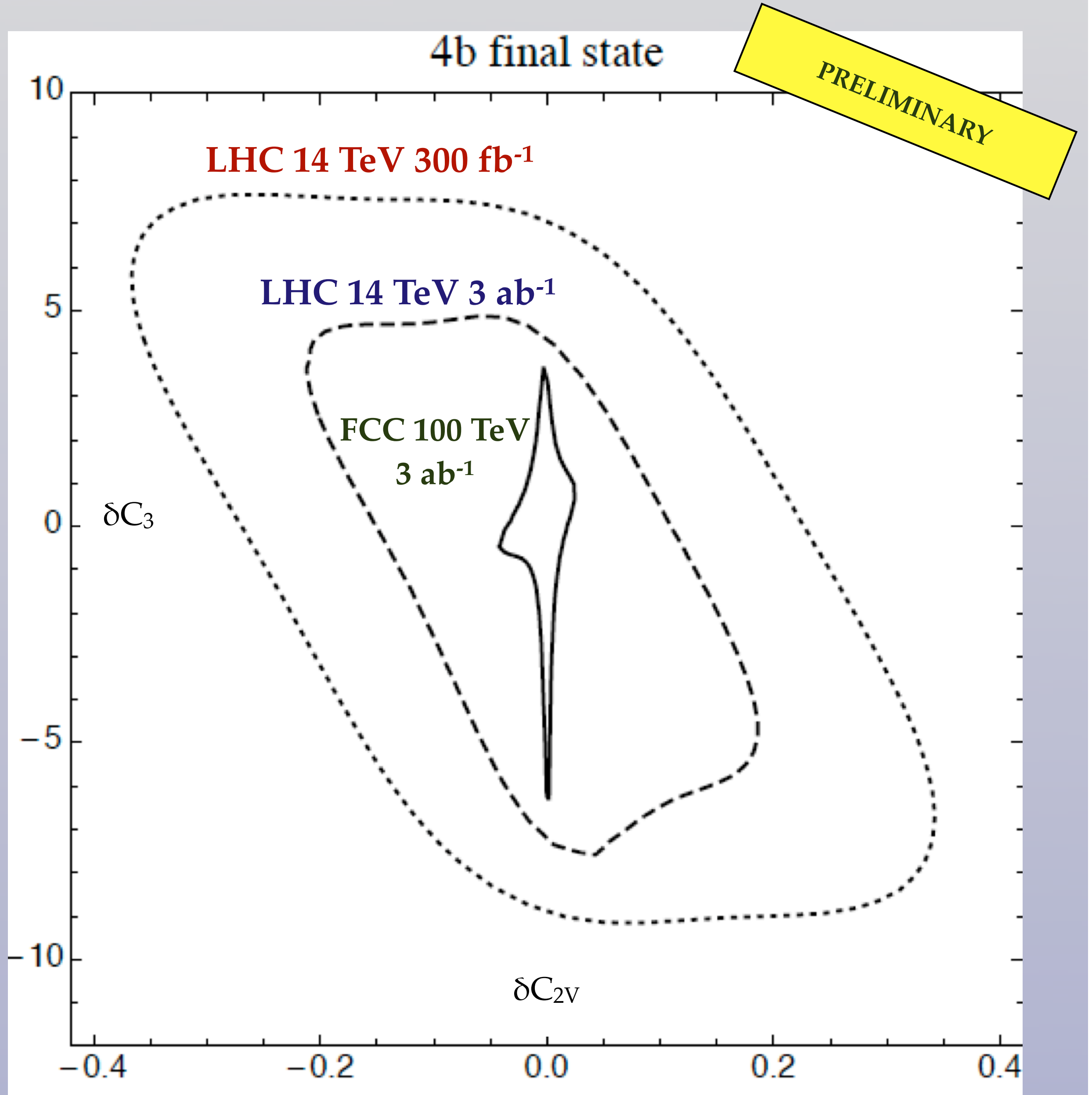
Analysis strategy

- For $\mathbf{m_{hh}}$ close to threshold, the **resolved contribution** dominates, while large $\mathbf{m_{hh}}$ is the **boosted regime**
- At the LHC, resolved and boosted configurations **similar,** while at the FCC the **boosted regime dominates**
- Boosted techniques crucial since **large** $\mathbf{m_{hh}}$ is the region more sensitive to **new strong BSM dynamics**



Results

- In the **4b final state,** 14 TeV with 300 fb^{-1} (3000 fb^{-1}) the **hhVV** coupling can be measured with **good precision: ~25-30% (10-15%)**
- As expected, the precision on the **Higgs trilinear coupling** is worse than in **gg->hh** (since backgrounds dominate *hh* threshold region)
- At the **FCC,** the **hhVV** coupling can be pinned down with **very high, few percent precision**
- We have included a 50% error in the backgrounds, to account for theory and experimental uncertainties
- Encouraging to begin to explore **Higgs pair-production in VBF** already at the **LHC Run II**



Summary and outlook

- **Higgs pair production** in the **vector-boson fusion channel** provides unique information of the mechanism underlying **electroweak symmetry breaking**
- Deviations from the SM value for the **hhVV** coupling induce large differences in event rates that grow strongly with $\mathbf{m_{hh}}$, where the di-Higgs system is **boosted** and **jet substructure techniques** are required
- Preliminary results indicate that in the **4b2j** final state we can probe at the **LHC deviations in $\mathbf{C_{2V}}$ as small as 25-30% (10-15%)** with **300 (3000) fb^{-1}**, while at the FCC we find **few-percent accuracy**
- Now completing the complementary **2b2τ2j** final state, with smaller rates but with reduced backgrounds