Boosting Strong Double Higgs Boson Production at the LHC and the FCC

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Based on ongoing work in collaboration with
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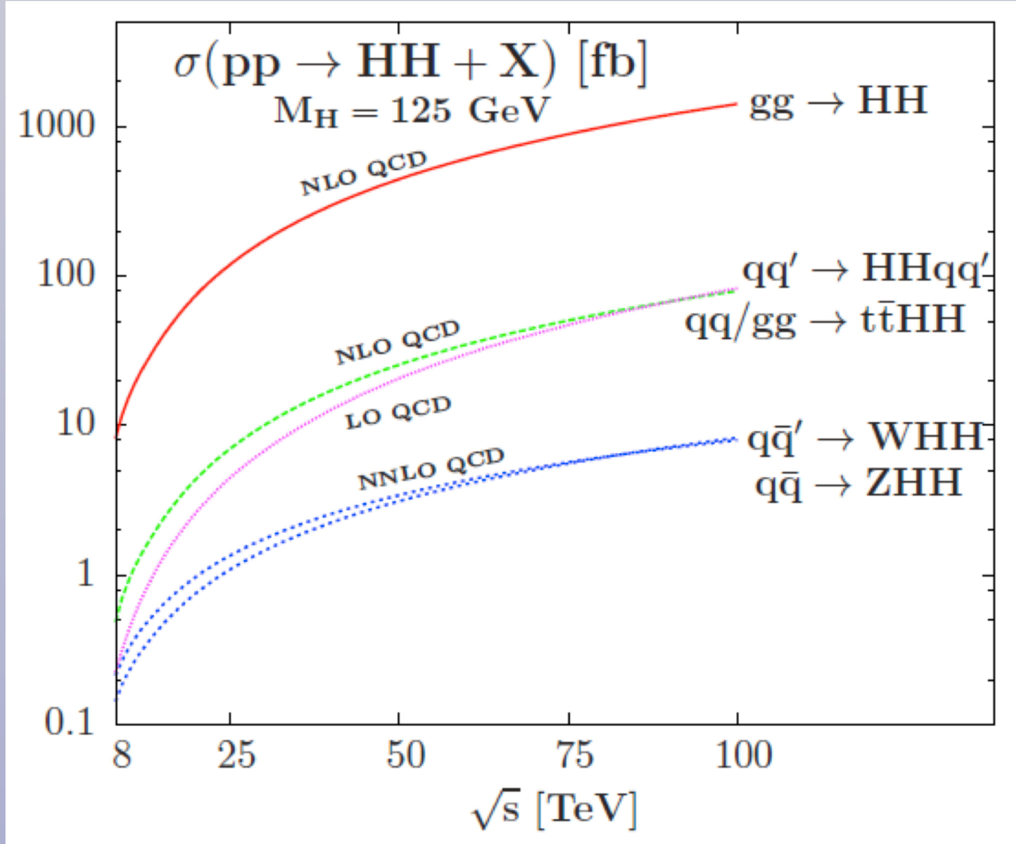
Motivation

- **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**
- Higgs pair production in Vector-Boson Fusion is small in the SM: **2 fb (80 fb)** at 14 TeV (100 TeV): provides direct information on the **hVV** and **hhVV coupling**
- Higgs pair production can be **substantially enhanced** in various BSM scenarios.
- In this talk concentrate on the feasibility of HH production in the **VBF channel** in **composite Higgs models**

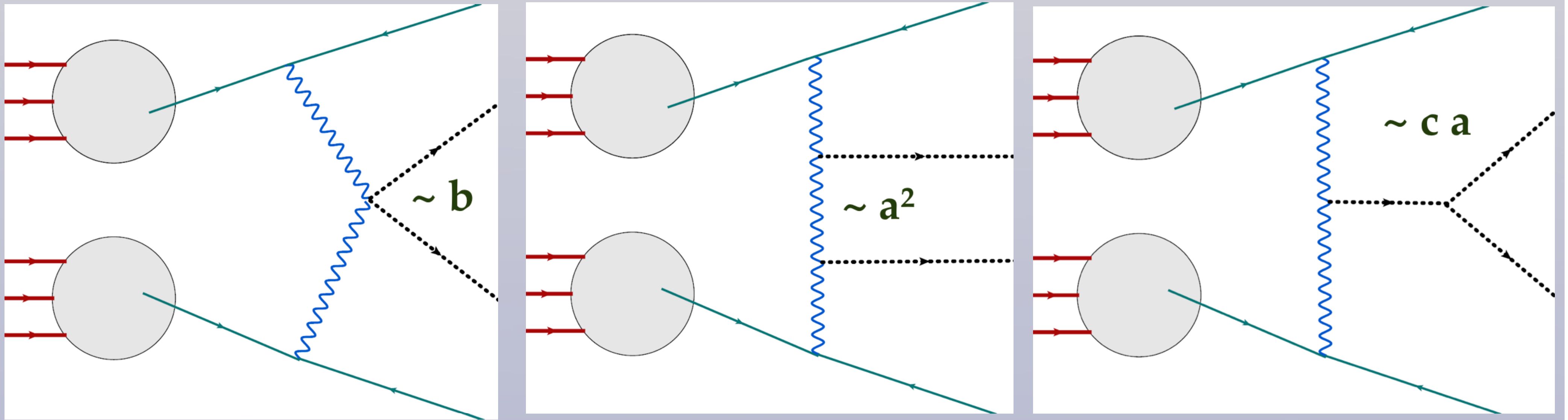


J. Baglio et al
arxiv:1212.5581

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

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



- 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**

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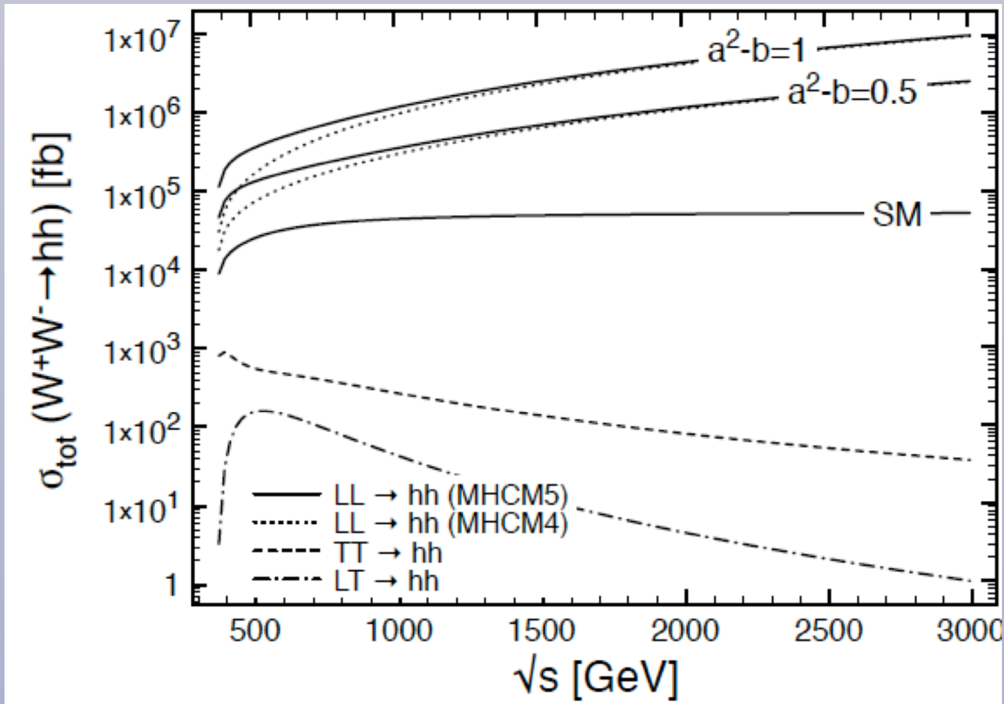
$$\frac{d\sigma_{LL\to hh}}{dt} \simeq \frac{(b-a^2)^2}{32\pi\, v^4}\,, \qquad \frac{d\sigma_{TT\to hh}}{dt} \simeq \frac{g^4(a^4 + (b-a^2)^2)}{64\pi\, s^2}\,,$$



- The more **striking signature** is that the new strong dynamics lead to a much harder distribution in $\mathbf{M_{HH}}$ as compared to the SM
- Original feasibility study (**R. Contino et al, arxiv: 1002.1011)** assumed a 180 GeV Higgs and focused on the dominant WW final state
- Our goal is to revisit the analysis for $\mathbf{m_H}$**=125 GeV** for the final states with larger BR. As a bonus, redo everything for FCC
- For **b** ≠ **a**, Higgs pair can be quite **boosted: jet substructure techniques** needed

Event Generation

- The low rates for Higgs pair production in VBF emphasize the need of final state with large branching fractions

- In this work we focus on the **4b2j** and **2b2tau2j** final states. **2b2W2j** in progress, but small rates even in the most optimistic BSM scenarios at 14 TeV: here 100 TeV crucial

- **Signal events** have been generated with **MadGraph5**, with the SM UFO model suitably modified: the **hhV, hhVV and hhh couplings** are rescaled in a way that **c_V=c_{2V}=c_3=1** are the SM values

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

- Events are generated in the range **$0 < c_{2V} < 2$, $-4 < c_3 < 6$** and then the analytical dependence of the cross-section in **c_V,c_{2V} and c_3** can be fitted from the code output **(as in R. Contino et al, arxiv:1309.7038)**

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

$$\delta_{c_{2V}} \equiv 1 - \frac{c_{2V}}{c_V^2} \qquad , \delta_{c_3} \equiv 1 - \frac{c_3}{c_V}$$

- 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**

- Other final states with smaller BR, not studied here, can become relevant at FCC100 TeV, like **bbγγ**

- **Realistic b-tagging and τ-tagging,** including mistag rates, along the lines of ATLAS/CMS, has been implemented. Only hadronic decays of the **τ** used in the analysis.

For **2b2τ2j** other backgrounds other than **ttjj** found to be negligible in **Dolan et al arxiv:1310.1084**

Selection cuts

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

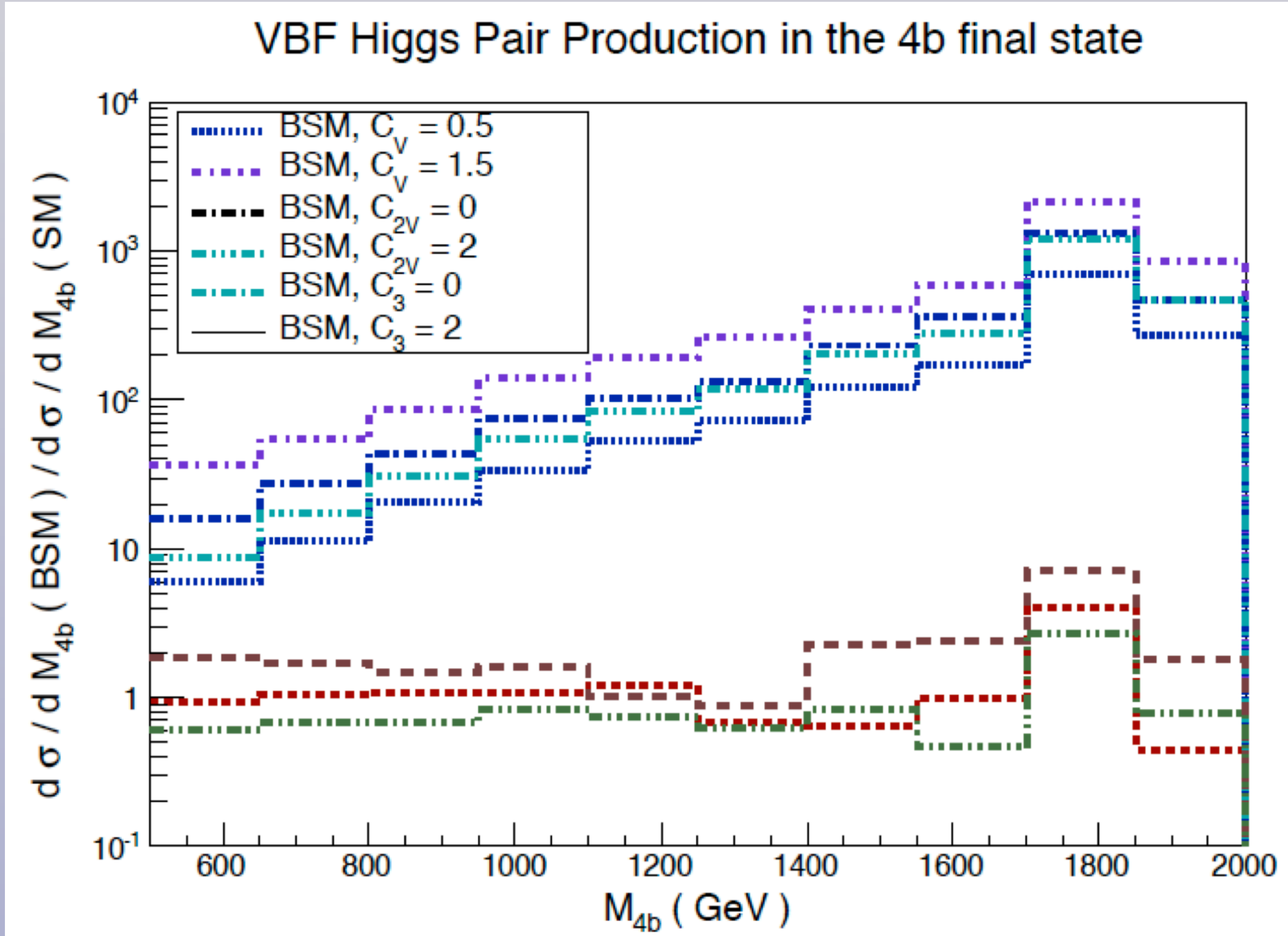
$$p_{Tj} \geq 25 \text{ GeV}, \quad p_{Tb} \geq 25 \text{ GeV}, \quad p_{T\tau} \geq 25 \text{ GeV}$$
$$|\eta_j| \leq 4.5, \quad |\eta_b| \leq 2.5, \quad |\eta_\tau| \leq 2.5$$
$$\Delta R_{jb} \geq 0.4, \quad \Delta R_{bb} \geq 0.2, \quad \Delta R_{j\tau} \geq 0.4, \quad \Delta R_{b\tau} \geq 0.4, \quad \Delta R_{\tau\tau} \geq 0.2,$$
$$m_{jj} \geq 900 \text{ GeV}, \qquad \Delta R_{jj} \geq 4.5.$$

- These cuts have been optimized for HL-LHC, FCC-specific cuts should improve signal discrimination
- Some representative **parton level cross-sections** after **basic selection cuts**
- In the best BSM scenarios, around **3000 (1000)** events for the **4b2j** (**2b2τ2j**) final states after selection cuts

σ [fb]	4b2j, 14 TeV	4b2j, 100 TeV	2b2τ2j, 14 TeV	2b2τ2j, 100 TeV
C_{2V}=0, C_3=0.8	1.10	9.2	0.27	2.6
C_{2V}=2, C_3=0.8	0.60	6.2	0.16	1.8
C_{2V}=0.8, C_3=-4	1.41	7.8	0.32	1.8

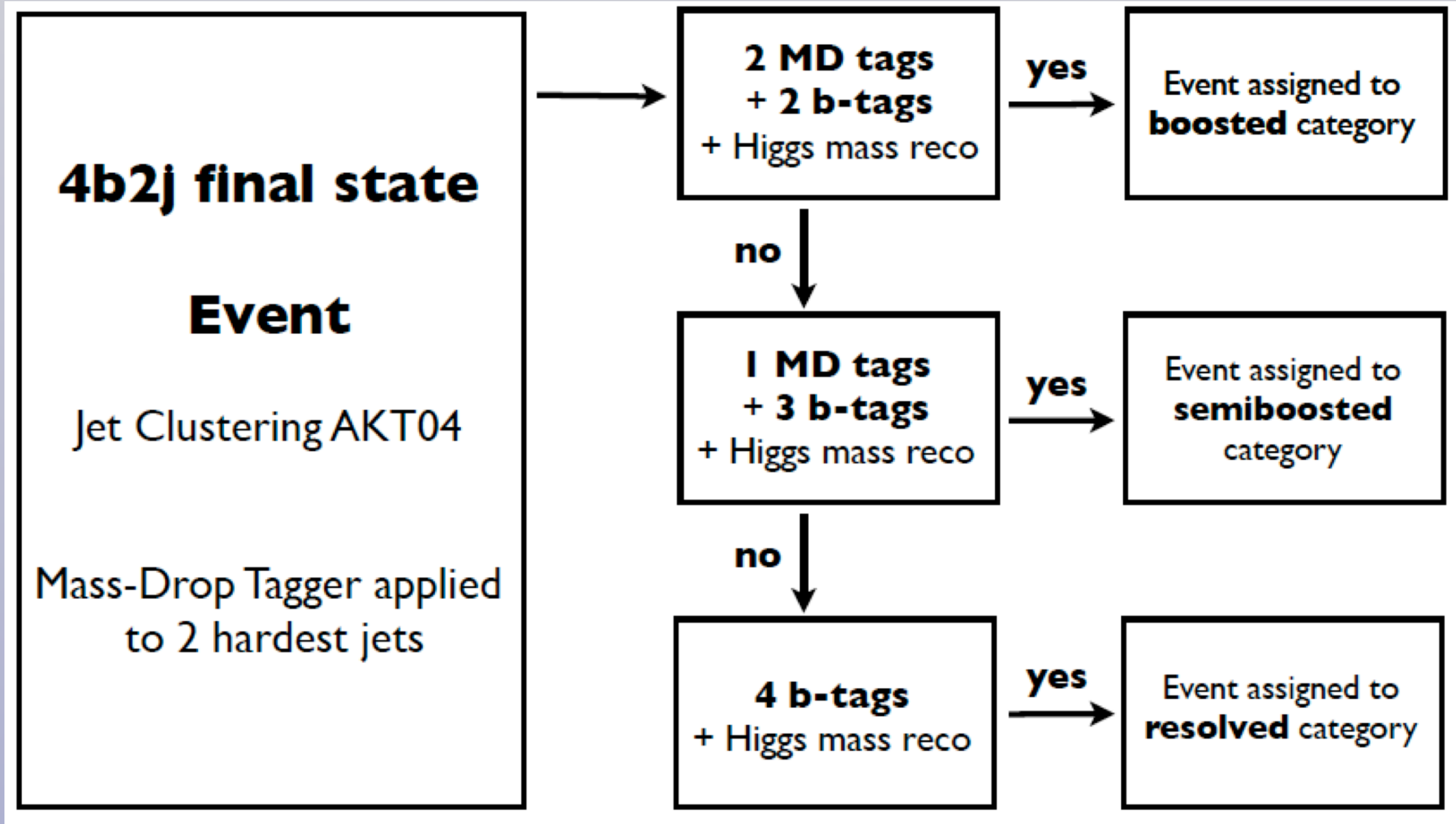
Boosting the diHiggs final state

- The ratio of BSM/SM cross-sections **grows strongly** as a function of $\mathbf{M_{HH}}$
- Exploiting the **hardness of the $\mathbf{M_{HH}}$ distribution** in composite Higgs models is the key to tame the overwhelming QCD backgrounds, and requires the use of **boosted jet techniques**



Scale-invariant tagging

- 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)
- Here we have used the same analysis chain for the two final states, schematically:



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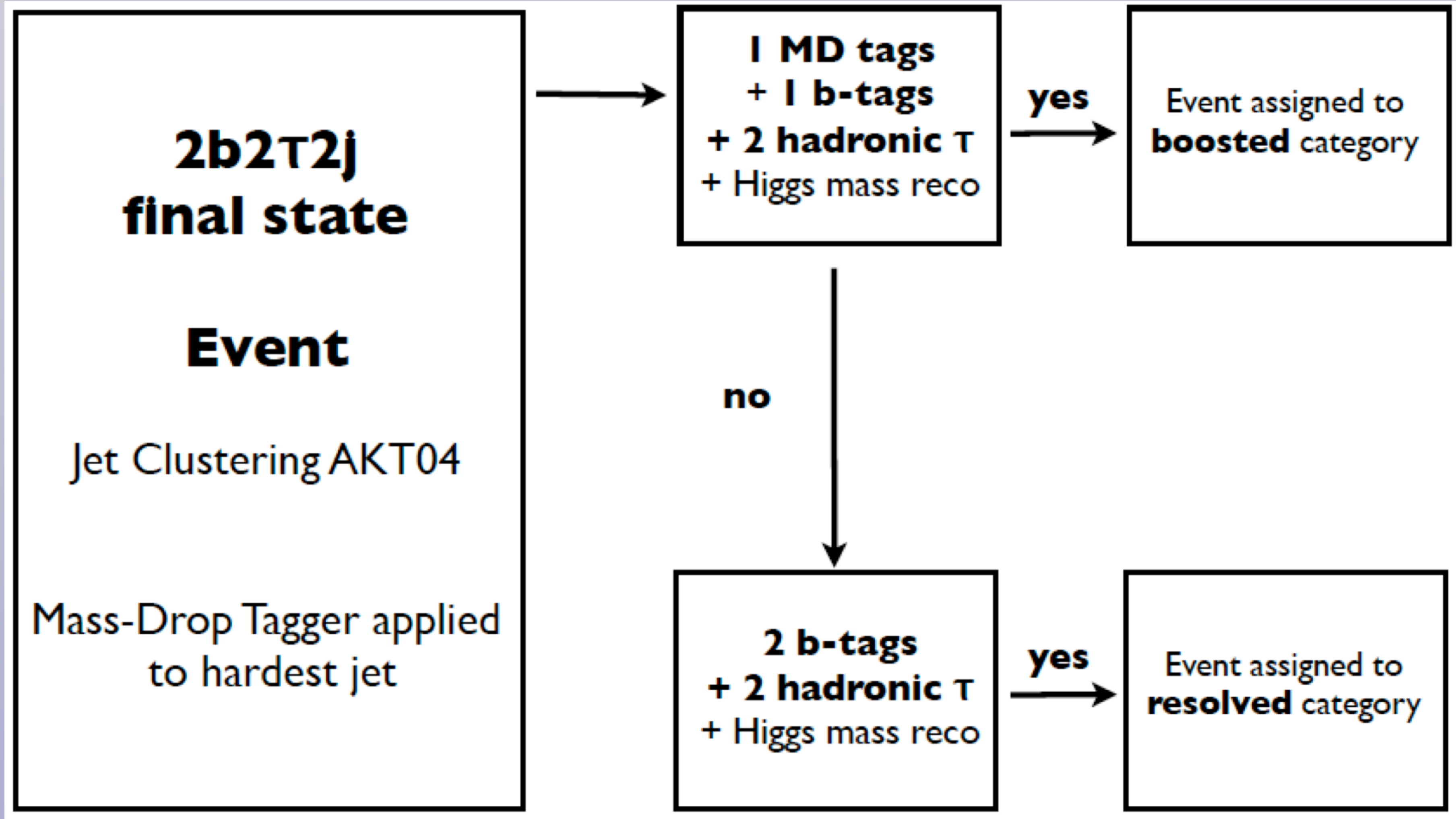
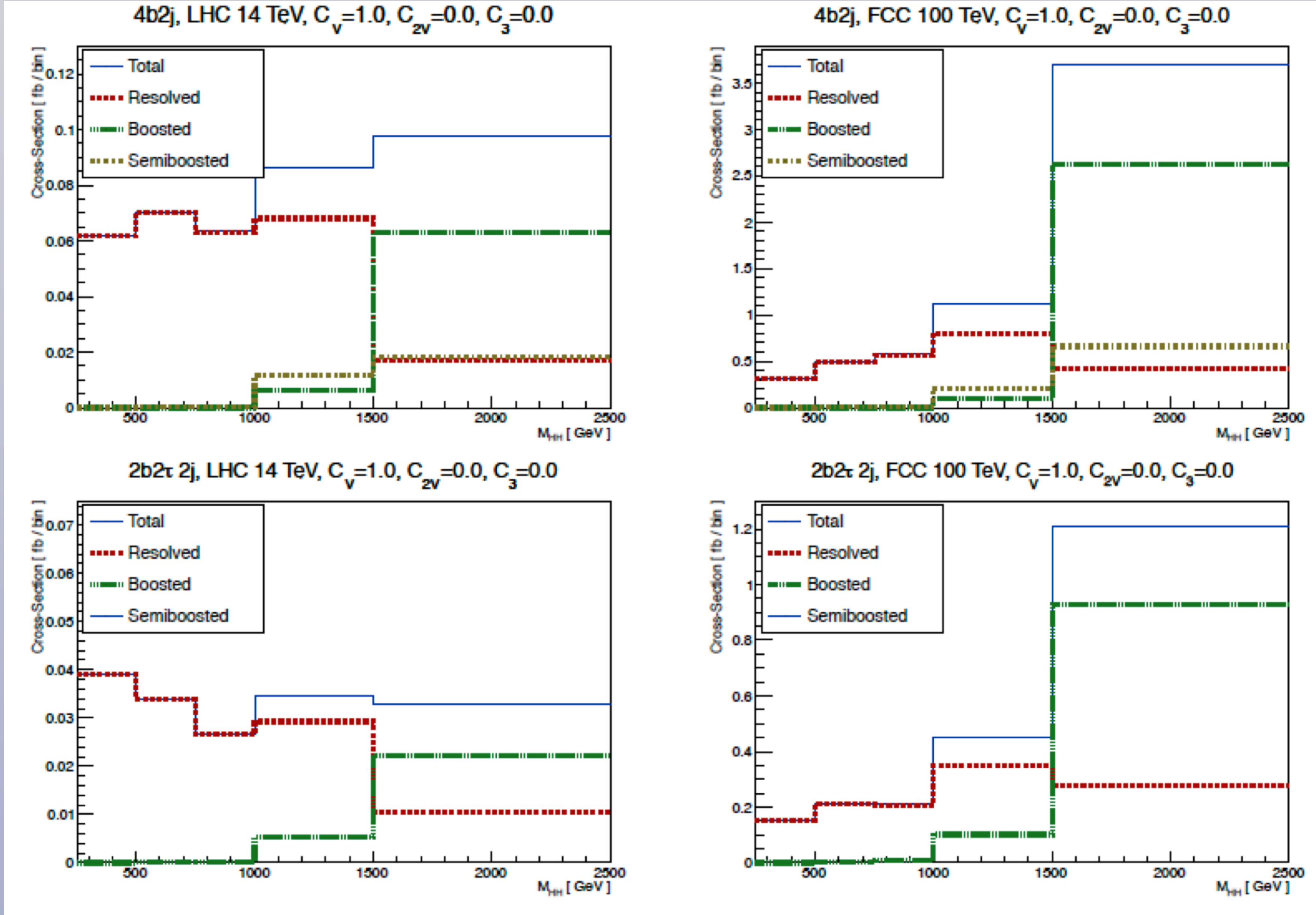


Scale-invariant tagging

- For M_{HH} close to threshold, the **resolved contribution** dominates, while large M_{HH} is the **boosted regime**
- At the LHC, resolved and boosted configurations **similar,** while at the FCC the **boosted regime dominates**
- Interesting **detector issues for the FCC**: how close the boosted b's and τ can be? Double b-tagging? Boosted-τ tagging?



Results: 4b2j final state

- This is the final state with **larger signal rates**, but also very **large QCD backgrounds**
- Going from LHC to FCC, signal **grows by 5-10** (qq initiated) and **background grows by 100** (gg init)
- Best sensitivity to $\mathbf{C_{2V}}$ from the tail of the $\mathbf{M_{HH}}$ distribution, $\mathbf{C_3}$ mostly relevant at threshold
- **Nevents** from **L=3 fb^{-1} at 14 TeV** and **L=10 fb^{-1} at 100 TeV**

PRELIMINARY

500 GeV < mHH < 750 GeV

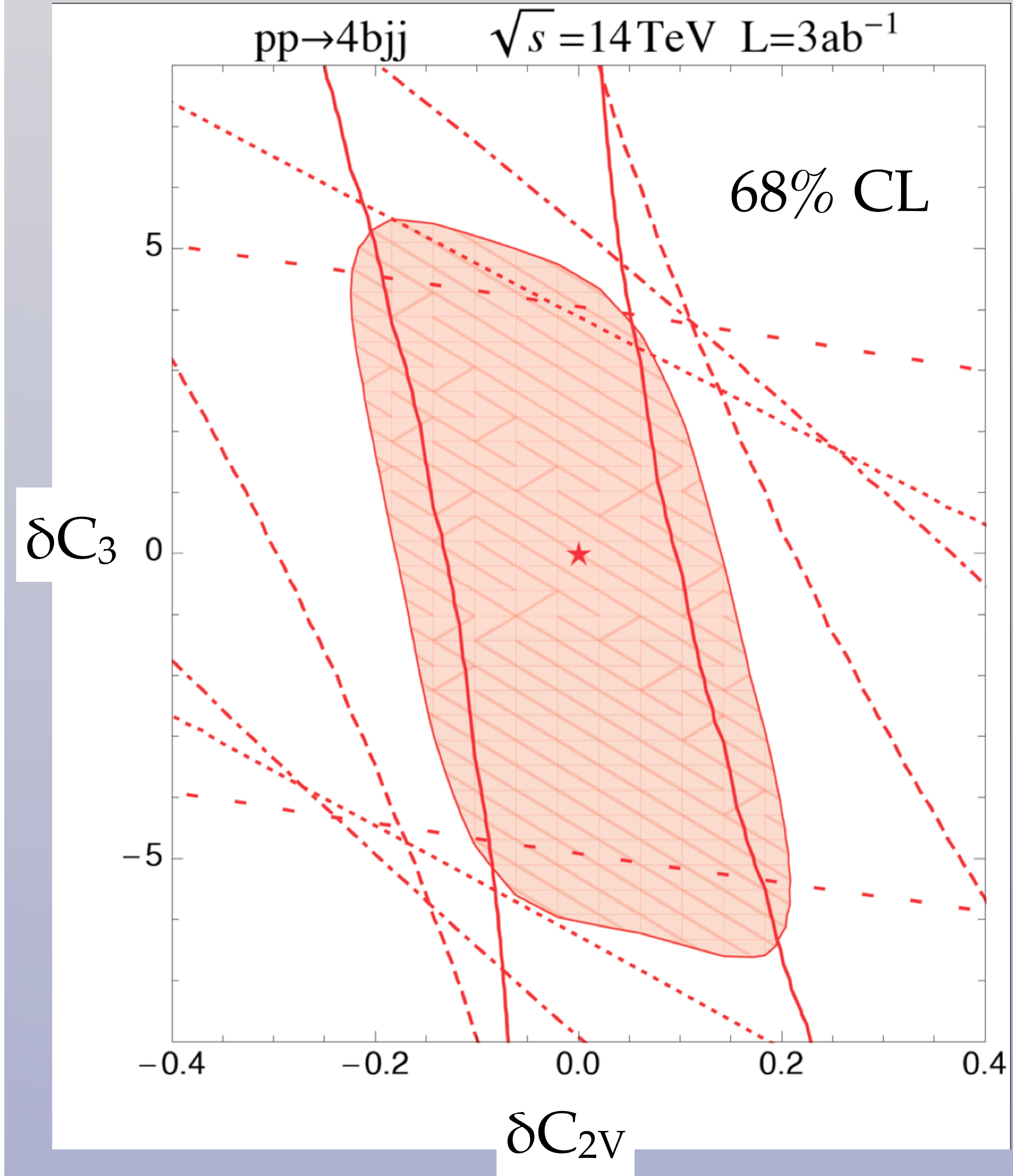
Nevents	Signal, 14 TeV	Back, 14 TeV	Signal, 100 TeV	Back, 14 TeV
$C_{2V}=0, C_3=0.8$	98	3000	2200	1.2M
$C_{2V}=0.8, C_3=-4$	66	3000	1300	1.2M

mHH > 1500 GeV

Nevents	Signal, 14 TeV	Back, 14 TeV	Signal, 100 TeV	Back, 14 TeV
$C_{2V}=0, C_3=0.8$	233	40	30K	190K
$C_{2V}=0.8, C_3=-4$	18	40	20K	190K

Results: 4b2j final state at 14 TeV

- **Sensitivity** to the values of $\mathbf{C_{2V}}$ and $\mathbf{C_3}$ can be summarized from a likelihood calculation of the $\mathbf{M_{HH}}$ distributions from signal and background **(as in R. Contino et al, arxiv:1309.7038)**

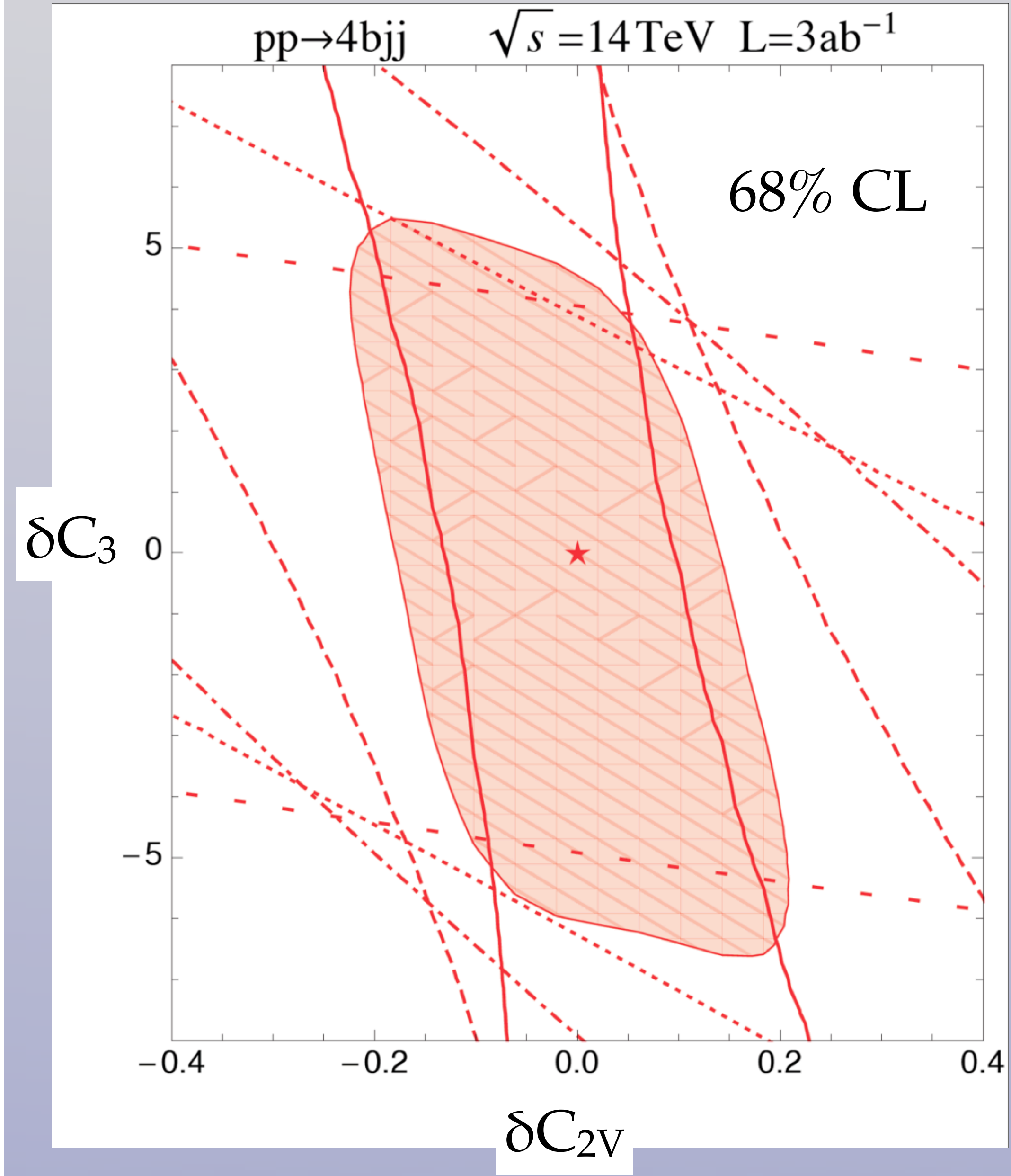


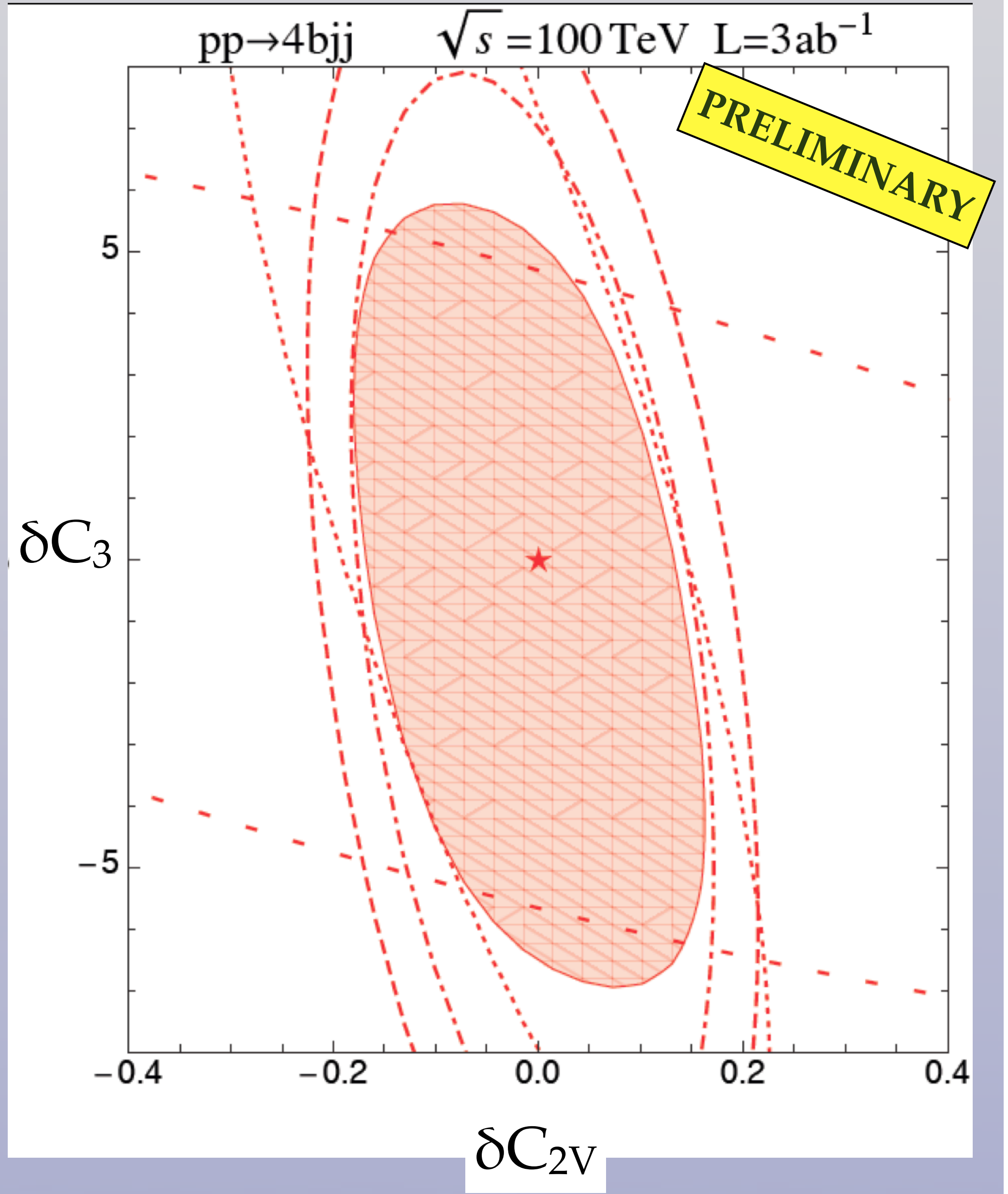
PRELIMINARY

- At HL-LHC we can probe **deviations from the SM value of $\mathbf{C_{2V}}$** at the level of **20%**
- The most stringent constraints come from the **boosted region with $\mathbf{M_{HH}}$ > 1.5 TeV**, where jet substructure is crucial
- The sensitivity to $\mathbf{C_3}$ is worse than in gg->HH since in the threshold region the backgrounds are much larger than signal

Results: 4b2j final state at 100 TeV

- **Sensitivity at 100 TeV** is only slightly better than at 14 TeV: increase in signal rates compensated by stronger growth of the QCD background





Results: 2b2τ2j final state

- **Smaller signal rates**, but also reduced backgrounds
- **Nevents** from **L=3 fb^{-1} at 14 TeV** and **L=10 fb^{-1} at 100 TeV**
- At HL-LHC, small number of events but **almost background free**
- At FCC, greatly improved sensitivity from **increased production rates**

PRELIMINARY

500 GeV < mHH < 750 GeV

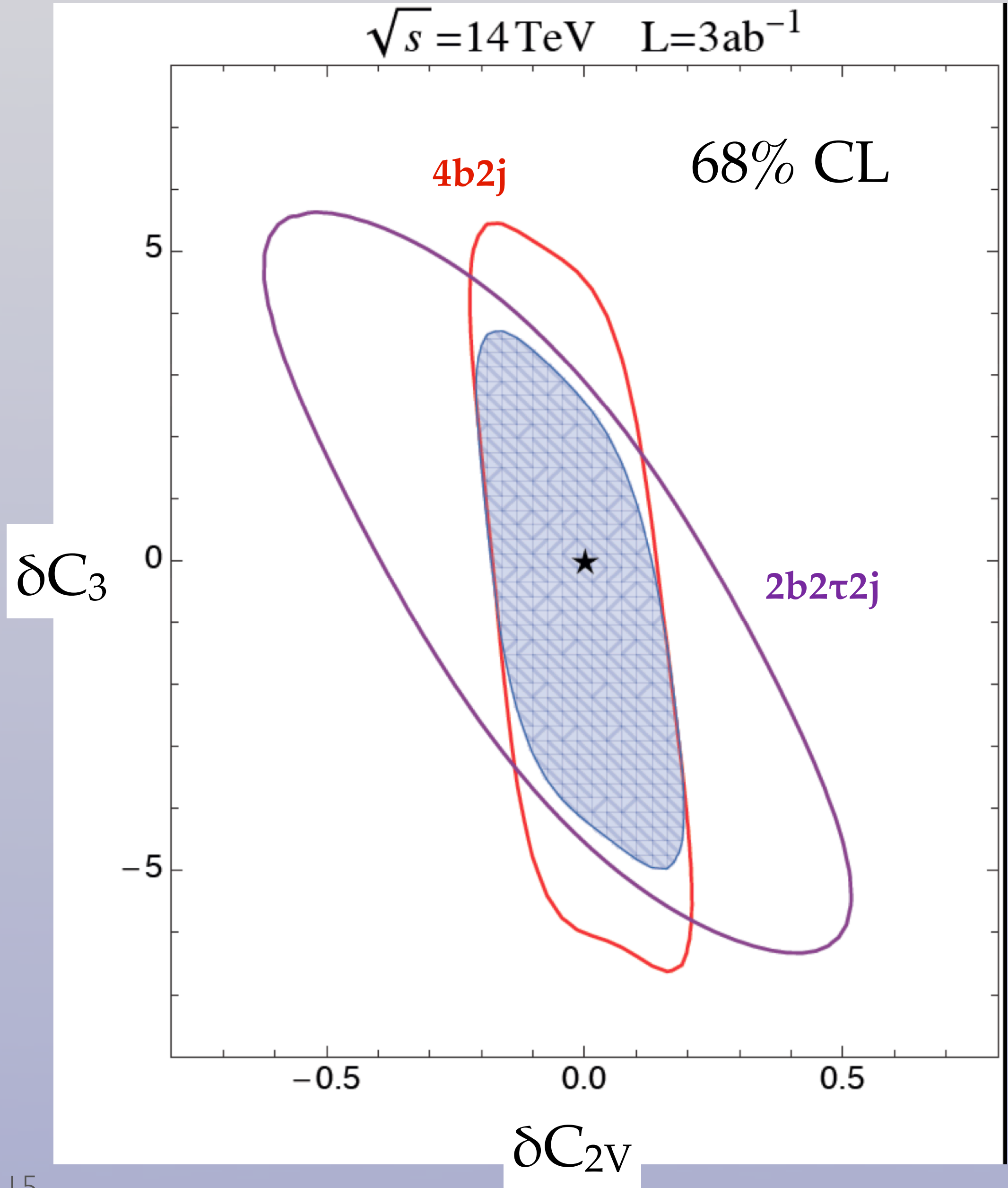
Nevents	Signal, 14 TeV	Back, 14 TeV	Signal, 100 TeV	Back, 14 TeV
C_{2V}=0, C_3=0.8	6	7	92	300
C_{2V}=0.8, C_3=-4	5	7	52	300

mHH > 1500 GeV

Nevents	Signal, 14 TeV	Back, 14 TeV	Signal, 100 TeV	Back, 14 TeV
C_{2V}=0, C_3=0.8	8	2	700	82
C_{2V}=0.8, C_3=-4	0.3	2	56	82

Results: 2b2τ2j final state at 14 TeV

- **Sensitivity** to the values of $\mathbf{C_{2V}}$ and $\mathbf{C_3}$ can be summarized from a likelihood calculation of the $\mathbf{M_{HH}}$ distributions from signal and background **(as in R. Contino et al, arxiv:1309.7038)**

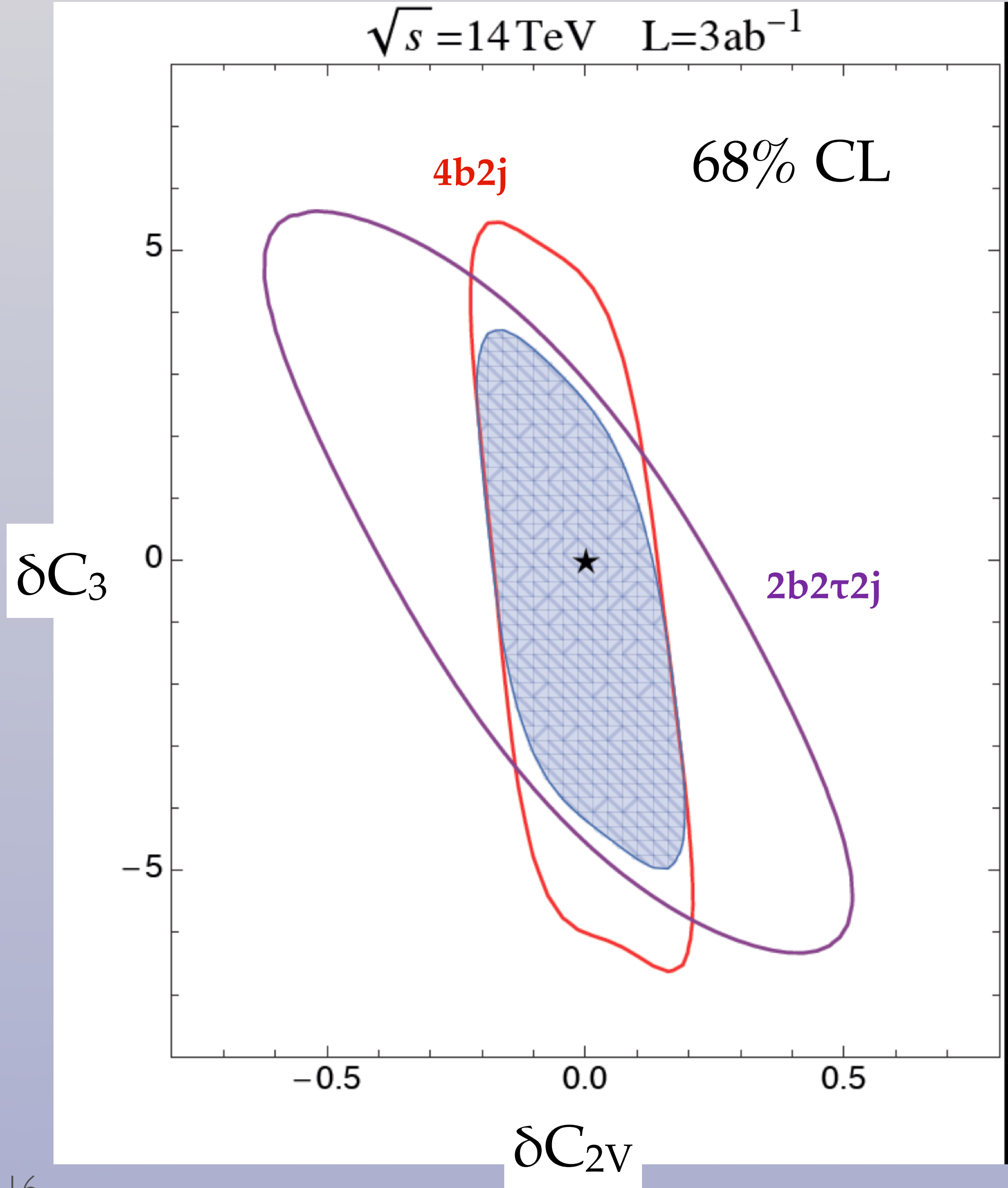


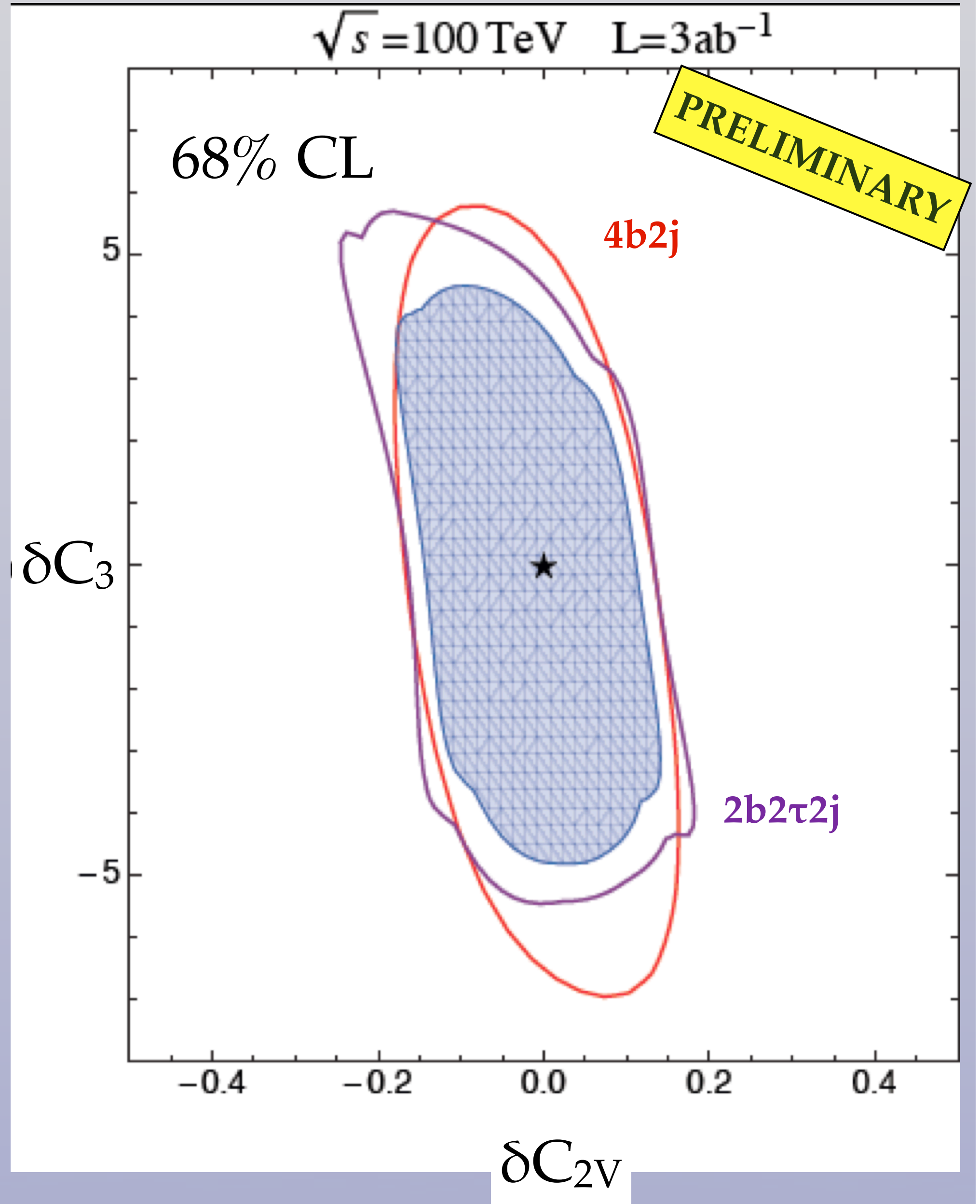
PRELIMINARY

- At HL-LHC constrains from the **2b2τ2j final state** are less severe on $\mathbf{C_{2V}}$ than those from 4b: deviations from the SM down to 40-50% can be excluded at the 68% CL
- The reduced sensitivity comes from the small number of signal events: can be improved using also the leptonic decays of the taus

Results: 2b2τ2j final state at 100 TeV

- **At 100 TeV** the sensitivity on the **2b2τ2j final state** is substantially improved thanks to the increase in signal cross-section, only partially compensated by the increase in the backgrounds





Summary and outlook

- **Higgs pair production** in the **vector-boson fusion channel** provides unique information of the mechanism underlying electroweak symmetry breaking
- The maximal sensitivity to deviations of the SM value of the **hhVV** coupling arise at large values of $\mathbf{M_{HH}}$ where the di-Higgs system is boosted and jet substructure techniques are required
- Preliminary results indicate that in the **4b2j (2b2τ2j)** final state we can probe at the **HL-LHC deviations** $\boldsymbol{\delta C_{2V}}$ **as small as 20% (50%)**
- **At a 100 TeV FCC** the final states with low event rates can be probed with higher precision