Higgs Pair Production via Vector Boson Fusion at the LHC

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DIS2014

Layout

- **Vector Boson Fusion di-Higgs production**
  - Goal of the analysis
  - LHC @13 TeV
- **New physics**
  - **Direct search for new physics**
    - Resonant di-Higgs production
  - **Indirect search for new physics**
    - Strong Double Higgs production
      - Parton level analysis
      - Hadron level analysis
- Results

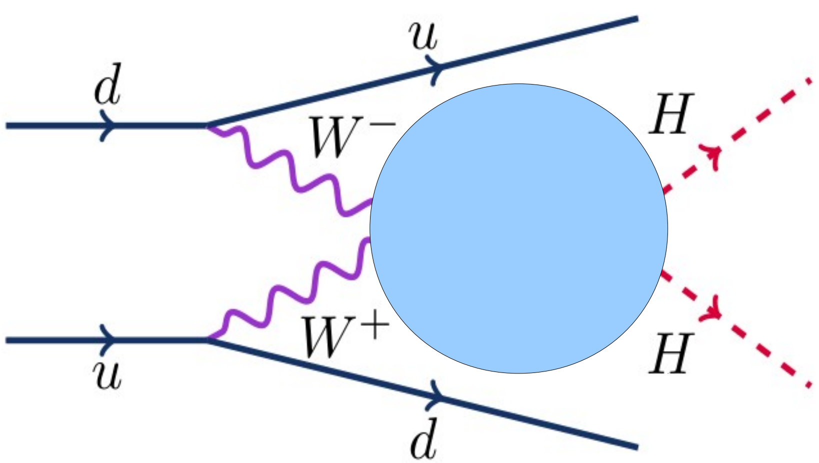
Vector Boson Fusion di-Higgs searches

- **Higgs pair production** is one of the most crucial processes for future LHC runs
  - stringent tests of our understanding of electroweak symmetry breaking

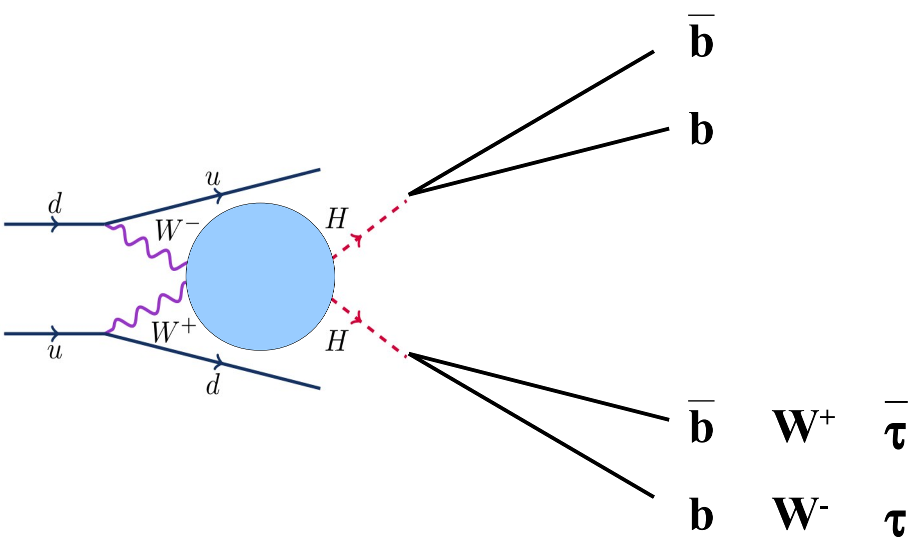
- In the SM, the dominant process is **gluon fusion**, with *33 fb* at 14 TeV
  - direct sensitivity to the **Higgs trilinear coupling c_3**

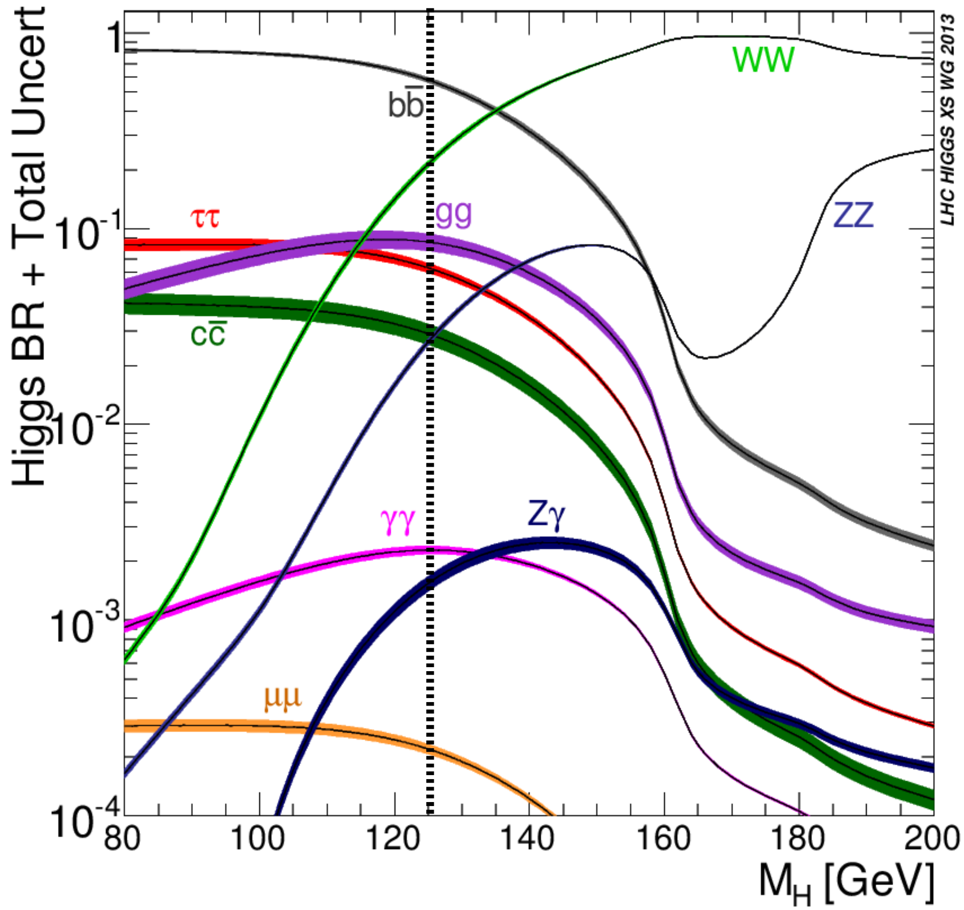
- Higgs pair production in **Vector-Boson Fusion** (VBF) is small in the SM, *2 fb* at 14 TeV
  - provides direct information on the HVV and HHVV coupling

- Higgs pair production can be substantially enhanced in various BSM scenarios
  - Production of an on-shell **resonance** decaying into two Higgs bosons
  - Modification of the **couplings** and indirect search of new physics



- **Final states considered**
  - Highest BR H→bb
  - Clean and QCD-free final state H→WW→lνlν





Three analyses

Resonant VBF di-Higgs search

Non-resonant VBF di-Higgs search at parton level

Non-resonant VBF di-Higgs search at hadron level

Resonant Higgs pair production

- Direct search [0]
  - If new particles have masses within LHC reach
  - On-shell decay into a Higgs boson pair
  - Couplings to gauge bosons play an important role

  - Benchmark: KK-graviton ($\tilde{k}$ = 0.1) [1,2]

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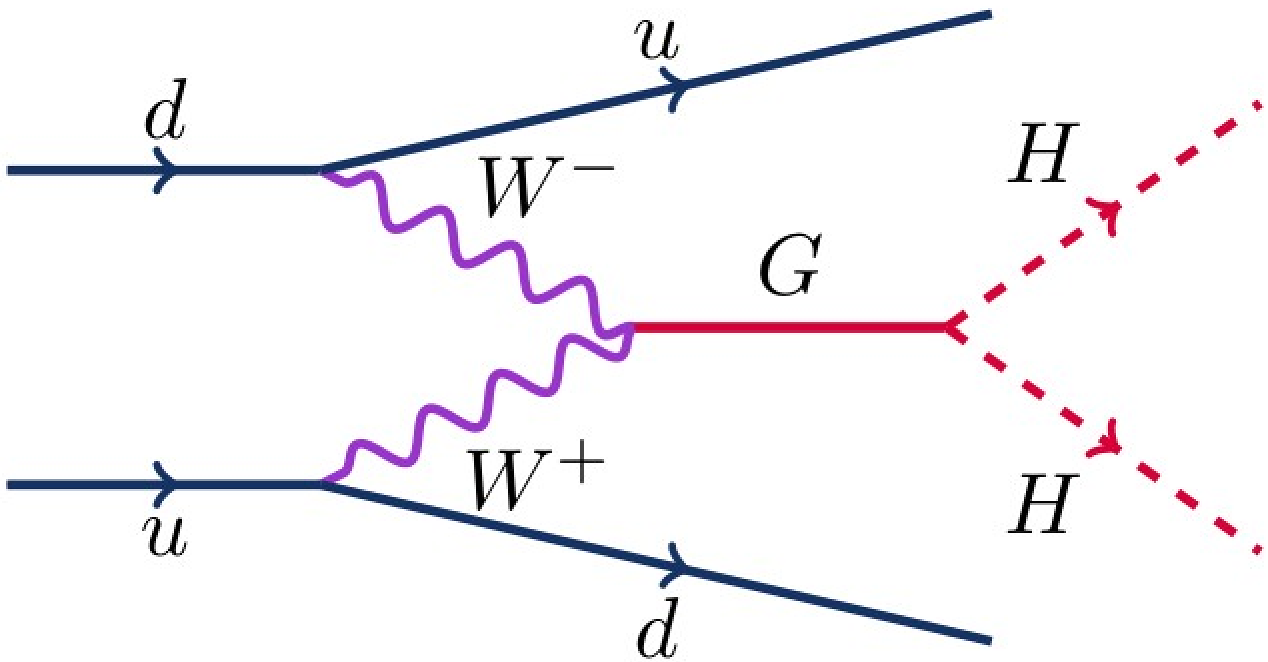
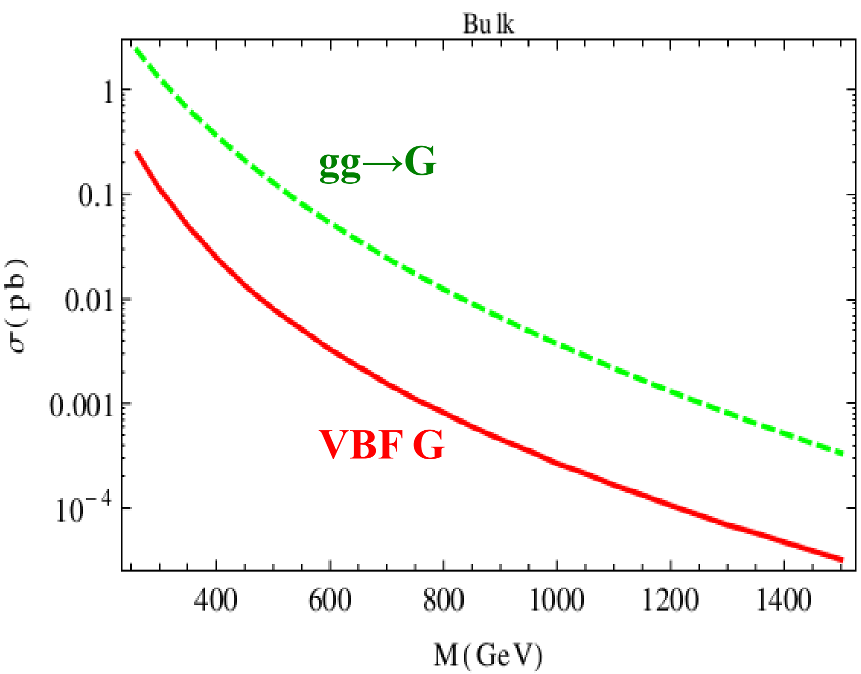
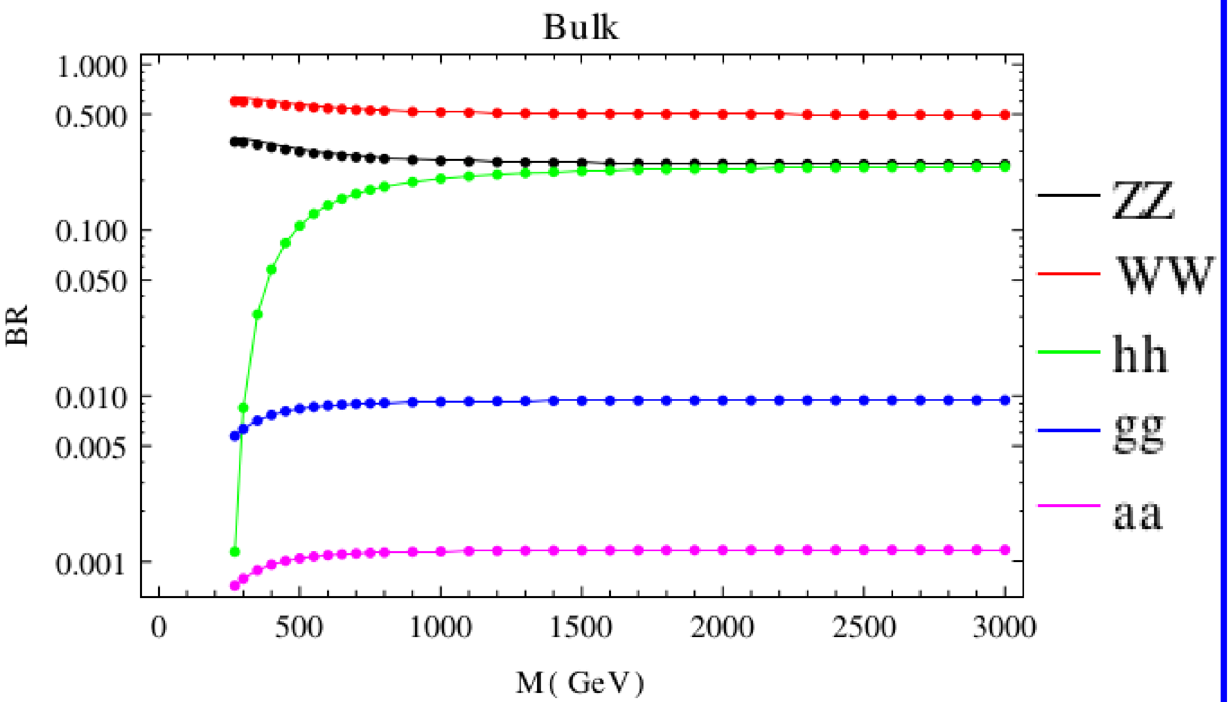


G → HH

- Production cross-section: VBF production ~ 1/10 of gluon fusion production
- Branching ratio: di-Higgs is one of the higest BR (~25%)

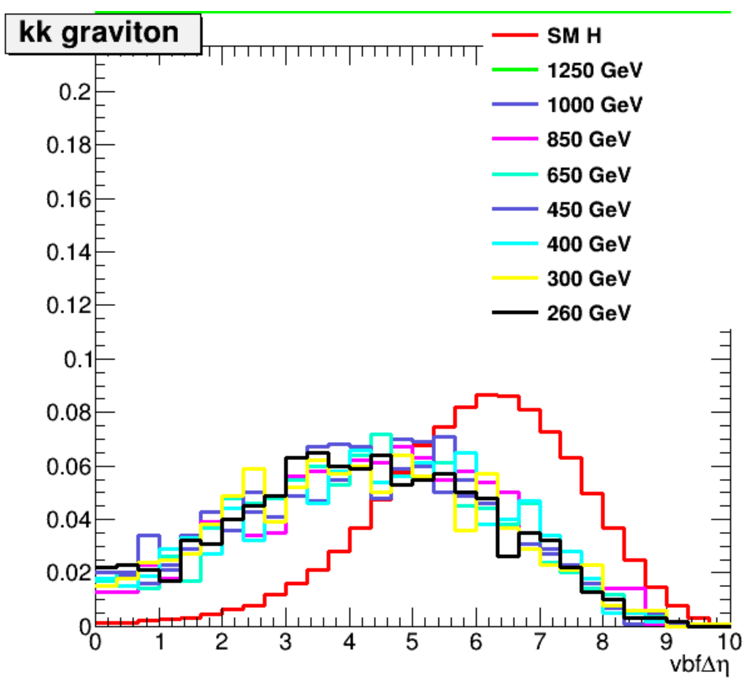




Selections

- Parton level analysis, with jets algorithm run on top of partons
- Exploit boosted topology from $H \rightarrow bb$ decays

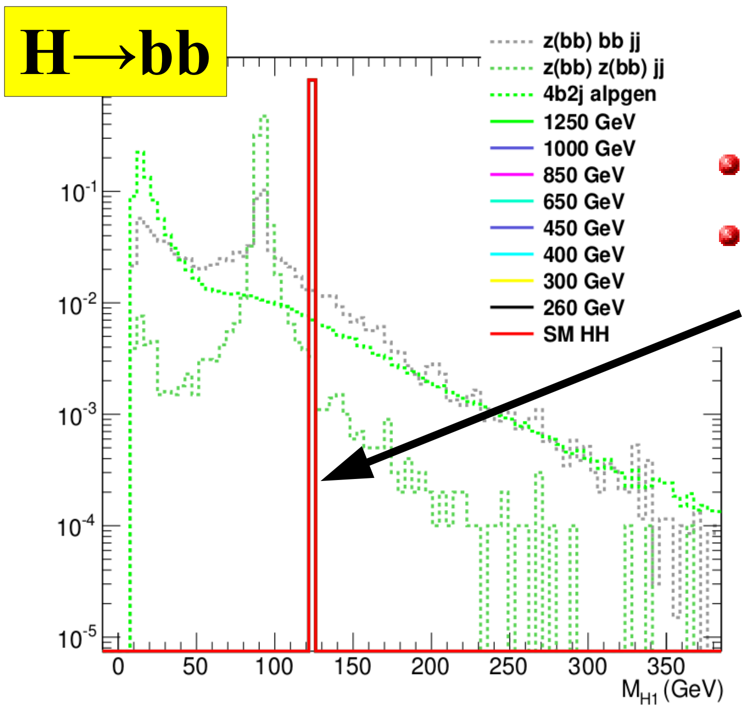
$G \rightarrow HH \rightarrow bbbb$ analysis



- Objects:
  - Jet $p_T > 30$ GeV
  - Jet $|\eta| < 4.7$
- **VBF topology:**
  - Invariant mass of 2 jets: $m_{jj} > 400$ GeV
  - No $\Delta\eta_{jj}$ cut is applied, due to p_T-dependence of the KK-graviton vertices with vector bosons
- **Boosted di-Higgs system:**
  - $M_{HH} > 250$ GeV
  - $p_T^{HH} > 60$ GeV
  - $\Delta\eta_{HH} < 2$

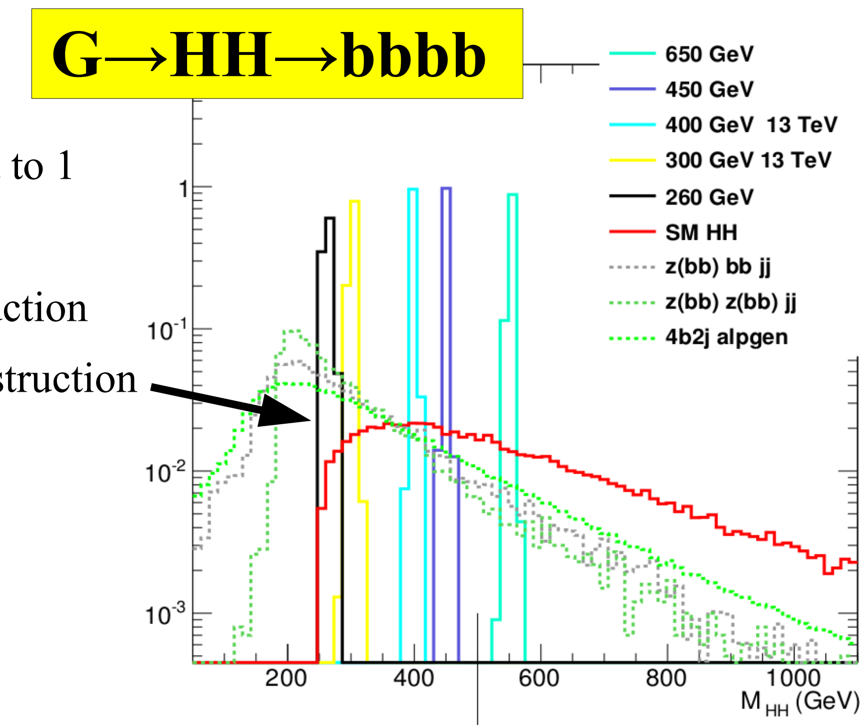
Caveat

- No selections concerning H→bb and G→HH→bbbb invariant mass are applied
  - To be addressed in a dedicated study after showering and hadronization (ongoing study...)
  - Very conservative result



m_{bb}

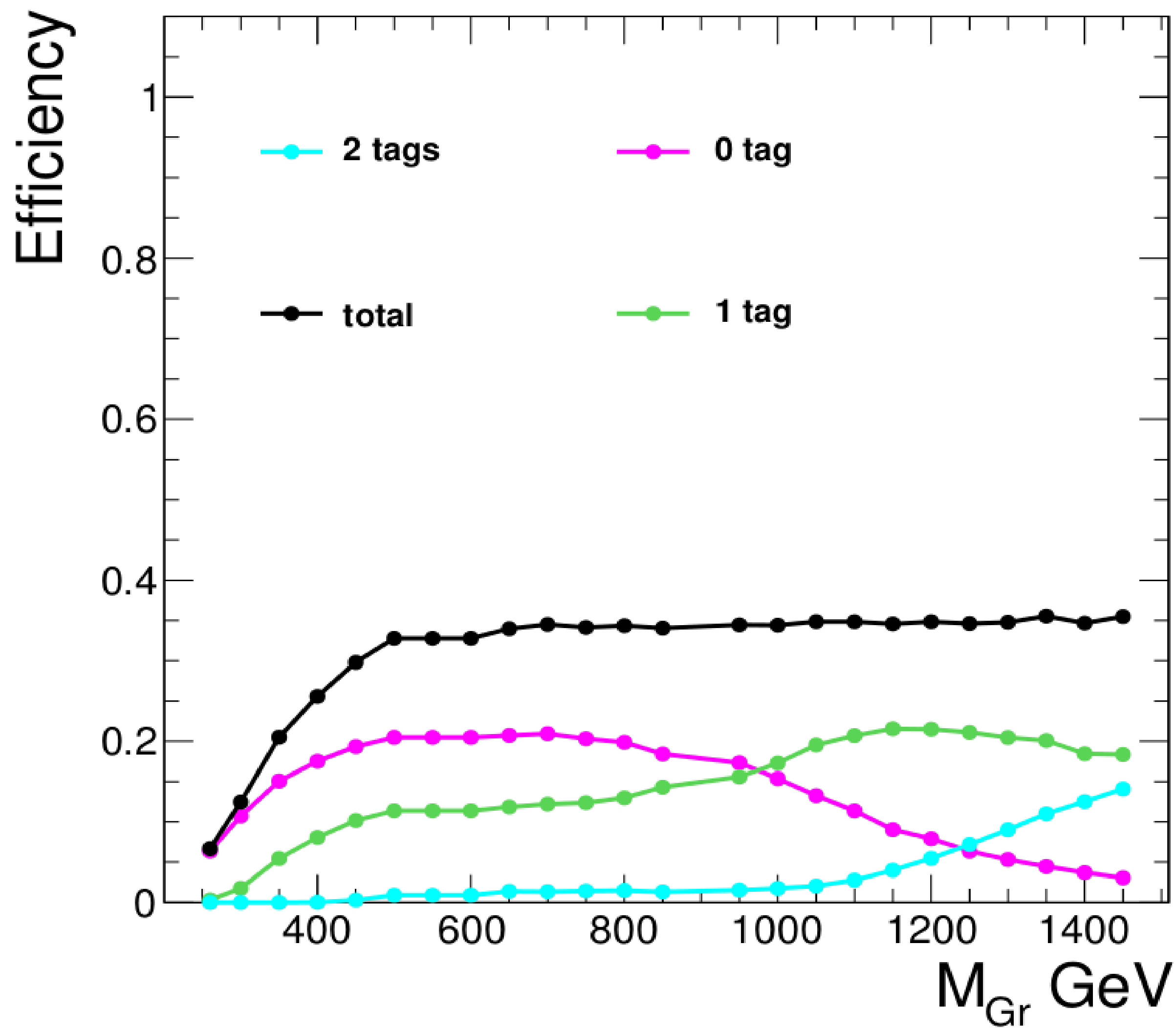
- Distributions normalized to 1
- Improvements from:
  - Higgs mass reconstruction
  - Graviton mass reconstruction



m_{4b}

Boosted jets

- The higher the G mass the higher is the probability for the two Higgs to be boosted and the two b-jets to be merged
  - We recover an uniform analysis efficiency combining different categories



Disclaimer

- Feasibility study to establish more competitive channels and search strategies
- Analysis performed at parton level, no showering and hadronization effects are taken into account
- Perfect b-tag efficiency is considered withing experimental acceptance volume
- Simple cut based analysis performed

- Complete studies, with showering effects, reconstruction effects and possible additional final states are ongoing

Yields

- Yields with 3 ab^{-1} at 13 TeV
- High signal yields
- Still big background contamination, but it can be reduced by means of m_{bb} and m_{4b} selections

	$pp \to Gr(HH)jj$ σ (pb)	σ*eff (pb)	Nevents (3000/fb)
1450 GeV	6.91E-06	8.17E-07	2.45E+00
1250 GeV	1.86E-05	2.14E-06	6.41E+00
1050 GeV	7.87E-05	9.13E-06	2.74E+01
850 GeV	2.63E-04	3.00E-05	9.01E+01
650 GeV	1.28E-03	1.40E-04	4.20E+02
450 GeV	8.87E-03	8.80E-04	2.64E+03
400 GeV	1.41E-02	1.20E-03	3.60E+03
300 GeV	1.55E-02	6.42E-04	1.93E+03
260 GeV	5.72E-03	1.27E-04	3.80E+02

Non-resonant VBF di-Higgs search at parton level

- Indirect search [0]
  - Effective lagrangian up to dimension 6 operators [3,4]
  - Modification of coupling parameters
    - $\mathbf{c_V}\, g_{HVV}^{SM}$ HVV → partially constrained through single Higgs searches
    - $\mathbf{c_{2V}}\, g_{HHVV}^{SM}$ HHVV → the only process to measure it is via VBF HH
    - $\mathbf{c_3}\, g_{HHH}^{SM}$ HHH → accessible also via gluon fusion HH
  - SM: $\mathbf{c_V = c_{2V} = c_3 = 1}$

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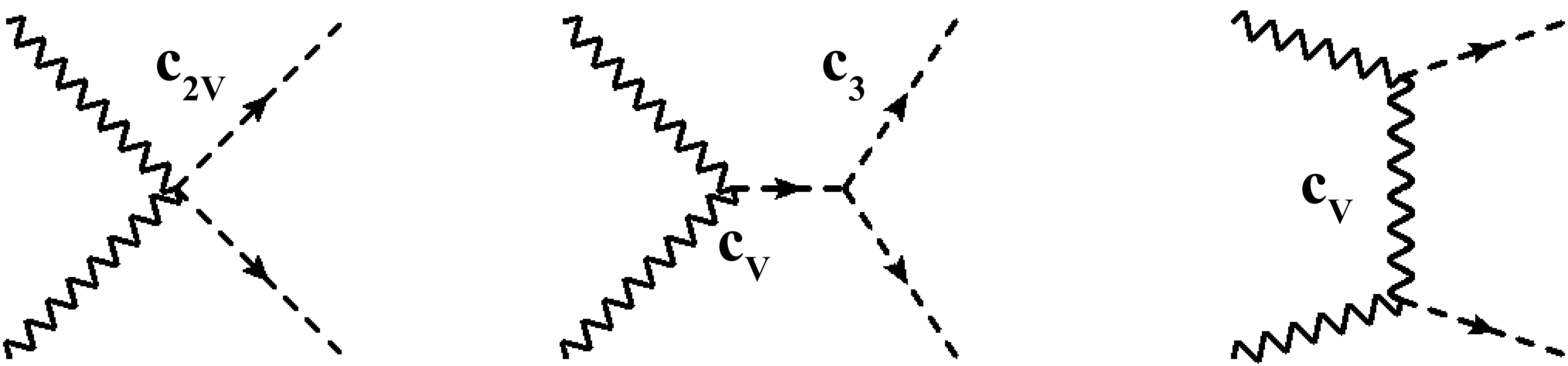
$0.5 < c_V < 1.5$

$0.0 < c_{2V} < 2.0$

$0.0 < c_3 < 2.0$



Selections

- Objects:
  - Light and b jet and $p_T > 25$ GeV
  - Light (b) jet $|\eta| < 4.5$ (2.5) and lepton $|\eta| < 2.5$
- **VBF** topology:
  - Invariant mass of 2 jets: $m_{jj} > 500$ GeV
  - High separation: $\Delta R_{jj} > 4.0$

Two analyses:

- **4b + 2j**
  - Tighter VBF cuts to suppress QCD background
    - $m_{jj} > 800$ GeV
  - $m_{bb} \sim 125$ GeV $\pm$ 15% for both the bb pairs

Main backgrounds:

- **QCD 4b + 2j**
- **Z(bb) + 2b + 2j**

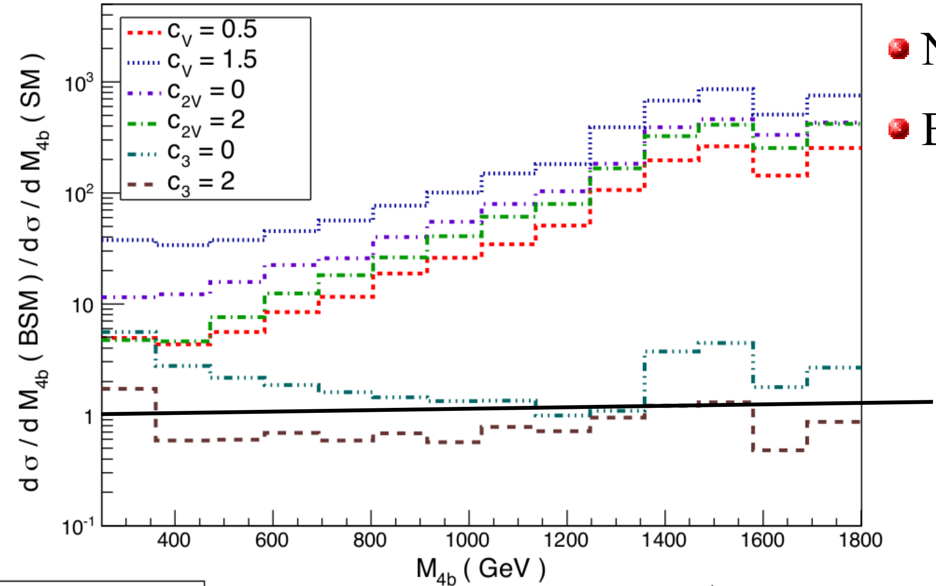
- **2b + 2l2ν + 2j**
  - Exploit $H \to WW$ kinematic
    - Invariant mass of di-lepton system $m_{ll} < 70$ GeV
    - Transverse mass of di-W system $m_T < 125$ GeV
  - $m_{bb} \sim 125$ GeV $\pm$ 15%

- **WW + 2b + 2j**
  - Mainly dominated by **tt + 2j**

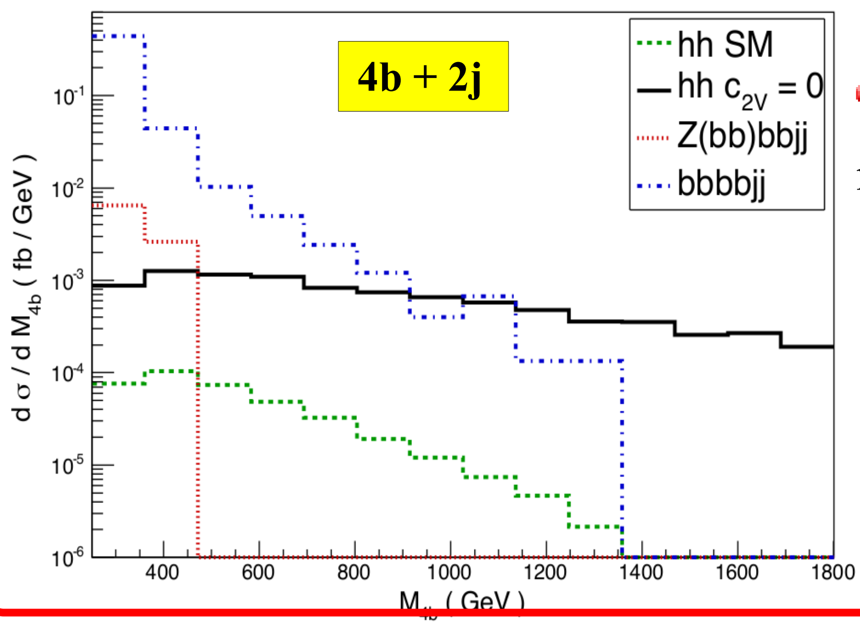
High energy regime

- For $(c_V - c_{2V}) \neq 0$ the VV → HH cross section grows with the partonic energy
  - Modification from SM prediction → high energies

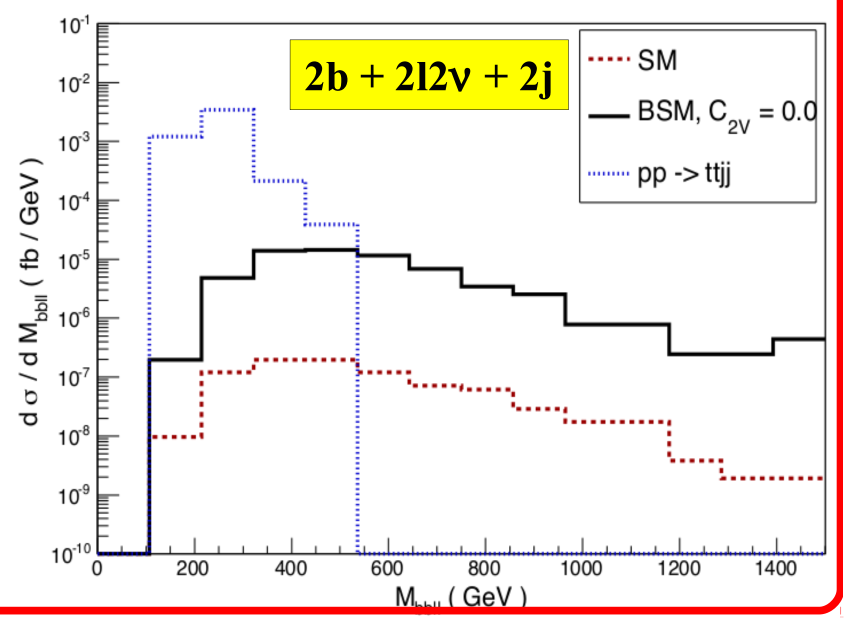
- **4b + 2j**
  - $m_{4b} > 1000$ GeV
- **2b + 2l2ν + 2j**
  - $m_{llbb} > 500$ GeV
  - $p_T^{bb} > 200$ GeV



- Normalized to SM HH
- Enhancement up to x100 !



- Suppression of most of background



Yields

- After all the selections applied
  - Selections efficiency quite high ~ 25% for non-SM VBF HH signal
  - Good sensitivity for non-SM VBF HH signal and coupling
  - HL-LHC is needed: L = 3 ab^{-1}

4b + 2j

Sample	$N_{\text{ev}} = \sigma_{IV} \cdot \mathcal{L}$ (3 ab^{-1})
SM	6.788
$c_V = 0.5$	587.5
$c_V = 1.5$	2039
$c_{2V} = 0$	1160
$c_{2V} = 2$	982.5
$c_3 = 0$	10.21
$c_3 = 2$	5.385
$4bjj$	355.5
$Zbbjj \to 4bjj$	< 7

2b + 2l2ν + 2j

Sample	$N_{\text{ev}} = \sigma_{III} \cdot \mathcal{L}$ (3 ab^{-1})
SM	0.1
$c_V = 0.5$	1.4
$c_V = 1.5$	45.2
$c_{2V} = 0.0$	10.3
$c_{2V} = 2.0$	8.1
$c_3 = 0.0$	0.2
$c_3 = 2.0$	0.1
$WWbbjj$	–
$t\bar{t}jj \to WWbbjj$	< 6.2

Non-resonant VBF di-Higgs search at hadron level

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- Parton level events **showered** and **hadronized** with **Pythia8**
- Jet clustering using **FastJet** with the anti-kT algorithm with **R=0.4**
- Final states:
  - **4b2j**
  - **2b2τ2j**
  - **2b2W2j** (in progress)
- Realistic b-tagging and τ-tagging, including mistag rate
- Only hadronic decays of τ used in the analysis.
- **14 TeV** and **100 TeV** hadron colliders are used as benchmarks

$0.0 < c_{2V} < 2.0$

$-4.0 < c_3 < 6.0$

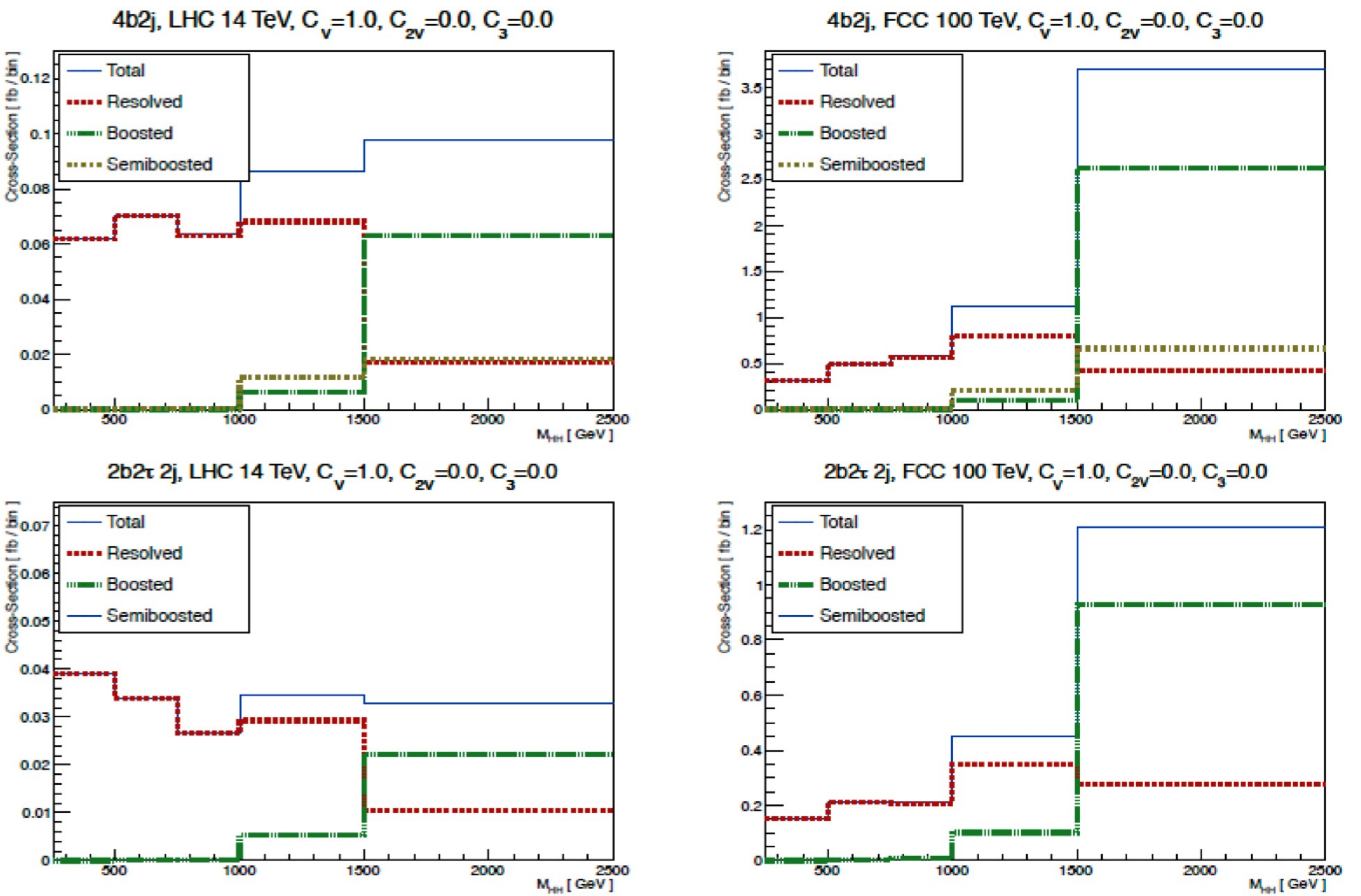
- c_{2V} and c_3 estimated by means of a likelihood fit [5]:

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

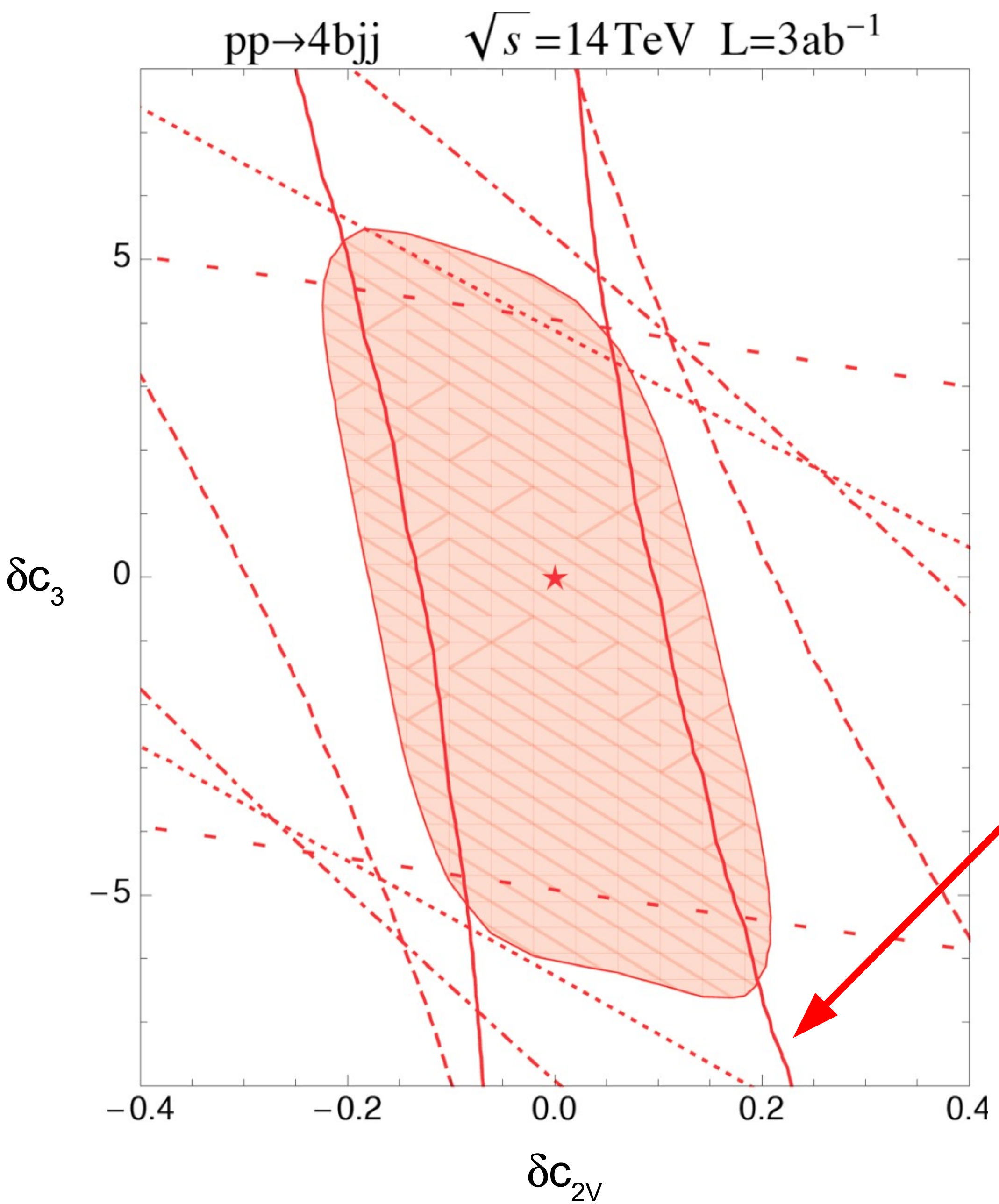
$$\delta_{c_{2V}} \equiv 1 - \frac{c_{2V}}{c_V^2} \qquad , \delta_{c_3} \equiv 1 - \frac{c_3}{c_V}$$

- Scale-invariant resonance tagging, which provides a smooth matching between boosted and resolved kinematics [6]

M_{HH} variable

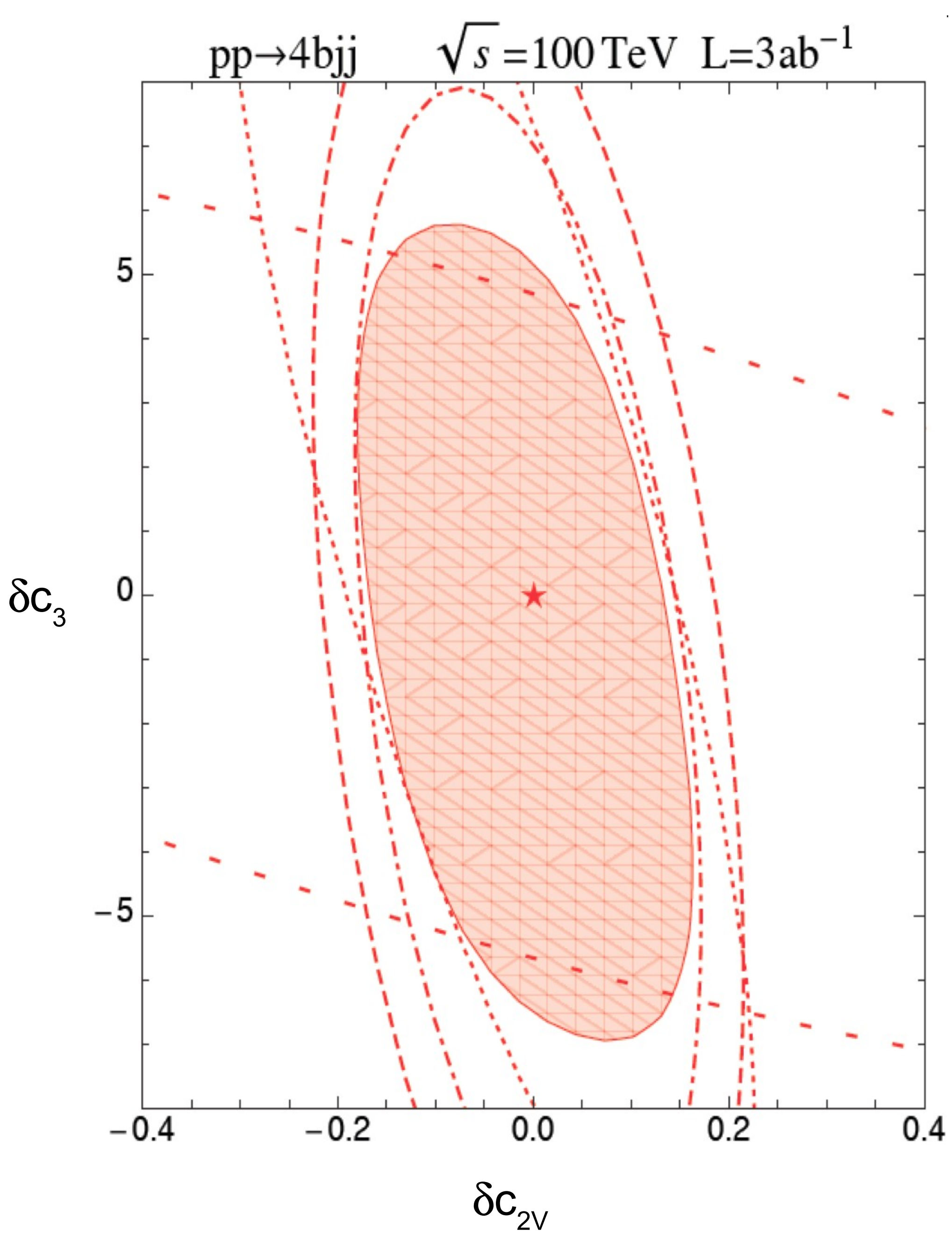


Non-resonant VBF di-Higgs search at hadron level



4b + 2j

- At HL-LHC deviations from the SM value of c_{2V} can be probed at the level of 20%
- The most stringent constraints come from the boosted region with $M_{HH} > 1.5$ TeV, where jet substructure is crucial
- The sensitivity to c_3 is worse than in gg→HH since in the threshold region the backgrounds are much larger than signal

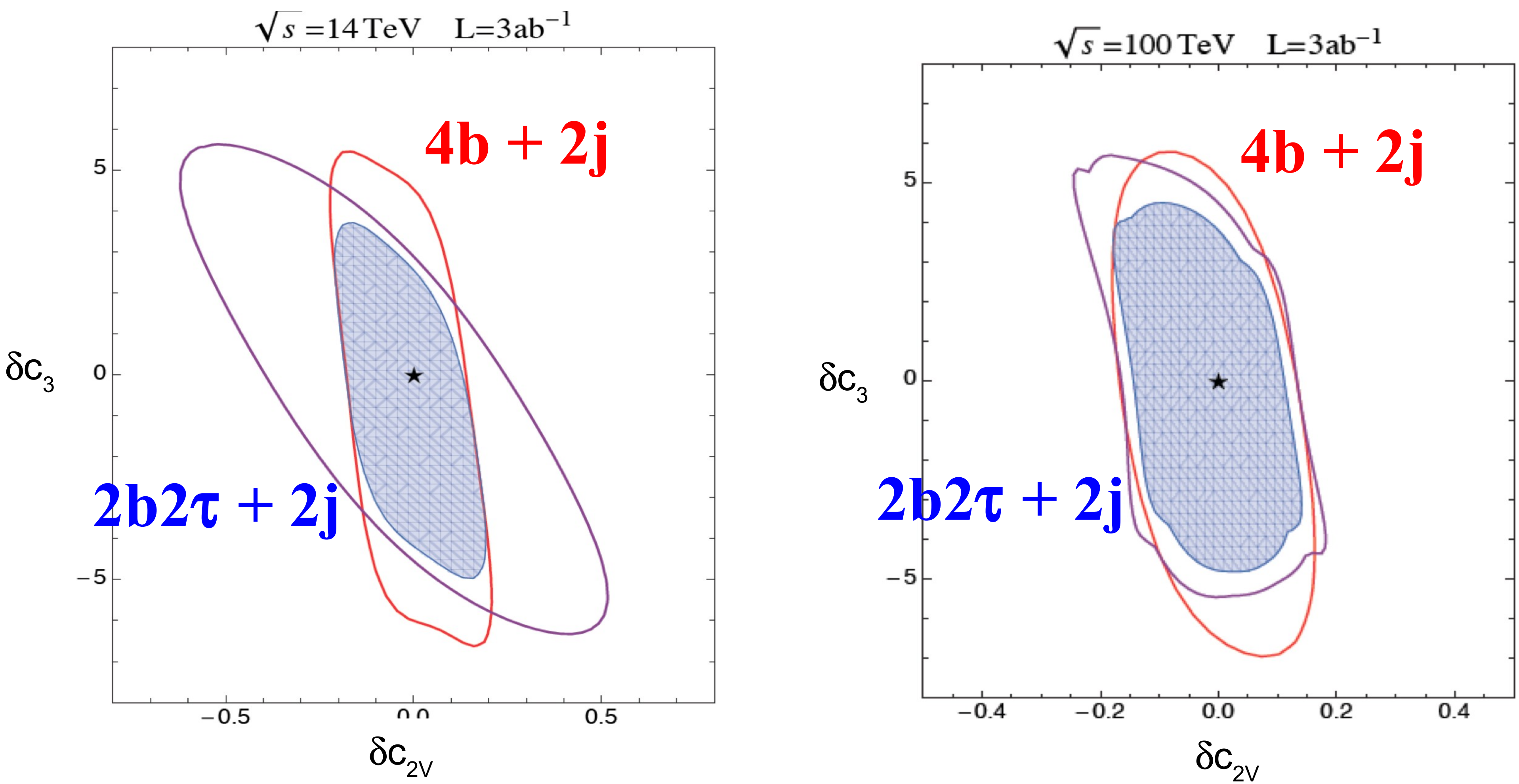


4b + 2j

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

Non-resonant VBF di-Higgs search at hadron level

- HL-LHC constrains from the 2b2τ2j final state are less severe on c_{2V} than those from 4b:
  - deviations from the SM down to 40-50%
  - reduced sensitivity comes from the small number of signal events
  - At 100 TeV the sensitivity on the 2b2τ2j final state is improved thanks to the increase in signal cross-section



Conclusions

- **Vector Boson Fusion di-Higgs production**
  - Goal of the analysis → new physics at LHC @ 13 TeV
  - **Direct search for new physics**
    - Resonant di-Higgs production
    - KK-graviton as a benchmark
    - VBF G → HH → bbbb final state considered
      - High signal yields
  - **Indirect search for new physics**
    - Strong Double Higgs production
    - Sensitivity to $\mathbf{c_{2V}}$ (HHVV vertex) → only accessible via VBF HH
      - **Parton level analysis:**
        - VBF HH → bbbb / WW(lνlν)bb final state considered
      - **Hadron level analysis:**
        - VBF HH → bbbb / ττbb final state considered
        - ~ 20% sensitivity to $\mathbf{c_{2V}}$ with HL-LHC

backup

Strong double Higgs production

- Cross section for signal with different coupling modification and different final states

Model	Final state	Cross section [fb]	$N_{\rm ev}$ $(\mathcal{L} = 3\,{\rm ab}^{-1})$
SM (no cut)	$hhjj$	0.83	2500
SM	$hhjj$	0.12	360
SM	$hhjj \to 4bjj$	0.049	150
$c_V = 0.5$		0.54	1600
$c_V = 1.5$		2.72	8100
$c_{2V} = 0$		1.23	3700
$c_{2V} = 2$		0.78	2300
$c_3 = 0$		0.14	420
$c_3 = 2$		0.042	130
SM	$hhjj \to l^+l^- \not{E}_T\, 2b\, jj$	$8.6 \cdot 10^{-4}$	2.6
$c_V = 0.5$		$2.0 \cdot 10^{-3}$	6
$c_V = 1.5$		$9.8 \cdot 10^{-2}$	290
$c_{2V} = 0$		$1.9 \cdot 10^{-2}$	54
$c_{2V} = 2$		$1.1 \cdot 10^{-2}$	33
$c_3 = 0$		$2.4 \cdot 10^{-3}$	7
$c_3 = 2$		$7.4 \cdot 10^{-4}$	2.2

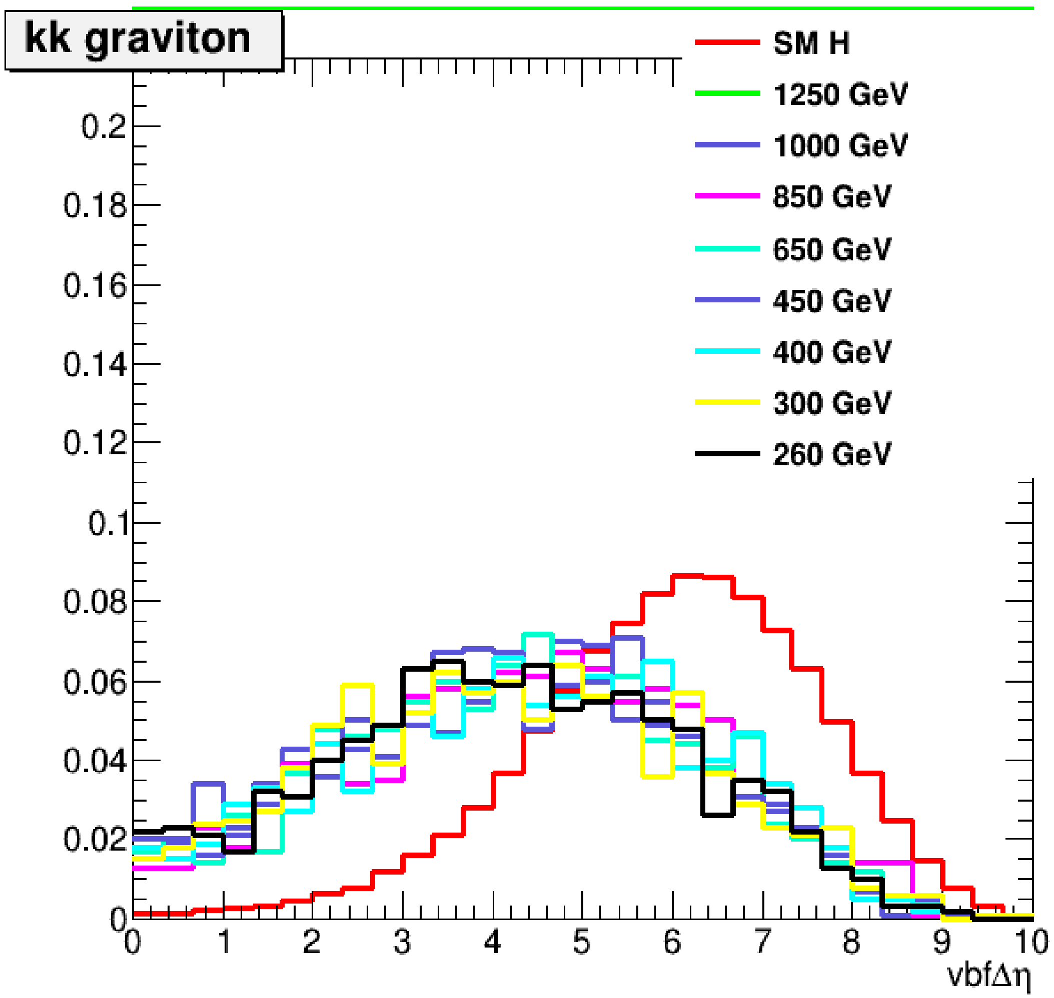
Transverse mass $H \to WW \to l\nu l\nu$

- Transverse mass used in $H \to WW \to l\nu l\nu$ analysis
  - Due to lack of information from neutrinos, invariant mass cannot be reconstructed
  - Transverse mass under the hypothesis $m_{ll} \sim m_{\nu\nu}$

$$m_T(WW) \equiv \left(\left(\sqrt{m_{ll}^2 + |\vec{p}_{Tll}|^2} + \sqrt{m_{ll}^2 + |\vec{p}_{Tmiss}|^2} \right)^2 - |\vec{p}_{Tll} + \vec{p}_{Tmiss}|^2 \right)^{1/2}$$

KK-Graviton

- KK-graviton $\Delta\eta_{jj}$ distribution
  - KK-graviton vertices with vector bosons implies no high-$\Delta\eta_{jj}$ distribution
  - Related spin 2 resonances



KK-Graviton efficiencies

- Cut flow efficiencies

Sample	basic cuts (eqs. 7,6)	jet merging (akt5)	$M_{jj} > 400$ GeV	$M_{HH} > 250$ GeV	$p_T^{HH} > 60$ GeV	$\Delta\eta_{HH} < 2$
1450 GeV	0.53	0.49	0.44	0.44	0.41	0.35
1250 GeV	0.52	0.47	0.43	0.43	0.40	0.35
1050 GeV	0.52	0.48	0.44	0.44	0.40	0.35
850 GeV	0.51	0.47	0.42	0.42	0.39	0.34
650 GeV	0.51	0.43	0.39	0.39	0.36	0.33
450 GeV	0.54	0.38	0.34	0.34	0.32	0.30
400 GeV	0.55	0.33	0.29	0.29	0.28	0.26
300 GeV	0.58	0.17	0.14	0.14	0.13	0.12
260 GeV	0.60	0.09	0.07	0.07	0.07	0.07
SM $H(b\bar{b})H(b\bar{b})$ jj	0.41	0.38	0.36	0.36	0.30	0.12
$Z(b\bar{b})$ $b\bar{b}$ jj	0.50	0.36	0.14	0.10	7.91E-02	4.55E-02
$Z(b\bar{b})Z(b\bar{b})$ jj	0.62	0.51	0.17	0.12	9.66E-02	6.61E-02
$b\bar{b}$ $b\bar{b}$ jj	0.70	0.20	0.11	6.73E-02	5.49E-02	4.55E-02

References

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