Multi-Higgs Production via Vector-Boson Fusion at Hadron Colliders

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November 23, 2019
Composite 2019, Guangzhou

Overview

1. Motivation
2. The Effective Field Theory
3. Monte-Carlo Simulation and Analysis
4. Conclusion

Motivation

Lagrangian

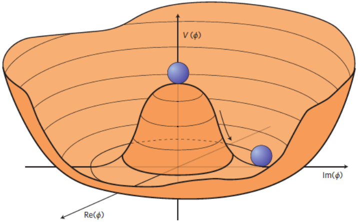
$$\mathcal{L}_H = (D^\mu H)^\dagger (D_\mu H) - V(H^\dagger H)$$

Higgs potential

$$V(H^\dagger H) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2$$

vacuum expectation value

$$v = \sqrt{\mu^2/\lambda}$$



[J. Ellis, 2013]

Motivation

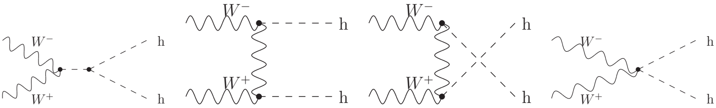
After the discovery of Higgs boson, further researches are needed to answer following questions

- Are the properties of Higgs boson agreed with the SM prediction?
- What is the shape of Higgs potential?
- How New Physics contributes to the Higgs sector?

The measurements of multi-Higgs final state are important to answer these questions.

Motivation

- The subdominant process of multi-Higgs production at hadron colliders is so-called vector-boson-fusion (VBF).
- This process involves two energetic forwarded jets, so we can suppress the background by VBF cuts.
- It is important for the measurement of Higgs-vector-boson interactions and Higgs self-interatcions.



The Effective Field Theory

We study the new physics by an effective Lagrangian

$$\mathcal{L}_{EFT} = \mathcal{L}_{\overline{SM}} + \mathcal{L}_{Vh} + \mathcal{L}_{VVh} + \mathcal{L}_{h}$$

$\mathcal{L}_{\overline{SM}}$: The SM Lagrangian after removing the Higgs-vector-boson interactions and Higgs self-interactions.
$\mathcal{L}_{Vh}$: The SM-like Higgs-vector-boson interactions.
$\mathcal{L}_{VVh}$: The tensor structure interactions of Higgs to vector boson.
$\mathcal{L}_{h}$: The effective Higgs self-interactions.

The Effective Field Theory

$$\mathcal{L}_{Vh} = g_{W,a1}\frac{2m_W^2}{v}hW^{+,\mu}W_\mu^- + g_{W,a2}\frac{m_W^2}{v^2}h^2W^\mu W_\mu + g_{Z,a1}\frac{m_Z^2}{v}hZ^\mu Z_\mu + g_{Z,a2}\frac{m_Z^2}{2v^2}h^2Z^\mu Z_\mu$$

The SM is recovered when $g_{W,a1} = g_{W,a2} = g_{Z,a1} = g_{Z,a2} = 1$.

$$\mathcal{L}_{VVh} = -g_{W,b1}\frac{h}{v}W_{\mu\nu}^+W^{-\,\mu\nu} - g_{W,b2}\frac{h^2}{2v^2}W_{\mu\nu}^+W^{-\,\mu\nu} - g_{Z,b1}\frac{h}{2v}Z_{\mu\nu}Z^{\mu\nu} - g_{Z,b2}\frac{h^2}{4v^2}Z_{\mu\nu}Z^{\mu\nu}$$

This part is absent at tree level in the SM, and all coefficients vanish.

$$\mathcal{L}_h = -\lambda_3\frac{m_h^2}{2v}h^3 - \frac{\kappa_5}{2v}h\partial^\mu h\partial_\mu h - \lambda_4\frac{m_h^2}{8v^2}h^4 - \frac{\kappa_6}{4v^2}h^2\partial^\mu h\partial_\mu h$$

When $\lambda_3 = \lambda_4 = 1$ and $\kappa_5 = \kappa_6 = 0$, the SM is recovered.

The Effective Field Theory

	$VV \to h$	$VV \to hh$
Parameters involved	$g_{V,a1}$, $g_{V,b1}$ -	$g_{V,a1}$, $g_{V,b1}$ $g_{V,a2}$, $g_{V,b2}$, λ_3, κ_5

- $g_{V,a1}$ and $g_{V,b1}$ can be measured by single Higgs production.
- λ_3 and κ_5 also contribute to $gg \to hh$ process.
- $g_{V,a2}$ and $g_{V,b2}$ only contribute to the double Higgs production, which we are interested.
- $g_{V,a2}$ has been well studied in [F. Bishara *et al.*, 2016]

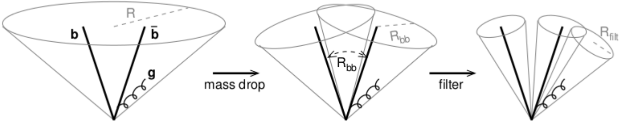
Monte-Carlo Simulation

- **Parton Level Events:** WHIZARD [W. Kilian *et al.*, 2007]
- **PDF:** CTEQ6L1 [J. Pumplin *et al.*, 2002]
- **Parton Shower and Hadronization:** PYTHIA8 [T. Sjostrand *et al.*, 2014]
- **Jet Reconstruction:** Fastjet [M. Cacciari *et al.*, 2012]
- **Background Events:** WHIZARD and ALPGEN [M. L. Mangano *et al.*, 2002]

Analysis Strategy

- We are interested in $pp \to hhjj \to 4b2j$ at $14(100)$ TeV;
- Jets are reconstructed by anti-k_t algorithm [M. Cacciari *et al.*, 2008] with $R = 0.4$ and $P_t > 20$ GeV;
- If the highest energy jet has $E_j > 500(800)$ GeV, we calculate its maximum of y_{jj} and m_{jj} with other jets;
- If $y_{jj,max} > 3.6(4.0)$ and $m_{jj,max} > 500(800)$ GeV, these two jets are tagged as the associated jets in the VBF process;
- The constituents of other jets are reclustered by CA algorithm [Y. L. Dokshitzer *et al.*, 1997] with $R = 1.2$;
- Two hardest CA jets with $P_t > 200$ GeV and $m_j >$100 GeV are used to do the MassDrop analysis [J. M. Butterworth *et al.*, 2008].

Mass-Drop (MD) tagger [J. M. Butterworth *et al.*, 2008]



- Obtain hard jet j by some jet algorithm.
- Undo the last step of the splitting of jet j to get two subjets j_1 and j_2, and $m_{j1} > m_{j2}$;
- If they satisfy

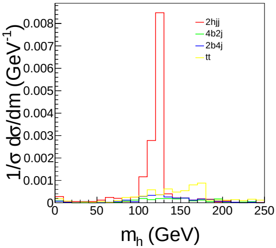
$$m_{j1} < \mu m_j, \ \frac{\min(P_t(j_1), P_t(j_2))}{m_j^2} \Delta R^2_{j1,j2} > y_{cut}$$

we can say that j is a heavy particle with substructure.

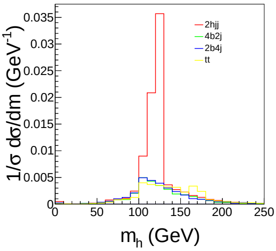
- Otherwise redefine j to be equal to j_1 and repeat.

Analysis Results of 14 TeV LHC

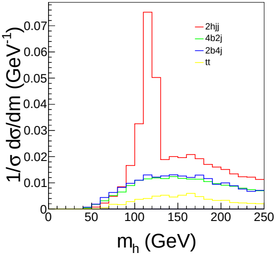
We reconstruct the Higgs bosons in SM, and find



(a) 2-boosted



(b) 1-boosted



(c) 0-boosted

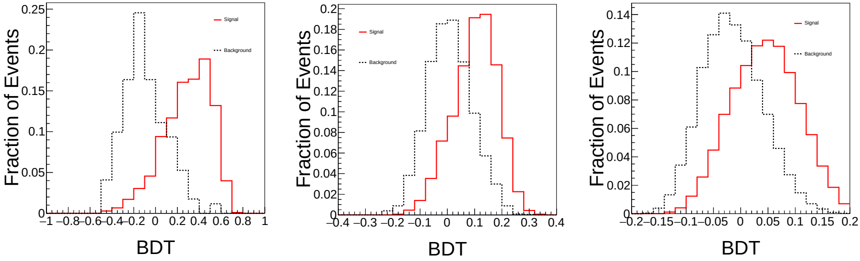
Analysis Results of 14 TeV LHC

Assuming $\mathcal{L} = 3000$ fb^{-1}, b-tagging efficiency $\epsilon_b = 0.7$, and miss tagging rate $\epsilon_{miss} = 0.001$

Process	$\sigma \times \mathcal{L}$	$n_b = 4$	VBF
SM signal	993	238	171
$pp \to 4b2j$	2.28×10^8	5.47×10^7	1.86×10^7
$pp \to 2b4j$	2.38×10^{10}	1.14×10^4	4180
$pp \to t\bar{t} \to 2b4j$	7.89×10^8	387	58

	2-boosted	1-boosted	0-boosted
SM Signal	4	21	146
$pp \to 4b2j$	1.17×10^5	1.56×10^6	1.69×10^7
$pp \to 2b4j$	28	349	3810
$pp \to t\bar{t} \to 2b4j$	3	13	42

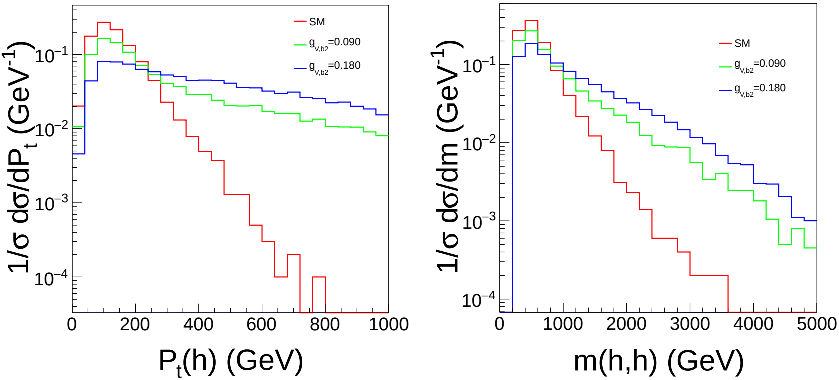
Analysis Results of 14 TeV LHC



(a) 2-boosted (b) 1-boosted (c) 0-boosted

	2-boosted	1-boosted	0-boosted
SM Signal with BDT cut	3	13	90
Background with BDT cut	2.06×10^4	3.05×10^5	4.42×10^6
S/B	1.40×10^{-4}	4.30×10^{-5}	2.04×10^{-5}
$S/\sqrt{S+B}$	0.020	0.024	0.043

Analysis Results of 14 TeV LHC

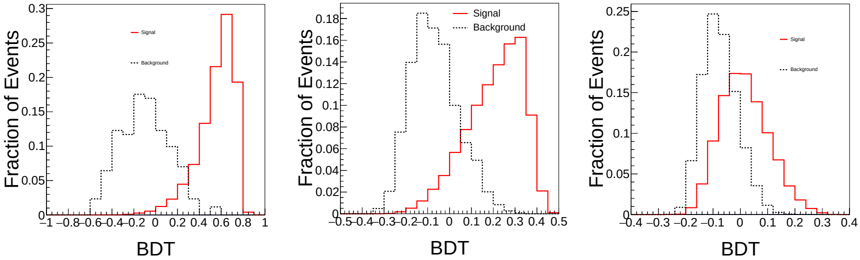


Analysis Results of 14 TeV LHC

Process	$\sigma \times \mathcal{L}$	$n_b = 4$	VBF
$g_{V,b2} = 0.18$ signal	5088	1222	694
$pp \to 4b2j$	2.28×10^8	5.47×10^7	1.86×10^7
$pp \to 2b4j$	2.38×10^{10}	1.14×10^4	3.85×10^4
$pp \to t\bar{t} \to 2b4j$	7.89×10^8	387	58

	2-boosted	1-boosted	0-boosted
$g_{V,b2} = 0.18$ Signal	184	235	275
$pp \to 4b2j$	1.17×10^5	1.56×10^6	1.69×10^7
$pp \to 2b4j$	28	349	3.81×10^4
$pp \to t\bar{t} \to 2b4j$	3	13	42

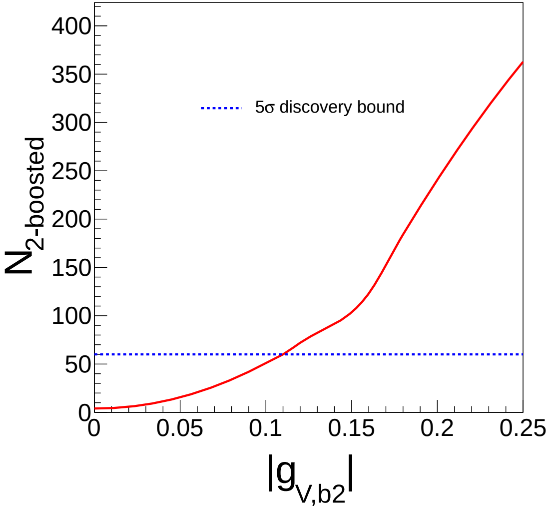
Analysis Results of 14 TeV LHC



(a) 2-boosted (b) 1-boosted (c) 0-boosted

	2-boosted	1-boosted	0-boosted
$g_{V,b2} = 0.18$ Signal with BDT cut	90	49	31
Background with BDT cut	0	0	3.84×10^4
S/B	∞	∞	2.51×10^{-3}
$S/\sqrt{S+B}$	9.48	7.00	0.156

Analysis Results of 14 TeV LHC



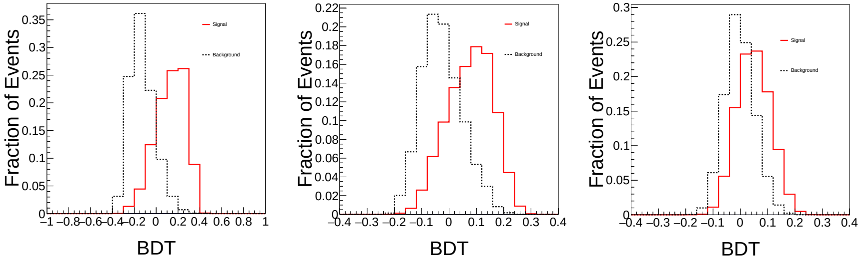
Analysis Results of 100 TeV Collider

Assuming $\mathcal{L} = 30$ ab^{-1},

Process	$\sigma \times \mathcal{L}$	$n_b = 4$	VBF
SM signal	4.28×10^5	1.03×10^5	8.96×10^4
$pp \to 4b2j$	5.02×10^{10}	1.21×10^{10}	8.51×10^9
$pp \to 2b4j$	5.04×10^{12}	2.47×10^6	1.83×10^6
$pp \to t\bar{t} \to 2b4j$	3.93×10^{11}	1.93×10^5	6.20×10^4

	2-boosted	1-boosted	0-boosted
SM Signal	4265	1.76×10^4	6.77×10^4
$pp \to 4b2j$	3.65×10^8	2.01×10^9	6.13×10^9
$pp \to 2b4j$	8.35×10^4	4.40×10^5	1.31×10^6
$pp \to t\bar{t} \to 2b4j$	8244	2.20×10^4	3.18×10^4

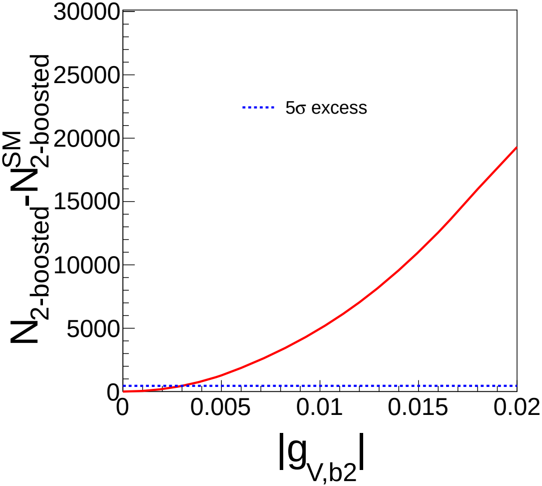
Analysis Results of 100 TeV Collider



(a) 2-boosted (b) 1-boosted (c) 0-boosted

	2-boosted	1-boosted	0-boosted
SM Signal with BDT cut	298	12	90
Background with BDT cut	0	0	78
S/B	∞	∞	1.15
$S/\sqrt{S+B}$	17.27	3.43	6.923

Analysis Results of 100 TeV Collider



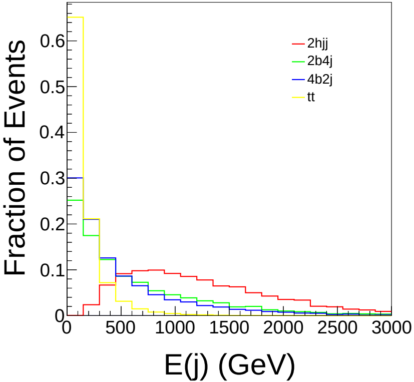
Conclusion

- After the discovery of Higgs boson, the measurements of its properties are necessary to search for new physics
- We analyse the VBF process $pp \to hhjj \to 4b2j$ at 14 TeV LHC and 100 TeV collider.
- Potential new physics effects are described by an EFT Lagrangian defined at mass eigenstates.
- The bounds on $g_{V,b2}$ are obtained.

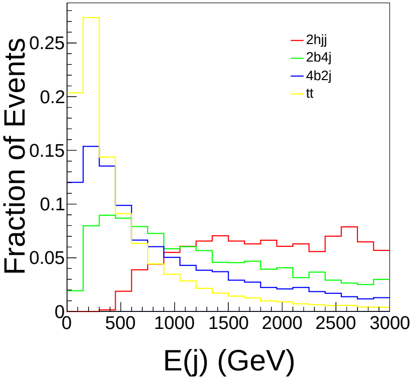
Thank You

Backup slides

The Distribution of The Jet with Highest Energy



(a) 14 TeV



(b) 100 TeV

The Input of BDT Analysis

- $P_t(h_i)$: the transverse momentum of reconstructed Higgs boson.
- $m(h_i)$: the invariant mass of reconstructed Higgs boson.
- $P_t(j_i)$: the transverse momentum of forwarded jet.
- $E(j_i)$: the energy of forwarded jet.
- $\eta(j_i)$: the pseudorapidity of forwarded jet.
- $m(j,j)$: the invariant mass of two forwarded jet.
- $y(j,j)$: the rapidity of two forwarded jet.
- $P_t(j_i^{sub})$: the transverse momentum of subjet of the Higgs.
- $m(h,h)$: the invariant mass of two Higgs.