Search for pair production of boosted Higgs bosons via vector-boson fusion in the bbbb final state using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Zhen Wang

University of Science and Technology of China

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

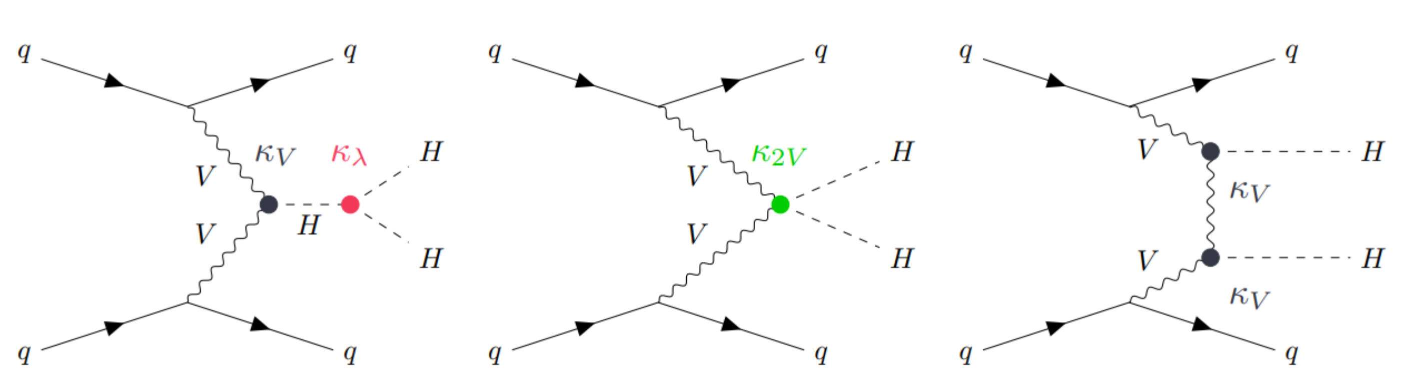
HiggsPotential 2024, Hefei

doi.org/10.1016/j.physletb.2024.139007

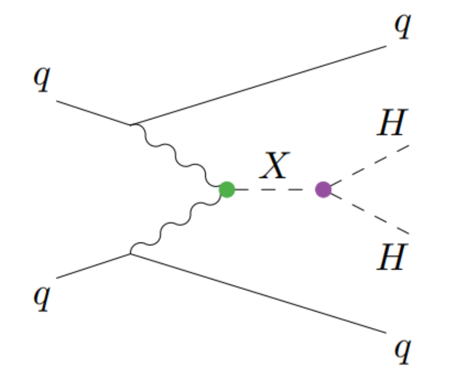
Contents

VBF HH → 4b Motivation

- Search for **resonant** & **non-resonant** boosted VBF HH4b with Full-Run2 data



Non-resonant Production



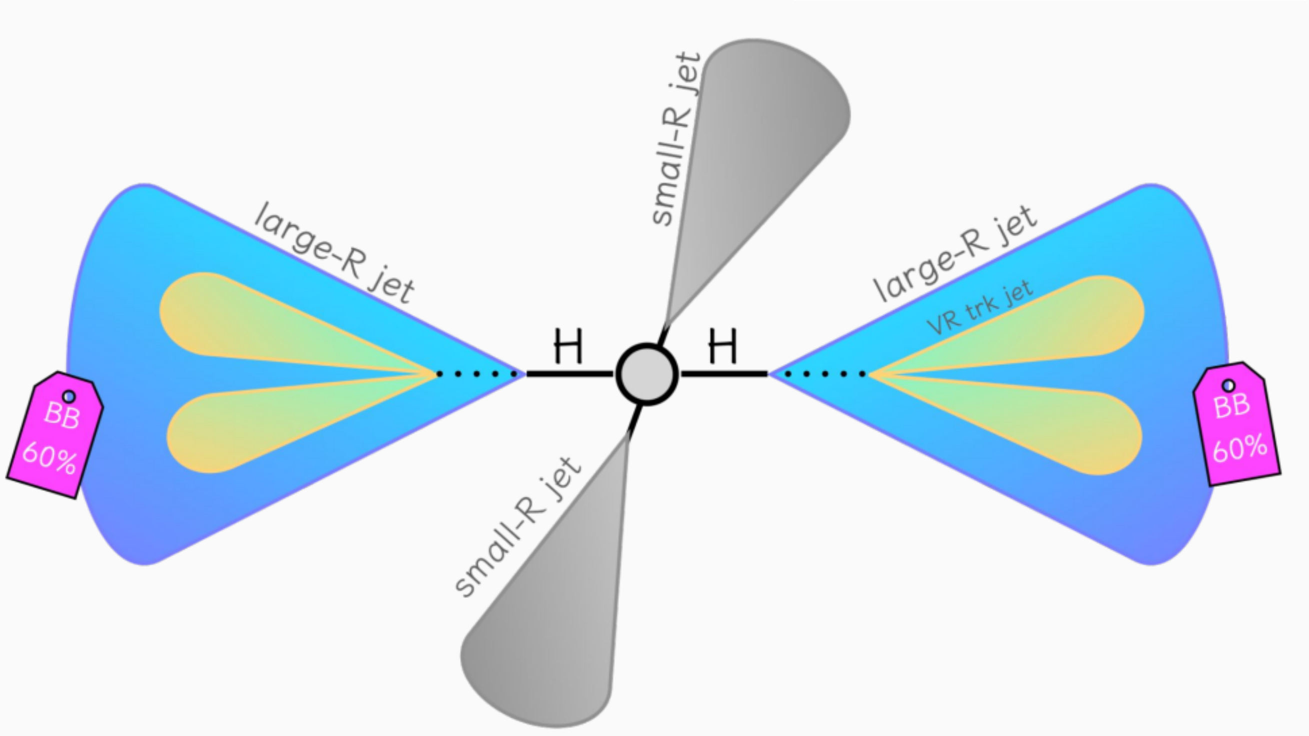
Resonant Production

- **Sub-dominant production VBF : $1.726fb@13TeV, m_H = 125\ GeV$, (ggF σ=31.05fb)**
- **Set constrains on κ_{2V} with HHVV coupling , previously published results :**
  - ATLAS: $\kappa_{2V} \in [-0.03, 2.11]$ @ 95% (resolved search)
  - CMS: $\kappa_{2V} \in [0.6, 1.4]$ @ 95% (boosted search) with $\kappa_{2V} = 0$ excluded
- **Search limits on X→HH production [2HDM, Composite Higgs, Radion, etc.]**

VBF HH → 4b Final States

- Targets: the boosted HH system with two collimated b-jets from each Higgs (largest branching ratio from $HH \rightarrow b\bar{b}b\bar{b}$ ~34%).
- Xbb-tagger tags each $H \rightarrow b\bar{b}$ at 60% WP (2 large-R jets with R=1.0).
- 2 resolved small-R (R=0.4) VBF jets

	$b\bar{b}$	WW^*	gg	$\tau^+\tau^-$	$c\bar{c}$	ZZ^*	$\gamma\gamma$
$b\bar{b}$	33.9%	24.9%	9.5%	7.3%	3.4%	3.1%	0.3%
WW^*		4.6%	3.5%	2.7%	1.2%	1.1%	< 0.1%
gg			0.7%	1.0%	0.5%	0.4%	< 0.1%
$\tau^+\tau^-$				0.4%	0.4%	0.3%	< 0.1%
$c\bar{c}$					< 0.1%	0.2%	< 0.1%
ZZ^*						< 0.1%	< 0.1%
$\gamma\gamma$							< 0.1%

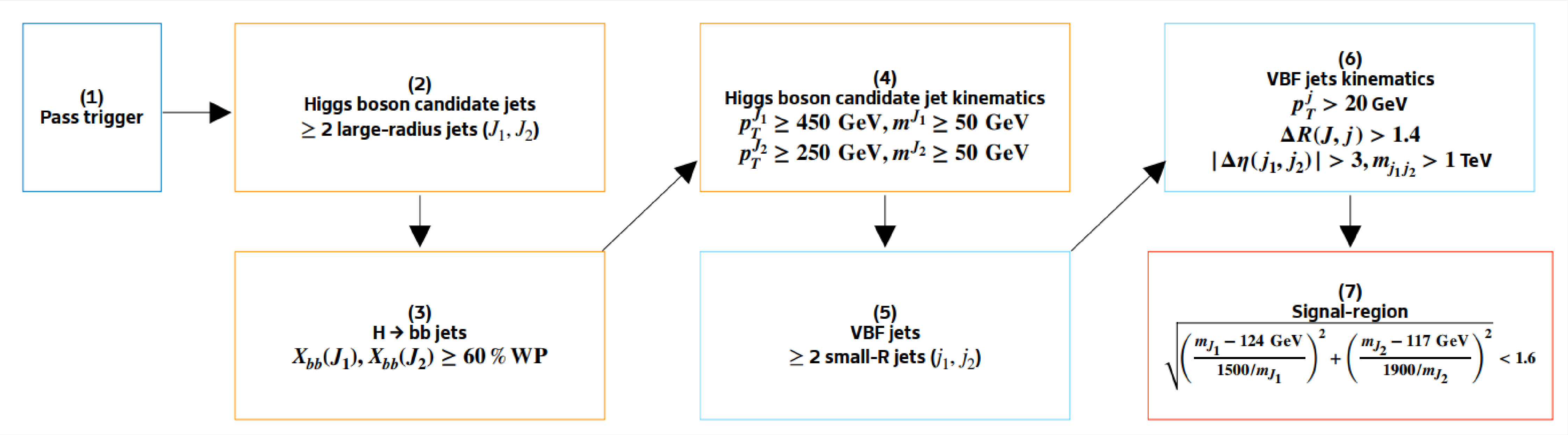


VBF HH → 4b Samples

- Data: 140 fb^{-1} Full-Run2 data
- Non-resonant signal:
  - Powheg+Pythia8 NLO ggF HH ($\kappa_\lambda = 1$ & 10)
  - Madgraph+Pythia8 LO VBF HH (combination of κ_λ, κ_{2V} , κ_V), some low-stats samples with large-R jet filter included.
- Resonant signal:
  - **2HDM** for NW ($\Gamma_X = 40$MeV): m_X =[1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0] TeV
  - **Composite model** ($\Gamma_X = 2\%, 20\%\ mass$): [1.0, 1.5, 2.0] TeV
  - **Radion** for broad width ($\Gamma_X = 20\%\ mass$): [1.0, 2.0] TeV
- Background:
  - Fully data-driven estimation of backgrounds
  - Di-jet and $t\bar{t}$ MC are used for Xbb WP optimizations

VBF HH → 4b Selections

- Selections are optimized to work for both resonant and non-resonant analysis.
- Extra veto in non-resonant analysis to remove events from resolved SR.



50% and 70% WPs give worse results

VBF HH → 4b Selections

Cutflow

$\kappa_{2V} = 0$ signal sample

Selection	Event	Fraction [%]	Total Fraction [%]
Initial	1288.197	100.000	100.000
Jet Cleaning	1279.591	99.332	99.332
PassTrigBoosted	248.139	19.392	19.262
PassTwoFatJets	168.376	67.855	13.071
PassTwoHbbJets	61.703	36.646	4.790
PassVBFJets	45.747	74.140	3.551
PassFatJetPt	39.160	85.602	3.040
PassVBFCut	26.371	67.341	2.047
PassSR	20.030	75.956	1.555
OverlapRemoval	16.038	80.069	1.245

$m_X = 1.5$ TeV signal sample

Selection	Event	Fraction [%]	Total Fraction [%]
Initial	205200.997	100.000	100.000
Jet Cleaning	203857.627	99.345	99.345
PassTrigBoosted	162773.447	79.847	79.324
PassTwoFatJets	116712.187	71.702	56.877
PassTwoHbbJets	44592.211	38.207	21.731
PassVBFJets	32857.167	73.684	16.012
PassFatJetPt	31561.205	96.056	15.381
PassVBFCut	21421.006	67.871	10.439
PassSR	16300.886	76.098	7.944

- Optimized to work for both non-resonant and resonant signal samples.
- OR only applied on non-resonant analysis to remove resolved events where combination is expected.
- Trigger and Xbb tagging step are the most powerful

VBF HH → 4b Regions

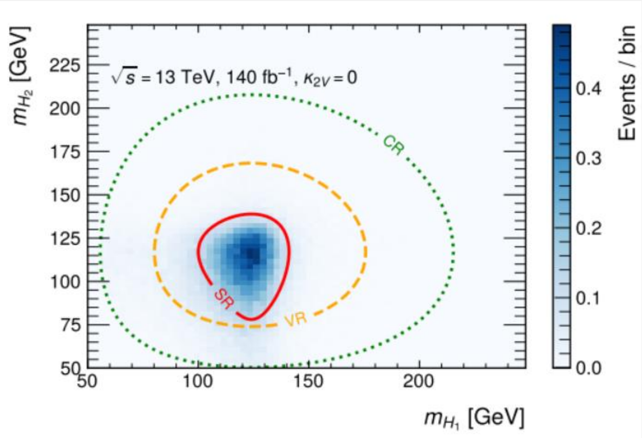
- SR:

$$\text{SR region}: \sqrt{\left(\frac{m_{J_1} - 124\ \text{GeV}}{1500/m_{J_1}}\right)^2 + \left(\frac{m_{J_2} - 117\ \text{GeV}}{1900/m_{J_2}}\right)^2} < 1.6$$

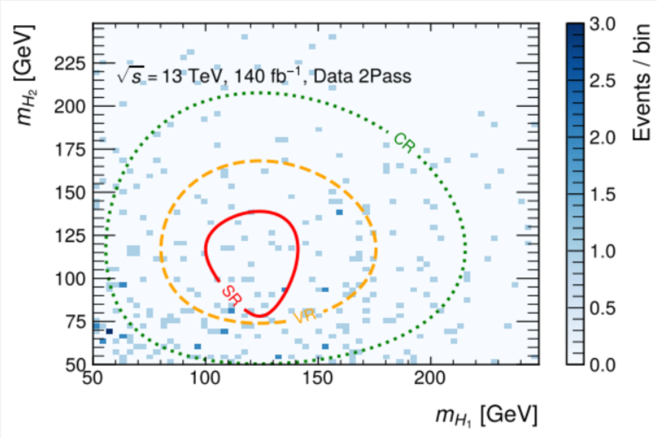
- 14% improvements compared with resolved analysis
- VR/CR:

$$\text{VR/CR region}: \sqrt{\left(\frac{m_{J_1} - 124\ \text{GeV}}{0.1\log(m_{J_1})}\right)^2 + \left(\frac{m_{J_2} - 117\ \text{GeV}}{0.1\log(m_{J_2})}\right)^2} < 100/170$$

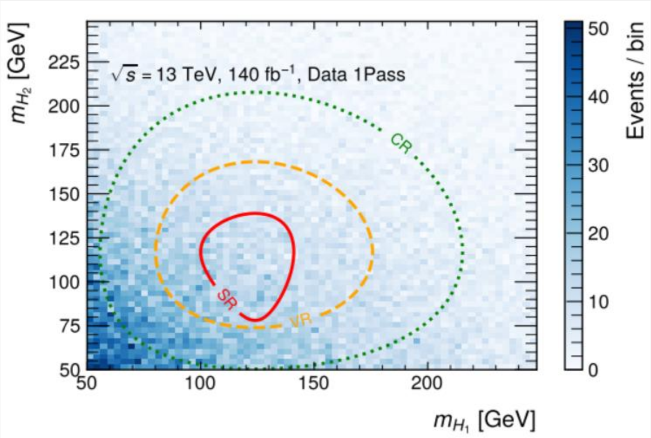
- Relaxed than resolved analysis to improve statistics
- Derive data-driven background based on those regions



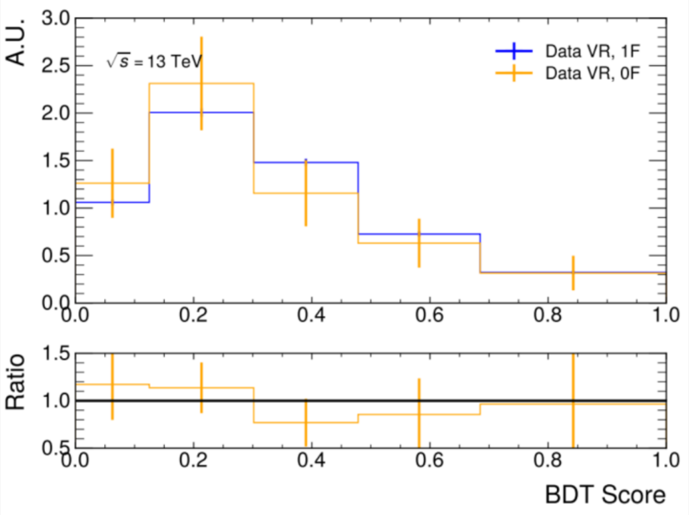
"Data 0F": No jets failed Xbb



"Data 1F": one jet failed Xbb



VBF HH → 4b Background Estimation



- The shapes from 0F and 1F looks close.

	SR	VR	CR
0F	Blinded	58	128
1F	2649	6299	14921

- Inclusive normalization factor is derived from CR and applied on SR

$$B^{pred}_{SR,0F} = \frac{N^{obs}_{CR,0F}}{N^{obs}_{CR,1F}} \times B^{pred}_{SR,1F}$$

$$\frac{N(\mathrm{CR,\ 0F})}{N(\mathrm{CR,\ 1F})} = 0.0086 \pm 0.0008$$

- Normalization uncertainty derived from difference from CR and VR

$$\frac{N^{obs}_{VR,0F}}{N^{obs}_{VR,1F}} / \frac{N^{obs}_{CR,0F}}{N^{obs}_{CR,1F}} - 1 \approx 7.3\%$$

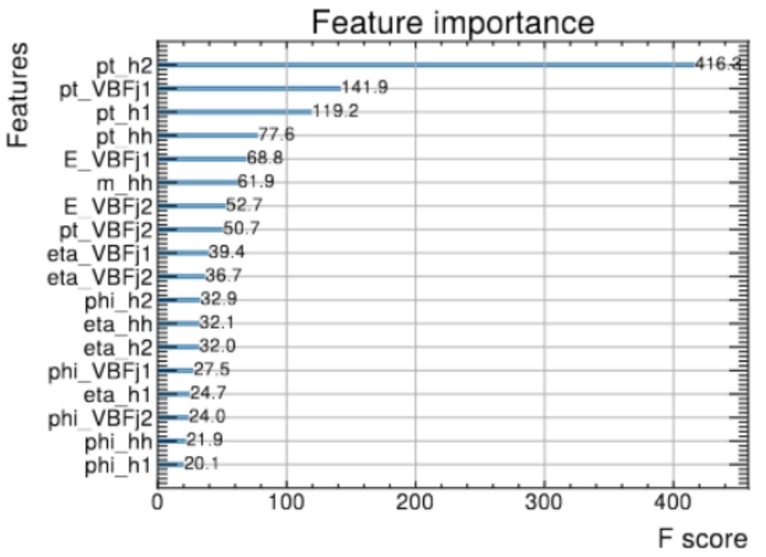
- Shape systematics derived from difference between 0F and 1F in VR. Factoring out normalization uncertainty

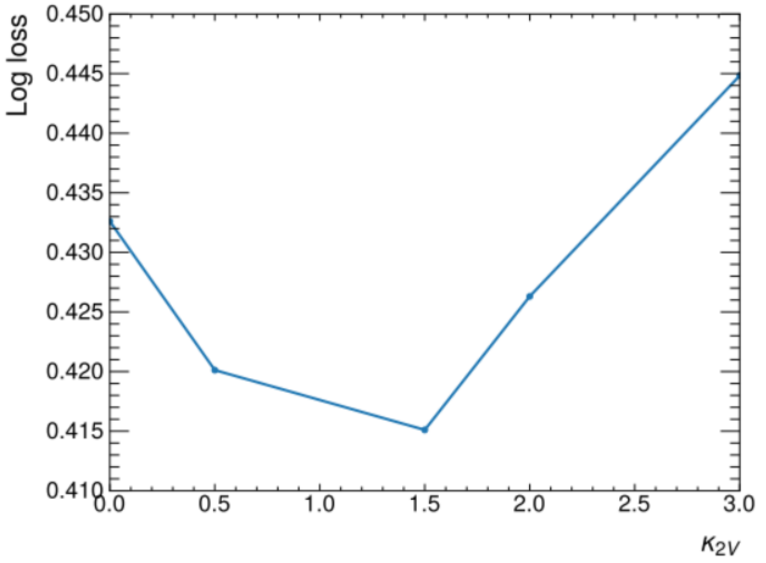
VBF HH → 4b Non-resonant categorization

- XGBoost BDT score as main observable in the statistical analysis
  - Signal: $\kappa_{2V} = 0$ sample
  - Bkg: data-driven + SM VBF & ggF
- Training done in SR, without Higgs mass as input features (make BDT independent of SR)

Relevant Objects	Kinematics used in training
Higgs Candidate ($H_i, i = 1, 2$)	$p_T^{H_i}, \eta_{H_i}$
Di-Higgs System (HH)	$p_T^{HH}, \eta_{HH}, m_{HH}$
VBF Jets ($j_i, i = 1, 2$)	$p_T^{j_i}, \eta_{j_i}, E_{j_i}$

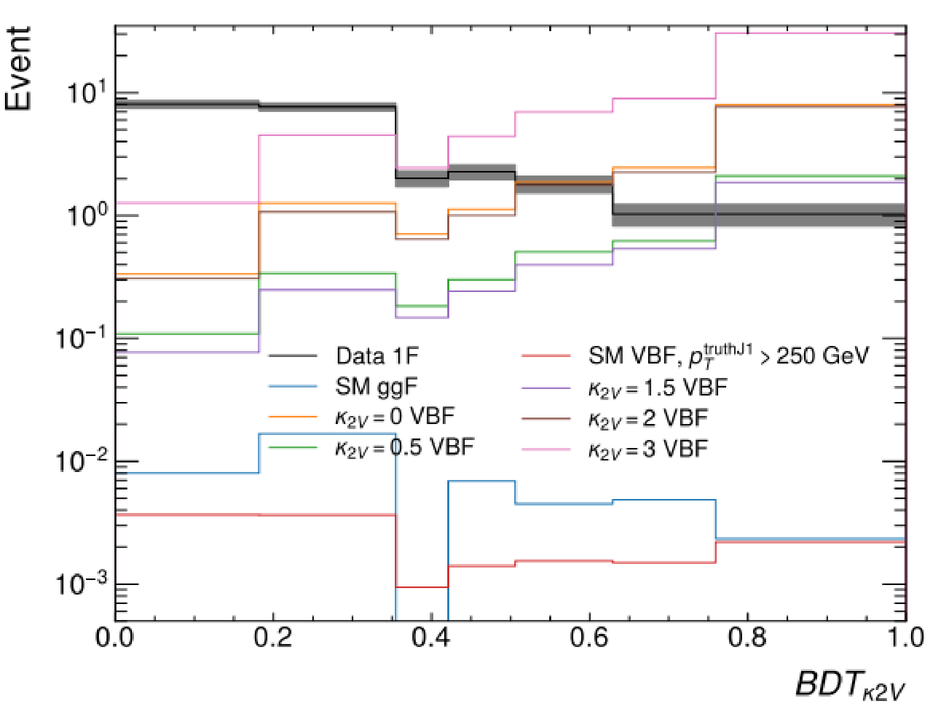
- 80% for training and 20% for stat analysis.
- Hyperparameter optimization with log-loss function to evaluate the model quality





VBF HH → 4b Non-resonant binning

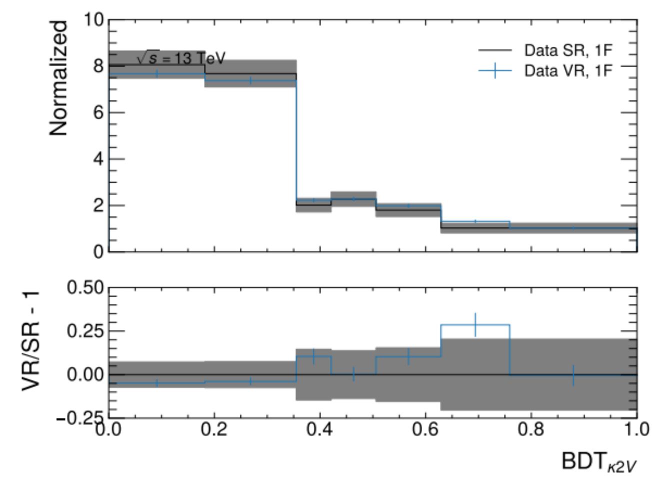
- BDT score as the main observable
- Binning optimization strategy:
  - Number of bins set n_{bin}^{i} with bin edge randomly decided
  - Stat. only model generated with current binning
  - Generation is repeated for 10k times and note binning B_i with largest significance Z_i
  - Repeat the process above with n_{bin}^{i} starting from 2. Stop when $Z_{i+1} < Z_i$



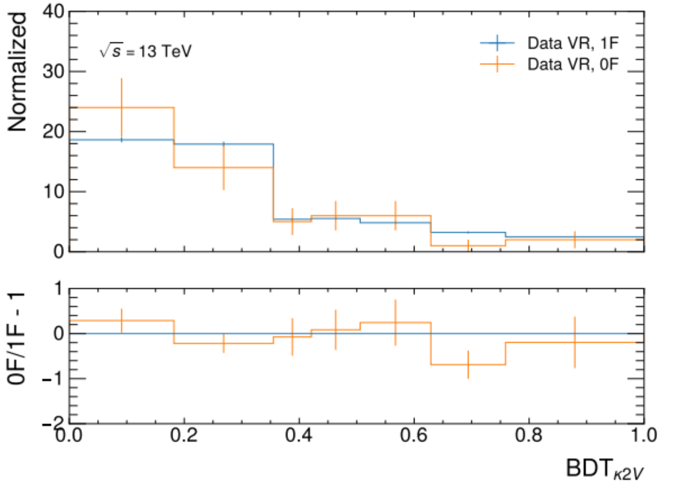
- Final binning:
  - [0.0, 0.182, 0.355, 0.421, 0.506, 0.629, 0.759, 1.0]

VBF HH → 4b Non-resonant Shape Uncertainty

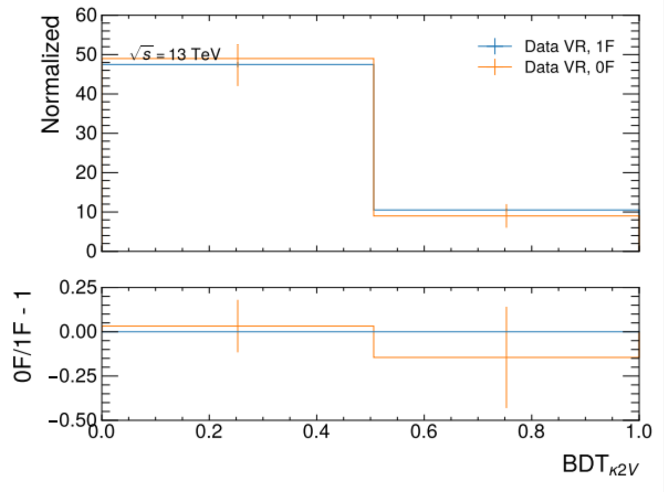
- Confirm trend in SR,1F and VR,1F is similar.
- BDT response in VR,1F and VR,0F to extract shape uncertainty (with huge statistical fluctuations)
- Would be highly over-constrained without smoothing
- 2-bin smoothing to reduce stat fluctuation
- Final shape systematics to be used in fits



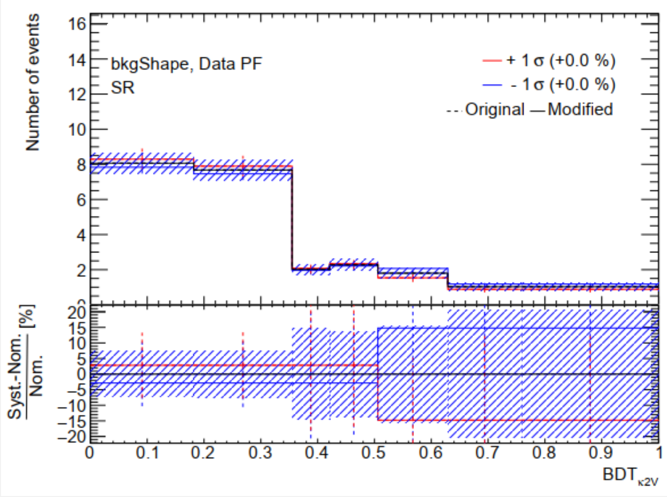
a



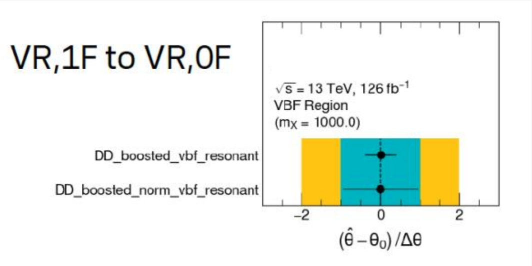
b

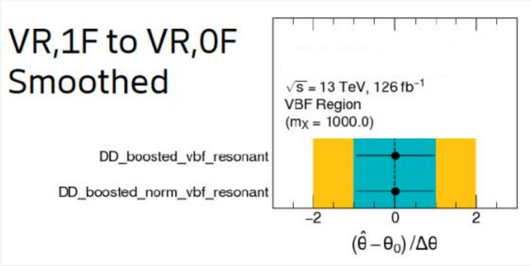


c



d





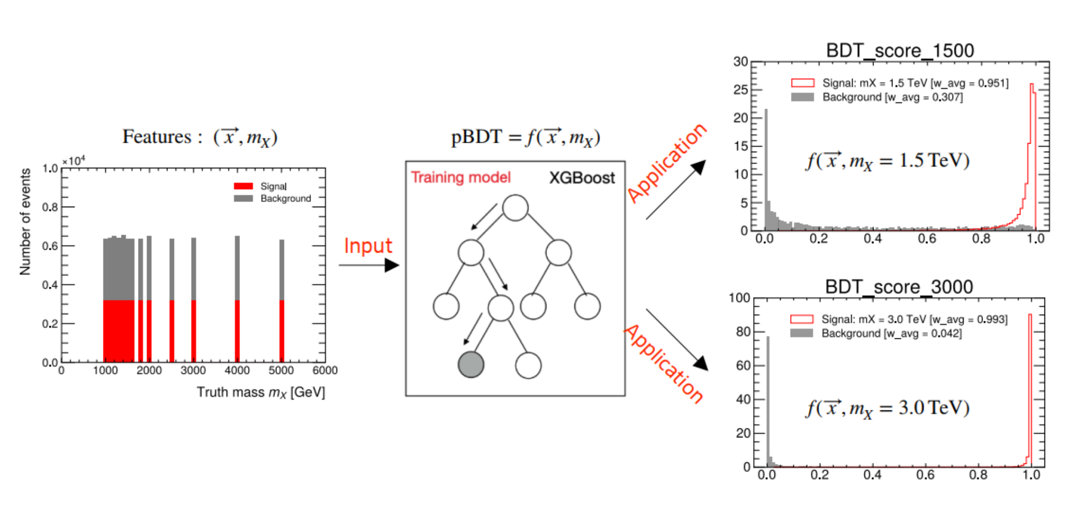
VBF HH → 4b Resonant Categorization

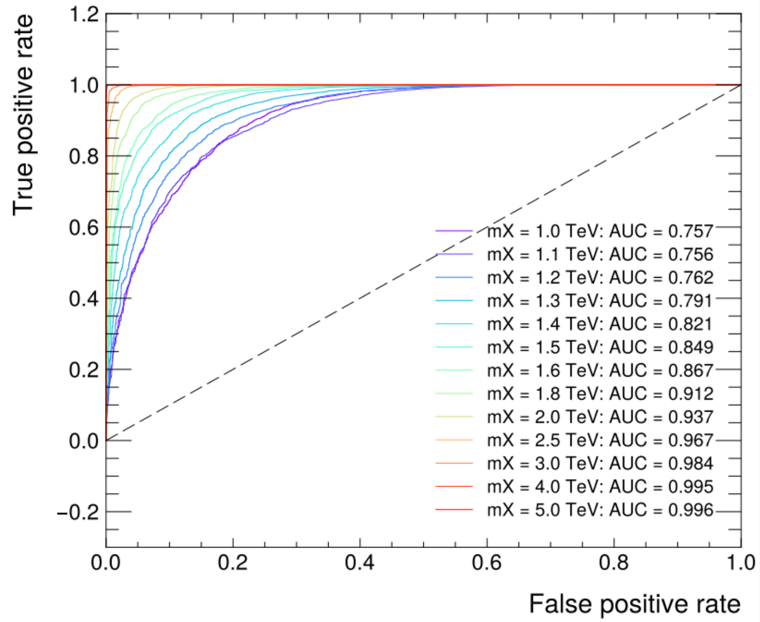
Tsung-Dao Lee Institute

- Parametric version of BDT
- Discriminate all signal mass hypothesis and data-driven backgrounds
- Parametric variable: truth resonant mass
  - Bkg: random truth mass
- Additional kinematic features similar to non-resonant

$H1$, $H2$ (large-R jet)	p_T, η
HH	p_T, η, m_{HH}
VBF jet 1, jet 2	p_T, η, E

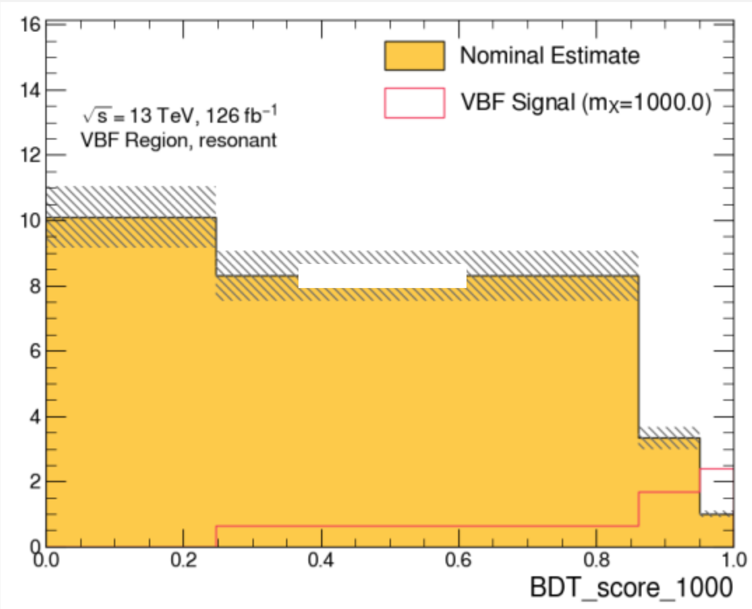
- Low stat: looser selections for training only
  - Relax Xbb WP to 70% and remove VBF cuts
  - Evaluate with full SR selections
- Hyper-parameter optimization: high AUC with no sign of overfitting

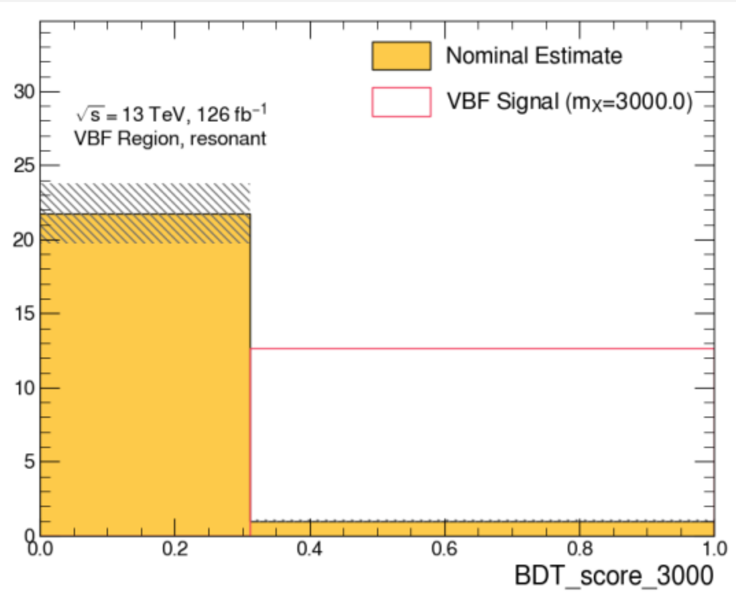




VBF HH → 4b Resonant pBDT binning

- For each mass hypothesis pBDT score is different → different binnings.
- Low number of bins due to high separation power of the pBDT with high masses.
- Binnings optimised using "Transformation D" method, as implemented in TRExFitter
  - Assure at least 1 bkg event in each bin



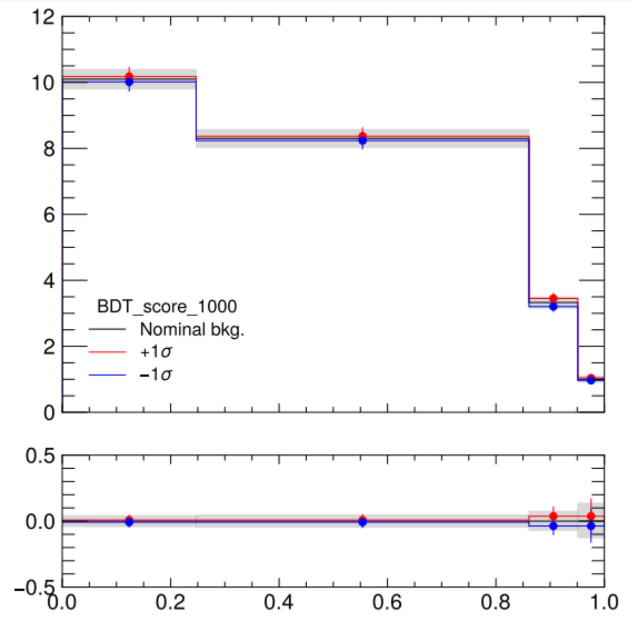


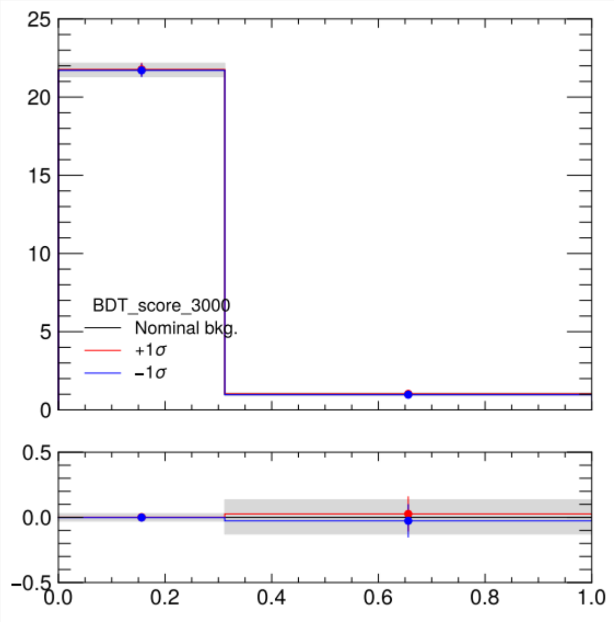
Mass points [TeV]	z_s	z_b	Exact binning
1.0	2	2	[0.0, 0.247, 0.861, 0.951, 1.0]
1.1	4	1	[0.0, 0.003, 0.778, 0.909, 0.947, 1.0]
1.2	3	1	[0.0, 0.139, 0.871, 0.95, 1.0]
1.3	3	0	[0.0, 0.701, 0.949, 1.0]
1.4	2	1	[0.0, 0.3, 0.951, 1.0]
1.5	2	2	[0.0, 0.006, 0.433, 0.944, 1.0]
1.6	1	4	[0.0, 0.008, 0.1, 0.524, 0.936, 1.0]
1.8	1	4	[0.0, 0.002, 0.027, 0.253, 0.901, 1.0]
2.0	1	3	[0.0, 0.002, 0.048, 0.868, 1.0]
2.5	1	2	[0.0, 0.001, 0.603, 1.0]
3.0	1	1	[0.0, 0.312, 1.0]
4.0	1	1	[0.0, 0.057, 1.0]
5.0	1	1	[0.0, 0.053, 1.0]

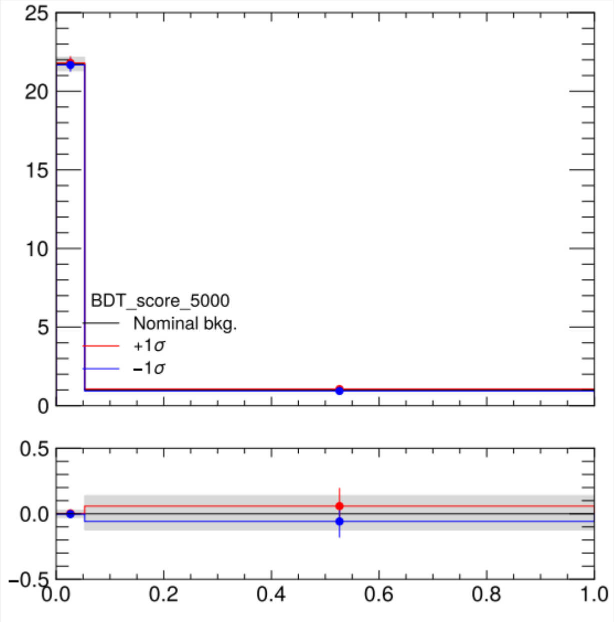
VBF HH → 4b Resonant pBDT Shape uncertainty

- Shape uncertainty is derived similarly with non-resonant analysis.

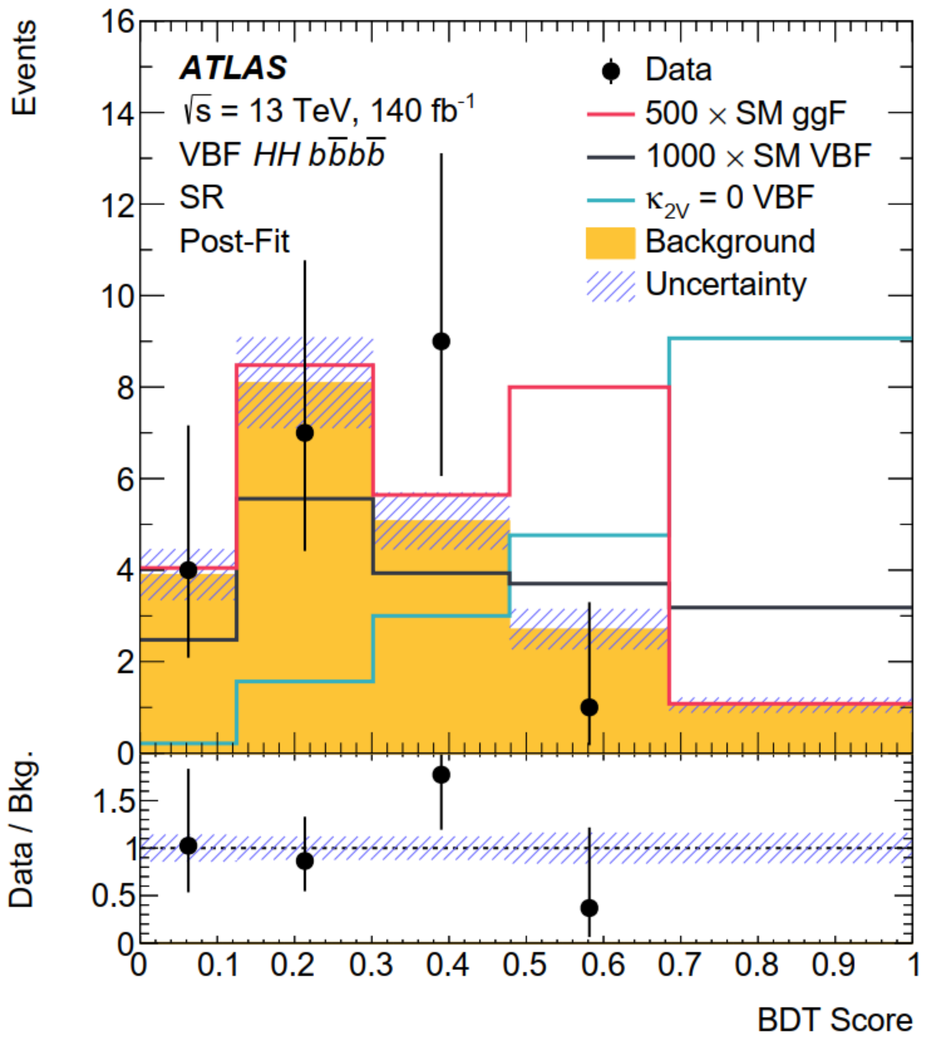
- Verify similarity between SR,1F and VR,1F
- Derive sys. from differences between VR,1F and VR,0F
- Use smoothing to reduce stat. fluctuations



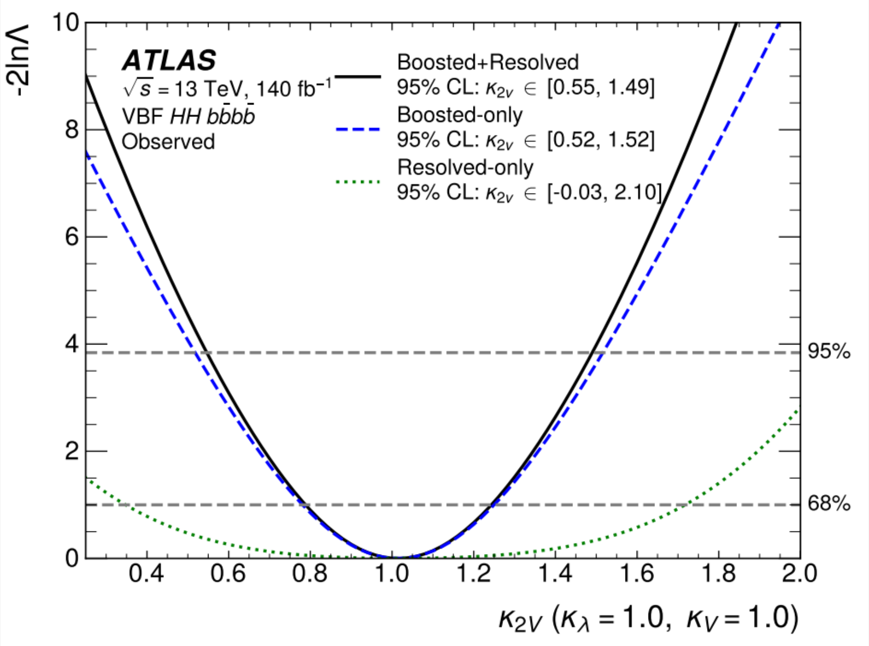




VBF HH → 4b Non-resonant Result



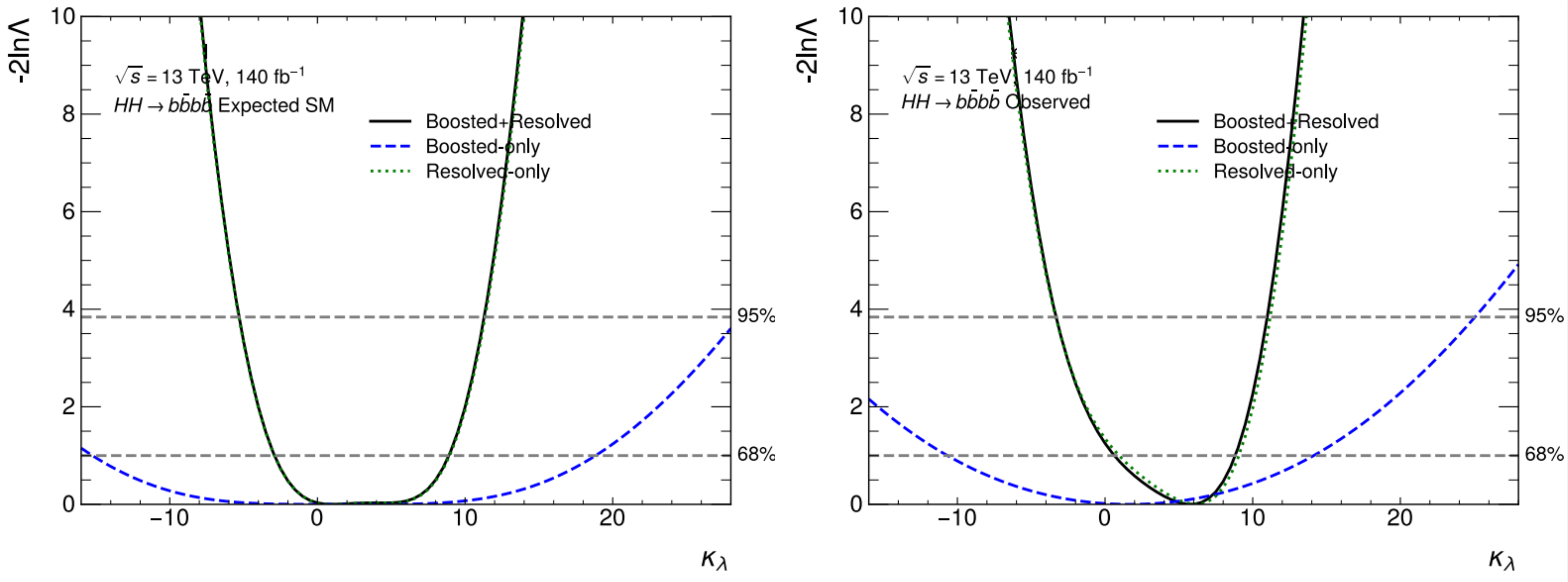
- **Agreements** between data and background distributions under fluctuation
- No events found in the last BDT bin



- Constraints on $\kappa_{2V} \in [0.6,1.5]$ at 95% CL excluding $\kappa_{2V} = 0$ at 3.8σ

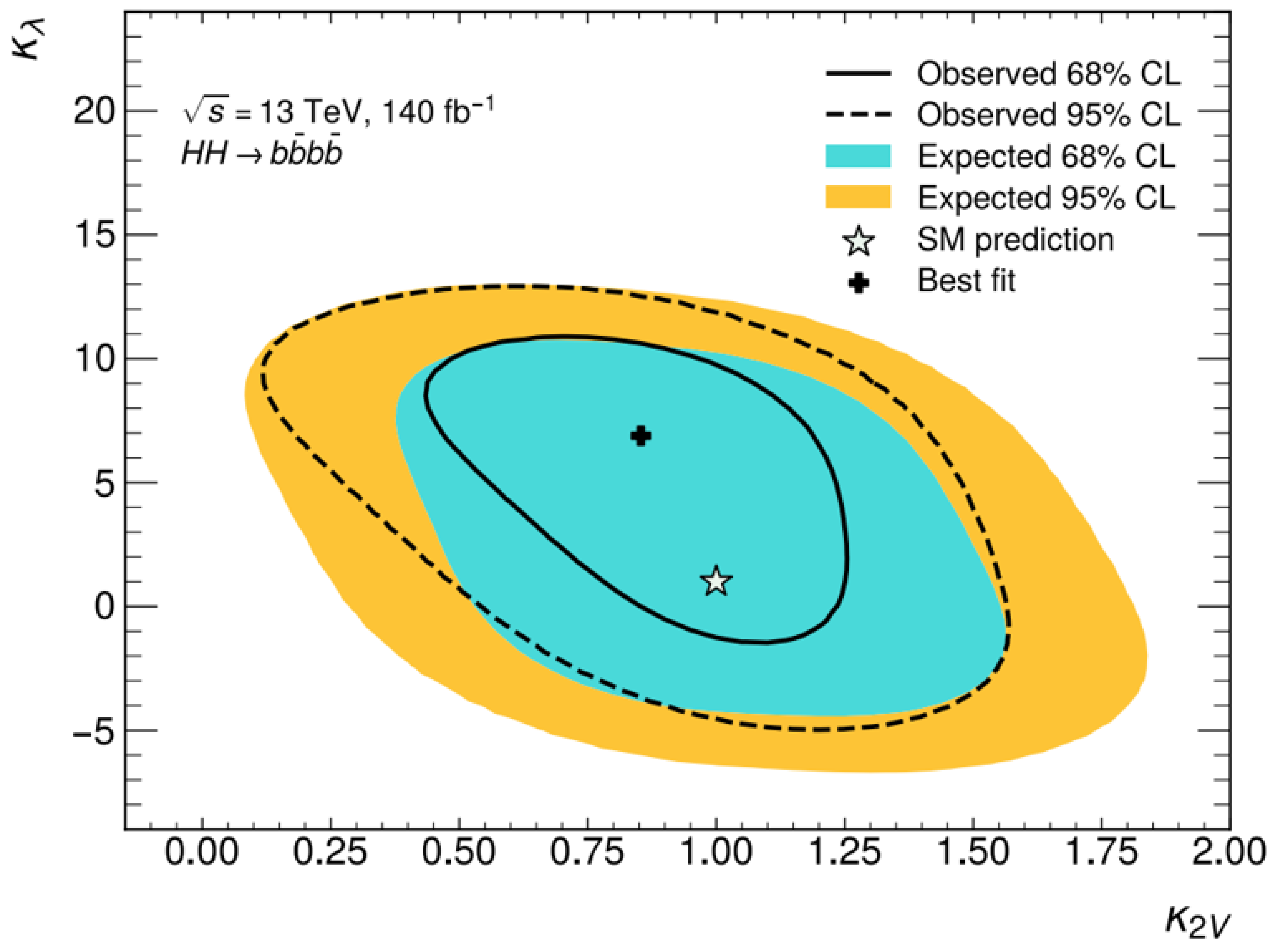
VBF HH → 4b Non-resonant Result

- Combination of previous resolved result without considering correlation of systematics



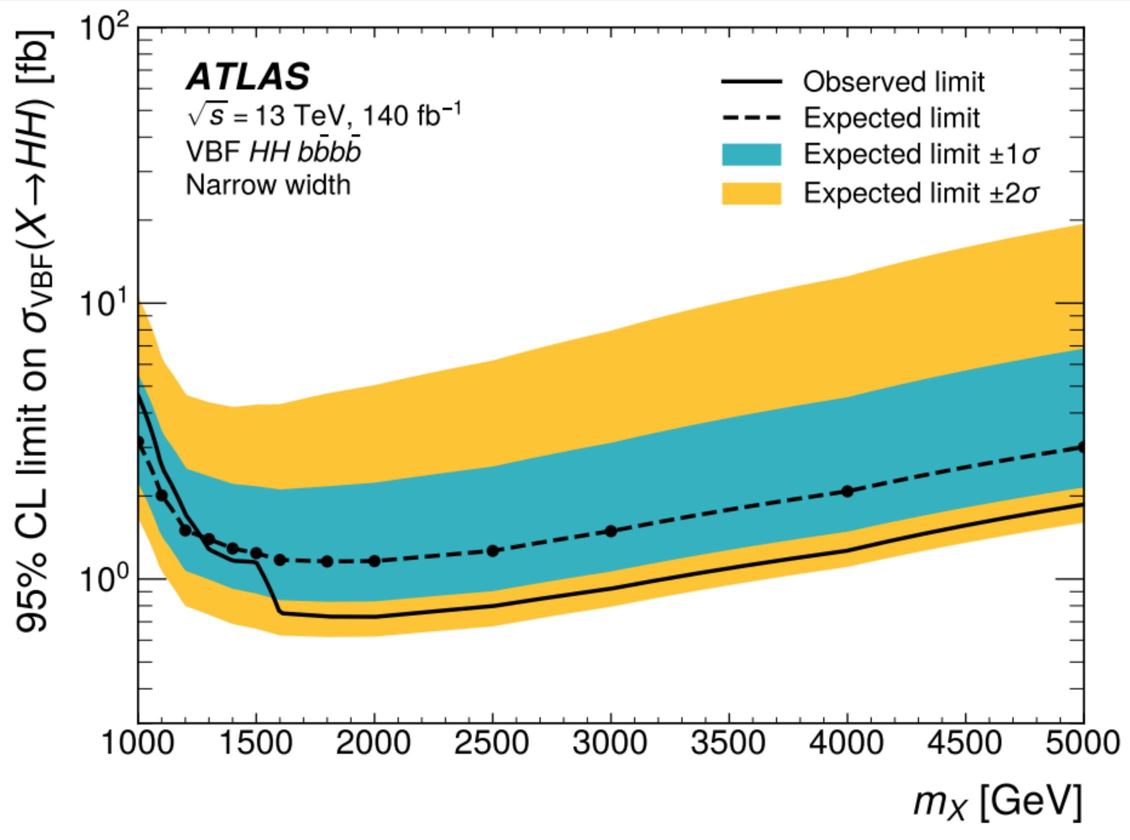
- κ_λ sensitivity driven by resolved channel

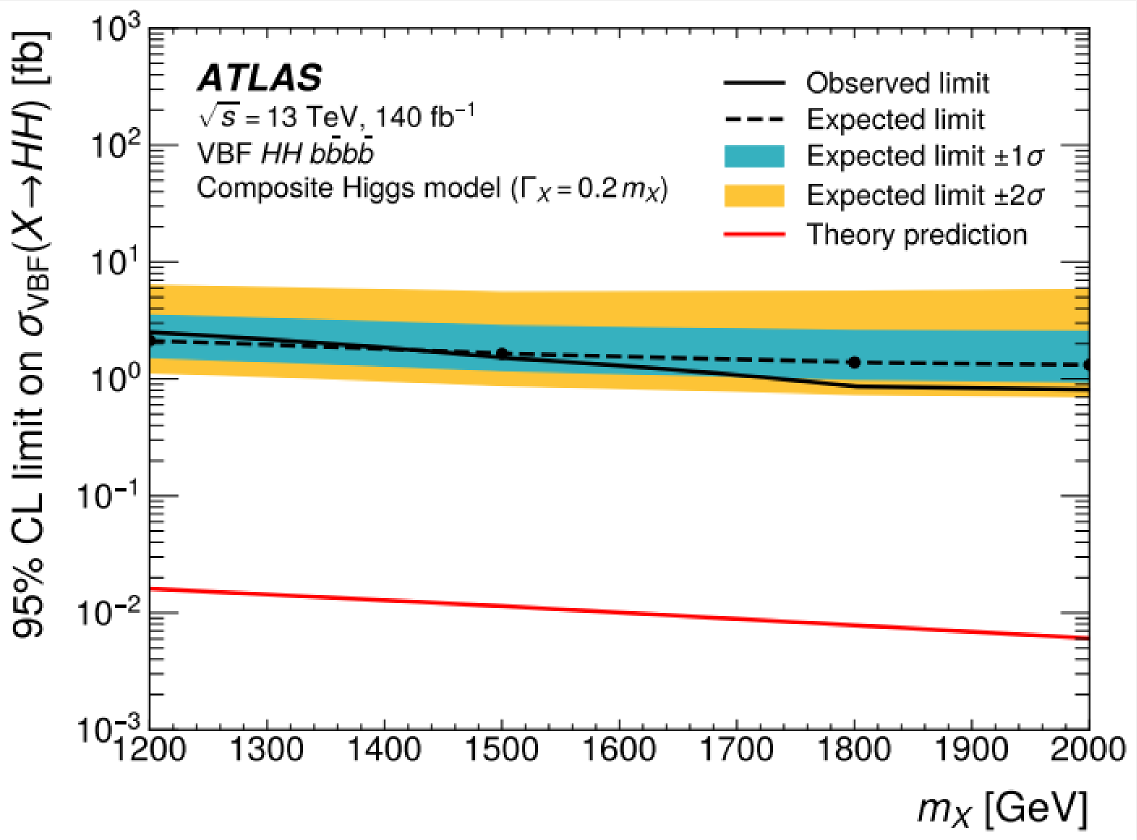
VBF HH → 4b Non-resonant 2D Scan



- κ_λ sensitivity driven by resolved analysis
- κ_{2V} sensitivity driven by boosted analysis

VBF HH → 4b Resonant Results





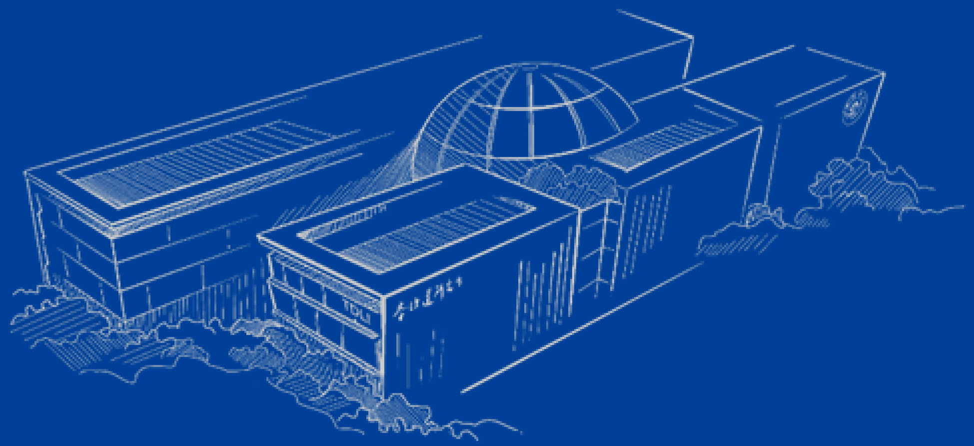
- Upper limits set for narrow and broad width resonance assumptions
- Loss in sensitivity at high mass caused by low efficiency of double b-tagging algorithm

Summary

TSUNG-DAO LEE INSTITUTE

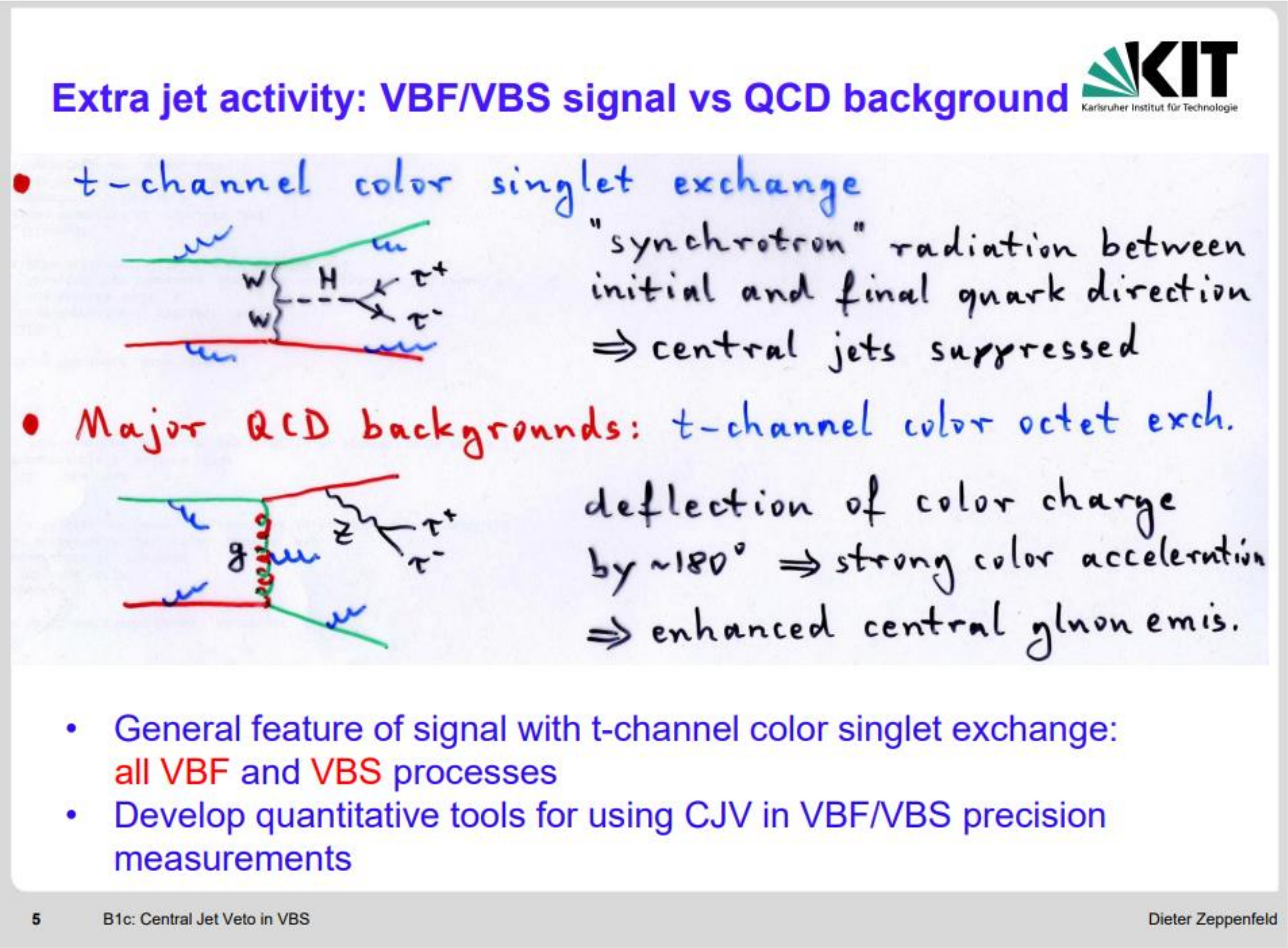
- A search for boosted VBF HH4b is reported
- Boosted decision trees are used for categorization
- No deviation from SM prediction is observed
- Non-resonant resolved+boosted combination excluding $\kappa_{2V} = 0$ at 3.8σ $\kappa_{2V} \in [0.6,1.5]$
- Resonant analysis set limits on new resonance up to 5 TeV

谢谢！



VBS $W\gamma$ jj

https://indico.scc.kit.edu/event/507/contributions/5055/attachments/2604/3726/b1c_zeppenfeld.pdf



Third jet activity in VBF/VBS

Diagrams with gluon emission from the incoming or outgoing quarks interfere destructively, resulting in a suppression of centrally produced jets

VBF->HH Regions

SR region definition choices

$$X_1 = \sqrt{\left(\frac{m_{H1} - 124\text{GeV}}{a_1/m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{GeV}}{a_2/m_{H2}}\right)^2} < r$$

$$X_2 = \sqrt{\left(\frac{m_{H1} - 124\text{GeV}}{2 \cdot a_1/(m_{H1} + m_{H2})}\right)^2 + \left(\frac{m_{H2} - 117\text{GeV}}{a_2/m_{H2}}\right)^2} < r$$

$$X_3 = \sqrt{\left(\frac{m_{H1} - 124\text{GeV}}{a_1/m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{GeV}}{2 \cdot a_2/(m_{H1} + m_{H2})}\right)^2} < r$$

X_{HH} form	r	a_1	a_2	Z_A
Old X_{HH}	1.6	-	-	3.368
X_1	1.6	1500	1900	3.704
X_2	1.6	1500	1800	3.690
X_3	2.0	1200	1900	3.676

$$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{1500/m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{1900/m_{H2}}\right)^2} < 1.6.$$

Different strategies are studied

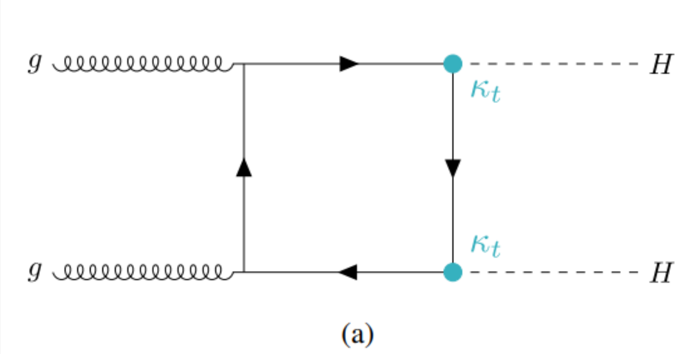
Technical Information

- Analysis based on xAODAnaHelpers, in addition to:
  - XhhCommon framework for objects calibration
    - [EXOT8 → Mini-NTuples]
  - HH4b-reconstruction-framework for analysis selection
    - [Mini-NTuples → Nano-NTuples]
  - Independent HistFactory-based Statistical Packages using pyhf and TRexFitter.
  - GLANCE: ANA-HDBS-2022-02
  - CDS INT note: ATL-COM-PHYS-2023-033

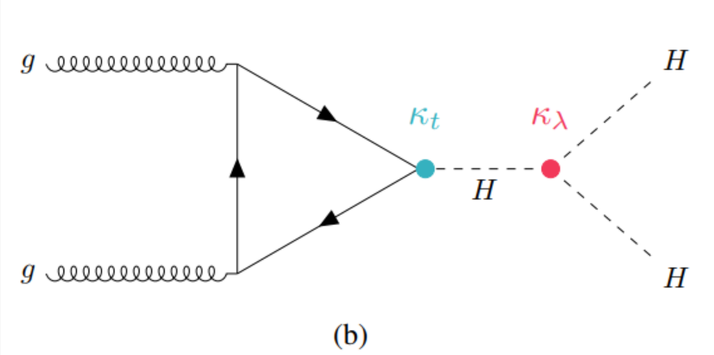
Search for resonant and non-resonant boosted Higgs boson pair production in the *bbbb* final state via vector-boson-fusion (VBF) production using the full Run 2 data with the ATLAS detector

Alessandra Betti[r], Ashutosh Kotwal[b], Arely Cortes Gonzalez[c], Bo Liu[q], Cigdem Issever[c], Clara Leitgeb[k], Daariimaa Battulga[c], Dilia Maria Portillo Quintero[f], Frederic Renner[k], Janna Katharina Behr[k], Jem Aizen Mendiola Guhit[m], Karl Ver Hage Falb[m], Kunlin Ran[k], Liaoshan Shi[g], Marco Valente[f], Marcus Vinicius Gonzalez Rodrigues[k], Maximilian Swiatlowski[f], Michael Kagan[d], Mohamed Belfkir[o], Nikolaos Konstantinidis[g], Rachel Jordan Hyneman[d], Rafael Teixeira De Lima[d], Rui Zhang[a], Russell Bate[p], Salah Nasri[o], Sau Lan Wu[a], Sebastien Rettie[l], Shu Li[e], Thomas Andrew Schwarz[m], Valentina Cairo[l], Yanlin Liu[m], Yuan Feng[q], Yuwen Ebony Zhang[g], Zhen Wang[e], Zhijun Liang[q]

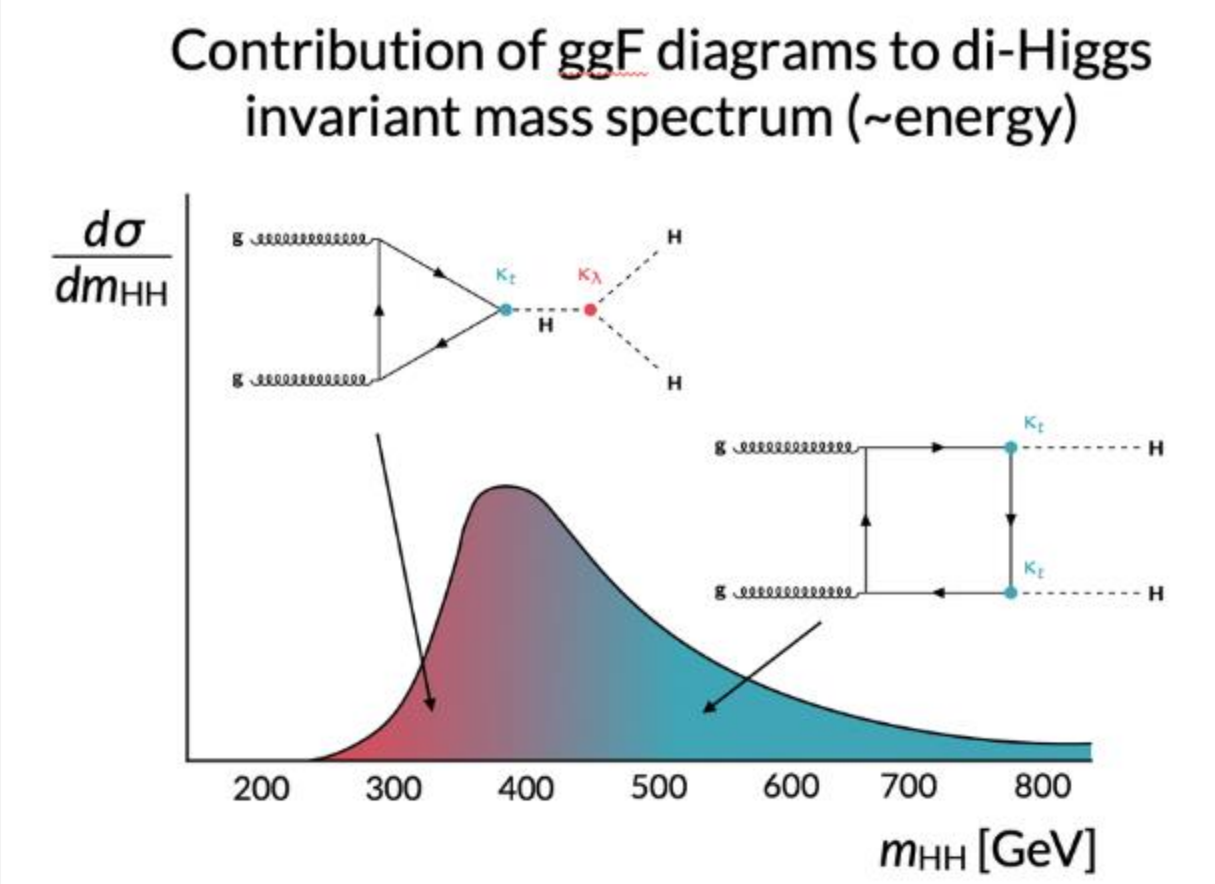
DiHiggs production modes



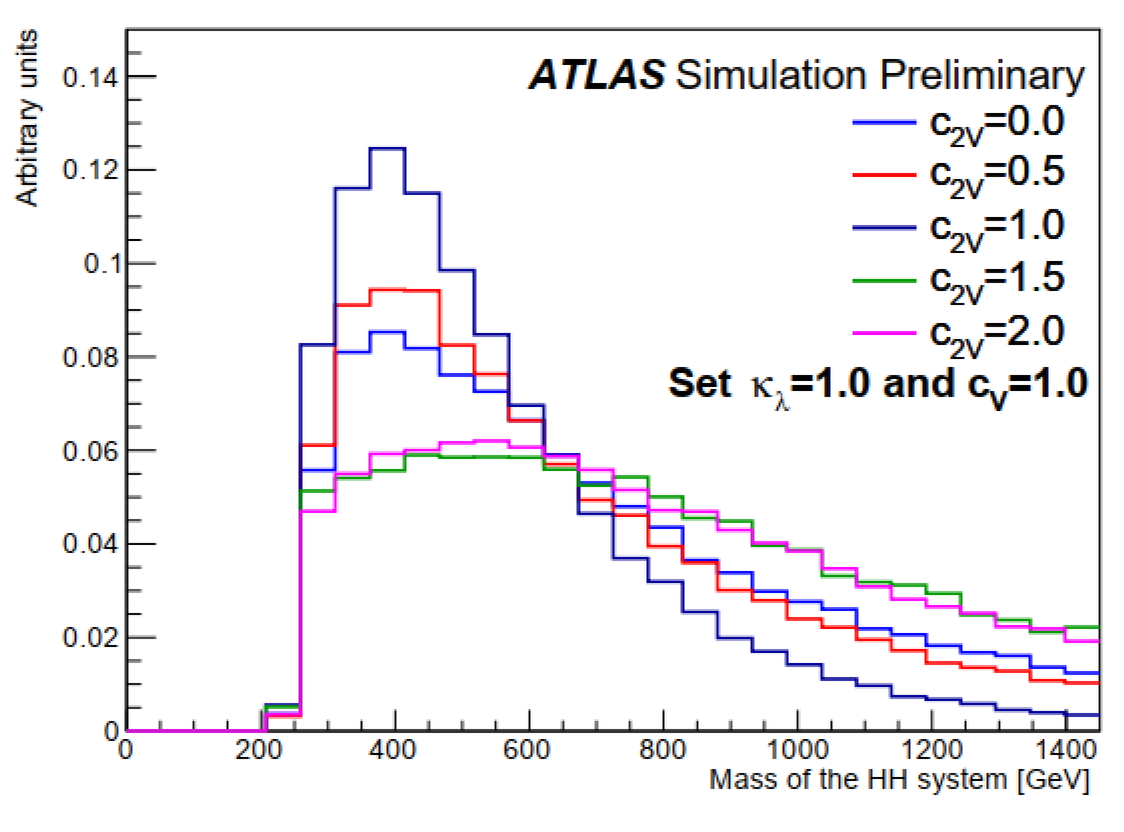
Box diagram

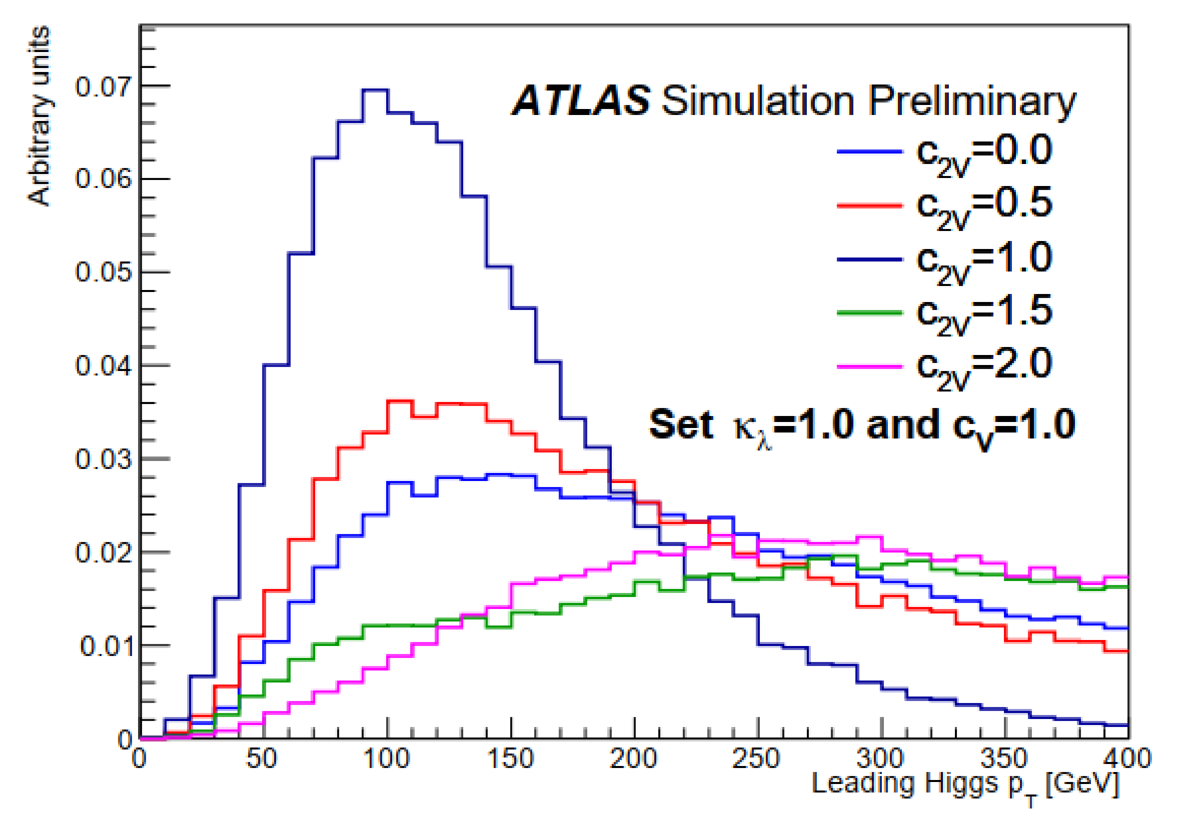


Triangle diagram



Varying κ_{2V}





BSM k2v scenarios produce a larger fraction of boosted Higgs decays

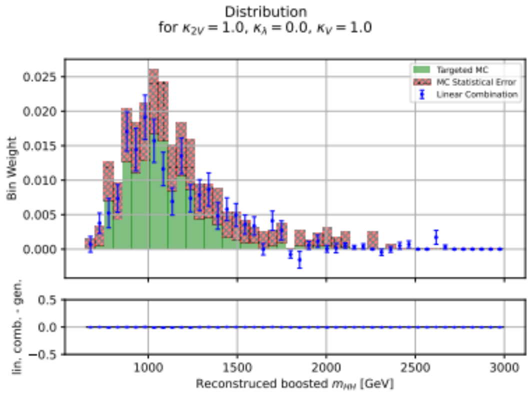
QCD multijet background falls off exponentially as jet pT increases

→ Better S/B

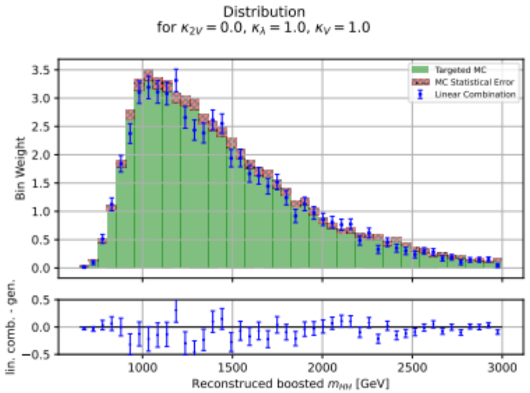
Varying k_l produces soft Higgs

Backup

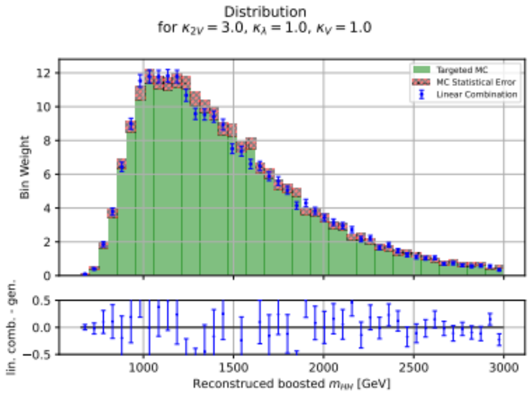
Validation of non-resonant signal sample combination



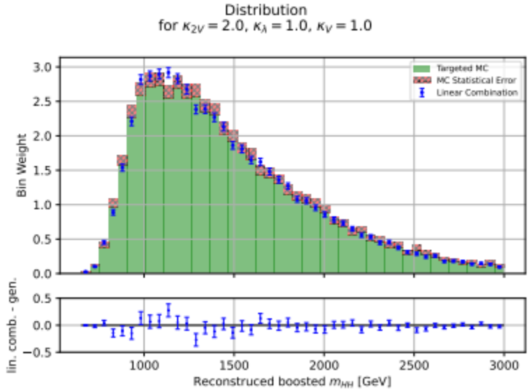
(a) Validation against MC with $\kappa_\lambda = 0$



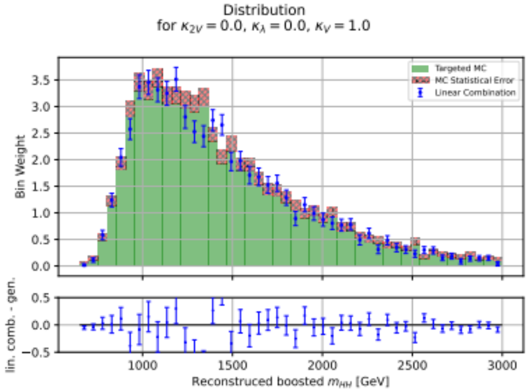
(b) Validation against MC with $\kappa_{2V} = 0$



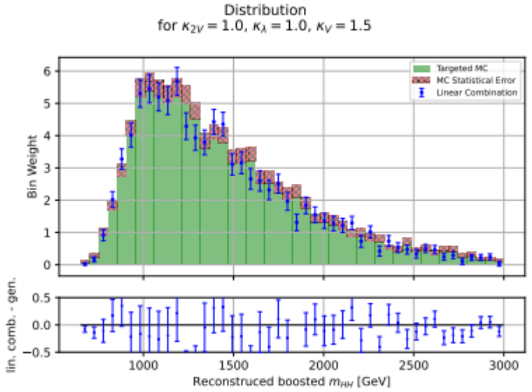
(c) Validation against MC with $\kappa_{2V} = 3$



(d) Validation against MC with $\kappa_{2V} = 2$



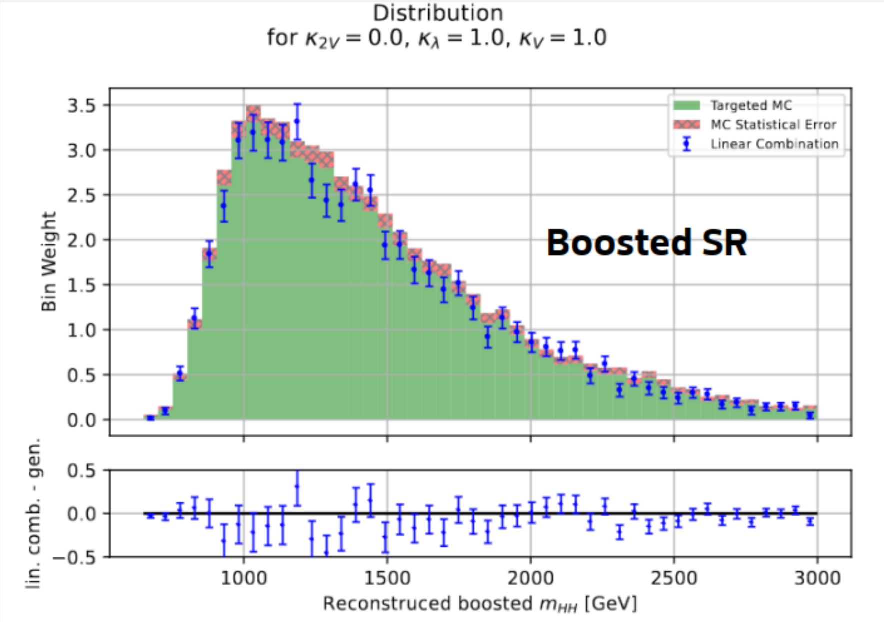
(e) Validation against MC with $\kappa_{2V} = 0$, $\kappa_\lambda = 0$, $\kappa_V = 1$



(f) Validation against MC with $\kappa_V = 1.5$

Non-resonant Signal Sample Combination

- Linear combination of VBF samples ($\kappa_\lambda\ \kappa_{2V}\ \kappa_V$) are used to model the full parameter space ($\kappa_\lambda\ \kappa_{2V}$ has loose constrains and MC generation is computationally expensive and time-consuming)
- Performed the combination on reco-level m_{HH}
- Same basis as in resolved analysis is used.



κ_{2V}	κ_λ	κ_V
1	1	1
1.5	1	1
1	2	1
1	10	1
1	1	0.5
1	-5	0.5

Triggers

- Lowest unprescaled single large-R jet triggers are used
- Trigger turns on at ~450 GeV, attempts to reduce does not have improvements.
- pT > 450GeV on leading large-R jet to ensure plateau + mass > 50 GeV

Year	Trigger chain
2015	HLT_j360_a10_lcw_sub_L1J100
2016	HLT_j420_a10_lcw_L1J100
2017	HLT_j420_a10t_lcw_jes_40smcINF_L1J100
2018	HLT_j420_a10t_lcw_jes_35smcINF_L1J100

mass requirement