The International Doctorate Network in Particle Physics, Astrophysics and Cosmology

14th IDPASC School

Selection Optimisation of Dim-8 SMEFT Operators in Boosted VBF hh→bbbb at Reconstruction-Level

Thiziri AMEZZA

LPNHE PARIS

15 July 2025

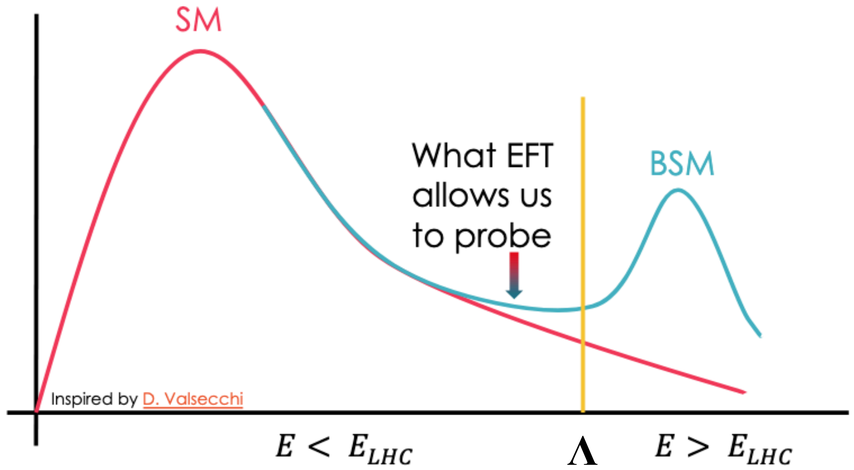
Supervised by: Dr. Reina Camacho Toro (LPNHE)
Dr. Joany Manjarres (L2IT)

VBF HH Effective Field Theory

- VBF di-Higgs production has unique sensitivity for the so far unmeasured quartic Higgs-gauge coupling (**HHVV coupling κ_{2V}**) at leading order.
- Use **SM-Effective Field Theory (SMEFT) production**
  - Build higher-dimensional Lagrangian terms from SM fields

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i^{d=6} O_i^{d=6}}{\Lambda^2} + \sum_i \frac{C_i^{d=8} O_i^{d=8}}{\Lambda^4} + ..$$

    - Λ cut-off scale for new physics, typically around TeV.
    - ***Ci*** are the so-called Wilson coefficients.
    - ***Oi*** operators that account for new-physics contribution.
  - The EFT does not predict what happens above Λ



- Genuine quartic couplings appear first at dim-8 EFT operators
  - Provides possibility to study deviations of the quartic Higgs-Gauge coupling from the VBF HH process without contributions of the trilinear coupling
  - Using the extended **aqgc** model (the same model used in VBS analysis), focuses only on quartic couplings. This model builds upon the Eboli model by introducing new operators.
  - Dim-6 operators are tightly constrained → can be probed across various processes and final states.
  - Dim-8 operators are never explored in di-Higgs.

The Operators of the aqgc Model

- Can Check sensitivity of VBF di-Higgs to the operators of this model:
  - **S operators**: contain four covariant derivatives of the Higgs field (Longitudinal)
  - **M operators**: contain two Higgs covariant derivatives and two field strength tensors (Mixed: Longitudinal-Transveral)
  - **T operators**: contain four field strength tensors (Transversal)
- Can map which operator affects which vertices → **VBF HH and VBS affected by the same operators!**

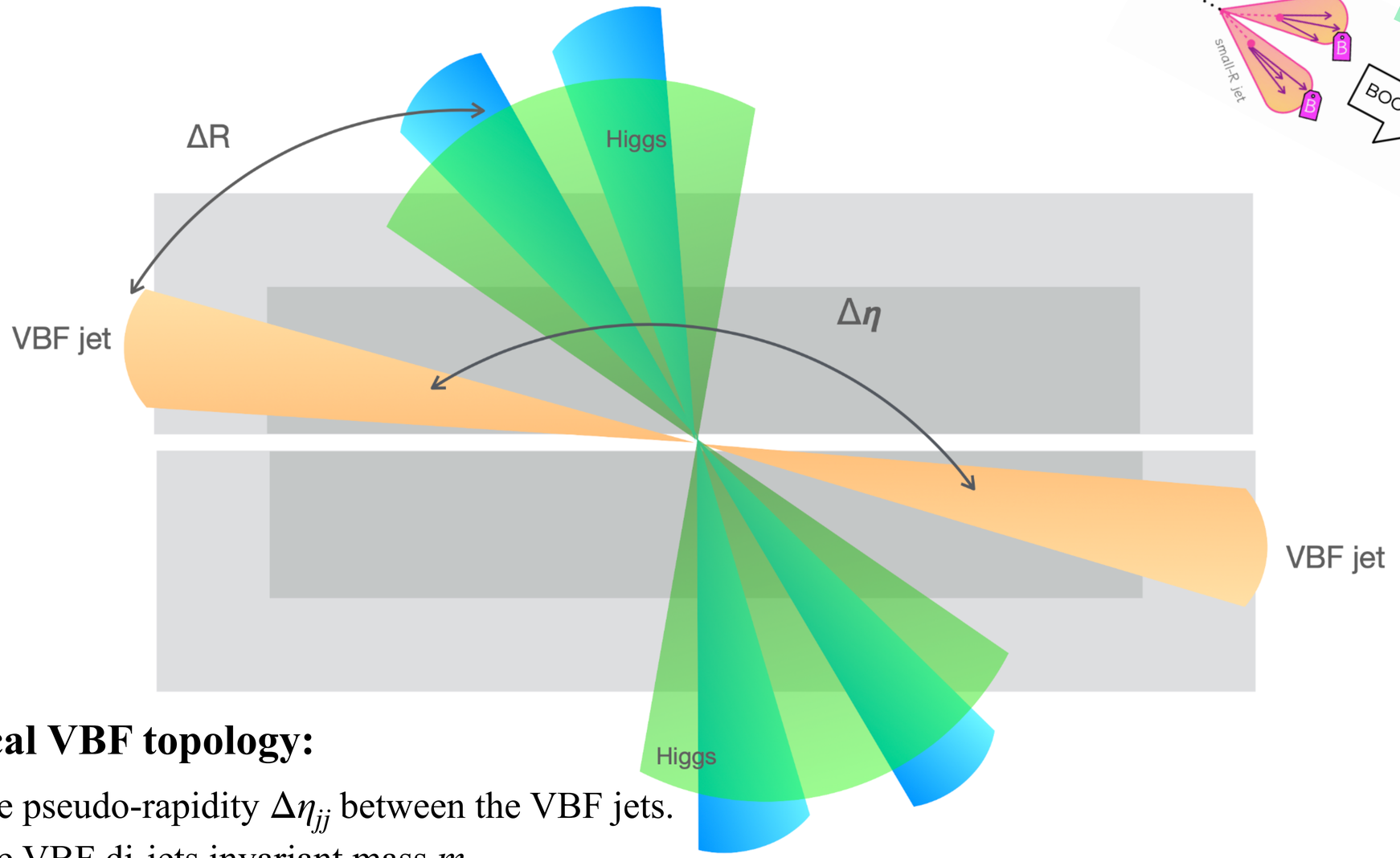
CP	operator	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$	$ZZHH$	$WWHH$	$Z\gamma HH$	$\gamma\gamma HH$
++	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	✓	✓			✓					✓	✓		
	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓			✓		✓	✓
	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓				
	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓				
	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓				
−−	$\mathcal{O}_{M,8}$	?	?	?	?	?	?	?	?	?				
	$\mathcal{O}_{M,9}$	?	?	?	?	?	?	?	?	?		✓		
−+ +−	$\phi_{M,1}$, $\phi_{M,2}$, $\phi_{M,4}$, $\phi_{M,5}$	?	?	?	?	?	?	?	?	?	✓		✓	✓
	$\phi_{M,3}$, $\phi_{M,6}$	?	?	?	?	?	?	?	?	?				
	$\phi_{T,1}$, $\phi_{T,2}$, $\phi_{T,3}$, $\phi_{T,4}$, $\phi_{T,5}$, $\phi_{T,6}$	?	?	?	?	?	?	?	?	?				

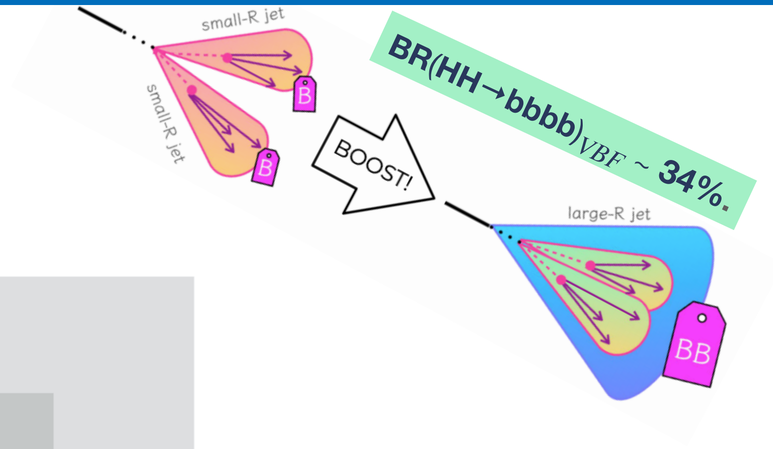
New operators

VBS

VBF

Boosted VBF Topology (HH → bbbb)





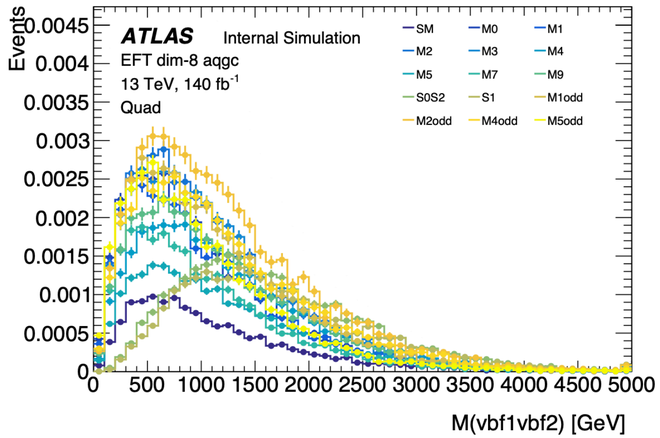
- **Typical VBF topology:**
  - Large pseudo-rapidity $\Delta\eta_{jj}$ between the VBF jets.
  - Large VBF di-jets invariant mass m_{jj}.
  - Higgs pair located in between the two VBF jets with a ΔR separation angle.

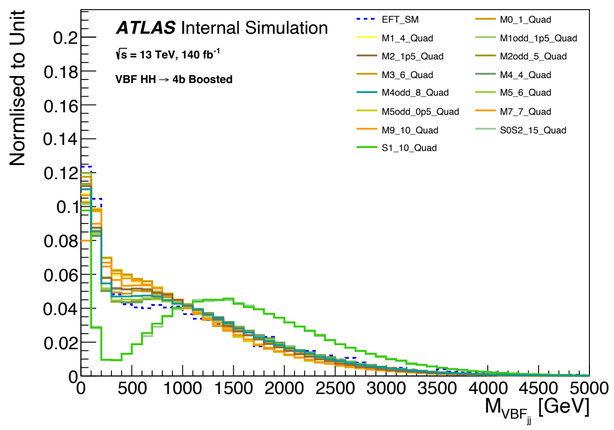
Boosted VBF Topology (HH → bbbb) at Reconstruction Level

Truth level

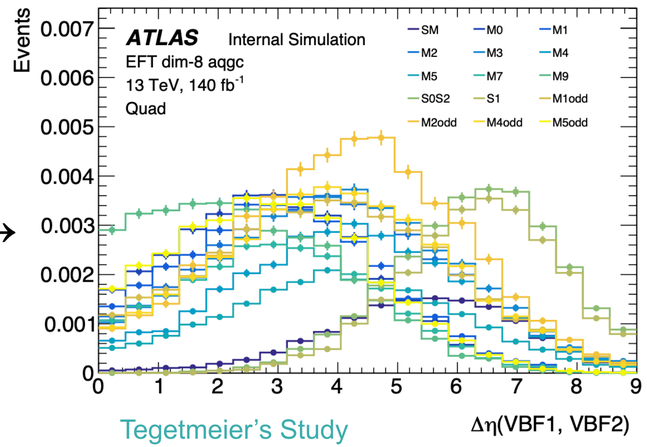
Reco level

$m_{jj} \rightarrow$

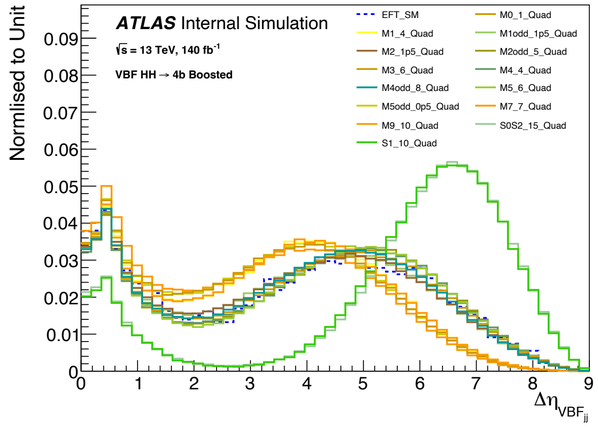




$\Delta\eta_{jj} \rightarrow$



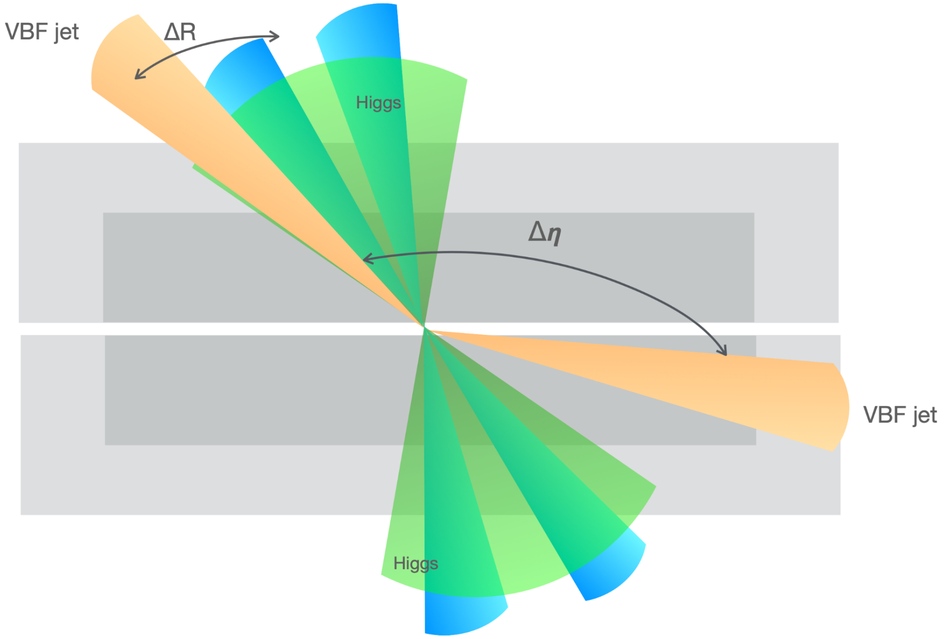
Tegetmeier's Study



- The low $\Delta\eta_{jj}$ must be populated by events that have a Higgs overlapping with a VBF jet.

- **Expectations at Truth-Level:**
  - EFT operators show a large VBF invariant mass m_{jj}.
  - For M-type operators the pseudo-rapidity distribution $\Delta\eta_{jj}$ between the two VBF jets is more central than for the SM.
- **Reconstruction Level:**
  - Unexpected peak at low m_{jj} and low $\Delta\eta_{jj}$.

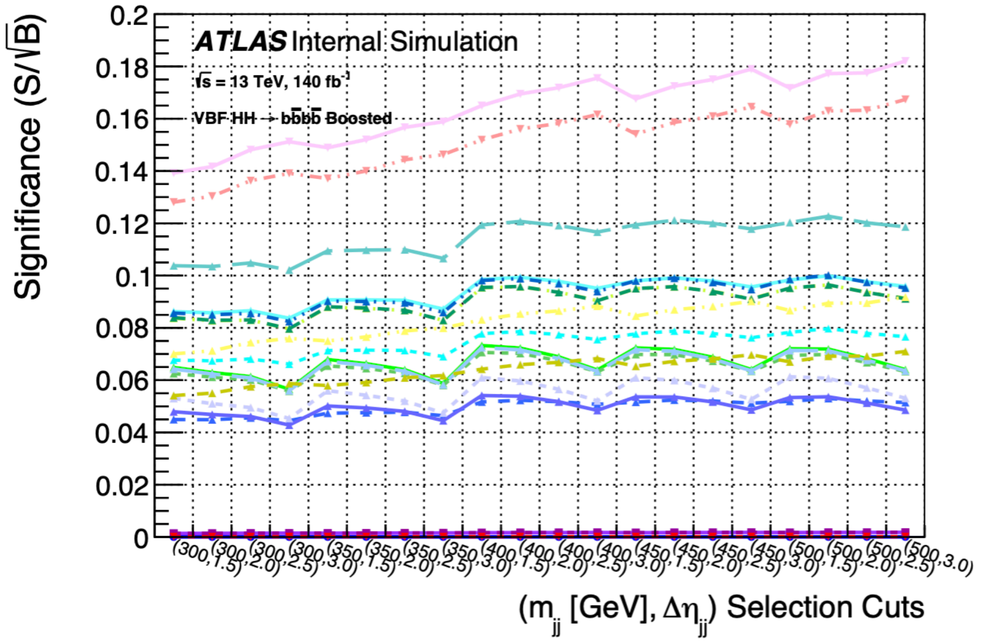
    → Probably due to miss assignment of the jet in VBF selection



Event Selections

- **VBF Selection:**
  - Events are required to have two VBF jets & a ΔR(VBF jet, H) between the VBF Jet and the Higgs candidates
    → The ***Nominal selection*** for VBF selections to recover signal events:
    - ΔR(VBF jet, H) > 1.4 → sort the small-R jets by pT → select the pair with the highest pT.
  - We look at the background using data-driven technique and check the significance for different selections.
  - We perform different cuts on m_{jj} and $\Delta\eta_{jj}$ in order to optimise our VBF di-jets selection.

- **Selection Significance:** The significance ($S/\sqrt{(B)}$) of EFT dim-8 operators and $\kappa_{2V} = \{0, 1, 2\}$ at different m_{jj} and $\Delta\eta_{jj}$ cuts.



- For most terms, especially κ_{2V} and *S*-operators, the cuts m_{jj}>500 GeV and $\Delta\eta_{jj}$>3.0 provides the highest sensitivity across all the selections, while *M*-operators show more varied optimal cuts.
- The scan in m_{jj} and $\Delta\eta_{jj}$ do not seem to have a sizeable impact.
- Still room for improvement and to optimise the Boosted VBF (HH→ bbbb) analysis.

  → We are considering to include a one VBF jet category in the study to recover those events were the VBF jets is removed because too close from the Higgs.

- The boosted VBF (HH → bbbb) analysis is the heart of my PhD thesis, further investigations and in-depth studies to be conducted as part of the ongoing research throughout the project.

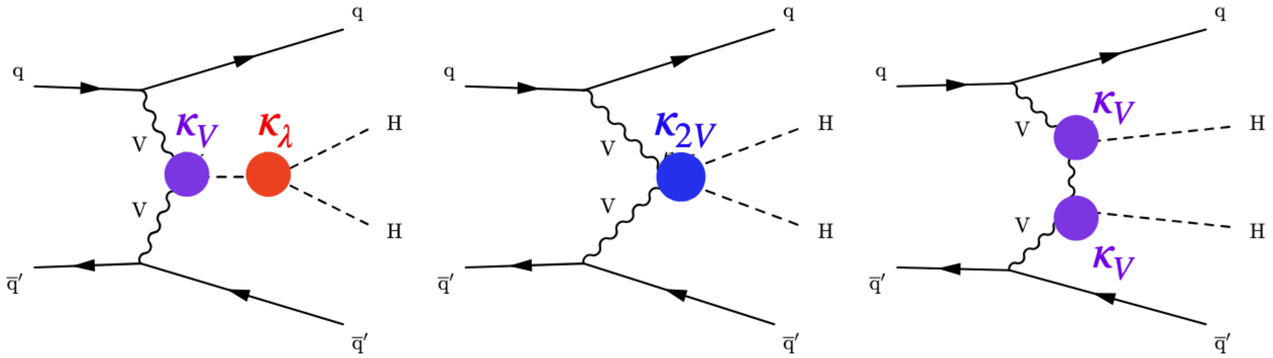
Backup

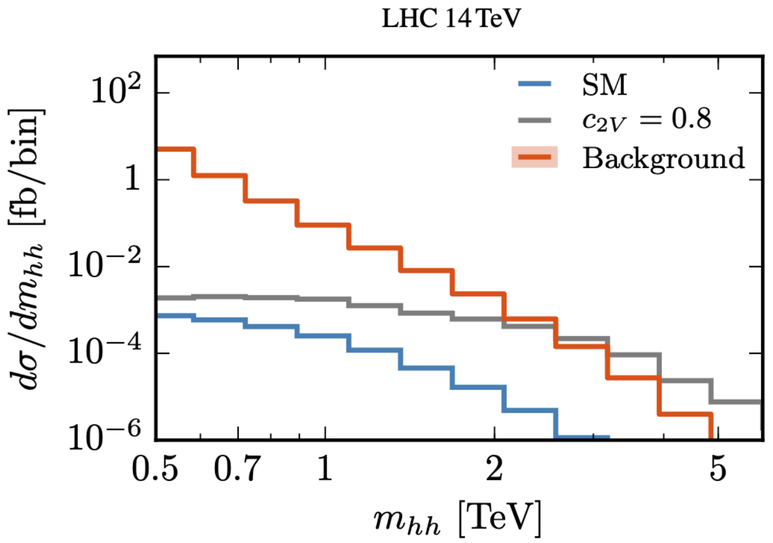
Double-Higgs (HH) Production Mechanism

- Vector boson fusion (VBF) has unique sensitivity to the quartic Higgs-gauge (HHVV) coupling κ_{2V}

  → The **focus** of our analysis is on VBF di-Higgs (HH) production.

  - Relevant for Higgs self-coupling κ_λ at tree-level
  - Very sensitivity to the HHVV coupling κ_{2V} because the SM predict strict cancellations between κ_{2V} and κ_V





- Smaller κ_{2V} implies larger cross section, harder m_{HH} Spectrum, boosted VBF signature

  - **SM:** $\kappa_{2V} = \kappa_V = \mathbf{1}$ → Sensitive to Higgs boson self-couplings κ_λ.
  - Modifications in κ_{2V} w.o an additional mechanism will lead to unitarity violation.
  - When κ_V and κ_{2V} deviate from their SM value, the cross-sections grows linearly with the centre-of-mass energy of the incoming vector bosons, providing a smoking gun signature for BSM physics.
  - **New Physics** can manifest as $\kappa_{2V} \neq \kappa_V$. → breaks cancellations; enhanced production rate, especially at high m_{HH}

  - If new physics is heavy, can we integrate higher-dimensional operators in the Lagrangian.

    → Useful tool for heavy new physics: **Effective Field Theory**

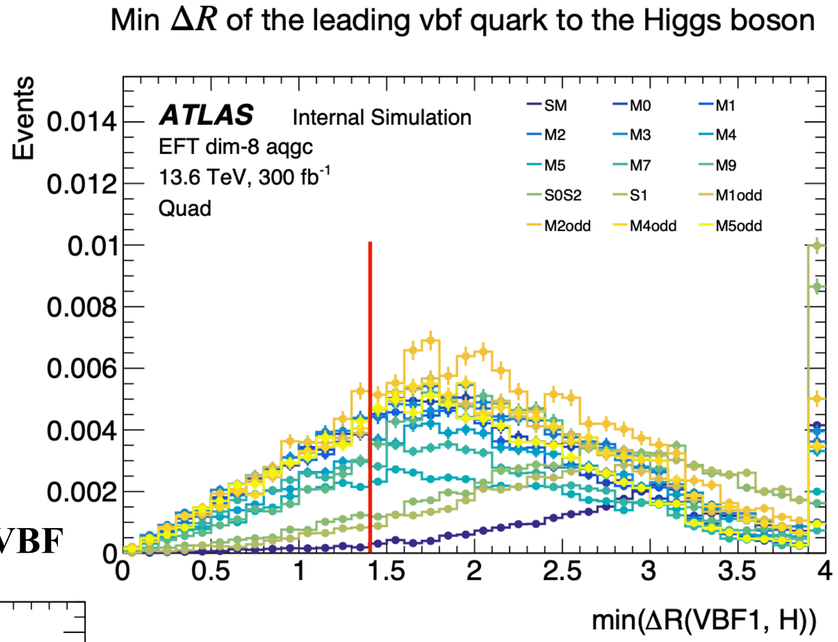
Boosted VBF Topology (HH → bbbb)

- At truth level **min(ΔR(jet, H))** between the VBF jets and the Higgs, shows a large overlap (right plots) for events with ΔR<1.4.

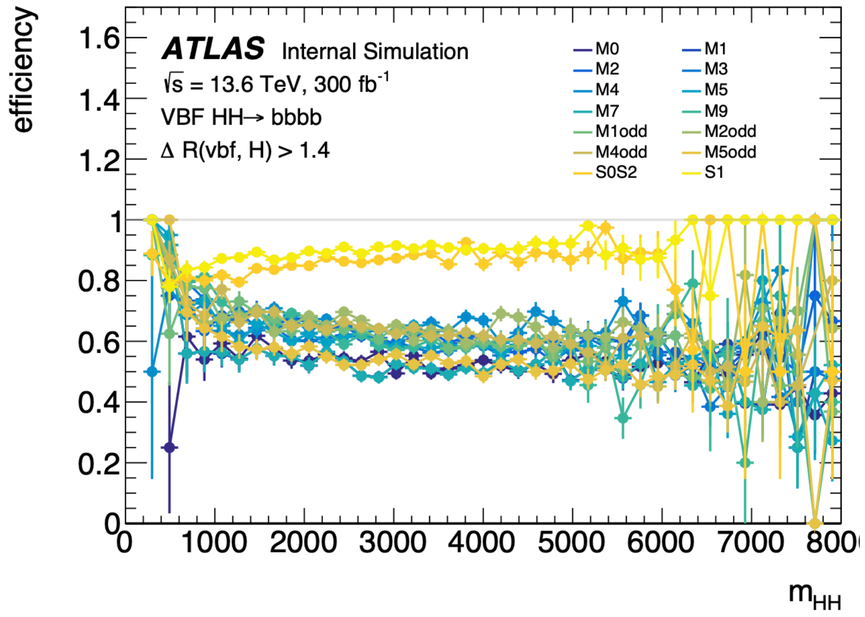
  → a cut placed in this variable will reduce drastically the signal efficiency.

- Bottom-left plots show the truth level efficiency for the ΔR(jet, H) > 1.4 cut to select events with no overlap Higgs with both jets.

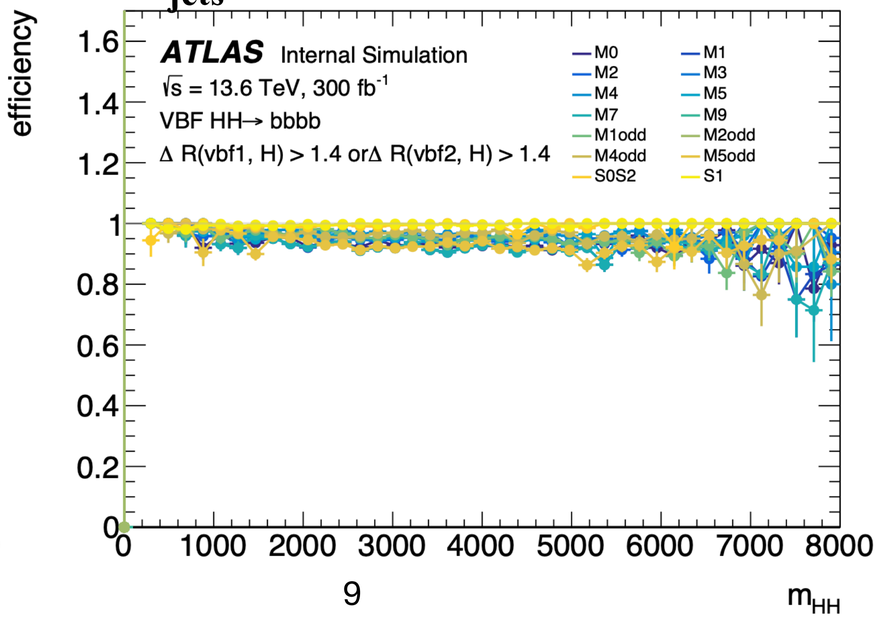
  → around 30-50% of events are lost for M operators (10-20% of the efficiency for S operators)



No overlap Higgs for both VBF jets



No overlap Higgs at least one of the VBF jets



- Requiring only one VBF jet that not overlap with Higgs

  → Recover most of the efficiency.

Event Selections

- **VBF Selections:**
  - Events are required to have two VBF jets
  - A ΔR(VBF jet, H) between the VBF Jet and the Higgs candidates

    → Try different VBF selections to recover signal events:

    - ***Nominal (First) selection:*** ΔR(VBF jet, H) > 1.4 → sort the small-R jets by pT → select the pair with the highest pT.
    - **Optimising the selection:** Remove ΔR(VBF jet, H) At least two no-b-tagged jets → combinations of possible VBF jet pairs
      → Two case to consider:

      - ***Second selection:*** select the VBF pair with highest pT
        → Later on we apply a ΔR(VBF jet, H) > 1.4 cut.
      - ***Third selection:*** select the VBF pair with highest invariant mass m_{jj}
        → Later on we apply a ΔR(VBF jet, H) > 1.4 cut.

- We look at the background using data-driven technique and check the significance for different selections.
- We perform different cuts on m_{jj} and $\Delta\eta_{jj}$ in order to optimise our VBF di-jets selection.

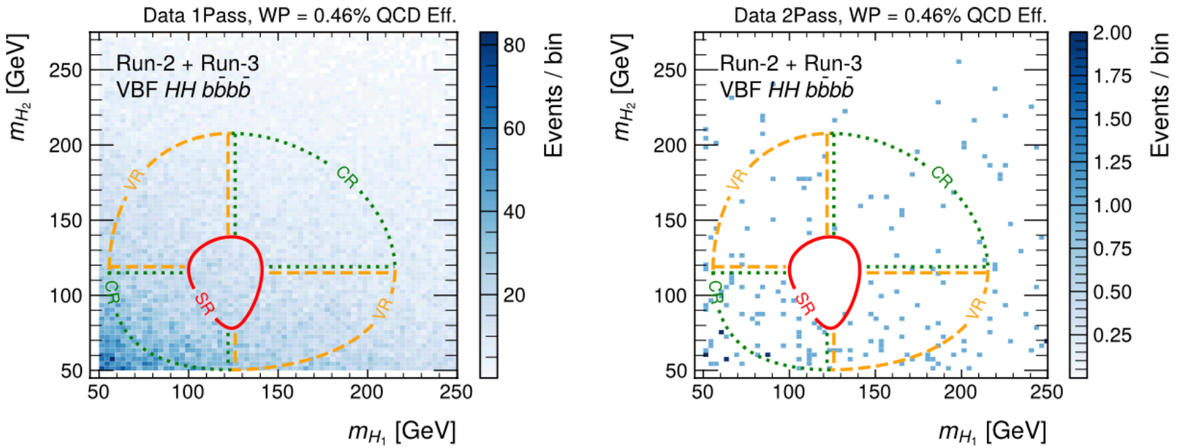
Background Estimation for Boosted VBF (HH → bbbb)

- Background estimation using data-driven technique in boosted VBF HH→bbbb from simple re-scaling (w)
- Apply re-scaling normalisation factor (w) to events in the 1Pass region to the 2Pass region

  - $\mathbf{SR}_{2Pass} = \boldsymbol{w} \times \mathbf{SR}_{1Pass}$ where, $w = \frac{CR2Pass}{CR1Pass}$

    - 1Pass : either H1 or H2 pass GN2Xv01_QCDEff flat-mass WP
    - 2Pass : both H1 and H2 pass GN2Xv01_QCDEff flat-mass WP

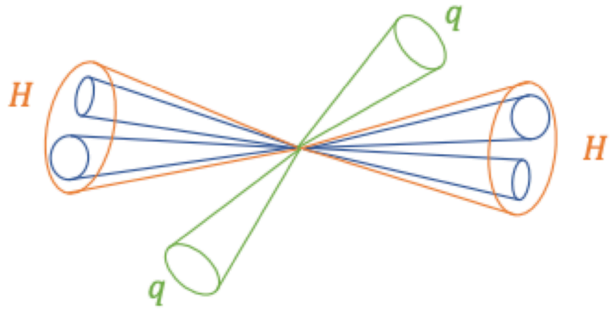
    - SR: $\sqrt{\left(\frac{m_{H1}-124}{1500/m_{H1}}\right)^2+\left(\frac{m_{H2}-117}{1900/m_{H2}}\right)^2} < \mathbf{1.6\ GeV}$



- **Selection Conditions:**

  - **Higgs Selections:**

    - Leading pT large-R jets that pass the 0.46% QCD Eff. WP
    - p_T(H1) > 520 GeV & p_T(H2) > 250 GeV



  - **VBF Selections:**

    - Testing the former three selections (First/Nominal, Second and Three selections).
    - Testing different cuts on m_{jj} and $\Delta\eta_{jj}$ to optimise our VBF di-jets selection.