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Search for Higgs pair (HH→4b) production for new physics with the ATLAS experiment

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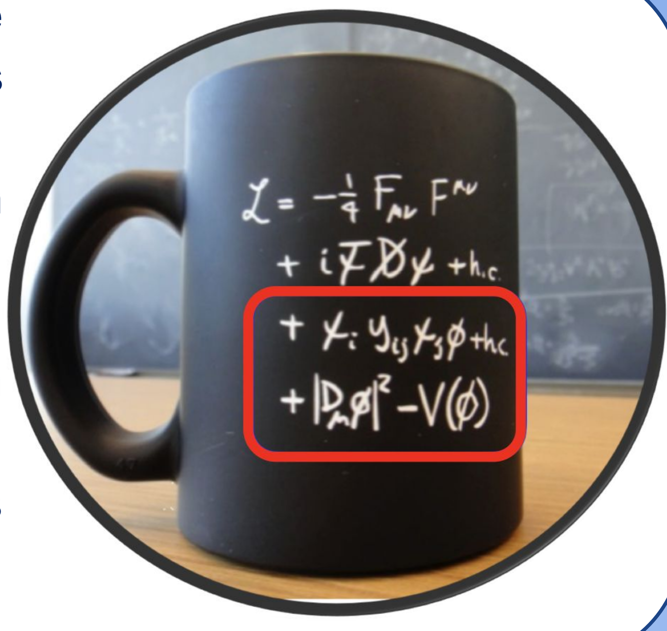
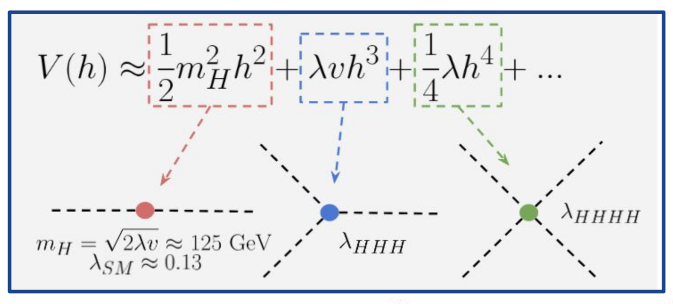
on behalf of the LPNHE ATLAS Group, 2024

The precise investigation of the Electroweak Symmetry Breaking mechanism stands as one of the most ambitious objectives of the Large Hadron Collider (LHC) at CERN. While the experimental confirmation of the existence of EWSB in 2012 through the discovery of the Higgs boson (H) by the ATLAS and CMS collaborations provided significant validation, a decade of subsequent measurements has further reinforced the alignment of its properties with the predictions of the Standard Model. Nevertheless, the experimental testing of fundamental aspects such as the doublet structure of the scalar field and the shape of the potential, which underlies the EWSB mechanism, remains an unexplored.
In this context, our group at LPNHE searches for non-resonant di-Higgs production through Vector Boson Fusion (VBF), particularly the HH→bbbb decay channel in a boosted regime. This investigation serves as an ideal benchmark to test the doublet structure of the Higgs boson postulated in the Brout-Englert-Higgs (BEH) mechanism, as well as a window into potential new physics beyond the Standard Model (BSM).
In this poster we present our initial efforts dedicated to the in-situ calibration of the large-radius jet energy/mass scale for boosted Higgs bosons that decay into b-quarks as well as the calibration of the Higgs identification algorithms, this is as a first step towards improving the HH searches.

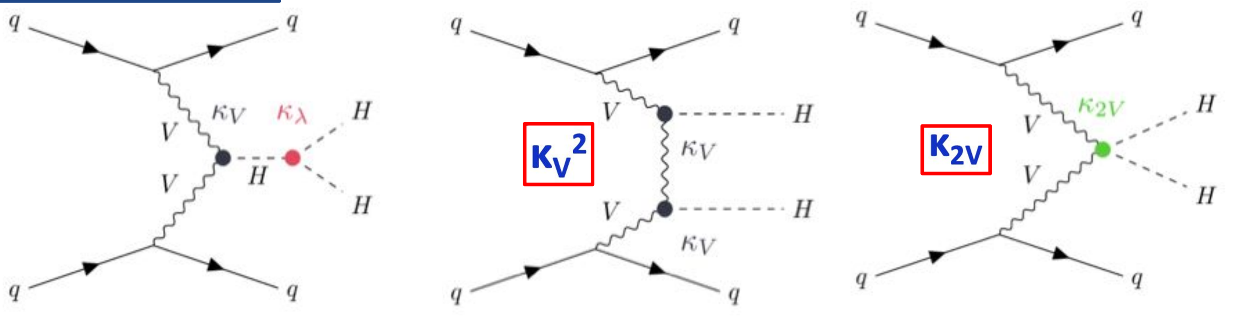


1. Di-Higgs Production



- HH production will be one of the most crucial measurements of HL-LHC.
- **Target:** Non-resonant di-Higgs production in vector-boson fusion (VBF) processes.

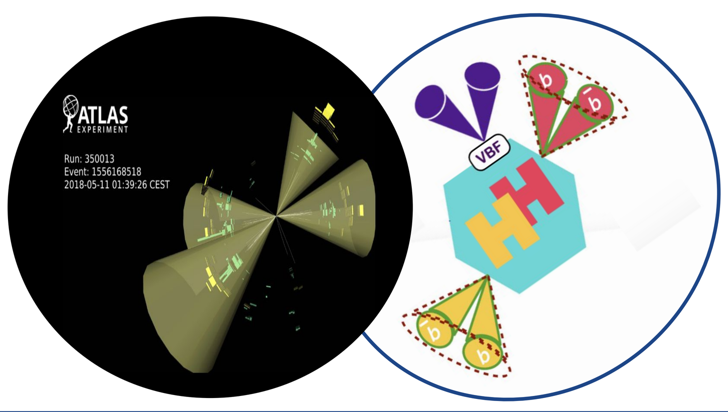
- **VBF N3LO:**
  $\sigma_{VBF}^{SM} \approx 1.72$ fb
  $\sqrt{s} = 13$ TeV



- Direct access to the trilinear Higgs self-coupling (k_λ) and the quartic VVHH Higgs coupling k_{2V}.
- **SM predicts** $k_{2V} = k_V = 1$.
  - ➔ Sensitive to Higgs boson self-couplings.
- **New Physics** can manifest as $k_{2V} \neq k_V^2$.
- The **bbbb** channel is the most abundant final state of all **HH** events with a branching ratio ~34%.
- **Challenge:** Large QCD background & low statistics at high p_T

	$b\bar{b}$	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%

- **Focus on:** VBF HH (**HH→4b**) production in boosted topologies to reduce QCD background.



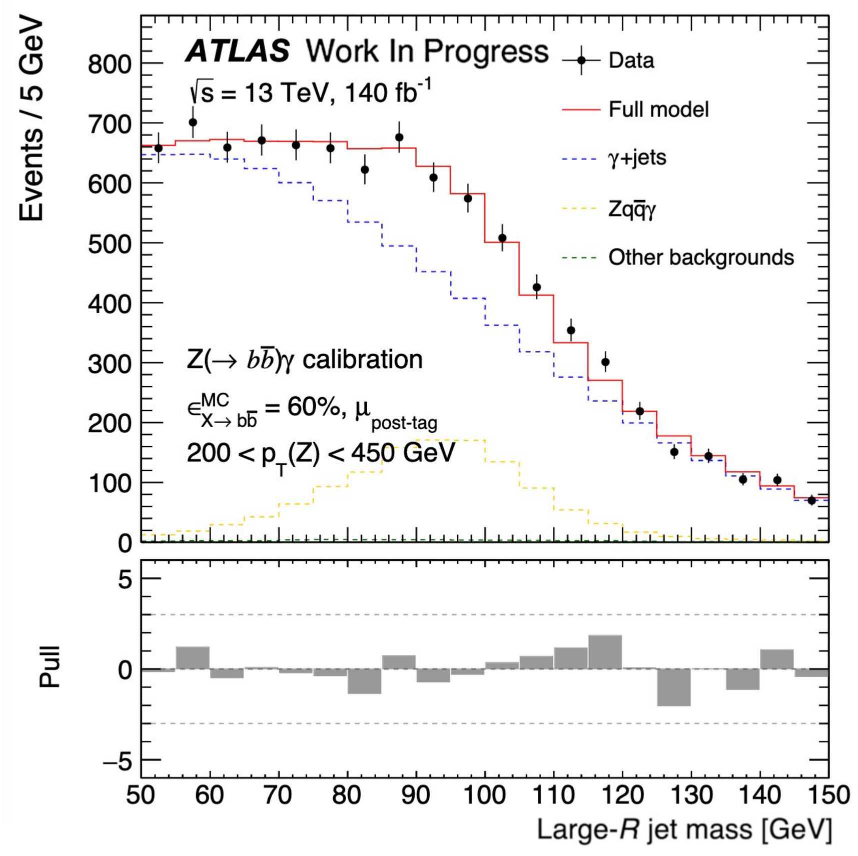
- At least two large-radius (bb)-jets ($\Delta R = 1.0$)
- At least 2 small-radius jets ($\Delta R = 0.4$) with large pseudo-rapidity separation and large invariant mass as VBF jets.
- Neural network based algorithm used to identify Higgs (bb) jet candidates.

2. bb-tagger and Calibration

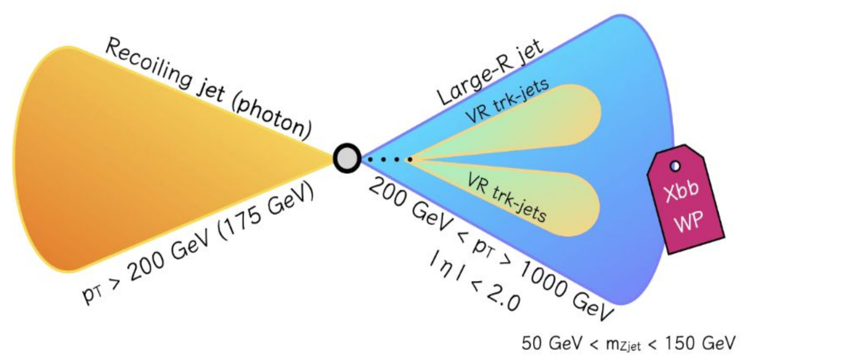
- Tagging large-R jets coming from H→bb decay using GN2X, a graph neural network using large-R jets kinematics and track variables as inputs.
- Signal calibration is done with Z(→bb)γ and Z(→bb) + jets using high-p_T Z bosons for p_T < 450 GeV and p_T > 450 GeV respectively.
- Scale factor are derived from the signal strength ratio post-tag/pre-tag:

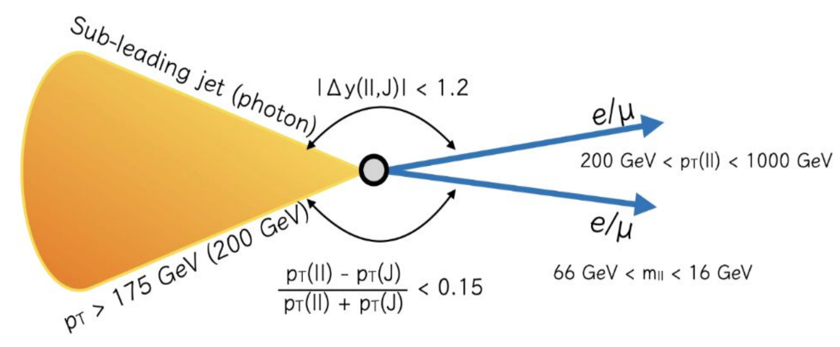
$$SF = \frac{\epsilon_{data}}{\epsilon_{MC}} = \frac{N^{data}_{passed}/N^{data}_{total}}{N^{MC}_{passed}/N^{MC}_{total}} = \frac{N^{data}_{passed}/N^{MC}_{passed}}{N^{data}_{total}/N^{MC}_{total}} = \frac{\mu_{post-tag}}{\mu_{pre-tag}}$$

- μ(post-tag) is estimated with a likelihood fit to data.
- The main background is γ+jets for Z(→bb)γ and di-jets for Z(→bb) + jets.
- Calibration is done at different working points, corresponding signal efficiencies.



- This calibration will bring great improvement to di-Higgs analysis, especially HH → 4b!





3. bb-Jet energy/mass calibration

Inclusive Large-R jet calibration

Derived from QCD inclusive jets. But can it be applied to Higgs (bb) jet candidates?

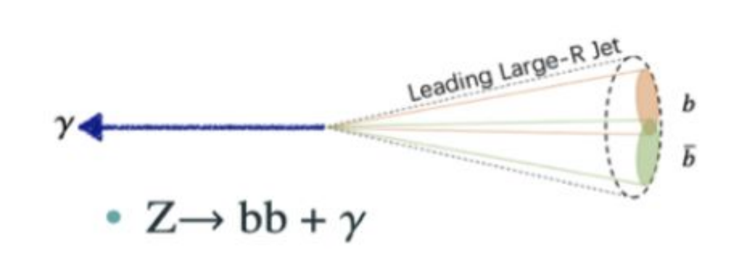
- b-jets lose energy due to charged leptons not clustered within the jet cone.
- In the inclusive jet calibration neutrinos and muons are excluded.
- Main target is to improve **H → bb** response and resolution.

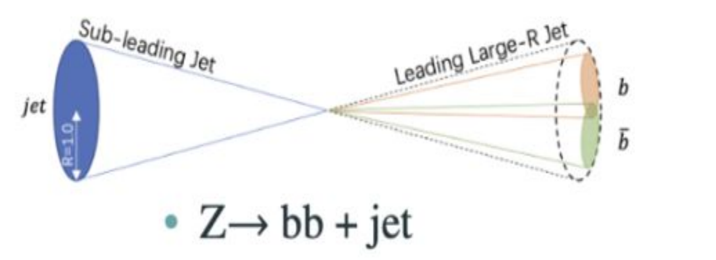
Current Calibration: MC-based energy/mass calibration → In situ calibration → Fully calibrated large-R (bb)jet

Future Calibration? Implement an additional MC-based bb-jet calibration

MC-based energy/mass calibration → b-JES/JMS (MC) → In situ calibration → b-jet In situ calibration → Fully calibrated large-R (bb)jet

But such correction needs to be validated in data! Can we do it using **Z(→bb)+X** events?





Z decaying to bb recoiling against a photon covers low and medium p_T

Z decaying to bb recoiling against a jet allows to cover high p_T

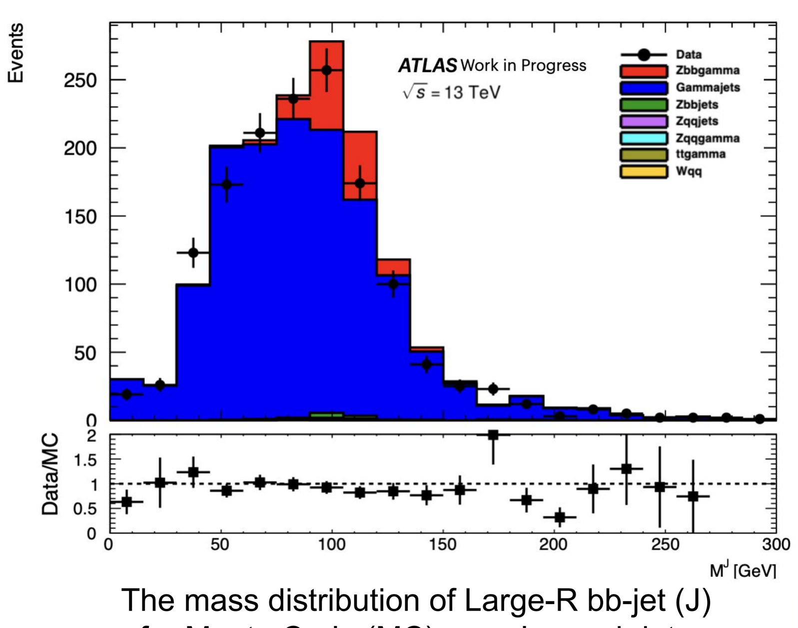
Data-based validation for the calibration

- In-situ calibration using a **Direct Balance (DB) technique** requires a well measured reference object.
- The response ***R*** is calculated by balancing the Large-R (bb)-Jet $\mathbf{p_T}$ against a well-calibrated reference object with approximately no other hadronic activity.

$$R^{\text{in-situ}}_{\text{MC,data}} = \langle R_{DB} \rangle = \left\langle \frac{p_T^{\text{Large-R (bb)jet}}}{p_T^{\text{ref}}} \right\rangle, \quad \text{where} \quad p_T^{\text{ref}} = p_T^{\gamma} \cdot |\cos(\Delta\phi(\gamma, \text{Large - R jet}))|$$

- Extract the correction factor **C** from from the balance equation: $C = \frac{R^{\text{in-situ}}_{\text{MC}}}{R^{\text{in-situ}}_{\text{data}}}$

State of Work:



The mass distribution of Large-R bb-jet (J) for Monte Carlo (MC) samples and data

- For now we are exploring the **Z(→bb)+γ.**
- In future we hope to be able to add the **Z(→bb)+jet**.
- Reasonable Data/MC agreement for the mass of Large-R jets bb-jet.
- In order to do this correction we need to isolate the **Z(→bb) + γ signal**. Ongoing work!

On the road towards a HH evidence!