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Search for triple Higgs boson production in the 6b final state at 13TeV with the ATLAS detector

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2025.10.31

CLHCP2025, Henan, China

Phys. Rev. D 111, 032006

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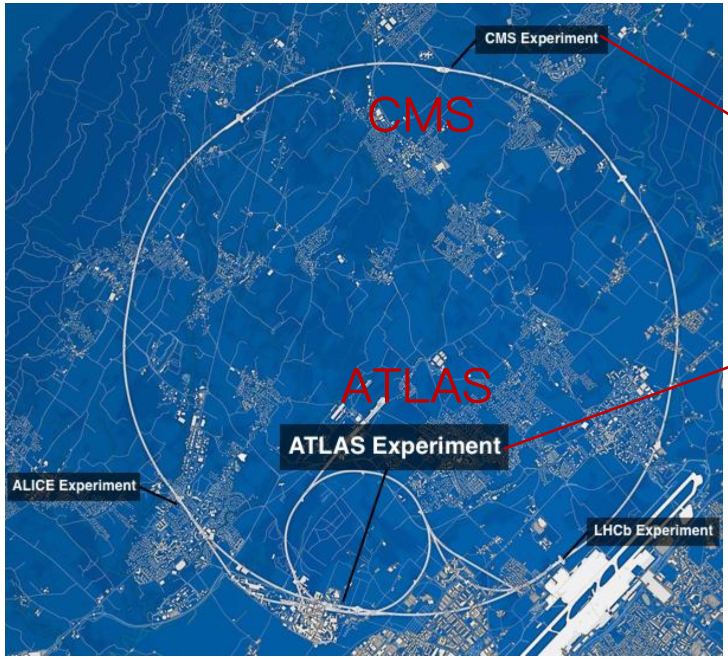
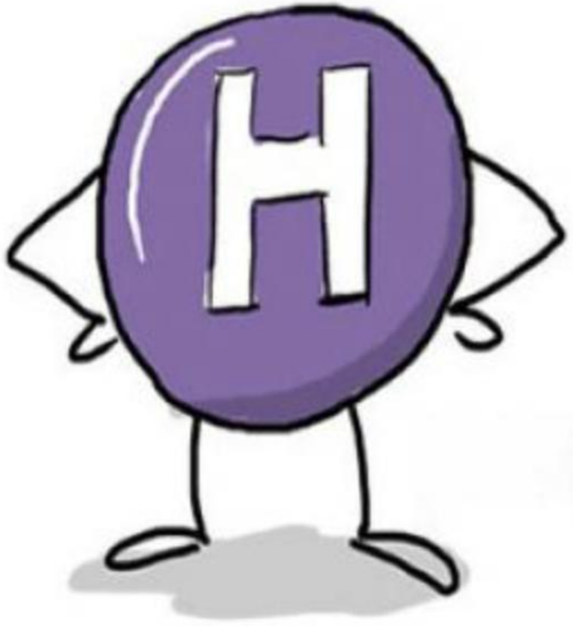
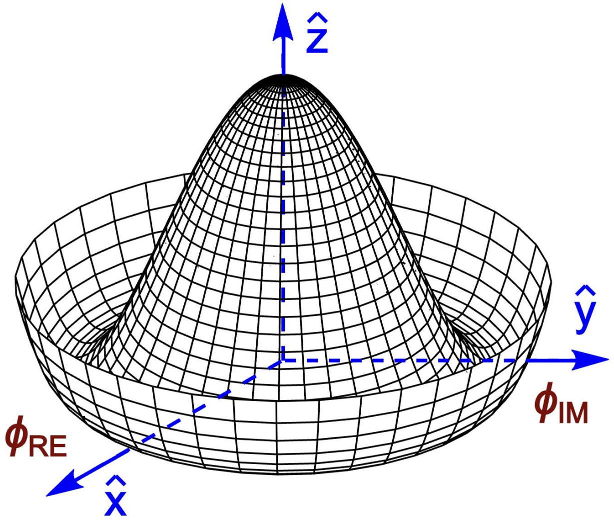
Higgs potential

- Since the discovery of the Higgs boson in 2012, understanding its properties has been a central task
- Studying the Higgs potential reveals the structure of the Higgs field

$$\mathbf{V(H)} = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{m_H^2 H^2} + \boldsymbol{\lambda_3 \nu H^3} + \boldsymbol{\lambda_4 H^4} + \mathbf{O(H^5)}$$

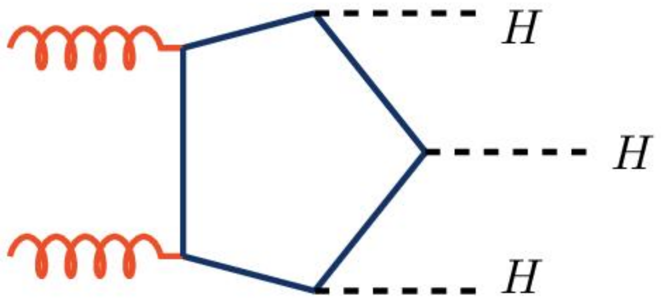


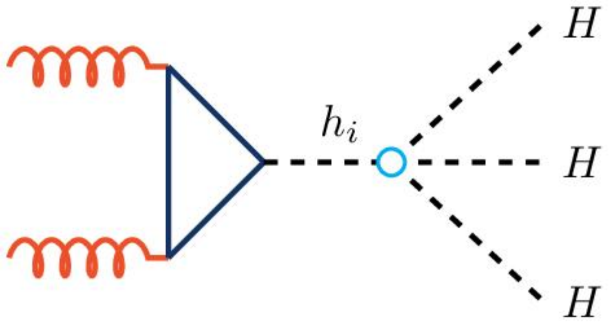


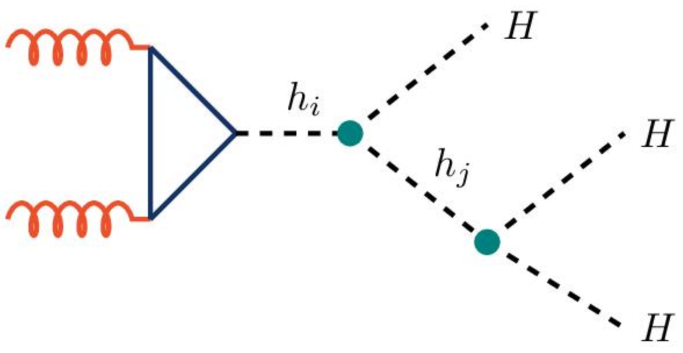


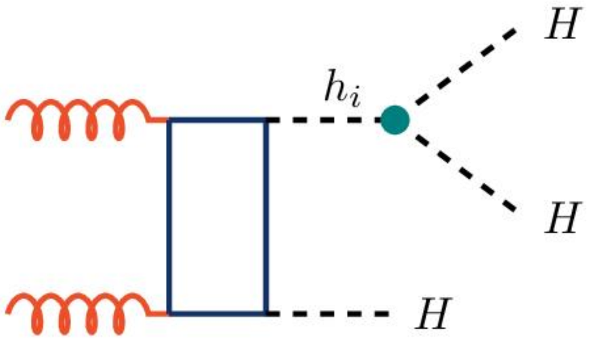
Physics Motivation for HHH->6b

- New topology
  - SM tri-Higgs production is sensitive to tri-linear and quartic Higgs self-couplings (λ_3 & λ_4)
  - Constrain modifications to SM coupling values (K_3 & K_4, no experimental bounds before)
  - Quartic couplings can only be accessed directly this way
- Small SM tri-Higgs ggF production cross-section at $\sqrt{s} = 13\ TeV$ ~ 0.08 fb at NNLOg
- Some BSM theories predict nontrivial tri-Higgs production
- Rare process → 6b final state (large branching ratio: $H \to b\bar{b}$ ~58%)



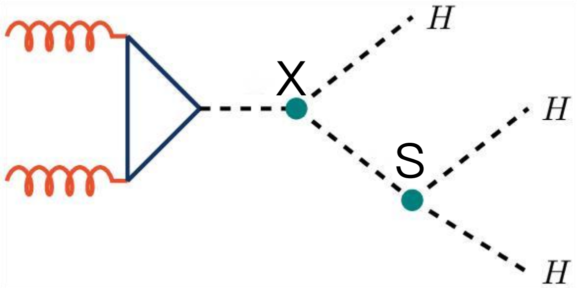


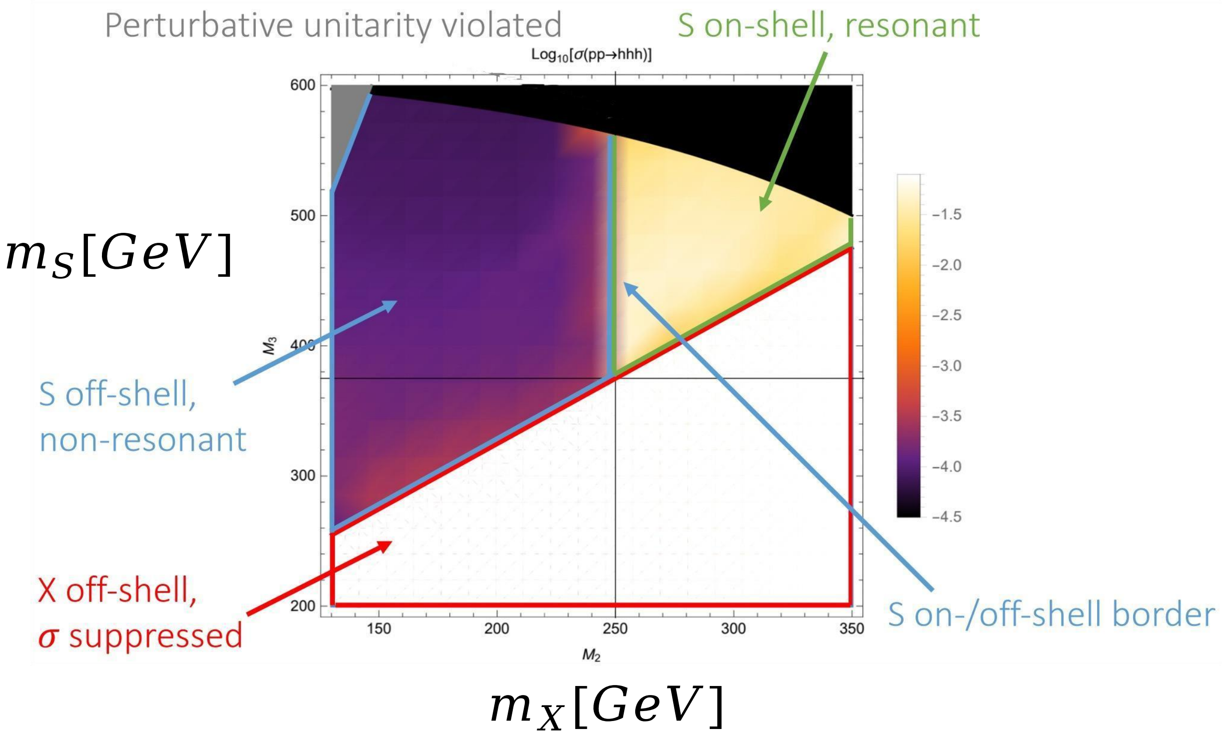




BSM of Higgs 6b production

- Two Real Singlet Model(TRSM)
  - Extending the SM by adding two real scalar bosons X and S
  - The production cross section can reach values up to ~ $50fb$ (LO)
  - Resonant + non–resonant, all LO ggF production modes (BSM + SM)





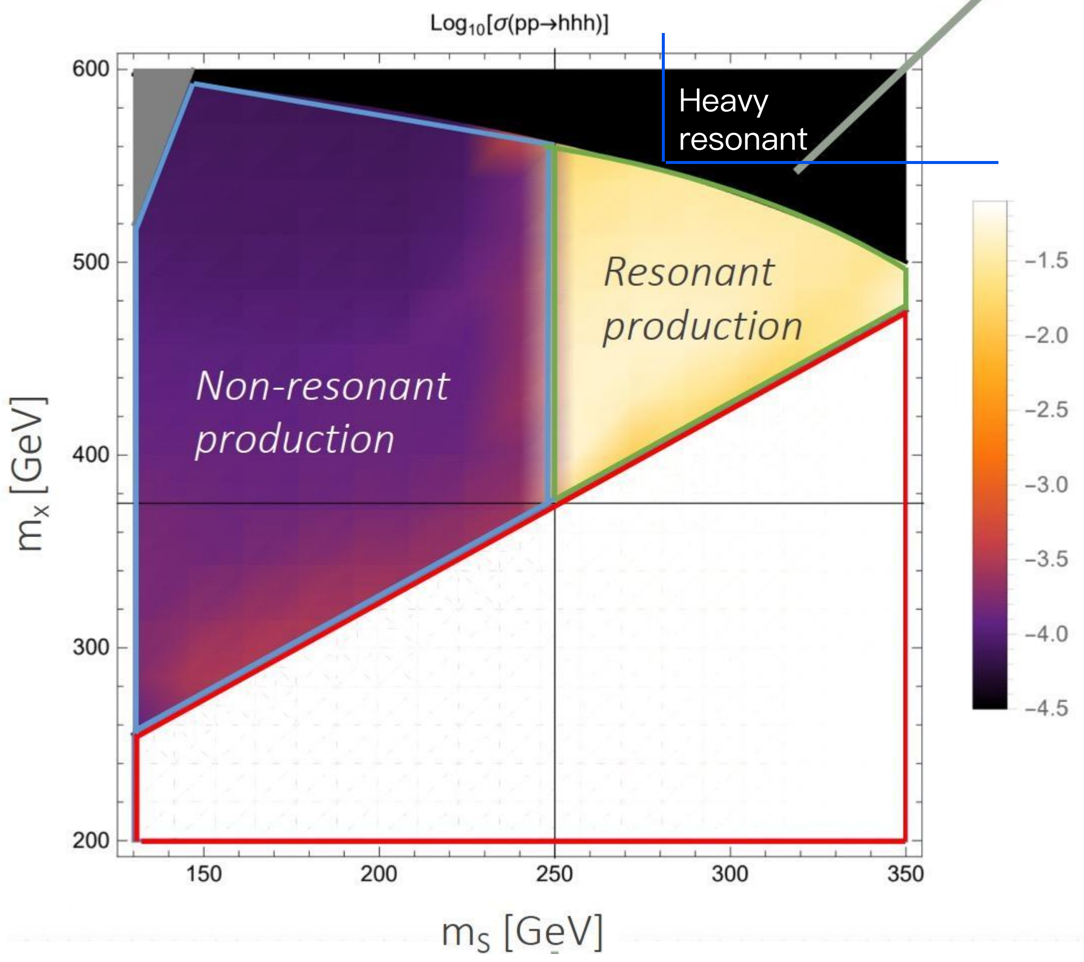
- Simple model for dark matter and CP violation (DM–CPV)
  - Dark matter as a vector–like dark fermion
  - Interacts with SM through scalars similar as the scalars in TRSM
  - Negligible differences are found in HHH event kinematics between TRSM and DM–CPV
- Simplified TRSM model
  - TRSM breaks unitarity at high masses, and becomes dominated by the non–resonant diagrams. Simplify model to avoid TRSM problems.
  - Only consider resonant ggF production (x → SH → HHH).

Analysis overview

- Data: run2 dataset ($126\ fb^{-1}$)
- Three interpretations based on the kinematics of the signal models.
  - Non-resonant: $m_S < 2m_H(250GeV)$
  - Resonant: $m_S > 2m_H(250GeV)$
  - Heavy resonant: $m_S > 275GeV$, $m_X > 550GeV$; (narrow & wide decay widths)
- Each search follows the same general analysis strategy
- Dominant background: QCD multi-jet production Estimate by data-driven method
- A profile likelihood fit is performed on **Deep Neural Network (DNN)** score to obtain the final results

$550 < m_X < 1500$ GeV $275 < m_S < 1000$ GeV

Generic heavy resonance



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Event selection

ATLAS Run–2 data ($126\,fb^{-1}$)
selected by triggers

≥ 6 jets
≥ 4 jets with pT > 40 GeV
≥ 4 jets passing DL1dv01 77% WP

≥ 6 b-tags
Signal Region (SR)

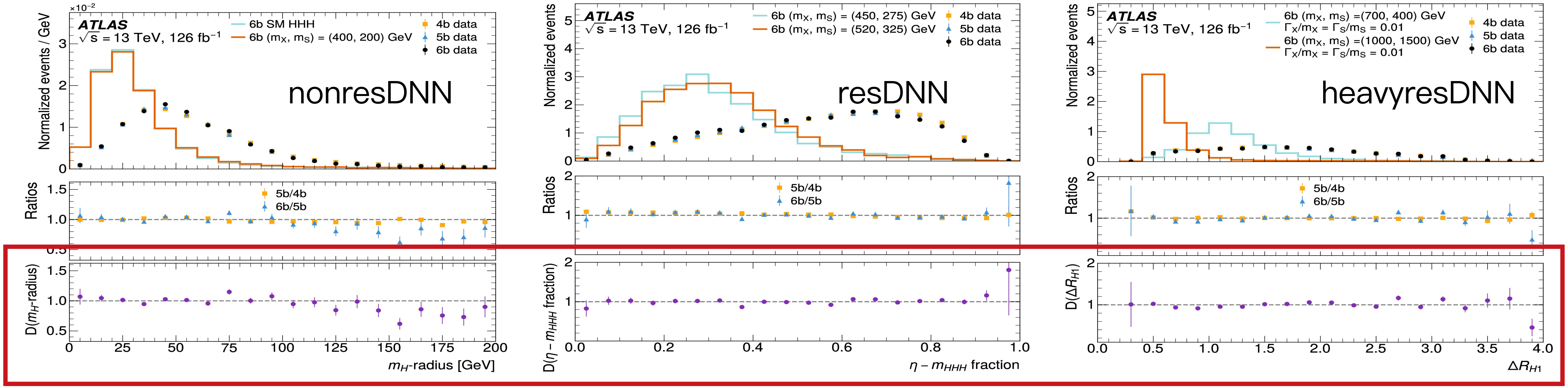
= 5 b-tags
Control Region (CR)
Background estimation
& validation

= 4 b-tags
Control Region (CR)
Background estimation
& validation

Deep Neural Network(DNN)

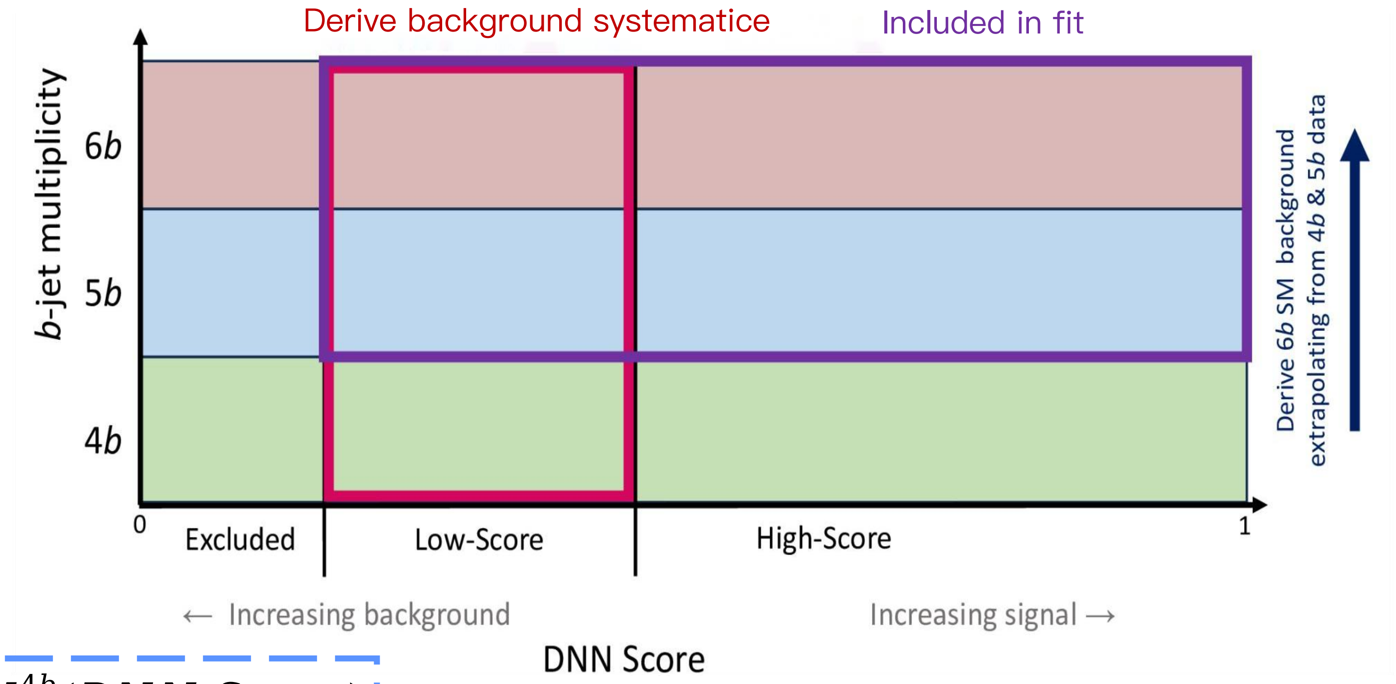
- Three DNNs are trained for discriminant and fitting
- Training samples
  - Background: 5b data
  - Signal: nonresDNN (6b SM HHH + 6b TRSM non-resonant), resDNN (all 6b resonant TRSM), heavyresDNN (all 6b heavy resonance)
- For each DNN, ten variables (good shape separation, minimal correlation with the b-jet multiplicity)

  are chosen as inputs. extrapolation uncertainty estimate by Double ratio $\mathbf{D} = \frac{\mathbf{R_{6b/5b}}}{\mathbf{R_{5b/4b}}} \sim \mathbf{1}$



Background Estimation

- Dominant background: QCD multi–jet production
- Data–driven method
- Assumption: properties of the background do not significantly sensitive to b–jet multiplicity (validate by double ratio $\mathbf{D} = \frac{\mathbf{R_{6b/5b}}}{\mathbf{R_{5b/4b}}} \sim \mathbf{1}$)
- Extrapolation: $4b \rightarrow 5b \rightarrow 6b(SR)$, extrapolate shape in b–tag multiplicity, normalized to 6b yields
  - Excluded region: large shape difference between 4b, 5b and 6b, exclude from fit
  - Low–score region: B–tag extrapolation, validate background estimate, derive shape systematics
  - High–score region: 6b SR



$$Background\ model_i = N_i^{5b} \times \frac{N^{6b}}{N^{5b}} \times \frac{N_i^{5b}/N_i^{4b}(DNN\ Score)}{N^{5b}/N^{4b}}$$

normalised to 6b yields

Extrapolate the shape of DNN score

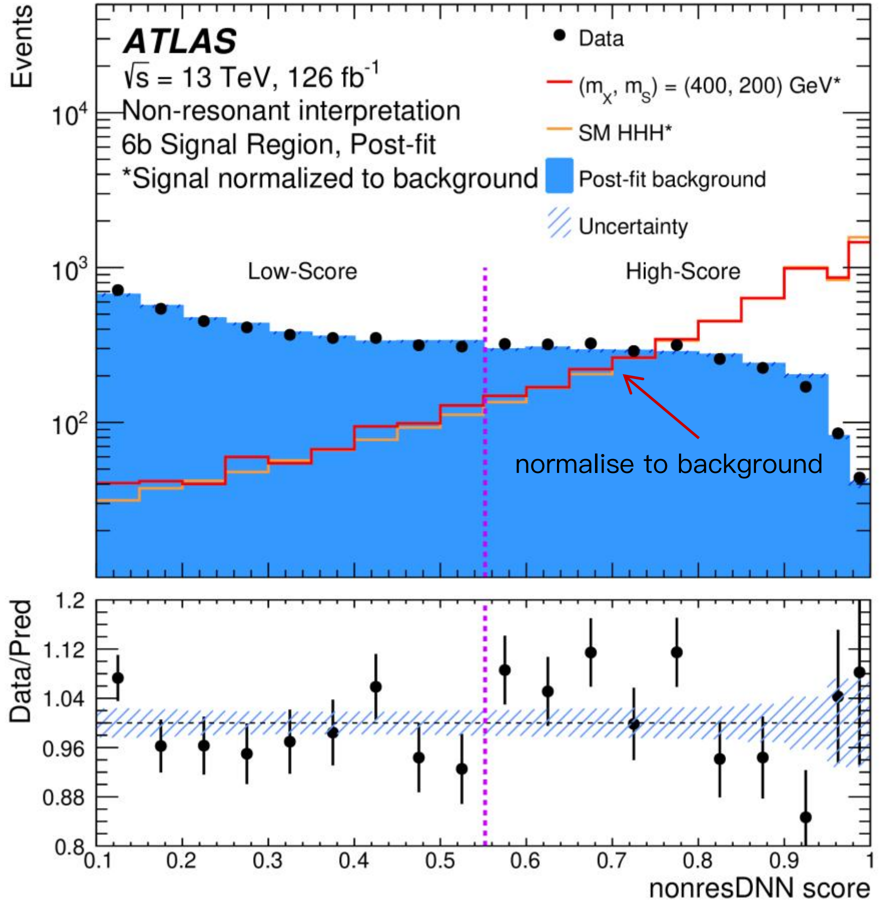
Uncertainties

Uncertainty source	Relative impact of systematic uncertainties [%]			
	SM-like	TRSM non-resonant	TRSM resonant	Heavy resonance
All uncertainties	24	20–46	33–42	24–53
Experimental	22	20–45	33–41	24–53
Detector response	7.4	6.6–14	16–24	4.1–15
Luminosity and pileup	<1	<1	<1	<1
Flavor tagging	3.2	2.8–5	6.9–8.8	1.5–5.6
Jet reconstruction	2.7	2.3–6.5	3.6–7.1	1.0–6.3
Trigger efficiency	2.0	1.8–3.5	6–10	1.4–4.2
Background modeling	16	14–36	18–30	20–45
Theoretical	1.5	<1	<1	<1
MC statistical	<1	<1	<1	<1

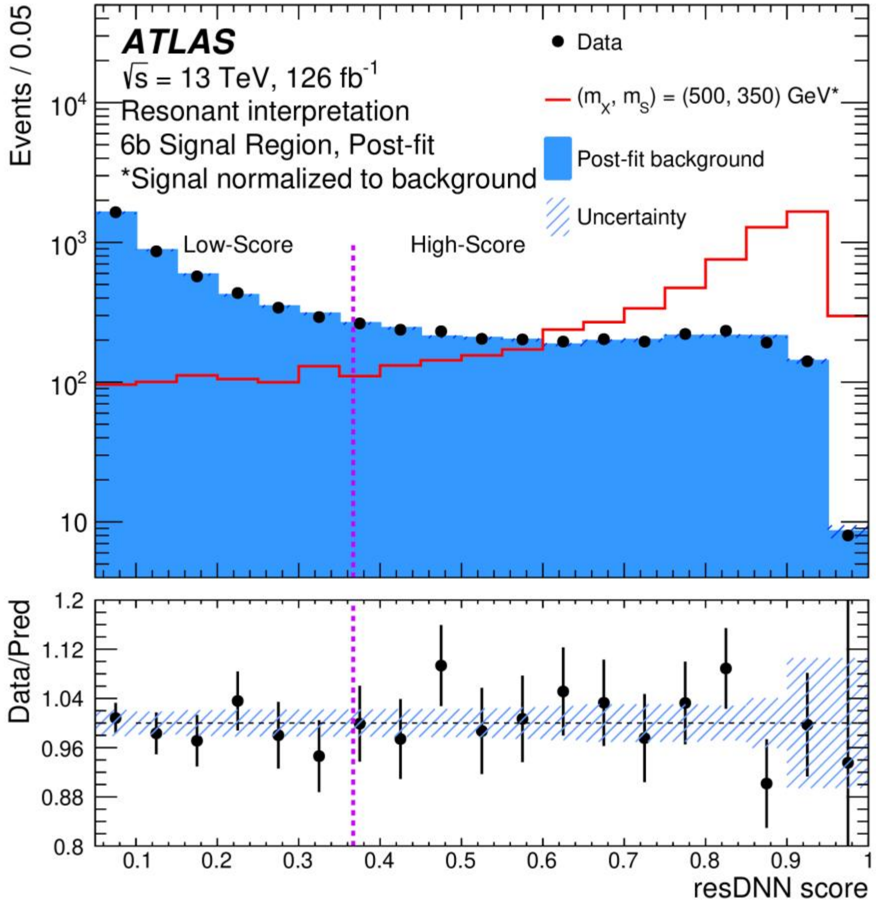
- Background shape uncertainty is the dominant one in experimental uncertainties.
  The expected limits are changed from 14% to 45%.
- Theoretical uncertainties: (α_s+PDF) & QCD scale.

Non-resonant & resonant interpretations

- In all cases, the observed data agree well with the background, and no significant excess is seen.
- In non-resonant interpretation: largest deviation is at $(m_X, m_S) = (550{,}200)$ GeV with 0.19σ
- In resonant interpretation: signal strength $\mu = 0$.



Non-resonant



Resonant

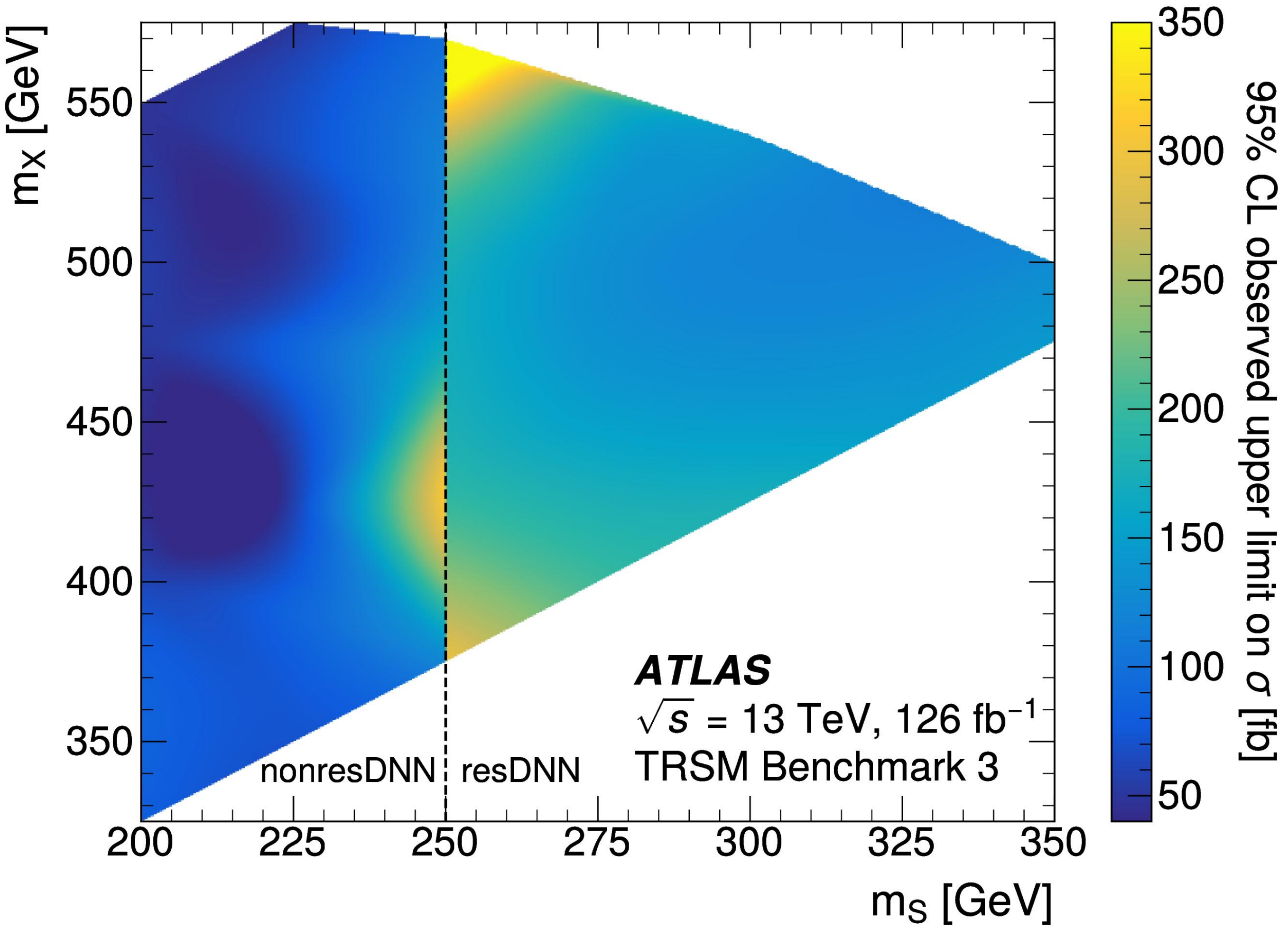
Non-resonant & resonant interpretations

- Cross-section upper limits in the (m_X, m_S) plane of non-resonant interpretation and resonant interpretation. (Observed: 48~310 fb)

- Observed cross-section upper limit: 59 fb

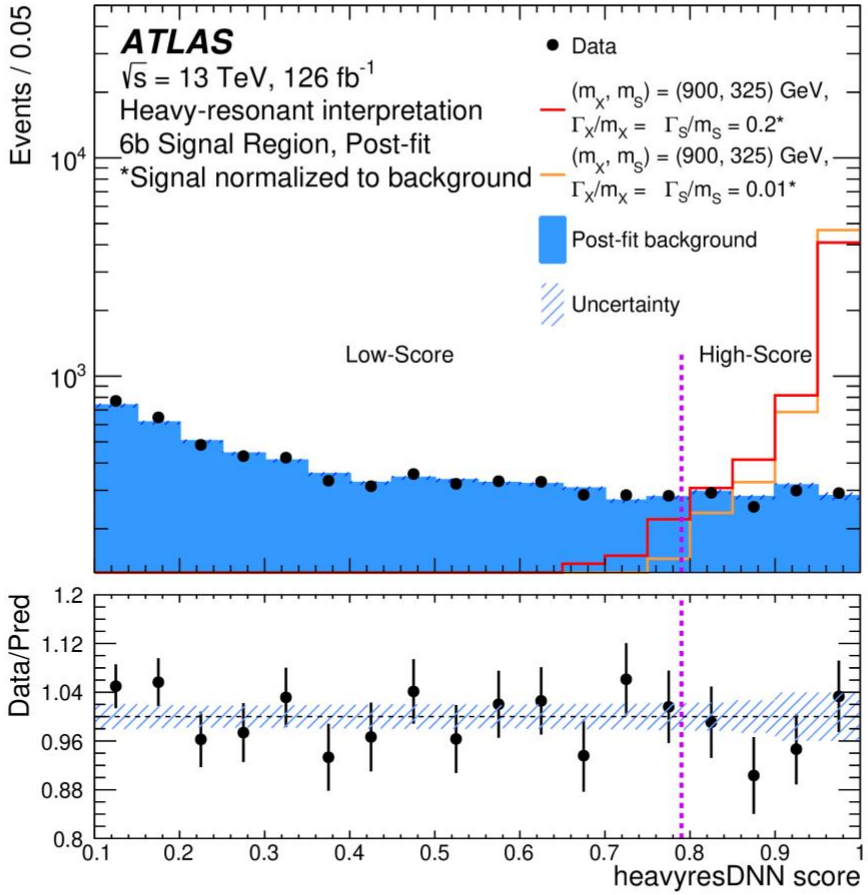
- SM HHH production:

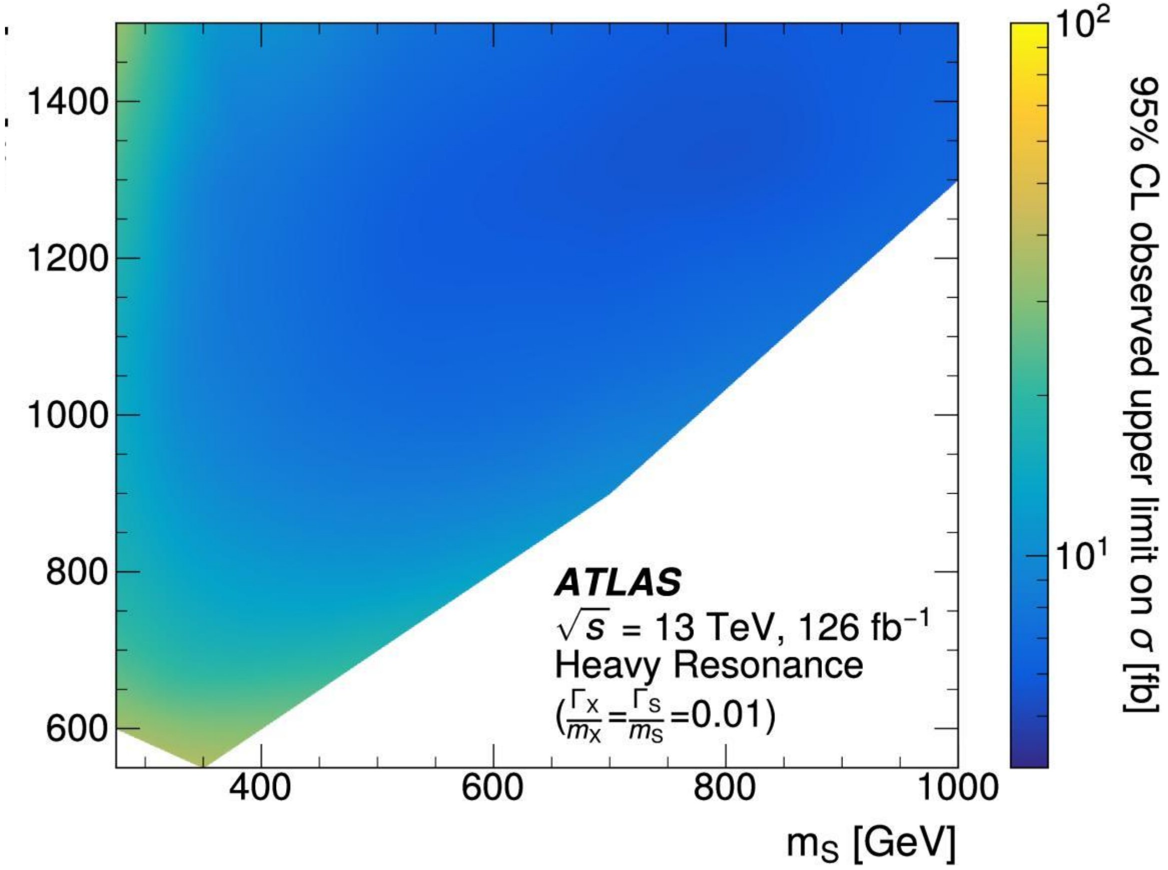
$$\mu = \frac{\sigma_{HHH}}{\sigma_{HHH}^{SM}} \sim 750$$



Heavy resonant interpretation

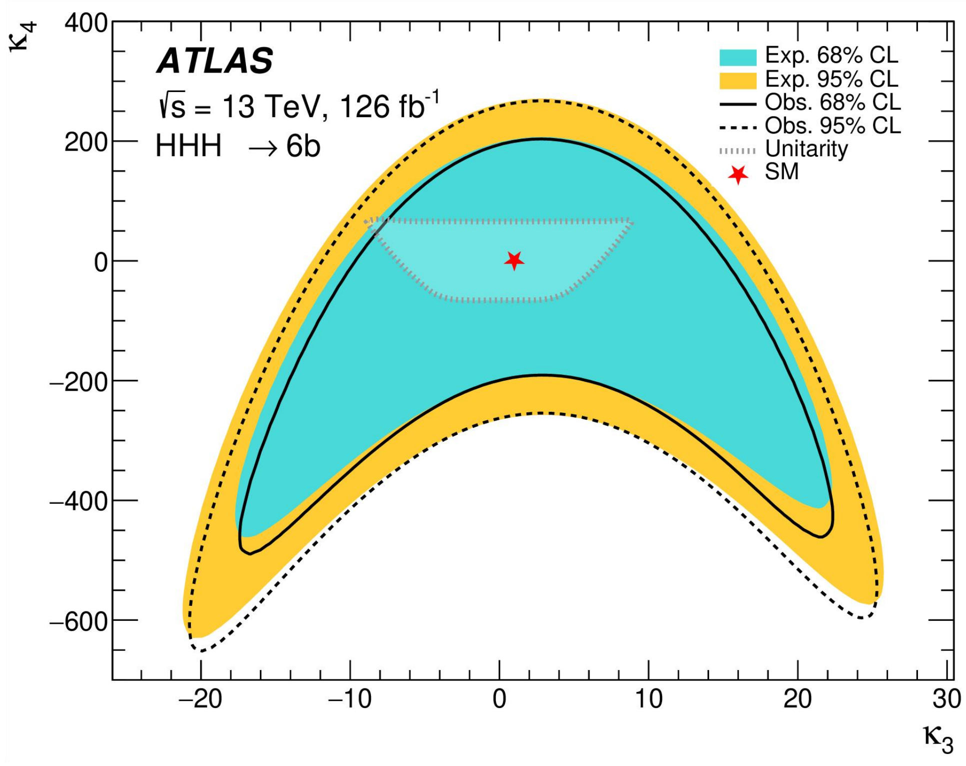
- In all cases, the observed data agree well with the background, and no significant excess is seen.
- In heavy resonant interpretation: largest deviation is at (m_X, m_S) = (1500,275) GeV with 0.51σ
- Observed limits for the narrow heavy resonance signals: 5.7~38 fb

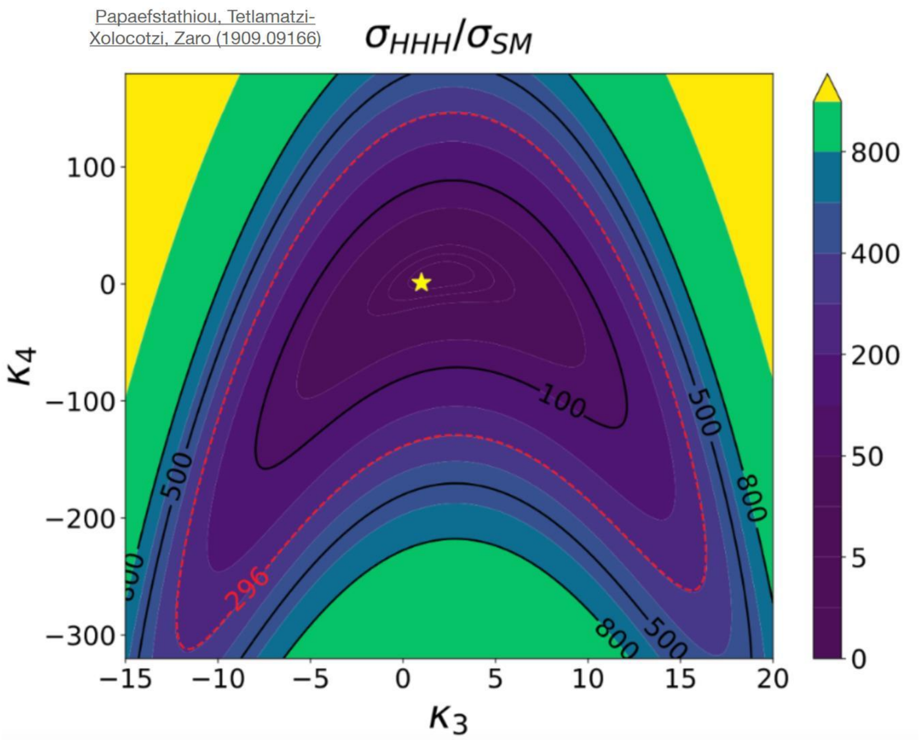




κ_3 and κ_4 scan

- Constraints on quartic coupling modifier set for the first time
- At the 95% CL none of the phase space inside the unitarity bounds is excluded





Theoretical dependence

Summary

- Search for tri-Higgs production in 6b final state with $126 fb^{-1}$ ATLAS run2 data. It's the first search of such topology at the LHC

- Three different DNNs are used in non-resonant (including a search for SM like signals), resonant and heavy resonant interpretations. Data-driven method is used to estimate background

- No significant excess observed in the search for SM like and various BSM signals Constrains of K_3 and K_4 (for the first time) are presented

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Thanks for your listening

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Backup

Different interpretations

The event kinematics differ depending on the type of production – resonant vs non-resonant

Resonant HHH production

- Both X and S in TRSM are in-shell

$m_S > 2m_H(250GeV)$ resonant TRSM

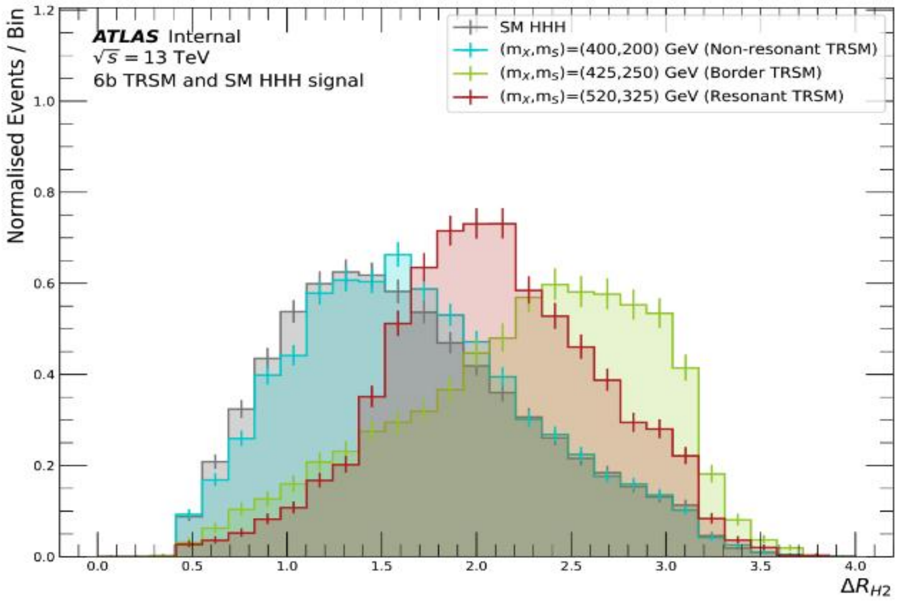
$m_S = 2m_H(250GeV)$ border TRSM

Non-resonant HHH production

- S in TRSM is off-shell, i.e.

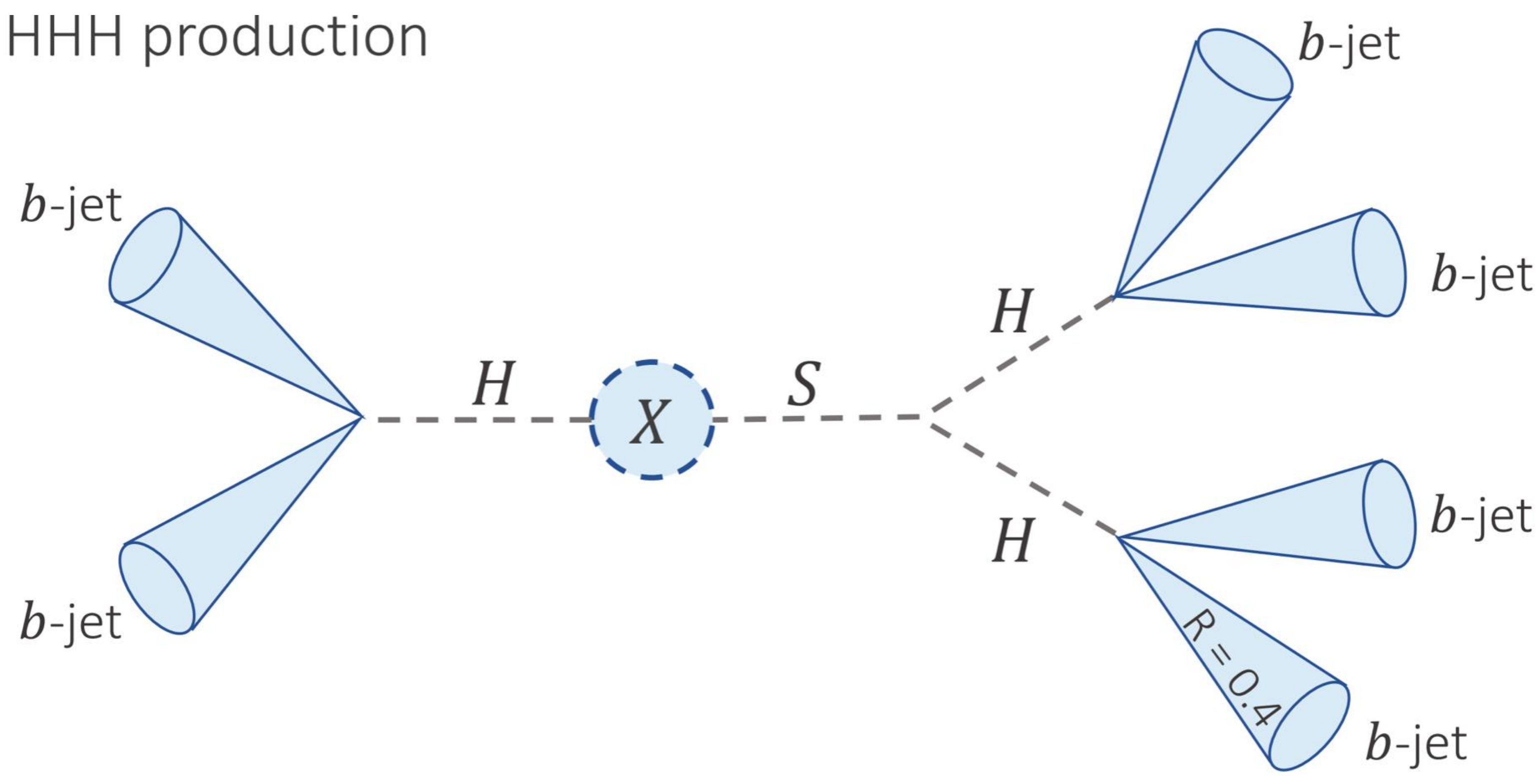
$m_S < 2m_H(250GeV)$

non-resonant TRSM



Object definition

- PFlow jets, $p_T > 20$ GeV, $\eta < 2.5$
- B–tagged by DL1d 77% working point
- μ-in–jet correction for semi–leptonic b–hadron decay



DNN input

TABLE I. Summary of the input variables used in each DNN. Check marks denote which input is used for each DNN.

Variable	Definition	Nonres	Res	Heavyres
m_H-radius	Distance between the event (m_{H1}, m_{H2}, m_{H3}) vector and expected vector for signal events, $(120, 115, 110)$GeV.	✓		✓
m_{H1}	Reconstructed mass of the highest p_{T} Higgs boson candidate.	✓		✓
$\mathrm{RMS}(m_{\mathrm{jj}})$	Root-mean-squared (RMS) of the invariant mass of all 15 possible jet pairs.	✓		✓
$\mathrm{RMS}(\Delta R_{\mathrm{jj}})$	RMS of the angular separation between all 15 possible jet pairs.	✓	✓	✓
$\mathrm{RMS}(\eta)$	RMS of the pseudorapidity of the Higgs boson candidates.	✓		✓
Skewness ΔA_{jj}	Skewness of $\cosh(\Delta\eta_{ik}) - \cos(\Delta\phi_{ik})$, where i, k are all 15 possible jet pairs.		✓	
$H_T^{6\mathrm{j}}$	Scalar sum of the p_{T} of the 6 jets selected to reconstruct the 3 Higgs boson candidates.		✓	
$\cos\theta$	In the (m_{H1}, m_{H2}, m_{H3}) coordinate system, θ is the angle between the vector from the origin to the event's reconstructed mass of the Higgs boson candidates, and the vector from the origin to $(120, 115, 110)$GeV.		✓	
$\mathrm{Aplanarity}_{6\mathrm{j}}$	The fraction of p_{T} from the 6 jets selected lying outside the plane formed by the 2 highest p_{T} jets [58].	✓	✓	✓
$\mathrm{Sphericity}_{6\mathrm{j}}$	Isotropy of the momenta of the 6 jets selected to reconstruct the 3 Higgs boson candidates [58].		✓	
Transverse $\mathrm{Sphericity}_{6\mathrm{j}}$	Isotropy of the p_{T} of the 6 jets used for Higgs reconstruction, within the $x - y$ plane [58].	✓		
Sphericity	Isotropy of the momenta of all jets in the event [58].			✓
$\eta - m_{HHH}$ fraction	$\frac{\sum_{i,k} 2p_{\mathrm{T}}^i * p_{\mathrm{T}}^k * (\cosh(\Delta\eta(ik)) - 1)}{m_{HHH}^2}$, where i, k are all 15 possible jet pairs, and m_{HHH} is the reconstructed tri-Higgs invariant mass.		✓	
ΔR_{H1}	Angular separation between the jets paired to form the highest p_{T} Higgs boson candidate.	✓	✓	✓
ΔR_{H2}	Angular separation between the jets paired to form the second-highest p_{T} Higgs boson candidate.	✓	✓	✓
ΔR_{H3}	Angular separation between the jets paired to form the lowest p_{T} Higgs boson candidate.	✓	✓	✓

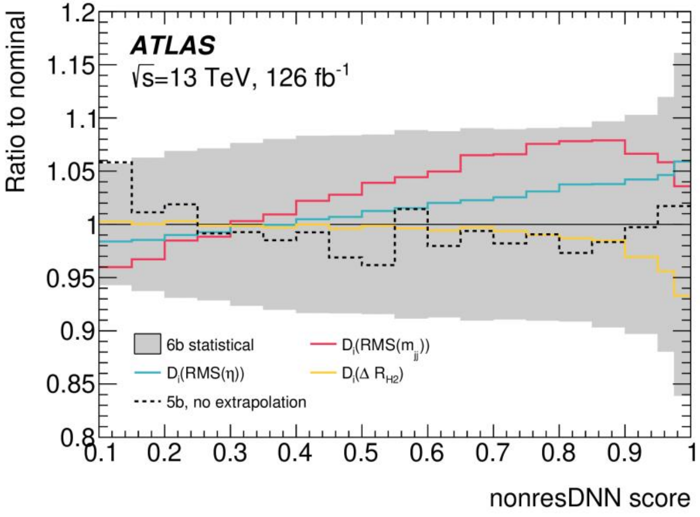
Background estimation

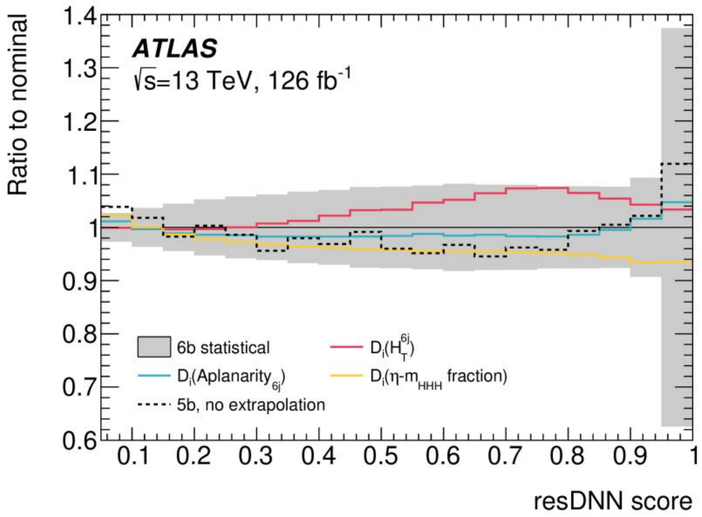
- The non–closure in the extrapolation method in low–score region is used to estimate the systematic uncertainty.

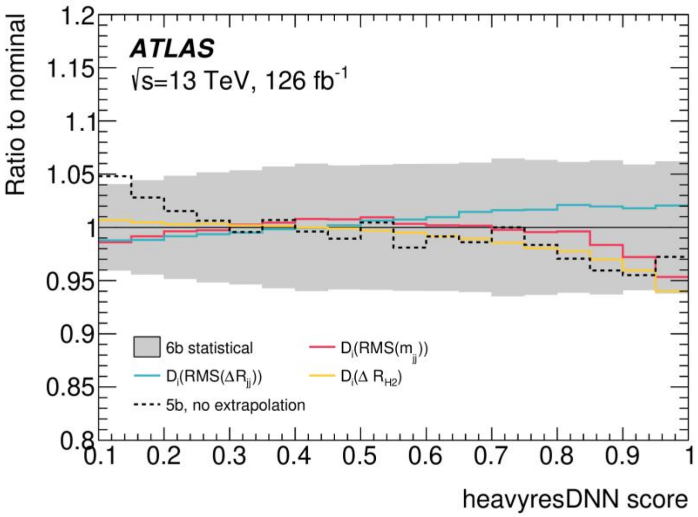
$$D(\nu) = \frac{\left(N^{6b}/N^{5b}\right)_{(\nu)}}{N^{6b}/N^{5b}} \div \frac{\left(N^{5b}/N^{4b}\right)_{(\nu)}}{N^{5b}/N^{4b}}$$

ν:DNN input variables

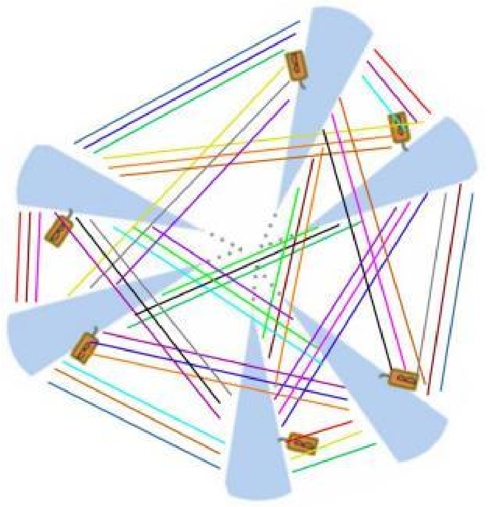
- 3 Kinematic shape variations employed for each interpretation.
- The shape variations are always smaller than the statistical uncertainty.







Jet pairing



- Reconstruct high–level kinematic variables that are effective at signal/background discrimination

- Three Higgs boson candidates:
  6 jets are selected & paired. 15 ways to pair them

- Pairing algorithm:

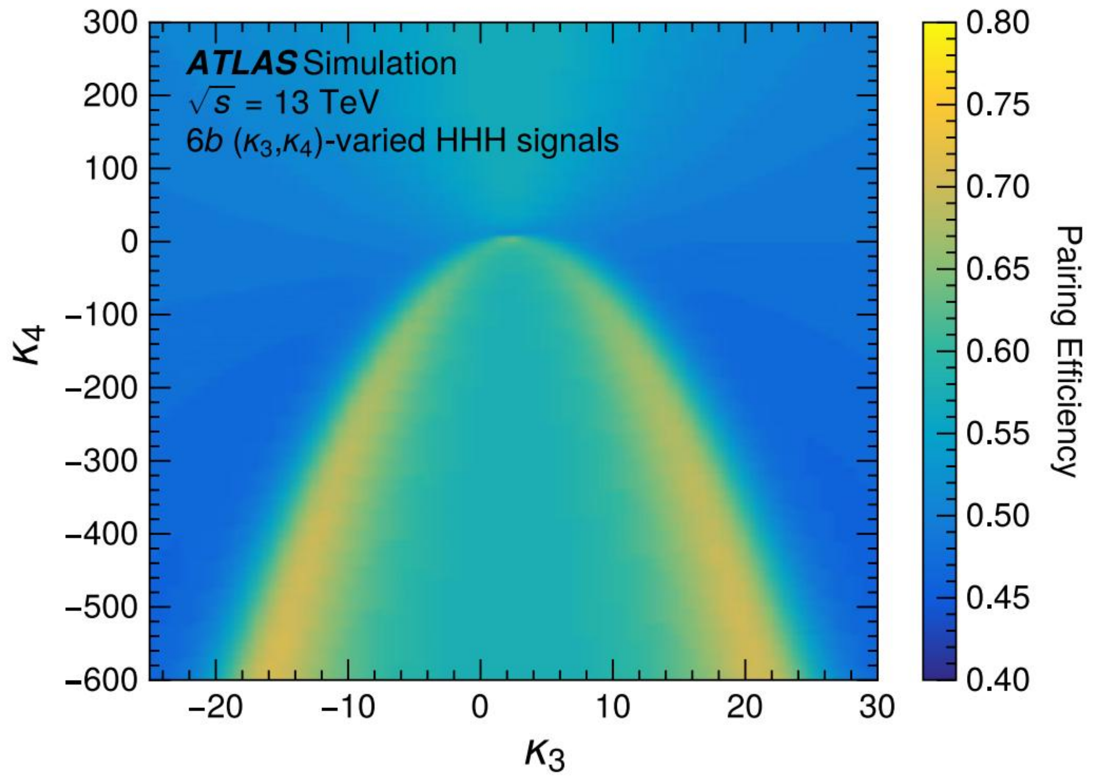
  minimizing $|m_{H1} - 120GeV| + |m_{H2} - 115GeV| + |m_{H3} - 110GeV|$

- Pairing efficiencies:
  - SM–like ~ 60%
  - Resonant TRSM ~ 50%
  - Heavy resonant ~ 80%

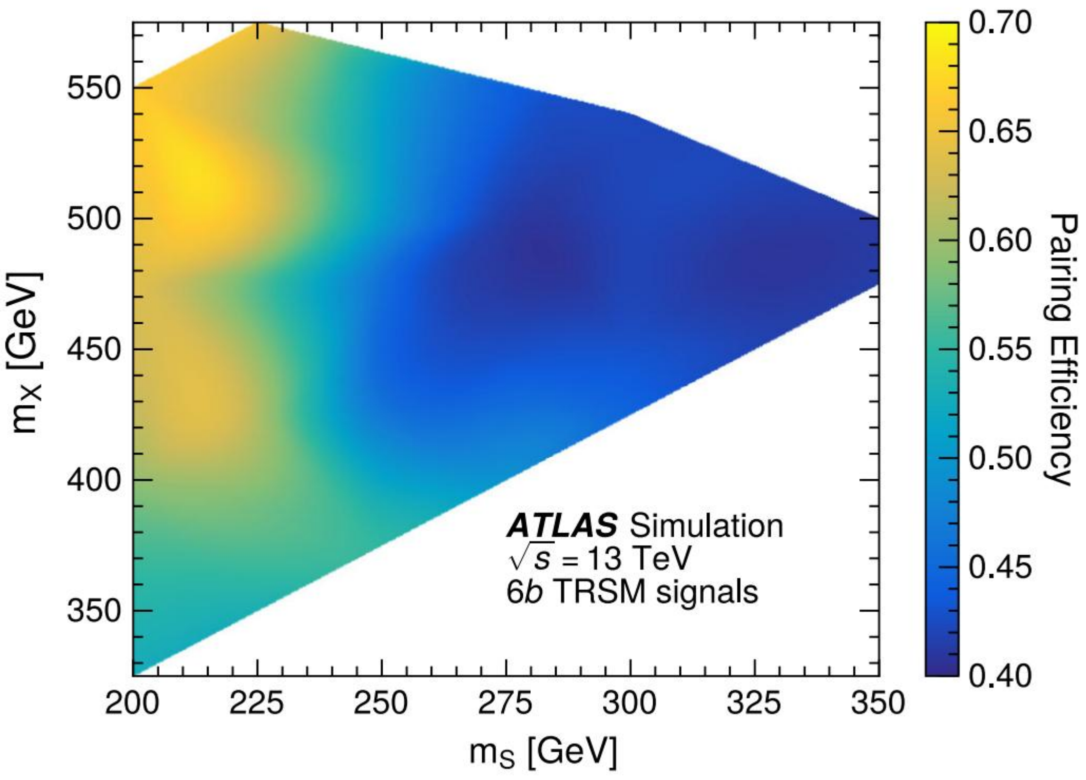
For 6b events:

For 5b (4b) events:

Jet pairing efficiency

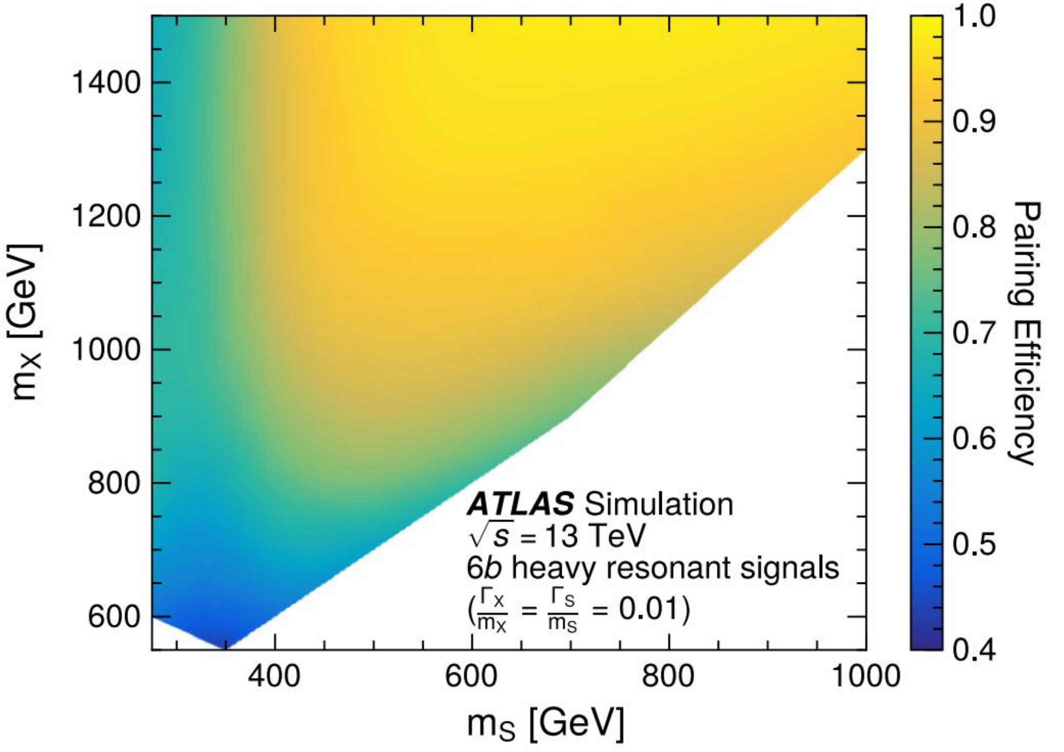


SM-like

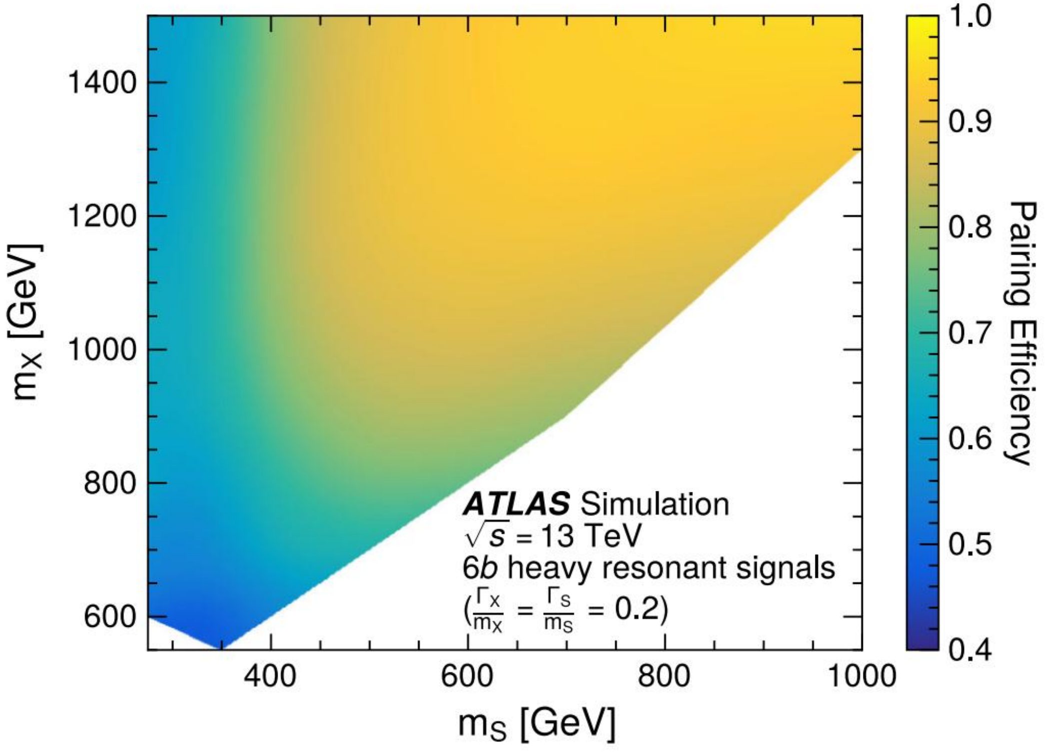


TRSM

Jet pairing efficiency



narrow heavy resonant



wide heavy resonant