Search for new resonance using the boosted Higgs pair production in the 4b final state

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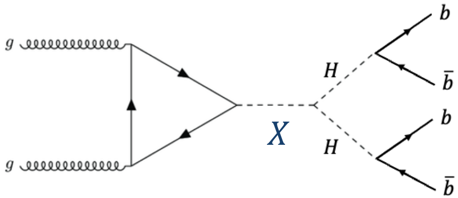
Introduction

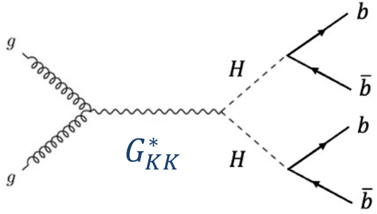
- HH is sensitive to new resonances predicted by various BSM theories
- HH decays into various final states and 4b final state has the largest BR (34%)
- There are two benchmark models :

① Spin-0 boson X

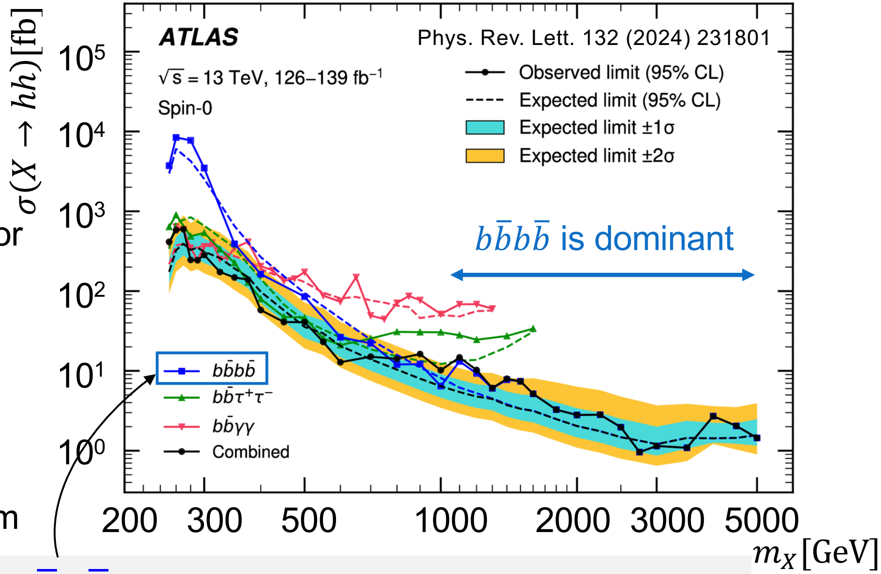


Particle predicted by Extended Higgs Sector e.g. 2HDM

② Spin-2 Kaluza-Klein graviton G^*_{KK}



Particle predicted by bulk Randall–Sundrum (RS) model



$HH \to b\bar{b}b\bar{b}$ is the most sensitive channel in the high mass region above 1TeV

Motivation and Strategy

Increased statistics

Run2 data + Run3 data collected up to 2024
→ ×2 data of previous analysis

Improved jet tagging algorithm

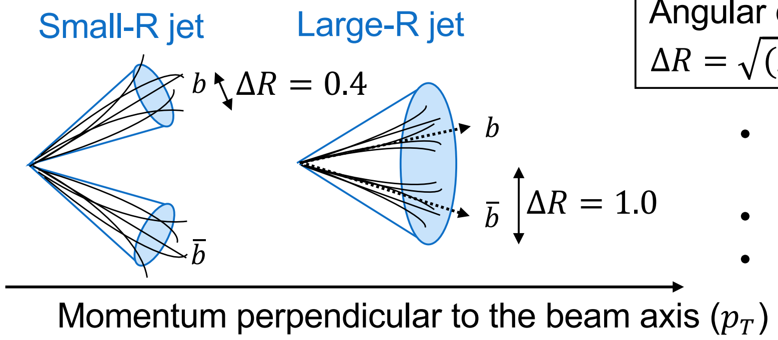
Use a transformer based algorithm for the first time
→ Improved background rejection

Improve the sensitivity in high resonance masses region

Targeting Moriond (March 2027)

Jet Reconstruction

Boosted $H \to b\bar{b}$ jet reconstruction



Angular distance
$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

- Heavy resonance produces highly boosted Higgs bosons
- The two b-quarks from each Higgs become collimated
- Each $H \to b\bar{b}$ is reconstructed as a **single Large-R jet**

	UFO (Unified Flow Object)	**BJR10**
Role	Standard reconstructed jet	b-jet regression
Calibration	JES/JMS (→ details in backup)	BJR10 (→ details in backup)
Used for	Trigger + event selection	Kinematic observable
Key point	Trigger SF are calibrated for this jet	Improved p_T / mass resolution

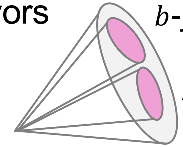
$H \to b\bar{b}$ Jet Tagging Algorithms

Improvements in jet tagging algorithm

Previous tagger (D_{Xbb})

- B, D hadron decay properties
- Track information

Identify two subjets flavors



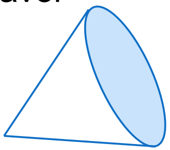
b-jet

$\bar{b}$-jet

New transformer-based tagger (GN2X, GN3X)

- Learning jet internal structure from track information

Identify large-R jet flavor



$Hb\bar{b}$-jet

GN3X includes calorimeter information and higher momentum track information

- GN2X shows ×~2 improvement compared to the D_{Xbb}
- GN3X shows ×~2 improvement compared to GN2X

→ Potential improvement in analysis sensitivity

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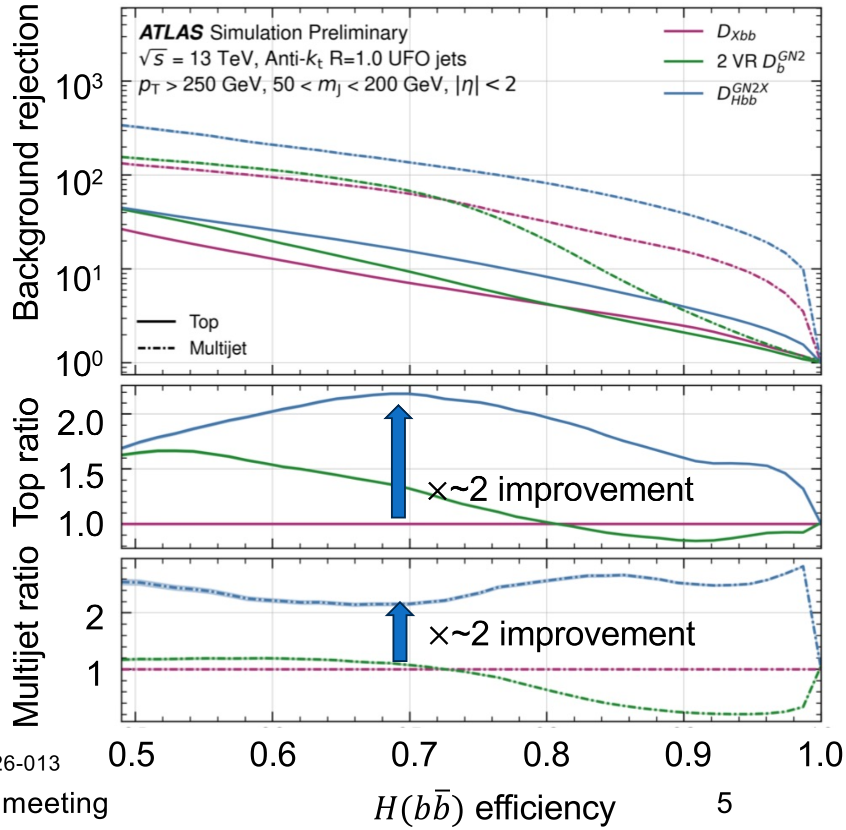

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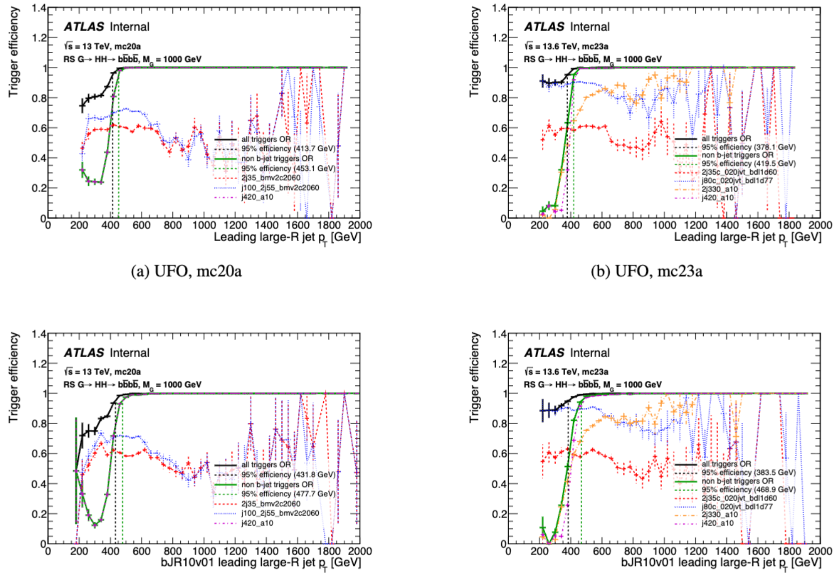
Trigger Efficiency

- Samples :
  - Spin-2 resonant signal ($m_{G^*_{KK}} = 1\ \mathrm{TeV}$)
  - mc20a/d/e, mc23a/d
- Triggers (→ details in backup) :
  - Large-R jet triggers
  - Resolved b-jet triggers

Trigger efficiency :

$$\varepsilon = \frac{\mathrm{N(w/\ trigger)}}{\mathrm{N(w/o\ trigger)}}$$

Observations :
- b-jet triggers improve low-p_T efficiency
- Run 3 shows improved trigger performance
- BJR10 reaches high efficiency at slightly higher p_T



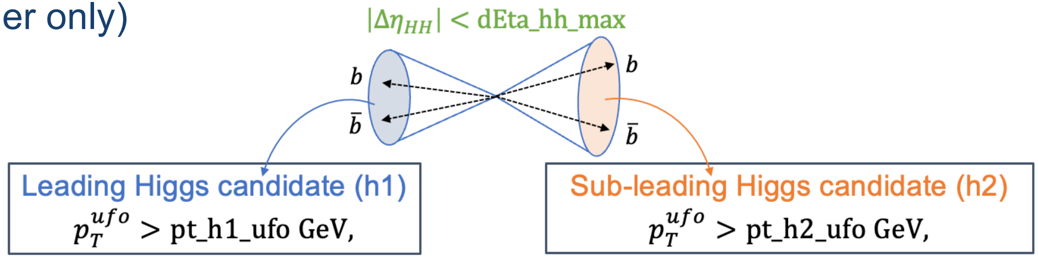
(a) UFO, mc20a (b) UFO, mc23a (c) BJR10, mc20a (d) BJR10, mc23a

Figure 3: Trigger efficiency as a function of the leading large-R jet p_T. The trigger efficiency is evaluated relative to the sample before trigger filtering. The black curves correspond to the OR of all considered triggers, including both large-R jet and resolved b-jet triggers, while the green curves correspond to the OR of the large-R jet triggers only, excluding the b-jet triggers. The remaining curves show the efficiencies of the individual trigger chains. The vertical dashed lines indicate the 95% efficiency points, defined as the value above which the efficiency remains above 95% for at least ten consecutive bins. Results are shown for the 1 TeV spin-2 resonant signal samples for mc20a and mc23a, using the UFO and BJR10 jet definitions.

Selection Optimization

- Samples :
  - Data : 2016~2018, 2022, 2023
  - MC : mc20a/d/e, mc23a/d
    - Spin-2 resonant signal (1, 3, and 5 TeV, Common signal cross-section : $\sigma = 1\ \mathrm{fb}$)
    - ttbar background

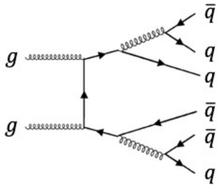
- Scan Conditions : WP × trigger strategy × preselection
  - WP : GN3X Flat-mass QCD WP
  - Trigger strategy
    - Inclusive (Large-R jet trigger OR b-jet trigger)
    - Boosted (Large-R jet trigger only)
  - Preselection
    - pt_h1_ufo
    - pt_h2_ufo
    - dEta_hh_max



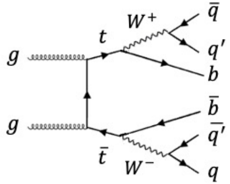
Background Estimation

Background

- The main background is the QCD multijet events.
- These events involve many processes and higher-order calculations are extremely complicated, so it is difficult to estimate using MC simulation.



QCD multijet events

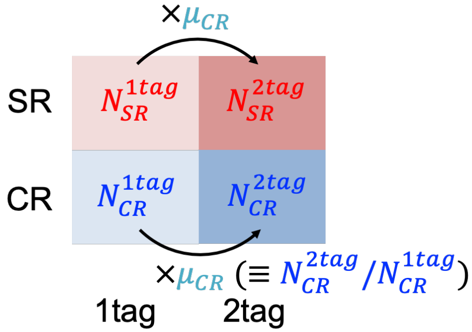


$t\bar{t}$ production events

Data-driven QCD Background Estimation

$$N_{QCD} = N_{\text{data}} - N_{t\bar{t}\ MC}$$
$$\mu_{CR\ QCD} = N^{2tag}_{CR\ QCD} / N^{1tag}_{CR\ QCD}$$
$$N^{2tag}_{SR\ QCD\ est} = \mu_{CR\ QCD} N^{1tag}_{SR\ QCD}$$

- Use the same analysis region as those used for ggF non-resonant analysis
- Uncertainty includes data statistics, ttbar statistics and QCD scale factor uncertainty.



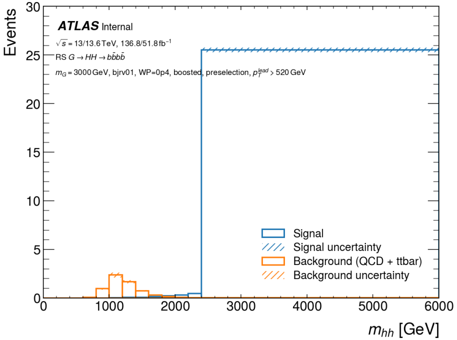
Significance Definition

- Data-driven QCD background has statistical uncertainties from the data sample itself, the $t\bar{t}$ subtraction, and the determination of the transfer factor.
- If we ignore these uncertainties, we would overestimate the sensitivity, especially in the low-statistics bins at high mass region.

Asimov significance with background uncertainty

$$Z_i = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right) - \frac{b^2}{\sigma_b^2}\ln\left(1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right)\right]}, Z = \sqrt{\sum_i^{bins} Z_i^2}$$

  - Bin-by-bin significance using m_{hh} distribution
  - Includes background statistical uncertainty σ_b
  - Combined in quadrature over all bins
- Adaptive rebinning:
  - High−mass tail has large statistical fluctuations
  - Merge tail bins until $\sigma_\mathrm{b}/b < 30\%$



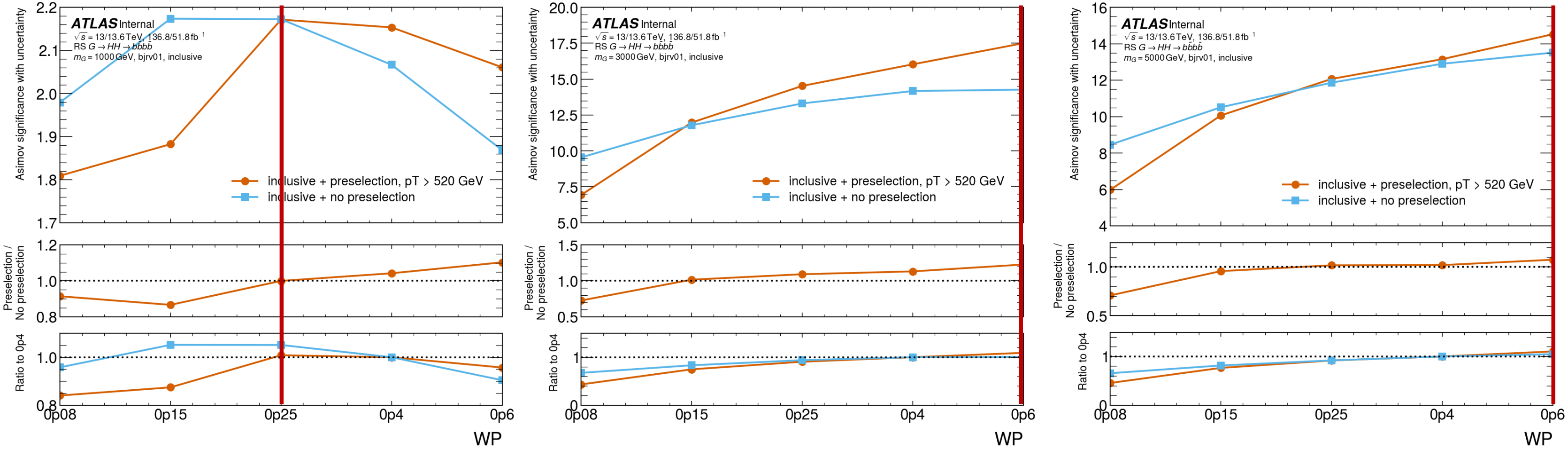
WP Optimization

- Optimal WP depends on the resonance mass
- WP 0p4 gives robust performance across all mass points
- Maximum sensitivity loss is $\lesssim 20\%$
- **Fix GN3X WP to 0.4%**

Optimal WP at 1TeV : 0.25%

Optimal WP at 3TeV : 0.6%

Optimal WP at 5TeV : 0.6%

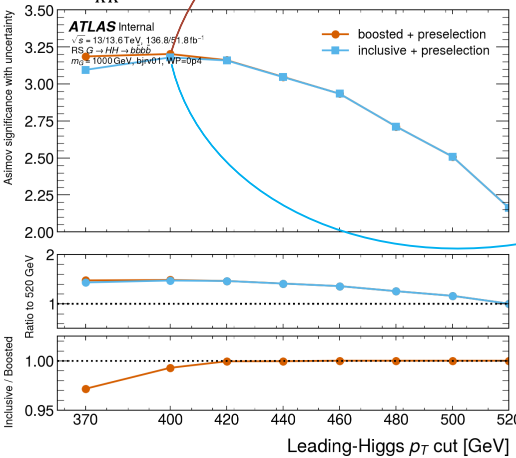


Trigger Strategy

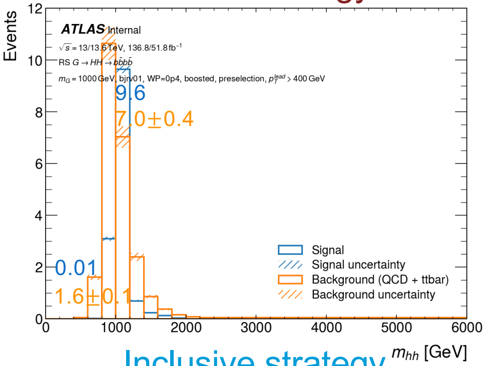
The boosted strategy performs better at all mass points, particularly at low p_T thresholds

$|\Delta\eta_{HH}| < 1.5$

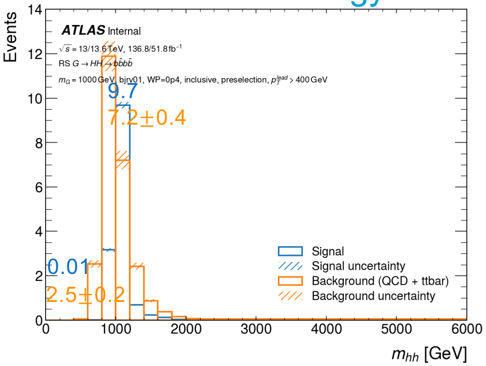
$m_{G^*_{KK}} = 1$ TeV, WP=0p4

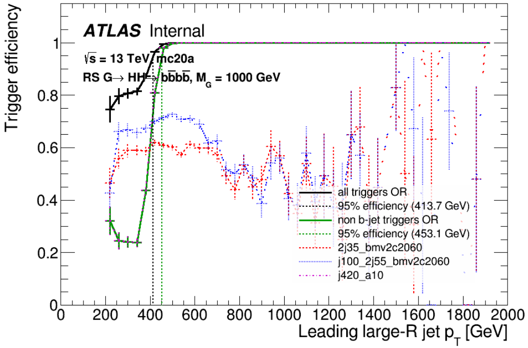


Boosted stratrgy



Inclusive strategy

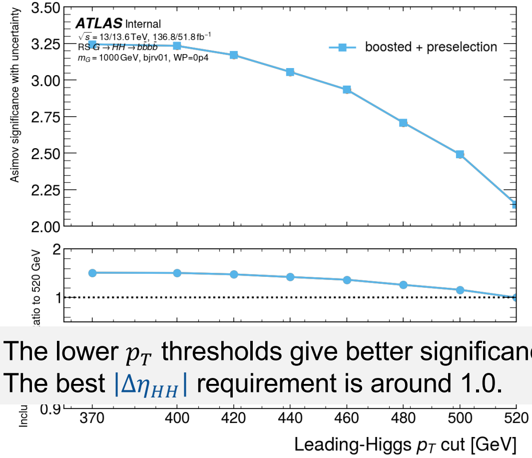


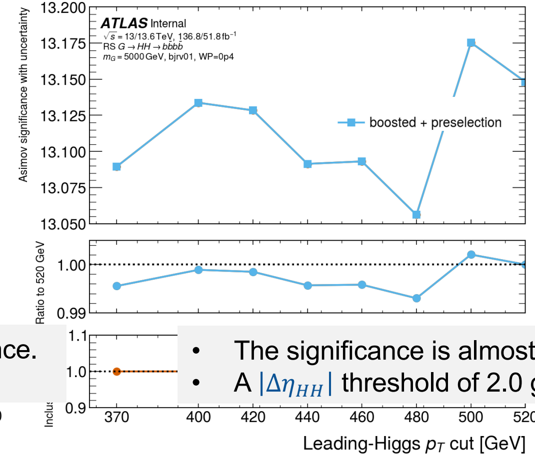


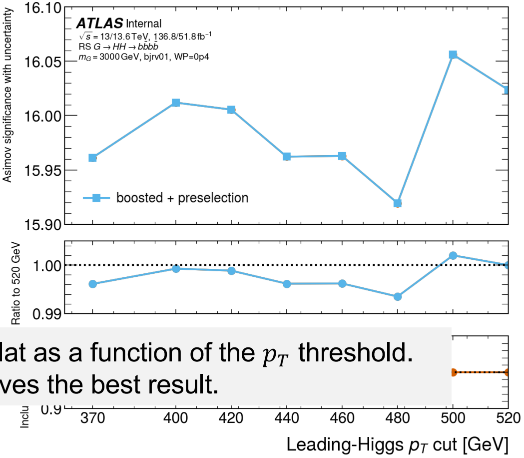
- The b-jet trigger mainly increases the low-mass background.
- It improves signal acceptance at low p_T, but the high-mass signal acceptance is already close to 100%.
- **Use the boosted trigger strategy**

Preselection

- Optimize leading-Higgs p_T and $|\Delta\eta_{hh}|$ cut
- $p_T^{ufo} > 400$ GeV gives robust performance across mass points
- Optimal $|\Delta\eta_{hh}|$ becomes looser at higher mass
- **Choose $p_T^{ufo} > 400$ GeV and $|\Delta\eta_{hh}| < 1.5$**







- The lower p_T thresholds give better significance.
- The best $|\Delta\eta_{HH}|$ requirement is around 1.0.

- The significance is almost flat as a function of the p_T threshold.
- A $|\Delta\eta_{HH}|$ threshold of 2.0 gives the best result.

Final Selection

Three independent scan conditions : WP × trigger strategy × preselection

- WP :
  - 0.4 %
- trigger strategy :
  - boosted (Large-R jet trigger only)
- preselection
  - Leading Higgs $p_T^{ufo} > 400$ GeV
    - 1 TeV significance reaches pleateau
    - High-mass sensitivity is almost unchanged with threshold
  - $|\Delta\eta_{hh}| < 1.5$
    - Intermediate value

SR Optimization

- Keep the current functional form and optimize numerical parameters only
  - Signal distributions are approximately elliptical
  - Enables direct comparison with the ggF non-resonant analysis

SR :

$$\left(\frac{m_{h1} - c_1}{a}\right)^2 + \left(\frac{m_{h2} - c_2}{b}\right)^2 \leq \textit{SR BOUND},$$

$$b = \begin{cases} b_{high} & if \;\; m_{h2} \geq c_2 \\ b_{low} & if \;\; m_{h2} < c_2 \end{cases}$$

CR :

$$100 < \sqrt{\left(\frac{m_{h1} - c_1}{0.1 \ln m_{h1}}\right)^2 + \left(\frac{m_{h2} - c_2}{0.1 \ln m_{h2}}\right)^2} \leq \textit{CR BOUND}$$

- Optimization metric
  - Same m_{hh} histogram-based significance as previous study
  - Same background estimation method

Best SR Definition

- Benchmark : 3 TeV signal sample
- Significance : +31% vs. default

Optimized SR

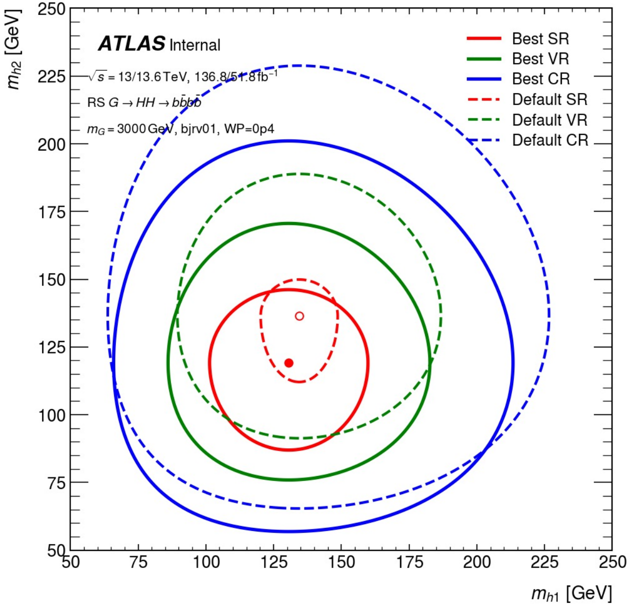
SR :

$$\left(\frac{m_{h1} - 130.6}{23.1}\right)^2 + \left(\frac{m_{h2} - 119.2}{b}\right)^2 \leq 1.6,$$

$$b = \begin{cases} 21.3 & if \;\; m_{h2} \geq 119.2 \\ 25.5 & if \;\; m_{h2} < 119.2 \end{cases}$$

CR :

$$100 < \sqrt{\left(\frac{m_{h1} - 130.6}{0.1 \ln m_{h1}}\right)^2 + \left(\frac{m_{h2} - 119.2}{0.1 \ln m_{h2}}\right)^2} \leq 154.3$$



Best SR
$c_1 = 130.6$, $c_2 = 119.2$
$a = 23.1$, $b_{low} = 25.5$, $b_{high} = 21.3$
SR bound = 1.6

Best CR
$p_1 = 0.1$, $p_2 = 0.1$
CR bound = 154.3

Best significance = 21.080107
Default significance = 16.011919
Improvement = 31.65%

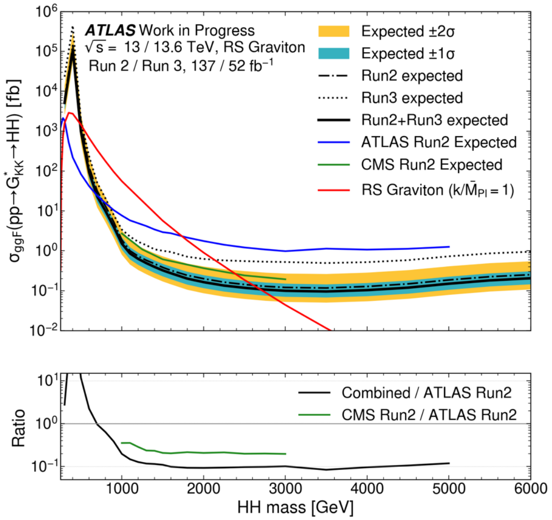
Apply the 3 TeV-optimized region to other samples :

- 1 TeV: −28%
- 1.5 TeV: −4%
- 3 TeV: +32%
- 4 TeV: +99%
- 5 TeV: +56%
- 6 TeV: +151%

Summary

- Run 2 + partial Run 3 data for high-mass resonant $HH \rightarrow b\bar{b}b\bar{b}$ search
- GN3X and optimized event selection
  - WP 0.4% + boosted trigger + $p_T^{ufo} > 400$GeV + $|\Delta\eta_{hh}| < 1.5$
- SR optimization
  - 3 TeV optimized SR gives significant gains in the high-mass region
  - Common SR adopted across all mass points

→ Improved sensitivity to high-mass resonant



GN2X achieved ×2~8 improvement in sensitivity with statistical uncertainties only

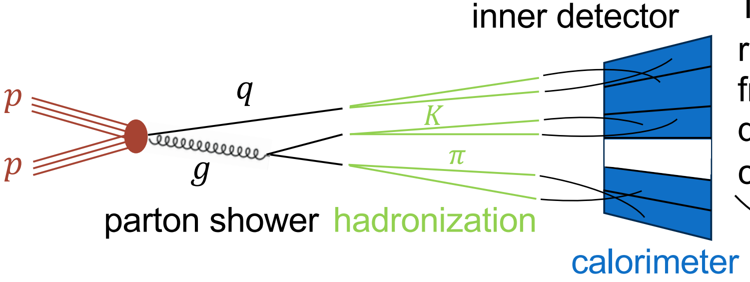
Next step :

- Perform the statistical analysis, including the systematic uncertainties, and evaluate the final expected sensitivity with GN3X.

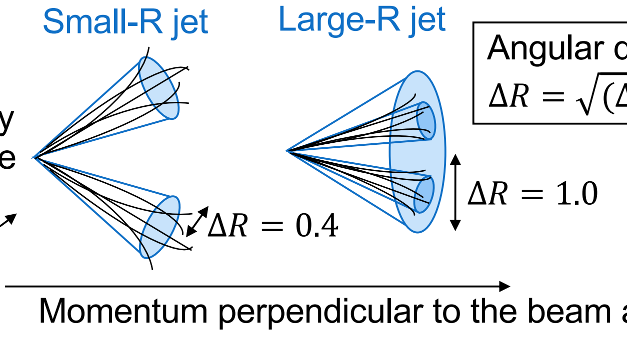
BackUp

Jet Reconstruction

Jet reconstruction



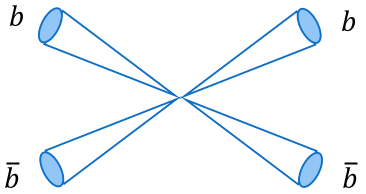
The jet is reconstructed from the energy deposited in the calorimeter.



Angular distance
$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

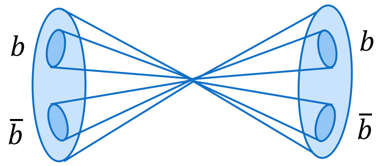
Analysis channels

Target low resonance mass ($m_{G^*_{KK}} < 1\ \mathrm{TeV}$)



4 small-R jets

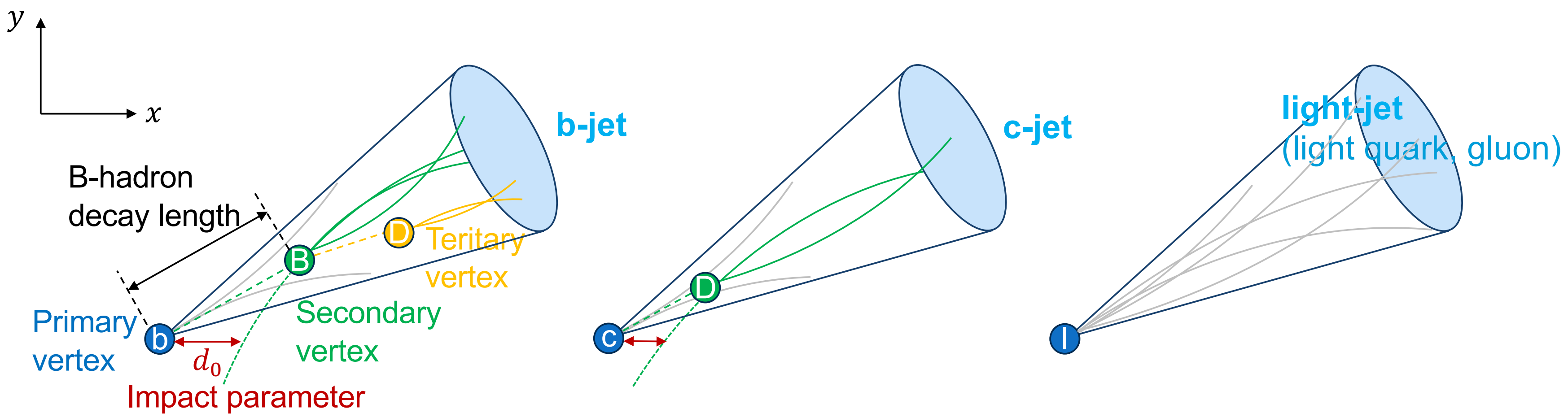
Target high resonance mass ($1\ \mathrm{TeV} \leq m_{G^*_{KK}}$)



2 large-R jets

Focus on this channel

Jet Flavour Tagging



- Jet kinematics
- Jet topology
- Impact parameters
- Track vertices
- Track correlations

} Jet flavour tagging algorithm → Probability that the jet is

- b-jet : p_b
- c-jet : p_c
- light-jet : p_{light}

JES / JMS

- Detector-level jets do **not exactly match the true jet**
- Response :

$$R_V = \left\langle \frac{V^{reco}}{V^{true}} \right\rangle$$

  - If $R_{p_T} = 0.96$, reconstructed p_T is 96% of true p_T on average
- Correction :

$$c_V = \frac{1}{R_V}$$

  - If $R_{p_T} = 0.96$, $c_{\text{JES}} = \frac{1}{0.96} \simeq 1.042 \rightarrow$ increases the jet p_T by about **4.2%**

JES (Jet Energy Scale)	**JMS (Jet Mass Scale)**
Corrects **jet energy /** p_T	Corrects **jet mass**
Addresses energy & momentum response	Addresses mass response
$E^{reco} = c_{\text{JES}} E^0$	$m^{reco} = c_{\text{JMS}} c_{\text{JES}} m^0$

$$E^2 = p^2 + m^2, \quad p_T = \frac{\sqrt{E^2 - m^2}}{\cosh \eta}$$

When JMS changes the mass,

$$m \rightarrow c_{\text{JMS}} m$$

while keeping E fixed, the jet p_T changes accordingly.

BJR10

- In semi-leptonic b-decays,

$$b \to \mu + \nu + X$$

  - Neutrino : not directly detected
  - Muon : does not deposit all its energy in the calorimeter
  - Therefore, typically **b-jet energy is underestimated** : $p_T^{UFO} < p_T^{true}$
- **BJR10 predict the missing-energy correction**

$$\lambda = \frac{p_T^{Truth}}{p_T^{UFO}} \;\to\; p_T^{corrected} = \lambda\, p_T^{UFO}$$

  - Example :

$$p_T^{UFO} = 400\ \mathrm{GeV}, \qquad p_T^{Truth} = 500\ \mathrm{GeV}$$

$$\lambda = \frac{500}{400} = 1.25 \;\Rightarrow\; p_T^{corrected} = 500\ \mathrm{GeV}$$

- **Transformer encoder** learns from the jet's **tracks, constituents, and kinematics** to estimate how much energy is missing.
- Better jet energy resolution $\to$ better invariant−mass resolution
  - A sharper jet-energy measurement can make the m_{HH} or resonance-mass peak **narrower**, potentially allowing a more focused signal region.

Trigger Conditions

Trigger bucketing

year	Boosted triggers	Resolved b-jet triggers
2016	• HLT_j420_a10_lcw_L1J100	• HLT_2j35_bmv2c2060_split_2j35_L14J15.0ETA25 • HLT_j100_2j55_bmv2c2060_split
2017	• HLT_j420_a10t_lcw_jes_40smcINF_L1J100 • HLT_2j330_a10t_lcw_jes_40smcINF_L1J100	• HLT_2j15_gsc35_bmv2c1040_split_2j15_gsc35_boffperf_split_L14J15.0ETA25 • HLT_j110_gsc150_boffperf_split_2j35_gsc55_bmv2c1070_split_L1J85_3J30
2018	• HLT_j420_a10t_lcw_jes_35smcINF_L1J100 • HLT_2j330_a10t_lcw_jes_35smcINF_L1J100	• HLT_2j35_bmv2c1060_split_2j35_L14J15.0ETA25 • HLT_j110_gsc150_boffperf_split_2j45_gsc55_bmv2c1070_split_L1J85_3J30
2022	• HLT_j420_35smcINF_a10sd_cssk_pf_jes_ftf_preselj225_L1J100 • HLT_2j330_35smcINF_a10sd_cssk_pf_jes_ftf_presel2j225_L1J100	• HLT_j80c_020jvt_j55c_020jvt_j28c_020jvt_j20c_020jvt_SHARED_2j20c_020jvt_bdl1d77_pf_ftf_presel2c20XX2c20b85_L1J45p0ETA21_3J15p0ETA25 • (HLT_2j35c_020jvt_bdl1d60_2j35c_020jvt_pf_ftf_presel2j25XX2j25b85_L14J15p0ETA25)
2023	• HLT_j420_35smcINF_a10sd_cssk_pf_jes_ftf_preselj225_L1J100 • HLT_2j330_35smcINF_a10sd_cssk_pf_jes_ftf_presel2j225_L1J100	• HLT_j80c_020jvt_j55c_020jvt_j28c_020jvt_j20c_020jvt_SHARED_2j20c_020jvt_bgn177_pf_ftf_presel2c20XX2c20b85_L1J45p0ETA21_3J15p0ETA25 • HLT_j75c_020jvt_j50c_020jvt_j25c_020jvt_j20c_020jvt_SHARED_2j20c_020jvt_bgn177_pf_ftf_presel2c20XX2c20b85_L1J45p0ETA21_3J15p0ETA25 • (HLT_2j35c_020jvt_bgn160_2j35c_020jvt_pf_ftf_presel2j25XX2j25b85_L14J15p0ETA25)

(reference trigger ; not included in pass_bjet_triggers)

Trigger Efficiency Study

- Samples used:
  - Spin-2 graviton signal ($m_G = 1000, m_G = 2000, m_G = 3000, m_G = 6000$)
- Triggers :
  - Large-R jet triggers, b-jet triggers
- Kinematics :
  - Leading large-R jet p_T, mass
  - Default, bjR10v00, bjR10v01
- Easyjet Ntuple Production
  - Production tag: fake_0p50p0
  - Submission scripts: scripts
  - Triggers: triggers-HH4b.yaml
  - RunConfig:
    - Toggling do_trigger_filtering=false while keeping all other settings identical.
    - Used trigger decision flags (trigPassed_*) to access individual trigger chains

Trigger efficiency :

$$\varepsilon = \frac{\mathrm{N(w/\ trigger)}}{\mathrm{N(w/o\ trigger)}}$$

Leading large-R jet p_T $(m_G = 1000)$

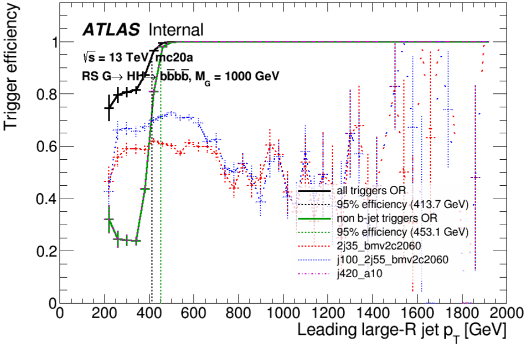
All results : link

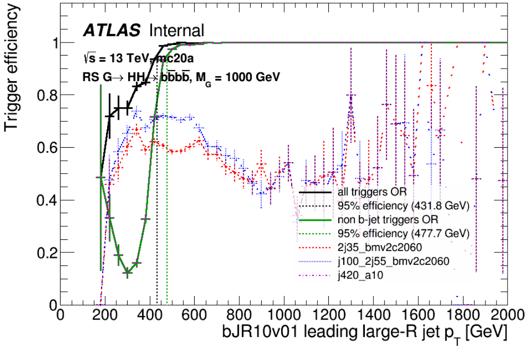
Clean turn-on with a clear gain from b-jet triggers

Default

bjR10v01

mc20a





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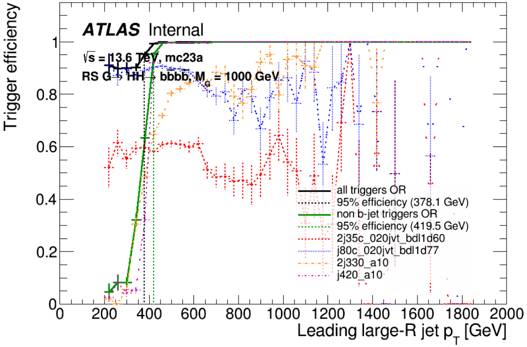
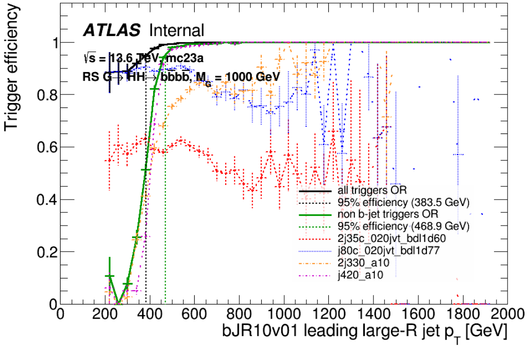




efficiency plateau threshold ~ 480 GeV

Leading large-R jet p_T $(m_G = 3000)$

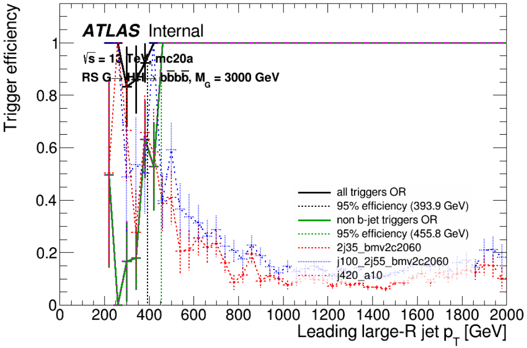
All results : link

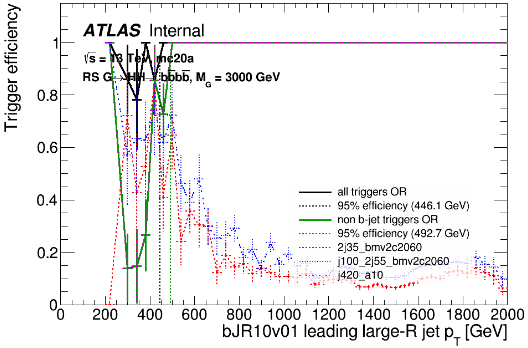
Irregular turn-on and small plateau dips make the 95% threshold less robust

Default

bjR10v01

mc20a





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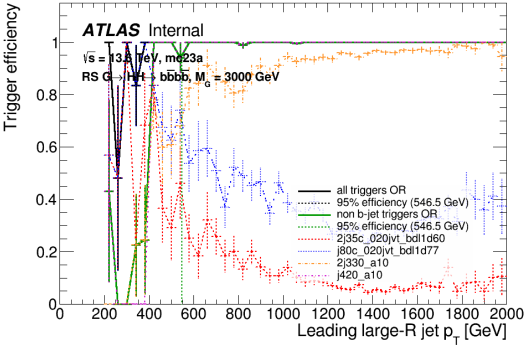
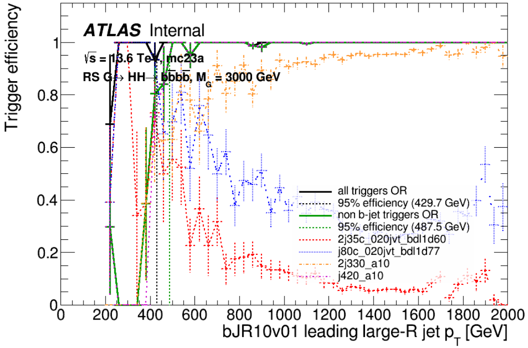




Leading large-R jet p_T ($m_G = 5000$)

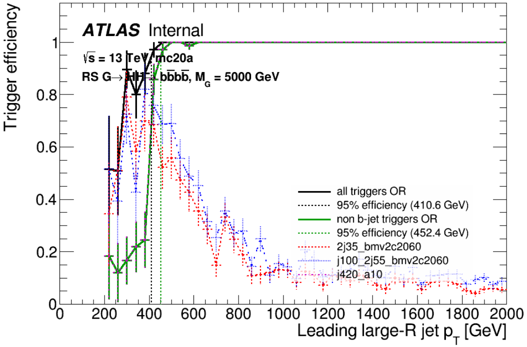
All results : link

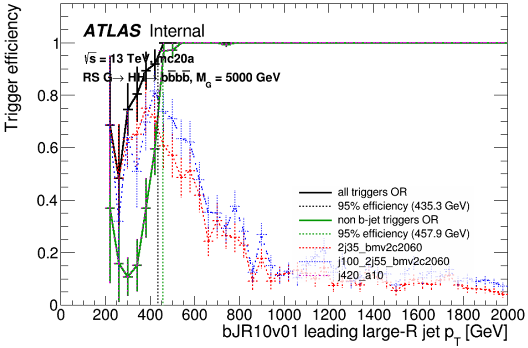
Irregular turn-on and plateau dips persist, but the overall trigger improvement remains visible

Default

bjR10v01

mc20a





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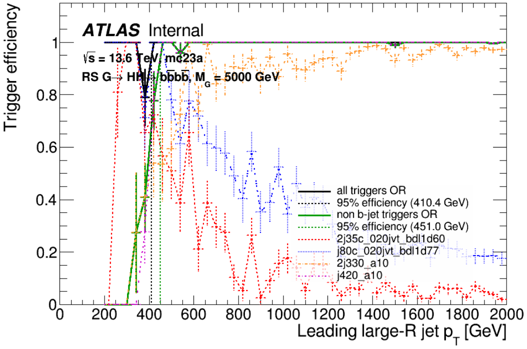
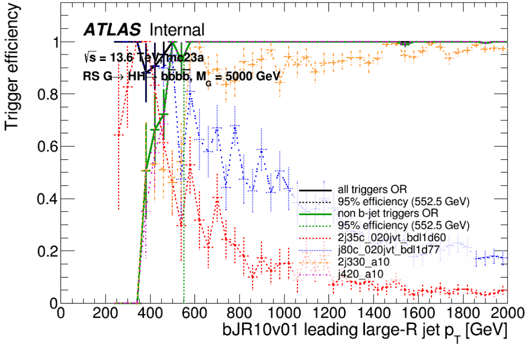




Flat-Mass QCD WP

GN3X Discriminant

$$D_{Hb\bar{b}} = log\,\frac{p_{Hb\bar{b}}}{\sum_b f_b\,p_b + \sum_{h\neq Hb\bar{b}} f_h\,p_h}$$

- Probabilities for several jet classes : $p_{Hbb},\ p_{Hcc},\ p_{H\tau\tau},\ p_{QCD},\ p_{top},\ p_W, \ldots$

Flat-Mass QCD Working Point

- A fixed threshold can have different QCD efficiencies at different m_J.
- Change the cut with m_J, p_T so that the QCD efficiency stays flat → reducing mass sculpting.

$$D_{Hb\bar{b}} > D_{cut}(m_J, p_T)$$

so that

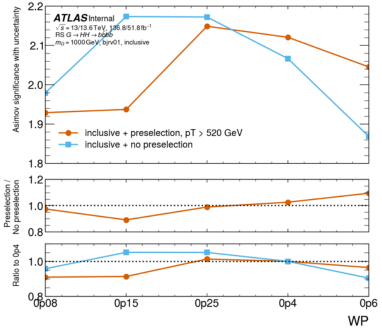
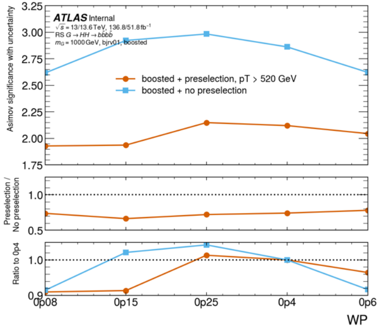
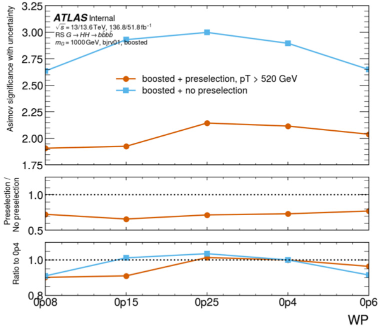
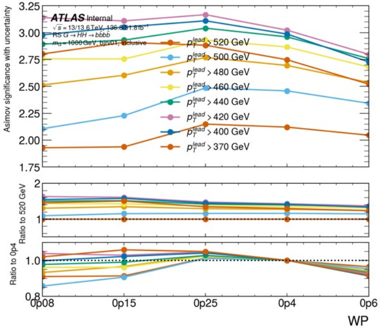
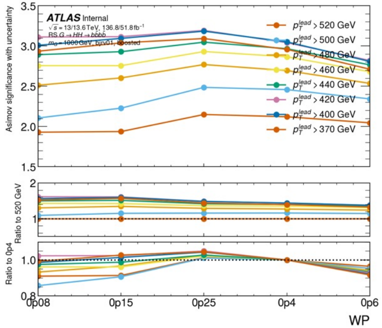
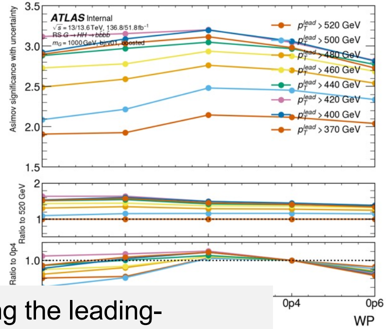
$$\epsilon_{QCD}(m_J, p_T) \simeq \text{constant}$$

- i.e. 0.15% WP mean only about 0.15% of QCD jets pass the tagger selection

$m_{G^*_{KK}} = 1$ TeV, dEta_hh_max = 1.5

The optimal WP is around 0p25.

For the boosted strategy, no preselection gives a higher significance.

baseline	pass_boosted & pass_boosted_ggF		pass_boosted & pass_boosted_VBF
trigger	Inclusive	Boosted	Boosted
Preselection vs No preselection			
Preselection: leading Higgs p_T^{ufo} scan			

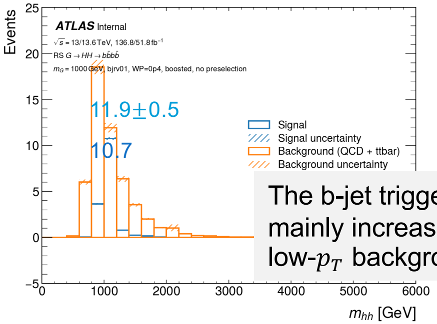
Lowering the leading-Higgs p_T threshold generally improves the significance.

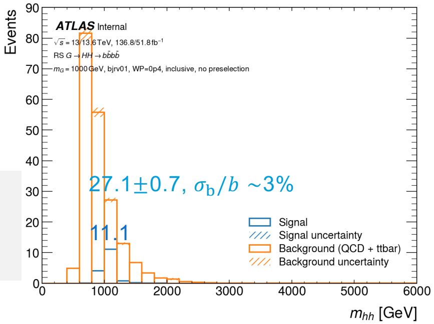
m_{hh} Distribution

Tight WPs reduce the background but increase the relative background uncertainty. Therefore, the preselection benefit is reduced when background uncertainty is included.

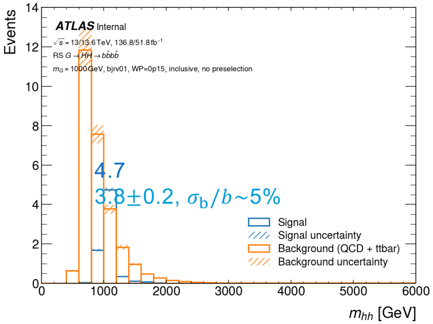
baseline	pass_boosted & pass_boosted_ggF		
trigger, WP	Boosted, WP=0p4	Inclusive, WP=0p4	Inclusive, WP=0p15

No preselection

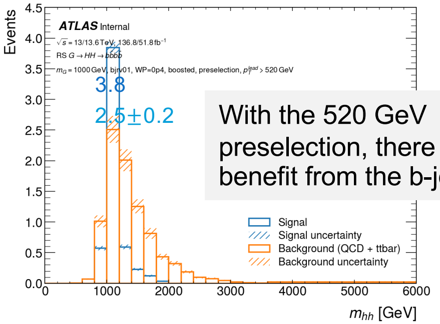




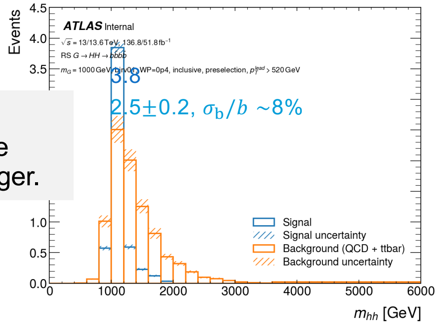
The b-jet trigger mainly increases the low-p_T background.

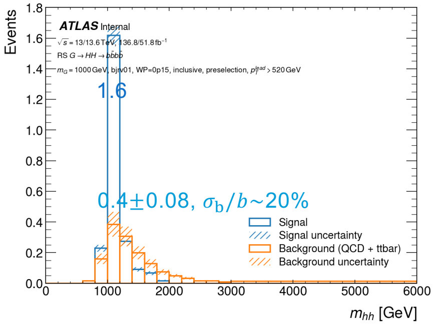


Preselection: leading Higgs $p_T^{ufo} > 520$



With the 520 GeV preselection, there is little benefit from the b-jet trigger.

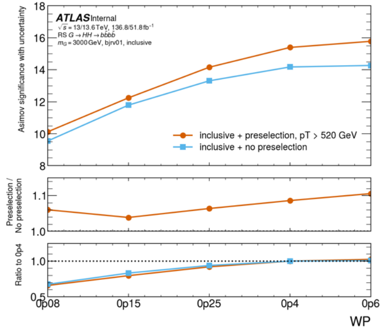




$m_{G^*_{KK}}$ = 3 TeV, dEta_hh_max = None

The significance increases toward looser WPs.
The optimal WP is around 0p6.

The 520 GeV preselection becomes beneficial.

<table>
<tr><th>baseline</th><th colspan="2">pass_boosted & pass_boosted_ggF</th><th>pass_boosted & pass_boosted_VBF</th></tr>
<tr><th>trigger</th><th>Inclusive</th><th>Boosted</th><th>Boosted</th></tr>
<tr><td>Preselection vs No preselection</td>
<td>
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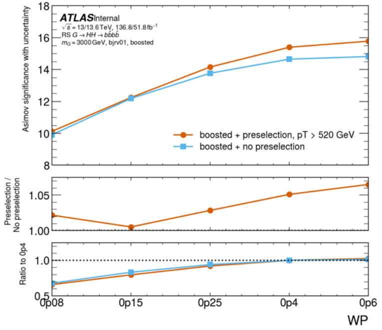
<td>
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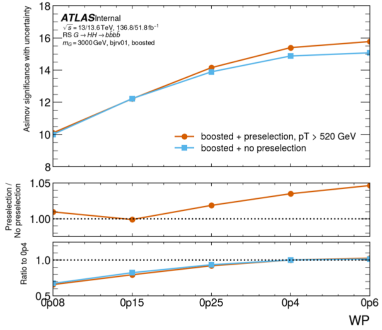
<td>
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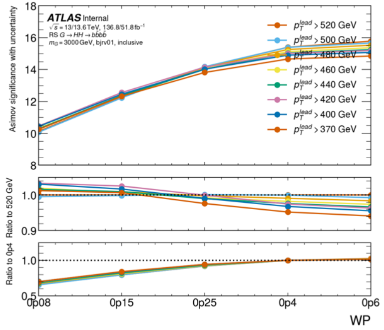
<tr><td>Preselection: leading Higgs p_T^{ufo} scan</td>
<td>
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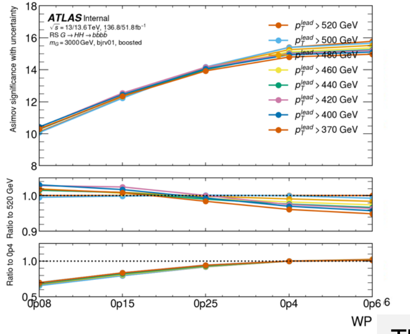
<td>
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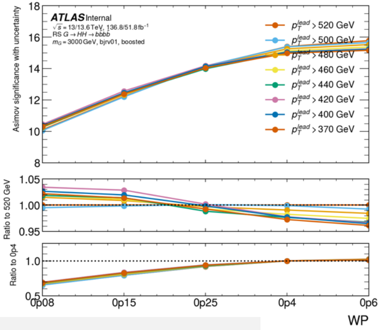
<td>
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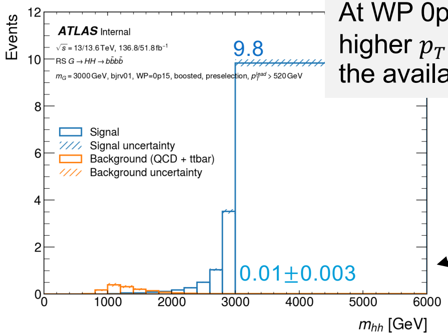
The significance is almost independent of the p_T threshold.

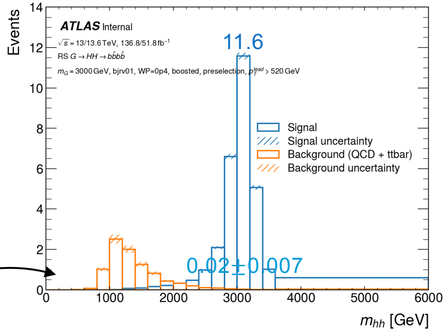
m_{hh} Distribution

baseline	pass_boosted & pass_boosted_ggF	
trigger, WP	Boosted, WP=0p15	Boosted, WP=0p4

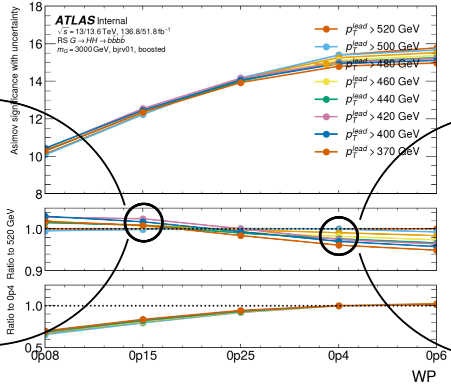
Preselection: leading Higgs $p_T^{ufo} > 520$



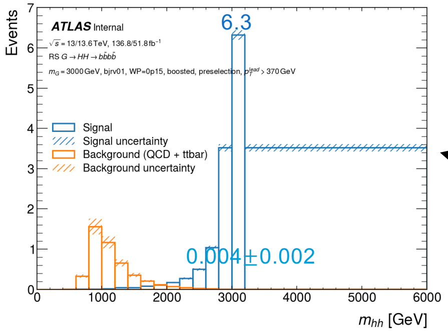
At WP 0p15, the higher p_T threshold can reduce the available shape information.

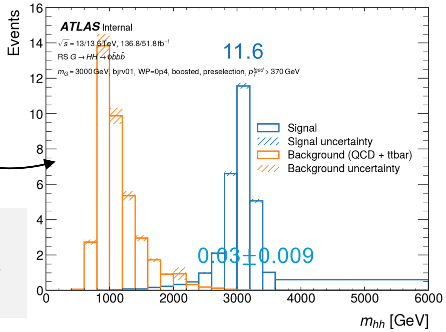


Preselection: leading Higgs p_T^{ufo} scan



Preselection: leading Higgs $p_T^{ufo} > 370$



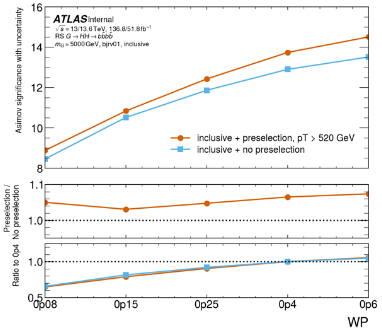
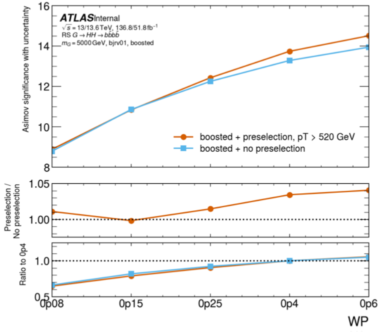
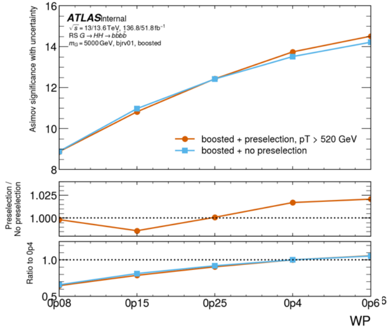
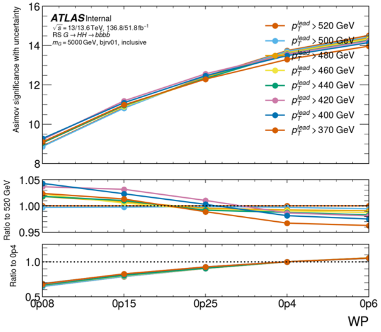
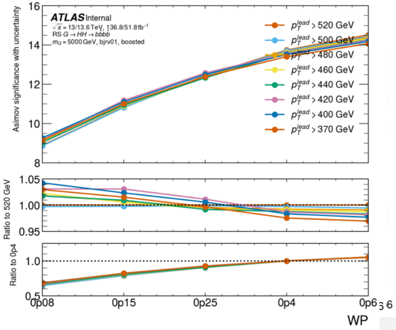
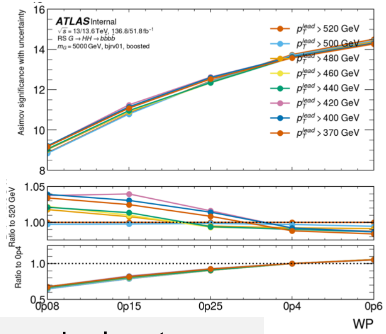


At WP 0p4, lowering the threshold mainly increases the background.

$m_{G_{KK}^{*}}$ = 5 TeV, dEta_hh_max = None

The optimal WP is around 0p6.

The 520 GeV preselection gives a slightly higher significance.

baseline	pass_boosted & pass_boosted_ggF		pass_boosted & pass_boosted_VBF
trigger	Inclusive	Boosted	Boosted
Preselection vs No preselection			
Preselection: leading Higgs p_T^{ufo} scan			

The significance is almost independent of the p_T threshold.

WP Scan Summary

Fixed condition :

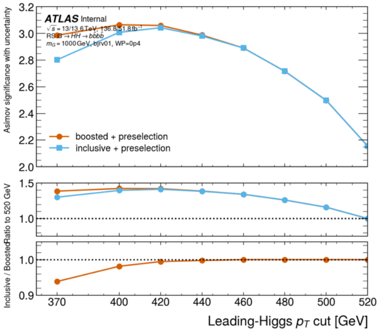
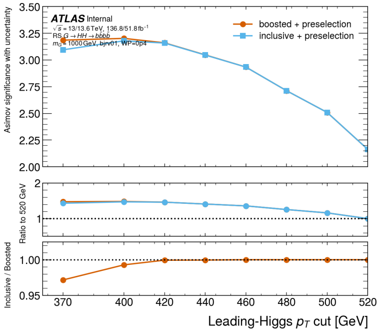
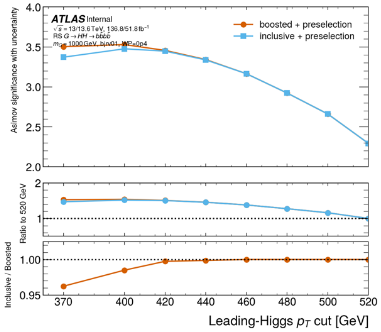
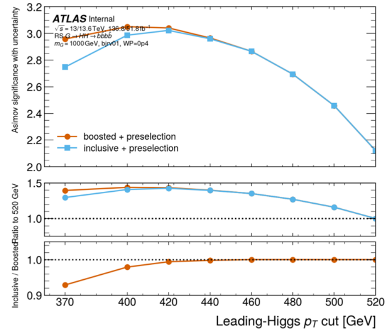
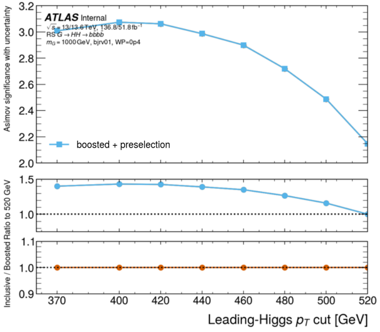
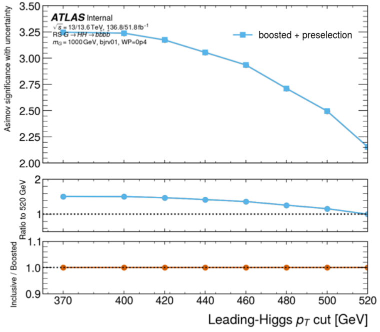
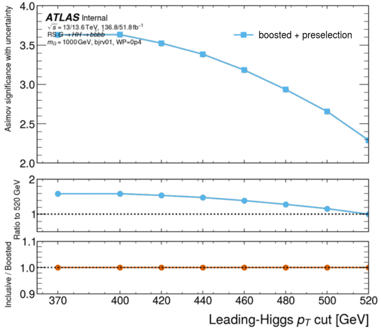
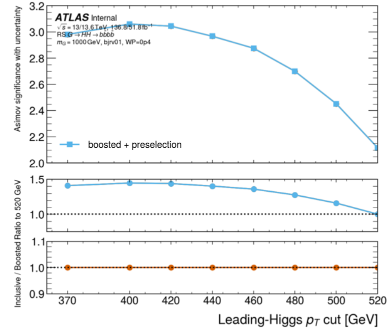
- WP : **0p4**
  - The optimal WP depends on the resonance mass
  - Sensitivity loss: ≤ ~20%
  - Consistenty with previous study and VBF non-resonant analysis

Scan remaining conditions :

- baseline
- trigger strategy
- preselection

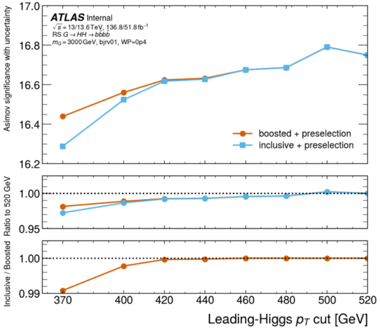
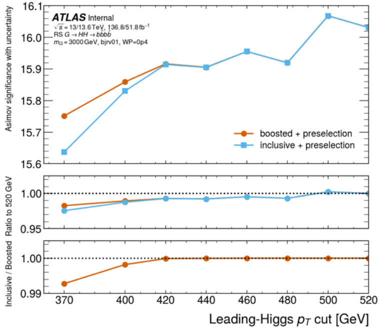
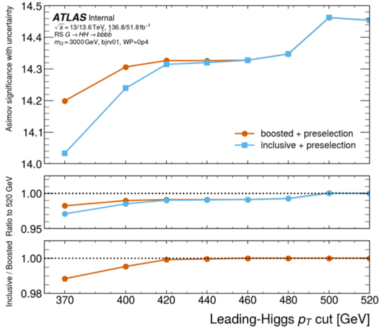
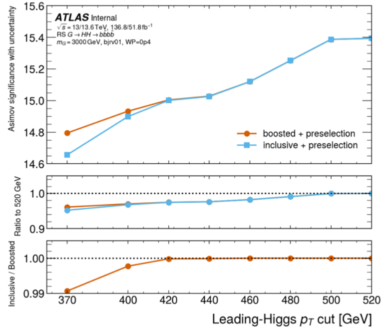
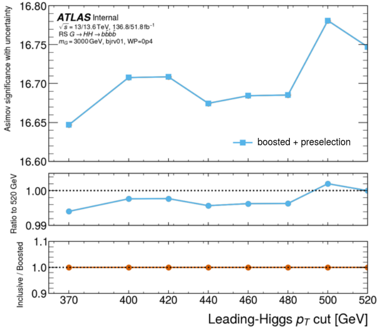
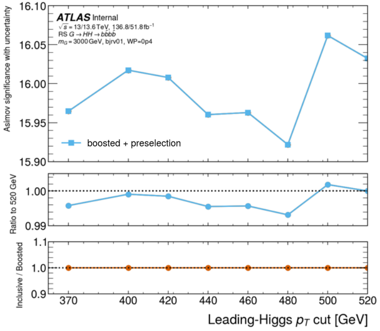
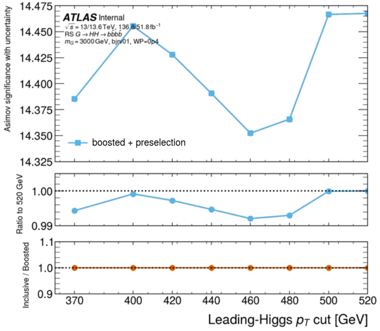
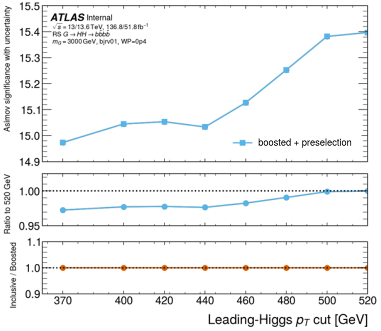
$m_{G^*_{KK}} = 1$ TeV, WP=0p4

- The lower p_T thresholds give better significance.
- The best $|\Delta\eta_{HH}|$ requirement is around 1.0.
- The boosted strategy performs better, especially at low p_T.
- The two baseline selections give very similar results.

baseline	$\|\Delta\eta_{HH}\| < 2.0$	$\|\Delta\eta_{HH}\| < 1.5$	$\|\Delta\eta_{HH}\| < 1.0$	None
pass_boosted & pass_boosted_ggF				
pass_boosted & pass_boosted_VBF				

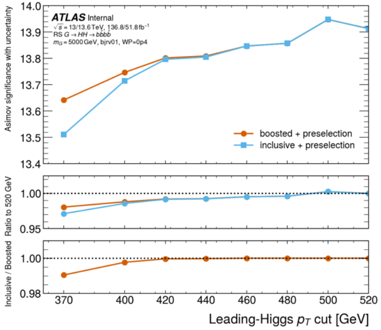
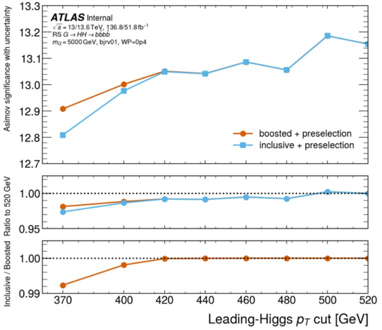
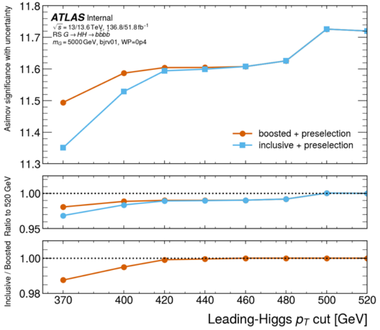
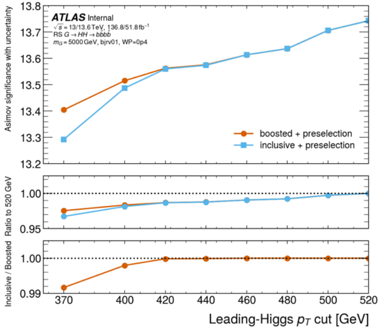
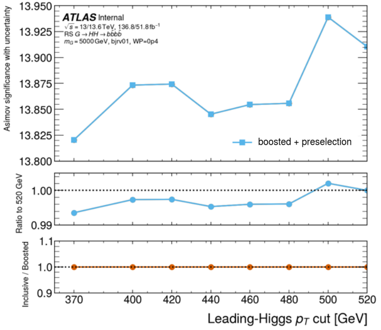
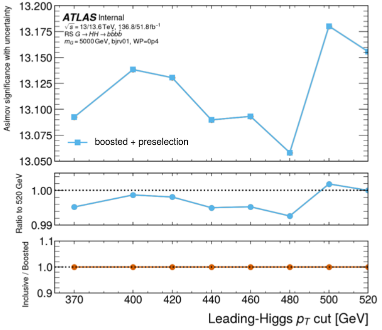
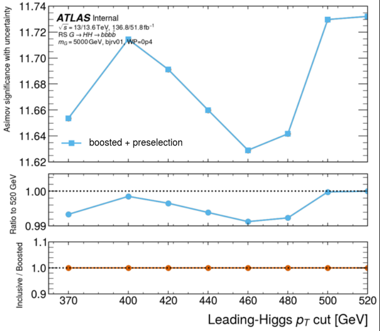
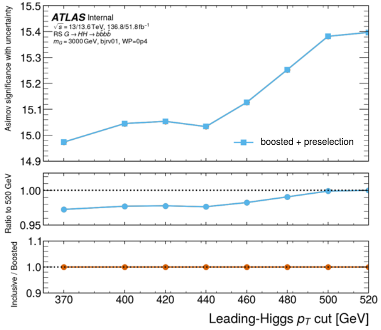
$m_{G_{KK}^*} = 3$ TeV, WP=0p4

- The significance is almost flat as a function of the p_T threshold.
- A $|\Delta\eta_{HH}|$ threshold of 2.0 gives the best result.
- The boosted strategy performs better, especially at low p_T.
- The two baselines give very similar results.

baseline	$\lvert\Delta\eta_{HH}\rvert < 2.0$	$\lvert\Delta\eta_{HH}\rvert < 1.5$	$\lvert\Delta\eta_{HH}\rvert < 1.0$	None
pass_boosted & pass_boosted_ggF				
pass_boosted & pass_boosted_VBF				

$m_{G^*_{KK}} = 5$ TeV, WP=0p4

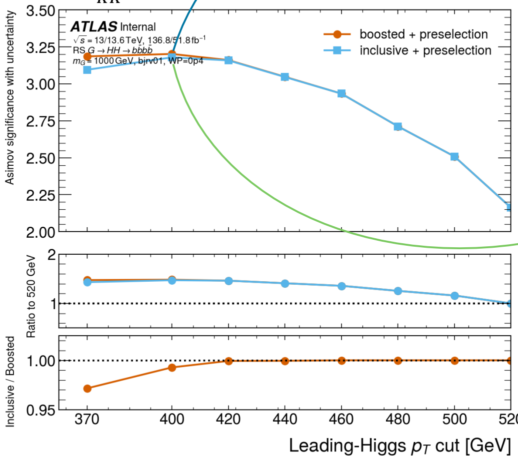
- The p_T dependence is also very small at 5 TeV.
- The best $|\Delta\eta_{HH}|$ requirement is around 2.0 or no cut.
- The boosted strategy performs better, especially at low p_T.
- The two baselines give very similar results.

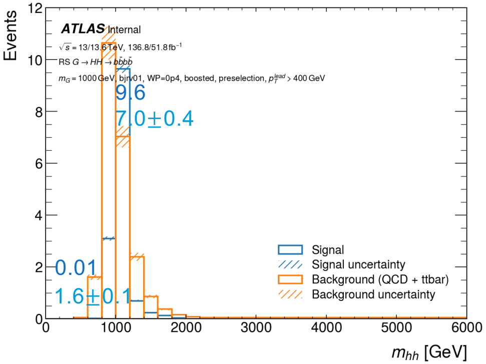
baseline	$\lvert\Delta\eta_{HH}\rvert < 2.0$	$\lvert\Delta\eta_{HH}\rvert < 1.5$	$\lvert\Delta\eta_{HH}\rvert < 1.0$	None
pass_boosted & pass_boosted_ggF				
pass_boosted & pass_boosted_VBF				

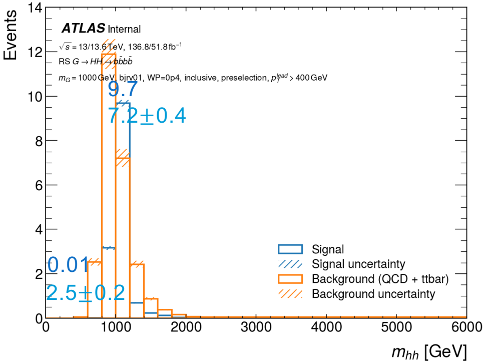
Trigger Strategy

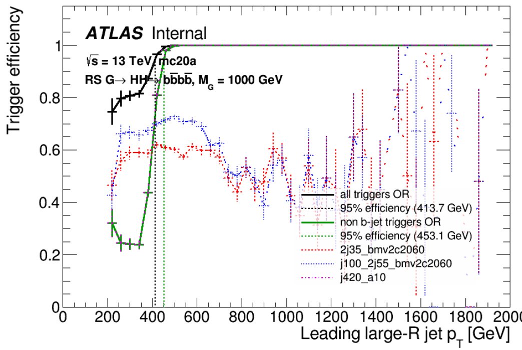
The boosted strategy performs better at all mass points, particularly at low p_T thresholds

pass_boosted & pass_boosted_ggF
$|\Delta\eta_{HH}| < 1.5$
$m_{G^*_{KK}} = 1$ TeV, WP=0p4







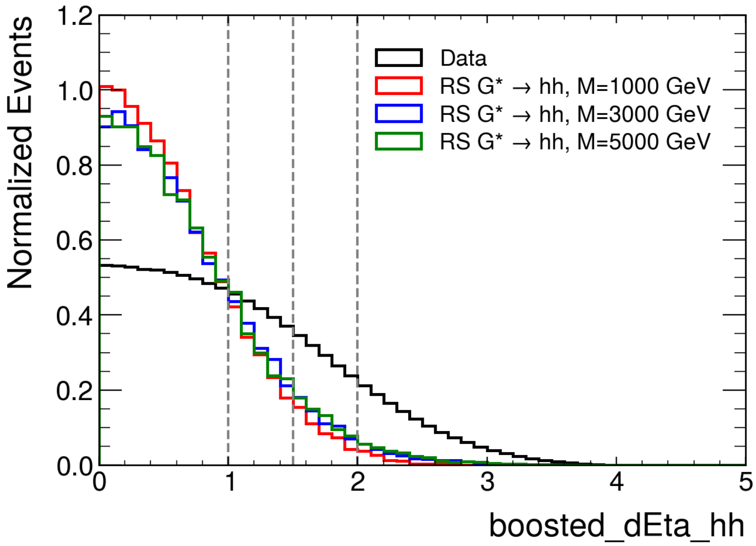


- The b-jet trigger mainly increases the low-mass background.
- It improves signal acceptance at low p_T, but the high-mass signal acceptance is already close to 100%.
- Therefore, the b-jet trigger gives little sensitivity gain.

$|\Delta\eta_{hh}|$ Cut

- At 1 TeV, $|\Delta\eta_{hh}| < 1.5$ gives the best result.
- At higher masses, looser requirements are preferred.

sample	$\lvert\Delta\eta_{HH}\rvert$	Total events	Lost events	Loss [%]	Efficiency [%]
data	1.0	19023622	9305058	48.91	51.09
data	1.5	19023622	5349395	28.12	71.88
data	2.0	19023622	2568917	13.50	86.50
$m_{G^*_{KK}} = 1$ TeV	1.0	13146	2686	20.43	79.57
$m_{G^*_{KK}} = 1$ TeV	1.5	13146	750	5.71	94.29
$m_{G^*_{KK}} = 1$ TeV	2.0	13146	140	1.06	98.94
$m_{G^*_{KK}} = 3$ TeV	1.0	16981	4176	24.59	75.41
$m_{G^*_{KK}} = 3$ TeV	1.5	16981	1425	8.39	91.61
$m_{G^*_{KK}} = 3$ TeV	2.0	16981	390	2.30	97.70
$m_{G^*_{KK}} = 5$ TeV	1.0	16939	4204	24.82	75.18
$m_{G^*_{KK}} = 5$ TeV	1.5	16939	1526	9.01	90.99
$m_{G^*_{KK}} = 5$ TeV	2.0	16939	453	2.67	97.33



- At 1 TeV, tight cut removes a relatively large amount of background while retaining a signal.
- At high mass, the background is already small, so retaining signal acceptance becomes more important.

Final Selection

Four independent scan axes : WP × baseline × trigger strategy × preselection

- WP : 0p4
- baseline : pass_boosted & pass_boosted_VBF
- trigger strategy : boosted (Large-R jet trigger only)
- preselection
  - Leading Higgs $p_T^{ufo} > 400$ GeV
    - 1 TeV significance reaches pleateau
    - High-mass sensitivity is almost unchanged with threshold
  - $|\Delta\eta_{hh}| < 1.5$
    - Intermediate value