Search for resonant pair production of Higgs bosons in the 4b final state 13 TeV at ATLAS

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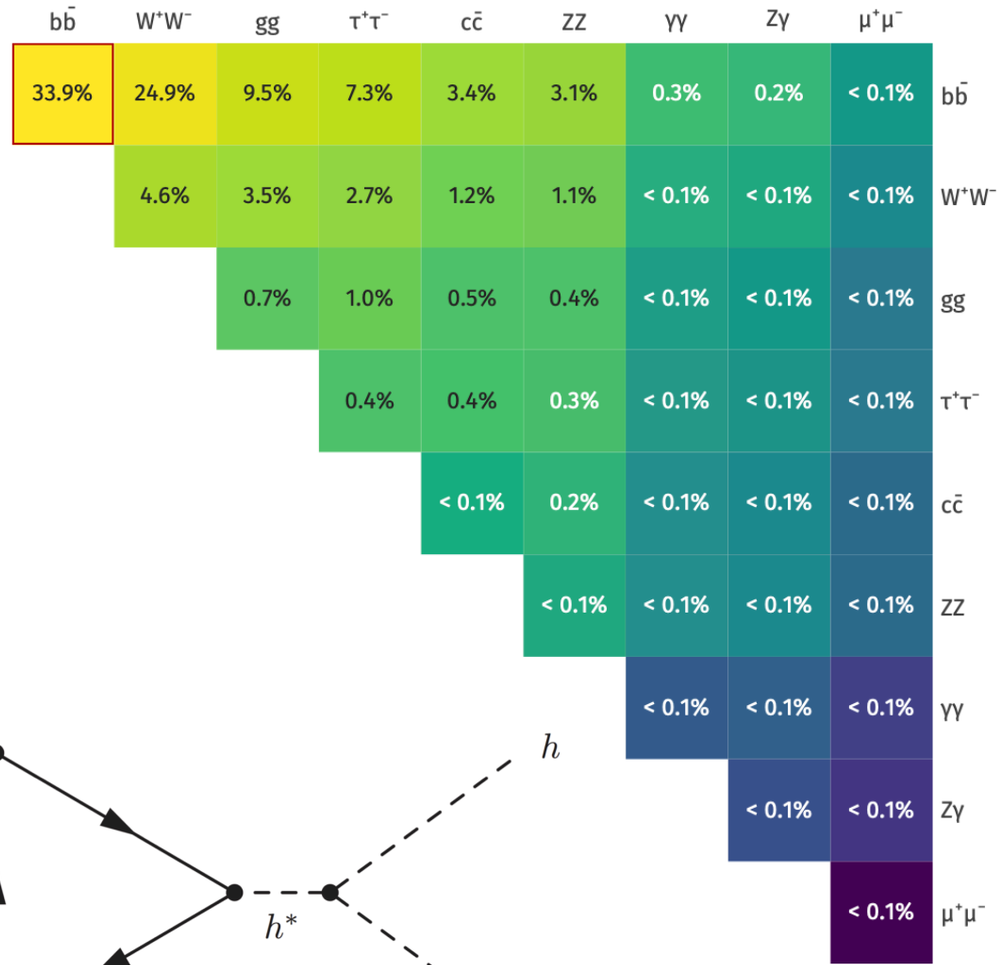
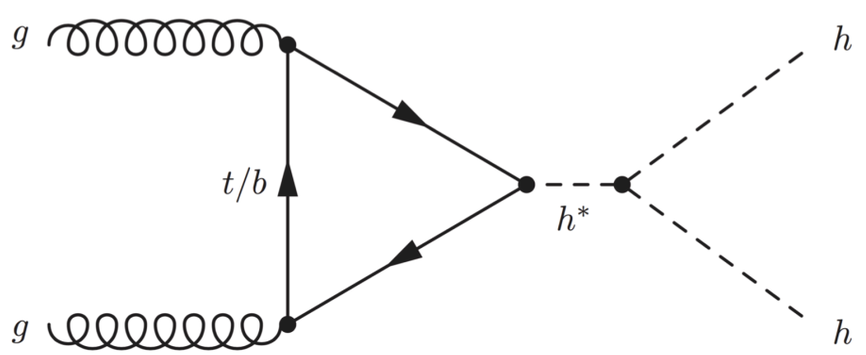
Introduction

- Search for Higgs pair production is a major LHC physics goal
- Many models of BSM physics predict enhanced rates of Higgs
  - New resonances decaying to Higgs boson pairs
    - KK graviton G_{KK}, extended Higgs sectors H, radions, ...
- H→bb (58% in SM)
  - Largest cross section in 4b final states
  - Possible to probe boosted regime
  - Challenging due to huge QCD background
  - This talk will focus on new resonances searches





Paper link

Analysis strategy

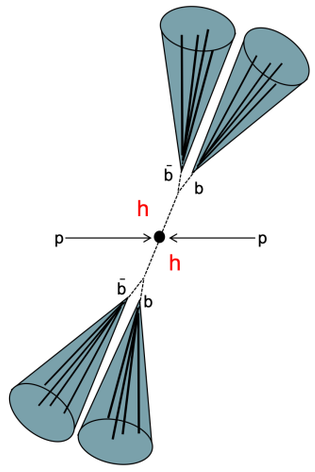
- Two complementary analyses

Resolved

Targets 260 GeV ≤ m_{HH} ≤ 1500 GeV

Demands 4 b-tagged anti-kT R=0.4 jets

$p_T > 40$ GeV, $|\eta| < 2.5$, $\varepsilon(b) = 70\%$W.P.



Boosted

Targets 800 GeV ≤ m_{HH} ≤ 3 TeV

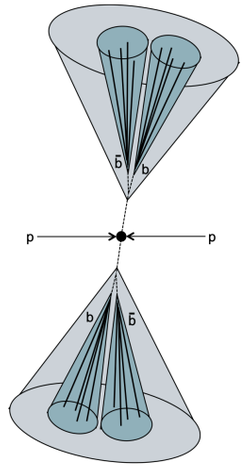
Demands 2 anti-k_T R=1.0 jets

$p_{T1} > 450$ GeV, $p_{T2} > 250$ GeV, $|\eta| < 2$

b-tagging performed using anti-k_T R=0.2 track-jets

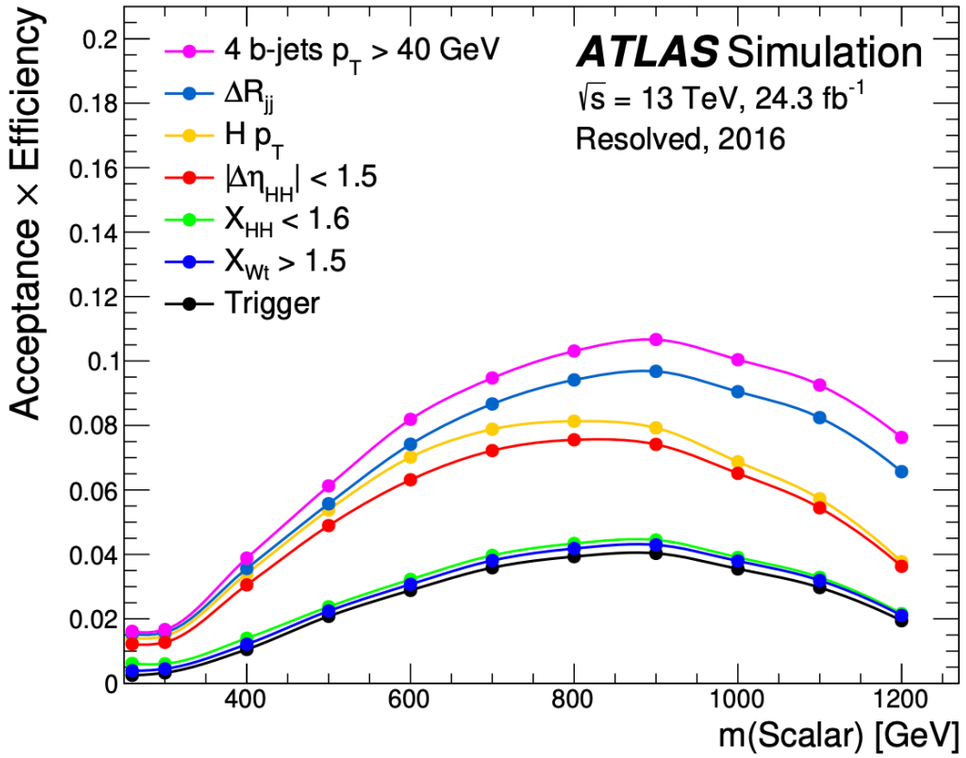
demand 1 or 2 b-tagged track-jets per large-R jet

Three orthogonal samples based on number of track jets

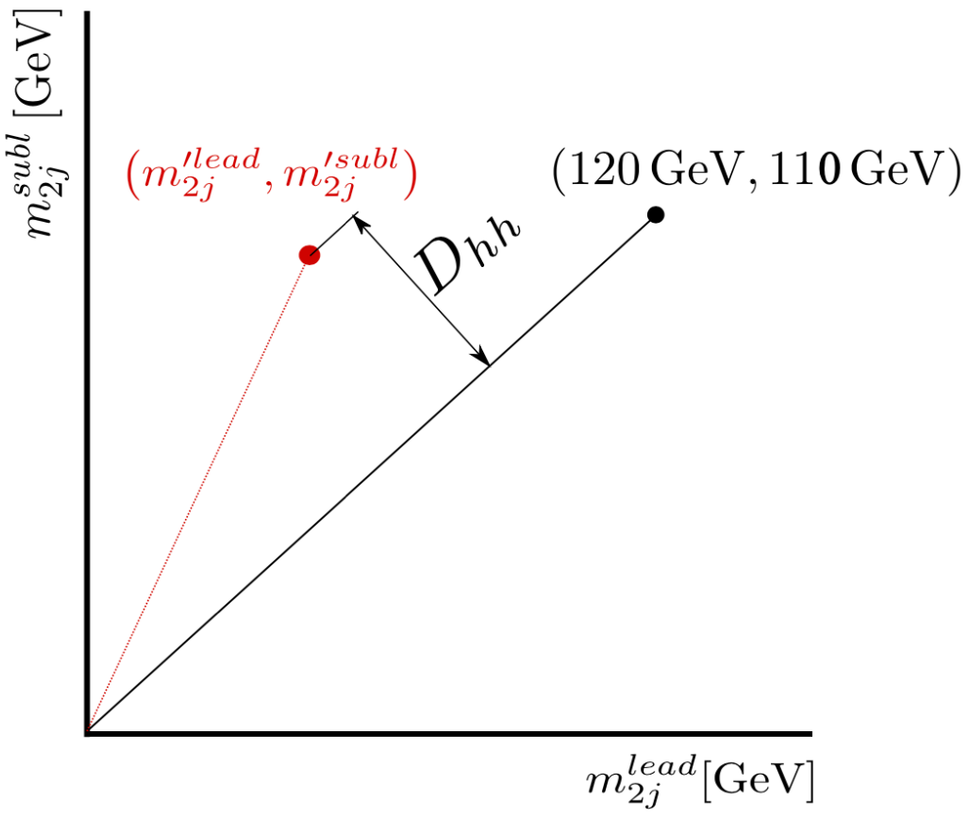


- Data drive method is used for background estimation
  - m_{H1}-m_{H2} mass-plane is constructed to define the Signal Region (SR), Control Region (CR) and Sideband Region (SB)
  - Derive a "correction" from low-b-tag events to high-b-tag event in CR, and apply this correct to SR
  - m_{HH} is the discriminant.

Resolved analysis: additional selections



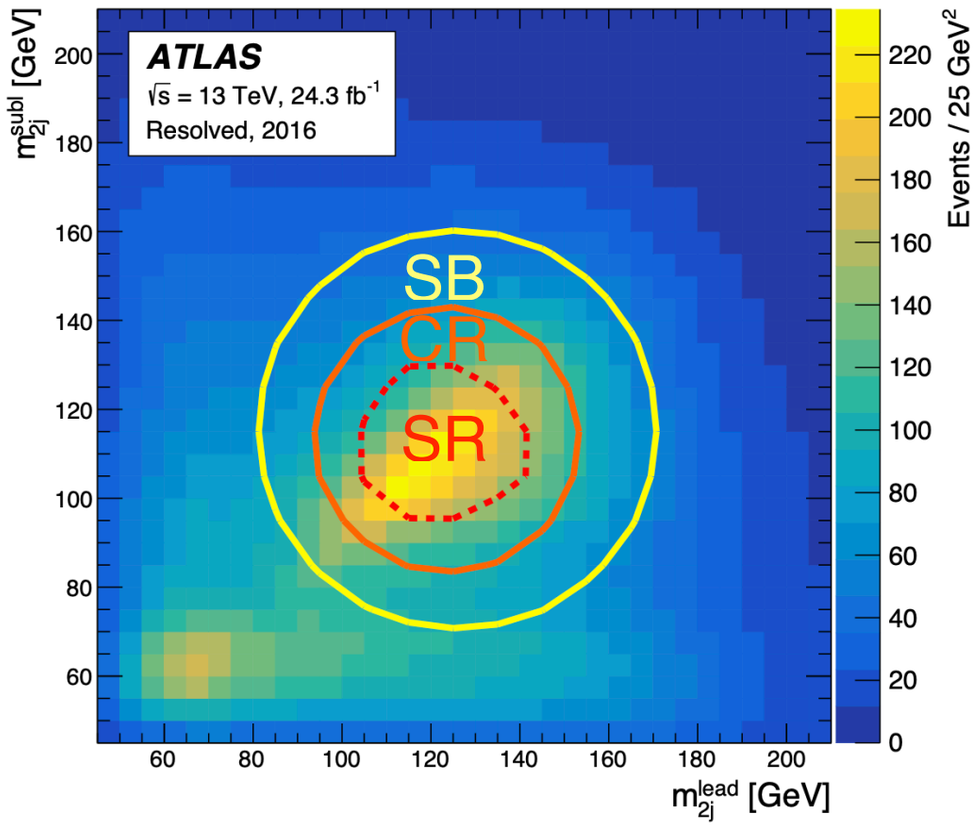
(a) Scalar Signal.

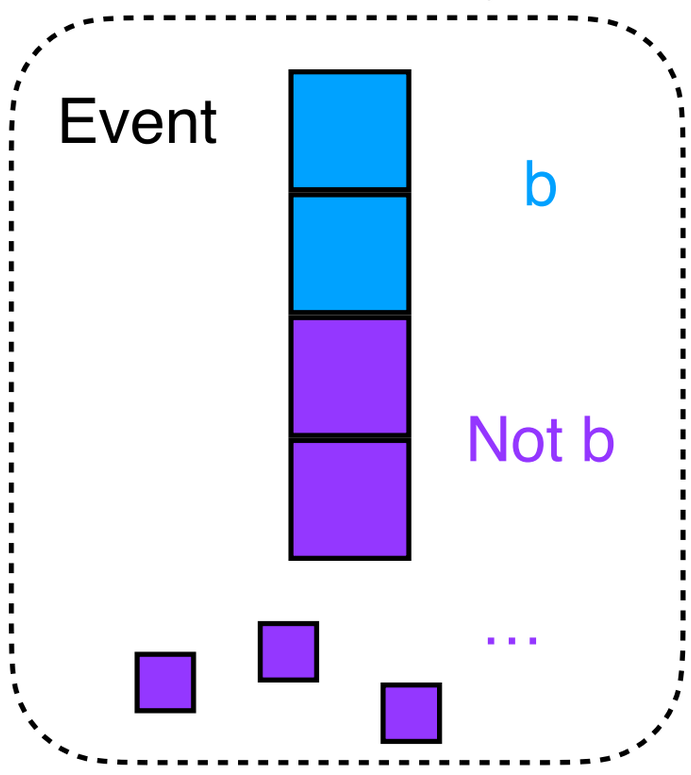


- Combination of jets into Higgs boson candidates are found using D_{HH} and candidates must satisfy m4j-dependent requirement placed on ΔRjj
- Further selections based on:
  - p_T of Higgs boson candidates (m_{4j}-dependent) and $|\Delta\eta|$ between the Higgs candidates
- Consistency of candidates with m_H required using X_{hh}: $X_{hh} = \sqrt{\left(\frac{m_{2j}^{lead} - 120\,\mathrm{GeV}}{0.1 m_{2j}^{lead}}\right)^2 + \left(\frac{m_{2j}^{subl} - 110\,\mathrm{GeV}}{0.1 m_{2j}^{subl}}\right)^2} < 1.6$
- Hadronic top veto using X_{wt} variable: $X_{Wt} = \sqrt{\left(\frac{m_W - 80\,\mathrm{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 173\,\mathrm{GeV}}{0.1 m_t}\right)^2}$

Resolved analysis: background modelling

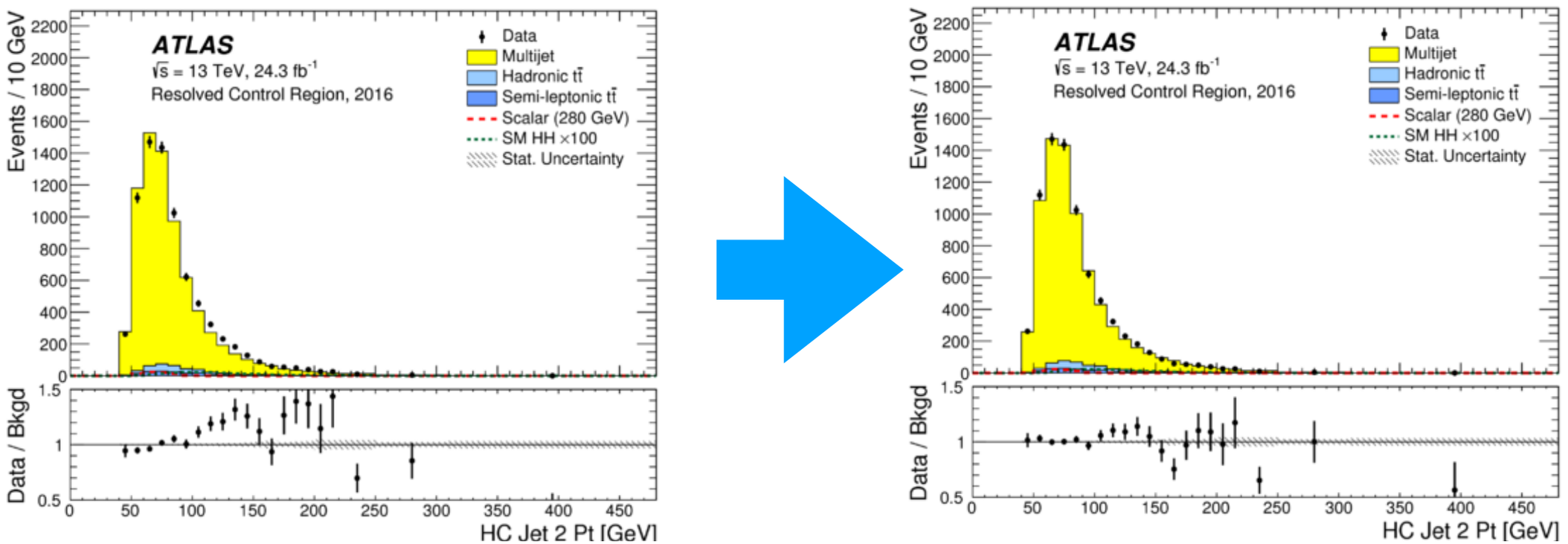
- Principal background is multijet, with ~5% $t\bar{t}$
  - Contribution of backgrounds such as Z+jets, ZZ, ZH, H+jets and bbH were estimated to be negligible
  - Multijet modelling is entirely data-driven
  - $t\bar{t}$ normalisation is data-driven, shape is taken from MC-simulation
- Multijet background consists of various processes
  - MC insufficiently accurate or precise
- Use "2-tag sample" to model the background
  - Select events with 2 b-tagged jets, then combine with 2 randomly-selected non-b-jets to form Higgs candidates
  - 2-tag is not a priori a good model for the 4-tag background
    - different composition
    - kinematic effects of b-tagging and trigger efficiency





Resolved analysis: background modelling II

- Apply kinematic reweighting, based on ratio of 4-tag:2-tag data in five variables:
  - p_T of 2nd and 4th leading Higgs boson candidate constituent jets
  - $<|\eta|>$ of the constituent jets
  - $\Delta R(j,j)$ of the two closest constituent jets
  - $\Delta R(j,j)$ of the other two constituent jets
- Ratio is fitted using splines and an iterative reweighting is applied in order to account for correlations between the variables



Resolved analysis: systematics

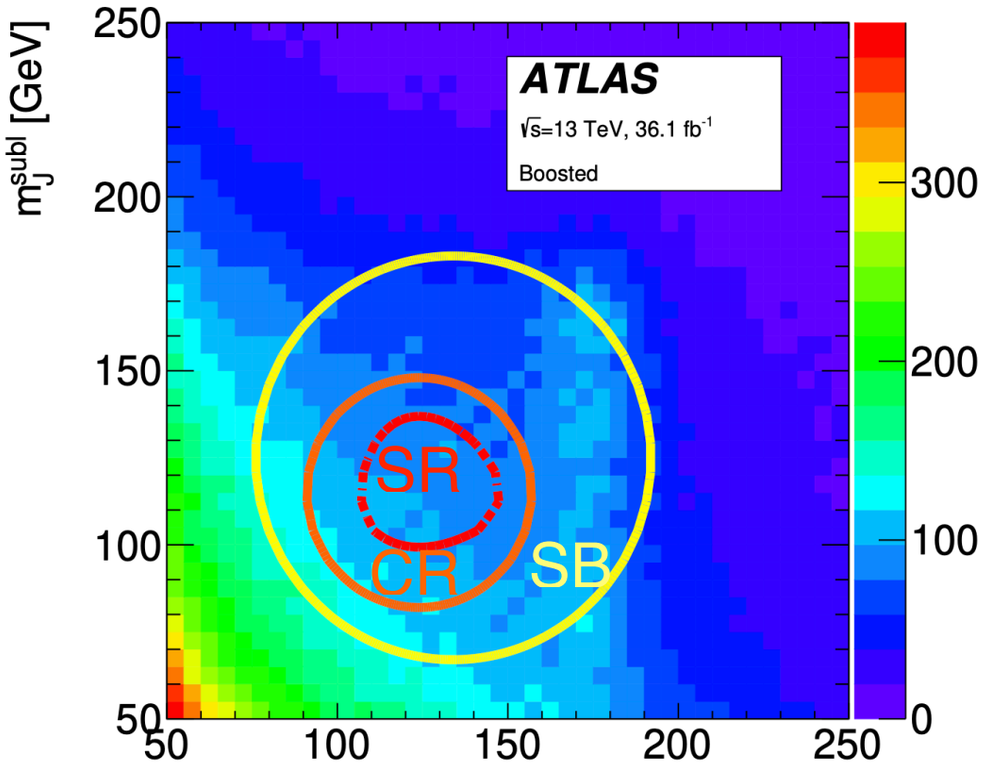
Prefit uncertainty in percentage

	2015				2016			
Source	Background	Scalar	SM HH	G_{KK}	Background	Scalar	SM HH	G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15

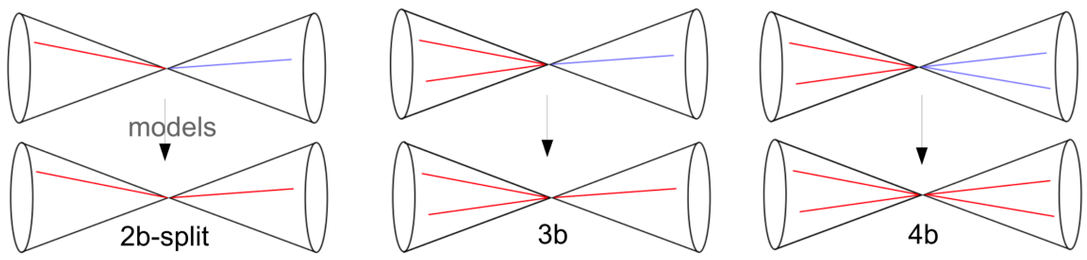
- Signal uncertainties dominated by b-tagging
- Statistical uncertainties (including correlations) on the background normalisation are propagated to final
- Background shape uncertainties assessed using an alternative model using CR rather than sideband
  - Alternative model in good agreement with baseline and data
  - Uncertainty split to two components, to avoid over-constraints

Boosted analysis: background modelling

- Principal background is multijet, while proportion of $t\bar{t}$ varies from 5-20% with number of b-tagged track jets
  - Again, contribution of backgrounds such as Z+jets, ZZ, ZH, H+jets and bbH were estimated to be negligible
  - Multijet modelling is entirely data-driven
  - $t\bar{t}$ normalisation is data-driven, shape is taken from MC-simulation



- Use lower-tagged data to model background in n-tagged regions
- Iterative reweighting is applied, based on three variables:
  - p_T of leading large-R jet
  - p_T of leading track-jet in both large-R jets
- Normalisation of multi jet and $t\bar{t}$ are set in each sample by a fit to m_J^{lead}



Boosted analysis: systematics

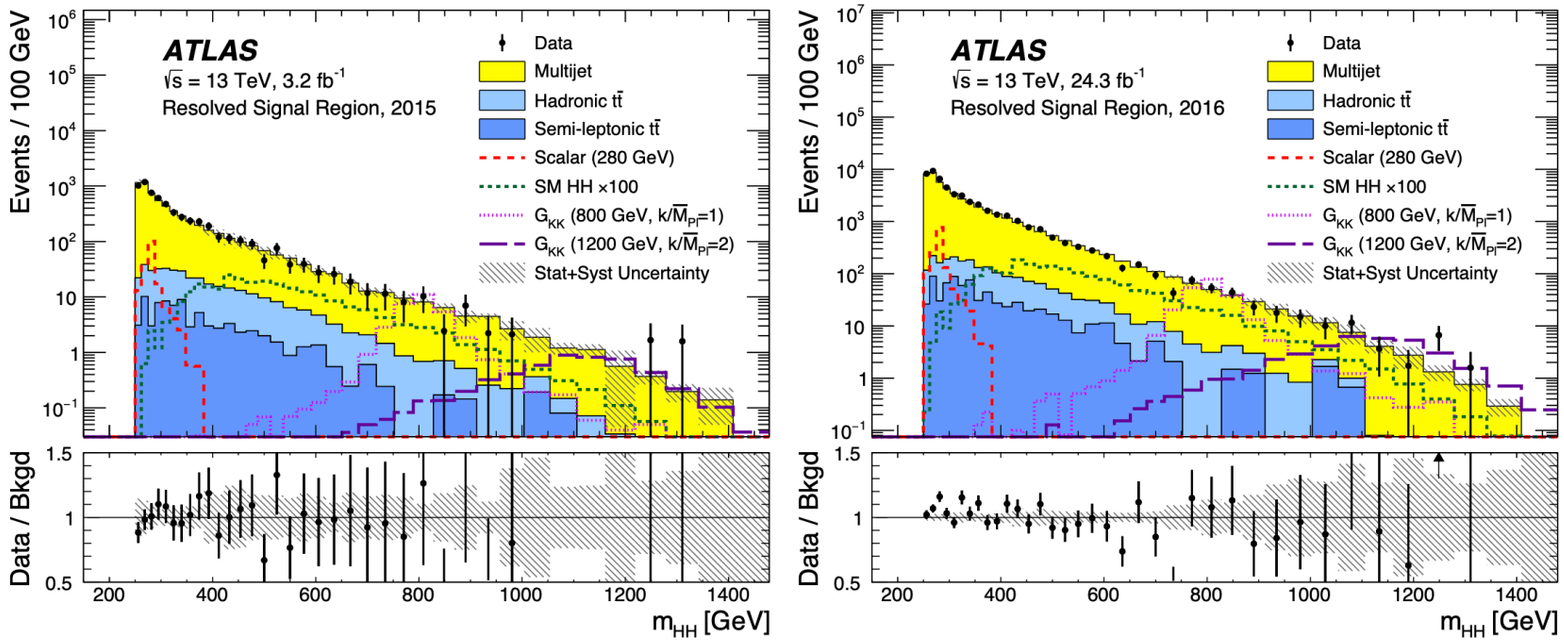
Prefit uncertainty in percentage

	Two-tag split		Three-tag		Four-Tag	
Source	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)
Luminosity	-	2.1	-	2.1	-	2.1
JER	0.3	0.7	1.4	0.9	0.5	1.1
JMR	0.5	12	1.4	12	7.9	13
JES/JMS	0.4	1.7	2.0	1.9	1.3	3.7
b-tagging	0.8	27	0.5	2.0	1.1	28
Bkg Est	2.8	-	5.8	-	16	-
Statistical	0.6	1.2	1.3	1.0	3.1	1.6
Total Sys	3.0	30	6.6	13	18	32

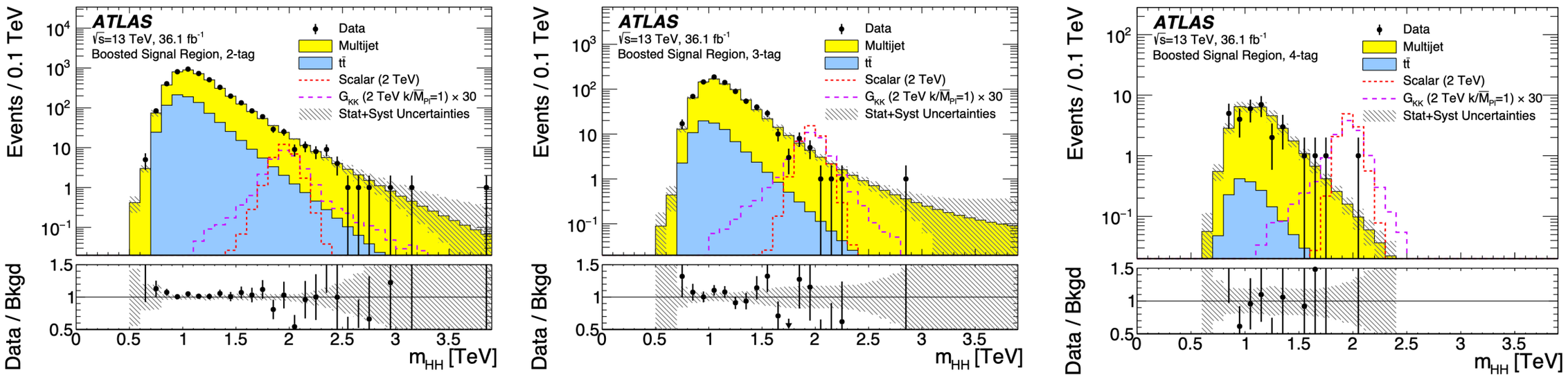
- Largest signal systematic arises from b-tagging, followed by JMR
- b-tagging impact suppressed in 3-tag sample because variation affects both tagged and non-tagged jets
- Normalisation statistical uncertainties propagated from m_J^{lead} fit
- Normalisation systematic uncertainty arises from control region variations: largest
  - data/prediction discrepancy taken as uncertainty
- Shape uncertainty from comparison in control region, split into two components

Discriminant

Resolved

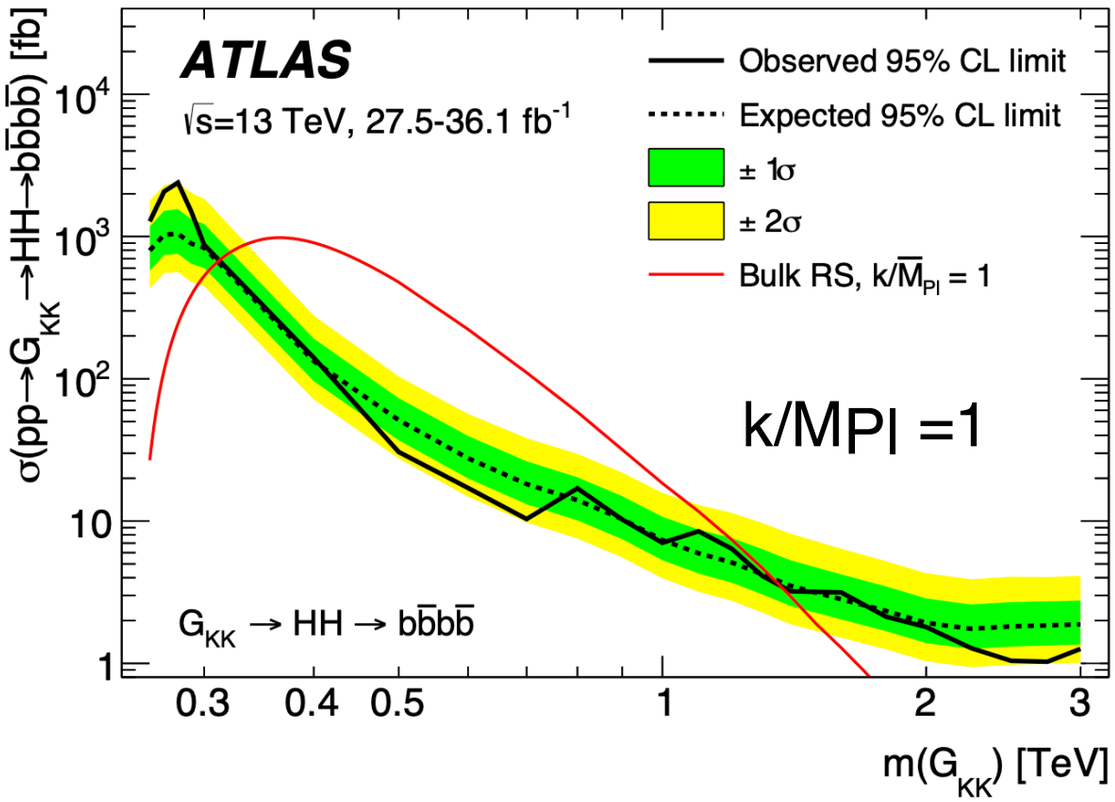


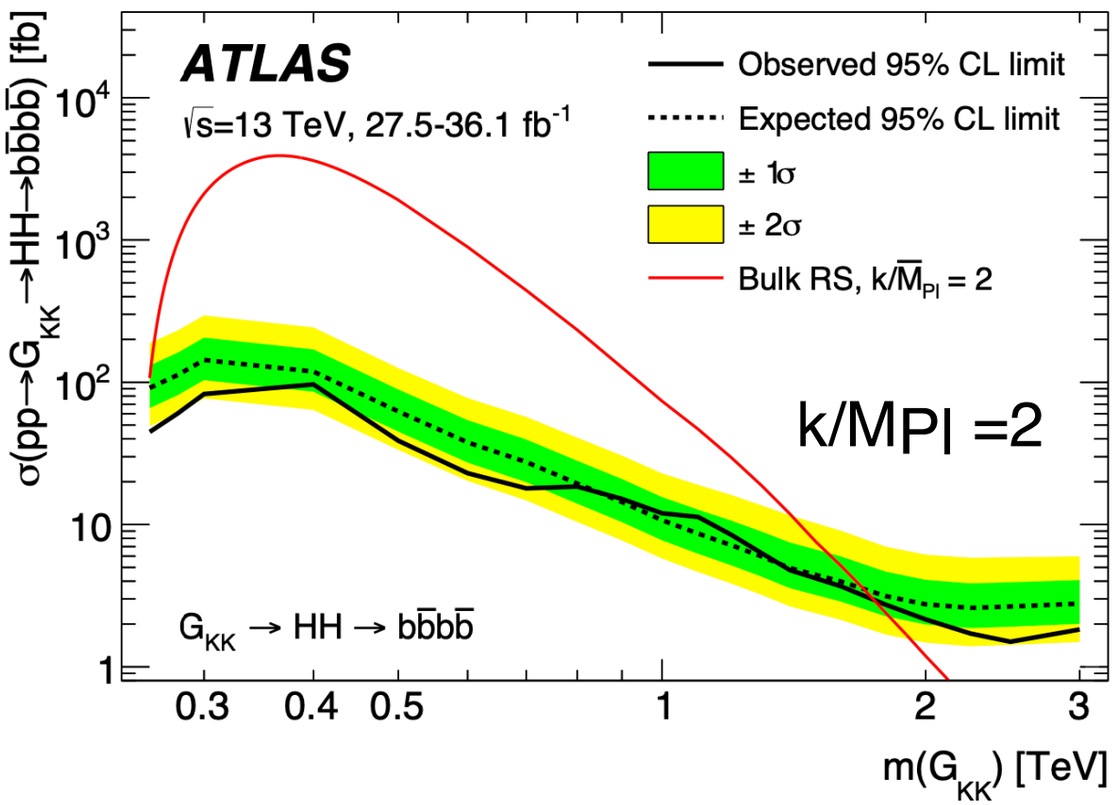
Boosted



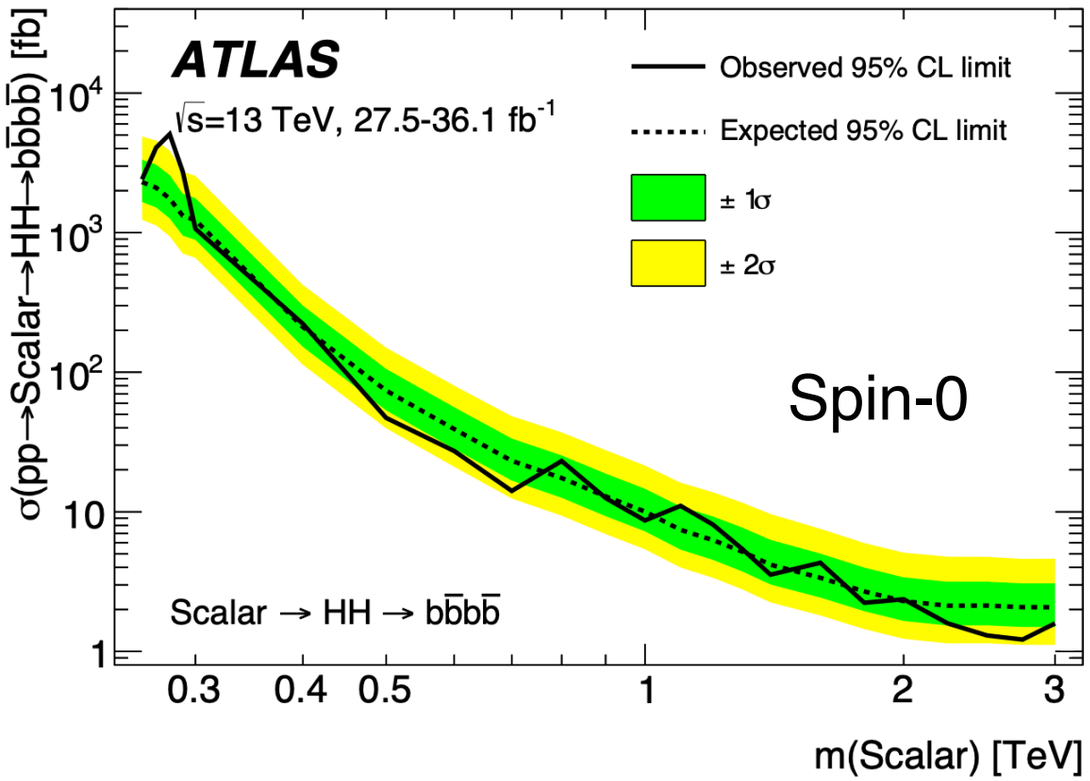
Observed data is in agreement with predicted background.

Results





- 95% C.L. exclusions of Bulk RS model
  - 320 GeV < m_{G^*} < 1400 GeV for k/MPl =1
  - 260 GeV < m_{G^*} < 1850 GeV for k/MPl =2

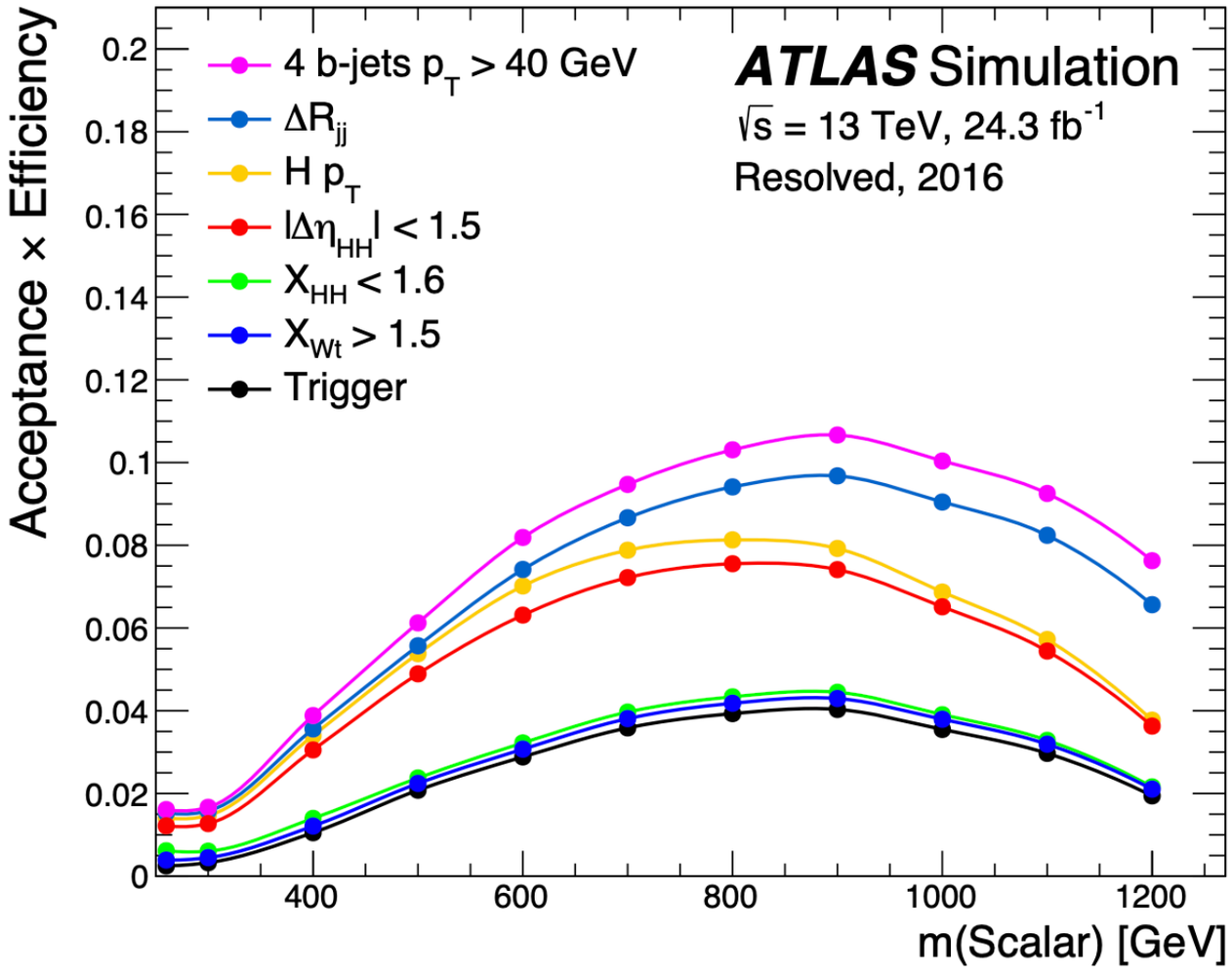


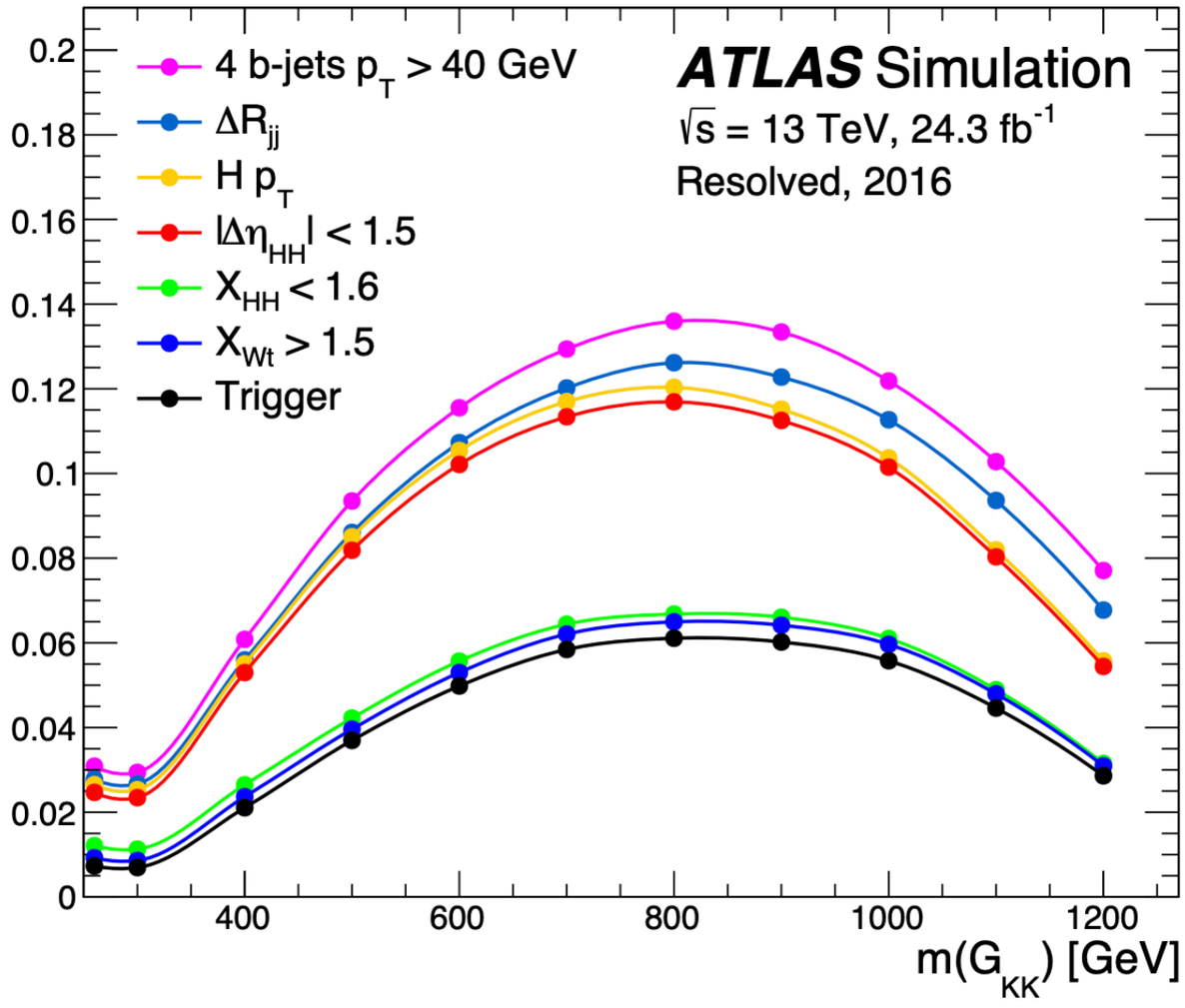
Summary

- Search for resonant Higgs boson pair production in the 4b channel is presented using 2015+2016 ATLAS data
  - A search with full Run2 data (2015-2018) is currently ongoing
- No significant excess of data above predicted background was observed
- Cross-section limits were set on spin-0 and spin-2 signals between 260 and 3000 GeV

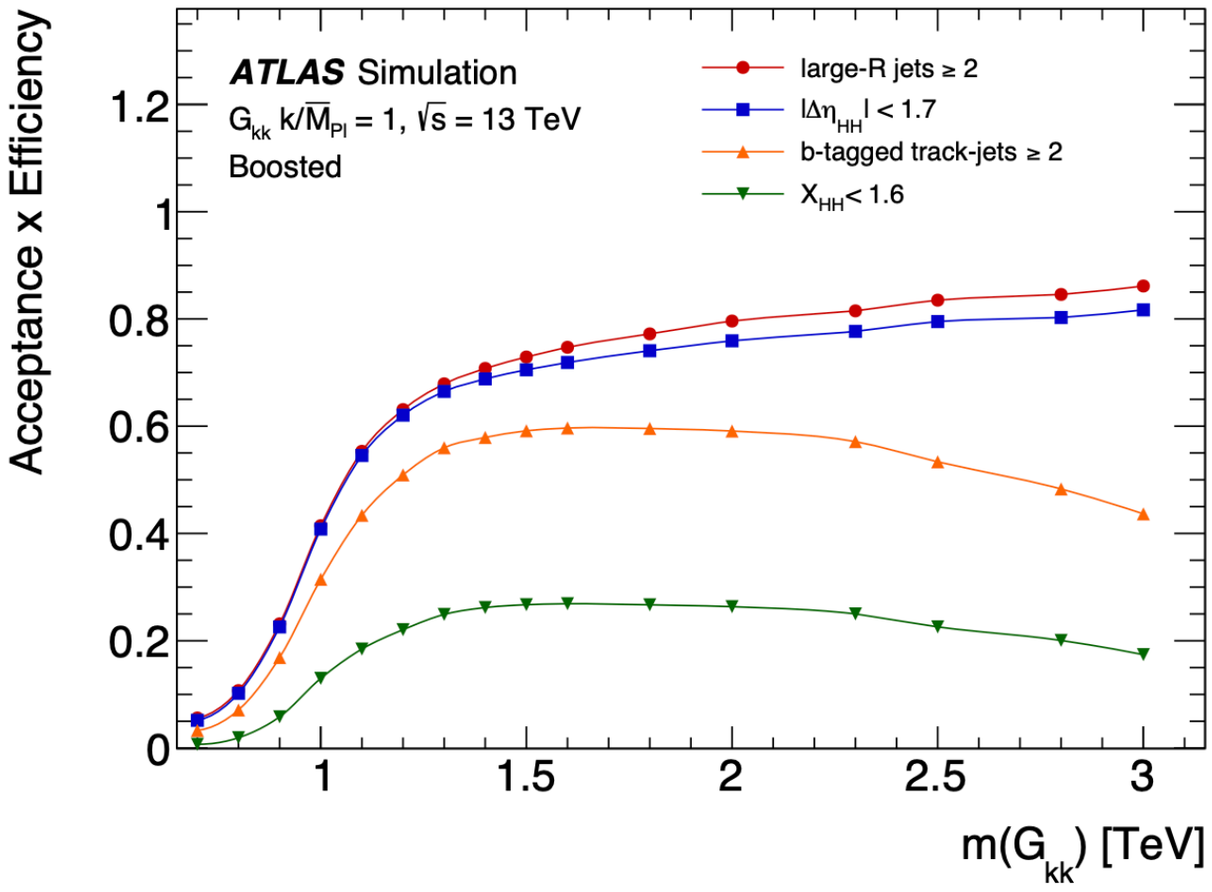
Backup

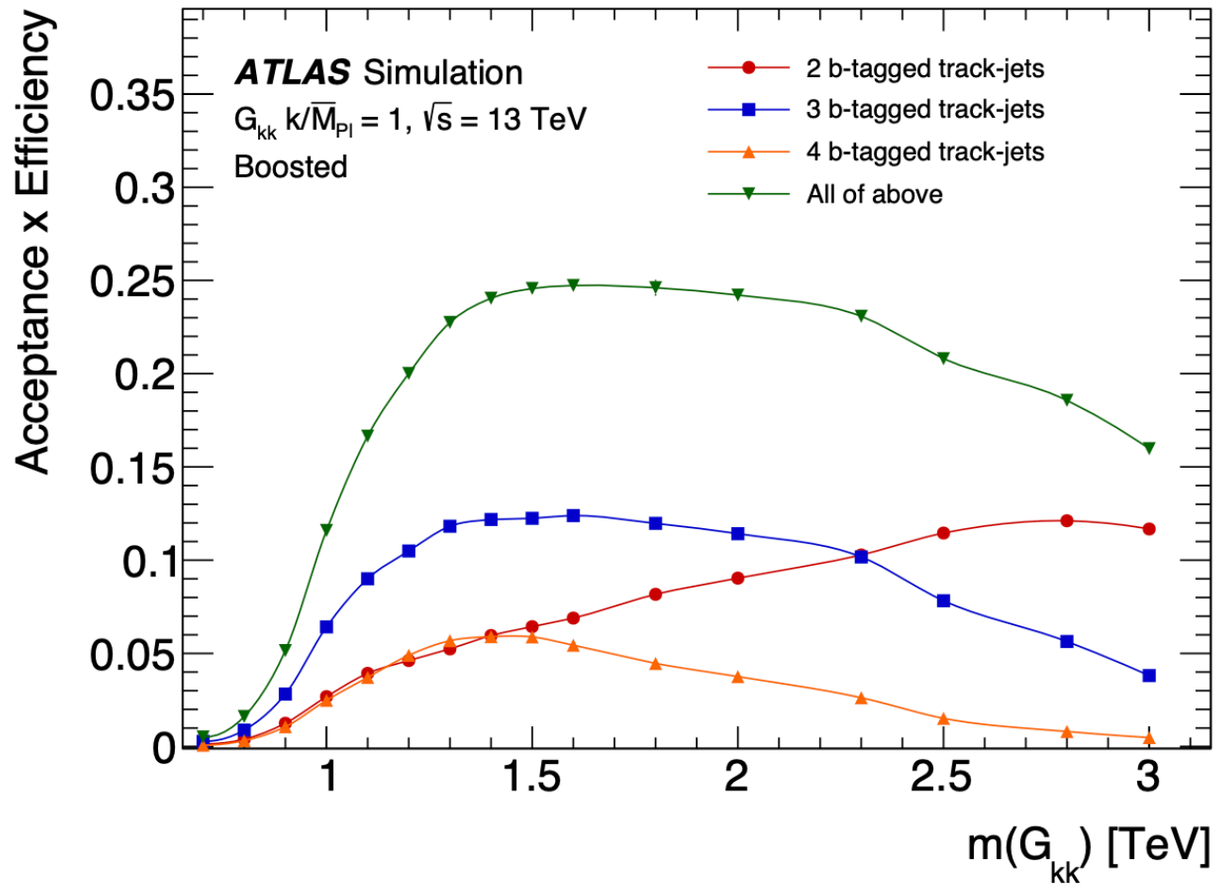
Resolved


ATLAS Simulation
√s = 13 TeV, 24.3 fb-1
Resolved, 2016
4 b-jets pT > 40 GeV
ΔRjj
H pT
|Δηhh| < 1.5
Xhh < 1.6
XWt > 1.5
Trigger
Acceptance × Efficiency
m(Scalar) [GeV]


ATLAS Simulation
√s = 13 TeV, 24.3 fb-1
Resolved, 2016
4 b-jets pT > 40 GeV
ΔRjj
H pT
|Δηhh| < 1.5
Xhh < 1.6
XWt > 1.5
Trigger
m(GKK) [GeV]

Boosted analysis: selection





- Requirement that leading large-R jet $p_T > 450$ GeV ensures 100% trigger efficiency
  - Veto events that passed resolved selection
- R=0.2 track-jets for b-tagging must satisfy $p_T > 10$ GeV, $|\eta| < 2.5$
- Maximise sensitivity by considering three orthogonal samples
  - Events containing either 2, 3 or 4 b-tagged track-jets matched to Higgs boson candidates

Tables

Sample	2015 SR	2016 SR	2015 CR	2016 CR
Multijet	866 ± 70	6750 ± 170	880 ± 71	7110 ± 180
$t\bar{t}$, hadronic	52 ± 35	259 ± 57	56 ± 37	276 ± 61
$t\bar{t}$, semileptonic	13.9 ± 6.5	123 ± 30	20 ± 9	168 ± 40
Total	930 ± 70	7130 ± 130	956 ± 50	7550 ± 130
Data	928	7430	969	7656
G_{KK} (800 GeV)	12.5 ± 1.9	89 ± 14		
Scalar (280 GeV)	24.0 ± 7.5	180 ± 57		
SM HH	0.607 ± 0.091	4.43 ± 0.66		

Resolved

Source	2015 Background	2015 Scalar	2015 SM HH	2015 G_{KK}	2016 Background	2016 Scalar	2016 SM HH	2016 G_{KK}
Luminosity	–	2.1	2.1	2.1	–	2.2	2.2	2.2
Jet energy	–	17	7.1	3.7	–	17	6.4	3.7
b-tagging	–	13	12	14	–	13	12	14
b-trigger	–	4.0	2.3	1.3	–	2.6	2.5	2.5
Theoretical	–	23	7.2	0.6	–	23	7.2	0.6
Multijet stat	4.2	–	–	–	1.5	–	–	–
Multijet syst	6.1	–	–	–	1.8	–	–	–
$t\bar{t}$ stat	2.1	–	–	–	0.8	–	–	–
$t\bar{t}$ syst	3.5	–	–	–	0.3	–	–	–
Total	7.5	31	16	15	1.8	31	16	15

Boosted

	Two-tag	Three-tag	Four-tag
Multijet	3390 ± 150	702 ± 63	32.9 ± 6.9
$t\bar{t}$	860 ± 110	80 ± 33	1.7 ± 1.4
Total	4250 ± 130	782 ± 51	34.6 ± 6.1
G_{KK} (2 TeV)	0.97 ± 0.29	1.23 ± 0.16	0.40 ± 0.13
Scalar (2 TeV)	28.2 ± 9.0	35.0 ± 4.6	10.9 ± 3.5
Data	4376	801	31

Source	Two-tag Background	Two-tag G_{KK}	Two-tag Scalar	Three-tag Background	Three-tag G_{KK}	Three-tag Scalar	Four-tag Background	Four-tag G_{KK}	Four-tag Scalar
Luminosity	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1
JER	0.25	0.74	1	1.4	0.93	0.93	0.45	1.1	1.5
JMR	0.52	12	12	1.4	12	13	7.9	13	14
JES/JMS	0.43	1.7	2.1	2.0	1.9	2.2	1.3	3.7	5.7
b-tagging	0.83	27	29	0.48	2	2.9	1.1	28	28
Bkgd estimate	2.8	-	-	5.8	-	-	16	-	-
Statistical	0.6	1.2	1.3	1.3	1.0	1.1	3.1	1.6	1.9
Total Syst	3.1	30	32	6.6	13	14	18	31	32