Studies using final states with boosted $b\bar{b}$ resonances in ATLAS

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Motivation for high-p_T $b\bar{b}$ resonances

- BR(H_{125}→bb)=57% and yet it has not yet been conclusively observed nor thoroughly studied
  - One of the top objectives for LHC's Run-2
- Cutting at higher-p_T gives better signal-to-background
  - bkg is predominantly gluon→bb and has softer p_T spectrum
- 1/3 of higgs-pair production events give bbbb (0.57^2)
- In non-resonant Higgs-pair production at 14TeV, the Higgs p_T spectrum peaks at ~150GeV
  - Nearly 1/4 of events have both Higgs bosons with pT>200GeV
- Numerous BSM scenarios with TeV-scale resonances decaying as X→hh

This talk

CERN-PH-EP-2014-064

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Measurement of the cross section of high transverse momentum $Z \to b\bar{b}$ production in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

The ATLAS Collaboration

Abstract

This Letter reports the observation of a high transverse momentum $Z \to b\bar{b}$ signal in proton–proton collisions at $\sqrt{s} = 8$ TeV and the measurement of its production cross section. The data analysed were collected in 2012 with the ATLAS detector at the LHC and correspond to an integrated luminosity of 19.5 fb^{-1}. The $Z \to b\bar{b}$ decay is reconstructed from a pair of b-tagged jets, clustered with the anti-k_t jet algorithm with $R = 0.4$, that have low angular separation and form a dijet with $p_T > 200$ GeV. The signal yield is extracted from a fit to the dijet invariant mass distribution, with the dominant, multi-jet background mass shape estimated by employing a fully data-driven technique that reduces the dependence of the analysis on simulation. The fiducial cross section is determined to be

$$\sigma^{\rm fid}_{Z\to bb} = 2.02 \pm 0.20\,(\text{stat.}) \pm 0.25\,(\text{syst.}) \pm 0.06\,(\text{lumi.})\ \text{pb} = 2.02 \pm 0.33\ \text{pb},$$

in good agreement with next-to-leading-order theoretical predictions.

ATLAS NOTE

ATLAS-CONF-2014-005

March 4, 2014

A search for resonant Higgs-pair production in the $b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 8$ TeV

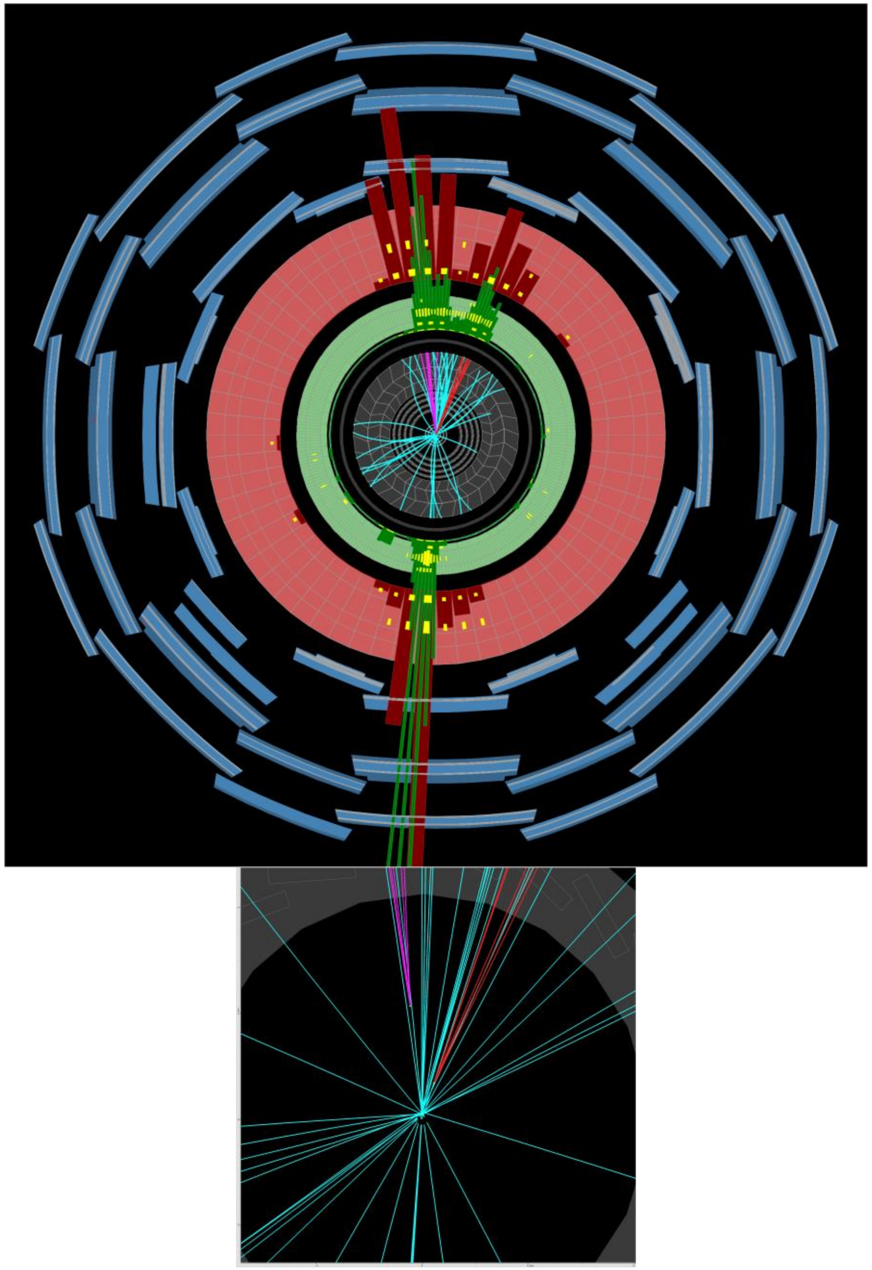
The ATLAS Collaboration

Abstract

A search for TeV-scale resonances decaying via a pair of Higgs bosons to the $b\bar{b}b\bar{b}$ final state is performed using 19.5 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by ATLAS in 2012. The search assumes a Standard Model Higgs boson with a mass of 125 GeV. The decay of each Higgs boson is reconstructed from a pair of b-tagged jets that have small angular separation and form a dijet system with transverse momentum greater than 200 GeV. The bulk Randall-Sundrum model with a warped extra dimension and a coupling of $k/\bar{M}_{\rm Pl} = 1.0$ is used as a benchmark to search for resonances, corresponding to the first Kaluza-Klein excitation mode of the graviton G^*, in the range between 500 GeV and 1500 GeV. No evidence of a signal is found, and upper limits on $\sigma(pp \to G^*) \times \text{BR}(G^* \to HH \to b\bar{b}b\bar{b})$ are derived, giving an observed limit of 7 fb at the 95% confidence level for a KK graviton mass of 1 TeV. The benchmark model is excluded at the 95% confidence level for KK graviton masses between 590 GeV and 710 GeV.

Observation/measurement of high-p_T $Z \to bb$

- First observation of high-p_T $Z \to bb$ in all-hadronic final state
  - Using 2012 ATLAS data
- Validates reconstruction and analysis tools for $H \to bb$
- Test bench for improving analysis techniques for $H \to bb$
  - E.g. m_{bb} resolution
- Validates b-jet energy scale
- Test NLO + parton shower generators, like POWHEG and aMC@NLO, in hadronic resonance decays



Z→bb preselection

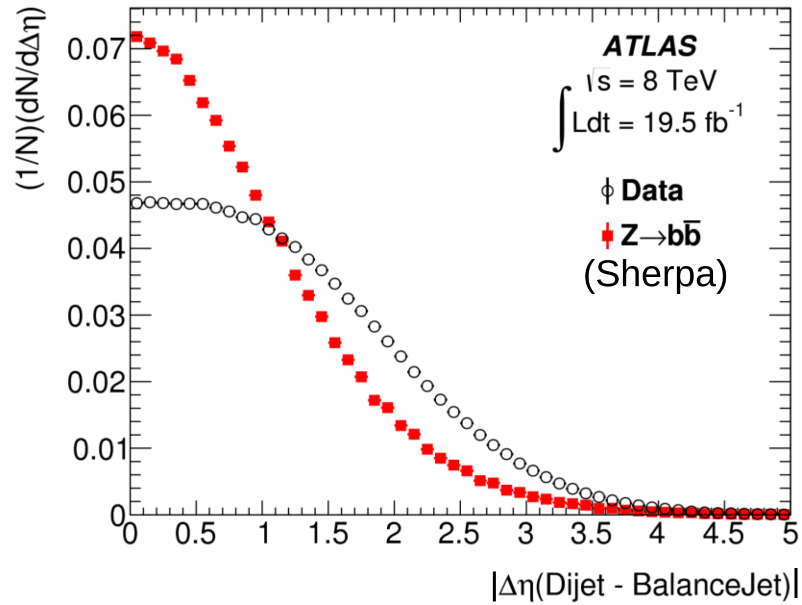
Z→bb candidate preselection:

-Trigger: 6 jet triggers with online b-tagging
- Trigger efficiency ~90%

- 2 b-tagged anti-k_t R=0.4 jets,
  - $|\eta|<2.5$, $p_T>40$GeV

- ΔR(jet1,jet2)<1.2, dijet pT>200GeV

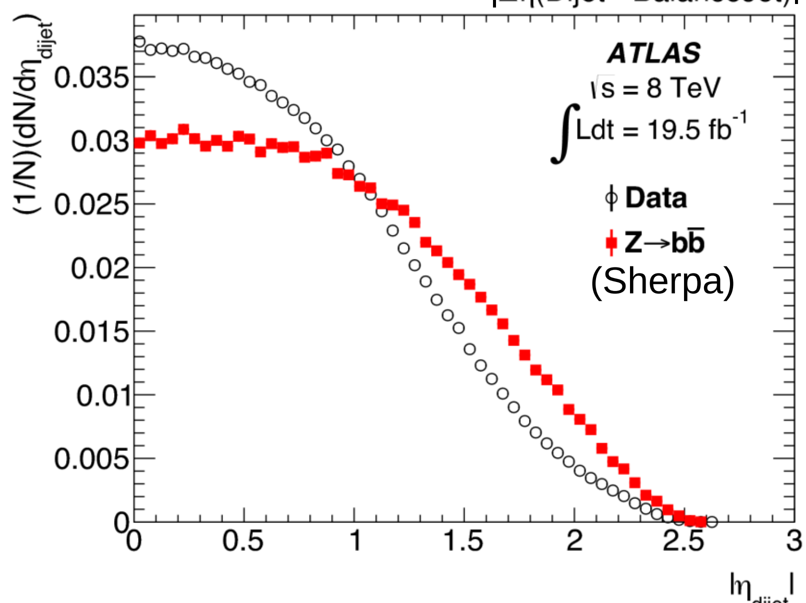
Bkg dominated by QCD multijets (gluon→bb)



Data-driven m_{dijet} modelling of QCD:

- 2 variables uncorrelated with m_{dijet}:
  - $\Delta\eta$(dijet, balancing jet)
  - η_{dijet}

- Combine in an MVA and use it to define
  - a "signal-depleted" Control Region (CR)
  - a "signal-enhanced" Signal Region (SR)

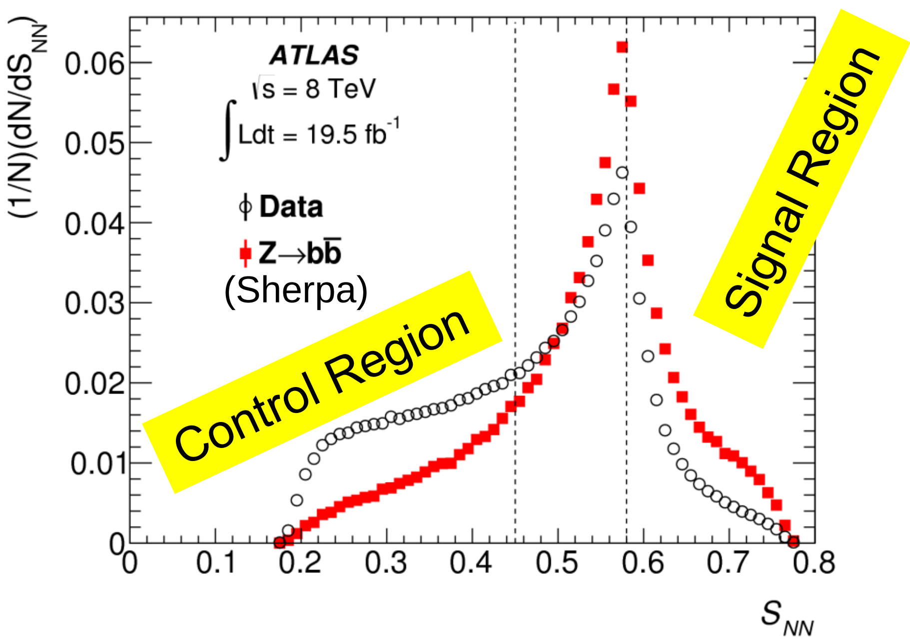


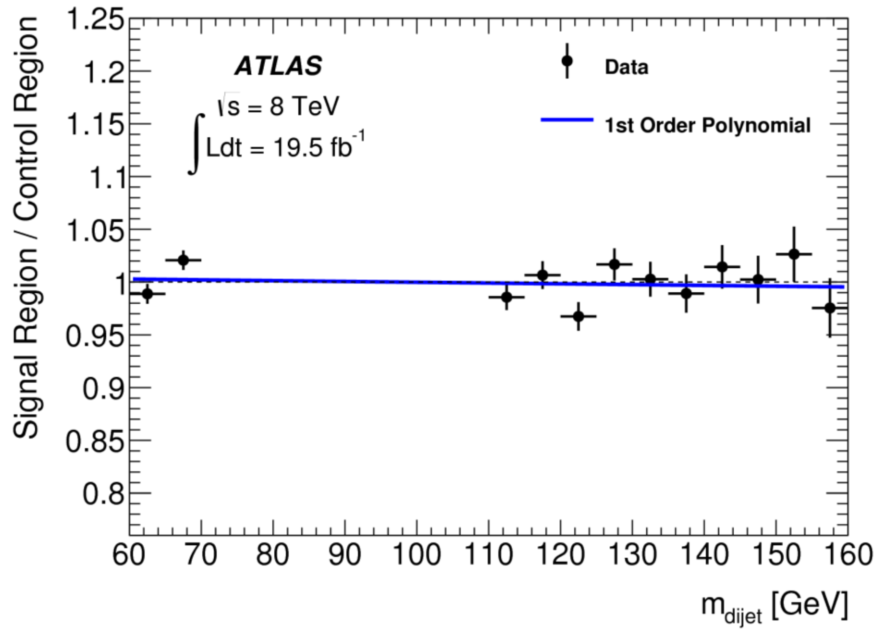
Z→bb selection and bkg modelling

Signal modelling of η_{dijet} , $\Delta\eta$(dijet, balancing jet) and S_{NN} tested in $Z\to\mu\mu$ sample in data and Sherpa

SR/CR ratio flat in m_{dijet} (tested also in multijet MC)

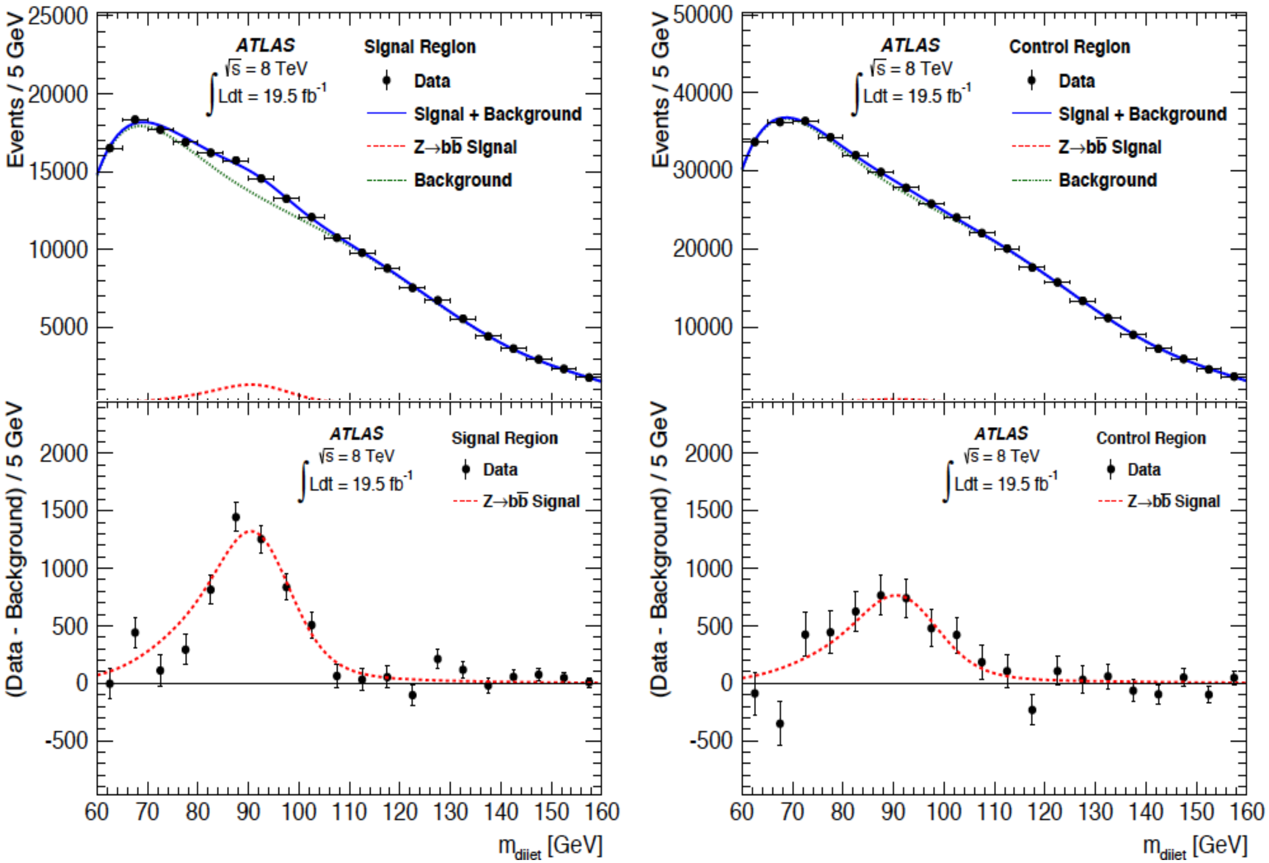
s/b~6% in SR, ~2% in CR





Signal extracted by extended max-likelihood fit to the SR and CR simultaneously:

- QCD shape: 7th degree Bernstein polynomial, identical in SR and CR
- Signal shape (Sherpa): modelled by three Gaussians (Pythia-8 for systematics)
  - Free params: N_{signal} in SR and mean of narrowest Gaussian
- top bkg, W+jets and Z→cc (all very small) modelled using Monte Carlo



Fit results:

N_{signal} = 6420±640 events

$\delta M_Z = -1.5 \pm 0.7^{+3.4}_{2.5}$ GeV

(validation of the b-jet energy scale in ATLAS)

Z→bb results and theory predictions

Systematic uncertainties

Source of uncertainty	$\Delta N_{Z\to b\bar{b}}(\%)$	$\Delta C_{Z\to b\bar{b}}(\%)$	$\Delta\sigma^{\text{fid}}_{Z\to b\bar{b}}(\%)$
Jet energy scale	$+3.0/-1.5$	± 8.4	$+6.5/-5.0$
Jet energy resolution	± 5.3	± 0.2	± 5.1
b-tagging	± 0.1	± 3.6	± 3.6
Trigger modelling	N/A	± 6	± 6
Control Region bias	$+4.9/-5.5$	N/A	$+4.9/-5.5$
Signal S_{NN} modelling	± 0.9	∓ 2.0	± 2.9
Signal m_{dijet} shape	± 2.2	N/A	± 2.2
$Z\to c\bar{c}$ normalisation	± 0.4	N/A	± 0.4
$t\bar{t}$ normalisation	± 1.2	N/A	± 1.1
$W\to q\bar{q}'$ normalisation	± 1.0	N/A	± 1.0

Z→bb results and theory predictions

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$W\to q\bar{q}'$ normalisation	± 1.0	N/A	± 1.0

Result:

$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\,(\text{stat.}) \pm 0.25\,(\text{syst.}) \pm 0.06\,(\text{lumi.})\ \text{pb} = 2.02 \pm 0.33\ \text{pb}$$

Theory predictions

$$\text{POWHEG}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02\,^{+0.25}_{-0.19}(\text{scales})\,^{+0.03}_{-0.04}(\text{PDF})\,\text{pb}$$

$$\text{aMC@NLO}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 1.98\,^{+0.16}_{-0.08}(\text{scales}) \pm 0.03(\text{PDF})\,\text{pb}$$

X→HH→bbbb candidate preselection:

- Trigger: 5 jet triggers with online b-tagging (~as Z→bb)
  - Trigger efficiency >99.5%
- 4 b-tagged anti-k_t R=0.4 jets with $|\eta|<2.5$, $p_T>40$GeV
- Two dijets with $\Delta R(\text{jet,jet})<1.5$, pT>200GeV

In addition:

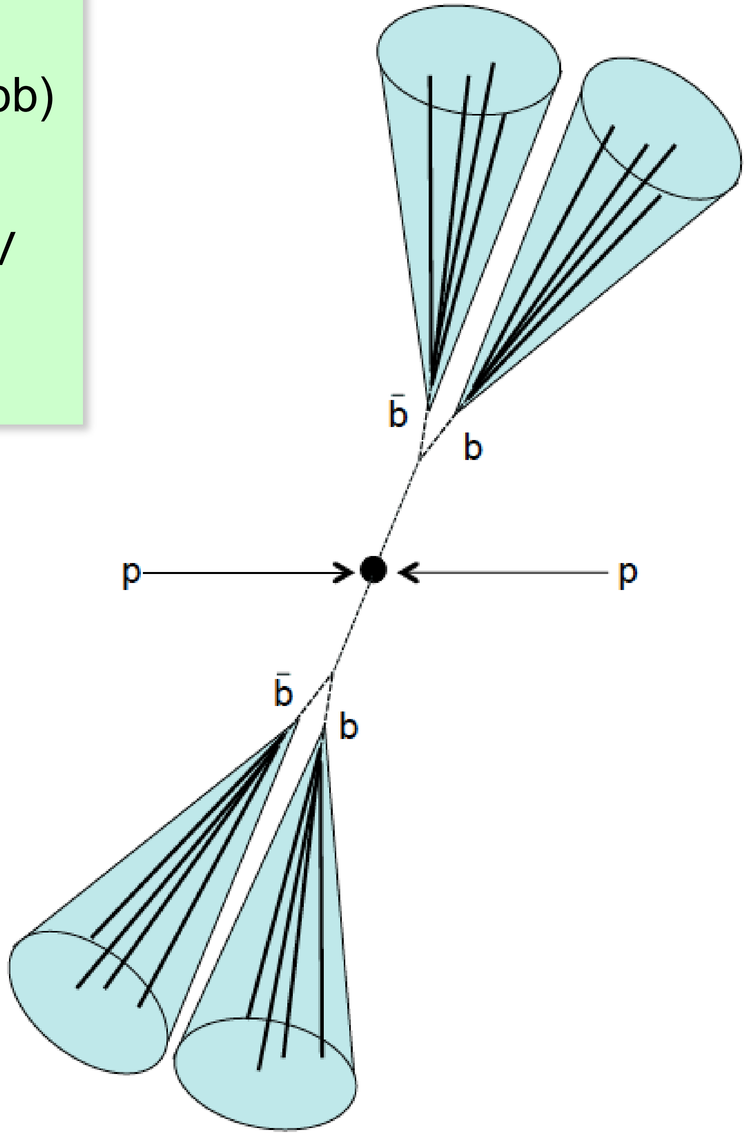
- ttbar veto:

$$X_{tt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} > 3.2$$

- HH signal region:

$$X_{HH} = \sqrt{\left(\frac{m_1 - 124}{0.1 m_1}\right)^2 + \left(\frac{m_2 - 115}{0.1 m_2}\right)^2} < 1.6$$

Background: QCD multijets (~90%) and tt (~10%)

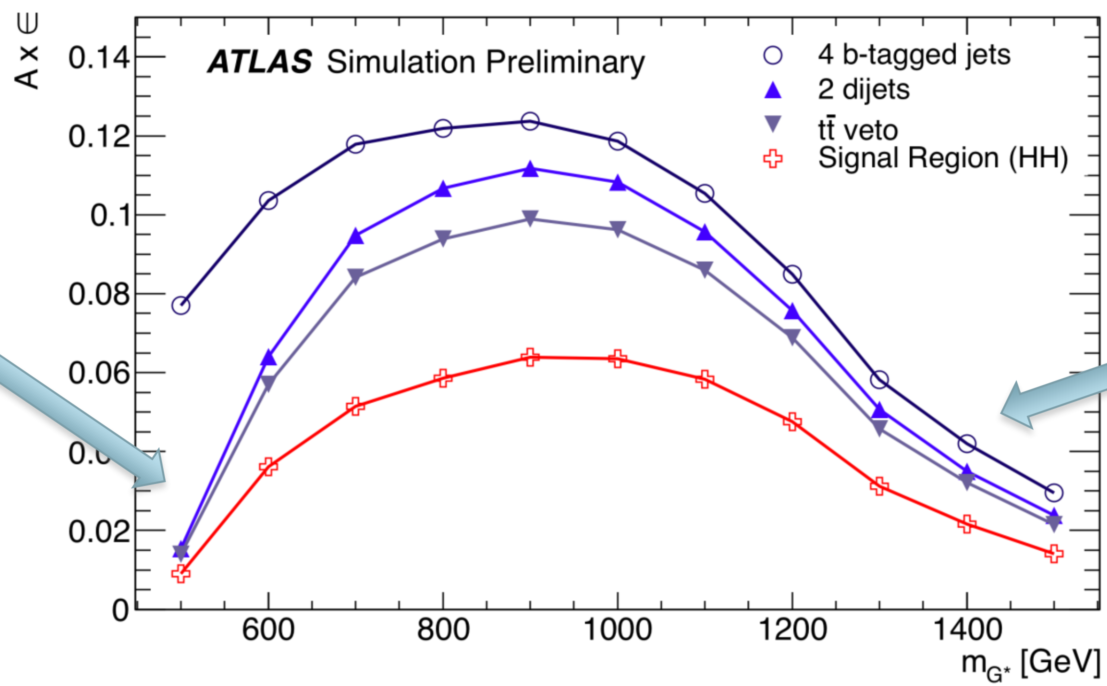


Signal Model for X→HH→bbbb

Used the Randal-Sundrum graviton G* (spin=2)

- BR(G*→HH) ~7%
- Coupling k/mPl = 1.0 (as in G*→ZZ/WW→llqq/lvqq searches in ATLAS)
- Decay width smaller than detector resolution

Efficiency drop due to kinematic selection



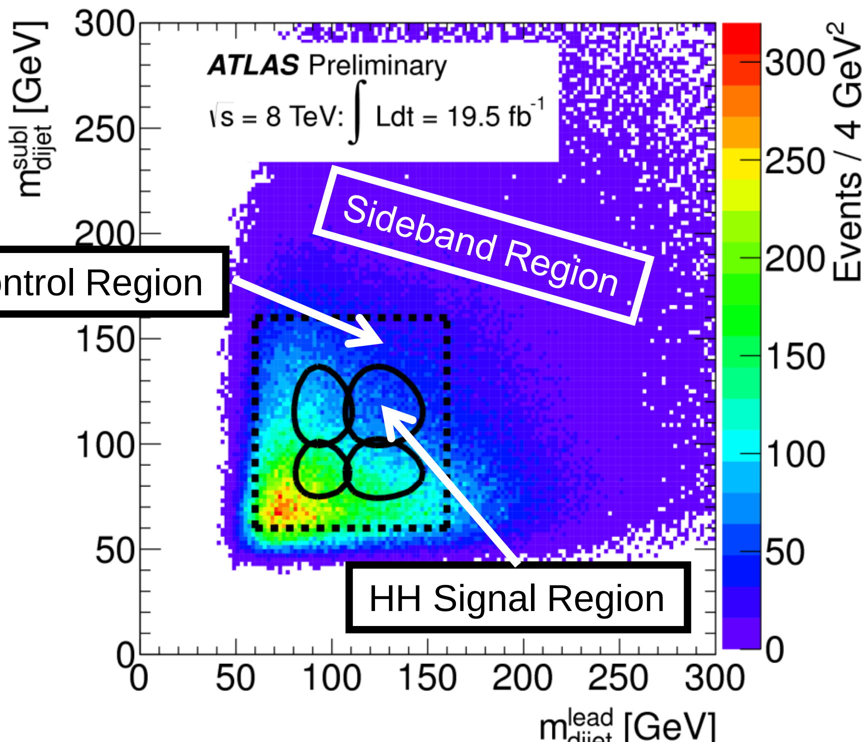
Efficiency drop due to merging of jets

X→HH→bbbb background modeling

Data-driven estimation of QCD bkg:

- Use events where only one of the two dijets is required to be b-tagged (2-tag model)

- "2-tag to 4-tag" normalization in HH signal region from corresponding normalization in sideband region



Type	Sideband Region	Control Region
Multijet	903 ± 3	935 ± 3
$t\bar{t}$	19.0 ± 0.2	26.7 ± 0.3
Z+jets	11 ± 1	17 ± 1
Total Bkgd	933 ± 3	979 ± 3
4-tag Data	933	933

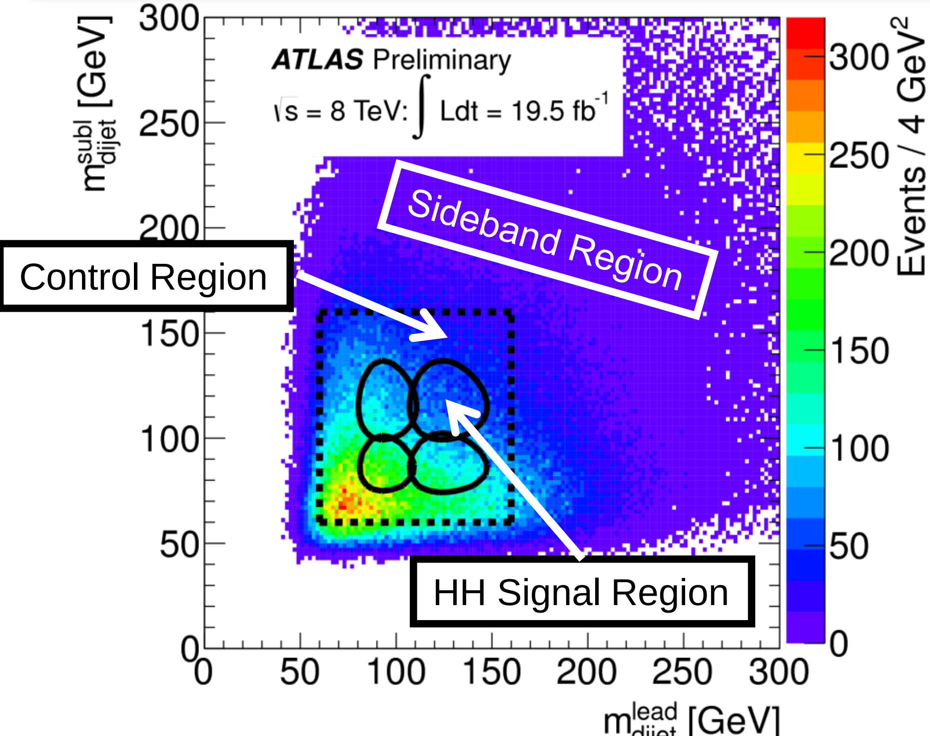
Difference taken as systematic uncertainty on QCD normalization

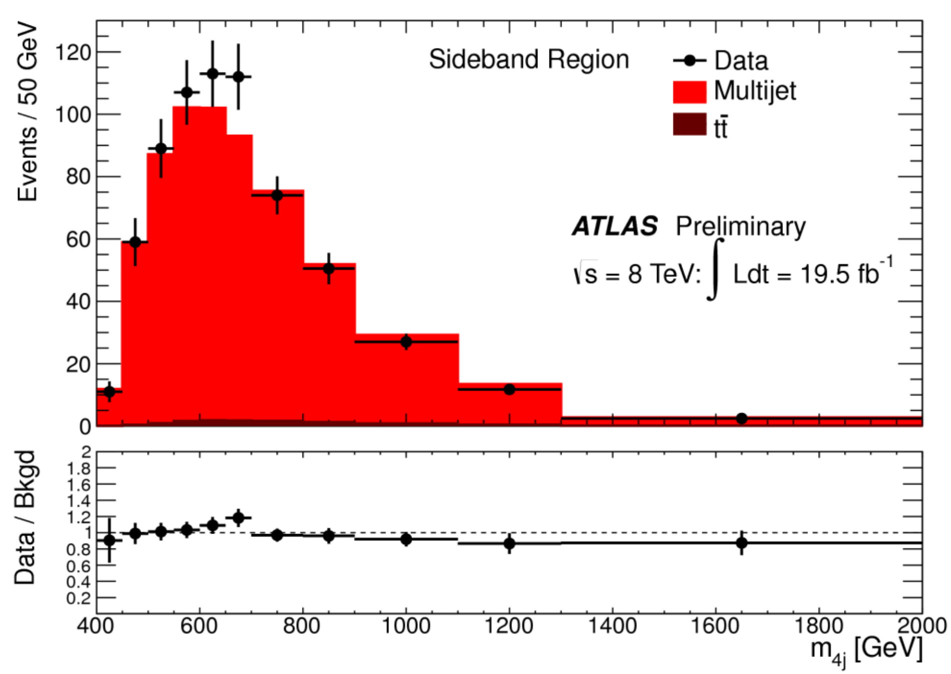
Data-driven estimation of QCD bkg:

- Use events where only one of the two dijets is required to be b-tagged (2-tag model)

- "2-tag to 4-tag" normalization in HH signal region from corresponding normalization in sideband region

- m4j shape: from 2-tag model in HH signal region, after correcting for kinematic biases due to additional b-tagging in 4-tag selection





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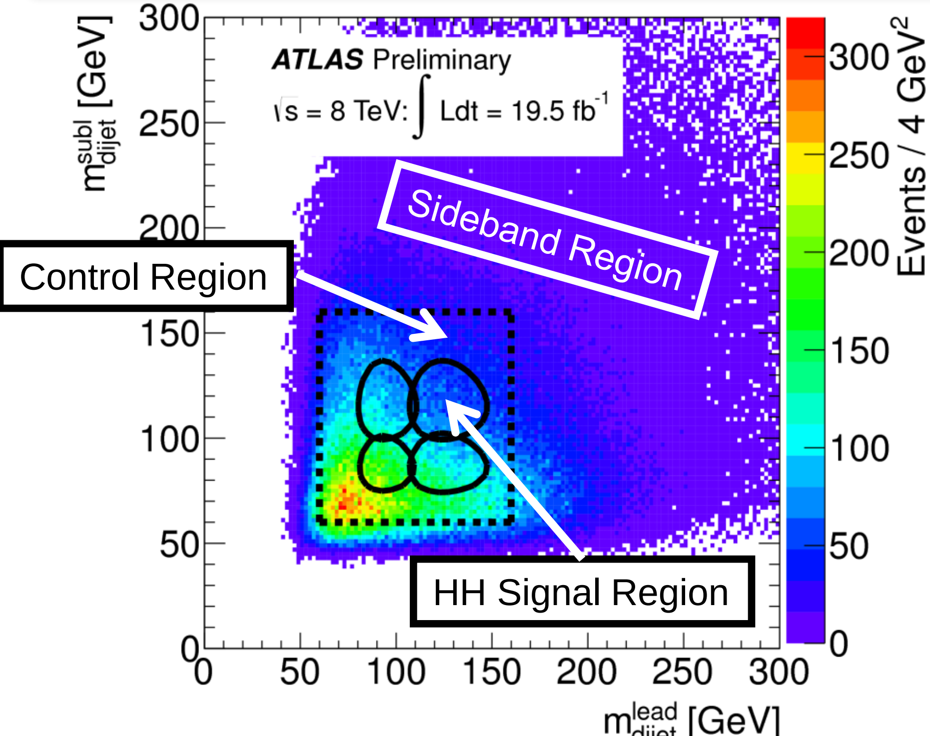
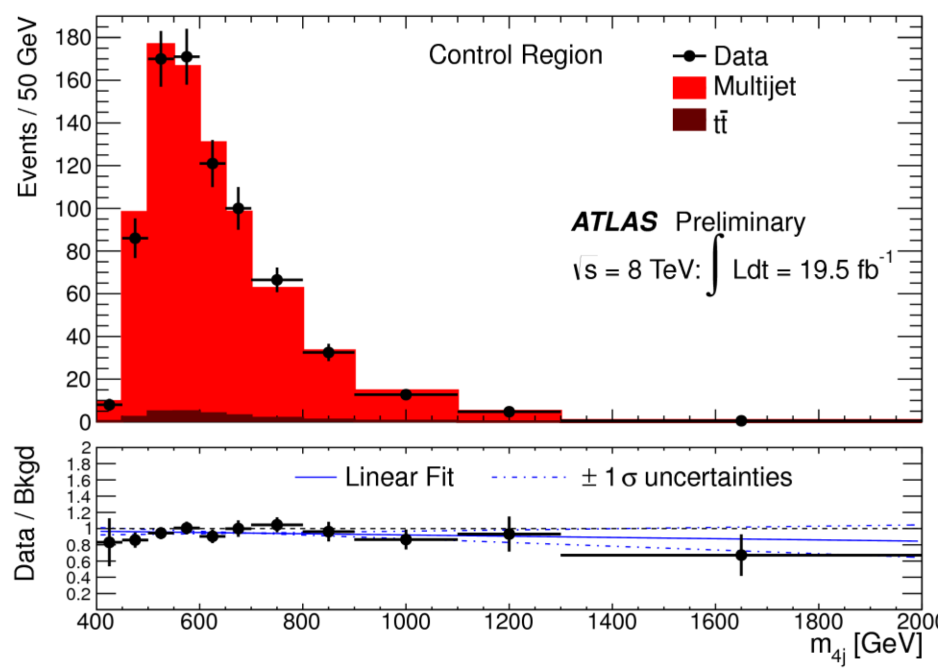




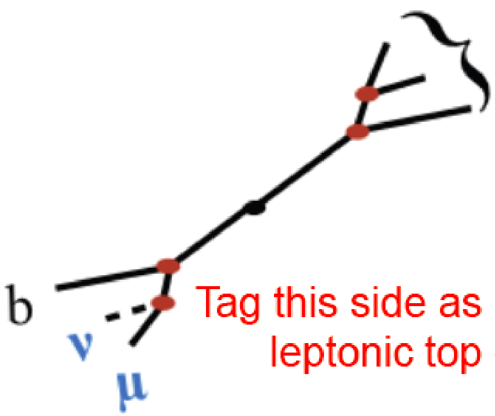
Data-driven ttbar background estimate

- ttbar yield in signal region given by:

$$N_{t\bar{t}}^{Bkg} = \frac{\epsilon^2}{1-\epsilon^2} \times N_{t\bar{t}}^{CR}$$

Per dijet efficiency to pass ttbar veto

- Measured in data using semi-leptonic control region (SLCR).



Require dijet candidate and measure ε

Tag this side as a boosted leptonic top decay.

- Measure ε = 0.624 ± 0.043 (stat) ± 0.062 (sys.)

ttbar yield in ttbar Control Region (TTCR)

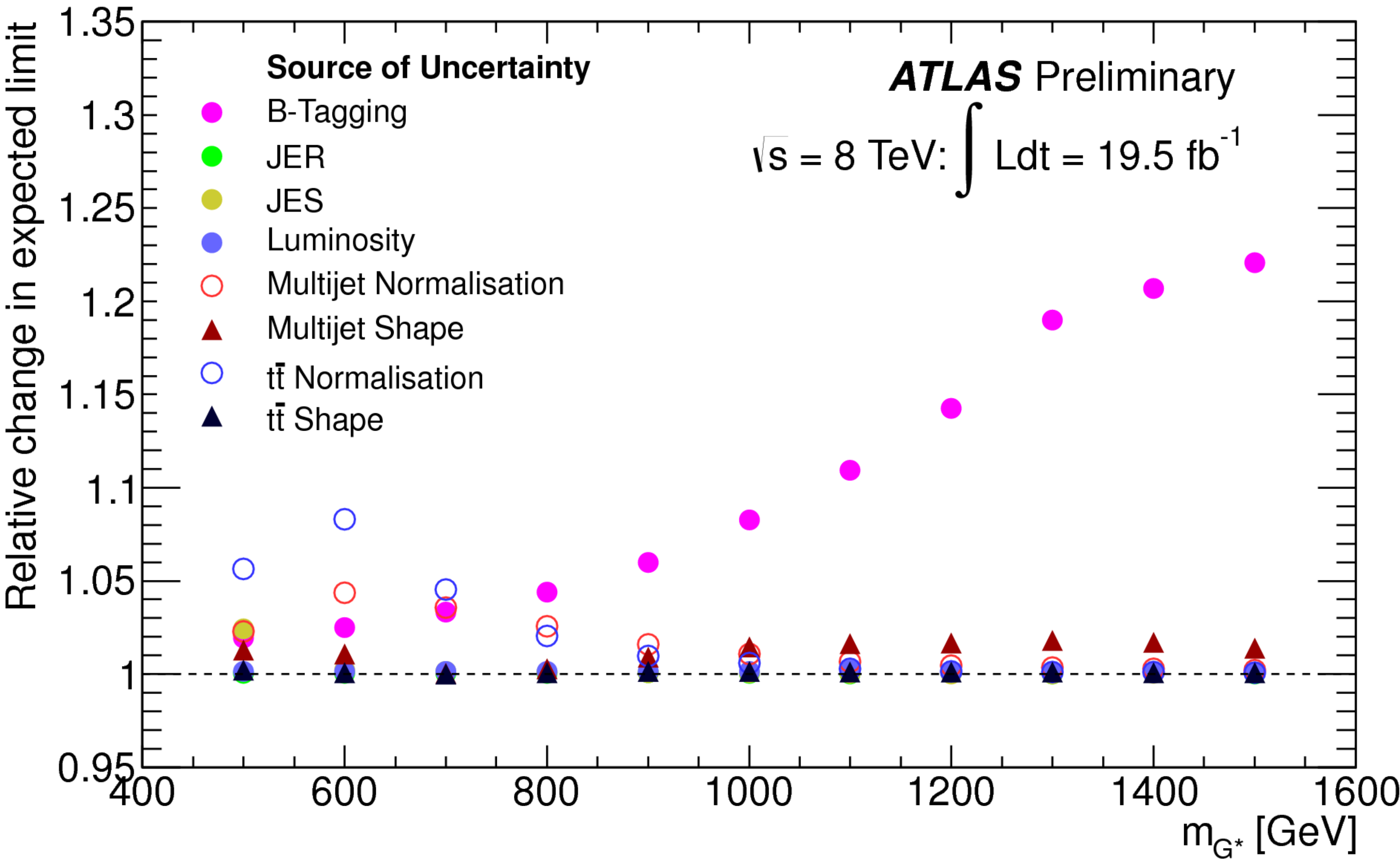
- ttbar veto requirement reversed
- ttbar yield determined by subtracting multijet contribution.
- Gives 16.0 ± 6.9.

Two assumptions:

- Dijet efficiencies uncorrelated.
- ε in SLCR same as ε in signal region.

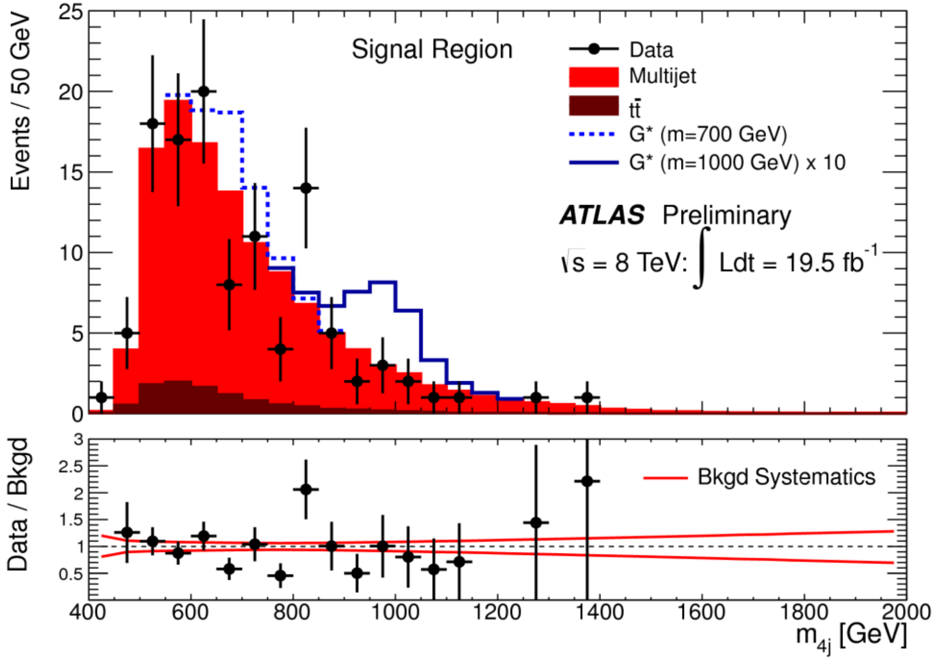
Tested in MC. Closure to 10% level.

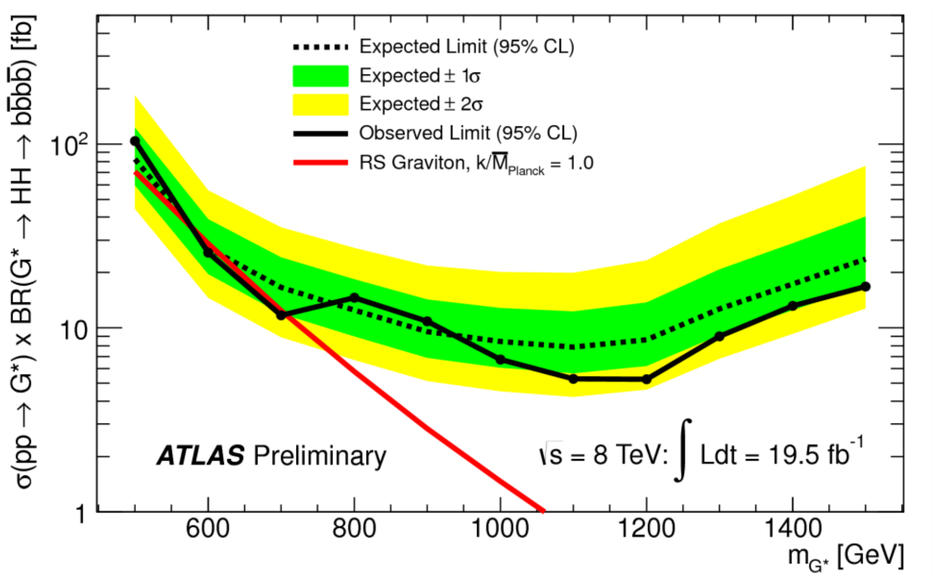
- Gives N_{tt} = 10.2 ± 6.0 events (error driven by stat in TTCR)
- cf MC prediction of N_{tt} = 14.3 ± 0.3 events



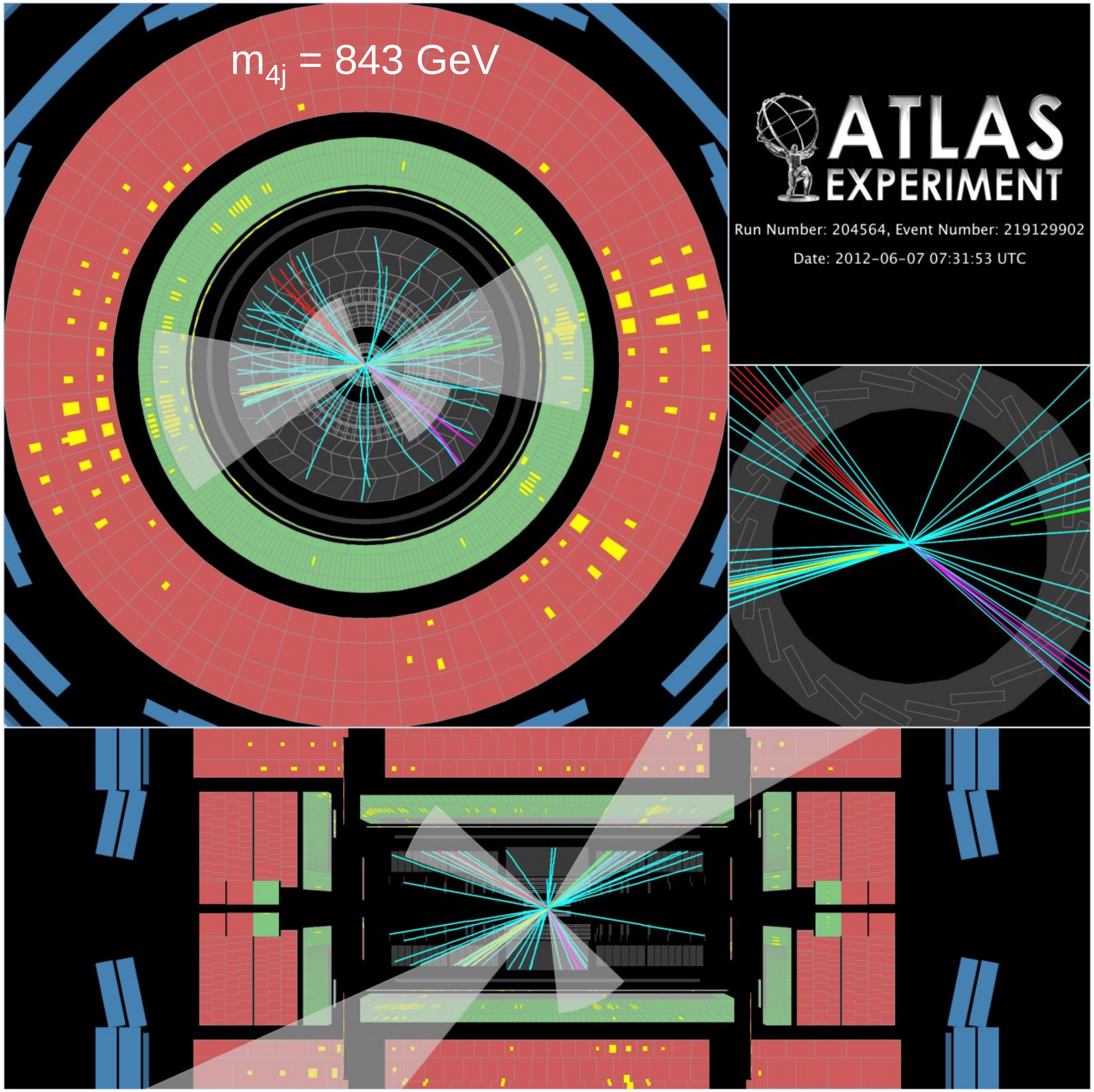
Source of Uncertainty
B-Tagging
JER
JES
Luminosity
Multijet Normalisation
Multijet Shape
tt̄ Normalisation
tt̄ Shape
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb-1
Relative change in expected limit
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
400
600
800
1000
1200
1400
1600
mG* [GeV]

Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114
G^* (m_{G^*} = 500 GeV)	12.5 ± 0.4
G^* (m_{G^*} = 700 GeV)	12.5 ± 0.2





X→HH→bbbb candidate



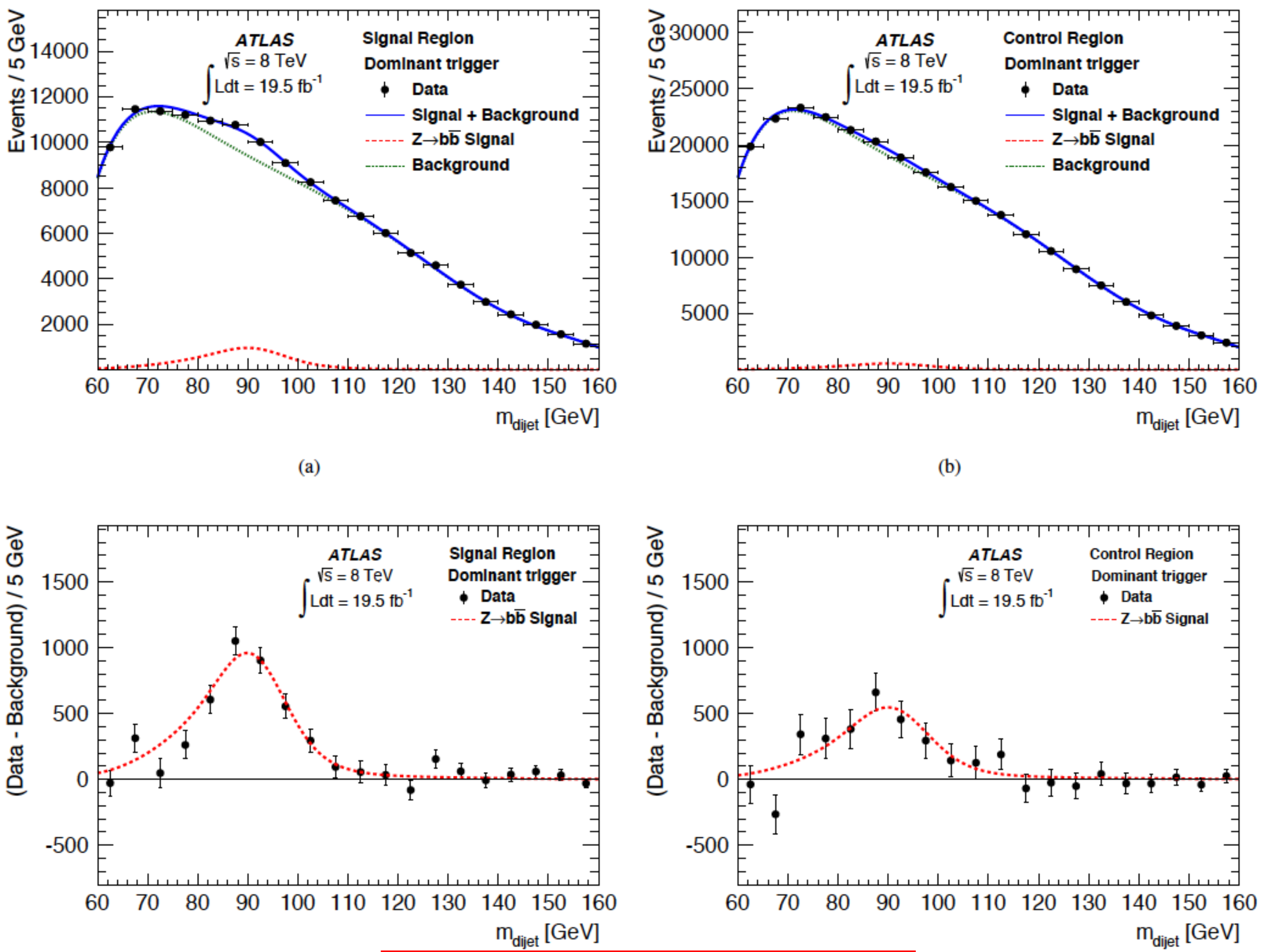
Summary and Outlook

- High-p_T bb resonances lead to interesting topologies and are set to play an increasingly significant role in LHC physics

- σxBR($X \rightarrow HH \rightarrow bbbb$) down to ~10fb explored (for m_X~1TeV), but no evidence for any signal found in the range 0.5 TeV < m_X < 1.5 TeV

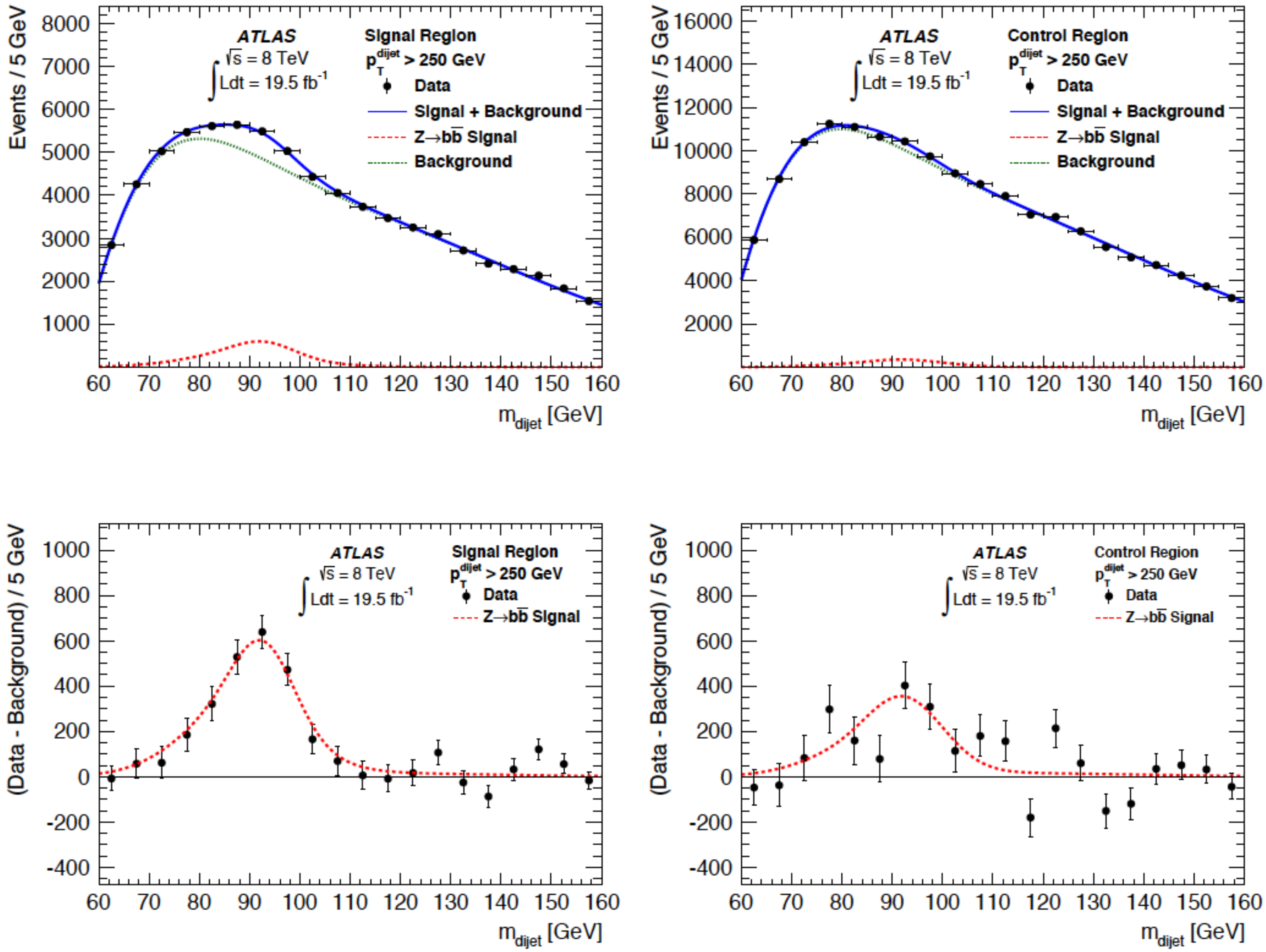
- HH→4b appears to be the most sensitive final state for resonant Higgs-pair production at the LHC
  - Exciting prospects for the future LHC programme

Back up slides



$$\sigma^{\mathrm{fid}}_{Z\to b\bar{b}} = 1.99 \pm 0.25\,(\mathrm{stat.})\,\mathrm{pb}$$

Z→bb cross check: p_T>250GeV



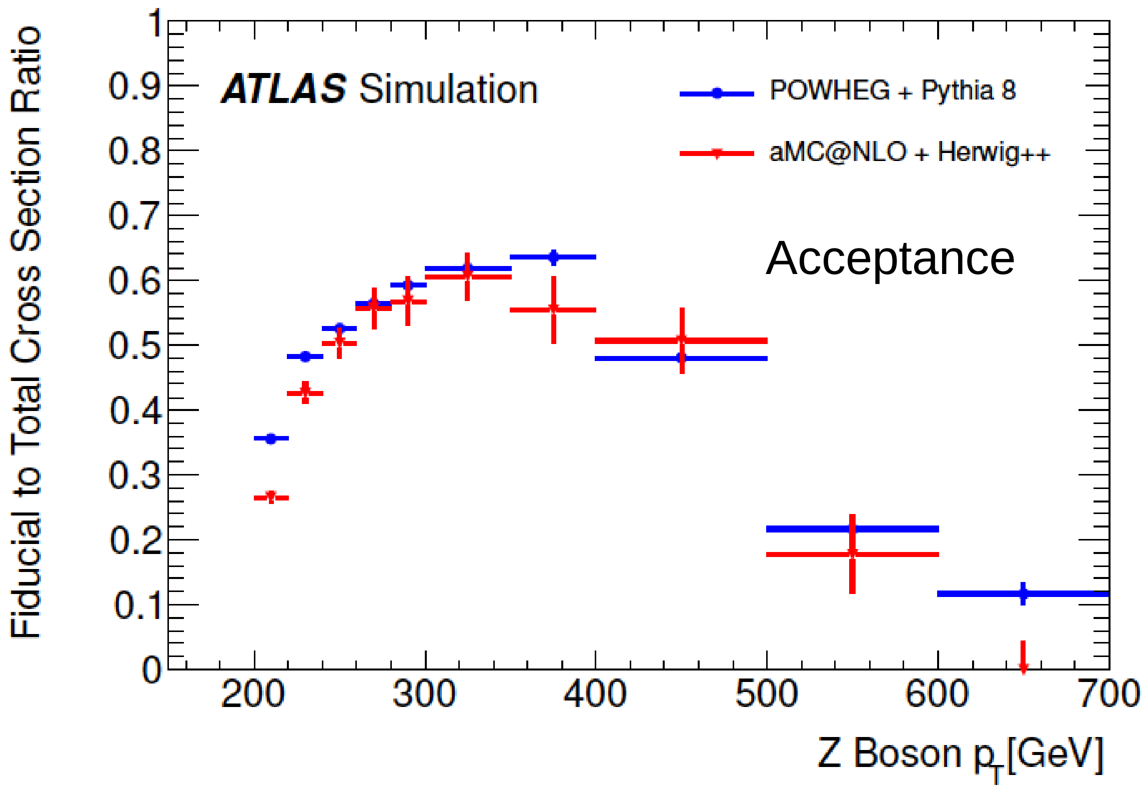
$$\sigma^{fid}_{Z\to b\bar{b}} = 2.11 \pm 0.28\,(\mathrm{stat.})\,\mathrm{pb}$$

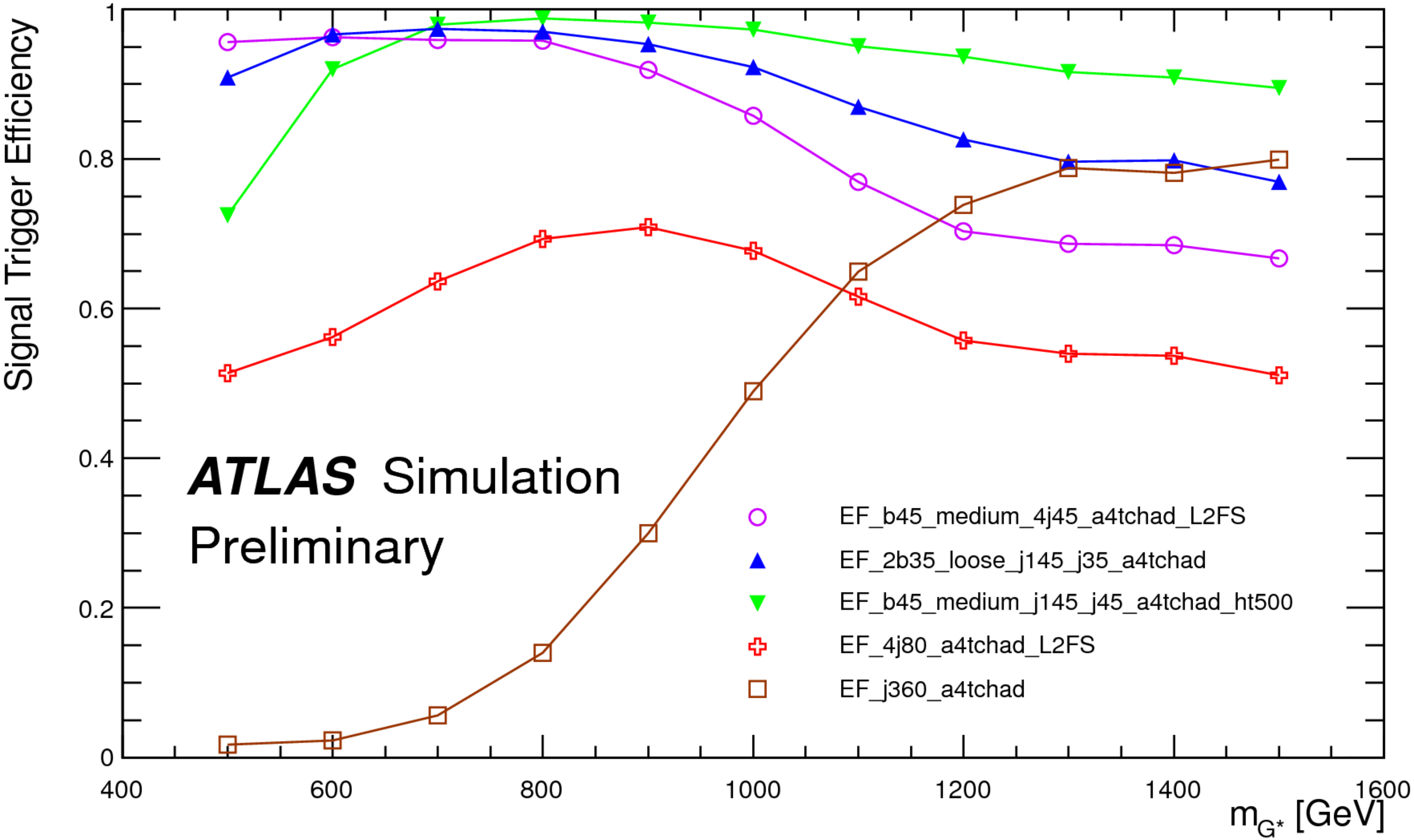
Fiducial cross section definition at particle level:

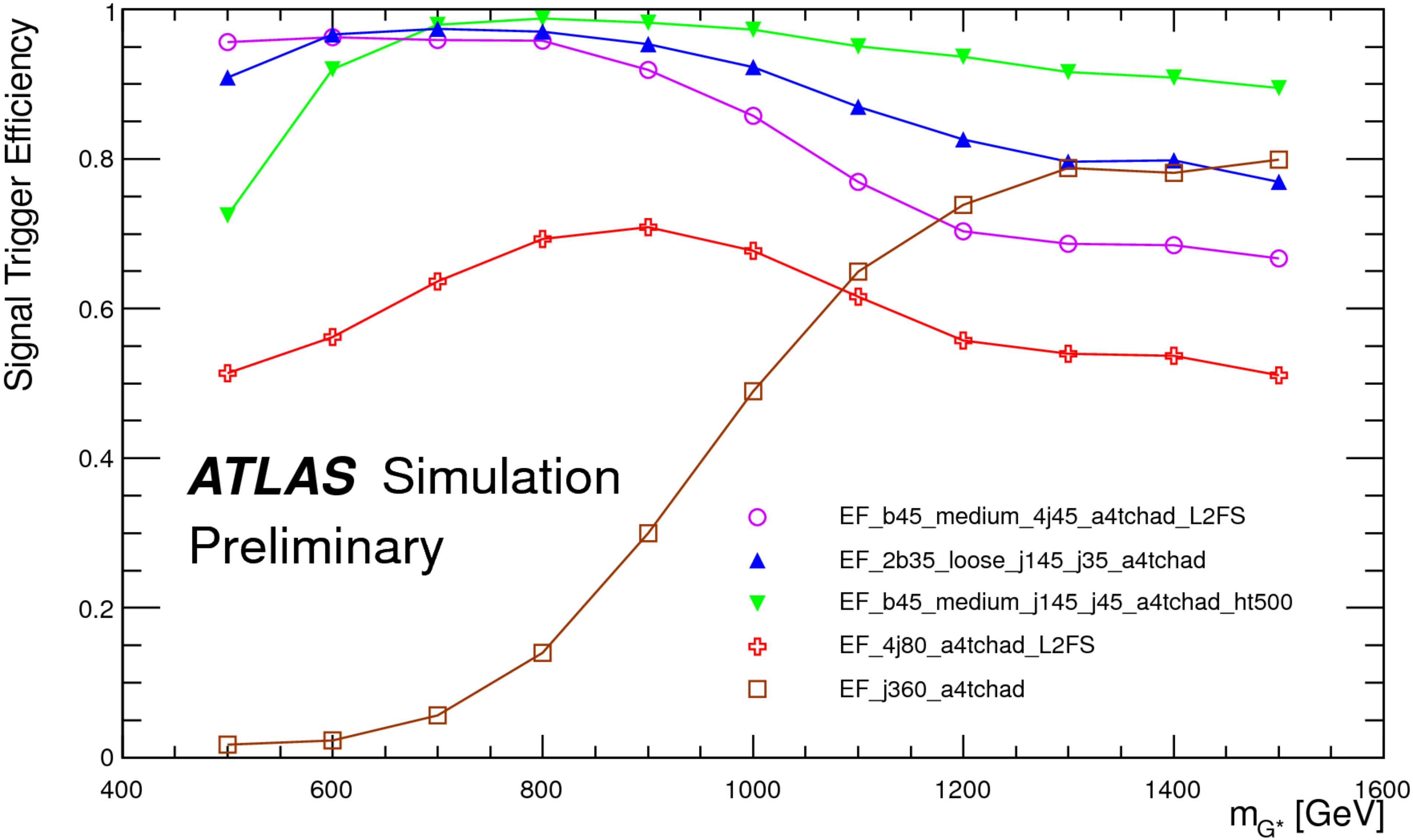
- 2 anti-k_t R=0.4 b-jets, with $|\eta|<2.5$, $p_T>40$GeV

- ΔR(jet1,jet2)<1.2, dijet pT>200GeV

- 60 GeV < m_{dijet} < 160 GeV




Signal Trigger Efficiency
0
0.2
0.4
0.6
0.8
1
400
600
800
1000
1200
1400
1600
m_G* [GeV]
ATLAS Simulation
Preliminary
EF_b45_medium_4j45_a4tchad_L2FS
EF_2b35_loose_j145_j35_a4tchad
EF_b45_medium_j145_j45_a4tchad_ht500
EF_4j80_a4tchad_L2FS
EF_j360_a4tchad


Signal Trigger Efficiency
1
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400
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m_G* [GeV]
ATLAS Simulation
Preliminary
EF_b45_medium_4j45_a4tchad_L2FS
EF_2b35_loose_j145_j35_a4tchad
EF_b45_medium_j145_j45_a4tchad_ht500
EF_4j80_a4tchad_L2FS
EF_j360_a4tchad