UCL

Exotic Results from b-Jet Searches

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Why *b*-jets in Exotics

- **Many BSM models predict decays to *b*-quarks**
  - 3rd generation
  - Interesting
- **Higgs has preferential decay to *b*-jets**
  - Higgs boson may allow us to be sensitive to BSM physics
  - DM, Graviton
- ***b*-Tagging can increase sensitivity to certain models**
  - Reduction of QCD backgrounds (e.g. gg from QCD)

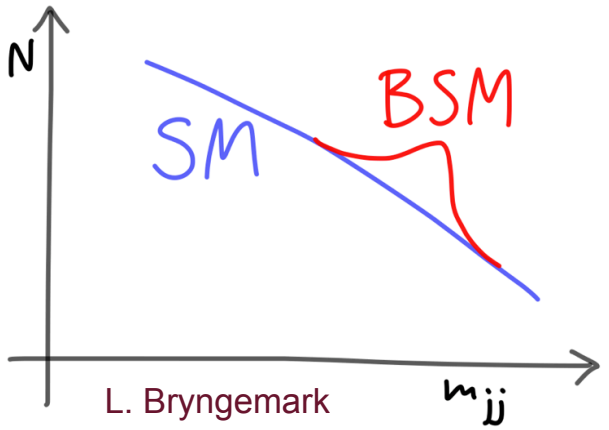
- **How much data excluding IBL**
  - 3.5 ifb
- **Why exclude IBL**
  - There exists plots to say that tagging performance is bad
  - Not supported by *b*-tagging group

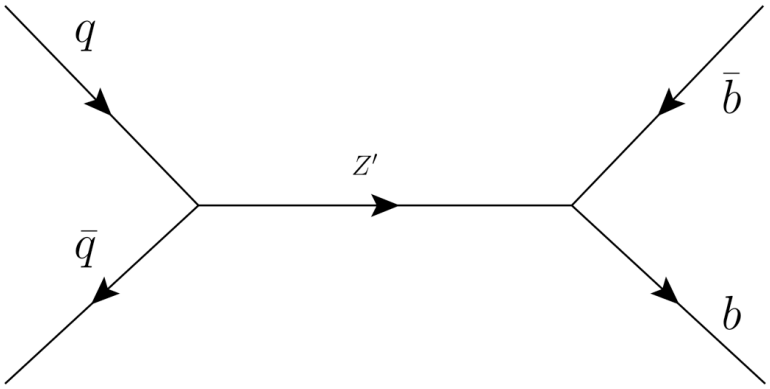
High-p_T *b*-tagging

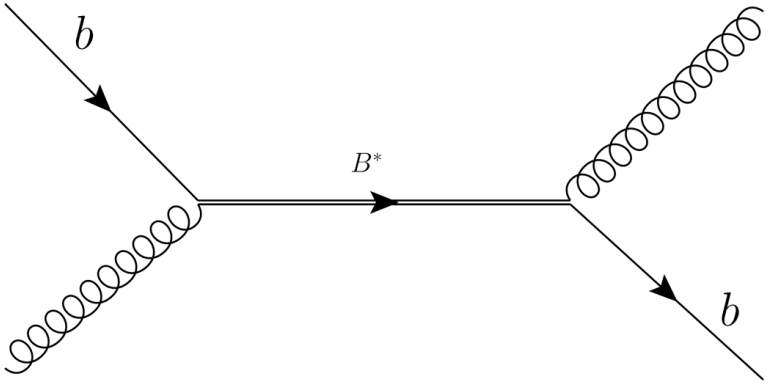
- **What is the performance**
  - Ask Valerio?
- **And it is calibrated**
  - Description of fact that *b*-tagging is calibrated up to ~1 TeV

b-Tagged Dijet Analysis

- **Search for resonance in invariant mass spectrum of b-tagged jets**
  - Fit QCD background using smoothly falling function.
  - Follows a similar path to dijet analysis
- **In addition, b-tagging is applied.**
  - Three categories - 0, 1 and 2 b-tags
- **Search for generic di-jet resonance**
  - Gaussian with width similar to benchmark models.
  - Two Benchmark models, which we will set limits on.
    1) **Z' => bb**, double b-jet final state.
    2) **b* => bg**, single b-jet final state.



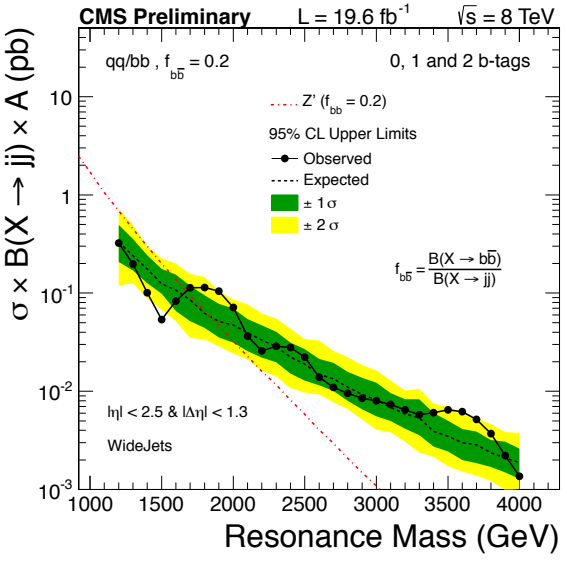




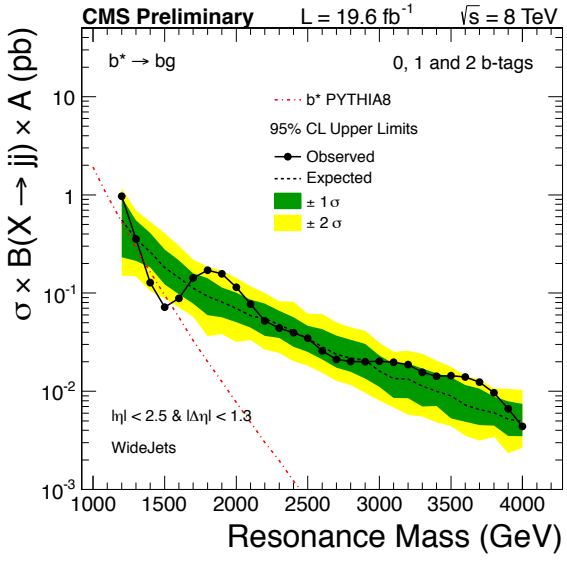
- Many BSM models predict heavy particles that decay into bb or bg.
  - Z', b*, RS Graviton...
  - b-Tagging can be used to reduce light dominated QCD background
  - Hence increased sensitivity to these models.

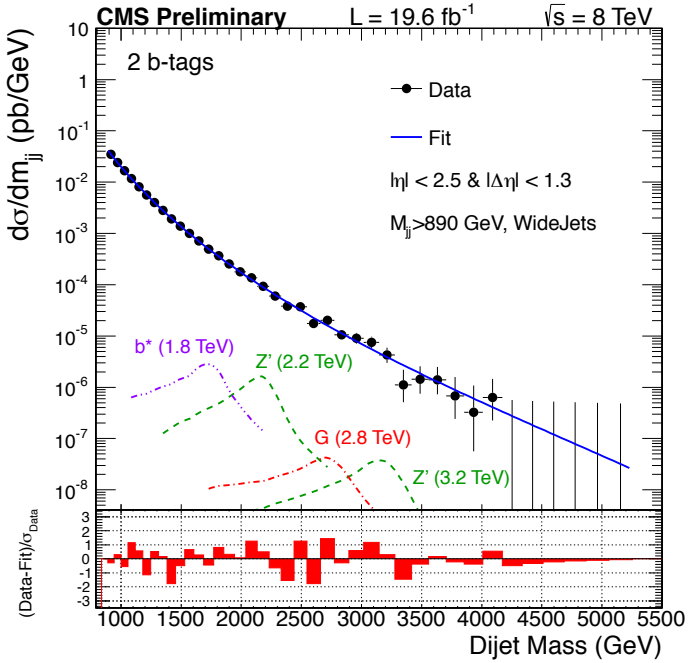
- Generic search performed searching for high mass resonance decaying to b-tagged jets.
  - Performed at CDF and CMS - (*CMS-PAS-EXO-12-023*)
  - No ATLAS result from Run-1

Z' excluded at 1.7 TeV



b excluded at 1.5 TeV*





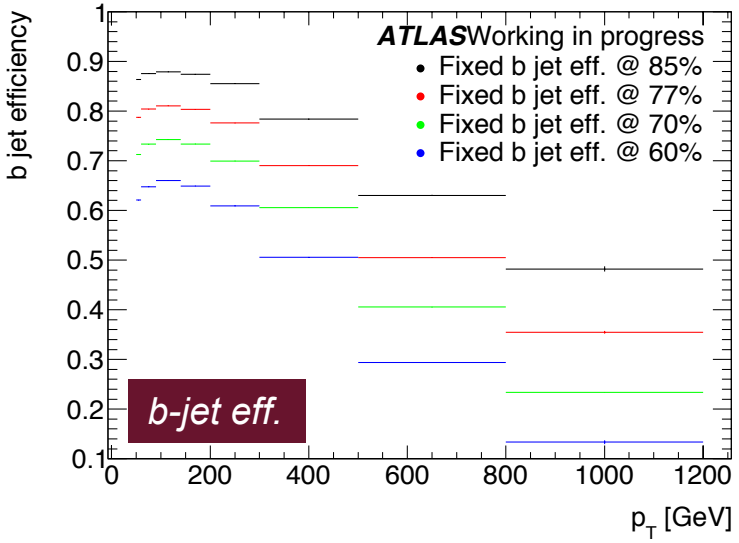
- **Data Used**
  - 25ns data with luminosity of **3.27 fb^{-1}** (Periods D-J)
  - Exclude runs with IBL Off

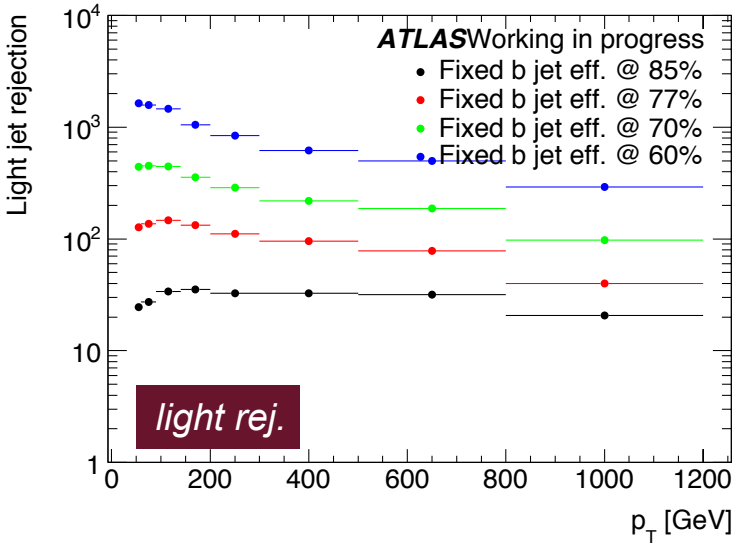
- **Trigger**
  - **HLT_j360**, lowest unprescaled single jet trigger

- **Event Selection** (Full list in backup)
  - Same as dijet analysis
  - **m_{jj} > 1100 GeV**, on the trigger plateau.
  - **|y*| < 0.6**, where $y^* = 0.5*(y_1 - y_2)$
    - Central region more sensitive to BSM physics.

- **MV2c20**
  - **Fixed cut 85% efficiency working point**
  - MV2c20 > -0.7887
  - Loose WP provides best sensitivity compared to others.

- b-jet efficiency ~ 50% at jet-p_T ~ 1 TeV
- Light-jet rejection ~ 30
  - Approx. flat, good for background modelling.



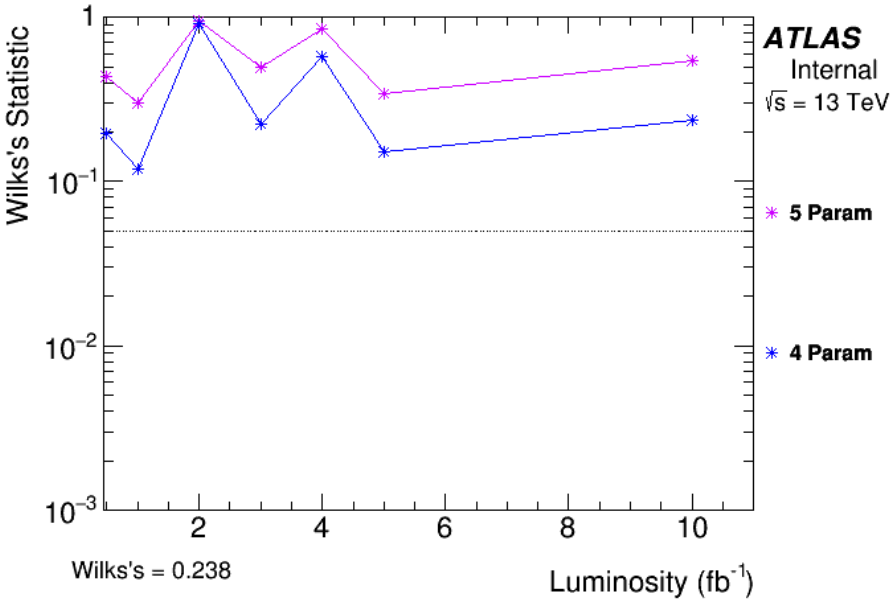


- Fit to background using smoothly falling function:

$$f(x) = p_1(1-x)^{p_2}(x)^{p_3+p_4\ln x+p_5\ln x^2}$$

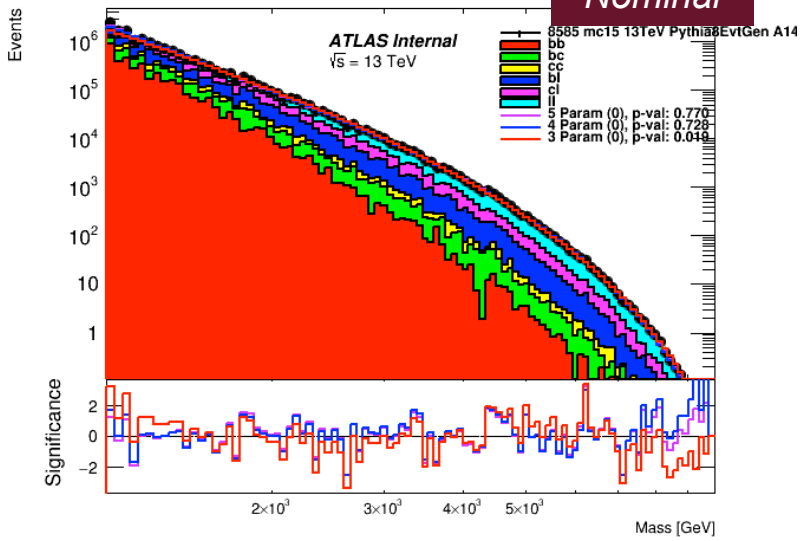
where, $x = m_{jj}/\sqrt{s}$

- Default option is 3 parameter (p_4, p_5 = 0)
  - Use Wilks' statistic to determine if we need to change to 4-parameter fit
  - 3 Parameter sufficient to 10 fb^{-1} with MC

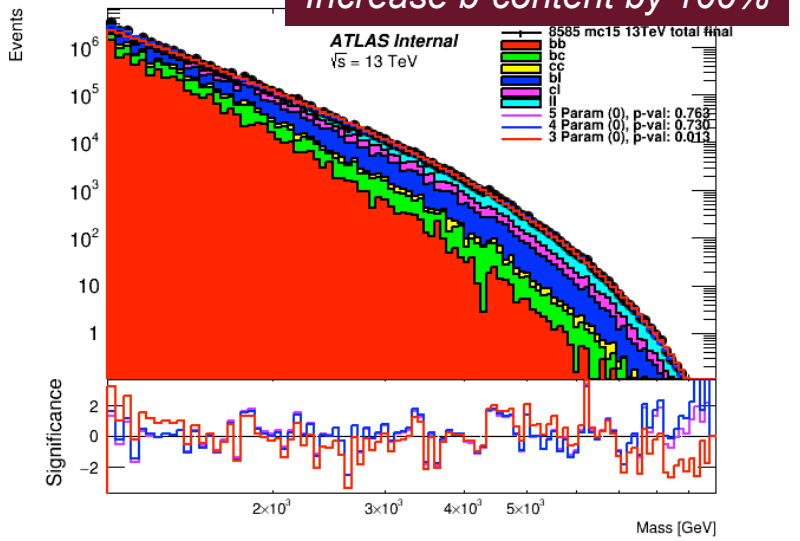


- Performing cross-checks confirming that we are robust to changes in flavour fraction
  - At high mass background is dominated by lights.

Nominal



Increase b-content by 100%

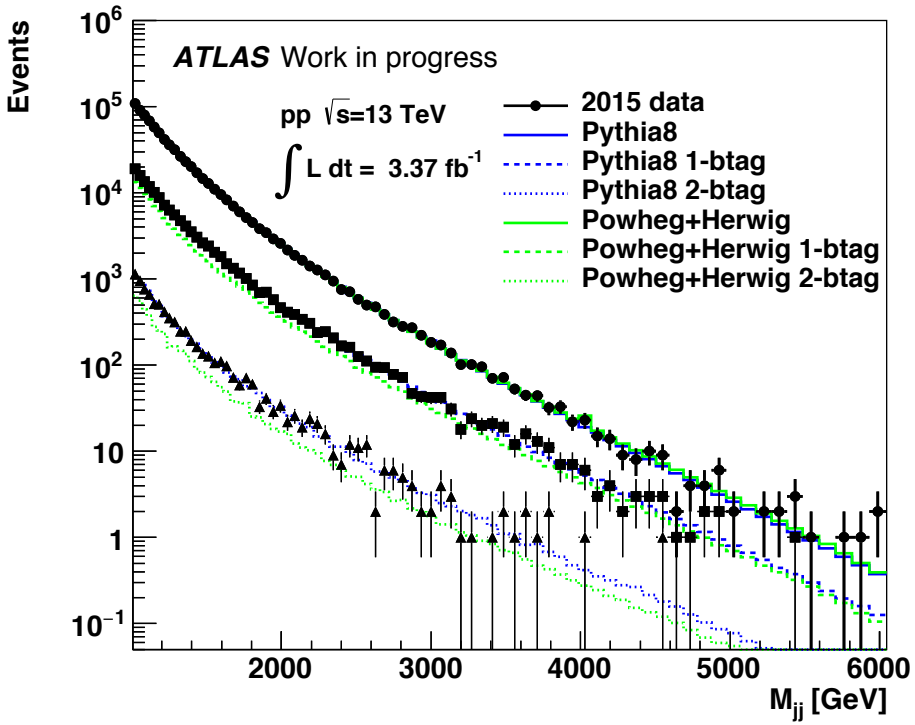


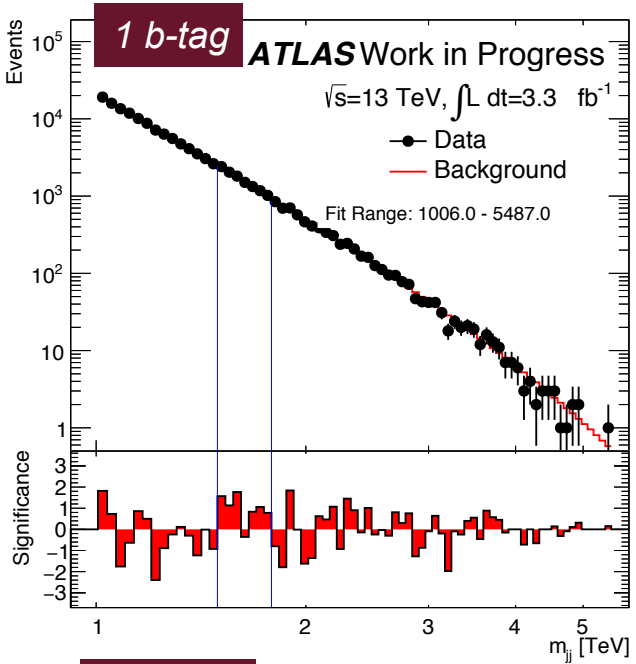
Data - Bump Hunter

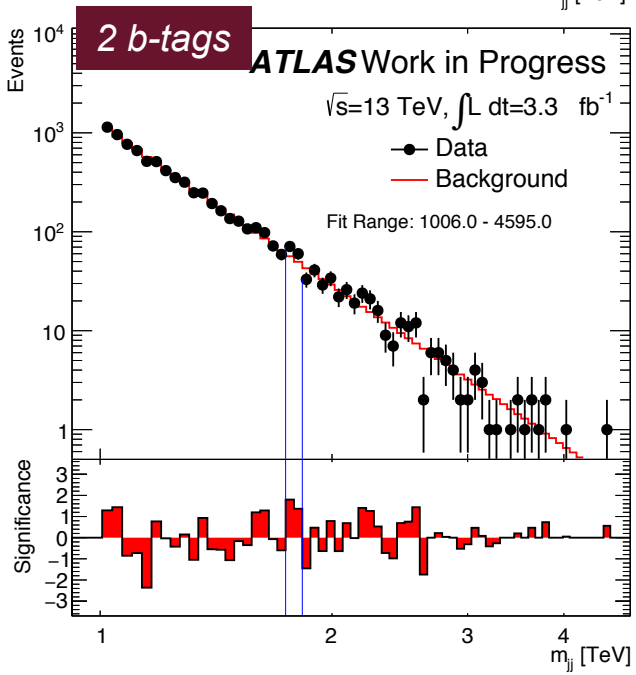
b-tagged di-jet

- Mass spectra in three tag categories
  - 3.27 fb^{-1} of data, full data set.
  - Background fitted with smoothly falling function
- Bump Hunter searches for resonances
  - Looks for a Gaussian signal
  - Searches for statistically significant deviations.

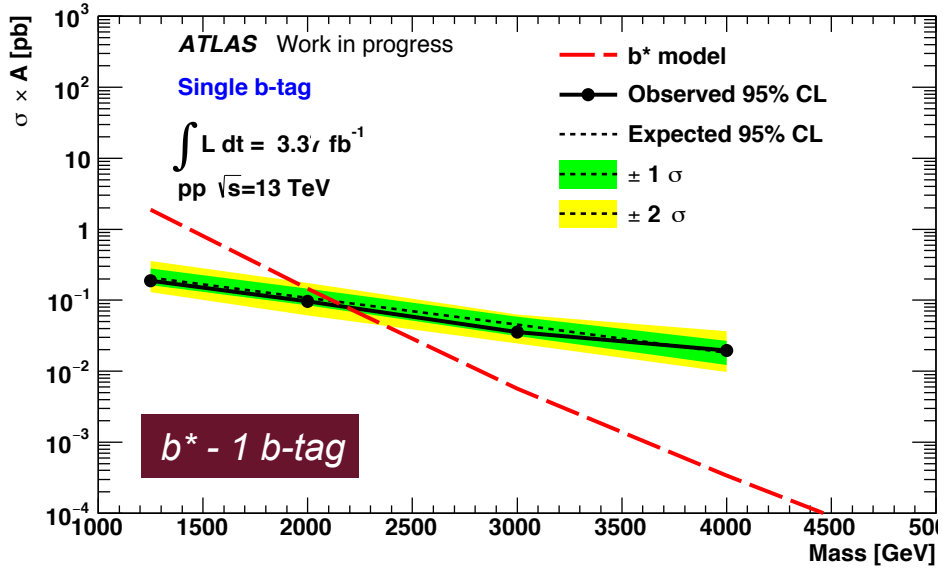
- **No excess found more significant than 2σ**

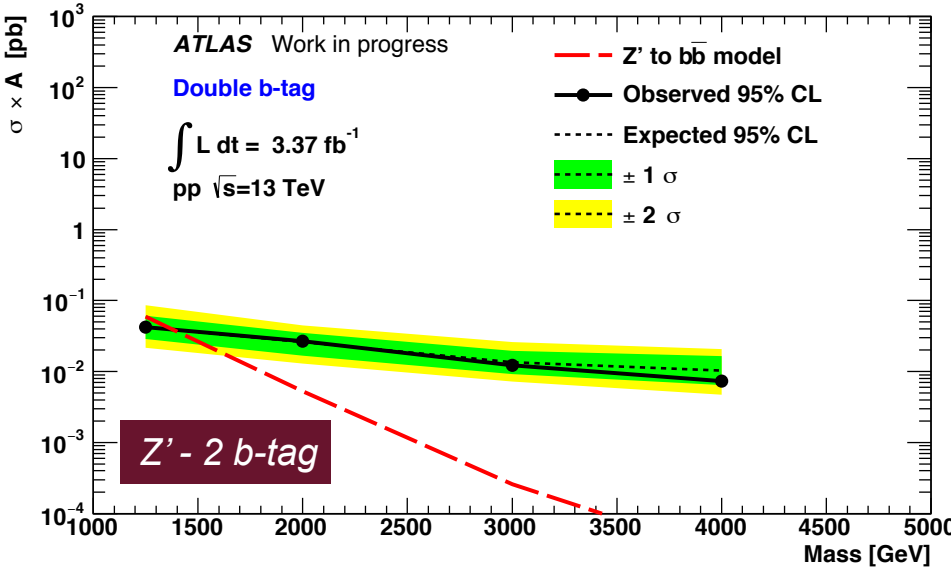






- Machinery up and running, using Di-jet statistical package
  - Deviations found by bump-hunter, test statistics by running pseudo-experiments.
  - 95% C.L. upper limiting
  - Use Bayesian approach for limit setting.
  - No Correction for acceptance.
  -
- Systematics: Some still need to be added to the limit setting program.
  - ✓ Luminosity uncertainty - 9%
  - ✓ JES uncertainty - 1σ up and down
  - ✓ JER uncertainty - 1σ up and down
  - ➡ BJES uncertainty - to be added
  - ➡ B-tagged scale factor uncertainties - to be added





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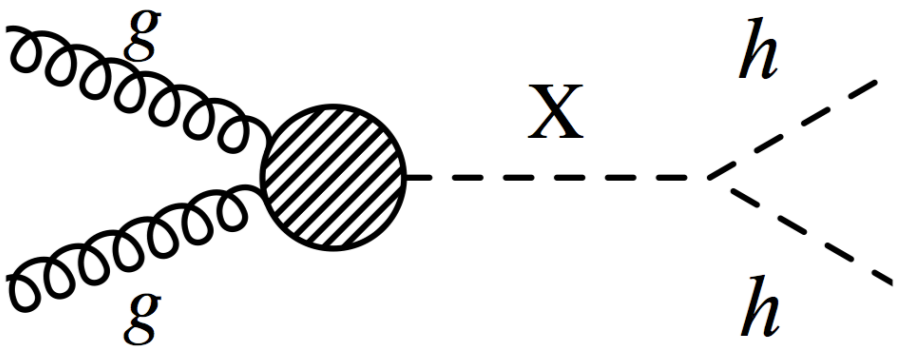
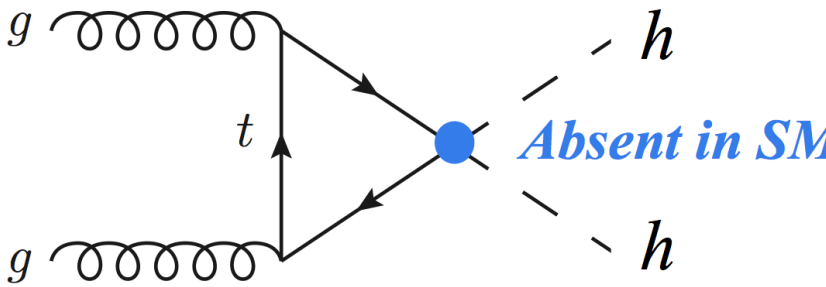
Di-Higgs Exotic Search:
X => hh => 4b

Exotics can create di-higgs events in two main ways:

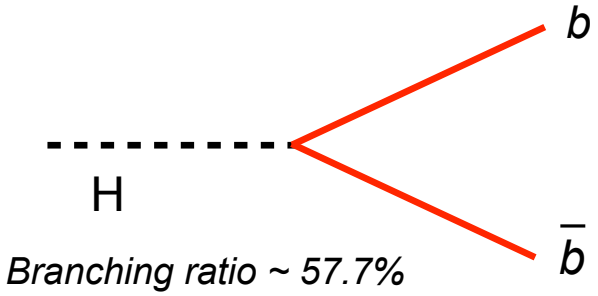
- **Resonant *hh* production**
  - Several models produce this
  - E.g. KK-Graviton, 2HDM, ect...



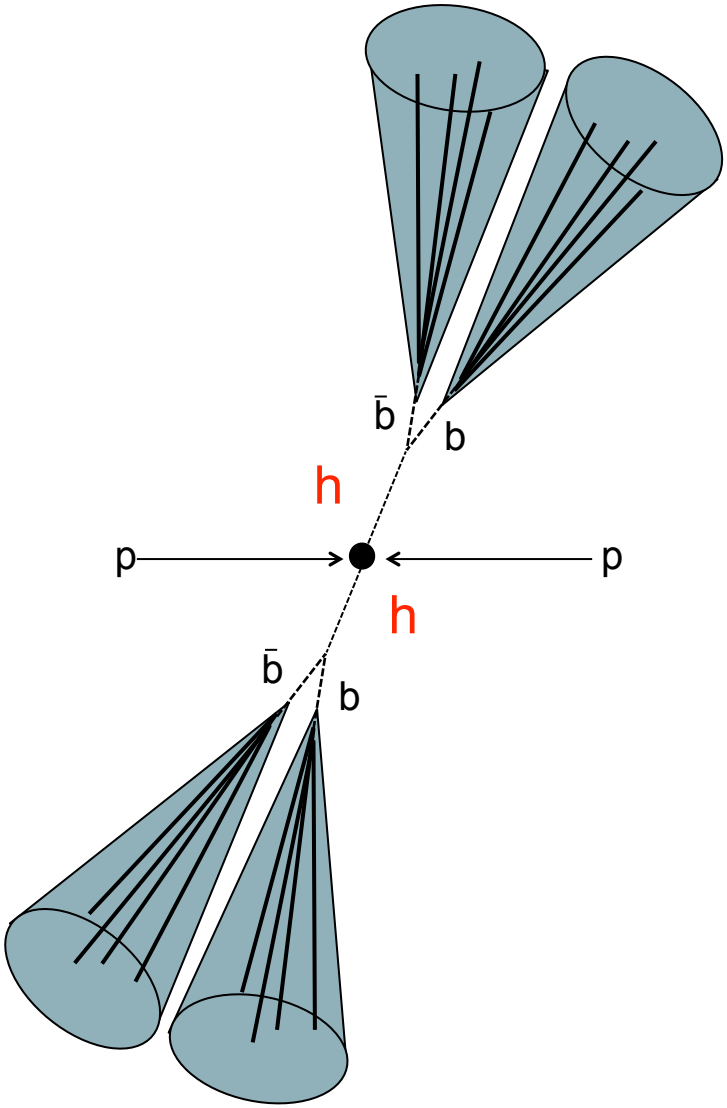
- **Non-resonant *hh* enhancement**
  - This can occur in several BSM models
  - Composite Higgs, Little Higgs ...



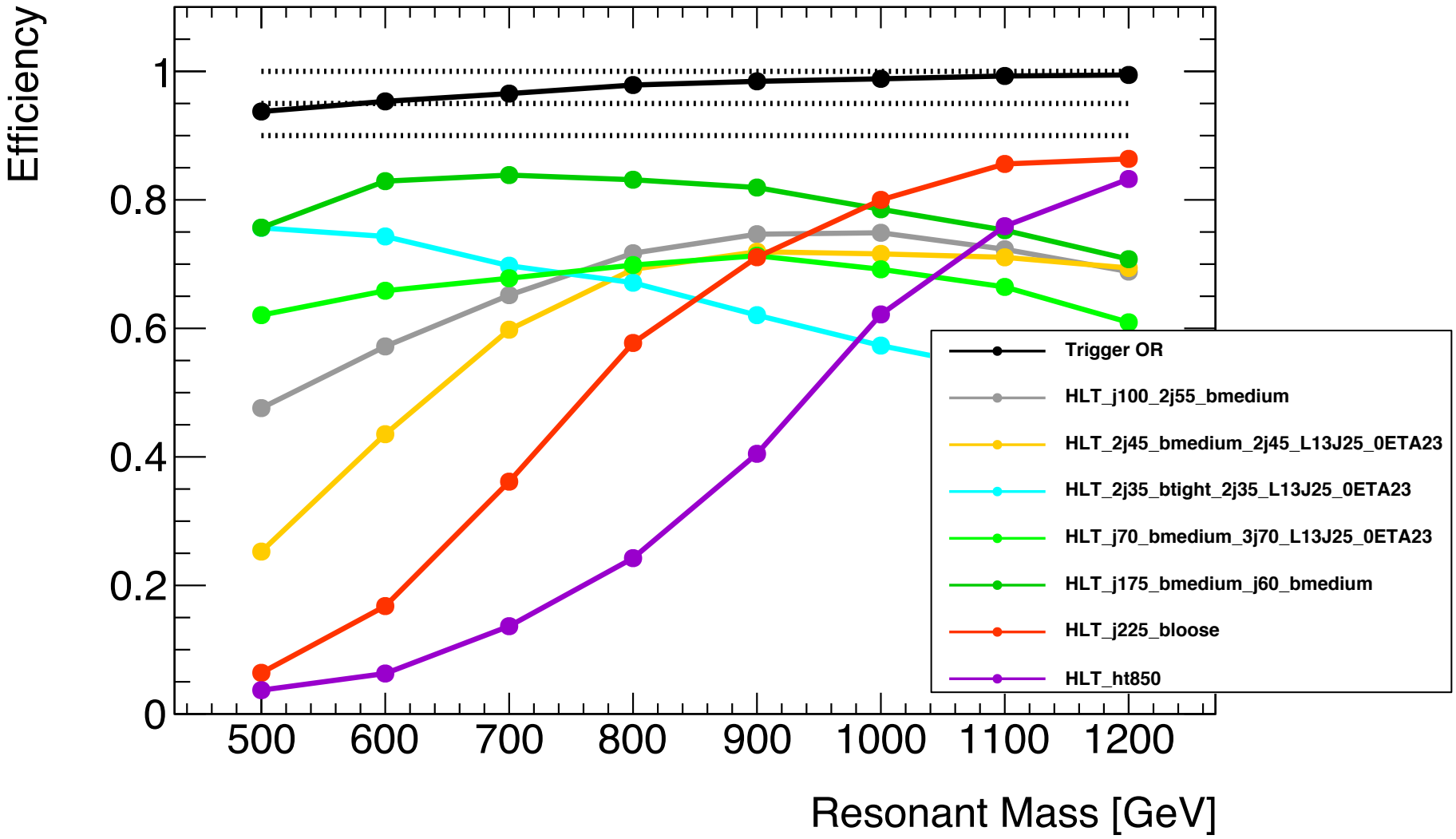
- ***hh* => *bbbb* is the dominant decay**
  - Strong coupling to heavy *b*-quark
  - Branching ratio of 33%



- **4 *b*-tagged Jets**
  - Anti-k_T, with R = 0.4
  - MV2c20 @ 70% Efficiency WP
- **2 "Higgs Candidates" from pairs of *b*-jets**
  - $\Delta R < 1.5$ between *b*-jets
  - Higgs Candidate $P_T > 150$ GeV
  - Mass of Higgs Candidate ~ M_H
- **Kinematic Cuts on:**
  - P_T of Higgs candidate
  - $\Delta\eta$ of Higgs candidate
- **ttbar veto**
  - If additional jet exists (jet $p_T > 30$ GeV)
  - Add. jet and lowest MV2c20 jet make "W cand."
  - m_t comes from all three jets.
  - Veto if $X_{tt} = \sqrt{(\frac{m_W - 80.4}{\sigma_{m_W}})^2 + (\frac{m_t - 172.5}{\sigma_{m_t}})^2} < 3.2$



This is "Resolved Selection", effective for resonances < ~ 1 TeV

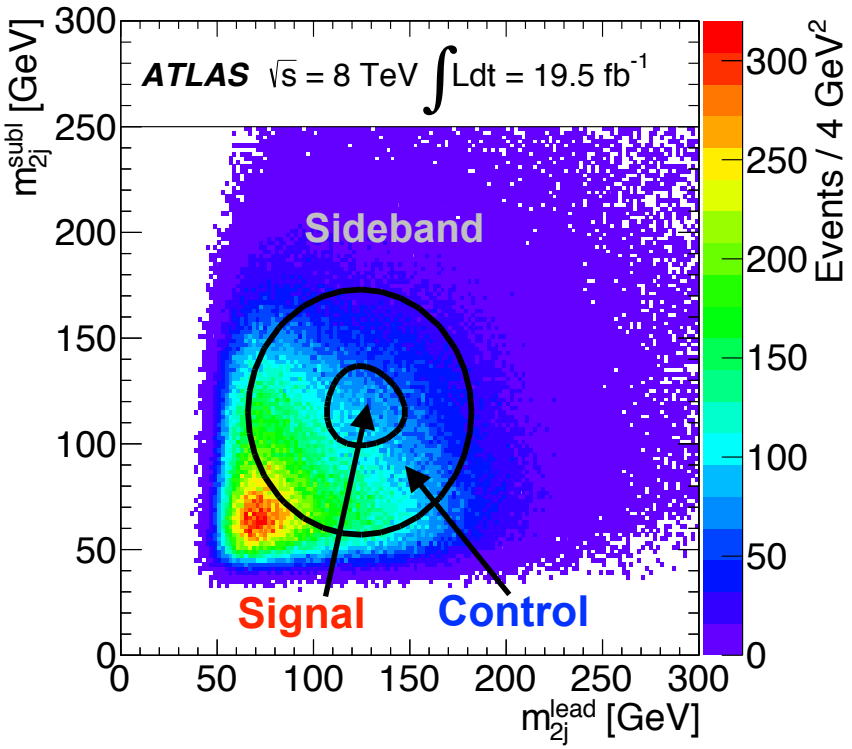


- **Use a cocktail of *b*-jet triggers.**
  - Can achieve 95% efficiency

- **QCD Background Estimation**
  - Multi-jet is dominant background
  - Use ratio of 4-tag to 2-tag categories to estimate.

$$\mu_{\mathrm{QCD}} = \frac{N_{\mathrm{QCD}}^{4-\mathrm{tag}}}{N_{\mathrm{QCD}}^{2-\mathrm{tag}}} = \frac{N_{\mathrm{data}}^{4-\mathrm{tag}} - N_{t\bar{t}}^{4-\mathrm{tag}} - N_{Z}^{4-\mathrm{tag}}}{N_{\mathrm{data}}^{2-\mathrm{tag}} - N_{t\bar{t}}^{2-\mathrm{tag}} - N_{Z}^{2-\mathrm{tag}}}$$

- **Sideband Region:**
  - Derive 2 => 4 tag modelling
- **Control Region:**
  - Test 4 tag modelling
- **Signal Region:**
  - Search for excesses



- **Signal Region:** $X_{hh} < 1.6$

$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{\mathrm{lead}} - 124.0}{\sigma_{m_{2j}^{\mathrm{lead}}}}\right)^2 + \left(\frac{m_{2j}^{\mathrm{subl}} - 115.0}{\sigma_{m_{2j}^{\mathrm{subl}}}}\right)^2}$$

- **Control Region**
  - $X_{hh} > 1.6$ (Not in signal region)

$$\sqrt{(m_{2j}^{\mathrm{lead}} - 124.0)^2 + (m_{2j}^{\mathrm{subl}} - 115.0)^2} < 58\,\mathrm{GeV}$$

- **Sideband Region**

$$\sqrt{(m_{2j}^{\mathrm{lead}} - 124.0)^2 + (m_{2j}^{\mathrm{subl}} - 115.0)^2} > 58\,\mathrm{GeV}$$

- **ttbar Background Estimation**
  - ttbar contributes ~ 10% for resolved analysis
  - Inverse ttbar veto to create control sample.
  - Predict ttbar background using:

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

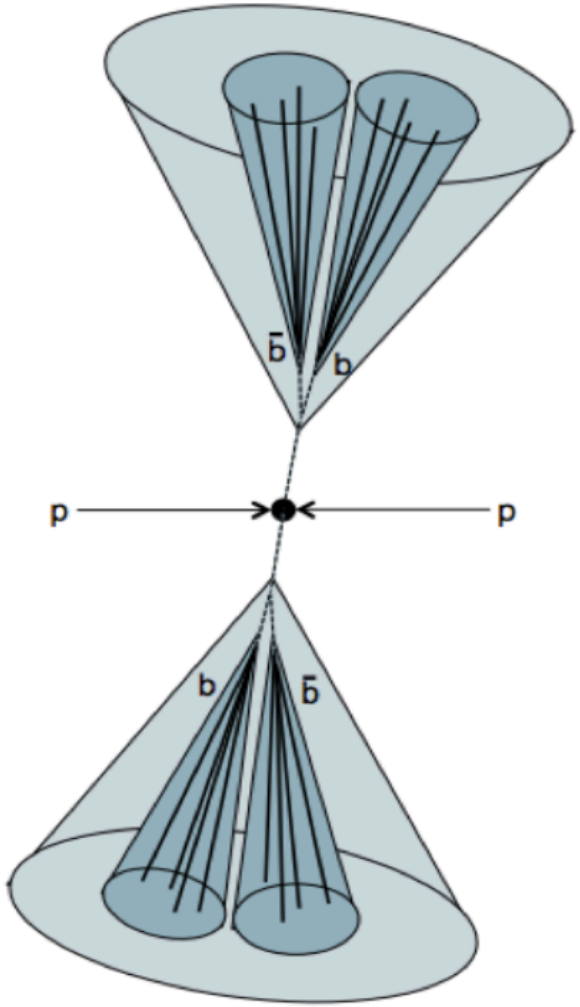
- **ttbar veto**
  - If additional jet (p_T > 30 GeV)
  - Form a "W candidate" from add. jet and lowest MV2c20 jet
  - m_t formed from all three jets
  - Veto if:

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

- **Background Estimates**
  - Data compared to estimation in three mass regions.
  - In addition small Z +Jets background taken from MC

Sample	Preselection	Sideband Region	Control Region
QCD	1088.65 ± 3.06	538.93 ± 2.15	487.52 ± 2.05
$t\bar{t}$	57.4 ± 7.58	15.95 ± 3.99	32.44 ± 5.7
Total	1146.05 ± 8.17	554.88 ± 4.54	519.95 ± 6.05
Data	Blinded	583.0 ± 24.15	509.0 ± 22.56

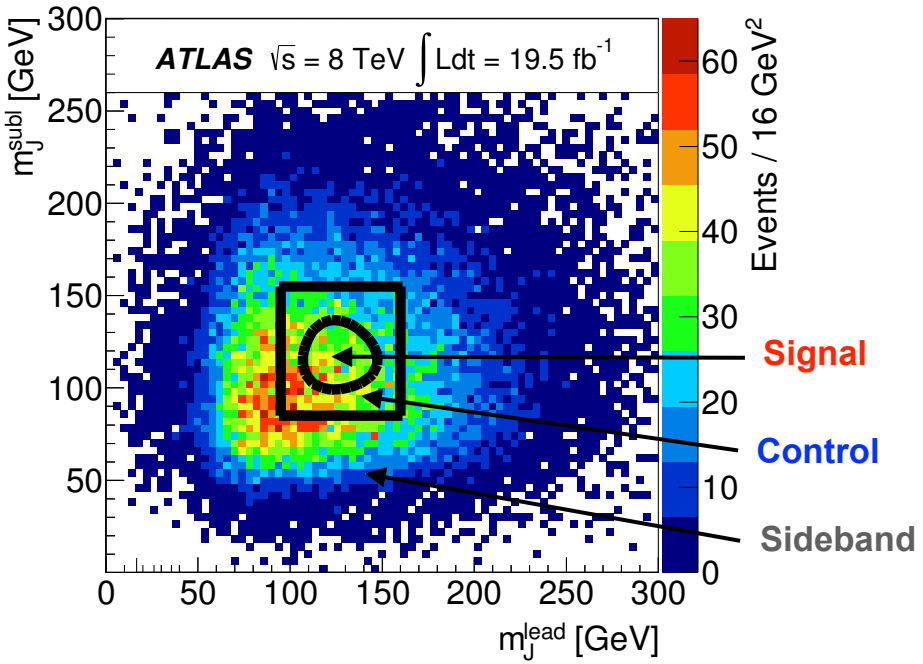
- **2 Fat Jets = "Higgs Candidates"**
  - Anti-k_T LC Topo, with R = 1.0
  - Apply trimmiming
  - Mass of jet ~ M_H
- **Matching to b-tagged track jets**
  - Track Jets with R = 0.2
  - Tagged with MV2c20 @ 70% WP
  - 3 and 4 tag signal regions
- **Kinematic Cuts on:**
  - P_T of Higgs candidate
  - Δη of Higgs candidate
- **Trigger Selection**
  - Much simpler than resolved analysis
  - Single jet trigger: *"HLT_j360_a10r"*
  - 95% Efficiency across range.



"Boosted Selection"
For resonances > ~ 1 TeV

- **QCD Background Estimation**
  - Use similar technique as resolved
  - Use 2-tag category to estimate QCD background in 3-tag and 4-tag

- **Sideband Region:**
  - Derive 2 => 3/4 tag modelling
- **Control Region:**
  - Test 3/4 tag modelling
- **Signal Region:**
  - Search for excesses



- **ttbar and Z+Jets Estimation**
  - Shape from MC
  - Normalisation using fit to large-R jet mass in sideband region

Sample	Sideband Region	Control Region
Multijet		53.8 ± 0.6
$t\bar{t}$		9.8 ± 0.3
Z+jets		.57 ± 0.17
Total	278 ± 1	65.2 ± 0.7
Data	281	68

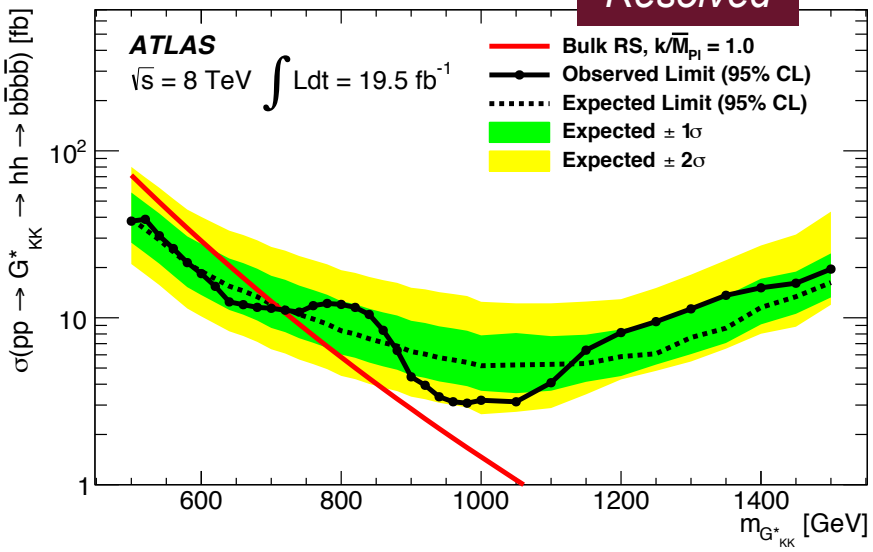
Run 1!!

Results: Limits on KK Graviton

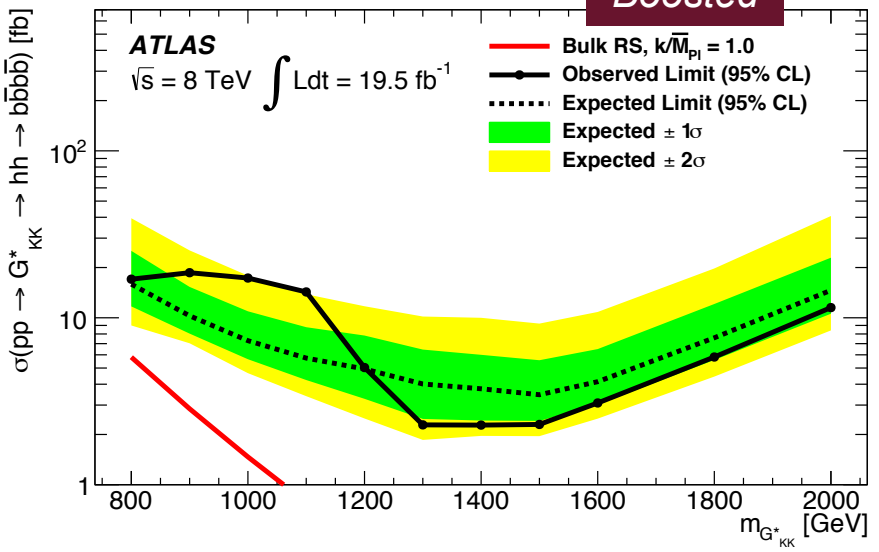
X => hh => 4b

Run 1

Resolved

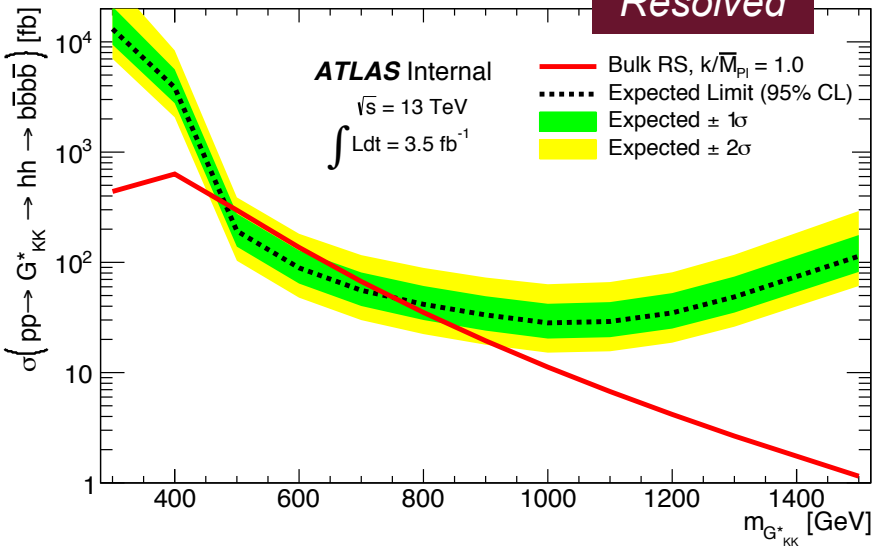


Boosted

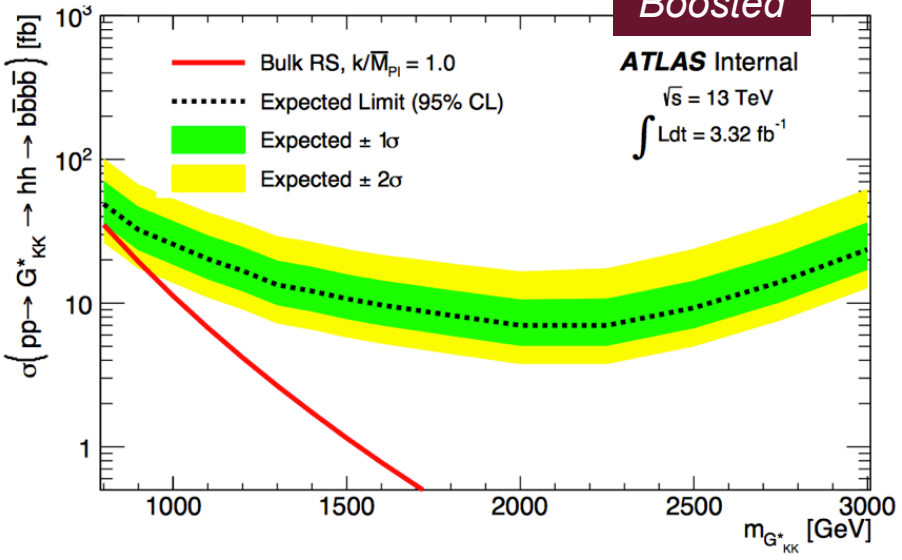


Run 2

Resolved



Boosted



Mono-Higgs Exotic Search:
hX => bb + MET

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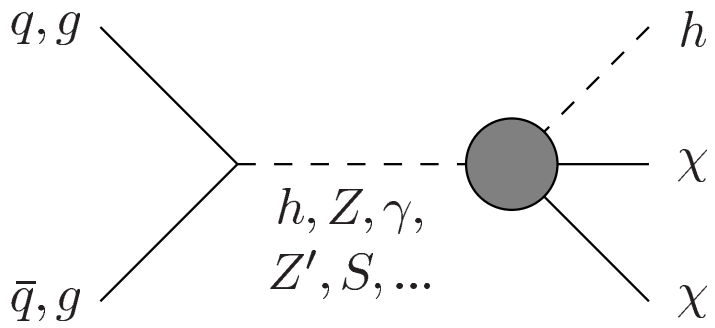
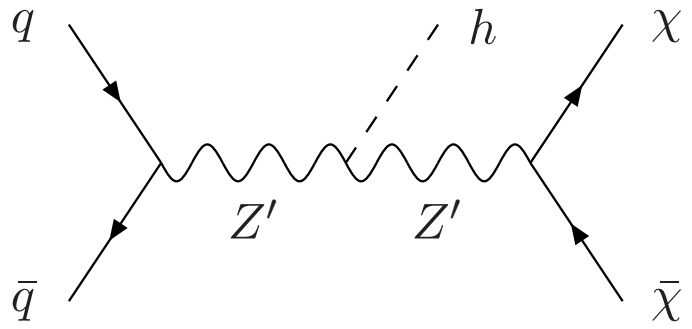
A few competing models for production of this analysis:

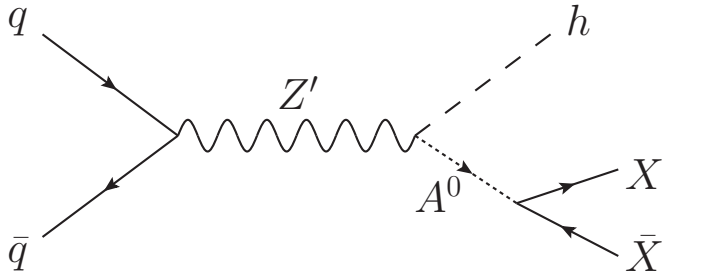
- **Effective Field Theories**
  - Black-box process at vertex



- **Simplified *Z'* Model**
  - Assume Higgs radiates from *Z'* mediator
  - Mediator then can decay into DM



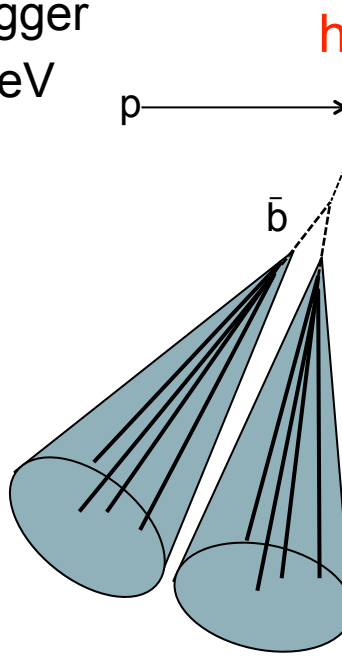
- **Simplified *Z'*-2HDM Model**
  - Mediator *Z'* decays to hA^0
  - A^0 can then decay to dark matter



- **General Cuts**
  - *"HLT_xe80"* Trigger
    - MET > 80 GeV
  - 0 Leptons

- **Boosted Analysis**
  - *"HLT_xe80"* Trigger
    - MET > 80 GeV
  - 0 Leptons

- **Resolved Analysis**
  - *"HLT_xe80"* Trigger
    - MET > 80 GeV
  - 0 Leptons



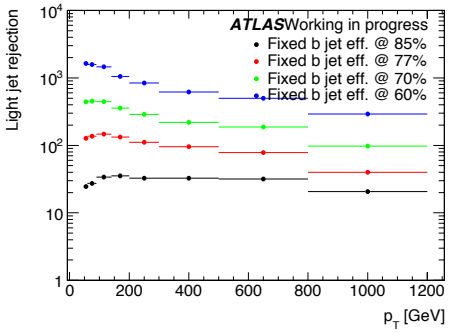
Summary

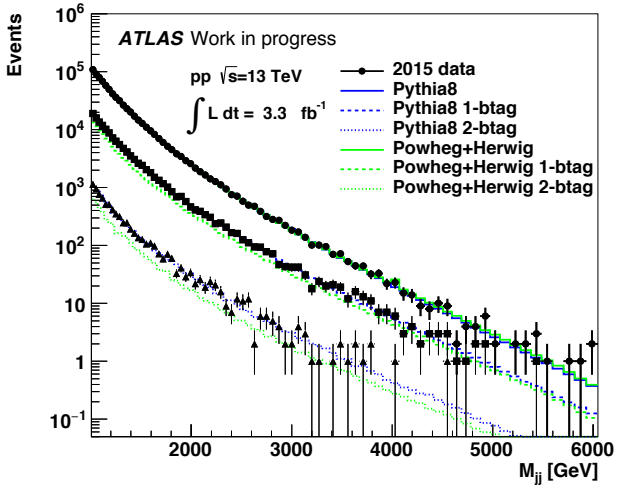
- b-tagged di-jet search following di-jet analysis
  - Shared cuts and framework
  - In addition applying b-tagging (1 b-tag and 2 b-tags)

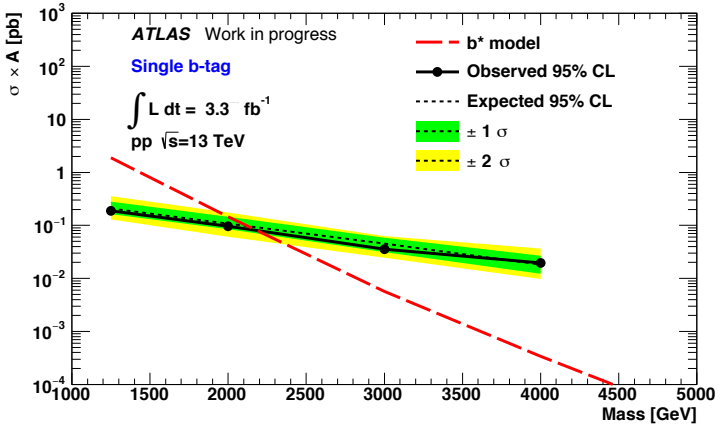
- 3.27 fb^{-1} of data used for this analysis.
  - Show good agreement with QCD MC
  - We find no deviations from the background fit with significance greater than 2σ.
  - 95% C.L. upper limits set for b* and Z'
    - No acceptance correction
    - Some systematics need to be added

- Many studies ongoing...
  - Further sensitivity studies
  - Robustness of fit to flavour fraction
  - More systematic studies (b-tag. uncertainties)
  - BJES finalisation.
  - Inclusion of *Z'* => *cc* and *light.* (Ready to request)

- On course for Moriond!
  - Ed. board and documentation in place.







Backup!

Backup:
b-Tagged Dijet Analysis

- b-Tagged di-jet resonance search
- **Aiming for a paper for Moriond**
- Documentation in Place
  - CDS Entry
  - SVN Area
- Ed Board Assembled
  - A. Glazov (Chair), F. Parodi, L. Tompkins
  - First Ed Board Meet - 11th November
  - Agenda can be found here
- Plots shown today are still preliminary

- **Data Used**
  - 25ns data with luminosity of **3.27 fb^{-1}** (Periods D-J)
  - Exclude runs with IBL Off - Due to huge drop in b-tagging performance.
  - GRL: *data15_13TeV.periodAllYear_DetStatus-v70-pro19-04_ DQDefects-00-01-02_PHYS_StandardGRL_All_Good_25ns.xml*

- **Trigger**
  - **HLT_j360**, lowest unprescaled single jet trigger

- **Event Selection**
  - Reject events with problematic calo. reconstruction (LAr, Tile and Core Errors)
  - At least two jets.
  - **Leading-jet p_T > 440 GeV**, Subleading jet p_T > 50 GeV
  - **m_{jj} > 1100 GeV**, such that we are on the trigger plateau.
  - **|y*| < 0.6**, where $y^* = 0.5*(y_1 - y_2)$
    - Central region more sensitive to BSM physics.

- **Jet Selection**
  - Standard jet calibration (with JES correction applied)
  - 2015 loose jet quality cuts applied.

- Luminosity - 9% uncertainty

- Background
  - Fit function and fit parameters

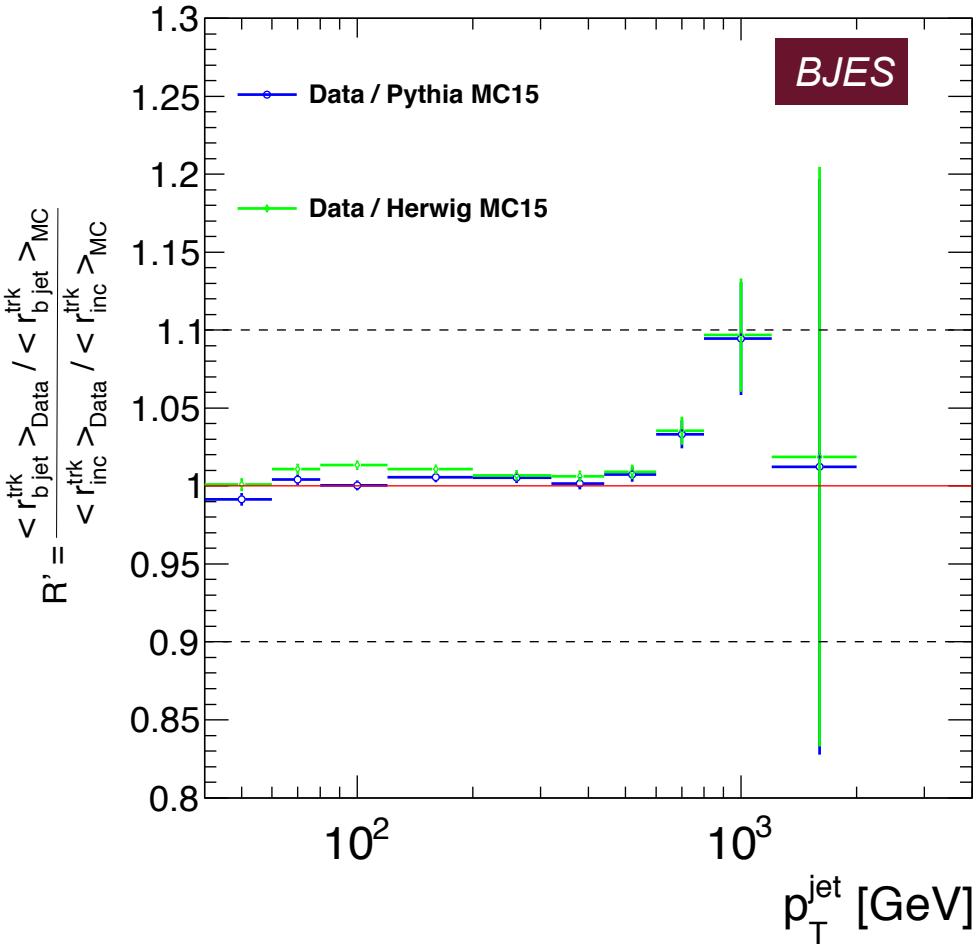
- Signal
  - JES Uncertainty
    - Branches available in analysis nTuple
    - < 4%
  - JER Uncertainty
    - Assume to be negligible
  - JER Uncertainty
    - Studies performed, large for high p_T jet (p_T > 800 GeV)
  - B-tagging scale factor uncertainty

- Studies to be carried out
  - Then will be added to limit setting procedure.

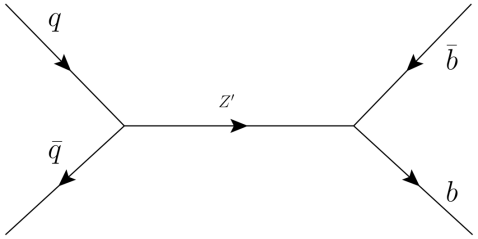
- Calculate using ratio of tracks within jet cone to reconstructed calo jet.
  - Use a double ratio between b-tagged jets and inclusive jets
- Below 1% on top of JES for $p_T < 600$ GeV
  - Then increases to ~10% as p_T increases.
- Ongoing study
  - Further work required
  - Study in to if there is a component in bJES due to tracks not entering the ratio.
- Regularly presented in JES/JER Meetings

$$R' = \frac{< r^{trk}_{bjet} >_{Data} / < r^{trk}_{bjet} >_{MC}}{< r^{trk}_{inc} >_{Data} / < r^{trk}_{inc} >_{MC}}$$

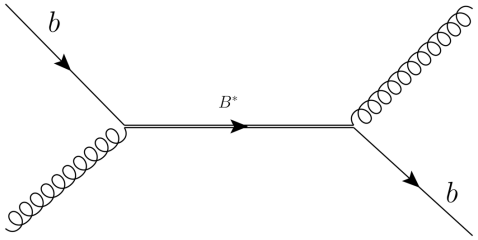
where $r^{trk} = \frac{\sum \vec{p_T}^{trk}}{p_T^{jet}}$



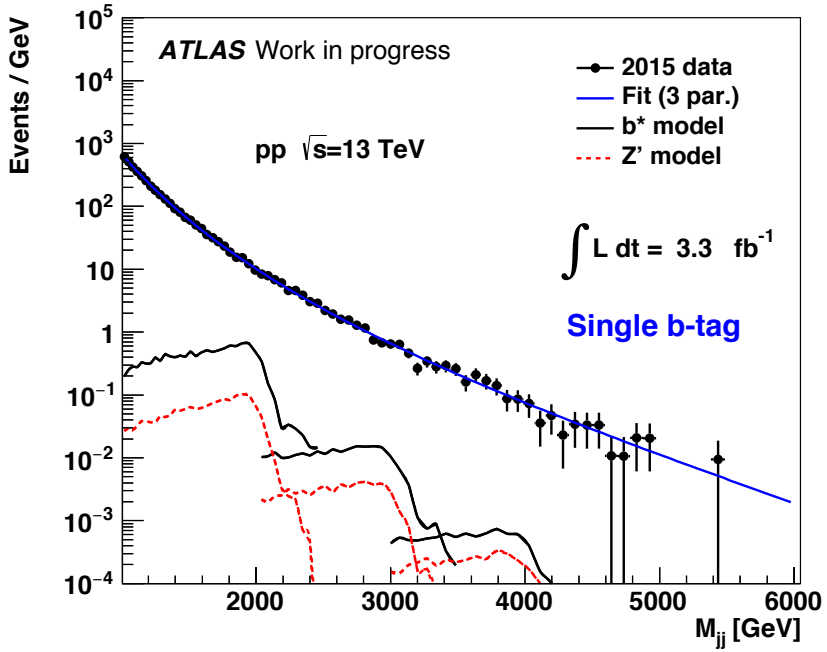
- Two benchmark models - We can set limits here.
  - **Z' => bb** - 1.25, 2, 3 and 4 TeV
  - **b* => b+X** - 1.25, 2, 3, 4 and 5 TeV
  - Templates taken from MC samples

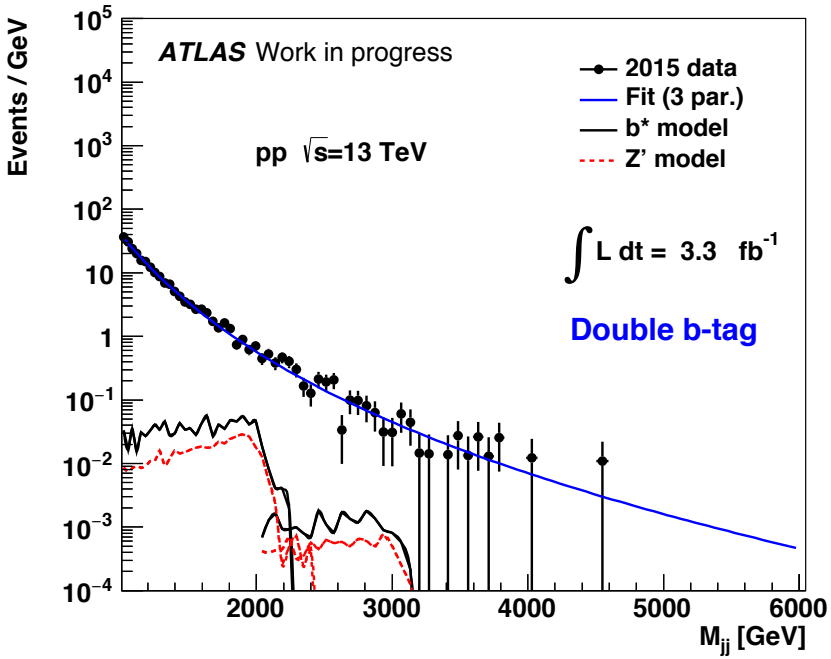


- One cross-check channel
  - **q*** - 2.5, 3, 3.5 and 4.5 TeV

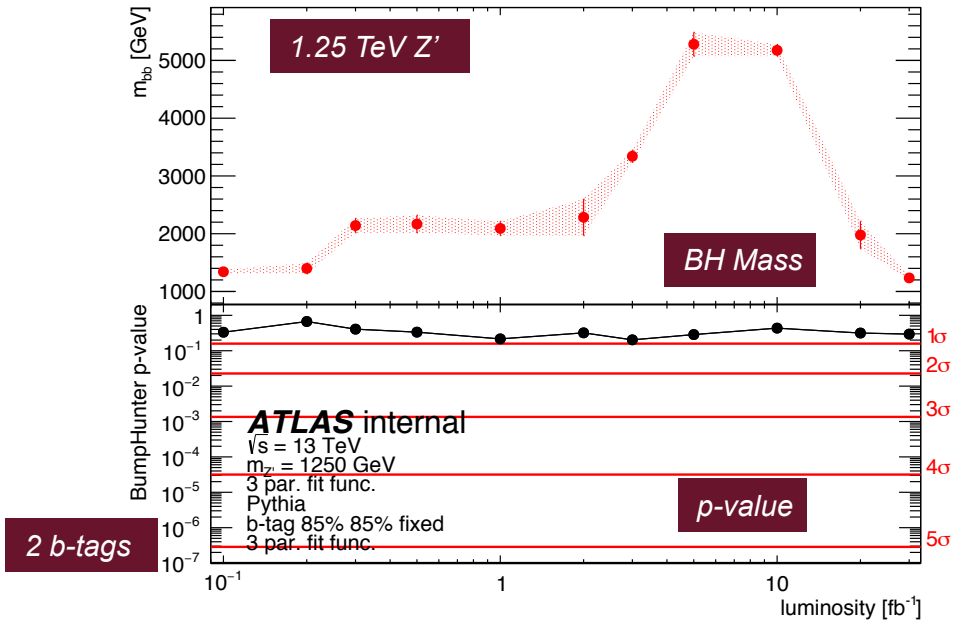


- Generic search performed for a Gaussian signal.
  - Resonance width taken from the benchmark

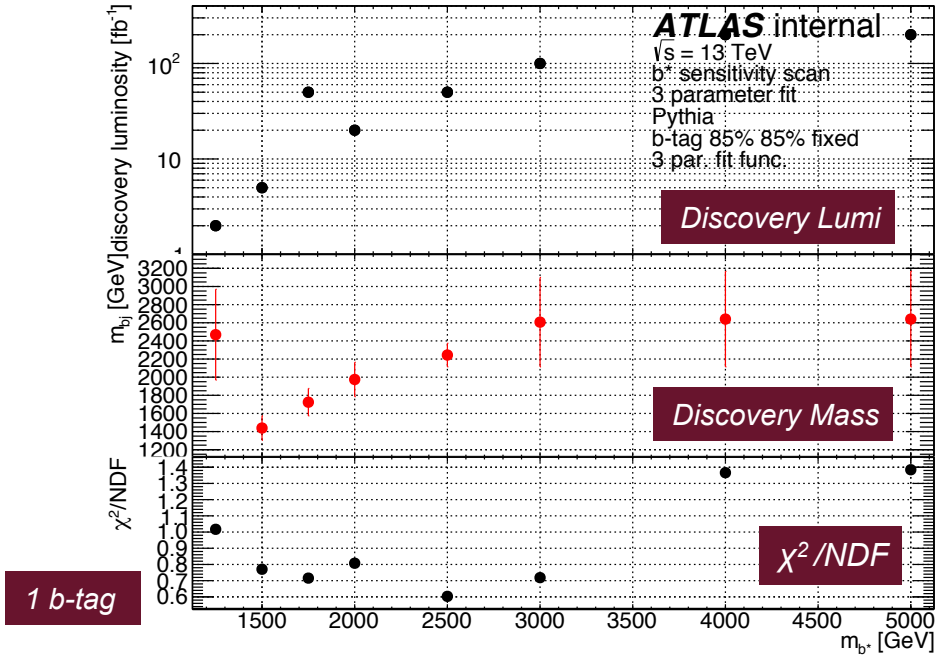




- **Low sensitivity to Z'**
  - Low cross section
  - Search for 1.25 TeV Z' slowly converging towards signal value at 30 fb^{-1}
  - Also want to include *Z' => cc* and *Z' => light-jet* signals.

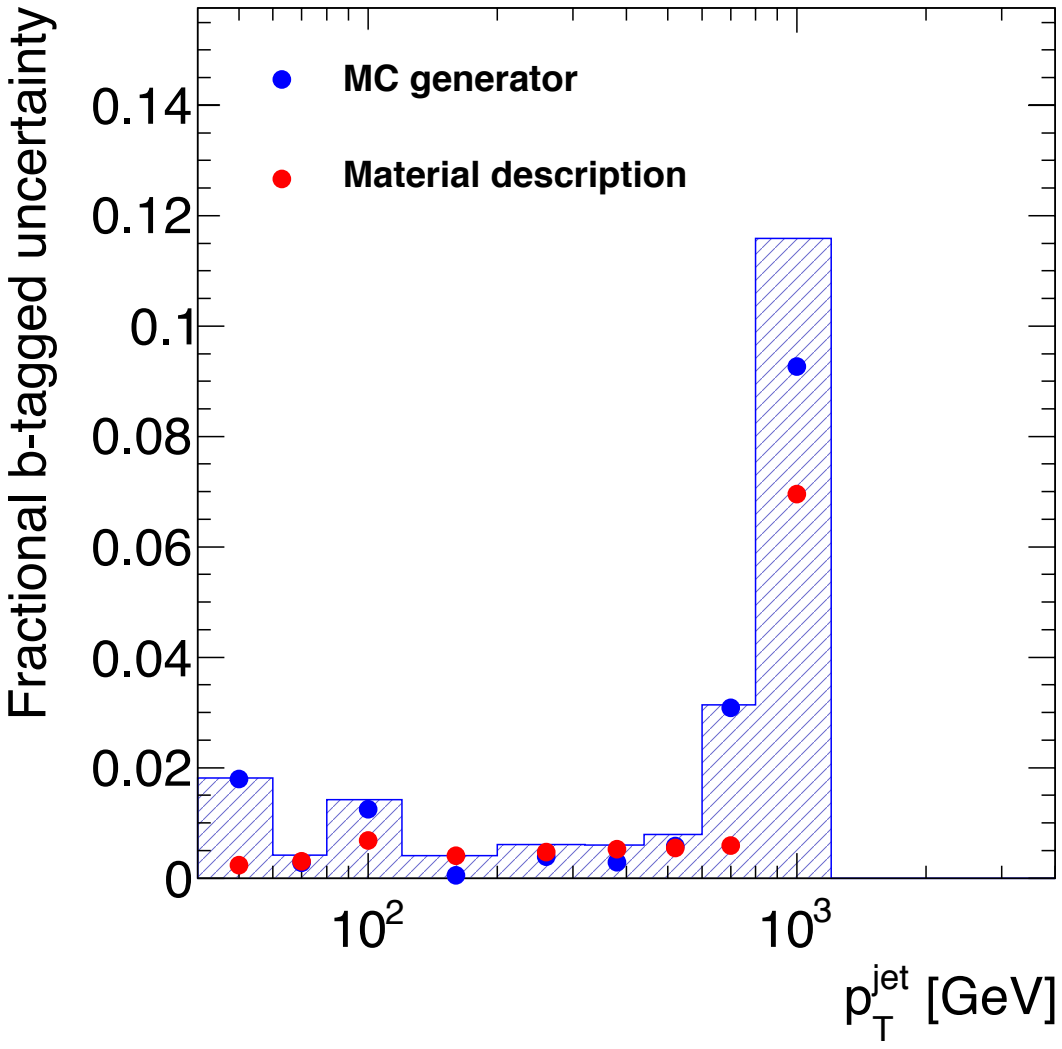


- **Discovery potential for b***
  - Larger cross-section than Z'
  - Fit is stable for single b-tag
  - Sensitivity curve is not smooth
  - Under investigation



b-tagged di-jet

BJES Uncertainty



Data/MC Jet pT Comparison

b-tagged di-jet