Search for Resonances Below 1 TeV in the Mass Distribution of jet pairs with Two Jets Identified as b-Jets in Proton-Proton Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector

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for the di-b-jet analysis team

<u>Exotic Approval</u>

26 May 2016

Search for resonances below 1.2 TeV in the mass distribution of jet pairs with two jets identified as b-jets in proton-proton collisions at $\sqrt{s}$=13 TeVwith the ATLAS detector.

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Abstract

Searches for mass resonances in the b-tagged dijets invariant mass spectrum below 1.2 TeV have been performed with the ATLAS detector at the LHC. The dijet mass distribution from 0.57 TeV to 1.2 TeV is studied. The sensitivity was optimized considering a 750 GeV narrow resonance and the search was initially performed blinded in the 700-800 GeV mass region. The 2015 proton-proton collision data at $\sqrt{s}$ = 13 TeV is used, corresponding to an integrated luminosity of 3.2 fb^{-1}. No significant deviations from the Standard Model expectation have been observed and upper limits have been set on the two b tagged dijet masses at 95% confident level.

INT Note in CDS - Here

Conf Note in CDS - Here

Contents

1) Introduction

2) Event and Jet Selection

3) Description of b-Jet Triggers

4) Kinematic Distributions

5) Statistical Techniques

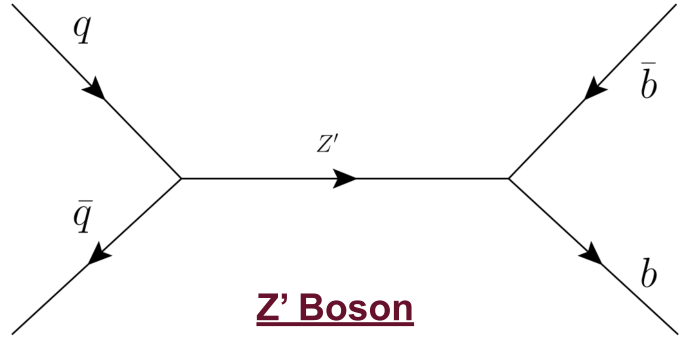
6) Systematic Uncertainties

7) Search Result

8) Conclusions

Introduction: Motivation

- **Many BSM models predict resonances that decay to b-quark(s)**
  - E.g. Z' Boson

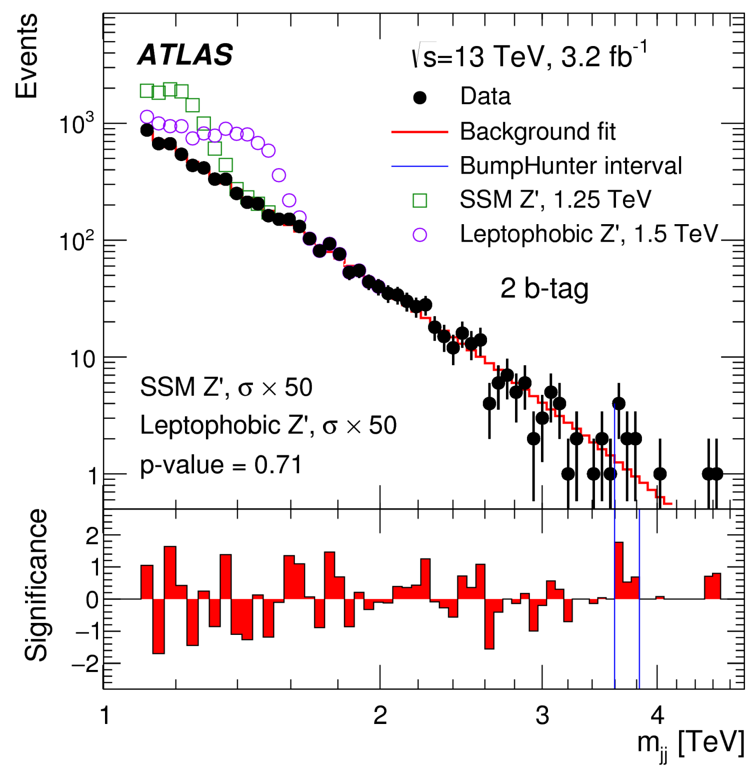


Z' Boson

- **b-Tagging Increases Sensitivity**
  - Large QCD background
    - Dominated by light jets
    - *(light = u, d, s and gluon)*
  - Increased sens. to these models

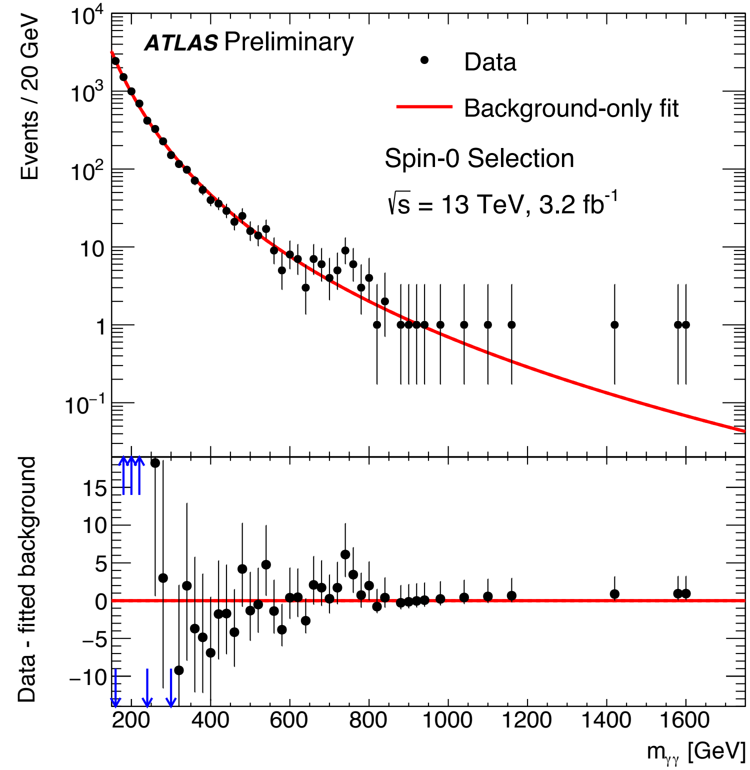
- **Perform Resonance Search**
  - Similar strategy as inclusive dijet
  - Fit using smoothly falling function
  - Use BumpHunter to find excesses

- **Moriond High Mass Paper**
  - m_{jj} > 1.1 TeV
  - >= 1 b-tag and 2 b-tag category
  - No significant excesses found
  - arXiv:1603.08791



Introduction: Low Mass Analysis

- **Motivation to go to lower masses**
  - **Cross over between γγ and bb?**
  - Assume scalar couples to bb and γγ only
    - Estimate $\sigma_{\gamma\gamma}$ and Γ from diphoton
    - Theorists calculate σ_{bb}, *(arXiv:1512.04933)*
      - ~0.4 pb @ 8 TeV
      - ~2.1 pb @ 13 TeV



- **Weak limits on BSM at low mass**
  - Limits on above model are weak
    - < 1pb @ 8 TeV, (arXiv:1506.08329)
    - No limits @ 13 TeV
  - **We should study this region…**

- **New Trigger Strategy Required**
  - Last time limited by trigger turn on
    - **HLT_j360** *(Unprescaled single jet trigger)*
  - We can use b-jet trigger
    - **HLT_j175_bmedium_j60_bmedium**
    - $566 < m_{jj} < 1200$

Can be done with 2015 Data

LHCP Note!

Event and Jet Selection

- **Trigger and Data**
  - **3.2 fb^{-1}**, excluding IBL off data
  - **Double b-jet trigger:**
    HLT_j175_bmedium_j60_bmedium
- **Jet Selection**
  - Anti-k_T EM Topo Jets, R=0.4
  - **Leading Jet, p_T > 230 GeV**
  - **Sublead. Jet p_T > 90 GeV**
  - Both jets, $|\eta|$ < 2.4
- **Event Selection**
  - **566 < m_{jj} < 1200 GeV**
    - Previously blinded 700-800 GeV
  - **$|y^*|$ < 0.6**, $y^* = 0.5 * \Delta y$
    - Central region more sensitive to BSM
- **Offline b-Tagging**
  - **MV2c20 @ 70% WP**
    - Online tagging limits b-jet eff.
    - Gain Light jet rej. from offline

Data - *Full 3.2 fb^{-1}*

Selection criteria	N_{events}	Remain (%)	Rel. remain (%)
all	1139851904	100	100
GRL, evt cleaning	33811024	3.0	3.0
trigger	3606231	0.32	10.7
jet η	3448909	0.30	95.6
b-tag leading jet	1769740	0.16	51.3
b-tag sub-leading jet	971029	0.085	54.9
leading jet $>$ 230 GeV	269327	0.024	27.7
sub-leading jet $>$ 90 GeV	259379	0.023	96.3
$y^* < 0.6$	155186	0.014	59.8
$m_{jj} >$ 566 GeV	32460	0.003	20.9

MC Z' -> bb - *m_Z = 800 GeV*

Selection criteria	N_{events}	Remain (%)	Relative remain (%)
all	19800	100%	100%
evt cleaning	11414.3	57.6%	57.6%
leading jet $>$ 230 GeV	10574.7	53.4%	92.6%
sub-leading jet $>$ 90 GeV	10458.4	52.8%	98.9%
jet η	10256.9	51.8%	98.1%
$y^* < 0.6$	7319.8	37.0%	71.4%
two b-tag	2649.9	13.4%	36.2%
trigger	2239.7	11.3%	84.5%
$m_{jj} >$ 566 GeV	1709.1	8.6%	76.3%

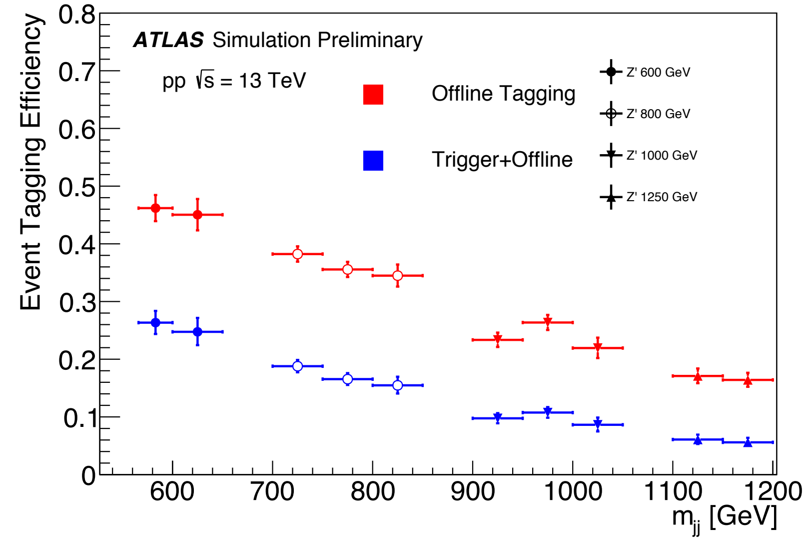
Event and Jet Selection - Extras

- **Offline b-Tagging**
  - **MV2c20 @ 70% OP**
    - Online tagging limits b-jet eff.
    - Gain Light jet rej. from offline
- **Operating Point Selection**
  - Preliminary
  - Various b-tagging OP
  - Acceptance efficiency of Z'
    - $m_{Z'}$ = 800 GeV
    - Emulating trigger efficiency
  - Expected # events from sideband fit
  - Expected Gaussian limits
    - Width 10% of mass

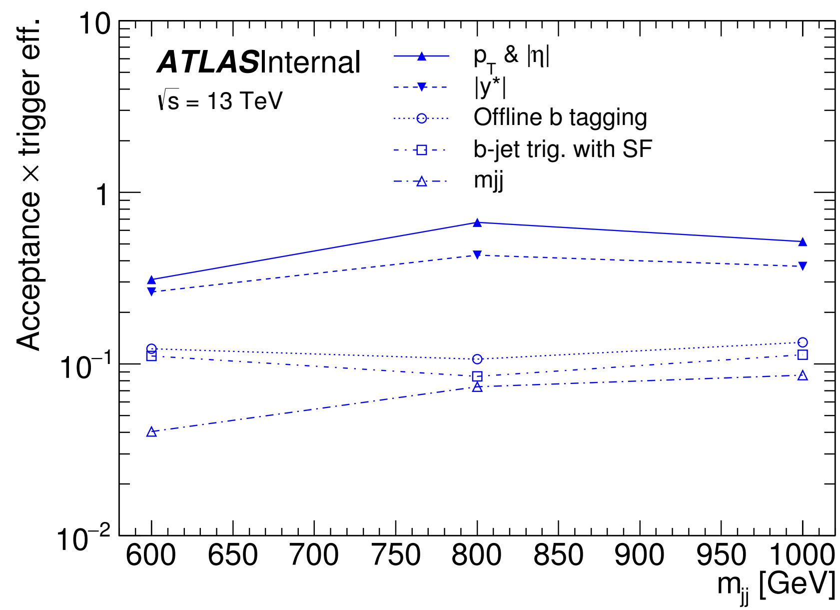
b-tag OP	Eff (%)	N_{evt}^{exp}(bkg) in SR	Exp limit (pb)
85	9	8800	1.2
77	9	6000	1.0
70	8	4400	1.0
60	6	2800	1.1

Preliminary Study for OP selection only!

Signal Tagging Efficiency



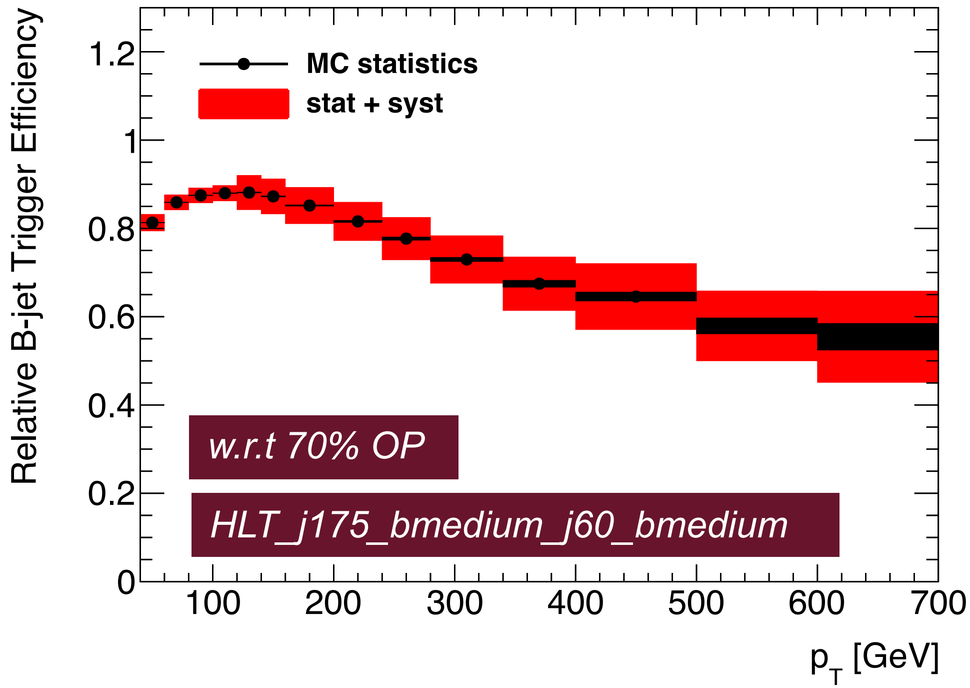
Signal Efficiency



b-Jet Triggers: Introduction

- **b-Jet Triggers to get to low masses**
  - 2015 data: IP3D+SV1 Algorithm

- **HLT_j175_bmedium_j60_bmedium**
  - bMedium OP
    - Tighter than 70% eff. OP
  - Cut in MC doesn't match Data



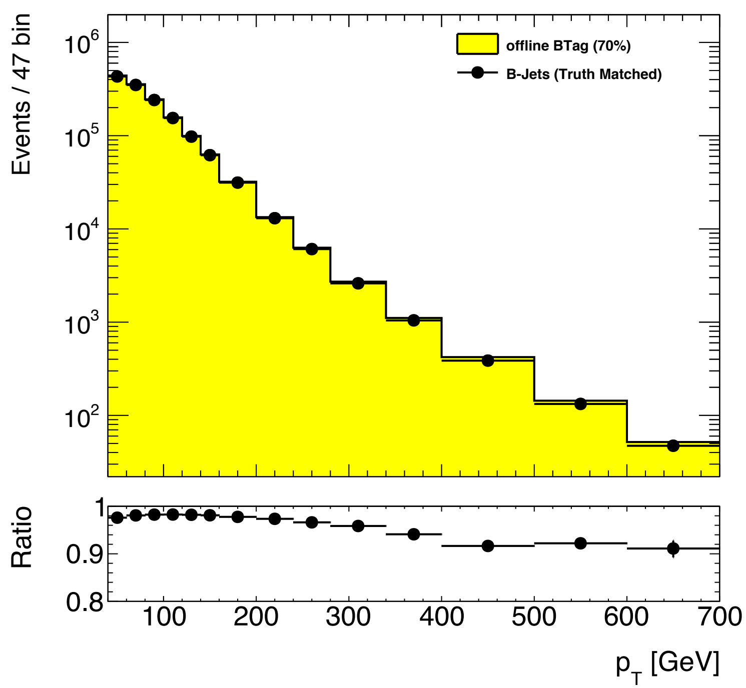
- **b-Jet Trigger Strategy**
  - Derive b-Jet Trigger Efficiencies
    - Data driven technique
    - Details on the next slide
  - Efficiencies are applied to signal samples to emulate trigger
  - Not required for background - Exact light-jet and c-jet rejections not needed
    - Use fit to model background rather than MC

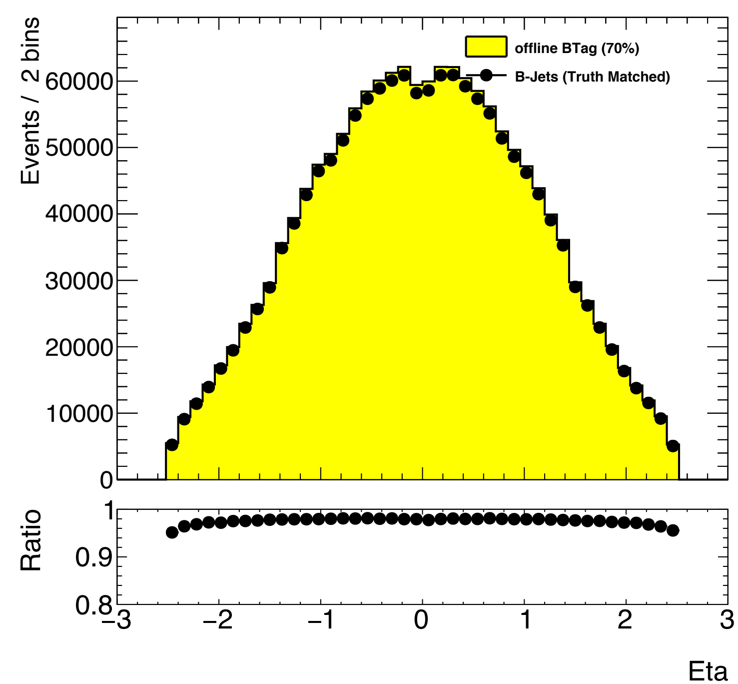
$$\text{b-Jet Trig Eff. wrt offline} = \frac{\text{\# b-Jets pass offline and online b-tagging}}{\text{\# b-Jets offline b-tagging}}$$

b-Jet Triggers: Event Selection

- **High purity b-jet sample: Di-lepton tt selection**
  - **Single lepton bperf trigger**: *HLT_(mu26_imedium/e26_tight_iloose/e26_lhtight_iloose)_2j35_bperf*
    - Calculate online b-tagging algorithms on all jets with p_T > 35 GeV
  - **1 medium electron & 1 medium muon** (p_T > 30 GeV)
  - **2 b-tagged jets**, MV2c20 @ 70% *(p_T > 30 GeV, $|\eta|$ < 2.4)*

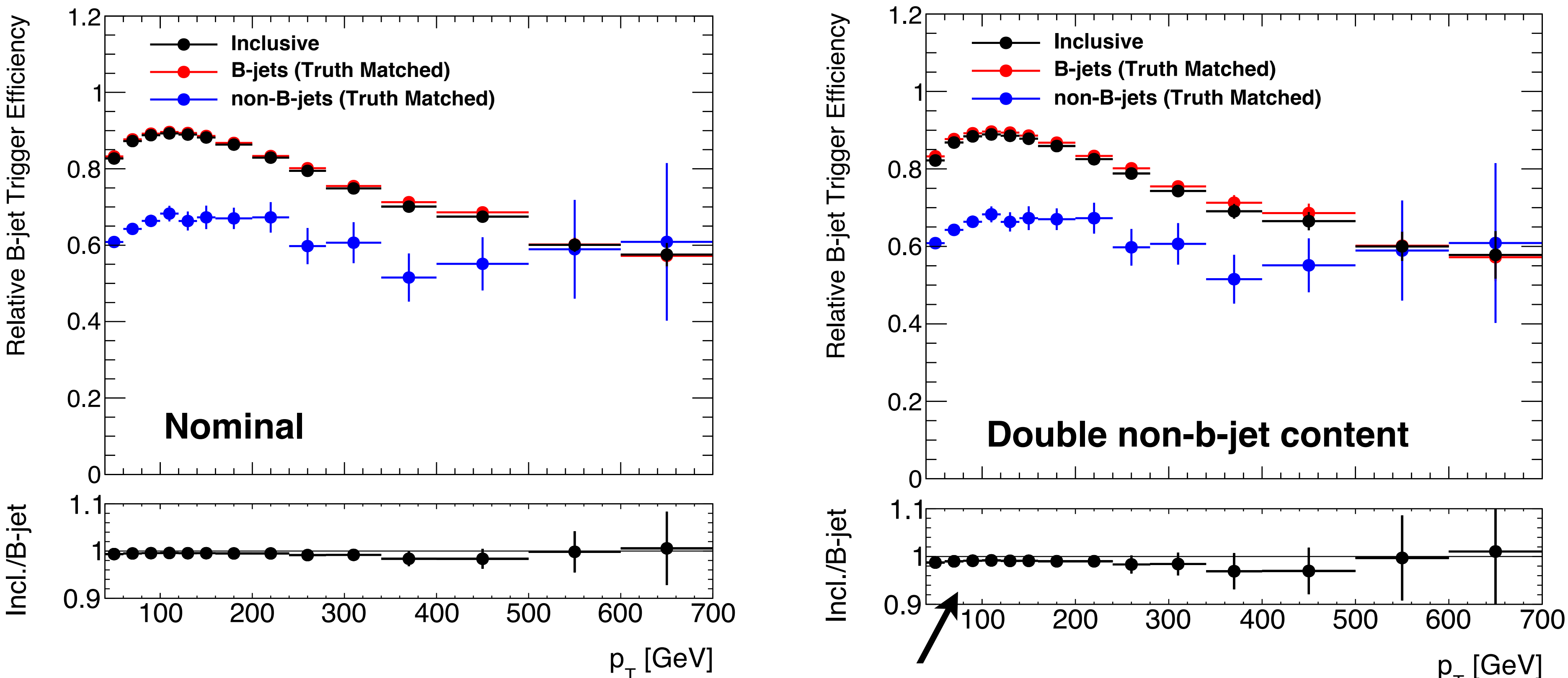
- **Testing the b-jet purity**
  - Use truth matching to estimate purity of sample
  - High purity (>95%) at low p_T, decreases to ~90% at 700 GeV





b-Jet Triggers: Sample Dependance Syst.

- **Correction account for non b-jet impurities**
  - Truth match b-jets and non-b-jets *(light, c)*
  - Correction to account for difference between inclusive and truth matched b-jets
- **Systematics to deal with MC mismodelling of flavour composition**
  - ➡ Vary the non-b-jet component of the tt sample by + 100%
  - ➡ Difference from 100% purity taken as a symmetric systematic



Difference from 1 taken as systematic

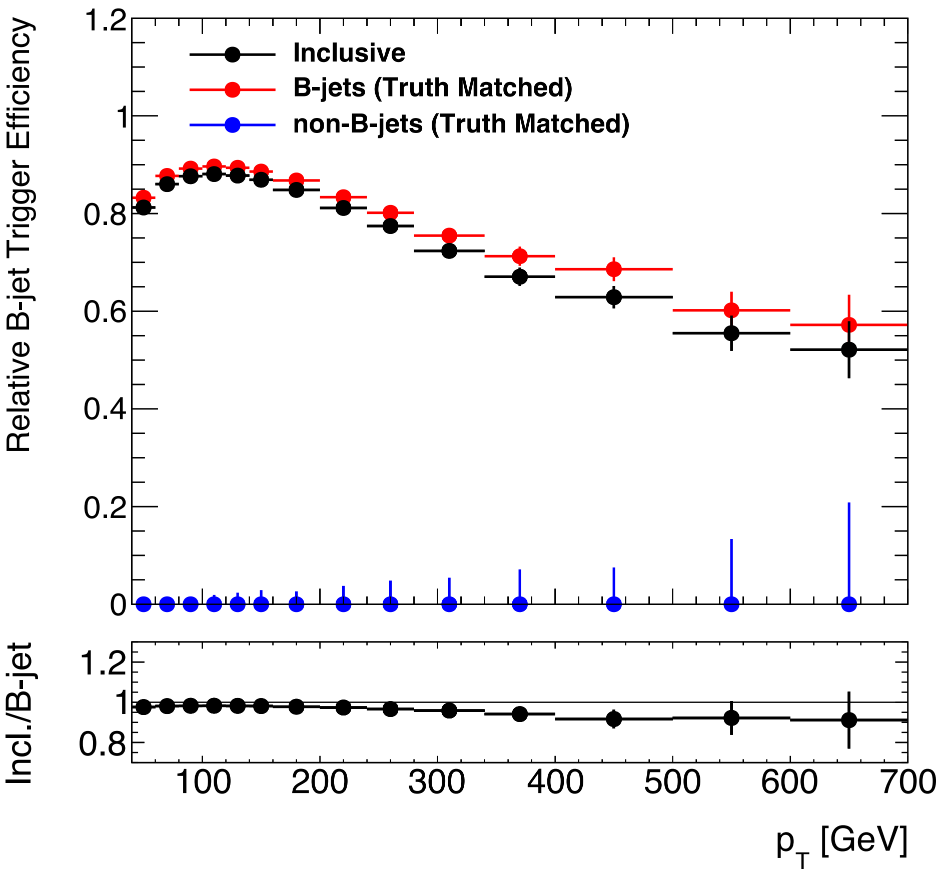
b-Jet Triggers: Sample Dependance Syst.

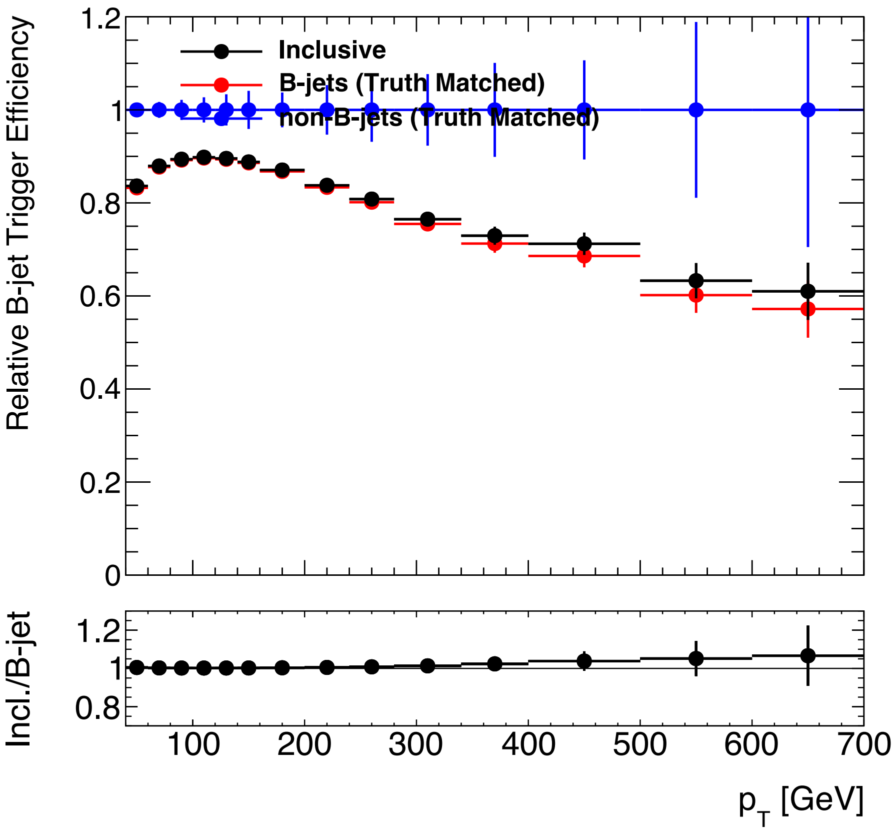
- **Systematic for MC mismodelling of the light-jet efficiency of the trigger**

➡ Consider light-jet trigger efficiency of 0 and 1

➡ The two variations have an effect on the inclusive to truth-matched ratio

➡ Take largest difference from a ratio of 1 as systematic





b-Jet Triggers: Estimating Efficiency

Jet p_T < 120 GeV

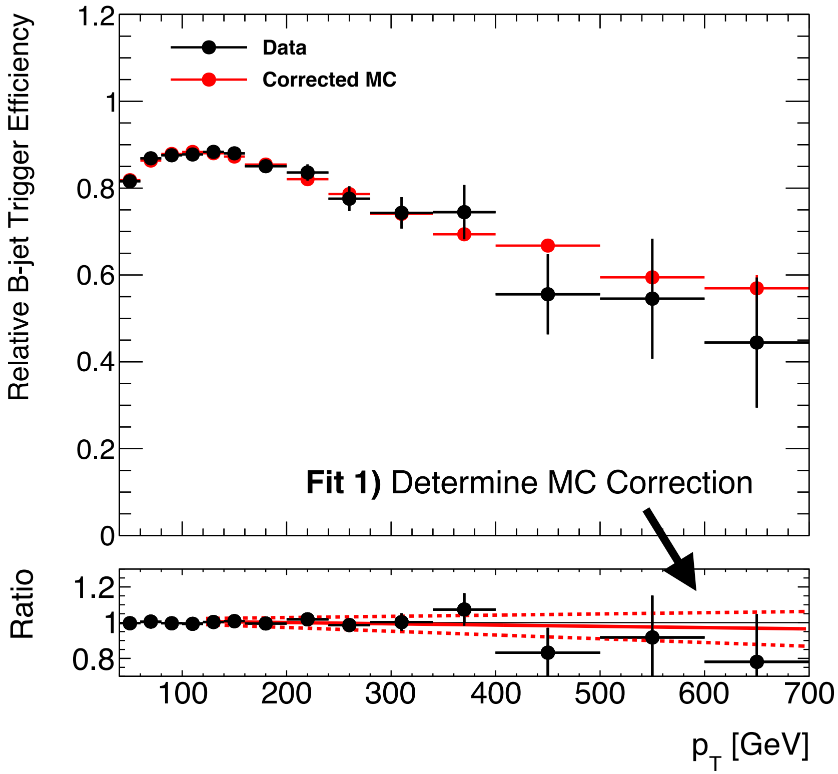
- **Data Eff. taken as central value**

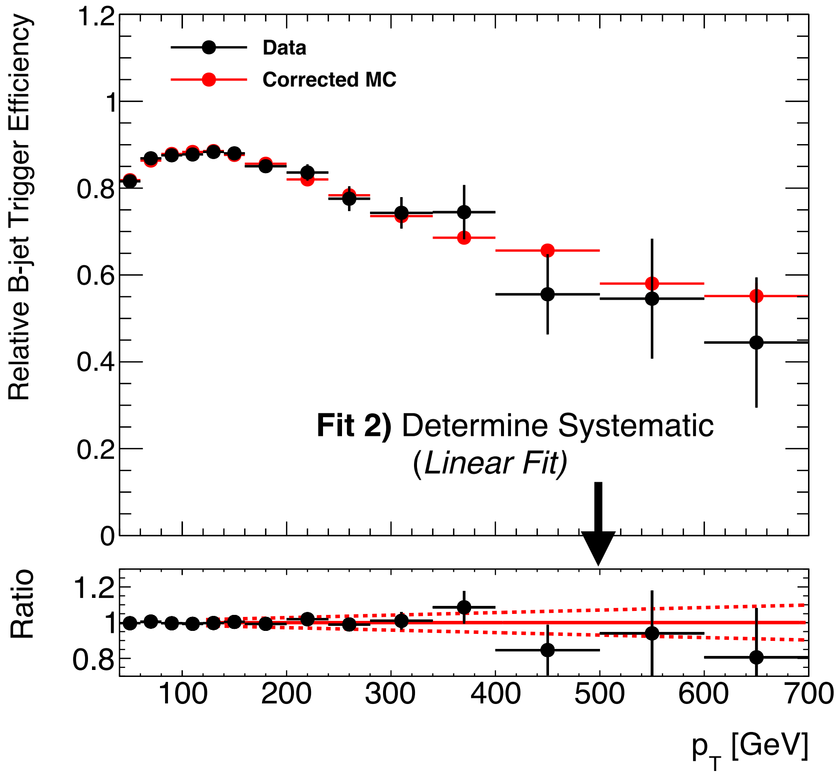
- Data/MC difference taken as syst.
- Precision of data also as syst.

Jet p_T > 120 GeV

1) **Linear fit to Data/MC eff. ratio**
   - Used to correct tail in MC eff.
   - This gives central value
2) **Linear and** 3) **Quadratic fit to Data/Corrected MC ratio**

- Largest bin by bin error of 3 fits taken
- Taken as symmetric systematic





b-Jet Triggers: Estimating Efficiency

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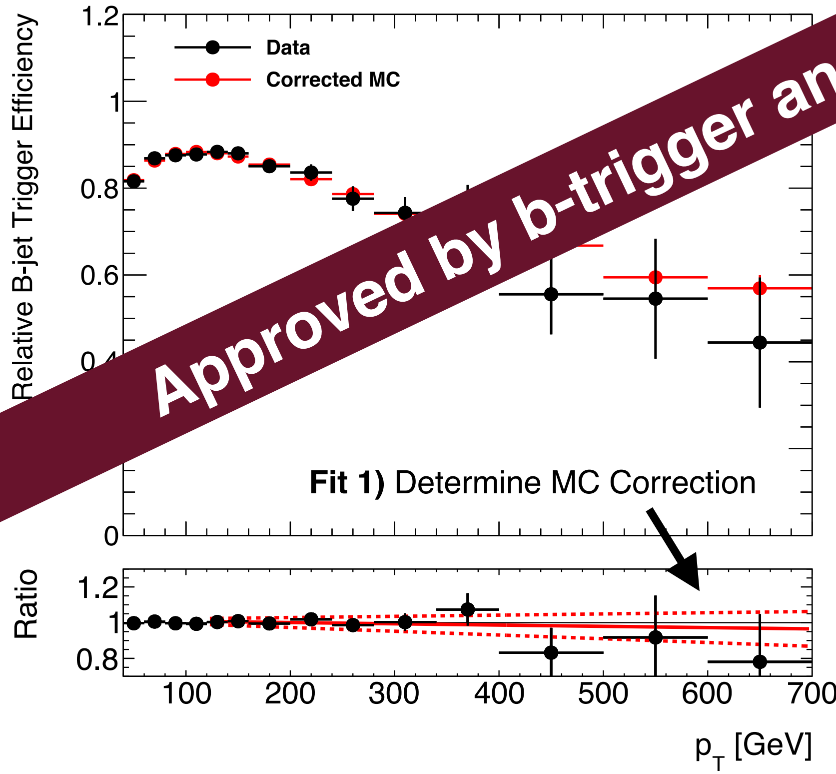
- Precision of data also as syst.

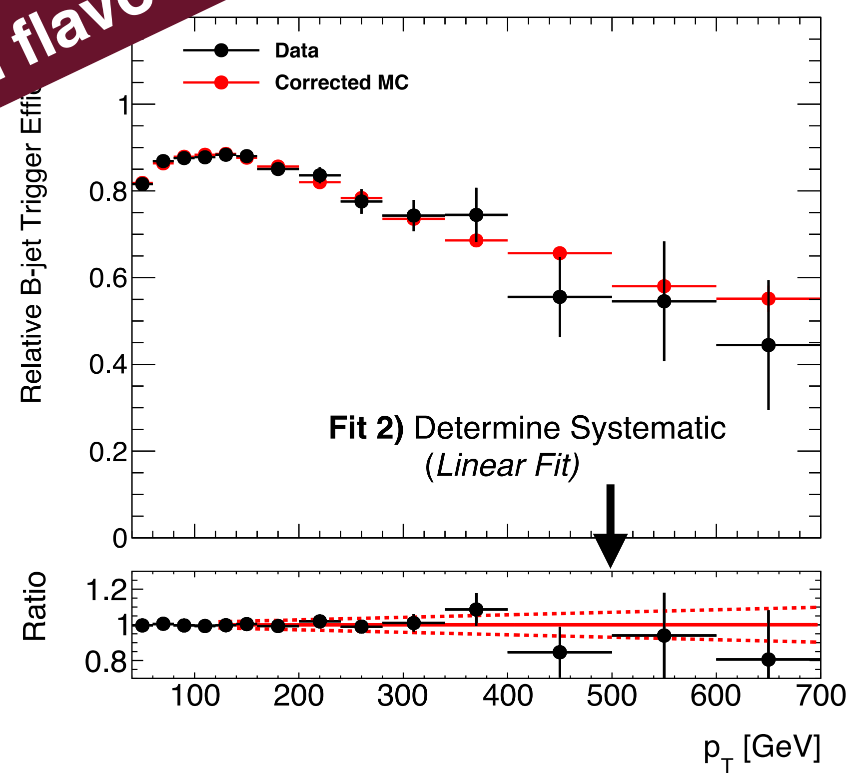
Jet p_T > 120 GeV

1) **Linear fit to Data/MC eff. ratio**
   - Used to correct tail in MC eff.
   - This gives central value
2) **Linear and** 3) **Quadratic** ... **Data/Corrected MC** ...

- Largest bin by ... of 3 fits taken
- Taken as ... systematic

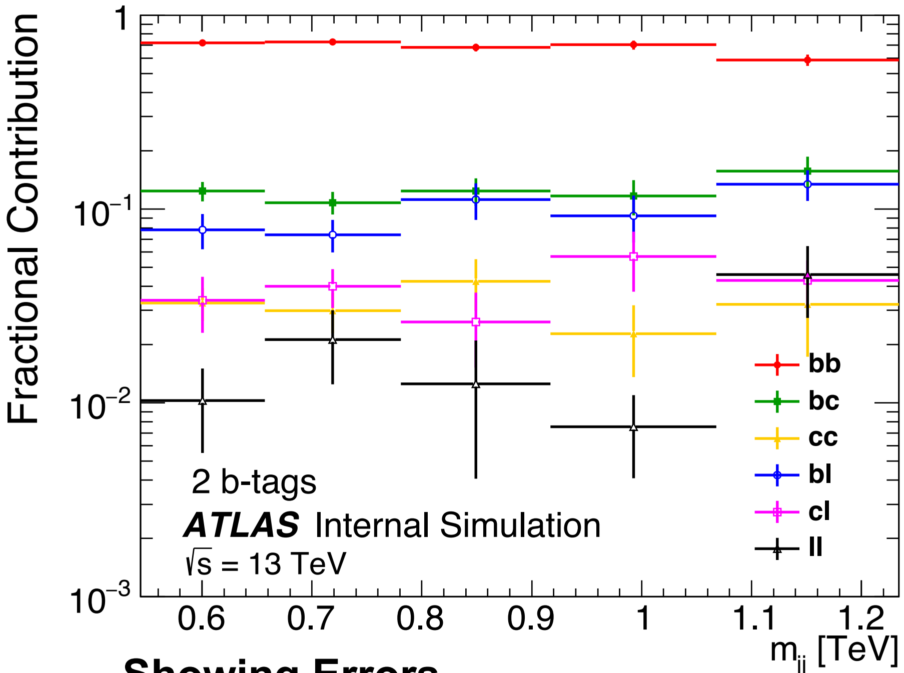
Approved by b-trigger and flavour tagging group



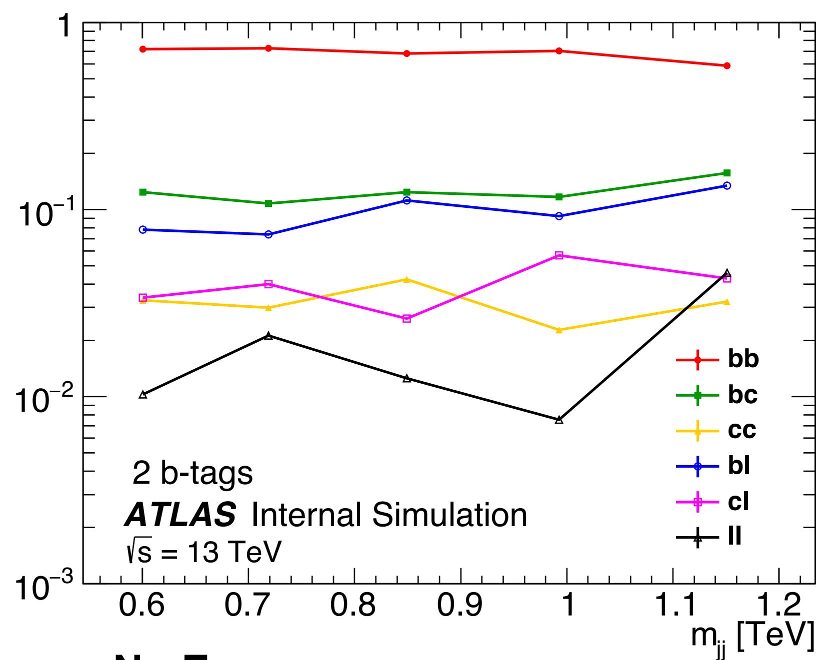


Kinematics: Flavour Composition

- **Flavour Composition from MC**
  - Applying b-tagging, emulating online b-tagging
- **Emulating online b-tagging**
  - Light/Charm online b-tagging efficiencies not known
  - Estimated from fit to non-b-jet efficiencies (slide 1)



Showing Errors



No Errors

- **Dominated by bb**
- **Flavour fractions are changing smoothly**

Statistics: Fitting

- **Using Dijet Fitting Procedure**
  - Used in high-mass inclusive dijet and b-tagged dijet search
  - 5 parameter (para.) Dijet Function :

    => 3 para.; $p_4 = p_5 = 0$

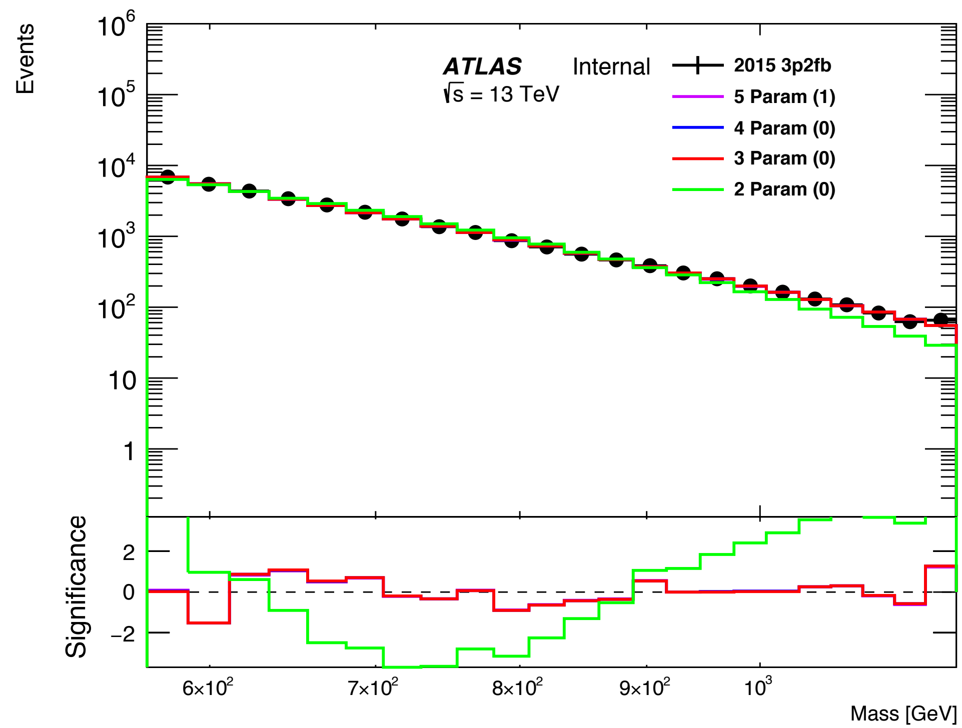
    => 4 para.; $p_5 = 0$

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

- **Function Choice; Wilks' Statistic**
  - Begin with by choosing the 3 para. function.
  - Use Wilks' test statistic to compare 3 to 4, if it drops below a threshold switch to 4
  - Repeat for 4 to 5.

In data we choose
3 Parameter

Wilks' Stat = 0.83

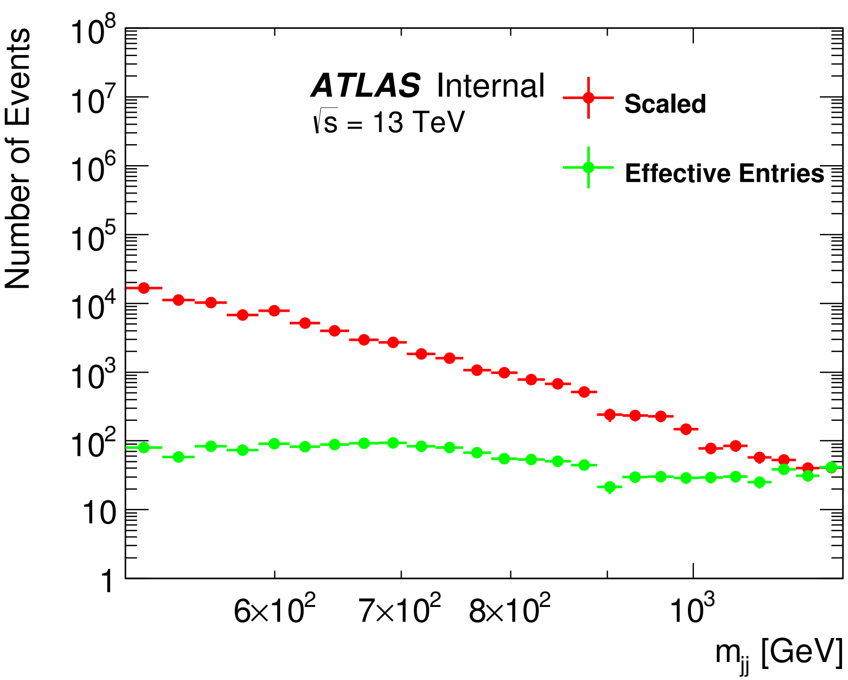


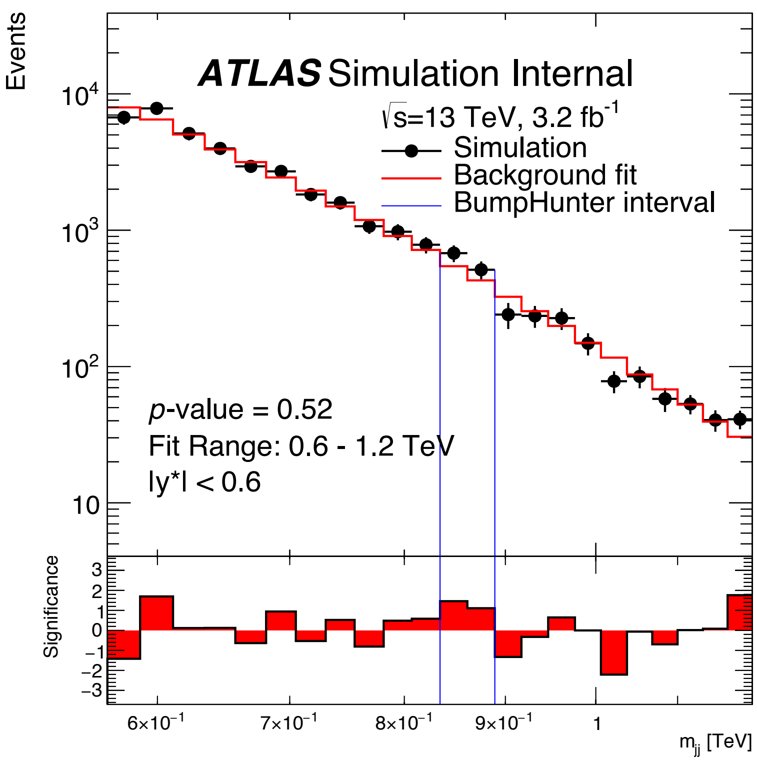
Statistics: Spurious Signal - MC

- **Confirm that fits discrepancies are not significantly occurring**
  - Fit discrepancy = A difference in shape between fitting function and background
  - Fit discrepancy may hide true signal or create fake signal
  - Test fit function by performing fits to a representative background only data set

- **Monte Carlo:** *Pythia8 Dijet Sample*
  - Same cuts as data, trigger emulated using p_T dependant trigger efficiencies *(slide 10)*
  - Problems with statistics, Effective Entries < Scaled Entries

    => Not poisson-like errors

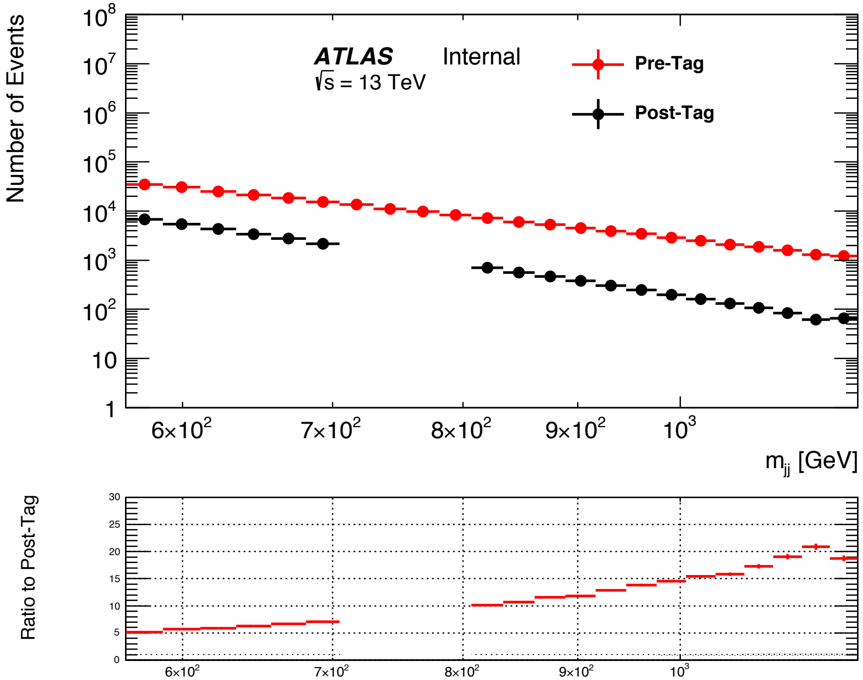


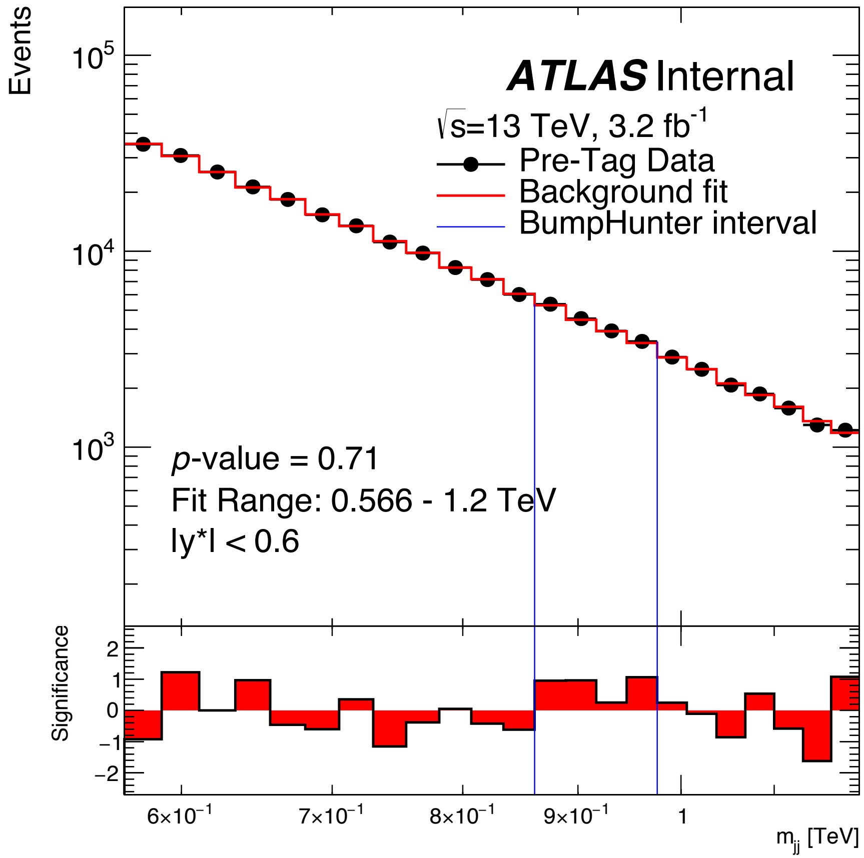


Statistics: Spurious Signal - Data, Trigger Only

- **Fit to Data with Trigger Applied**
  - b-Tagging not applied.
  - Dominated by bl, but this give us a similar, but different control region to test fitting

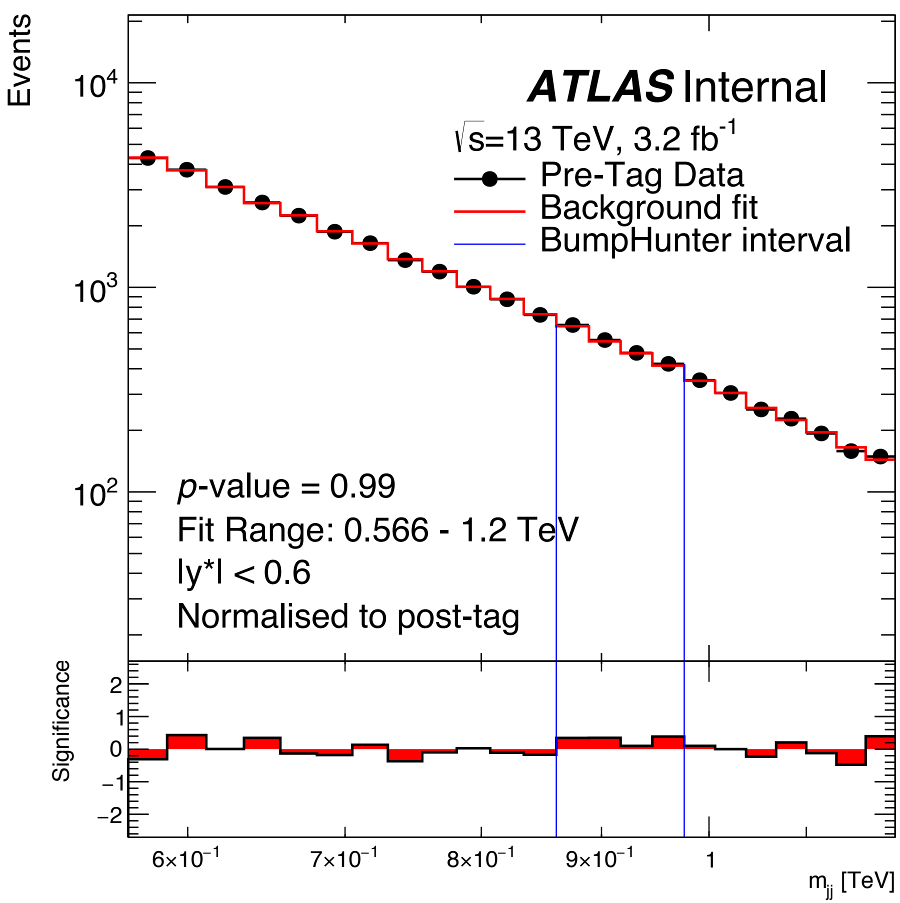
- **Overall fit is good quality**
  - No significant discrepancies
  - Possible structure in ratio

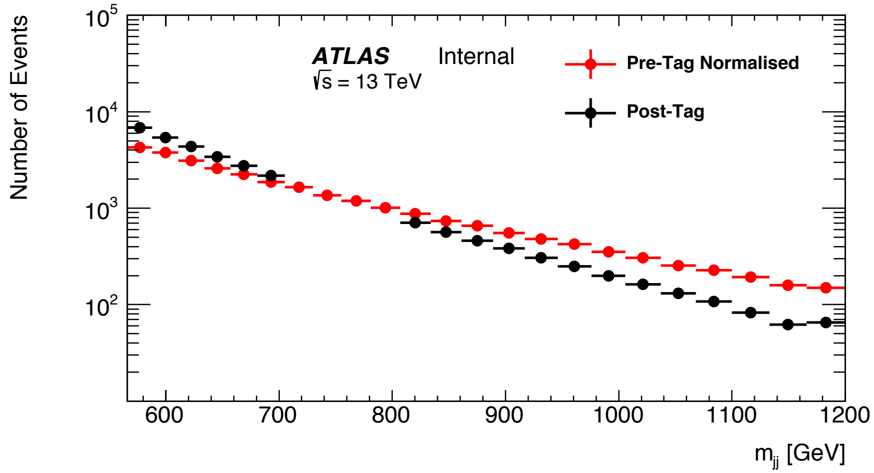


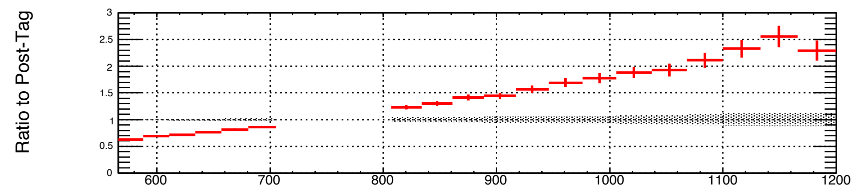


Spurious Signal: Scaled Down

- **Scale Pre-Tag to Post-Tag**
  - Actual Fluctuations in Data
    ~ 1/sqrt($N_{Pre\text{-}Tag}$)
  - Toys for p-value fluctuations
    ~ 1/sqrt($N_{Post\text{-}Tag}$) {Larger fluctuations}
  - Fit and search for bumps







We see that at post-tag scale:

fit discrepancies <<
poisson fluctuations of post-tag

99% of toys have **worse** fit

Spurious Signal: Scaled Down

- **Scale Pre-Tag to Post-Tag**
  - Actual Fluctuations in Data

    ~ 1/sqrt($N_{Pre\text{-}Tag}$)
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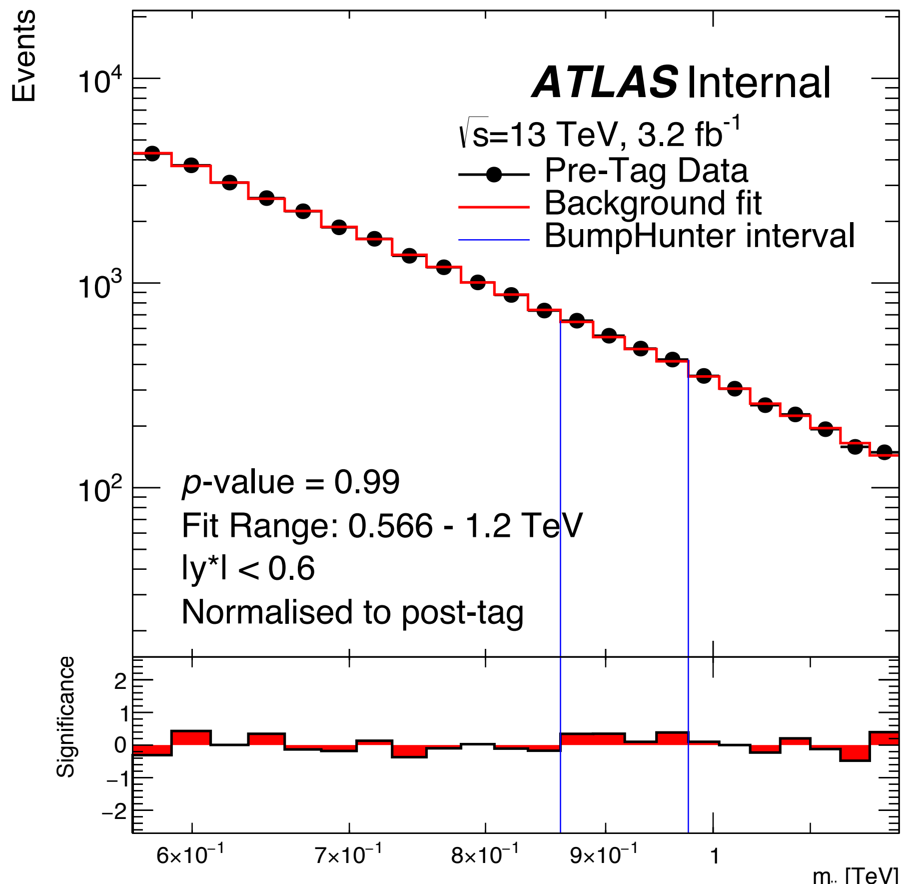

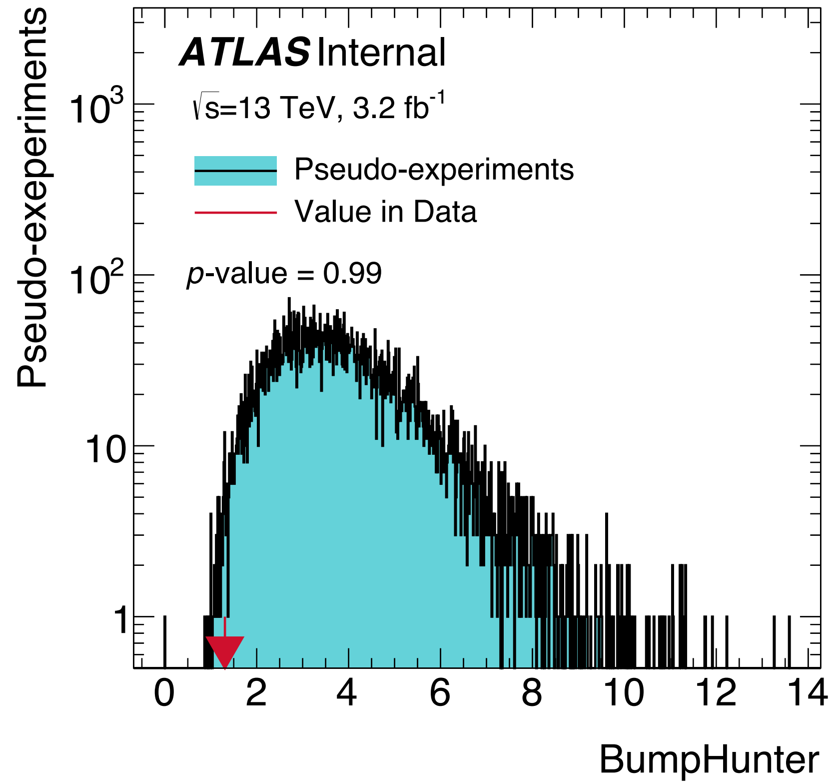

We see that at post-tag scale:

fit discrepancies <<
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99% of toys have **worse** fit

Statistics: Signal Modelling

- **DM Scalar Z' Model**
  - Using LHCDMWG model
    - Done for convenience, this model exists and fits our needs.
  - Mass points; 600, 750, 800, 1000, 1200 GeV
  - Decays to *uu, dd, ss, cc* and *bb*; dominant decay is *bb,* couplings here
    - DM mass set to 10 TeV to ignore this coupling
  - Production does not include gg fusion via a quark loop.
  - But, this model can be used to calculate scalar acceptance

- **Leptophobic Z' model**
  - Model used in Moriond high mass paper
  - SM couplings to quarks, no couplings to leptons
  - Masses; 600, 750, 800, 1000 GeV
  - Problem => Z' @ 750 GeV is Z' => had had

    => Z' @ other mass points are Z' => bb

    - Looking to resolve through truth matching

- **Gaussian Limits**
  - Will set limits on a generic gaussian signal

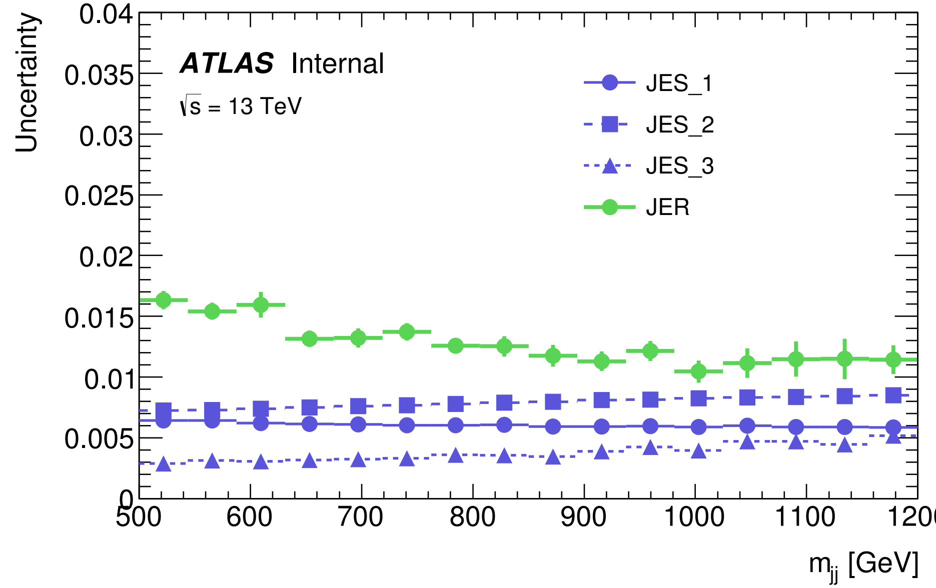
Systematics

- **Monte-Carlo (Signal)**
  - Luminosity (5%)
  - JES - Reduced 3NP
  - JER - Reduced 1NP
  - **b-tagging SF (~30%)**
  - **b-Jet trigger Efficiency (~10-30%)**

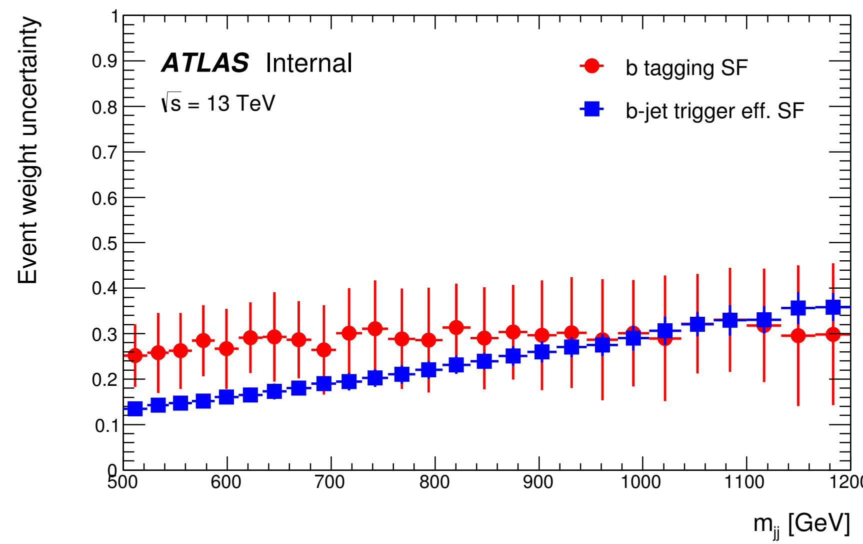
- **Background**
  - Fit function choice
    - Comparison to alt. func. (4 para.)
  - Uncertainty on fit parameters
    - Taken from pseudo-experiments

Rec. mass (GeV)	*JES (para1/para2/ para3)*	*JER*	*b-tagging SF*	*b-jet trigger eff. SF*
600	*2.5% / 2% / 1.3%*	*1.6%*	*30%*	*16%*
800	*2.4% / 2% / 1.1%*	*1.3%*	*30%*	*20%*
1000	*2% / 1.9% / 1%*	*1.1%*	*30%*	*30%*

Jet Uncertainties

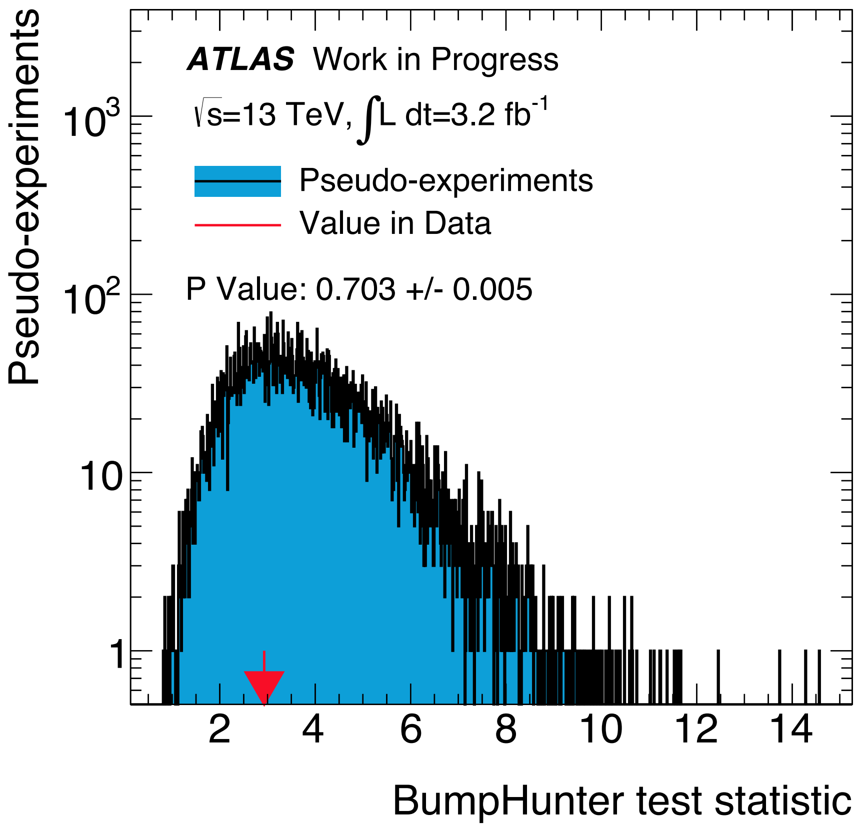


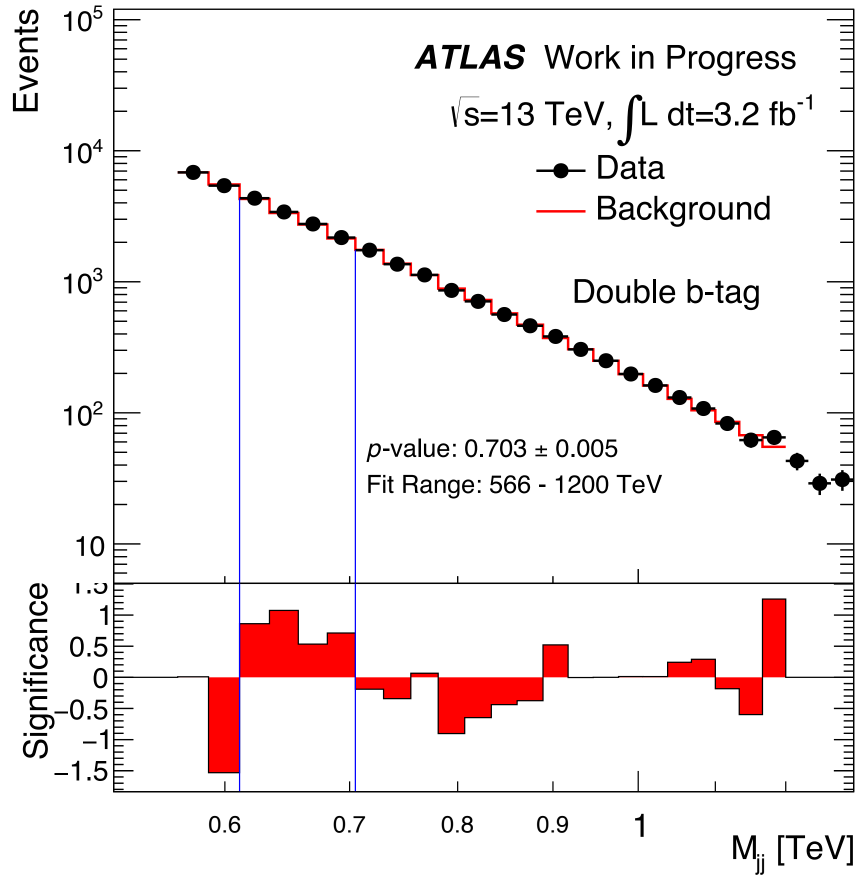
b-Tagging SF Uncertainty



Results: Search Phase

- **Currently Looking at Fitting to Sidebands**
  - 3 Parameter Fit Function
  - **Use BumpHunter Algorithm**
    - Finds most discrepant excess
    - Calculate p-values of discrepancy
      - 10,000 pseudo-exp.





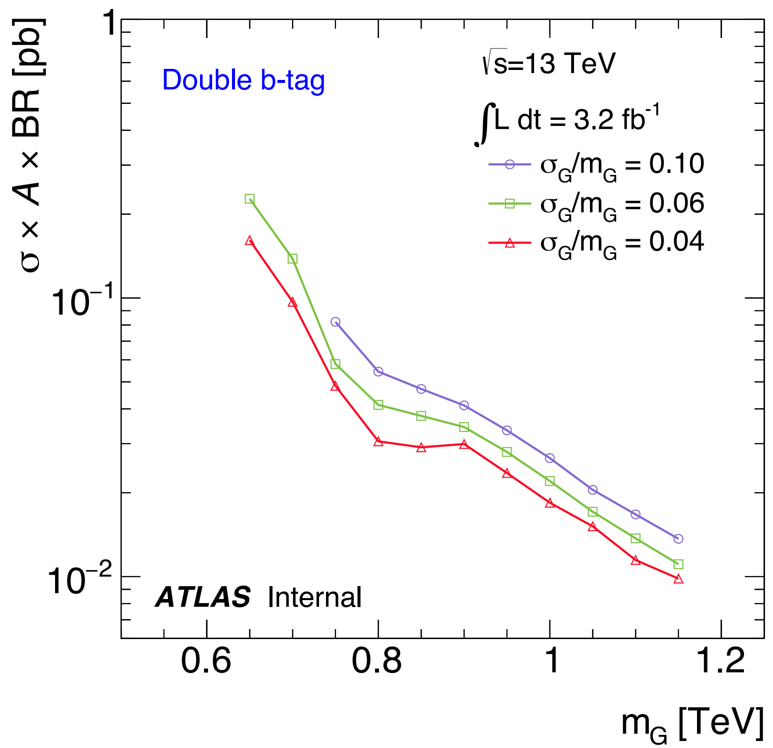
bH p-Value = 0.703

No significant discrepancy found!

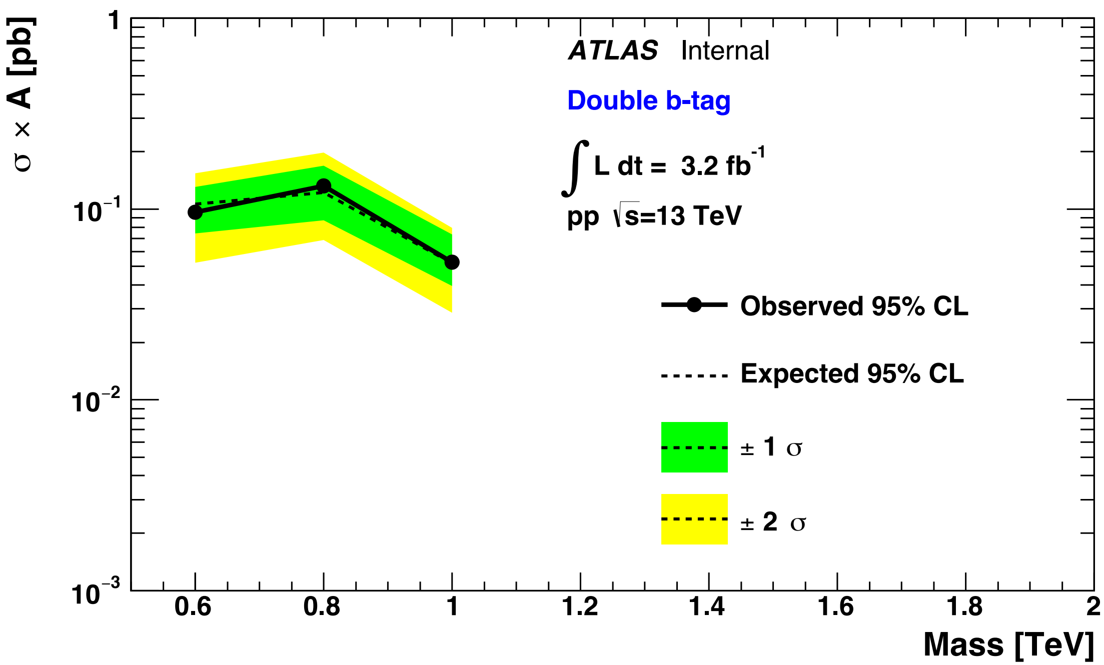
Results: Limit Setting

No significant discrepancy found

Therefore move to limit setting



- **Generic Gaussian Limits**
  - Three different resonance widths
  - 10% signal width uncertainty
    - *Sum of all uncertainties that affect signal width*
  - Lumi. uncertainty
  - Fit function uncertainties



- **Leptophobic Z'**
  - $m_{Z'}$ = 600 GeV unstable
    - m_{jj} cut of 566 GeV
    - Will not use mass point
  - Full systematics included
  - We want more mass points

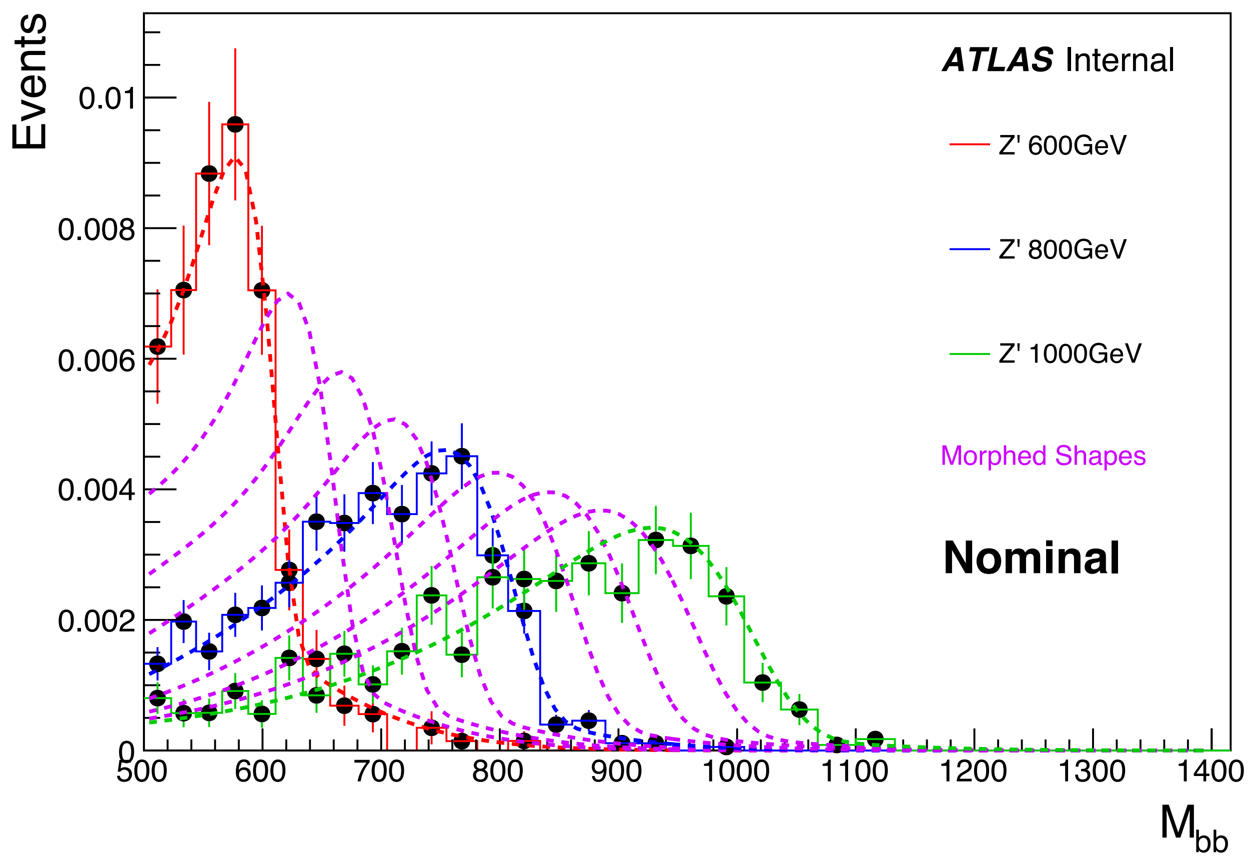
Signal Morphing

Talk With Details

UCL

- **Parameterise Signal Shape**
  - Gaussian + Reverse Landau fit.
  - Fit to all signal points
  - Interpolate fit parameters
- **Process repeated for systs.**
  - JES 3NP, JER 1NP
  - Trigger, bTag SF
  - Fit and interpolate

This gives us more mass points: ***600, 650, 700, 750, 800, 850, 900, 950, 1000 GeV***



Estimating 750 GeV Limit

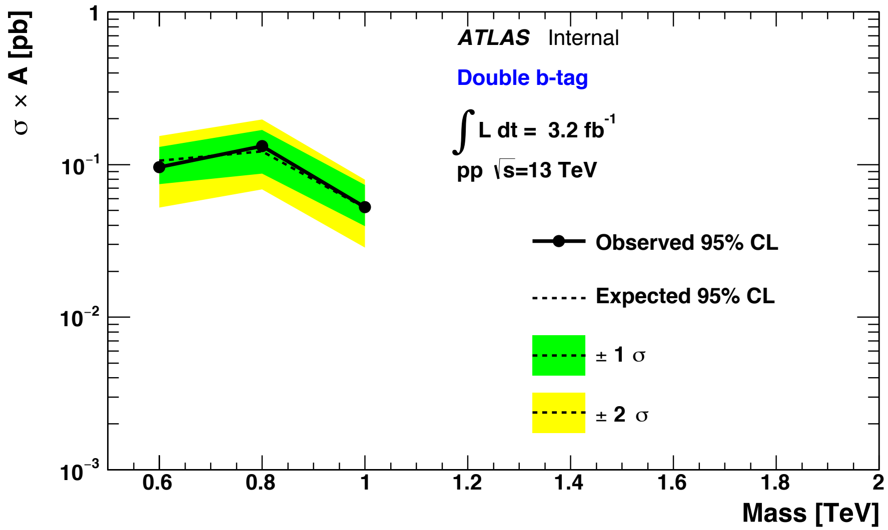
- **Target ~2.1 pb @ 13 TeV**
  - Scalar couples to bb and γγ only
    - Estimate $\sigma_{\gamma\gamma}$ and Γ from diphoton
    - Theorists calculate σ_{bb}

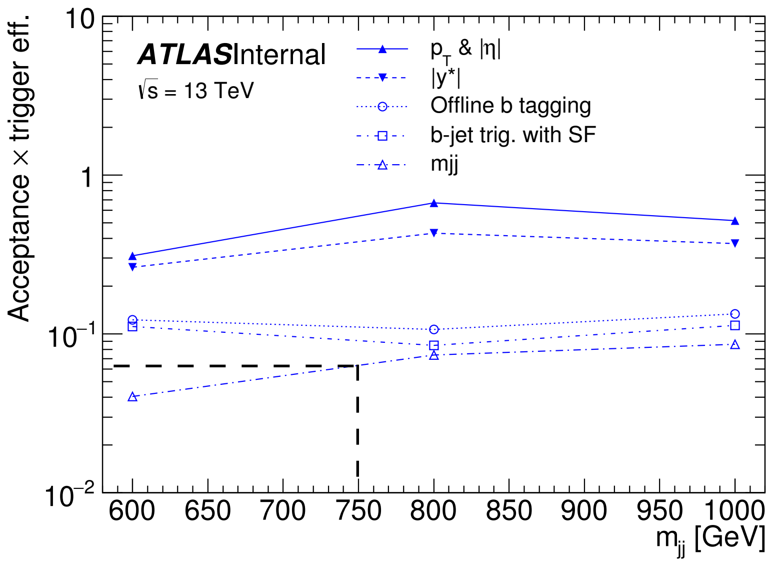
      (arXiv:1512.04933)

- **σ_{bb} x A ~ 0.1 pb**
  - From our limit plot

- **A ~ 0.07**
  - Interpolation

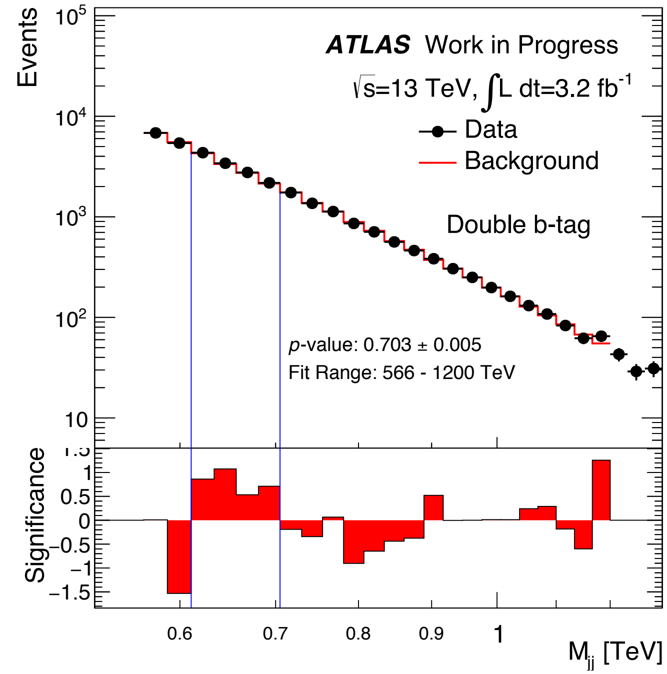
- **σ_{bb} ~ 1.5 pb**
  - Very coarse approximation
  - Not a finalised number
  - We should be able to exclude above model

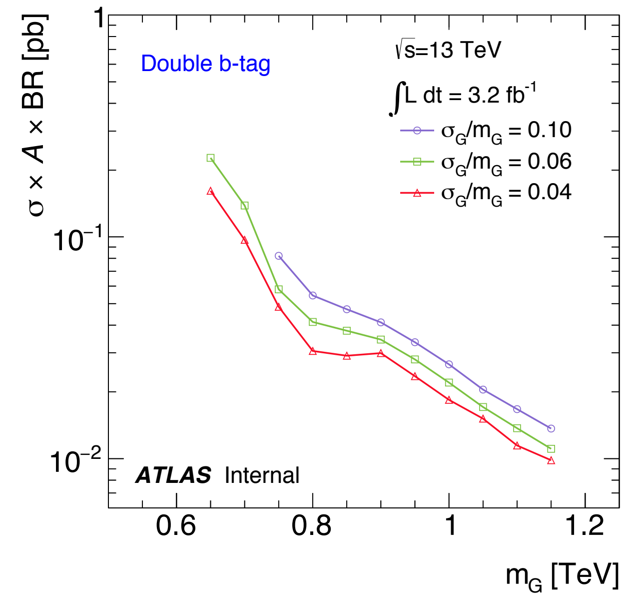




Conclusions

- **Low Mass b-Tagged Analysis**
  - Resonance decaying to bb poorly constrained at 750 GeV
  - **Use b-Triggers to get to low mass**
    - b-Jet efficiency measured
    - Systematics studied
- **No significant discrepancy found**
    - bH p-value = 0.703
- **Systematics Ready**
  - Dominated by b-tagging and b-jet trigger
- **Limits in progress**
  - Gaussian limit done
  - Leptophobic Z' in progress
    - Using signal morphing to get more
- **We should be able to exclude 2.1 pb**
  - This was our target





Comments

- **Fig 20, 25 and 34 have the same mistake in the legend: the p-value is for the plot, not for the bump.**

=> In these figures we use BumpHunter p-value and we want to phrase it such a way to represent this. Our concern is p-value of the plot makes it sound like we are using a chi2 like QoF test.

A proposal: *"Shown is the p-value of the largest discrepancy from the fit, calculated using the BumpHunter test statistic and pseudo-experiments"*

Other suggestions welcomed

l. 161: "considering bin boundaries" sounds strange. You can chose them yourselves.

-> The sentence refers to the bin optimisation according to the m_jj resolution. Rephrased as "Considering the result in Figure 5 and that the bin widths are chosen to approximate the m_jj resolution as derived from simulated QCD processes, the mass spectrum being investigated begins at 566 GeV."

Table 3: On data all numbers before the trigger are completely meaningless.

-> Agreed. The "all" here refers to all the events in the derivation. By "trigger" we mean asking the trigger to be fired in the events in the derivation. We made it clearer in the table and propose to leave the flow as is.

Sec. 4: In l. 174 you say that the b-medium efficiency is 72% which sounds like an absolute efficiency. However from 181 you always say that the efficiency is wrt the 70% OP of the off-line b-tag. Does this mean, that the true efficiency is only 50%. However in fig. 6 the efficiency looks on average much higher than 70%. Also in table 6-8 the trigger efficiency is 80-90% after off-line b-tagging.

-> The b-medium efficiency is ~72% compared to truth. There's a correlation between online and offline b-tagigng therefore the online+offline tagging efficiency on truth is expected to be higher than 50%. The analysis always and only computes the online efficiency with respect to offline and not truth. This is for deriving the trigger systematics as discussed in the section. It is expected that the online efficiency in Figure 6 is much higher as this sample is enriched in both truth and offline b-tagged jets. We propose to drop line 174 as this is the only place where the absolute online b-tagging efficiency is mentioned and is not an ingredient of the analysis.

Table 7-8: What is the reason why you loose so many events in the event cleaning and why is this so mass dependent?
-> To be tested.

P2 is much larger than typical suppression exponents in PDFs. How good is the fit if you force p2=0?
-> To be tested.

Table 7-8: What is the reason why you loose so many events in the event cleaning and why is this so mass dependent?
-> To be tested.

sec. 7.3.3/7.3.4 Are the systematics from the b-tagging and the b-trigger correlated?

-> There may be some correlation but are treated as uncorrelated. The b-tagging algorithms are different (IP3D+SV1 versus MV2c20) and the tracks are also slightly different. The main source of systematic uncertainty for the online b-tagging is due to the high-pT extrapolation which is based on fitting the data/MC b-jet trigger efficiency in events enriched with pure b-jets. The main source of systematic uncertainty for the offline b-tagging at high-pT is derived by applying MC-based smearing according to the tracking CP recommendations.

Koji Comments

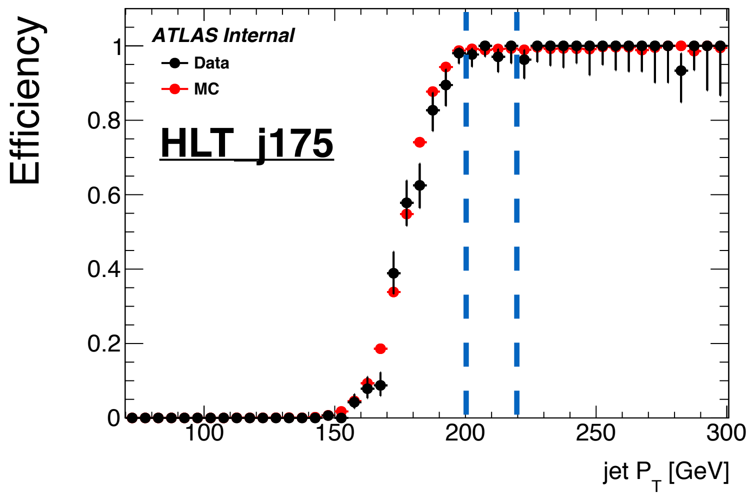
- l.142 : … 60% OP showing the … true b-jet acceptance --> Just curious why. The 60% OP is tighter than the bmedium (corresponding to ~72% OP), and then why does the bmedium trigger limits the acceptance?
- Fig. 5 : Is this the m_jj distribution only after the jet pT cuts denoted in the figure, or also including the y* cut? I suppose you can access lower mass if the y* cut is applied. Is this considered when you define the fit range starting at 566 GeV?
- Table 3 : The relative offline b-tagging efficiency is 50-55% for those jets passing the b-jet trigger. I guess this is probably expected? given the difference between the online and offline b-tagging algorithms as described in Sec. 4, but it's still a bit surprising to me as the online and offline b-tagging OPs are similar.
- l.207 : Probably useful to better clarify what's the main difference between the bperf trigger and bmedium trigger. The former must be looser than the latter and the offline b-tagging OP used in the analysis.
- Fig. 6
    - What's causing the turn-on of the efficiency around 120 GeV?
    - Just to clarify: non b-jet contamination (e.g, 2-10% at pT>120 GeV) is corrected in Fig. 6 to be able to apply this efficiency to pure b-jet signal, right?
- l.233-340 : This approach is fine, but it looks quite (maybe too) conservative. The b-jet trigger systematics is not the largest systematics as shown in Fig. 24(b), but I guess this has some non-negligible impact on the final limit, doesn't it? If you remove this artificially large non b-jet systematics shown in Fig. 11, does the result change?
- Fig. 14(a), 15(a) : Do you understand the different jet pT slopes in data and Pythia MC? I looked back the high-mass analysis note, and I don't see such a large difference after double tagging (Fig. 35a of ATL-COM-PHYS-2015-1324). Do I miss something here?
- l.304 : Nice to see the spurious signal studies with BumpHunter, but more relevant is spurious signal from signal +background fit to the background-only data (or MC) for limit setting. Has this been considered?
- Table 6-8 : Just curious why the event cleaning kills signal events so significantly. This cleaning is suggested to be applied only to data, isn't it? Not big deal for final result, though.

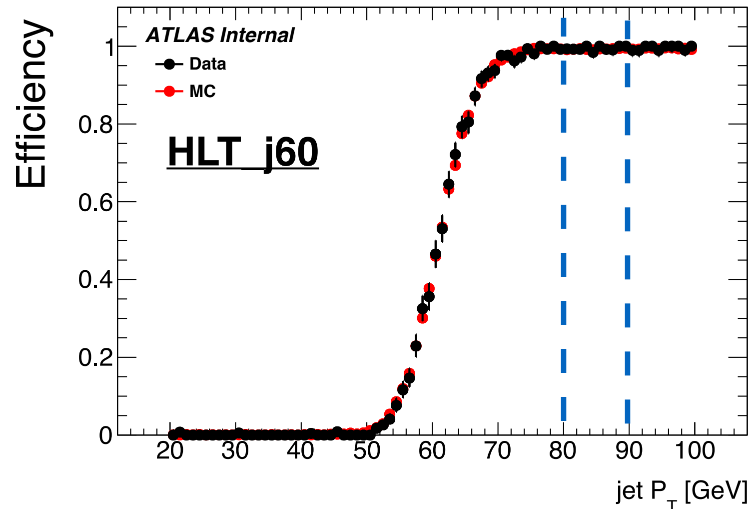
Working on Responses!

Backup!

Leading Jet P_T Cut

ATL-COM-PHYS-2015-1322





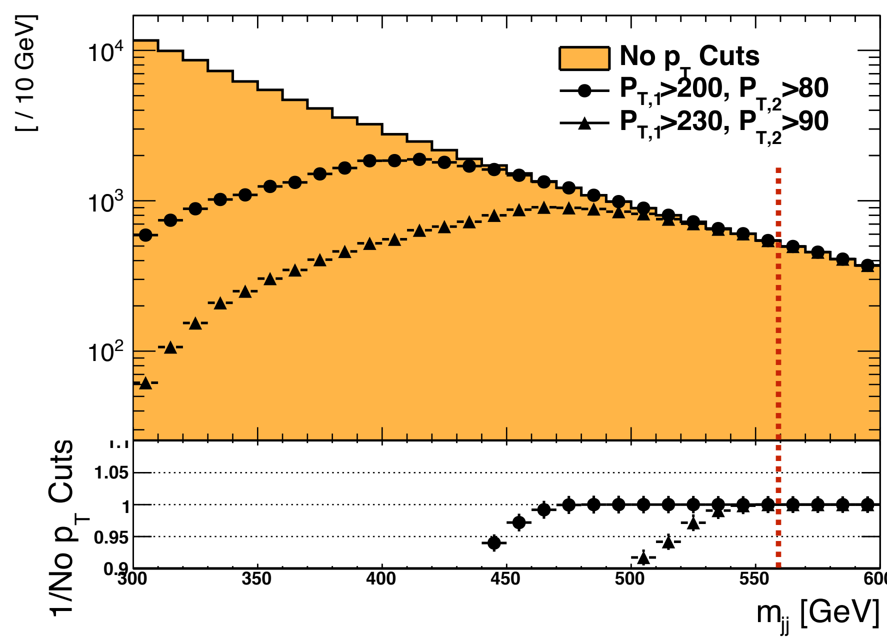
Cuts motivated by 99% Eff. Point
=> On trigger plateau

Leading Jet P_T > 220 GeV

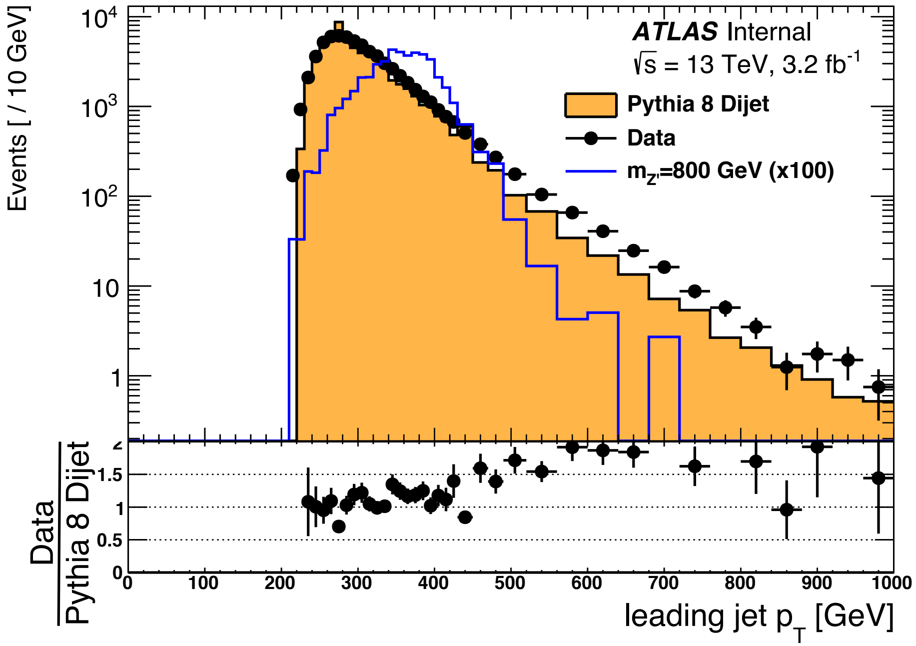
Sublead. Jet P_T > 90 GeV

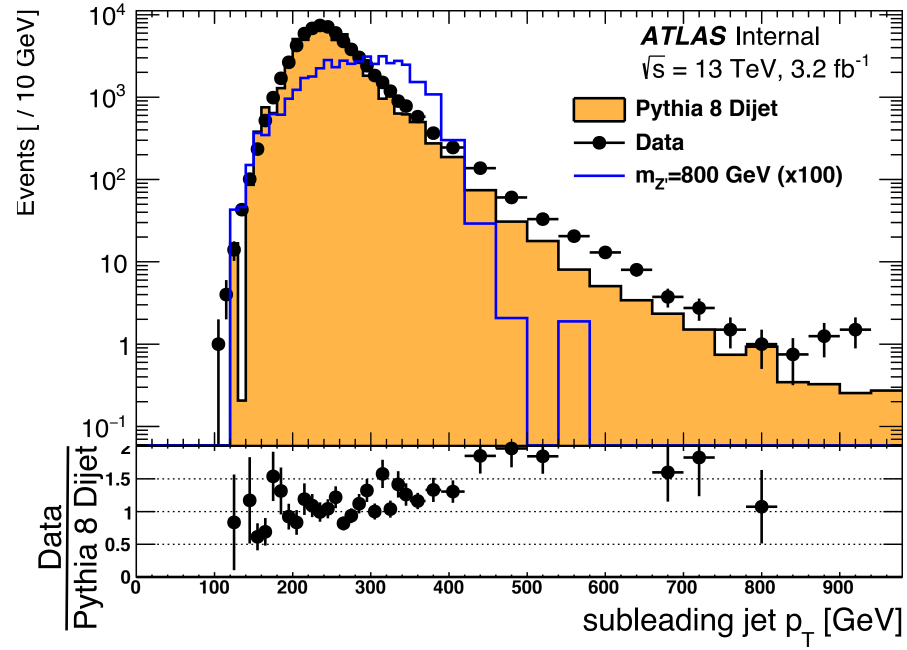
=> m_{jj} determined from turn-on

m_{jj} > 566 GeV



Kinematics: Validation Plots



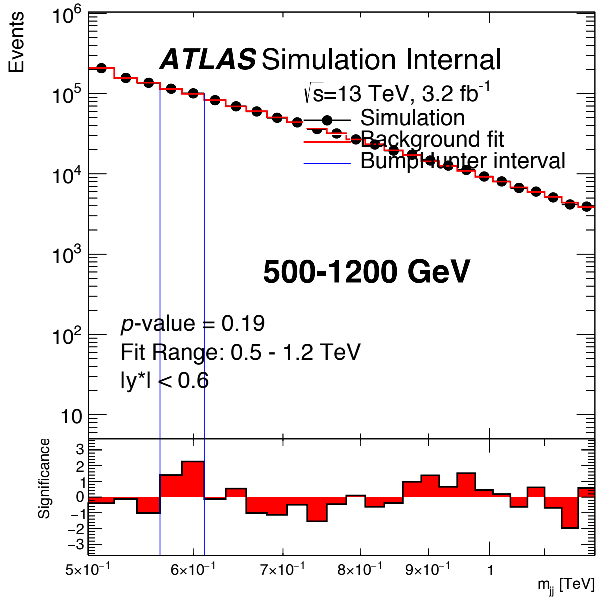


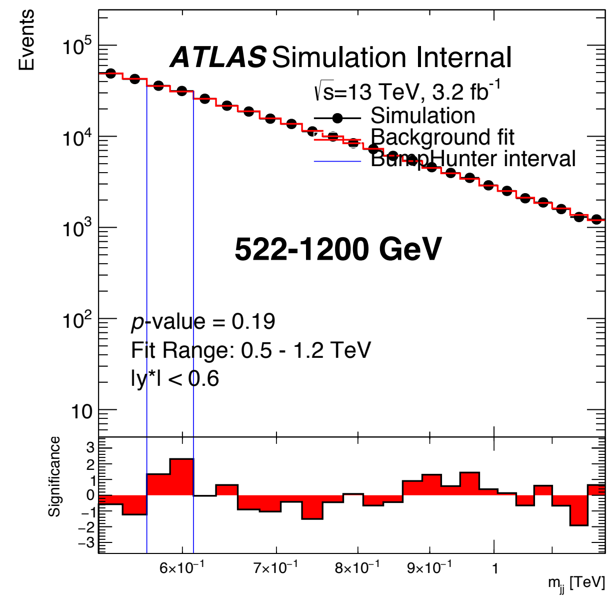
- **Emulating online b-tagging**
  - Light/Charm online b-tagging efficiencies not known
  - Thus some mismodelling expected

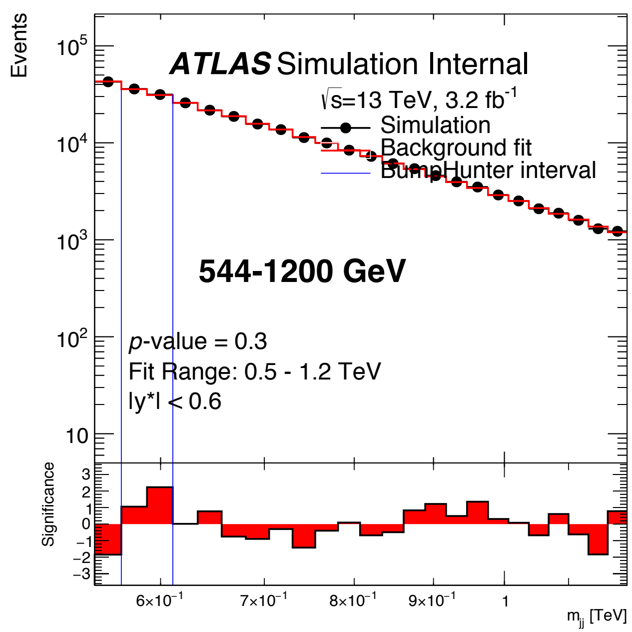
- **Many more validation plots available**

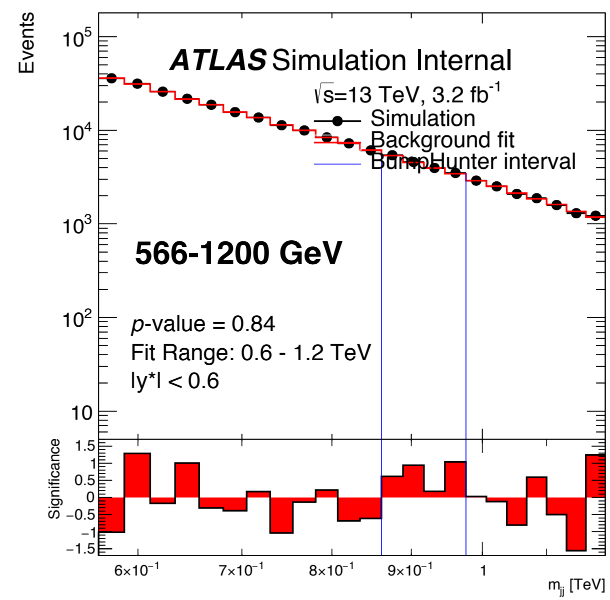
- **Z' with m_Z = 750 GeV being simulated now**

Spurious Signal: Full Set of Ranges









Timescale

	Request EB (latest)	First EB meet (latest)	Support note to JDM & EB	JDM Approval	Sup. Note to Exotics	Exotics Approval	Conf to ATLAS	Approval Meeting	Start of Conference
LHCP Jun 13-18	April 20	May 4	May 4	May 11	May 18	May 25	June 1	June 8	June 13