High-mass di-jets, di-b-jets and Resonances Decaying in Four Jets

Laurie McClymont, Katherine Pachal,

On Behalf of Analysis Teams

Exotics and Higgs BSM Workshop, Grenoble

15 April 2016

- **Two Analysis that we will focus on**

  ➡ **Exotic dijet analysis**
  - Resonance and Angular

  ➡ **Exotic b-Tagged dijet search**

- **We will look at:**

  1) Introduction to Analyses

  2) Current Status of Analyses

  3) Future Plans for Analyses
  - Sensitivities in 2016
  - Possible Improvements

  4) Discussion Session

UCL

1) Introduction to Analyses

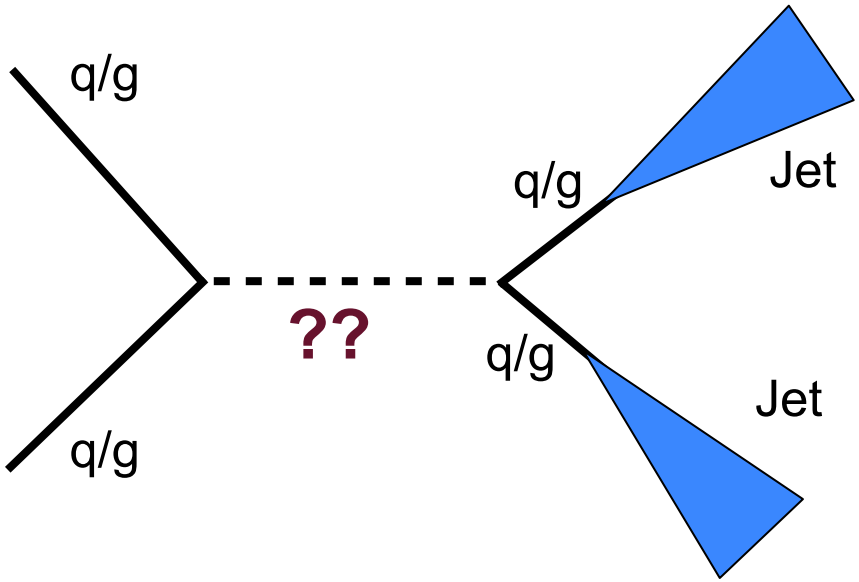
2) Current Status of Analyses

3) Future Plans for Analyses

4) Discussion Session

Exotic Dijet Motivation

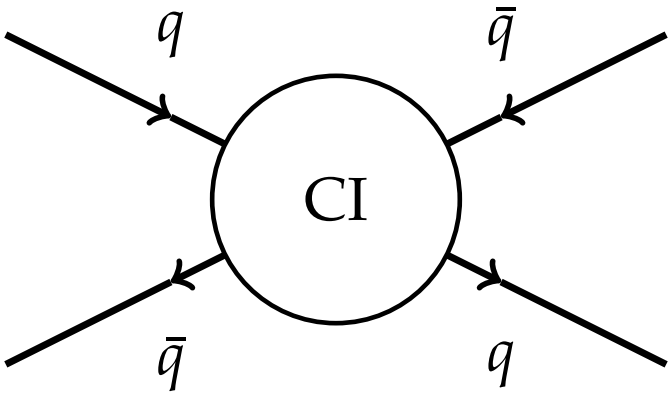
- **A powerful and general search for Beyond Standard Model Theories**
- **Many BSM models predict resonances that decay to pairs of q/g**



?? =

- Excited Quarks, *q**
- Quantum Black Holes *(QBH)*
- New Gauge Boson
  - ➡ Z' , W*
- Many many others...

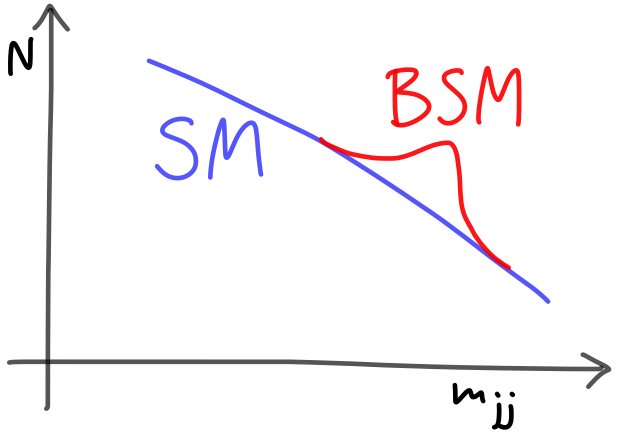
- **Sensitive to Contact Interactions (CI)**
  - At some energy scale new physics emerges
  - Modelled by an effective field theory
  - Can effect dijet kinematics

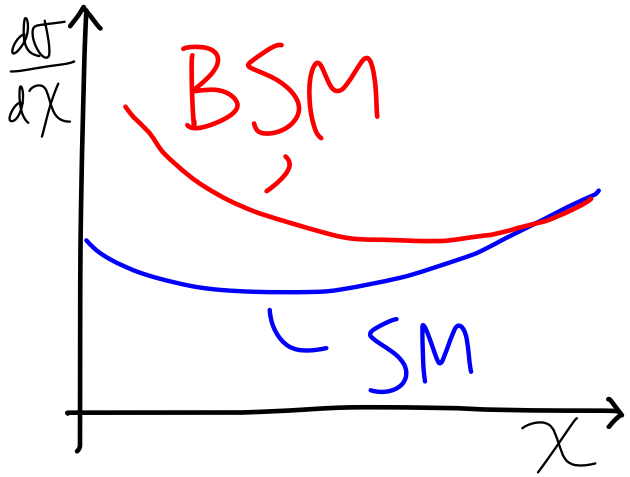


Exotic Dijet Analysis Introdution

- **Searching for BSM using dijet events:**
  => Two complementary approaches:

- **Resonance Analysis**
  - Study dijet invariant mass
  - Fit using smoothly falling function
  - Look for deviations from background
  - Powerful for low χ



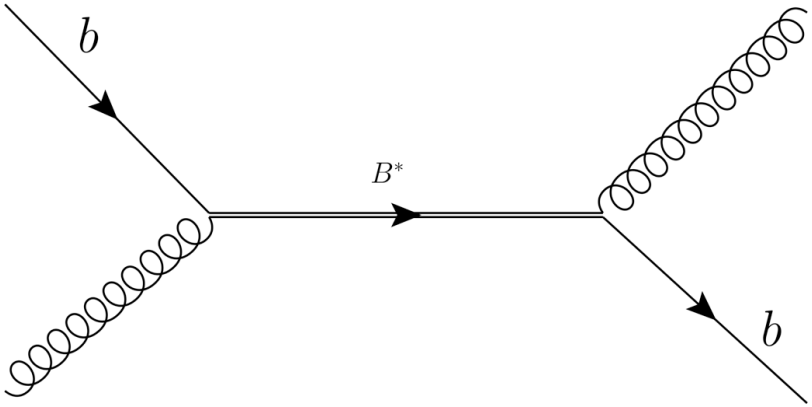


- **Angular Analysis**
  - Study, $\chi = e^{2|y*|} = e^{|y_1 - y_2|}$
  - Compare shape from Data to MC
  - Sensitive to contact interactions
  - Powerful at high m_{jj}

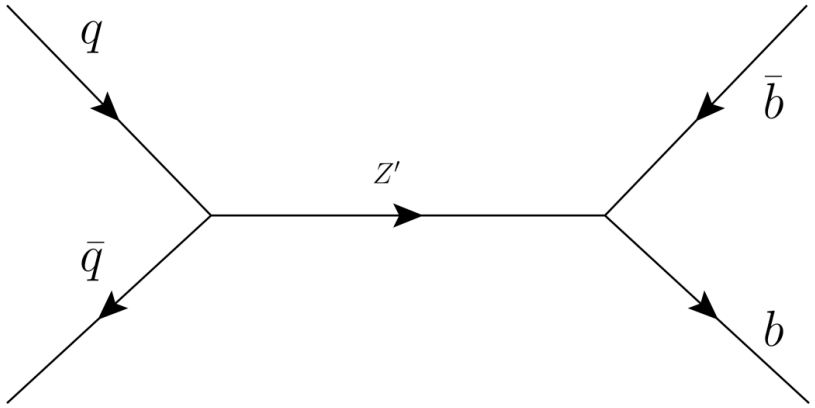
- **Closely related to Trigger Level Analysis (TLA) analysis**
  => *See Lydia's talk, which follows, for more info on this.*

b-Tagged Analysis Introduction

- **Many BSM models predict resonances decaying to b-quarks**



Excited b-quark (b*)



Z' Boson

- **Apply b-tagging to event selection**
  - Reduce light jet dominated background *(light = u, d, s and gluon)*
  - Increase sensitivity to these models.

- **Perform Resonance Search - Similar to dijet search**
  - Fit to QCD background and search for discrepancies
  - Can use both 1 b-tag and 2-tag information
  - Use two models above as benchmark models

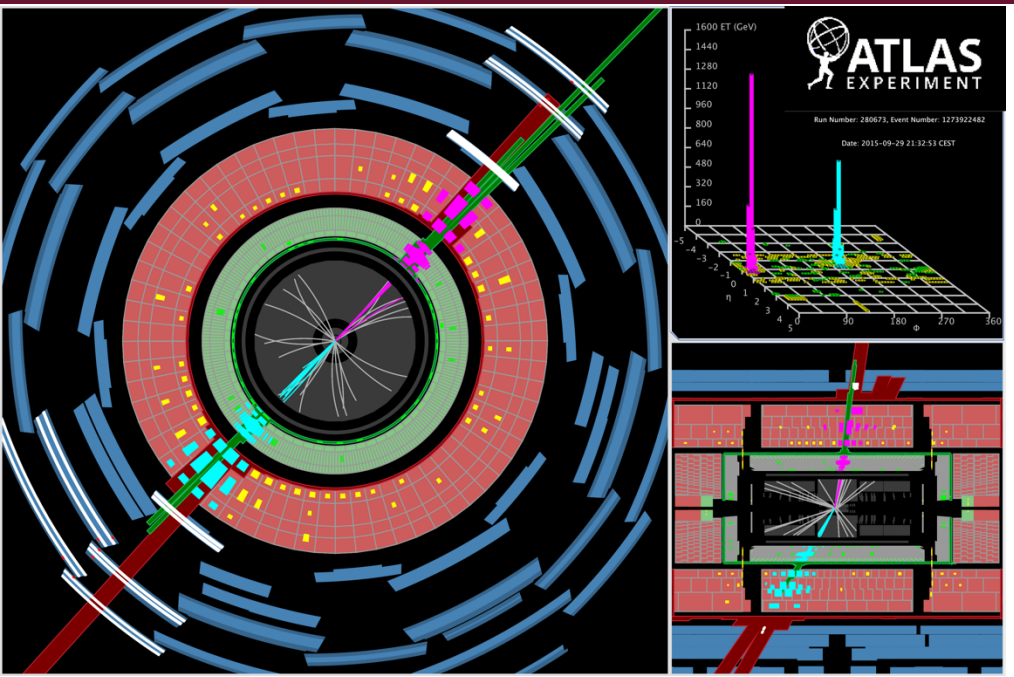
1) Introduction to Analyses

2) Current Status of Analyses

3) Future Plans for Analyses

4) Discussion Session

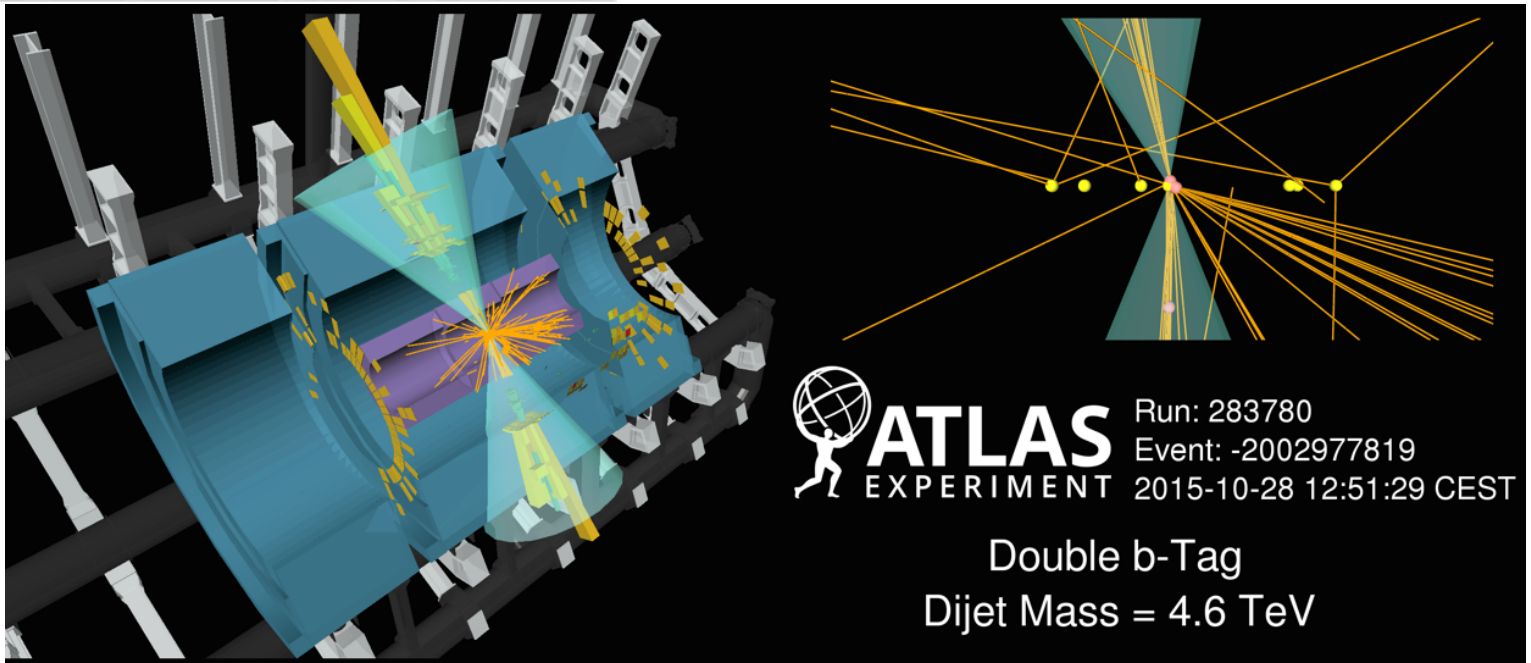
13 TeV!!



Highest m_{jj} Events Seen at ATLAS

m_{jj} = 6.9 TeV
(Resonance)

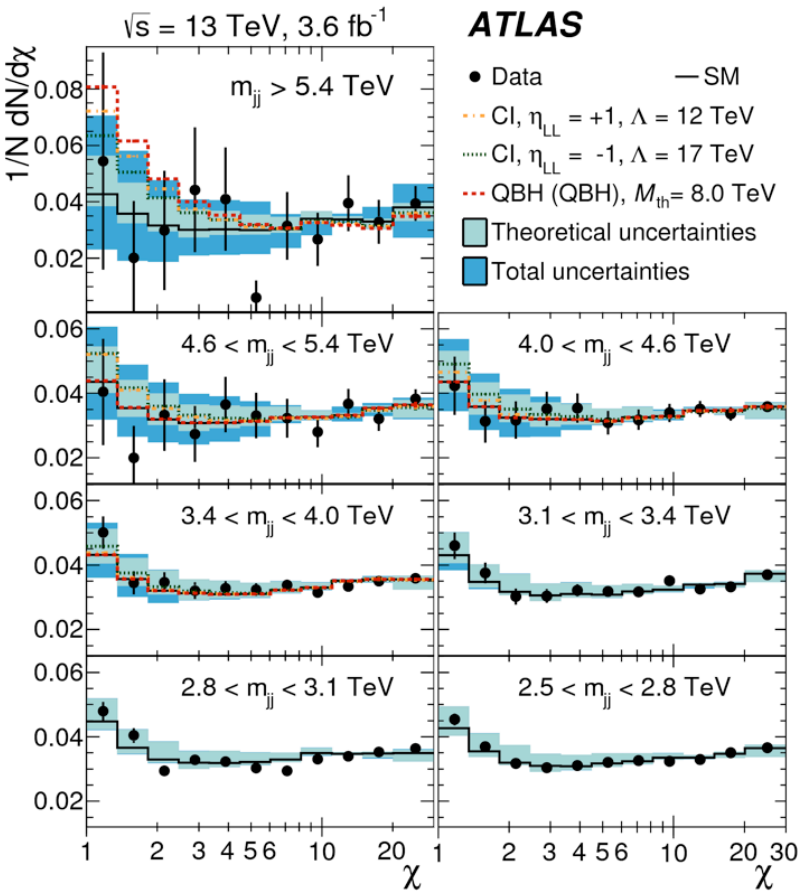
m_{bb} = 4.6
(2 b-tag)

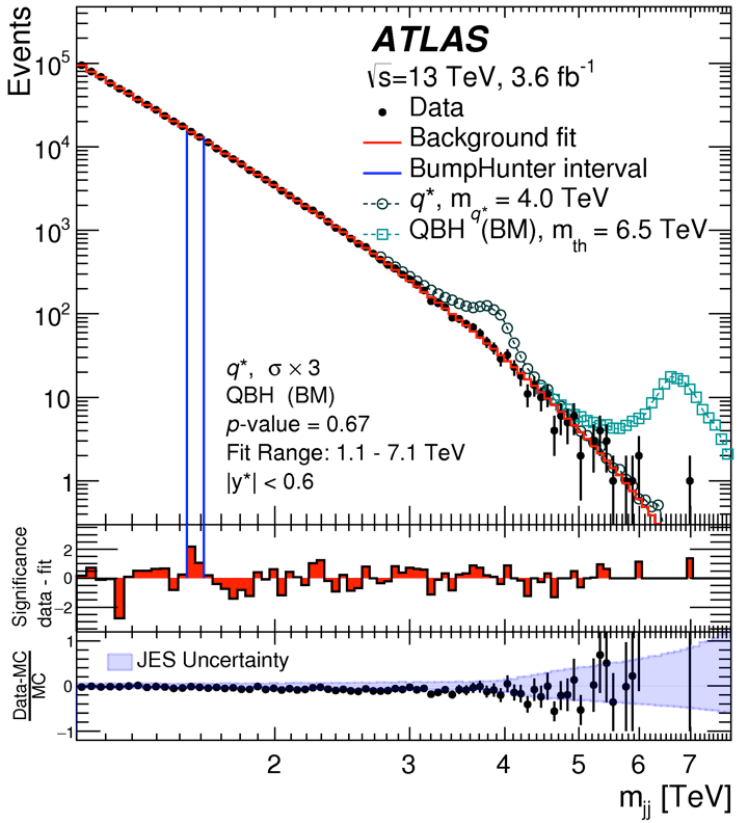


arXiv:1512.01530

- **EOYE Result for Resonance and Angular**
  - First 13 TeV public result from ATLAS
  - 3.6 fb^{-1} including IBL off data

Event Selection	Angular	Resonance
Trigger	HLT_J360	
m_{jj}	> 1.1 TeV	> 2.5 TeV
$\|y^*\|$ $y^*=0.5*\Delta y$	< 0.6	< 1.7



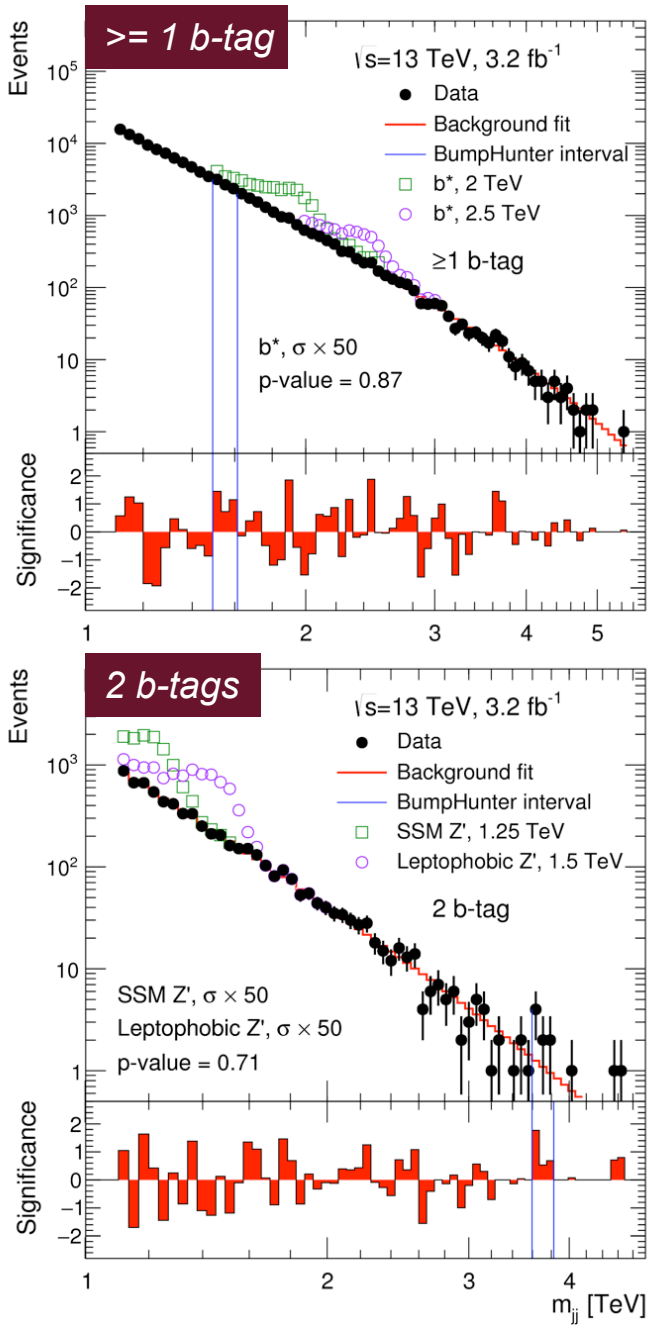


No significant deviation found

b-Tagged Dijet Resonance Analysis

arXiv:1603.08791

- **Moriond Result for b-Tagged Dijet Analysis**
  - First such analysis at ATLAS
  - 3.2 fb^{-1}, excluding IBL-off data
- **Event Selection** (Full list in backup)
  - Very similar to dijet resonance search
    - **HLT_j360**
    - **m_{jj} > 1.1 TeV**
    - **|y*| < 0.6**
- **b-Tagging = MV2c20 @ 85% Eff. WP**
  - Two b-Tagging categories;
    - Inclusive 1 b-tag
    - 2 b-tag categories
- **No significant deviation found**



Summary of Observed 95% C.L. Upper Limits

Analysis	Model	ATLAS Run-1	ATLAS Run-2	CMS
Dijet Res.	Quantum black hole, ADD (BlackMax/QBH gen.)	5.6 TeV / 5.7 TeV	8.1 / 8.3 TeV	—
	Quantum black hole, RS (QBH gen.)	—	5.3 TeV	—
	Excited Quark (q*)	4.1 TeV	5.2 TeV	5.0 TeV
	W' Boson	2.5 TeV	2.6 TeV	2.6 TeV
	Z' Boson, $g_q = 0.3$ *(Other g_q in backup)*	—	2.5 TeV	—
Dijet Angular	Contact Interactions *(Destructive, $\eta_{LL} = +1$)*	8.1 TeV	12.0 TeV	—
	Contact Interactions *(Constructive, $\eta_{LL} = -1$)*	12.0 TeV	17.5 TeV	—
b-Tagged Dijet	b* Quark	—	2.1 TeV *($\sqrt{s}$ = 13 TeV)*	1.54 TeV *($\sqrt{s}$ = 8 TeV)*
	Z' Boson	—	1.5 TeV *(Leptophobic, $\sqrt{s}$=13 TeV)*	1.68 TeV *(Sequential SM, $\sqrt{s}$=8 TeV)*

ATLAS Results

Dijet; 8 TeV, 17.3/20.3 fb^{-1} : arXiv:1504.00357 / arXiv1407.1376
Dijet; 13 TeV, 3.6 fb^{-1} : arXiv:1512.01530
Di-b-jet; 13 TeV, 3.2 fb^{-1} : arXiv:1603.08791

CMS Results

Dijet; 13 TeV, 2.9 fb^{-1} : arXiv:1512.01224
Di-b-jet; 8 TeV, 19.6 fb^{-1}: CMS PAS EXO-12-023

1) Introduction to Analyses

2) Current Status of Analyses

3) Future Plans for Analyses

4) Discussion Session

Aims for Dijet Analysis

- **2016 Data**
  - Dijet resonance and angular analysis
  - Get more sensitivity!!

- **Timescales**
  - **ICHEP** - CONF Note for (3-10 August 2016)
  - **Winter Conferences** - More substantial paper for
    => Including more data, more interpretations

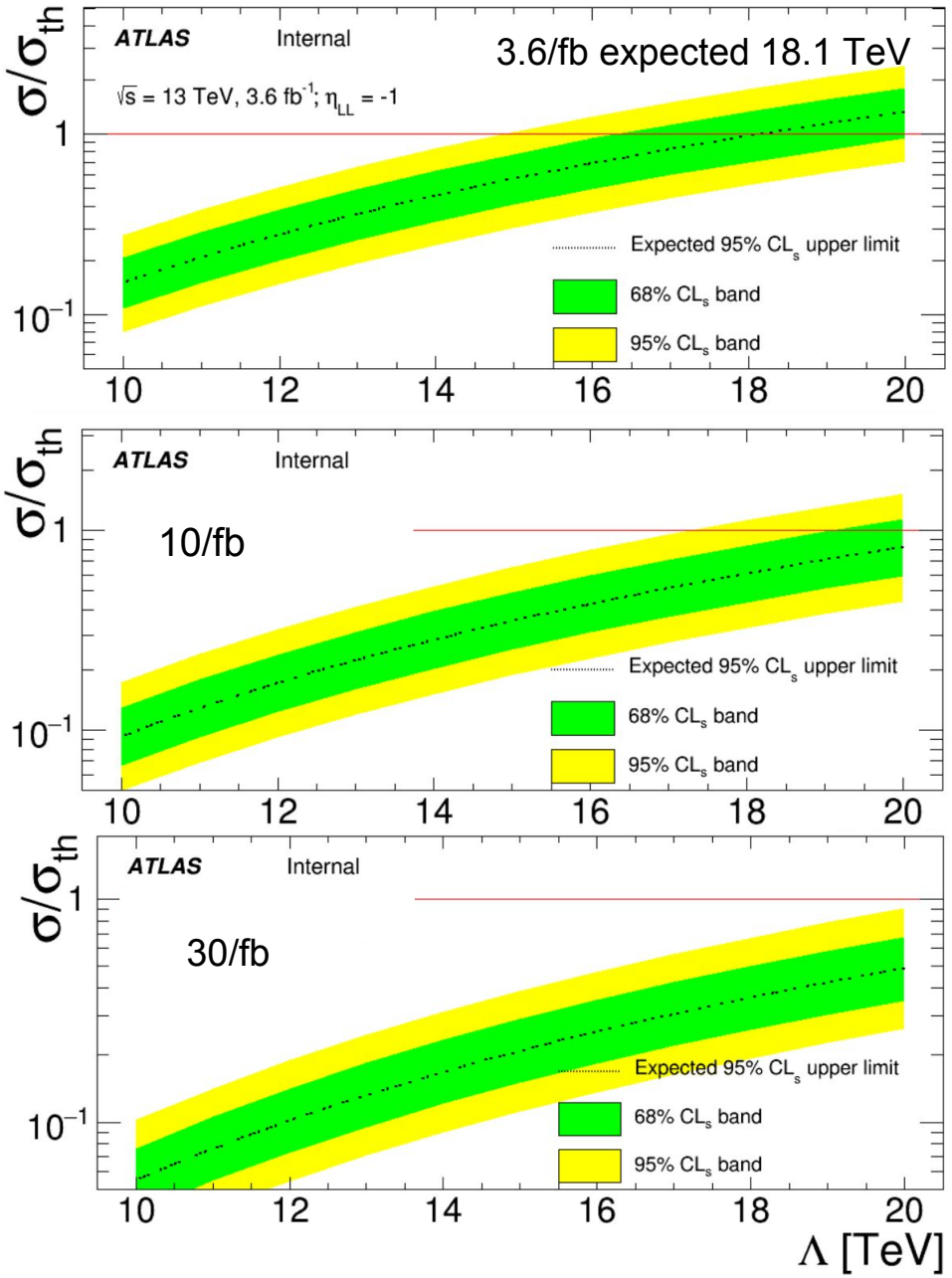
- **Investigating possible improvements**
  - Reclustered jets
  - Sliding window
  - Fχ variable
  - W* optimisation

Angular Sensitivity for 2016

- **Expected Limits for 2016?**
  - 2015 analysis structure
  - Look at 10 and 30 fb^{-1}
  - Constructive CI ($\eta_{LL} = -1$)
    - Current limit - 17.5 GeV

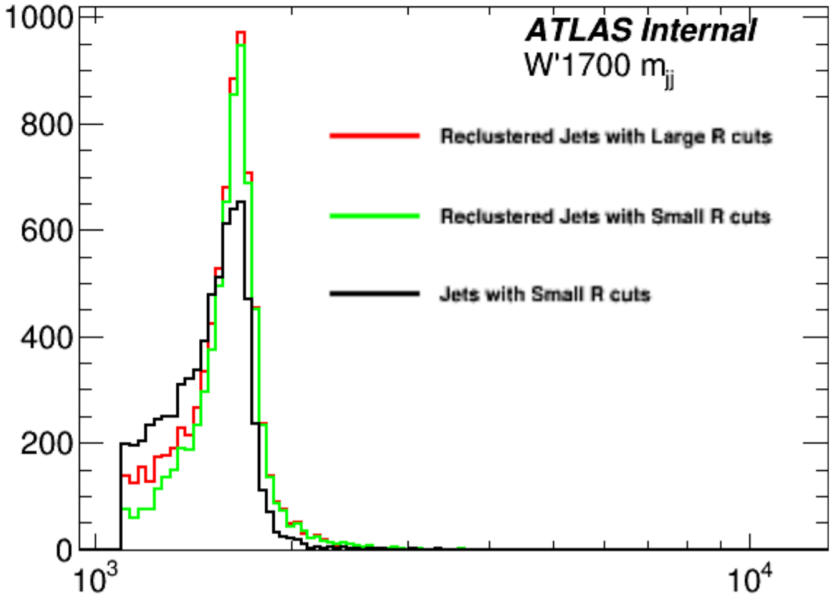
Lumi (fb^{-1})	σ/σ_{TH}, $\Lambda = 20$ TeV
3.6	1.31
10	0.82
30	0.49

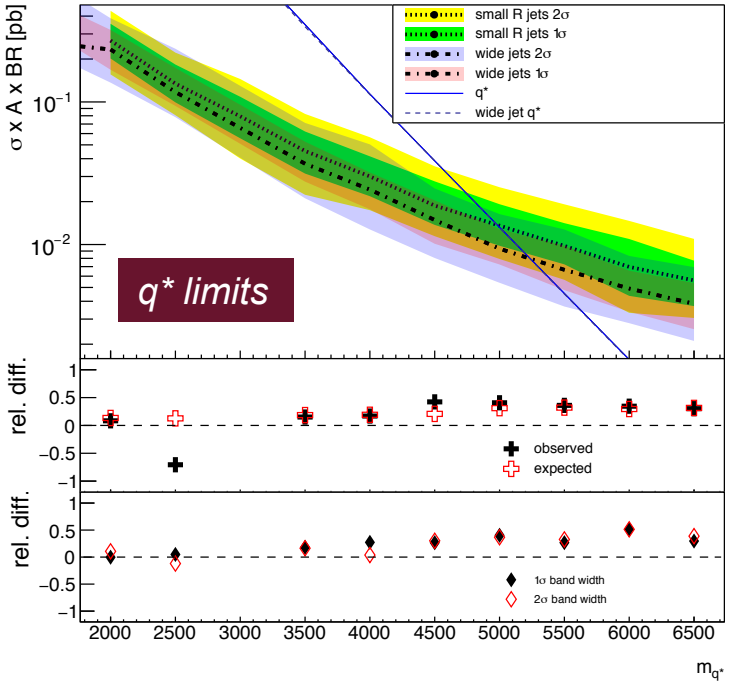
- **CI signal at high Λ**
  - Currently use Λ = 7 and 10 TeV
  - Analytical extrapolation for large
  - Larger data set may need a more refined validation strategy



Dijet Improvements: Reclustered Jets

- **Reclustered Jets (Recl. Jets)**
  - Recluster jets within R=1.0 of leading or subleading jet
  - Use resonance dijet cuts
    - Applied to small-R jet or recl. jets
- **Why?**
  - Reduced sensitivity to FSR
  - CMS used wide jets for EOYE
    - Competitive with lower lumi.
- **What do we get**
  - More background, jets migrate to higher p_T
  - Better signal resolution
  - Mix of limit changes





Model	Change	Small R Jets		Recl. Jets	
		Obs.	Exp.	Obs.	Exp.
q*	Improve	5.2 TeV	4.9 TeV	5.5 TeV	5.2 TeV
W'	Worsen	2.6 TeV	2.6 TeV	2.3 TeV	2.5 TeV
QBH	No Change	8.3 TeV	8.3 TeV	8.3 TeV	8.4 TeV

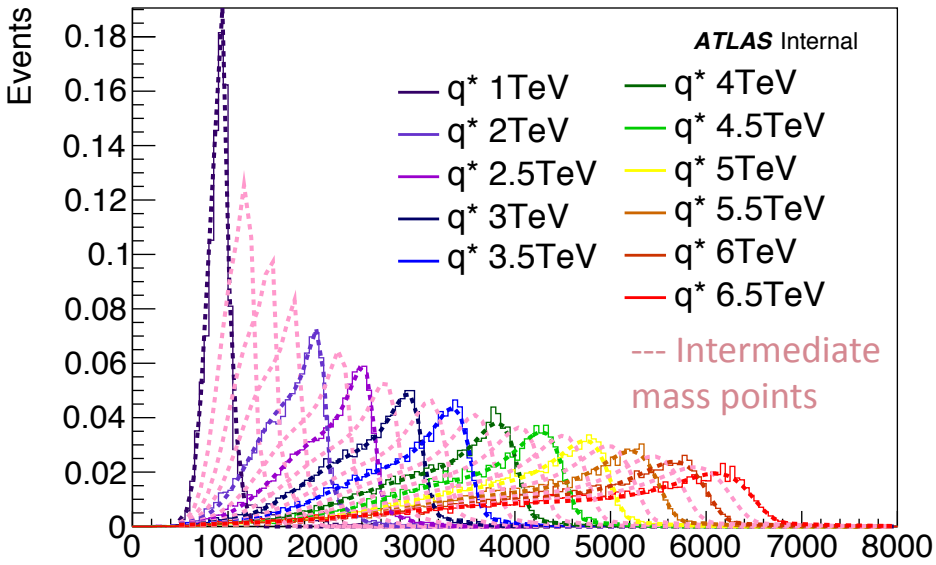
Dijet Improvements: Sliding Window

- **Fit in mass windows**
  - Take a window 3 TeV in width
  - Within window fit signal + background
    - Background: 3 or 4 para. fit function
    - Signal: Mass centre of window.
  - Move window in jumps of 50 GeV

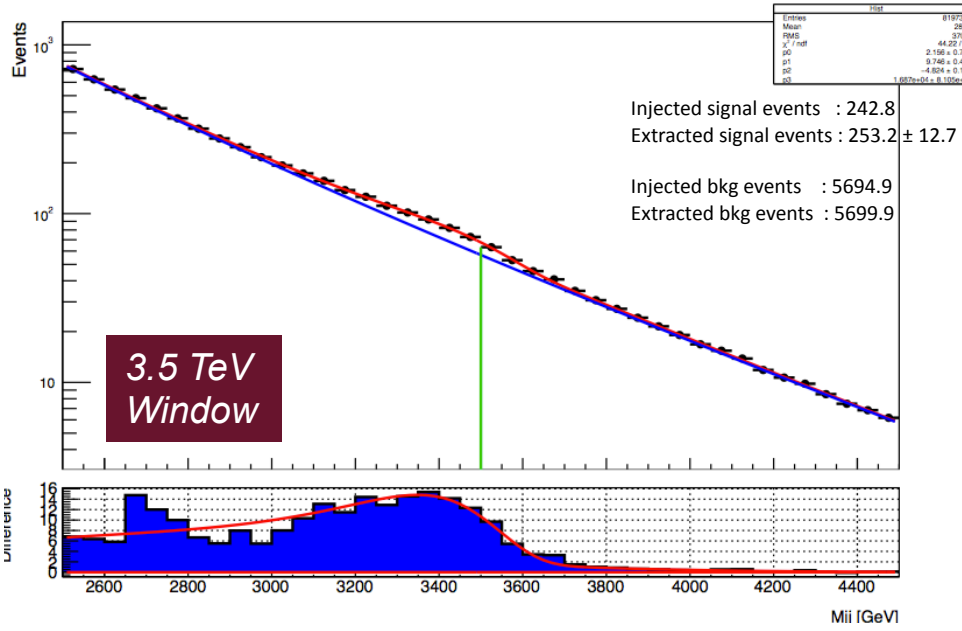
- **Signal Morphing**
  - Need more signal mass points
  - Signal shape for q*
    Gaussian + Reverse Landau fit.
  - Interpolate parameters.

- **Testing the procedure**
  - MC: QCD dijet + 3.5 TeV q* signal
  - Slide over windows and fit S+B
  - 3.5 TeV is the largest signal window.

Red curve – 3 Parameter Background + signal shape for mass at center of window
Blue curve – Background only fit from red curve
Green line – Marks the center of window

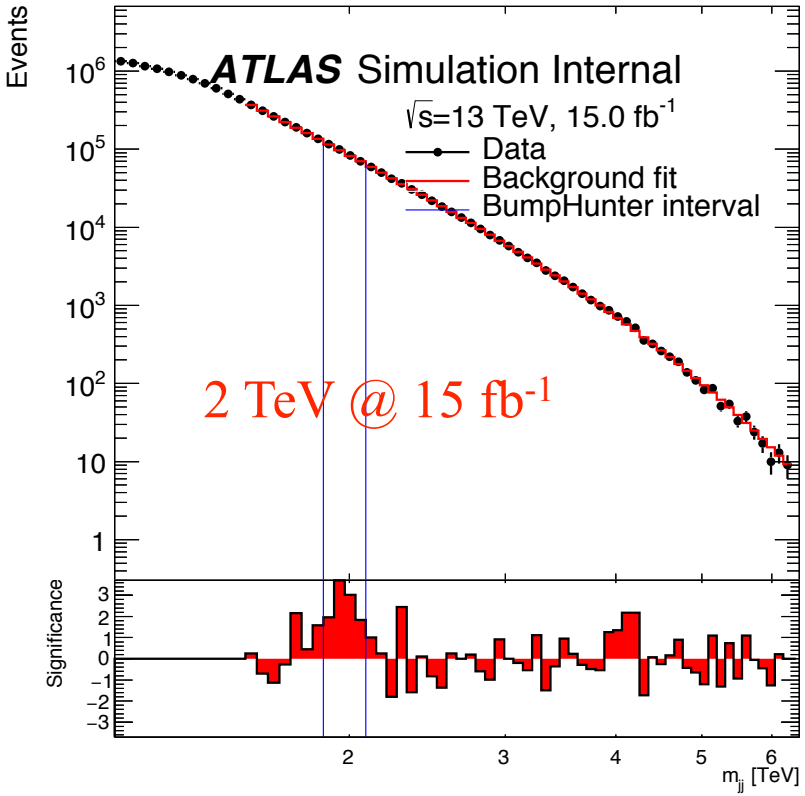


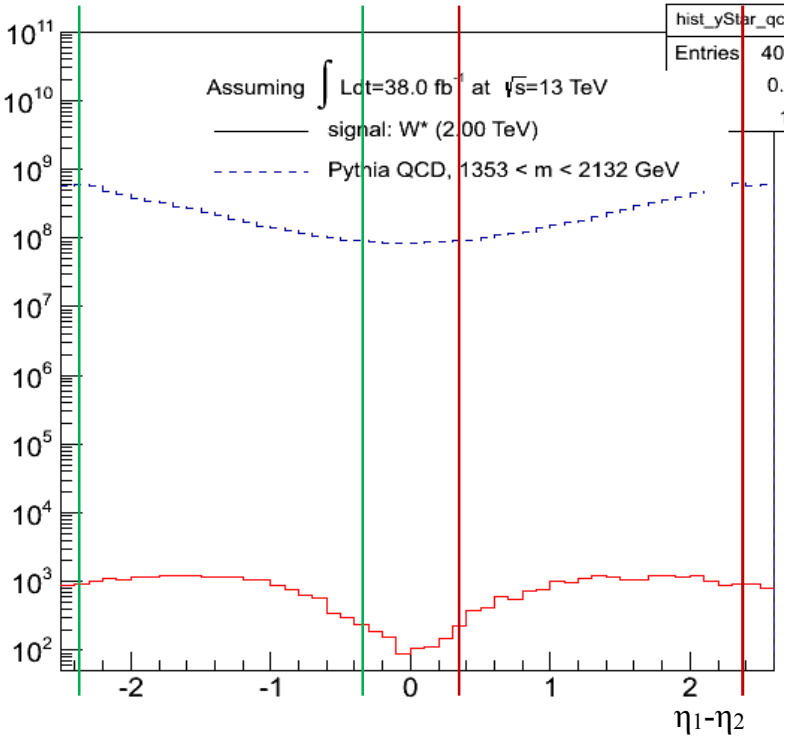
All dotted curves: morphed
All Solid curves: MC shapes



Dijet Improvements: W* Optimisation

- **y* cut optimisation**
  - QCD bkg. increases at large y*
  - Dip in W* events at low y*
    - **0.175 < |y*| < 1.18**





- **y* Cut performance**
  - Fitting tested with QCD MC
    - Good fitting performance
  - Also tested with injected W*

- **Discovery of W***
  - 2 TeV W* @ 15 fb^{-1}
  - 3 TeV W* @ 35 fb^{-1}

Dijet Improvements: F_χ

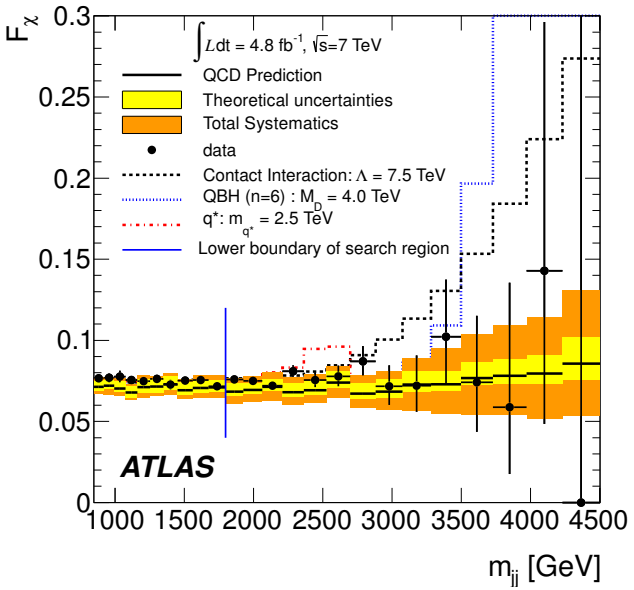
$$F_\chi(m_{jj}) = \frac{N_{|y^*|<0.6}(m_{jj})}{N_{|y^*|<1.7}(m_{jj})}$$

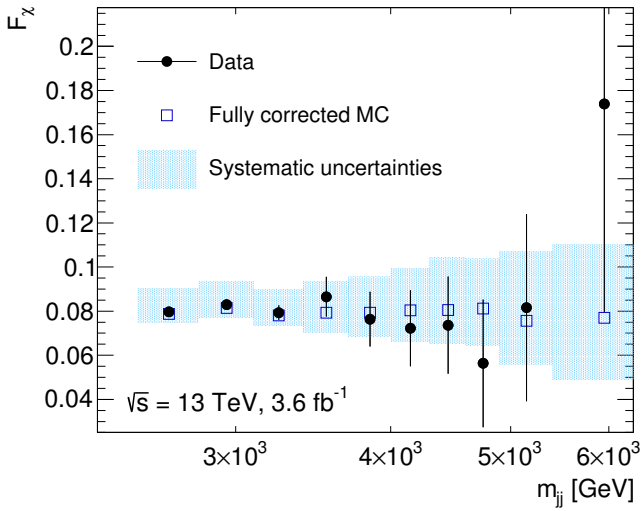
- **F_χ Variable**
  - Ratio of resonance and angular selection.
  - Contains same information as χ dist.

- **Why use F_χ?**
  - Enhanced resonant sensitivity
    => Bin more finely in m_{jj} as only two χ bins.
  - Data driven approach can be found
    => F_χ is flat if no angular dependance in m_{jj}

- **Previous use (or not)**
  - Used in √s = 7 TeV angular analysis
  - Dropped in √s = 8 TeV analysis
    => Partly due to large data/MC discrepancy

- **Current status**
  - F_χ reconstructed from 2015 angular analysis
  - Consistent Data/MC within systematics
  - On going work including sensitivity studies



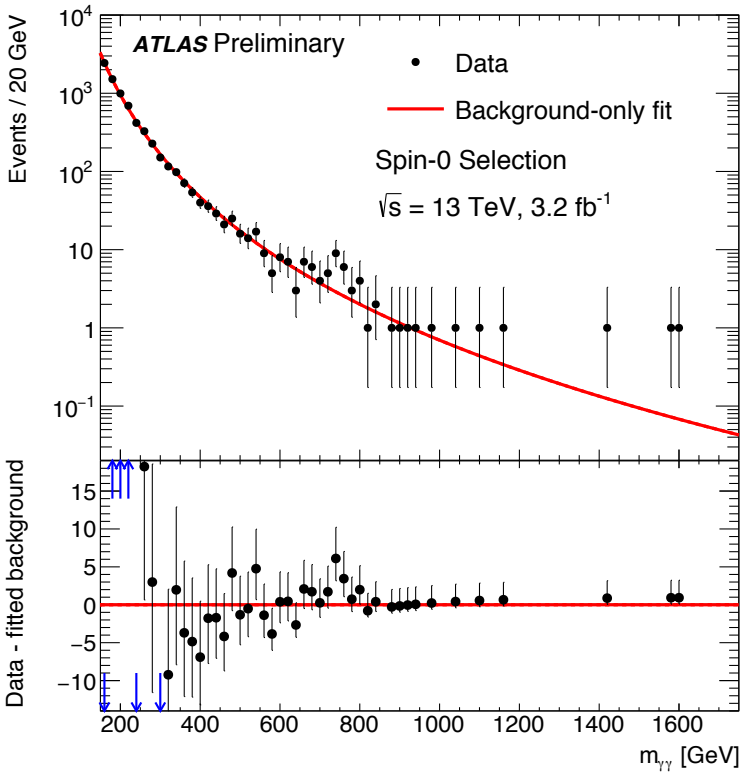


Dibjet - 2016 Timescales

- **Motivation to go to lower masses**
  - Cross over between $m_{\gamma\gamma}$ and m_{bb}
  - Benchmark models can decay to b-quarks
    => Extended Higgs sector (2HDM)
    => Randall-Sundrum graviton
  - Can we set limits on relevant models...
  - Or even confirm resonance

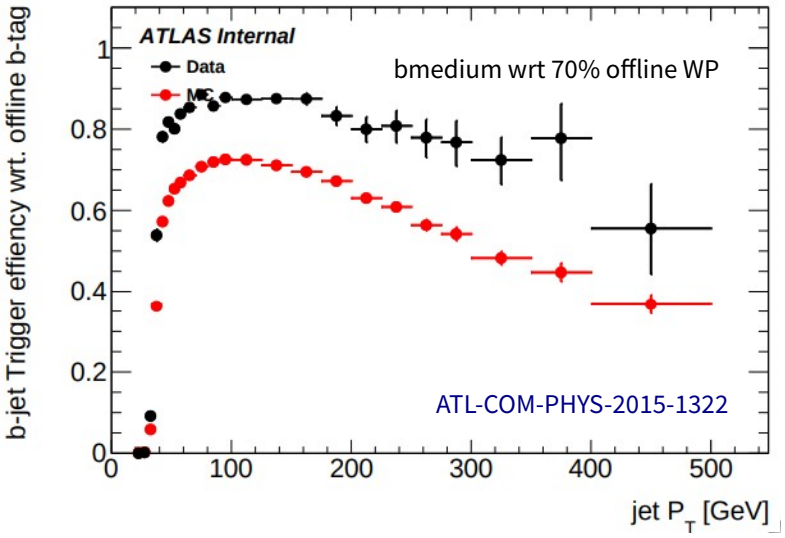
- **We can get to lower masses**
  - Possible with use of new triggers
    - b-jet triggers
    - 4-jet triggers

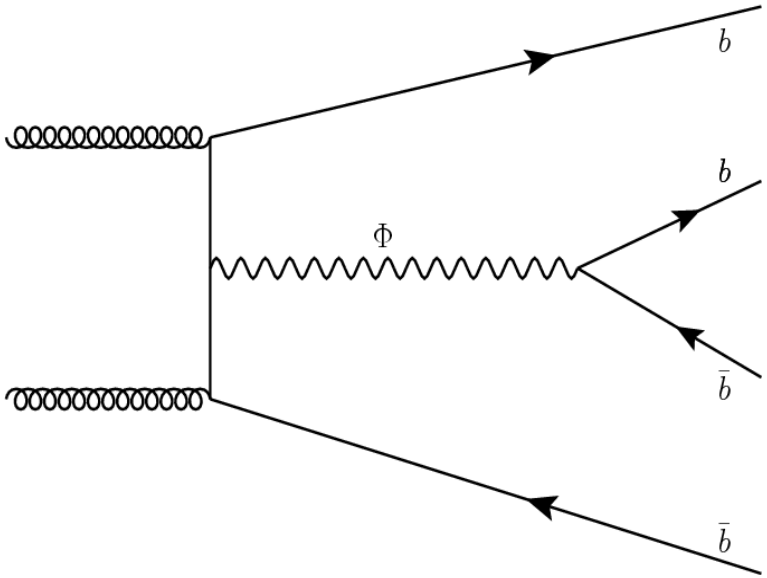
- **Currently two parallel plans**
  - **Reuse 2015 data for LHCP 2016**
    - Simple model can be excluded
    - Fast paced analysis (13-18th June)
  - **Use 2016 data for ICHEP 2016**
    - More luminosity
    - Slightly slower analysis (3rd-10th August)



Extending to Lower Masses

- **b-Jet Triggers**
  - **HLT_j175_bmedium_j60_bmedium**
  - Trigger on two offline b-tagged jets.
  - We get to m_{jj} = 500 GeV
  - b-jet trigger efficiencies exist

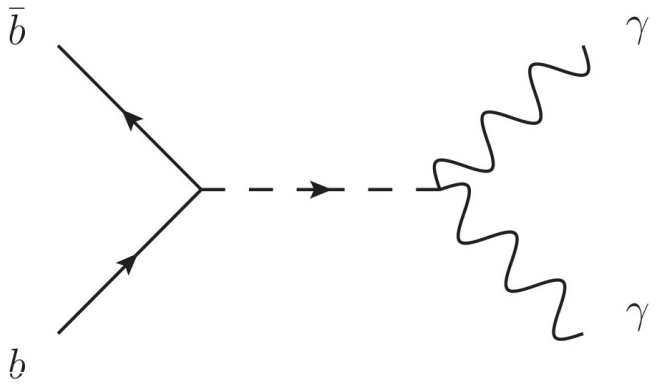




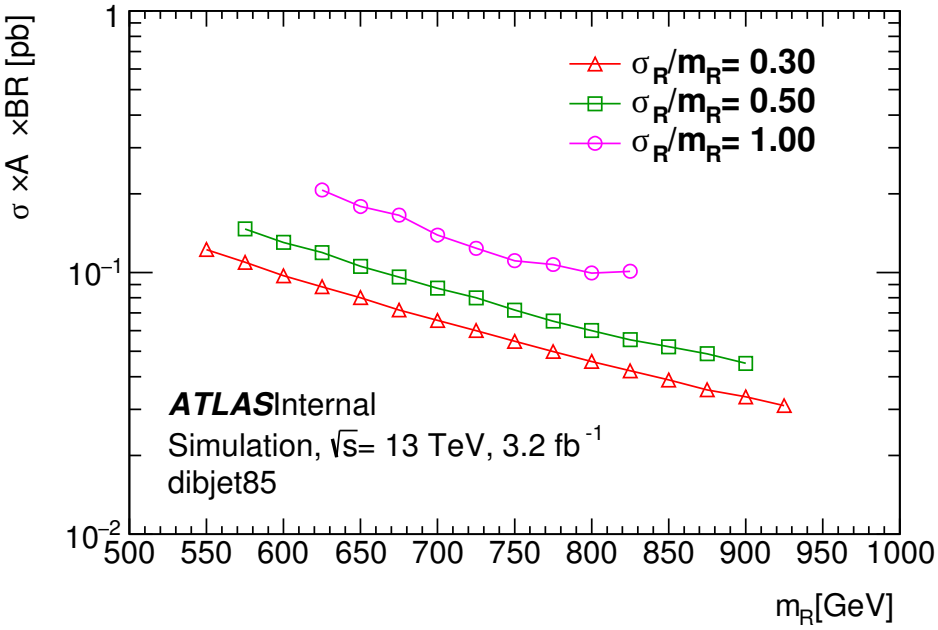
- **Four Jet Trigger**
  - **HLT_4J85**
  - For bb production
  - Trigger on 4th jet, p_T > 85 GeV
  - We should get to m_{jj} = 400 GeV
  - Possibility for > 2 b-tag

Sensitivity Study using b-Jet Triggers

- **Consider simple scalar model**
  - Couples to only γγ and bb
  - Measured of $\sigma_{\gamma\gamma}$ and Γ
  - We get $\sigma_{bb} \sim 2.1$ pb for s = 13 TeV
  - No limit exists at 13 TeV



- **Quick sensitivity study on 2015 data**
  - Fit to data range $500 < m_{jj} < 1000$
    - Blind 500-700 GeV
  - Estimate 10% acceptance (from Z')
  - Find expected gaussian limits
  - No systematics considered



- **Event Selection** (full list in backup)
  - **HLT_j175_bmedium_j60_bmedium**
  - 2 b-tagged jets (70% WP)

- **$\sigma_{bb} \sim 2$ pb limit can be set (optimistic)**
- **We can try and exclude with 2015 data!**

Conclusions

- **Exotic dijets a powerful and general search for BSM physics.**
  - Addition of b-tagging adds sensitivity to certain models

- **Papers from 2015 data done!**
  - **Dijet resonance and angular => EOYE**
    - First Run-2 paper from ATLAS
  - **b-Tagged dijet => Moriond**
    - First such result from ATLAS
  - **Improved limits set on range of models**

- **Summer notes for both analyses**

  - **Dijet resonance and angular => ICHEP**
    - Many improvements to analysis in pipeline

  - **b-Tagged dijet => LHCP and/or ICHEP**
    - Moving to lower masses
    - Limits at 750 GeV

- **Exciting 2016 for dijet analyses!!**

Backup!

Still to Add on Talk

- **A general motivation to dijets for exotics slide?**
  - Contact Interactions, is there simple introduction to these (i.e. A simple Feynman) ?
- **Bulk up "Aims for Dijet analysis" slide (12)?**
  - Is the aim just be better and more sensitive
    - Or is there a wider aim, e.g. dibjet has clear aim to look at 750 GeV resonance
- **Sensitivity studies for dijet resonance?**
  - Do they exist?
- **List of other things that can be / need to be done**
  - Dijet: new models?
  - Dibjet: high pT b-tagging?
- **Manpower summary**
  - This really depends on what contacts/coveners want/need
  - Could be a good place to acknowledge current institutes working on it
- **Conclusions (obvs.)**

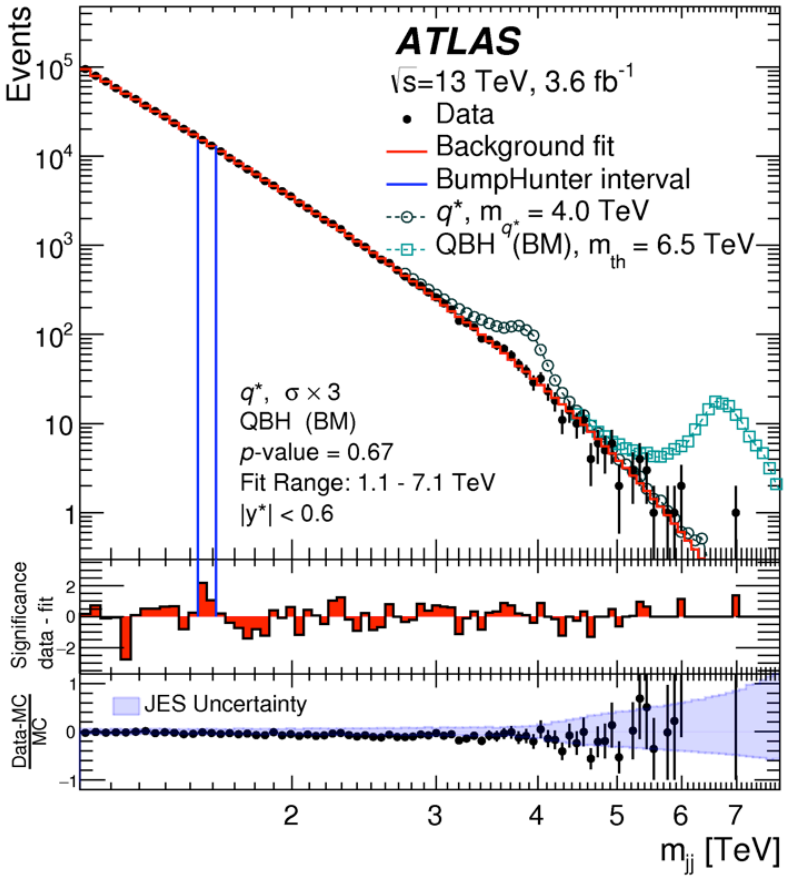
- **Please Add to this!**

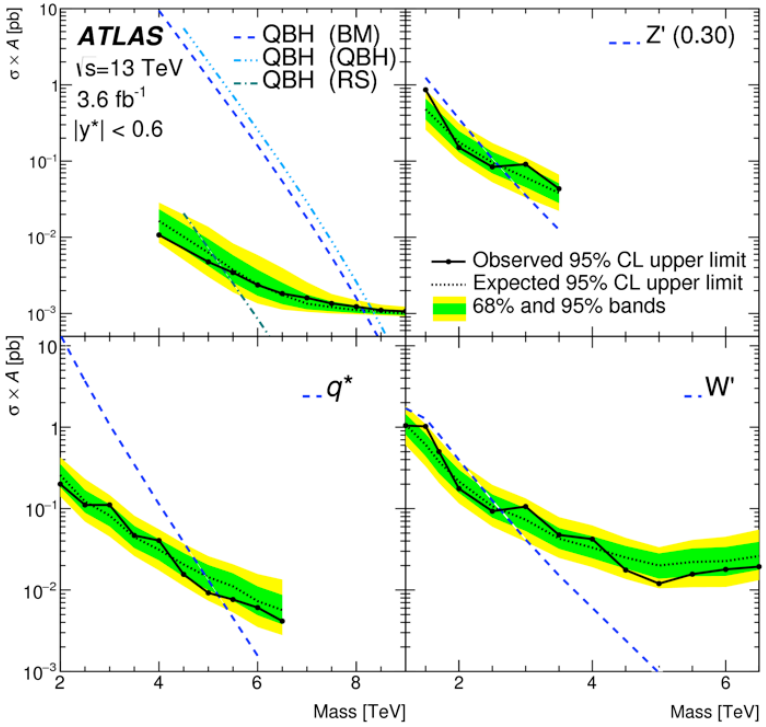
EOYE Dijet Resonance Analysis

arXiv:1512.01530

- **EOYE Result for Dijet Resonance and Angular**
  - First 13 TeV public result from ATLAS
  - 3.6 fb^{-1} including IBL off data

- **Event Selection** (Full list in backup)
  - **HLT_j360**, Lowest unprescaled trigger
  - **m_{jj} > 1.1 TeV**, on the trigger plateau
  - **|y*| < 0.6**, where y*=0.5*(y_1 - y_2)
    - Central region more sensitive

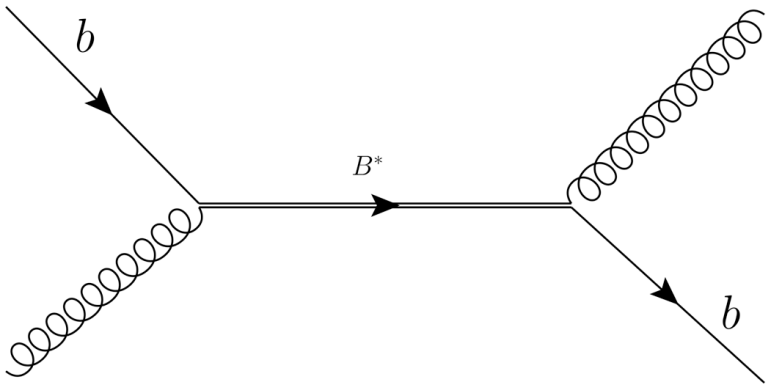


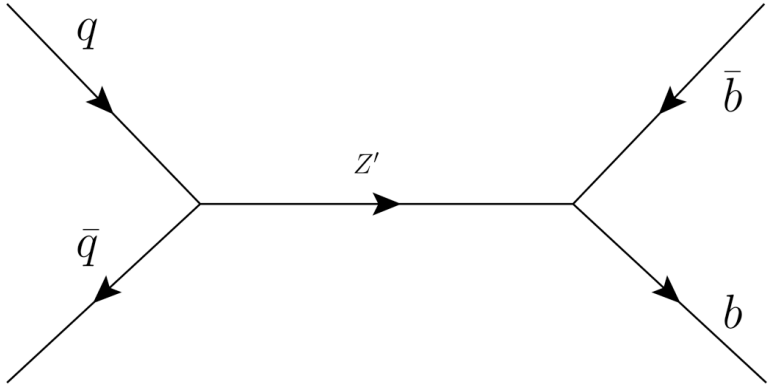


- **Resonance Results**
  - No significant deviation from background fit
  - Improved limits compared to Run 1:
    - Quantum black hole, q*, W‘ and Z’
    - Generic Gaussian Limits

b-Tagged Analysis Introduction

- **Many BSM models predict resonances decaying to b-quarks**
  - b* to b+g and Z‘ to bb





- **Apply b-tagging to event selection**
  - Reduce light jet dominated background *(light = u, d, s and gluon)*
  - Increase sensitivity to these models.

- **Perform Resonance Search - Similar to dijet search**
  - Fit to QCD background and search for discrepancies
  - Use two b-tagging categories for different benchmark models
    - Inclusive 1 b-tag and 2 b-tag.

Backup:
b-Tagged Dijet Analysis

- **Data Used**
  - 25ns data with luminosity of **3.2 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.

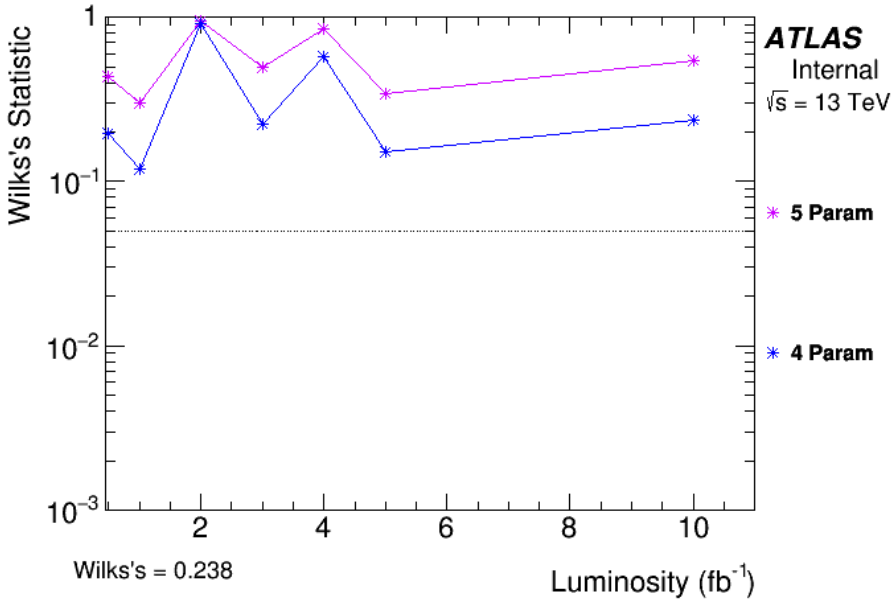
- Fit to background using smoothly falling function:

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

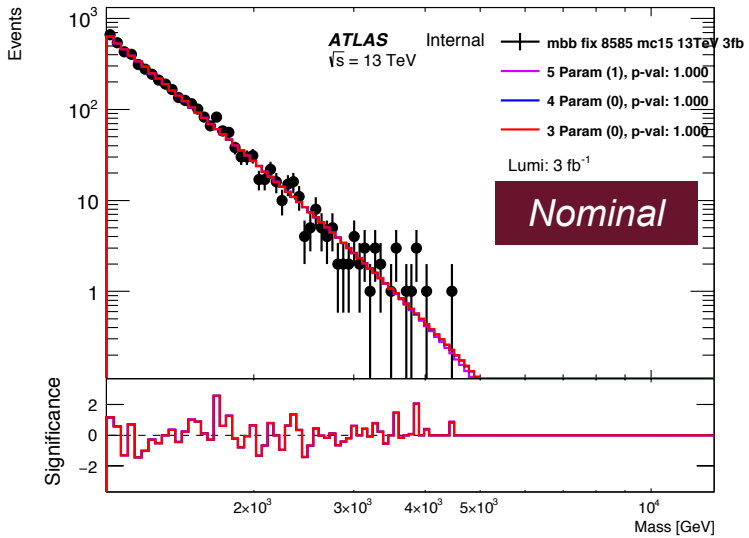
where, $x = m_{jj}/\sqrt{s}$

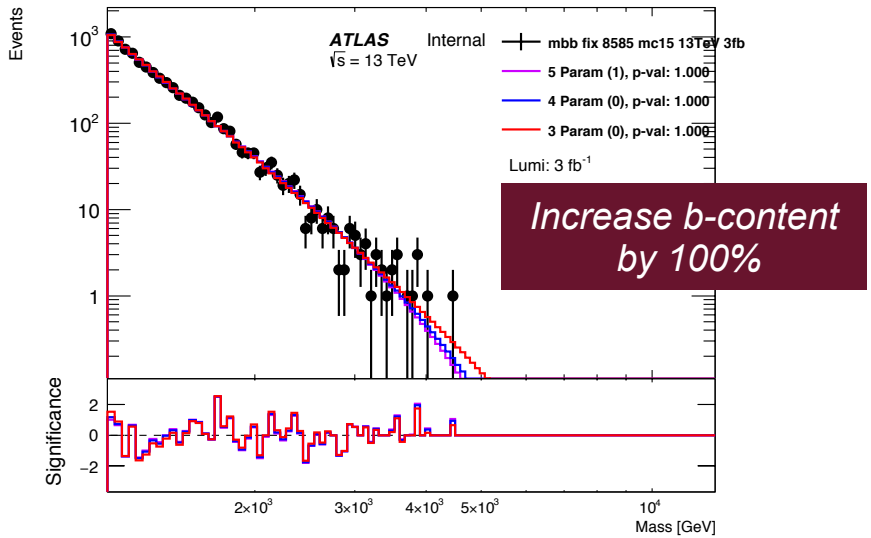
- This comes in 3, 4 and 5 parameter functions.
  - 3 and 4 parameter set $p_5 = 0$ and then $p_4 = 0$.

- Use Wilks' statistic to choose fit function
  - Default option is 3 parameter fit function.
  - Use Wilks' to test if we need to change function
  - MC tests show we expect to be able to use 3 parameter fit up to 10 fb^{-1}



- Performing cross-checks confirming that we are robust to changes in flavour fraction





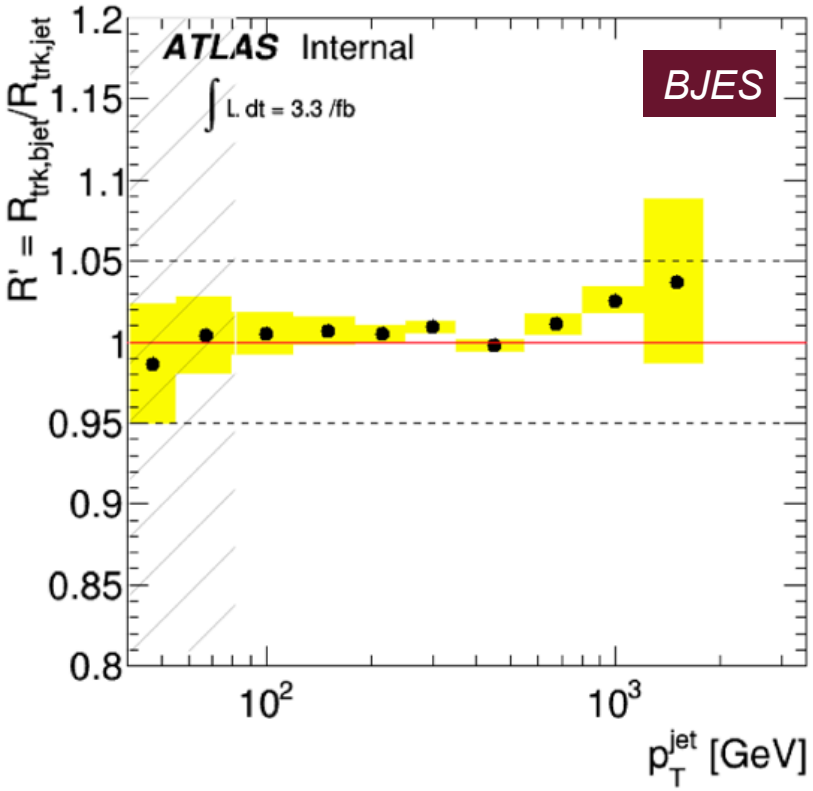
- Luminosity - 9% uncertainty
- Background
  - Fit function and fit parameters
- Signal
  - JES Uncertainty
    - Branches available in analysis nTuple
    - < 4%
  - JER Uncertainty
    - Assume to be negligible
  - BJES Uncertainty
    - Studies performed
  - B-tagging scale factor uncertainty
- Studies to be carried out
  - Then will be added to limit setting procedure.

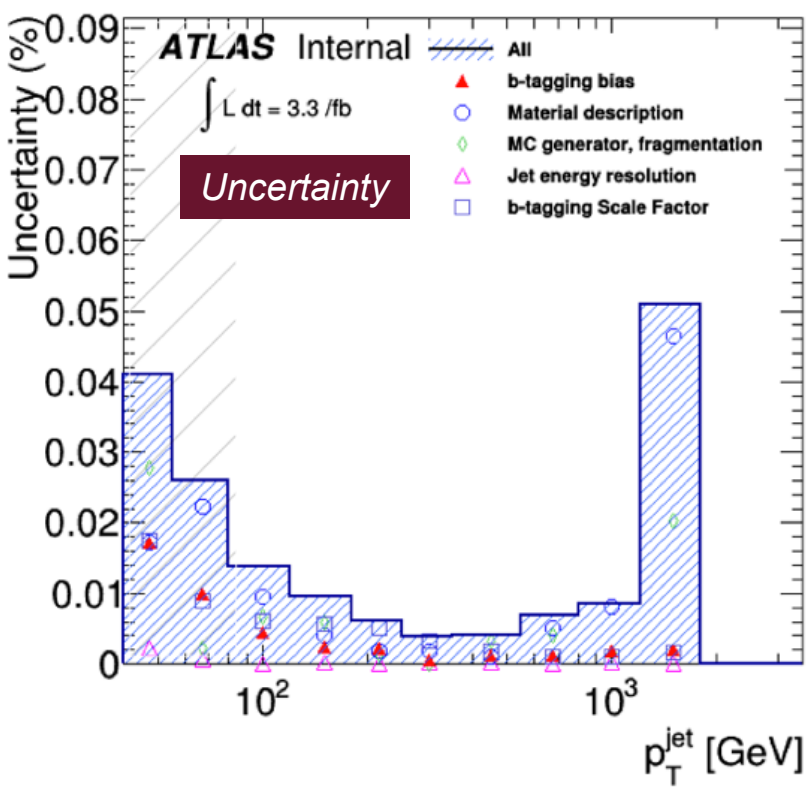
- Calculate using ratio of tracks within jet cone to reconstructed calo jet.
  - Use a double ratio between b-tagged jets and inclusive jets

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

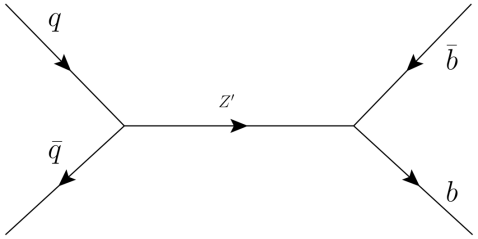
where $$r^{trk} = \frac{\sum \vec{p_T}^{trk}}{p_T^{jet}}$$

- Ongoing study
  - Further work required
  - Regularly presented in JES/JER Meetings

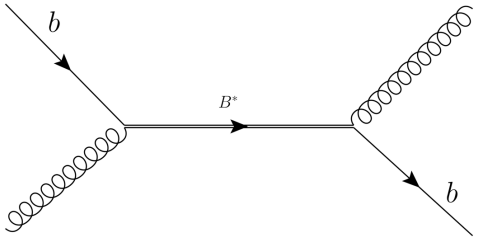




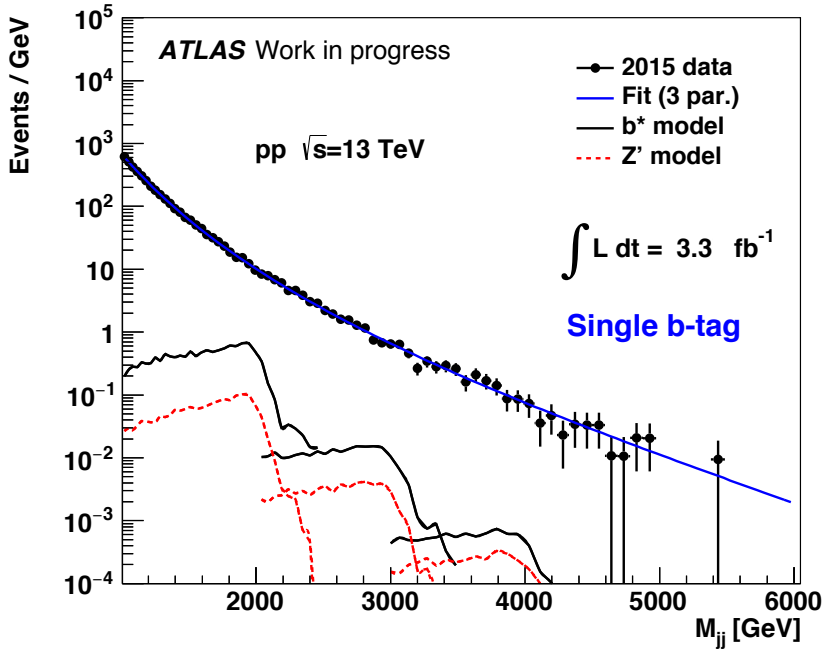
- Two benchmark models - We can set limits here.
  - **Z' => bb** - 1.25, 2, 3 and 4 TeV
  - **b* => b+X** - 1.25, 2, 3, 4 and 5 TeV
  - Templates taken from MC samples

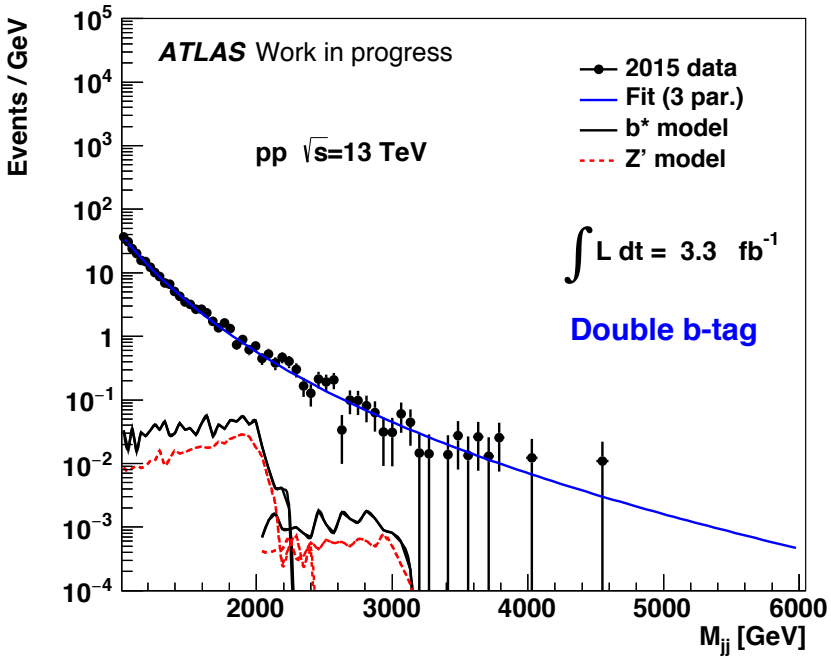


- One cross-check channel
  - **q*** - 2.5, 3, 3.5 and 4.5 TeV



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





Data/MC Jet pT Comparison

b-tagged di-jet