High-Mass Di-Jet Analyses

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Exotics and Higgs BSM Workshop, Grenoble

15 April 2016

Introduction

- **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

  4) Discussion Session

1) **<u>Introduction to Analyses</u>**

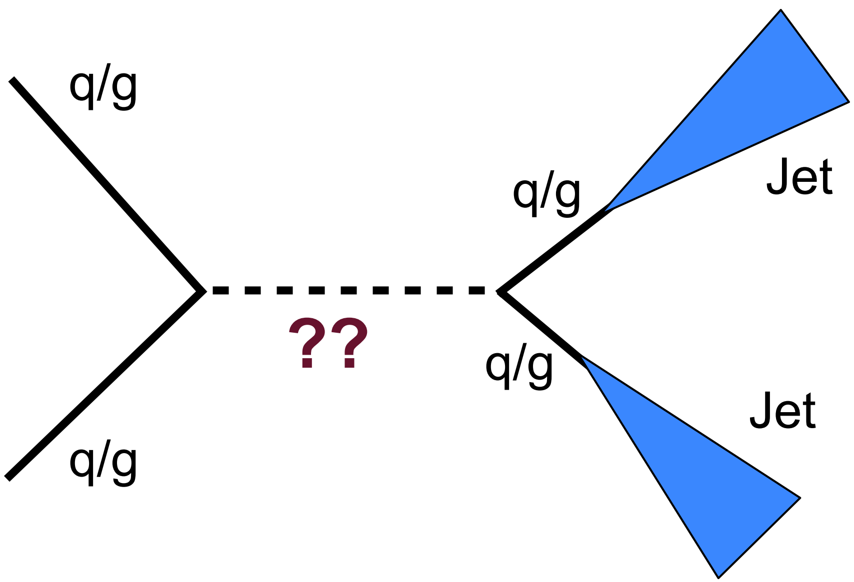
2) Current Status of Analyses

3) Future Plans for Analyses

4) Discussion Session

Exotic Dijet Motivation

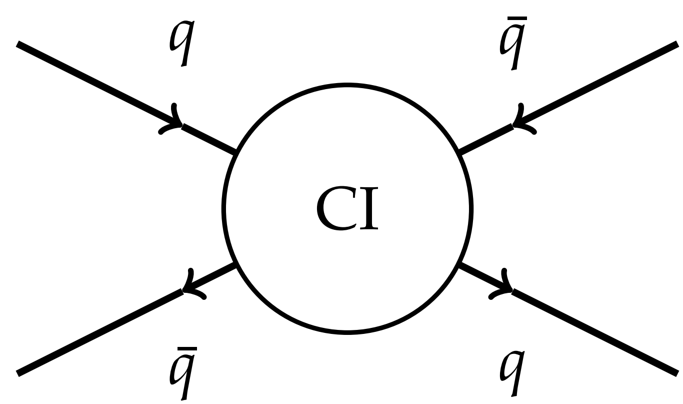
- **A powerful and general search for Beyond Standard Model Theories**
- **Many BSM models predict resonances that decay to pairs of q/g**



?? =

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

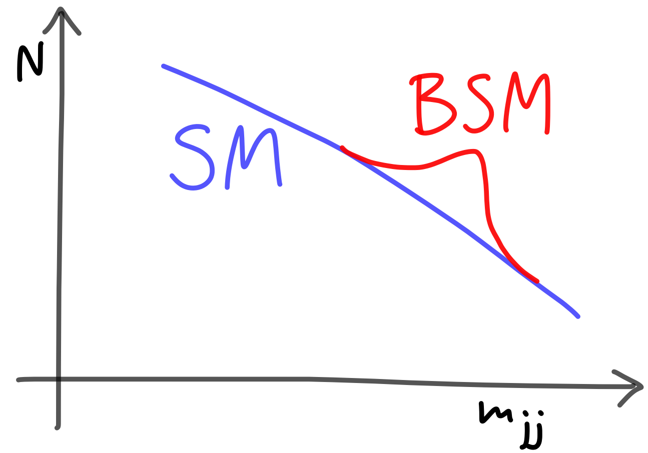
- **Sensitive to Contact Interactions (CI)**
  - At some energy scale new physics emerges
  - Modelled by an effective field theory:
    - **Λ**, Compositeness scale
    - **η**, Constructive or Destructive?
  - Effects jet kinematics

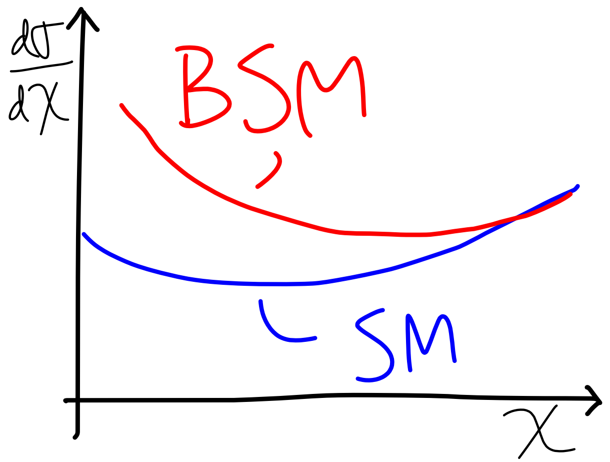


Exotic Dijet Analysis Introdution

- **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



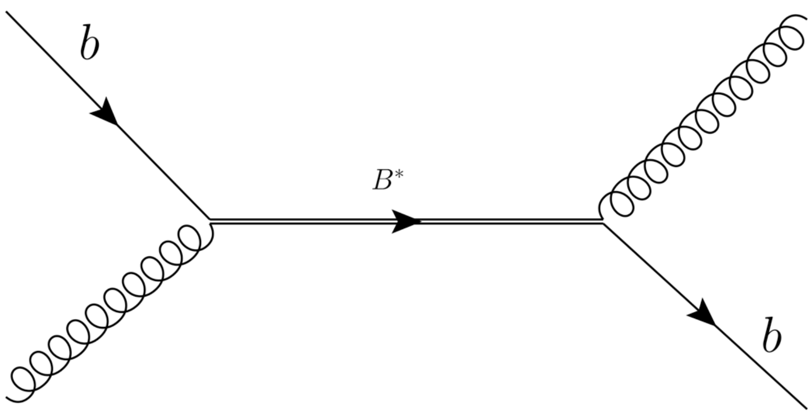


- **Angular Analysis**
  - Study, $\chi = e^{2|y*|} = e^{|y_1 - y_2|}$
  - Compare shape from Data to MC
  - Sensitive to contact interactions

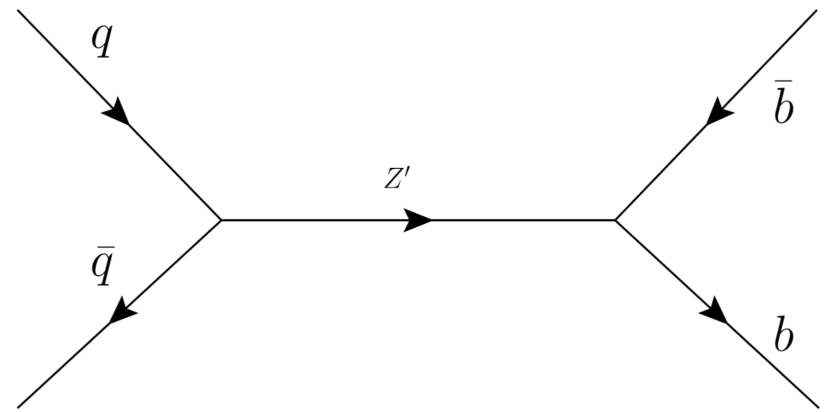
- **Closely related to low mass dijet analyses**
  => *See Lydia's talk, which follows, for more info on this.*

b-Tagged Analysis Introduction

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



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
  - 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

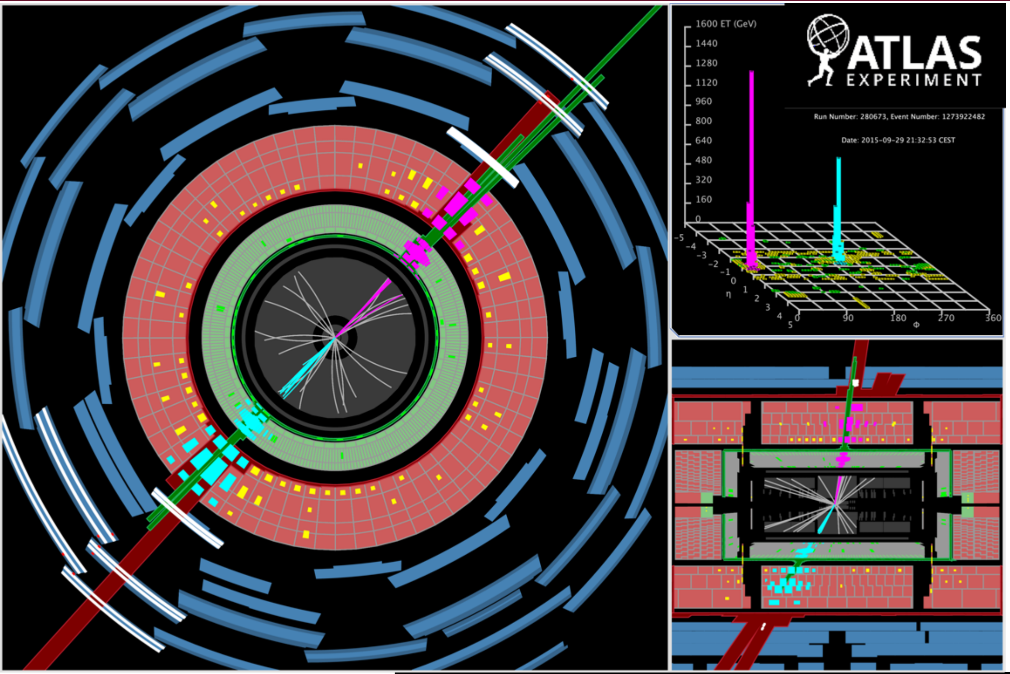
1) Introduction to Analyses

2) Current Status of Analyses

3) Future Plans for Analyses

4) Discussion Session

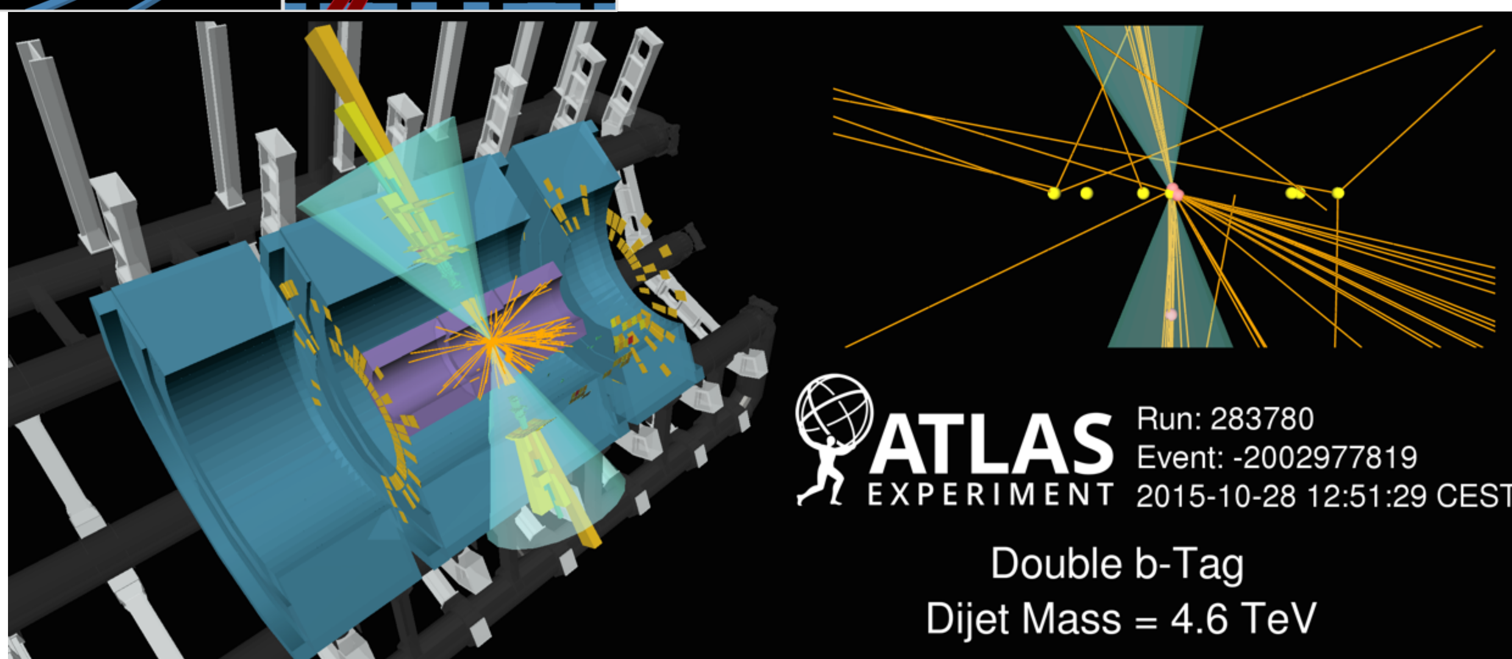
13 TeV!!



Highest m_{jj} Events Seen at ATLAS

m_{jj} = 6.9 TeV
(Resonance)

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



EOYE Dijet Resonance Analysis

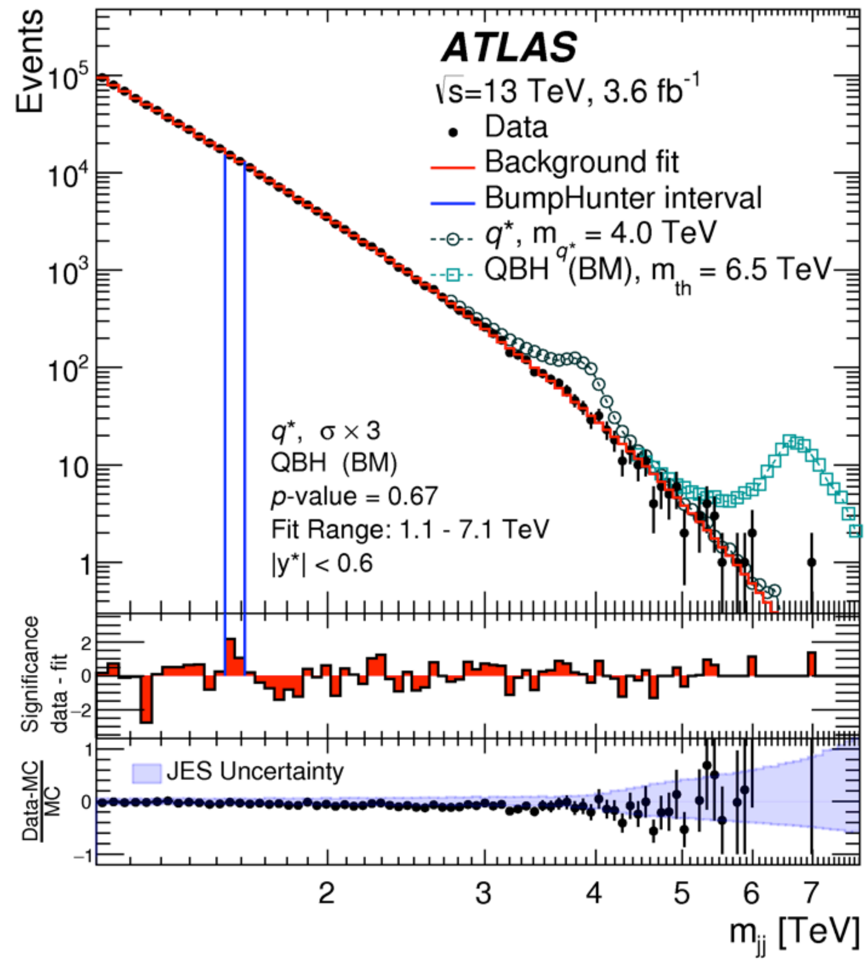
arXiv:1512.01530

- **EOYE Result for Resonance and Angular**
  - First 13 TeV public result from ATLAS
  - 3.6 fb^{-1} including IBL off data
- **Event Selection** (Full list in backup)
  - **HLT_j360**
  - **m_{jj} > 1.1 TeV**, on trigger plateau
  - **|y*| < 0.6**, *y*= 0.5 *Δy*
- **Background Fit**

$$f(z) = p_1 (1 - z)^{p_2} (z)^{p_3}$$

where, $z = m/\sqrt{s}$

- **Search for Discrepancies**
  - BumpHunter algorithm is used
    - Discrepant region found *(1.53-1.61 TeV)*
  - p-Value found using pseudo-experiments



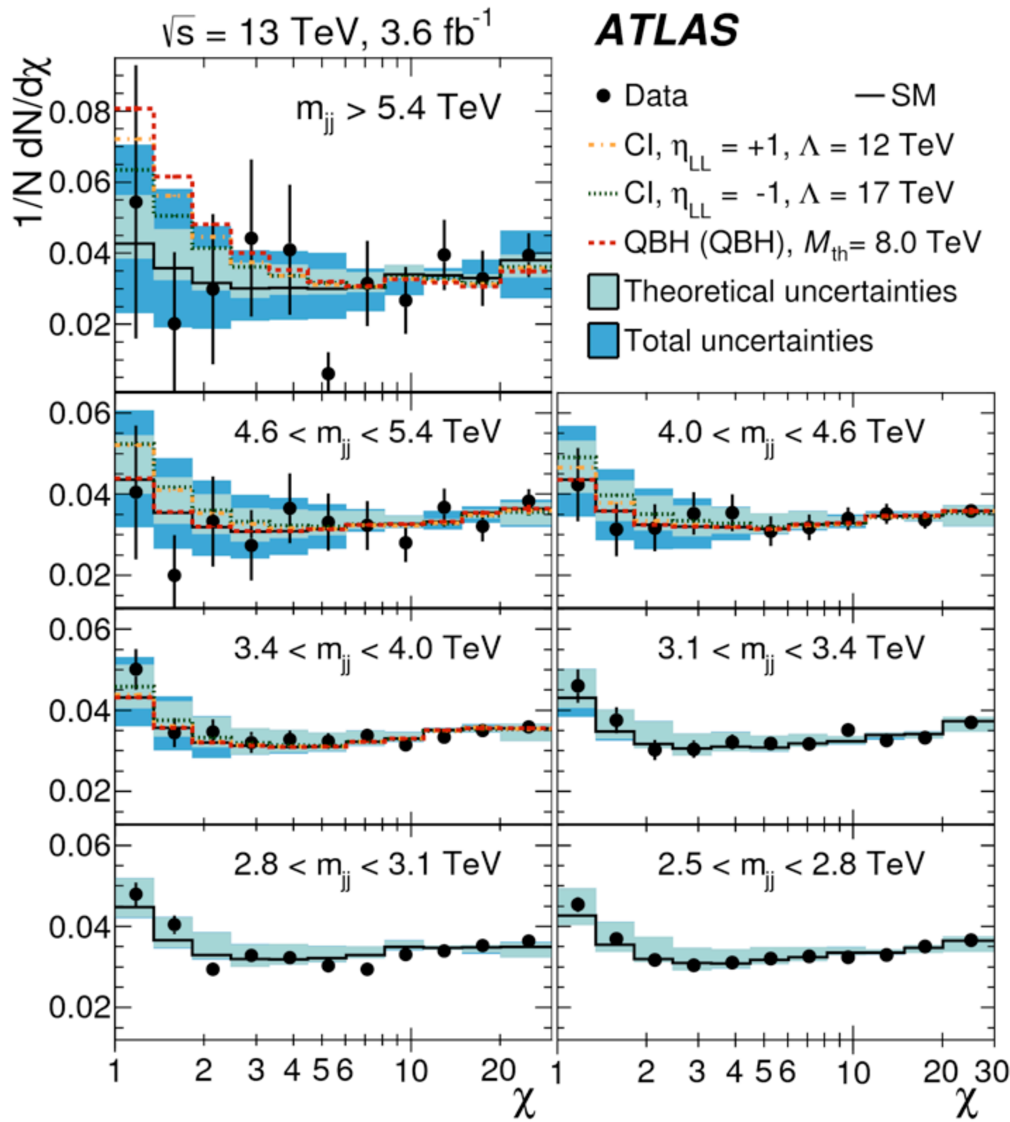
p-Value = 0.67

No Significant Deviation

EOYE Dijet Angular Analysis

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** (Full list in backup)
  - **HLT_j360**
  - **m_{jj} > 2.5 TeV**
  - **|y*| < 1.7**, *y*= 0.5 *Δy*
- **MC Shape for Comparison**
  - Pythia, normalised to data
  - NLO corrected (QCD and EW)
- **Test Compatibility of Data and MC**
  - CL_S method used



p-Value = 0.35

No Significant Deviation

 [b-Tagged Dijet Resonance Analysis](#) [arXiv:1603.08791](https://arxiv.org/abs/1603.08791) UCL

- **Moriond Result for b-Tagged Dijet Analysis**
  - First such analysis from ATLAS
  - 3.2 fb^{-1}, excluding IBL-off data

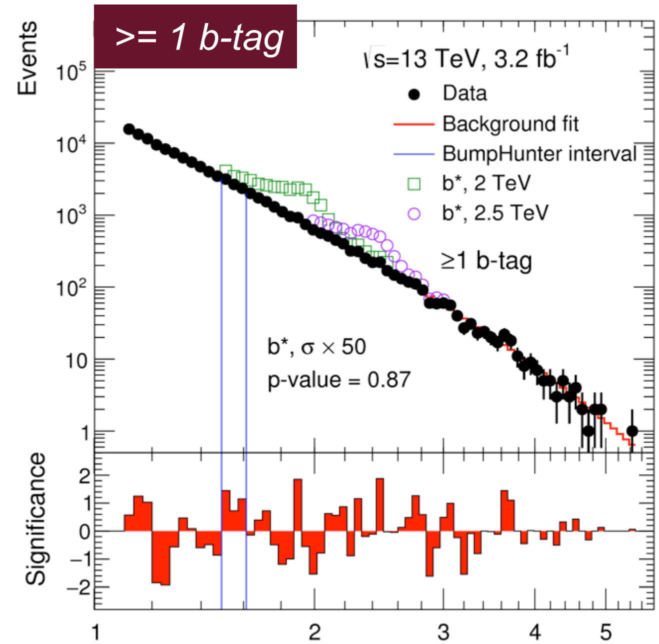
- **Event Selection** (Full list in backup)
  - Very similar to dijet resonance search
    - **HLT_j360**
    - **m_{jj} > 1.1 TeV**
    - **$|y^*|$ < 0.6**

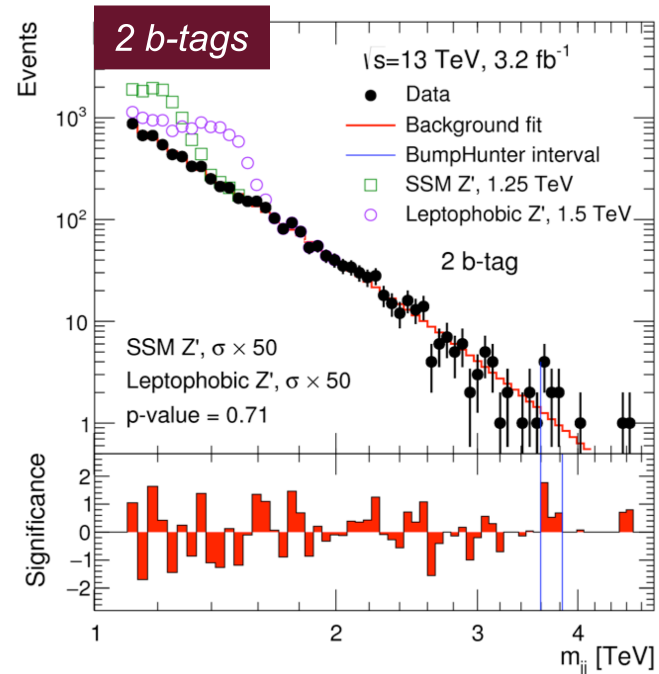
- **b-Tagging = MV2c20 @ 85% Eff. WP**
  - Two b-Tagging categories;
    - Inclusive 1 b-tag
    - 2 b-tag categories

- **Same Strategy as Dijet Resonance**
  - Same fit function
  - Find discrepancies using bumpHunter

bumpHunter p-Values = 0.87, 0.71
(>= 1 b-tag, 2 b-tag)

No Significant Deviation





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 / 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

Dijet Analysis in 2016

- **2016 Data**
  - Dijet resonance and angular analysis
  - Get more sensitivity!!
- **Timescales**
  - **ICHEP** - CONF Note (3-10 August 2016)
  - **Winter Conference** - More substantial paper
    => Including more data, more interpretations
- **Global Fit at Higher Lumi.**
  - With more data, global fit may become a challenge
  - We might need to consider other options...

- **Investigating possible improvements**

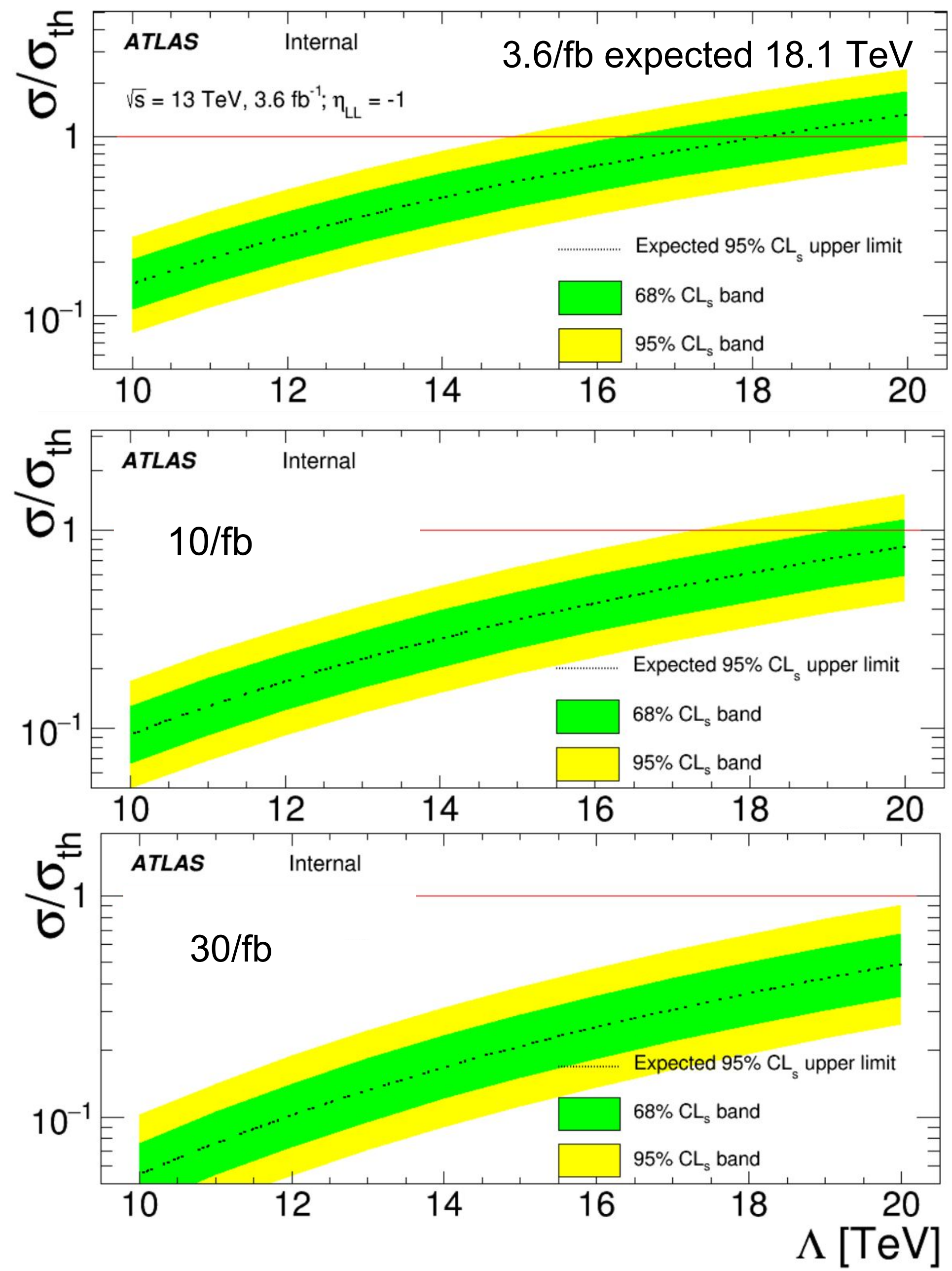
  - ***Resonance***
    - Reclustered jets
    - Sliding Window Fit
    - W* optimisation
  - ***Angular***
    - Signal at high Λ
    - Floating background normalisation
    - $F\chi$ variable

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 TeV

Lumi (fb^{-1})	$\sigma_{Limit}/\sigma_{TH}$, *Λ = 20 TeV*
3.6	1.31
10	0.82
30	0.49

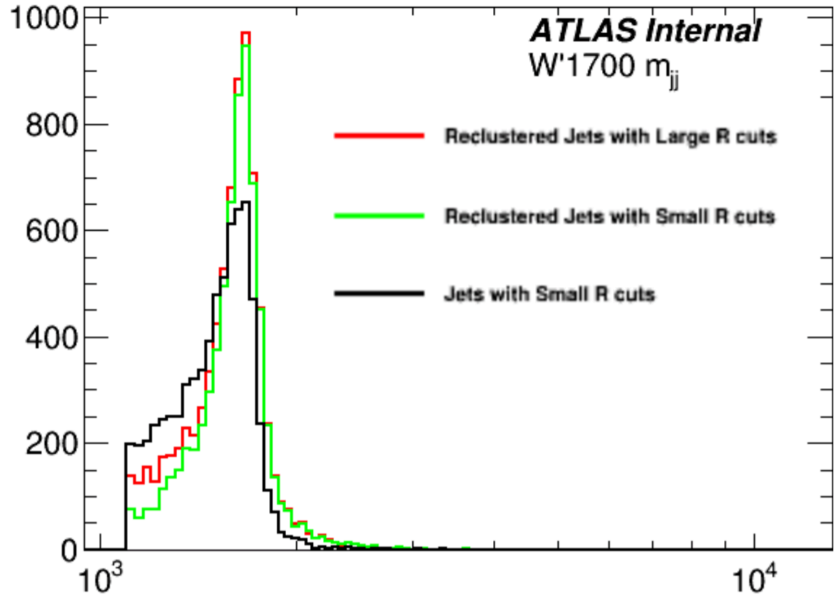
- **CI signal at high Λ**
  - Currently use Λ = 7 and 10 TeV
  - Analytical extrapolation for large Λ
  - Larger data set may need a more refined validation strategy

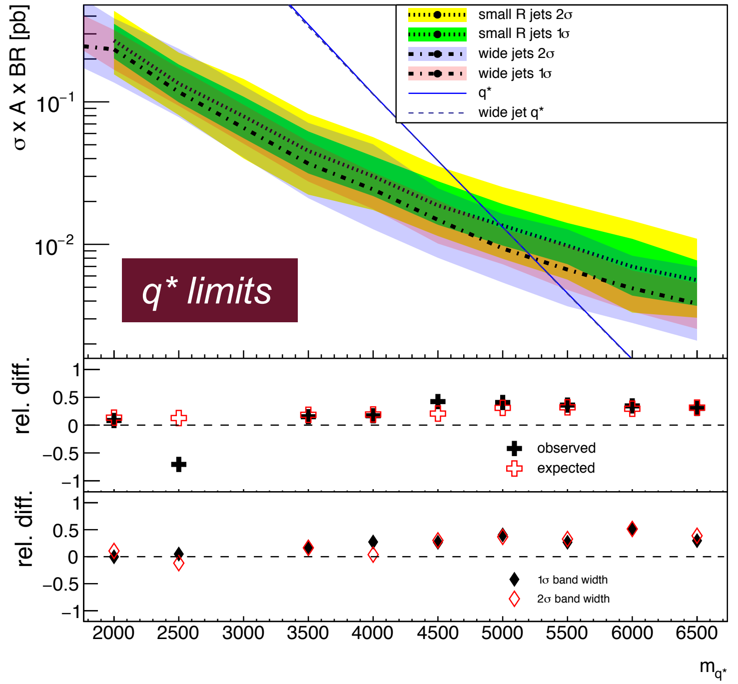


Dijet Improvements: Reclustered Jets

- **Reclustered Jets (Recl. Jets)**
  - Recluster jets within R=1.0 of leading or subleading jet
- **Why?**
  - Reduced sensitivity to FSR
  - CMS used wide jets for EOYE
    - Competitive with lower lumi.
- **What do we get**
  - More background, migrate to higher m_{jj}
  - Better signal resolution
  - Mix of limit changes, preliminary results

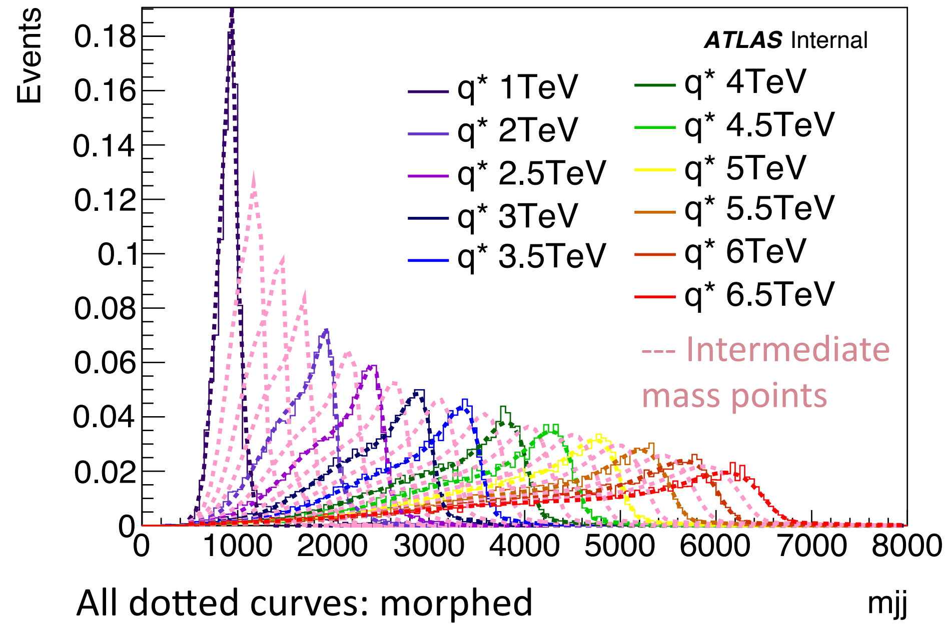
Model	Change	Small R Jets		Recl. Jets	
		Obs.	Exp.	Obs.	Exp.
q*	Improve	5.2 TeV	4.9 TeV	5.5 TeV	5.2 TeV
W'	Mixed	2.6 TeV	2.6 TeV	2.3 TeV	2.5 TeV
QBH	No Change	8.3 TeV	8.3 TeV	8.3 TeV	8.4 TeV



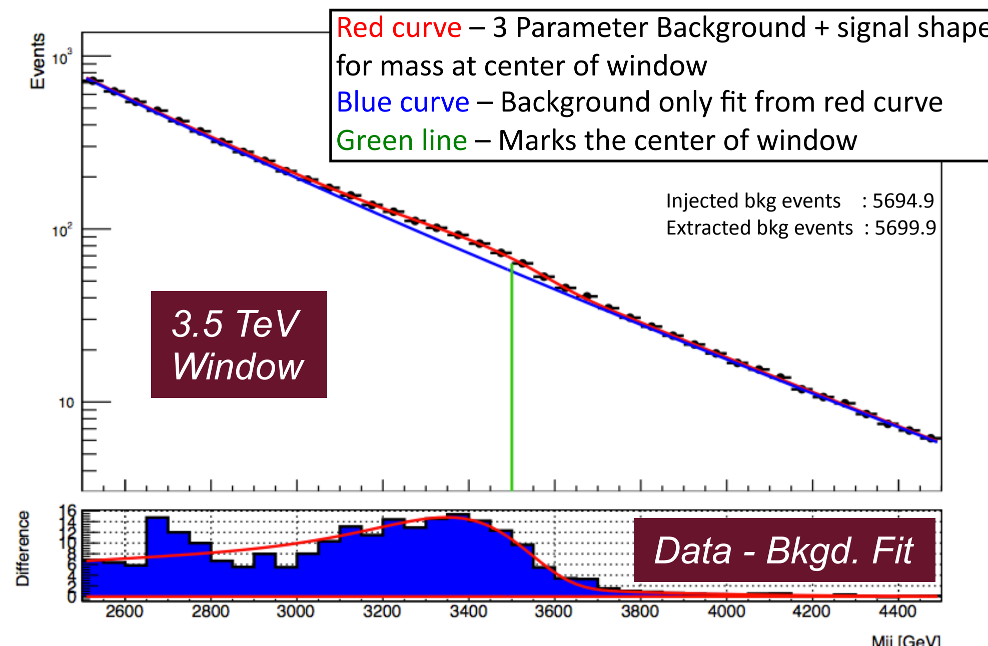


Dijet Improvements: Sliding Window

- **Fit in mass windows**
  - Within window fit S + B
  - Why?
    - Don't need to fit full mass range
      - More robust for large lumi
    - Use full signal information
- **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
  - Window width: 2 TeV
  - Window jumps size: 50 GeV
  - Fit S+B
    - Bkgd: Dijet Fit Func.
    - Signal: q*, m_{q^*} = window centre



All dotted curves: morphed
All Solid curves: MC shapes

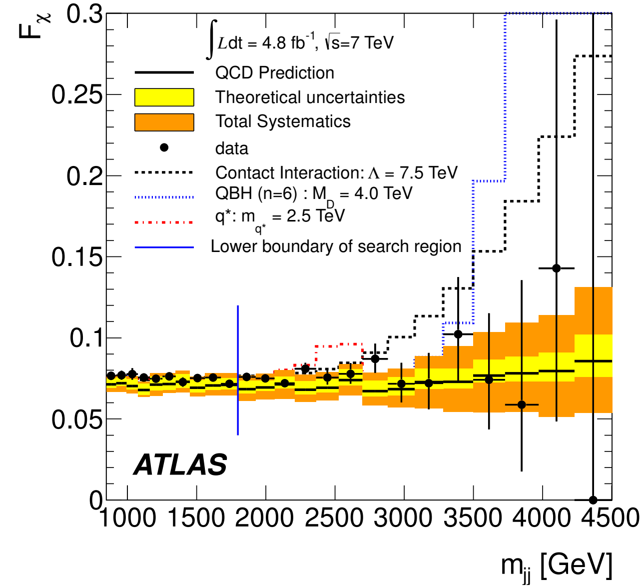


Dijet Improvements: F_χ

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

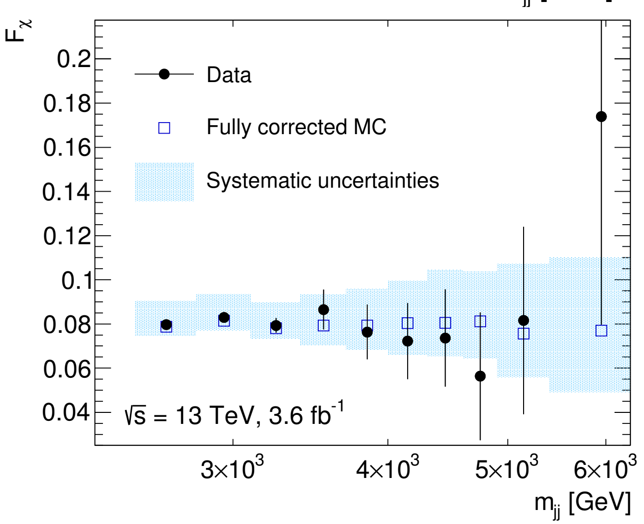
$$F_\chi(m_{jj}) = \frac{N_{|y^*|<0.6}(m_{jj})}{N_{|y^*|<1.7}(m_{jj})}$$

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



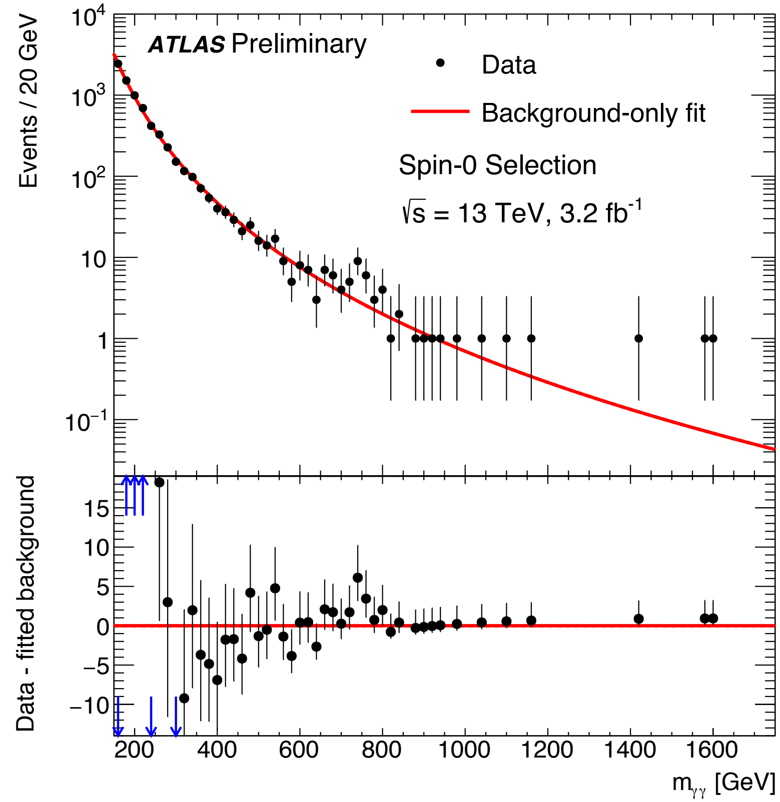
- **Previous use (or not)**
  - **Used in 7 TeV** angular analysis
  - **Dropped in 8 TeV** analysis
    => Partly due to large data/MC discrepancy

- **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 γγ and bb?**
  - Weak limits on BSM in bb at low mass
    - Further discussion, e.g. [arXiv:1512.04933]
  - **We should study this region...**



- **Currently two parallel plans**

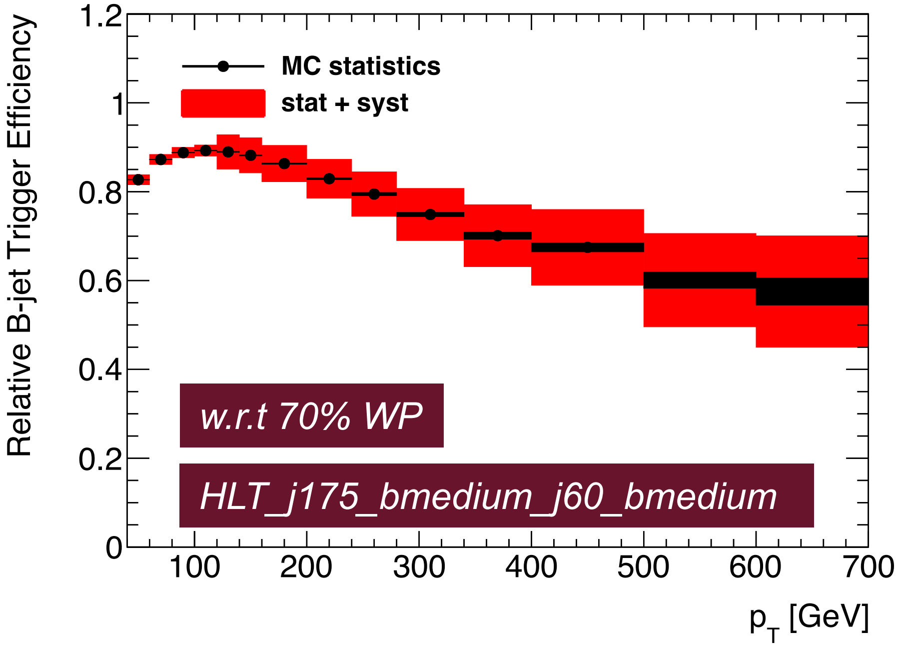
- **Reuse 2015 data for LHCP 2016**
  - **Focus on low mass, 750 GeV**
  - Fast paced analysis (13-18th June)

- **Use 2016 data for ICHEP 2016**
  - More luminosity; **High and low mass analyses**
  - More time for this analyses (3rd-10th August)

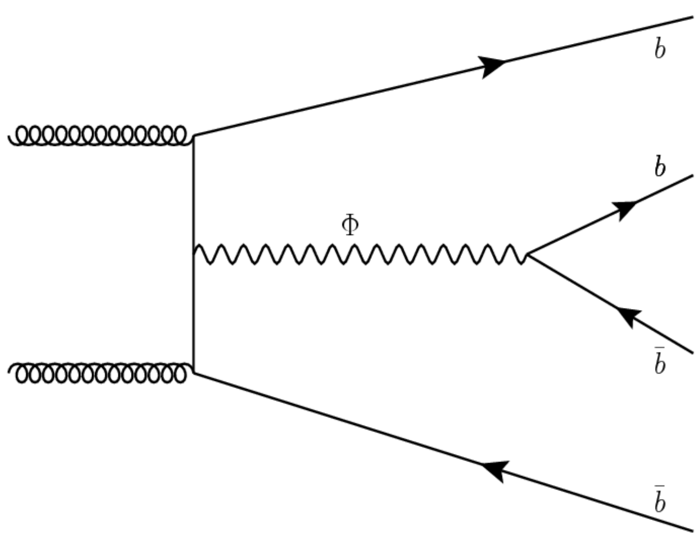
Extending to Lower Masses

- **We can get to lower masses**
  - 2015: limited by trigger usage.
  - Possible with use of new triggers

- **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

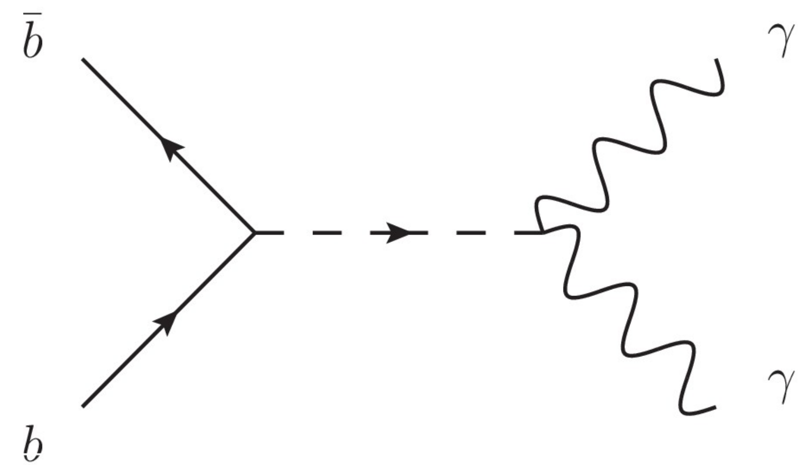


- **Four Jet Trigger**
  - **HLT_4J85**
  - For bb production
  - Trigger on 4th jet, p_T > 85 GeV
  - We should get to m_{jj} = 400 GeV
  - Possibility for > 2 b-tag
  - Currently requesting MC

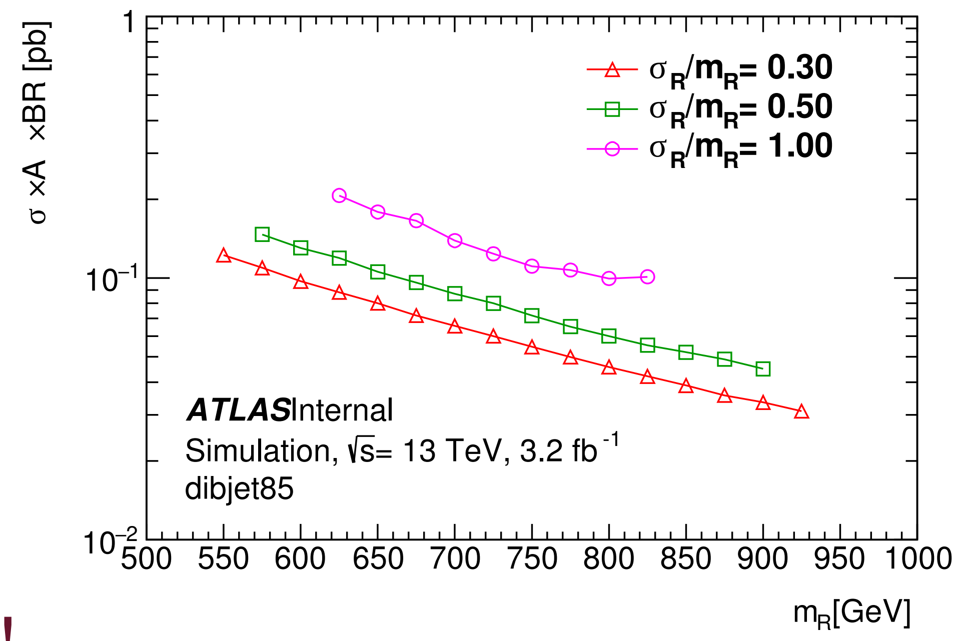


Sensitivity Study using b-Jet Triggers

- **Consider simple scalar model**
  - **Couples to only γγ and bb**
  - Using 'observed' $\sigma_{\gamma\gamma}$ and Γ
  - We get $\boldsymbol{\sigma_{bb}}$ **~ 2.1 pb** for 13 TeV
  - No limit exists at √s = 13 TeV



- **Quick sensitivity study on 2015 data**
  - Fit to data, **500 < m_{jj} < 1000 GeV**
    - **Blind 700-800 GeV**
  - ~10% acceptance (from Z')
  - Find **expected** Gaussian limits
  - No systematics considered yet



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

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

Longer term plans for di-b-jet

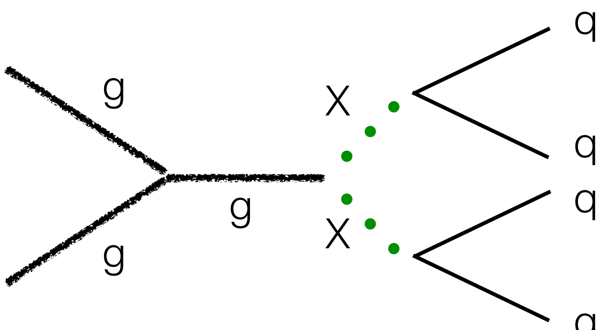
- **Combination of channels**
  - **2015**: **>= 1 b-tag, 2 b-tag**
  - But: Z' => bb; often is only single tagged
    b* => bg; gluon splitting leads to double b-tagged
  - **2016**: **Combine the channels to get better limits?**
    - We would need to use exclusive 1 b-tag

- **Validation of high-pT data**
  - Inclusive dijet performs data validation
  - **No such checks from dibjet, can we help here?**
    - Problem may be enough statistics after b-tagging

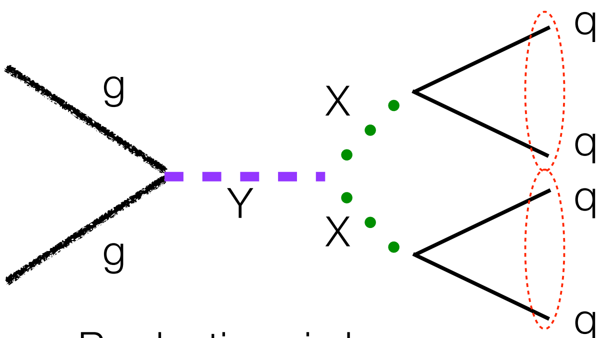
- **High P_T b-tagging**
  - Optimisation of high-P_T b-tagging may be possible
  - We would gain a lot from any improvements

Future: 4j searches

- Exotic models:
    - Colorons (current samples generated using benchmark model here: arxiv:1305.3818)
    - scalar gluons à la arxiv:0810.3919v2
    - pair produced DM mediators
    - Many more or less directly motivated models….
- Current state: SUSY RPV stop search in 2015 data now in signoff (CONF-SUSY-2015-15)
    - Poorly suited to exotics signals. Want to remove b-tagging, loosen cuts to aim at higher masses appropriate for a range of exotic models
    - Some manpower committed: will begin sensitivity studies & design for new analysis over the summer and anticipate aiming for winter result on 2016 data



Pair production: resolved



Production via heavy mediator: boosted pairs

Related 8 TeV results

CMS	coloron, RPV stop	arXiv: 1412.7706v2
ATLAS	RPV stop	arXiv: 1601.07453

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 public 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
    - Set limits at 750 GeV

- **Also, have low mass dijet analyses => Next Talk!**

Exciting 2016 for Dijet Analyses!!

Discussion Session

- **Dijet high-mass limits improve like the square root of luminosity**
  - How do we keep interest post-ICHEP?
- **Further automation of analyses**
  - Some interest with this already
- **Choosing comparable models**
  - Can we compare to other analyses, e.g. mono-jet...
  - How best to include in summary plots
- **Can di-b-jet help with validation of high-p_T data?**
  - Nothing currently done, can we help?
  - Lack of statistics may be a problem

Backup!

What's In the Backup

- **Cuts + Systmatics**
  - EOYE dijet res and ang
  - Moriond di-b-jet
  - b-Trigger Sensitivity Studies

- **For Inclusive Dijet**
  - Wilks' Statistic
  - Fits to large lumis.
  - Z' limits
  - Dijet Improvement: W* optimisation
  - Dijet Improvement full set of dijet

- **Dibjet**
  - b-Tagging Efficiency
  - bJES
  - Fit for b-Trigger Sens. Study

- Data Used
  - 25ns data with luminosity of 3.6 fb^{-1}, Include runs with IBL Off
  - GRL

- 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

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

- Data Used
  - 25ns data with luminosity of 3.6 fb^{-1}, Include runs with IBL Off
  - GRL

- 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
  - $m_{jj} > 2500$ GeV, such that we are on the trigger plateau.
  - $|y^*| < 1.7$, where $y^*=0.5*(y_1 - y_2)$
  - $|y^B| < 1.1$, where $y^*=0.5*(y_1 + y_2)$

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

- Data Used
  - 25ns data with luminosity of 3.2 fb^{-1} (Periods D-J) Exclude runs with IBL Off
  - GRL
- 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
  - $|\eta| < 2.5$, in tracking geometry for b-tagging
  - b-Tagging, MV2c20 fixed 70% efficiency WP
- Jet Selection
  - Standard jet calibration (with JES correction applied)
  - 2015 loose jet quality cuts applied.

- Data Used
  - 25ns data with luminosity of 3.2 fb^{-1} (Periods D-J) Exclude runs with IBL Off
  - GRL
- Trigger
  - HLT_j175_bmedium_j60_bmedium
- Event Selection
  - Reject events with problematic calo. reconstruction (LAr, Tile and Core Errors)
  - At least two jets.
  - Leading-jet $p_T > 200$ GeV, Subleading jet $p_T > 80$ GeV
  - $m_{jj} > 500$ GeV
  - $|y^*| < 0.6$, where $y^*=0.5^*(y_1 - y_2)$, central region more sensitive
  - $|\eta| < 2.5$, in tracking geometry for b-tagging
  - b-Tagging, MV2c20, 85% efficiency WP
- Jet Selection
  - Standard jet calibration (with JES correction applied)
  - 2015 loose jet quality cuts applied.

- Luminosity
- Theoretical Uncertainties
  - Simulations of QCD angular distributions
- PDF Uncertainty
- Choice of renormalisation and factorisation scales
- **JES Uncertainty**
  - **Dominant**
  - At most 25% at high m_{jj} values

- Luminosity
- Background
  - Fit function choice
  - Fit parameter errors
- Signal
  - PDF Acceptance
  - JES Uncertainty

- Luminosity
- Background
  - Fit function and fit parameters
- Signal
  - JES Uncertainty
  - BJES Uncertainty
    - Combine JES and BJES = 6% across pT range
  - JER Uncertainty

  - **B-tagging scale factor uncertainty**
    - Dominant
    - Increases with jet pT
    - 20%-50% for mass 1.1-5 TeV

Background Modelling - Wilks' Statistic

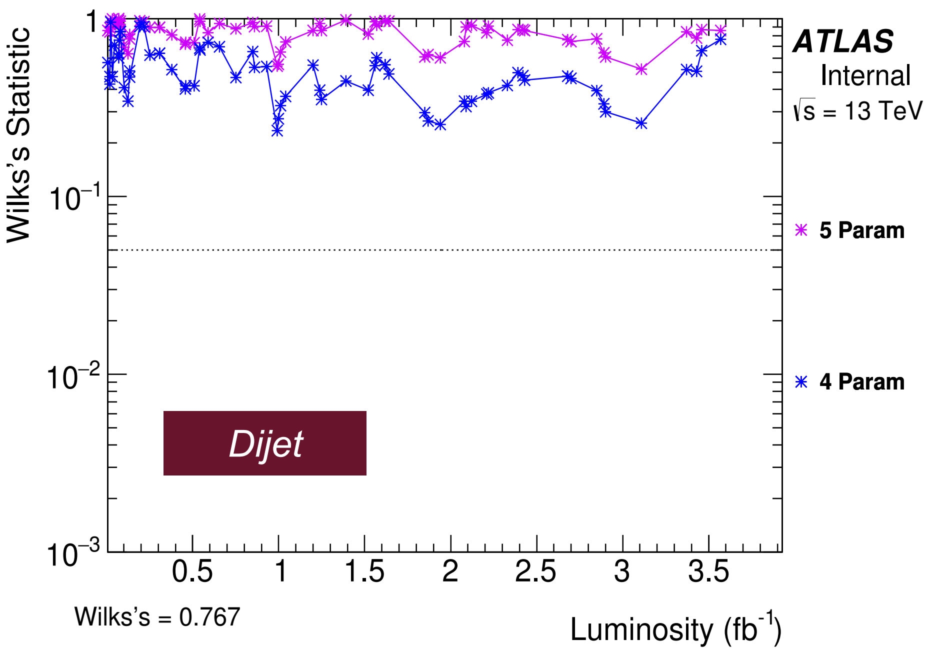
- Fit to background using smoothly falling function:

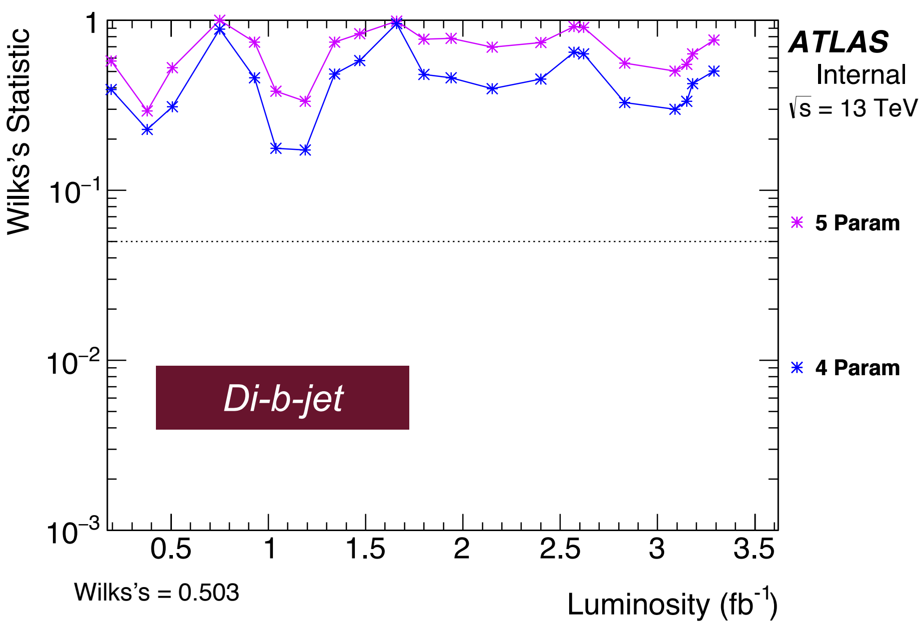
$$\boxed{f(x) = p_1(1-x)^{p_2}(x)^{p_3+p_4\ln x+p_5\ln x^2} \qquad \text{where,} \qquad x = m_{jj}/\sqrt{s}}$$

- 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.
  - If statistic drops below 0.05 then switch

$$\boxed{-\,2log\,(\Lambda) = -2log\left(\frac{L(H_0|x)}{L(H_1|x)}\right)}$$

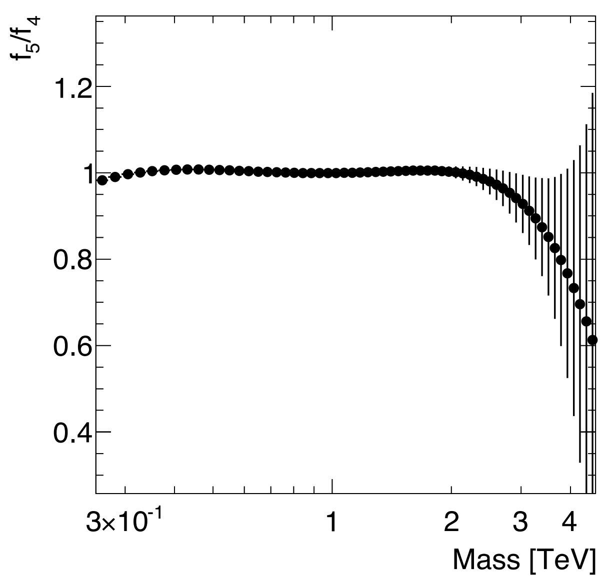


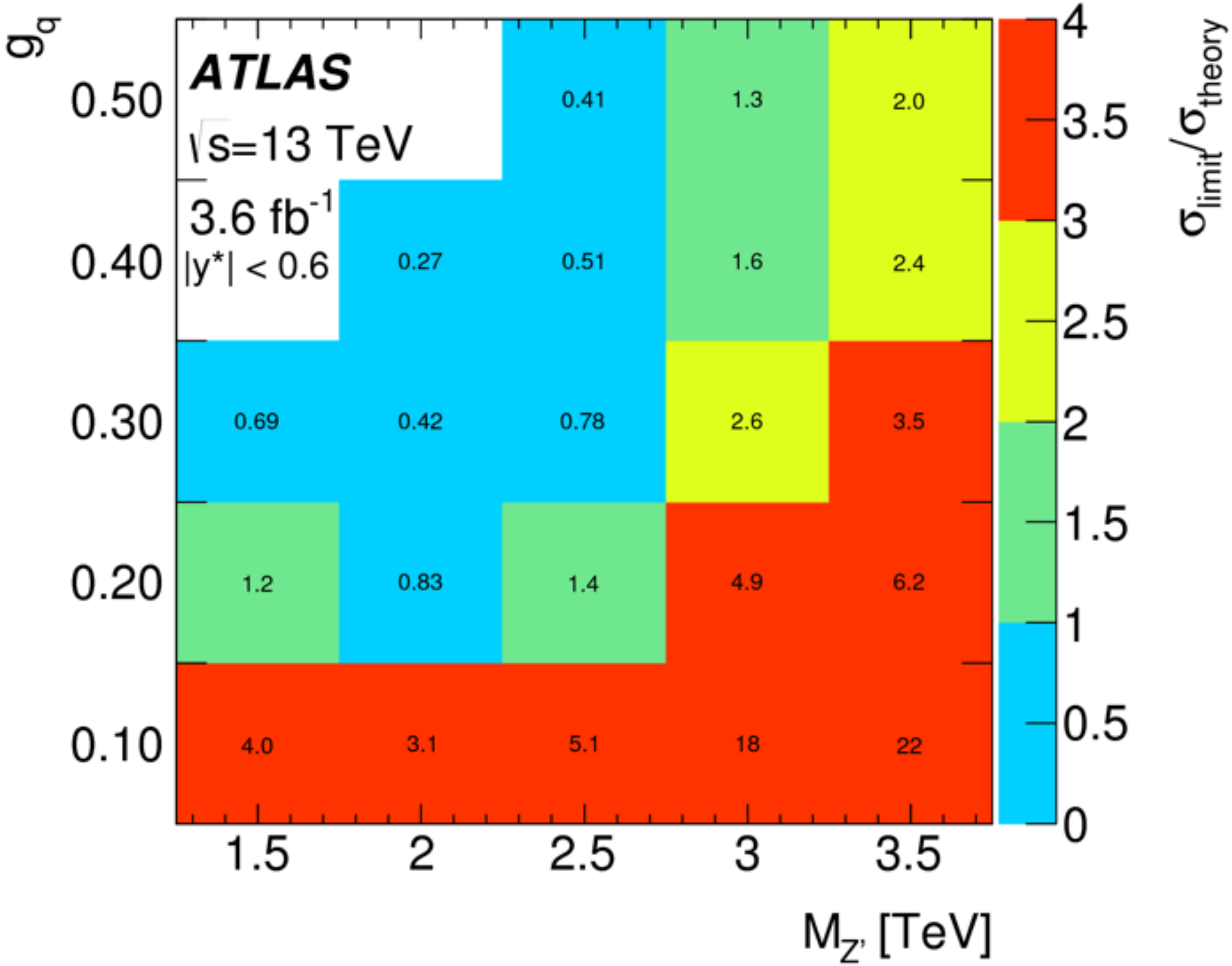


Global Fit At Large Luminosities

- **In 2016 and beyond we will get more luminosity**
- **At some point this will effect our fit**
  - We will need more parameters in our fit function
  - We may also need to consider other options than global fit
- **Example 8 TeV Analysis**
  - At lower luminosities 4 and 5 parameter function both good
  - At higher luminosities 5 parameter function was needed to describe tail
  - This may also happen at 13 TeV in 2016 and beyond

	BumpHunter p-Value	
Function	Partial Dataset ($5.06\ fb^{-1}$)	Full Dataset ($20.1\ fb^{-1}$)
4 Para. Dijet	0.18	0.075
5 Para. Dijet	0.37	0.86



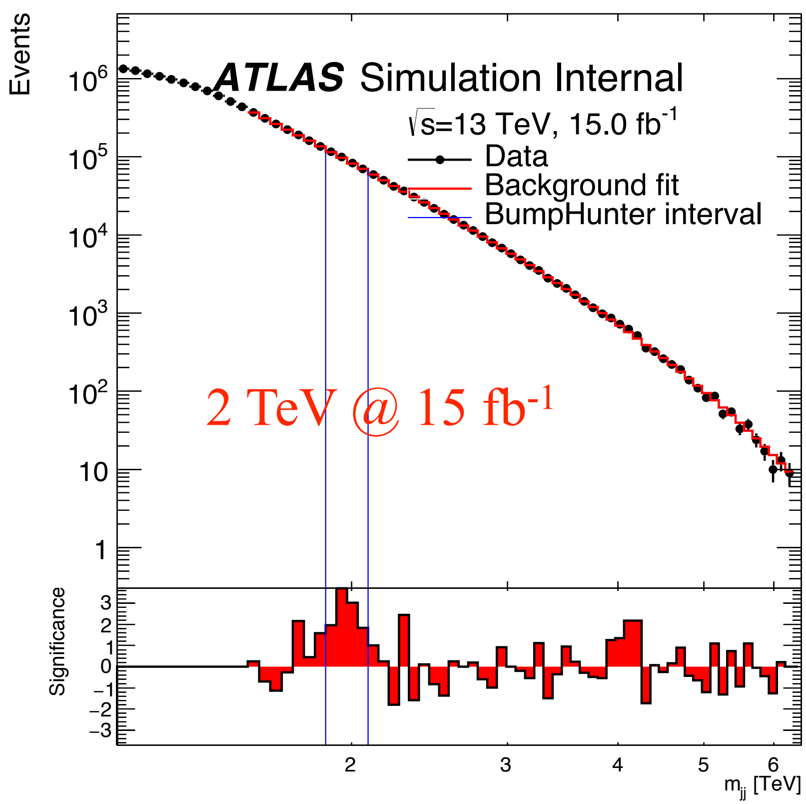


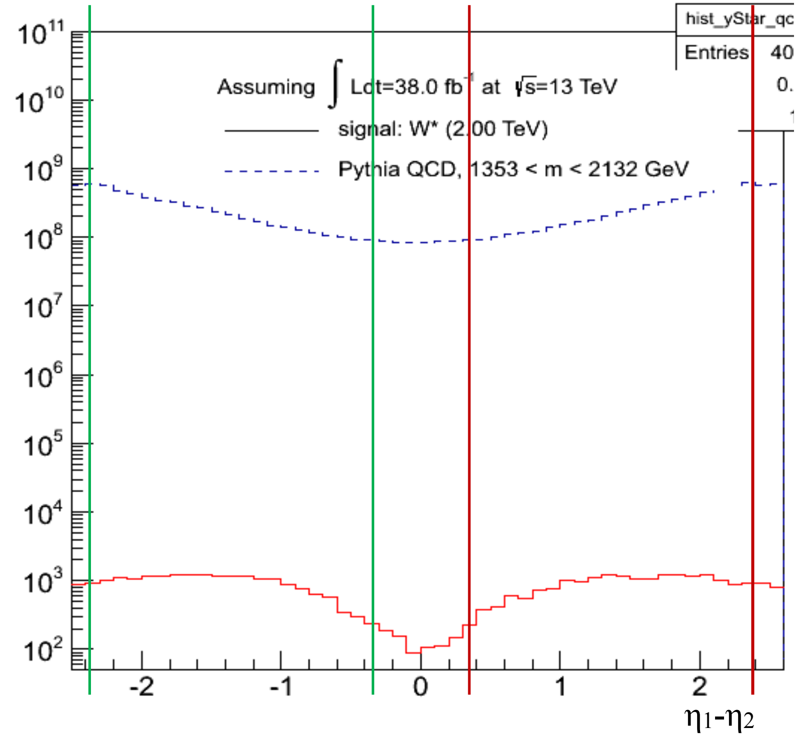
Model dependent limits on resonant phenomena with resonance selection

2D with Z' mass and coupling to SM fermions

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: Reclustering Full Limits

A x σ Upper Limits

q*

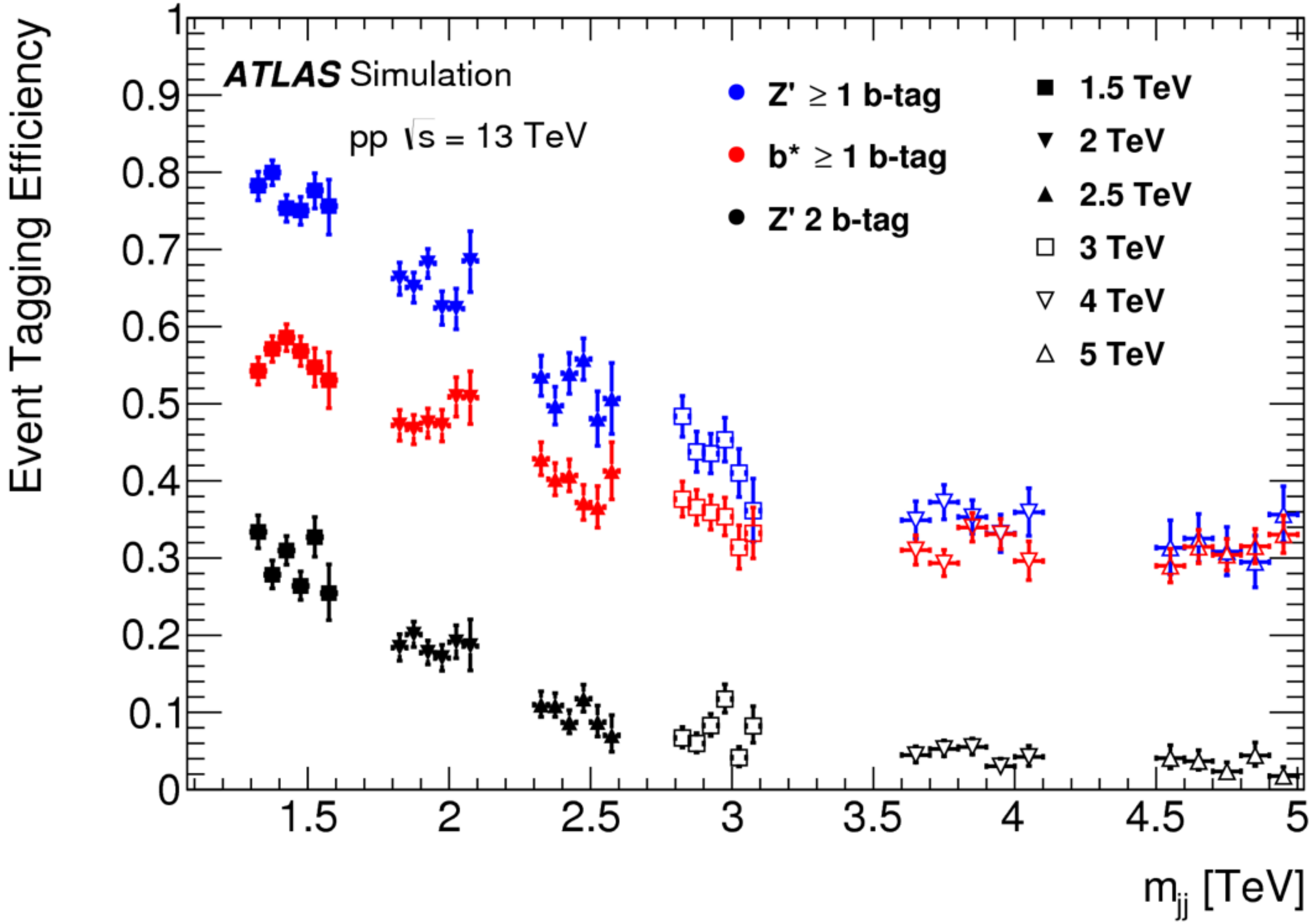
Mass (TeV)	2.0	2.5	3.5	4.0	4.5	5.0	5.5	6.0	6.5
Wide Jet	233.4	117.28	36.879	24.285	14.863	9.351	6.649	4.914	3.841
Small R	269.57	134.36	45.290	30.037	18.757	13.566	9.781	6.970	5.605

W’

Mass (TeV)	1.2	1.5	1.7	2.0	2.5	3.5	4.0	4.5	5.0	5.5	6.0	6.5
Wide Jet	848.39	531.01	331.39	210.56	122.9	37.598	27.618	18.628	14.767	13.261	13.147	14.461
Small R	1087.3	590.19	363.16	228.13	116.90	40.148	33.497	23.436	19.412	21.014	21.743	27.521

QBH

Mass (TeV)	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
Wide Jet	7.598	4.915	3.190	2.263	1.672	1.328	1.090	1.040	1.009
Small R	8.473	5.750	3.523	2.472	1.693	1.308	1.187	1.119	1.065


ATLAS Simulation
pp √s = 13 TeV
Z' ≥ 1 b-tag
b* ≥ 1 b-tag
Z' 2 b-tag
1.5 TeV
2 TeV
2.5 TeV
3 TeV
4 TeV
5 TeV
Event Tagging Efficiency
m_jj [TeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.5
2
2.5
3
3.5
4
4.5
5

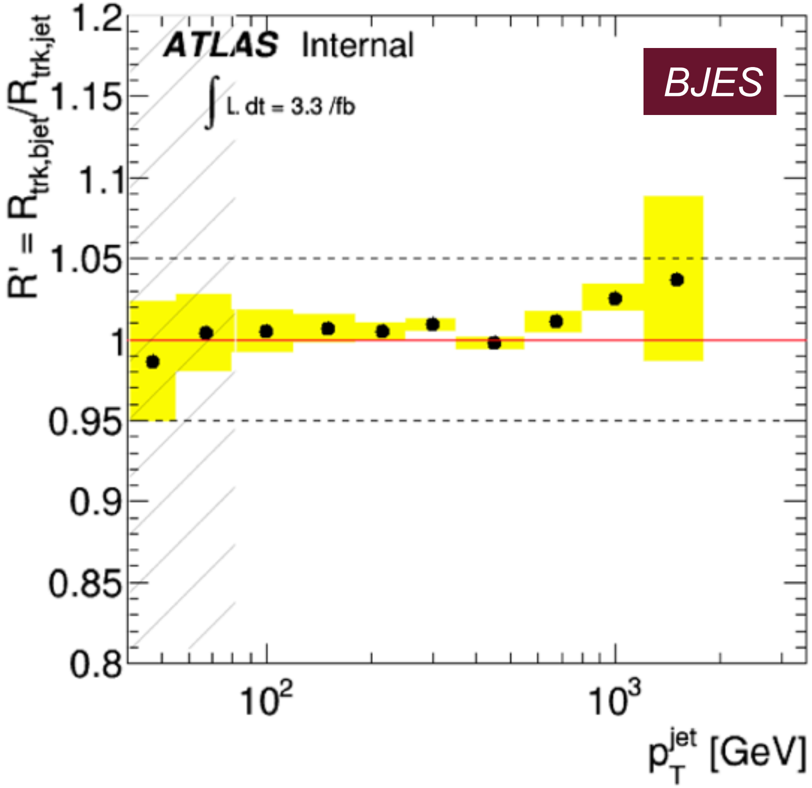
b-Jet Energy Scale

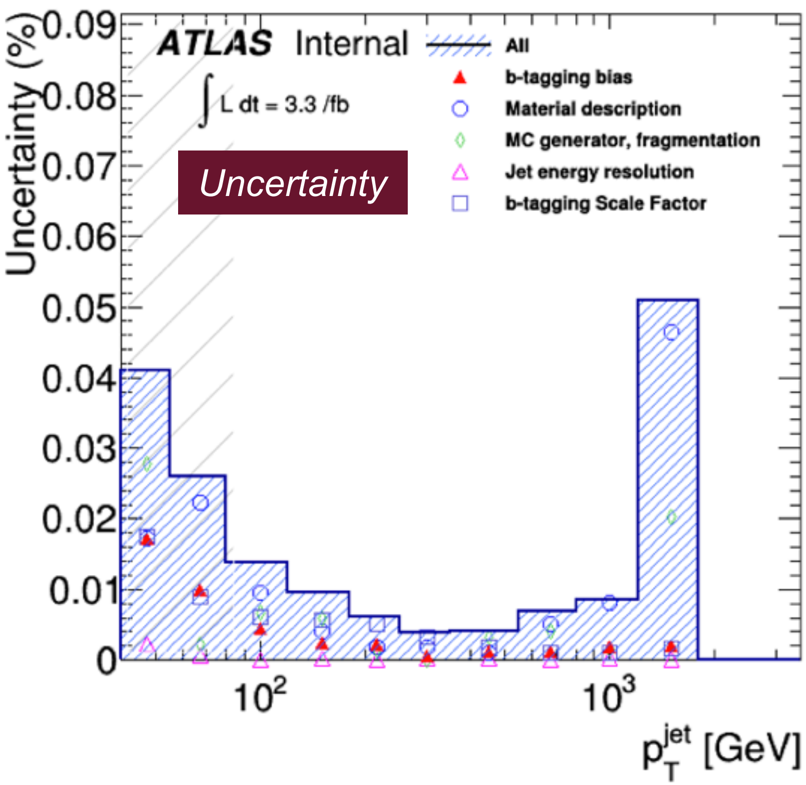
b-tagged di-jet

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





- Background fit to data
  - Blinded 700-800 GeV Region