Resonances in the Dijet Mass

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Overview

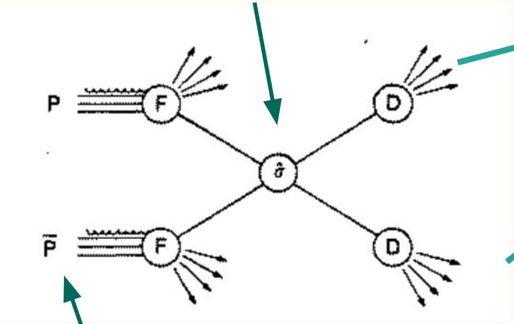
- Motivation
- Example Models
  - Excited Quarks
  - Quantum Black Holes
  - Z' DM Mediator
- Modeling the Background
- Selection Criteria
- Results

Motivation

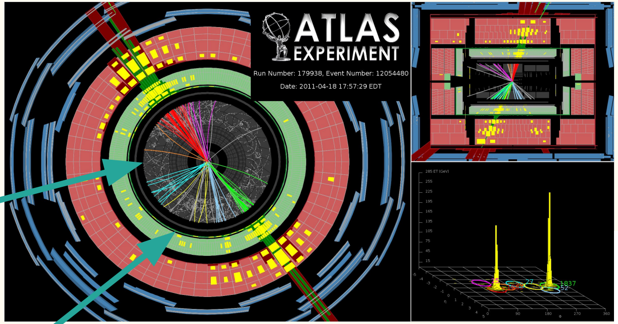
- New particles that directly interact with partons of the proton can product partons when they decay
- Common feature in many BSM models accessible at the LHC
- A new resonant state decaying to two jets may introduce an excess in m_{jj} distribution, near the mass of the resonance
- The production rates for BSM dijet final states can be large, allowing searches at high masses
- Excited quarks, quantum black holes, and W', W*, and Z' bosons would produce peaks in the invariant mass distribution
- Contact interactions would introduce smooth changes in the high-mass tail of the m_{jj} distribution that could be detected in the analysis of the χ distributions (Recall Alex's Talk)

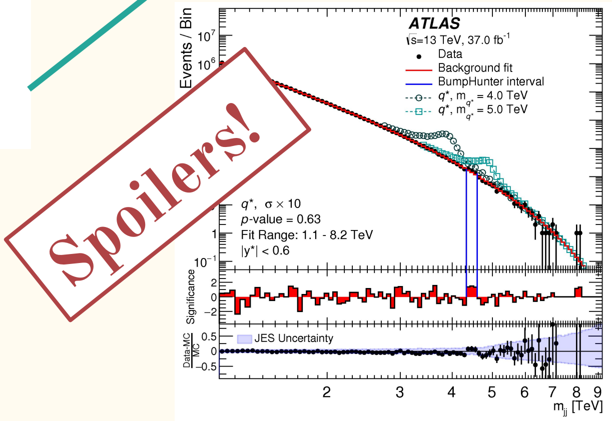
Bump Hunting 101

Could represent elastic scattering of 2 quarks (BG) or new particle production

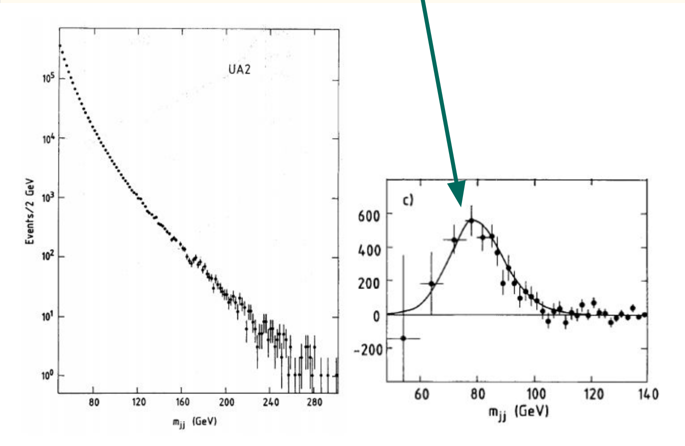


Relic of an old diagram





Successful s-channel dijet resonance observation!! (1990)



Excited Quarks (q*)

- Composite models predict them
- Excited state should not be much lighter than the substructure scale → predicted to be pretty heavy
- Predicted to decay predominantly into ordinary quarks and gluons
- They assume spin-½ excited quarks with same coupling constants as SM quarks
- Only decay of excited quark → up or down quark simulated (BR 85%)

Quantum Black Holes

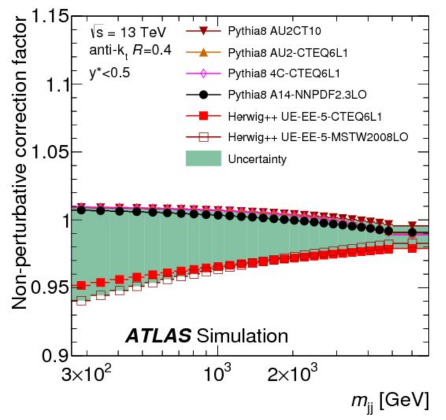
- Not accessible at LHC based on limits on the Planck scale, smallest black hole mass ~ $2x10^{-8}$ kg
- If extra spatial dimensions exist → Planck scale could be smaller → the fundamental scale of gravity could be lowered
- Most optimistic scenarios of extra dimensions → lowest Planck scale → LHC is a black hole factory
- In this model the branching ratio to dijets is 96%
- ADD scenario and dimensions n=6
- QBH would appear as in excess in m_{jj} distribution localized near the threshold mass for QBH production M_{th}

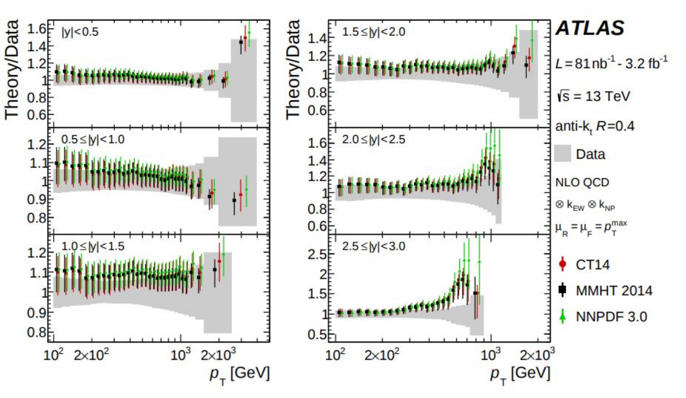
Z' DM Mediator

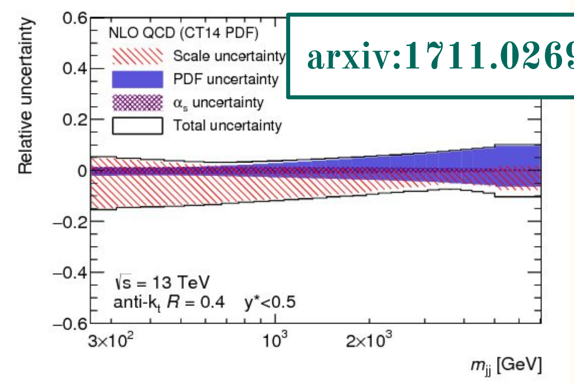
- Z' dark matter mediator model
- Z' can in principle have large couplings to both DM and SM fermions
- Any mediator produced from SM particles in the initial state can also decay back into SM states
- Searches for a DM mediator complementary to usual missing ET searches. Resonance searches complementary to direct detection constraints as well.
- The model assumes axial-vector couplings to all SM quarks and to a Dirac fermion dark matter candidate. Leptophobic.
- In this scenario the Z' BR to DM is negligible, so that production rate and resonance width depends only on g_q and the mass of the resonance

Modeling the QCD Background

- Background dominated by 2 → 2 scattering of partons predicted by perturbative QCD
- No searches use MC simulation to model the QCD background
- Theoretical uncertainties in QCD (PDFs, renormalization and factorization scales, strong coupling constant, non-perturbative effects, ...)
- Use a fit to parametrize the background (Occam's Razor → Use the data itself for the background)







arxiv:1711.02692

Data-Driven BG Estimate: Sliding-Window Fit

- Limitations at the high mass tail
- Before: $f(z) = p_1(1-z)^{p_2} z^{p_3} z^{p_4 \log z}$ where $z = m_{jj}/s^{1/2}$
- Increases in luminosity → cannot rely in f(z) → opportunity to develop new techniques...
- Traditional global fit with p_4 is still viable for this analysis → opportunity to use new method
- Fit data in each window → fit value at center of window is BG description
- Window size chosen such that 3-parameter f(z) describes data well in window
- Nominal window size ~ ½ of total bins
- Nominal window size wide enough for all considered models to fit within one window.

Selection Criteria

	p_T^{leading}	$p_T^{\text{subleading}}$	$\lvert y^*\rvert$	$\lvert y_B\rvert$	m_{jj}
Resonance	> 0.44 TeV	> 0.06 TeV	< 0.6	-	> 1.1 TeV
W^*	> 0.44 TeV	> 0.06 TeV	< 1.2	-	> 1.7 TeV
Angular	> 0.44 TeV	> 0.06 TeV	< 1.7	< 1.1	> 2.5 TeV

p_T requirement ensures a trigger efficiency of at least 99.5% for collisions that enter into the analysis

Rapidity of an outgoing parton: $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$

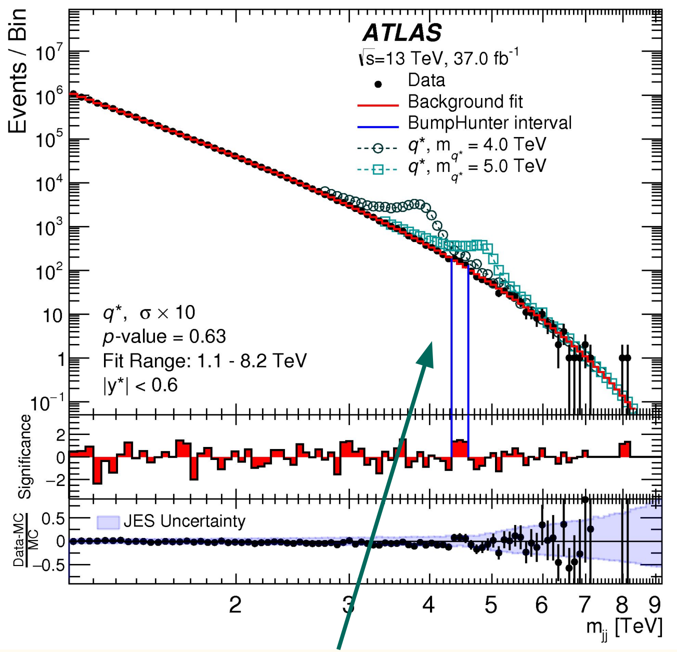
Rapidity difference between the two jets: $y* = \frac{y_1 - y_2}{2}$

Wider $|y^*|<1.2$ region optimized for signals produced at forward angles (W* peaks at $|y^*|>1.0$)

All other benchmark models peak at $y^*=0$

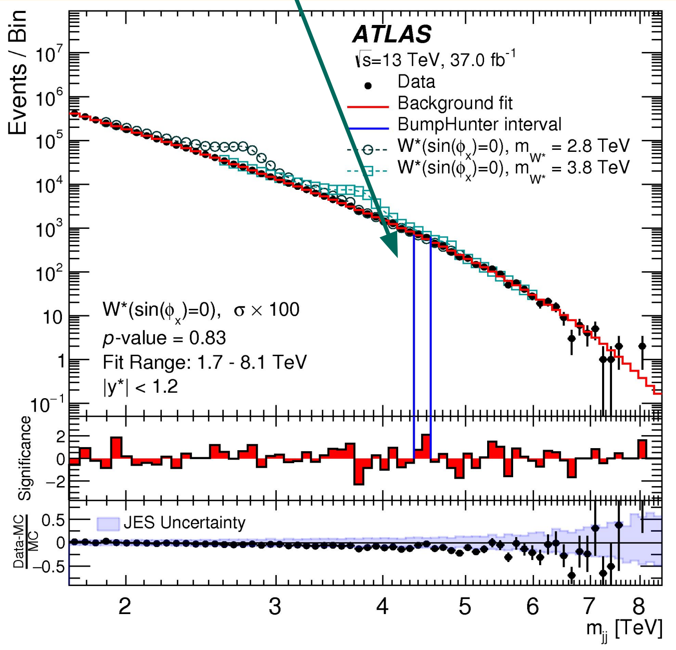
The selection is only fully efficient for $m_{jj} > 1.1$ TeV (1.7 TeV)

Reconstructed Dijet Mass Distribution



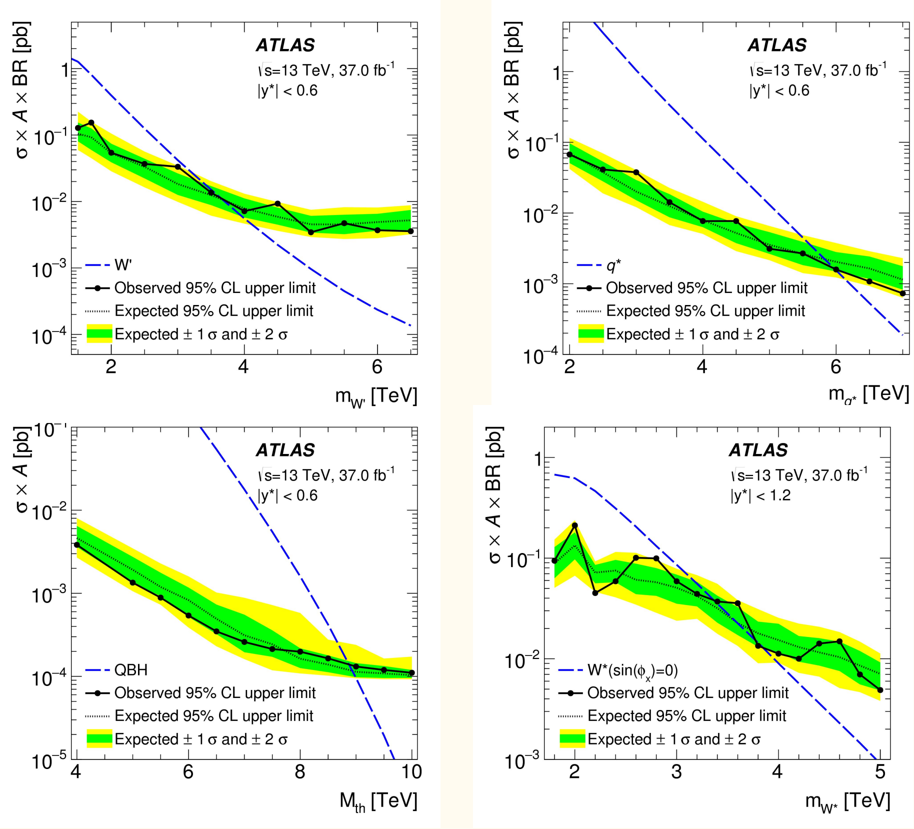
4326 - 4595 GeV: most discrepant interval in |y*|<0.6 region with p-value 0.63

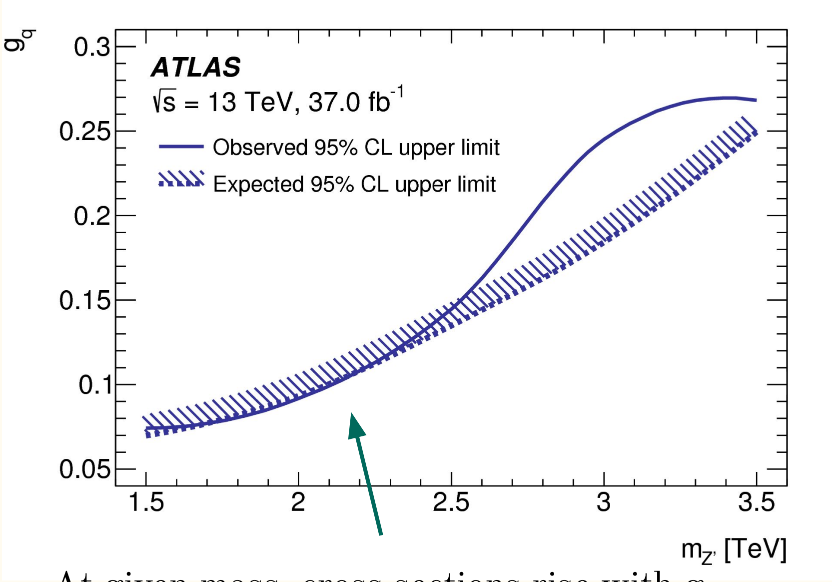
For |y*|<1.2 p-value of 0.83



BumpHunter algorithm quantifies statistical significance of localized excess in m_{jj}

Model Specific Limits





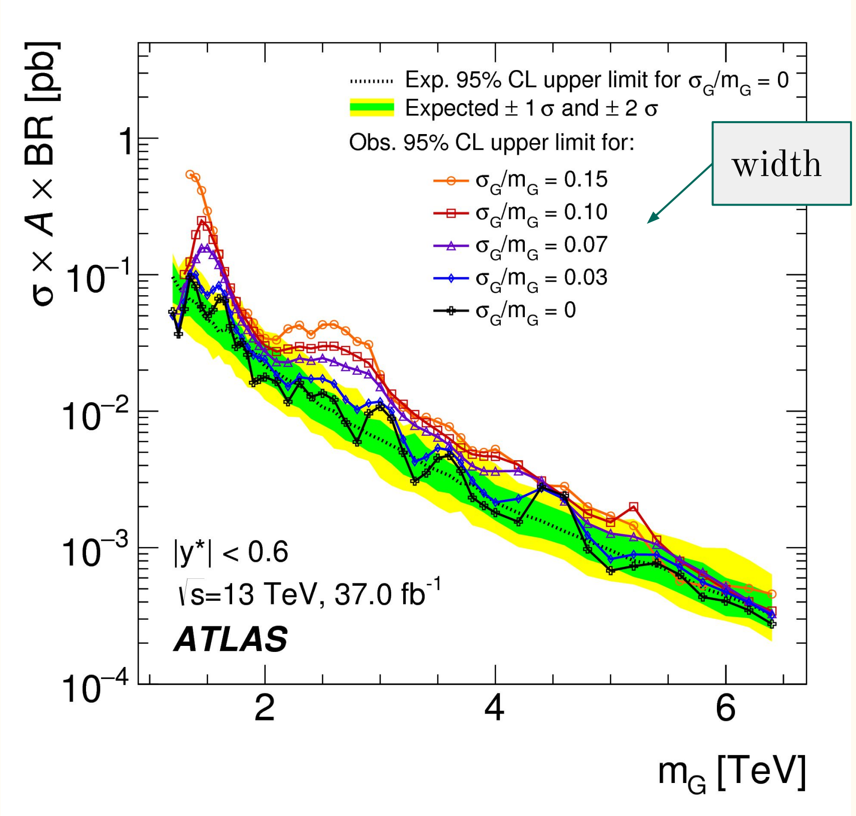
At given mass, cross sections rise with g_q → upper left excluded

At high coupling $g_q > 0.6$ the width of the Z' mass increases to 15% and beyond, loss of sensitivity. Search limited to $g_q < 0.5$.

Model Independent Limits

Resonance Shapes:

- Narrow width: width dominated by experimental resolution
- Difference in widths dominated by difference in # of decay channels
- Limits worsen for wider signals



95% CL Lower Limits on Masses

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' ($g_q = 0.1$)	2.1 TeV	2.1 TeV
Z' ($g_q = 0.2$)	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{\mathrm{LL}} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{\mathrm{LL}} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

Largest m_{jj} detected 8.12 TeV

Larger than largest mass detected!

Extrapolating into region with no data.

Conclusion

- Limits set on the masses of excited quarks, qbh, W’ and Z’ bosons, excited chiral W* bosons, on contact interaction scales, and generic Gaussian-shaped signal production.
- Improvements on previous limits from 7% for QBH masses to 40% for W’ masses
- Any new model predicting excesses in the dijet mass has generic limits set on that excess as a function of width

Backup.

Table 3. Searches for dijet resonances at hadron colliders. For each search we list the experiment, year of data publication, center-of-mass energy, integrated luminosity, techniques used to define the resonance shape and the background, dijet mass range of the data, the cut applied on the center of mass scattering angle, and the primary reference for the search.

Expt.	Yr.	$\sqrt{s}$ (TeV)	$\int L\,dt$ (pb^{-1})	Resonance Shape	Background Shape	m_{JJ} (TeV)	$\cos\theta^*$ Cut	Ref. #
UA1	86	0.63	0.26	BW $\oplus$ Gaussian	LO QCD	$.07 - 0.3$	-	12
UA1	88	0.63	0.49	BW $\oplus$ Gaussian	LO QCD	$.11 - 0.3$	bins	25
CDF	90	1.8	0.026	BW $\oplus$ Gaussian	LO QCD	$.06 - 0.5$	-	26
UA2	90	0.63	4.7	Gaussian	Fit Func.	$.05 - 0.3$	-	27
CDF	93	1.8	4.2	BW $\oplus$ Resolution	LO QCD	$.14 - 1.0$	-	28
UA2	93	0.63	11	Gaussian	Fit Func.	$.05 - 0.3$	.60	29
CDF	95	1.8	19	PYTHIA $\oplus$ Sim.	Fit Func.	$.15 - 0.9$	.67	30
CDF	97	1.8	106	PYTHIA $\oplus$ Sim.	Fit Func.	$.18 - 1.0$	.67	31
D0	04	1.8	109	PYTHIA $\oplus$ Sim.	NLO QCD	$.18 - 1.2$	.67	32
CDF	09	1.96	1130	PYTHIA $\oplus$ Sim.	Fit Func.	$.18 - 1.3$	-	33
ATLAS	10	7	0.32	PYTHIA $\oplus$ Sim.	Fit Func.	$.20 - 1.7$	.57	34
CMS	10	7	2.9	PYTHIA $\oplus$ Sim.	Fit Func.	$.22 - 2.1$	.57	35
ATLAS	11w	7	36	PYTHIA $\oplus$ Sim.	Fit Func.	$.50 - 2.8$	.57	36
CMS	11	7	1000	PYTHIA $\oplus$ Sim.	Fit Func.	$.84 - 3.7$	.57	37
ATLAS	11s	7	1000	PYTHIA $\oplus$ Sim.	Fit Func.	$.72 - 4.1$	.54	38