

# Search for new physics in dijet and multijet final states with Run 2 data at 13 TeV

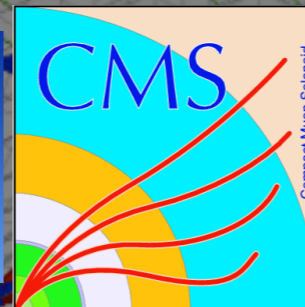
**Saptaparna Bhattacharya**



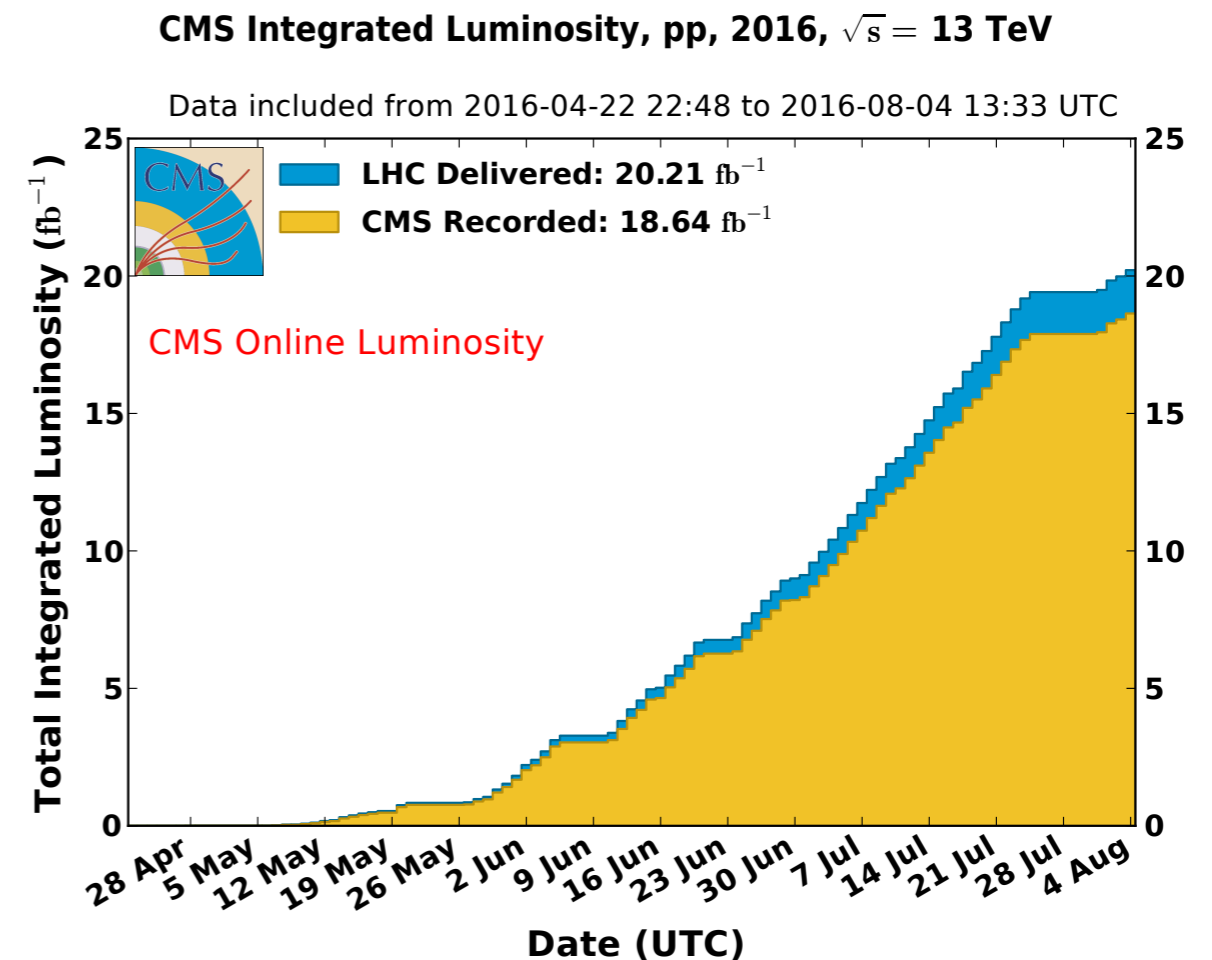
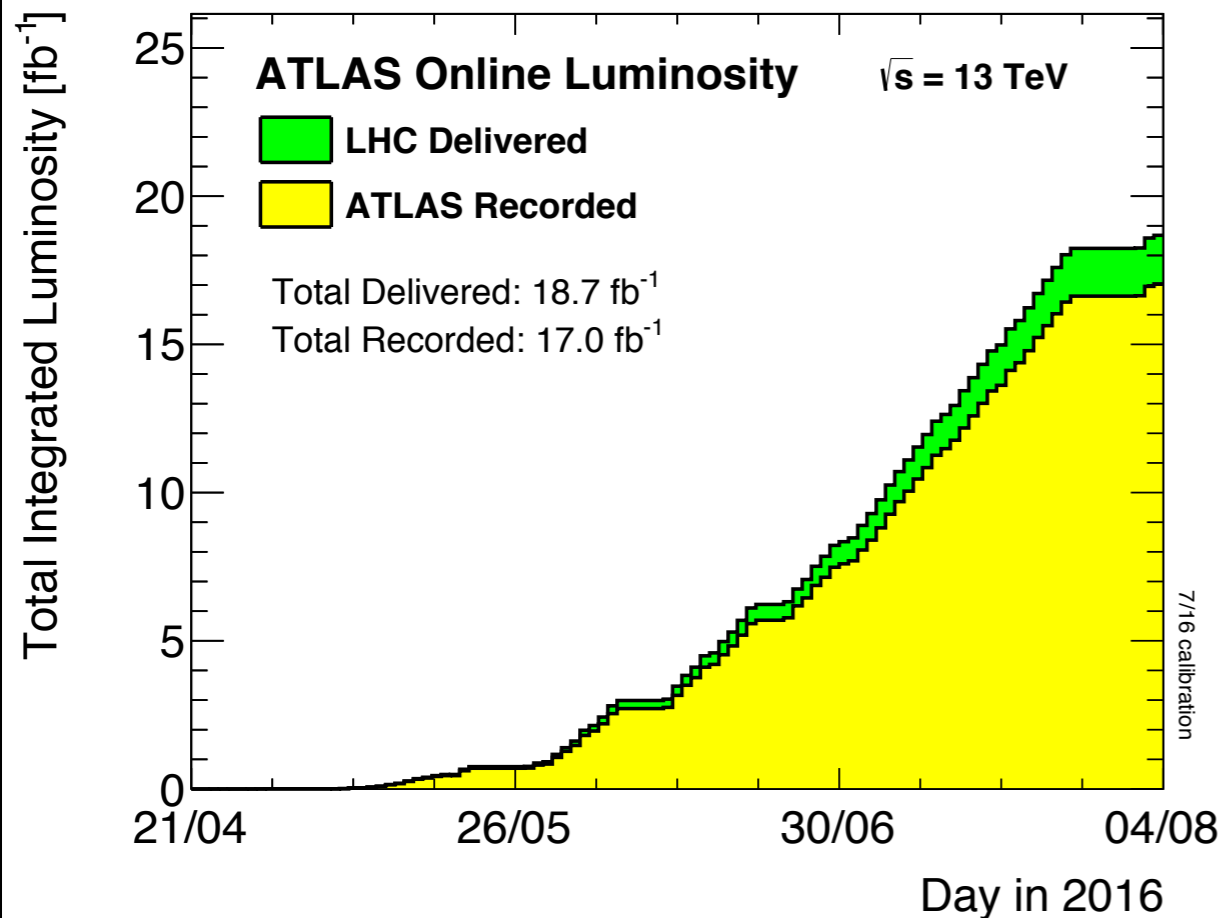
**Northwestern University**



**ATLAS**  
EXPERIMENT



# Total data collected



Both experiments have nearly 20/fb at  $\sqrt{s} = 13$  TeV!



# Motivation: Jet based final states

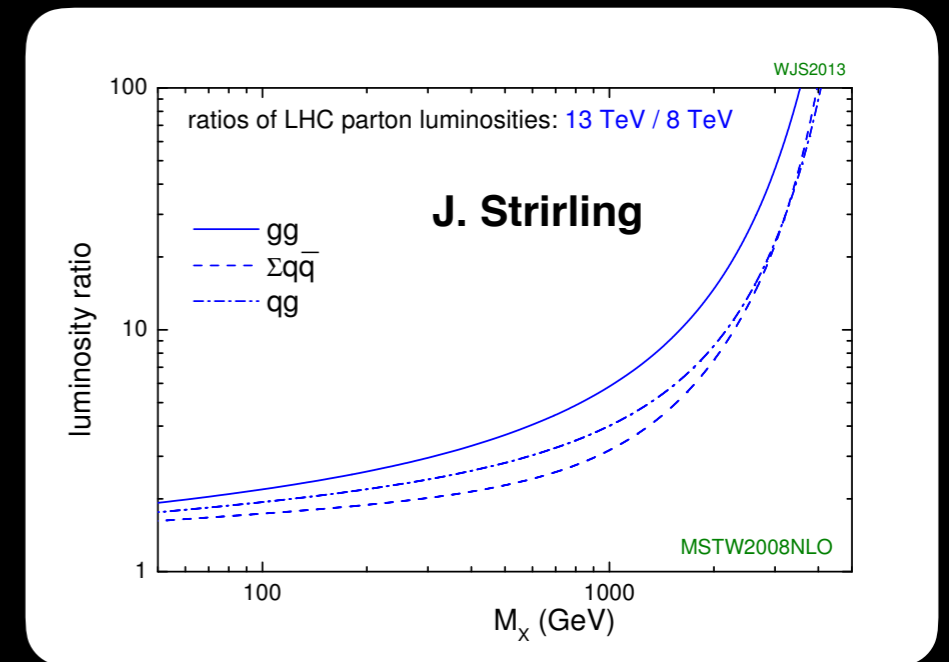
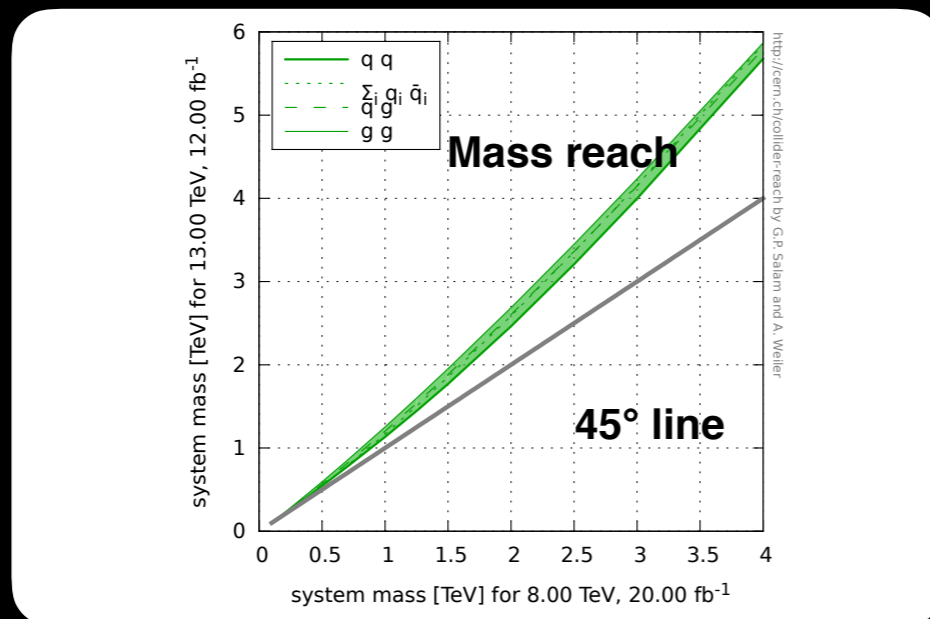
- $2 \rightarrow 2$  scattering processes are described well by QCD in the Standard Model (SM). Departure from SM implies New Physics (NP).

- Useful variables: Dijet invariant mass ( $m_{jj}$ ), dijet angular distribution, typically expressed as:

$$\chi_{\text{dijet}} = \exp(|(y_1 - y_2)|)$$

where  $y_1$  and  $y_2$  are rapidities of the outgoing partons/jets.

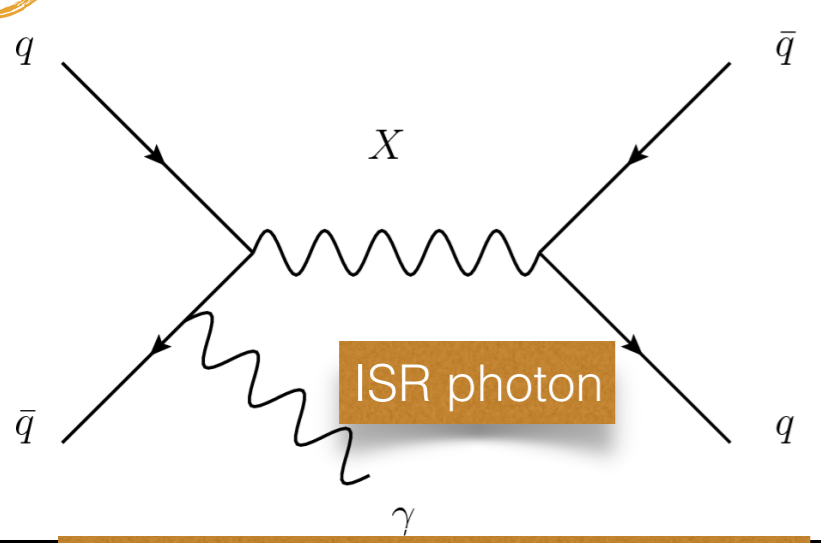
- The  $m_{jj}$  reach is higher at  $\sqrt{s} = 13$  TeV with respect to  $\sqrt{s} = 8$  TeV



Parton luminosity

Hot off the press! ✨ ✨ ✨ ✨ ✨

# Low-mass dijet analysis: ATLAS



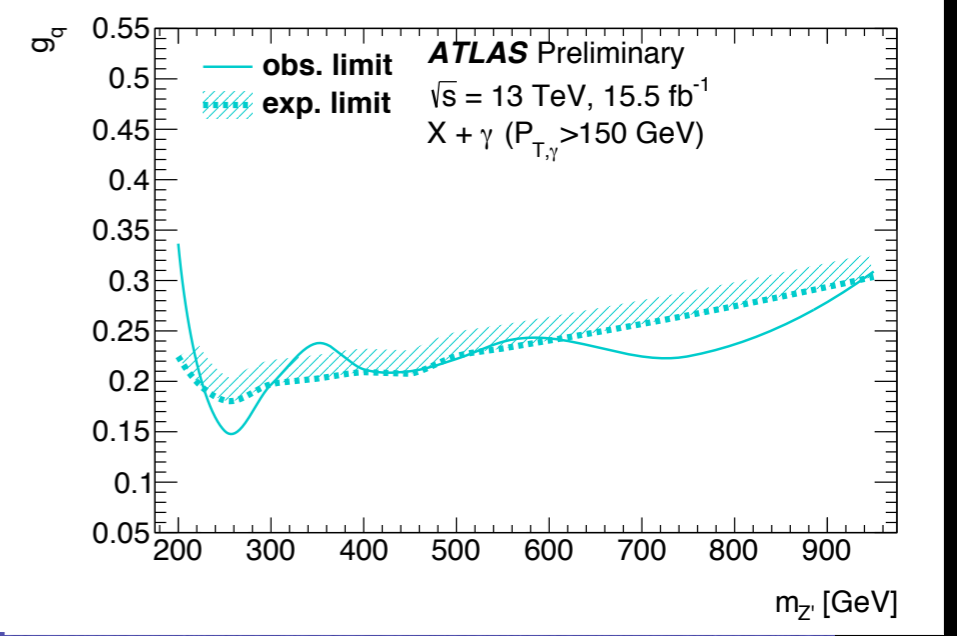
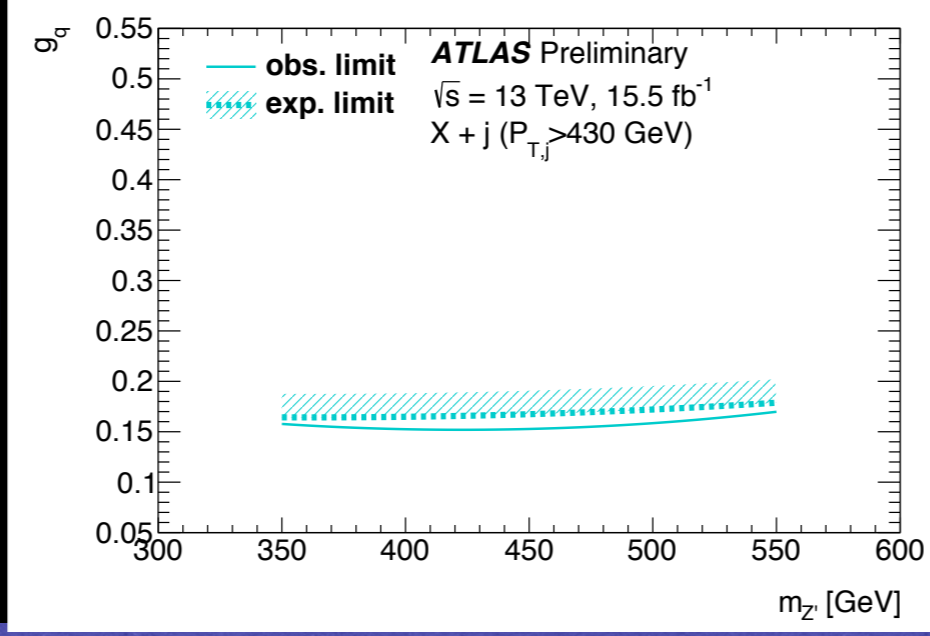
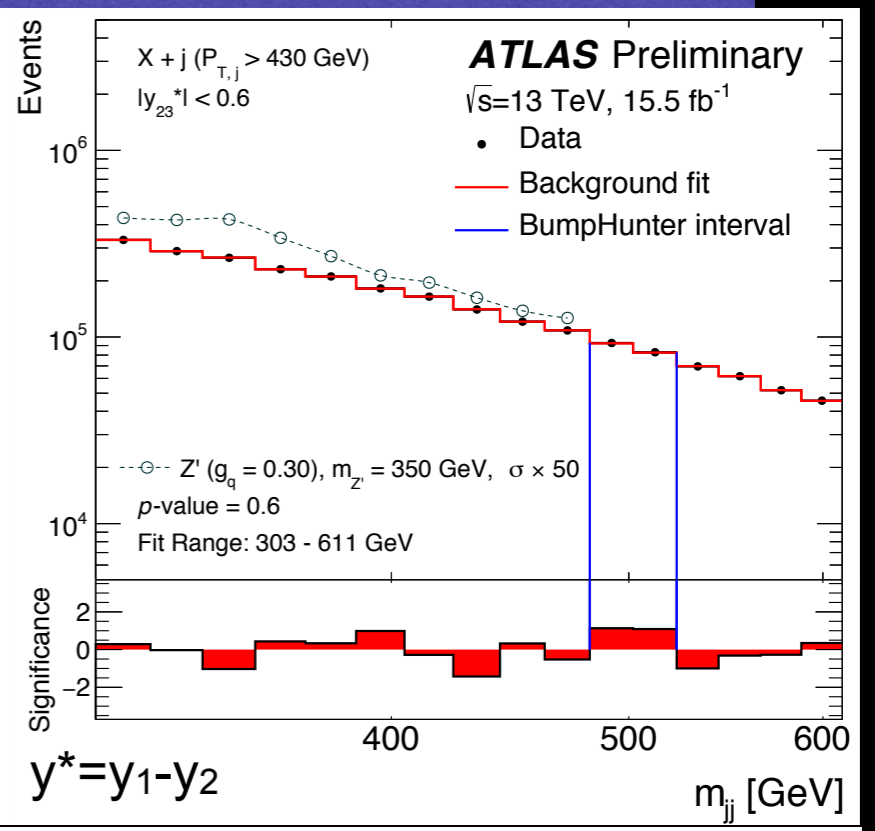
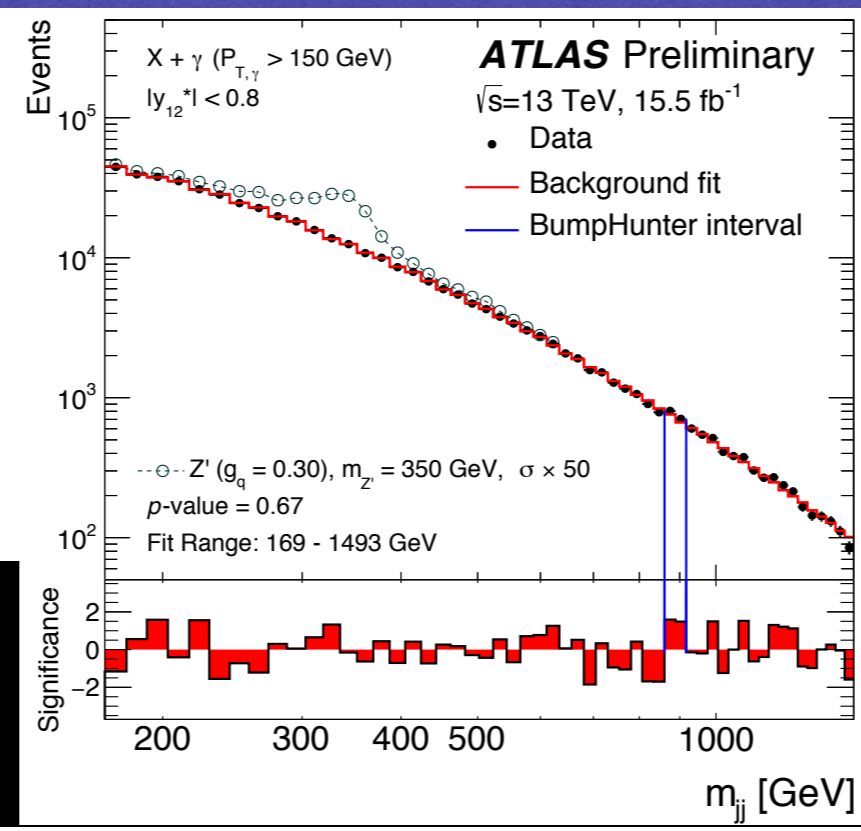
Analysis sensitive to ISR jets too

$$\mathcal{L} = g_q \bar{q} \gamma^\mu q Z'_\mu$$

**Coupling values above the solid curve are excluded**

**X + jet search: excludes at 95% CL lepto-phobic axial-vector Z' bosons for  $g_q$  above 0.16 at mass  $m_{Z'} = 350$  GeV and  $g_q$  above 0.18 at  $m_{Z'} = 550$  GeV**

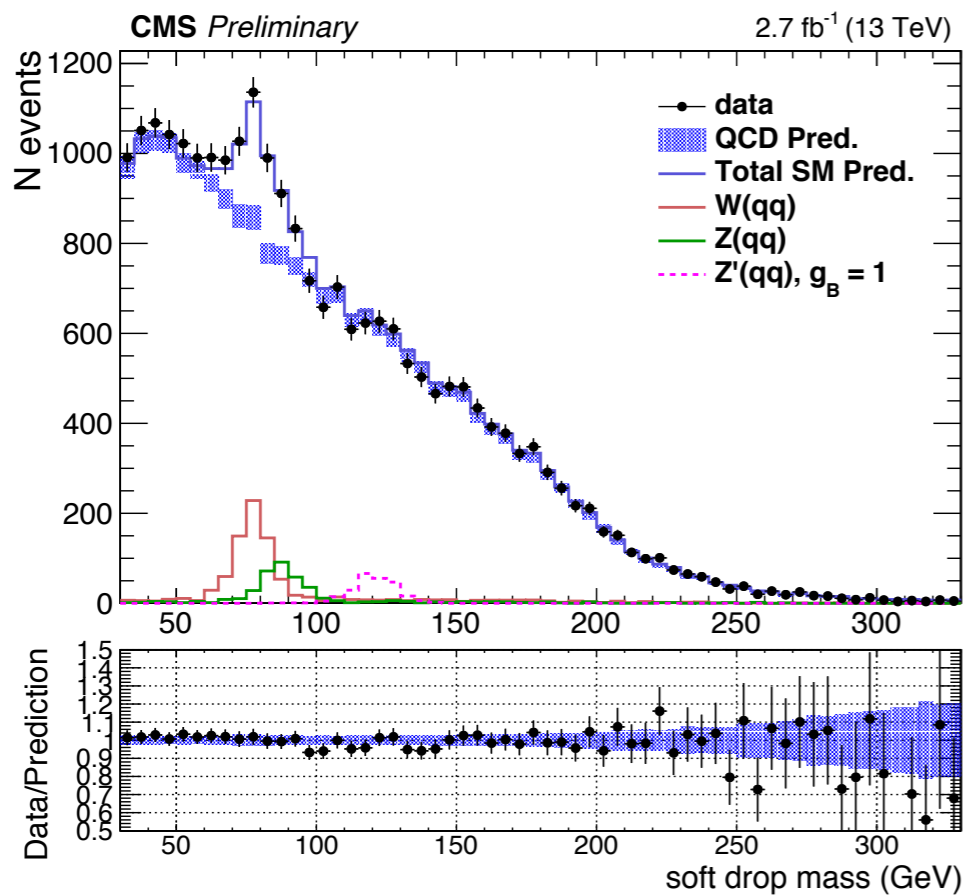
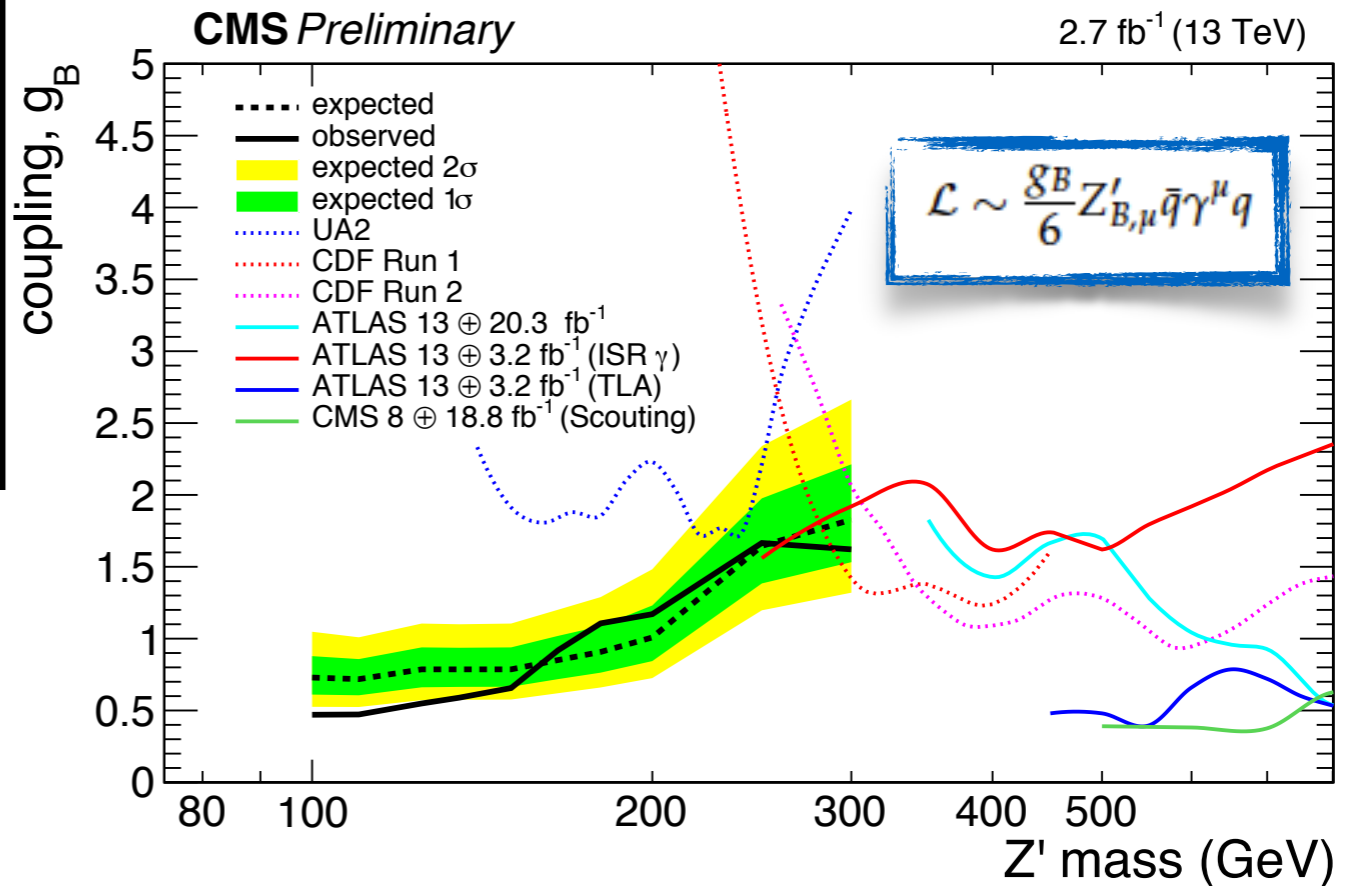
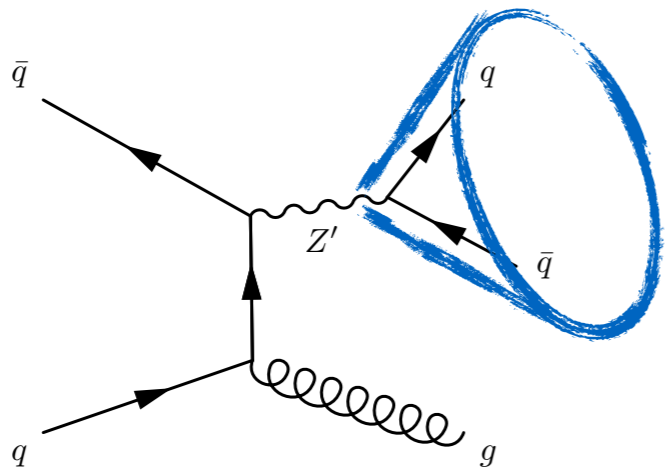
**X+gamma: Z' bosons for  $g_q$  above 0.15 at mass  $m_{Z'} = 250$  GeV are excluded**





Hot off the press!

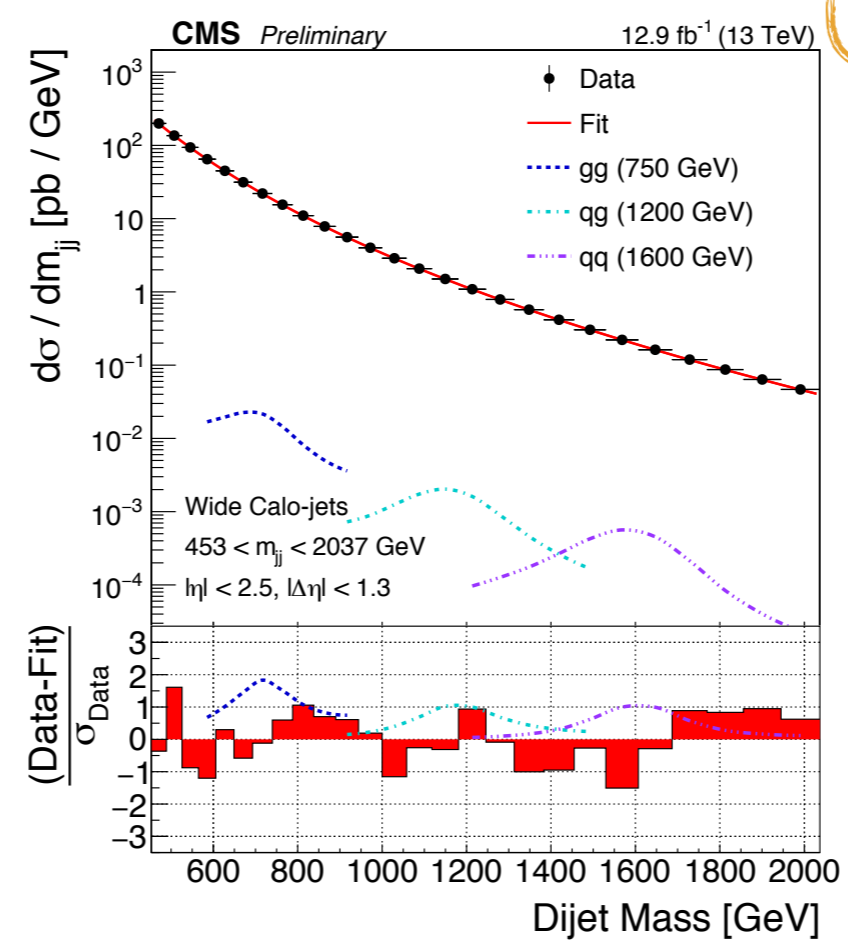
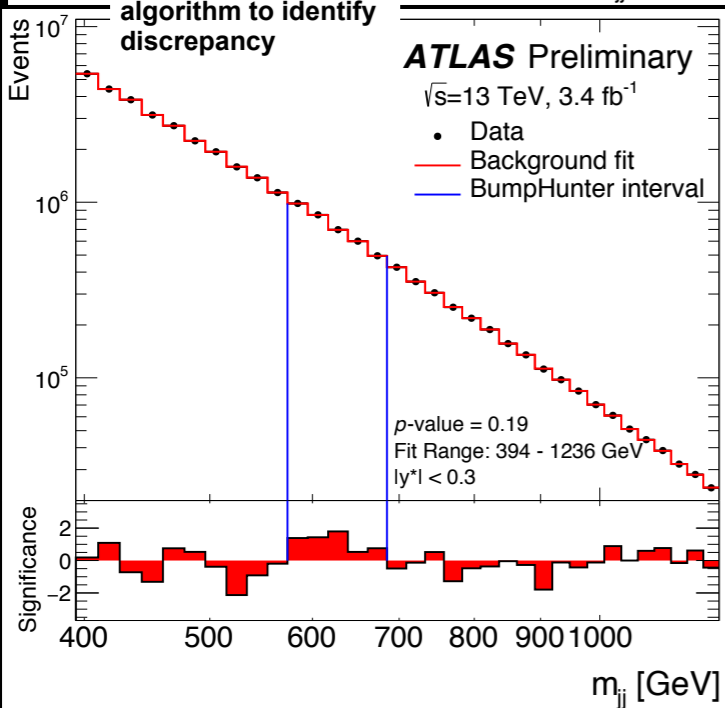
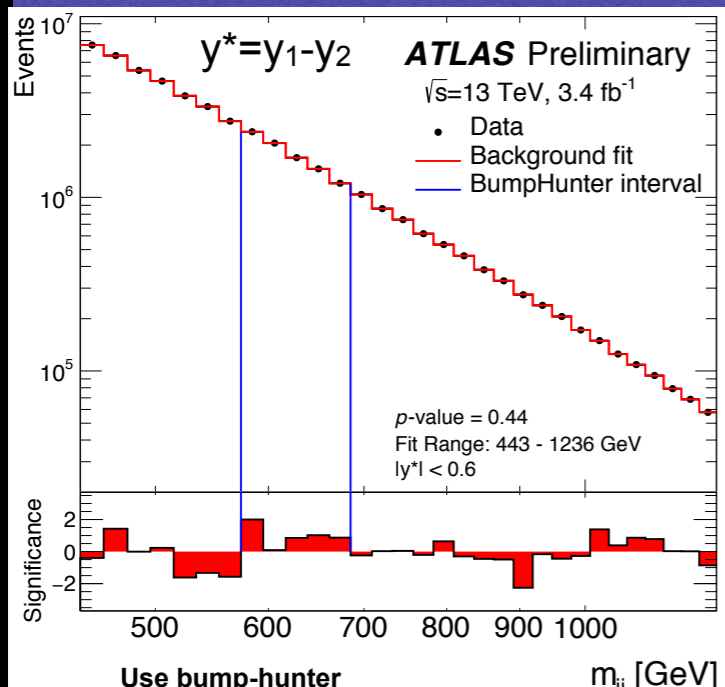
# Low-mass dijet analysis: CMS



- Uses boosted topology: soft drop criterion
- Background determined from side-band regions in data
- First results in the region below 140 GeV
- Most sensitive in the mass regime less than 300 GeV

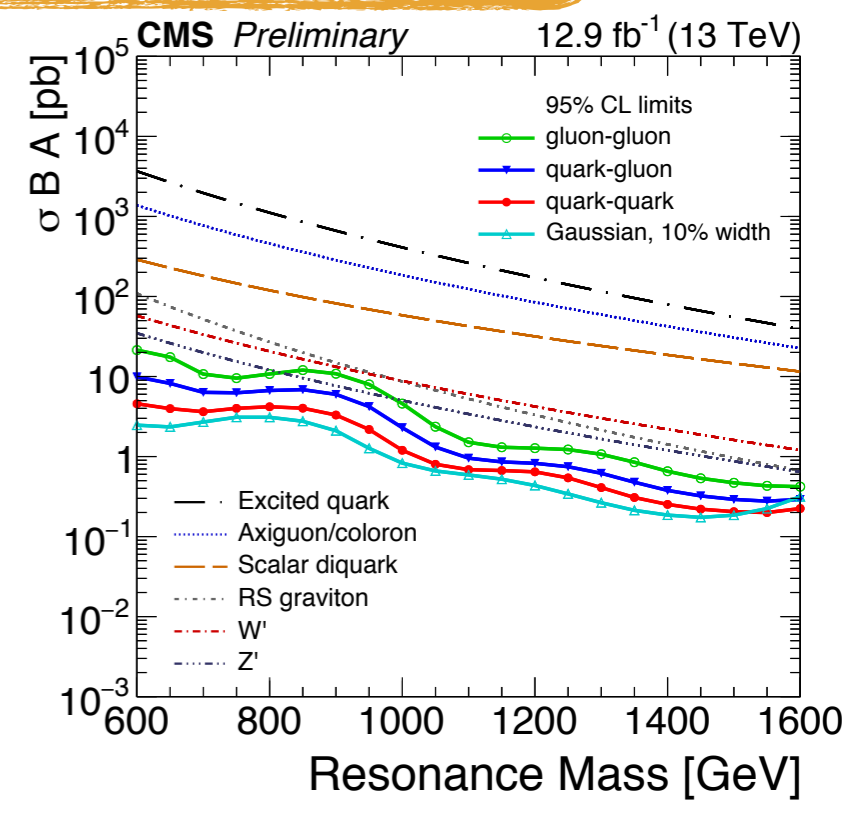
# Trigger Level Searches with Dijets

Hot off the press!



Used the novel technique of data scouting

- To sustain a high rate in the data scouting stream, 4 momenta of the calorimetric jets is stored
- Rate at HLT is 1 kHz
- Scouting data are stored immediately after the HLT selection



**ATLAS:** Searched for dijet resonances between 0.4 (0.45) and 1.1 TeV at ATLAS using  $y^* < 0.3$  (0.6)

**CMS:** Used to search for dijet resonances between 0.6 TeV and 1.6 TeV at CMS

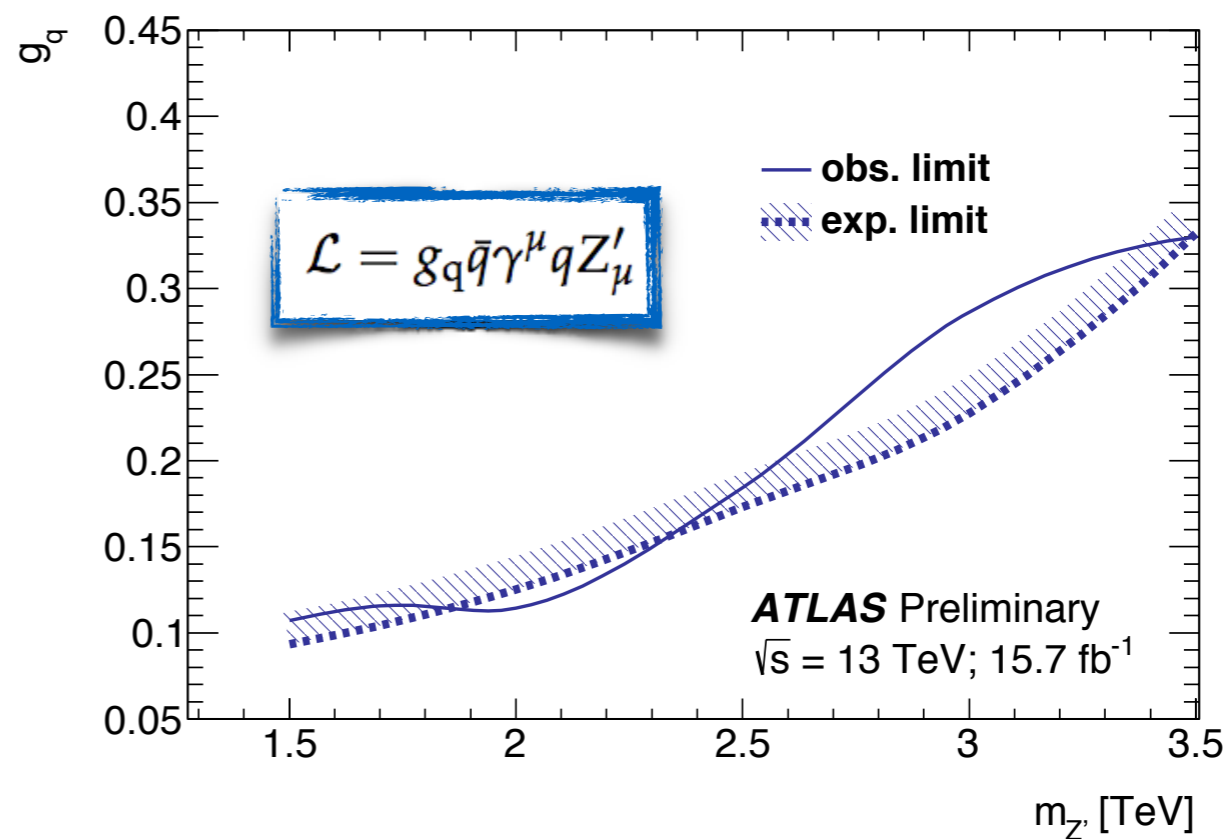
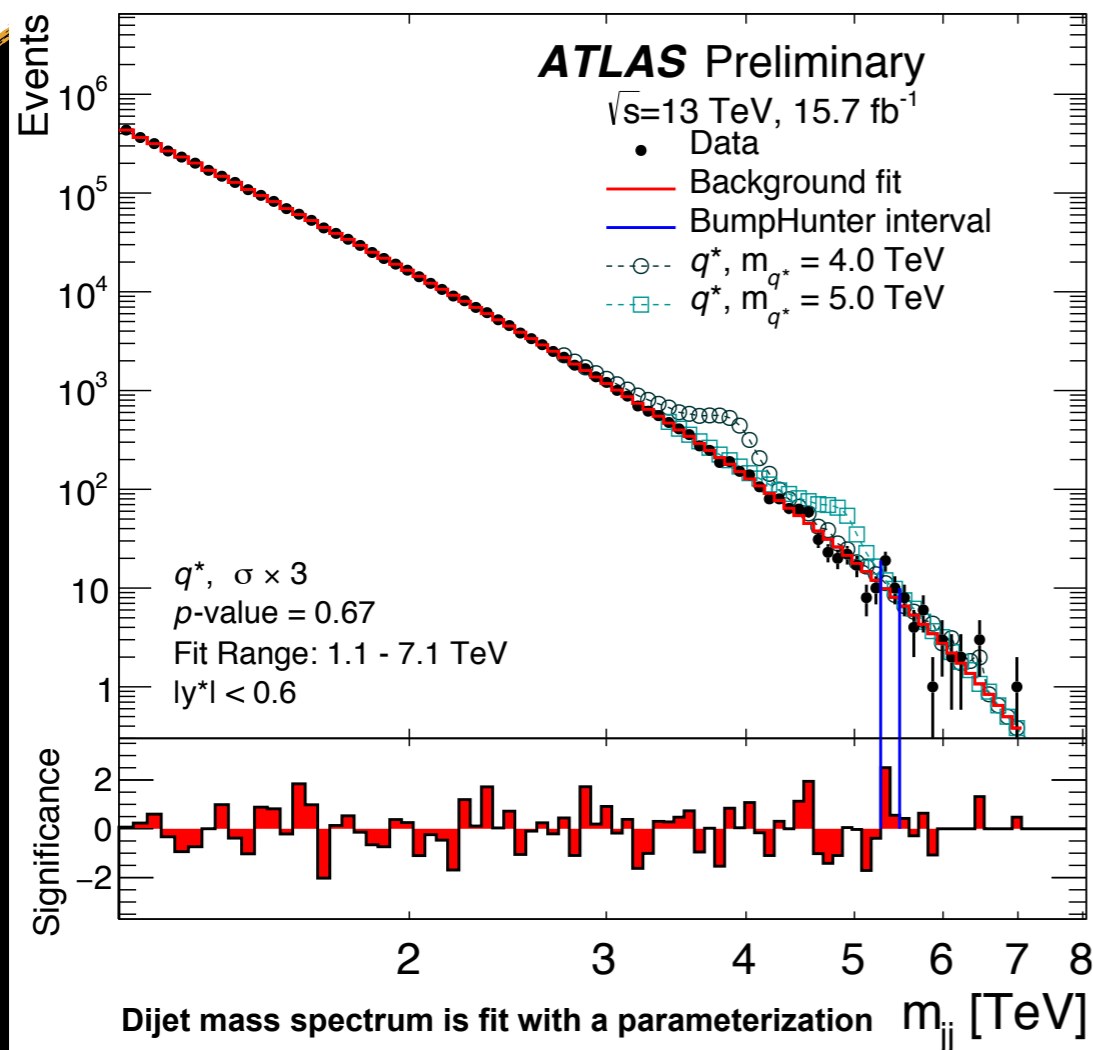
Refer to Dustin Anderson's talk on data scouting (<http://indico.cern.ch/event/432527/contributions/1071749/>)

**No evidence for a 750 GeV dijet resonance. Both experiments set limits**

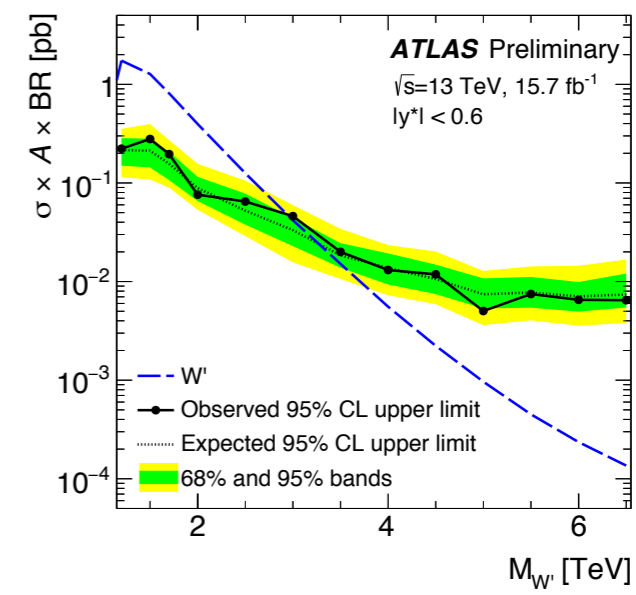
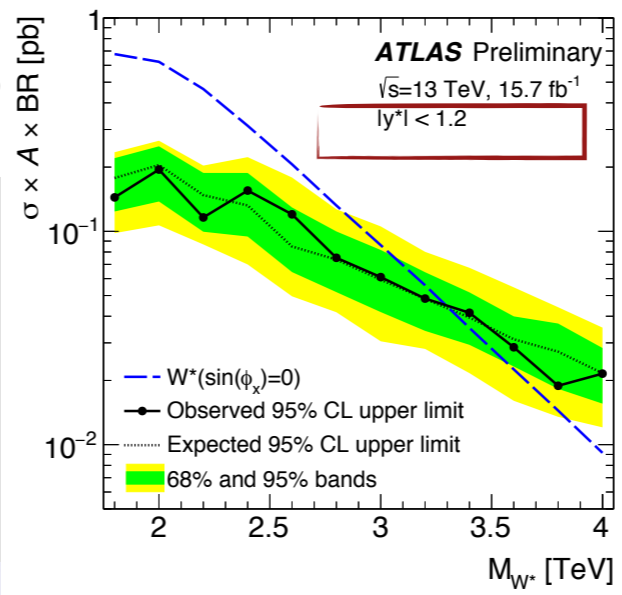


Hot off the press!

# High-mass dijet analysis: ATLAS

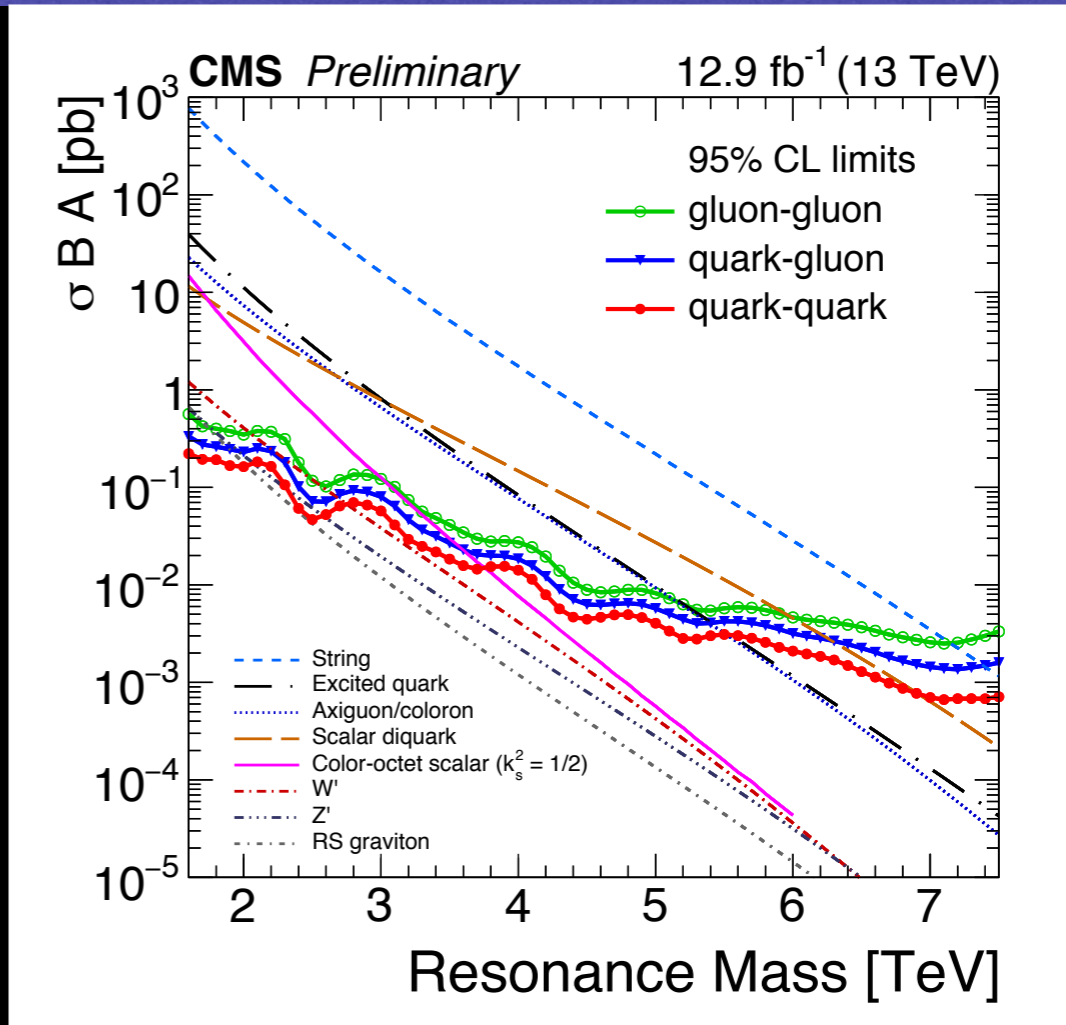
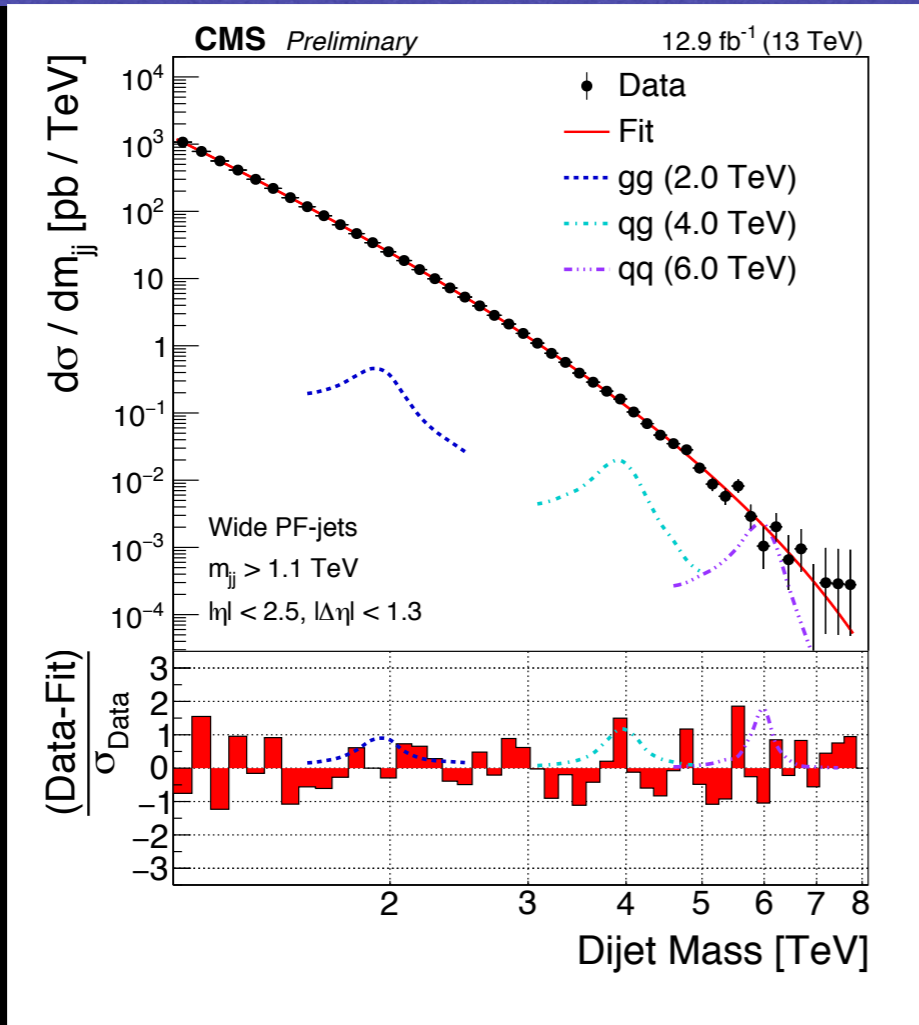


Model	95% CL Exclusion limit	
	Observed	Expected
Quantum black holes, ADD (BLACKMAX generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
$W'$	2.9 TeV	3.3 TeV
$W^*$	3.3 TeV	3.3 TeV
Contact interactions ( $\eta_{LL} = +1$ )	12.6 TeV	13.7 TeV
Contact interactions ( $\eta_{LL} = -1$ )	19.9 TeV	23.7 TeV



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# High-mass dijet analysis: CMS



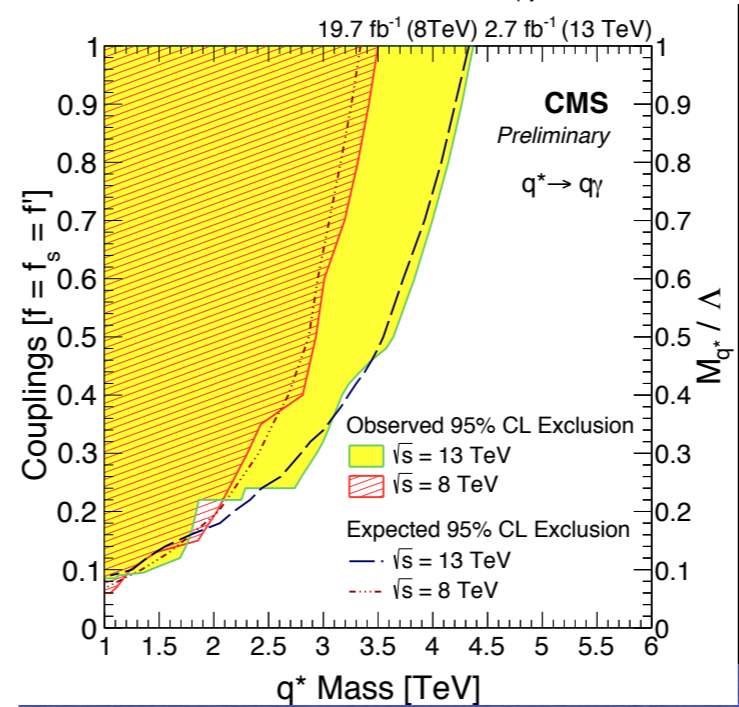
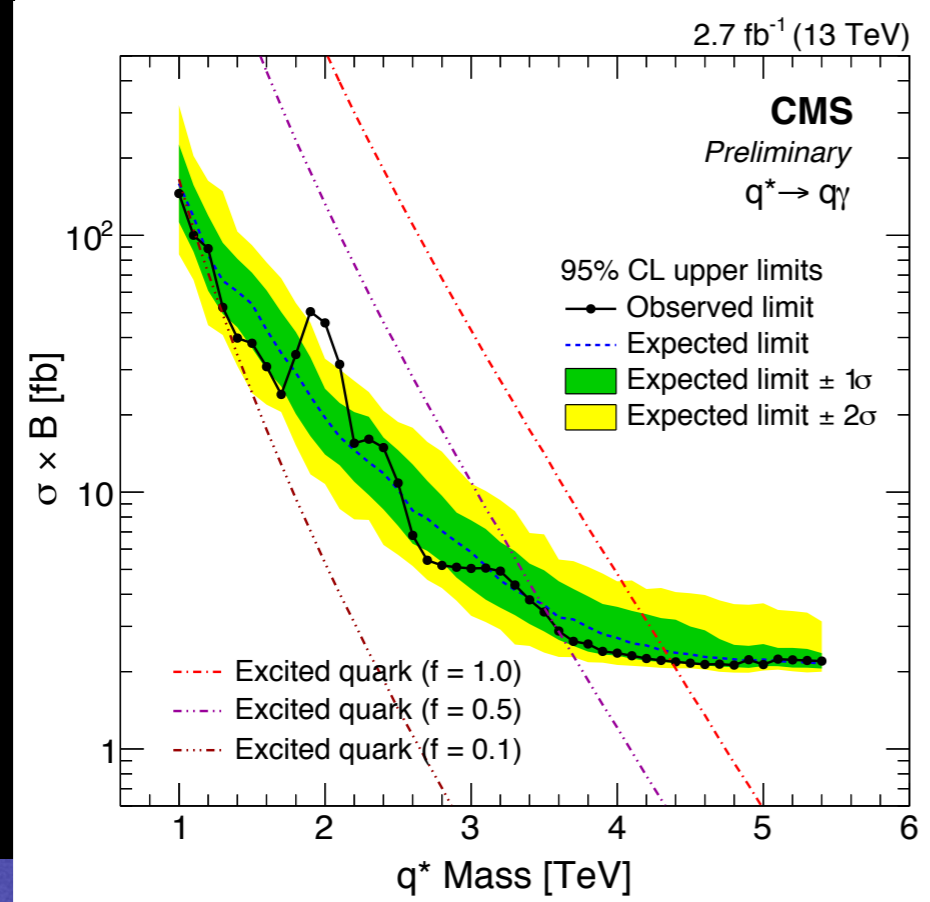
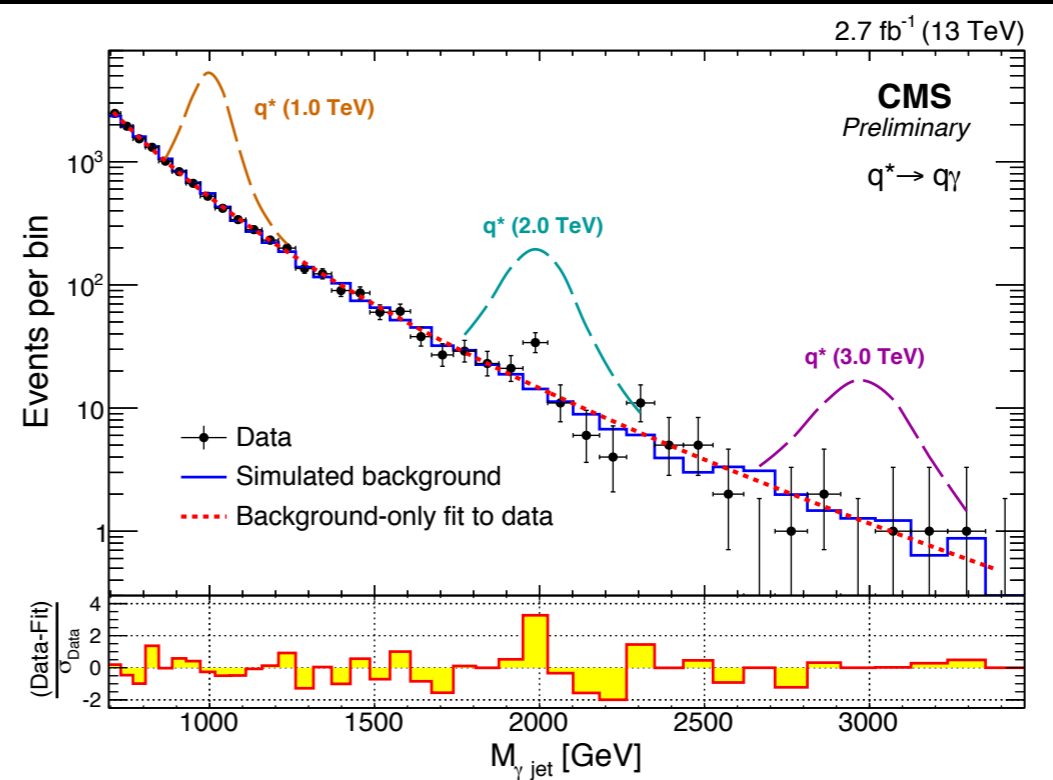
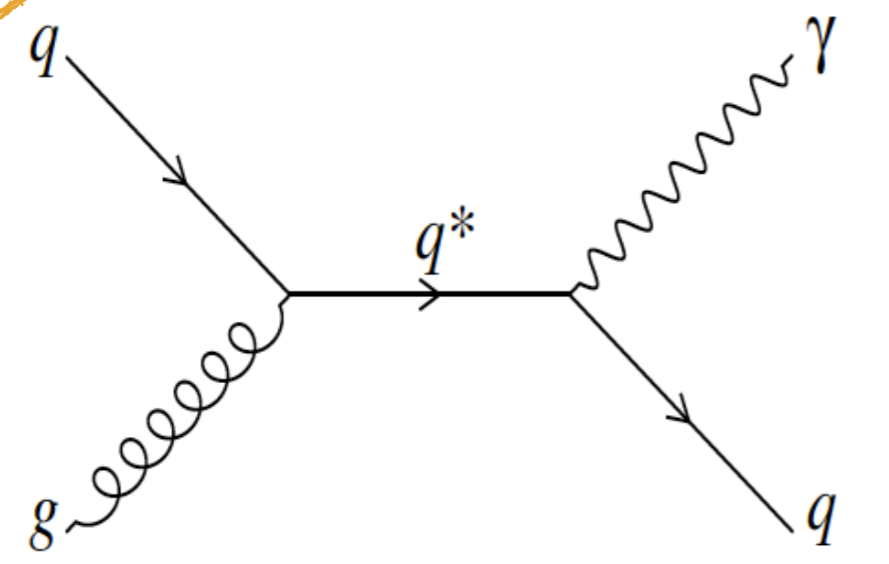
- Dijet mass spectrum is fit with a parameterization
- Limits are set on generic quark-quark, quark-gluon and gluon-gluon resonances.
- Mass limits extended on eight models

Model	Final State	Observed (expected) mass limit [TeV]		
		12.9 fb <sup>-1</sup> 13 TeV	2.4 fb <sup>-1</sup> 13 TeV	20 fb <sup>-1</sup> 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	q $\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ( $k_s^2 = 1/2$ )	gg	3.0 (3.3)	—	—
W'	q $\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z'	q $\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	q $\bar{q}, gg$	1.9 (1.8)	—	1.6 (1.3)



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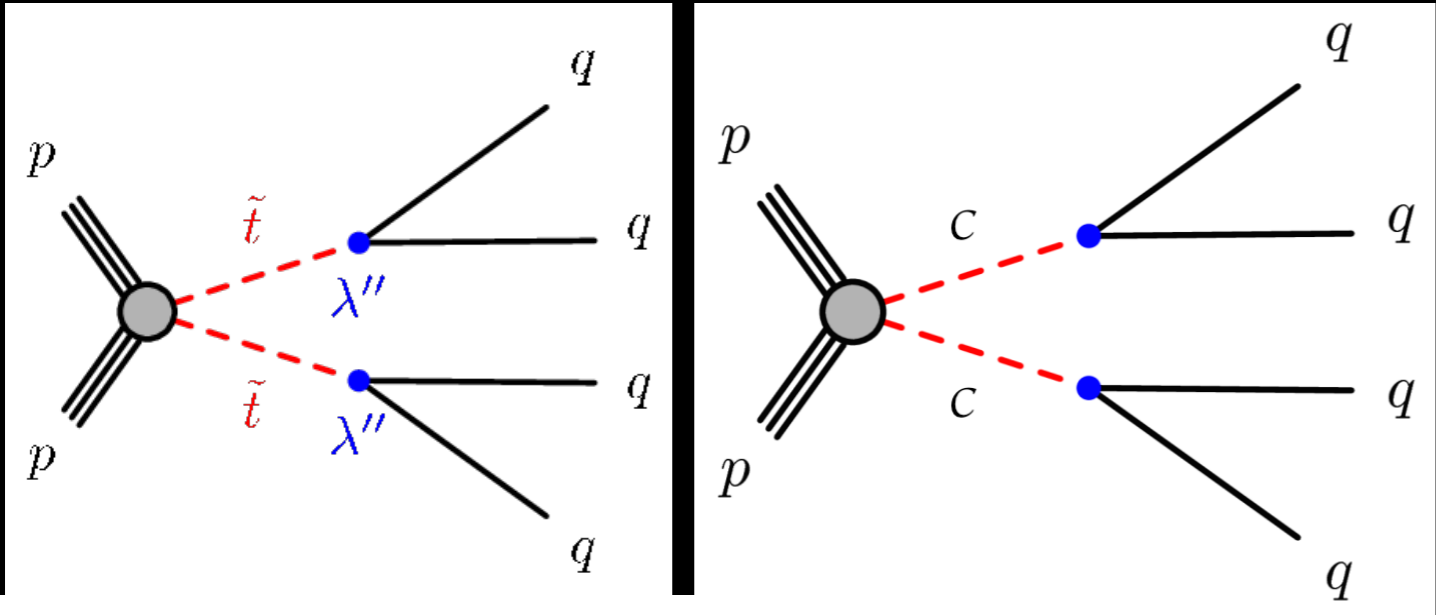
# Search for excited quarks



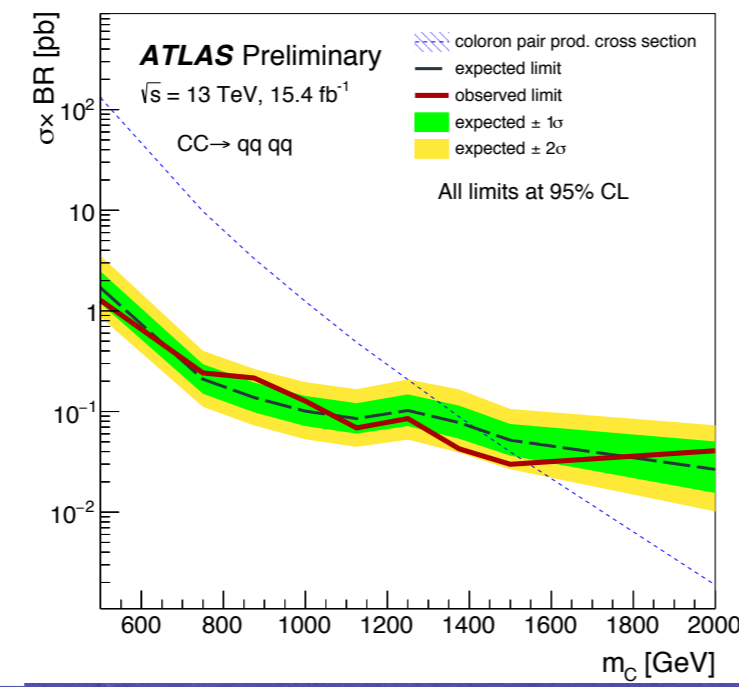
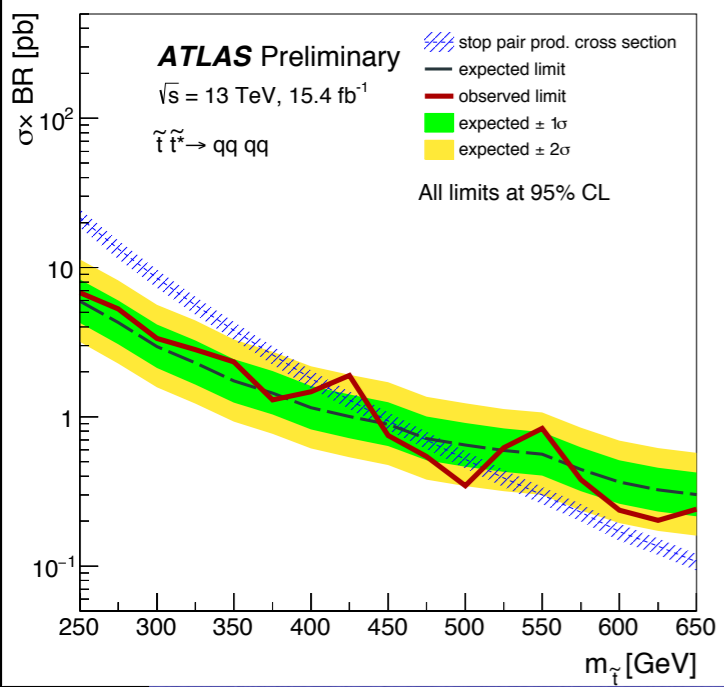
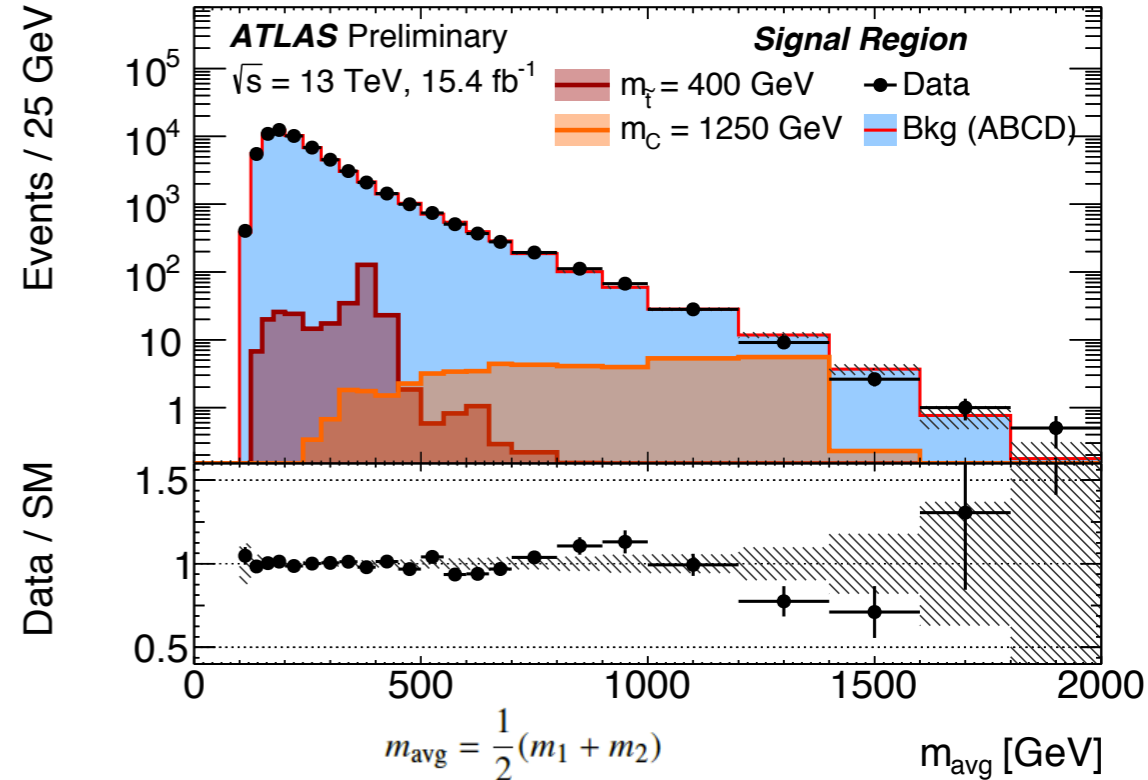
- An excited quark state with mass  $1.0 < M_q < 4.37$  TeV is excluded at 95% CL. The exclusion varies between 4.37 and 1.36 TeV based on the coupling.
- CMS Run II significantly extends the Run I limit

Hot off the press! ★★★★★

# Search for new physics in a four jet final state



$$W_{RPV} = \kappa_i L_i H_d + \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k$$



- Limits sets on the stop quark, decaying to 2 jets through an RPV coupling
- Mass limits: 250 to 405 GeV and from 445 to 510 GeV are excluded at 95% CL
- Coloron pair production also explored
- Excluded for masses between 250 and 1500 at 95% CL



# Search for microscopic black holes in a multijet final state

- In (3+1) dimensional universe the Planck Scale is much higher with respect to the electro-weak scale.
- n-flat extra dimensions are introduced in the ADD model to mitigate this hierarchy problem.
- The multi-dimensional Planck Scale is raised according to the following equation:

$$M_{pl}^2 = 8\pi M_D^{n+2} r^n$$

Apparent Planck Scale ( $10^{16}$ )

True Planck Scale 0(TeV)

number of extra dimensions	$r$
$n = 1$	$\sim 10^{12}$ m
$n = 2$	$\sim 10^{-3}$ m
$n = 3$	$\sim 10^{-8}$ m
$\vdots$	
$n = 6$	$\sim 10^{-11}$ m

- In models like Randall Sundrum (RS1), this new extra dimension is warped and the true Planck Scale is defined as a function of the warp factor (k) and radius (R):

$$M_D = \frac{M_{Pl}}{\sqrt{8\pi}} \exp(-\pi k R)$$

# Search for microscopic black holes in a multijet final state

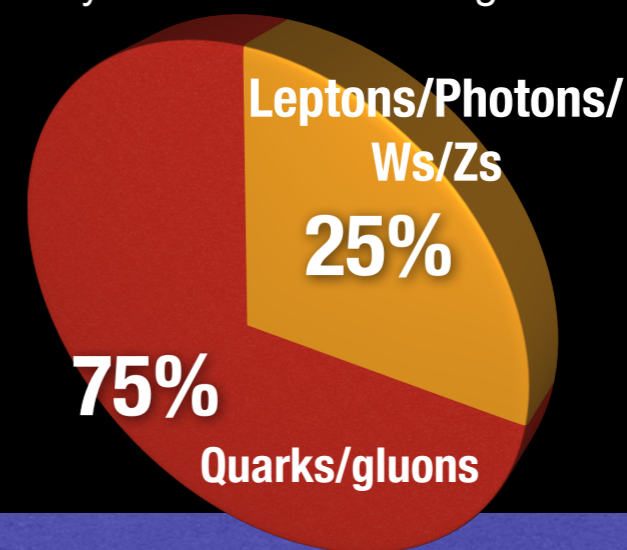
- Microscopic black holes, at energies greater than  $M_D$ , are produced when the impact parameter between two colliding particles is less than the Schwarzschild radius.
- The Schwarzschild radius of an  $n$ -dimensional black hole is given by:

$$r_S = \frac{1}{\sqrt{\pi M_D}} \left[ \frac{M_{BH}}{M_D} \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{\frac{1}{n+1}}$$

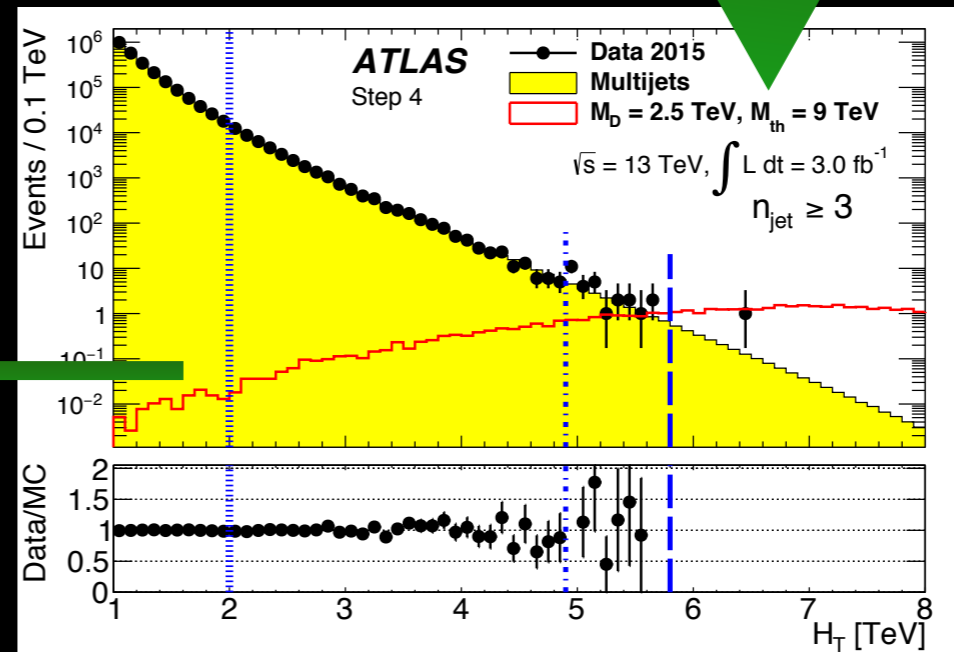
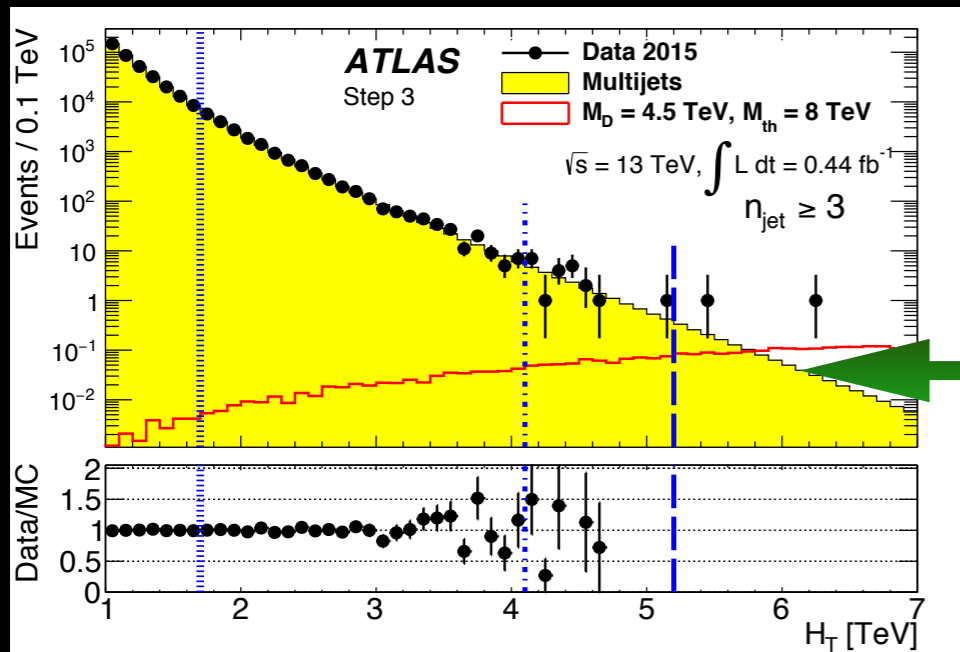
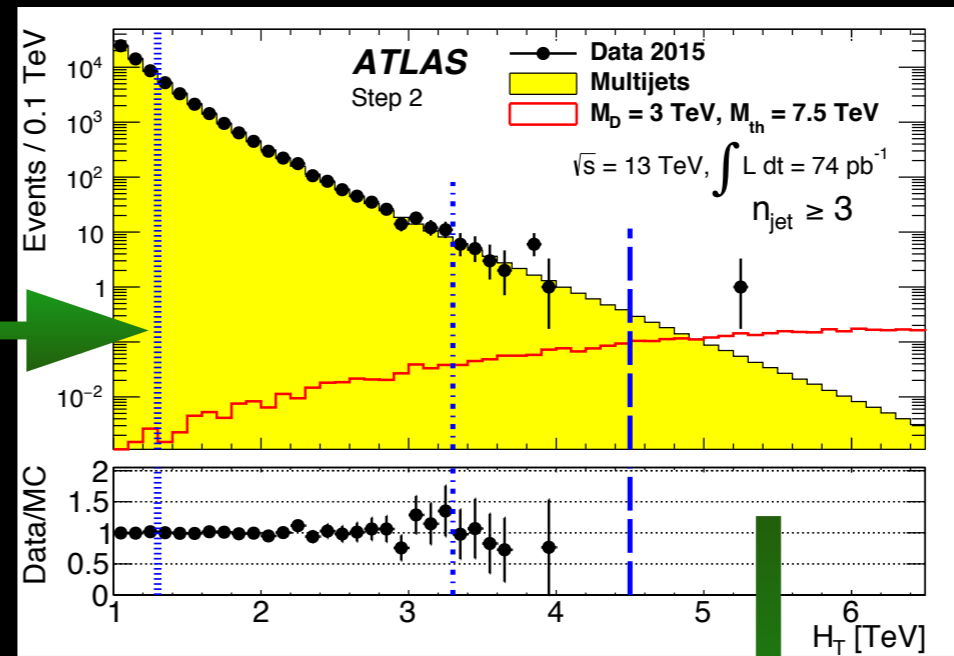
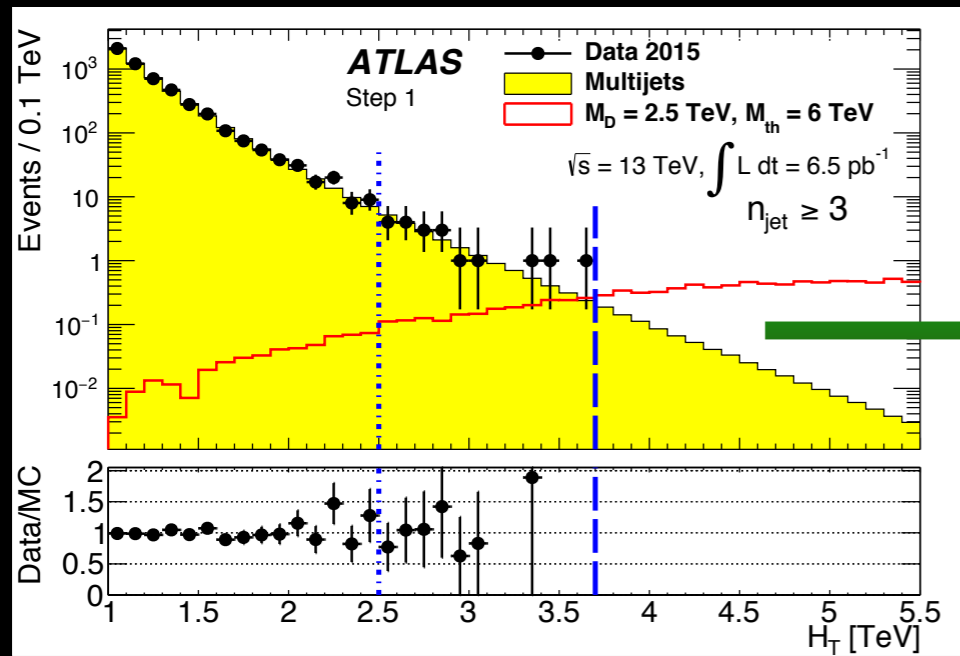
- Therefore, from semiclassical considerations, the cross section can be calculated as:

$$\sigma(M_{BH}) \approx \pi r_S^2$$

- Semi-classical black holes are shortlived (lifetime of  $10^{-27}$  s) and decay via thermal Hawking radiation.
- Microscopic black holes, decay democratically into in all Standard Model (SM) degrees of freedom
- The final state is composed of high transverse momenta objects
- This signature can be distinguished from the multijet background relatively easily



# Background Estimation: ATLAS



Use bootstrapping to compute background

Define control (C:  $H_T < V$ ), validation (V:  $V < H_T < S$ ) and signal ( $H_T > S$ ) regions



# Background Estimation: CMS

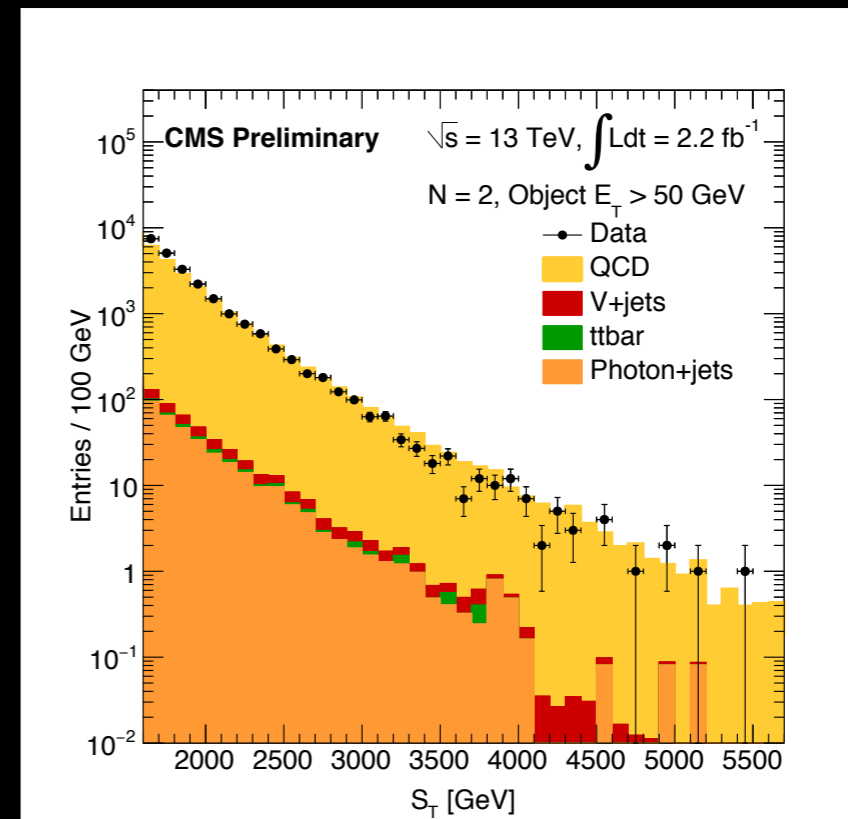
The background is estimated from data

The background is estimated in a signal depleted regime (multiplicity = 2)

ST shape invariance is checked over all multiplicities

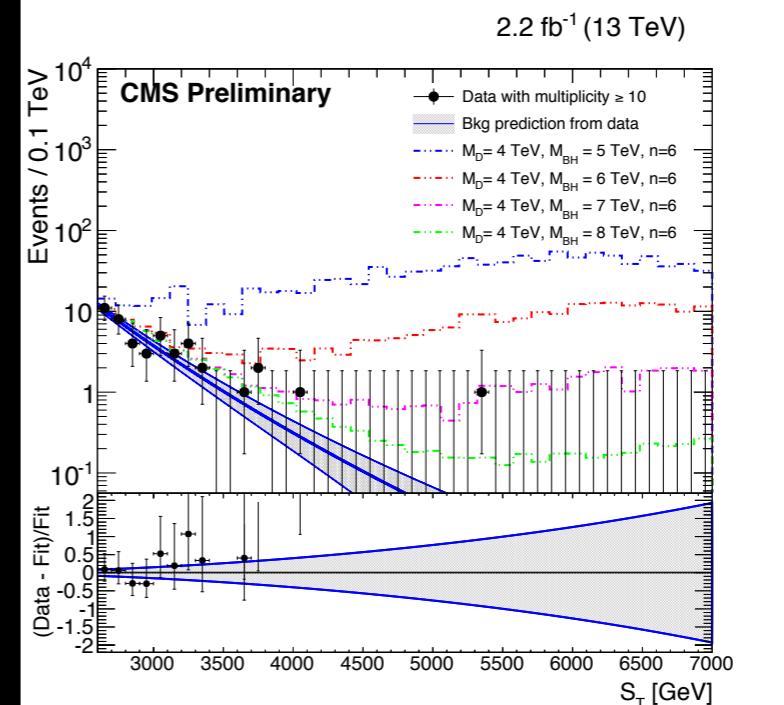
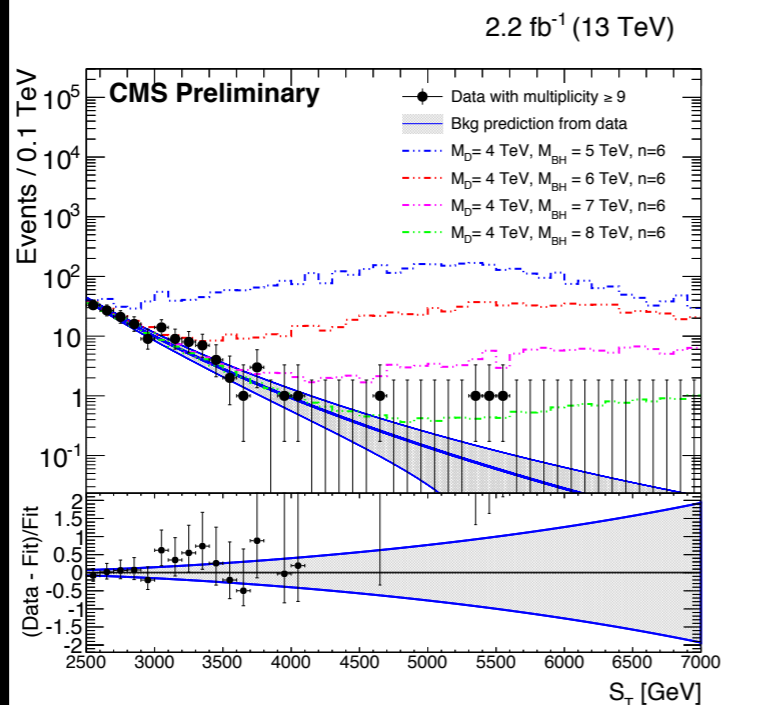
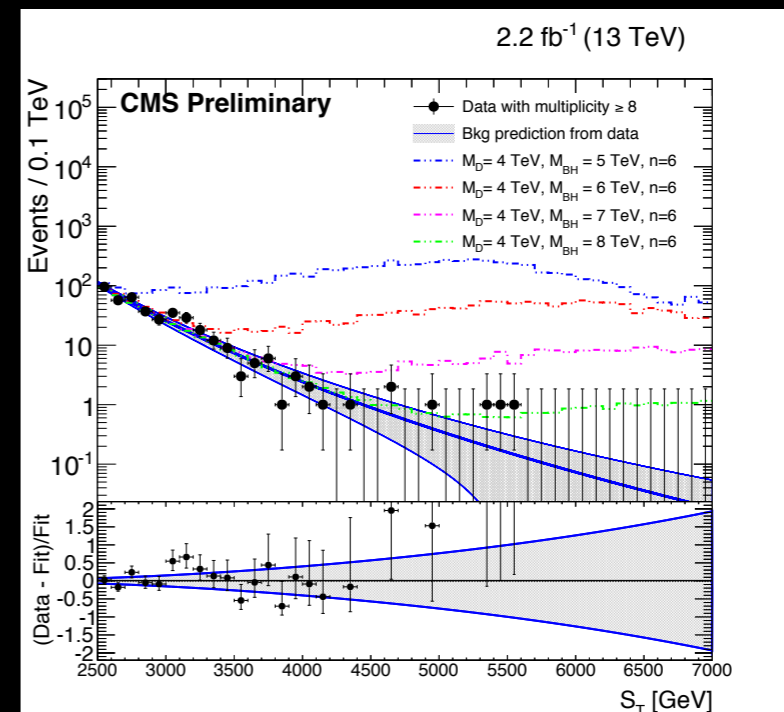
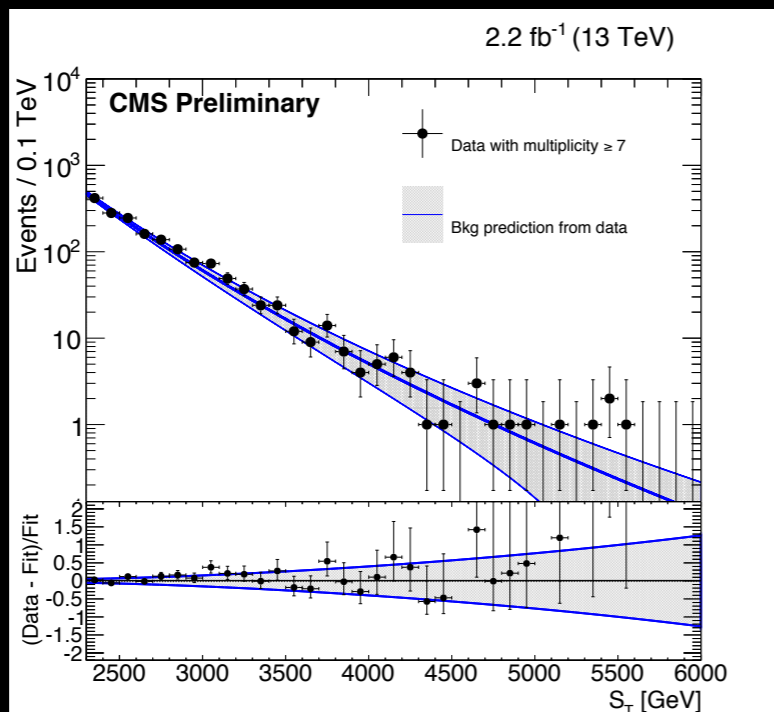
The background prediction from the multiplicity = 2 regime is applied to higher multiplicities by appropriate normalization in a region of low signal contamination

- Fitting range: 1400-2400 GeV
- Use 3-parameter function with multiplicity = 2 as the background template.

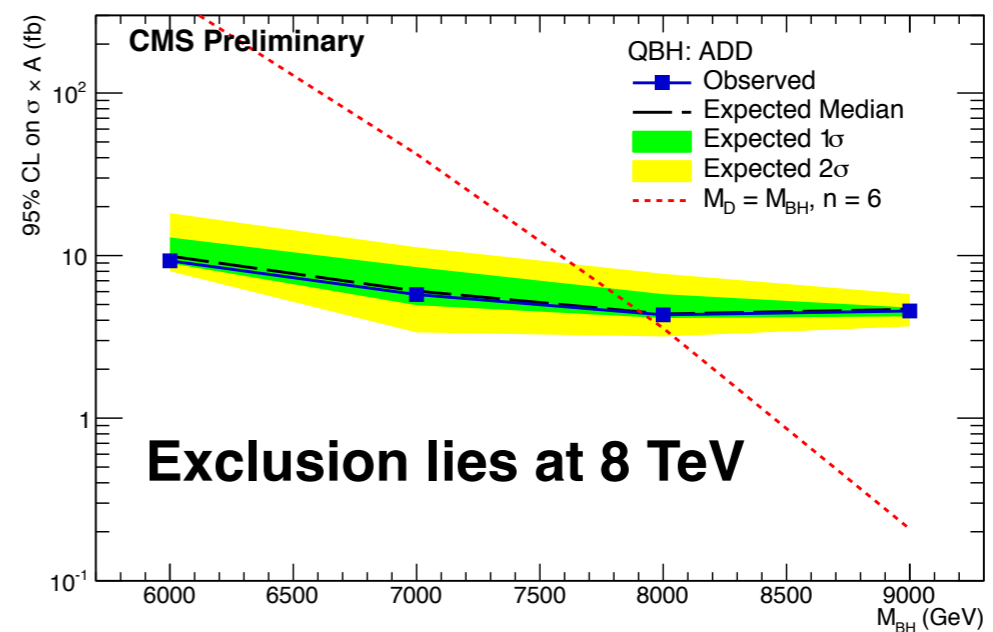
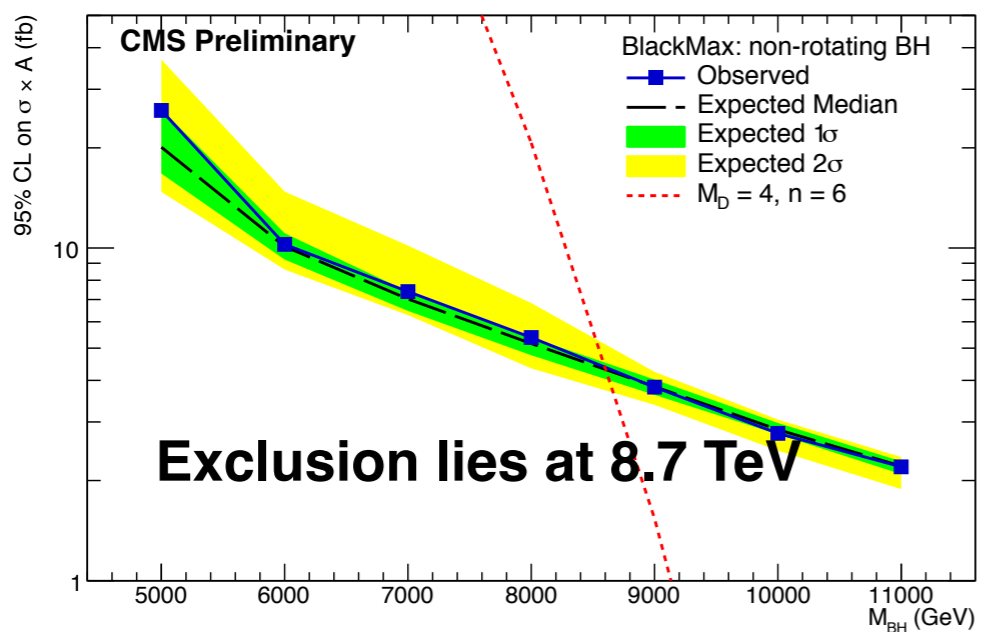
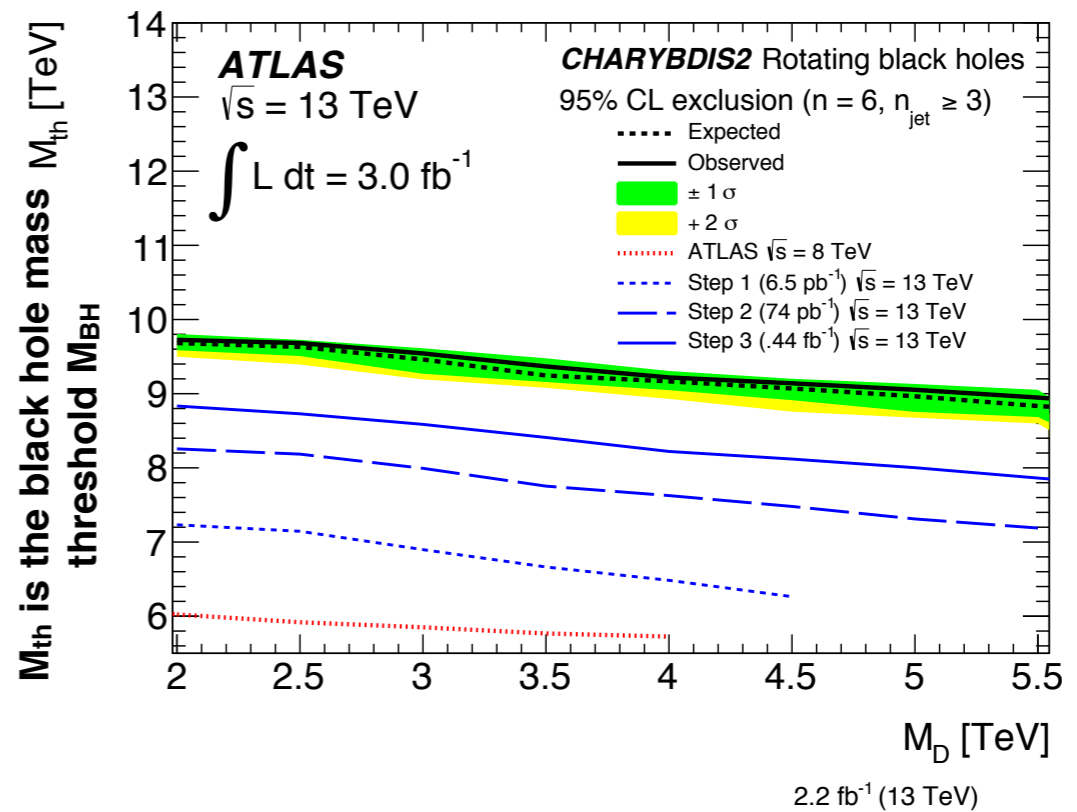
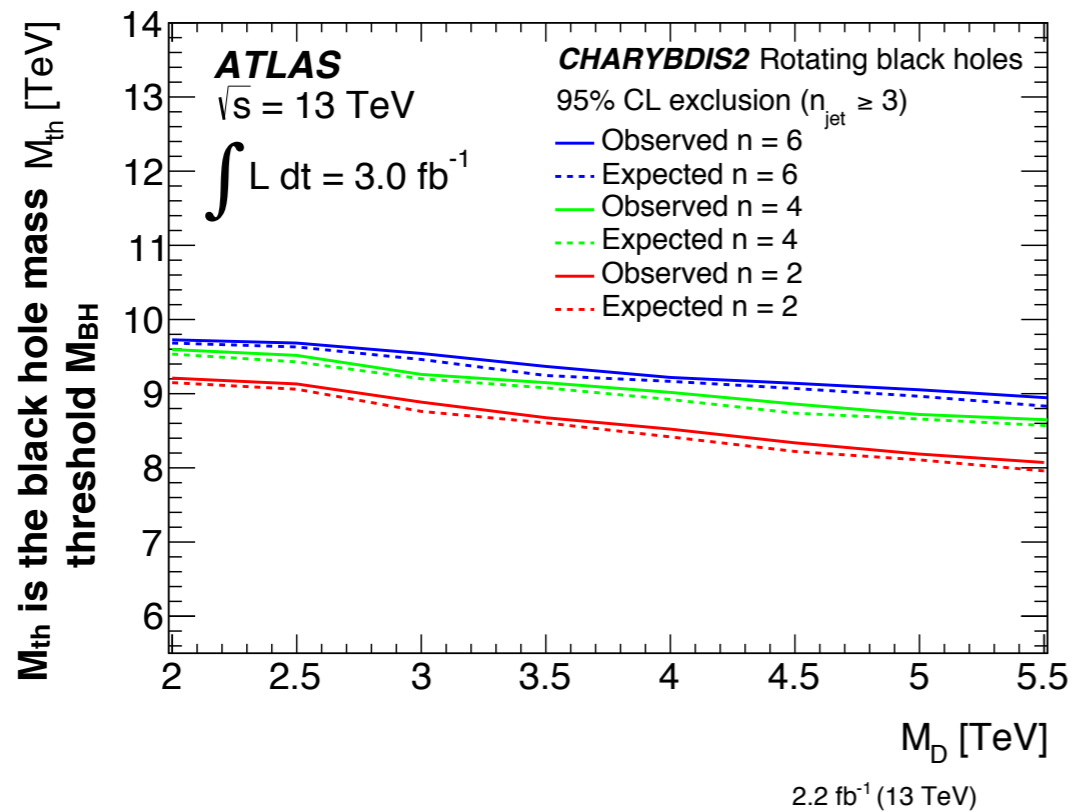


- Essentially one performs a counting experiment using the variable  $S_T$ , where  $S_T$  is defined as the **scalar sum of the transverse energy ( $E_T$ ) of jets, leptons and photons.  $ME_T$  is also added to  $S_T$  if  $ME_T > 50$  GeV**
- The **multiplicity** of an event is defined as the **number of jets + leptons + photons** in that event.  $ME_T$  is not counted as a separate object

# Background Estimation: CMS

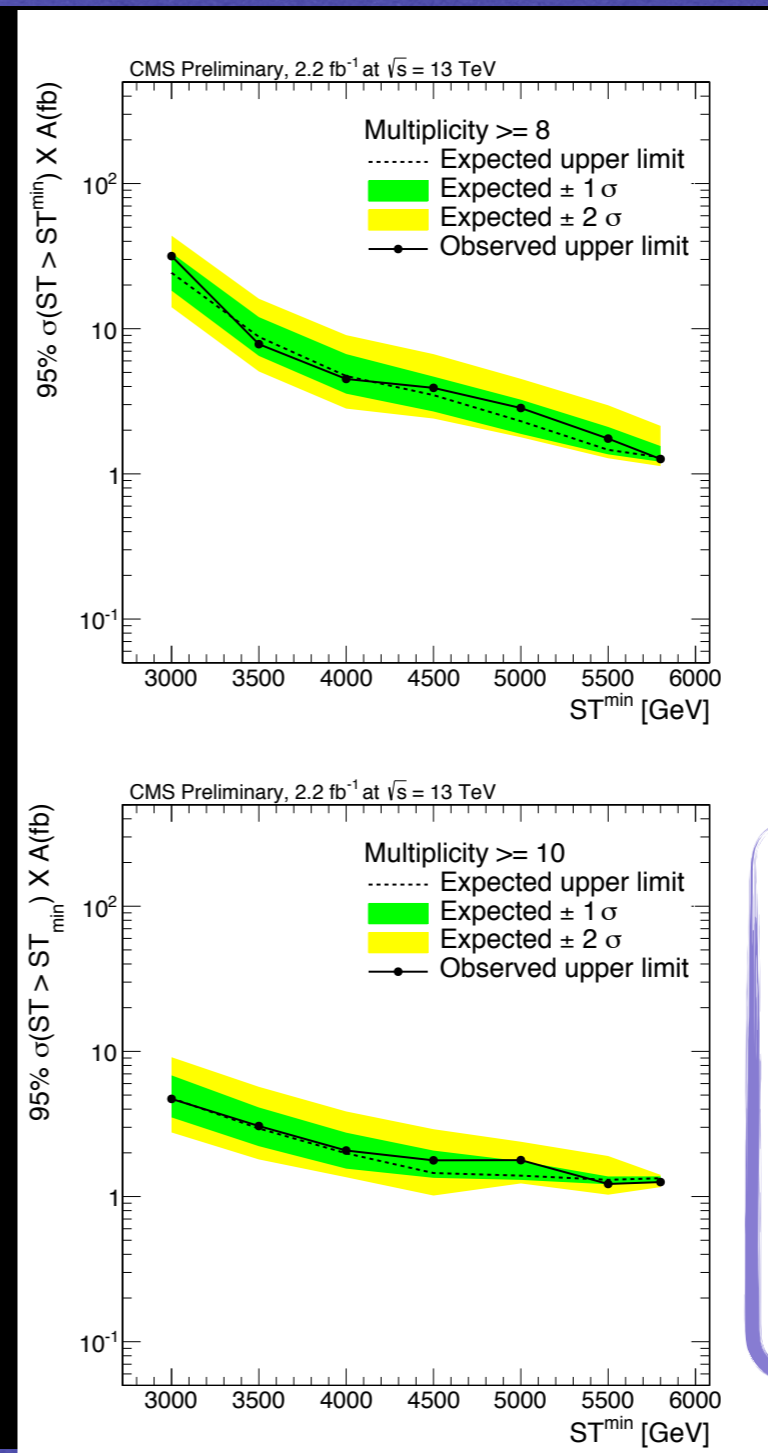
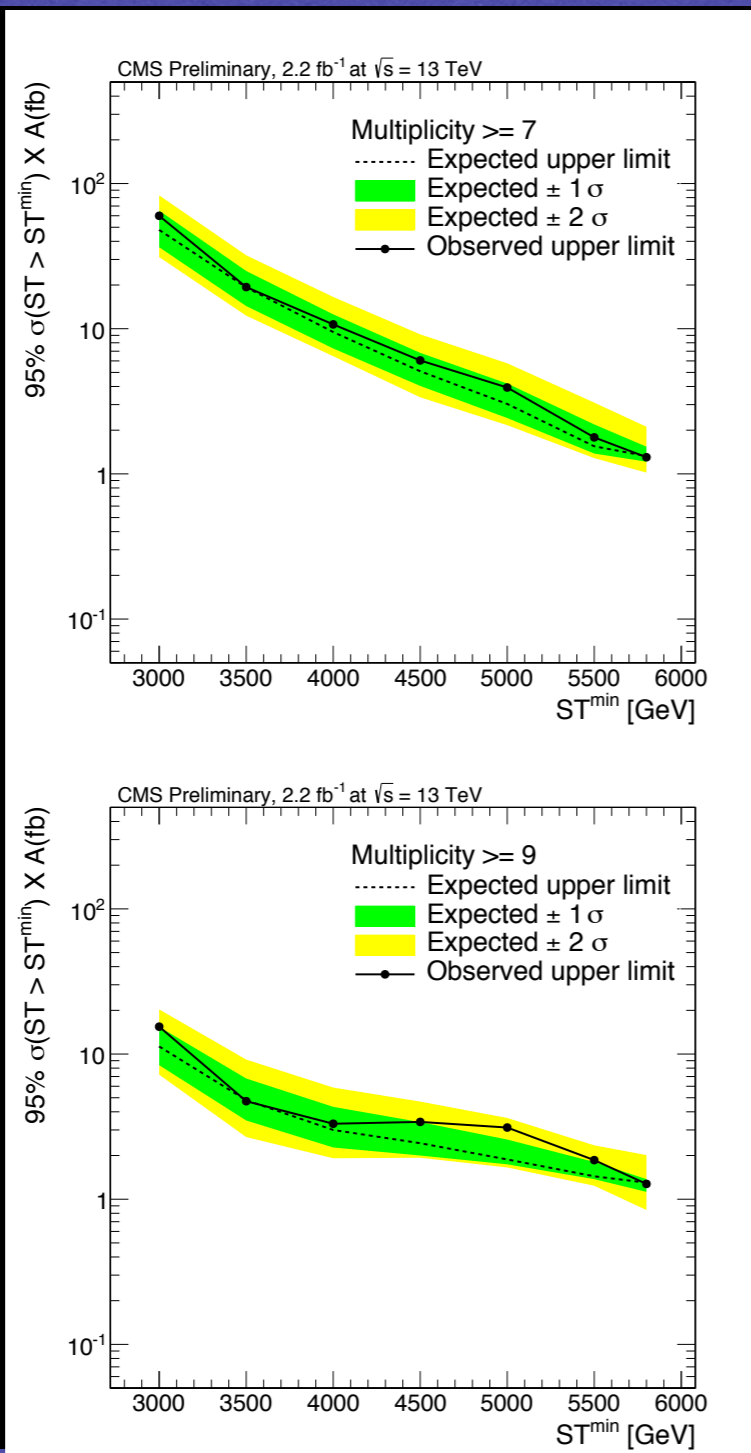


# Model dependent results





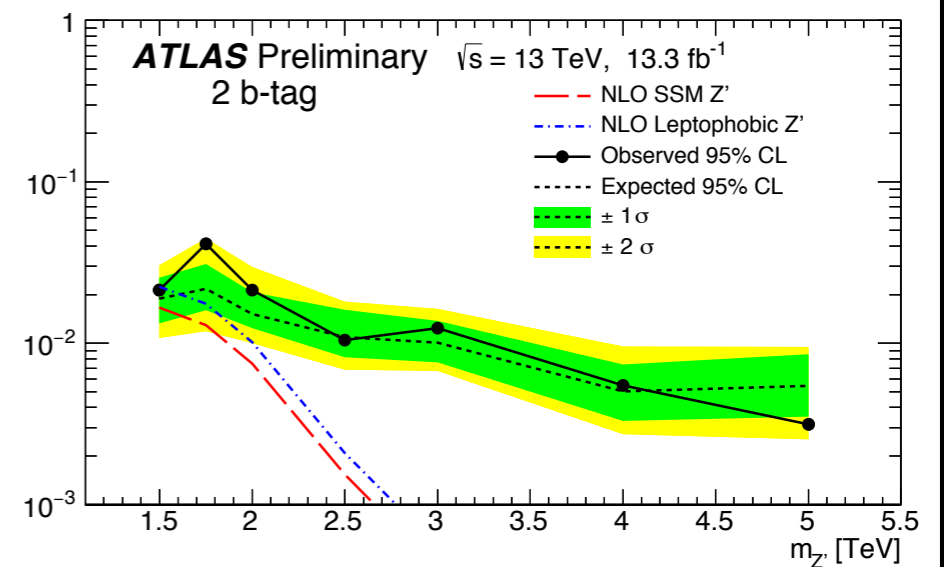
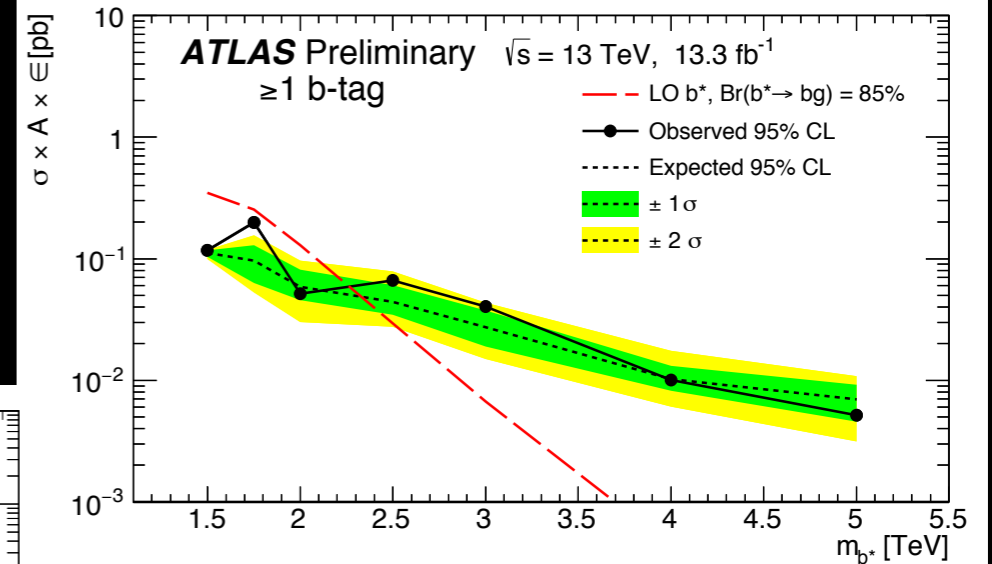
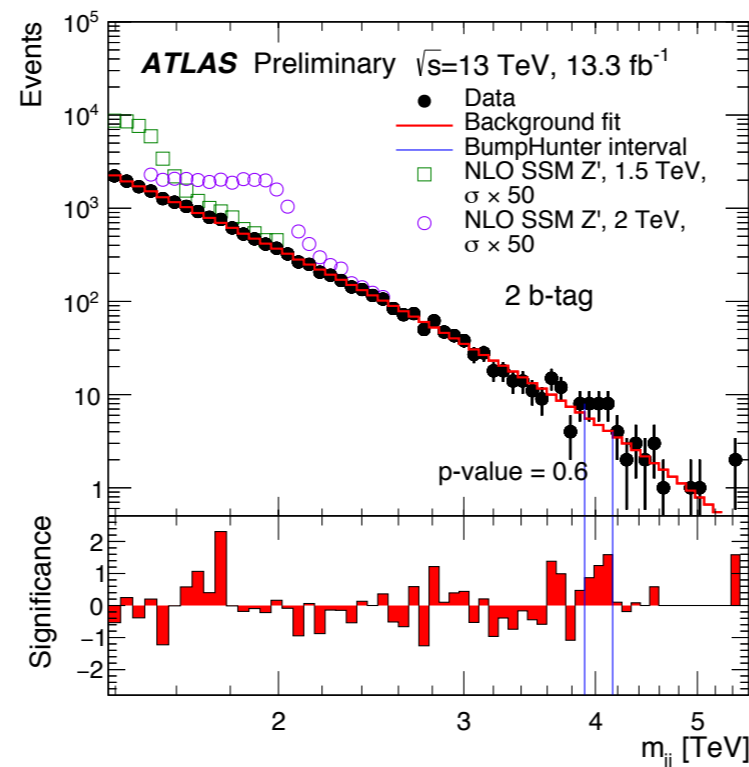
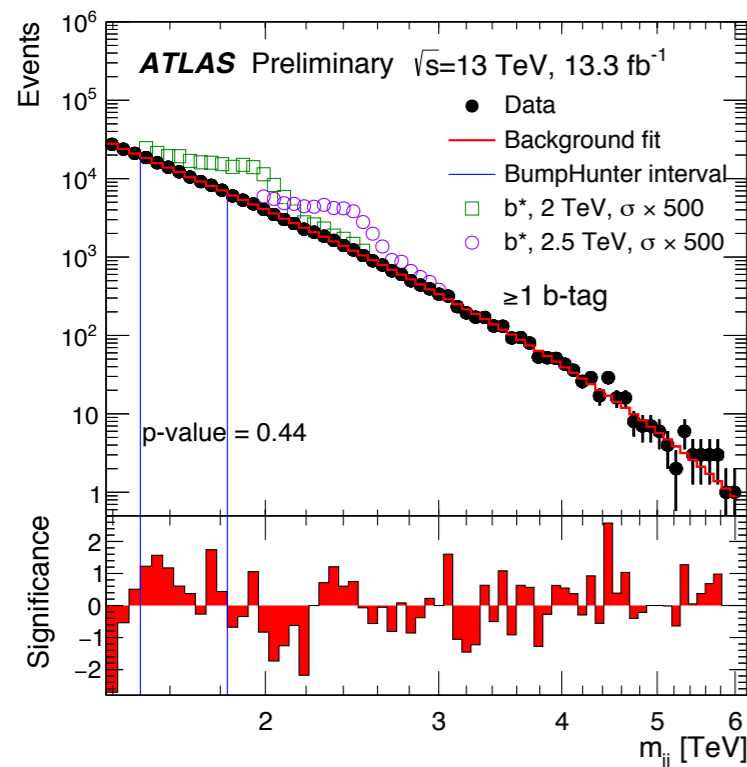
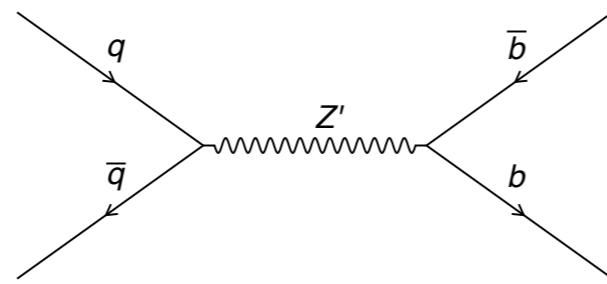
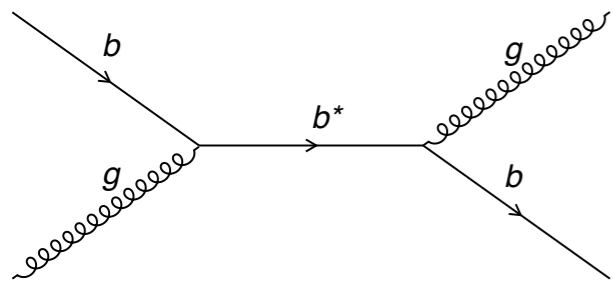
# Model independent result



Model independent limits can be applied to various models of NP

# Search for new physics with heavy flavor jets: ATLAS

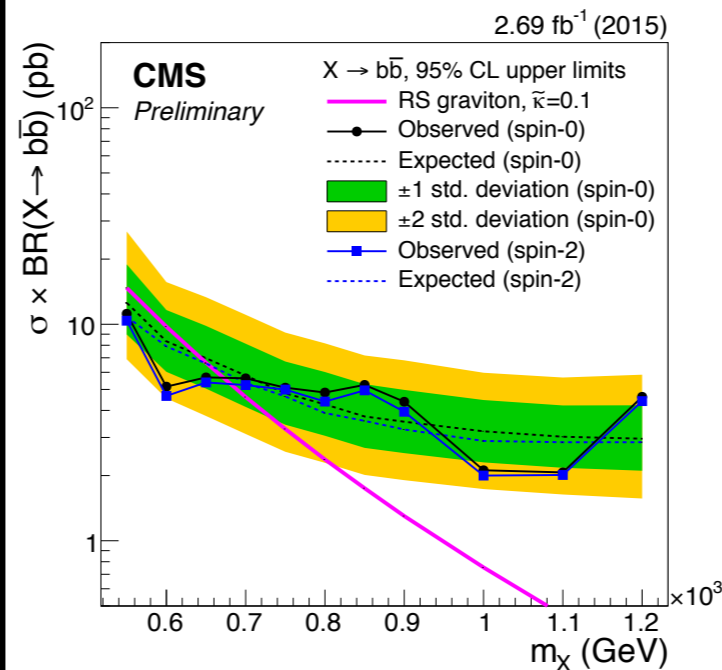
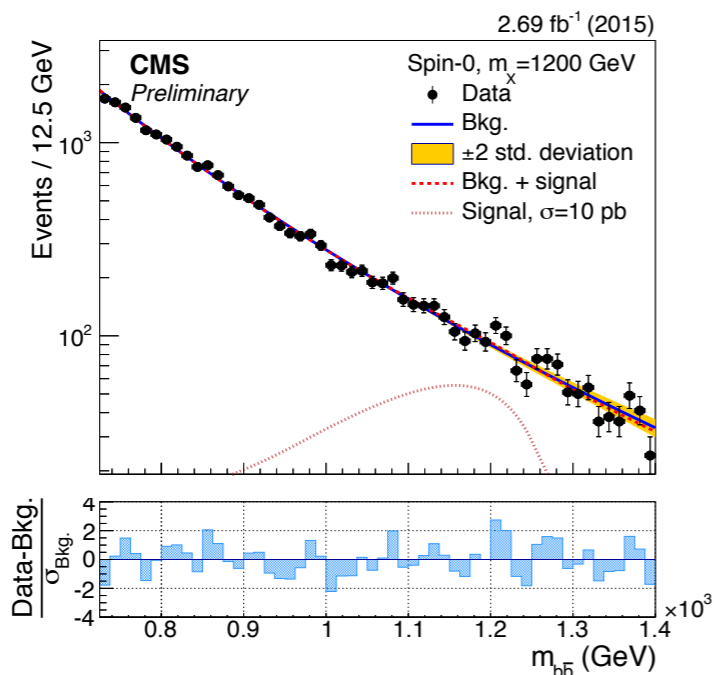
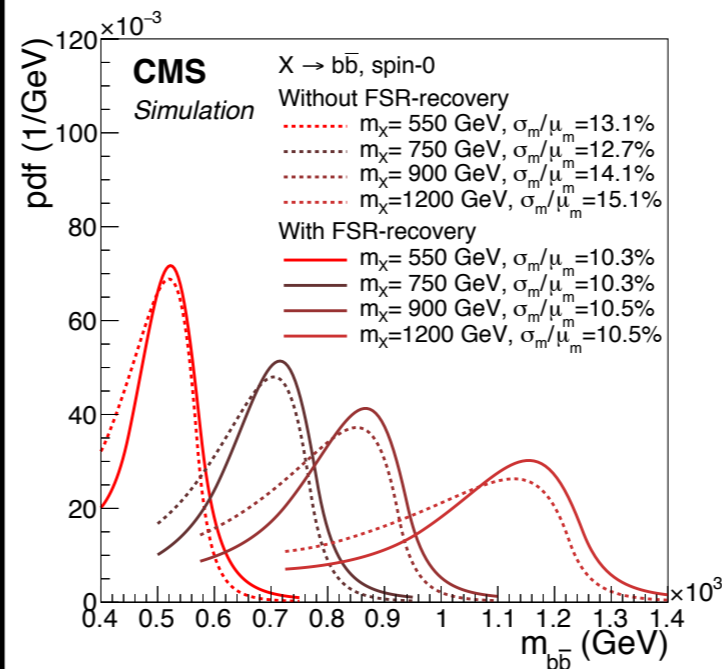
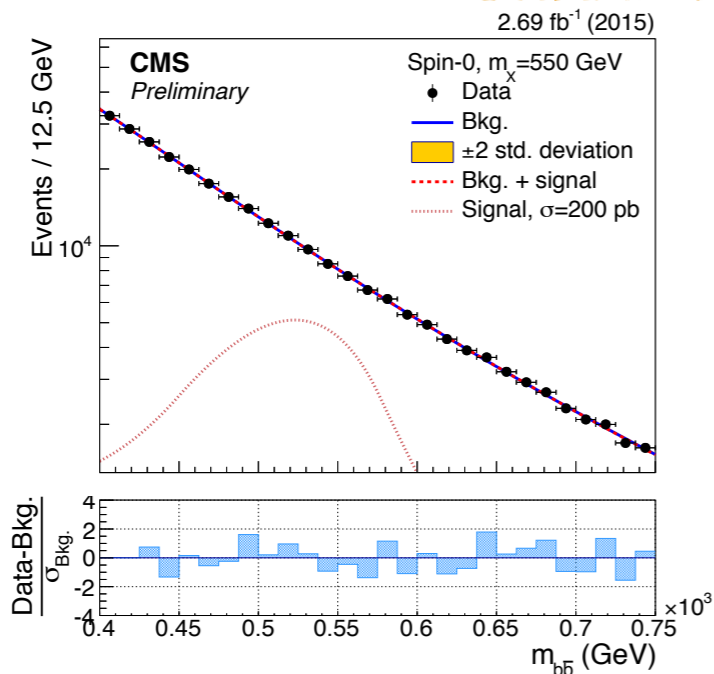
Hot off the press!



- Analysis sensitive to generic high-mass particles decaying to two jets that originate from one or two b-quarks
- Visible cross sections ranging from 0.2 to 0.001 pb in the mass range 1.4–5.5 TeV are excluded

# Search for new physics with heavy flavor jets: CMS

Hot off the press!



- No significant excess over the expectation from the background is observed.
- Limits on production cross sections times branching ratio are obtained for values of the resonance mass ranging from 550 to 1200~GeV.



# Summary

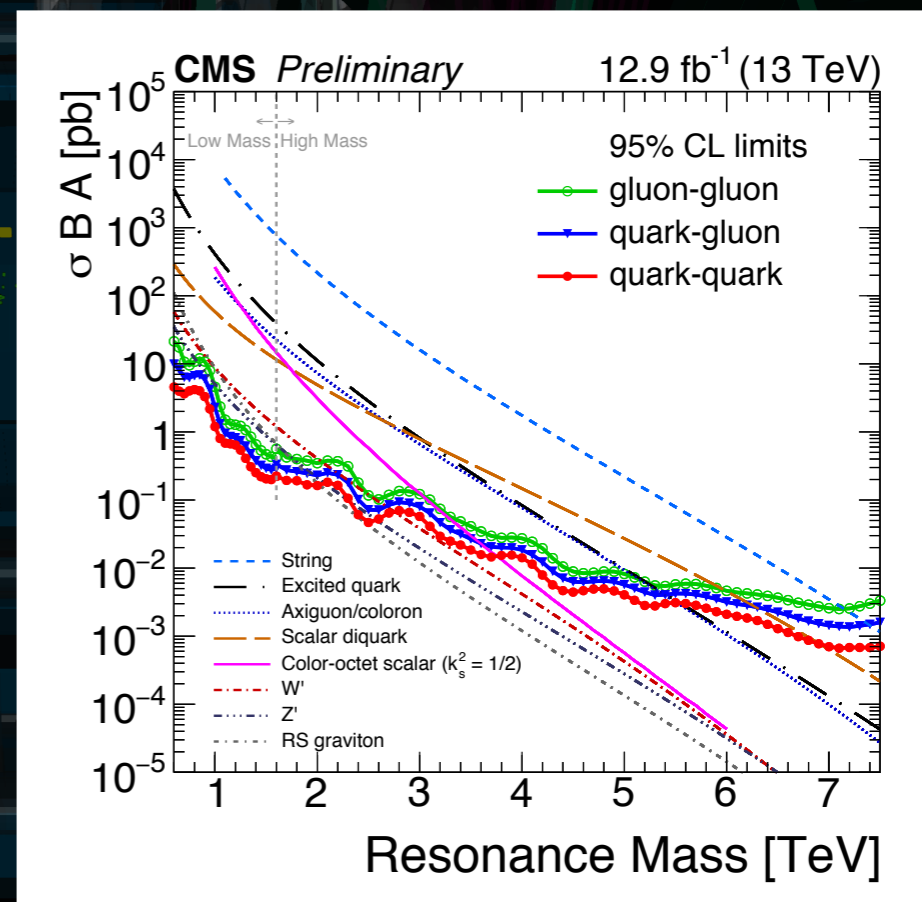
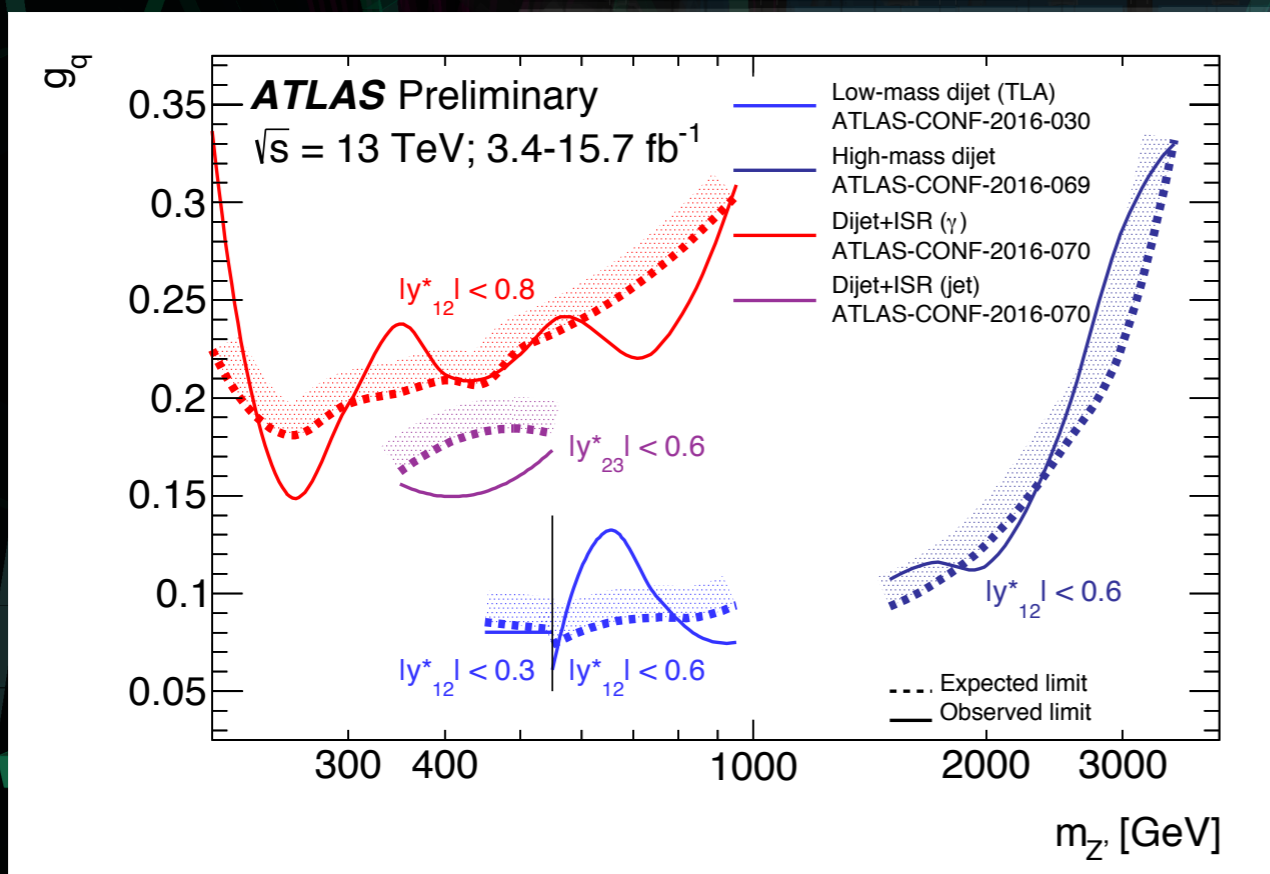


<http://atlas.ch>

Phenomenal work by analysts at ATLAS and CMS!

Run: 280673  
 Event: 1273922482  
 2015-09-29 15:32:53 CEST

Stay tuned for new results!



# Dijet and multijet searches in ATLAS

## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	$\ell, \gamma$	Jets†	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$\geq 1 j$	Yes	3.2	$M_D$ 6.58 TeV	$n = 2$ 1604.07773
	ADD non-resonant $\ell\ell$	$2 e, \mu$	-	20.3	$M_S$ 4.7 TeV	$n = 3$ HLZ 1407.2410
	ADD QBH $\rightarrow g$	$1 j$	-	20.3	$M_{\text{BH}}$ 5.9 TeV	1511.2986
	ADD QBH	$2 j$	-	15.7	$M_{\text{th}}$ 8.7 TeV	$n = 6$ ATLAS-CONF-2016-069
	ADD BH high $\Sigma p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH 1606.02265
	ADD BH multijet	-	$\geq 3 j$	-	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2 e, \mu$	-	-	$G_{KK}$ mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	$G_{KK}$ mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$ 1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 e, \mu$	$1 J$	Yes	$G_{KK}$ mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$ ATLAS-CONF-2016-062
	Bulk BS $G_{KK} \rightarrow HH \rightarrow bbb$	-	$4 b$	-	$G_{KK}$ mass 360-860 GeV	ATLAS-CONF-2016-019
Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	$g_{KK}$ mass 2.2 TeV	$BR = 0.925$ 1505.07018	
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 4 j$	Yes	KK mass 1.46 TeV	Tier (1,1), $BR(A^{(1,1)} \rightarrow tt) = 1$ ATLAS-CONF-2016-013	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	13.3	$Z'$ mass 1.95 TeV	ATLAS-CONF-2016-015
	SSM $Z' \rightarrow \tau\tau$	$2 \tau$	-	19.5	$Z'$ mass 2.02 TeV	1502.07177
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	$Z'$ mass 1.5 TeV	1603.08791
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	$1 j$	Yes	$W'$ mass 2.4 TeV	$g_V = 1$ ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0 e, \mu$	$1 J$	Yes	$W'$ mass 3.0 TeV	$g_V = 3$ ATLAS-CONF-2016-055
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	-	$2 J$	-	$V'$ mass 2.31 TeV	$g_V = 3$ 1607.05621
HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	$W'$ mass 1.92 TeV	1410.4103	
LRSM $W'_R \rightarrow tb$	$1 e, \mu$	$2 b, 0-1 j$	Yes	$W'$ mass 1.76 TeV	1408.0886	
LRSM $W'_R \rightarrow tb$	$0 e, \mu$	$\geq 1 b, 1 J$	-	$W'$ mass 1.76 TeV		
CI	CI $qqqq$	-	$2 j$	-	$\Lambda$ 19.9 TeV $\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	$2 e, \mu$	-	-	$\Lambda$ 25.2 TeV $\eta_{LL} = -1$	1607.03669
	CI $uutt$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	$\Lambda$ 4.9 TeV $ C_{RR}  = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1 j$	Yes	$m_A$ 1.0 TeV	$g_q=0.25, g_\gamma=1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$1 j$	Yes	$m_A$ 710 GeV	$g_q=0.25, g_\gamma=1.0, m(\chi) < 150 \text{ GeV}$ 1604.01306
	ZZ $\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	$M_\chi$ 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	-	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	T mass 855 GeV	T in (T,B) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
	VLQ $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu$	$\geq 2/\geq 1 b$	-	B mass 755 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4 j$	Yes	Q mass 690 GeV	1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	$2(SS)/\geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	$T_{5/3}$ mass 990 GeV	ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	$q^*$ mass 4.4 TeV	only $b^*$ and $d^*$ , $\Lambda = m(q^*)$ 1512.05910
	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	$q^*$ mass 5.6 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	$b^*$ mass 2.3 TeV	ATLAS-CONF-2016-060
	Excited quark $h^* \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1 b, 2-0 j$	Yes	$h^*$ mass 1.5 TeV	$f = f, f = 1$ 1512.02222
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921	
Other	LSTC $a_\tau \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	$a_\tau$ mass 960 GeV	1407.8150
	LRSM Majorana $\nu$	$2 e, \mu$	$2 j$	-	$N^0$ mass 2.0 TeV	$m(W_R) = 2.4 \text{ TeV}$ , no mixing DY production, $BR(H_i^{\pm\pm} \rightarrow ee)=1$ 1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	$2 e$ (SS)	-	-	$H^{\pm\pm}$ mass 570 GeV	DY production, $BR(H_i^{\pm\pm} \rightarrow \ell\tau)=1$ ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	$H^{\pm\pm}$ mass 400 GeV	1411.2921
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
	Multi-charged particles	-	-	-	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$ 1504.04188
Magnetic monopoles	-	-	-	monopole mass 1.34 TeV	DY production, $ g  = 1g_D$ , spin 1/2 1509.08059	

Multijet and dijet

qiles  
Dijet and heavy flavor dijet

qiles

Dijet and heavy flavor dijet

qiles

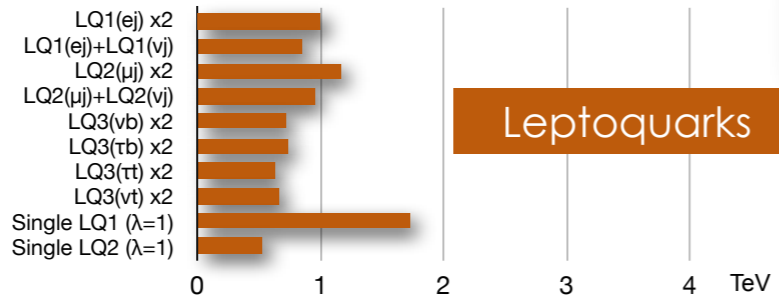
Photon + jet

\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

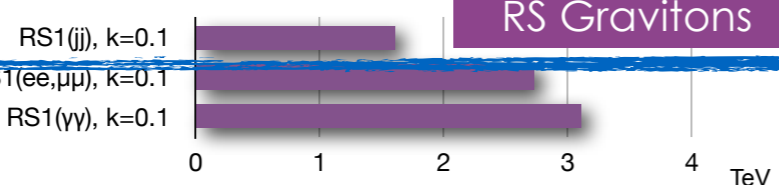
†Small-radius (large-radius) jets are denoted by the letter j (J).

# Dijet and multijet searches in CMS

**Dijet**

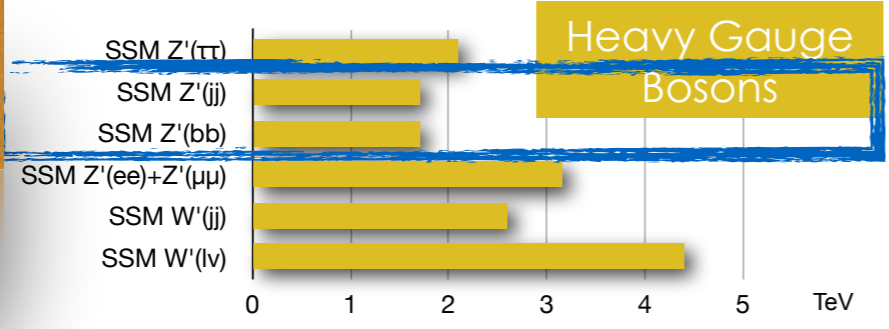


**Leptoquarks**

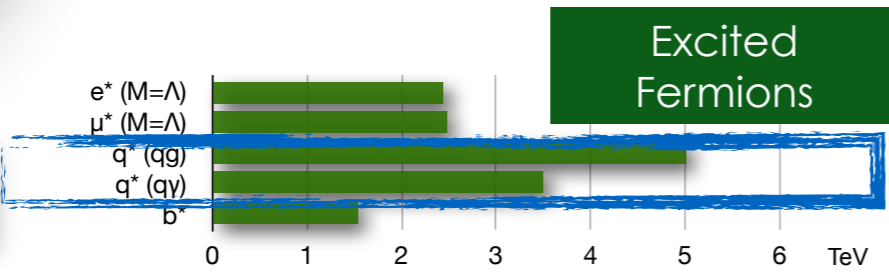


**RS Gravitons**

## CMS Preliminary

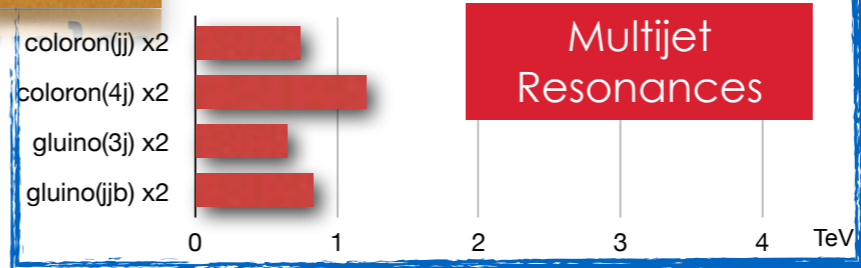


**Heavy Gauge Bosons**

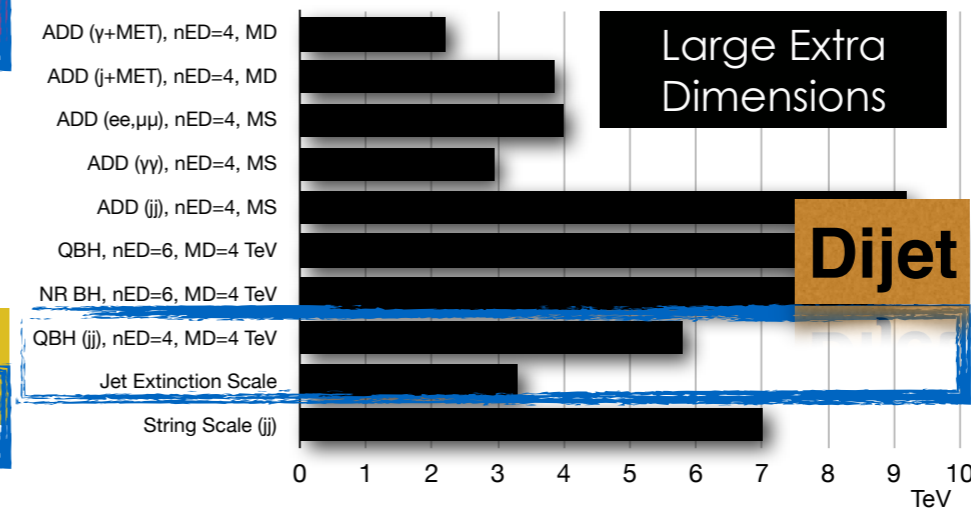


**Excited Fermions**

**Multijet**

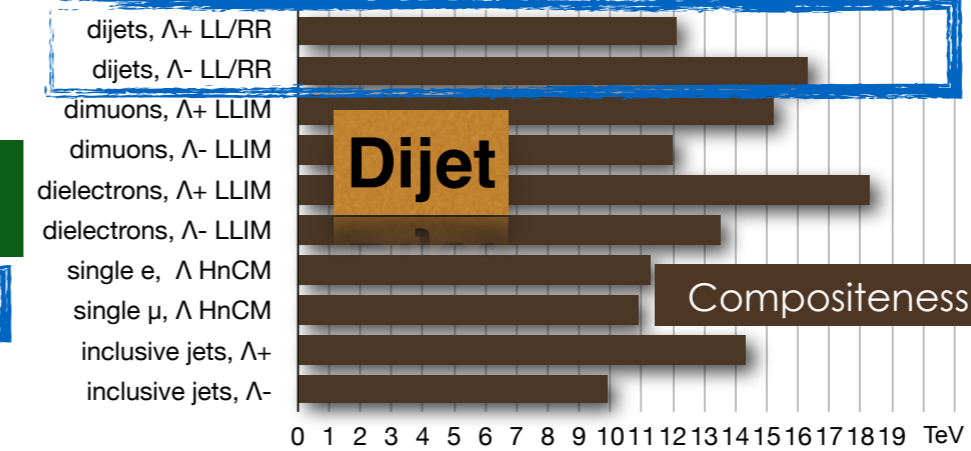


**Multijet Resonances**



**Large Extra Dimensions**

**Dijet**



**Dijet**

**Compositeness**

**Dijet and heavy flavor jets**

**Dijet and Photon + Jet**



# References: ATLAS

- **Search for TeV-scale gravity signatures in high-mass final states with leptons and jets with the ATLAS detector at  $\sqrt{s} = 13$  TeV (arxiv:1606.02265; PLB 760 (2016) 520-537)**
- **Search for new phenomena in dijet mass and angular distributions from pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector (arxiv:1512.01530; PLB 754 (2016) 302-322)**
- **Search for light dijet resonances with the ATLAS detector using a Trigger-object Level Analysis in LHC pp collisions at  $\sqrt{s}=13$  TeV (ATLAS-CONF-2016-030)**
- **Search for new light resonances decaying to jet pairs and produced in association with a photon in proton-proton collisions at  $\sqrt{s}=13$  TeV with the ATLAS detector (ATLAS-CONF-2016-029)**
- **Search for resonances below 1.2 TeV from the mass distribution of b-jet pairs in proton-proton collisions at  $\sqrt{s}=13$  TeV with the ATLAS detector (ATLAS-CONF-2016-060)**

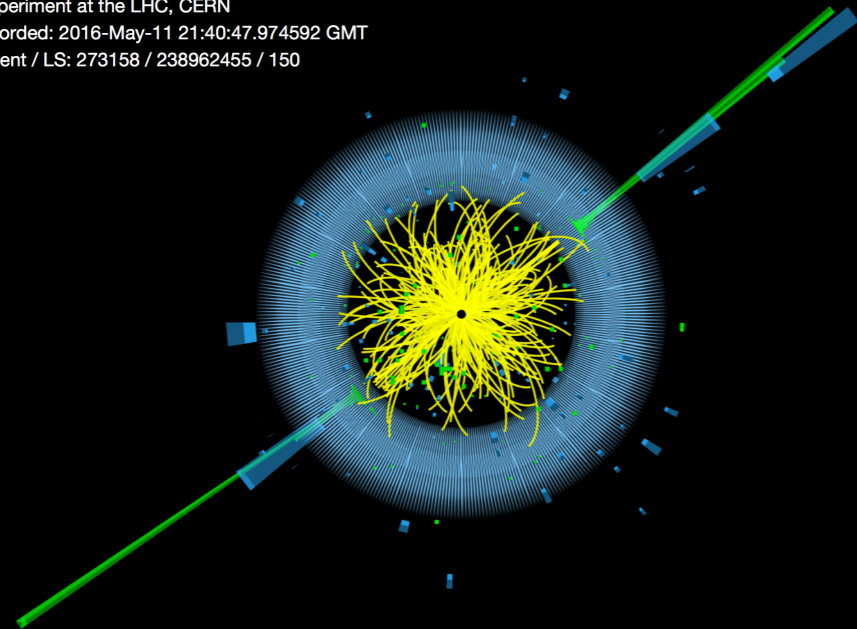
# References: CMS

- **Search for light vector resonances decaying to quarks at 13 TeV (EXO-16-030)**  
<https://cds.cern.ch/record/2202715?ln=en>
- **Search for high-mass resonances in dijet final state with 2016 data (EXO-16-032)**  
<http://cds.cern.ch/record/2205150?ln=en>
- **Search for excited quarks in photon jet final state (EXO-16-015)**  
<http://cds.cern.ch/record/2204915?ln=en>
- **Search for Black Holes with Early Run 2 Data (EXO-15-007)**  
<http://cds.cern.ch/record/2116453?ln=en>
- **Search for a narrow heavy decaying to bottom quark pairs in the 13 TeV data sample (HIG-16-025)**  
<http://cds.cern.ch/record/2204928?ln=en>

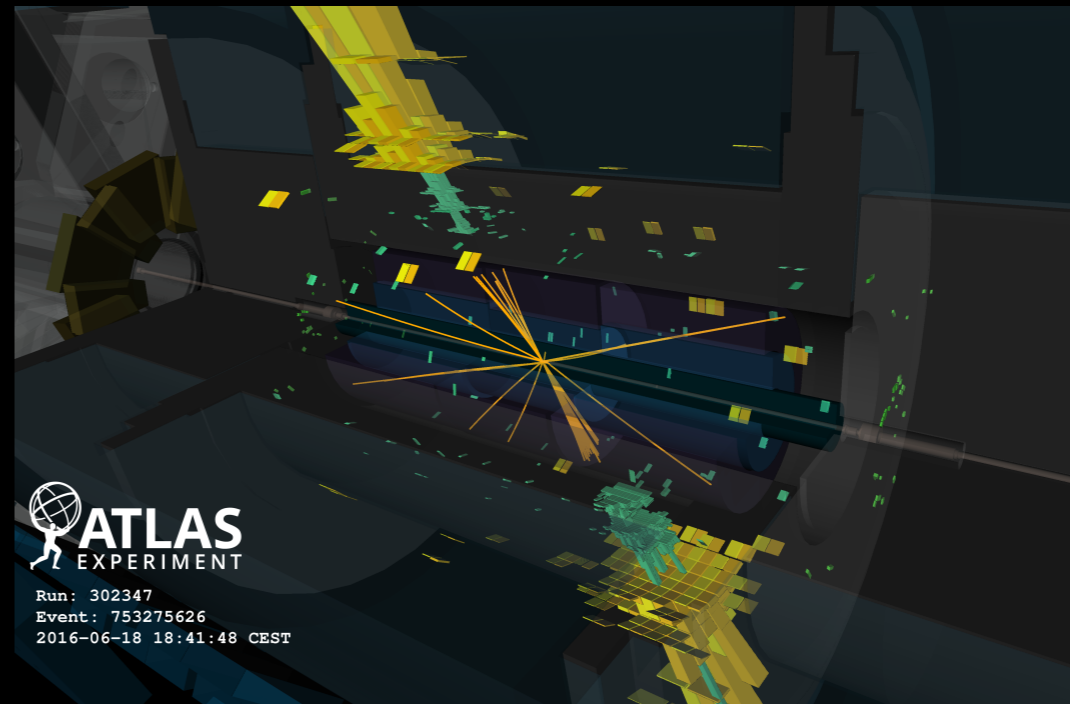
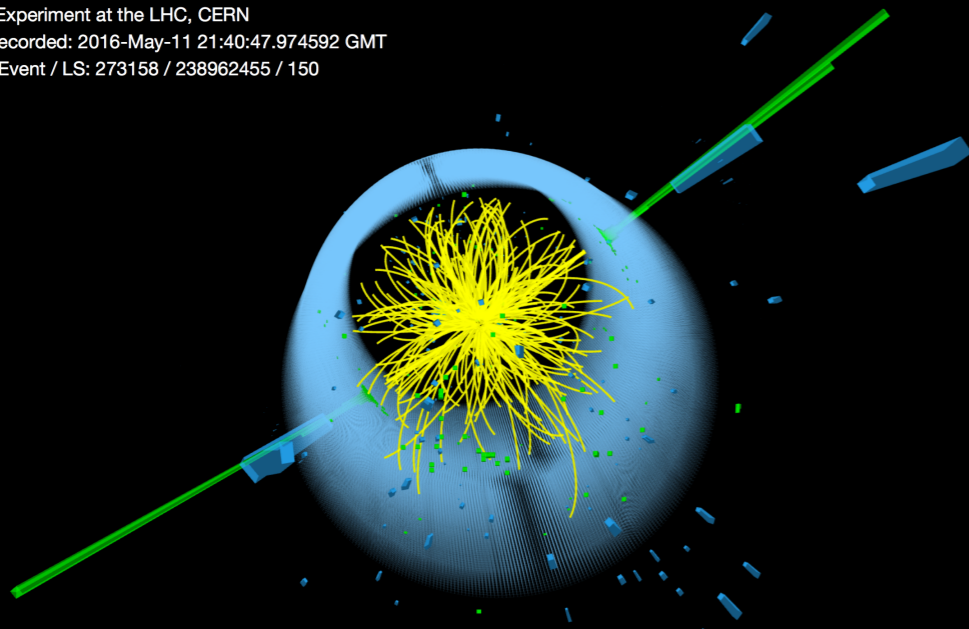
# Event displays of dijet events!



CMS Experiment at the LHC, CERN  
Data recorded: 2016-May-11 21:40:47.974592 GMT  
Run / Event / LS: 273158 / 238962455 / 150

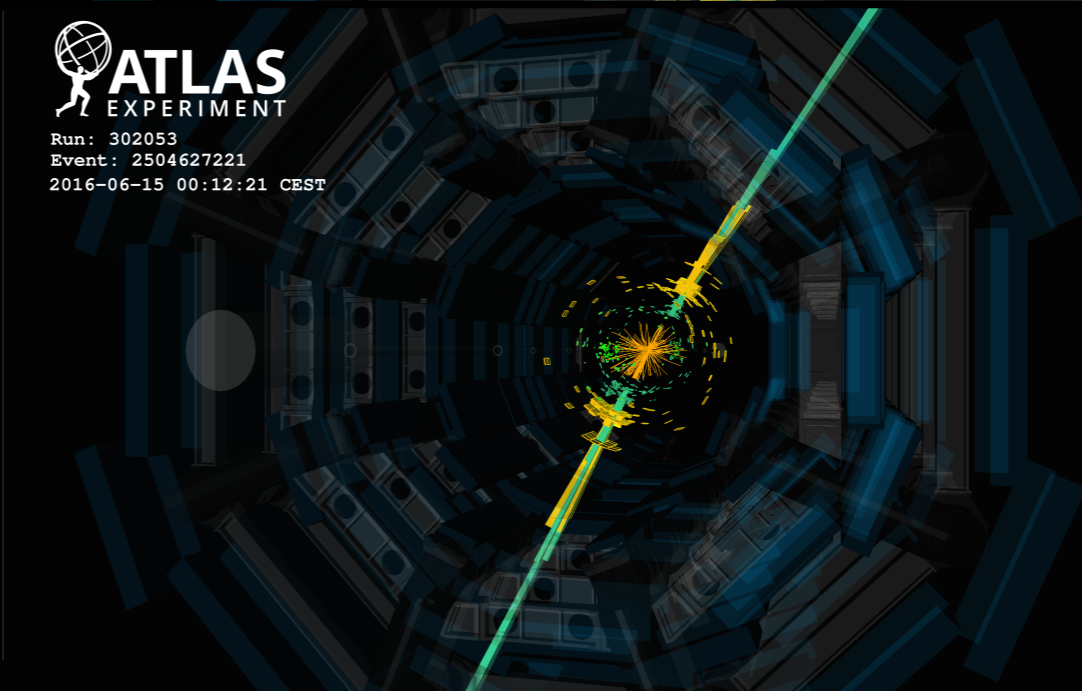


CMS Experiment at the LHC, CERN  
Data recorded: 2016-May-11 21:40:47.974592 GMT  
Run / Event / LS: 273158 / 238962455 / 150



**ATLAS**  
EXPERIMENT

Run: 302053  
Event: 2504627221  
2016-06-15 00:12:21 CEST

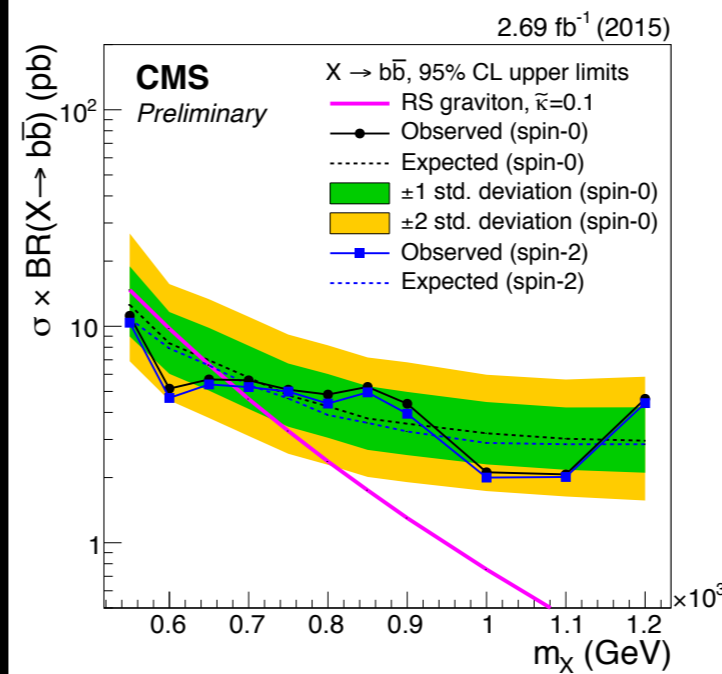
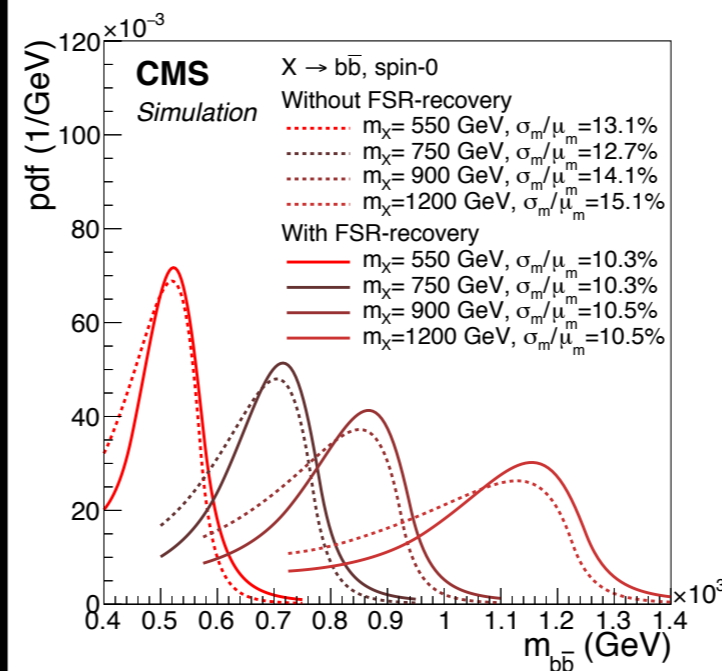
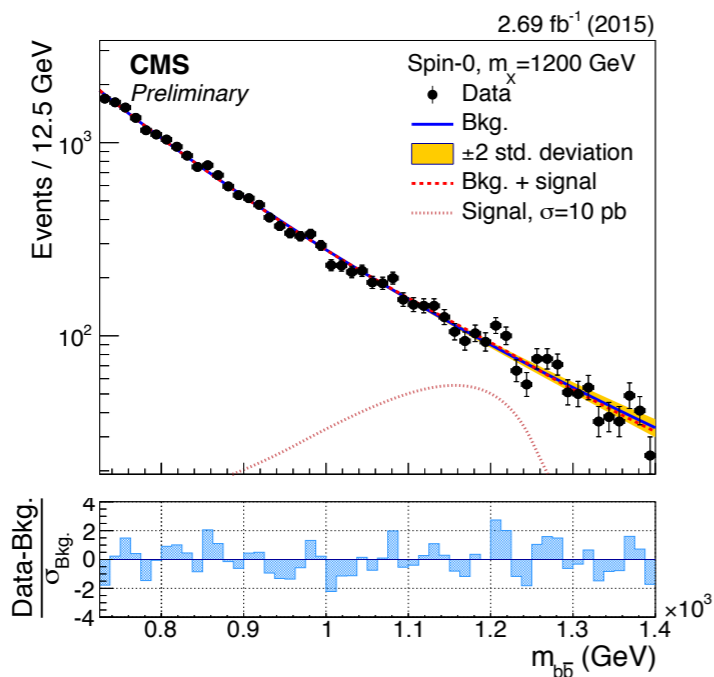
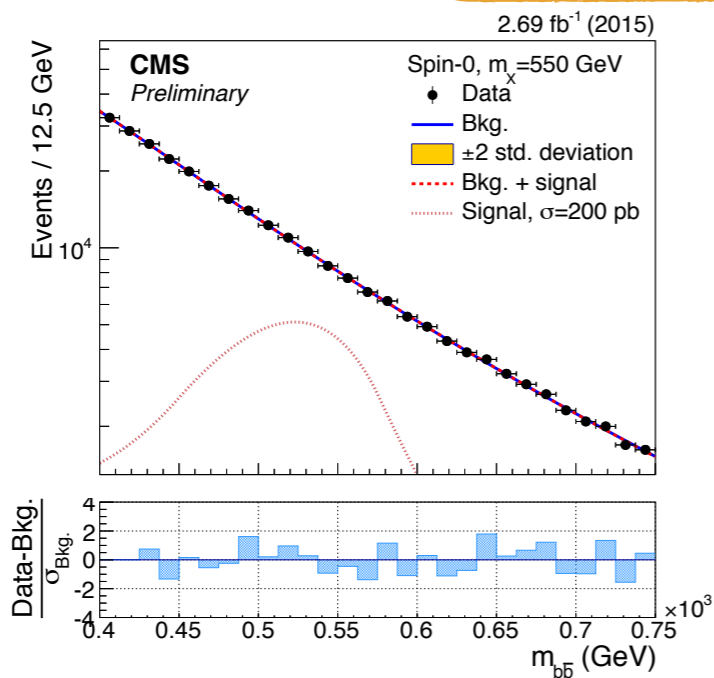


# Additional Material



# Search for new physics with heavy flavor jets: CMS

Hot off the press!



- No significant excess over the expectation from the background is observed.
- Limits on production cross sections times branching ratio are obtained for values of the resonance mass ranging from 550 to 1200~GeV.

# Dark Matter Interpretation

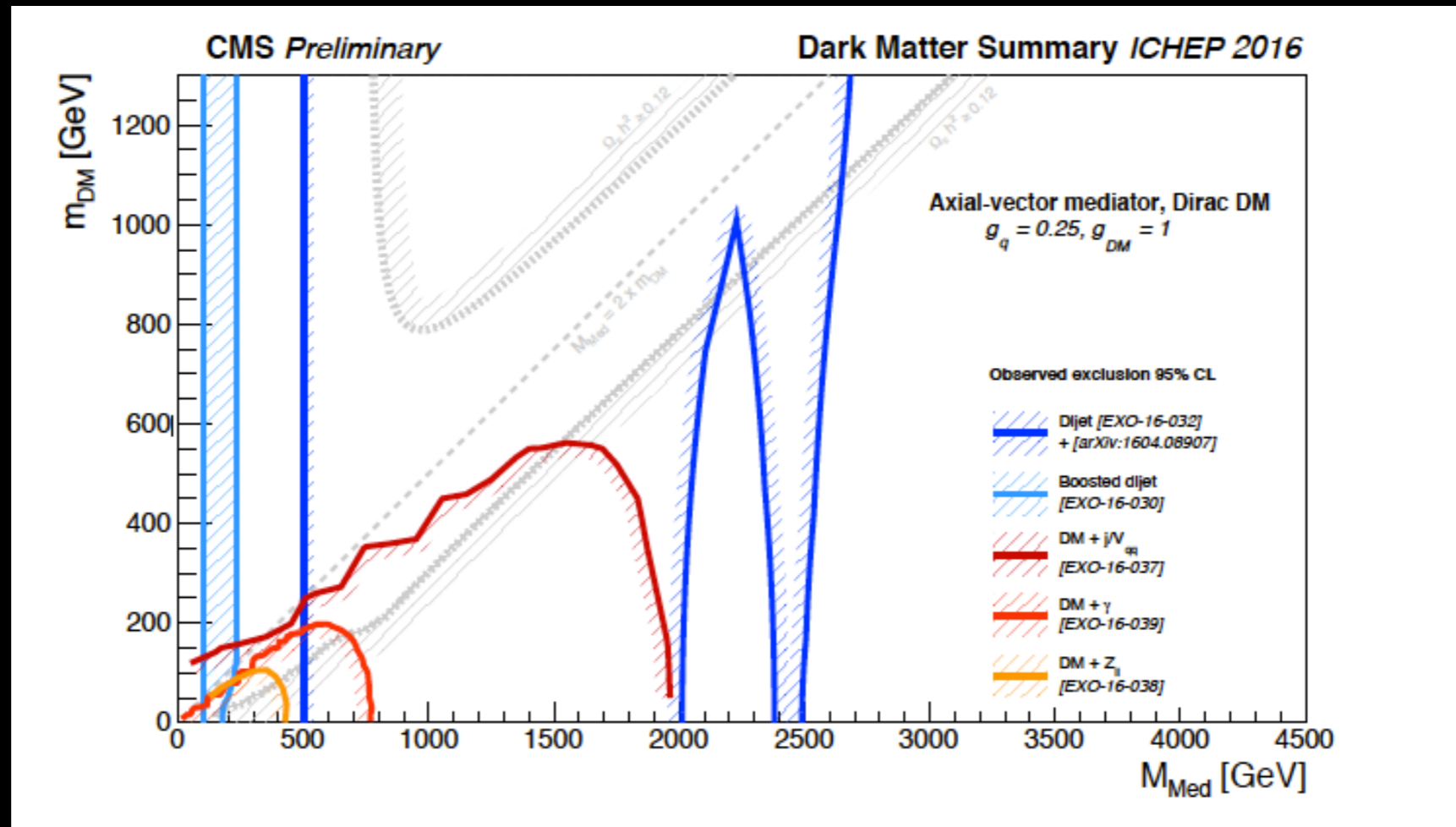


Figure 1. 95% CL exclusion regions in  $M_{\text{med}} - m_{\text{DM}}$  plane for di-jet searches and different  $E_T$  based DM searches from CMS in the leptophobic Axial Vector model. Following the recommendation of the LHC DM working group [1, 2], the exclusions are computed for a universal quark coupling  $g_q = 0.25$  and for a DM coupling of  $g_{\text{DM}} = 1.0$ . It should also be noted that the absolute exclusion of the different searches as well as their relative importance, will strongly depend on the chosen coupling and model scenario. Therefore, the exclusion regions, relic density contours, and unitarity curve shown in this plot are not applicable to other choices of coupling values or model.

# Dark Matter Interpretation

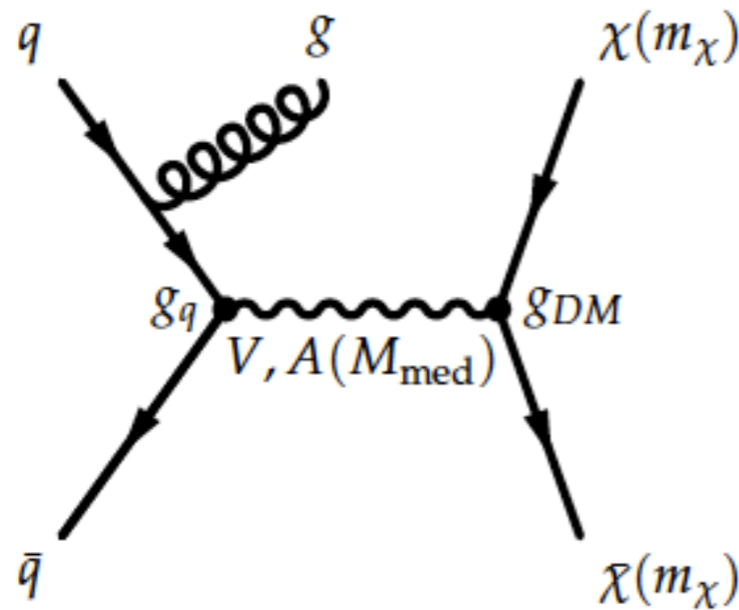


Figure 2.1: Representative Feynman diagram showing the pair production of Dark Matter particles in association with a parton from the initial state via a vector or axial-vector mediator. The cross section and kinematics depend upon the mediator and Dark Matter masses, and the mediator couplings to Dark Matter and quarks respectively:  $(M_{\text{med}}, m_{\chi}, g_{\chi}, g_q)$ .

$$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi \quad (2.1)$$

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi. \quad (2.2)$$

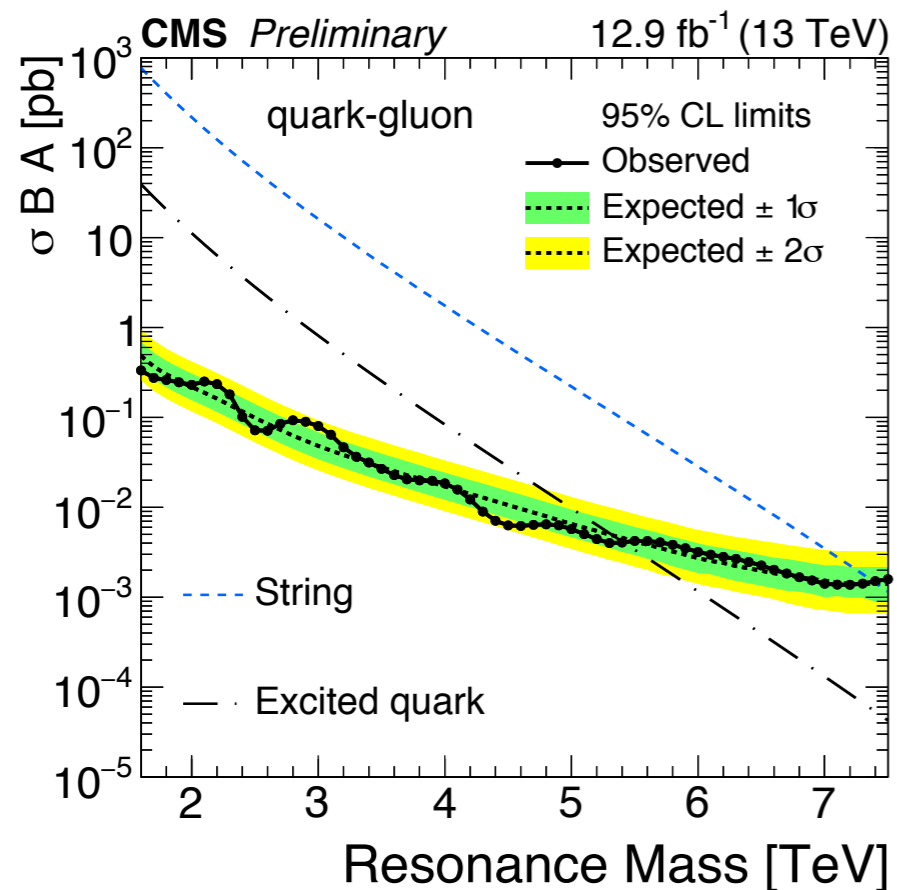
<https://arxiv.org/abs/1507.00966>

# Organization of additional material

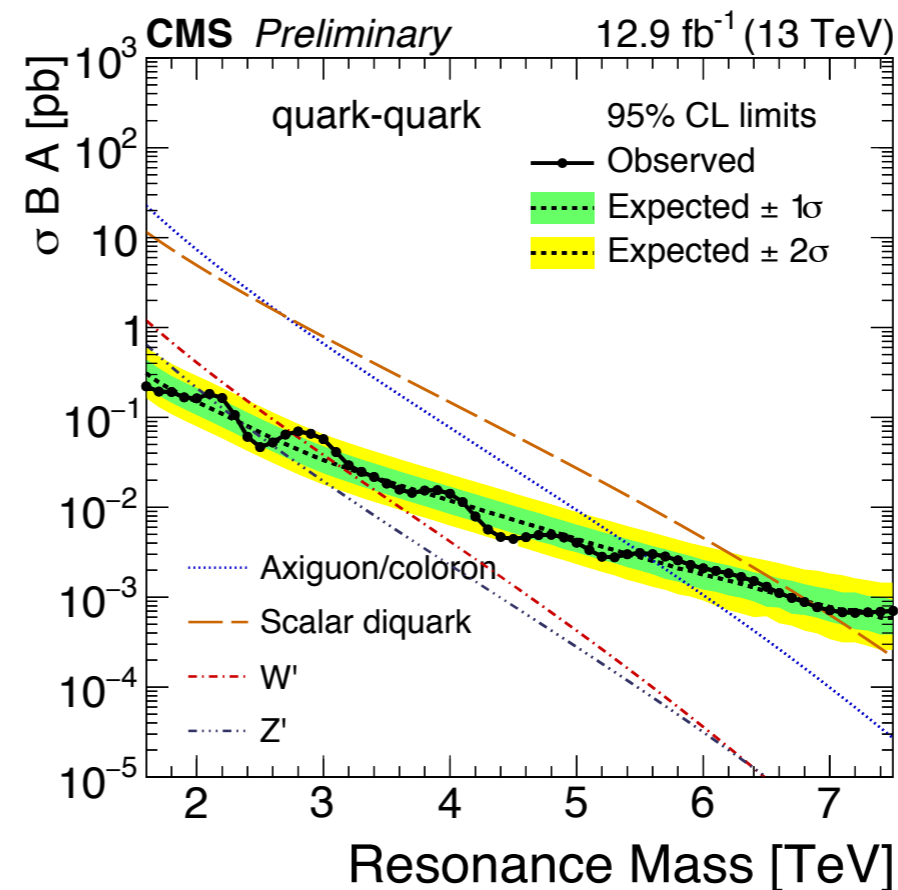
- **High mass dijet studies: Slide 25-26**
- **Low mass dijet studies: Slide 27-28**
- **Event display for dijet events: Slide 29**
- **Low mass search using jet substructure technique: Slide 30-32**
- **Trigger level searches: Slide 33**
- **Excited quarks: Slide 34-36**
- **Search for microscopic black holes: 37-41**
- **ATLAS searches: 42-45 (more material will be added)**



# Additional Material: High mass dijet analysis

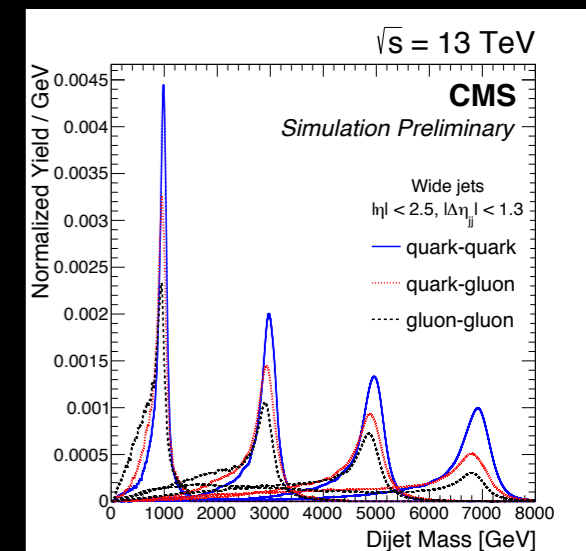


quark-gluon final state



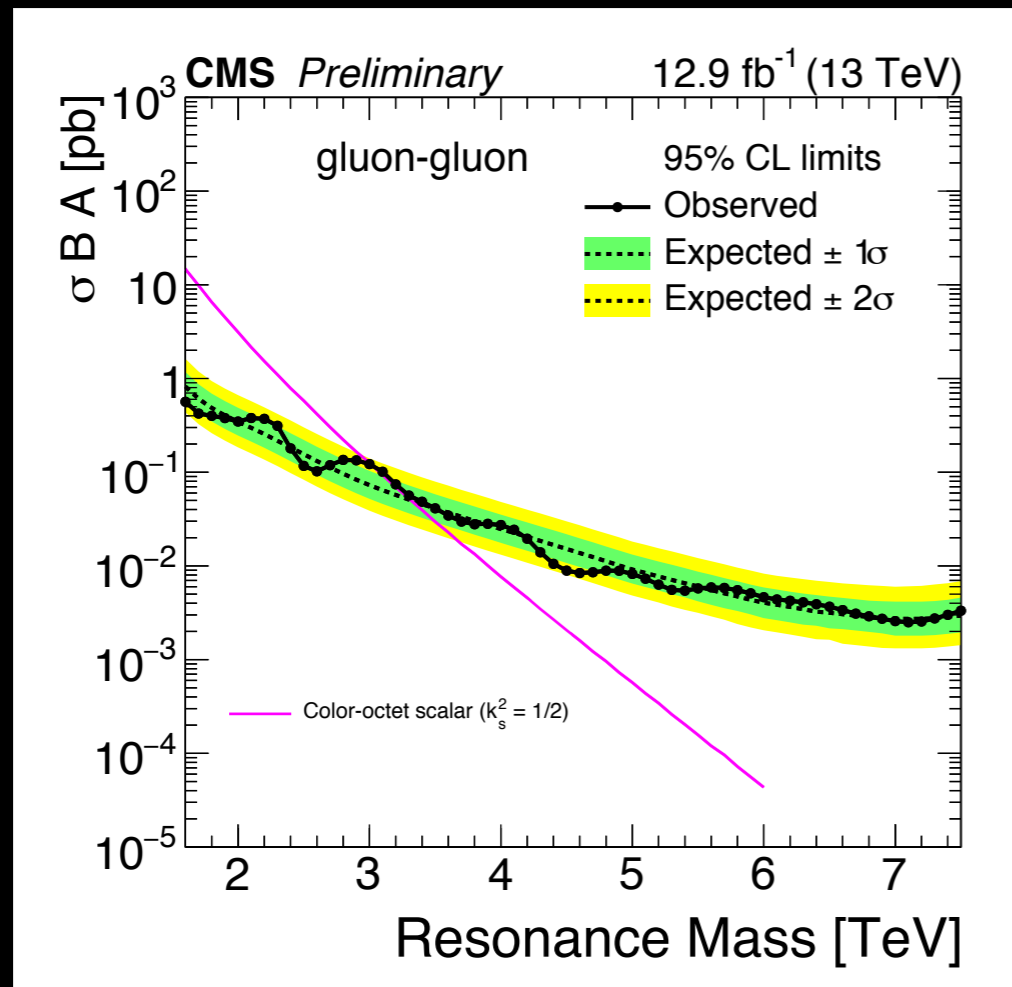
quark-quark final state

## Signal shapes

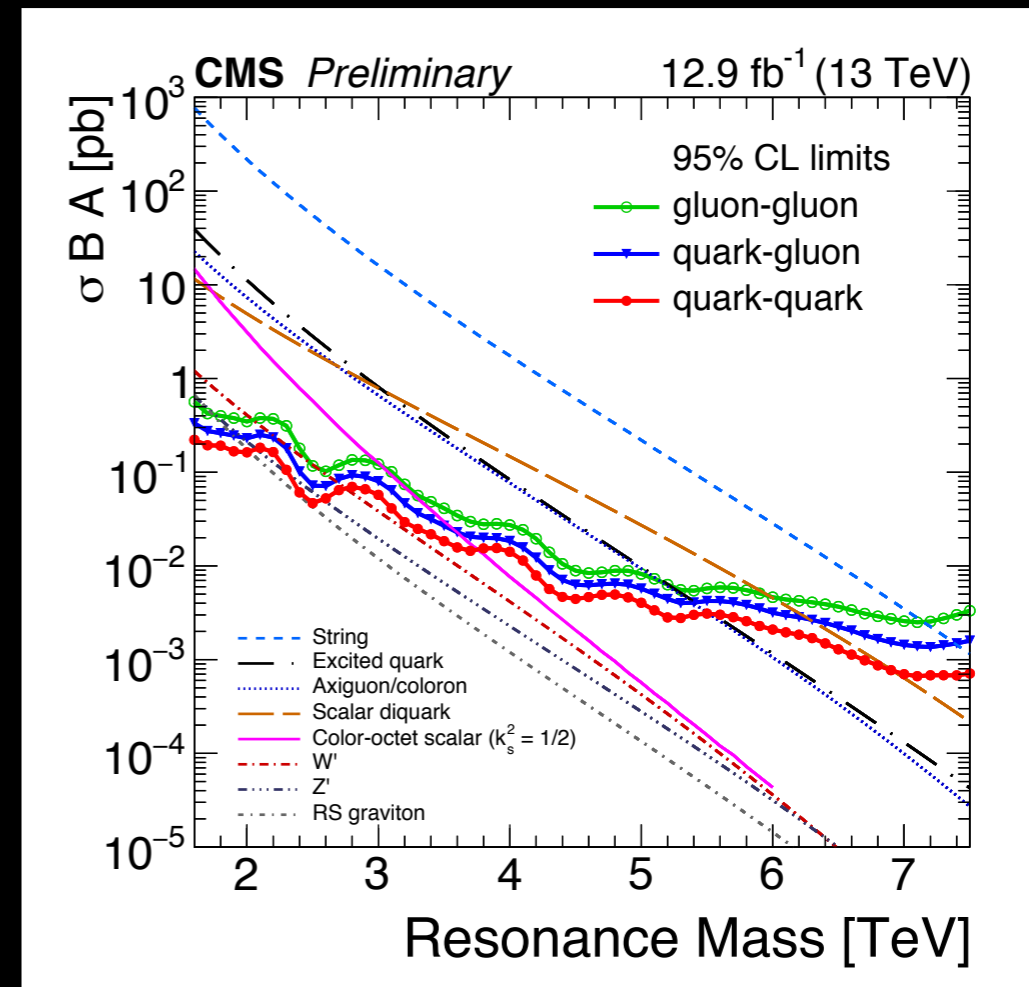


Wide jets used:  
 defined on Slide  
 31

# Additional Material: High mass dijet analysis

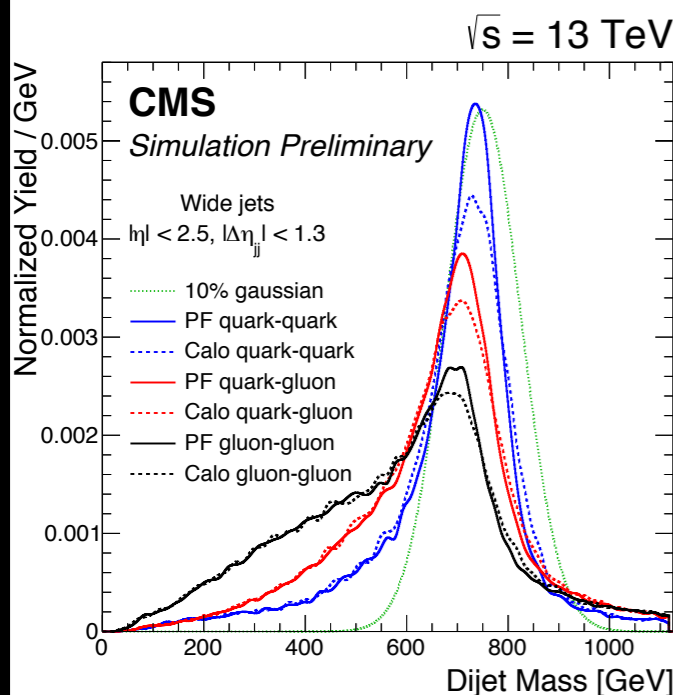


gluon-gluon final state

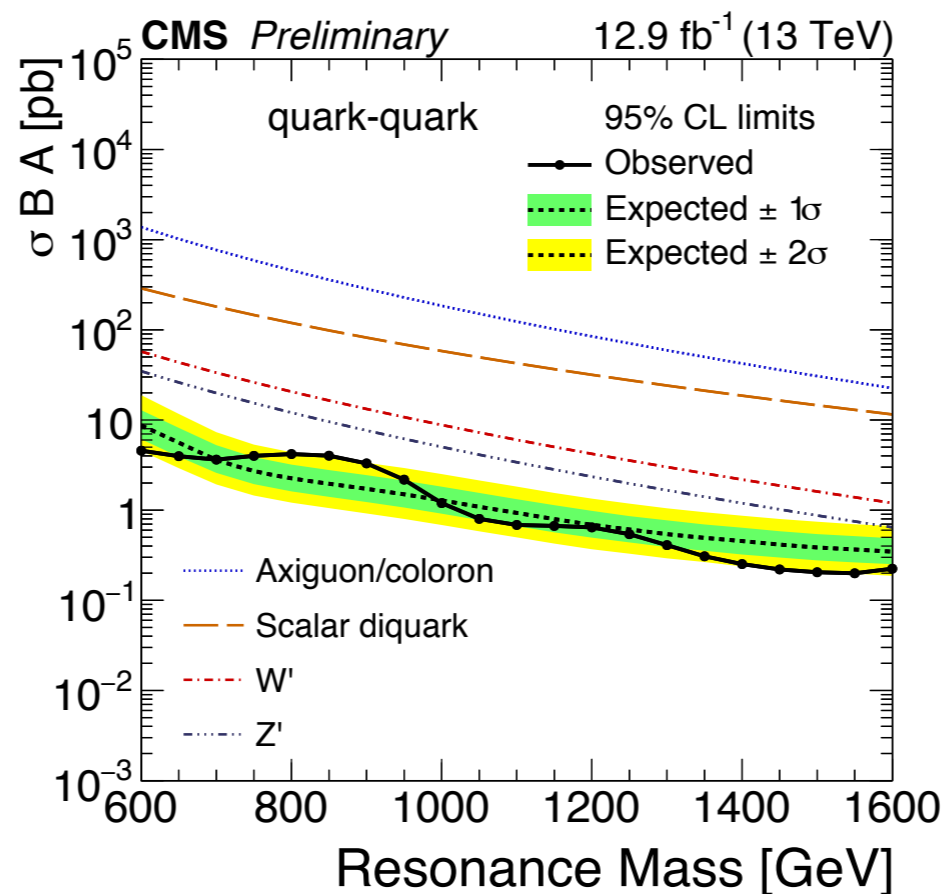


Summary

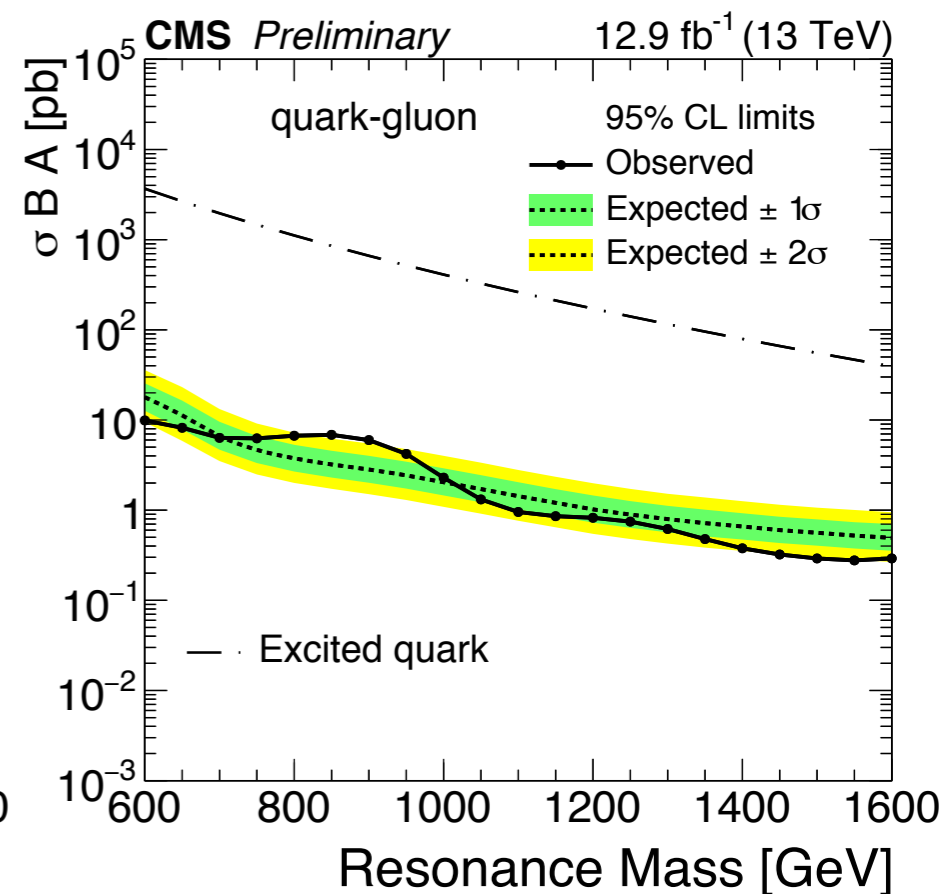
# Additional Material: Low mass dijet analysis



**Signal shapes**



**quark-quark final state**

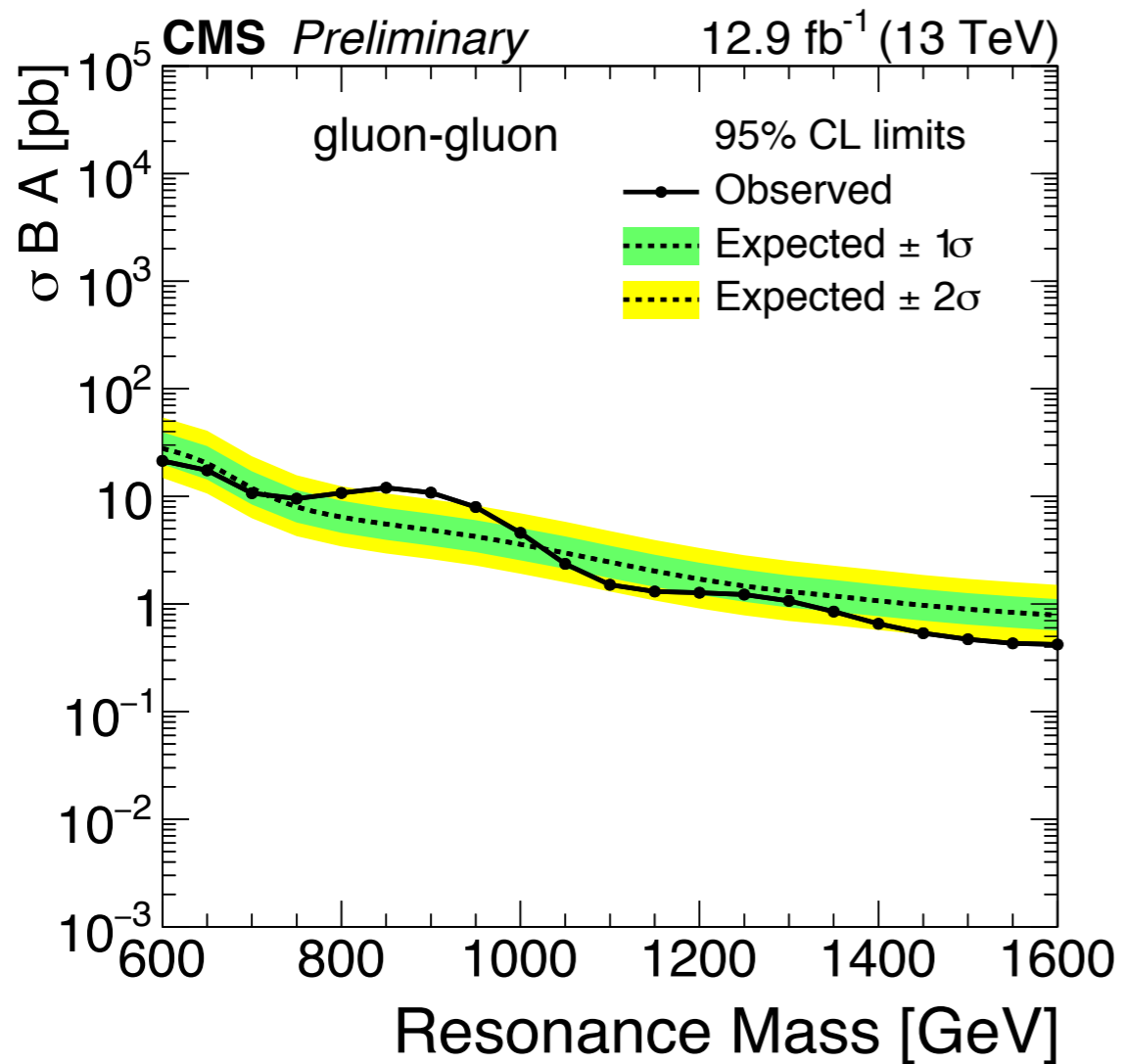


**quark-gluon final state**

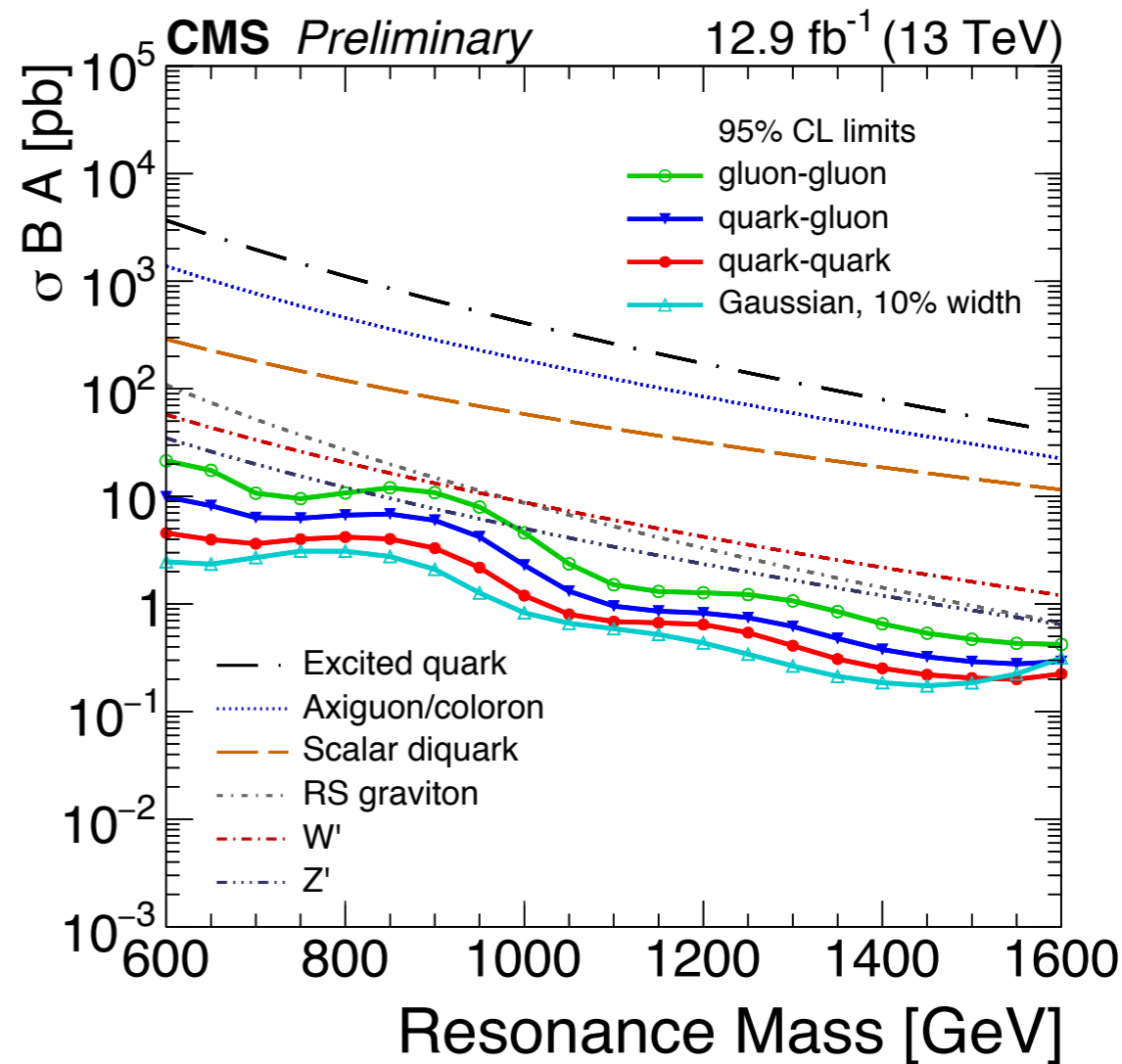
Quark-quark, quark-gluon, and gluon-gluon resonance shapes used for setting physical limits in the dijet resonance search. 10% Gaussian for comparison with ATLAS



# Additional Material: Low mass dijet analysis



gluon-gluon final state



Summary

# Dijet analysis: Event Displays

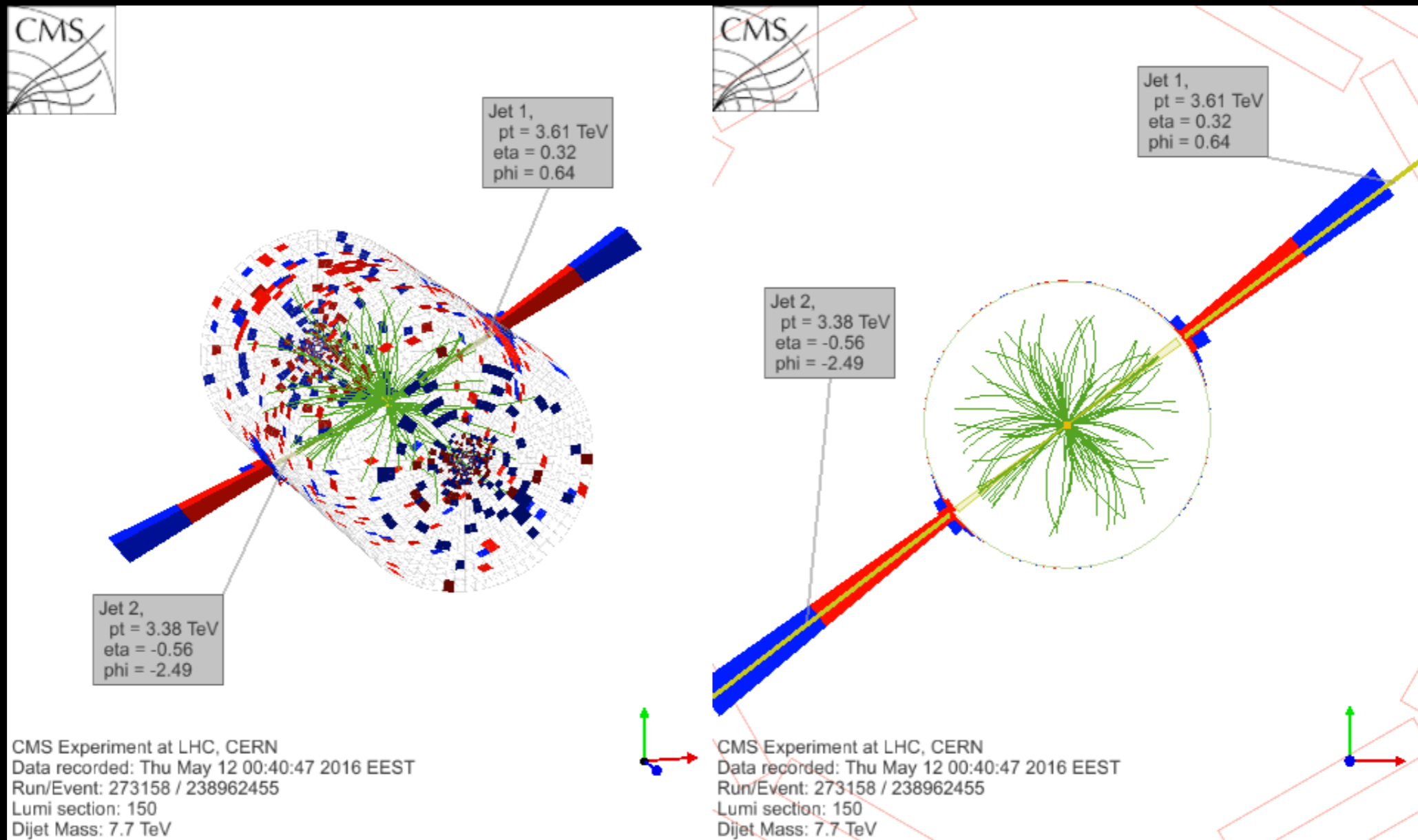
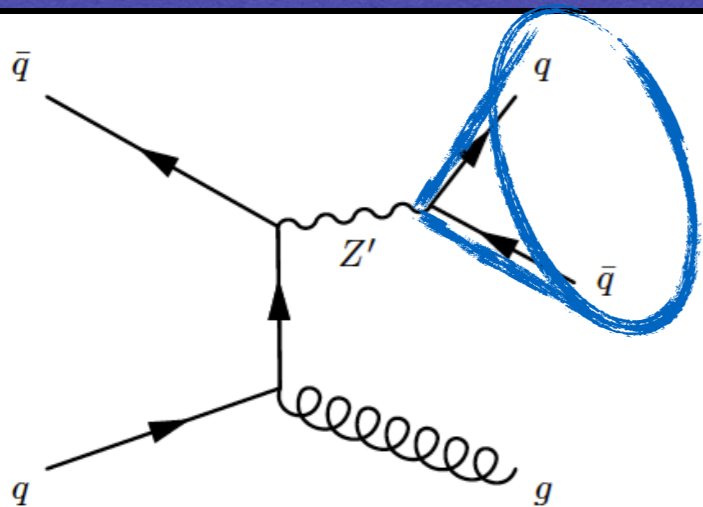


Figure 2: The event with the highest dijet invariant mass: three dimensional view (left), 2D view in the  $\rho$ - $\phi$  plane (right). The  $p_T$ ,  $\eta$ , and  $\phi$  values of the two wide jets are indicated. The invariant mass of the two wide jets is 7.7 TeV.

Hot off the press!

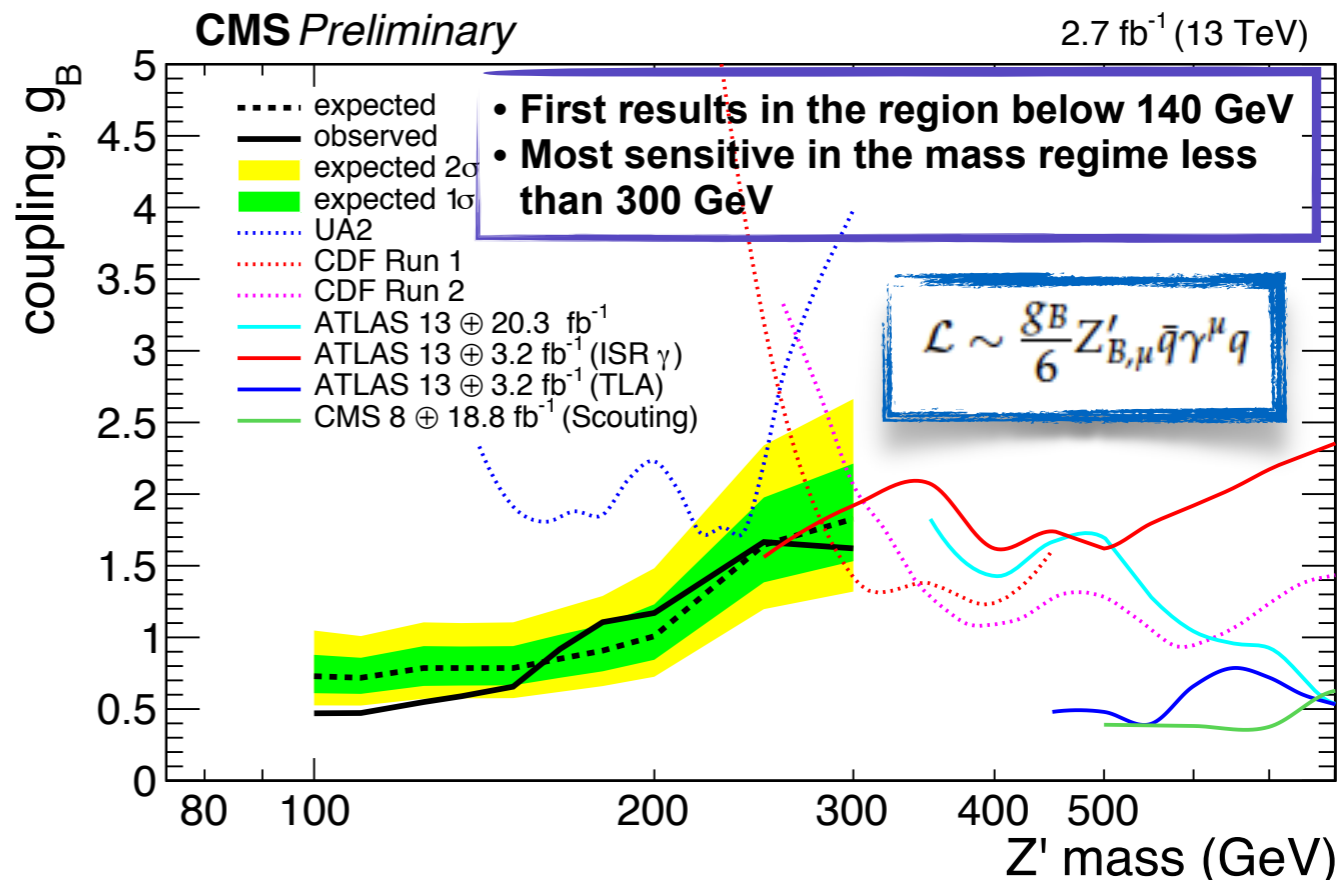
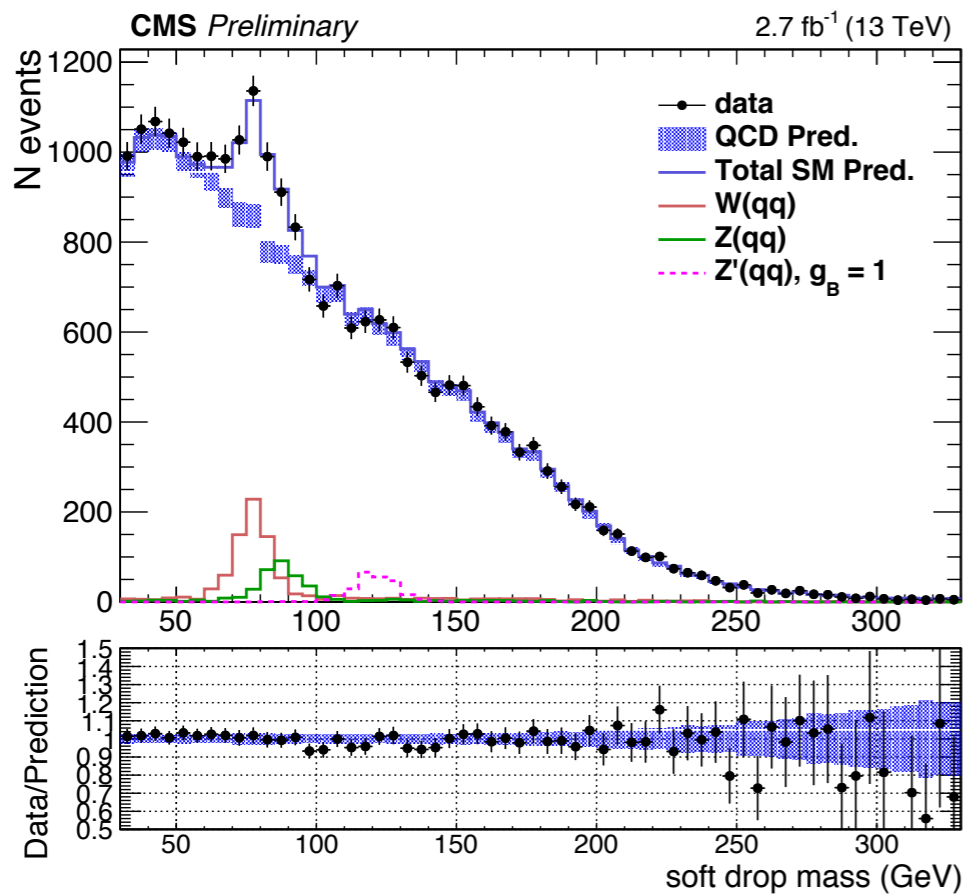
# Low-mass dijet analysis: CMS



## Boosted topology

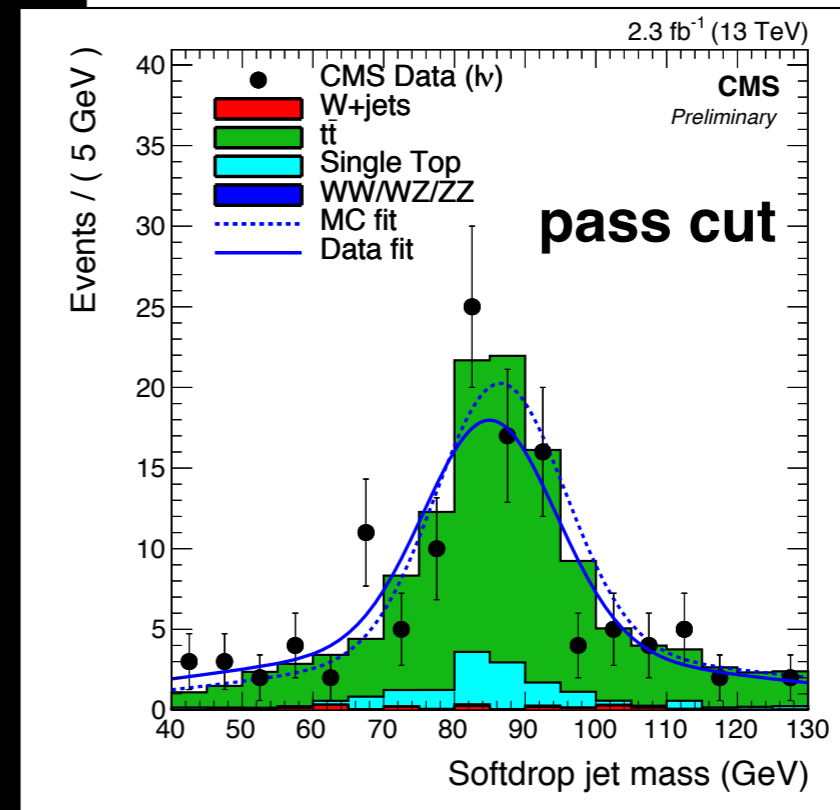
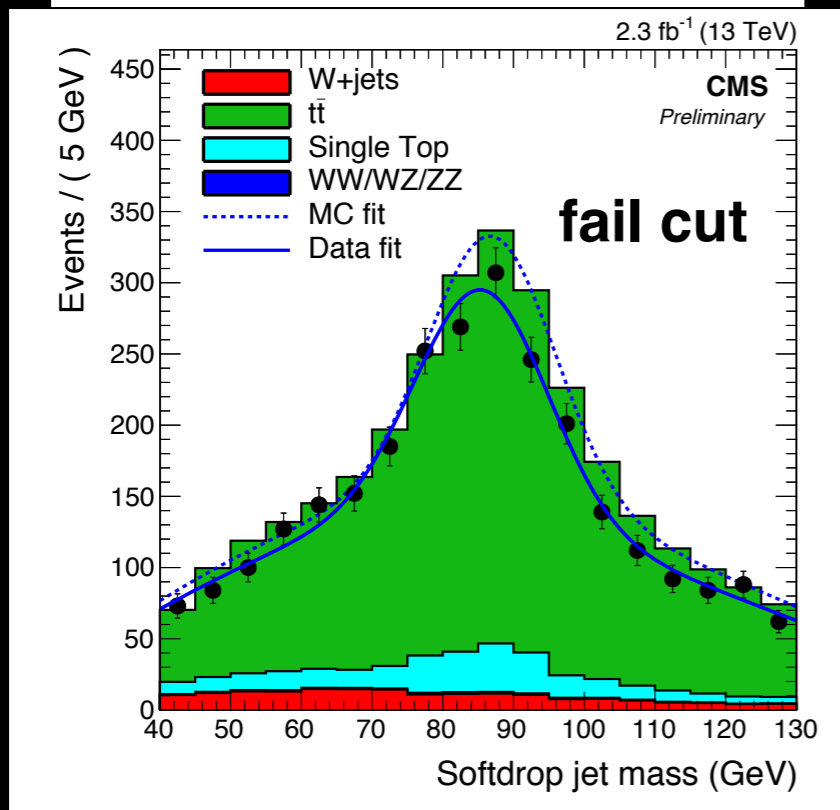
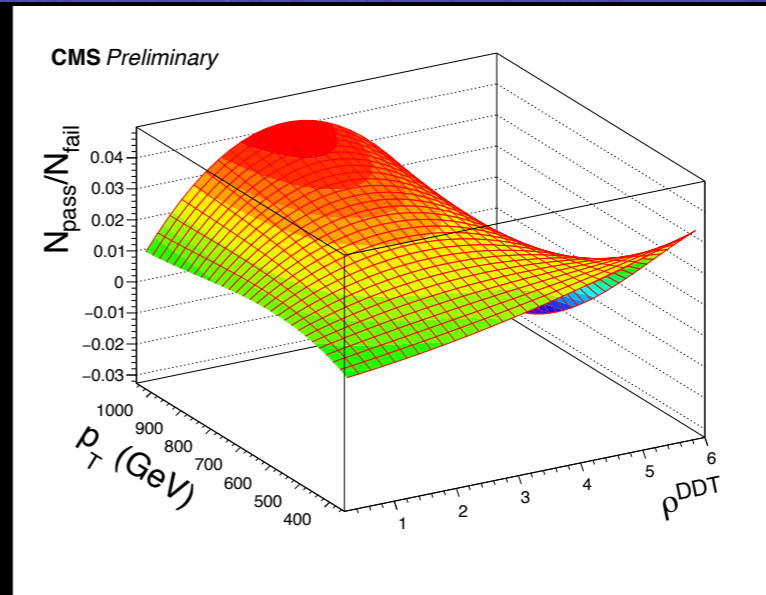
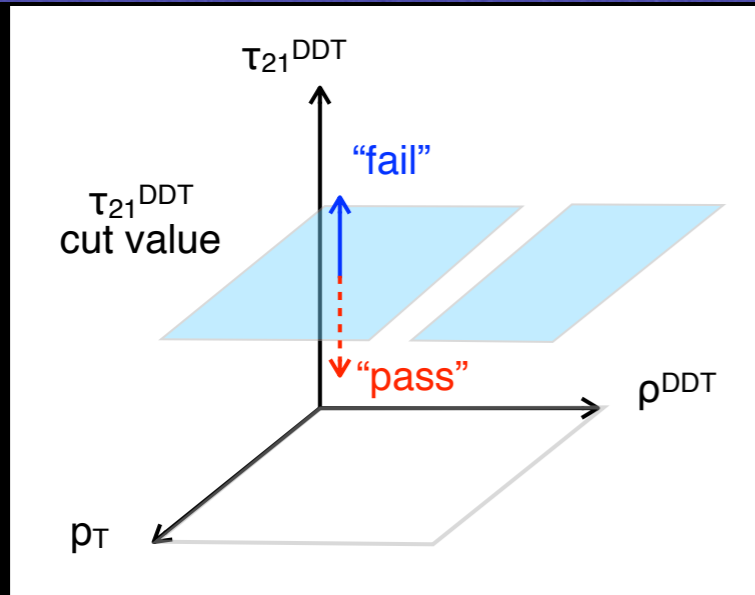
Soft Drop Condition: 
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta$$

- $R_0$  is the radius of the jet,  $p_{T\text{i}}$  is the transverse momenta of the constituents,  $\Delta R_{12}$  is the distance between the constituents in the  $\eta$ - $\Phi$  plane
- $z_{\text{cut}}$  is the soft drop threshold and  $\beta$  is an angular exponent

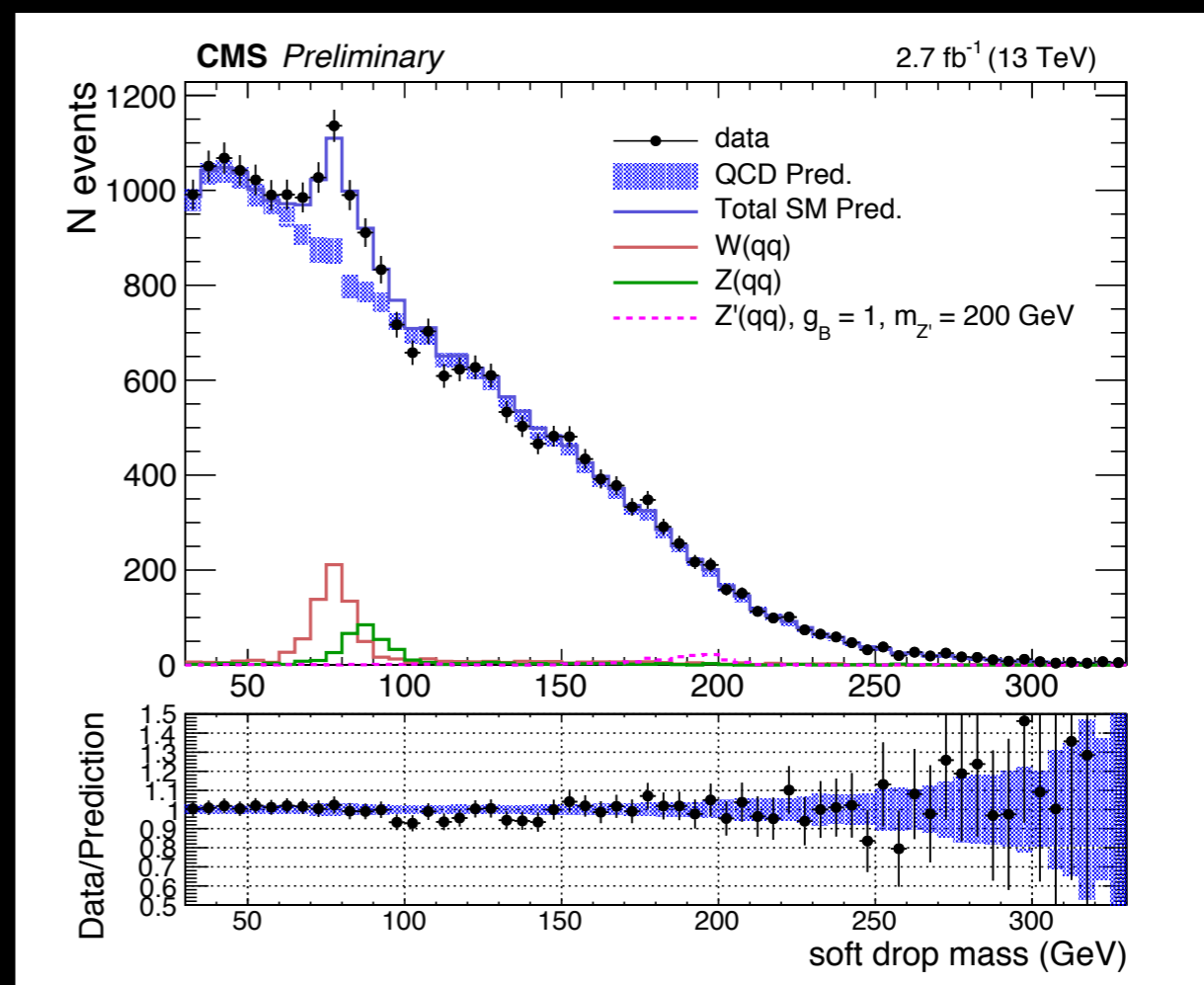
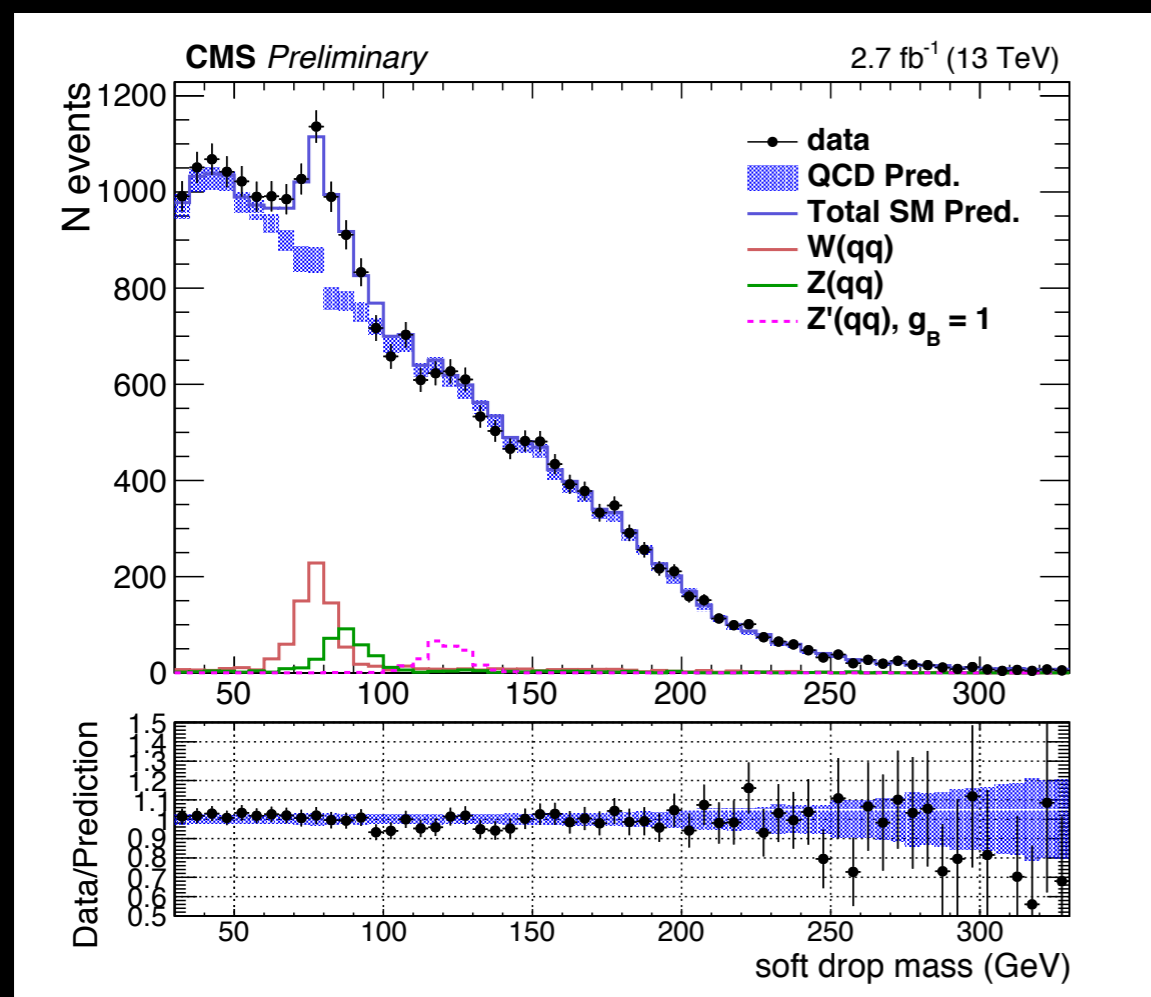




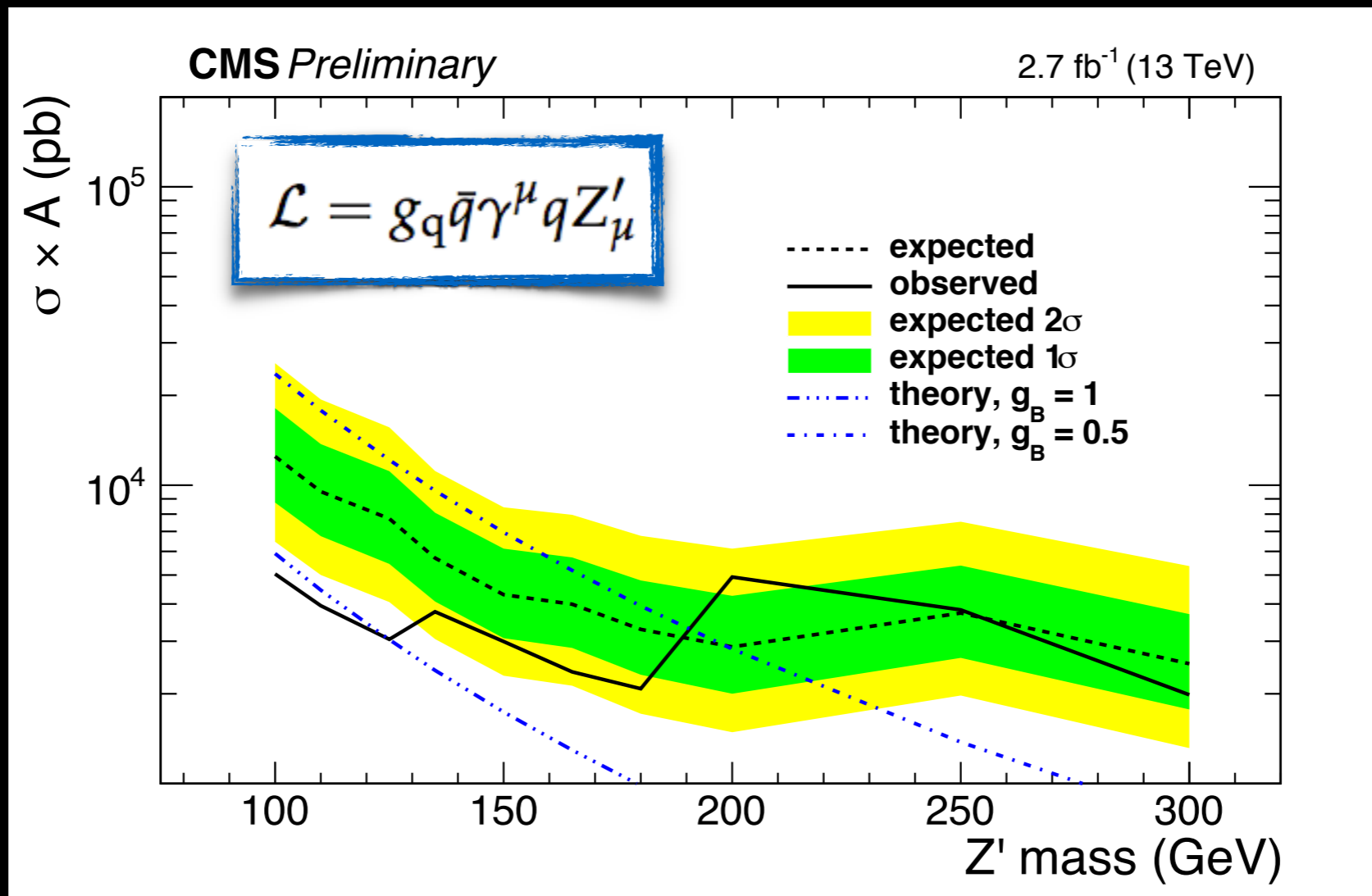
# Additional Material: Low mass search using jet substructure technique



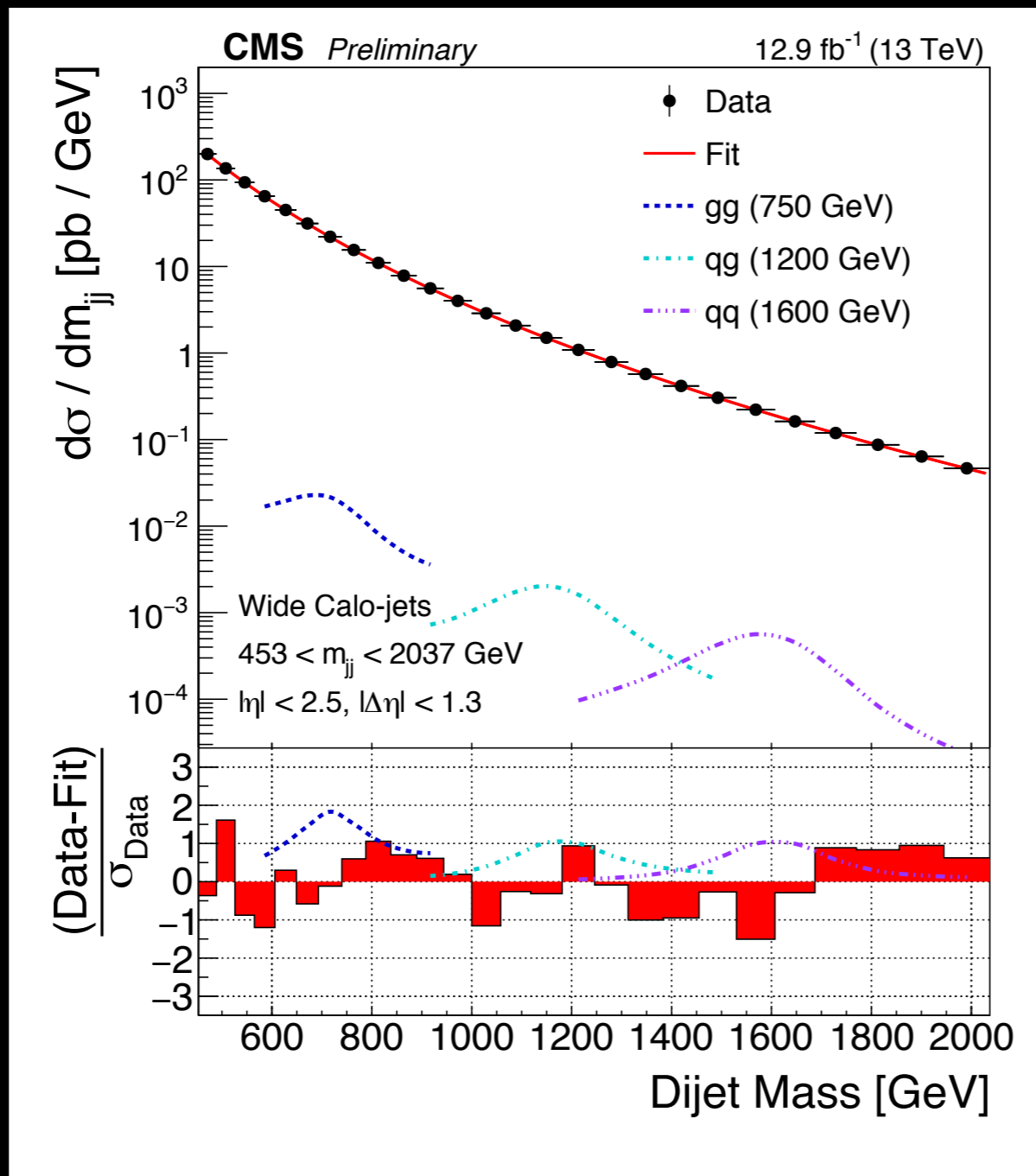
# Additional Material: Low mass search using jet substructure technique



# Additional Material: Low mass search using jet substructure technique



# Additional Material: Trigger Level Searches with Dijets



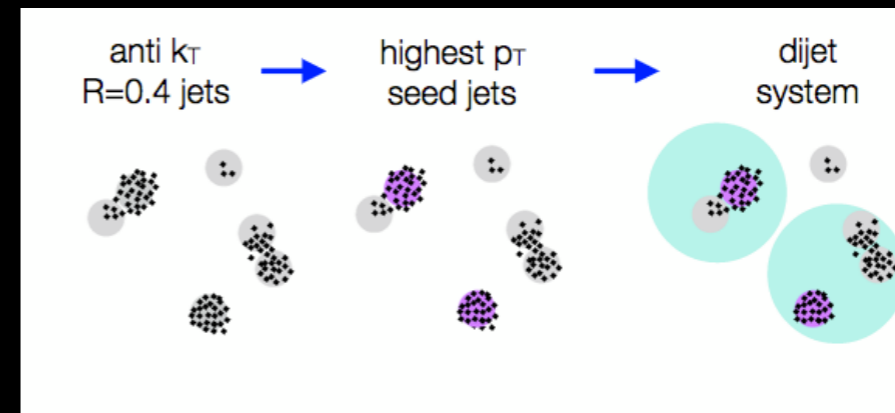
- To sustain a high rate in the data scouting stream, 4 momenta of the calorimetric jets is stored
- Rate at HLT is 1 kHz
- Scouting data are stored immediately after the HLT selection



# CMS dijet resonance search reconstruction

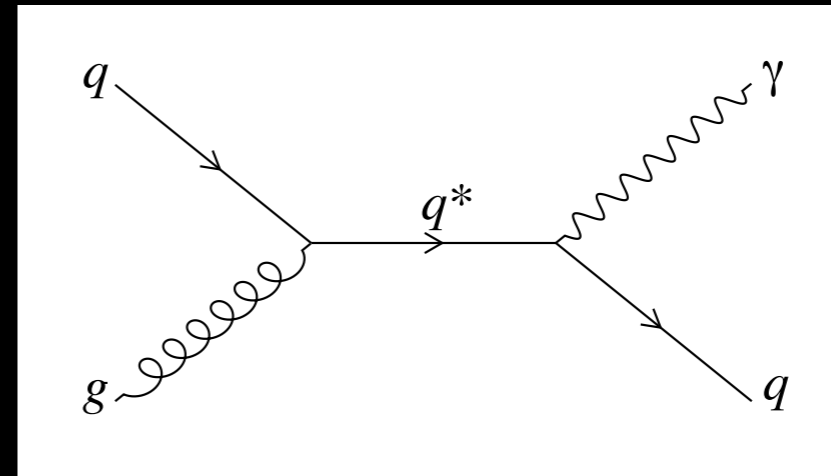
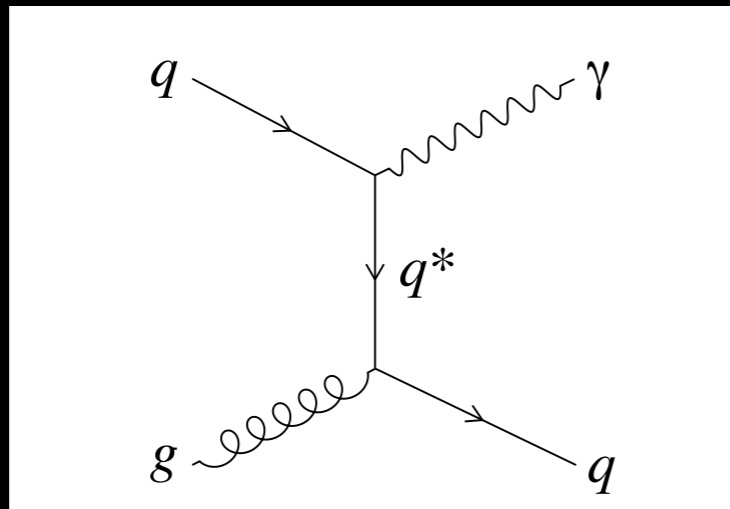
## Dijet reconstruction with wide jets

- Uses two leading jets in an event as seeds. Merges neighboring jets to nearest leading jet if  $\Delta R < 1.1$
- Recover loss in mass response/resolution due to radiation

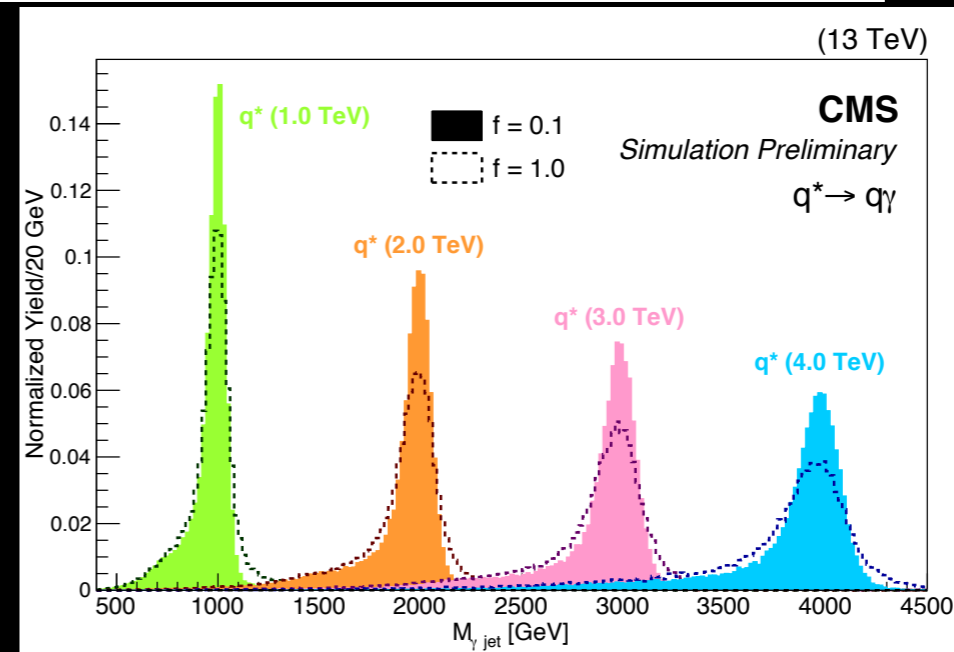
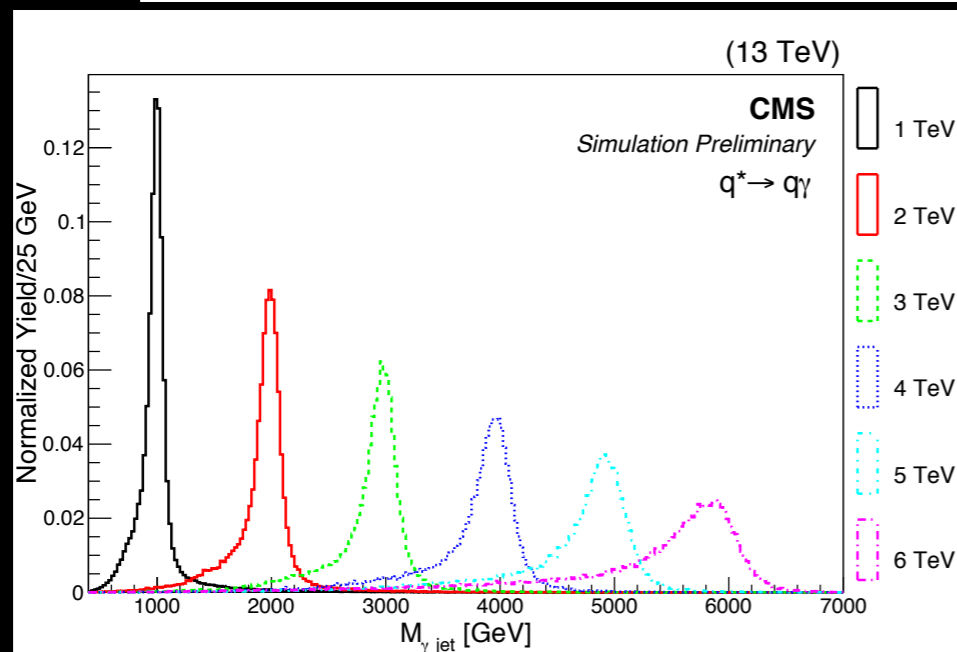


- The low mass search uses wide jets reconstructed from calo-jets
- The high mass search uses wide jets reconstructed from particle-flow jets

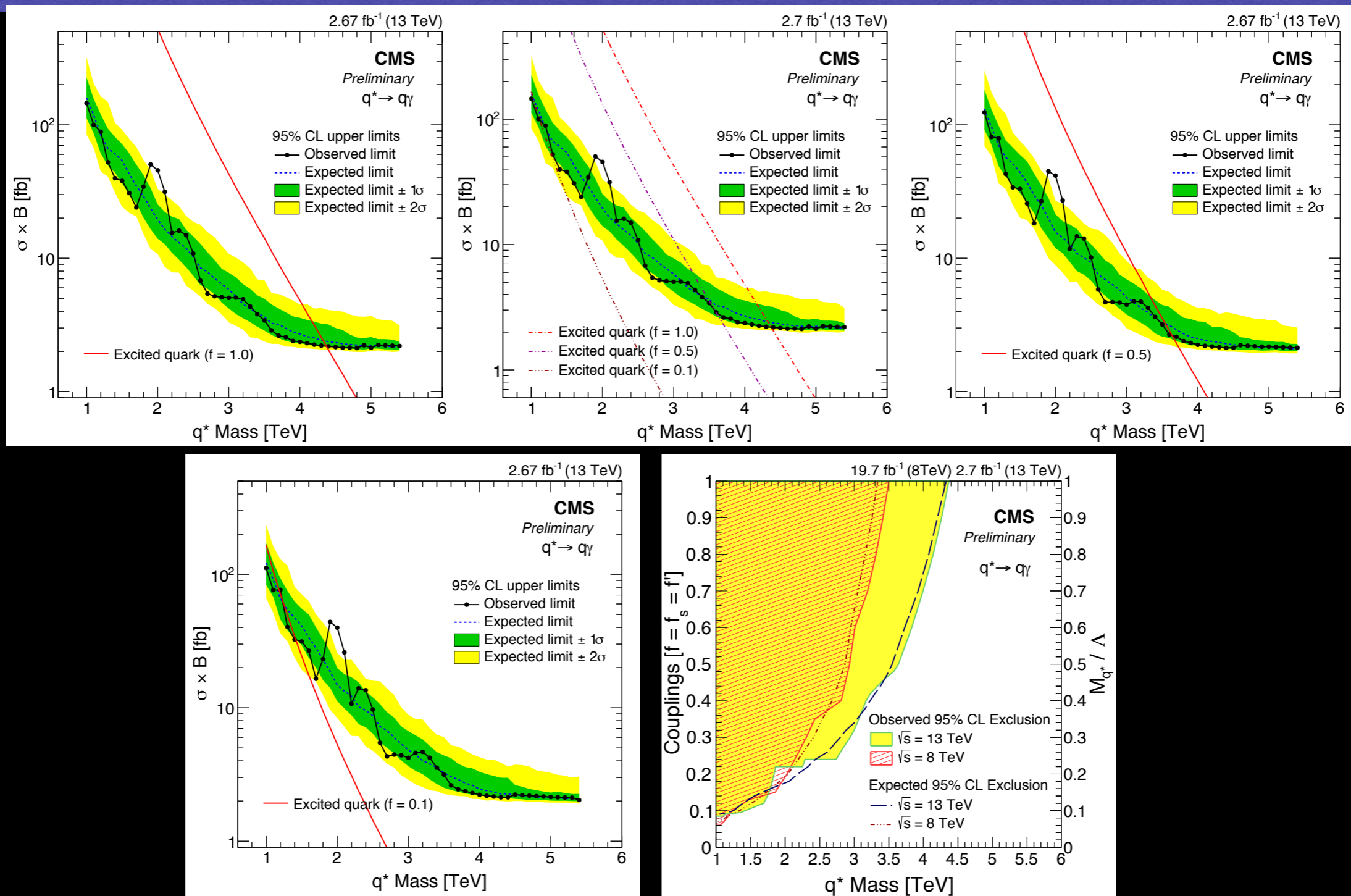
# Additional Material: Search for excited quarks



$$\mathcal{L}_{int} = \frac{1}{2\Lambda} \bar{q}_R^* \sigma^{\mu\nu} \left[ g_s f_s \frac{\lambda_a}{2} G_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q_L$$



# Additional Material: Search for excited quarks



# Additional material: Search for Black Holes (Analysis Strategy in CMS)

- The analysis is done following the procedure established in Run 1
- Essentially one performs a counting experiment using the variable  $S_T$ , where  $S_T$  is defined as the scalar sum of the transverse energy ( $E_T$ ) of **jets**, **leptons** and **photons**.  $ME_T$  is also added to  $S_T$  if  $ME_T > 50 \text{ GeV}$
- A  $E_T > 50 \text{ GeV}$  threshold is placed on all objects
- The **multiplicity** of an event is defined as the **number of jets + leptons + photons** in that event.  $ME_T$  is not counted as a separate object
- The background is estimated through a **data driven technique pioneered in Run I**
- The background is extracted from the low multiplicity regime (or signal depleted regime) and applied to higher multiplicity regimes using the invariance of the  $S_T$  spectrum above a certain turn-on threshold carefully chosen by looking into the invariance in data and QCD Monte Carlo
- For a model specific scenario, the value of  $S_T$  along with the choice of the multiplicity regime is optimized
- For model independent limits, **all multiplicity regimes are used to quantify the reach of this analysis**
- The systematic uncertainties associated with the data driven technique are extracted and taken into consideration when quantifying the reach of this analysis



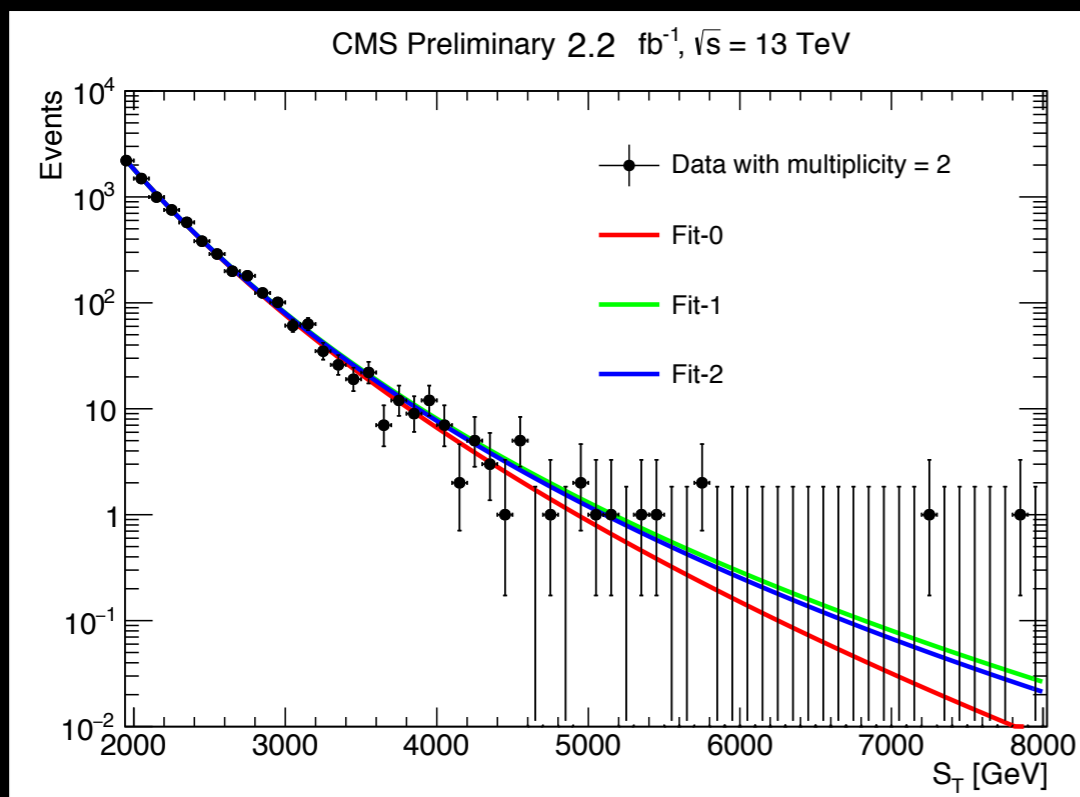
# Background Estimation: CMS

There different fitting functions are used to parametrize the background (same technique as Run I)

$$\frac{P_0(1+x)^{P_1}}{x^{P_2+P_3} \log(x)}$$

$$\frac{P_0}{(P_1 + P_2x + x^2)^{P_3}}$$

$$\frac{P_0}{(P_1 + x)^{P_2}}$$



- Fitting range: 1400-2400 GeV
- Use 3-parameter function with multiplicity = 2 as the background template.

The background is estimated from data

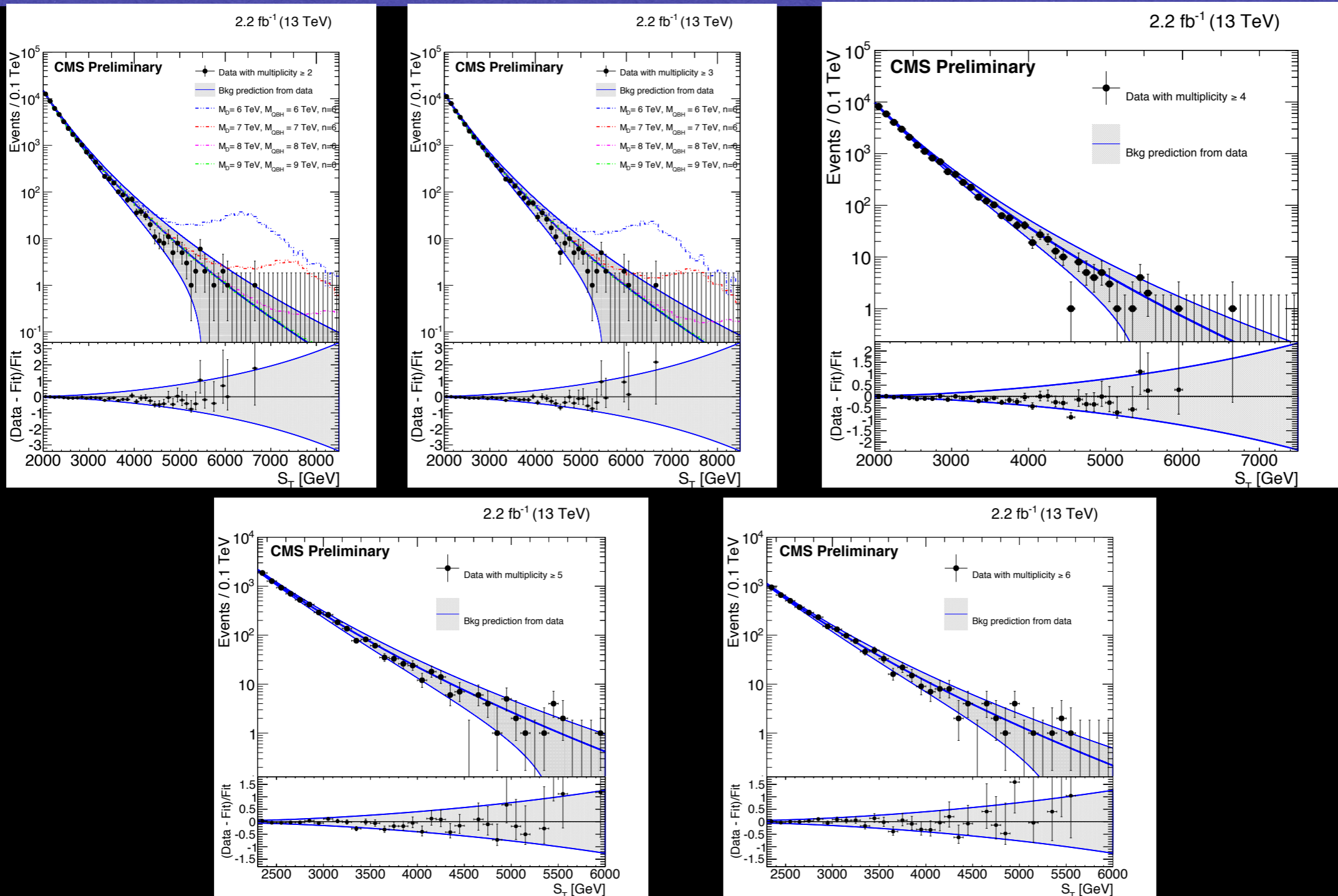
The background is estimated in a signal depleted regime (multiplicity = 2)

ST shape invariance is checked over all multiplicities

The background prediction from the multiplicity = 2 regime is applied to higher multiplicities by appropriate normalization in a region of low signal contamination

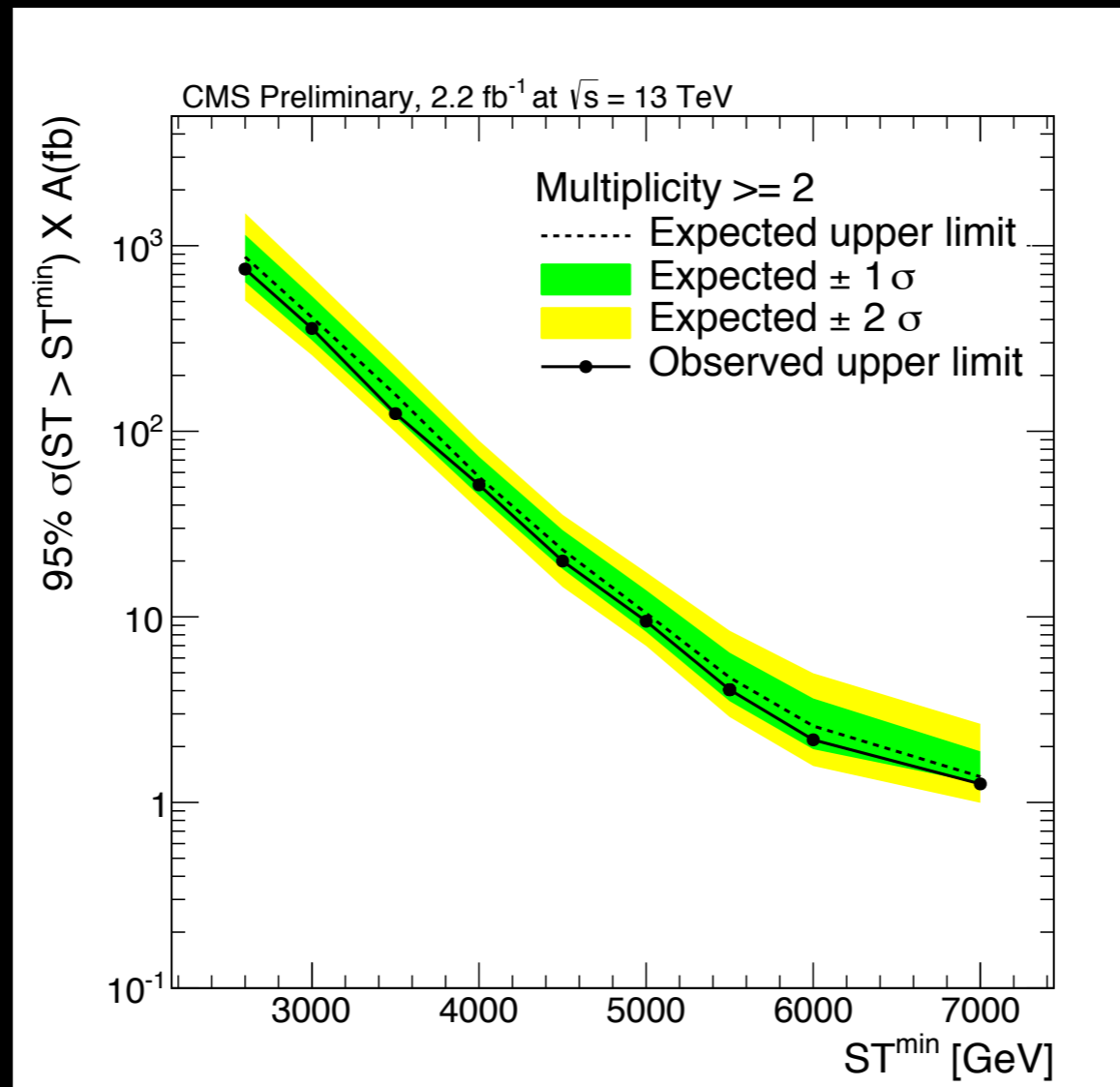
- Essentially one performs a counting experiment using the variable  $S_T$ , where  $S_T$  is defined as the scalar sum of the transverse energy ( $E_T$ ) of jets, leptons and photons.  $ME_T$  is also added to  $S_T$  if  $ME_T > 50$  GeV

# Additional Material: Search for microscopic black holes

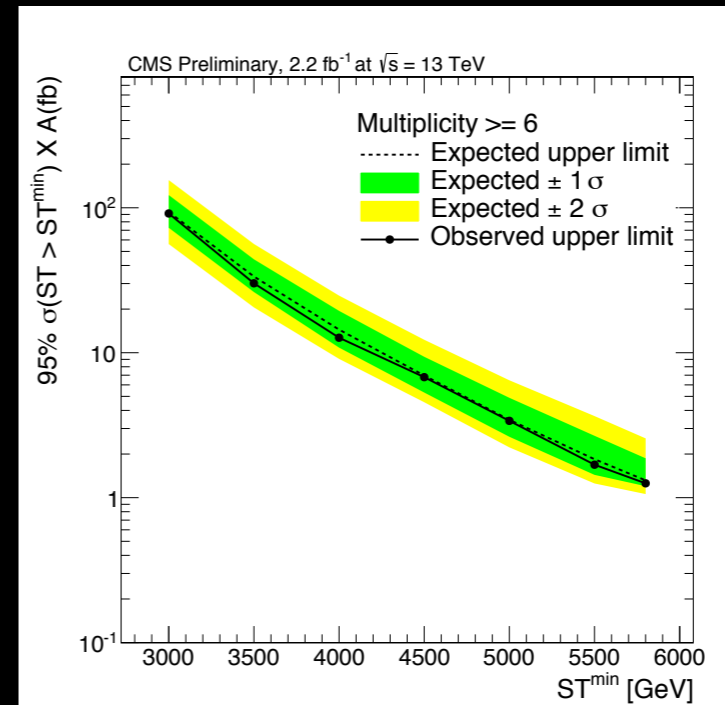
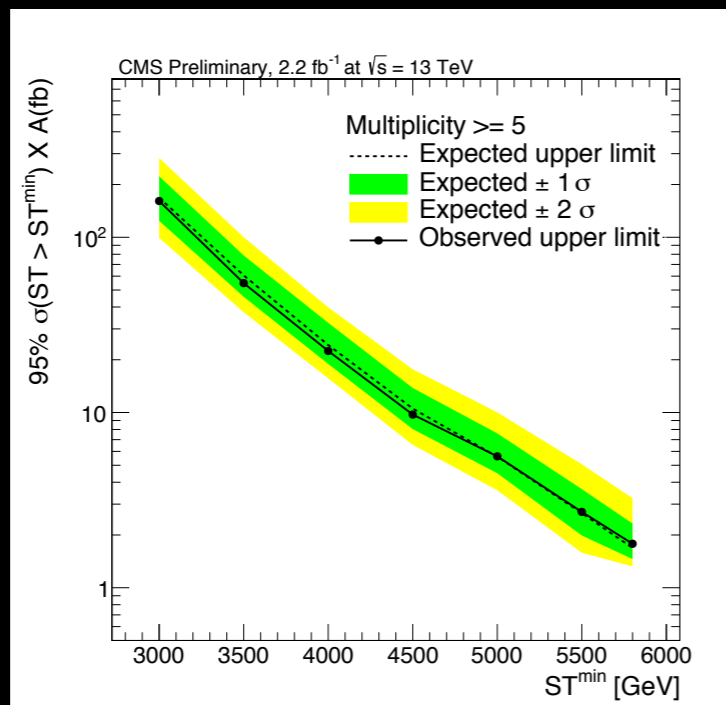
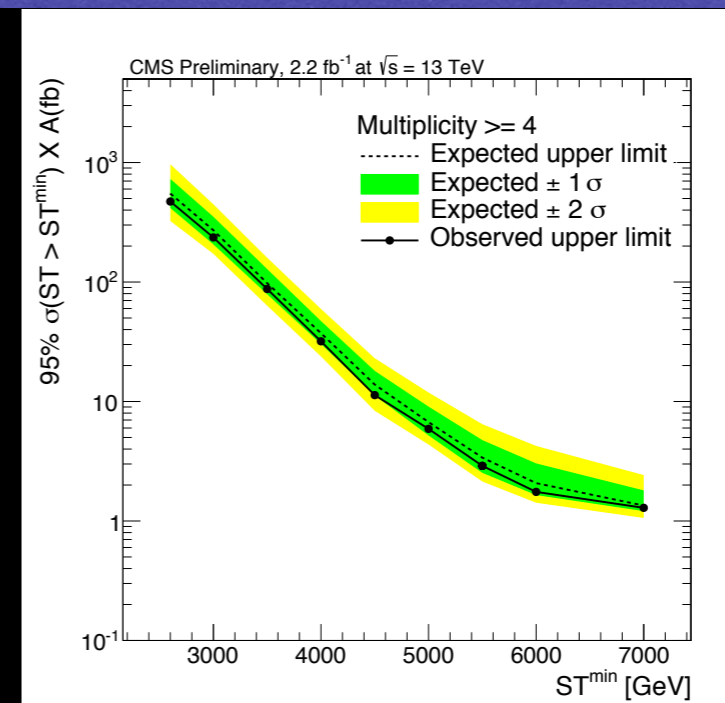
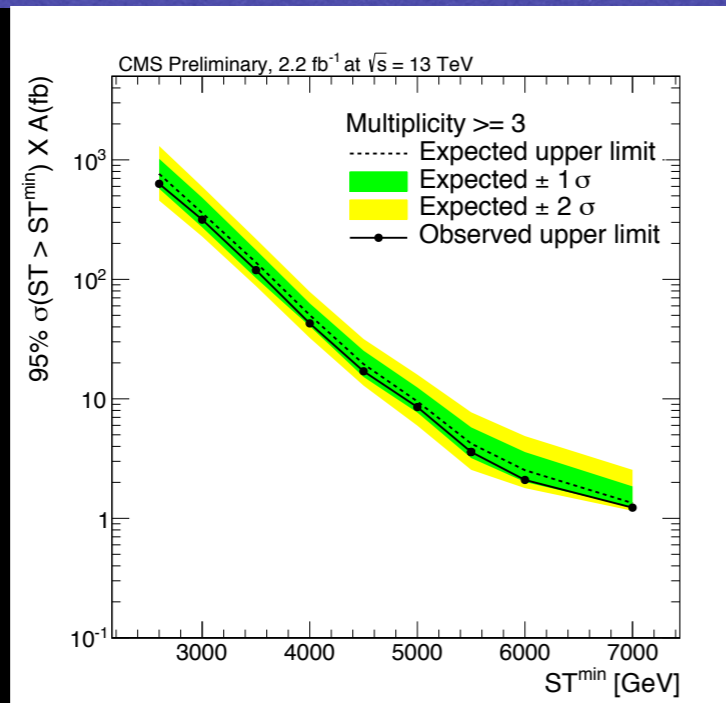


## Additional Material: Search for microscopic black holes

- Model independent limits are calculated as a function of  $S_{Tmin}$  for each inclusive multiplicity scenario.
- Full CIs is used as opposed to Asymptotic CIs for more accurate calculation.

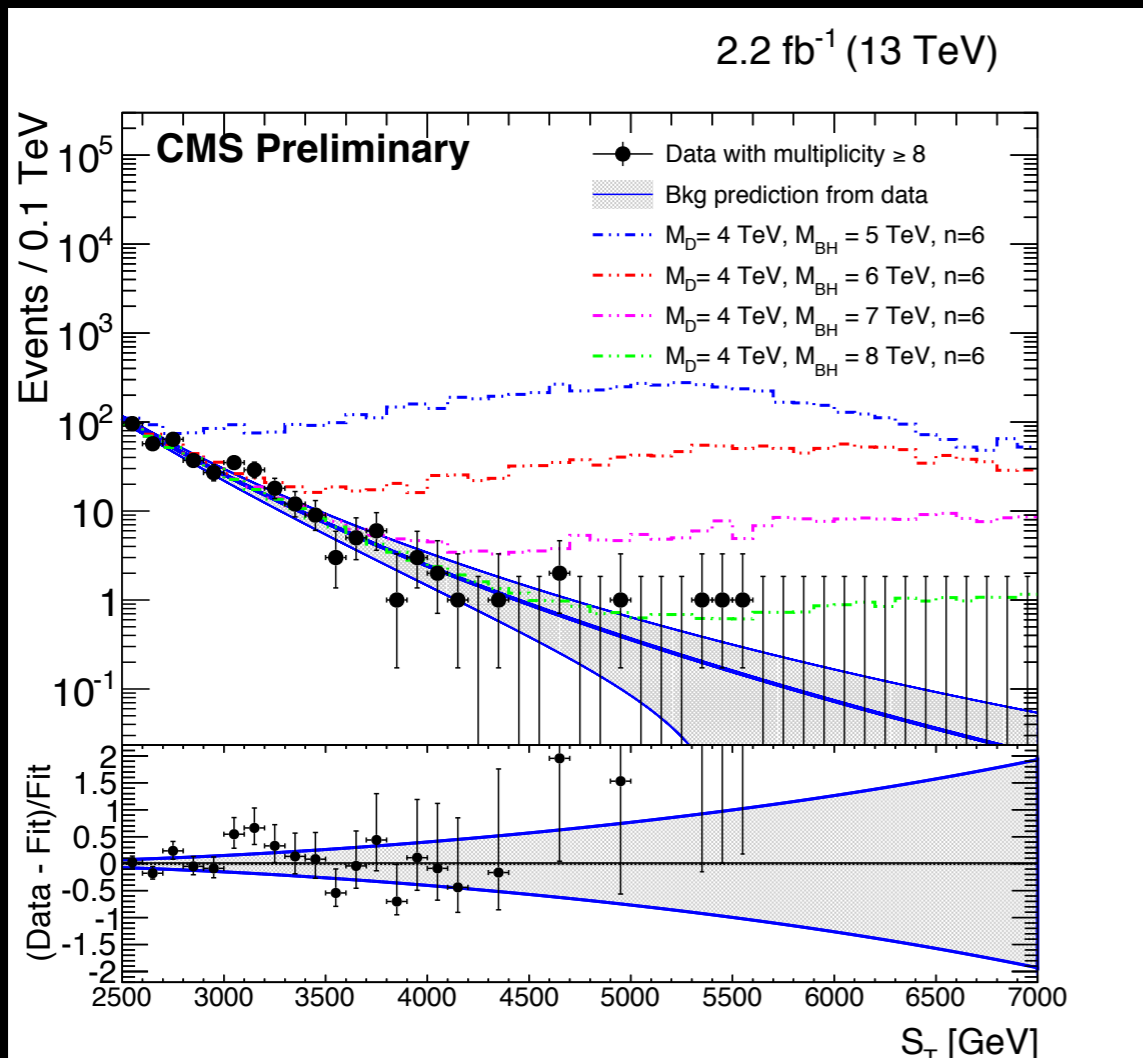


# Additional Material: Search for microscopic black holes

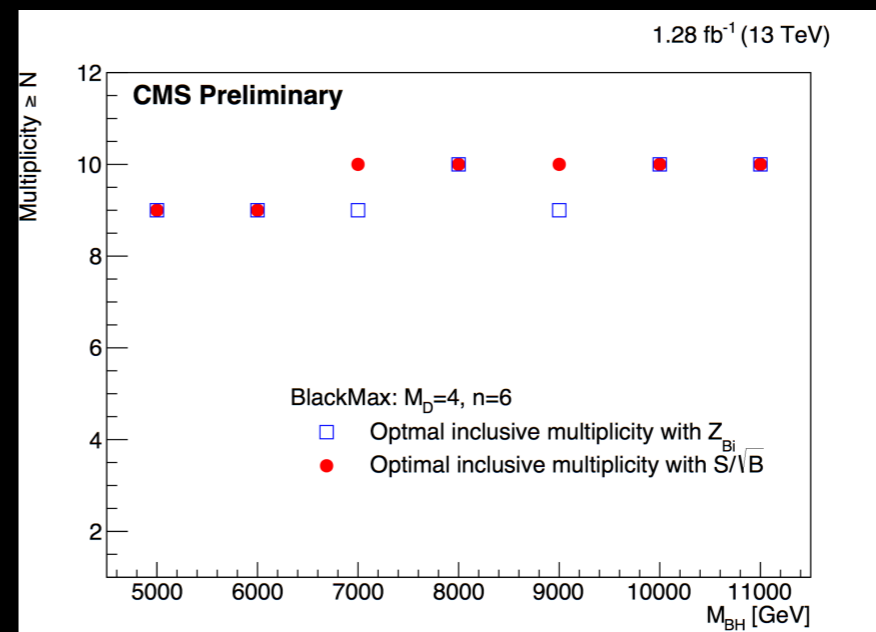
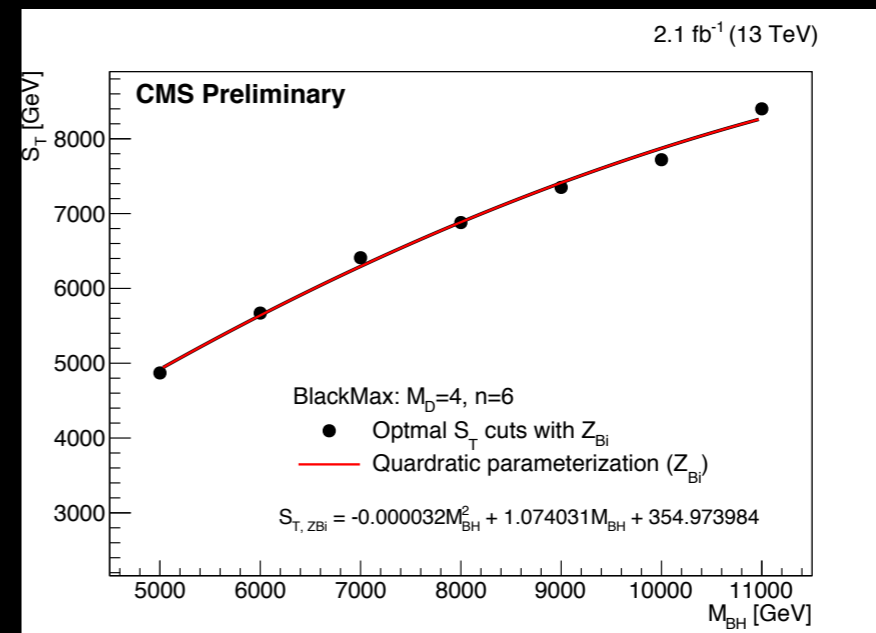




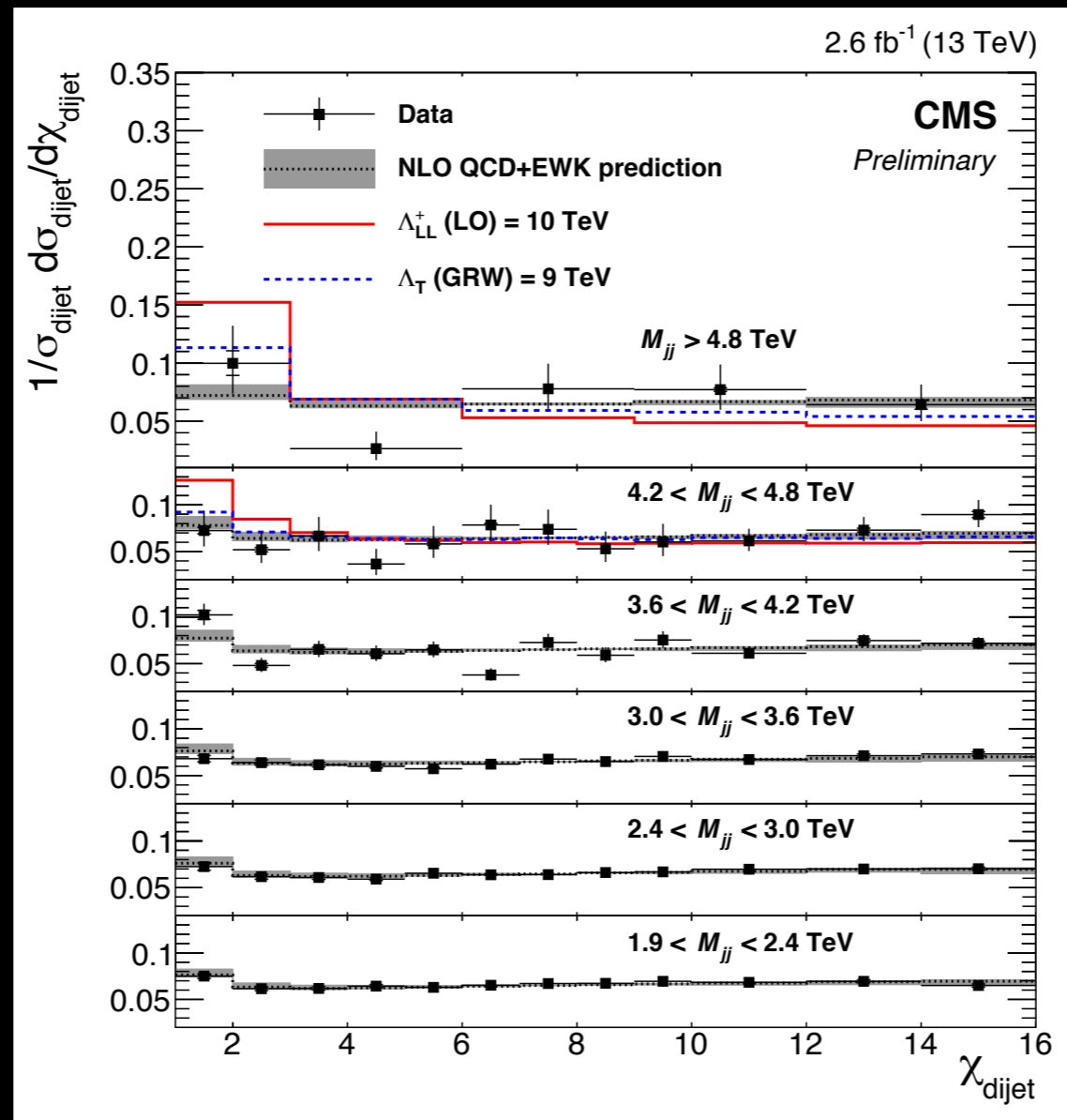
# Additional Material: Search for microscopic black holes



Observed and expected limits for  $\sigma$  (upper limit cross section)  $\times A$  (acceptance) in inclusive  $N$  objects are reported

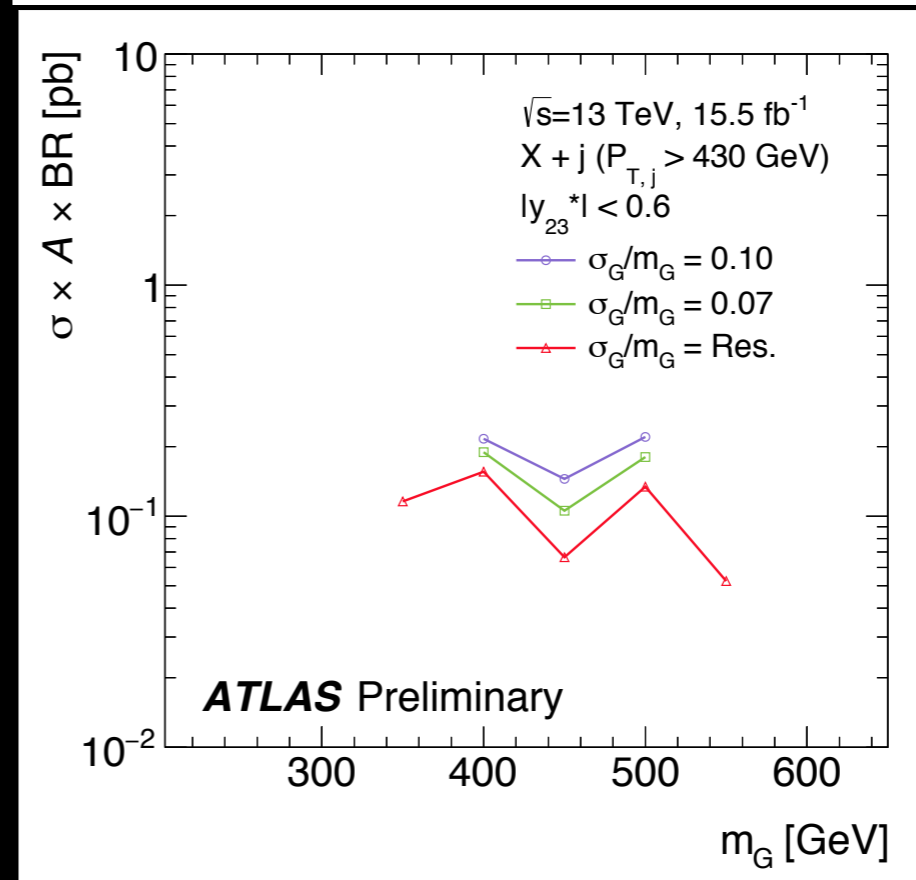
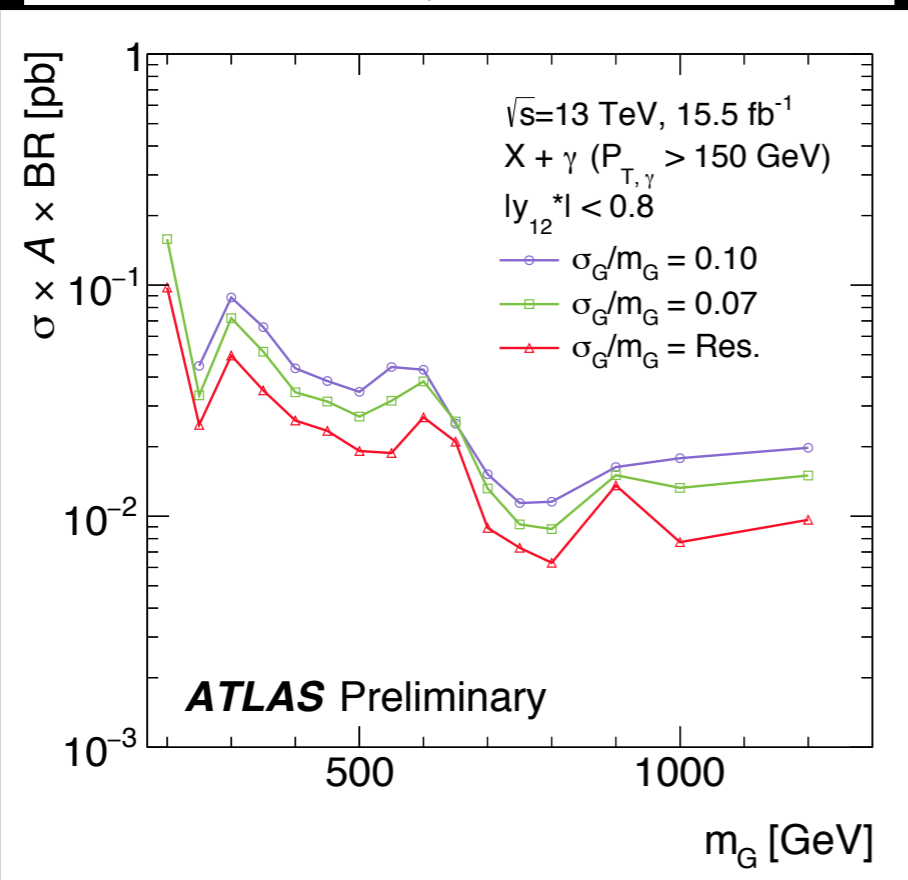
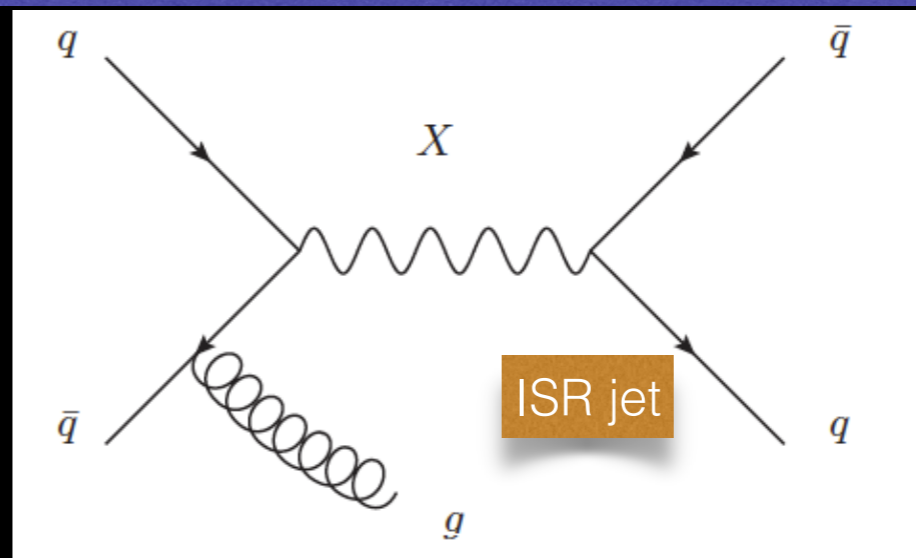
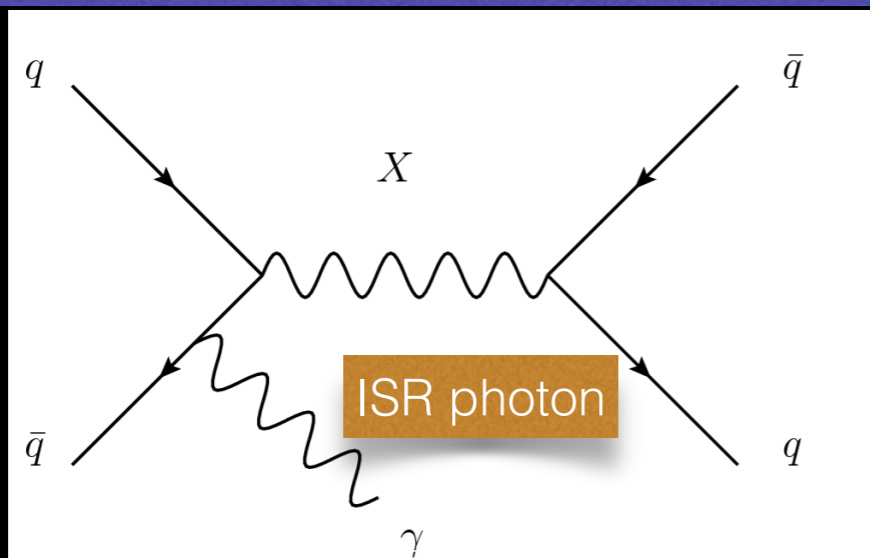


# Dijet results: CMS

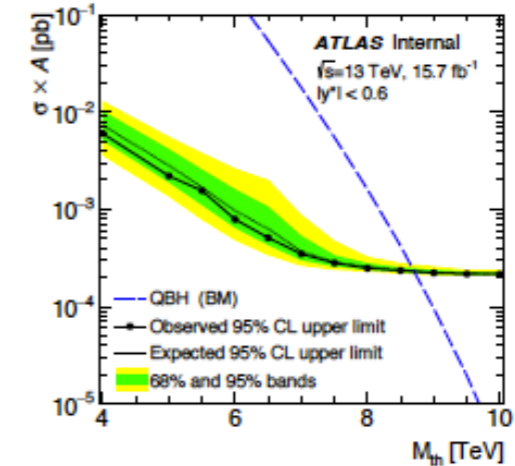
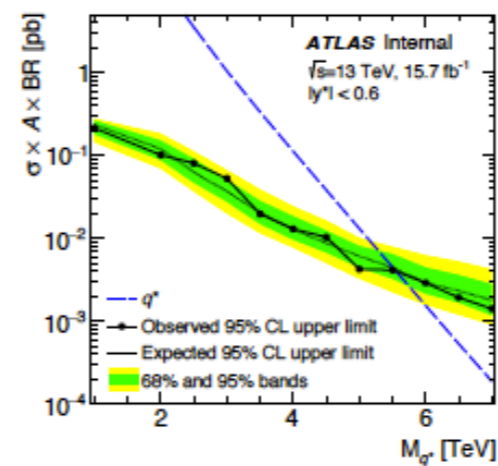
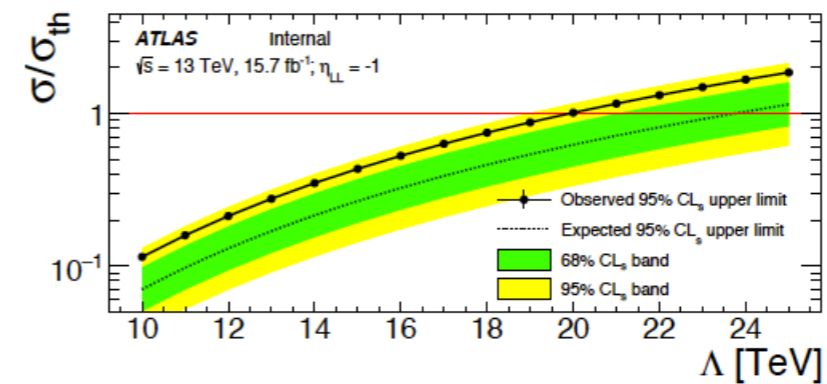
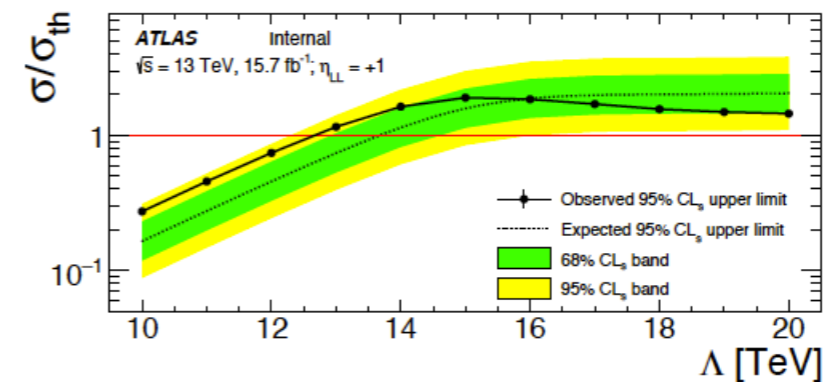
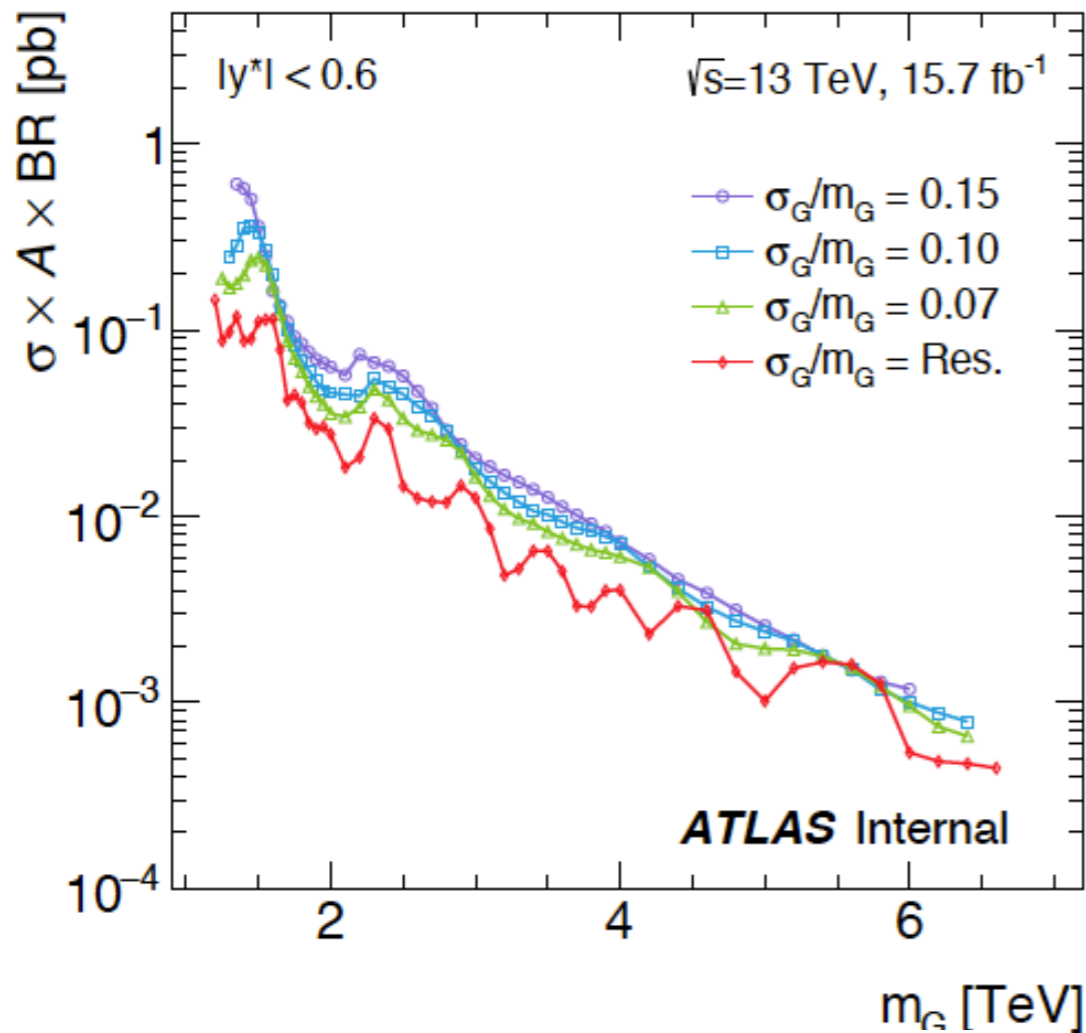


Search for new physics in dijet angular distributions

# Low-mass dijet analysis: ATLAS



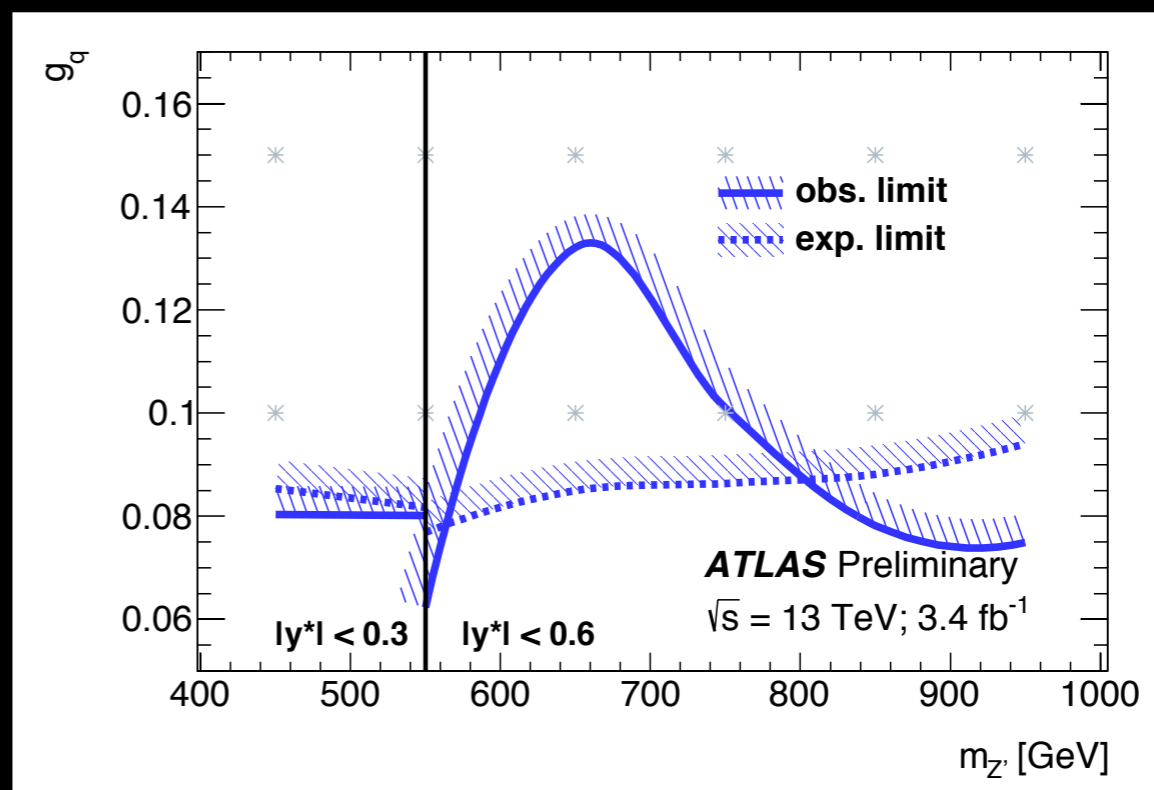
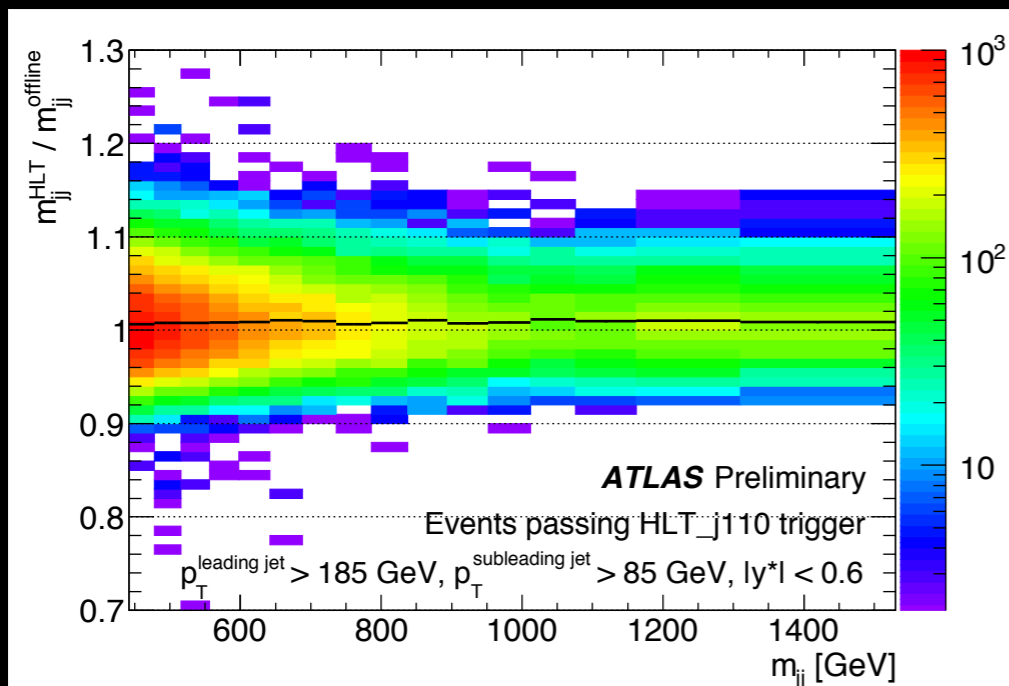
# High-mass dijet analysis: ATLAS



Model	95% CL Exclusion limit	
	Observed	Expected
Quantum black holes, ADD (BLACKMAX generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
$W'$	2.9 TeV	3.3 TeV
$W^*$	3.3 TeV	3.3 TeV
Contact interactions ( $\eta_{LL} = +1$ )	12.6 TeV	13.7 TeV
Contact interactions ( $\eta_{LL} = -1$ )	19.9 TeV	23.7 TeV



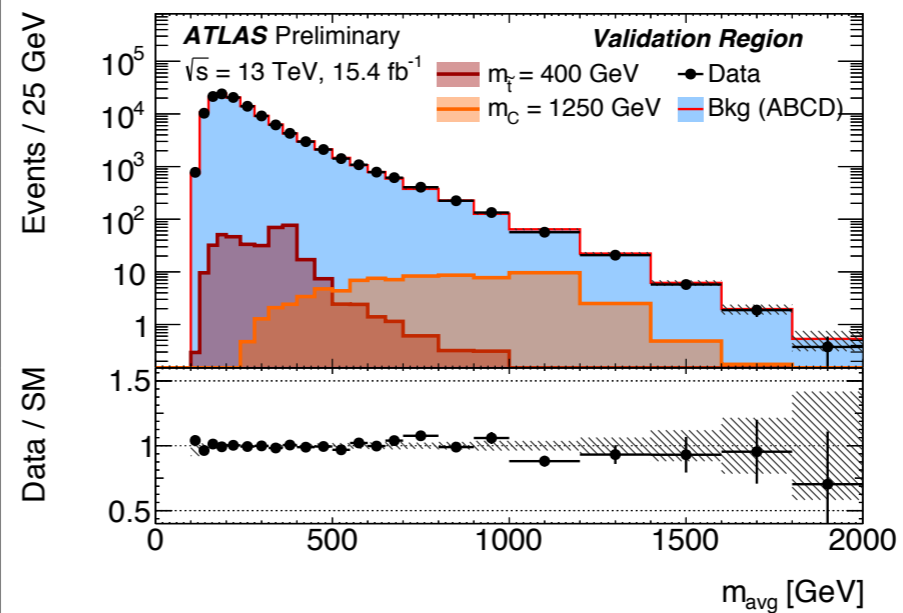
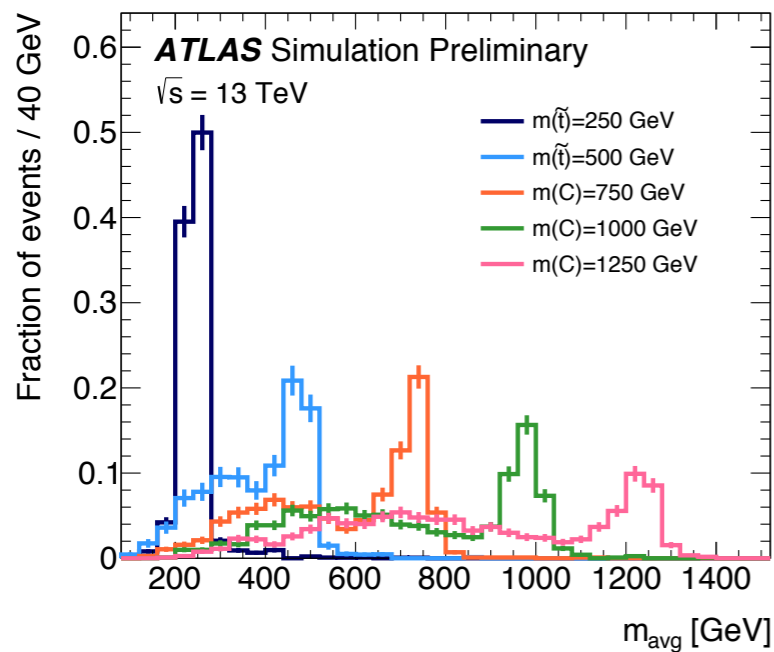
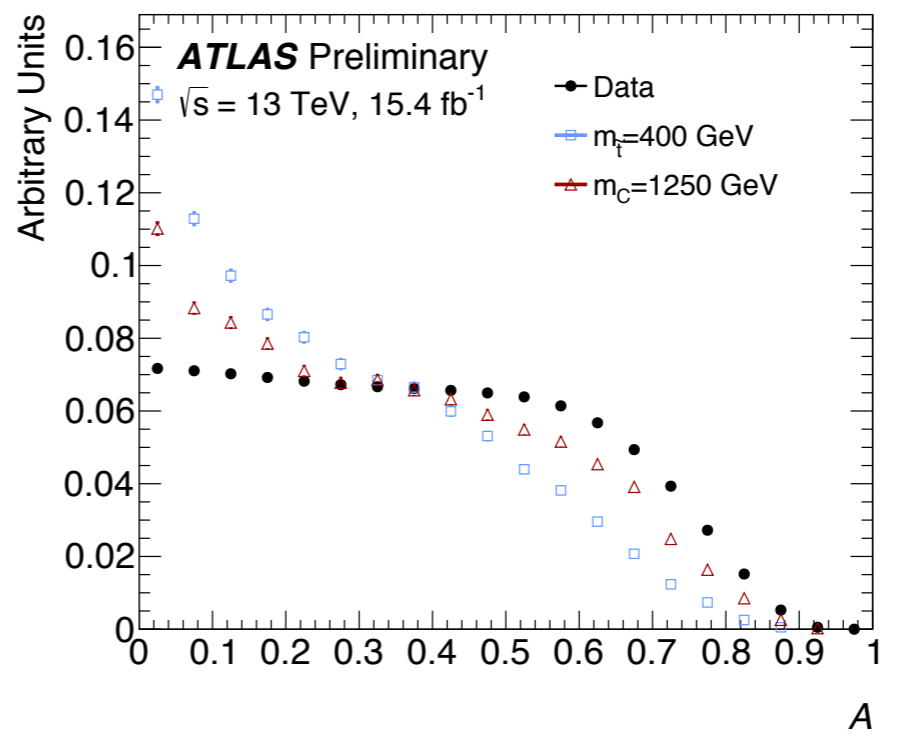
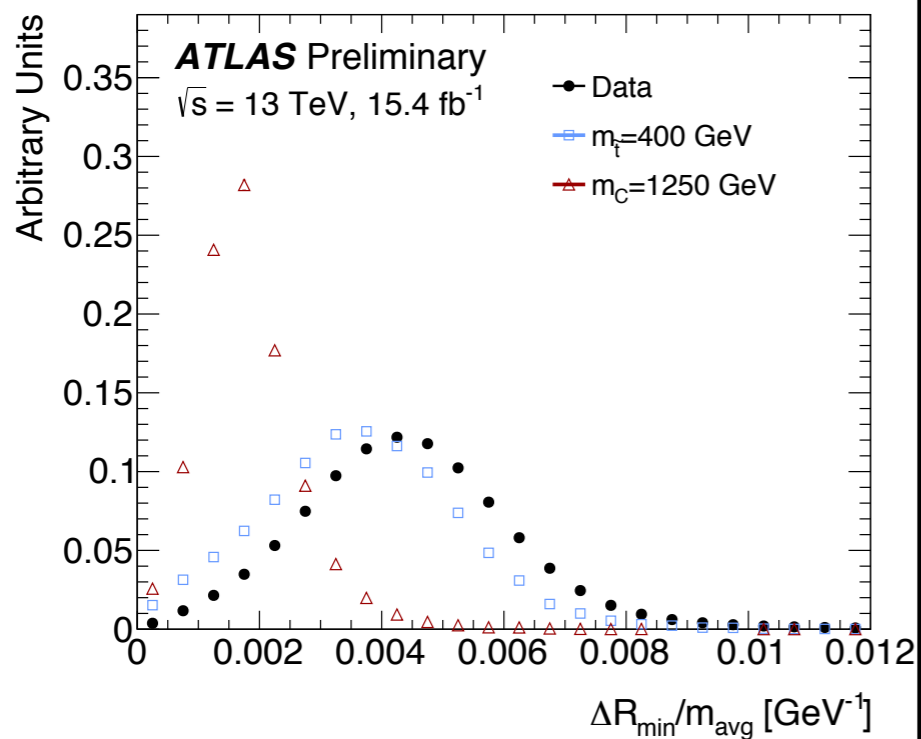
# Trigger level dijet analysis: ATLAS



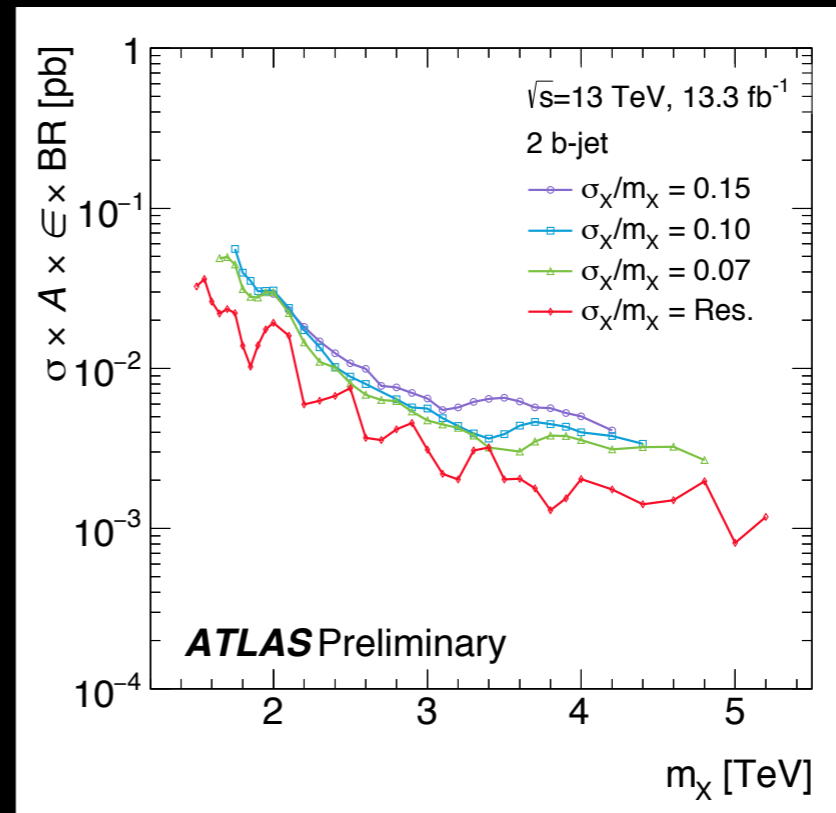
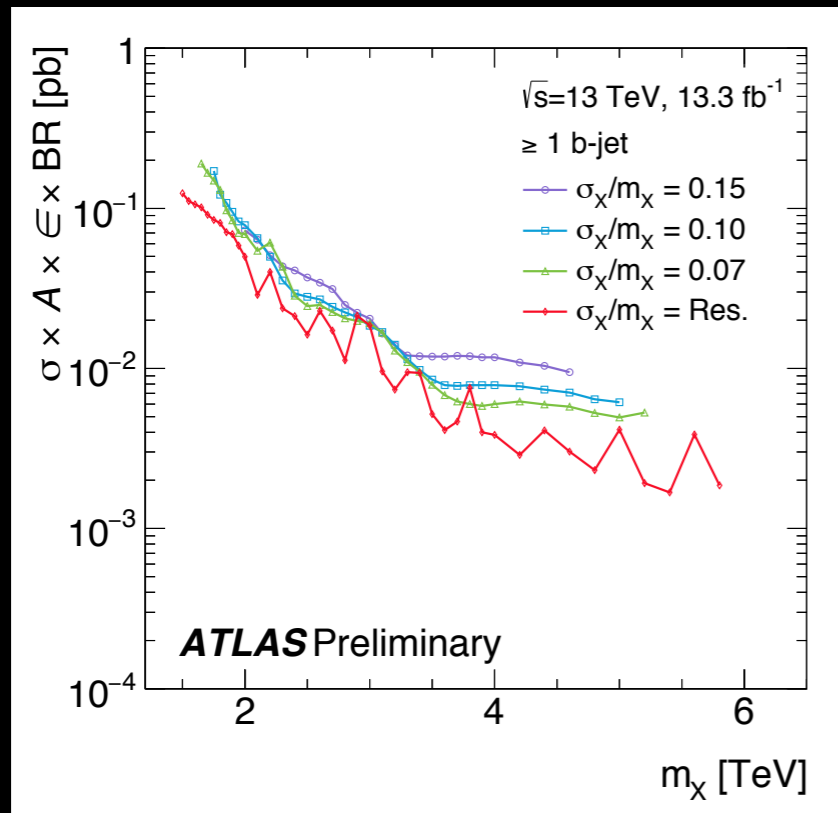
Dijet invariant mass built from leading and subleading trigger (HLT) jets compared to  $m_{jj}$  for offline jets in data, as a function of randomly chosen HLT or offline  $m_{jj}$  to reduce resolution biases. Events are selected using the HLT\_j110 single jet trigger. Selected events have leading jet  $p_T > 185$  GeV, subleading jet  $p_T > 85$  GeV and  $|y^*| < 0.6$ . The average  $m_{jj}$  response of trigger jets relative to offline jets is shown in black and it is within 1% of unity, independent of jet  $m_{jj}$  (<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-030/>)

Couplings above the solid lines are excluded. Markers indicate the mass and coupling points that have been simulated. The solid and dashed curves represent the observed and expected limit, respectively. They are obtained from the simulated points, correctly accounting for the scaling of the signal cross-section with  $g_{q2}$ . Limits for masses including and above 550 GeV are derived from the  $m_{jj}$  distribution with  $|y^*| < 0.6$  while those at and below 550 GeV are derived using the distribution with  $|y^*| < 0.3$ .

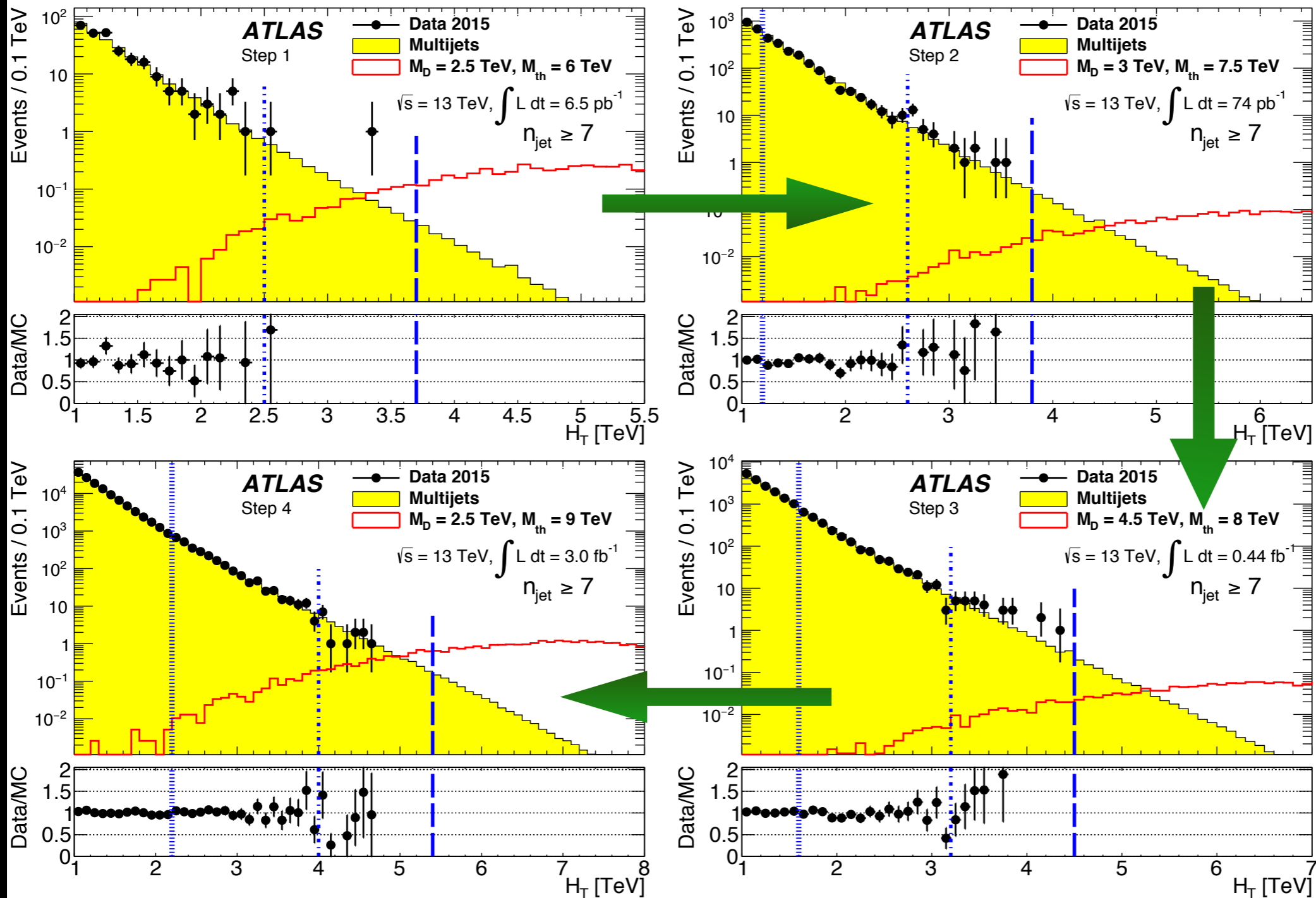
# Quad-jet analysis: ATLAS



# Search for new physics with heavy flavor jets



# Background Estimation: ATLAS



Use bootstrapping to compute background

Define control ( $C < H_T < V$ ), validation ( $V < H_T < S$ ) and signal ( $H_T > S$ ) regions