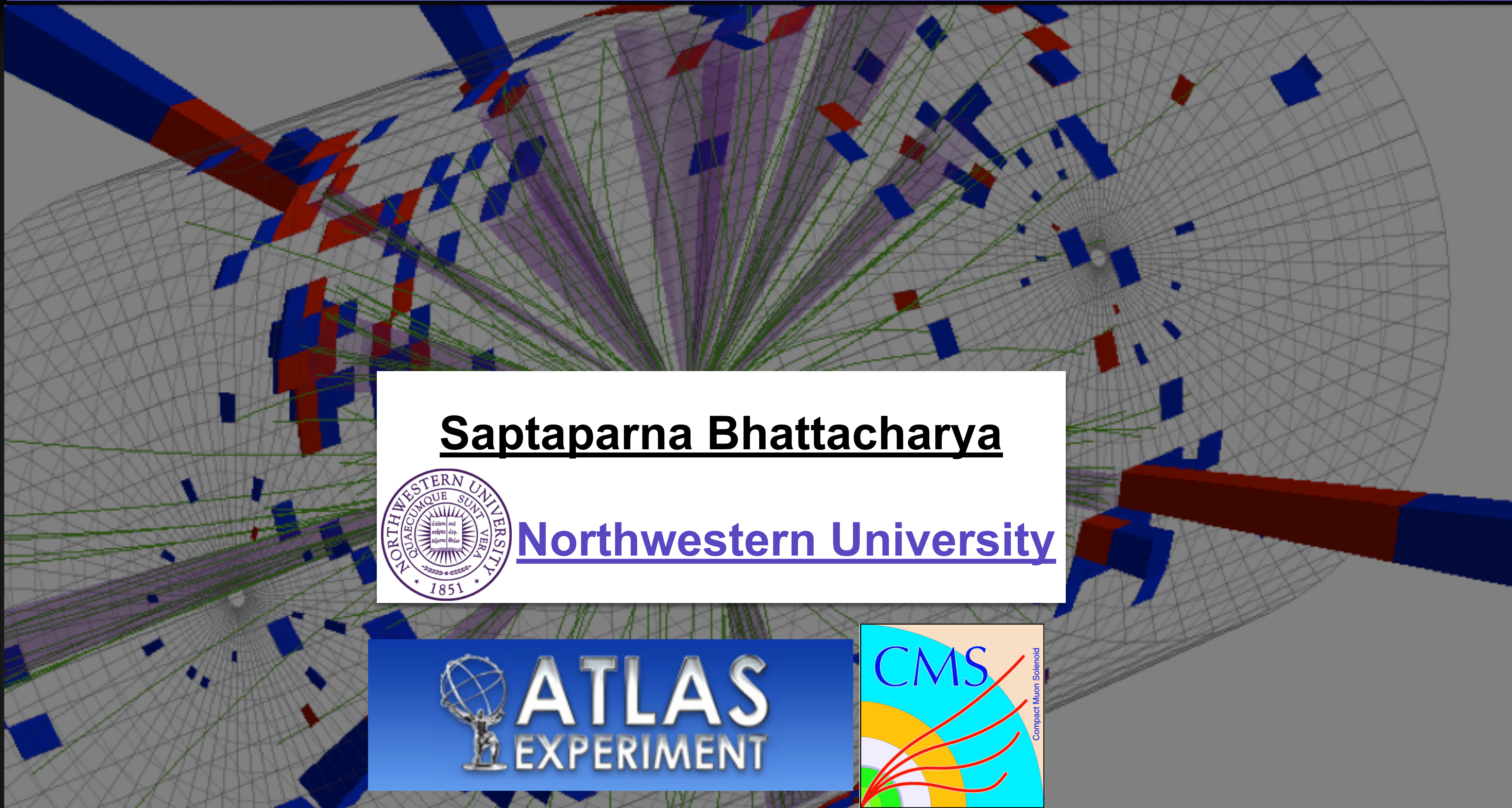
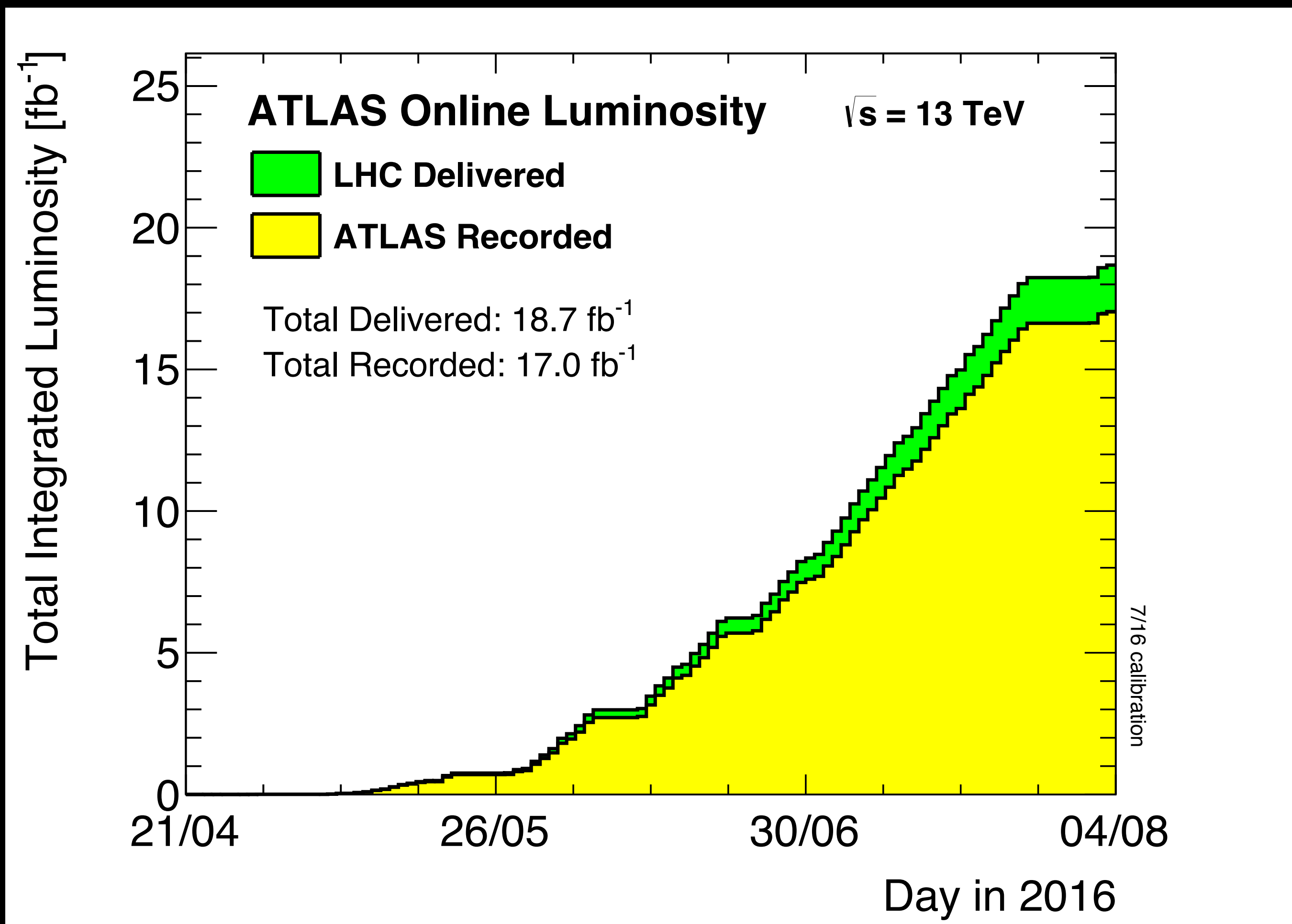
Search for new physics in dijet and multijet final states with Run 2 data at 13 TeV

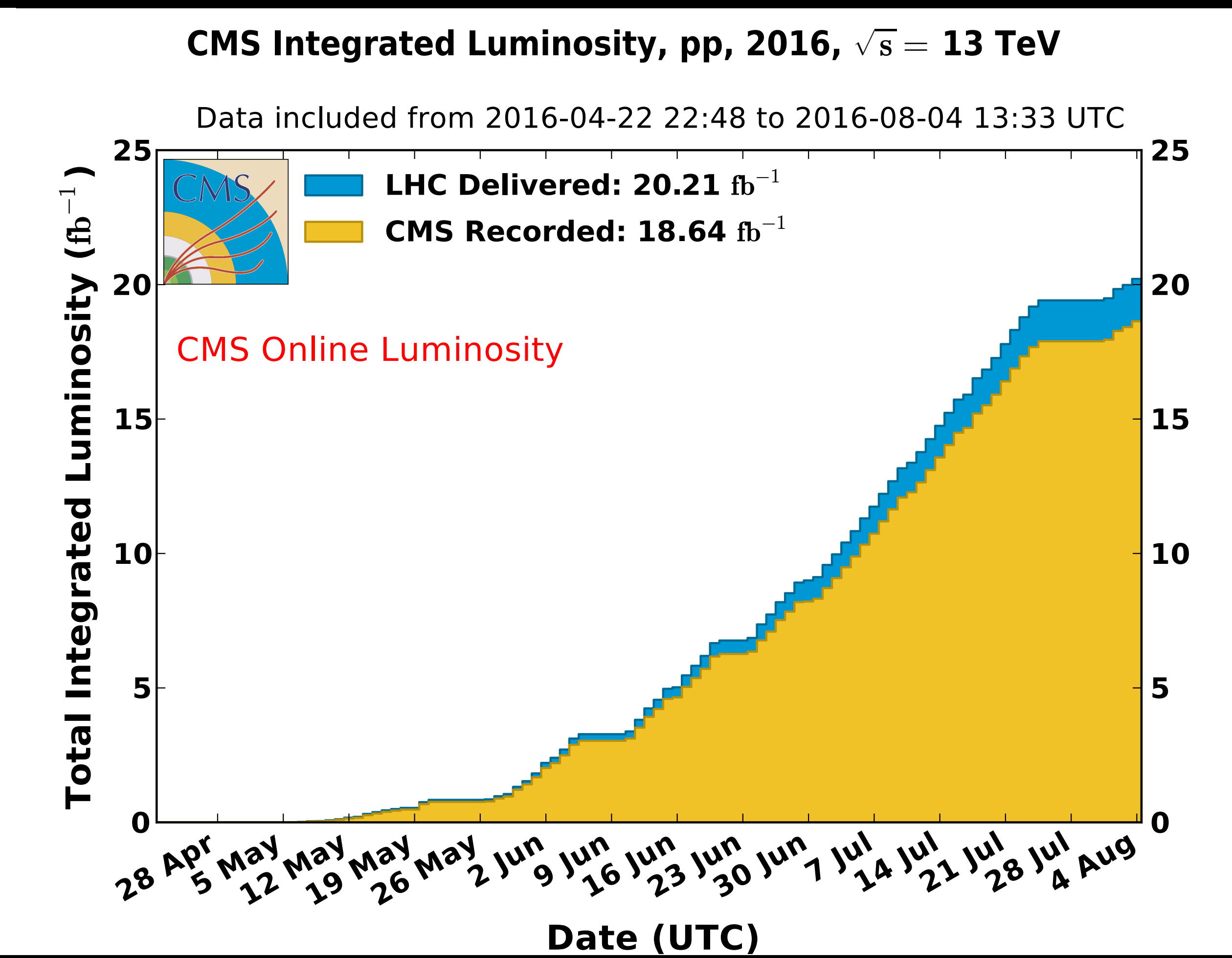


Saptaparna Bhattacharya

Northwestern University

Total data collected





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

Motivation: Jet based final states

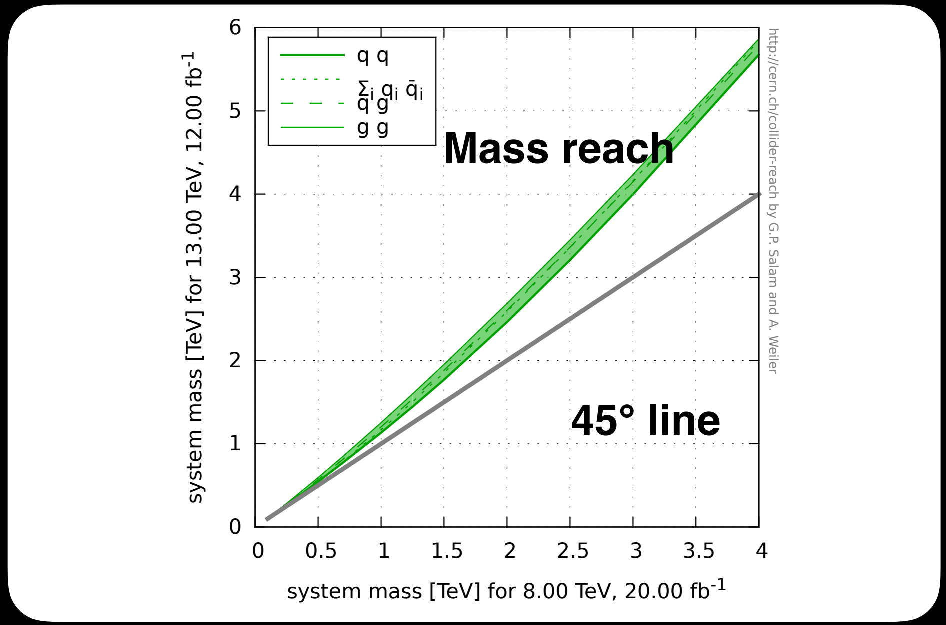
- 2 → 2 scattering processes are described well by QCD in the Standard Model (SM). Departure from SM implies New Physics (NP).

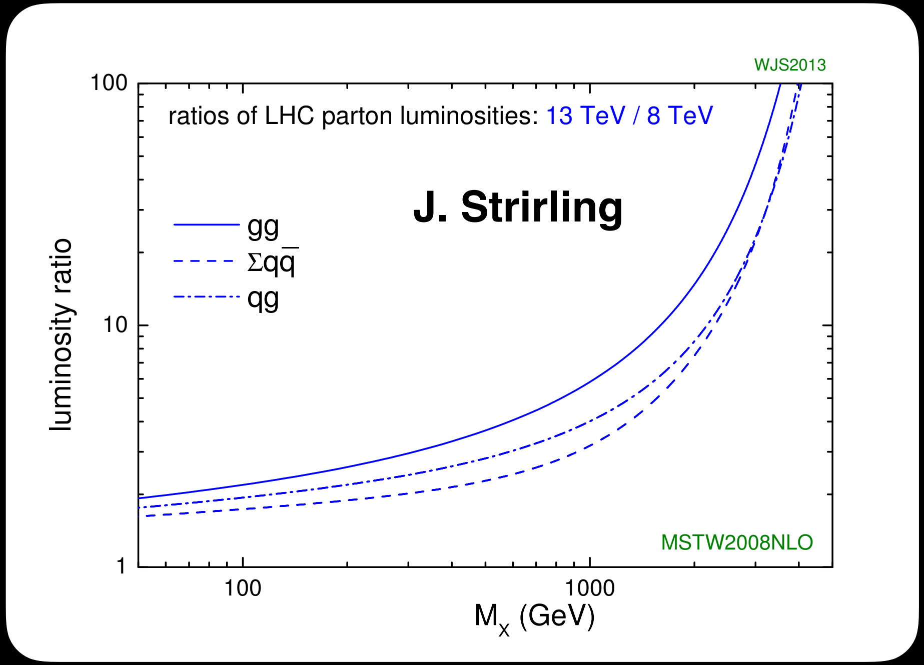
- Useful variables: Dijet invariant mass (m_{jj}), dijet angular distribution, typically expressed as:

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

where y1 and y2 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

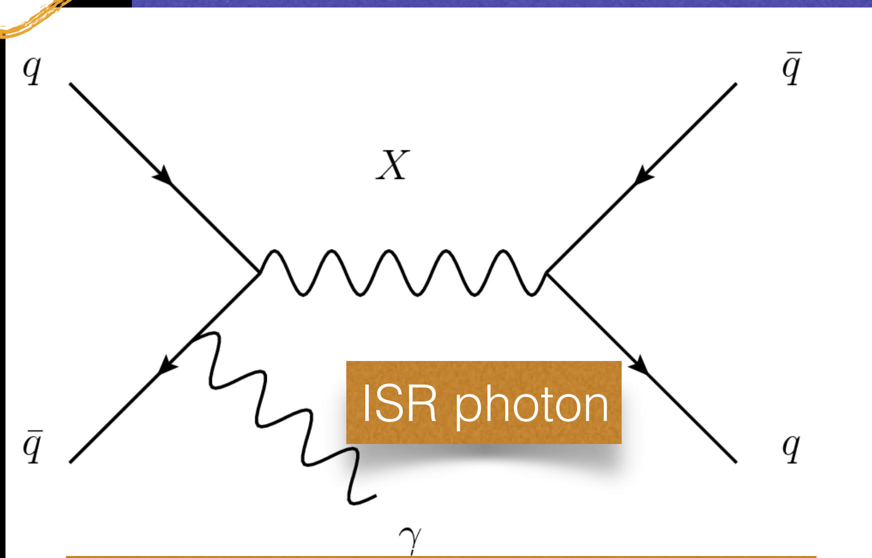




Parton luminosity

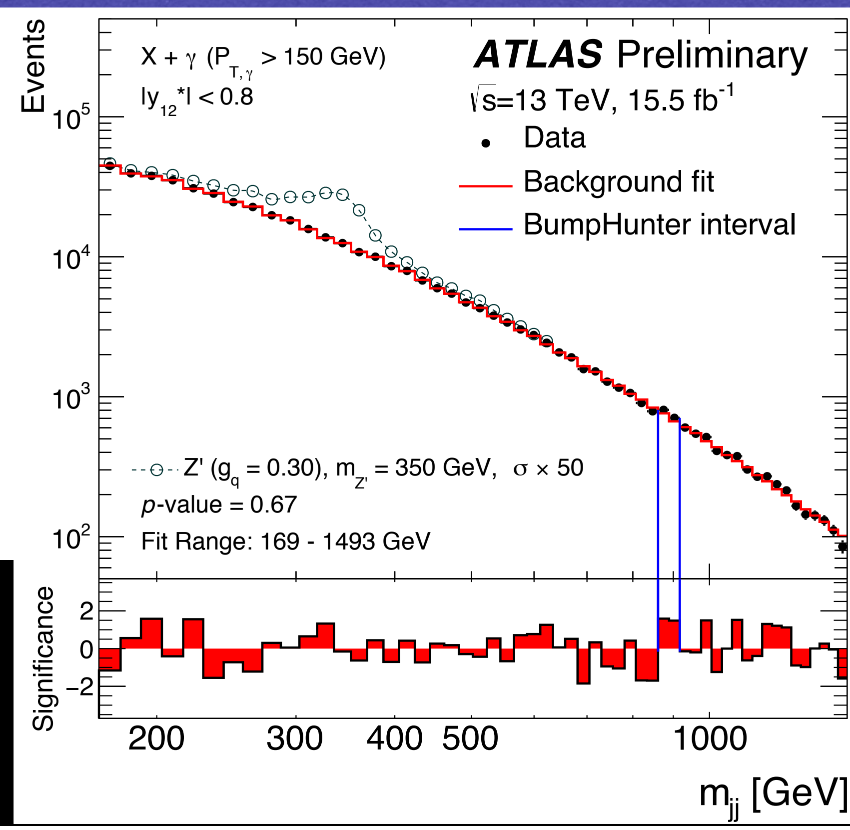
✨✨ Hot off the press! ✨✨

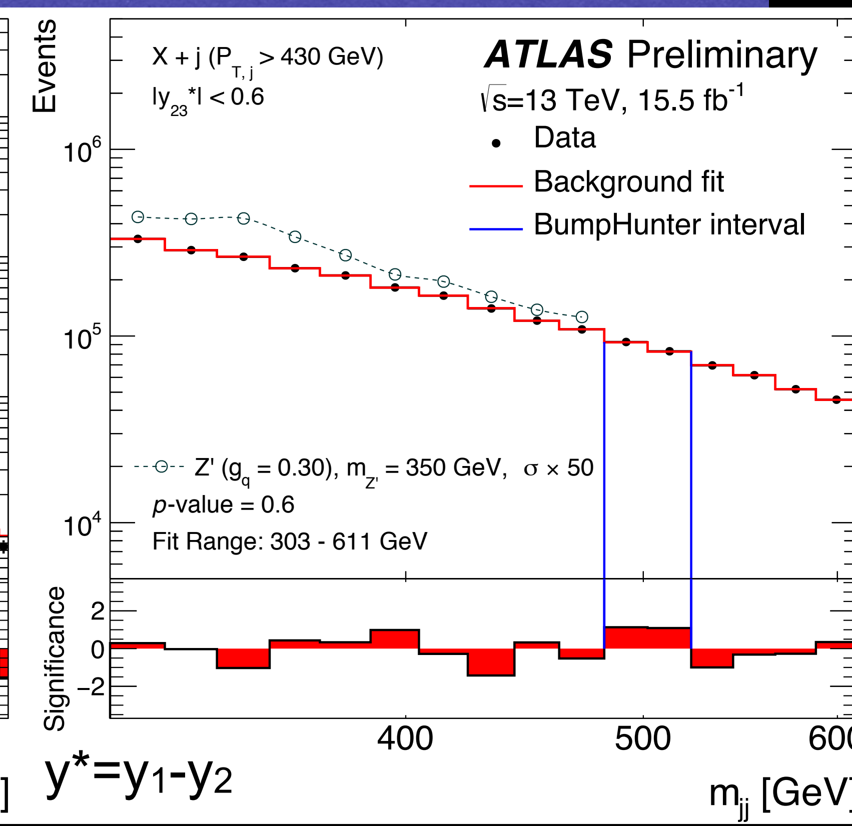
Low-mass dijet analysis: ATLAS



Analysis sensitive to ISR jets too

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



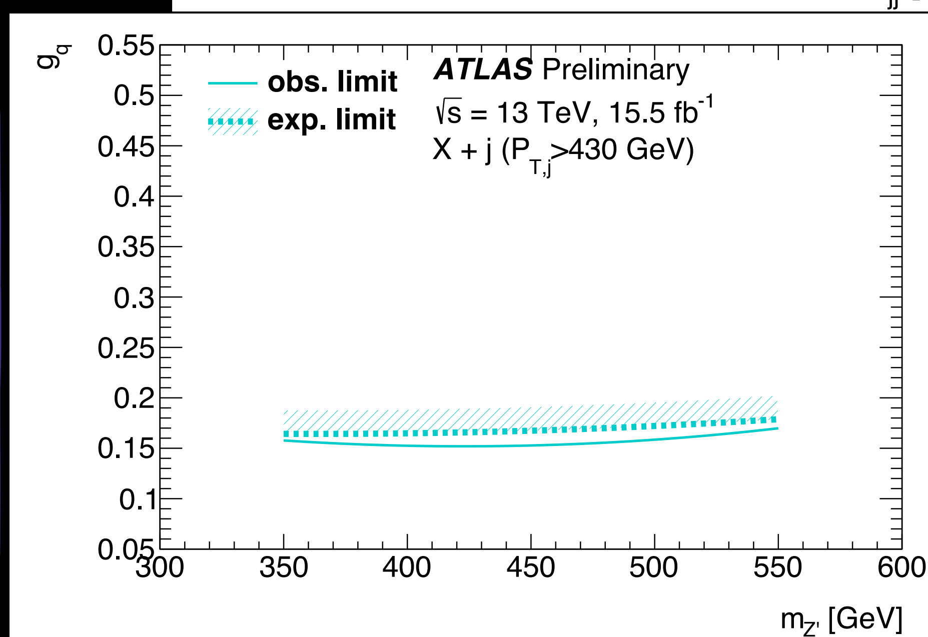


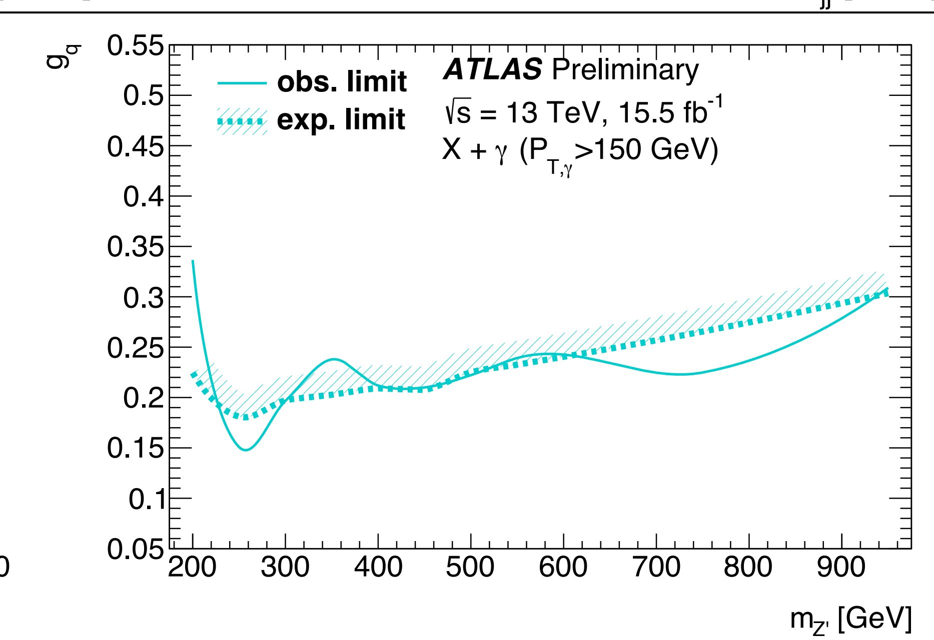
$y^* = y_1 - y_2$

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 mZ′ = 350 GeV and g_q above 0.18 at mZ′ = 550 GeV

X+gamma: Z′ bosons for g_q above 0.15 at mass mZ′ = 250 GeV are excluded

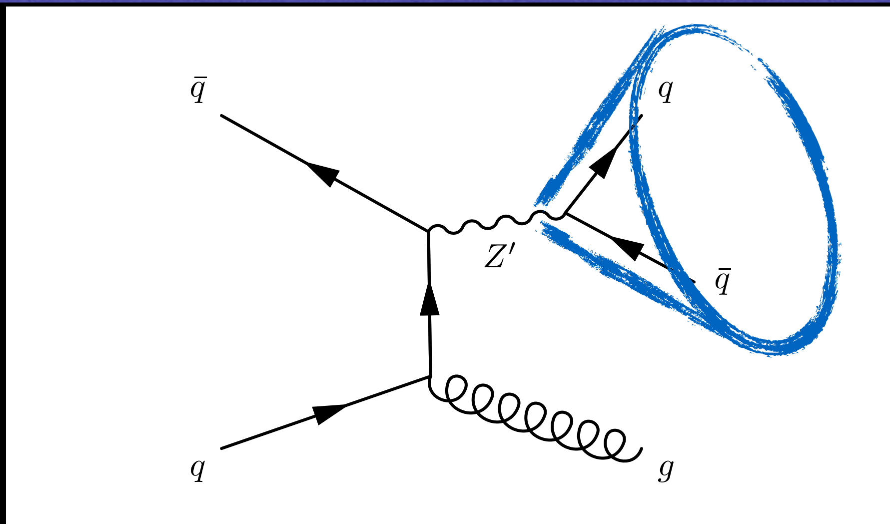


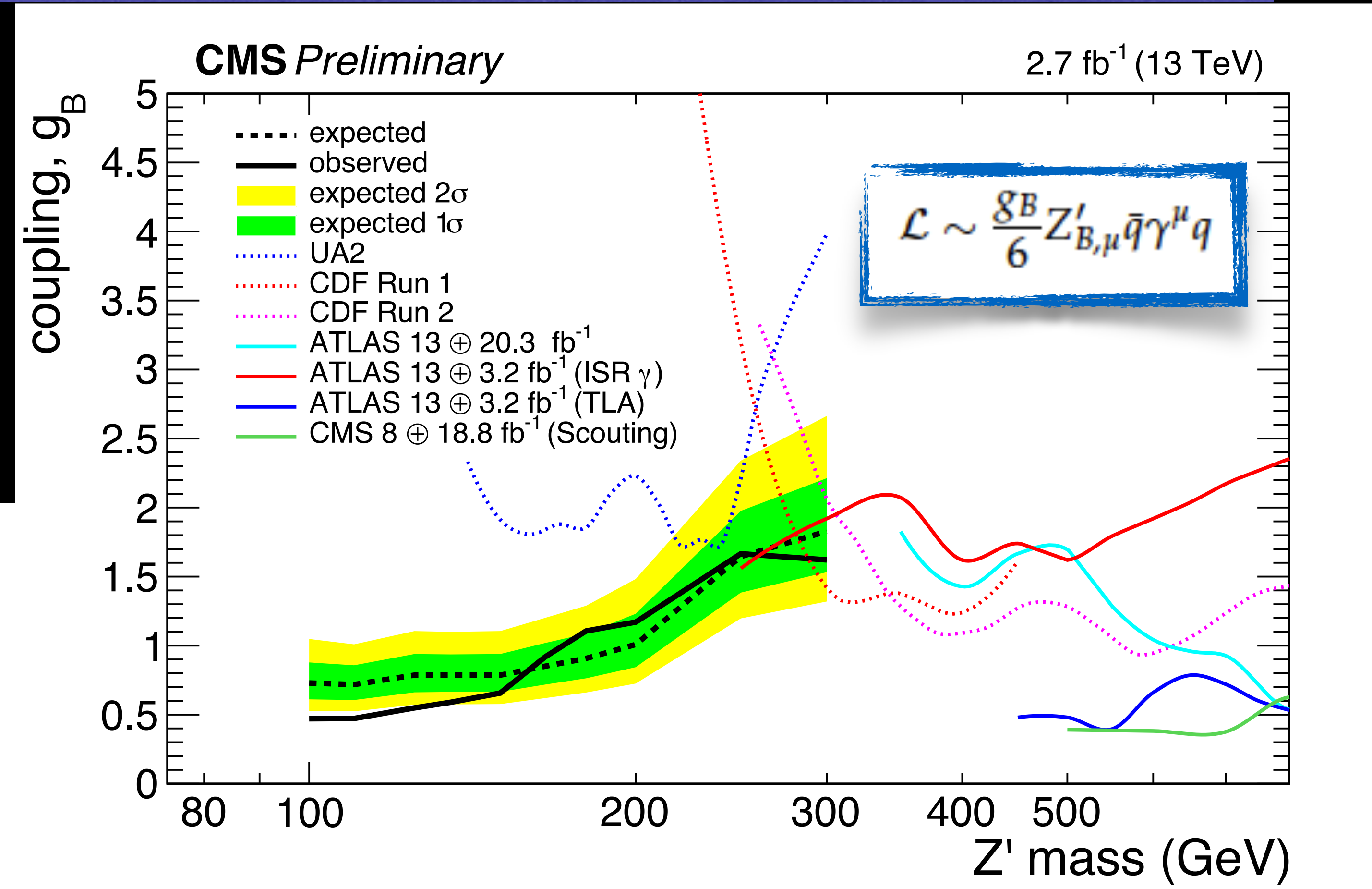


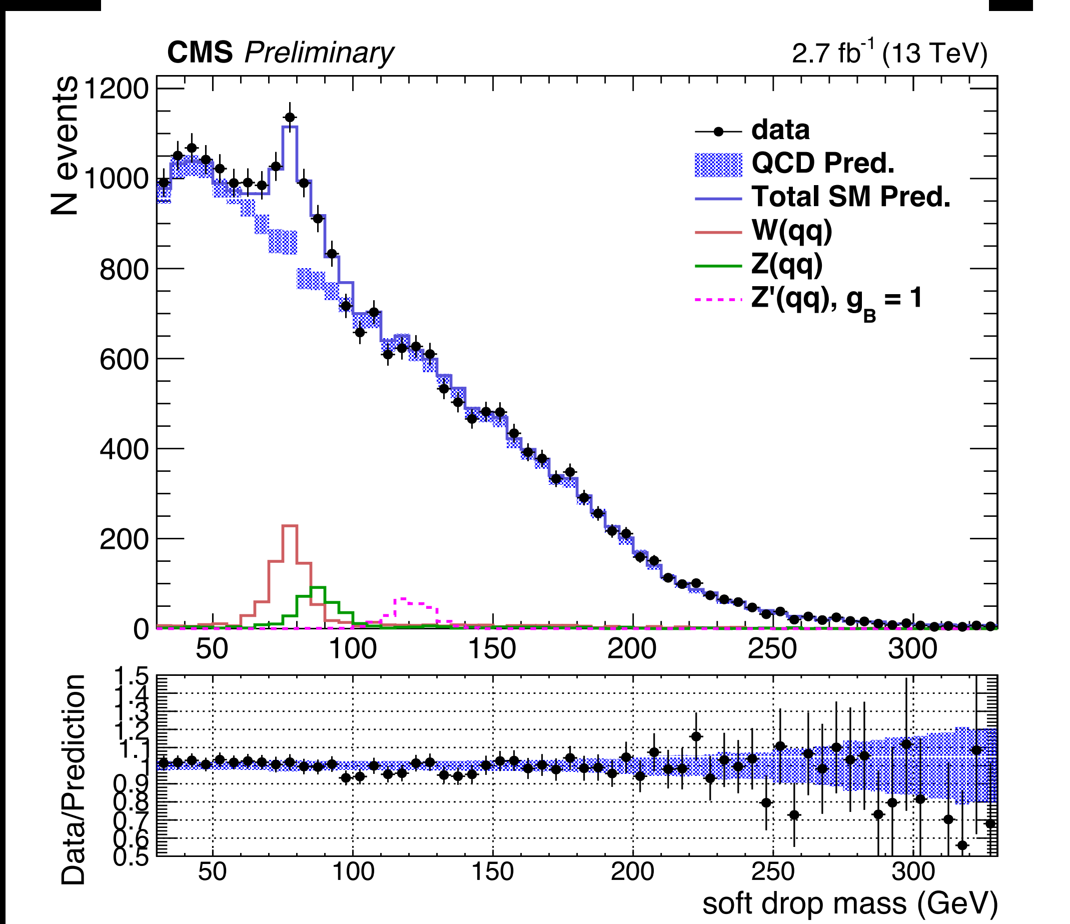
ICHEP 2016, Chicago **August 5th, 2016**

Hot off the press!

Low-mass dijet analysis: CMS

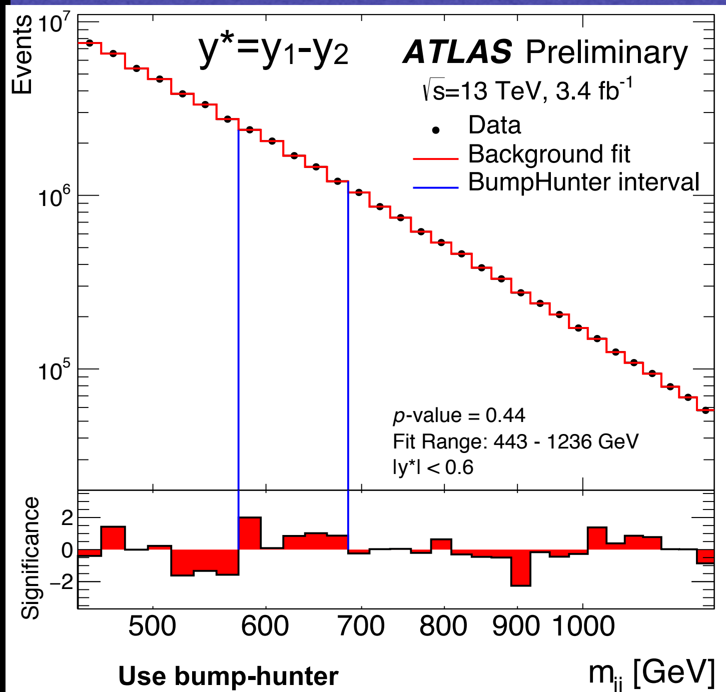




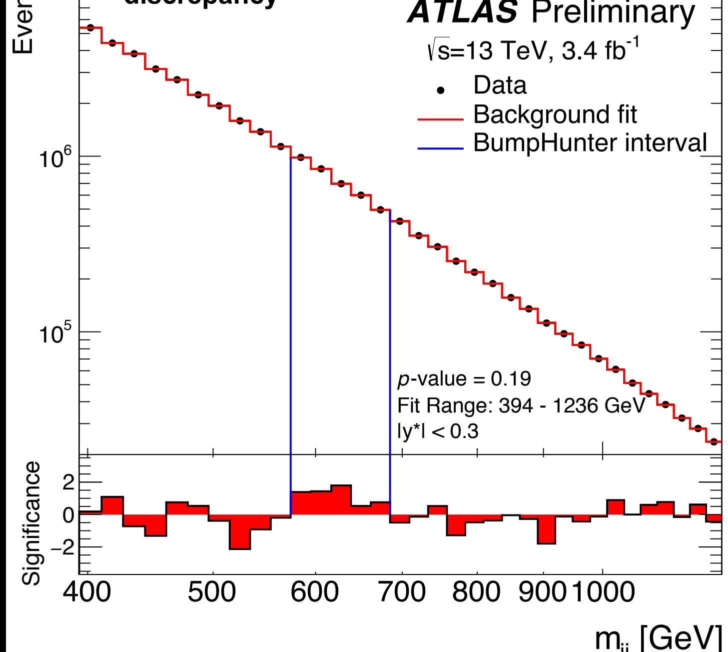


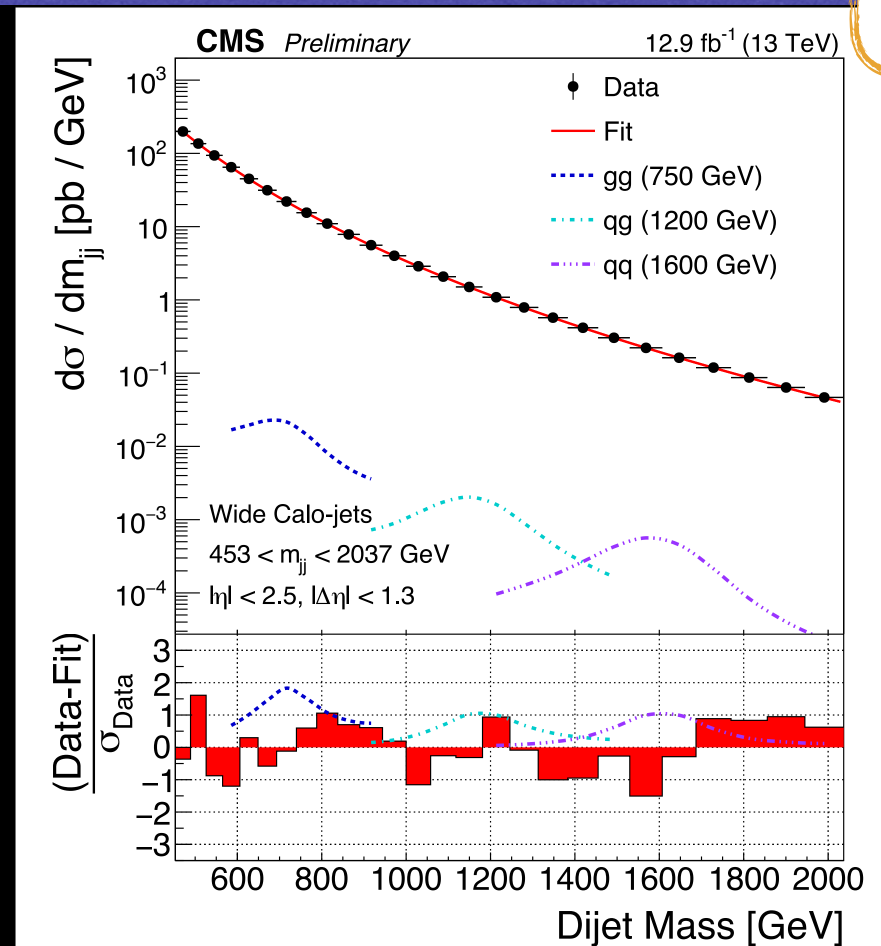
- **Uses boosted topology: soft drop criterion**
- **Background determined from side-band regions in data**
- **First results in the region below 140 GeV**
- **Most sensitive in the mass regime less than 300 GeV**

Trigger Level Searches with Dijets



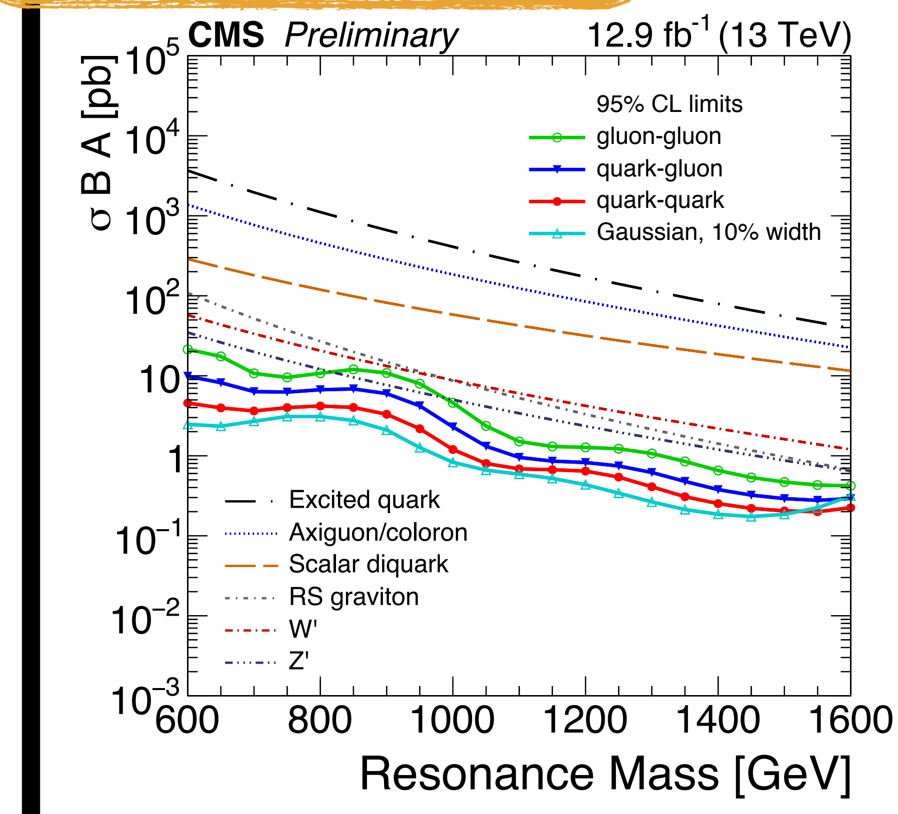
Use bump-hunter algorithm to identify discrepancy





Used the novel technique of data scouting

✨✨ Hot off the press! ✨✨



- 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)

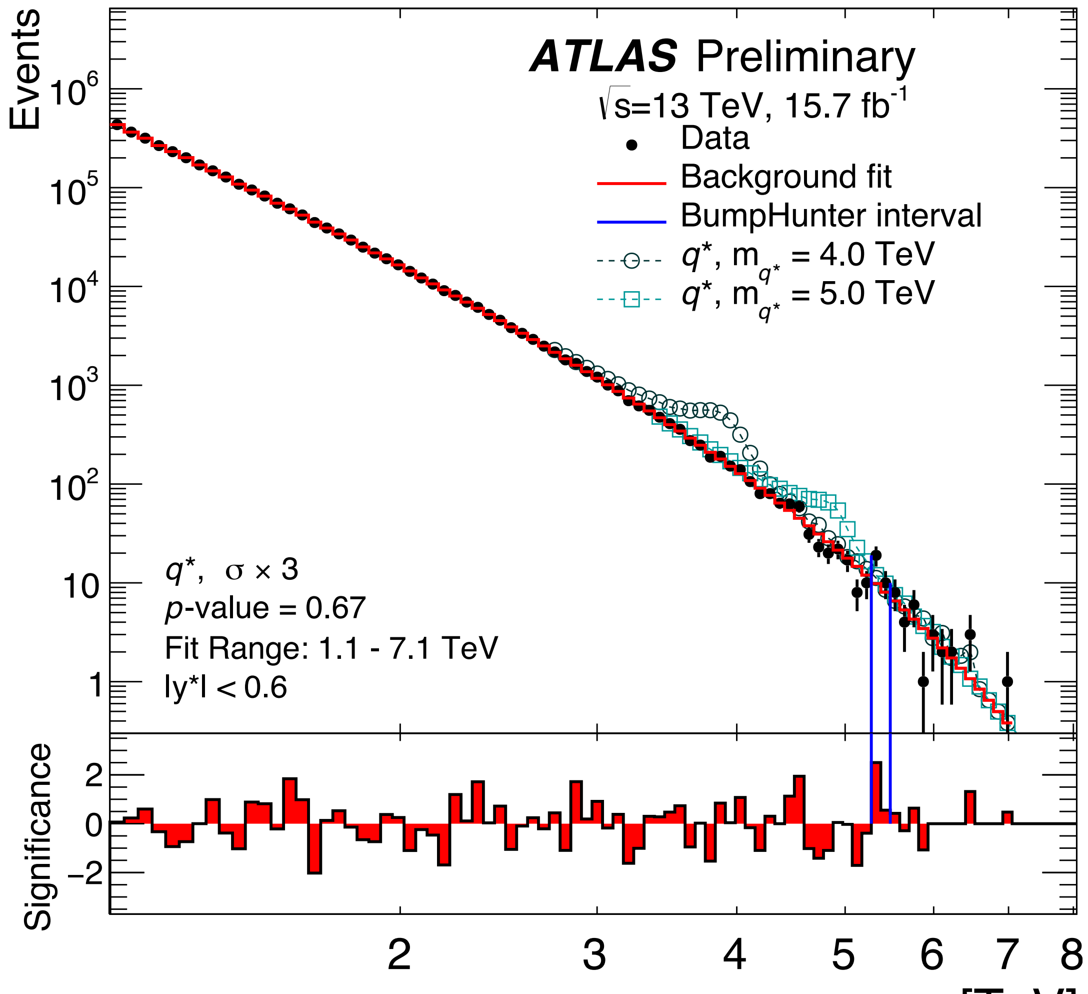
CMS: Used to search for dijet resonances between 0.6 TeV and 1.6 TeV at CMS

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

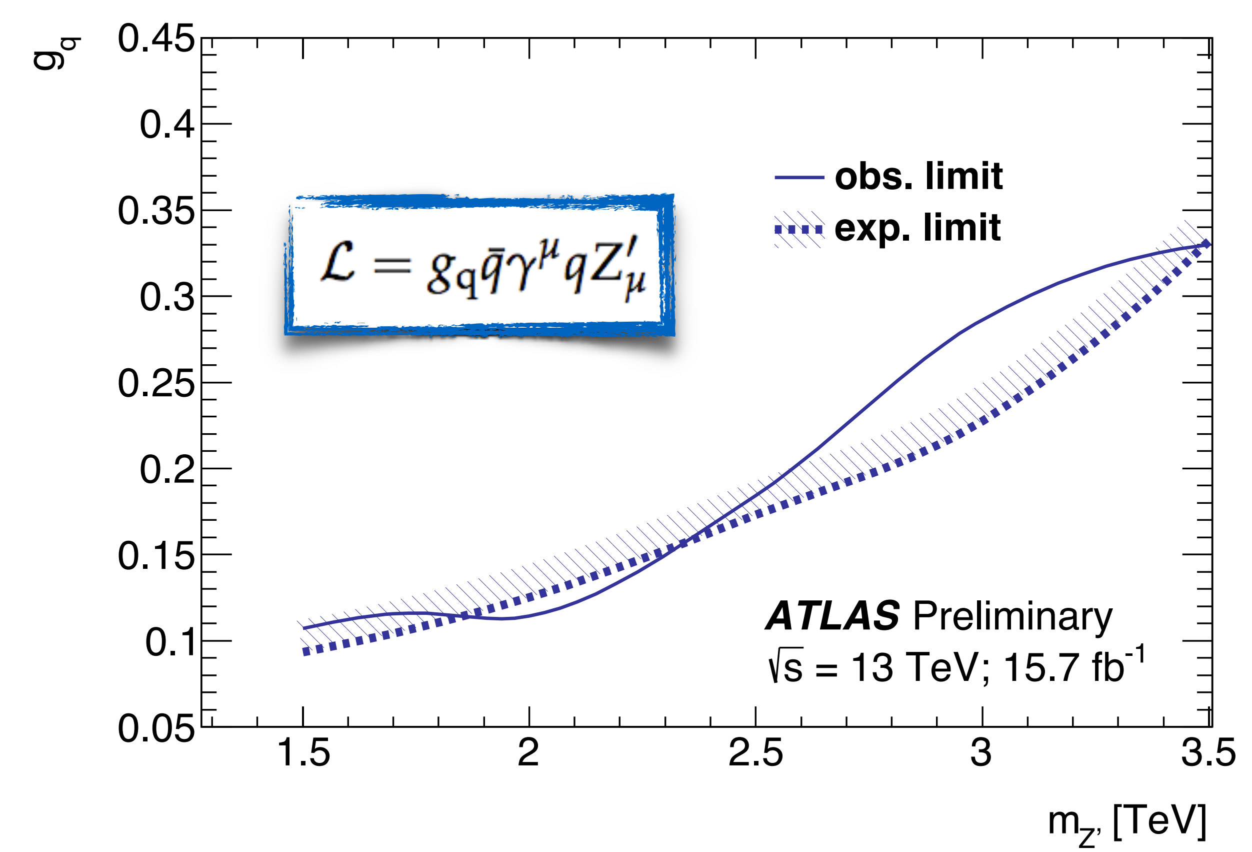
No evidence for a 750 GeV dijet resonance. Both experiments set limits

Hot off the press!

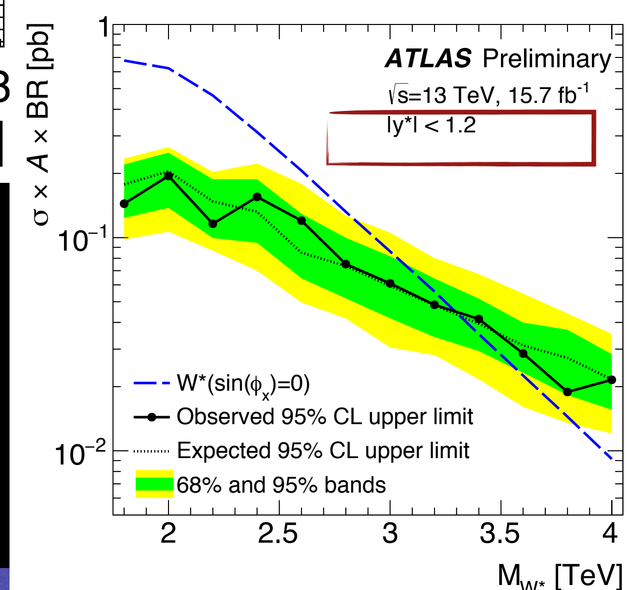
High-mass dijet analysis: ATLAS

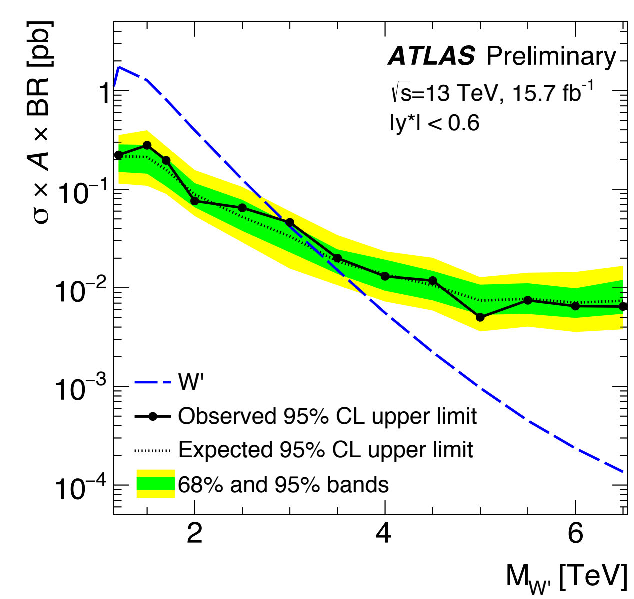


Dijet mass spectrum is fit with a parameterization



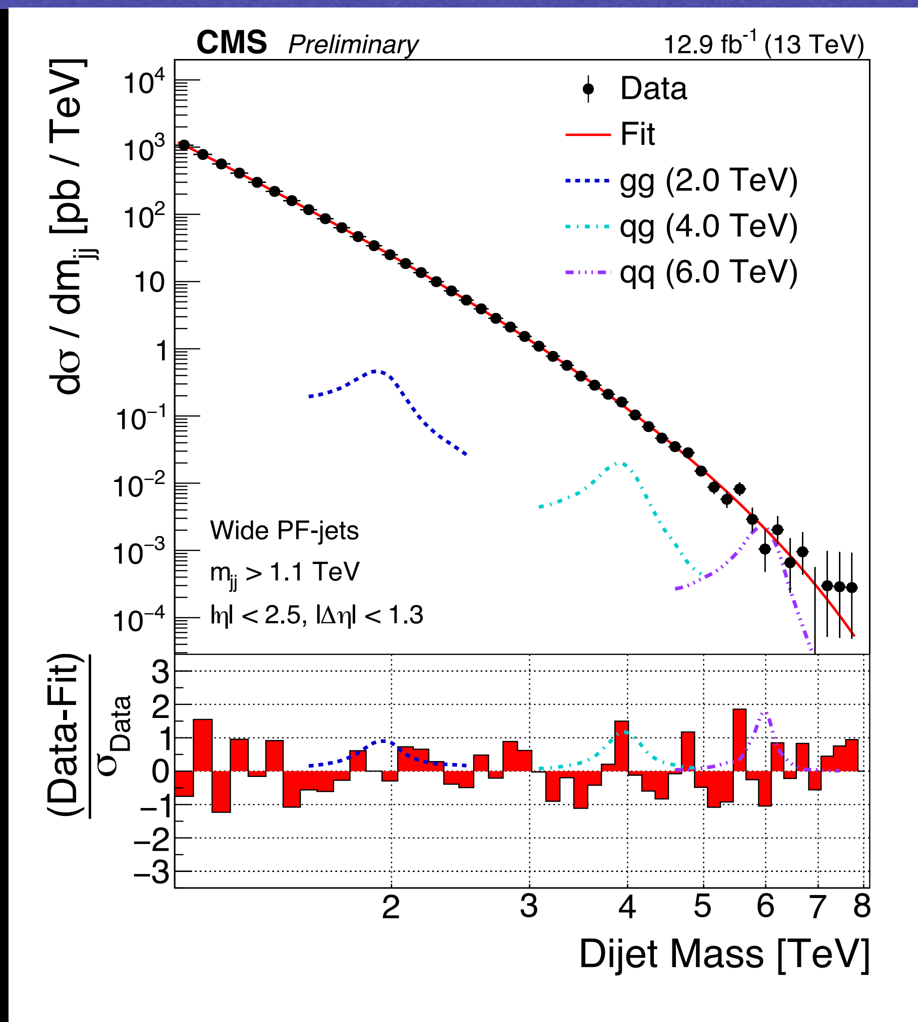
Model	95% CL Exclusion limit Observed	95% CL Exclusion limit Expected
Quantum black holes, ADD (BlackMax generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions (η_{LL} =+1)	12.6 TeV	13.7 TeV
Contact interactions (η_{LL} =-1)	19.9 TeV	23.7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

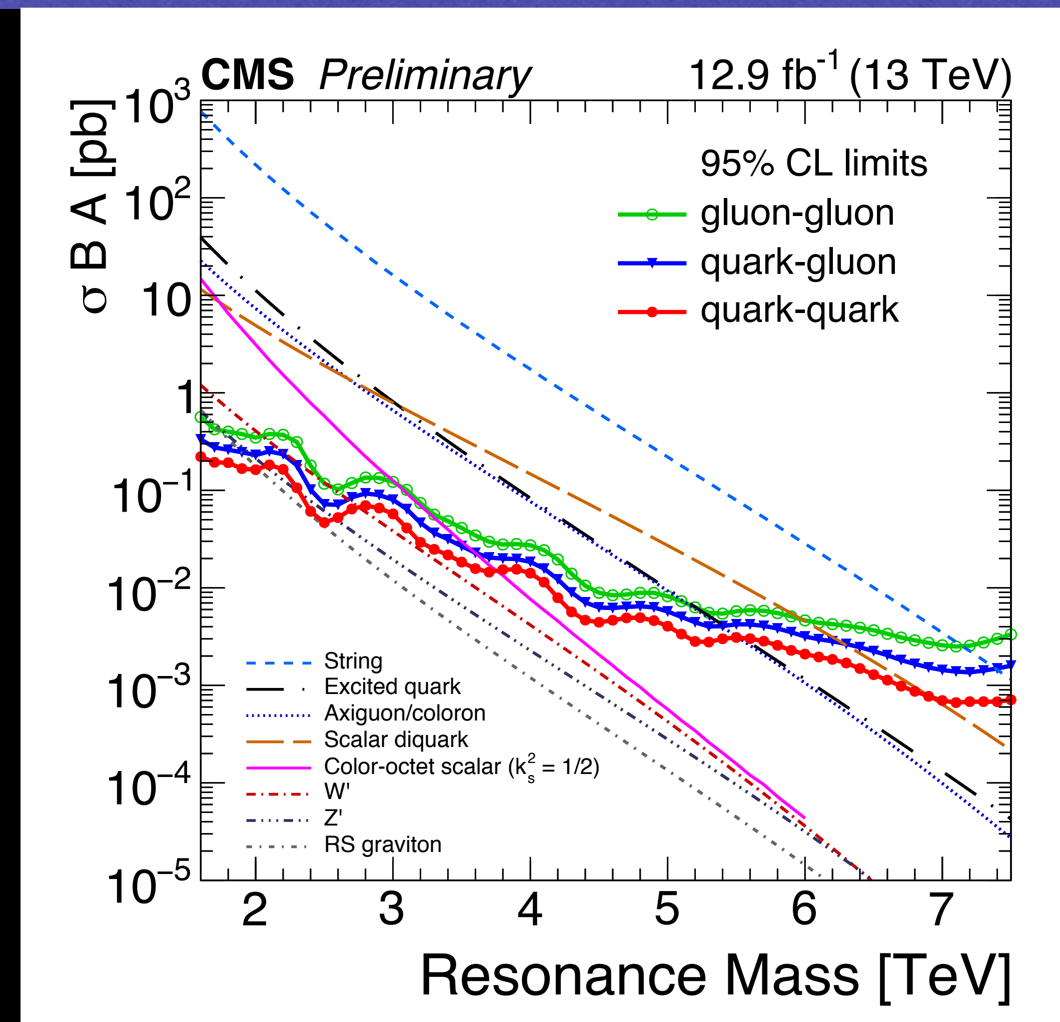




Hot off the press!

High-mass dijet analysis: CMS



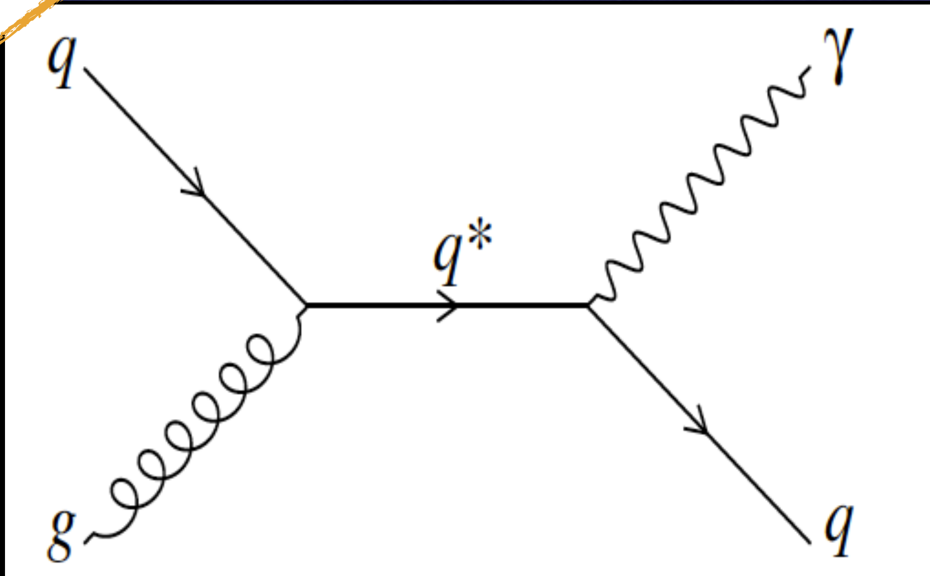


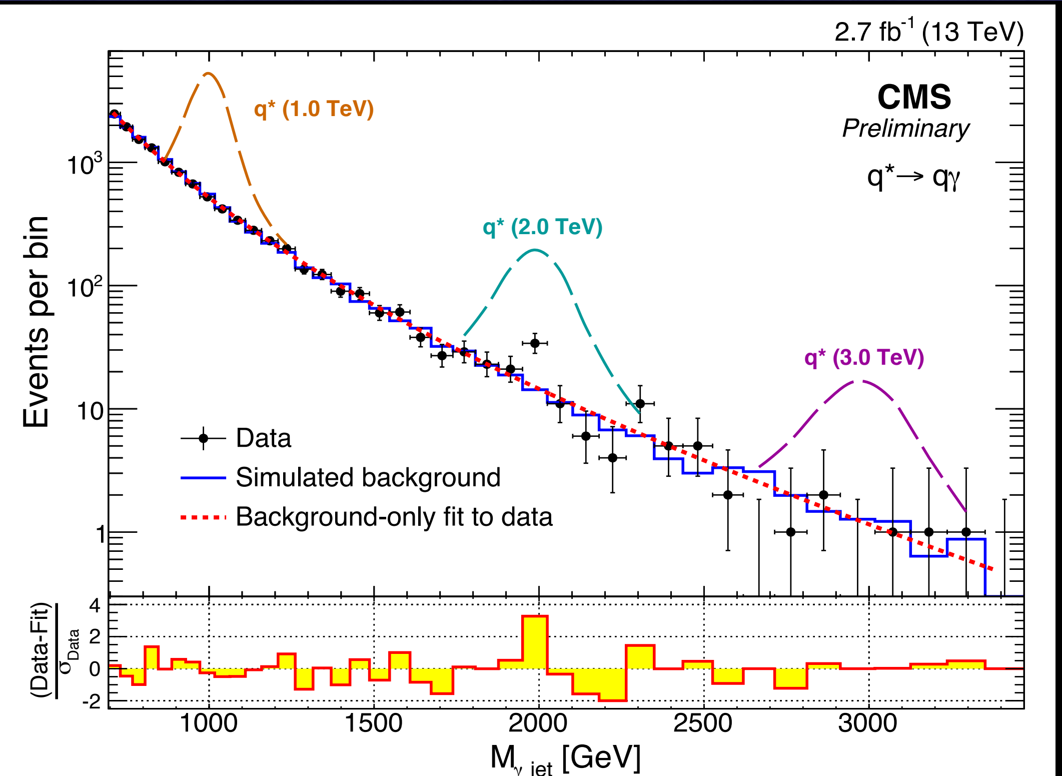
- **Dijet mass spectrum is fit with a parameterization**
- **Limits are set on generic quark-quark, quark-gluon and gluon-gluon resonances.**
- **Mass limits extended on eight models**

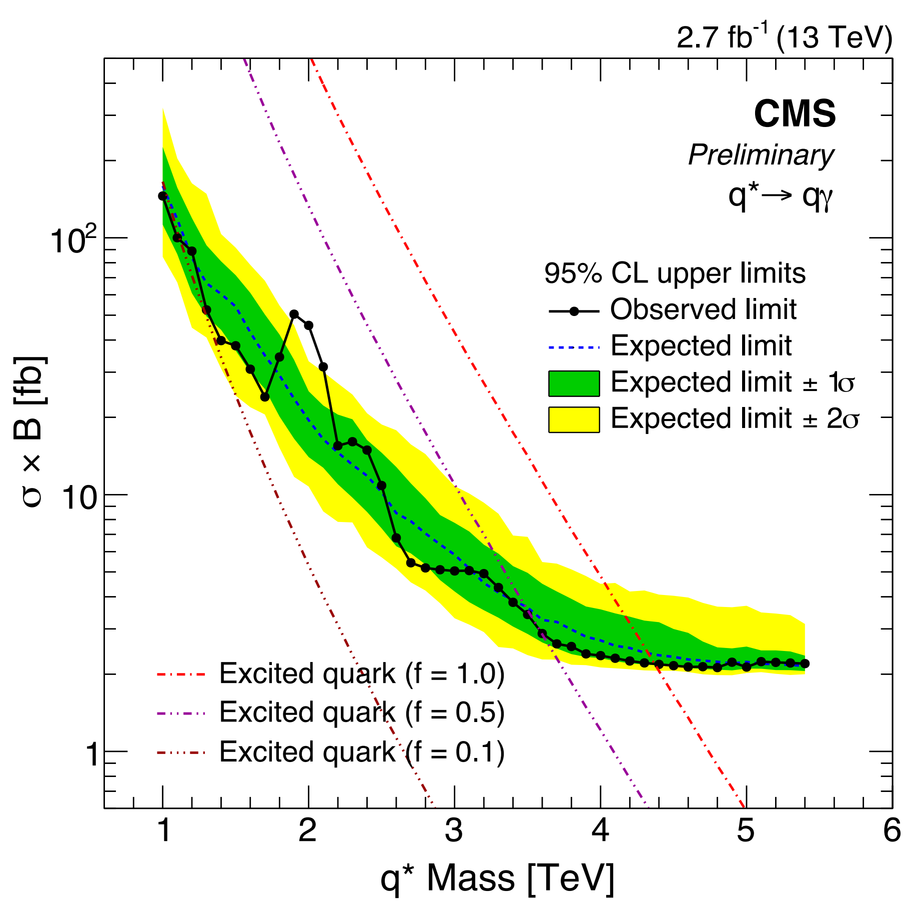
Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
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)

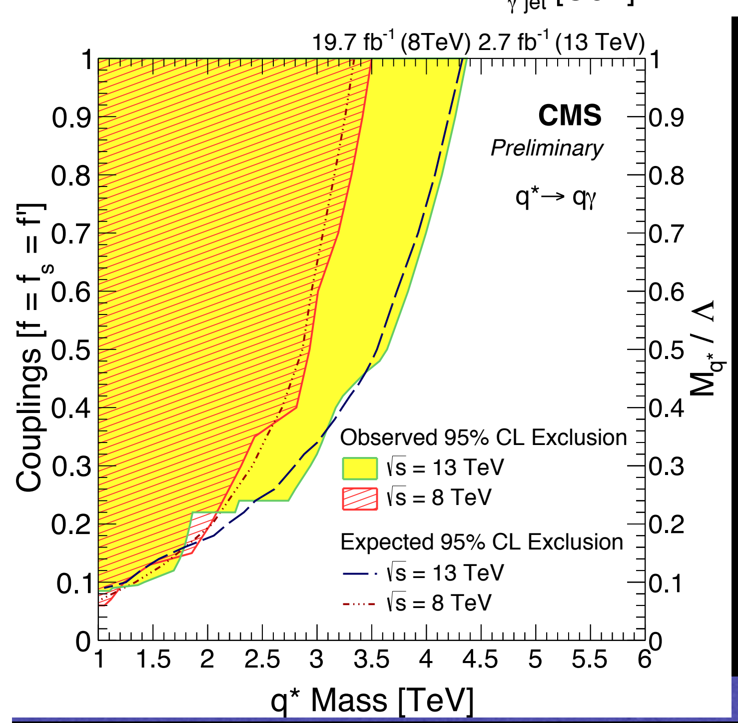
Search for excited quarks

✨✨ Hot off the press! ✨✨





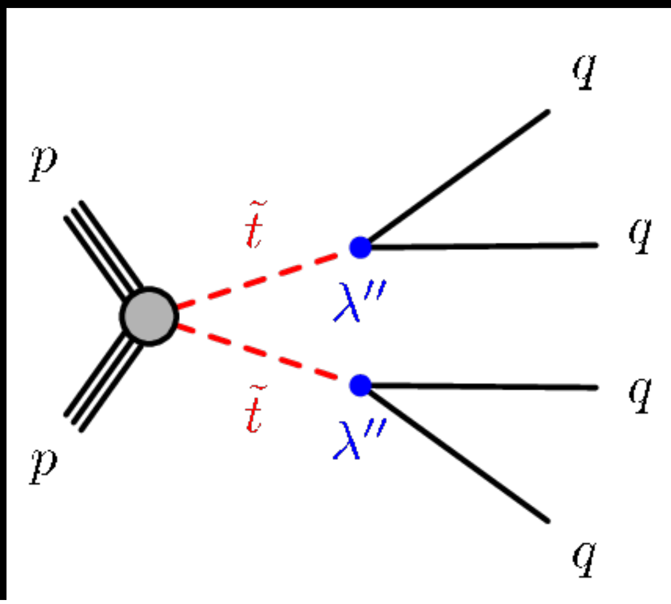


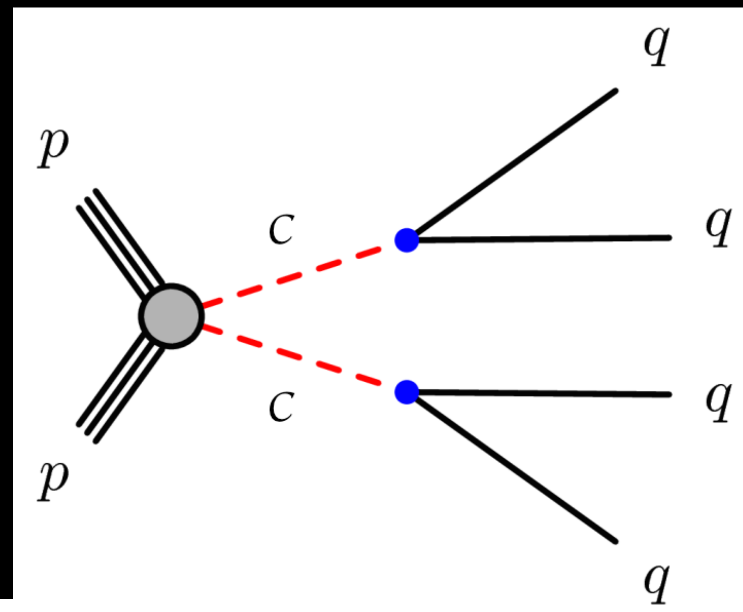


- **An excited quark state with mass 1.0 < Mq < 4.37 TeV is excluded at 95% CL . The exclusion varies between 4.37 and 1.36 TeV based on the coupling.**
- **CMS Run II significantly extends the Run I limit**

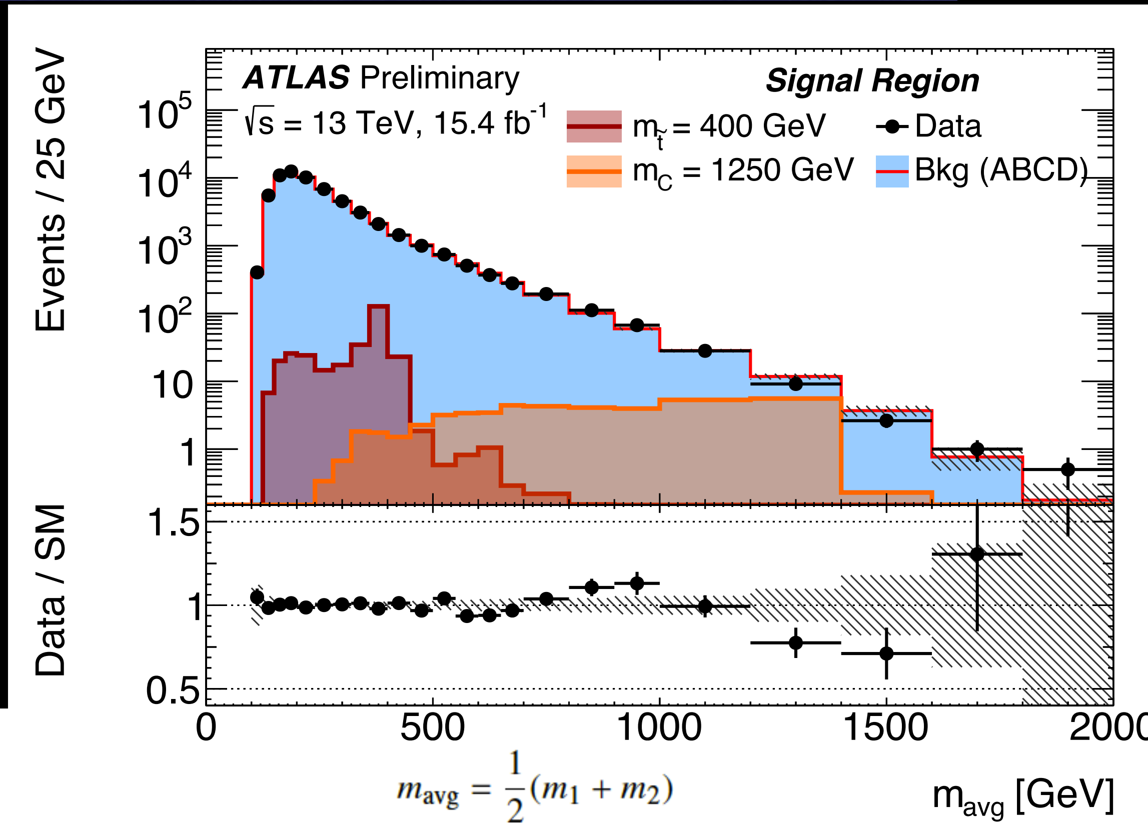
✨✨ Hot off the press! ✨✨

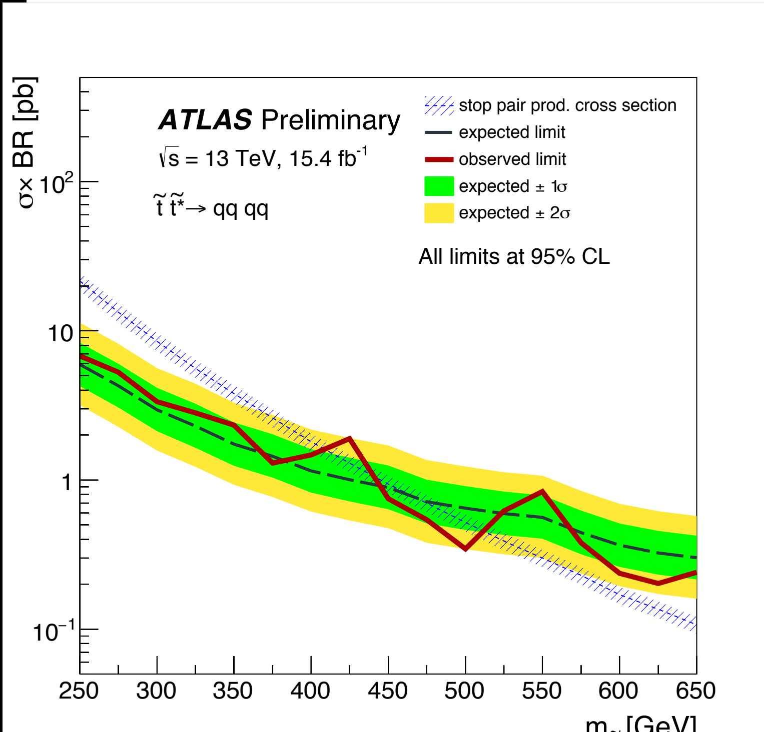
Search for new physics in a four jet final state

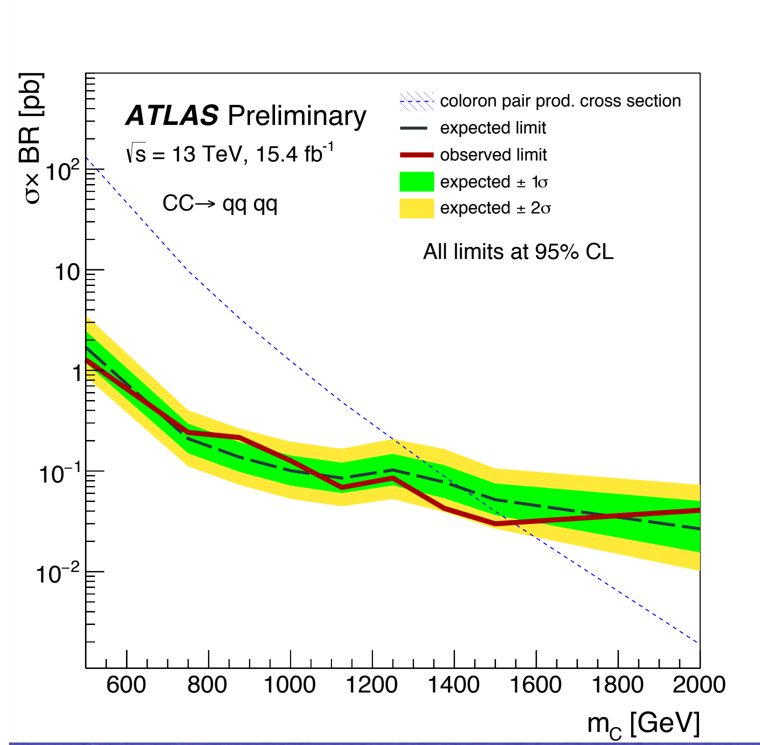




$$W_{\rm RPV} = \kappa_i L_i H_d + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$







- **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 O(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 MD, 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:

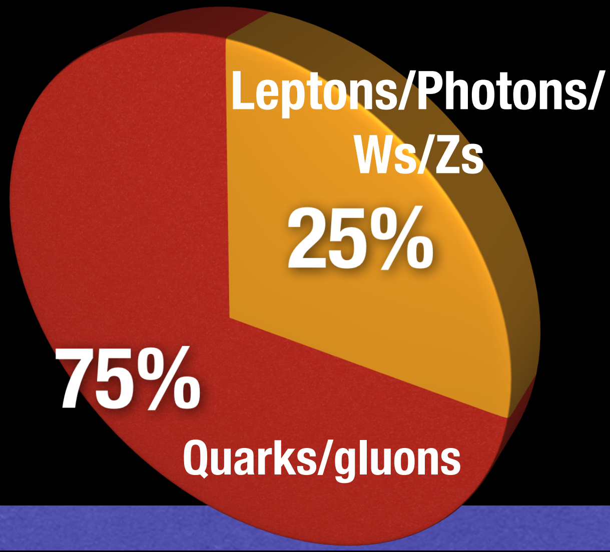
$$r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{\rm BH}}{M_D} \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{\frac{1}{n+1}}$$

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

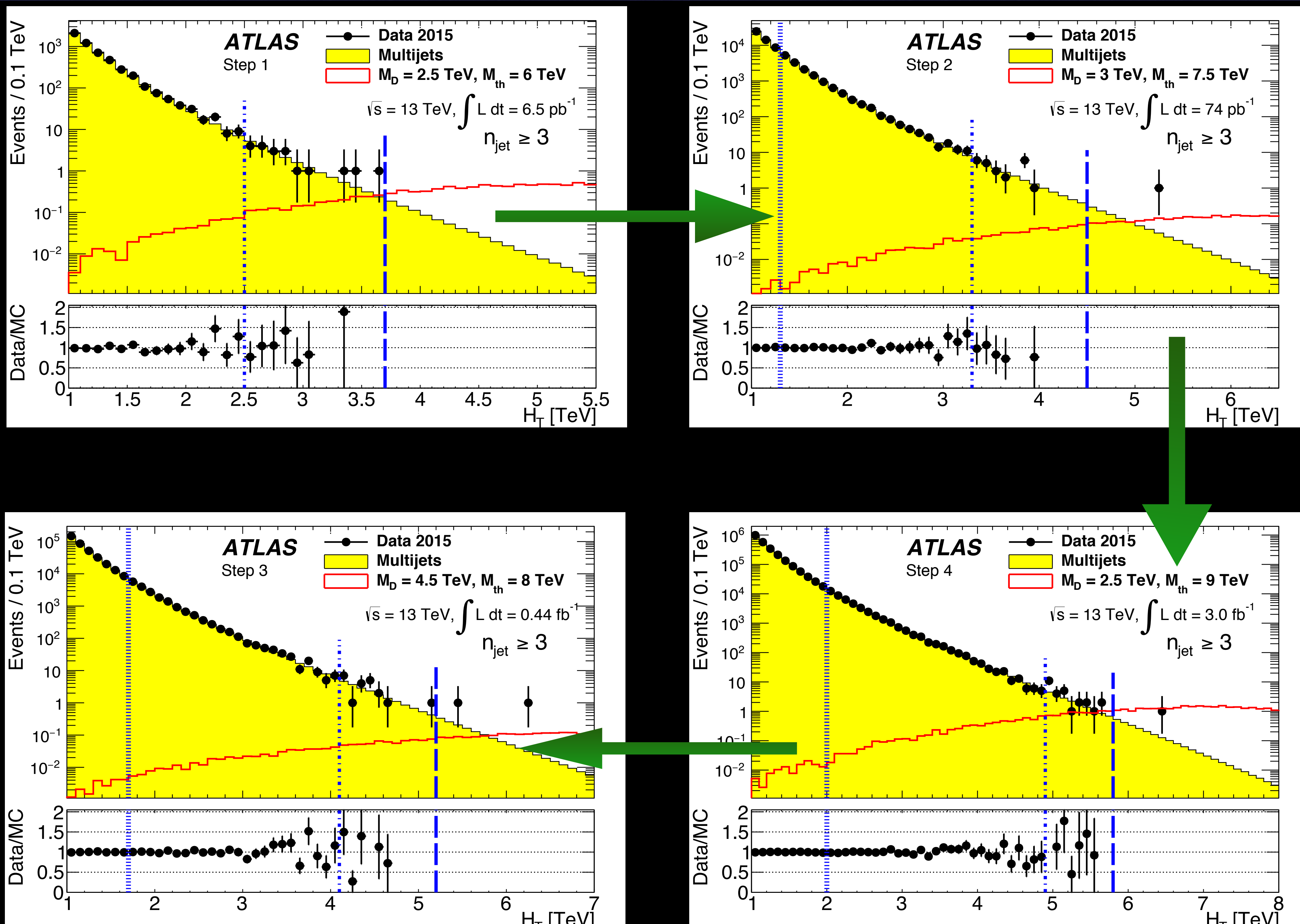
$$\sigma(M_{\rm BH}) \approx \pi r_S^2$$

- 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



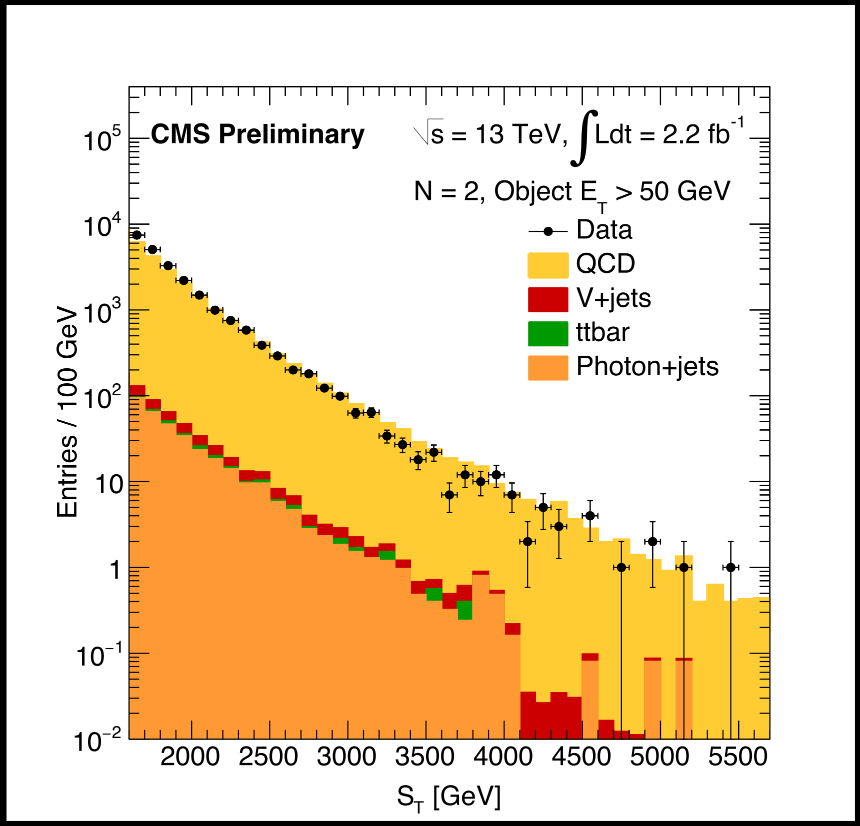
Background Estimation: ATLAS



Use bootstrapping to compute background

Define control (C < H_T < V), validation (V < 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

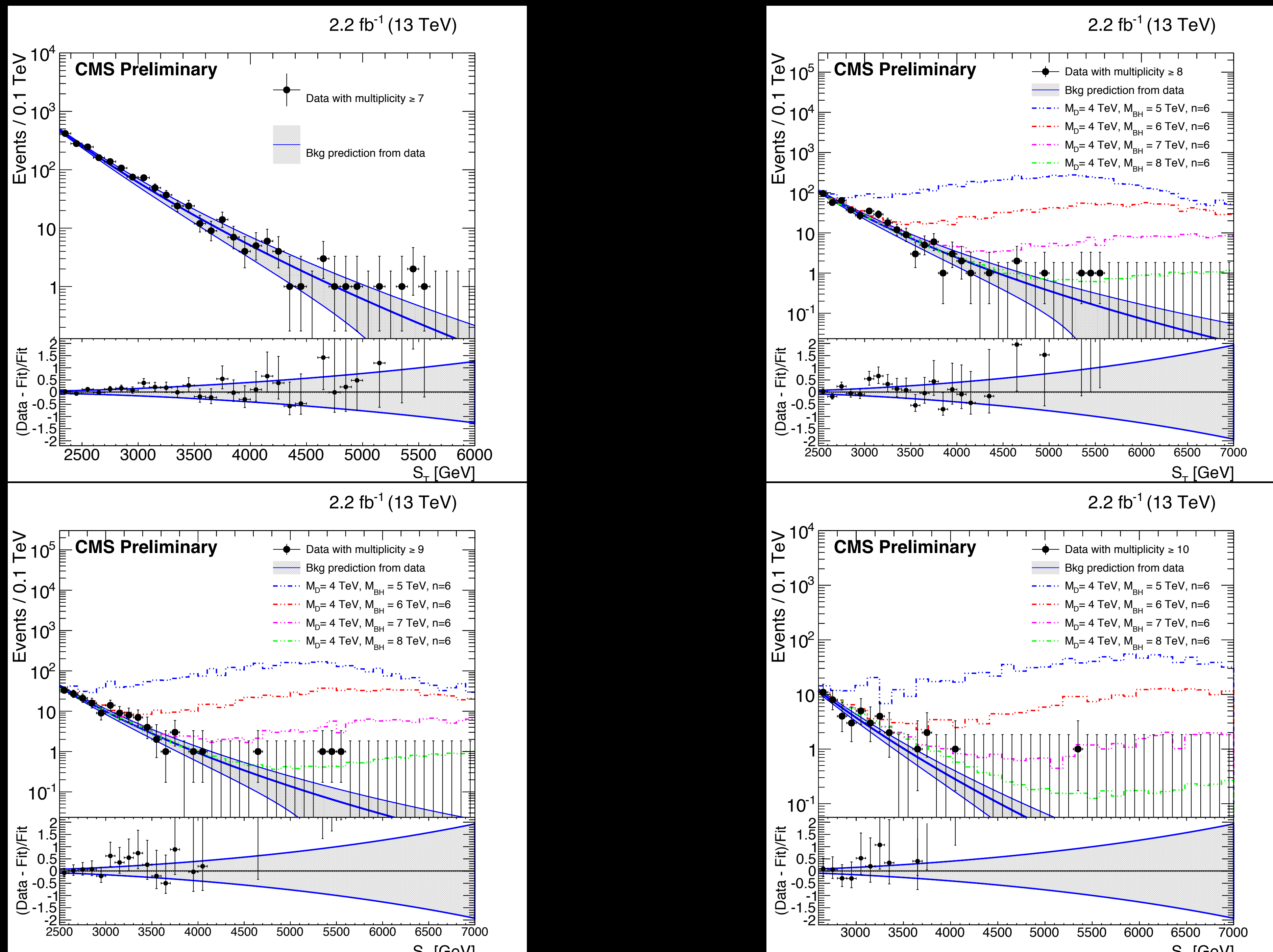
The background prediction from the multiplicity = 2 regime is applied to higher multiplicities by appropriate normalization in a region of low signal contamination

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

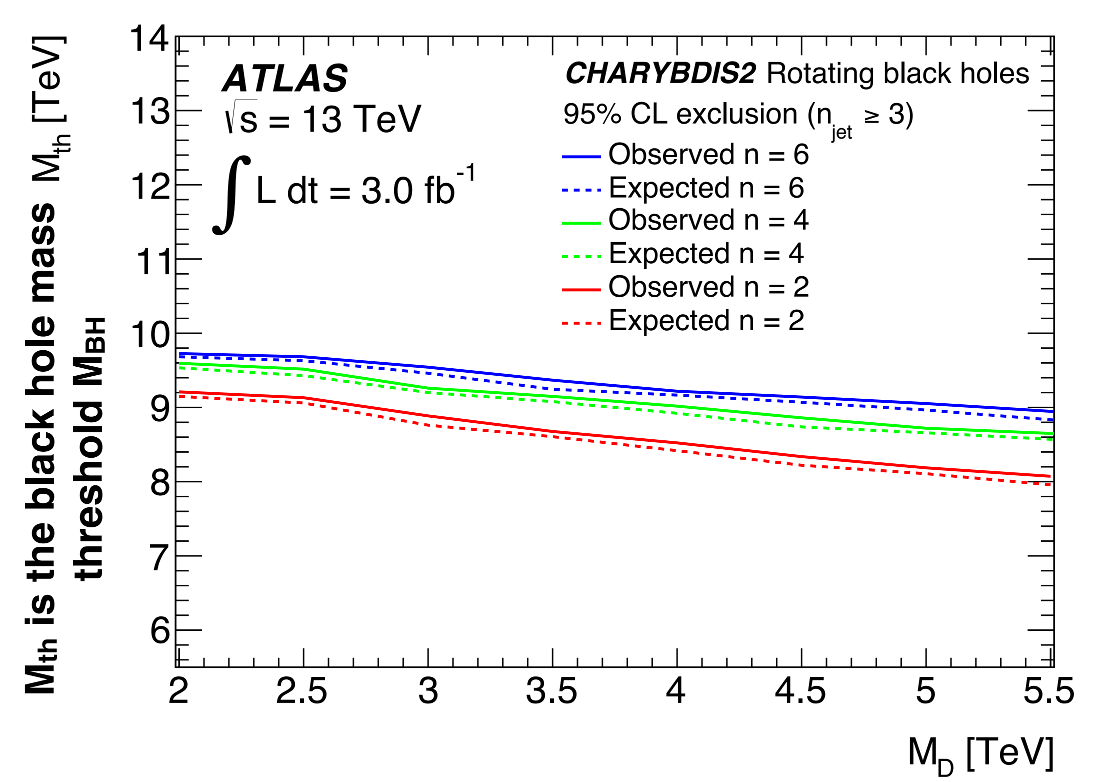
- Essentially one performs a counting experiment using the variable S_T, where S_T is defined as the **scalar sum of the transverse energy (E_T) of jets, leptons and photons. ME_T is also added to S_T if ME_T > 50 GeV**

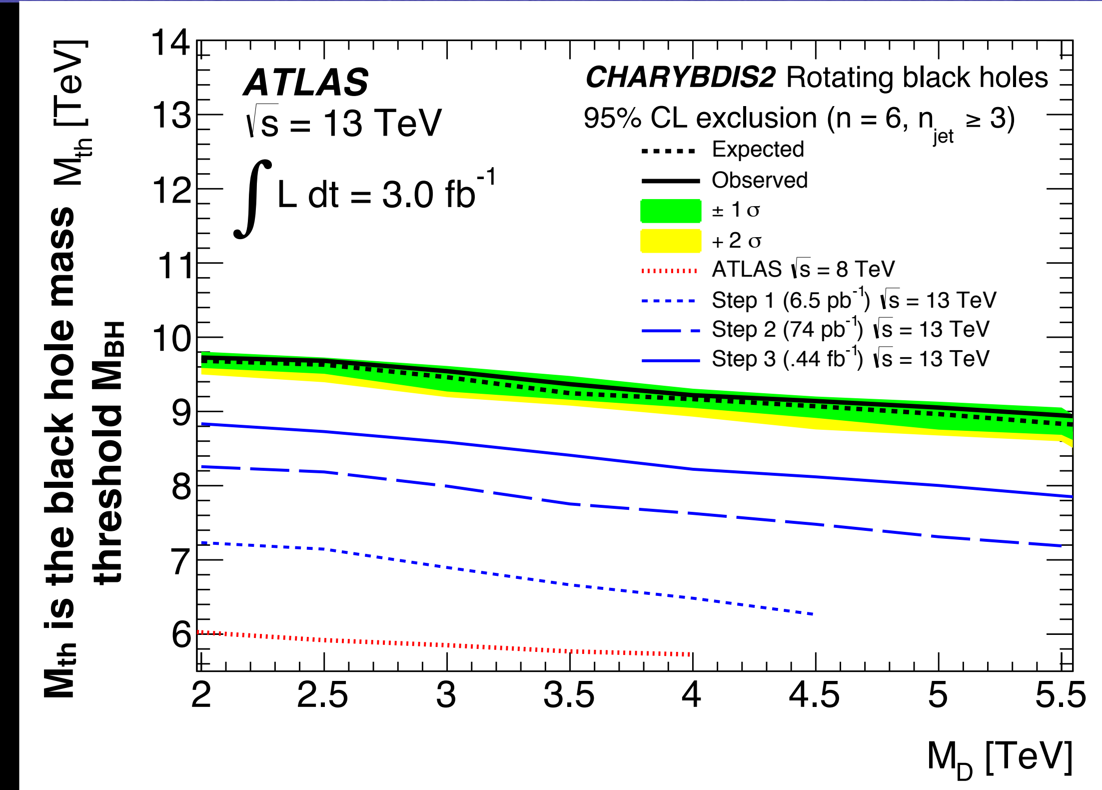
- The **multiplicity** of an event is defined as the **number of jets + leptons + photons** in that event. **ME_T** is not counted as a separate object

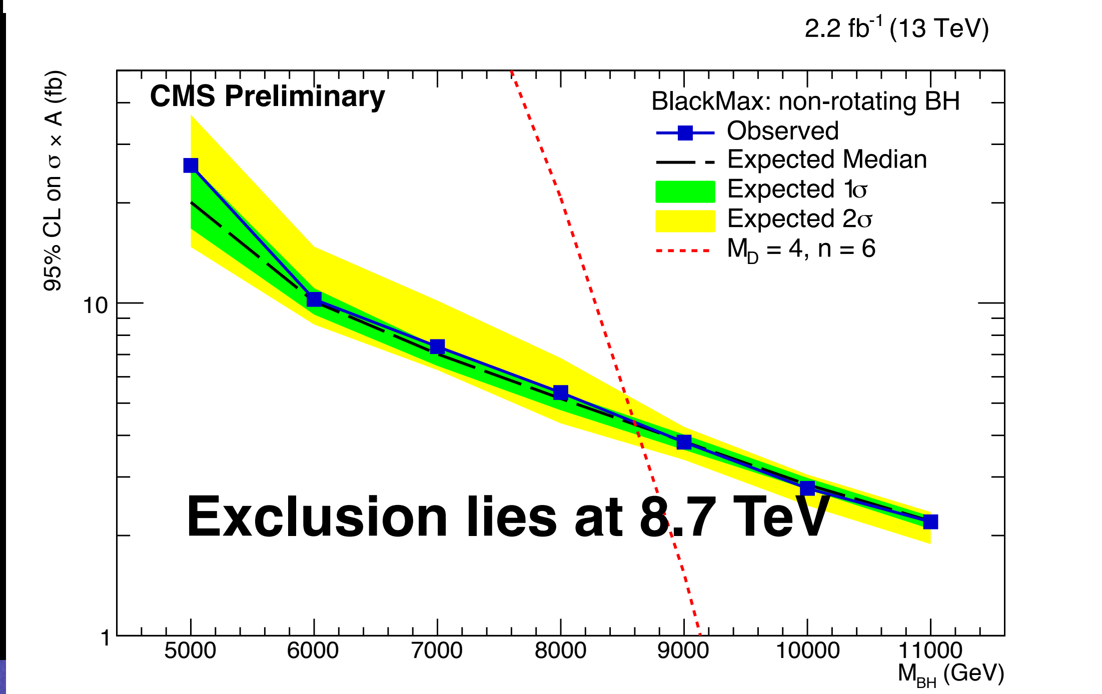
Background Estimation: CMS

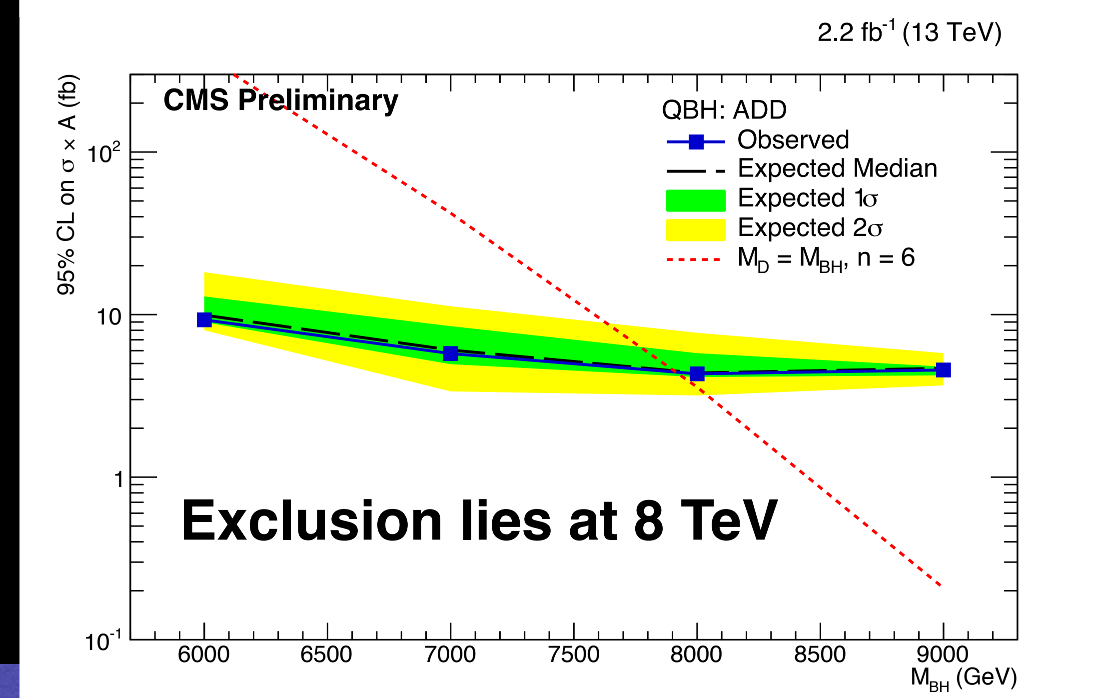


Model dependent results

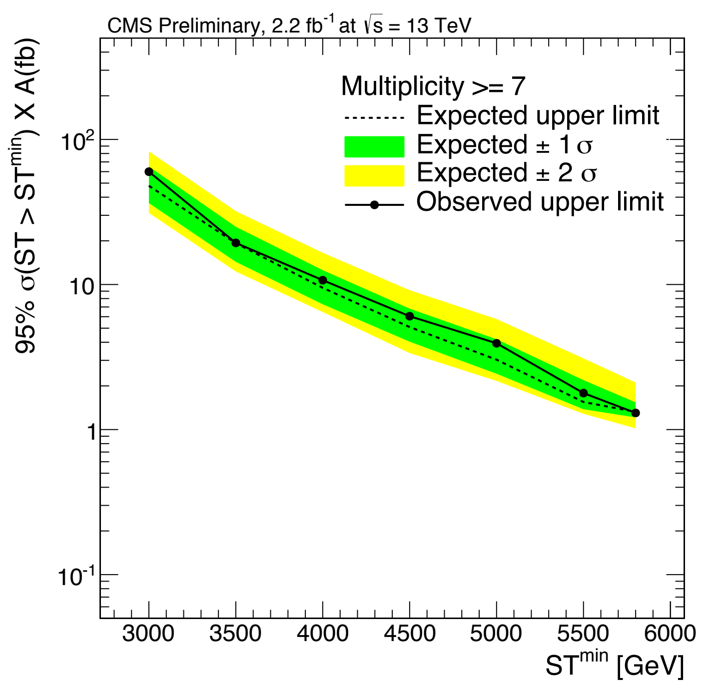


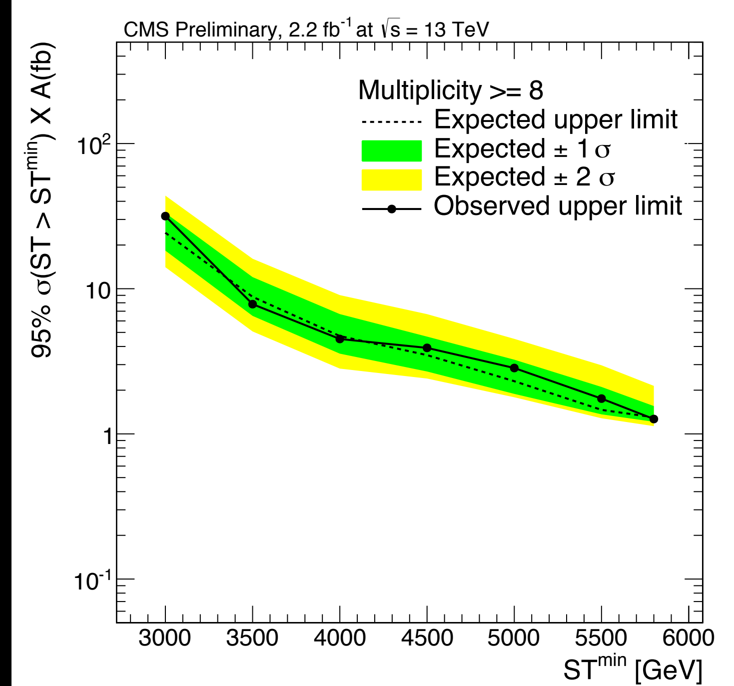


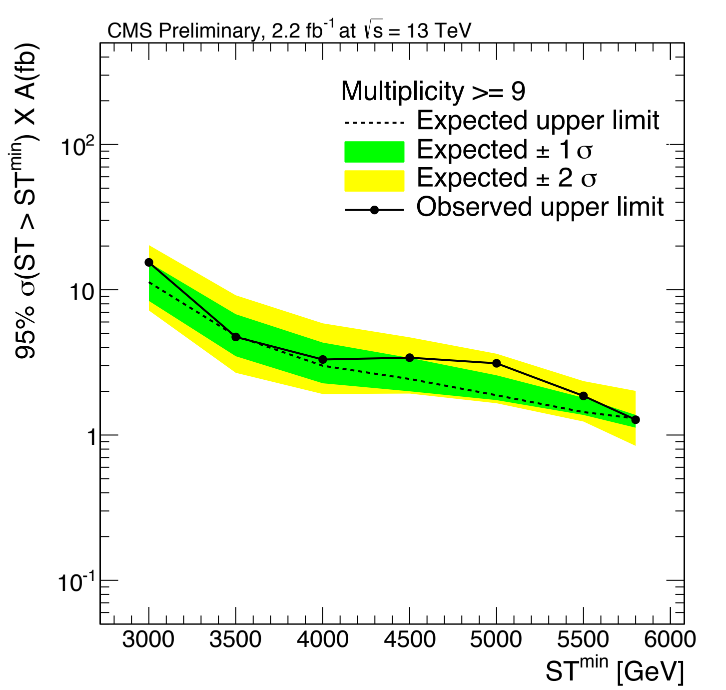


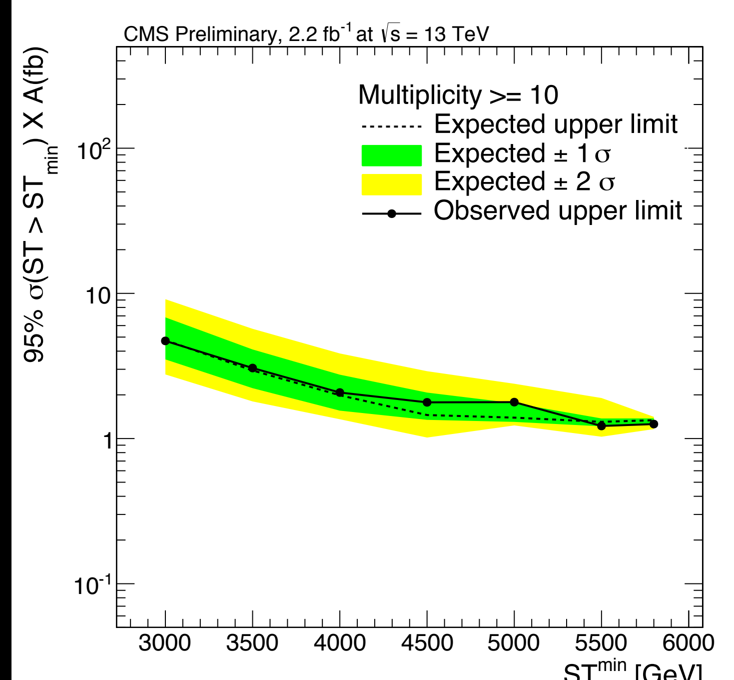


Model independent result





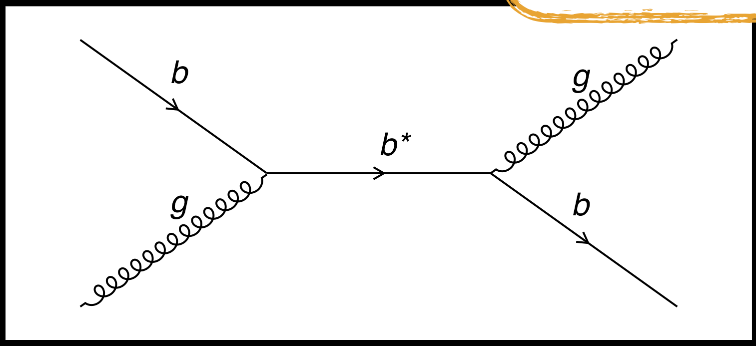


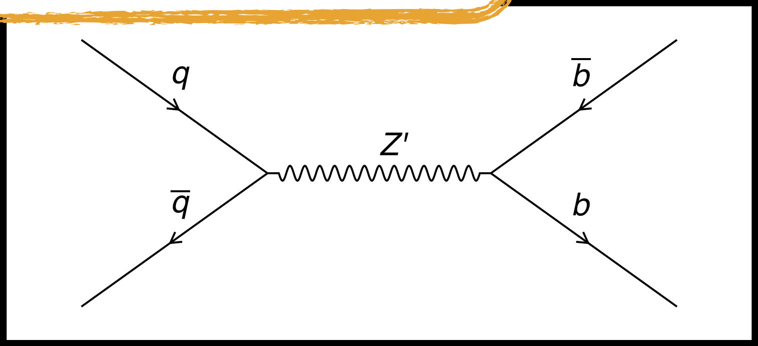


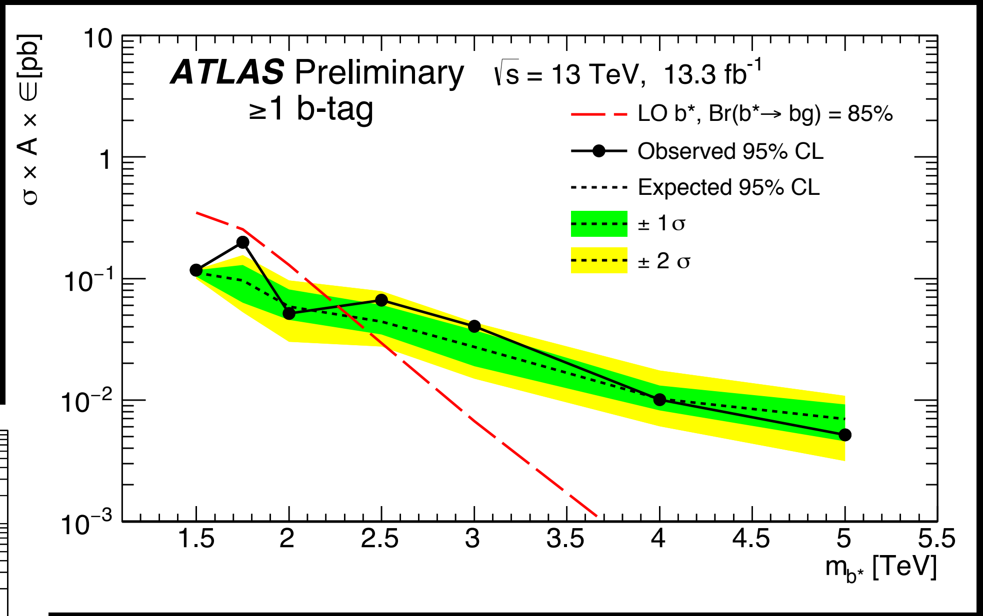
Model independent limits can be applied to various models of NP

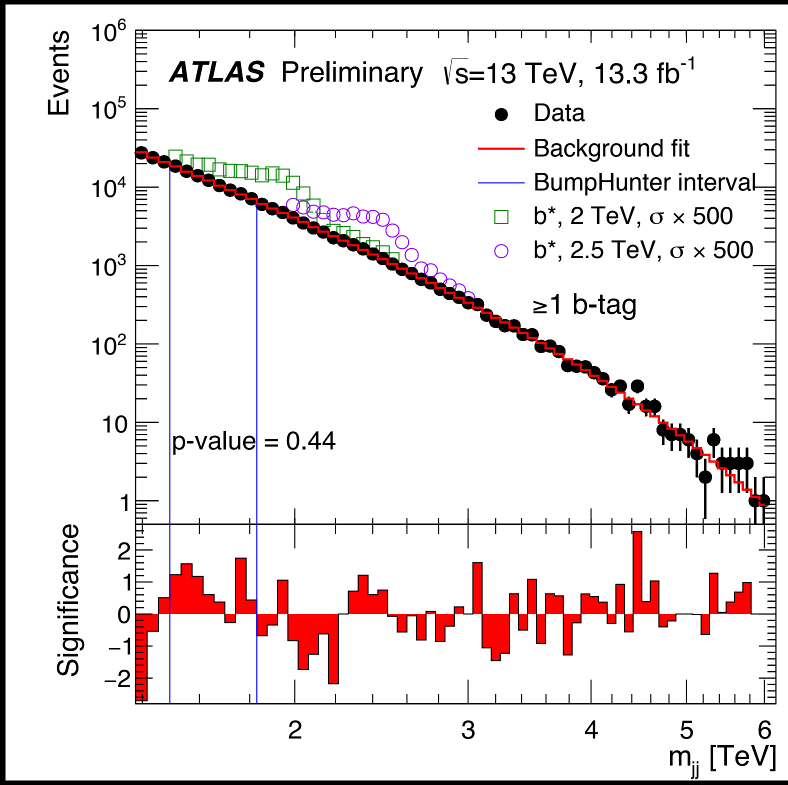
Search for new physics with heavy flavor jets: ATLAS

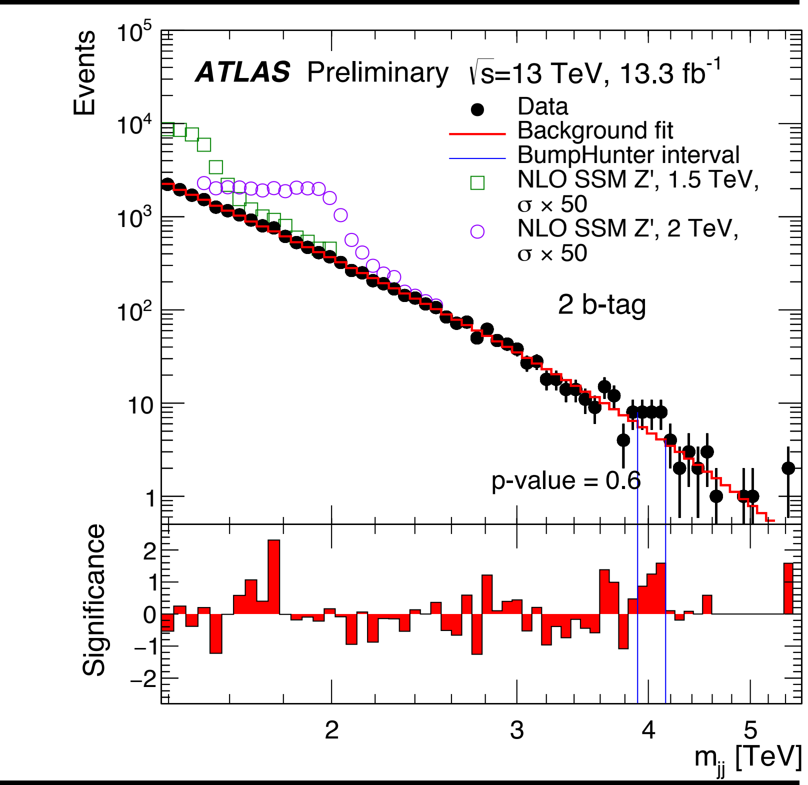
✨✨Hot off the press!✨✨

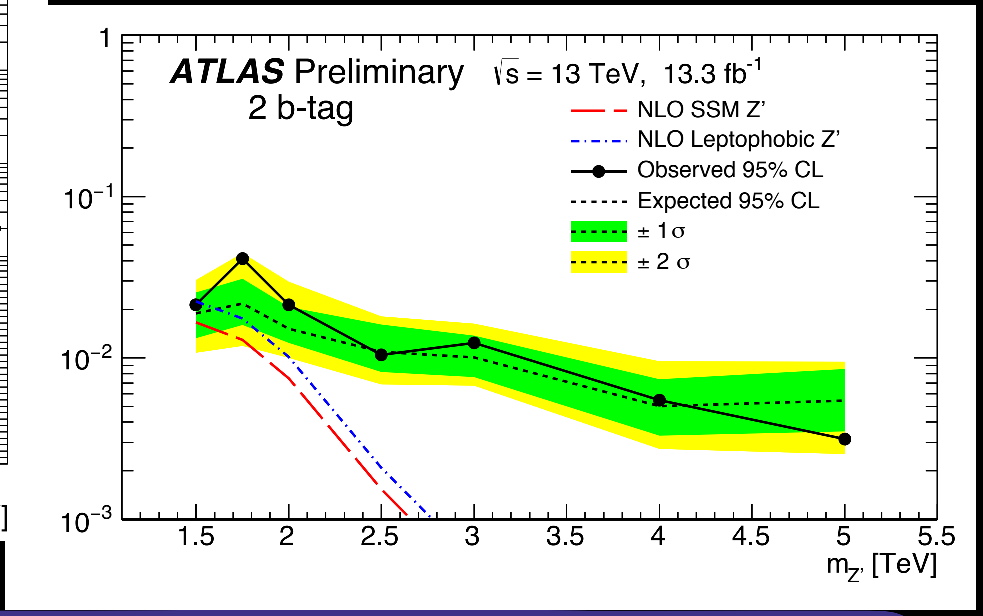








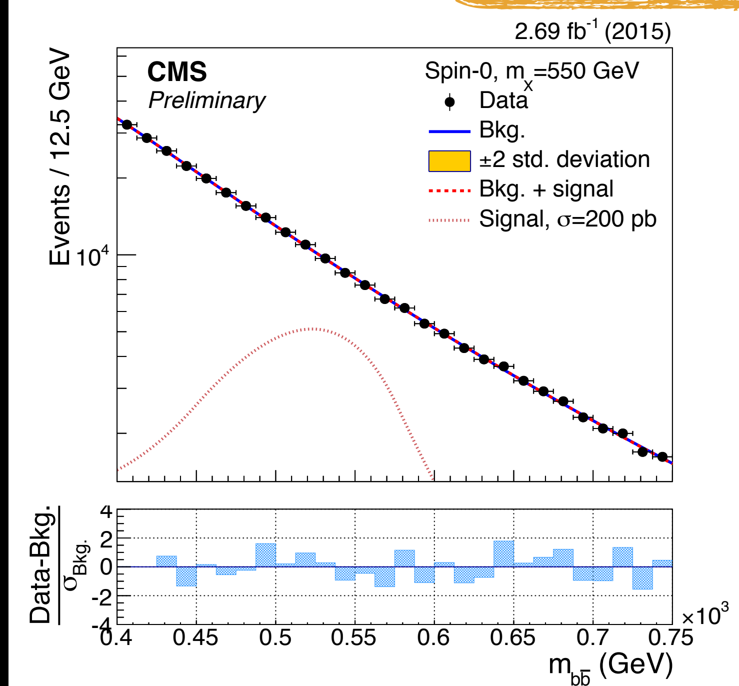


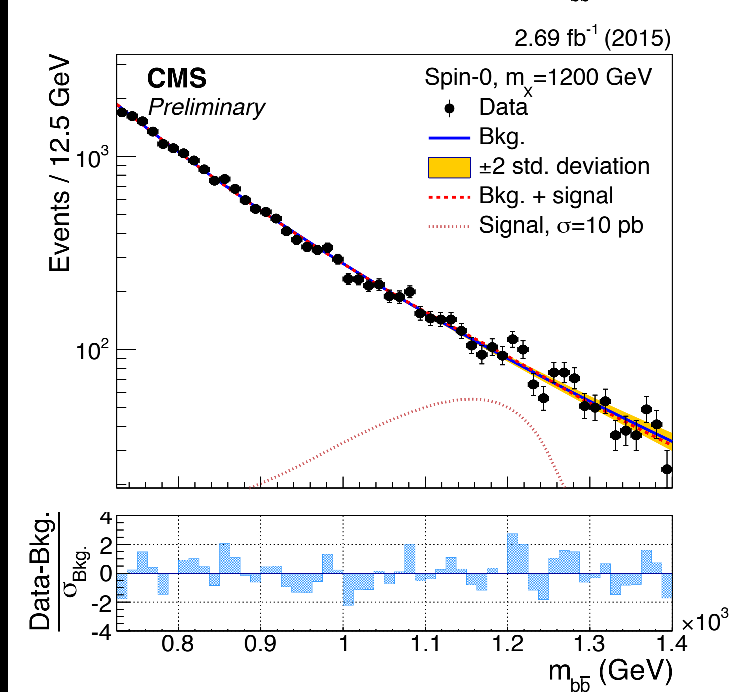


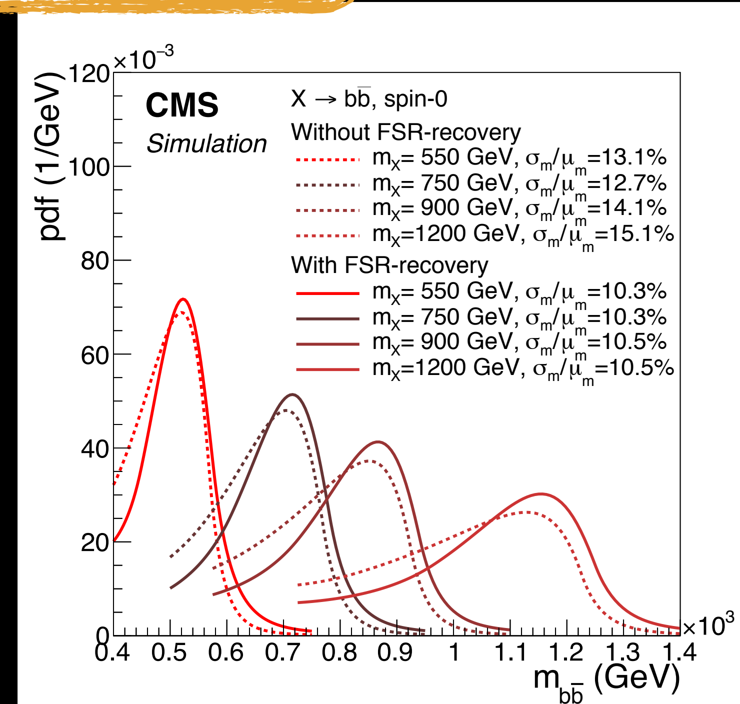
- **Analysis sensitive to generic high-mass particles decaying to two jets that originate from one or two b-quarks**
- **Visible cross sections ranging from 0.2 to 0.001 pb in the mass range 1.4–5.5 TeV are excluded**

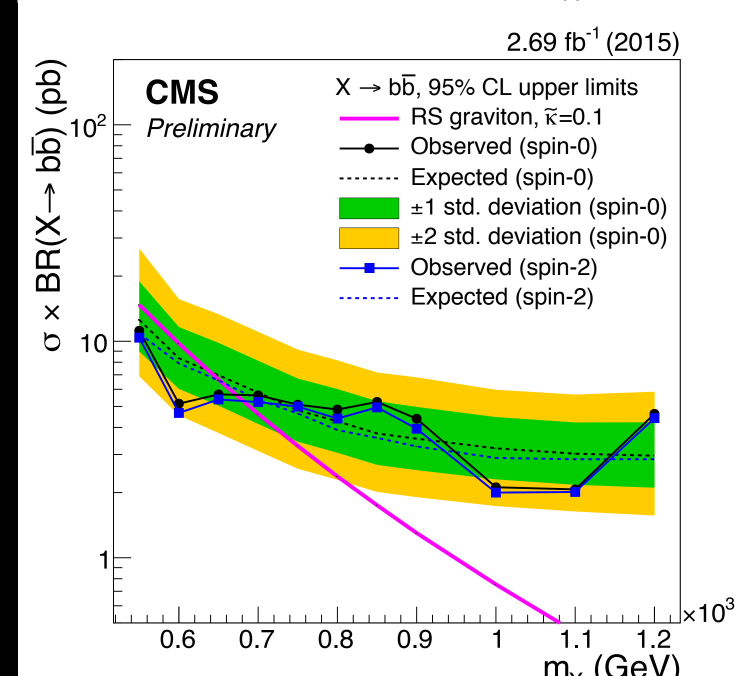
Search for new physics with heavy flavor jets: CMS

✨✨Hot off the press!✨✨









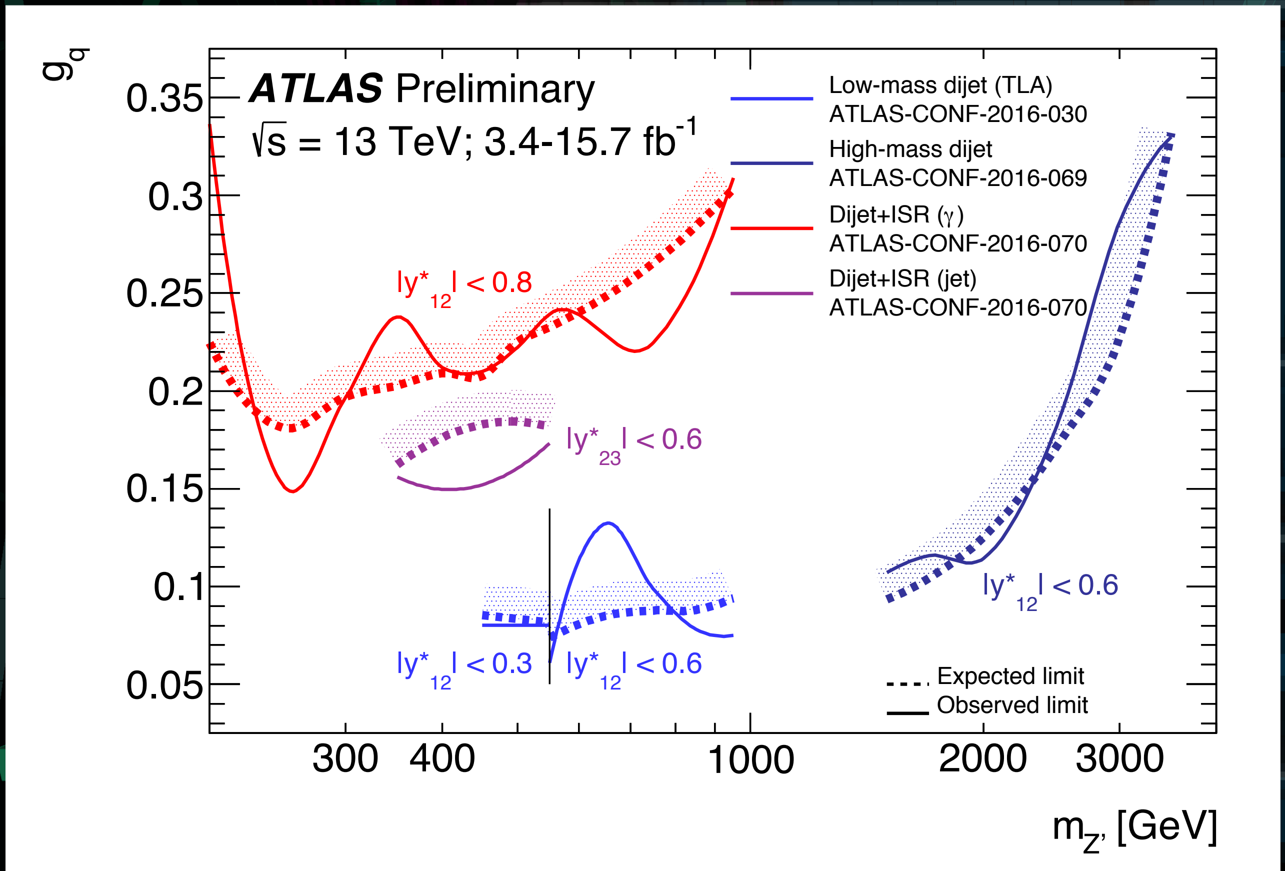
- **No significant excess over the expectation from the background is observed.**
- **Limits on production cross sections times branching ratio are obtained for values of the resonance mass ranging from 550 to 1200~GeV.**

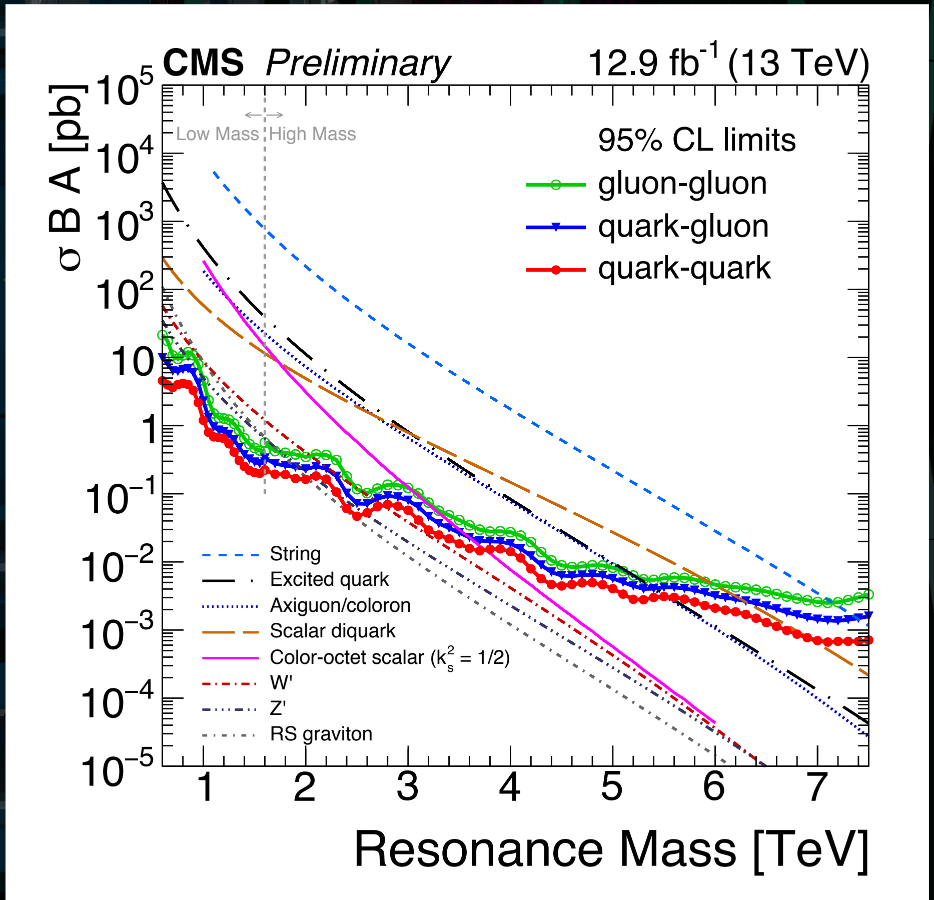
Summary

ATLAS EXPERIMENT
http://atlas.ch
Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST

Phenomenal work by analysts at ATLAS and CMS!

Stay tuned for new results!

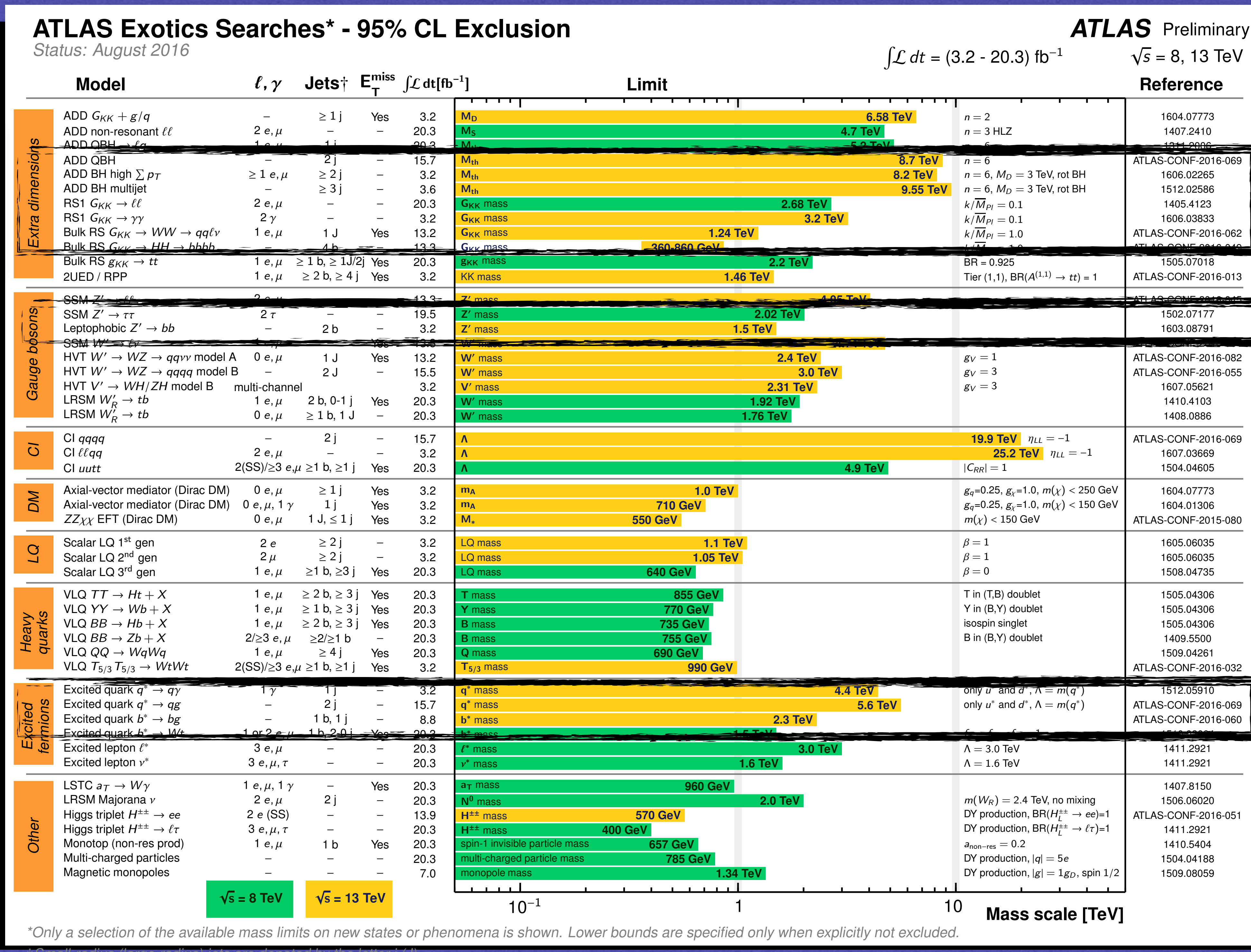




Dijet and multijet searches in ATLAS

Multijet and dijet

Dijet and heavy flavor dijet

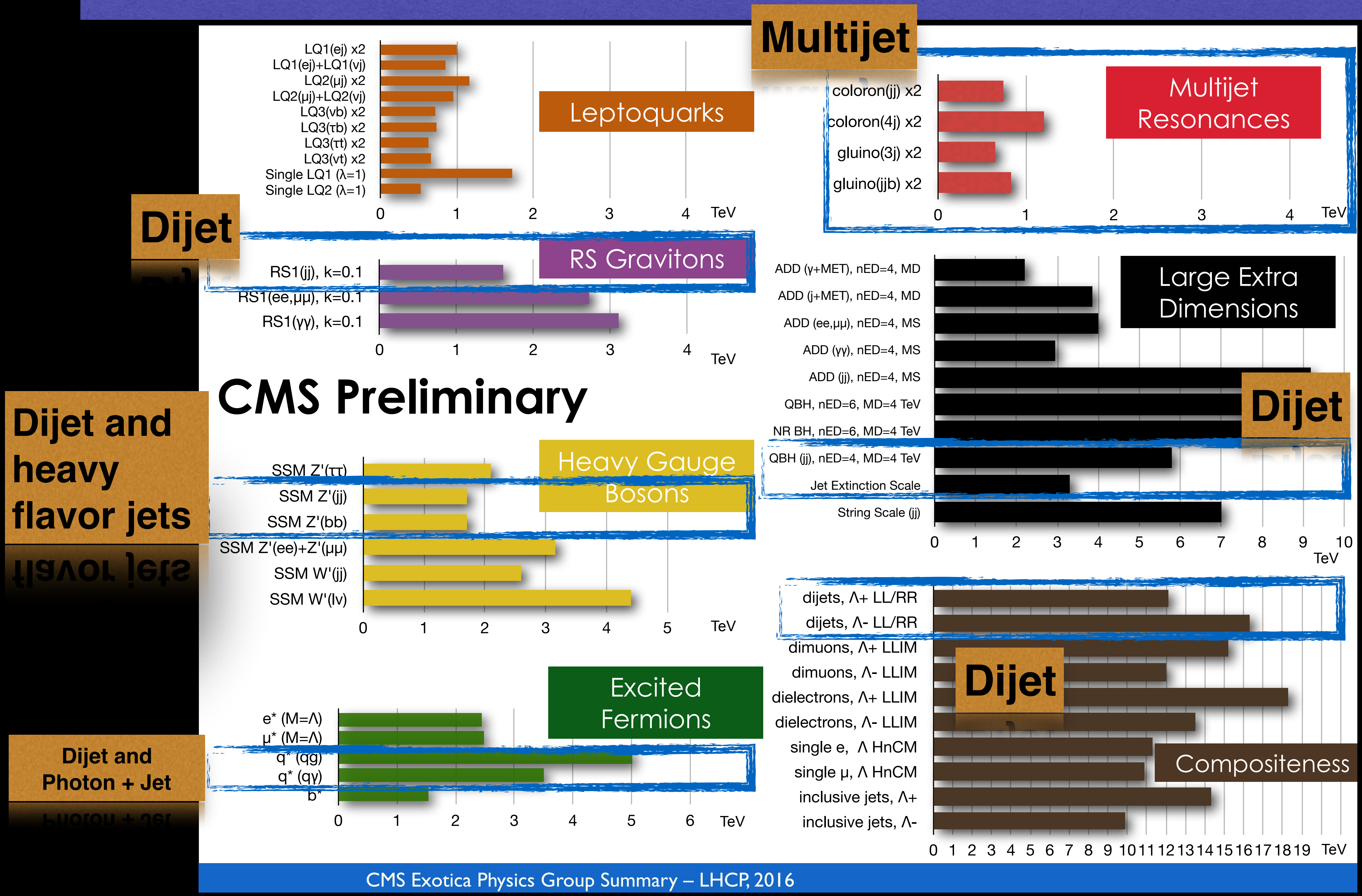


Photon + jet

ICHEP 2016, Chicago

August 5th, 2016

Dijet and multijet searches in CMS



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

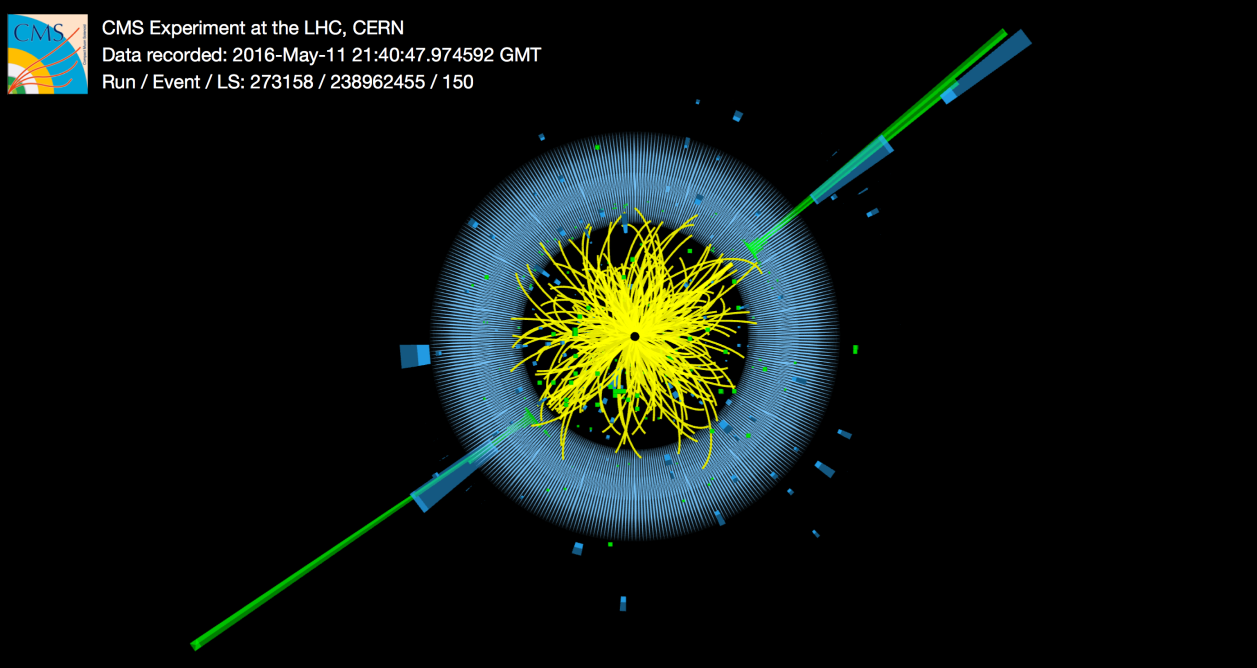
- Search for high-mass resonances in dijet final state with 2016 data (EXO-16-032)
http://cds.cern.ch/record/2205150?ln=en

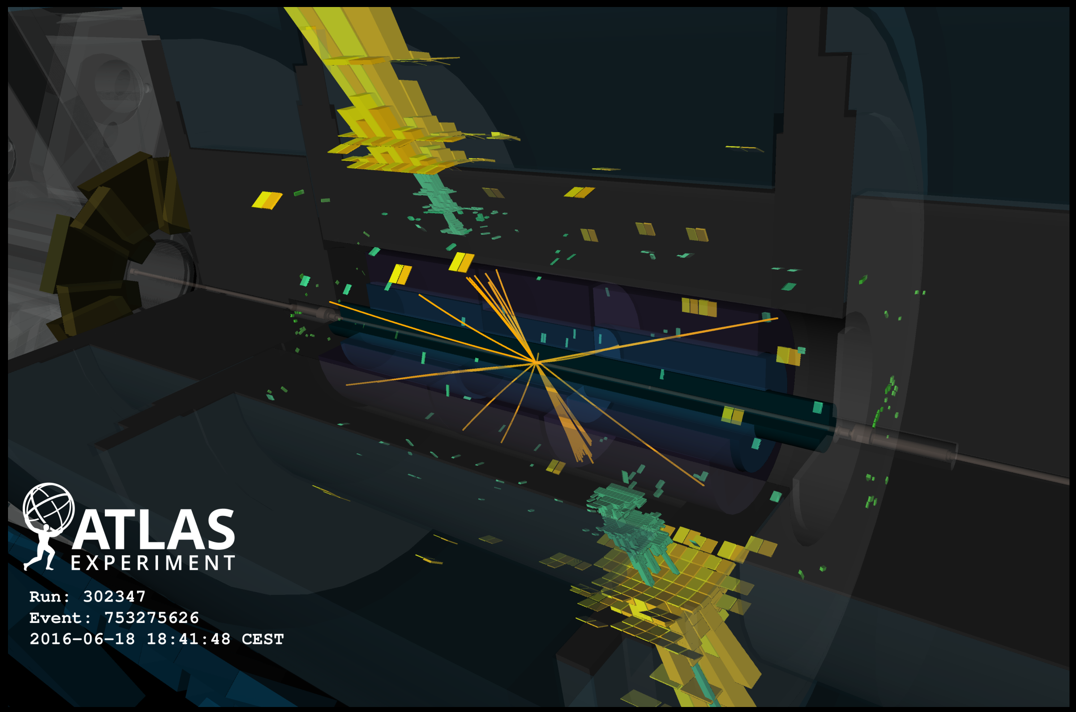
- Search for excited quarks in photon jet final state (EXO-16-015)
http://cds.cern.ch/record/2204915?ln=en

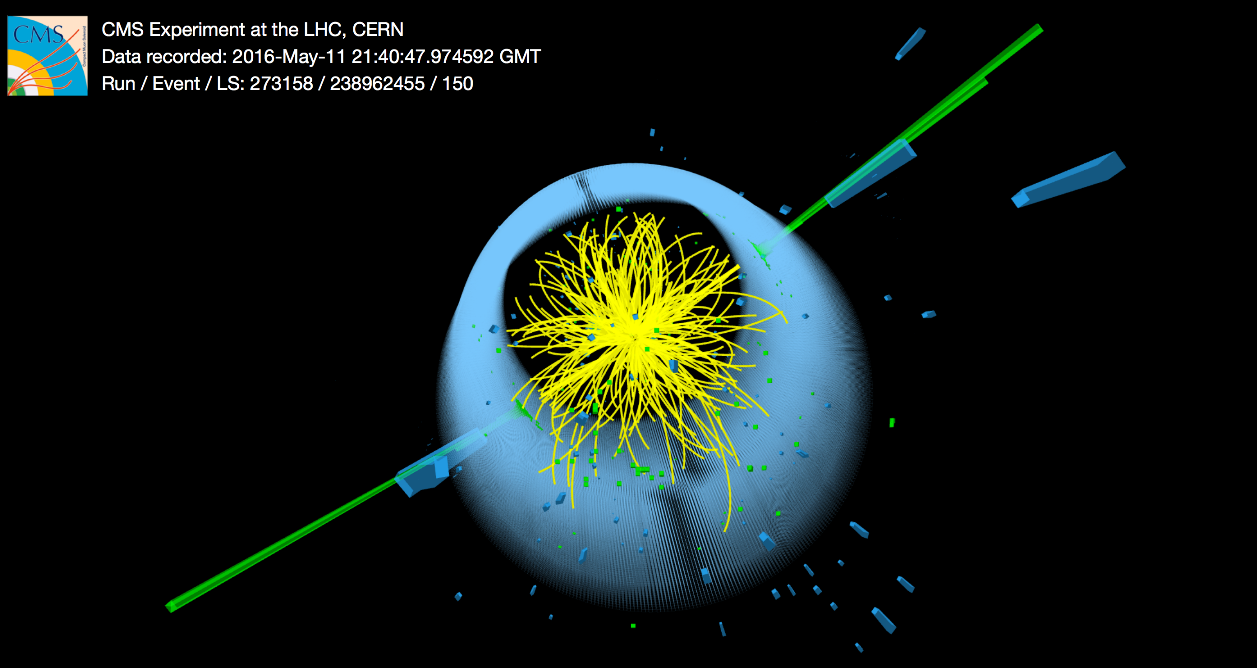
- Search for Black Holes with Early Run 2 Data (EXO-15-007)
http://cds.cern.ch/record/2116453?ln=en

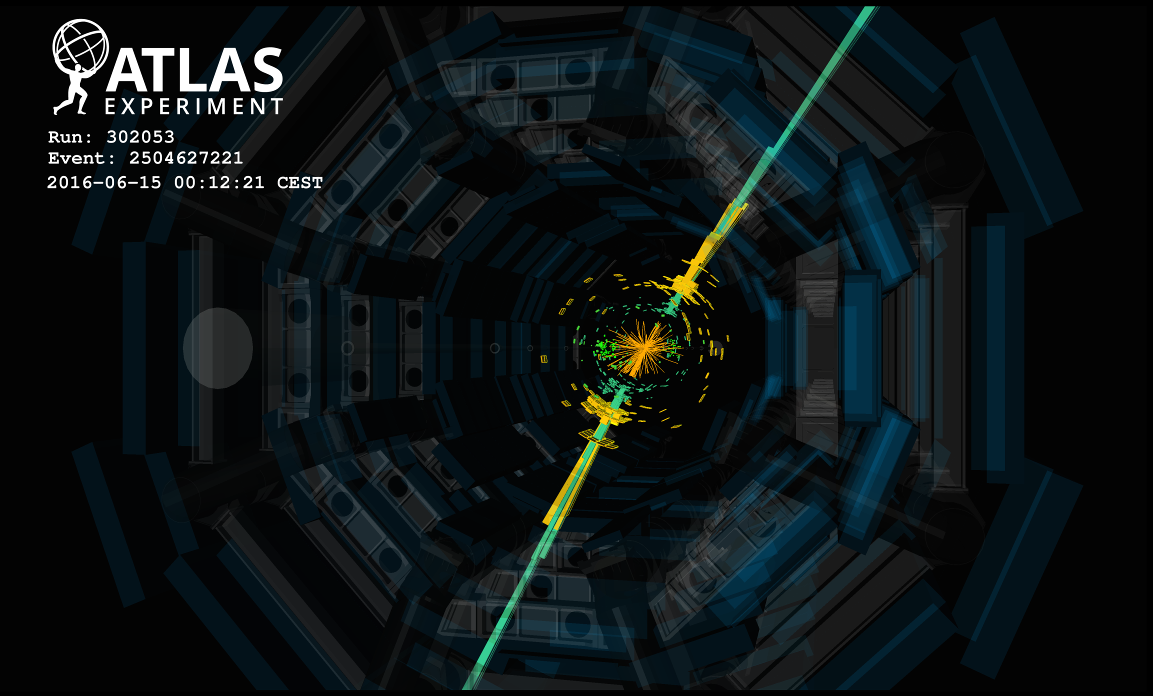
- Search for a narrow heavy decaying to bottom quark pairs in the 13 TeV data sample (HIG-16-025)
http://cds.cern.ch/record/2204928?ln=en

Event displays of dijet events!





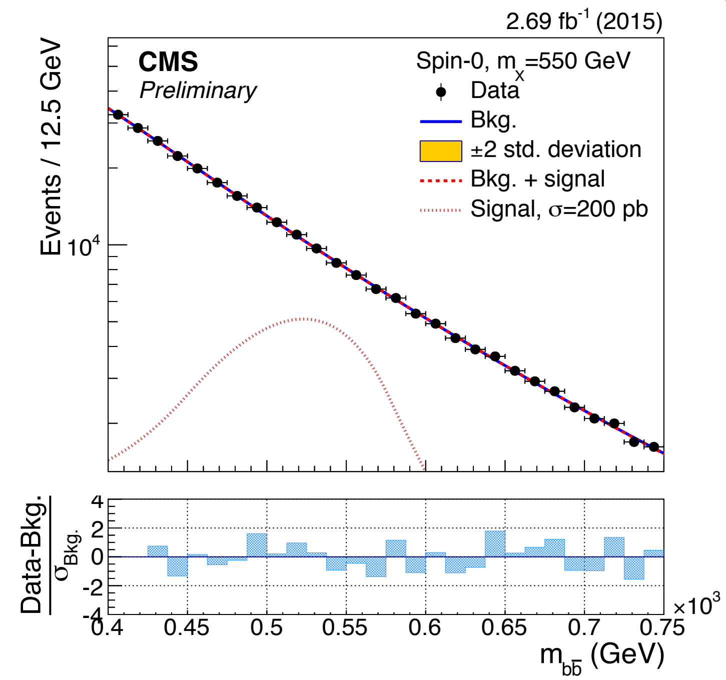


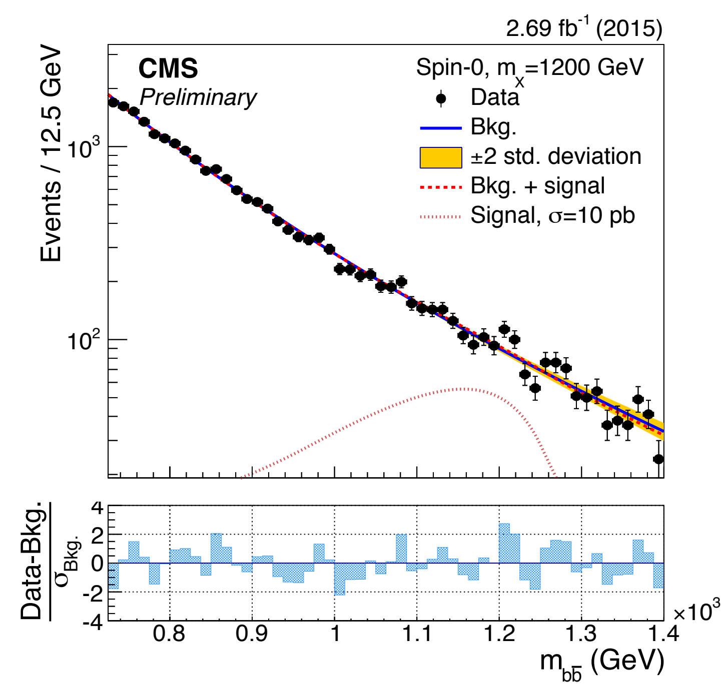


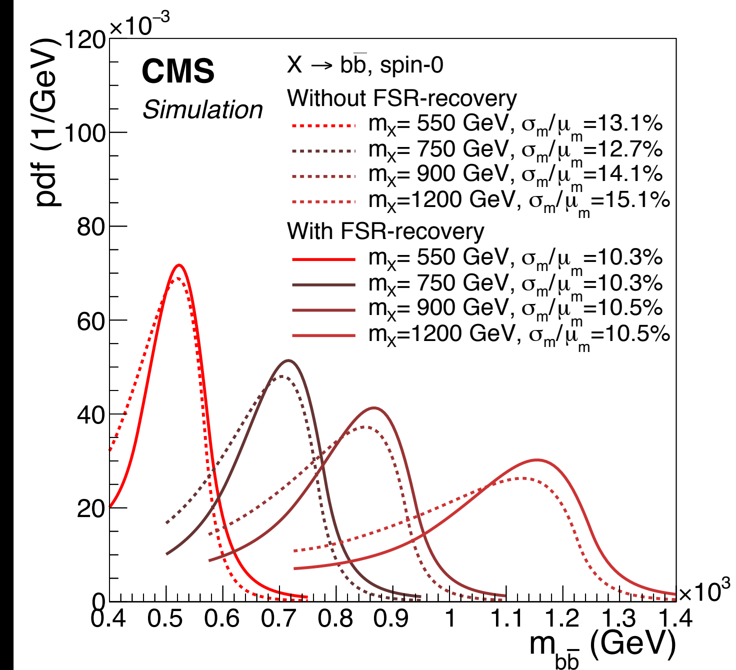
Additional Material

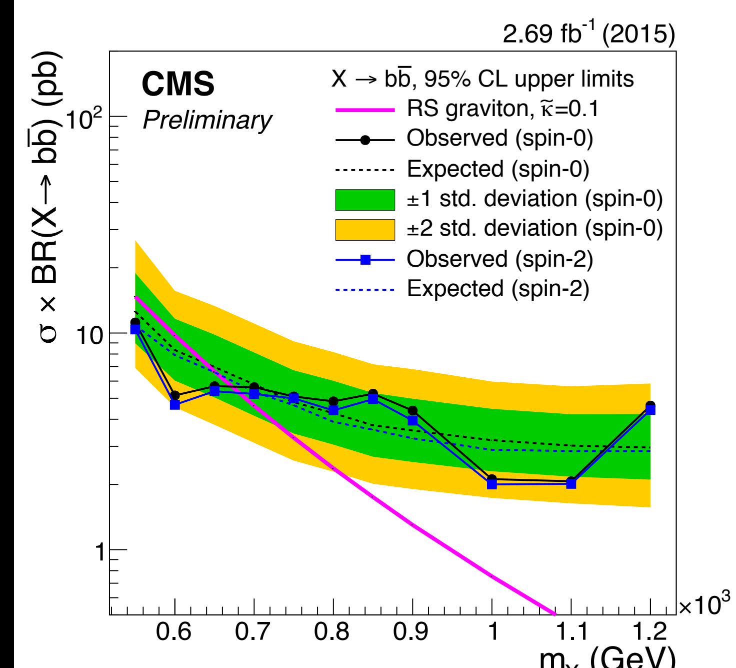
Search for new physics with heavy flavor jets: CMS

✨✨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

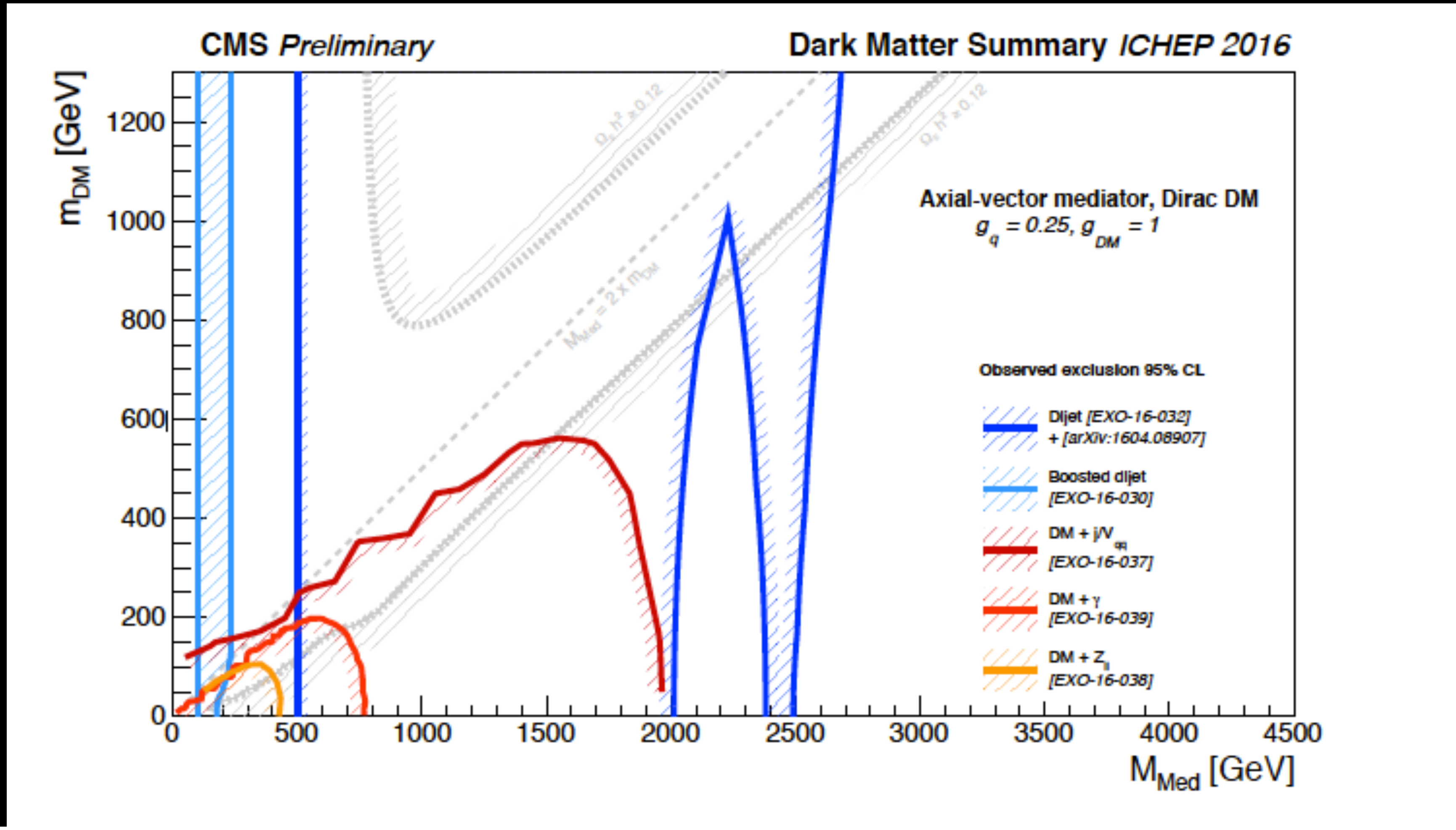


Figure 1. *95% CL exclusion regions in $M_{\rm med} - m_{\rm DM}$ plane for di-jet searches and different $\not{E}_T$ based DM searches from CMS in the lepto-phobic Axial Vector model. Following the recommendation of the LHC DM working group [1, 2], the exclusions are computed for a universal quark coupling $g_q = 0.25$ and for a DM coupling of $g_{\rm DM} = 1.0$. 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

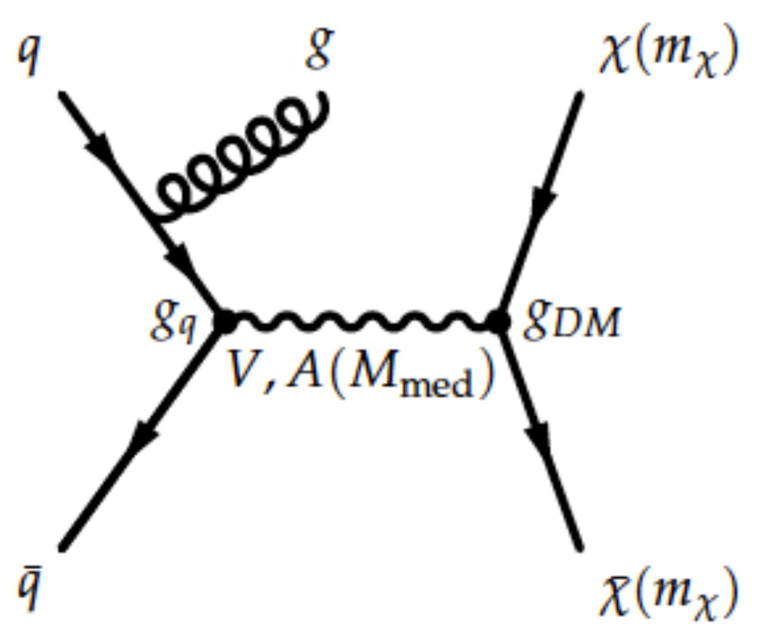


Figure 2.1: Representative Feynman diagram showing the pair production of Dark Matter particles in association with a parton from the initial state via a vector or axial-vector mediator. The cross section and kinematics depend upon the mediator and Dark Matter masses, and the mediator couplings to Dark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

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

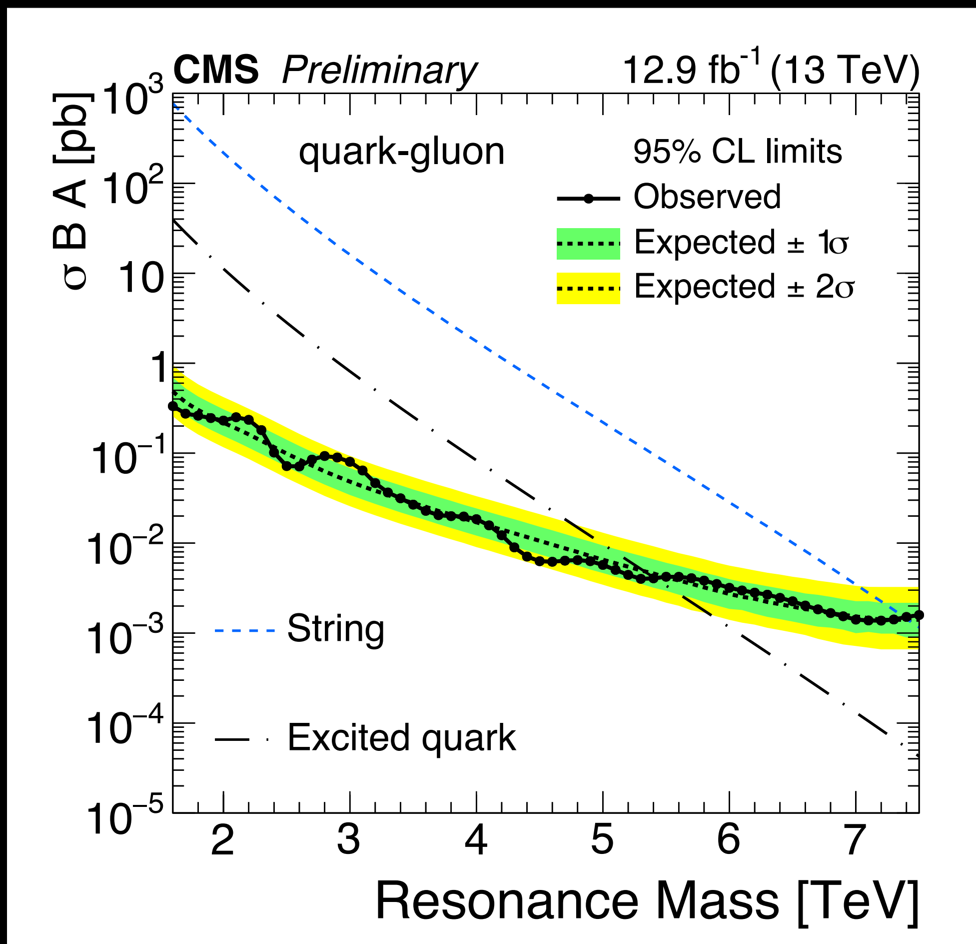
$$\mathcal{L}_{\mathrm{axial-vector}} = g_{\mathrm{q}} \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi. \tag{2.2}$$

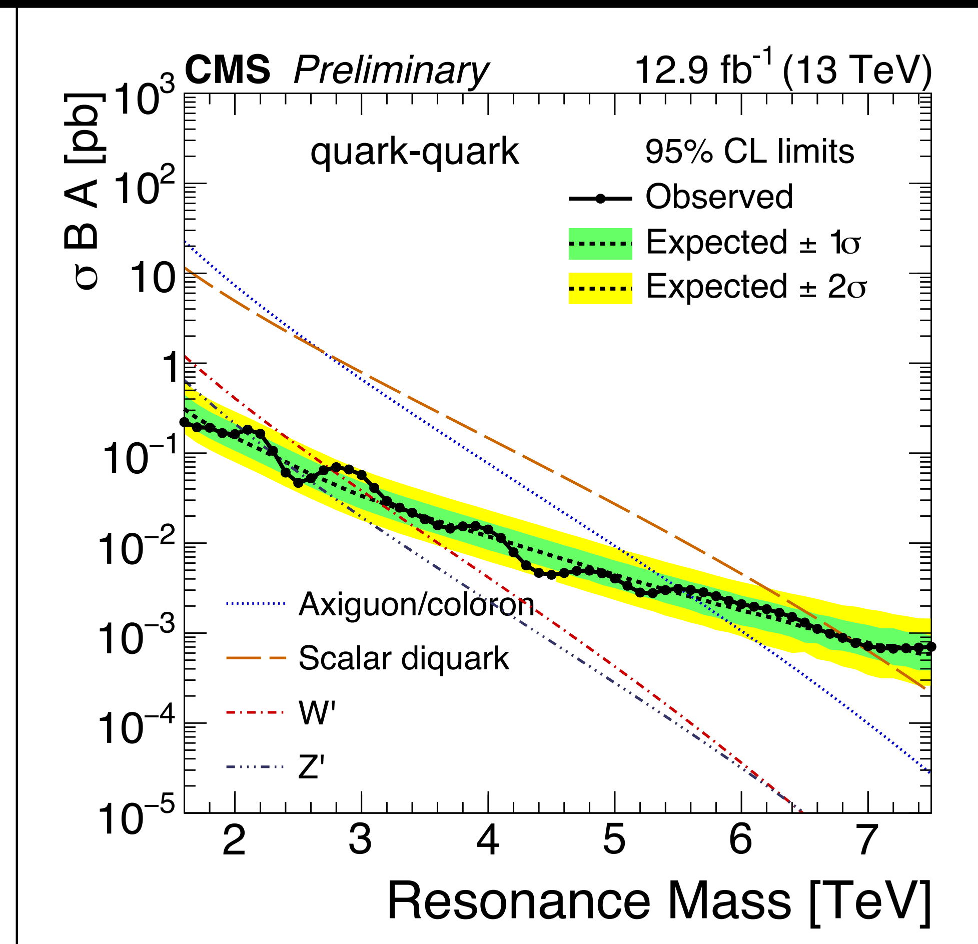
https://arxiv.org/abs/1507.00966

Organization of additional material

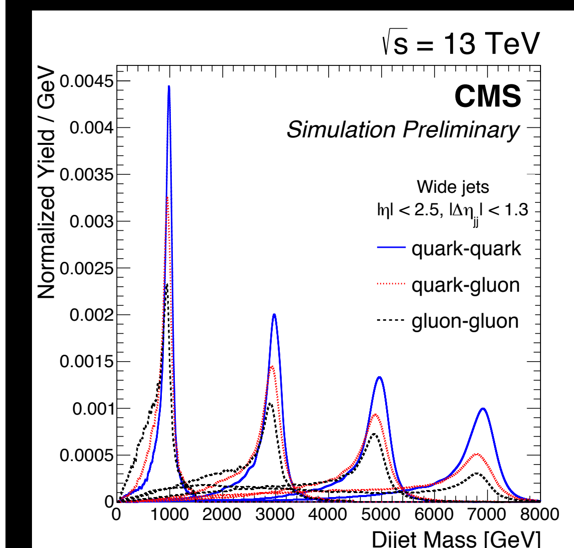
- High mass dijet studies: Slide 25-26
- Low mass dijet studies: Slide 27-28
- Event display for dijet events: Slide 29
- Low mass search using jet substructure technique: Slide 30-32
- Trigger level searches: Slide 33
- Excited quarks: Slide 34-36
- Search for microscopic black holes: 37-41
- ATLAS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

Additional Material: High mass dijet analysis





Signal shapes

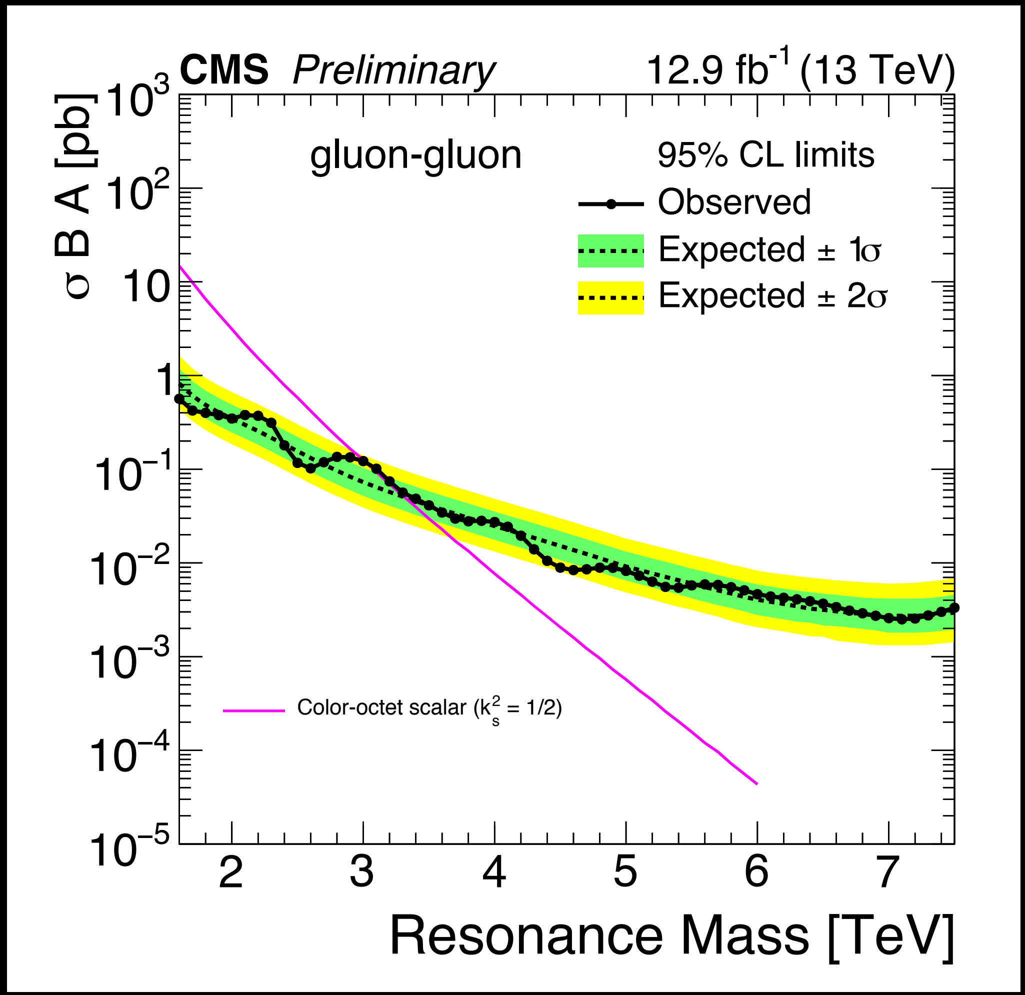


quark-gluon final state

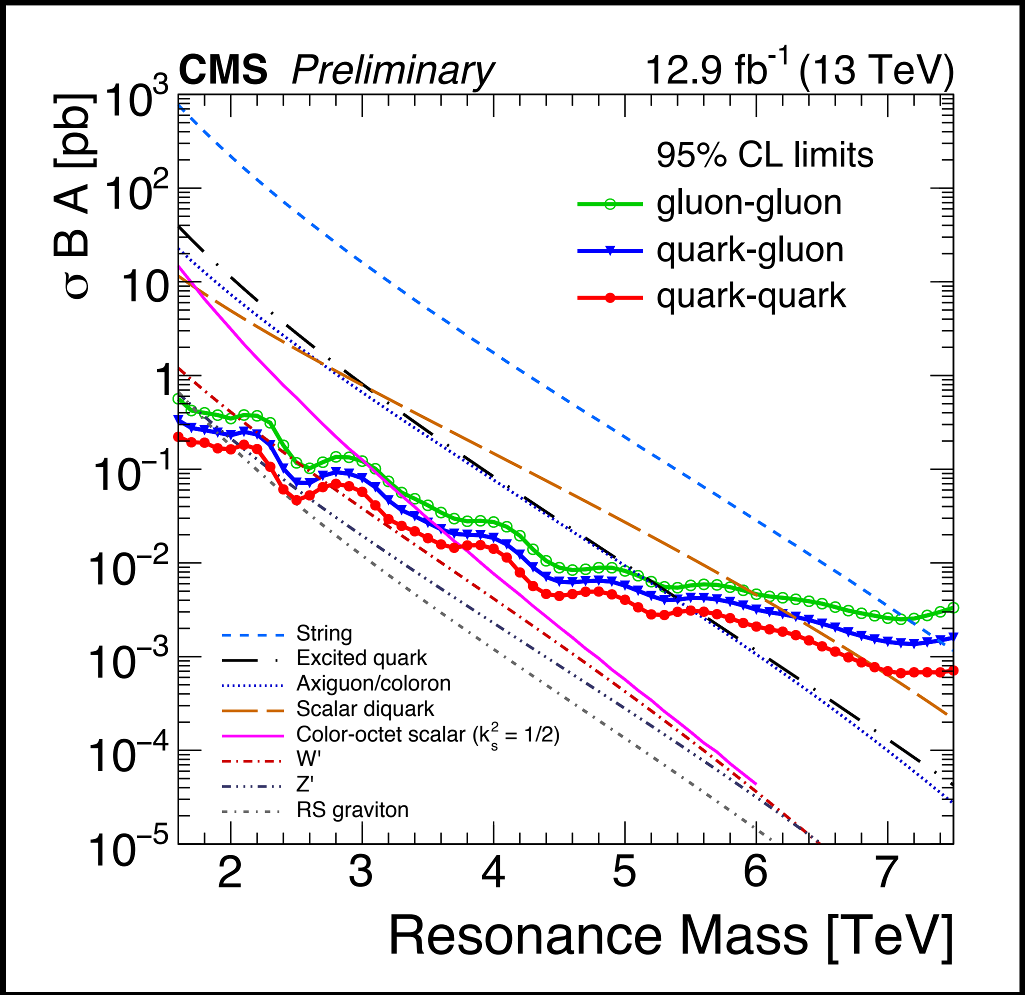
quark-quark final state

Wide jets used: defined on Slide 31

Additional Material: High mass dijet analysis

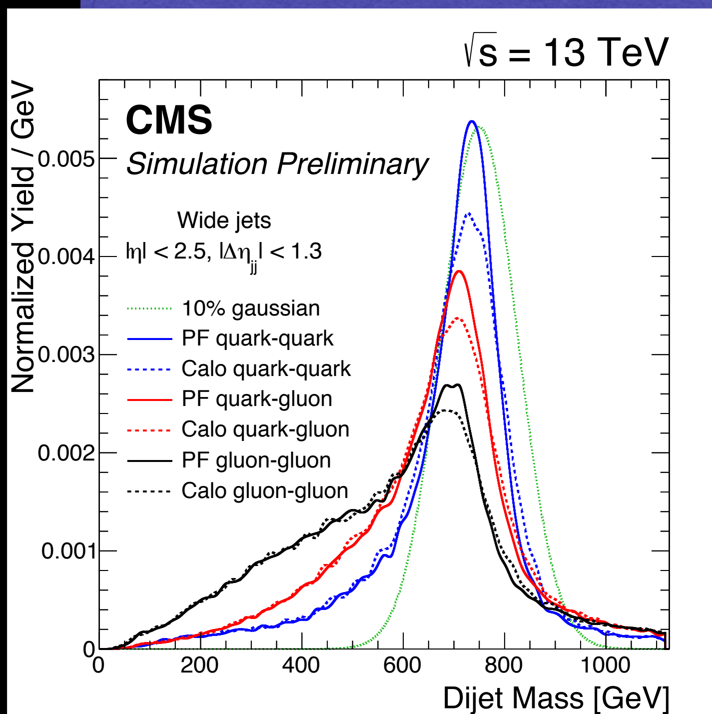


gluon-gluon final state

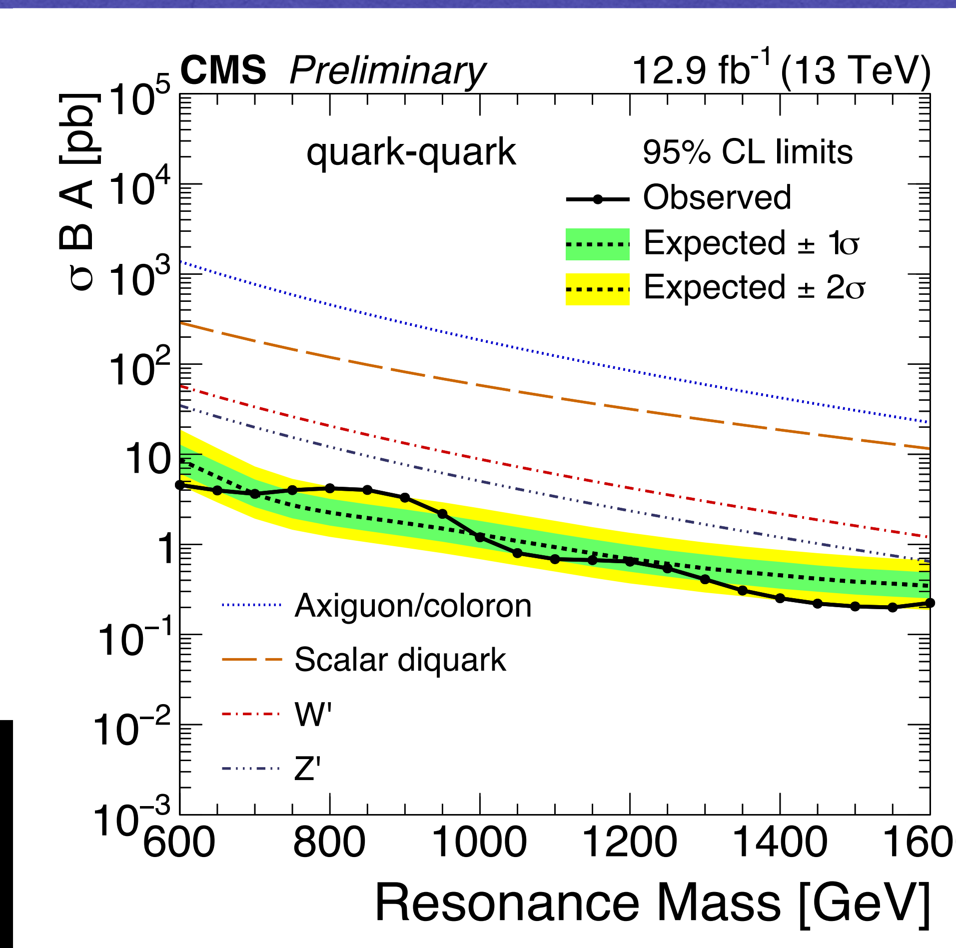


Summary

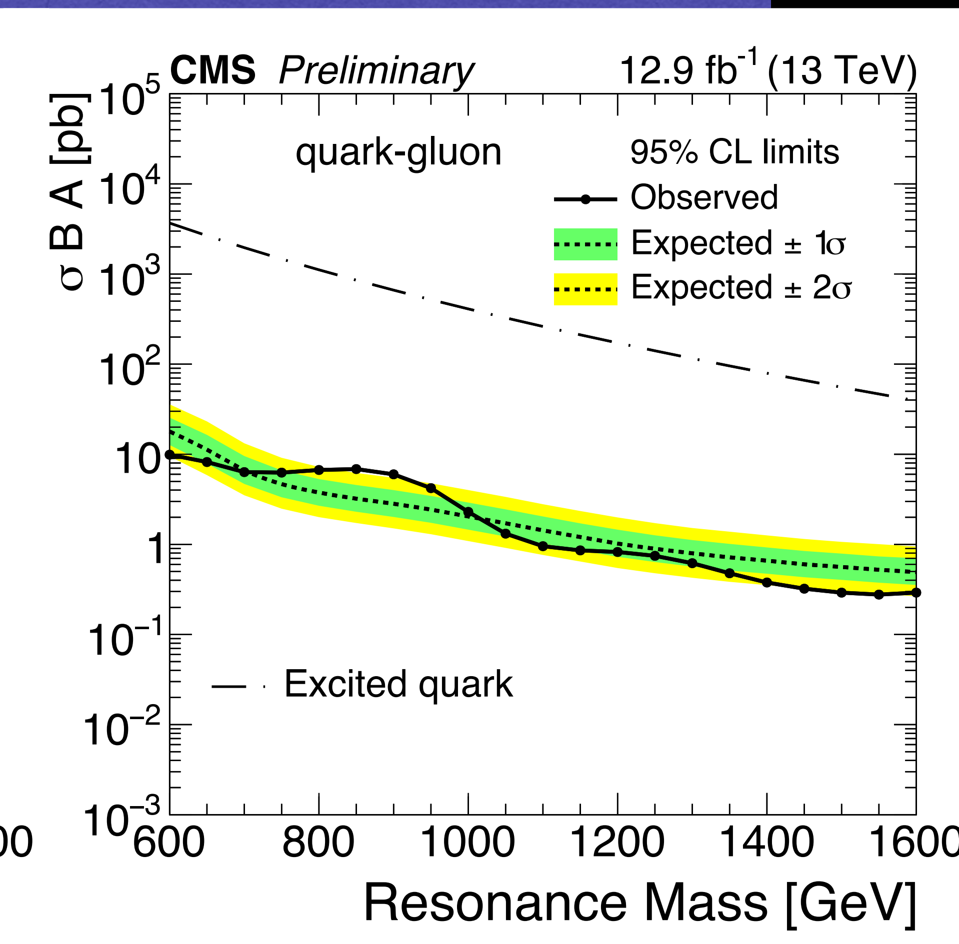
Additional Material: Low mass dijet analysis



Signal shapes



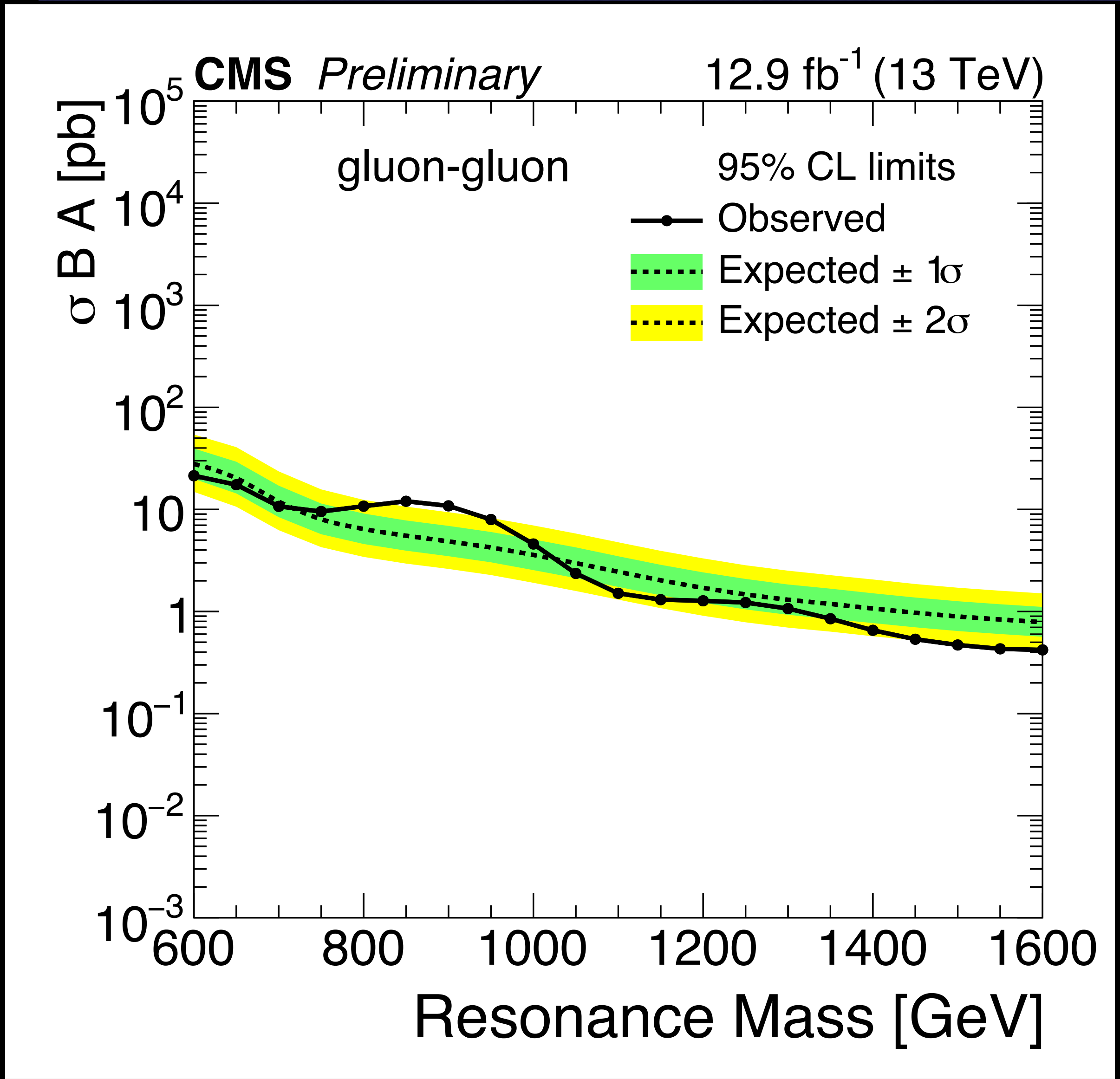
quark-quark final state



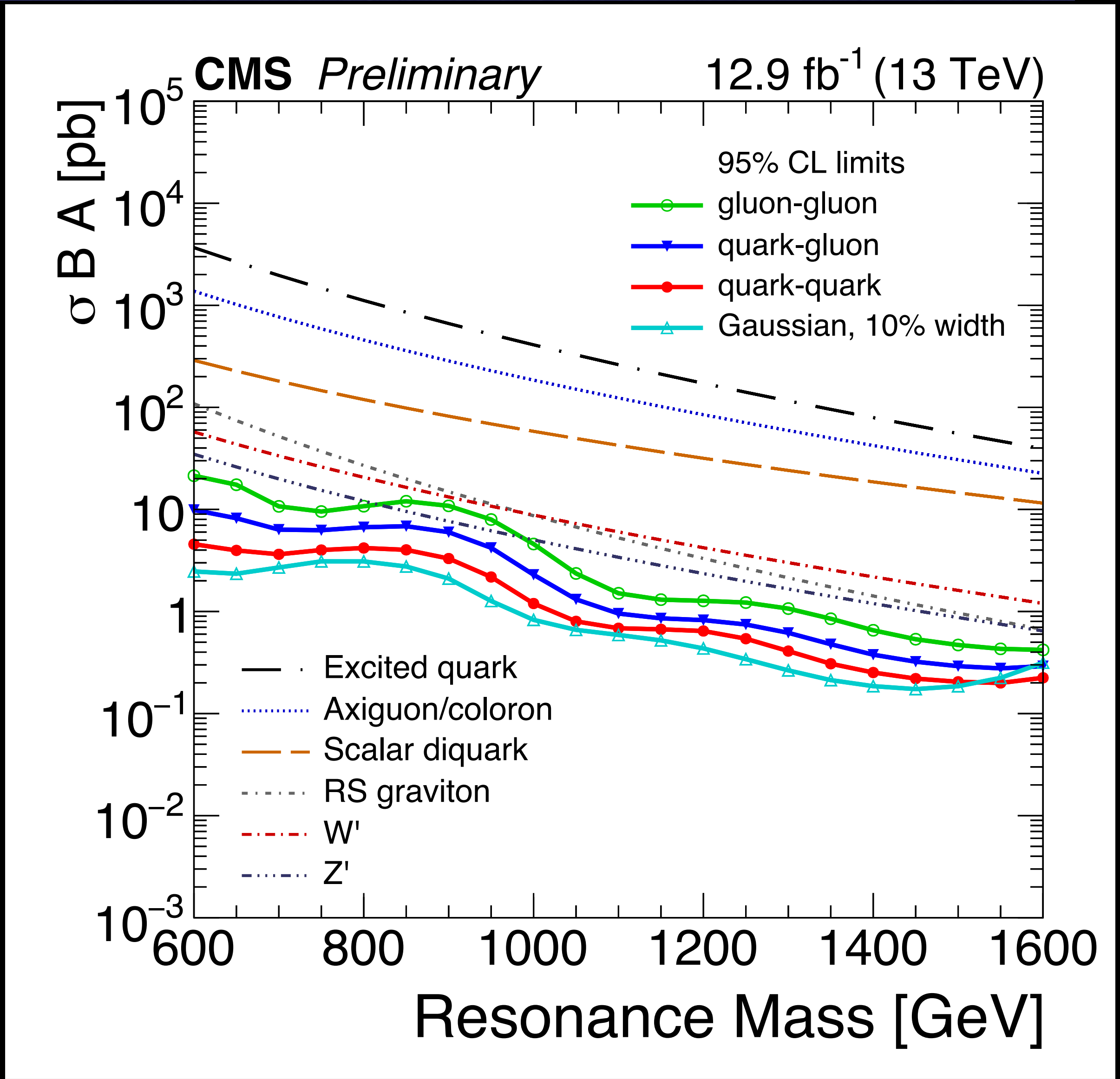
quark-gluon final state

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

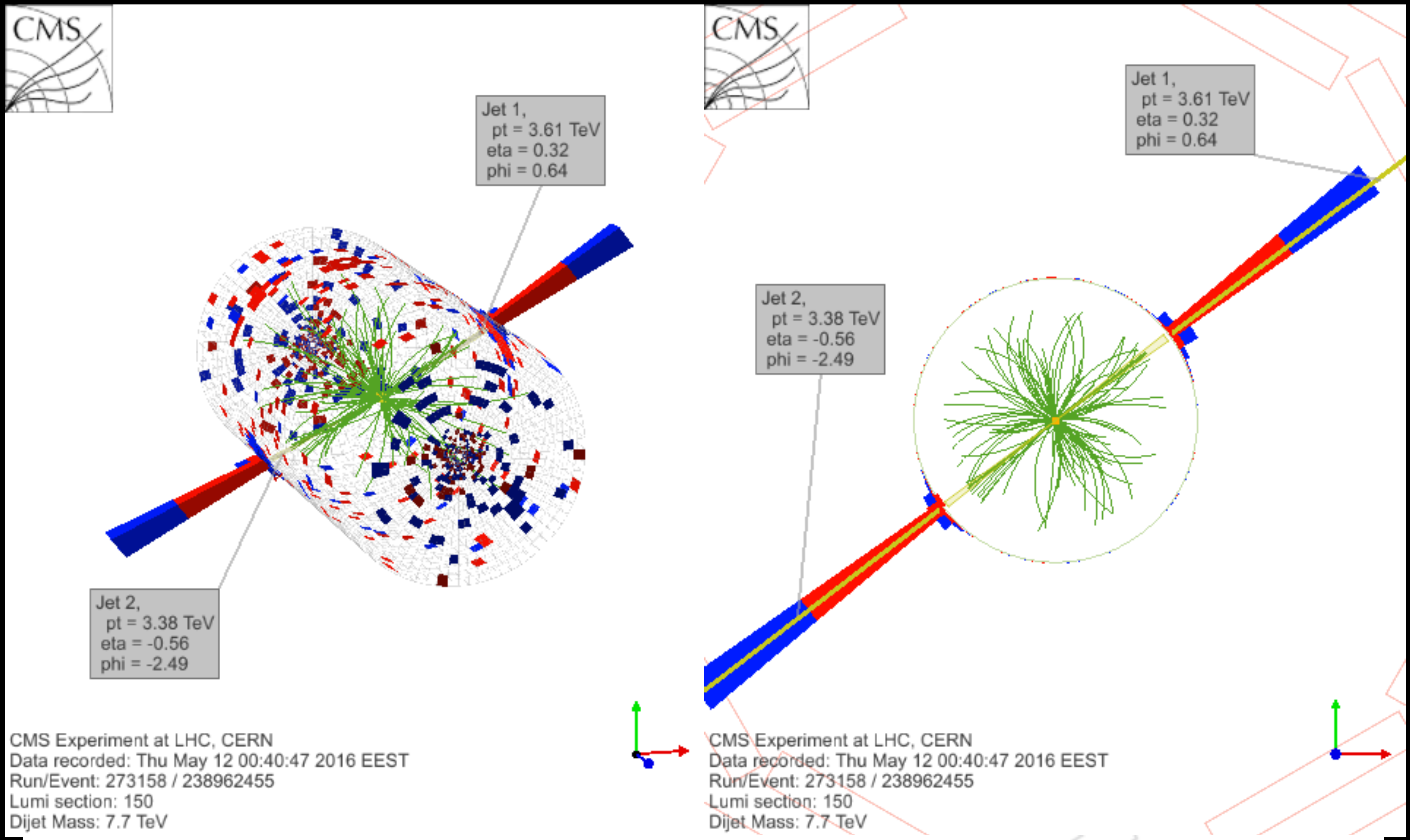
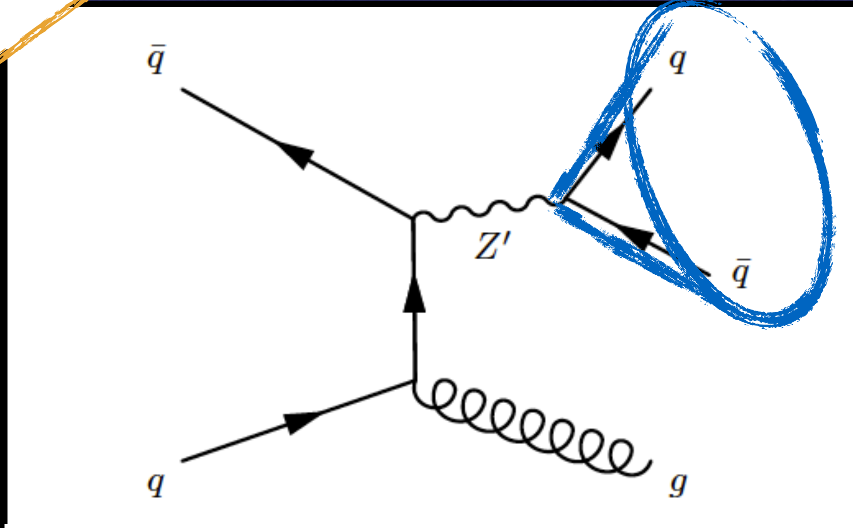


Figure 2: The event with the highest dijet invariant mass: three dimensional view (left), 2D view in the ρ-ϕ plane (right). The p_T, η, and ϕ values of the two wide jets are indicated. The invariant mass of the two wide jets is 7.7 TeV.

Hot off the press!

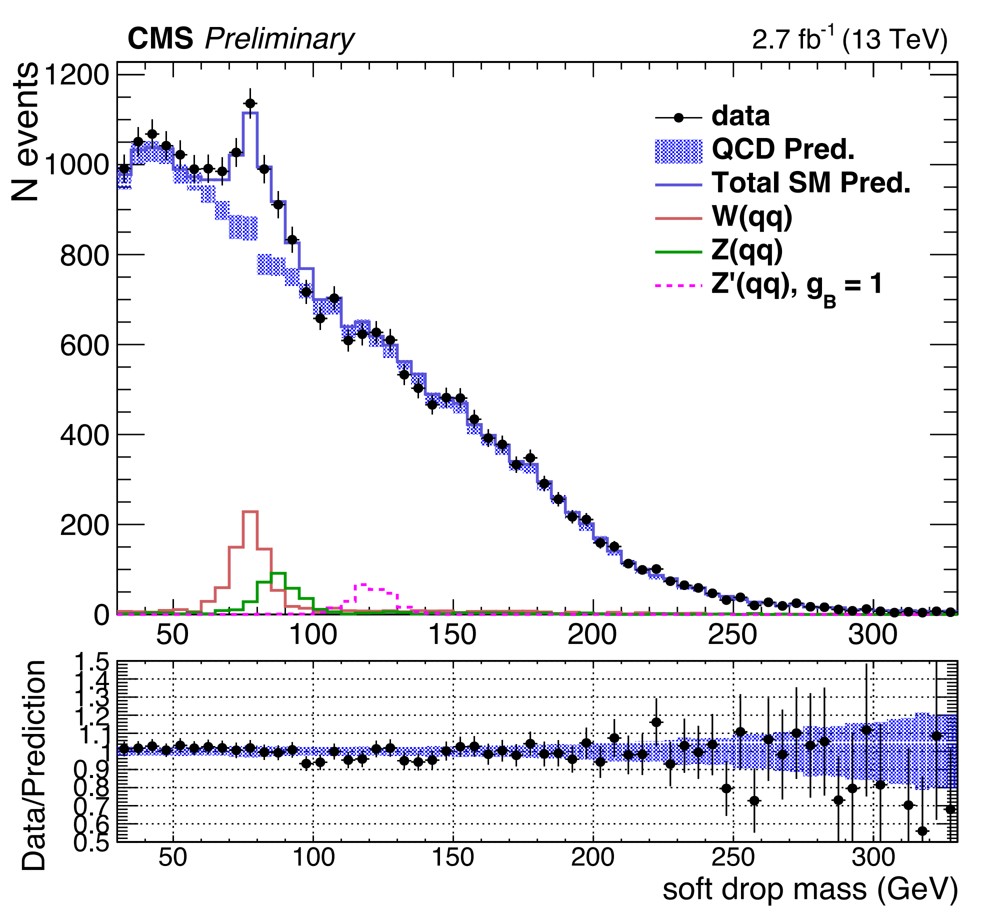
Low-mass dijet analysis: CMS

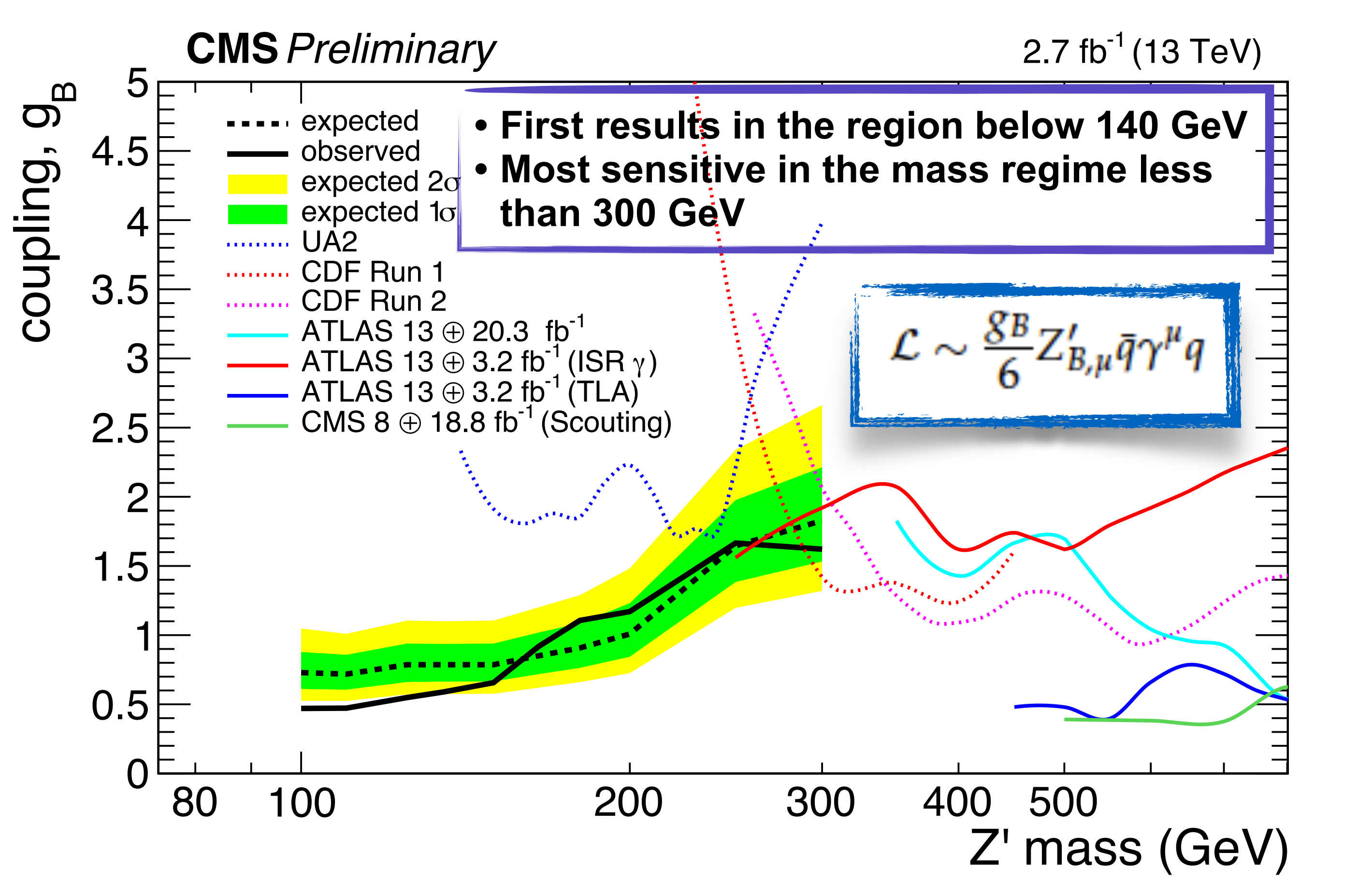


Boosted topology

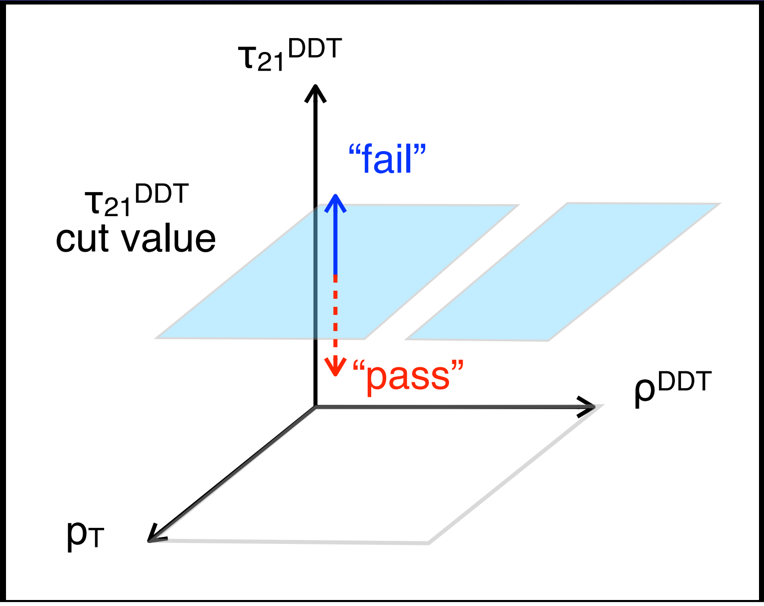
$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

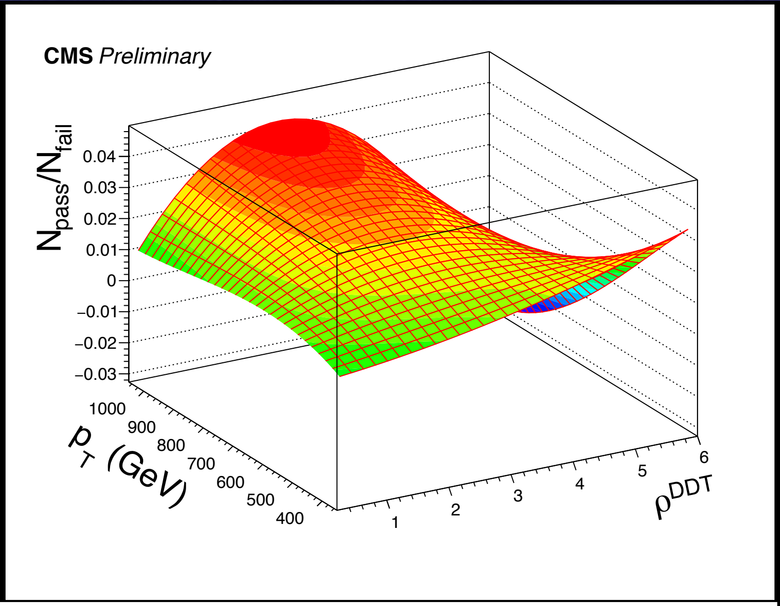
- R_0 is the radius of the jet, p_{Ti} is the transverse momenta of the constituents, ΔR_{12} is the distance between the contituents in the η-Φ plane
- z_{cut} is the soft drop threshold and β is an angular exponent

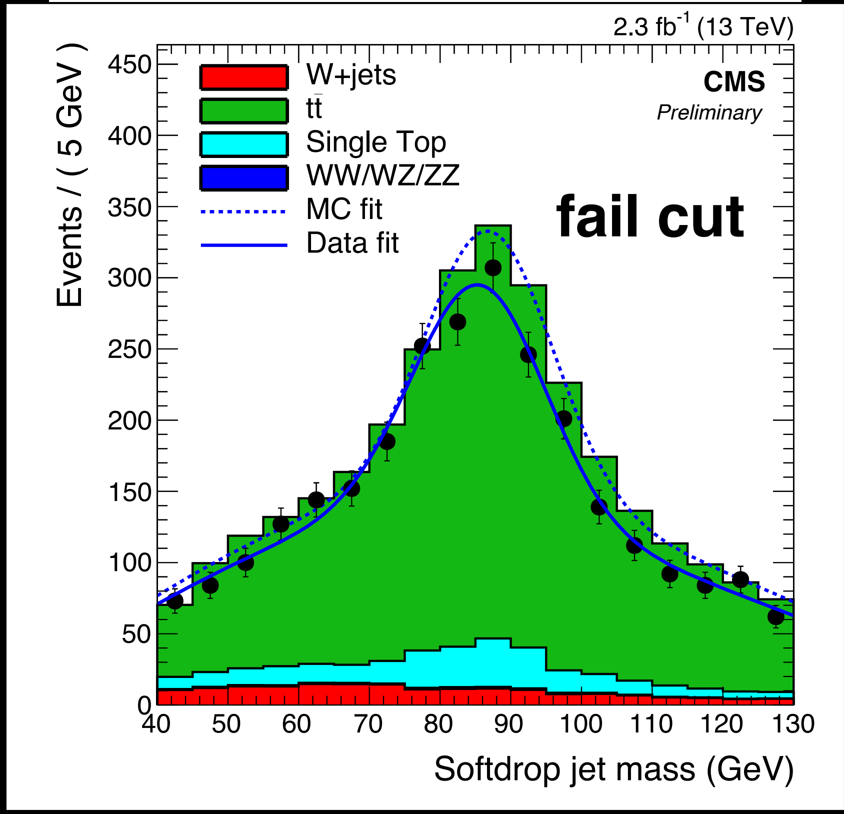


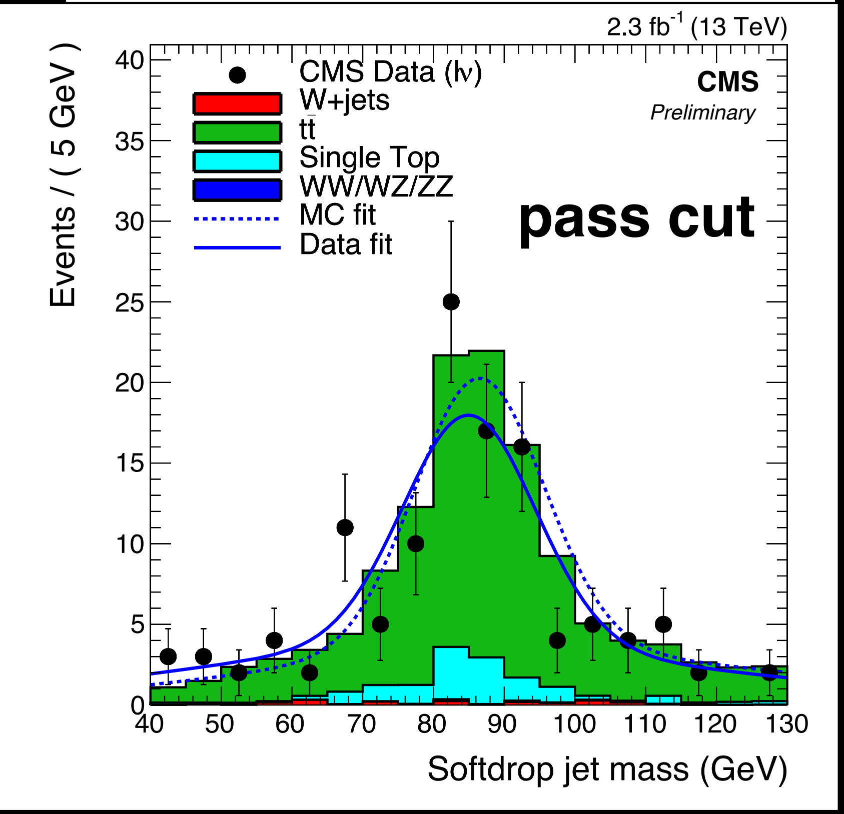


Additional Material: Low mass search using jet substructure technique

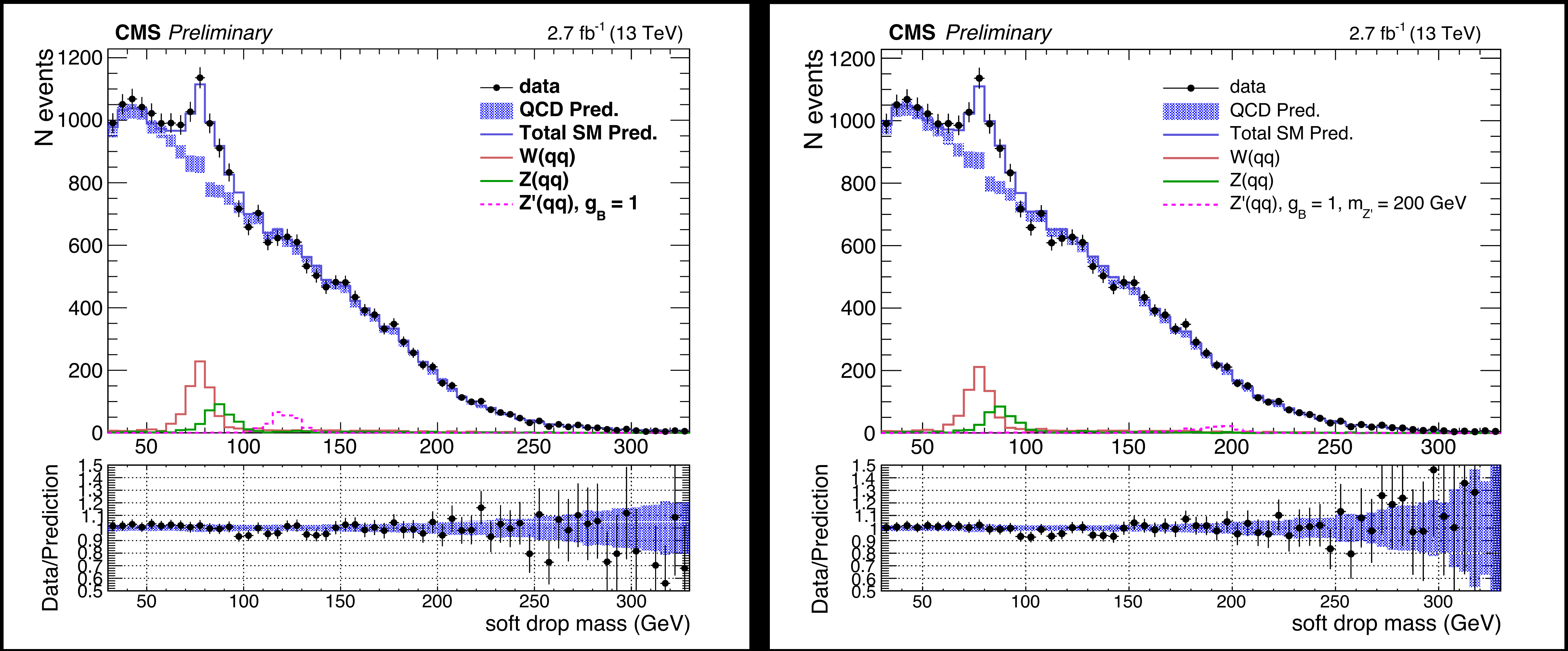




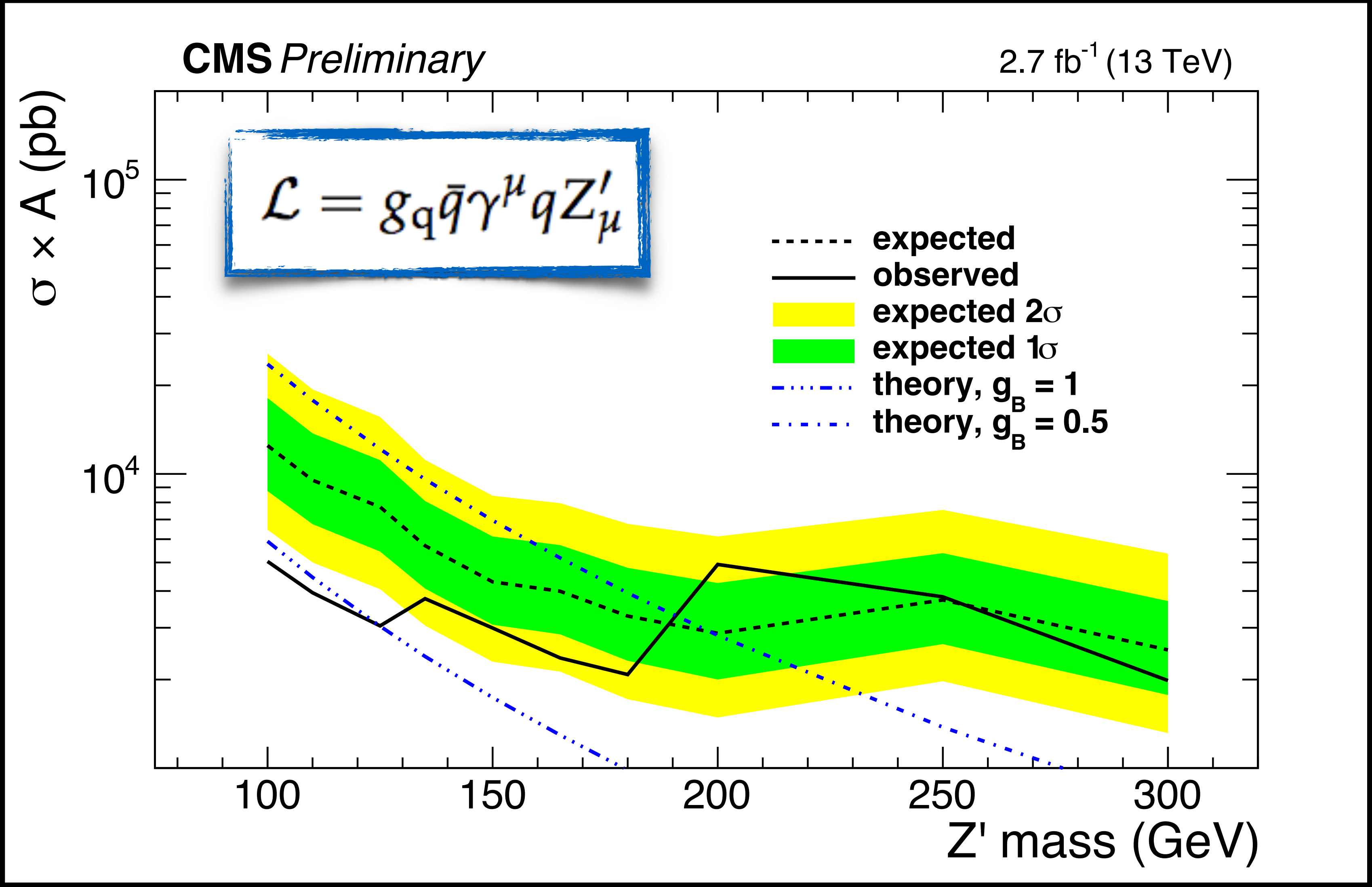




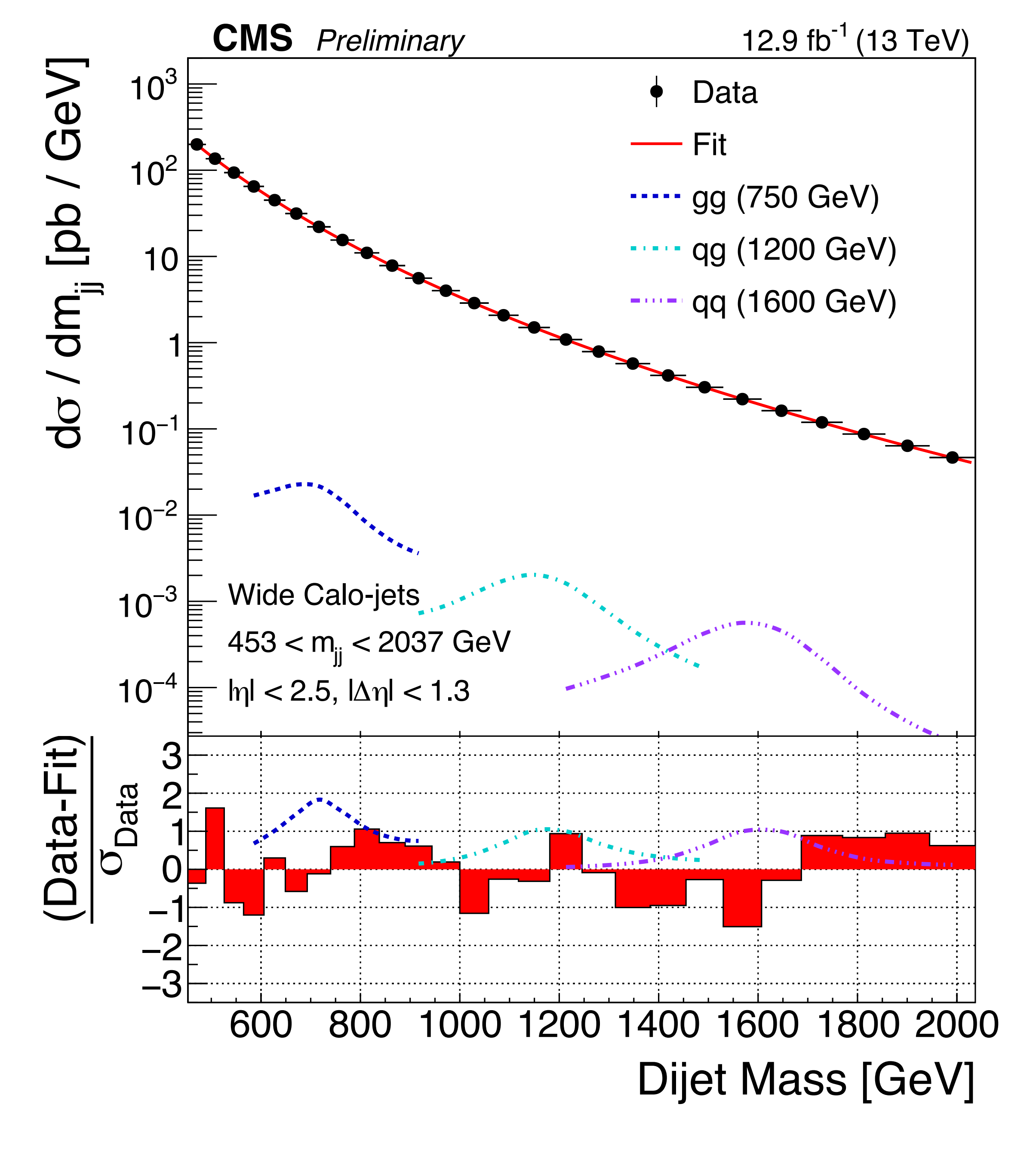
Additional Material: Low mass search using jet substructure technique



Additional Material: Low mass search using jet substructure technique



Additional Material: Trigger Level Searches with Dijets

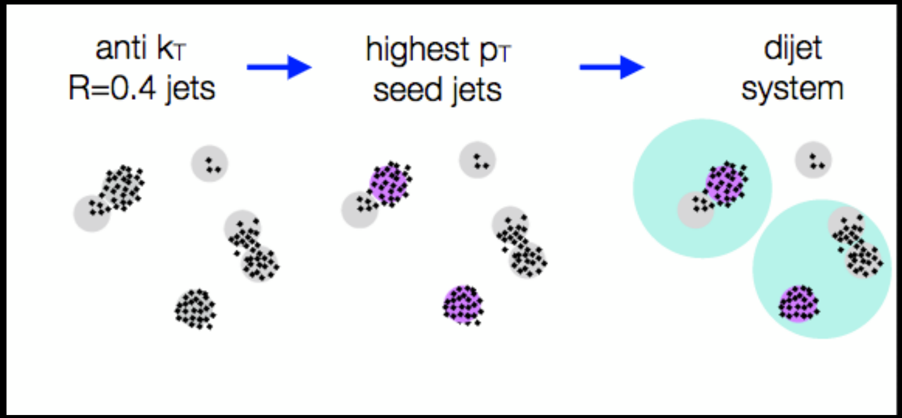


- To sustain a high rate in the data scouting stream, 4 momenta of the calorimetric jets is stored
- Rate at HLT is 1 kHz
- Scouting data are stored immediately after the HLT selection

CMS dijet resonance search reconstruction

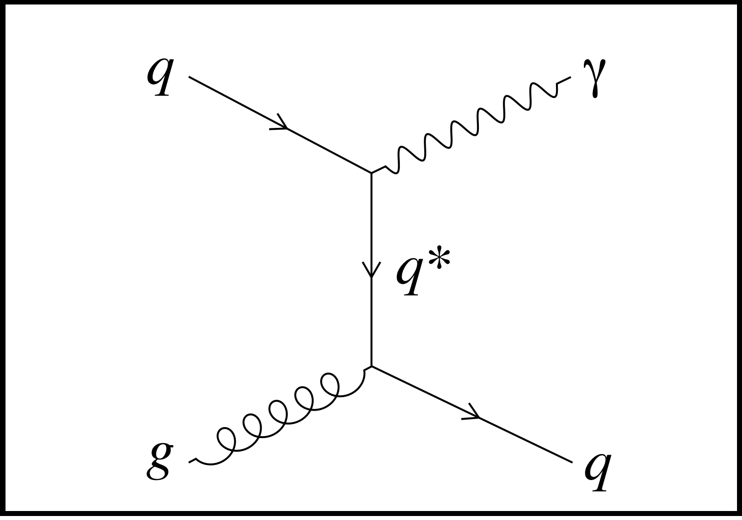
Dijet reconstruction with wide jets

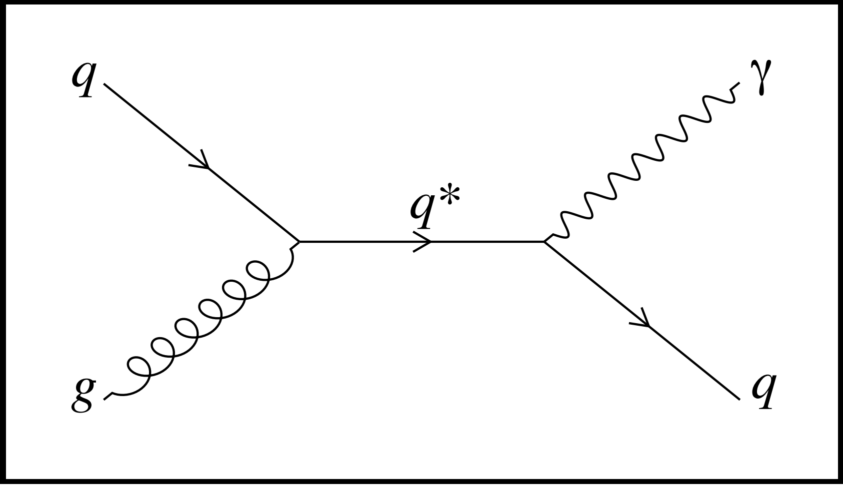
- Uses two leading jets in an event as seeds. Merges neighboring jets to nearest leading jet if $\Delta R < 1.1$
- Recover loss in mass response/resolution due to radiation



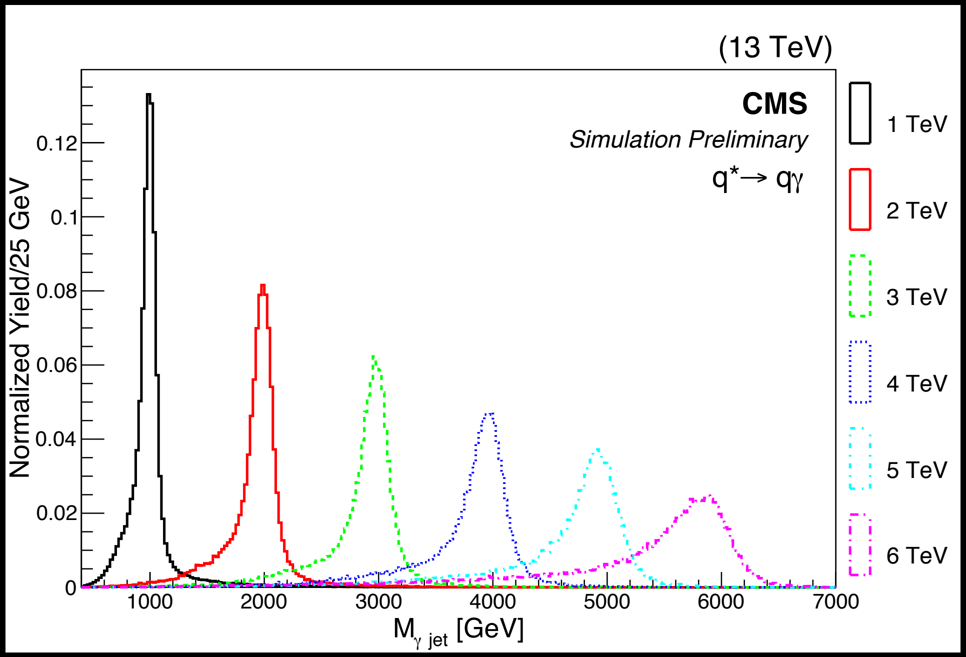
- The low mass search uses wide jets reconstructed from calo-jets
- The high mass search uses wide jets reconstructed from particle-flow jets

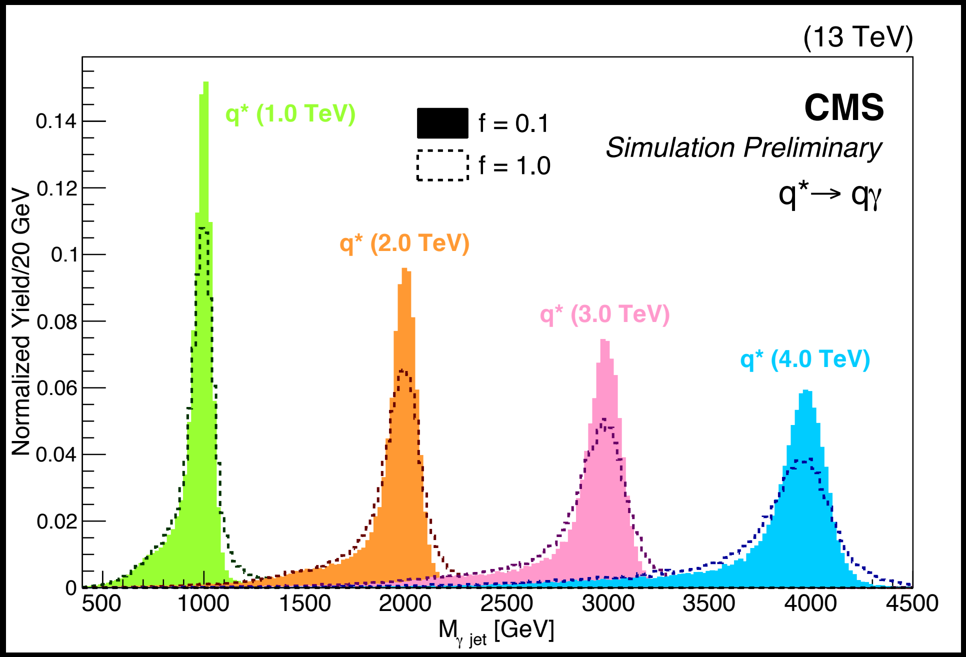
Additional Material: Search for excited quarks



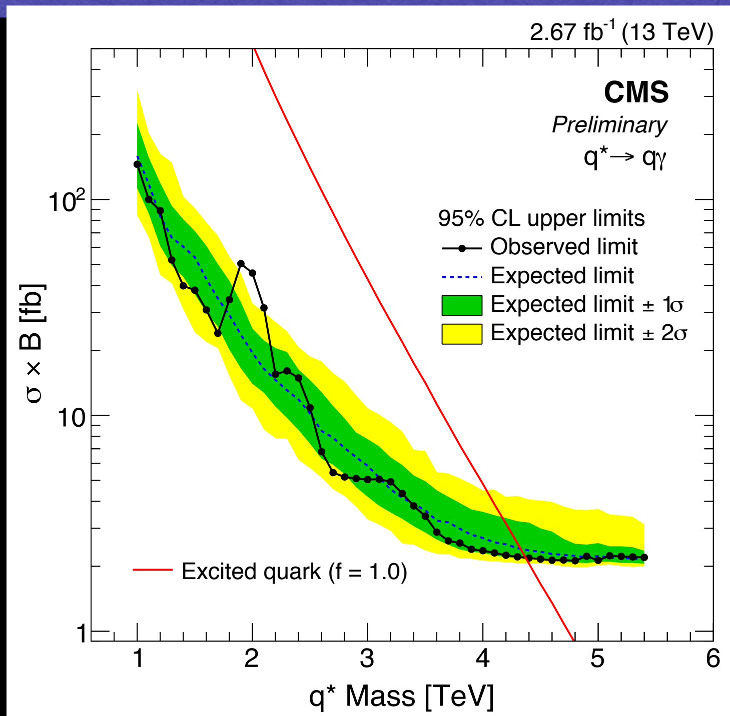


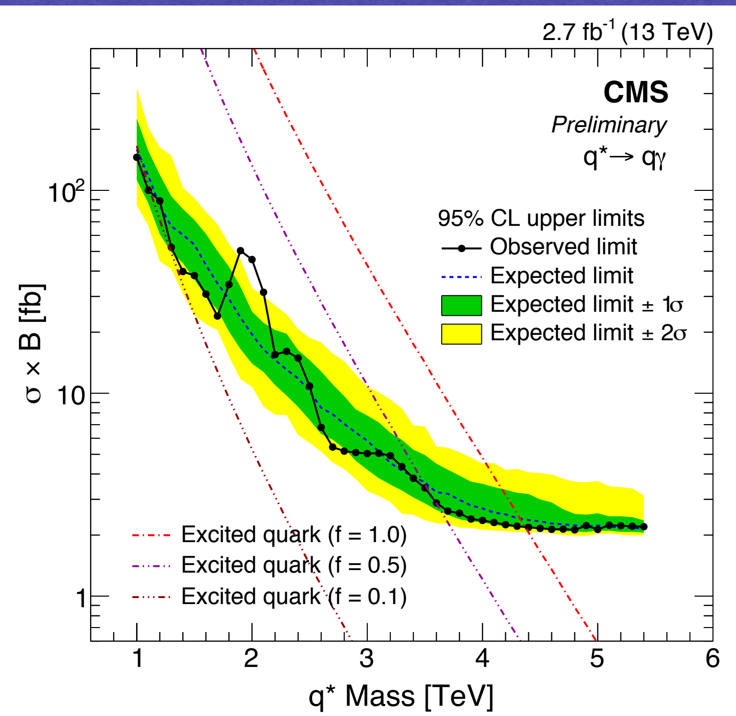
$$\mathcal{L}_{int} = \frac{1}{2\Lambda}\bar{q}^{*}_{R}\,\sigma^{\mu\nu}\left[g_s f_s \frac{\lambda_a}{2} G^{a}_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] q_L$$

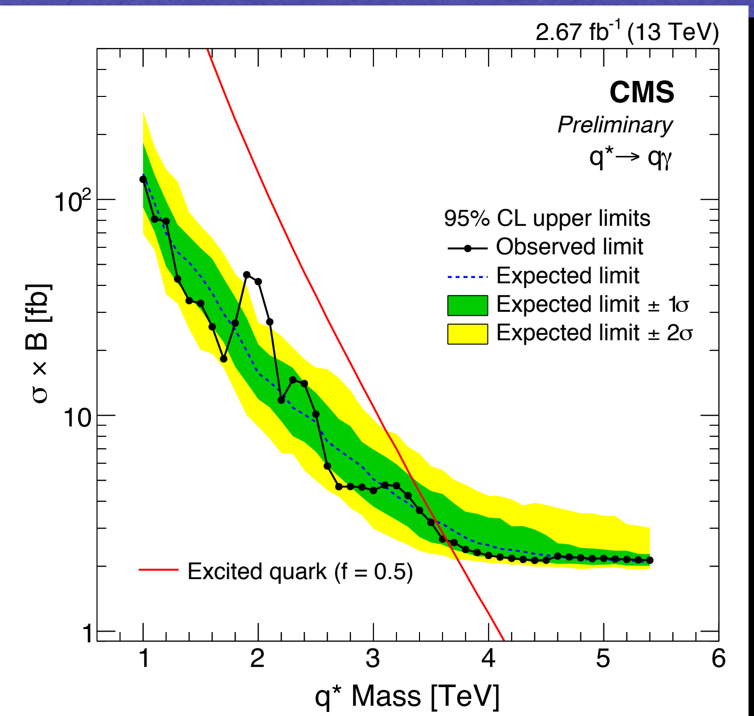


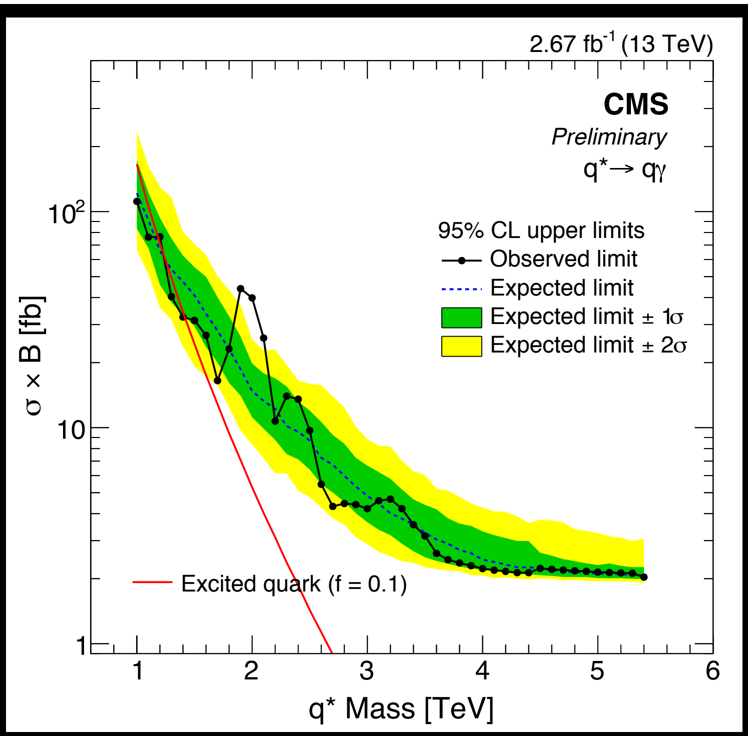


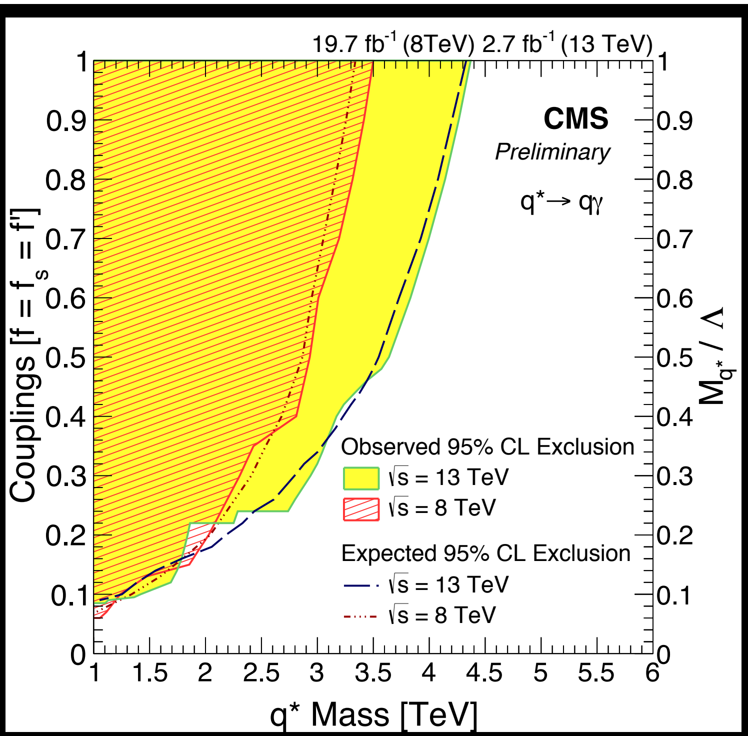
Additional Material: Search for excited quarks











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 GeV**
- A **E_T > 50 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

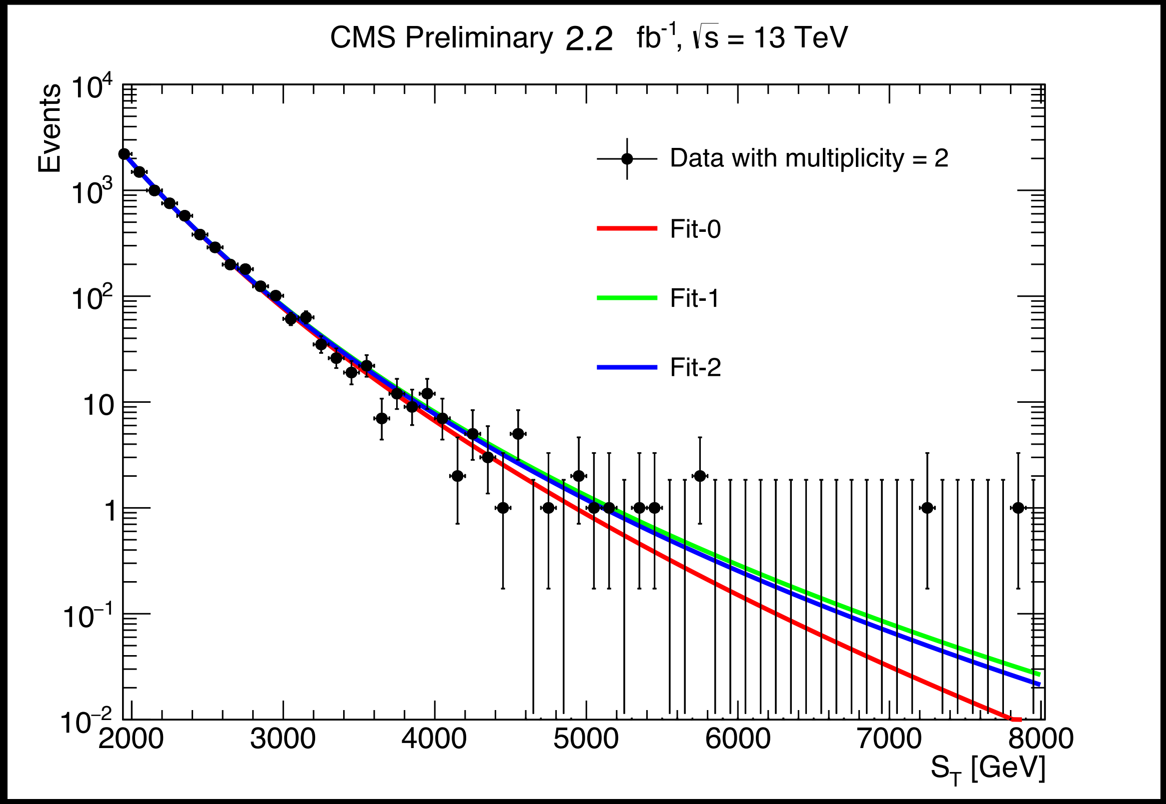
Background Estimation: CMS

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

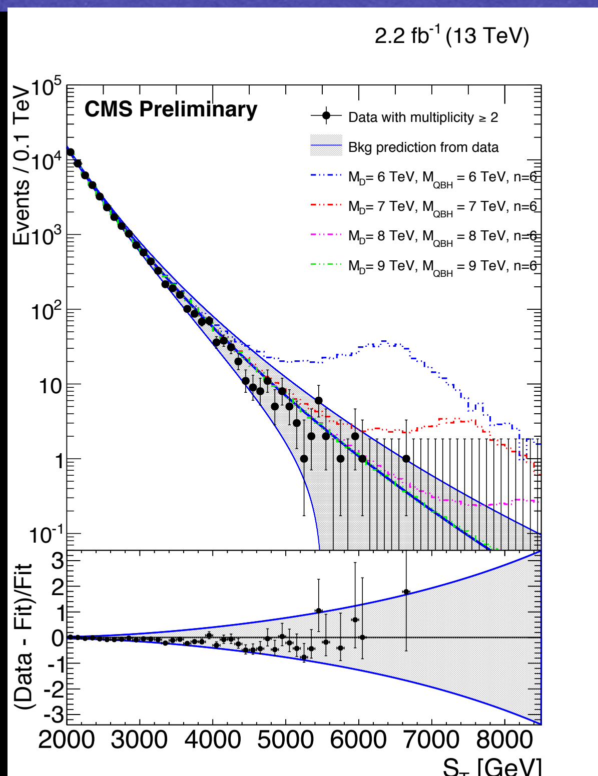
The background is estimated in a signal depleted regime (multiplicity = 2)

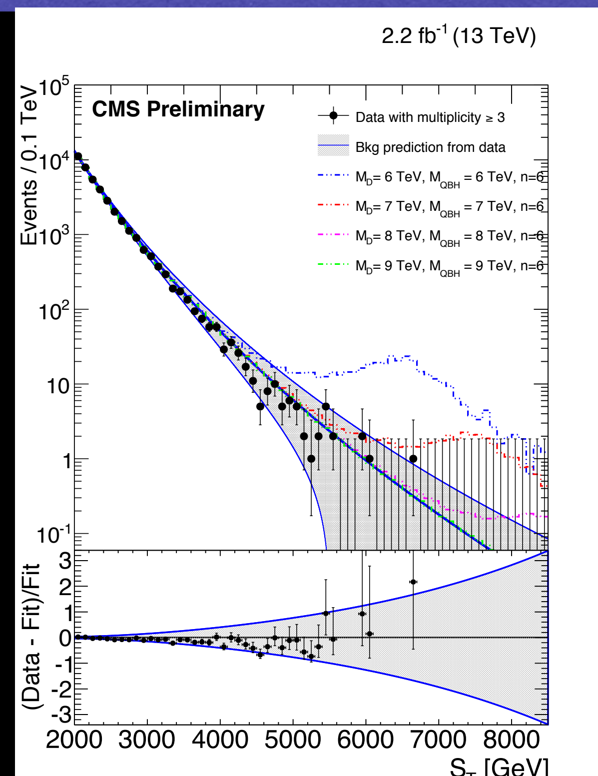
ST shape invariance is checked over all multiplicities

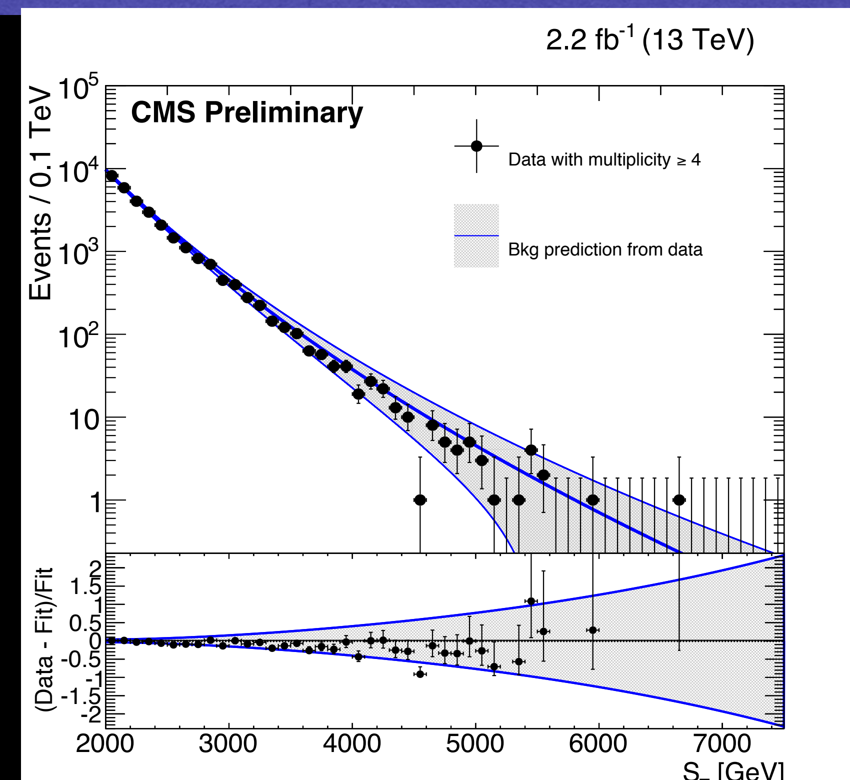
The background prediction from the multiplicity = 2 regime is applied to higher multiplicities by appropriate normalization in a region of low signal contamination

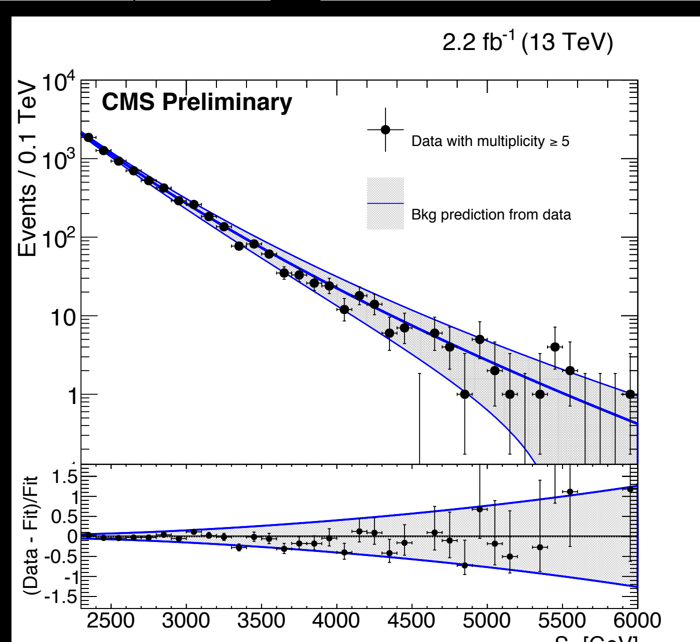
- Essentially one performs a counting experiment using the variable **S_T**, whe **S_T** is defined as the scalar sum of the transverse energy **(E_T)** of **jets**, **leptons** and **photons. ME_T** is also added to **S_T** if **ME_T > 50 GeV**

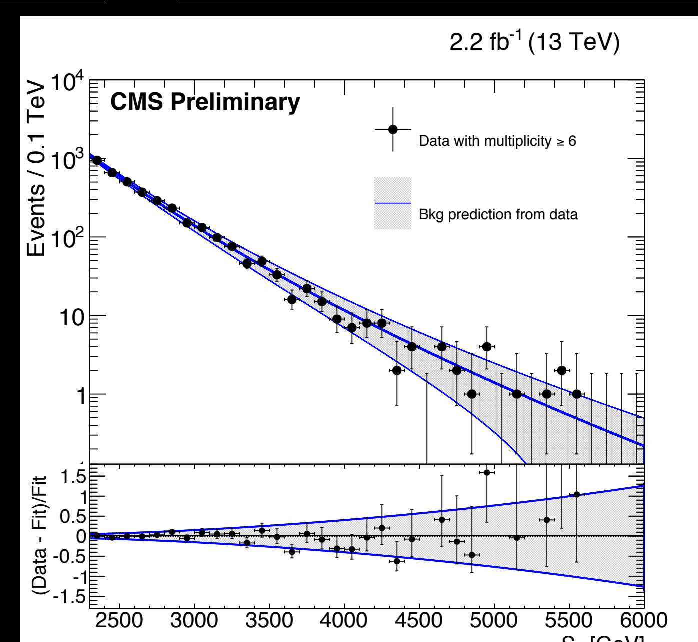
Additional Material: Search for microscopic black holes







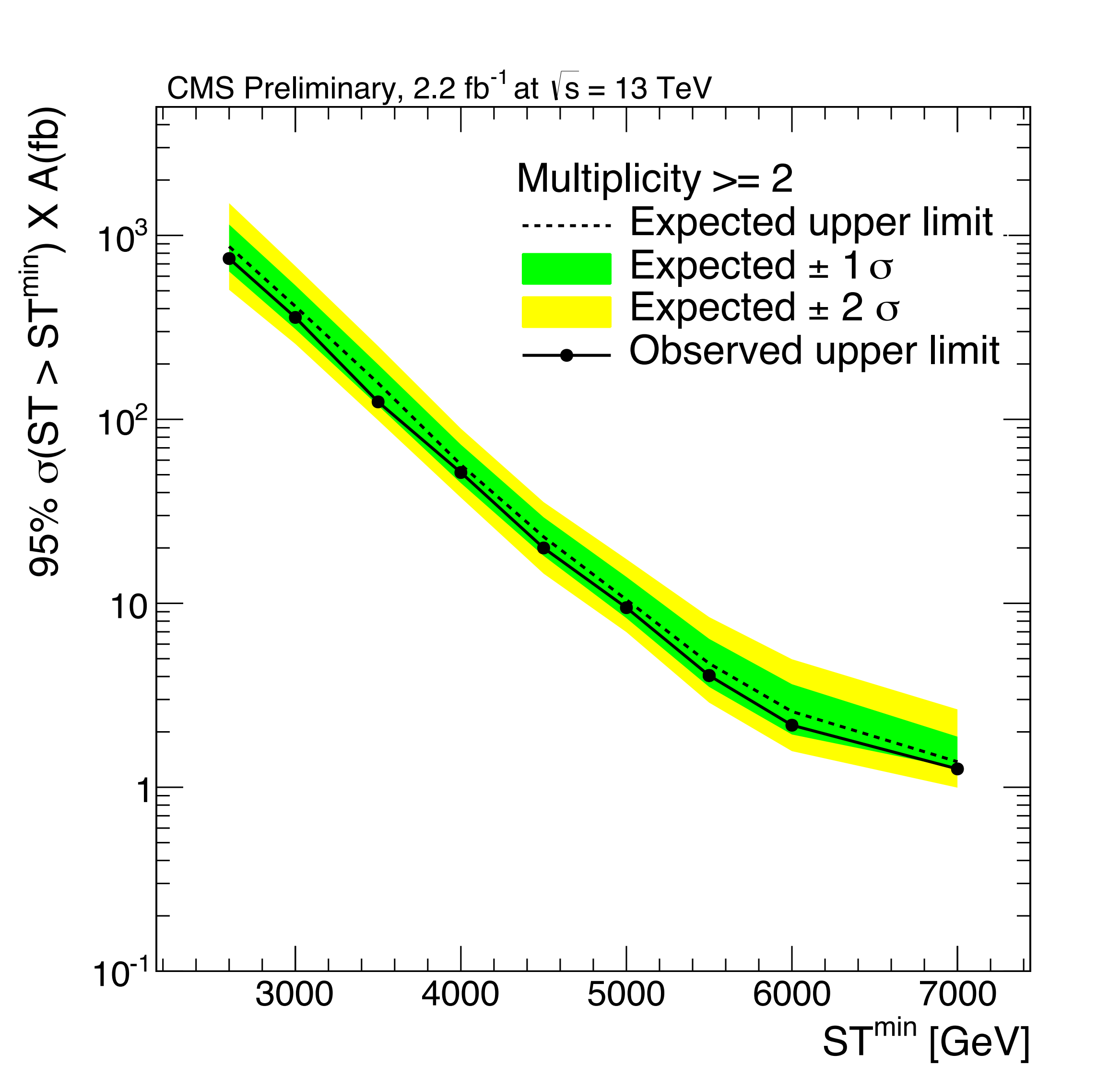




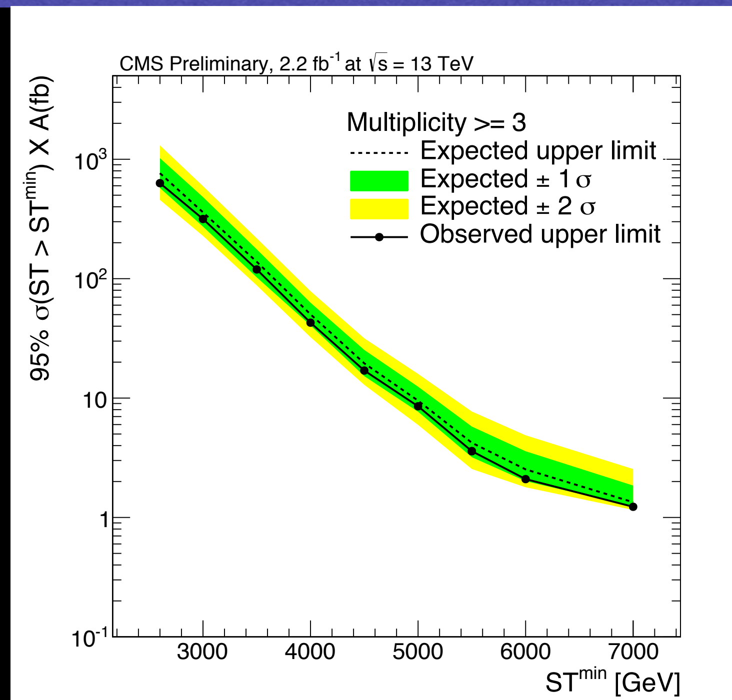
Additional Material: Search for microscopic black holes

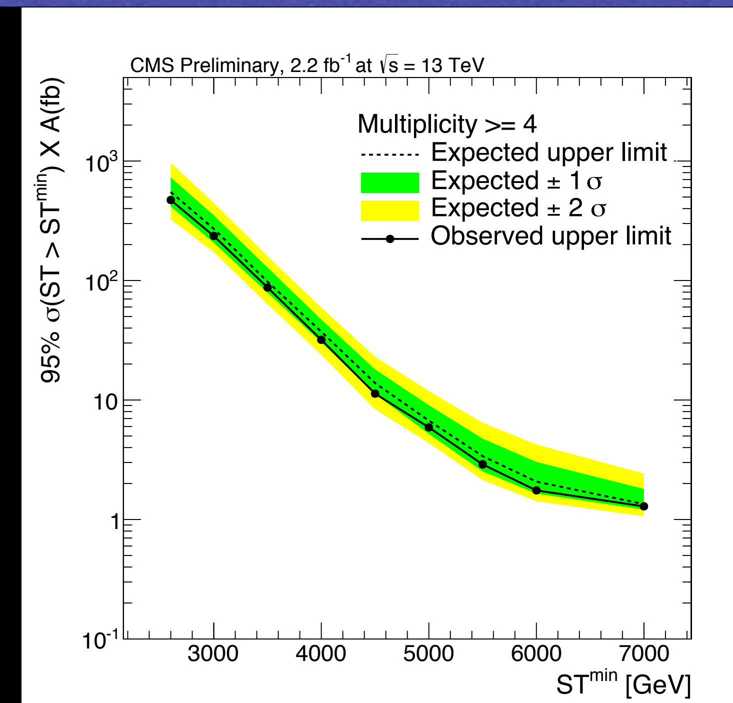
- Model independent limits are calculated as a function of S_{Tmin} for each inclusive multiplicity scenario.

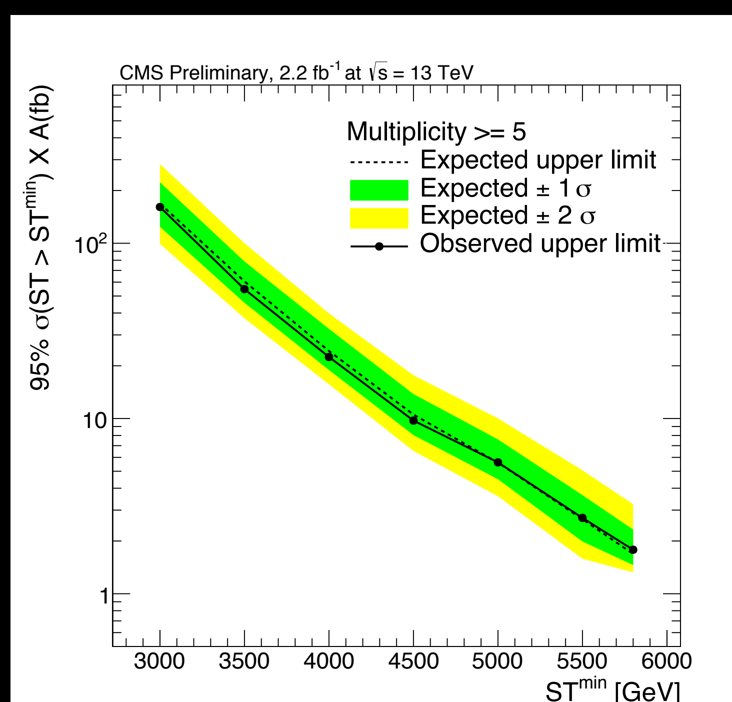
- Full CIs is used as opposed to Asymptotic CIs for more acurate calculation.

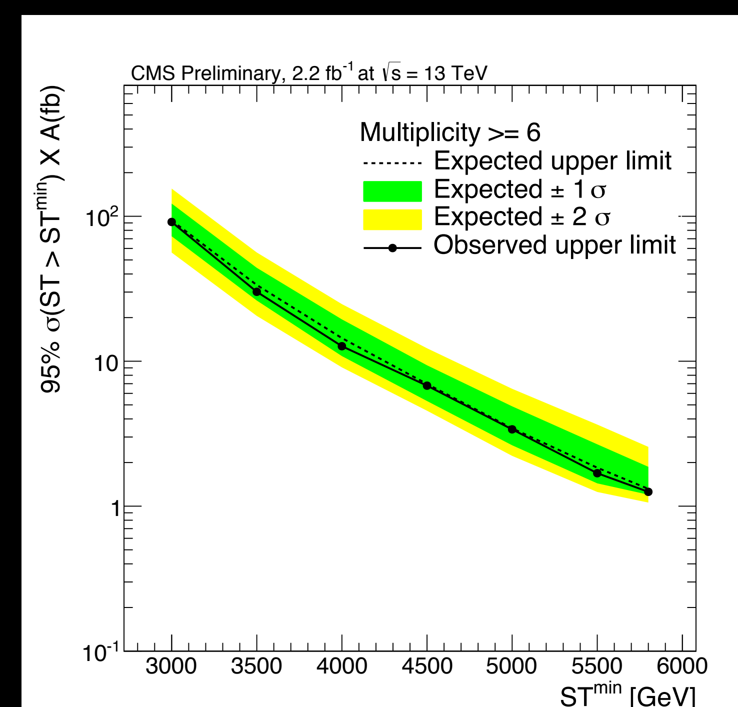


Additional Material: Search for microscopic black holes

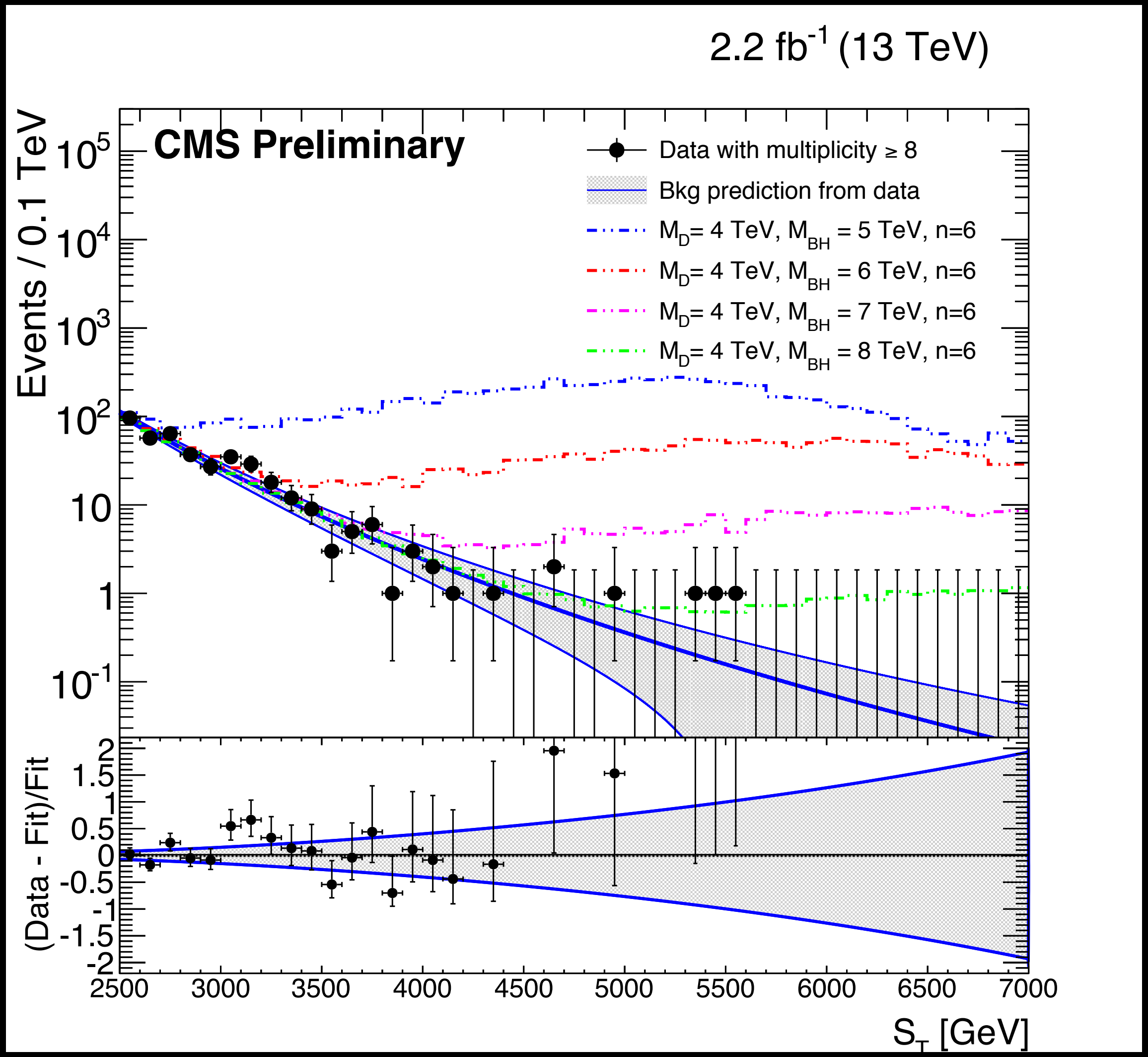




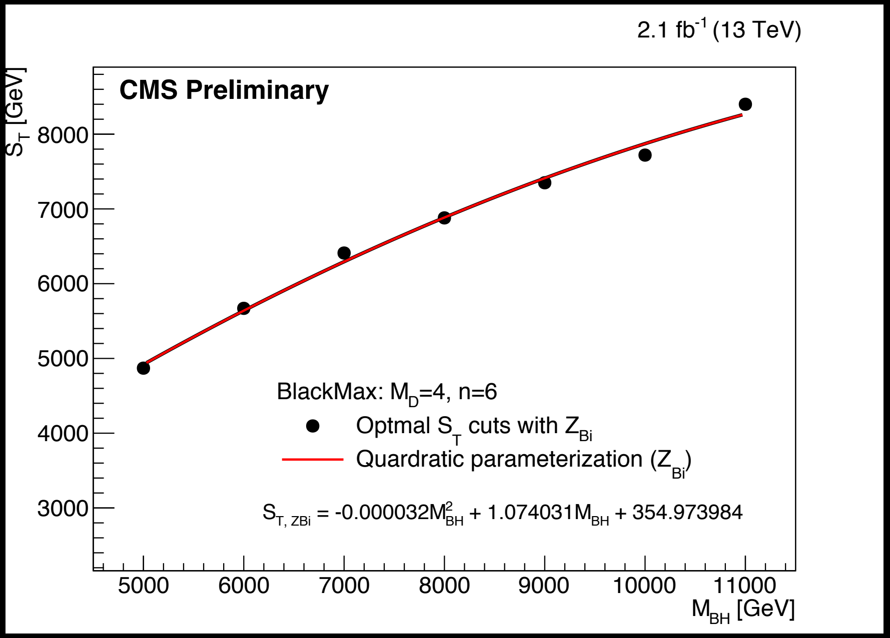


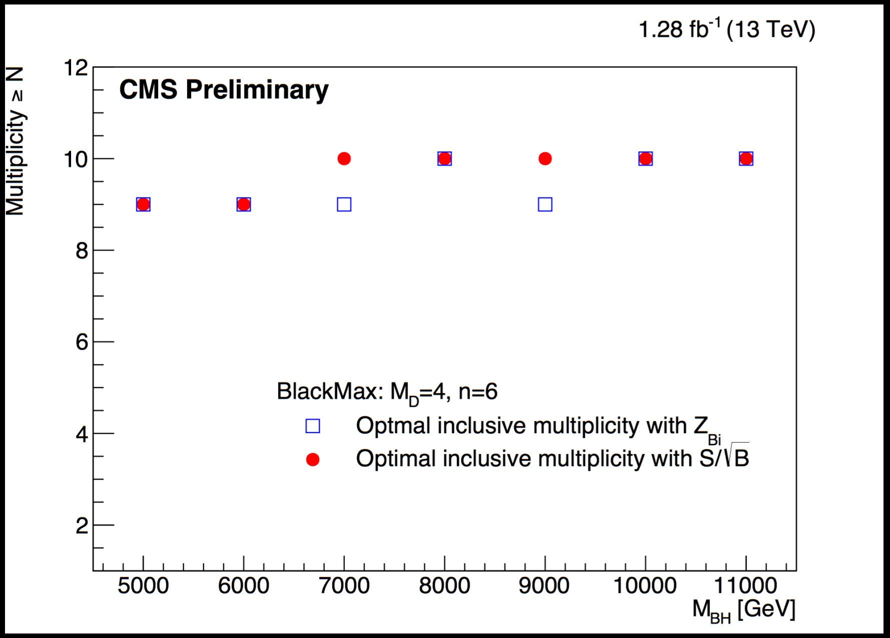


Additional Material: Search for microscopic black holes

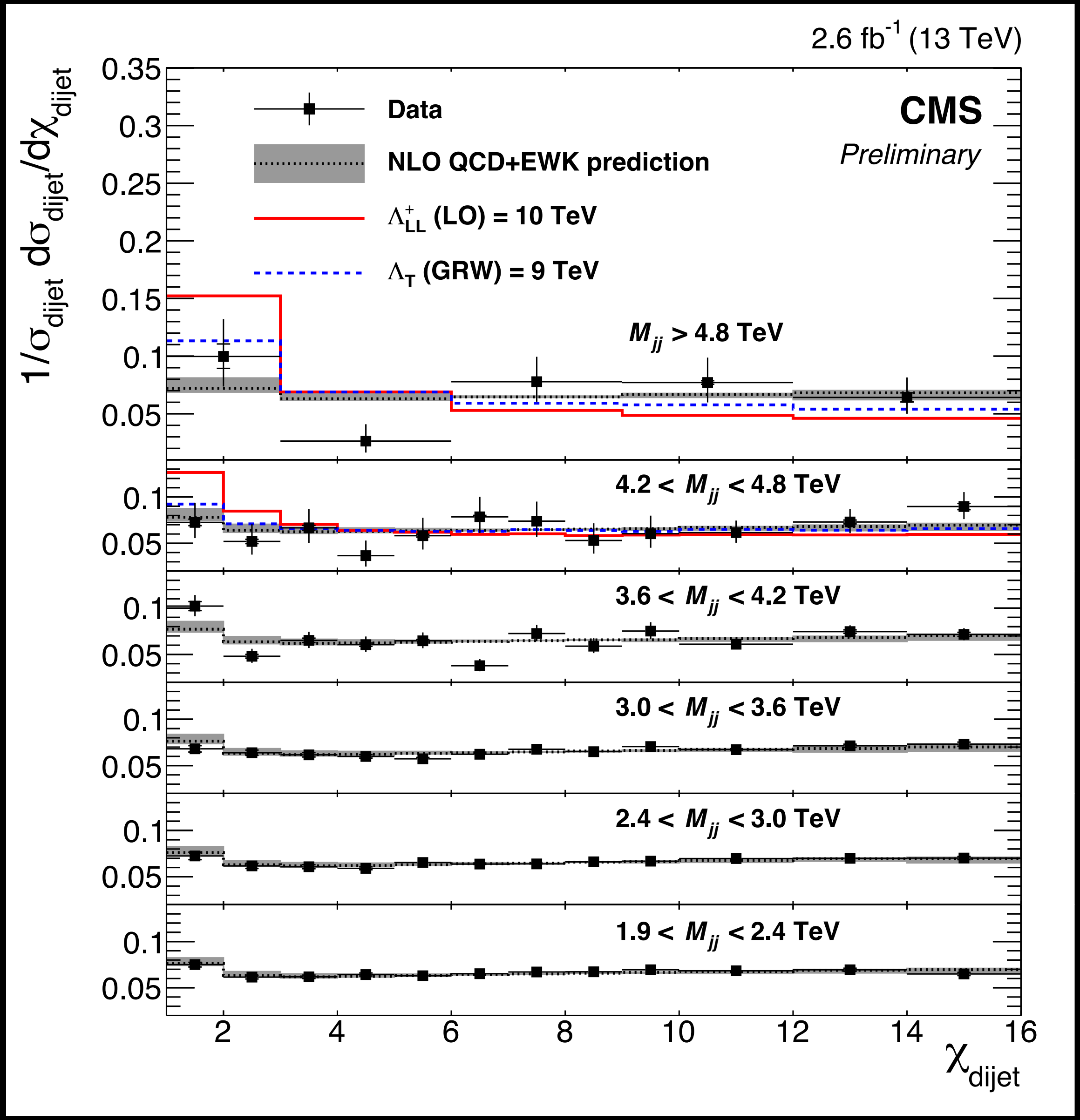


Observed and expected limits for σ (upper limit cross section) X A (acceptance) in inclusive N objects are reported



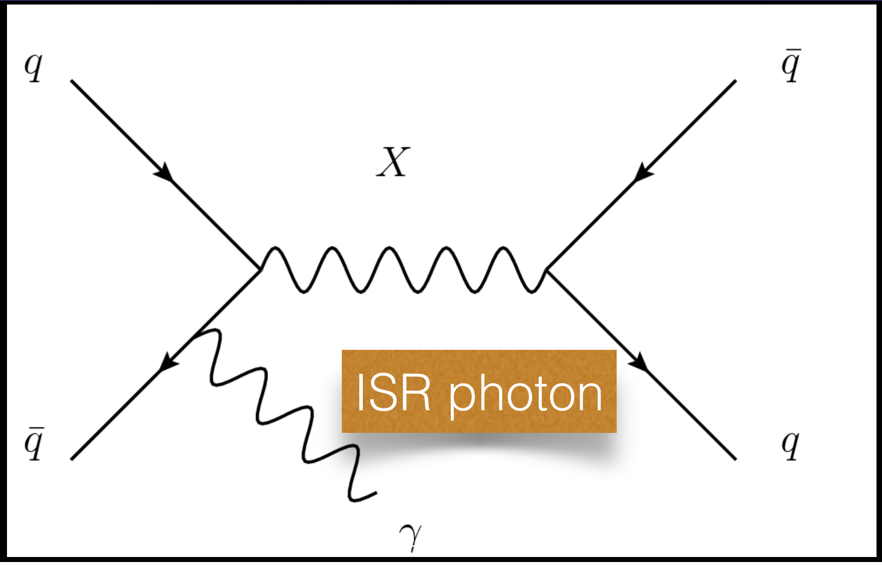


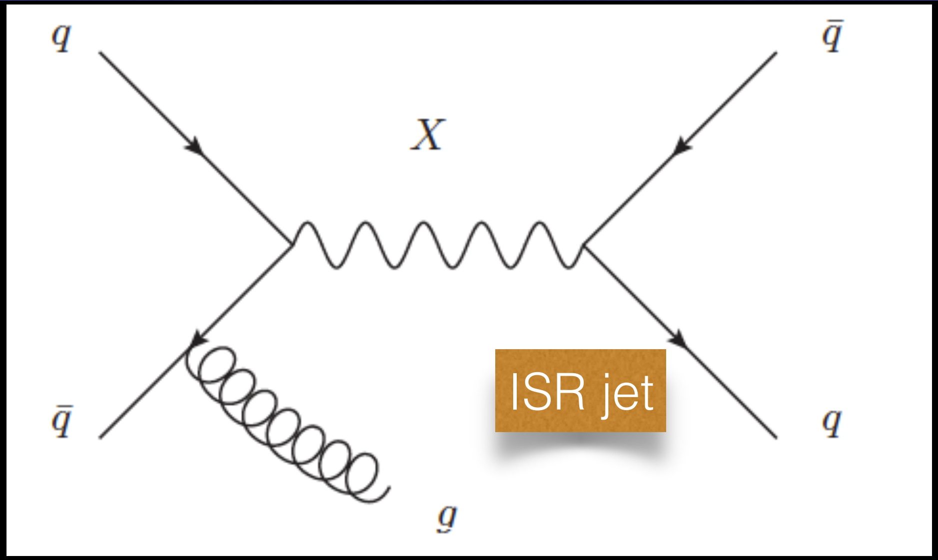
Dijet results: CMS

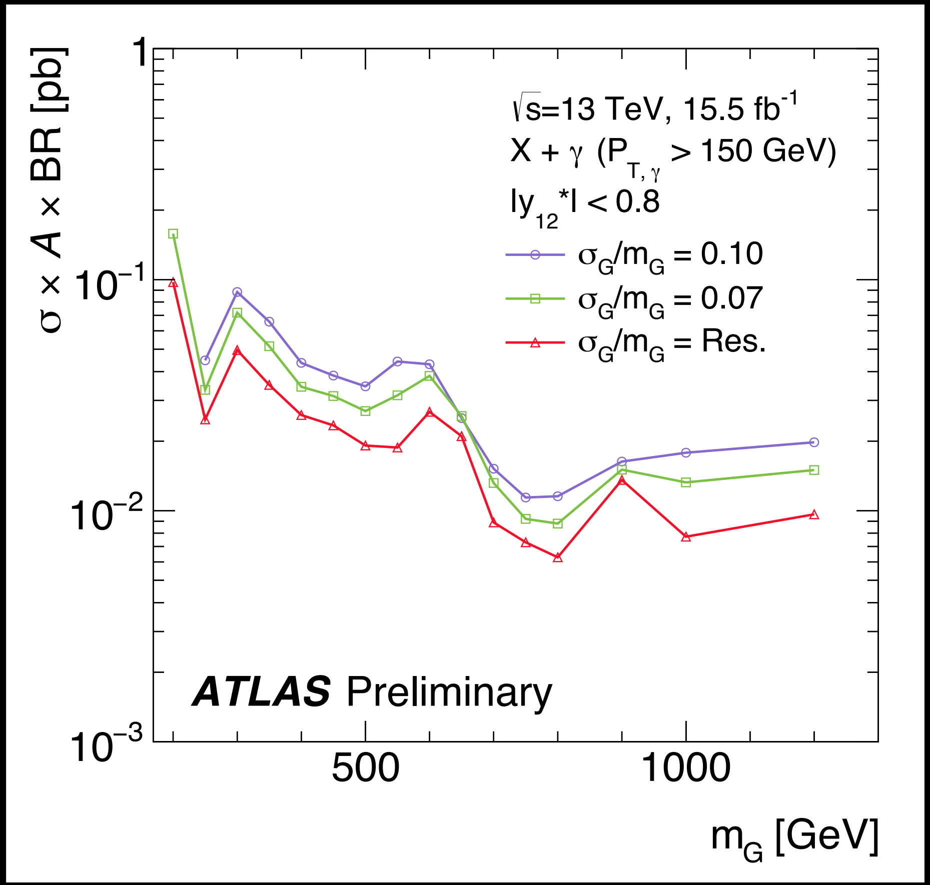


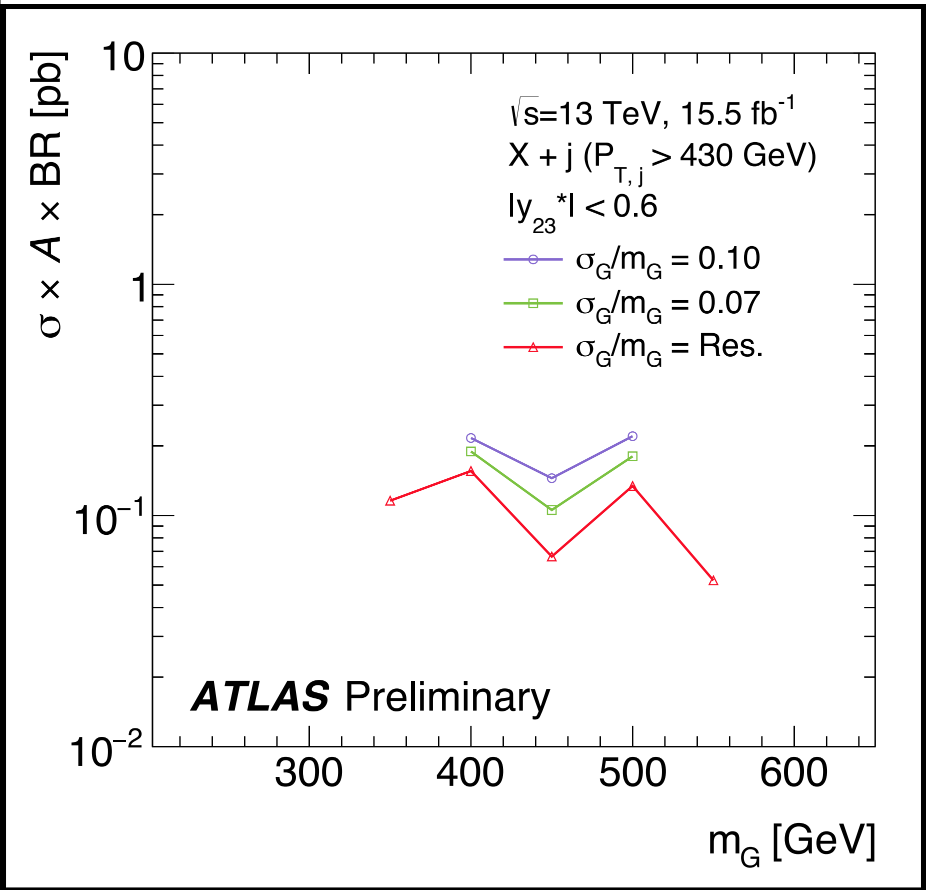
Search for new physics in dijet angular distributions

Low-mass dijet analysis: ATLAS

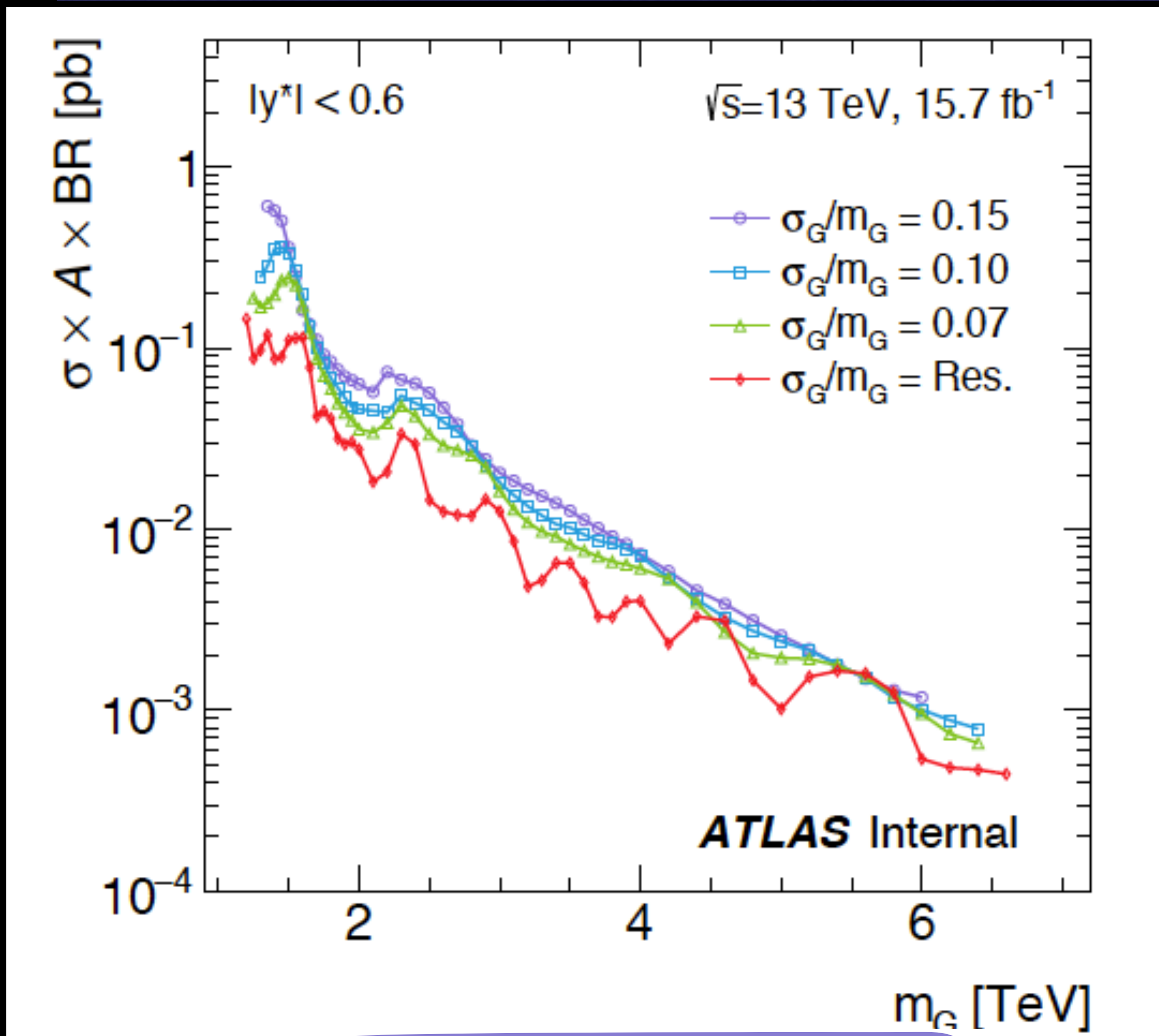


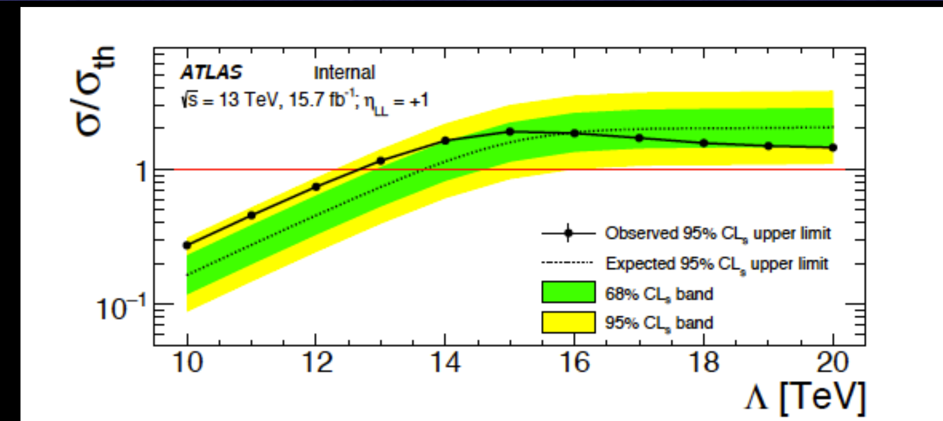




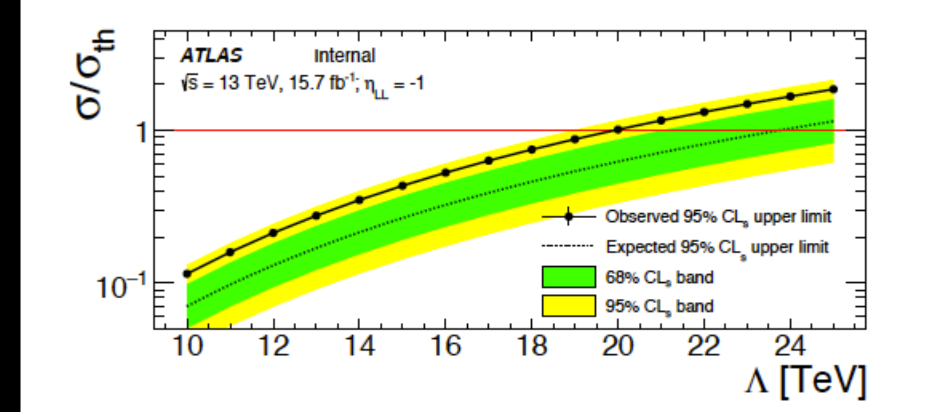


High-mass dijet analysis: ATLAS

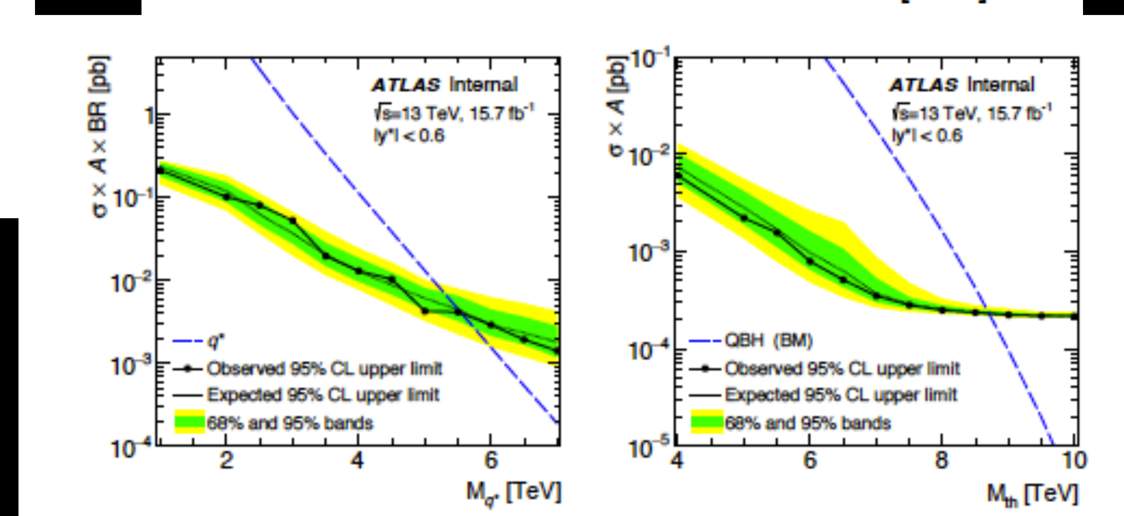




(a)

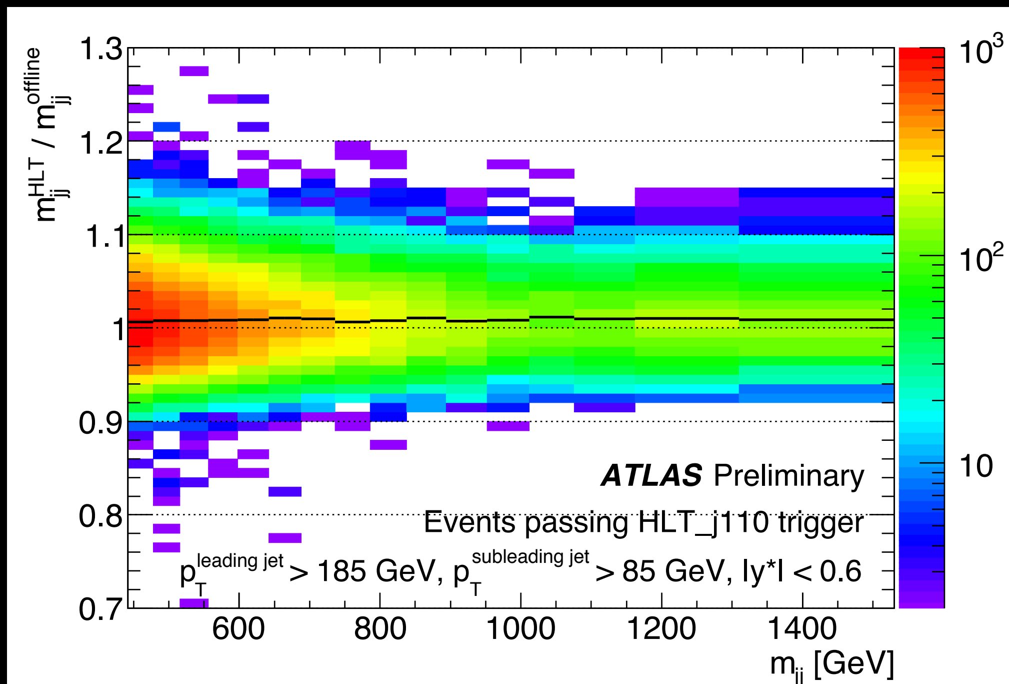


Model	95% CL Exclusion limit Observed	Expected
Quantum black holes, ADD (BlackMax generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions (η_{LL} =+1)	12.6 TeV	13.7 TeV
Contact interactions (η_{LL} =-1)	19.9 TeV	23.7 TeV

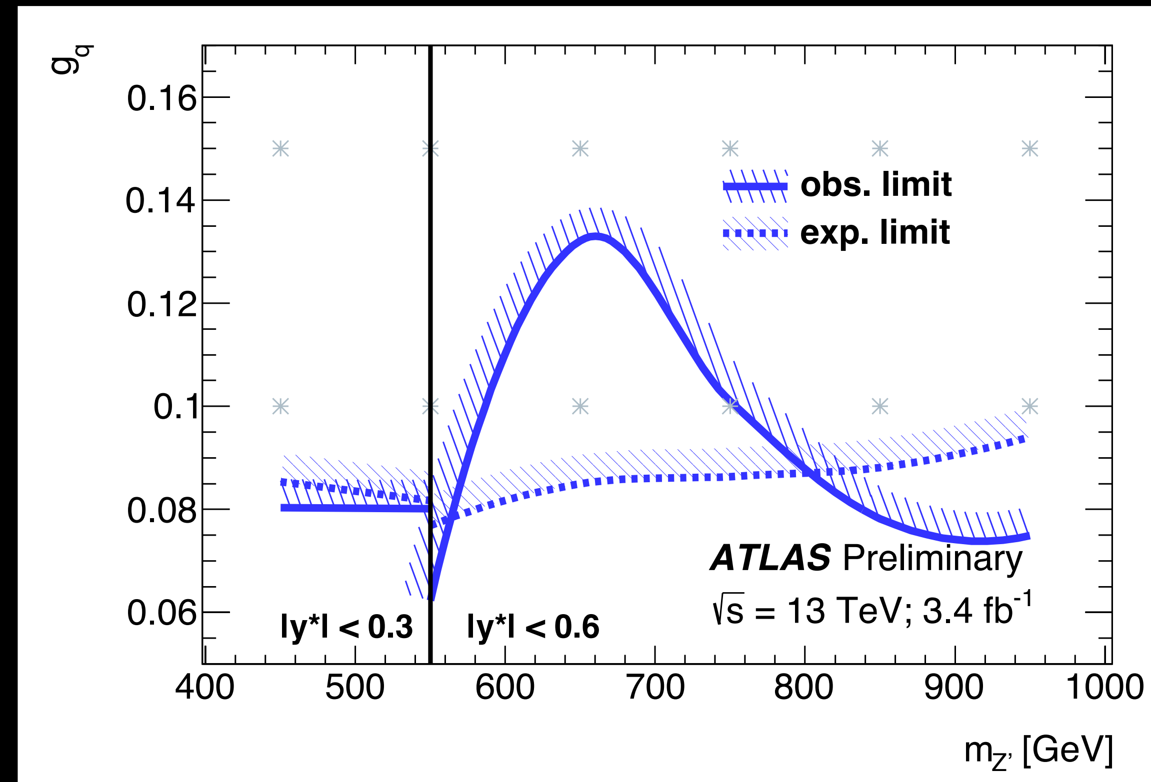


(a) q^* (b) BlackMax

Trigger level dijet analysis: ATLAS

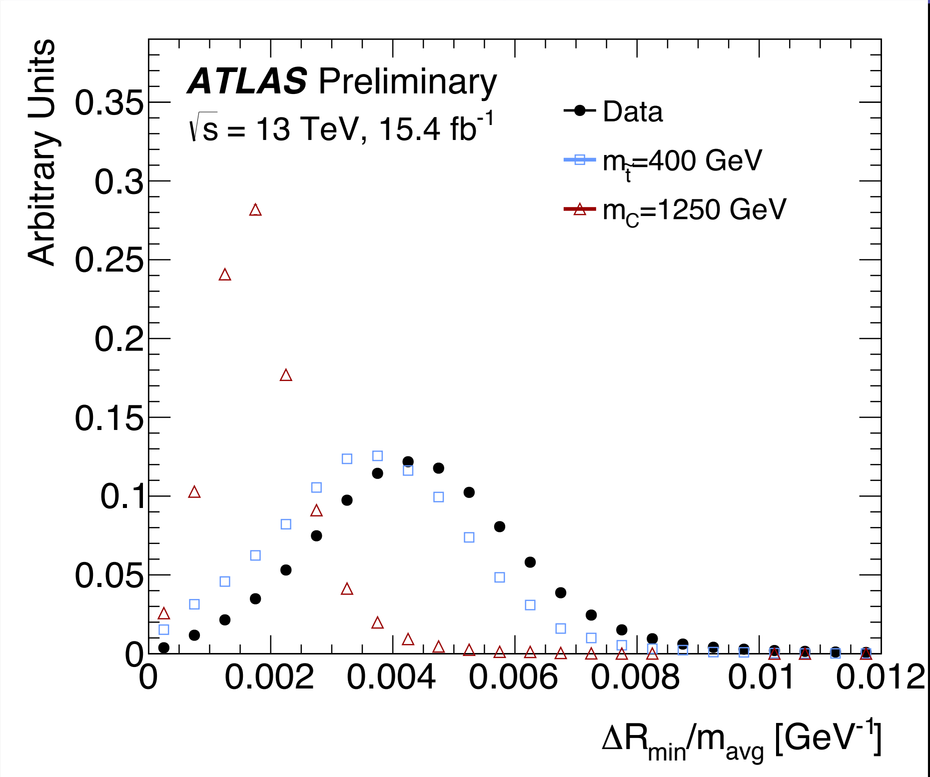


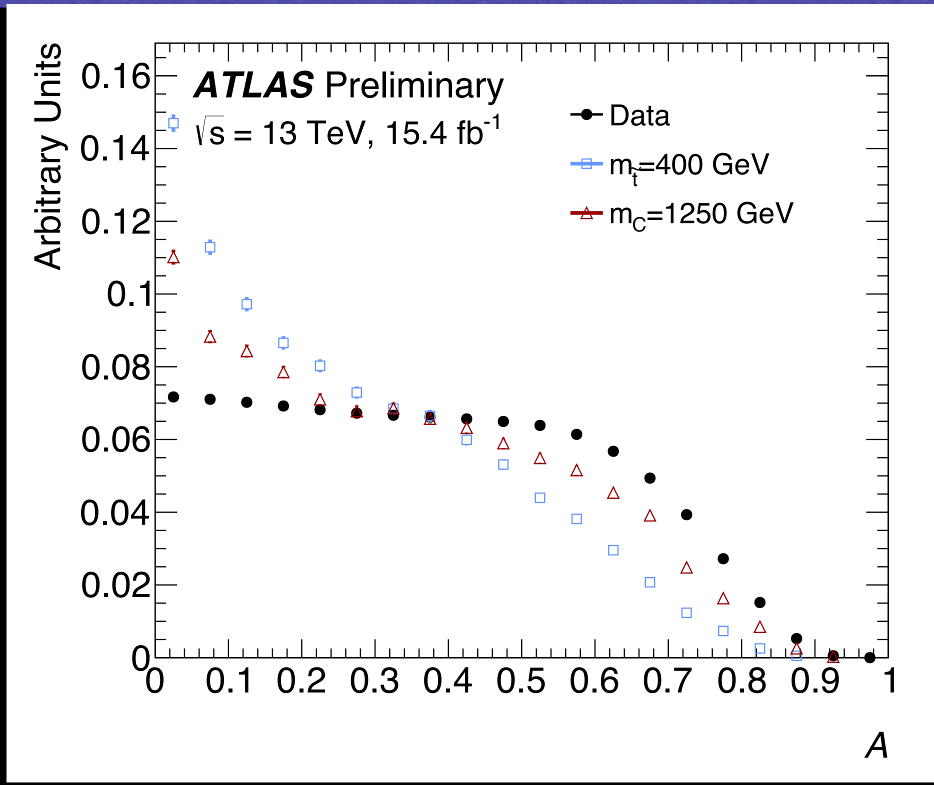
Dijet invariant mass built from leading and subleading trigger (HLT) jets compared to mjj for offline jets in data, as a function of randomly chosen HLT or offline mjj to reduce resolution biases. Events are selected using the HLT_j110 single jet trigger. Selected events have leading jet p T > 185 GeV, subleading jet p T > 85 GeV and |y*| < 0.6. The average mjj response of trigger jets relative to offline jets is shown in black and it is within 1% of unity, independent of jet mjj (https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-030/)

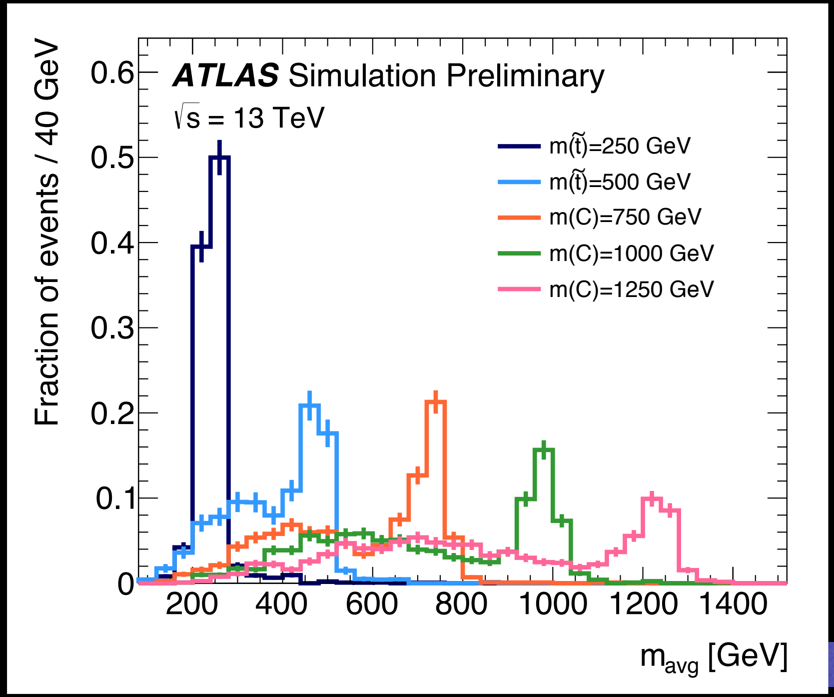


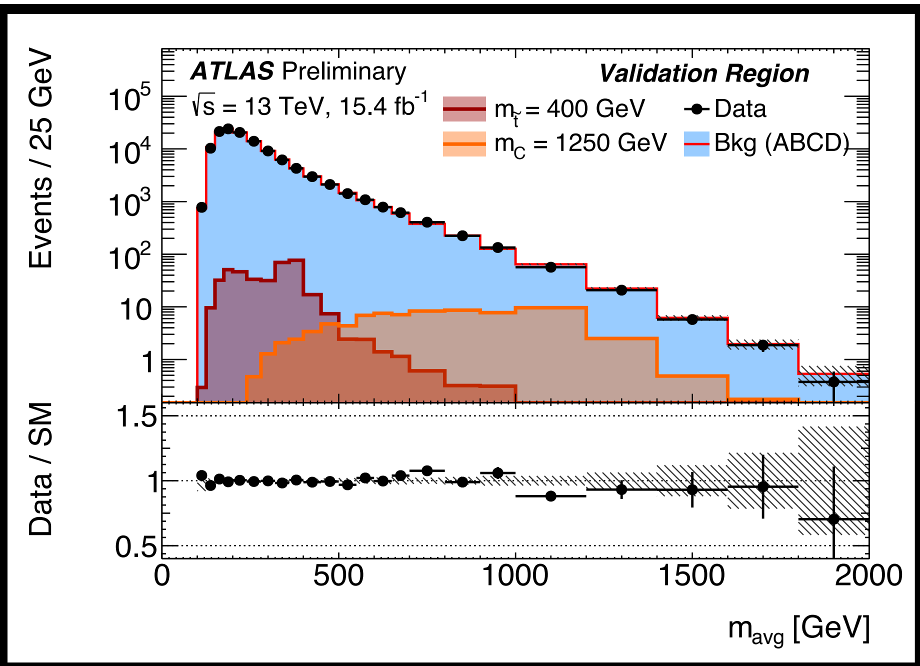
Couplings above the solid lines are excluded. Markers indicate the mass and coupling points that have been simulated. The solid and dashed curves represent the observed and expected limit, respectively. They are obtained from the simulated points, correctly accounting for the scaling of the signal cross-section with gq2. Limits for masses including and above 550 GeV are derived from the mjj 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

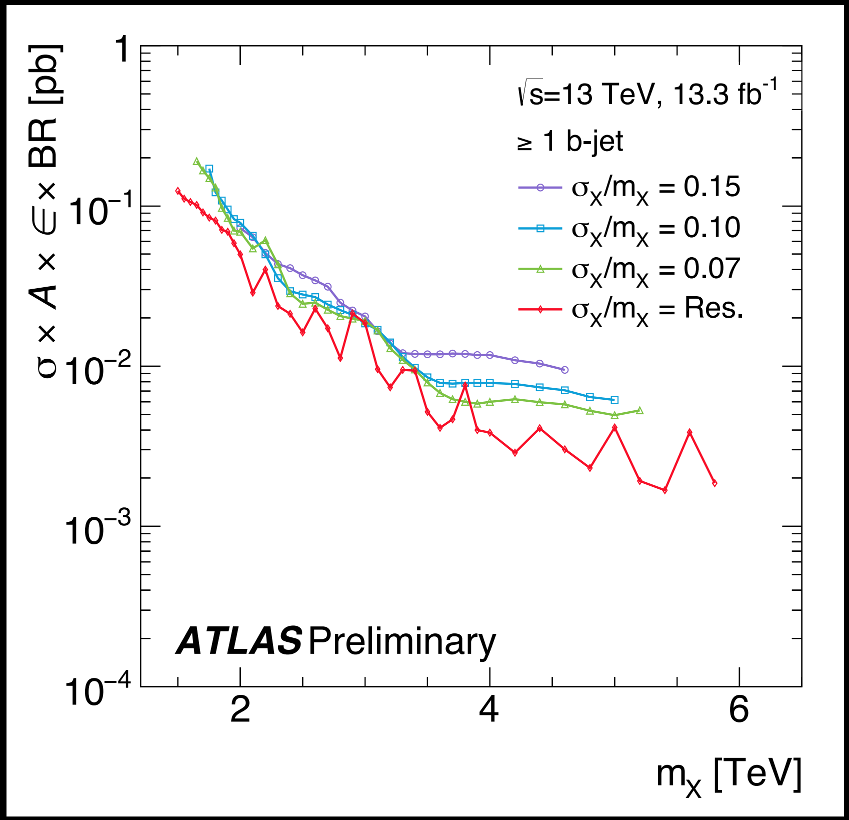


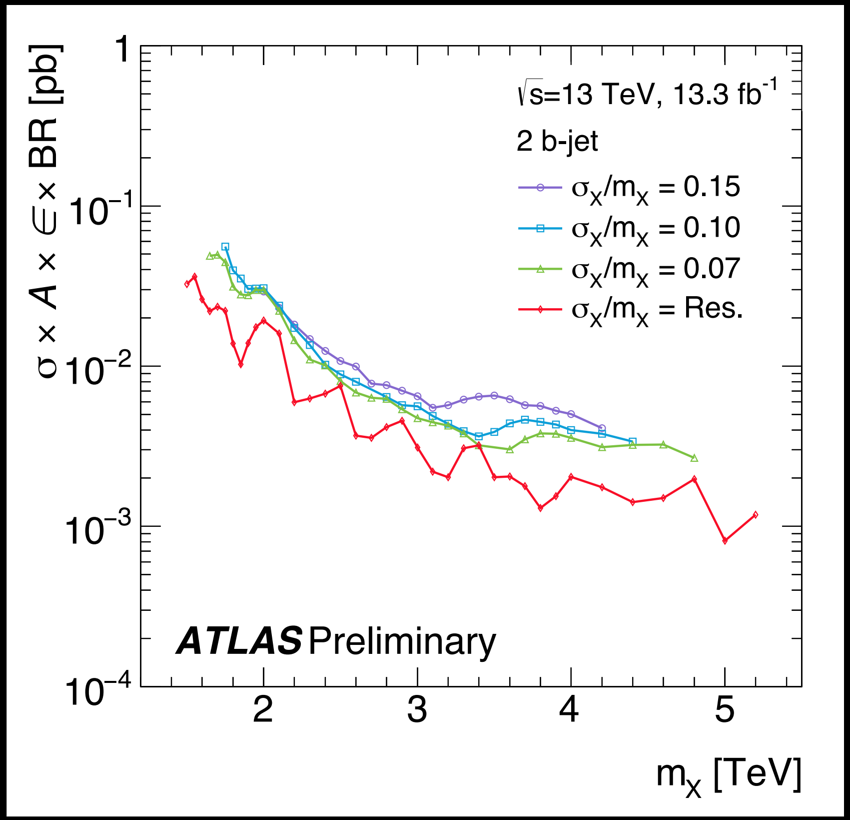




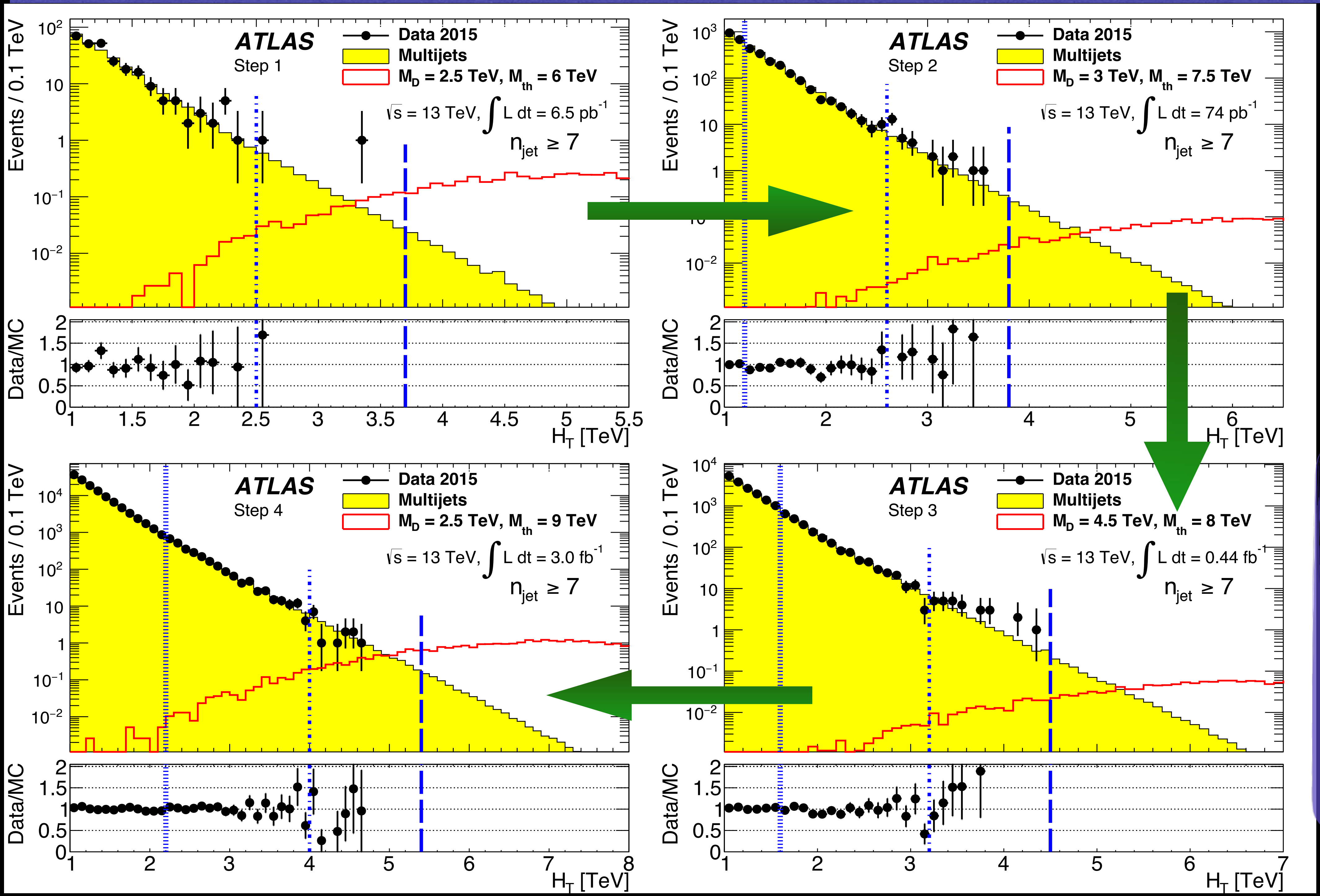


Search for new physics with heavy flavor jets





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