Search for new phenomena using jets at CMS

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On behalf of the CMS collaboration

Outline

- For the interest of time, I choose to focus on searches with at least two jets in the final state. I will not, hence, cover monojet, lepto-quark, multijet searches some of which will be presented in other talks.

- Brief Motivation

- Dijet resonance searches:

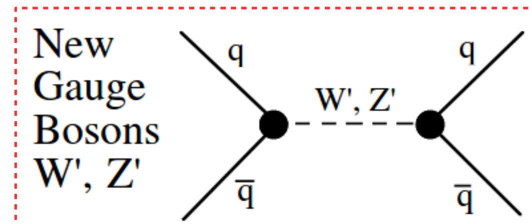
  - Very low mass regime: 50 GeV – 0.3 TeV (CMS-EXO-17-001, CMS-EXO-18-012)
  - Low – intermediate mass regime: 0.3 – 1.0 TeV (CMS-EXO-19-004)
  - High mass regime: 2.0 – 8.5 TeV (CMS-EXO-19-012)

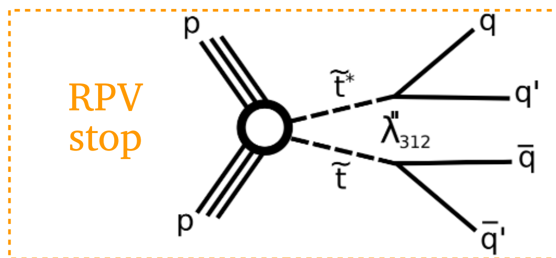
- Summary

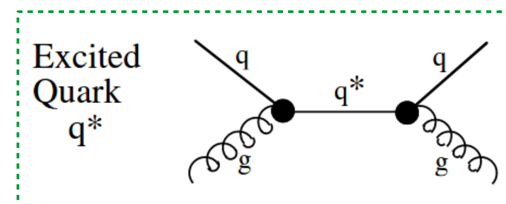
BSM models with jets in the final state

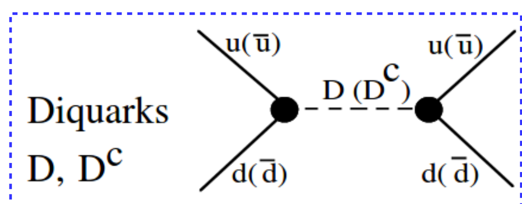
- Lots of new physics models predict new particles that decay into quarks and hence can be explored using jets.

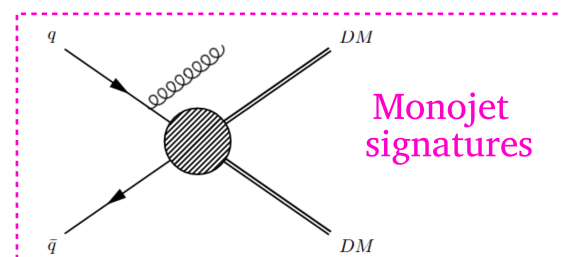
  - Extended gauge group models (Z', W')
  - Supersummetry
  - Quark compositeness
  - Superstring inspired models
  - Dark Matter models





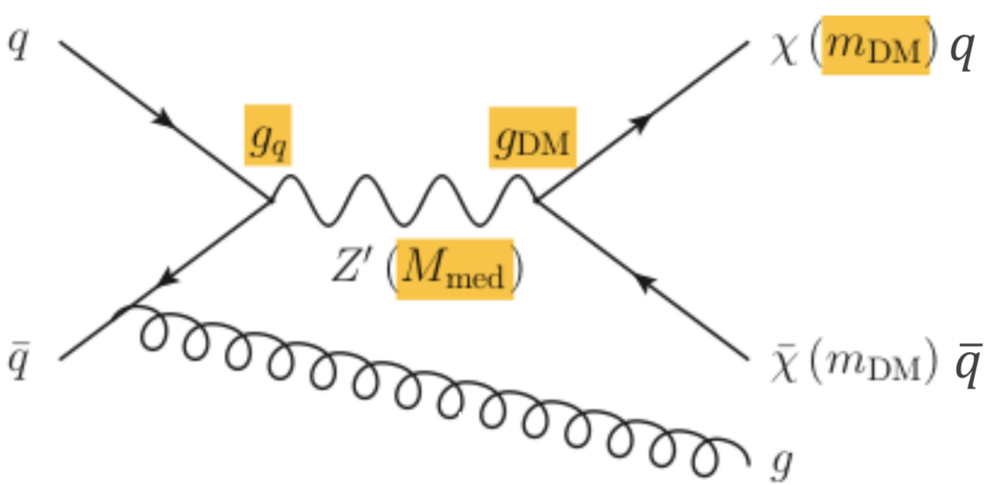






Dark Matter & Dijet searches

- Many simplified dark matter models predict the existence of dark matter mediators that couple both to quarks and dark matter particles.
- If dark matter mediators can be produced in proton-proton collisions at the LHC, they may also decay back into quarks!
- Dijet searches provide a powerful tool in the search for dark matter particles in a indirect way, by constraining new mediators decaying into pair of jets.



Spin 1 Mediators

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

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q\,.$$

Benchmark models

https://arxiv.org/pdf/1507.00966
https://arxiv.org/pdf/1603.04156
https://arxiv.org/pdf/1703.05703

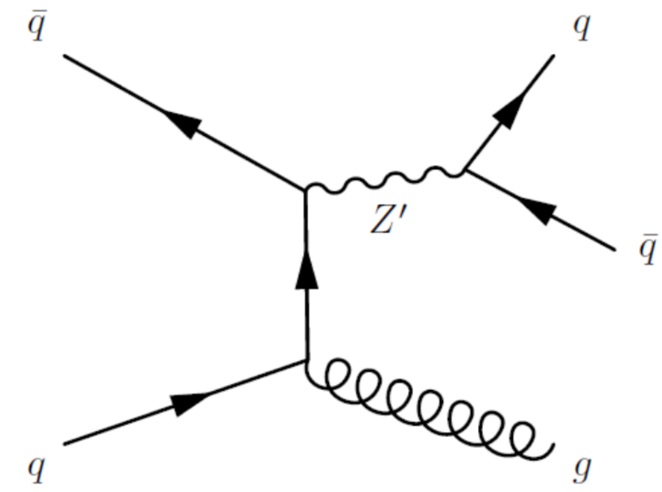
Boosted dijet search
Low mass regime
(50 - 450 GeV)

Introduction

- Search for a Z' resonance produced in association with a jet using data collected in 2016 & 2017.

- Uses an ISR jet to satisfy the trigger requirements at low dijet masses.

- Search is performed using the jet mass, groomed with soft-drop algorithm.

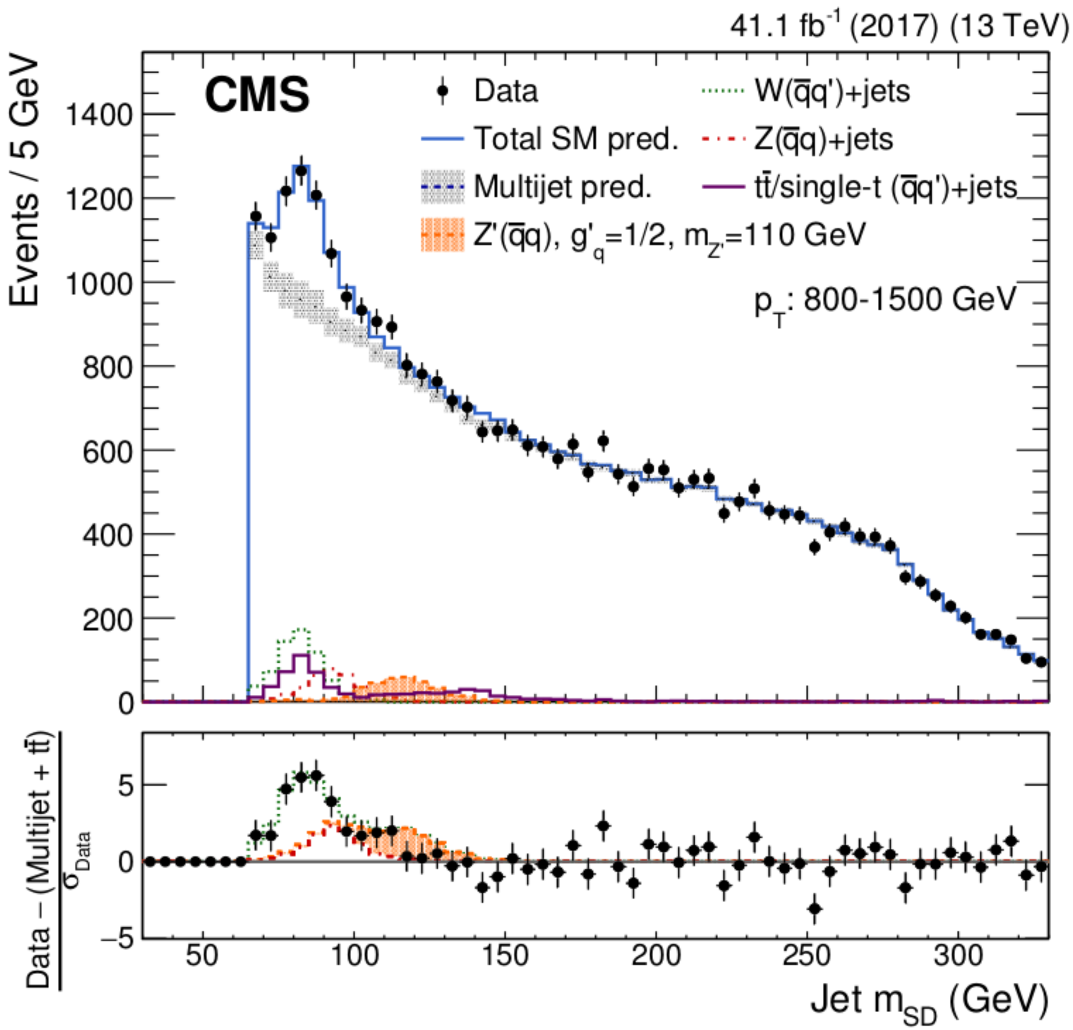


AK8 (CA15) jet selection

- jet pT > 525 (575) GeV
- $|\eta|<2.5$
- Remove events with isolated leptons

JHEP 01 (2018) 097
arXiv:1905.10331

Dijet mass prediction vs Data



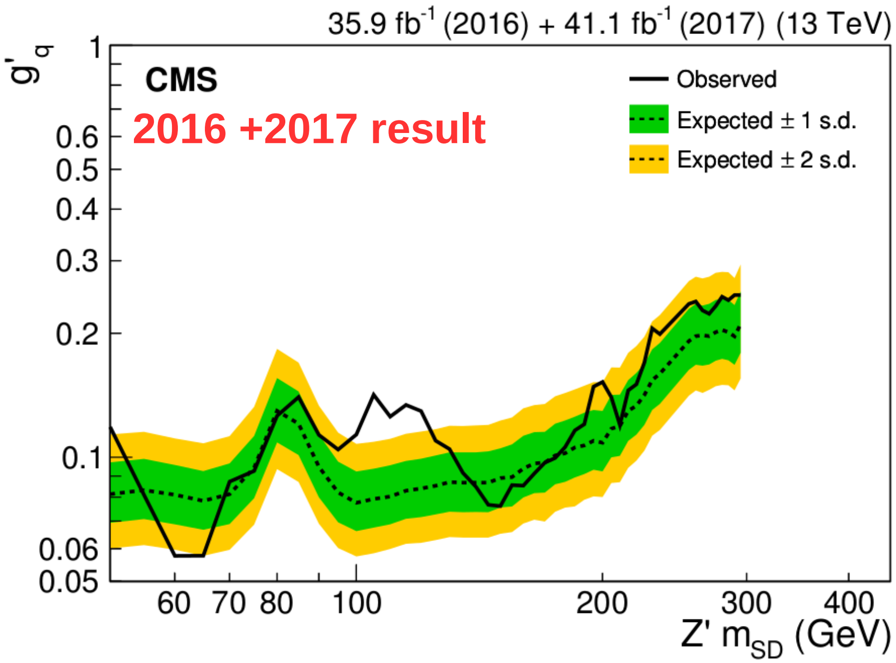
- Jet substructure techniques are utilized to identify two-prong signal vs one-prong backgrounds and calculate the “softDrop” jet mass.
- The dominant QCD background is estimated from data, using control regions defined by events failing the jet-substructure criteria.
- Nice agreement between data and prediction is achieved!

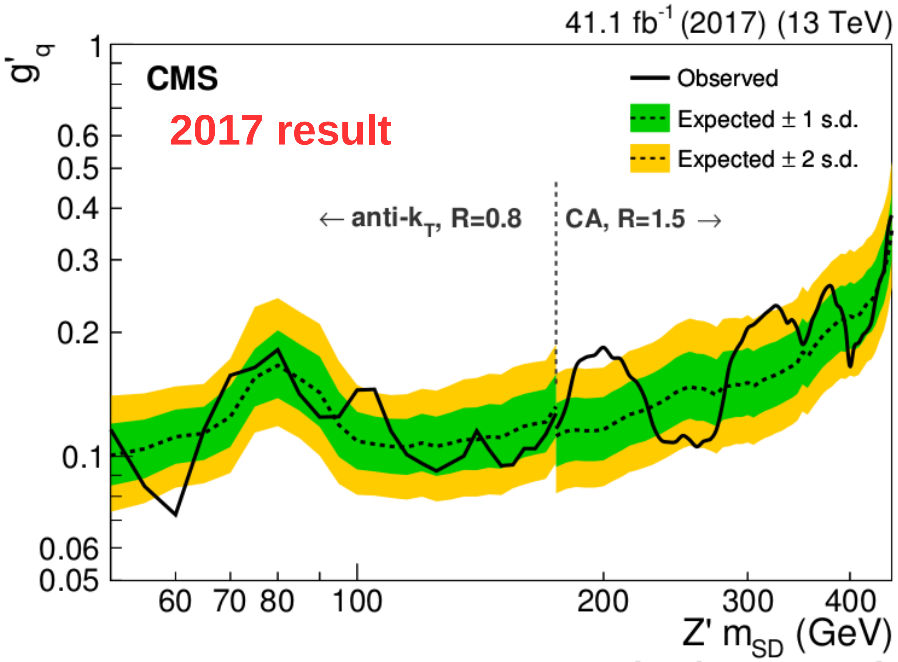
Phys. Rev. D 100, 112007 (2019)

Softdrop mass paper:
https://arxiv.org/pdf/1402.2657.pdf

Coupling limits

Phys. Rev. D 100, 112007 (2019)



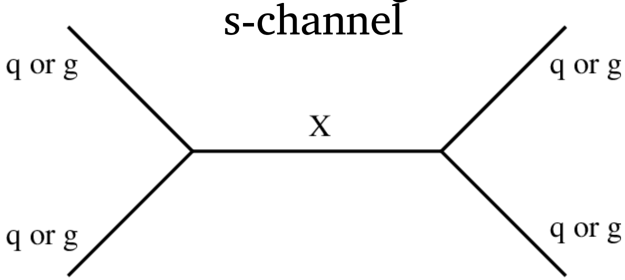


- Using **2017** data the search was extended to masses up to **450** GeV – it is the first time this region is probed with substructure techniques.
- Combining the **2016** and **2017** results, the search provides the most sensitive limits to date for masses **50-300** GeV!
- Also take a look at similar analysis, using an ISR photon to satisfy trigger requirements, that reaches masses as low as **10** GeV. (Phys. Rev. Lett. 123, 231803 (2019)) .

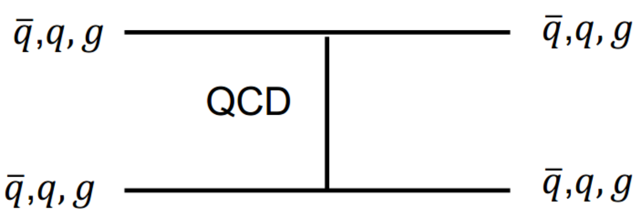
Resolved Dijet Searches

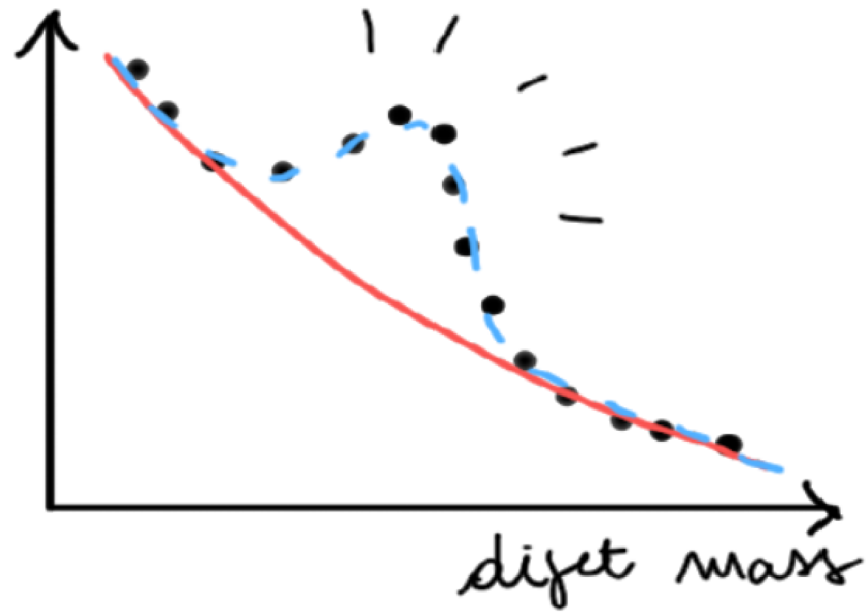
- Intermediate mass regime (300 – 1000 GeV)
- High mass regime (2.0 – 8.5 TeV)

Resonant signal
s-channel



SM background
t-channel





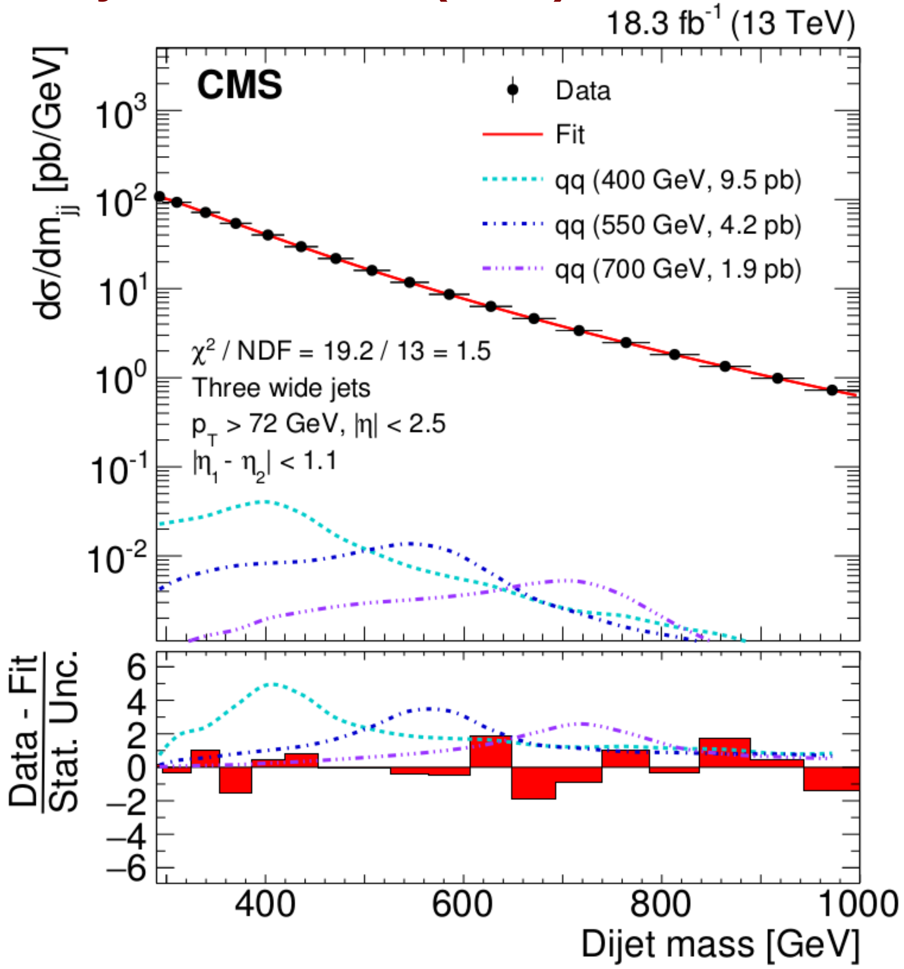
Physics observables & selections:

- Resolved dijet searches look for signal in the dijet mass distribution of the two most energetic jets.
- A cut in the $|\Delta\eta| = |\eta_2 - \eta_1|$ between the two leading jets is used, to suppresses the QCD background (dominantly t-channel production) and enhance the signal (s-channel production).

Intermediate mass regime 2016 "Scouting" data

- Scouting allows us to go much lower in trigger threshold and hence resonance masses.
- Looking at **three-jet final state** (two leading jets forming the dijet system and an ISR jet), provides sensitivity to even lower resonance masses than in previous searches using scouting data.

Phys. Lett. B 805 (2020) 135448



Selection criteria

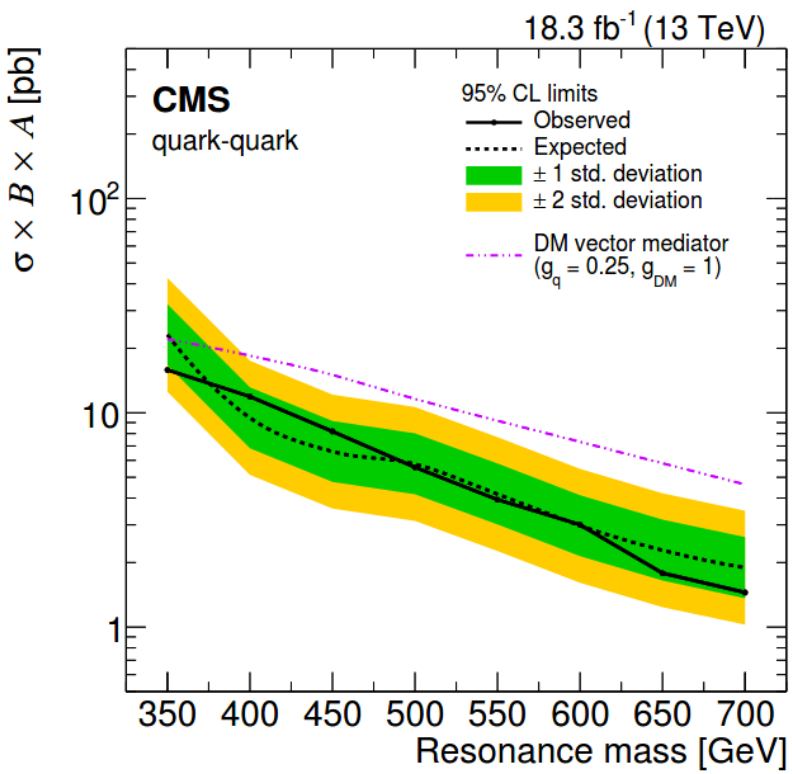
- Require at least 3 jets with jet $p_T > 72$GeV.
- $|\Delta\eta| < 1.1$ between the two most energetic jets.
- The two leading jets are chosen as the ones originating from the resonance decay.

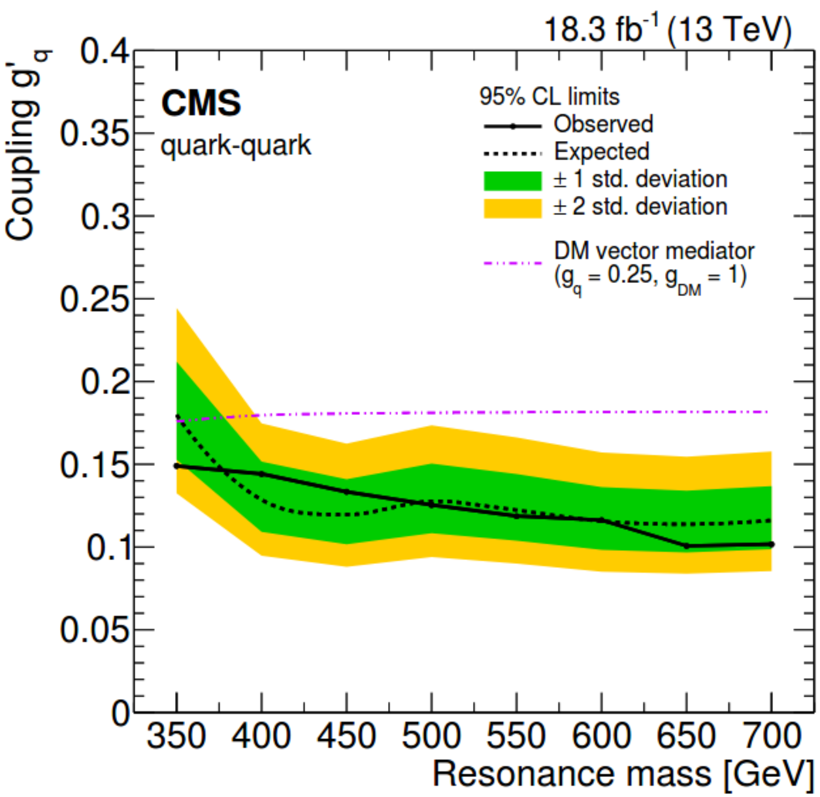
Background estimation

- The dijet mass distribution is fit with a parametrization:

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(p_2 x - 1)}{x^{p_1 + p_3 \log x + p_4 \log^2 x}}$$

Cross section & coupling limits

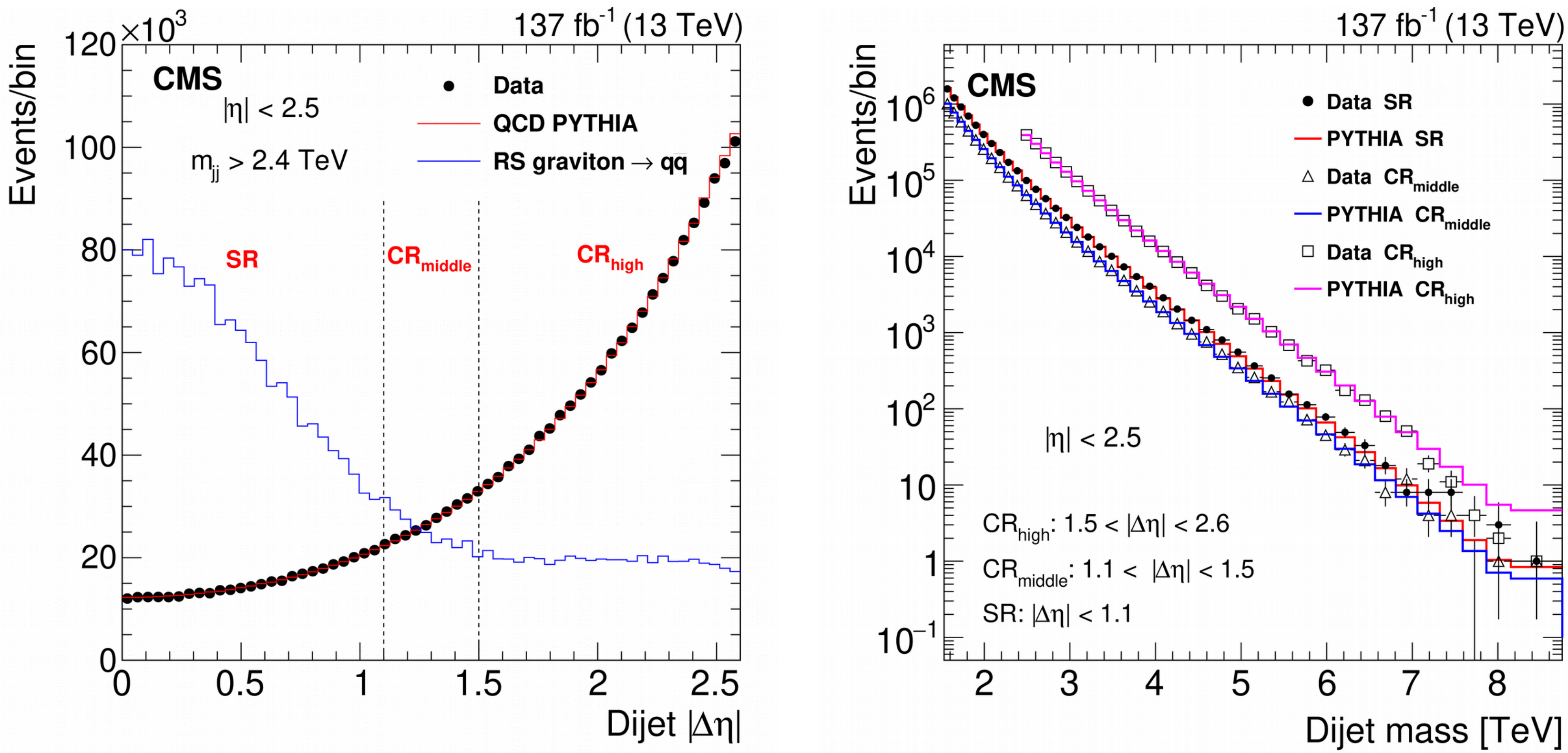




- Limits extended to resonance masses as low as 350 GeV – **a region previously unreachable with two jet final states.**
- This search yields the most stringent upper limits in the mass range between 350 and 450 GeV!

High mass regime (2.0 – 8.5 TeV) with a new analysis method

New data-driven method introduced using |Δη| sidebands, that significantly reduces systematic uncertainties!



JHEP 05 (2020) 033

Apart from our signal region (|Δη| < 1.1), two control regions are defined:

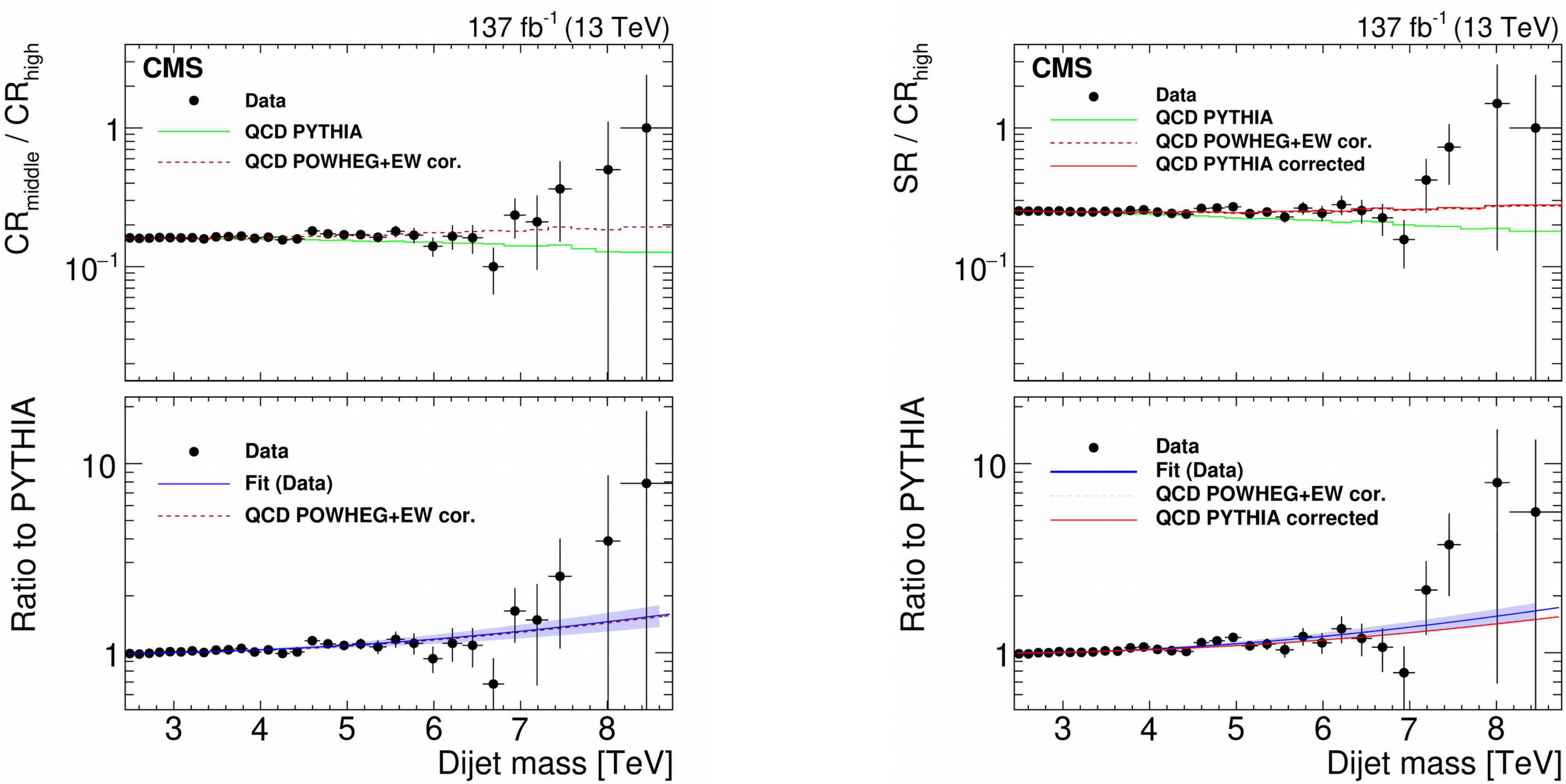
- CR_{middle} (1.1<|Δη|<1.5) used to correct the transfer factor and constrain our systematics.
- CR_{high} (1.5<|Δη|<2.6) used to predict the dijet mass spectrum of the QCD background.
- The invariant mass of the dijet system in the signal and control regions are very similar.

Ratio Method in a nutshell

$N(i)^{\text{Prediction}}_{\text{SR}} = R(m_{\text{jj}}/\sqrt{s})N(i)^{\text{Data}}_{\text{CR}_{\text{high}}}$	• Provides a bin-by-bin prediction by multiplying the CR_{high} data by a transfer factor.
$R(m_{\text{jj}}/\sqrt{s}) = C(m_{\text{jj}}/\sqrt{s})N(i)^{\text{Sim.}}_{\text{SR}}/N(i)^{\text{Sim.}}_{\text{CR}_{\text{high}}}$	• Transfer factor comes mainly from simulation with a correction $C(m_{\text{jj}}/\sqrt{s})$ obtained from data.
$R_{\text{aux}}(i) = N(i)_{\text{CR}_{\text{middle}}}/N(i)_{\text{CR}_{\text{high}}}$ $R^{\text{Data}}_{\text{aux}}/R^{\text{Sim.}}_{\text{aux}}$	• We estimate the correction from data using $\text{CR}_{\text{middle}}$.

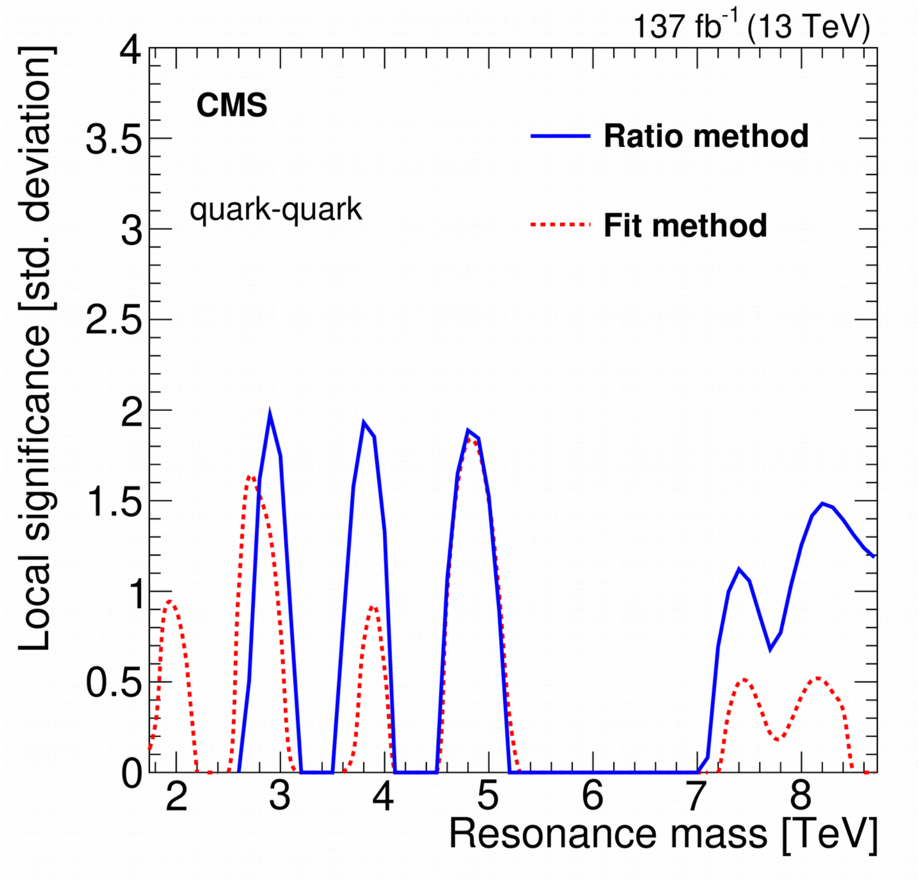
To extract the signal yield, we simultaneously fit SR, $\text{CR}_{\text{middle}}$ and CR_{high}, treating the correction parameters as freely floating nuisance parameters and signal contamination taken into account.

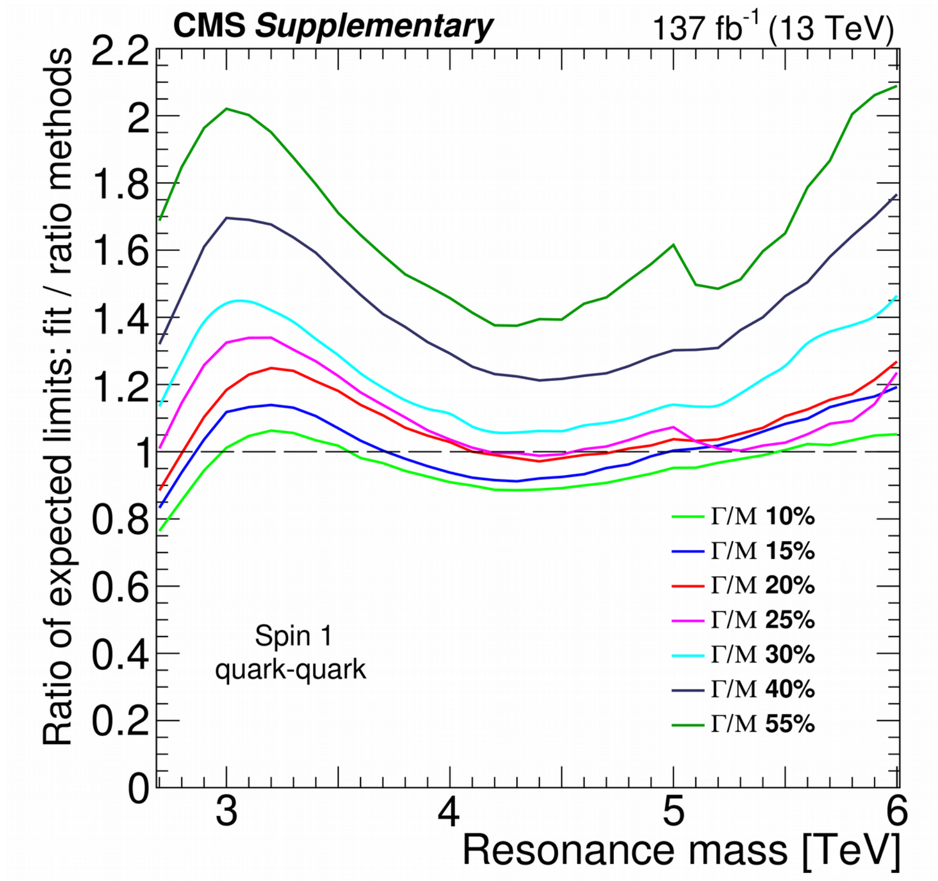
Ratio Method: Transfer factors



- Both the main and auxiliary transfer factors are flat as a function of dijet mass and very similar between data and simulation.
- Missing higher QCD orders from the simulation and electroweak effects are well described by the functional form used, and can account for the differences seen between data and simulation.

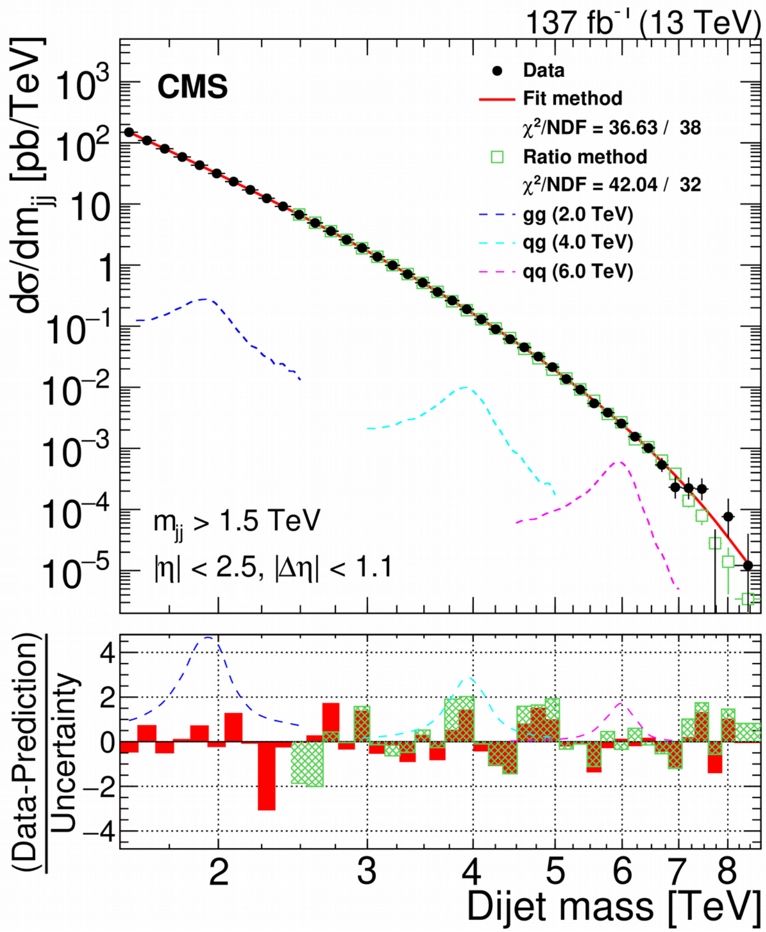
Ratio Method: Sensitivity gain





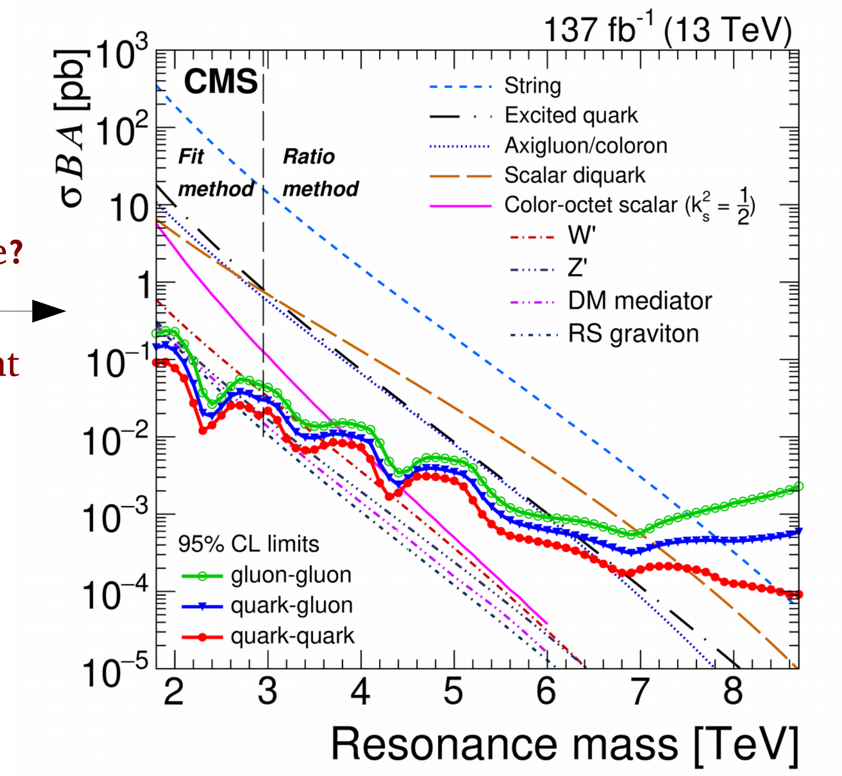
- The Ratio Method yields larger significances than the parametric fit, due to its more rigid background parametrization and smaller systematic uncertainties.
- Very significant (by factors of two) gain in sensitivity with the new background prediction method, as the resonance width increases!

Dijet Mass prediction & limits



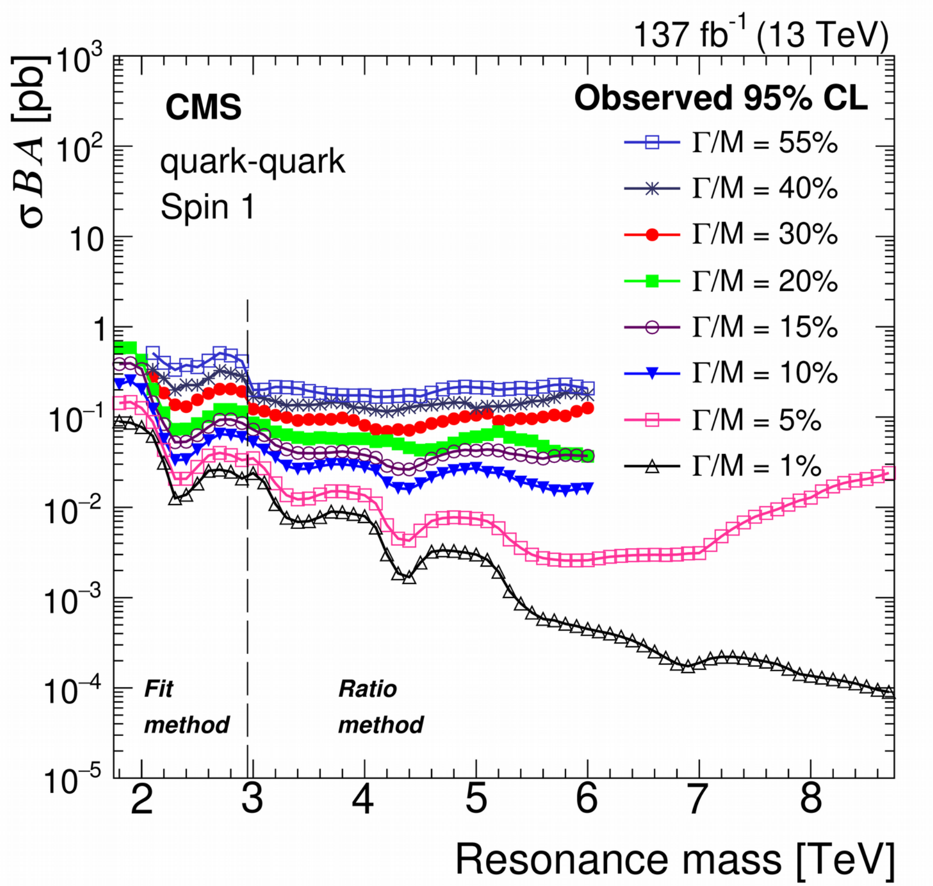
No evidence for resonance**?**

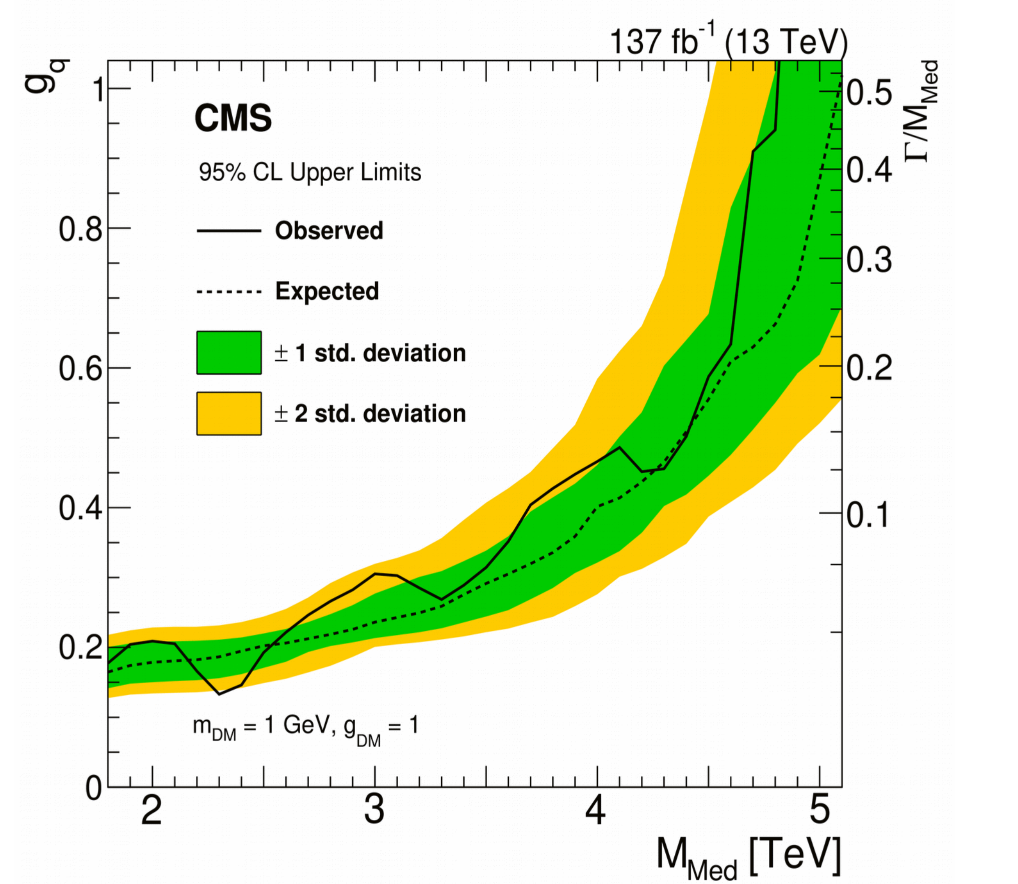
We set limits to constraint various models**!**



- The data are well modeled by both background estimations which agree with each other.
- Comparing model independent cross section limits to theoretical predictions of various benchmark models improve previous resonance mass limits by **up to 800 GeV.**

Wide spin 1 resonances: limits



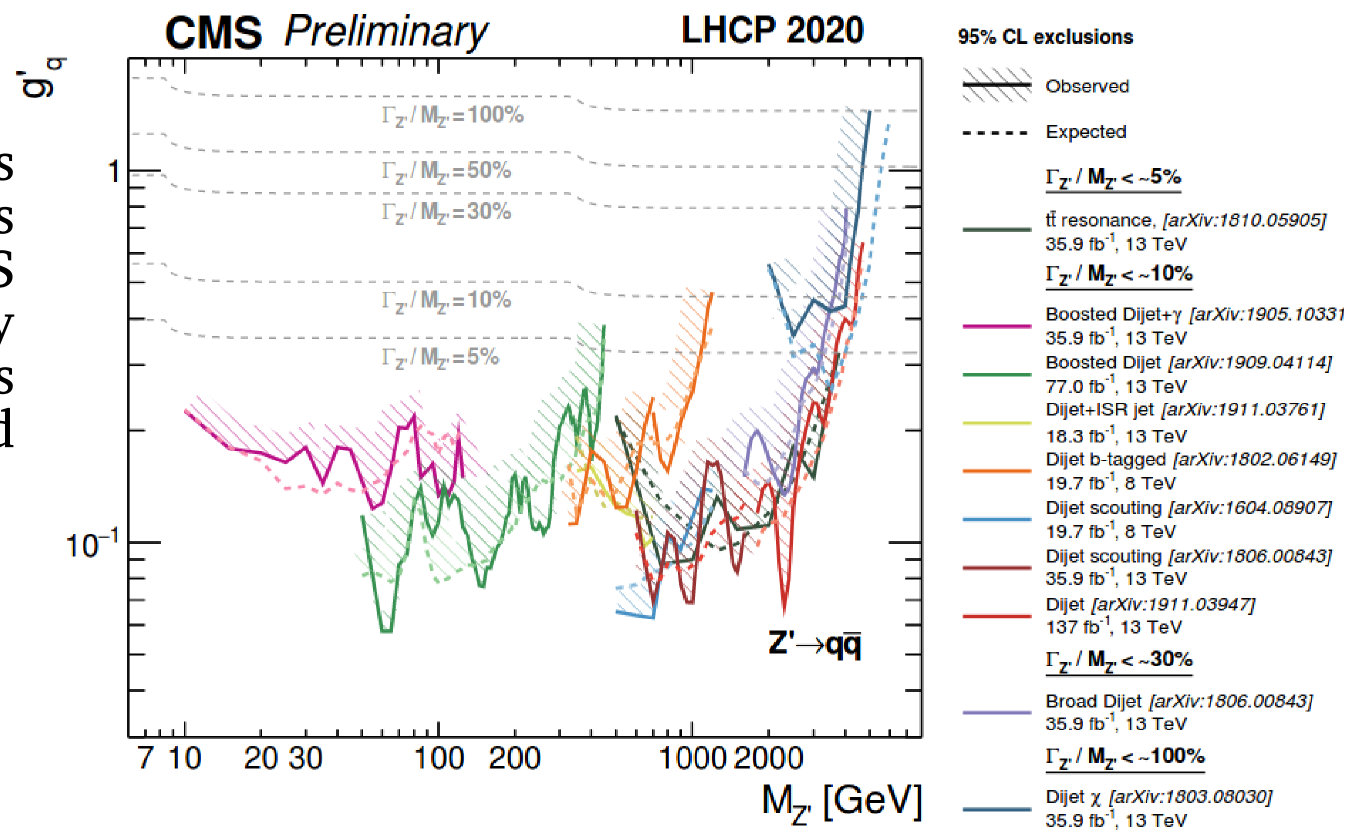


- Due to the significant reduction of systematics we are able to extend the previous wide resonance search to much larger widths and up to **55%!**
- Ratio Method's sensitivity gain allowed us to extend the coupling limit up to mediator masses of **4.7** TeV (from **3.7** TeV in the previous publication).

Summary

- We have presented the results of three powerful dijet searches in CMS, covering a wide range of resonance masses.

- Novel analysis methodologies and data taking techniques are being utilized in CMS improving our sensitivity and extending our searches in previously unexplored phase spaces.



- More analyses and exciting results with the full Run II dataset and jets in the final state are on their way - Stay tuned!

Backup slides

The Large Hadron Collider

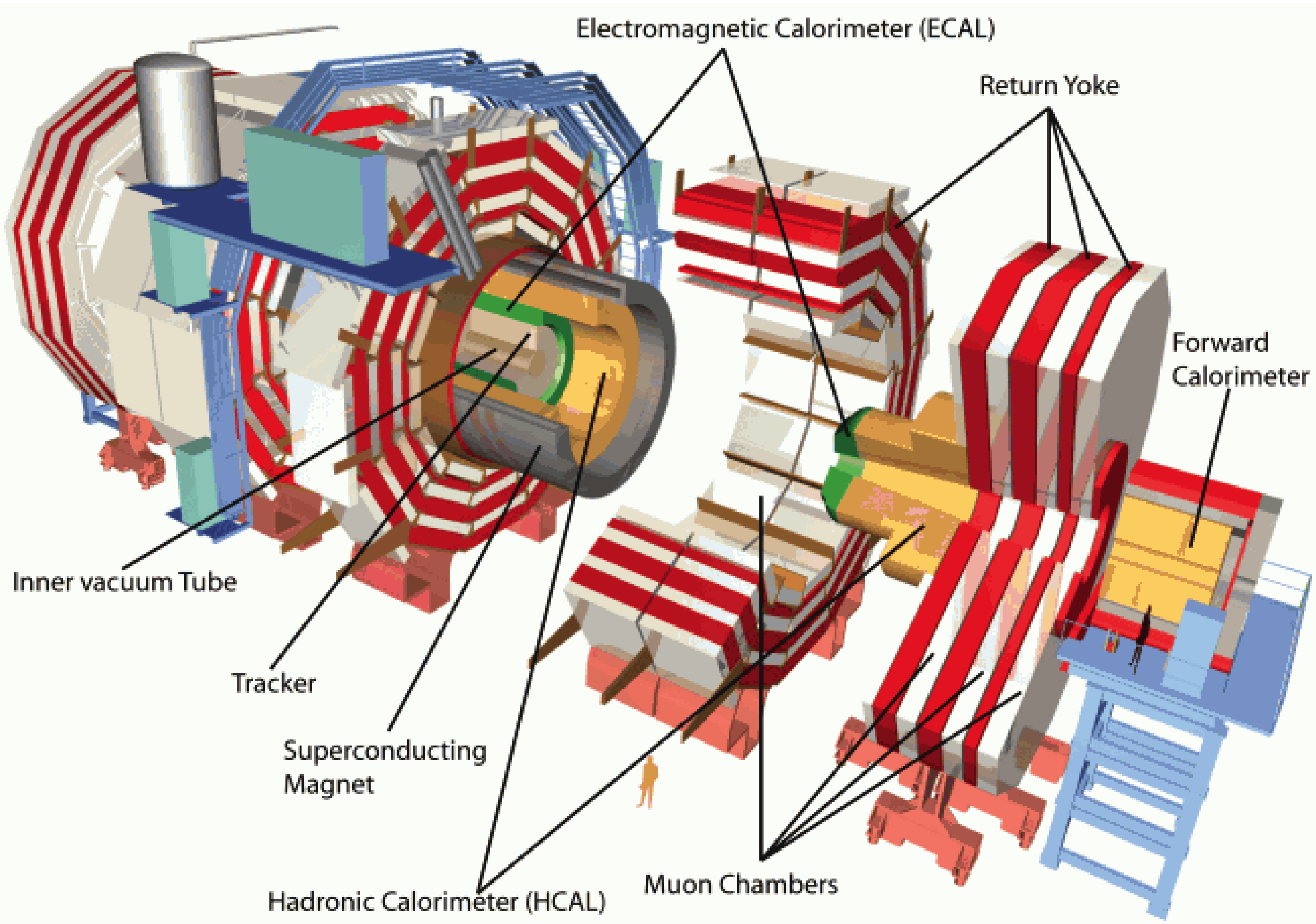
The Large Hadron Collider (LHC) is the largest and most powerful collider worldwide : two proton beams intersect in four collision points, one of which is the location of the CMS Experiment.

The main goal of the LHC experiments, after the discovery of the Higgs Boson, is to shed light on key questions like:

- The nature of dark matter.
- The origin of the dramatic matter-antimatter asymmetry in the universe.
- The hierarchy problem.
- The unification of couplings and forces.
- The origin of flavor.

The CMS experiment

The Compact Muon Solenoid (CMS) detector is one of the two largest and most powerful particle physics detectors ever built. It is designed to detect a wide range of particles and phenomena produced in high-energy collisions in the LHC.



The CMS apparatus is composed of different layers of sub-detector systems:

- Inner tracker.
- The Crystal Electromagnetic Calorimeter (ECAL).
- The hermetic hadron calorimeter (HCAL).
- Powerful superconducting solenoid ($\sim$3.8 Tesla).
- Muon Chambers.

Boosted dijet searches backup slides

N_i series & N-subjetiness

- N-subjetiness (**τ_N**) are inclusive jet shape variables designed to identify boosted hadronically-decaying objects like electroweak bosons and top quarks.

- Given a reconstructed jet, one identifies N candidate subjets within the reconstructed jet (one way to do this is to use the exclusive-kT clustering algorithm, forcing it to return exactly N jets).

- The **τ_N** is defined as : $\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k} \}$.

  k runs over the constituent particles in a given jet and $\Delta R_{J,k} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the distance in the η-φ plane between a candidate subjet J and a constituent particle k.

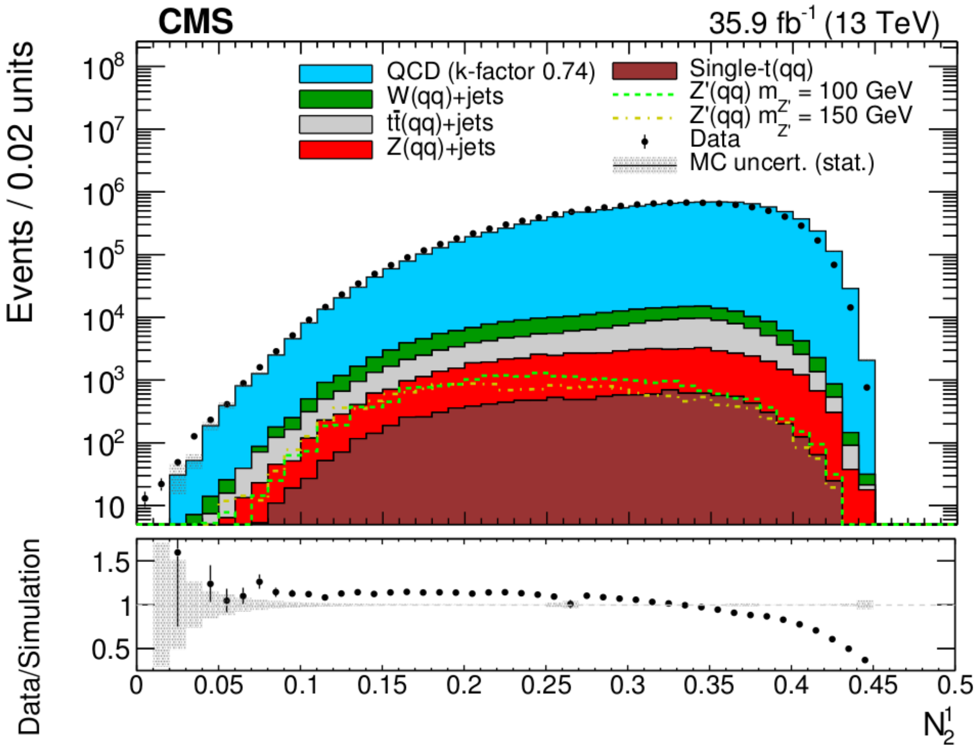
- For more details about the N-subjetiness variables take a look at the paper [1]

- The **Ni** series are similar to the N-subjettiness ratio observables, are defined **without respect to subjet axes**, giving improved behavior in the unresolved limit [2].

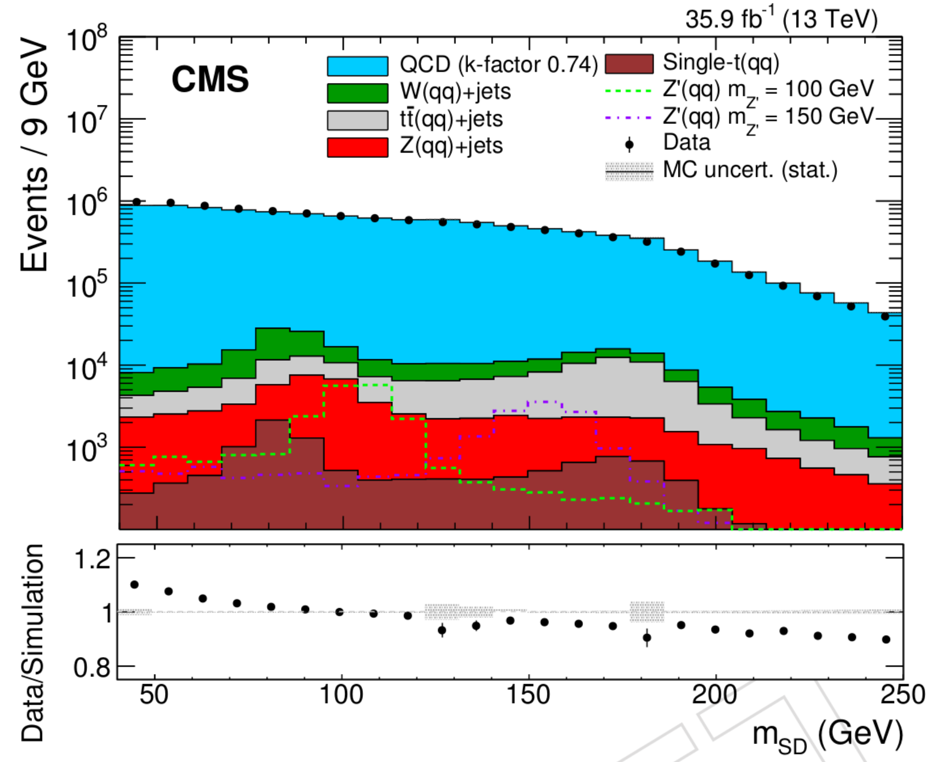
[1] https://arxiv.org/pdf/1011.2268.pdf
[2]https://link.springer.com/content/pdf/10.1007/JHEP12(2016)153.pdf

Two-prong jet substructure & soft-drop mass

Substructure discriminant

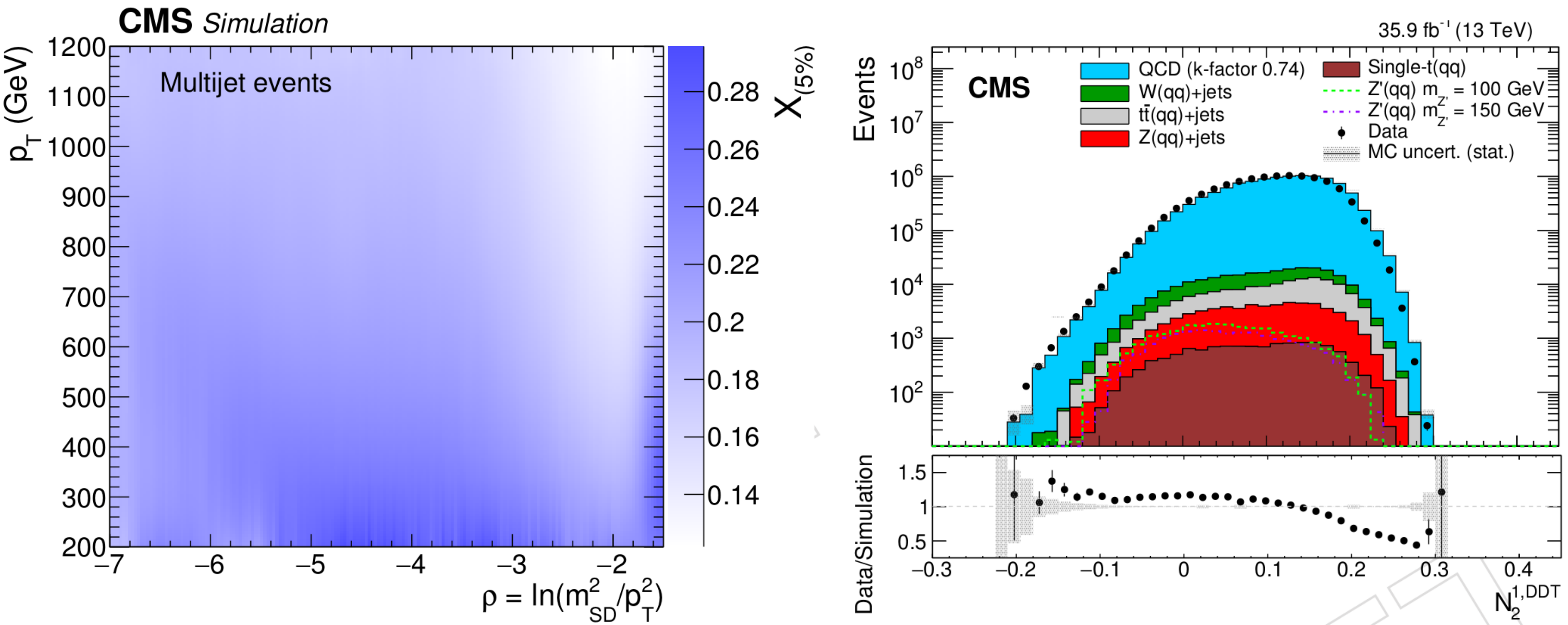


Soft-drop jet mass



- Calculate the soft-drop mass to identify dijet resonances as local excesses over a smooth background.
- Visible disagreement between simulation and data: Background contributions will be estimated from data.
- Substructure variable N_2^1 (similar to N-subjetiness) is used to select jets with two-prong jet substructure, improving signal significance (see next slide).

Decorrelation of Jet mass & N_2^1

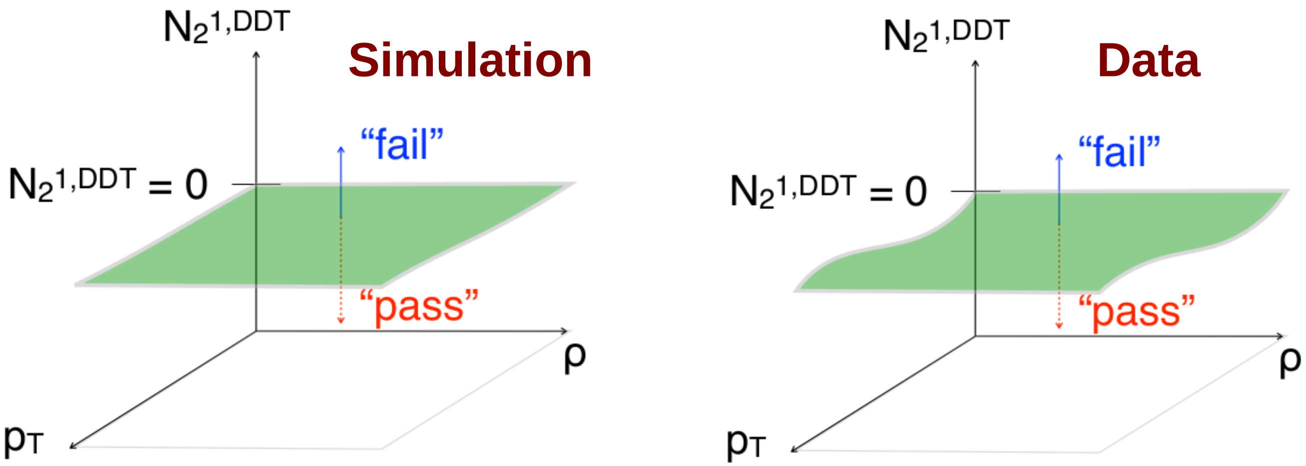


- Jet mass and N_2^1 are correlated: a criterion on the latter can bias the former.
- To solve this, a Designed Decorrelated Tagger (DDT) as a function of jet p_T and mass is introduced: $N_2^{1,DDT}(\rho, p_T) \equiv N_2^1(\rho, p_T) - X_{(5\%)}(\rho, p_T)$
- $X_{(5\%)}$ is derived from simulated N_2^1 distribution by requiring the events passing the $N_2^{1,DDT} < 0$ selection to be a fixed 5% of QCD multi-jet events for all ρ and p_T.

Dominant background estimation

- The decorrelation of $N_2^{1,\mathrm{DDT}}$ from ρ and p_T, ensures that the events passing and failing the selection have the same shape of the QCD jet mass distribution, yielding a constant "pass-to-fail" ratio in simulation.

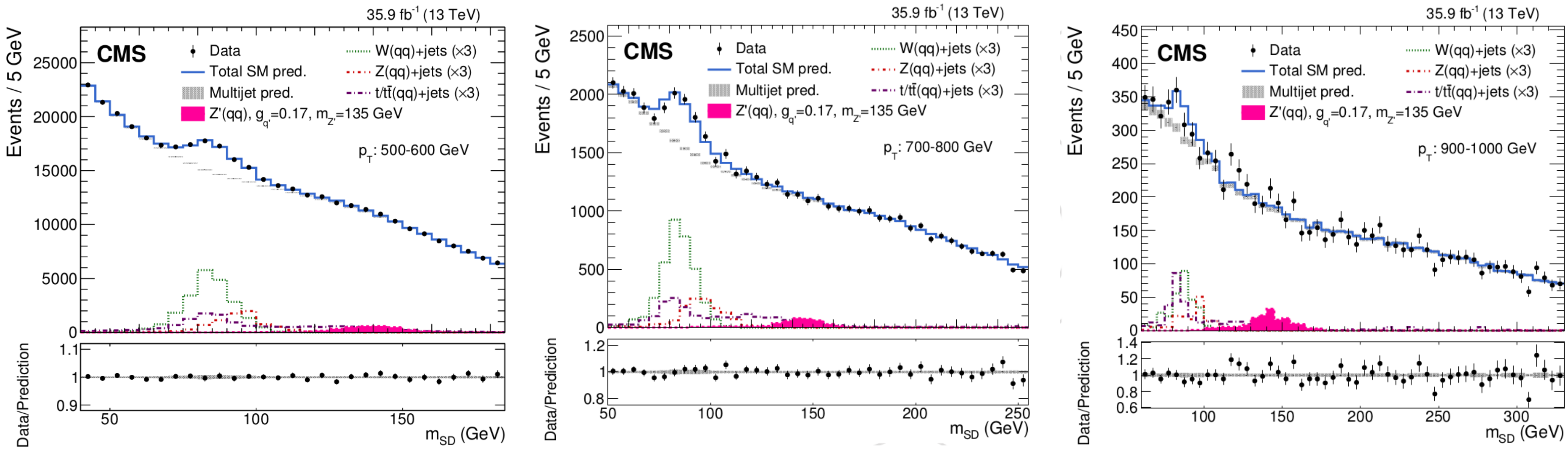
$$n^{\mathrm{QCD}}_{\mathrm{pass}}(m_{\mathrm{SD}}, p_{\mathrm{T}}) = R_{\mathrm{p/f}}(\rho(m_{\mathrm{SD}}, p_{\mathrm{T}}), p_{\mathrm{T}})\, n^{\mathrm{QCD}}_{\mathrm{fail}}(m_{\mathrm{SD}}, p_{\mathrm{T}})$$

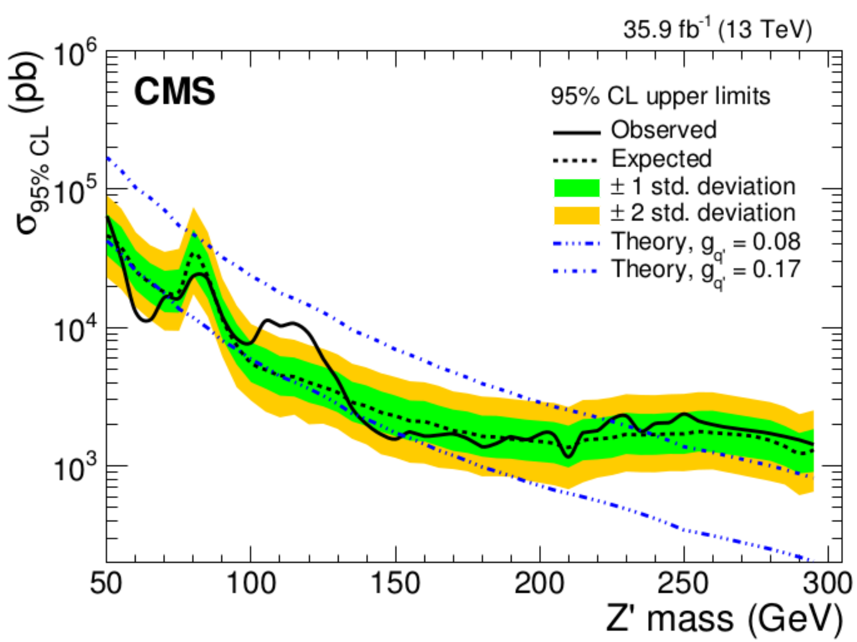


- The transfer factor $R_{p/f}$ is allowed to deviate from constant in the data to account for residual differences between data and simulation.

- Measure soft-drop mass distribution in a Control Region (with events failing the substructure selection) and "transfer" it to the signal region using simulation.

Data vs predictions & limits





- The number of observed events is consistent with the predicted background from SM processes in all jet p_T ranges examined.
- The results are interpreted in terms of **95%** confidence level (CL) upper limits on the production cross section of a Z' resonance with mass up to **300** GeV.

High mass dijet searches backup slides

Background estimations

Background modeling with empirical parametrization

A fit with empirical parametrization is performed to the data in the signal region with its parameters treated as unconstrained nuisance parameters.

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

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

Data-driven background modeling – Ratio Method

- Ratio method provides a bin-by-bin prediction of the QCD background by multiplying the data in the CR_{high} by a transfer factor estimated mainly from simulation:

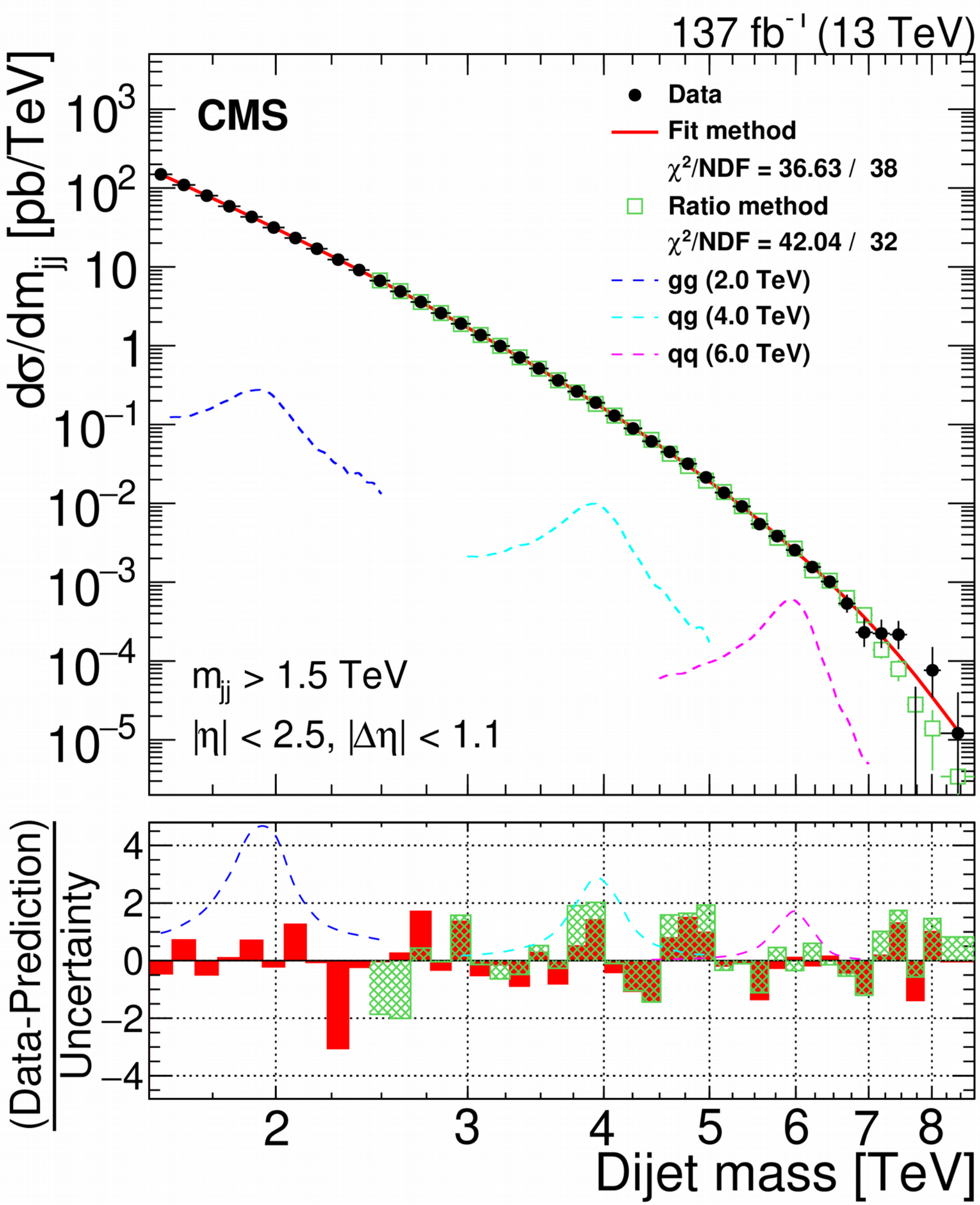
  $N(i)^{\text{Prediction}}_{\text{SR}} = R(m_{jj}/\sqrt{s})N(i)^{\text{Data}}_{\text{CR}_{\text{high}}}$ where $R(m_{jj}/\sqrt{s}) = C(m_{jj}/\sqrt{s})N(i)^{\text{Sim.}}_{\text{SR}}/N(i)^{\text{Sim.}}_{\text{CR}_{\text{high}}}$

- The term ($C(m_{jj}/\sqrt{s})$) is a correction applied to the main transfer factor to account for differences between data and leading order simulation.

- To obtain the correction we use the CR_{middle} region to define an auxiliary transfer factor $R_{\text{aux}}(i) = N(i)_{\text{CR}_{\text{middle}}}/N(i)_{\text{CR}_{\text{high}}}$ and its ratio between data and simulation $R^{\text{Data}}_{\text{aux}}/R^{\text{Sim.}}_{\text{aux}}$.

- The correction is obtained by performing a fit to this ratio with a two-parameter empirical function: $C(m_{jj}/\sqrt{s}) = p_0 + p_1(m_{jj}/\sqrt{s})^3$

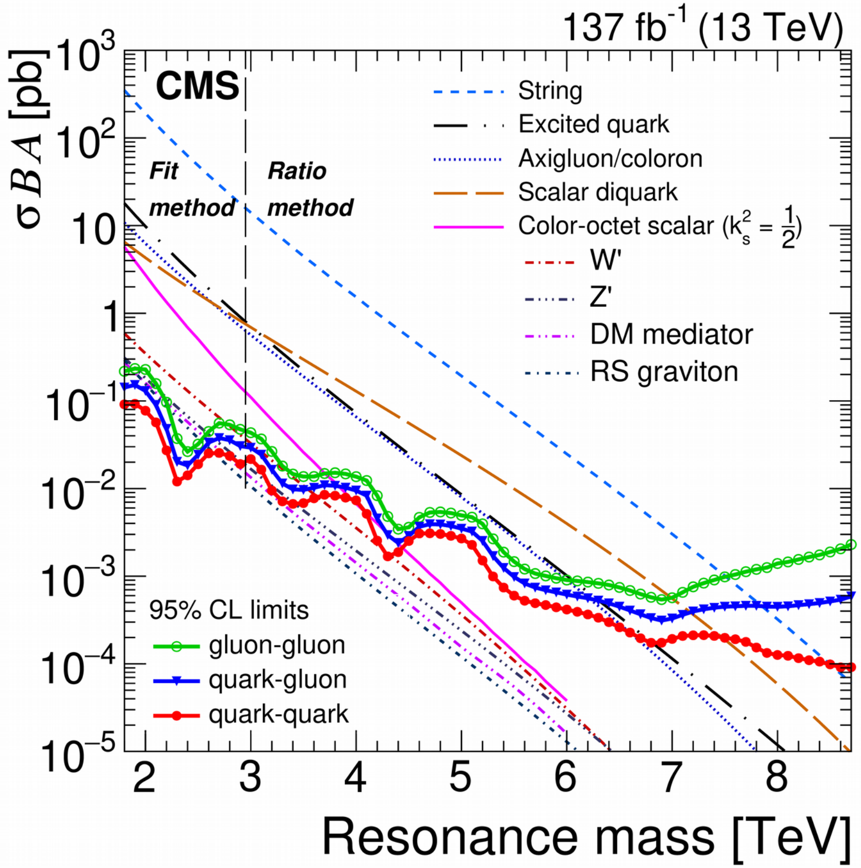
Dijet Mass prediction



- The data are well modeled by both background estimations which agree with each other.

- **There is no evidence for a dijet resonance.**

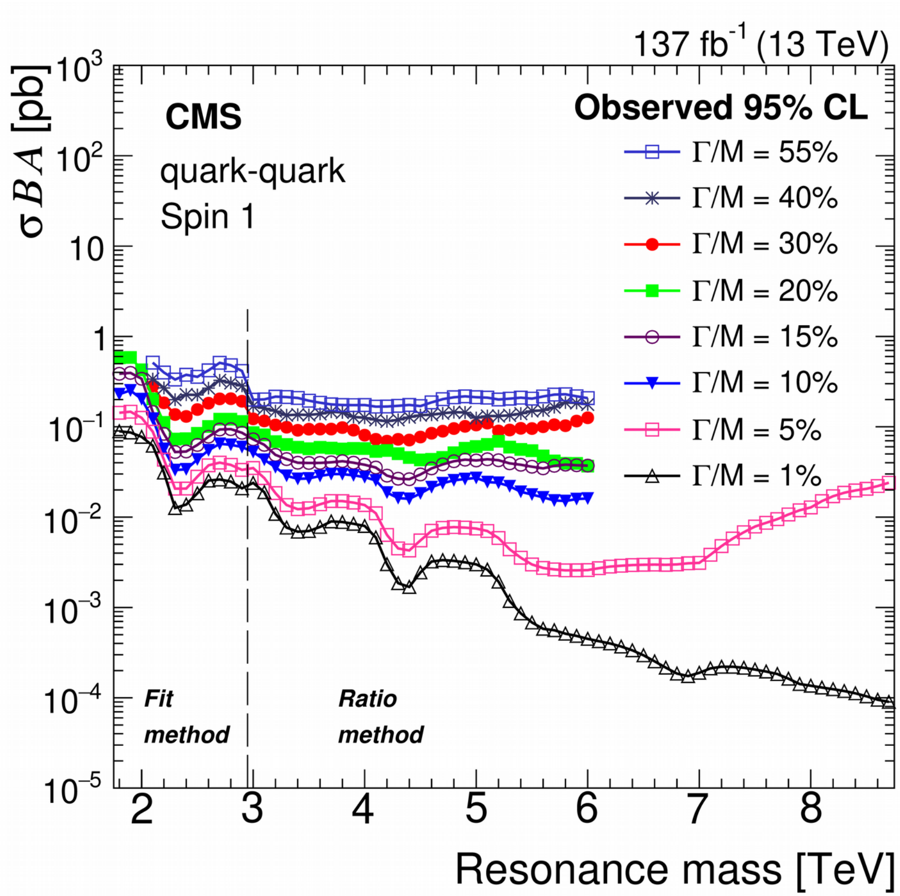
Narrow resonances: cross section limits

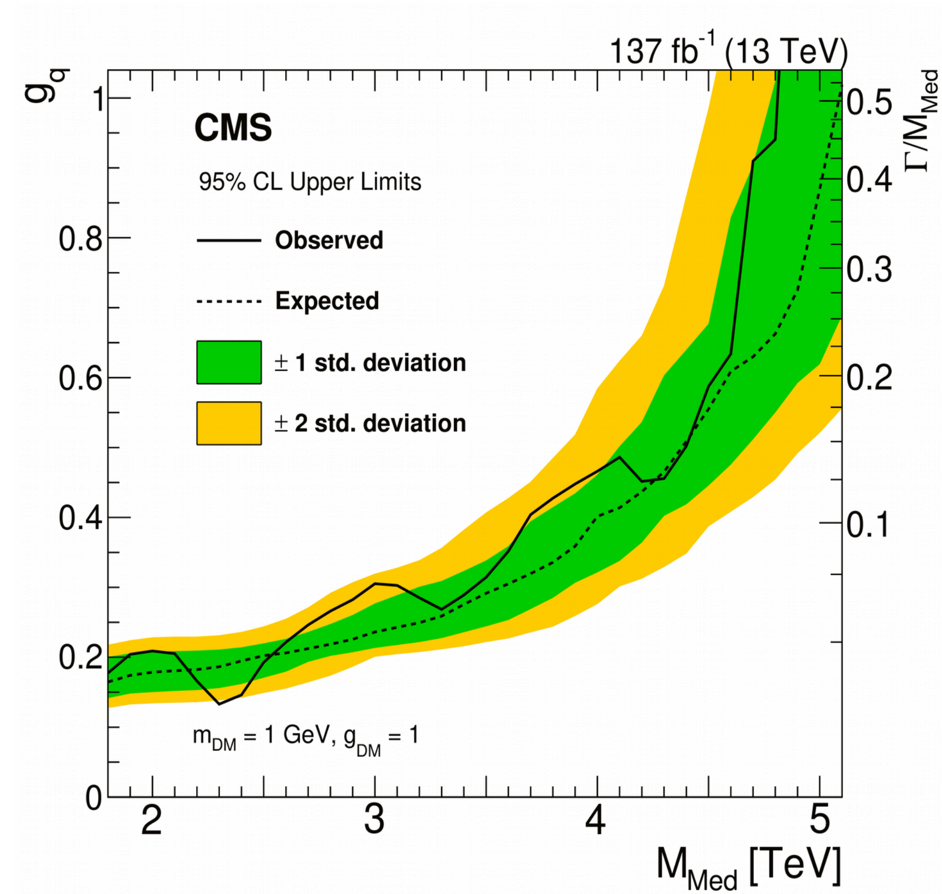


Model	Final state	Observed (expected) mass limit [TeV]
String	q g	7.9 (8.1)
Scalar diquark	q q	7.5 (7.9)
Axigluon/coloron	q $\overline{\mathrm{q}}$	6.6 (6.4)
Excited quark	q g	6.3 (6.2)
Color-octet scalar ($k_s^2 = 1/2$)	g g	3.7 (3.9)
W′ SM-like	q $\overline{\mathrm{q}}$	3.6 (3.9)
Z′ SM-like	q $\overline{\mathrm{q}}$	2.9 (3.4)
RS graviton ($k/\overline{M}_{\mathrm{Pl}} = 0.1$)	q $\overline{\mathrm{q}}$, g g	2.6 (2.6)
DM mediator ($m_{\mathrm{DM}} = 1\,\mathrm{GeV}$)	q $\overline{\mathrm{q}}$	2.8 (3.2)

- Cross section limits of each final state are compared to theoretical predicted cross sections of various benchmark models to set mass exclusion limits.
- Mass exclusion limits improved by 200 to 800 GeV compared to previous publication.

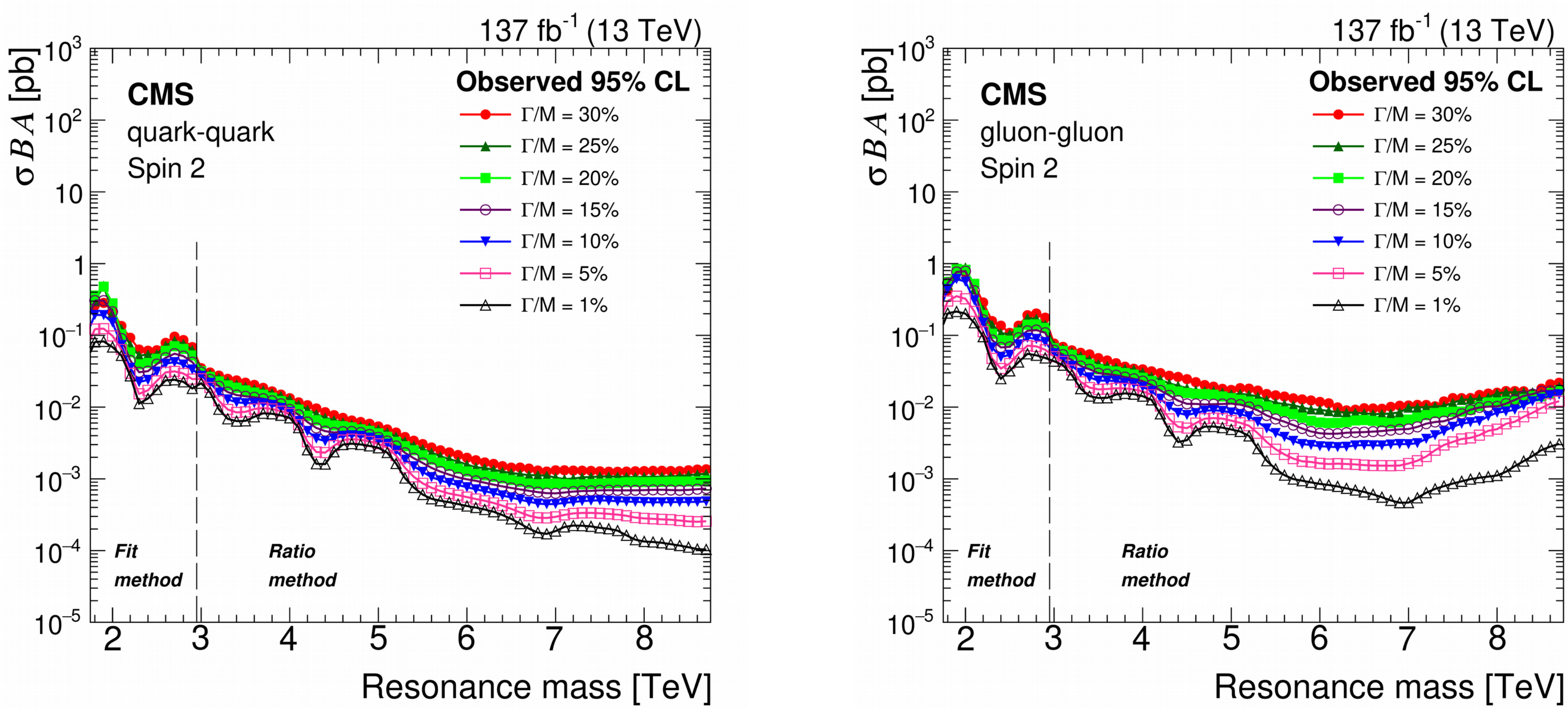
Wide spin 1 resonances: limits





- The cross section limits weaken as width increases due to large low mass tails of the signal dijet mass distributions.
- We use the spin-1 cross section limits to set limits on the coupling of a leptophobic Z' mediator that couples both to quarks and dark matter particles.
- Ratio Method's sensitivity gain allowed us to extend the coupling limit up to mediator masses of 4.7 TeV.

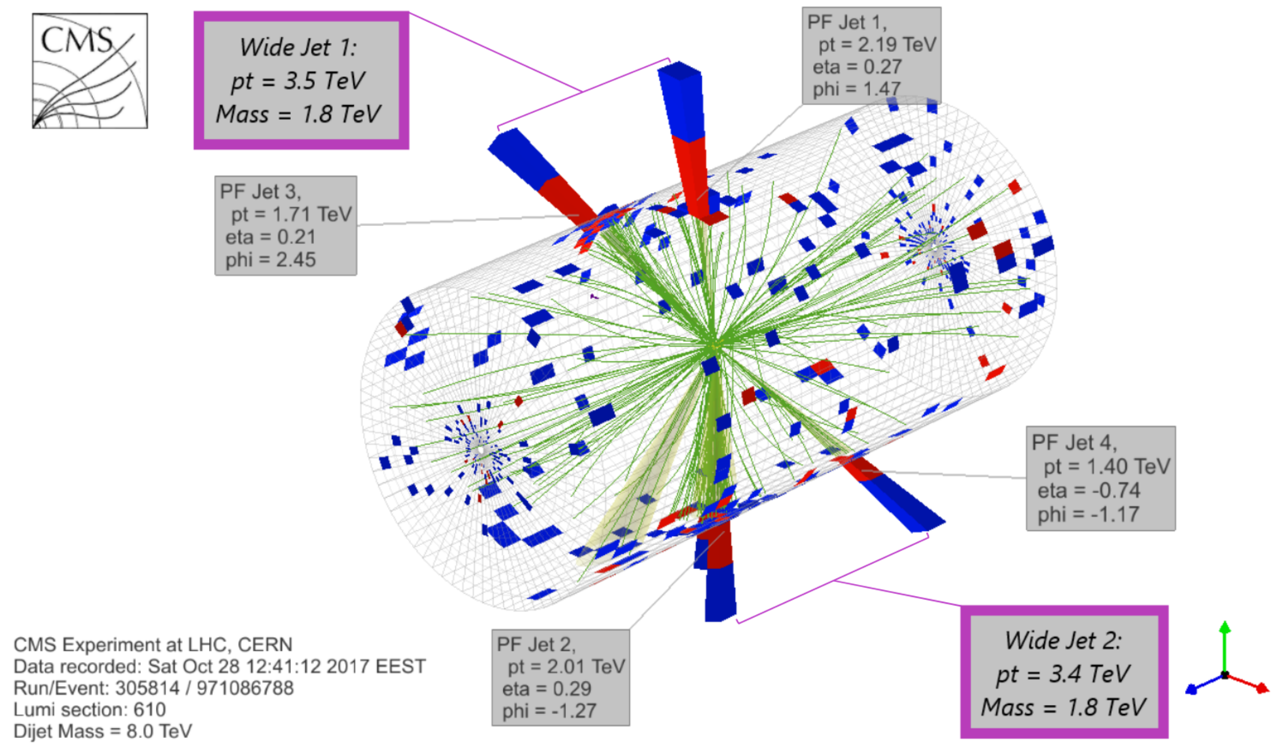
Wide spin 2 resonances: limits



- We set limits on the cross section for the production of broad, spin-2 resonances (Γ/M>experimental resolution) decaying to either a pair of quarks or a pair of gluons with a natural width up to **Γ/M=30%.**
- The cross section limits weaken as width increases, especially for gluon-gluon resonances, due to increasingly larger low mass tails of the signal dijet mass distributions.

Interesting high mass event

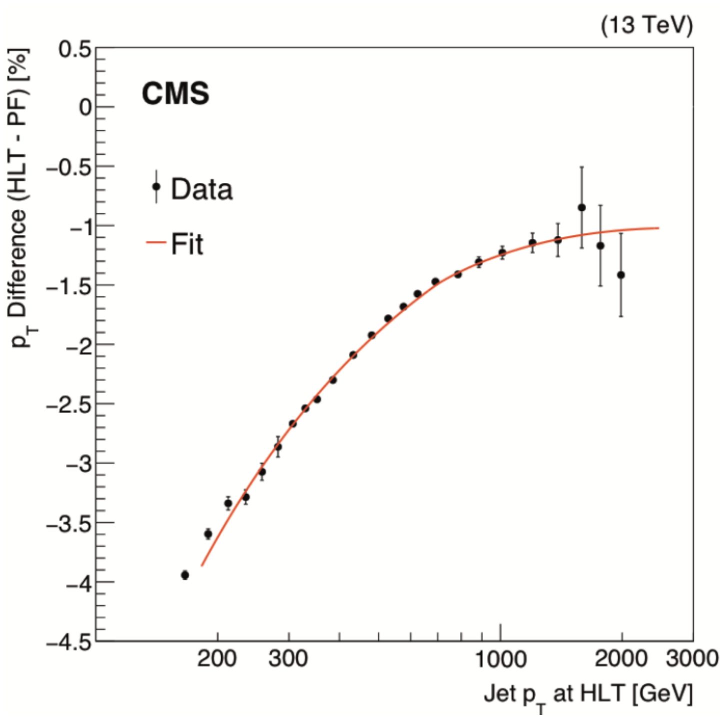
- 8 TeV dijet mass event with 4 AK4 resolved jets in 2017 data!
  - Each AK4 pair has mass ~1.8 TeV.
- Candidate for a resonance
  - See theory paper by Dobrescu, Harris & Isaacson arXiv:1810.09429
  - **Signal**: scalar diquark decay to vector-like quarks.
  - Sensitivity will be increased by four-jet search in four-jet mass vs. pair mass with relaxed cuts.

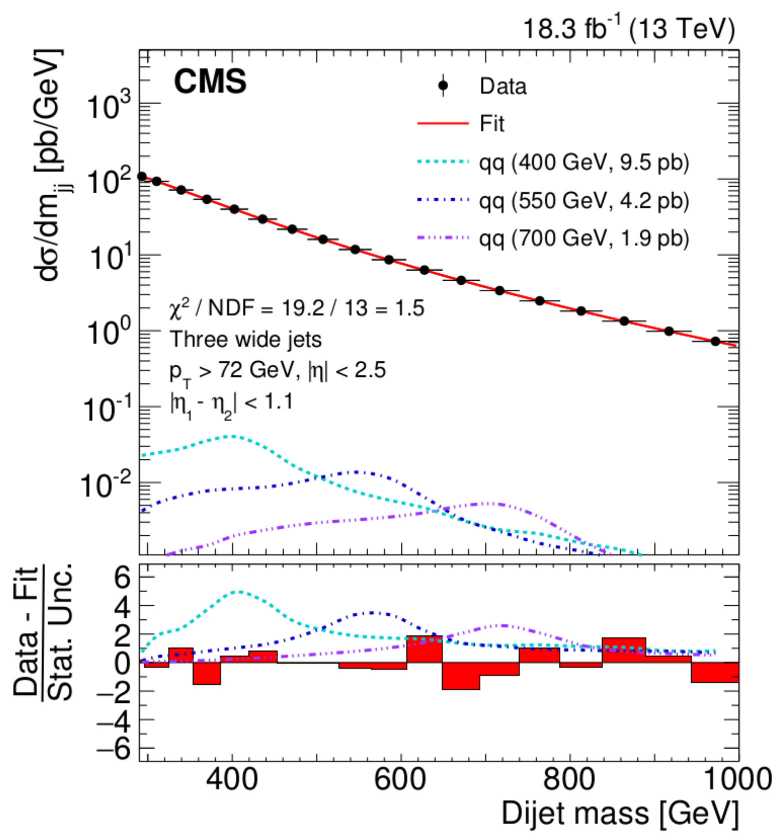


Intermediate mass regime 2016 “Scouting” data

- A reduced data format called **“scouting”** data is used (**0.5%** compared to the full event size yielding much smaller bandwidth), allowing us to go much lower in trigger thresholds and hence to **lower resonance masses.**

- Looking at **three-jet final state** (two leading jets forming the dijet system and an ISR jet)**,** provides sensitivity to even lower resonance masses than in previous searches using scouting data.





Selection criteria

- Require at least **3** jets with jet p_T > **72**GeV.
- $|\Delta\eta|$<**1.1** between the two most energetic jets.
- The two leading jets are chosen as the ones originating from the resonance decay.

- The HLT calorimetric jets are calibrated to Particle Flow jets to account for differences in the reconstruction.

- The dijet mass distribution is fit with a parametrization: $$\frac{d\sigma}{dm_{jj}} = \frac{p_0(p_2 x - 1)}{x^{p_1 + p_3 \log x + p_4 \log^2 x}}$$

Z’ Coupling: Summary plot