



# Search for narrow and broad dijet resonances at CMS

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On behalf of the CMS collaboration

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# Outline

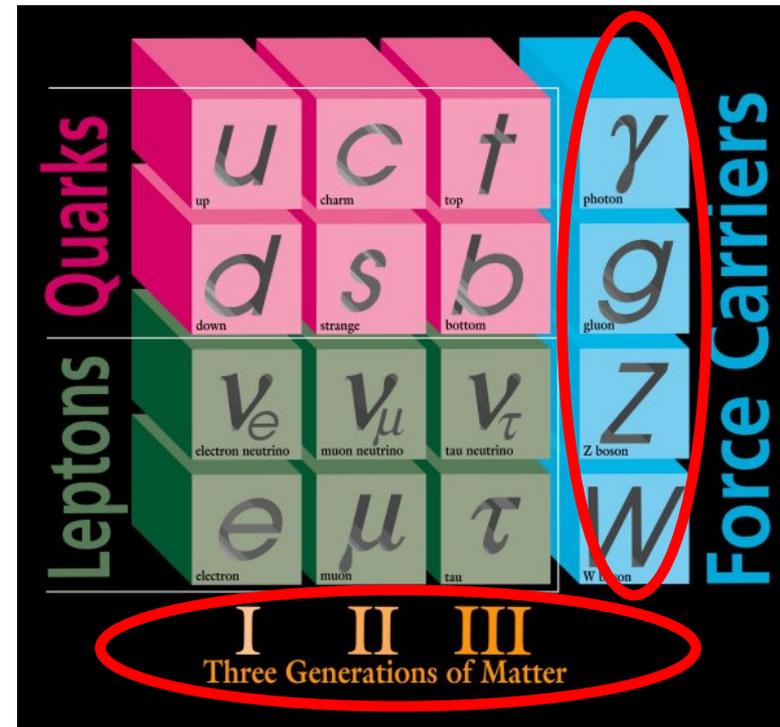


- Introduction
- Measurement and data
- Search for narrow and broad dijet resonances
- Limits on new particles and a dark matter mediator
- Conclusions

**Results of "Search for narrow and broad dijet resonances and constraints on a dark matter mediator and other new particles", arXiv:1806.00843, sub. to JHEP**

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- The standard model describes all observations so far
- But it leaves many questions:
  - ➔ Why three generations of matter ?
  - ➔ Are there more forces than strong, electroweak and gravity ?
  - ➔ Can we unify strong and electroweak ?
  - ➔ Can we include gravity in our theory, and why is gravity so weak ?
  - ➔ Where is the dark matter particle ?

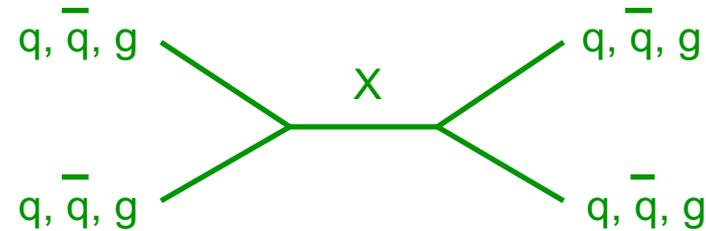


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- Our search is motivated by these fundamental questions.

- **Search:** Dijet Resonances



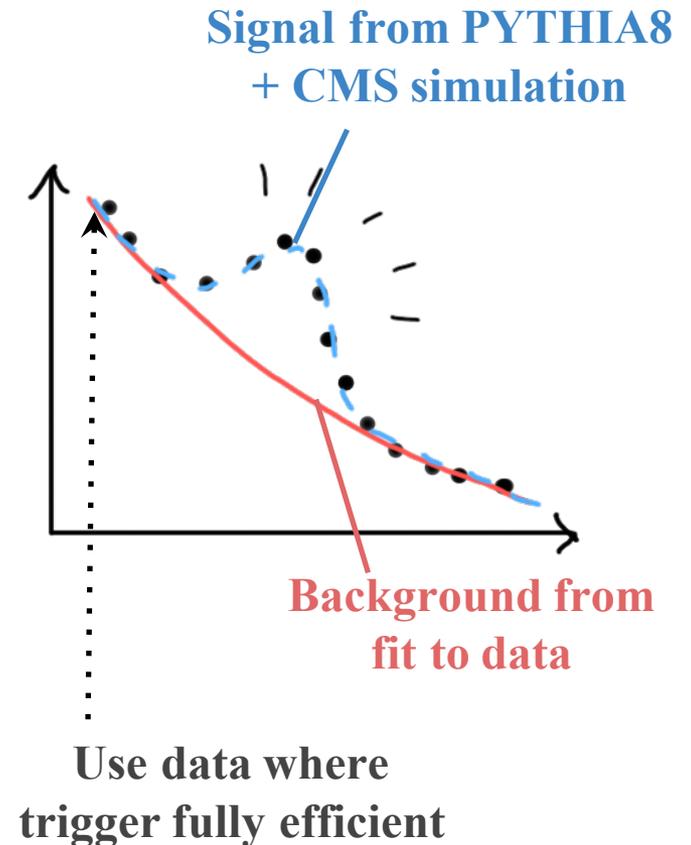
- **Model Independent:** Search for narrow or broad  $qq$ ,  $qg$ , or  $gg$  resonances.
- **Powerful:** LHC is a dijet resonance factory at the highest energy scale
- **Wide:** search for **particles** from many models  $\leftrightarrow$  **fundamental questions**
  - ➔ **String resonances** from string theory  $\leftrightarrow$  including gravity in particle physics
  - ➔ **Excited quarks** from quark compositeness  $\leftrightarrow$  explain three generations
  - ➔ **W', Z' and scalar diquarks** from grand unified theory  $\leftrightarrow$  unify forces
  - ➔ **Gravitons** from Randall-Sundrum model of extra dimensions  $\leftrightarrow$  gravity weak
  - ➔ **Axiguons, Colorons and Color Octet Scalars**  $\leftrightarrow$  new strong forces
  - ➔ **Dark Matter Mediators** from quark - DM interactions  $\leftrightarrow$  dark matter



# Overview of Search Strategy



- **Search:** single bump on a falling spectrum
- **Trigger:** Use data above dijet mass threshold where CMS trigger is fully efficient
- **Quality:** Check critical data distributions comparing with MC only to “guide the eye”.
- **Data:** Measure dijet mass distribution  $d\sigma/dm$
- **Background:** Use parameterization to fit data for the background.
- **Signal:** PYTHIA + CMS simulation gives shape of qq, qg and gg resonances
- **Interpretation:** Estimate significance of potential signals, set limits.



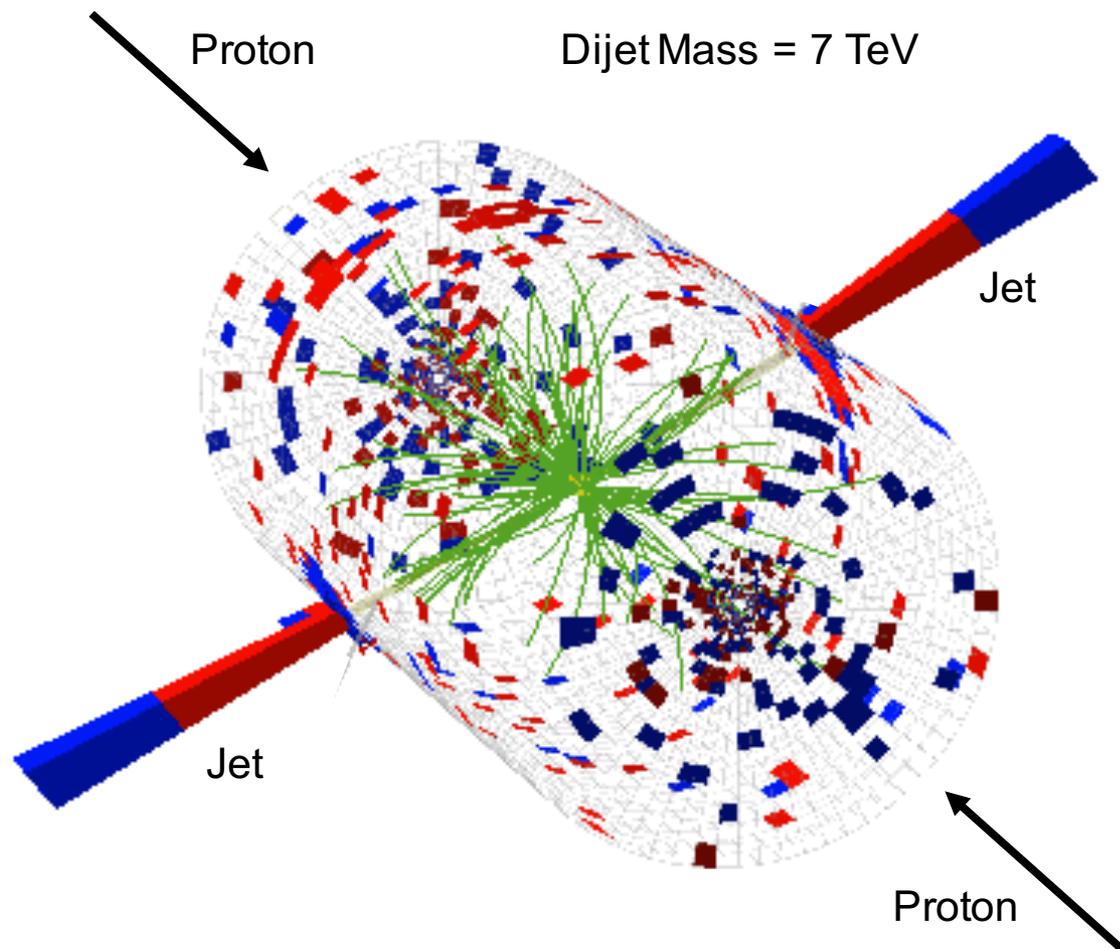


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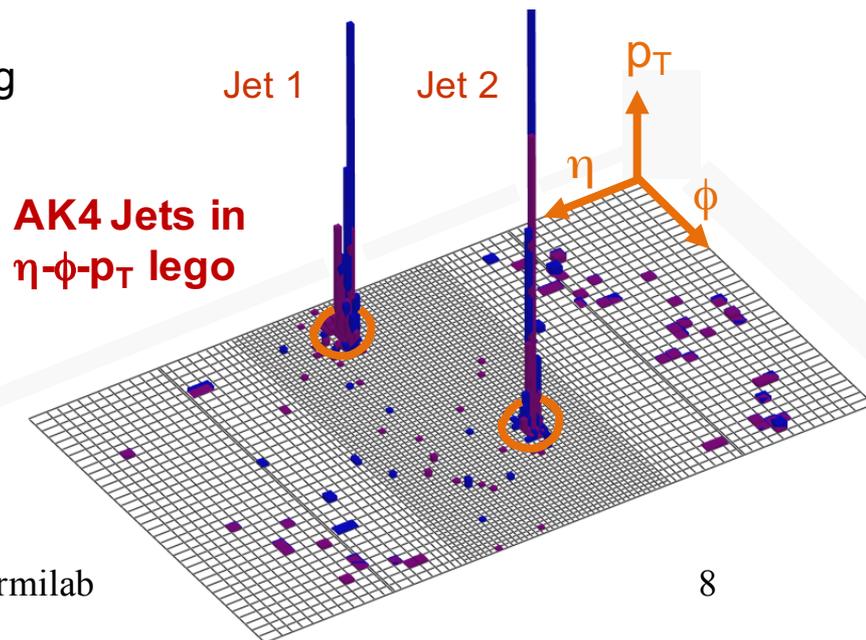
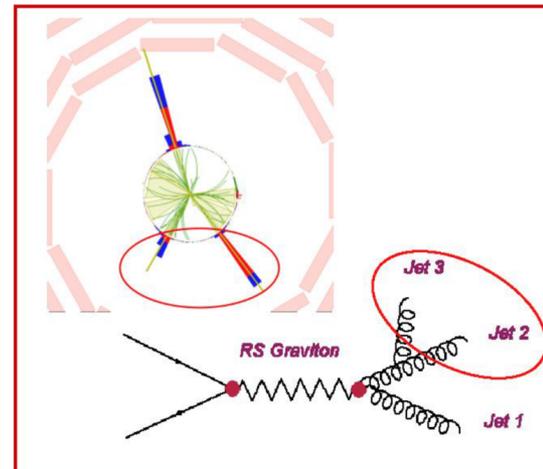
# Measurement

# Dijet Events

- High mass dijets give spectacular signatures in CMS detector.
- Outgoing partons give two collimated sprays of particles
- Produce high transverse momentum tracks and calorimeter energy deposits
- Back-to-back in azimuthal angle
- Clear example of the  $2 \rightarrow 2$  dijet process



## Wide Jet Reconstruction



- Dijet reconstruction with Wide Jets
  - ➔ Recombines final state radiation into dijet
  - ➔ Gives better sensitivity to resonances
- Dijet Reconstruction
  - ➔ Anti- $K_T$  jets with distance parameter 0.4 (AK4)
  - ➔  $|\eta| < 2.5$  and  $p_T > 30$  GeV passing Jet ID
  - ➔ Wide jets formed by merging other AK4 jets into two leading AK4 jets
    - ➔ If within  $\Delta R = 1.1$  of one of the two leading AK4 jets in  $\eta$ - $\phi$  space
- Event Selection
  - ➔  $|\Delta\eta| < 1.3$  suppresses QCD (t-channel) and enhances signal (s-channel)
  - ➔ Dijet Mass  $>$  Trigger Cut for full efficiency

- We use two types of jet reconstruction

**1. Particle Flow:** jets from particles, mainly charged hadrons ( $\pi^\pm$ ), photons (from  $\pi^0$ ), and neutral hadrons (n)

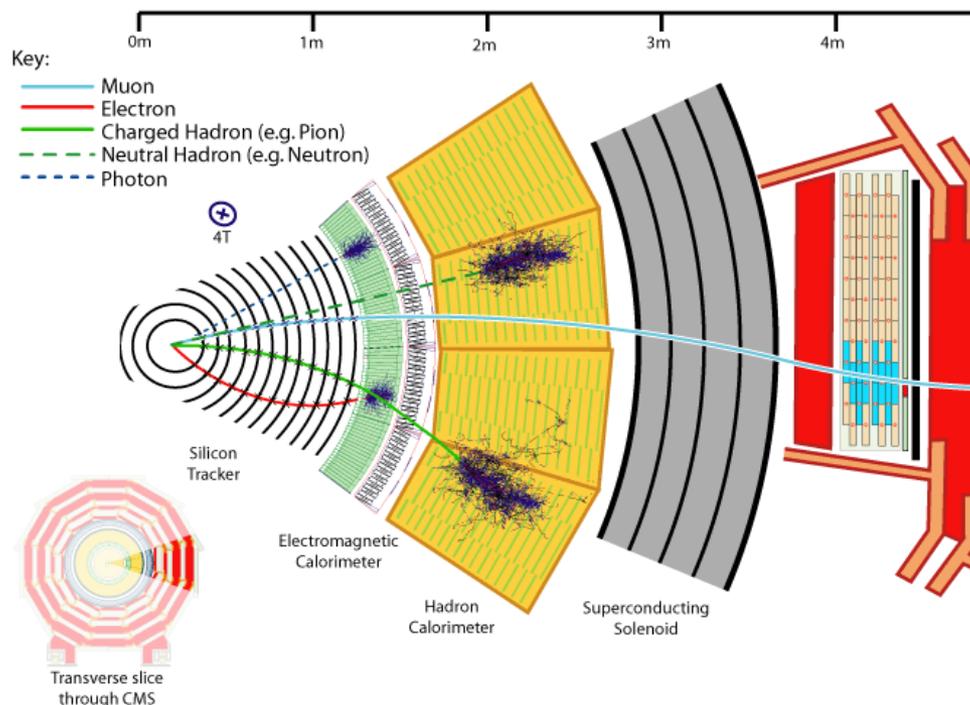
➔ For **high-mass search** using jets fully reconstructed offline

**2. Calorimeter:** Jets from calorimeter energy deposits

➔ For **low-mass search** using jets reconstructed in the high level trigger

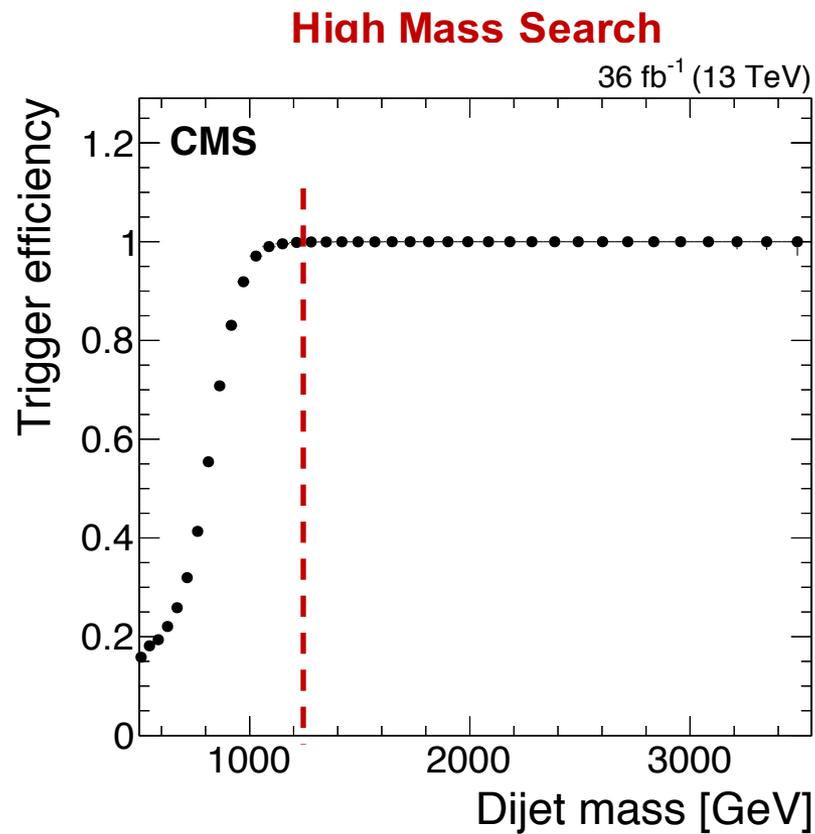
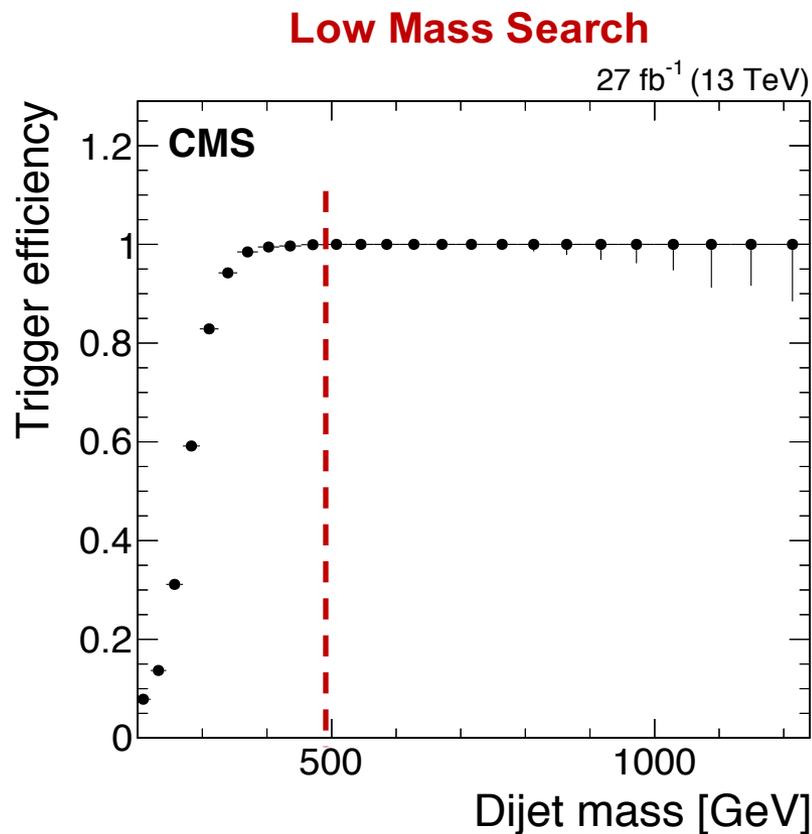
➔ Saved in compact “data scouting” dataset

## CMS Detector & Reconstruction



# Trigger Efficiency

- We start the search at a dijet mass value that is fully efficient
  - ➔ High mass search uses full 36 fb<sup>-1</sup> from 2016 run
  - ➔ Low mass search uses first 27 fb<sup>-1</sup>

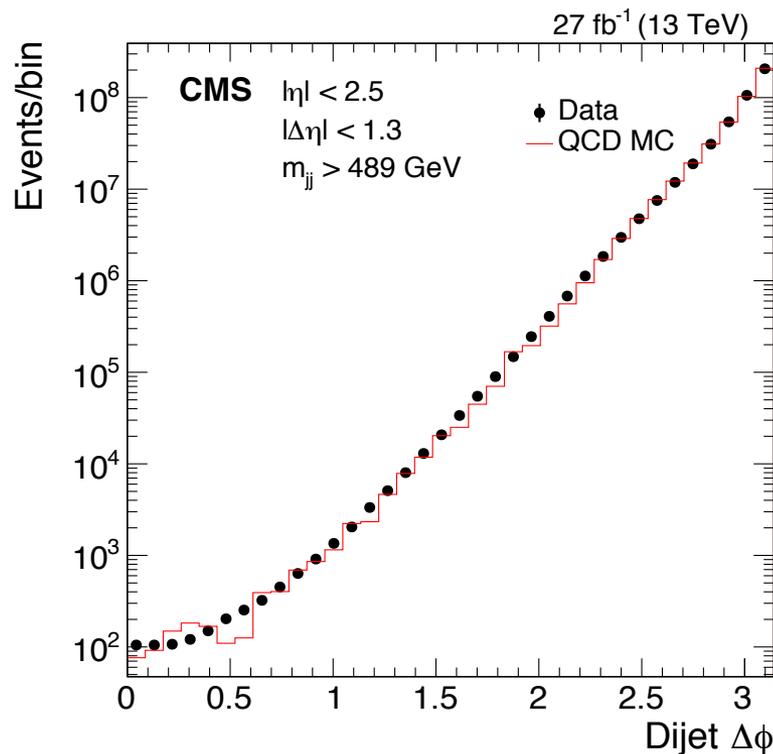




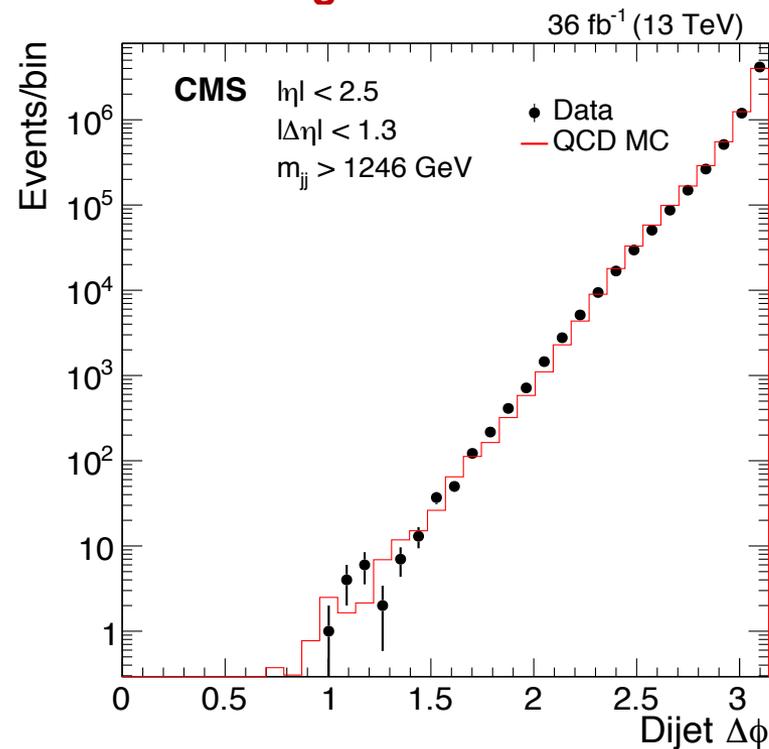
# Data Quality: $\Delta\phi$

- Dijet  $\Delta\phi$  shows back-to-back peak at  $\pi$  for dijet events
  - ➔ Clear sign of real data originating from parton-parton scattering
  - ➔ Radiation causes a small percentage of events at low  $\Delta\phi$

## Low Mass Search



## High Mass Search

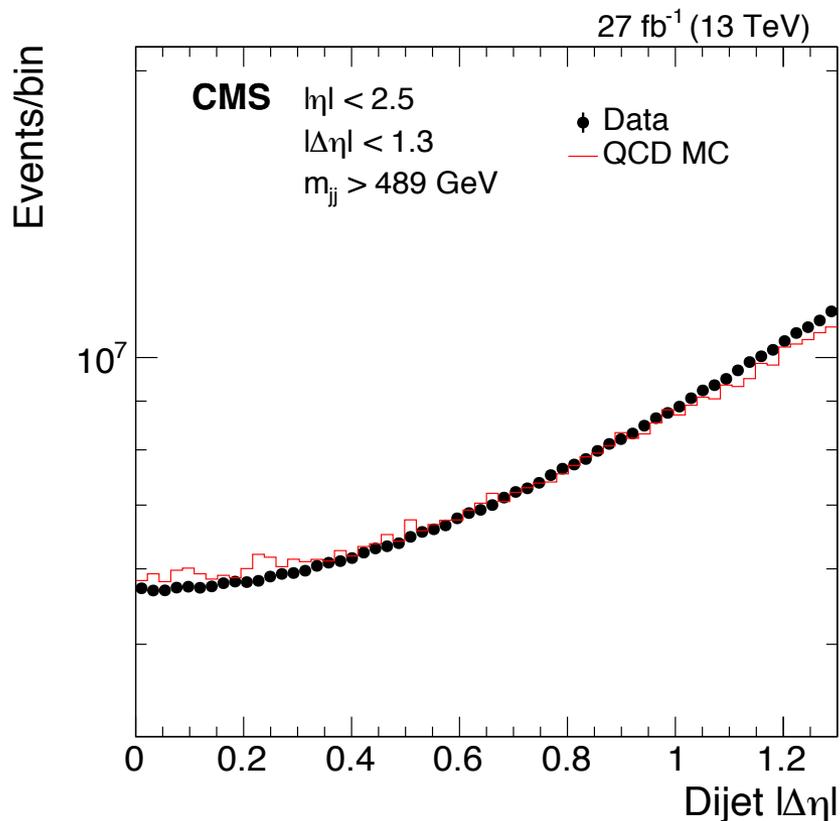




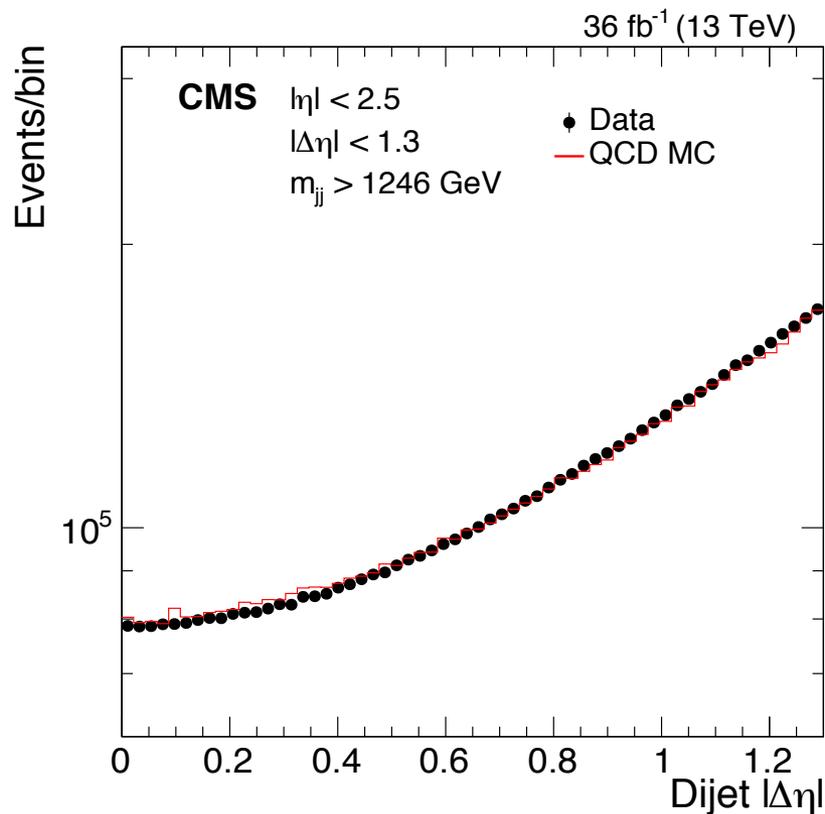
# Data Quality: $\Delta\eta$

- Dijet  $\Delta\eta$  demonstrates the t-channel angular distribution of dijets
  - ➔ Peaking at high  $|\Delta\eta|$  as expected from parton-parton scattering via QCD

## Low Mass Search



## High Mass Search





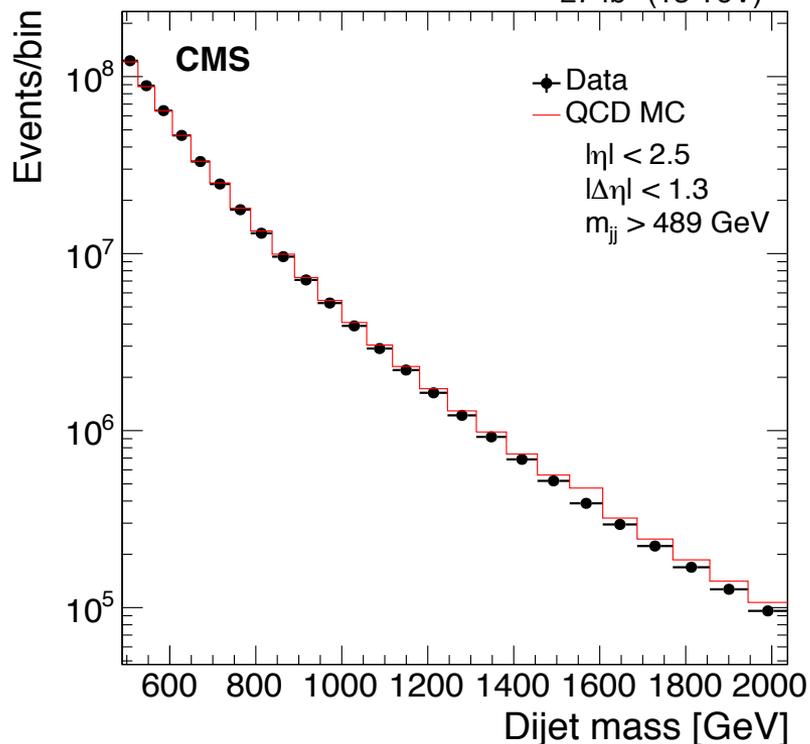
# Data Quality: Dijet Mass



- Dijet mass distribution falls steeply and smoothly like QCD
  - ➔ Data is shown in bins of width approximately equal to experimental dijet mass resolution

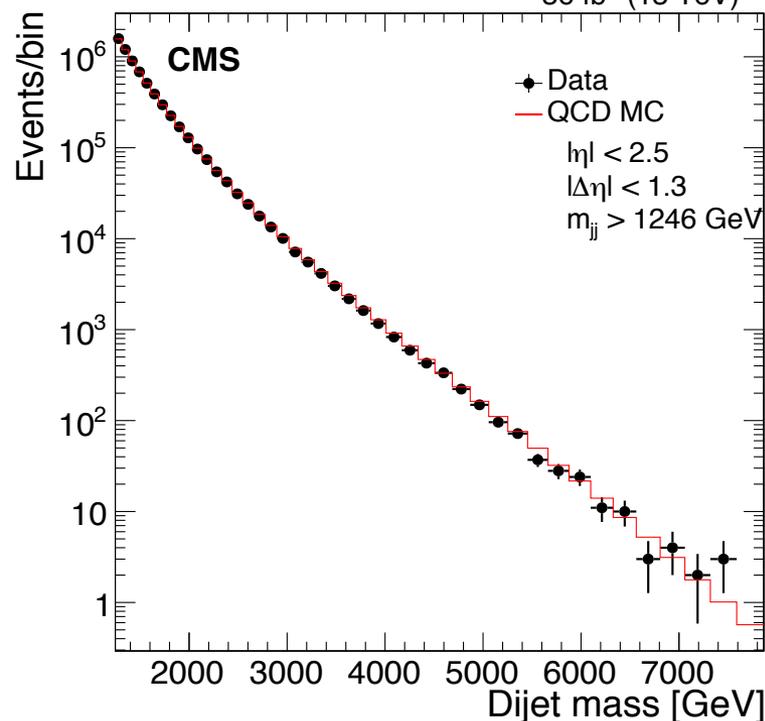
## Low Mass Search

27 fb<sup>-1</sup> (13 TeV)



## High Mass Search

36 fb<sup>-1</sup> (13 TeV)





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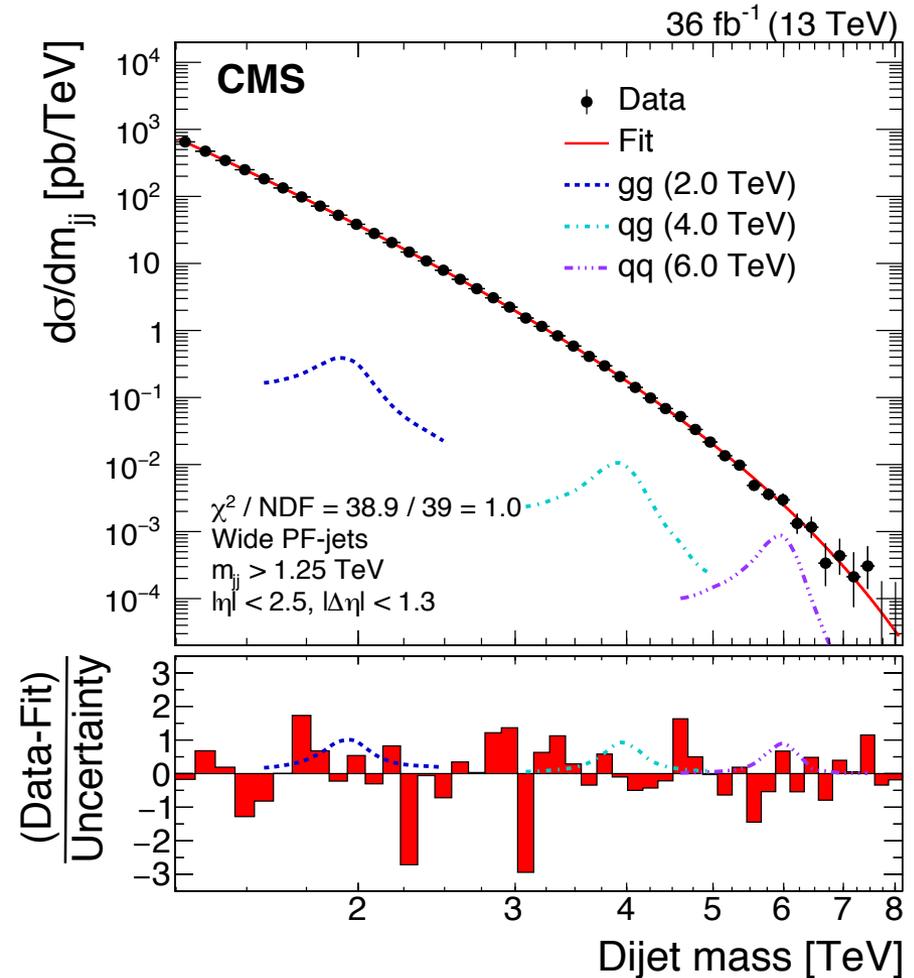
# Search for Narrow Dijet Resonances

# High Mass Spectrum & Fit

- Data is fit with our standard 4 parameter function:

$$\frac{d\sigma}{dm_{jj}} = p_0 \frac{(1-x)^{p_1}}{x^{p_2+p_3} \ln x}, \quad x = \frac{m_{jj}}{\sqrt{s}}$$

- Data well described by fit
  - $\chi^2 / \text{NDF} = 38.9 / 39$
- No evidence for a dijet resonance 😞
- Narrow resonances would make a bump up in 3-4 bins

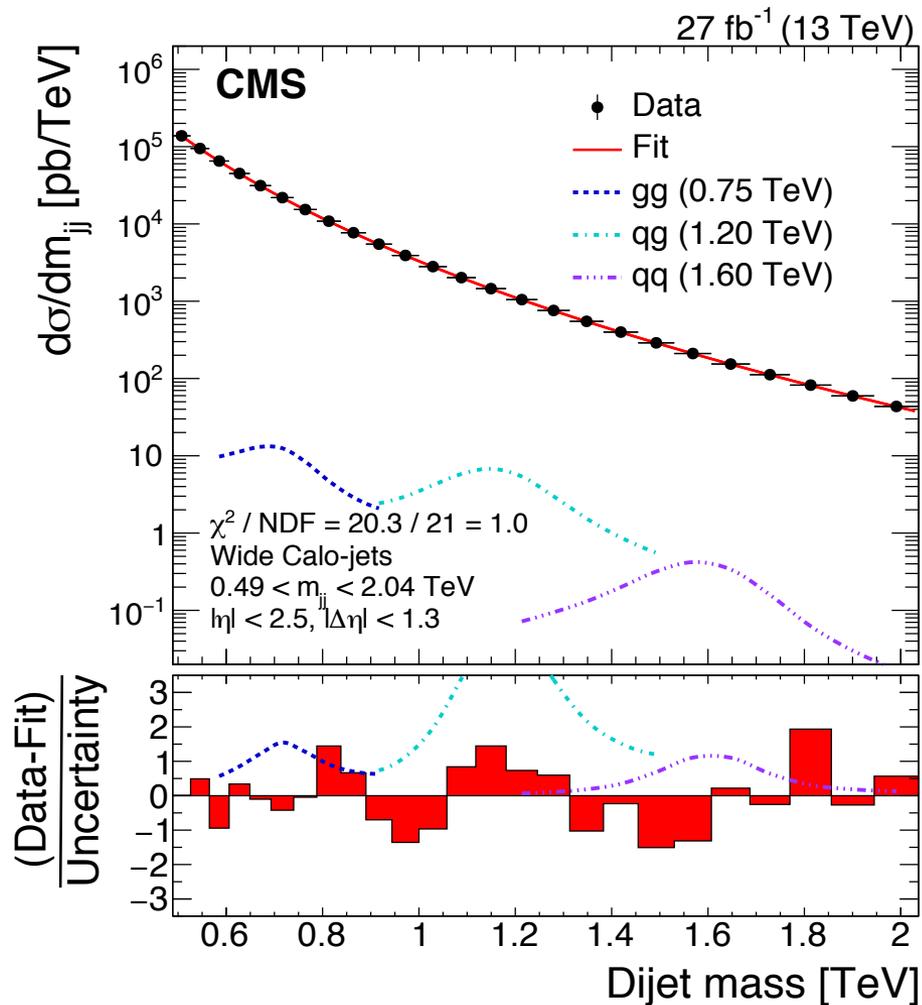


# Low Mass Spectrum & Fit

- Dijet mass data is fit with a five parameter function

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

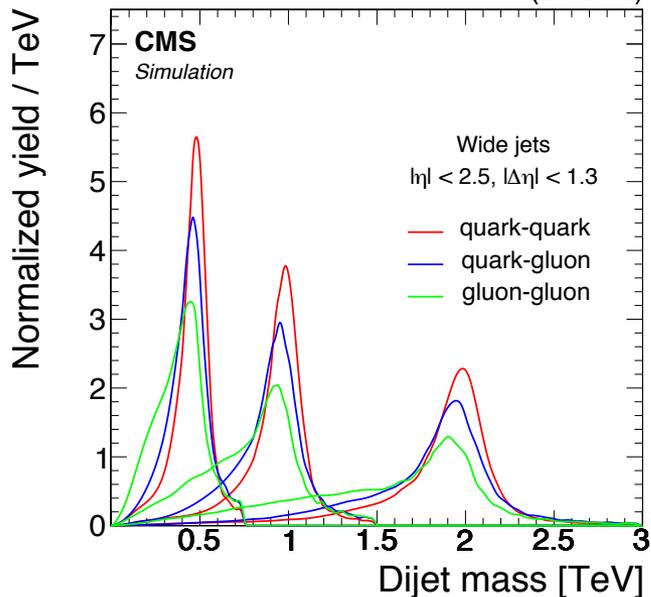
- Five parameters were needed to pass F-test and get best  $\chi^2$ 
  - ➔ 4 par :  $\chi^2/\text{NDF} = 27.9 / 21$  **marginal**
  - ➔ 5 par :  $\chi^2/\text{NDF} = 20.3 / 20$  **good**
  - ➔ 6 par :  $\chi^2/\text{NDF} = 20.1 / 19$  **no need**
- No evidence for a dijet resonance



- Shapes peak at resonance mass with a tail to low dijet mass
  - ➔ Width & tail is larger for gluon-gluon than for quark-quark resonances because:
    1. Final state radiation is larger for gluons, causing more radiation to fall outside jet
    2. PDF's fall more steeply for gluons, skewing the resonance shape more to low mass

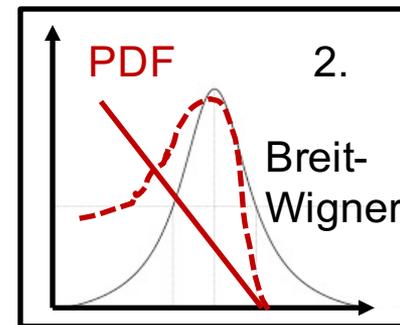
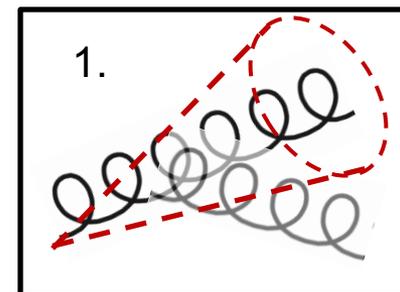
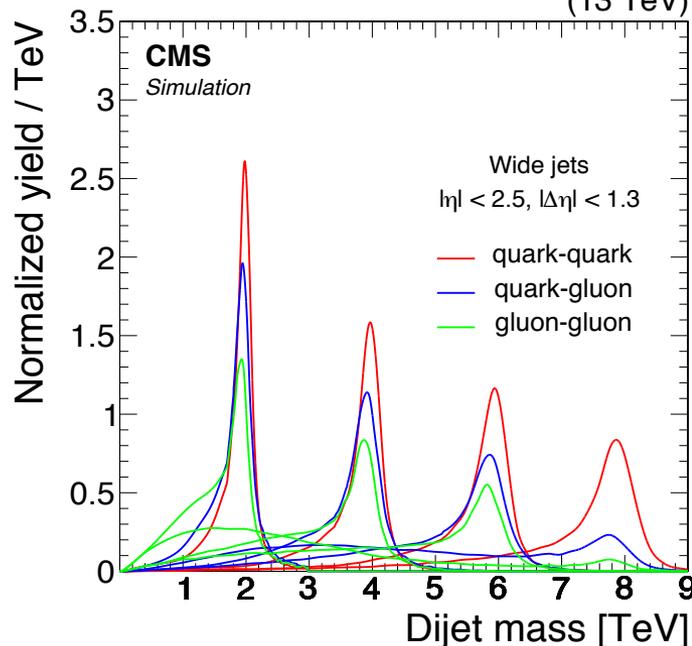
## Low Mass Search

(13 TeV)



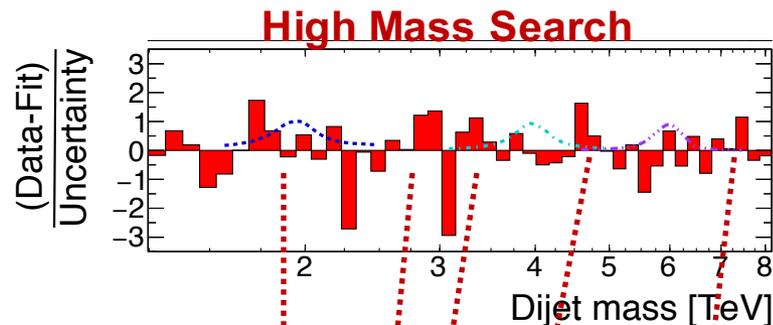
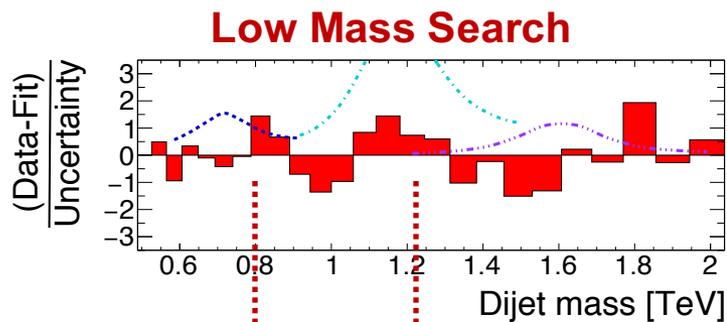
## High Mass Search

(13 TeV)

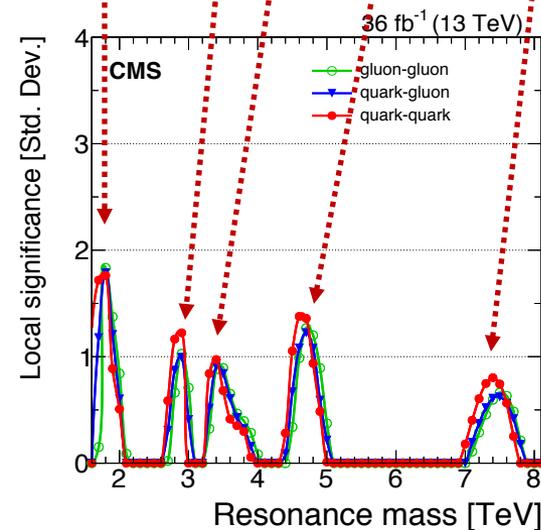
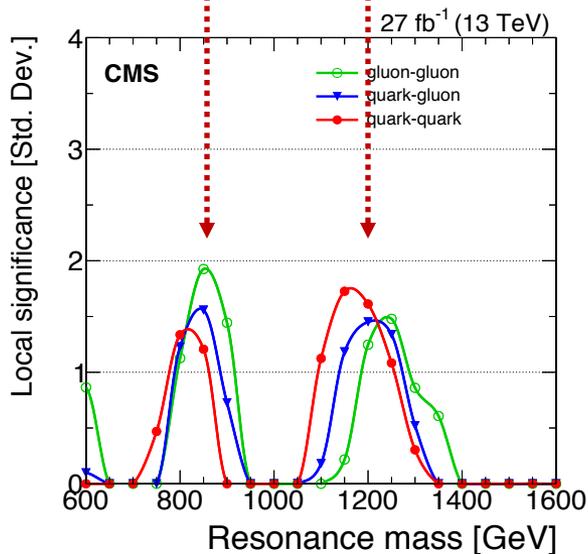


# Significance of Narrow Signals

- Bumps in data are checked to see if they are narrow resonance signals
  - ➔ Local significance of each  $< 2\sigma$ . No evidence for a narrow resonance. 😞



Pulls



Signal Significance



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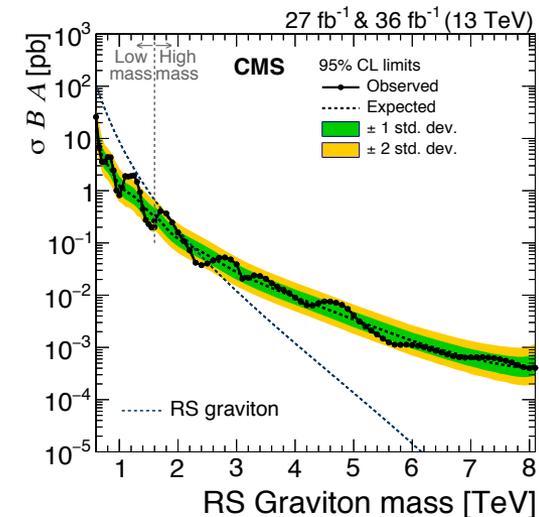
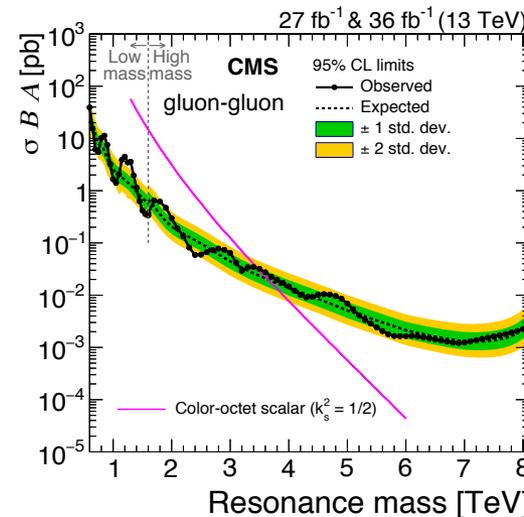
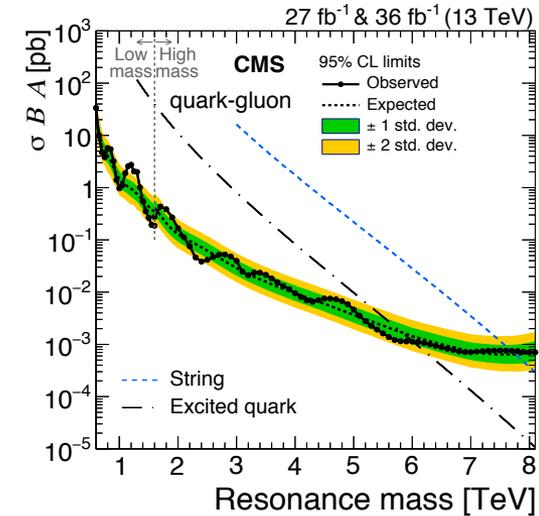
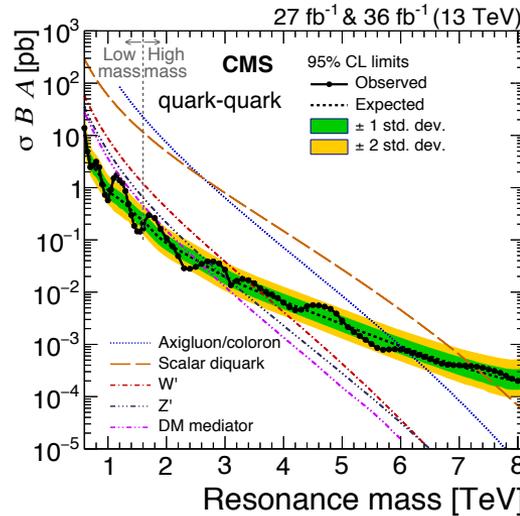
# Limits



# Narrow Resonance Limits and Models



- Cross section upper limits for each type of resonance search
  - ➔ qq, qg, gg and RSG
  - ➔ Low mass  $\leq 1.6$  TeV
  - ➔ High mass  $\geq 1.6$  TeV
- Compared to predictions of 10 models of BSM physics !
- Bumps in data give bumps in observed limits.
  - ➔ Again within  $2\sigma$  of expected limits

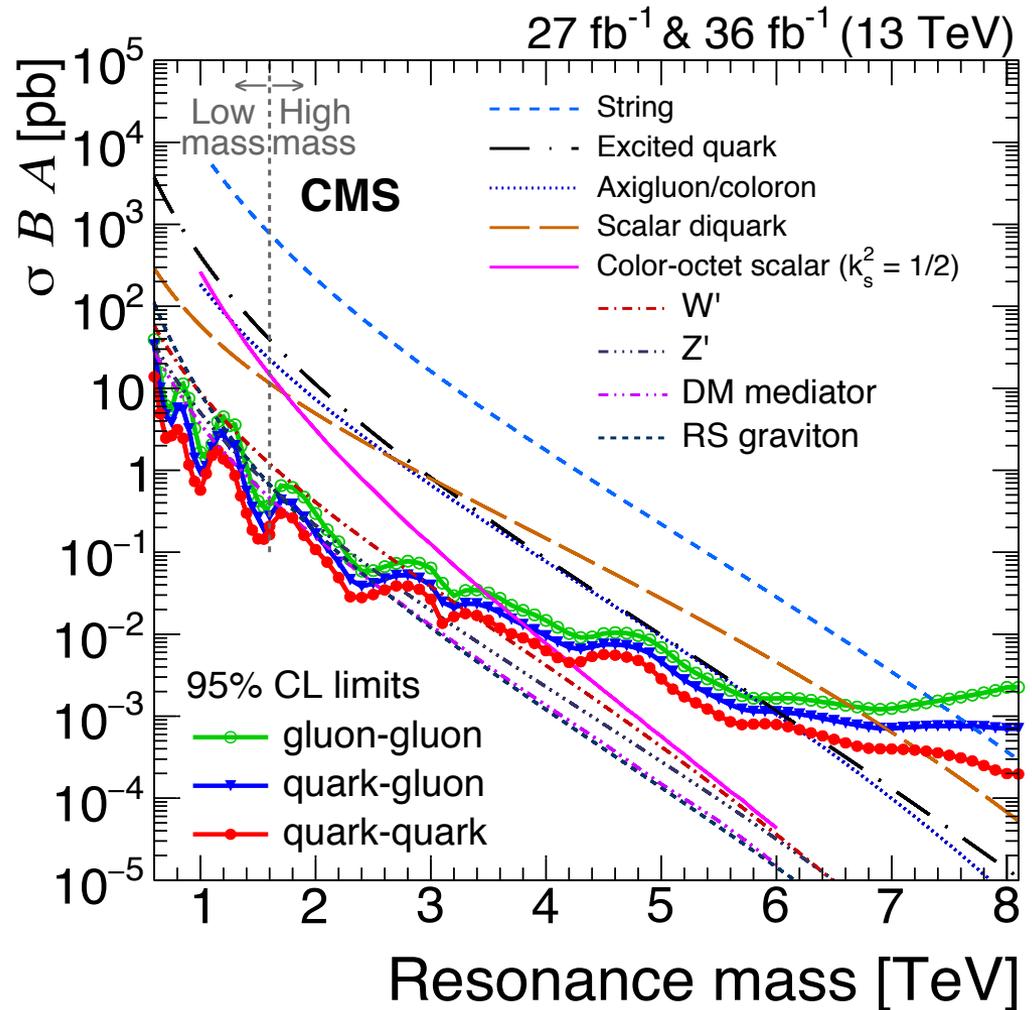




# Understanding Limits: Model $\sigma$ and Resonance Resolution



- Model cross sections span four orders of magnitude !
  - ➔ Largest cross section for strongly produced resonances
    - String, Excited Quark, Axigluon/Coloron have  $\sigma \sim \alpha_s^2$
    - Scalar diquark produced from valence quarks, large PDF.
  - ➔ Smaller cross section for weakly produced resonances
    - $W'$ ,  $Z'$  produced electroweakly
    - DM mediator & RS graviton
    - Color Octet Scalar produced from gluons, so small PDF
- Limits improve with better resolution and smaller tail
  - ➔ quark-quark resonances have best resolution and least tail





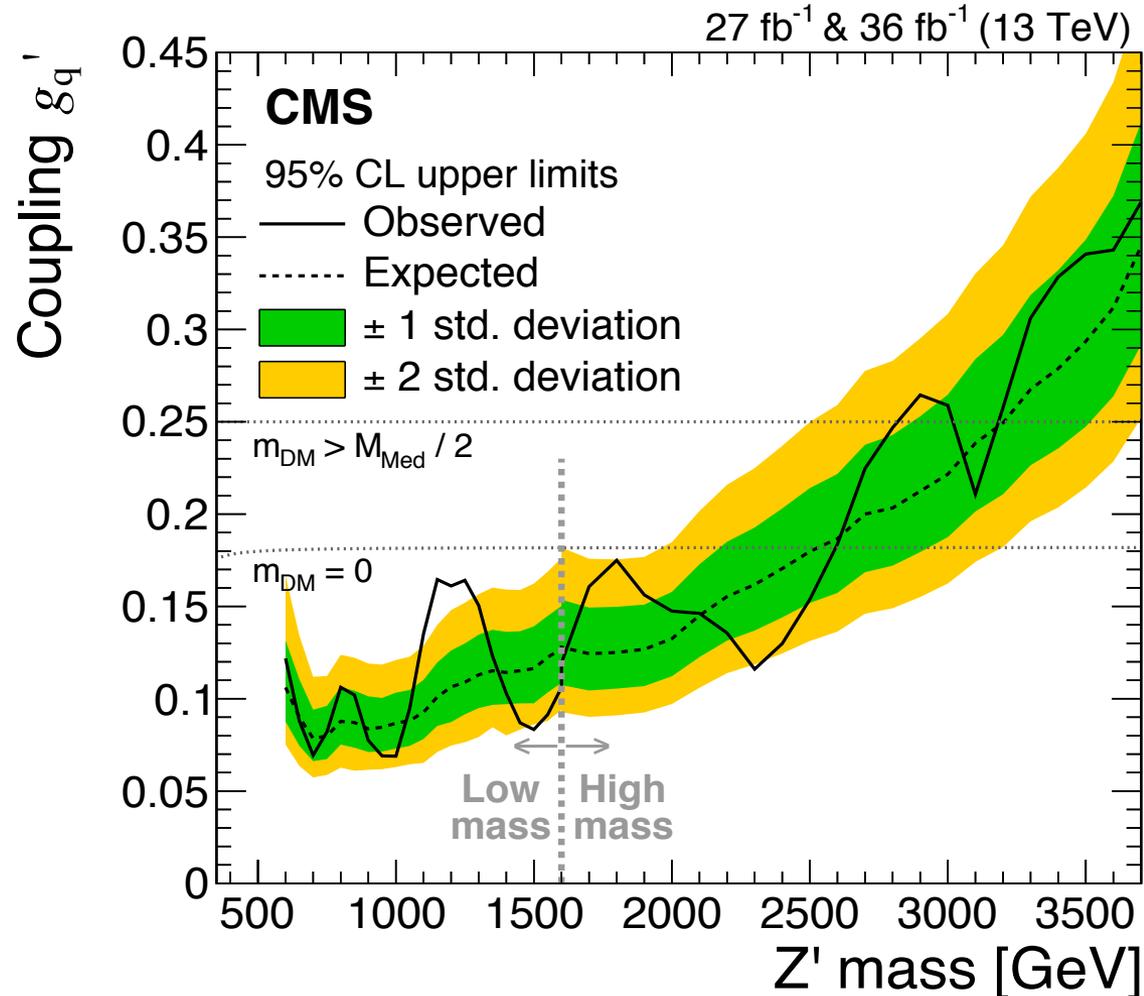
# Mass limits on Models

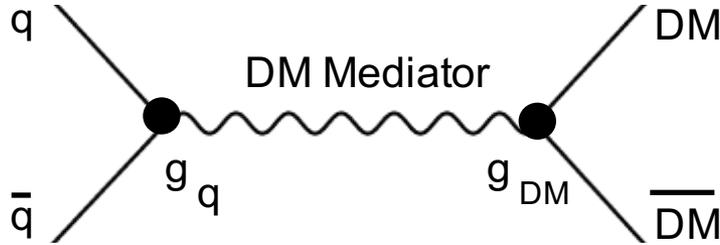
- Limits from **this search** are better than the prior run 2 search with **less luminosity**, and a lot better than run 1 with **less collision energy**.

Model Cross Section ↑

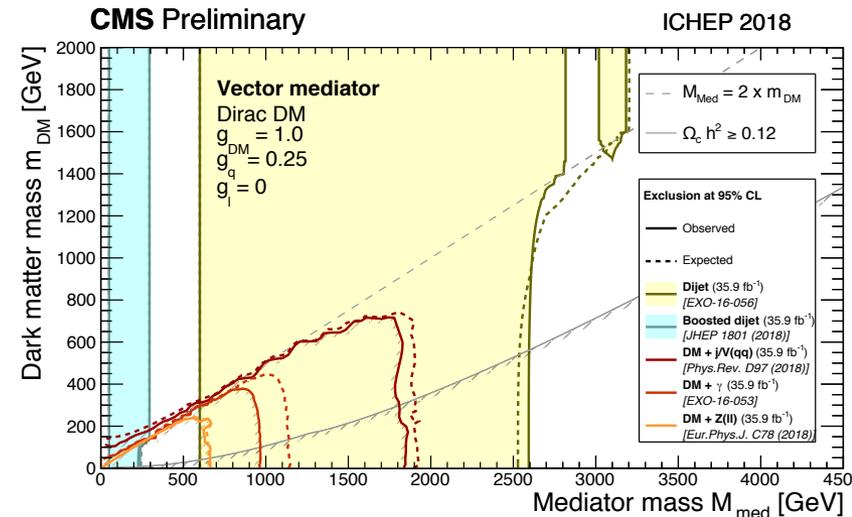
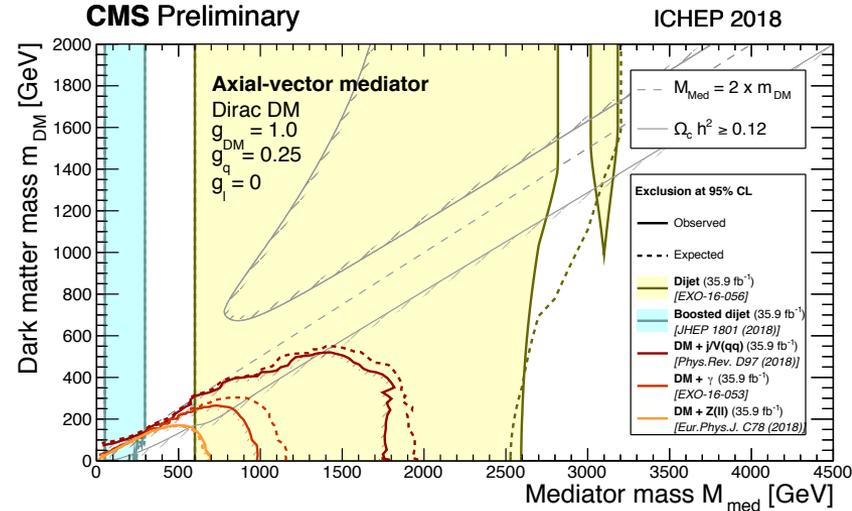
Model	Obs. (exp.) mass limit [TeV]		
	$\int \mathcal{L} = 36 \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}$	13 fb <sup>-1</sup> 13 TeV	20 fb <sup>-1</sup> 8 TeV
String Resonance (qg)	7.7 (7.7)	7.4 (7.4)	5.0 (4.9)
Scalar Diquark (qq)	7.2 (7.4)	6.9 (6.8)	4.7 (4.3)
Axigluon / Coloron (q $\bar{q}$ )	6.1 (6.0)	5.5 (5.6)	3.7 (3.9)
Excited Quark (qg)	6.0 (5.8)	5.4 (5.4)	3.5 (3.7)
Octet Scalar (gg)	3.4 (3.6)	3.0 (3.3)	----
W' Boson (q $\bar{q}$ )	3.3 (3.6)	2.7 (3.1)	2.2 (2.2)
Z' Boson (q $\bar{q}$ )	2.7 (2.9)	2.1 (2.3)	1.7 (1.8)
DM Mediator (q $\bar{q}$ )	2.6 (2.5)	2.0 (2.0)	----
RS Graviton (q $\bar{q}$ , gg)	1.8 (2.3)	1.9 (1.8)	1.6 (1.3)

- Mass limits depend on the coupling assumed by the model.
  - ➔ As search sensitivity increases we exclude smaller couplings.
- This  $Z'$  with coupling  $g_q'$  decays to only quarks
- Dotted lines show the  $g_q'$  for which this model has same cross section as our DM mediator model.





- LHC DM working group model of an interaction between quarks and DM
  - ➔ A lepto-phobic spin-1 mediator that only couples to quarks and DM
  - ➔ Universal quark coupling  $g_q = 0.25$  and dark matter coupling  $g_{DM} = 1.0$
- Dijet limits on a dark matter mediator in yellow  increase slowly with  $m_{DM}$ 
  - ➔ Because branching fraction to dijets increases

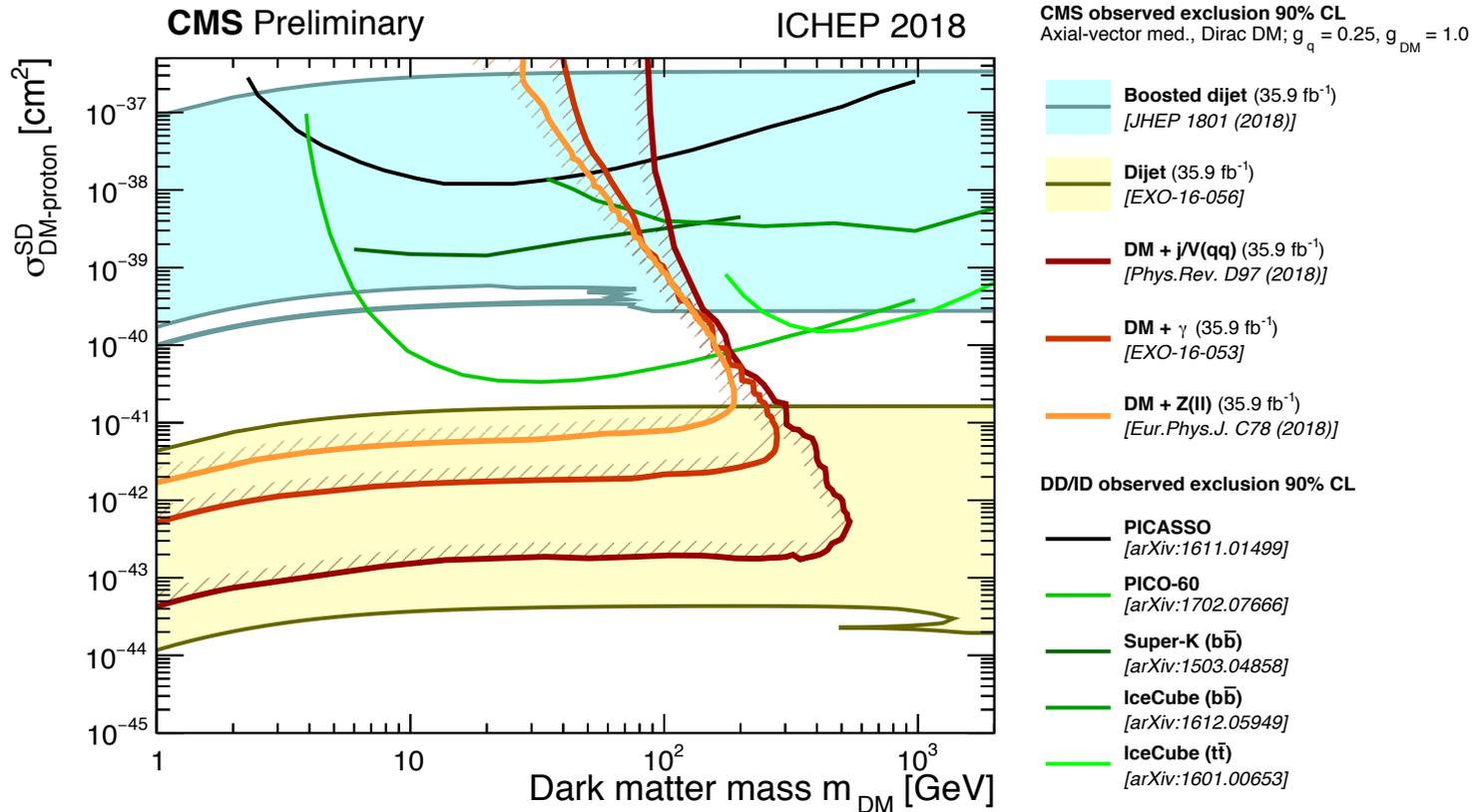




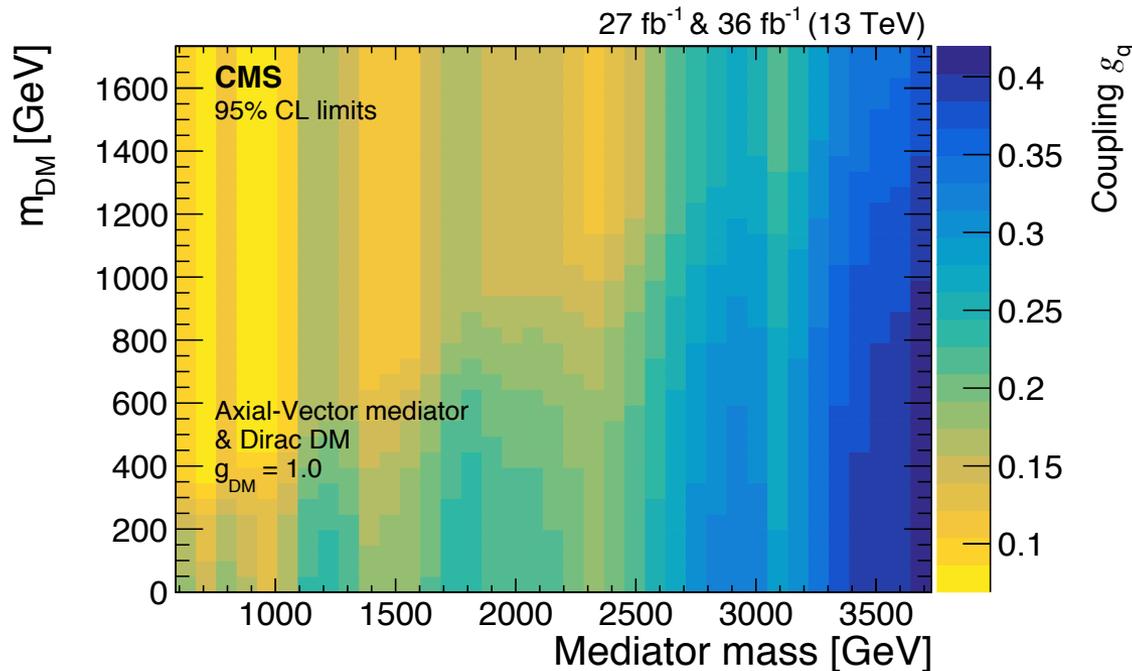
# CMS compared to direct detection



- Our dijet search in yellow  excludes regions complementary to DM detection experiments and CMS DM + X searches 😊
  - ➔ Spin-dependent DM-proton cross sections from exclusions of axial-vector mediators.



- Narrow resonance search can be used to set limits on the coupling  $g_q$ 
  - ➔ Limits on  $g_q$  between 0.08 and 0.42 depending on Mediator and DM mass
  - ➔ To exclude higher values of  $g_q$ , which correspond to higher natural widths, we search for broad resonances

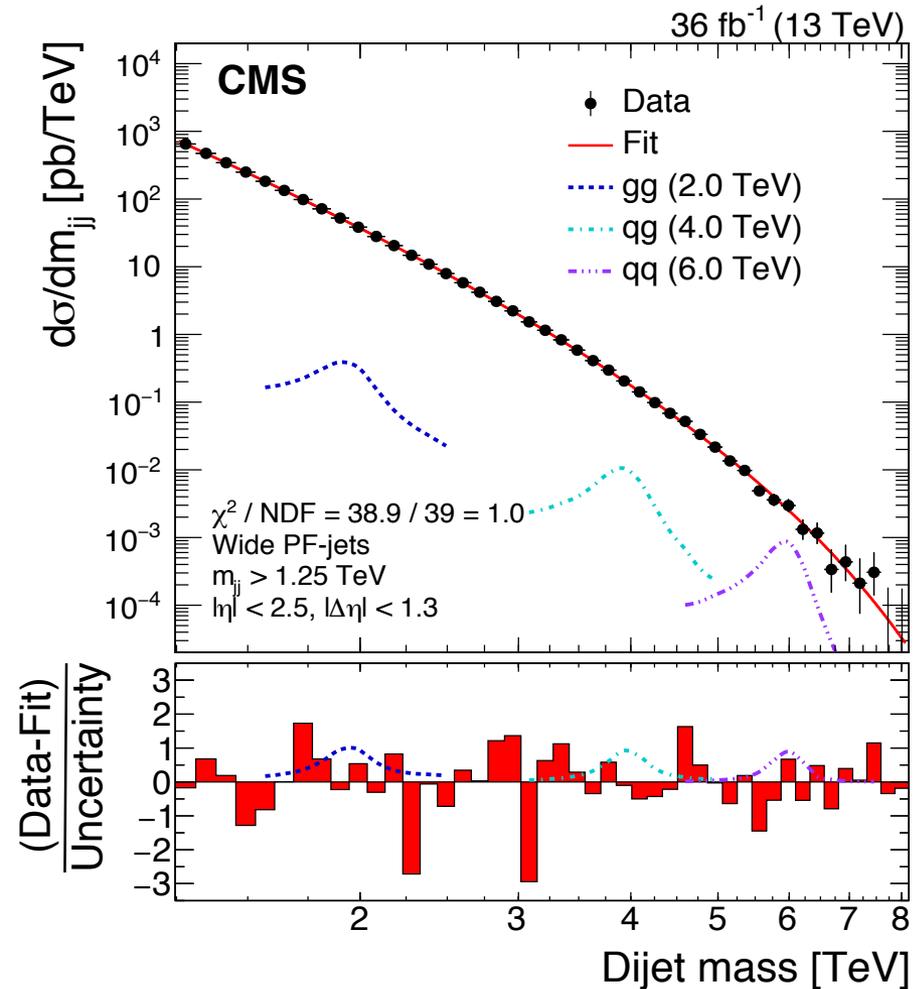




# Broad Dijet Resonances

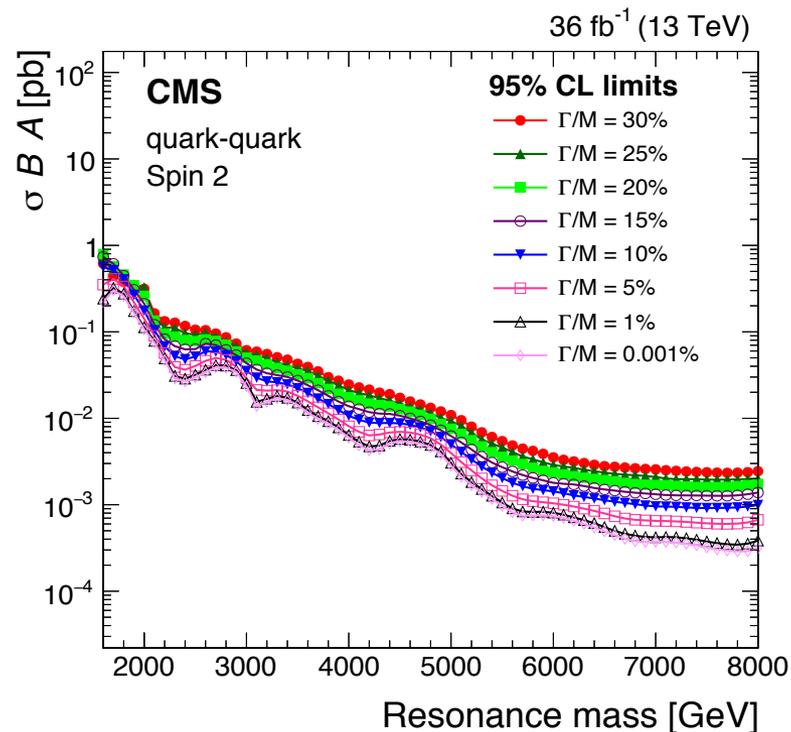
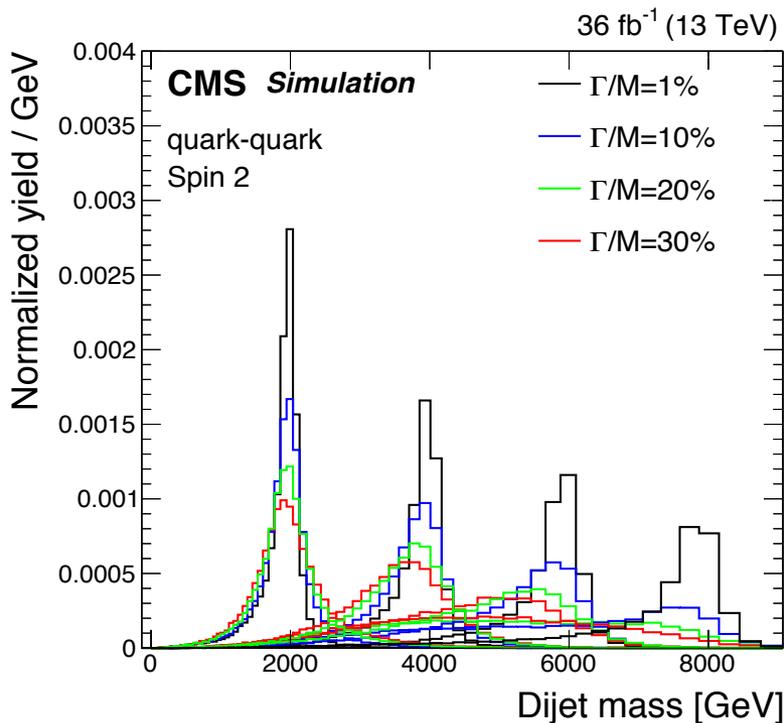
# Search Strategy

- Narrow resonance observed shapes are dominated by experimental resolution.
  - ➔ Natural width doesn't affect shape
- Broad resonance observed shapes are affected by natural width of resonance
- Use same high-mass data to search for broad resonances also
  - ➔ There is no evidence for either a narrow or broad resonance in data
- Set limits using the shapes of broad resonances



# Limits vs. width

- Natural widths  $\Gamma / M$  from narrow (0.001%) to broad (30%)
- Limits get worse as the resonance natural width increases
  - ➔ Increasing background underneath peak leads to worse limit



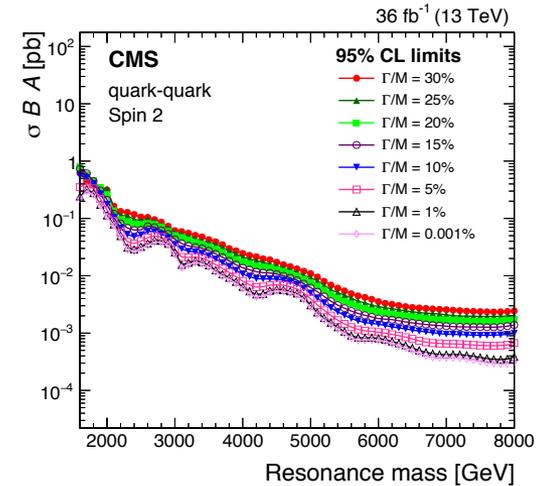
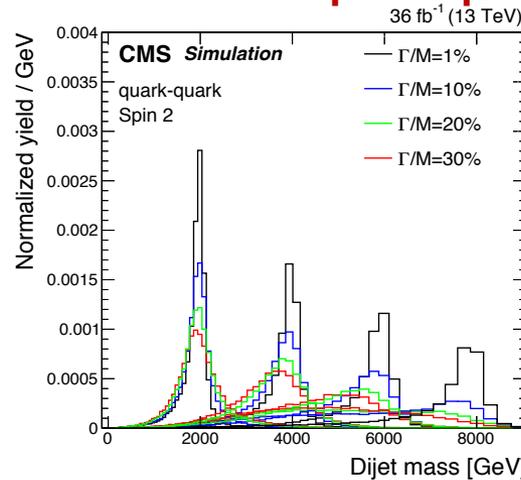
- gluon-gluon resonances have a longer tail than quark-quark resonances & worse limits

➔ Again due to final state radiation and PDF effects from a steeper gluon distribution.

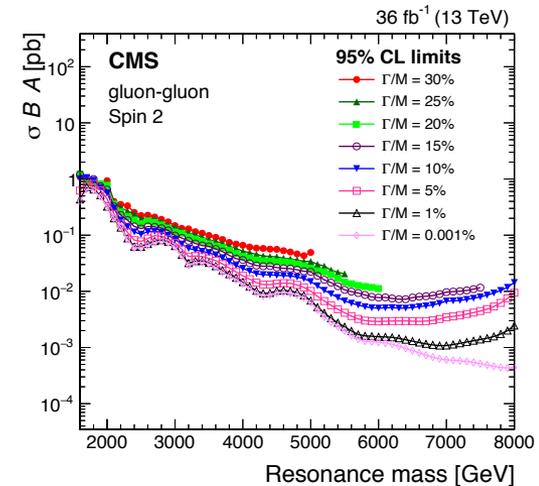
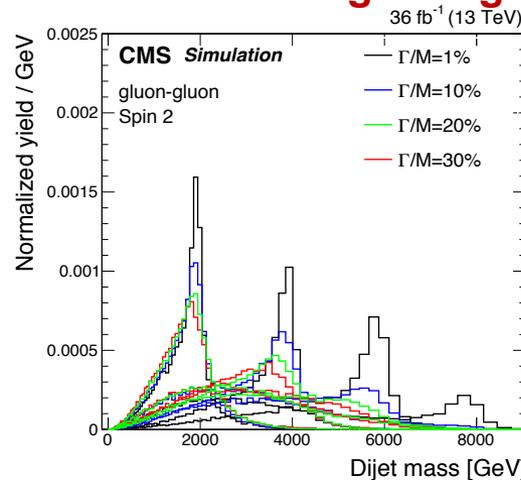
- At the highest resonance masses and widths the gg resonance is “all tail”.

➔ Limit results are not presented when the signal is “all tail”.  
 ➔ Search less robust.

## quark-quark resonances



## gluon-gluon resonances





# Broad signal shapes: spin dependence



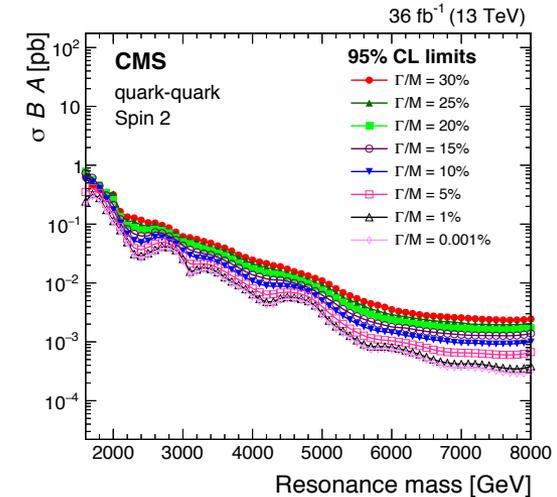
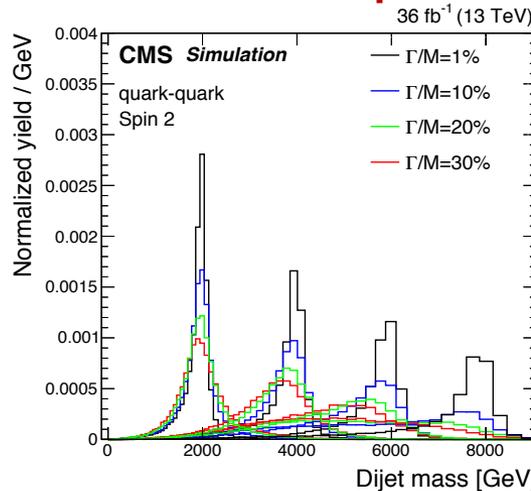
- Spin 1 qq resonances have a longer tail than spin 2
  - ➔ Due to spin dependence of the width to mass relationship (in backup)

- Limits are not presented at the highest masses and widths where spin 1 resonances are “all tail”

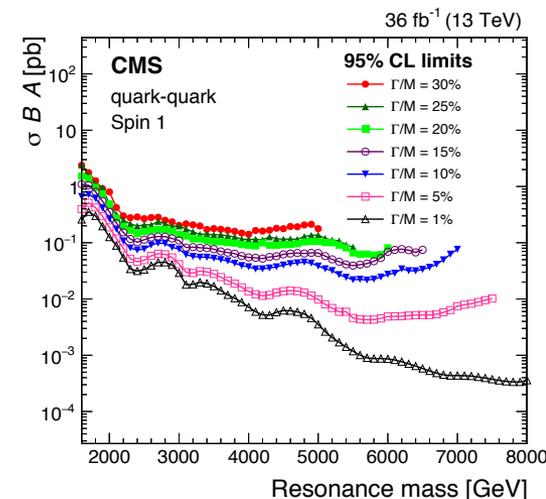
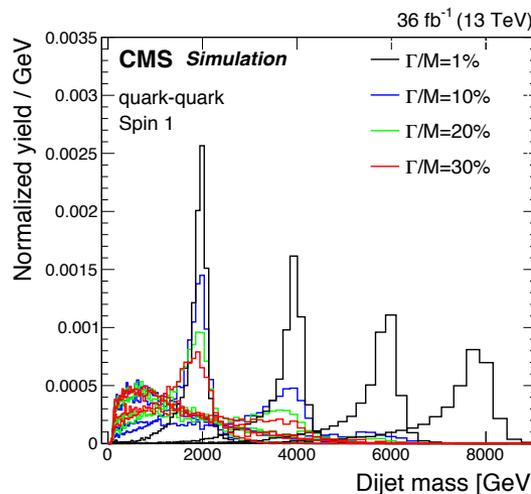
➔ Limits are robust out to 5 TeV for all resonance widths considered.

- DM mediator search uses Spin 1 limits up to 4.1 TeV

## spin 2 resonances

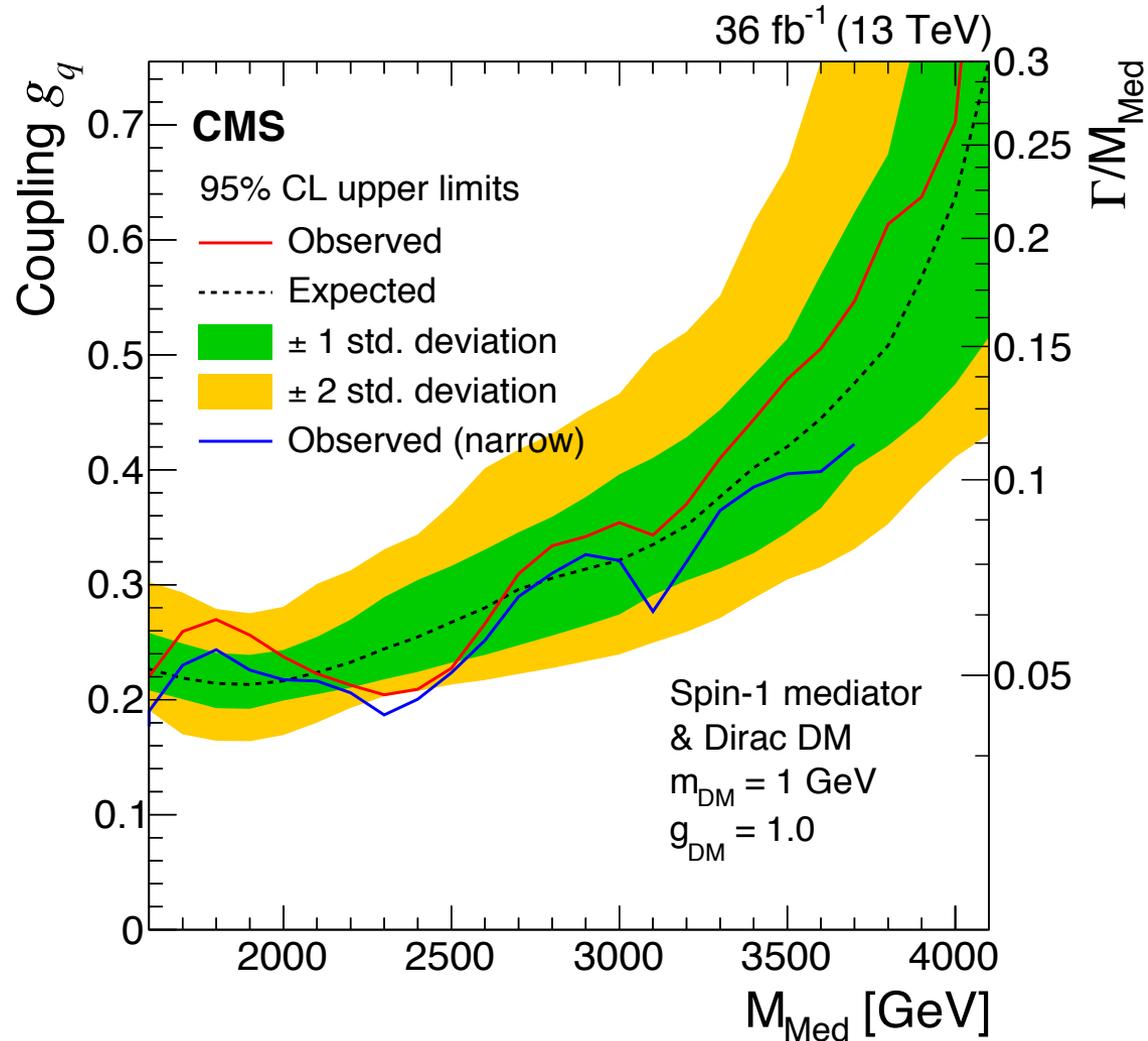


## spin 1 resonances



- With the spin 1 qq resonance limits we set limits on the coupling to a DM mediator
  - ➔ Observed limits for a spin-1 resonance using the actual width in **red**
  - ➔ Observed limits for the generic qq narrow resonance from a spin-2 resonance in **blue**

- Broad resonance search extends limits to larger couplings and masses 😊





# Conclusions

- We have searched for narrow and broad dijet resonances with  $36 \text{ fb}^{-1}$
- Dijet mass spectra are smooth and consistent with background
  - ➔ No evidence for dijet resonances 😞
- We set upper limits on the cross section of dijet resonances, and set stringent mass limits on new particles from many models of new physics
  - ➔ String Resonances, Scalar Diquarks, Axigluons/Colorons, Excited Quarks, Color Octet Scalars,  $W'$  and  $Z'$  Bosons, RS gravitons, and DM mediator
  - ➔ Limits on a DM Mediator complementary to direct detection experiments 😊
- Stay tuned for more searches with increasing luminosity and energy
  - ➔  $78 \text{ fb}^{-1}$  at 13 TeV results should be available this summer
  - ➔  $\sim 150 \text{ fb}^{-1}$  at 13 TeV dataset by end of this year for run 2
  - ➔  $\sim 300 \text{ fb}^{-1}$  at 14 TeV from 2021-23 for run 3
  - ➔  $\sim 3000 \text{ fb}^{-1}$  at 14 TeV from 2026-38 for HL-LHC



# Backup



- **Background mainly t-channel**

- ➔ Scattering at all angles but more in forward-backward direction ( $\theta^*$  small)
- ➔ Like Rutherford scattering

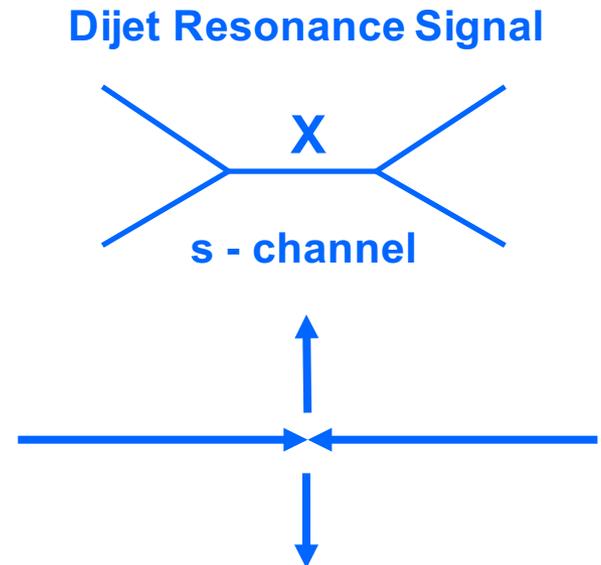
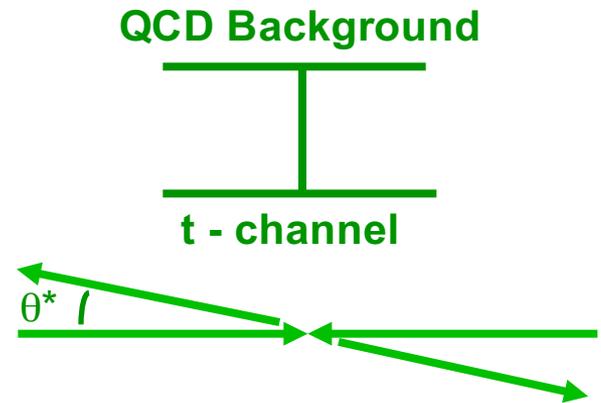
- **Signal mainly s-channel**

- ➔ Scattering at all angles but more perpendicular to beam than background

- Optimal cut is on dijet  $\eta$  separation

$$|\Delta\eta| = |\eta_1 - \eta_2| < 1.3$$

- ➔ Equivalent to  $\theta^* > 55$  deg,  $|\cos \theta^*| > 0.57$ .
- ➔ Selecting more perpendicular scatters in the parton-parton center of mass frame

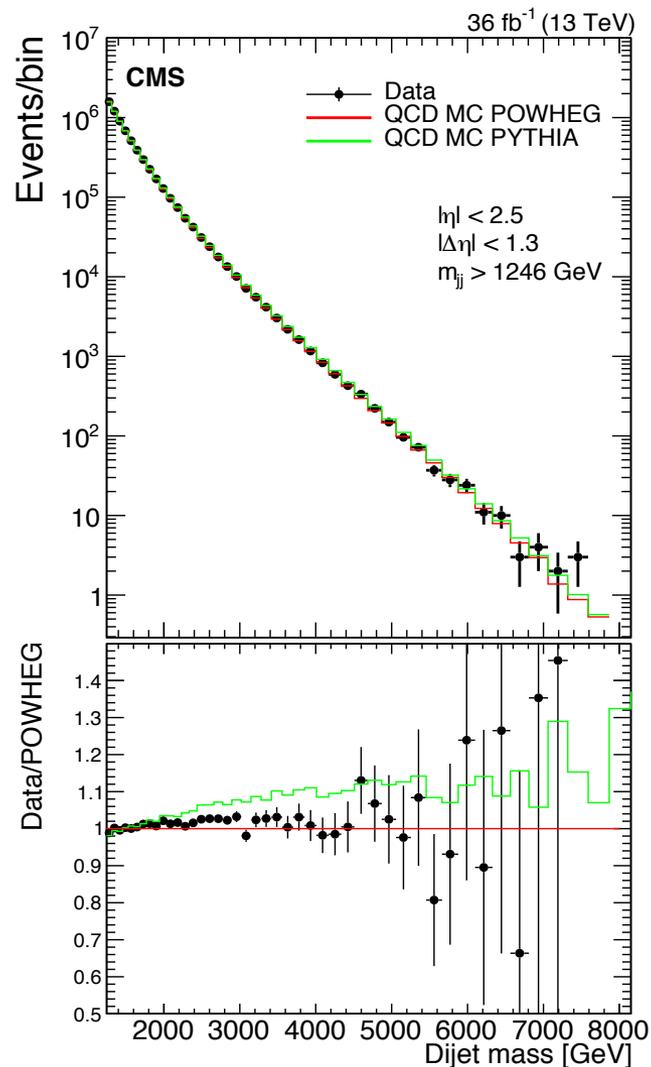




# Dijet mass & QCD predictions



- QCD MC predictions have significant uncertainties that are challenging to evaluate
  - ➔ **PDF**: probability for parton in proton uncertain from prior measurements, fits, and QCD evolution
  - ➔ **Scattering Cross Section**: uncertain from order of calculation, PYTHIA leading order, POWHEG next-to-leading order.
  - ➔ **Simulation**: uncertain in its modeling of jet energy
- Modeling the background with QCD MC is not sufficiently accurate for our search
  - ➔ Systematic uncertainties in the QCD MC could give false resonance signals of high significance
- We therefore use a parameterization to model the background in our search

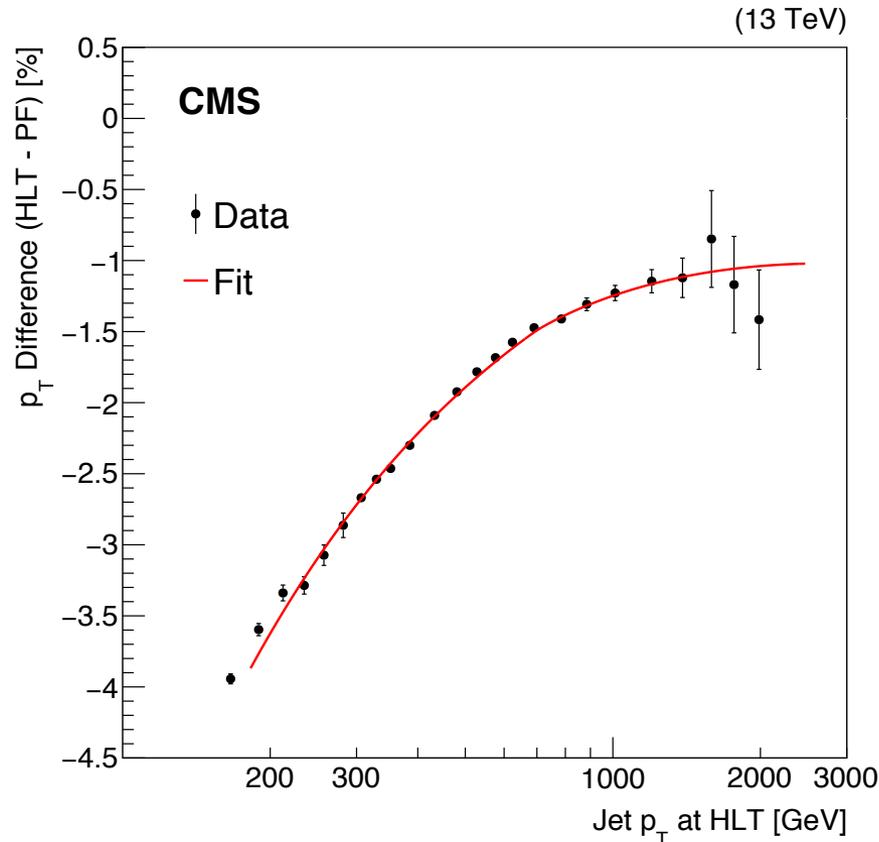




# Calibration of low mass search



- We use a dijet balance tag and probe method on a small sample to calibrate CaloJets at HLT to Particle Flow jets offline

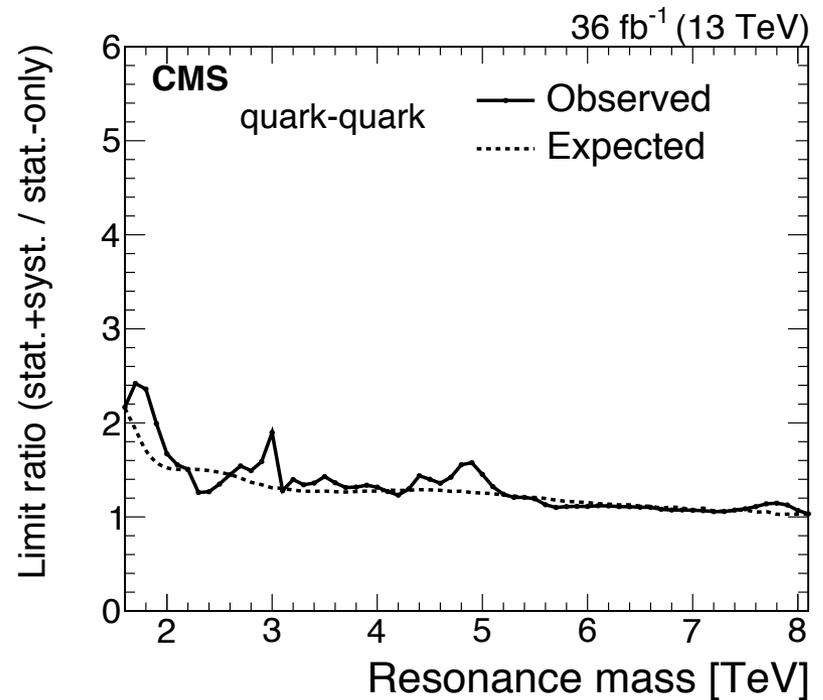
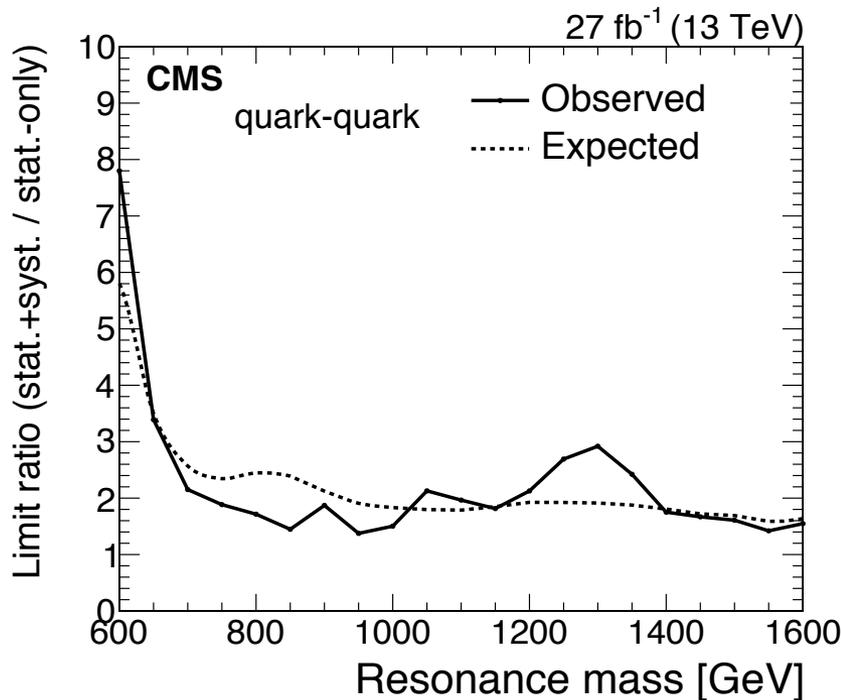




# Systematics Effect on Limits



- The uncertainty in the background parameter values increases the cross section limit significantly at resonance mass

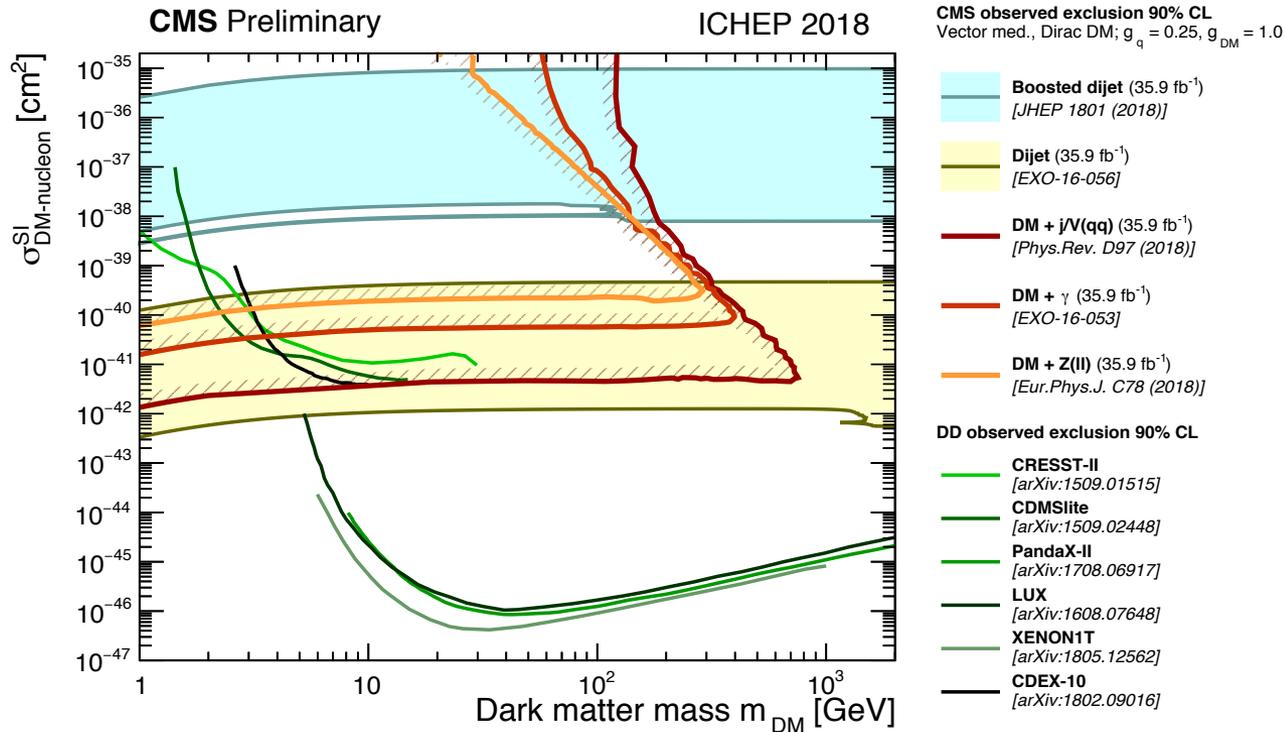




# Spin Independent DM Searches

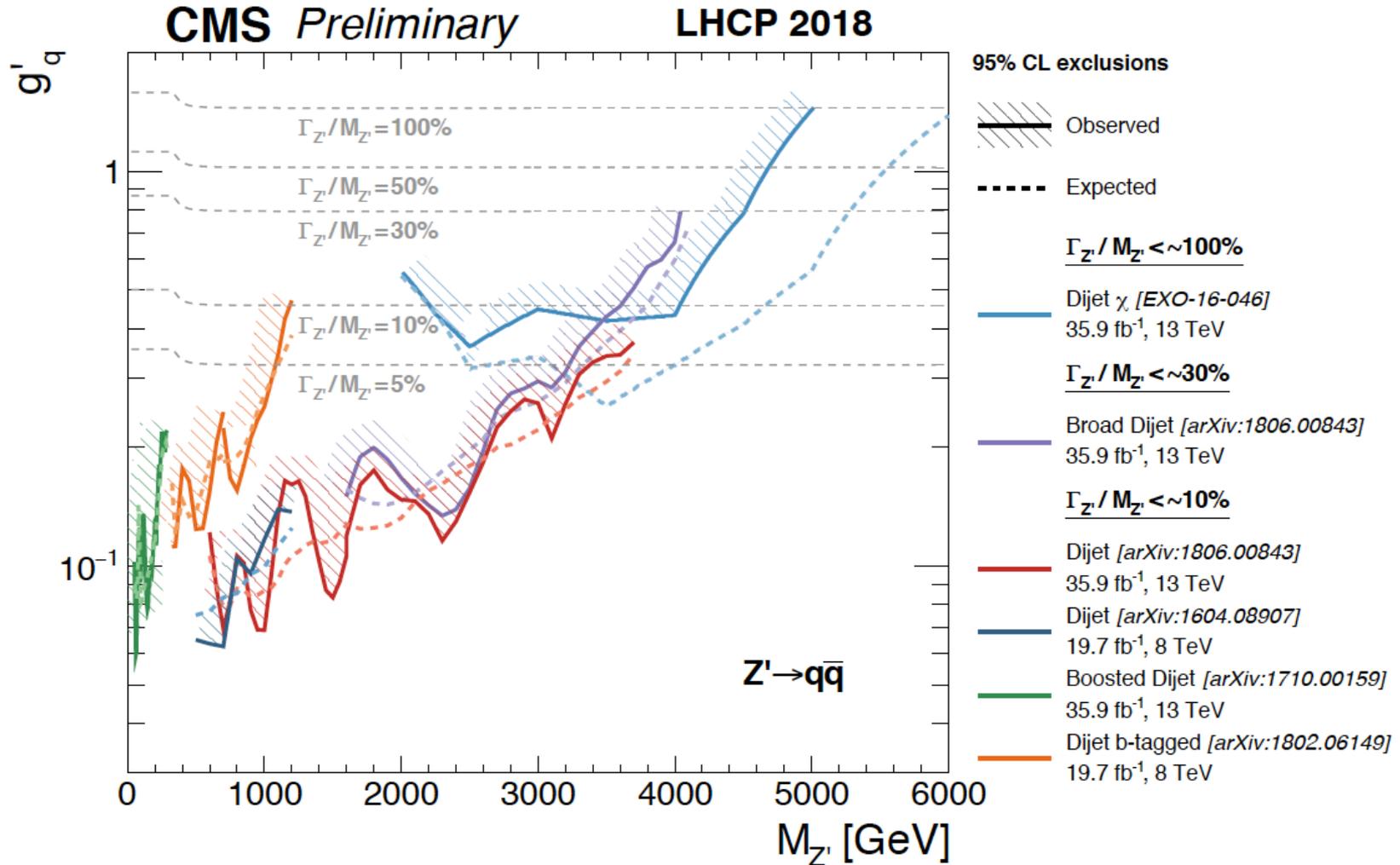


- CMS spin independent DM Nucleon interaction exclusions compared to direct detection experiments
  - ➔ From CMS exclusions of vector mediators



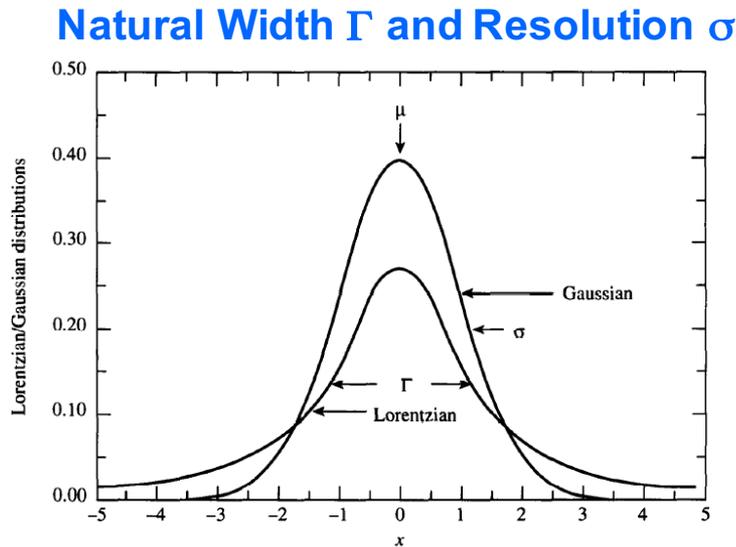


# Dijet Searches for a DM mediator



# Narrow and broad resonances

- Narrow resonance search uses signals with negligible natural width.
  - ➔ Giving approximately valid observed shapes for all resonances with a natural half-width  $\Gamma/2$  smaller than the experimental dijet mass resolution  $\sigma$



## Narrow Resonance Resolution

Reco	TeV	qq	gg
Calo	0.5	11%	15%
	2.0	6.3%	7.5%
PF	2.0	5.2%	6.2%
	8.0	4.0%	4.8%

- Conduct a resonance search explicitly modelling various natural widths
  - ➔ Obtain limits that are valid for broad resonances
  - ➔ Check the approximations within the narrow resonance search



# Spin dependence of natural width



- Spin-1 resonances shapes are more difficult to observe than spin-2
- Shape depends on relationship between width  $\Gamma$  and resonance mass  $M$ 
  - ➔ The Breit-Wigner distribution, nominally written in terms of  $\Gamma(M) M$  below, must be rewritten in terms of  $\Gamma(m) m$ , where  $m$  is the di-parton mass.

$$\hat{\sigma} \propto \frac{\pi}{m^2} \frac{[\Gamma^{(i)} M] [\Gamma^{(f)} M]}{(m^2 - M^2)^2 + [\Gamma M]^2}$$

- This depends on the resonance spin and the decay channel
  - ➔ For spin-1  $\rightarrow qq$ ,  $\Gamma \sim M \rightarrow m$ , so  $\Gamma(m) m \sim m^2$  giving  $\Gamma M \rightarrow \Gamma M (m^2/M^2)$
  - ➔ For spin-2  $\rightarrow qq, gg$ ,  $\Gamma \sim M^3 \rightarrow m^3$ , so  $\Gamma(m) m \sim m^4$  giving  $\Gamma M \rightarrow \Gamma M (m^4/M^4)$
- The low mass tail of the spin-2 particle is suppressed by a factor of  $(m^4/M^4)$  compared to the spin-1 particle.
  - ➔ The spin-1 particle has a longer low-mass tail and is more difficult to observe