Searches for Hadronic Resonances at CMS

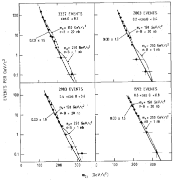
David Yu | Brown University

LHCP 2019, Puebla, Mexico

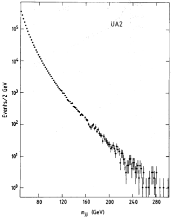
May 21, 2019

Harris and Kousouris, 2011

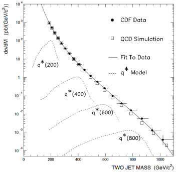
Hadronic resonance searches: a long history



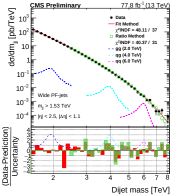
(a) UA1, 260 nb^{-1}, $\sqrt{s} = 630$ GeV



(b) UA2, 4.7 pb^{-1}, $\sqrt{s} = 630$ GeV



(c) CDF, 106 pb^{-1}, $\sqrt{s} = 1.8$ TeV

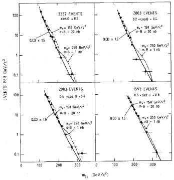


(d) CMS, 77 fb^{-1}, $\sqrt{s} = 13$ TeV

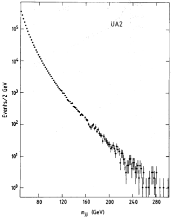
- Search for bumps in the m_{jj} spectrum on top of smooth QCD background.

Harris and Kousouris, 2011

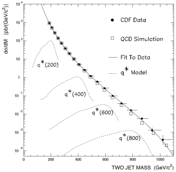
Hadronic resonance searches: a long history



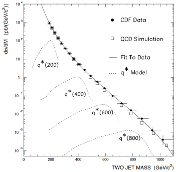
(a) UA1, 260 nb^{-1}, $\sqrt{s} = 630$ GeV



(b) UA2, 4.7 pb^{-1}, $\sqrt{s} = 630$ GeV



(c) CDF, 106 pb^{-1}, $\sqrt{s} = 1.8$ TeV



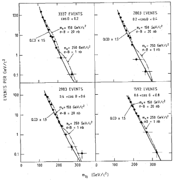
(d) CMS, 77 fb^{-1}, $\sqrt{s} = 13$ TeV

- Search for bumps in the m_{jj} spectrum on top of smooth QCD background.

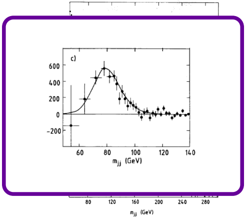
But only one observation!

Harris and Kousouris, 2011

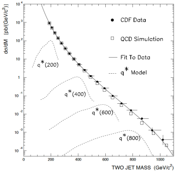
Hadronic resonance searches: a long history



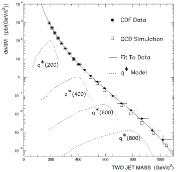
(a) UA1, 260 nb^{-1}, $\sqrt{s} = 630$ GeV



(b) UA2, 4.7 pb^{-1}, $\sqrt{s} = 630$ GeV



(c) CDF, 106 pb^{-1}, $\sqrt{s} = 1.8$ TeV



(d) CMS, 77 fb^{-1}, $\sqrt{s} = 13$ TeV

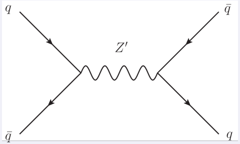
- Search for bumps in the m_{jj} spectrum on top of smooth QCD background.

1990: observation of $W/Z \to qq$ by UA2

Searches @LHC

Hadronic resonance searches remain a promising discovery mode for many models of new physics

Addition W'/Z' bosons

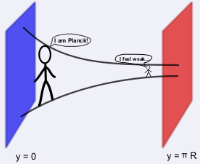


- Potential dark matter mediator (see A. Hall's talk).

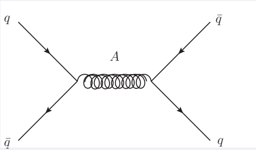
Excited quarks

$$\mathcal{L} = \frac{1}{2\Lambda}\bar{q}^*_R\sigma^{\mu\nu}\left(g_s f_s t_a G^a_{\mu\nu} + g f\frac{\vec{\tau}\cdot\vec{W}_{\mu\nu}}{2} + g' f'\frac{Y}{2}B_{\mu\nu}\right)q_L + \text{h.c.}$$

RS gravitons



Extended color sector



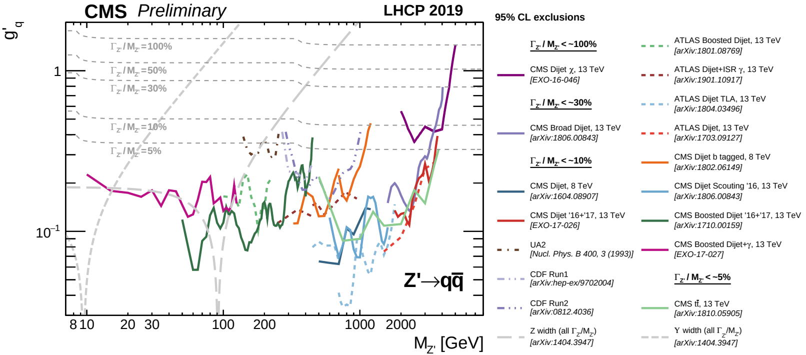
- Axigluons, colorons, S_8 model.

Leptophobic Z' model

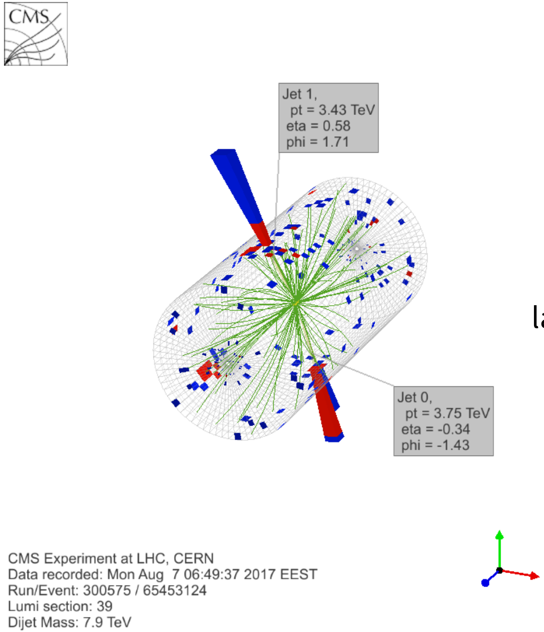
- For comparison of results, introduce a common simplified model, **leptophobic vector Z', with uniform quark coupling g_q:**

$$\mathcal{L}_{\mathrm{V}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q$$

- Simple scaling: $\sigma \propto g_q^2$.



1. High mass dijets
2. Low mass dijets
3. Very low mass dijets
4. Beyond dijets

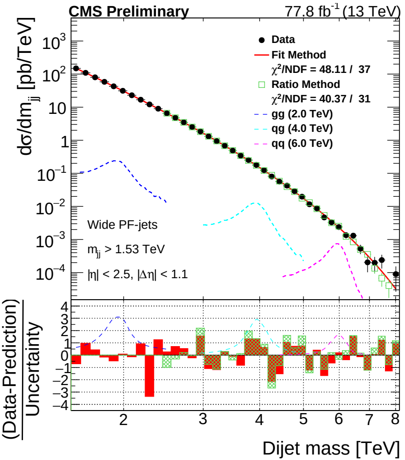


Dijet event with the 2nd largest invariant mass in 2017

High mass dijets

Dijet search ingredients

- Trigger on high-p_T jets.
- Form jets from particle flow candidates (anti-k_T algorithm, $R = 0.4$).
  - Choose 2 with highest p_T.
  - Combine subleading jets within $\Delta R < 1.1$.
- Cut on angular separation: $|\eta_1 - \eta_2| < 1.1$.
- Estimate background with fit or $\Delta\eta$ sideband.



High mass dijets: background estimation

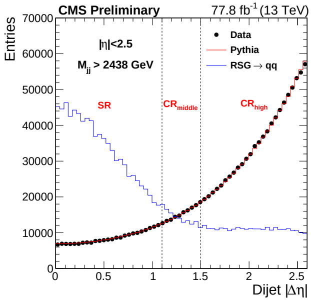
Fit method

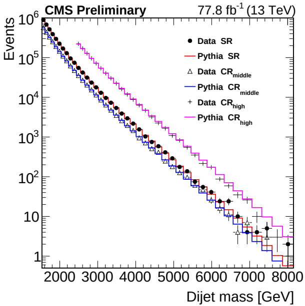
- Lower m_{jj}: fit background with empirical, smoothly falling function.
- Optimize function choice with statistical tests.

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

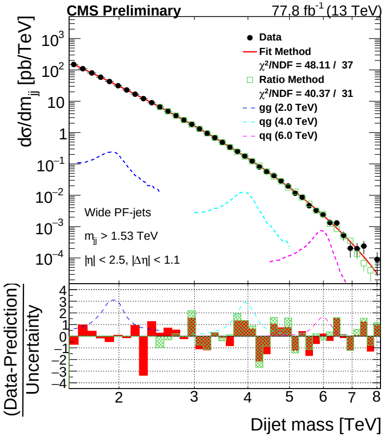
Sideband method

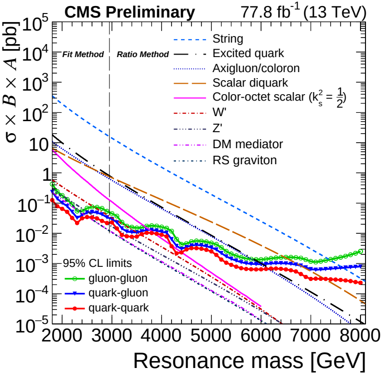
- New for 2017: background shape from $|\Delta\eta| > 1.1$ events + MC transfer factor.
- Fewer degrees of freedom than fit method.





High mass dijets: results

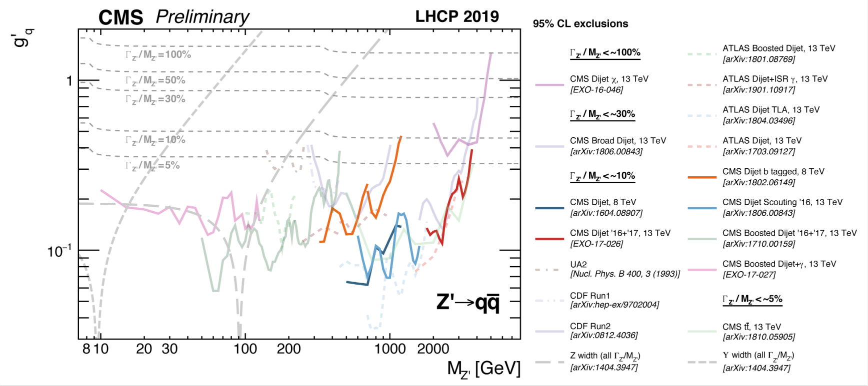




- No significant excesses observed; limits set on qq, qg, and gg signals.
  - Largest excess near $m_{jj} \sim$ 4 TeV, local sig. 1.9σ (qq).
- Two highest mass events at 7.9 TeV and 8 TeV.

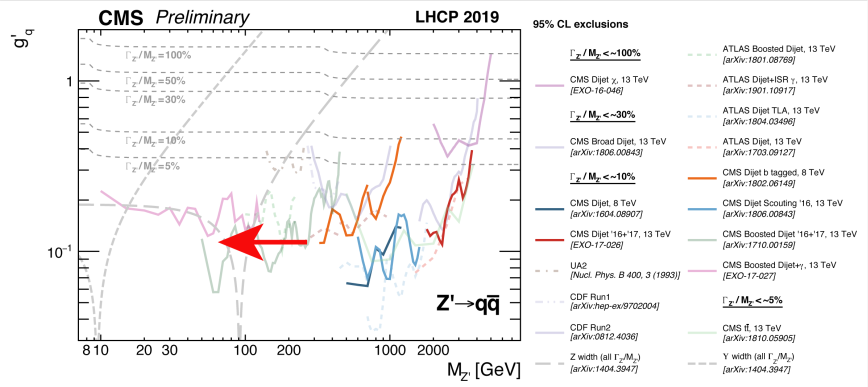
Detailed limits in backup.

High mass dijets: constraints on Z' model



- High mass dijet search spans 1.8 TeV – 8 TeV.
- Trigger-level events ("scouting") extend down to 450 GeV.
- b-tagged triggers extend down to 325 GeV.

High mass dijets: constraints on Z' model



- High mass dijet search spans 1.8 TeV – 8 TeV.
- Trigger-level events ("scouting") extends down to 450 GeV.
- b-tagged triggers extend down to 325 GeV.

How do we probe resonances below 325 GeV**?**

1 High mass dijets

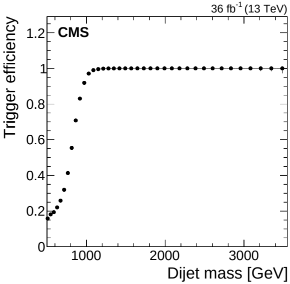
2 Low mass dijets

3 Very low mass dijets

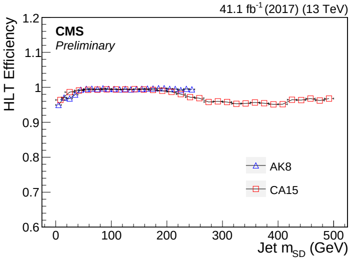
4 Beyond dijets

Triggering on dijets

- m_{jj} range for dijet search limited by trigger.
- Solution: **require significant ISR**; resonance boosted into a single jet.
- Trigger on AK8 jets with large mass and p_{T}.
- Efficient for $p_{\mathrm{T}} > 525$ GeV (AK8), 575 GeV (CA15).

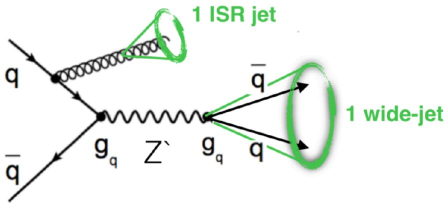


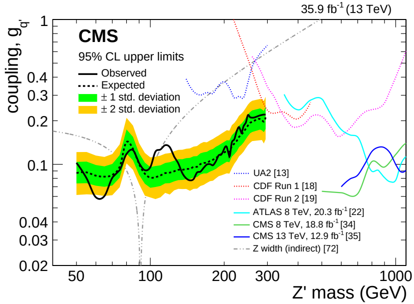
(a) Dijet trigger eff. (2016 paper)



(b) AK8 trigger eff.

NEW Z'+ISR jet





- 2016 analysis (1710.00159): 2.9σ (global)/2.2σ (local) excess at 115 GeV.

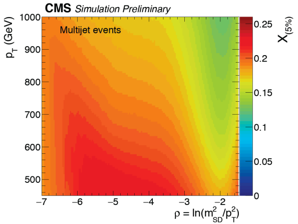
- Significant initial state radiation can overcome trigger limitation.
- Boosted dijet system ($p_{\mathrm{T}} > 525$ GeV) reconstructed as a single wide jet (anti-k_{T}, $R = 0.8$ or CA, $R = 1.5$).
- Signal jets have 2-pronged substructure.
- Scan jet mass distribution for bumps (coarse p_{T} categories from 525 GeV – 1500 GeV).

New for 2017

- Add wider jets (CA15) to extend sensitivity to $m_{Z'} = 450$ GeV.

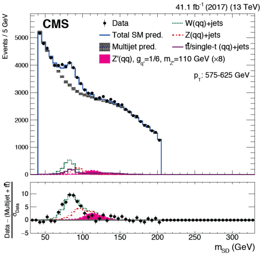
Z'+ISR jet: method

- Substructure algorithms distinguish 2-pronged signal from QCD background:
  - pileup-per-particle identification (PUPPI),
  - soft drop jet mass,
  - energy correlation functions ($N_2^{1,\mathrm{DDT}}$).

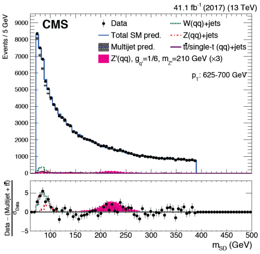


Background estimation

- QCD background from events failing decorrelated tagger.
- Shape modulated by data-vs-MC polynomial "transfer factor."
- Calibration in situ using W/Z peak.



(a) AK8

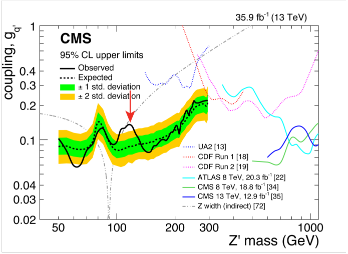


(b) CA15

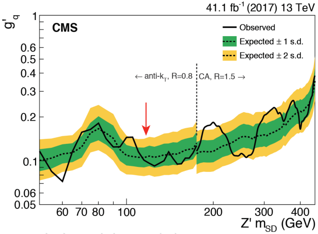
See substructure talks from C. Pollard, Z. Kang, D. Miller.

Z'+ISR jet: results

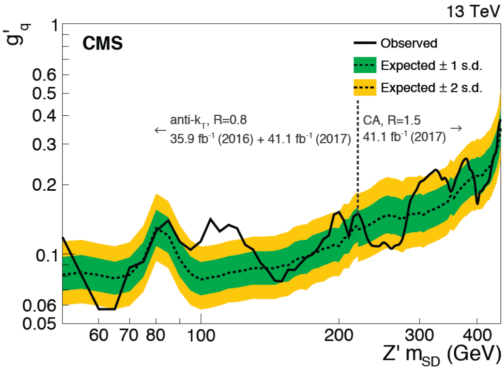
- Limits set on $\sigma(pp \to Z' \to qq)$, g_q, and m_{DM} vs m_{med}.
- No excess at $m_{Z'} = 115$ GeV in 2017 data.
- With CA15 jets, extend coverage to 50 GeV — 450 GeV.



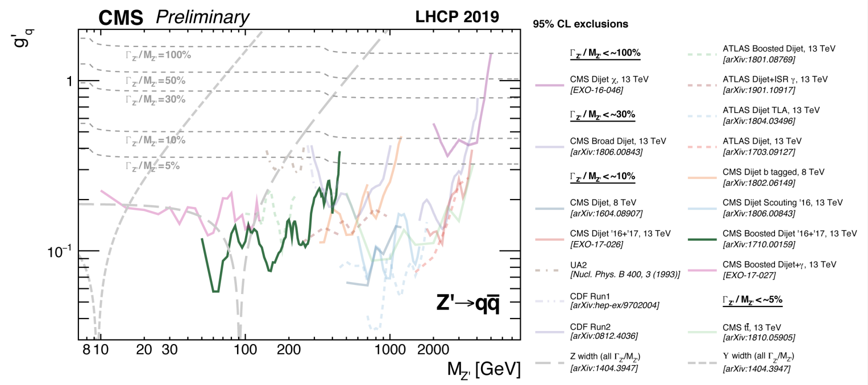
(a) 2016



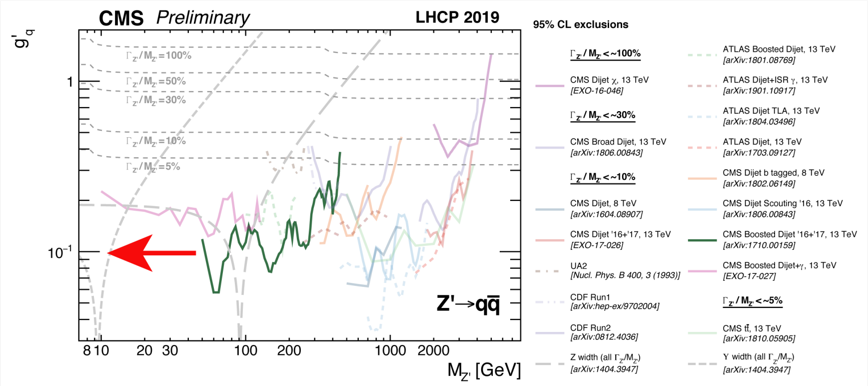
(b) 2017



2016+2017



Dijet+ISR jet probes down to $m_R = 50$ GeV.



Dijet+ISR jet probes down to $m_R = 50$ GeV.

Can we go even lower?

1 High mass dijets

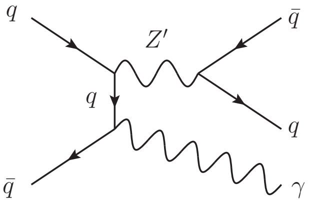
2 Low mass dijets

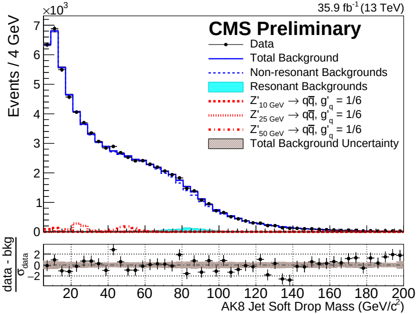
3 Very low mass dijets

4 Beyond dijets

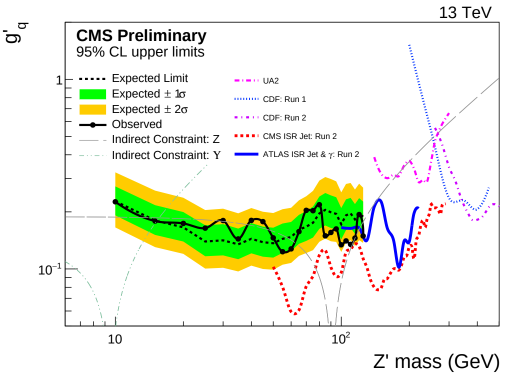
NEW Z'+ISR photon

- Jet triggers limited to $p_T \gtrsim$ 500 GeV, hence $m_{jj} \gtrsim$ 50 GeV.
- Even lower resonance masses: use photon triggers.
  - 2016: $p_T^{\gamma} > 175$ GeV.
- Require photon with $p_T > 200$ GeV and $|\eta| < 2.1$.
- Otherwise, analysis is very similar to Z'+ISR jet.
  - $N_2^{1,\mathrm{DDT}}$ set to 10% background efficiency.



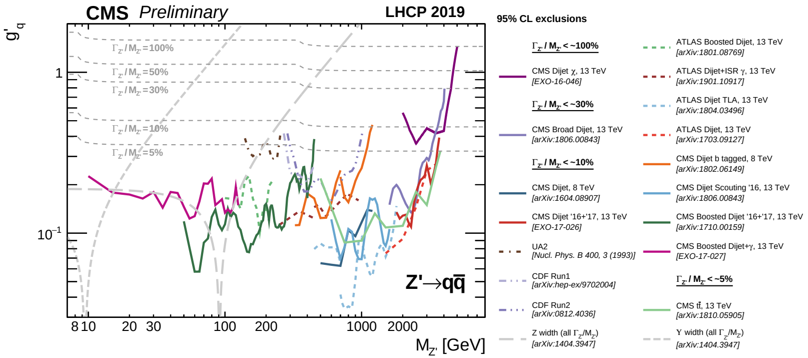


Z'+ISR photon: results



- Probe Z' masses down to $m_{Z'} = 10$ GeV!
- No significant excesses; limits set from 10 GeV − 125 GeV.

Z' summary

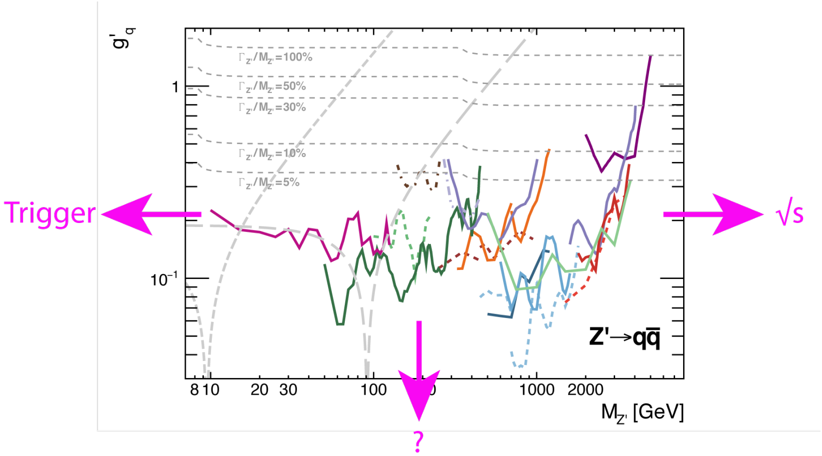


CMS dijet limits span 10 GeV – 8000 GeV.

Note: $\Gamma_{Z'}/M_{Z'}$ cutoffs are model dependent.

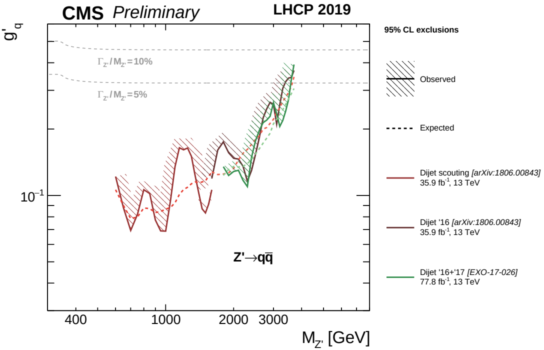
1. High mass dijets
2. Low mass dijets
3. Very low mass dijets
4. Beyond dijets

Beyond dijets



Where do we go from here?

Beyond dijets

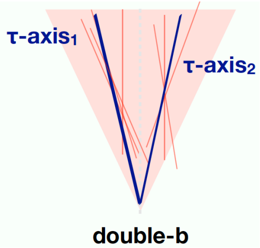


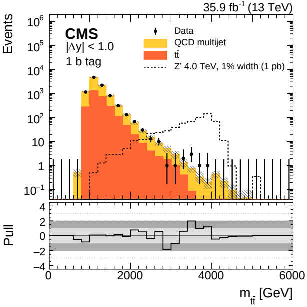
Future luminosity gains will be slow: $g_q^{95\%\,\mathrm{CL}} \sim \mathcal{L}^{1/4}$:(

How about flavor tagging?

Flavor-tagged resonances

- Boosted scalar to bb, using $Z'(qq)$+ISR techniques + dedicated double b-tagging.
  - Inspired by boosted $H \to bb$.
- 50 GeV $< m_\Phi < 2m_t$.

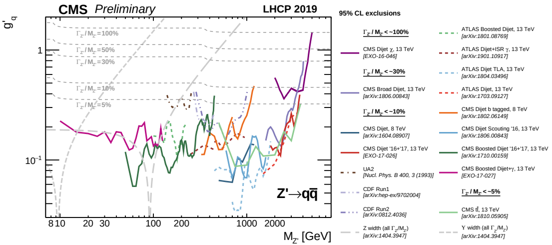




- $t\bar{t}$ resonance search in 0-, 1-, and 2-ℓ final states.
- 0.5 TeV $< m_X <$ 7 TeV.
- See plenary by J. Ngadiuba for details.

Conclusion

- CMS searches for hadronic resonances cover a wide mass range, 10 GeV – 8000 GeV.



- Many techniques developed to span two orders of magnitude of m_{jj}:
  - Dijet bump hunting.
  - Trigger-level analysis (scouting).
  - Boosted production with substructure.
  - Bottom- and top-tagging.

- Look forward to the full Run 2 analyses!

References

Short Title	Paper
Dijet 2016+2017	PAS EXO-17-026
Dijet scouting, 2012	1604.08907
Dijet 2016	1806.00843
Dijet χ	1803.08030
$Z'(qq)$+jet 2016+2017	PAS EXO-18-012
$Z'(qq)$+jet 2016	1710.00159
$Z'(qq)$+photon	PAS EXO-17-027
$\Phi(bb)$+jet	1810.11822
$t\bar{t}$ resonances	1810.05905

Backup

Coupling conversion

Back

- Cross section for narrow s-channel resonance R [1110.5302]:

$$\hat{\sigma}(\sqrt{\hat{s}}) = \frac{16\pi\mathcal{N}\Gamma_R^2}{(\hat{s}-m_R^2)^2 + m_R^2\Gamma_R^2}$$

$$\sigma(1+2\to R) \approx 16\pi^2\mathcal{N} \times \mathrm{BR}(R\to 1+2) \times \left[\frac{1}{s}\frac{dL}{d\tau}\right]_{\tau=m_R^2/s} \times \frac{\Gamma_R}{m_R},$$

where:

- $\Gamma_R \propto g_q^2$ =resonance mass/width,
- $\mathcal{N} = \frac{N_{S_X}}{N_{S_1}N_{S_2}}\frac{C_X}{C_1C_2}$ = spin and color multiplicity factor,
- $\sqrt{s}$ = collision energy,
- $\left[\frac{1}{s}\frac{dL}{d\tau}\right]_{\tau=m_R^2/s}$ = parton luminosity factor,
- $\left((\hat{s}-m_R^2)^2 + m_R^2\Gamma_R^2\right)^{-1} \approx \frac{\pi}{m_R\Gamma_R}\delta(\hat{s}-m_R^2)$, from narrow width approximation.

$\Rightarrow$ For Z' model,
$\sigma(R) \propto g_q^2$.

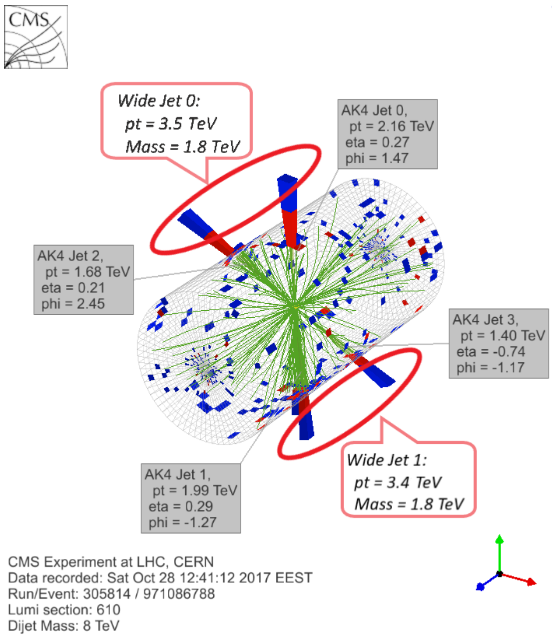
Υ/Z width constraint

- From 1404.3947, constraint on $(m_{Z'}, g_q)$ space from hadronic Z width (Z' modifies Zqq vertex).

$$\frac{\Delta\Gamma_Z^{\text{had}}}{\Gamma_Z^{\text{had}}} = \frac{2g_q c_Z c_W s_W (2V_u + 3V_d)}{3g(1 - m_{Z'}^2/m_Z^2)(2V_u^2 + 3V_d^2 + 5/16)}$$

where $V_{u,d} = \pm 1/4 - (3 \pm 1)s_W^2/6$.

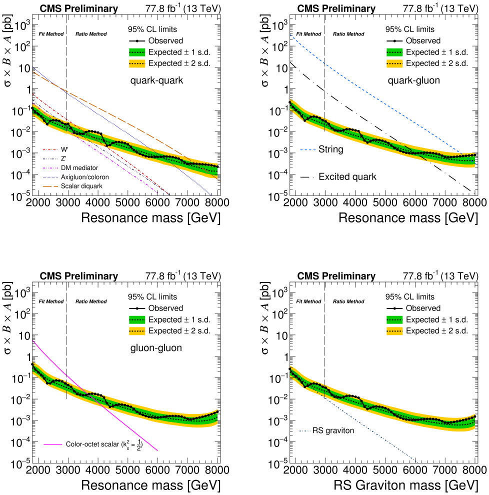
- Similarly, $\Delta R_\Upsilon \equiv B(\Upsilon \to Z'^*/\gamma^* \to jj)/B(\Upsilon \to \mu\mu) < 2.1$ gives Υ indirect constraint.



Dijet event with the largest invariant mass in 2017

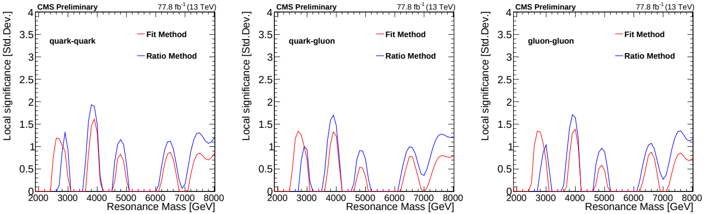
High mass dijets: limits

Back



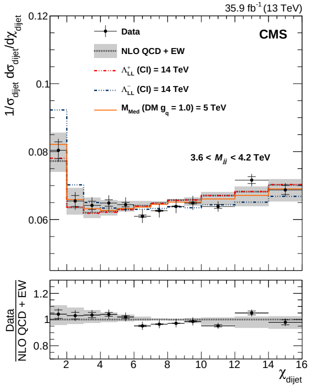
- Limits on:
  - quark-quark (Z'),
  - quark-gluon (q^*),
  - gluon-gluon (color octet scalar),
  - mixed (RS graviton).

High mass dijets: significances



(a) quark-quark (b) quark-gluon (c) gluon-gluon

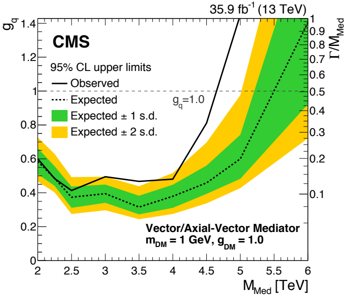
Dijet χ: angular analysis



Dijet χ

- For wide or non-resonant dijets, look in angular distributions.

$$\chi = e^{2\Delta y} \approx \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



- $dN/d\chi \approx$constant for QCD background; signal peaks at low χ.

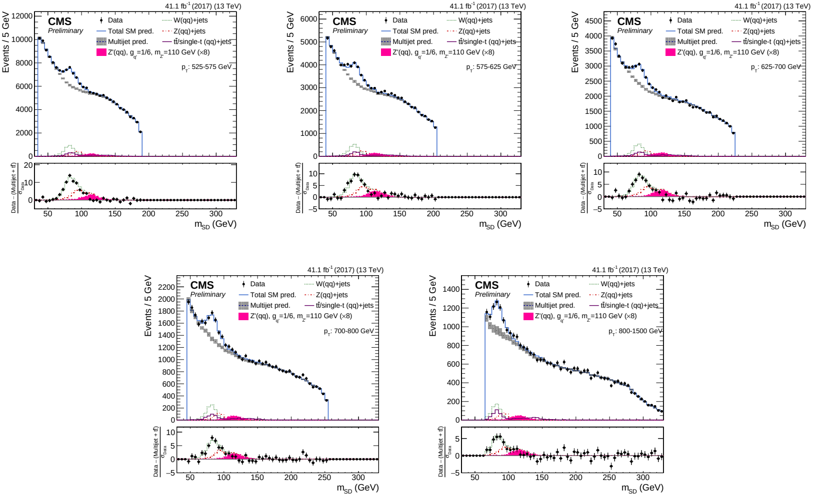
Energy correlation functions

- Energy correlation functions: for n_J jet constituents with energy fractions z_i,

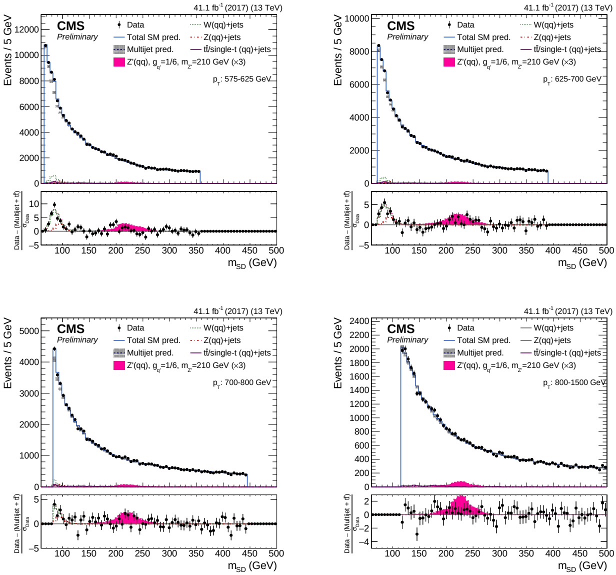
$$
\begin{aligned}
{}_1e_2^\beta &= \sum_{1\leq i<j\leq n_J} z_i z_j \Delta R_{ij}^\beta \\
{}_2e_3^\beta &= \sum_{1\leq i<j<k\leq n_J} z_i z_j z_k \min\left\{\Delta R_{ij}^\beta \Delta R_{jk}^\beta,\right. \\
&\qquad \left.\Delta R_{jk}^\beta \Delta R_{ki}^\beta,\ \Delta R_{ki}^\beta \Delta R_{ij}^\beta\right\}
\end{aligned}
$$

2-pronged tagger: $N_2^\beta = {}_2e_3^\beta/({}_1e_2^\beta)^2$.

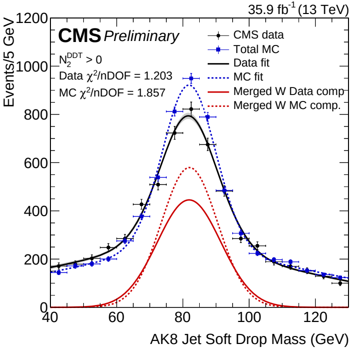
Z'+jet: AK8 distributions



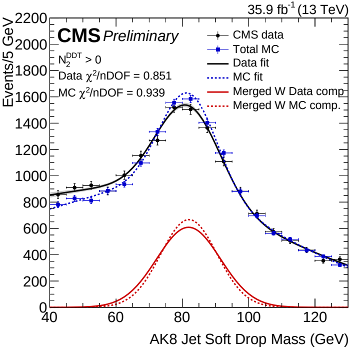
Z'+jet: CA15 distributions



Z'+photon: calibration



(a) Pass $N_2^{1,\,\mathrm{DDT}}$



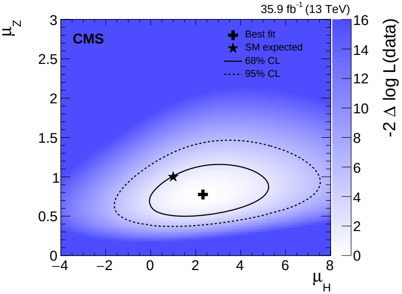
(b) Fail $N_2^{1,\,\mathrm{DDT}}$

- Calibrate jet mass scale, mass resolution, and $N_2^{1,\,\mathrm{DDT}}$ efficiency using W bosons from semileptonic $t\bar{t}$.

Boosted $H \to b\bar{b}$ analysis

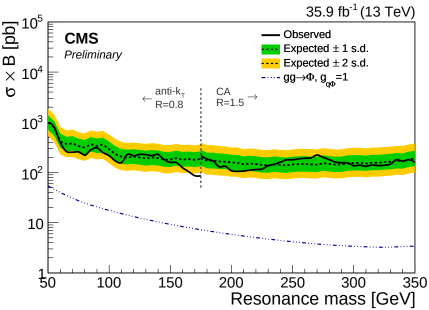
1709.05543
Back

- Search for $H \to b\bar{b}$ with $p_T > 450$ GeV.
  - Dataset: 35.9 fb^{-1}, $\sqrt{s} = 13$ TeV.
- Same analysis technique as boosted $\Phi/A \to b\bar{b}$.
- Simultaneously constrain $Z \to b\bar{b}$.

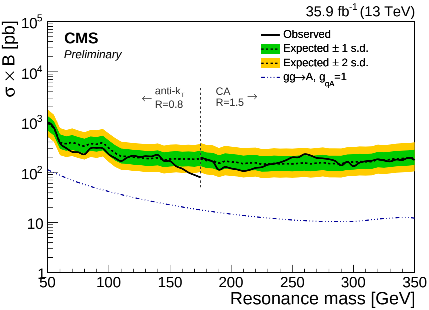


	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	–
Observed UL signal strength	< 5.8	< 7.2	–
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

Scalar limits

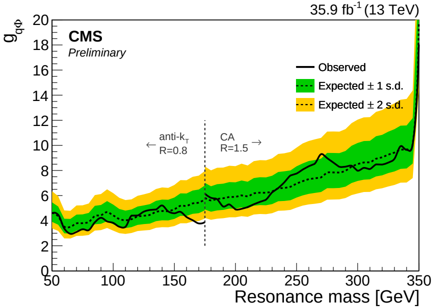


(a) Scalar $g_{q\Phi}$

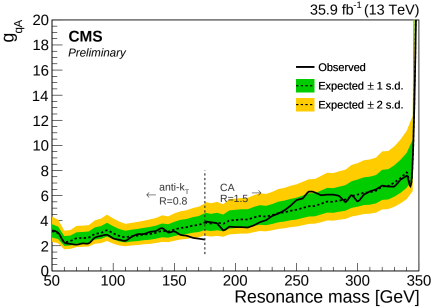


(b) Pseudoscalar g_{qA}

Pseudoscalar limits



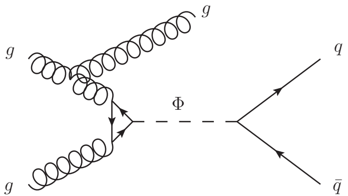
(a) Scalar $g_{q\Phi}$

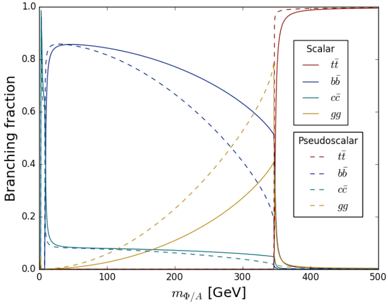


(b) Pseudoscalar g_{qA}

Scalar mediator model

- Scalar/pseudoscalar mediator: assume minimal flavor violation to avoid FCNCs.
- $\Rightarrow$ couplings proportional to SM Higgs Yukawas, $g_f y_f$. Preferential coupling to third generation fermions.
- For simplicity, take uniform scaling constant, $g_f = g_{q\Phi/A}$.



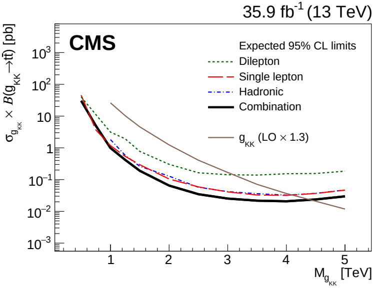


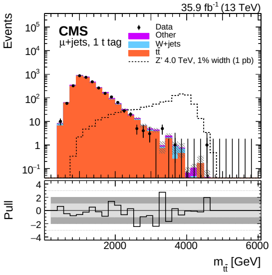
$$\mathcal{L}_\Phi = \frac{\Phi}{\sqrt{2}} \sum_f (g_f y_f \bar{f}_i f_i) + g_{\mathrm{DM}} \Phi \bar{\chi} \chi$$

$$\mathcal{L}_A = \frac{iA}{\sqrt{2}} \sum_f (g_f y_f \bar{f}_i \gamma_5 f_i) + i g_{\mathrm{DM}} A \bar{\chi} \gamma_5 \chi$$

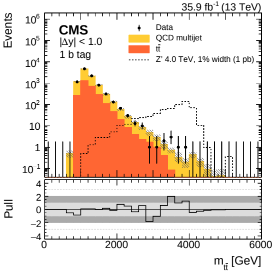
$Z' \to t\bar{t}$

- Combined search for $t\bar{t}$ resonances in 0, 1, and 2 lepton final states.
- Top tagging: algorithms identify top quarks from QCD background (resolved and boosted).





(a) 1 lepton



(b) 0 lepton