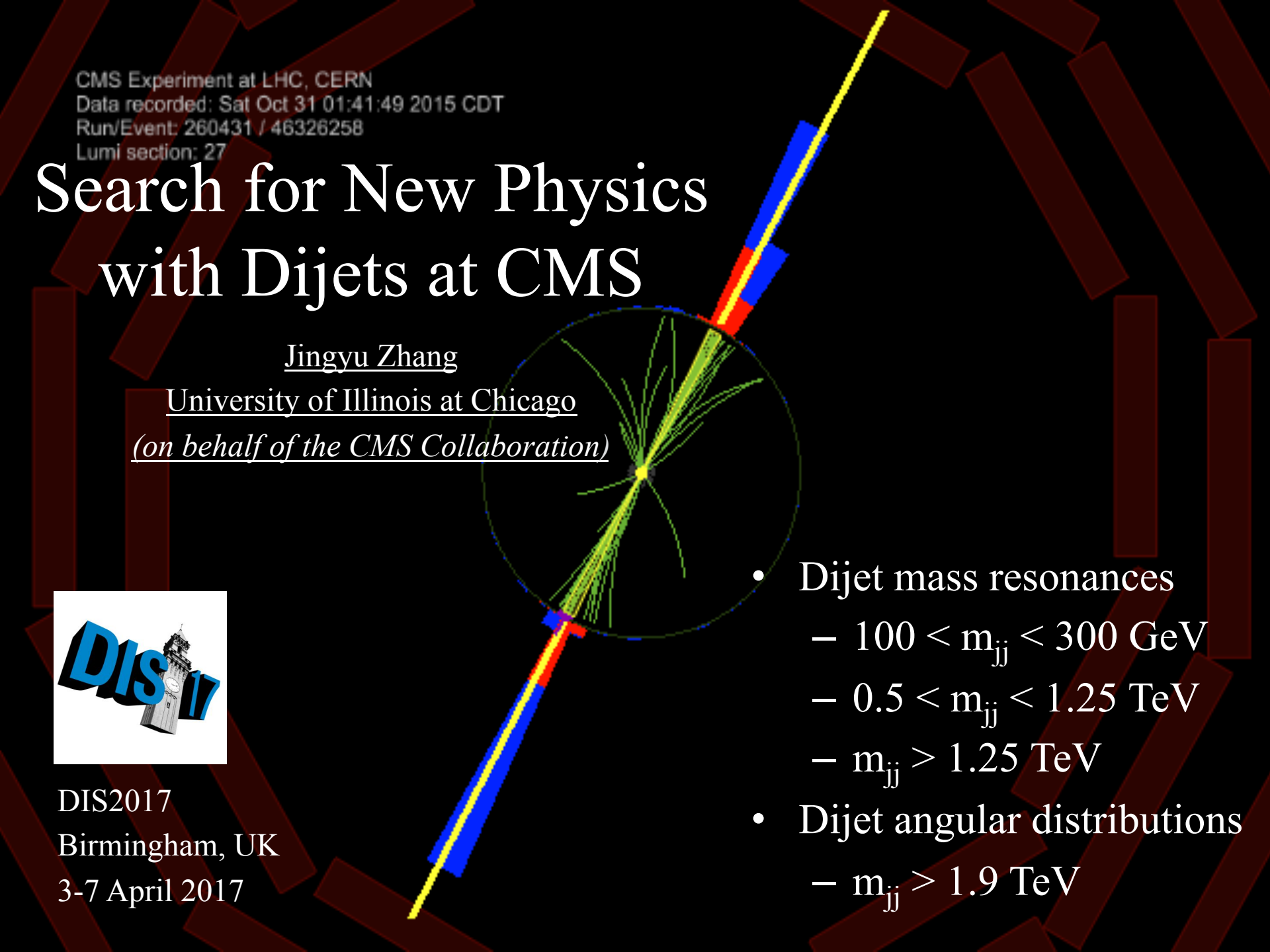


Search for New Physics with Dijets at CMS

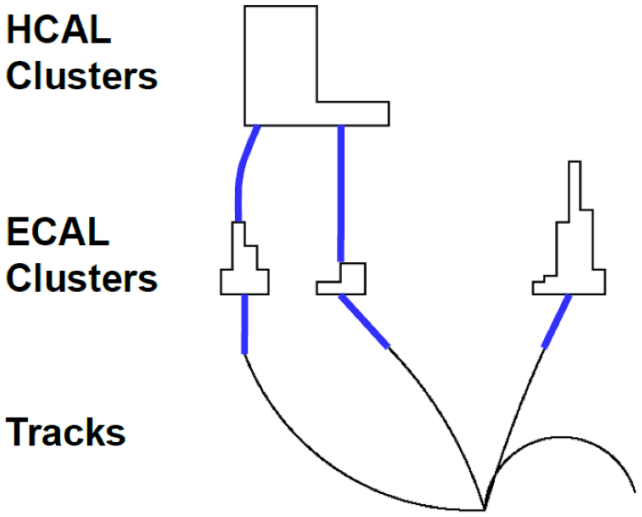
Jingyu Zhang
University of Illinois at Chicago
(on behalf of the CMS Collaboration)

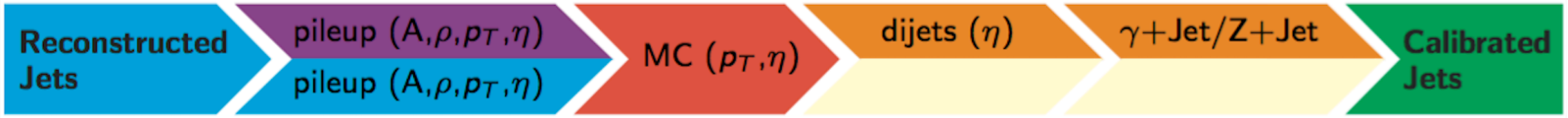
- Dijet mass resonances
  - $100 < m_{jj} < 300$ GeV
  - $0.5 < m_{jj} < 1.25$ TeV
  - $m_{jj} > 1.25$ TeV
- Dijet angular distributions
  - $m_{jj} > 1.9$ TeV

DIS2017
Birmingham, UK
3-7 April 2017

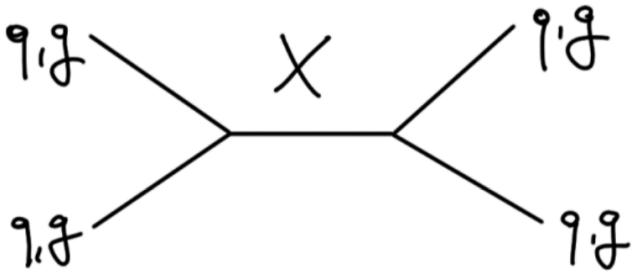
Jet Reconstruction

- Use "anti-k_T" clustering algorithm
- PF-jets are reconstructed and identified using particle flow technique, which utilize an optimal combination of all information of CMS sub-detectors
- Calo-jets are reconstructed using only information from the calorimeters
- Jet energies are calibrated and corrected with a multilevel approach



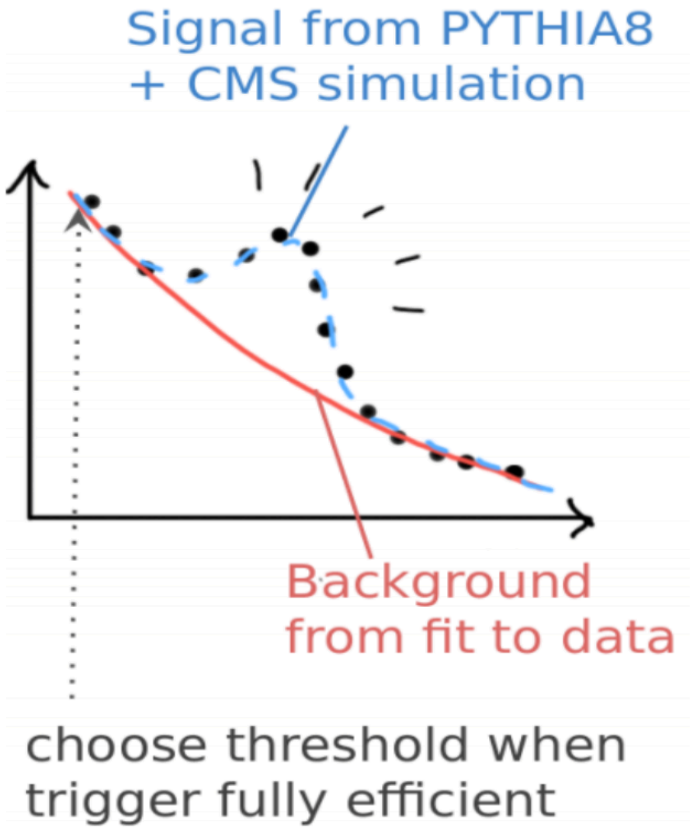


Search for Dijet Mass Resonances



- Search for narrow resonances
  - Nature width << dijet mass resolution
- Numerous New Physics models can be probed
  - String resonances from string theory
  - Exited quarks from quark compositeness
  - Diquarks from grand unified models
  - Axigluons, Colorons, and Color Octet Scalars
  - Heavy W and Z boson W' and Z'
  - Gravitons from Randall-Sundrum model extra dimensions
  - Dark matter mediators

- Look for bumps above fit of the QCD dijet background
- Search is performed in the dijet invariant mass region where trigger is fully efficient



Trigger Selection

	Main data stream (All CMS trigger)	**Data scouting (Low p_T jet triggers)**
Rate	~1 kHz	~4 kHz
Event Content	Full (PF-jets)	Reduced (only Calo-jets)
Trigger threshold	HT 900	HT 250
m_{jj} threshold when fully efficient	1.25 TeV	490 GeV

- Use scouting trigger to search for new physics in the phase space not accessible via standard trigger selection
- Explore dijet mass spectrum with $m_{jj} >$ 490 GeV

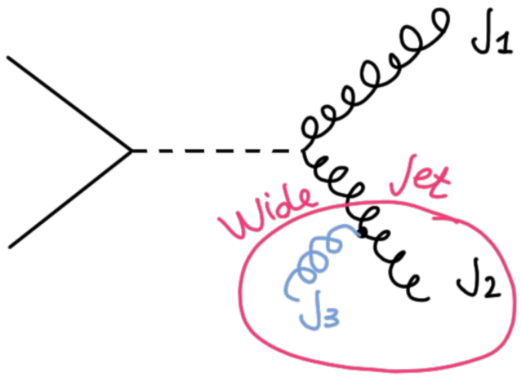
Event Selection

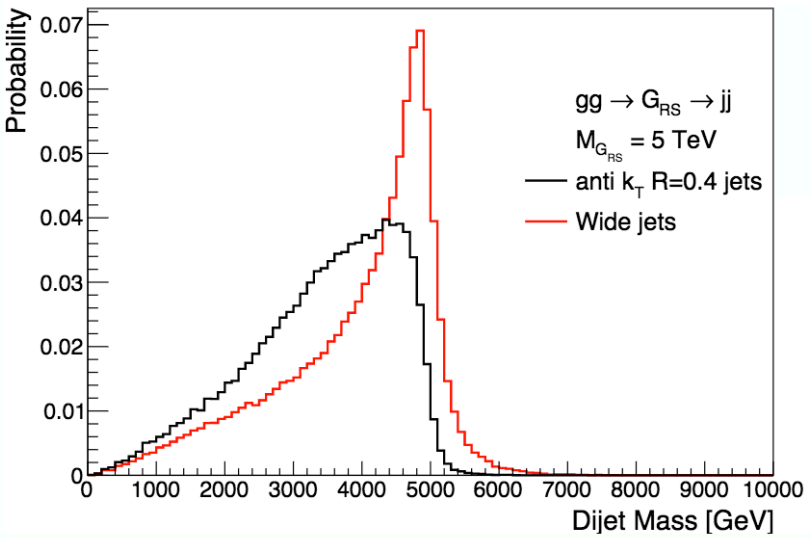
- Two AK4 jets, $p_T > 30$ GeV, $|\eta| < 2.5$
- $|\Delta\eta| < 1.3$ to suppress t-channel QCD background
- Hard QCD radiations are included (wide jets)
  - If the neighboring jets of the two leading jets are close to the two leading jets:

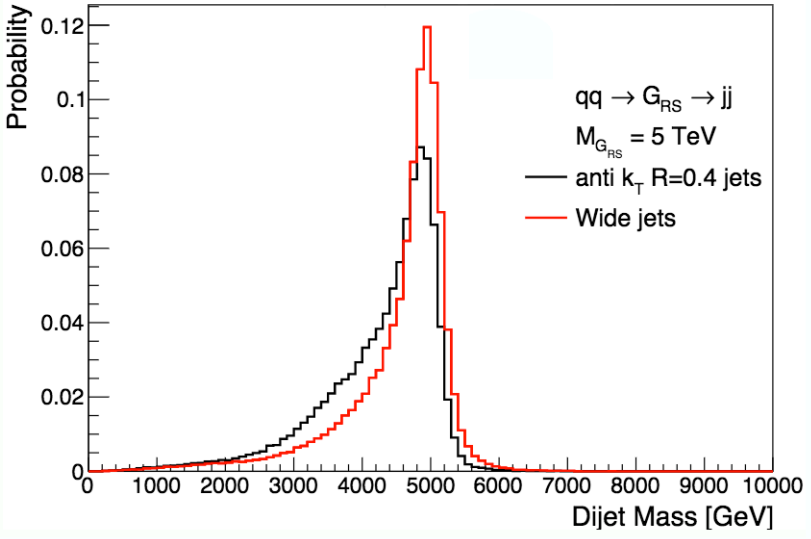
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.1$$

the neighboring jets are added

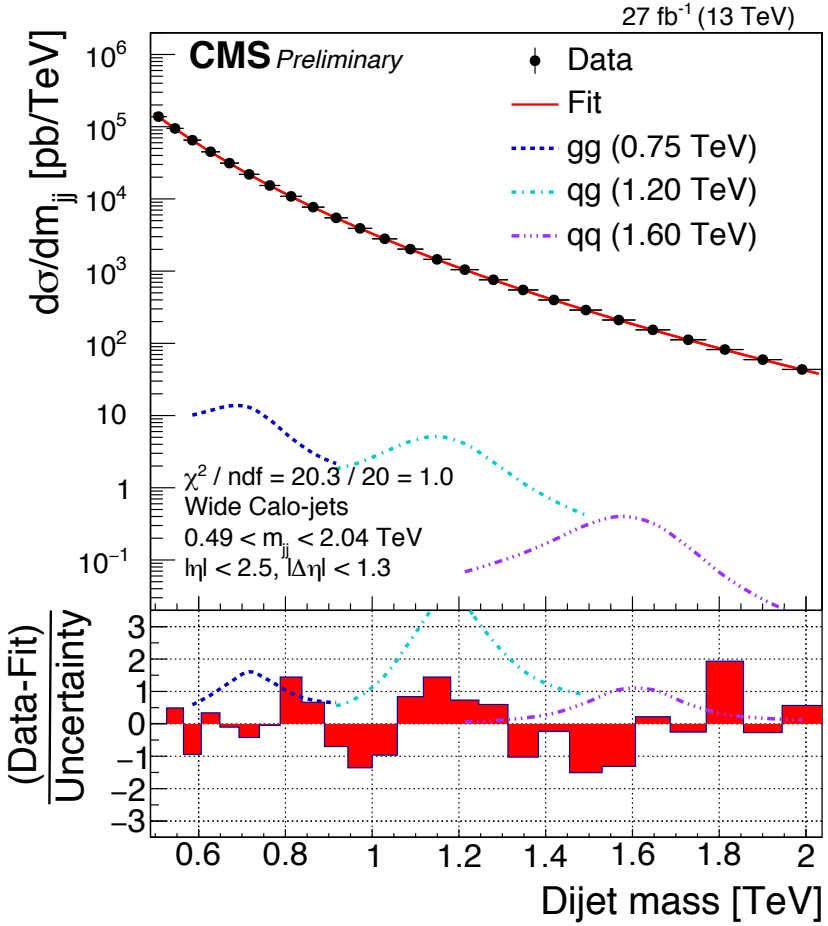
  - Dijet mass resolution improved

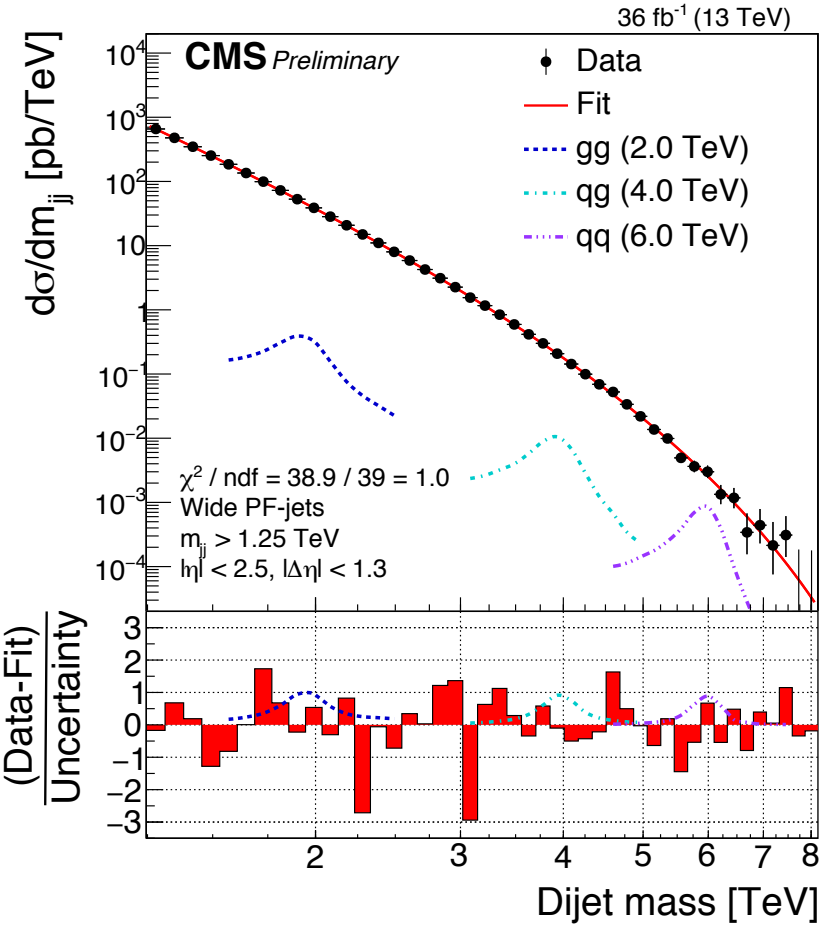






Dijet Mass Spectrum Fit



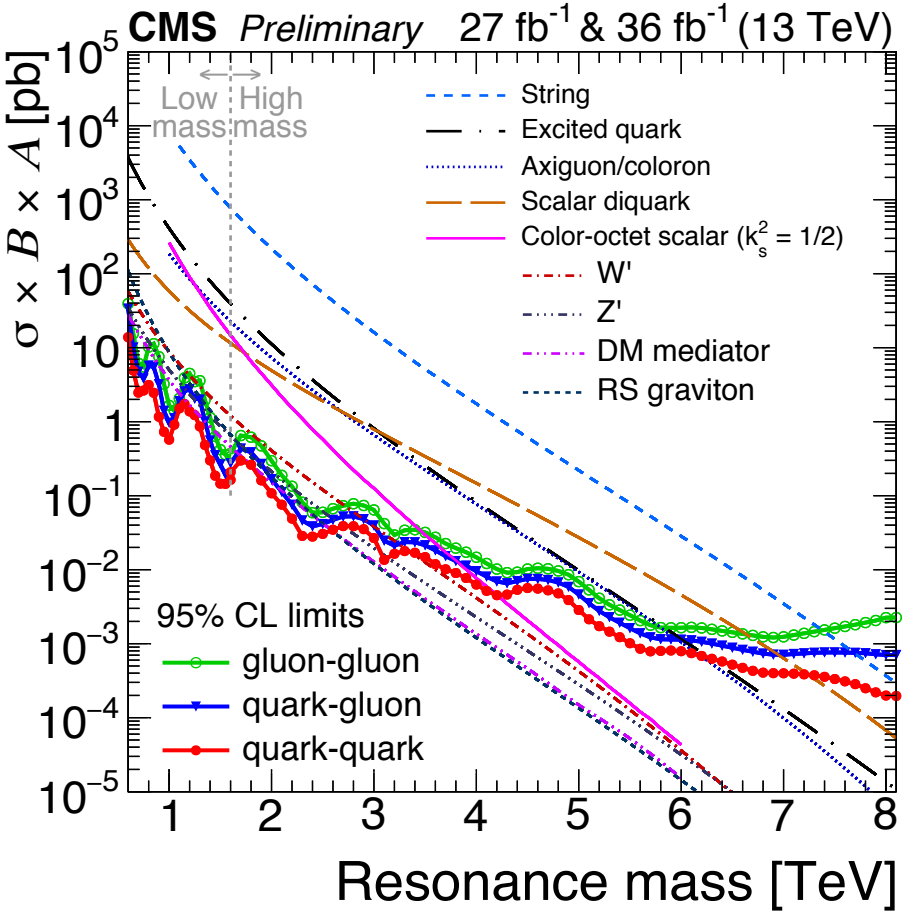


CMS-PAS-EXO-16-056

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

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

Model Independent Limits



CMS-PAS-EXO-16-056

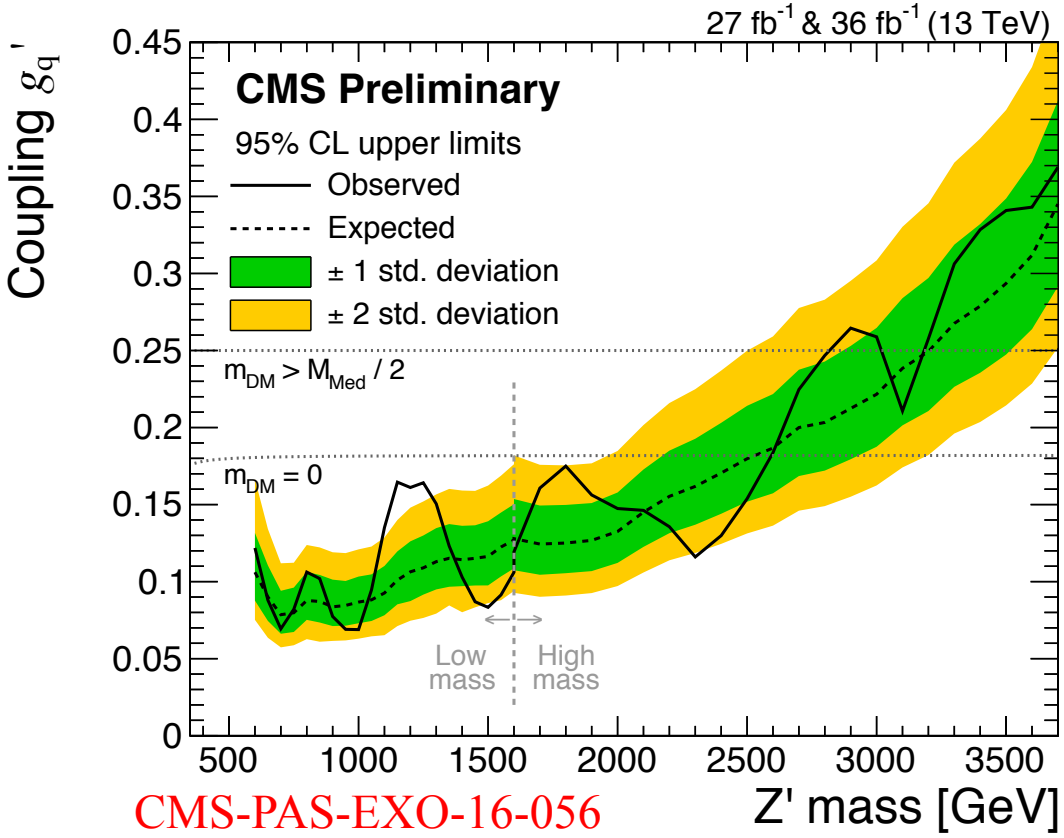
- Model independent cross section limits on gg, qg, and qq resonances

Limits on Dijet Mass Resonances

Model	Final State	Observed (TeV)	Expected (TeV)
String	qg	7.7	7.7
Scalar diquark	qq	7.2	7.4
Axigluon/coloron	$q\bar{q}$	6.1	6.0
Excited quark	qg	6.0	5.8
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4	3.6
W′	$q\bar{q}$	3.3	3.6
Z′	$q\bar{q}$	2.7	2.9
RS Graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.7	2.1
DM Mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6	2.5

- Most stringent limits on a variety of new physics models

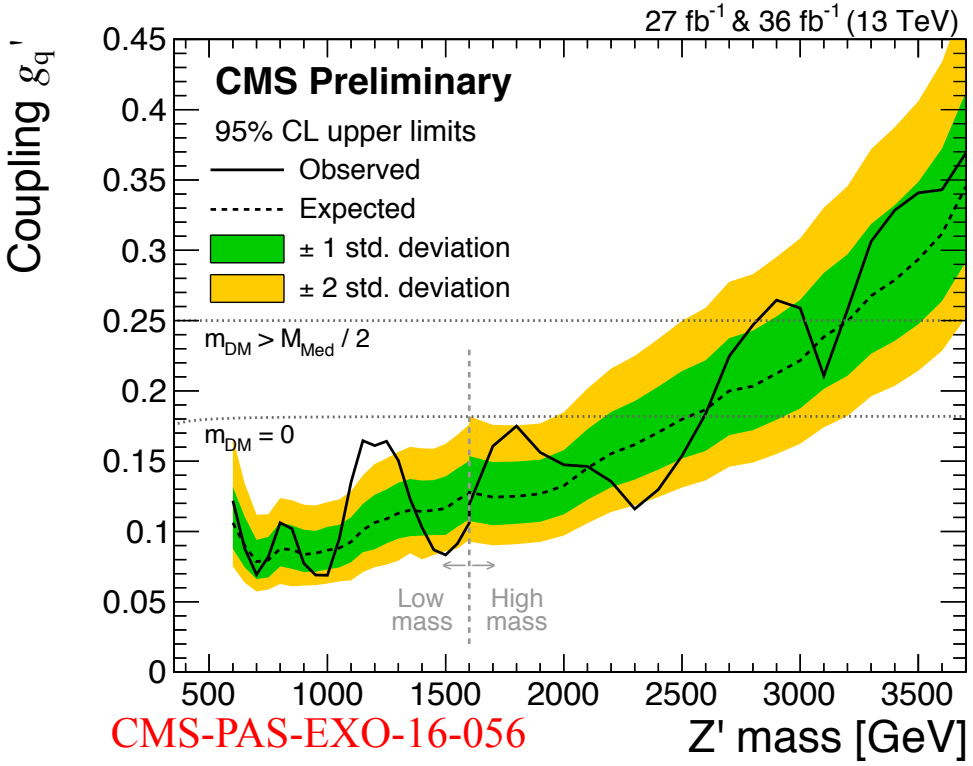
Limits on Z'-quark Coupling



CMS-PAS-EXO-16-056

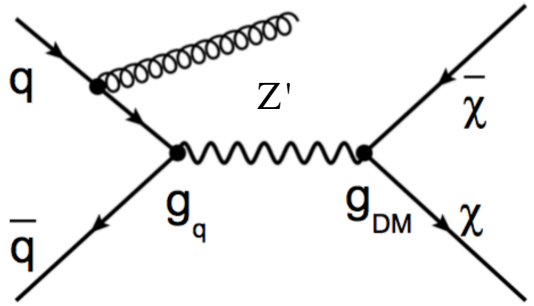
- Limits set on the universal quark coupling g_q' of leptophobic Z' as a function of the mass of Z'
- Limits for g_q' are used to constrain dark matter mass as a function of the mass of the mediator for dark matter-quark interaction

Dark Matter Interpretation



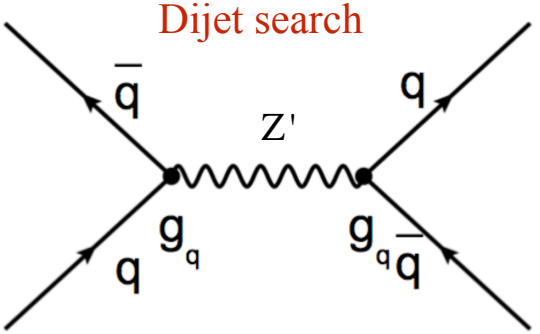
CMS-PAS-EXO-16-056

Mono-X search



$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{DM} M_{Z'}}{12\pi}\left(1-4\frac{m^2_{DM}}{M^2_{Z'}}\right)^{3/2}$$

Dijet search

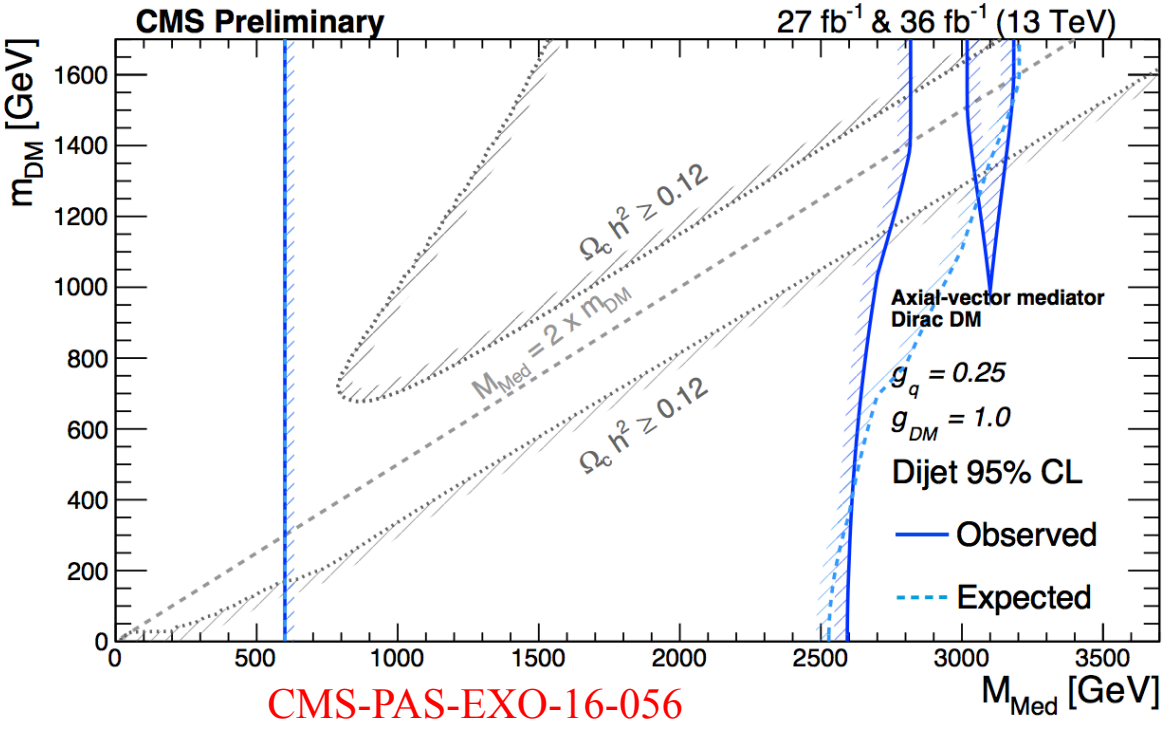


$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_{q} M_{Z'}}{4\pi}\left(1-4\frac{m^2_{q}}{M^2_{Z'}}\right)^{3/2}$$

- Benchmark model: axial-vector mediator

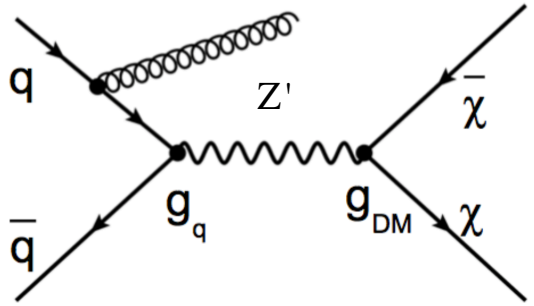
$$\mathcal{L}_{\text{axial-vector}} = -g_{DM} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$

Dark Matter Limits



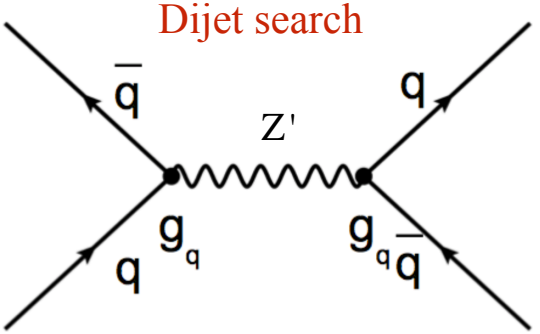
CMS-PAS-EXO-16-056

Mono-X search



$$\Gamma^{\chi\bar{\chi}}_{\text{axial-vector}} = \frac{g^2_{DM} M_{Z'}}{12\pi}\left(1-4\frac{m^2_{DM}}{M^2_{Z'}}\right)^{3/2}$$

Dijet search

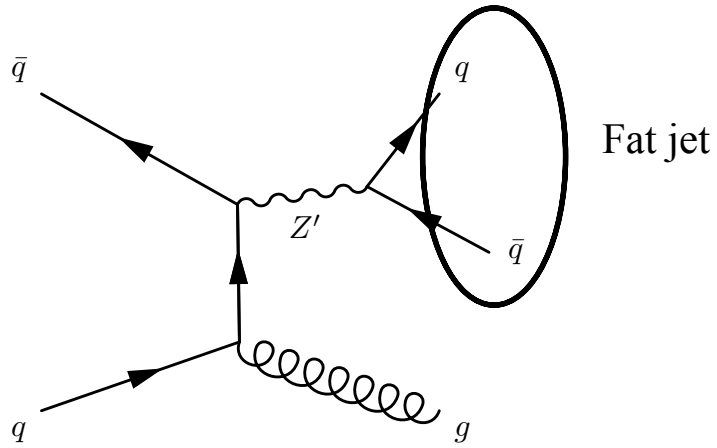


$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g^2_{q} M_{Z'}}{4\pi}\left(1-4\frac{m^2_{q}}{M^2_{Z'}}\right)^{3/2}$$

- Benchmark model: axial-vector mediator

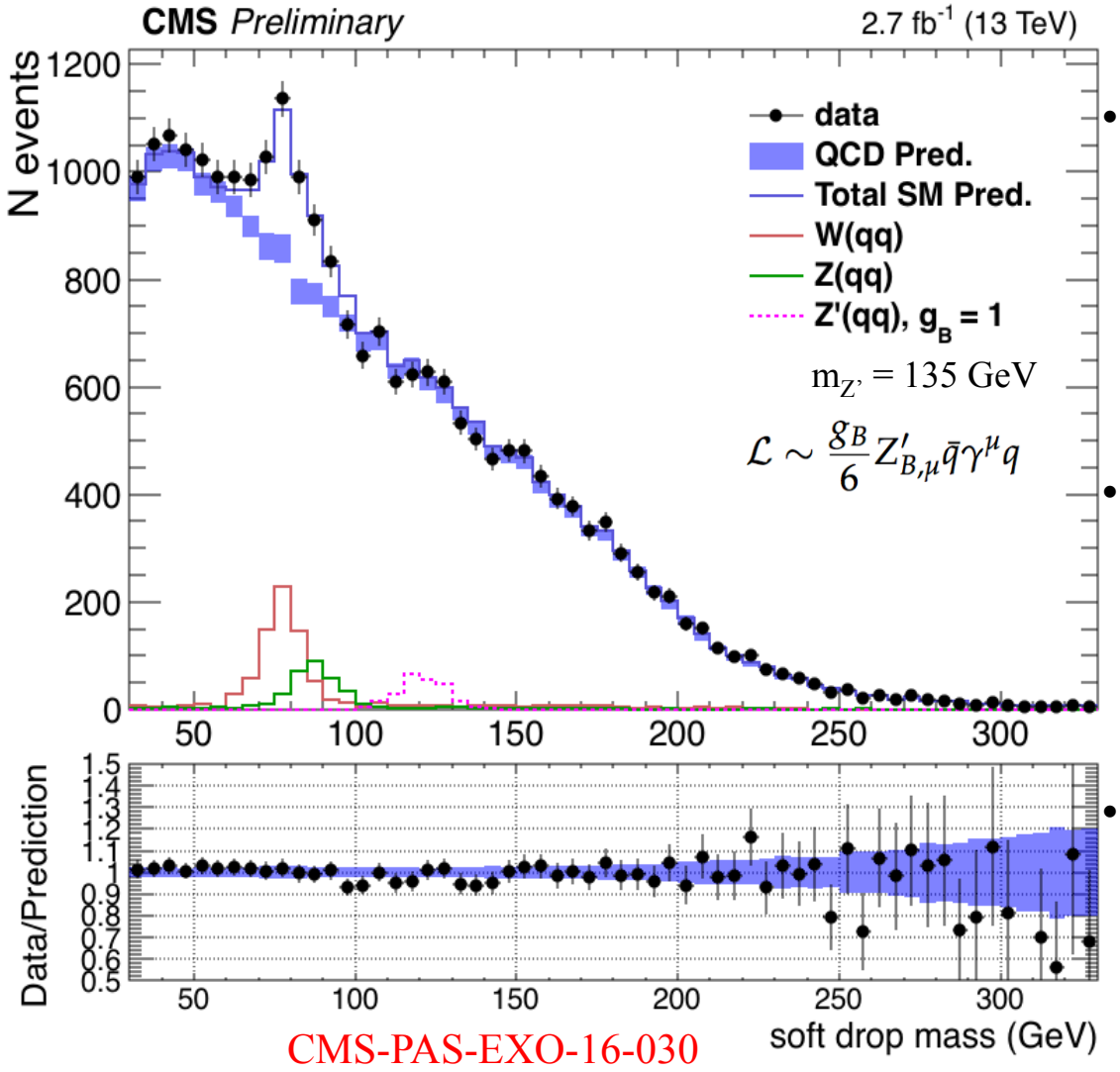
$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$

Search for Light Dijet Mass Resonances



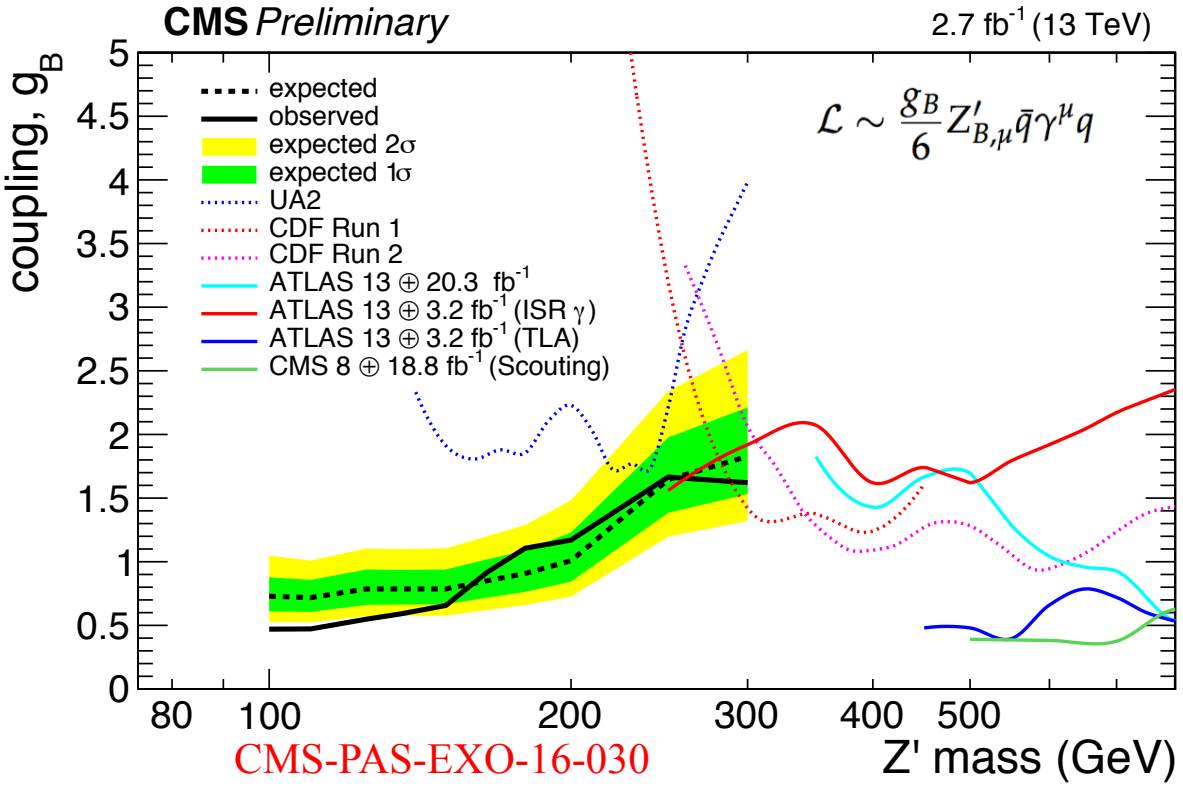
- Search for leptophobic Z' decay to dijets in range 100 GeV < m_{jj} < 300 GeV
  - Never probed at the LHC
- Require a high p_T jet produced in association with the Z'
  - Provide enough energy to exceed trigger threshold
- Require Z' to be reconstructed within a single fat jet
  - Reduce combinatorial backgrounds
  - Search for Z' in the jet mass distribution
  - AK8 jet p_T > 500 GeV
- Analysis presented corresponds to 2.7 fb^{-1} data

Results



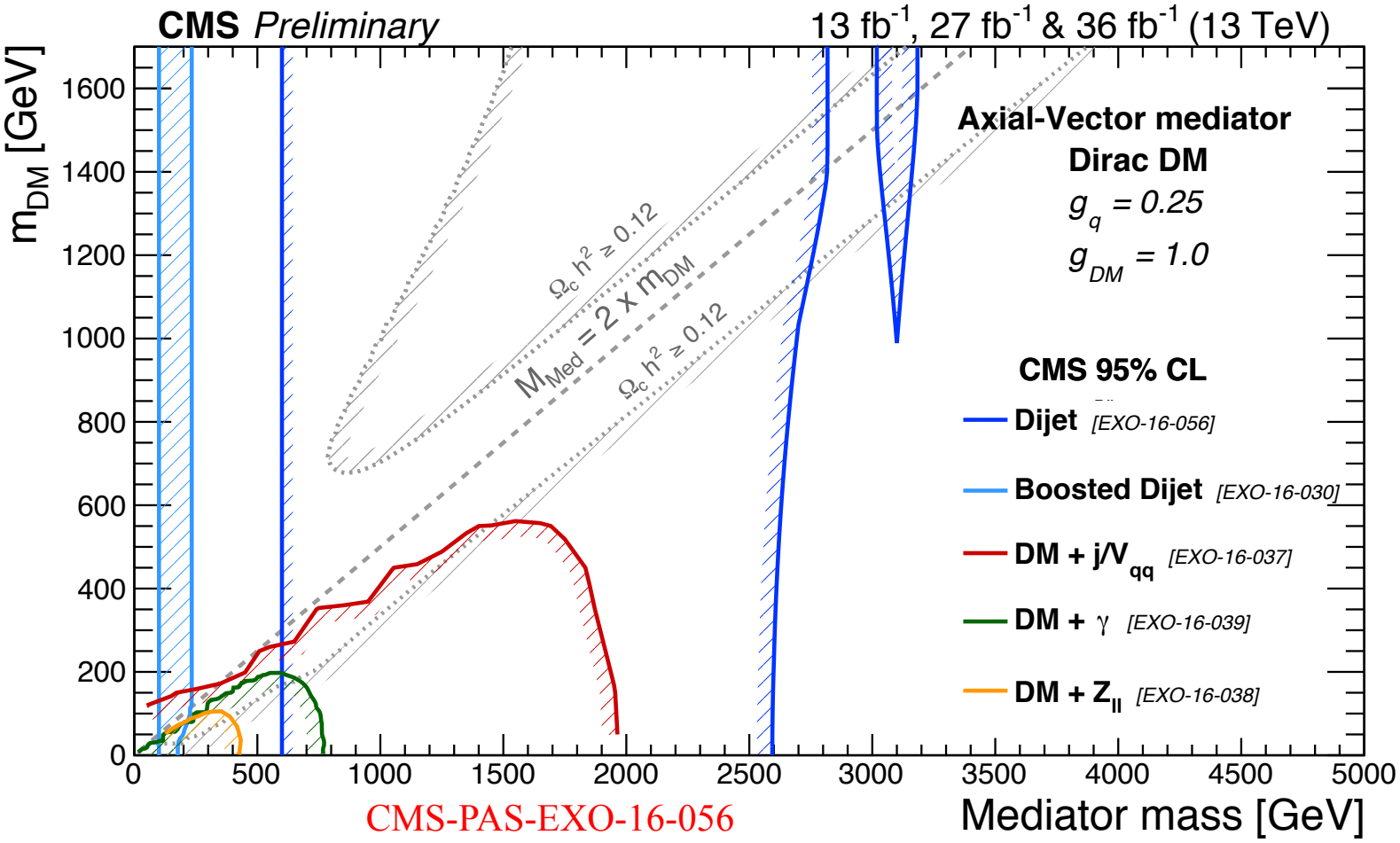
- Jet mass distribution in range 50–300 GeV
  - Use soft drop groomer to remove soft and wide angle radiations
- W and Z peaks are clearly visible in data
  - Use N-subjettiness ratio to tag 2-prung jet substructure
- No sign of narrow resonance found in range 100–300 GeV range

Limits on Z'-quark Coupling



- Limits extracted for the universal quark coupling g_B as a function of the mass of Z'
- Better sensitivity than UA2 and CDF dijet resonance searches
- Most stringent limit on Z'-quark coupling in $100 < M_{Z'} < 300$ GeV

Dark Matter Limits

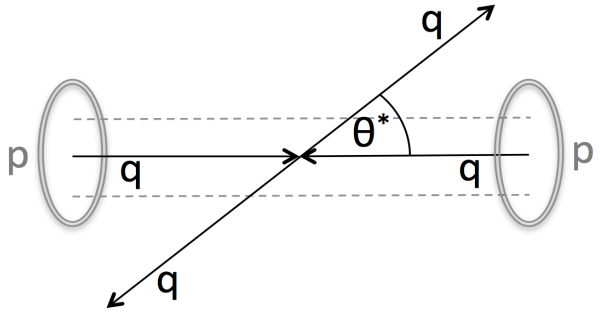


- Latest dark matter limits from dijet searches (and mono-X searches)

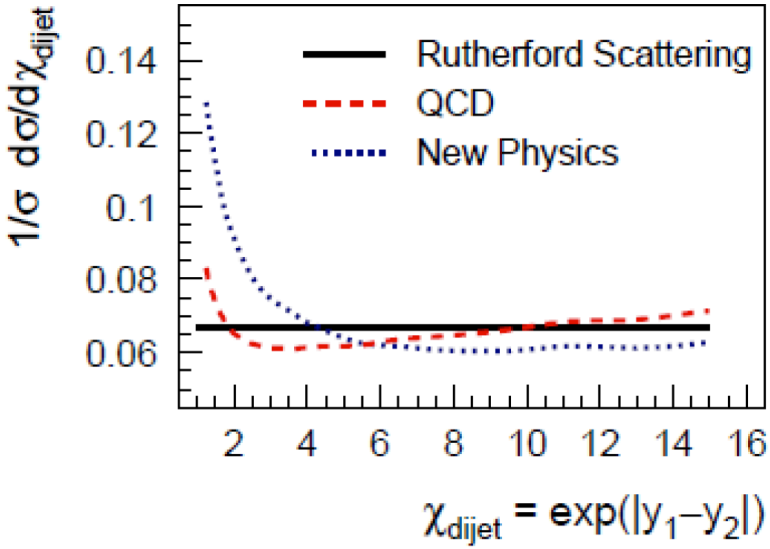
Search for New Physics with Dijet Angular Distributions

- Probe parton-parton scattering angle

$$\chi_{dijet} = e^{|y_1 - y_2|} \sim \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



- $d\sigma / d\chi_{dijets}$ is relatively flat for leading QCD processes ($qg \to qg, qq' \to qq', gg \to gg$)
  - Small sensitivity to PDF uncertainties
- Observable: $1/\sigma d\sigma / d\chi_{dijets}$
  - Measure normalized distribution in bins of dijet mass
  - Reduced sensitivity to detector effects
- New Physics will change the χ_{dijet} distribution at low χ_{dijet} at high M_{jj}
  - Contact Interactions
  - Virtual graviton exchange from ADD Model
  - Quantum Black Holes
- Analysis presented corresponds to 2.7 fb^{-1}



Data Analysis and Theory predictions

- Event Selection
  - Two PF AK4 jets with $p_T > 30$ GeV
  - Well understood calorimeter region: $y < |2.5|$

- Data distributions are unfolded to particle level

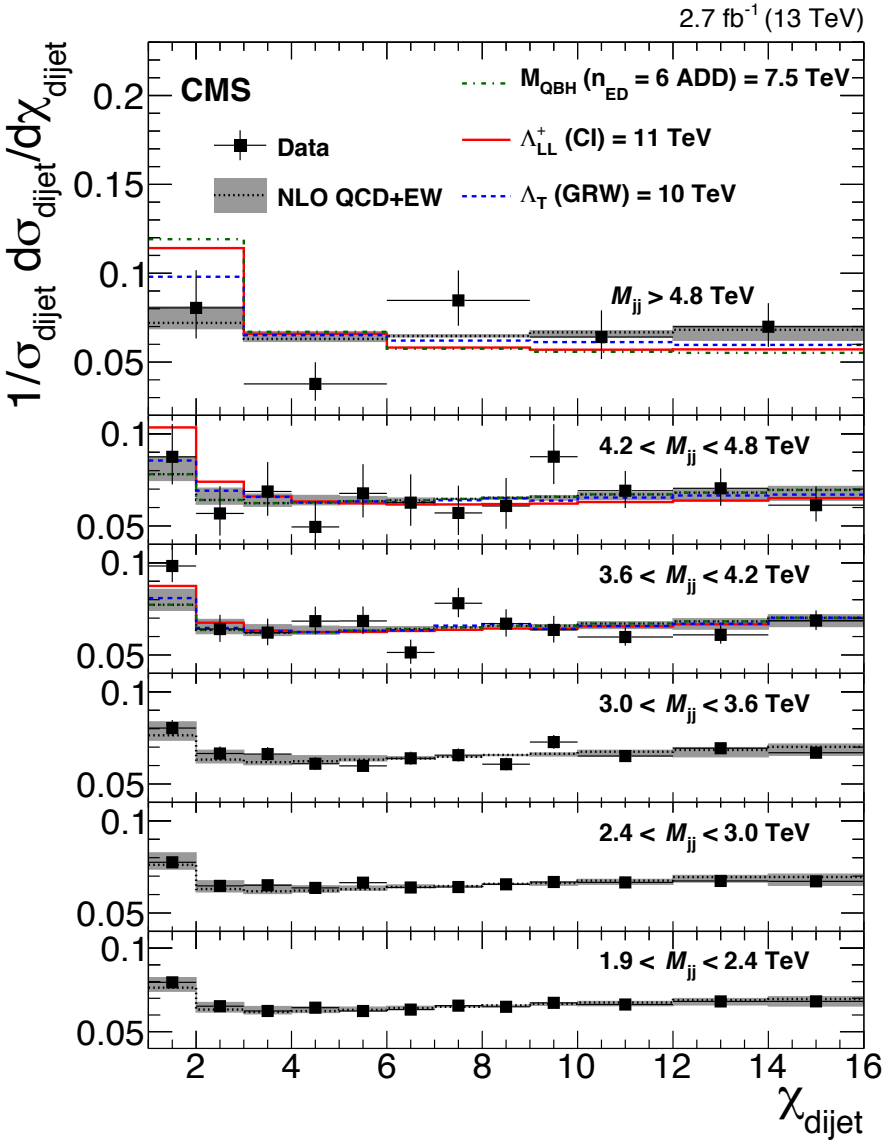
Λ	$(\eta_{LL}, \eta_{RR}, \eta_{RL})$
$\Lambda^{\pm}_{LL}$	$(\pm 1, 0, 0)$
$\Lambda^{\pm}_{RR}$	$(0, \pm 1, 0)$
$\Lambda^{\pm}_{VV}$	$(\pm 1, \pm 1, \pm 1)$
$\Lambda^{\pm}_{AA}$	$(\pm 1, \pm 1, \mp 1)$
$\Lambda^{\pm}_{(V-A)}$	$(0, 0, \pm 1)$

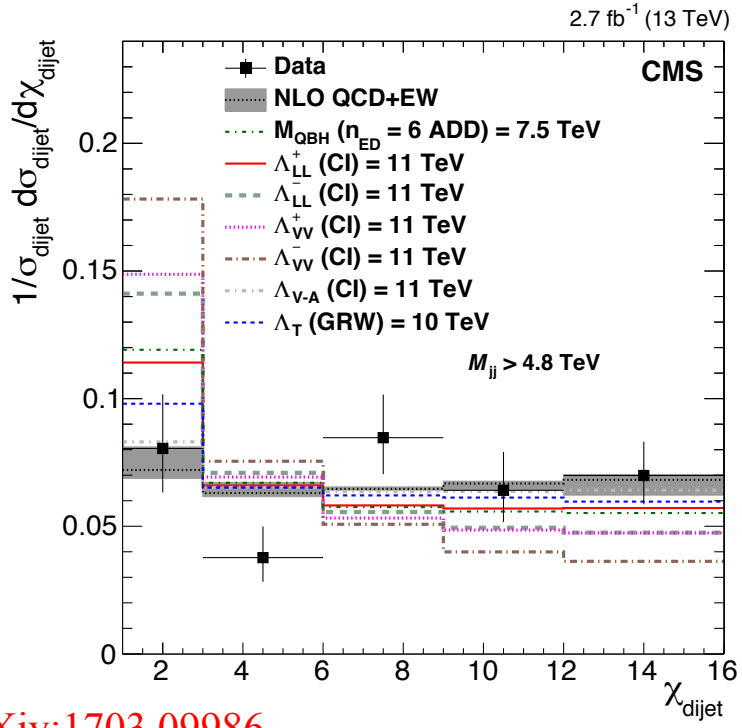
- Theoretical predictions
  - NLO QCD calculation using NLOJET++ 2.0.1
  - EWK correction is 5% in highest mass bin
  - CI + next to leading order CI and QCD interference predictions

$$\mathcal{L}_{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)\right]$$

  - Quantum black hole production predictions from QBH 3.0 and are corrected to NLO in QCD
  - ADD predictions from Pythia8 and are corrected to NLO in QCD

Results





arXiv:1703.09986

- Unfolded data in good agreement with QCD+EW theory prediction

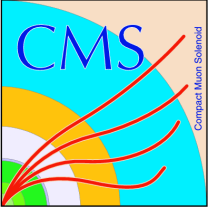
Limits on New Physics Models

Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{LL/RR}$ (NLO)	11.5	12.1±1.2
$\Lambda^{-}_{LL/RR}$ (NLO)	14.7	17.3±3.4
Λ^{+}_{VV} (NLO)	13.3	13.9±1.2
Λ^{-}_{VV} (NLO)	18.6	22.2±5.4
Λ^{+}_{AA} (NLO)	13.3	13.9±1.2
Λ^{-}_{AA} (NLO)	18.6	22.1±5.1
$\Lambda^{+}_{(V-A)}$ (NLO)	8.4	9.5±1.6
$\Lambda^{-}_{(V-A)}$ (NLO)	8.4	9.5±1.7
ADD Λ_T (GRW)	9.4	9.8±1.2
ADD M_S (HLZ) $n_{ED} = 2$	10.1	10.6±1.3
ADD M_S (HLZ) $n_{ED} = 3$	11.2	11.7±1.4
ADD M_S (HLZ) $n_{ED} = 4$	9.4	9.8±1.2
ADD M_S (HLZ) $n_{ED} = 5$	8.5	8.9±1.1
ADD M_S (HLZ) $n_{ED} = 6$	7.9	8.2±1.0
$n_{ED} = 6$ ADD QBH M_{QBH}	7.8	7.7±0.3
$n_{ED} = 1$ RS QBH M_{QBH}	5.3	5.3±0.4

- Most stringent limits on contact interaction with VV, AA, and V-A scenarios
- Most stringent limits on ADD models

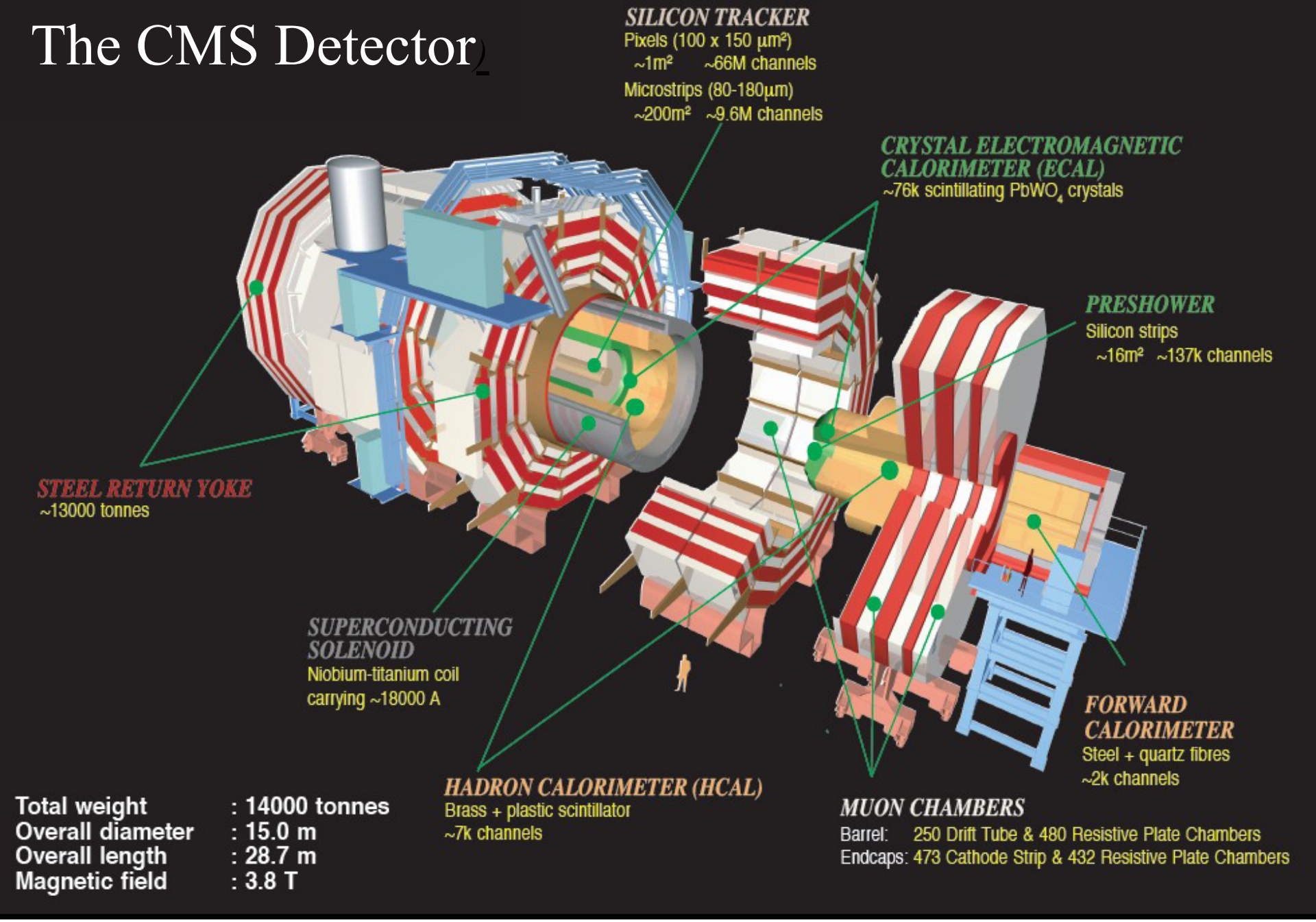
Summary

- Several new physics models are explored using dijet mass resonances and dijet angular distributions
  - Dijet mass distribution
    - **$0.5 < m_{jj} < 1.25$ TeV** for PF-jets
    - **$m_{jj} > 1.25$ TeV** for Calo-jets
    - Limits extracted for many new physics models including dark matter
    - CMS-PAS-EXO-16-056
  - Z' resonance using jet substructure
    - **$100 < m_{jj} < 300$ GeV**
    - Limits extracted for the Z'-quark coupling
    - CMS-PAS-EXO-16-030
  - Dijet angular distributions
    - Limits extracted for contact interactions, large extra dimensions, quantum black holes
    - arXiv:1703.09986 (submitted to JHEP)
- Results from low mass dijet resonance search and dijet angular analysis with full 2016 data are coming soon

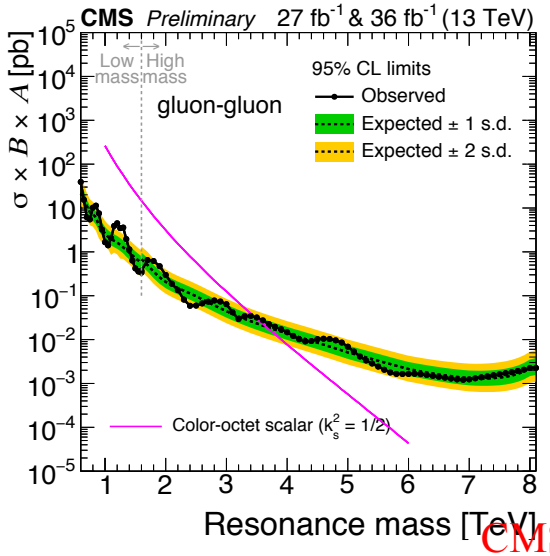


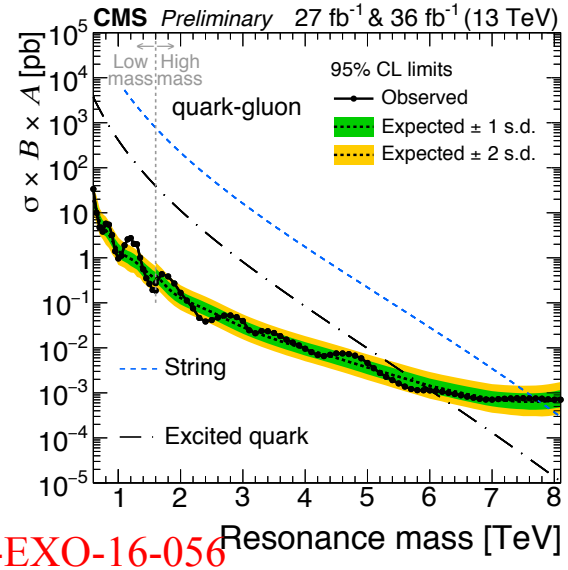
Back Up

The CMS Detector

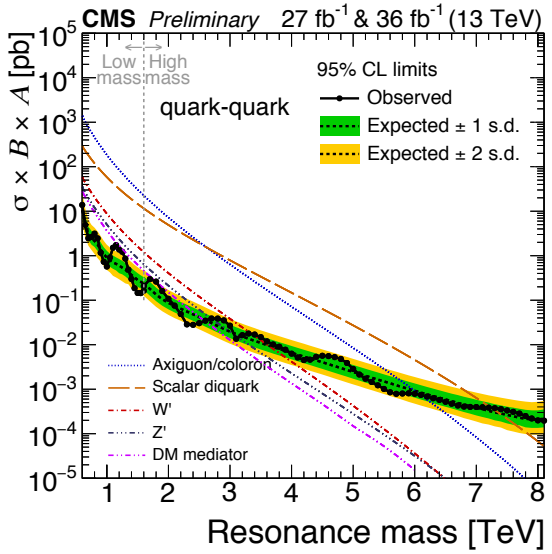


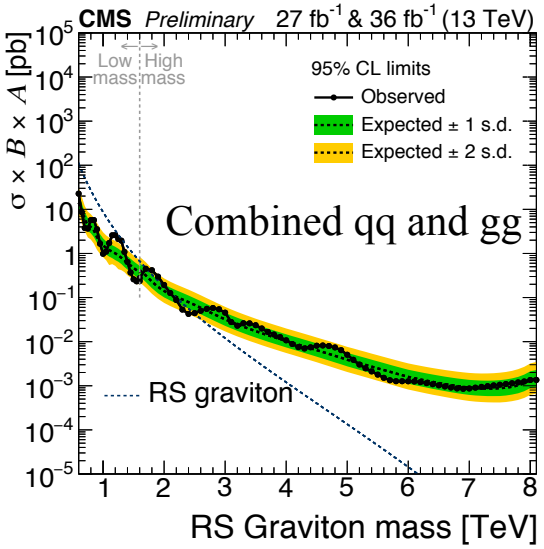
Model Independent Dijet Mass Resonance Limits





CMS-PAS-EXO-16-056





Dijet Angular Distribution measurement in Run1

4.2 TeV

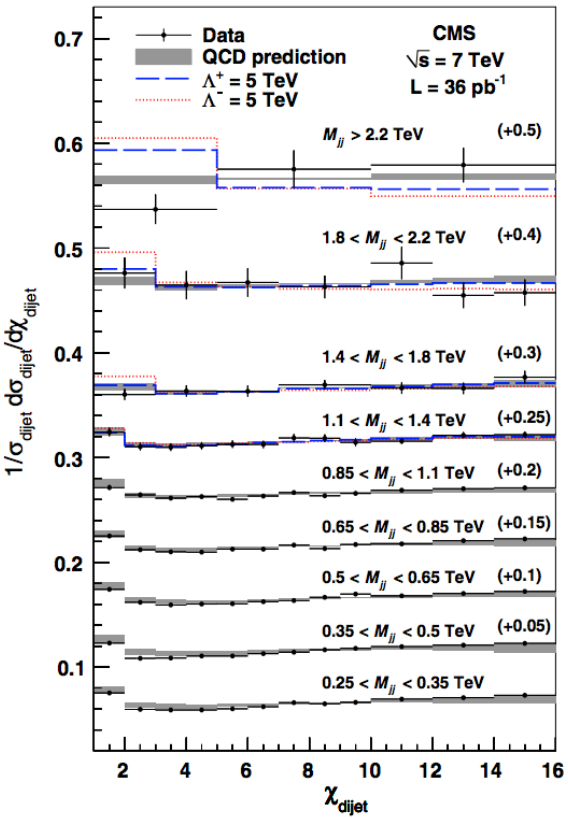
M_{jj}

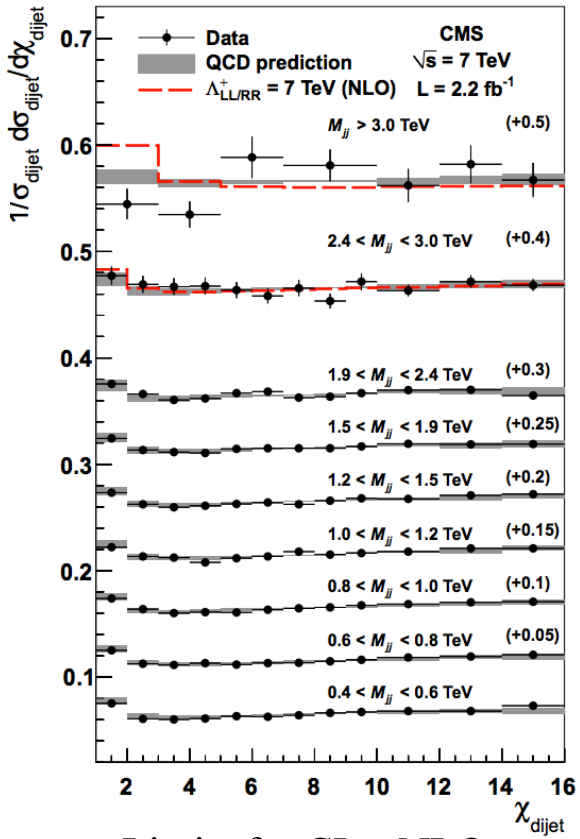
0.25 TeV

Limits on CI for at LO

PhysRevLett.106(2011)201804

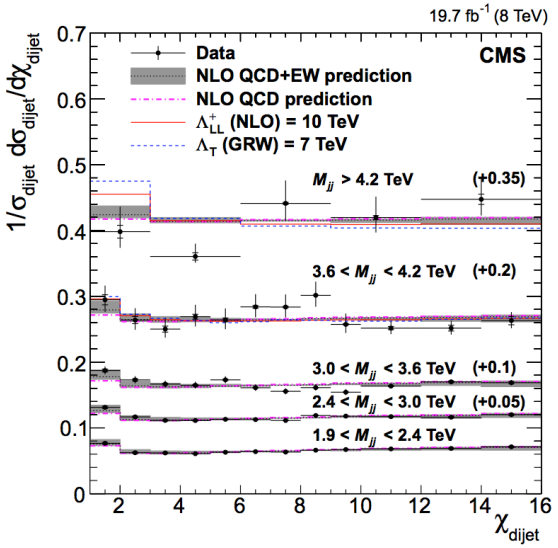
- Λ+: 5.6 TeV
- Λ-: 6.7 TeV





Limits for CI at NLO (JHEP05(2012)055)

- Λ+: 7.5 TeV
- Λ-: 10.5 TeV



Limits on CI at NLO and ADD

Phys.Lett.B746(2015)79

- Λ+: 9.0 TeV
- Λ- : 11.7 TeV
- ADD (GWR): 7.1 TeV
- ADD (HLZ): 5.0 TeV (n_{ED}=6)